Detecting CP violation with B decays

Lecture 2: Detecting

N. Tuning

Detecting CP violation with B decays

1) CP violation: CKM and the SM
2) Detecting: Detector requirements
3) B-decays: $\sin 2\beta$, ϕ_s, $B_s^0 \rightarrow D_s^+ K^-$

Detector requirements?

- Known:
  - B mass
  - B lifetime

  } ***So?***

- Production: Accelerator?
  - ee: B-factories
  - pp: LHCb

- Decay: Choice of Detectors?
  - B decay flight time: vertexing
  - Tracking
  - Particle identification of final state products
  - Backgrounds
  - Trigger

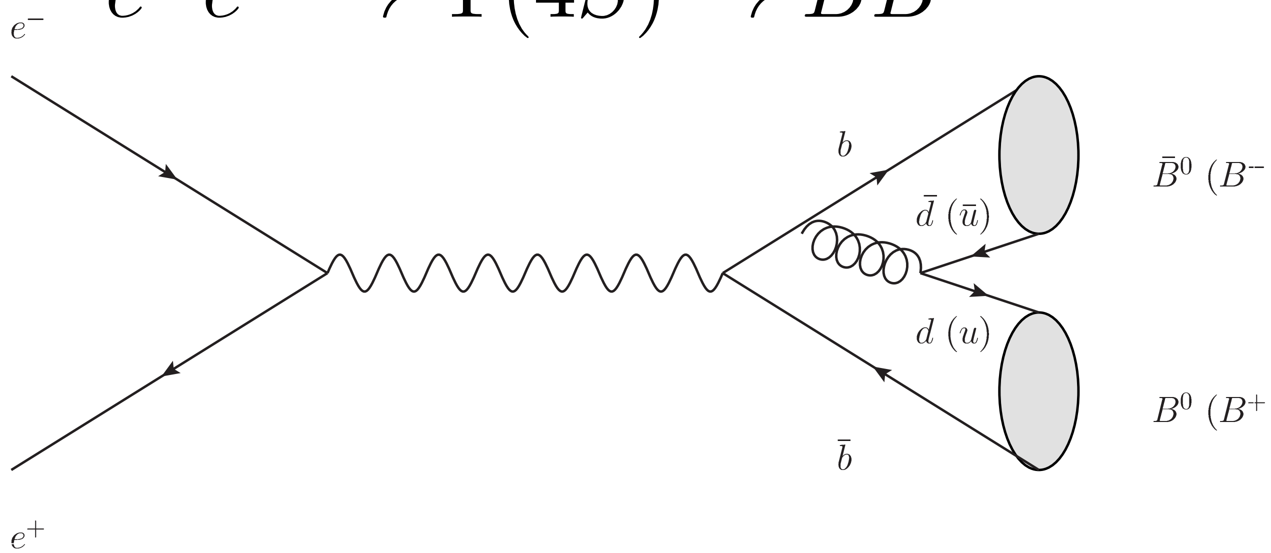
B physics: where?

- The golden decay $B^0 \rightarrow J/\Psi K_s$

Production of B mesons: B-factories

- Center-of-mass energy of 10.58 GeV

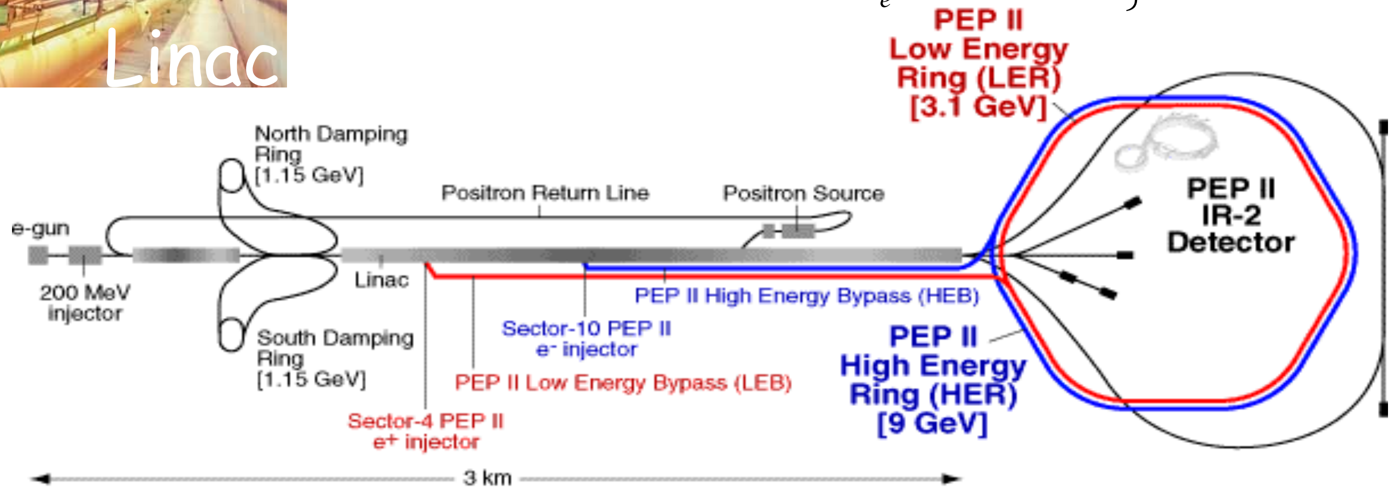
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

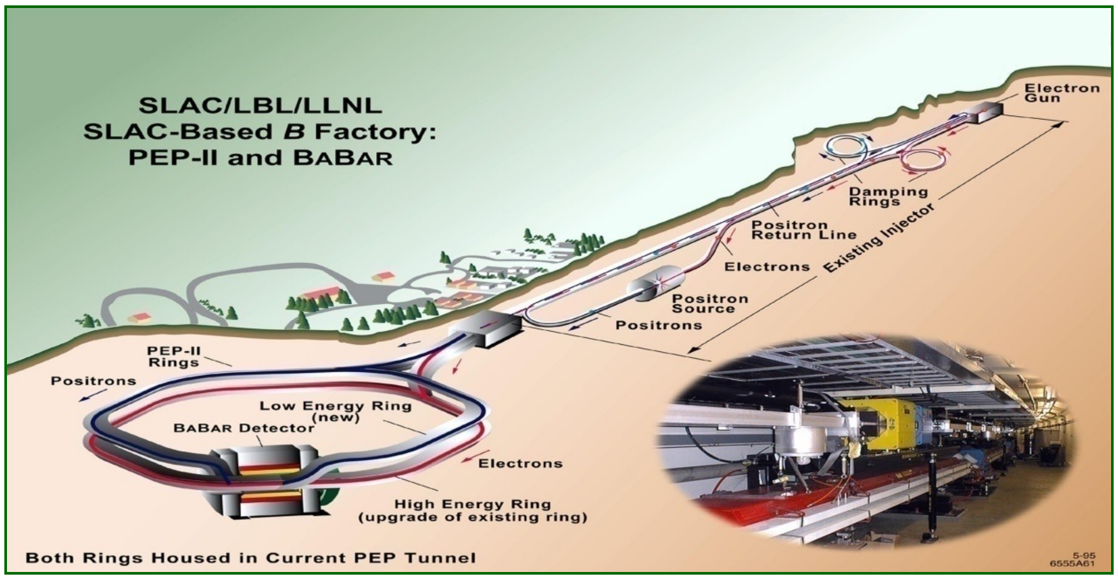


- B mesons at rest? Difficult to measure the decay time…

SLAC: LINAC + PEPII

$$\left.\begin{array}{l} E_{e^+} = 3.1 \text{ GeV} \\ E_{e^-} = 9 \quad \text{GeV} \end{array}\right\} \beta\gamma = 0.56, \sqrt{s} = M\left(\Upsilon_{4S}\right)$$





PEP-II accelerator schematic and tunnel view

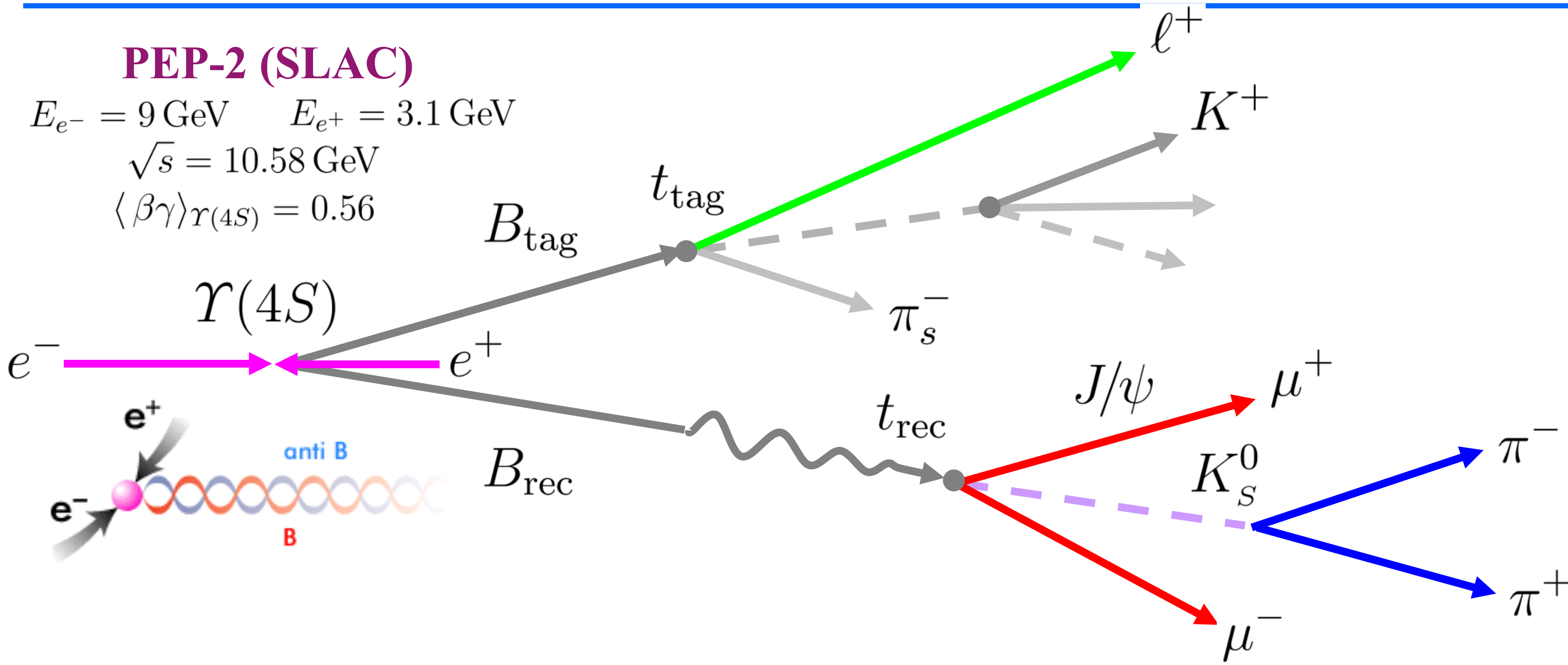
Coherent Time Evolution at the $\Upsilon(4S)$

PEP-2 (SLAC)

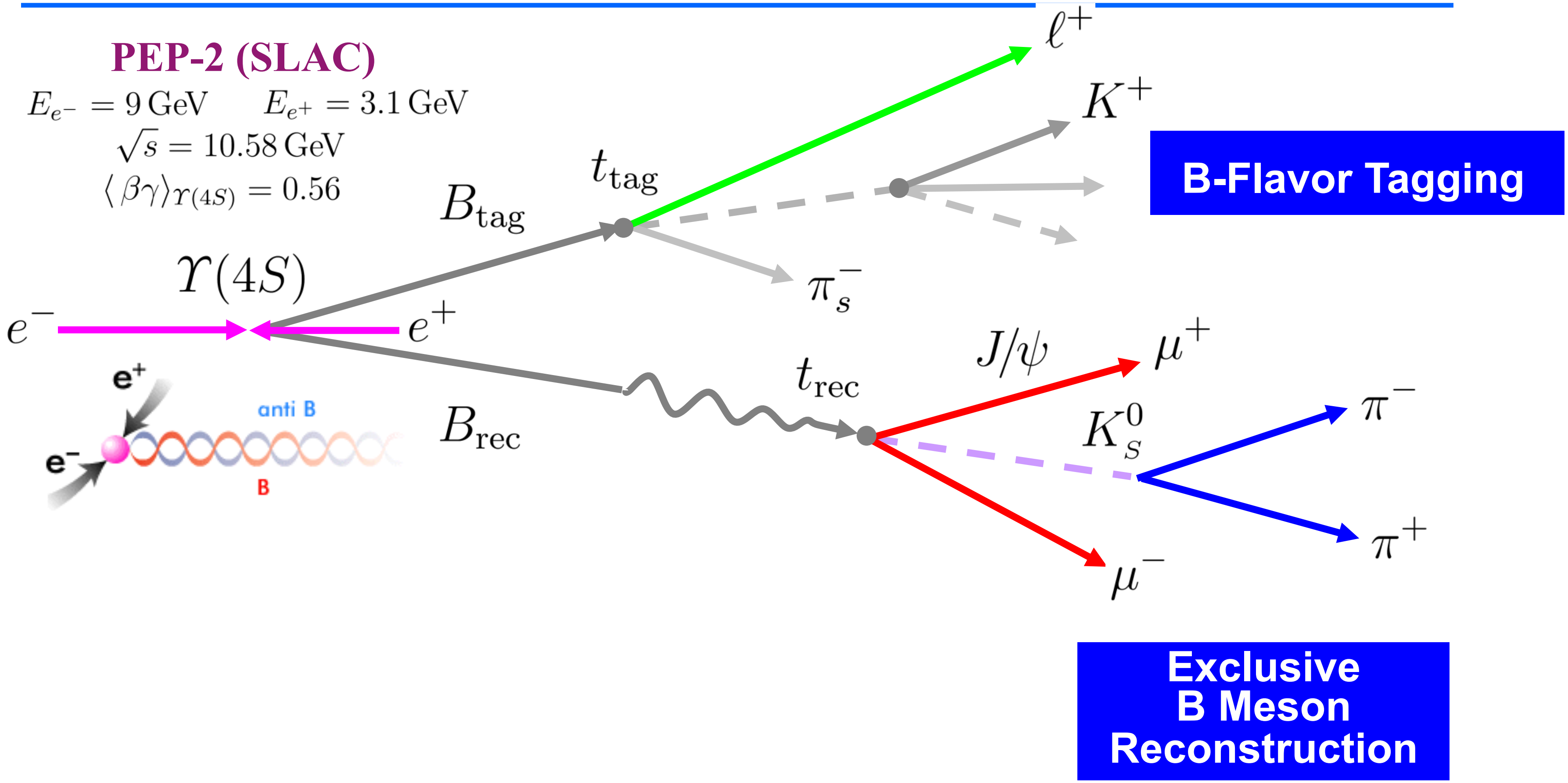
$E_{e^-} = 9\,\text{GeV} \qquad E_{e^+} = 3.1\,\text{GeV}$

$\sqrt{s} = 10.58\,\text{GeV}$

$\langle \beta\gamma \rangle_{\Upsilon(4S)} = 0.56$



Coherent Time Evolution at the $\Upsilon(4S)$



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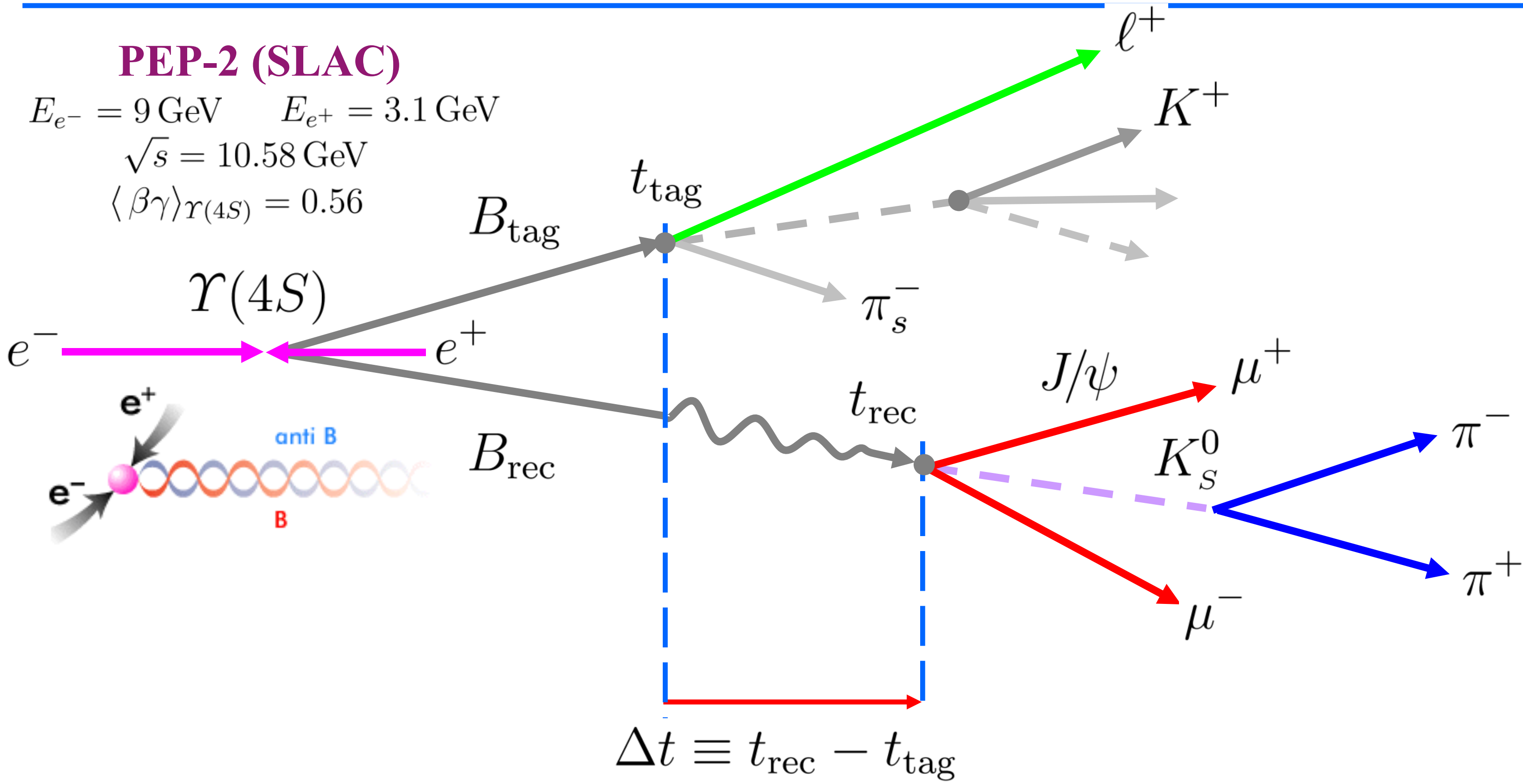


