Introduction to Collider Physics (I)

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Peking University

参考文献:

1) Tao Han, hep-ph/0508097
2) John Illipoulos, arXiv: 1305.6779

Why collider?

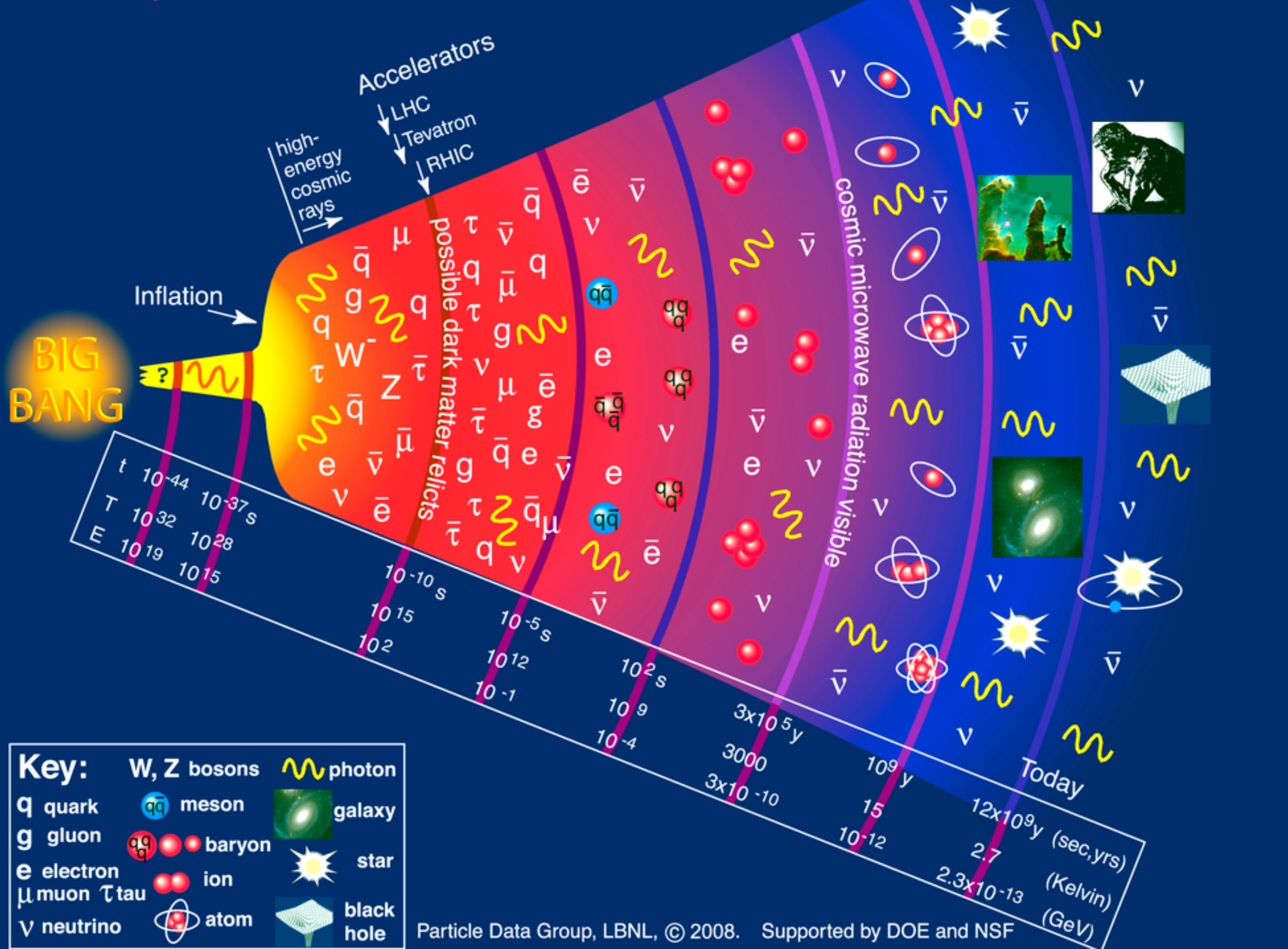
- We live in a cold and empty universe: only the stable relics and leftovers of the Big Bang remain. The unstable particles have decayed away with time, and the symmetries have been broken as the universe has cooled.

- But every kind of particle that ever existed is still there, in the equations that describe the particles and forces of the universe.

  The vacuum "knows" about all of them.

- We can use accelerators to make the equations come alive, by pumping sufficient energy into the vacuum to create the particles and uncover the symmetries that existed in the earliest universe.

History of the Universe



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

费米子和玻色子

费米子:

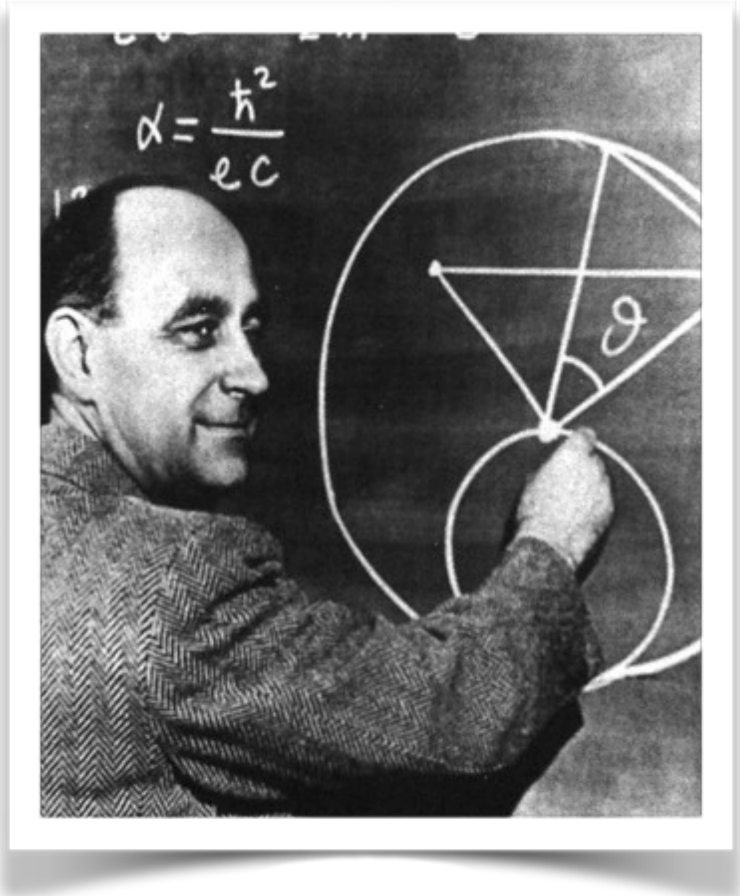
遵守**Pauli**不相容原理

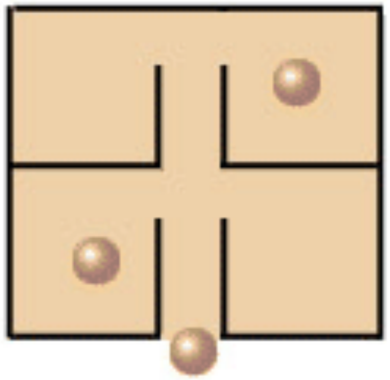
自旋为半整数

玻色子:

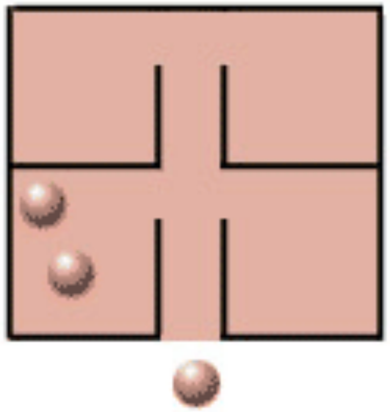
不遵守**Pauli**不相容原理

自旋为整数





Enrico
Fermi



Satyendra
N. Bose

物质场粒子： 轻子

- 不参与强相互作用
- 整数或零电荷
- 味:

e^-	“电子”	(1897)	在原子中
μ^-	“Muon” (206 m_e)	(1937)	在宇宙射线中首次观测到
τ^-	“Tau” (17 m_μ)	(1975)	在SLAC观测到 (Stanford Linear Accelerator Center)
ν_e	“Electron 中微子”	(1956)	
	泡利以之解释Beta衰变中能动量不守恒 (1930)		
ν_μ	“Muon 中微子”	(1962)	
ν_τ	“Tau 中微子”	(2000)	

物质场粒子：夸克

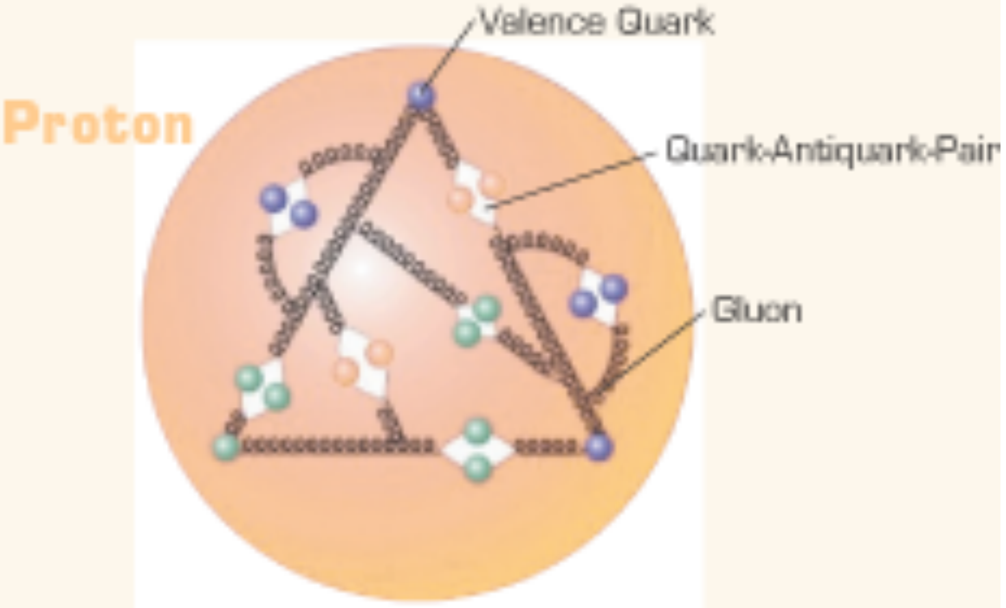
- 参与强相互作用
- 带分数电荷

$$Q = \left\{\begin{matrix} {}^{2}\!/_{3} \\ -{}^{1}\!/_{3} \end{matrix}\right\} \times \text{ Proton charge}$$

- 质子和中子的组成成分

(udd) (uud)

$$\begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix} \quad \begin{matrix} \text{“up”} \\ \text{“down”} \end{matrix}$$



第一次实验证据:

Stanford Linear Accelerator Center
(Giant Electron Microscope)

- 味:

u	“up”		
d	“down”		
s	“strange”		
c	“charmed”	(1974)	
b	“bottom”	(1977)	“Beauty”
t	“top”	1995	“Truth”

@ Fermilab (Tevatron)

标准模型的物质场

- 费米子 (自旋1/2)

轻子

(无强相互作用)

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \qquad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \qquad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L$$

$$e^-_R \qquad \mu^-_R \qquad \tau^-_R$$

夸克

$$\begin{pmatrix}u\\ d\end{pmatrix}_L \begin{pmatrix}u\\ d\end{pmatrix}_L \begin{pmatrix}u\\ d\end{pmatrix}_L \qquad \begin{pmatrix}c\\ s\end{pmatrix}_L \begin{pmatrix}c\\ s\end{pmatrix}_L \begin{pmatrix}c\\ s\end{pmatrix}_L \qquad \begin{pmatrix}t\\ b\end{pmatrix}_L \begin{pmatrix}t\\ b\end{pmatrix}_L \begin{pmatrix}t\\ b\end{pmatrix}_L$$

$$u_R \quad u_R \quad u_R \qquad c_R \quad c_R \quad c_R \qquad t_R \quad t_R \quad t_R$$

$$\underbrace{d_R \quad d_R \quad d_R \qquad s_R \quad s_R \quad s_R \qquad b_R \quad b_R \quad b_R}_{3代}$$

- 标量场 (自旋为0)

希格斯玻色子： 唯一知道不同代的粒子间不同之处的粒子

(希格斯机制 —— 对称性自发破缺)

相互作用传播子

相互作用（通过交换自旋为1的规范玻色子）

电磁相互作用 (QED)

光子 (无质量)

强相互作用 (QCD)

胶子 (无质量) (1979)

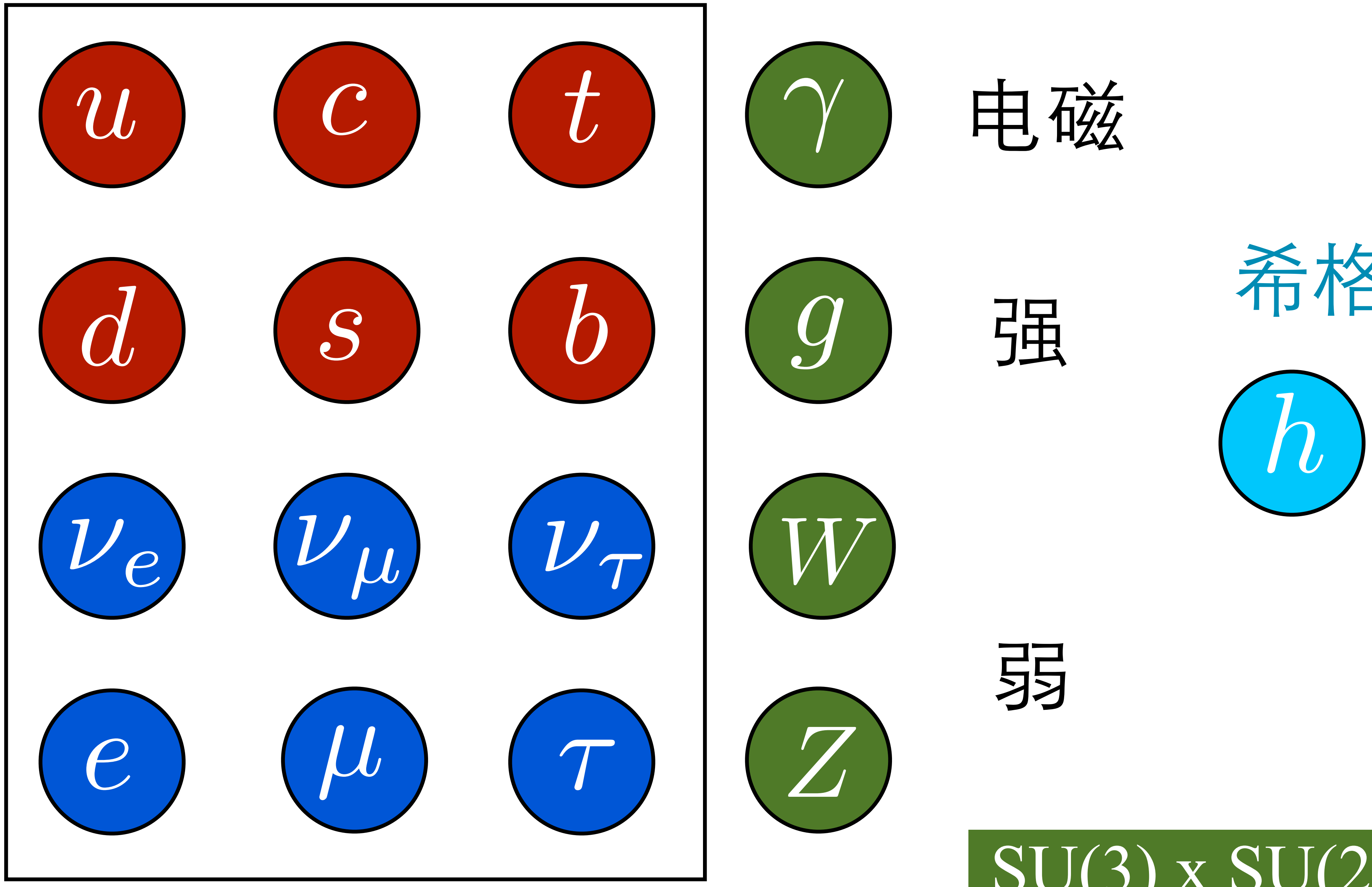
弱相互作用

$W^{\pm}$ 和 Z 规范玻色子 (1983)

$\left(\text{有质量} \begin{array}{l} M_W = 80.4 \text{ GeV} \\ M_Z = 91.187 \text{ GeV} \end{array} \quad 1 \text{ GeV} = 10^9 \text{ eV} \right)$

粒子物理的标准模型

新“元素”周期表



夸克

轻子

电磁

强

弱

希格斯粒子

自旋0

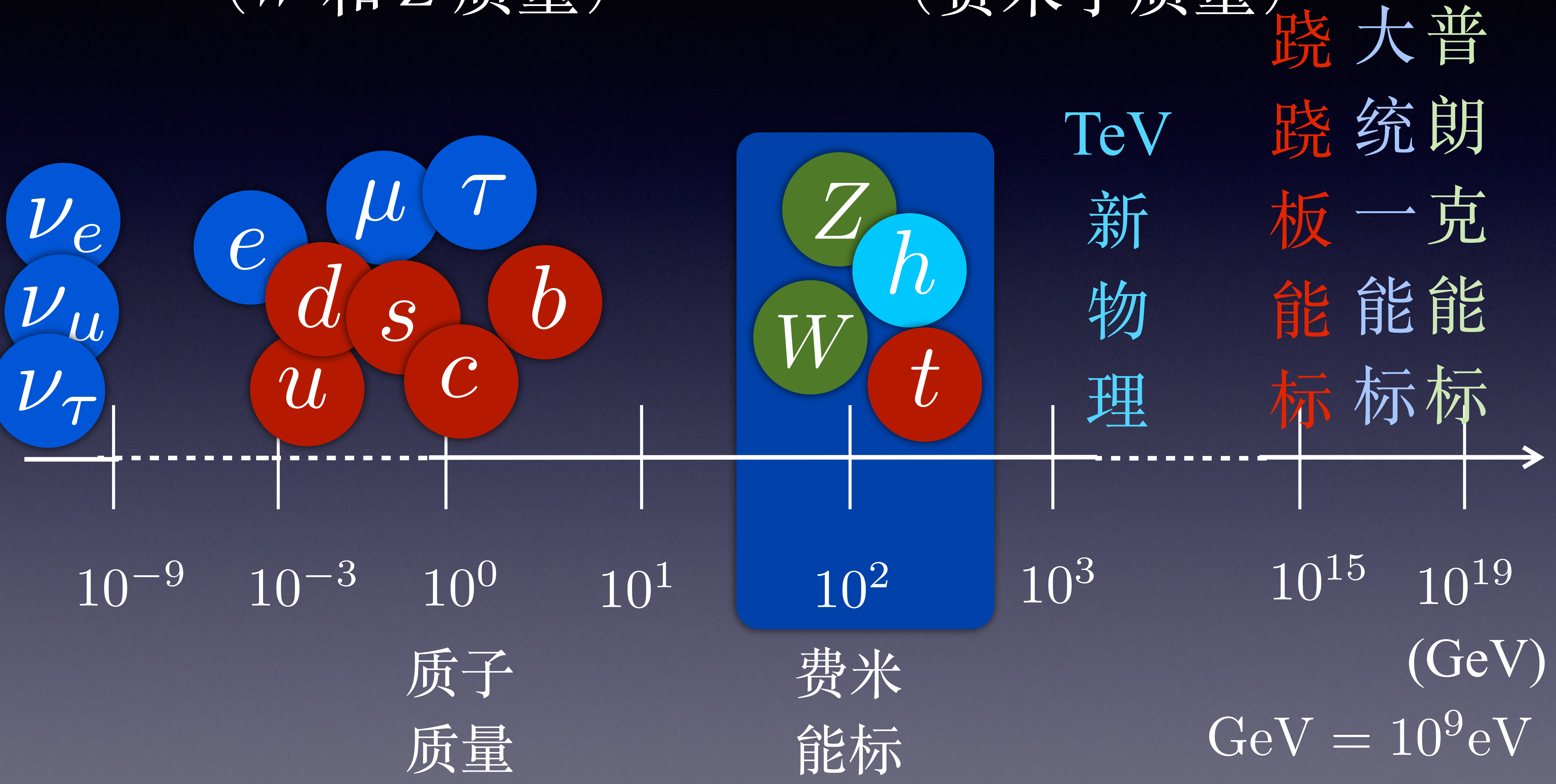
自旋1/2

自旋1

SU(3) x SU(2) x U(1)
规范对称性

标准模型的两大疑难

电弱对称性破缺起源 和 味对称性破缺起源
（W 和 Z 质量） （费米子质量）



顶夸克或许是我们和新物理间的唯一联系

能量和空间尺度

加速器： 强力的“显微镜”

