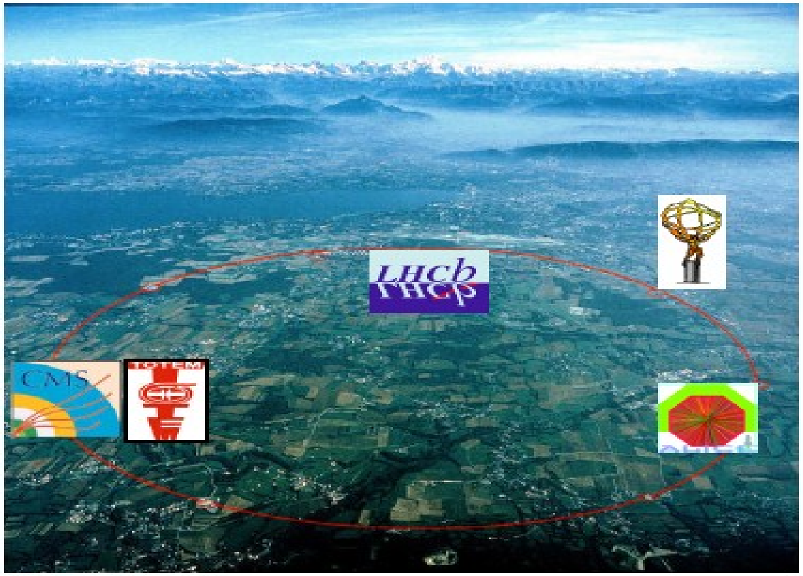
Physics Program

of the experiments at

Large Hadron Collider

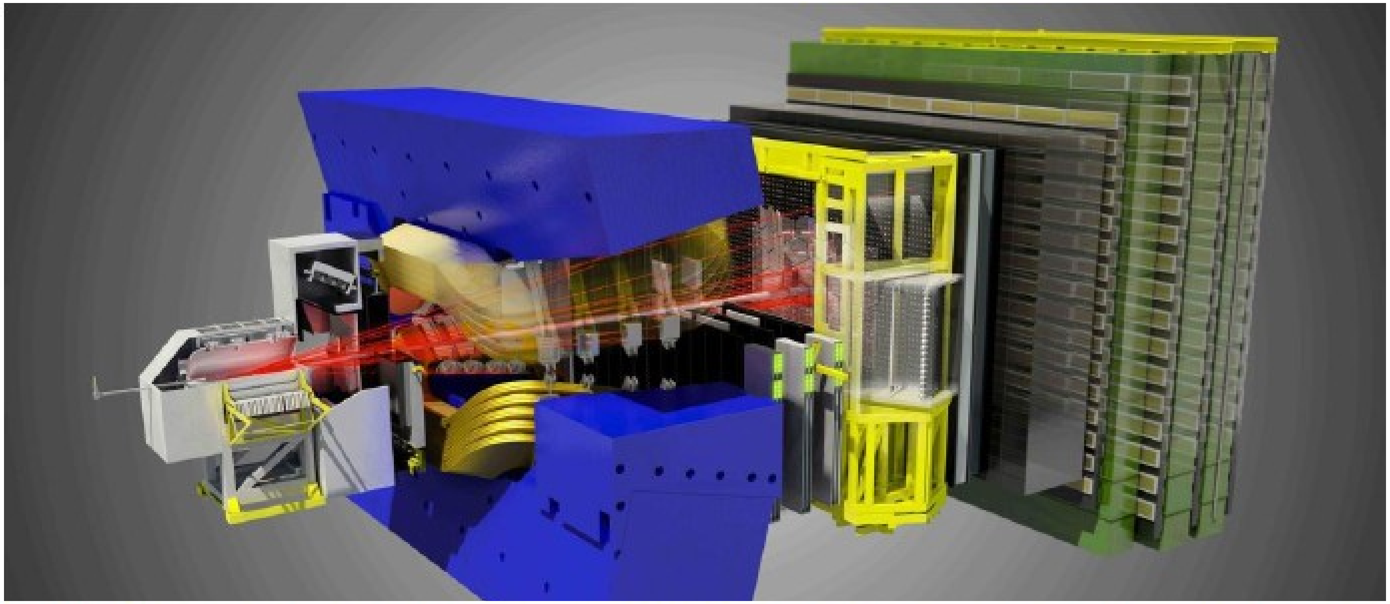


LHCb experiment

B-physics

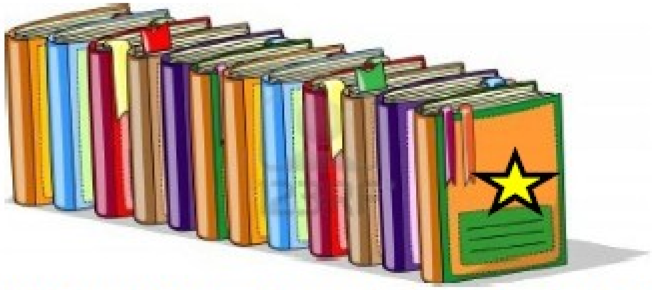
LHCb collaboration

LHCb detector



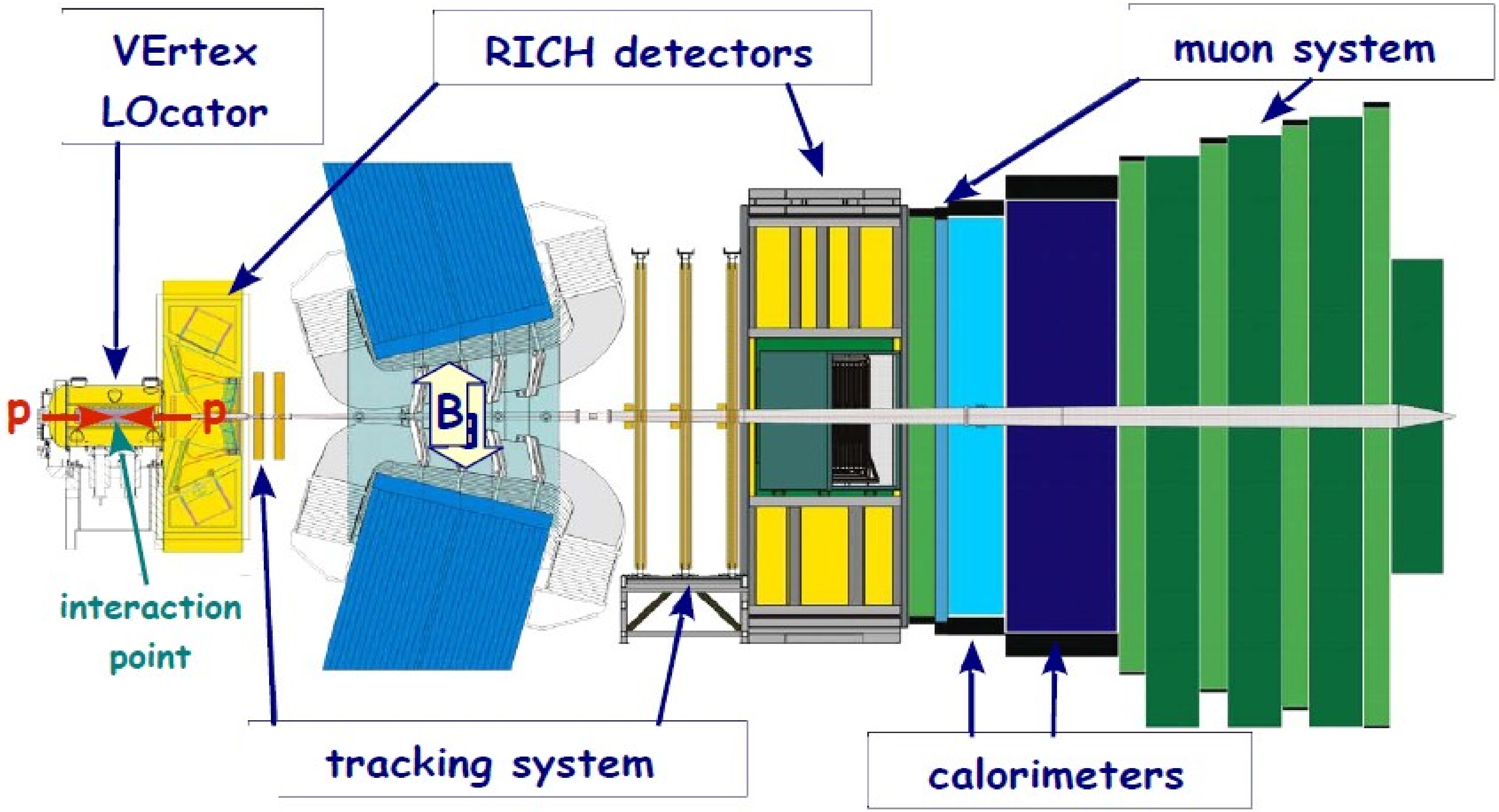
The LHCb experiment has an unusual shape for running in collider mode

