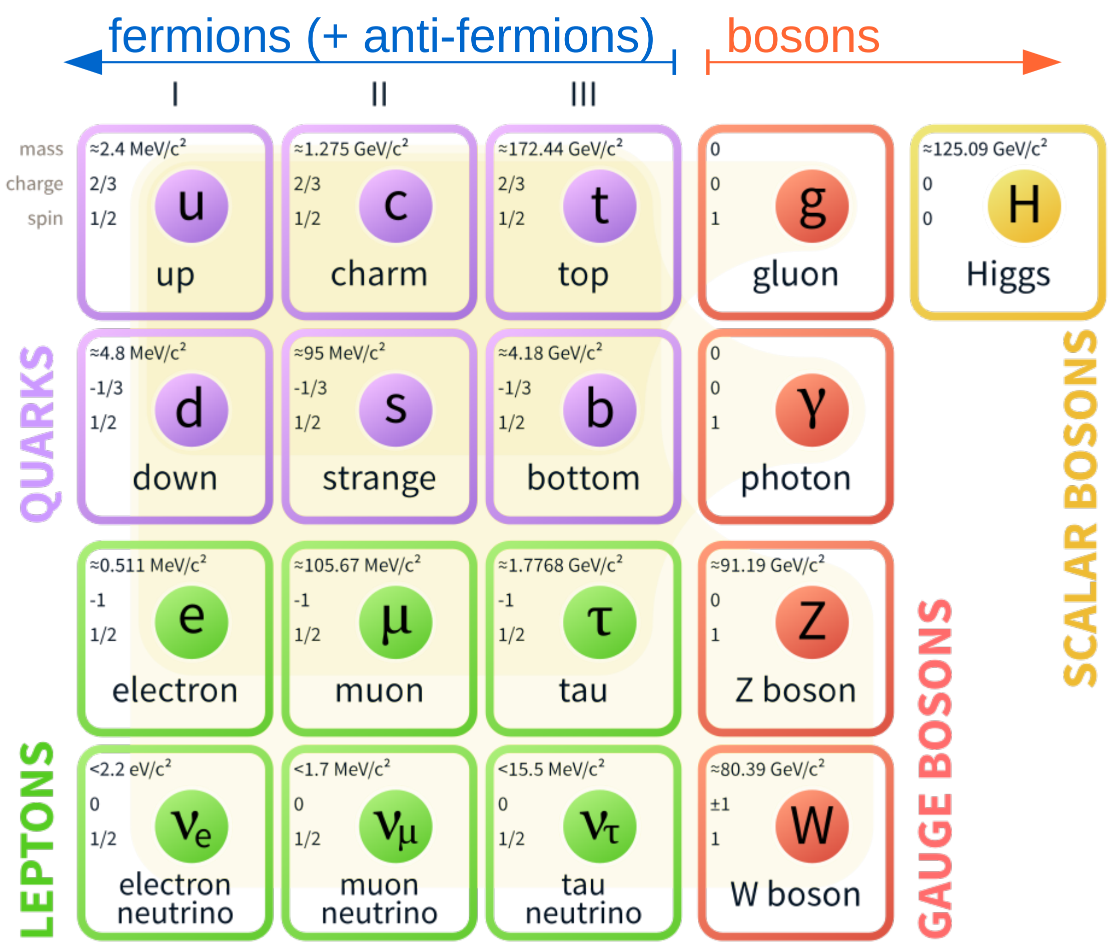
Heavy flavour physics at LHCb

- Why Flavour Physics
- The LHCb experiment
- Digression : Lepton Flavour Universality
- Highlight on selected LHCb results
  - → the current flavour anomalies

Flavour physics in the Standard Model



26 free parameters :

- → 3 coupling constants
- → 2 Higgs field parameters
- → 12 fermions masses
- → 4 quark *mixing* parameters
- → 4 neutrino *mixing* parameters
- → 1 QCD CP violating phase (?)

↘ 20 are concerning flavour physics

Flavour physics is at the heart of the Standard Model

Mysteries of flavour physics

Why are there so many different fermions ?

What is responsible for their organisation into generations / families ?

Why are there 3 generations / families each of quarks and leptons ?

Why are there flavour symmetries ?

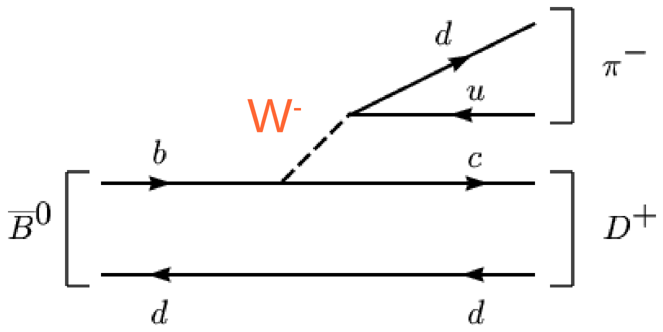
What breaks the flavour symmetries ?

What causes matter–antimatter asymmetry ?

What is Heavy Flavour physics ?

Flavour changing interactions :

- electroweak processes
- at the quark level



What is Heavy Flavour physics ?

Flavour changing interactions :

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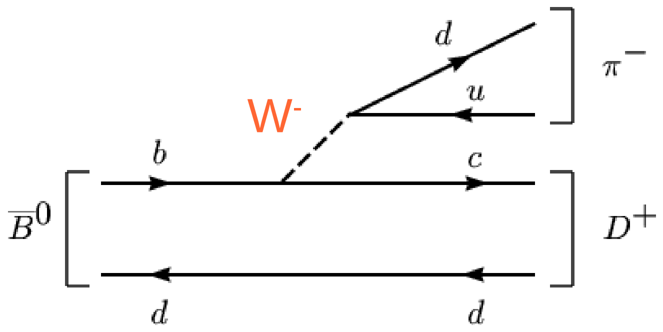
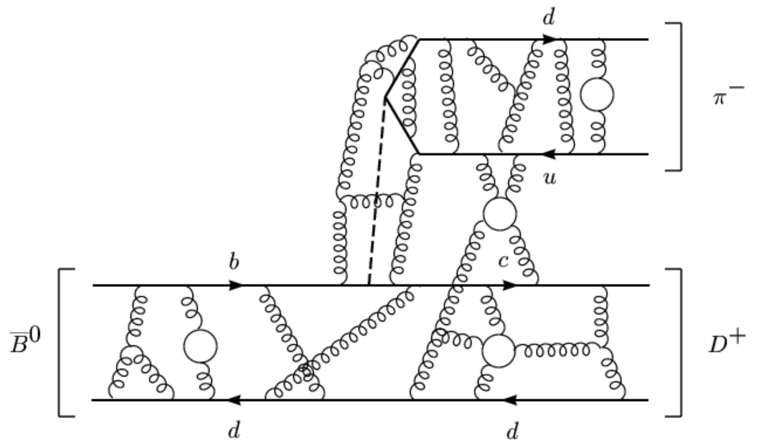
But quarks feel the strong interaction and hadronise

- quark level parameters can not be accessed directly
- hadronic physics effects need to be under control





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Heavy quarks ?

- $\Lambda_{QCD} / m_q << 1$ & $\alpha_s(m_q) << 1$
- hadronic physics can be handled perturbatively

u,*d* → to light !

m ≈ 2 - 5 MeV

s → maybe

m ≈ 100 MeV

c,*b* → just right !

m ≈ 1 - 4 GeV

t → too heavy !

m ≈ 170 GeV

What is Heavy Flavour physics ?

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Heavy quarks ?

- Λ_{QCD} / m_q << 1 & $\alpha_s(m_q)$<<1
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Heavy flavor physics :

- study b- (and c-) hadrons decays
- very rich phenomenology

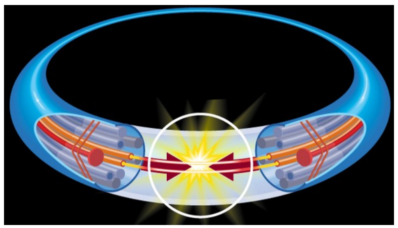
Main objectives :

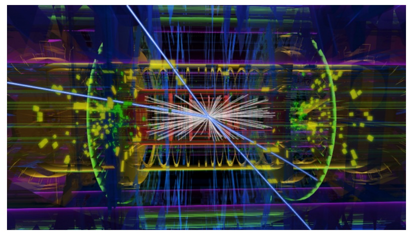
- Test the SM / Search for physics beyond the SM (BSM)
- compare precise theoretical prediction with precise experimental measurements

Search for physics beyond the Standard Model (BSM)

Direct

$E=mc^2$





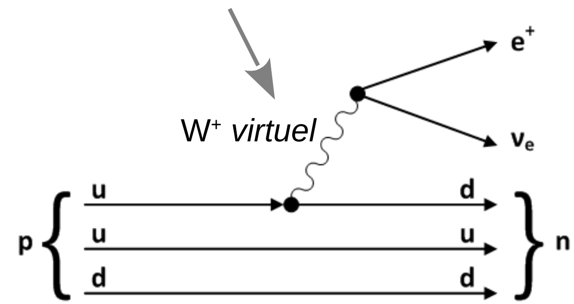
High energy

Direct observation :

- → produce “new” particles on shell and detect decay products
- → more intuitive, “really” produced
- → limited by collision energy

Indirect

$\Delta E.\Delta t < h/2\pi$



High precision

Indirect observation :

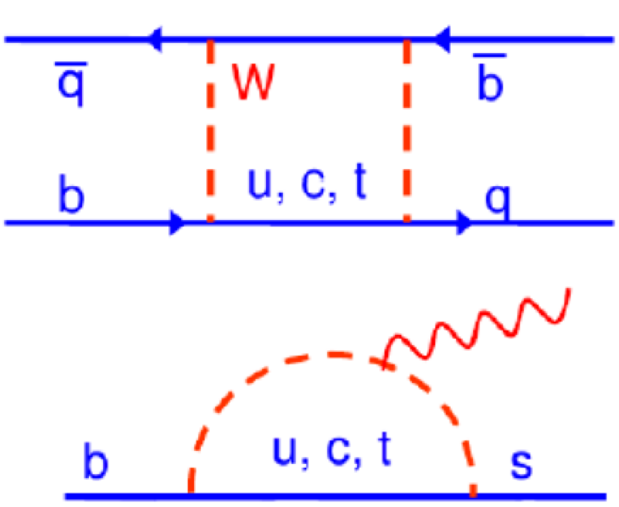
- → virtual “new” particles can be discovered in loop processes
- → less intuitive, “quantum” level
- → not limited by collision energy, limited by precision (of measurements and theoretical predictions)

Complementary approaches → both are needed !

BSM searches with heavy flavour

Contribution to New Physics as a correction to the Standard Model

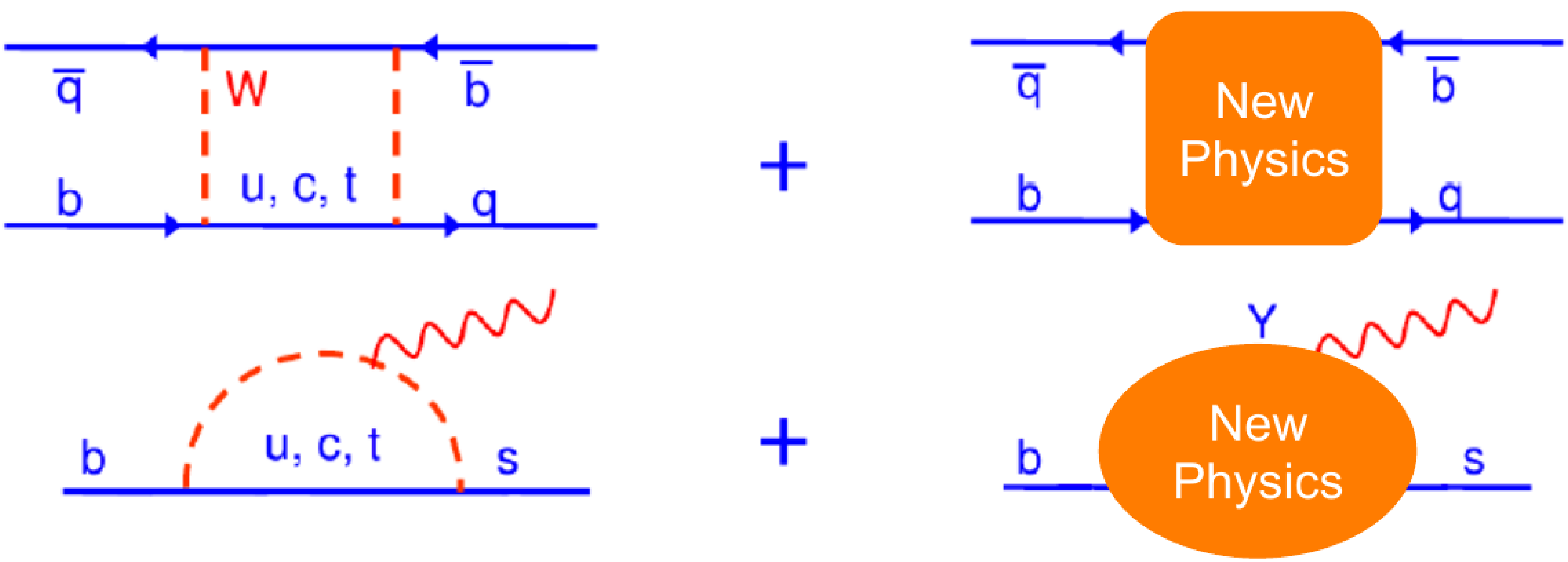
Standard Model



BSM searches with heavy flavour

Contribution to New Physics as a correction to the Standard Model

Standard Model | New Physics



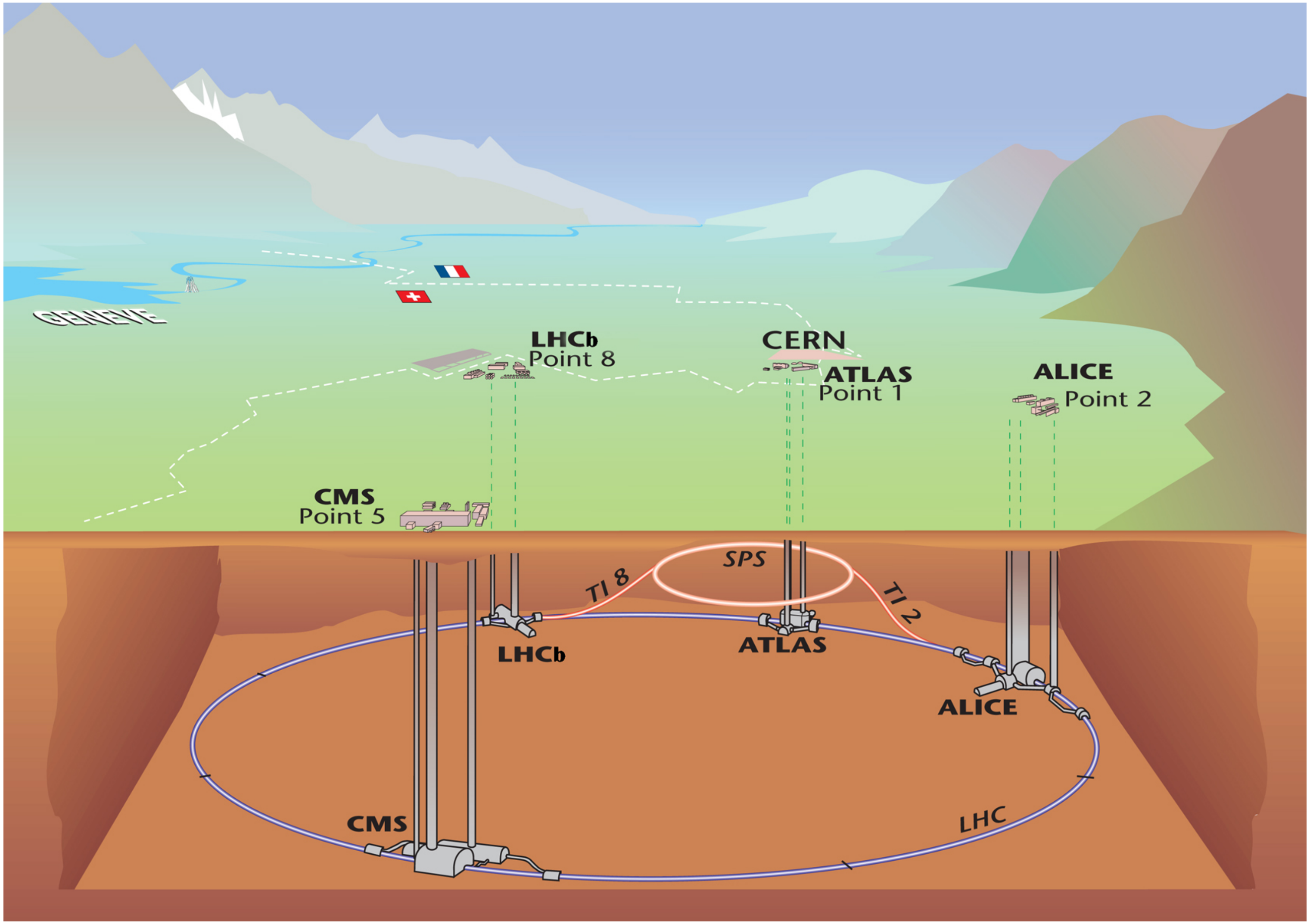
$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda^2}} \right)$$

↘ What is the scale of New Physics Λ? What are its coupling C_{NP}?

The LHCb experiment

- The LHCb detector
  and its upgrades

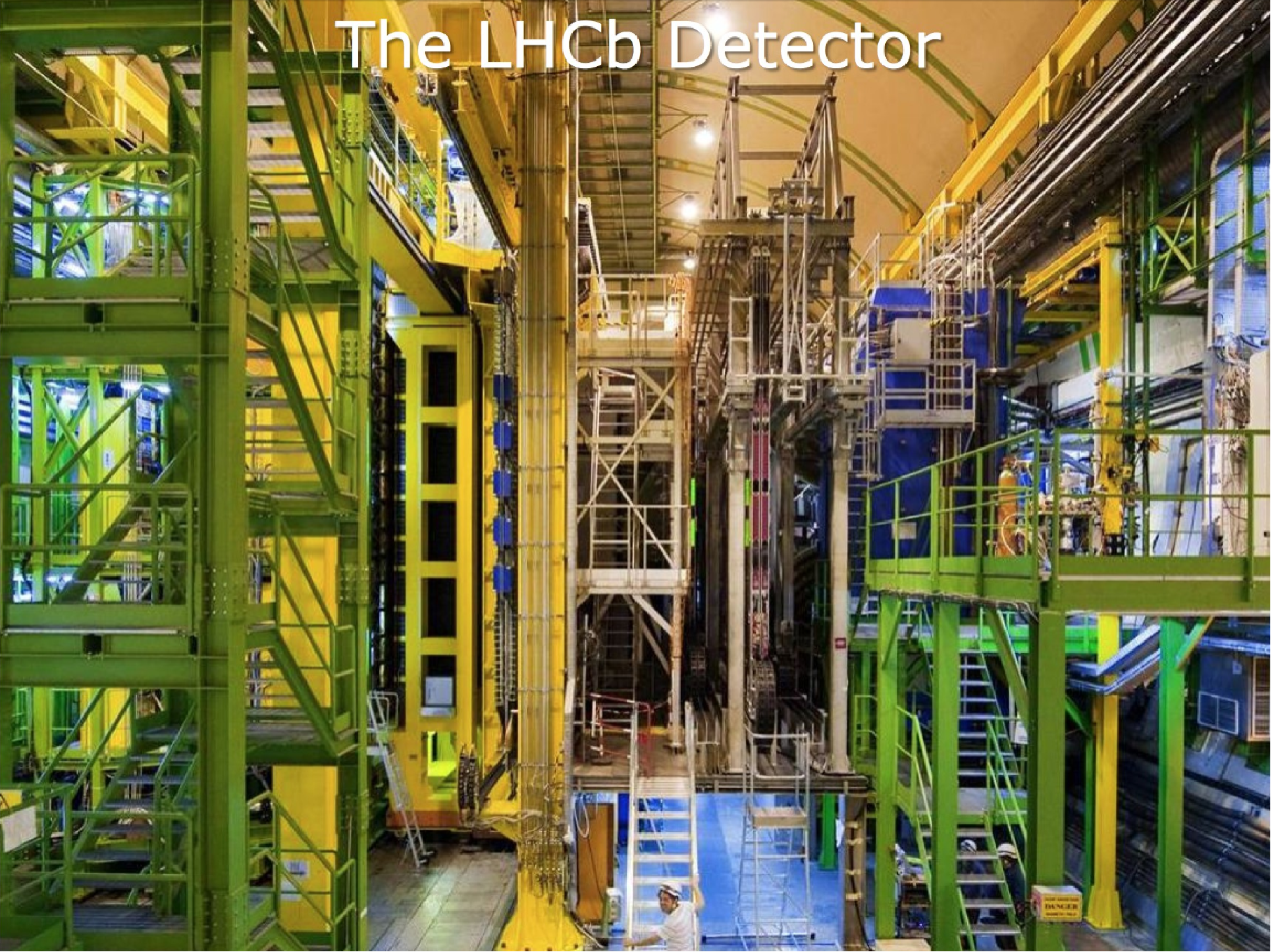
LHCb @ LHC



One of the 4 main LHC experiments

↘ Designed for heavy flavour physics precision measurements

The LHCb Detector



The LHCb collaboration

934 members
65 institutes
17 countries

Beauty and Charm production at the LHC

LHC is a Flavor Factory, e.g. @ 7 TeV :

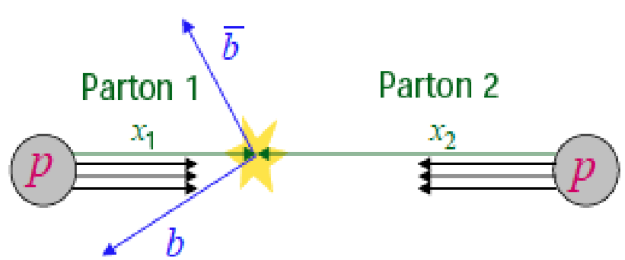
- $\sigma(pp \rightarrow c\bar{c}\ X) = \sim 6$ mb [LHCb-CONF-2010-013]
- $\sigma(pp \rightarrow b\bar{b}\ X) = \sim 0.3$ mb [PLB 694 (2010) 209]
  - → note : the cross section grows lineraly with the energy
- B factories : $\sigma(e^+e^- \rightarrow b\bar{b})@\Upsilon(4S) = \sim 1$ nb

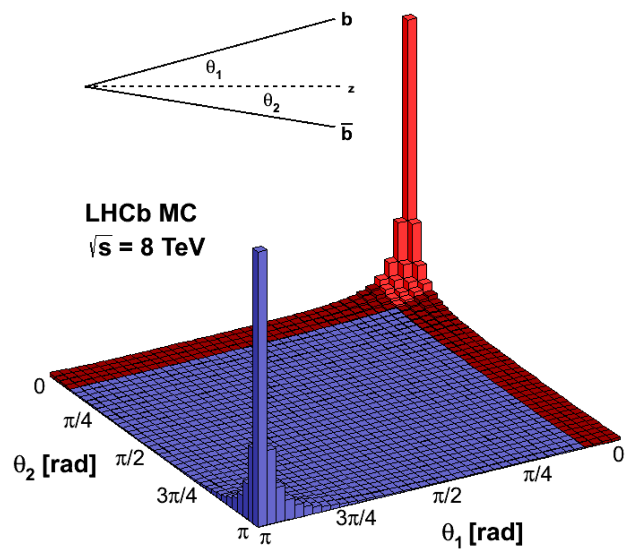
Challenging background condition :

- $\sigma(pp \rightarrow X)_{inel} = 60$ mb [JINST 7 (2012) P01010]

All B hadron species are produced : B^0, B_s, B_c, ...