Vertexing & Time Difference Determination

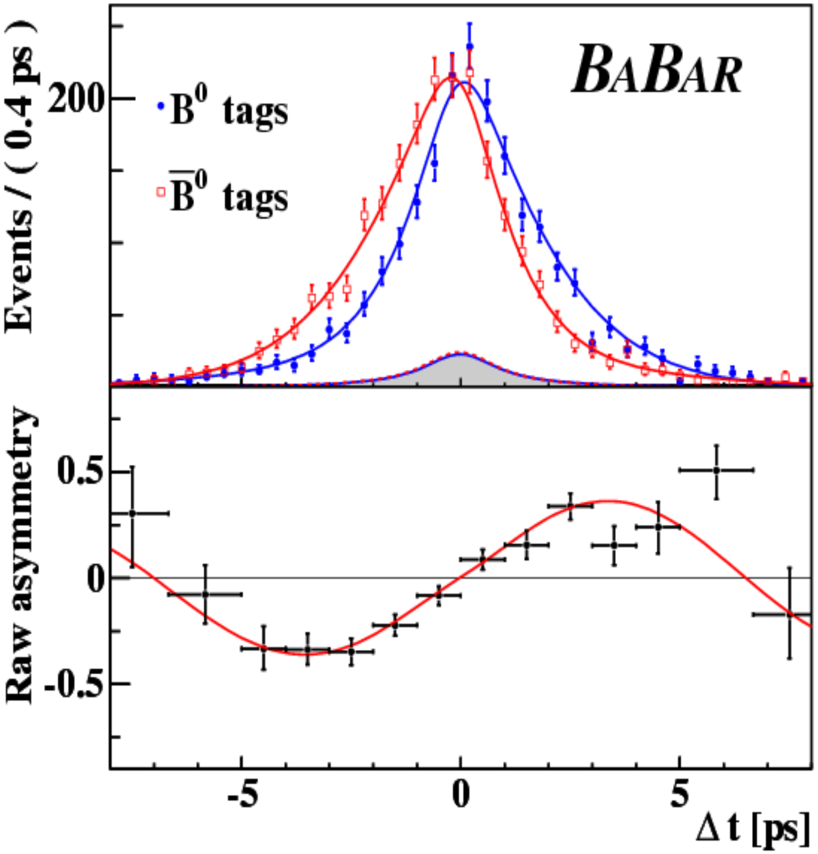
$$\Delta t \approx \Delta z / c \langle \beta\gamma \rangle_{\Upsilon(4S)}$$

$$\langle \Delta z \rangle_{B\bar{B}} \approx 260\,\mu\mathrm{m}$$

Intermezzo: Time-dependent CP asymmetry

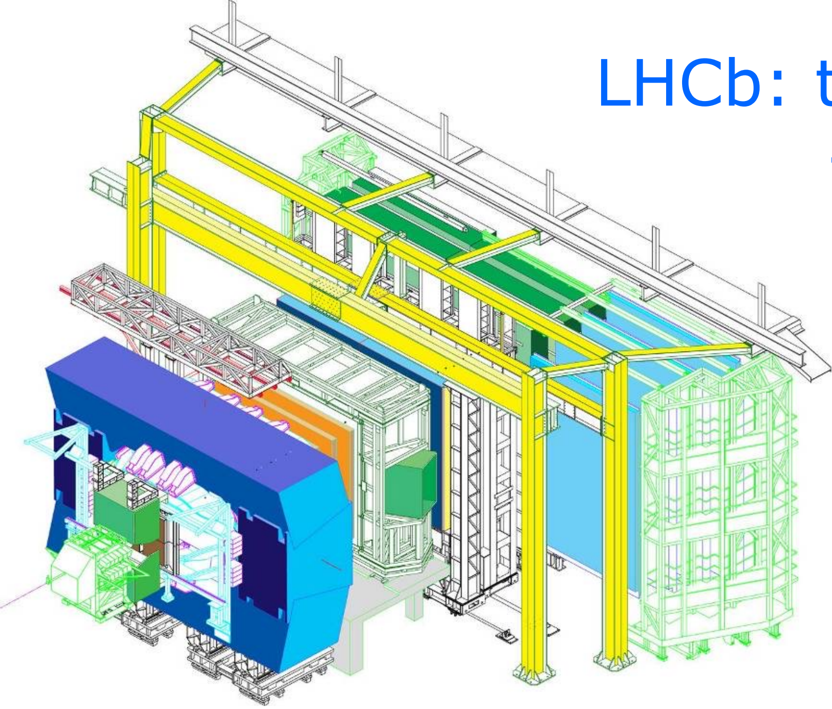
$$B^0 \rightarrow J/\psi K_s$$

$$A_{CP}(t) = \frac{N_{\overline{B^0}\rightarrow f} - N_{B^0\rightarrow f}}{N_{B^0\rightarrow f} + N_{\overline{B^0}\rightarrow f}} = \sin(2\beta)\sin(\Delta m t)$$

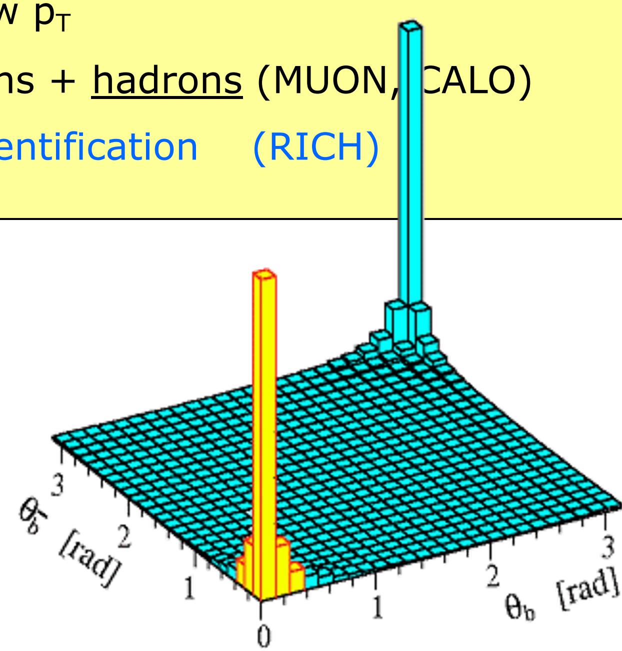


BaBar (2002)

LHCb: the Detector



- High cross section
  - LHC energy
    - B_s produced in large quantities
- Large acceptance
  - b's produced forward
- Small multiple scattering
  - Large boost of b's
- Trigger
  - ↓ Low p_T
  - Leptons + hadrons (MUON, CALO)
- Particle identification (RICH)



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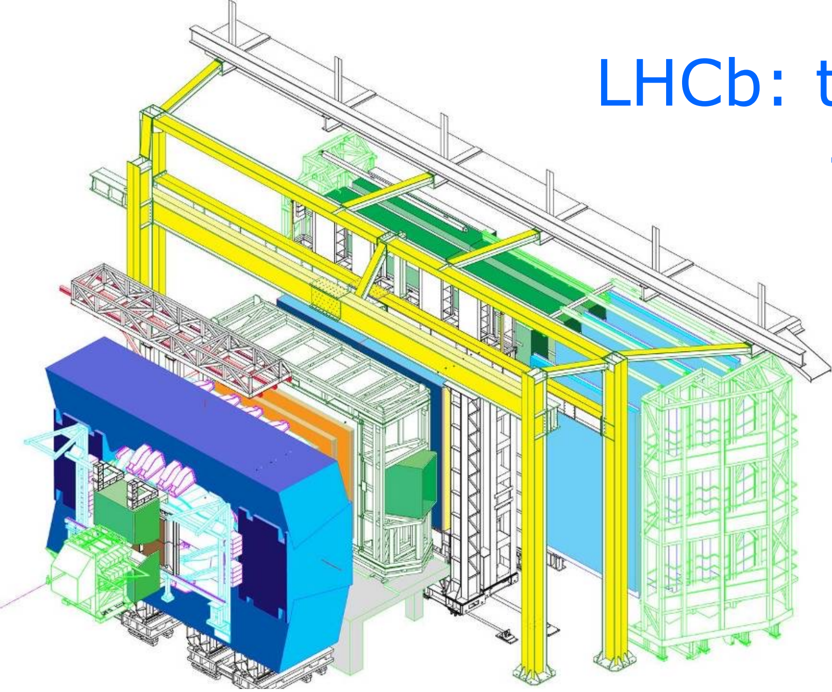

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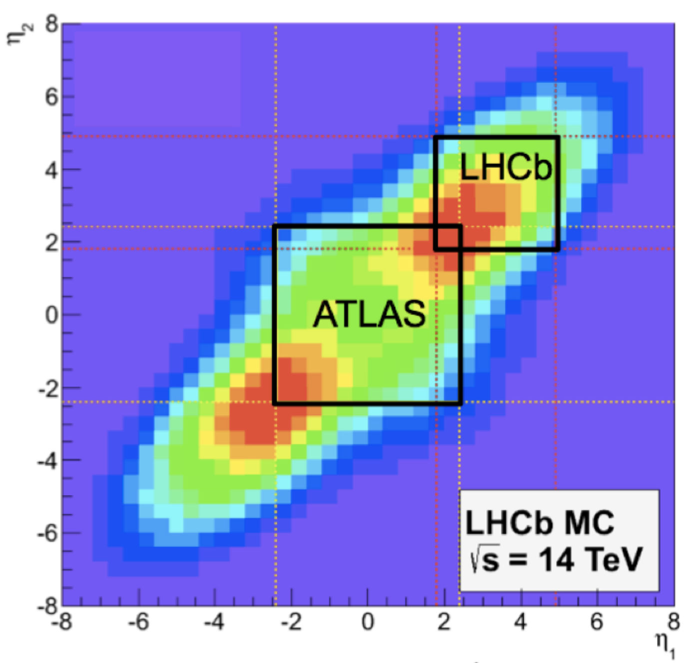
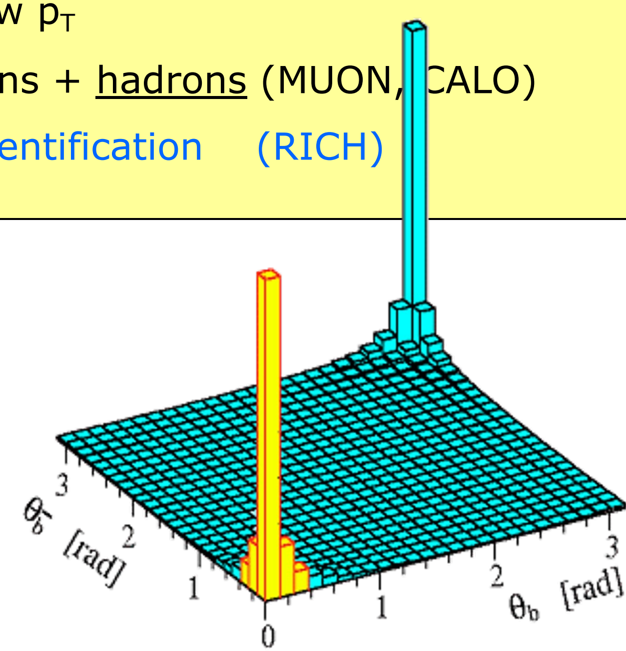
$b\bar{b}$ production





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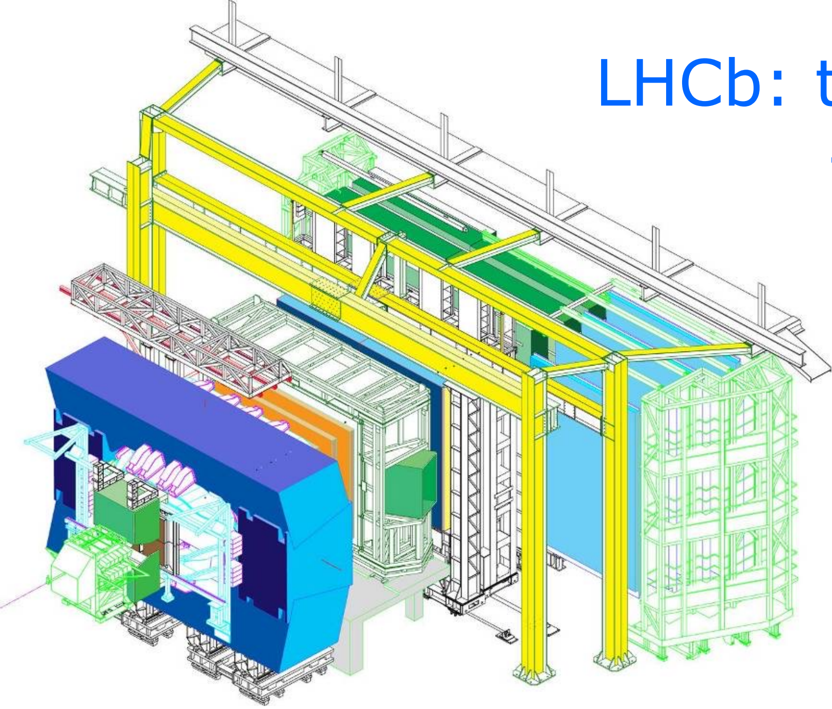

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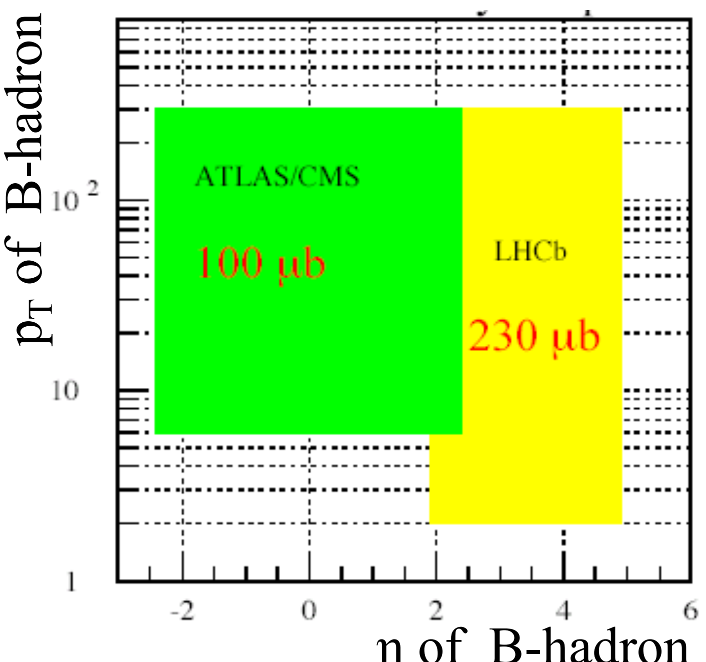
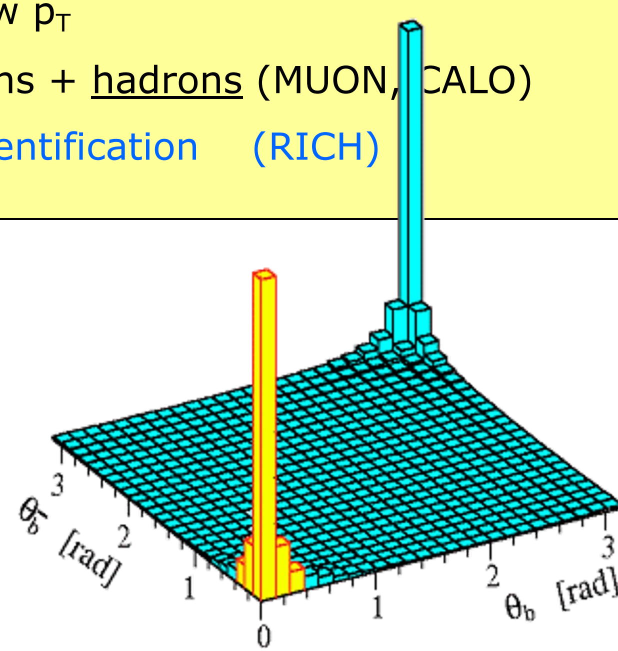
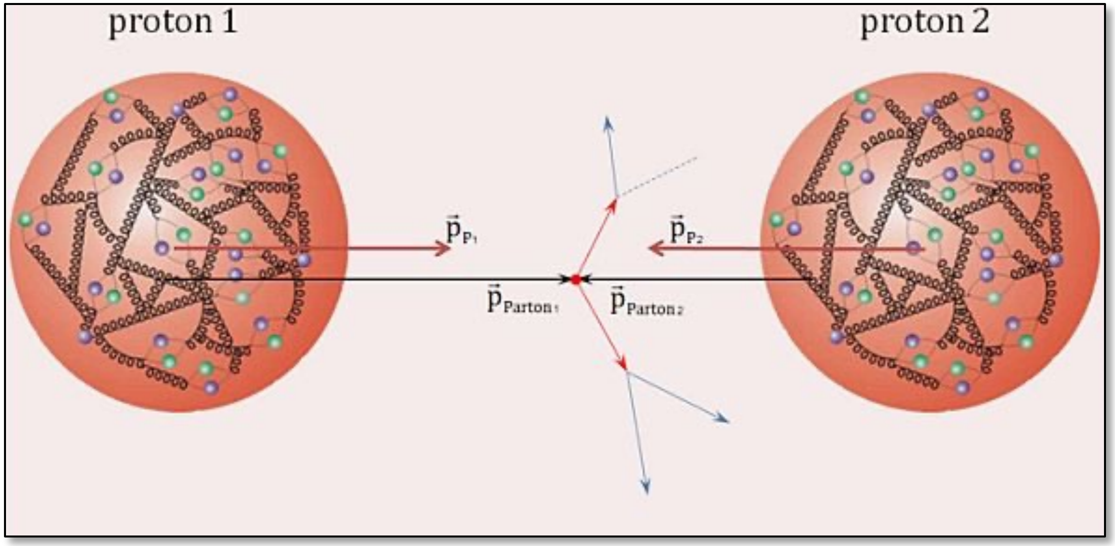
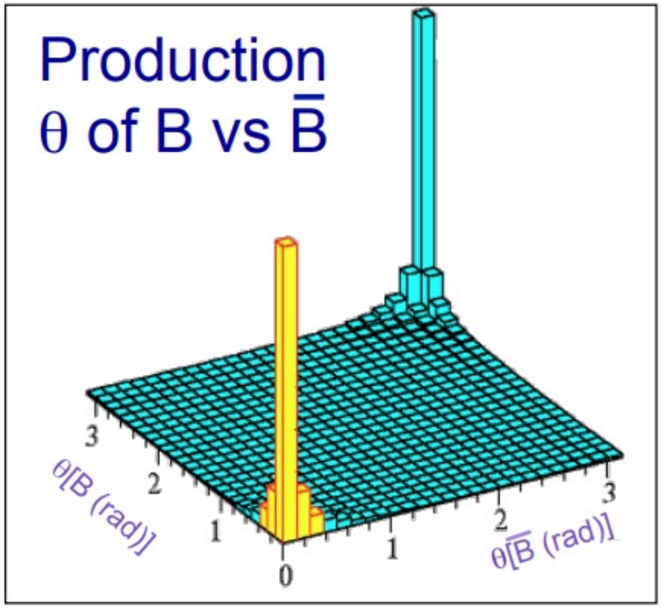




B hadron production



- Dominant production mechanism is through gluon fusion
- Momenta of the incoming partons are strongly asymmetric
- Center of mass energy of the produced bb pair is boosted
- Both b hadrons are produced in the same forward (or backward) direction



Detector requirements?

