SUSY AND EXOTICS SEARCHES @ LHC

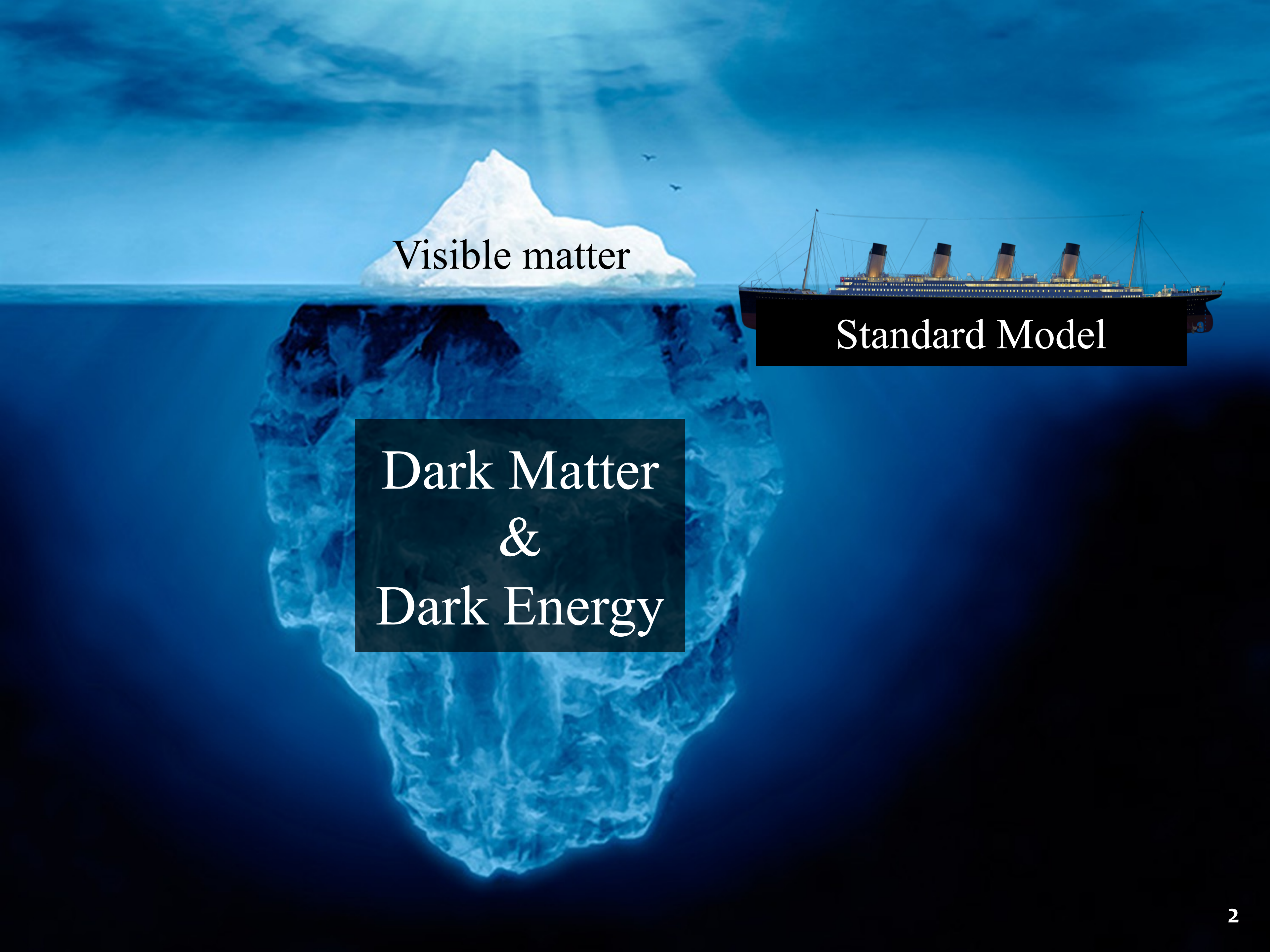
Xuai Zhuang (庄胥爱)

xuai.zhuang@cern.ch

IHEP, Beijing, China

Aug.9-17, Beijing, pre-SUSY2021

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences



Visible matter

Standard Model

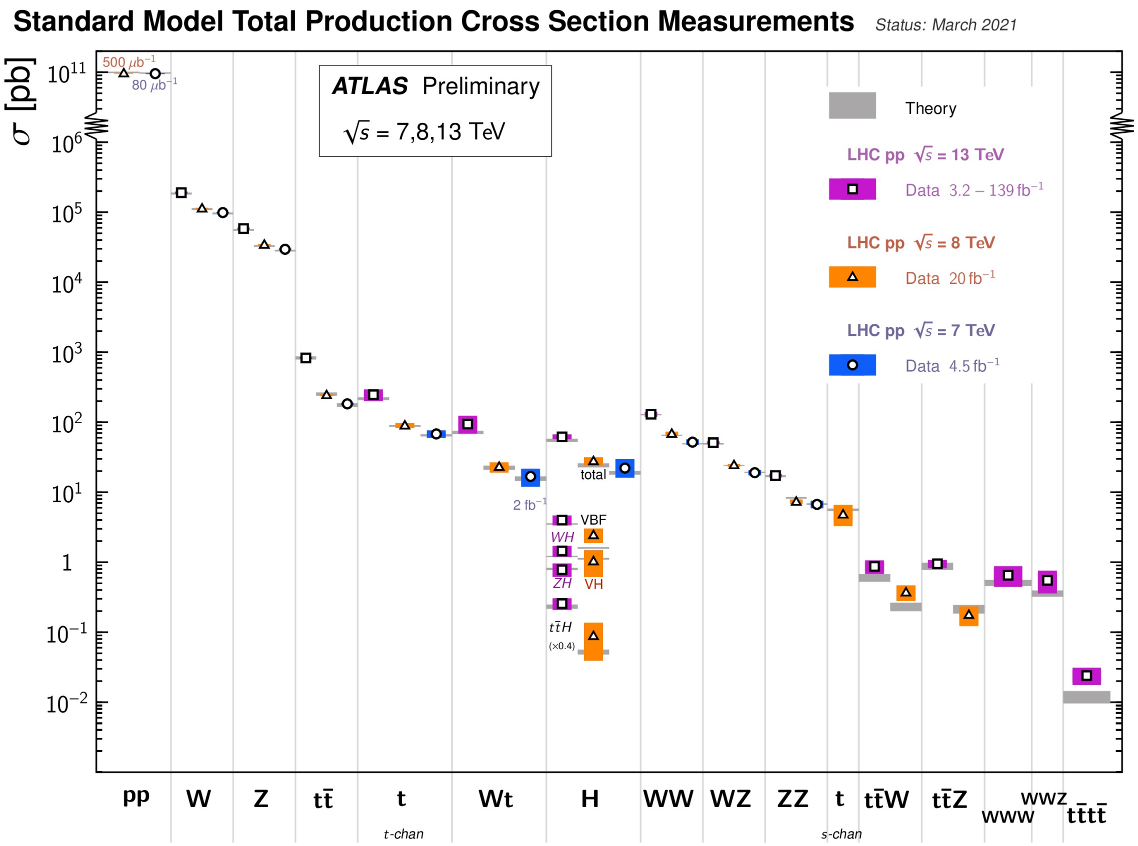
Dark Matter

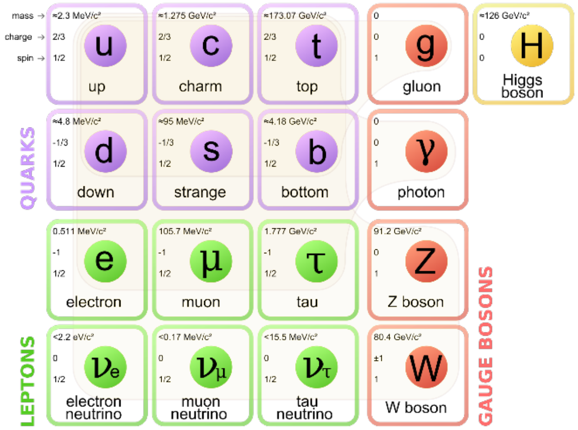
&

Dark Energy

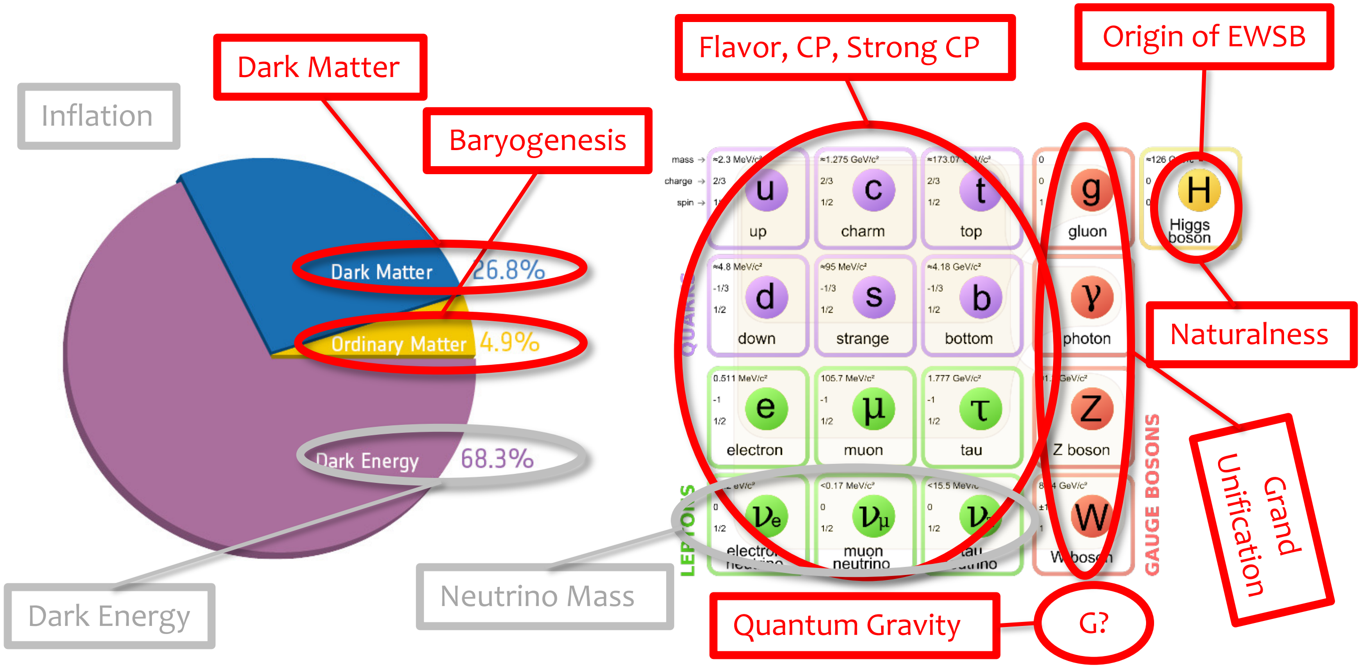
Introduction

- **SM fits the experimental data very well in EW scale.**
- **Discovery of Higgs boson makes SM self-consistent.**





- **Many big questions not answered by SM !**

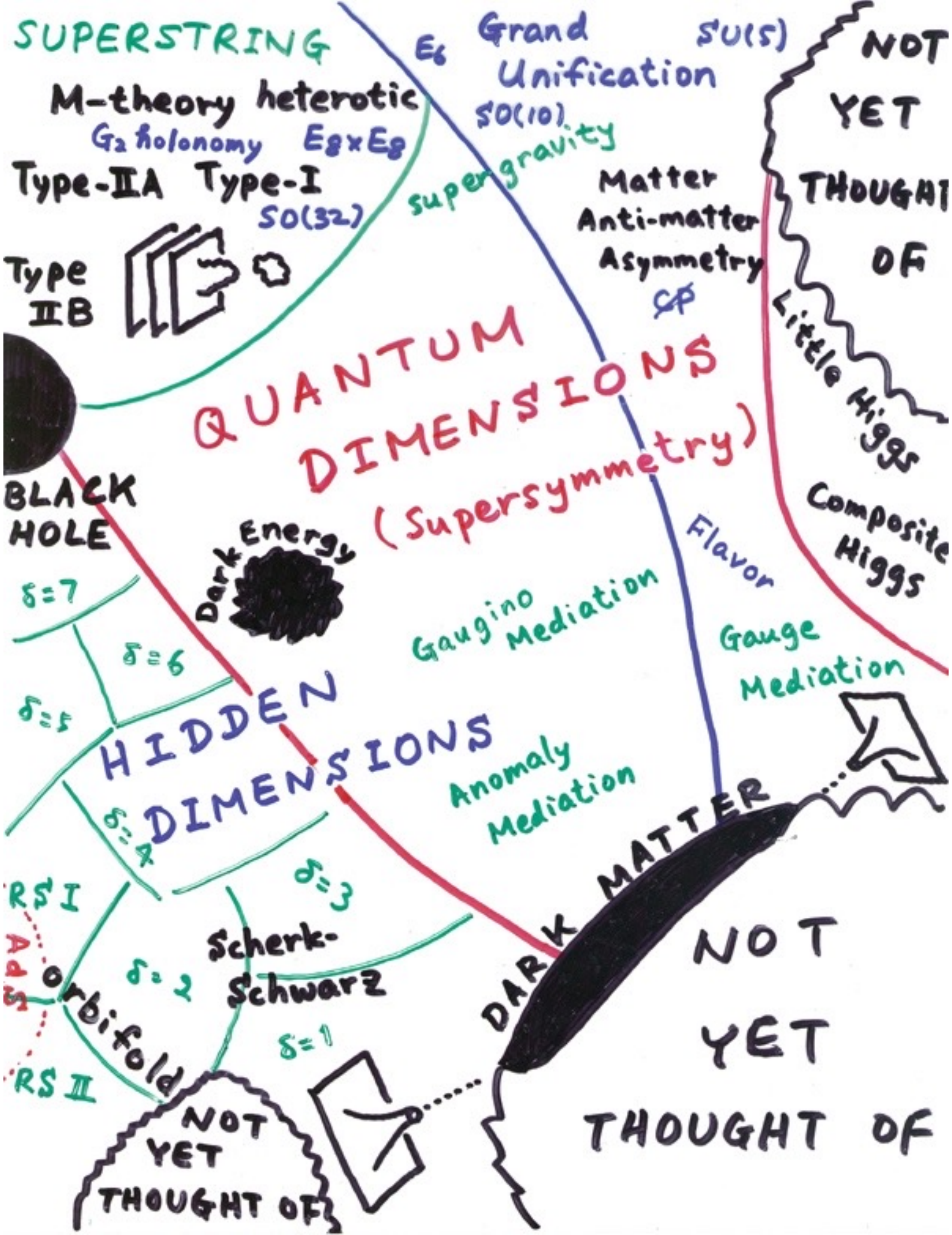


Exploration at energy frontier

Picture modified from Jonathan Feng at 2017 ICFA Seminar

- **Need a more fundamental theory in which SM is only a low-energy approximation ➔ New Physics.**

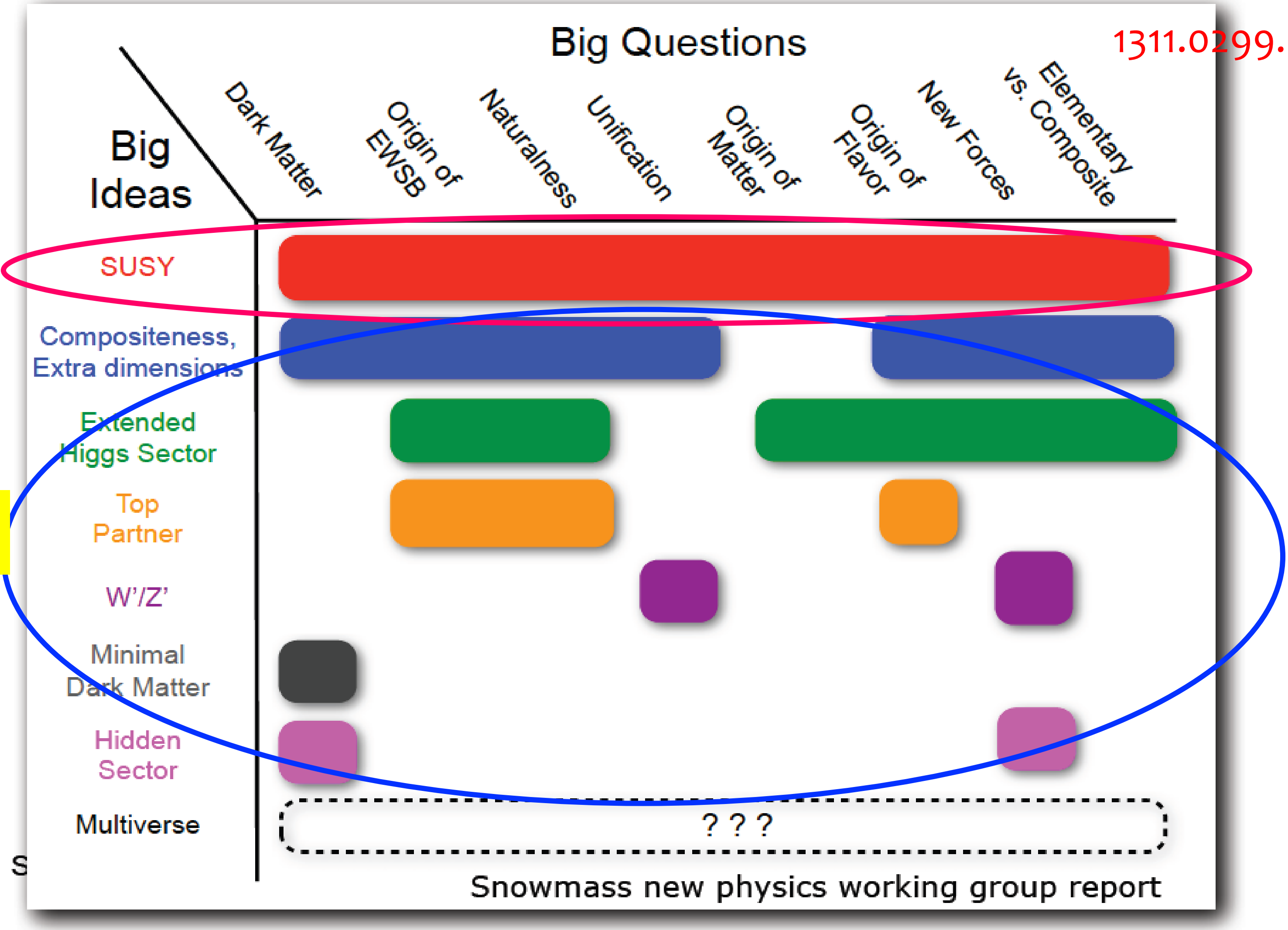
BSM ideas


SUPERSTRING
M-theory
heterotic
G₂ holonomy
E8×E8
Type-IIA
Type-I
SO(32)
Type IIB
BLACK HOLE
E6
Grand Unification
SU(5)
SO(10)
Supergravity
Matter Anti-matter Asymmetry
CP
NOT YET THOUGHT OF
Little Higgs
Composite Higgs
QUANTUM DIMENSIONS (Supersymmetry)
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
HIDDEN DIMENSIONS
Anomaly Mediation
DARK MATTER
RS I
AdS
orbifold
RS II
Scherk-Schwarz
NOT YET THOUGHT OF
NOT YET THOUGHT OF

New Physics beyond the SM

SUSY

exotics



1311.0299.pdf

Snowmass new physics working group report

S. S

Outline

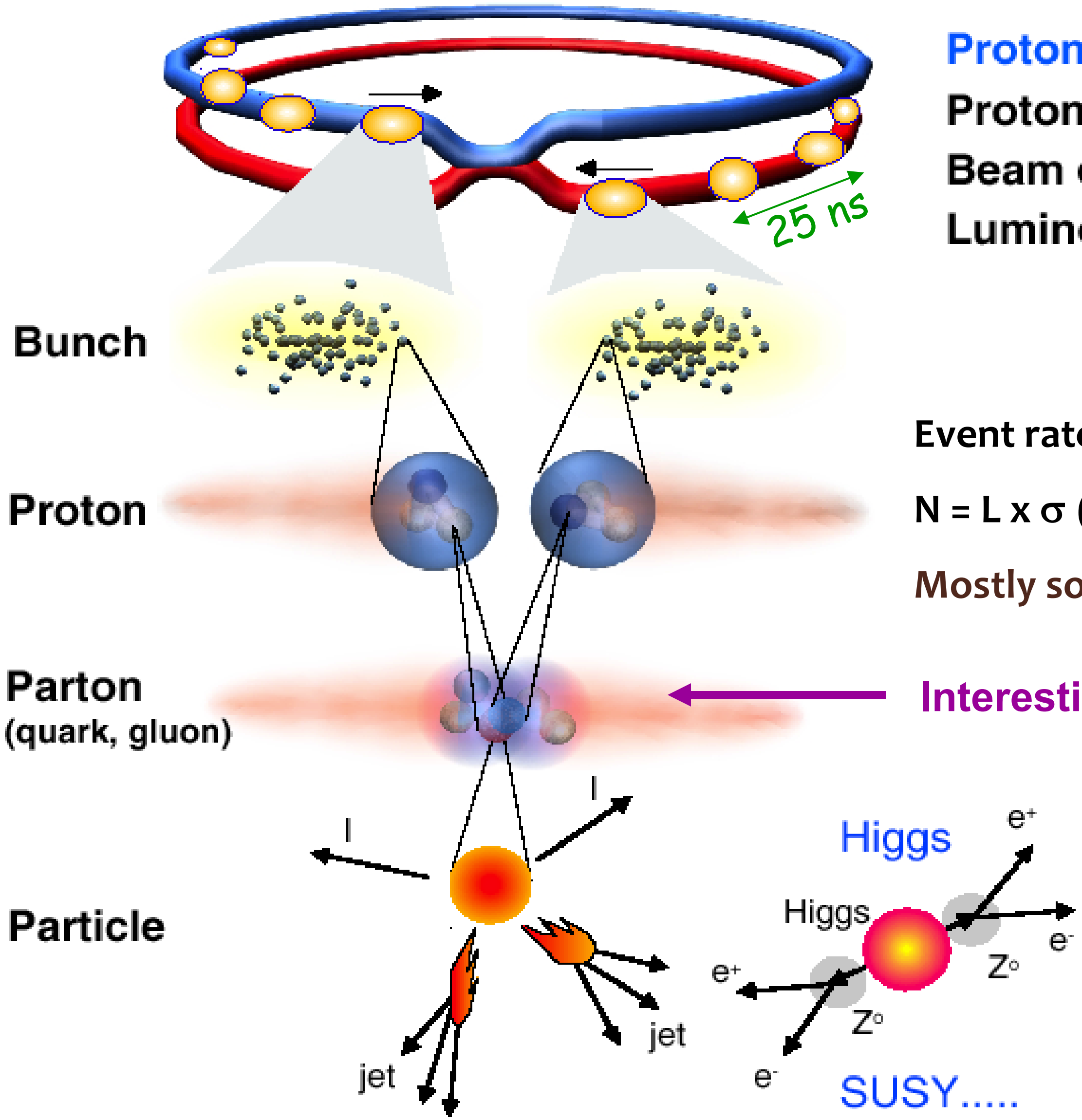
- LHC & ATLAS/CMS detectors
- BSM Searches @ LHC
- Prospects @ Future proton colliders
- Summary

LHC & ATLAS/CMS detectors

LHC 大型强子对撞机

- 周长 **27** 公里，隧道深**100**米，跨越瑞士法国国境
- 世界最大，能量最高的加速器，进行最前沿的粒子物理研究
- **质心系能量14TeV** (Tevatron的7倍)，可以发现**5TeV**以下的**较重的新粒子**
- **积分亮度10^{34} cm^{-2} s^{-1}** (Tevatron 的100倍)，可以发现微小衰变截面的**稀有事例**

Collisions at LHC



Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate:

$N = L \times \sigma(pp) \approx 10^9$ interactions/s

Mostly soft (low p_T) events

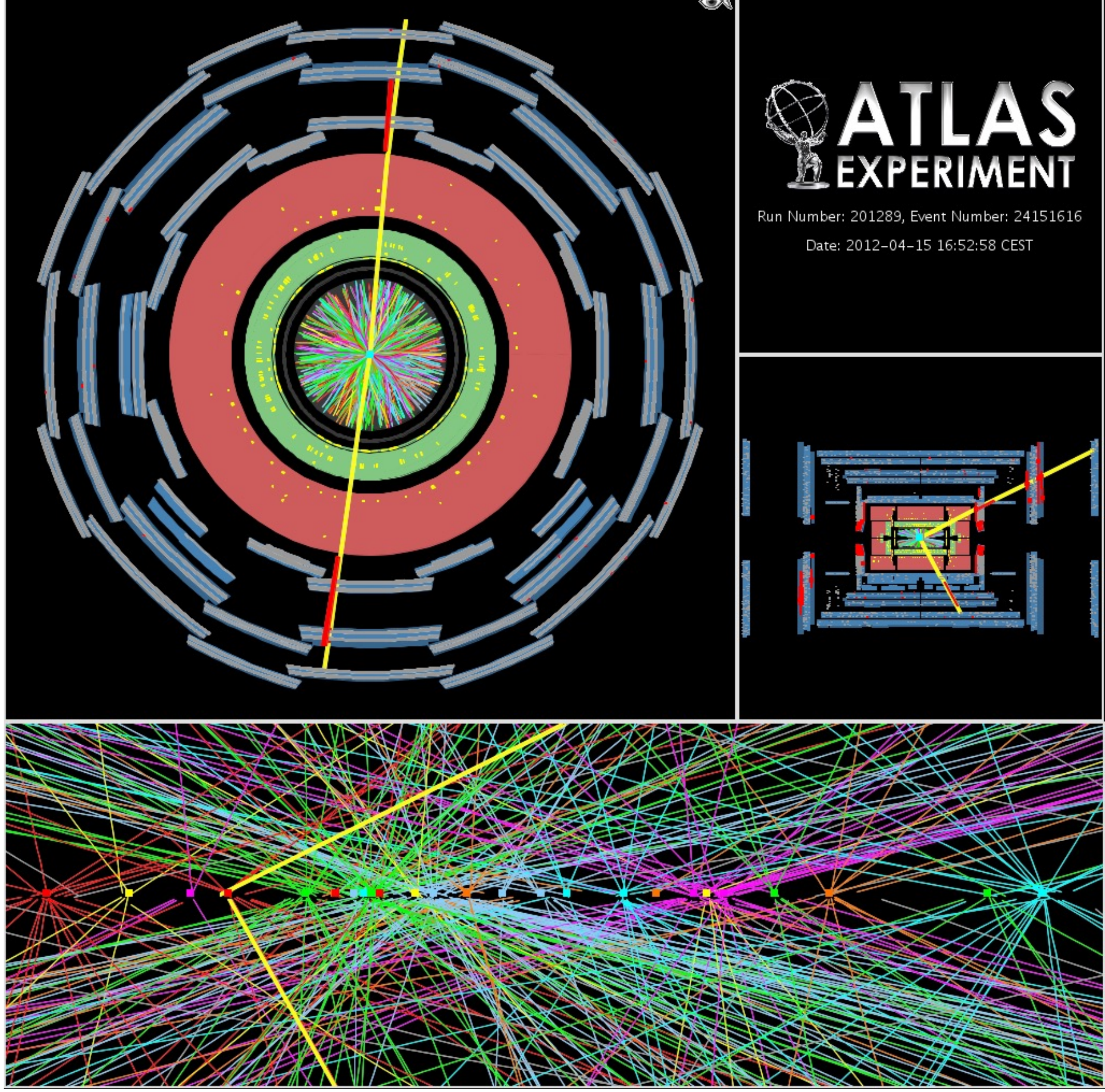
Interesting hard (high-p_T) events are rare

Selection of 1 in 10,000,000,000,000

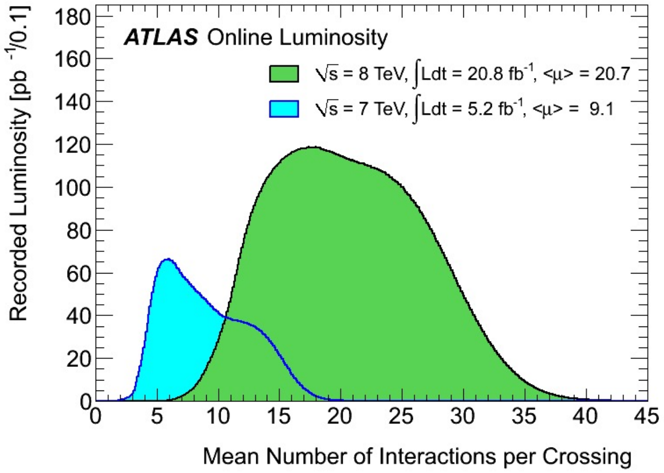
→ very powerful detectors needed

Excellent LHC performance is a (nice) challenge for the experiment:

- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**

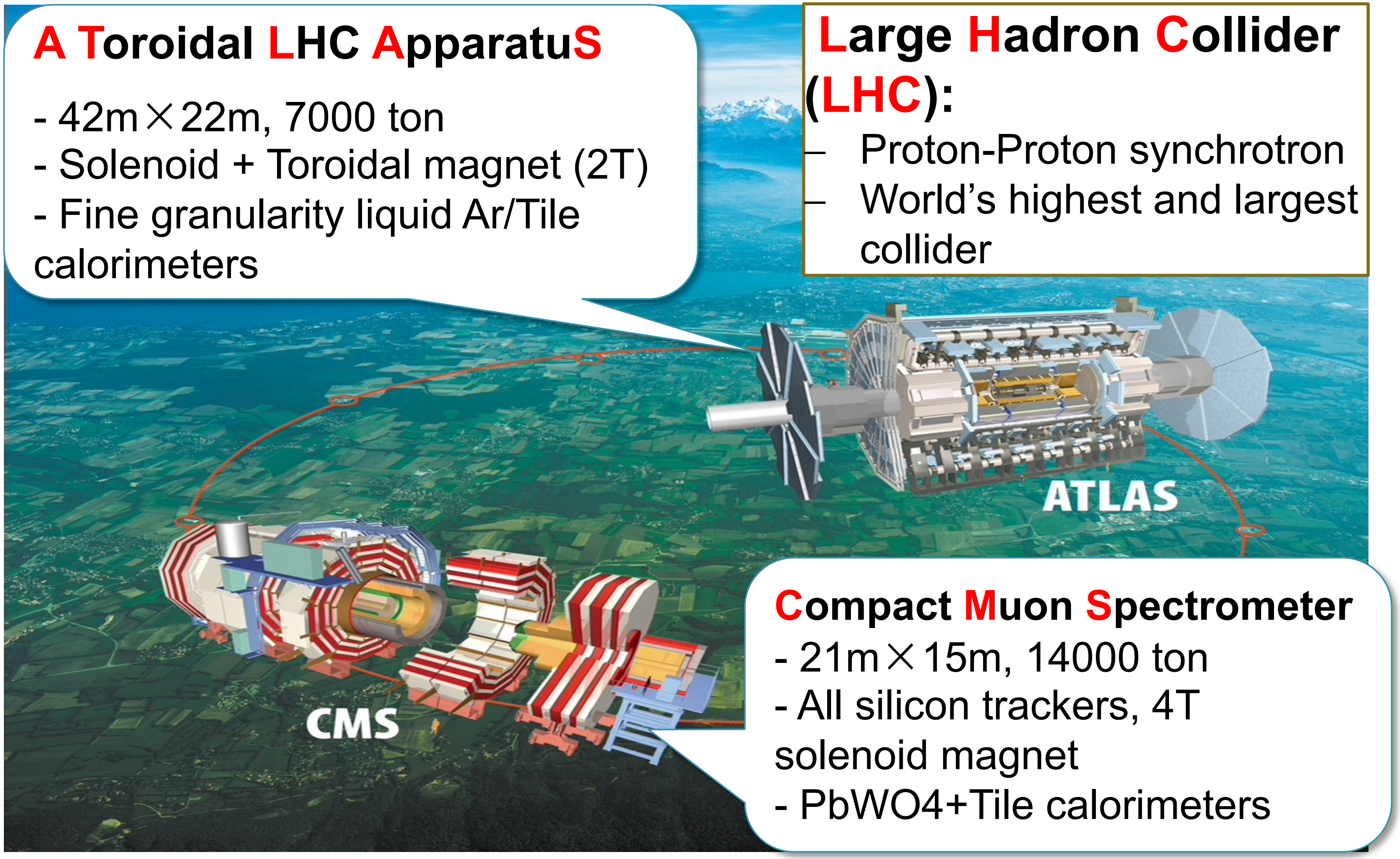


Inner Detector for a Z → μμ event with 25 primary vertices



ATLAS and CMS detector @ LHC

ATLAS and CMS: two multi-purpose detectors @LHC



A Toroidal LHC ApparatuS

- 42m×22m, 7000 ton
- Solenoid + Toroidal magnet (2T)
- Fine granularity liquid Ar/Tile calorimeters

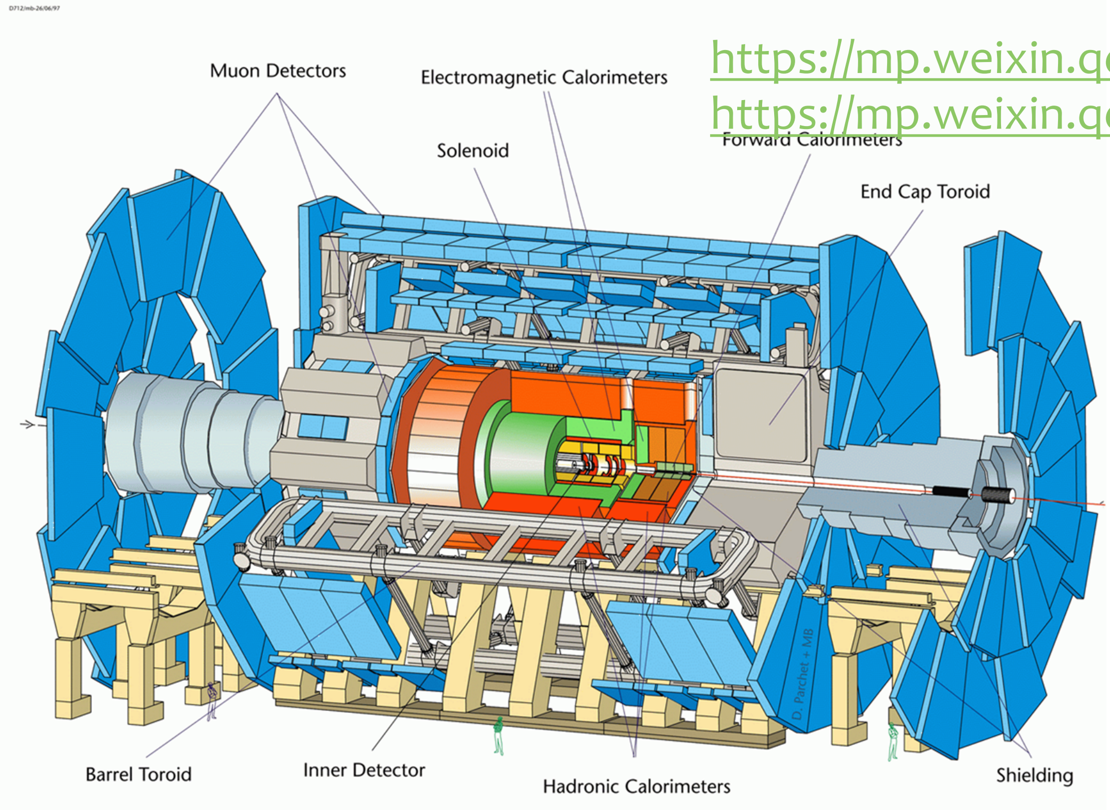
Large Hadron Collider (LHC):

- Proton-Proton synchrotron
- World’s highest and largest collider

Compact Muon Spectrometer

- 21m×15m, 14000 ton
- All silicon trackers, 4T solenoid magnet
- PbWO4+Tile calorimeters

https://mp.weixin.qq.com/s/_UtuSypTu1Dl1lnDuo6VTw
https://mp.weixin.qq.com/s/cJ6J3M-y36qNMicy7-jVQw

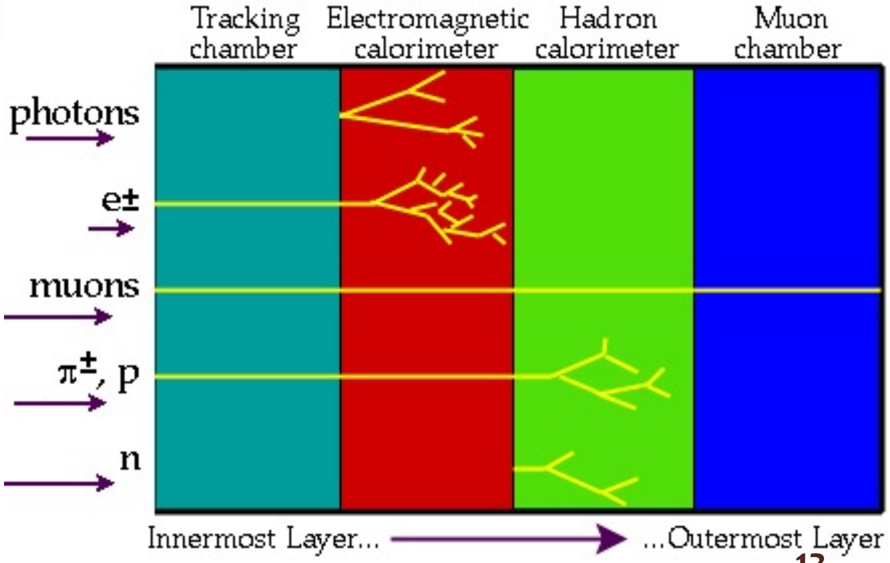


ATLAS

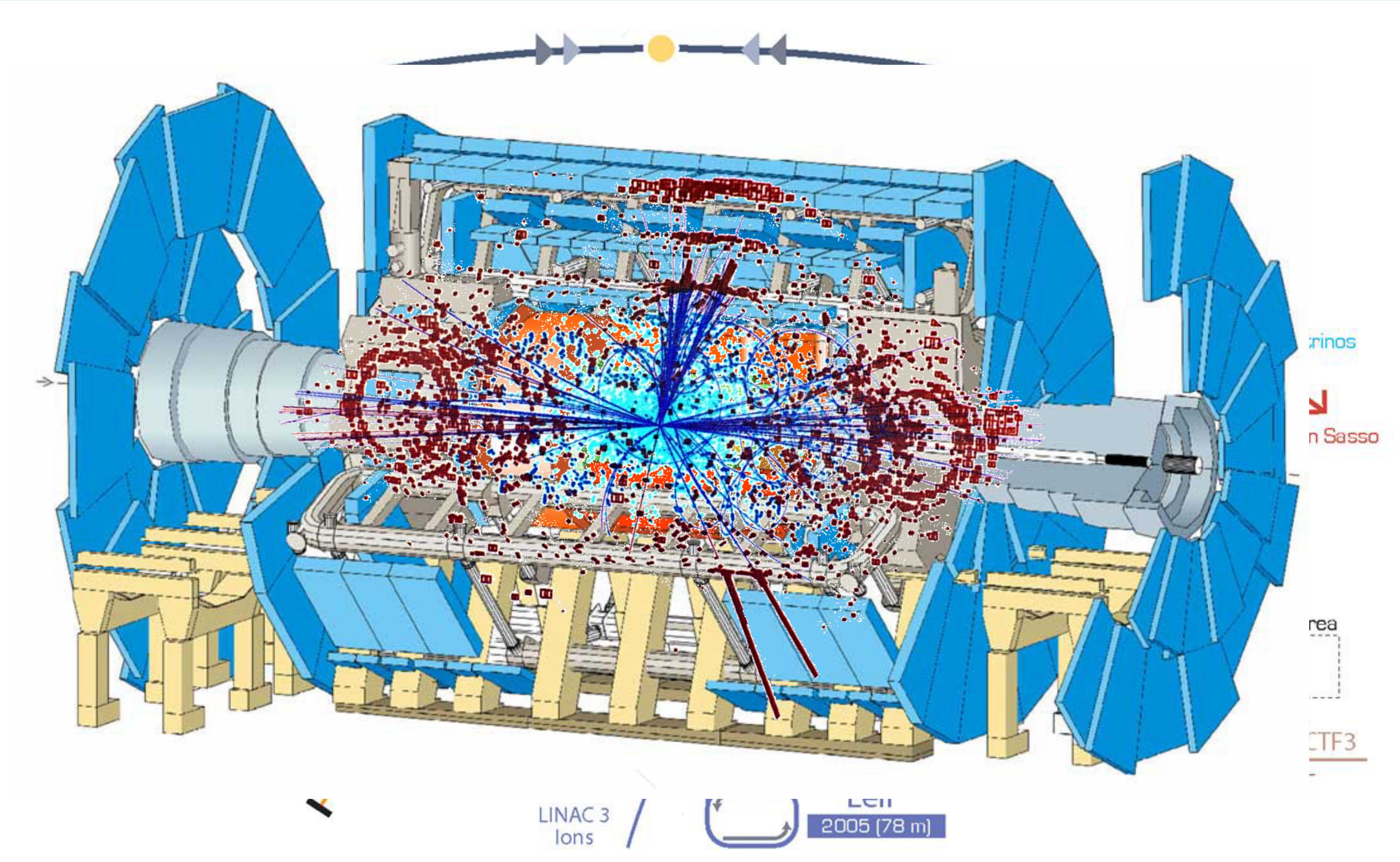
A Toroidal LHC ApparatuS

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 3000 km of cables

- **Tracking ($|\eta|<2.5$, B=2T) :**
  - **Si pixels and strips**
  - **Transition Radiation Detector (e/π separation)**
- **Calorimetry ($|\eta|<5$) :**
  - **EM : Pb-LAr**
  - **HAD: Fe/scintillator (central), Cu/W-LAr (fwd)**
- **Muon Spectrometer ($|\eta|<2.7$) :**
  - **air-core toroids with muon chambers**