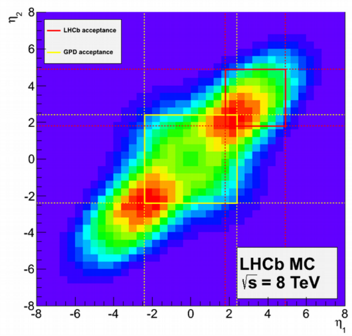
bb/cc pairs are produced predominantly
in the forward or backward directions



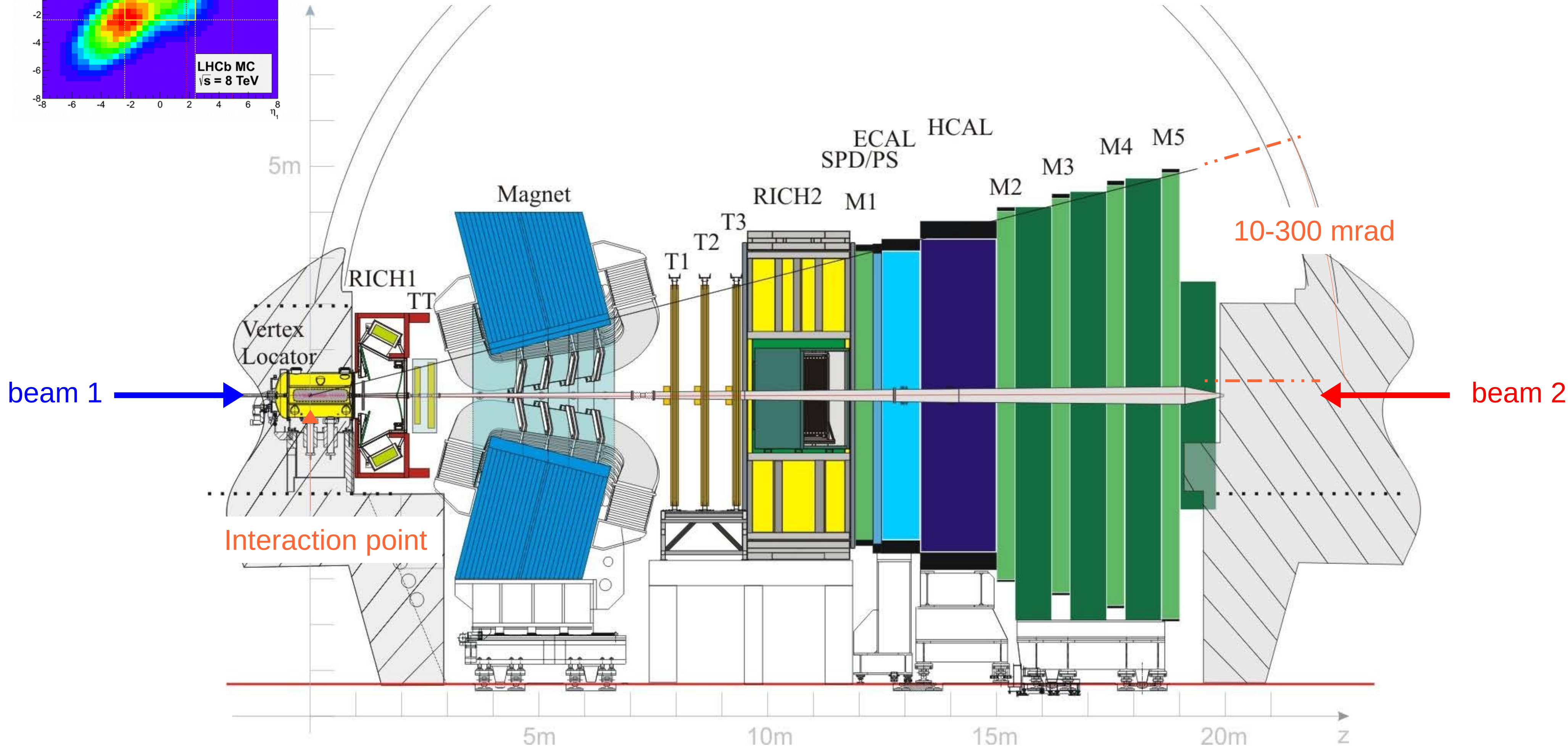


A forward spectrometer (1/2)

B forward-peaked production

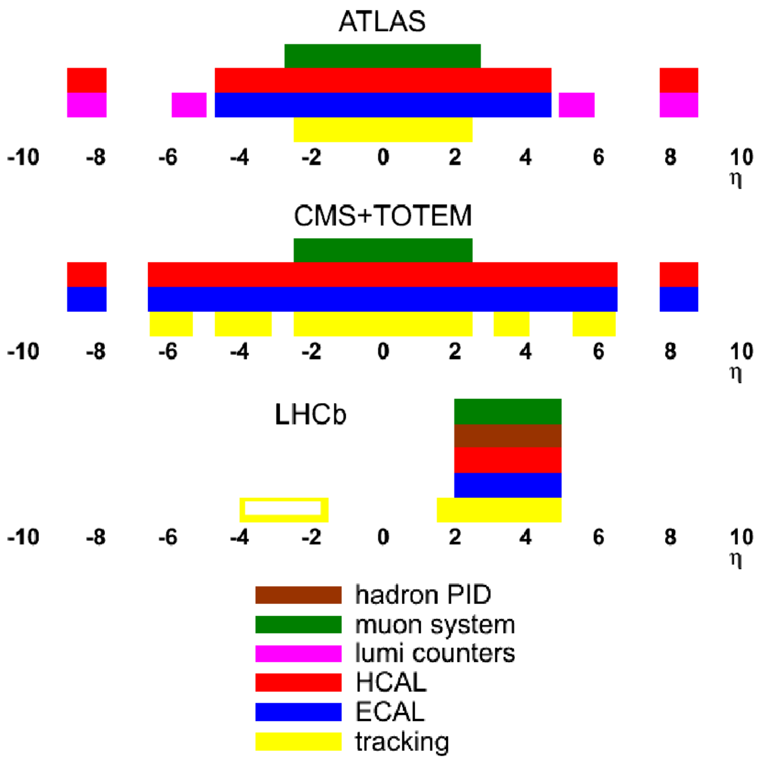


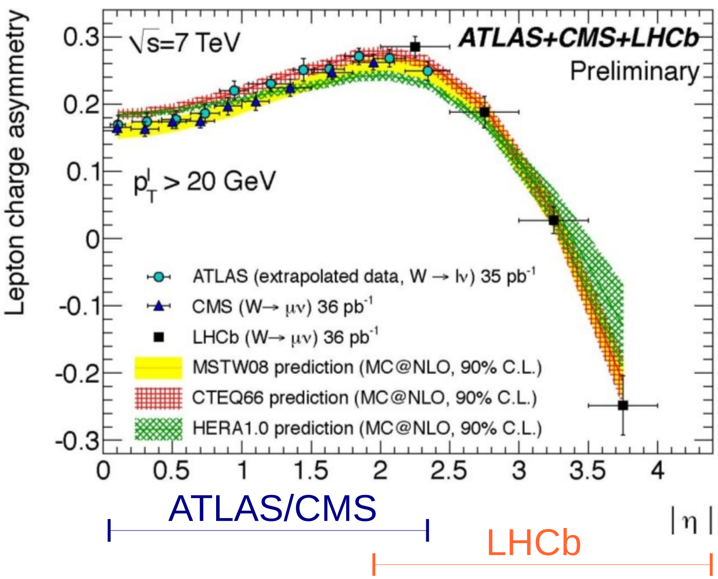
LHCb is a forward spectrometer (operating in collider mode)



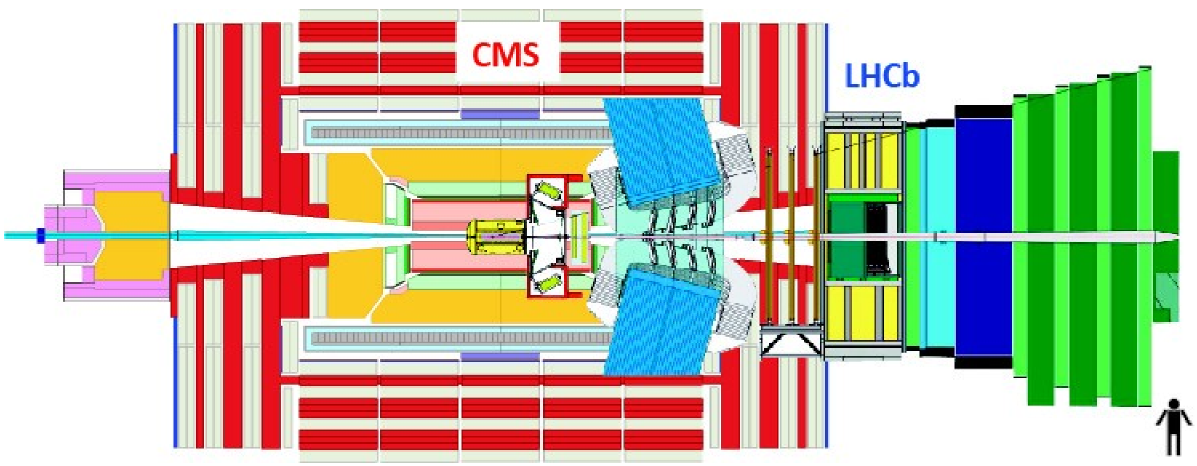
A forward spectrometer (2/2)

With unique rapidity coverage at LHC → complementary measurements

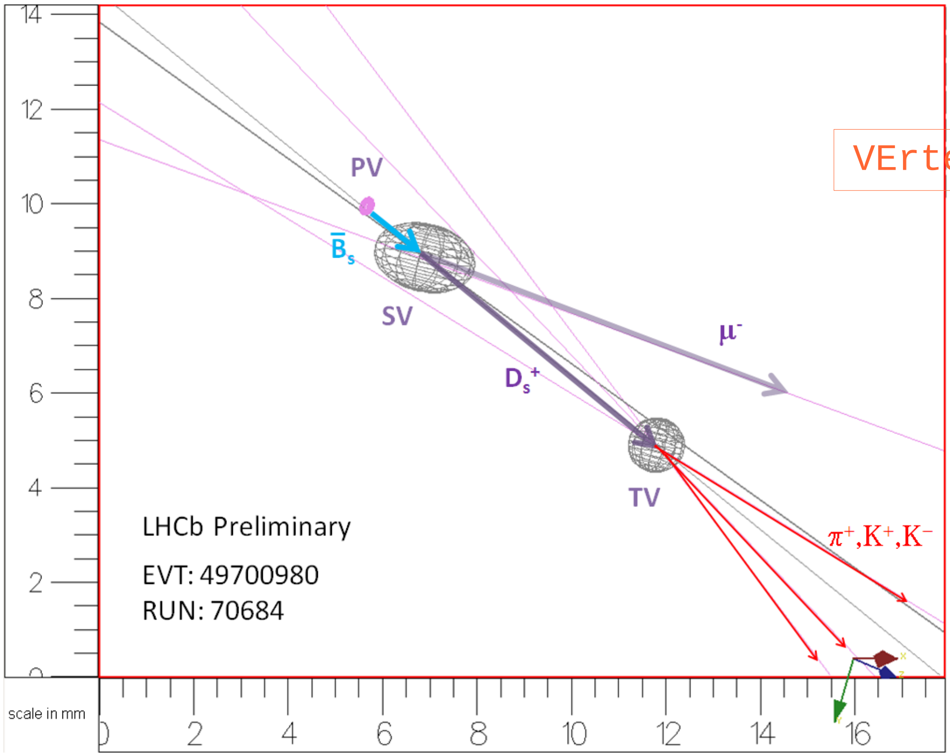


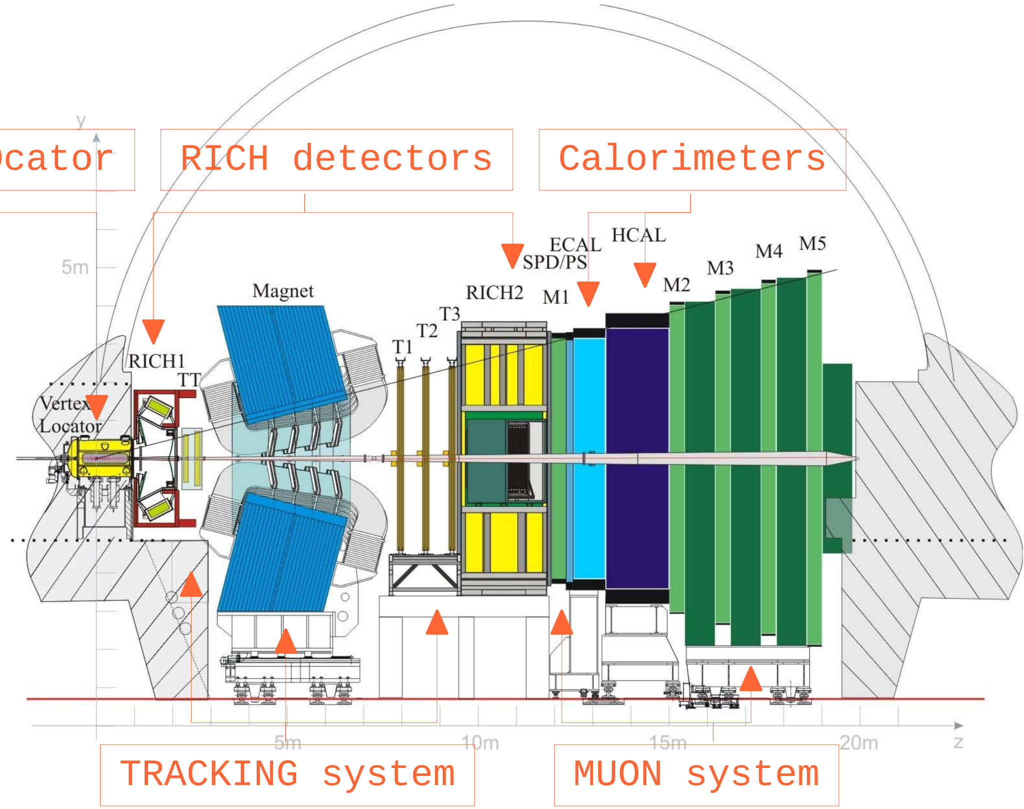


- LHCb acceptance : $2 < \eta < 5$
- fully covered by tracking and particle identification



A forward spectrometer optimised for heavy flavors





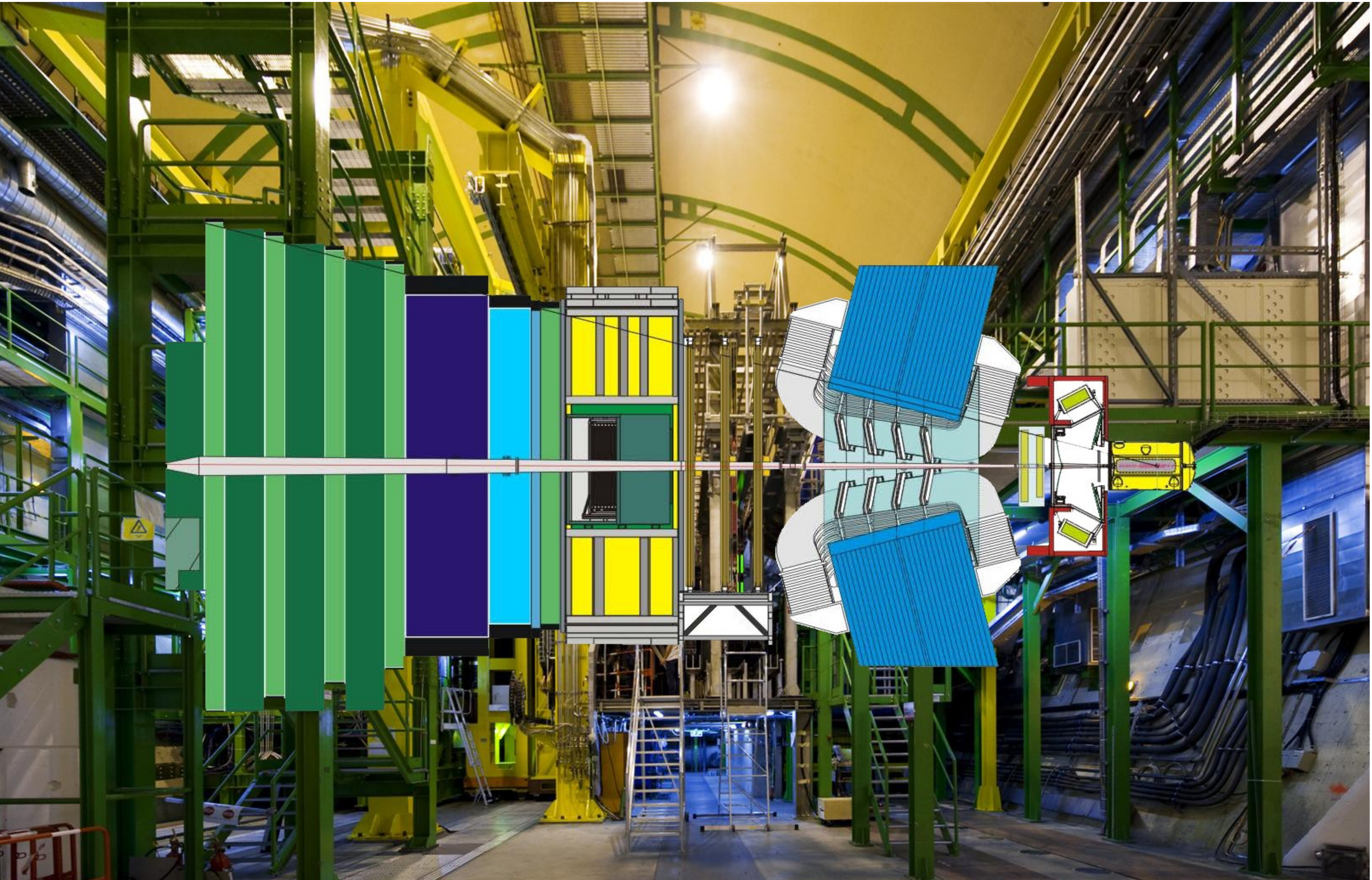
Key requirements

- B and D decay identification and resolve fast B_s oscillation
- Final state reconstruction and background rejection
- collect high statistic

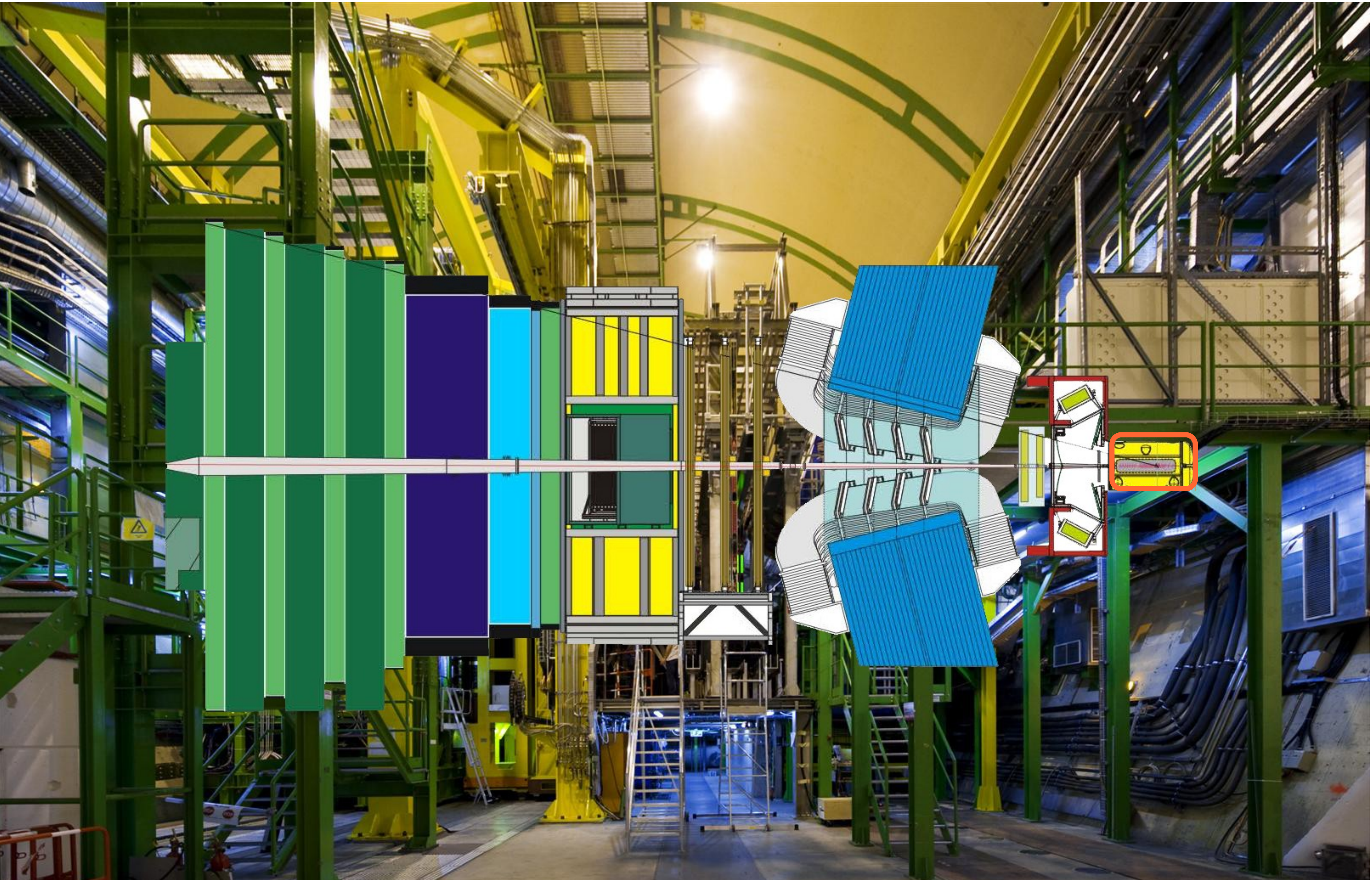
Detector design :

- High precision vertexing and tracking
  - VELO, TRACKING system
- Particle identification
  - RICH, CALO + MUON system
- Trigger
  - L0 (hardware) + HLT (software)