- Known:
  - B mass
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  } ***So?***

- Production: Accelerator?
  - ee: B-factories
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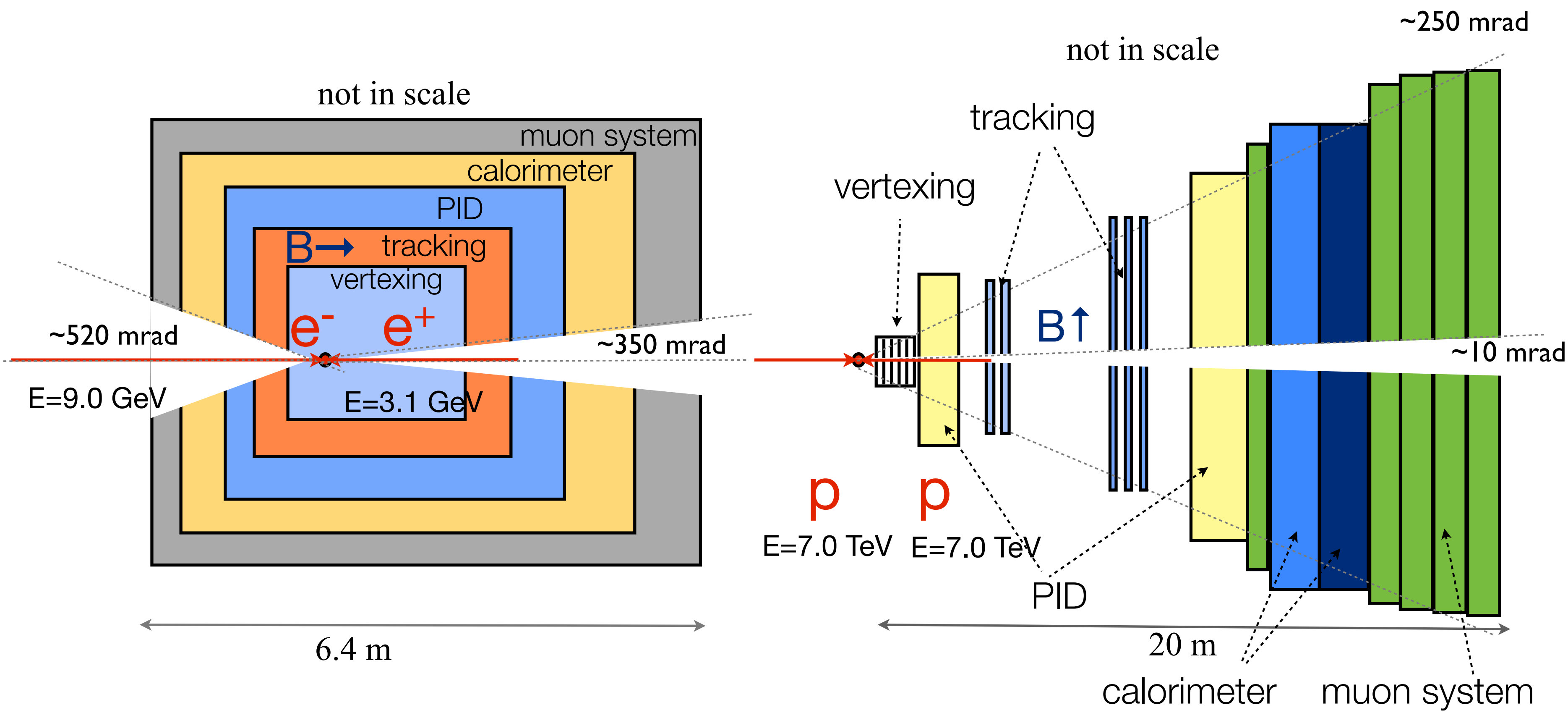
- Decay: Choice of Detectors?
  - B decay flight time: vertexing
  - Tracking
  - Particle identification of final state products
  - Backgrounds
  - Trigger

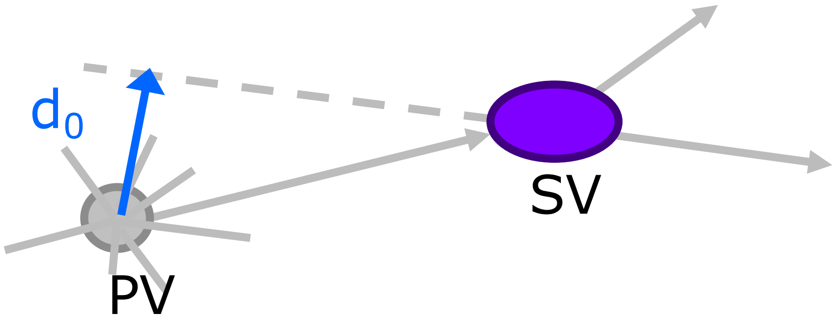
Different detectors



Courtesy: N.Neri, IDPASC school, May 2013

What is the key physical parameter?

- Impact parameter resolution is mandatory for reconstruction of heavy flavour vertices.
- Secondary vertex reconstruction depends on impact parameter resolution
- lifetimes of $\sim 10^{-13}$ s (100 fs) require IP precision $<10\ \mu m$

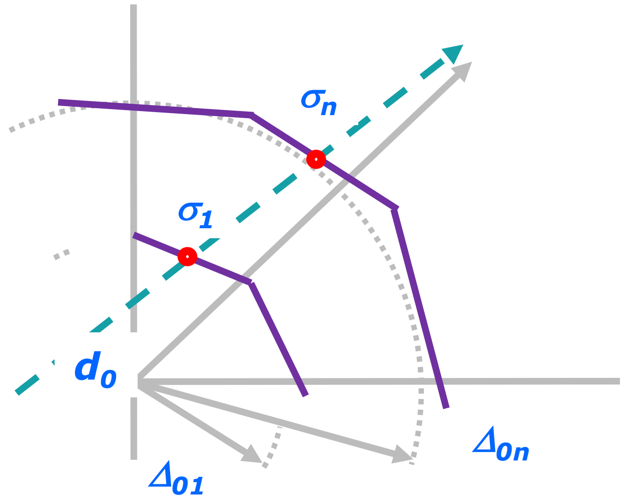


IP resolution

- Impact parameter resolution depends on 3 main factors

1. Intrinsic hit position resolution
2. Extrapolation distance between hits and vertex
3. Multiple scattering between collision point and measured points from detector material

IP resolution



- Impact parameter resolution depends on 3 main factors

$$\sigma_{\mathrm{d}_0}^2 = \frac{\pi}{2}\sigma_{IP}^2 = \frac{\pi}{2}\left[\frac{\Delta_{0n}^2\sigma_1^2 + \Delta_{01}^2\sigma_n^2}{\Delta_{1n}^2} + \theta_0^2\Delta_{01}^2\right]$$

1. Intrinsic hit position resolution

$$\sigma_1^2$$

2. Extrapolation distance between hits and vertex

$$\Delta_{01}^2$$

3. Multiple scattering between collision point and measured points from detector material

$$\theta_0 = \frac{13.6}{p}\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

Courtesy: K.Akiba, A. Papadelis
http://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_A_Papadelis.pdf

Distance to the vertex

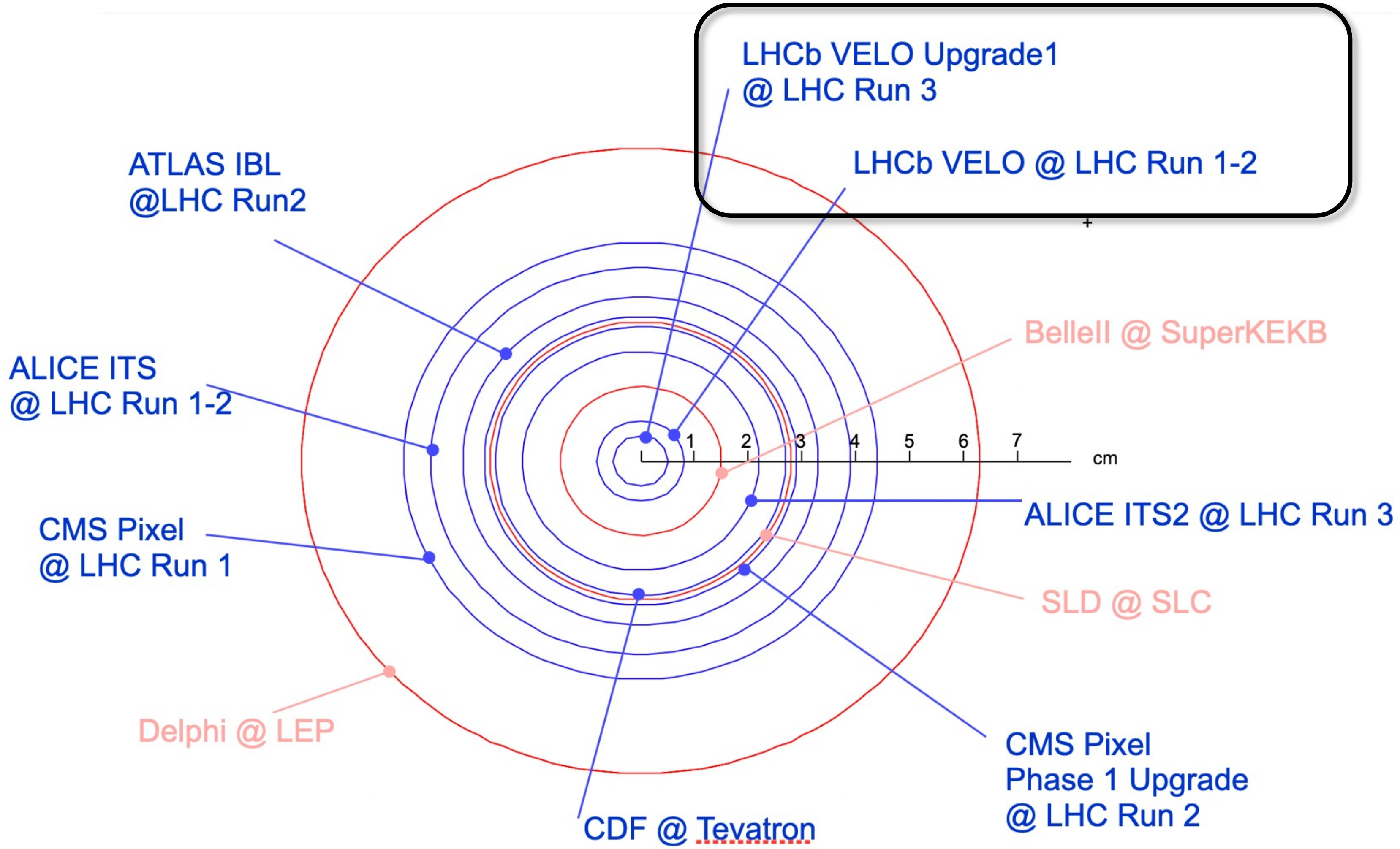
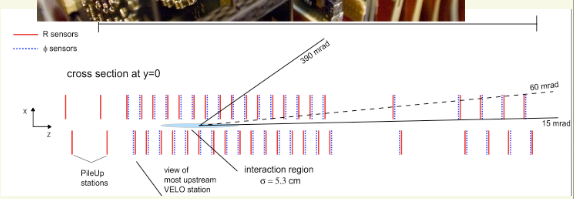


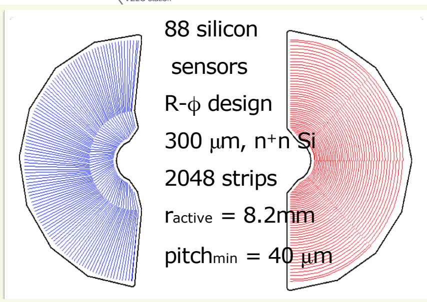
Fig.: Minimum radius of silicon vertex detectors at hadron and lepton colliders, up to start of LHC Run 3.

Courtesy: K.Akiba

Vertexing: detector choice

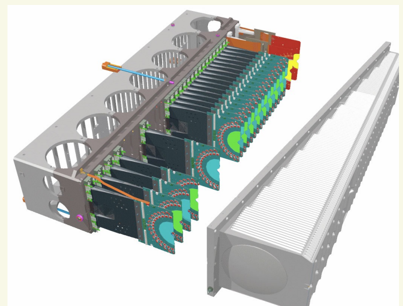
Sensors



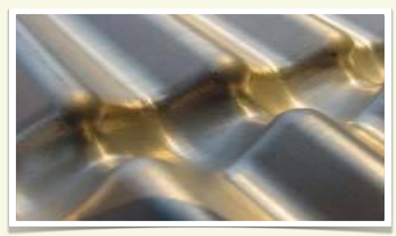


Moves away every fill and centers around the beam with self measured vertices

Vacuum



Operates in vacuum



Separated from primary vacuum by thin RF foil with complex shape
– Protection from beam pickup

Cooling

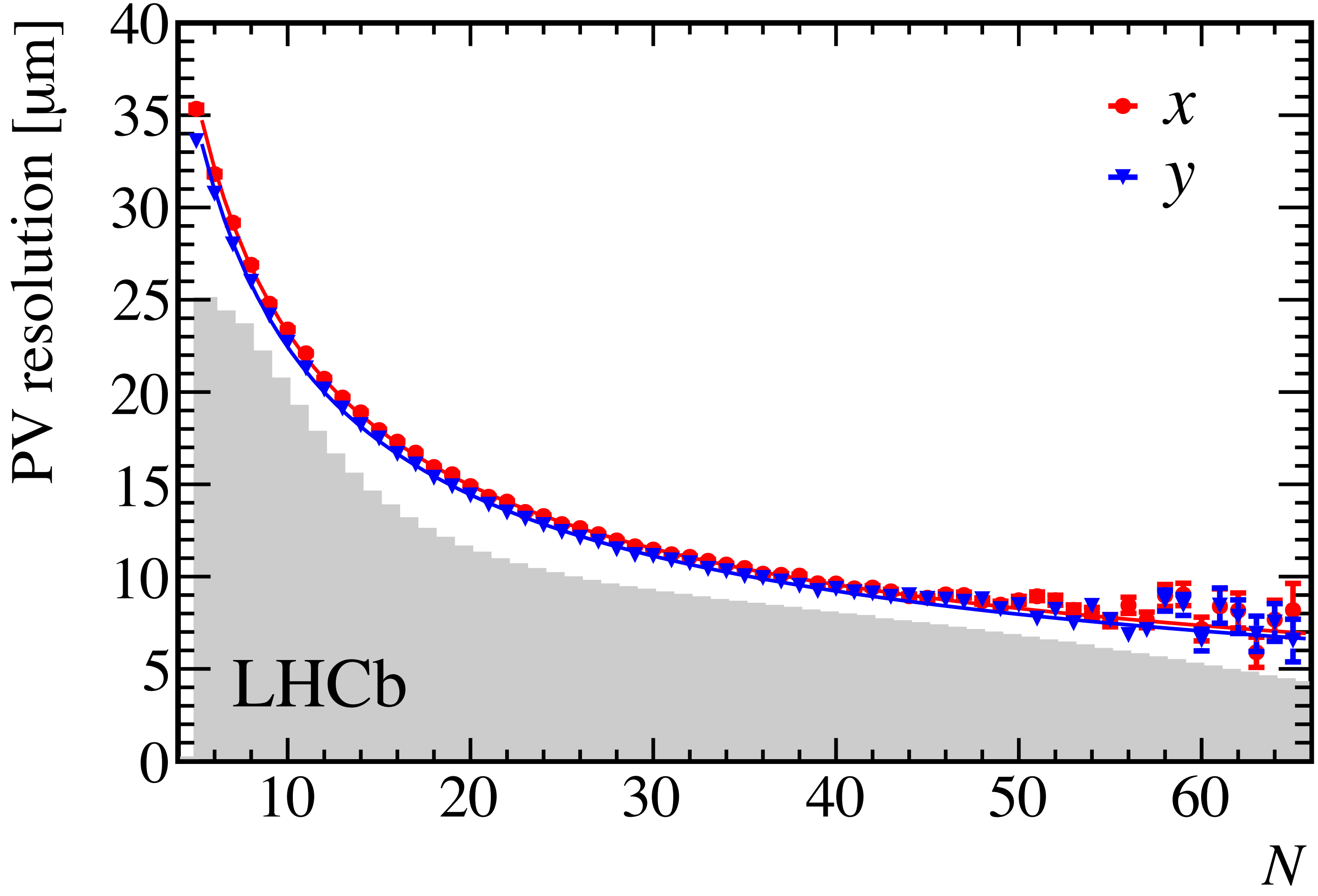
Evaporation of CO_2 keeps the temperature stable.

Radiation exposure

LHC RUN I	Delivered Luminosity	Highest Fluence* per fb^{-1}
CMS pixel	~29.5 fb^{-1}	$3x10^{12}$ 1MeV n_{eq}/cm^2 At 39 mm
VELO	~3.4 fb^{-1}	$5x10^{13}$ MeV n_{eq}/cm^2 At 8 mm

