

Pre-SUSY 2021 @ Beijing



Introduction to Collider Physics

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References

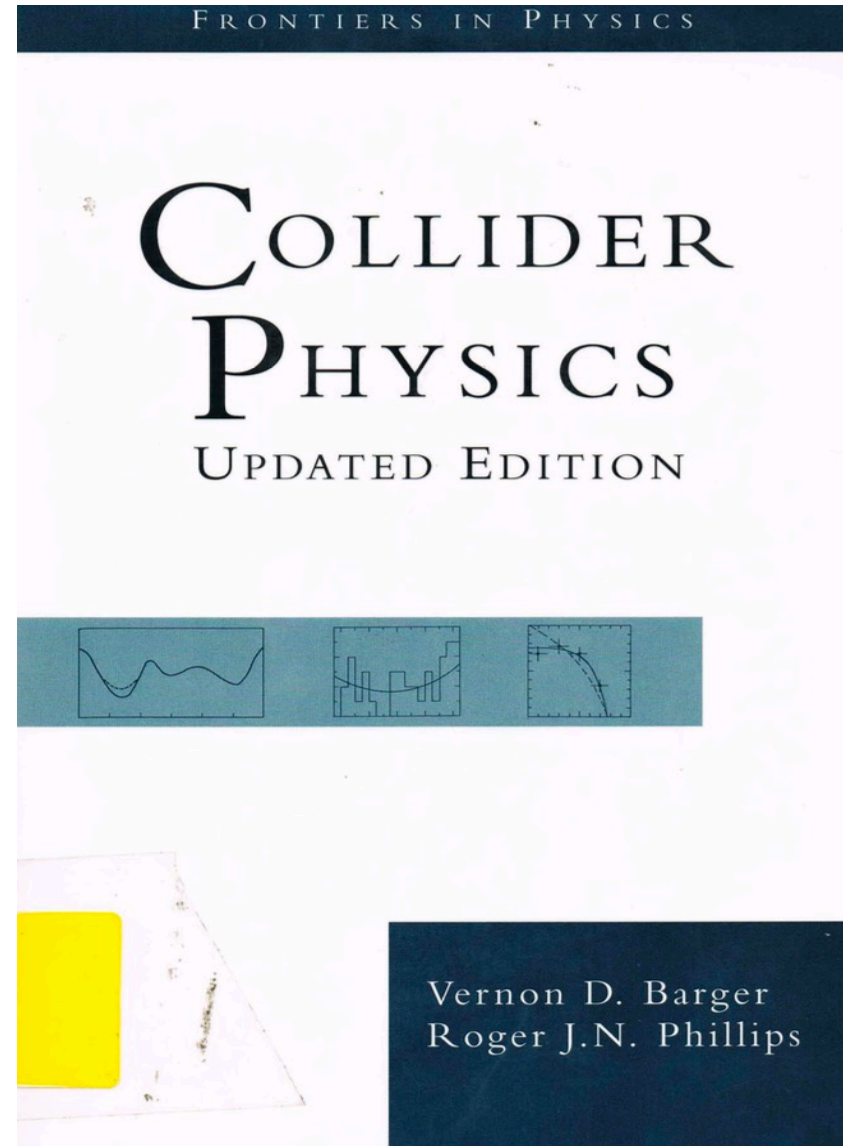
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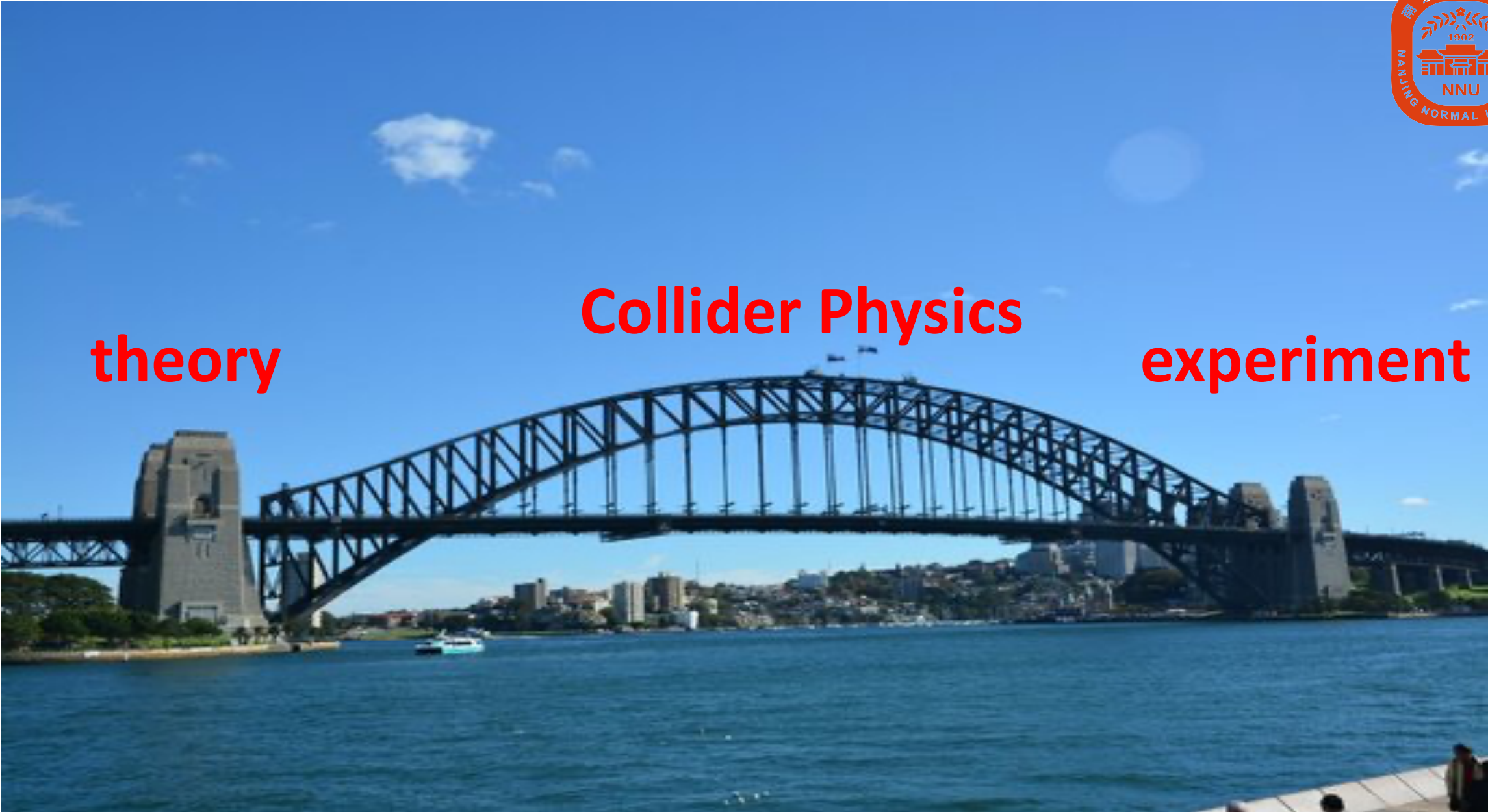
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The background of the slide is a photograph of the Sydney Harbour Bridge, a large steel arch bridge spanning the water. The bridge is dark steel, and the water is a deep blue. In the distance, the city skyline is visible under a clear blue sky with a few wispy clouds. The bridge's two large stone pylons are visible on either side of the arch.

theory Collider Physics experiment



Outline

- ❖ **Basic Knowledge of Collider**
- ❖ **Hadron and Lepton Collider Physics**
- ❖ **Simulation Tools and Machine Learning**
- ❖ **Conclusions**

1. Basic Knowledge of Collider

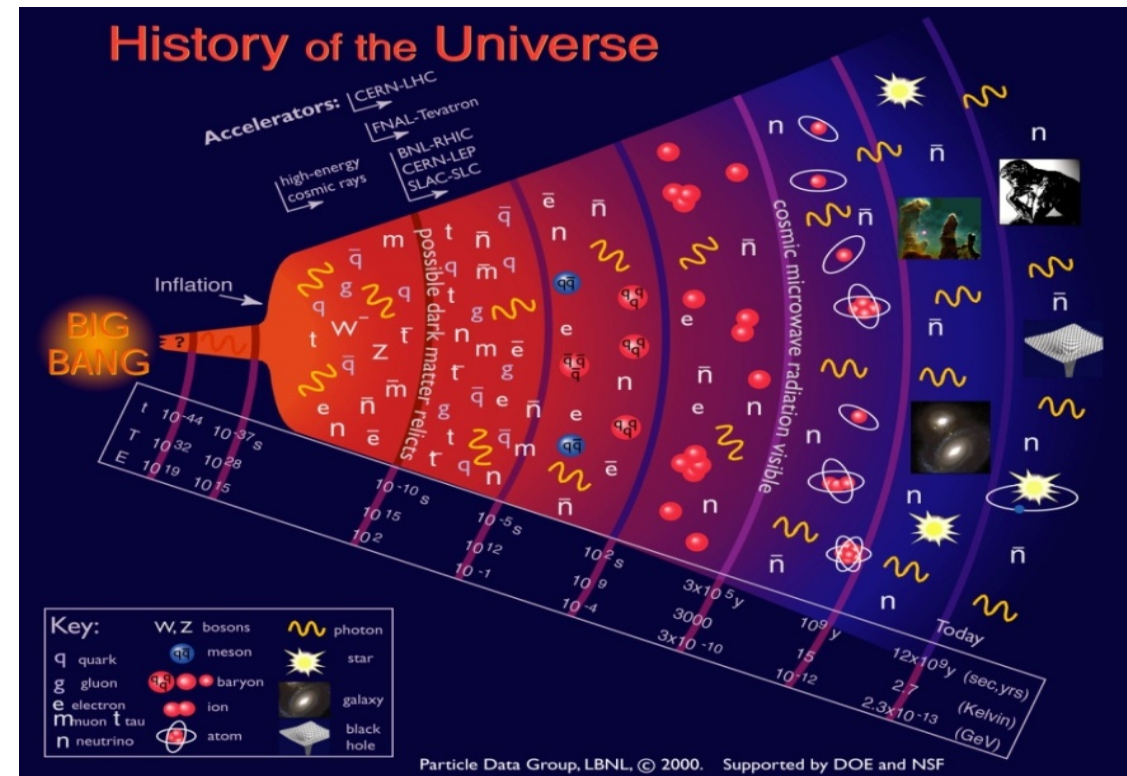
微观世界 物质结构和相互作用

(See DS Yang and CF Qiao's talks)

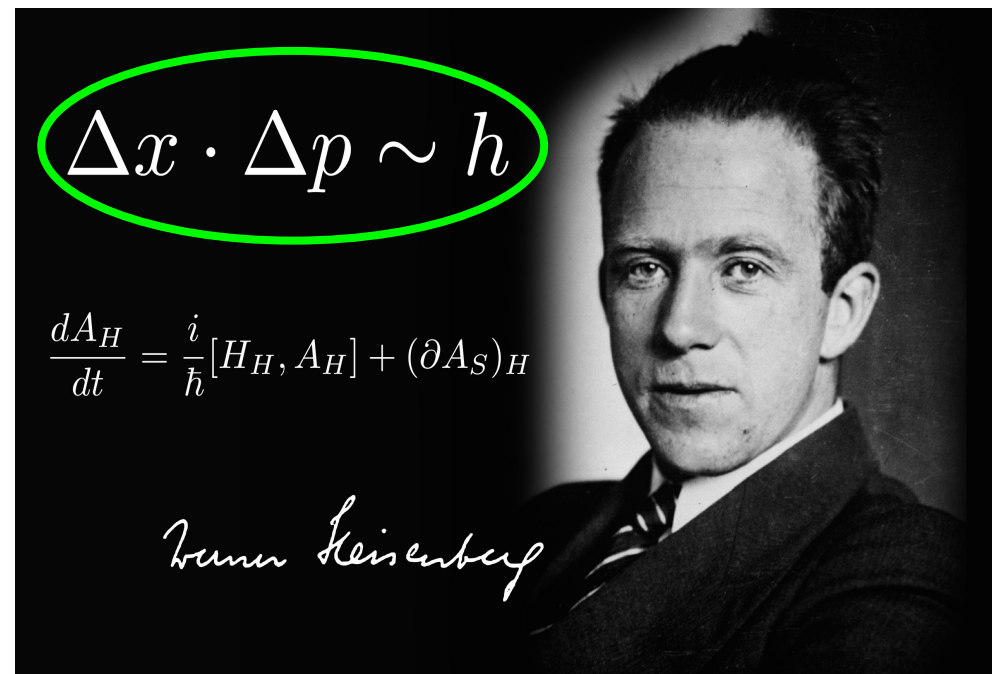
如何演化

从哪里来？

到哪里去？



1. Basic Knowledge of Collider





1. Basic Knowledge of Collider

对撞机的主体结构一般包括：**储能环、加速器和探测器**。

储能环：储存粒子以备提高亮度（电场和磁场），

加速器：将粒子加速成狭窄而集中的束流，然后在对撞点碰撞，

探测器：对产生的粒子的动量和能量等进行测量。

触发系统（trigger）、计算中心进行分析得到各种物理可观测量。



1. Basic Knowledge of Collider

Energy :

two particles: $(m_1 \mathbf{p}_1)$ and $(m_2 \mathbf{p}_2)$

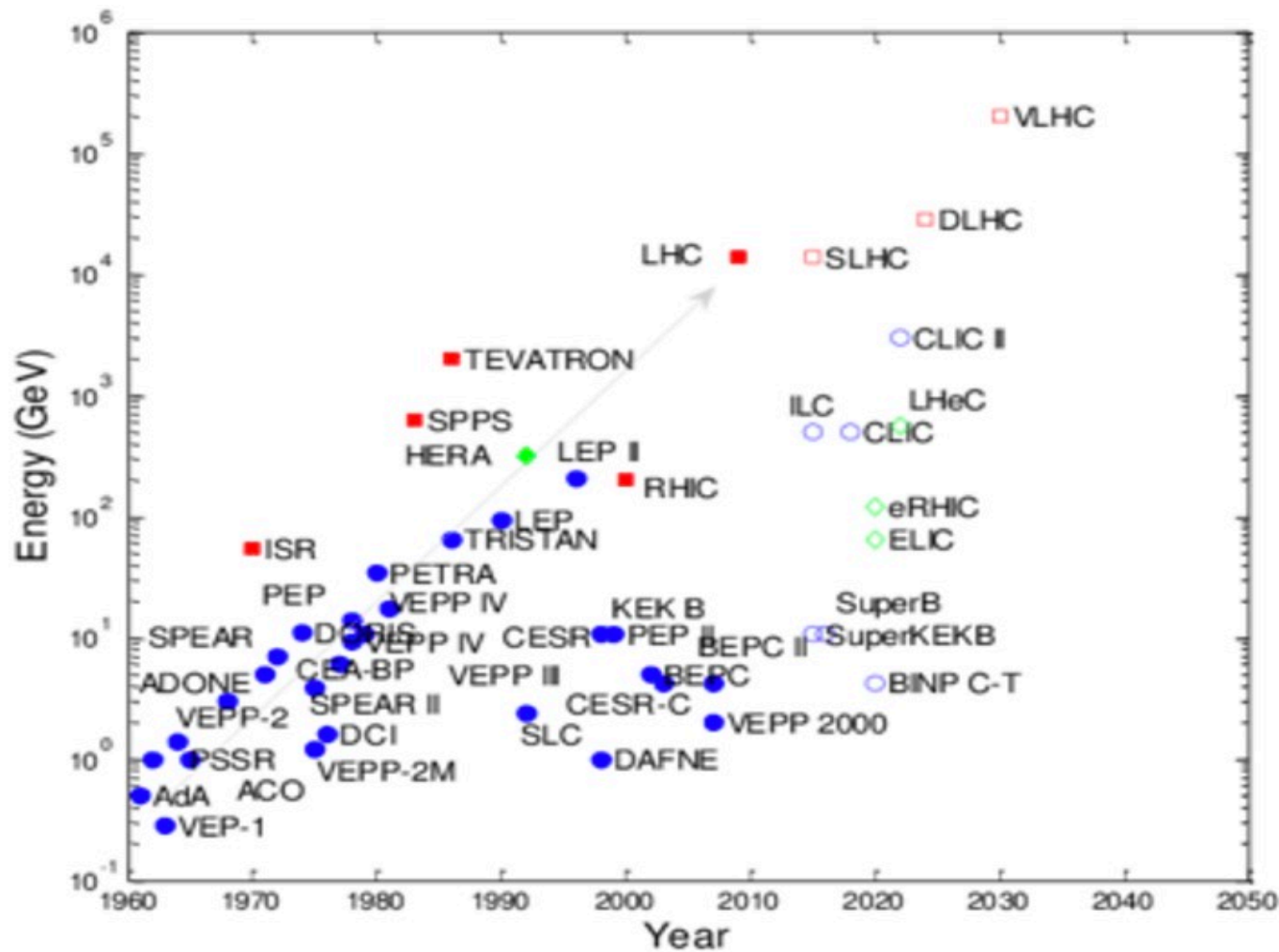
$$s \equiv (p_1 + p_2)^2 = \begin{cases} (E_1 + E_2)^2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ m_1^2 + m_2^2 + 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2). \end{cases}$$

Since $E \gg m$,

$$E_{CM} \equiv \sqrt{s} \approx \begin{cases} 2E_1 \approx 2E_2 & \text{in the c.m. frame } \vec{p}_1 + \vec{p}_2 = 0, \\ \sqrt{2E_1 m_2} & \text{in the fixed target frame } \vec{p}_2 = 0. \end{cases}$$

**higher threshold
than fixed target**

1. Basic Knowledge of Collider



LHC Run-3: 14 TeV



1. Basic Knowledge of Collider

Energy Loss :