LHCb detector

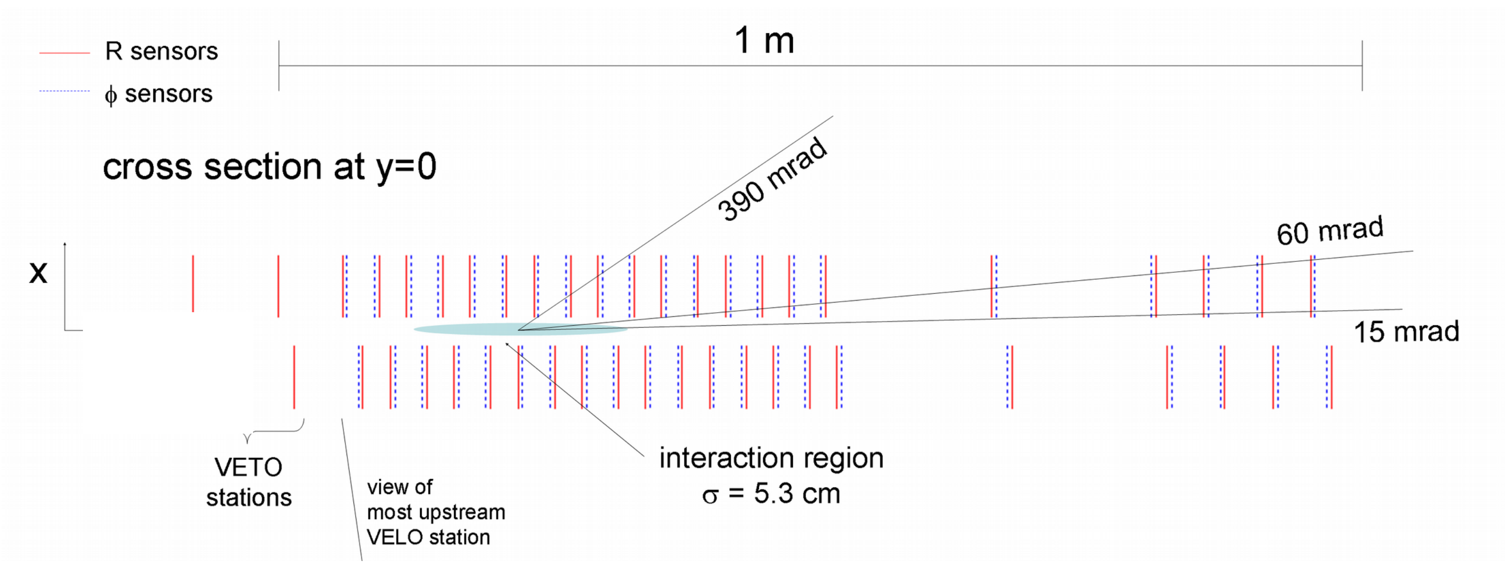


The VErtex LOcator (VELO) (0/3)



The VErtex LOcator (VELO) (1/3)

Reconstruction of primary and decay vertices, track seeds

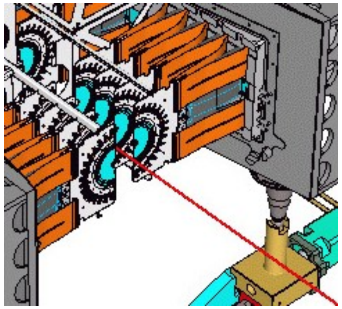


21 modules of R-Φ sensors

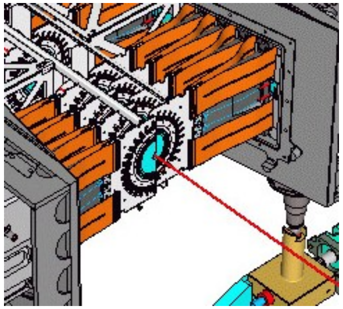
Movable device (retracted for safety during beam injection) :

- 35 mm from beam out of physics
- **8 mm from beam during physics**

Operated in vacuum

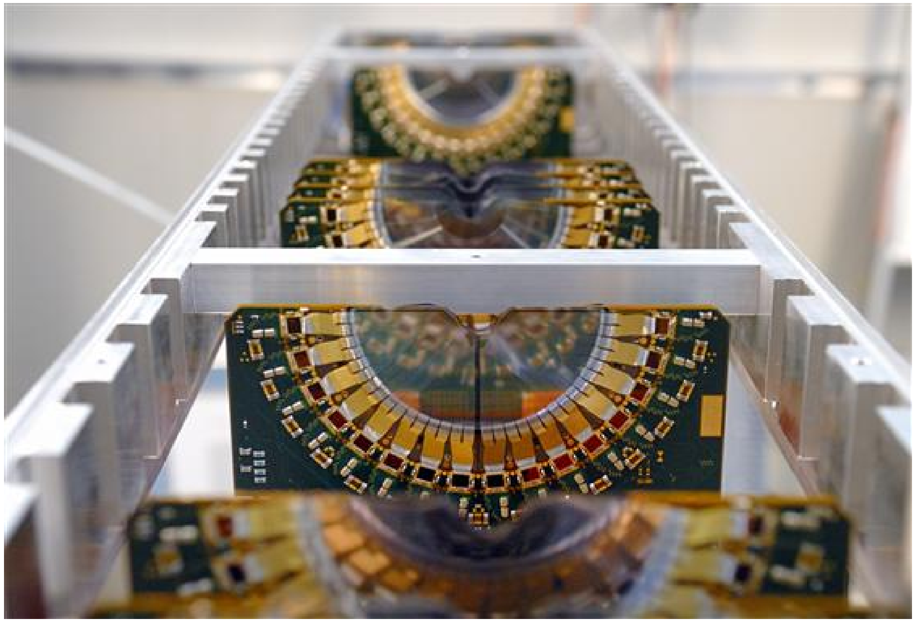


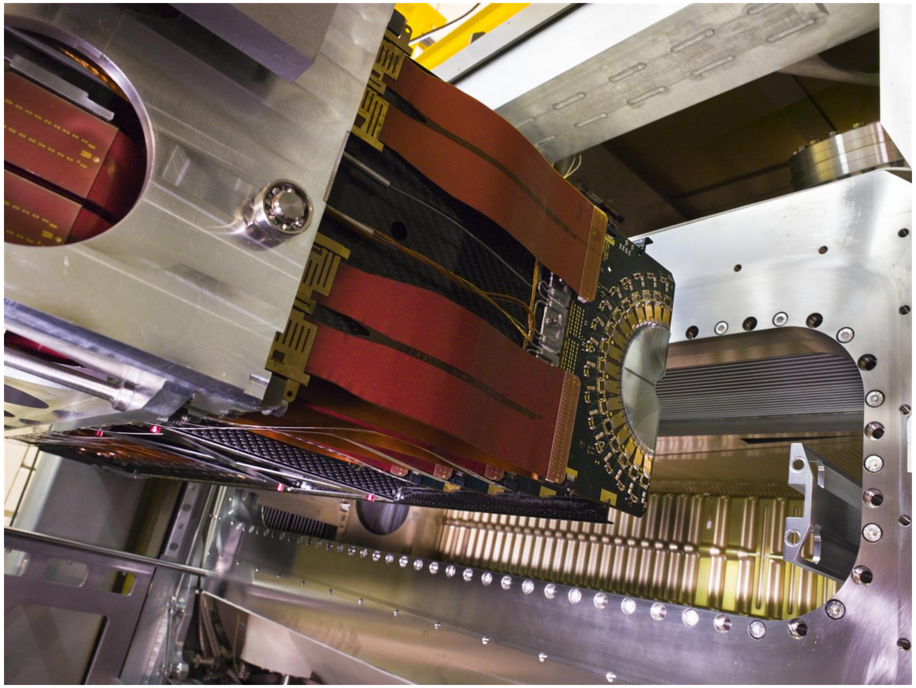
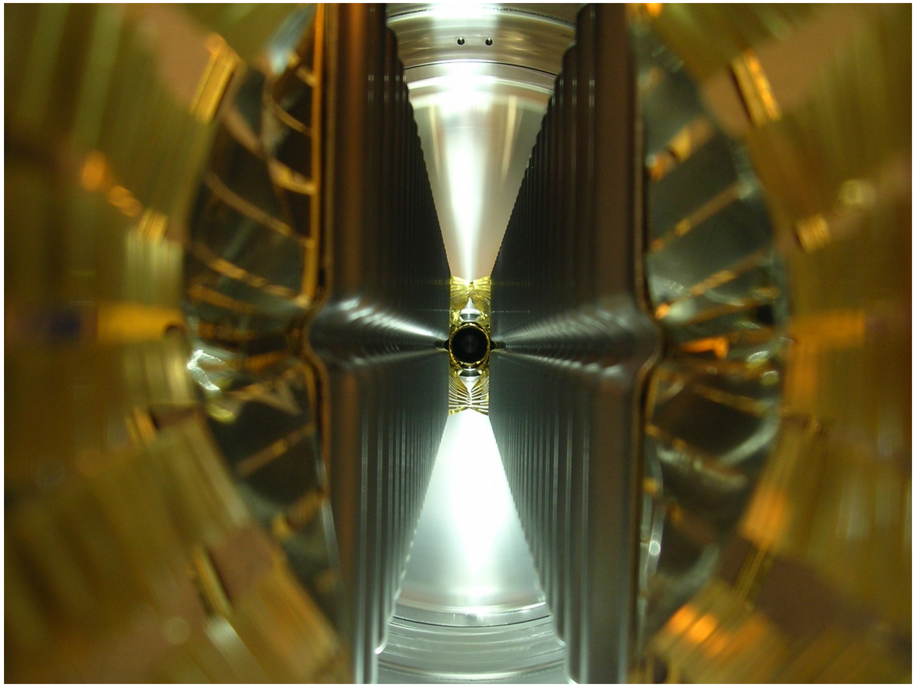
OPEN



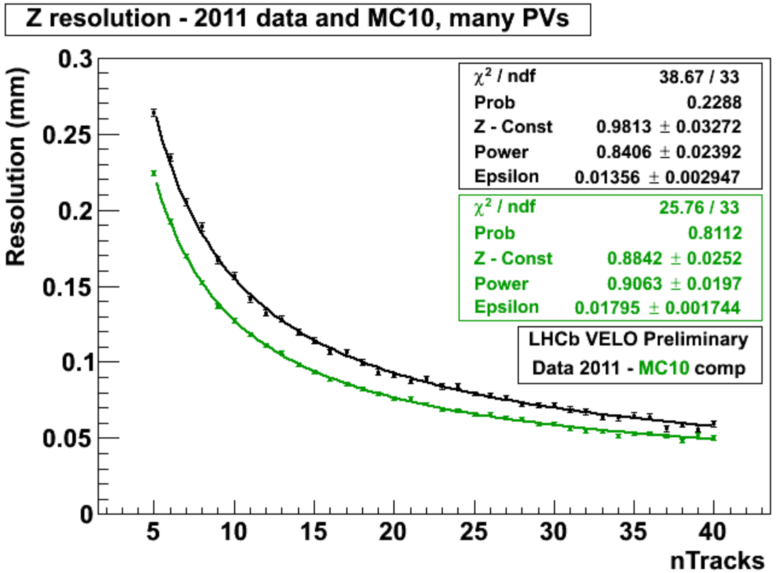
CLOSE

The VErtex LOcator (VELO) (2/3)

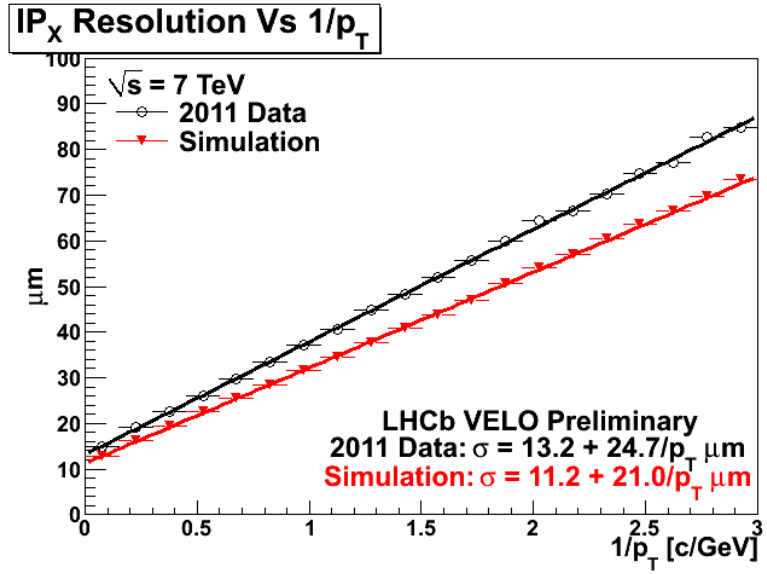


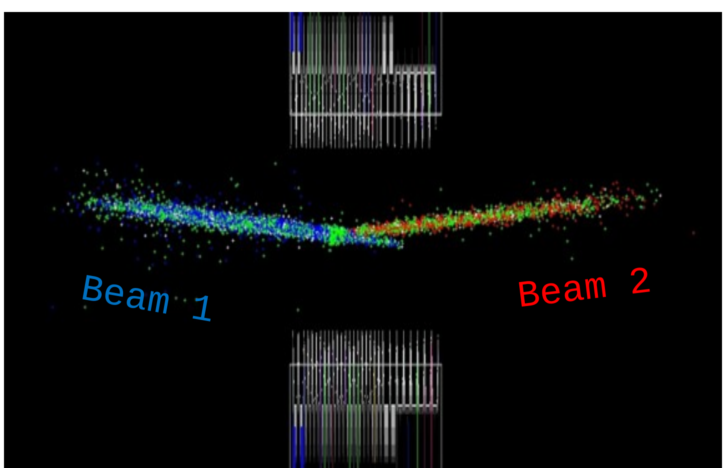
The VErtex LOcator (VELO) (3/3)



For 25 tracks : $\sigma_X \approx \sigma_Y \approx 16$ µm, $\sigma_Z \approx 76$ µm

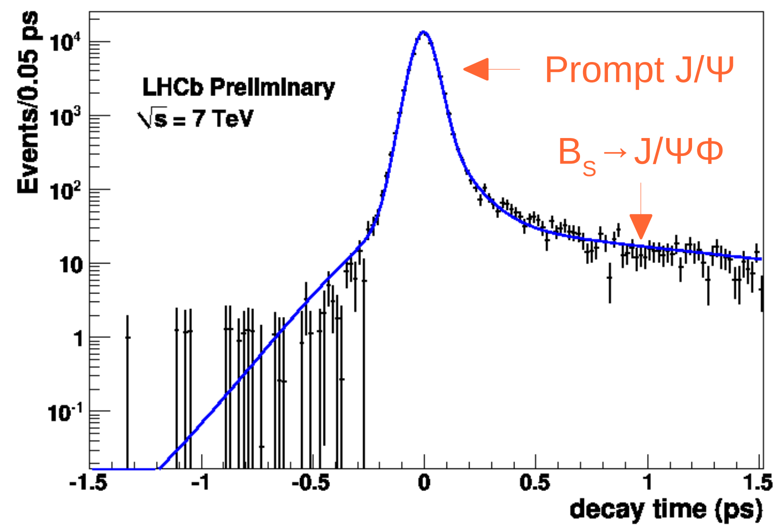


Impact parameter resolution
for high p_T track : ~ 20 µm



Reconstructed beam-gaz vertices
(used for luminosity measurement)

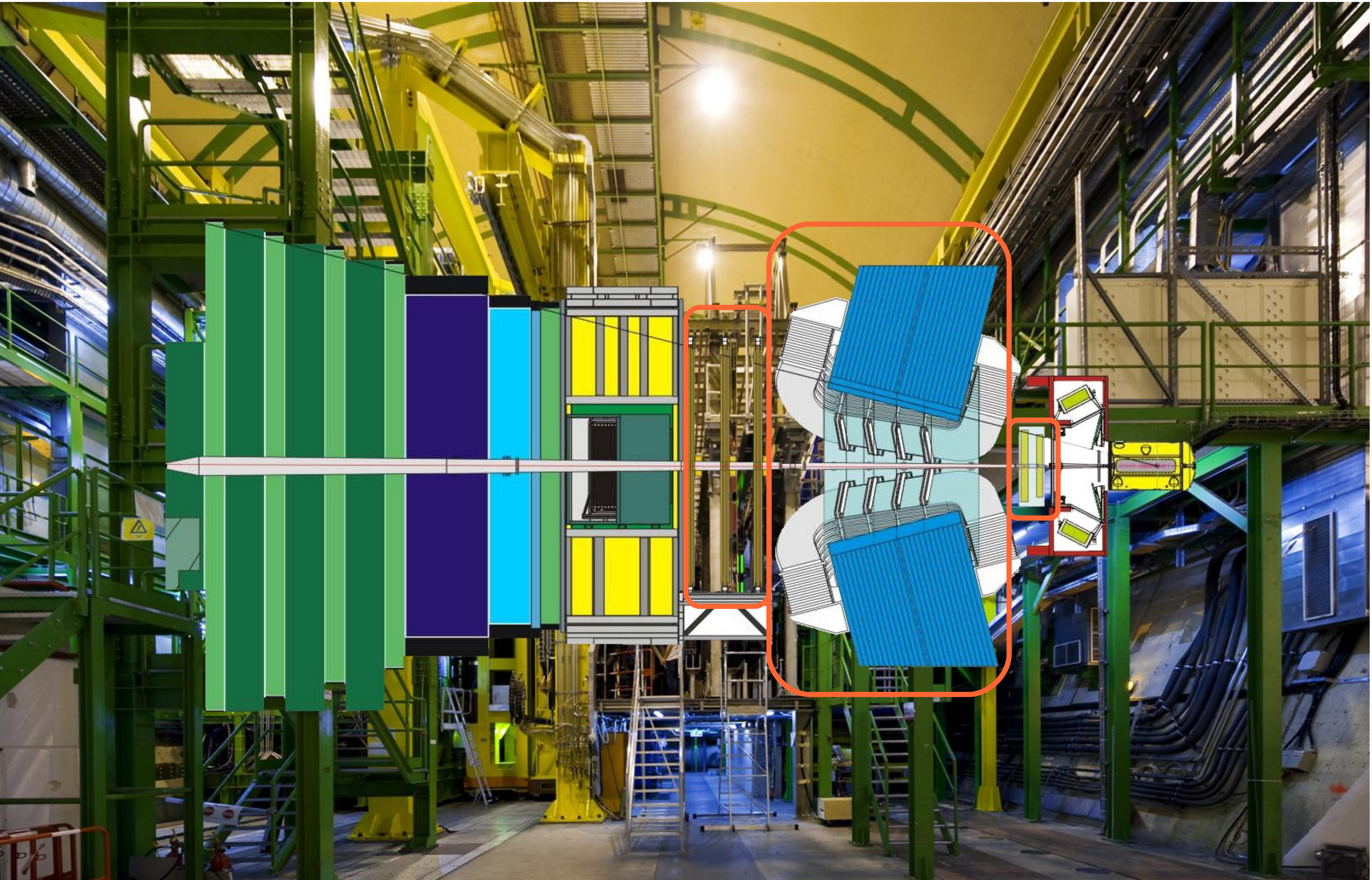
[PLB **693** 69]



Proper time resolution : σ_t = ~ 45 fs
(cf. $\lambda = 2\pi/\Delta m_s$ ~350 fs)

[CONF-2012-002]

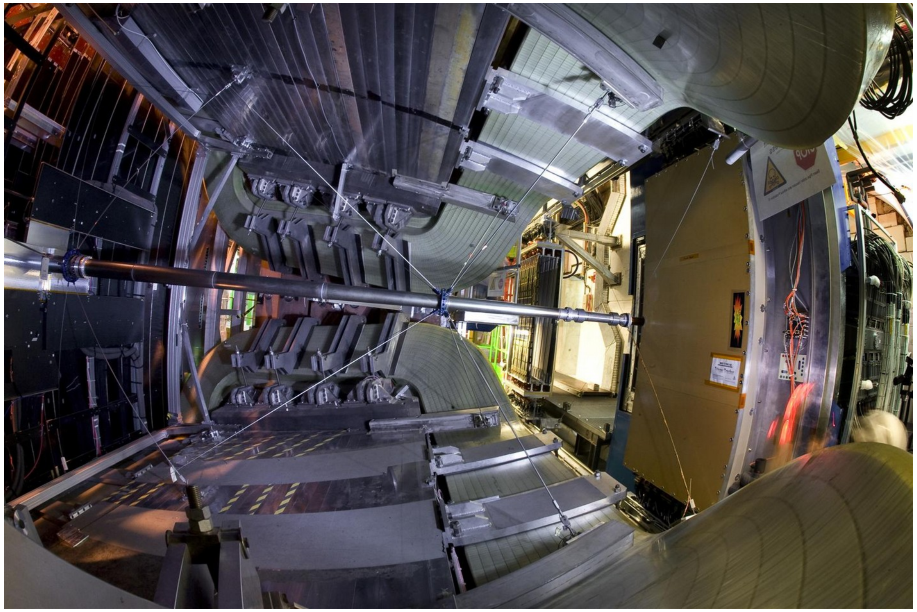
The Tracking System (0/2)



The Tracking System (1/2)

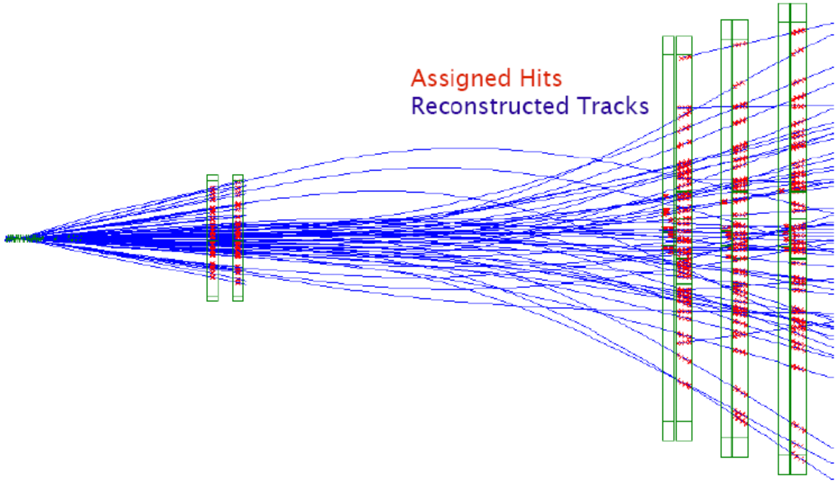
System :

- 1 tracking station before magnet (TT) :
  - → 4 layers of Si-Strips sensors
- Magnet
  - → ∫Bdl = ~ 4 Tm ; polarity switched regularly
- 3 tracking stations after magnet, 4 layers each split into:
  - → Inner Tracker (Si-sensors)
  - → Outer Tracker (straw tube)



Track finding :

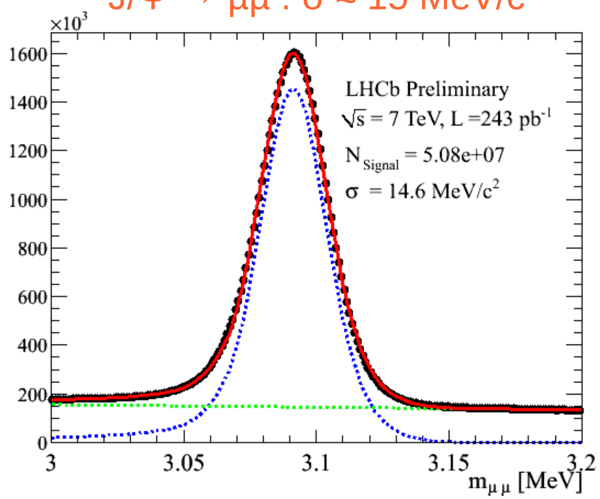
- Long tracks : high-momentum tracks traversing the full LHCb tracking setup
  - → combine track seeds in VELO and T-stations and add TT hits
  - → measured with highest precision
  - → most numerous in the main LHCb acceptance



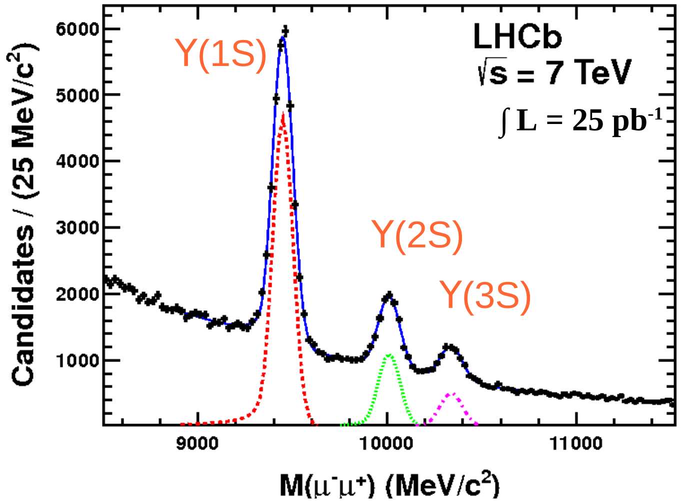
The Tracking System (2/2)

