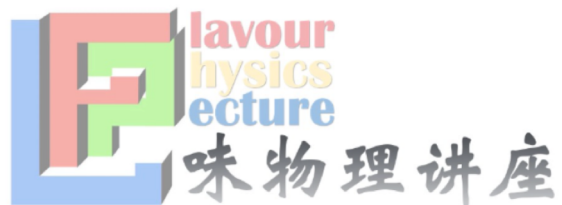


Detector for Flavour

重味物理探测器的现在和未来



中国科学院
高能物理研究所
李一鸣



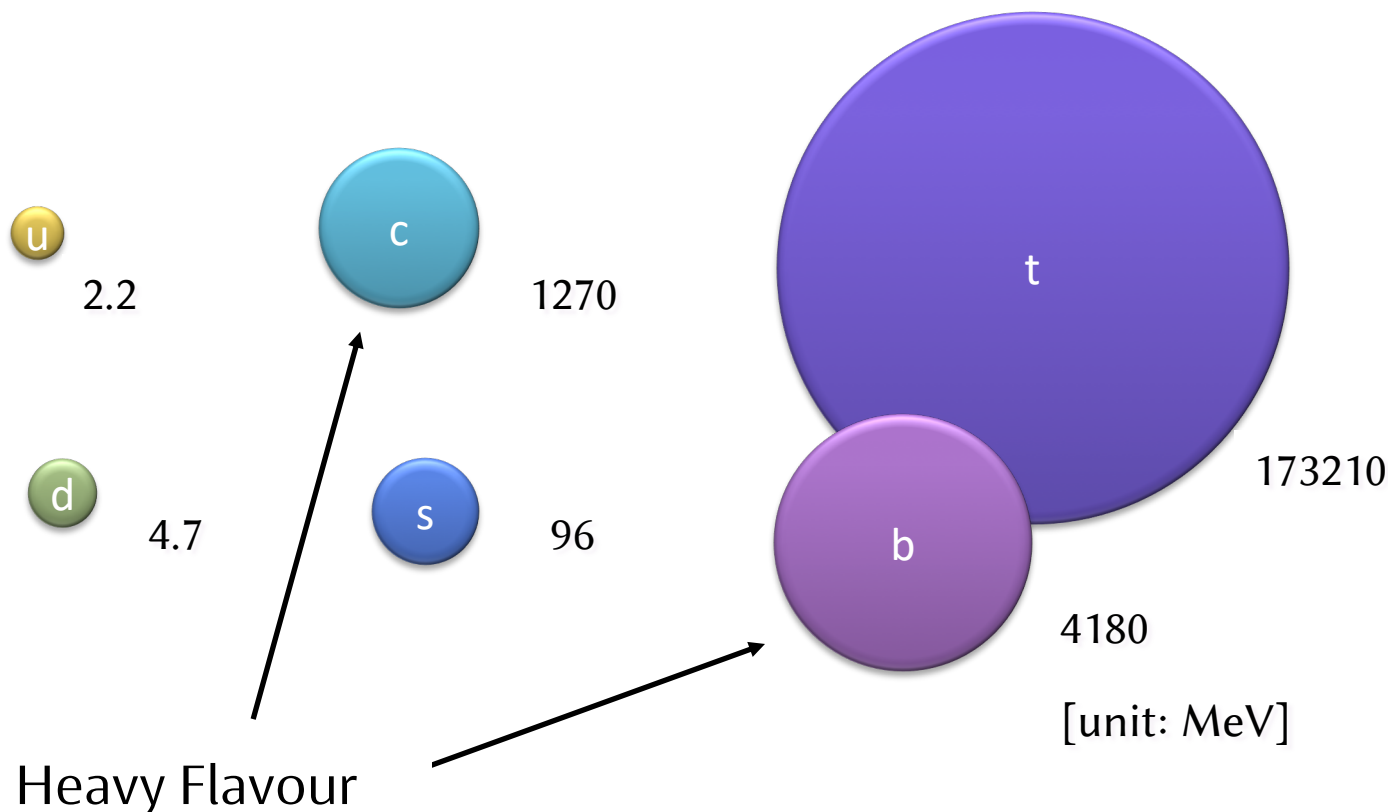
2022年5月19日

报告内容

- 重味物理研究什么？谁在研究？
- 探测器设计特点：以LHCb为例
 - 寻迹系统
 - 粒子鉴别
 - 味道标记
 - 数据处理
- 未来的重味物理实验

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 矩阵的参数是如何决定的？

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

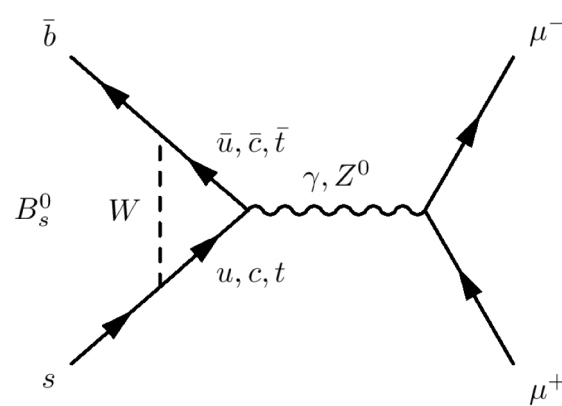
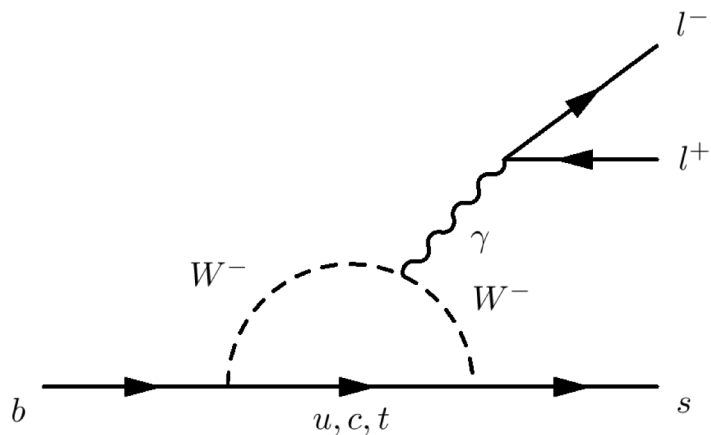
味物理的重要问题

- 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？

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

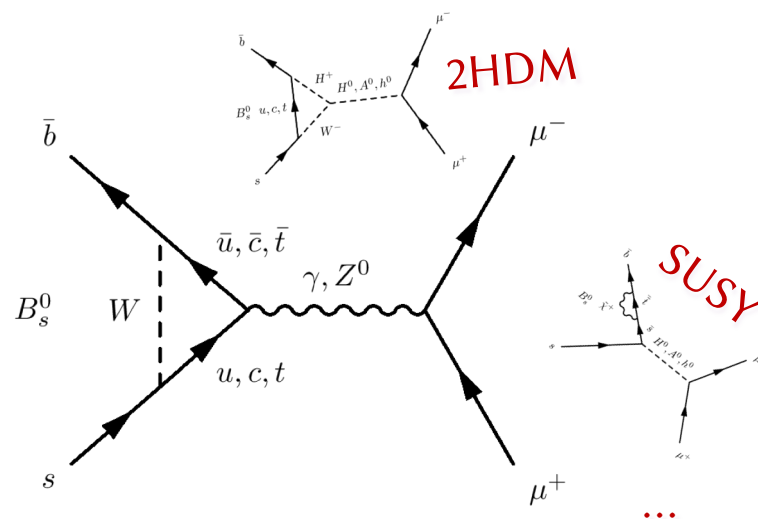
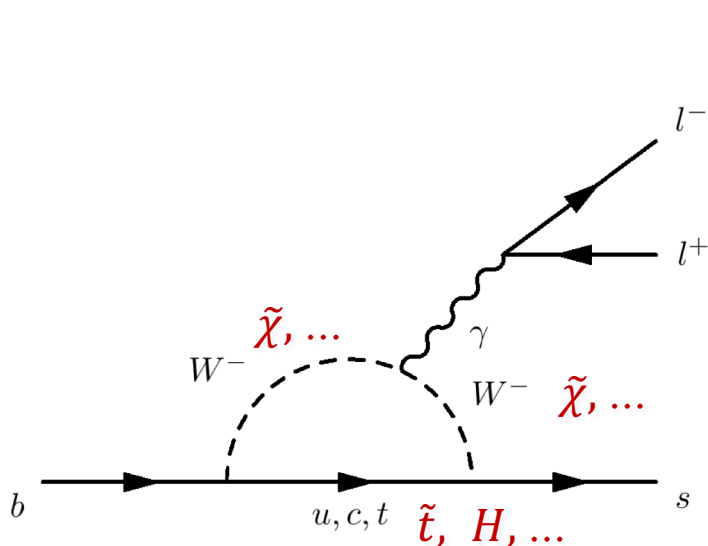
重味物理：探索新物理的手段

- 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

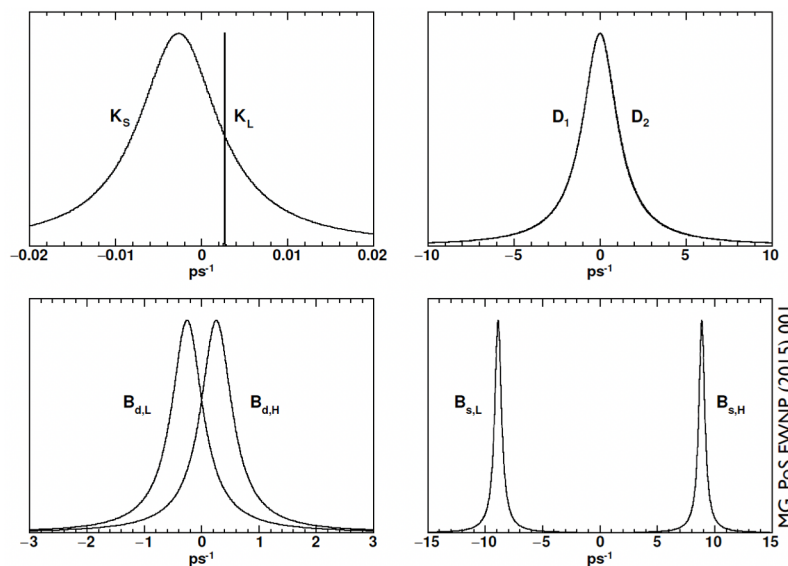


重味物理实验特点

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

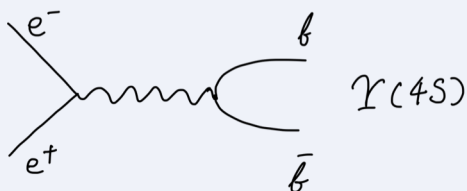
$$\Delta m = m_H - m_L$$

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

重味强子的产生

B工厂/强子对撞/Z工厂

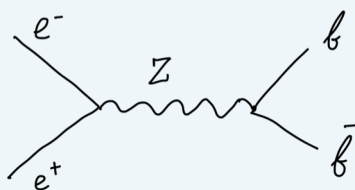
B 工厂



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

- 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

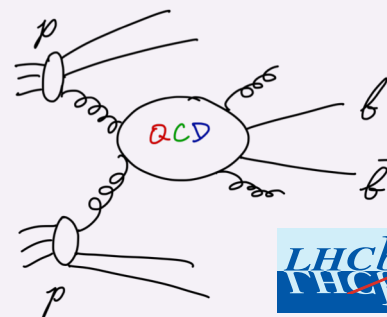


@LEP

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

- 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

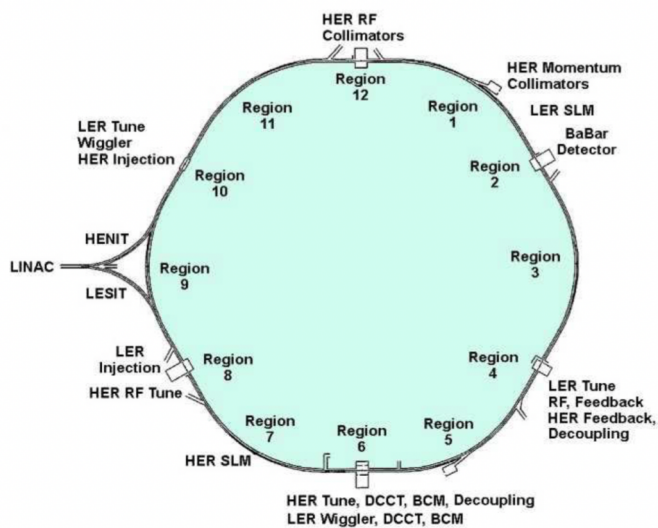
高能强子对撞



@LHC

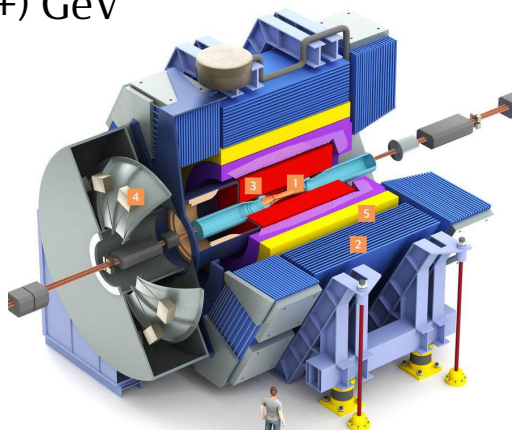
$$\sigma(b\bar{b}) \sim \mathcal{O}(10^2) \mu\text{b}$$

- 产生截面大
- 多种b强子
- 通常很大boost



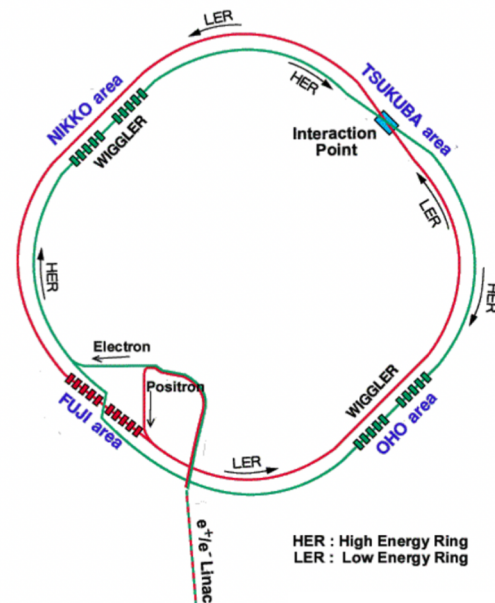
PEP-II @ SLAC
9.0 (e⁻)/ 3.1 (e⁺) GeV

~ 470 M $B\bar{B}$



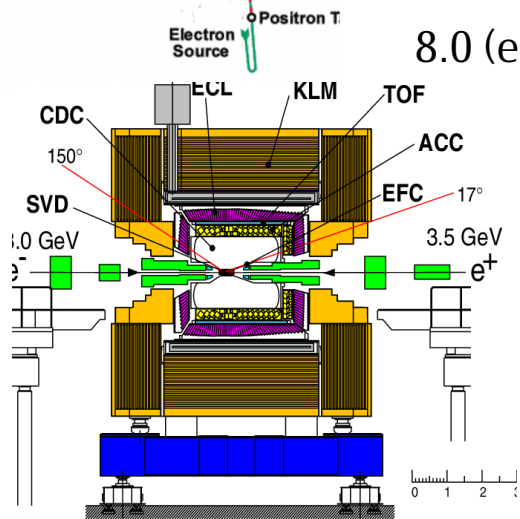
COLOUR KEY

- Superconducting magnet coil
- Drift/tracking chamber
- Electron/photon detector
- Muon/hadron detector
- Support tube
- Vertex detector

