

重味物理探测器实验：以 LHCb 为例

中国科学院
高能物理研究所
李一鸣

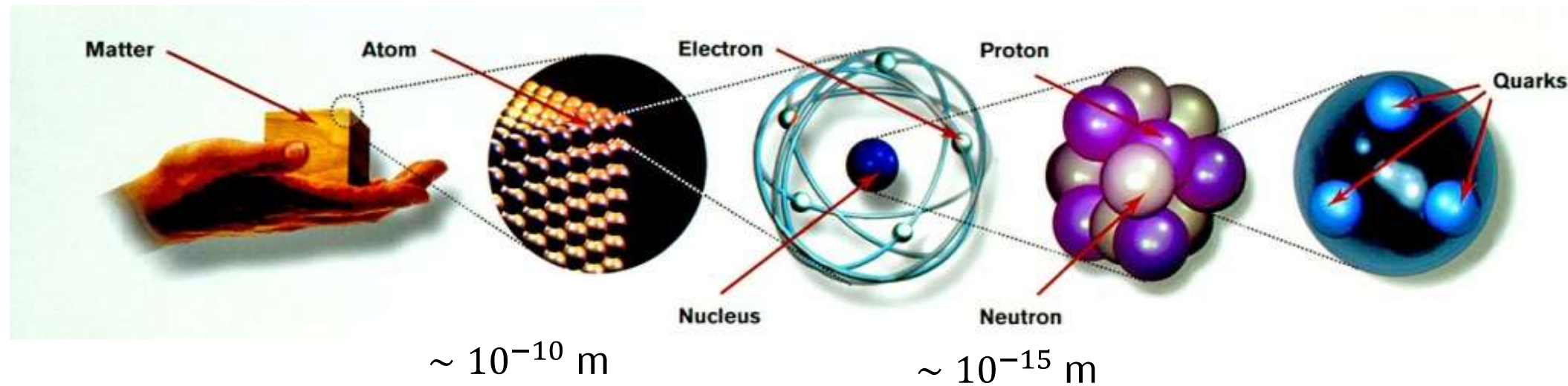
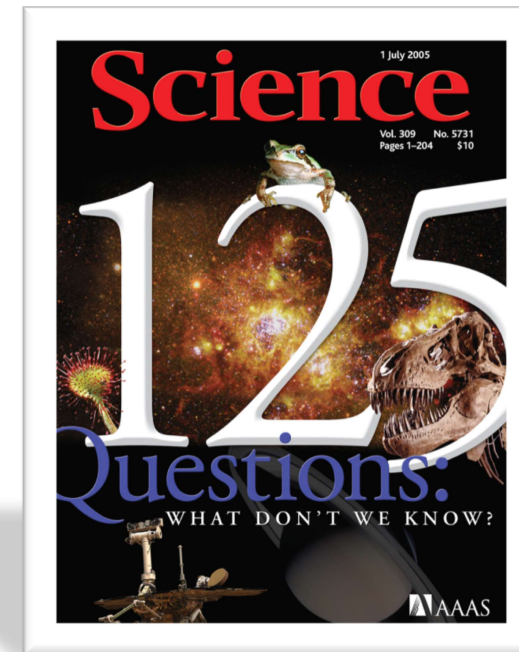
2023 年 8 月 1 日 中国科学院大学科创培训

内容提要

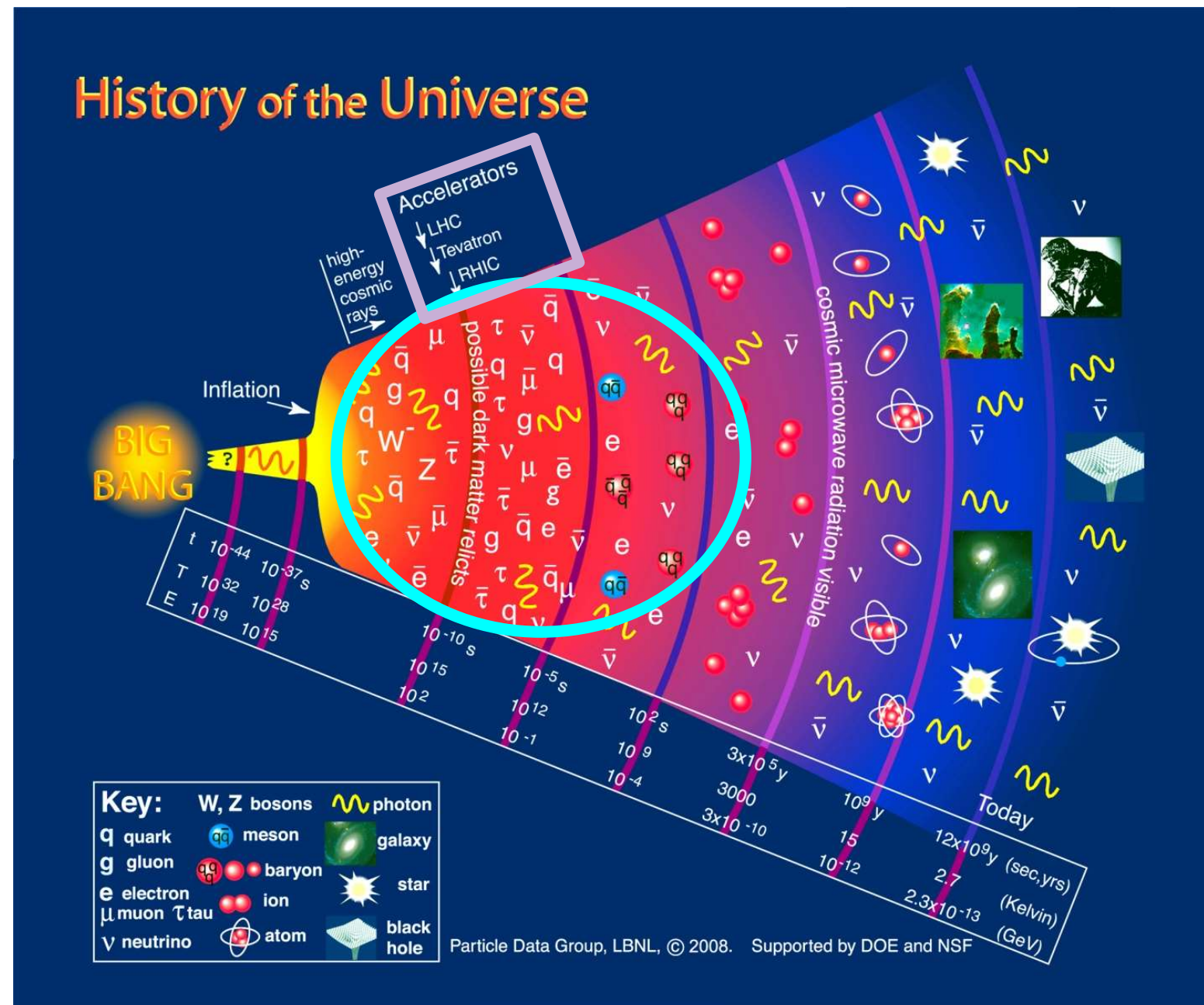
- 高能物理干嘛的？重味物理又是干嘛的？
- 用高能对撞研究重味物理… 撞完后呢？
- 未来还能做什么？

基本问题：物质基本结构与相互作用

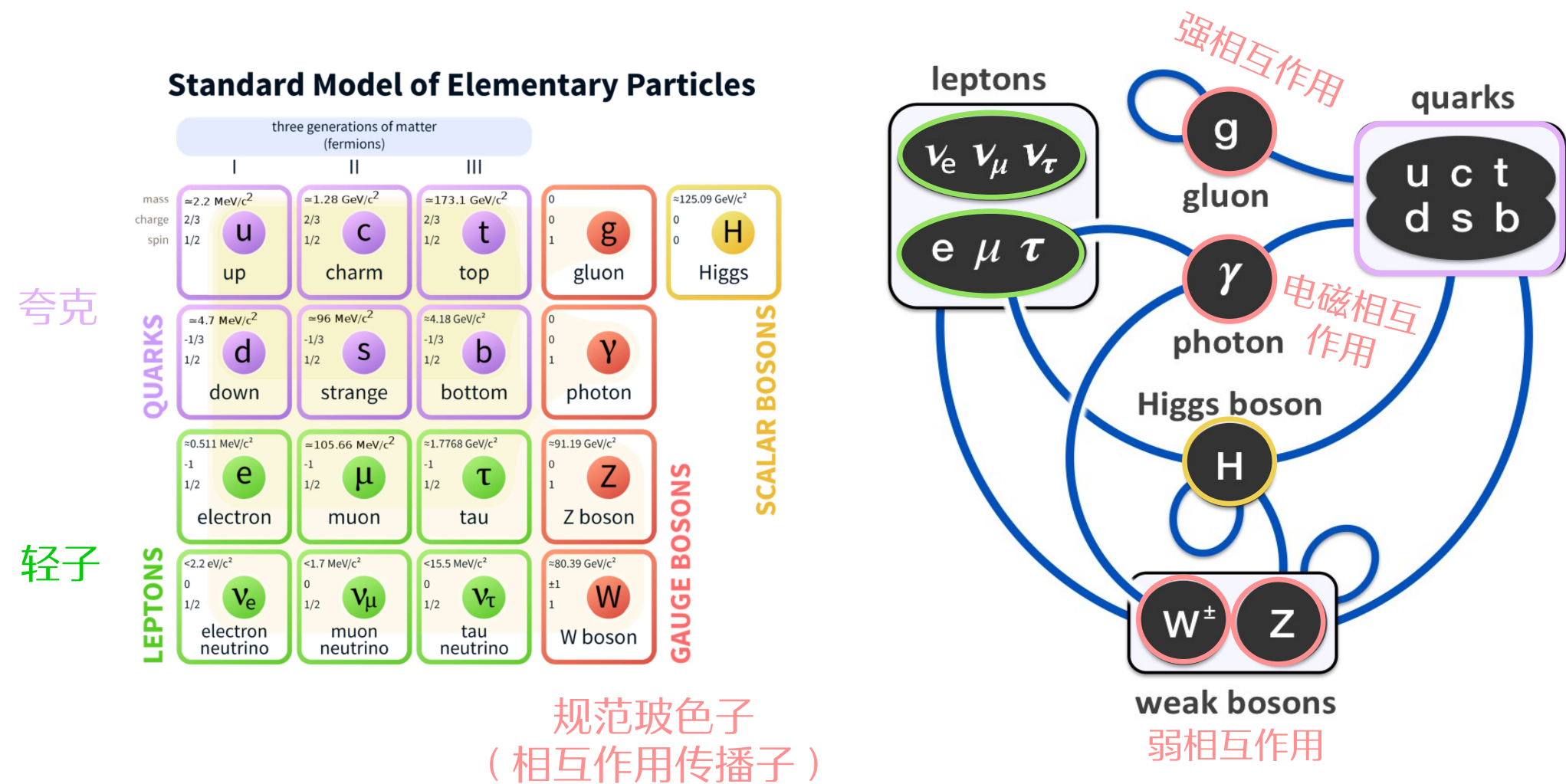
- ❏ 物质世界的基本组成单元是什么？
- ❏ 物质之间相互作用可否归结为统一的物理规律？



基本问题：宇宙的组成和演化

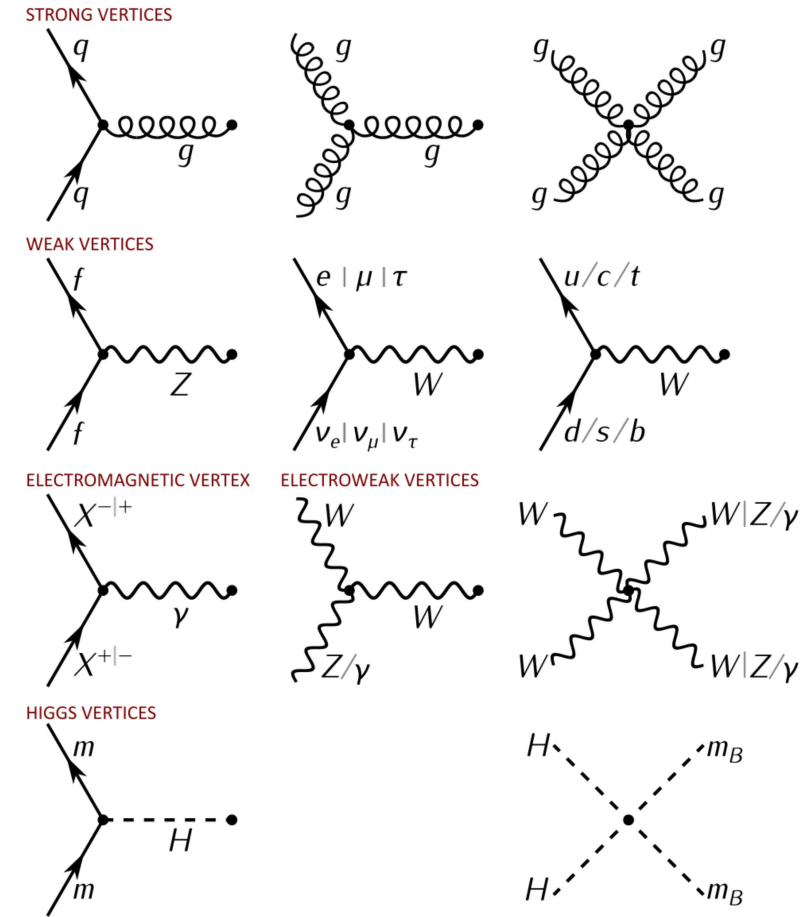


粒子物理标准模型



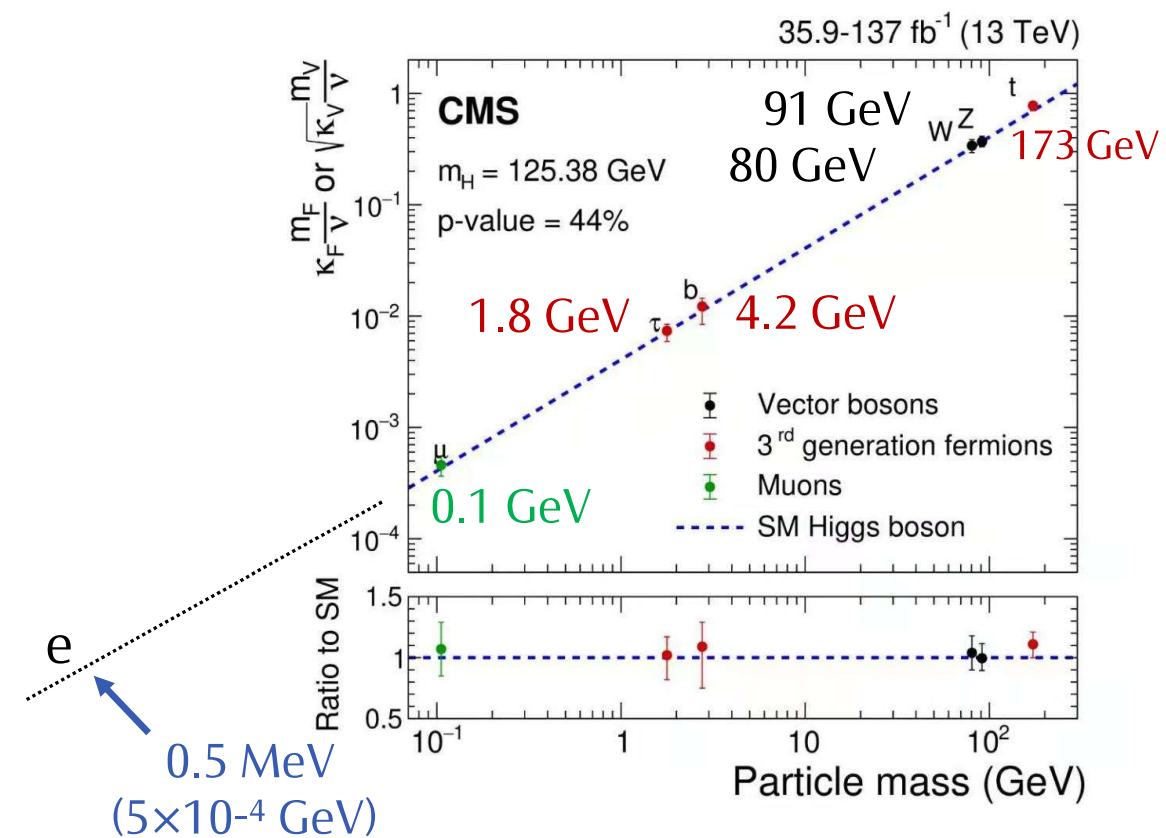
粒子物理标准模型的数学描述

$$\begin{aligned}
 & \frac{1}{2} \partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2} i g_s^2 (\bar{q}_i^c \gamma^\mu q_j^c) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2 c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \\
 & \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2 c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2 M^2}{g^2} + \right. \\
 & \left. \frac{2 M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-) \right] + \frac{2 M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\mu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \\
 & \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4 (\phi^+ \phi^-)^2 + 4 (\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2 (\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \\
 & \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2 (2 s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2 c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^4 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{i g}{4 c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4 s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3} s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3} s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2 \sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2 \sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{i g}{2 \sqrt{2}} \frac{m_h^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_h^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2 M \sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{i g}{2 M \sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_h^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_h^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_h^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{i g}{2} \frac{m_h^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2 c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

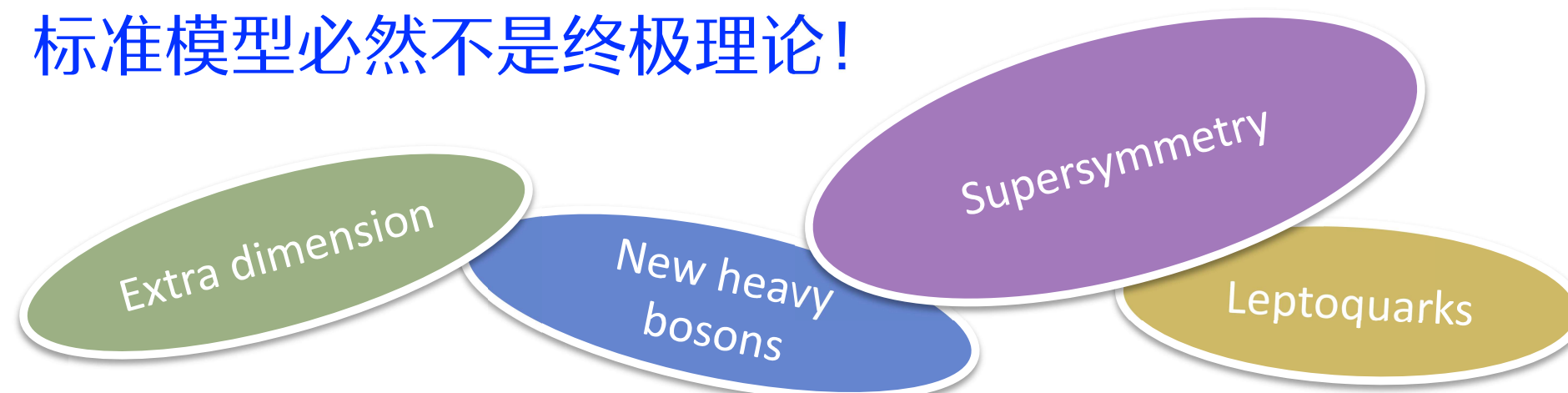


问题还有很多

- 基本粒子的质量为什么差别那么大？
- 希格斯粒子的质量哪里来的？
- 标准模型的真空不稳定？！
- 宇宙中物质-反物质不对称性从何而来？
- 暗物质的本质是什么？
- ...