高能加速的粒子束，帮助我们看清细微的结构

$$E \sim \frac{1}{x}$$

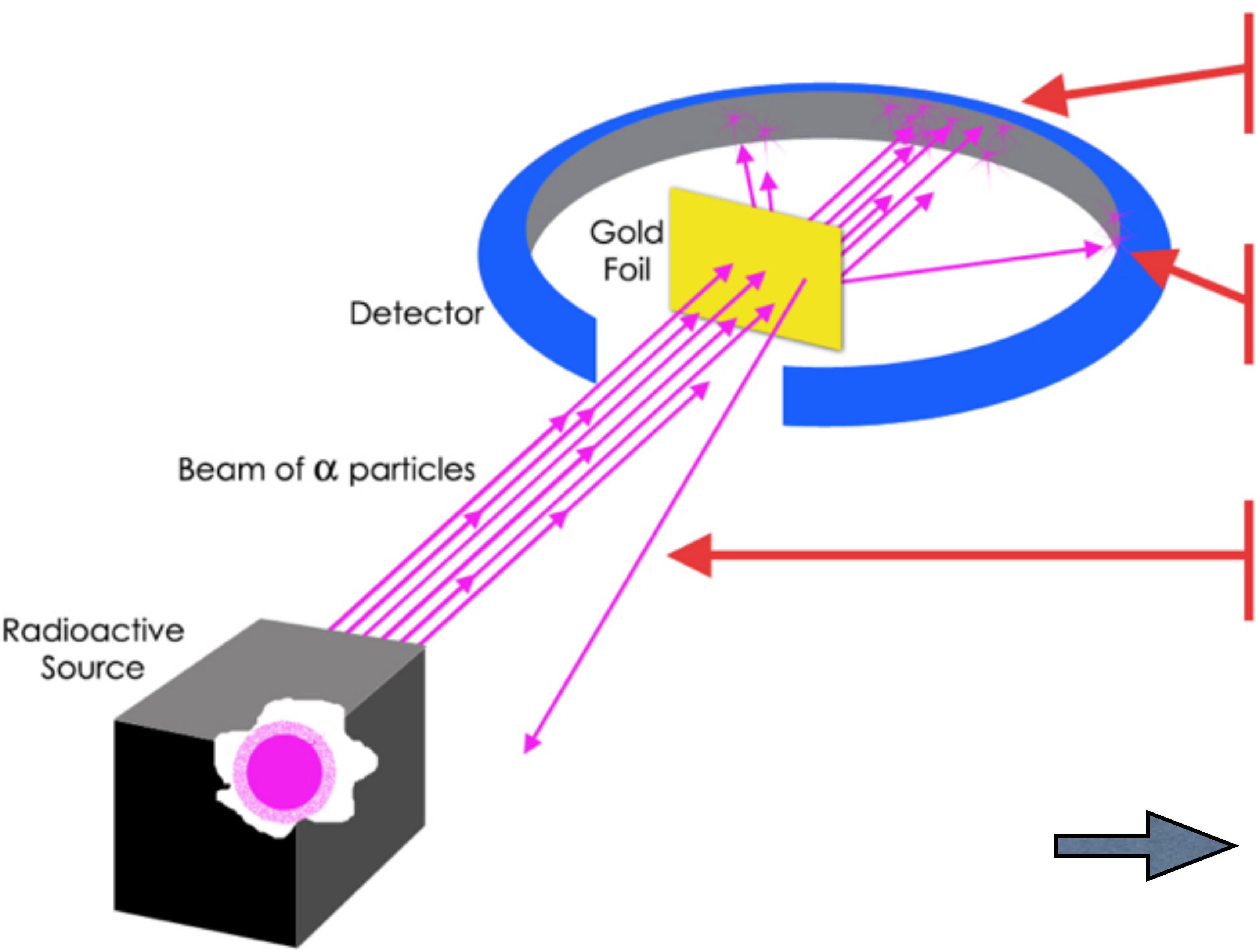
低能量粒子束

高能量粒子束

卢瑟福散射实验

对撞实验鼻祖

Rutherford's Gold Foil Experiment

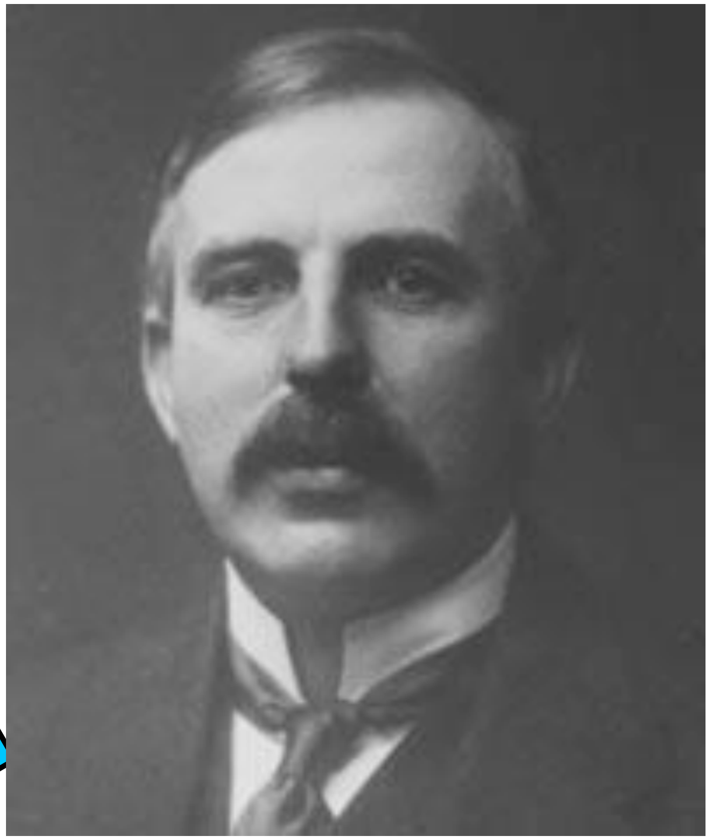


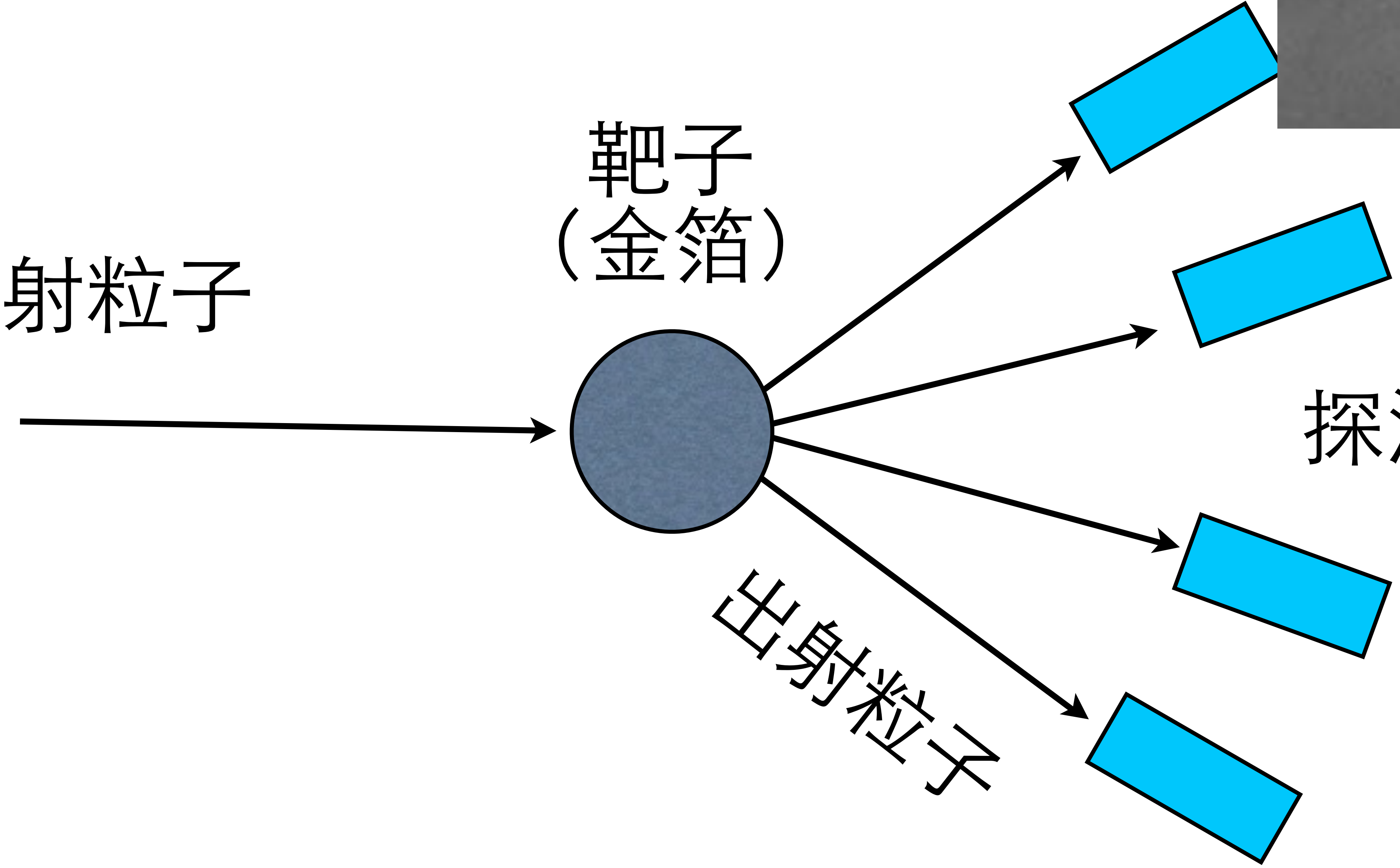
Observation	Interpretation
Most α particles travel through the foil undeflected	The atom is mostly empty space
Some α particles are deflected by small angles	The nucleus is positively charged, as is the α particle
Occasionally, an α particle travels back from the foil	The nucleus carries most of the atom's mass

→ 原子的行星模型

卢瑟福散射实验

对撞实验鼻祖





靶子
（金箔）

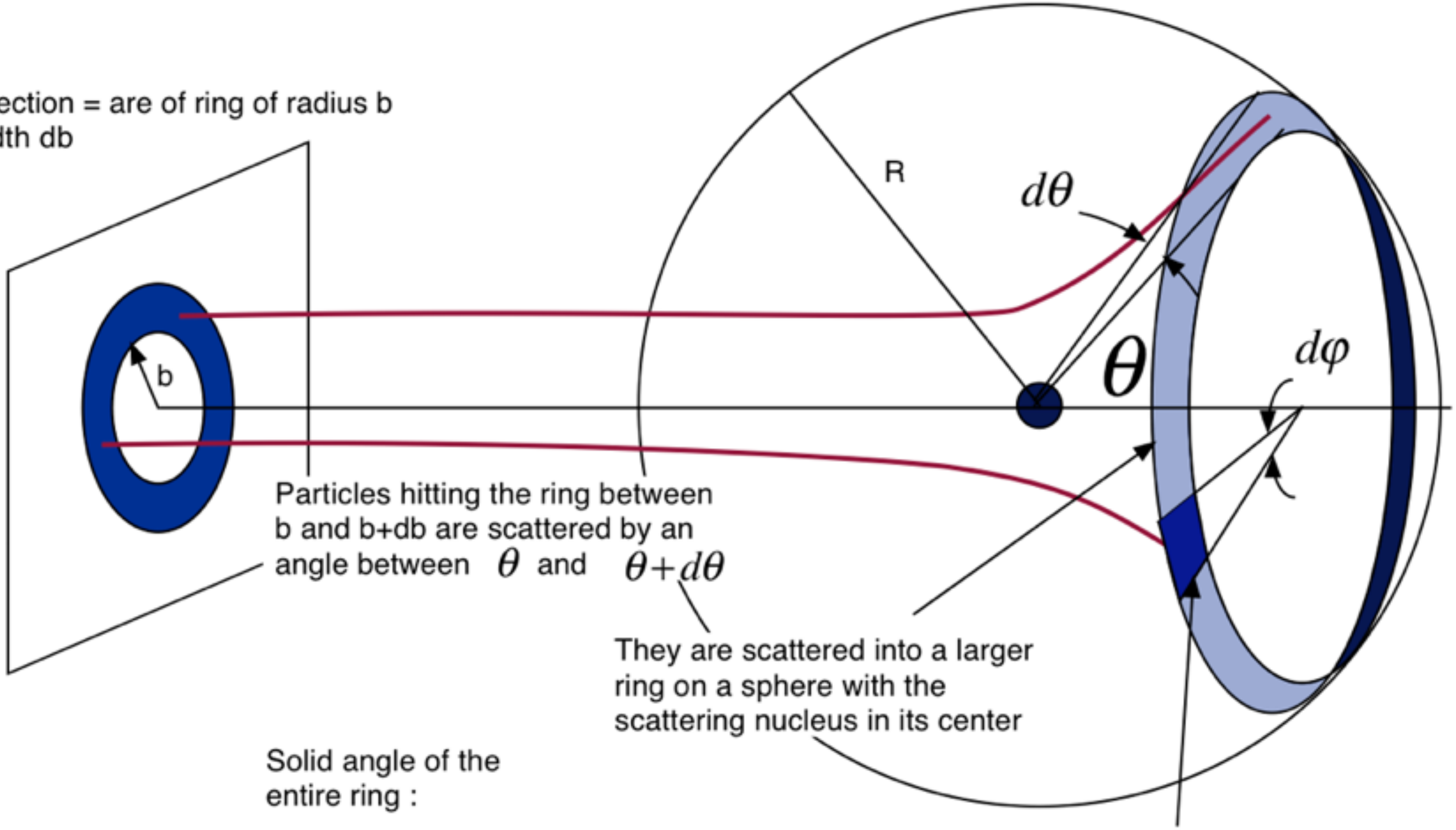
入射粒子

探测器

出射粒子

散射截面

粒子束和靶或另一粒子束之间相互作用的有效面积



cross section = are of ring of radius b and width db

Particles hitting the ring between b and b+db are scattered by an angle between θ and $\theta + d\theta$

They are scattered into a larger ring on a sphere with the scattering nucleus in its center

Solid angle of the entire ring :

$$d\Omega = \frac{2\pi R \sin(\theta) R d\theta}{R^2} = 2\pi \sin(\theta) d\theta$$

solid angle of small area:

$$d\Omega = \frac{d\varphi R \sin(\theta) R d\theta}{R^2} = \sin(\theta) d\theta d\varphi$$

1 Barn = 10^{-24} cm^2

散射截面（σ）

- 量纲：$[\sigma] = m^2$

$$1\text{barn} = 10^{-24}(\text{cm})^2 = 10^{-28}m^2 = 100(\text{fm})^2$$

$$1\text{mb} = 10^{-3}\text{b}$$

$$1\mu\text{b} = 10^{-6}\text{b}$$

$$1\text{nb} = 10^{-9}\text{b}$$

$$1\text{pb} = 10^{-12}\text{b}$$

$$1\text{fb} = 10^{-15}\text{b}$$

汤姆逊散射

低能光子-非相对论性（近乎静止）电子之间散射

经典物理反射和衍射

$$\sigma_{\text{Tot}}^{\text{classic}} = 2\pi r_e^2$$

r_e 电子经典半径

$$\frac{e^2}{r_e} = m_e c^2 \Longrightarrow r_e = \frac{e^2}{m_e c^2} \sim \frac{1/137}{0.511\text{MeV}} \sim 2.8\text{fm}$$

量子力学计算给出

$$\sigma_{\text{Tot}} = \frac{8}{3}\pi r_e^2 = 67(\text{fm})^2 = 0.67\text{barn}$$

高能对撞机

估算质子-质子对撞机

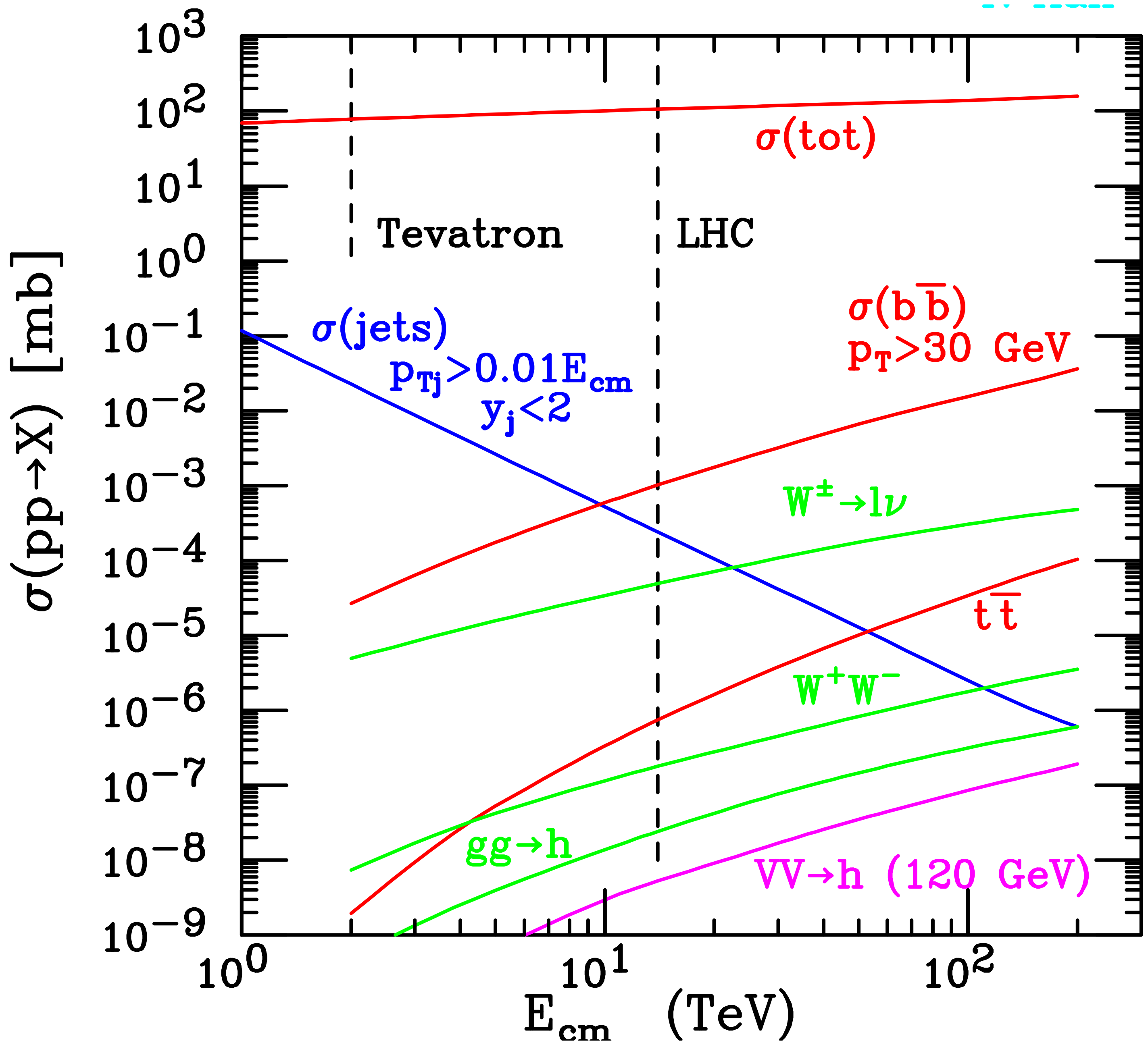
$$\sigma \sim \pi\lambda_p^2 \sim \frac{\pi}{\mathrm{GeV}^2} = \frac{\pi(\mathrm{fm})^2}{10^6(1/197)^2} \sim 10^{-3}\mathrm{barn} = \mathrm{mb}$$

14TeV大型强子对撞机

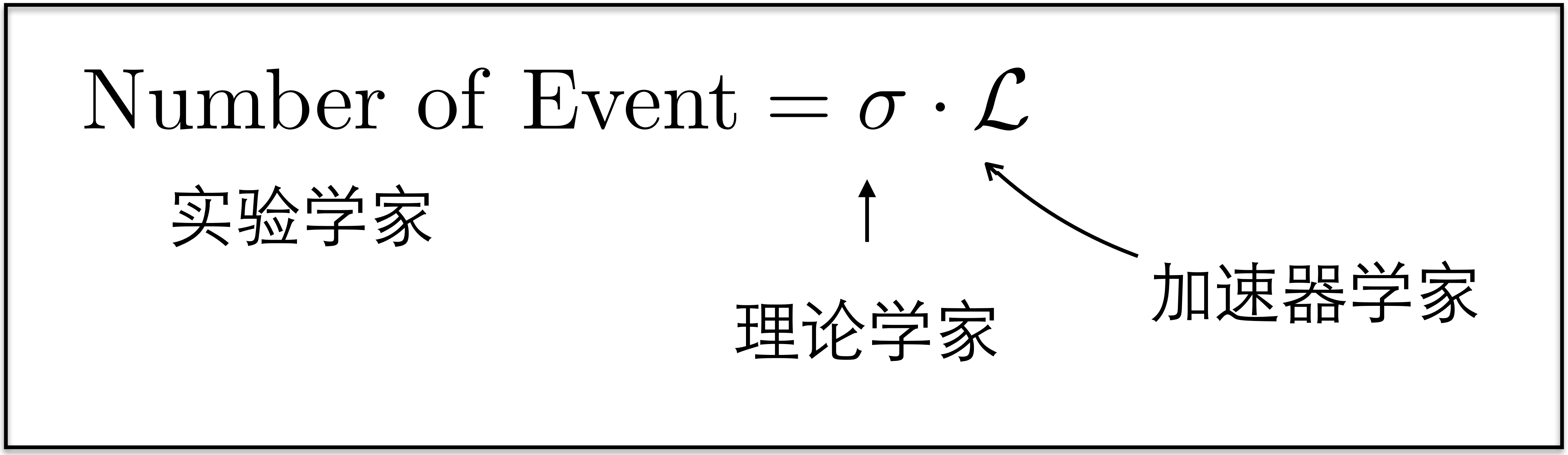
$$\sigma(pp)_{\mathrm{total}} \sim 110\mathrm{mb}$$

1.96TeV Tevatron

$$\sigma(p\bar{p})_{\mathrm{total}} \sim 60\mathrm{mb}$$



事例数



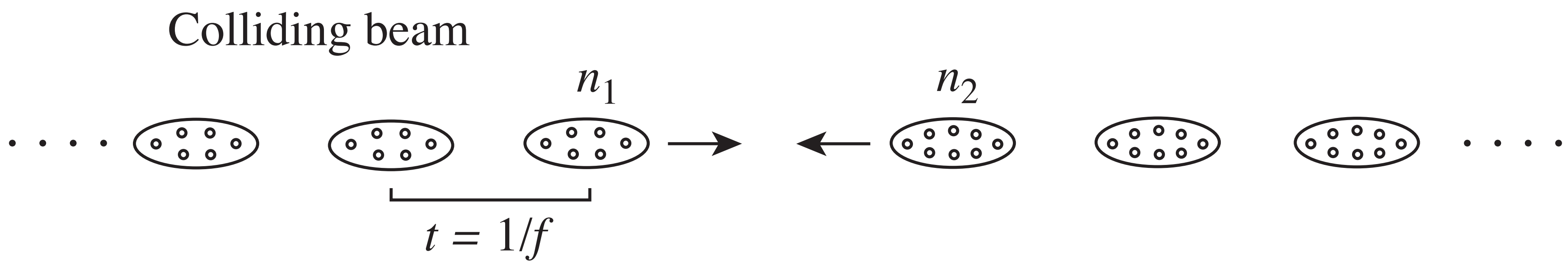
$$\text{Number of Event} = \sigma \cdot \mathcal{L}$$