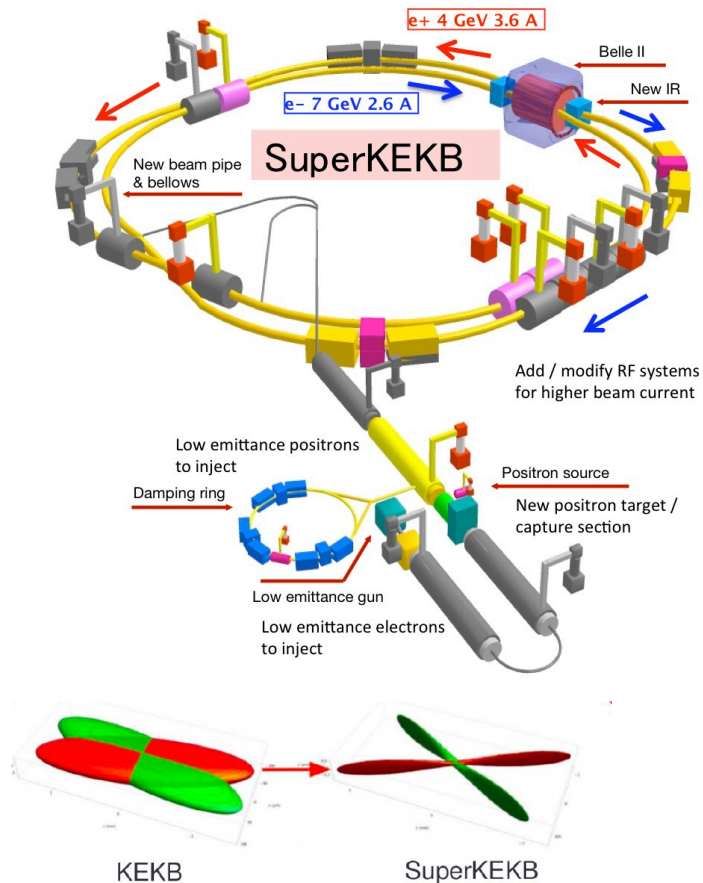


KEKB @ KEK
8.0 (e⁻)/ 3.5 (e⁺) GeV

~ 770 M $B\bar{B}$

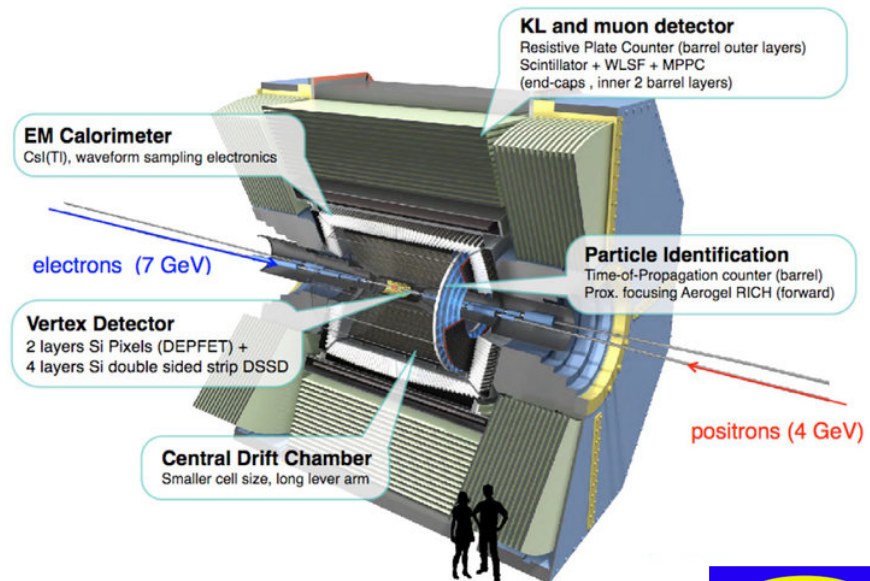


SuperKEKB 和 Belle II



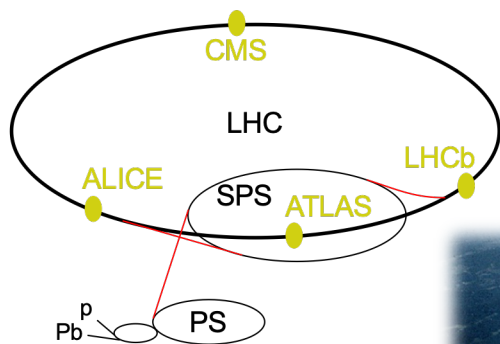
“nano-beam” scheme
Beam squeezing: x20 smaller at IR

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

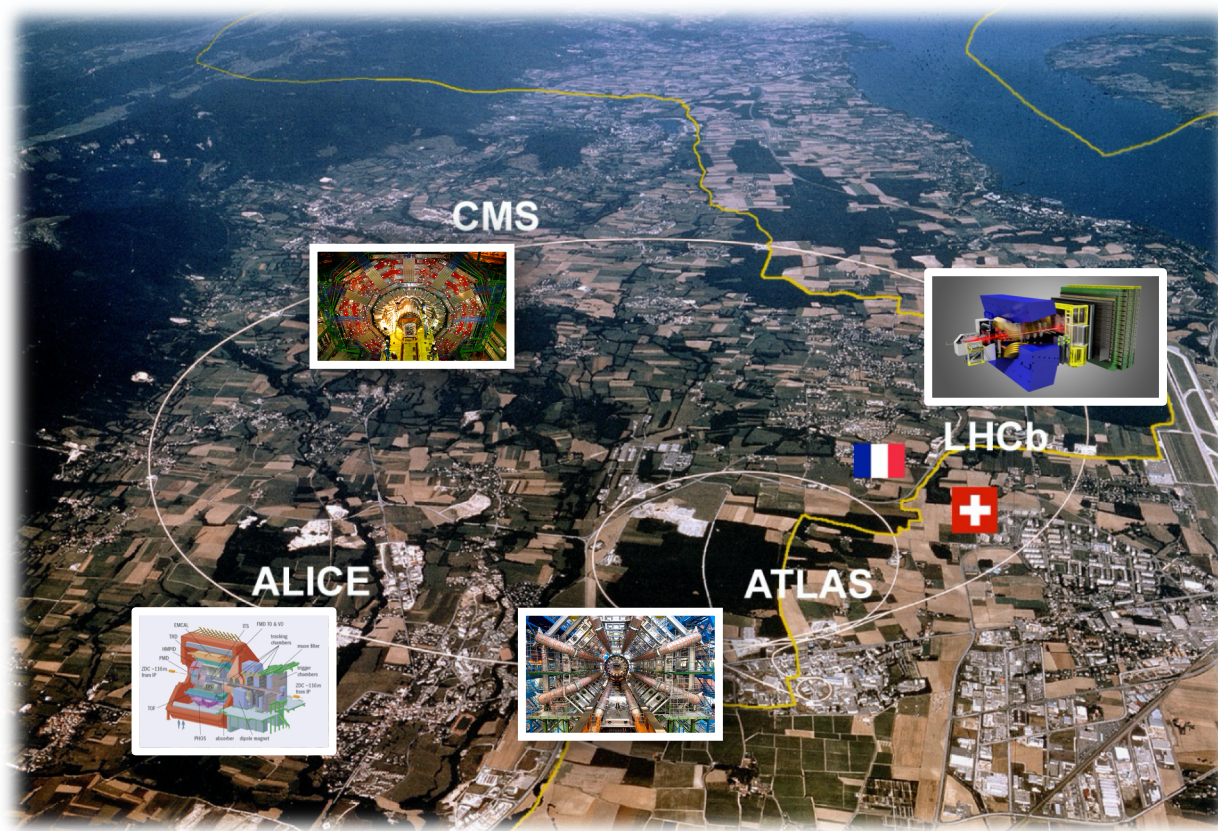


3月24日味物理讲座, 王小龙
<https://indico.ihep.ac.cn/event/15900/>

大型强子对撞机

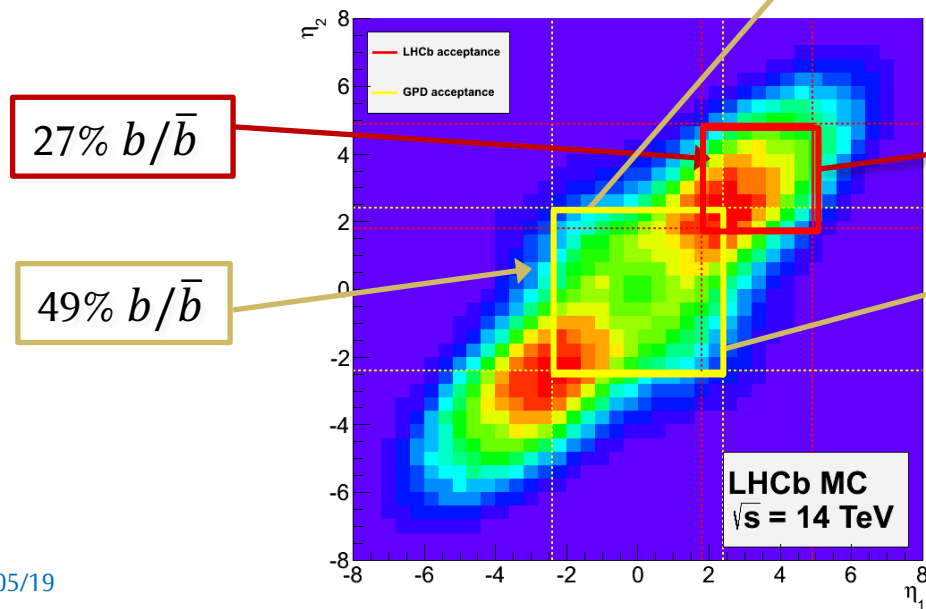
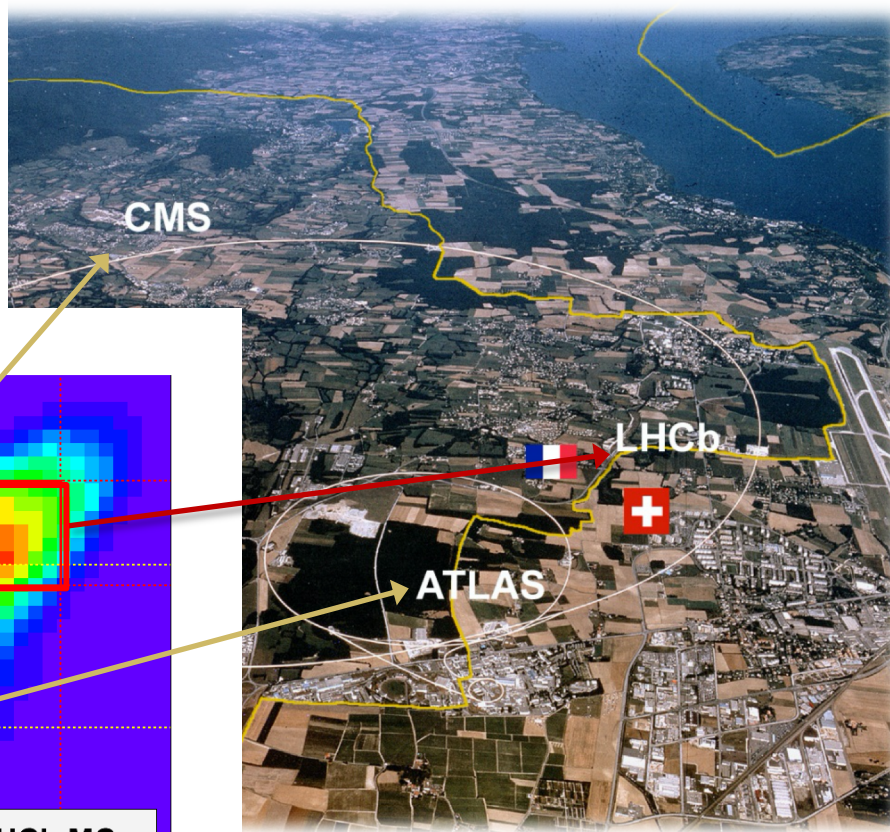
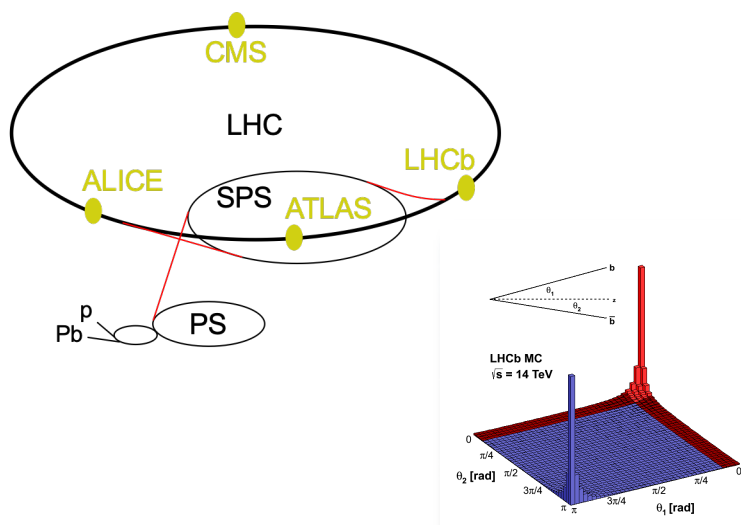