Momentum resolution : σ(p)/p = 0.4-0.6% (5-100 GeV/c)

$J/\Psi \rightarrow \mu\mu$: $\sigma \approx 15$ MeV/c²

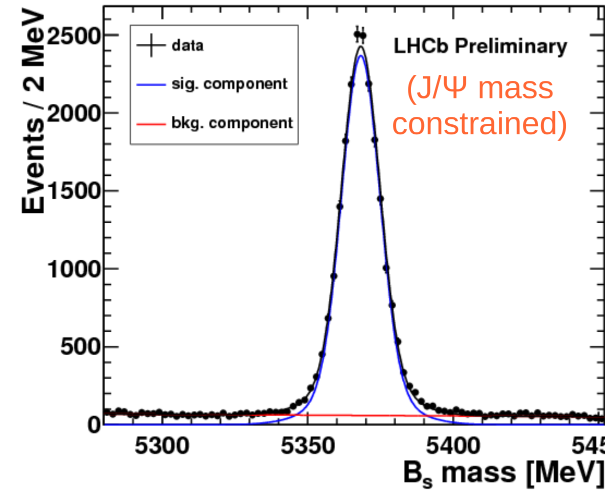


$\Upsilon(1S) \rightarrow \mu\mu$: $\sigma \approx 54$ MeV/c²



[Eur.Phys. J. C, (72),6]

$B_s \rightarrow J/\Psi\Phi$: $\sigma \approx 8$ MeV/c²



[CONF-2012-002]

cf. [CMS DPS-2010-040] ~ 16 MeV/c²
[ATLAS CONF-2011-050] ~ 22 MeV/c²

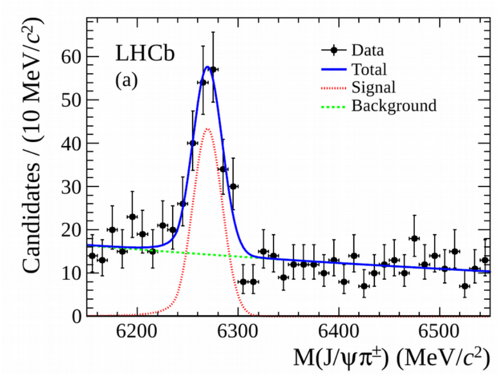
Momentum scale and detector alignment well controlled :

B hadron mass world's best measurements (2010 data only, 37pb⁻¹)

Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(B^+)$	5279.38 ± 0.35	5279.10 ± 0.55	5279.17 ± 0.29
$M(B^0)$	5279.58 ± 0.32	5279.63 ± 0.62	5279.50 ± 0.30
$M(B^0_s)$	5366.90 ± 0.36	5366.01 ± 0.80	5366.3 ± 0.6
$M(\Lambda^0_b)$	5619.19 ± 0.76	5619.7 ± 1.7	–
$M(B^0) - M(B^+)$	0.20 ± 0.20	0.33 ± 0.06	0.33 ± 0.06
$M(B^0_s) - M(B^+)$	87.52 ± 0.32	–	–
$M(\Lambda^0_b) - M(B^+)$	339.81 ± 0.72	–	–

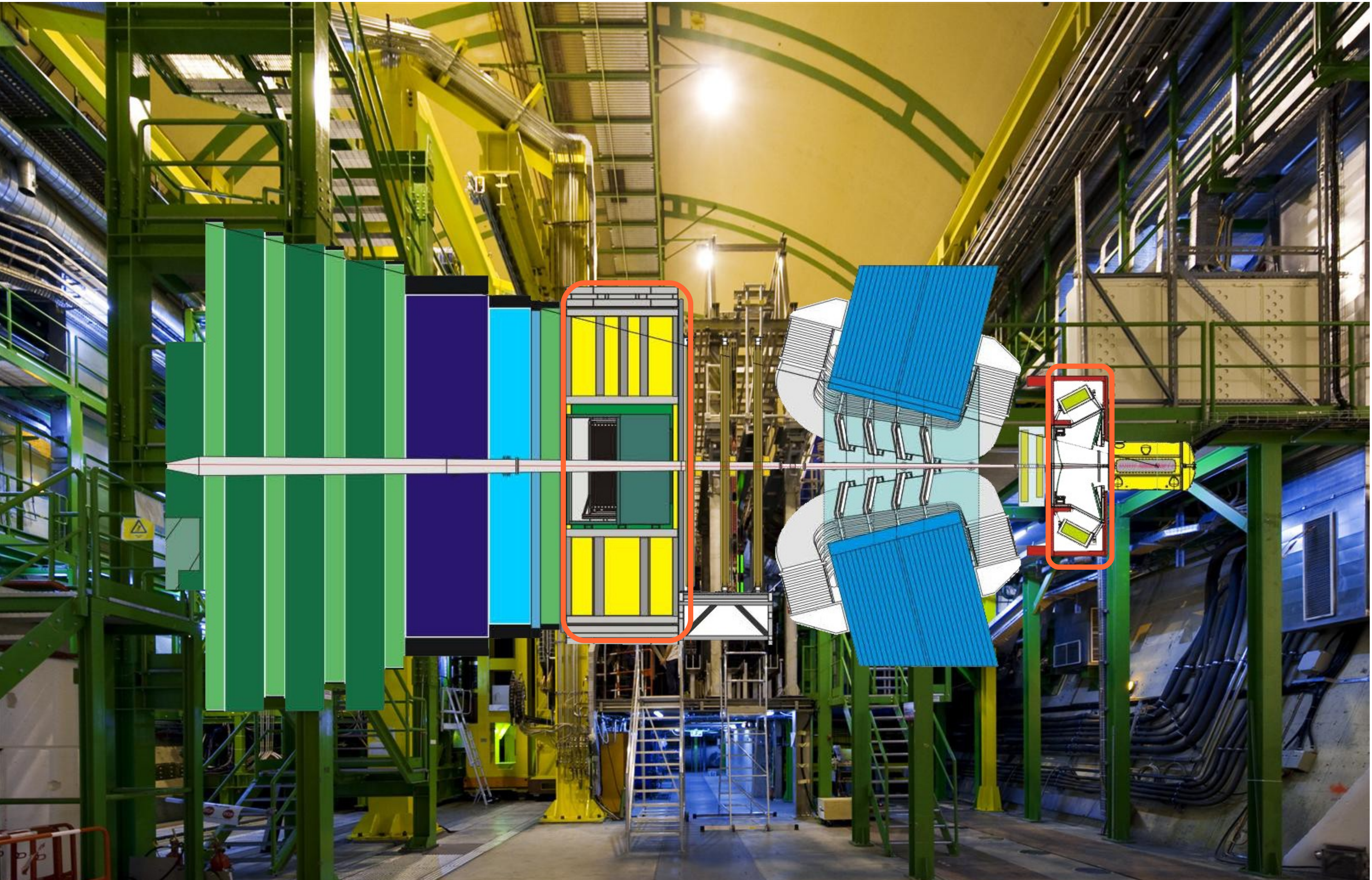
[PLB 708 (2012) 241]

B_c^+ mass also measured

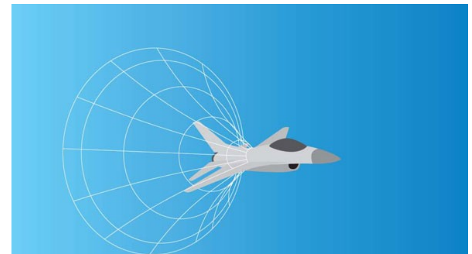


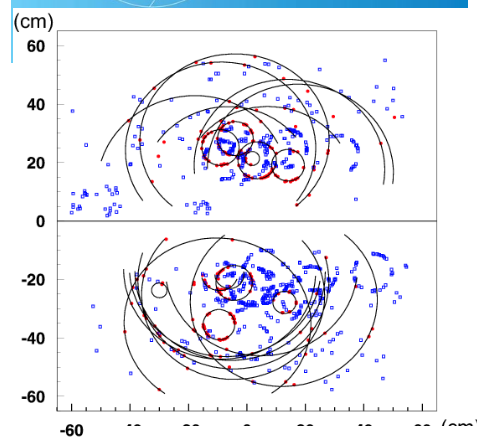
[arXiv:1209.5634]

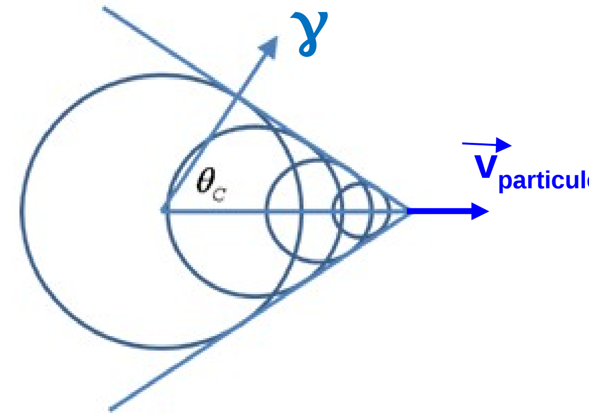
The RICH detectors (Particle Identification) (0/3)



The RICH detectors (PID) (1/3)







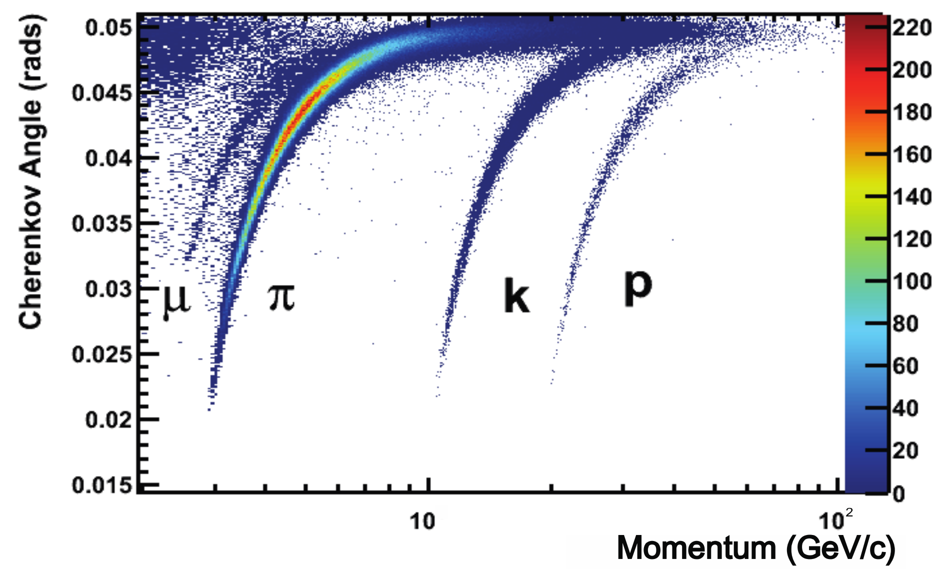
Cerenkov effect :

- Cerenfov effect : when a particle travels faster than light in a medium,

  it emits photons
- the photons are emitted in a cone with a opening angle proportional to the speed of the particle

LHCb's RICHs : Cerenkov imaging detector

- allow to identify charged hadrons

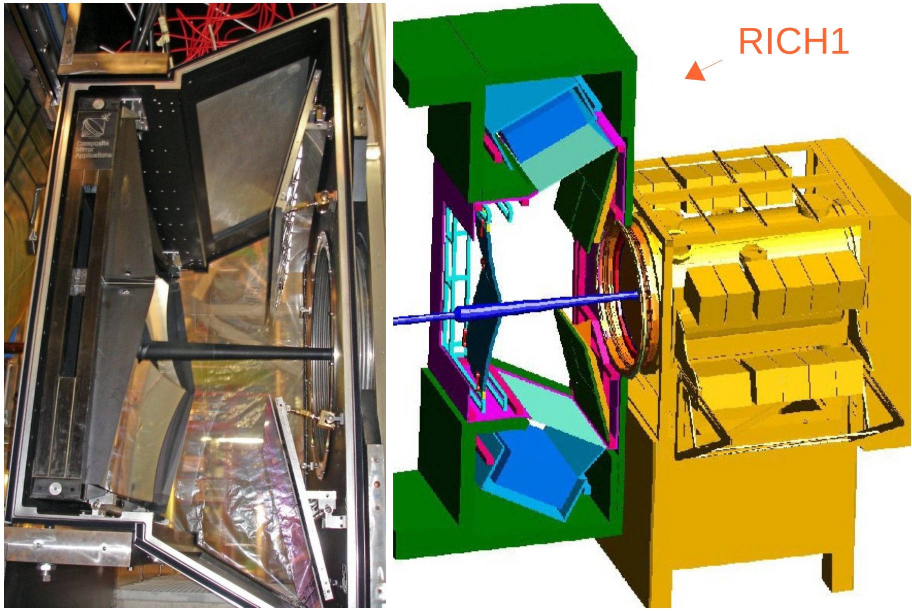


The RICH detectors (PID) (2/3)

K/π separation over the full 1-100 GeV/c range

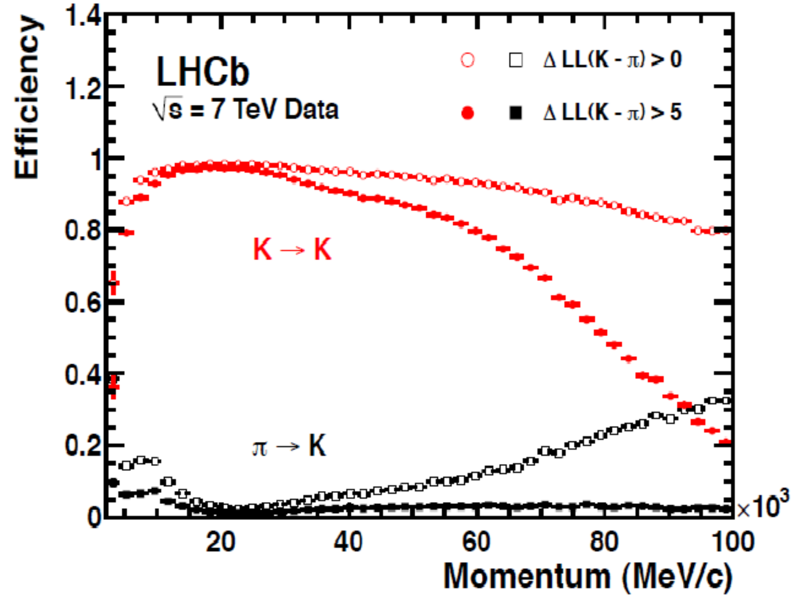
The detectors :

- RICH1 :
  - → full angular acceptance
  - → covers low momentum range : 1-60 GeV/c
  - → aerogel & C_4F_{10} radiators
- RICH2 :
  - → limited angular acceptance (~±15→~±100 mrad)
  - → high momentum range : ~15 GeV/c - > 100 GeV/c
  - → CF_4 radiator
- Hybrid Photon Detectors (HPDs)
  - → 500 each with 1024 pixels
  - → High efficiency, low noise



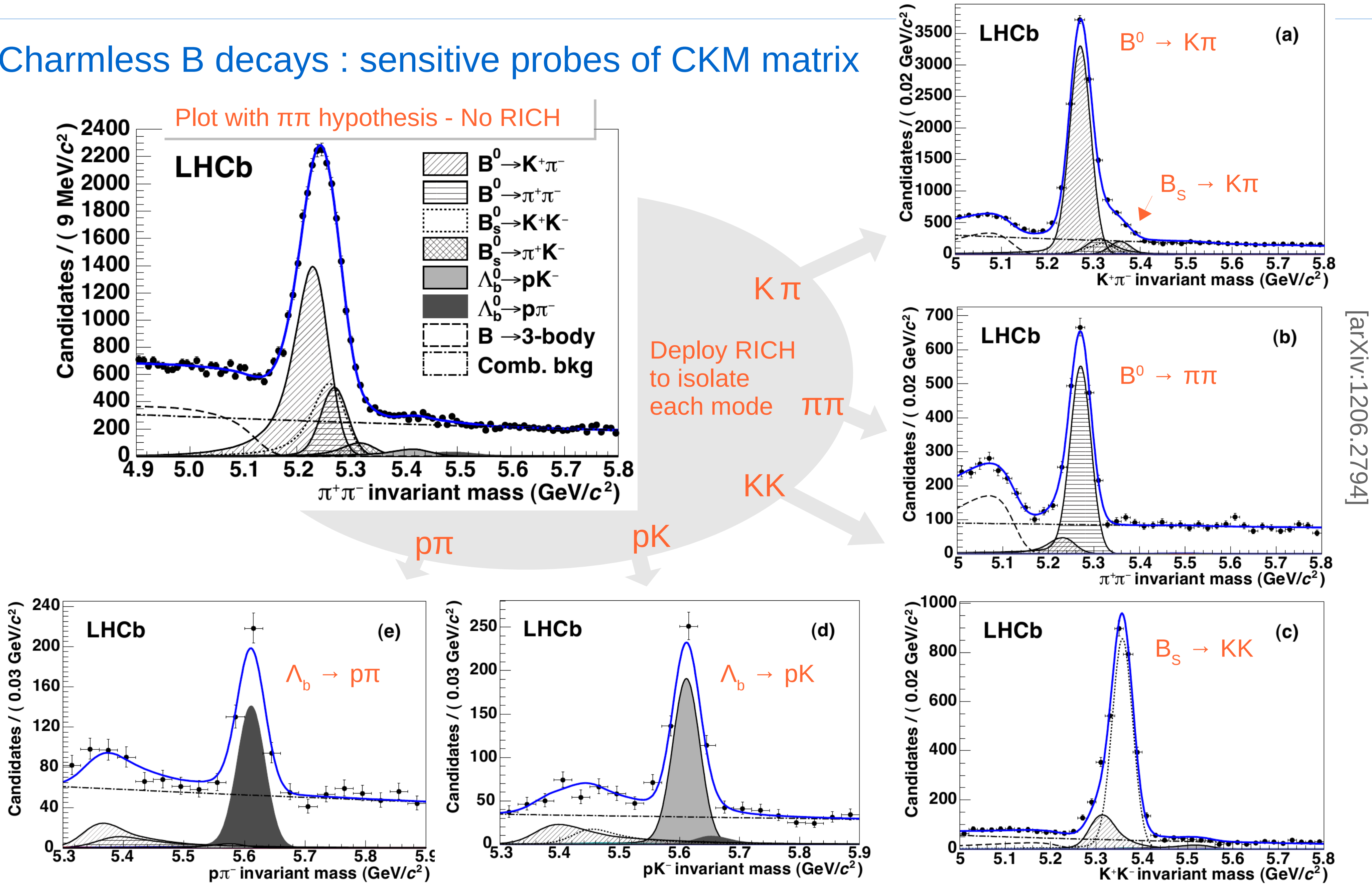
Performances

- ε ≈ 95 % for 5% π-K misID probability
- performances well described by simulation

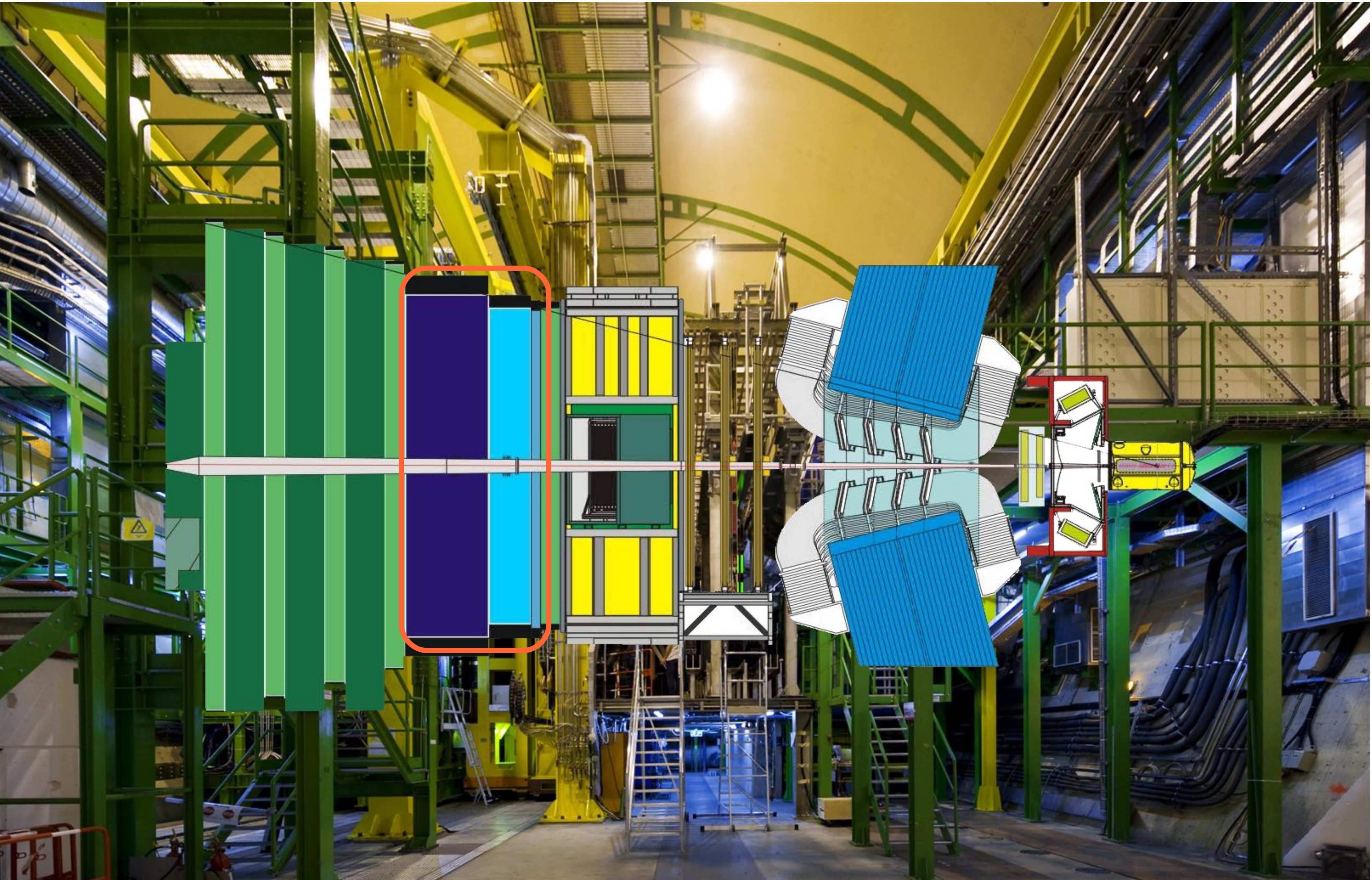


The RICH detectors (PID) (3/3)

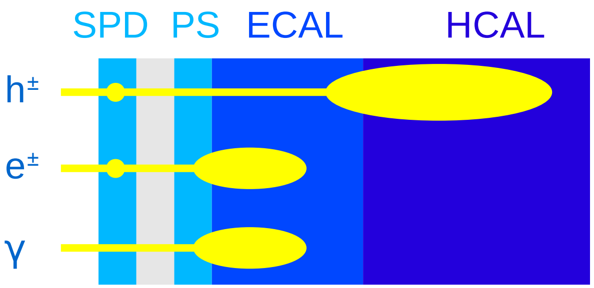
Charmless B decays : sensitive probes of CKM matrix