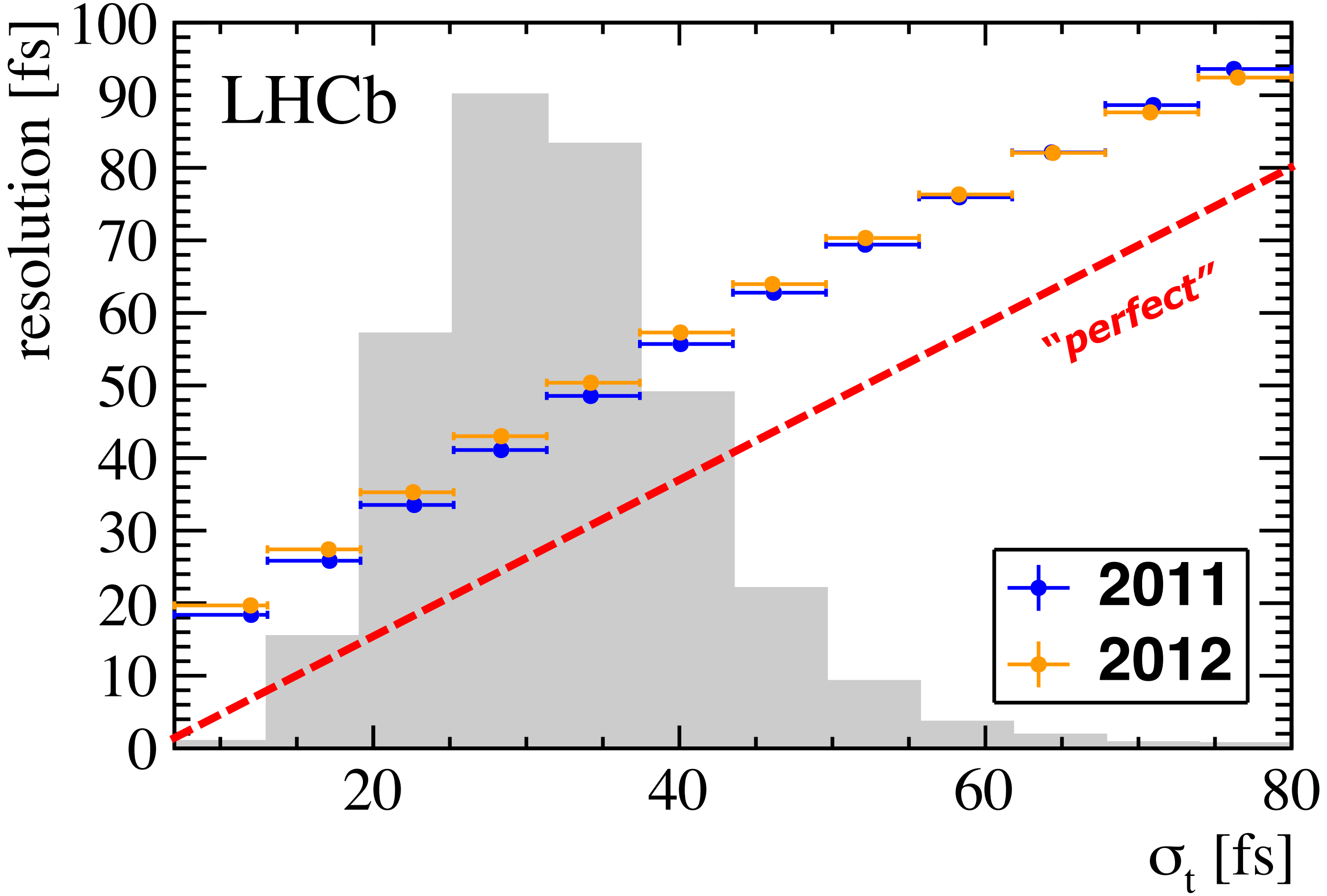
Courtesy: K.Akiba

LHCb vertex performance

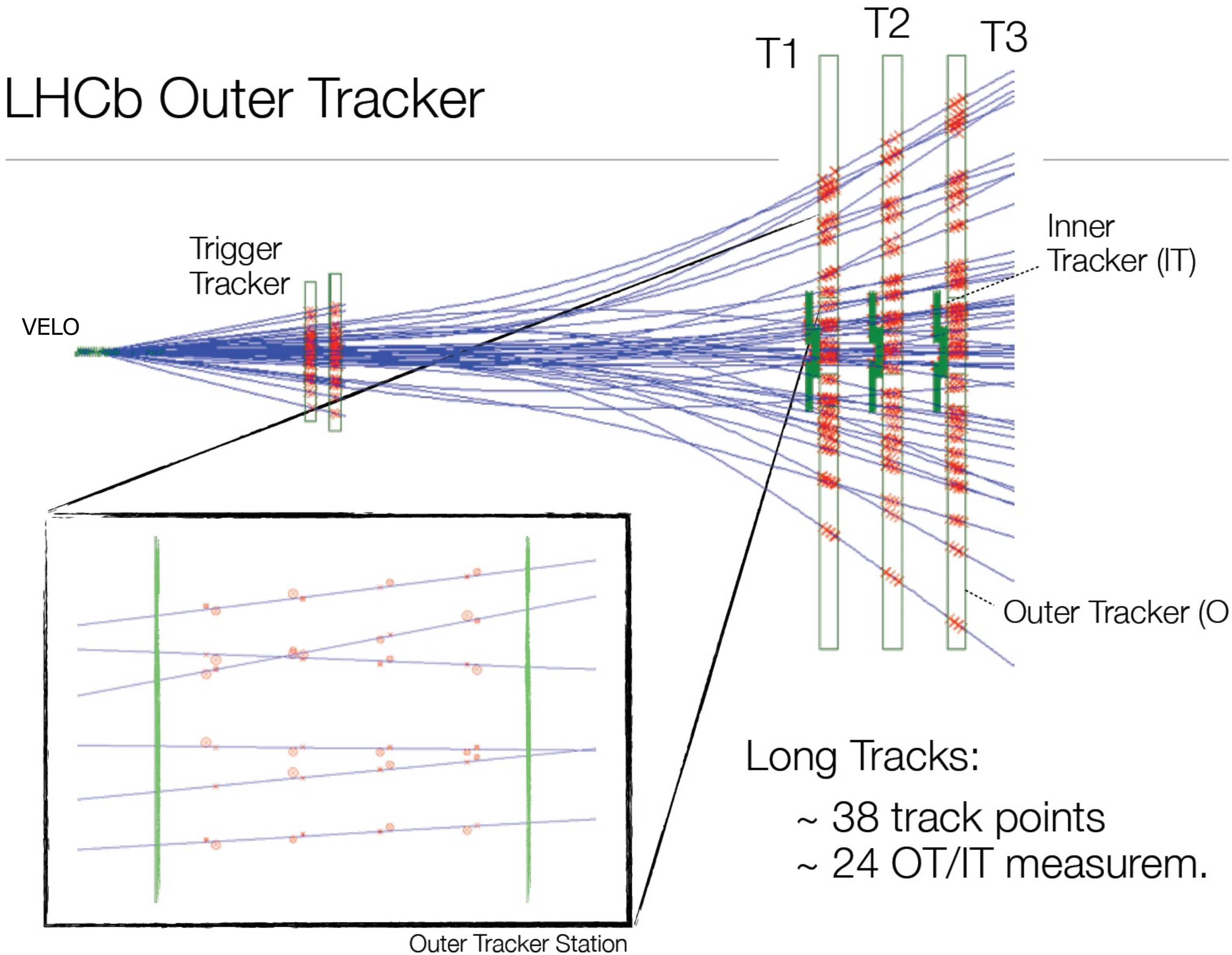


LHCb secondary vertex performance: Decay time

- Estimate decay time uncertainty from track parameters
- Measure the resolution: *calibration*



Tracking

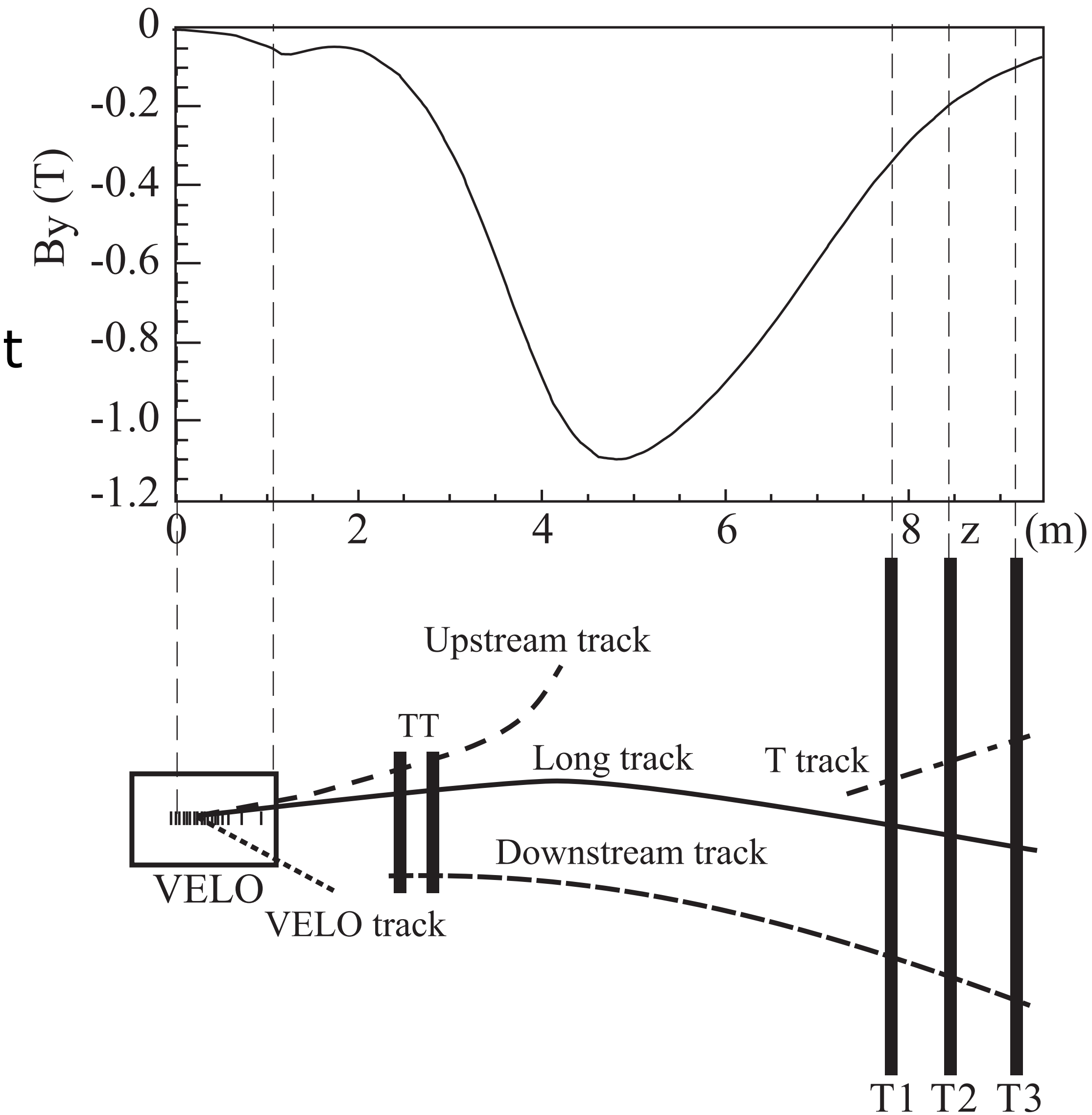


Long Tracks:

~ 38 track points
~ 24 OT/IT measurem.

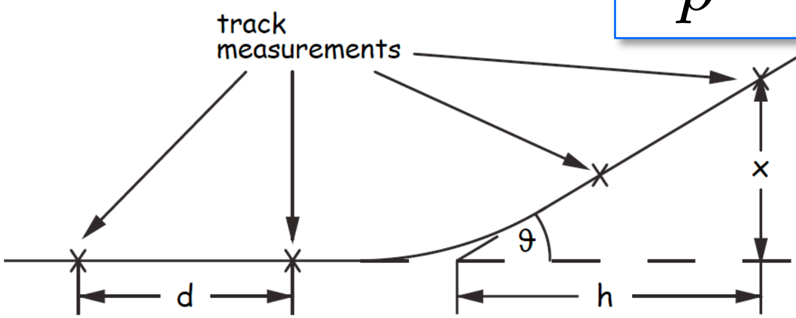
Tracking

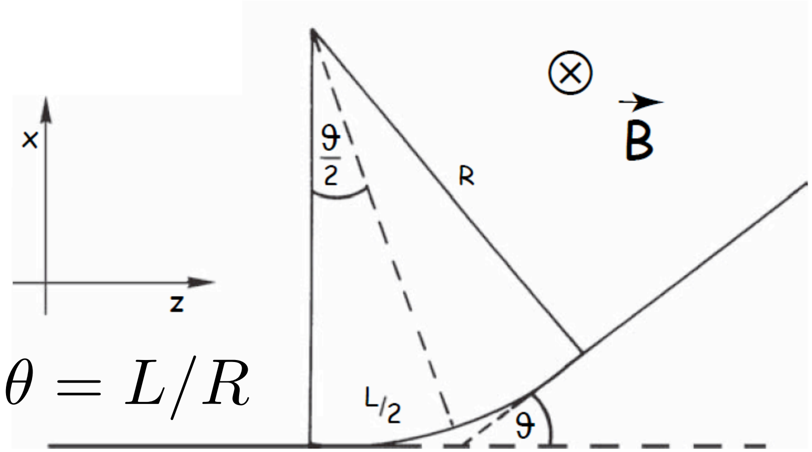
- Find tracks
  - Efficiency
  - Tag-and-probe
- Momentum measurement
  - Mass resolution



Momentum resolution

$$\frac{\sigma_p}{p} \sim \frac{\sigma_\theta}{\theta}$$

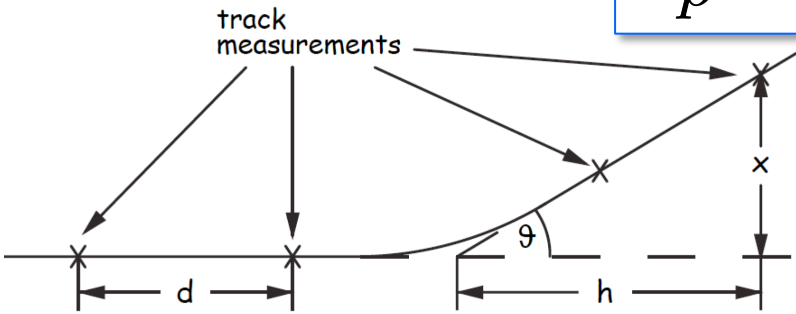


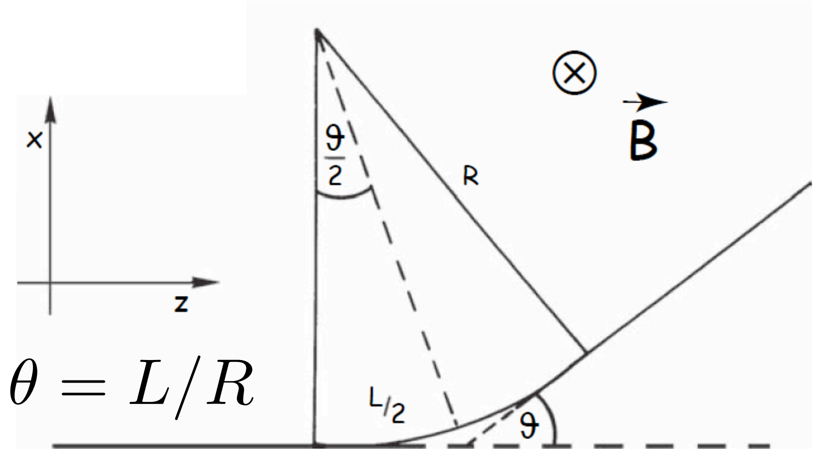


$$\theta = L/R$$

Momentum resolution

$$\frac{\sigma_p}{p} \sim \frac{\sigma_\theta}{\theta}$$





$$\theta = L/R$$

Contribution from measurement error

$$\frac{\sigma_p}{p} \sim \frac{\sigma_x}{h} \frac{p}{qBL}$$

1) Hit error σ_x
2) Lever arm h
3) Magnetic field BL

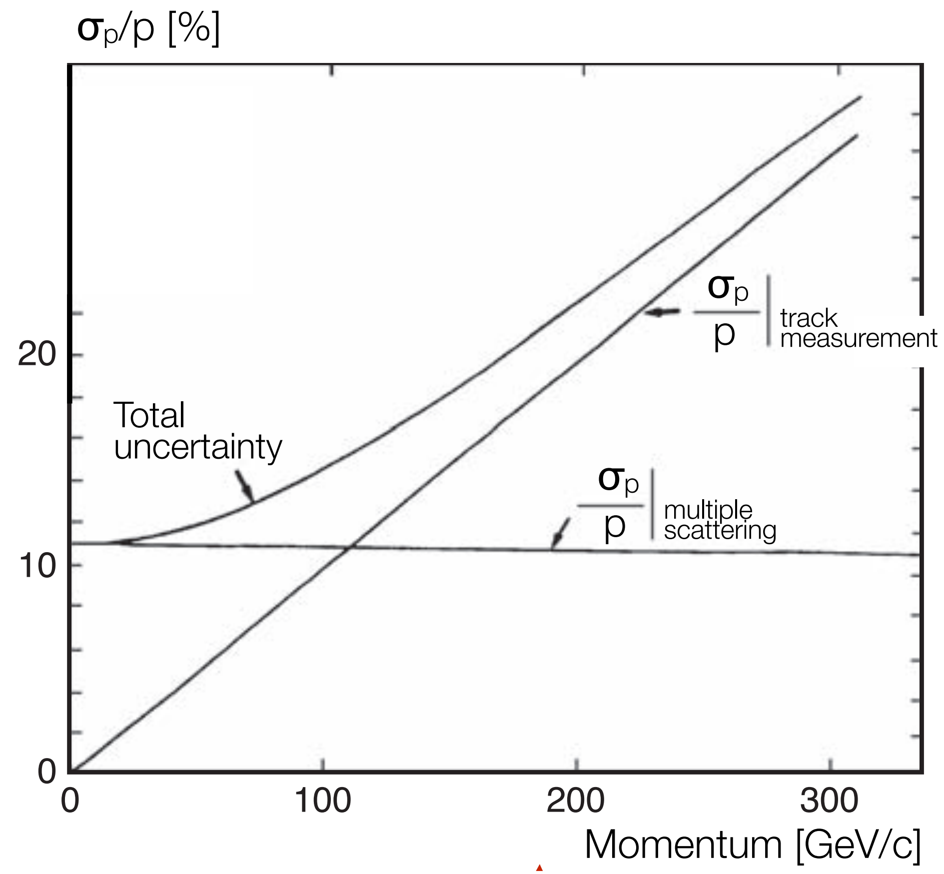
Contribution form multiple scattering

$$\left(\frac{\sigma_p}{p}\right)_{ms} \propto \frac{1}{\sqrt{LX_0}B}$$

$$\left(\frac{\sigma_{p_t}}{p_t}\right)^2 = \text{const} \cdot \left(\frac{p_t}{BL^2}\right)^2 + \text{const} \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2$$

Courtesy:N. Neri, IDPASC School of Flavor Physics Valencia 2-7 May 2013

Momentum resolution

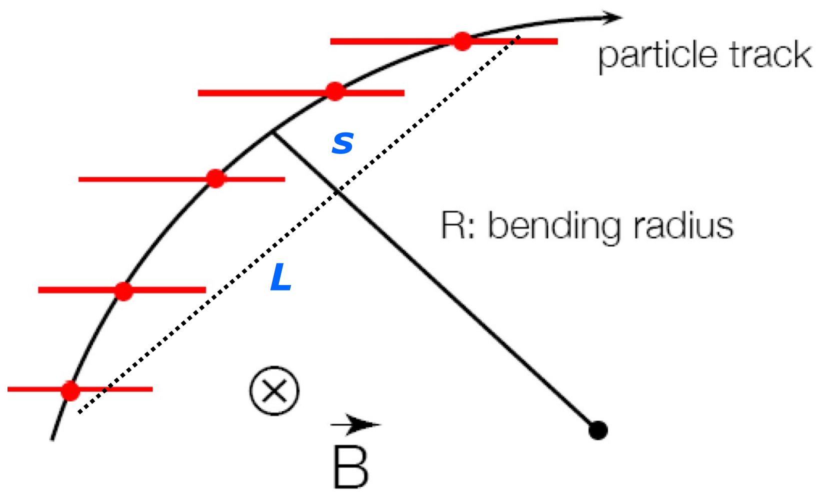


$$\left(\frac{\sigma_{p_t}}{p_t}\right)^2 = \text{const} \cdot \left(\frac{p_t}{BL^2}\right)^2 + \text{const} \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2$$

Courtesy:N. Neri, IDPASC School of Flavor Physics Valencia 2-7 May 2013

A quick example: how to design your tracker?

- Momentum measurement:
  - P[GeV] = 0.3 B [T] R[m]
  - Sagitta: $s = \frac{L^2}{8R}$



- So, let's say
  - L = 4 m
  - B = 1 T
  - p = 100 GeV
- Then
  - Bending radius: R = 100/0.3 = 330 m
  - Sagitta: s = 16/8*330 = 6 mm
- If we want a 1% error on P then we need approximately:
  - $\frac{\sigma_p}{p} \approx \frac{\sigma_s}{s} = \ \ 1\% = 60\ \mu m$

Tracking: detector choice

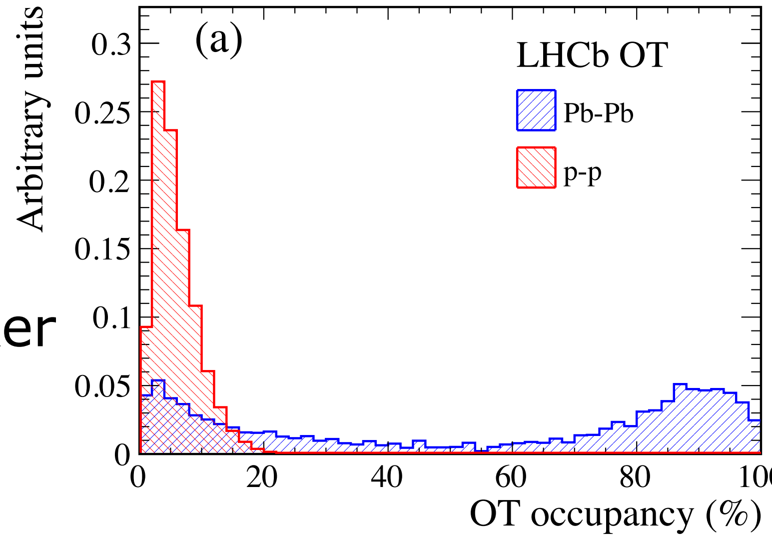
- Important criteria:
  - Resolution: technology!
  - Occupancy: cell size!