实验学家

理论学家

加速器学家

亮度 (luminosity)



瞬时亮度

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

$$[\mathcal{L}] = \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

# of particles passing each other per unit time through unit transverse area at the interaction point

$n_{1,2}$: particle in each bunch in beam 1,2

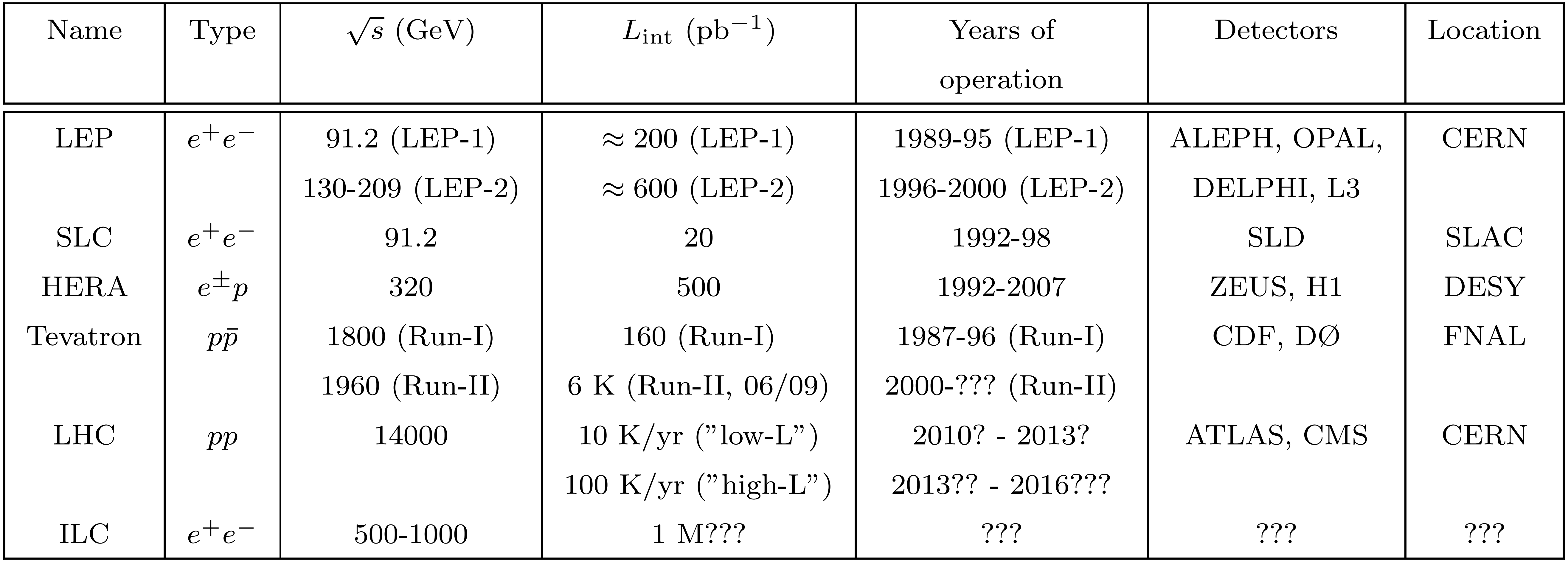
f : beam crossing frequency

Σ : transverse profile of the bream

$$1\mathrm{cm}^{-2}\mathrm{s}^{-1} = 10^{-33}\mathrm{nb}^{-1}\mathrm{s}^{-1}$$

积分亮度: $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} = 1\mathrm{nb}^{-1}\mathrm{s}^{-1} = 10\mathrm{fb}^{-1}/\mathrm{year}$

Past, current and Further collider



Name	Type	$\sqrt{s}$ (GeV)	L_{int} (pb^{-1})	Years of operation	Detectors	Location
LEP	e^+e^-	91.2 (LEP-1)	$\approx$ 200 (LEP-1)	1989-95 (LEP-1)	ALEPH, OPAL,	CERN
		130-209 (LEP-2)	$\approx$ 600 (LEP-2)	1996-2000 (LEP-2)	DELPHI, L3	
SLC	e^+e^-	91.2	20	1992-98	SLD	SLAC
HERA	$e^\pm p$	320	500	1992-2007	ZEUS, H1	DESY
Tevatron	$p\bar{p}$	1800 (Run-I)	160 (Run-I)	1987-96 (Run-I)	CDF, DØ	FNAL
		1960 (Run-II)	6 K (Run-II, 06/09)	2000-??? (Run-II)		
LHC	pp	14000	10 K/yr (”low-L”)	2010? - 2013?	ATLAS, CMS	CERN
			100 K/yr (”high-L”)	2013?? - 2016???		
ILC	e^+e^-	500-1000	1 M???	???	???	???

加速器和对撞机

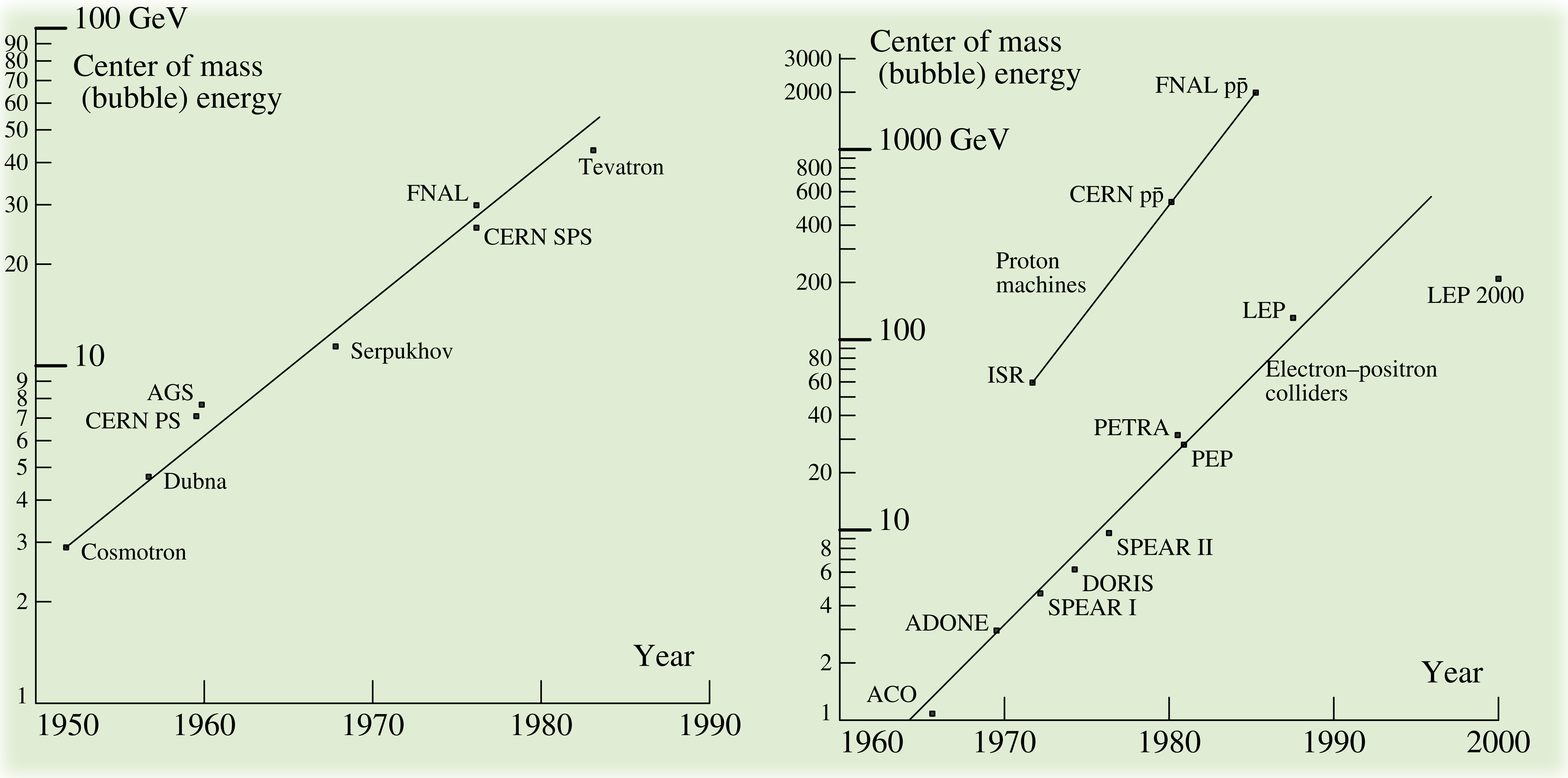
二战之后高能物理才成为一门公认的学科

（富人的游戏）

能量上限由机器的环半径和磁场强度决定

- 上世纪50年代，半径~10-20米（房子中）
- 上世纪60年代，半径~100米　（地下）
- 上世纪70年代，半径~1000米（地下）
- 上世纪80年代，半径~4000米（地下）

对撞机年表



我们只能加速稳定粒子：$e^{\pm}, p, \bar{p}, \gamma$

正负电子对撞机

优势:

1）实验室系和质心系相同

—>可以充分利用能量

2）入射粒子束的性质已知

—>运动学性质确定

3）背景干净

4）有可能使用极化入射粒子

—> 探测相互作用的手征性

劣势:

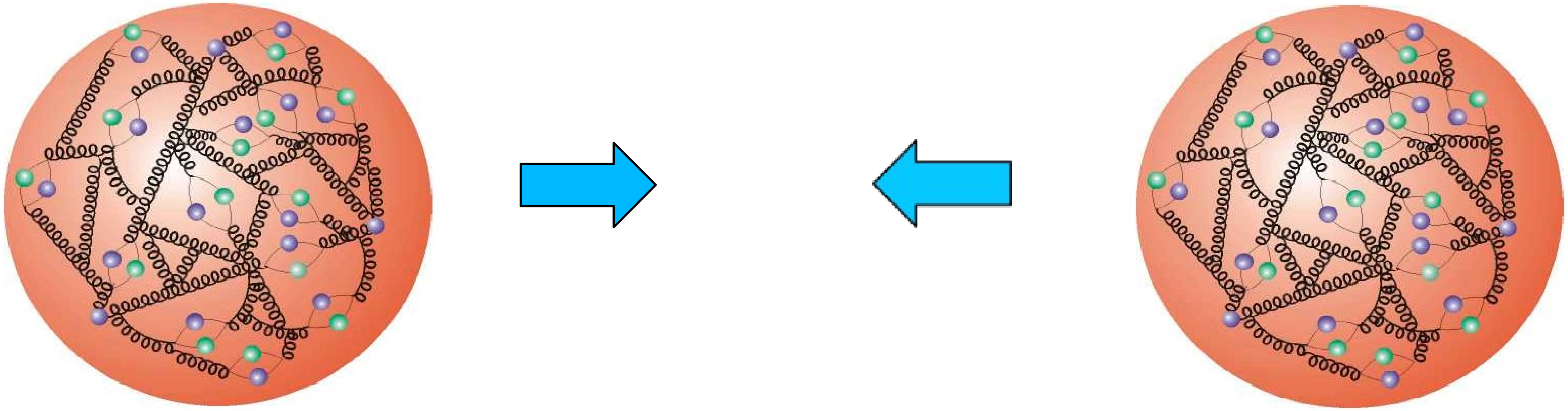
1）圆型对撞机辐射严重

$$\Delta E \sim \frac{1}{R}\left(\frac{E}{m_e}\right)^4$$

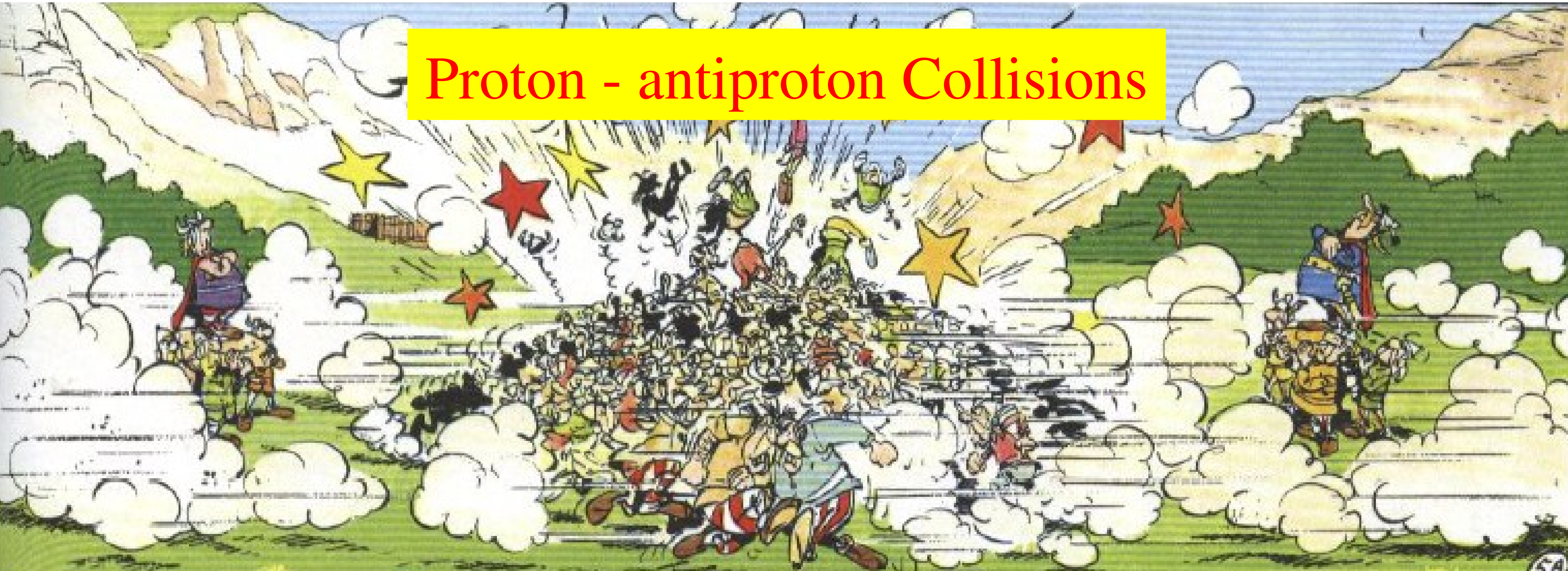
—> 直线加速 (昂贵)

2）积分亮度不高

强子对撞机

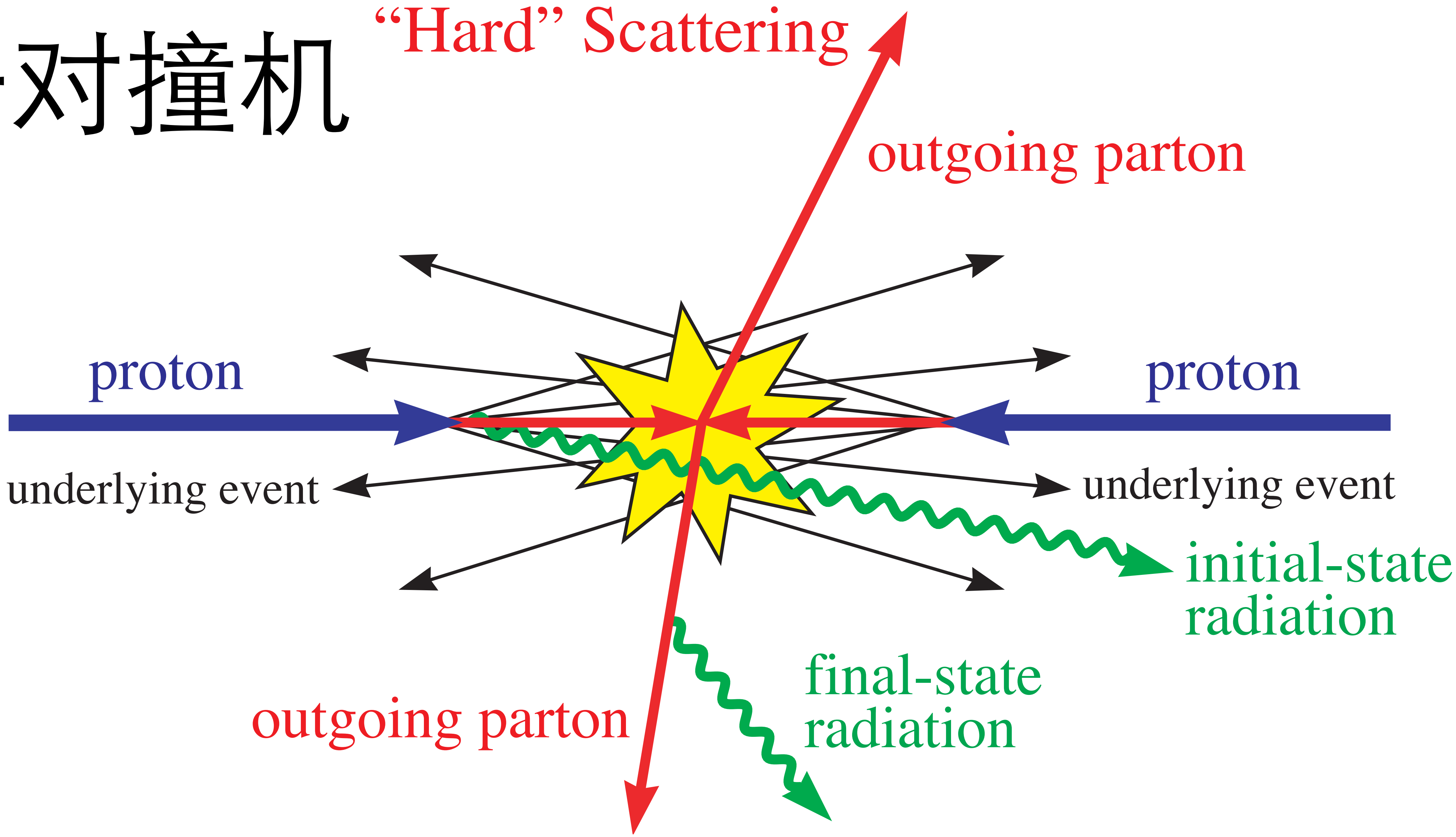


Proton: Bag of quarks and gluons (partons)



Proton - antiproton Collisions

强子对撞机



优势：

1） 高能量
2） 高亮度
3） 过程丰富
qq/qg/gg/bb

劣势：

1） 背景太大
2） 无法确定初态
3） 无法确定质心系能量

你相信奇迹吗？

Rare Events, such as *Higgs production*, are difficult to find!

Need good detectors, triggers, readout to reconstruct the mess into a piece of physics.