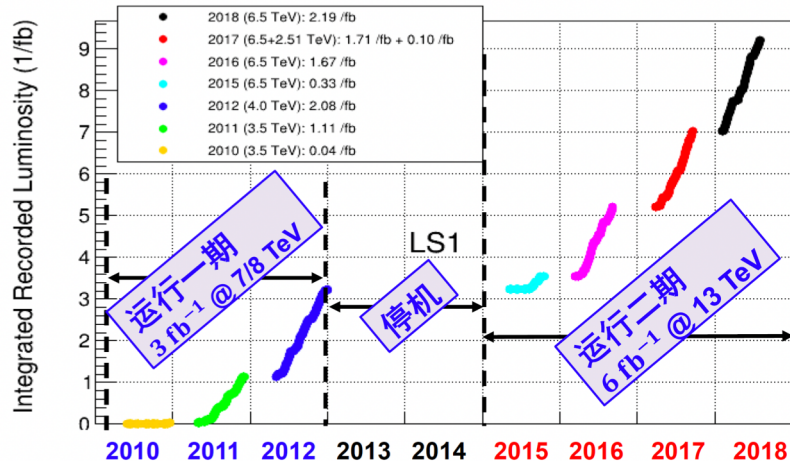
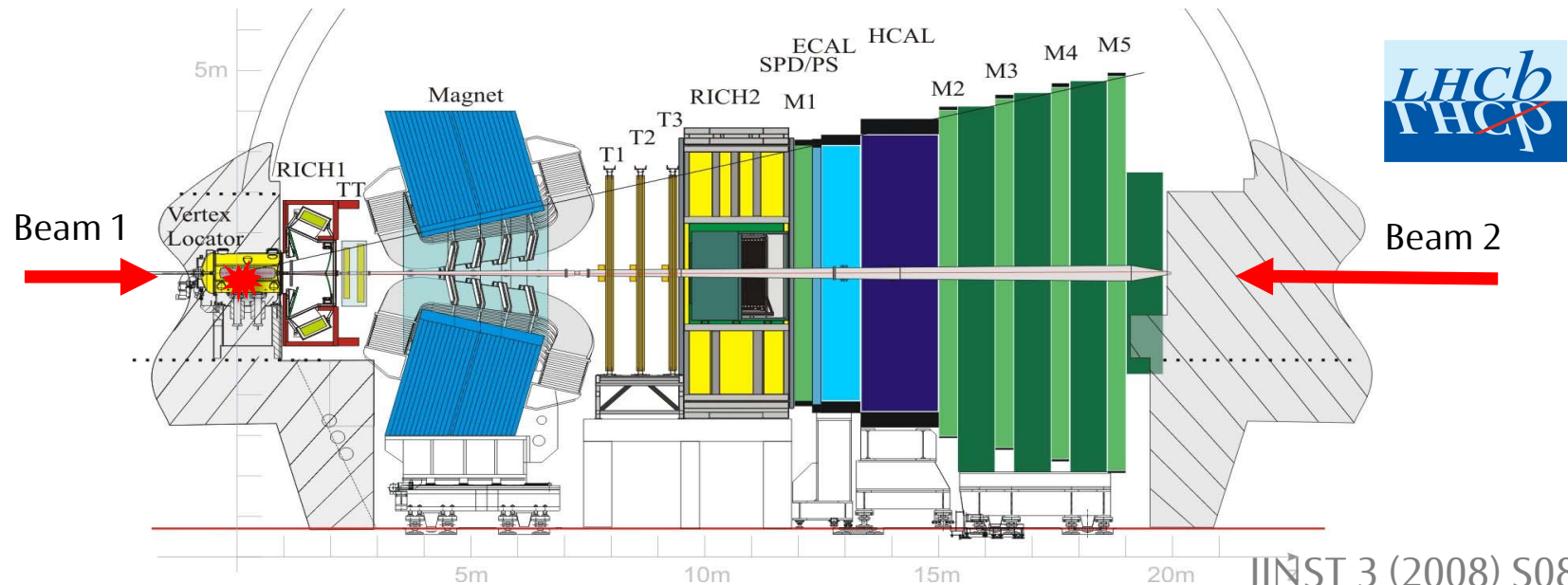
pp 对撞/ 质心能量 13 TeV / 周长 27km



大型强子对撞机

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

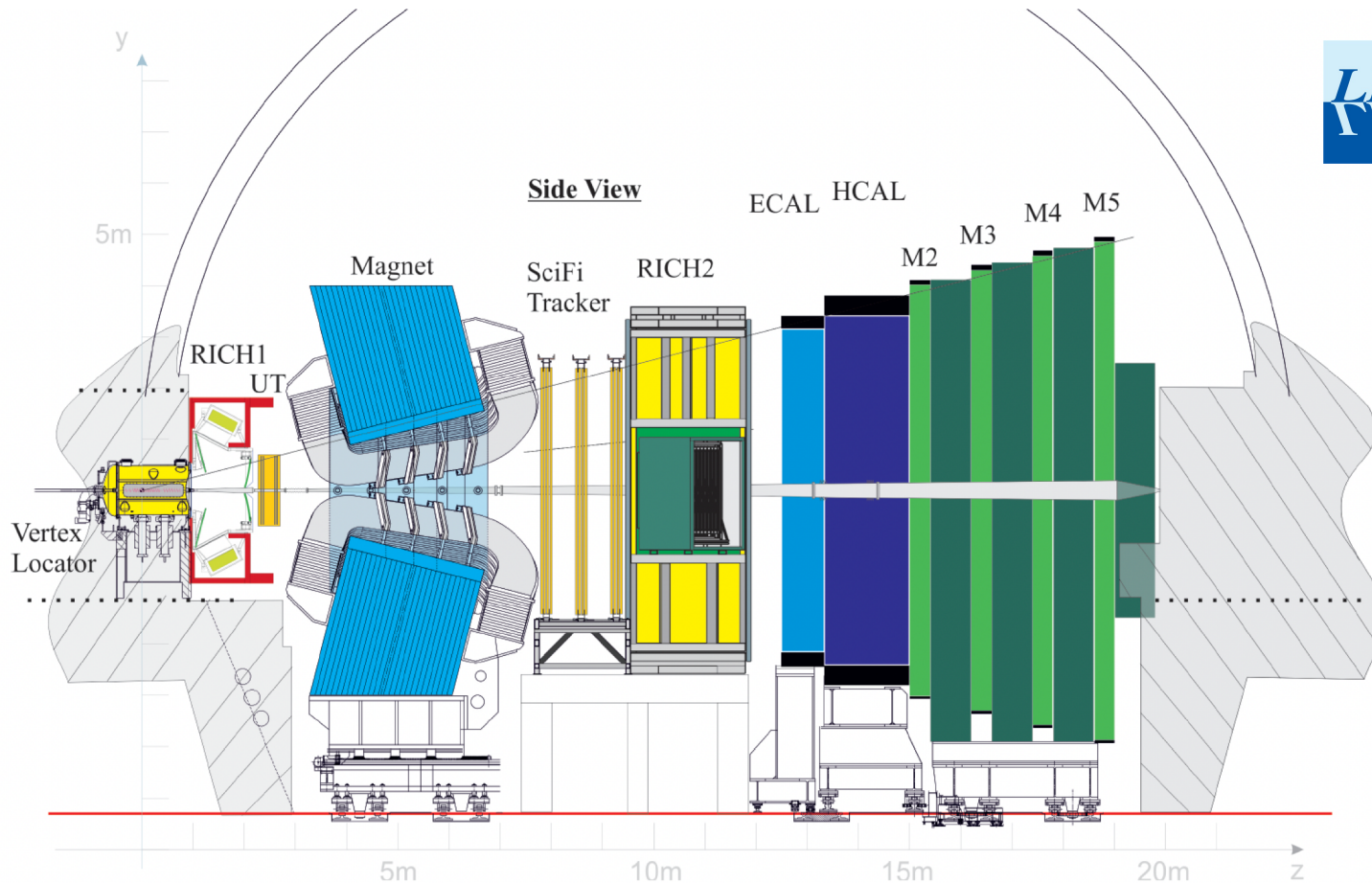




JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

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



$\mathcal{L}: 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
 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

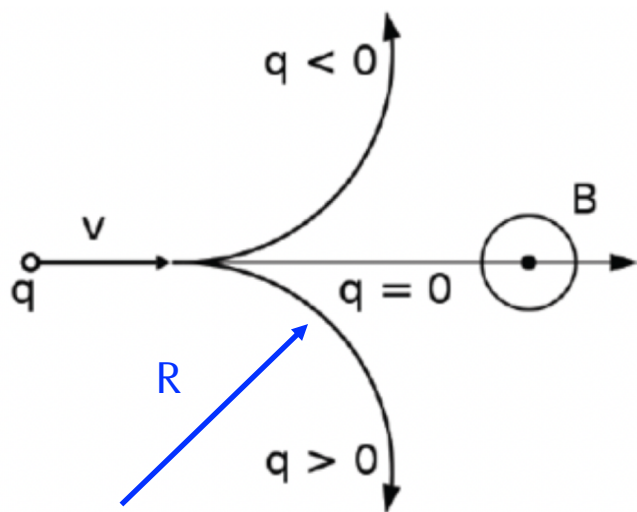
味标记

数据处理

重味物理探测器的要素：以LHCB为例

带电径迹重建

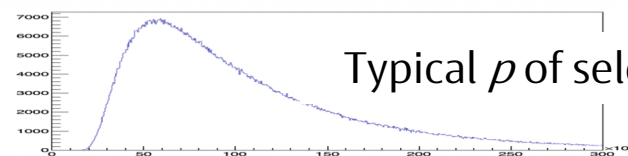
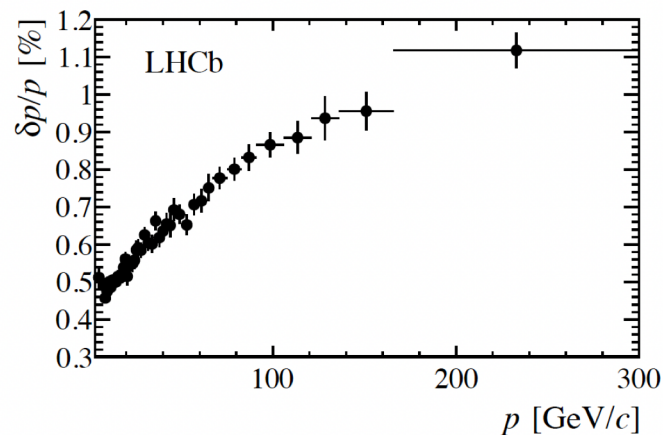
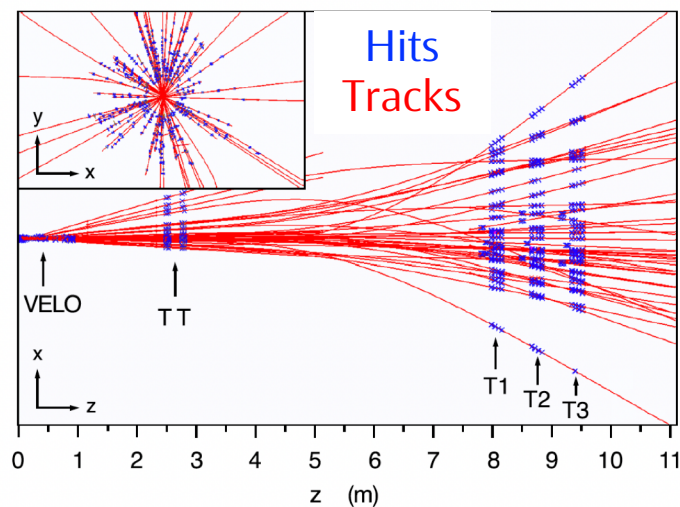
■ 磁场 + 探测器



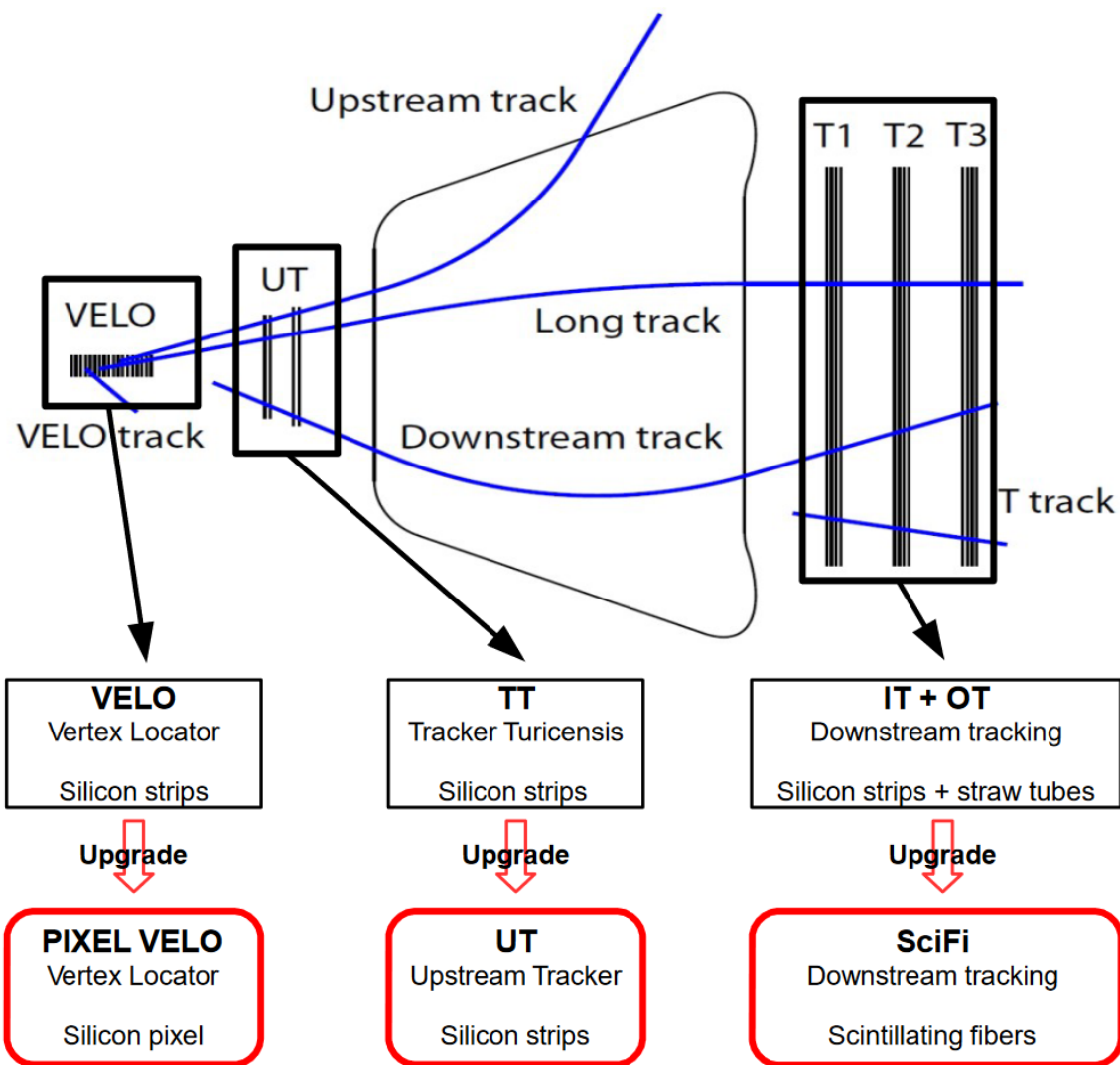
$$R = p / (q B)$$

偏转方向 → 电荷 q

偏转半径 → 动量 p

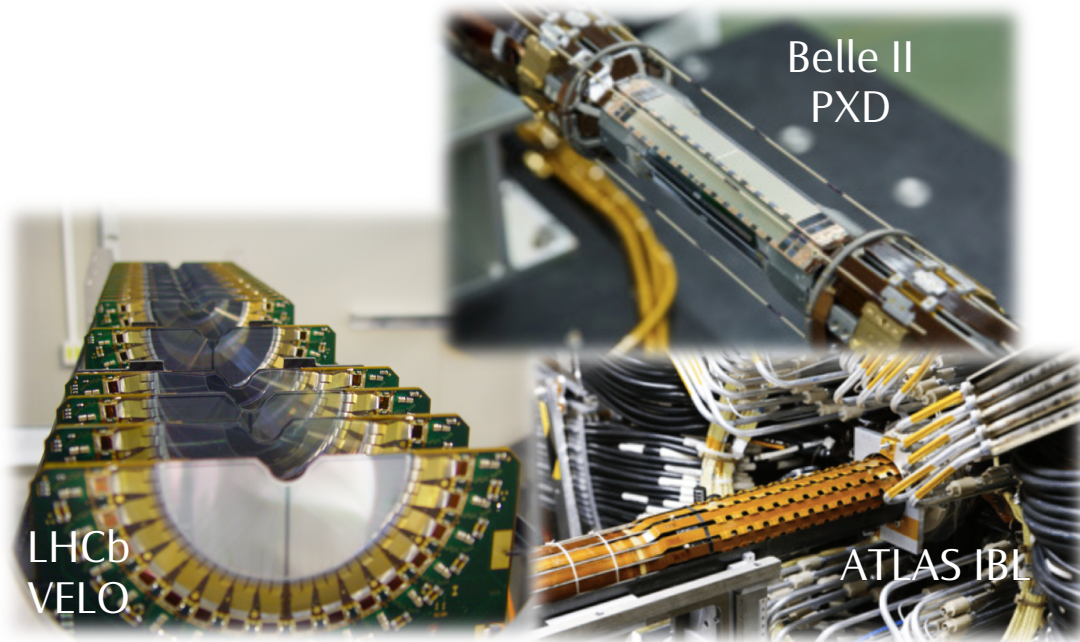
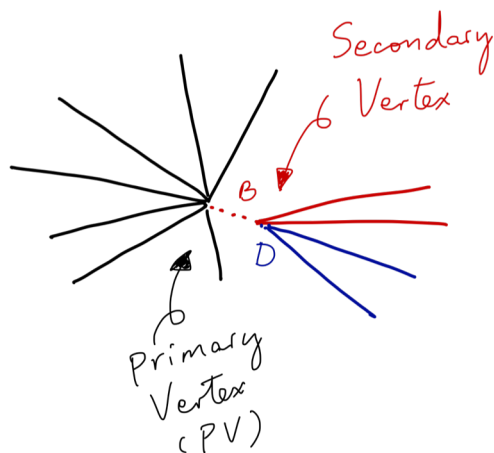