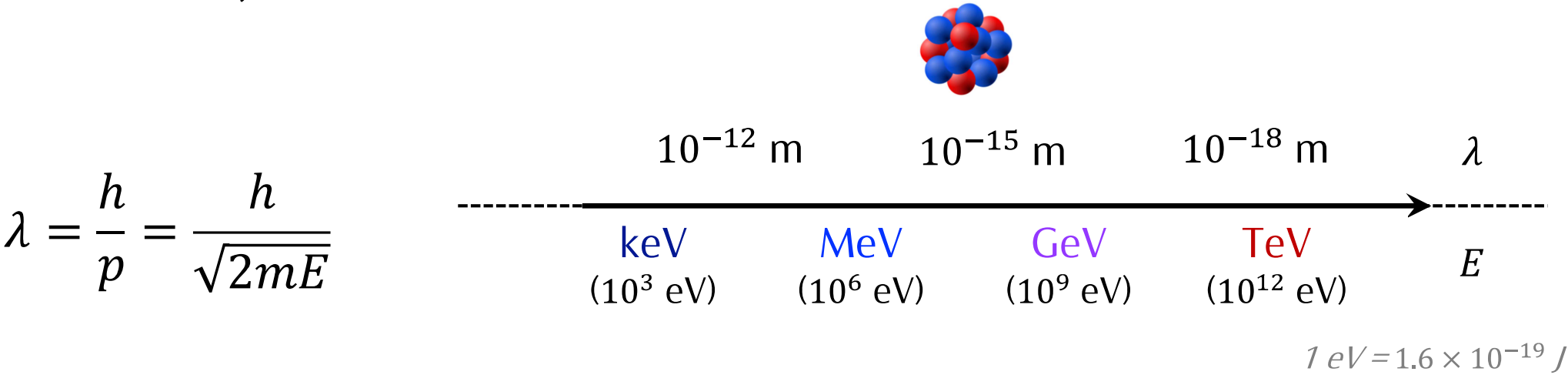


标准模型必然不是终极理论！



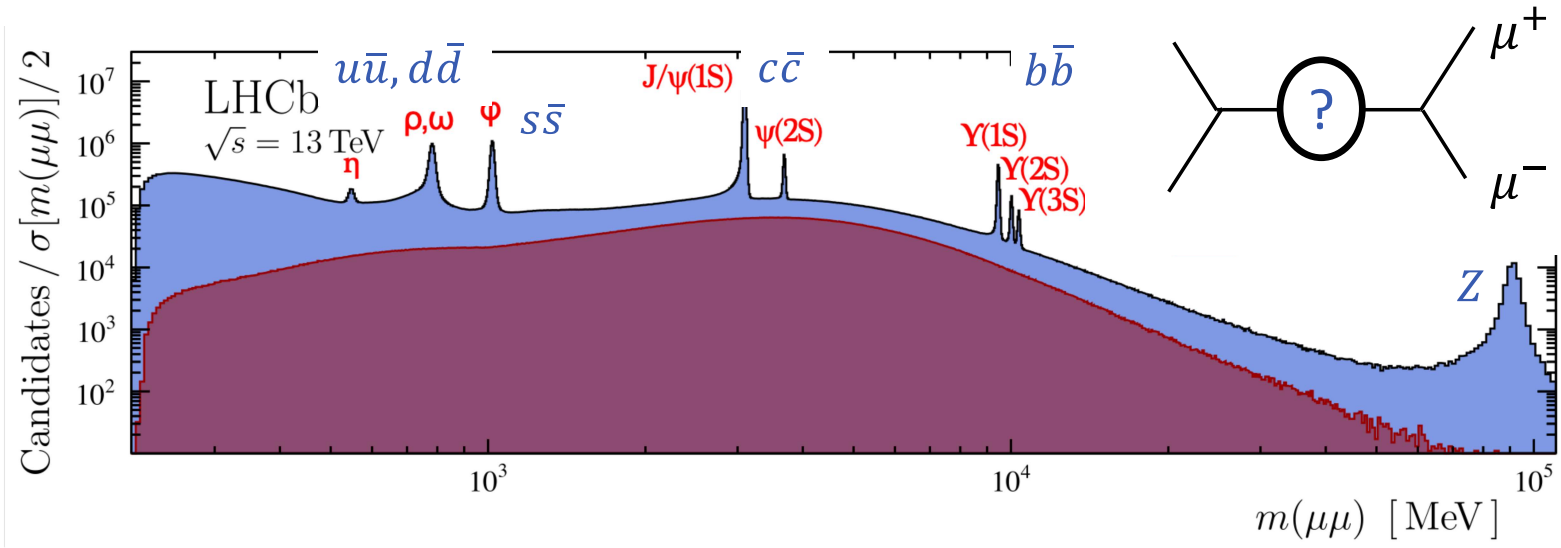
为什么需要高能粒子对撞

- 能量越高，可以探索到越小的尺度



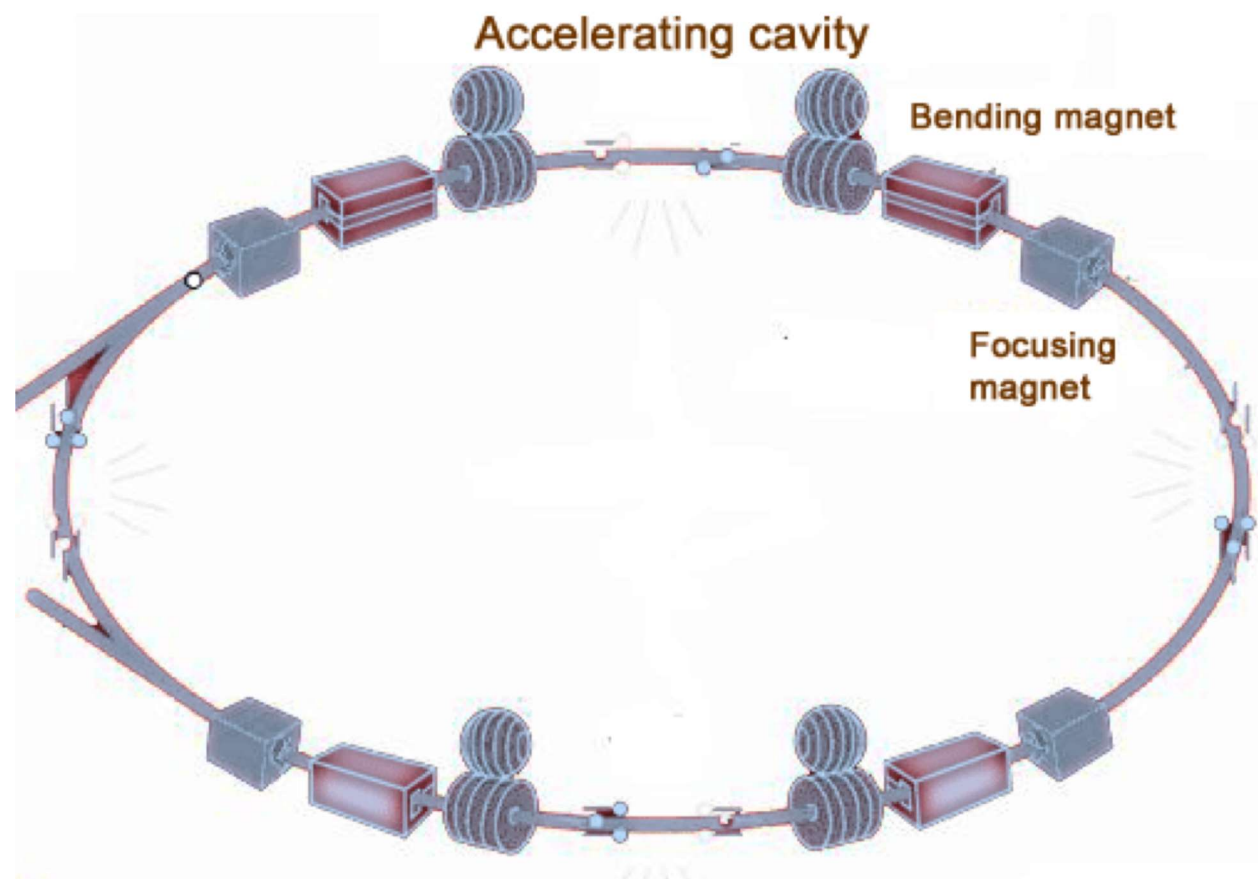
- 高能标下的新粒子和新现象

$$E = m_0 c^2$$



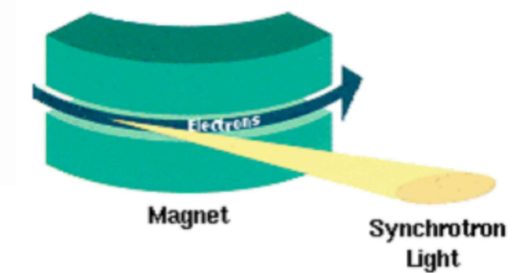
粒子加速器

- 粒子加速器：提供高能粒子束流 (e, p, γ , n, ...)
 - 核物理与粒子物理
 - 材料、生物、化学
 - 医学诊断和治疗



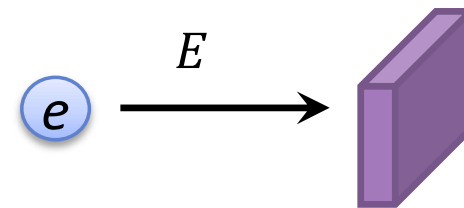
同步辐射

$$\text{能损} \propto \gamma^4 = \left(\frac{E}{m_0 c^2} \right)^4$$



从加速器到对撞机

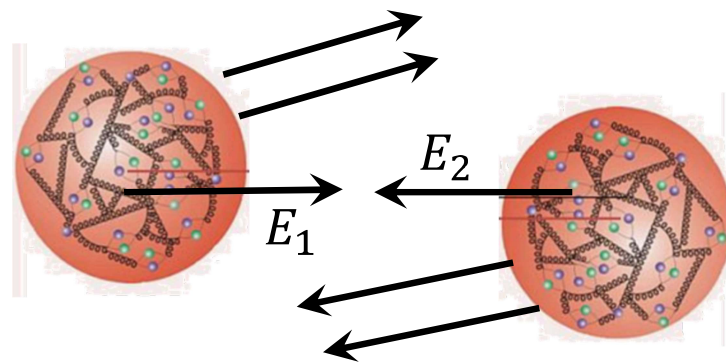
固定靶实验



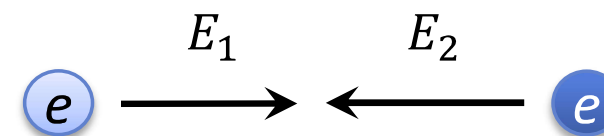
质心能量

$$\sim \sqrt{2mE}$$

强子对撞



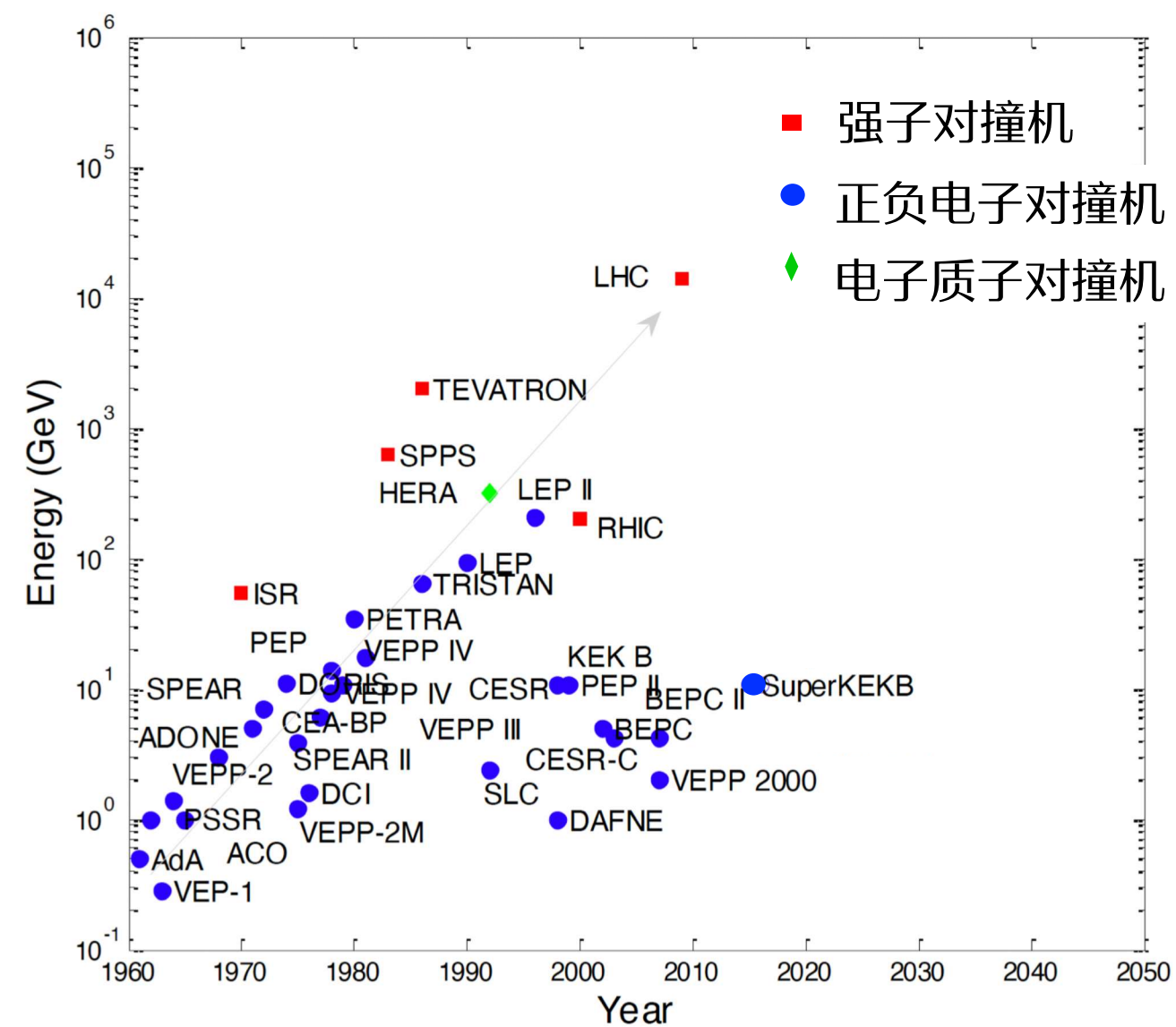
电子对撞



$$\sim 2\sqrt{E_1 E_2}$$

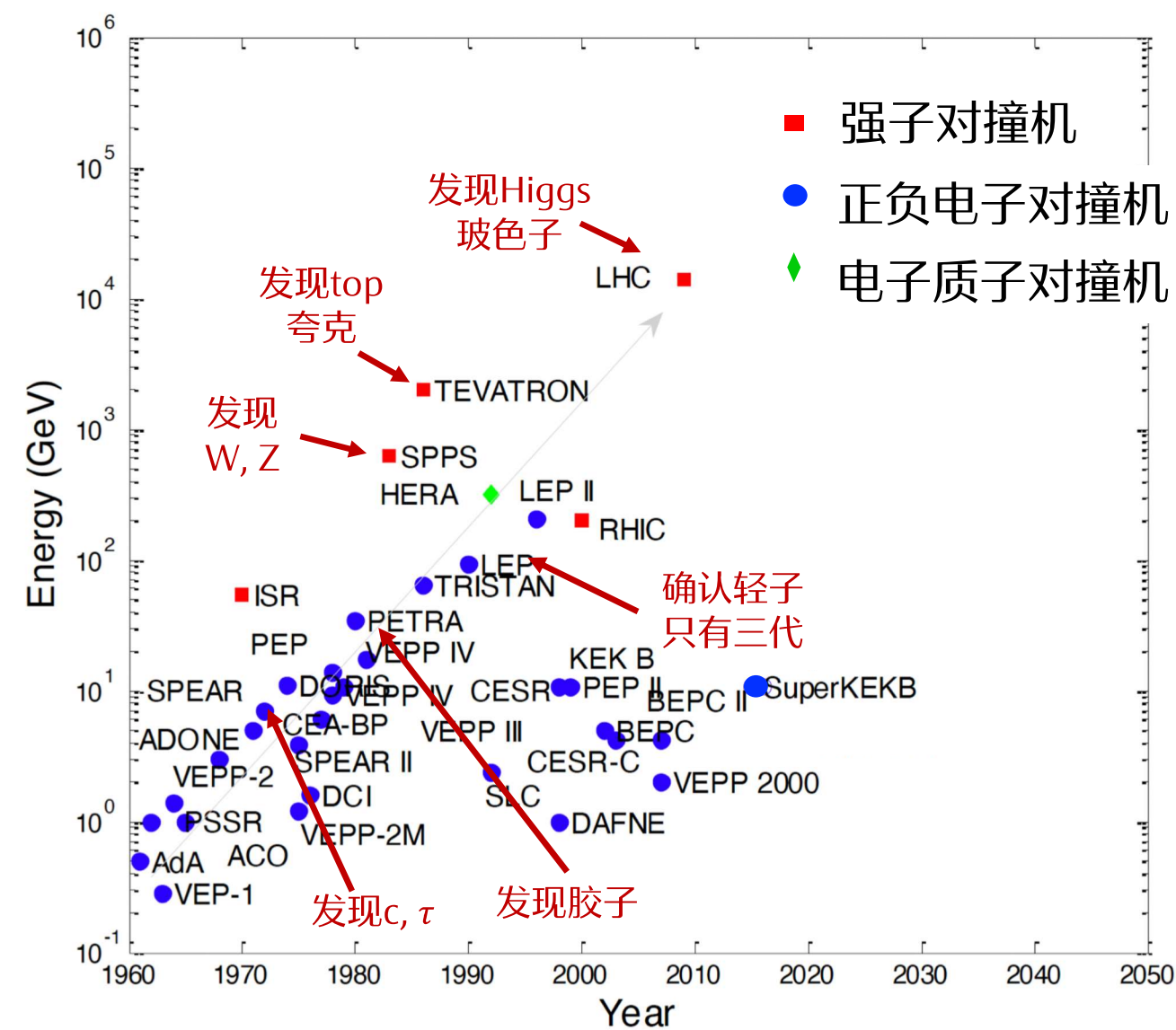
对撞机的历史

粒子物理发展的历史，也是一部不断探索高能量前沿的历史



对撞机的历史

■ 粒子物理发展的历史，也是一部不断探索高能前沿的历史



亮度

- 不仅需要高能量，也需要高亮度！

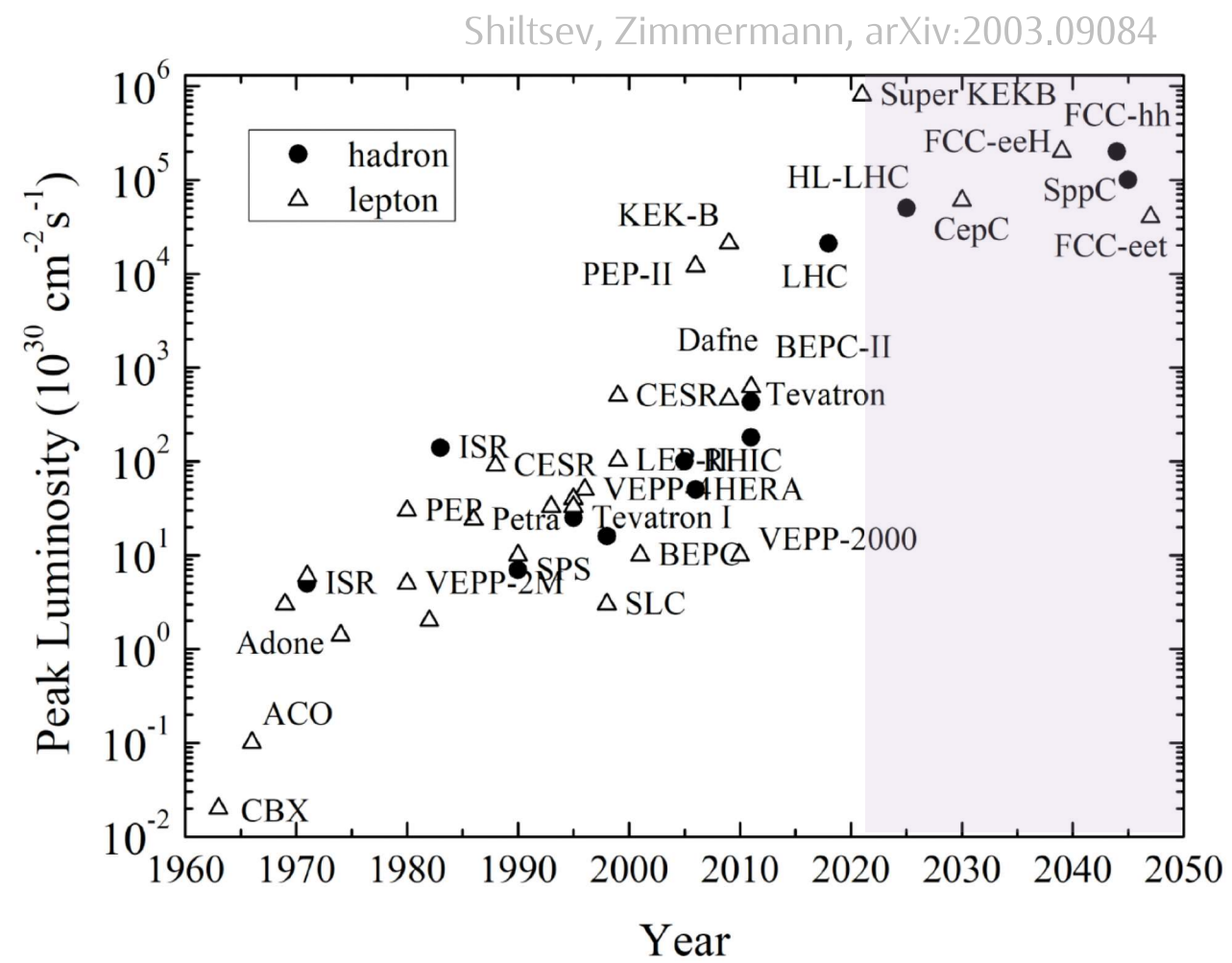
$$N = \sigma \cdot \mathcal{L} \cdot t$$

事例数

反应截面
(取决于物理过程)

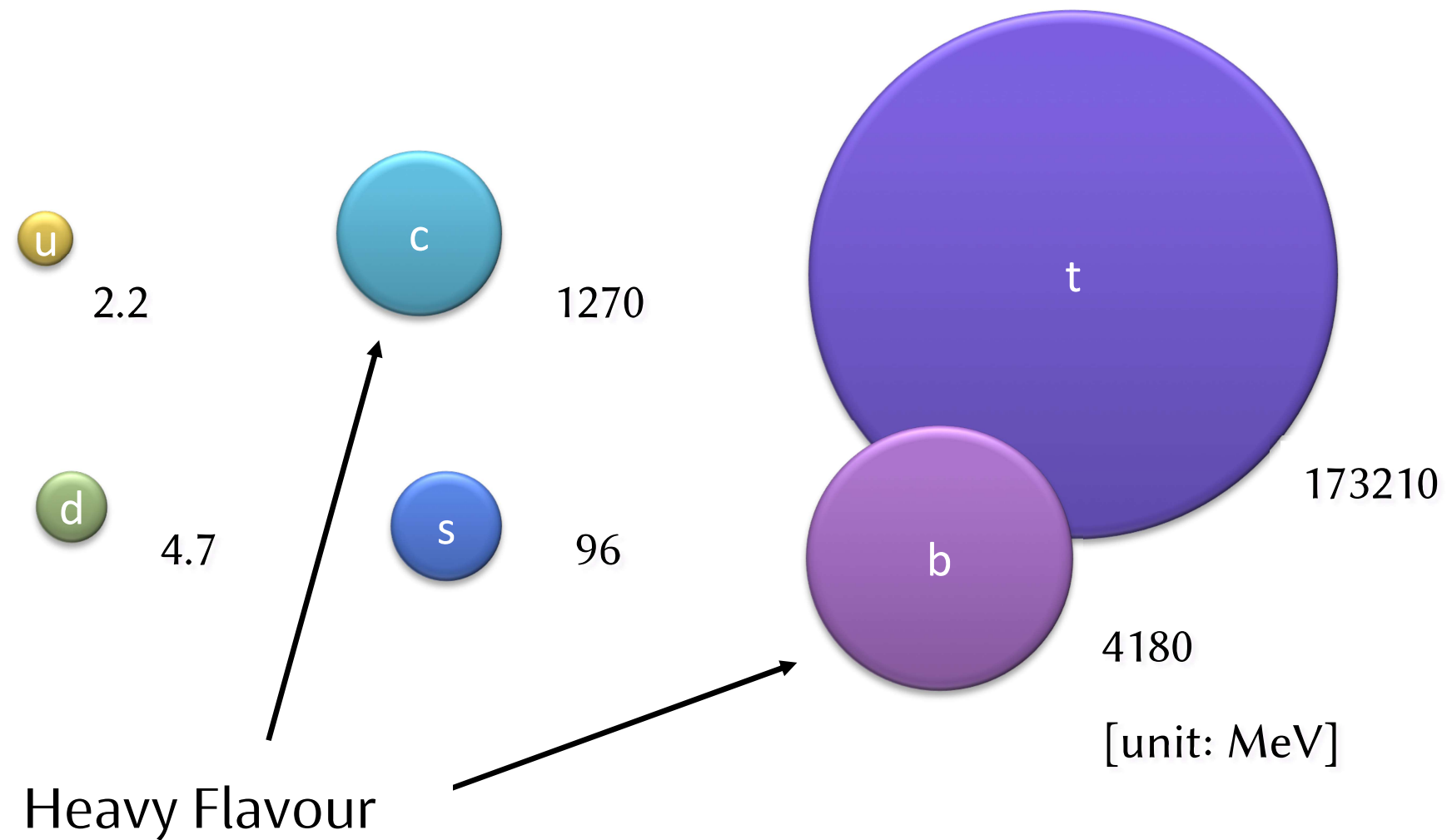
亮度
(取决于加速器性能)

时间



味物理的重要问题

- 为什么标准模型中有且只有三代夸克？为什么质量等级差这么多？



味物理的重要问题

- 为什么标准模型中有且只有三代夸克？为什么质量等级差这么多？
- CKM 矩阵：描述 up-type (u, c, t) 与 down-type (d, s, b) 夸克弱相互作用耦合强度；CKM 参数是如何决定的？

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9705 - 0.9770 & 0.21 - 0.24 & 0 - 0.014 \\ 0.21 - 0.24 & 0.971 - 0.973 & 0.036 - 0.070 \\ 0 - 0.014 & 0.036 - 0.070 & 0.997 - 0.999 \end{pmatrix}$$

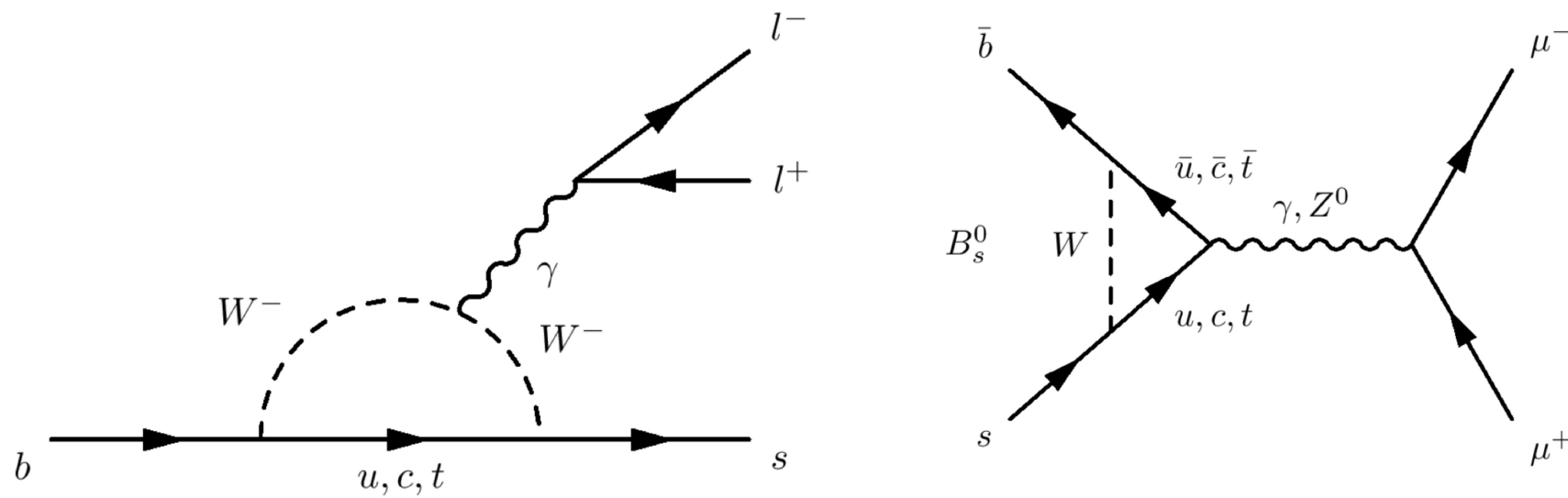
味物理的重要问题

- 为什么标准模型中有且只有三代夸克？为什么质量等级差这么多？
- CKM 矩阵的参数是如何决定的？
- CKM 机制中的CP破坏如何帮助我们理解宇宙中的正反物质不对称？

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

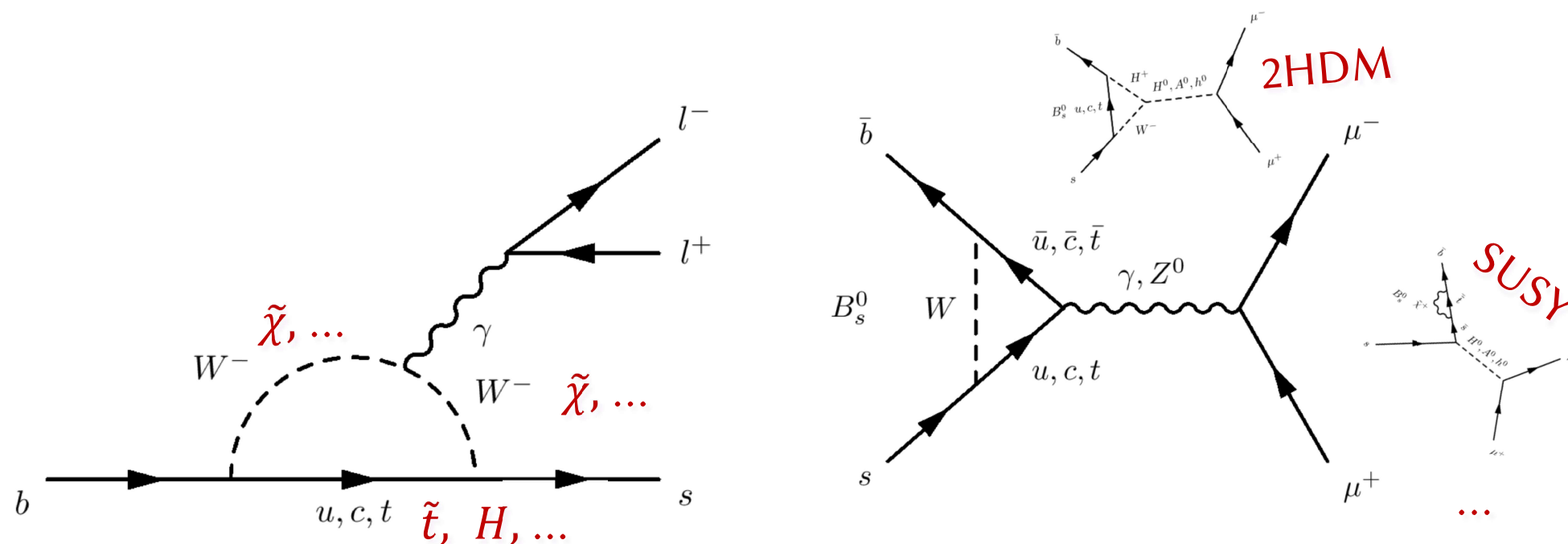
重味物理：探索新物理的手段

- 底夸克弱衰变中的不少过程在标准模型中是被压低的



重味物理：探索新物理的手段

- 底夸克弱衰变中的不少过程在标准模型中是被压低的
- 新物理的贡献可能变得显著！
- 对低能标过程的精确测量可以提供高能标下物理的信息

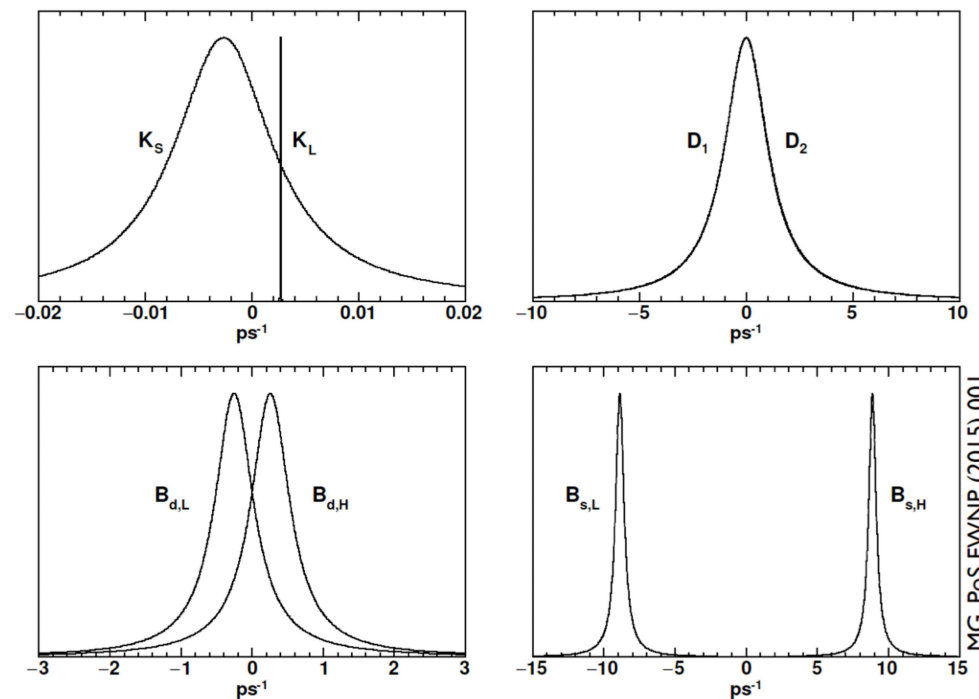


重味物理实验特点

底强子只能发生弱衰变

- 底强子寿命较长: $\tau(B^\pm) \sim 1.6 \text{ ps}$
=> **可观测**! 设法增大Boost以更好测量
- 各末态的分支比都较低

可观的 $B^0 - \bar{B}^0$ 振荡



$$|M_{L,H}\rangle = p|M^0\rangle + q|\bar{M}^0\rangle$$

Mass eigenstates Flavour eigenstates

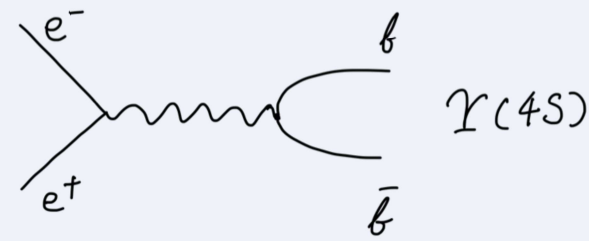
$$\Delta m = m_H - m_L$$

$$P(M^0 \rightarrow \bar{M}^0)(t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} [\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)]$$

重味强子的产生

■ B工厂 / 强子对撞 / Z工厂

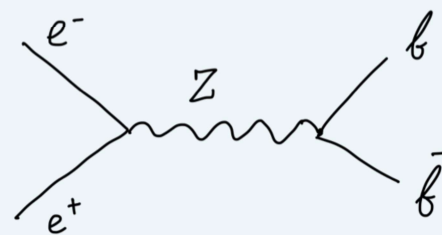
B 工厂



$$\sigma(B\bar{B}) \sim 1 \text{ nb}$$

- 正负B介子对
- 非对称束流能量
- $E_{\text{beam}} + \text{tag B}$ 约束
- 本底干净

Z 工厂

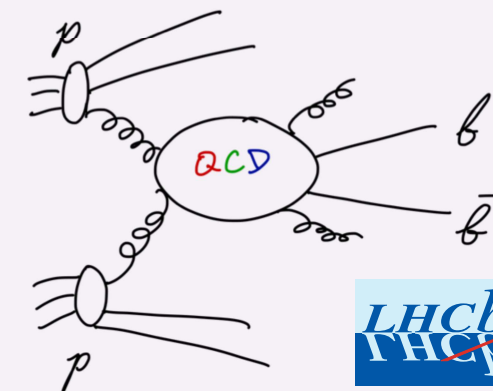


@LEP

$$\sigma(Z \rightarrow b\bar{b}) \sim \mathcal{O}(10^{-1}) \text{ nb}$$

- 多种b强子:
 $B, B_s, B_c, \Lambda_b, \Xi_b, \dots$
- $E_{\text{beam}} + \text{tag B}$ 约束
- 本底干净