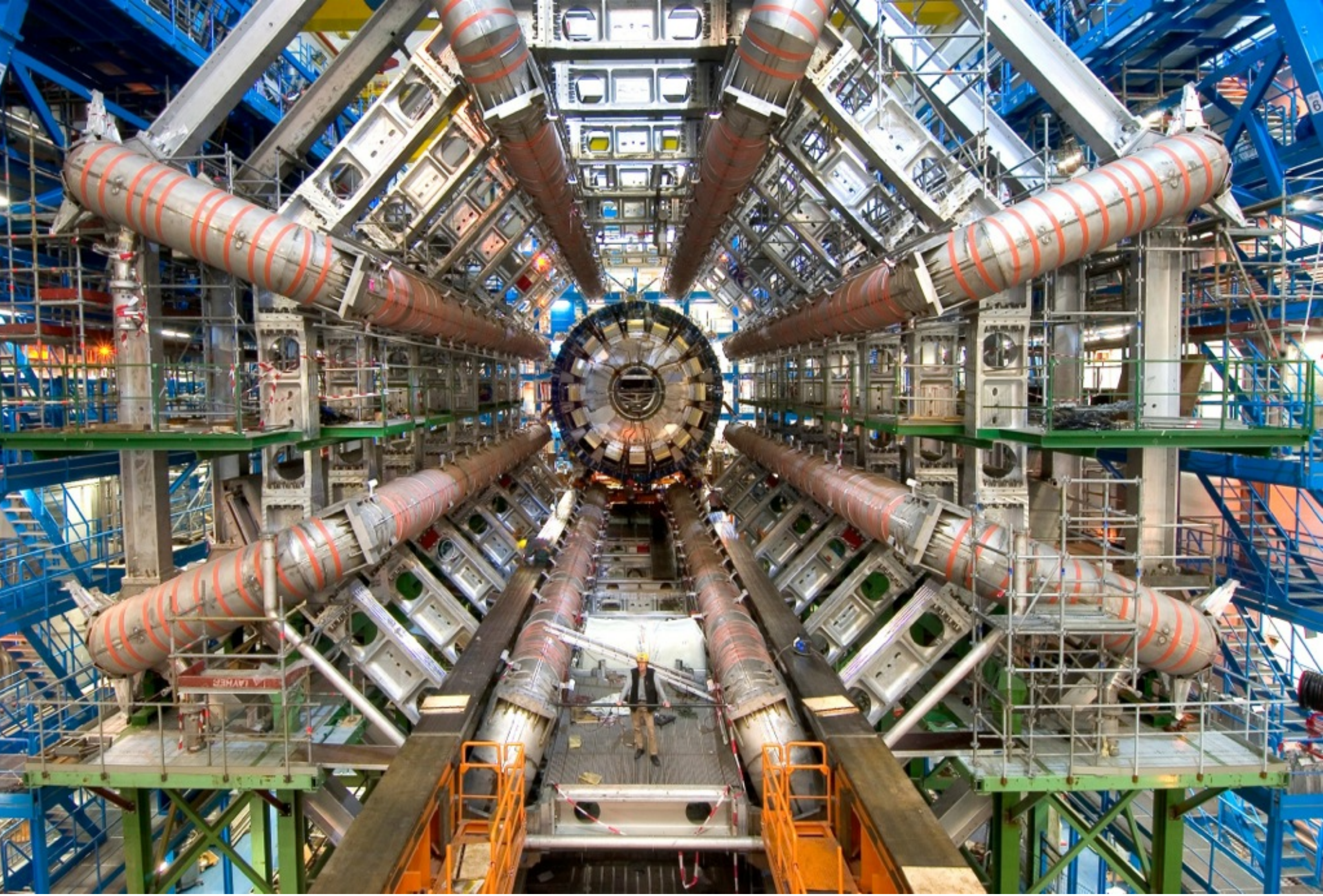
大型强子对撞机

质心系能量14TeV

大型强子对撞机

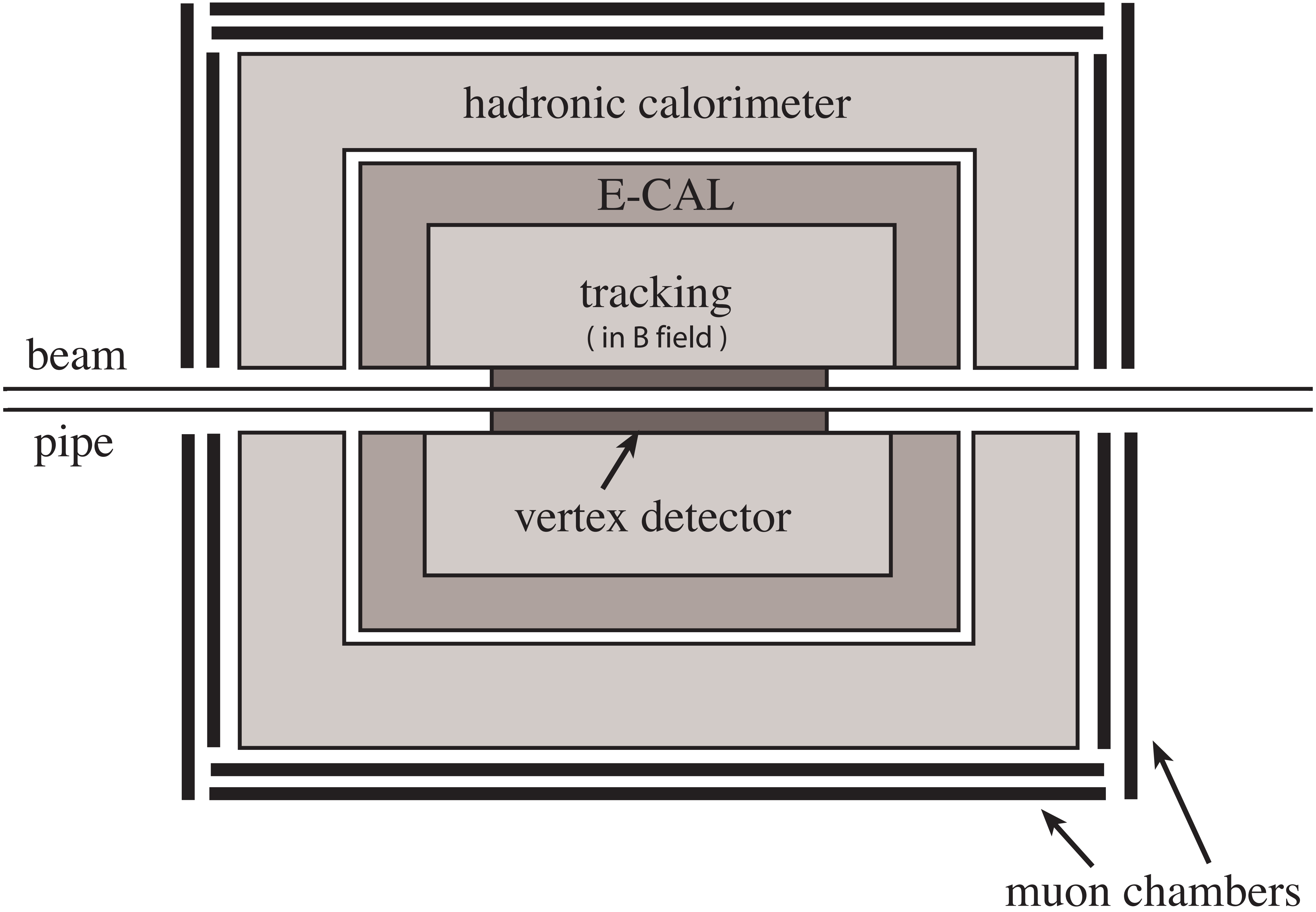
质心系能量14TeV

CMS： 长21米，高15米，宽15米，12.5千吨



ATLAS：长46米，高25米，宽25米，7千吨

探测器


hadronic calorimeter
E-CAL
tracking
(in B field)
beam
pipe
vertex detector
muon chambers

What we "see" as particles in the detector: (a few meters)

For a relativistic particle, the travel distance:

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

- stable particles directly "seen":

$$p,\ \bar{p},\ e^{\pm},\ \gamma$$

- quasi-stable particles of a life-time $\tau \geq 10^{-10}$ s also directly "seen":

$$n, \Lambda, K_L^0, ...,\ \mu^{\pm},\ \pi^{\pm}, K^{\pm}...$$

- a life-time $\tau \sim 10^{-12}$ s may display a secondary decay vertex, "vertex-tagged particles":

$$B^{0,\pm},\ D^{0,\pm},\ \tau^{\pm}...$$

- short-lived not "directly seen", but "reconstructable":

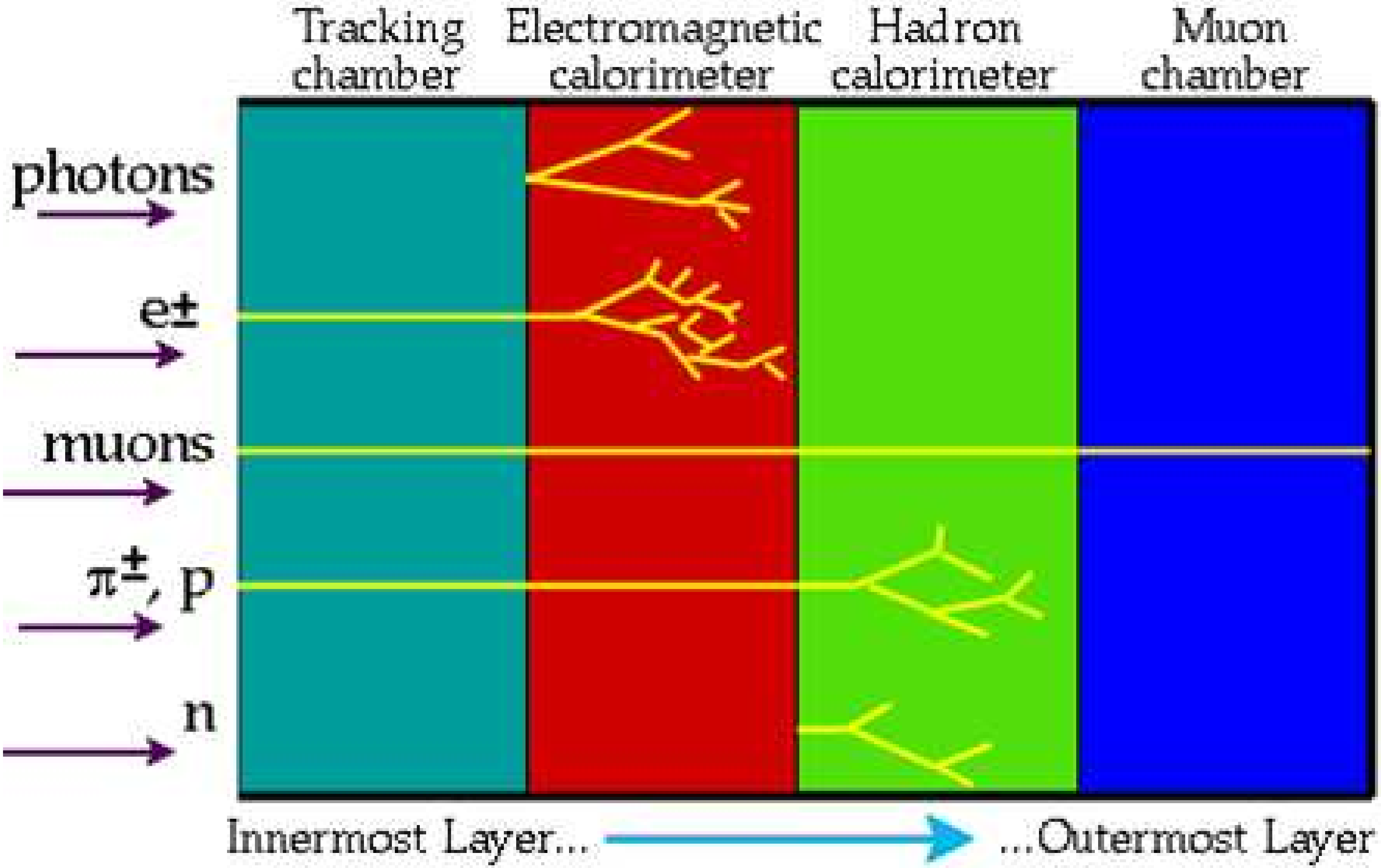
$$\pi^0,\ \rho^{0,\pm}...\ ,\quad Z, W^{\pm}, t, H...$$

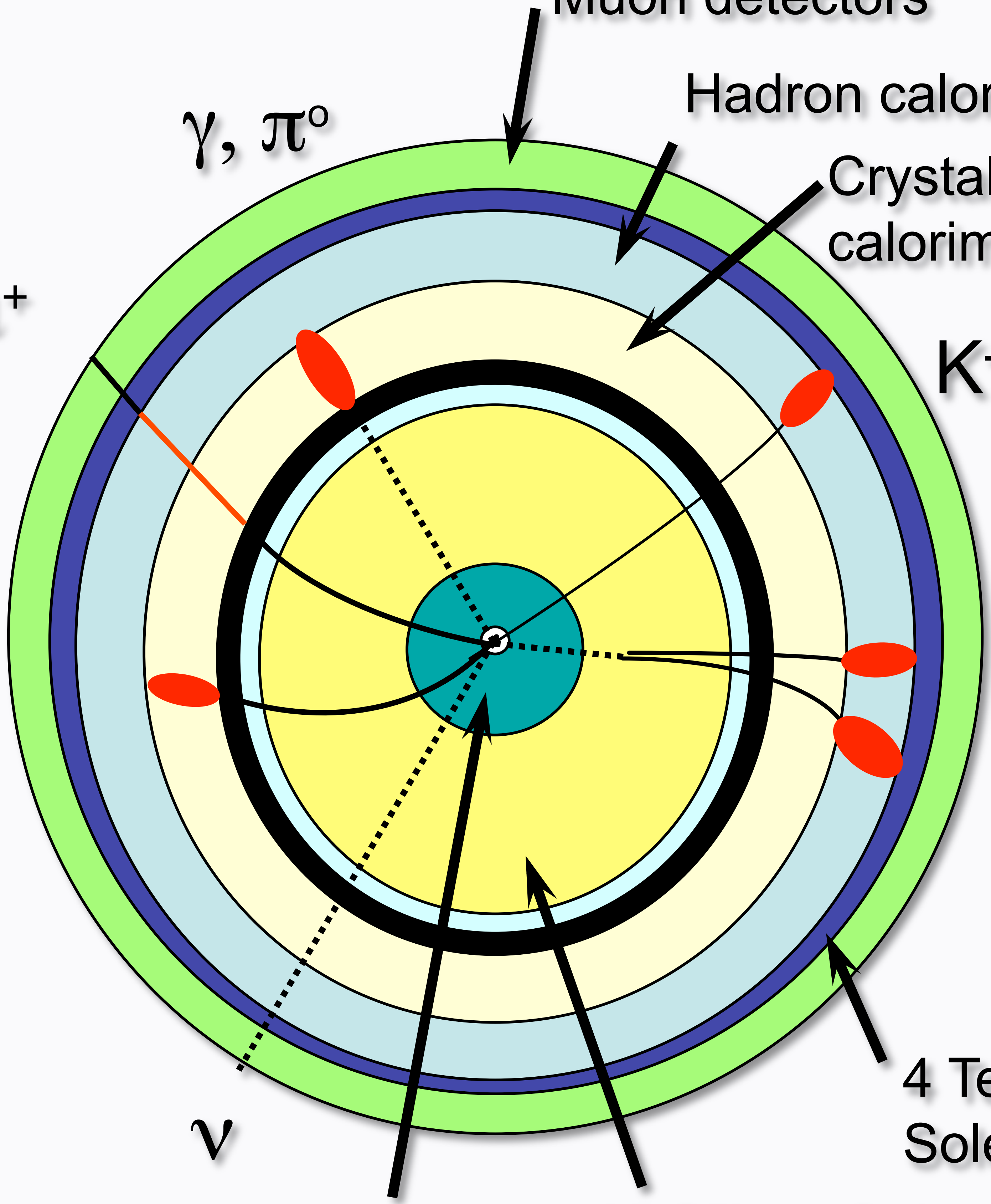
- missing particles are weakly-interacting and neutral:

$$\nu,\ \tilde{\chi}^0, G_{KK}...$$

Tao Han, TASI

† For stable and quasi-stable particles of a life-time $\tau \geq 10^{-10} - 10^{-12}$ s, they show up as





Muon detectors

γ, π^o

Hadron calorimeter

Crystal Electromagnetic
calorimeter

μ^+

K^-, π^-, $\bar{p}$,…

e^+

$K^o \rightarrow \pi^+\pi^-$, …e

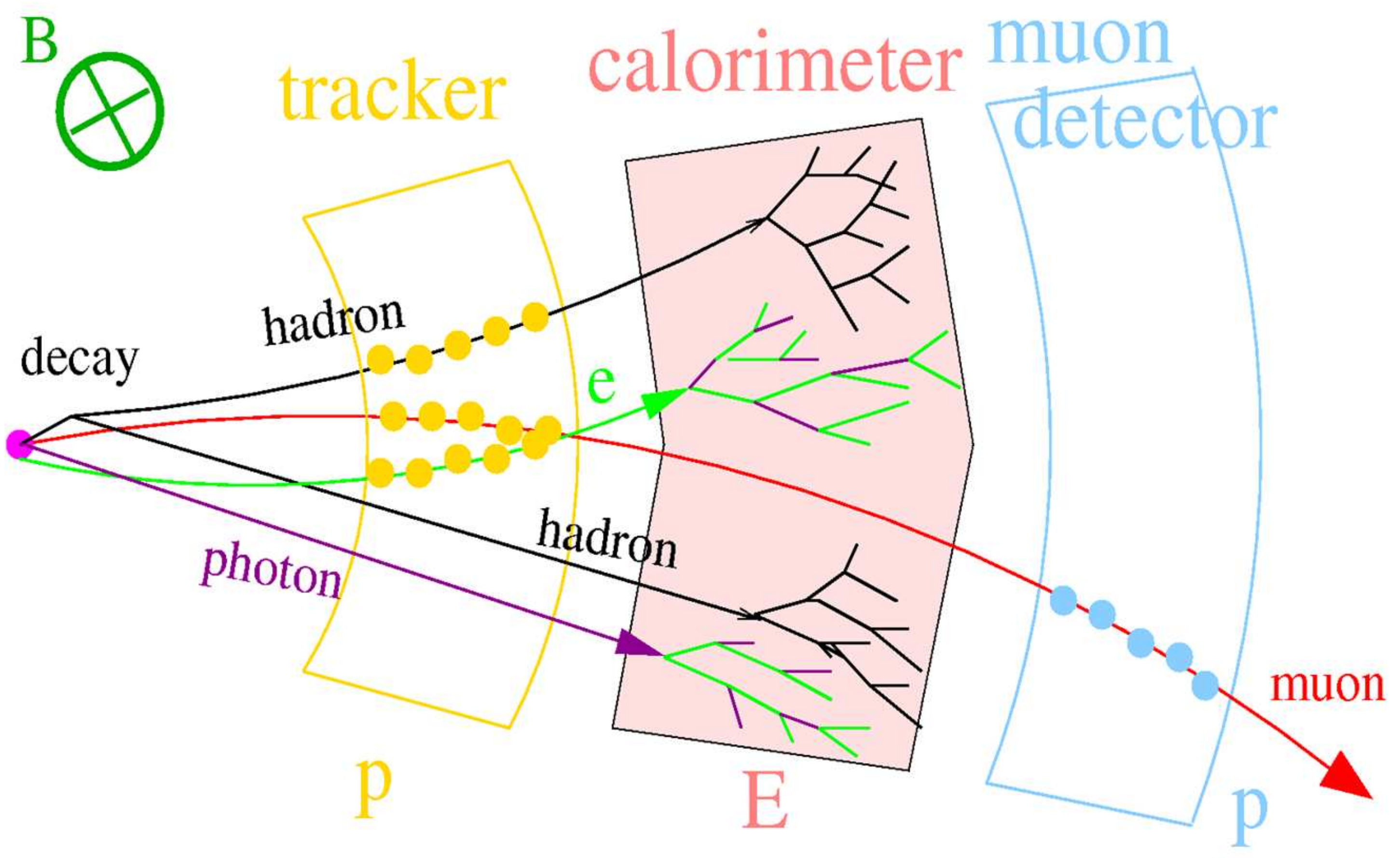
ν

4 Tesla
Solenoid

Silicon
Pixels

All Silicon Strip
Tracker

A closer look:



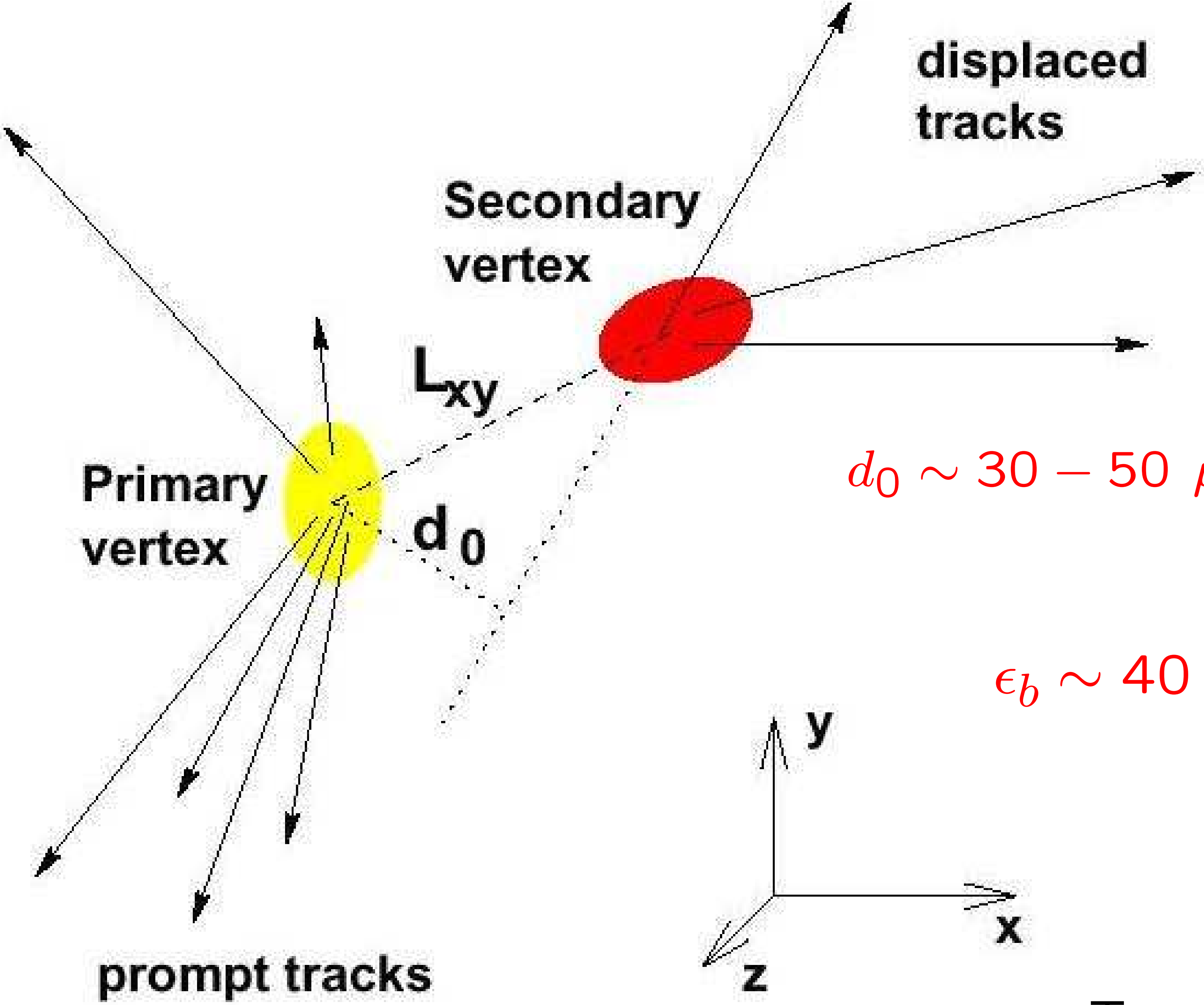
Theorists should know:

$$\begin{aligned} \text{For charged tracks :} \quad & \Delta p/p \;\propto\; p, \\ \text{typical resolution :} \quad & \sim\; p/(10^4 \text{ GeV}). \\ \text{For calorimetry :} \quad & \Delta E/E \;\propto\; \frac{1}{\sqrt{E}}, \\ \text{typical resolution :} \quad & \sim\; (5-80\%)/\sqrt{E/\text{GeV}}. \end{aligned}$$

$$p(\mathrm{GeV}) = 0.3 Q B(\mathrm{Tesla}) R(\mathrm{m})$$

Tao Han, TASI

† For vertex-tagged particles $\tau \approx 10^{-12}$ s, heavy flavor tagging: the secondary vertex:



$d_0 \sim 30-50\ \mu$m

$\epsilon_b \sim 40-60\%$

Tao Han, TASI

† For short-lived particles: $\tau < 10^{-12}$ s or so,
make use of final state kinematics to reconstruct the resonance.

† For missing particles:
make use of energy-momentum conservation to deduce their existence.

$$p_1^i + p_2^i = \sum_f^{obs.} p_f + p_{miss}.$$

But in hadron collisions, the longitudinal momenta unkown,
thus transverse direction only:

$$0 = \sum_f^{obs.} \vec{p}_{f\ T} + \vec{p}_{miss\ T}.$$

often called "missing p_T" ($\not{p}_T$) or "missing E_T" ($\not{E}_T$).

Theoretical Calculation

How does SM predict … ?