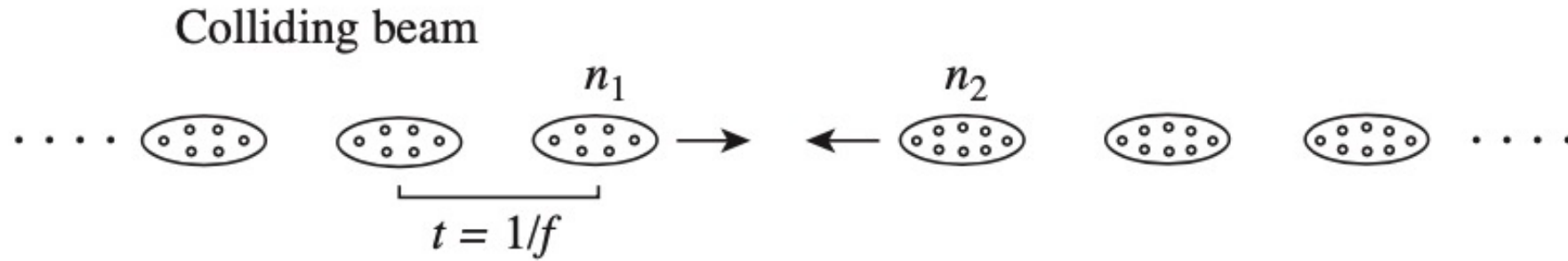
一个半径为R的环形对撞机，质量为m能量为E的束流每转一圈的能量损失

同步辐射 $\Delta E \propto \frac{1}{R} \left(\frac{E}{m} \right)^4$

对撞机半径越大或者粒子质量越重能量损失就越小。

1. Basic Knowledge of Collider

Luminosity :



$$\mathcal{L} \propto f n_1 n_2 / a$$

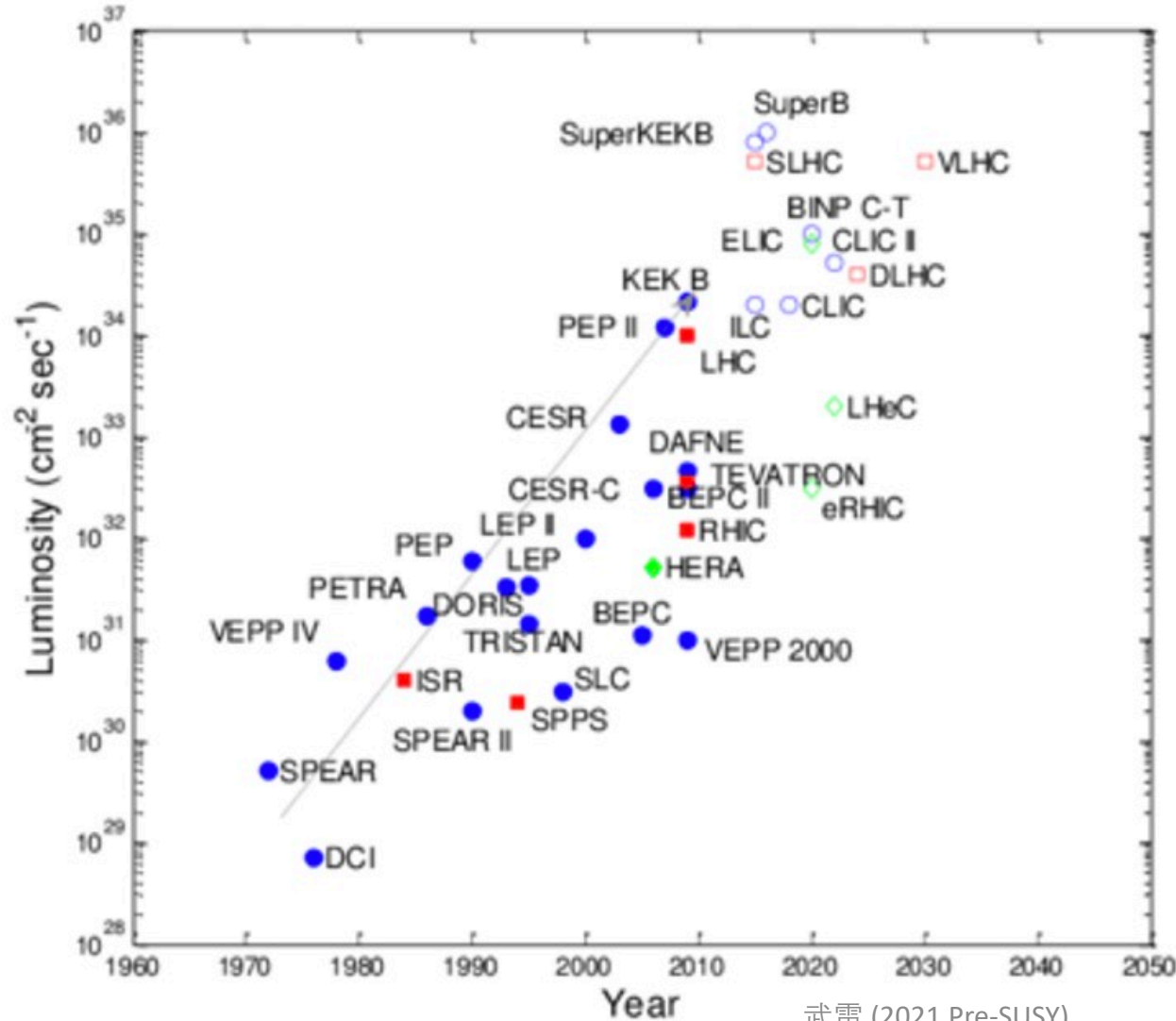
n: particles in each bunch in beam;

a: the transverse profile of the beams;

f: is beam crossing frequency.

$$10^{33} \text{ cm}^{-2} \text{ s}^{-1} = 1 \text{ nb}^{-1} \text{ s}^{-1} \approx 10 \text{ fb}^{-1} / \text{year}.$$

1. Basic Knowledge of Collider

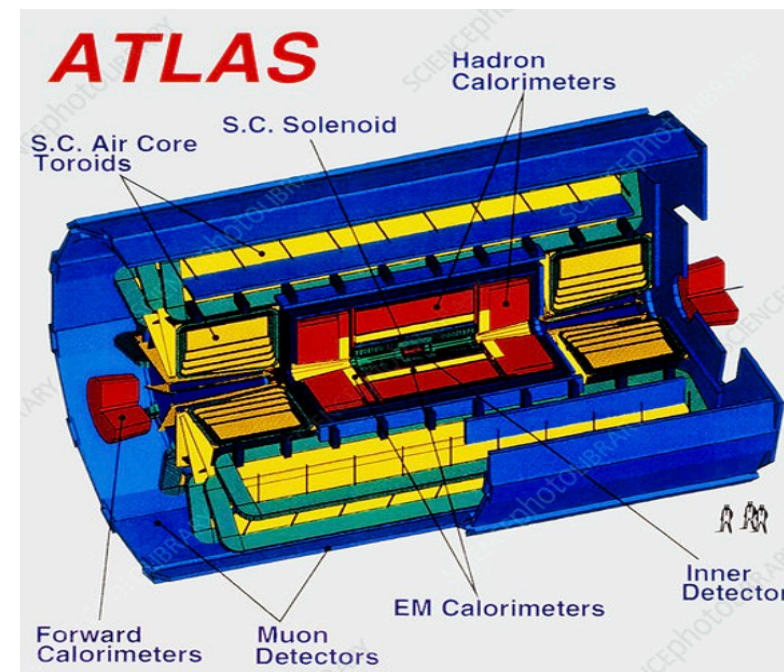
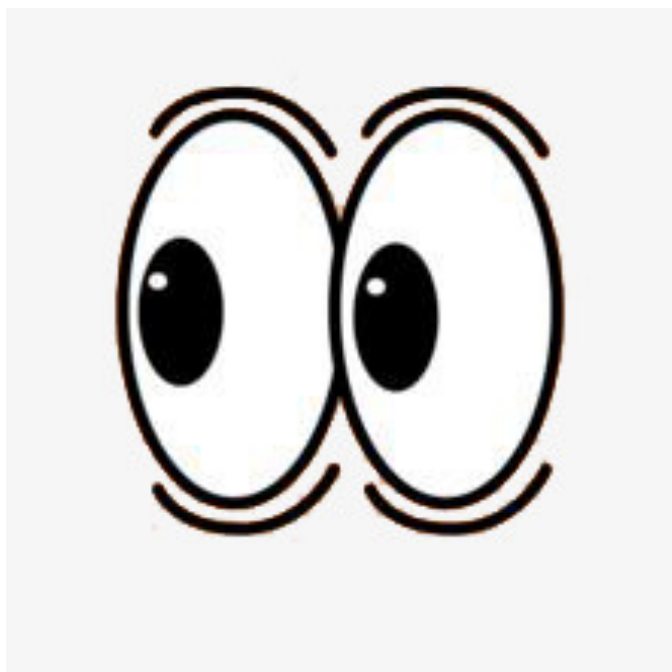


Super-B: $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$

1. Basic Knowledge of Collider



Detector :





1. Basic Knowledge of Collider

Theory v.s. Observation

Quarks/Gluons
(top)



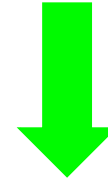
Jets (hadrons)

Leptons/photon
(tau)



Lepton/photon

EW gauge bosons



Lepton/jets



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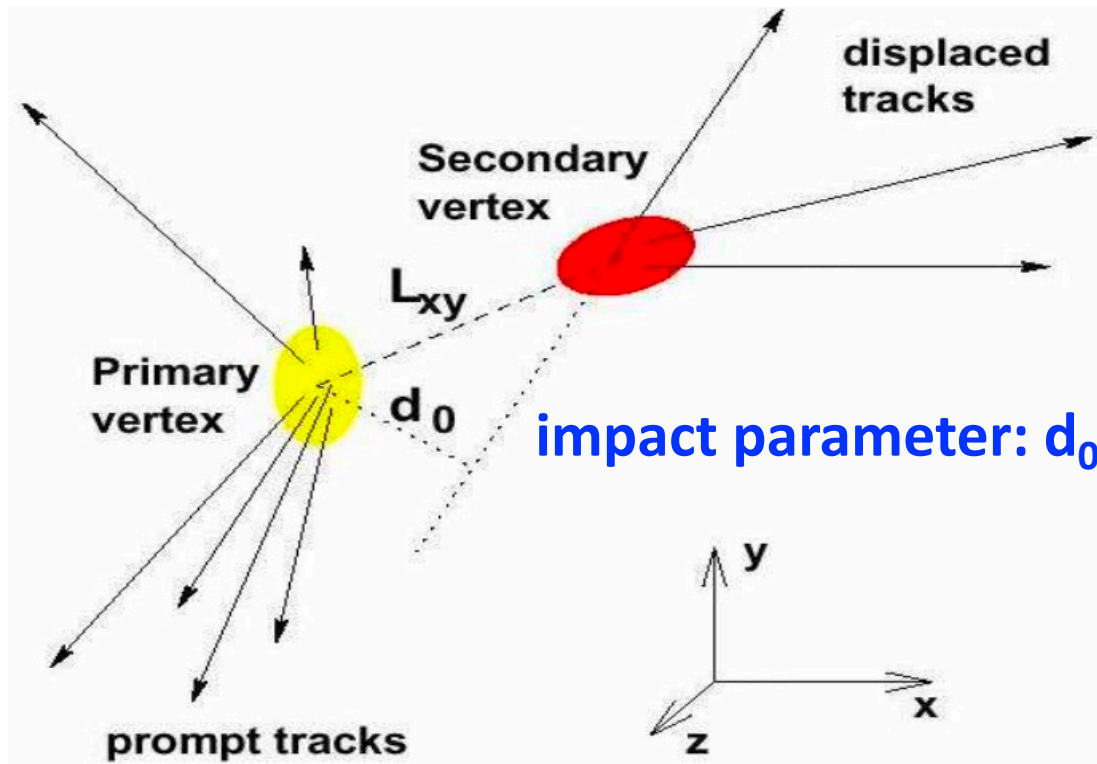
Decay Length:

$$d = (\beta c\tau)\gamma \approx (300 \mu m) \left(\frac{\tau}{10^{-12} s} \right) \gamma$$

- Quasi-stable: life-time $\tau > 10^{-10} s$, neutral hadrons n , $\mu^\pm$, $\pi^\pm$, $K^\pm$
- Short-lived resonances: instantaneous decay, Z , $W^\pm$, t , $(H...)$
- Displaced vertex: life-time $\tau \sim 10^{-12} s$, such as B , D , τ ; travel distance ($c\tau \sim 100 \mu m$) before decaying into charged tracks,
- Unseen particles: neutrino, DM

1. Basic Knowledge of Collider

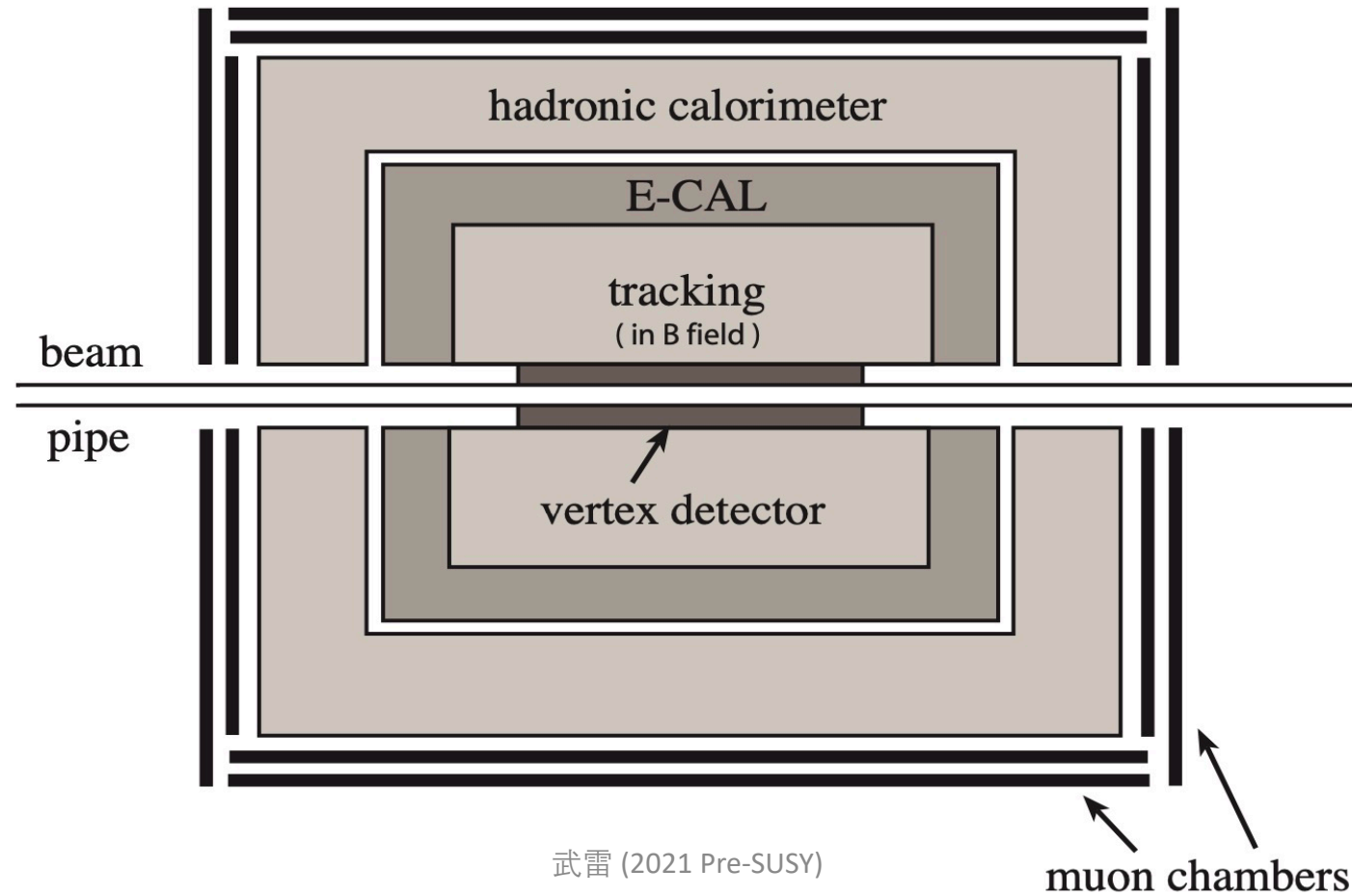
Displaced Vertex:



at least 2 tracks for 2nd vertex

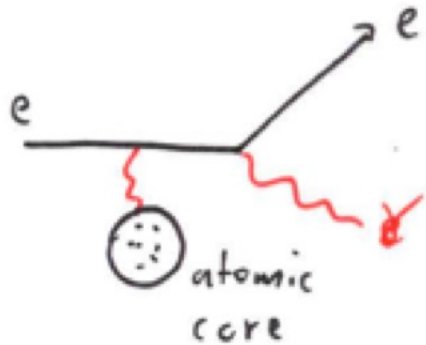
1. Basic Knowledge of Collider

Particle detection is based on its interactions with detector matter.