LHCb径迹重建系统



顶点重建

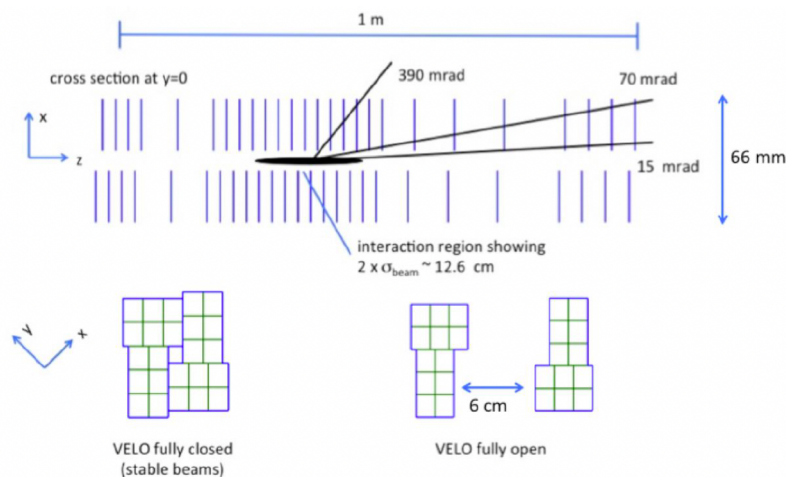
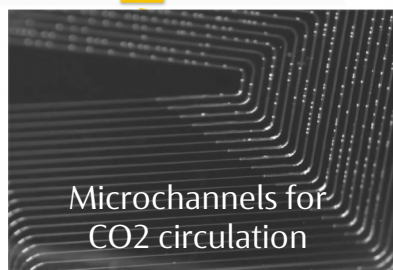
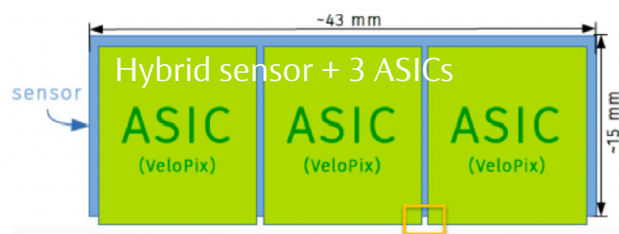
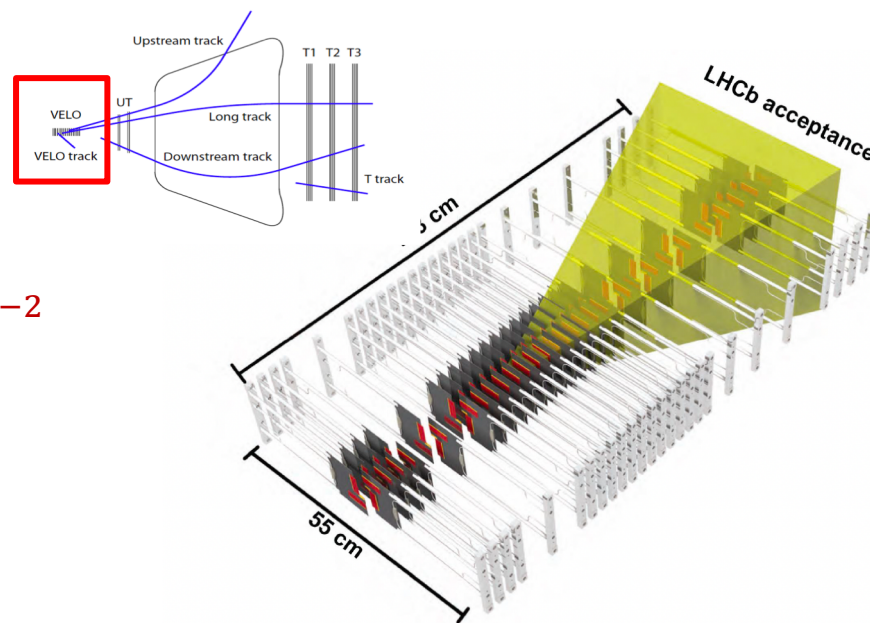
- 基态 B 介子弱衰变 $\tau(B) \sim 1.6 \text{ ps}$
 - 从产生（初级对撞顶点）到衰变（次级顶点）可飞行一段距离
 - 几百微米到几毫米，取决于boost
- 需要极高定位精度的径迹探测器重建出衰变顶点
 - 点定位精度100um以内，甚至可达几微米
- 如果存在事例堆积(pile-up)，顶点探测器还需区分出不同PV



VELO 顶点探测器

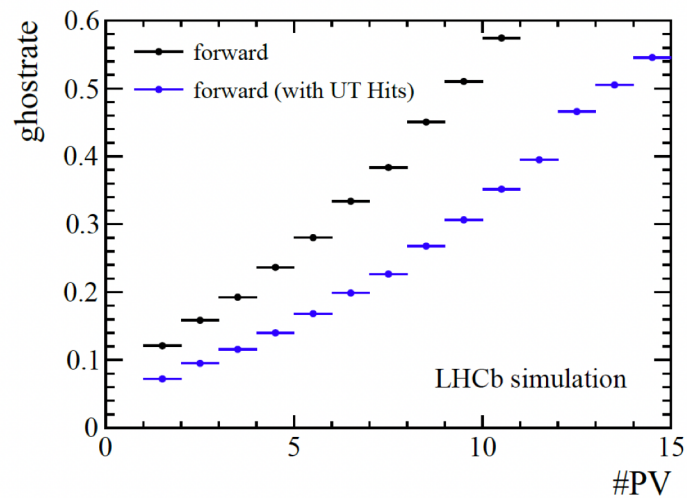
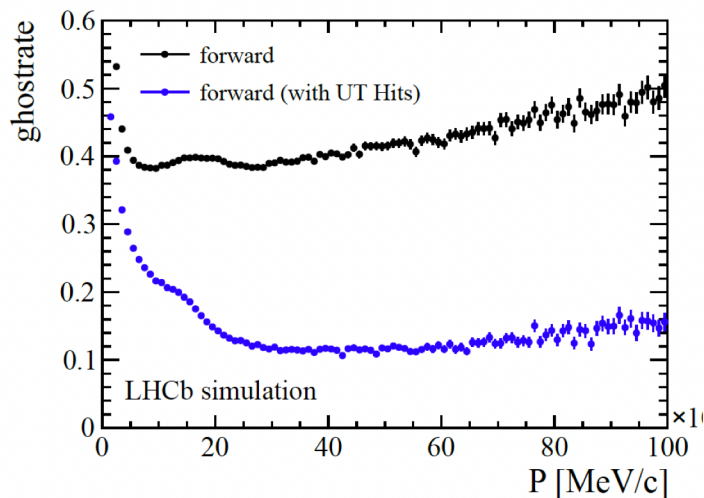
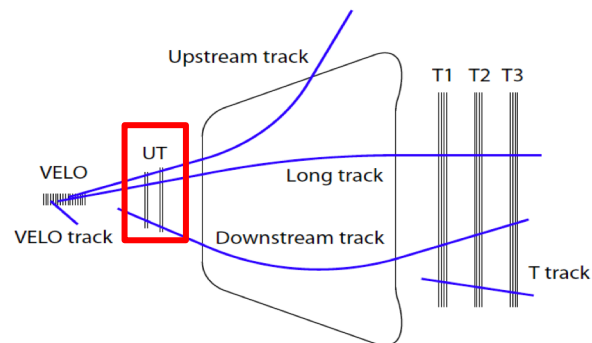
由硅微条升级为硅像素探测器

- 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



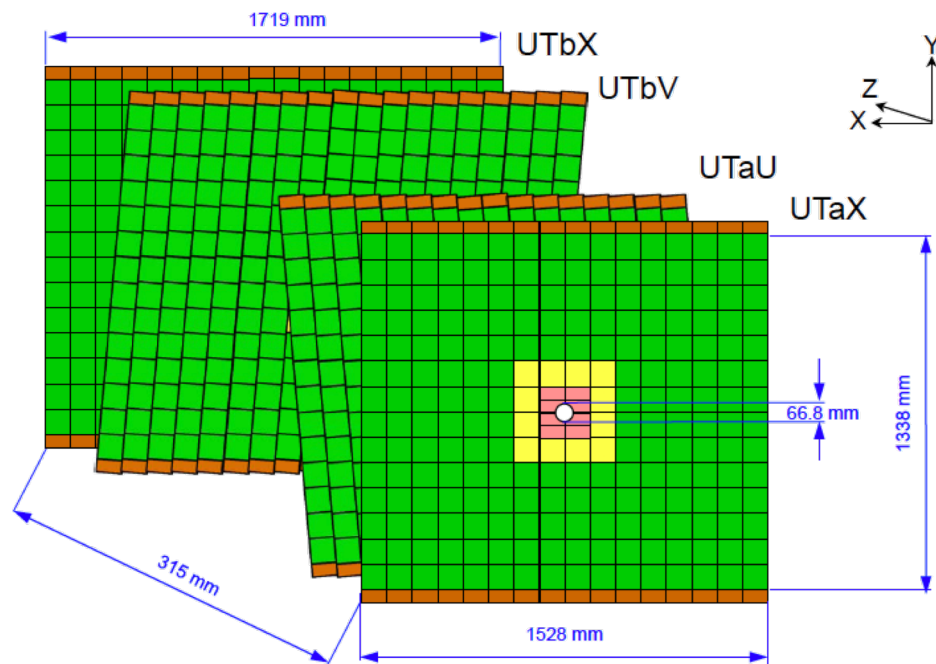
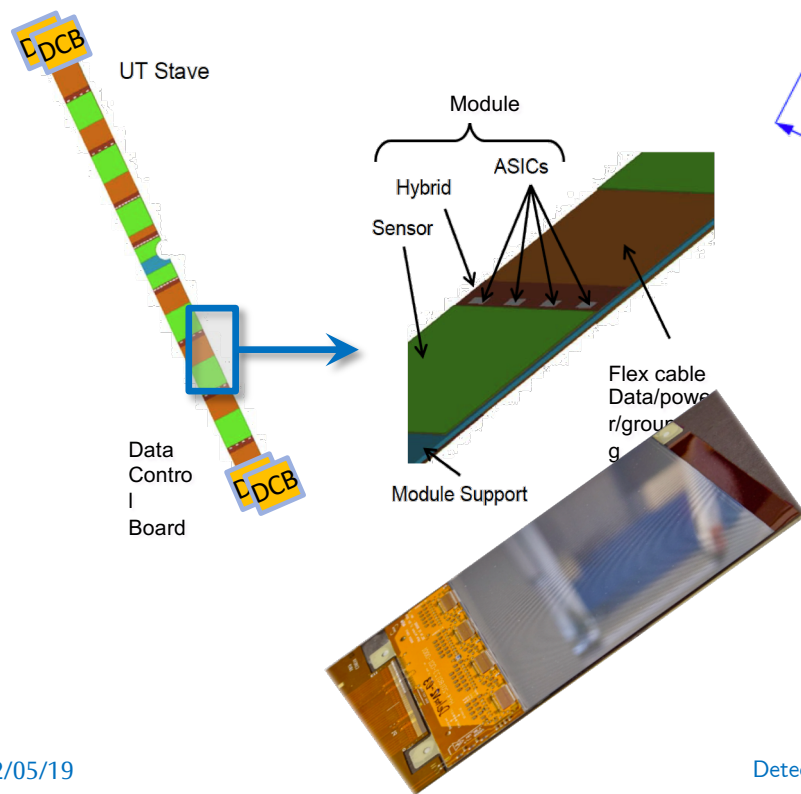
UT 上游径迹探测器

- 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

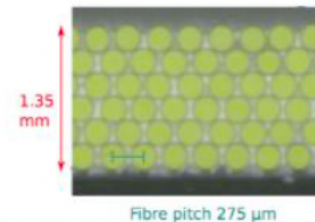
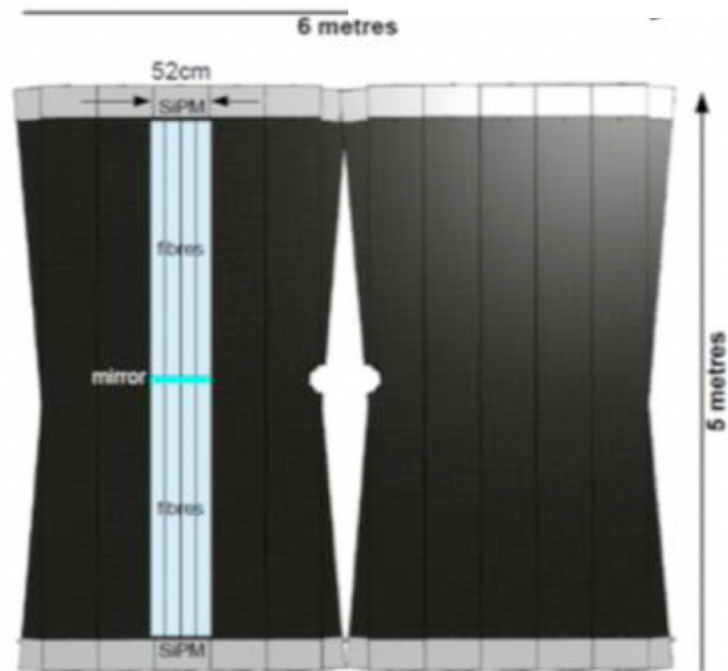
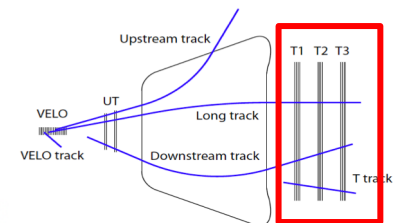
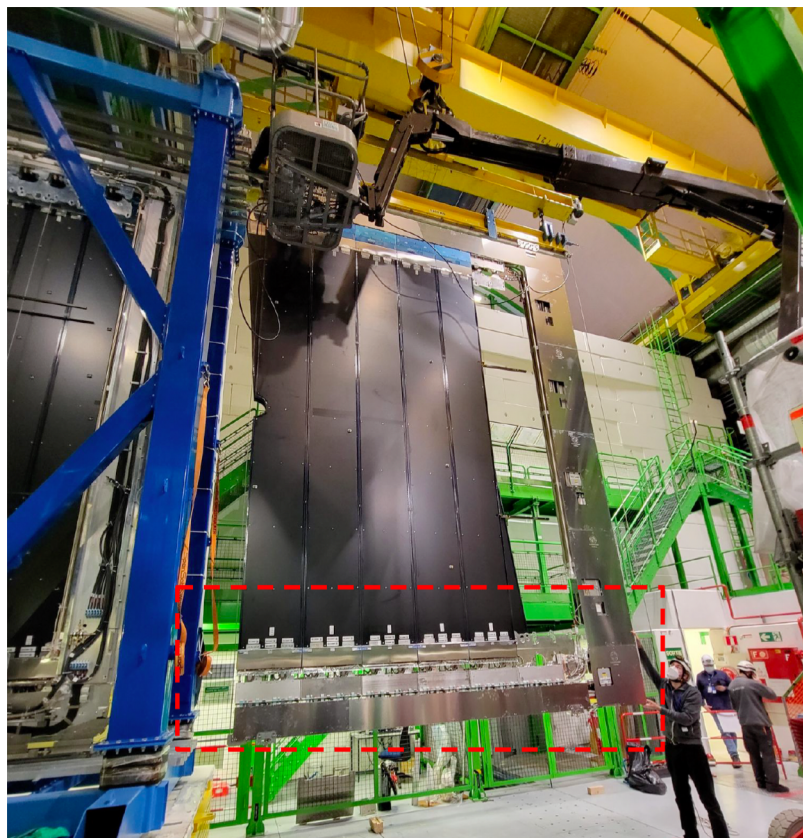
基于硅微条传感器