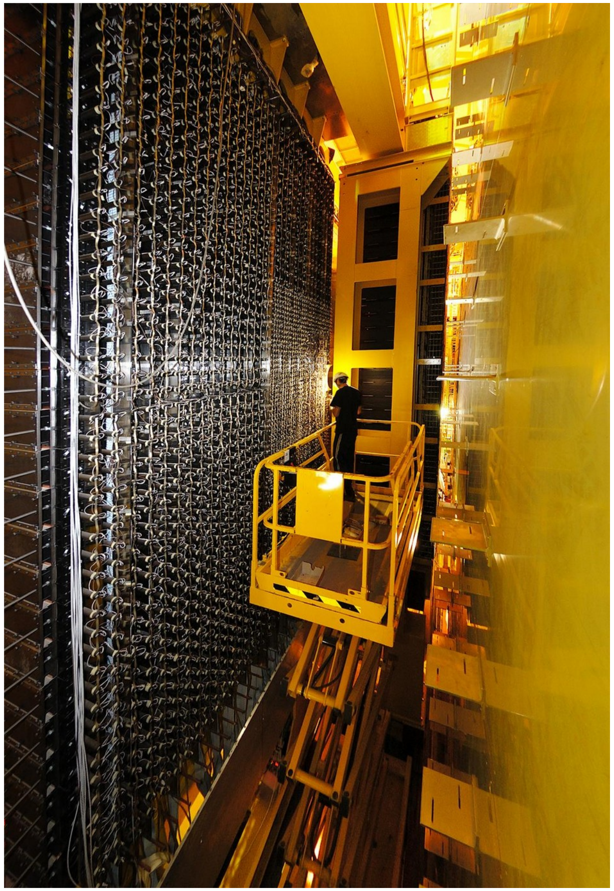


The Calorimeters (Particle Identification) (0/2)



The Calorimeters (Particle Identification) (1/2)





The ECAL detector

Scintillator Pad Detector / PreShower :

- robust e/γ and e/hadron separation
- single layer scintillator tiles separated by Pb sheet (2.5 X_0)
- $\varepsilon(e^{\pm})$ = 90% for 5% e-hadron MisID

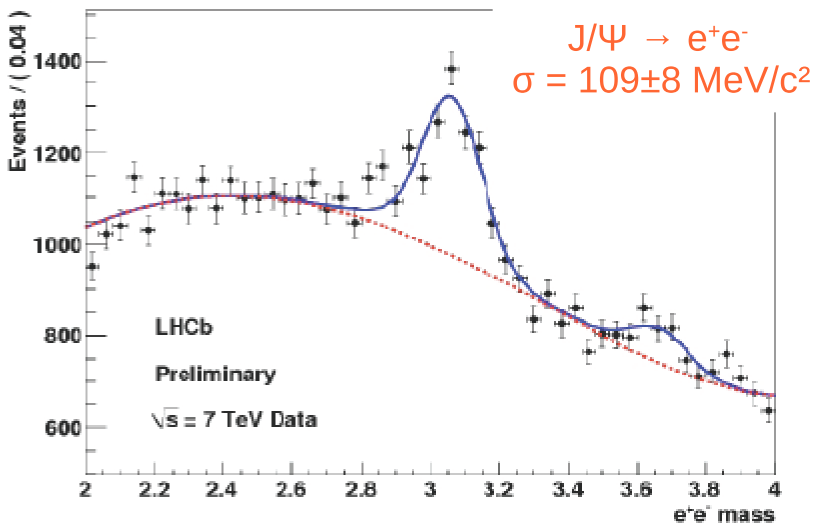
Electromagnetic CALorimeter :

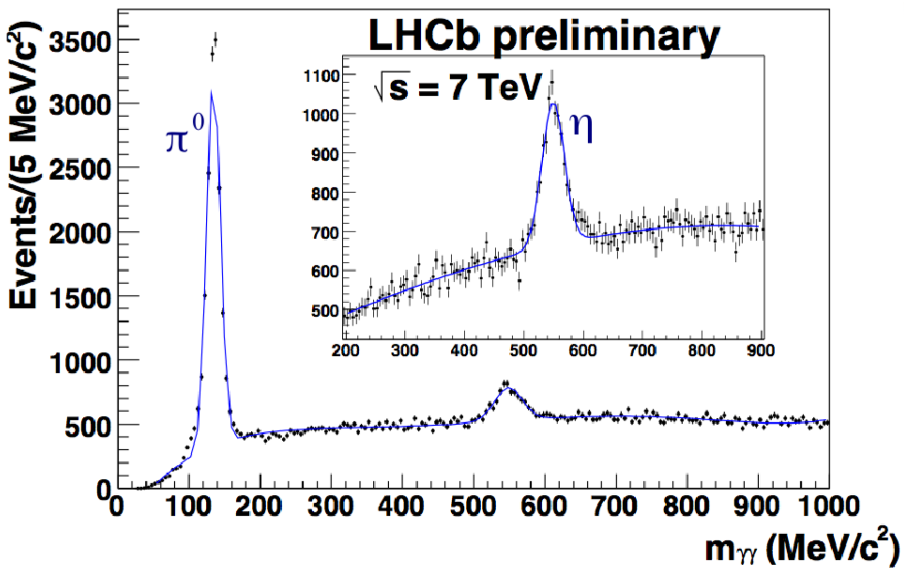
- e and γ energy measurement
- trigger on electromagnetic decay channels
- Pb plates / scintillator tiles (25 X_0)
- $\sigma(E)/E = 10\%/\sqrt{E(\text{GeV})} + 1\%$ (nominal)

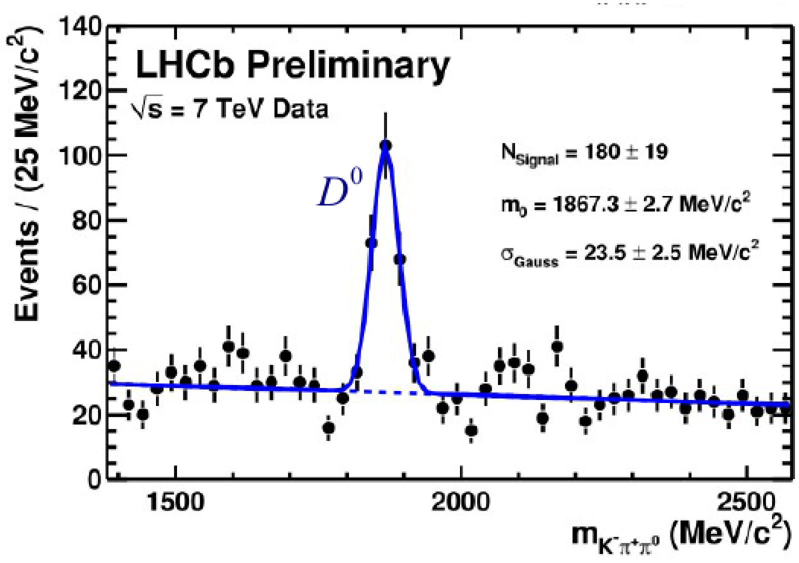
Hadronic CALorimeter :

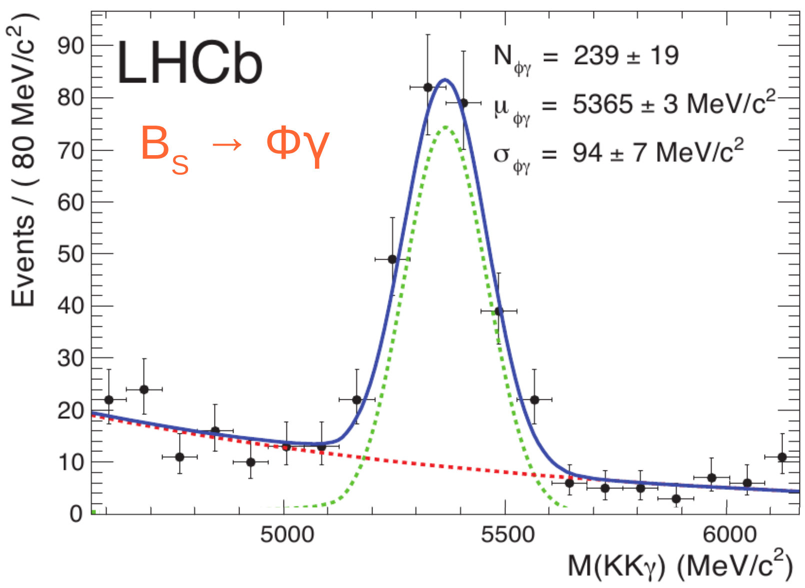
- energy measurement for hadron
- trigger on hadronic decay channels
- Fe plates / scintillator tiles
- $\sigma(E)/E = 69\%/\sqrt{E(\text{GeV})} + 9\%$ (nominal), moderate but enough for triggering

The Calorimeters (Particle Identification) (2/2)



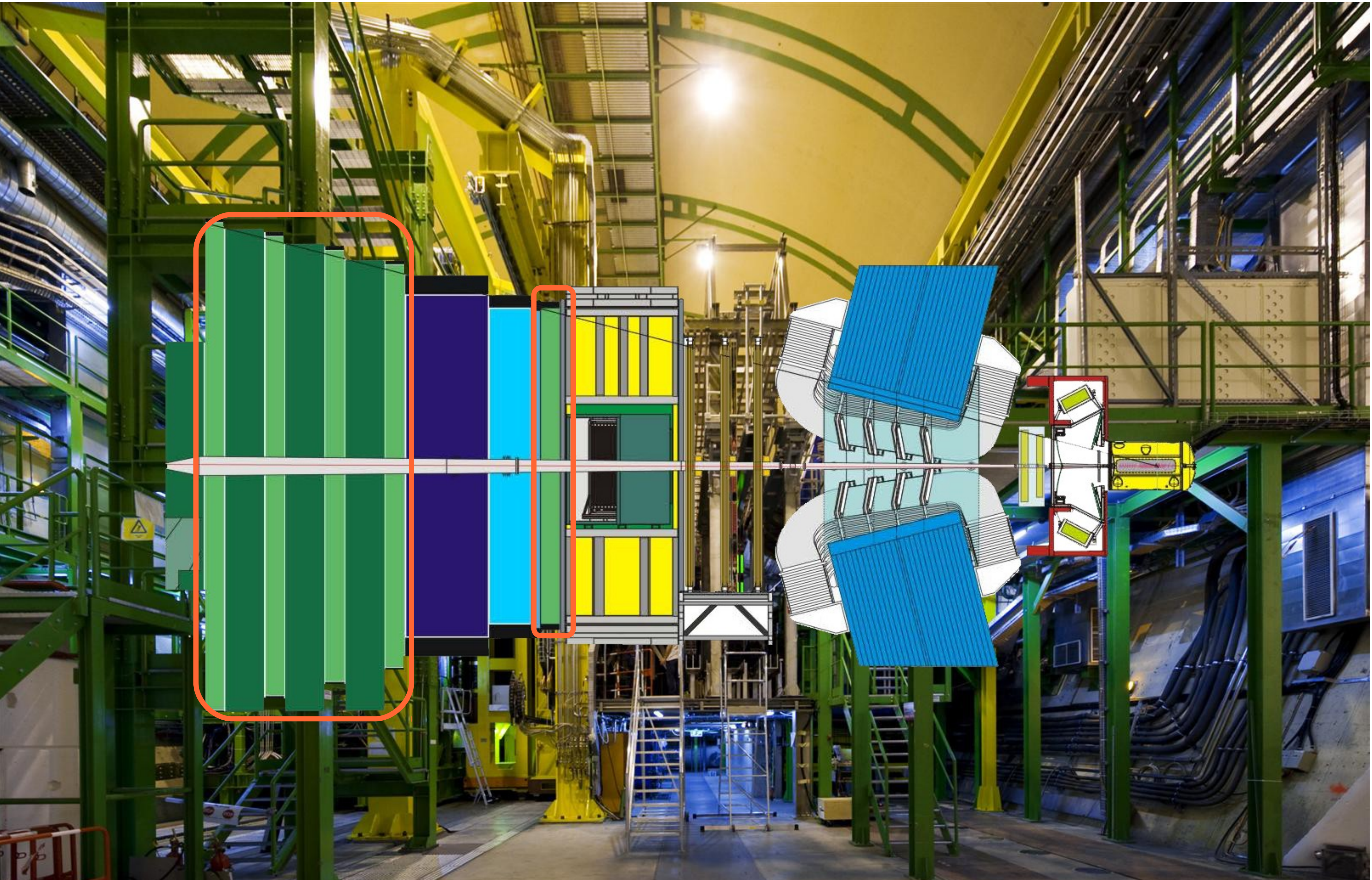






[arXiv:1202.6267]

The Muon system (Particle Identification) (0/1)

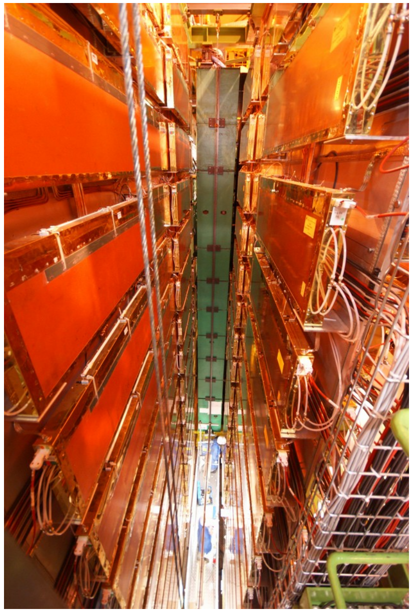


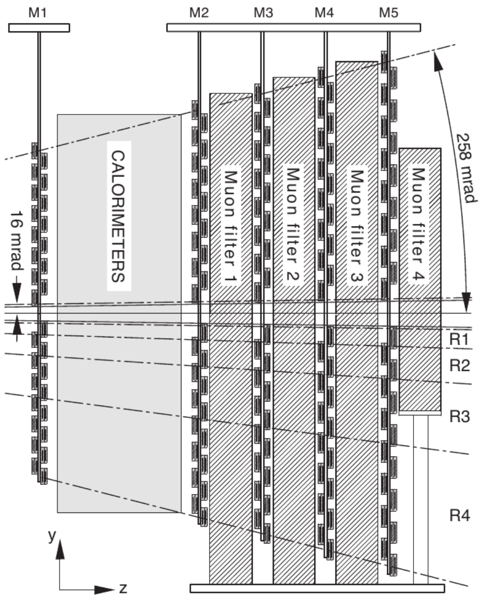
The Muon system (Particle Identification) (1/1)

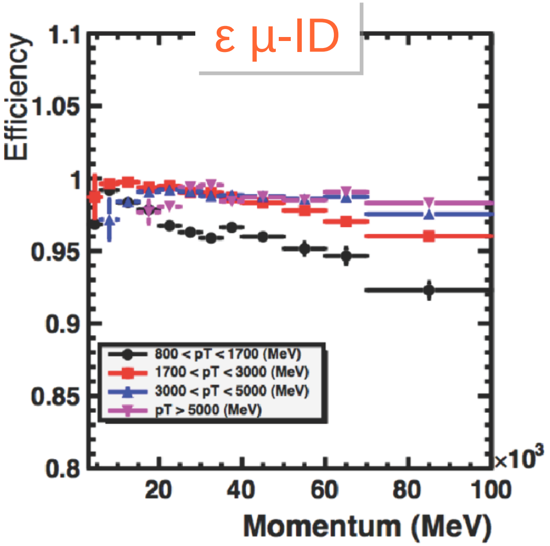
5 stations interleaved with iron absorbers

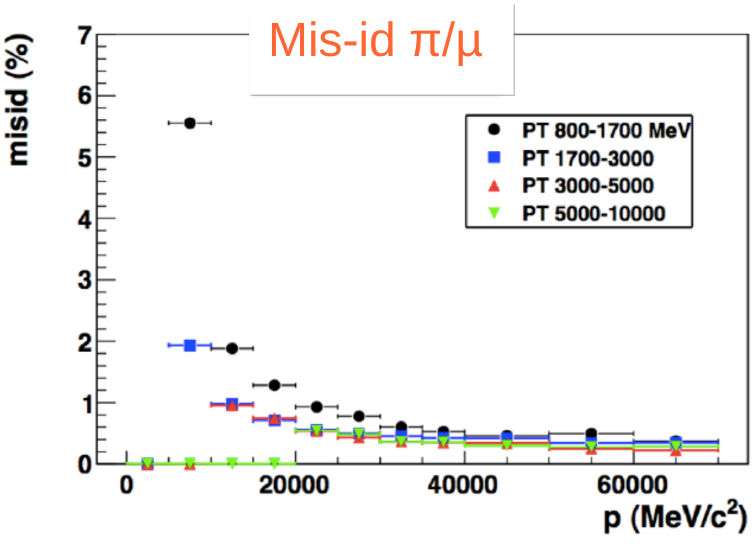
- → muon identification
- → trigger on muonic decay channels
- → Muon ID ε(μ) = 97 %

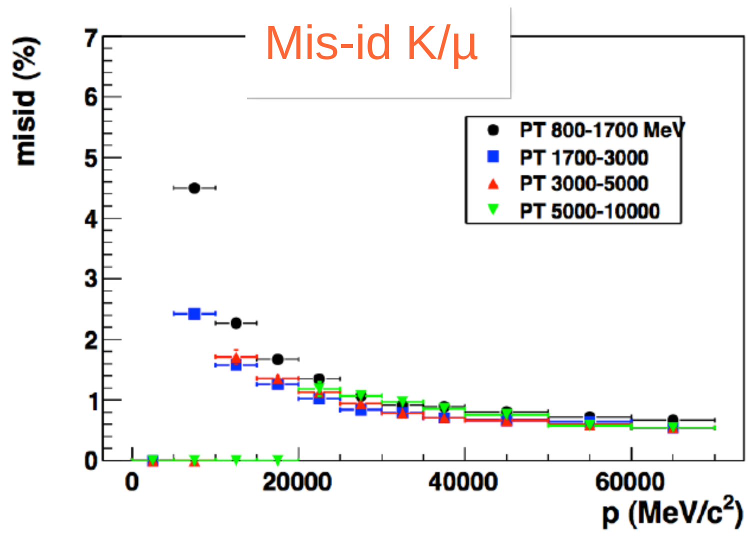
  for 1-3% π-μ MisID



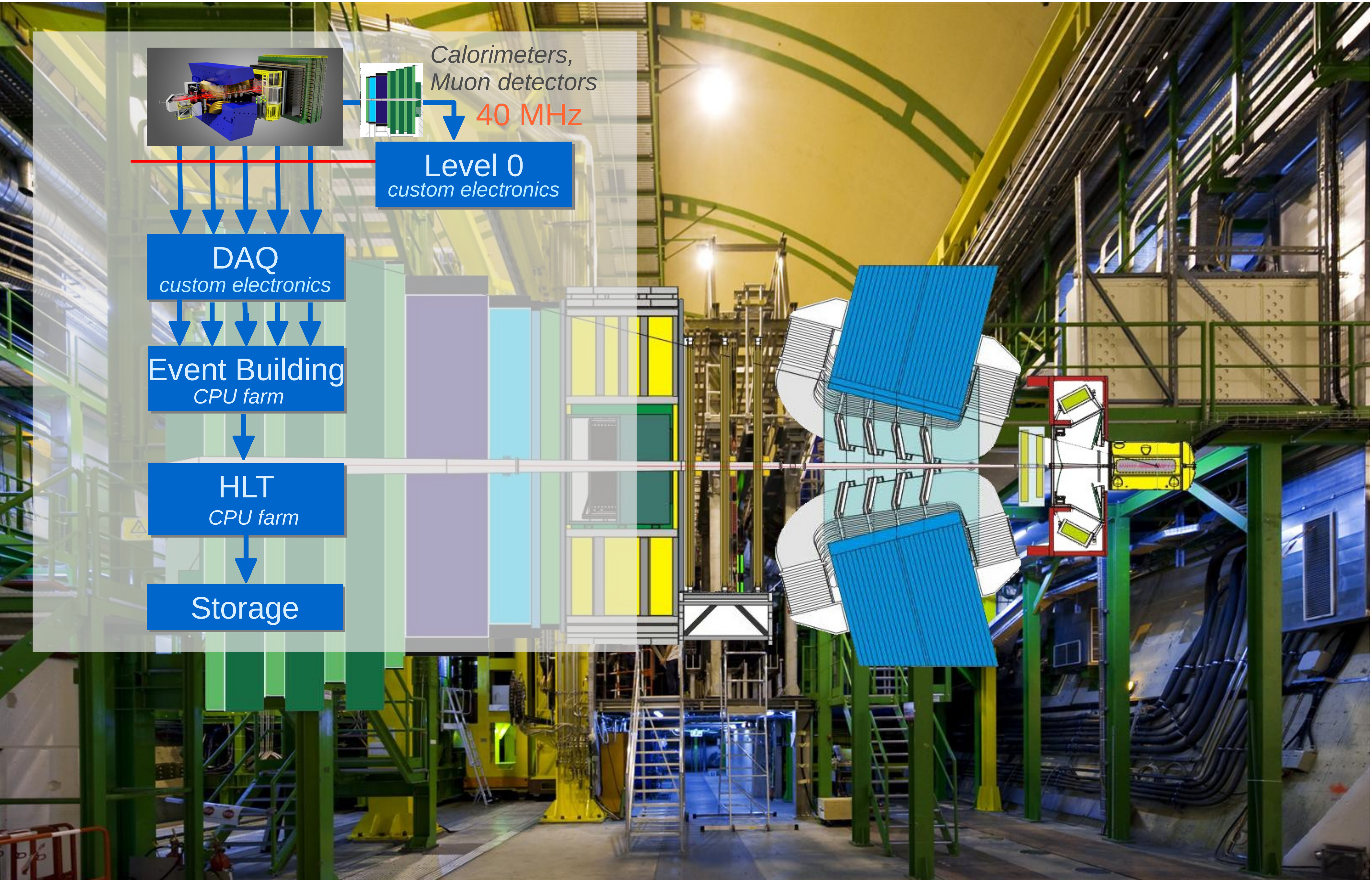




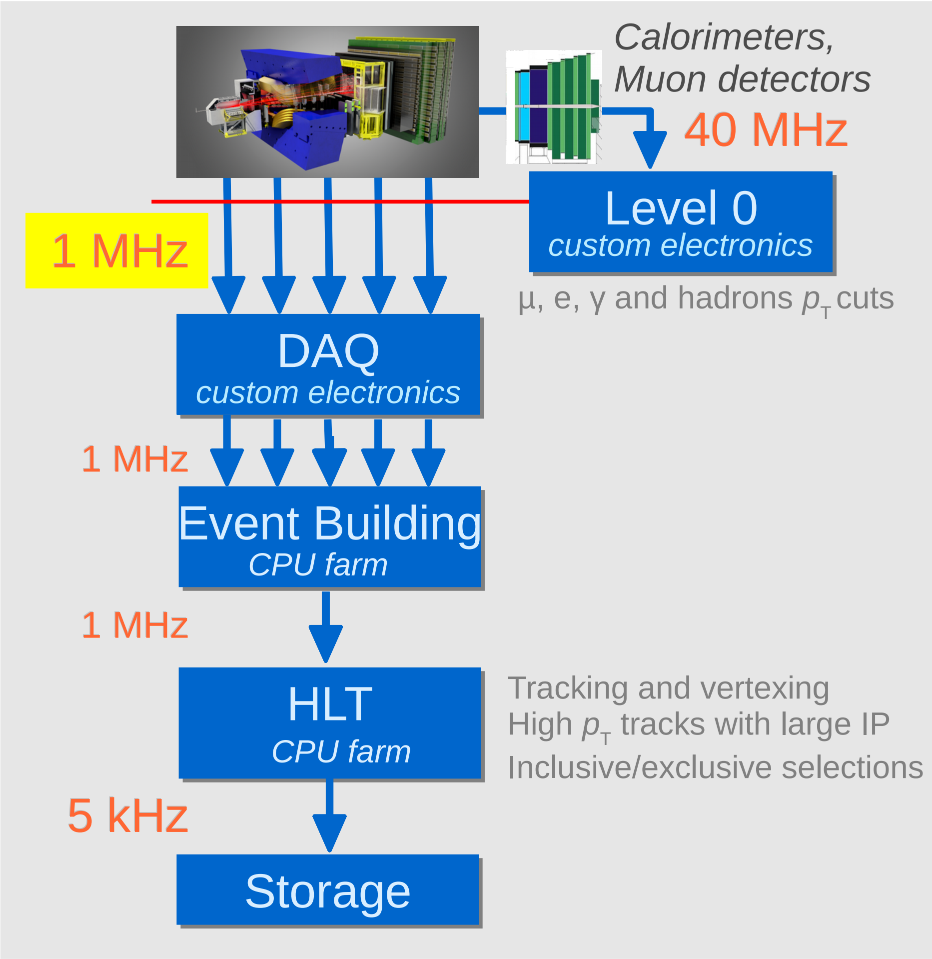




Data acquisition (0/1)