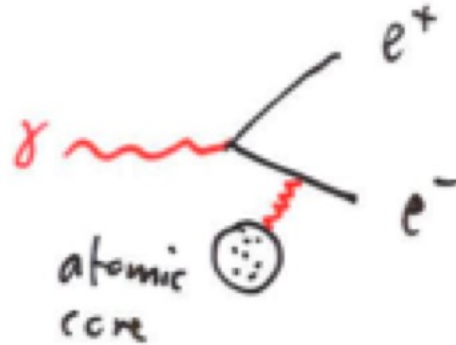


1. Basic Knowledge of Collider

e^+/e^- : Bremsstrahlung

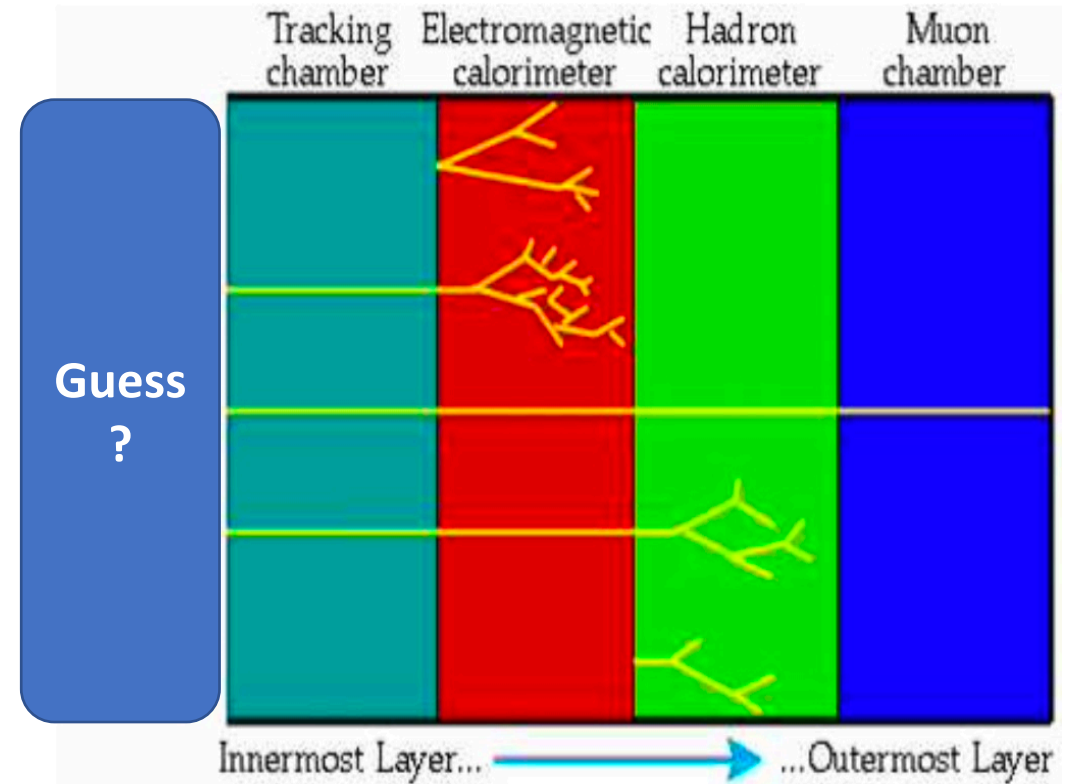


Photons: Pair-production



Hadrons:

Similar principle as electromagnetic calorimeters, but showers are produced via strong interaction



Tagging efficiency
($b \sim 80\%$, $c \sim 40\%$)



1. Basic Knowledge of Collider

Triggering:

Modern detectors usually can trigger on:

- ❖ muons by a muon chamber,
- ❖ electrons/photons as electromagnetic objects,
- ❖ τ /hadrons and jets as hadronic objects,
- ❖ global energy sum and missing transverse energy,
- ❖ some combinations of the above.

Objects	ATLAS	
	η	p_T (GeV)
μ inclusive	2.4	6 (20)
e /photon inclusive	2.5	17 (26)
Two e 's or two photons	2.5	12 (15)
1-jet inclusive	3.2	180 (290)
3 jets	3.2	75 (130)
4 jets	3.2	55 (90)
τ /hadrons	2.5	43 (65)
$\cancel{E}_T$	4.9	100
Jets+ $\cancel{E}_T$	3.2, 4.9	50,50 (100,100)

1. Basic Knowledge of Collider

Events:

Diagram illustrating the formula for the number of events (N) at a collider:

$$N = L \times \sigma \times A \times \varepsilon$$

The components of the formula are defined as follows:

- N : Number of events
- L : Integrated luminosity (fb^{-1})
- σ : Cross section (fb)
- A : Acceptance (100%, fiducial)
- ε : Selection efficiency



1. Basic Knowledge of Collider

Uncertainty:

$$x = 2.34 \pm 0.05 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$$

Statistical uncertainties:

1. rely on the number of samples N ;
2. relative uncertainty reduces as $1/\sqrt{N}$

Systematical uncertainties:

1. can't be calculated solely from sampling fluctuations;
2. don't reduces as $1/\sqrt{N}$, less known than statistical error

Quoting stat. and syst. separately gives us an idea whether taking more data would be helpful!

$$\sigma_{\text{tot}}^2 = \sigma_1^2 + \sigma_2^2 + \dots + \sigma_n^2$$

1. Basic Knowledge of Collider

Significance:



4 sigma effect

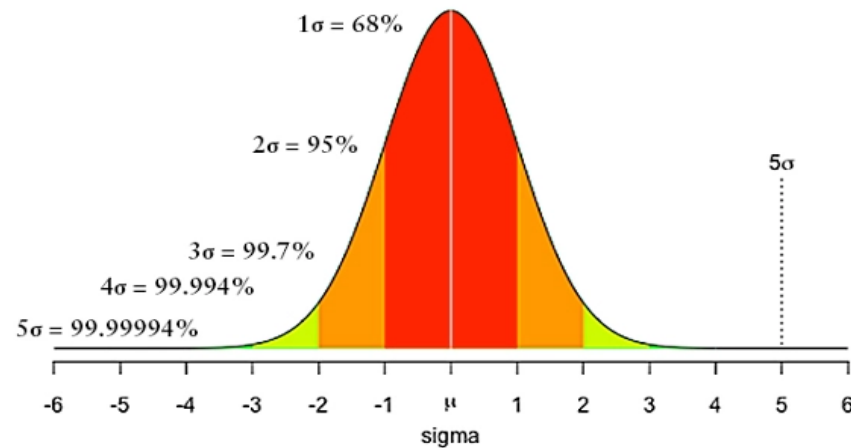
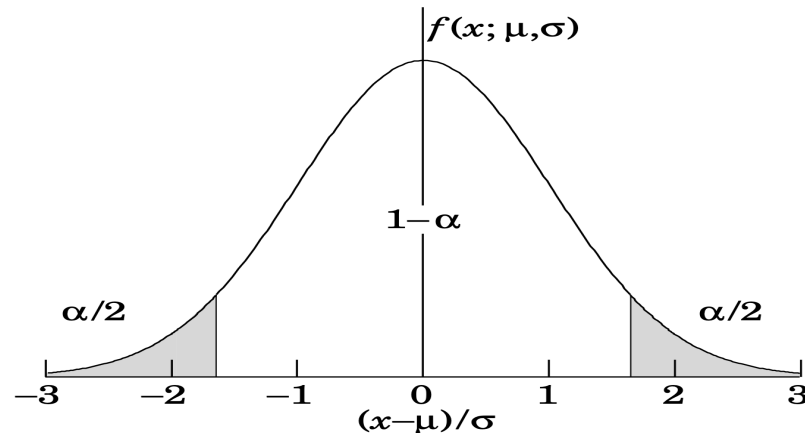


5 sigma effect



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Significance :



Probability that the measured value x will fall within $\pm\delta$ of the true value μ

$$1 - \alpha = \frac{1}{\sqrt{2\pi}\sigma} \int_{\mu-\delta}^{\mu+\delta} e^{-(x-\mu)^2/2\sigma^2} dx$$

The choice $\delta = \sigma$ gives an interval called the **standard error** which has $1 - \alpha =$ **68.27%** if σ is known.



1. Basic Knowledge of Collider

Significance :

I. Discovery sensitivity for counting experiment with b known:

(a) $\frac{s}{\sqrt{b}}$

(b) Profile likelihood ratio test & Asimov: $\sqrt{2 \left((s+b) \ln \left(1 + \frac{s}{b} \right) - s \right)}$

II. Discovery sensitivity with uncertainty in b , σ_b :

(a) $\frac{s}{\sqrt{b + \sigma_b^2}}$

(b) Profile likelihood ratio test & Asimov:

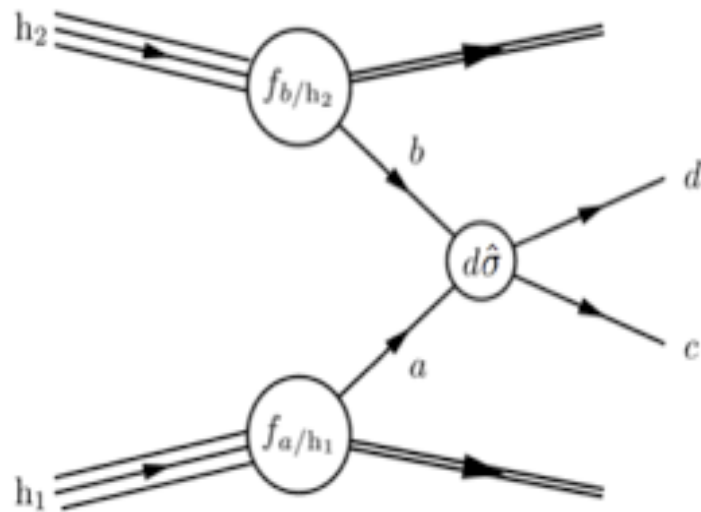
$$\left[2 \left((s+b) \ln \left[\frac{(s+b)(b + \sigma_b^2)}{b^2 + (s+b)\sigma_b^2} \right] - \frac{b^2}{\sigma_b^2} \ln \left[1 + \frac{\sigma_b^2 s}{b(b + \sigma_b^2)} \right] \right) \right]^{1/2}$$

2. Hadron and Lepton Collider Physics



Hadron Collider:

Master Formulae



$$\beta = \frac{x_a - x_b}{x_a + x_b}$$

Velocity of Parton frame wrt Lab frame

$$a, b = \{u, d, s, c, b, g\}$$

$$\sigma = \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R)$$

$$= \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R),$$

Flux Factor

$$1/(2\hat{s}) = 1/(2x_a x_b s)$$

μ_R 和 μ_F 分别是重整化和因子化标度

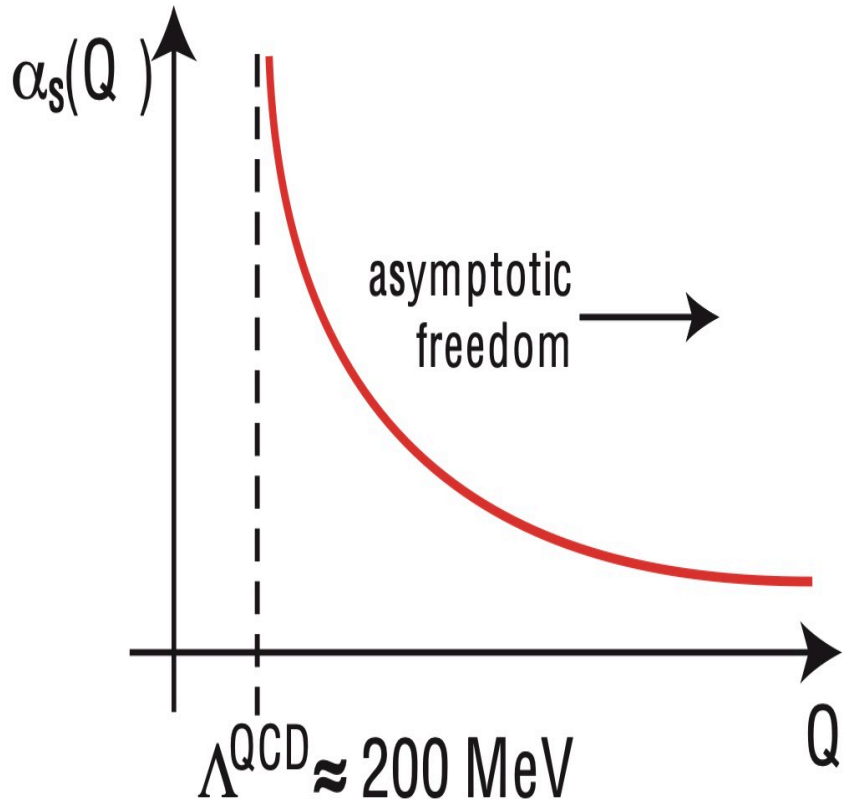
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Hard Scattering:

$$\begin{aligned}\sigma &= \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R) \\ &= \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \\ &\quad \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R),\end{aligned}$$

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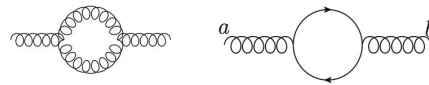


(See CF Qiao's talks)

Running of the QCD coupling

- Scale dependence (running) of α_s is expressed through the renormalization group equation (RGE)

$$\frac{d\alpha_s(\mu^2)}{d \ln \mu^2} = \beta(\alpha_s(\mu^2)), \quad \beta(\alpha_s) = -\alpha_s^2(b_0 + b_1\alpha_s + b_2\alpha_s^2 + \dots)$$



$$b_0 = \frac{11C_A - 2n_f}{12\pi}, \quad b_1 = \frac{17C_A^2 - 5C_An_f - 3C_Fn_f}{24\pi^2} = \frac{153 - 19n_f}{24\pi^2},$$

n_f : number of light quarks; C_A, C_F : QCD colour factors

- Negative sign of beta function: asymptotic freedom
 - coupling becomes weaker at high momentum scales

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1. calculable in perturbative QCD as series expansion in strong coupling α_s

$$\hat{\sigma}_{ab \rightarrow X} = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots$$

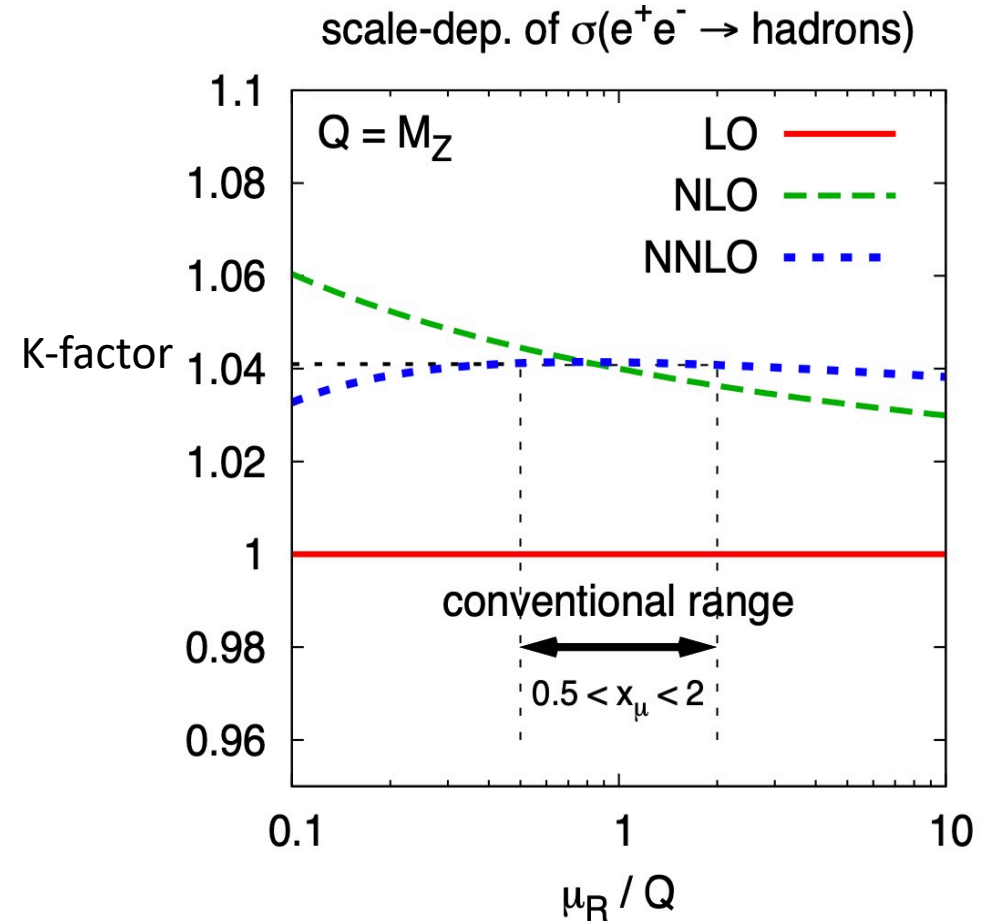
Leading order

Next-to-leading order

Next-to-next-to-leading order

2. only hard emissions above factorization scale μ_F

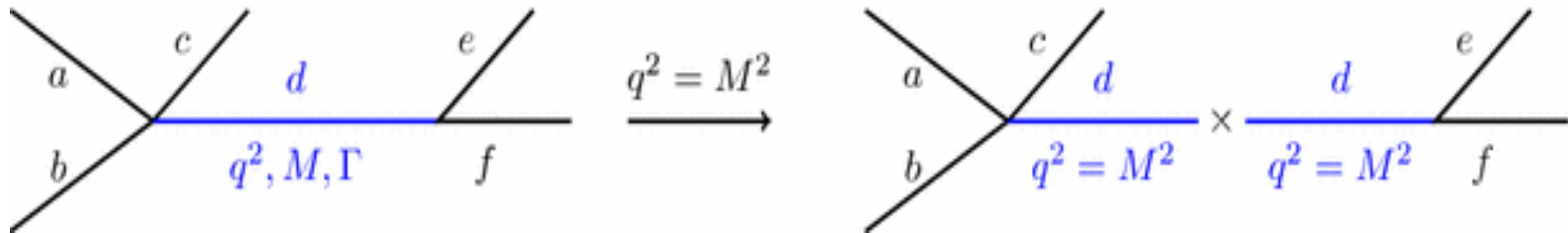
(See XG Wu's talks)



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Narrow Width Approximation:



$$\sigma(a+b \rightarrow c+e+f) = \sigma(a+b \rightarrow c+d) \times Br(d \rightarrow e+f)$$

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Parton Distribution Function (PDFs):

$$\begin{aligned}\sigma &= \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R) \\ &= \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \\ &\quad \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R),\end{aligned}$$

2. Hadron and Lepton Collider Physics



the probability to find partons (quarks and gluons) in a hadron as a function of the fraction x of the proton's momentum carried by the parton.