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

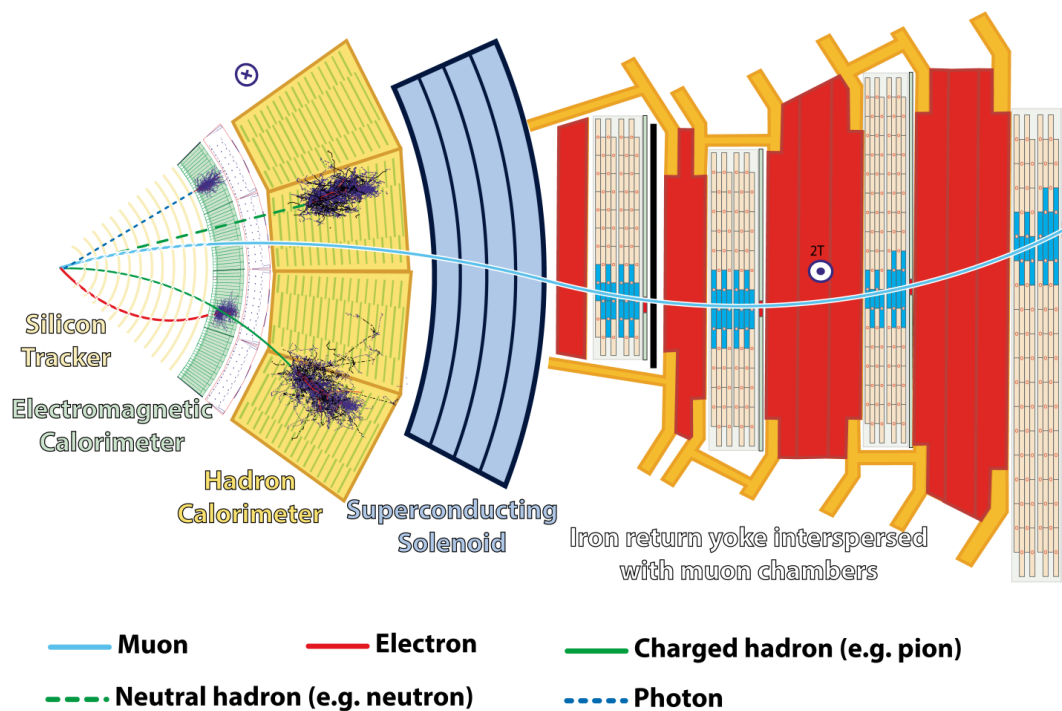
SciFi 闪烁体光纤下游探测器

- 闪烁体光纤+SiPM读出
- X方向单点分辨率好于100 μm



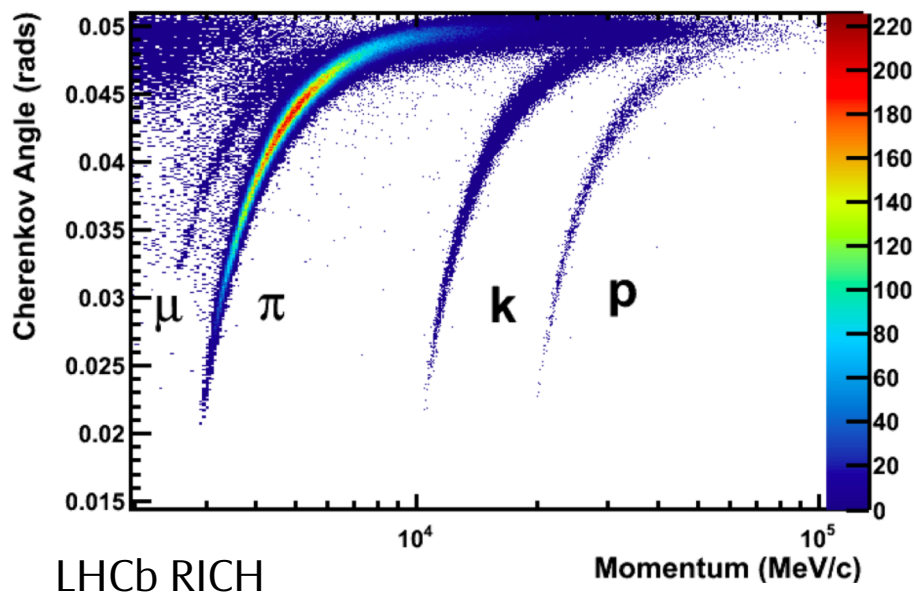
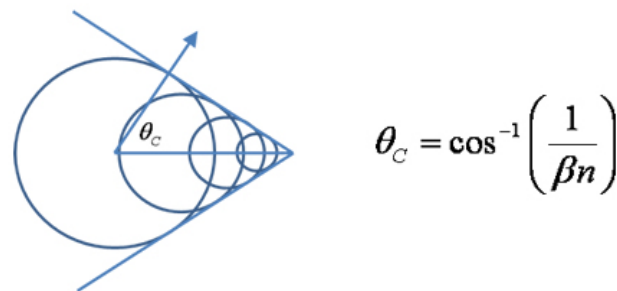
粒子鉴别

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

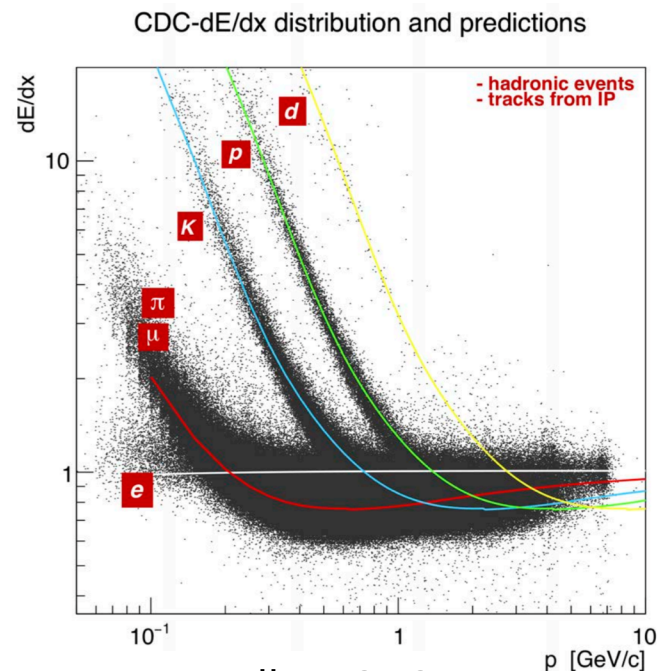


强子鉴别

- 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



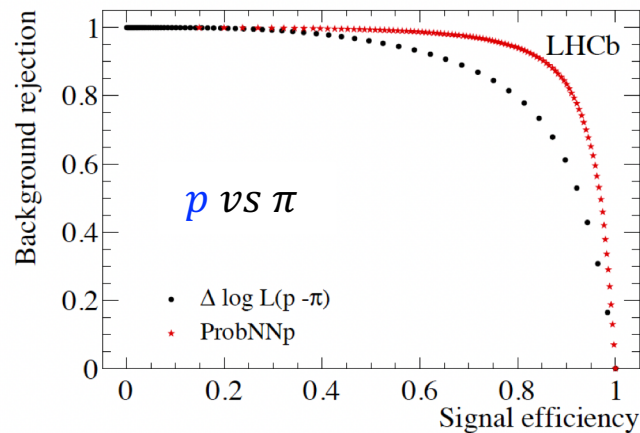
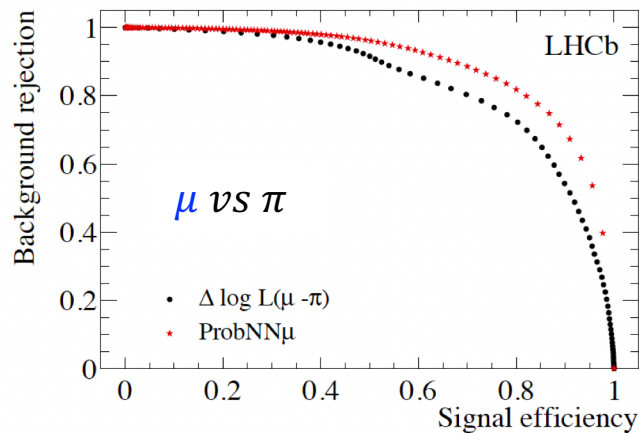
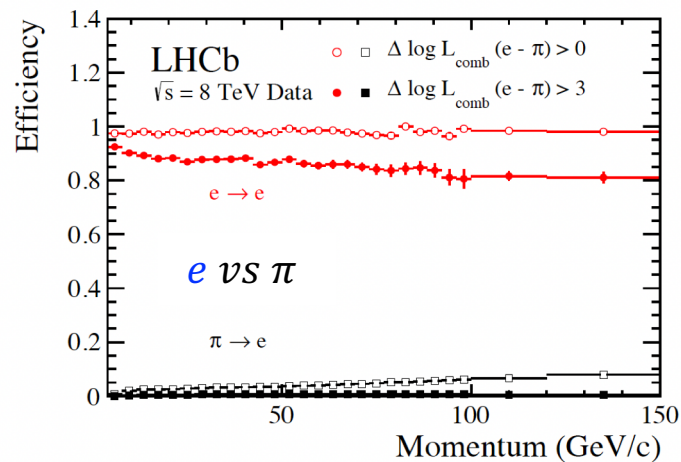
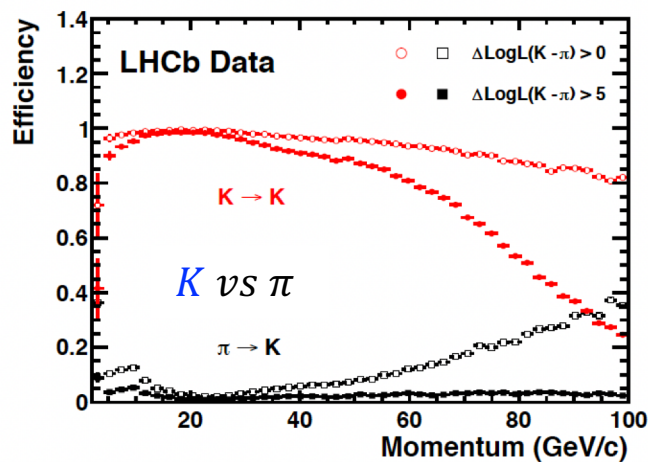
LHCb RICH



Belle II CDC

LHCb PID性能

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

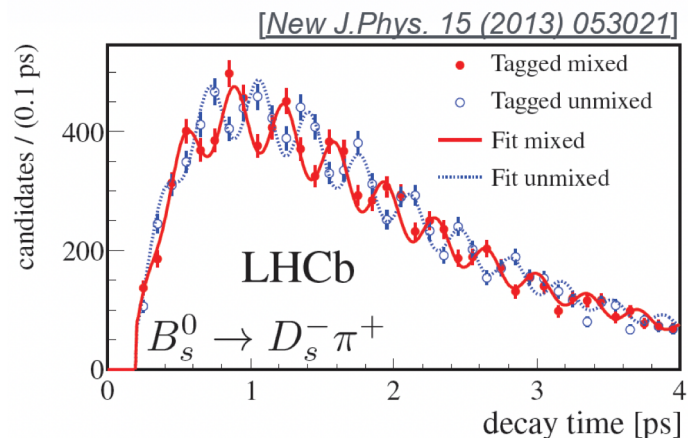


味道标记 Flavour Tagging

- 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

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}_q^0(t) \rightarrow f) - \Gamma(B_q^0(t) \rightarrow f)}{\Gamma(\bar{B}_q^0(t) \rightarrow f) + \Gamma(B_q^0(t) \rightarrow f)}$$

$$= \frac{\mathcal{S}_f \sin(\Delta m t) - \mathcal{C}_f \cos(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \mathcal{A}_{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right)}$$



■ 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.

