LHCb Experiment

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Outline

- Part I

- Basics on Flavor Physics & CP violation

- Part II

- The LHCb Experiment
- Selected topics on physics at LHCb

Selected topics on physics at LHCb

Part II

An example

- CPLEAR Experiment (1999)

Initial state at t = 0

$$\bar{p}p \rightarrow \begin{cases} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{cases}$$

S = 0 S = 0

$$K^- = (\bar{u}s)$$

$$K^+ = (u\bar{s})$$

Decay final state at time t

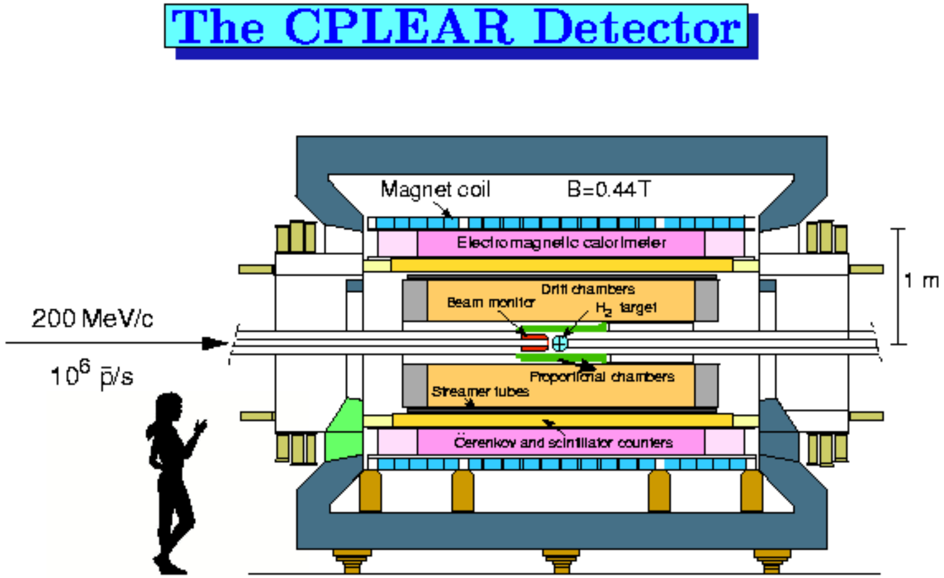
$CP(\pi^+\text{-}\pi^-) = +1$

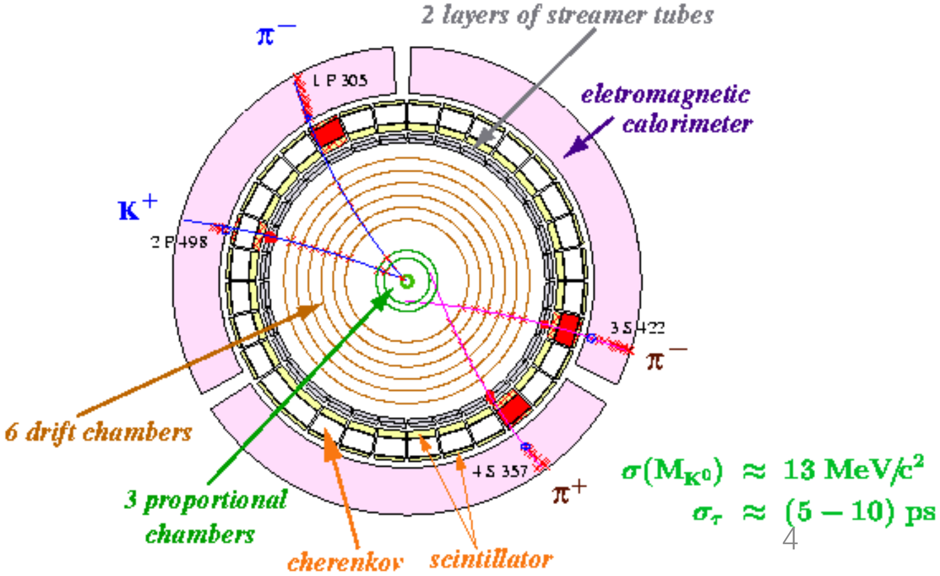
$\pi^+\text{-}\pi^-$

$$\text{Spin}(\pi) = 0$$

$$L_{\pi\text{-}\pi} = 0$$

i.e. CP eigenstate

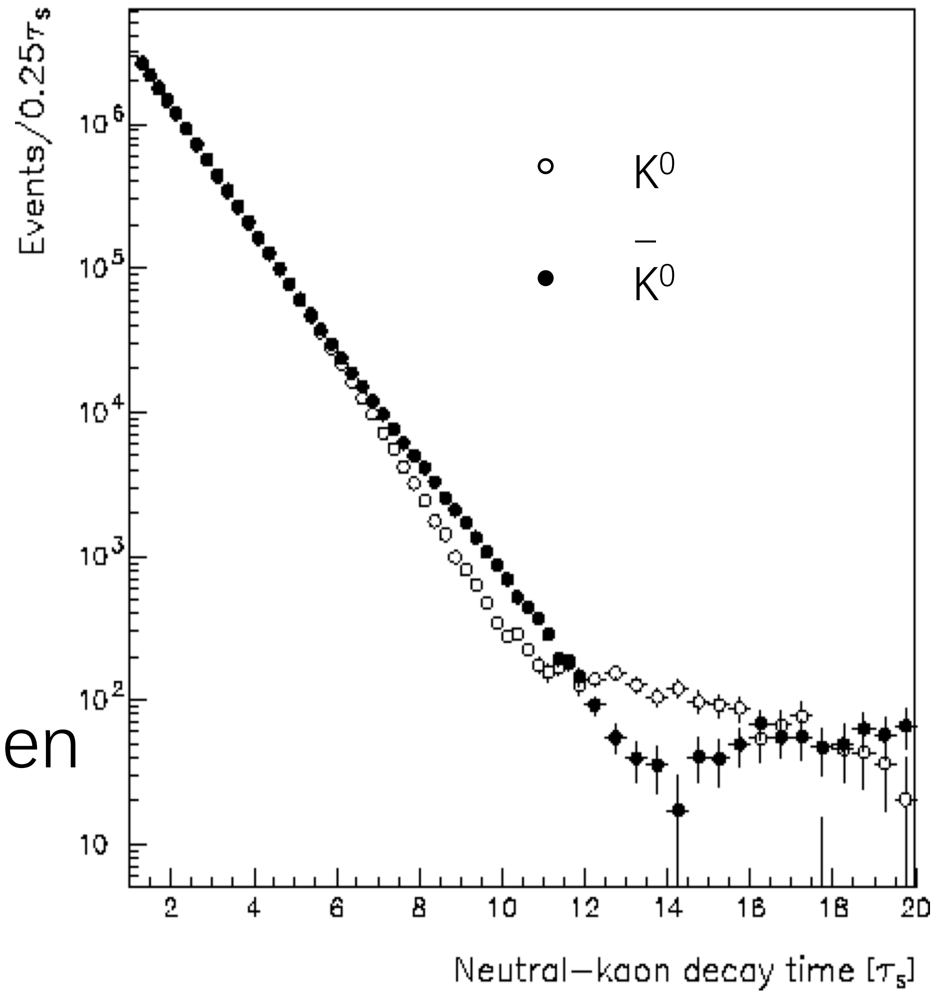




CP violation in $K^0, \bar{K}^0$ decays

K^0 at $t = 0$ decays into $\pi^+ \pi^-$
vs
$\bar{K}^0$ at $t = 0$ decays into $\pi^+ \pi^-$

any difference = CP violation



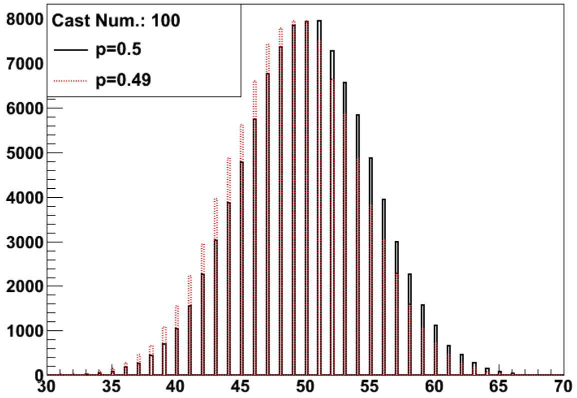
- Measurements of CP violation
  - → check the (small) difference between $P \to f$ vs. $\bar{P} \to \bar{f}$

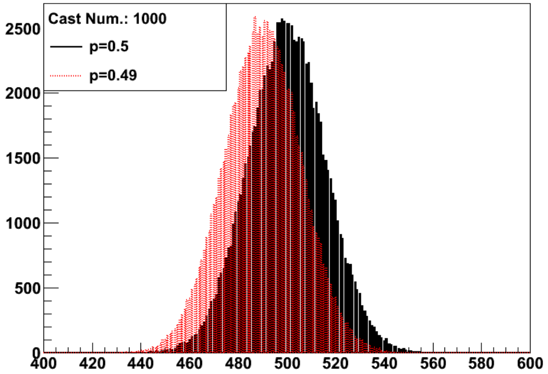
How to check a fake coin?

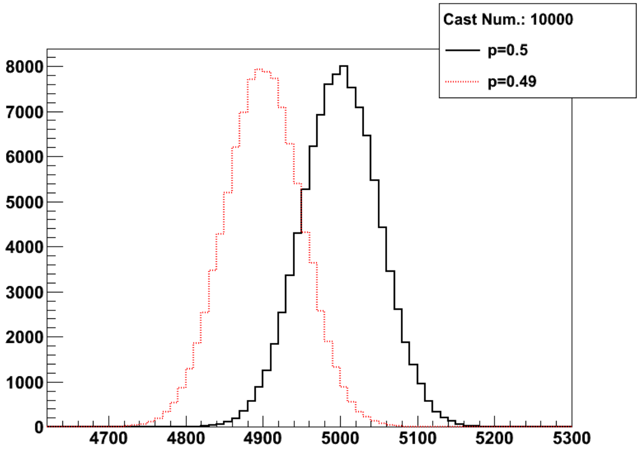
True : $q_u : q_d = 0.50 : 0.50$

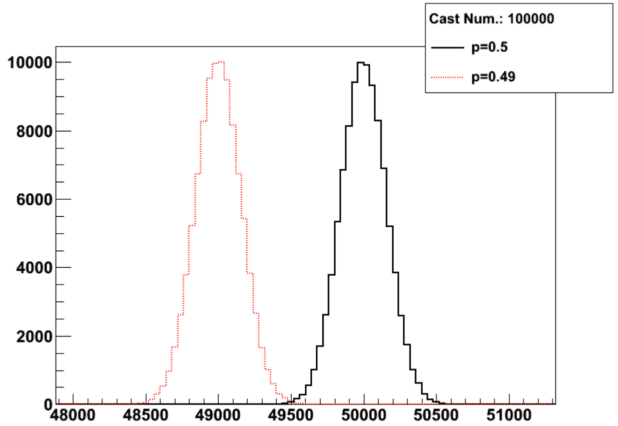
Fake : $q_u : q_d = 0.49 : 0.51$

$$p(n) = \frac{N!}{n!(N-n)!} q_u^n q_d^{N-n}$$









- To reduce statistical error

$$N \to \infty$$

- Control systematic error
  - effect of the air ?
  - earth magnet ?
  - wrong counting ?
  - ……

FLORIDA VOTE COUNT TOTALS Nov. 26, 2000

PRESIDENT	Nov. 7	First Recount	Certified
R Bush	2,909,176	2,911,872	2,912,790
D Gore	2,907,451	2,910,942	2,912,253
Bush Lead	1725	930	537

Source: State of Florida   Systematic Uncertainty ≈ 0.1%

25 electoral votes at stake

…compare the result with a standard coin !

Standard

test

For a real experiment

$$N_{eff} = \int Ldt \times \sigma_{pp\to P,\bar{P}}$$

Production cross-section

Int. Luminosity

$$\times \varepsilon$$

Detection efficiency

$$\times (1-2w)^2$$

Wrong tag

- High luminosity machine
- High cross-section process
- State of art detector

For a real experiment :

$$N_{eff} = \int L\mathrm{d}t \times \sigma_{pp \to P,\bar{P}}$$

Production cross-section

Int. Luminosity

$$\times \varepsilon$$

Detection efficiency

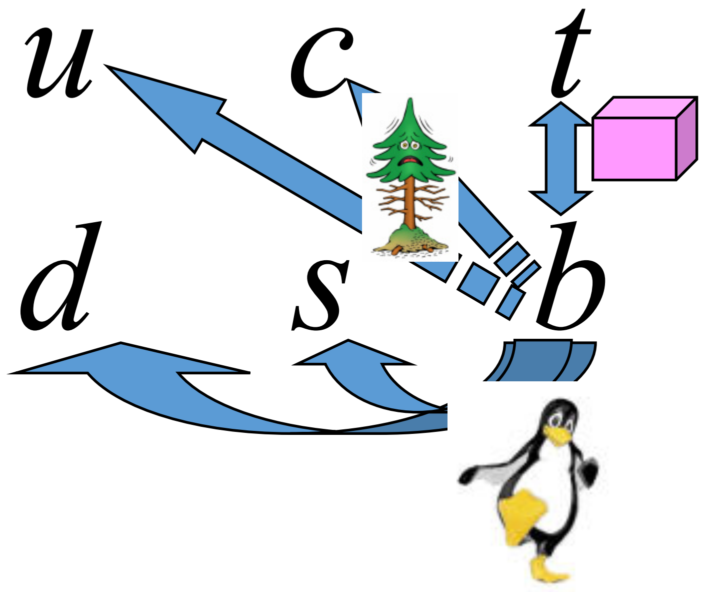
$$\times (1 - 2w)^2$$

Wrong tag

- High luminosity machine
- High cross-section process
- State of art detector

Why the b-quark ?

- Heaviest quark that forms hadronic bound states (m~4.7 GeV)
- Must decay outside 3rd family
  - All decays are CKM suppressed
  - Long lifetime (~1.6 ps)
- High mass: many accessible final states



- Dominant decay process: “tree” b→c transition
- Very suppressed “tree” b→u transition
- FCNC: “penguin” b→s,d transition
- Flavour oscillations (b→t “box” diagram)
- CP violation – expect large CP asymmetries in some B decays

CKM Matrix

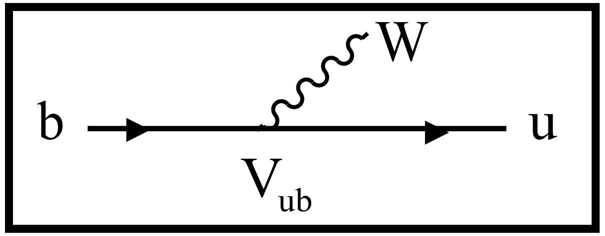
- V_{CKM} describes rotation between the weak eigenstates (d',s',b') and mass eigenstates (d,s,b)

weak states | CKM matrix | mass states

V_{ij} proportional to transition amplitude from quark j to quark i

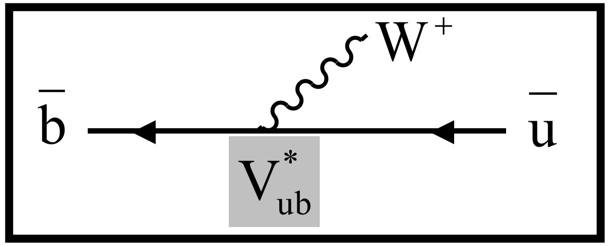
Quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Antiquarks

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



Wolfenstein Parameterization

Wolfenstein parameterization to $O(\lambda^3)$:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

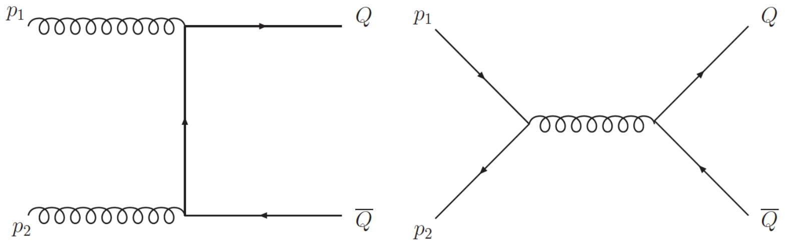
Next-to leading order corrections in λ will be important in LHC era:

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4/8\,(1+4A^2) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 + A\lambda^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

$$(\bar{\rho}\bar{\eta}) = (1-\lambda^2/2)(\rho\eta)$$

b productions at LHC

- LHC is also a flavor factory

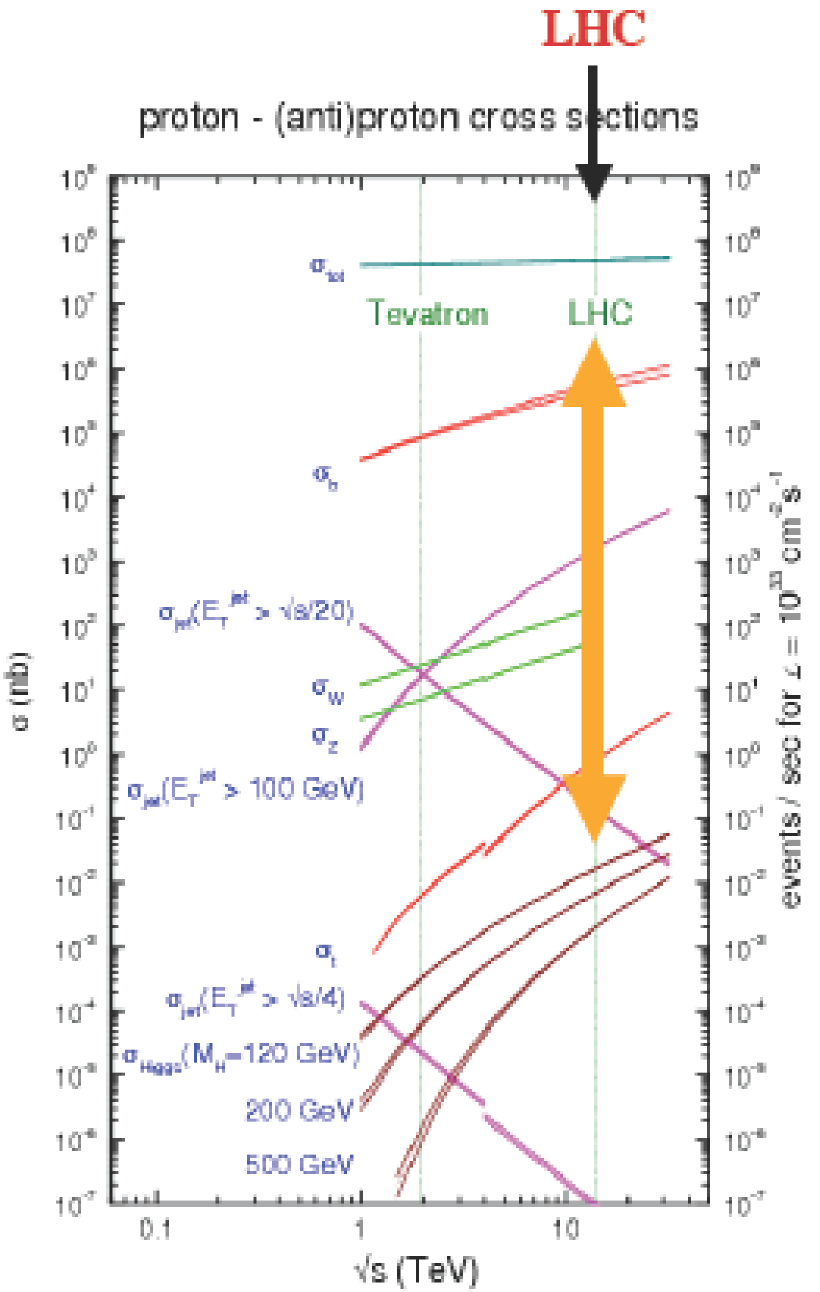


$$\sigma_{pp}^{\text{inel}} \sim 60 \text{ mb}$$

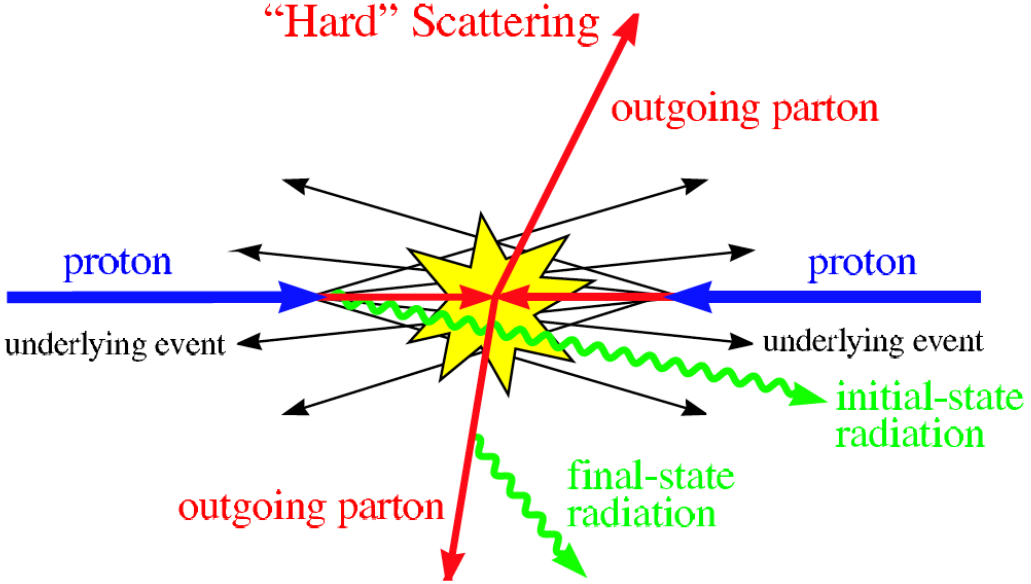
$$\sigma(pp \to c\bar{c}X) \sim 6 \text{ mb}, \sigma_{pp}^{\text{inel}}/10$$

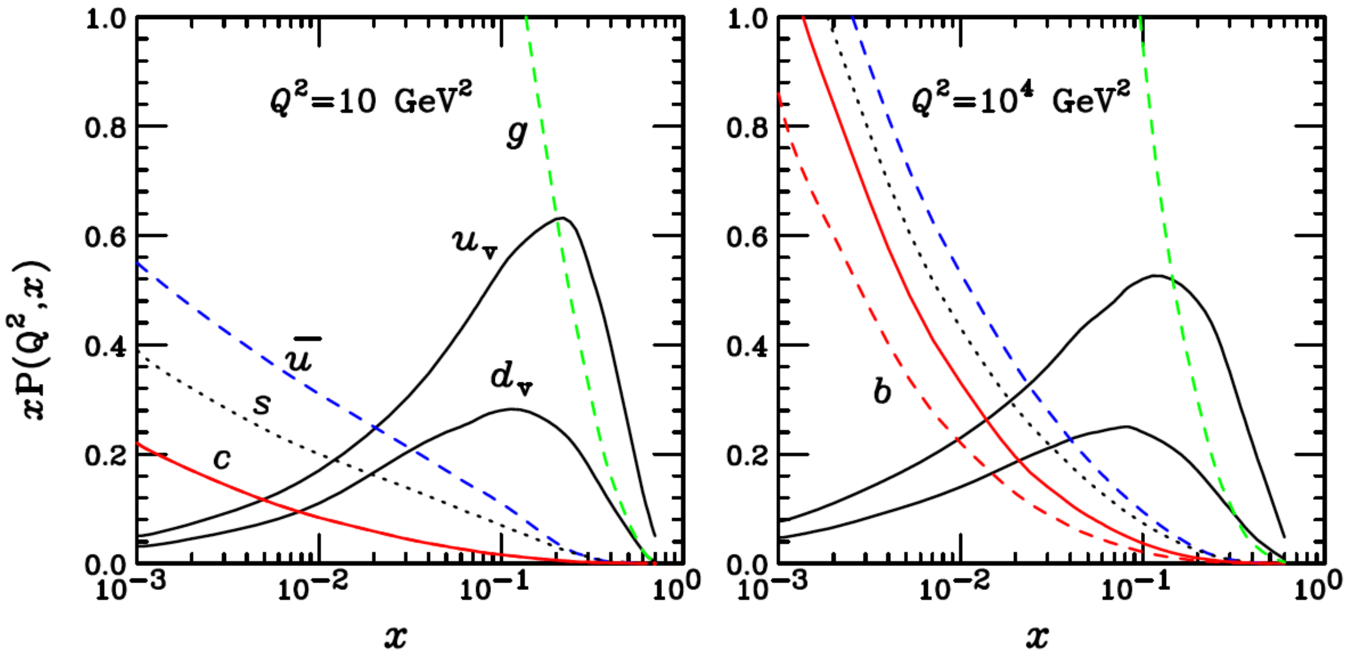
$$\sigma(pp \to b\bar{b}X) \sim 0.3 \text{ mb}, \sigma_{pp}^{\text{inel}}/200$$

$$(\sqrt{s} = 7 \text{ TeV})$$



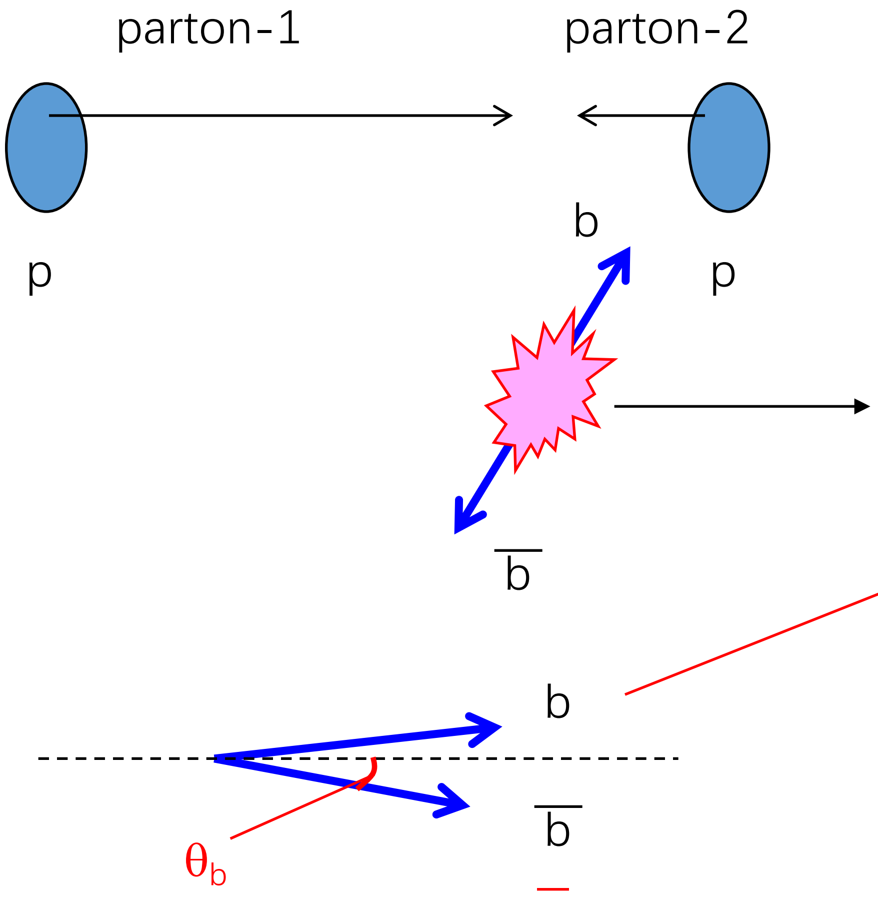
QCD factorization

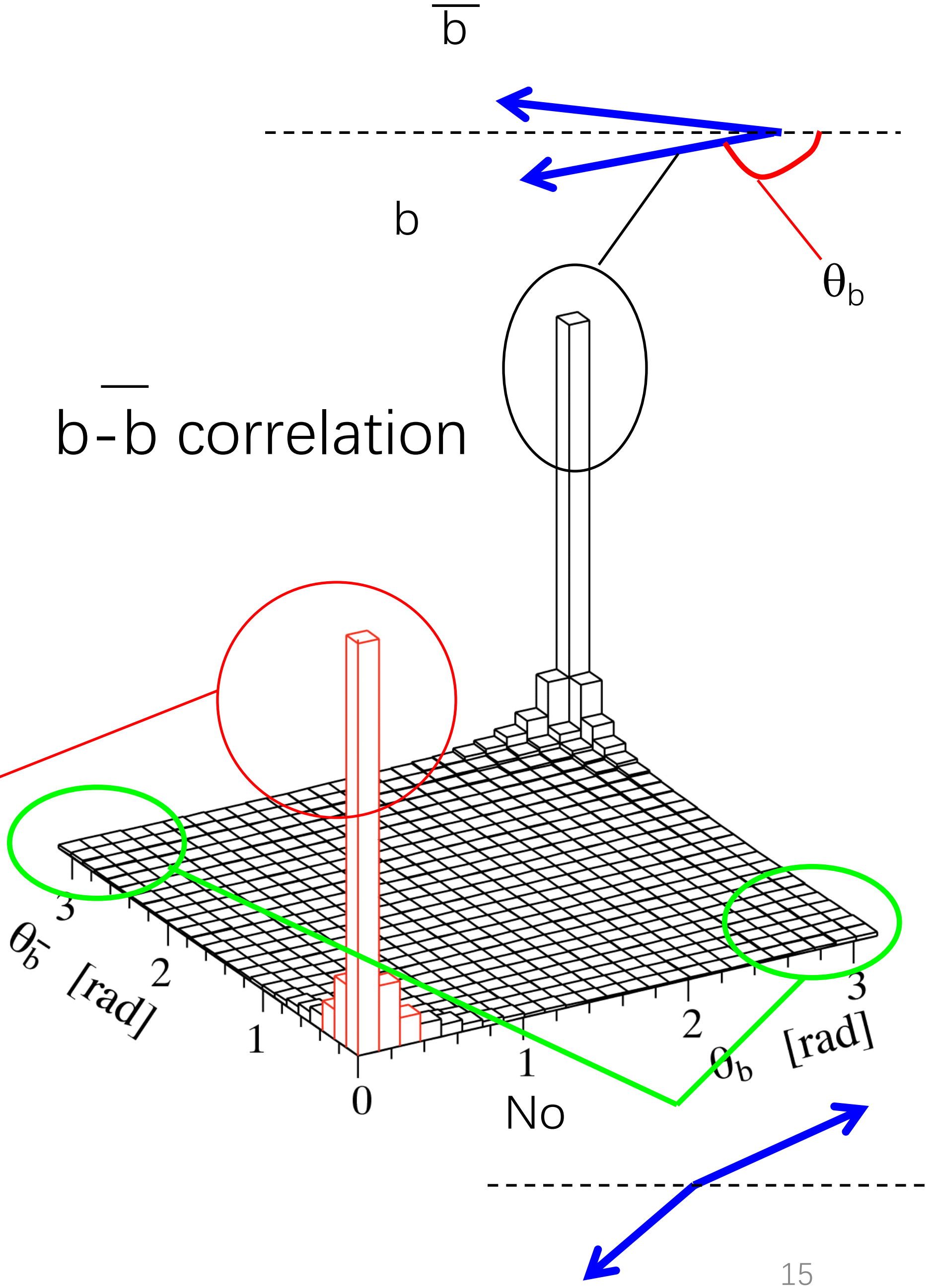




$$\sigma(AB \to F\ X) = \sum_{a,b} \int dx_1 dx_2\ P_{a/A}(x_1, Q^2) P_{b/B}(x_2, Q^2)\ \hat{\sigma}(ab \to F)$$