高能强子对撞

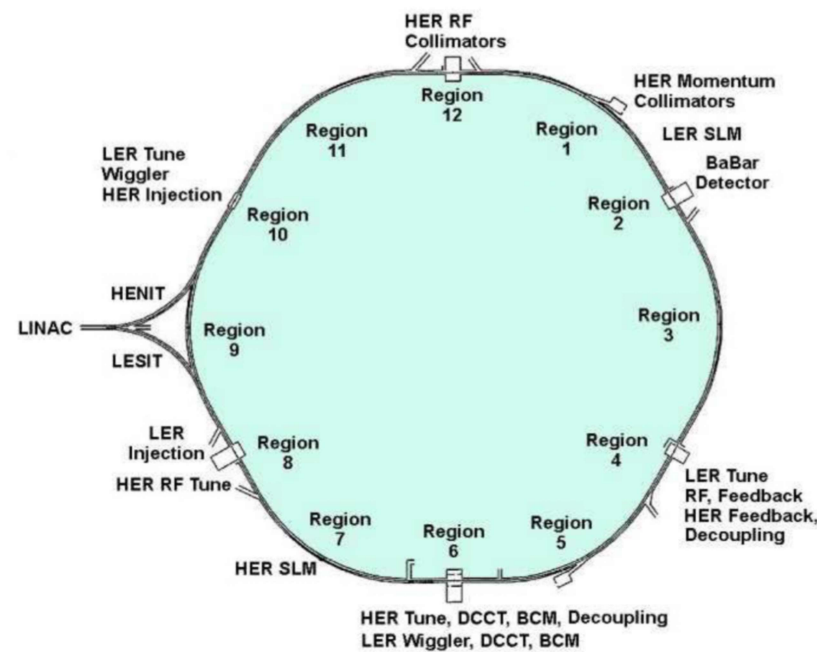


@LHC



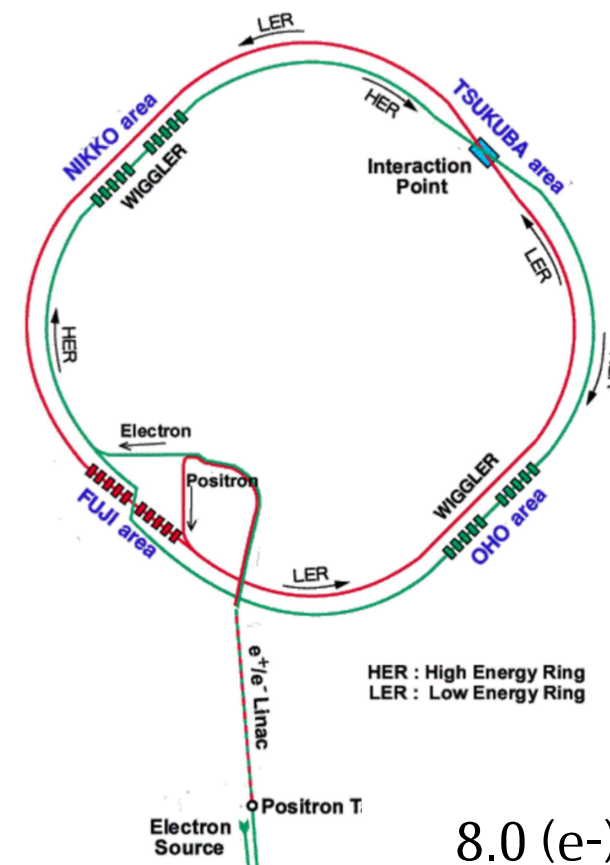
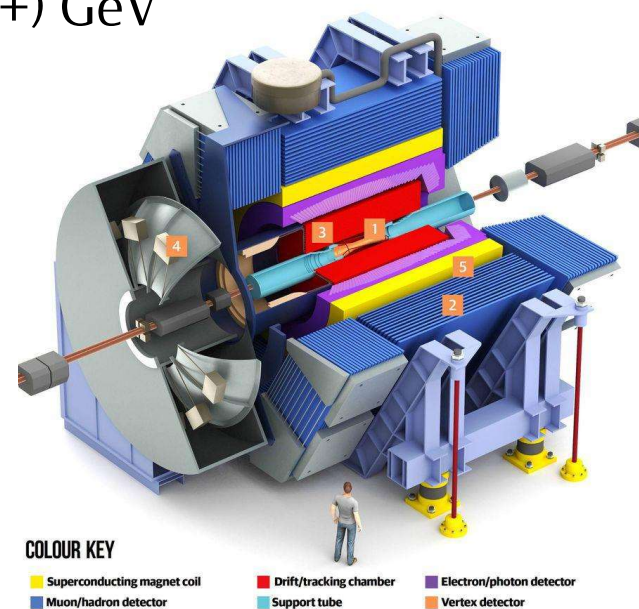
$$\sigma(b\bar{b}) \sim \mathcal{O}(10^2) \mu\text{b}$$

- 产生截面大
- 多种b强子
- 通常很大boost



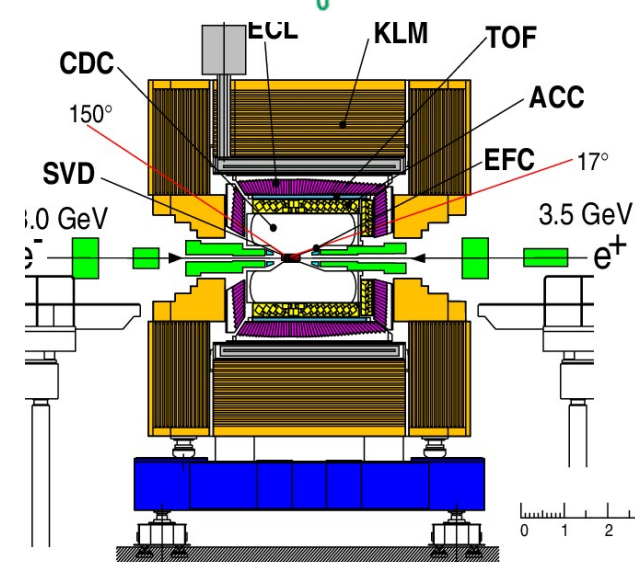
PEP-II @ SLAC
9.0 (e⁻)/ 3.1 (e⁺) GeV

~ 470 M $B\bar{B}$

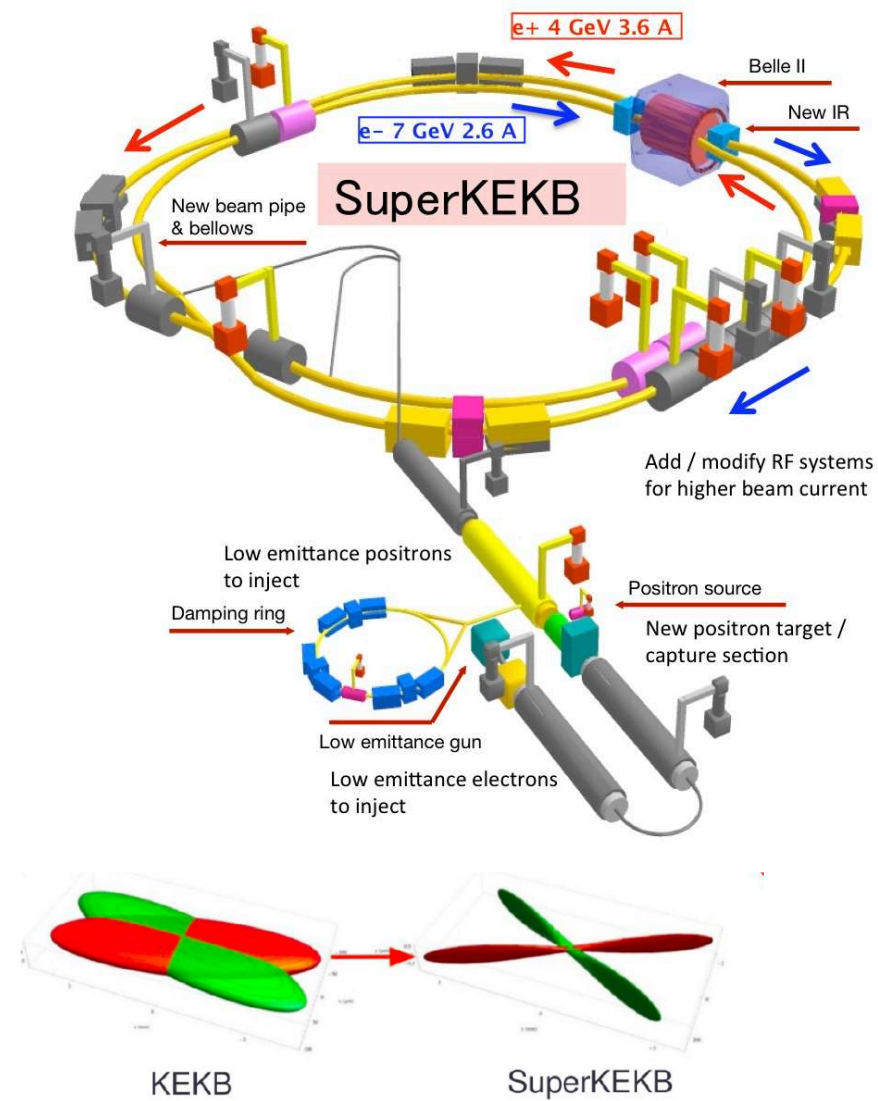


KEKB @ KEK
8.0 (e⁻)/ 3.5 (e⁺) GeV

~ 770 M $B\bar{B}$

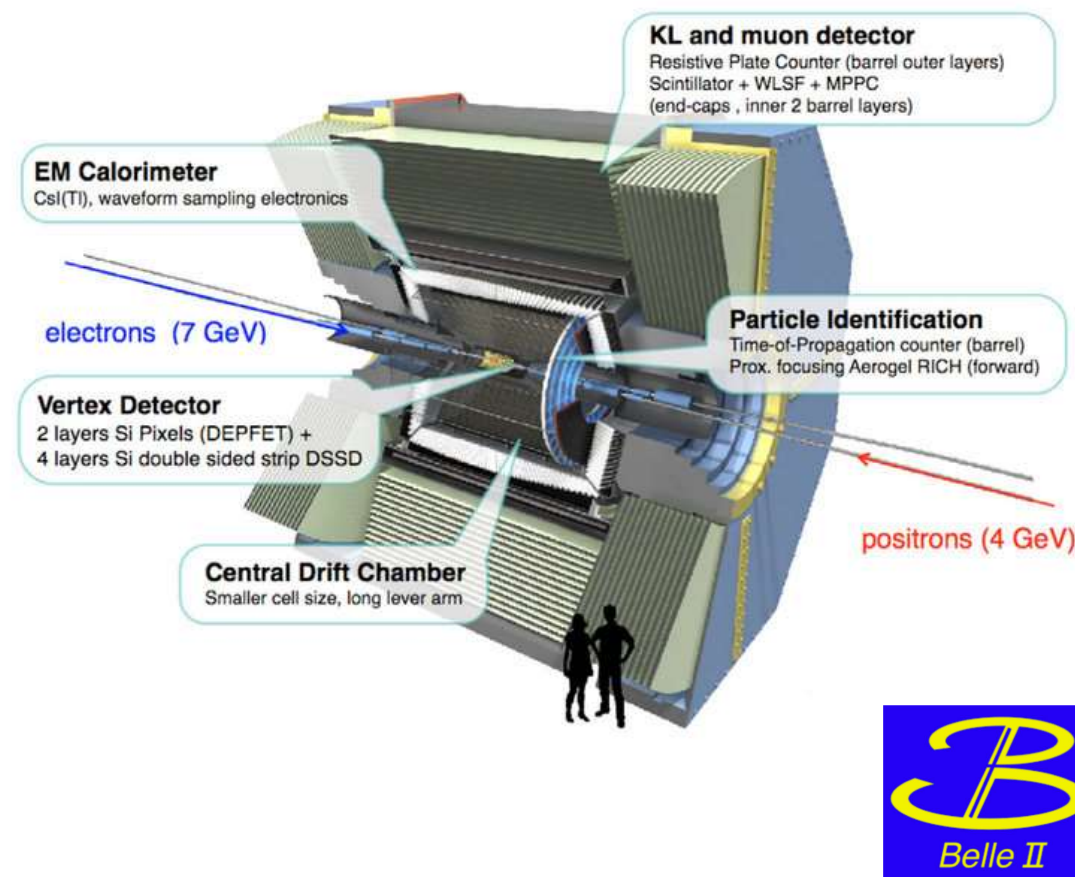


SuperKEKB 和 Belle II

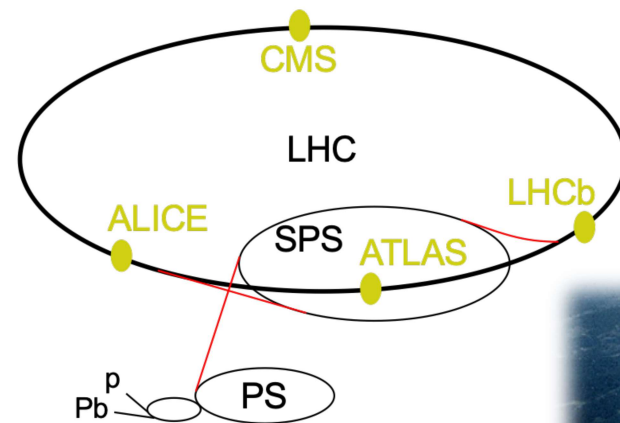


“nano-beam” scheme
Beam squeezing: x20 smaller at IR

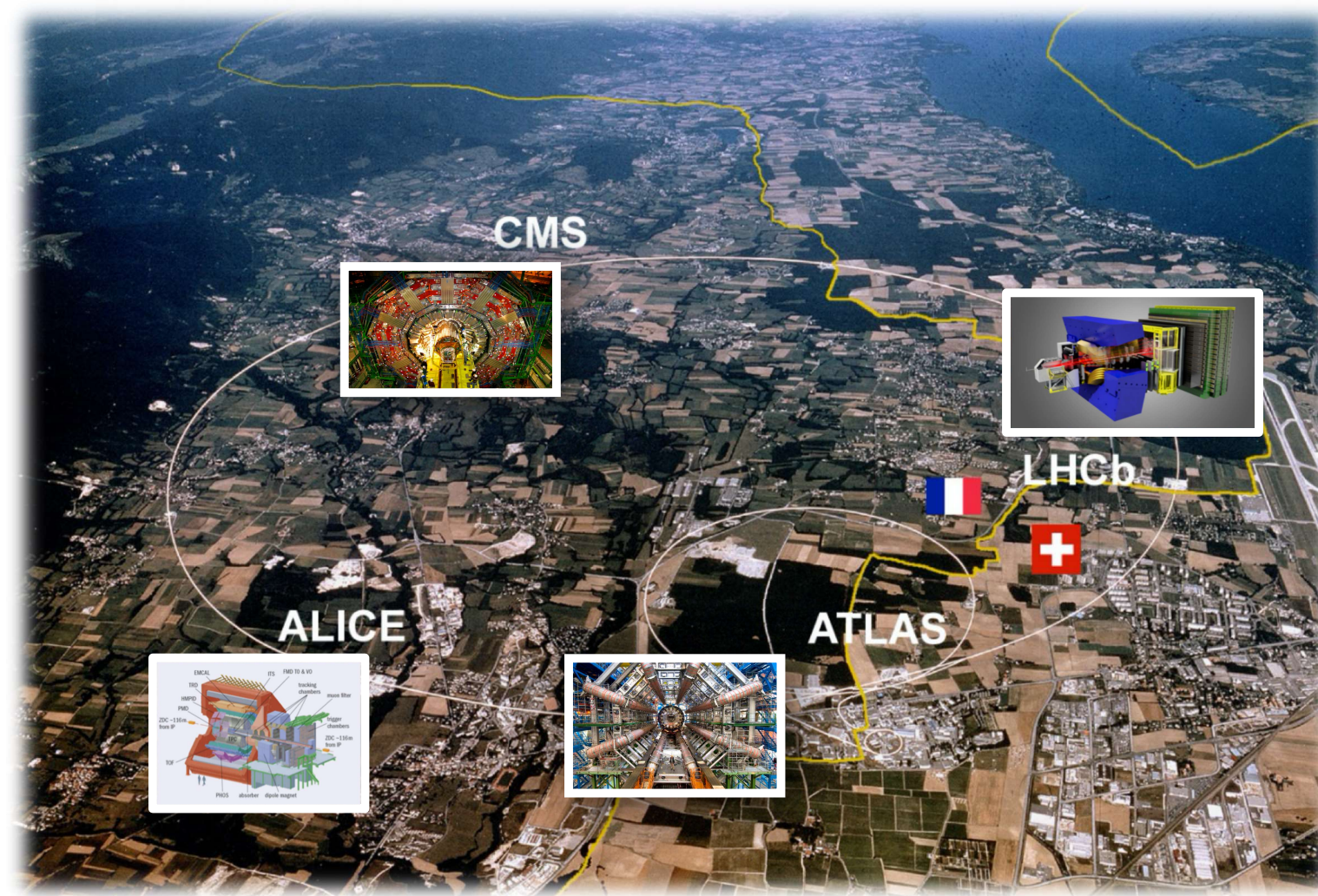
$\mathcal{L}: 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
 $\rightarrow 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
 计划到2025年取数 50 ab^{-1}
 (Belle $\times 50$)



大型强子对撞机

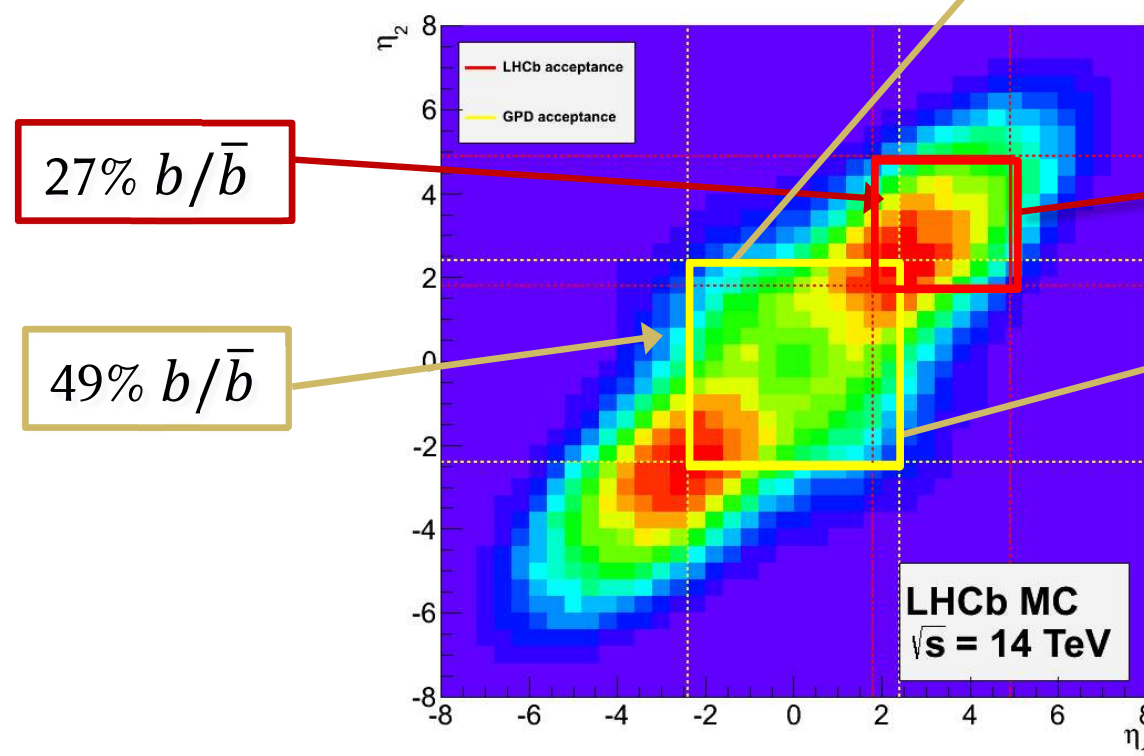
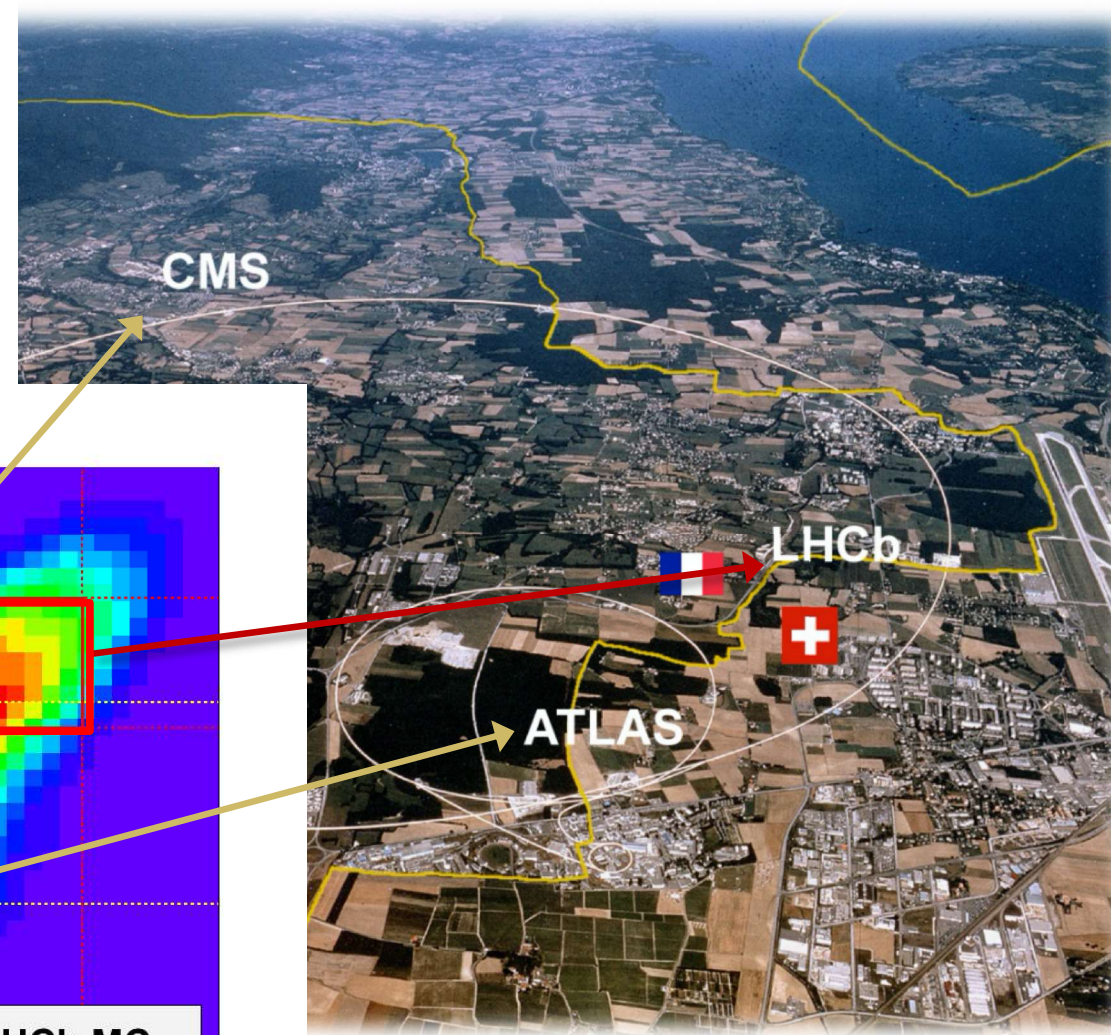
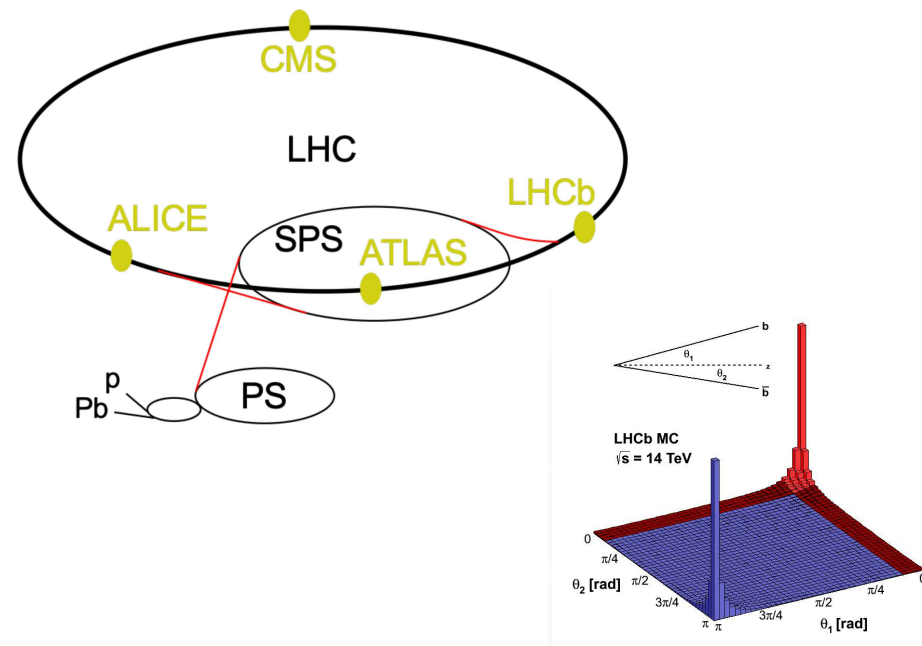


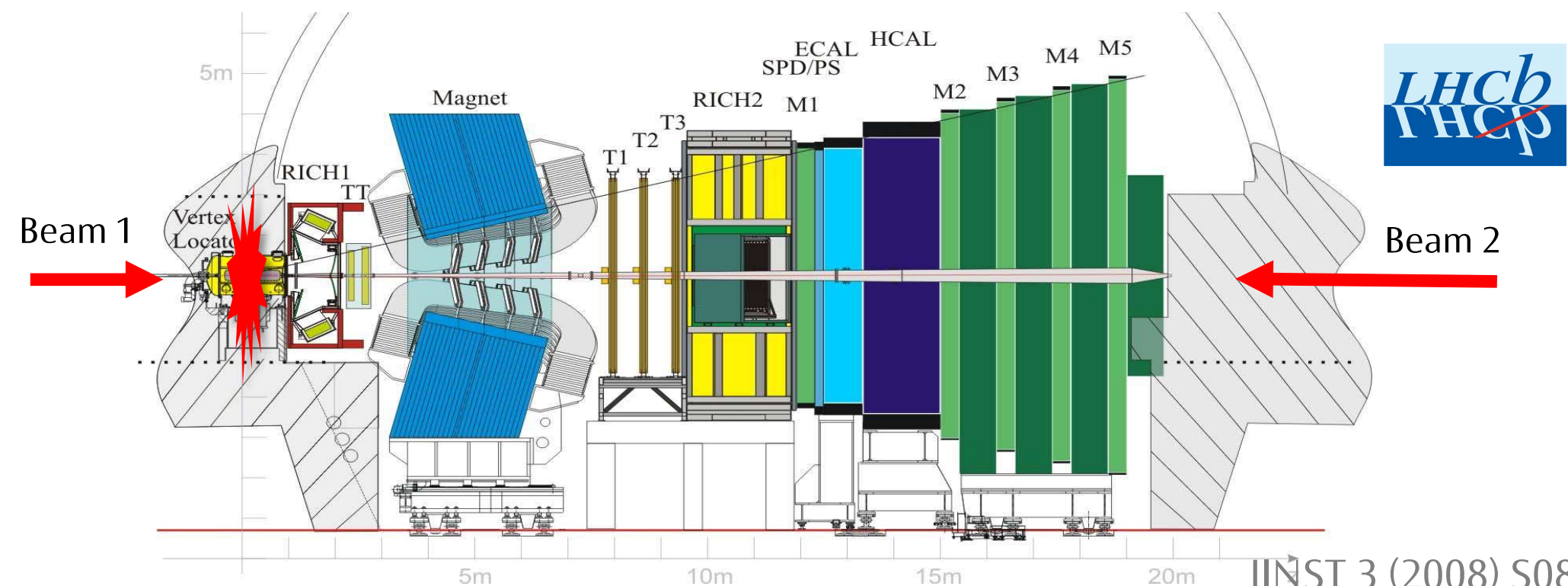
pp 对撞 / 质心能量 13 TeV / 周长 27km



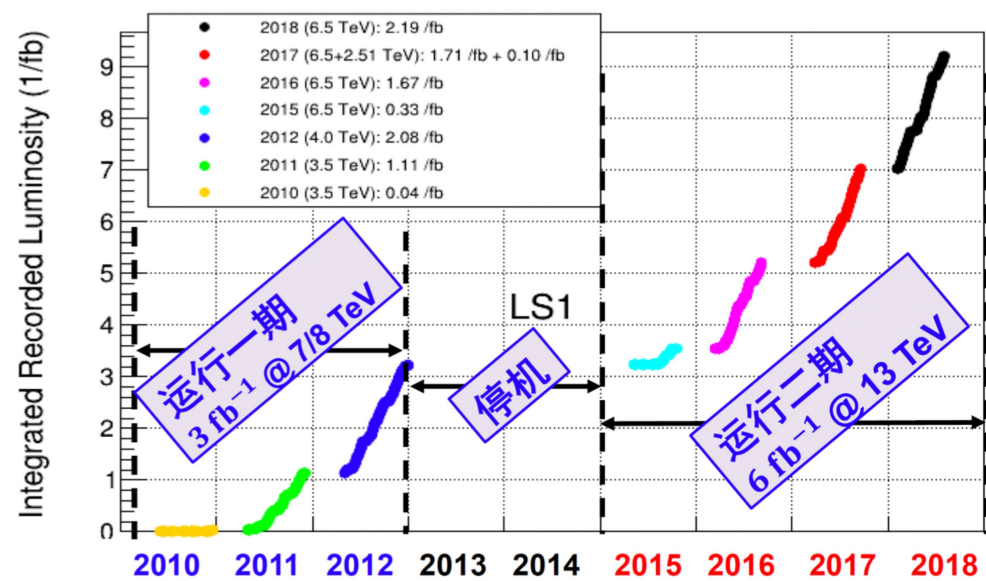
大型强子对撞机

$$\sigma(b\bar{b}): 200\sim 500 \mu\text{b} @ 7\text{-}14 \text{ TeV}$$



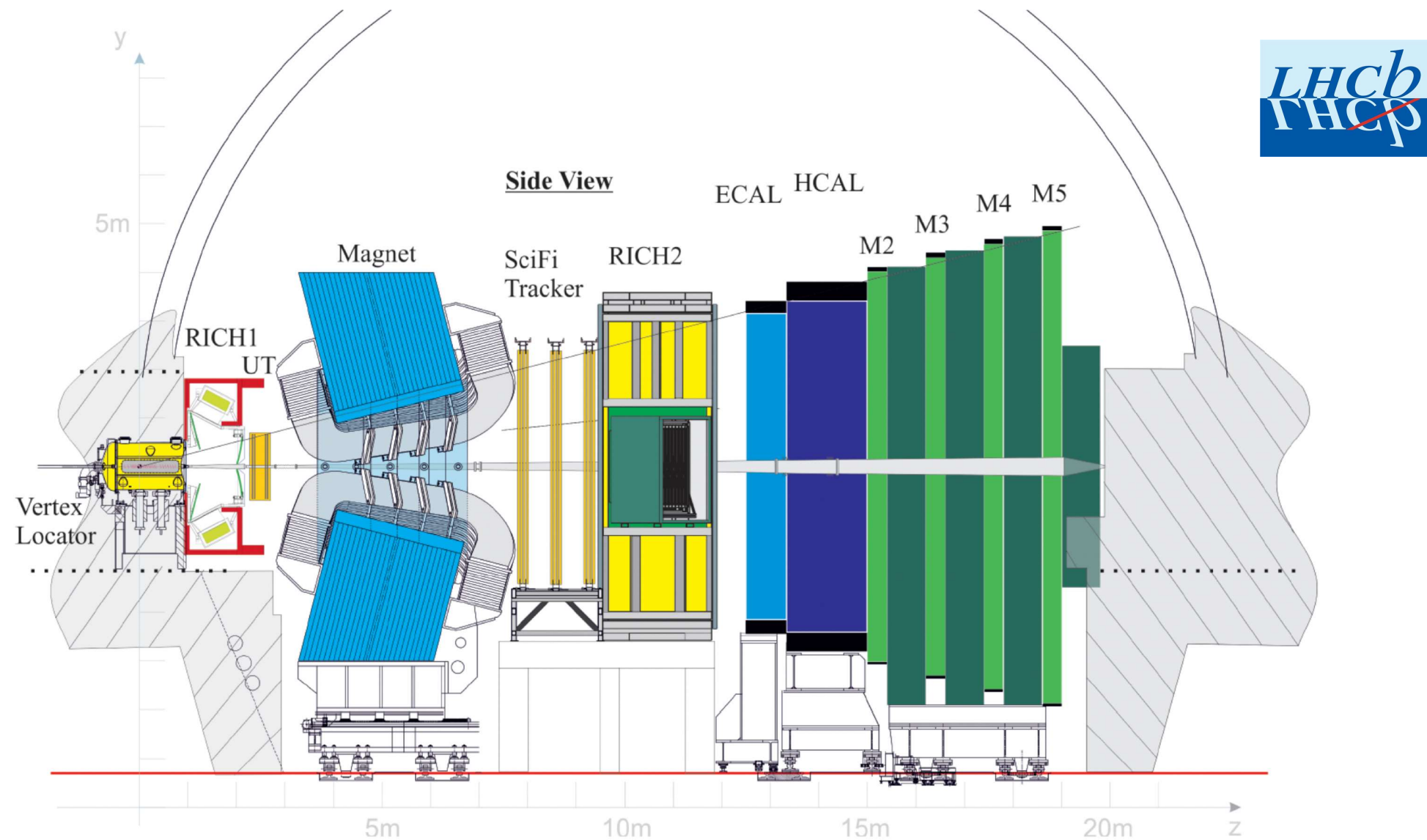


JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022



Vertex res.	$\sigma_{IP} = 20 \mu m$
Time res.	$\sigma_{\tau} = 45 fs$ for $B_s^0 \rightarrow J/\psi \phi$ or $D_s^+ \pi^-$
Momentum res.	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass	$\sigma_m = 8 MeV/c^2$ for $B \rightarrow J/\psi X$
Hadron ID	$\epsilon(K \rightarrow K) \sim 95\%$ mis-ID $\epsilon(\pi \rightarrow K) \sim 5\%$
Muon ID	$\epsilon(\mu \rightarrow \mu) \sim 97\%$ mis-ID $\epsilon(\pi \rightarrow \mu) \sim 1 - 3\%$
ECAL res.	$\Delta E/E = 1\% \oplus 10\%/\sqrt{E (GeV)}$