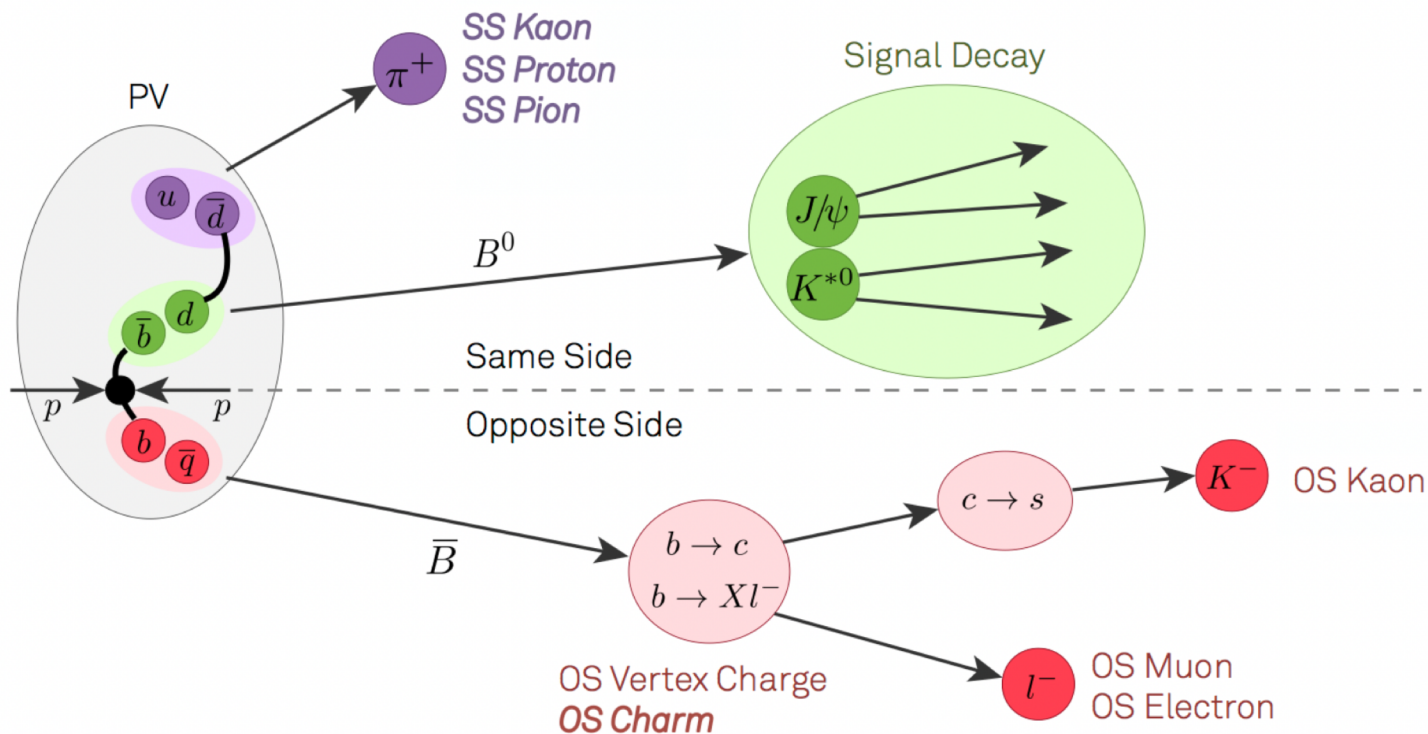
$$\epsilon_{\text{tag}} = \frac{N_{\text{right}} + N_{\text{wrong}}}{N_{\text{right}} + N_{\text{wrong}} + N_{\text{untagged}}}$$

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

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

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 ($t=0$)

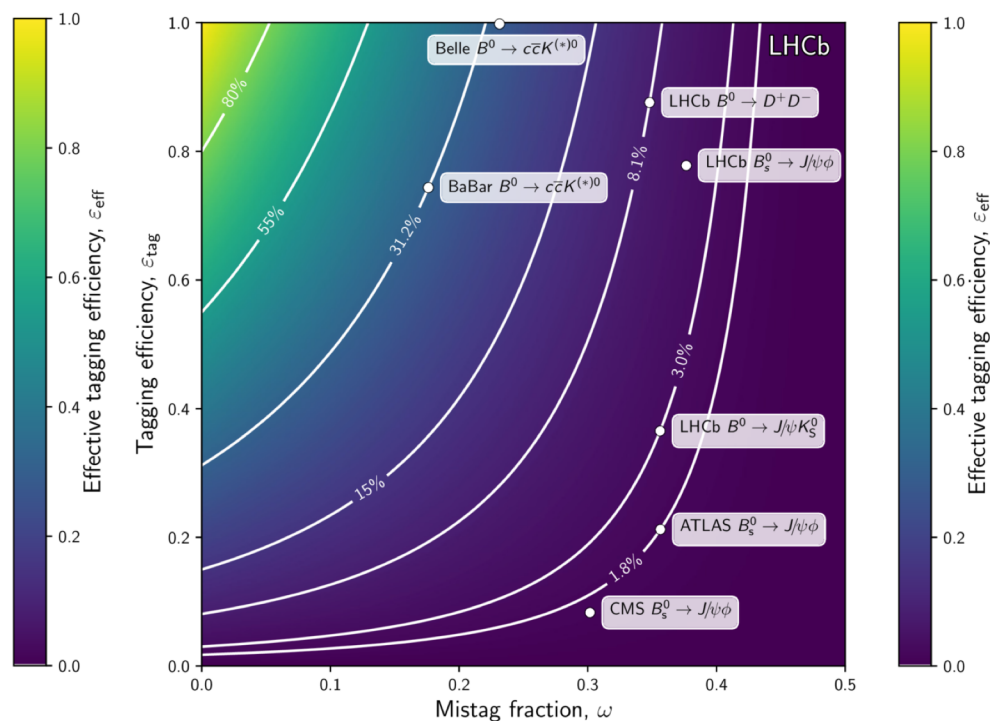
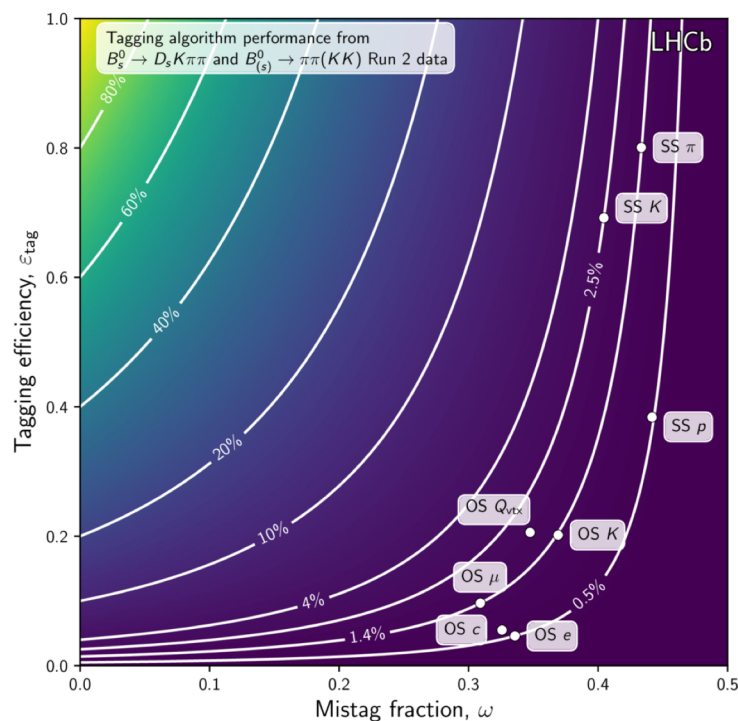


Opposite side (OS): exploit the charge of the particle (lepton, kaon, charm decays) or of the **reconstructed secondary vertex produced from the other b -hadron** in the event to infer signal b -hadron initial flavour ($t=0$)

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

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

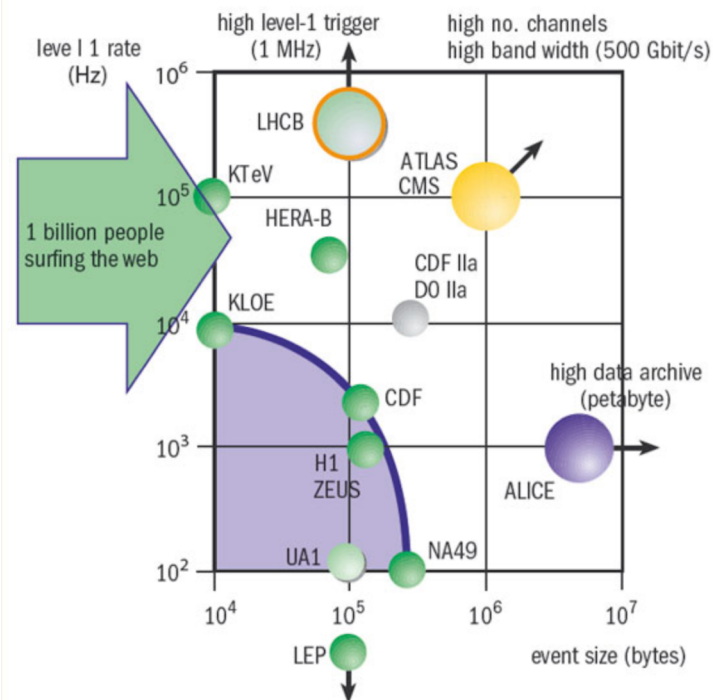
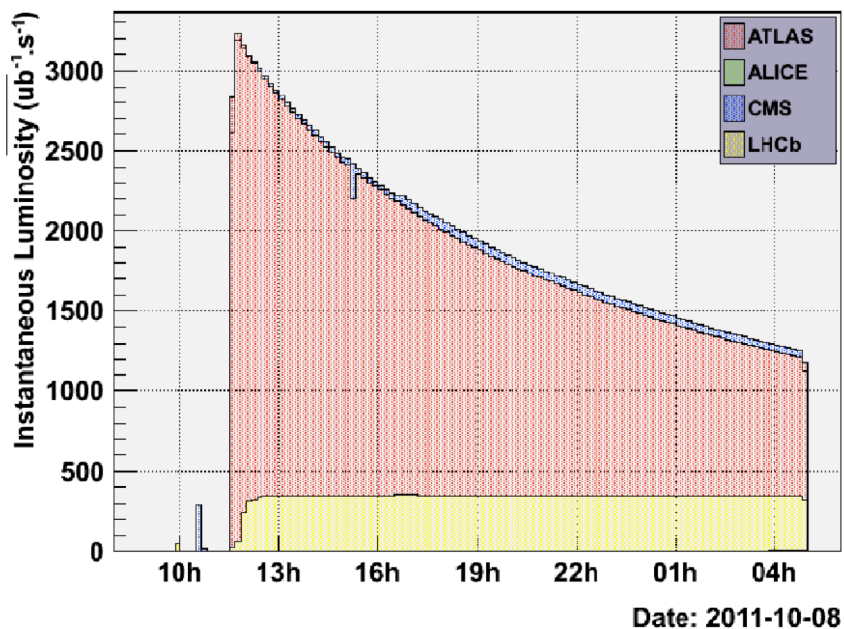


数据处理挑战

■ B衰变末态多

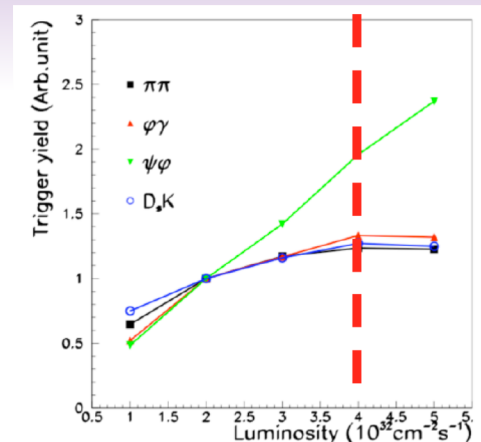
- 必须保证所有感兴趣的末态能被触发!

■ 虽然LHCb上即时亮度低于ATLAS/CMS, 触发率更高

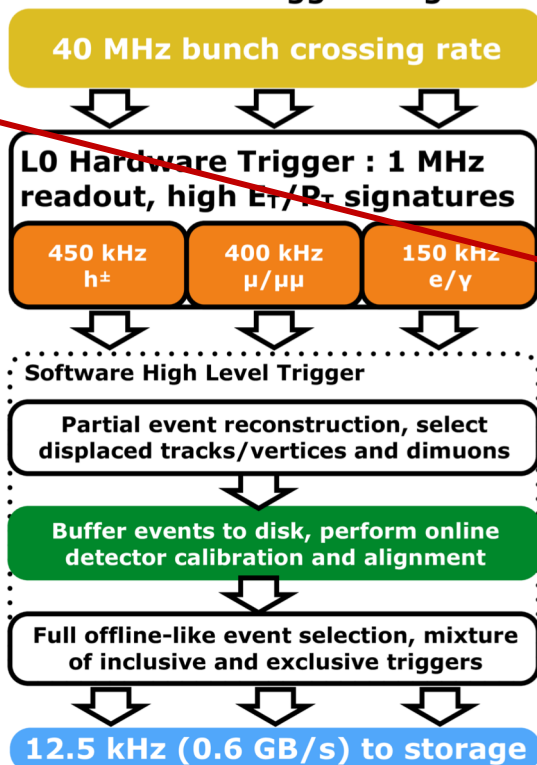


LHCb触发系统的演化

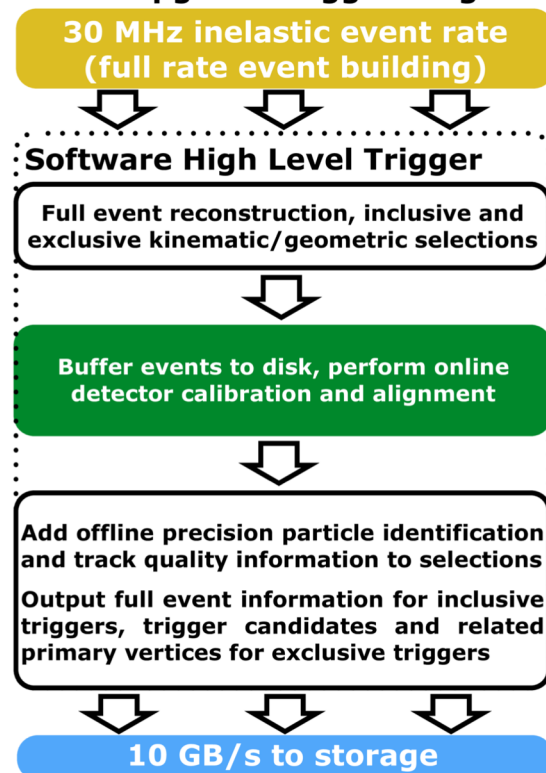
- 为什么不能一开始高亮度运行？
 - 1MHz硬件触发：纯强子末态在高亮度下触发饱和
 - 探测器占用率过高；辐照引起寿命减少
- 升级关键：移除硬件触发！