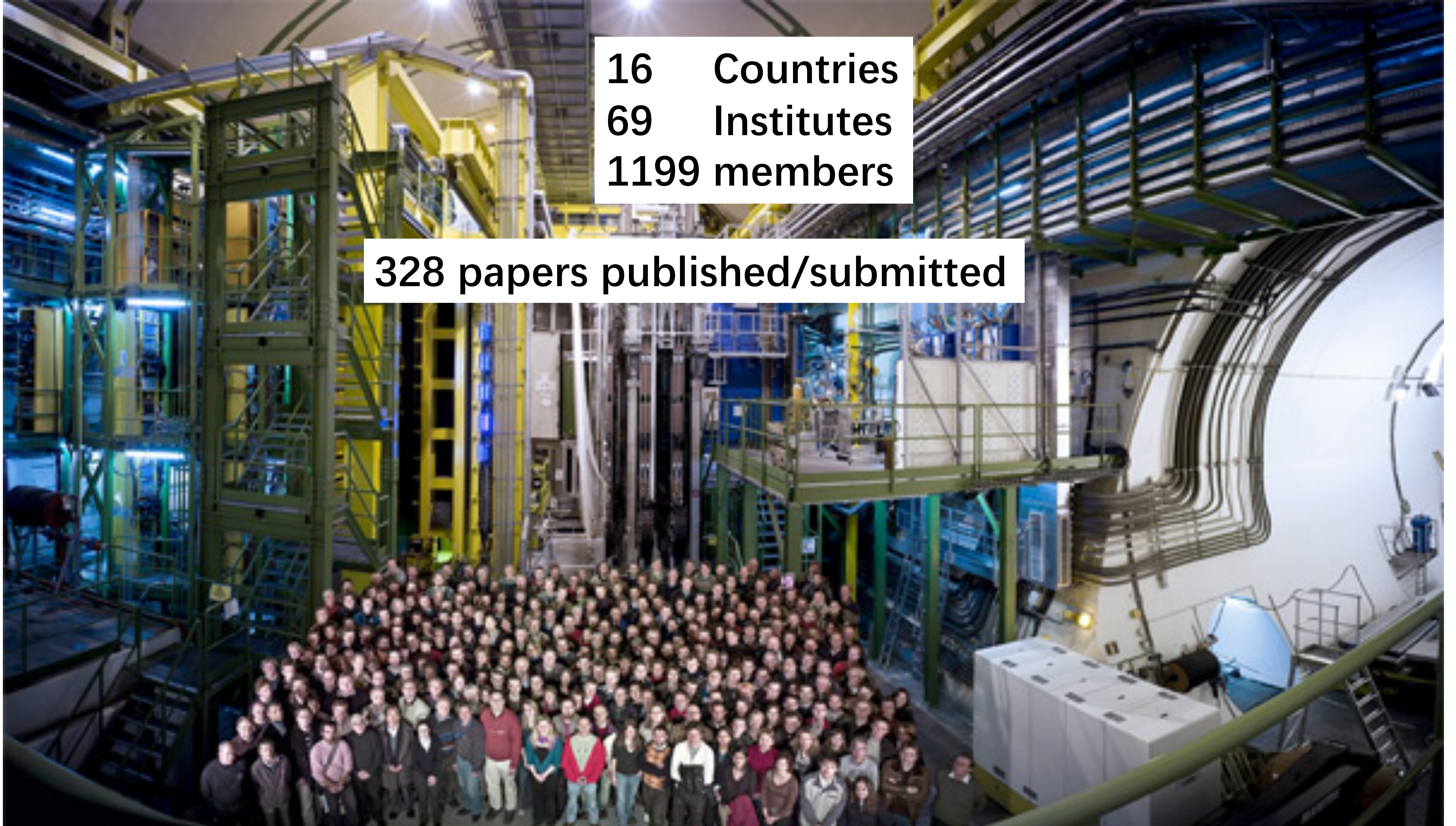
Kinematics of $b\bar{b}$ pair production



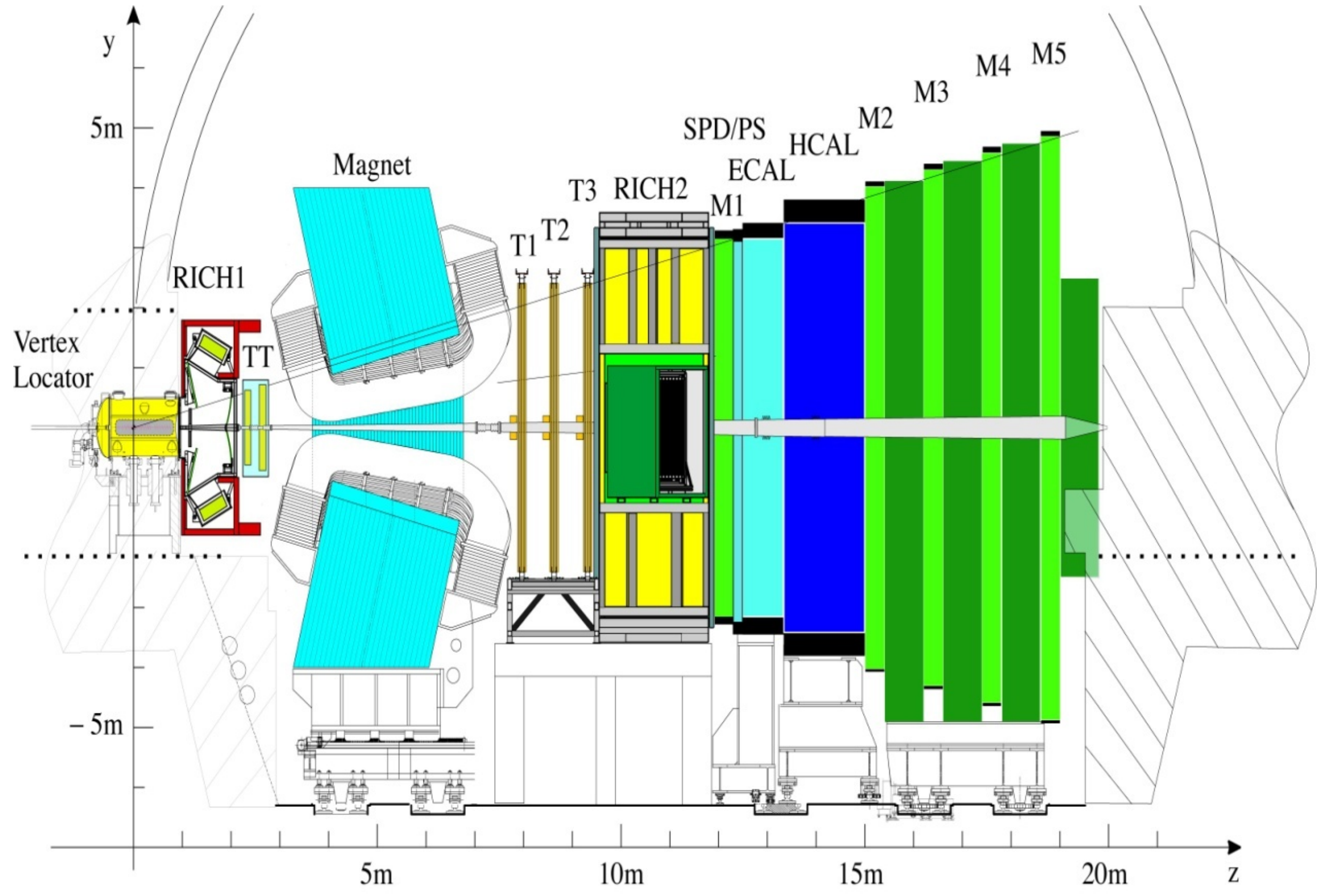


16 Countries
69 Institutes
1199 members

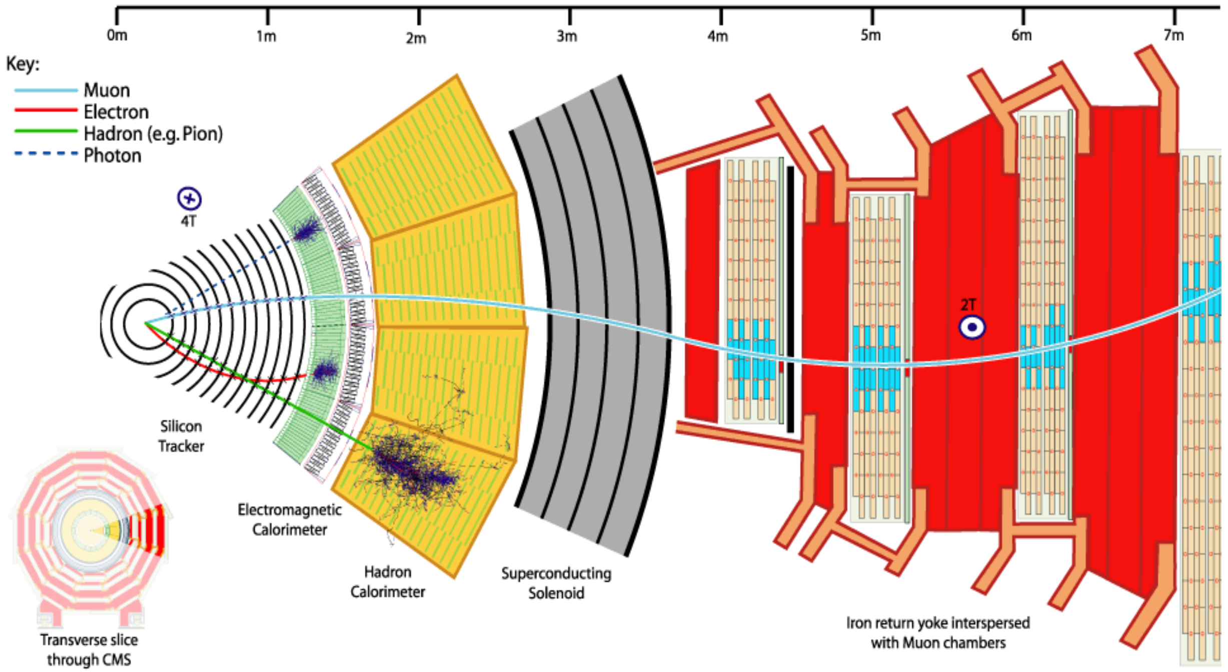
328 papers published/submitted

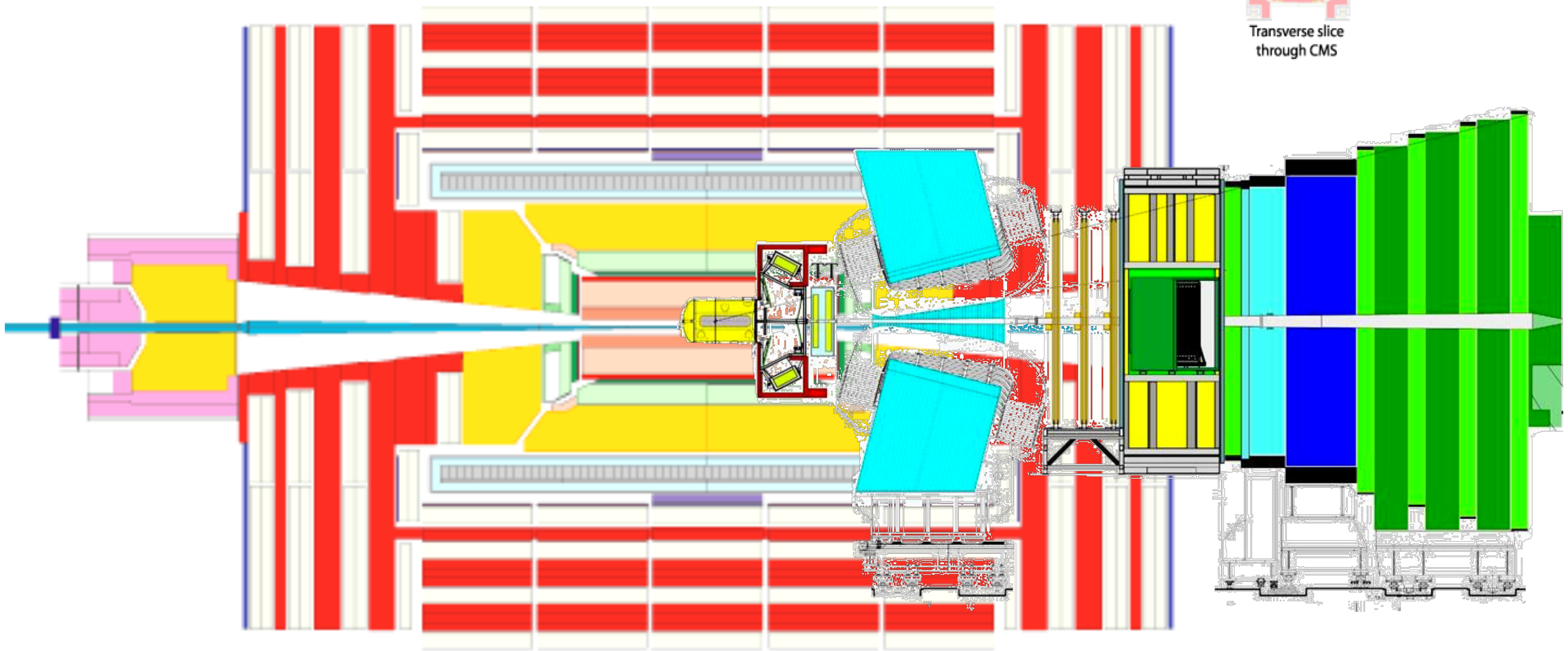


LHCb: forward spectrometer



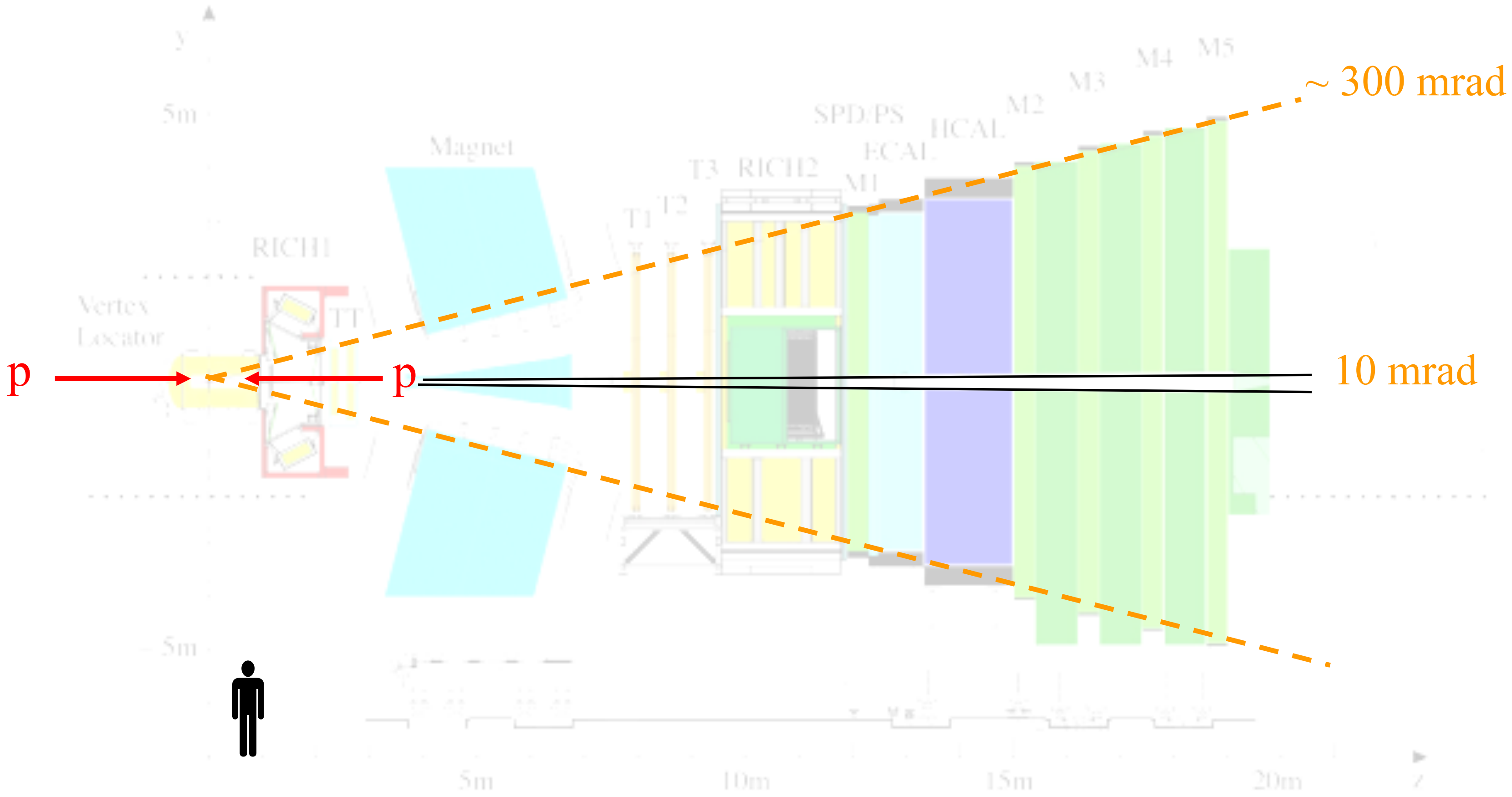
CMS & LHCb

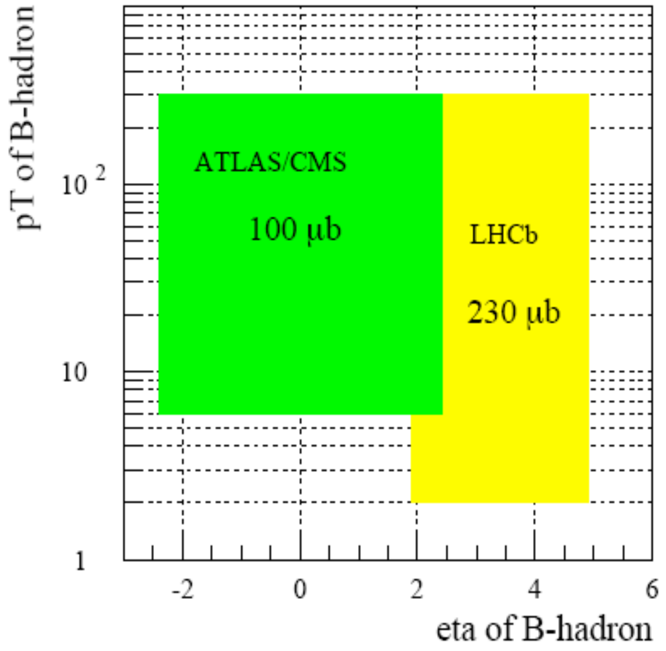

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Hadron (e.g. Pion)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS



Detector performance

1. Geometry

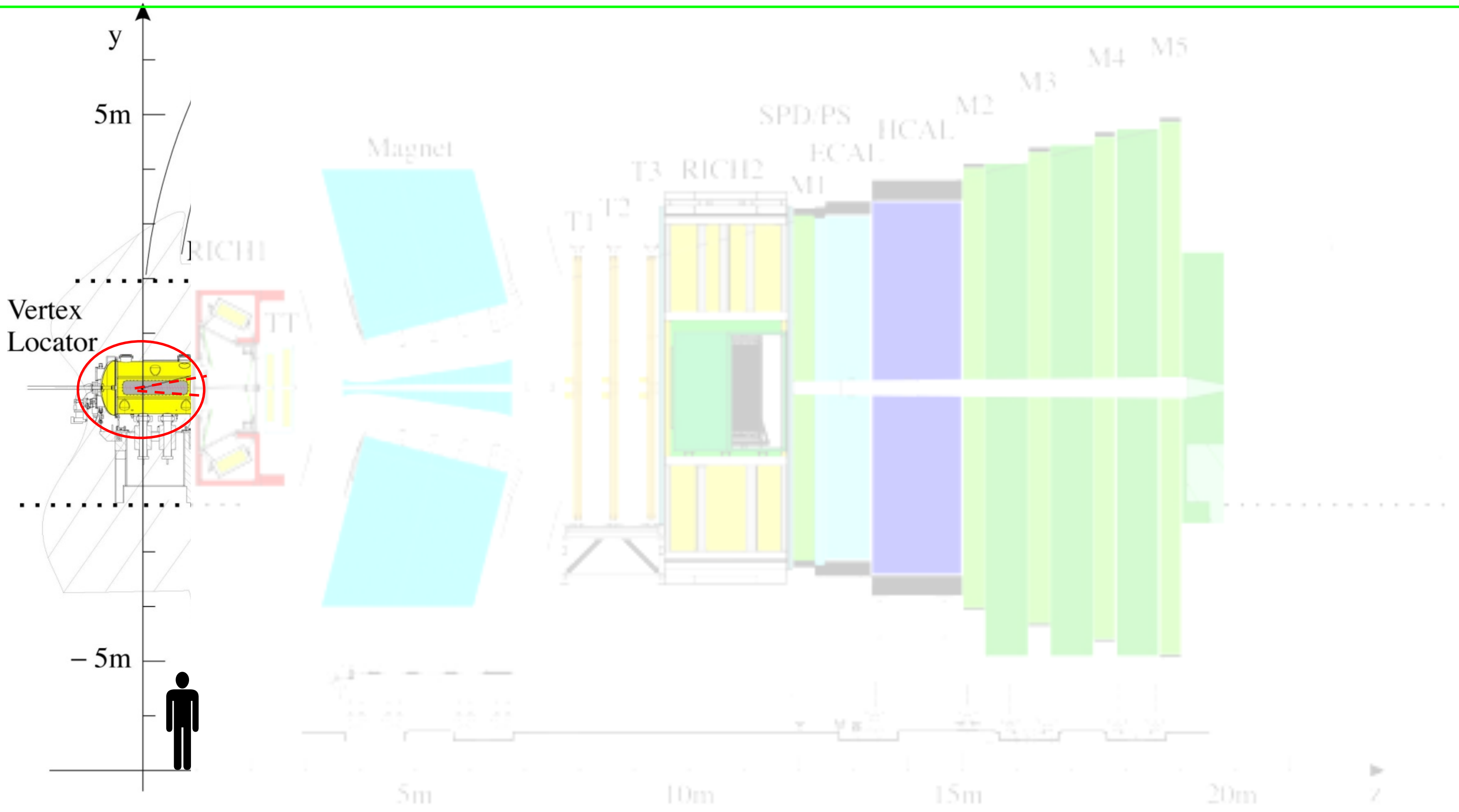




Inner acceptance 10 mrad from conical beryllium **beam pipe**

Detector performance

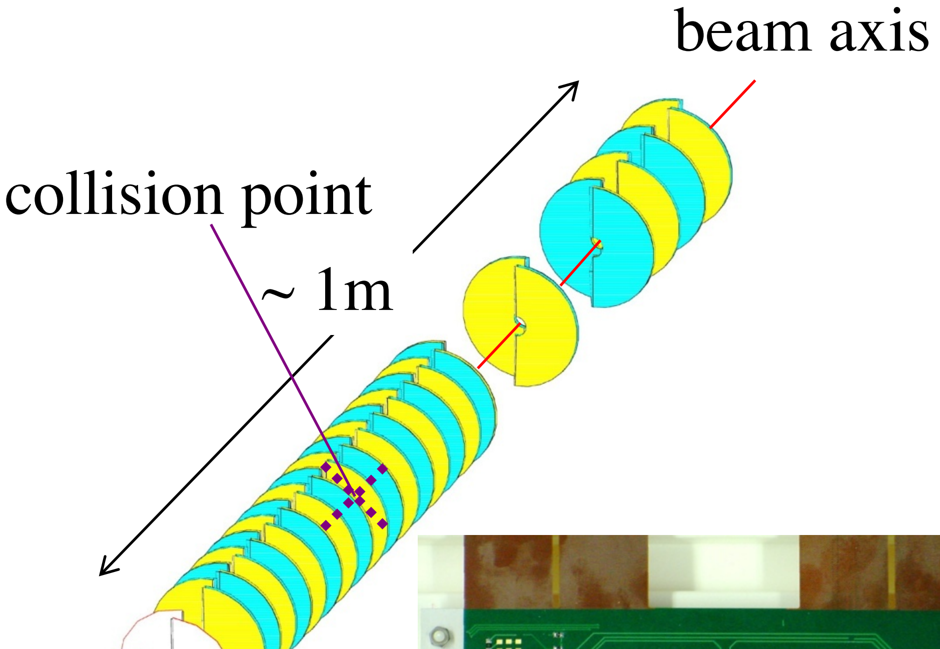
2. Vertex and Tracking

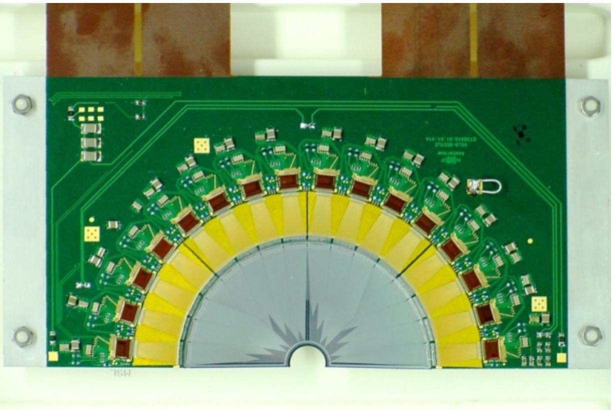


Vertex locator around the interaction region

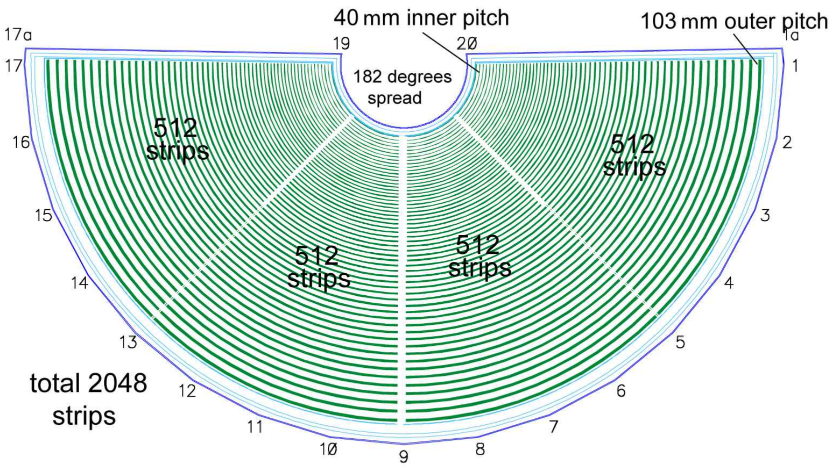
Silicon strip detector with ~ 30 μm impact-parameter resolution