LHCb Upgrade I



arXiv:2305.10515

$\mathcal{L}: 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 计划到2030年取数 50 fb^{-1} (~ 现有 $\times 5$)

寻迹和顶点重建

末态鉴别

味标记

数据处理

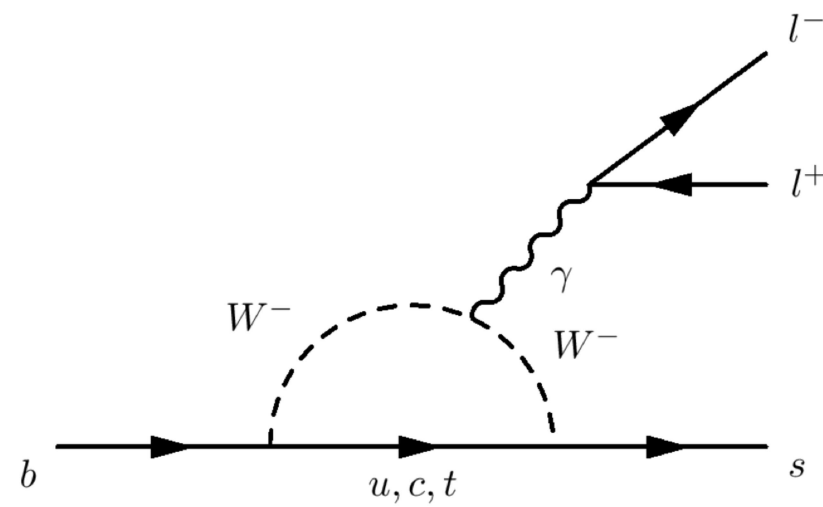
重味物理探测器的要素：以LHCB为例

探测器

- 探测收集对撞产物，测量物理性质，还原对撞时的物理过程

‘长寿命’ 粒子：
($\tau > \text{ns}$)

$e^{\pm}, \mu^{\pm},$
 $p, \pi^{\pm}, K^{\pm},$
 $\gamma, \dots$



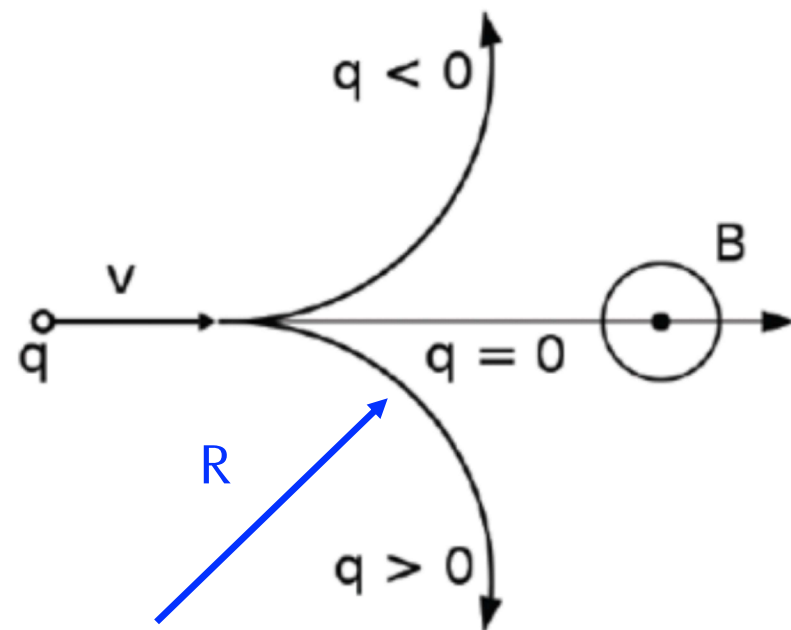
物理性质：

能量，
动量，
角度分布，
...



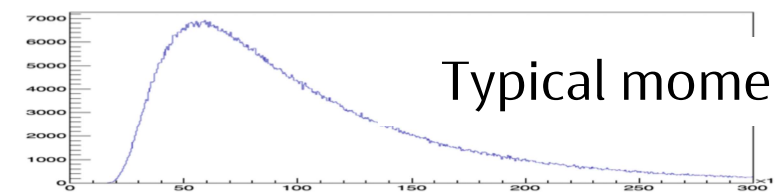
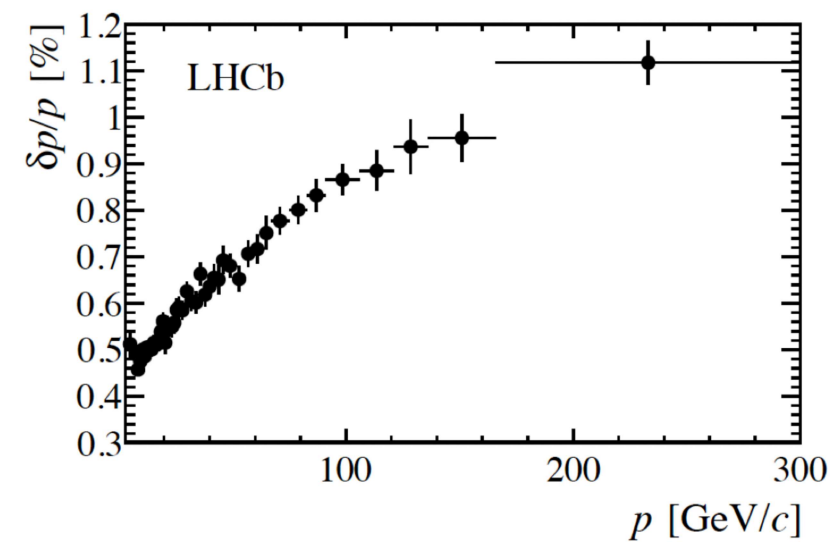
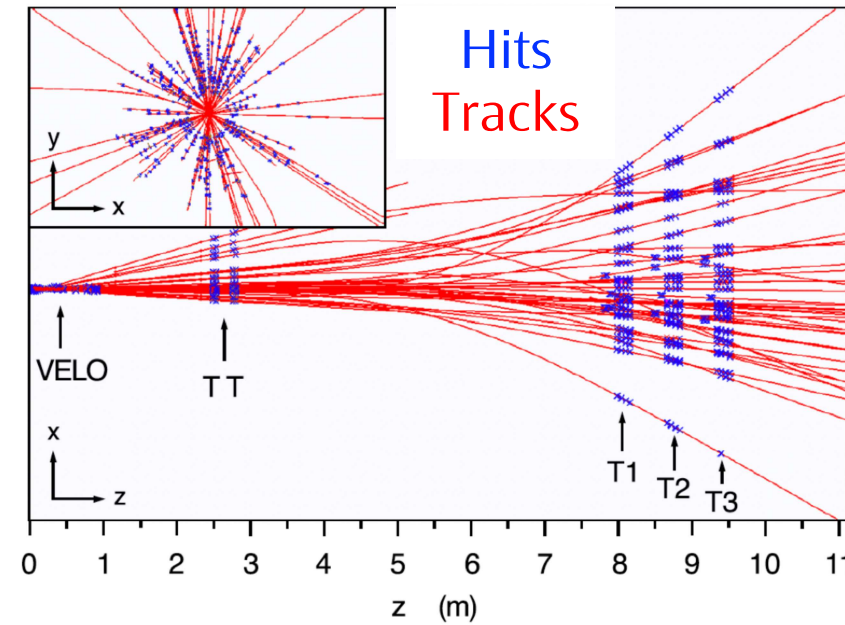
带电径迹重建

■ 磁场 + 径迹探测器



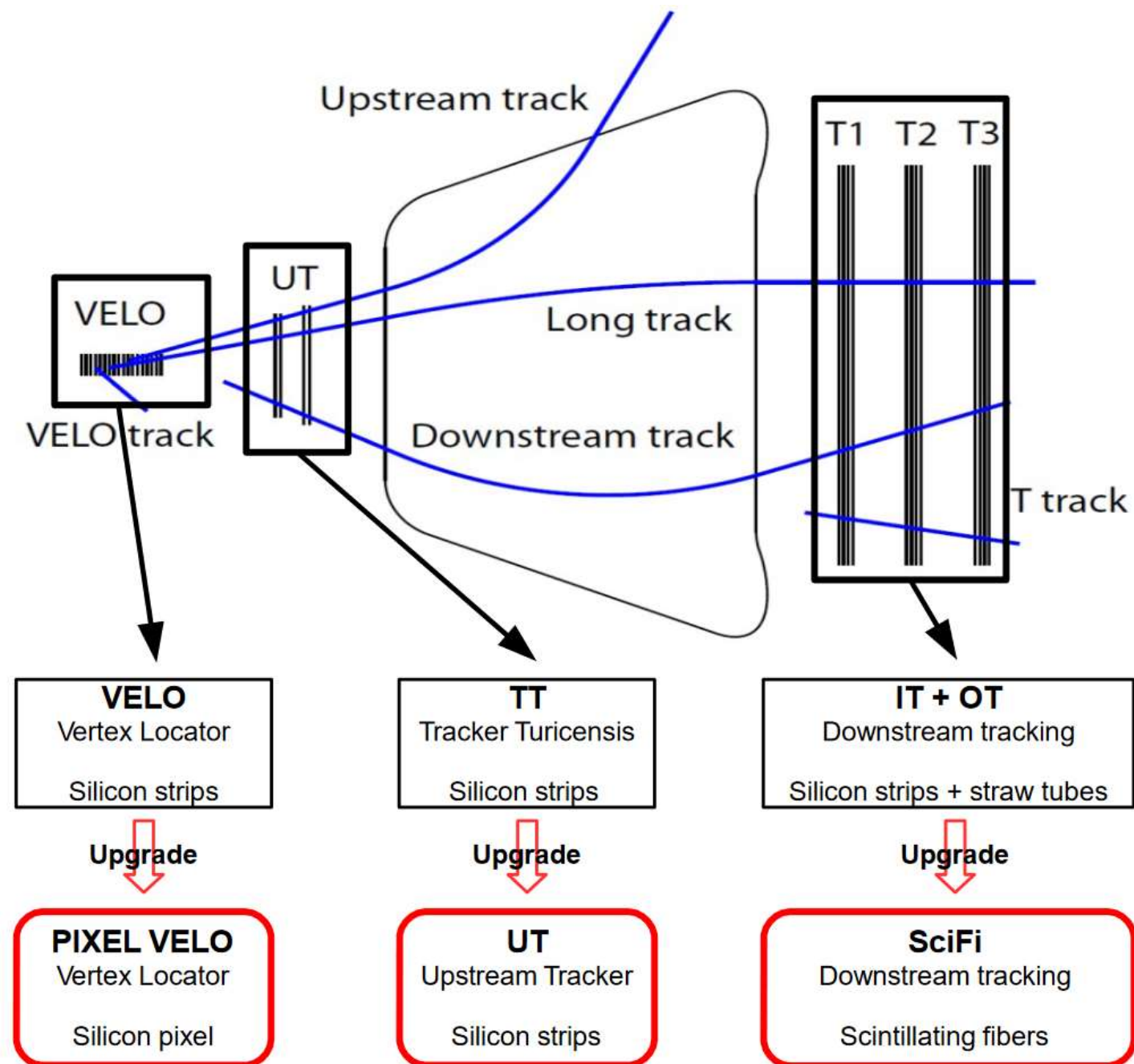
$$R = p / (q B)$$

偏转方向 → 电荷 q
偏转半径 → 动量 p



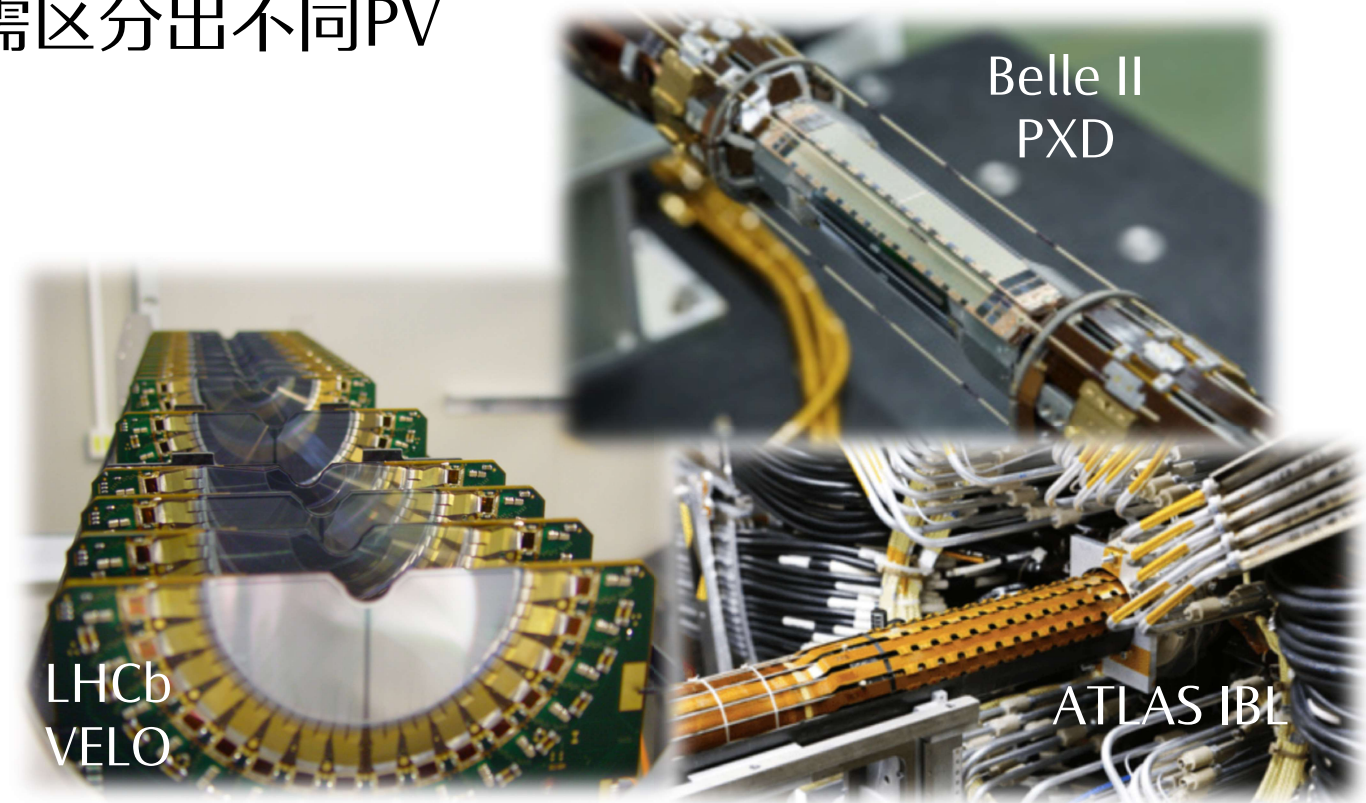
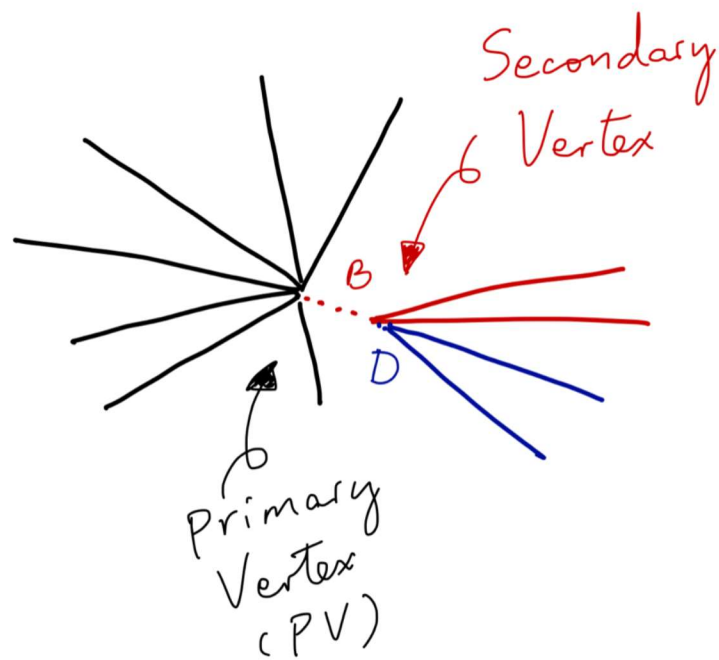
Typical momentum of selected B^+

LHCb径迹重建系统



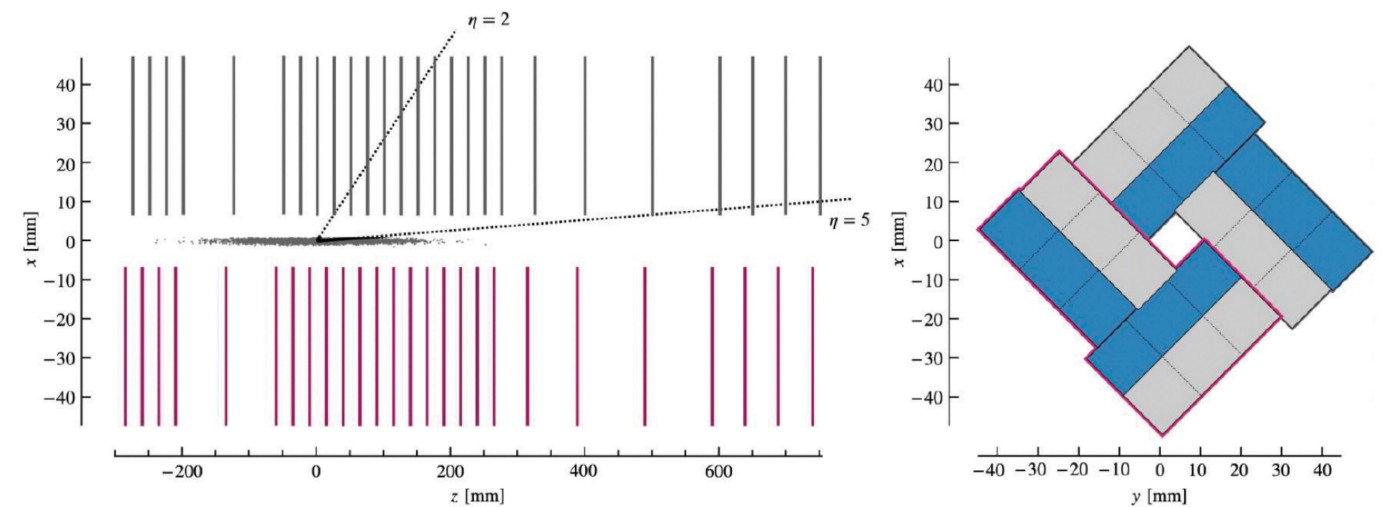
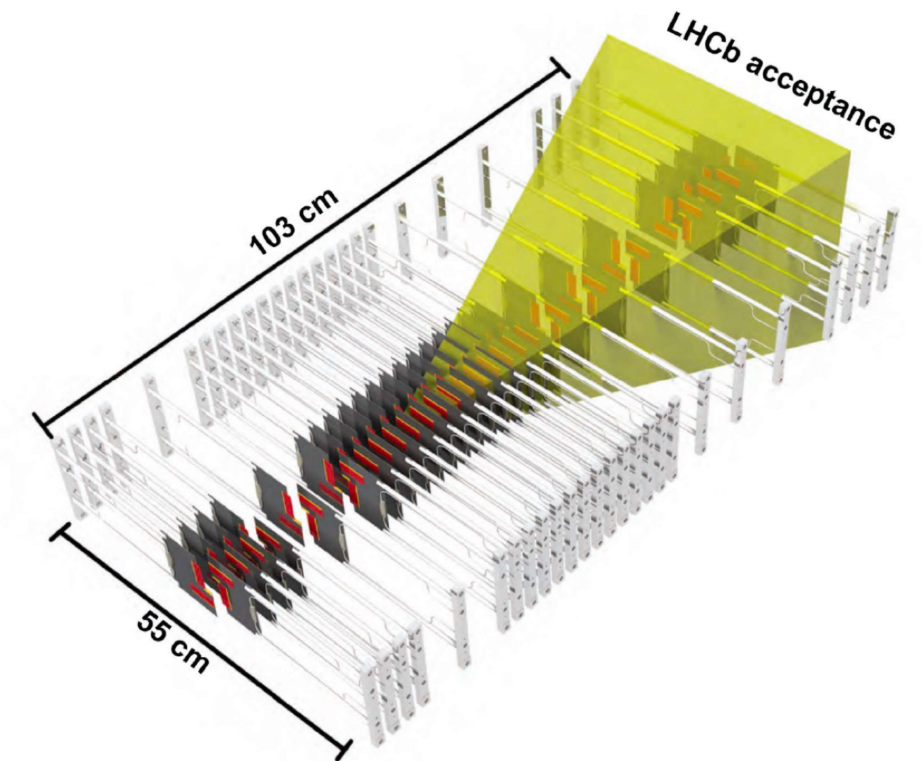
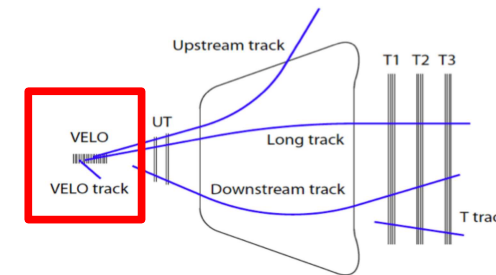
顶点重建

- 基态 B 介子弱衰变 $\tau(B) \sim 1.6 \text{ ps}$
 - 从产生（初级对撞顶点）到衰变（次级顶点）可飞行一段距离
 - 几百微米到几毫米，取决于boost
- 需要极高定位精度的径迹探测器重建出衰变顶点
 - 点定位精度100um以内，甚至可达几微米
- 如果存在事例堆积(pile-up)，顶点探测器还需区分出不同PV



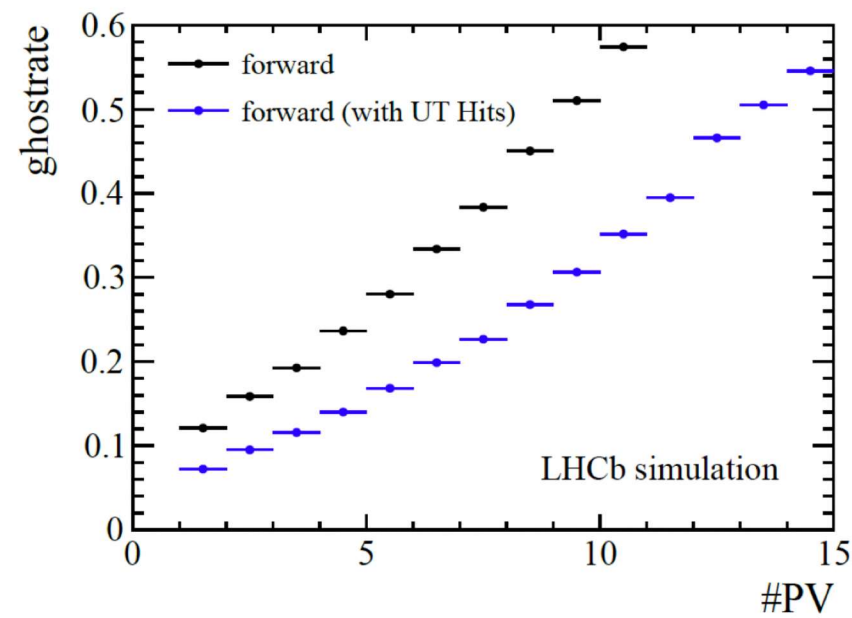
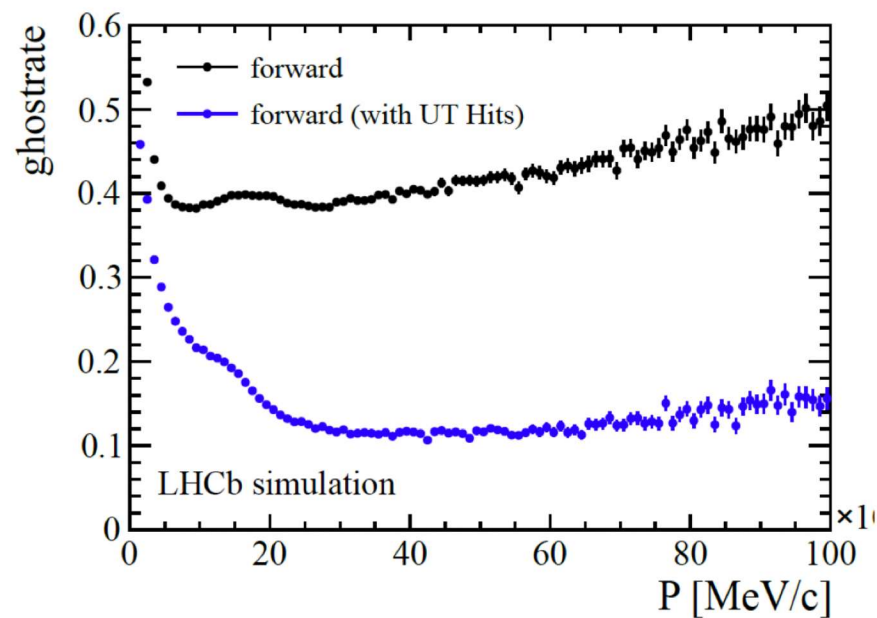
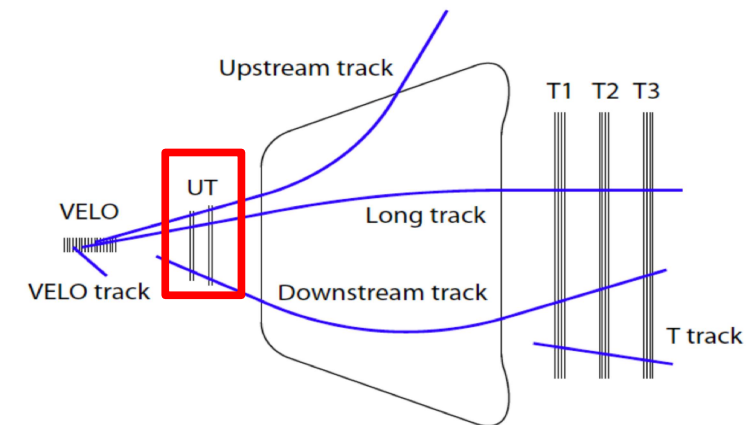
VELO 顶点探测器