ATLAS/CMS: sub-detectors surrounding the entire collision point (like an onion)



LHCb: ~20m of stacked sub-detectors (like books on a shelf)
→ easy access to sub-detectors

LHCb detector

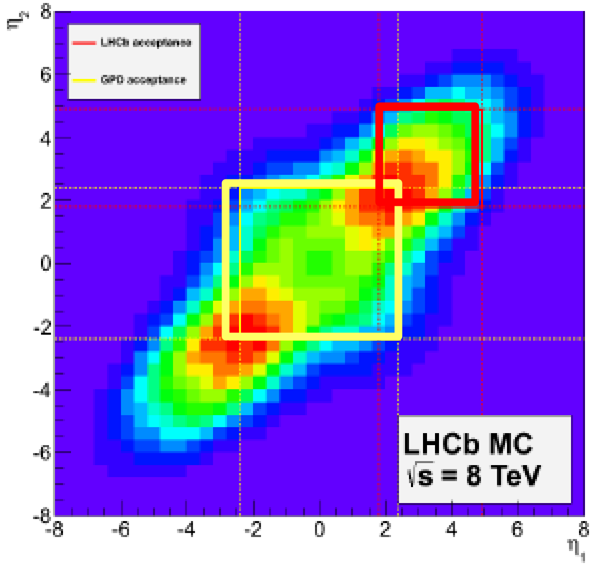


[The LHCb Detector at the LHC. JINST 3 (2008) S08005]

Forward spectrometer, fully instrumented in $2 < \eta < 5$

LHCb: a forward spectrometer

B forward-peaked production

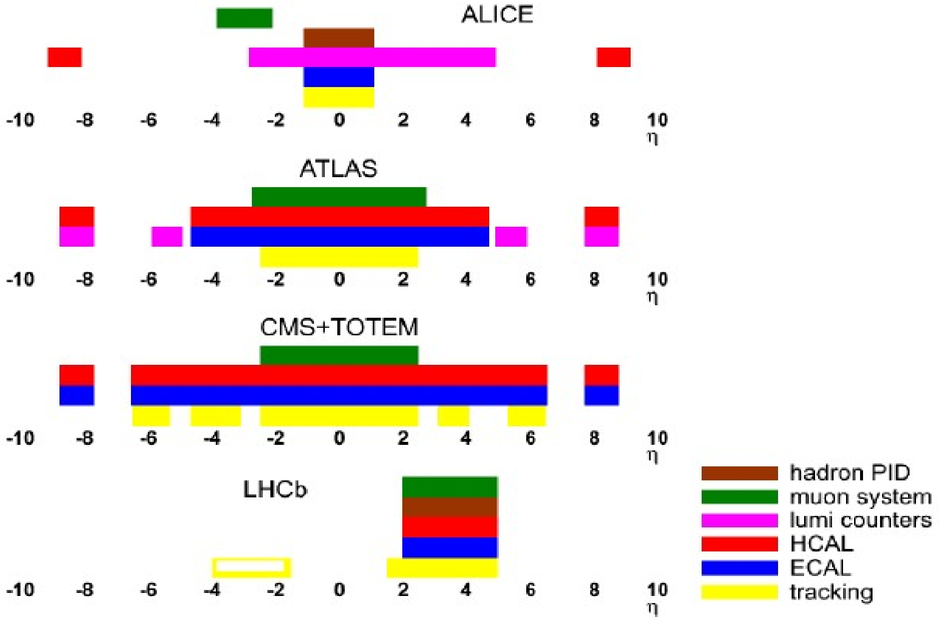


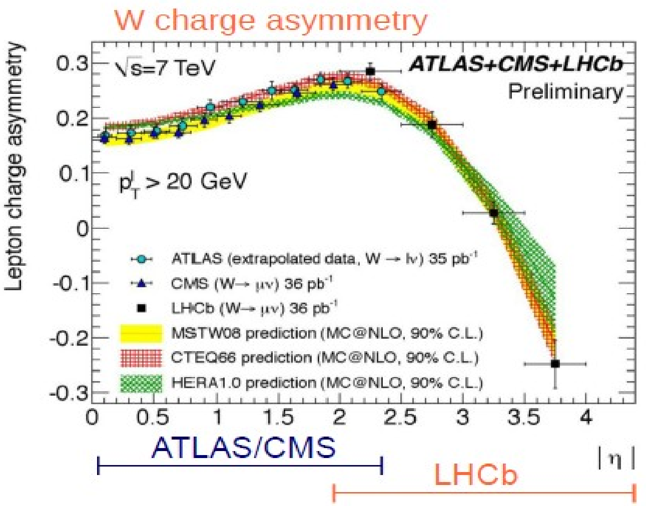
LHCb is a forward spectrometer

(operating in collider mode)

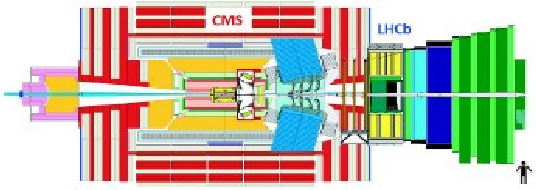
LHCb: a forward spectrometer

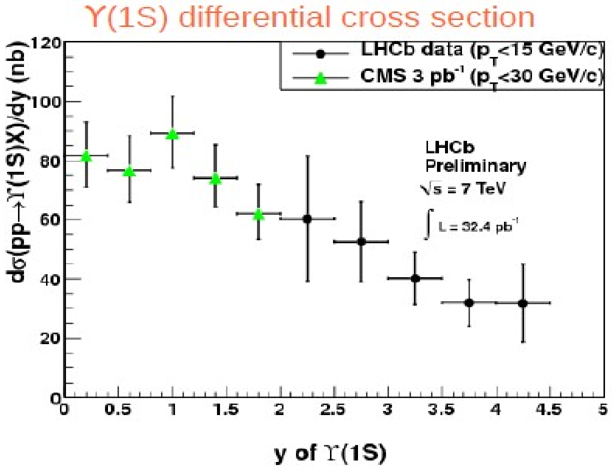
With unique rapidity coverage at LHC → complementary measurements