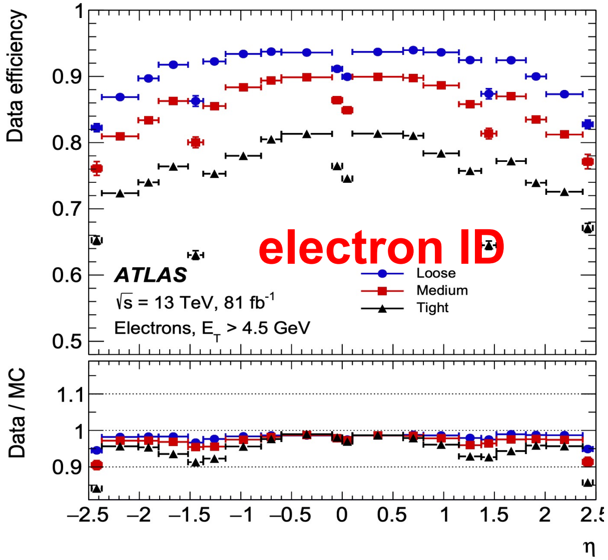


CERN’s particle accelerator chain

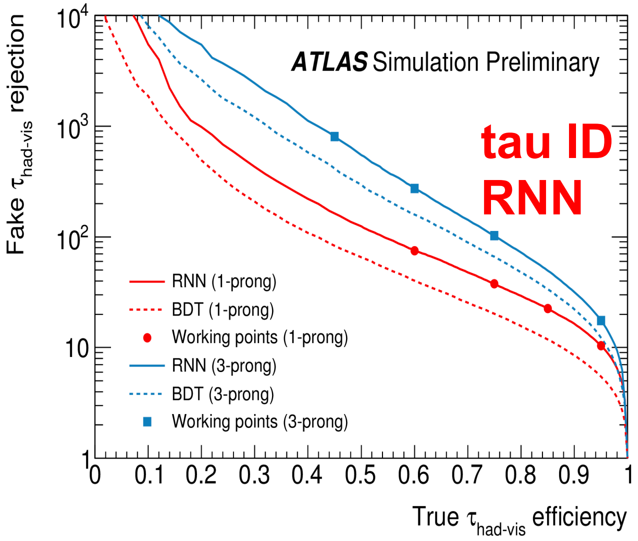


Detector performance Highlights

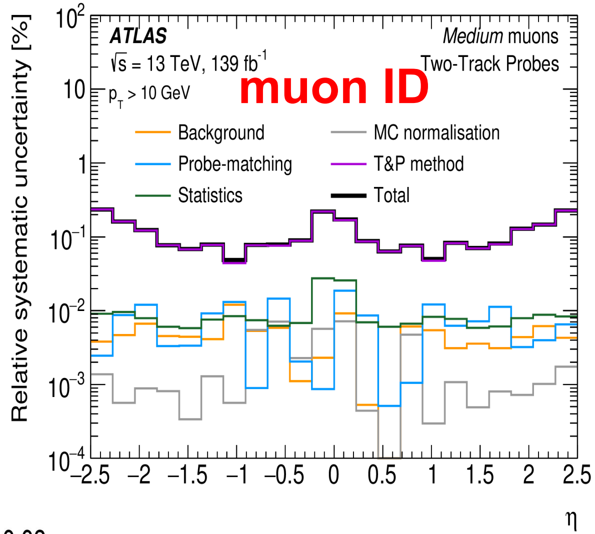
Bumper crop of results from Run 2 only possible thanks to excellent understanding of detector performance, and development of reconstruction and identification algorithms



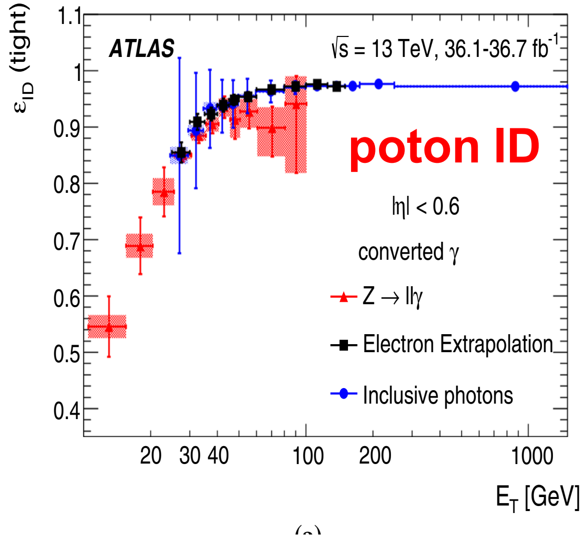
electron ID



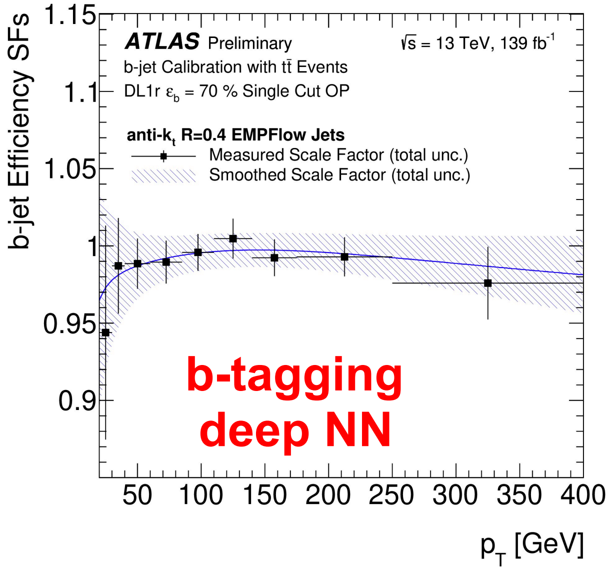
tau ID
RNN



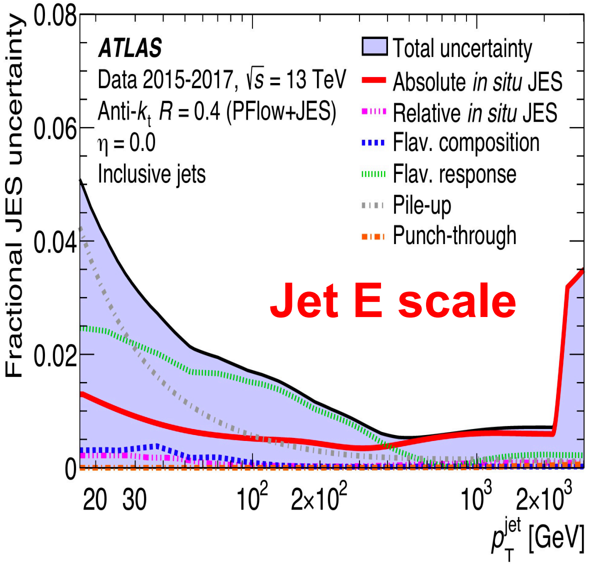
muon ID



poton ID



b-tagging
deep NN

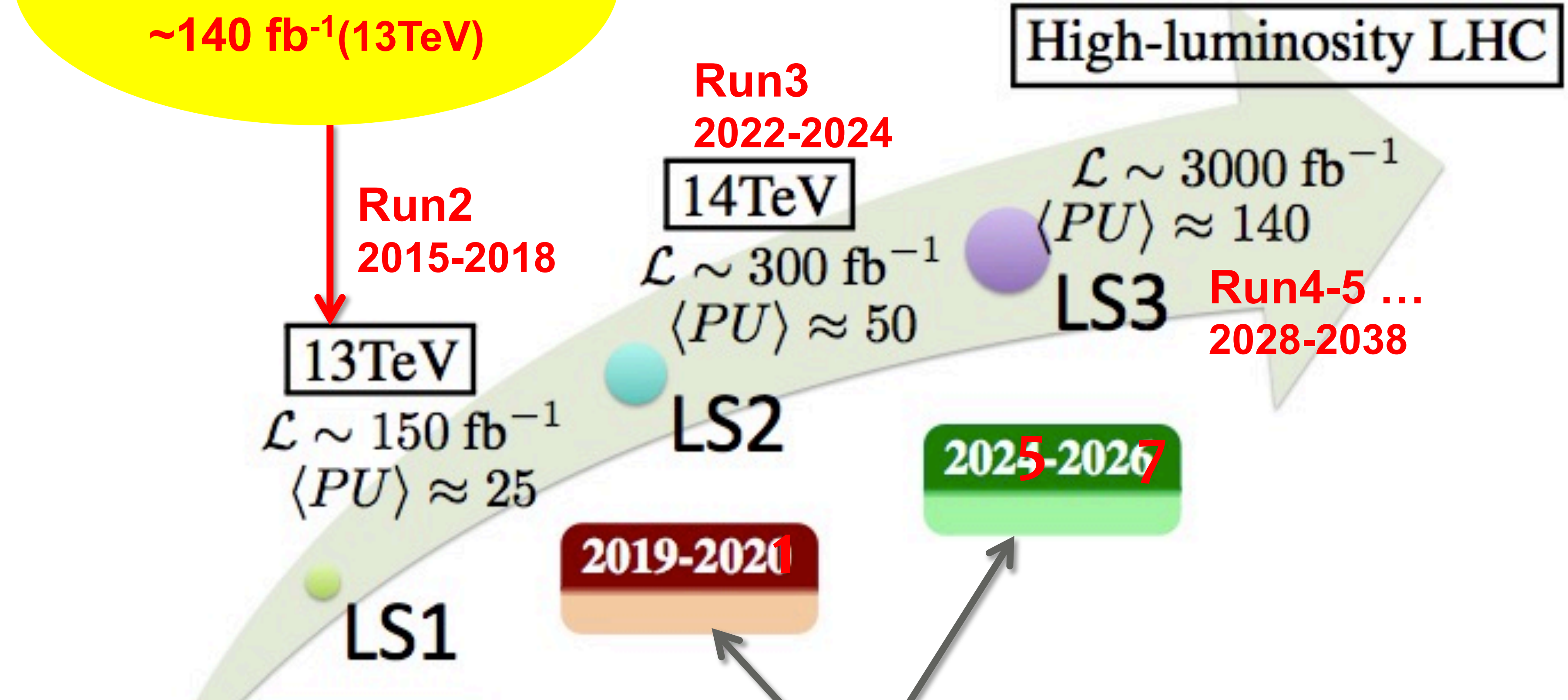


Jet E scale

BSM Searches @ LHC

The results are based on 36-140 fb^{-1} @ 13 TeV (RUN2 2015-2018) ~ 2-5% of total

We are here :
2015-2018:
~140 fb^{-1}(13TeV)



Run1

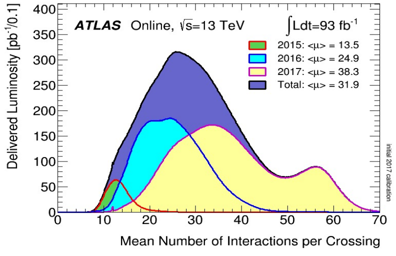
2010-2012
~25 fb^{-1}

Run2
2015-2018

Run3
2022-2024

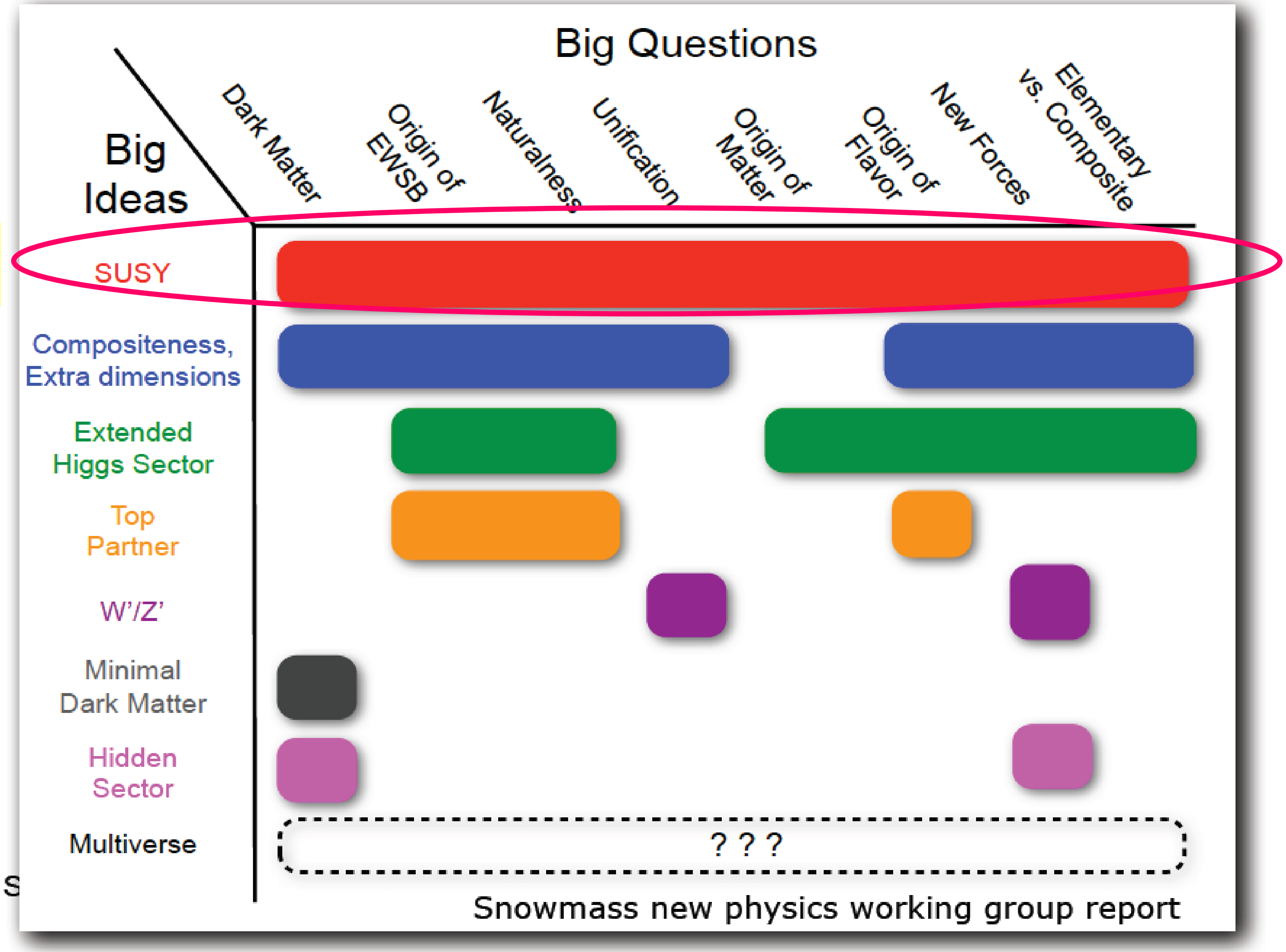
Run4-5 …
2028-2038

Long Stop



New Physics beyond the SM

SUSY

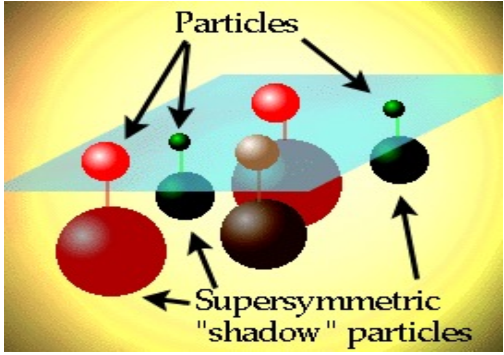


Snowmass new physics working group report

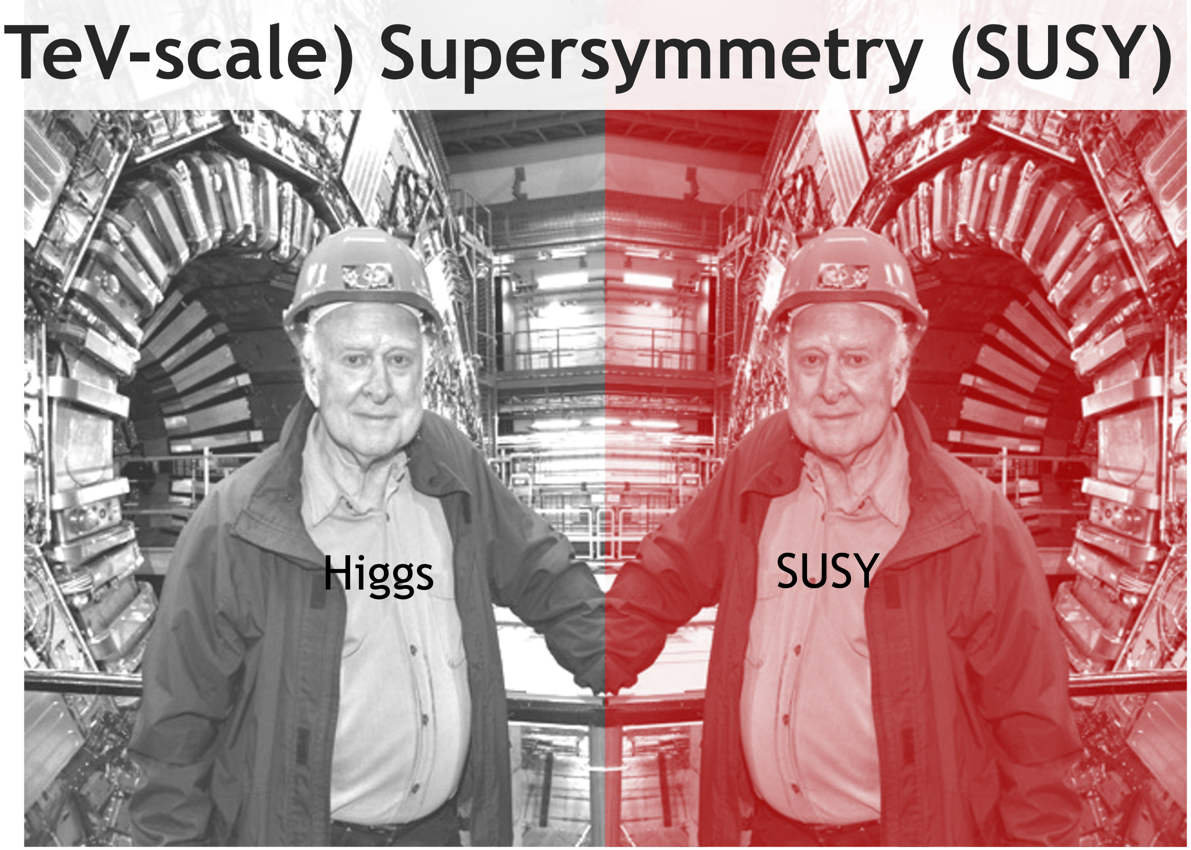
S. S

What is SUSY?

How SUSY do help?



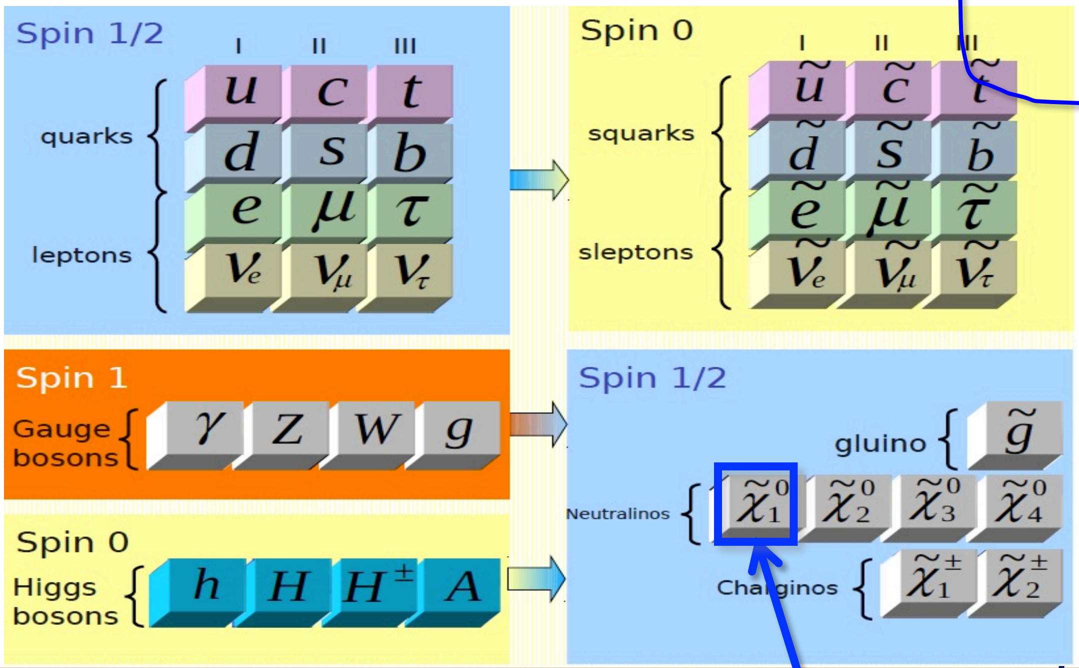
(TeV-scale) Supersymmetry (SUSY)

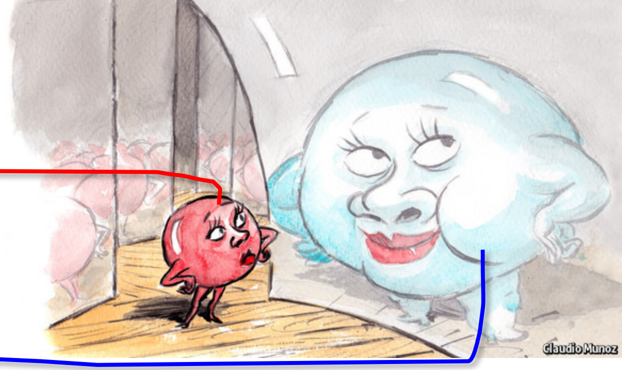


P. Higgs at CMS

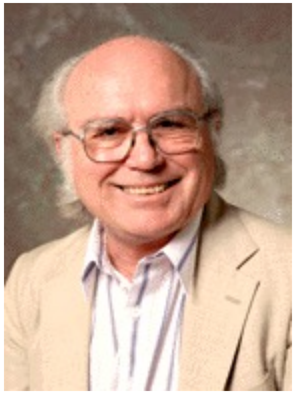
SUSY Introduction

OUR WORLD… **NEW WORLD?**





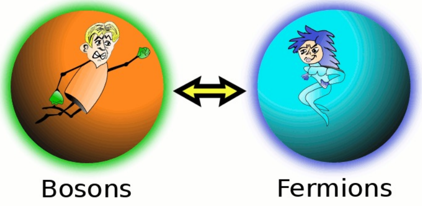
Julius Wess
(1934 – 2007)



Bruno Zumino
(1923 – 2014)

(Julius Wess and Bruno Zumino, 1974)

- Establishes a symmetry between fermions (matter) and bosons (forces)
- Motivation:
  - Unification (fermions-bosons, matter-forces)
  - Solves some deep problems of the SM
  - Provide Dark Matter candidate
  - ……



Q |boson> = |fermion>
Q |fermion> = |boson>

Spin differ by 1/2

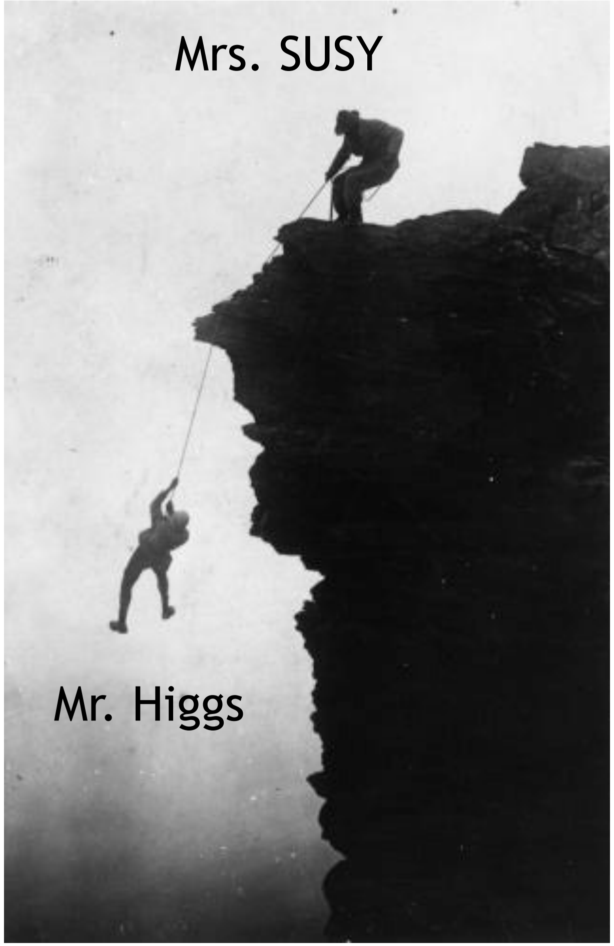
Minimal Supersymmetric Standard Model

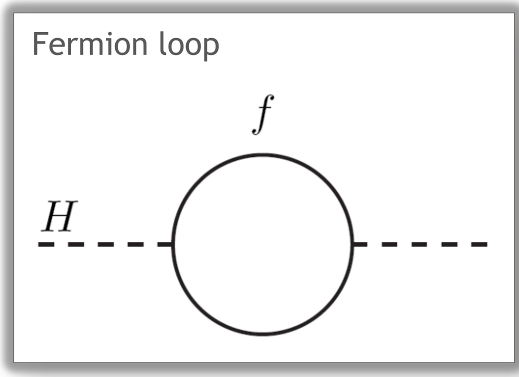
Standard Model Particles and Fields		Supersymmetric Partners			
		Interaction Eigenstates		Mass Eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = u, d, c, s, t, b$	quark	$\tilde{q}_L, \tilde{q}_R$	**squark**	$\tilde{q}_1, \tilde{q}_2$	**squark**
$l = e, \mu, \tau$	lepton	$\tilde{l}_R, \tilde{l}_L$	**slepton**	$\tilde{l}_1, \tilde{l}_2$	**slepton**
$l = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	**sneutrino**	$\tilde{\nu}$	**sneutrino**
g	gluon	$\tilde{g}$	**gluino**	$\tilde{g}$	**gluino**
$W^\pm$	W-boson	$\tilde{W}^\pm$	**wino**	$\tilde{\chi}^\pm_{1,2}$	**chargino**
H_u^+, H_d^-	charged Higgs boson	$\tilde{H}_u^+, \tilde{H}_d^-$	**charged higgsino**		
B	B-field	$\tilde{B}$	**bino**	$\tilde{\chi}^0_{1,2,3,4}$	**neutralino**
W^0	W^0-field	$\tilde{W}^0$	**wino**		
H_u^0, H_d^0	neutral Higgs boson	$\tilde{H}_u^0, \tilde{H}_d^0$	**neutral higgsino**		

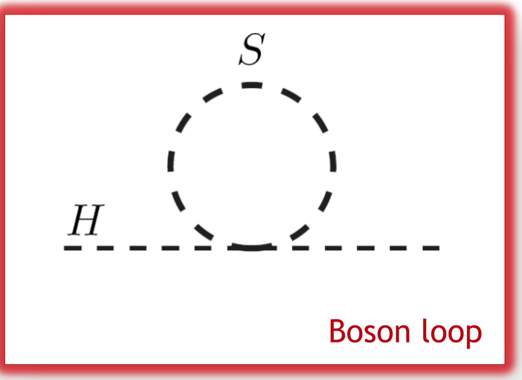
SUSY Introduction

☐ **Solve hierarchy problem** without "fine tuning"

  - Fermion and boson loops contribute with **different signs** to the Higgs radiative corrections
  - Supersymmetric partner contributions to Higgs mass **cancel** SM contributions



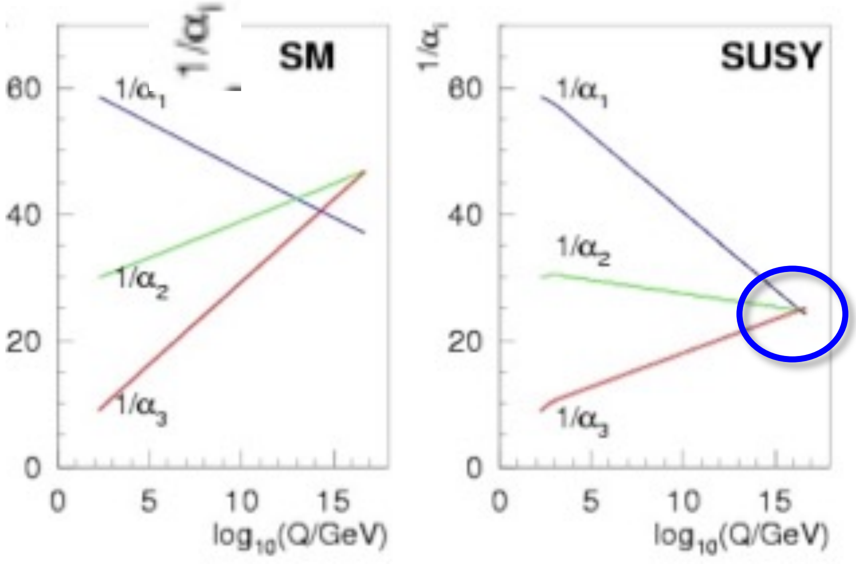


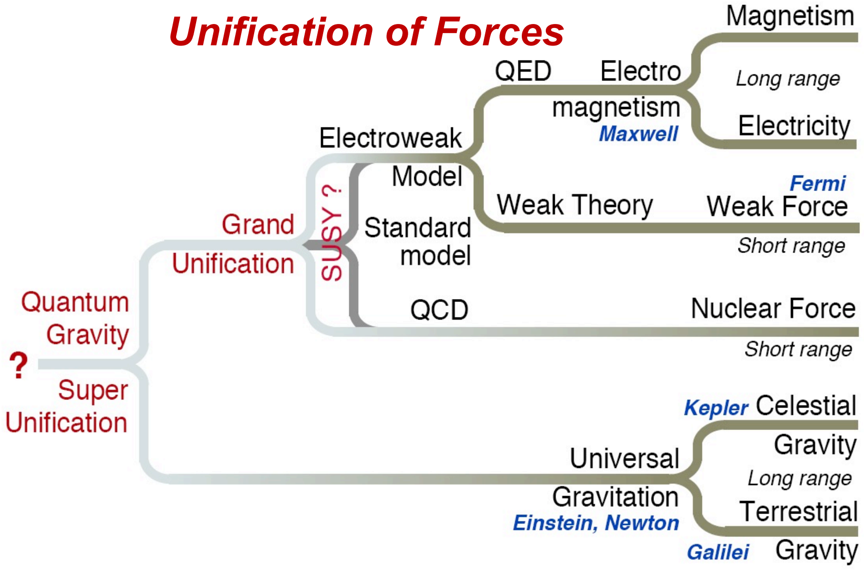


$$M_h^2 = M_{h,tree}^2 + \Delta M_h; \qquad SM : \Delta M_h \sim \Lambda^2; \qquad SUSY : \Delta M_h \sim m_{soft}^2 \log(\Lambda / m_{soft})$$

SUSY Introduction

- ☐ **Unification of gauge couplings**
  - New particle content changes running of couplings
  - Requires SUSY masses below few TeV

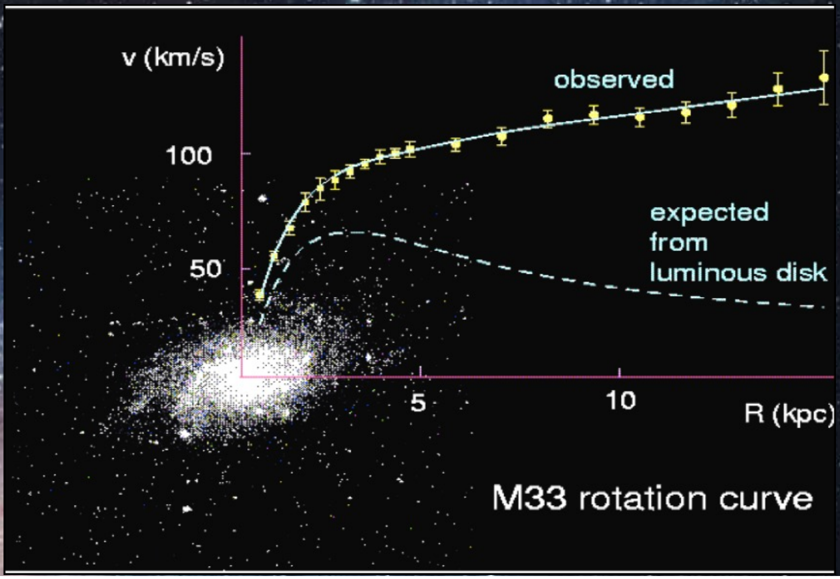



Unification of Forces

Magnetism
Long range
Electricity
Electro magnetism
Maxwell
QED
Electroweak
Model
Standard model
Weak Theory
Fermi
Weak Force
Short range
SUSY ?
Grand Unification
QCD
Nuclear Force
Short range
Quantum Gravity
?
Super Unification
Kepler Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei

Provide Dark Matter candidate

天文学家发现宇宙中很大一部分是我们看不见的 暗物质 （明物质只占4.6%）



M33 rotation curve

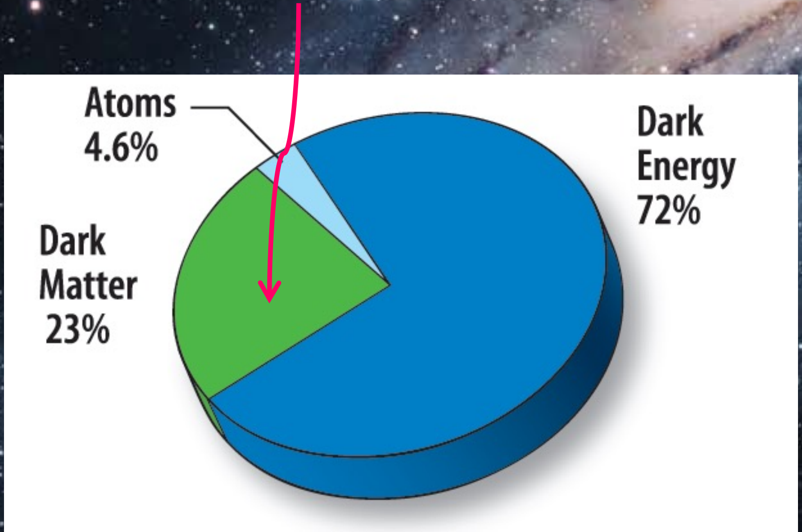
Provide perfect dark mater candidate - WIMP(lightest neutralino in R-parity conserving models)

- ☐ stable
- ☐ electrically neutron
- ☐ same density as DM

$0.094 < \Omega_{CDM}h^2 < 0.136$ **(95% CL)**

→ 通过寻找SUSY，可以为暗物质寻找提供实验证据！

‘Supersymmetric’ particles ?



How to hunt SUSY?

(TeV-scale) Supersymmetry (SUSY)

P. Higgs at CMS

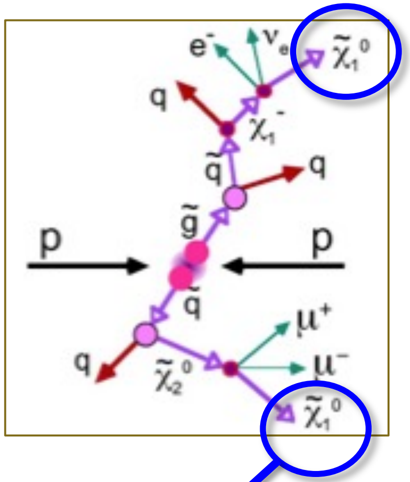
How do we start? - SUSY Signature

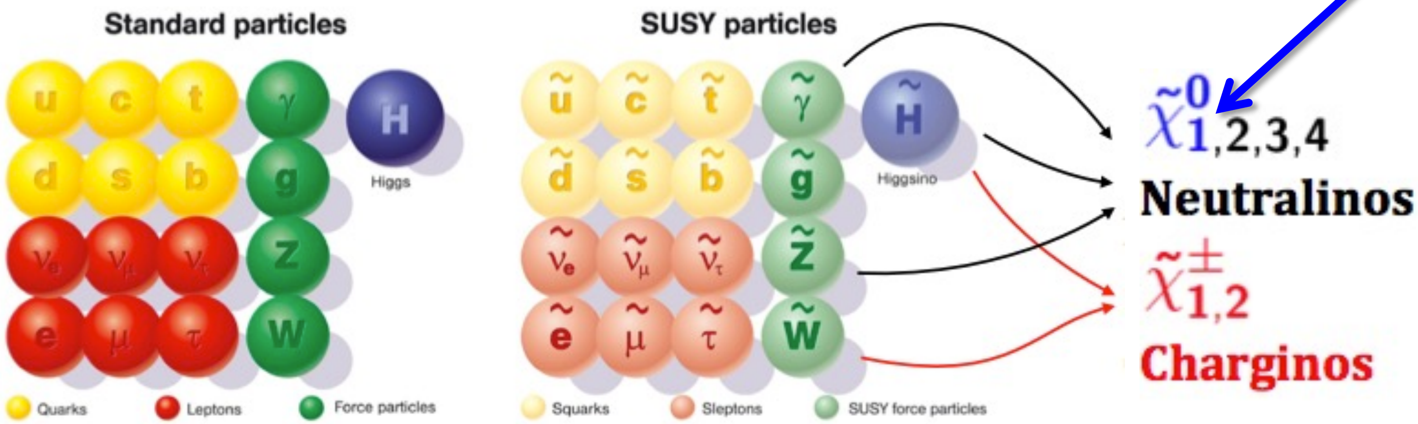
- **Conserved R parity** (originally introduced for stability of proton)

$$R = (-1)^{3(B-L)+2S}$$

R=+1 (SM)
R=-1 (SUSY)

  - SUSY particles produced/annihilated in pairs
  - Lightest SUSY particle (LSP) stable (DM candidate)
  - Typical signature: jets/leptons/photons + **MET** **(key signature: large MET)**



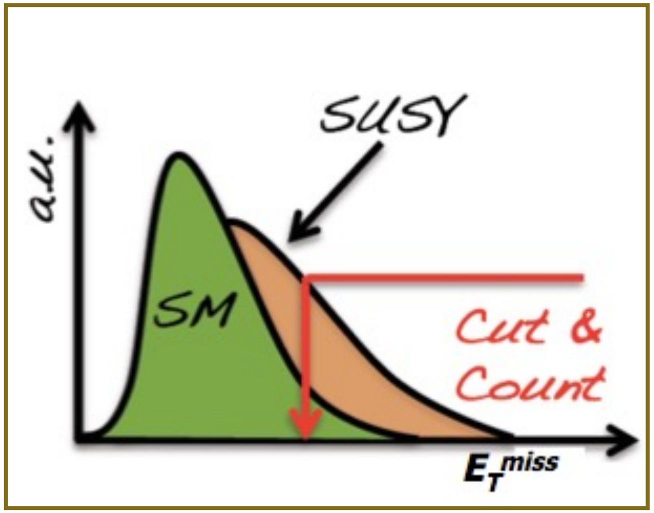


How do we search for SUSY?