随标度演化满足**DGLAP**

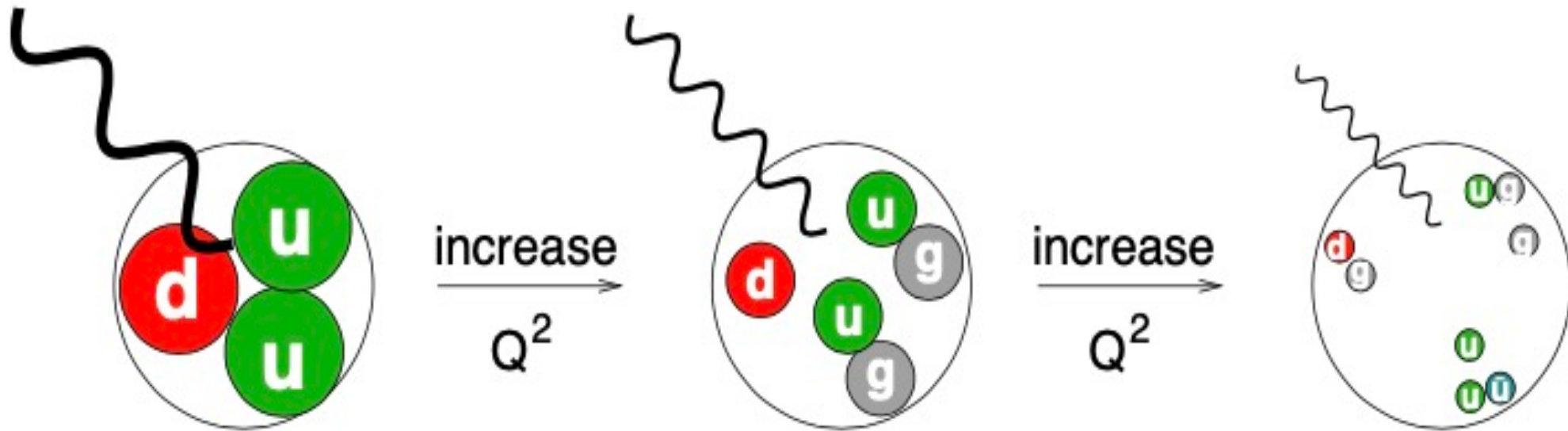
劈裂函数: 从部分子 i 上辐射出部分子 j 的几率

$$Q^2 \frac{\partial}{\partial Q^2} f_i(x, Q^2) = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ij}(z) f_j(x/z, Q^2)$$

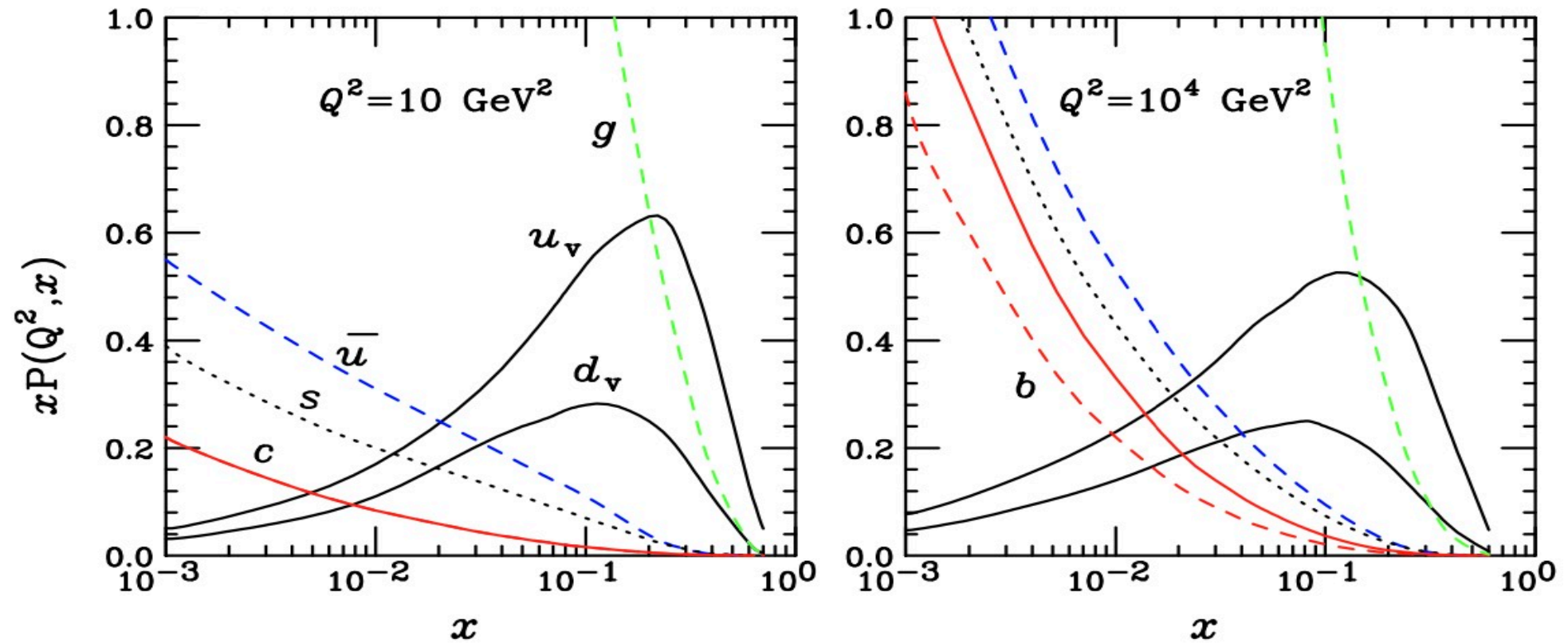
积分: 对所有可能的动量劈裂分数 z 进行积分。

PDFs 目前只能通过和大量的实验数据拟合确定, **PDFs 是普适的**。

2. Hadron and Lepton Collider Physics



2. Hadron and Lepton Collider Physics



Valence quarks and gluons have large x , typically $x \sim 0.08 - 0.3$.

“Sea quarks” have small x , and are significantly enhanced at higher Q^2 .

2. Hadron and Lepton Collider Physics



Phase Space:

$$\begin{aligned}\sigma &= \sum_{a,b} \int_0^1 dx_a dx_b \int f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) d\hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R) \\ &= \sum_{a,b} \int_0^1 dx_a dx_b \int d\Phi_n f_a^{h_1}(x_a, \mu_F) f_b^{h_2}(x_b, \mu_F) \\ &\quad \times \frac{1}{2\hat{s}} |\mathcal{M}_{ab \rightarrow n}|^2(\Phi_n; \mu_F, \mu_R),\end{aligned}$$

2. Hadron and Lepton Collider Physics



对于N体末态的相空间，独立的运动学变量个数 $d=3N-4$ ($N \geq 2$)。考虑到实际初态相对束流轴是转动不变的，则 $d=3N-5$ 。

$$d\Phi_N = \prod_{f=1}^N \frac{d^3 p_f}{(2\pi)^3 2E_f} (2\pi)^4 \delta^4(p_i + p_j - \sum p_f)$$

例如：2→2(或者1→2)过程，仅有的独立的运动学变量是散射角 θ 。

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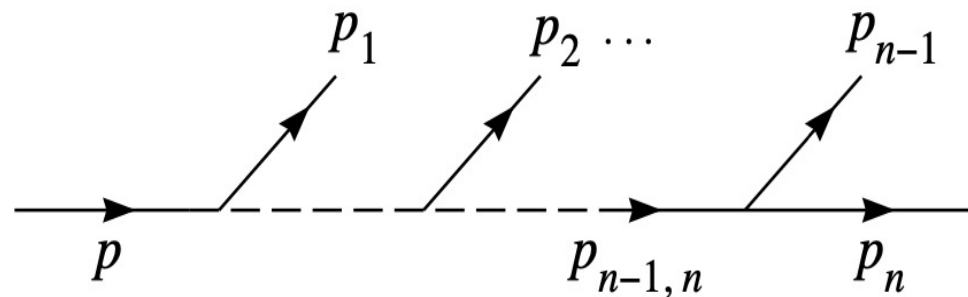
级联法

$$dPS_1 \equiv (2\pi) \frac{d^3\vec{p}_1}{2E_1} \delta^4(P - p_1)$$

$$dPS_2 \equiv \frac{1}{(2\pi)^2} \delta^4(P - p_1 - p_2) \frac{d^3\vec{p}_1}{2E_1} \frac{d^3\vec{p}_2}{2E_2}$$

$$dPS_3 \equiv \frac{1}{(2\pi)^5} \delta^4(P - p_1 - p_2 - p_3) \frac{d^3\vec{p}_1}{2E_1} \frac{d^3\vec{p}_2}{2E_2} \frac{d^3\vec{p}_3}{2E_3}$$

(Dalitz 图)

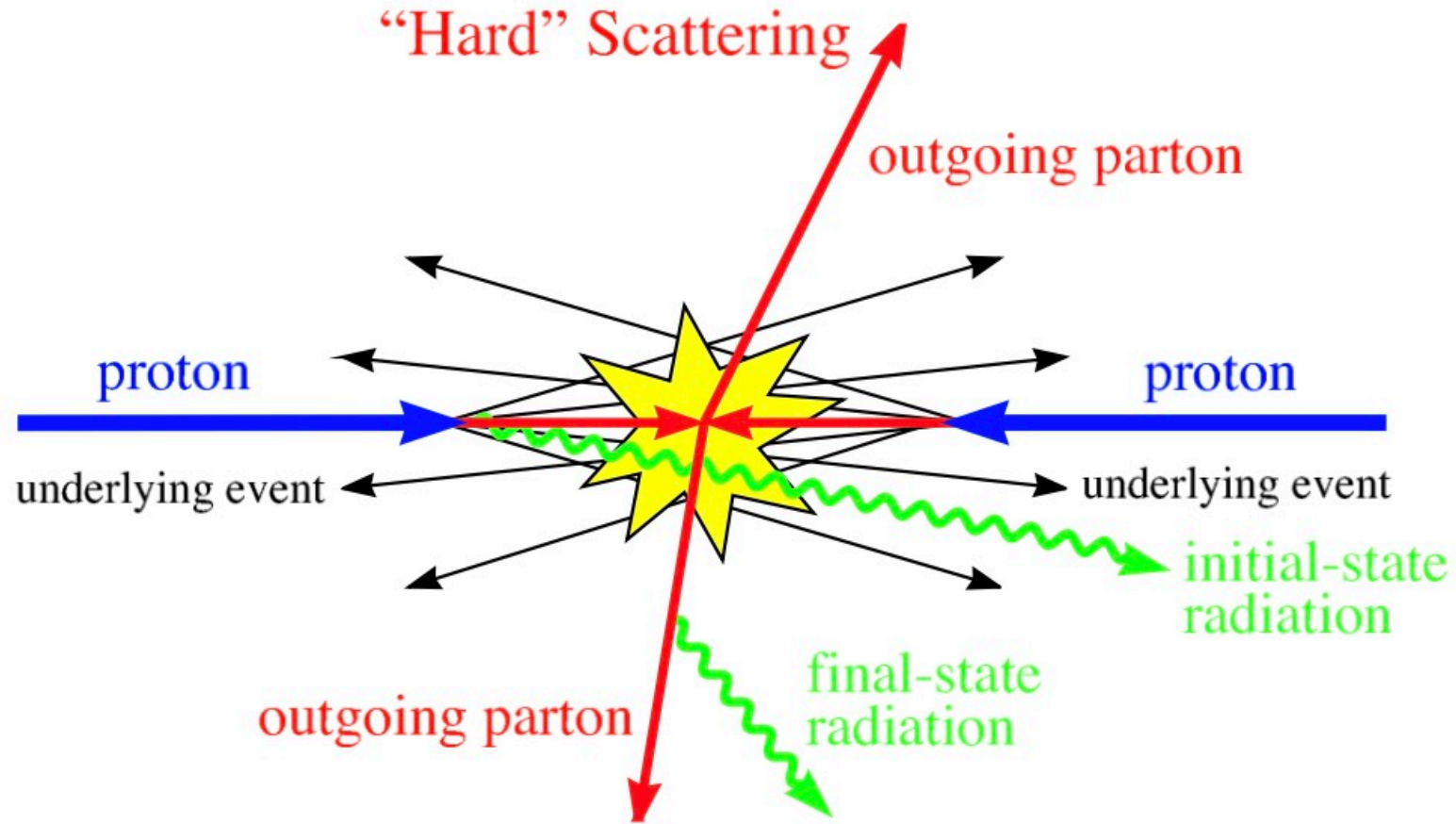


$$dPS_n(P; p_1, \dots, p_n) = dPS_{n-1}(P; p_1, \dots, p_{n-1,n}) \\ dPS_2(p_{n-1,n}; p_{n-1}, p_n) \frac{dm_{n-1,n}^2}{2\pi}$$

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Parton Shower:



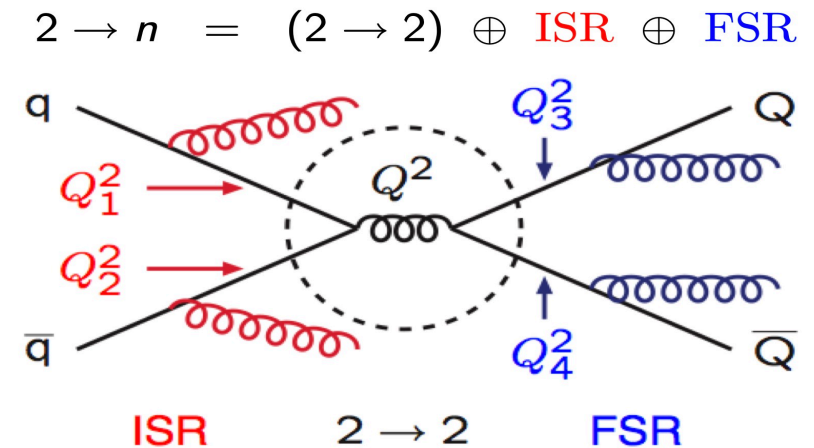
2. Hadron and Lepton Collider Physics



Collinear and soft emissions take place at all time scales between,

$$1/Q < T < 1/\Lambda_{\text{QCD}}$$

Computation of the dominant collinear and soft radiation is done by shower algorithms.



Shower evolution is viewed as a probabilistic process, which occurs with unit total probability.

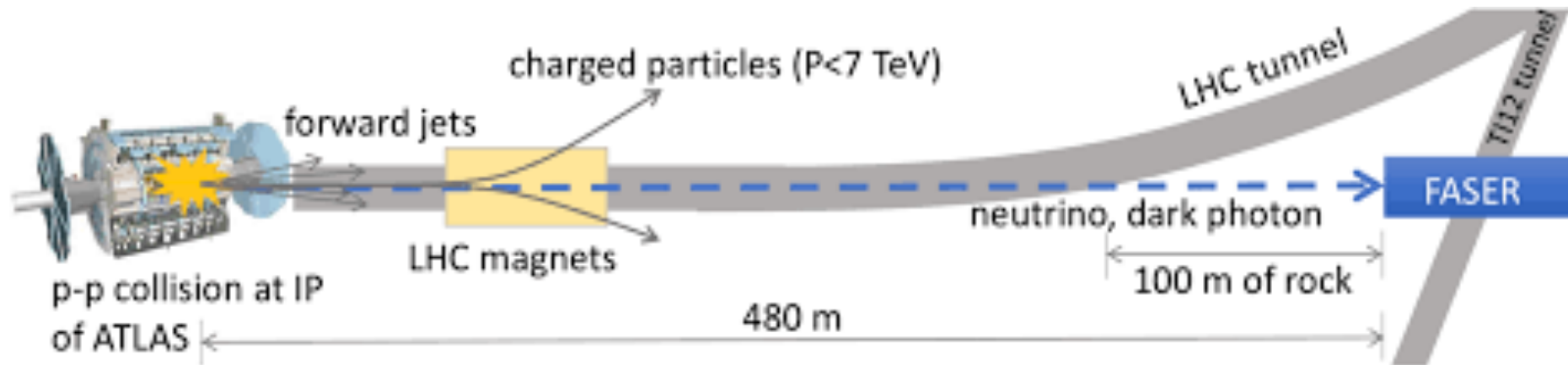
See QS Yan's talk

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New Instruments @ LHC:

Long Lived Particles

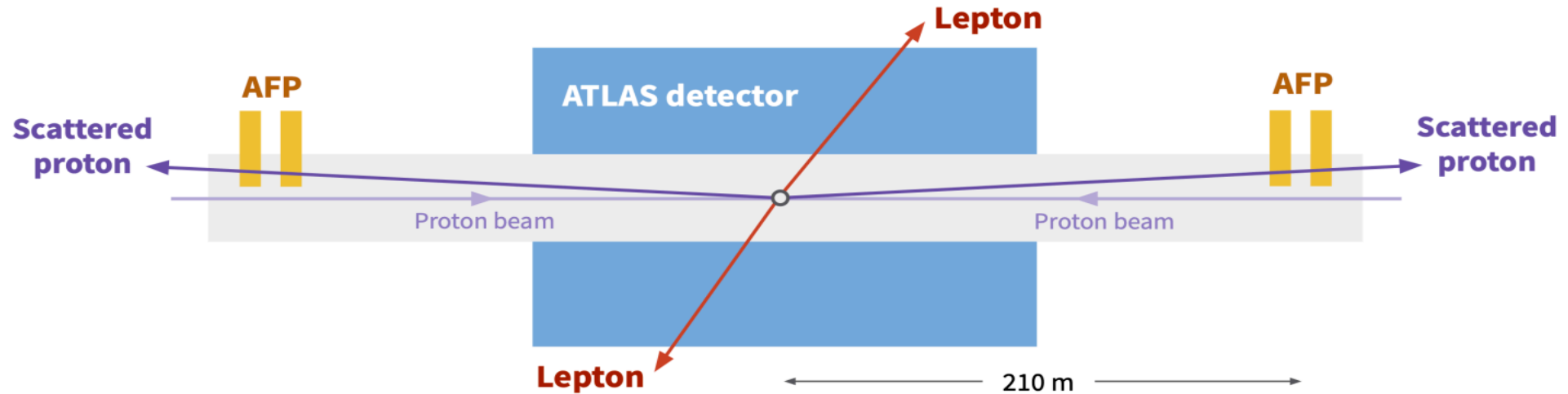


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New Instruments @ LHC:

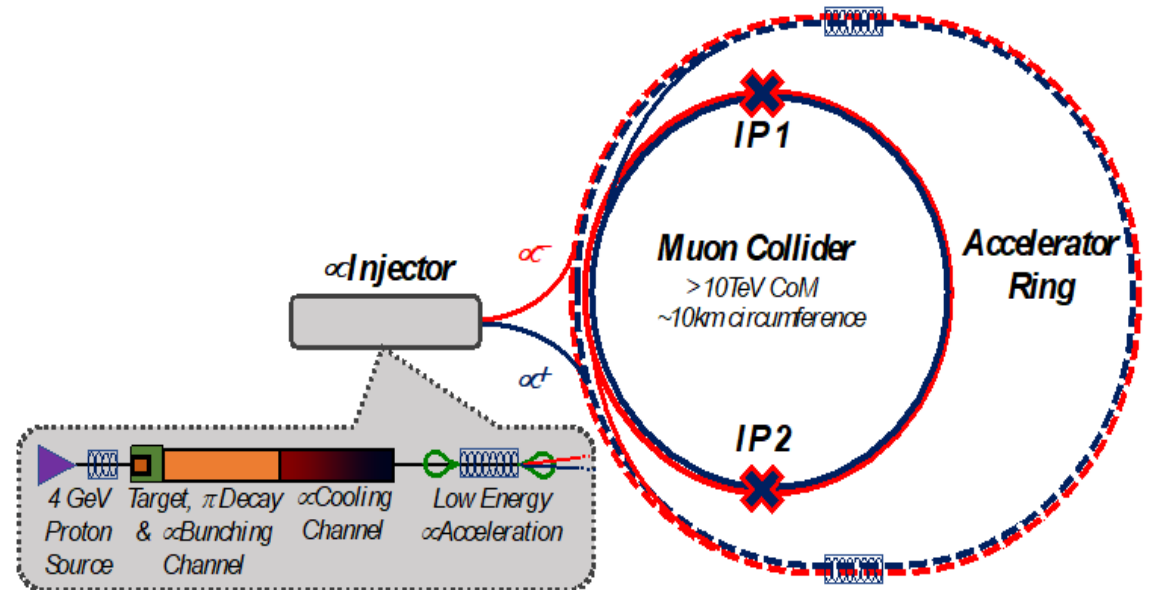
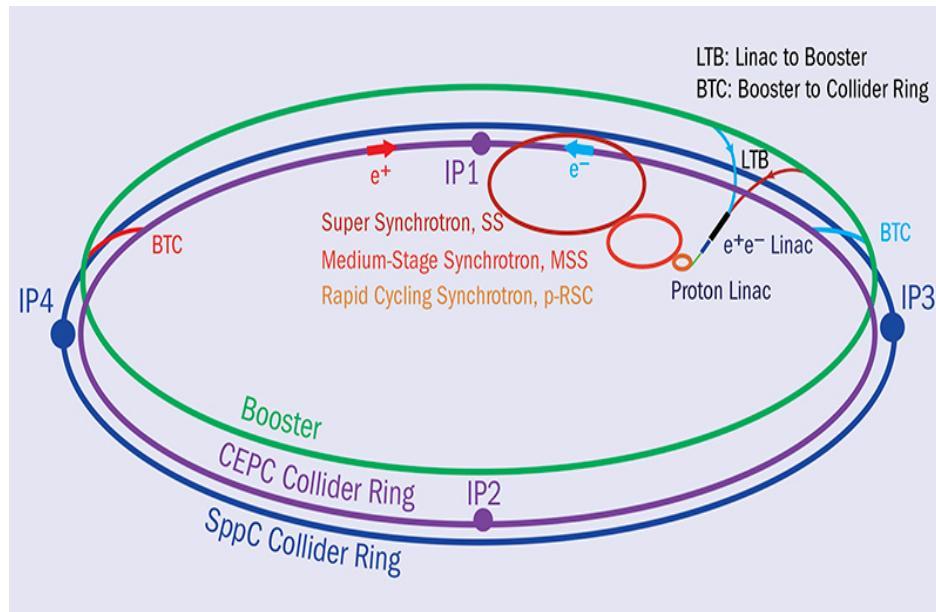
Forward Physics



2. Hadron and Lepton Collider Physics

Lepton Collider ($e^+e^-/\mu^+\mu^-$):

$$\Delta E \propto \frac{1}{R} \left(\frac{E}{m} \right)^4$$



实际对撞能量确定、环境干净、精度高！

2. Hadron and Lepton Collider Physics



- 1. Resonant production**
- 2. Polarized beam**
- 3. Forward-Backward asymmetry**
- 4. Recoil Mass Reconstruction**
- 5. Effective Photon Approximation**

2. Hadron and Lepton Collider Physics

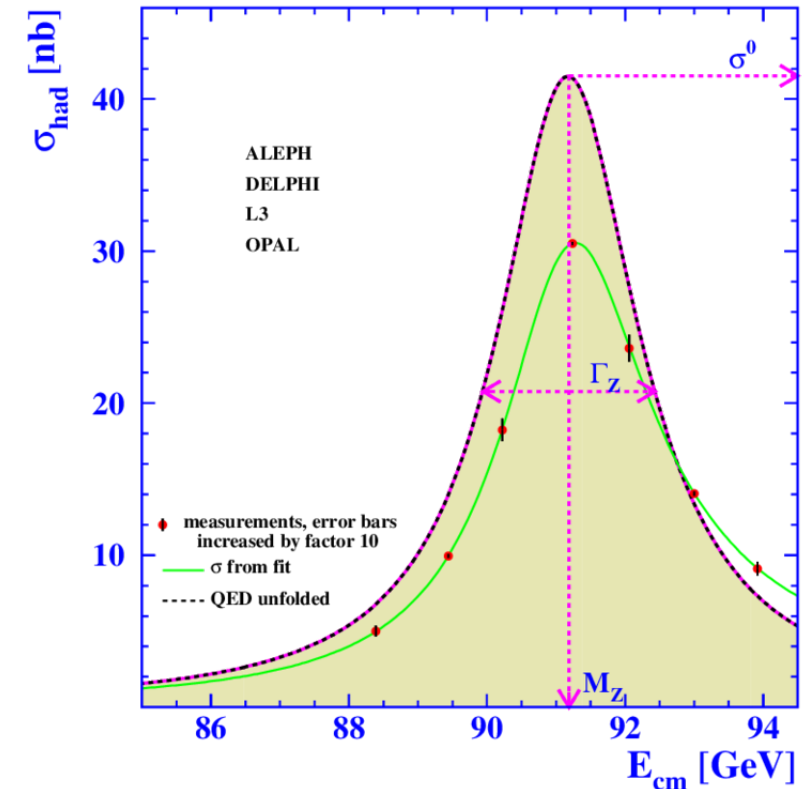


Resonant Production:

$$\sigma(e^+e^- \rightarrow V \rightarrow X) = \frac{4\pi(2j+1)\Gamma(V \rightarrow e^+e^-)\Gamma(V \rightarrow X)}{(s - M_V^2)^2 + \Gamma_V^2 M_V^2} \frac{s}{M_V^2}$$

Note: energy spread of the machine < the physical width

Z-line Shape



2. Hadron and Lepton Collider Physics

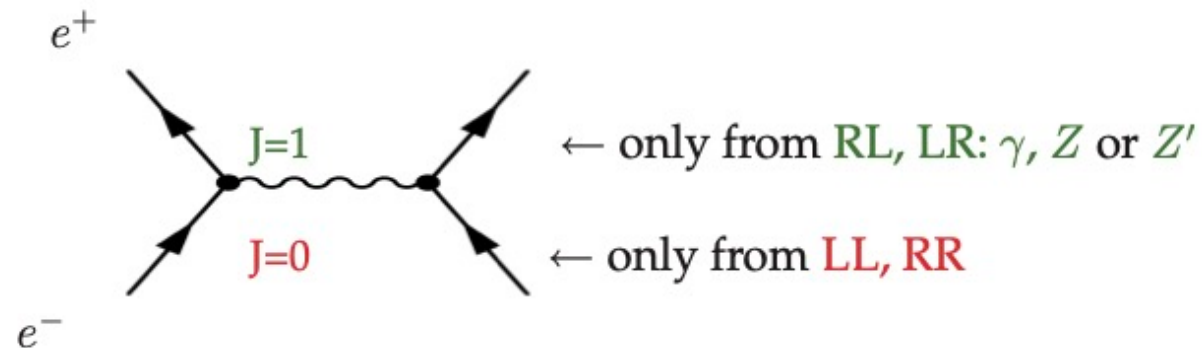


Polarization:

Longitudinally-polarized beams

ILC

$$\sigma_{P_{e^-} P_{e^+}} = \frac{1}{4} \left\{ (1 + P_{e^-})(1 + P_{e^+})\sigma_{RR} + (1 - P_{e^-})(1 - P_{e^+})\sigma_{LL} \right. \\ \left. + (1 + P_{e^-})(1 - P_{e^+})\sigma_{RL} + (1 - P_{e^-})(1 + P_{e^+})\sigma_{LR} \right\},$$

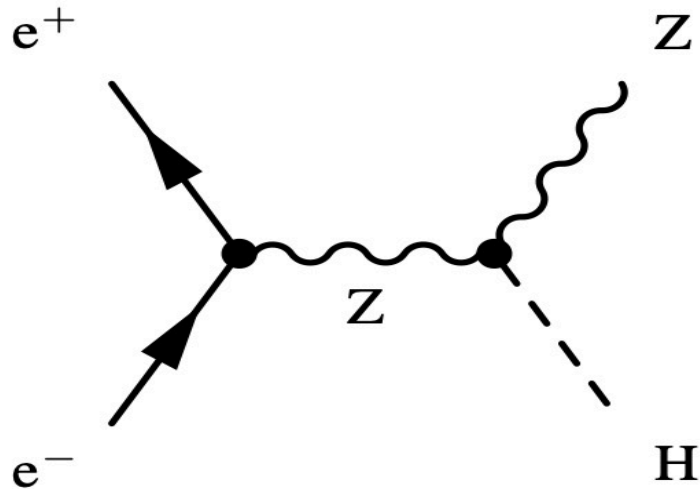


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recoiling mass method:

CEPC



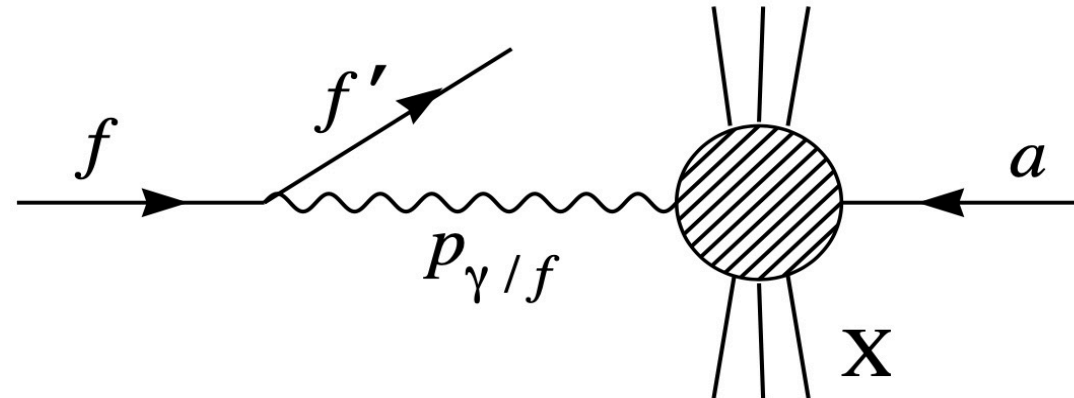
$$\begin{aligned} m_{\text{rec}}^2 &= (\sqrt{s} - E_{\ell\ell})^2 - \mathbf{p}_{\ell\ell}^2 = s - 2\sqrt{s}E_{\ell\ell} + E_{\ell\ell}^2 - \mathbf{p}_{\ell\ell}^2 \\ &= s - 2\sqrt{s}(E_{\ell 1} + E_{\ell 2}) + m_{\ell\ell}^2, \end{aligned}$$

2. Hadron and Lepton Collider Physics



Equivalent Photon Approximation:

The EPA deals with the processes in which t-channel photon exchanges yield the dominant contribution.



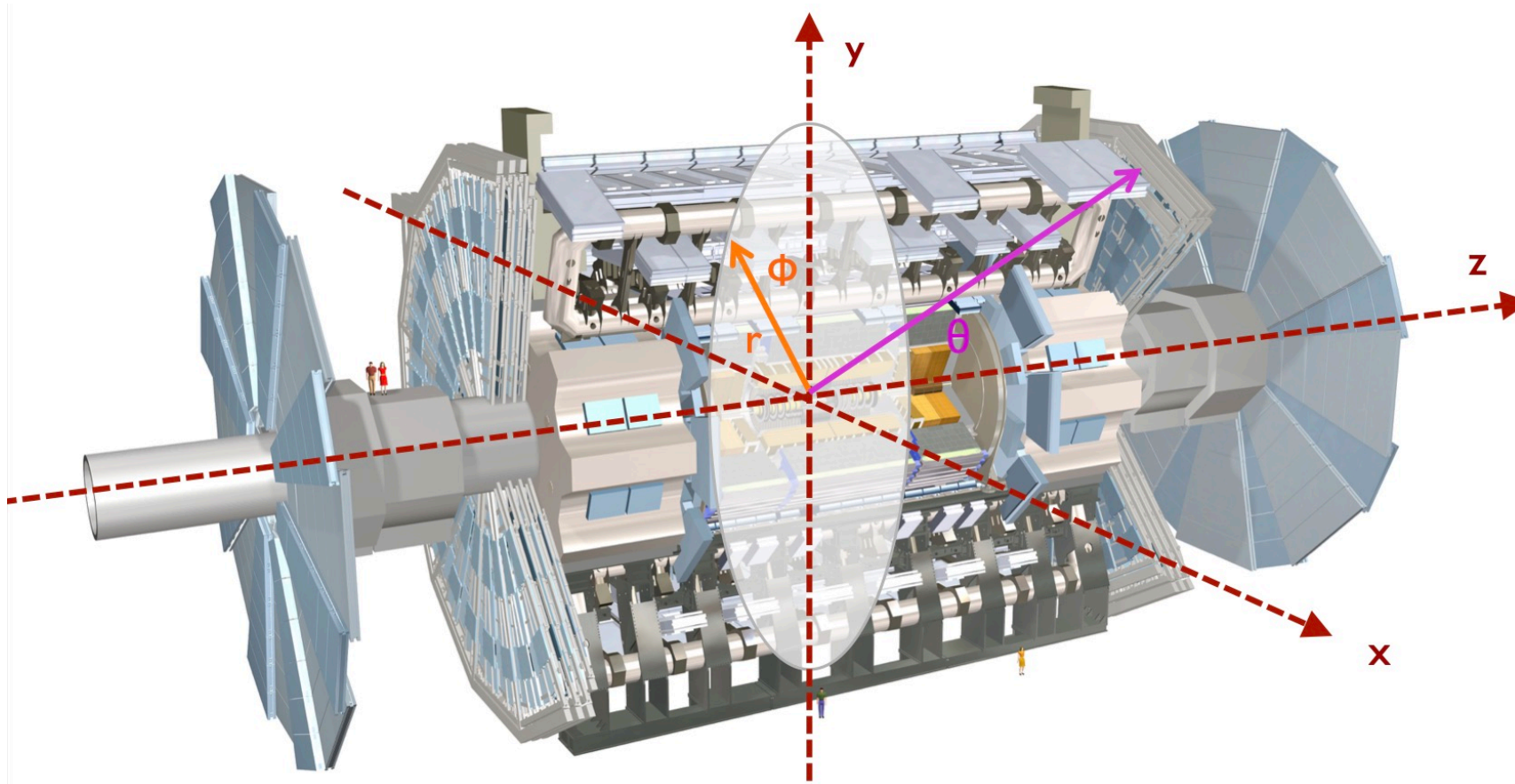
$$P_{\gamma/e}(x) = \frac{\alpha}{2\pi} \frac{1 + (1-x)^2}{x} \ln \frac{E^2}{m_e^2}$$

$$\sigma(e^- a \rightarrow e^- X) \approx \int dx P_{\gamma/e}(x) \sigma(\gamma a \rightarrow X)$$

2. Hadron and Lepton Collider Physics



Kinematics:



武雷 (2021 Pre-SUSY)

2. Hadron and Lepton Collider Physics



Pseudorapidity

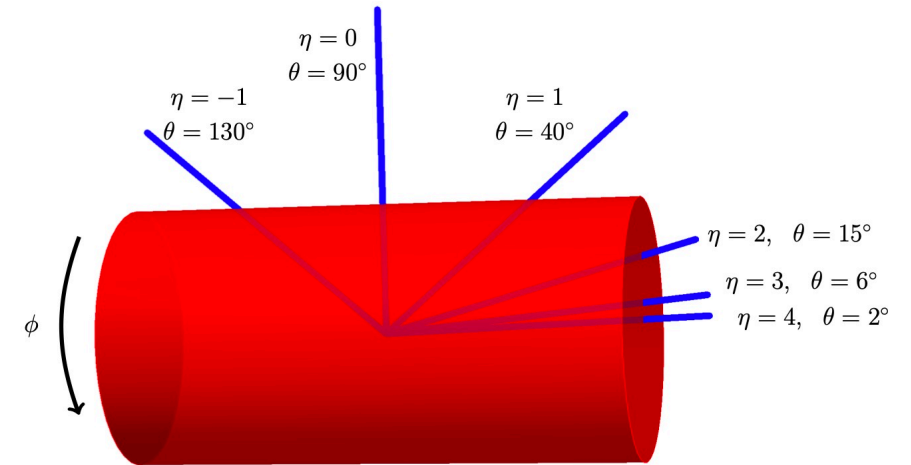
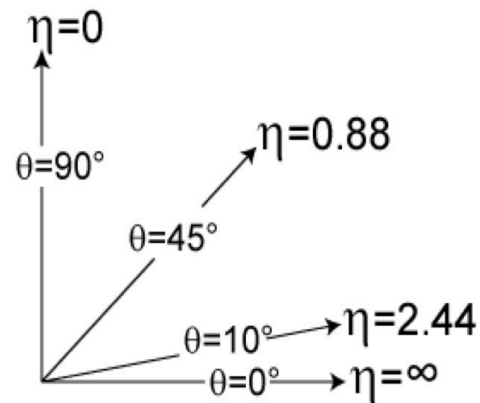
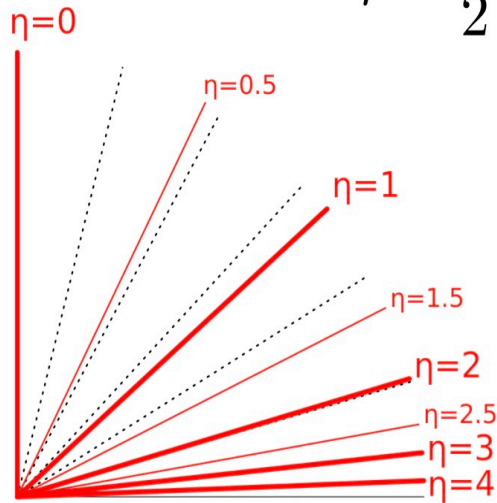
$$\eta = \frac{1}{2} \ln \frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}$$

$$\eta = \frac{1}{2} \ln \left(\tan \frac{\theta}{2} \right)$$

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

$$\eta \simeq y$$

if $E \gg m$



2. Hadron and Lepton Collider Physics



Transverse momentum

$$\sum p_T(i) = 0$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$p_x = p_T \cos \phi$$

$$p_y = p_T \sin \phi$$

$$p_z = p_T \sinh \eta$$

$$|p| = p_T \cosh \eta$$

$$E_T = \frac{E}{\cosh \eta}$$

2. Hadron and Lepton Collider Physics



Missing transverse momentum

$$\vec{p}_{\cancel{T}} \equiv - \sum_j \vec{p}_T$$

Missing transverse energy

$$E_{\cancel{T}} \equiv |\vec{p}_{\cancel{T}}|$$

2. Hadron and Lepton Collider Physics



Scalar sum of the missing transverse momentum in certain objects

$$H_T = \sum_{\text{leptons } j} |\vec{p}_T^j|$$

Invariant mass of some objects

$$m_{\text{objects}} = \left| \sum_{\text{objects } j} p_j^\mu \right|^2$$

2. Hadron and Lepton Collider Physics



Transverse mass

$$m_T \equiv \sqrt{(E_T^1 + E_T^2)^2 - (p_T^1 + p_T^2)^2}$$

Transverse energy:

$$E_T = \sqrt{m^2 + p_T^2}$$

If both p_1 and p_2 are purely transverse ($\eta = 0$), then $m_T = m$.