◆ In Quantum Mechanics

Schrodinger Equation:

$$i\frac{\partial\Psi}{\partial t}=H\Psi$$

1. Figure out what H is.
2. Insert H in S.E.
3. Calculate Predictions

◆ In Relativistic Quantum Field Theory

SM gives the Interaction Lagrangian $\mathcal{L}$

$\mathcal{L}$

⇓

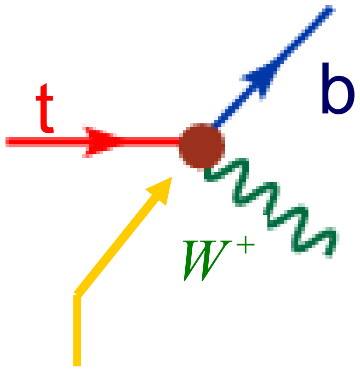
Feynman Rules
Feynman Diagrams

⇓

S-Matrix Elements

⇓

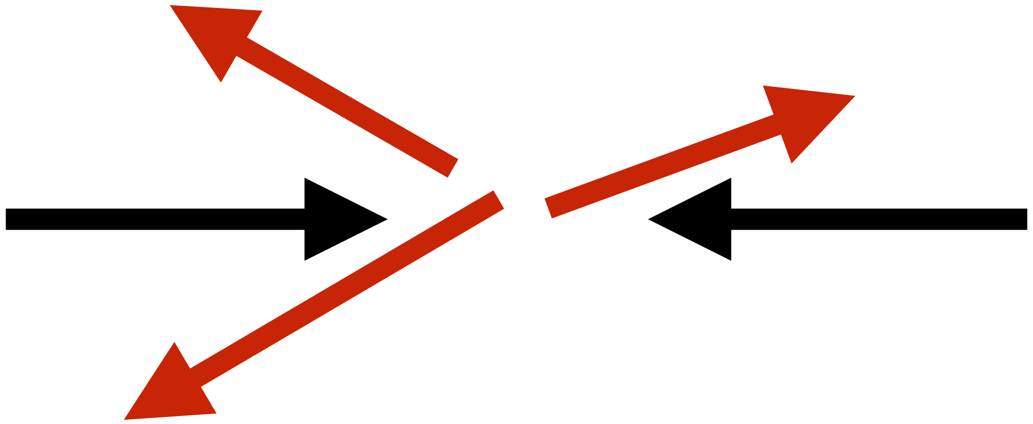
Predictions



Vertex; coupling

Master Formula

$$2 \to N: \quad A + B \to 1 + 2 + \cdots + N$$



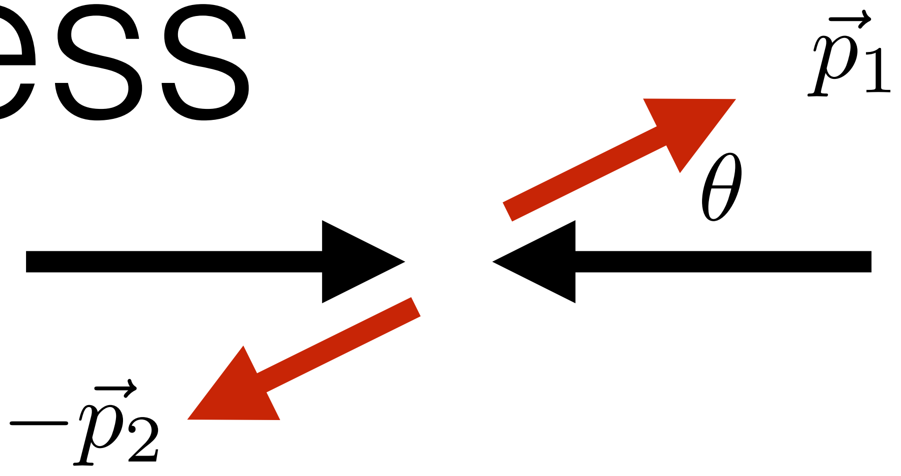
$$d\sigma = \frac{1}{2s}\underbrace{\left(\prod_{i=1}^{N}\frac{d^3p_i}{(2\pi)^3}\frac{1}{2E_i}\right)\cdot(2\pi)^4\delta^4(p_A+p_B-\sum p_i)}_{\text{相空间}}\cdot|\mathcal{M}(p_A,p_B\to\{p_i\}|^2$$

matrix element
square

$|\mathcal{M}|^2$ is invariant,

$d\sigma$ is invariant under boost along beam line

2 to 2 process



After integrating out $d^3 p_2$

$$d\sigma_{\rm cm} = \frac{1}{2s}\frac{p_1^2 dp_1 d\Omega}{(2\pi)^3}\frac{1}{2E_1}\frac{1}{2E_2}(2\pi)\delta(E_{\rm cm}-E_1-E_2)|\mathcal{M}|^2$$

$$E_1 = \sqrt{p_1^2 + m_1^2} \quad E_2 = \sqrt{p_2^2 + m_2^2}$$

$$\frac{d\sigma}{d\cos\theta} = \begin{cases} \frac{1}{16\pi}\frac{|\mathbf{p}_1|}{s^{3/2}} & \text{if } \sqrt{s} > m_1 + m_2 \\ 0 & \text{otherwise,} \end{cases}$$

$$|\mathbf{p}_1| = \frac{1}{2}\sqrt{\frac{(s-m_1^2-m_2^2)^2 - 4m_1^2 m_2^2}{s}}$$

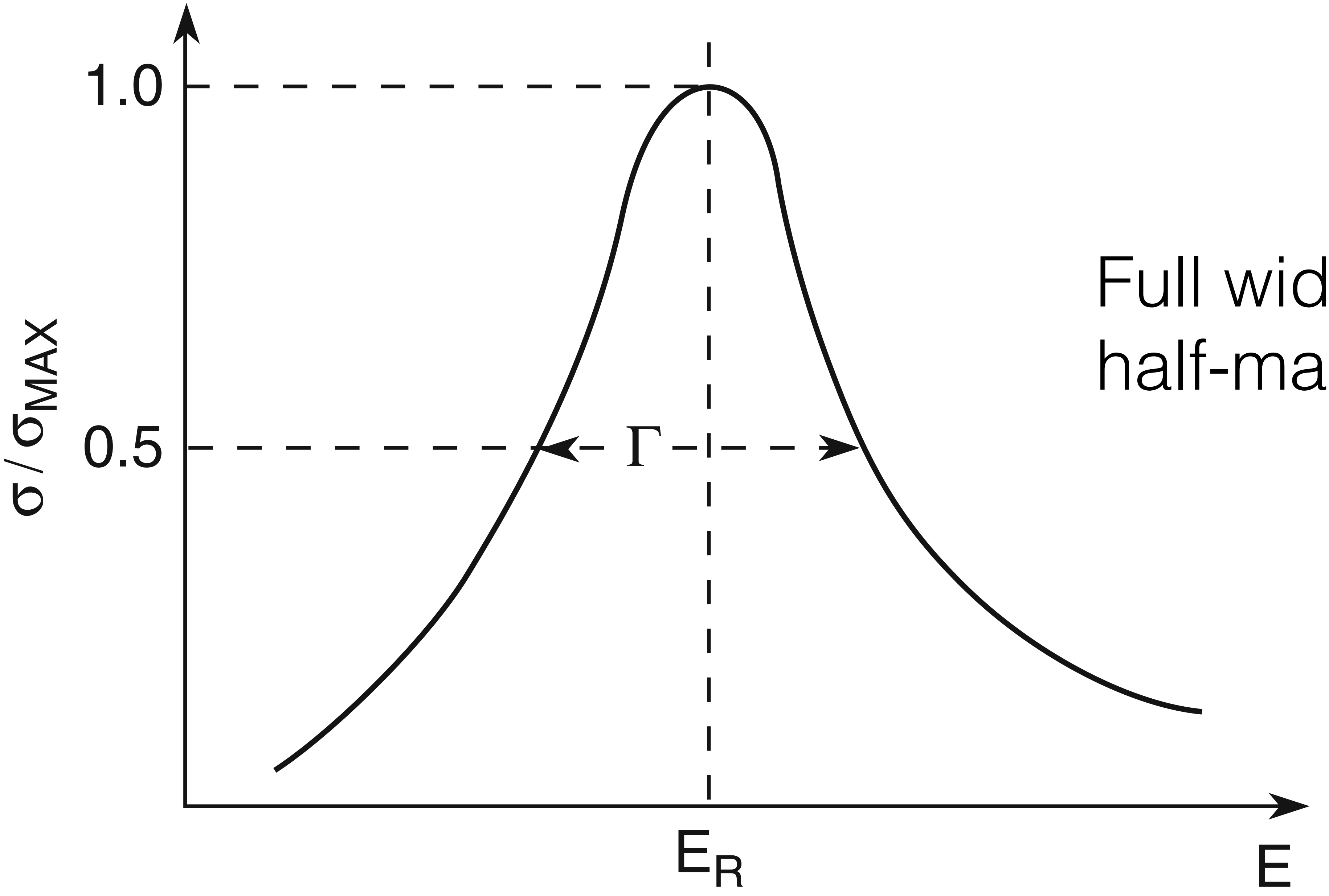
$$\frac{d\sigma}{d\cos\theta} = \frac{1}{32\pi s}\sqrt{1-\frac{4m^2}{s}}\,\overline{|\mathcal{M}|}^2 \qquad \text{if } m_1 = m_2 = m$$

One could calculate the amplitude square using automation package!

But I am going to do it in a old fashion

Resonance

Mass, Width (lifetime),isospin, Parity, …



Full width at half-maximum

E_R: Resonance mass

resonance in elastic scattering

$$a + b \to R \to a' + b'$$

$$\psi(t) = \psi(0)e^{-i\omega_R t}e^{-\frac{t}{2\tau}} = \psi(0)e^{-\frac{iE_R}{\hbar}t}e^{-\frac{\Gamma}{2\hbar}t}$$

$$\omega_R = E_R/\hbar \qquad \tau = \hbar/\Gamma$$

Probability of finding the particle at a time t is

$$I(t) = \psi^*\psi = \psi(0)^2 e^{-t/\tau} = I(0)e^{-t/\tau}$$

The Fourier transform of $\psi(t)$

$$\chi(E) = \int \psi(t)e^{iEt}dt = \psi(0)\int e^{-t[(\Gamma/2)+iE_R-iE]}dt =$$

$$= \frac{K}{(E_R - E) - i\Gamma/2}.$$

K: normalization factor

Elastic Scattering

$$a + b \to R \to a' + b'$$

$$\sigma(E) = \sigma_0 \boxed{\chi^*(E)\chi(E)} = \sigma_0 \frac{K^2}{[(E_R - E)^2 + \Gamma^2/4]}$$

Prob. of finding particle in Energy E

$$1 = \chi^*(E_R)\chi(E_R) = 4K^2/\Gamma^2 \quad \longrightarrow \quad K^2 = \Gamma^2/4$$

$$\sigma_0 = \pi(2\lambdabar)^2 = 4\pi\lambdabar^2$$

$$\boxed{\sigma_{el}(E;J) = 4\pi\lambdabar^2 \frac{(2J+1)}{(2s_a+1)(2s_b+1)}\left[\frac{\Gamma^2/4}{(E_R - E)^2 + \Gamma^2/4}\right].}$$

Inelastic scattering

$$a + b \to R \to c + d$$

$$\sigma = 4\pi\lambda^2 \frac{(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma_{ab}\Gamma_{cd}/4}{(E-E_R)^2 + \Gamma^2/4}$$

$\lambda = \hbar/p$ is the de Broglie wavelength of particle a,b in the c.m. frame

$$\Gamma_{ab} = \Gamma(R \to a + b)$$

$$\Gamma_{cd} = \Gamma(R \to c + d)$$

$$\Gamma = \Gamma_{\text{Total}} = \sum_i \Gamma_i$$

Drell-Yan W-boson production

$$u\bar{d} \to W^+ \to e^+\nu$$

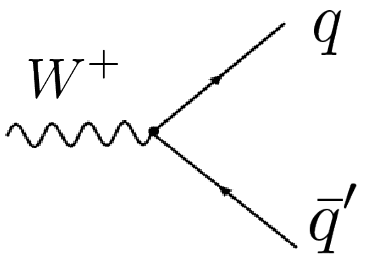
$$\sigma\big(u\overline{d} \to W^+ \to e^+\nu_e\big) = \frac{1}{N_c}\frac{4\pi\lambdabar^2 \Gamma_{u\overline{d}}\Gamma_{e\nu}/4}{(2s_d+1)(2s_u+1)\big[(E-M_W)^2+\Gamma^2/4\big]}\frac{2J+1}{3}$$

At the energy $E = M_W$

$$\sigma_{max}(u\bar{d} \to W^+ \to e^+\nu) = \frac{4\pi\Gamma_{u\bar{d}}\Gamma_{e\nu}}{3M_W^2\Gamma^2} = \frac{4\pi}{81M_W^2} \simeq 9.4\text{nb}$$

W-boson Decay

- Hadronic mode

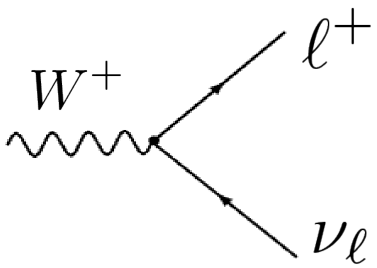


$$Br \sim \frac{6}{9}$$

$$\begin{pmatrix} u & u & u & c & c & c \\ \bar{d} & \bar{d} & \bar{d} & \bar{s} & \bar{s} & \bar{s} \end{pmatrix}$$

hard to detect,
due to huge QCD backgrounds

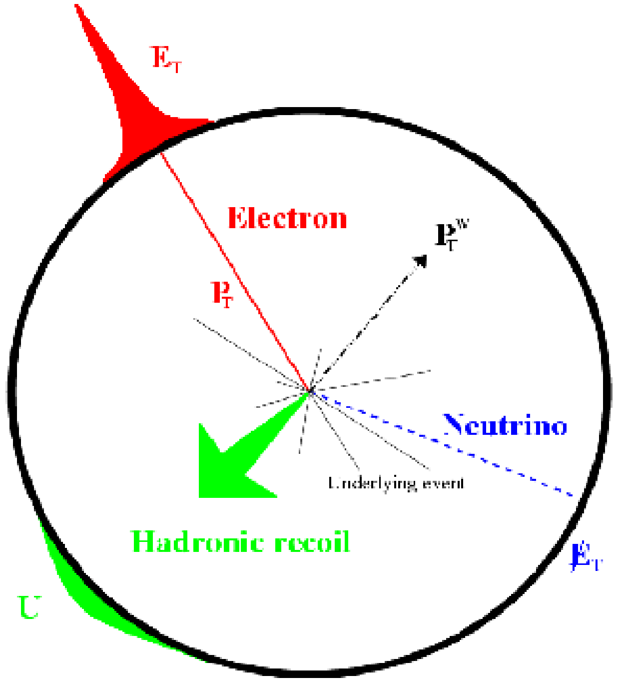
- Leptonic mode



$$Br \sim \frac{3}{9}$$

$$\begin{pmatrix} e^+ & \mu^+ & \tau^+ \\ \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}$$

easy to identify,
but lack of p_z^ν



unknown p_z^ν ⇒ cannot reconstruct invariant mass $m_W = \sqrt{(p_e + p_\nu)^2}$

Narrow width approximation

$$\sigma_{max}(u\bar{d} \to W^+ e^+ \nu + e) = \frac{4\pi\Gamma_{u\bar{d}}\Gamma_{e\nu}}{3M_W^2\Gamma^2} = \frac{4\pi\Gamma_{u\bar{d}}}{3M_W^2\Gamma}\frac{\Gamma_{e\nu}}{\Gamma}$$

$$= \frac{4\pi\Gamma_{u\bar{d}}}{3M_W^2\Gamma} \otimes \mathrm{Br}(W \to e\nu)$$

W-boson
production

W-boson
decay

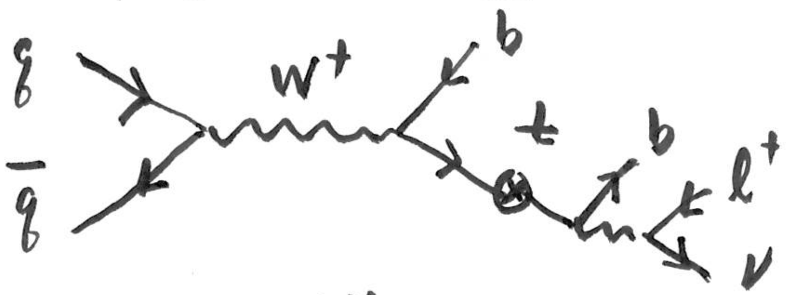
Key of New Physics Discovery

- 大的产生截面
  - * 新物理粒子的质量要轻
    (部分子分布函数随质增加迅速下降)
  - * QCD > Weak > EM
    $\alpha_s \sim \frac{1}{10}$　$\alpha_W \sim \frac{1}{30}$，$\alpha_{em} \sim \frac{1}{128}$
    (新粒子最好带有色荷)
  - * 产生过程末态粒子要少
    (相空间压低)
    一般而言，每增加一个粒子，无量纲化的
    相空间要减少两个数量级
    $2 \rightarrow 1$ 或 $2 \rightarrow 2$ (Weak)
    $2 \rightarrow n$ (QCD)
    $(n \geq 3)$

- 易于探测的实验信号
  - * 带电轻子 (e^-, μ^-)
  - * 大丢失的横向动量 ($\not{E}_T$)
    (容易探测但不能提供新物
    理的有用信息)
  - * 重味的喷注
    (低探测效率)

窄宽度近似 (NWA)

以顶夸克产生和衰变为例



在 $\Gamma_t << m_t$ 时可取极限 $\Gamma_t \to 0$

$$\int dp_t^2 \frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2} = \frac{\pi}{m_t\Gamma_t}$$

散射振幅模方可近似为

$$|\mathcal{M}|^2 = |\mathcal{M}_{decay}(\cdots, p_t)|^2 \frac{\pi}{m_t\Gamma_t}\delta(p_t^2-m_t^2)\,|\mathcal{M}_{prod}(\cdots, p_t)|^2$$

相空间近似为

$$d\Phi_4 = d\Phi_2 \frac{1}{2\pi} dp_t^2\, d\Phi_3(t\to b l^+\nu)$$

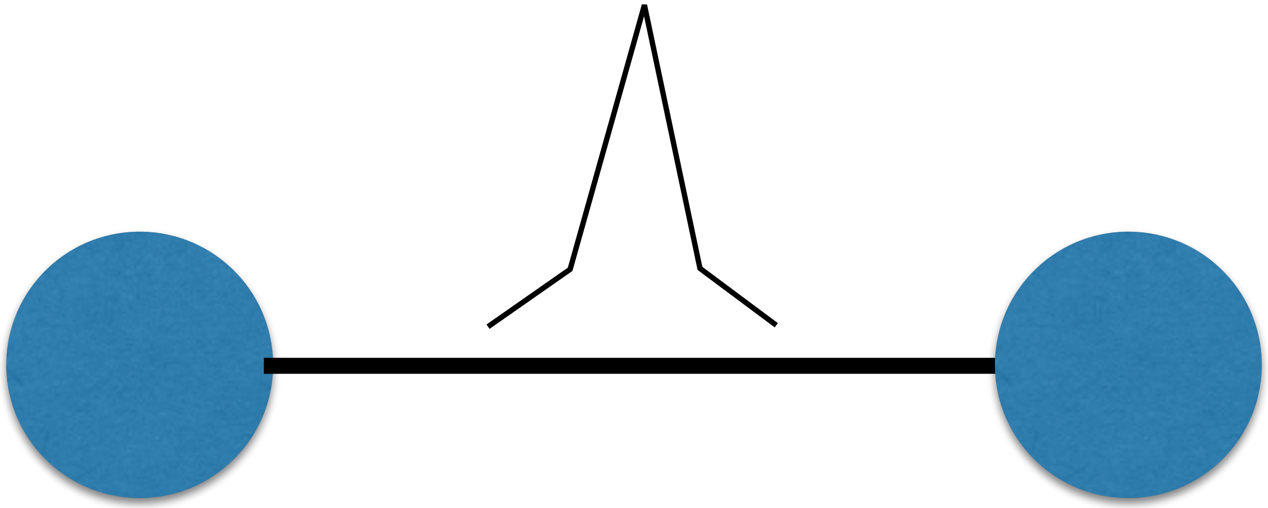
所以，

$$\sigma(q\bar{q}\to t\bar{b}\to \bar{b}bl^+\nu) = \int |\mathcal{M}|^2 d\Phi_4 \xrightarrow{\Gamma_t\to 0} \int |\mathcal{M}_{prod}(\cdots p_t)|^2 d\Phi_2\, dp_t^2\, \delta(p_t^2-m$$

$$\times \int \frac{1}{2m_t\Gamma_t} |\mathcal{M}_{decay}|^2 d\Phi_3$$

$$= \sigma_{prod}(q\bar{q}\to t\bar{b}) \times \underbrace{\frac{1}{\Gamma_t}\times\Gamma(t\to bl^+\nu)}_{Br(t\to bl^+\nu)}$$