Tracking: detector choice

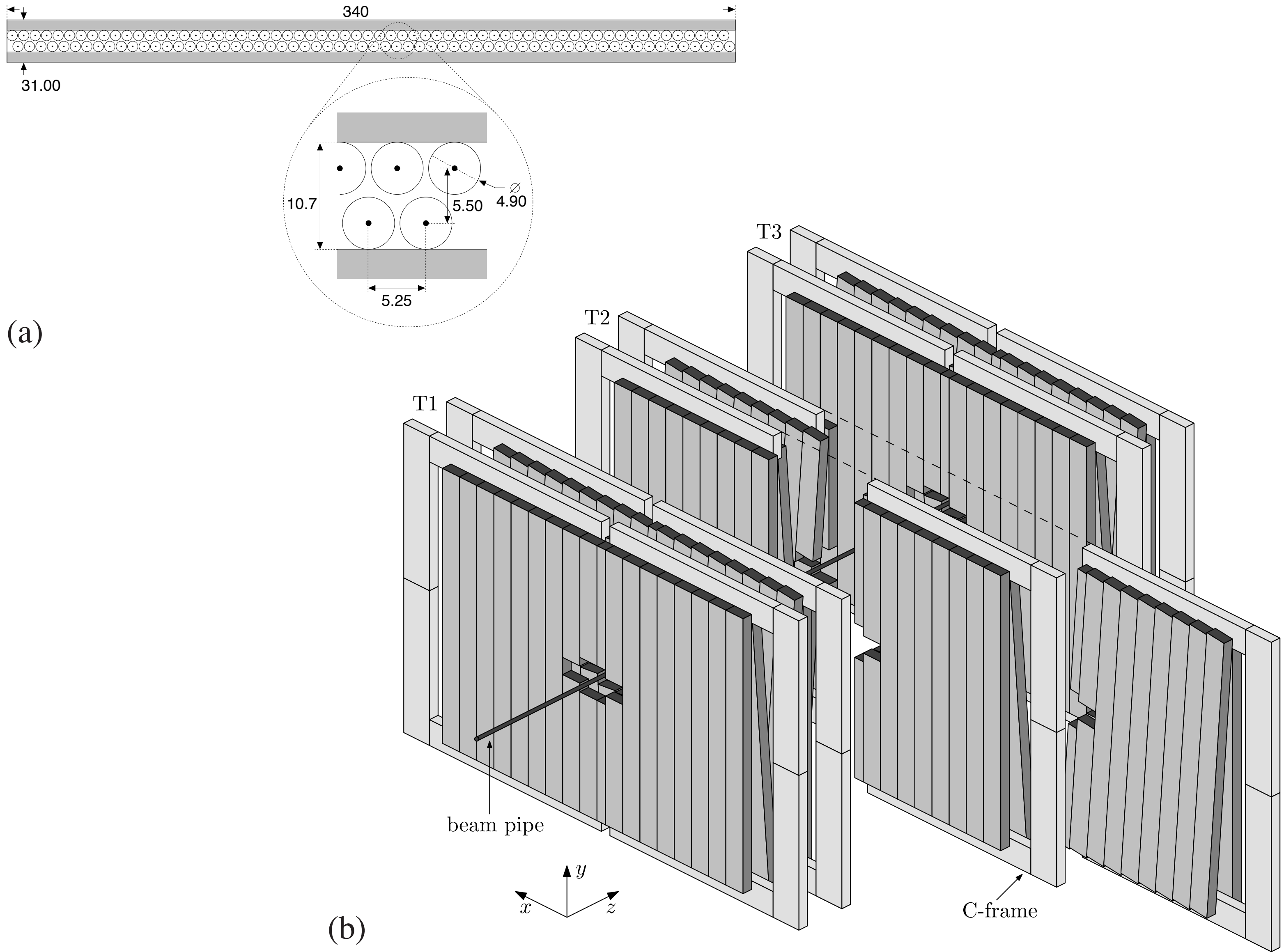
- Important criteria:
  - Resolution: technology!
  - Occupancy: cell size!
  - Cost…

- 2011-2018: Gas detector
  - Resolution: <200 μm

- 2022-2030: Scintillating Fiber tracker
  - Resolution: <200 μm



Tracking: gaseous straw tube detector



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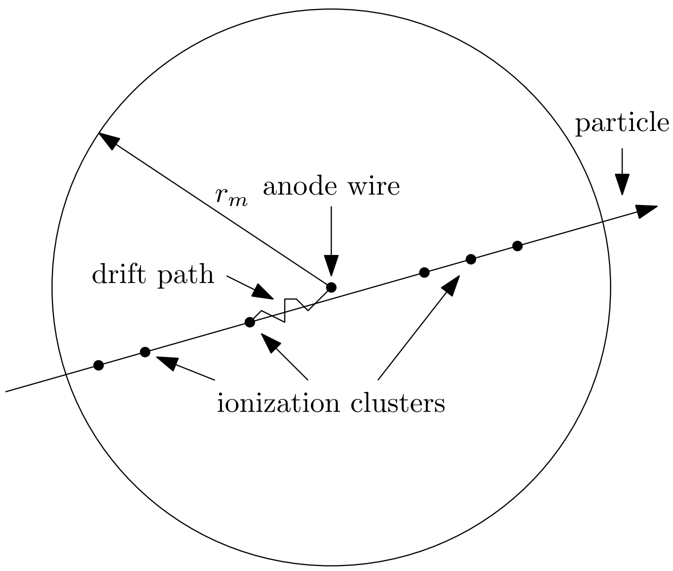
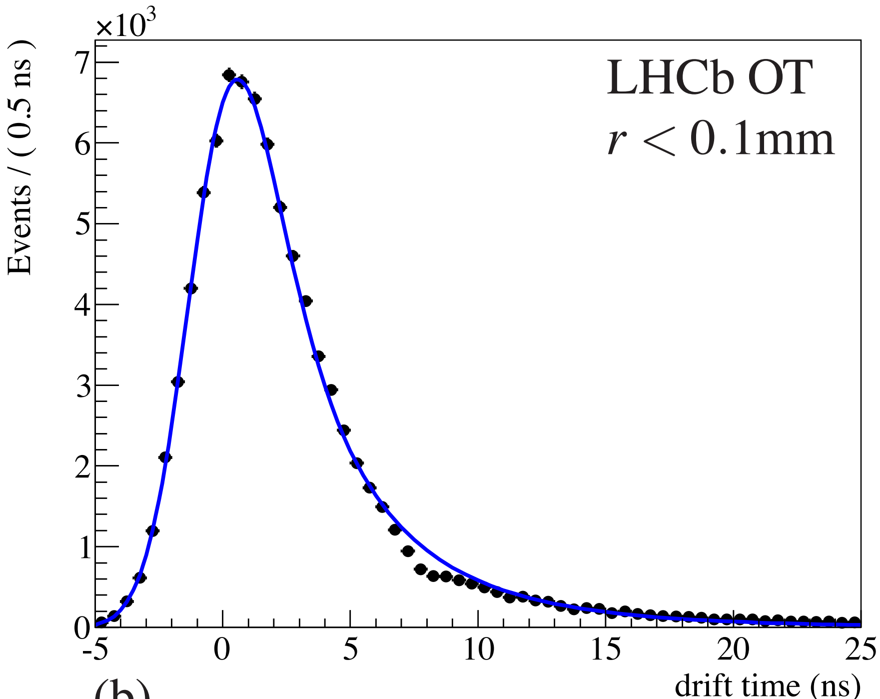


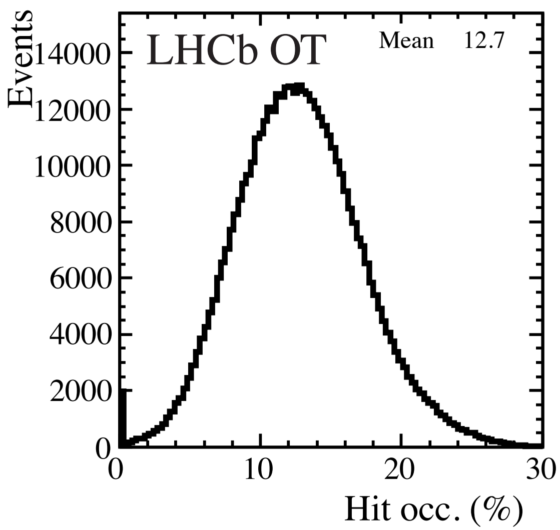
(a)



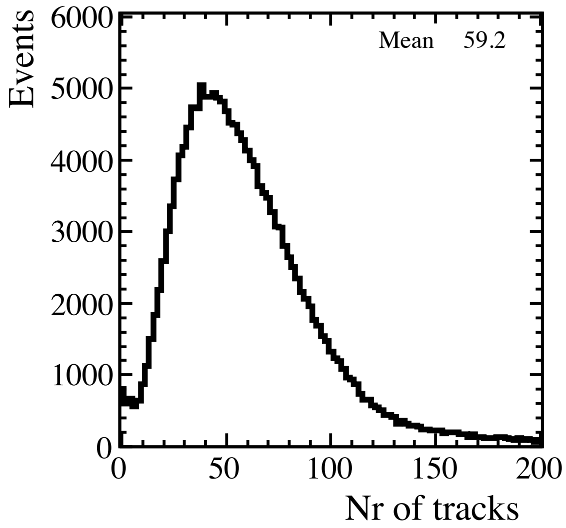
(b)

Tracking: gaseous straw tube detector

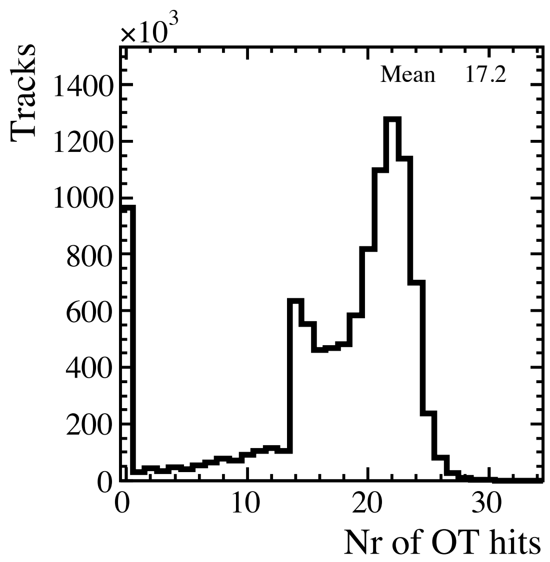
~13% of channels are hit



~ 60 tracks per event



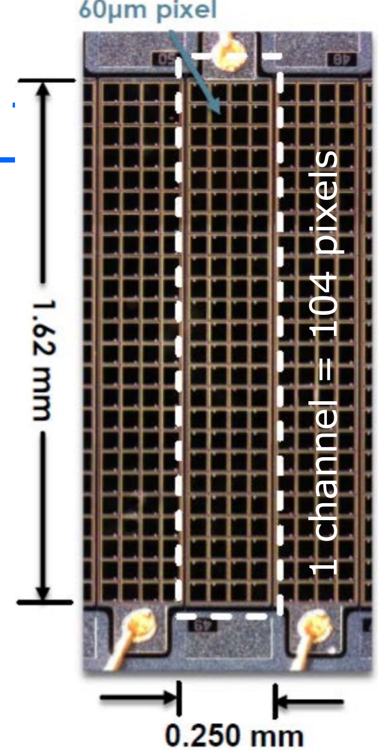
~ 22 hits per track

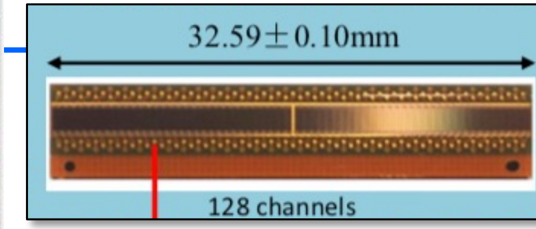


Tracking: scintillator fiber

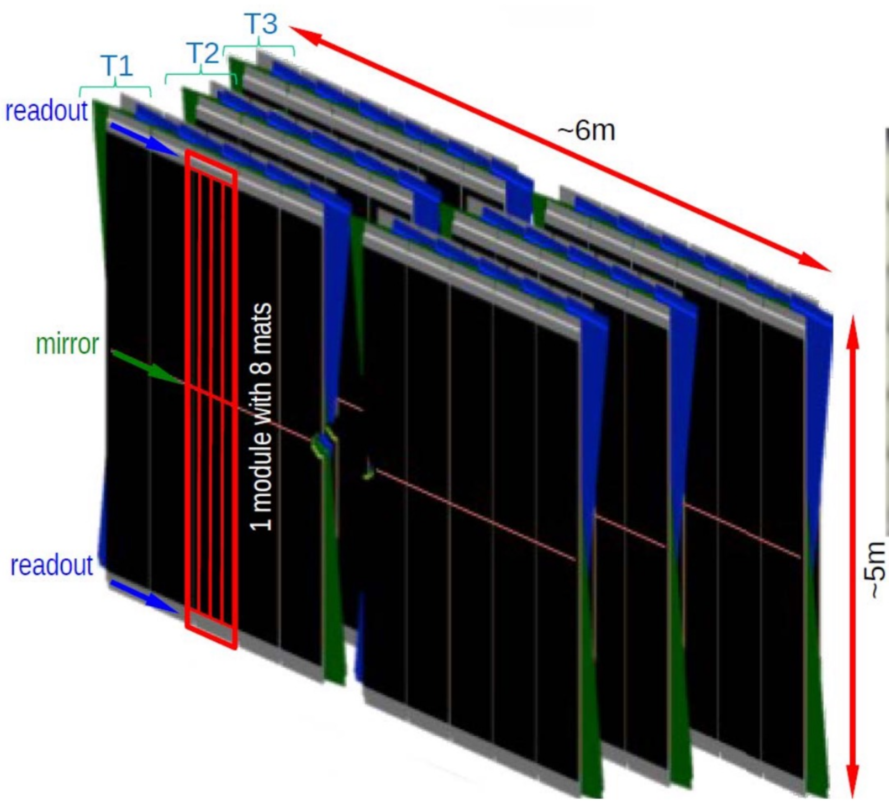
Detector:

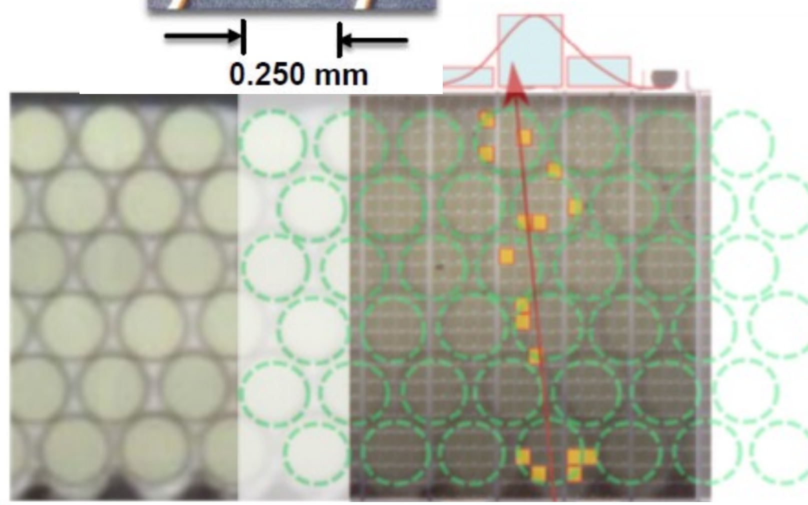
1) SciFi (scintillating fibers)
2) SiPM (silicon photomultiplier)





1 SiPM = 128 channels

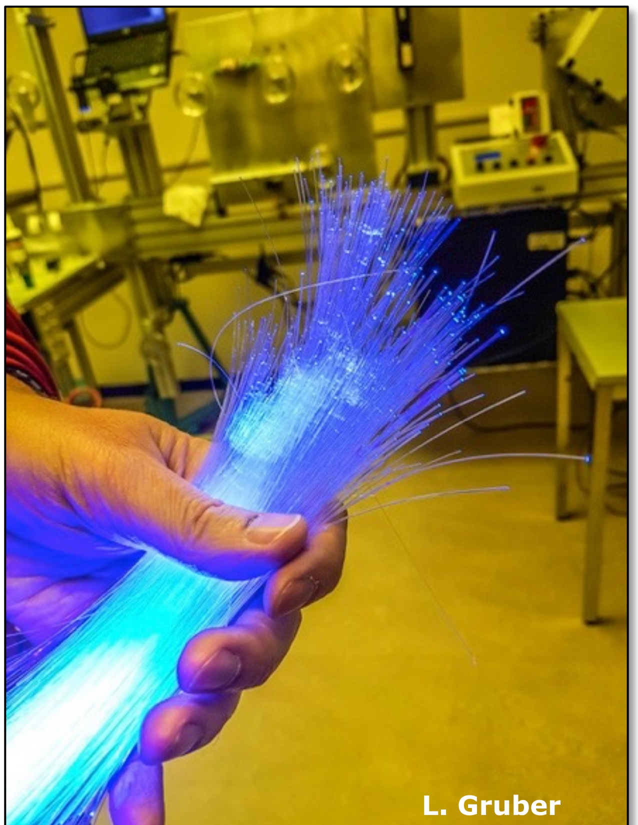


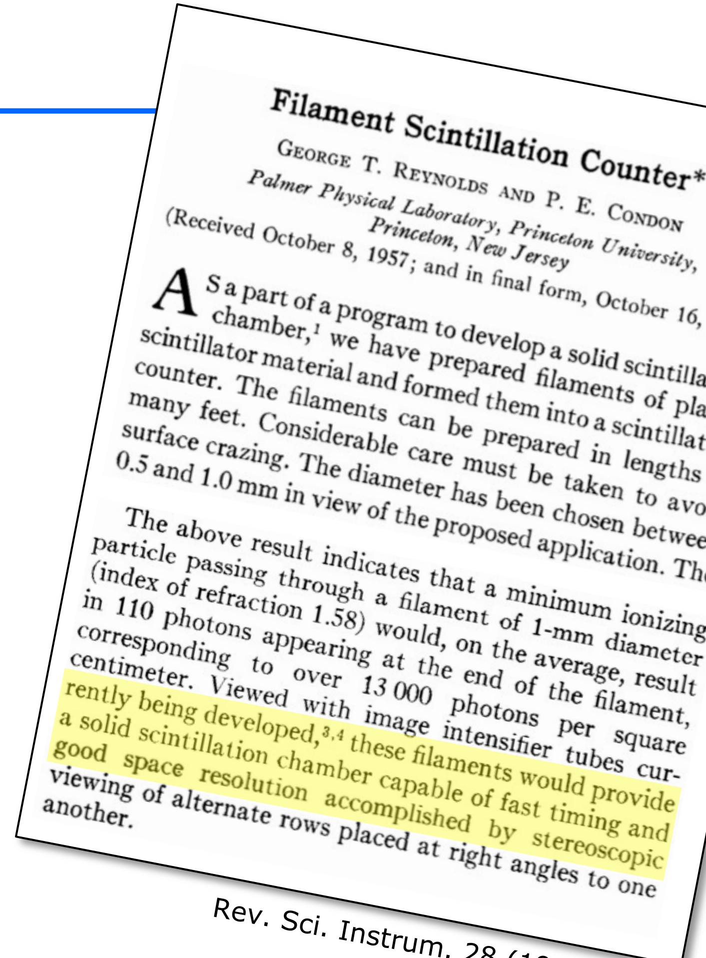


➔ <100 µm hit resolution
(we reached 70µm)

Scintillating fibers

- Core of polystyrene
- Thin cladding layers with lower refractive indices
- Light transport: internal reflection between core and cladding structure
  - Only few photons per fiber per track detected by SiPM !