- LHCb acceptance : 2 <η < 5
- fully covered by tracking and PID

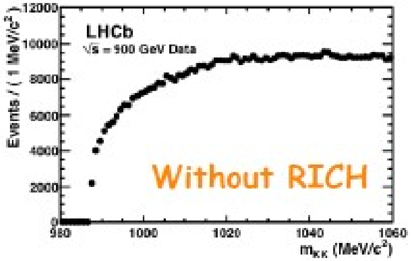


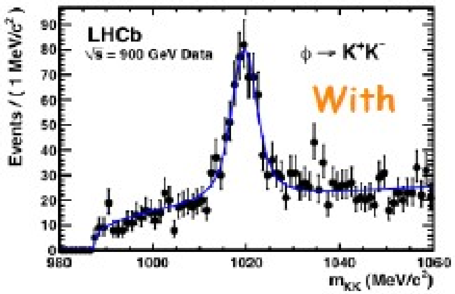


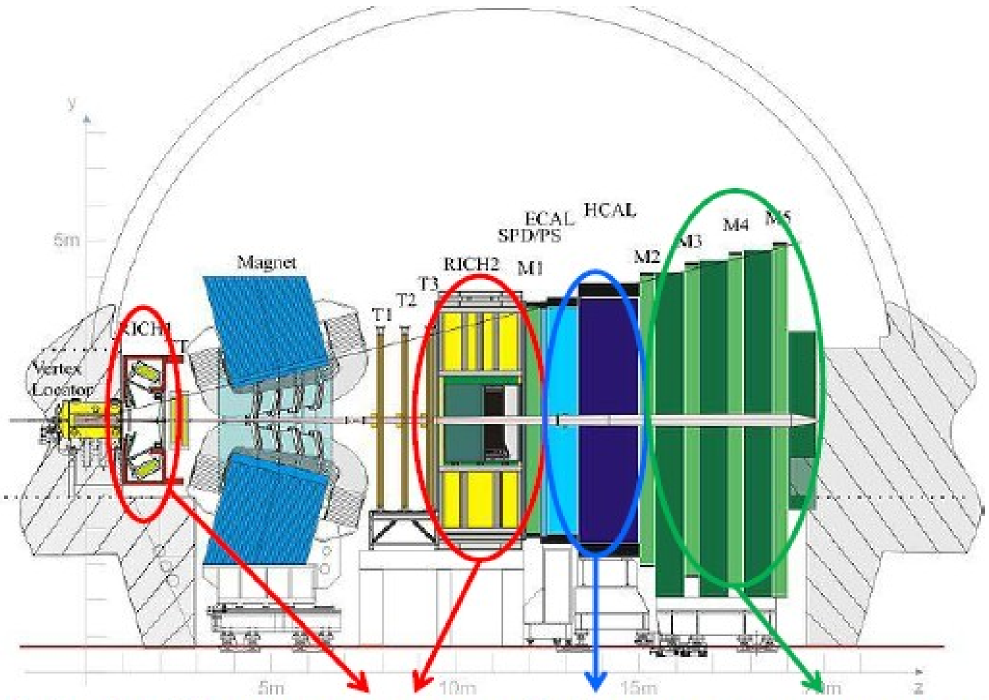
LHCb experiment

Required a sophisticated detector for precise measurements

1. Close to the beam
2. Vertex and Tracking capabilities
3. Distinguish particle in the final state (Particle identification)







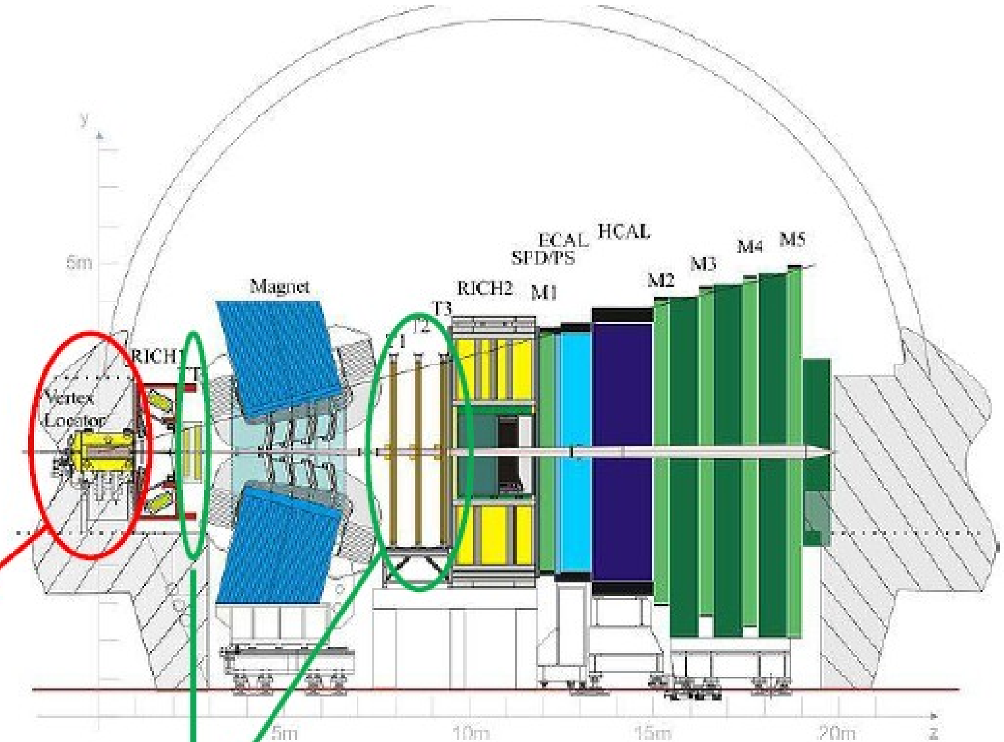
Particle Identification: RICHes + calorimeters + muon stations

- Allows to distinguish particles in the final states
- Peculiarity of LHCb: 2 RICH detectors:
  - Designed to distinguish K and π
  - Allows precise measurement of hadronic decays:
    - e.g. $B_s^0 \to D_s^- \pi^+$ vs $B_s^0 \to D_s^- K^+$
- Allows strong suppression of combinatorial background

LHCb experiment

Required a **sophisticated** detector for **precise** measurements

1. Close to the beam
2. Vertex and Tracking capabilities
3. Distinguish particle in the final state (Particle identification)



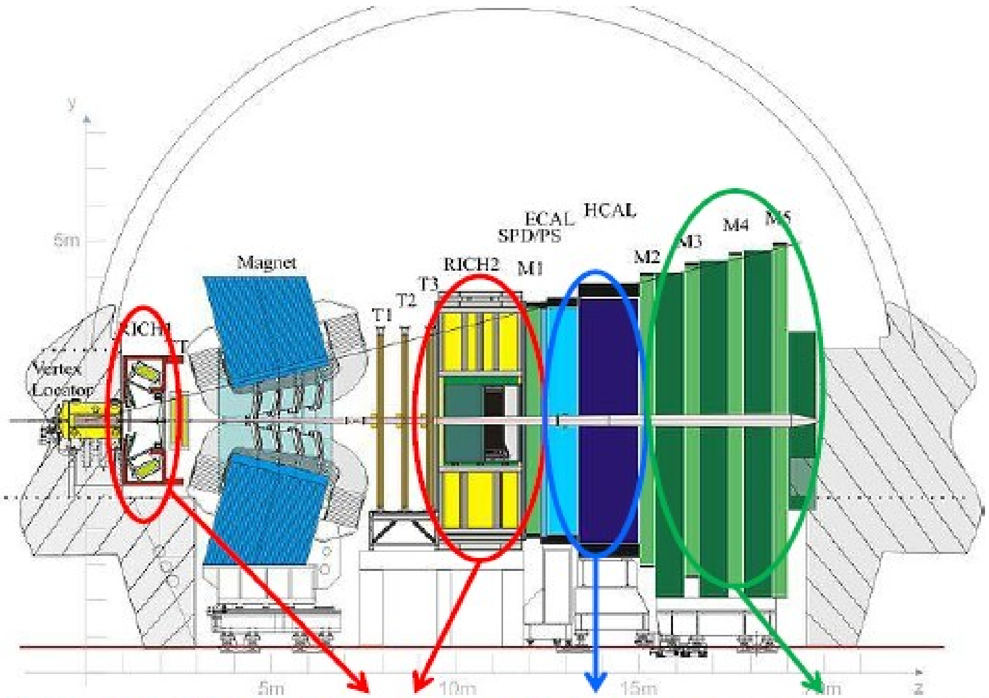
Vertex Locator: silicon strip detector
- Two moving halves
  - Openable during injection phase
  - Few mm from the beam line during data taking
- Excellent vertex resolution

Tracking system: silicon+straw tube technologies
- Excellent mass resolution: ~24MeV/c^2 for 2-body B decays
- Tracking efficiency >96% for long tracks

LHCb experiment

Required a <u>sophisticated</u> detector for <u>precise</u> measurements

1. Close to the beam
2. Vertex and Tracking capabilities
3. Distinguish particle in the final state (Particle identification)