- 左右两半，束流稳定时方可推入
- 离束流最接近只有 5.1mm
- 由硅微条升级为硅像素探测器
 - 碰撞参数IP分辨率提高/图像识别更容易
 - $\Phi_{max} \sim 7 \times 10^{14} \rightarrow 8 \times 10^{15} n_{eq} \text{ cm}^{-2}$
 - 材料减少: RF foil 150um; 微通道制冷



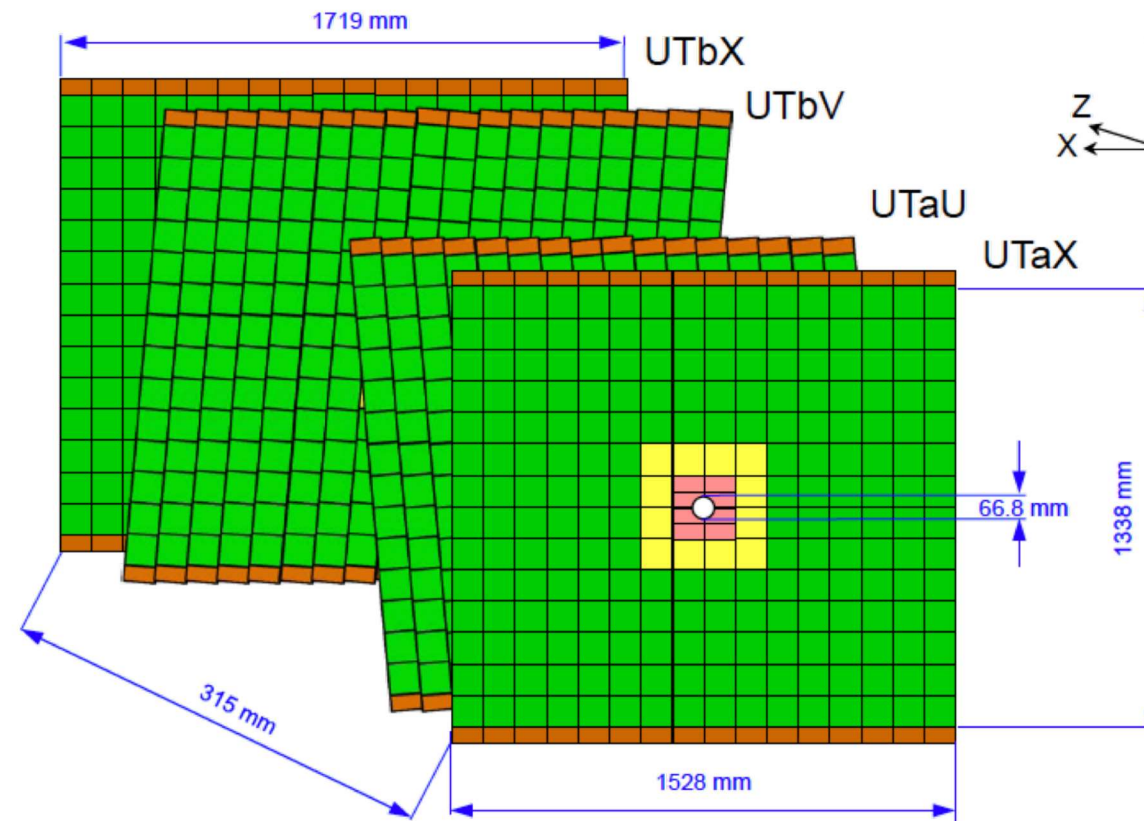
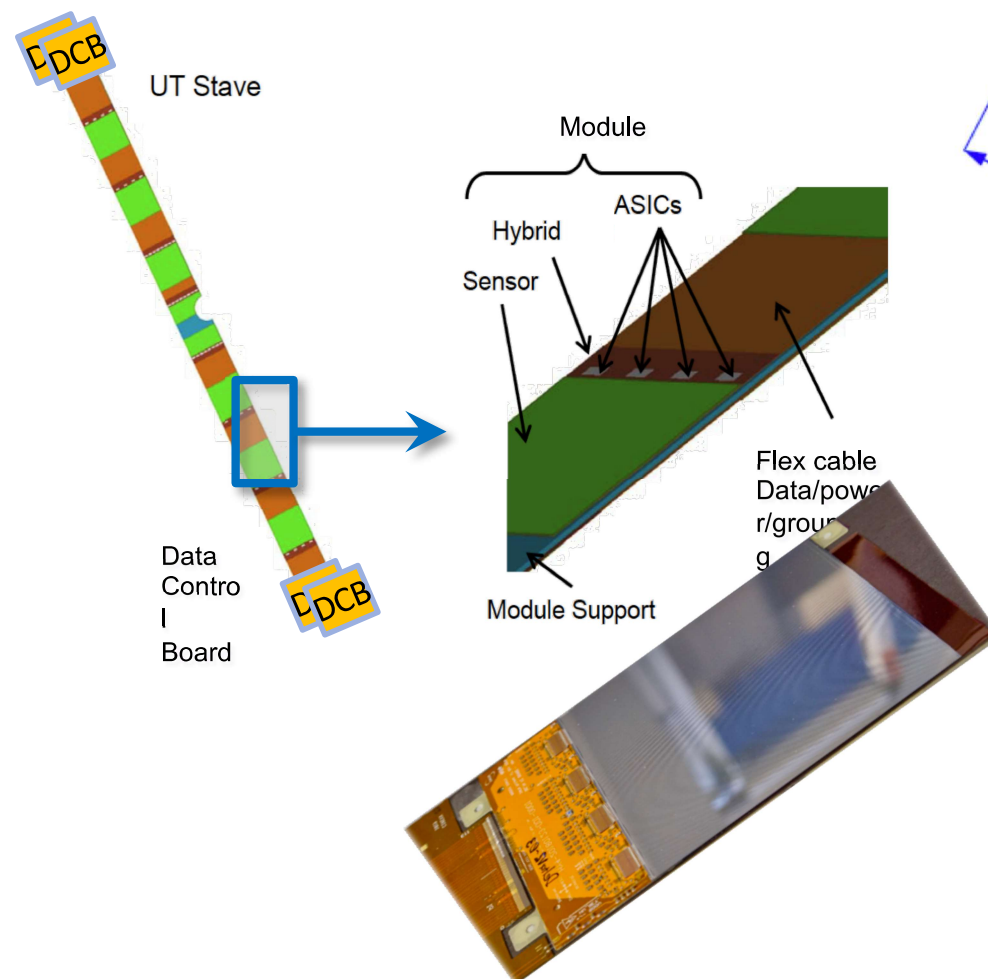
UT 上游径迹探测器

- 提高径迹重建效率加快寻迹速度
 - K_S, Λ 等粒子寿命长, 可能飞出VELO才衰变
- 加快寻迹速度
 - 减少“鬼径迹”, 加快径迹重建和触发算法



UT 上游径迹探测器

- 基于硅微条传感器
- 中国组承担研发、安装任务

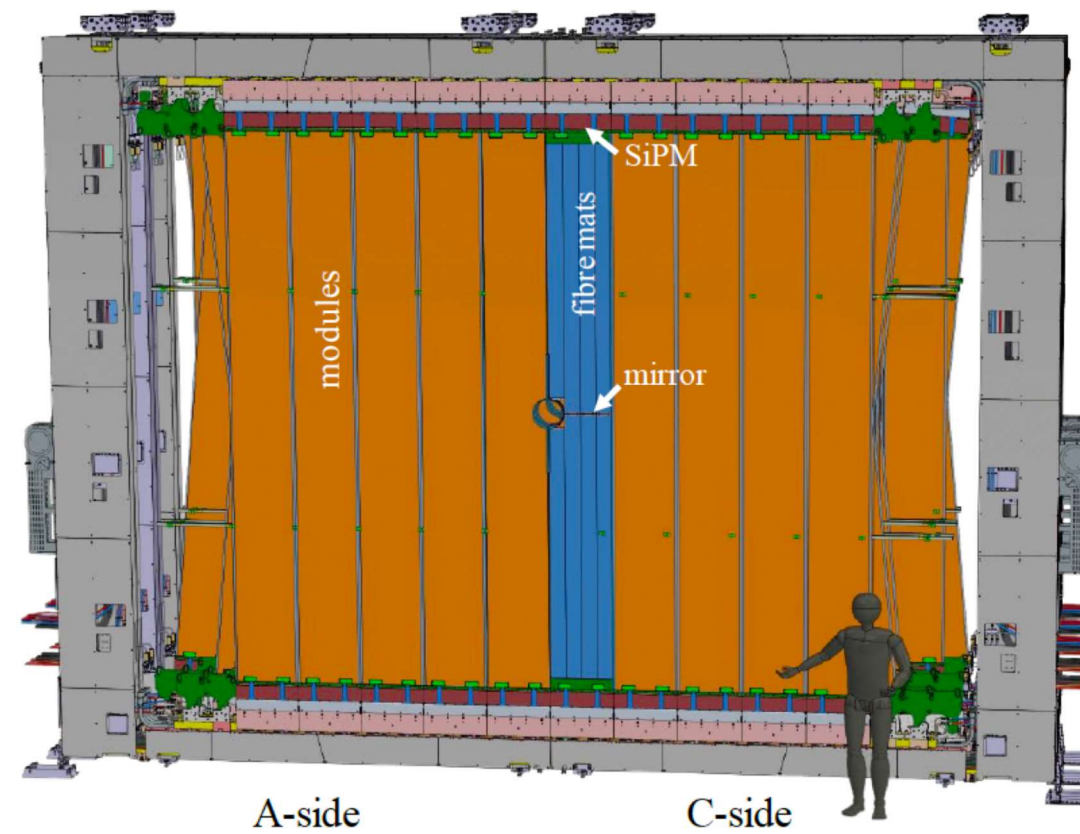
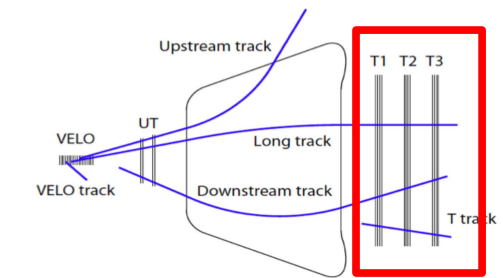


Sensor	Type	Pitch, μm	Length, mm	Strips	Sensor #
A	p-in-n	187.5	98	512	888
B	n-in-p	93.5	98	1024	48
C	n-in-p	93.5	49	1024	16
D	n-in-p	93.5	49	1024	16



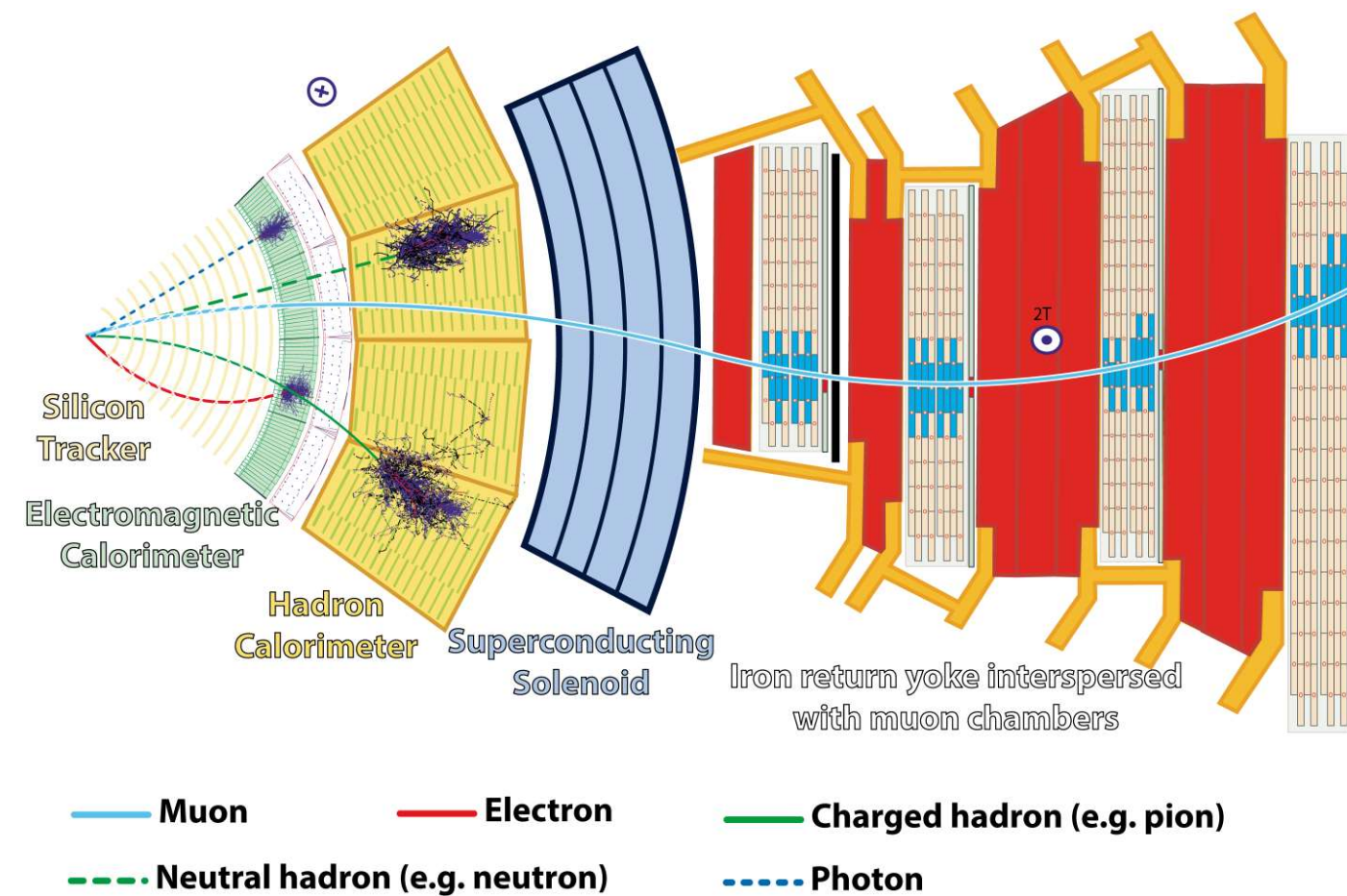
SciFi 闪烁体光纤下游探测器

- 闪烁体光纤+SiPM读出
- X方向单点分辨率好于100um
- 中国组承担电子学设计、生产任务



粒子鉴别

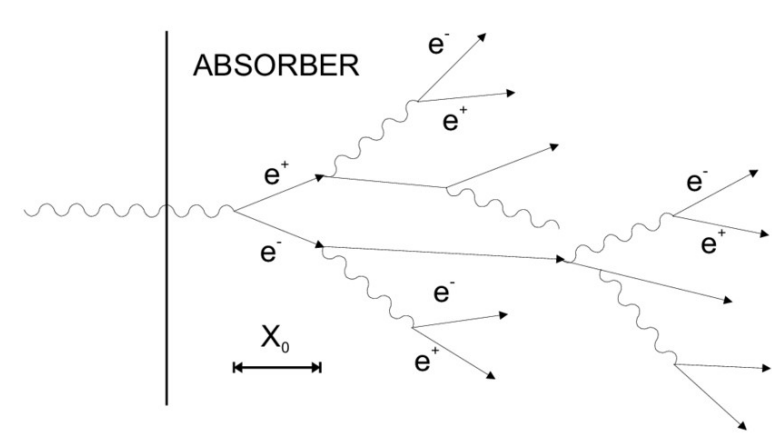
- 电子 / 光子：径迹探测 + 电磁量能器
- 缪子：缪子探测器（径迹）
- $P / K / \pi$?
 - 动量+质量假设 $\rightarrow$ 能量



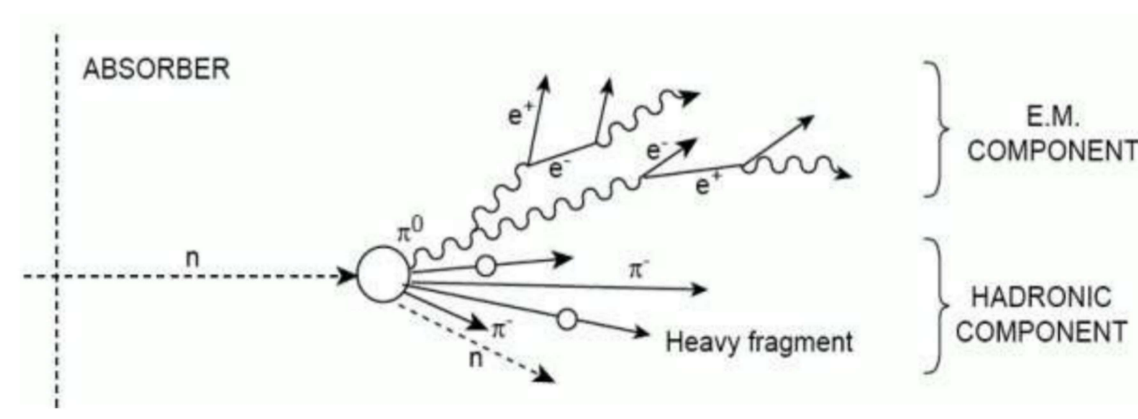
能量重建

光子/ 中性粒子/ 喷注

电磁量能器



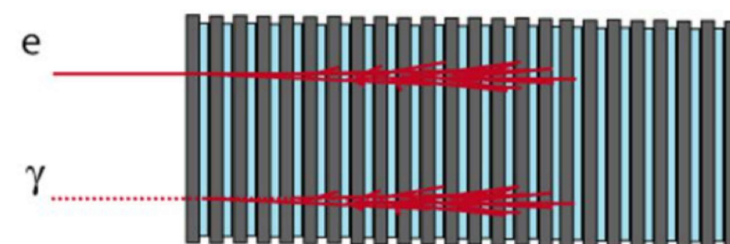
强子量能器



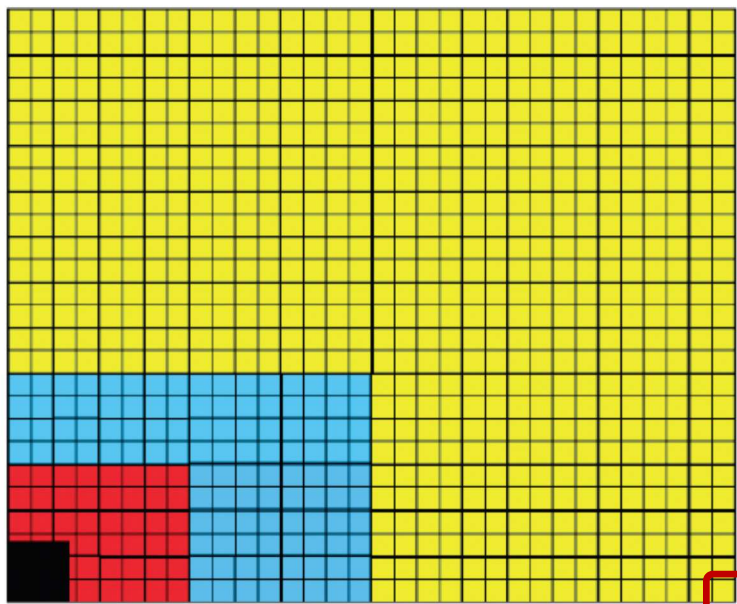
均一型量能器



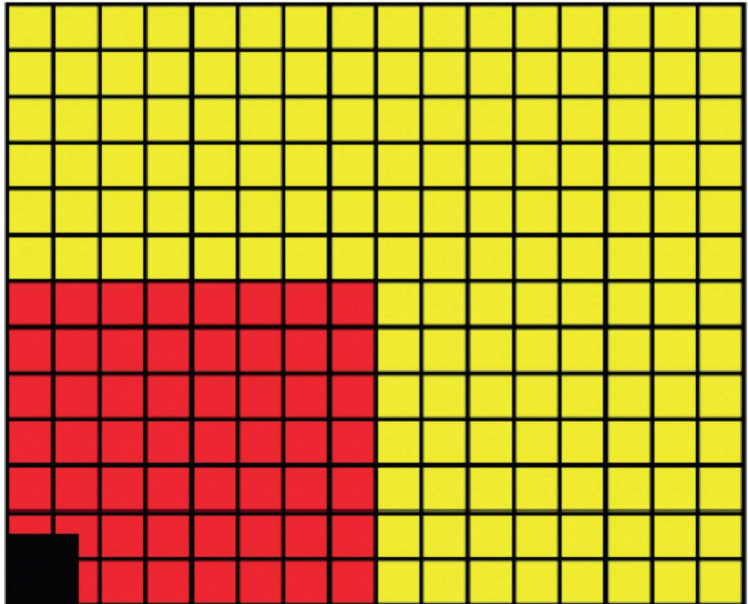
取样型量能器



LHCb ECAL + HCAL



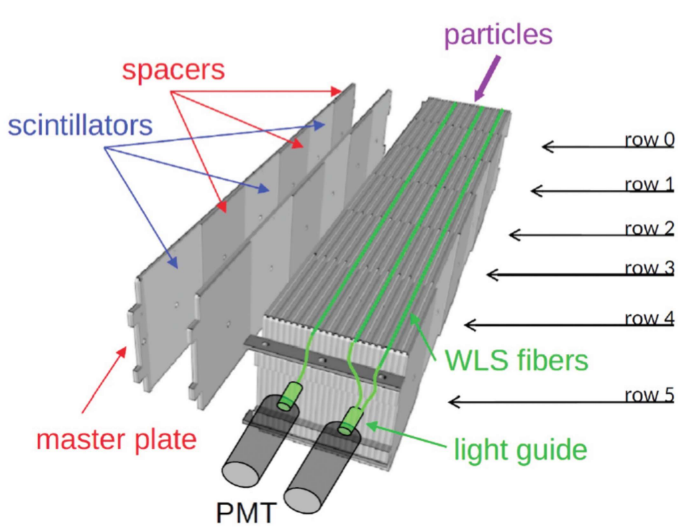
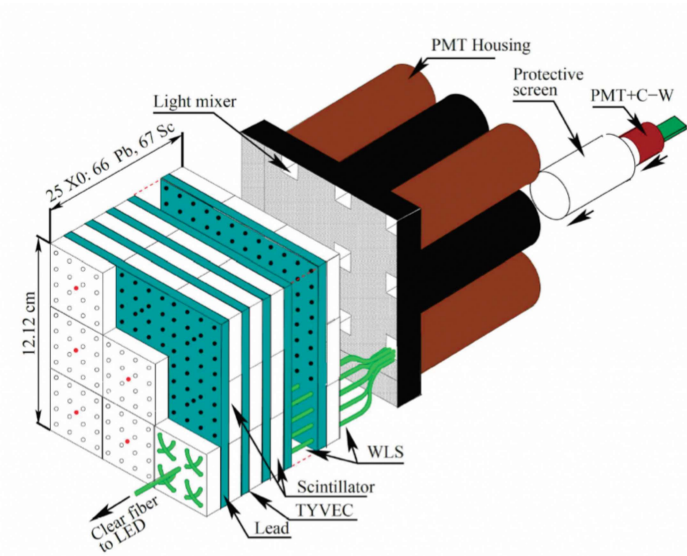
- Outer section :
121.2 mm cells
2688 channels
- Middle section :
60.6 mm cells
1792 channels
- Inner section :
40.4 mm cells
1536 channels



- Outer section :
262.6 mm cells
608 channels
- Inner section :
131.3 mm cells
860 channels

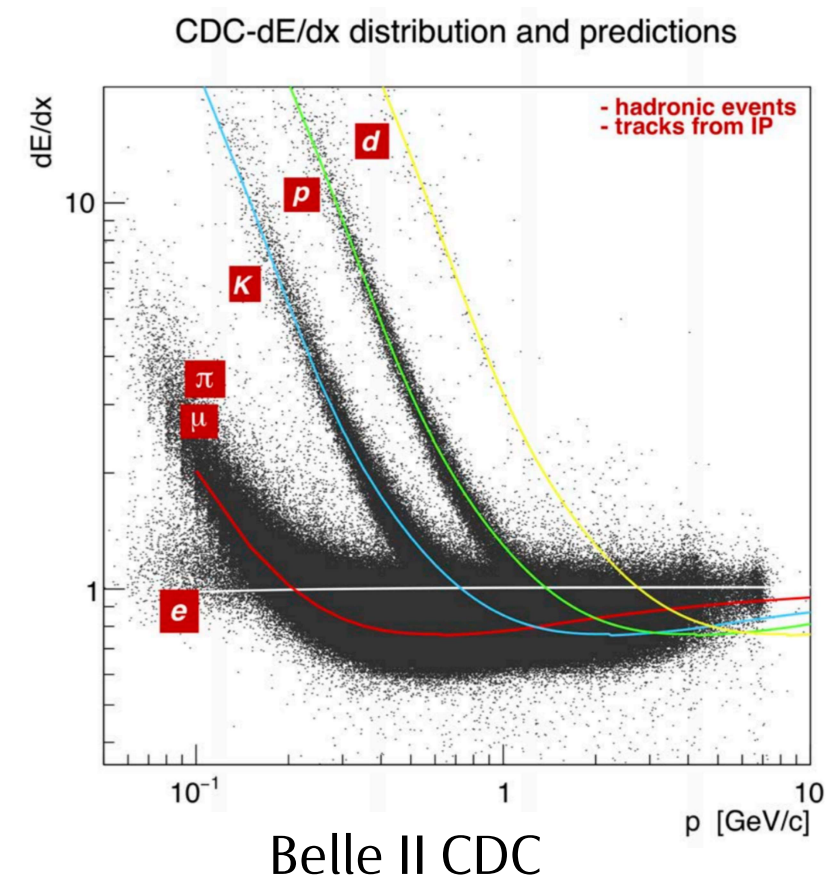
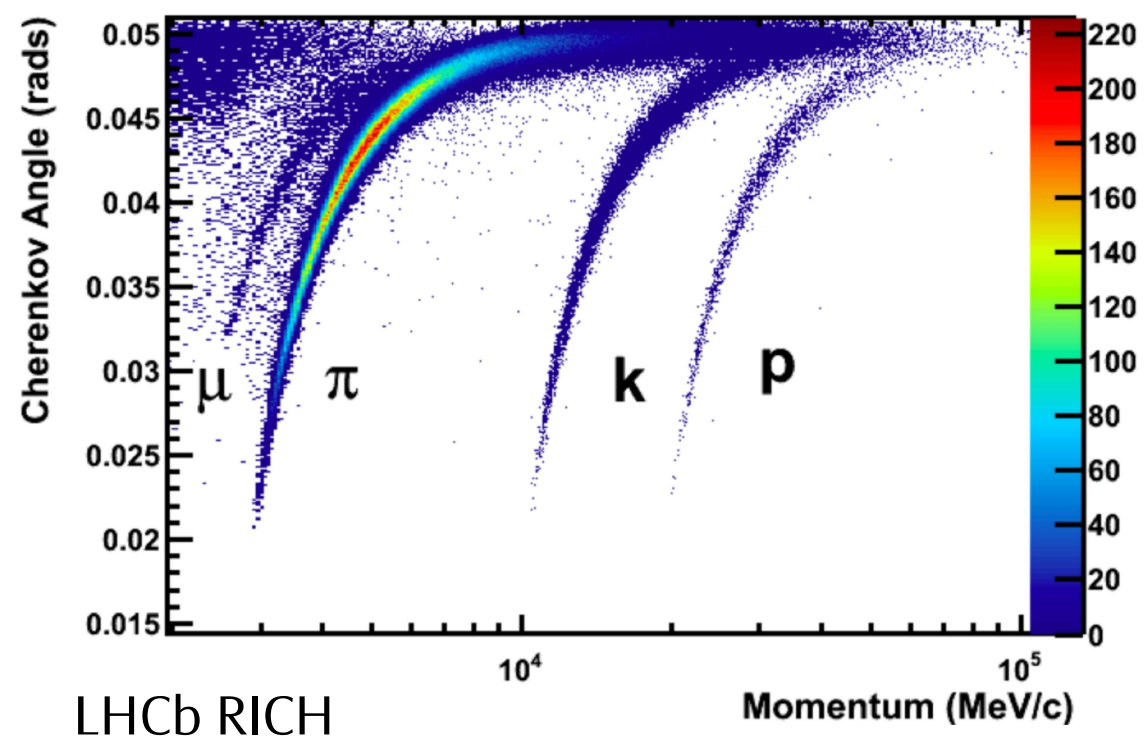
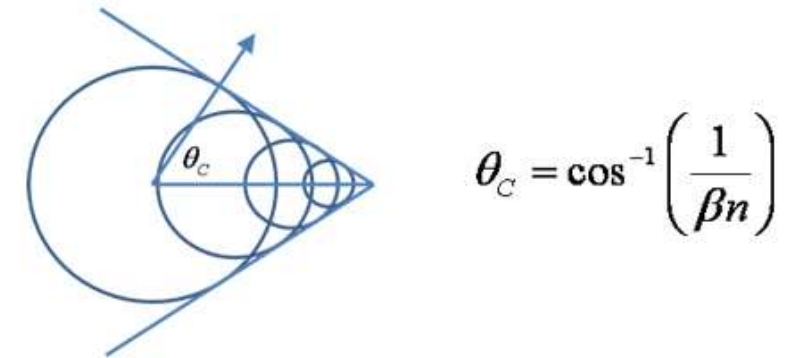
$$\frac{\sigma(E)}{E} = \frac{(9.0 \pm 0.5) \%}{\sqrt{E}} \oplus (0.8 \pm 0.2) \% \oplus \frac{0.003}{E \sin \theta} \quad \text{ECAL}$$

$$\frac{\sigma(E)}{E} = \frac{(67 \pm 5) \%}{\sqrt{E}} \oplus (9 \pm 2) \% \quad \text{HCAL}$$