Data acquisition (1/1)



By design :

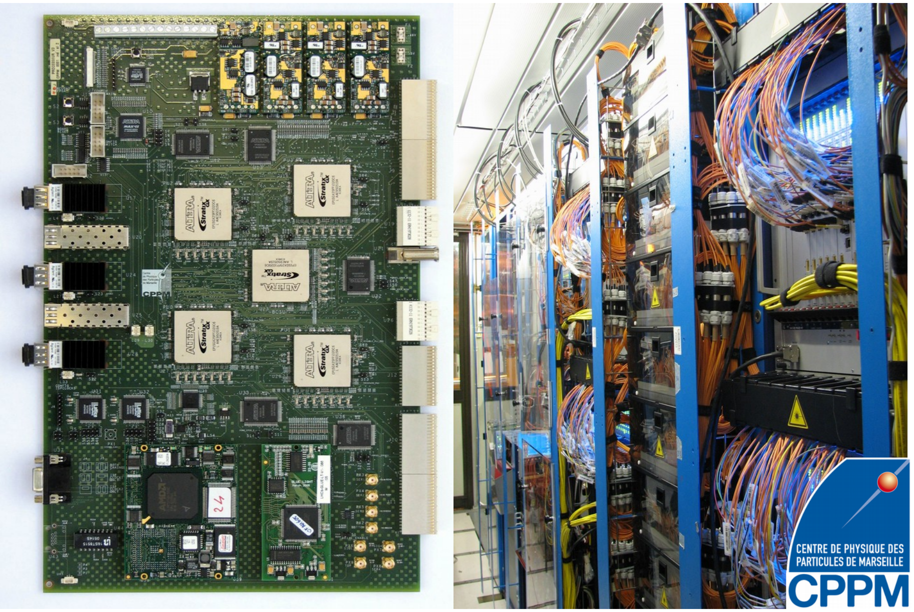
- full detector read-out @ 1MHz
- need to reduce the LHC collision rate from 40 MHz to 1Mhz

L0 : custom electronic @40Mhz, 4 μs latency

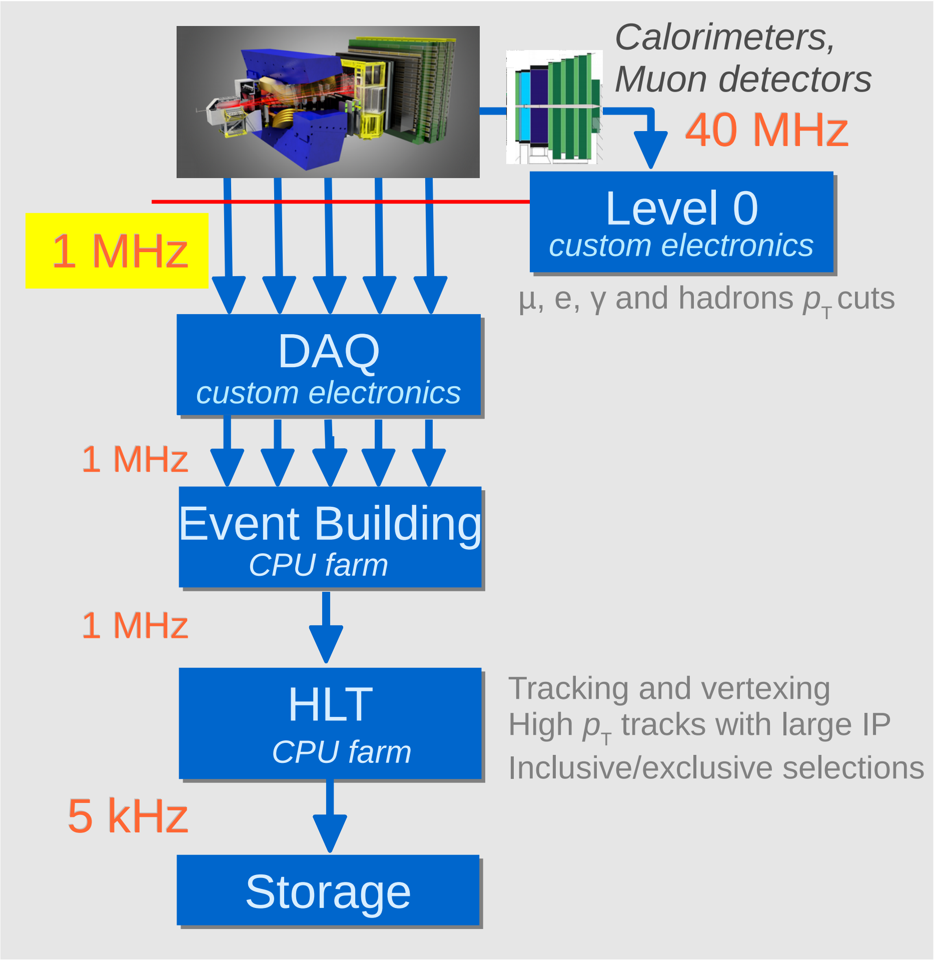
- based on Muon and calorimeters system
- search for high-p_T μ, e, γ, hadron candidates
- $p_T(\mu)>1.4$; $E_T(e/\gamma)>2.7$; $E_T(\text{hadron})>3.6$ [GeV]

L0Muon made in Marseille

- custom electronic boards



Data acquisition (1/1)



L0 : custom hardware trigger

HLT : software trigger

- ~30000 tasks in parallel on over 1500 nodes
- HLT1 : track and vertex reconstruction
  - Impact parameter cuts
- HLT2 : global event reconstruction and PID
  - select exclusive and inclusive modes

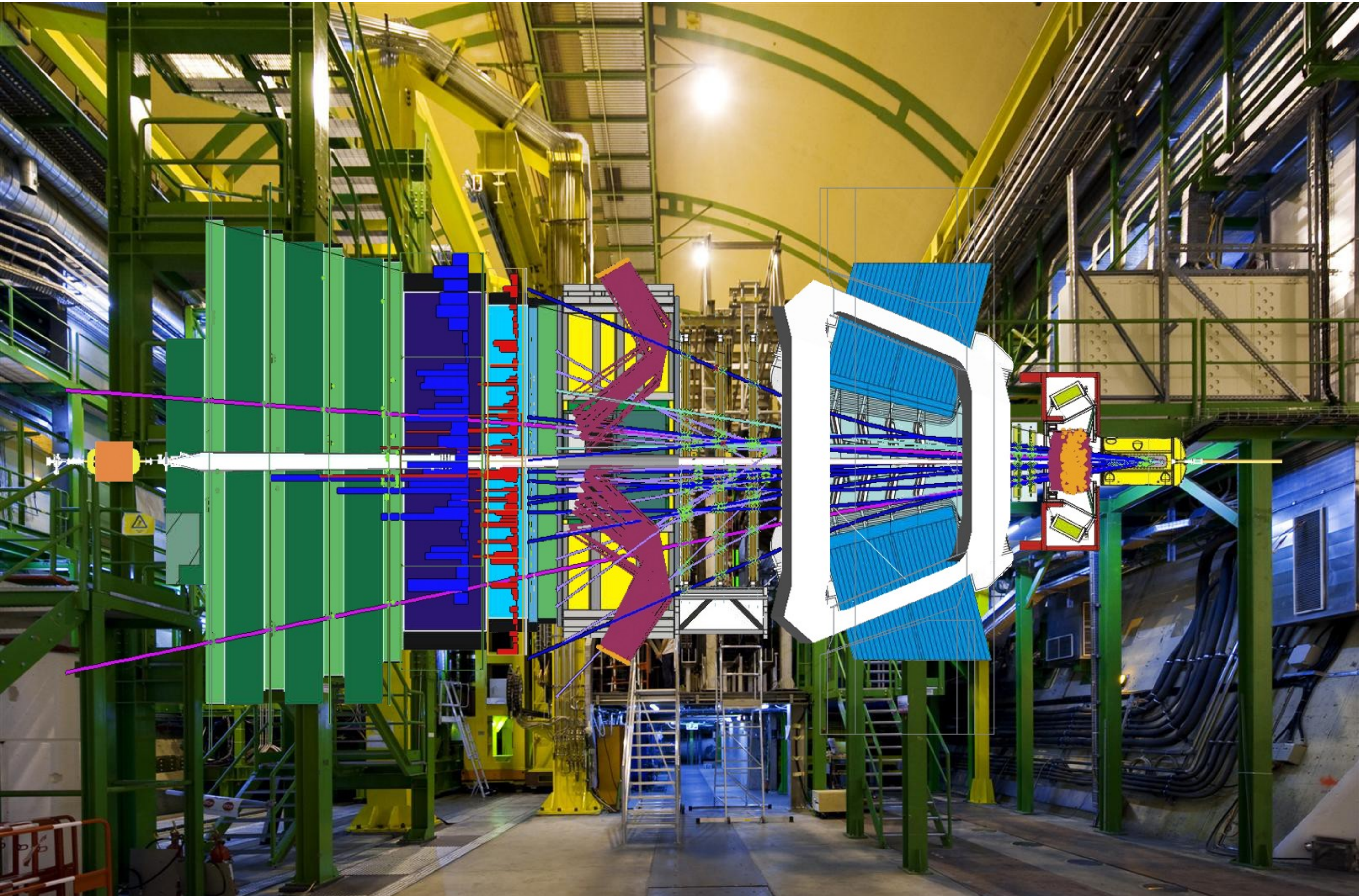
Offline : ~10^{10} events, 700 TB recorded/year

- centralized stripping selections to reduce the sample sizes to 0(10^7) events for physics analysis
- ~800 selections

Performances at 8 TeV in 2012 (L0xHLT)

- B decays with μμ : ε ≈ 90 %
- B decays with hadrons : ε ≈ 30 %
- Charm decays : ε ≈ 10 %

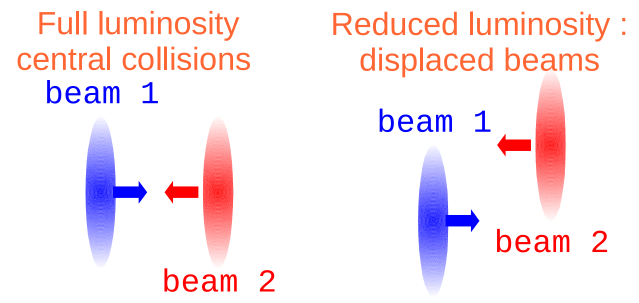
LHCb Operation



Luminosity

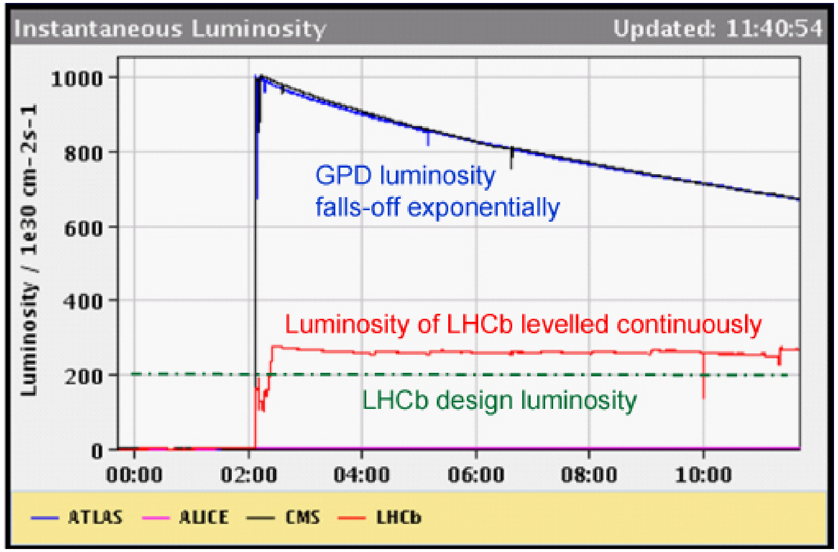
LHCb designed luminosity :

- $\mathcal{L}^{inst}$ = 2x10^{32} cm^{-2}s^{-1} with μ=0.4 (# of visible pp int./crossing)
- Precision physics depending on vertex structure
  - → easier in a low-pileup environment

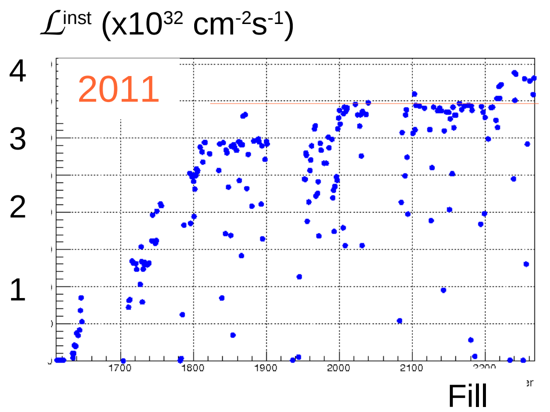


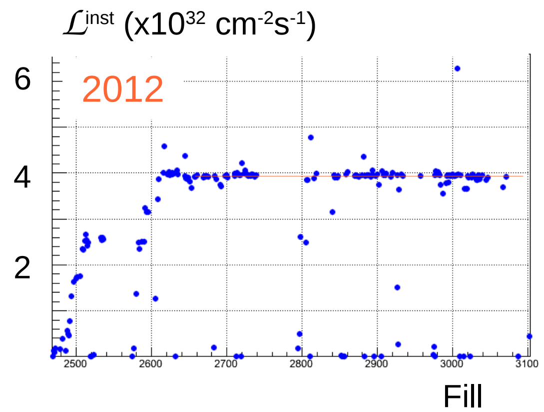
Luminosity levelling at LHCb

- run with constant luminosity
  - → beam overlap adjusted regularly
- automatic procedure between LHC&LHCb



2011 & 2012 instantaneous luminosities :

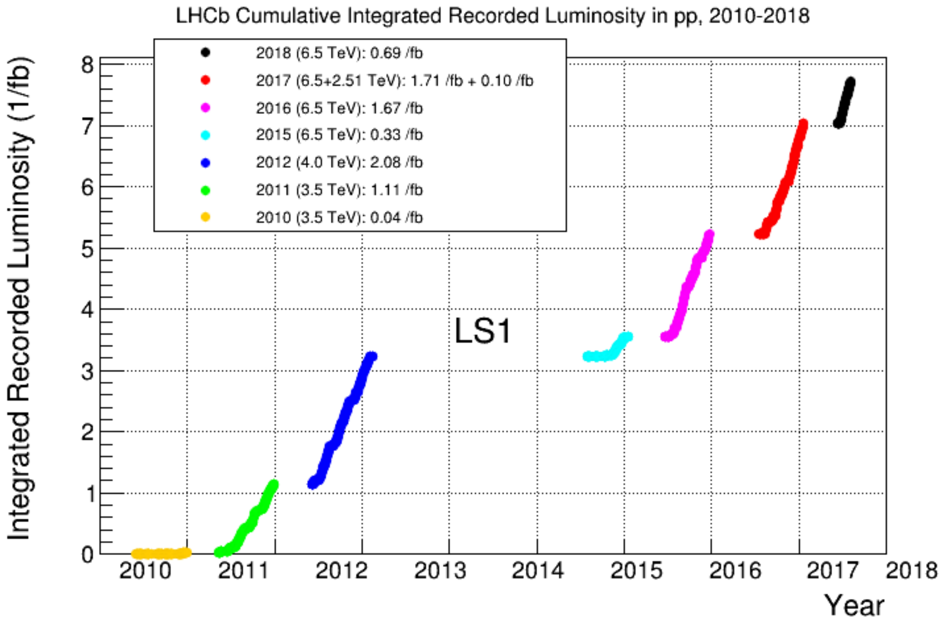




2011 : $\mathcal{L}^{inst}$ = ~ 3.5x10^{32} cm^{-2}s^{-1}, μ = ~1.5

2012 : $\mathcal{L}^{inst}$ = ~ 4.0x10^{32} cm^{-2}s^{-1}, μ = ~1.7

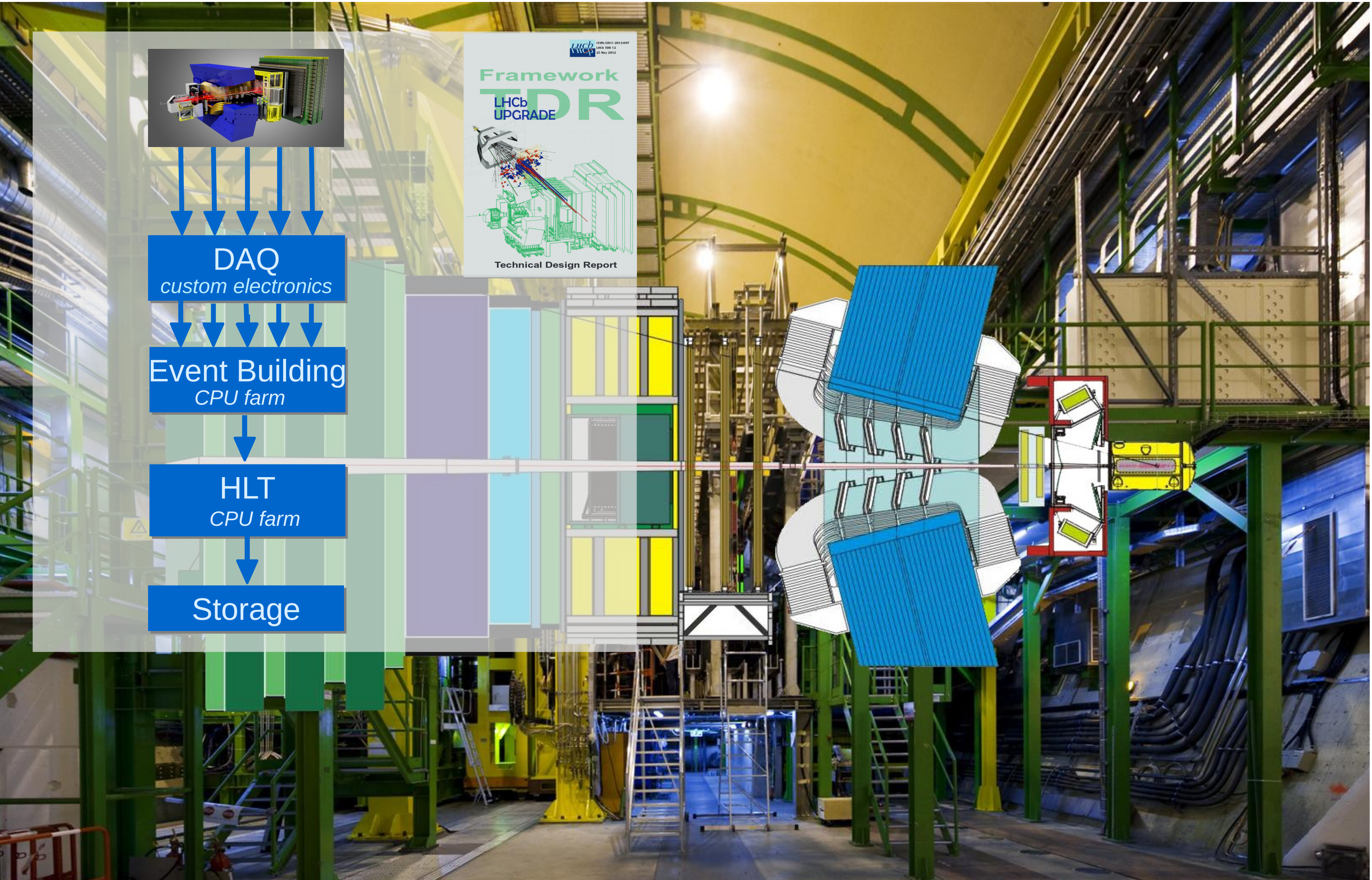
Data Taking



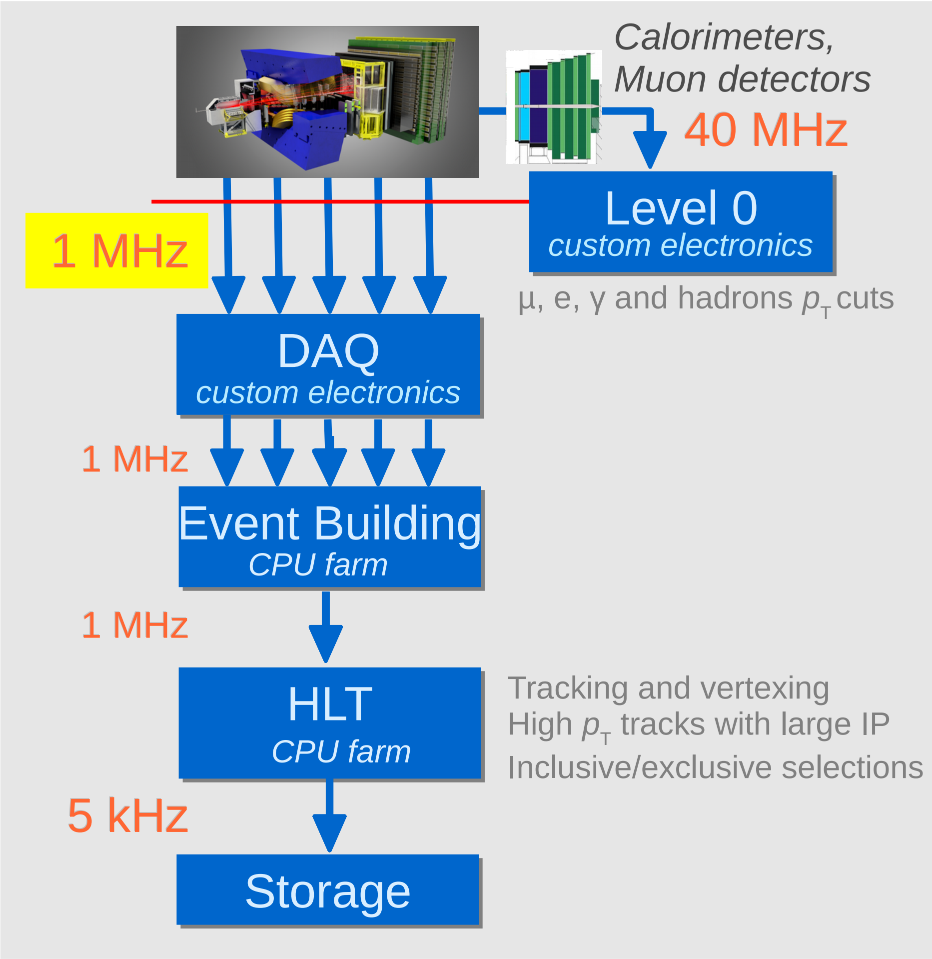
Recorded Luminosity :

- → Run1 :
  - 2011 : 1.1 fb^{-1} @ 7 TeV
  - 2012 : 2.1 fb^{-1} @ 8 TeV
- → Run2 (on going)
  - 2015-2017 : 3.7 fb^{-1} @ 13 TeV
  - 2018 : 0.7 fb^{-1} @ 13 TeV → as of today
- → Note : $\sigma(pp \to b\bar{b})_{Run2} \approx 2x \ \sigma(pp \to b\bar{b})_{Run1}$