Narrow width approximation



Production

$\Gamma/M \ll 1$

Decay

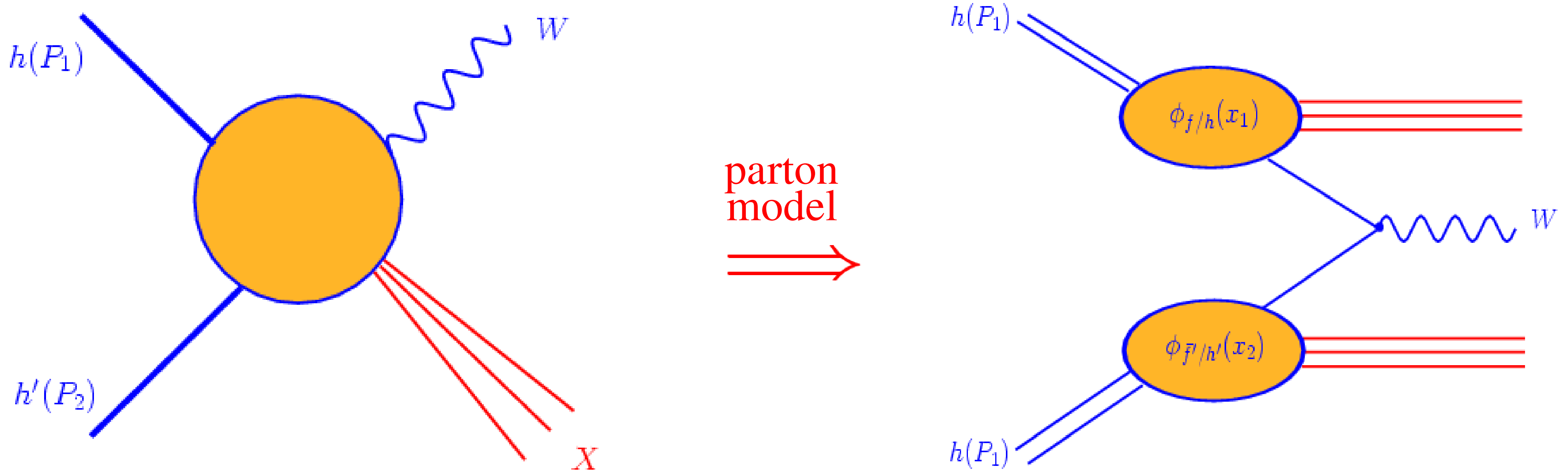
$$Q_{prod} = M$$

$$\tau_{prod} = 1/M$$

$$\tau_{decay} = 1/\Gamma$$

$$\frac{\Gamma}{M} = \frac{1/M}{1/\Gamma} = \frac{\tau_{prod}}{\tau_{decay}} \ll 1$$

W-boson production at Hadron collider

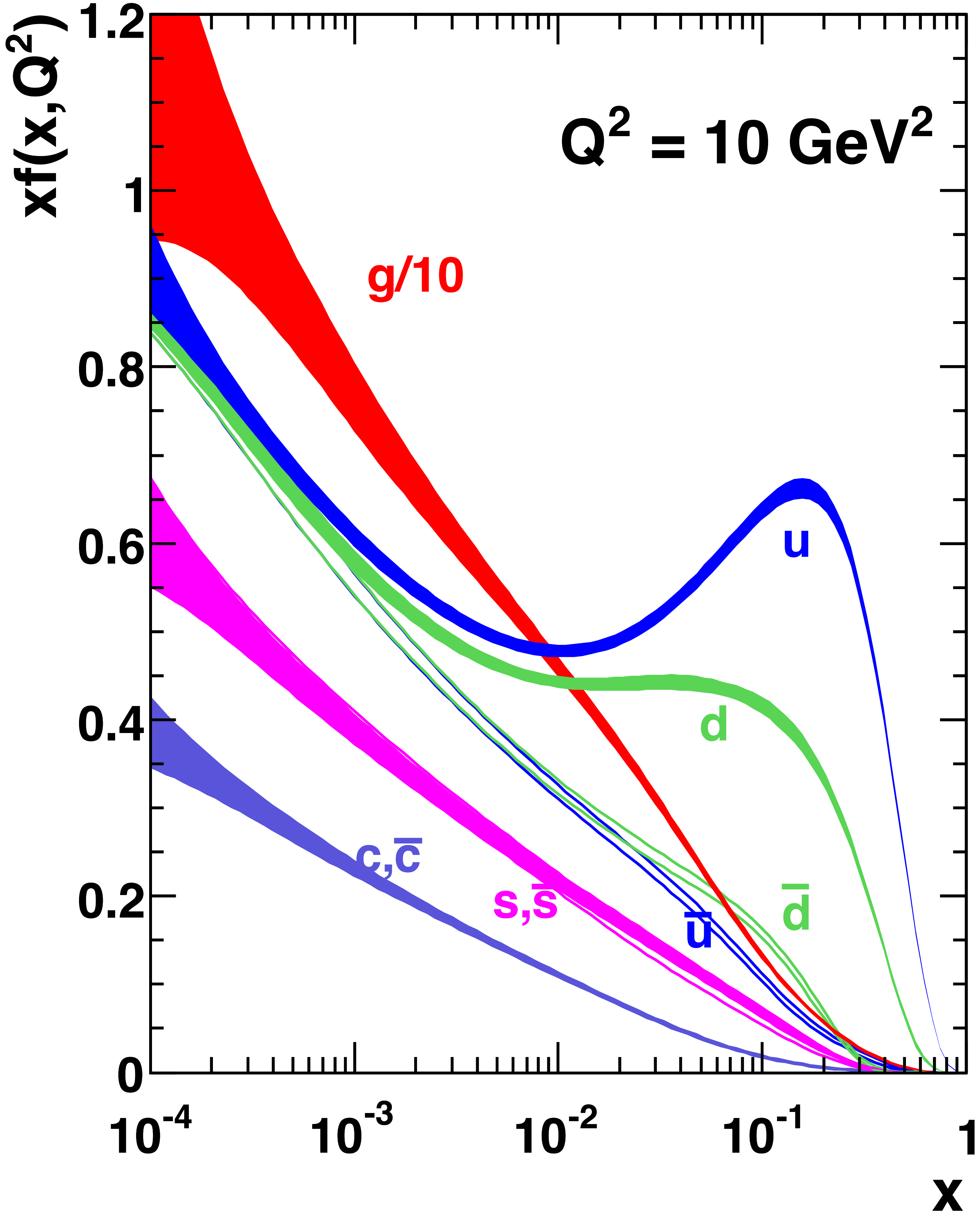


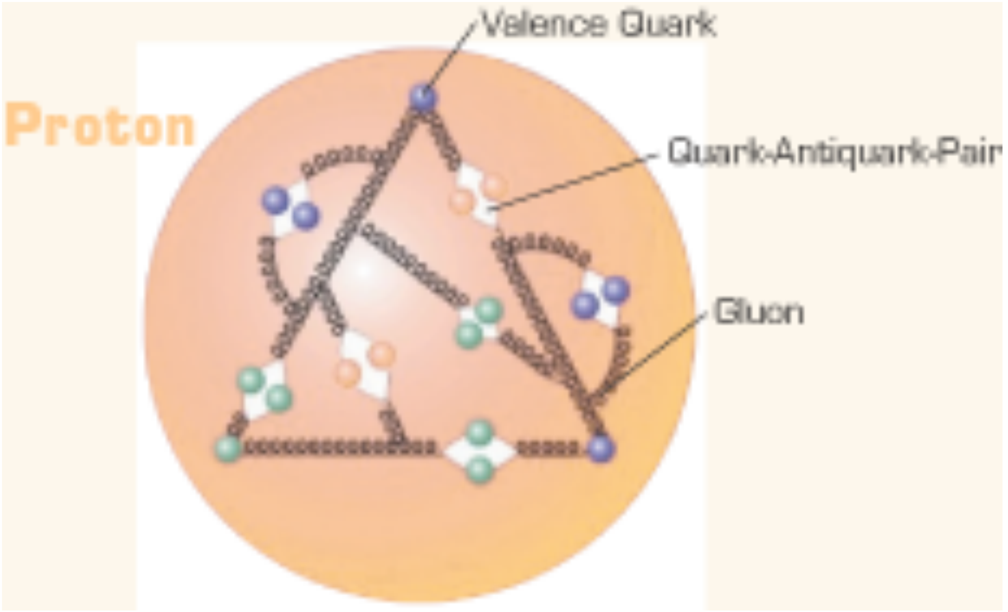
$$\sigma_{hh'\to W^+X} = \sum_{f,f'} \int_0^1 dx_1 dx_2 \left\{ \phi_{f/h}(x_1)\, \hat{\sigma}_{ff'}\, \phi_{\bar{f}'/h'}(x_2) + (x_1 \leftrightarrow x_2) \right\}$$

PDFs are known from deep inelastic scattering

partonic "Born" cross section of $f\bar{f}' \to W^+$

Parton distribution Functions

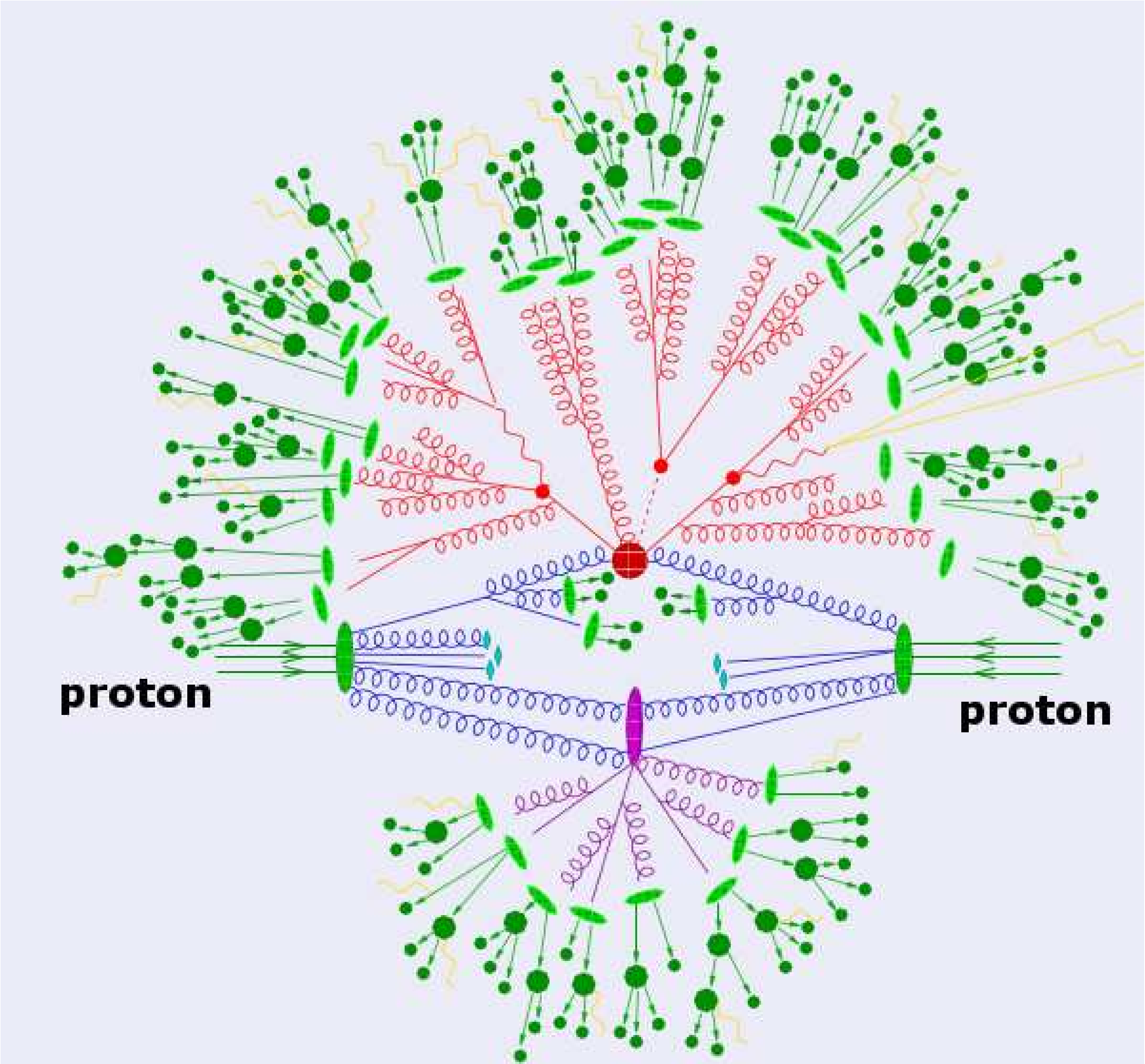




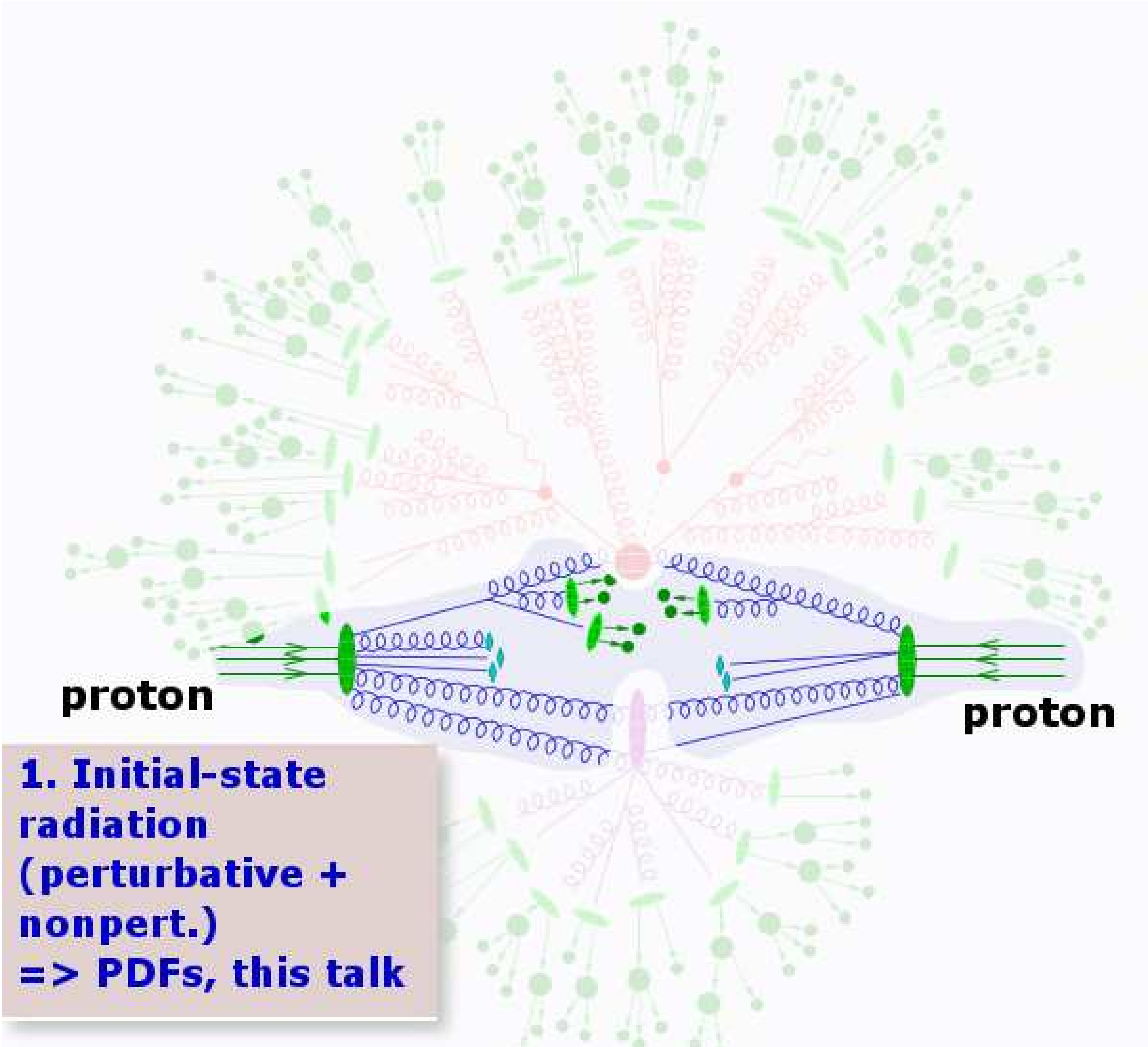
$$xf_{q/P}(x_i, Q)$$

Momentum fraction

Structure of the collision event

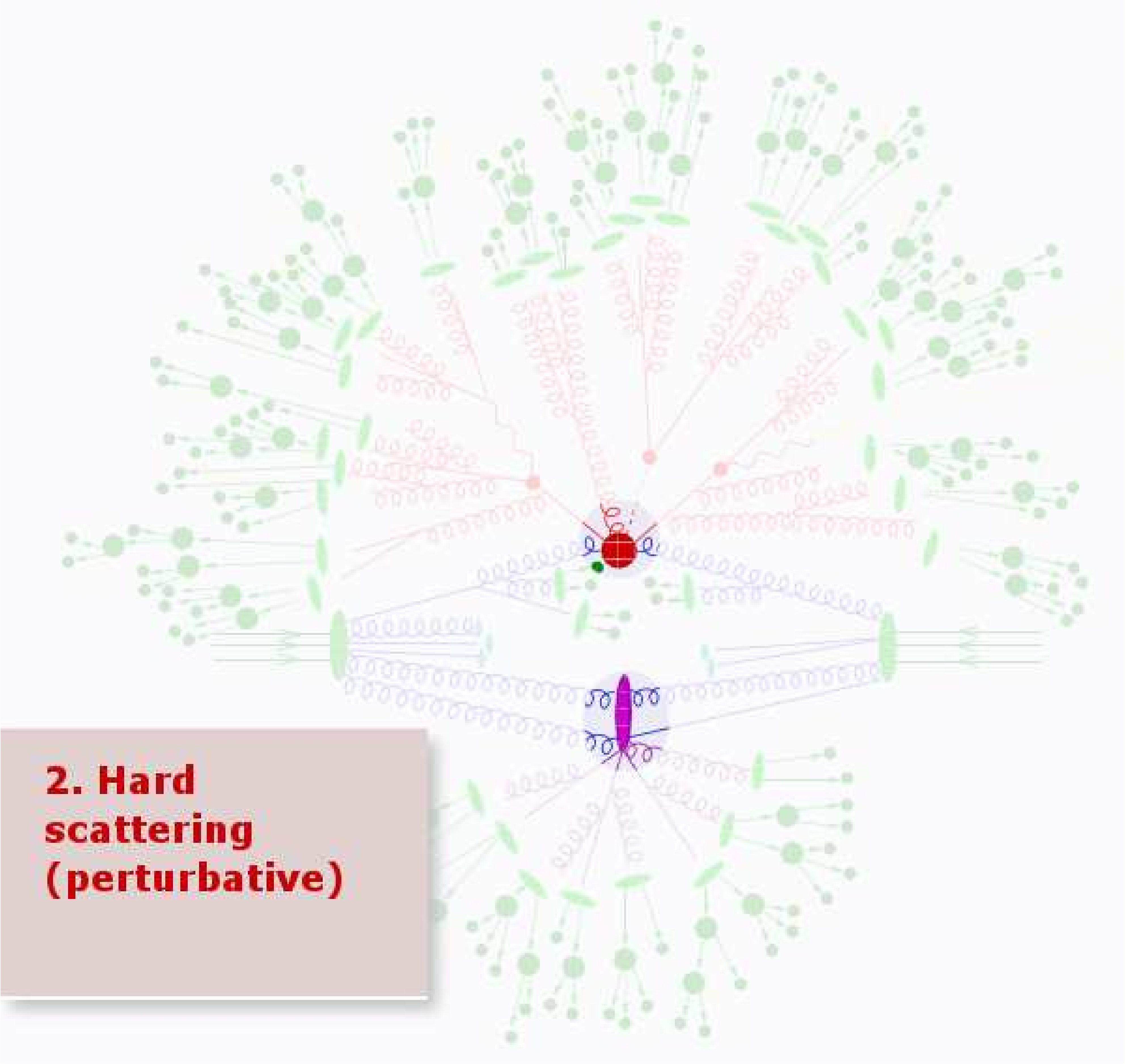


Structure of the collision event



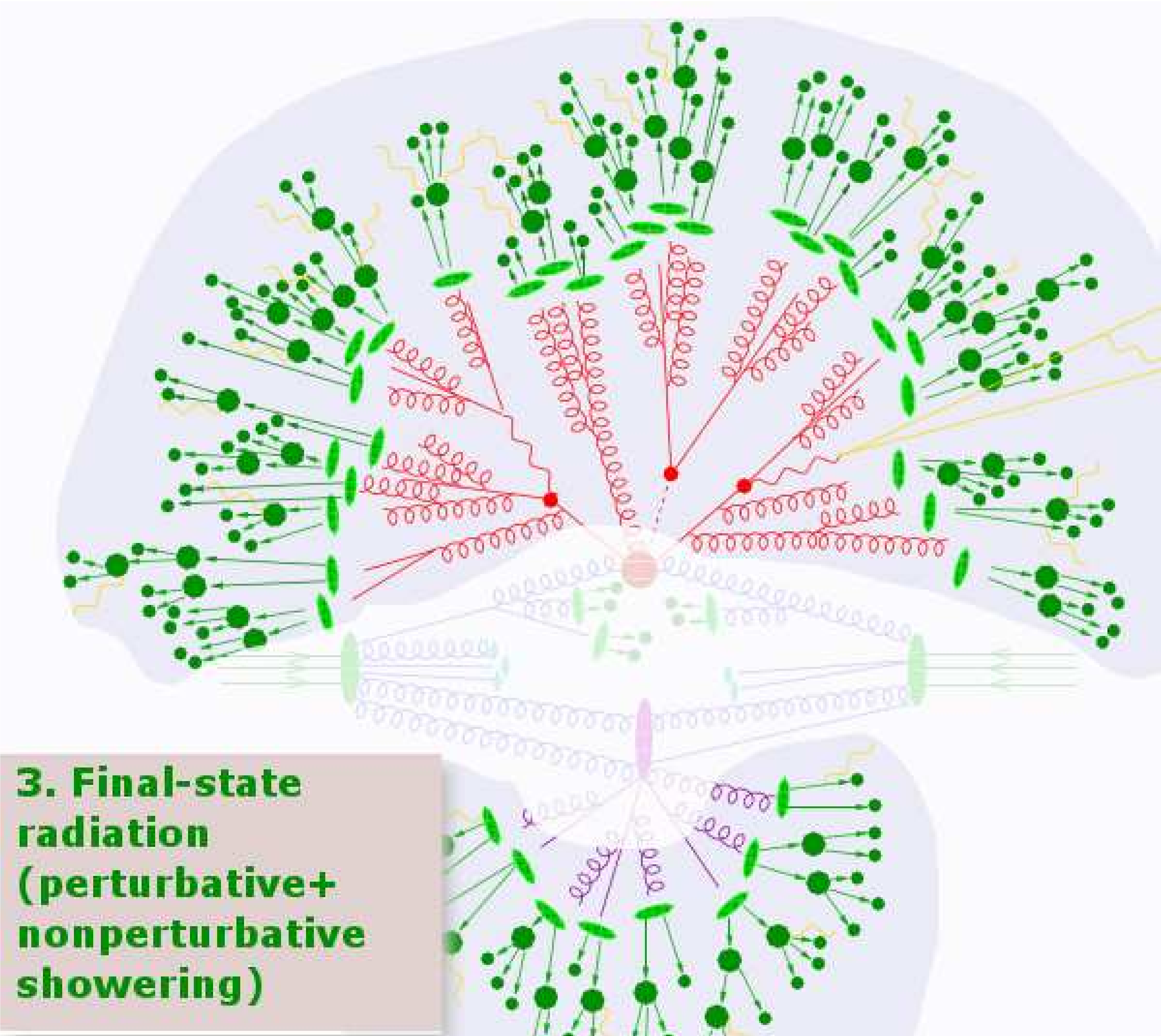
1. Initial-state radiation (perturbative + nonpert.)
=> PDFs, this talk