If p_1 and p_2 are purely longitudinal, then $m_T = 0$.

2. Hadron and Lepton Collider Physics

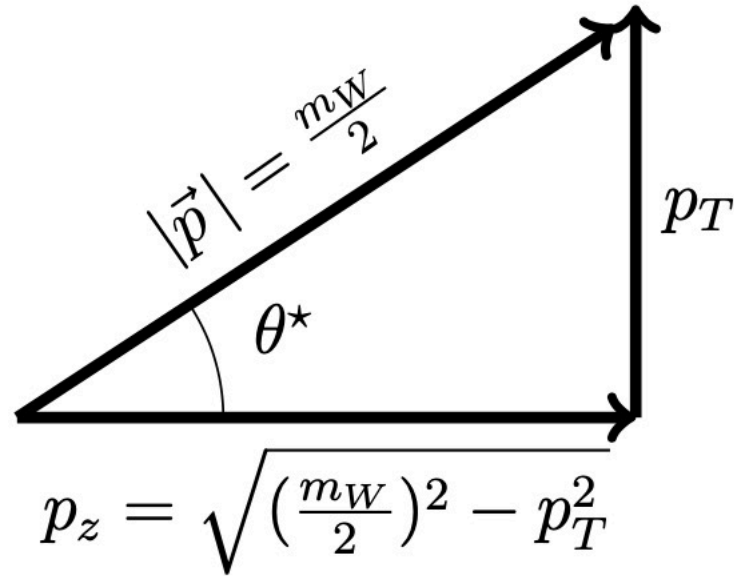


$$\frac{1}{\sigma_0} \frac{d\hat{\sigma}(q\bar{q} \rightarrow W \rightarrow e^- \nu)}{d \cos \theta^*} = \frac{3}{8} (1 + \cos^2 \theta^*)$$

$$p_W^\mu = (m_W, \vec{0})$$

$$p_e^\mu = (\frac{m_W}{2}, \vec{p})$$

$$p_\nu^\mu = (\frac{m_W}{2}, -\vec{p})$$



$$\cos \theta^* = \frac{p_z}{|\vec{p}|} = \sqrt{1 - \frac{4p_T^2}{m_W^2}}$$

2. Hadron and Lepton Collider Physics

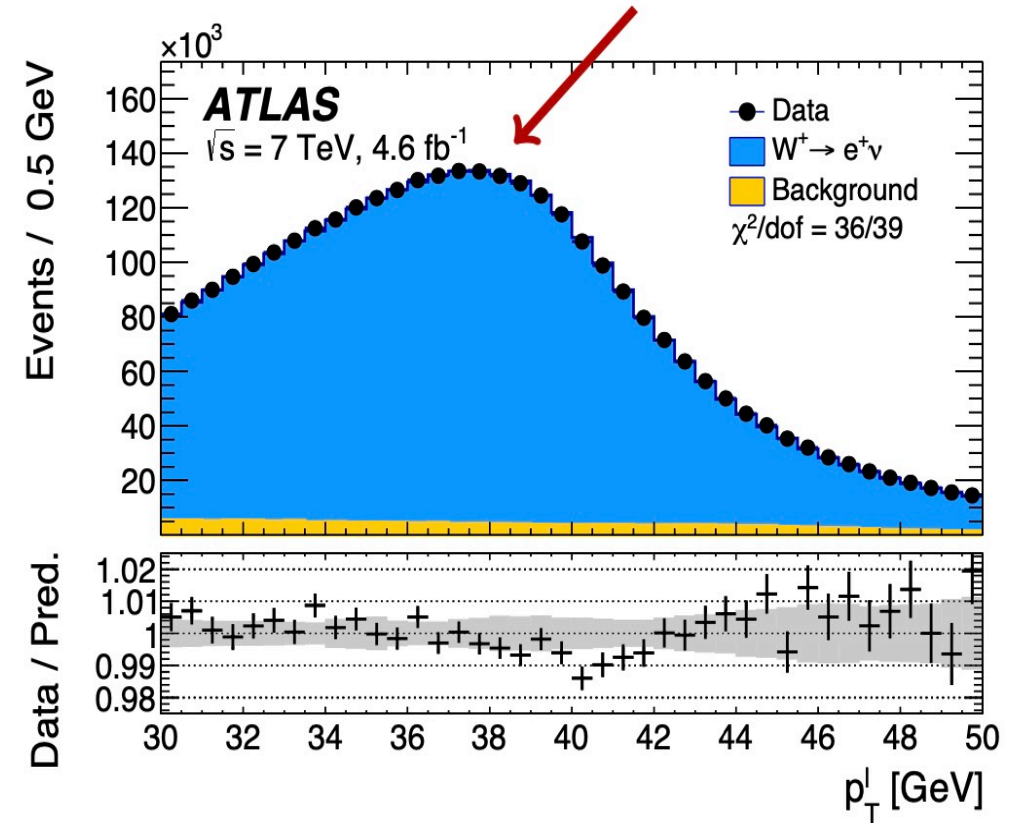


$$\frac{1}{\sigma_0} \frac{d\hat{\sigma}(q\bar{q} \rightarrow W \rightarrow e^- \nu)}{d \cos \theta^*} = \frac{3}{8} (1 + \cos^2 \theta^*)$$



$$\frac{1}{\sigma_0} \frac{d\hat{\sigma}(q\bar{q} \rightarrow W \rightarrow e^- \nu)}{dp_T} = \underbrace{\frac{3}{m_W^2} \frac{p_T}{\sqrt{1 - \frac{4p_T^2}{m_W^2}}}}_{\text{Jacobian factor}} \underbrace{\left(1 - \frac{2p_T^2}{m_W^2}\right)}_{1 + \cos^2 \theta^*}$$

Jacobian peak at $\sim \frac{m_W}{2}$



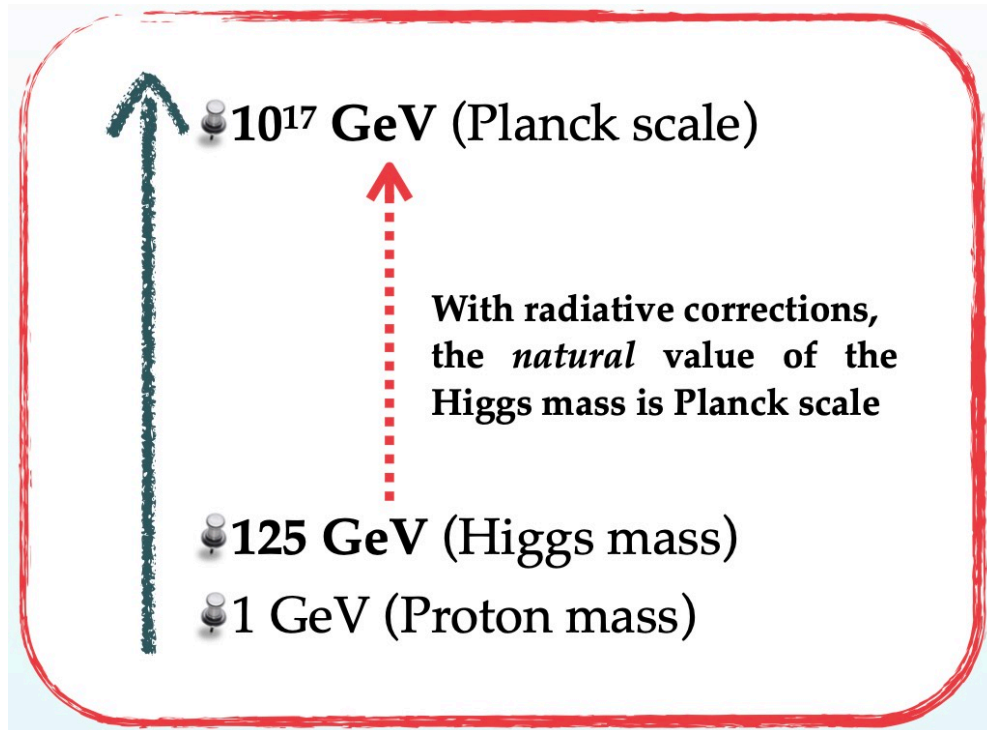
Measuring the location of this peak is one way the W boson mass is measured.

2. Hadron and Lepton Collider Physics

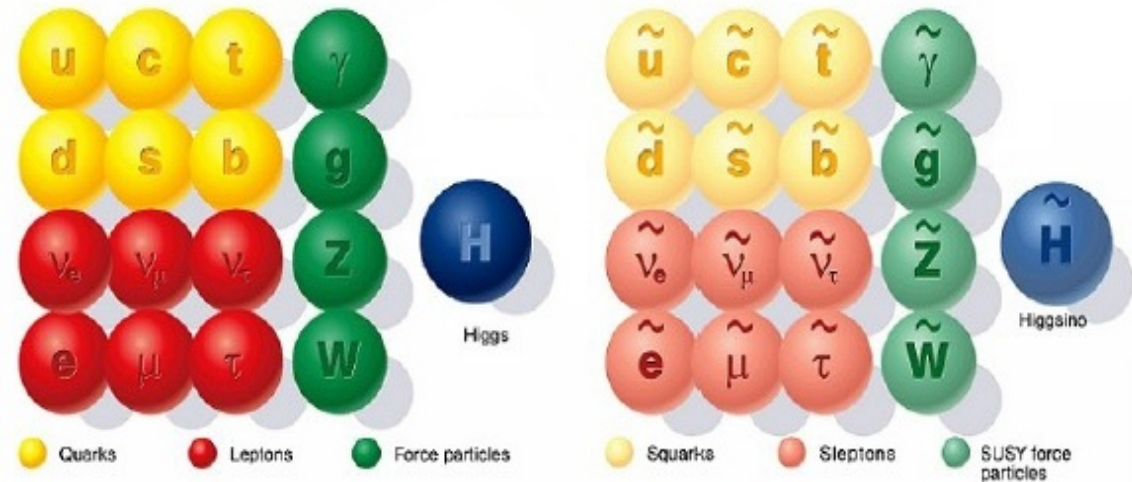


New Physics:

See Z Sun and Xuai Zhuang's talk



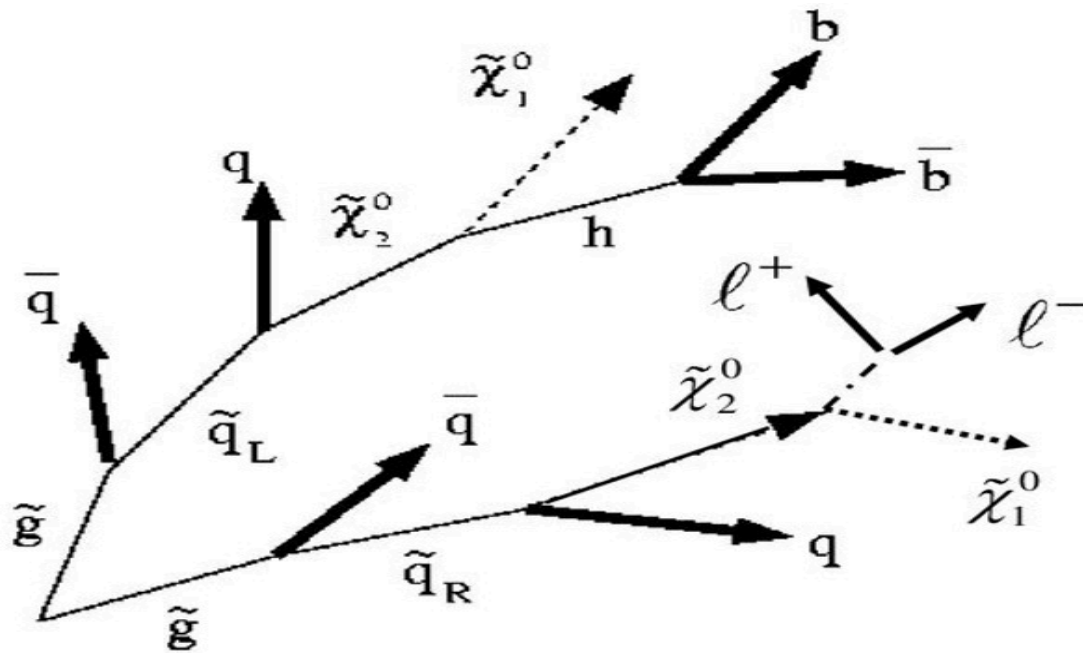
SUPERSYMMETRY



Standard particles

SUSY particles

2. Hadron and Lepton Collider Physics



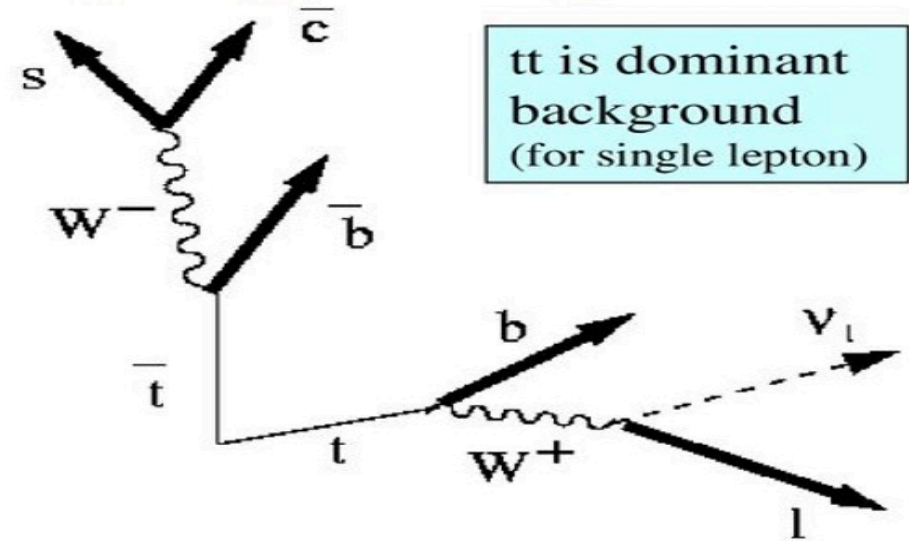
SUSY signature

m leptons (e/μ) + large E_T^{miss} + n jets

$m = 0, 1, 2, \dots$
(some soft)

some b jets

Topologies & Signatures



$t\bar{t}$ is dominant
background
(for single lepton)

$t\bar{t}$ signature

all jets: no E_T^{miss} + n jets ($n \sim 6$)

leptonic: e/μ + E_T^{miss} + n jets ($n \sim 4$)

dilepton: $2e/\mu$ + E_T^{miss} + n jets ($n \sim 2$)

~ 2 b jets

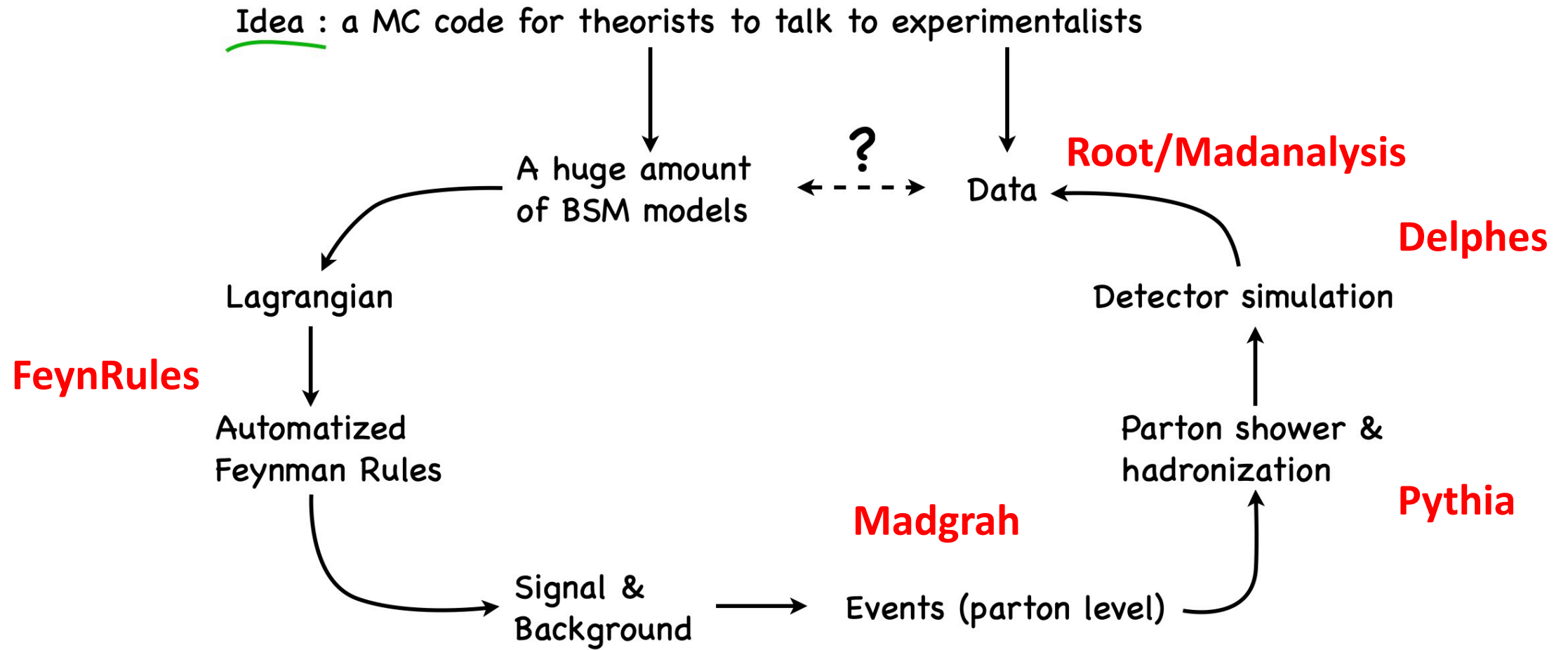
3. Simulation Tools and Machine Learning