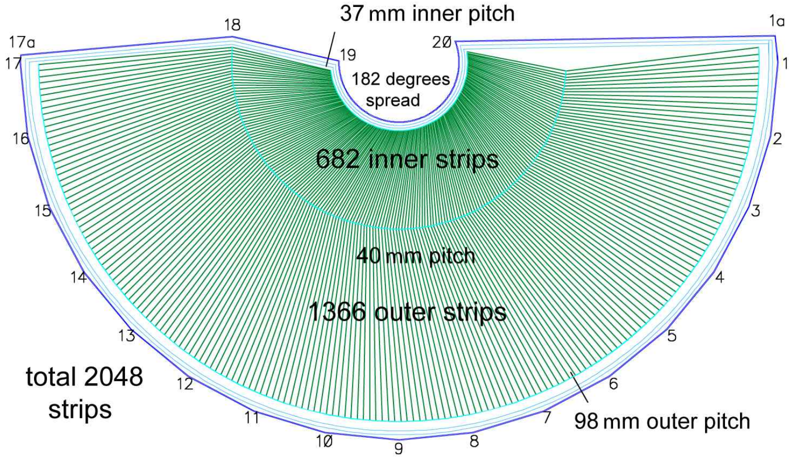
Vertex Locator





R-measuring sensor





ϕ-measuring sensor

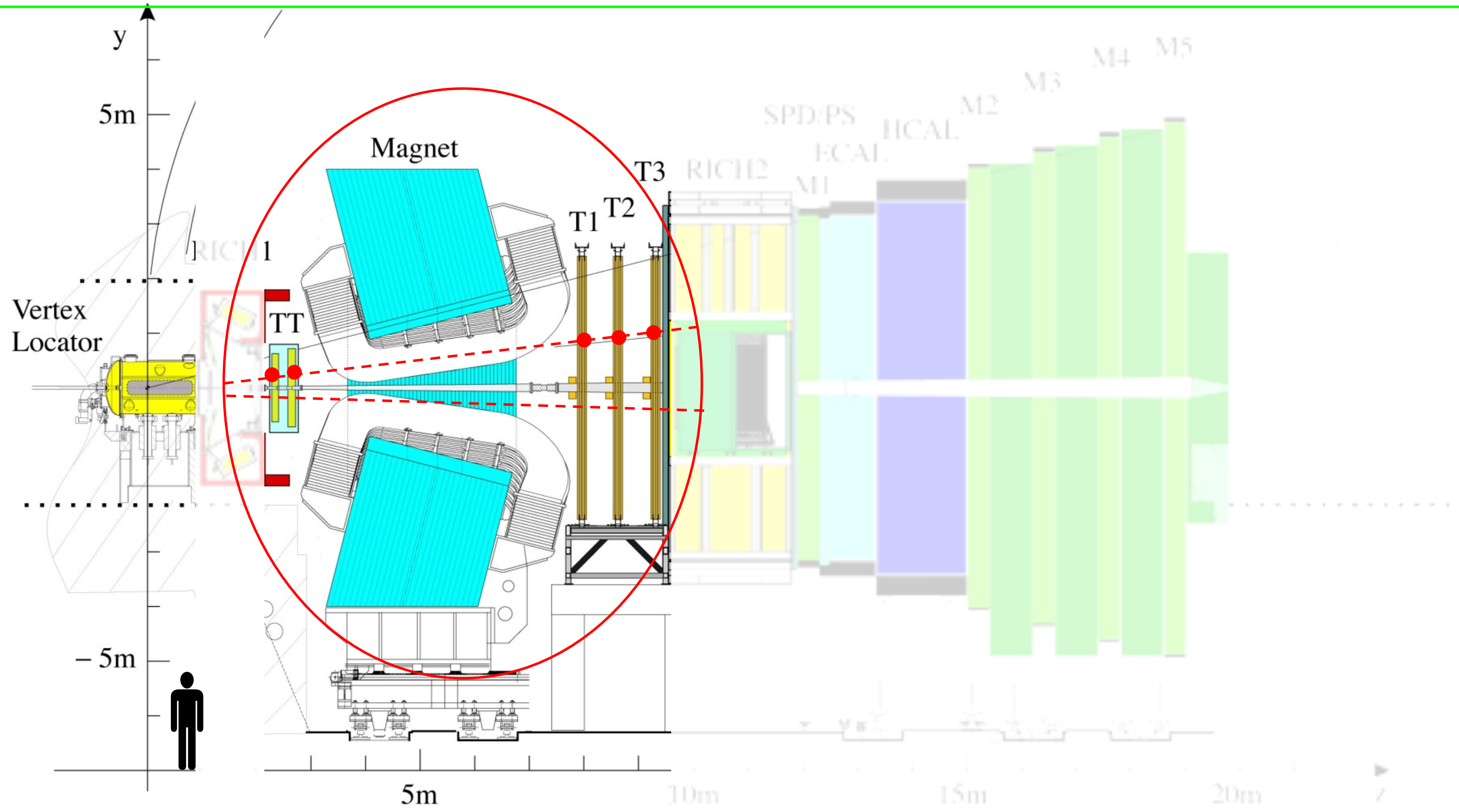
200μm n-on-n Si short strips
double metal layer for readout
with Beetle chip (1/4 μm CMOS)

total 172 k channels
occupancy < 1%

They have to be placed in secondary vacuum → complex mechanics

Detector performance

2. Vertex and Tracking



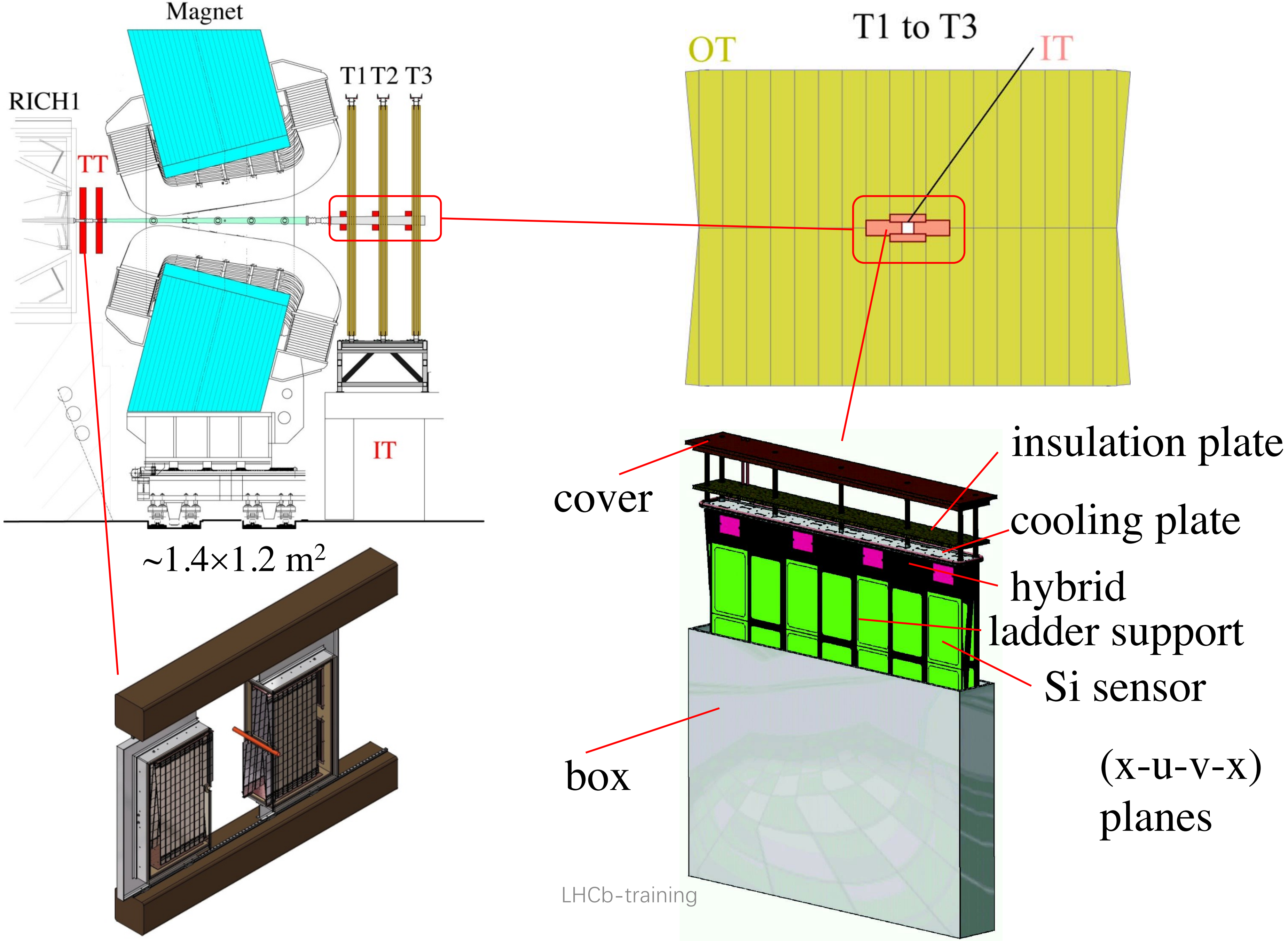
Tracking system and dipole magnet to measure angles and momenta

$\Delta p/p \sim 0.4\ \%$, mass resolution ~ 14 MeV (for $B_s \rightarrow D_sK$)

Magnetic field regularly reversed to reduce experimental systematics

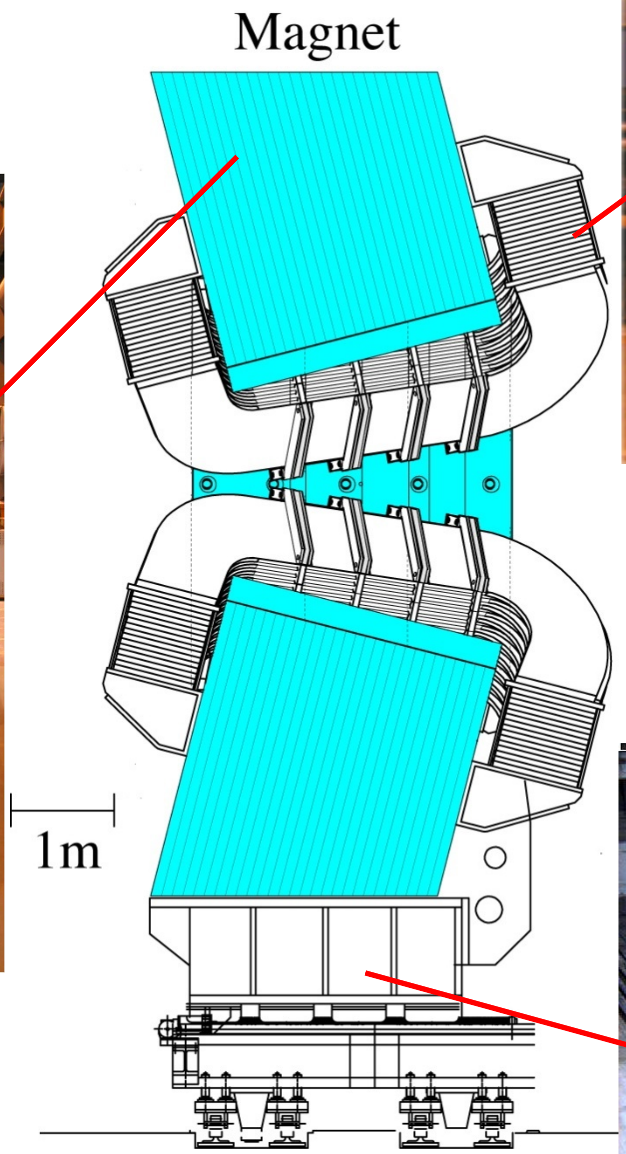
Silicon Tracker

Trigger Tracker and Inner Tracker

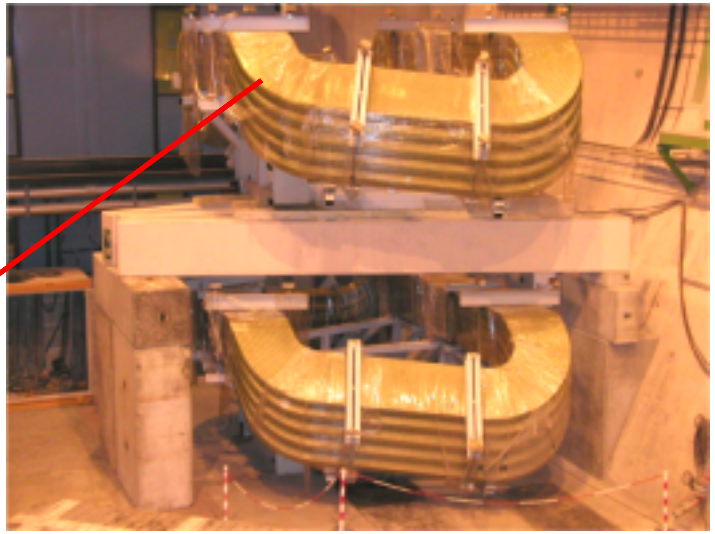


Magnet

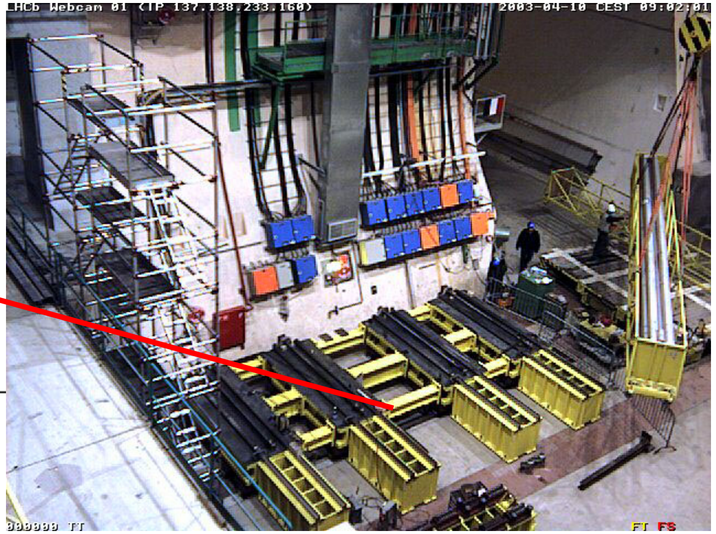
Fe plate for the yoke



All the coils

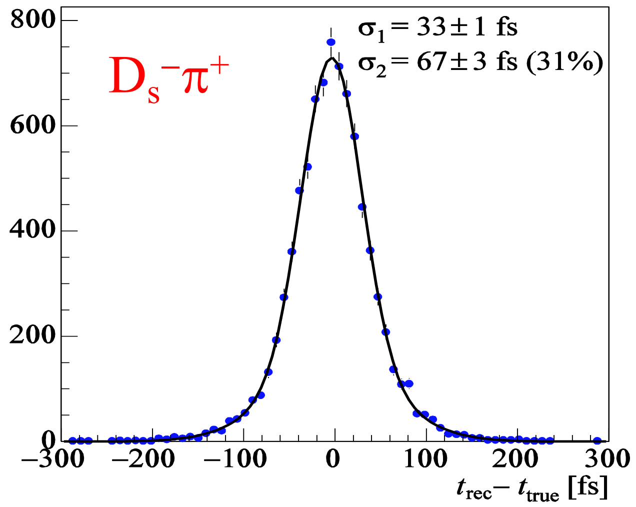


Magnet support at UX8



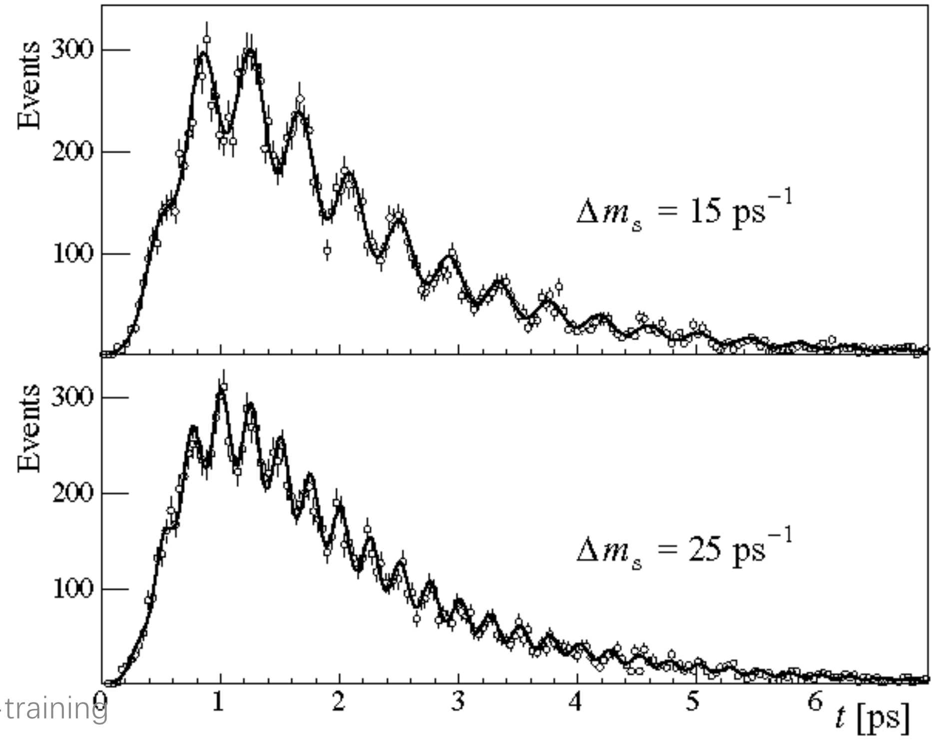
• **B_s oscillation frequency as an example**

Fully reconstructed decay
→ excellent momentum resolution
Decay length resolution ~ 200 μm
→ Proper time resolution ~ 40 fs



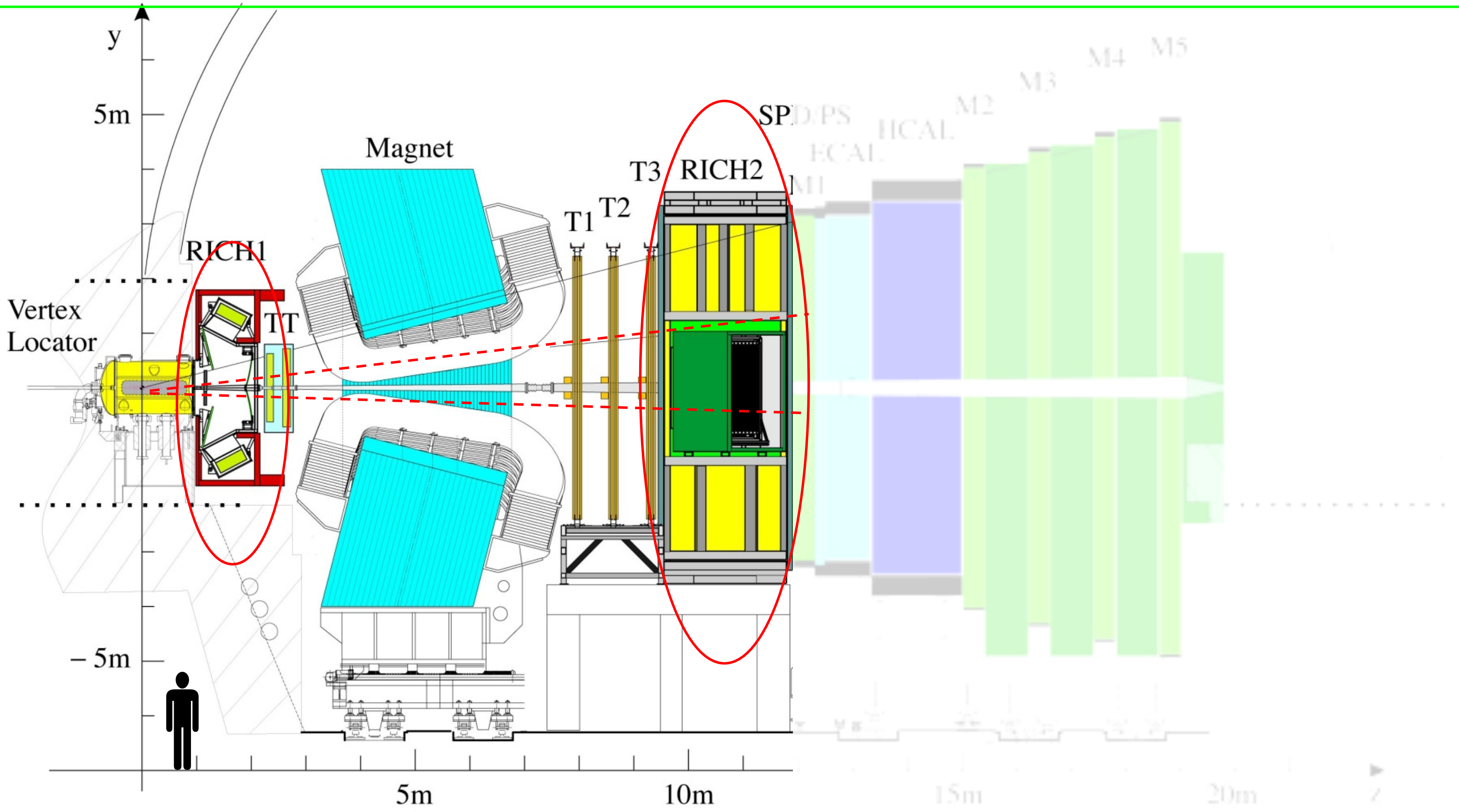
5σ measurement in one year for Δm_s up to 68 ps^{-1}

Once a B_s–B_s oscillation signal is seen, the frequency is precisely determined:
$\sigma(\Delta m_s) \sim 0.01\ ps^{-1}$



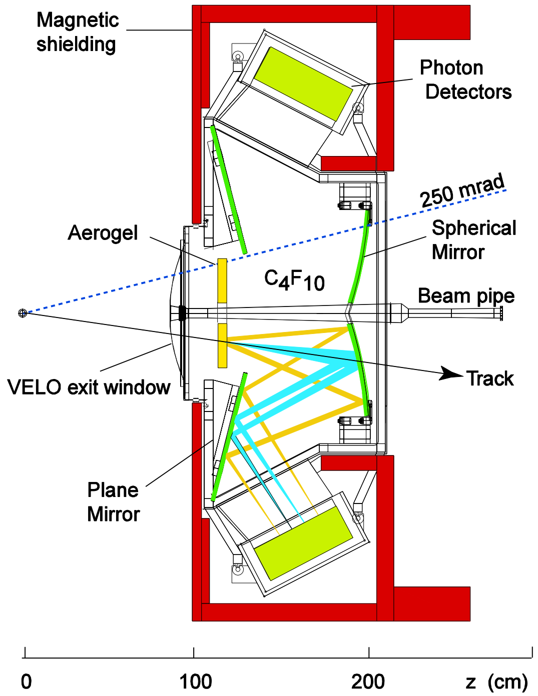
Detector performance

3. Particle Identification

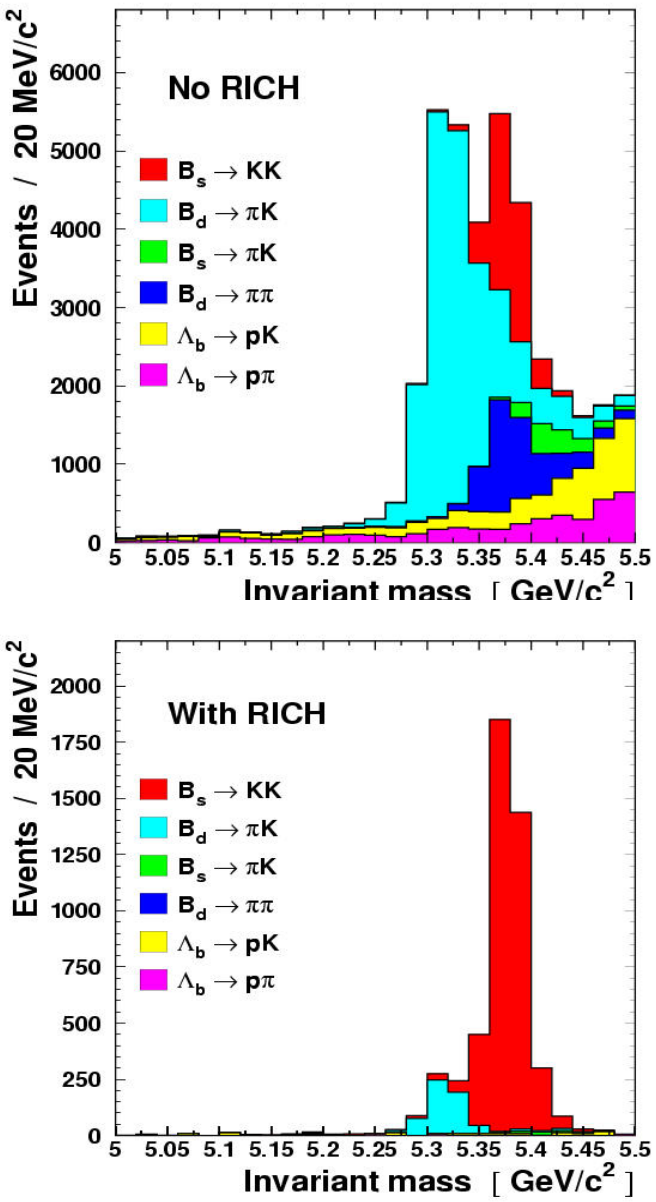


Two **RICH** detectors for charged hadron identification

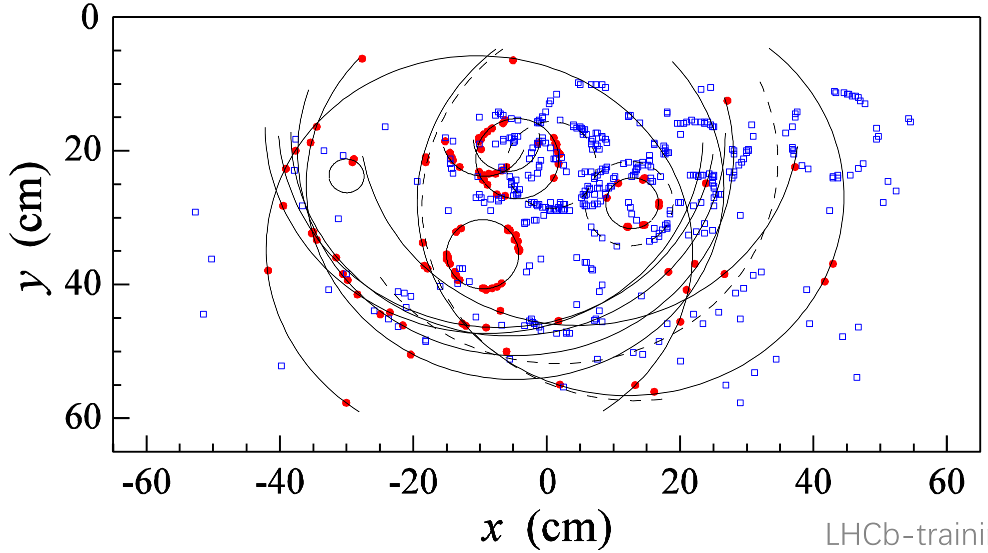
Provide > 3σ π–K separation for 3 < *p* < 80 GeV



Performance of particle ID

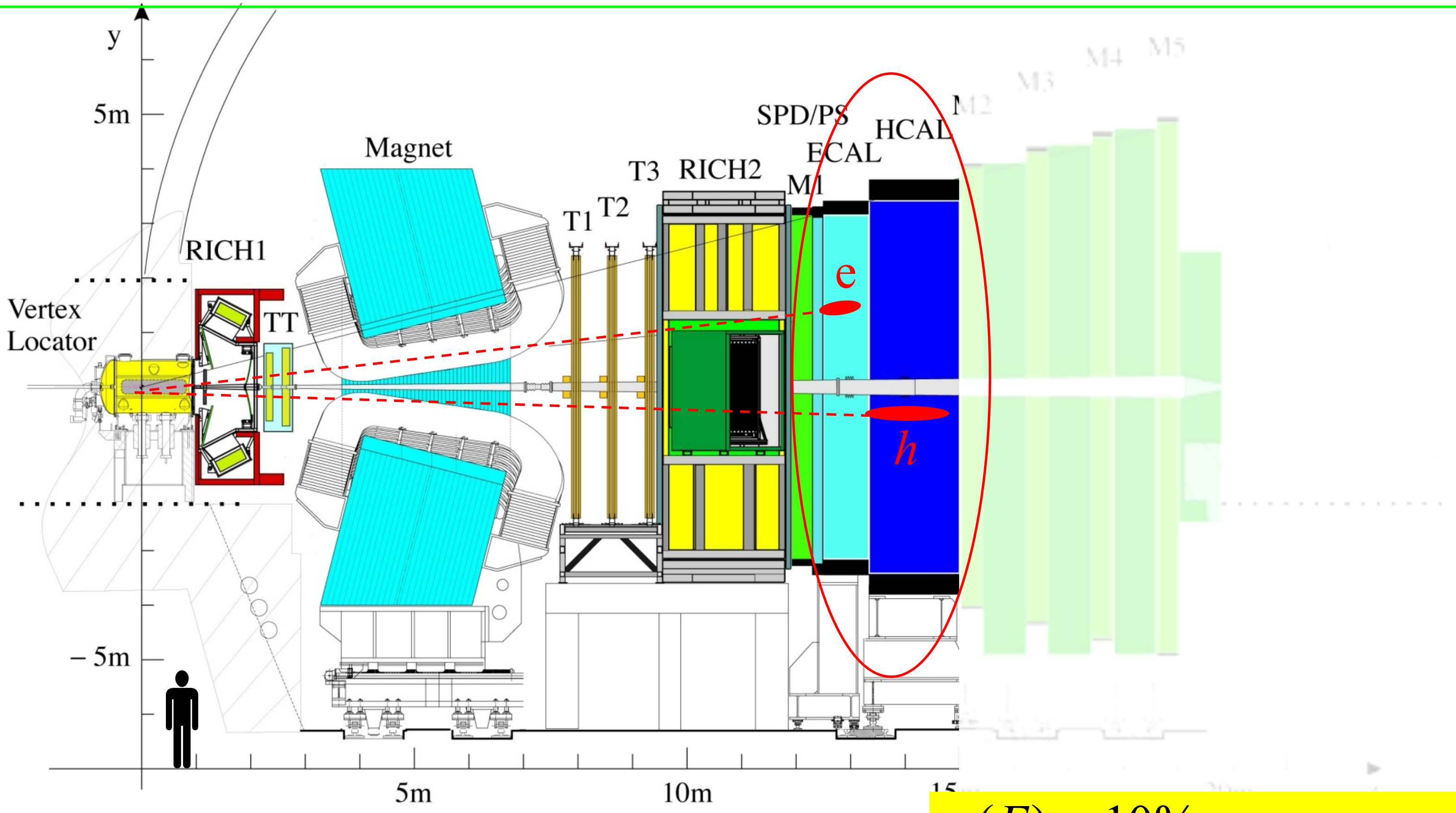


Typical event in the RICH1 photon detectors



Detector performance

4. Calorimeters



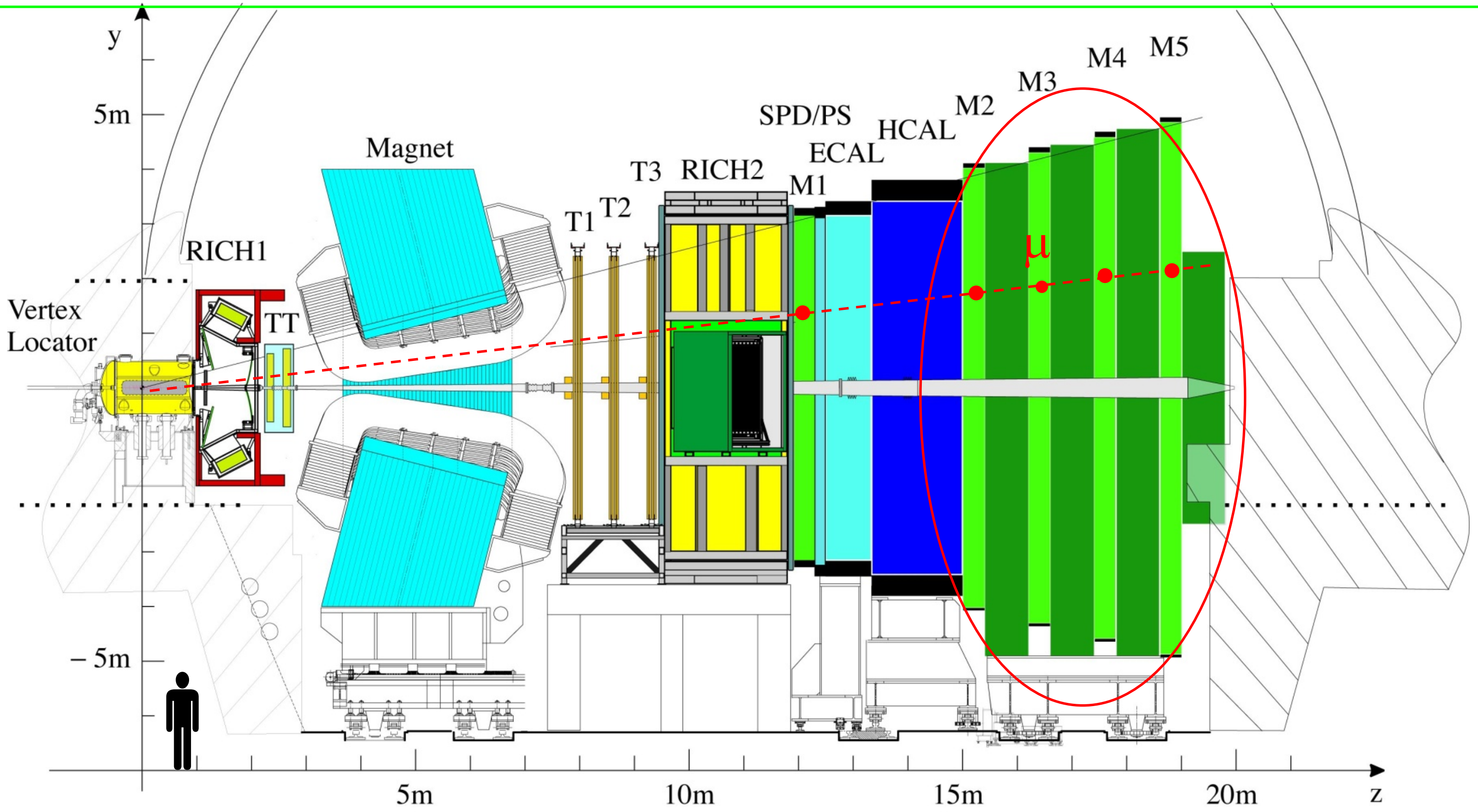
Calorimeter system to identify electrons, hadrons and neutrals. Important for the first level of the trigger

$$\frac{(E)}{E} = \frac{10\%}{\sqrt{E}} + 1.5\% \quad \text{(ECAL)}$$

$$= \frac{75\%}{\sqrt{E}} + 10\% \quad \text{(HCAL)}$$

Detector performance

5. Muon System



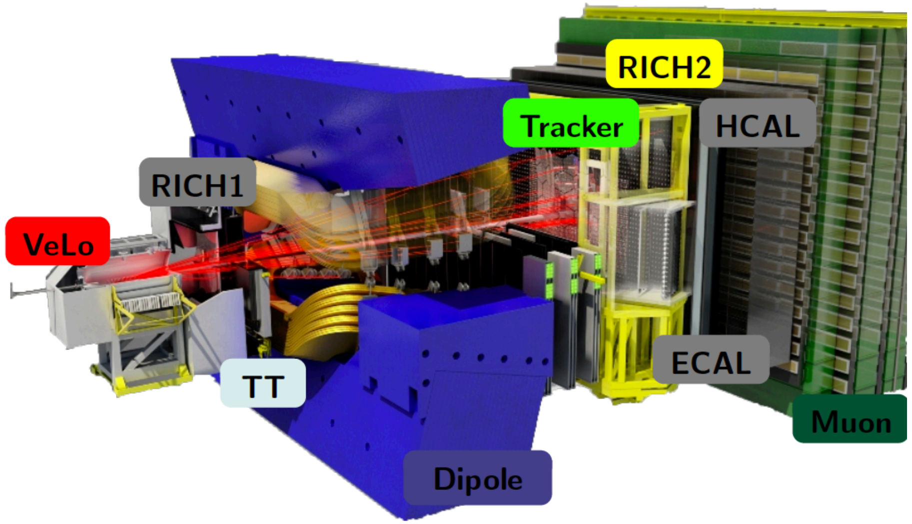
Muon system to identify muons, also used in first level of trigger