LHCb Run 2 Trigger Diagram



LHCb Upgrade Trigger Diagram



近期亮点

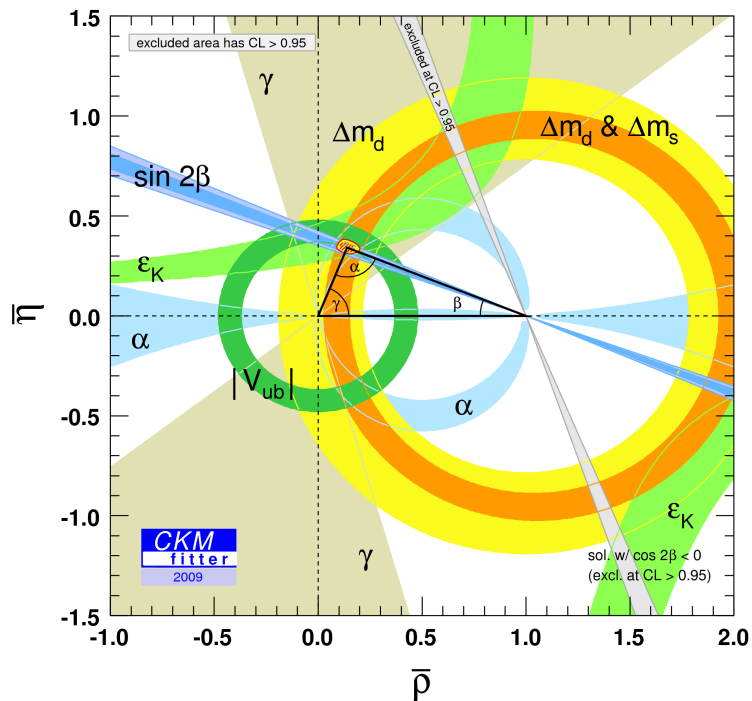
未来的实验

对重味探测器的新挑战

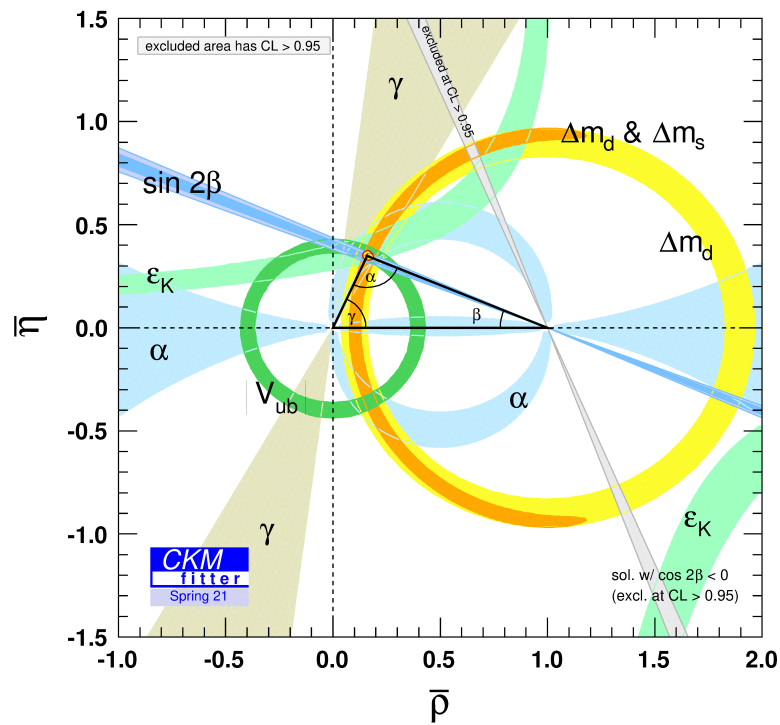
重味物理实验的未来

重味物理取得丰硕成果

2009



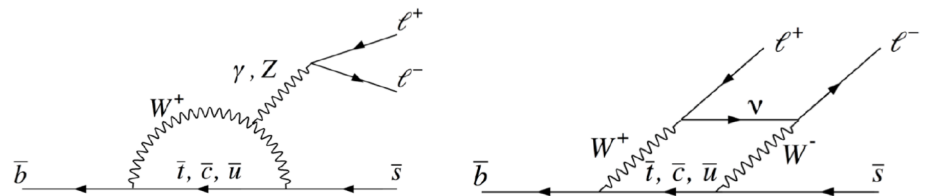
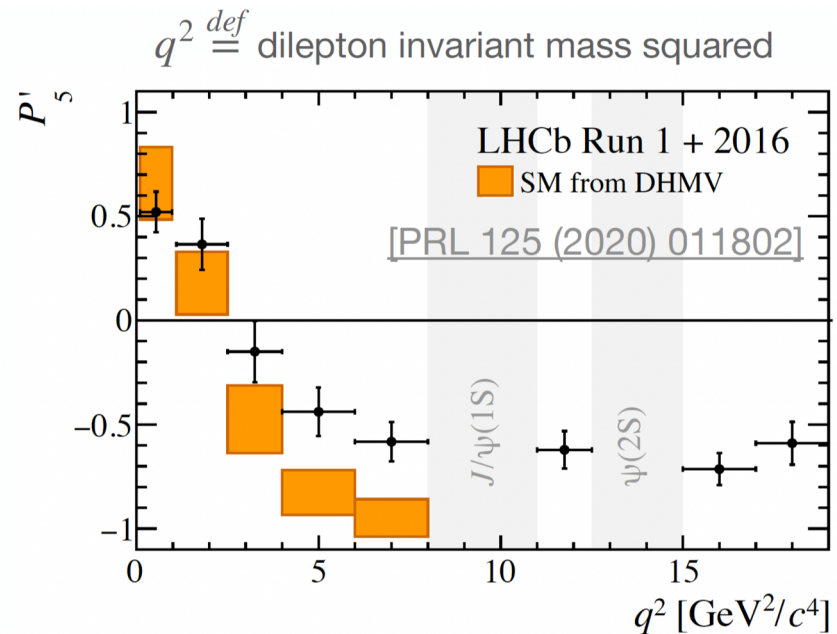
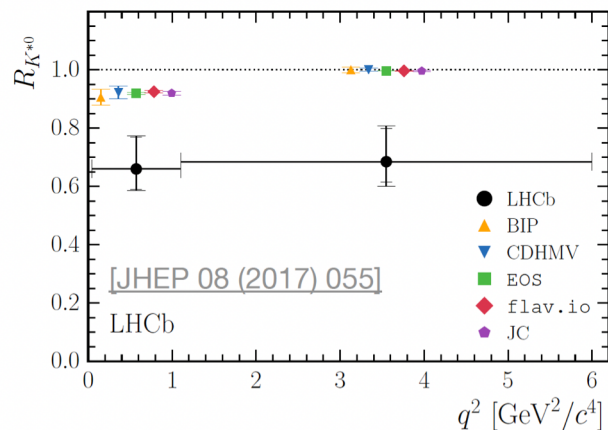
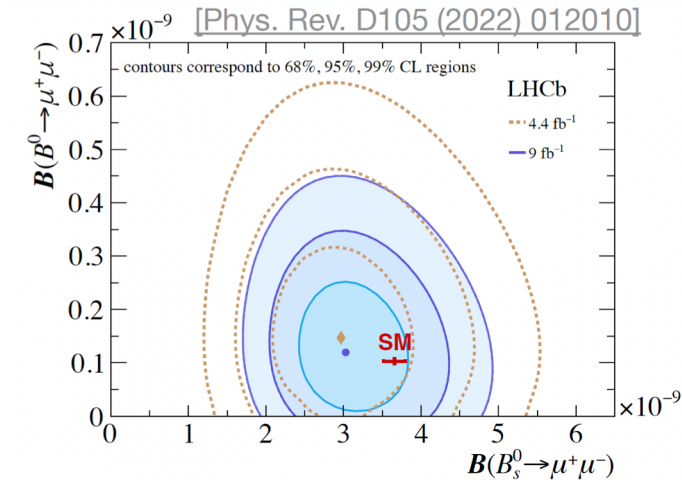
2021



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

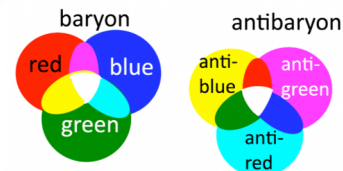
Tension with SM?

- 一系列稀有衰变的精确测量显示与SM有2-3sigma的差距

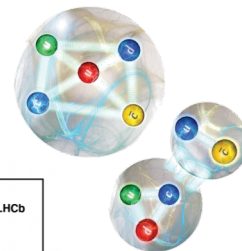
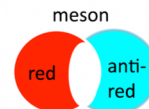


新强子态大发现

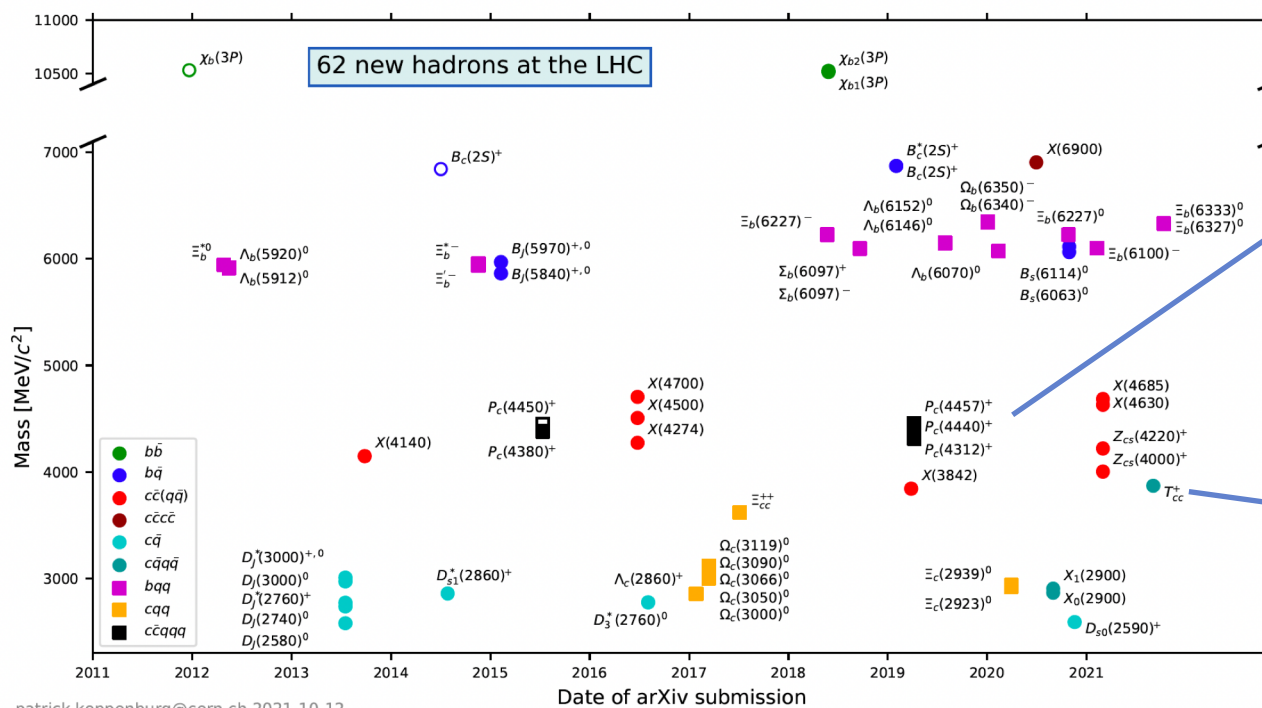
重子



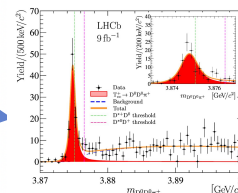
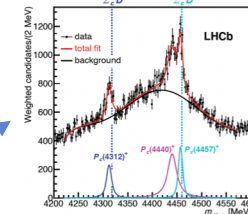
介子



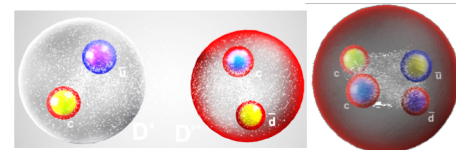
五夸克态?



patrick.koppenburg@cern.ch 2021-10-12



四夸克态?

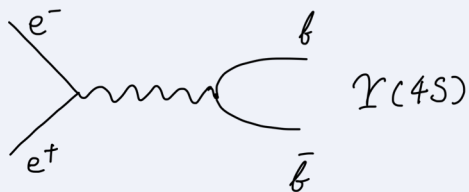


重味物理的未来

- 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	✓		(✓)

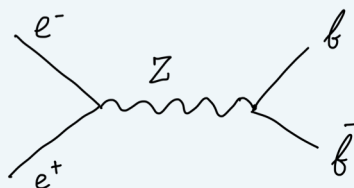
B 工厂



@ SuperKEKB

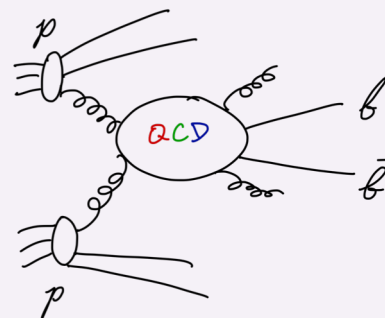


Z 工厂



@FCC-ee/ CEPC

高能强子对撞



@HL-LHC



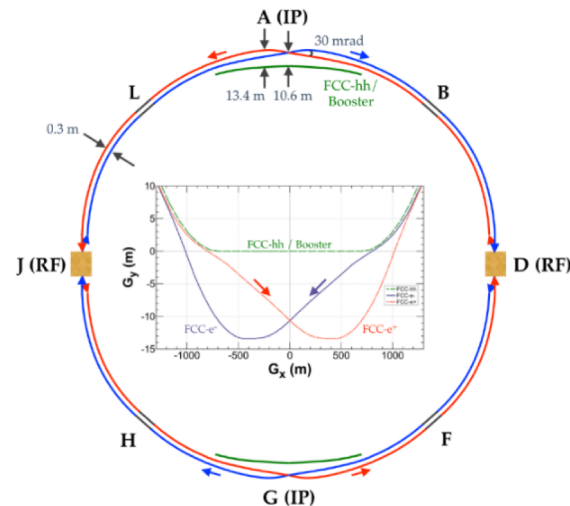
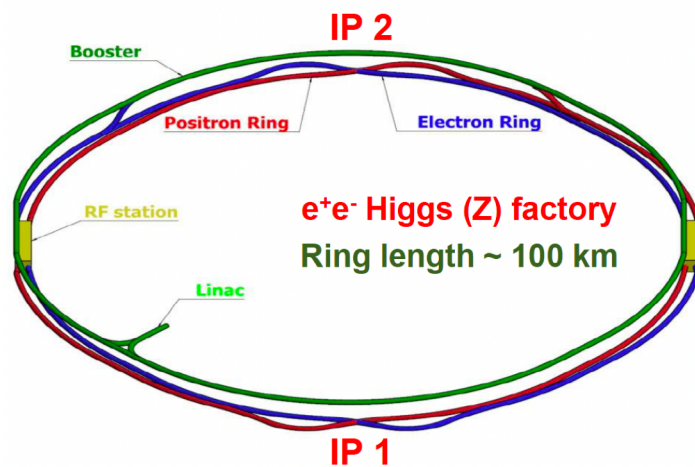
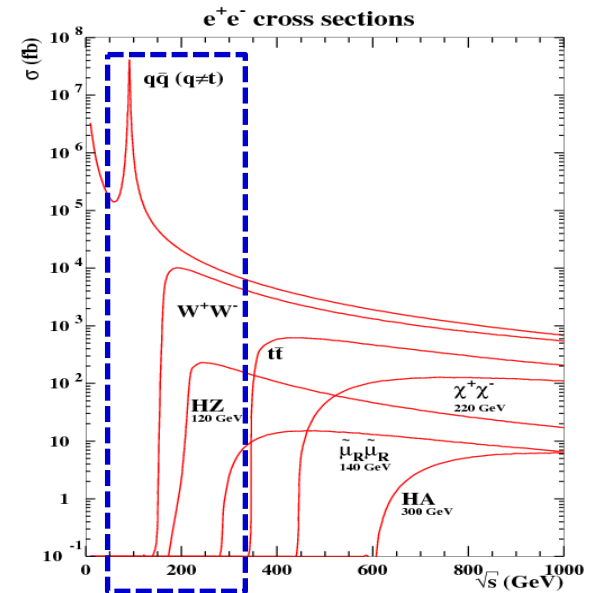
Higgs工厂和Z工厂