LHCb upgrade (0/3)

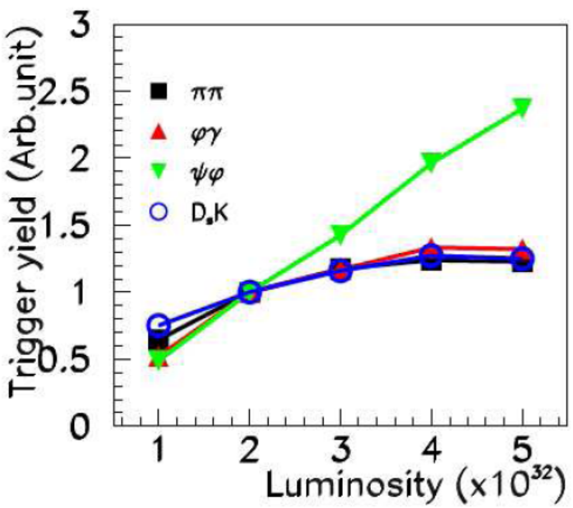


LHCb upgrade (1/3)



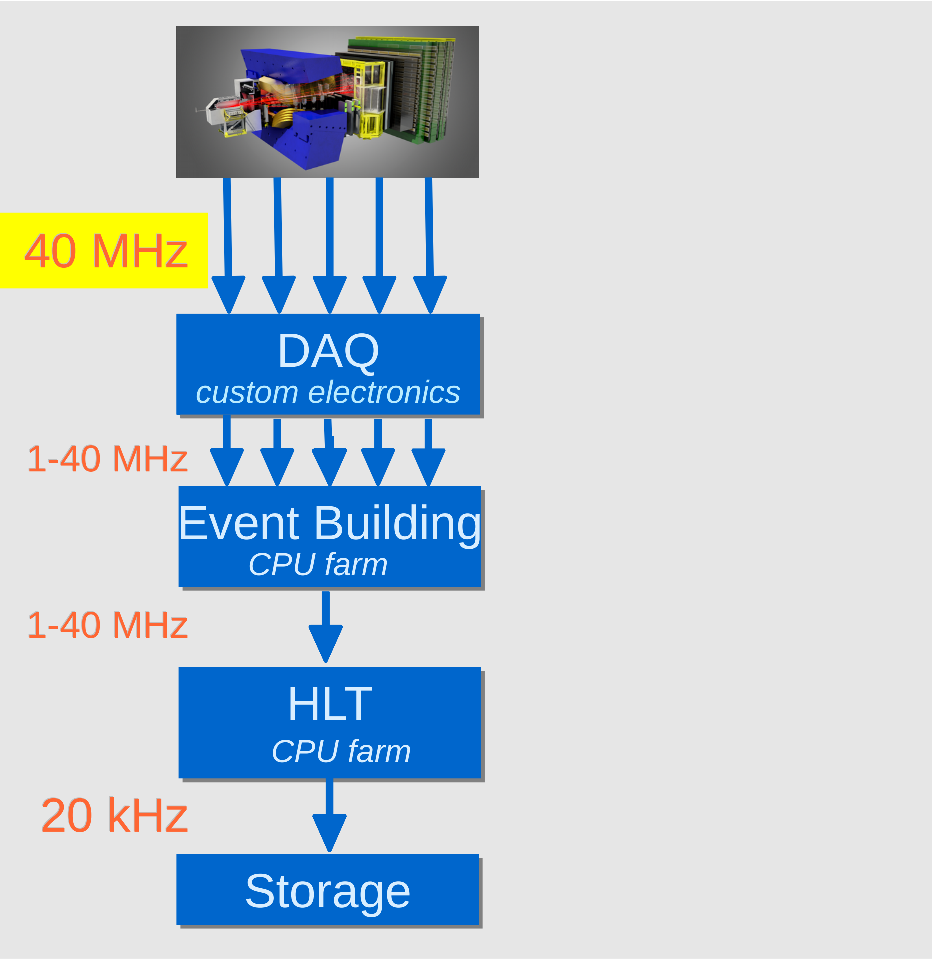
Upgrade goal : increase instantaneous luminosity

With current design : saturation of the yields



- p_T cuts must be raised to cope with the 1 MHz limitation on the read-out rate
- no gain beyond 2-3 1032 cm-2s-1 for hadronic modes

LHCb upgrade (2/3)



- In preparation for Run3 (2020)

To benefit from higher luminosity :

- remove L0 bottleneck
- read full detector at 40 MHz

Full read out at 40 MHz:

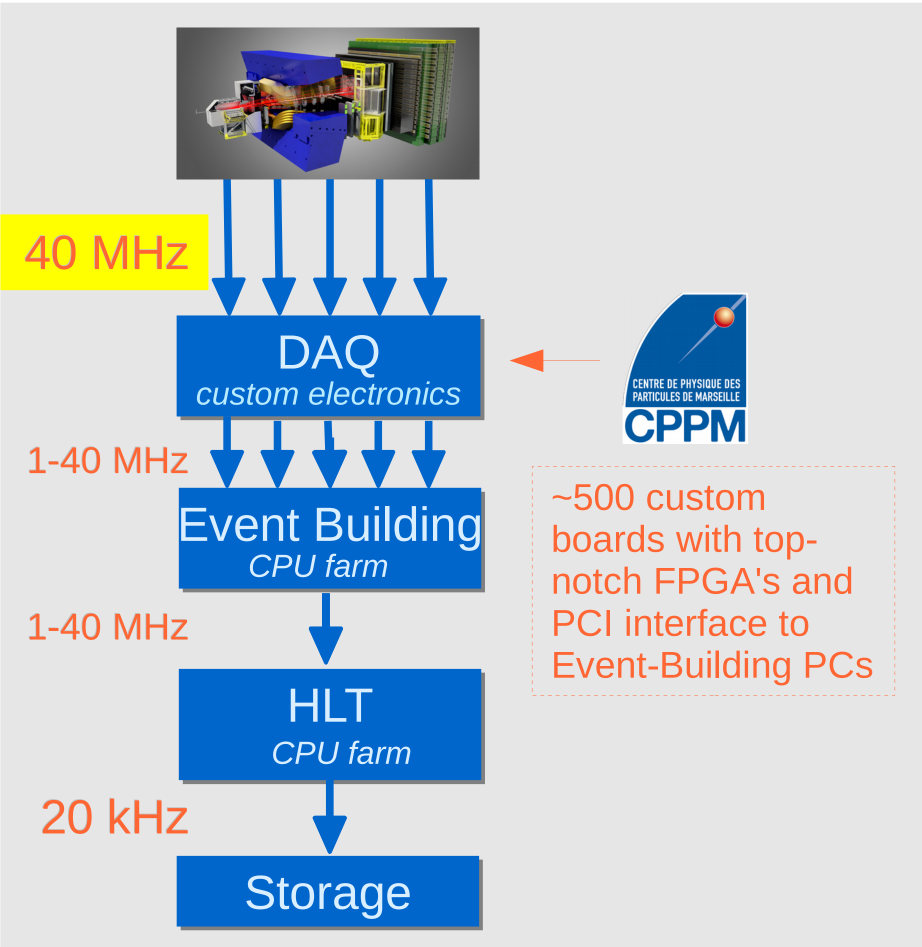
- replacement of all front-end and back-end electronics
- fast high-level software trigger

Replace some detector to cope with higher particle density

- optimize geometry for fast reconstruction
- sustain increased radiation dose

Final output bandwidth : 20 kHz

LHCb upgrade (2/3)



To benefit from higher luminosity :

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Full read out at 40 MHz:

- → replacement of all front-end and back-end electronics
- → fast high-level software trigger

Replace some detector to cope with higher particle density

- → optimize geometry for fast reconstruction
- → sustain increased radiation dose

Final output bandwidth : 20 kHz

LHCb upgrade (3/3)

- The 40 MHz detector :

VELO

radiation dose and occupancy
→ replace sensors

Si tracker

embedded FE
→ replace sensors

Calorimeters

occupancy
→ remove SPD & PS
→ reduce HV & PM gain

RICHs

embedded FE
→ replace HPDs
occupancy (RICH1)
→ redesign mirrors

Outer tracker

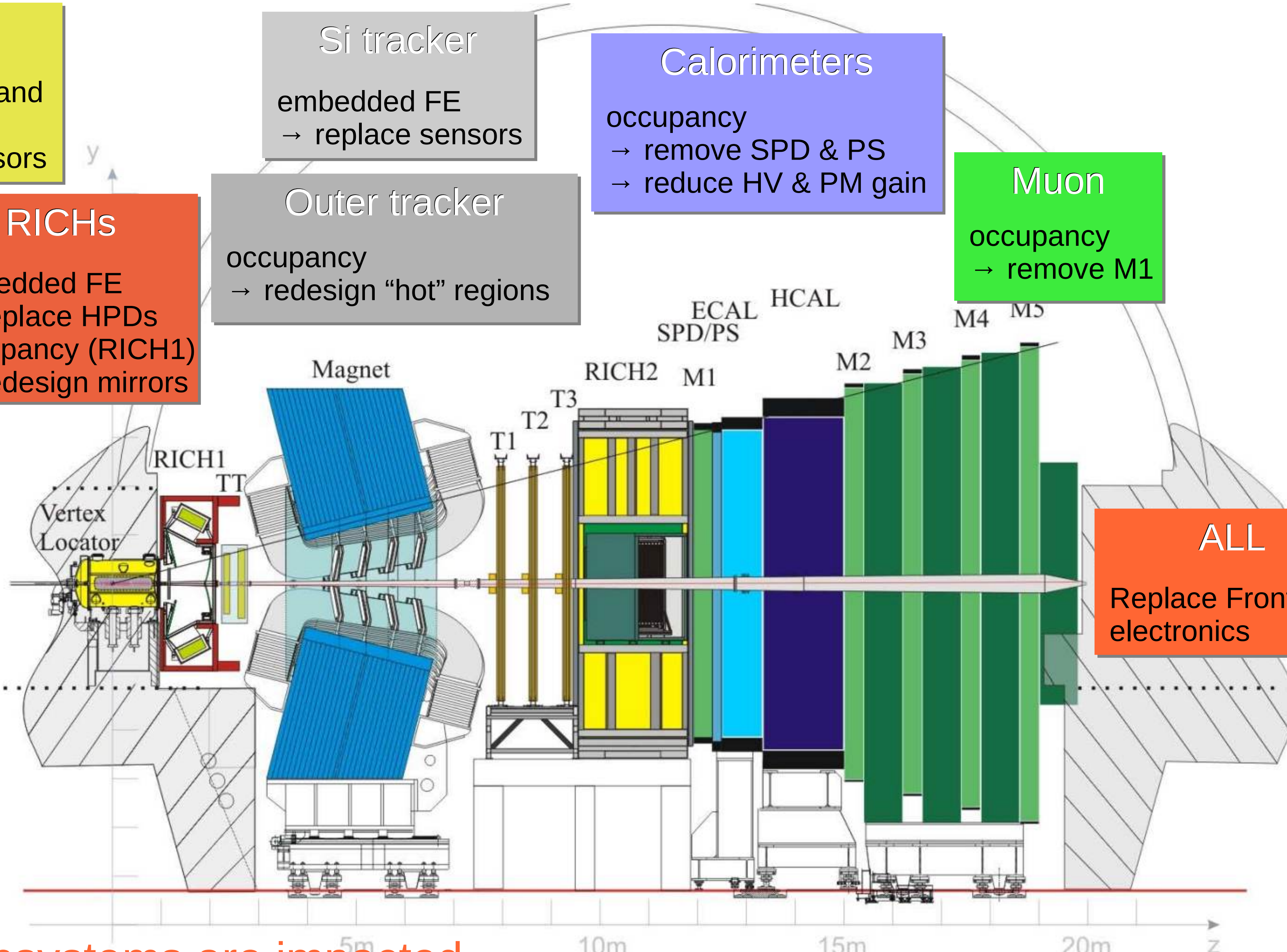
occupancy
→ redesign “hot” regions

Muon

occupancy
→ remove M1

ALL

Replace Front-end electronics



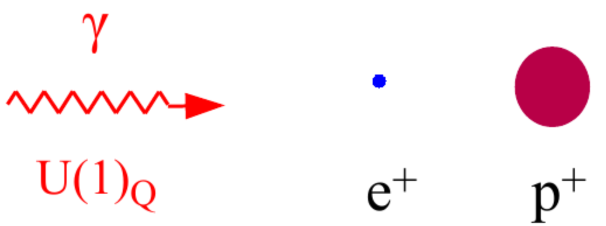
- all subsystems are impacted

LHCb future upgrade ?

Lepton Flavour Universality (LFU)

Introduction [*a digression on LFU*]

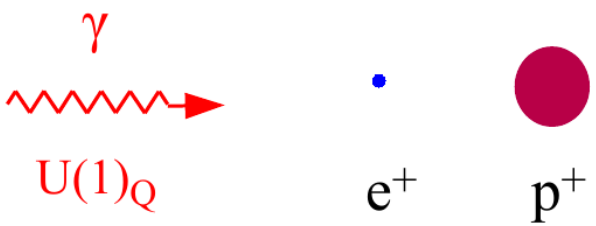
Let's go back ~ 100 years, and suppose we can test matter only with long wave-length photons...



These two particles seems to be "identical copies" but for their mass ...

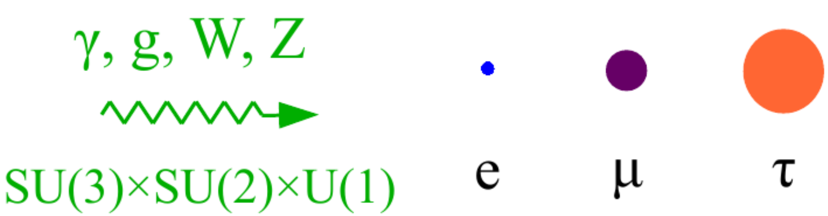
Introduction [*a digression on LFU*]

Let's go back ~ 100 years, and suppose we can test matter only with long wave-length photons...



These two particles seems to be "identical copies" but for their mass ...

That's exactly the same (misleading) argument we use to infer LFU...



These three (families) of particles seems to be "identical copies" but for their mass ...

The SM quantum numbers of the three families could be an "accidental" low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass

Highlight on some LHCb results

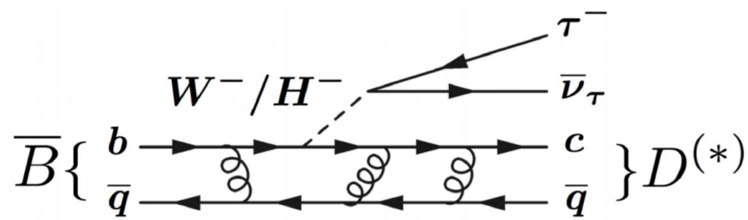
- biased selection with a focus on CPPM's activities
  - → The flavour anomalies :
    - – $b \to c$ transitions
    - – $b \to s$ transitions

Selected LHCb results

- *$b \to c$ transitions*
- $b \to s$ transitions

Anomalies in $b \to c\tau\nu$ transition

$$R(D) \equiv \frac{\mathcal{B}(B^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell)} \quad , \quad \ell \in \{\mu, e\}$$
$$\stackrel{\text{SM}}{=} 0.300 \pm 0.008 \, ,$$



$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu_\ell)} \, , \quad \ell \in \{\mu, e\}$$
$$\stackrel{\text{SM}}{=} 0.252 \pm 0.003$$

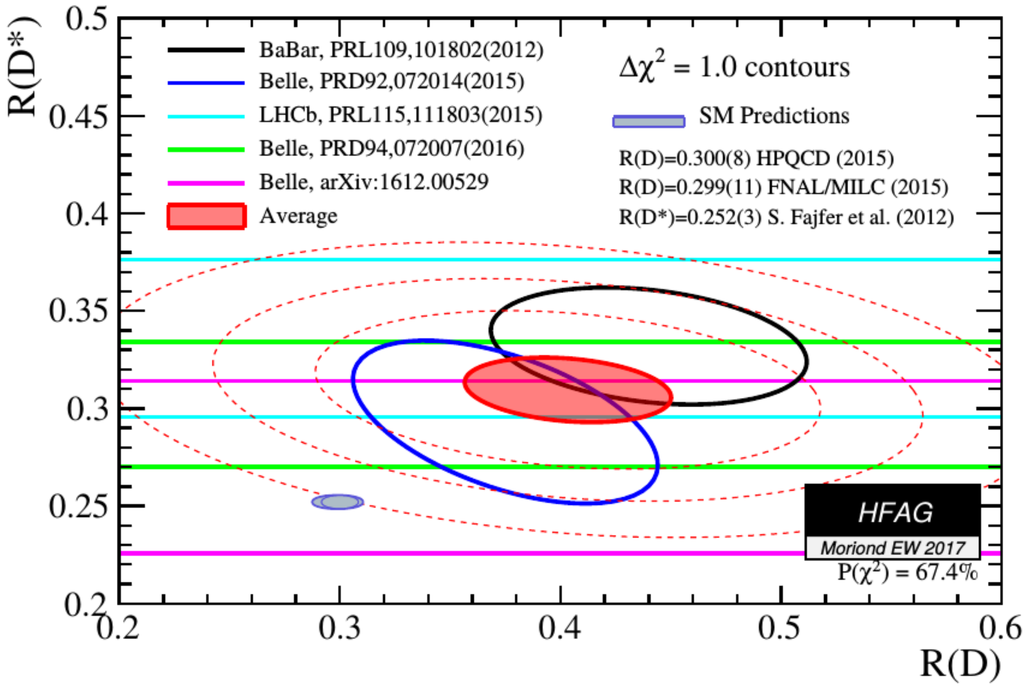
All measurements above the SM

Combining Belle, BaBar and LHCb

- measurements are ~4σ away form SM

At CPPM :

- participate in analysis of R(D) with Run2 data
- if central value, BSM could be discovered !



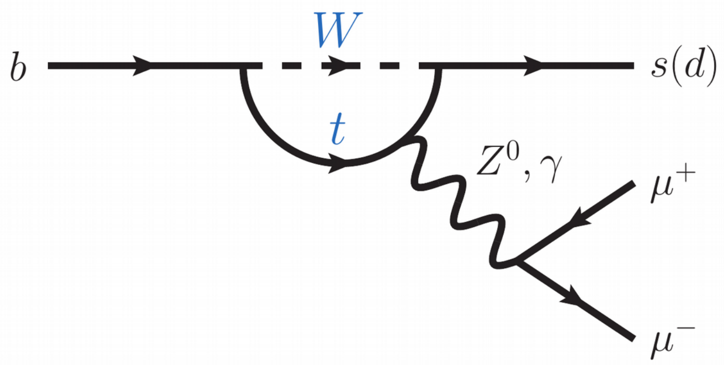
Selected LHCb results

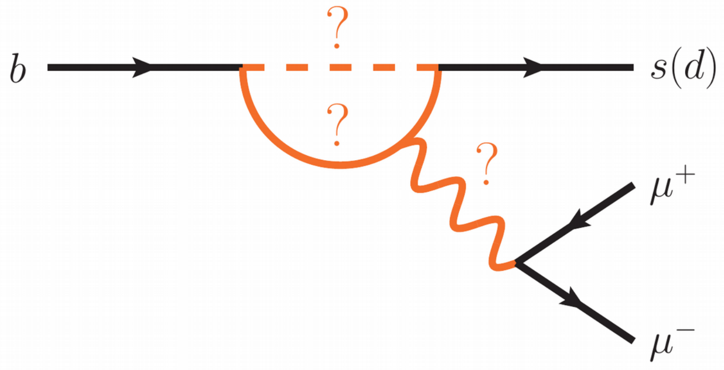
- *$b \to c$ transitions*
- $b \to s\ell\ell$ transitions

$b \to s\ell\ell$ transitions

$b \to s\ell\ell$ transitions are FCNC (flavour changing neutral current)

- → forbidden in the SM at the tree level
- → only exist at loop level → highly suppressed → rare decay !





Physics beyond the Standard Model (BSM) enter at the same level as the SM

BSM can modify a range of observables

- → branching fractions
- → angular distributions
- → CP/isospin asymmetries

Different type of decays give access to different observables

- → sensitive to different BSM contributions

Correlation between the observables allow to identify the type of new physics involved

- → important to measure all possible observables

A harvest of results

Ratios of $b \to s\mu\mu$ / $b \to see$ transitions

- R(K*) = $\Gamma(B^0 \to K^{*0}\ \mu^+\mu^-)$ / $\Gamma(B^0 \to K^{*0}\ e^+e^-)$

Branching fractions & isospin asymmetries

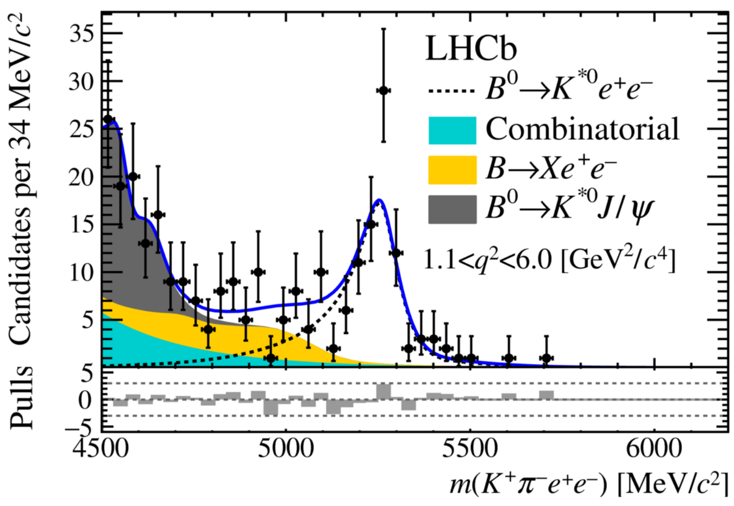
- $B \to K^{(*)}\ \mu^+\mu^-$

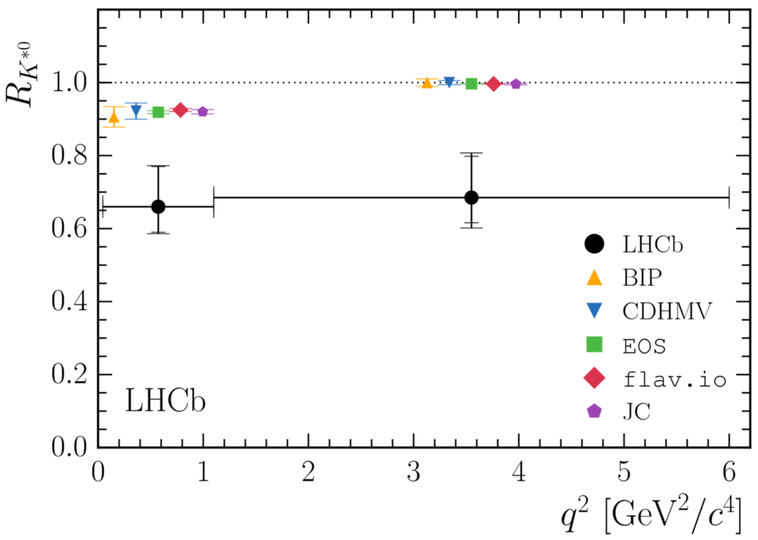
Branching fractions & angular analysis

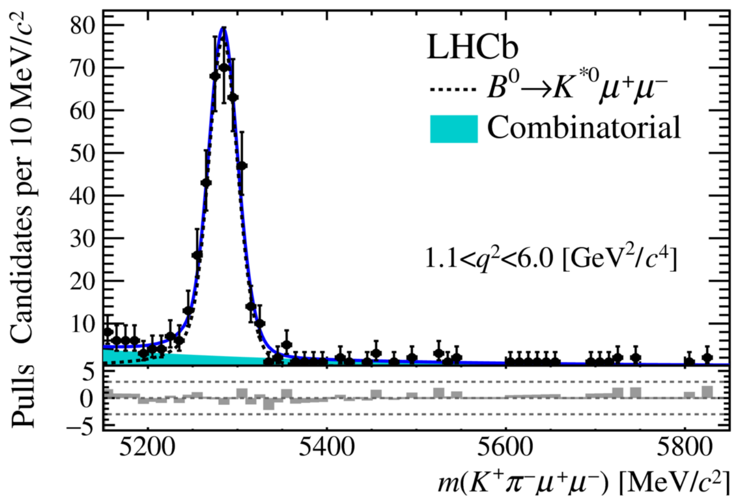
- $B \to K\ \mu^+\mu^-$
- $B_s \to \Phi\mu^+\mu^-$
- $\Lambda_b \to \Lambda\ \mu^+\mu^-$
- $B \to K\ e^+e^-$