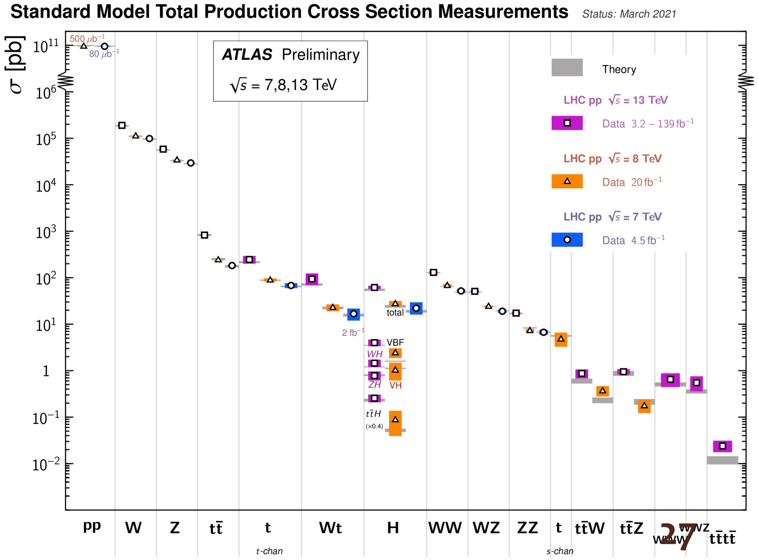
- **SUSY search strategy:** search for <u>deviation from SM</u> from the tails

- **SUSY sensitive variables:** Try to establish excess of events in some sensitive kinematic distribution

- **SM background:** the discovery of new physics can only be claimed when SM backgrounds are understood well or under control
  - SM bgs understood very well ☺
  - No hints for new physics ☹

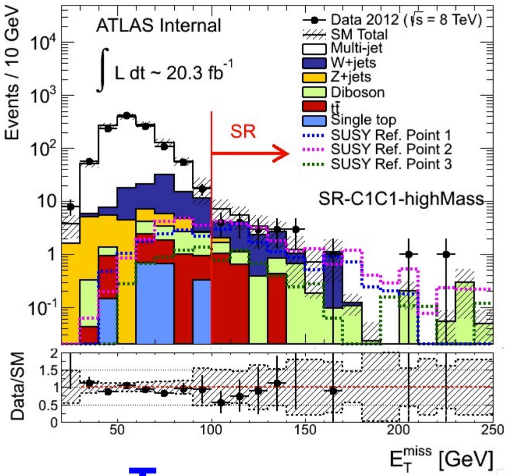


SM "backgrounds"– the big picture

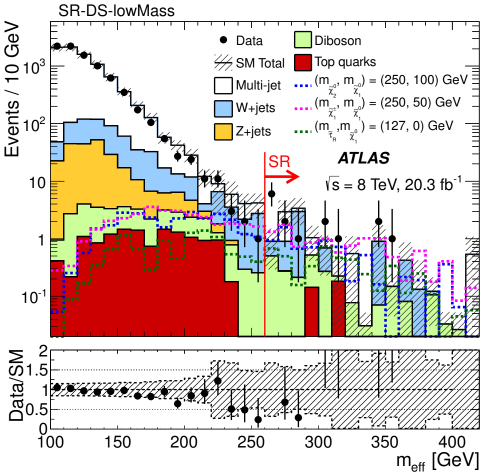


1: Define SRs using SUSY Sensitive Variables

E_T^{miss}



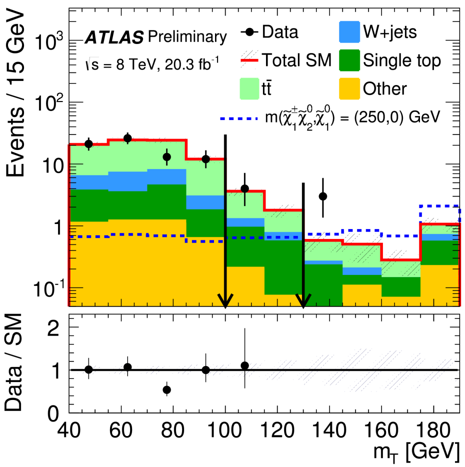
M_{eff}



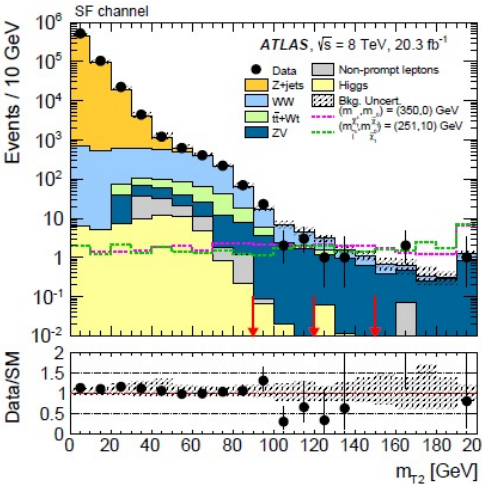
- E_T^{miss} from escaping LSP, to suppress bg from mis-measured jets and oth. SM BG
- Related to the sparticle mass scale, like effective mass (**M_{eff}**)

$$M_{\rm eff} \equiv \sum_{i=1}^{N_{\rm jets}} p_{\rm T}^{{\rm jet},i} + \sum_{j=1}^{N_{\rm lep}} p_{\rm T}^{{\rm lep},j} + E_{\rm T}^{\rm miss}$$

mT



mT2



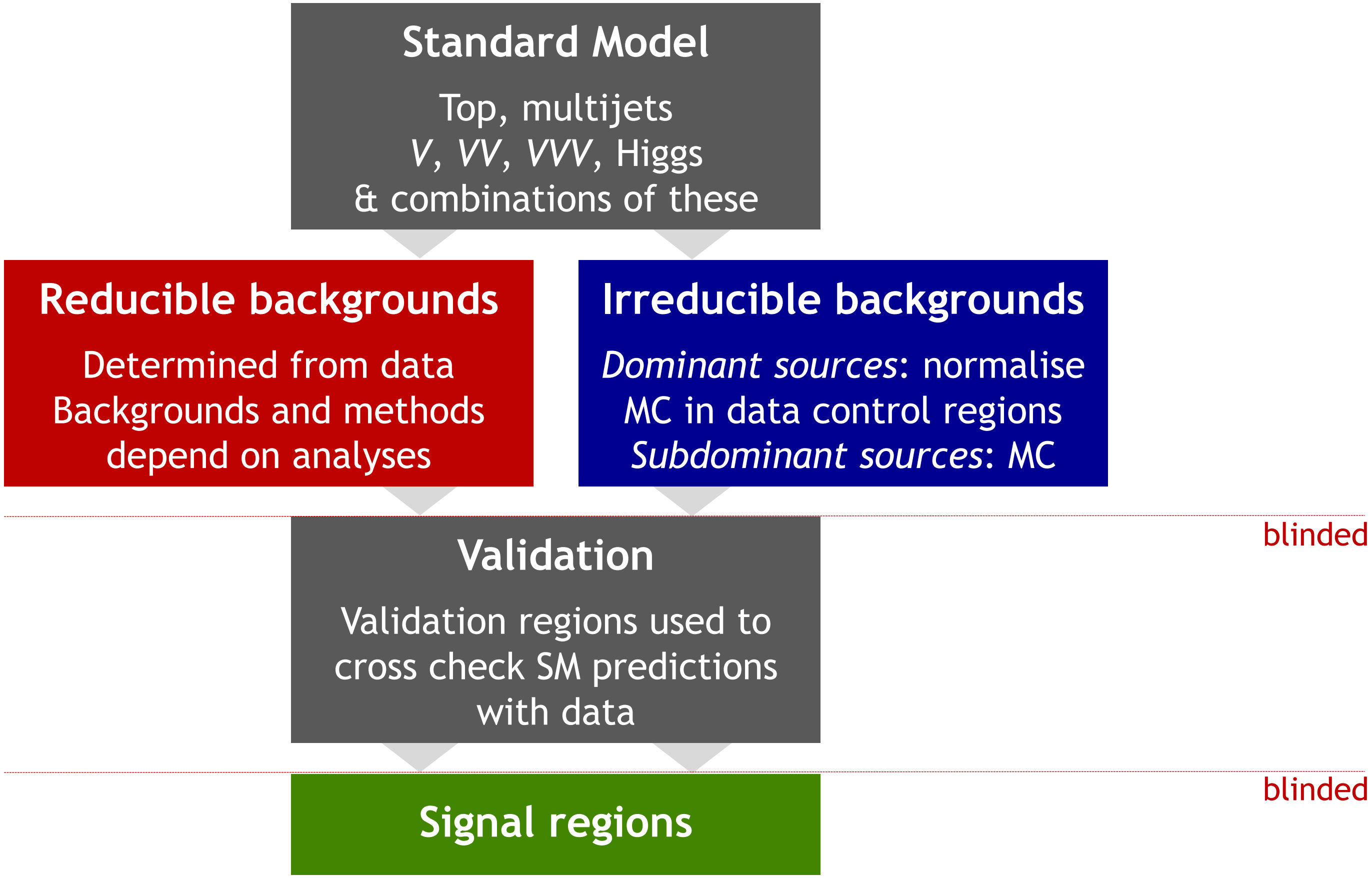
- **mT, mT2** (stransverse mass)**:** suppress BG with Ws

$$m_{\rm T2} = \min_{\mathbf{q}_{\rm T}}\left[\max\left(m_{\rm T}(\mathbf{p}_{\rm T}^{\ell 1}, \mathbf{q}_{\rm T}), m_{\rm T}(\mathbf{p}_{\rm T}^{\ell 2}, \mathbf{p}_{\rm T}^{\rm miss} - \mathbf{q}_{\rm T})\right)\right]$$

- Many others …

2: SM Background estimations (data-driven + MC)

SUSY searches rely primarily on the understanding of the SM BG



Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

blinded

Validation

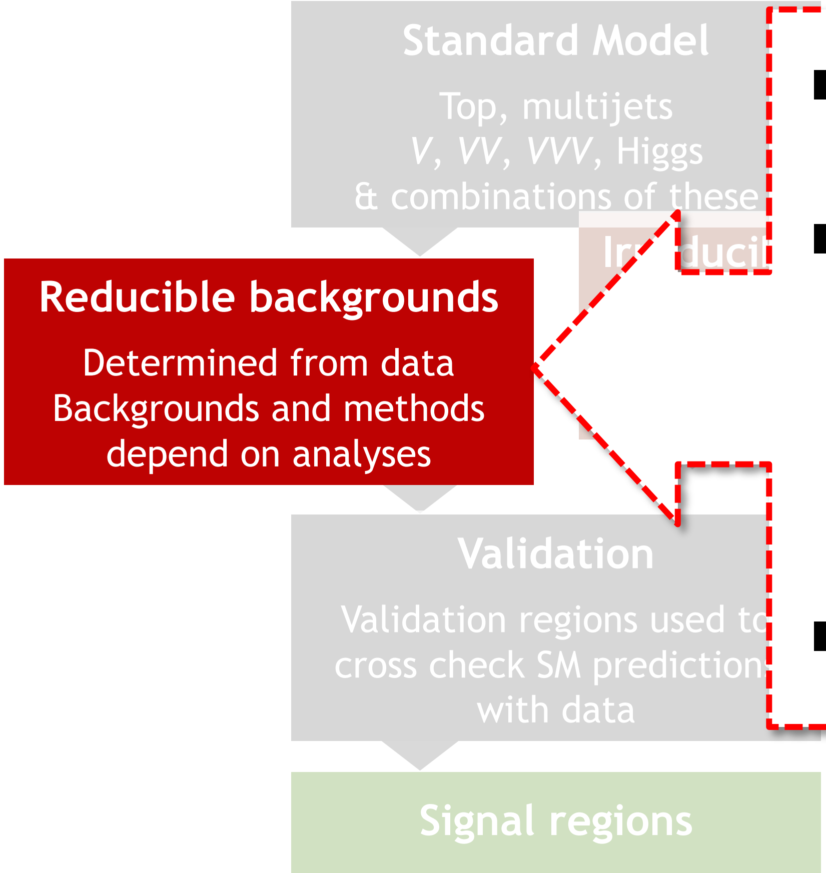
Validation regions used to cross check SM predictions with data

blinded

Signal regions

2: SM Background estimations (data-driven + MC)

SUSY searches rely primarily on the understanding of the SM BG



Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Ir duci

Reducible backgrounds

Determined from data
Backgrounds and methods depend on analyses

Validation

Validation regions used t
cross check SM prediction
with data

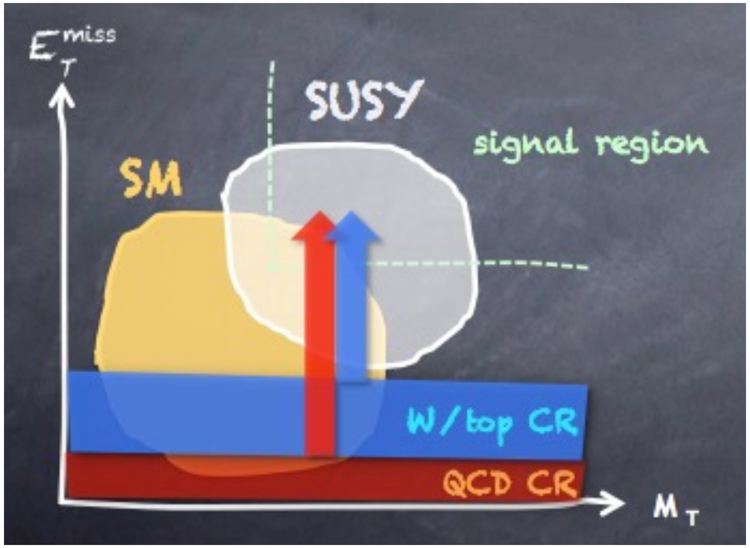
Signal regions

- **Multijet background**: "ABCD method" or fake factor method
- **Fake leptons or heavy-flavour jets** determined with "matrix method" in different-purity samples using "real" and "fake" probabilities measured in data.
- **……**

2: SM Background estimations (data-driven + MC)

SUSY searches rely primarily on the understanding of the SM BG

Normalise MC prediction in SRs using dedicated CRs → transfer factor: *T*



Standard Model

Top, multijets
V, *VV*, *VVV*, Higgs
& combinations of these

Irreducible backgrounds

Dominant sources: normalise MC in data control regions
Subdominant sources: MC

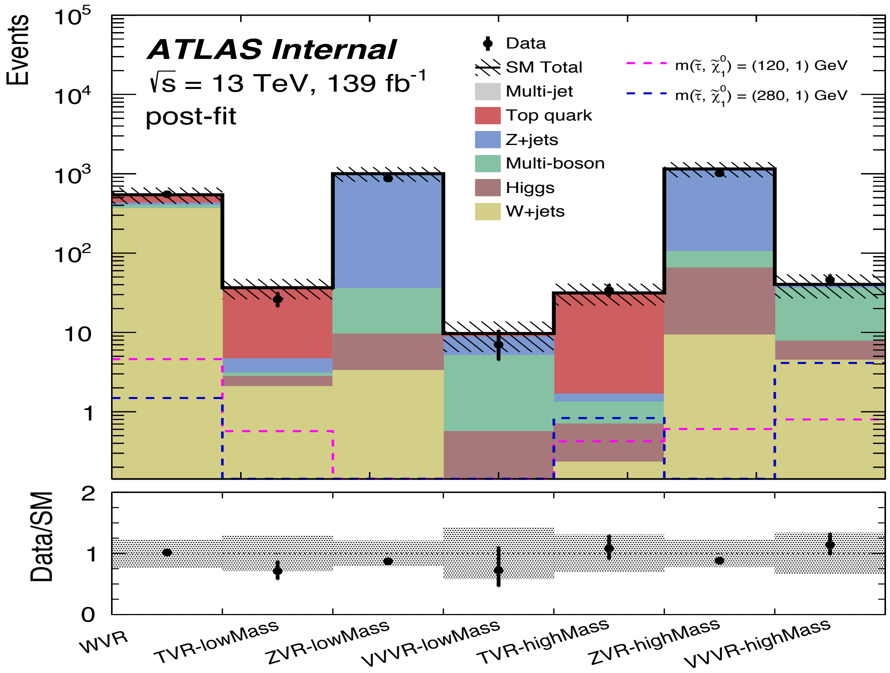
Validation

Validation regions used to cross check SM predictions with data

Signal regions

2: + MC)

SUS e SM
BG



Determined from data
Backgrounds and metho
depend on analyses

t sources: normalise
a control regions
dominant sources: MC

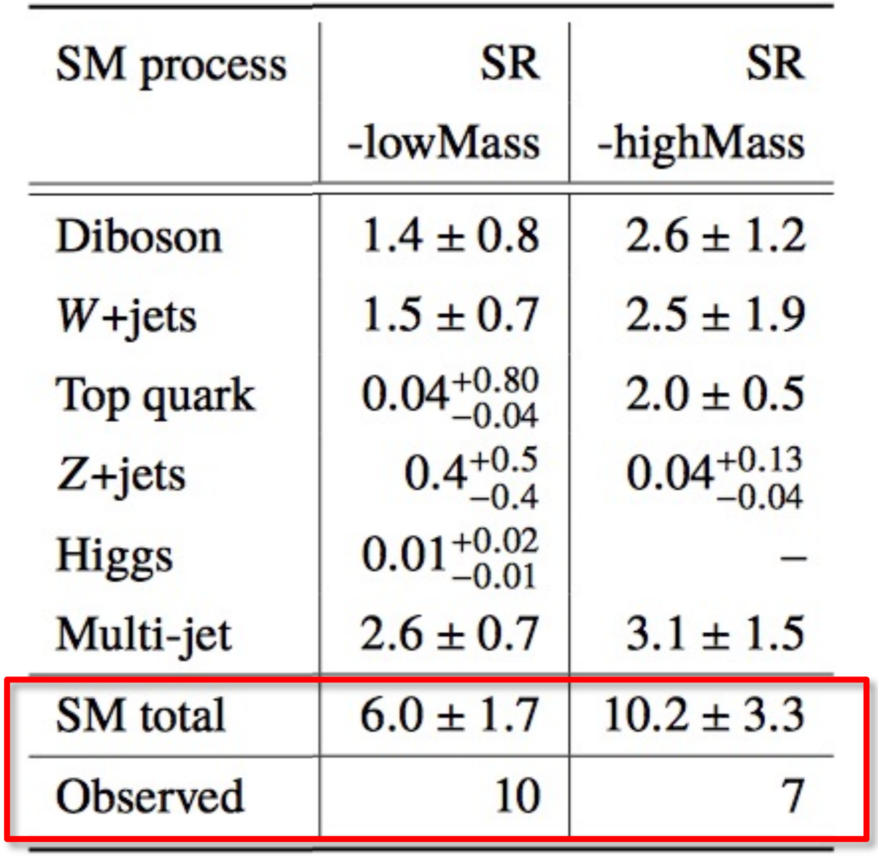
Validation

Validation regions used to cross check SM predictions with data

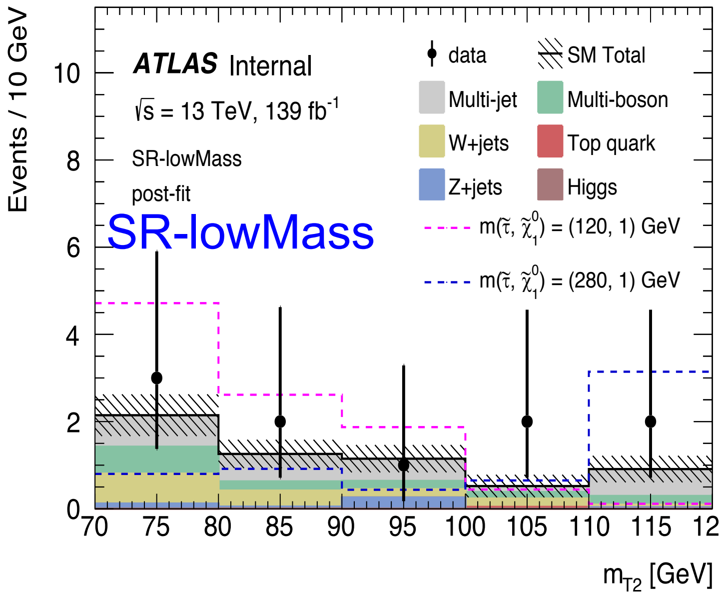
Signal regions

Syst. Uncer.:

- ✓ **Theory/modeling uncer.** (Generator/PS/PDF…)
- ✓ **Experimental uncer.** (energy scale/resolution of objects, lumi., PU modeling …)
- ✓ **Analysis specific uncer.** (bg esti.)



SM process	SR -lowMass	SR -highMass
Diboson	1.4 ± 0.8	2.6 ± 1.2
W+jets	1.5 ± 0.7	2.5 ± 1.9
Top quark	$0.04^{+0.80}_{-0.04}$	2.0 ± 0.5
Z+jets	$0.4^{+0.5}_{-0.4}$	$0.04^{+0.13}_{-0.04}$
Higgs	$0.01^{+0.02}_{-0.01}$	–
Multi-jet	2.6 ± 0.7	3.1 ± 1.5
SM total	6.0 ± 1.7	10.2 ± 3.3
Observed	10	7



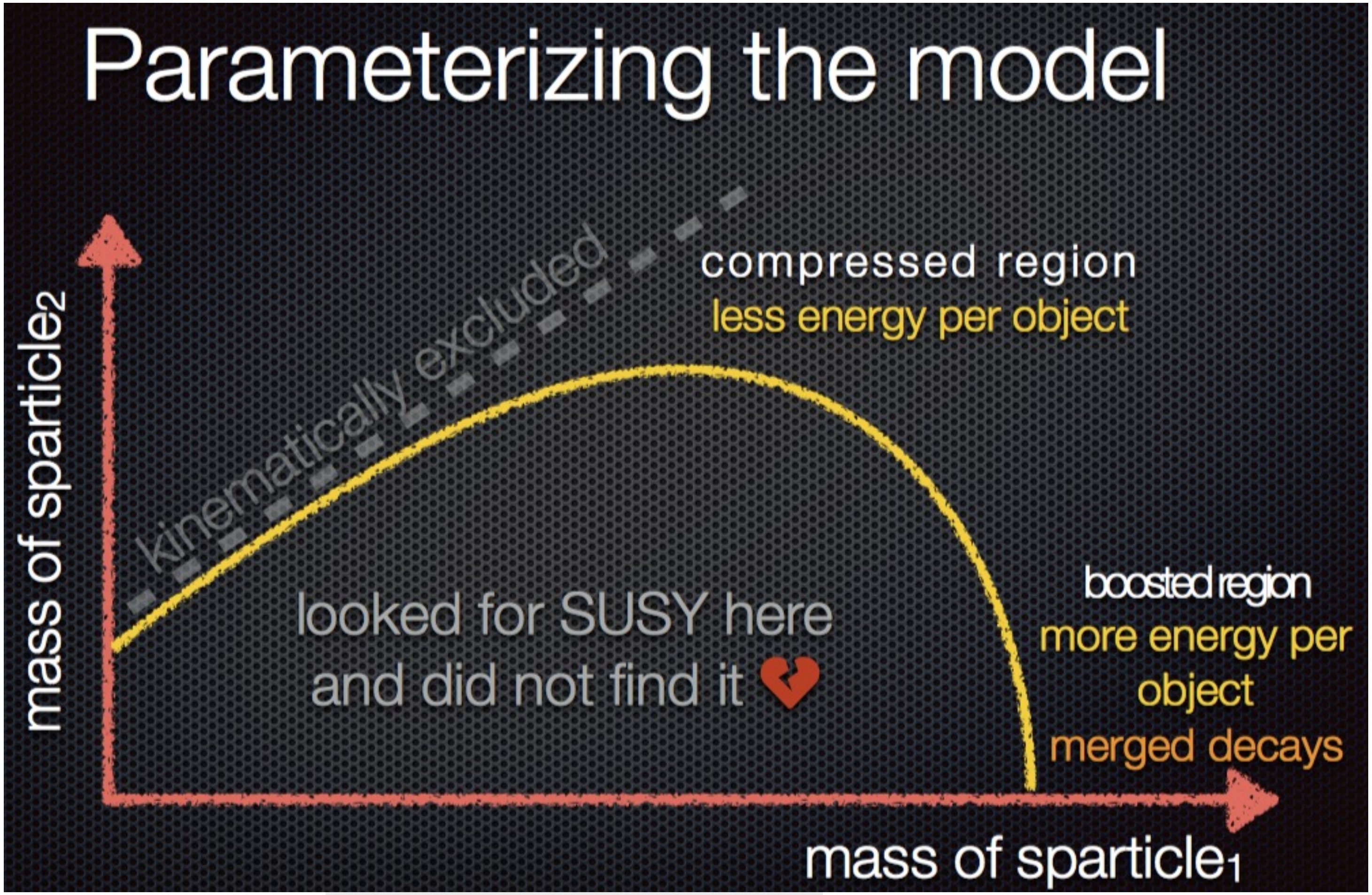
- No significant excess except for SR-lowMass

Validation

Validation regions used to cross check SM predictions with data

Signal regions

3: Compare SM predictions with data

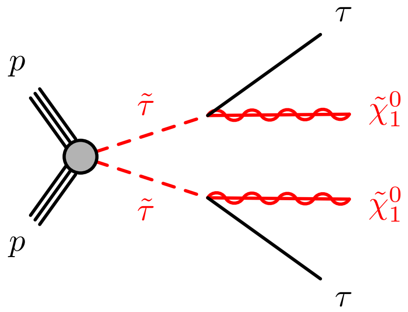


Parameterizing the model

compressed region
less energy per object

boosted region
more energy per object
merged decays

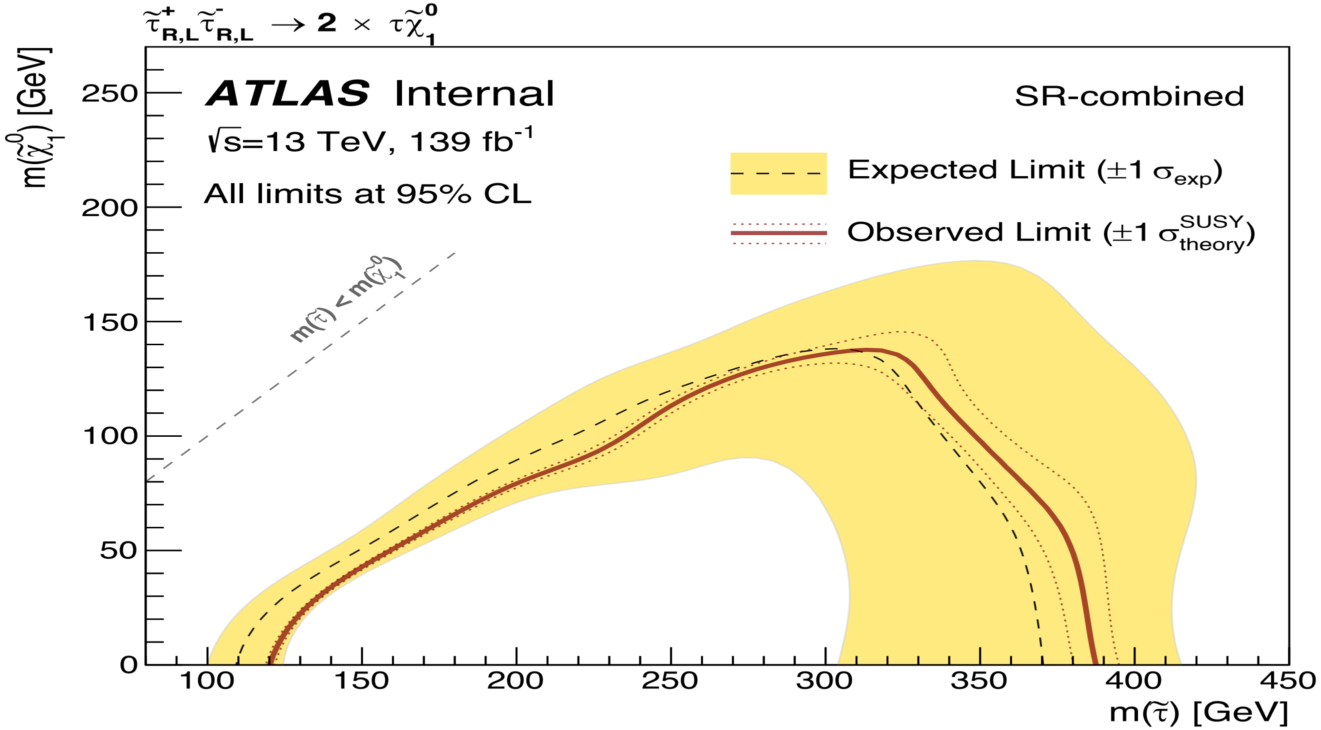
looked for SUSY here and did not find it 💔



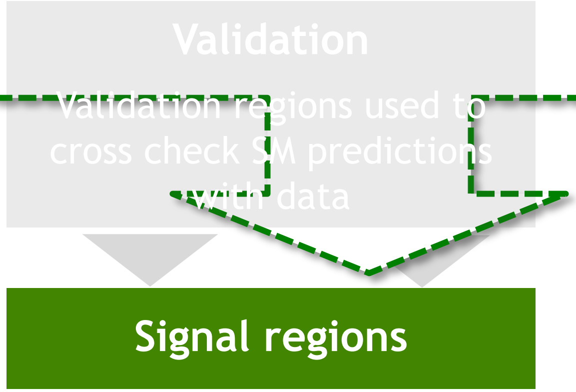
Validation regions used to cross check SM predictions with data

Signal regions

4: Interpretations



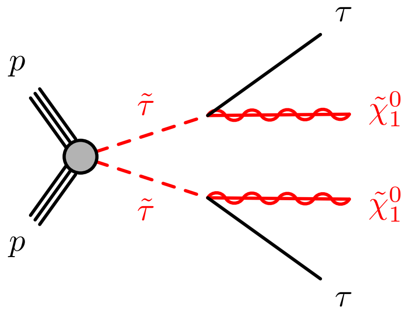
- excludes **stau masses** between **120-390 GeV**



Validation

Validation regions used to cross check SM predictions with data

Signal regions

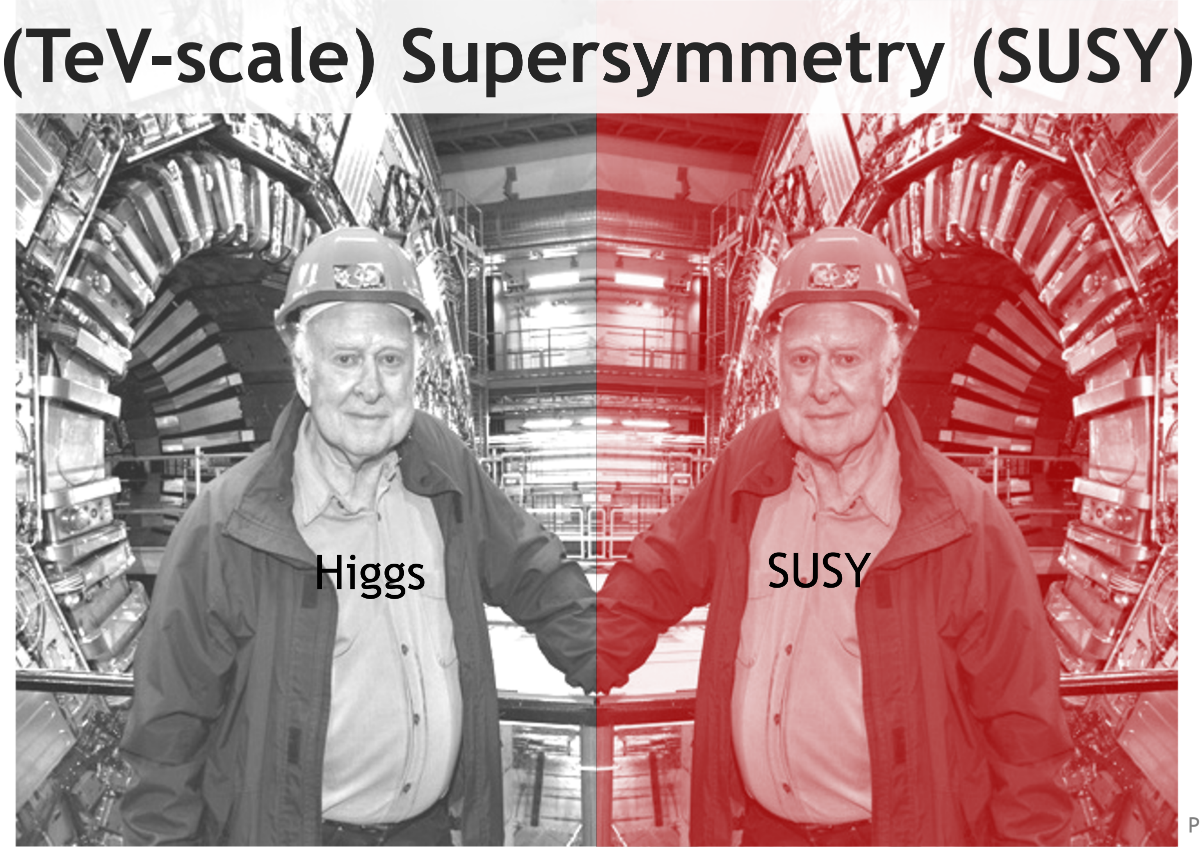


4: Interpretations

SUSY search results @ LHC

ATLAS public link
CMS public link

(TeV-scale) Supersymmetry (SUSY)



P. Higgs at CMS

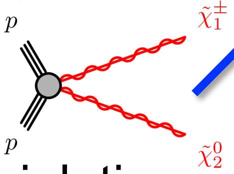
Overview of SUSY Search

Strong production:

- ❑ targeting gluinos and squarks
- ❑ ~t/~b should be lowest mass squarks for naturalness reasons
- ❑ by far largest cross-sections

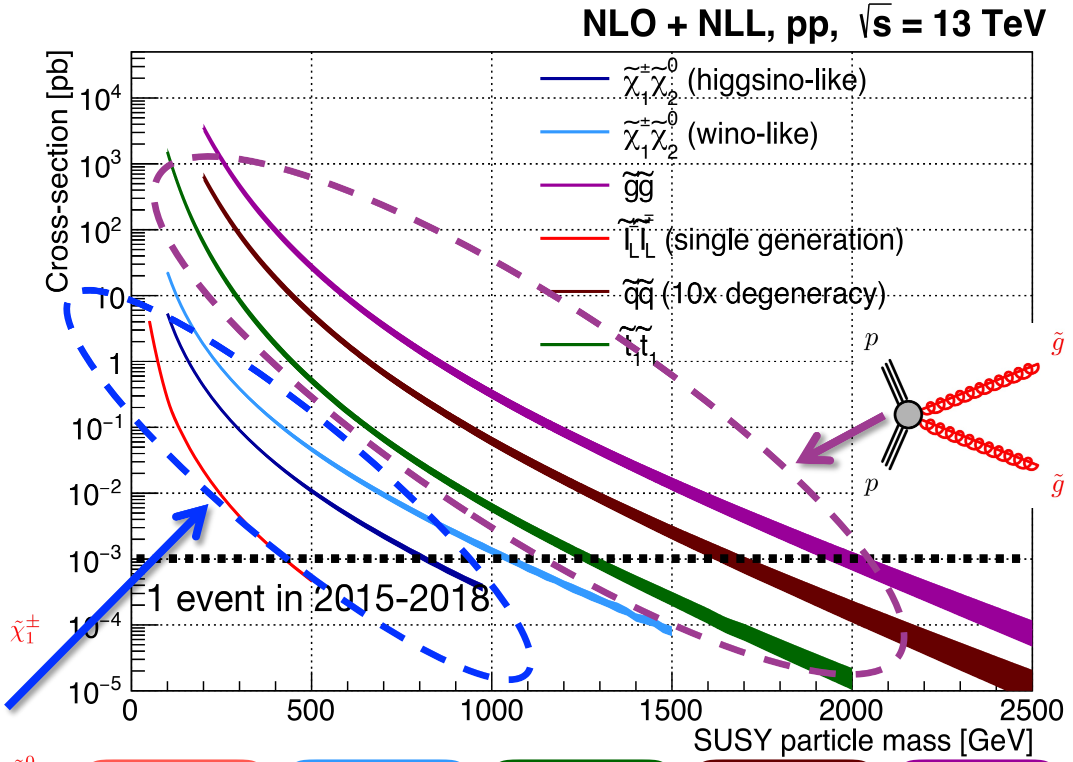
Electroweak production:

- ❑ targeting Electroweakinos & sleptons
- ❑ Lowest mass sparticles, clean signature



RPV/LL:

- ❑ targeting R-parity violating models and long lived sparticles
- ❑ More exotic models



slepton:	EWK:	stop:	squarks:	gluinos:
0.7 TeV	0.95 TeV	1.3 Tev	1.85 Tev	2.2 Tev

Current limits at the end of 2015-2018 data taking

■ **Interpretation**: several simplified models but starting to include new interpretations

Overview of SUSY Search

Strong production:

- ❑ targeting gluinos and squarks
- ❑ ~t/~b should be lowest mass squarks for naturalness reasons
- ❑ by far largest cross-sections

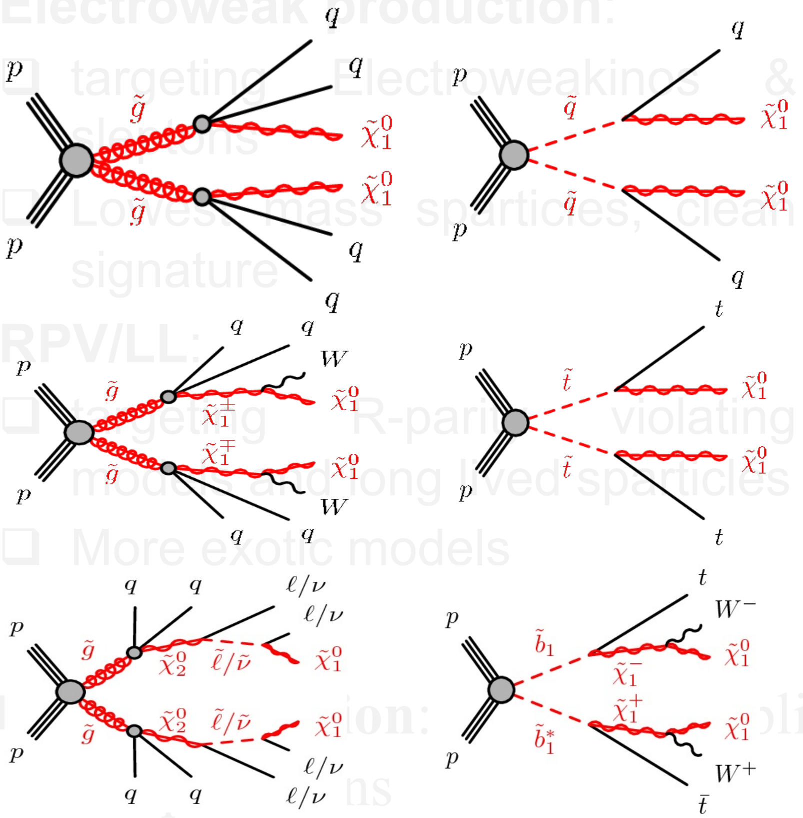
Electroweak production:

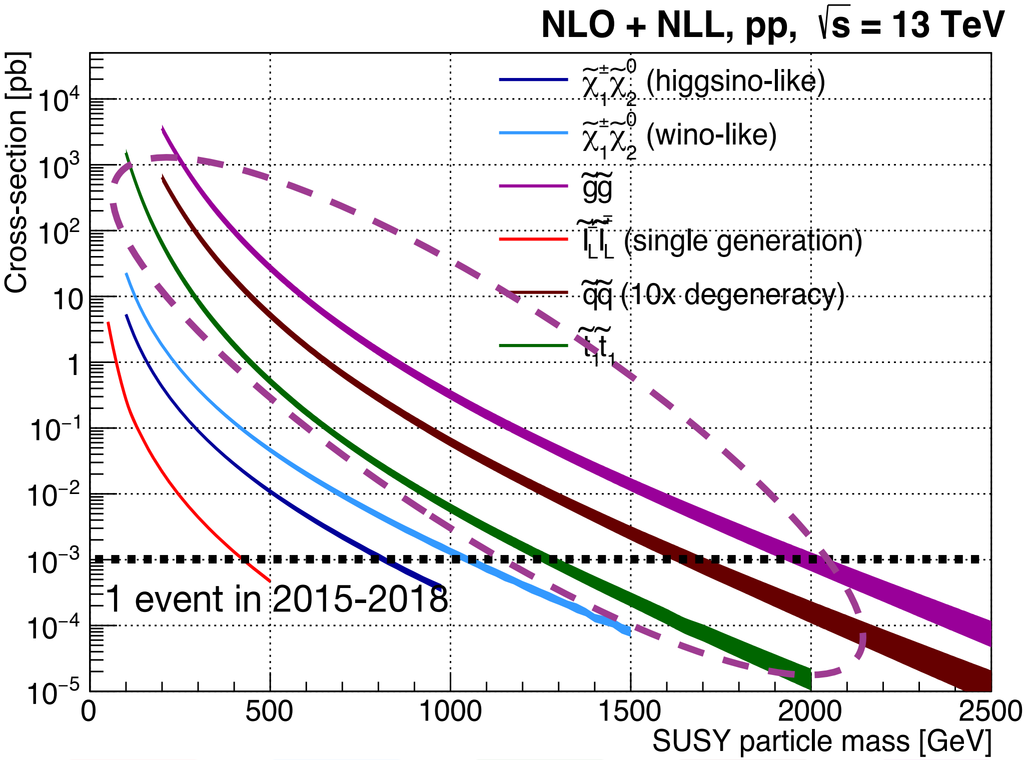
- ❑ targeting Electroweakinos & sleptons
- ❑ Lowest mass sparticles, clean signature

RPV/LL:

- ❑ targeting R-parity violating models and long lived sparticles
- ❑ More exotic models

[illegible]ion: [illegible]plif[illegible]ns





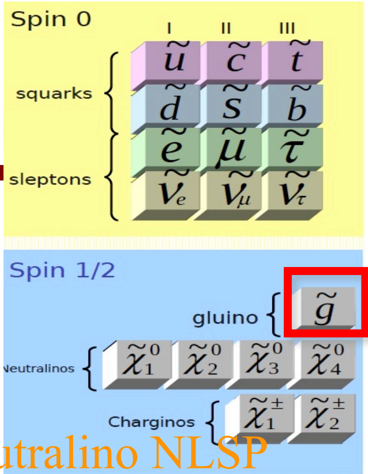
slepton: 0.7 TeV	EWK: 0.95 TeV	stop: 1.3 Tev	squarks: 1.85 Tev	gluinos: 2.2 Tev

Current limits at the end of 2015-2018 data taking

Signatures:

- ➢ **Large #jets and missing energy (N1/ν)**
- ➢ **#leptons: 0-n (from ~l/boson decay)**

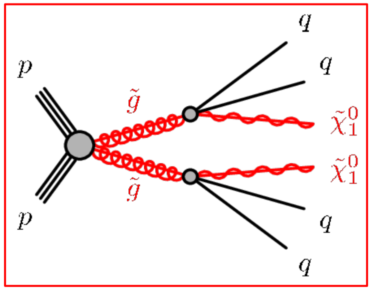
Gluino search

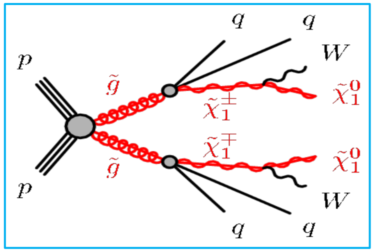


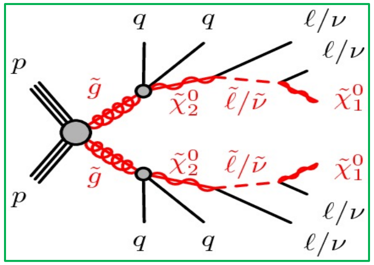
In **simplified model approach** :

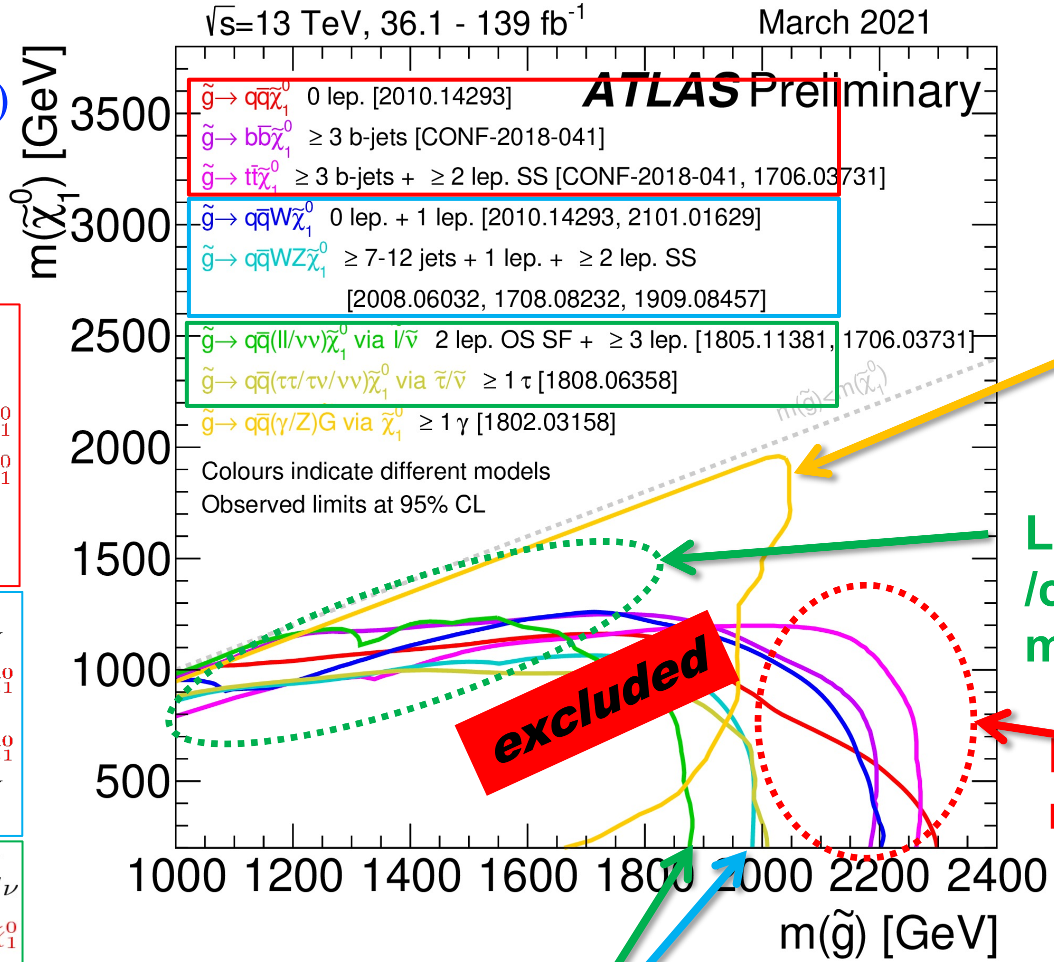
- M(~g) < O (1.9 - 2.2 TeV) @95% CL

Neutralino LSP

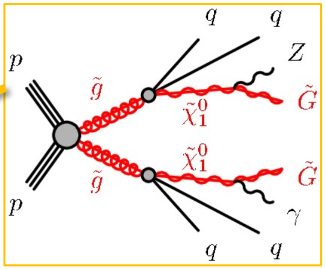








Neutralino NLSP
light gravitino LSP

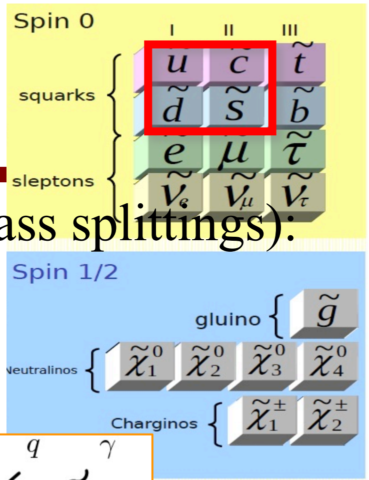


Low mass /compressed region: multi-lep. SRs

Large mass split region: full had. SR.