CEPC

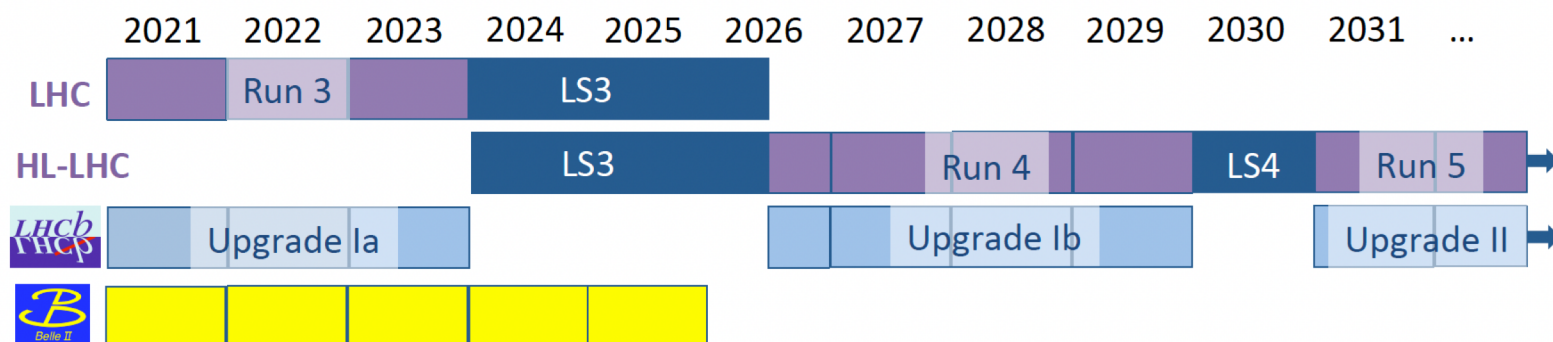
- 周长 ~ 100km
- 质心能量 90 ~ 240 GeV, 可升级至 360 GeV
- 产生 10^6 Higgs, 10^8 W, 10^{12} Z
- 2012.9 由中国科学家提出

FCC-ee

- 80 ~ 100 km
- 在 HL-LHC 结束后开始建设

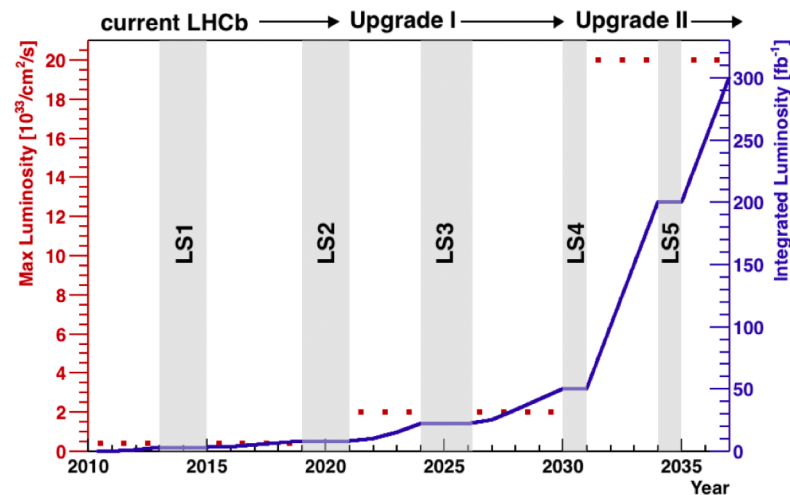


LHCb二期升级



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

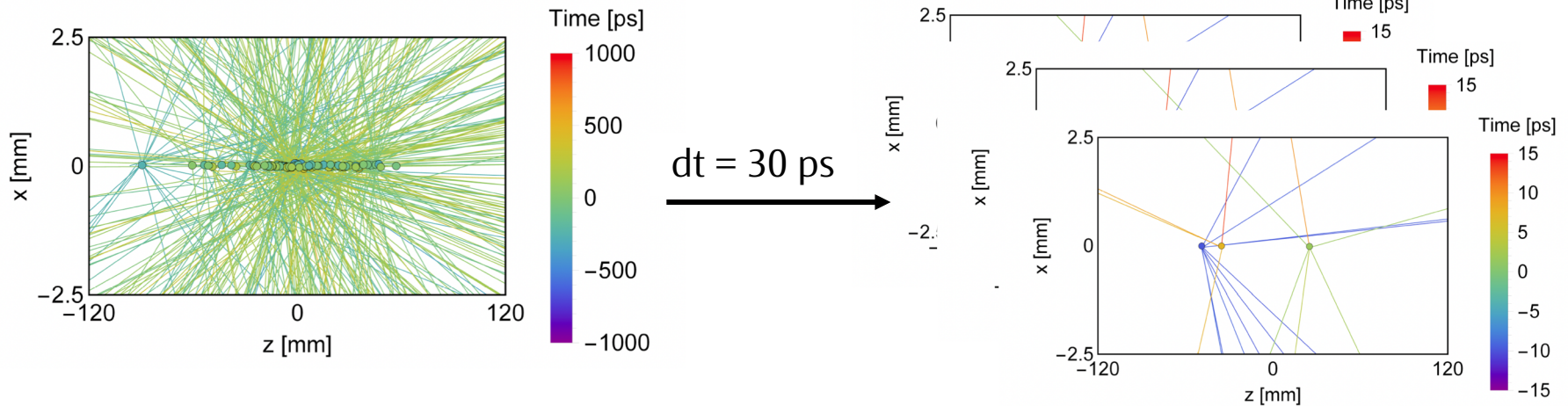


对探测器的新要求

- 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…

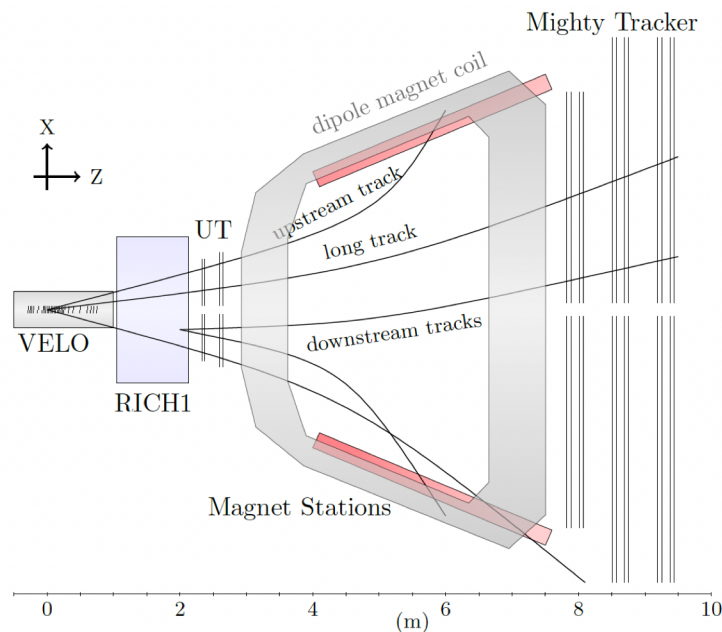
	Run 1-2	Upgrade I	Upgrade II
Luminosity / year[fb ⁻¹]	2	7	~ 50
Pileup	1.8	7	~ 50
Integ. Fluence [MeVn _{eq} /cm ²]	4.3×10^{14}	8×10^{15}	6×10^{16}
Readout rate [10 ⁶ hits/s]		600	~ 4500



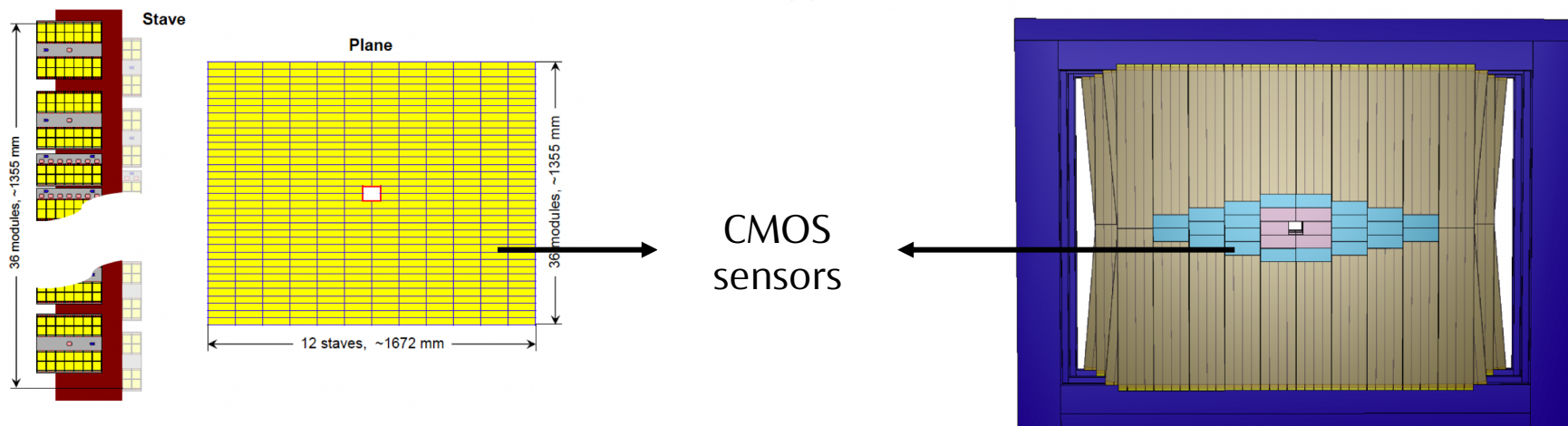
4D tracking sensors required!

寻迹系统

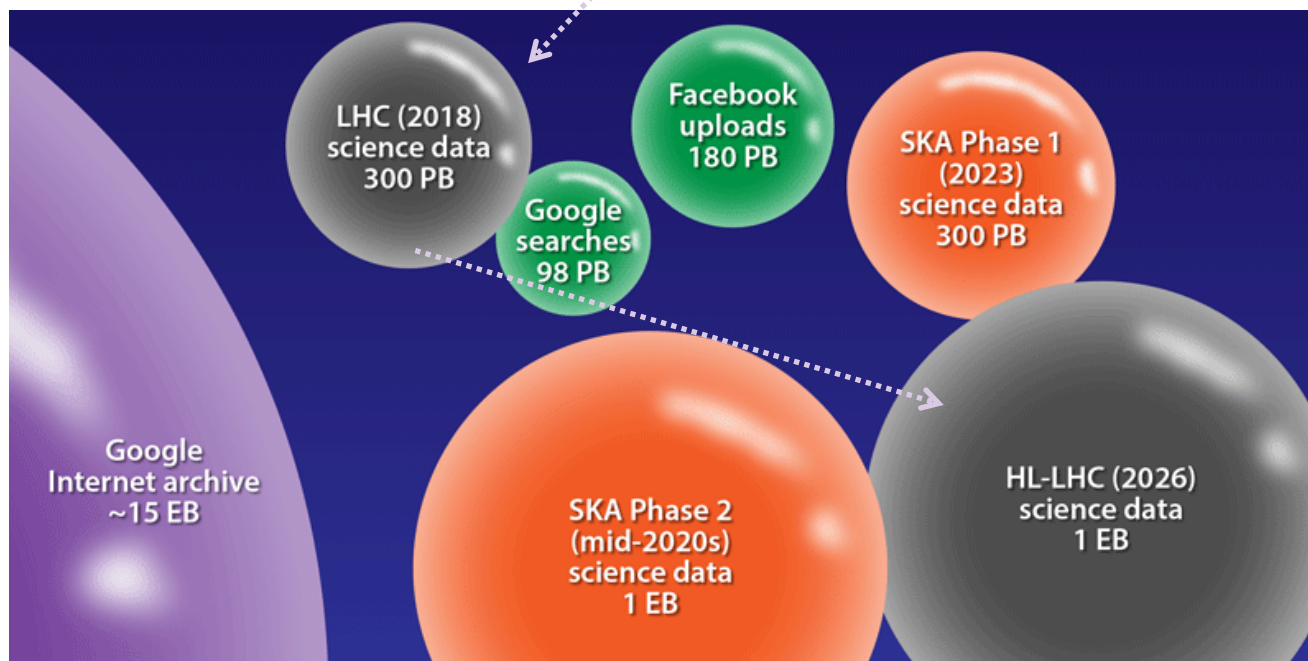
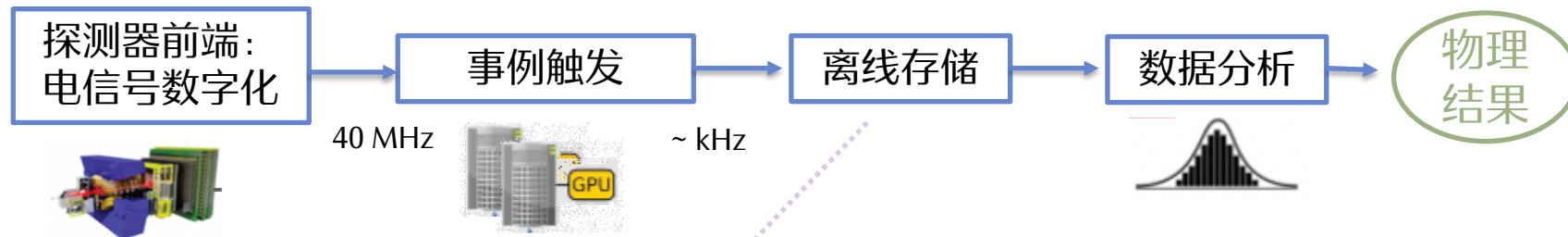
UT:
基于硅微条现有UT处
理不了UII的数据率;
占用率也将过高



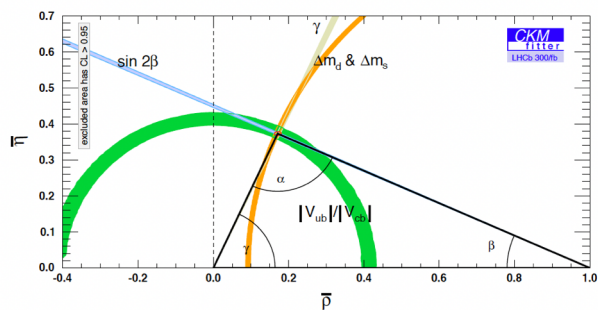
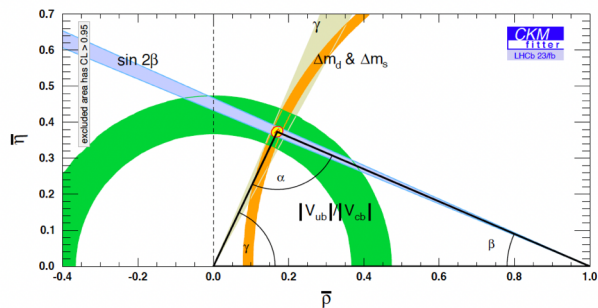
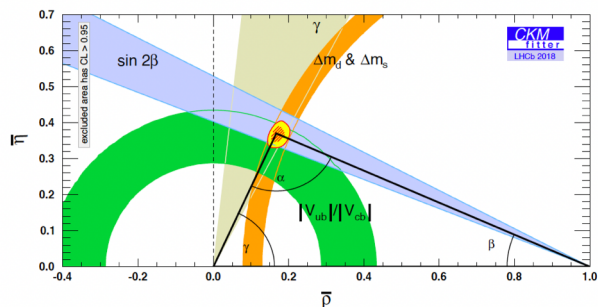
SciFi:
靠近束流部分光纤老化
严重, UIb/UII须更换



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_{SI}^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

- 重味物理探测实验的设计自有其特点
- B工厂和LHCb等实验推动重味物理取得丰硕成果
- 未来还有新的实验挑战等待着我们！

谢谢！

欢迎联系

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