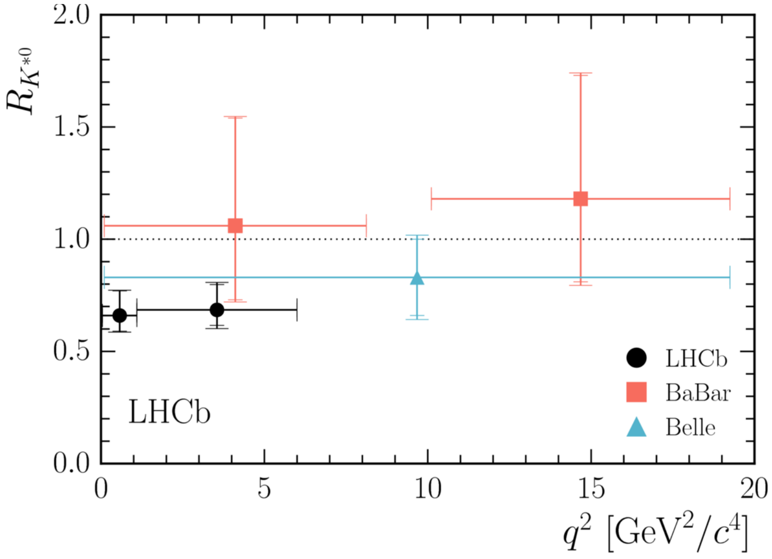
A harvest of results

$R(K^*) = \Gamma(B^0 \to K^{*0} \mu^+\mu^-) / \Gamma(B^0 \to K^{*0} e^+e^-)$

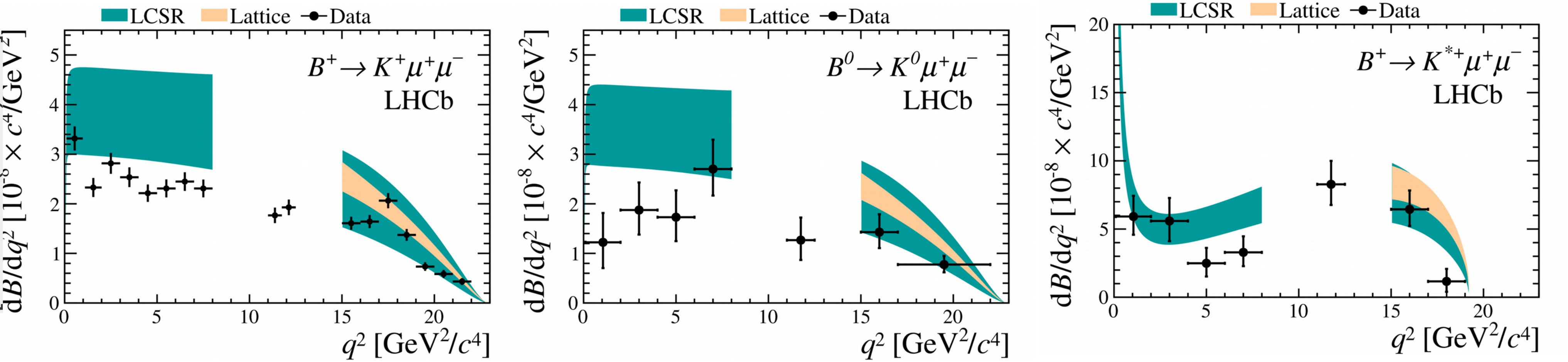








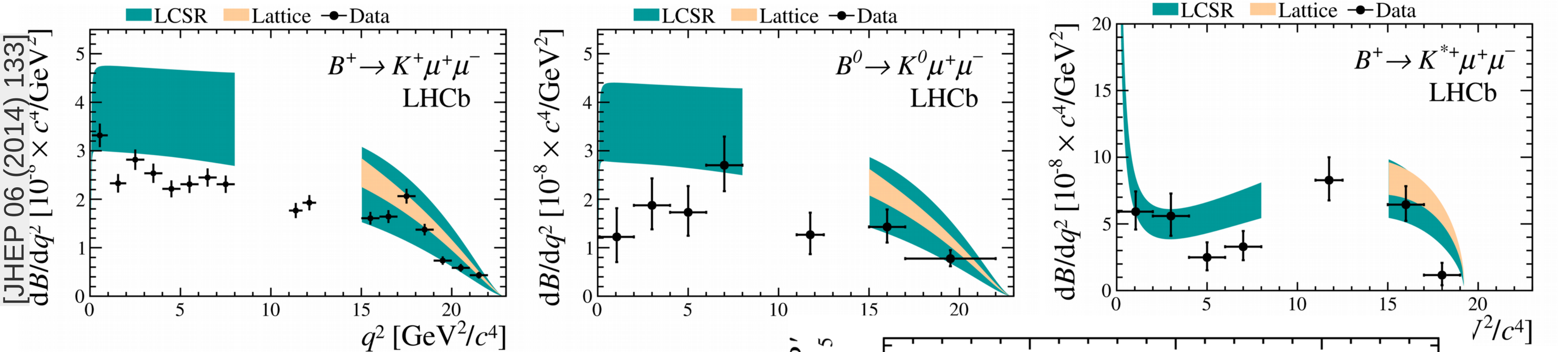
A harvest of results



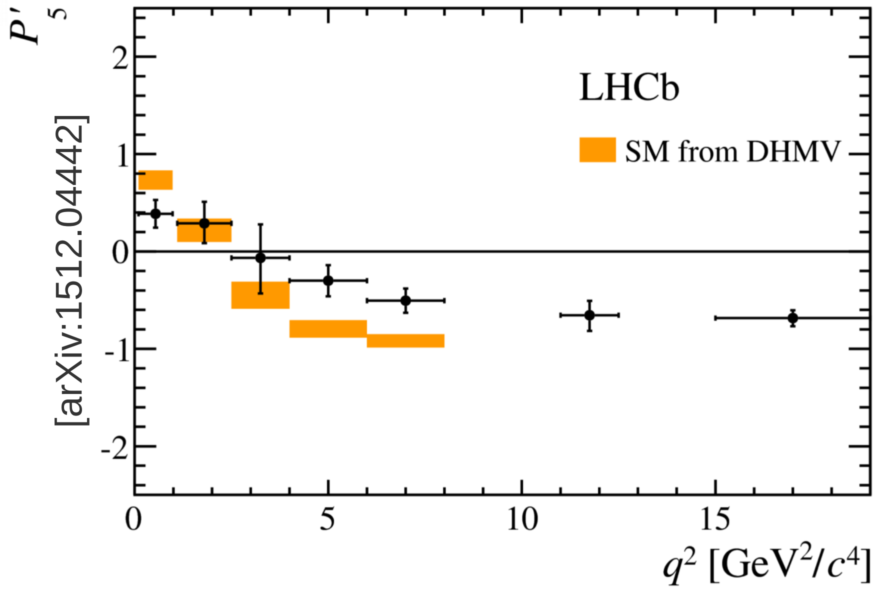
[JHEP 06 (2014) 133]

A harvest of results

[JHEP 06 (2014) 133]

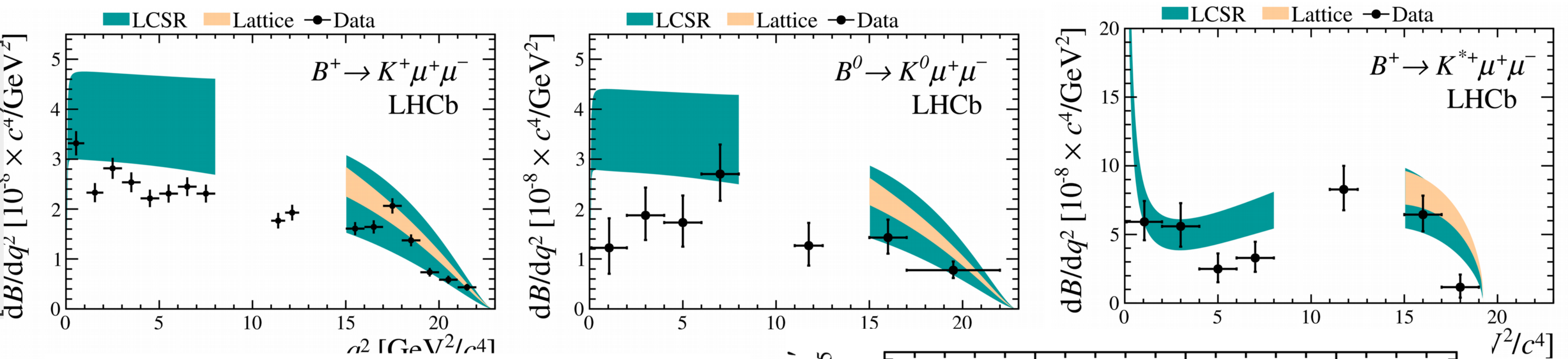


[arXiv:1512.04442]

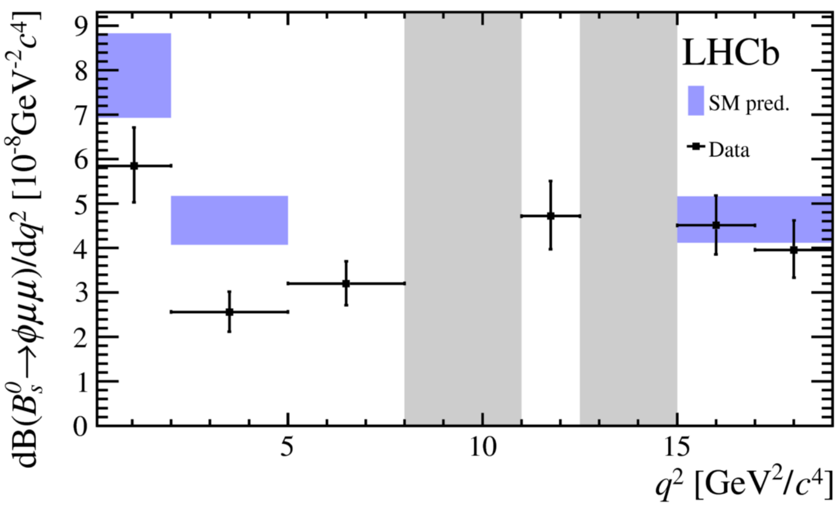


A harvest of results

[JHEP 06 (2014) 133]



[JHEP 09 (2015) 179]



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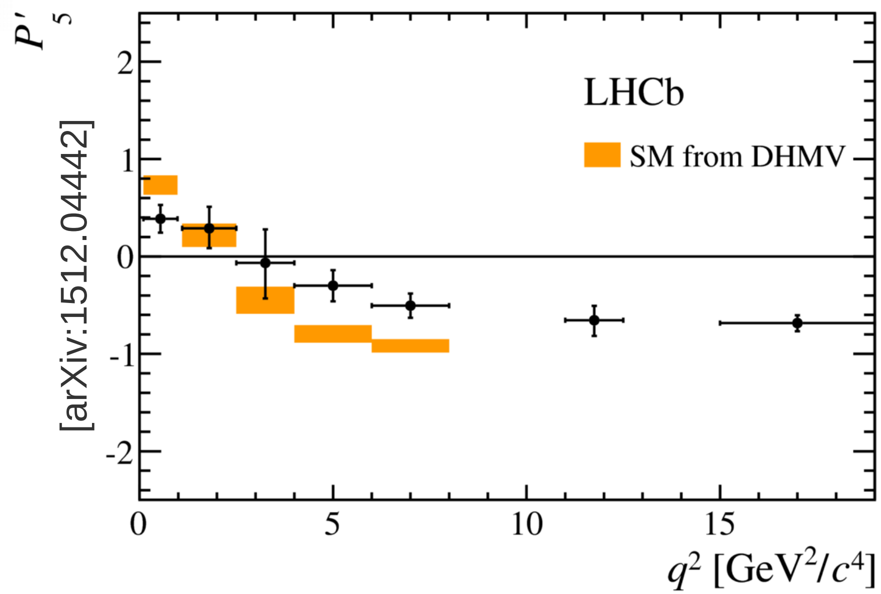
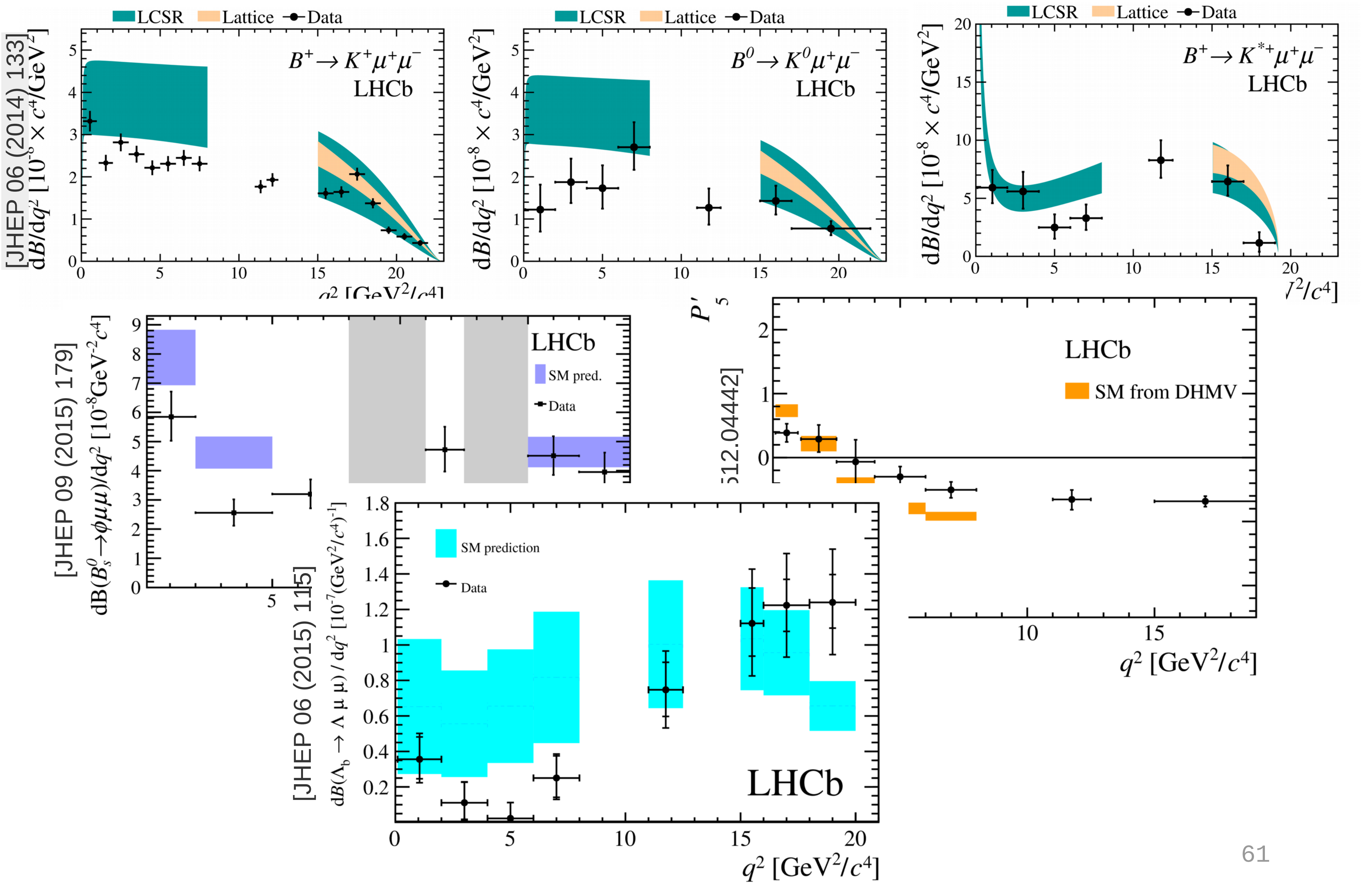


A harvest of results



Model independent analysis of $b \rightarrow s$ transitions

$M_{Z,W,t} \gg m_b \rightarrow$ low energy effective theory :

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

left-handed part ($C_i \mathcal{O}_i$)

right-handed part ($C_i' \mathcal{O}_i'$) suppressed in SM

i = 1,2...... tree
i = 3-6,8 .. gluon penguin
i = 7 .... photon penguin
i = 9,10 ... electroweak penguin
i = S .... Scalar penguin
i = P .... Pseudo scalar penguin

- Local operators O_i depends on hadronic form factor
  - → (dominant) source of theoretical uncertainties
- Wilson coefficients C_i describe the short distance effect
  - → can be modify by new physics : $C = C^{SM} + C^{NP}$
    (including operators not present or suppressed in the SM)

Results interpretation

Global fit (with all $b \to s\ell\ell$ observables)

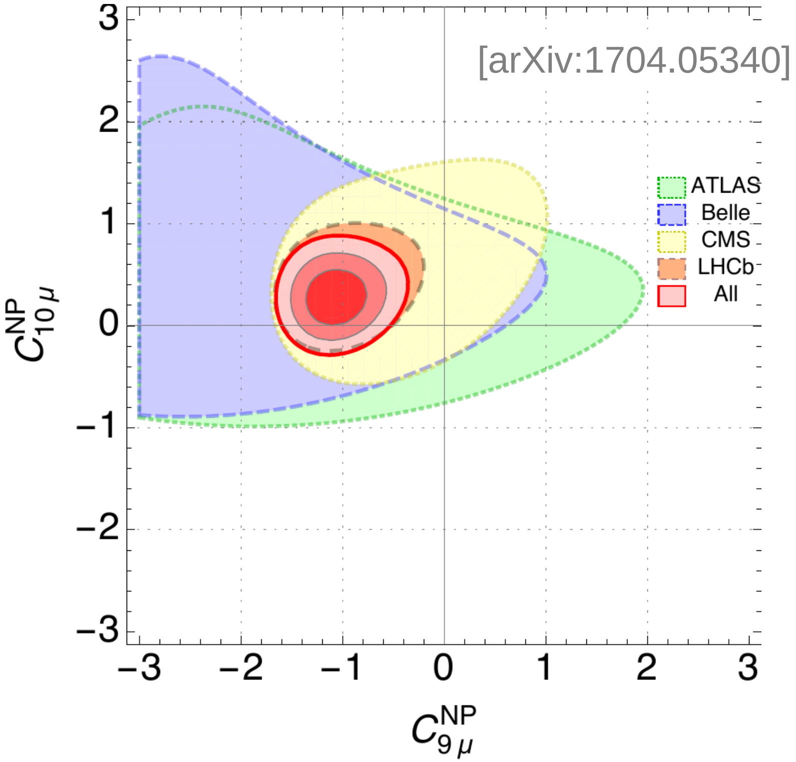
Favours new physics contribution to the coefficient C_9

→ significance almost 5 σ !

Implies a violation of the lepton universality

→ significance > 3 σ

More measurements needed !



CPPM $b \to s\ell\ell$ activities

CPPM worked on the B → μμ analysis

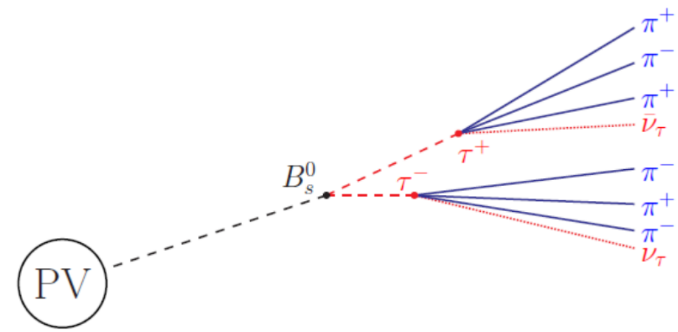
Now, focus on decays with τ in the final state

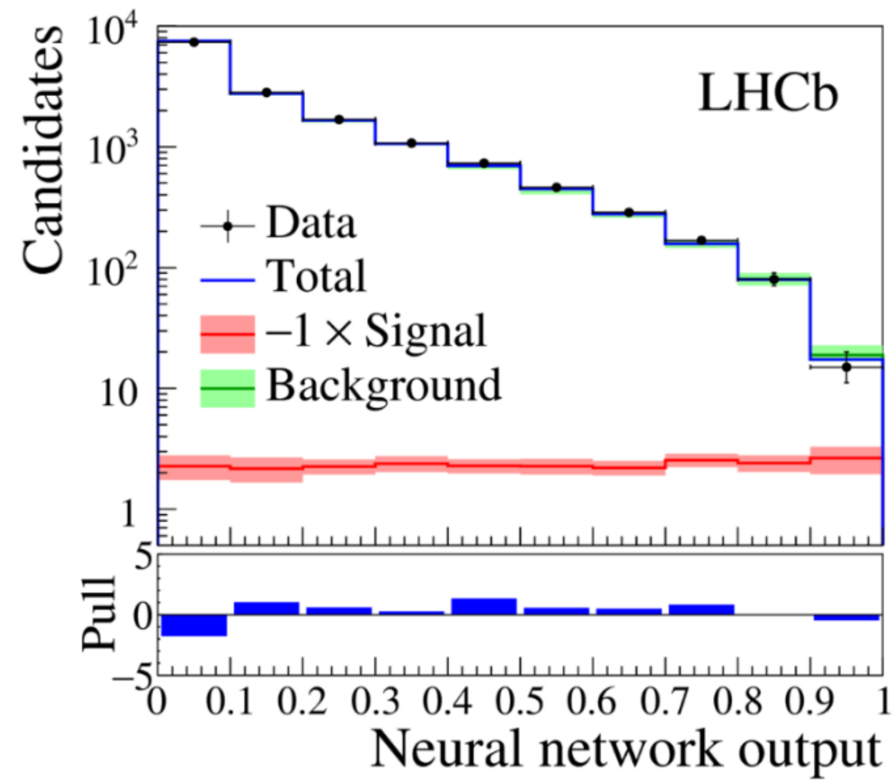
$B_{(s)} \to \tau^+\tau^-$ (just published)

- Analysis
  - → the τ decay in flight and are not reconstructed
  - → use the τ → πππν mode
  - - neutrino escapes detection
    - – missing energy
    - – no invariant mass reconstruction
- Results :
  - → upper limits on branching ratio :
  - - $BR(B_s \to \tau\,\tau) < 6.8\ 10^{-3}$ (first limit)
  - - $BR(B^0 \to \tau\,\tau) < 2.1\ 10^{-3}$ (best limit)

On going :

- → $B_s \to K^*\,\tau\,\tau$
- → $B_{(s)} \to \tau\,\mu$ (lepton flavour violation !)





[PRL118(2017)251802]

Conclusion and prospect

Still many open questions in and beyond the Standard Model

Without any sign of new physics in the direct search, the precision era is open !

The heavy flavour sector is still a promising sector for BSM discoveries

More data and measurements are needed to resolve the tensions that are building up in heavy hadrons decays

→ Lepton flavour non-universality ???