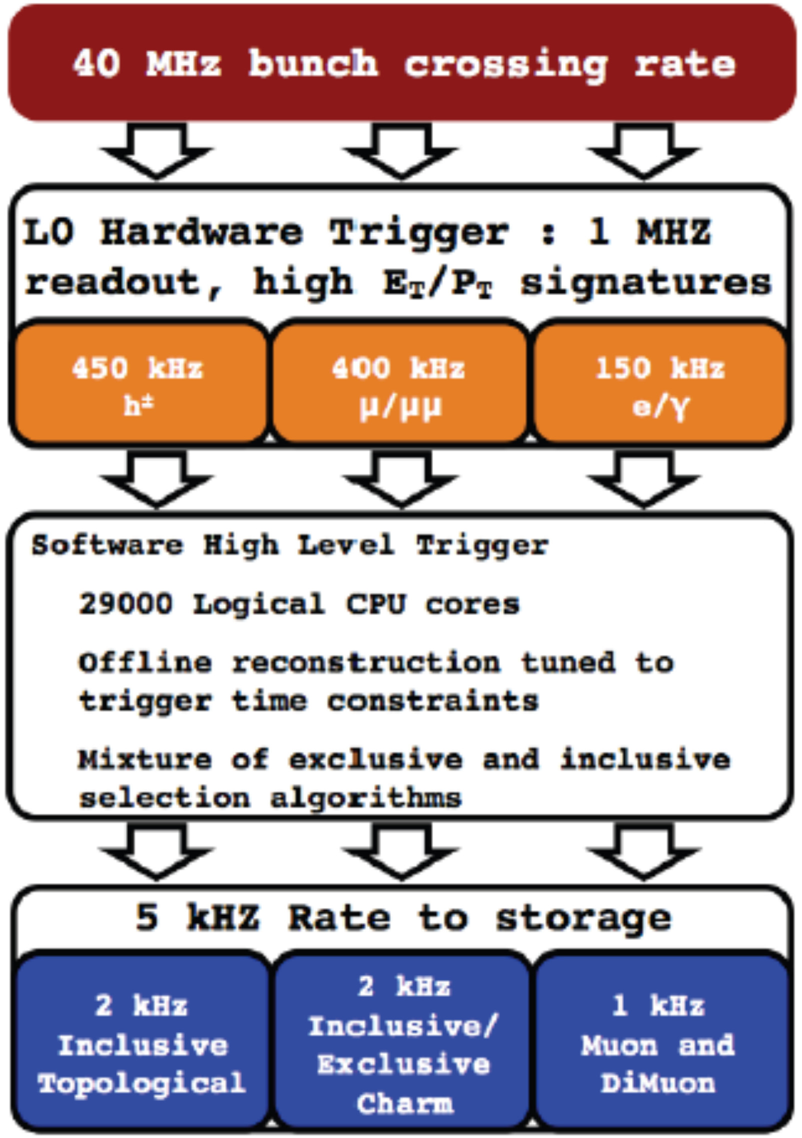
Efficiency ~ 94% for pion misidentification rate ~ 3%

LHCb Trigger

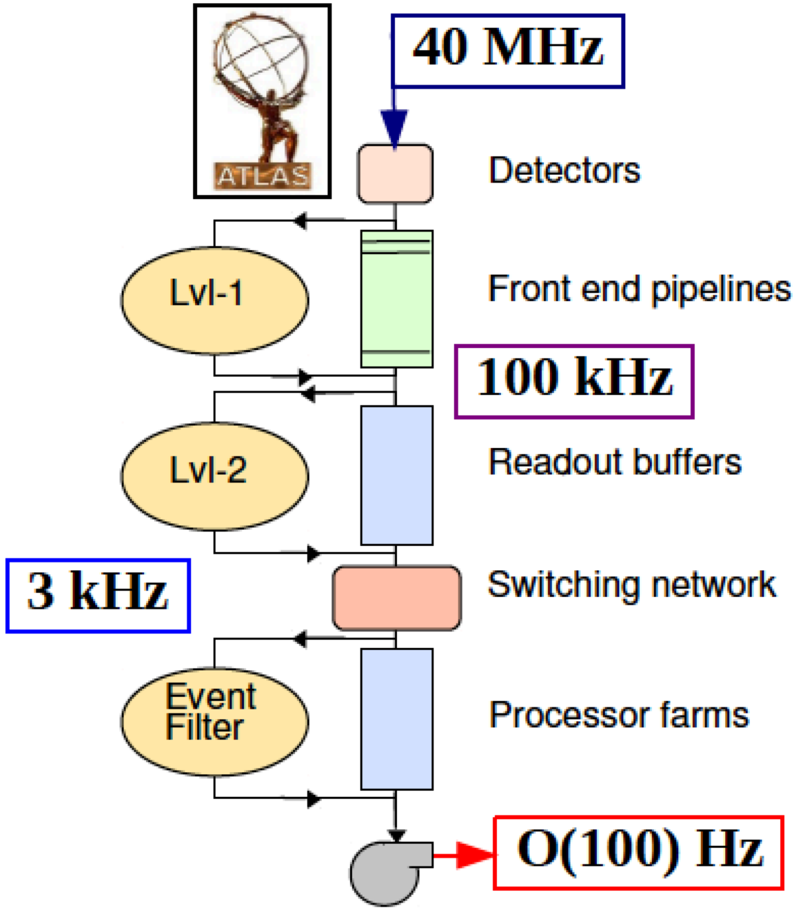
Versatile two stage trigger

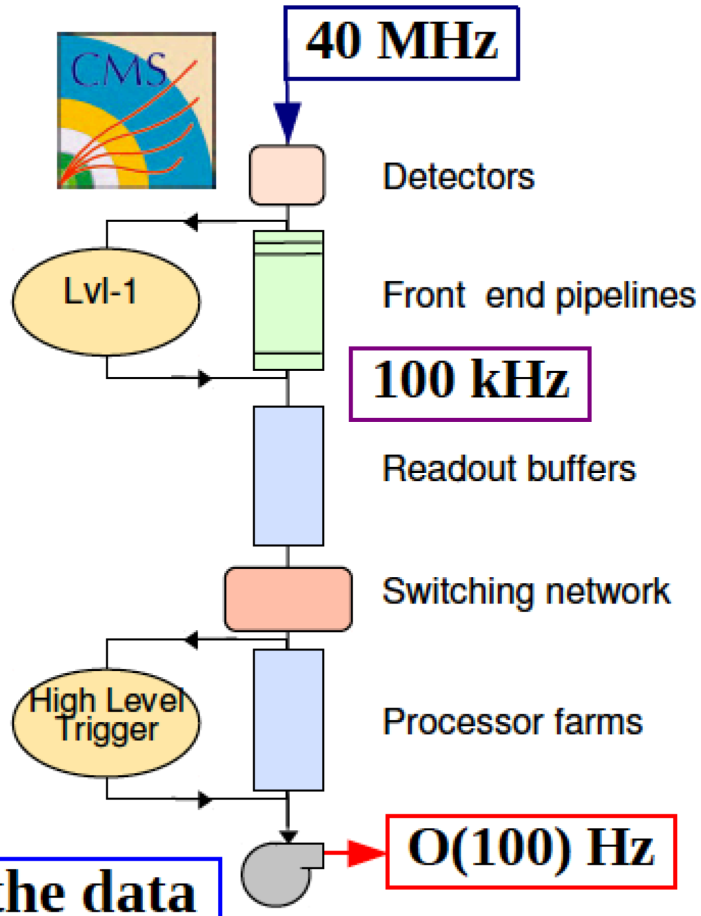
- Hardware-based L0 trigger: moderate P_T cut
- Full detector information sent to trigger farm @1.1 MHz
- 3 kHz output rate (2011), 5 kHz (2012)





Trigger in ATLAS & CMS

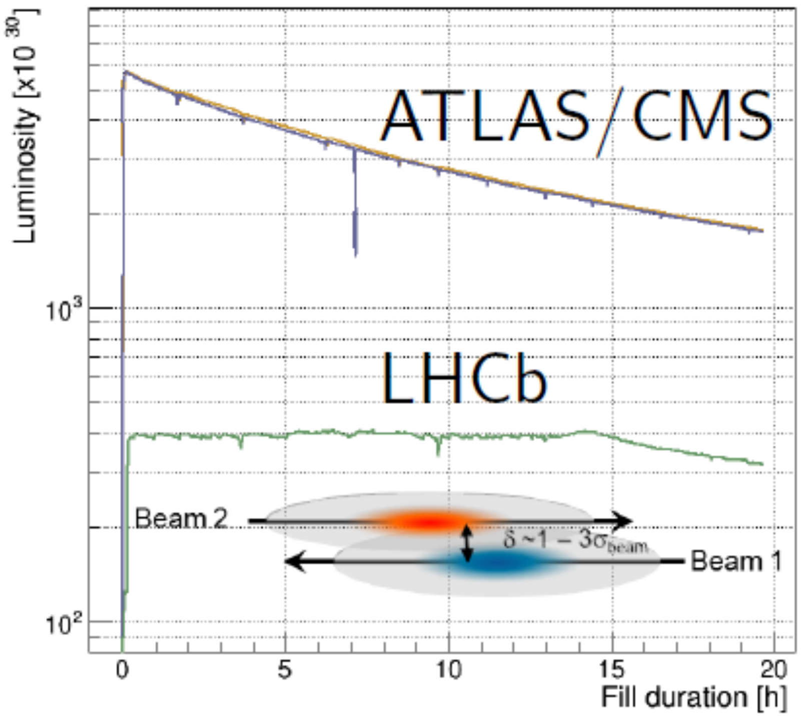


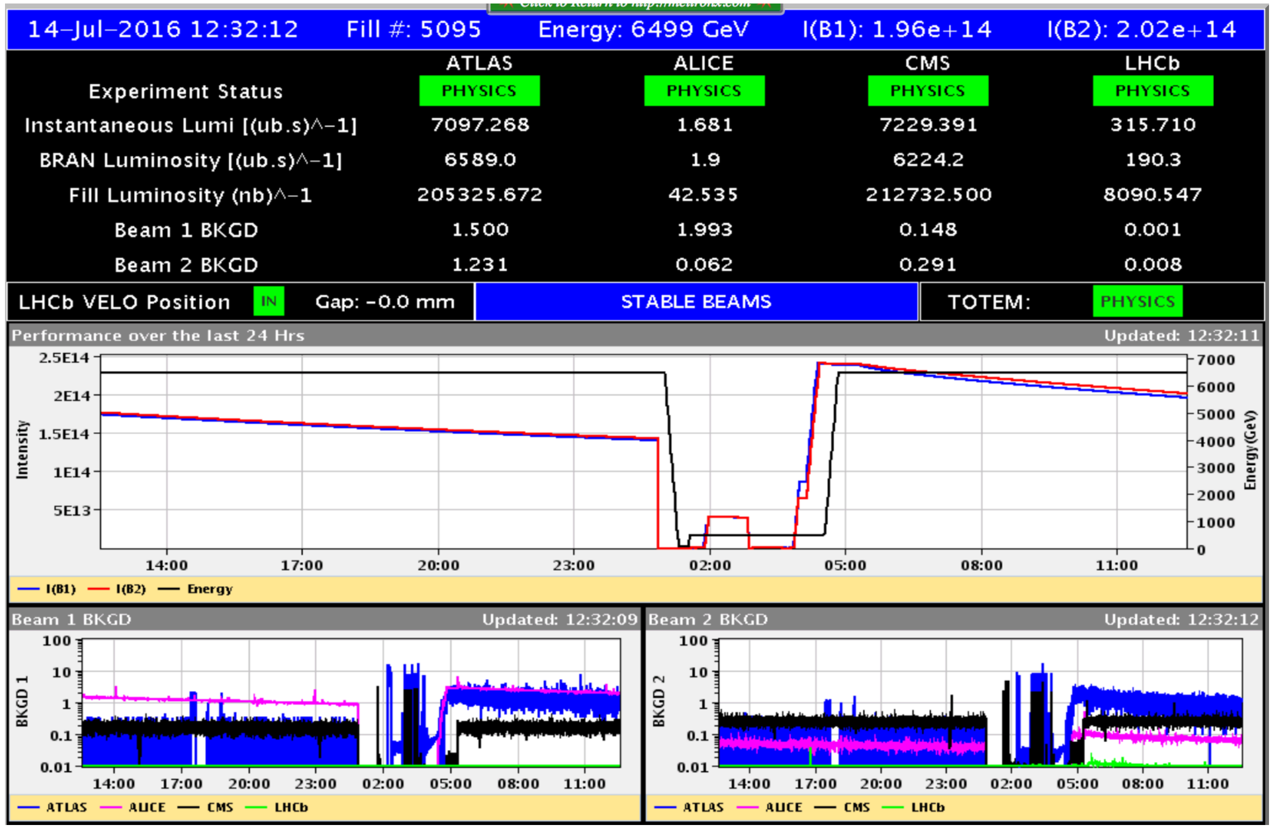


Reduce the data volume in stages

LHCb running conditions

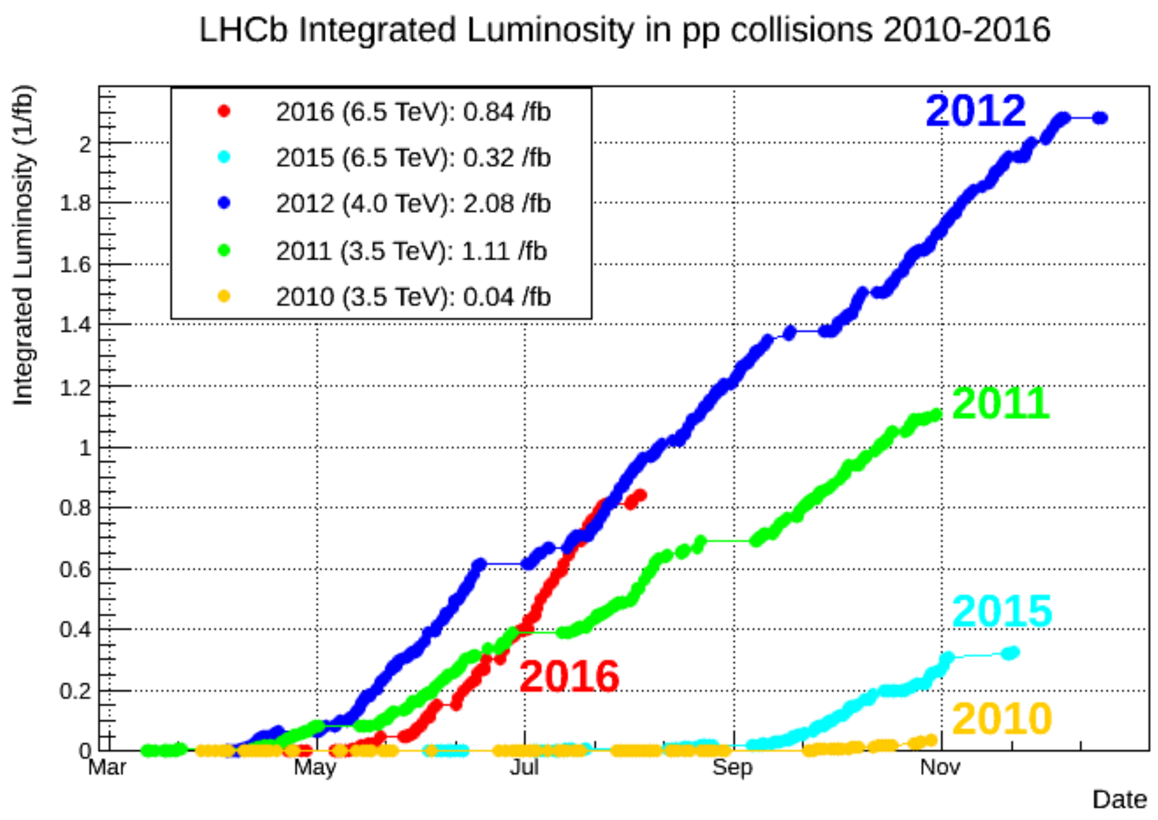
- $\mathcal{L} = \sim 4\times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ with reduced pile-ups vs. ATLAS & CMS
- *Luminosity levering*

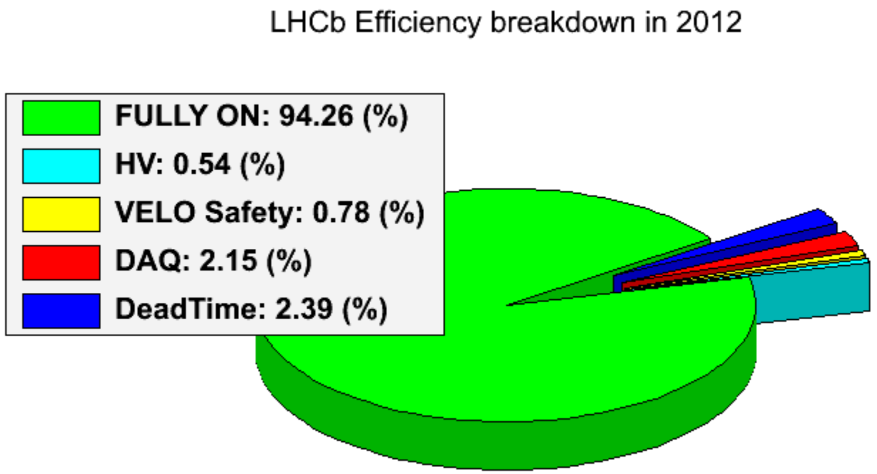




Data sample

- Most physics results based on 3.0 fb^{-1} collected in 2011/2012

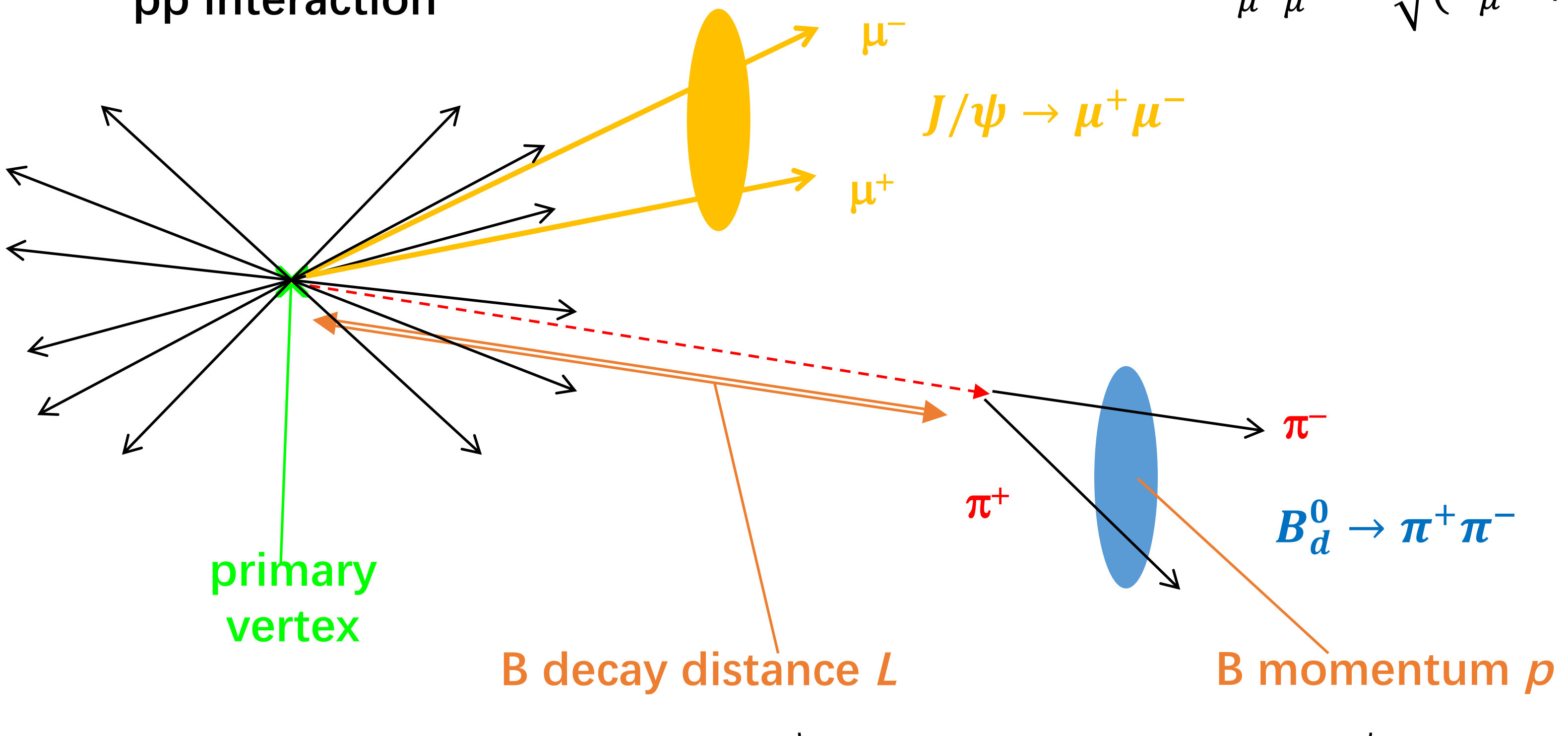




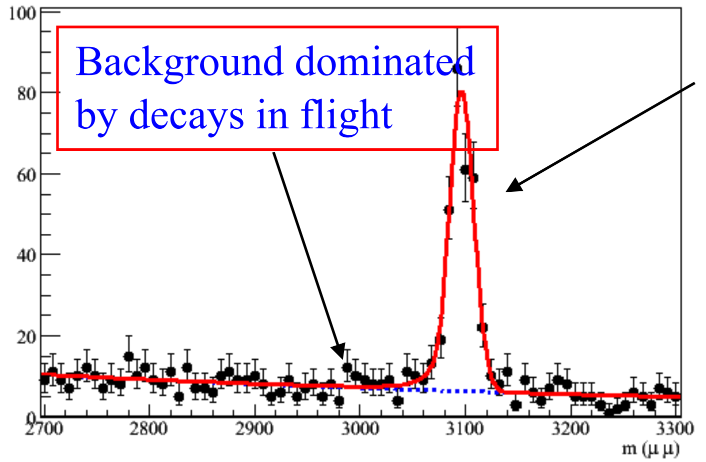
Unstable particle as the signal
- fight with combinatorial background

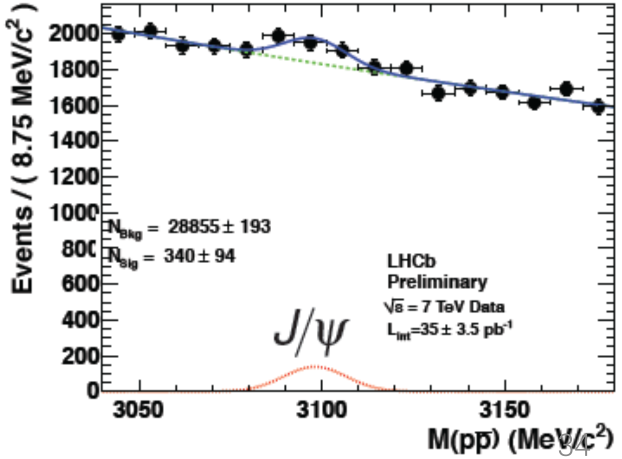
$$m_{\mu^+\mu^-} = \sqrt{(E_{\mu^+} + E_{\mu^-})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^-})^2}$$