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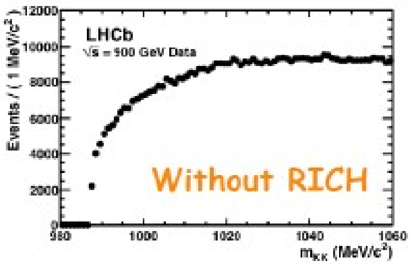
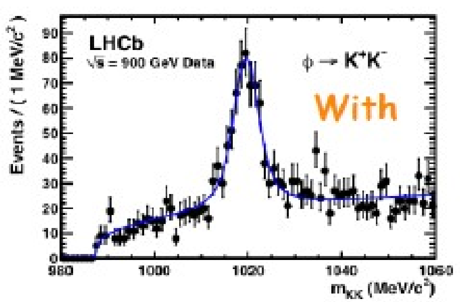
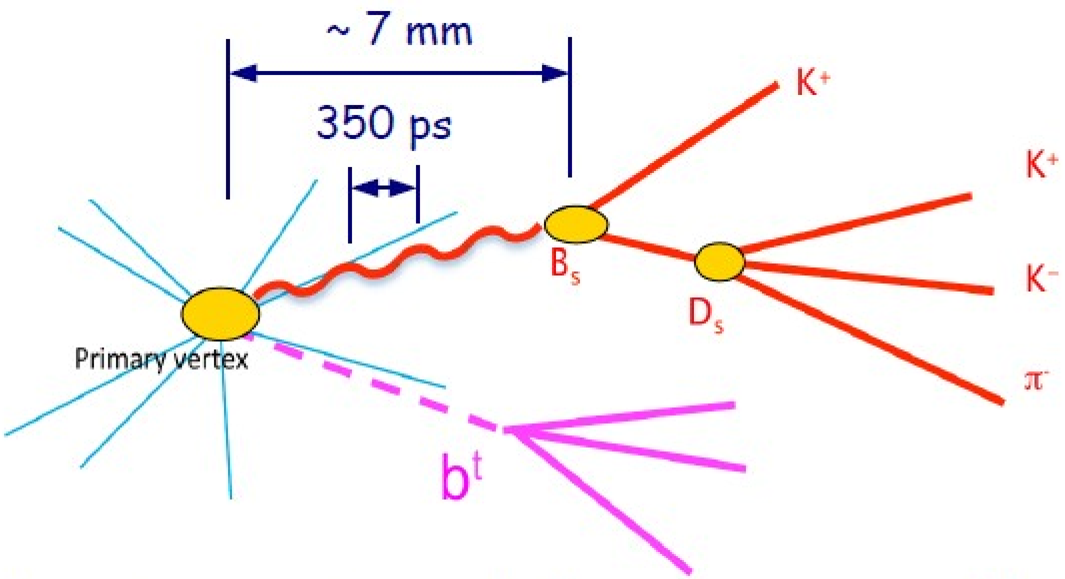




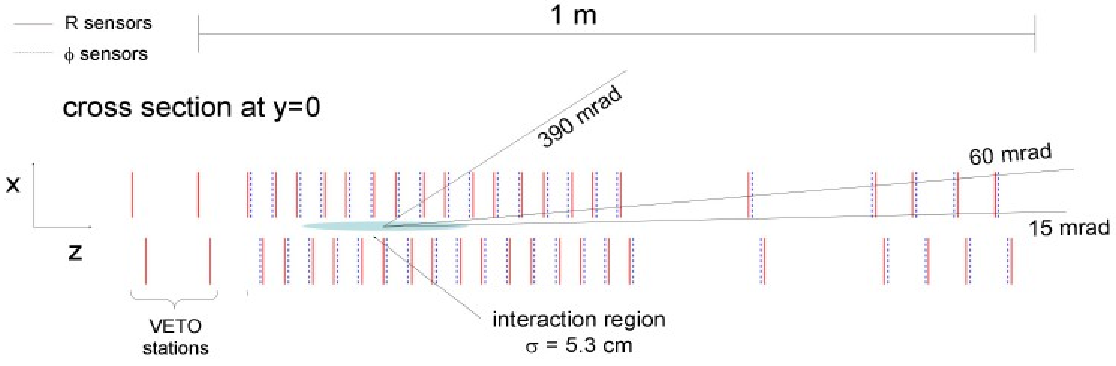
LHCb: a forward spectrometer optimised for heavy flavour



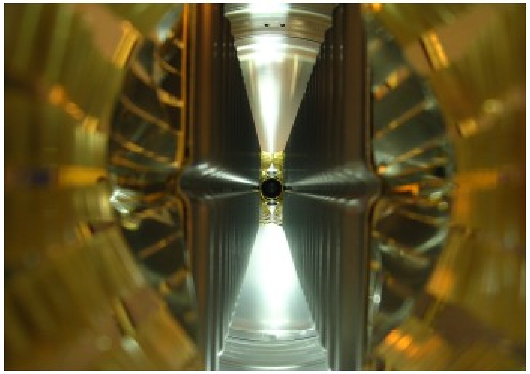
- **impact parameter resolution**
  - identify secondary vertices
- **proper time resolution**
  - resolve fast B^0_s-$\overline{B}^0_s$ oscillations
- **momentum, invariant mass resolution**
  - against combinatorial backgrounds
- **K/π separation**
  - against peaking backgrounds
  - flavour tagging
- **selective and efficient trigger, also for hadronic final states**
- **magnetic field reversed regularly to cancel detector asymmetries**

Vertex detection: the VErtex LOcator (VELO)

Reconstruction of primary and decay vertices, track seeds, + trigger input



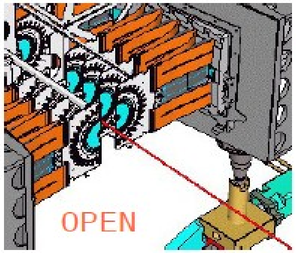
The VELO seen by the LHC beams

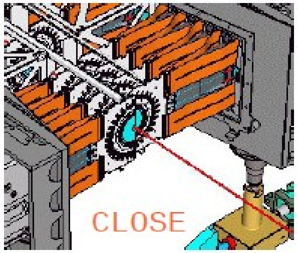


21 modules of R-Φ sensors

Movable device (retracted for safety during beam injection) :

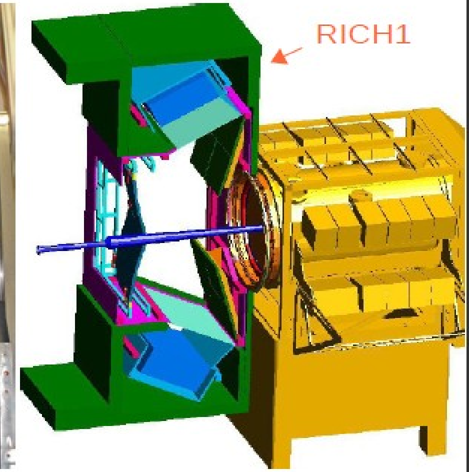
- 35 mm from beam out of physics
- 8 mm from beam during physics





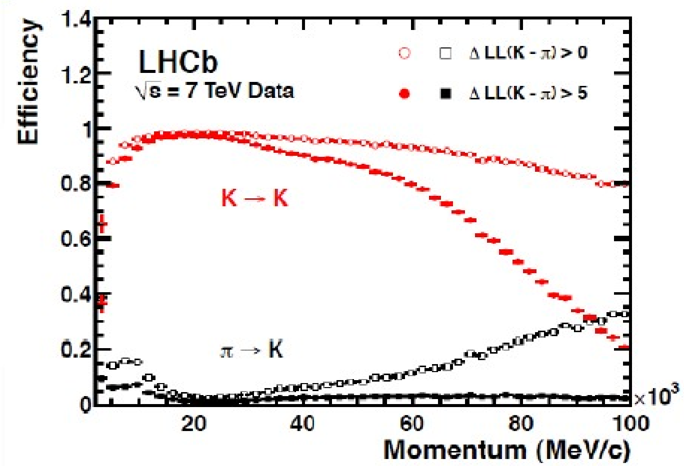
Particle identification: the RICH detectors