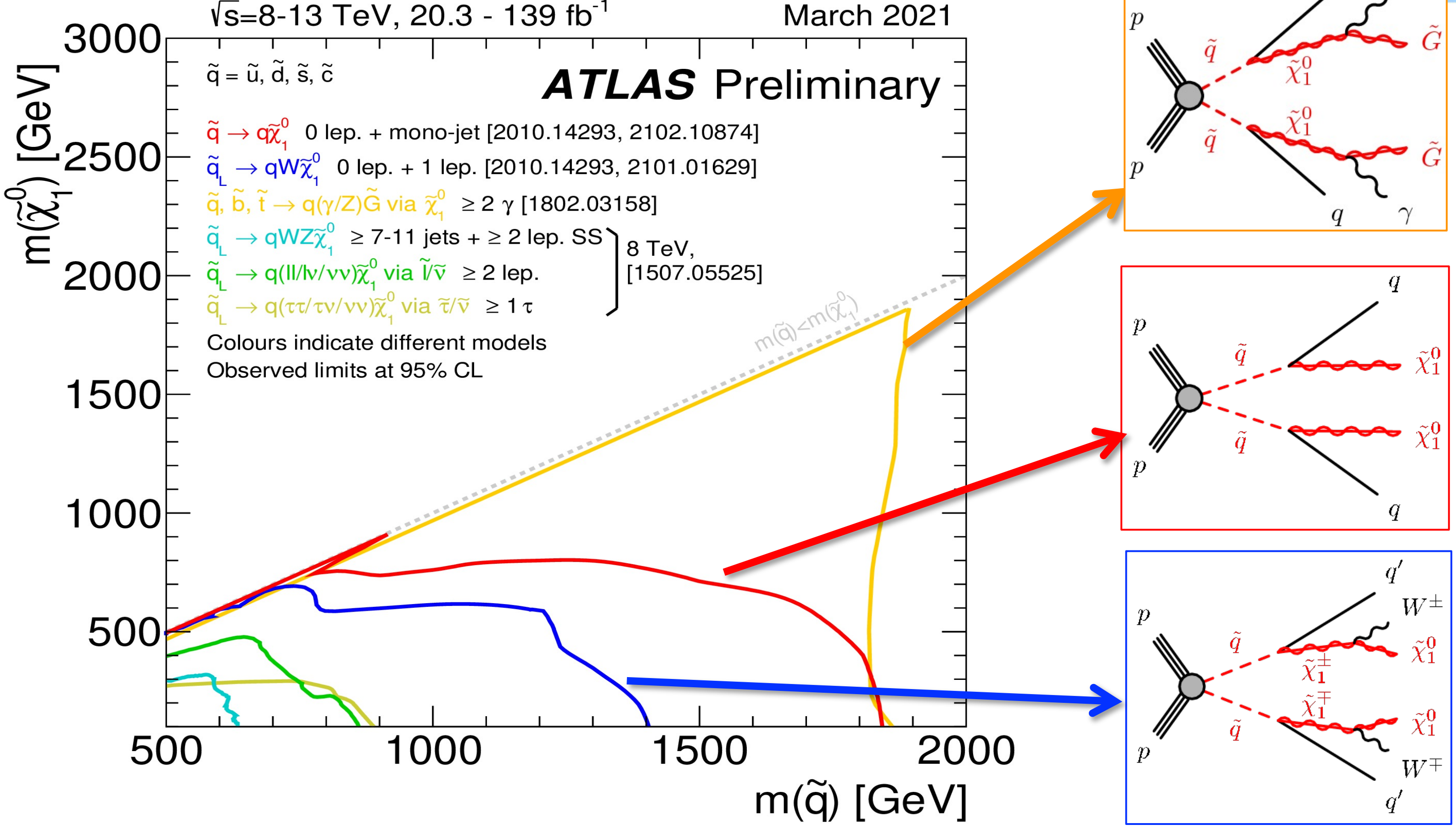
Weaker limits: decay via W/Z or cascade decay

Squark search



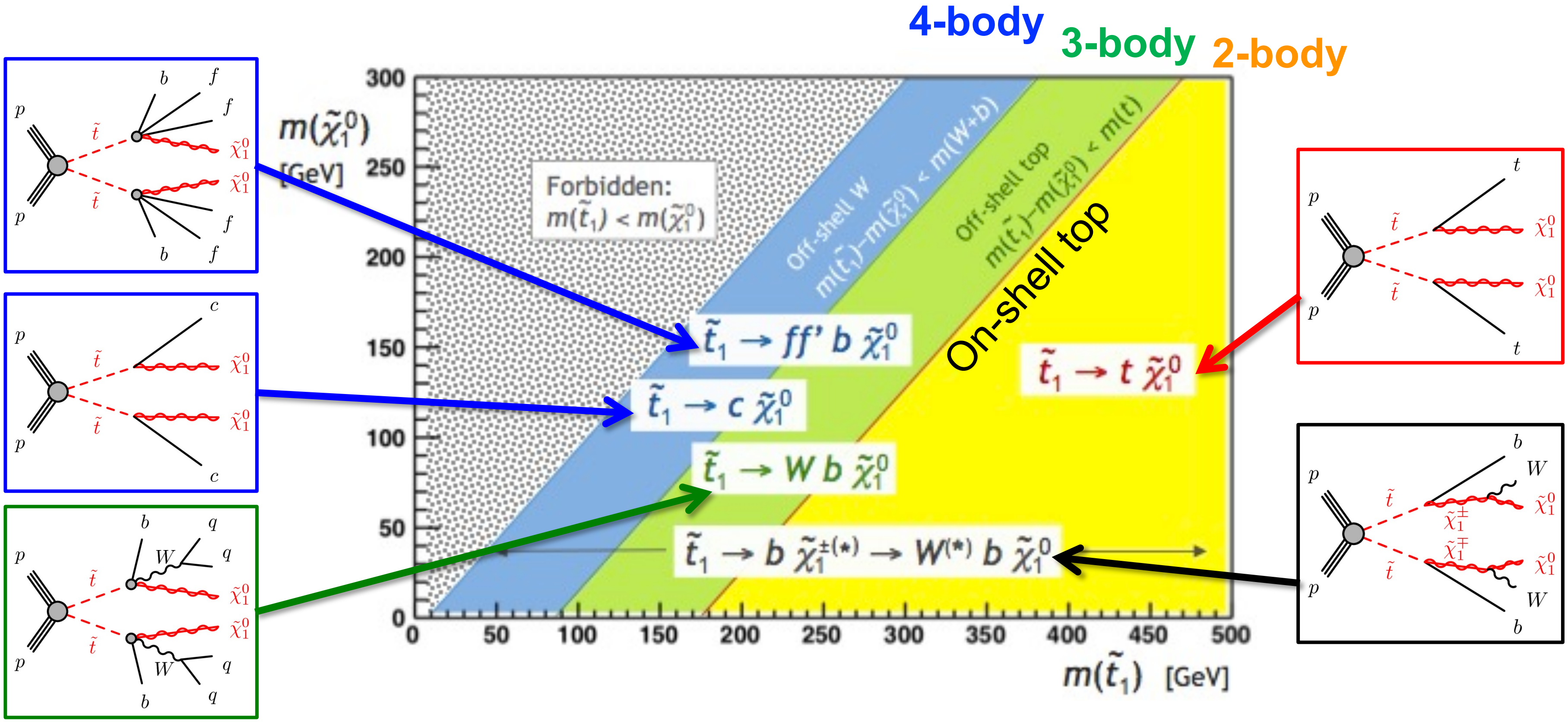
In **simplified model approach** (depending on decay mode and/or mass splittings):

- M(~g) < O (1.9 TeV) – O (2.2 TeV) @95% CL
- **M(~q) < O (1.4 TeV) – O (1.85 TeV) @95% CL**
- M(~t/~b) < O (0.7 TeV) – O (1.25/1.35 TeV) @95% CL

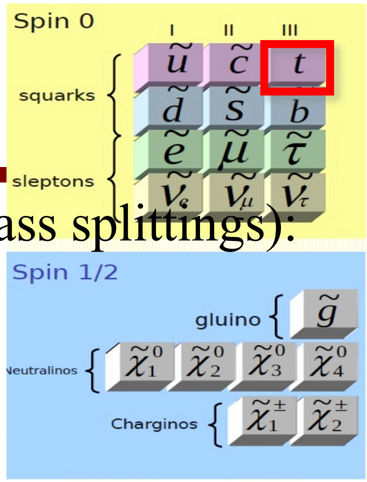


3rd Generation: stop

- Search for **stop** directly from ~t~t production
- **Large spectrum of possible stop decays**, covering range from low to heavy stop mass, various decay modes.

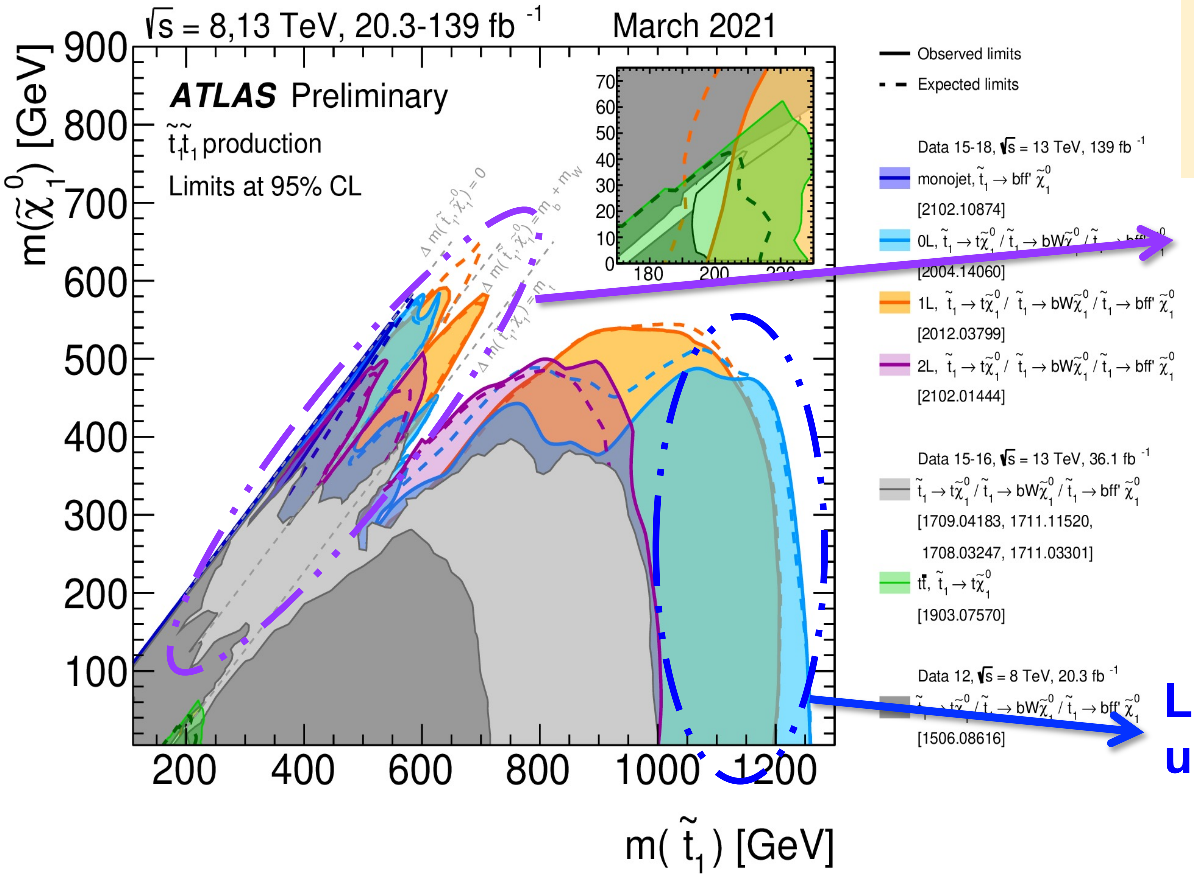


Stop search



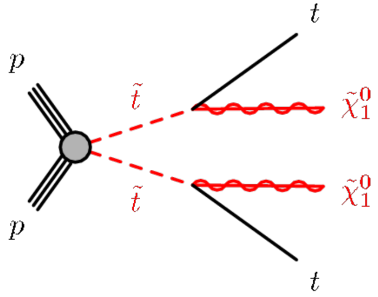
In **simplified model approach** (depending on decay mode and/or mass splittings):

- M(~g) < O (1.9 TeV) – O (2.2 TeV) @95% CL
- M(~q) < O (1.4 TeV) – O (1.85 TeV) @95% CL
- **M(~t/~b) < O (0.7 TeV) – O (1.25/1.35 TeV) @95% CL**



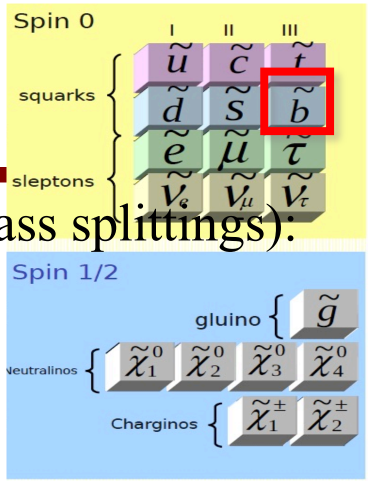
Can be even worse in some corners of simplified model space

Compressed scenario: still < 700 GeV



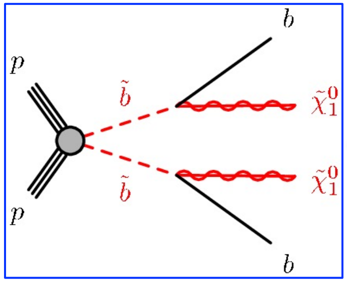
Large mass split scenario: up to 1.2 TeV

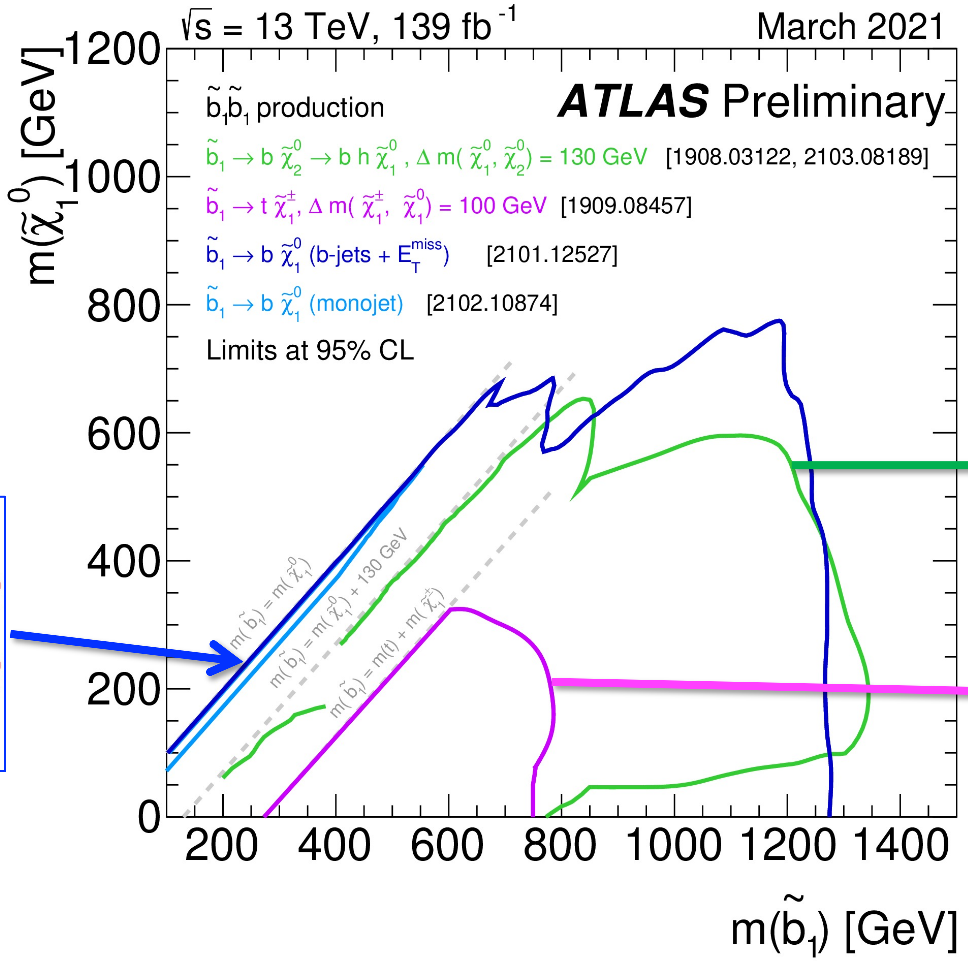
Sbottom search

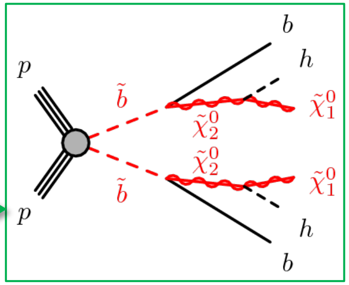


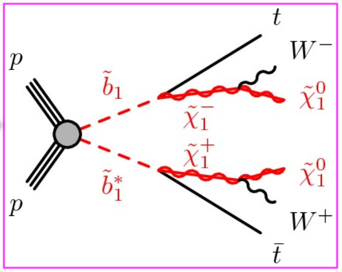
In **simplified model approach** (depending on decay mode and/or mass splittings):

- M(~g) < O (1.9 TeV) – O (2.2 TeV) @95% CL
- M(~q) < O (1.4 TeV) – O (1.85 TeV) @95% CL
- **M(~t/~b) < O (0.7 TeV) – O (1.25/1.35 TeV) @95% CL**



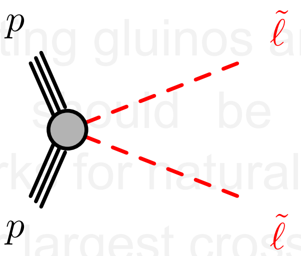






Overview of SUSY Search

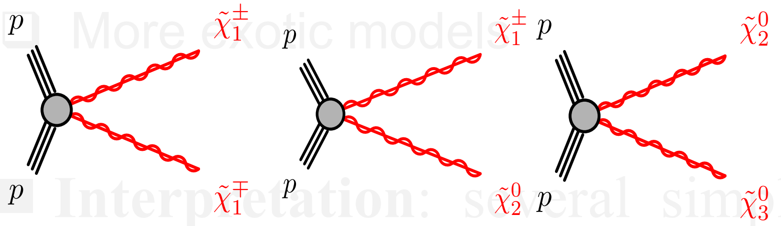
Slepton pair production

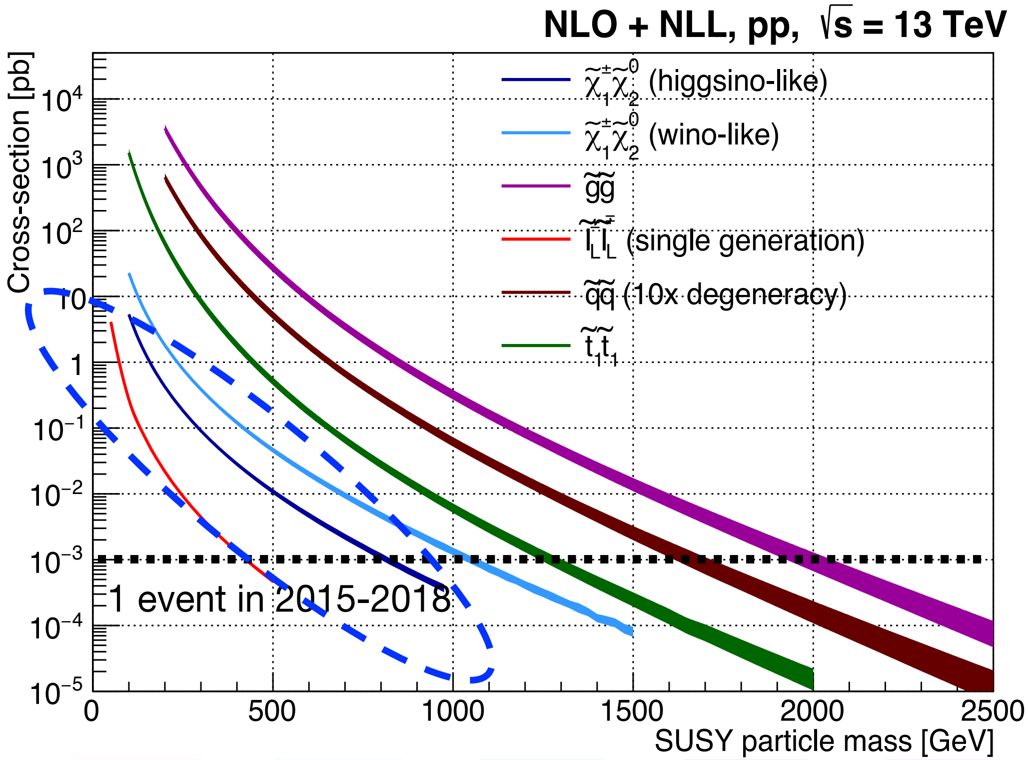


Electroweak production:

- ☐ targeting Electroweakinos & sleptons
- ☐ Lowest mass sparticles, clean signature

Gaugino pair production via ~l or boson decay





slepton: 0.7 TeV	EWK: 0.95 TeV	stop: 1.3 Tev	squarks: 1.85 Tev	gluinos: 2.2 Tev

Current limits at the end of 2015-2018 data taking

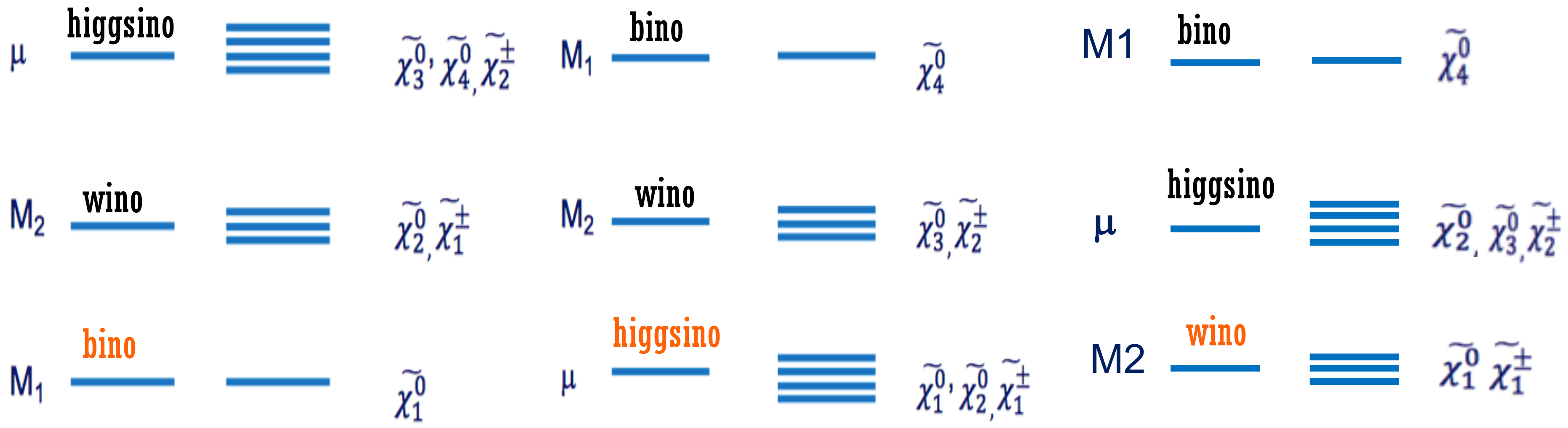
Signatures:

- ➢ leptons (~l or boson decay) + low-multiplicity jets + MET
- ➢ Sometimes full hadronic

EWK-ino production

Mass splitting of the EWKinos depends on M1, M2, μ and tanβ

Bino LSP **Higgsino LSP** **Wino LSP**



Standard wino-bino case: large Δm between N1 and C1/N2;

➔ MET + hard leptons

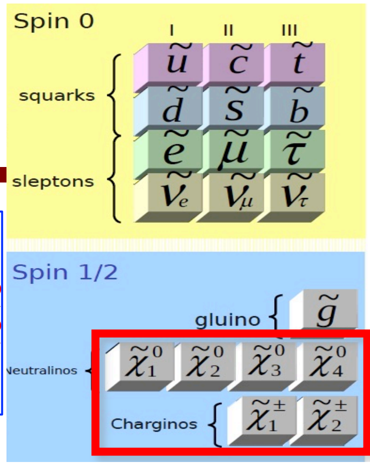
N1,N2,C1 almost degenerate: experimental challenging;

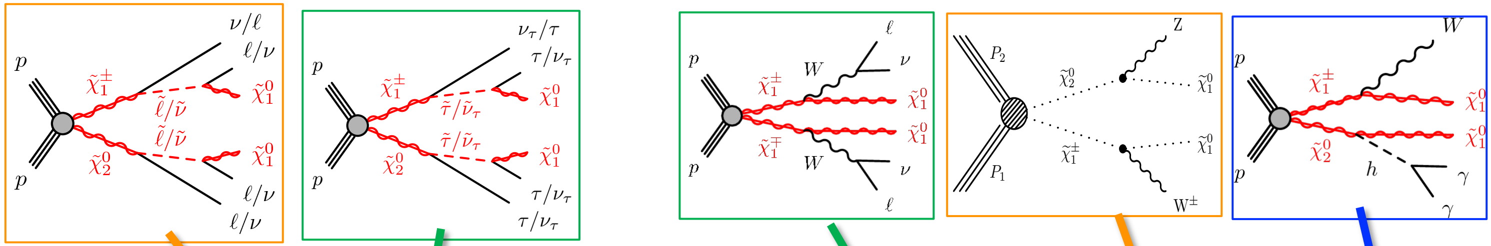
➔ MET + soft leptons

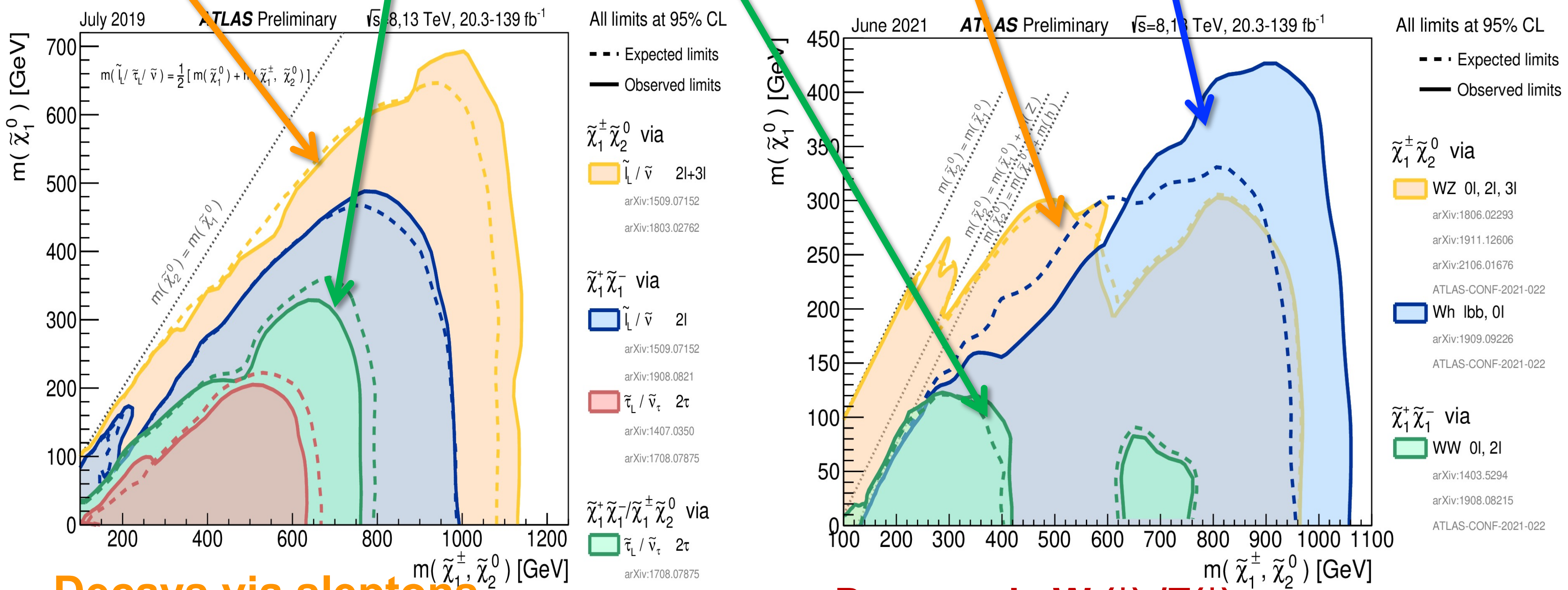
➔ Lower xsec than higgsino LSP;

➔ WW+MET dominant;

EWKino search (summary)





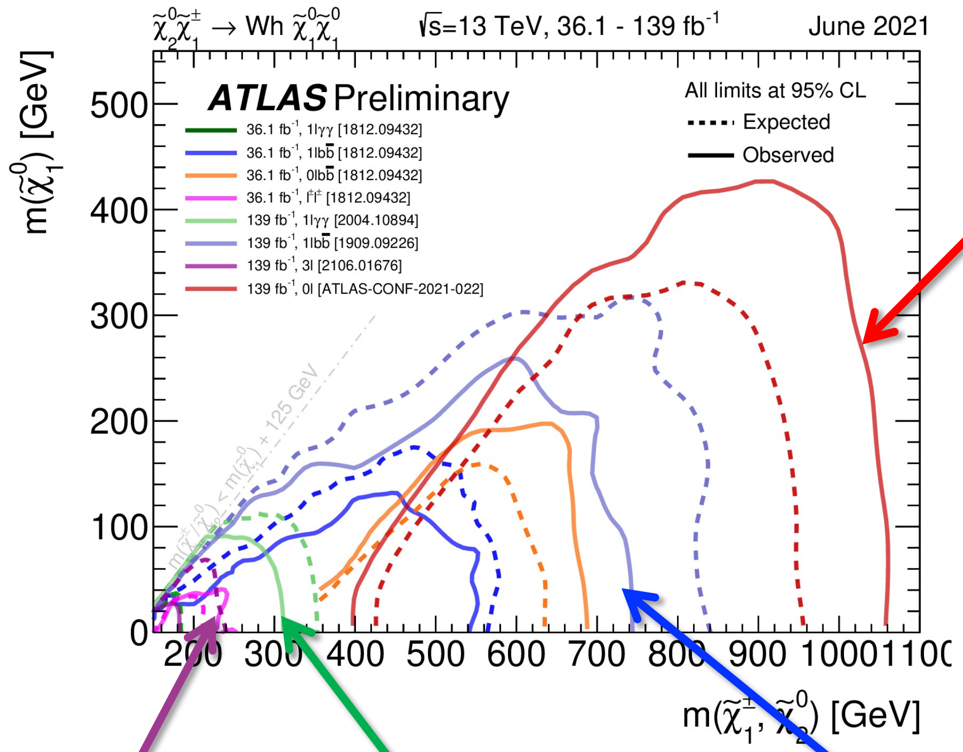


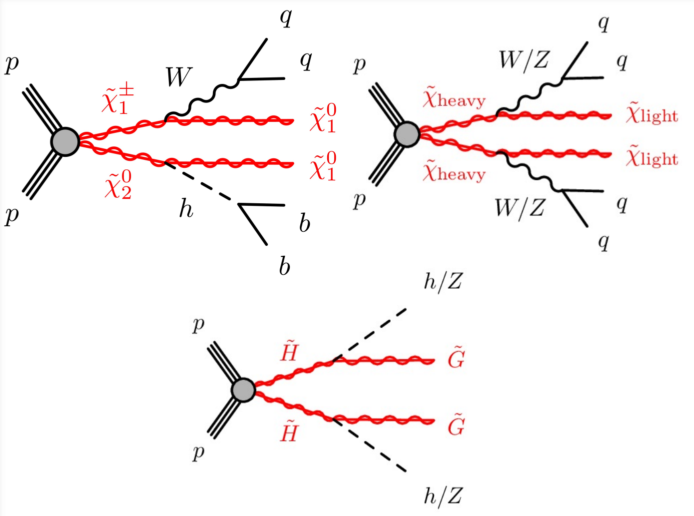
Decays via sleptons

Decays via W (*) /Z(*)

- ☐ **Powerful exclusions in decays via sleptons (C1/N2 up to 0.6-1.1 TeV)**
- ☐ **Comparable exclusions in decays via bosons inc. full hadronic FS (up to 400-1060 GeV)**

Electroweakinos: Wh

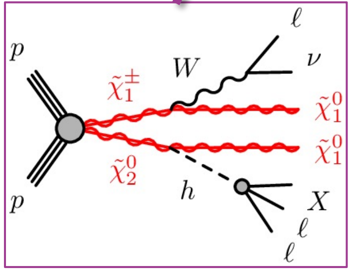


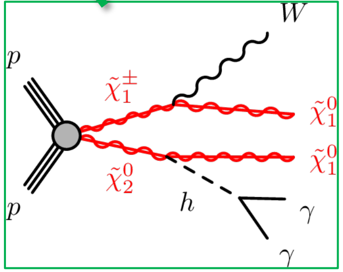


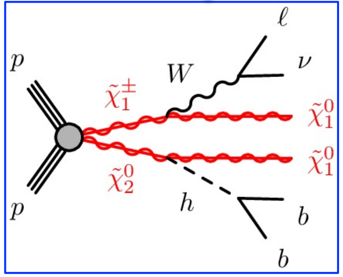
Signature:

two boosted W/Z/h + E_T^{miss}

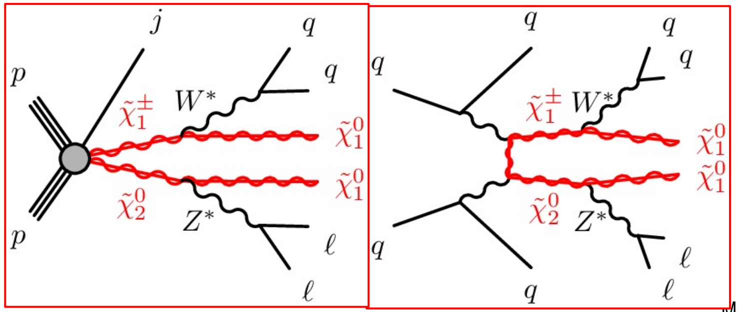
First search for fully hadronic signature at LHC

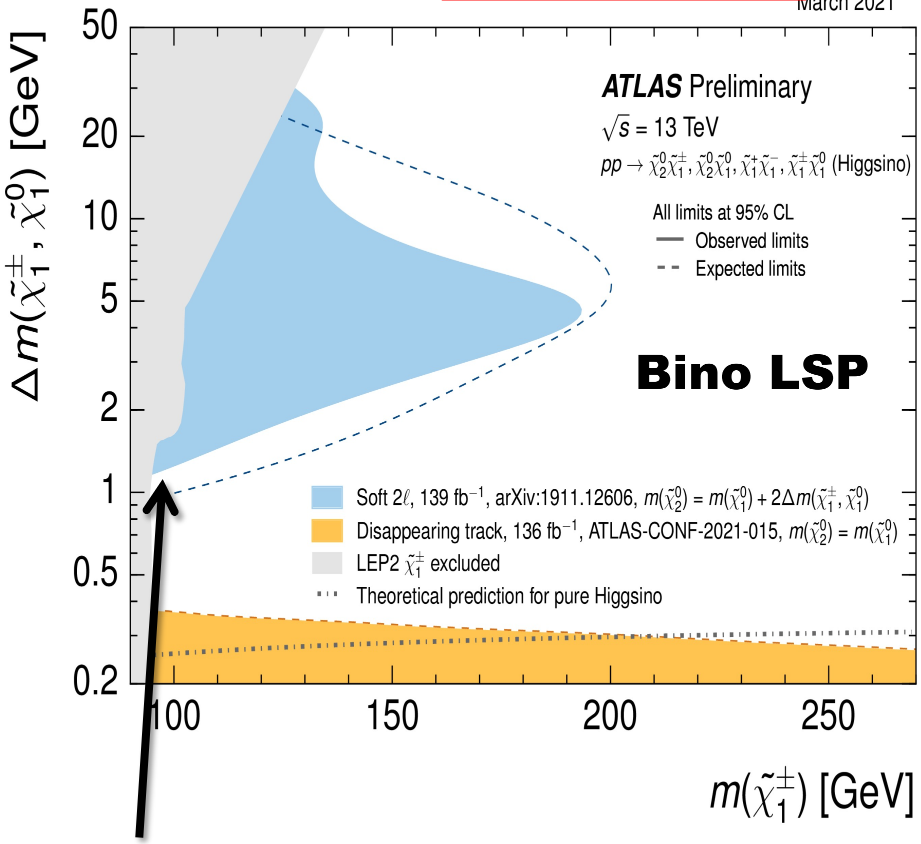






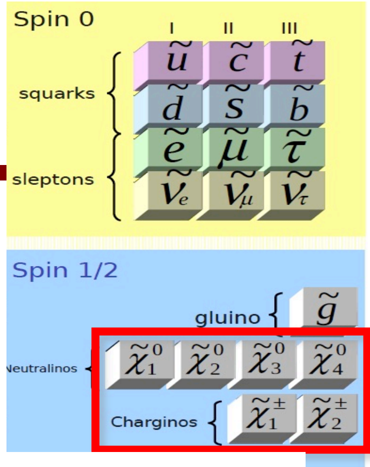
Higgsino search

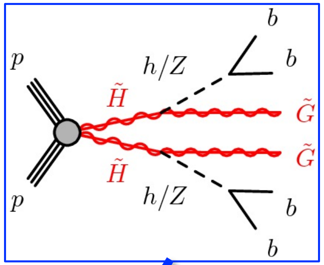


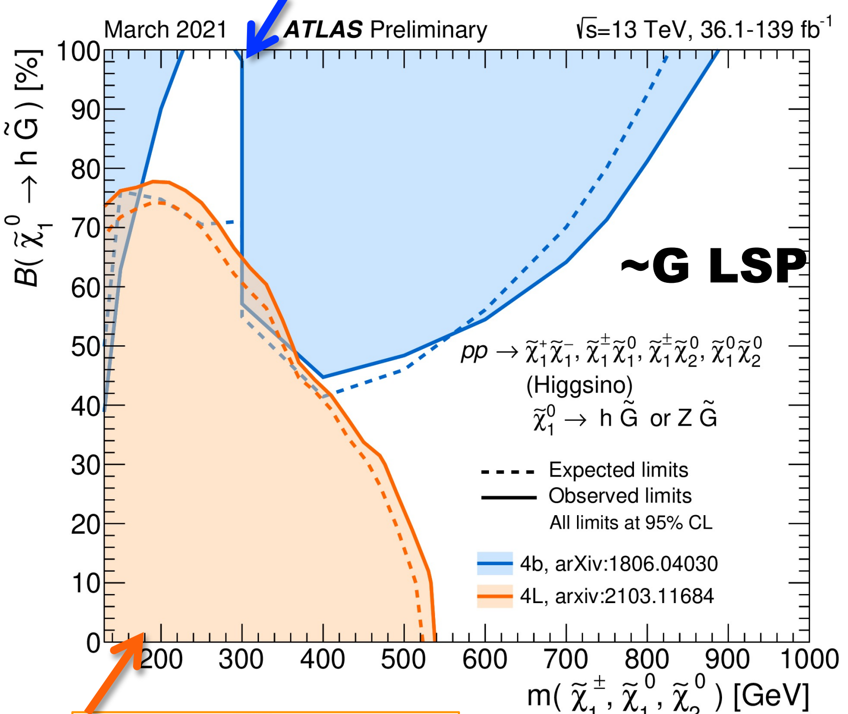


Bino LSP

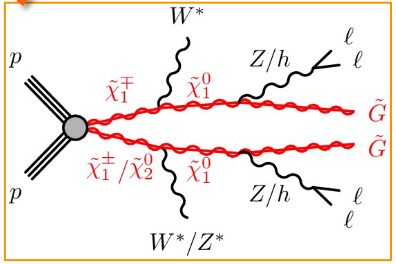
❑ **ΔM reached to 1 GeV**



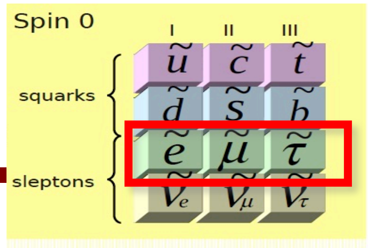




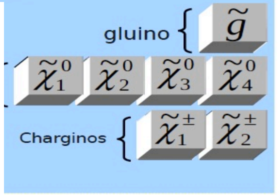
~G LSP

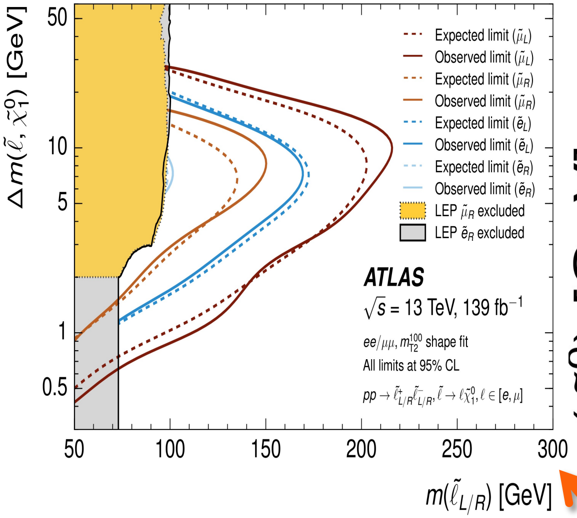


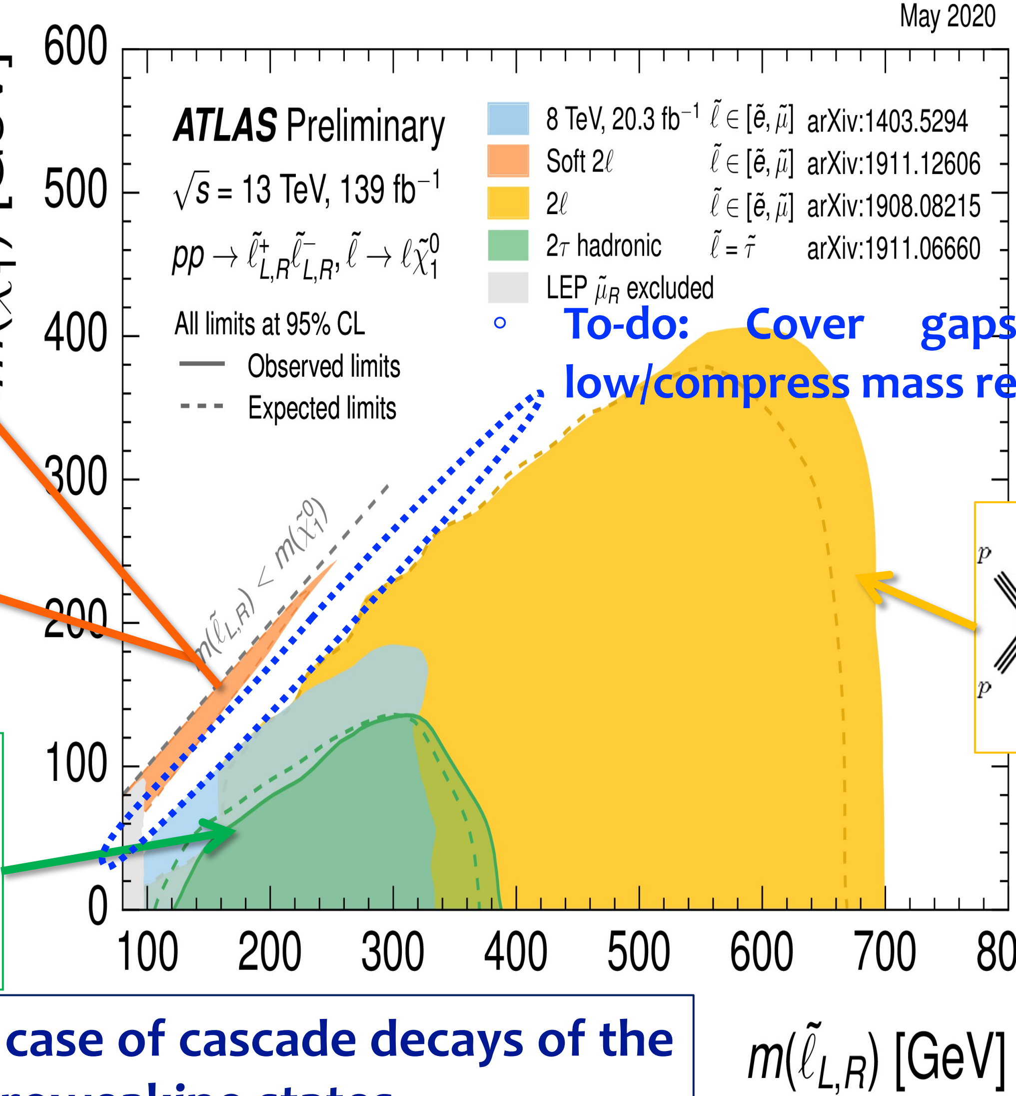
Slepton search



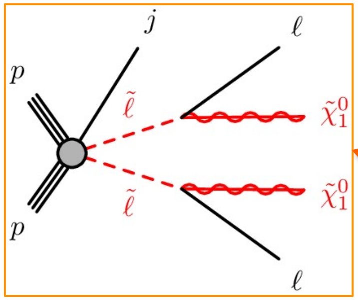
Spin 1/2

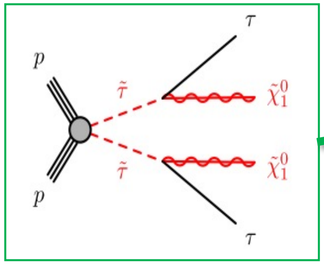


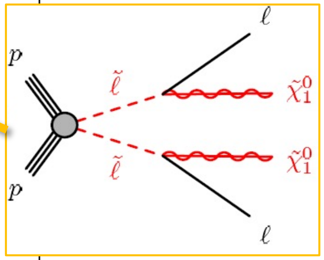




- **To-do: Cover gaps at low/compress mass region**





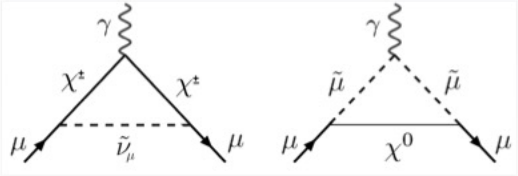


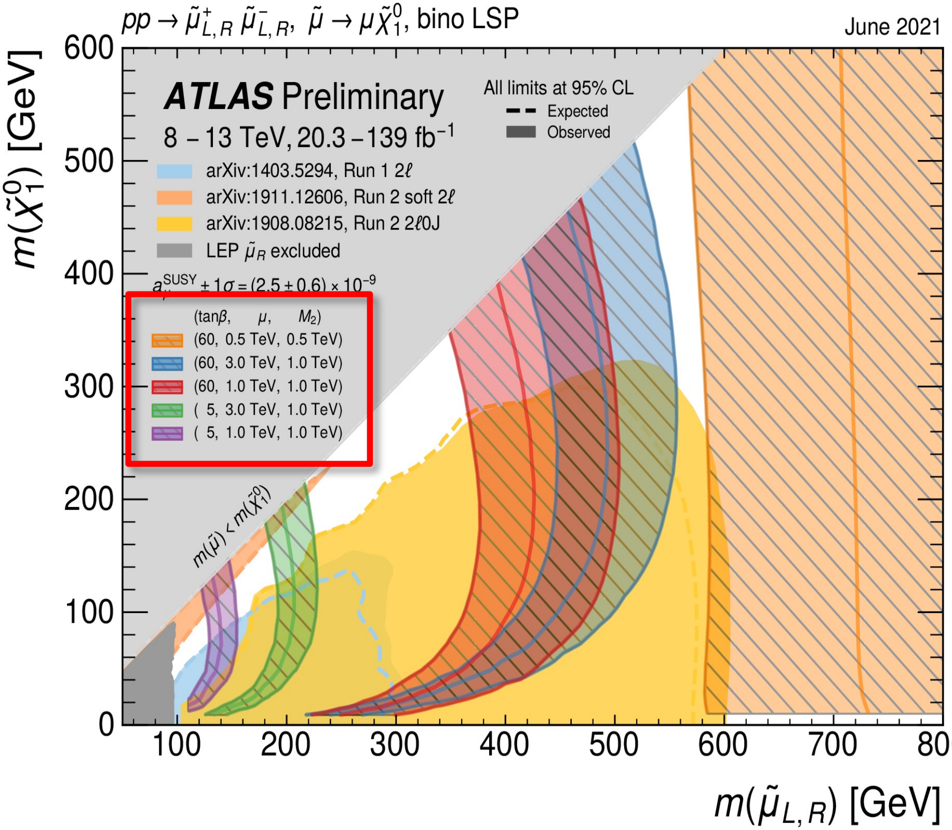
Limits maybe different in case of cascade decays of the sleptons into lighter electroweakino states