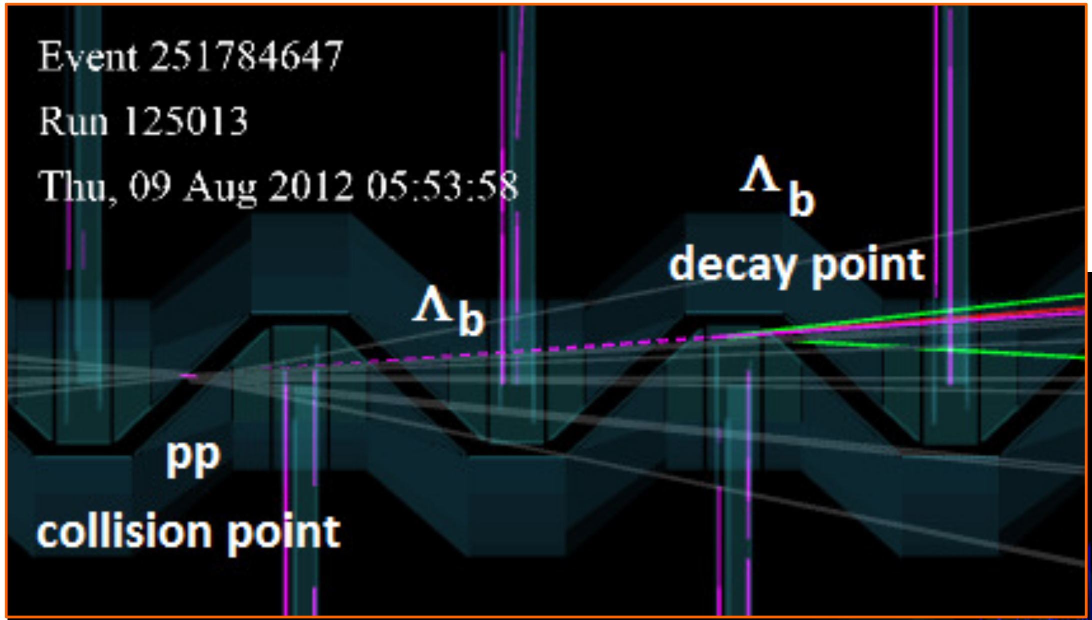
pp interaction

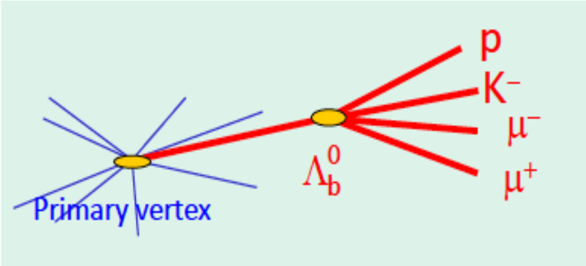


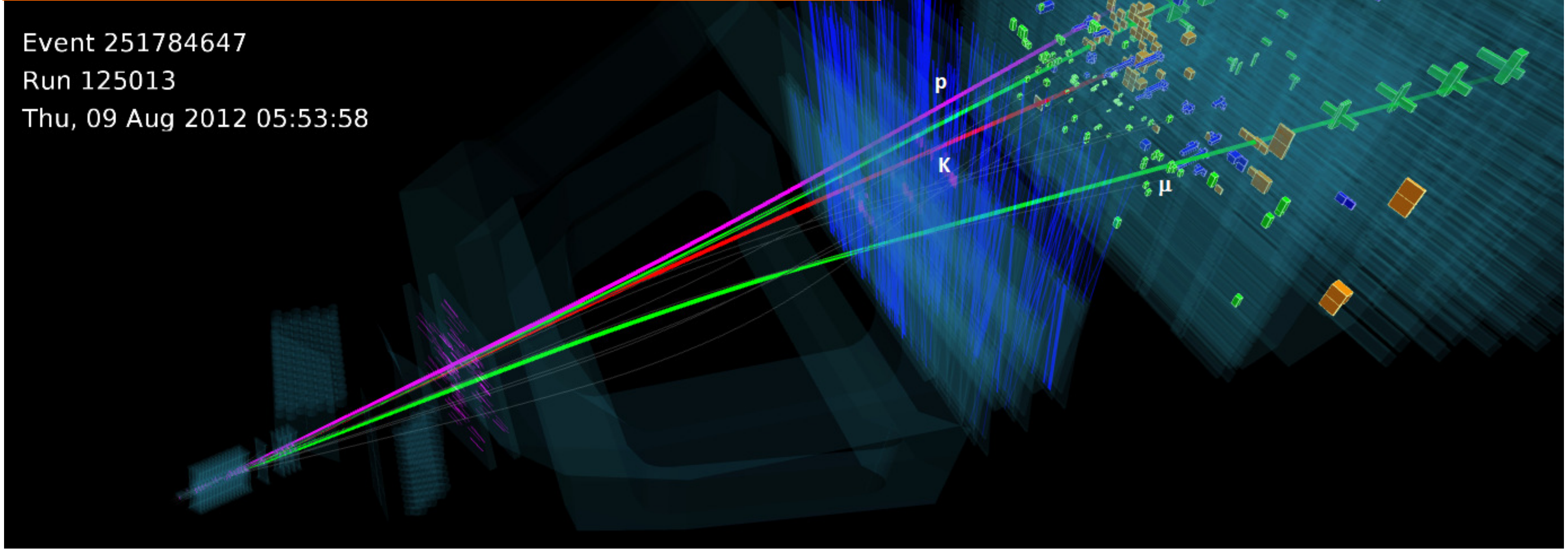
proper time: $t = \frac{L m_B}{p}$



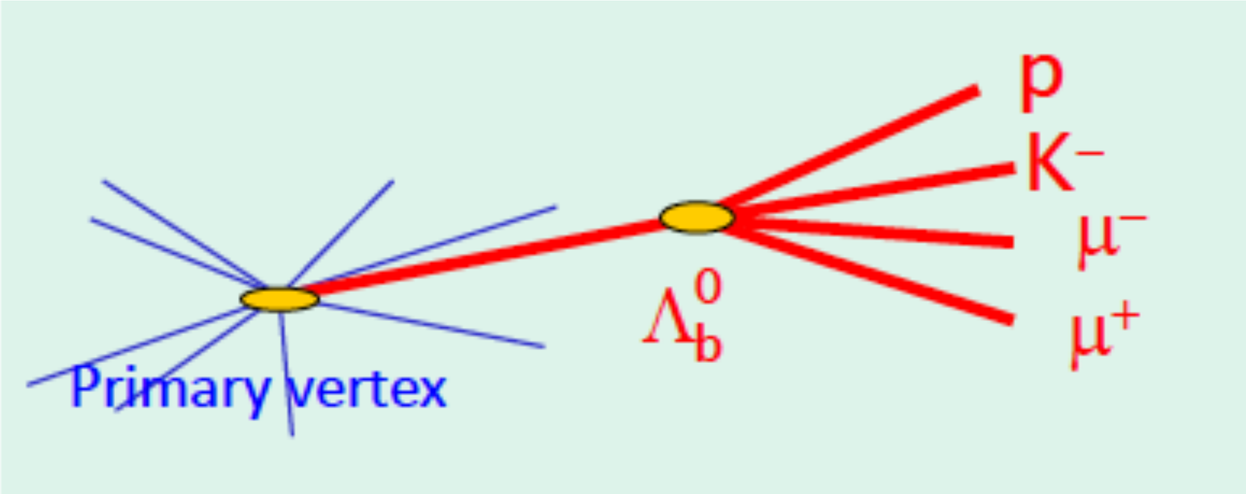


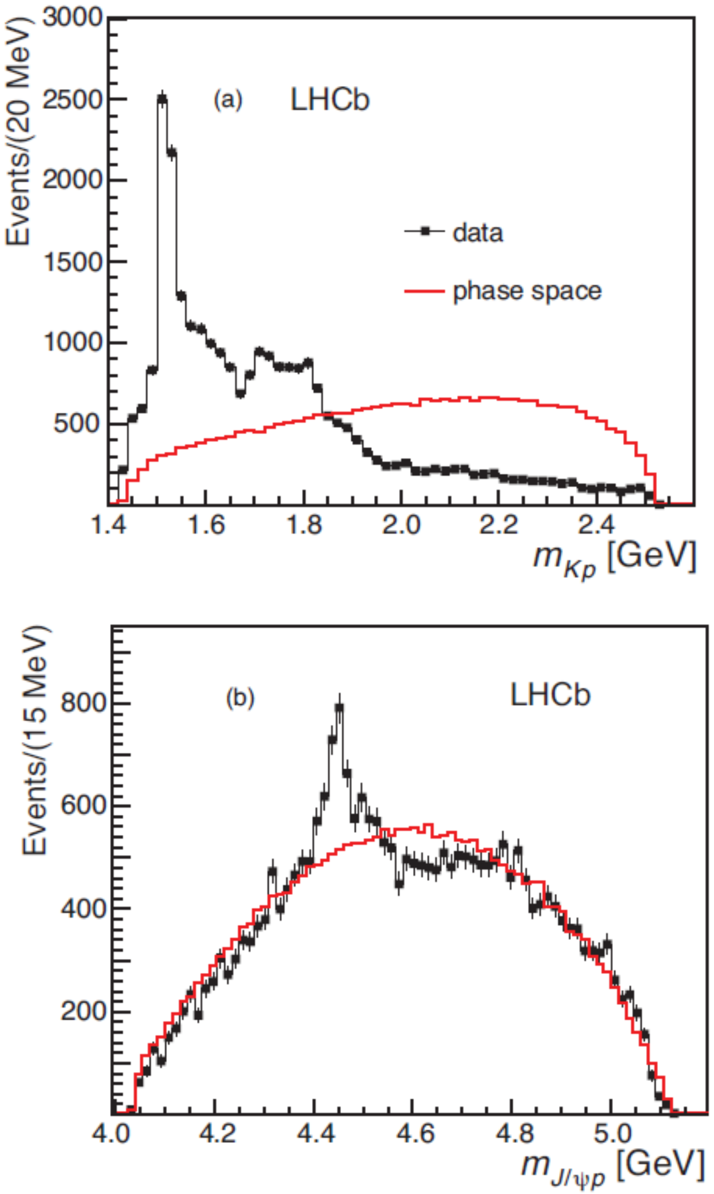

Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
Λb
decay point
Λb
pp
collision point


p
K−
μ−
μ+
Λb0
Primary vertex


Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
μ
p
K
μ

Resonances in b-decays





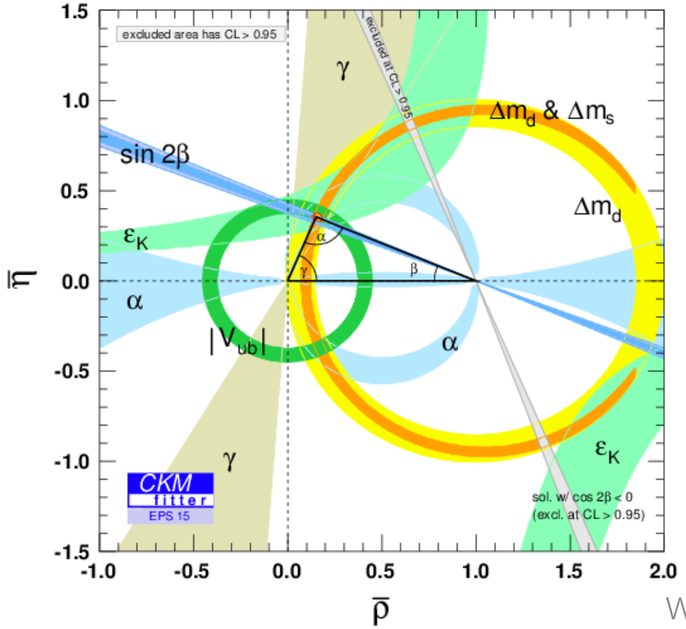
Physics program at LHCb

- Not only precision measurements in *b, c* sectors
  - CKM and CP-violation parameters
  - rare decays
  - testing lepton universality
  - ...
- But also a general purpose
  - electroweak measurements: $\sin\theta_W$, W/Z, top quark, ..
  - spectroscopy, exotic hadrons
  - soft QCD
  - heavy ions
  - ...

CKM triangle parameter γ

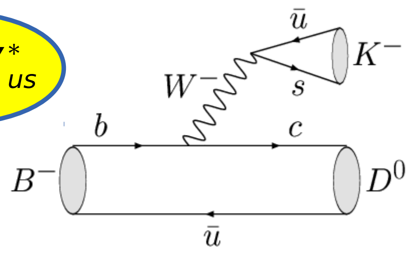
- γ can be measured from tree-level processes
  - → less sensitive to new physics effects
  - → a benchmark Standard Model reference point

$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

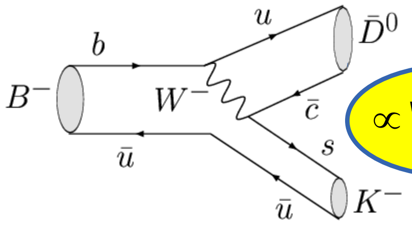


Favored

$\propto V_{cb}V_{us}^*$



Suppressed



$\propto V_{ub}V_{cs}^*$

However γ is the least know of the CKM triangles

CKM triangle parameter γ

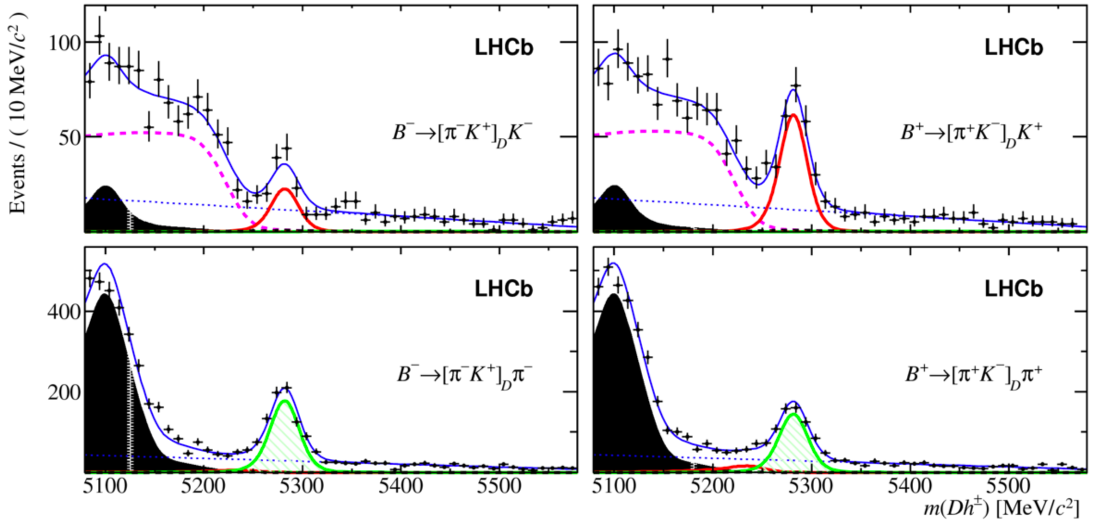
- Many modes used to measure γ at LHCb

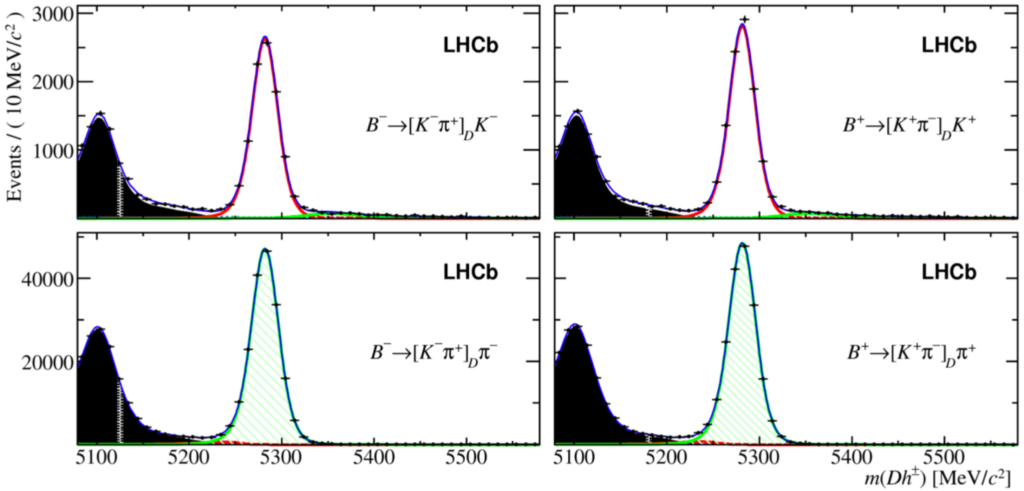
LHCb-PAPER-2016-003

$B^+ \to DK^+, D \to KK, \pi\pi, K\pi$

$D \to K\pi$ (ADS favored)

$D \to \pi K$ (ADS suppressed)





Large CP asymmetries - first 5σ observation in a single $B \to DK$ channel

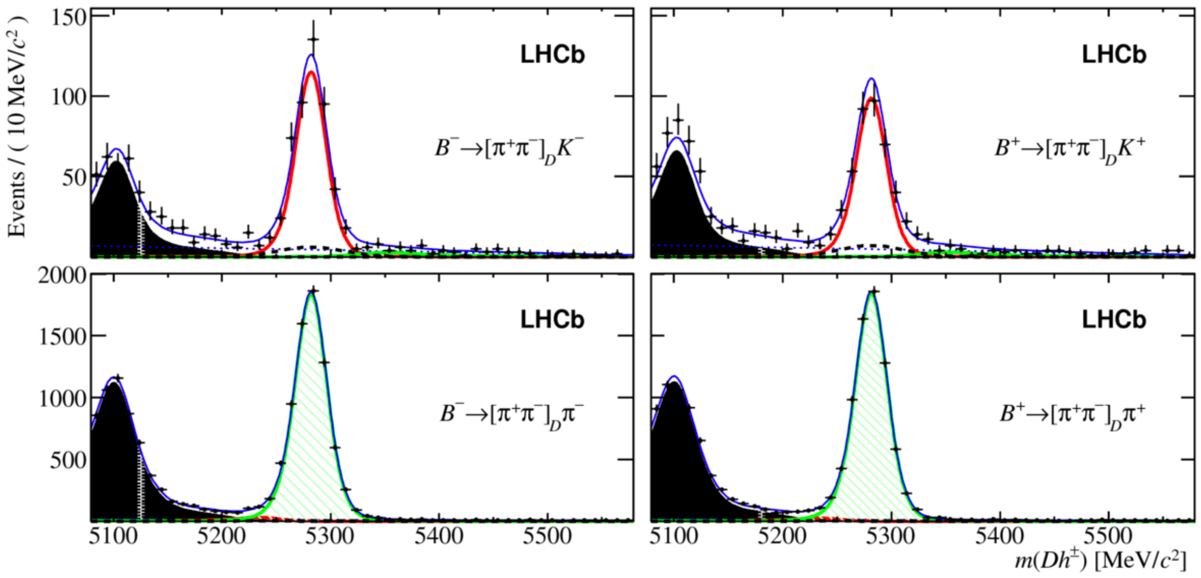
CKM triangle parameter γ

- Many modes used to measure γ at LHCb

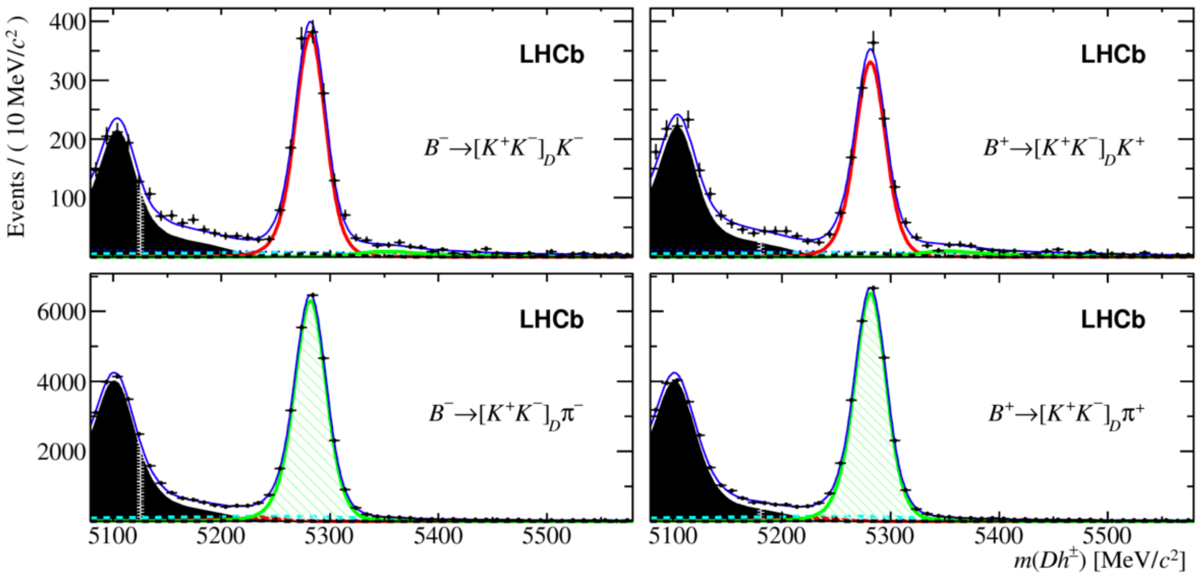
LHCb-PAPER-2016-003

$$B^+ \to DK^+, D \to KK, \pi\pi, K\pi$$

$D \to \pi\pi$ (GLW CP+)



$D \to KK$ (GLW CP+)



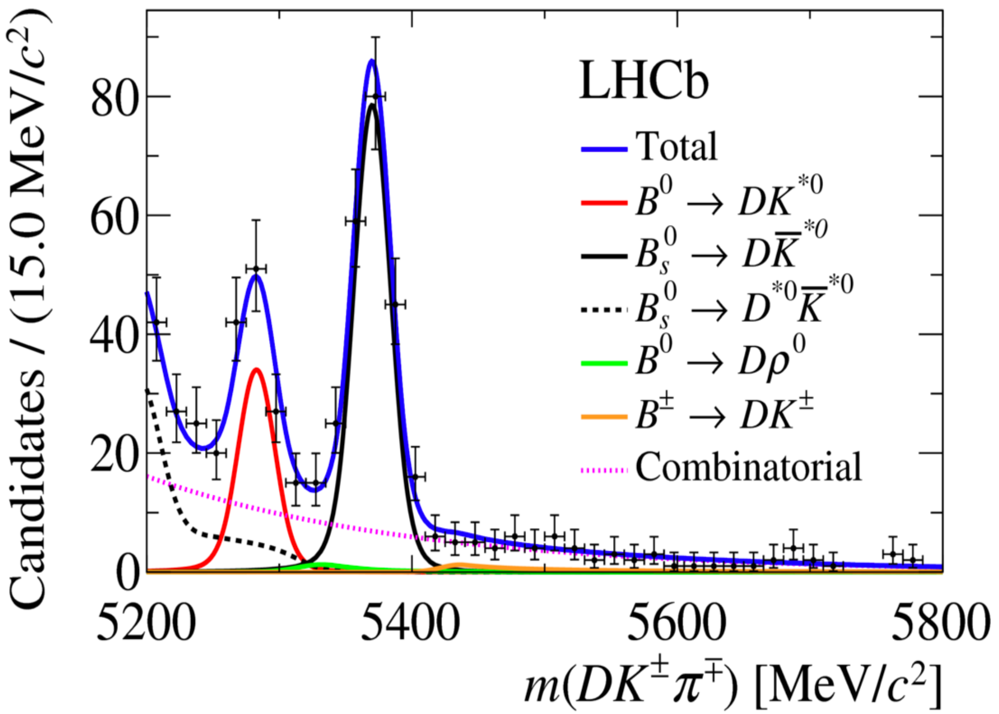
CKM triangle parameter γ

- Many modes used to measure γ at LHCb

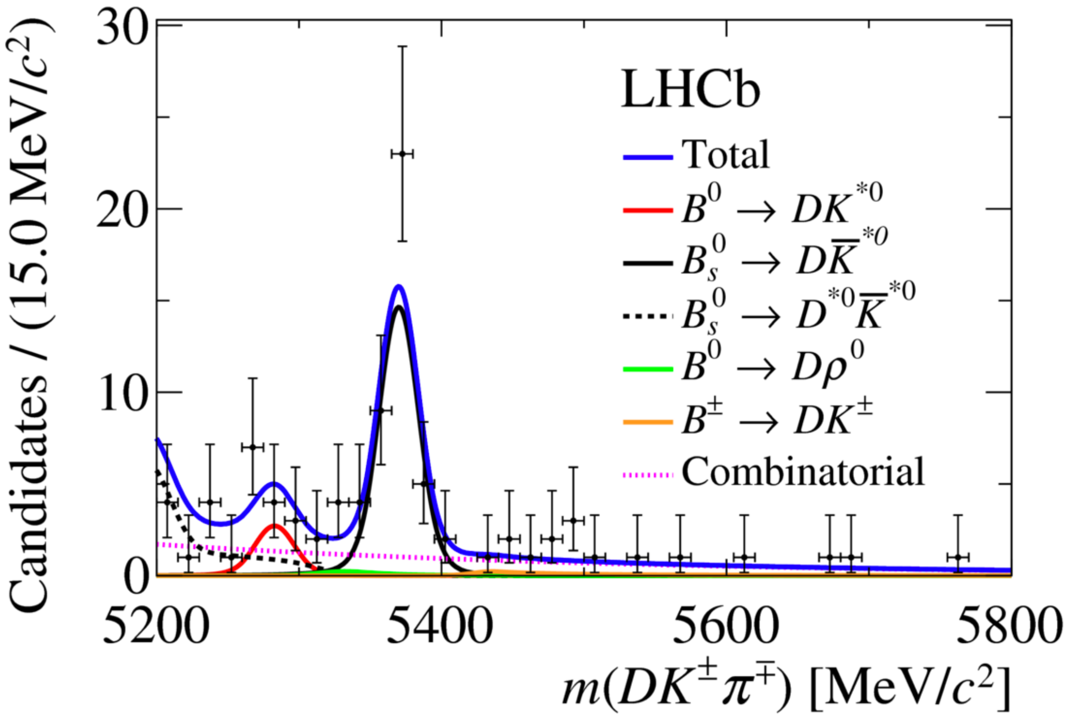
LHCb-PAPER-2016-006
LHCb-PAPER-2016-007

$B^0 \to DK^{*0}, D \to K_s\pi\pi, K_sKK$

$D \to K_s\pi\pi$



$D \to K_sKK$ (GLW CP+)



CKM triangle parameter γ

- γ combinations

LHCb-CONF-2016-001

$$A_{\rm ADS}^{\pi K} = -0.403 \pm 0.056 \pm 0.011\,,$$
$$A_{CP}^{KK} = 0.087 \pm 0.020 \pm 0.008\,,$$
$$A_{CP}^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012\,,$$
$$A_{\rm fav}^{K\pi} = -0.0194 \pm 0.0072 \pm 0.0060\,,$$
$$R_{\rm ADS}^{\pi K} = 0.0188 \pm 0.0011 \pm 0.0010\,,$$
$$R_{CP}^{KK} = 0.968 \pm 0.022 \pm 0.021 \pm 0.010\,,$$
$$R_{CP}^{\pi\pi} = 1.002 \pm 0.040 \pm 0.026 \pm 0.010\,,$$

$$x_- = 0.025 \pm 0.025 \pm 0.010 \pm 0.005\,,$$
$$y_- = 0.075 \pm 0.029 \pm 0.005 \pm 0.014\,,$$
$$x_+ = -0.077 \pm 0.024 \pm 0.010 \pm 0.004\,,$$
$$y_+ = -0.022 \pm 0.025 \pm 0.004 \pm 0.010\,,$$

$$R^{K_SK\pi} = 3.855 \pm 0.961 \pm 0.060\,,$$
$$A_{\rm fav}^{K_SK\pi} = 0.026 \pm 0.109 \pm 0.029\,,$$
$$A_{\rm sup}^{K_SK\pi} = 0.336 \pm 0.208 \pm 0.026\,,$$

$$\kappa_D^{K3\pi} = 0.32 \pm 0.10\,,$$
$$\delta_D^{K3\pi} = 2.97 \pm 0.66\,,$$
$$\kappa_D^{K2\pi} = 0.81 \pm 0.07\,,$$
$$\delta_D^{K2\pi} = 3.14 \pm 0.30\,,$$
$$r_D^{K3\pi} = 0.0552 \pm 0.0007\,,$$
$$r_D^{K2\pi} = 0.0440 \pm 0.0012\,.$$

$$x_D = 0.0037 \pm 0.0016\,,$$
$$y_D = 0.0066 \pm 0.0009\,,$$
$$\delta_D^{K\pi} = 3.35 \pm 0.21\,,$$
$$R_D^{K\pi} = 0.00349 \pm 0.00004\,,$$
$$A_{CP}^{\rm dir}(\pi\pi) = 0.0010 \pm 0.0015\,,$$
$$A_{CP}^{\rm dir}(KK) = -0.0015 \pm 0.0014\,.$$

$$A_{\rm fav}^{DK^{*0},K\pi} = -0.03 \pm 0.04 \pm 0.02\,,$$
$$R_+^{DK^{*0},K\pi} = 0.06 \pm 0.03 \pm 0.01\,,$$
$$R_-^{DK^{*0},K\pi} = 0.06 \pm 0.03 \pm 0.01\,,$$

$$A_{\rm ADS}^{K\pi\pi^0} = -0.20 \pm 0.27 \pm 0.04\,,$$
$$A_{CP}^{KK\pi^0} = 0.30 \pm 0.20 \pm 0.02\,,$$
$$A_{CP}^{\pi\pi\pi^0} = 0.054 \pm 0.091 \pm 0.011\,,$$
$$A_{\rm fav}^{K\pi\pi^0} = 0.010 \pm 0.026 \pm 0.005\,,$$
$$R_{\rm ADS}^{K\pi\pi^0} = 0.0140 \pm 0.0047 \pm 0.0021\,,$$
$$R_{CP}^{KK\pi^0} = 0.95 \pm 0.22 \pm 0.05\,,$$
$$R_{CP}^{\pi\pi\pi^0} = 0.98 \pm 0.11 \pm 0.05\,,$$

$$x_-^{DK\pi} = -0.02 \pm 0.13 \pm 0.14\,,$$
$$y_-^{DK\pi} = -0.35 \pm 0.26 \pm 0.41\,,$$
$$x_+^{DK\pi} = 0.04 \pm 0.16 \pm 0.11\,,$$
$$y_+^{DK\pi} = -0.47 \pm 0.28 \pm 0.22\,,$$

$$A_{\rm ADS}^{\pi K\pi\pi} = -0.313 \pm 0.102 \pm 0.038\,,$$
$$A_{CP}^{\pi\pi\pi\pi} = 0.100 \pm 0.034 \pm 0.018\,,$$
$$A_{\rm fav}^{K\pi\pi\pi} = 0.000 \pm 0.012 \pm 0.002\,,$$
$$R_{\rm ADS}^{\pi K\pi\pi} = 0.0140 \pm 0.0015 \pm 0.0006\,,$$
$$R_{CP}^{\pi\pi\pi\pi} = 0.975 \pm 0.037 \pm 0.019 \pm 0.005\,,$$

$$x_-^{DK^{*0}} = -0.15 \pm 0.14 \pm 0.03 \pm 0.01\,,$$
$$y_-^{DK^{*0}} = 0.25 \pm 0.15 \pm 0.06 \pm 0.01\,,$$
$$x_+^{DK^{*0}} = 0.05 \pm 0.24 \pm 0.04 \pm 0.01\,,$$
$$y_+^{DK^{*0}} = -0.65 \pm 0.24 \pm 0.08 \pm 0.01\,,$$