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



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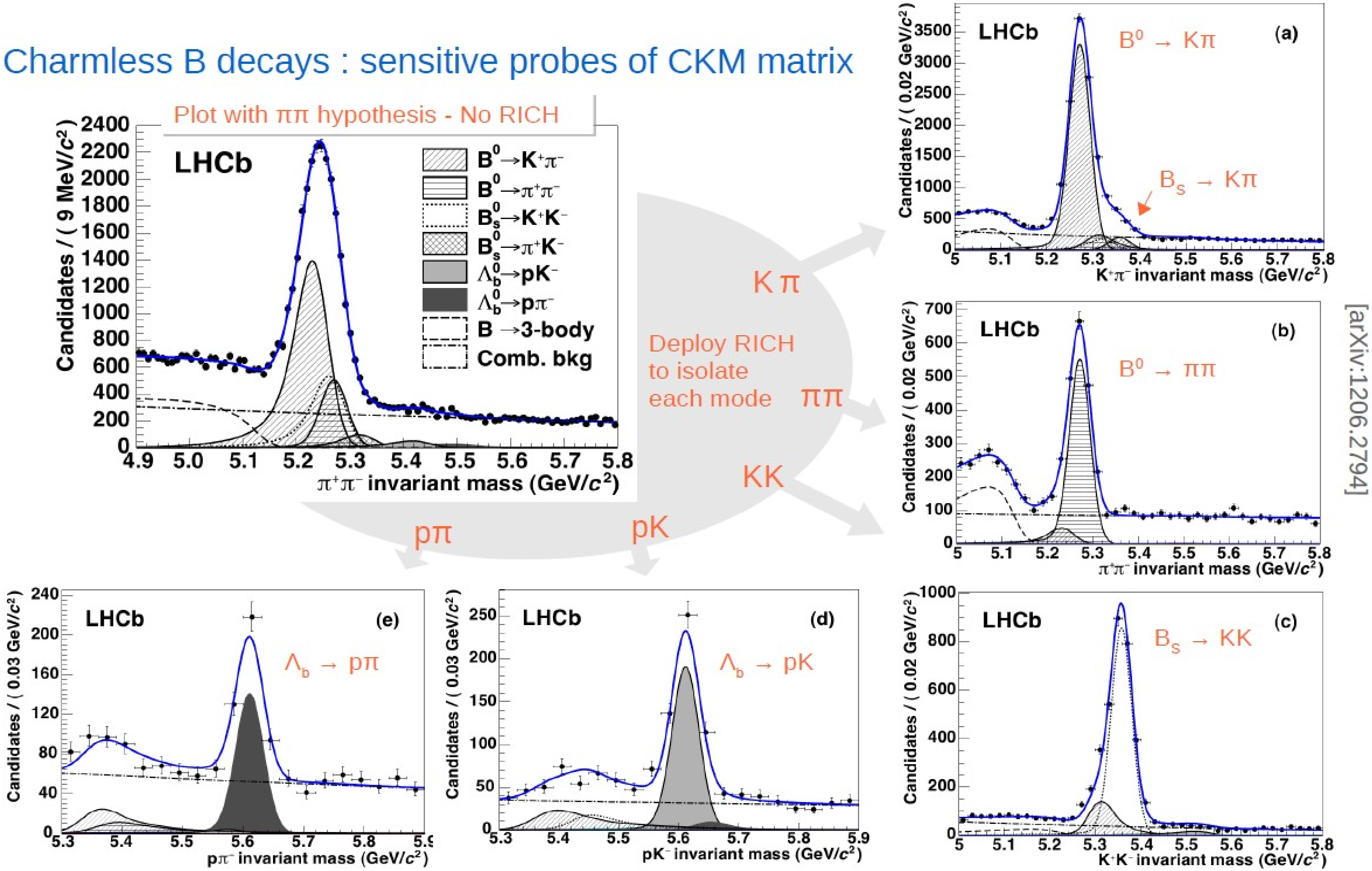
Performances

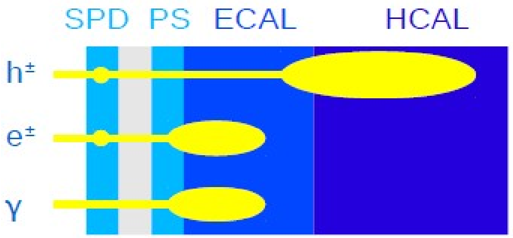
- $\varepsilon \approx 95\,\%$ for 5% π-K misID probability
- performances well described by simulation

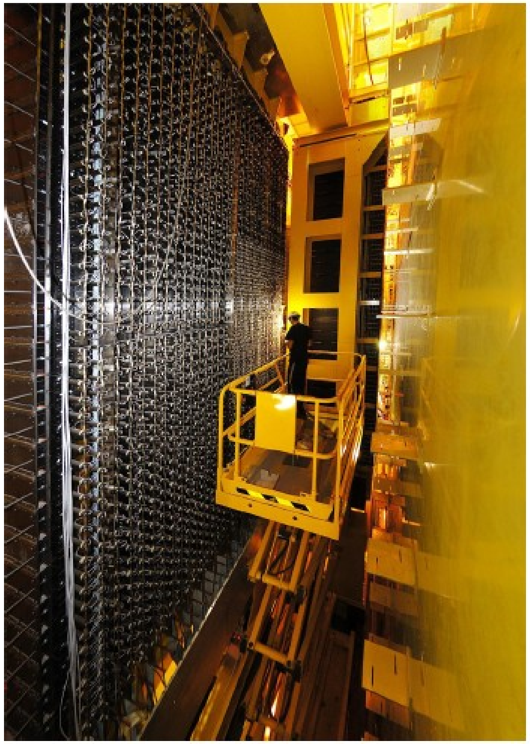
Particle identification

Charmless B decays : sensitive probes of CKM matrix



Particle identification: the calorimeters




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

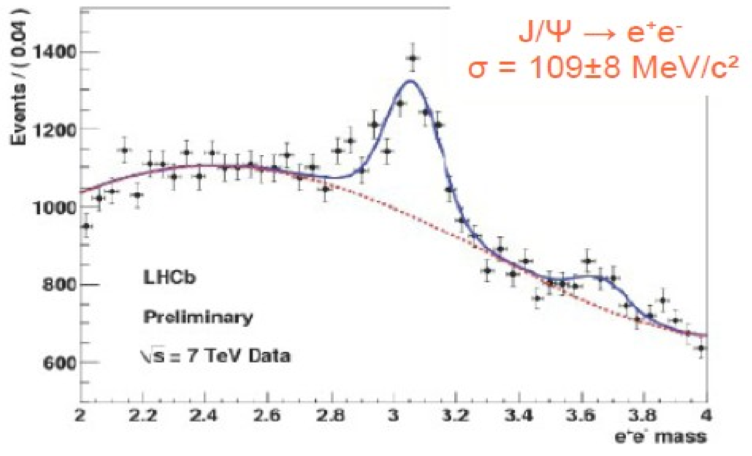
Electromagnetic CALorimeter :

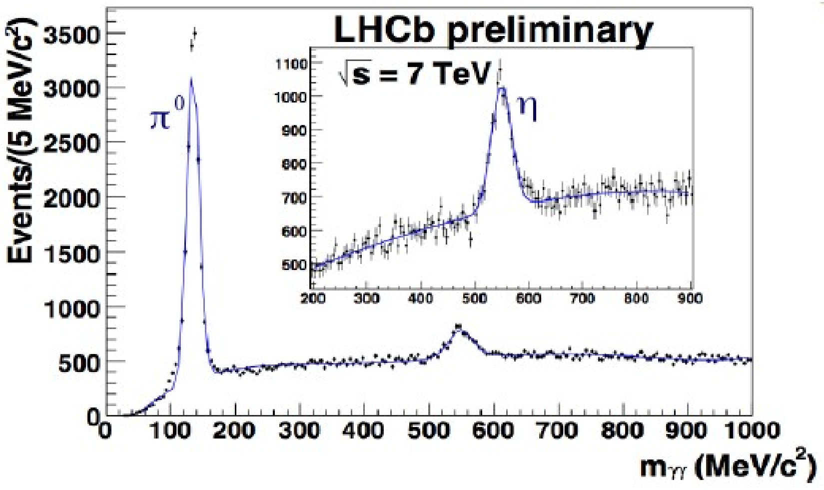
- e and γ energy measurement
- trigger on electromagnetic decay channels
- Pb plates / scintillator tiles (25 X_0)
- $\sigma(E)/E = 10\%/\sqrt{E(GeV)} + 1\%$ (nominal)