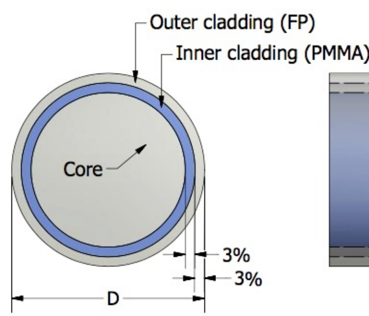
Filament Scintillation Counter*

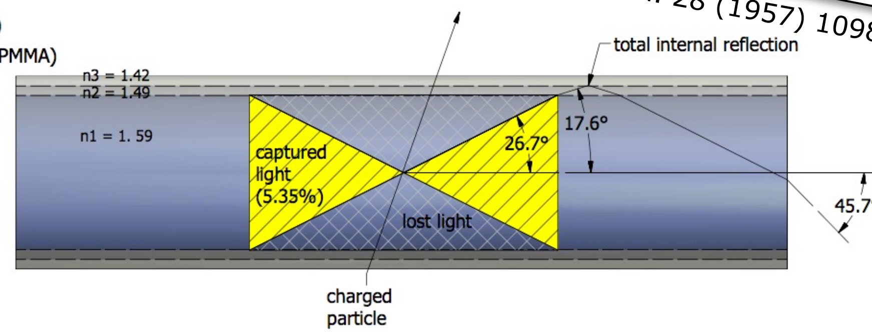
George T. Reynolds and P. E. Condon
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received October 8, 1957; and in final form, October 16,

As a part of a program to develop a solid scintilla chamber,[1] we have prepared filaments of pla scintillator material and formed them into a scintillat counter. The filaments can be prepared in lengths many feet. Considerable care must be taken to avo surface crazing. The diameter has been chosen betwee 0.5 and 1.0 mm in view of the proposed application. Th

The above result indicates that a minimum ionizing particle passing through a filament of 1-mm diameter (index of refraction 1.58) would, on the average, result in 110 photons appearing at the end of the filament, corresponding to over 13 000 photons per square centimeter. Viewed with image intensifier tubes currently being developed,[3,4] these filaments would provide a solid scintillation chamber capable of fast timing and good space resolution accomplished by stereoscopic viewing of alternate rows placed at right angles to one another.

Rev. Sci. Instrum. 28 (1957) 1098





Intermezzo: magnet choice?

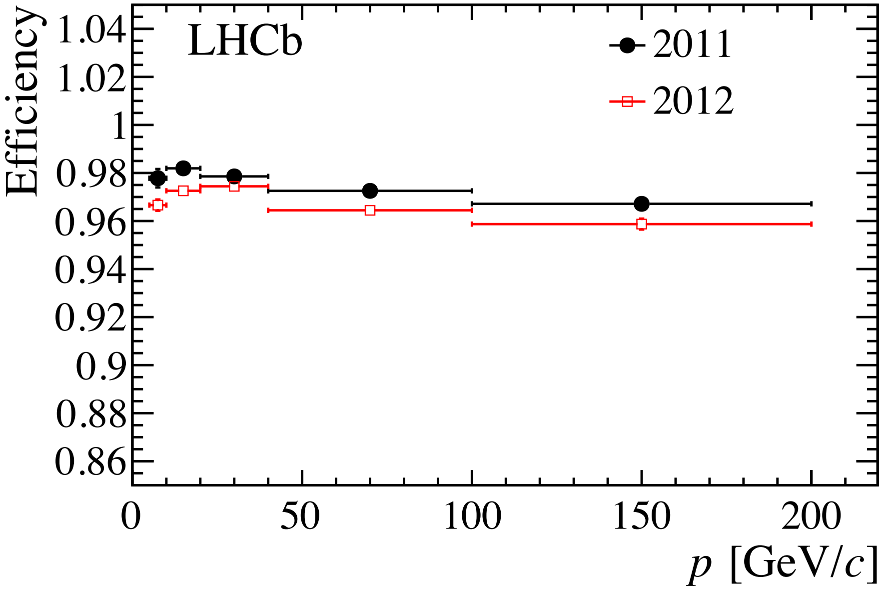
- first choice that has to be made for a HEP experiment layout
- difficult to replace
- Dipole fields will require a ”compensating” dipole for the accelerating/colliding particles
- It consumes a lot of power

Table 5.2: Power supply requirements

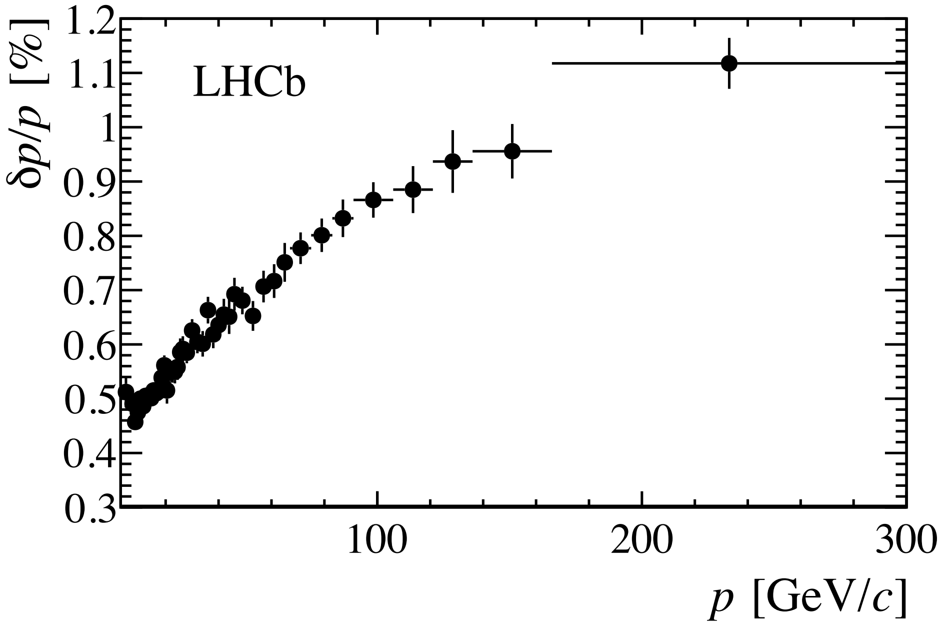
Network power	$\prod = 6.0$ MVA
Dissipated power	$P = 100$ kW
Total water flow	$\varphi = 3.5\ m^3/h$
Pressure drop	$\Delta p = 5$ bar at $\Delta T = 25$ ºC
Maximum inlet temperature	$T = 20$ ºC

LHCb tracking performance (p)

Track finding efficiency measured with "tag-and-probe"



High momenta become almost straight: resolution deteriorates



LHCb tracking performance: ”tag-and-probe”

How often VELO track is found?

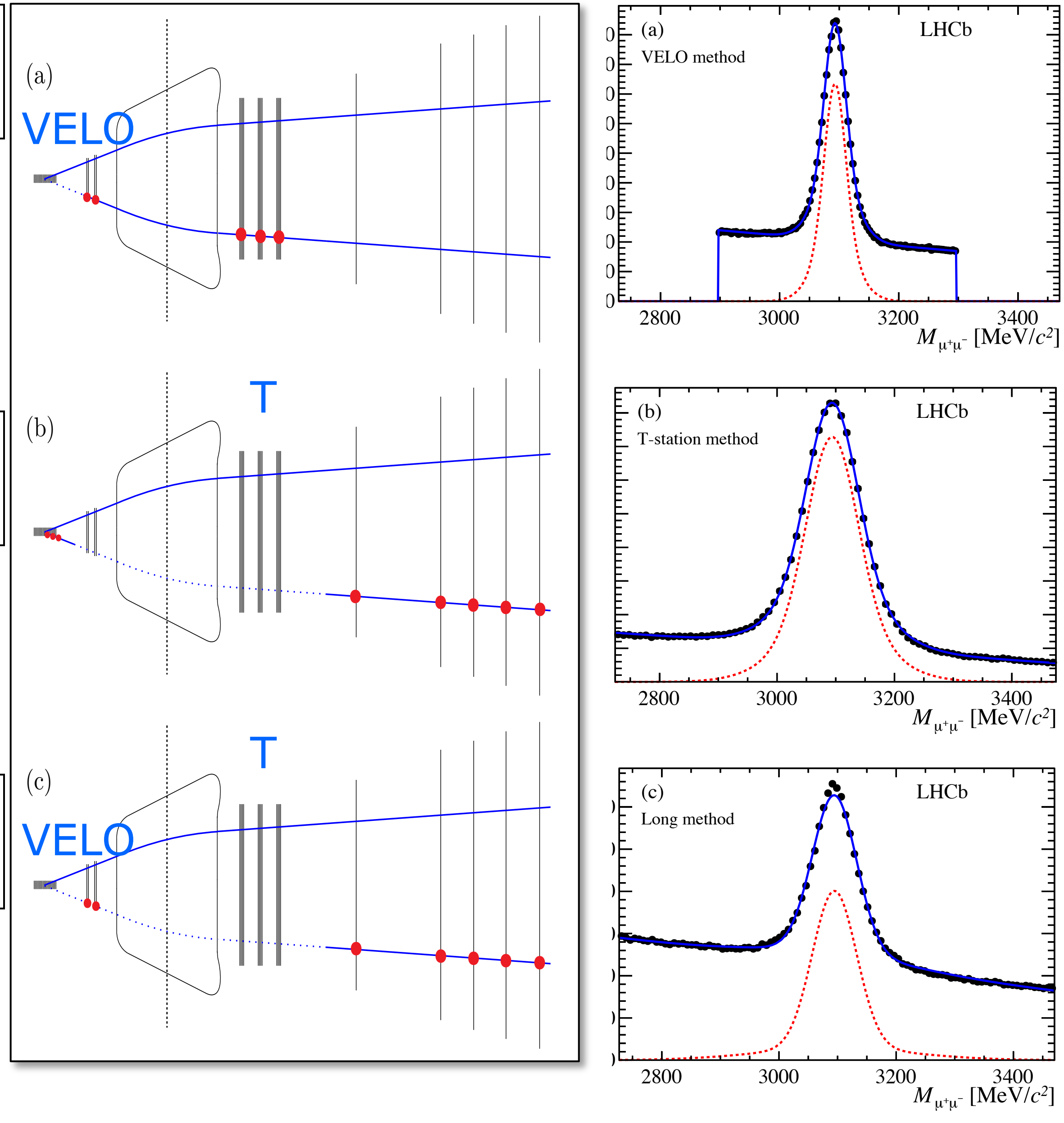
(using TT and T hits)

How often T track is found?

(using VELO and MUON hits)

How often Long track is found?

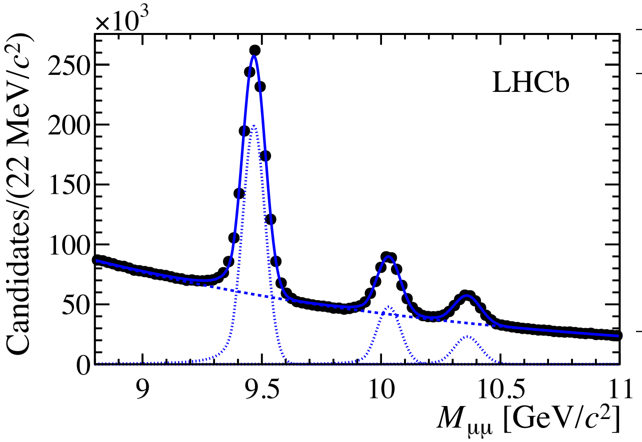
(using TT and MUON hits)



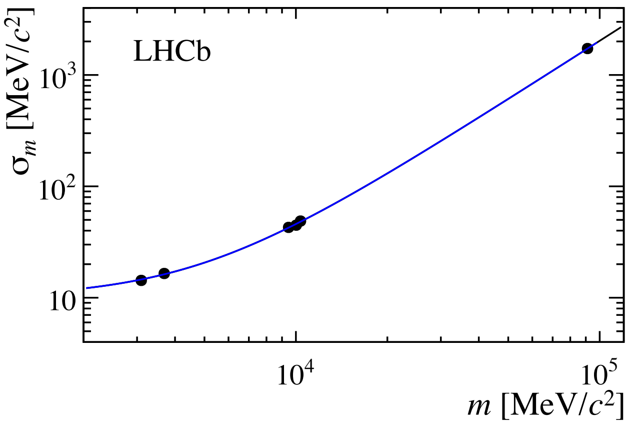
LHCb, arXiv:1408.1251

LHCb tracking performance (m)

- Mass resolution measured from resonances:



Resonance	Mass resolution (MeV/c^2)
J/ψ	14.3 ± 0.1
$\psi(2S)$	16.5 ± 0.4
$\Upsilon(1S)$	42.8 ± 0.1
$\Upsilon(2S)$	44.8 ± 0.1
$\Upsilon(3S)$	48.8 ± 0.2
Z^0	1727 ± 64



Particle identification

- Many different B-decays!
  - "BtooKstarpipiDsgamma"
  - …
- Need to distinguish:
  - e, μ, γ, π, K, p, …

B^0 Decay Modes ▾ Collapse all

$\overline{B}^0$ modes are charge conjugates of the modes below. Reactions indicate the weak decay vertex and do not include mixing. Modes which do not identify the charge state of the B are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% B^+B^- production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed D, D_s, D^*, and ψ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

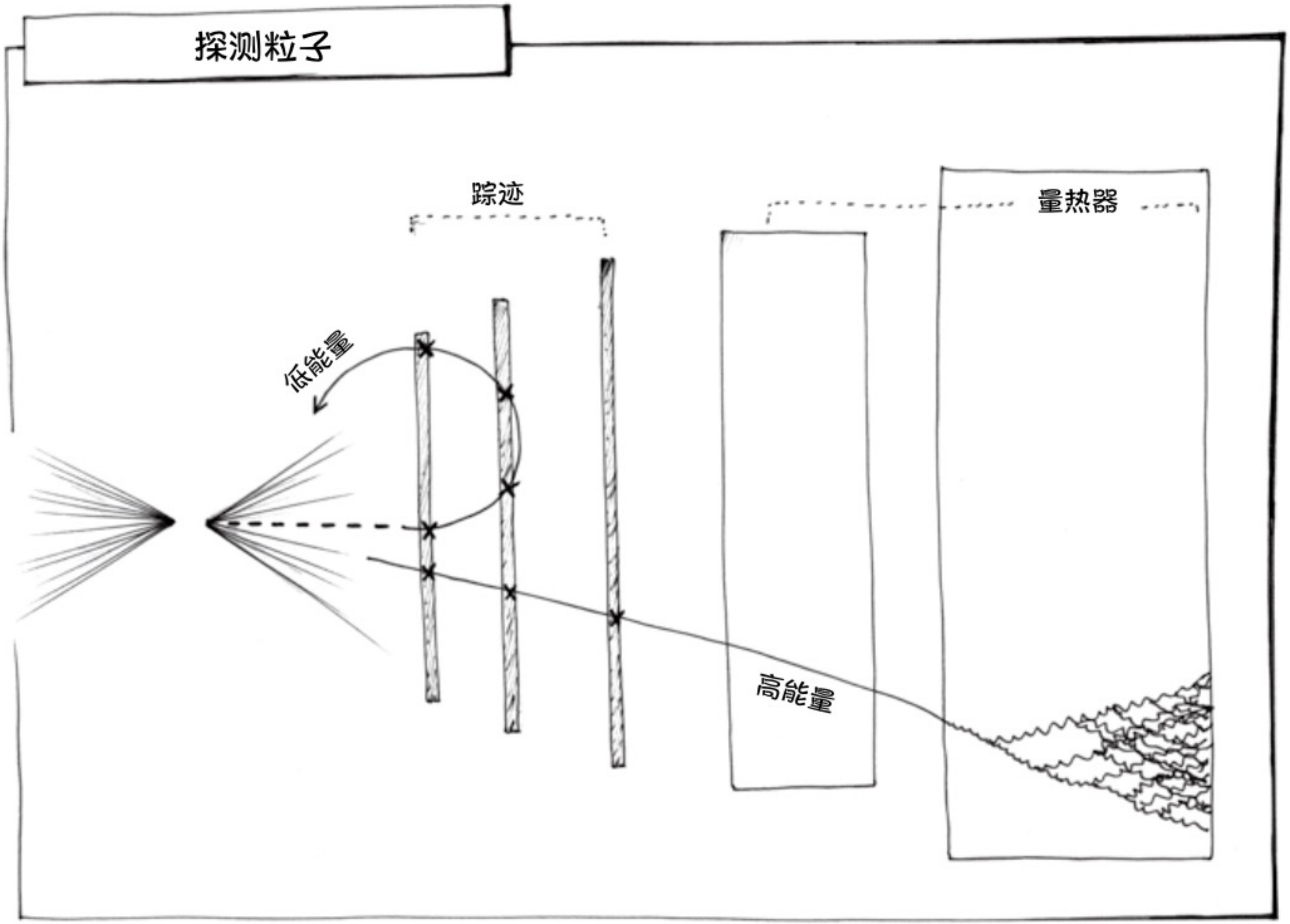
For inclusive branching fractions, e. g., $B \to D^\pm X$, the values usually are multiplicities, not branching fractions. They can be greater than one.

	Mode	Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$\ell^+\nu_\ell X$	$(10.33 \pm 0.28)\%$		
Γ_2	$e^+\nu_e X_c$	$(10.1 \pm 0.4)\%$		
Γ_3	$\ell^+\nu_\ell X_u$	$(1.51 \pm 0.19) \times 10^{-3}$		
Γ_4	$D\ell^+\nu_\ell X$	$(9.3 \pm 0.8)\%$		
Γ_5	$D^-\ell^+\nu_\ell$	$(2.24 \pm 0.09)\%$		2309
Γ_6	$D^-\tau^+\nu_\tau$	$(1.05 \pm 0.23)\%$		1909
Γ_7	$D^*(2010)^-\ell^+\nu_\ell$	$(4.97 \pm 0.12)\%$		2257