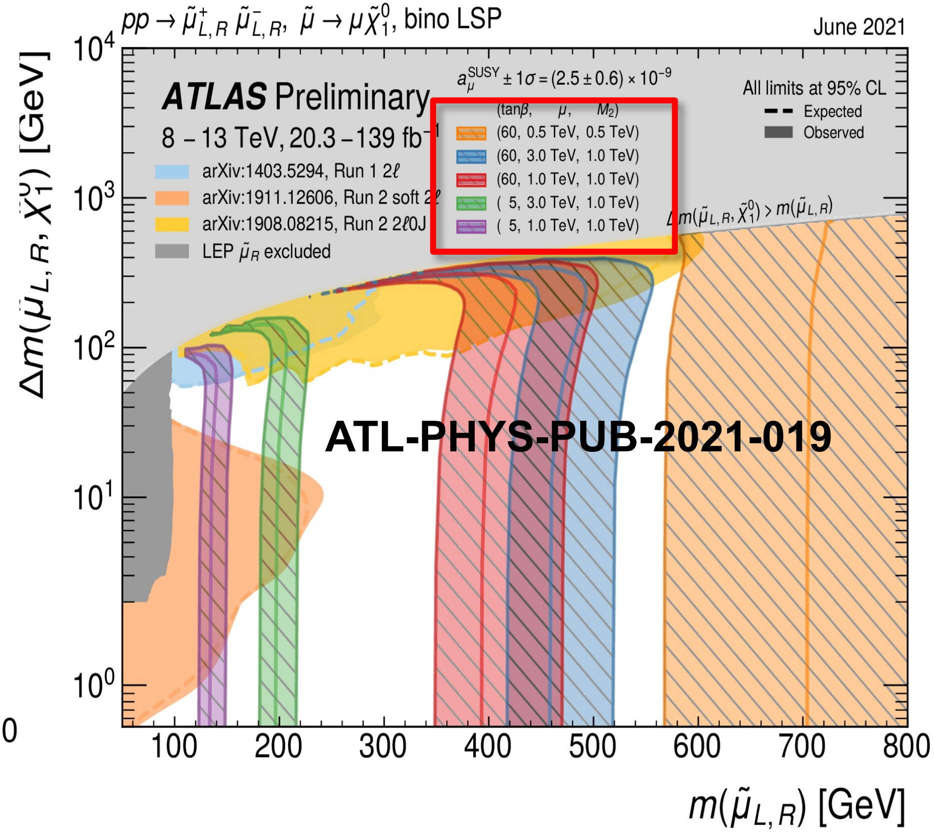
Smuon & g-2

EWKinos / sleptons contribute to muon's g-2

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11} \ (4.2\sigma)$$







Examples of pMSSM parameters compatible with μ g-2 anomaly

To-do: Cover gaps at low/compressed mass region from experiments

Overview of SUSY Search

Strong production:

❑ targeting gluinos and squarks

❑ ~t/~b should be lowest mass squarks for naturalness reasons

❑ by far largest cross-sections

Electroweak production:

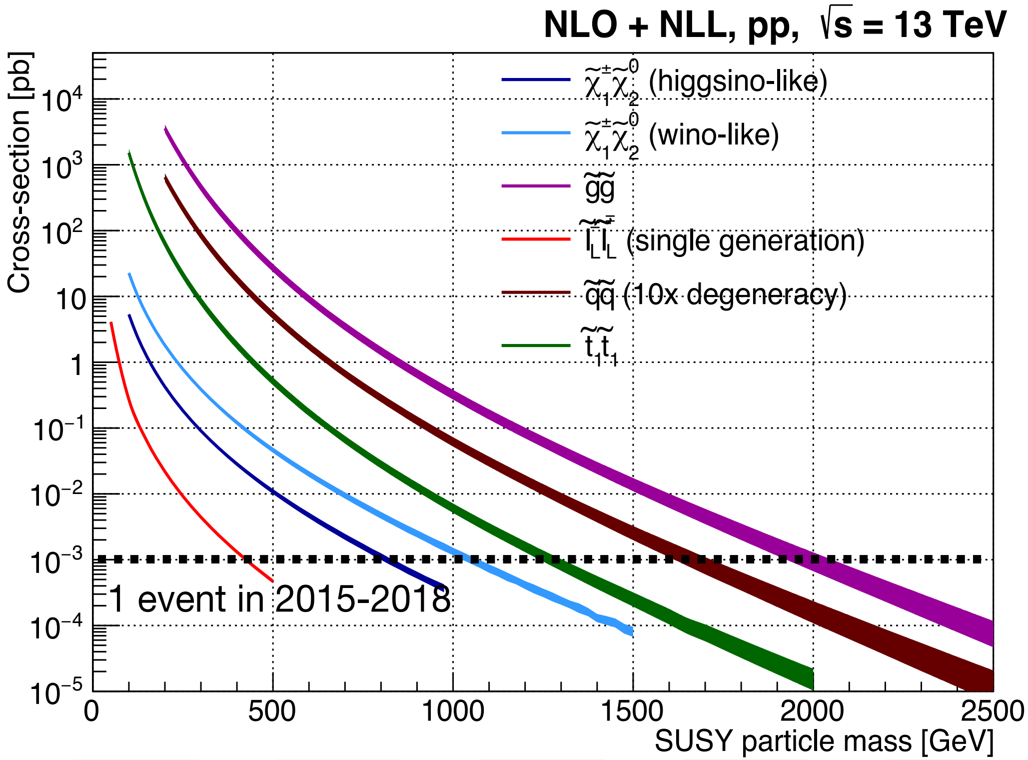
❑ targeting Electroweakinos & sleptons

❑ Lowest mass sparticles, clean signature

RPV/LL:

❑ targeting R-parity violating models and long lived sparticles

❑ More exotic models



slepton: 0.7 TeV

EWK: 0.95 TeV

stop: 1.3 Tev

squarks: 1.85 Tev

gluinos: 2.2 Tev

Current limits at the end of 2015-2018 data taking

■ **Interpretation**: several simplified models but starting to include new interpretations

RPV SUSY

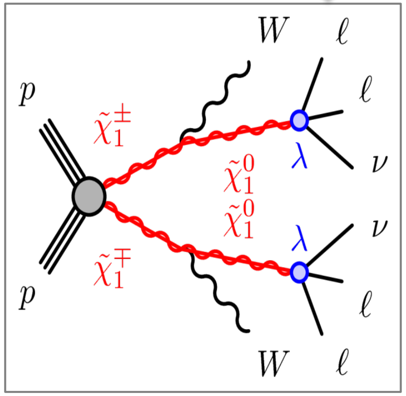
- Precision SM measurements support baryon and lepton number conservation, while some MSSM couplings do not
- Search for R-parity Violating SUSY

$R = (-1)^{3(B-L)+2S}$

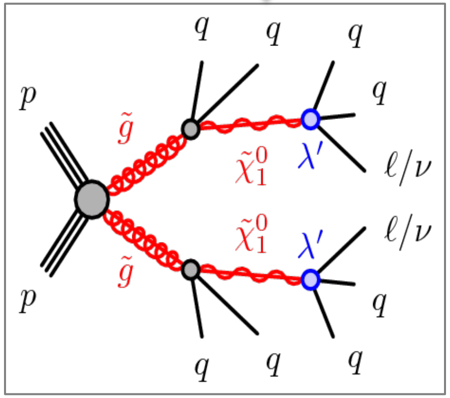
R=+1 (SM); R=-1 (SUSY)

- Super-potential with RPV of lepton or baryon number

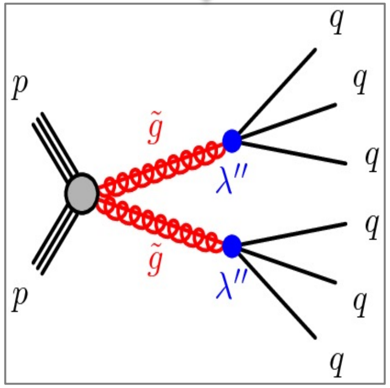
$$W_{R_p} = \frac{1}{2}\lambda_{ijk}L_iL_j\bar{E}_k + \lambda'_{ijk}L_iQ_j\bar{D}_k + \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k + \kappa_i L_i H_2$$



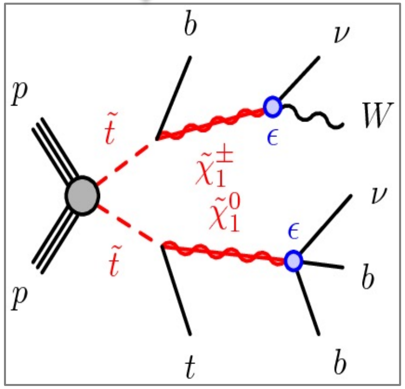
LLE



LQD



UDD



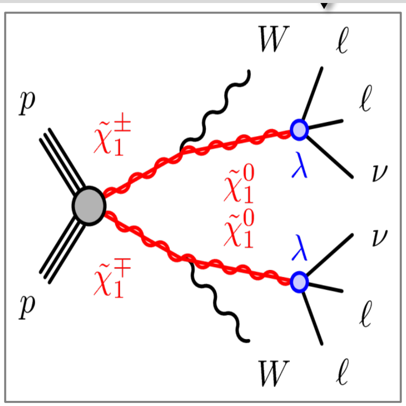
Bilinear LH

RPV SUSY

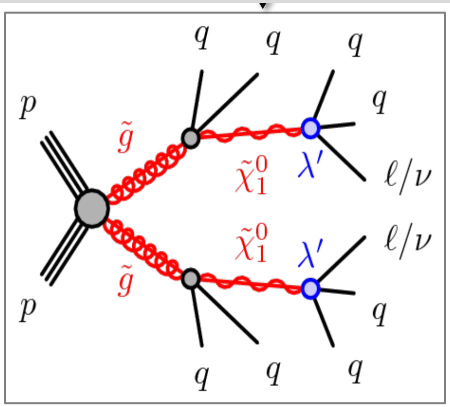
- **Precision SM measurements support baryon and lepton number conservation, while some MSSM couplings do not**
- **Search for R-parity Violating SUSY**

Signatures:

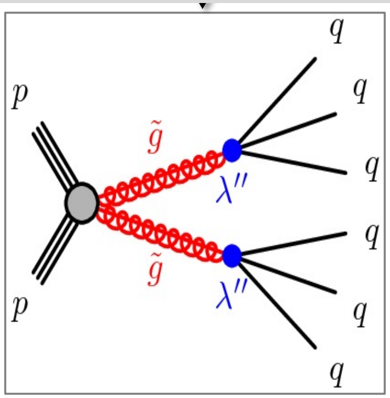
- **Small missing energy (ν)**
- **Final states depending on scenarios:**
  - LLE (decays via Lepton number-violating couplings): multi-leptons
  - LQD (decays via Lepton/Baryon number-violating couplings): lepton+jets
  - UDD (decays via Baryon number-violating couplings): multi-jets
  - LH: lepton+jets



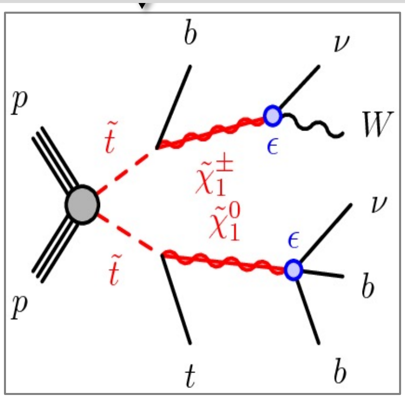
LLE



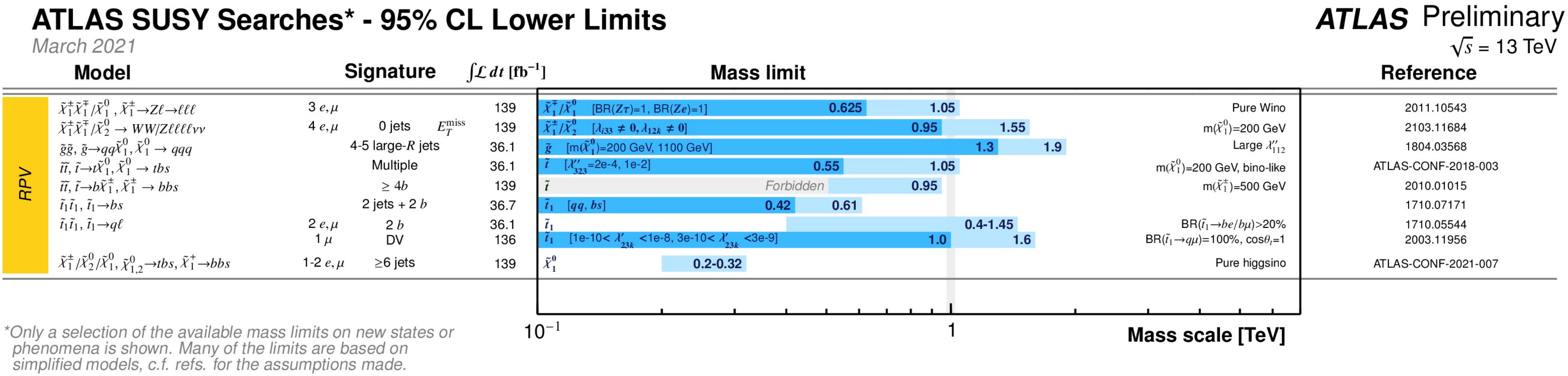
LQD



UDD



Bilinear LH



ATLAS SUSY Searches* - 95% CL Lower Limits

March 2021

ATLAS Preliminary

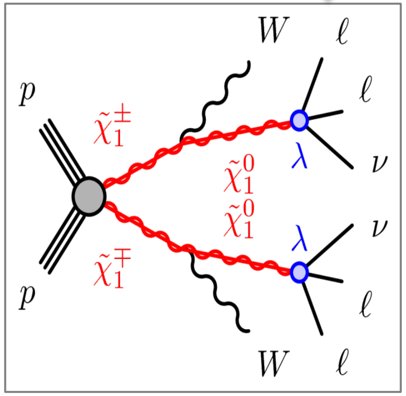
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit				Reference
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \to Z\ell \to \ell\ell\ell$	3 e,μ			139	$\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1]	0.625	1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$]	0.95	1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g} \to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV]	1.3	1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t} \to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2]	0.55	1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t} \to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \to bbs$		$\geq 4b$		139	$\tilde{t}$ Forbidden		0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs]	0.42	0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$		0.4-1.45	BR($\tilde{t}_1 \to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9]	1.0	1.6	BR($\tilde{t}_1 \to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0 \to tbs$, $\tilde{\chi}_1^+ \to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}_1^0$		0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007

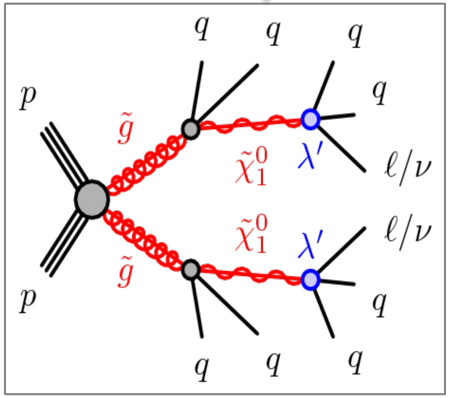
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Signatures:

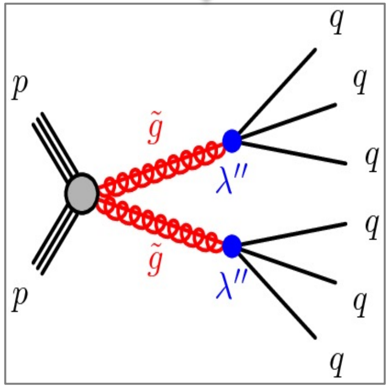
- ➢ **Small missing energy (ν)**
- ➢ **Final states depending on scenarios:**
  - LLE (decays via Lepton number-violating couplings): multi-leptons
  - LQD (decays via Lepton/Baryon number-violating couplings): lepton+jets
  - UDD (decays via Baryon number-violating couplings): multi-jets
  - LH: lepton+jets



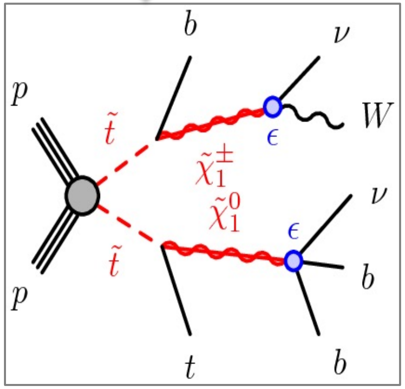
LLE



LQD



UDD

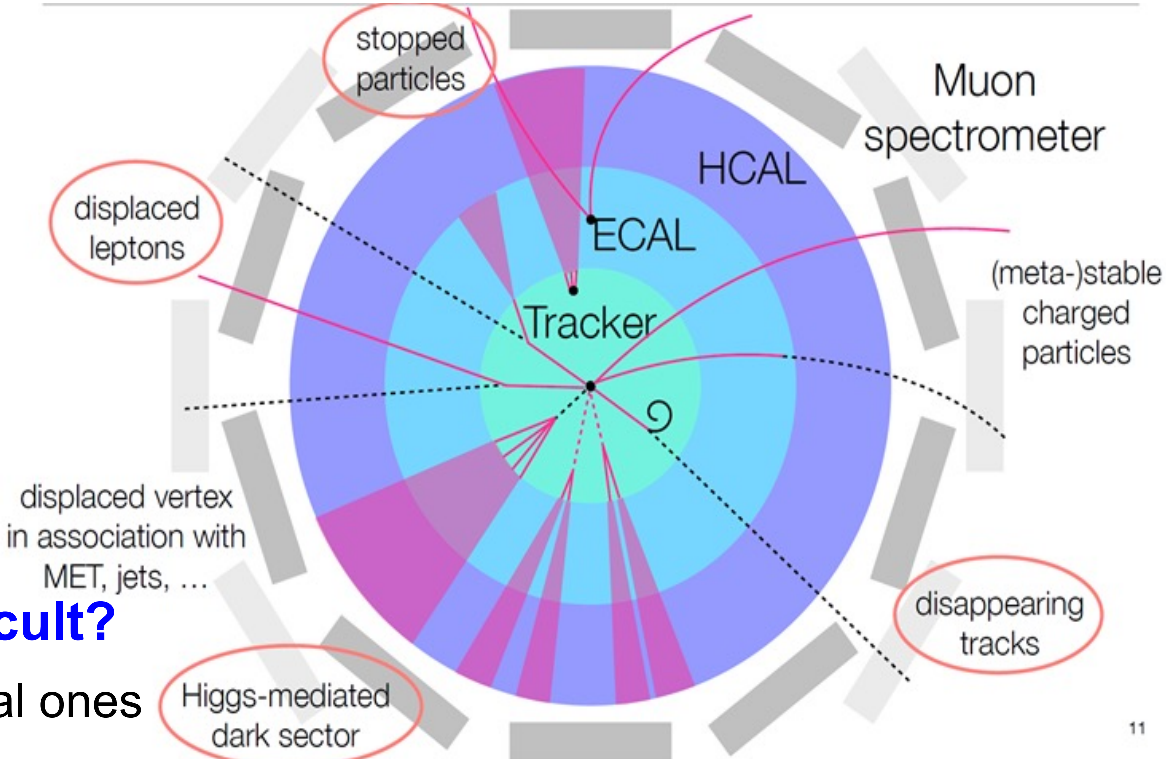


Bilinear LH

Long-lived Particles (LLP)

Long lifetimes result from a few simple physical mechanisms:

- Small couplings (ex. RPV SUSY)
- Limited phase space: small mass splitting (ex. compressed SUSY, …)
- Heavy intermediate states
- ……

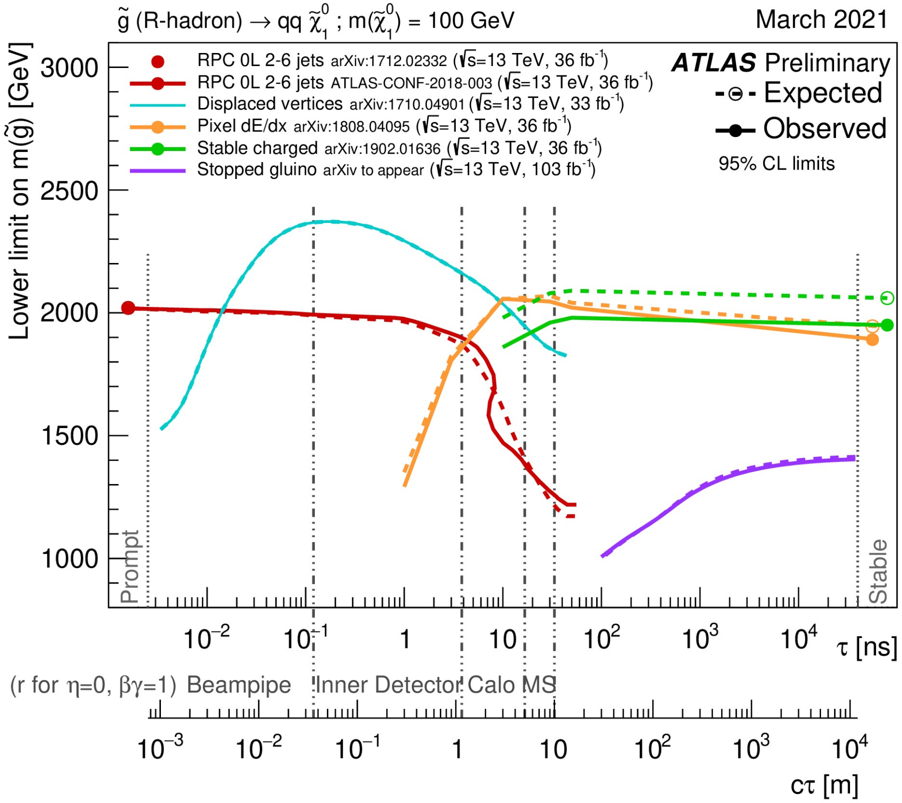


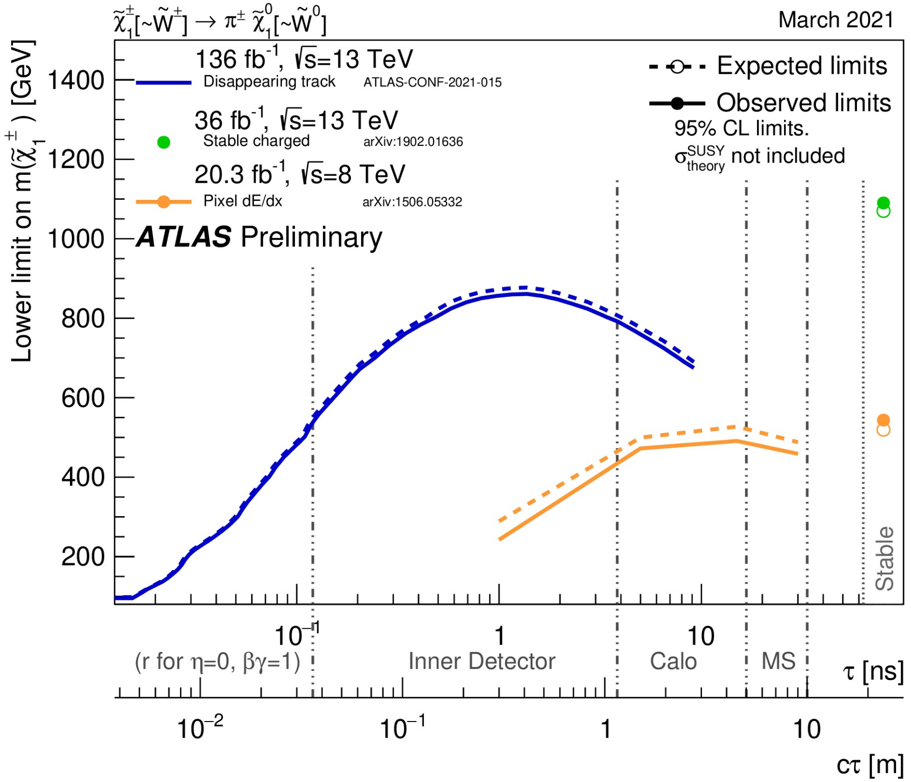
What makes LLPs so difficult?

- Not triggered by conventional ones
- Need special reconstruction
- Non-standard Backgrounds, non-simulated

Long-lived Particles (LLP)

SUSY Models - ATLAS

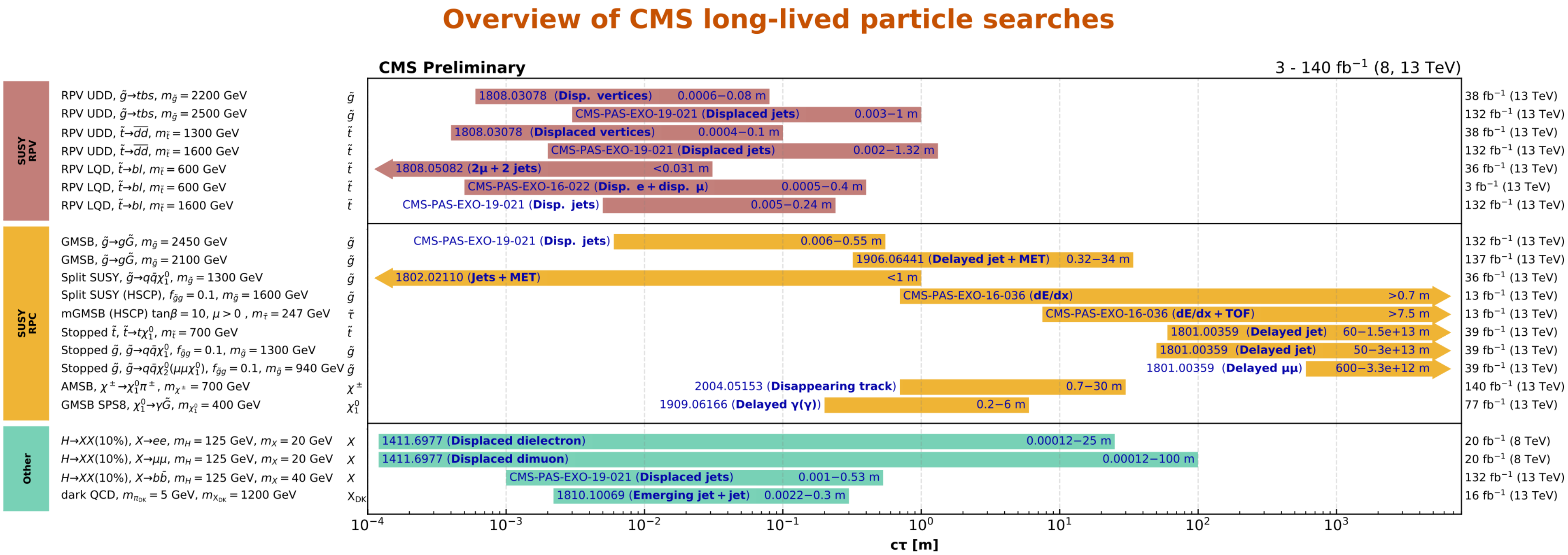




Long-lived R-hadron production

Long-lived chargino

Long-lived Particles (LLP)



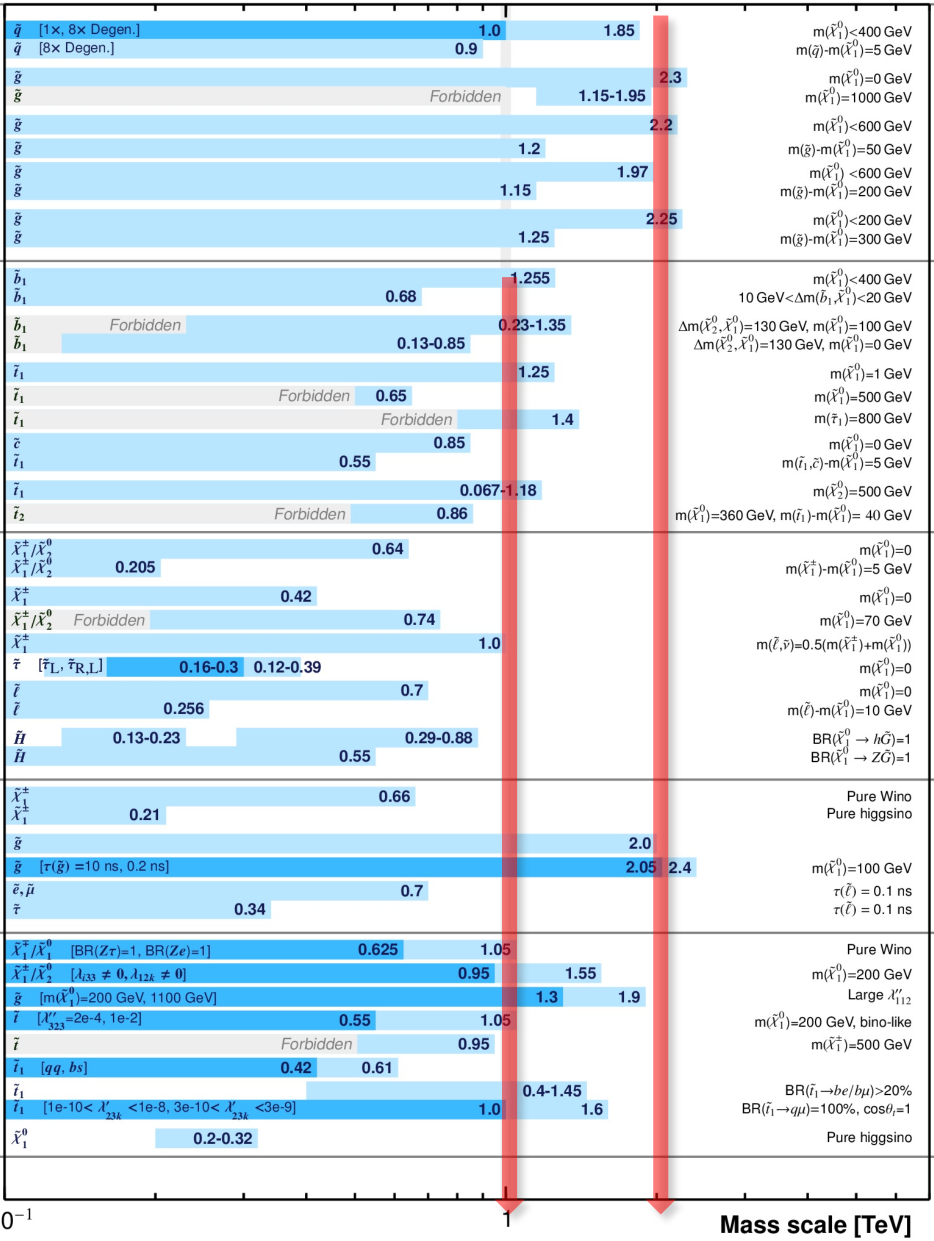
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

LHCP 2020

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2021

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}^0_1$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	36.1	$\tilde{q}$ [8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	139	$\tilde{g}$ 2.3	m($\tilde{\chi}^0_1$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}^0_1$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}^0_1$	1 e,μ	2-6 jets		139	$\tilde{g}$ 2.2	m($\tilde{\chi}^0_1$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	139	$\tilde{g}$ 1.97	m($\tilde{\chi}^0_1$) <600 GeV	2008.06032
		SS e,μ	6 jets		139	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	$E_T^{\rm miss}$	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ 1.255	m($\tilde{\chi}^0_1$)<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}^0_1$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	139	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}^0_2$,$\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$ 1.25	m($\tilde{\chi}^0_1$)=1 GeV	2004.14060,2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ Forbidden 0.65	m($\tilde{\chi}^0_1$)=500 GeV	2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	ATLAS-CONF-2021-008
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	139	$\tilde{t}_1$ 0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_2$, $\tilde{\chi}^0_2\to Z/h\tilde{\chi}^0_1$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	139	$\tilde{t}_1$ 0.067-1.18	m($\tilde{\chi}^0_2$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	139	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}^0_1$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	3 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.64	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.205	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1911.12606
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ 0.42	m($\tilde{\chi}^0_1$)=0	1908.08215
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b/2 γ	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ Forbidden 0.74	m($\tilde{\chi}^0_1$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ 1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ		$E_T^{\rm miss}$	139	$\tilde{\tau}$ [$\tilde{\tau}_{\rm L}$, $\tilde{\tau}_{\rm R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}^0_1$)=0	1911.06660
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}^0_1$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	$E_T^{\rm miss}$	139	$\tilde{\ell}$ 0.256	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	$E_T^{\rm miss}$	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{H}$ 0.55	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	2103.11684
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1$ 0.66	Pure Wino	ATLAS-CONF-2021-015
						$\tilde{\chi}^\pm_1$ 0.21	Pure higgsino	ATLAS-CONF-2021-015
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	139	$\tilde{e},\tilde{\mu}$ 0.7	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
						$\tilde{\tau}$ 0.34	$\tau(\tilde{\ell})$ = 0.1 ns	2011.07812
RPV	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$, $\tilde{\chi}^\pm_1\to Z\ell\to\ell\ell\ell$	3 e,μ			139	$\tilde{\chi}^\mp_1/\tilde{\chi}^0_1$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	139	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}^0_1$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}^\pm_1$, $\tilde{\chi}^\pm_1\to bbs$		$\geq 4b$		139	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}^\pm_1$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_1$, $\tilde{\chi}^0_{1,2}\to tbs$, $\tilde{\chi}^+_1\to bbs$	1-2 e,μ	$\geq$6 jets		139	$\tilde{\chi}^0_1$ 0.2-0.32	Pure higgsino	ATLAS-CONF-2021-007

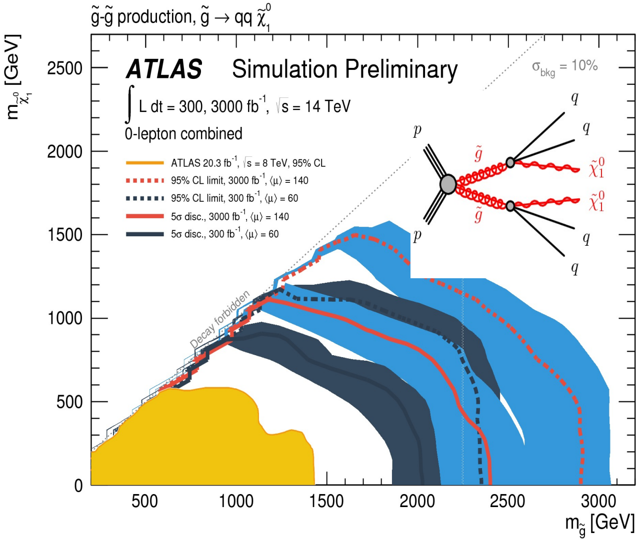
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

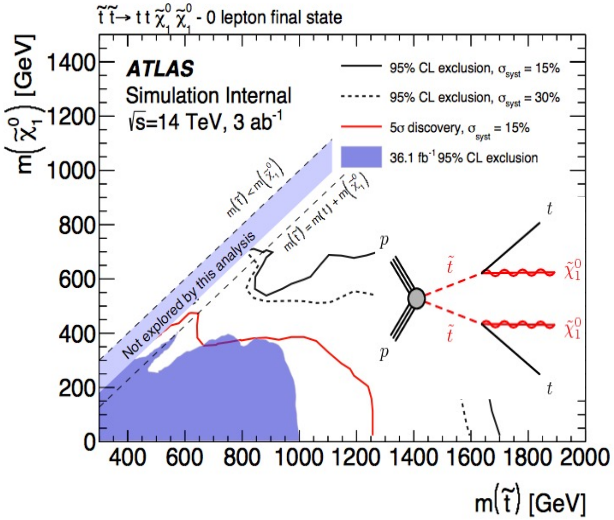
Prospects at HL-LHC: SUSY

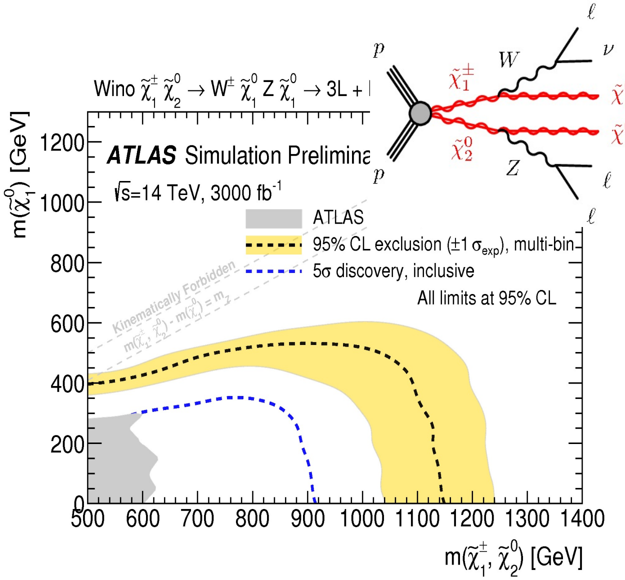
ATL-PHYS-PUB-2018-048

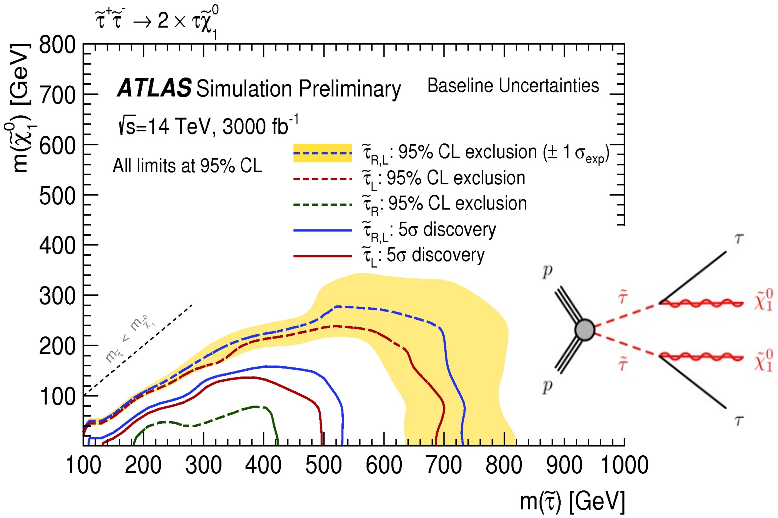
Discovery potential with 3000 fb^{-1}@14TeV

Gluinos ~ 2.5 TeV; Stop ~ 1.2 TeV ; EWKinos ~ 0.9 TeV; Staus ~ 0.5 TeV



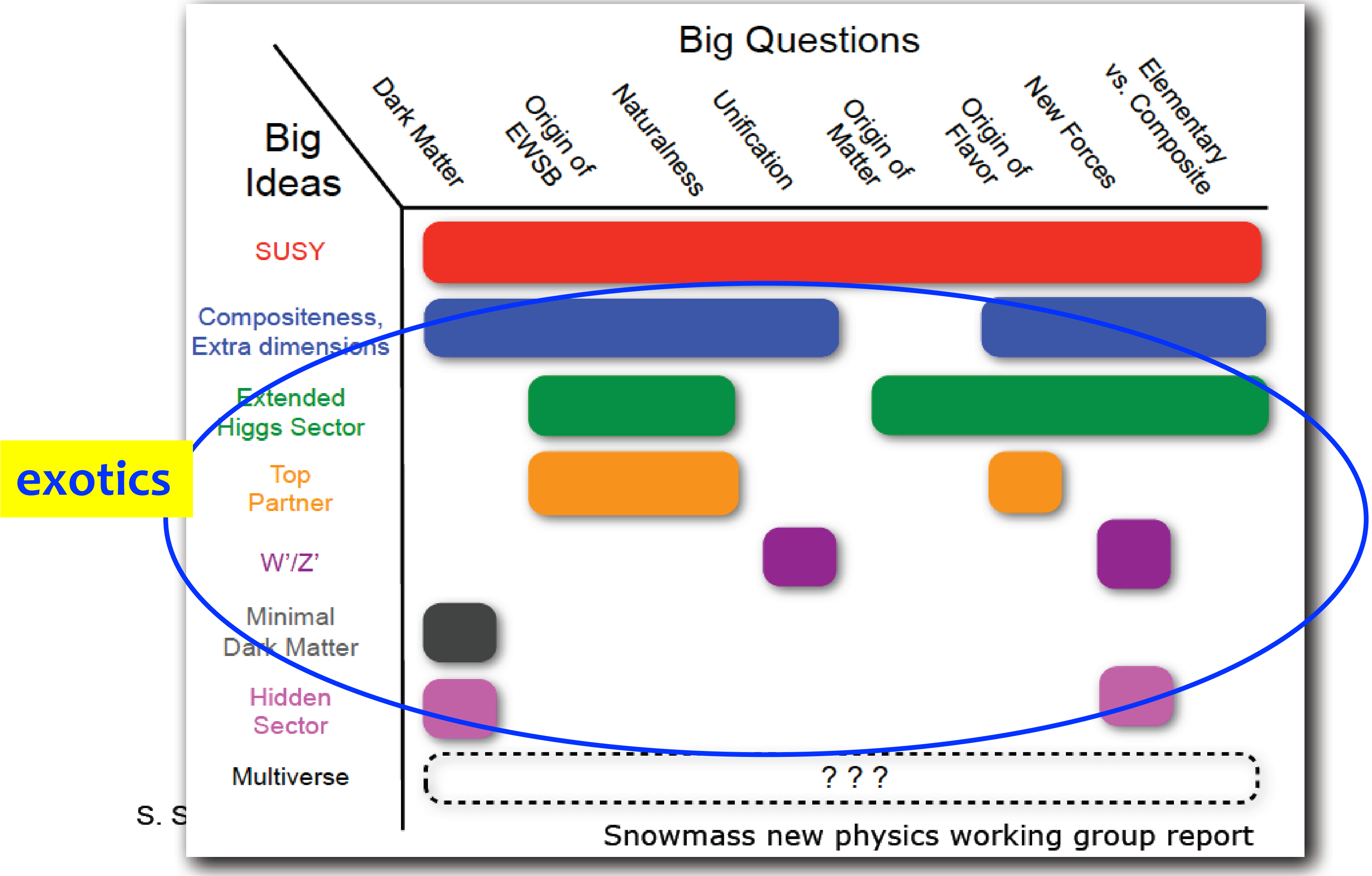






In most BSM scenarios, we expect the HL-LHC will increase the present reach in mass and coupling by 20 – 50% and potentially discover new physics that is currently unconstrained.