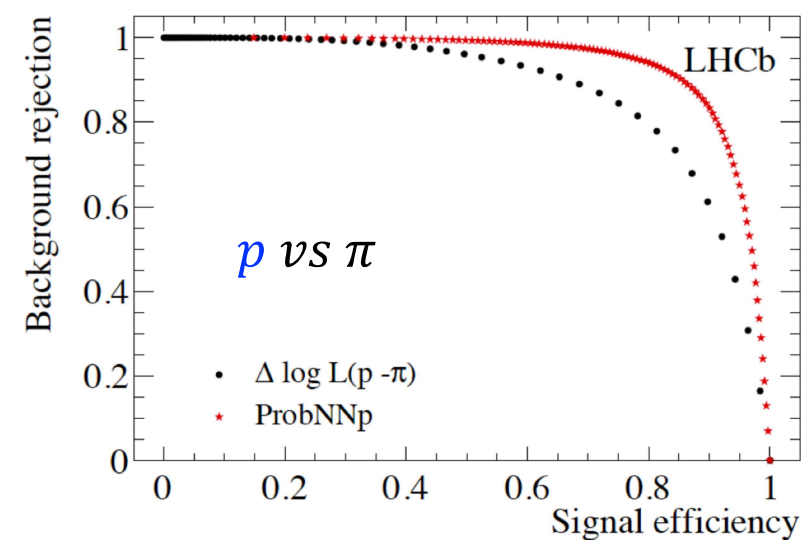
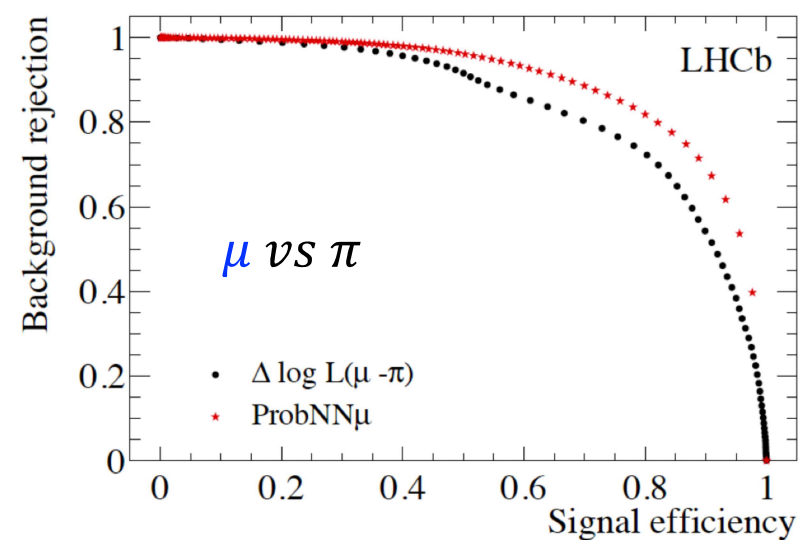
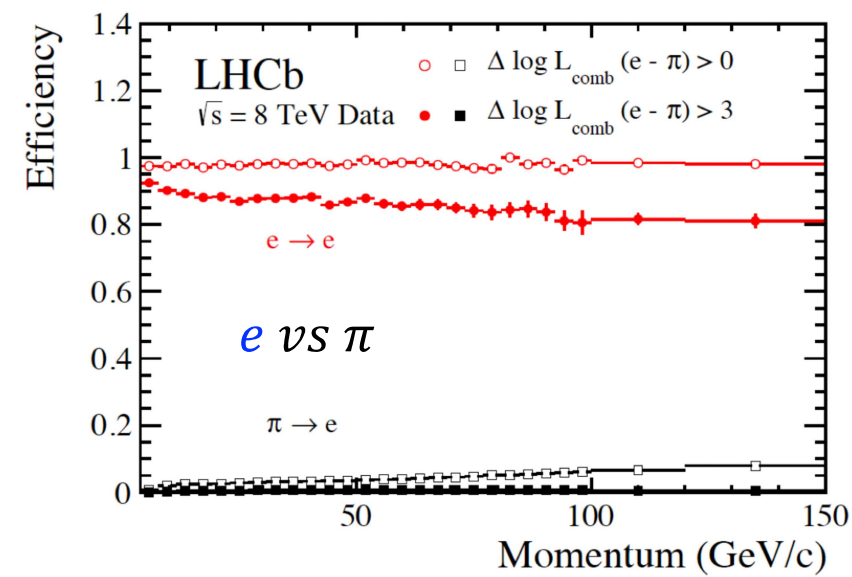
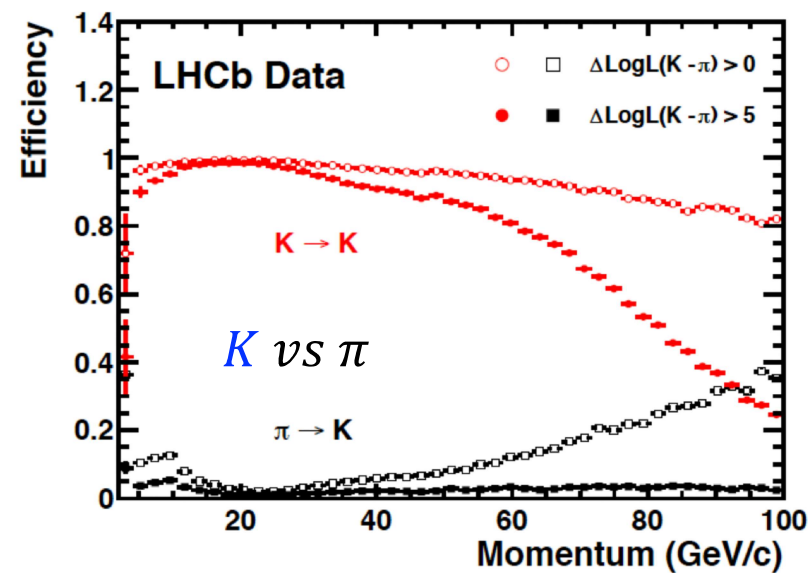
强子鉴别

- 带电强子径迹仅靠动量无法区分
- 需加入其他信息
 - 切伦科夫探测器/飞行时间探测器 -> 速度
 - 漂移室 -> dE/dx



LHCb PID性能

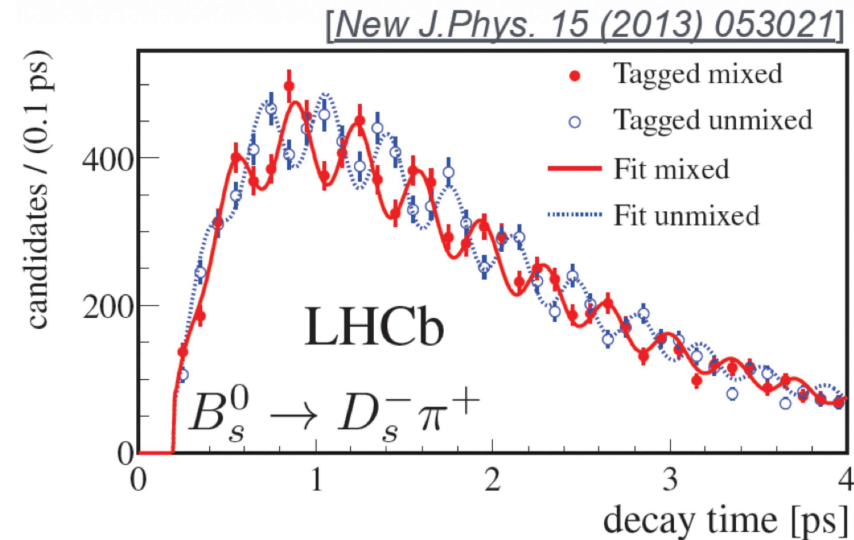
- 2-100 GeV动量范围内：K鉴别效率 ~ 95% / pion MisID ~ 10%



味道标记 Flavour Tagging

- 随时间演化的B介子振荡是研究CP破坏的重要方法
- 需要知道B介子产生时的初始味道

$$\begin{aligned}\mathcal{A}_{CP}(t) &= \frac{\Gamma(\bar{B}_q^0(t) \rightarrow f) - \Gamma(B_q^0(t) \rightarrow f)}{\Gamma(\bar{B}_q^0(t) \rightarrow f) + \Gamma(B_q^0(t) \rightarrow f)} \\ &= \frac{\mathcal{S}_f \sin(\Delta m t) - \mathcal{C}_f \cos(\Delta m t)}{\cosh(\frac{\Delta \Gamma t}{2}) + \mathcal{A}_{\Delta \Gamma} \sinh(\frac{\Delta \Gamma t}{2})}\end{aligned}$$



■ 味道标记算法的指标

- 标记效率 tagging efficiency
- 误标记率 mistag probability
- 有效标记效率 effective tag. eff.

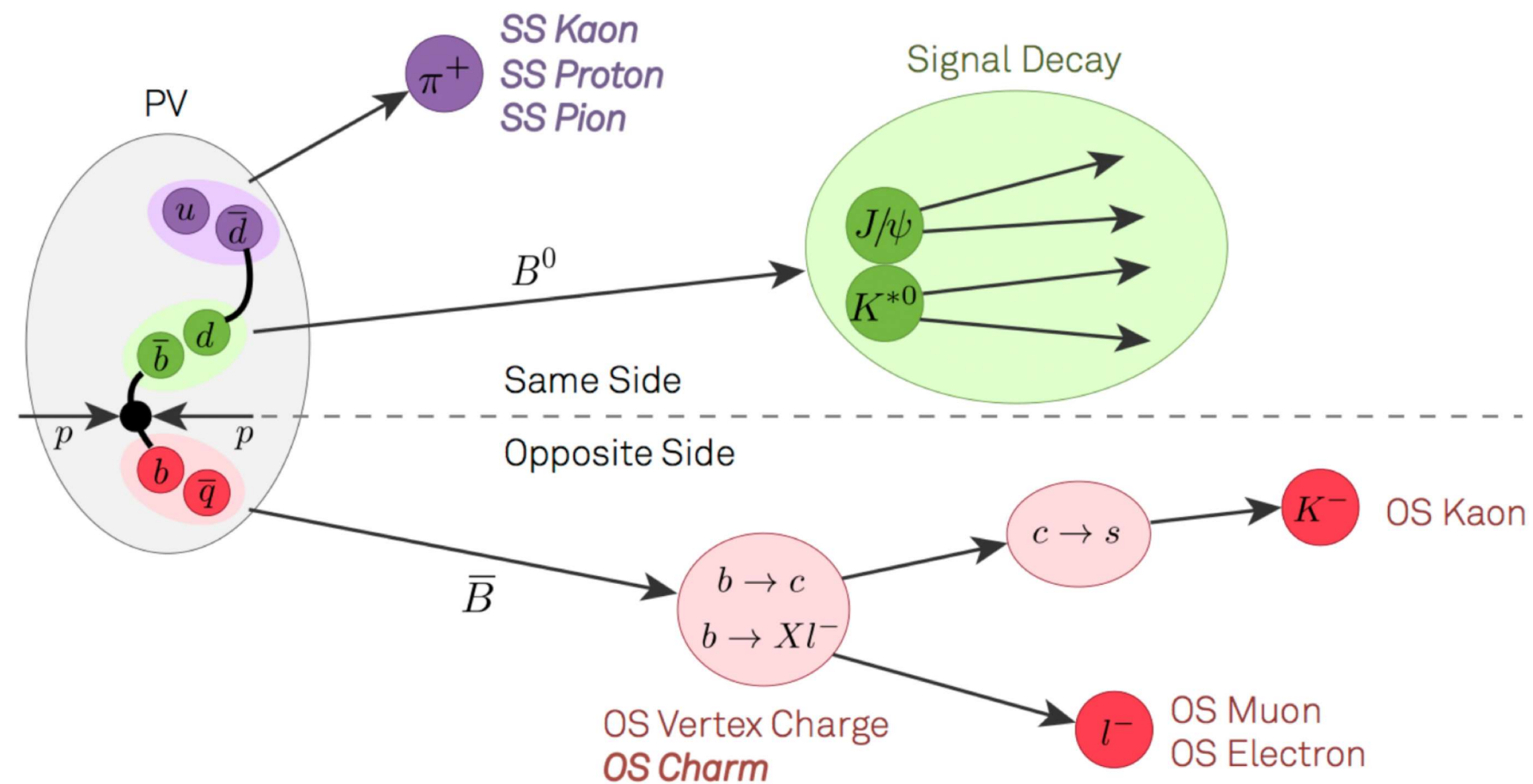
$$\epsilon_{\text{tag}} = \frac{N_{\text{right}} + N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}} + N_{\text{untagged}}}$$

$$\omega = \frac{N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}}}$$

$$\epsilon_{\text{eff}} = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} (1 - 2\omega)^2$$

味道标记原理

Same side (SS): exploit the charge of the **fragmentation particle** (pion, kaon, proton) produced next to the signal b -hadron in the hadronisation process to infer its initial flavour ($t=0$)

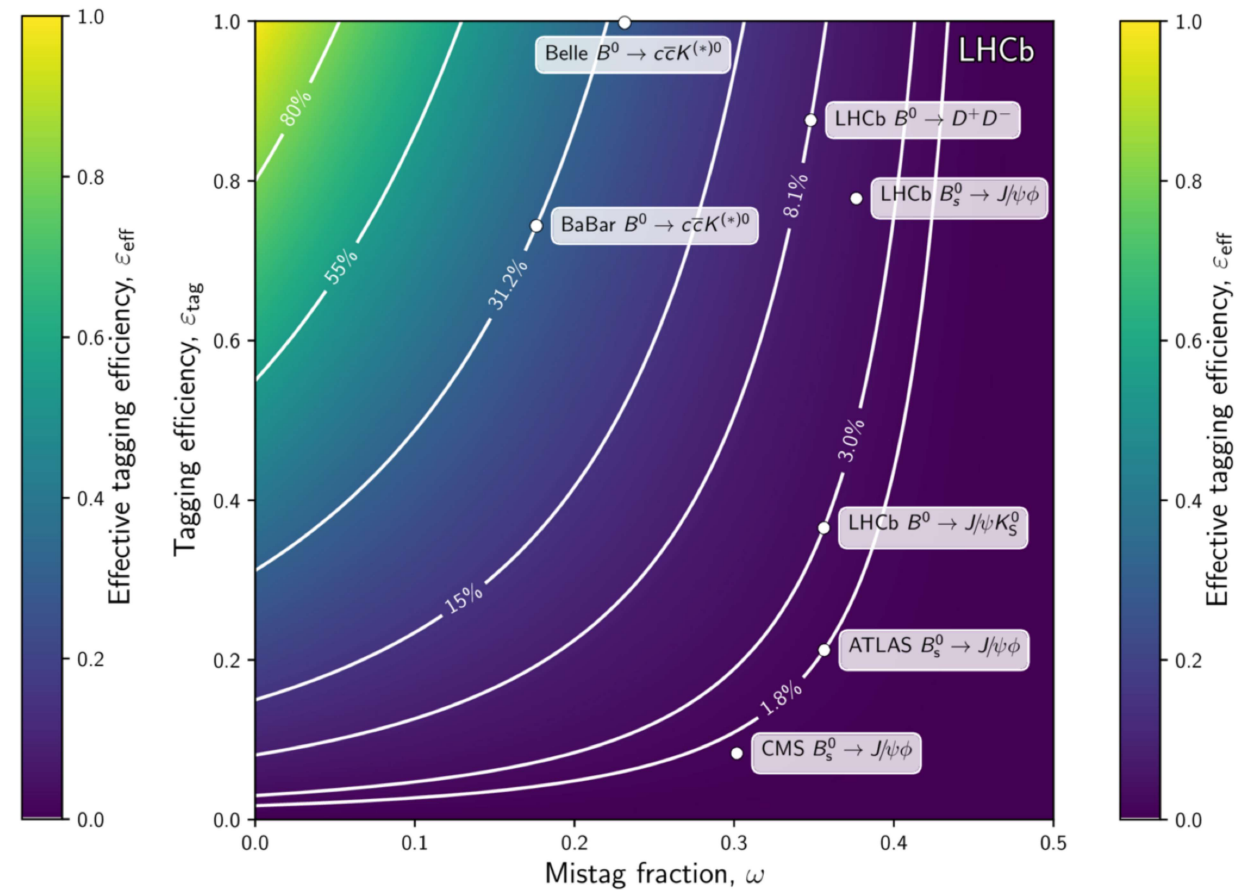
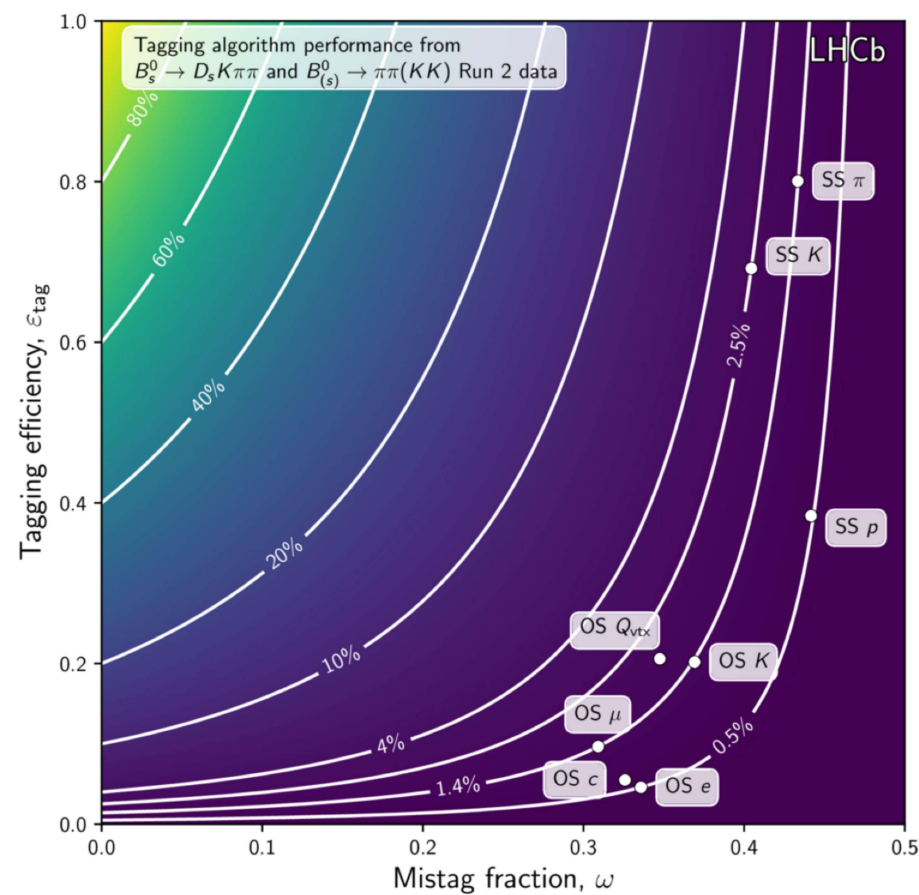


Opposite side (OS): exploit the charge of the particle (lepton, kaon, charm decays) or of the **reconstructed secondary vertex produced from the other b -hadron** in the event to infer signal b -hadron initial flavour ($t=0$)

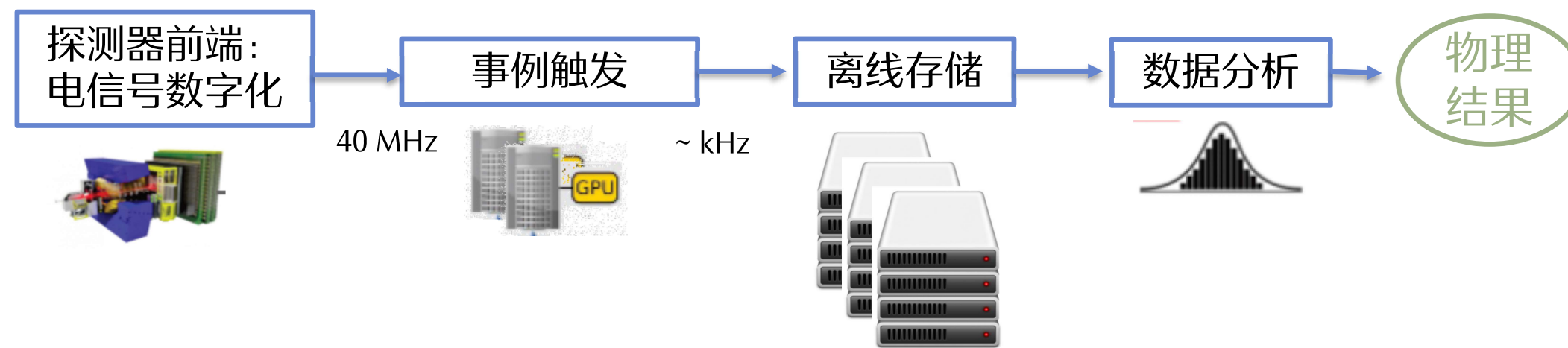
FT性能

- FT性能与衰变末态有关
- OS taggers: good mistag / low decision rate
- SS taggers: modest mistag / high decision rate

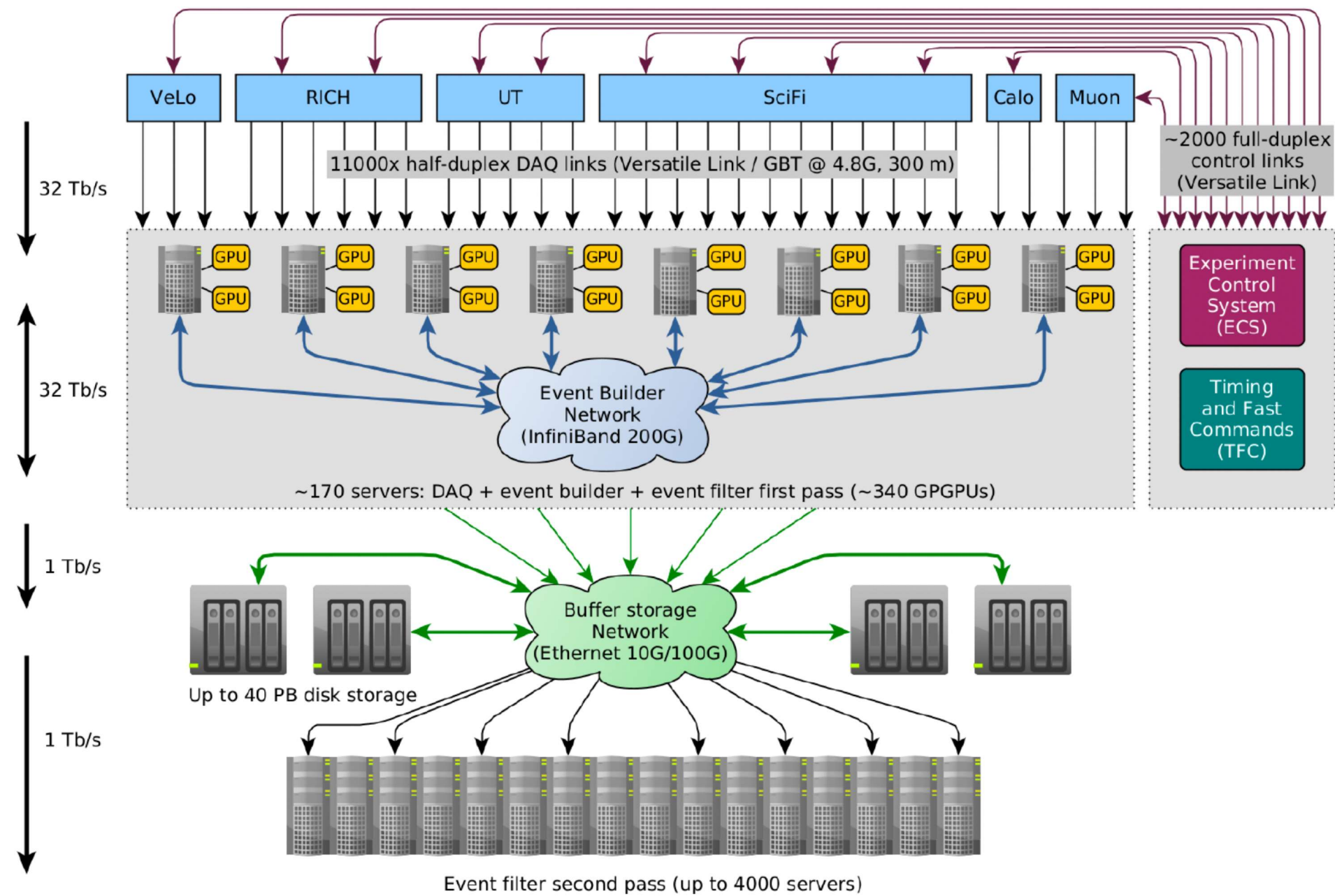
$$\sigma^{\text{stat}}(CP \text{ asym}) \propto \frac{1}{\sqrt{\epsilon_{\text{eff}} N}}$$