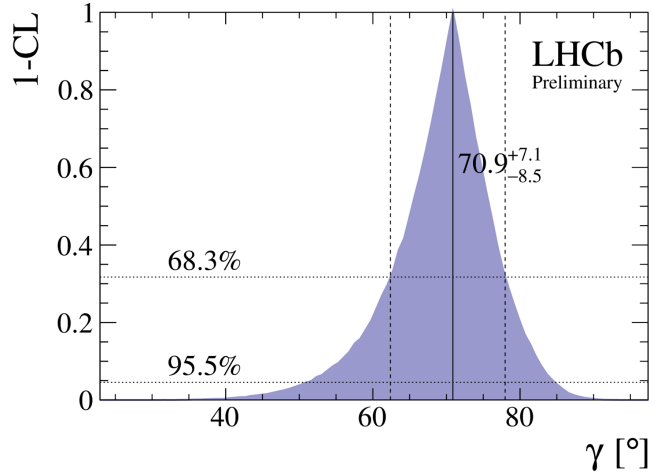
$$C_f = 0.53 \pm 0.25 \pm 0.05\,,$$
$$A_f^{\Delta\Gamma} = -0.37 \pm 0.42 \pm 0.20\,,$$
$$A_{\bar f}^{\Delta\Gamma} = -0.20 \pm 0.41 \pm 0.19\,,$$
$$S_f = -1.09 \pm 0.33 \pm 0.08\,,$$
$$S_{\bar f} = 0.36 \pm 0.33 \pm 0.08\,,$$

$$R_{CP}^{DK\pi\pi} = 1.040 \pm 0.064\,,$$
$$A_{\rm fav}^{DK\pi\pi,\,K\pi} = 0.013 \pm 0.019 \pm 0.013\,,$$
$$A_{CP}^{DK\pi\pi,\,KK} = -0.045 \pm 0.064 \pm 0.011\,,$$
$$A_{CP}^{DK\pi\pi,\,\pi\pi} = -0.054 \pm 0.101 \pm 0.011\,,$$
$$R_+^{DK\pi\pi,\,K\pi} = 0.0107 \pm 0.0060 \pm 0.0011\,,$$
$$R_-^{DK\pi\pi,\,K\pi} = 0.0053 \pm 0.0045 \pm 0.0006\,,$$

$$\phi_s = -0.010 \pm 0.039\,{\rm rad}\,.$$

$$\kappa_B^{DK^{*0}} = 0.958 \pm 0.008 \pm 0.024,$$
$$\bar R_B^{DK^{*0}} = 1.020 \pm 0.020 \pm 0.060,$$
$$\bar\Delta_B^{DK^{*0}} = 0.020 \pm 0.025 \pm 0.110.$$

$$\gamma = (70.9\,^{+7.1}_{-8.5})^\circ$$



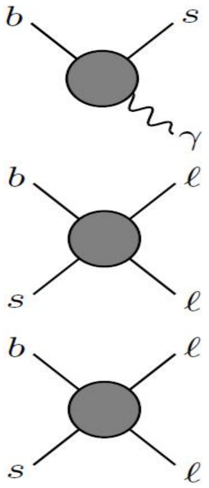
Rare decays

- $\boldsymbol{B \to f}$ described by effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^{*} \sum_i (\underbrace{C_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{C_i' \mathcal{O}_i'}_{\text{Right-handed}})$$

$\boldsymbol{C_i, C_i'}$ – Wilson coefficients: could be calculated peturbatively

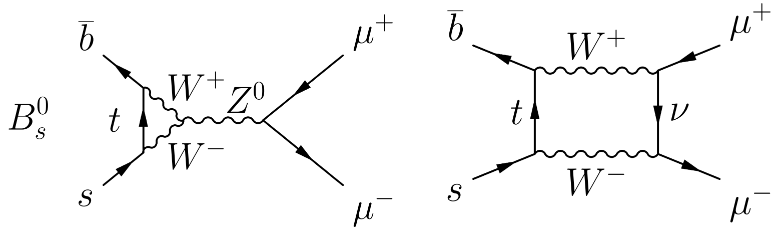
$\boldsymbol{O_i, O_i'}$ – local operators: $\langle \boldsymbol{f} | \boldsymbol{O_i} | \boldsymbol{B} \rangle$ non perturbative, can only be extracted by model & phenomenological analysis



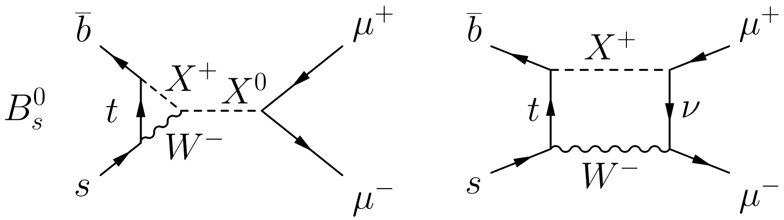
		$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$	photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$	vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$	axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$	(pseudo)scalar penguin		✓	

$B_{s,d} \to \mu\mu$

- Very rare in the Standard Model

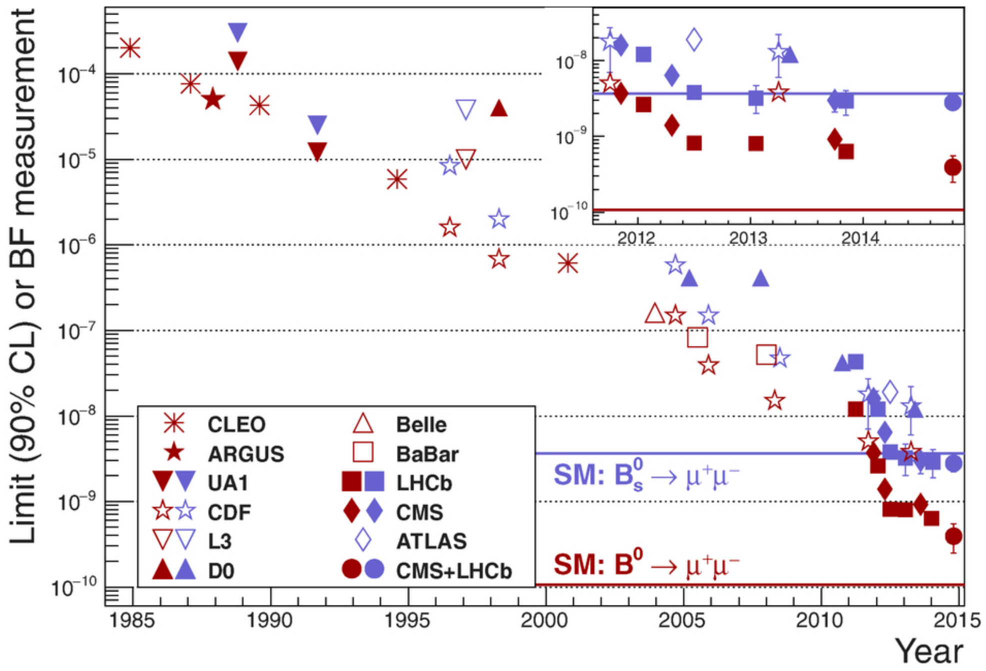


may be modified by NP



C. Bobeth et al., PRL 112(2014) 101801

$$\mathcal{B}^{\mathrm{SM}}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23)^{-9}$$
$$\mathcal{B}^{\mathrm{SM}}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09)^{-10}$$

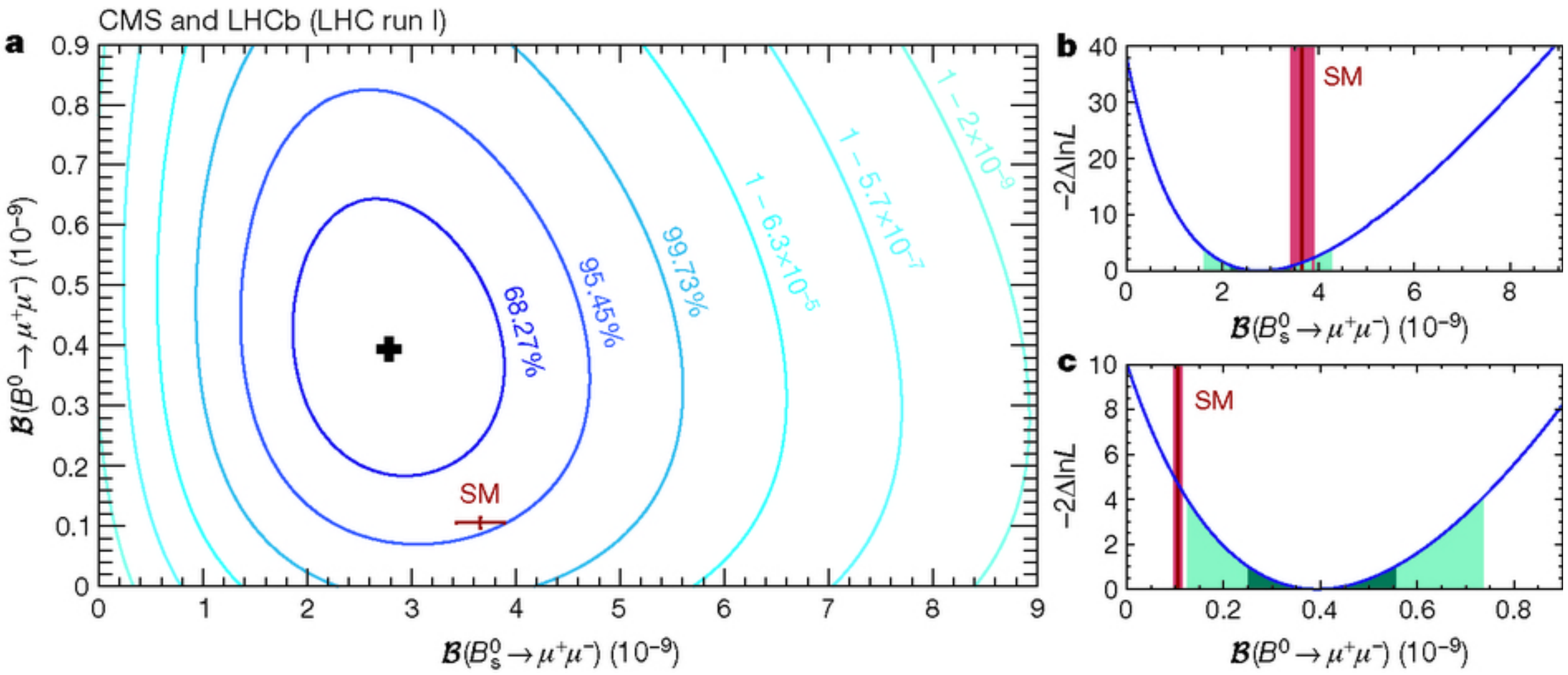


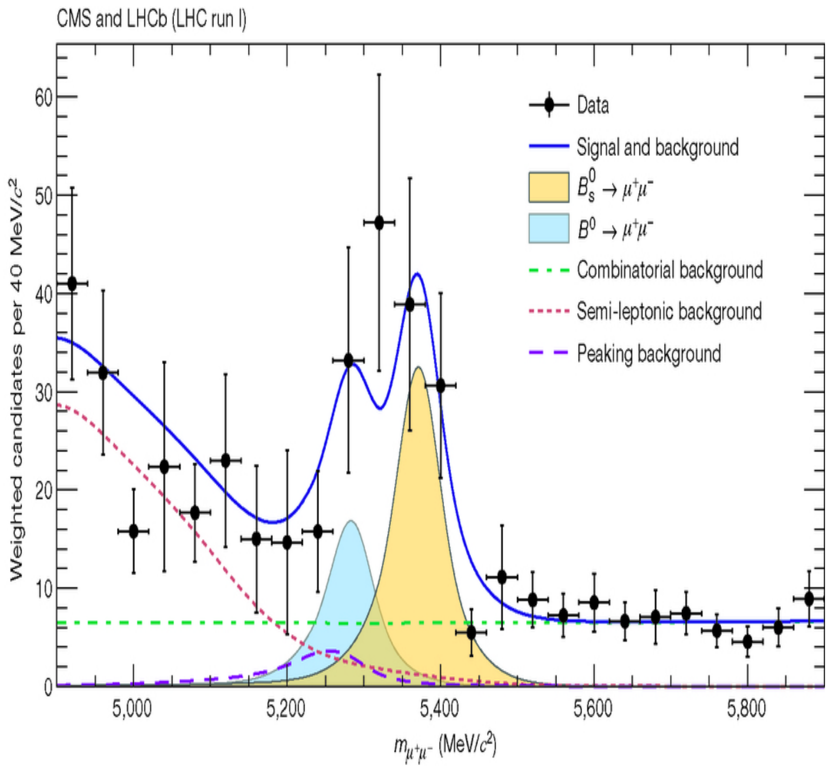
- Intensively searched
  for over 30 years

$B_{s,d} \to \mu\mu$

CMS and LHCb, Nature 522 (2015) 68

- Combination of CMS & LHCb
  - → first observation of $B_s \to \mu\mu$
  - → first evidence of $B_d \to \mu\mu$



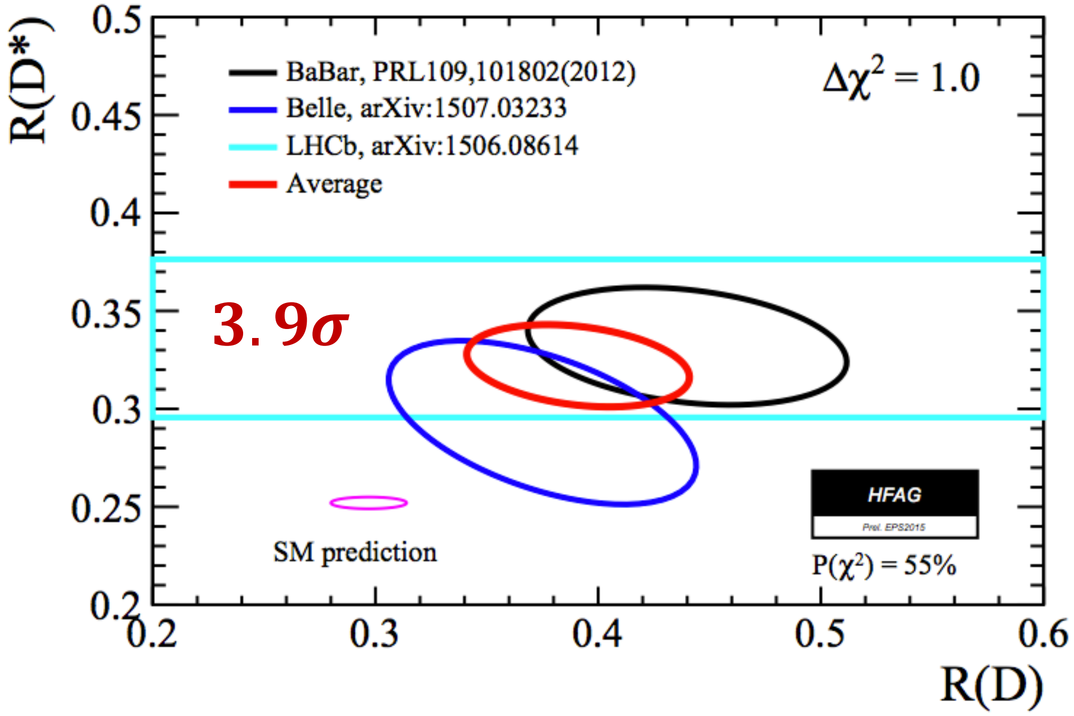


Possible anomalies

LHCb, PRL 115(2015) 112001

- Test lepton universality

$$R(D^*) = \mathcal{B}(B \to D^*\tau\nu)/\mathcal{B}(B \to D^*\mu\nu)$$



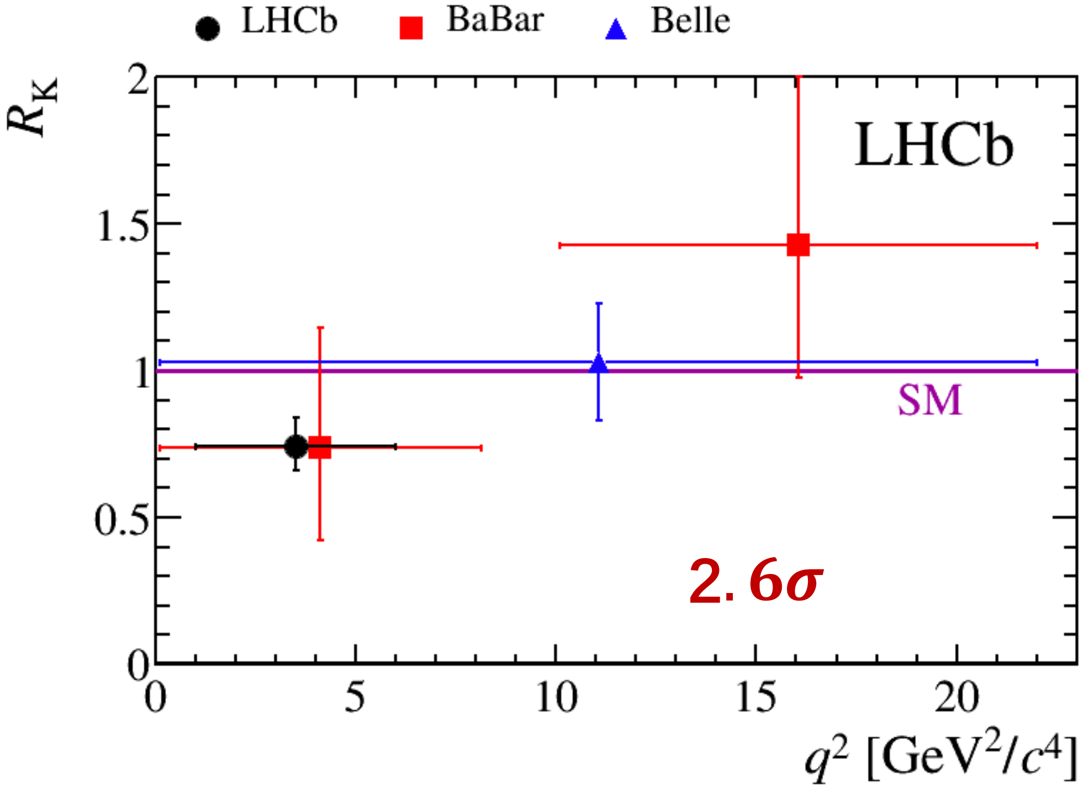
$$R(D) = \mathcal{B}(B \to D\tau\nu)/\mathcal{B}(B \to Dl\nu)$$

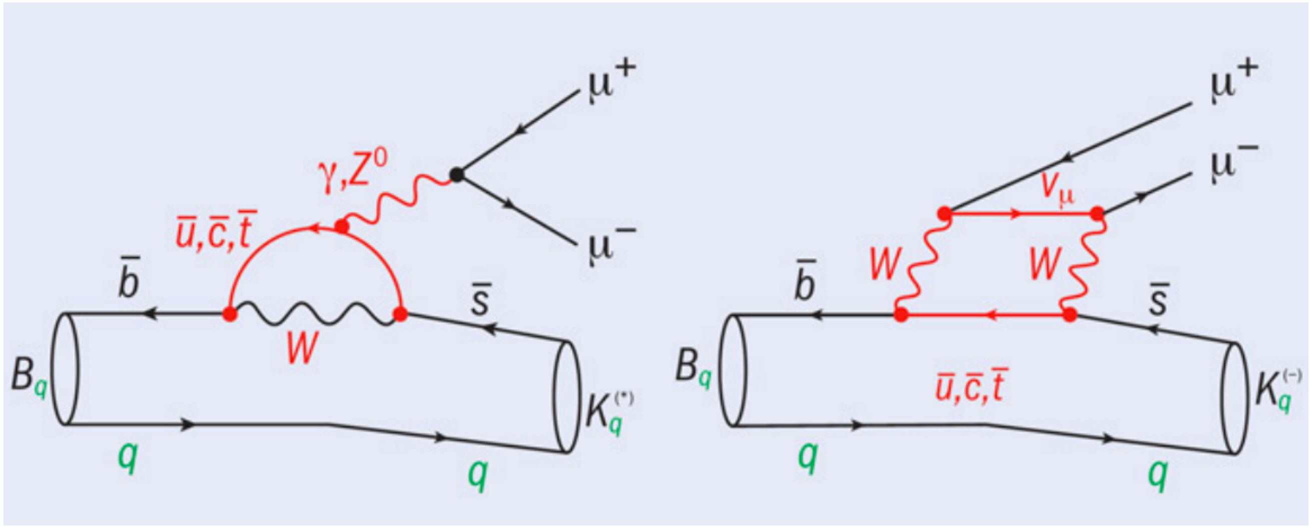
Possible anomalies

LHCb, PRL 113(2014) 151601

- Test lepton universality

$$R_K = \mathcal{B}(B^+ \to K^+\mu\mu)/\mathcal{B}(B^+ \to K^+ee)$$



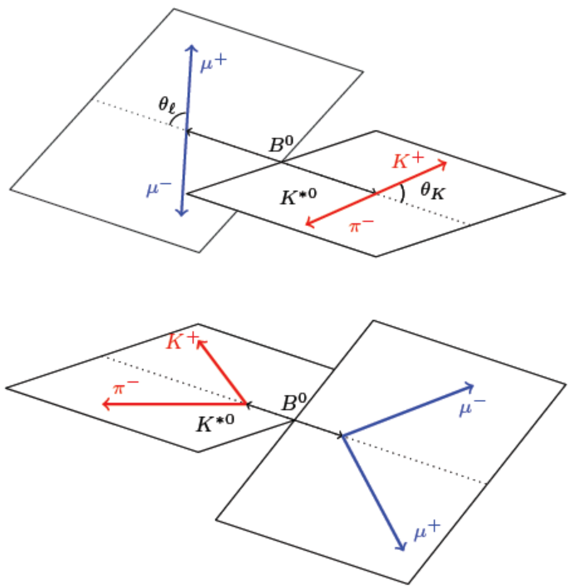


Possible anomalies

LHCb, JHEP 02(2016) 104

- Higher statistics for Not-So-Rare mode $B^0 \to K^* \mu\mu$

  → full angular CP-averaged angular distribution



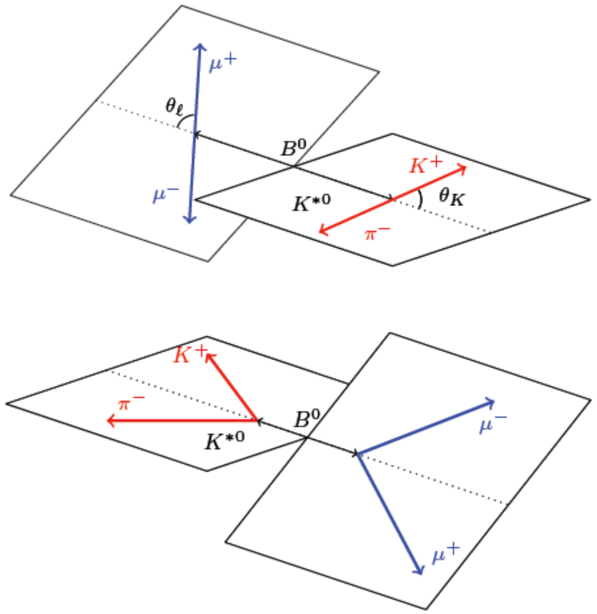
ϕ is the angle between decay planes in the B^0 rest frame

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\frac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

Possible anomalies

LHCb, JHEP 02(2016) 104

- Higher statistics for Not-So-Rare mode $B^0 \to K^* \mu\mu$
  - → full angular CP-averaged angular distribution
  - → optimized observables: leading $B^0 \to K^{*0}$ form-factor uncertainties cancel



ϕ is the angle between decay planes in the B^0 rest frame

$$P_1 = \frac{2\,S_3}{(1-F_L)} = A_T^{(2)}\,,$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{(1-F_L)}\,,$$

$$P_3 = \frac{-S_9}{(1-F_L)}\,,$$

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}\,,$$

$$P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}\,.$$

Possible anomalies

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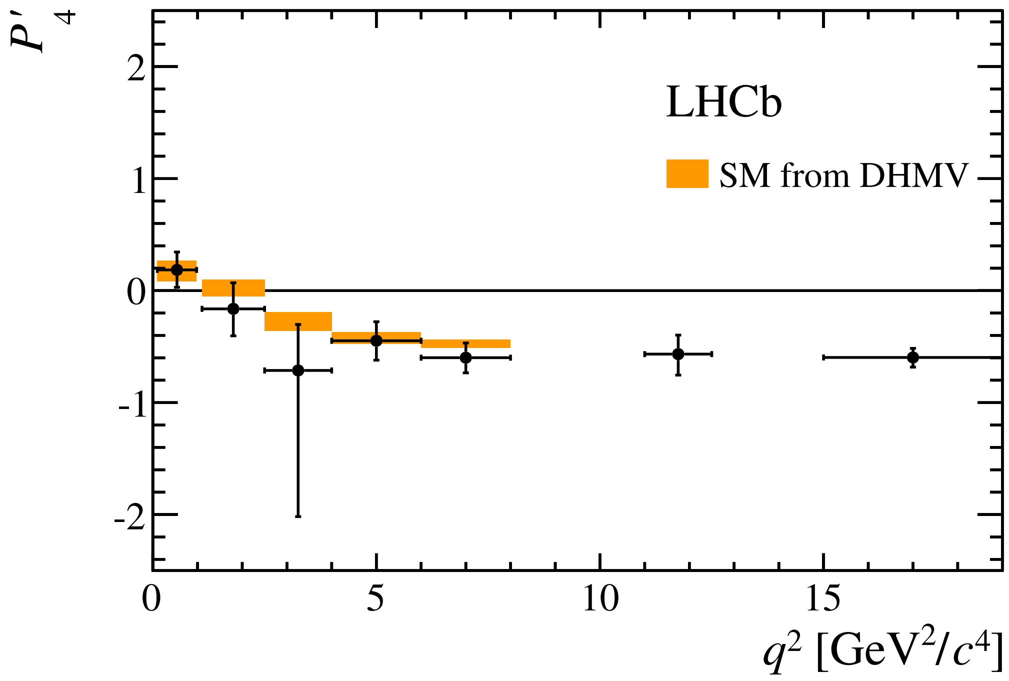

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Possible anomalies

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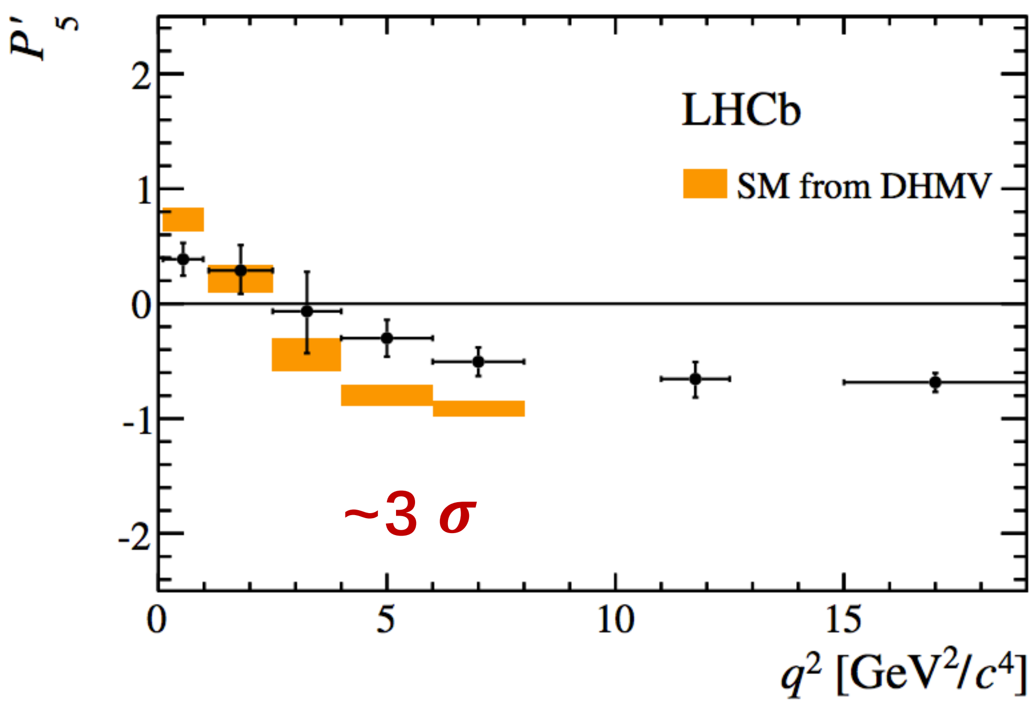

$$P_1 = \frac{2\,S_3}{(1-F_\mathrm{L})} = A_\mathrm{T}^{(2)}\,,$$

$$P_2 = \frac{2}{3}\frac{A_\mathrm{FB}}{(1-F_\mathrm{L})}\,,$$

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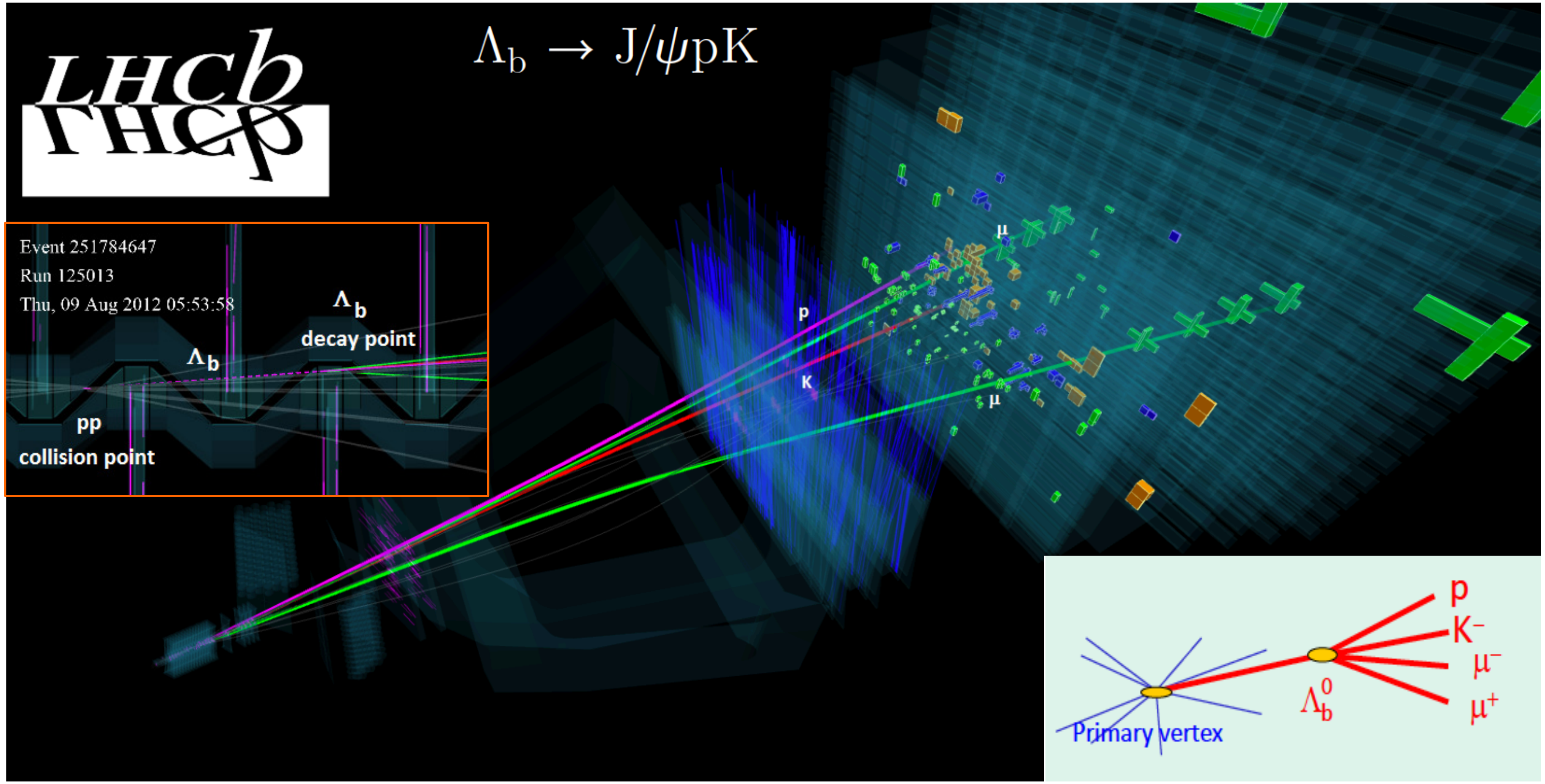
$$P'_6 = \frac{S_7}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}\,.$$

$\Lambda_b^0 \to J/\psi p K^-$ at LHCb



Observation of J/ψp Resonances Consistent With Pentaquark States

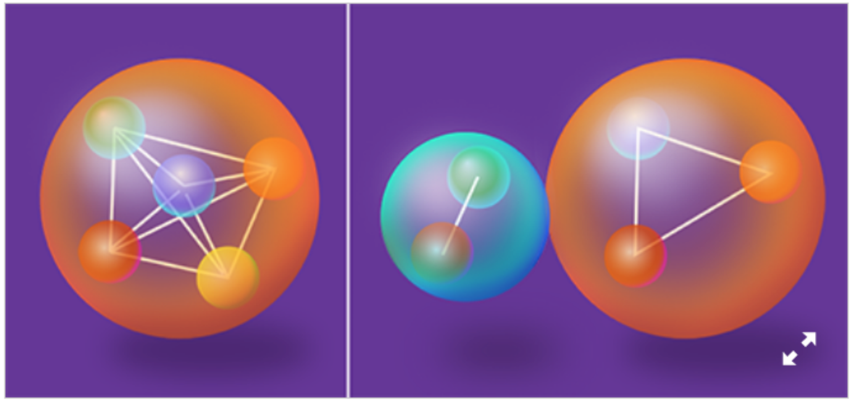
APS physics | Physics

Viewpoint: Elusive Pentaquark Comes into View

Kenneth Hicks, Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA

August 12, 2015 • *Physics* 8, 77

A new type of particle containing five quarks has been observed by the LHCb experiment.