Structure of the collision event



2. Hard scattering (perturbative)

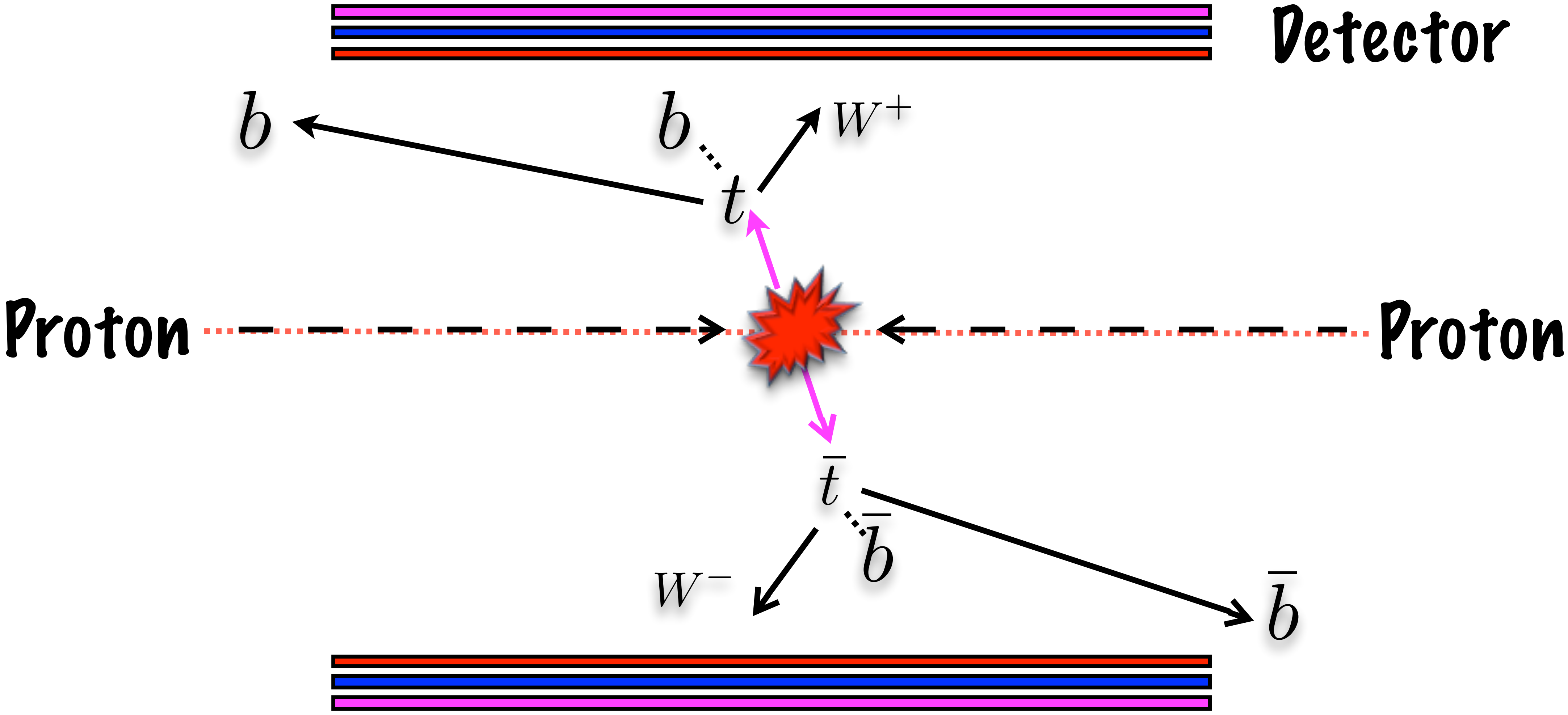
Structure of the collision event



3. Final-state radiation (perturbative+ nonperturbative showering)

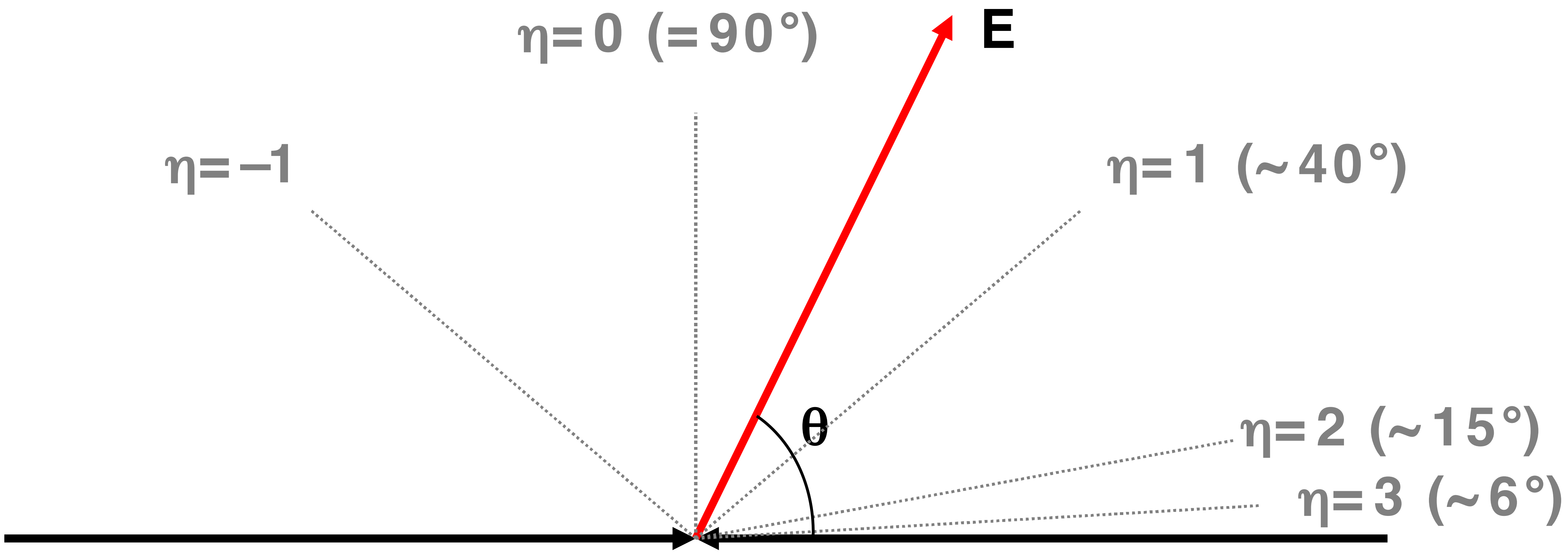
Differential Cross Section

* sensitive to spin-correlation
* useful to suppress background



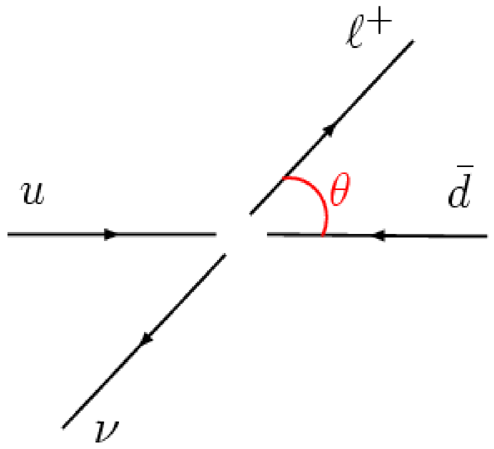
曲率 $\frac{1}{R} \sim \frac{0.3QB}{p}$

Large pT and
central region


η=0 (=90°)
E
η=−1
η=1 (~40°)
θ
η=2 (~15°)
η=3 (~6°)

Transverse momentum of the charged lepton (p_T^e)

- In (ud) c.m. system,

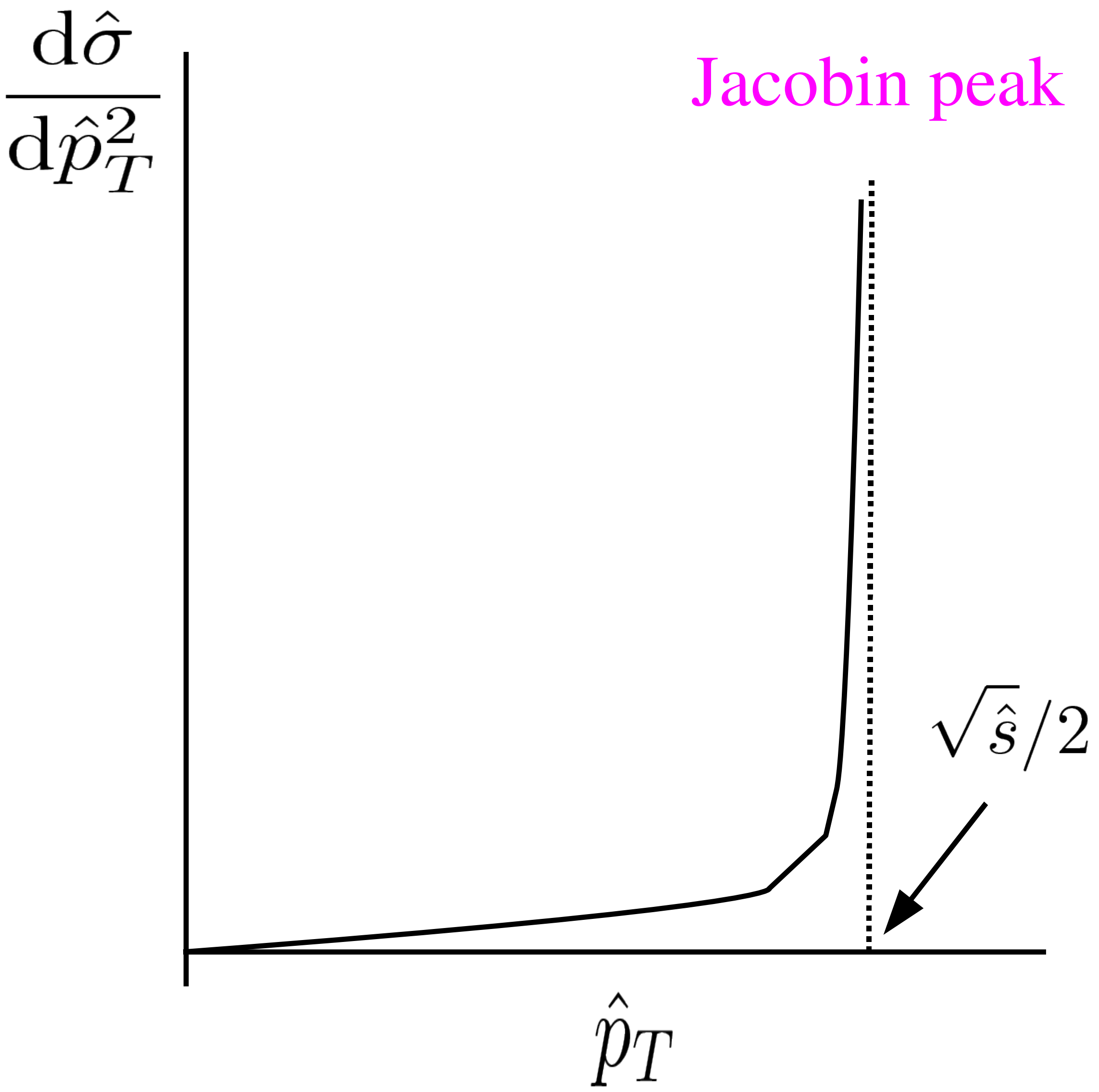


$$\hat{p}_T^2 = \frac{1}{4}\hat{s}\sin^2\theta$$

Jacobin factor

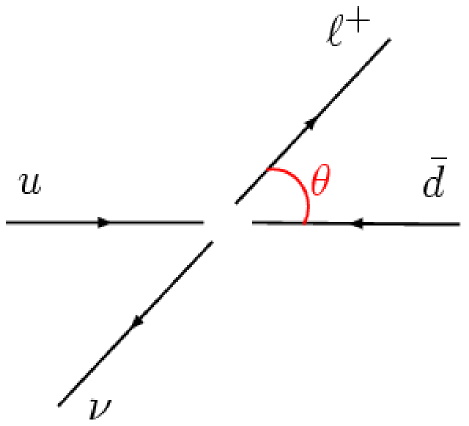
$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}\hat{p}_T^2} = -\frac{2}{\hat{s}}\frac{1}{\sqrt{1-\frac{4\hat{p}_T^2}{\hat{s}}}}$$

$$\Longrightarrow \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{p}_T^2} \sim \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\cos\theta} \times \frac{1}{\sqrt{1-4\hat{p}_T^2/\hat{s}}}$$



Transverse momentum of the charged lepton (p_T^e)

- In (ud) c.m. system,

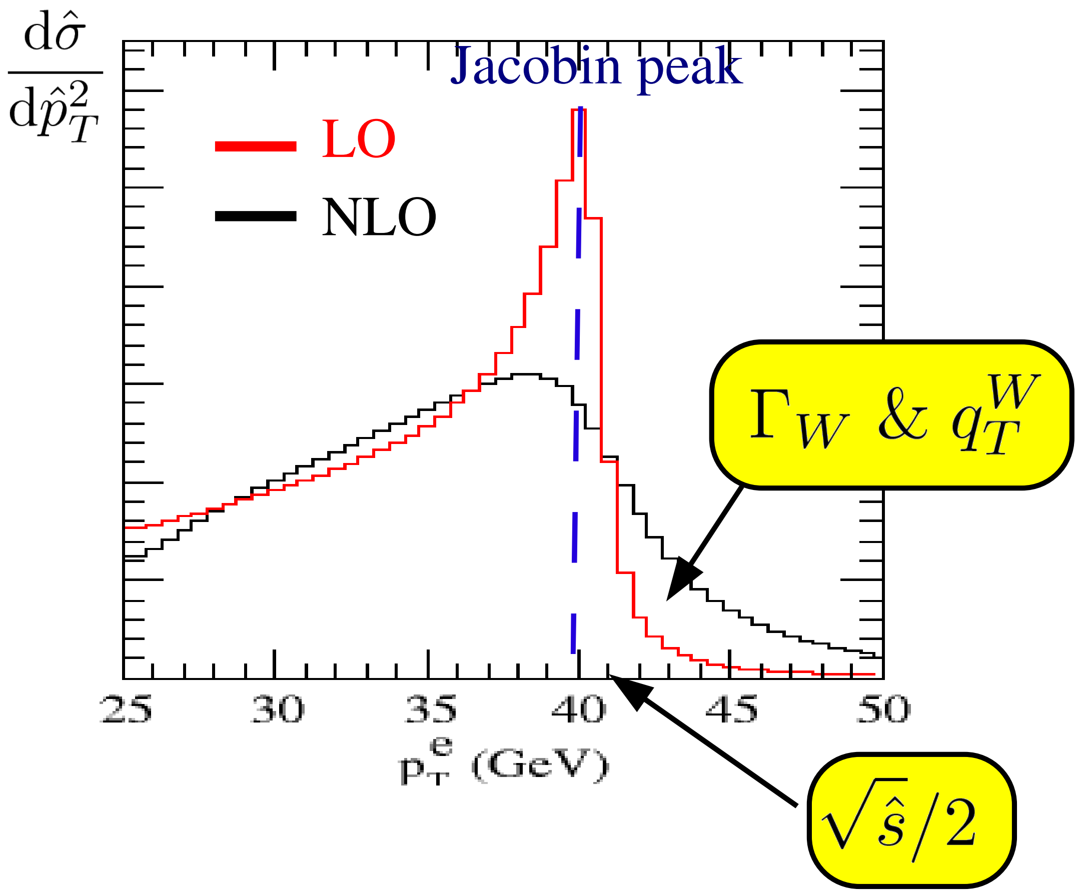


$$\hat p_T^2 = \frac{1}{4}\hat s \sin^2\theta$$

Jacobin factor

$$\frac{\mathrm{d}\cos\theta}{\mathrm{d}\hat p_T^2} = -\frac{2}{\hat s}\frac{1}{\sqrt{1-\frac{4\hat p_T^2}{\hat s}}}$$

$$\Longrightarrow \quad \frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat p_T^2} \sim \frac{\mathrm{d}\hat\sigma}{\mathrm{d}\cos\theta} \times \frac{1}{\sqrt{1-4\hat p_T^2/\hat s}}$$



sensitive region for measuring

M_W : $p_T^e \sim 30 - 45$ GeV

Γ_W : not a good observable

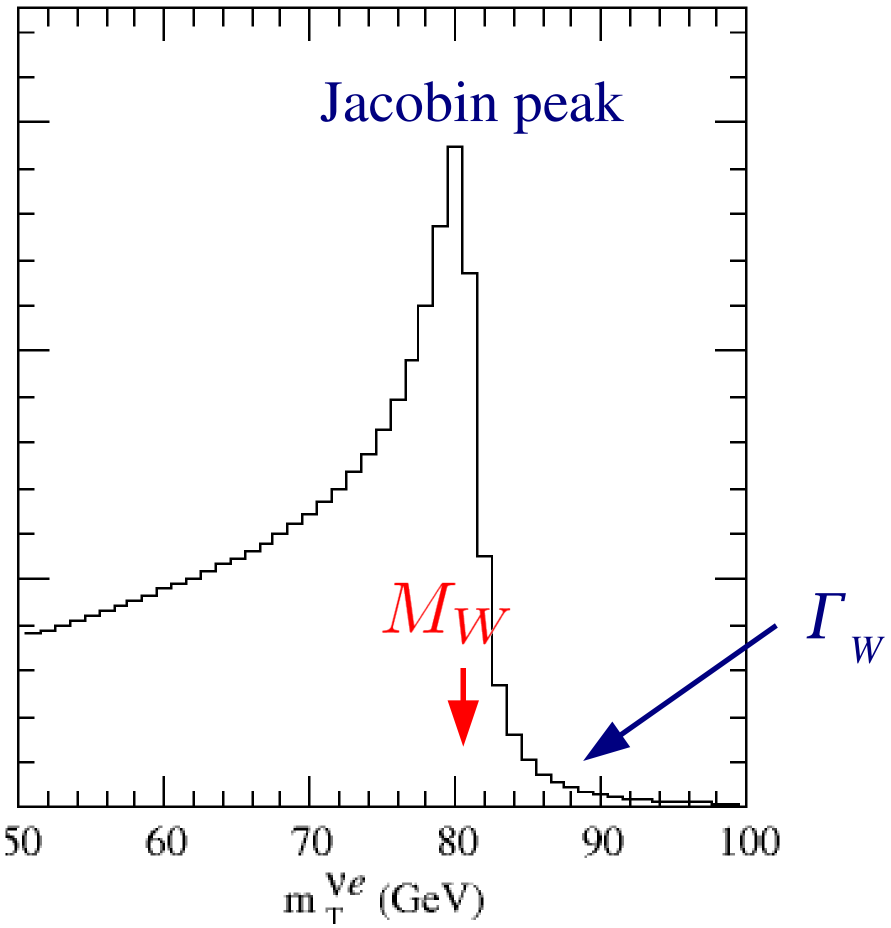
Transverse mass of the W-boson (M_T^W)

- Definition:

$$m_T^2(\ell,\nu) = 2\, p_T^\ell\, p_T^\nu (1 - \cos\phi_{\ell\nu})$$

$\downarrow$ from overall p_T imbalance

$$\Longrightarrow \quad \frac{d\hat{\sigma}}{dm_T^2} \sim \frac{1}{\sqrt{1 - m_T^2/\hat{s}}}$$



☞ unaffected by longitudinal boosts of $\ell\nu$ system

☞ not sensitive to q_T^W

☞ tail knows about Γ_W (direct measurement)

:

sensitive region for measuring

M_W : $M_T \sim 60 - 100\text{GeV}$

$\Gamma_W \quad M_T > 100$ GeV

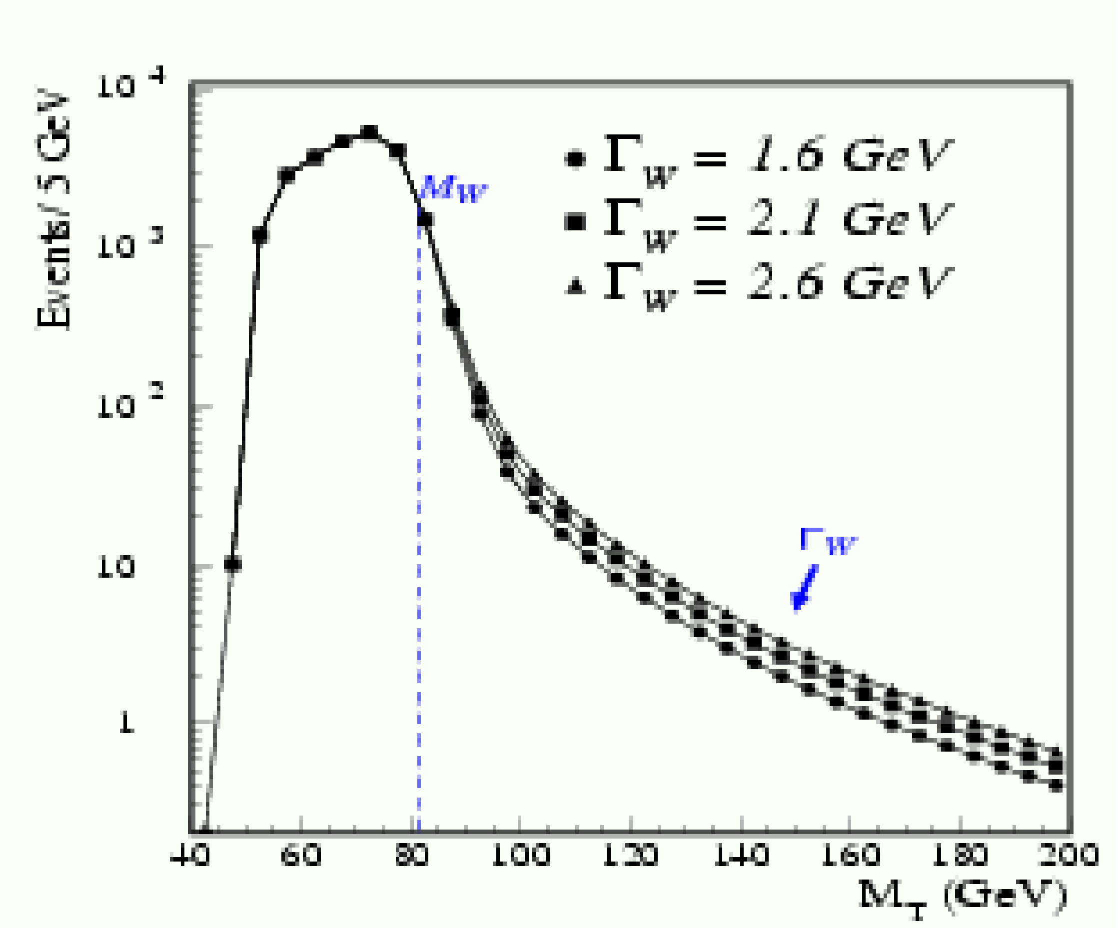
Transverse mass of the W-boson (M_T^W)