New Physics beyond the SM



Big Questions

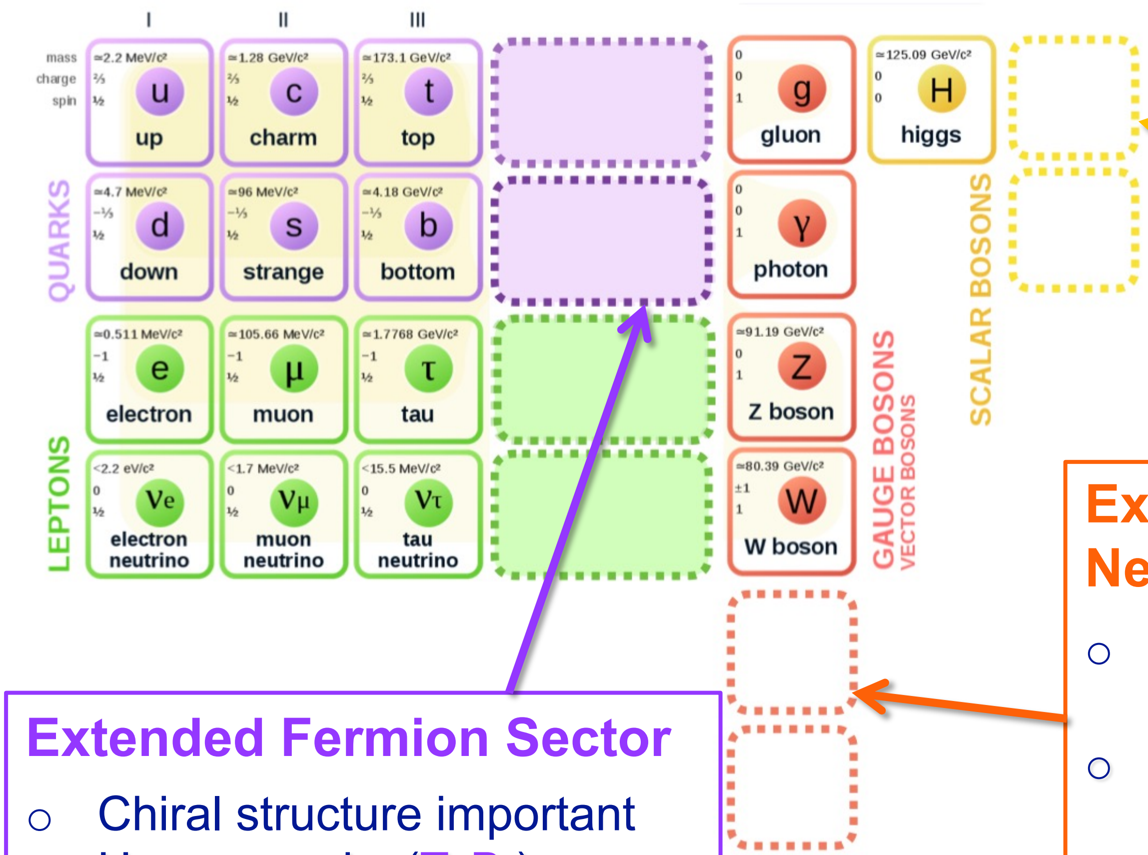
Big Ideas	Dark Matter	Origin of EWSB	Naturalness	Unification	Origin of Matter	Origin of Flavor	New Forces	Elementary vs. Composite
SUSY	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
Compositeness, Extra dimensions	🟦	🟦	🟦	🟦		🟦	🟦	🟦
Extended Higgs Sector		🟩	🟩		🟩	🟩	🟩	🟩
Top Partner		🟧	🟧			🟧		
W'/Z'				🟪			🟪	
Minimal Dark Matter	⬛							
Hidden Sector	🟪						🟪	
Multiverse	? ? ?							

Snowmass new physics working group report

exotics

S. S

Exotics - various extension of SM



Extended Higgs Sector

- ○ A common feature in SUSY models
- ○ Mixing with Higgs

Extended Fermion Sector

- ○ Chiral structure important
- ○ Heavy quarks (T, B)
- ○ Excited fermion (q*,l*,v* …)

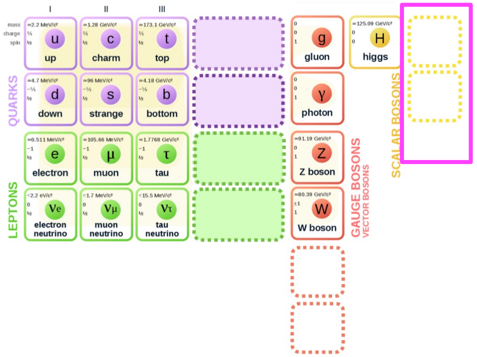
Extended Gauge Sector / New bosons

- ○ Extra dimension models (V KK,GKK, …)
- ○ Grand unification theories (leptoquarks, …)
- ○ Technicolor, composite Higgs (W’, Z’,…)

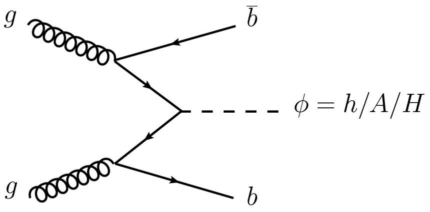
Compositeness

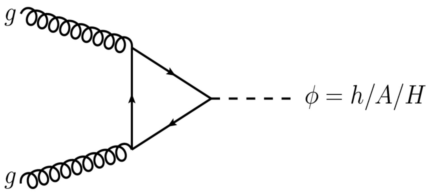
- ○ New forces/particles integrate out at low energies (SM)

Extended Higgs sector – BSM Higgs

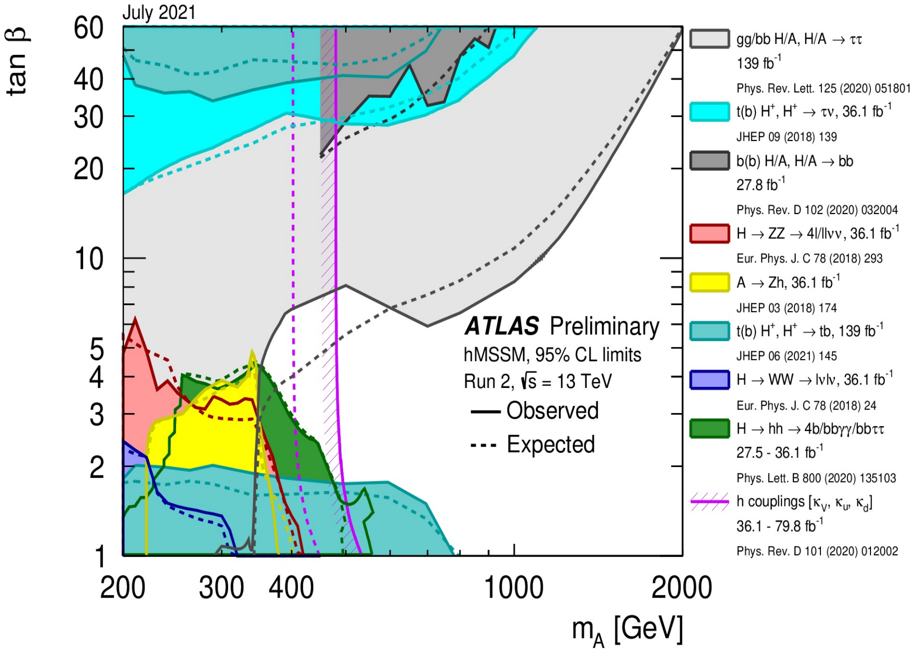


- **Many models: MSSM, 2HDM, etc.**
- **Benchmark models: MSSM-like**
    - **5 Higgs bosons:** h, H, A, $H^{\mp}$
    - **2 free parameters at tree level:** m_A, $\tan\beta = \nu_u/\nu_d$
- **Search for extra Higgs bosons (BSM Higgs)**

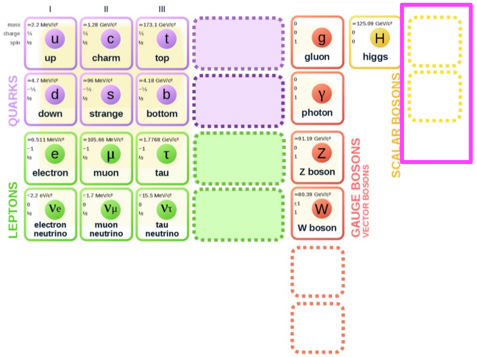




ATL-PHYS-PUB-2021-030

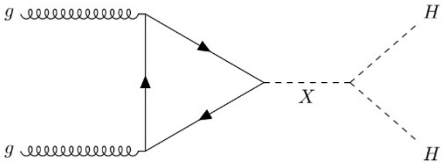


Extended Higgs sector – BSM Higgs

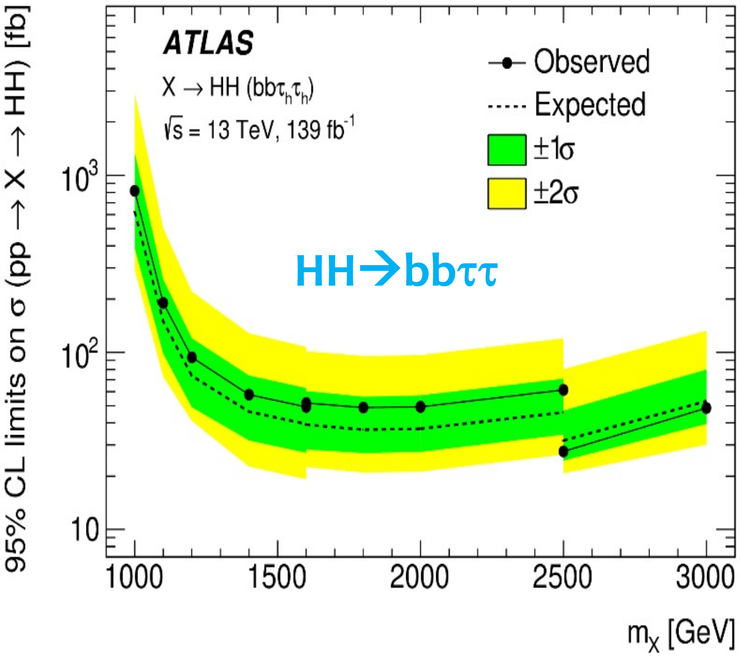


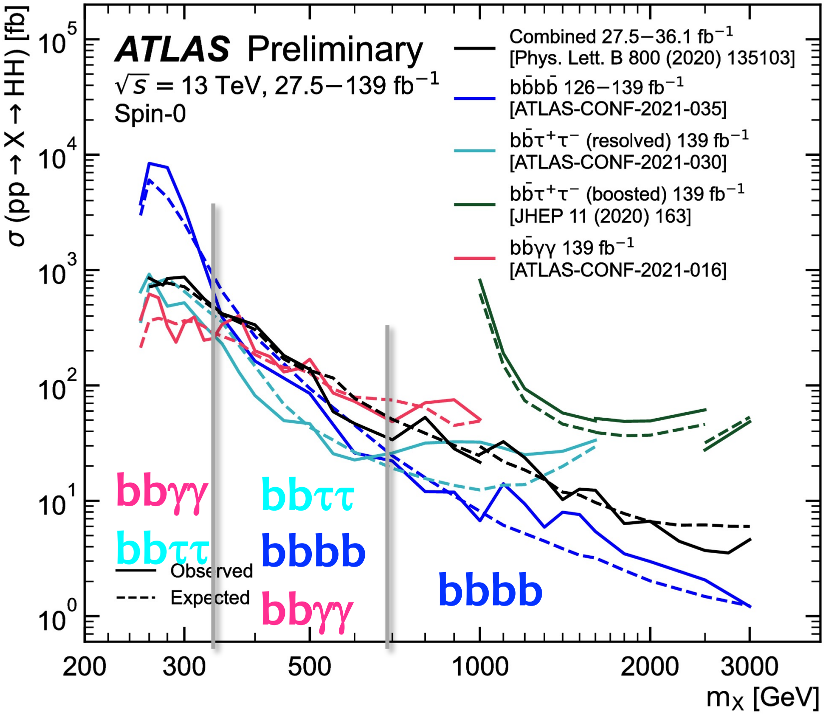
- **Many models: MSSM, 2HDM, etc.**
- **Benchmark models: MSSM-like**
  - **5 Higgs bosons:** h, H, A, $H^{\mp}$
  - **2 free parameters at tree level:** m_A, tan $\beta = \nu_u/\nu_d$
- **Search for extra Higgs bosons (BSM Higgs)**

ATL-PHYS-PUB-2021-031
JHEP 11 (2020) 163

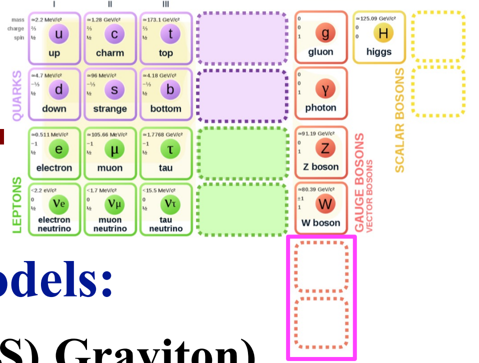


Di-higgs

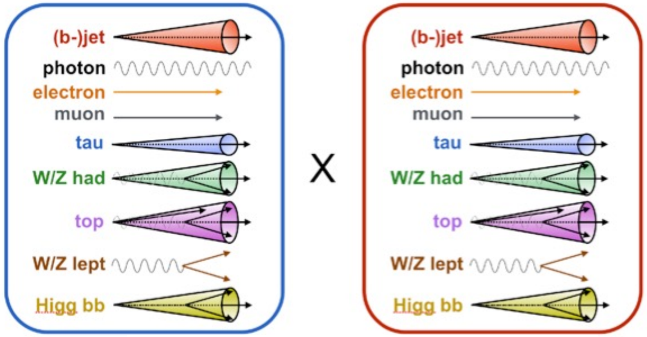




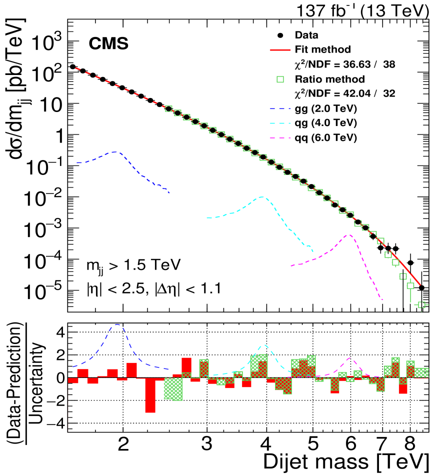
Extended gauge sector – Resonance (jj)

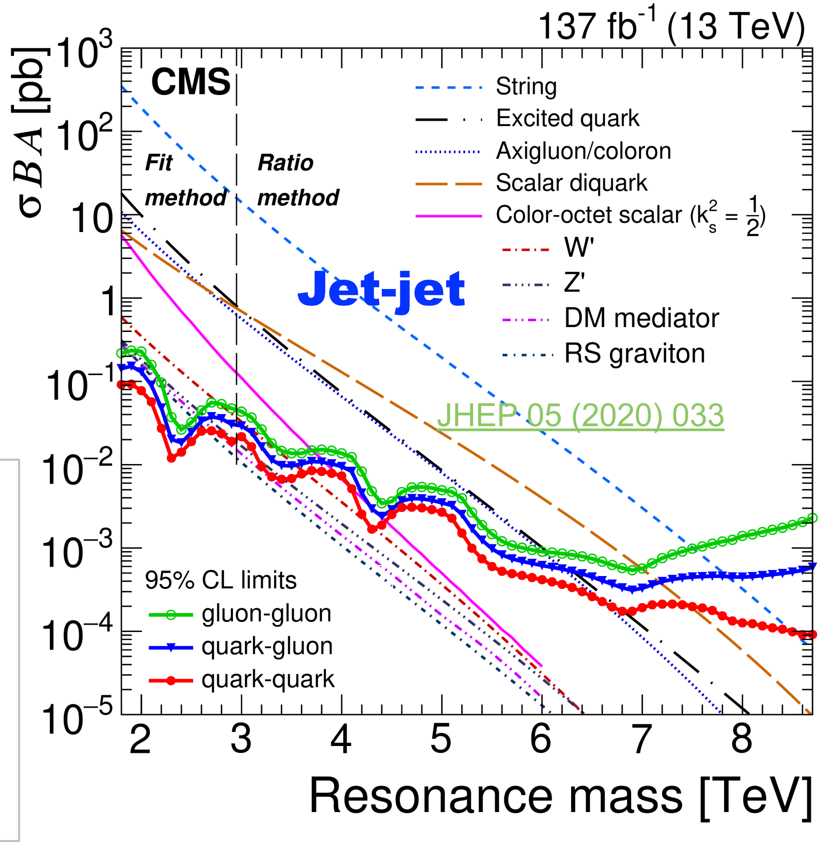


- Classic resonant signatures:



- Predicted by many BSM models:
  - ED (Randall-Sundrum (RS) Graviton), Heavy Vector Triplet (HVT: W′, Z′), …
  - DM mediator, the sequential standard model Z'_{SSM}, the GUT model Z'_{ψ}, …

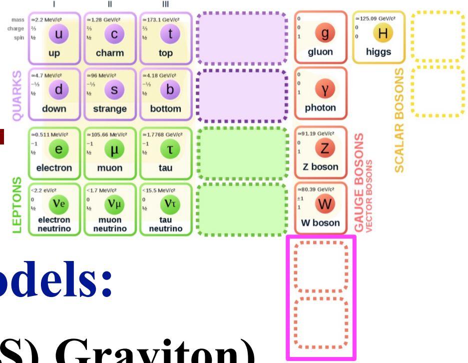




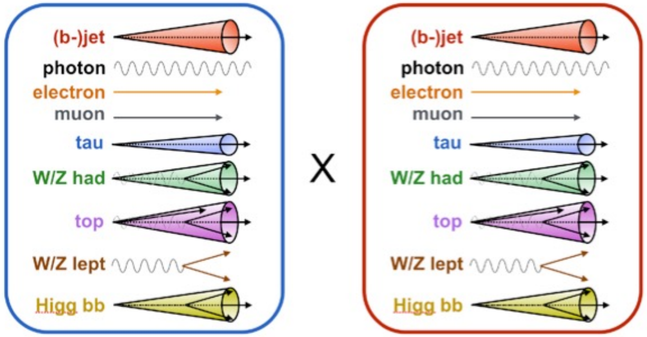
With Run-2 dataset, **multi-TeV** masses probed for the **benchmark** models :

- String ~ 7.5-8.5 TeV
- Excited quark ~ 6-7 TeV
- W’ ~ 3.3-3.6 TeV
- Z’ ~ 2.7-3.4 TeV

Extended gauge sector – Resonance (VV)

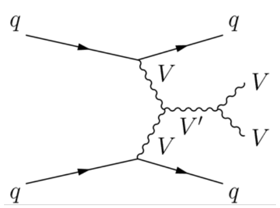


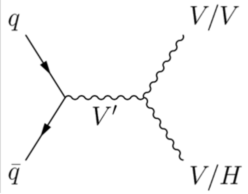
- Classic resonant signatures:

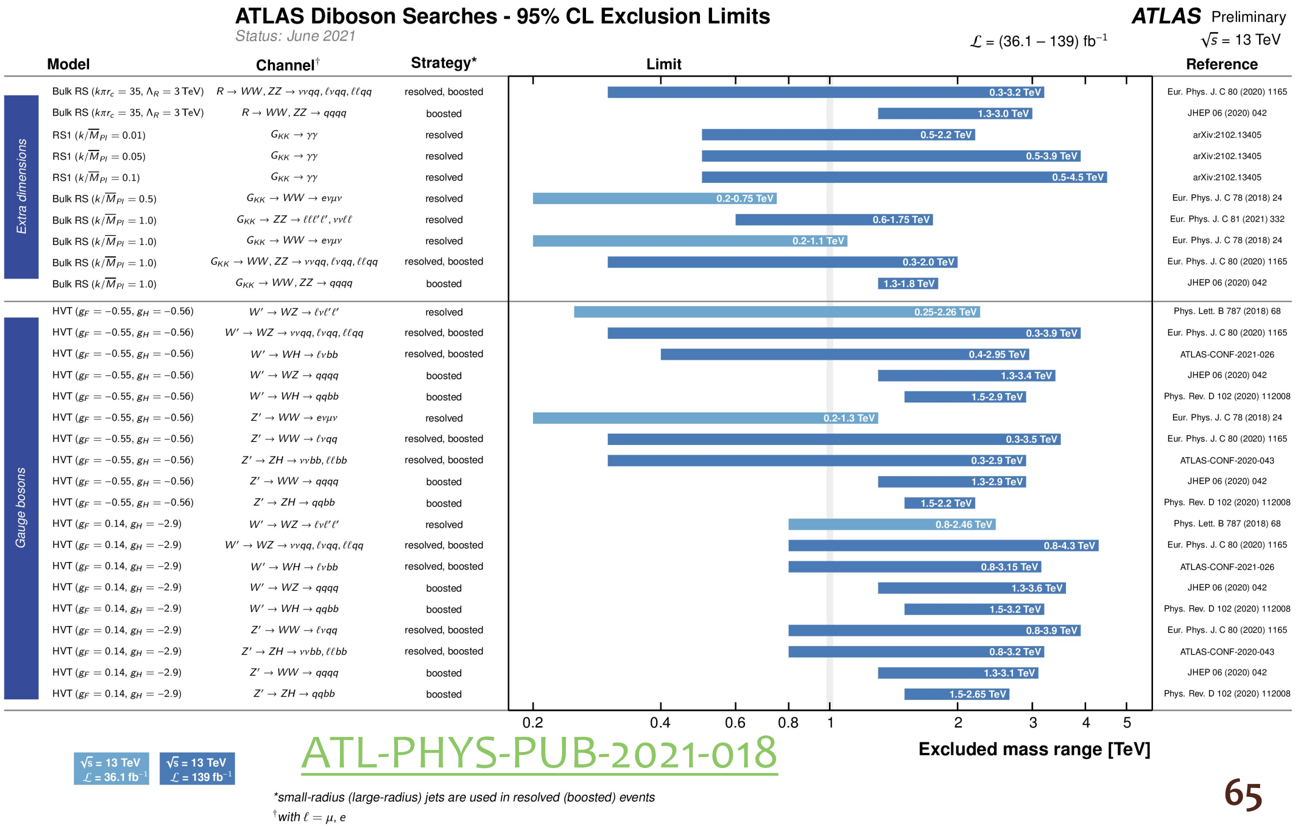


- Predicted by many BSM models:
  - ED (Randall-Sundrum (RS) Graviton), Heavy Vector Triplet (HVT: W′, Z′), …
  - DM mediator, the sequential standard model Z'_{SSM}, the GUT model Z'_{ψ}, …

- Spin-2 bulk RS Graviton $G_{KK} \to WW/ZZ$
- Heavy Vector Triplet (HVT)







ATLAS Diboson Searches - 95% CL Exclusion Limits
Status: June 2021

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
$\mathcal{L}$ = (36.1 – 139) fb^{-1}

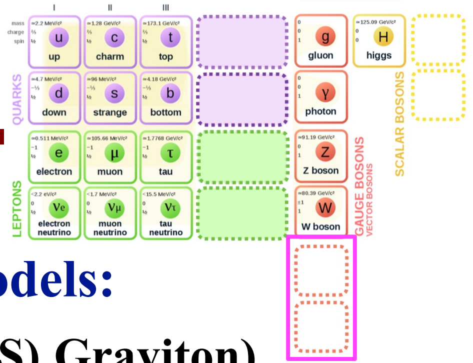
	Model	Channel†	Strategy*	Limit	Reference
Extra dimensions	Bulk RS ($k\pi r_c = 35, \Lambda_R = 3$ TeV)	$R \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.2 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k\pi r_c = 35, \Lambda_R = 3$ TeV)	$R \to WW, ZZ \to qqqq$	boosted	1.3-3.0 TeV	JHEP 06 (2020) 042
	RS1 ($k/\overline{M}_{Pl} = 0.01$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-2.2 TeV	arXiv:2102.13405
	RS1 ($k/\overline{M}_{Pl} = 0.05$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-3.9 TeV	arXiv:2102.13405
	RS1 ($k/\overline{M}_{Pl} = 0.1$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-4.5 TeV	arXiv:2102.13405
	Bulk RS ($k/\overline{M}_{Pl} = 0.5$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.2-0.75 TeV	Eur. Phys. J. C 78 (2018) 24
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to ZZ \to \ell\ell\ell'\ell', \nu\nu\ell\ell$	resolved	0.6-1.75 TeV	Eur. Phys. J. C 81 (2021) 332
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.2-1.1 TeV	Eur. Phys. J. C 78 (2018) 24
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-2.0 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to qqqq$	boosted	1.3-1.8 TeV	JHEP 06 (2020) 042
Gauge bosons	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.25-2.26 TeV	Phys. Lett. B 787 (2018) 68
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.4-2.95 TeV	ATLAS-CONF-2021-026
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WZ \to qqqq$	boosted	1.3-3.4 TeV	JHEP 06 (2020) 042
	HVT ($g_F = -0.55, g_H = -0.56$)	$W' \to WH \to qqbb$	boosted	1.5-2.9 TeV	Phys. Rev. D 102 (2020) 112008
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' \to WW \to e\nu\mu\nu$	resolved	0.2-1.3 TeV	Eur. Phys. J. C 78 (2018) 24
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.3-3.5 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.3-2.9 TeV	ATLAS-CONF-2020-043
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' \to WW \to qqqq$	boosted	1.3-2.9 TeV	JHEP 06 (2020) 042
	HVT ($g_F = -0.55, g_H = -0.56$)	$Z' \to ZH \to qqbb$	boosted	1.5-2.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT ($g_F = 0.14, g_H = -2.9$)	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.8-2.46 TeV	Phys. Lett. B 787 (2018) 68
	HVT ($g_F = 0.14, g_H = -2.9$)	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.8-4.3 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = 0.14, g_H = -2.9$)	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.8-3.15 TeV	ATLAS-CONF-2021-026
	HVT ($g_F = 0.14, g_H = -2.9$)	$W' \to WZ \to qqqq$	boosted	1.3-3.6 TeV	JHEP 06 (2020) 042
	HVT ($g_F = 0.14, g_H = -2.9$)	$W' \to WH \to qqbb$	boosted	1.5-3.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT ($g_F = 0.14, g_H = -2.9$)	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.8-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = 0.14, g_H = -2.9$)	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.8-3.2 TeV	ATLAS-CONF-2020-043
	HVT ($g_F = 0.14, g_H = -2.9$)	$Z' \to WW \to qqqq$	boosted	1.3-3.1 TeV	JHEP 06 (2020) 042
	HVT ($g_F = 0.14, g_H = -2.9$)	$Z' \to ZH \to qqbb$	boosted	1.5-2.65 TeV	Phys. Rev. D 102 (2020) 112008

$\sqrt{s}$ = 13 TeV $\mathcal{L}$ = 36.1 fb^{-1}
$\sqrt{s}$ = 13 TeV $\mathcal{L}$ = 139 fb^{-1}

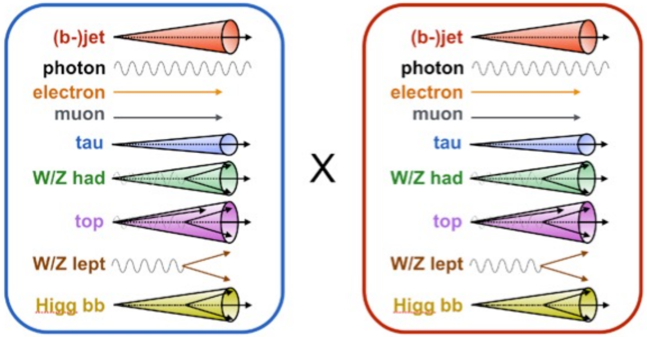
ATL-PHYS-PUB-2021-018

*small-radius (large-radius) jets are used in resolved (boosted) events
†with $\ell = \mu, e$

Extended gauge sector – Resonance (II)

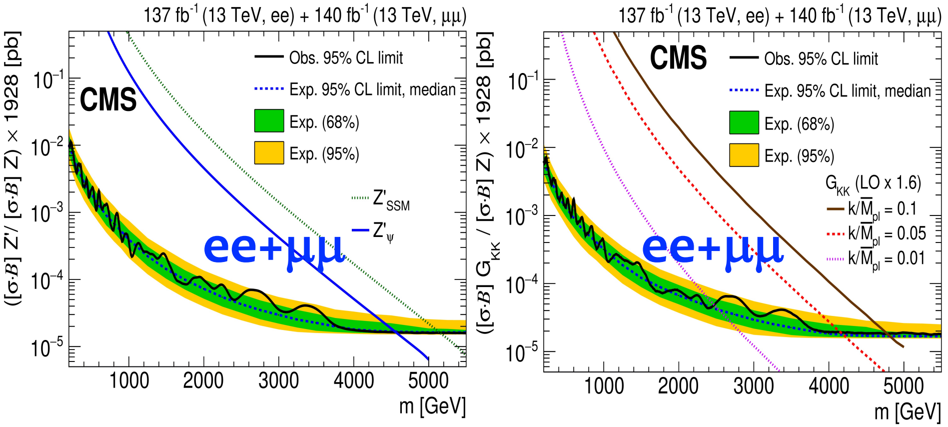


- **Classic resonant signatures:**

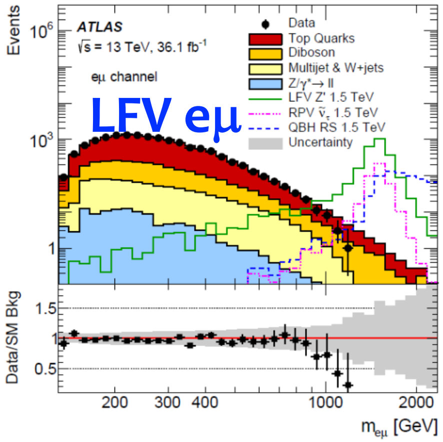


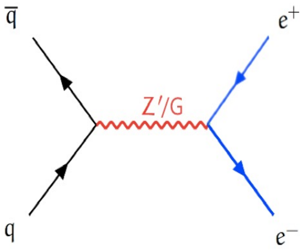
arXiv:2103.02708

- **Predicted by many BSM models:**
  - ED (Randall-Sundrum (RS) Graviton), Heavy Vector Triplet (HVT: W′, Z′), …
  - DM mediator, the sequential standard model Z'_{SSM}, the GUT model Z'_{ψ}, …



PRL 125 (2020) 251802



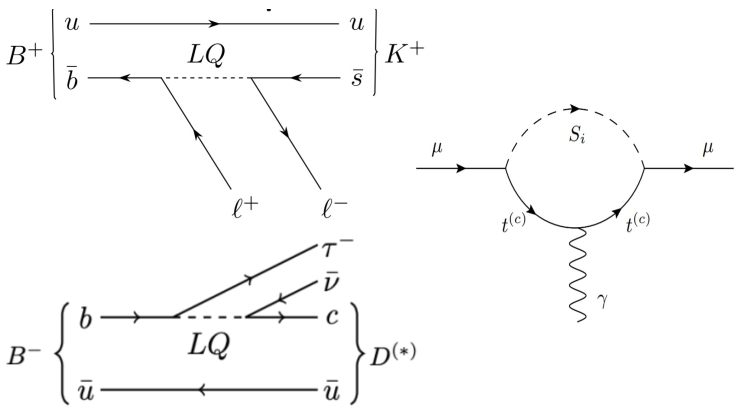


With Run-2 dataset, **multi-TeV** masses probed for the **benchmark** models :

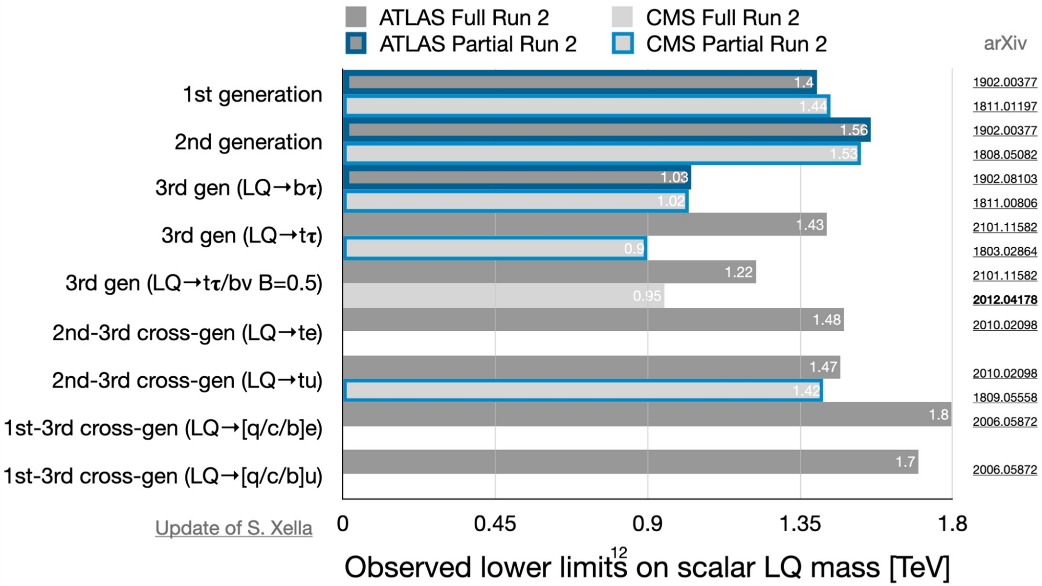
- ✓ G_{kk} ~ 2.5-4.8 TeV
- ✓ Z'_{SSM} ~ 4.5-5.1 TeV

Extended gauge sector – Leptoquarks (LQ)

- **Leptoquarks (LQs)** arise in many models, such as grand unified theories, compositeness models and superstring theories.
- **LQs:** carry colour charge, fractional electric charge, and both lepton and baryon quantum numbers.
- **Could explain B anomalies and μ g-2**

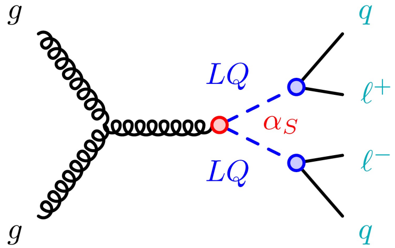


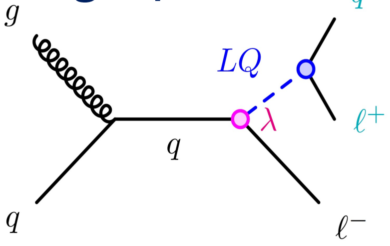
m(LQ_{mix}) > 0.9-1.8TeV

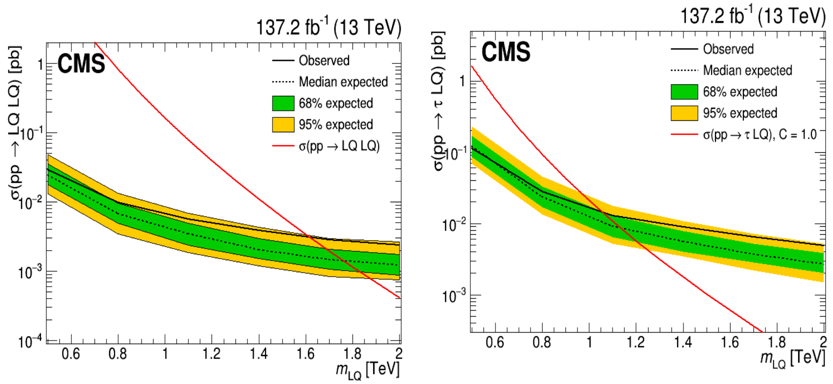


Pair production

Single production

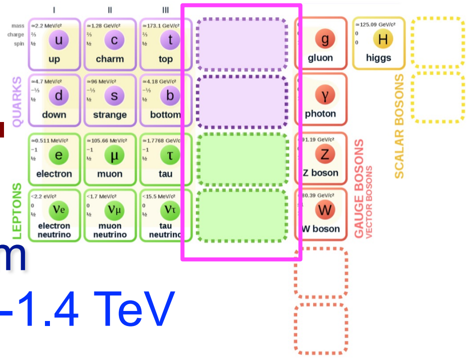




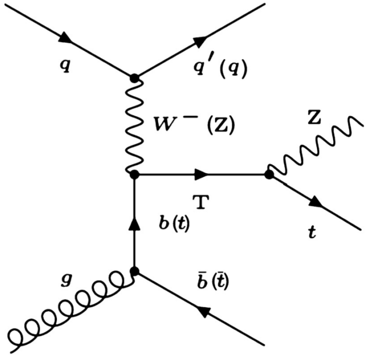


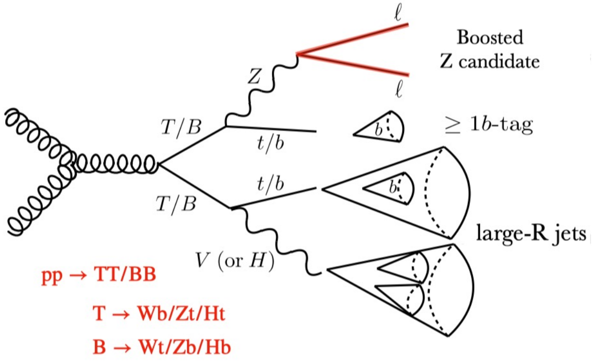
PLB 819 (2021) 136446

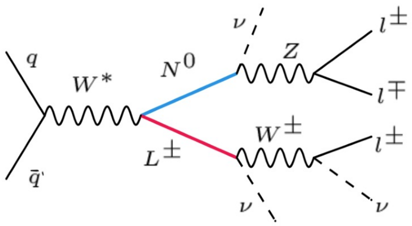
Extended fermion sector

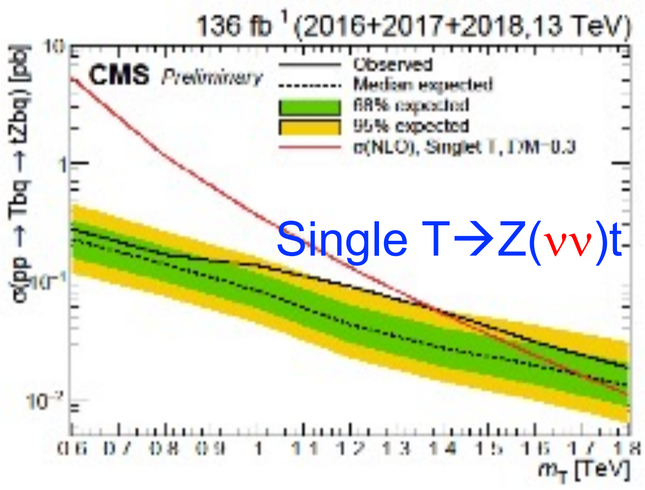


- Heavy Vector-like fermions (T, B, Tau …)
  - New heavy partner of top in loop to solve hierarchy problem
  - Among the best constraints on Singlet/Doublet BB, TT: 1.2-1.4 TeV
- Excited fermion (q*,l*,v* …) see#64