APS/Carin Cain

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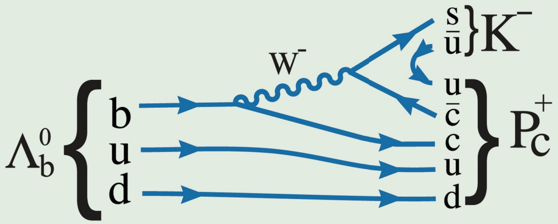


PRL 115, 072001 (2015)

Published by American Physical Society
APS physics
Volume 115, Number 7

Predicted at the birth date of the quark model

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

3

http://cds.cern.ch/record/352337/files/CERN-TH-401.pdf

Multiquark states have been discussed since the quark model was proposed

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH.401
17 January 1964

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

4

The *elusive pentaquark*

C. G. Wohl in PDG2008:

The only advance in particle physics thought worthy of mention in the American Institute of Physics "Physics News in 2003" was a false alarm. *The whole story - the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery"* - is a curious episode in the history of science.

Recent reviews:

- **K. H. Hicks, Eur. Phys. J. H37, 1 (2012);**
- **T. Liu, Y. Mao, B.-Q. Ma, Int. J. Mod. Phys. A29, 1430030 (2014).**

$\Theta(1540)^+$ $I(J^P) = 0(?^?)$ Status: ∗

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

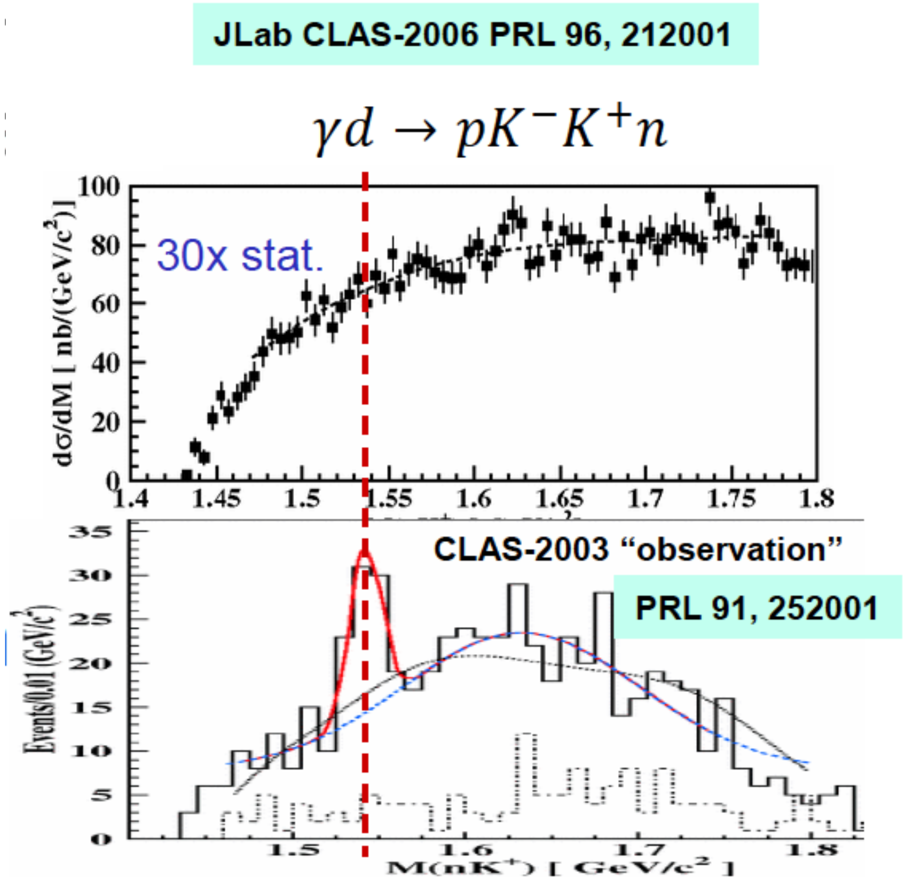
Written February 2006

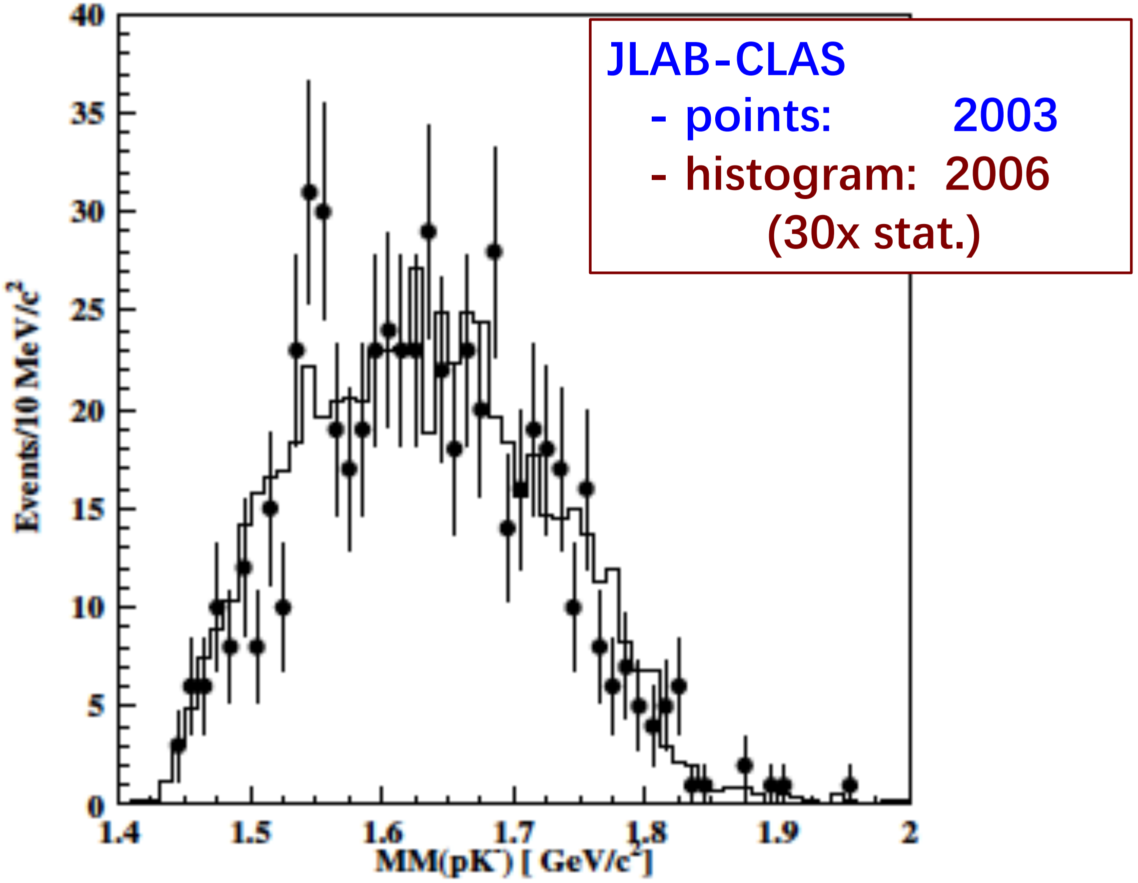
In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov *et*

...

To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

A *practical* course on statistical fluctuations



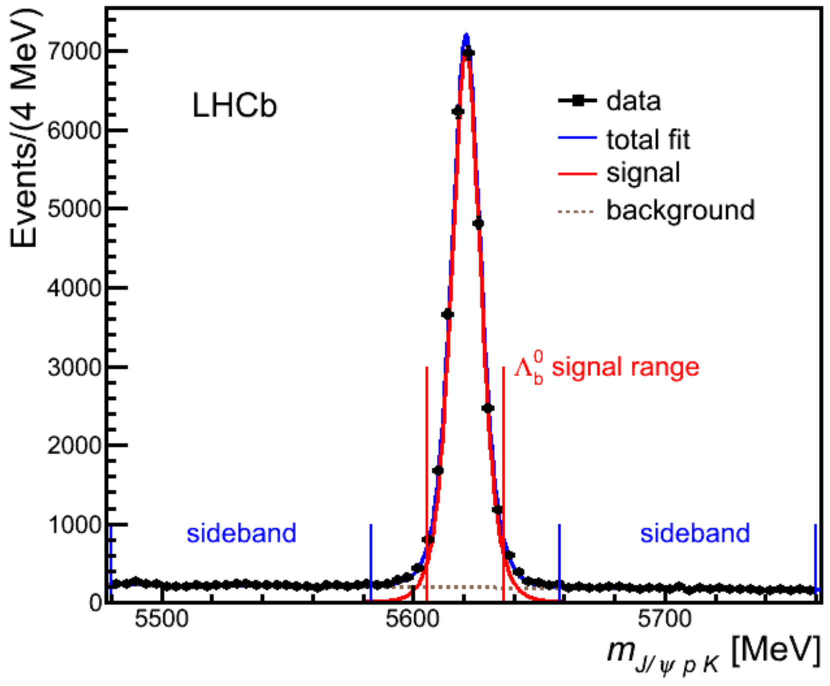


Surprise in $\Lambda_b^0 \to J/\psi p K^-$

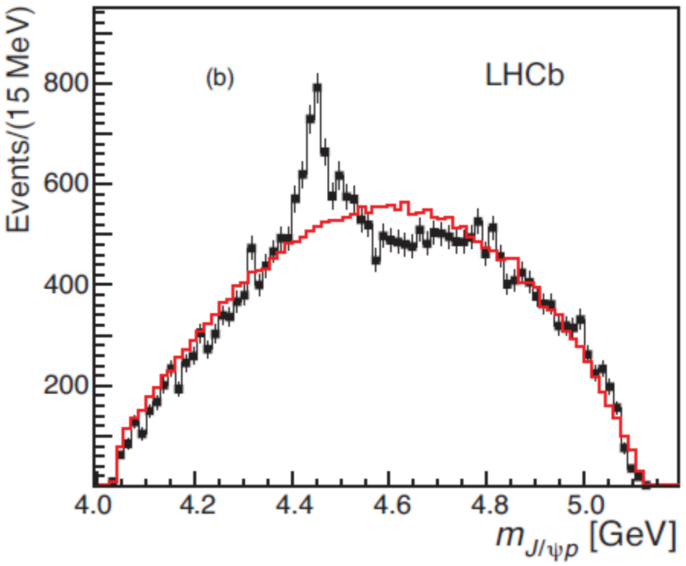
LHCb, PRL 115(2015) 072001

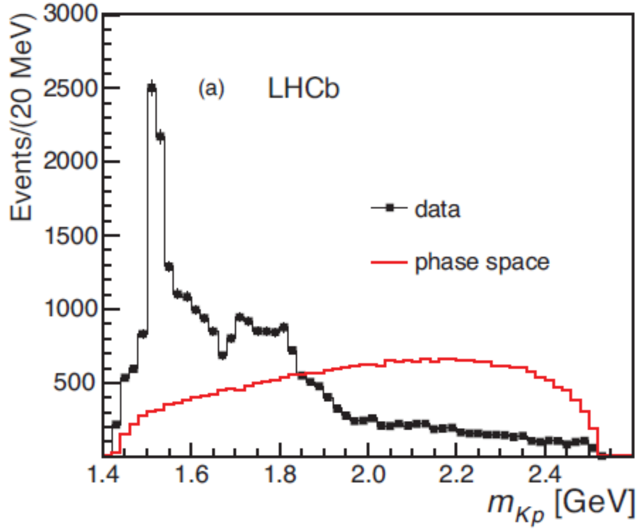
- Revisited with improved selection in 3 fb^{-1}.

~26000 signals in 3 fb^{-1}



$\Lambda_b^0 \to J/\psi p K^-$





$\Lambda_b^0 \to J/\psi p K^-$ at LHCb

- First observation of the decay with 1 fb^{-1}, unexpected large yield

LHCb, PRL 111(2013) 102003

- Used to measure Λ_b^0 lifetime

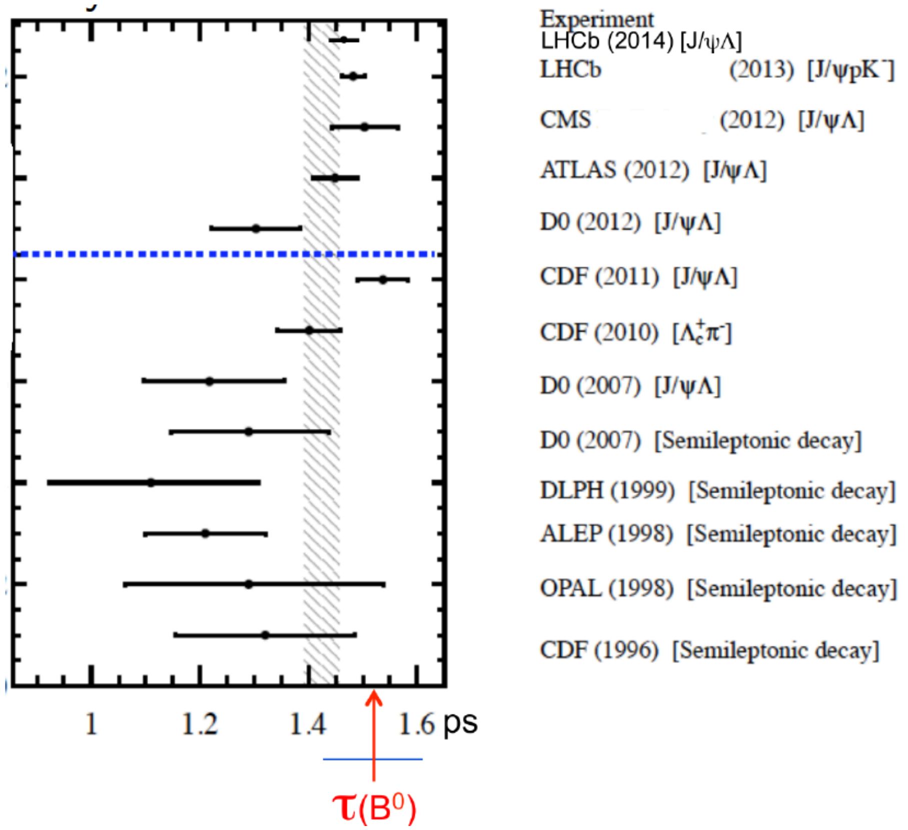
LHCb, PL B734 (2014) 122

- Absolute branching ratio measured

LHCb, Chin. Phys. C 40 (2016) 011001

$$\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.17 \pm 0.04 \pm 0.07 \pm 0.34^{+0.45}_{-0.28}) \times 10^{-4}$$

something strange seen in $m_{J/\psi p}$

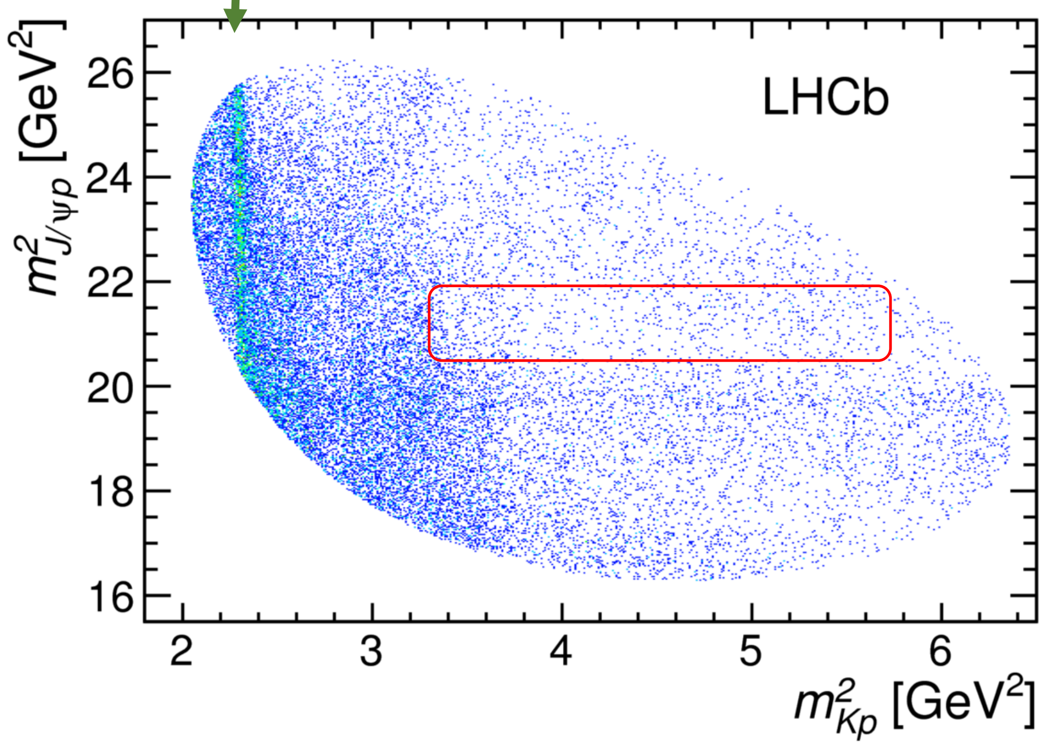


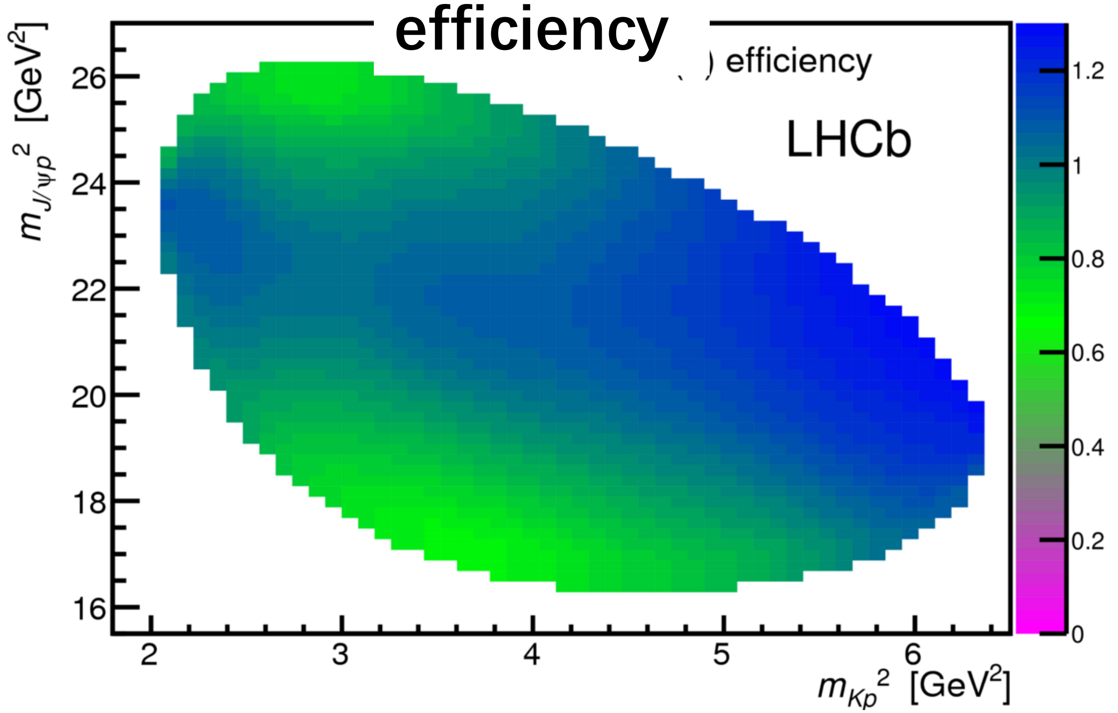
Surprise in $\Lambda_b^0 \to J/\psi p K^-$

LHCb, PRL 115(2015) 072001

- A clear feature shown in Dalitz plot

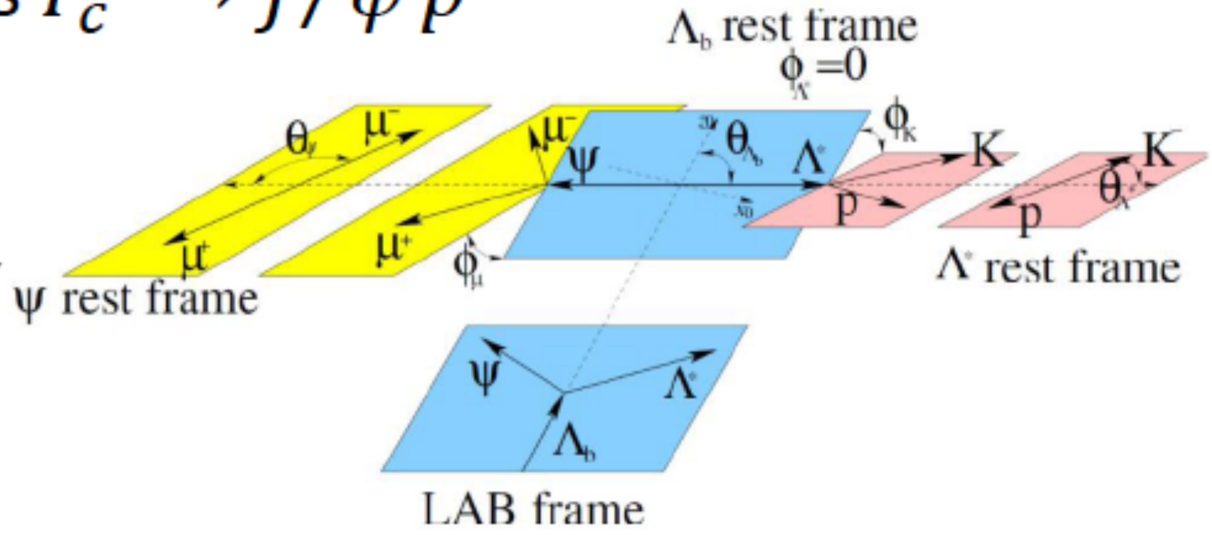
$\Lambda(1520) \to pK^-$



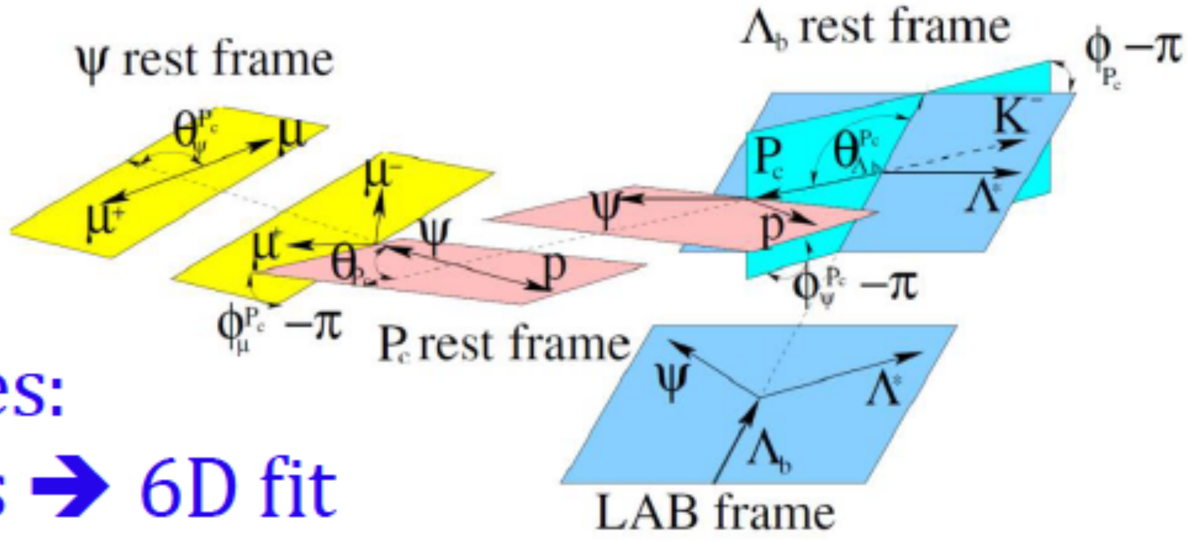


- Allows for $\Lambda^* \to pK^-$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$

$$\Lambda_b^0 \to J/\psi \Lambda^*,\quad \Lambda^* \to pK^-$$



$$\Lambda_b^0 \to P_c^+ K^-,\quad P_c^+ \to J/\psi p$$



- Independent variables: $m(pK^-)$ and 5 angles ➔ 6D fit

Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$

LHCb, PRL 115(2015) 072001

- 6D amplitude: m_{pK^-} & 5 decay angles
- 2 models for $\Lambda^* \to pK^-$ contributions based on PDG

  - *Extended model* allows all LS couplings of each resonance, and include poorly motivated states → 146 parameters

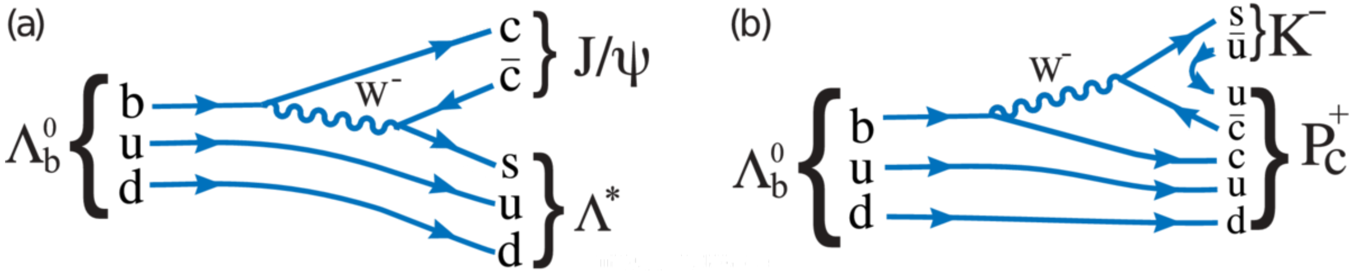
  - *Reduced model* uses only well motivated states → 64 parameters

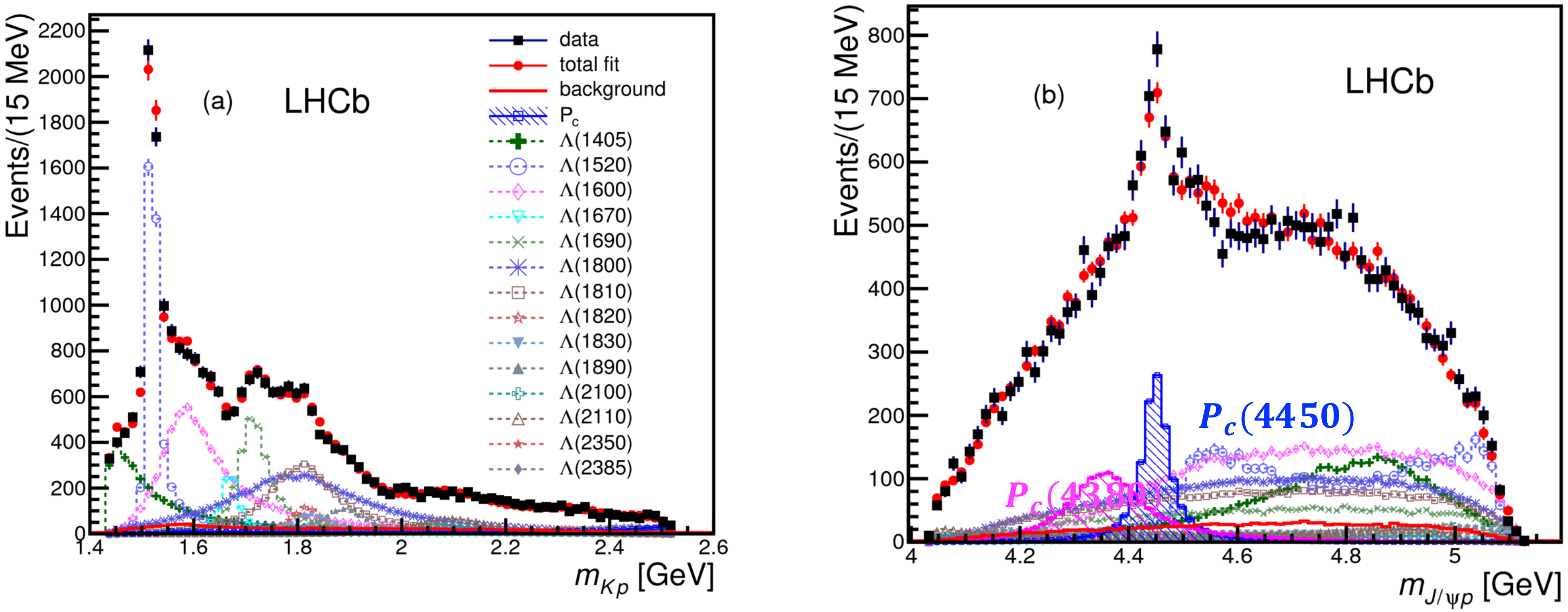
  - *Other possibilities* checked, including isospin violating decays of Σ^{*0}'s, adding two new Λ^* states with free mass & width, non-resonance contributions, …, would not change the conclusion

Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

- Need two new states in $J/\psi p$ to fit the data (no $J/\psi K^-$ states!)





Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

- Need two new states in $J/\psi p$ to fit the data (no $J/\psi K^-$ states!)

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

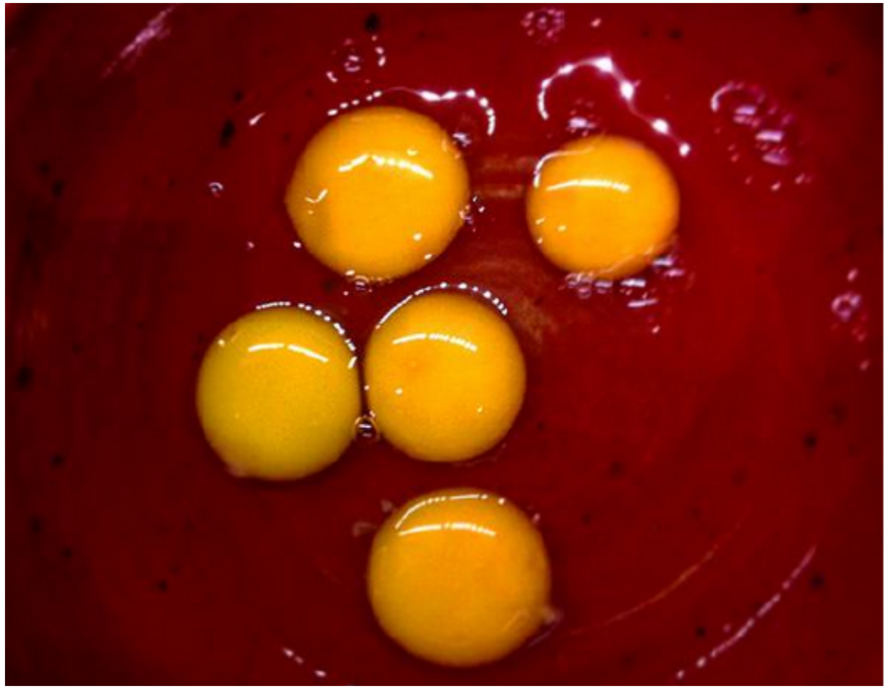
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\ {}^{+0.46}_{-0.36}\right) \times 10^{-5}$$

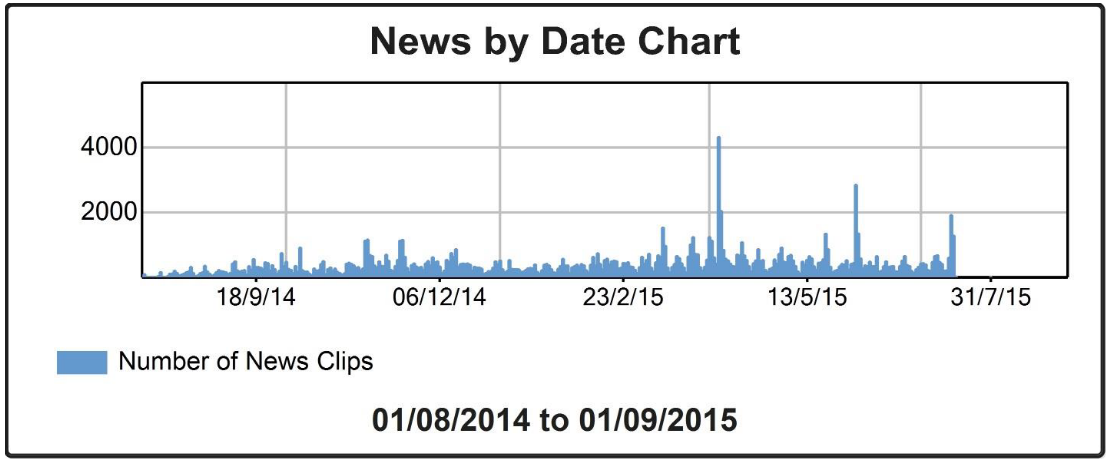
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\ {}^{+0.22}_{-0.18}\right) \times 10^{-5}$$

LHCb, Chin. Phys. C 40 (2016) 011001

"It's about the most exciting discovery in QCD I could imagine," says Frank Wilczek, of the Massachusetts Institute of Technology, and himself an architect of QCD. "To me the deep message is that 'diquarks' [hypothetical quark pairs] are a useful organizing principle within hadrons," he says, adding that the scene is now set for rapid progress: "It's like a phoenix rising from the ashes."

—诺贝尔奖获得者 Frank Wilczek

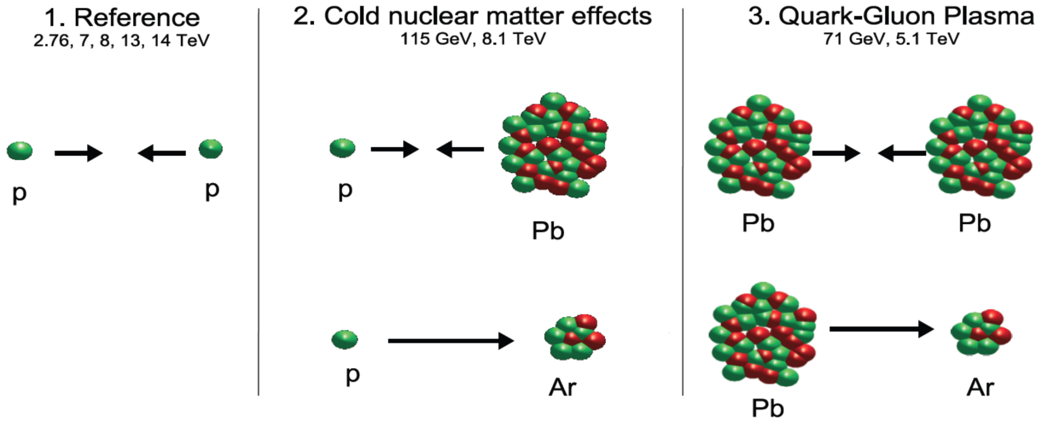




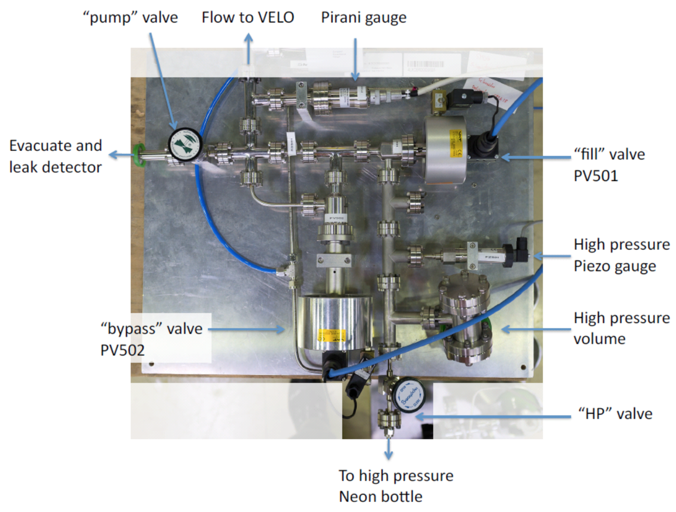
physicsworld
TOP 10
BREAKTHROUGH
2015

Heavy ion program at LHCb

- LHCb collects data from colliding beams & fixed targets

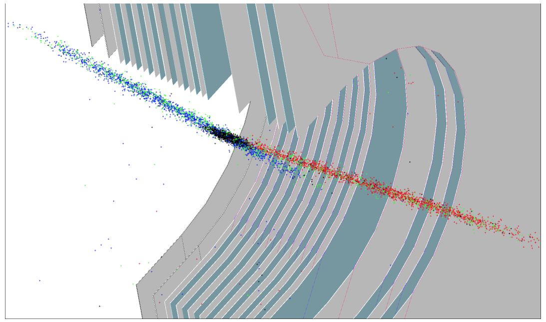


SMOG: System for Measuring the Overlap with Gas



- Injection of noble gas into interaction region
- Simple and robust system

- Used for a precise luminosity determination: 1.1% accuracy at RUNI



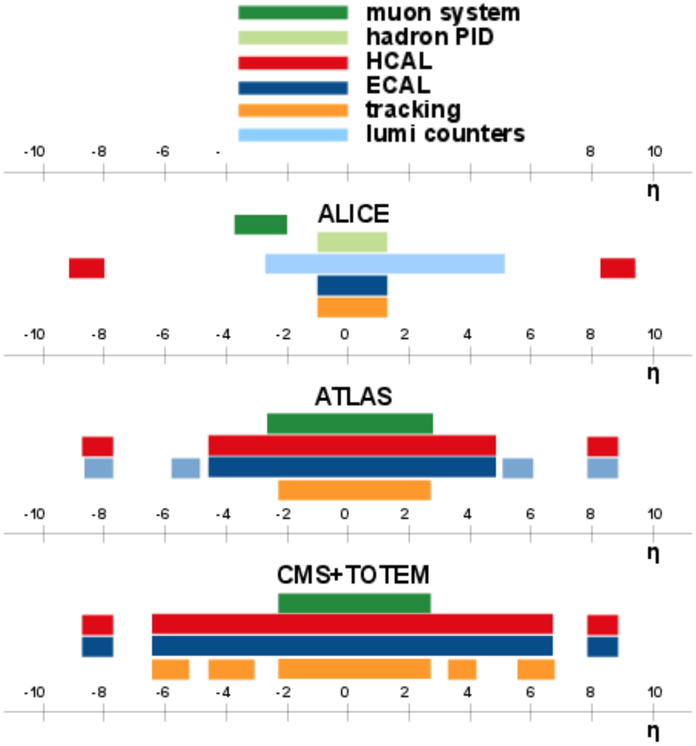
LHCb, JINST 9 (2014) P12005

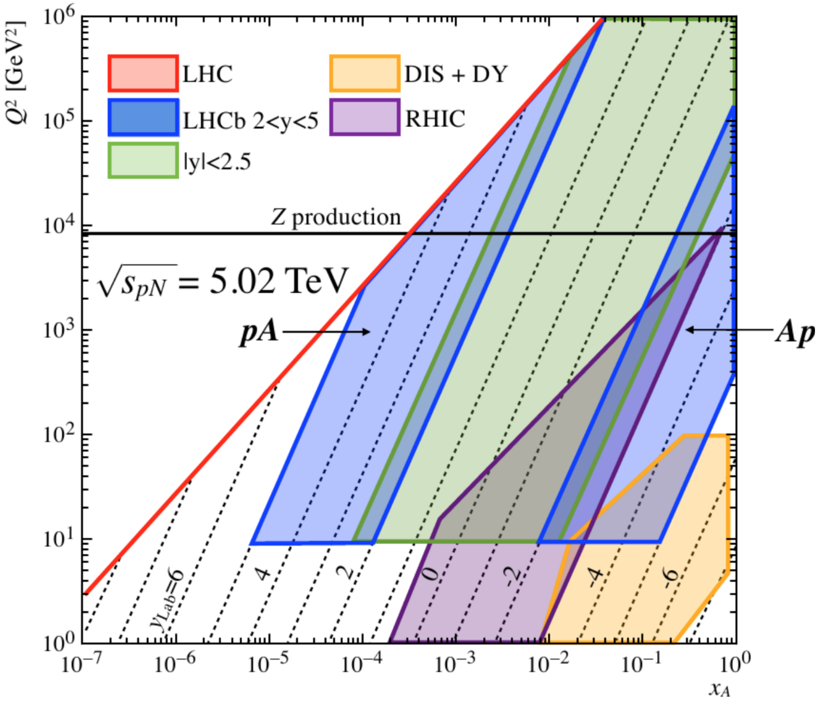
Heavy ion program at LHCb

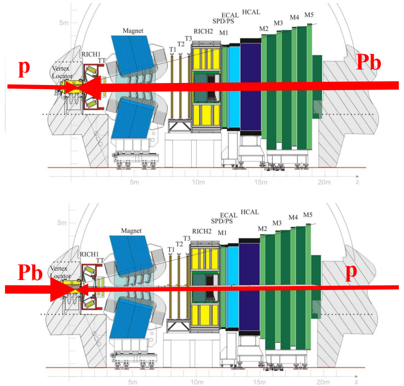
- LHCb fully instrumented in the forward region ($\mathbf{2 < \eta < 5}$)

  - heavy ion collisions in a unique kinematic area:

  low $\boldsymbol{p_T}$, large $\boldsymbol{y}$, very small or large $\boldsymbol{x}$



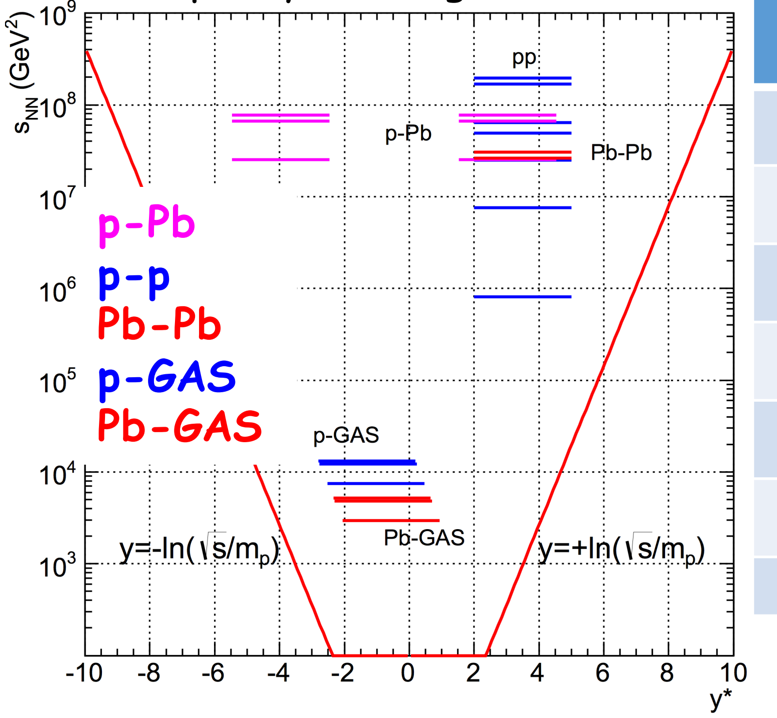




Heavy ion program at LHCb

- Data taking, more in 2016

LHCb rapidity coverage in rest frame



E_{beam}	pp	p-GAS	p-Pb	Pb-GAS	Pb-Pb
450 GeV	0.9 TeV				
1.38 TeV	2.76 TeV				
2.5 TeV	5 TeV	69 GeV			
3.5 TeV	7 TeV				
4.0 TeV	8 TeV	87 GeV	5 TeV	54 GeV	
6.5 TeV	13 TeV	110 GeV	8.2 TeV	69 GeV	5.1 TeV
7.0 TeV	14 TeV	115 GeV	8.8 TeV	72 GeV	5.5 TeV

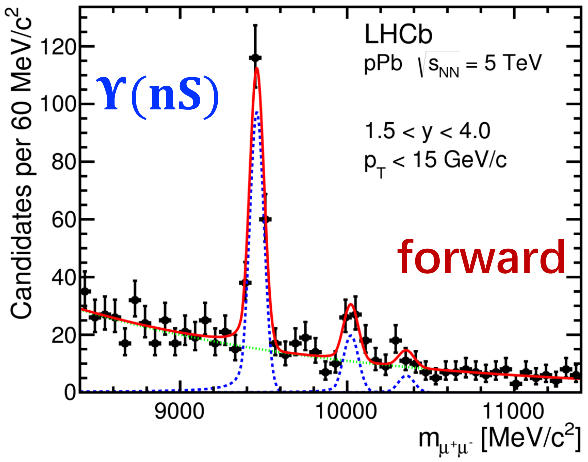
Already collected

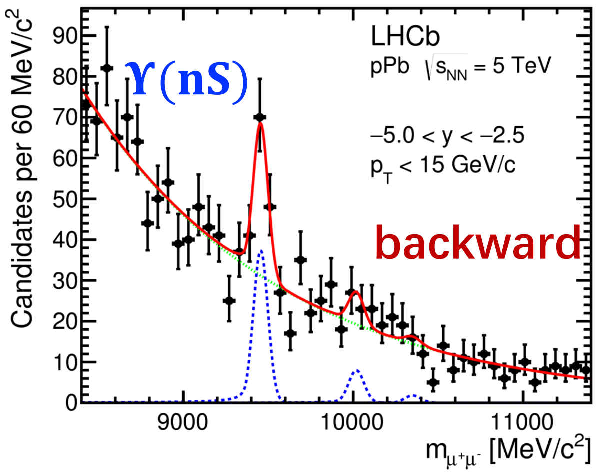
GAS targets: He, Ne, Ar, Kr, Xe

→ Different sizes of colliding system

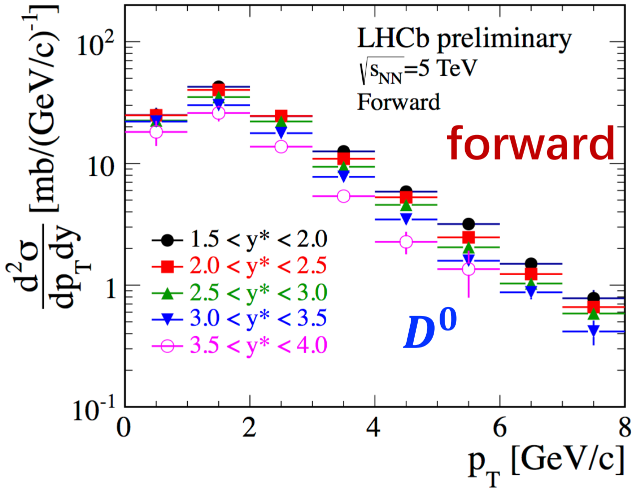
Heavy ion program at LHCb

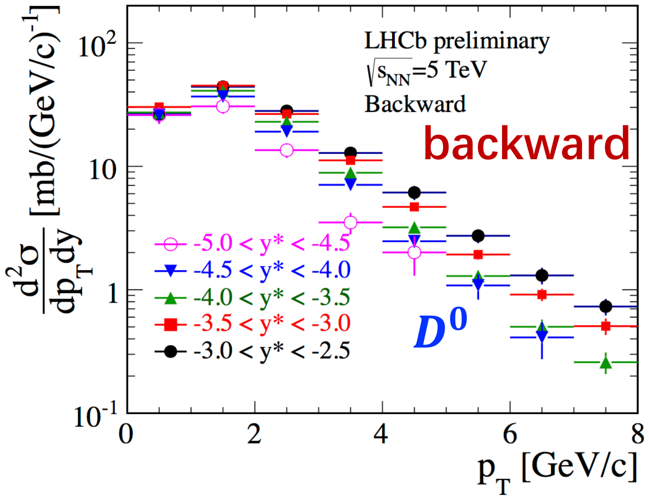
- Heavy flavor productions in $\boldsymbol{p}\mathbf{Pb}$ & $\mathbf{Pb}\boldsymbol{p}$: $\boldsymbol{J/\psi, \psi(2S), \Upsilon(ns), D}$





LHCb, JHEP 02 (2014) 072,
JHEP 07 (2014) 094,
JHEP 03 (2016) 133,
LHCb-CONF-2016-003

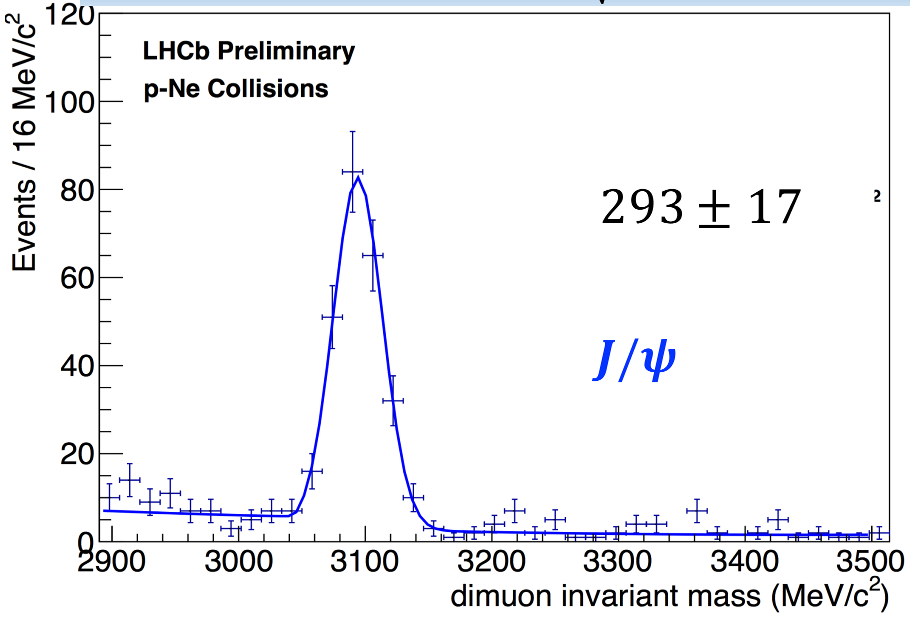




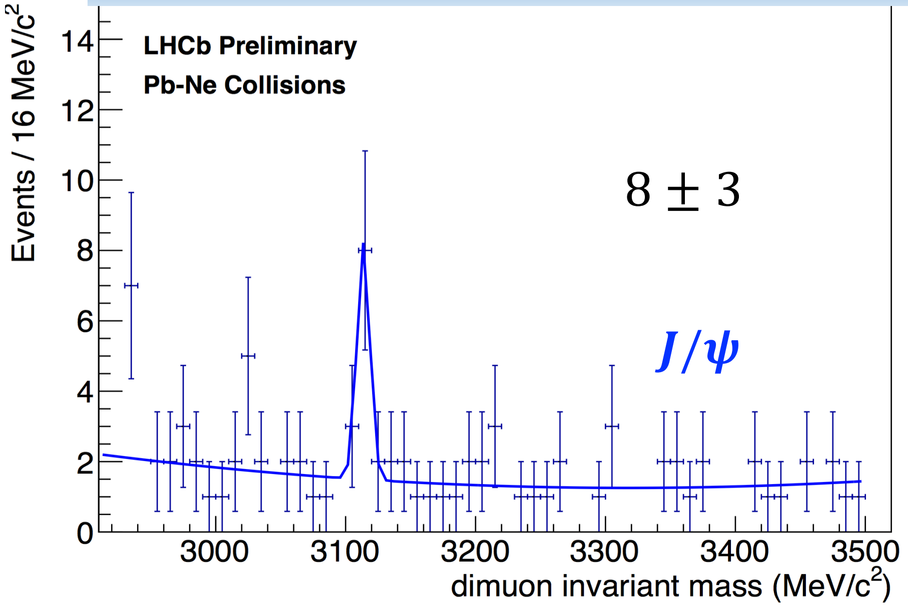
Heavy ion program at LHCb

- Fixed target runs

2015 pNe fixed target run at $\sqrt{s_{NN}} = 110$ GeV



2013 PbNe fixed target run at $\sqrt{s_{NN}} = 54$ GeV



- ***Expect more results in 2016***

LHCb Trigger in RUN II

TURBO stream introduced in 2015

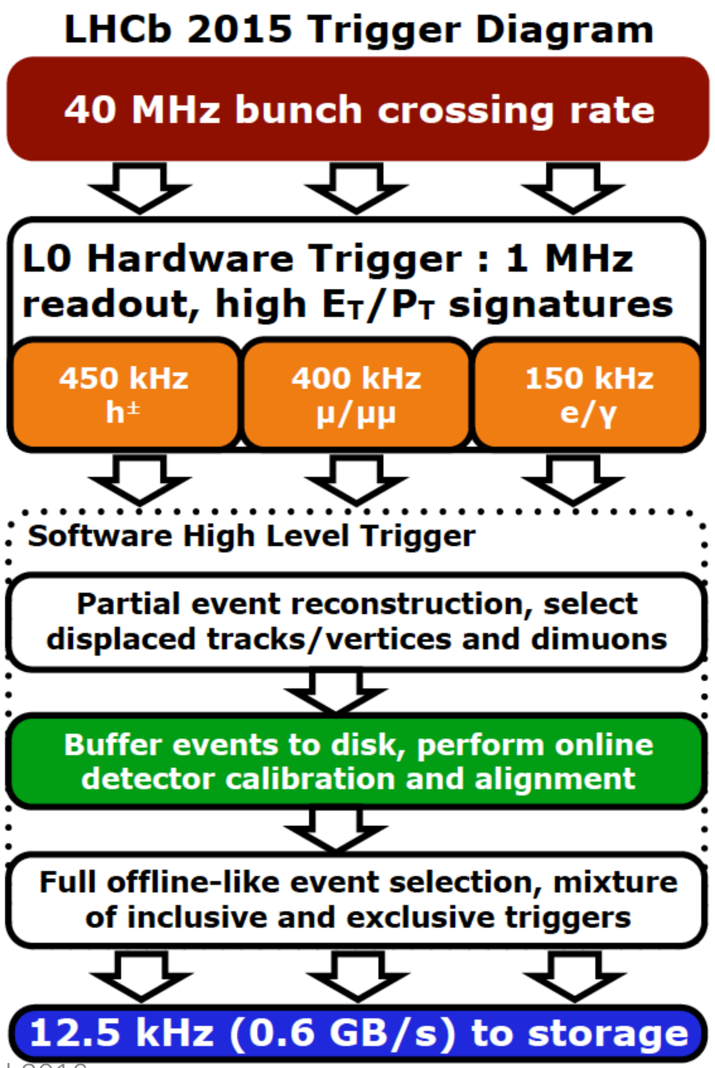
- 5 kHz of 12 kHz go to TURBO
- Only trigger information saved

  → smaller event, faster analysis

  → Used for high yield exclusive trigger lines: $J/\psi, D^0, D^+$, ...

First QUICK results at 13 TeV:

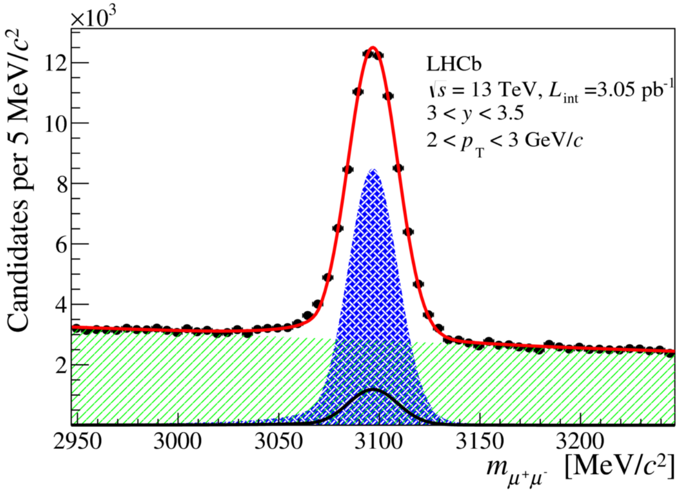
- J/ψ production JHEP 10 (2015) 172
- charm production JHEP 03 (2016) 159
- Z production LHCb-CONF-2016-002



J/ψ cross section at $\sqrt{s} = 13$ TeV

LHCb, JHEP 10 (2015) 172

- A quick measurement of J/ψ cross-section at $\sqrt{s} = 13$ TeV based on $3.02 \pm 0.12\ \mathrm{pb}^{-1}$ of data



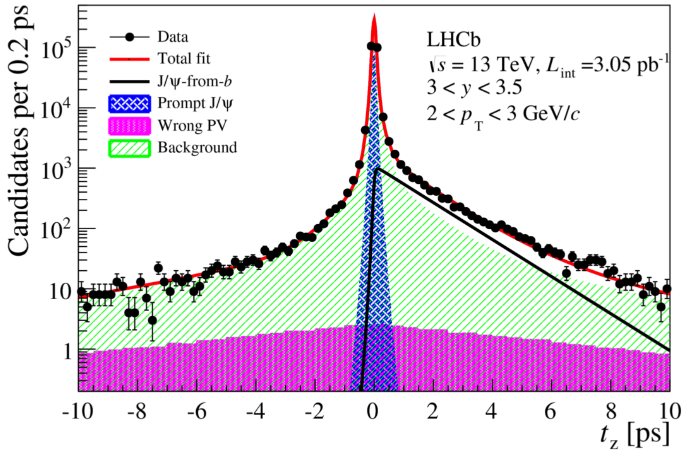
$$\sigma_{J/\psi}(\text{LHCb}) = 15.30 \pm 0.03 \pm 0.86\ \mu\text{b}$$

$$\sigma_{J/\psi/b}(\text{LHCb}) = 2.34 \pm 0.01 \pm 0.13\ \mu\text{b}$$

$$P_T < 14\ \text{GeV}/c, 2 < y < 4.5$$

quasi proper lifetime variable to separate J/ψ from prompt/from b

$$t_z = \frac{(z_{J/\psi} - z_{\text{PV}})M_{J/\psi}}{p_z}$$



Summary

LHCb has made great progress with LHC RUNI & RUNII data

- most precise single-experiment measurement of γ, and many other measurements consistent with SM
- tensions between experiment/theory seen in FCNC and other processes, but not conclusive
- discovery of two pentaquark states $P_c(4450)$ and $P_c(4380)$. Model independent analysis shown consistent result.
- promising results from the heavy ion program
- first results from RUNII data

Data sample will be tripled in RUN II, stay tuned!