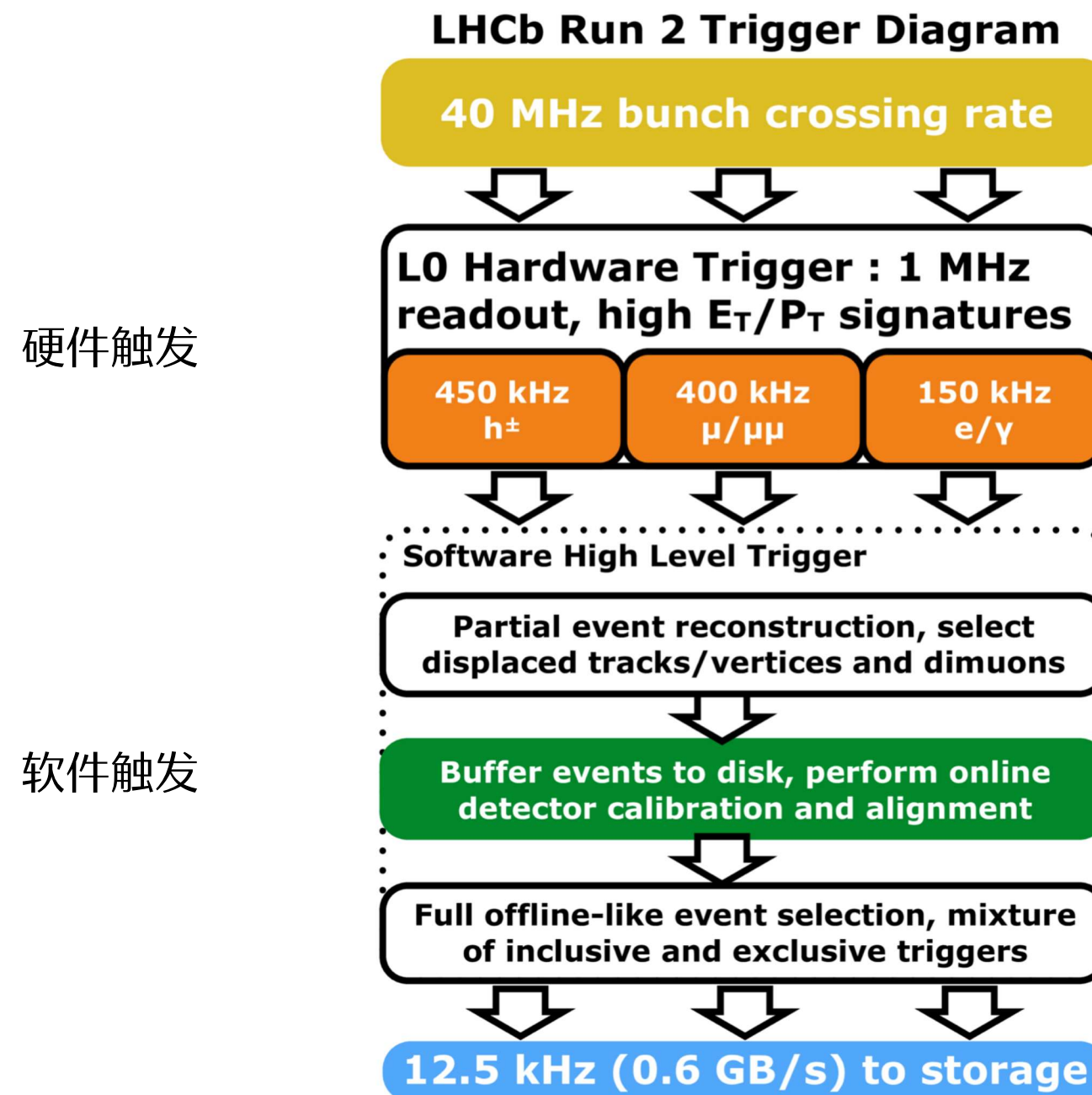
从对撞发生到物理结果：高能数据的获取与处理



在线数据获取系统



触发系统



升级前（截止2018年），
LHCb依赖缪子探测器和
量能器提供硬件触发

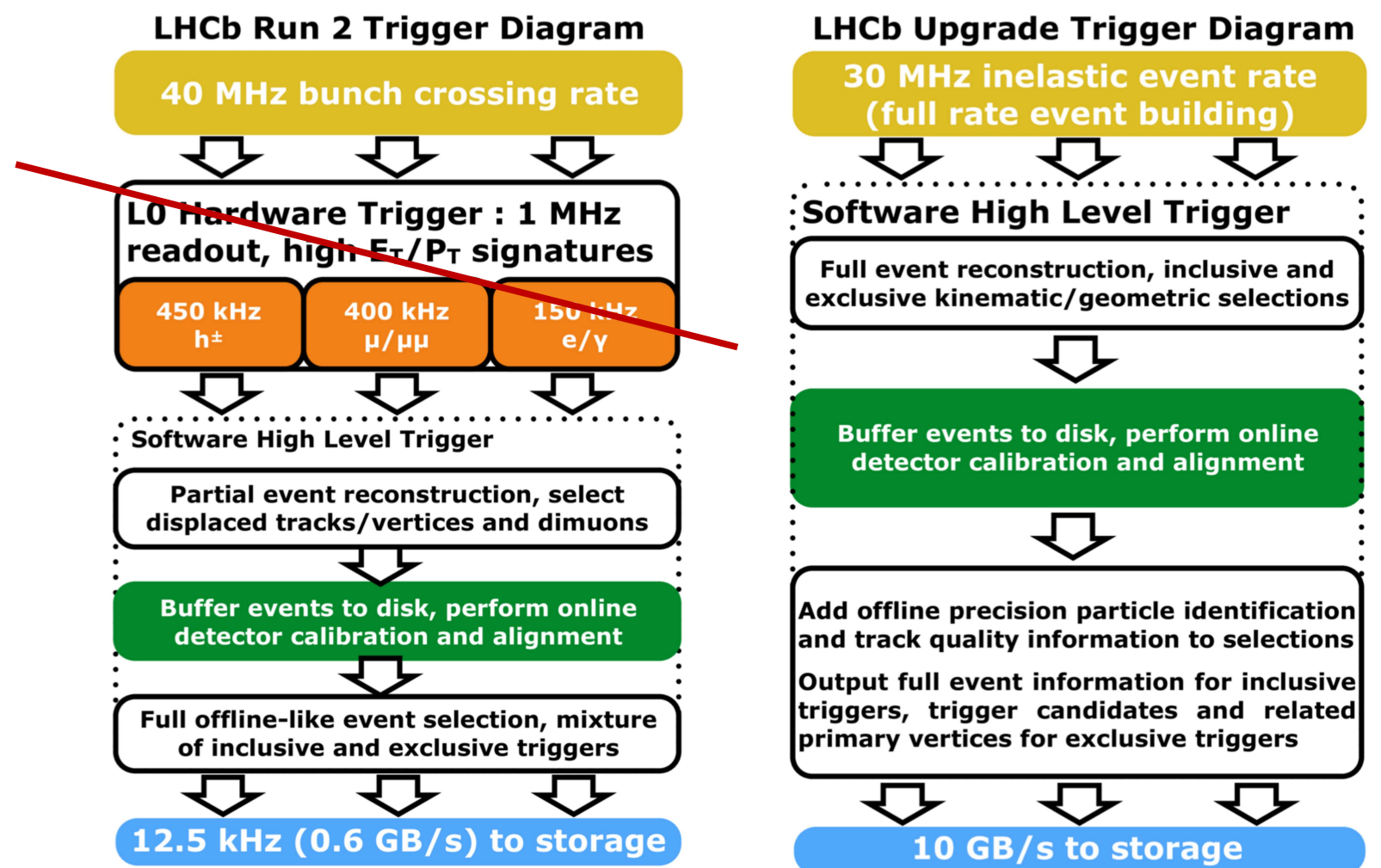
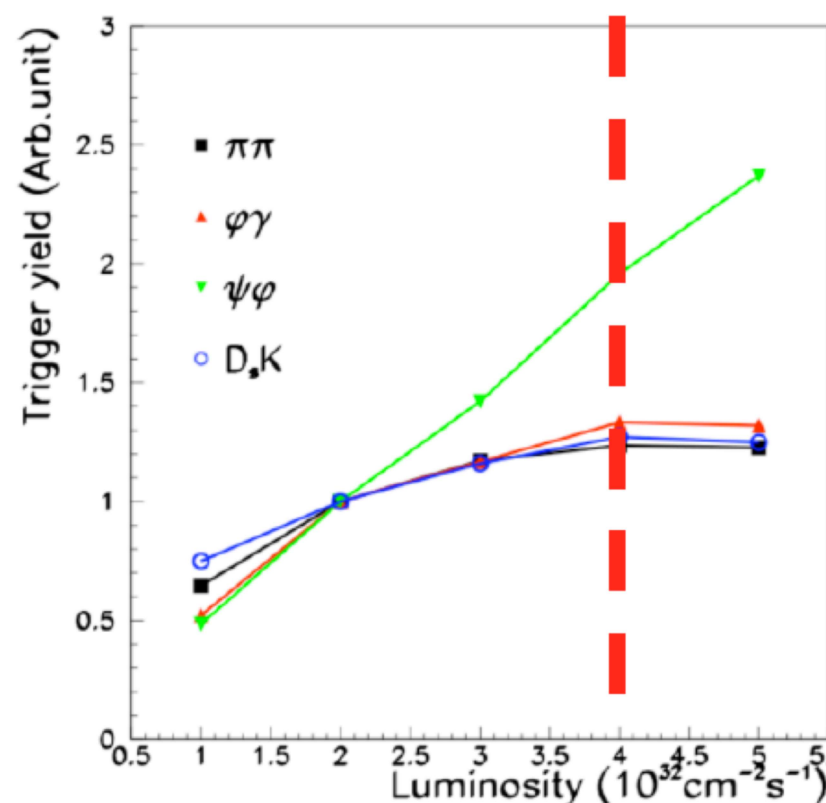
触发系统：LHCb升级的关键

■ LHCb升级目标： $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

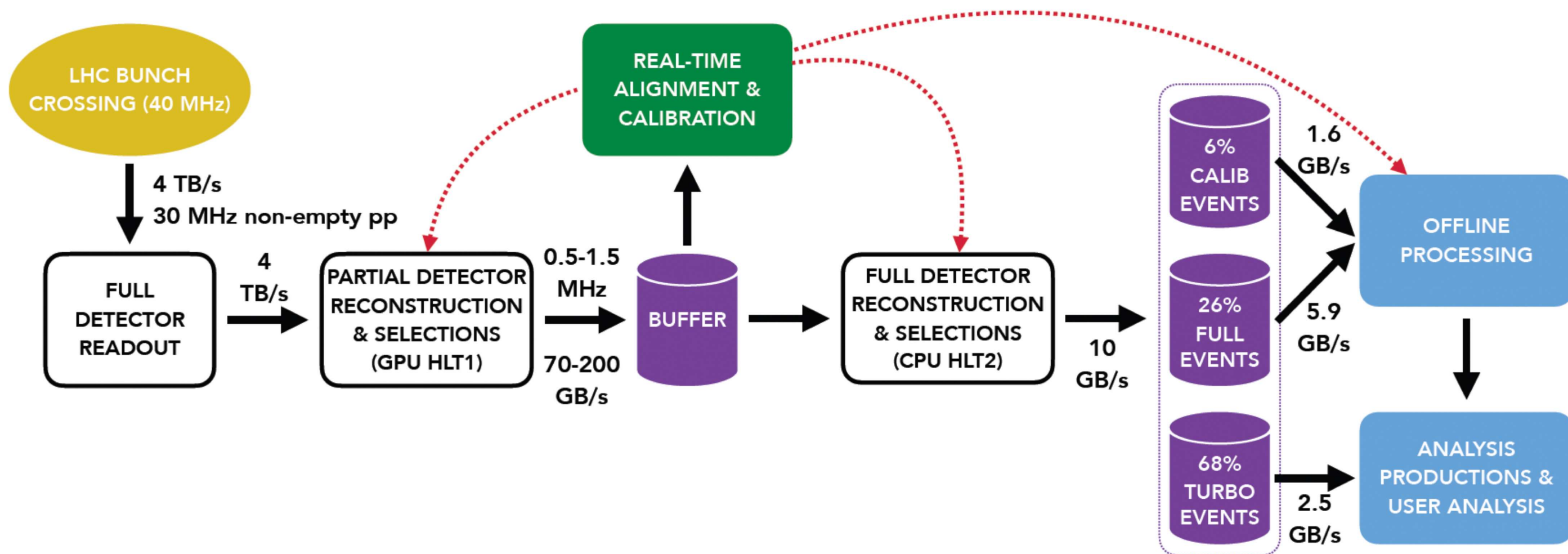
为什么不能一开始高亮度运行？

- 1MHz硬件触发：纯强子末态在高亮度下触发饱和
- 探测器占用率过高；辐照引起寿命减少

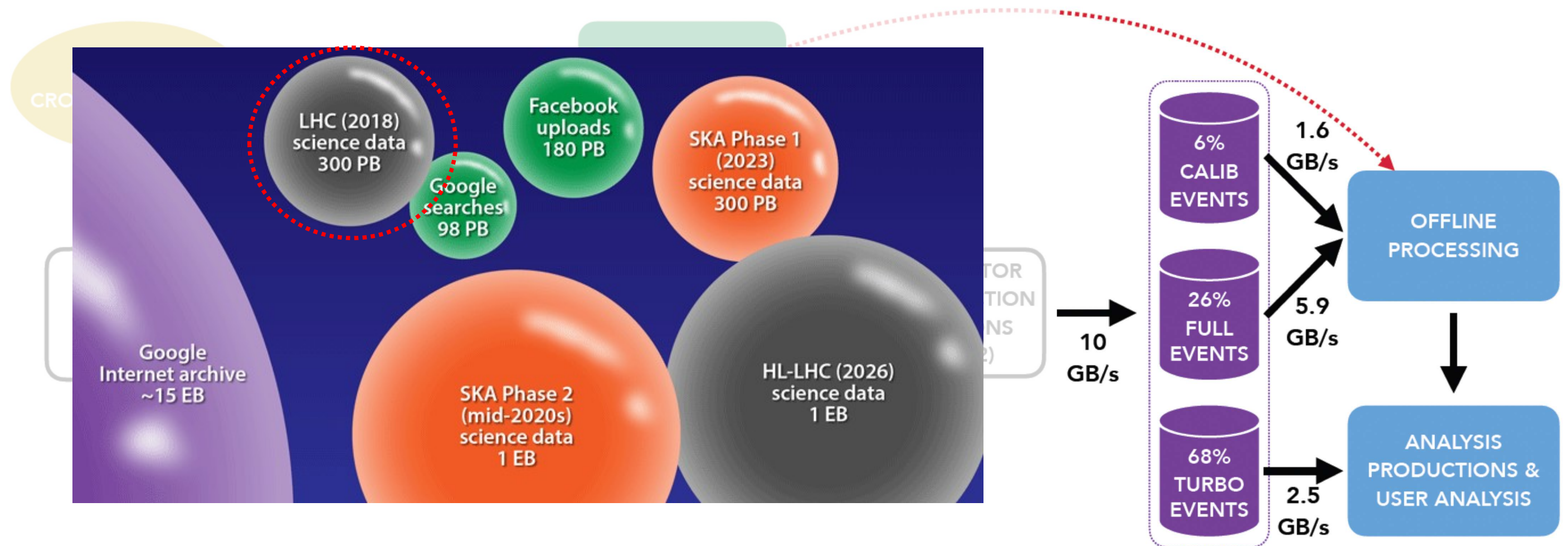
■ 升级关键：移除硬件触发！



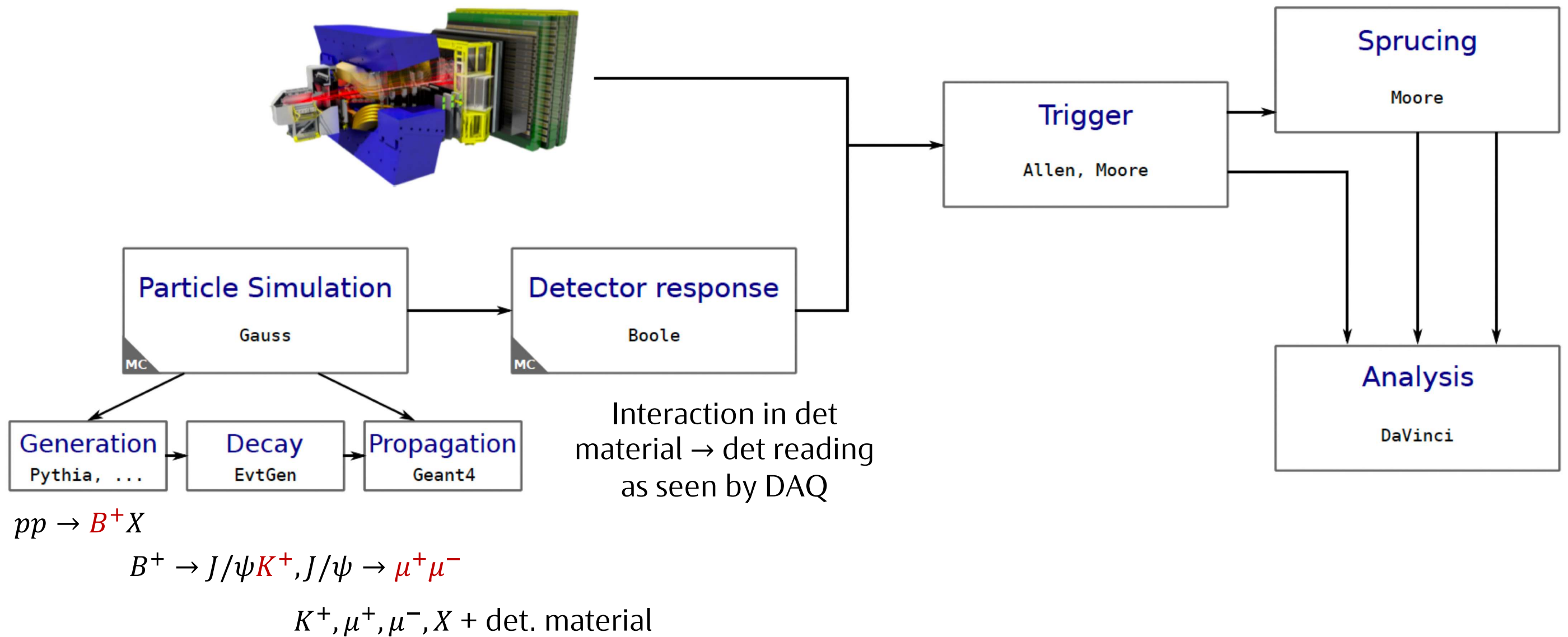
LHCb数据流



离线存储



探测器模拟



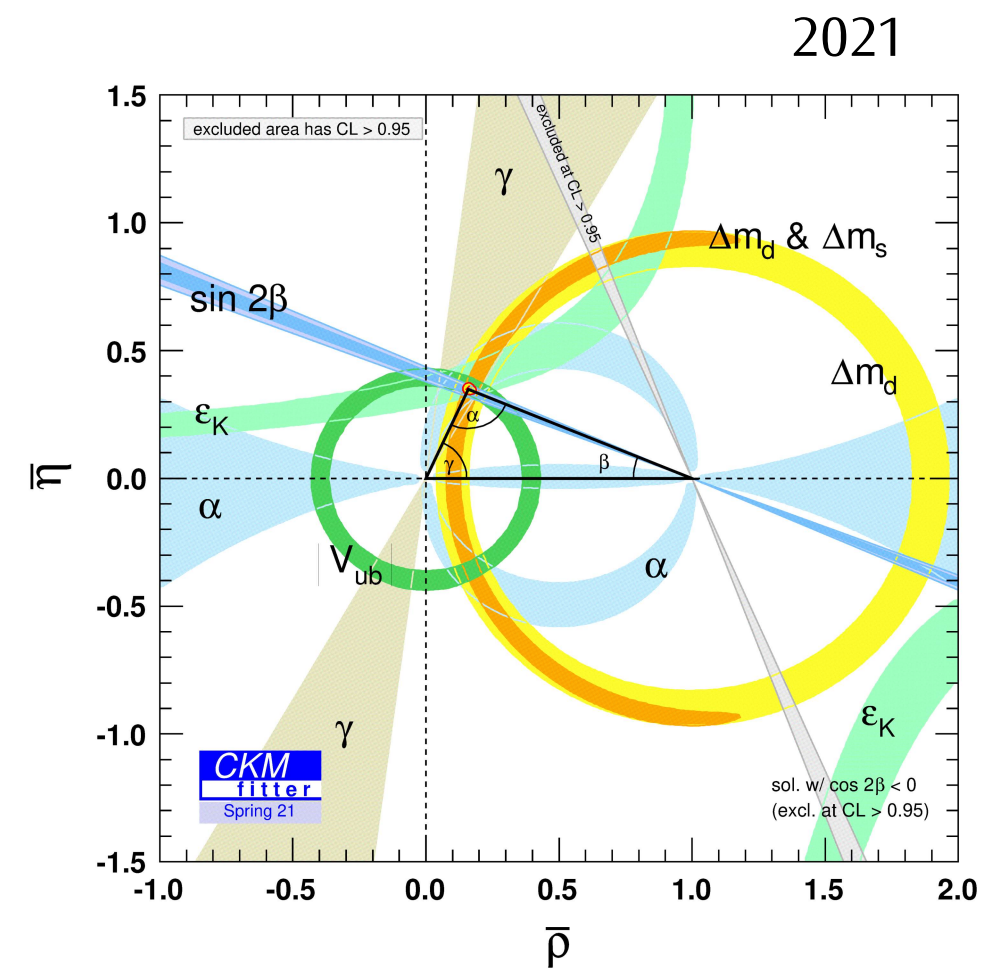
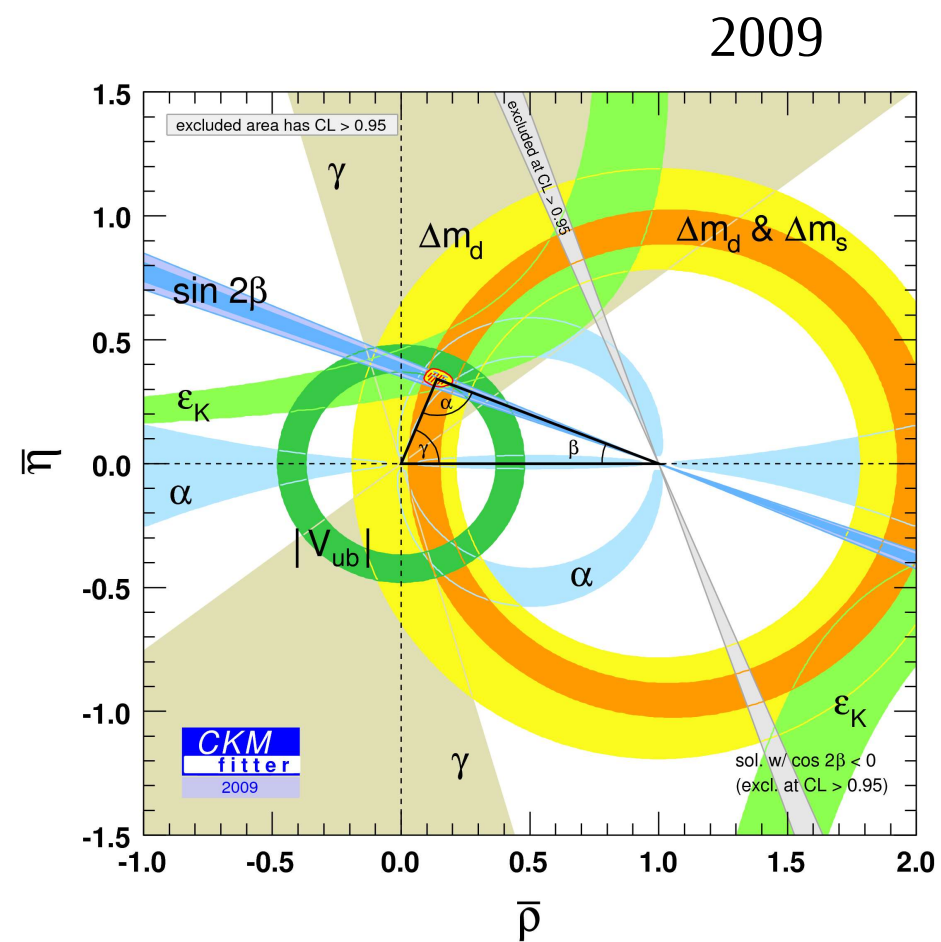
近期亮点

未来的实验

对重味探测器的新挑战

重味物理实验的未来

重味物理取得丰硕成果



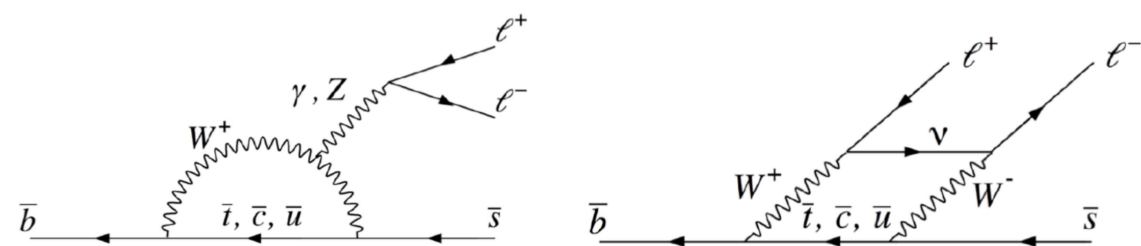
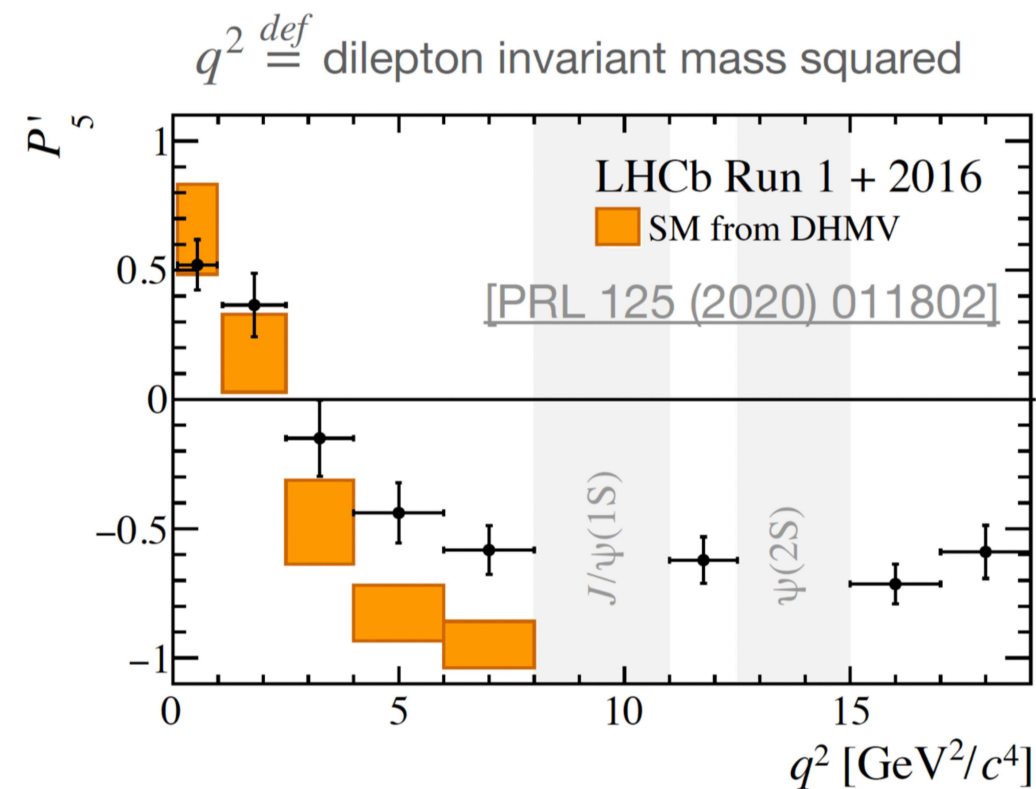
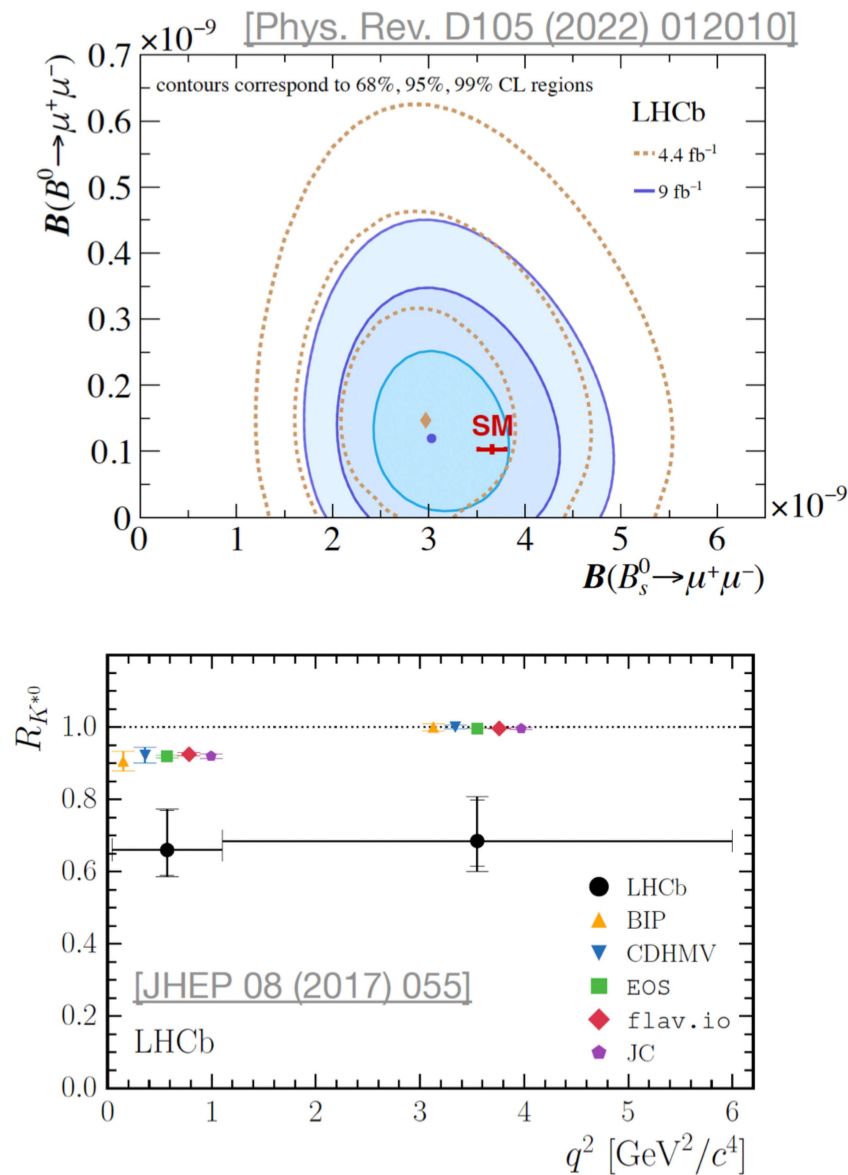
$$\gamma = (65.4^{+3.8}_{-4.2})^\circ$$

* 周晓康老师周四课程

Tension with SM?