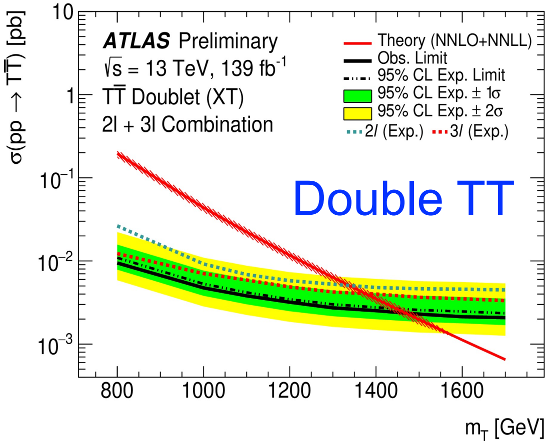




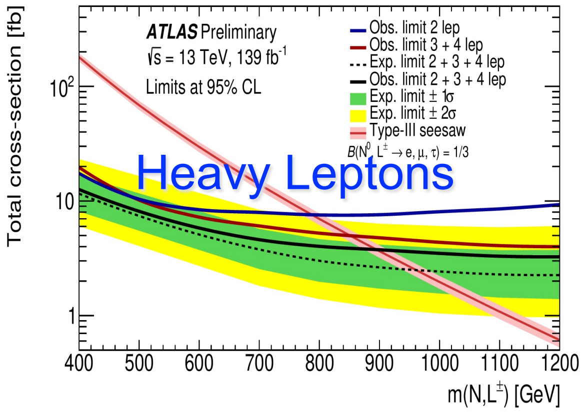


Single T→Z(νν)t

CMS-PAS-B2G-19-004



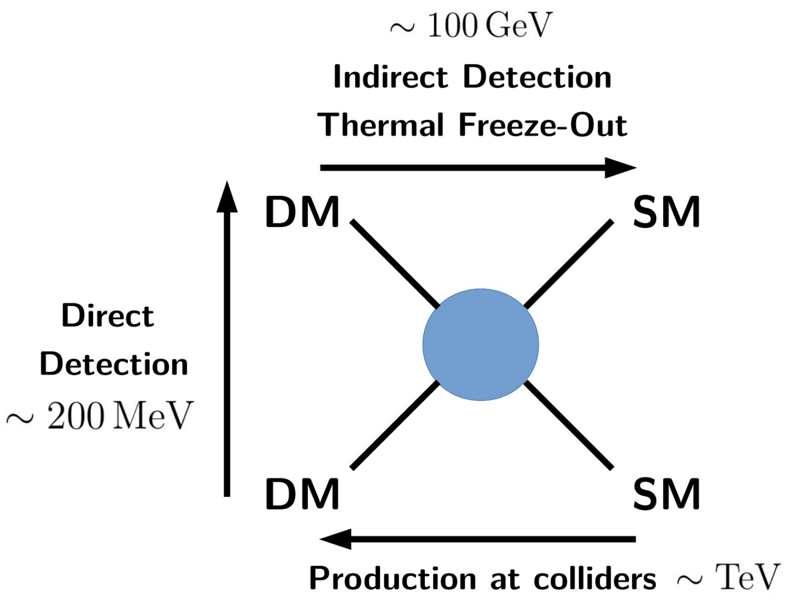
Double TT

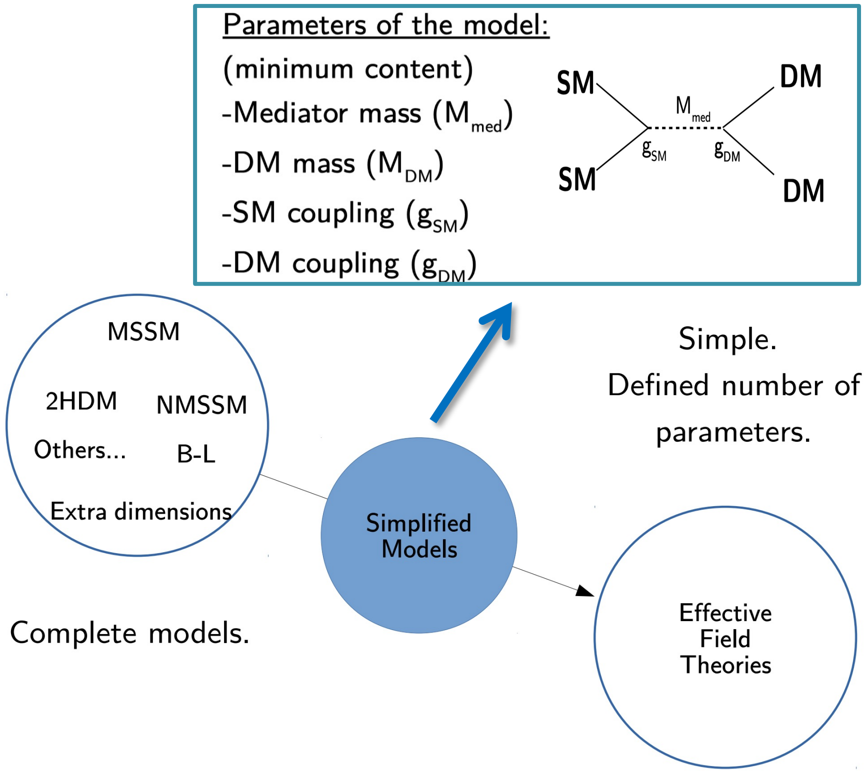


Heavy Leptons

$m(N, L^{\pm}) >$ 910 GeV

Dark Matter (DM)





Parameters of the model:
(minimum content)
-Mediator mass (M_{med})
-DM mass (M_{DM})
-SM coupling (g_{SM})
-DM coupling (g_{DM})

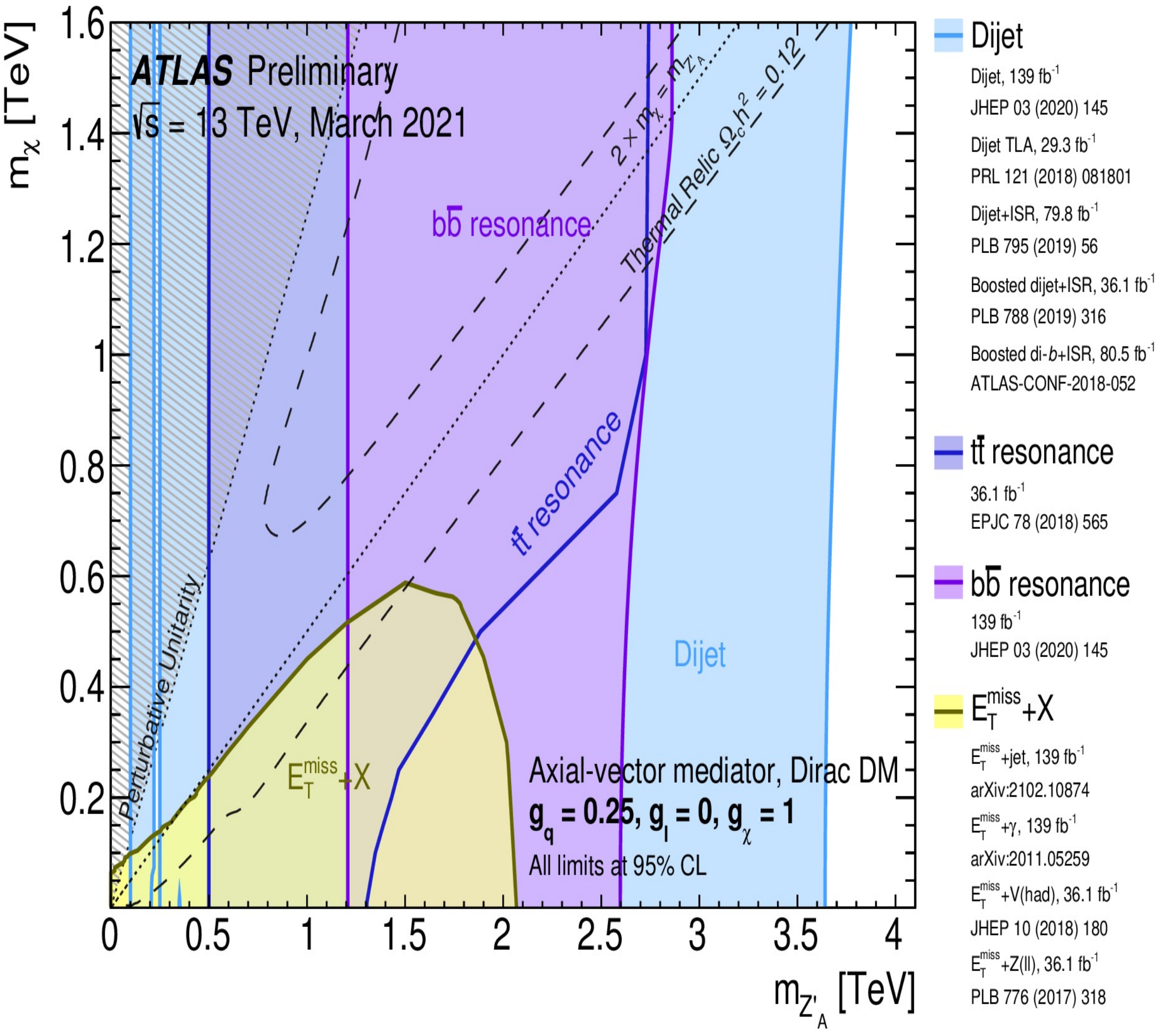
Simple.
Defined number of parameters.

Complete models.

- **Colliders:**
  - **Complete models (SUSY, axions, 2HDM, Higgs portal DM, …);**
  - **Simplified models (mono-X, mediator, …);**
- **Direct detection (XENON1T, PandaX, …)**

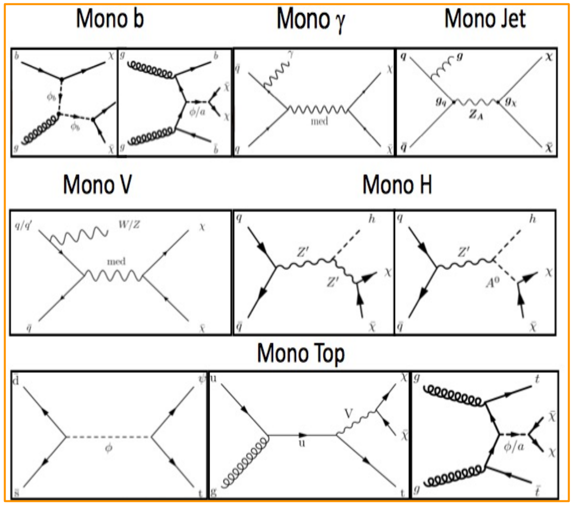
DM direct search at colliders

Searches with MET+X or mediator

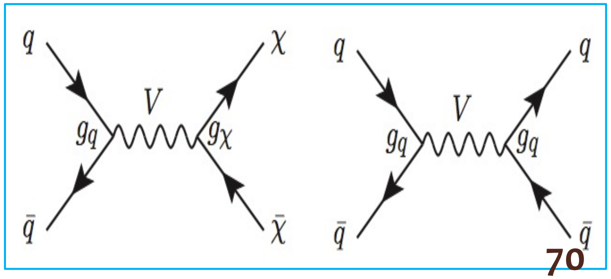


ATL-PHYS-PUB-2021-006

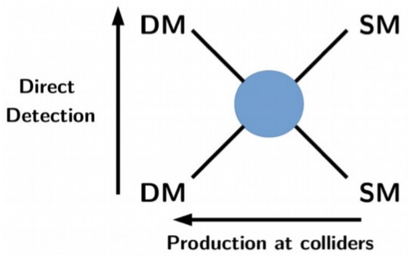
- Searches in the Mono-X final states: Many models constrained up to 2 TeV



- Searches also in the Di-Jet final states exclude up to 3.6 TeV for almost whole DM range



Collider vs Direct Detection



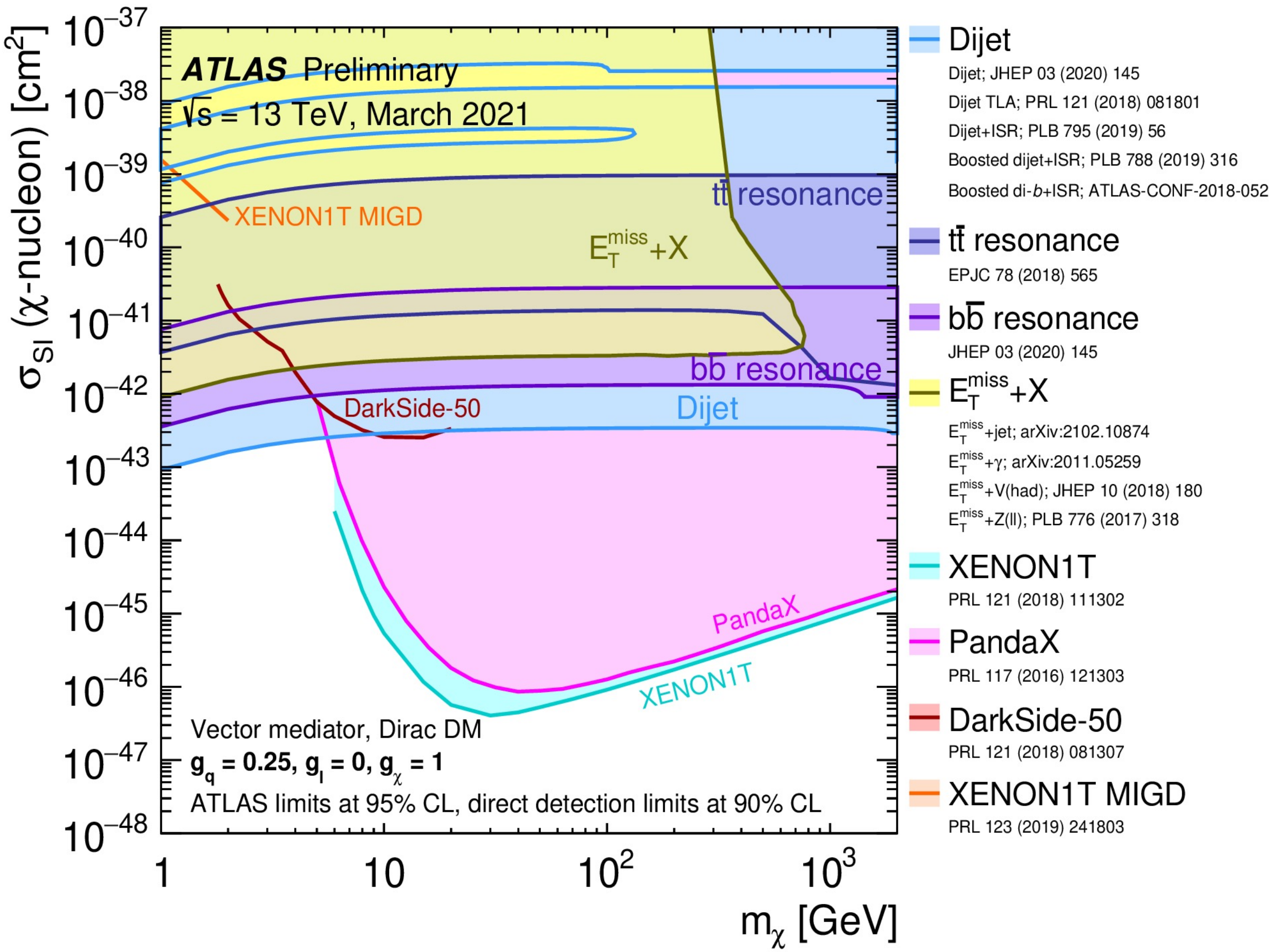
Complementarity:

Collider searches:

- Almost independent on DM mass.
- Better performance for low DM masses.

Direct detection searches:

- Better performance for DM masses > 10 GeV.



ATL-PHYS-PUB-2021-006

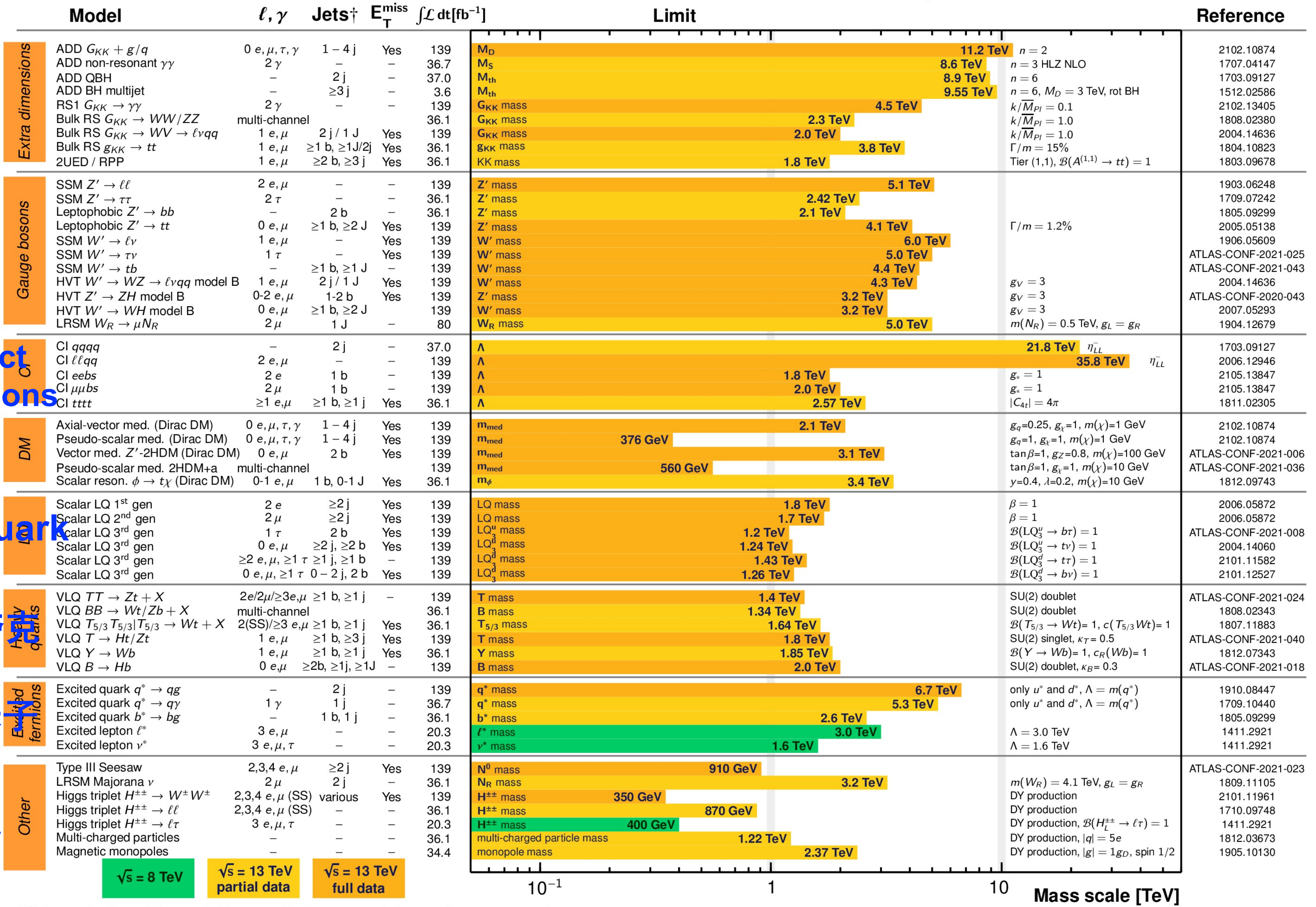
ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2021

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 – 139)\ \text{fb}^{-1}$

$\sqrt{s}$ = 8, 13 TeV



	Model	ℓ,γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit			Reference
额外维粒子 Extra dimensions	ADD $G_{KK}+g/q$	$0\ e,\mu,\tau,\gamma$	1 – 4 j	Yes	139	M_D	11.2 TeV	$n=2$	2102.10874
	ADD non-resonant $\gamma\gamma$	$2\ \gamma$	–	–	36.7	M_S	8.6 TeV	$n=3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th}	8.9 TeV	$n=6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
	RS1 $G_{KK}\to\gamma\gamma$	$2\ \gamma$	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl}=0.1$	2102.13405
	Bulk RS $G_{KK}\to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl}=1.0$	1808.02380
	Bulk RS $G_{KK}\to WV\to\ell\nu qq$	$1\ e,\mu$	2 j / 1 J	Yes	139	G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl}=1.0$	2004.14636
	Bulk RS $g_{KK}\to tt$	$1\ e,\mu$	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m=15\%$	1804.10823
	2UED / RPP	$1\ e,\mu$	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)}\to tt)=1$	1803.09678
W′, Z′ Gauge bosons	SSM $Z'\to\ell\ell$	$2\ e,\mu$	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z'\to\tau\tau$	$2\ \tau$	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z'\to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z'\to tt$	$0\ e,\mu$	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m=1.2\%$	2005.05138
	SSM $W'\to\ell\nu$	$1\ e,\mu$	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W'\to\tau\nu$	$1\ \tau$	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W'\to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W'\to WZ\to\ell\nu qq$ model B	$1\ e,\mu$	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V=3$	2004.14636
	HVT $Z'\to ZH$ model B	0-2 e,μ	1-2 b	Yes	139	Z' mass	3.2 TeV	$g_V=3$	ATLAS-CONF-2020-043
	HVT $W'\to WH$ model B	$0\ e,\mu$	≥1 b, ≥2 J		139	W' mass	3.2 TeV	$g_V=3$	2007.05293
	LRSM $W_R\to\mu N_R$	$2\ \mu$	1 J	–	80	W_R mass	5.0 TeV	$m(N_R)=0.5$ TeV, $g_L=g_R$	1904.12679
Contact interactions CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	$2\ e,\mu$	–	–	139	Λ	35.8 TeV	η_{LL}^{-}	2006.12946
	CI $eebs$	$2\ e$	1 b	–	139	Λ	1.8 TeV	$g_*=1$	2105.13847
	CI $\mu\mu bs$	$2\ \mu$	1 b	–	139	Λ	2.0 TeV	$g_*=1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert=4\pi$	1811.02305
暗物质 DM	Axial-vector med. (Dirac DM)	$0\ e,\mu,\tau,\gamma$	1 – 4 j	Yes	139	m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	$0\ e,\mu,\tau,\gamma$	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	$0\ e,\mu$	2 b	Yes	139	m_{med}	3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	ATLAS-CONF-2021-006
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med}	560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
	Scalar reson. $\phi\to t\chi$ (Dirac DM)	0-1 e,μ	1 b, 0-1 J	Yes	36.1	m_ϕ	3.4 TeV	y=0.4, λ=0.2, $m(\chi)$=10 GeV	1812.09743
leptoquark LQ	Scalar LQ 1st gen	$2\ e$	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta=1$	2006.05872
	Scalar LQ 2nd gen	$2\ \mu$	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta=1$	2006.05872
	Scalar LQ 3rd gen	$1\ \tau$	2 b	Yes	139	LQ_3^u mass	1.2 TeV	$\mathcal{B}(LQ_3^u\to b\tau)=1$	ATLAS-CONF-2021-008
	Scalar LQ 3rd gen	$0\ e,\mu$	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u\to t\nu)=1$	2004.14060
	Scalar LQ 3rd gen	≥2 e,μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d\to t\tau)=1$	2101.11582
	Scalar LQ 3rd gen	$0\ e,\mu$, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(LQ_3^d\to b\nu)=1$	2101.12527
额外夸克 Heavy quarks	VLQ $TT\to Zt+X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB\to Wt/Zb+X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3}\to Wt+X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3}\to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T\to Ht/Zt$	$1\ e,\mu$	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y\to Wb$	$1\ e,\mu$	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y\to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B\to Hb$	$0\ e,\mu$	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
重费米子 Excited fermions	Excited quark $q^*\to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1910.08447
	Excited quark $q^*\to q\gamma$	$1\ \gamma$	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda=m(q^*)$	1709.10440
	Excited quark $b^*\to bg$	–	1 b, 1 j	–	36.1	b^* mass	2.6 TeV		1805.09299
	Excited lepton ℓ^*	$3\ e,\mu$	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda=3.0$ TeV	1411.2921
	Excited lepton ν^*	$3\ e,\mu,\tau$	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda=1.6$ TeV	1411.2921
其他 Other	Type III Seesaw	2,3,4 e,μ	≥2 j	Yes	139	N^0 mass	910 GeV		ATLAS-CONF-2021-023
	LRSM Majorana ν	$2\ \mu$	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R)=4.1$ TeV, $g_L=g_R$	1809.11105
	Higgs triplet $H^{\pm\pm}\to W^\pm W^\pm$	2,3,4 e,μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm}\to\ell\ell$	2,3,4 e,μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass	870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm}\to\ell\tau$	$3\ e,\mu,\tau$	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm}\to\ell\tau)=1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass	1.22 TeV	DY production, $\lvert q\rvert=5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert=1g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV

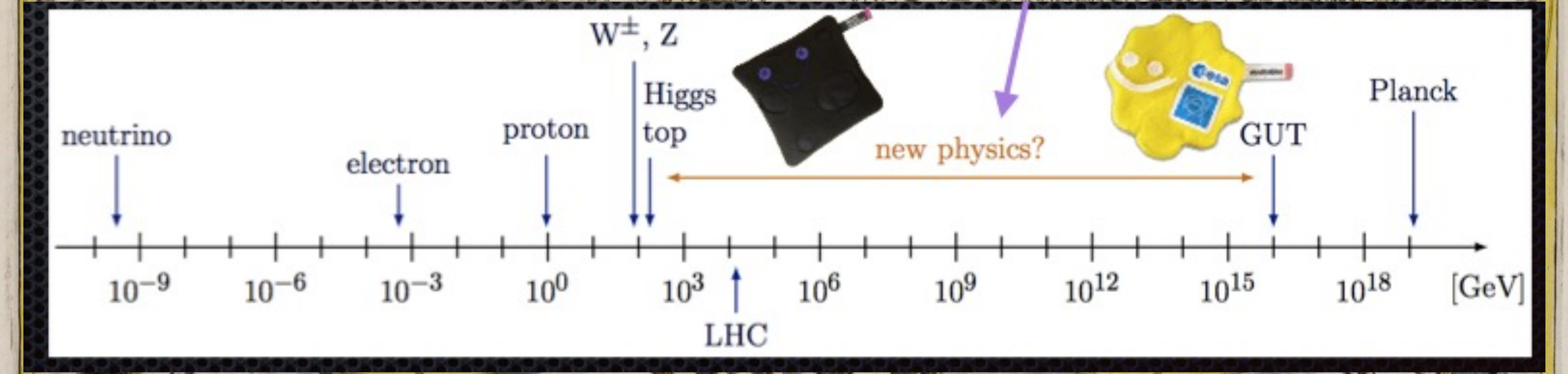
🟨 $\sqrt{s}$ = 13 TeV partial data

🟧 $\sqrt{s}$ = 13 TeV full data

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

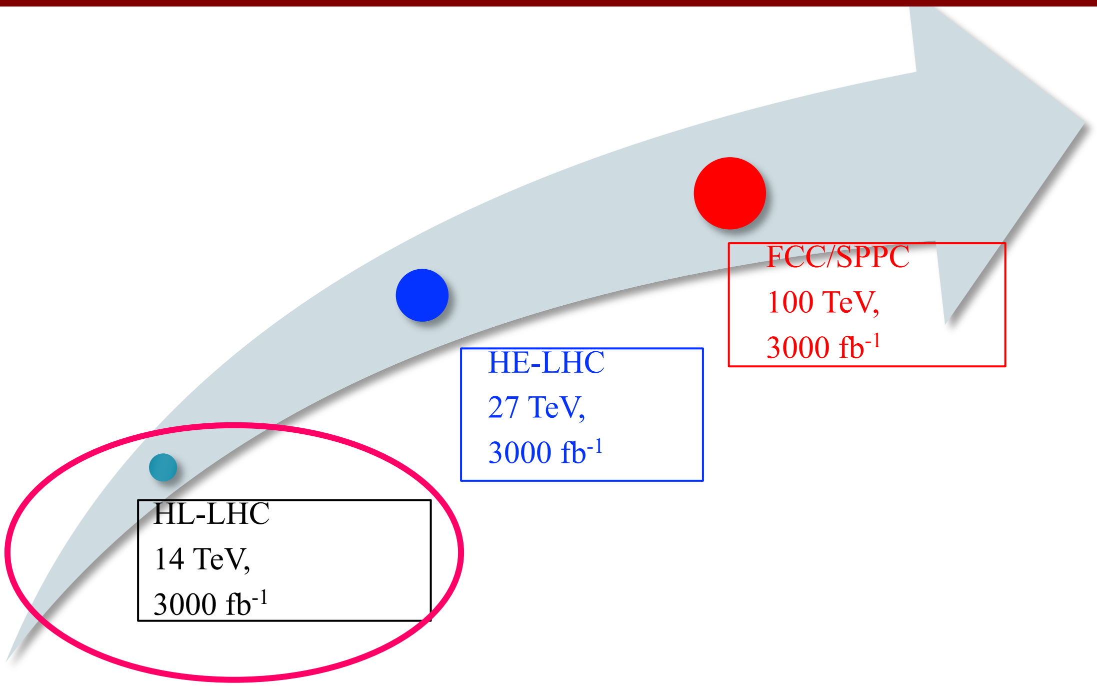
The journey into new physics territory has just only begun, and for sure, exciting times are ahead of us! (only ~5% dataset ready)



J Blaeu 1664

Prospects at Future colliders

Future Proton Colliders



HL-LHC
14 TeV,
3000 fb^{-1}

HE-LHC
27 TeV,
3000 fb^{-1}

FCC/SPPC
100 TeV,
3000 fb^{-1}

Long term prospects for 2 more collider scenarios have been studied (14, 27, 100 TeV @3000 fb^{-1})

Future hadron collider projects in a nutshell
-- The next discovery machine

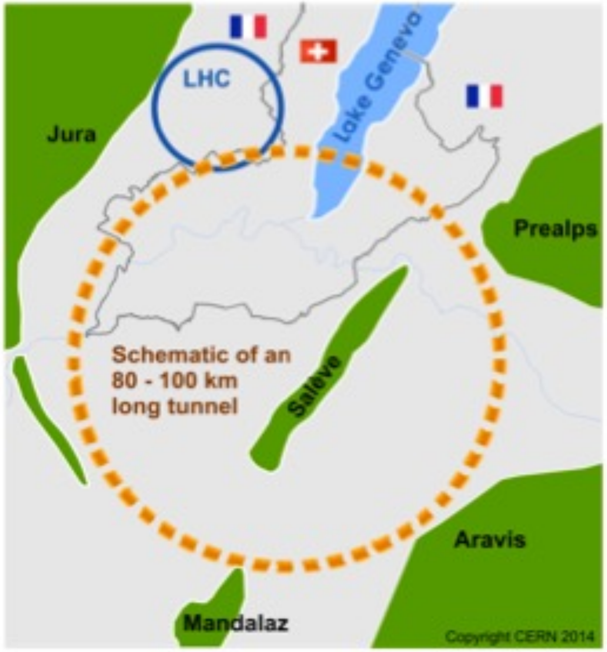
HL-LHC: E_{CM} = 14 TeV, 3 ab^{-1}, 2026~2035… (formally approved as *project* by CERN council last week)

Future Circular Collider FCC-hh (CERN):

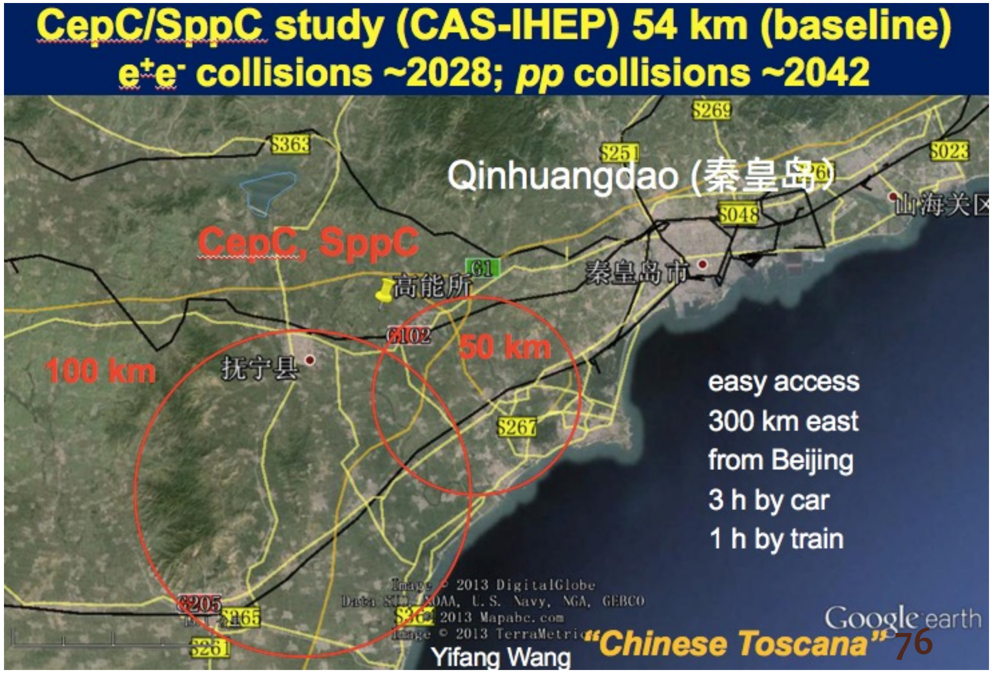
- E_{CM} ~ 100 TeV in 100 km ring, L ~ 2×10^{35} s^{-1}cm^{-2}
- ~16 T magnets, possibly HE-LHC (E_{CM} ~ 28 TeV) as intermediate stage
- Huge detectors for muon p_T measurement
- Possible start of physics ~ 2035

SppC (China):

- E_{CM} ~ 71 TeV in 55 km ring, L ~ 1×10^{35} s^{-1}cm^{-2}
- Requires very high gradient dipole magnets ~ 20 T
- Possible start of physics ~ 2042



Copyright CERN 2014



CepC/SppC study (CAS-IHEP) 54 km (baseline)
e^+e^- collisions ~2028; *pp* collisions ~2042

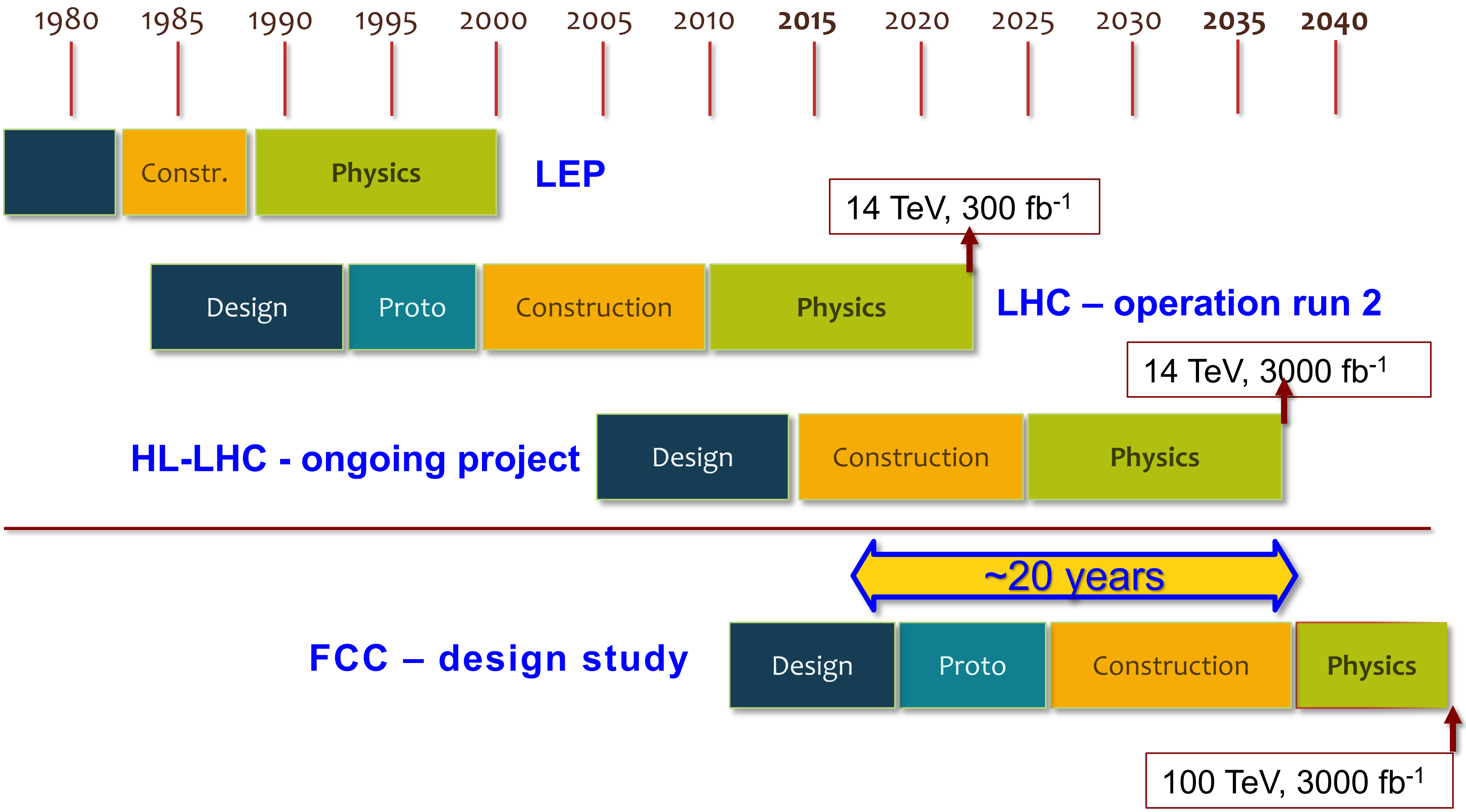
easy access
300 km east
from Beijing
3 h by car
1 h by train

Image © 2013 DigitalGlobe
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2013 Mapabc.com
Image © 2013 TerraMetrics

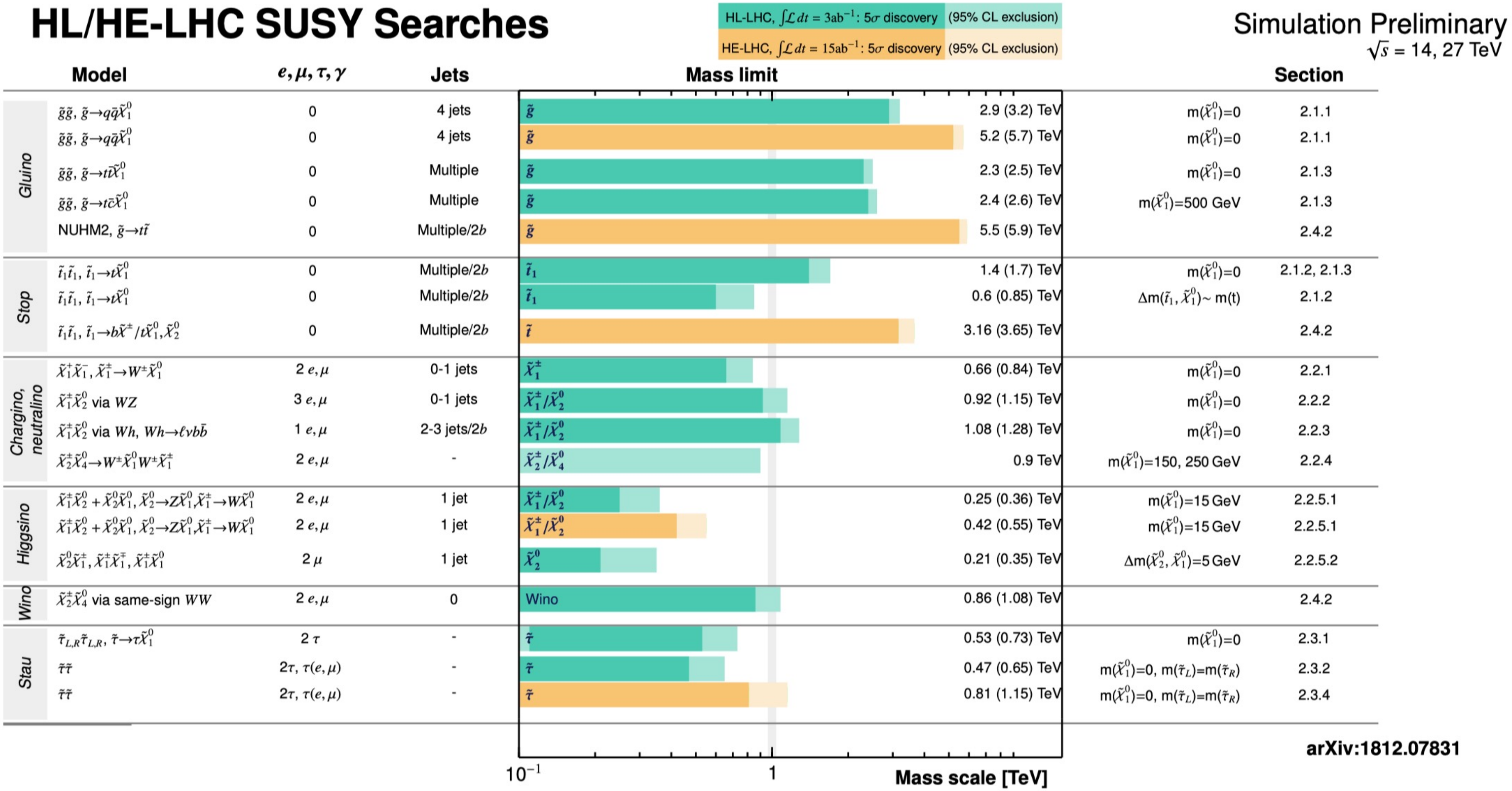
"Chinese Toscana"

Yifang Wang

CERN Circular Colliders & FCC



Prospects at HL/HE-LHC: SUSY



HL/HE-LHC SUSY Searches

HL-LHC, $\int\mathcal{L}dt = 3\text{ab}^{-1}$: 5σ discovery (95% CL exclusion)

HE-LHC, $\int\mathcal{L}dt = 15\text{ab}^{-1}$: 5σ discovery (95% CL exclusion)

Simulation Preliminary
$\sqrt{s}$ = 14, 27 TeV

	Model	e,μ,τ,γ	Jets	Mass limit			Section
Gluino	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	4 jets	$\tilde{g}$	2.9 (3.2) TeV	m($\tilde{\chi}_1^0$)=0	2.1.1
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	4 jets	$\tilde{g}$	5.2 (5.7) TeV	m($\tilde{\chi}_1^0$)=0	2.1.1
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	Multiple	$\tilde{g}$	2.3 (2.5) TeV	m($\tilde{\chi}_1^0$)=0	2.1.3
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{c}\tilde{\chi}_1^0$	0	Multiple	$\tilde{g}$	2.4 (2.6) TeV	m($\tilde{\chi}_1^0$)=500 GeV	2.1.3
	NUHM2, $\tilde{g}\rightarrow t\tilde{t}$	0	Multiple/2b	$\tilde{g}$	5.5 (5.9) TeV		2.4.2
Stop	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	Multiple/2b	$\tilde{t}_1$	1.4 (1.7) TeV	m($\tilde{\chi}_1^0$)=0	2.1.2, 2.1.3
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	Multiple/2b	$\tilde{t}_1$	0.6 (0.85) TeV	Δm($\tilde{t}_1$, $\tilde{\chi}_1^0$)~ m(t)	2.1.2
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}^\pm/t\tilde{\chi}_1^0,\tilde{\chi}_2^0$	0	Multiple/2b	$\tilde{t}$	3.16 (3.65) TeV		2.4.2
Chargino, neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^\pm\rightarrow W^\pm\tilde{\chi}_1^0$	2 e,μ	0-1 jets	$\tilde{\chi}_1^\pm$	0.66 (0.84) TeV	m($\tilde{\chi}_1^0$)=0	2.2.1
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	3 e,μ	0-1 jets	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.92 (1.15) TeV	m($\tilde{\chi}_1^0$)=0	2.2.2
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh, $Wh\rightarrow\ell\nu b\bar{b}$	1 e,μ	2-3 jets/2b	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	1.08 (1.28) TeV	m($\tilde{\chi}_1^0$)=0	2.2.3
	$\tilde{\chi}_2^\pm\tilde{\chi}_4^0\rightarrow W^\pm\tilde{\chi}_1^0 W^\pm\tilde{\chi}_1^\pm$	2 e,μ	-	$\tilde{\chi}_2^\pm/\tilde{\chi}_4^0$	0.9 TeV	m($\tilde{\chi}_1^0$)=150, 250 GeV	2.2.4
Higgsino	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0+\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_2^0\rightarrow Z\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\rightarrow W\tilde{\chi}_1^0$	2 e,μ	1 jet	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.25 (0.36) TeV	m($\tilde{\chi}_1^0$)=15 GeV	2.2.5.1
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0+\tilde{\chi}_2^0\tilde{\chi}_1^0$, $\tilde{\chi}_2^0\rightarrow Z\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\rightarrow W\tilde{\chi}_1^0$	2 e,μ	1 jet	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.42 (0.55) TeV	m($\tilde{\chi}_1^0$)=15 GeV	2.2.5.1
	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$, $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$	2 μ	1 jet	$\tilde{\chi}_2^0$	0.21 (0.35) TeV	Δm($\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$)=5 GeV	2.2.5.2
Wino	$\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ via same-sign WW	2 e,μ	0	Wino	0.86 (1.08) TeV		2.4.2
Stau	$\tilde{\tau}_{L,R}\tilde{\tau}_{L,R}$, $\tilde{\tau}\rightarrow\tau\tilde{\chi}_1^0$	2 τ	-	$\tilde{\tau}$	0.53 (0.73) TeV	m($\tilde{\chi}_1^0$)=0	2.3.1
	$\tilde{\tau}\tilde{\tau}$	2τ, $\tau(e,\mu)$	-	$\tilde{\tau}$	0.47 (0.65) TeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}_L$)=m($\tilde{\tau}_R$)	2.3.2
	$\tilde{\tau}\tilde{\tau}$	2τ, $\tau(e,\mu)$	-	$\tilde{\tau}$	0.81 (1.15) TeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}_L$)=m($\tilde{\tau}_R$)	2.3.4

arXiv:1812.07831

- **In most BSM scenarios, we expect the HL-LHC will increase the present reach in mass and coupling by 20 – 50% (half Run-2 data)**
- **HE-LHC will allow for exclusion of almost all SUSY natural scenarios in case of null observation**