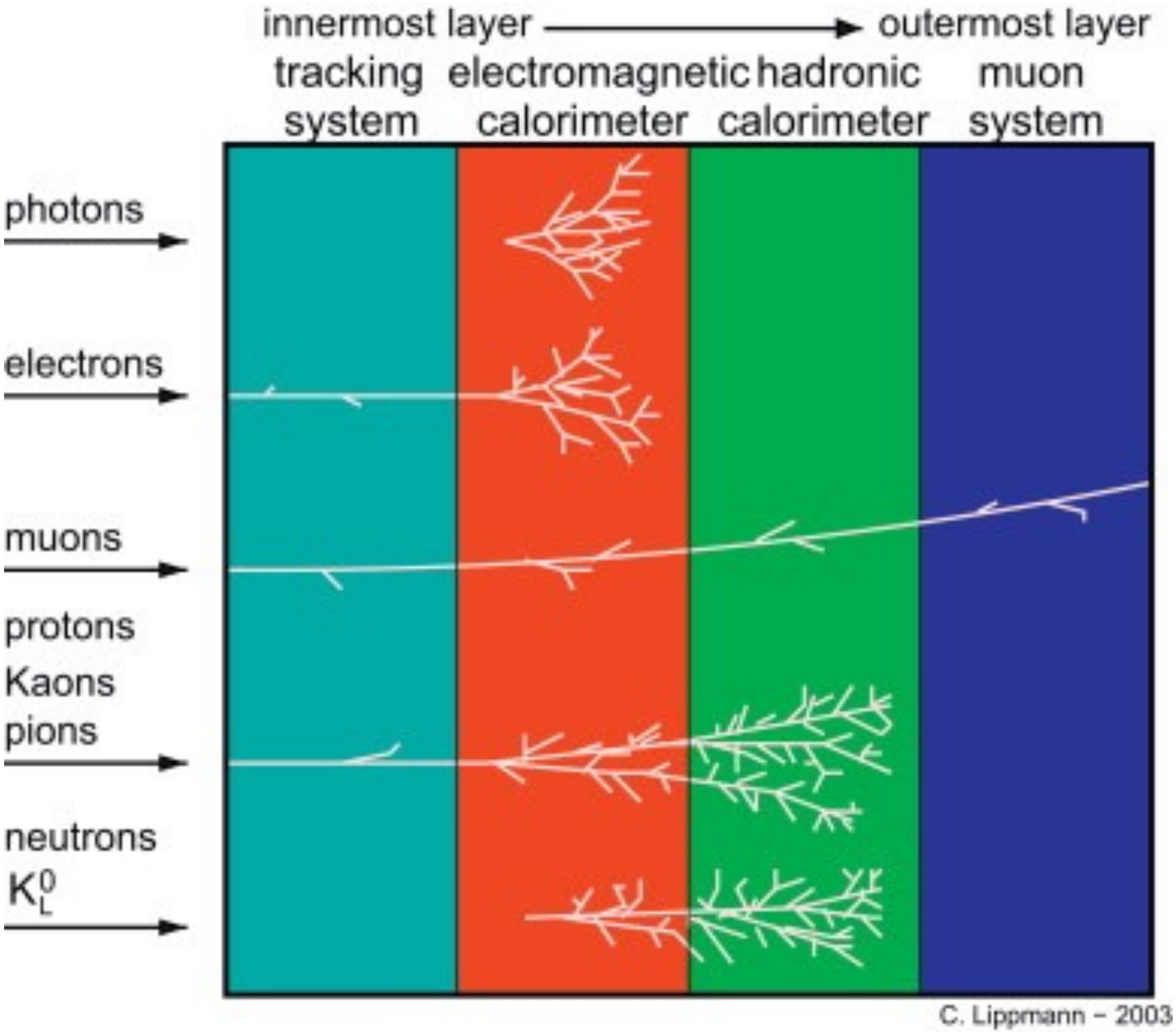
⋮

Γ_{535}	$\pi^0\nu\overline{\nu}$	$< 9 \times 10^{-6}$	CL=90%	2638
Γ_{536}	$K^0\ell^+\ell^-$	$(3.3 \pm 0.6) \times 10^{-7}$		2616
Γ_{537}	$K^0e^+e^-$	$(2.5^{+1.1}_{-0.9}) \times 10^{-7}$	S=1.3	2616
Γ_{538}	$K^0\mu^+\mu^-$	$(3.39 \pm 0.35) \times 10^{-7}$	S=1.1	2612
Γ_{539}	$K^0\nu\overline{\nu}$	$< 2.6 \times 10^{-5}$	CL=90%	2616
Γ_{540}	$\rho^0\nu\overline{\nu}$	$< 4.0 \times 10^{-5}$	CL=90%	2583
Γ_{541}	$K^*(892)^0\ell^+\ell^-$	$(9.9^{+1.2}_{-1.1}) \times 10^{-7}$		2565
Γ_{542}	$K^*(892)^0e^+e^-$	$(1.03^{+0.19}_{-0.17}) \times 10^{-6}$		2565
Γ_{543}	$K^*(892)^0\mu^+\mu^-$	$(9.4 \pm 0.5) \times 10^{-7}$		2560

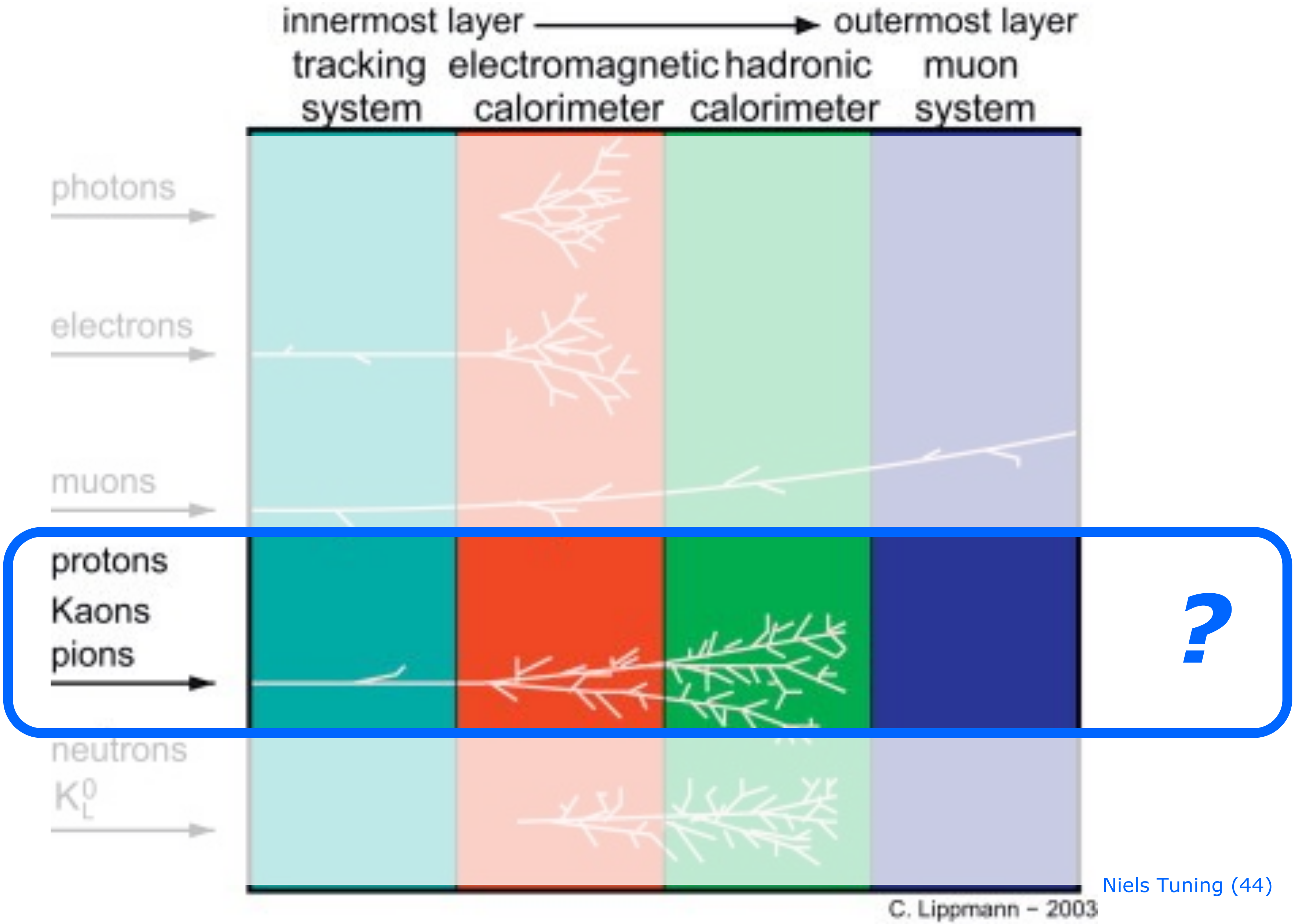
Particle identification: detector choice



Particle identification



Particle identification



Particle identification: detector choice

1) Time-of-flight ?

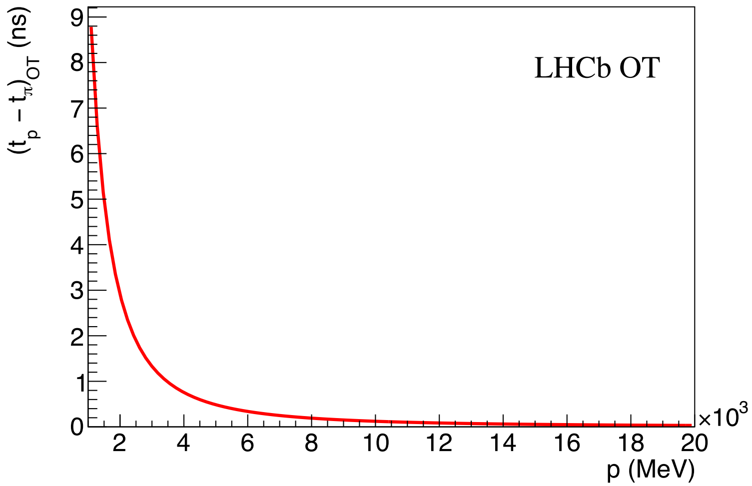
2) dE/dx ?

3) Cherenkov effect ?

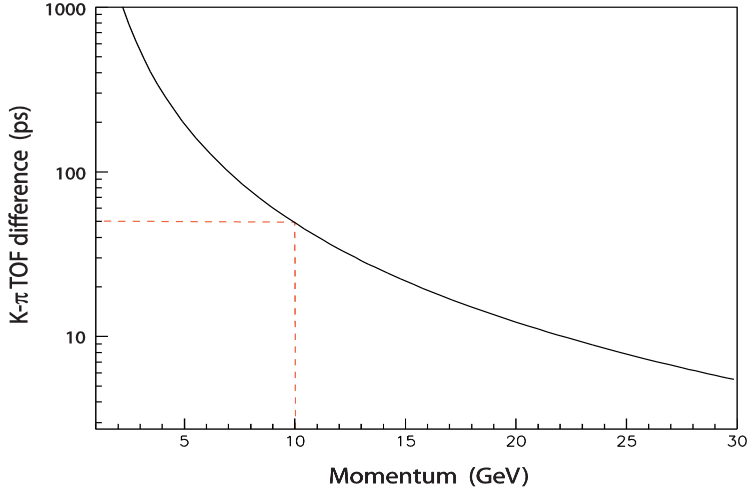
Particle identification: detector choice

1) Time-of-flight ?

Ex. 1: **1 ns resolution**: p<5 GeV
proton – pion difference at z= 8m



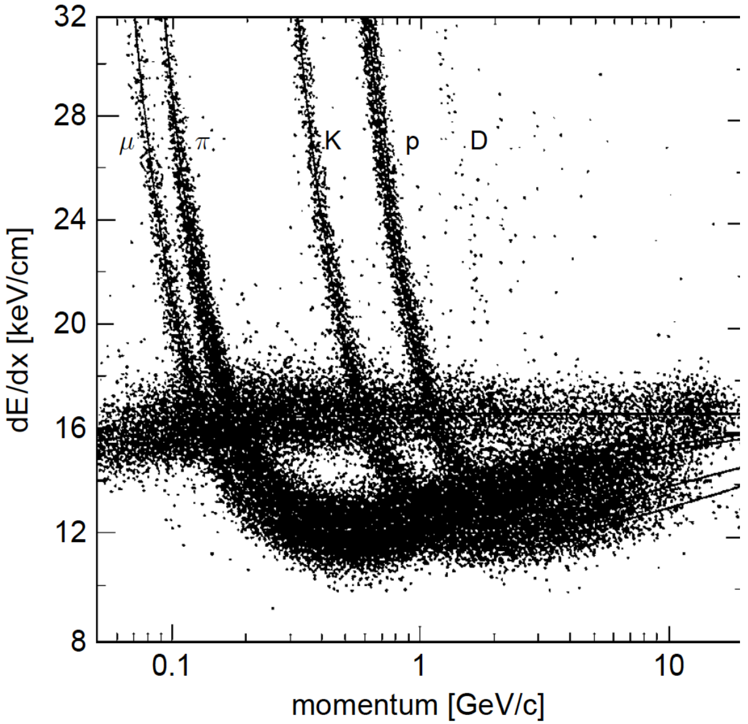
Ex. 2: **50 ps resolution:** p<10 GeV
kaon – pion difference at z=12m



Particle identification: detector choice

2) dE/dx ?

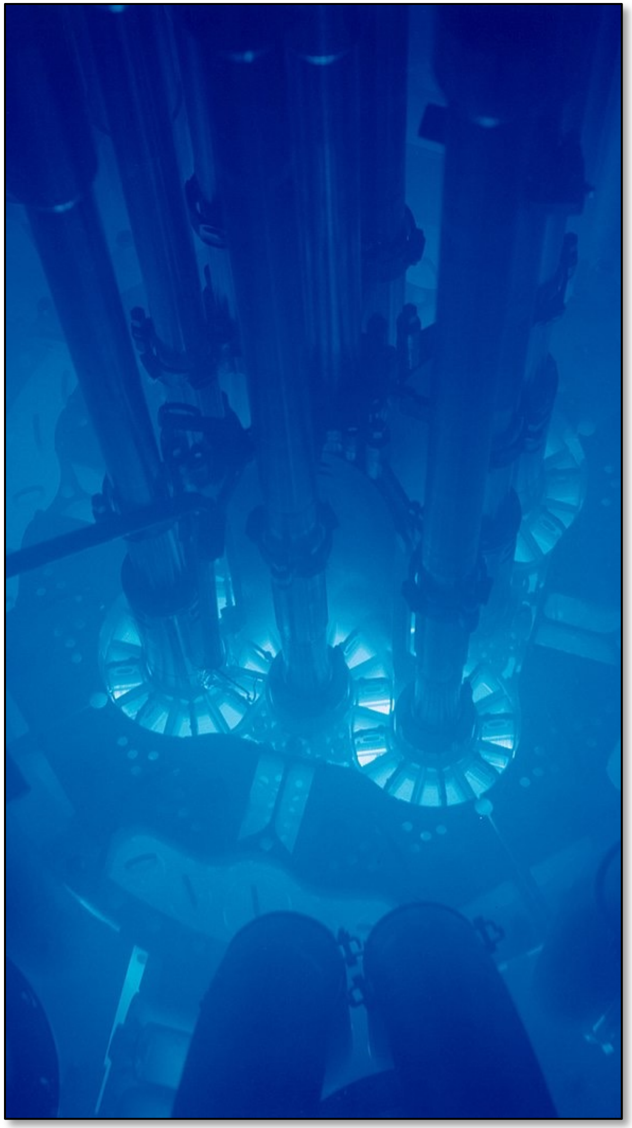
- Charged particles passing through matter: *ionization*
- Energy loss velocity dependent Bethe-Bloch formula: $dE/dx \propto \log(\beta^2\gamma^2) / \beta^2$
- *dE/dx* varies rapidly at low momenta
- *Advantage:* uses existing detectors needed (but requires accurate measurement of the charge)
- *Note:* signals for *all* charged particles
  But $m_\mu \approx m_\pi$, so they are not well separated (dedicated detectors do a better job)



Particle identification: detector choice

3) Cherenkov effect ?

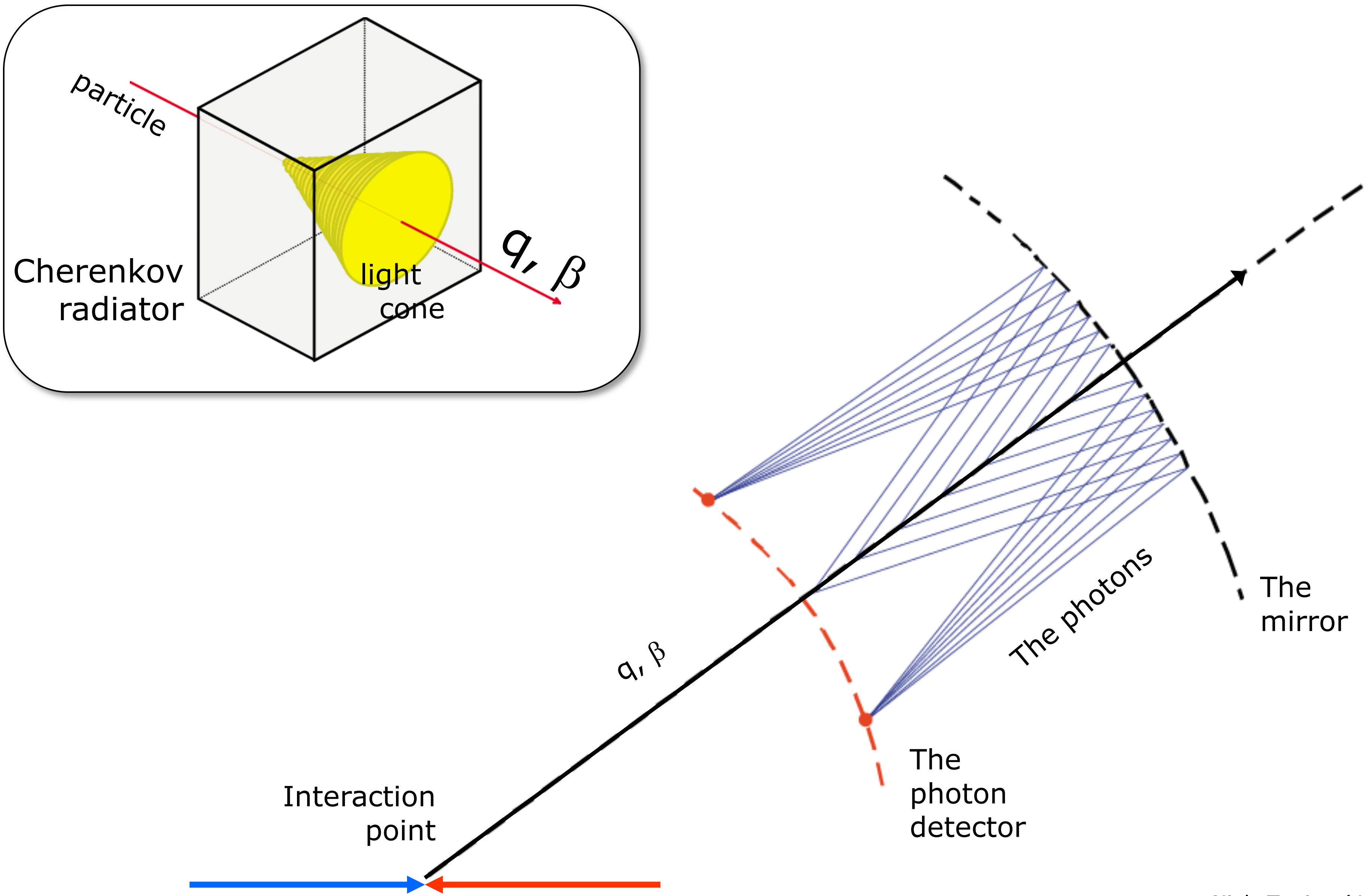
- when the velocity of charged particle in a dielectric medium exceeds the light speed in that medium
- The angle depends on the speed
- Measuring the angle is measuring the speed