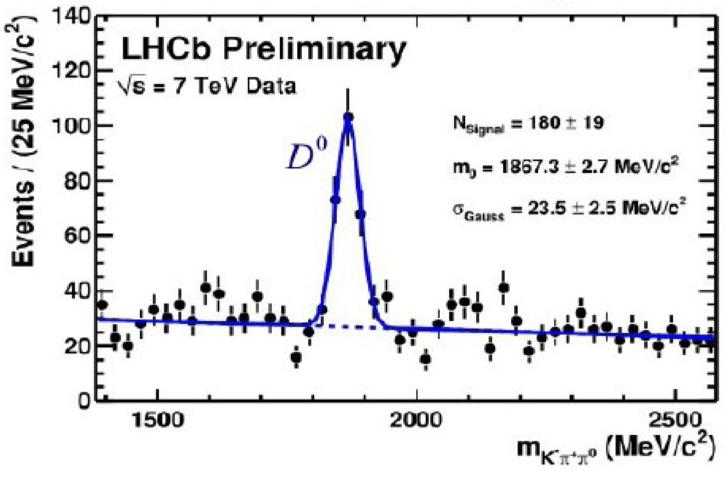
Hadronic CALorimeter :

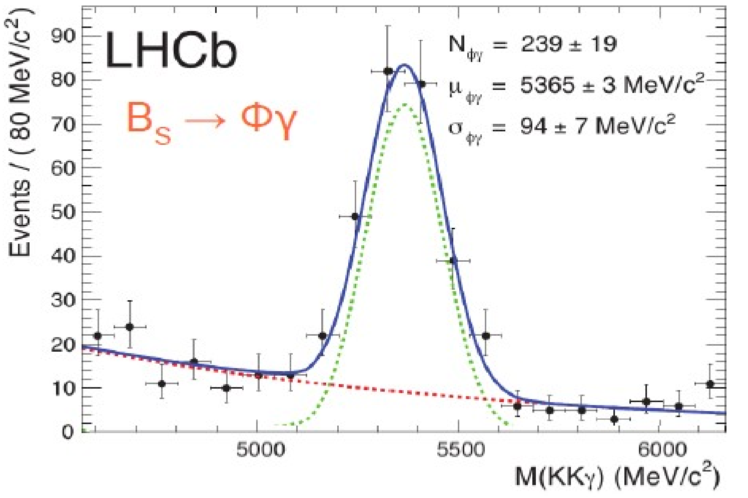
- energy measurement for hadron
- trigger on hadronic decay channels
- Fe plates / scintillator tiles
- $\sigma(E)/E = 69\%/\sqrt{E(GeV)} + 9\%$ (nominal), moderate but enough for triggering

Particle identification: e, γ and π^0



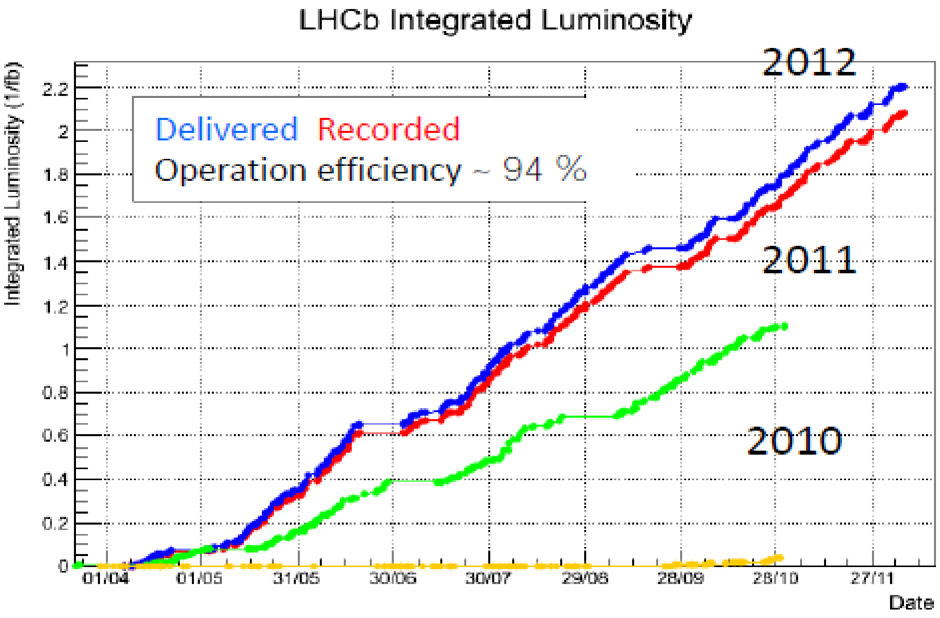






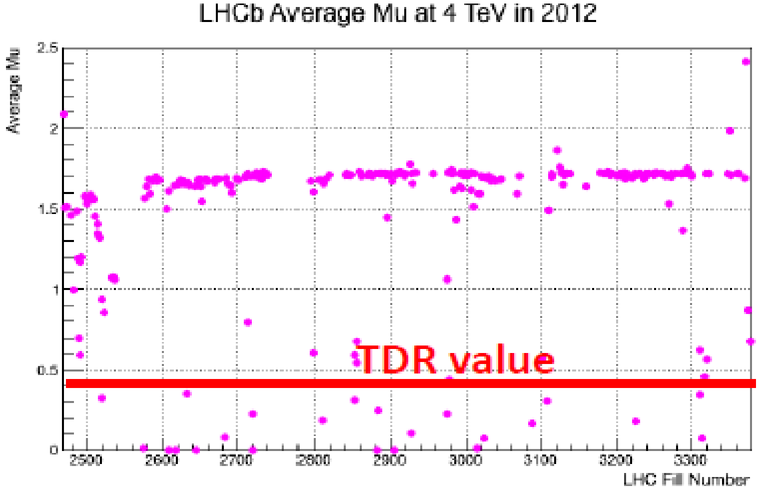
[arXiv:1202.6267]

LHCb operation status



LHCb designed to run at lower luminosity than ATLAS and CMS…
BUT
…we run at already at two times more than the designed one!

Running with an average number of processes per crossing more than 3 times bigger than the design ones

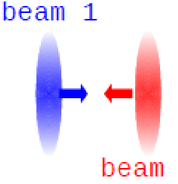


Luminosity

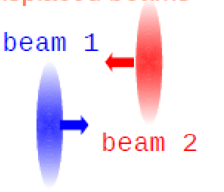
LHCb designed luminosity :

- $\mathcal{L}^{inst} = 2\times10^{32}\ cm^{-2}s^{-1}$ with μ=0.4 (# of visible pp int./crossing)
- Precision physics depending on vertex structure
  - → easier in a low-pileup environment

Full luminosity
central collisions

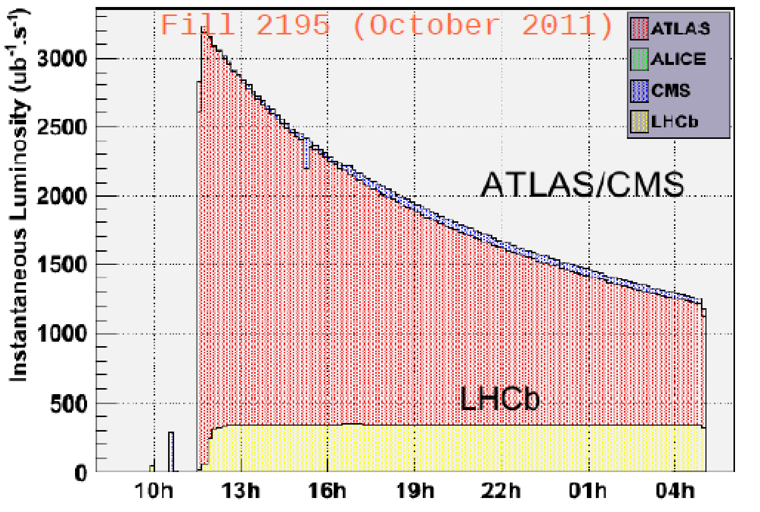


Reduced luminosity :
displaced beams

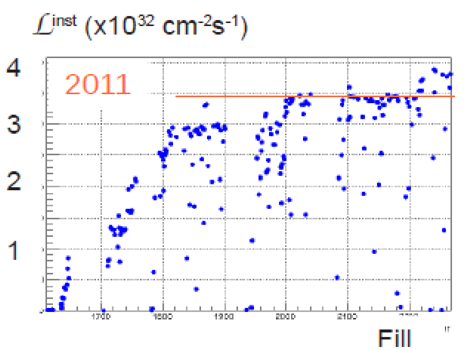


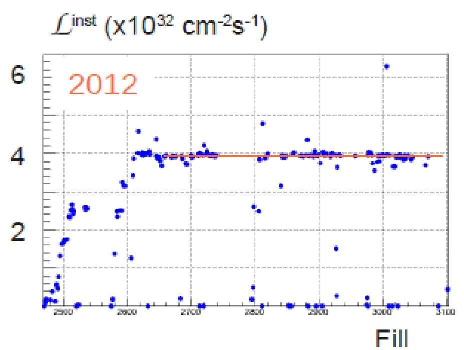
Luminosity levelling at LHCb

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



2011 & 2012 instantaneous luminosities :