- Definition:

$$m_T^2(\ell,\nu) = 2\, p_T^\ell\, p_T^\nu (1 - \cos\phi_{\ell\nu})$$

$\downarrow$ from overall p_T imbalance

$$\Longrightarrow \quad \frac{\mathrm{d}\hat\sigma}{\mathrm{d}m_T^2} \sim \frac{1}{\sqrt{1 - m_T^2/\hat s}}$$



☞ unaffected by longitudinal boosts of $\ell\nu$ system

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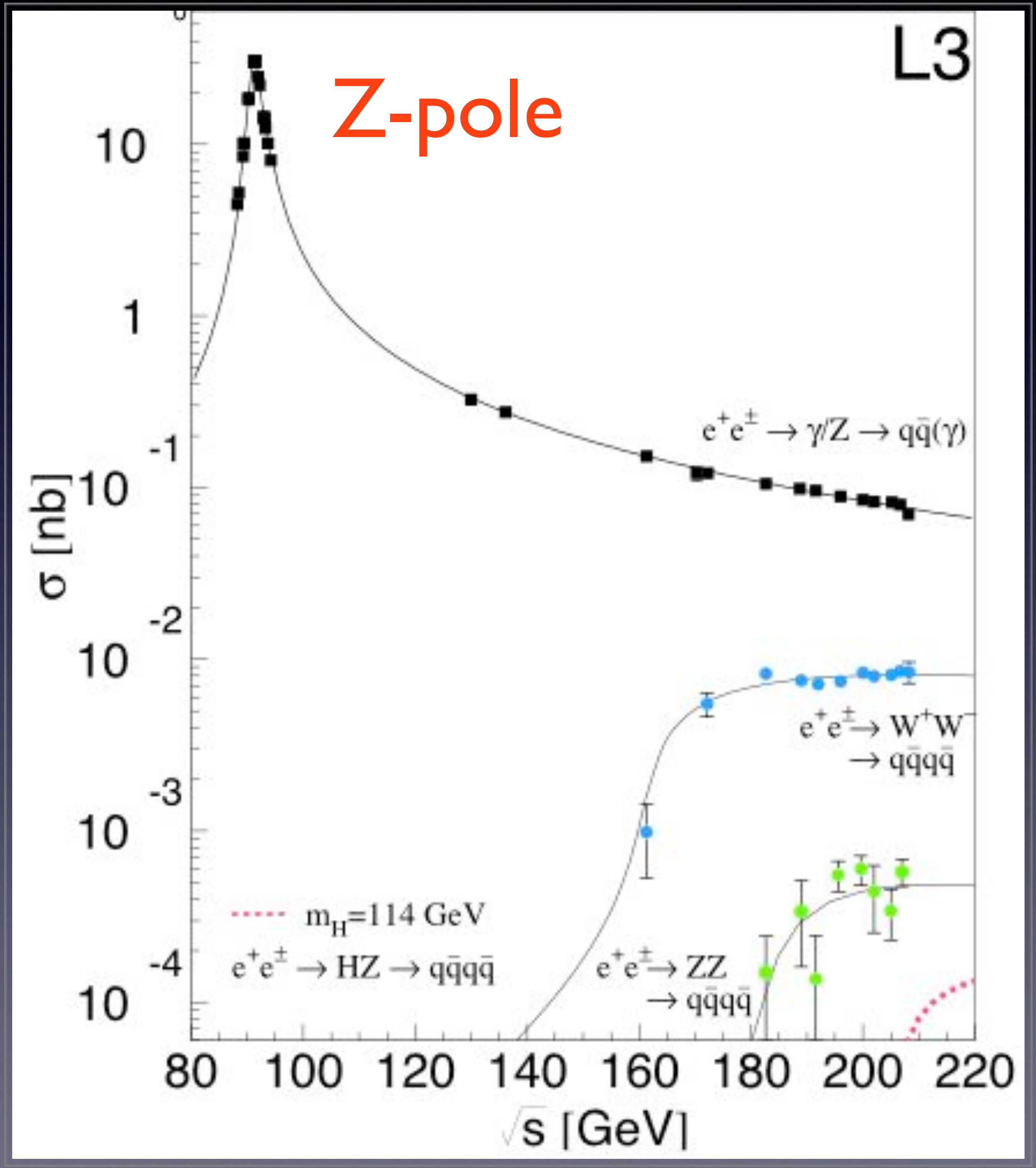
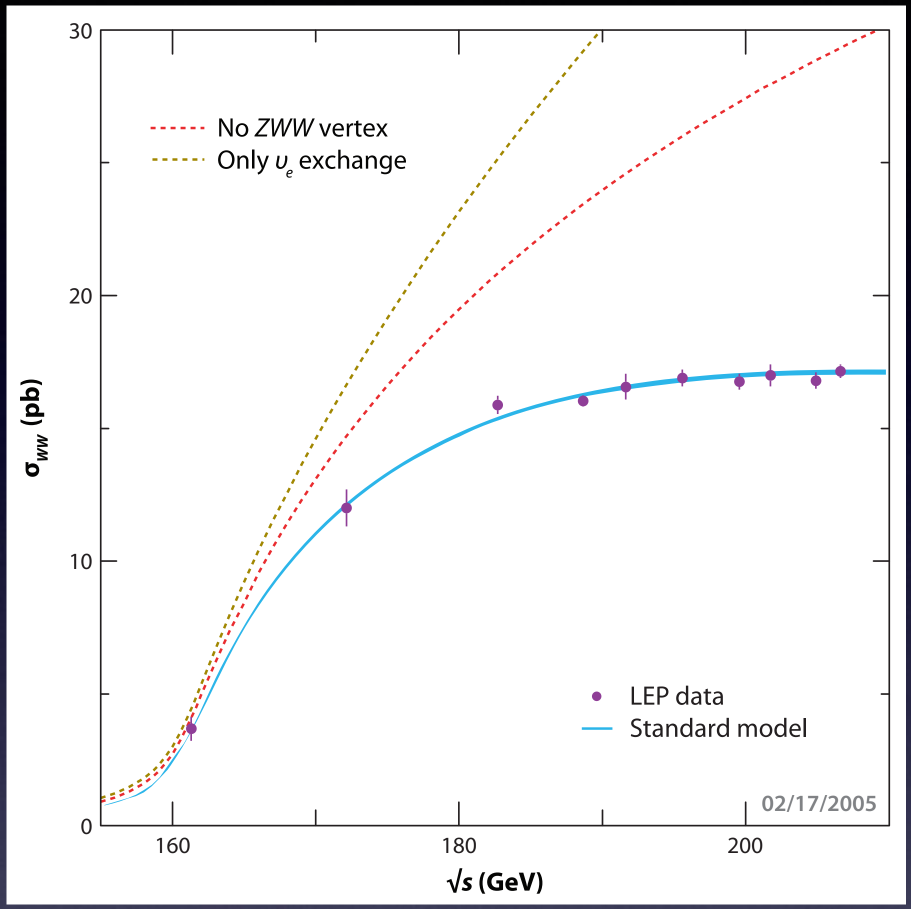
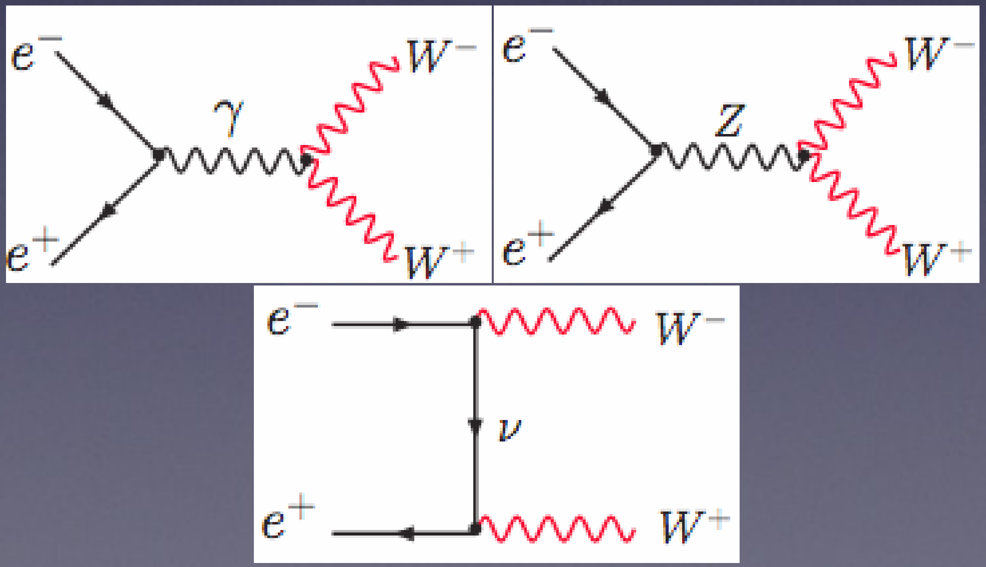
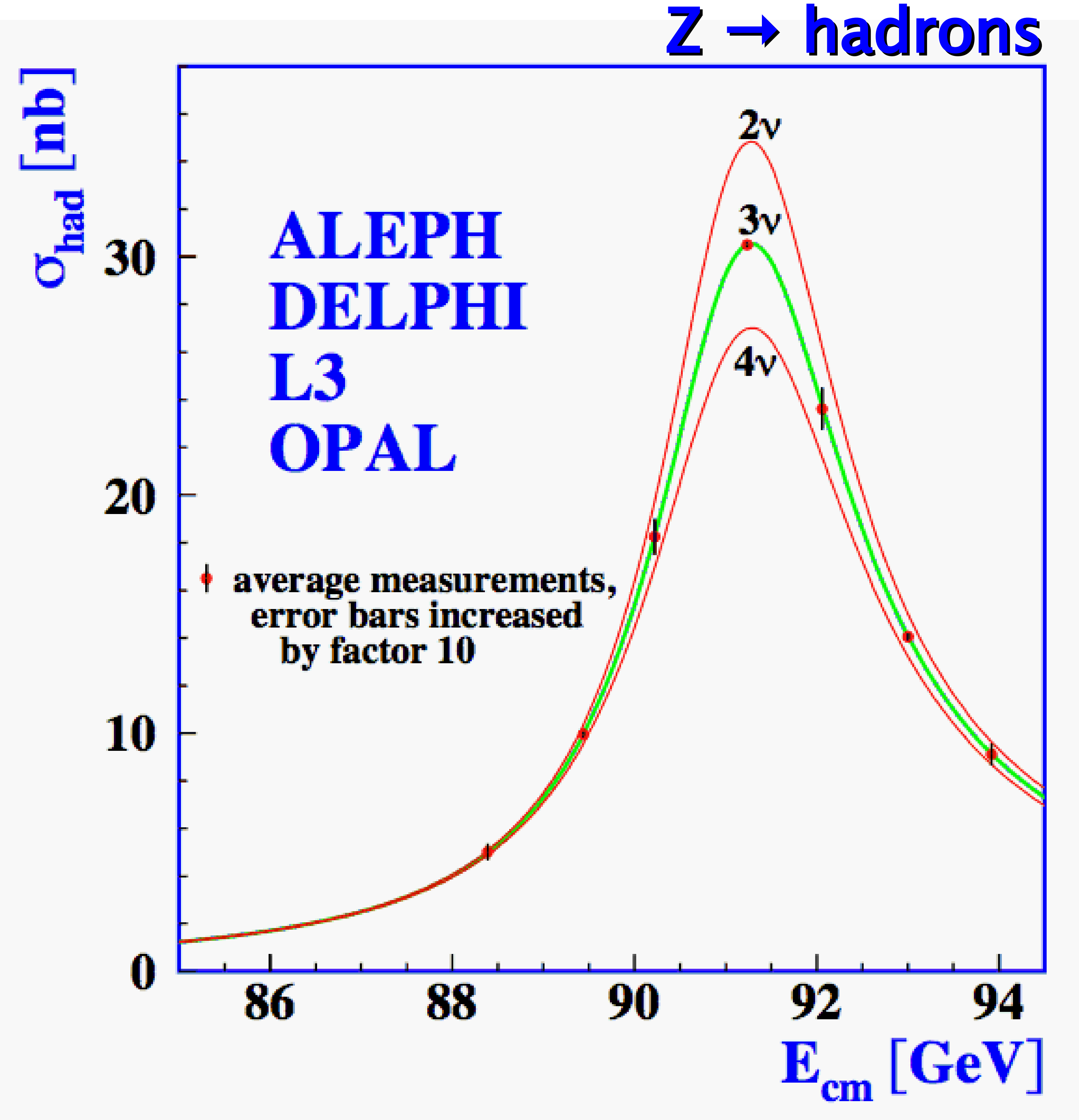
sensitive region:
M_W : $M_T \sim 60 - 100$ GeV
Γ_W : $M_T > 100$ GeV

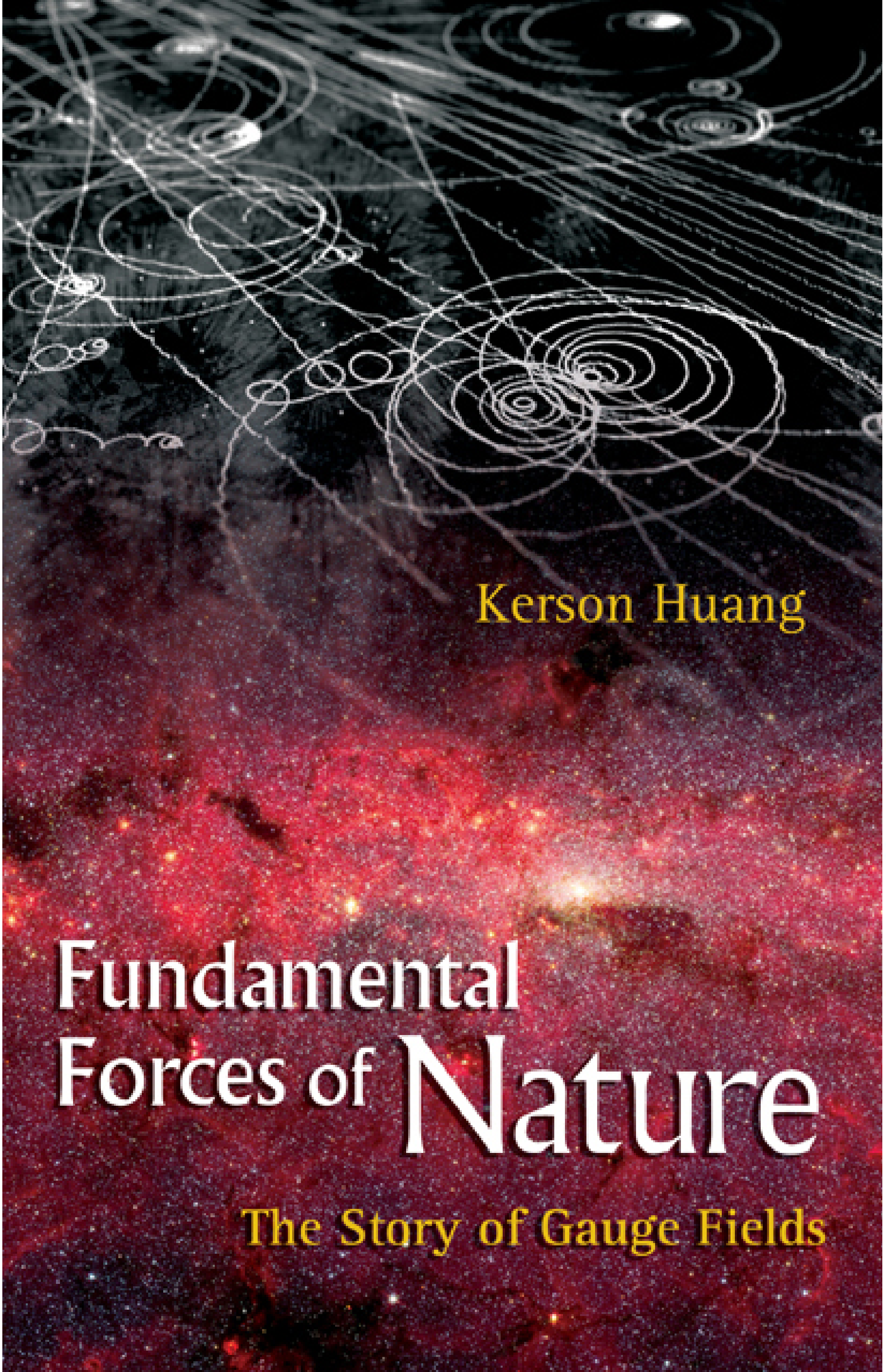
Electroweak theory tests at tree level







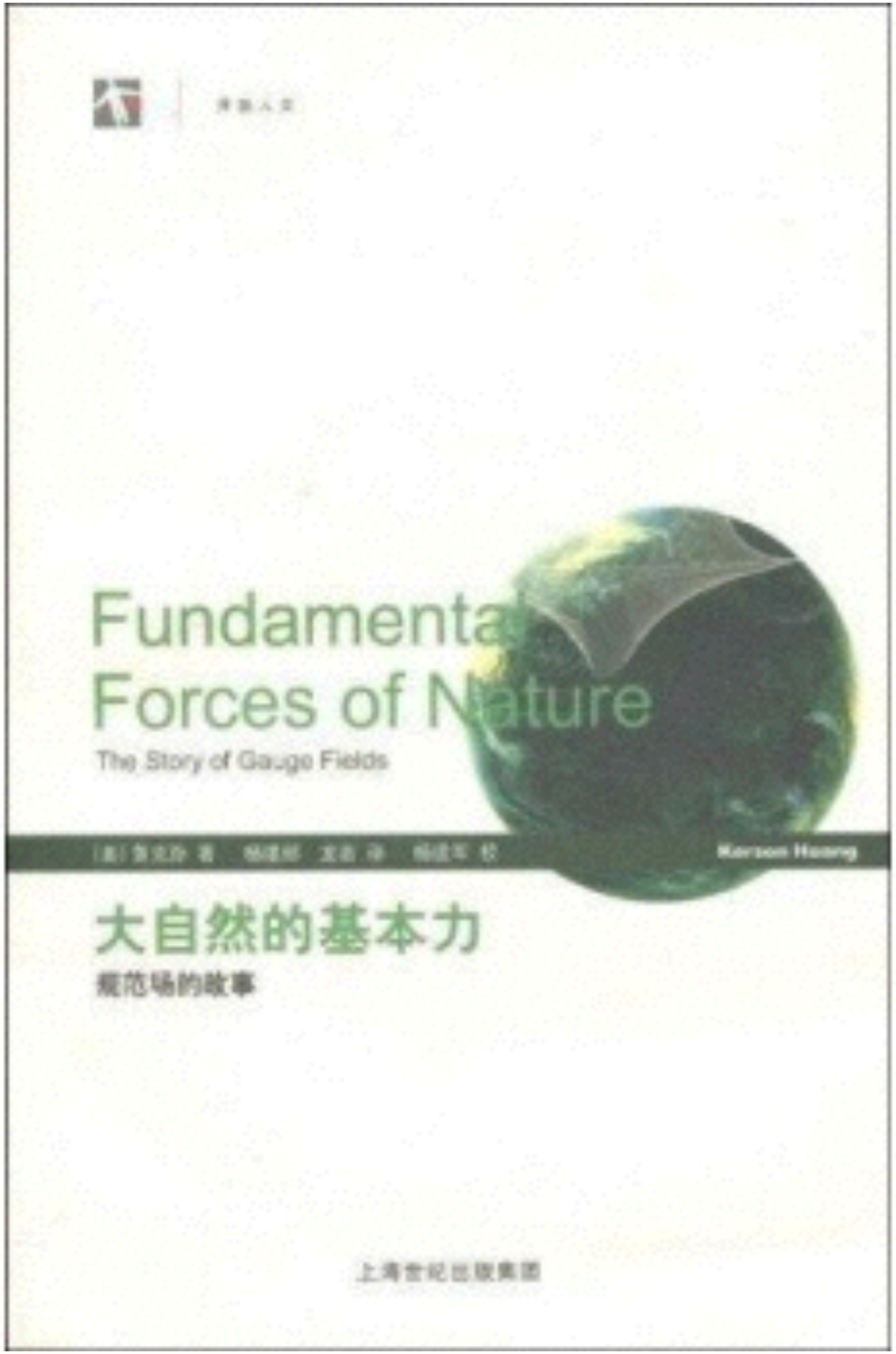

Z → hadrons
σ_{had} [nb]
E_{cm} [GeV]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10
0
10
20
30
86
88
90
92
94



Kerson Huang

Fundamental
Forces of Nature

The Story of Gauge Fields



Fundamental
Forces of Nature

The Story of Gauge Fields

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大自然的基本力

规范场的故事

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