General Method:

- 1、从理论的拉氏量出发，确定该粒子与SM粒子的所有耦合以及主要的新粒子之间耦合。根据耦合性质确定X在对撞机上的产生机制。
- 2、计算所选产生过程的截面。此时计算无需施加cuts，除非为了避免奇点。结合所考虑的对撞机亮度给出该产生过程的事例数 N_{th}
- 3、计算其所有衰变模式的分支比，得到各个衰变模式的信号事例数 N_{sig} 。按照计算出来的 N_{sig} 大小排序，优先考虑 N_{sig} 较大的过程并列出其主要的SM背景，计算这些SM背景得到事例数 N_{SM} 。
- 4、评估选择的信号在对撞机上是否可行。一般有意义的过程应满足三个条件：(a) 事例数不能太少；(b) 统计误差： $N_{sig}/\sqrt{N_{SM}} > n\sigma$ ，通常为n为3或者5。(c) 系统误差： $N_{sig}/N_{SM} \gg \sigma_{sys}$ 。

3. Simulation Tools and Machine Learning



See QS Yan's talk

3. Simulation Tools and Machine Learning



Machine Learning:

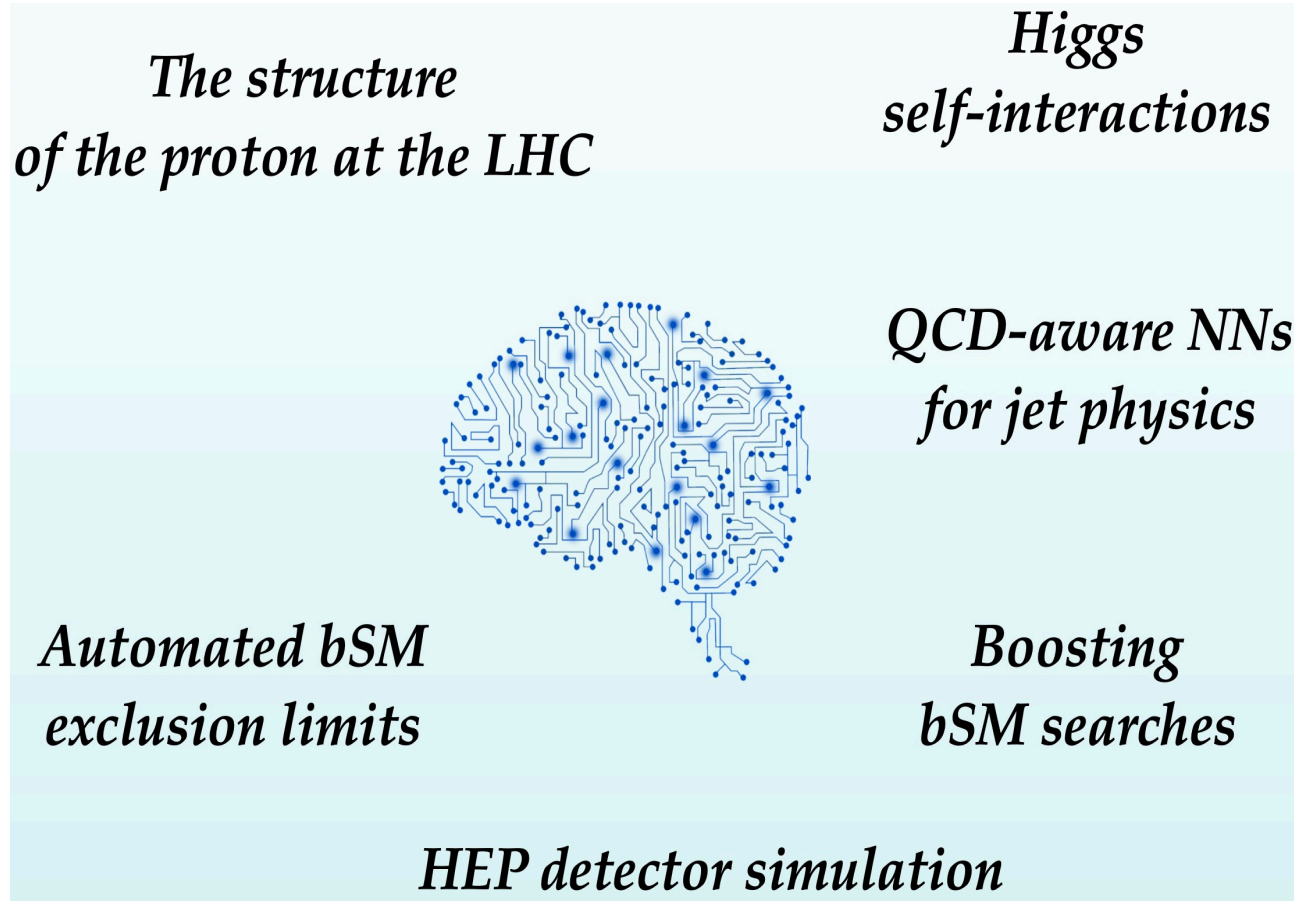


大量基本运算，简单



图像识别，困难

3. Simulation Tools and Machine Learning



Event Selection
Jet Classification
Tracking
Fast Simulation
Scan
.....

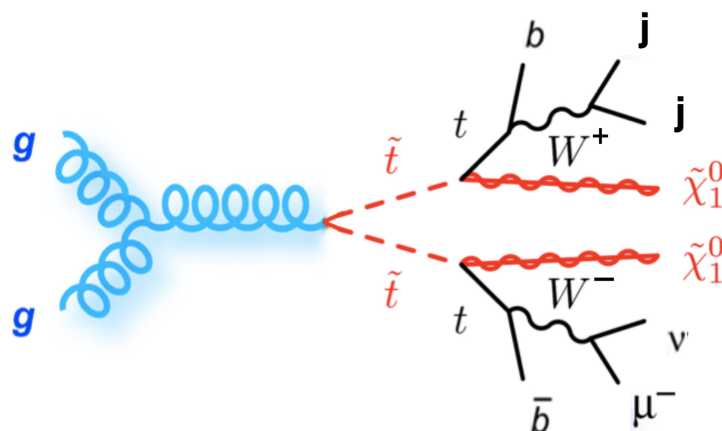
arXiv:1905.06047 [hep-ph]

3. Simulation Tools and Machine Learning



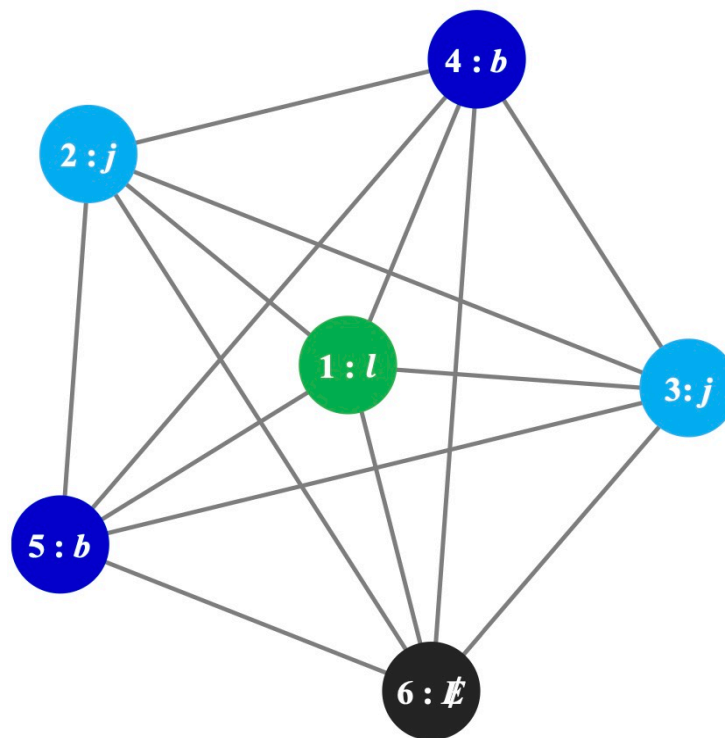
Events selections :

寻找新信号：事例图



top对产生过程

1807.09088



武雷 (2021 Pre-SUSY)

$\mathbf{x}$

	Photon	lepton charge	b-jet or light jet	MET	p_T (TeV)	E (TeV)	m (TeV)
$x_1 = ($	0	-1	0	0	0.0229	0.0289	0.0000)
$x_2 = ($	0	0	-1	0	0.2637	0.3304	0.0373)
$x_3 = ($	0	0	-1	0	0.1003	0.1888	0.0091)
$x_4 = ($	0	0	1	0	0.0980	0.1146	0.0133)
$x_5 = ($	0	0	1	0	0.0689	0.0773	0.0062)
$x_6 = ($	0	0	0	1	0.2107	0.2107	0.0000)

$\mathbf{d}$

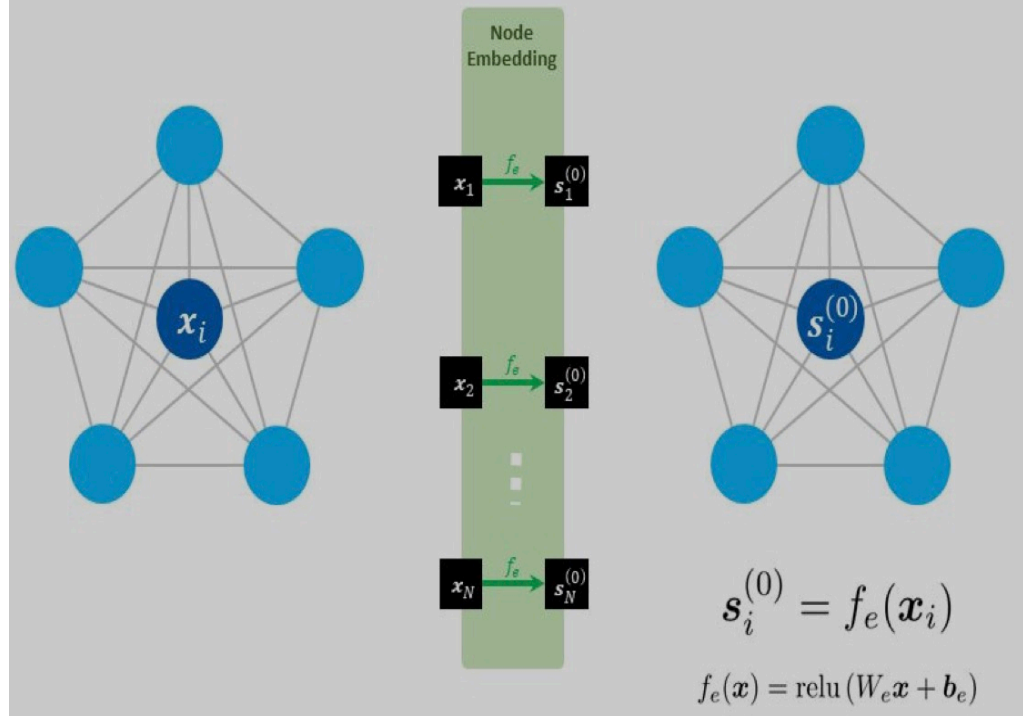
	1	2	3	4	5	6
1	0	1.3971	2.5649	1.2801	3.2752	3.0312
2	1.3971	0	1.9019	1.6688	3.0871	3.1717
3	2.5649	1.9019	0	3.4440	1.5805	1.7831
4	1.2801	1.6688	3.4440	0	2.2175	2.1387
5	3.2752	3.0871	1.5805	2.2175	0	0.4912
6	3.0312	3.1717	1.7831	2.1387	0.4912	0

3. Simulation Tools and Machine Learning

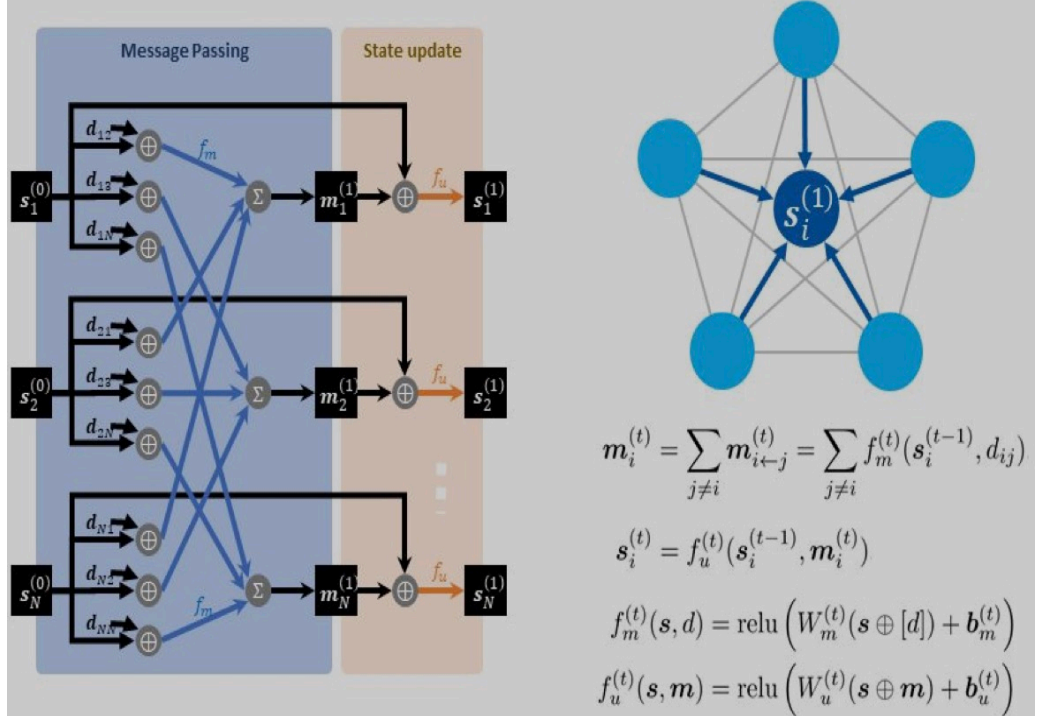


寻找新信号：事例图

First, embed the object intrinsic properties x_i into 30-dim state vectors $s_i^{(0)}$.



Do $T = 2$ times: Each node i collects the messages sent from other nodes j and update its state vector.

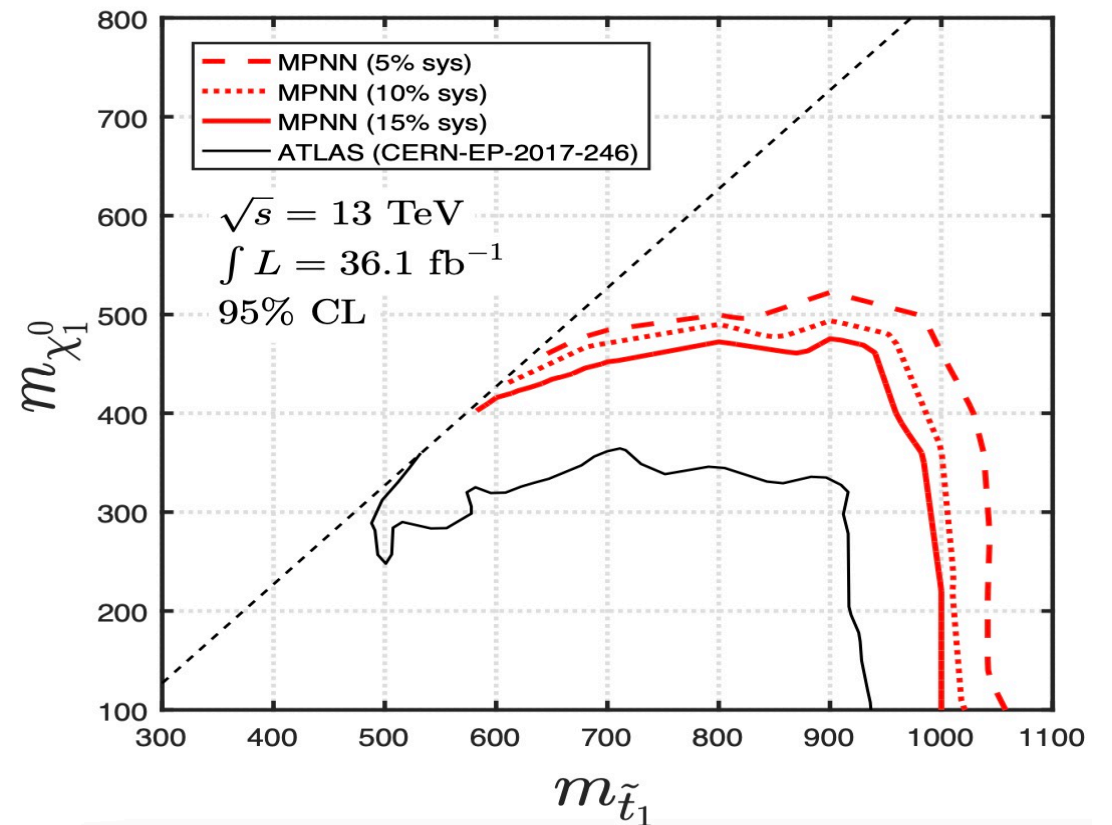
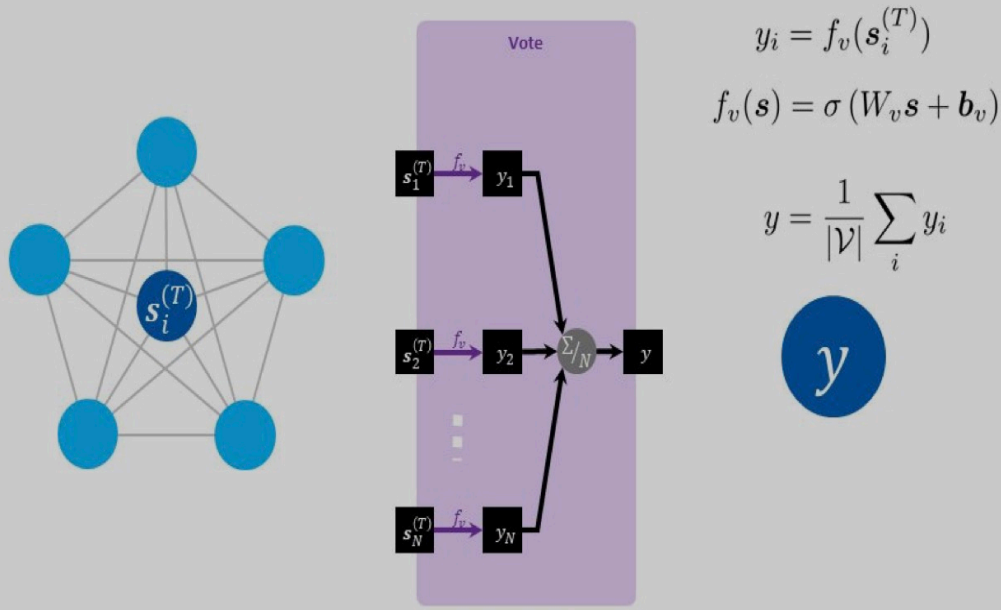