- 一系列稀有衰变的精确测量显示与SM有2-3sigma的差距

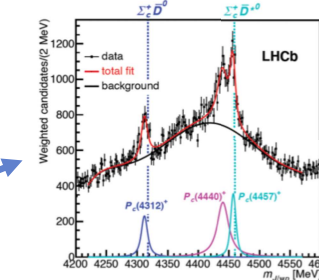
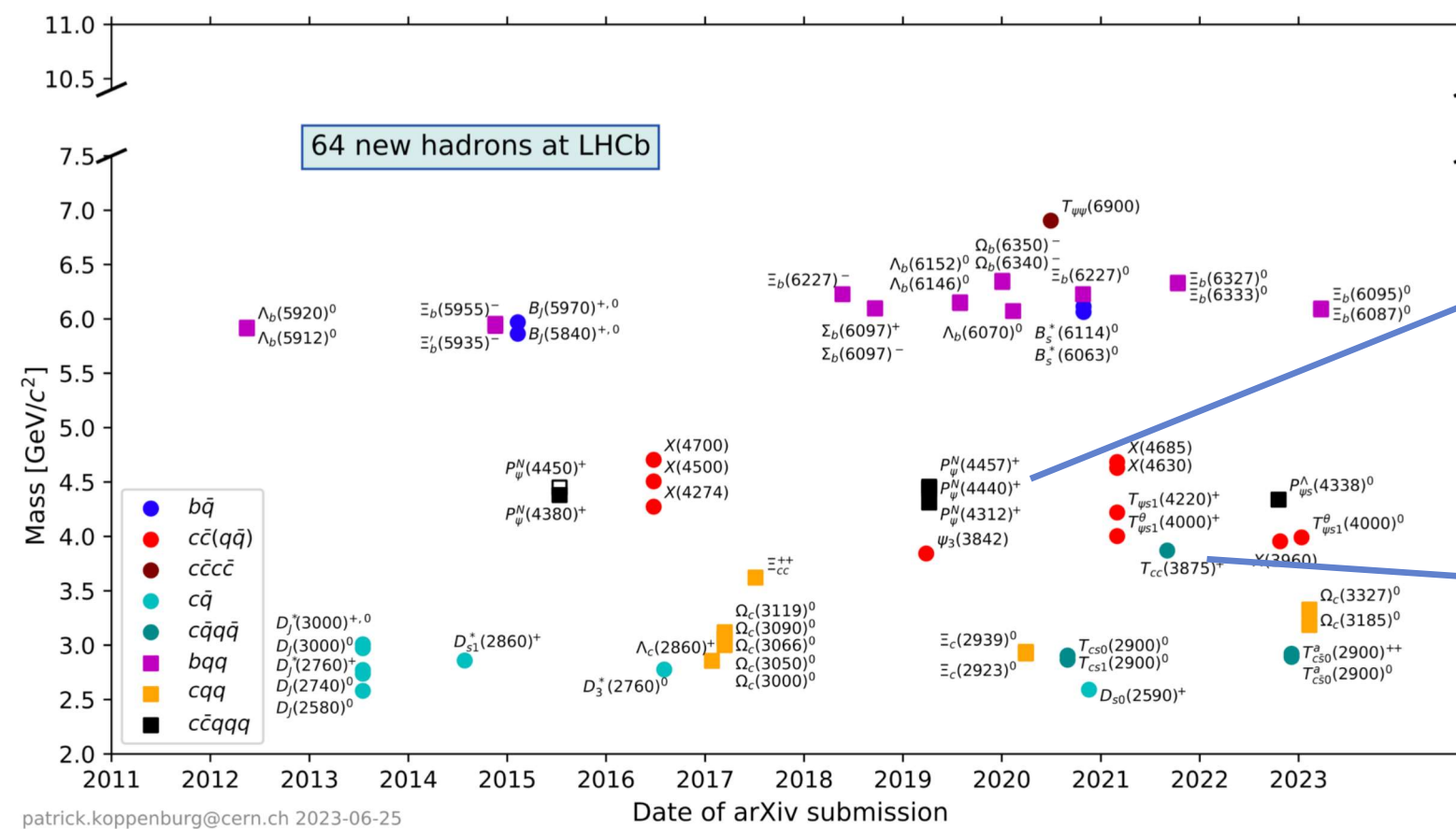
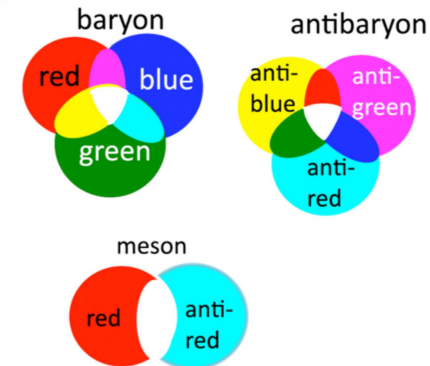
* 陈缮真老师周四课程



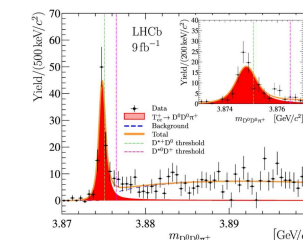
新强子态大发现

重子

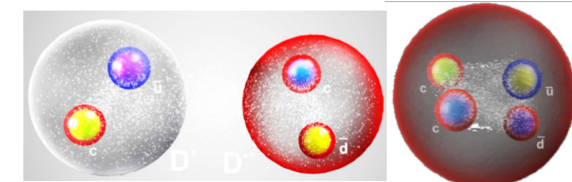
介子



五夸克态?



四夸克态?



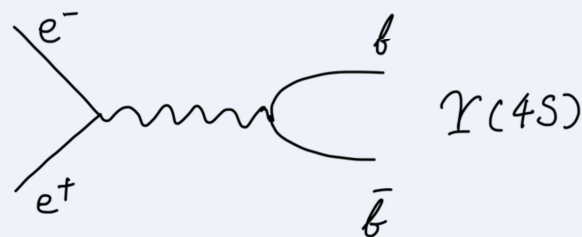
* 张冬亮老师周三课程

重味物理的未来

继续提高精度直至
新物理无处藏身！

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

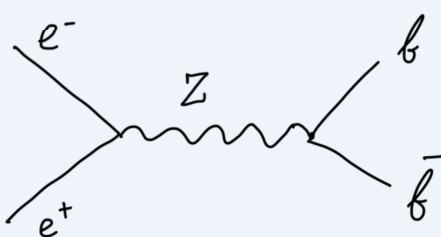
B 工厂



@ SuperKEKB

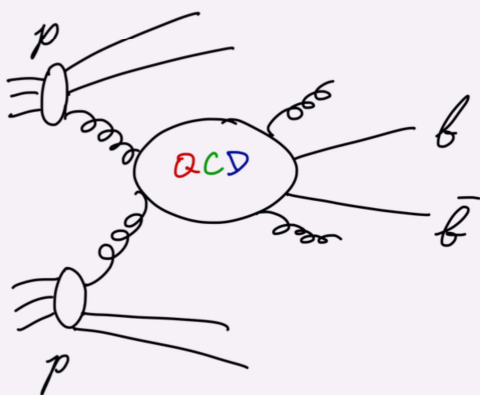


Z 工厂



@FCC-ee/ CEPC

高能强子对撞



@HL-LHC



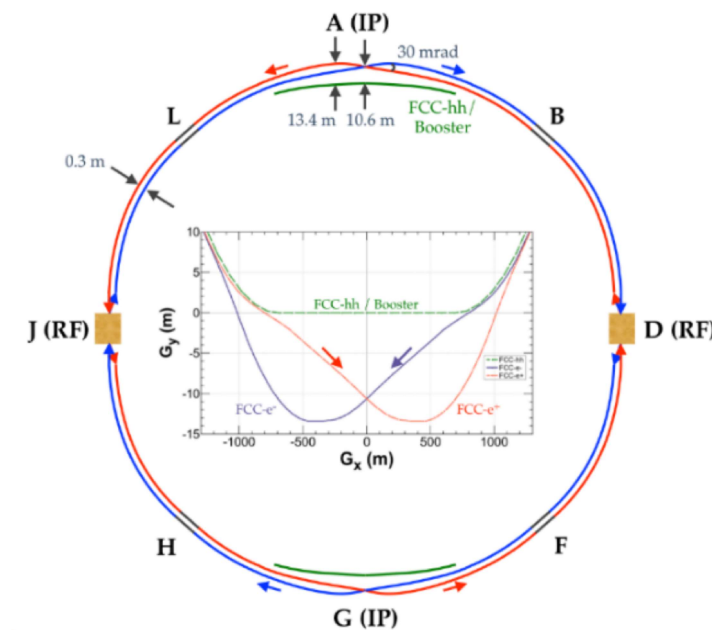
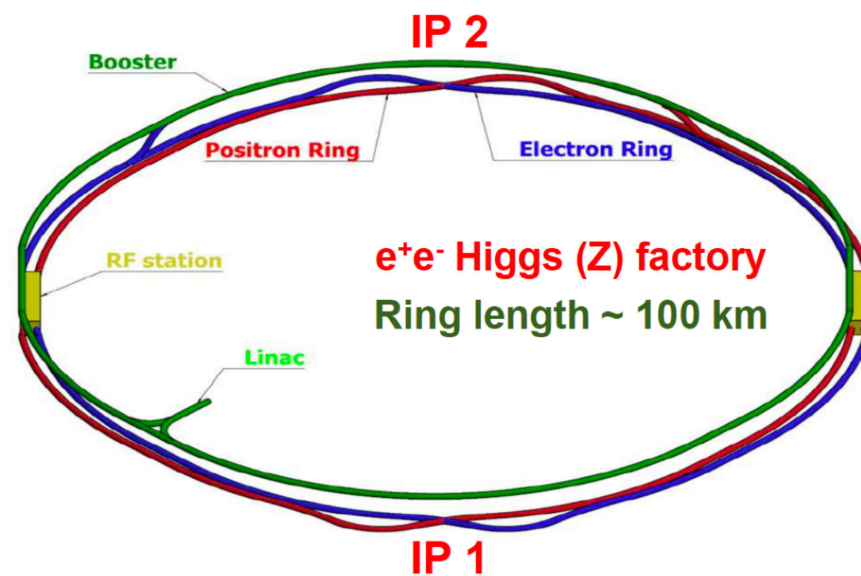
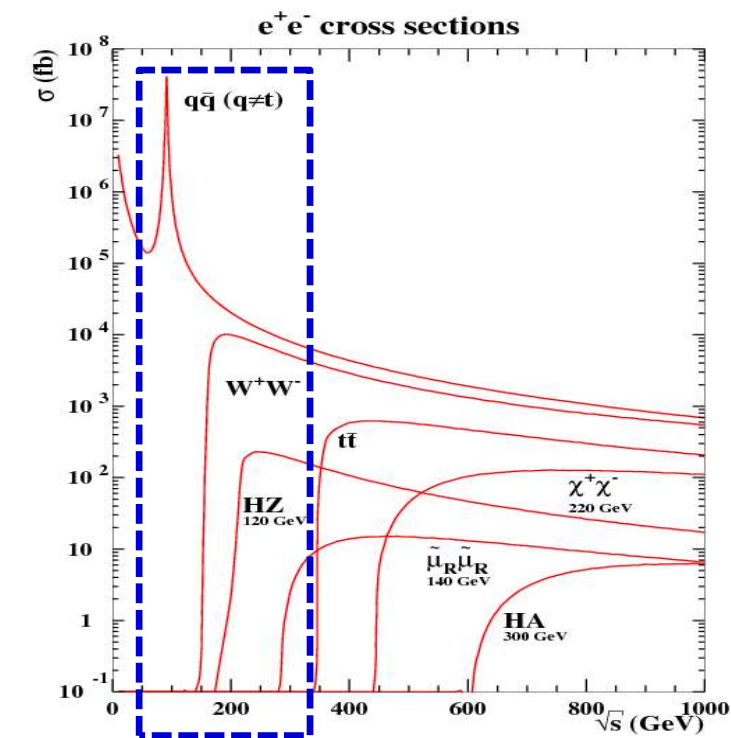
Higgs工厂和Z工厂

CEPC

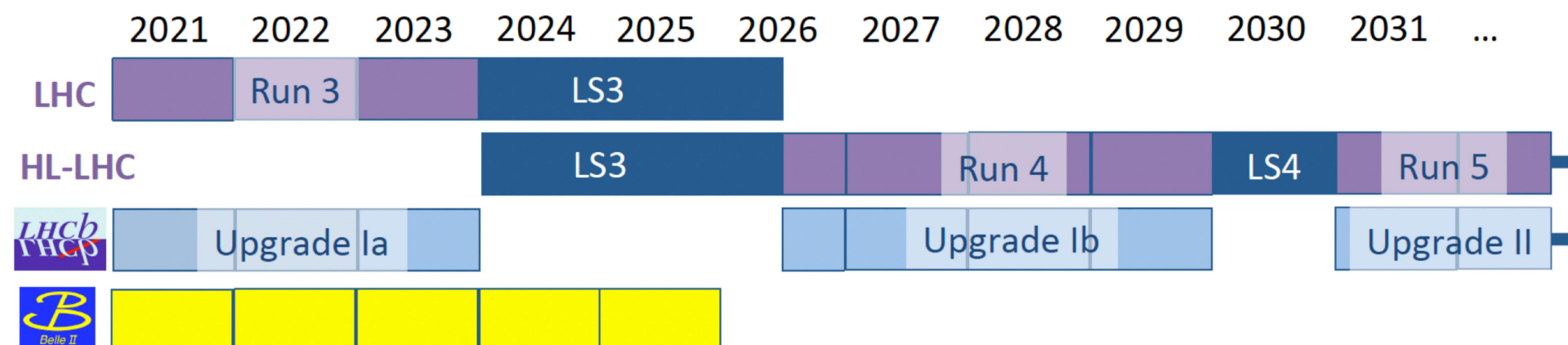
- 周长 ~ 100km
- 质心能量90 ~ 240GeV, 可升级至360GeV
- 产生 10^6 Higgs, 10^8 W, 10^{12} Z
- 2012.9 由中国科学家提出

FCC-ee

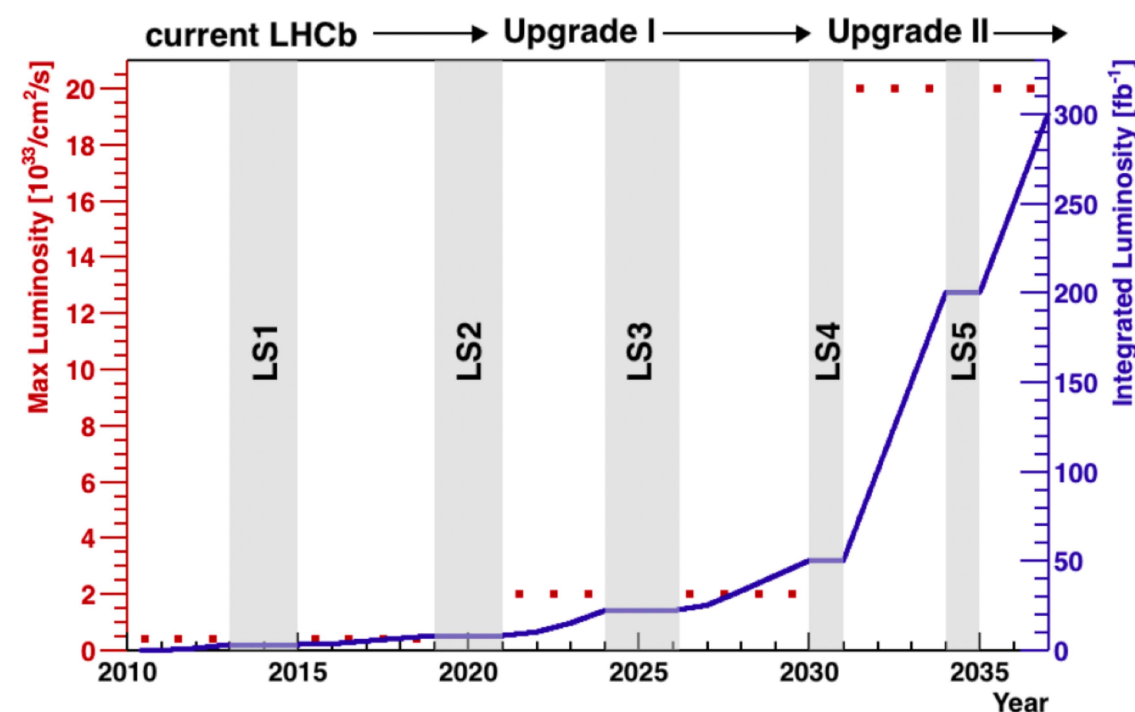
- 80 ~ 100km
- 在HL-LHC结束后开始建设



LHCb二期升级



- 为充分利用HL-LHC亮度，LHCb计划~2031进行二期升级，瞬时亮度再提高7.5倍至 $1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ 。
- 总积分亮度将达 300/fb



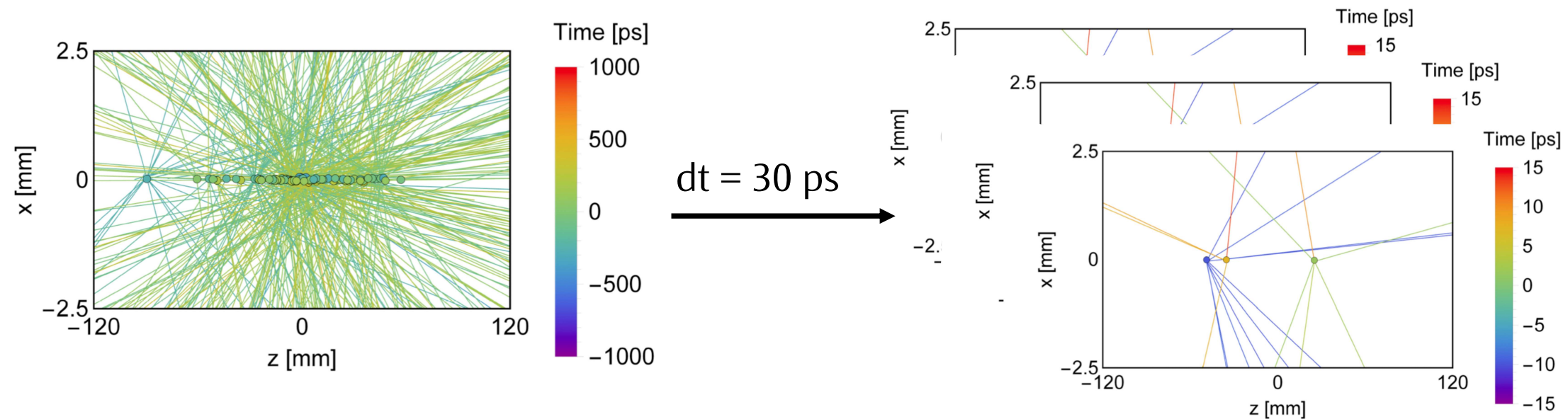
对探测器的新要求

- 更高颗粒度以降低占用率
- 能够处理事例堆积
- 更好的抗辐照性能
- 更强大的数据处理能力

- 举个例子…

VELO

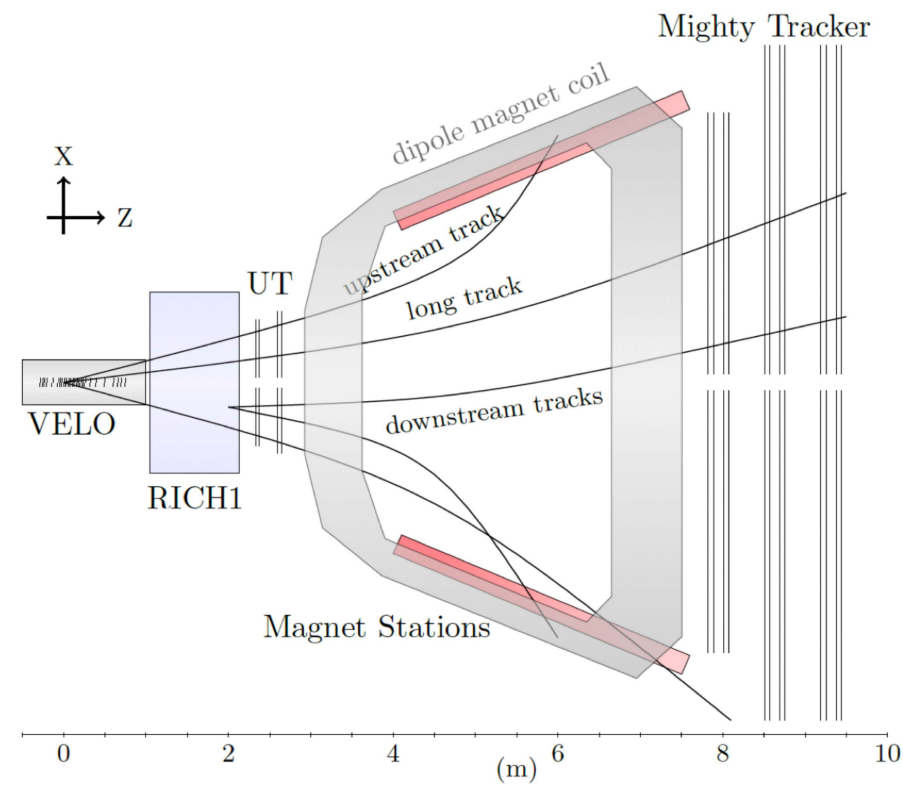
	Run 1-2	Upgrade I	Upgrade II
Luminosity / year[fb ⁻¹]	2	7	~ 50
Pileup	1.8	7	~ 50
Integ. Fluence [MeVn _{eq} /cm ²]	4.3×10^{14}	8×10^{15}	6×10^{16}
Readout rate [10 ⁶ hits/s]		600	~ 4500



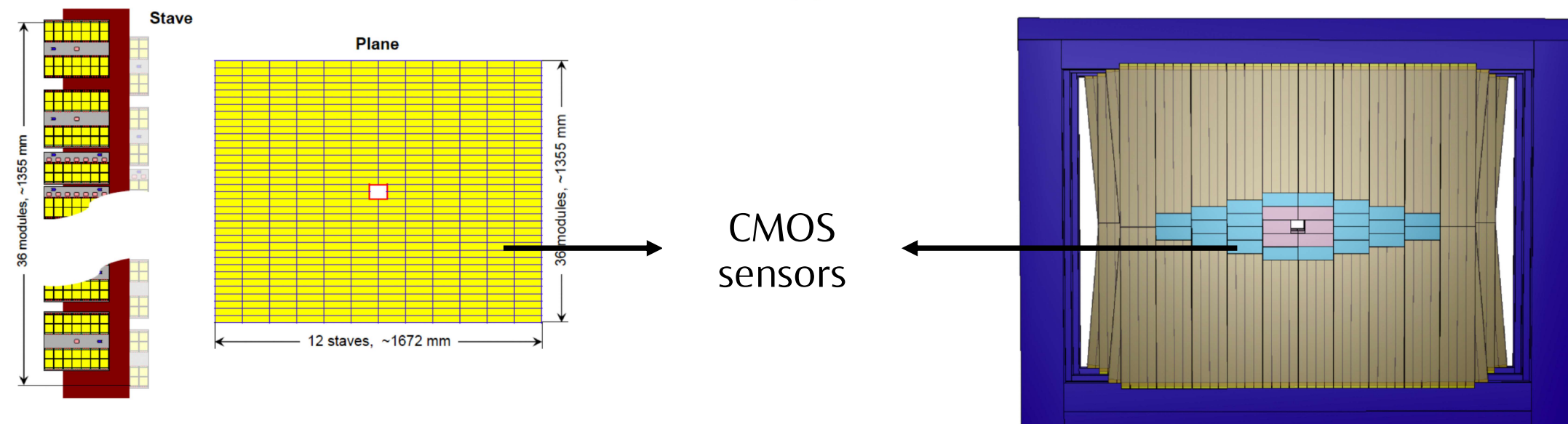
❏ 4D tracking sensors required!

寻迹系统

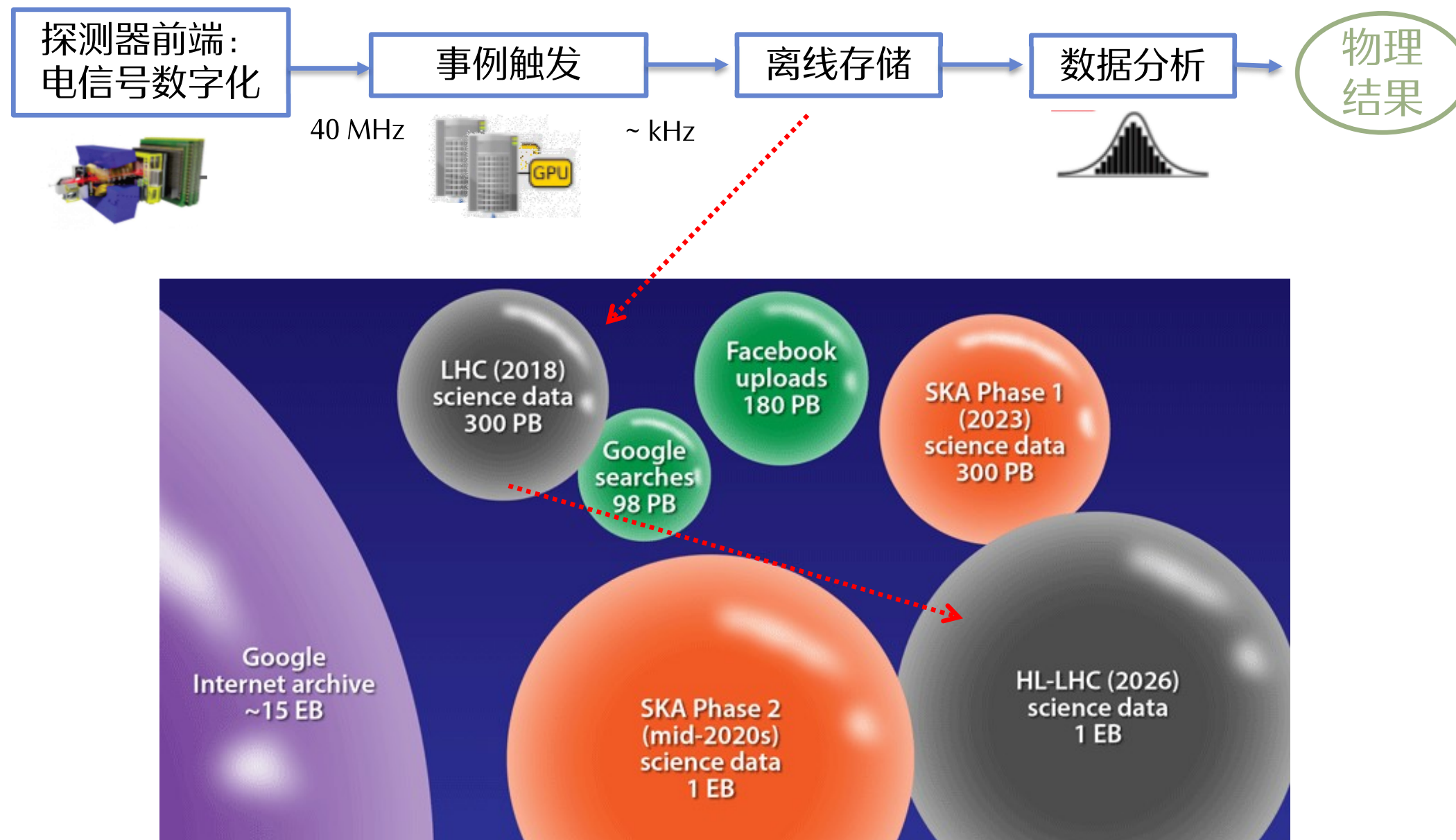
UT:
基于硅微条现有UT处
理不了UII的数据率;
占用率也将过高



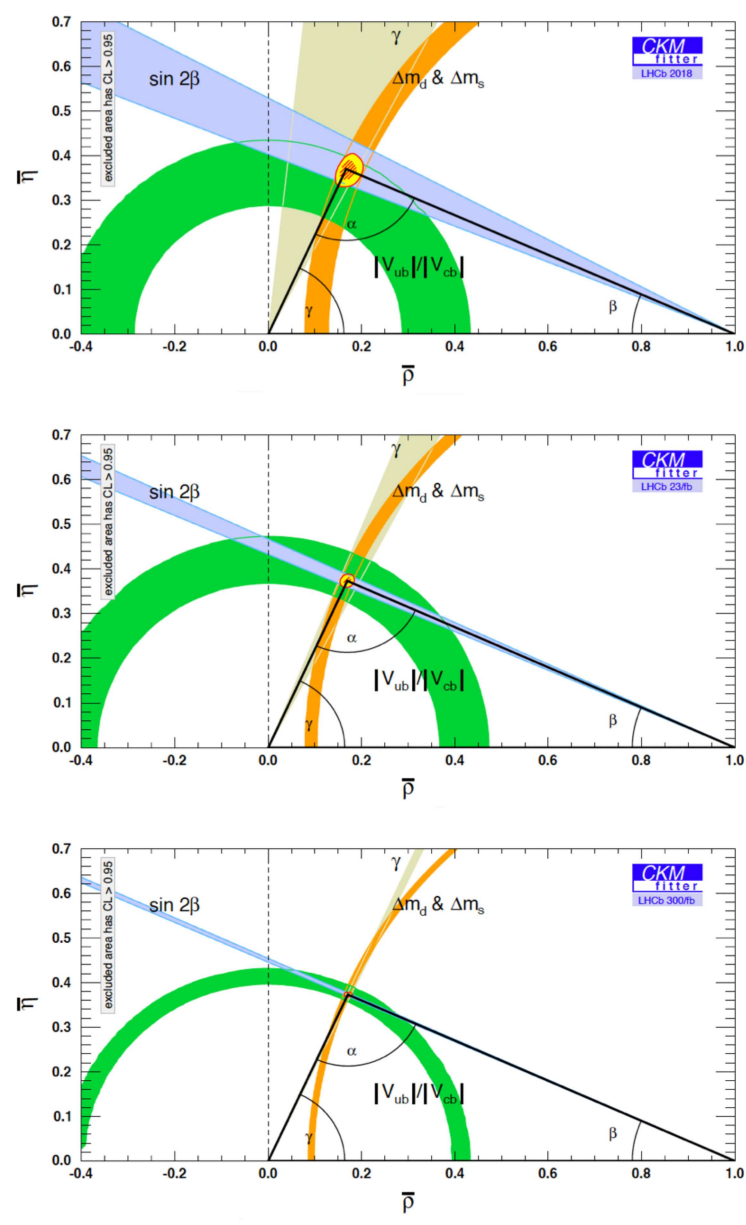
SciFi:
靠近束流部分光纤老化
严重, UIb/UII须更换



大数据挑战!



重味物理关键测量的未来展望



$\pm 33.0 \times 10^{-4}$	± 5.4	± 49	$\pm 28.0 \times 10^{-5}$	LHCb
				Current
$\pm 10.0 \times 10^{-4}$	± 1.5		$\pm 35.0 \times 10^{-5}$	Belle II
	± 1.5	± 14	$\pm 4.3 \times 10^{-5}$	ATLAS/CMS
				LHCb
				2025
$\pm 3.0 \times 10^{-4}$	± 0.35	± 22	$\pm 1.0 \times 10^{-5}$	
a_{sl}^s	$\gamma [^\circ]$	$\phi_s [mrad]$	A_Γ	HL-LHC

± 10.0	± 2.6	± 90	LHCb
			Current
± 3.6	± 0.50		Belle II
± 2.2	± 0.72	± 34	ATLAS/CMS
			LHCb
			2025
± 0.70	± 0.20	± 21	
$R_K [\%]$	$R(D^*) [\%]$	$\frac{B(B^0 \rightarrow \mu^+ \mu^-)}{B(B_s^0 \rightarrow \mu^+ \mu^-)} [\%]$	HL-LHC

总结

- 在高能物理对撞机上可以开展重要而丰富的重味物理研究
- 以LHCb为代表的探测器实验因其优秀而独特的设计性能取得一系列物理成果
- 未来还有新的实验挑战等待着我们！

谢谢！

欢迎联系
liyiming@ihep.ac.cn