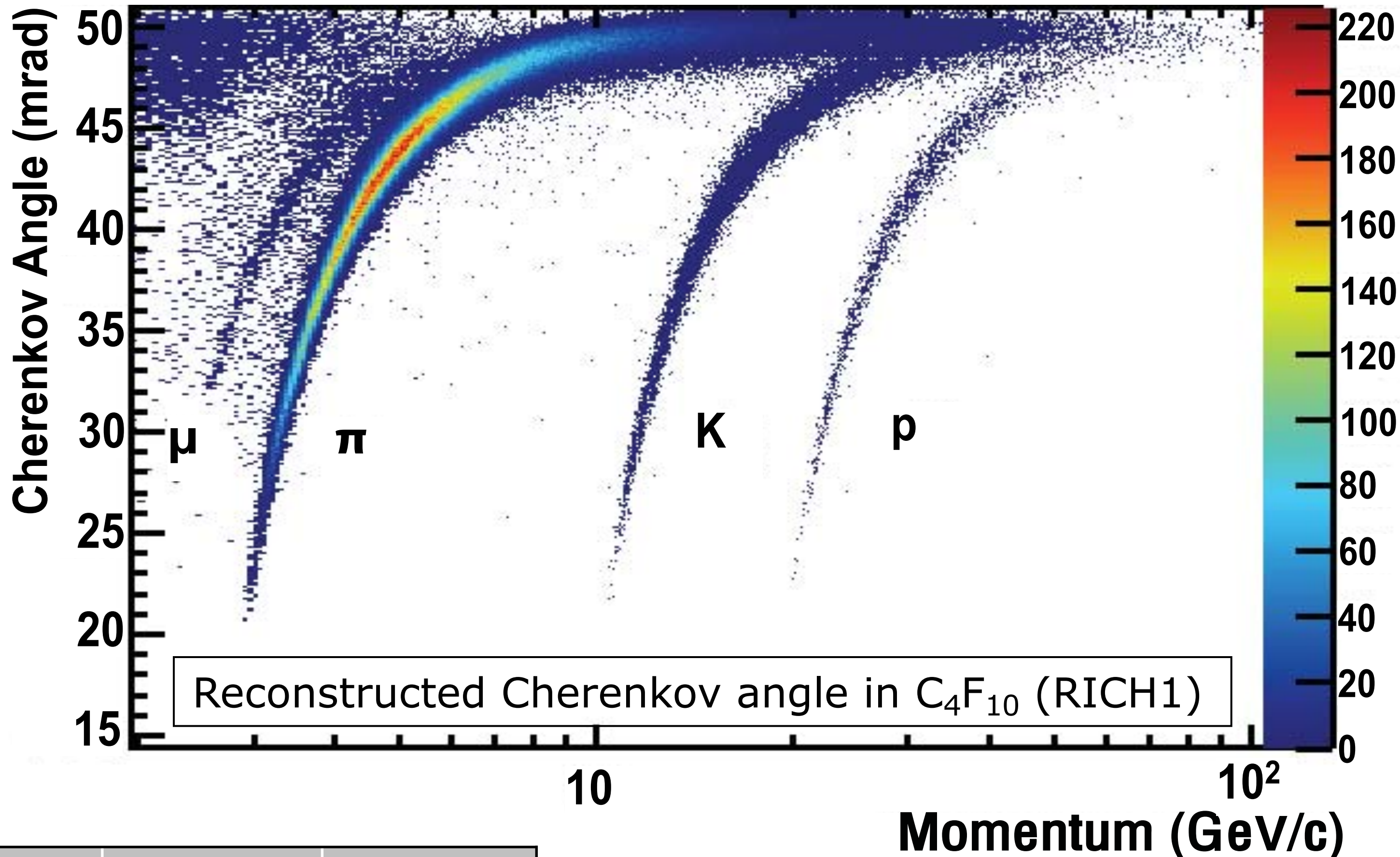
$$\cos(\theta_c) = \frac{1}{\beta n}$$

$\beta_{thr} = 1/n$

Particle identification: detector choice: RICH



Particle identification performance

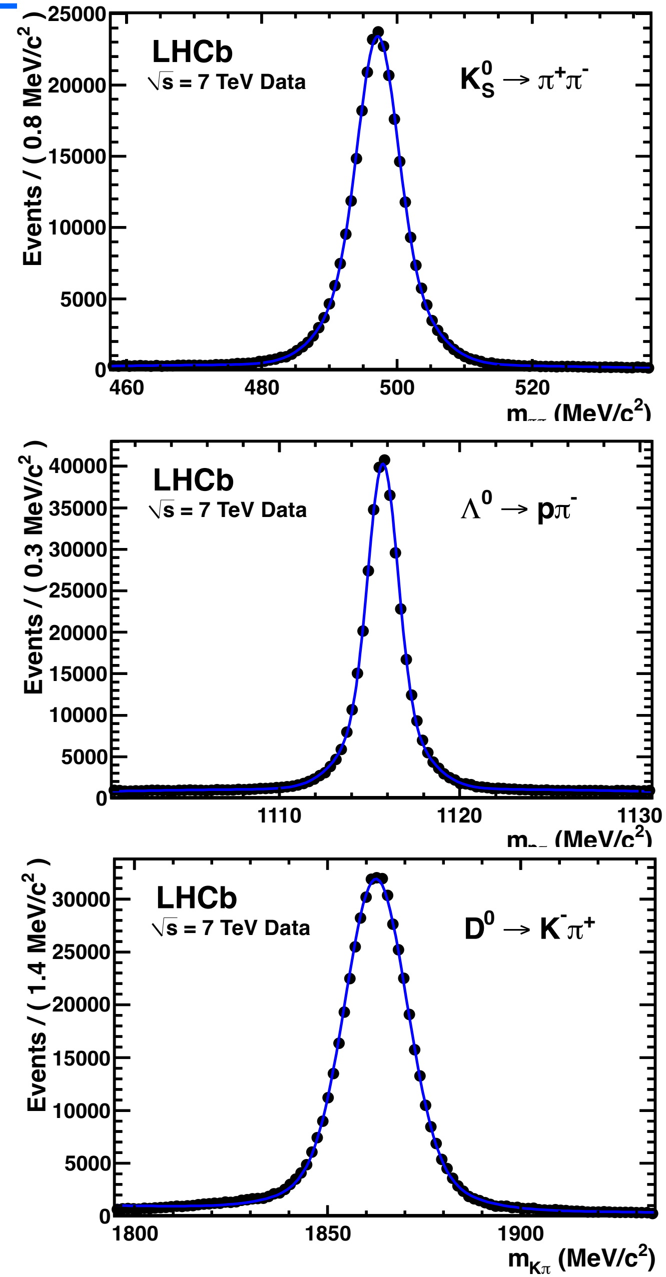


	RICH1	RICH2
Radiator	C_4F_{10}	CF_4
n	1.0014	1.0005
P (GeV)	2-40	15-100
Acc (mrad)	25-300	15-120

- Detector optimized with *two* different radiators

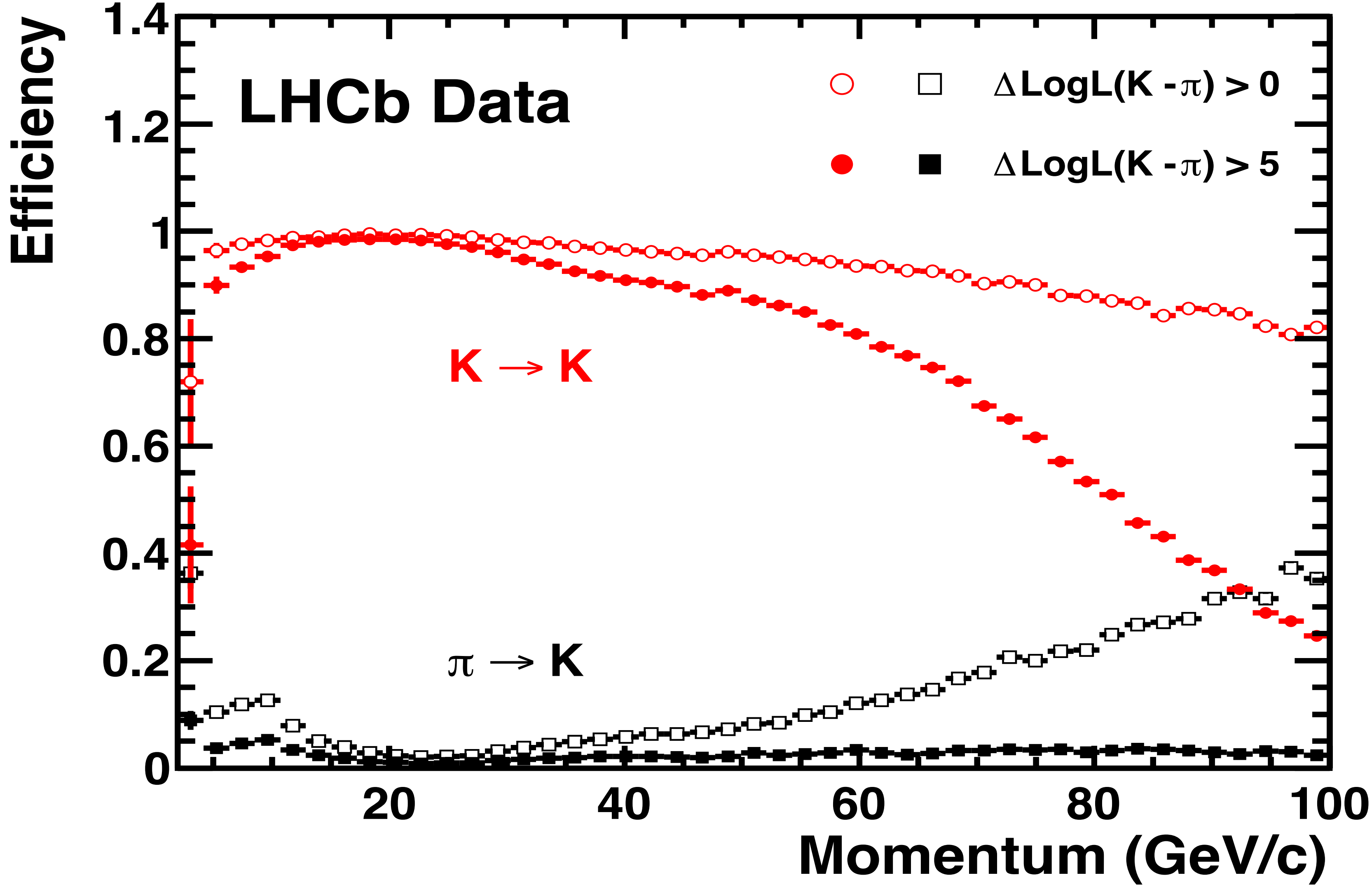
Particle identification performance

- Performance measured
  - π with $K_S{}^0 \rightarrow \pi\pi$
  - p with $\Lambda \rightarrow p\pi$
  - K,π with $D^* \rightarrow D^0(\rightarrow K\pi)$



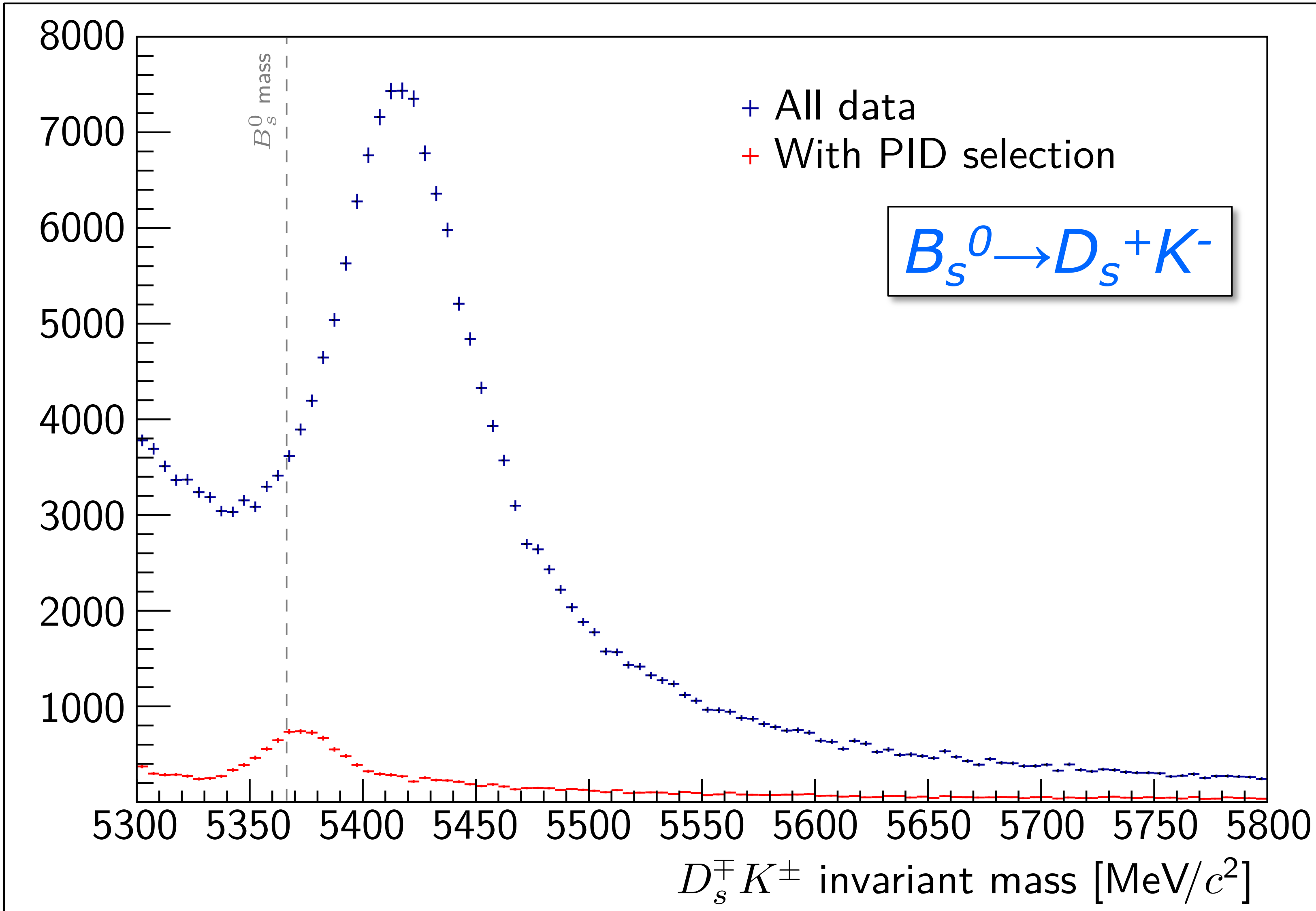
LHCb, arXiv:1211.6759

Particle identification performance

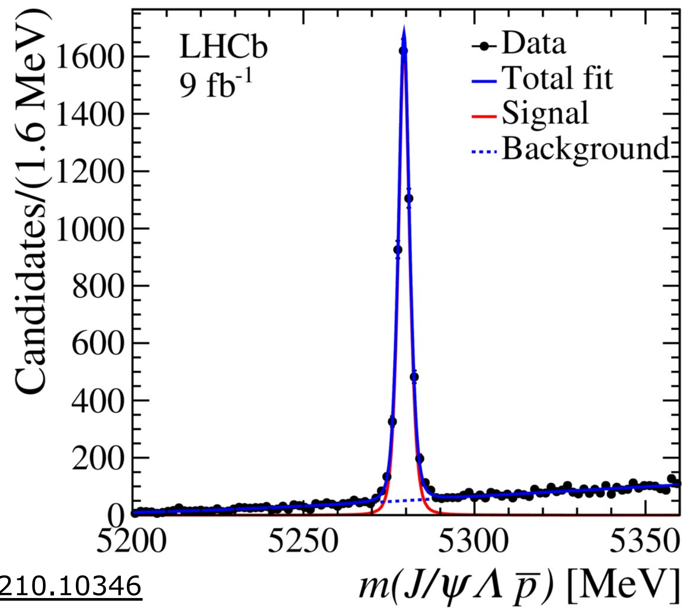


Particle identification performance

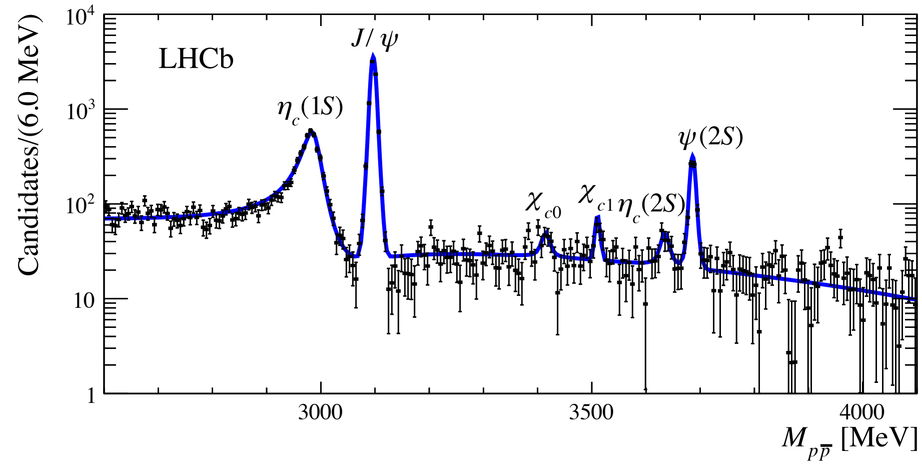
- $B_s^0 \to D_s^+ K^-$ much more rare than $B_s^0 \to D_s^+ \pi^-$ ...



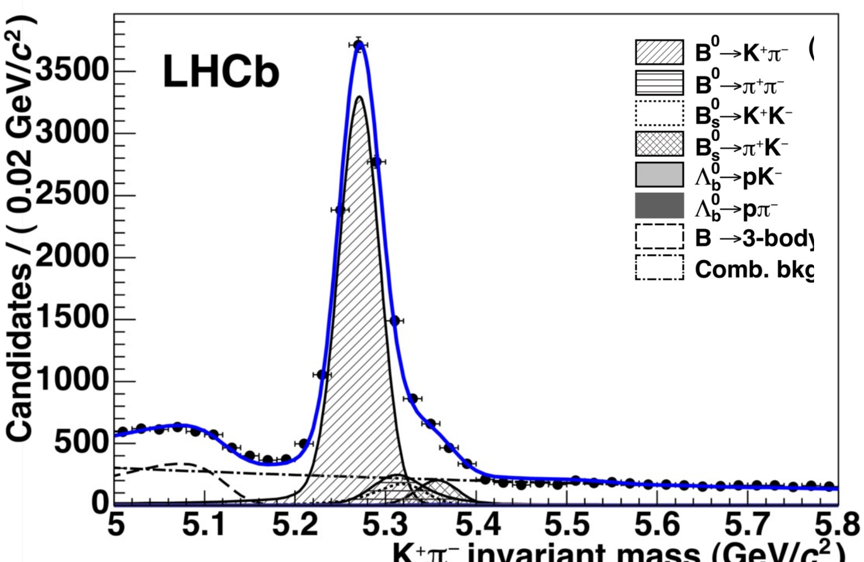
π,K,p identification: indispensable for flavour physics

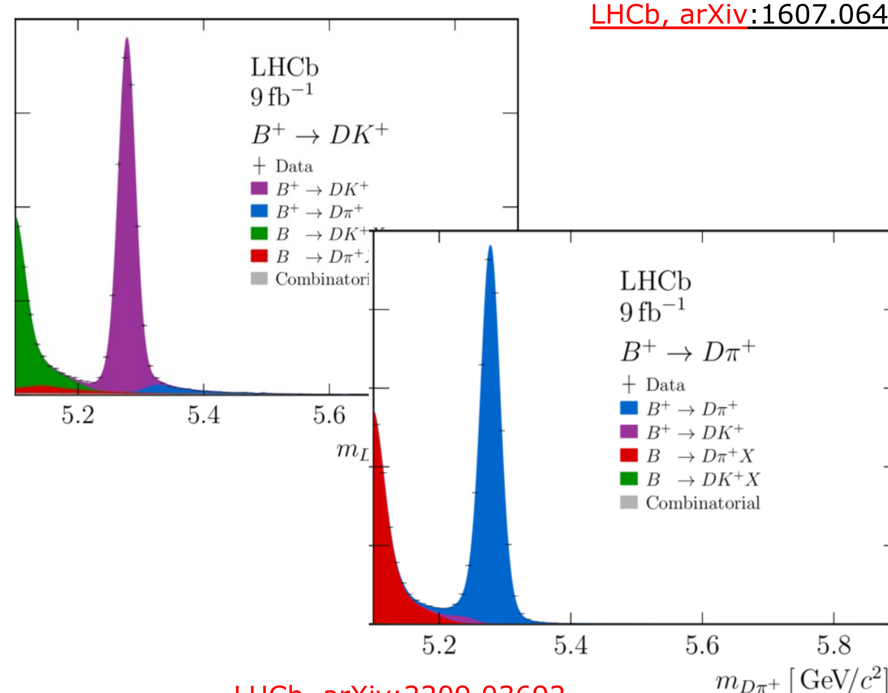


LHCb, arXiv:2210.10346



LHCb, arXiv:1607.06446





LHCb, arXiv:2209.03692

Detecting CP violation with B decays

1) CP violation: CKM and the SM
2) Detecting: Detector requirements
3) B-decays: sin2β, ϕ_s, $B_s^0 \rightarrow D_s^+ K^-$