EU Strategy- SUSY: ~g

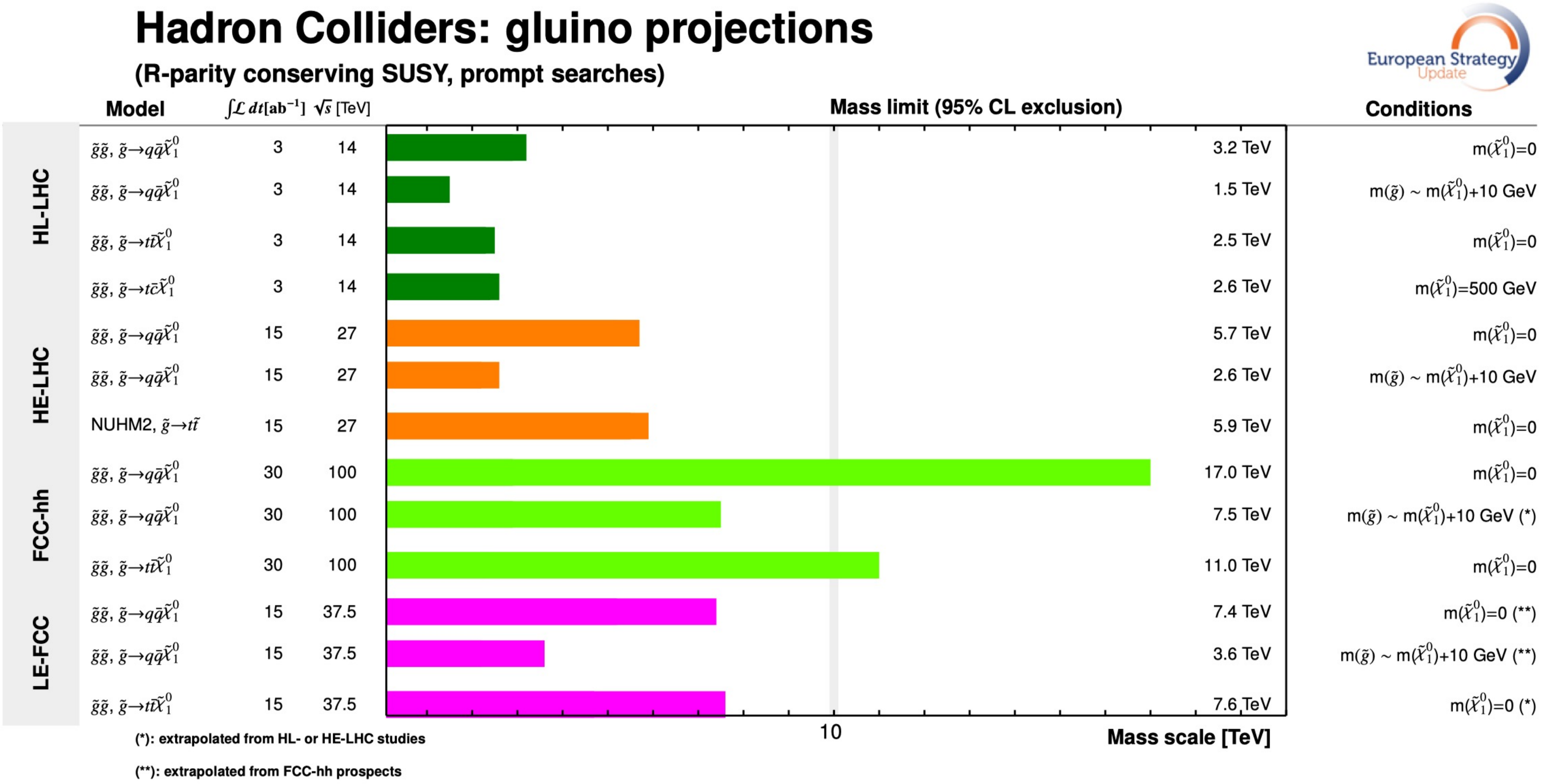
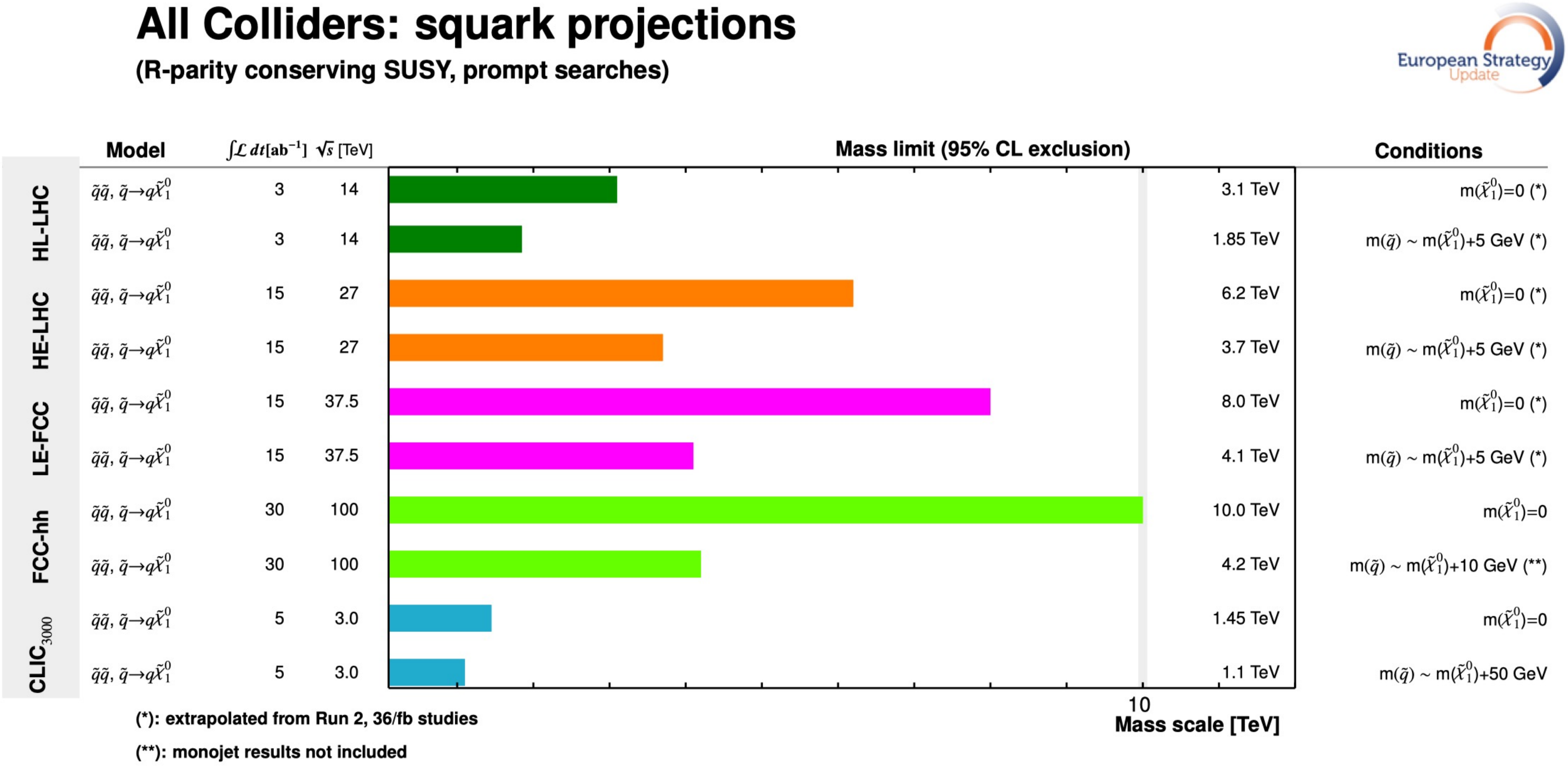


Fig. 8.6: Gluino exclusion reach of different hadron colliders: HL- and HE-LHC [443], and FCC-hh [139, 448]. Results for low-energy FCC-hh are obtained with a simple extrapolation.

EU Strategy- SUSY: ~q



	Model	$\int\mathcal{L}\,dt[\mathrm{ab}^{-1}]$	$\sqrt{s}$ [TeV]	Mass limit (95% CL exclusion)	Conditions
HL-LHC	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	3	14	3.1 TeV	m($\tilde{\chi}_1^0$)=0 (*)
	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	3	14	1.85 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+5 GeV (*)
HE-LHC	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	15	27	6.2 TeV	m($\tilde{\chi}_1^0$)=0 (*)
	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	15	27	3.7 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+5 GeV (*)
LE-FCC	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	15	37.5	8.0 TeV	m($\tilde{\chi}_1^0$)=0 (*)
	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	15	37.5	4.1 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+5 GeV (*)
FCC-hh	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	30	100	10.0 TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	30	100	4.2 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+10 GeV (**)
CLIC_{3000}	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	5	3.0	1.45 TeV	m($\tilde{\chi}_1^0$)=0
	$\tilde{q}\tilde{q},\ \tilde{q}\rightarrow q\tilde{\chi}_1^0$	5	3.0	1.1 TeV	m($\tilde{q}$) ~ m($\tilde{\chi}_1^0$)+50 GeV

(*): extrapolated from Run 2, 36/fb studies

(**): monojet results not included

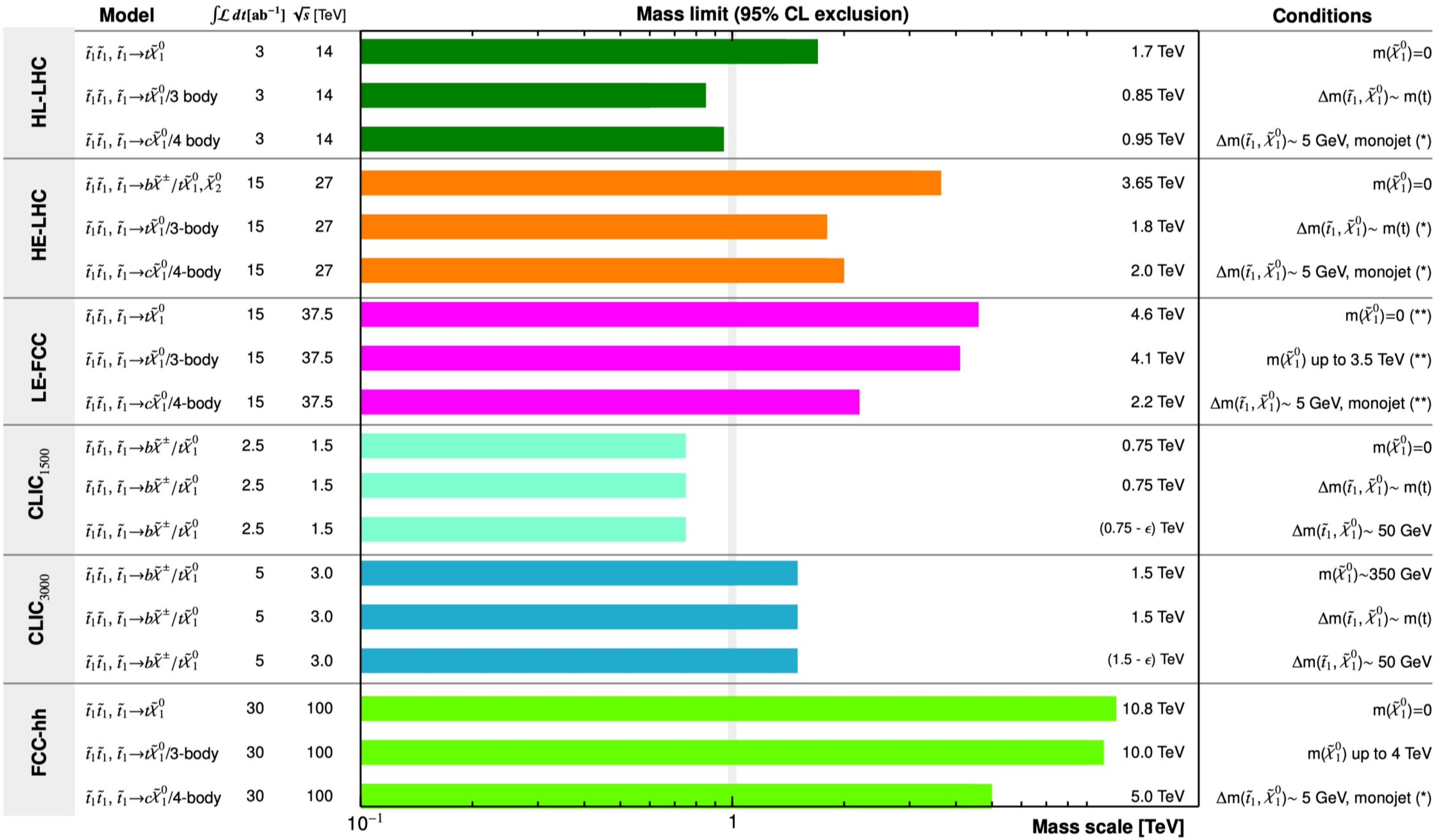
Fig. 8.7: Exclusion reach of different hadron and lepton colliders for first- and second-generation squarks.

EU Strategy - SUSY: ~t

All Colliders: Top squark projections

(R-parity conserving SUSY, prompt searches)

European Strategy Update



	Model	$\int\mathcal{L}\,dt$[ab^{-1}]	$\sqrt{s}$ [TeV]	Mass limit (95% CL exclusion)	Conditions
HL-LHC	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	3	14	1.7 TeV	m($\tilde{\chi}^0_1$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$/3 body	3	14	0.85 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ m(t)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$/4 body	3	14	0.95 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ 5 GeV, monojet (*)
HE-LHC	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1,\tilde{\chi}^0_2$	15	27	3.65 TeV	m($\tilde{\chi}^0_1$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$/3-body	15	27	1.8 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ m(t) (*)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$/4-body	15	27	2.0 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ 5 GeV, monojet (*)
LE-FCC	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	15	37.5	4.6 TeV	m($\tilde{\chi}^0_1$)=0 (**)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$/3-body	15	37.5	4.1 TeV	m($\tilde{\chi}^0_1$) up to 3.5 TeV (**)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$/4-body	15	37.5	2.2 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ 5 GeV, monojet (**)
CLIC_{1500}	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1$	2.5	1.5	0.75 TeV	m($\tilde{\chi}^0_1$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1$	2.5	1.5	0.75 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ m(t)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1$	2.5	1.5	(0.75 - ϵ) TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ 50 GeV
CLIC_{3000}	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1$	5	3.0	1.5 TeV	m($\tilde{\chi}^0_1$)~350 GeV
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1$	5	3.0	1.5 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ m(t)
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1$	5	3.0	(1.5 - ϵ) TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ 50 GeV
FCC-hh	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	30	100	10.8 TeV	m($\tilde{\chi}^0_1$)=0
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$/3-body	30	100	10.0 TeV	m($\tilde{\chi}^0_1$) up to 4 TeV
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$/4-body	30	100	5.0 TeV	Δm($\tilde{t}_1,\tilde{\chi}^0_1$)~ 5 GeV, monojet (*)

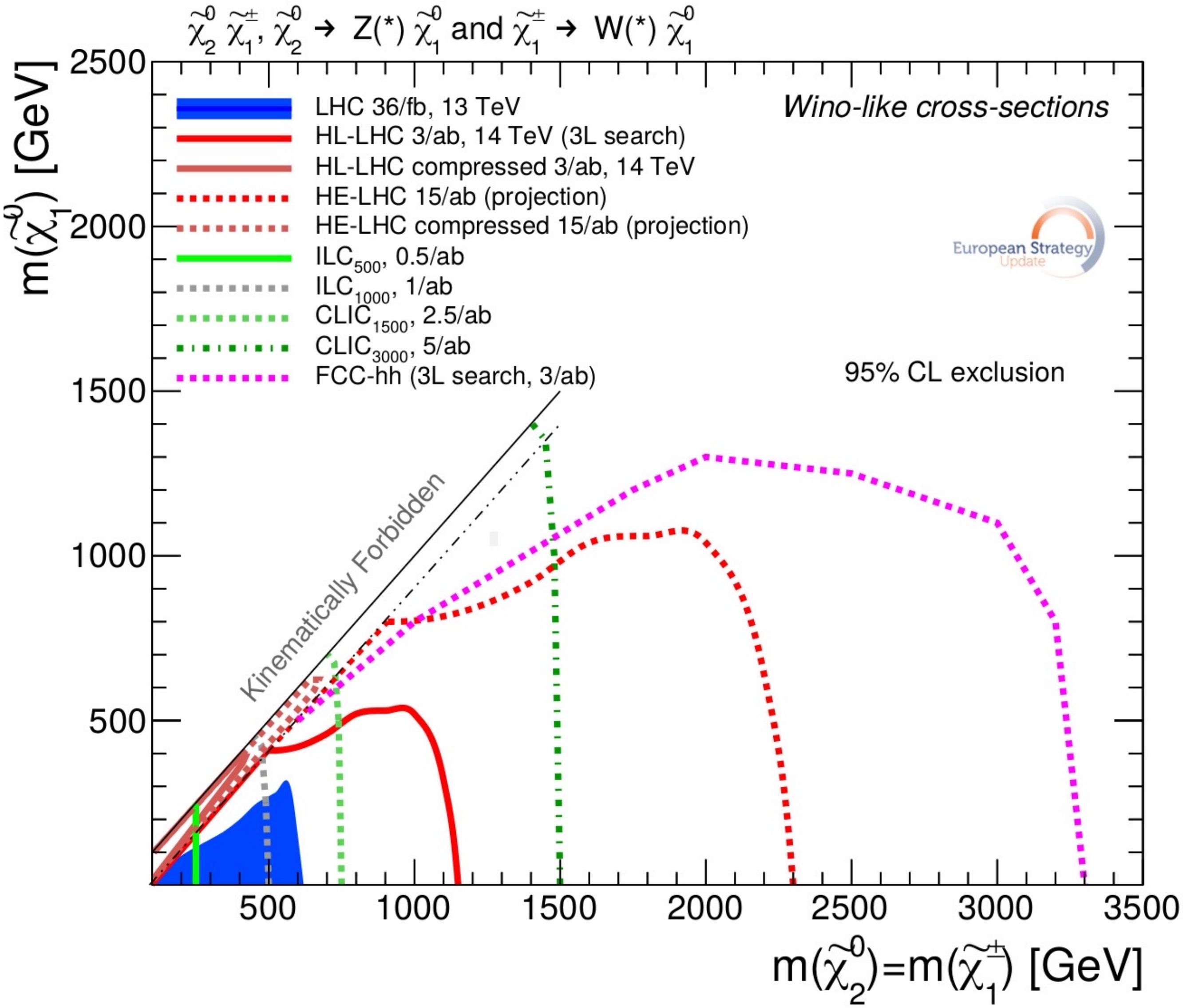
(*) indicates projection of existing experimental searches

(**) extrapolated from FCC-hh prospects

ϵ indicates a possible non-evaluated loss in sensitivity

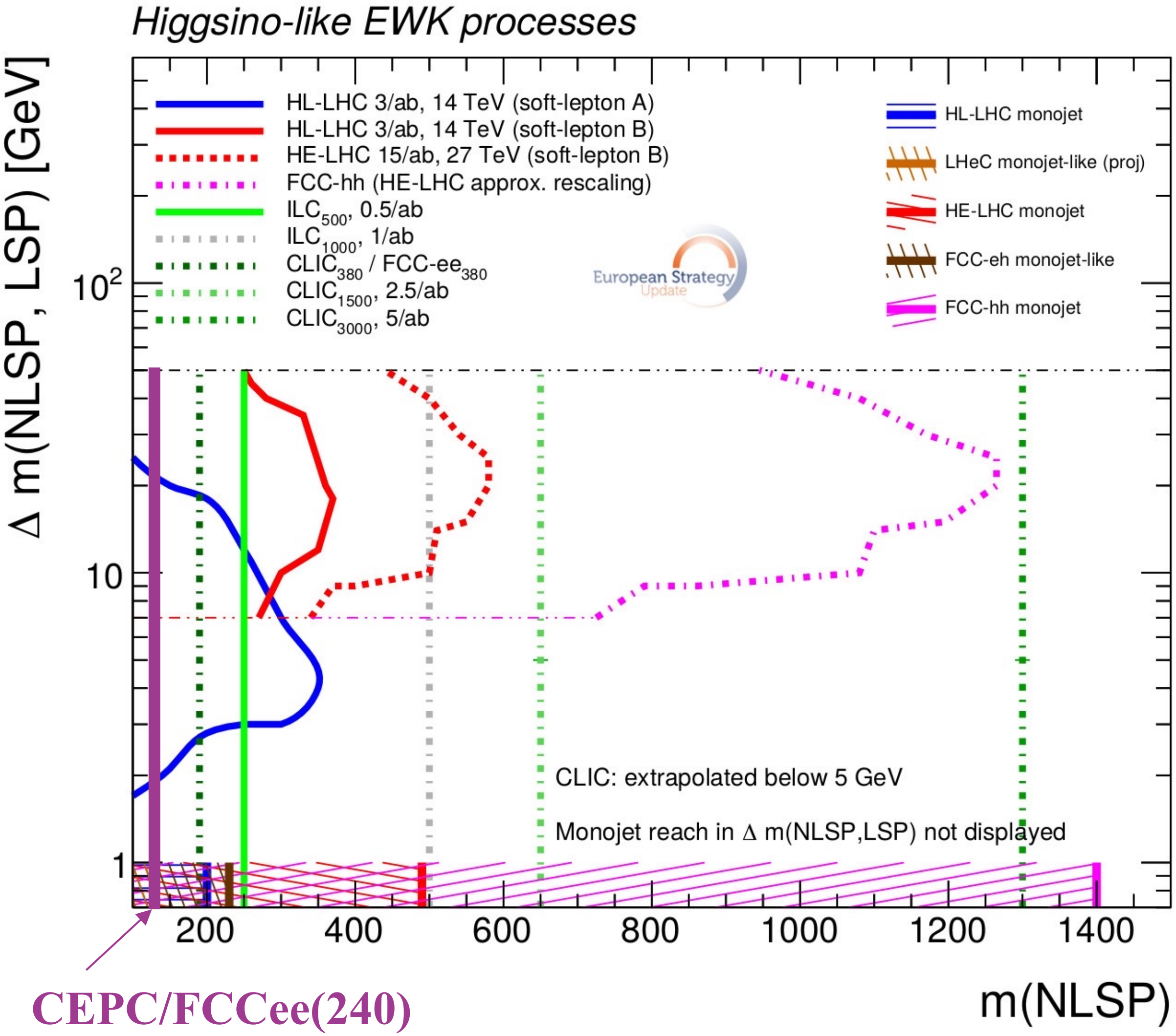
ILC 500: discovery in all scenarios up to kinematic limit $\sqrt{s}/2$

EU Strategy - SUSY: Wino



ILC 500/CEPC240: discovery in all scenarios up to kinematic limit: √s/2

EU Strategy- SUSY: Higgsino



CEPC/FCCee(240)

EU Strategy: SUSY-DM

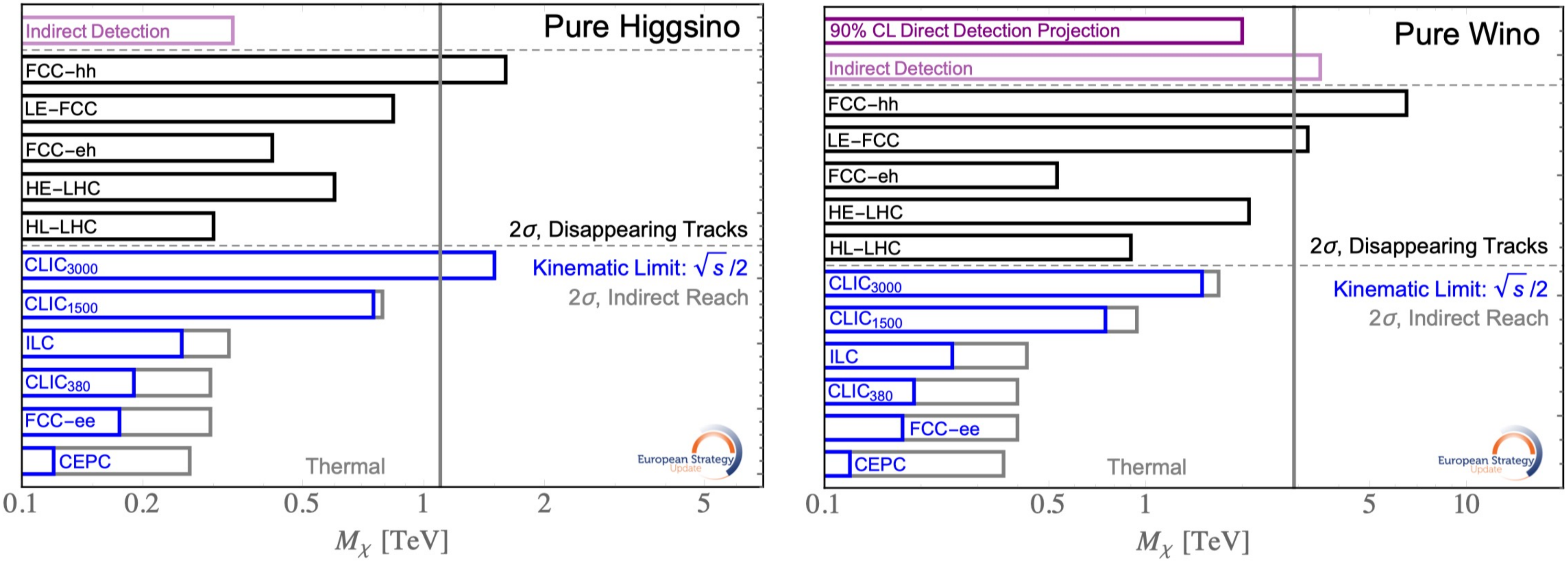


Fig. 8.14: Summary of 2σ sensitivity reach to pure Higgsinos and Winos at future colliders. Current indirect DM detection constraints (which suffer from unknown halo-modelling uncertainties) and projections for future direct DM detection (which suffer from uncertainties on the Wino-nucleon cross section) are also indicated. The vertical line shows the mass corresponding to DM thermal relic.

EU Strategy: DM

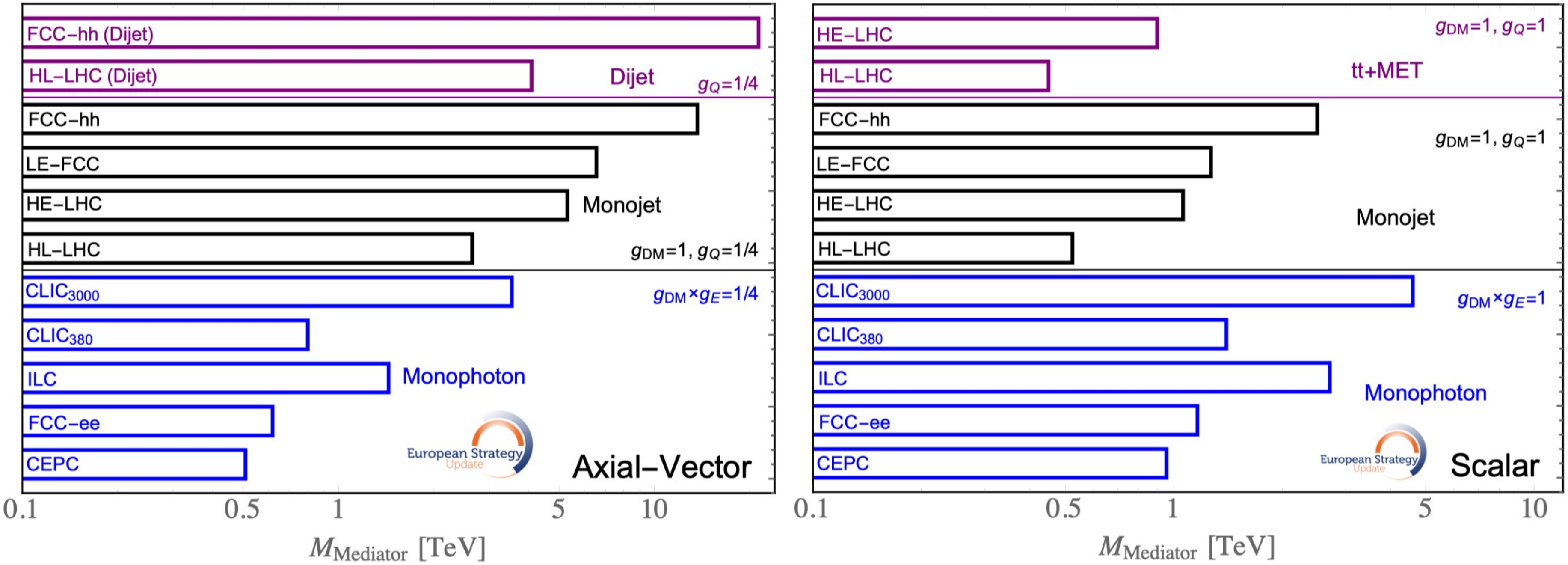
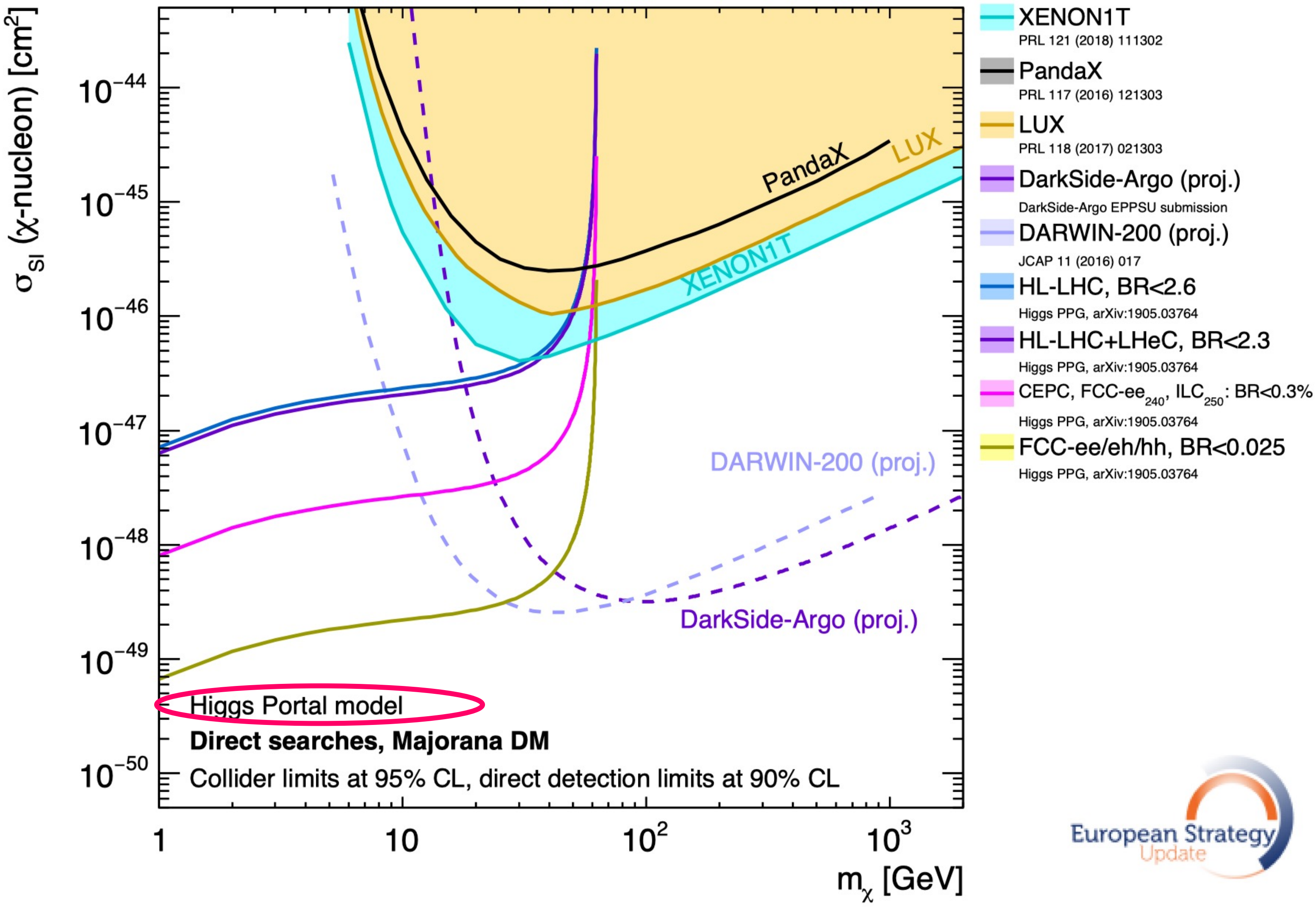


Fig. 8.15: Summary of 2σ sensitivity to axial-vector and scalar simplified models at future colliders for a DM mass of $M_{\mathrm{DM}} = 1$ GeV and for the couplings shown in the figure. References and details on the estimates included in these plots can be found in the text.

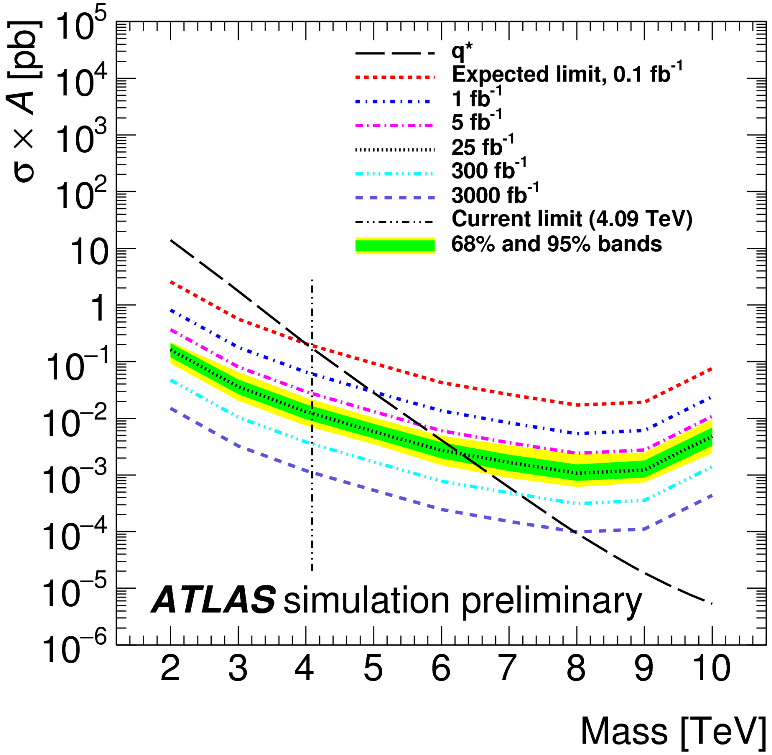
EU Strategy: DM



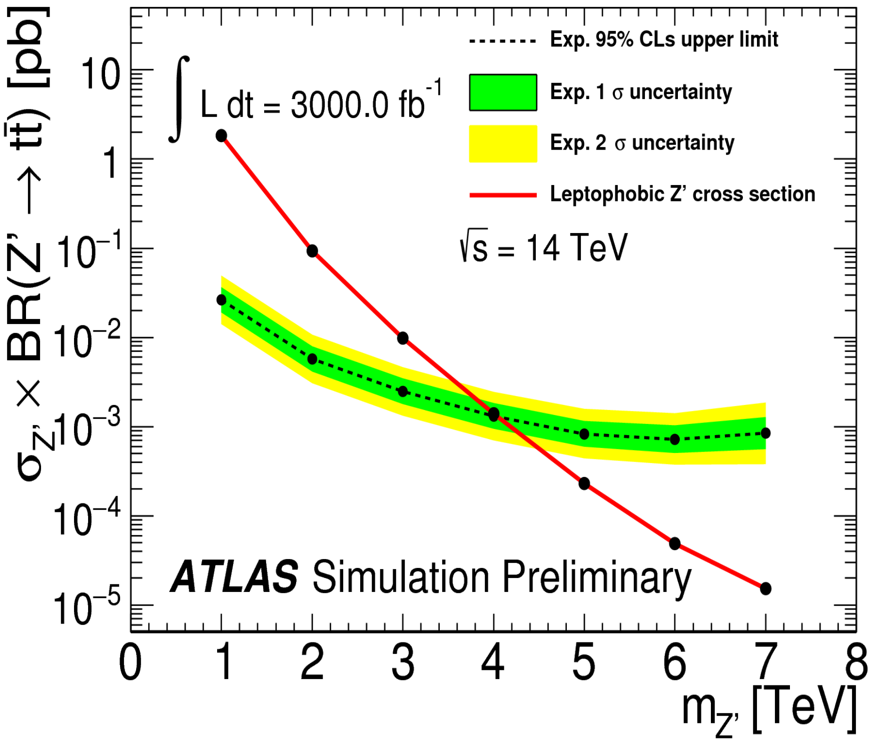
European Strategy Update

Prospects at HL/HE-LHC: Exotics

ATL-PHYS-PUB-2015-004



ATL-PHYS-PUB-2017-002



Exited quark q*→qg: di-jet

6-8 TeV | HL-LHC
14 TeV | HE-LHC
43 TeV | FCC_hh

Eur. Phys. J. Special Topics 228, 1109–1382 (2019)

Process	HE-LHC (FCC-hh)		
	95%CL limit (TeV) 15 (30) ab^{-1}	5σ reach (Tev) 1 (2.5) ab^{-1}	5σ reach (TeV) 15 (30) ab^{-1}
$Z'_{SSM} \to e^+e^-/\mu^+\mu^-$	13 (40)	10 (33)	13 (43)
$Z'_{SSM} \to \tau^+\tau^-$	6 (14)	3 (12)	6 (18)
$Z'_{FA} \to \mu^+\mu^-$	4 (25)	– (10)	2 (19)
$Z'_{TC} \to t\bar{t}$	10 (28)	6 (16)	8 (23)
$G_{RS} \to WW$	8 (28)	5 (15)	7 (22)
$Q^* \to jj$	14 (43)	10 (36)	12 (40)

Z'→ttbar

3-4 TeV | HL-LHC
6-13 TeV | HE-LHC
14-40 TeV | FCC_hh

Prospects at HL/HE-LHC: Exotics

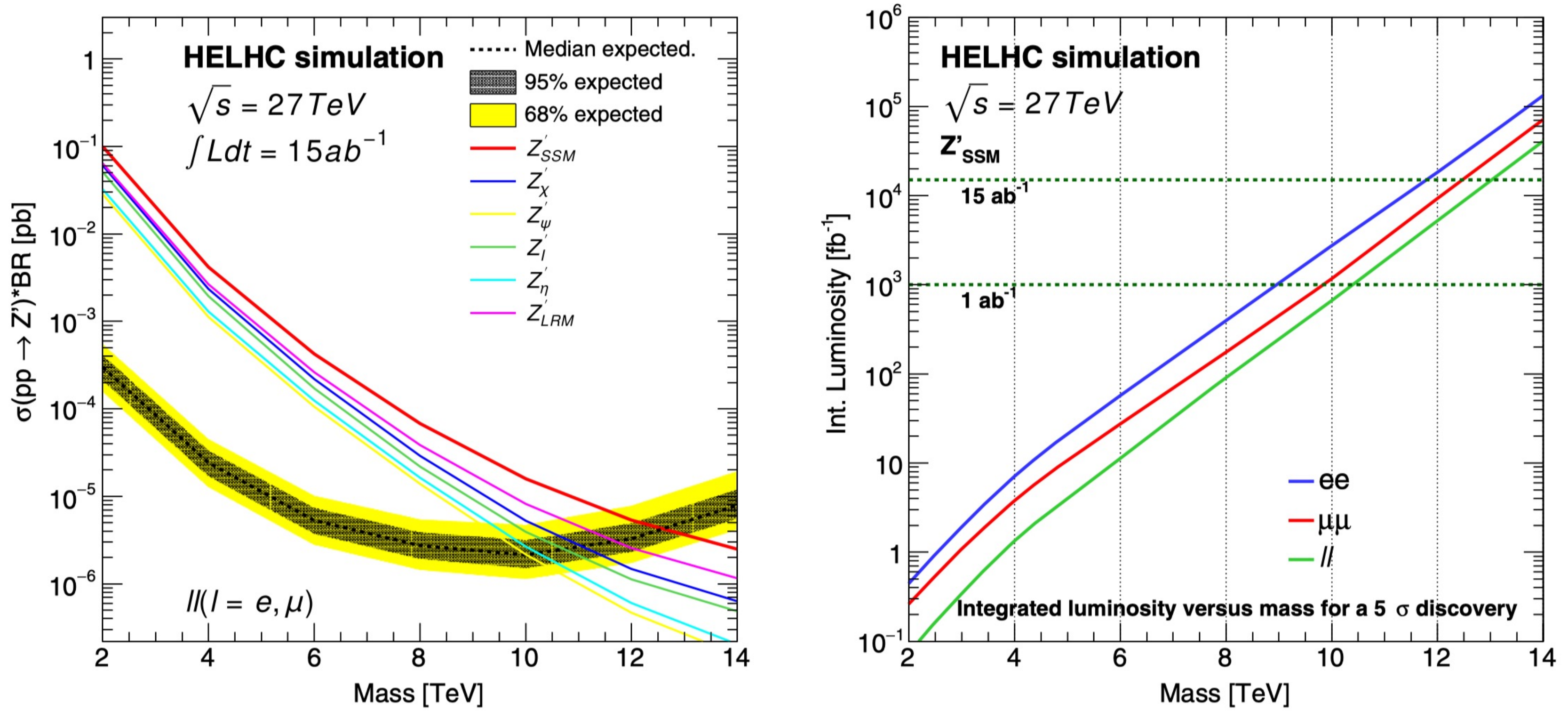


Fig. 1.4. Limit versus mass for the di-lepton channel (left) and luminosity for a 5σ discovery (right) for the ee and $\mu\mu$ combined channels.

Eur. Phys. J. Special Topics 228, 1109–1382 (2019)

Process	HE-LHC (FCC-hh)		
	95%CL limit (TeV) 15 (30) ab^{-1}	5σ reach (Tev) 1 (2.5) ab^{-1}	5σ reach (TeV) 15 (30) ab^{-1}
$Z'_{SSM} \rightarrow e^+e^-/\mu^+\mu^-$	13 (40)	10 (33)	13 (43)
$Z'_{SSM} \rightarrow \tau^+\tau^-$	6 (14)	3 (12)	6 (18)
$Z'_{FA} \rightarrow \mu^+\mu^-$	4 (25)	– (10)	2 (19)
$Z'_{TC} \rightarrow t\bar{t}$	10 (28)	6 (16)	8 (23)
$G_{RS} \rightarrow WW$	8 (28)	5 (15)	7 (22)
$Q^* \rightarrow jj$	14 (43)	10 (36)	12 (40)

New World !!!

LHC is discovery machines, new physics may come at any time , stay tuned!