3. Simulation Tools and Machine Learning



寻找新信号：事例图

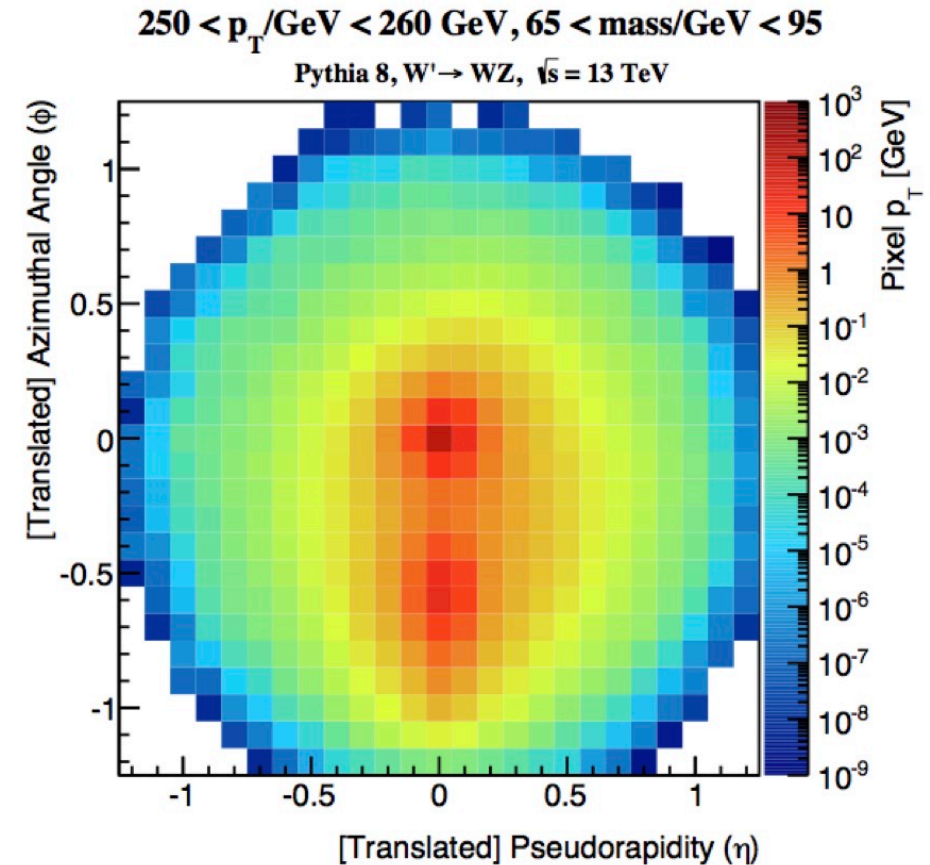
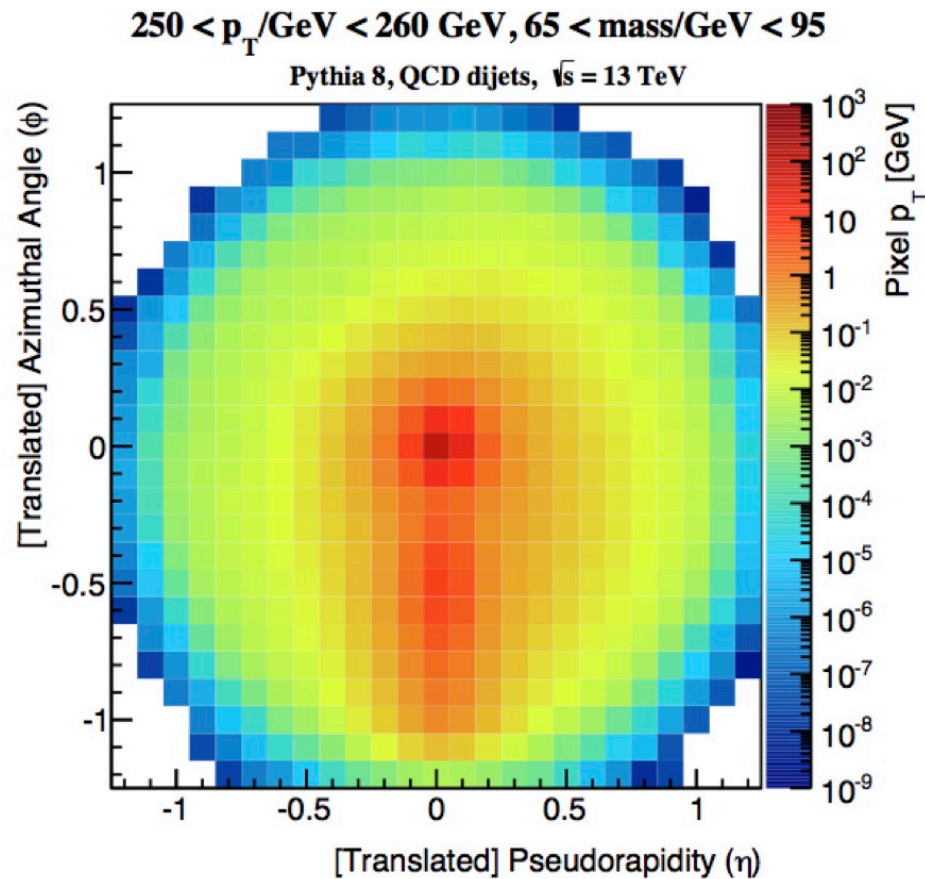
Next, each node votes a number y_i in $[0,1]$ as the likeness of the event to be signal-like, and finally we average the votes y_i from each node as **discrimination score** (a real number in $[0,1]$).



3. Simulation Tools and Machine Learning



Jet Classification :



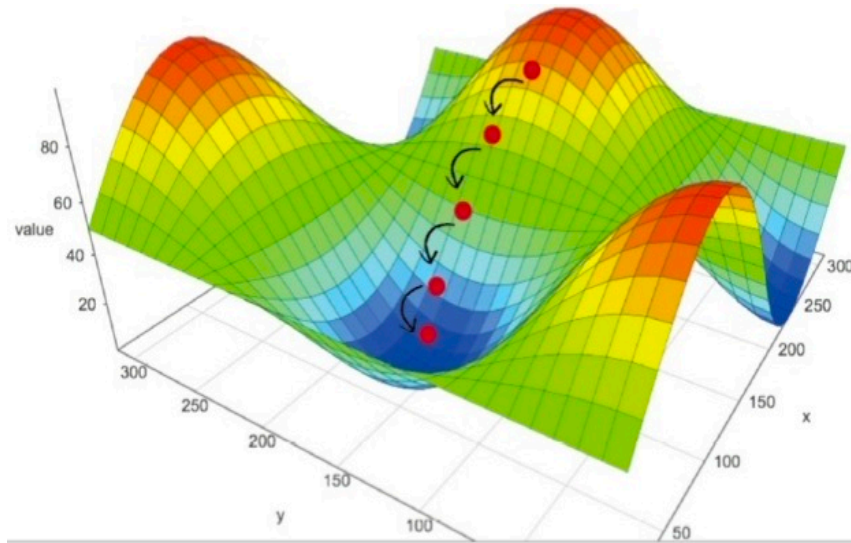
3. Simulation Tools and Machine Learning



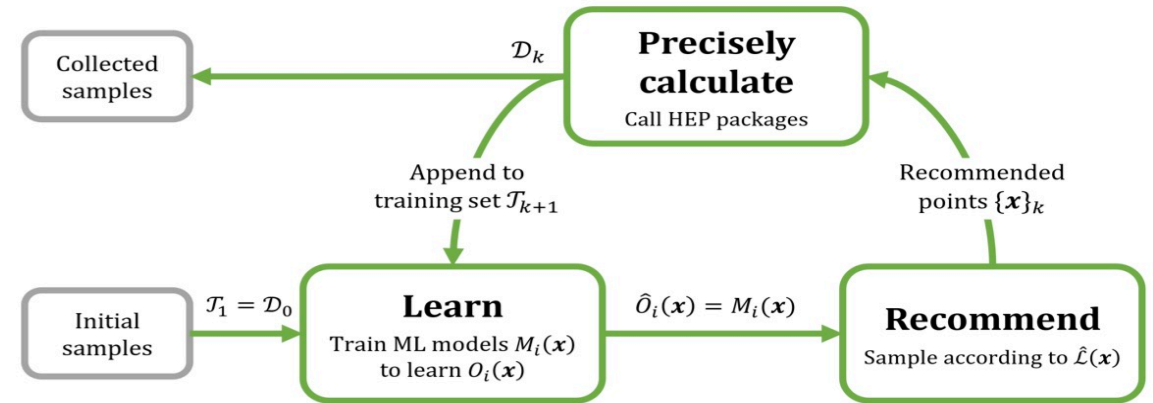
Scan :

检验新模型: Machine Learning Scan

$$\mathcal{L}(\mathbf{x}) = \prod_i \mathcal{L}_i(O_i(\mathbf{x}); O_i^*, \sigma_i^*)$$



1708.06615



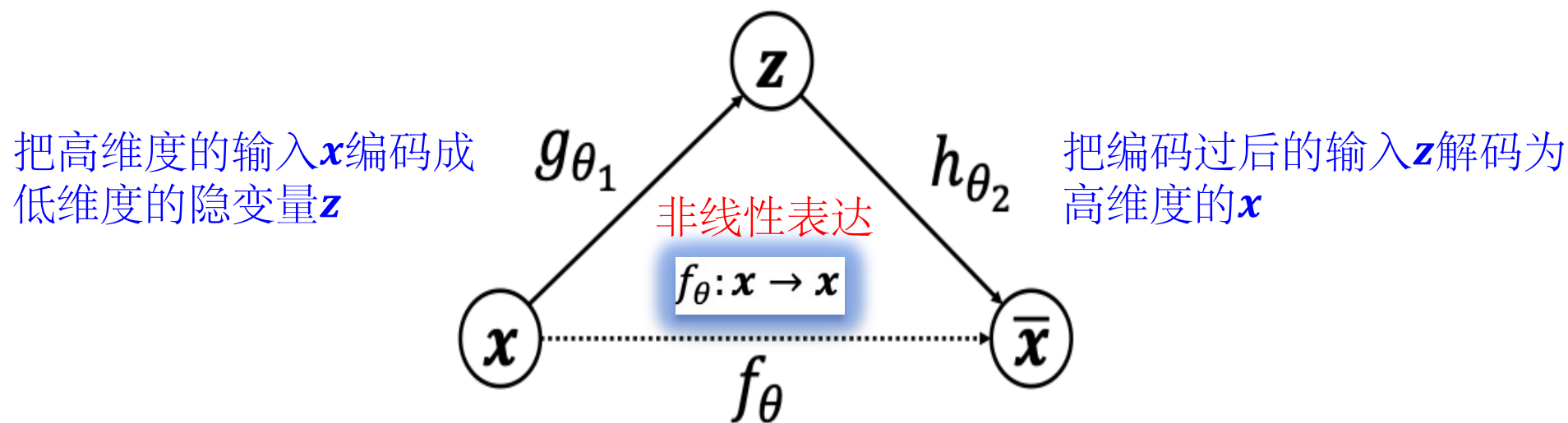
- 1、使用已收集的数据训练ML模型；
- 2、根据重建的likelihood区间重点抽样，并产生推荐数据；
- 3、利用程序包精确计算推荐数据的可观测量，将符合好的样本和新的随机样本重新加入训练集；
- 4、重复以上步骤，收集符合条件数据。

3. Simulation Tools and Machine Learning



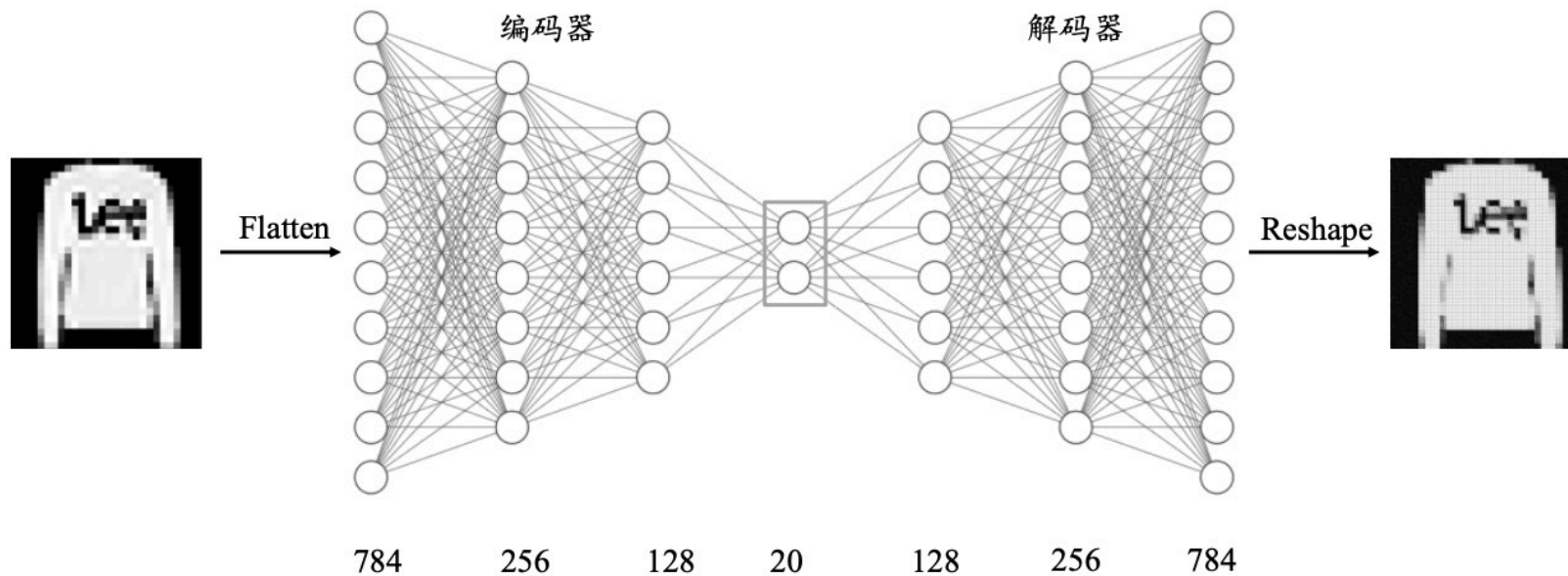
Auto-Encoder :

一种把样本 $\mathbf{x}$ 作为监督信号来学习的神经网络（自监督学习）



整个网络模型 f 叫做自动编码器(Auto-Encoder)

3. Simulation Tools and Machine Learning



自编码器的训练过程与分类器的基本一致，通过误差函数计算出重建向量 $\mathbf{x}$ 与原始输入向量 $\mathbf{x}$ 之间的距离，再利用自动求导机制同时求出encoder和decoder的梯度，循环更新即可。



Pre-SUSY 2021 @ Beijing



谢谢!

1. Basic Knowledge of Collider

Resolution:

Tracking :

$$\frac{\Delta p_T}{p_T} = ap_T \oplus b, \quad |\eta_\mu| \approx 2.5$$

For ATLAS (CMS), $a = 36\% \text{ TeV}^{-1}$ ($15\% \text{ TeV}^{-1}$),
 $b = 1.3\%/\sqrt{s} \sin \theta$ (0.5%).

ECAL :

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b, \quad |\eta_{e,\gamma}| \approx 3$$

For ATLAS (CMS), $a = 10\%$ (5%), $b = 0.4\%$ (0.55%)

HCAL :

$$\frac{\Delta E}{E} = \frac{a}{\sqrt{E}} \oplus b, \quad |\eta_h| \approx 5$$

For ATLAS (CMS), $a = 80\%$ (100%), $b = 15\%$ (5%)

2. Hadron and Lepton Collider Physics



Resonant Production:

1. Energy spread of the machine < the physical width

$$\sigma(e^+e^- \rightarrow V \rightarrow X) = \frac{4\pi(2j+1)\Gamma(V \rightarrow e^+e^-)\Gamma(V \rightarrow X)}{(s - M_V^2)^2 + \Gamma_V^2 M_V^2} \frac{s}{M_V^2}$$

2. Energy spectrum of the luminosity > the narrow resonant width

$$\sigma(e^+e^- \rightarrow V \rightarrow X) = \frac{4\pi^2(2j+1)\Gamma(V \rightarrow e^+e^-)BF(V \rightarrow X)}{M_V^3} \frac{dL}{d\tau} \Big|_{s=M_V^2}$$

3. Simulation Tools and Machine Learning



寻找新信号：事例图

Next, each node votes a number y_i in $[0,1]$ as the likeness of the event to be signal-like, and finally we average the votes y_i from each node as **discrimination score** (a real number in $[0,1]$).