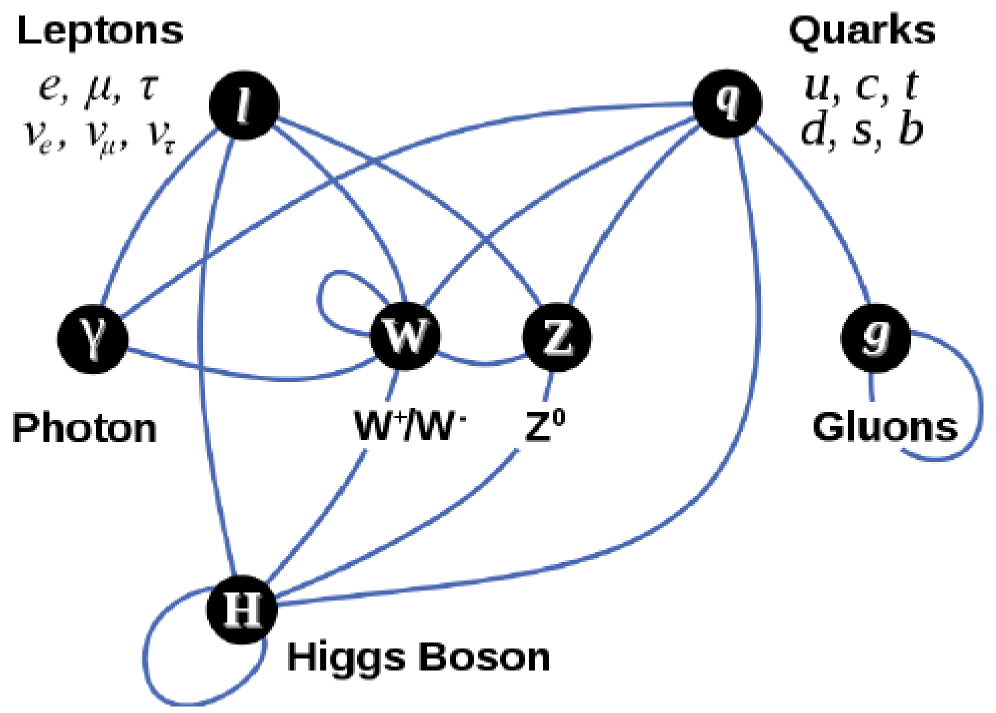
2011 : $\mathcal{L}^{inst}$ = ~ $3.5\times10^{32}\ cm^{-2}s^{-1}$, μ = ~1.5

2012 : $\mathcal{L}^{inst}$ = ~ $4.0\times10^{32}\ cm^{-2}s^{-1}$, μ = ~1.7

LHCb physics program

- Rare and very rare decays
- CP violation in Beauty and Charm physics
- Precision electroweak physics in the forward direction (Z/W bosons)
- Discovery of new exotic states using the excellent mass resolution of LHCb
- Search for unexpected long living particles and displaced vertices
- …

The Standard Model



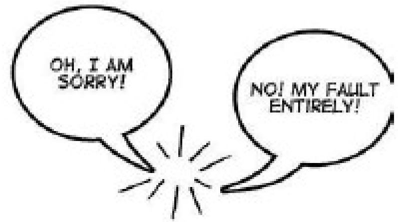
- Matter made of quarks and leptons
- The interactions between particles are mediated by particles called bosons.
- Masses generated through the Higgs mechanism

Standard Model confirmed by a wealth of experiments in the last 30 years...
... still NOT considered the final model ... it leaves some open questions

Few open questions

Why is the universe made of matter?

Matter and anti-matter were produced in the big bang



But matter and antimatter annihilate when they meet

Needed an asymmetry to allow it:

- CP violation in the Standard Model does not seem to be enough

Dark Matter

Presence of dark matter in the universe?

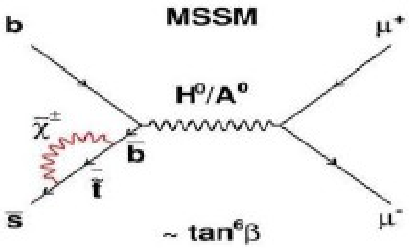
None particles in the Standard Model are satisfactory candidates for it

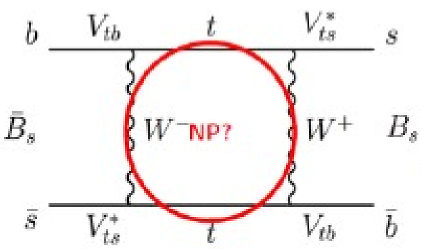
What is the dark matter made of?

Where can we look for New Physics?

Direct Search (Atlas and CMS): look for the production of new particles

Indirect Search (LHCb): look for effect due to the presence of new particles in the loop





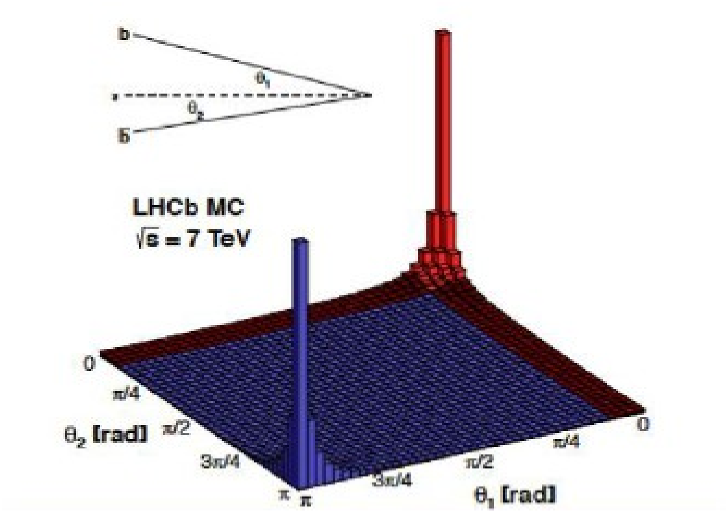
Enhancement of the branching fraction of very rare decays

Effects on the value of Standard Model parameters (precise measurements to look for discrepancy)

Precise measurements

- B-physics:
  - Precise theoretical prediction
  - Several final states accessible
  - Clear experimental signature
  - Indirect search (complementary approach to Atlas and CMS)

- 100,000 $b\bar{b}$ pairs produced per second
- $b\bar{b}$ pairs produced at low angle in the same forward or backward cone



B hadrons are made of quarks:

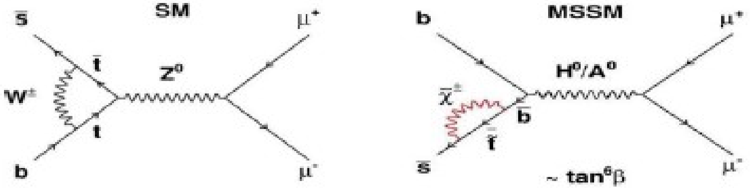
B mesons $(q\bar{b})$: $B^0(d\bar{b})$ and $B_s^0(s\bar{b})$

B baryon (qqb)

$B^0_{(s)} \to \mu^+\mu^-$ decay

Very rare decay in the SM:

Mode	SM prediction
$B_s \to \mu^+\mu^-$	$(3.54 \pm 0.30) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$(0.11 \pm 0.01) \times 10^{-9}$

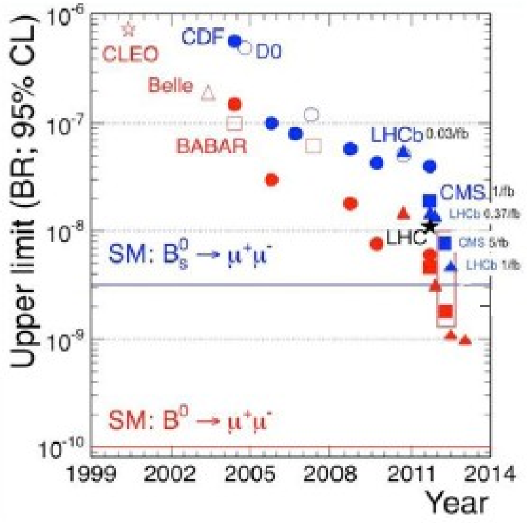


Features:

- Branching Fraction (BF) very well predicted in SM
- Fully reconstructable leptonic final state
- Never seen before, expected enhancement of the BF in several NP scenarios
- Useful to discriminate between NP scenarios

Searching it since 25 years

First attempt by ARGUS (1987)



Situation before October 2012 (95%CL):

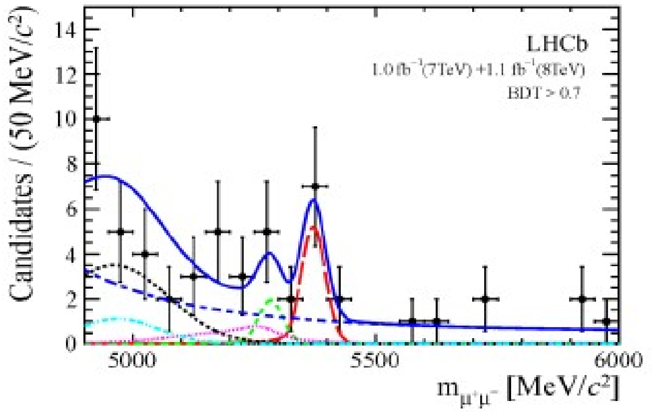
Atlas: $BF(B_s^0 \to \mu^+\mu^-) < 22 \cdot 10^{-9}$

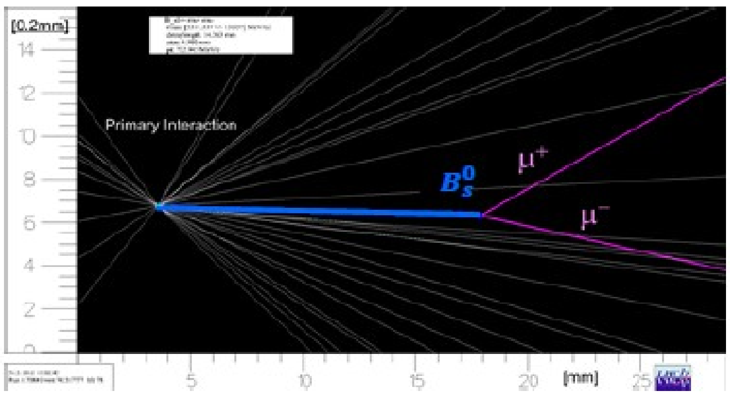
CMS: $BF(B_s^0 \to \mu^+\mu^-) < 7.7 \cdot 10^{-9}$

LHCb: $\boldsymbol{BF(B_s^0 \to \mu^+\mu^-) < 4.5 \cdot 10^{-9}}$

LHC combination: $BF(B_s^0 \to \mu^+\mu^-) < 4.2 \cdot 10^{-9}$

$B^0_{(s)} \to \mu^+\mu^-$ decay: first evidence





Measured Branching Fraction:

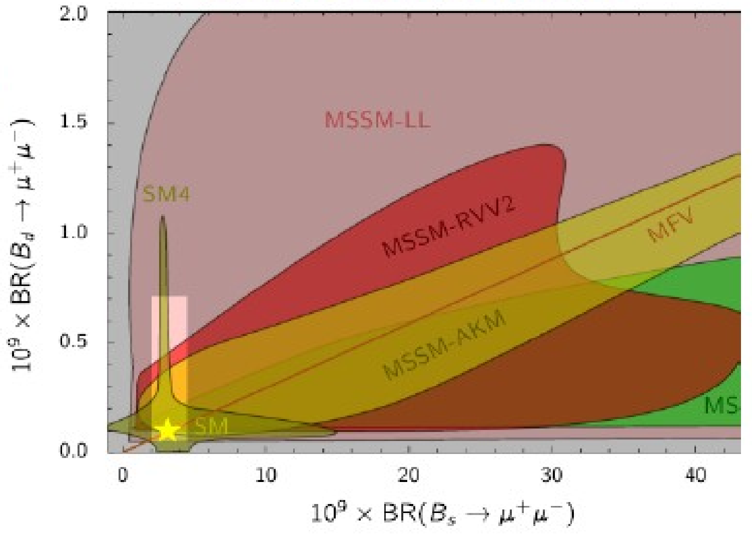
$$B_s^0 \to \mu^+\mu^- = (3.2^{+1.4}_{-1.2}(stat)^{+0.5}_{-0.3}\,(syst)) \cdot 10^{-9}$$

Tightest upper limit set:

$$B^0 \to \mu^+\mu^- < 9.4 \cdot 10^{-10}$$

- Results compatible with SM
- Strong constraint put on NP-scenarios

Physics implications:

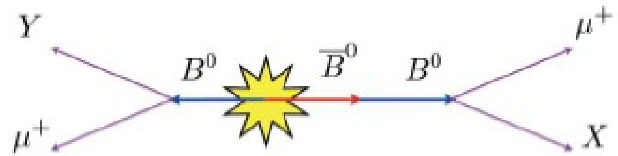


Flavour-specific matter antimatter asymmetry

Evidence of asymmetry **not consistent with the SM** by the DØ experiment (2010, updated 2011)

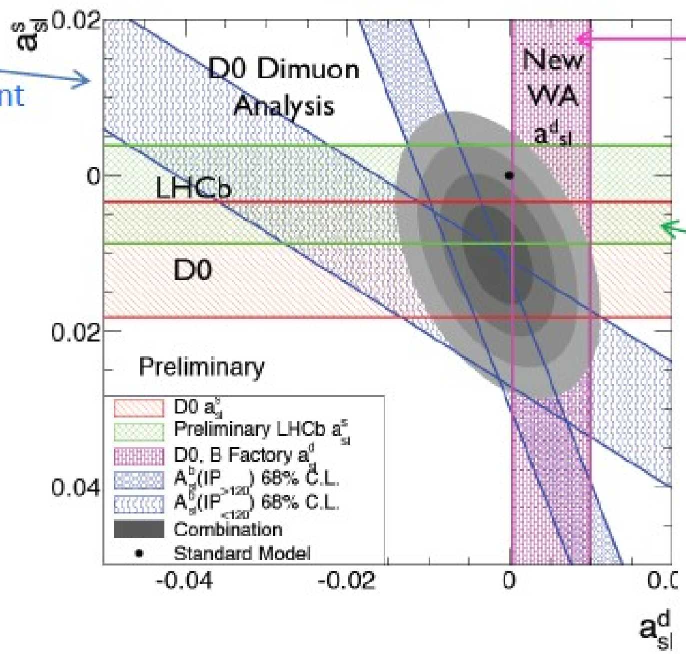
– More events with two negative muons than events with two positive muons

Sign of new physics?



$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

DØ experiment ($B^0 + B^0_s$)



DØ experiment + B-factories (B^0)

LHCb experiment (B^0_s)

LHCb result in agreement with SM

Needed more data for a conclusion

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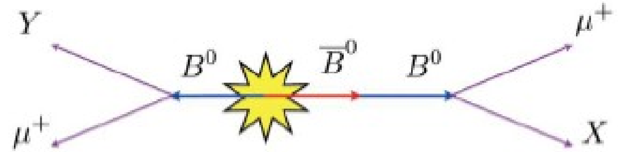

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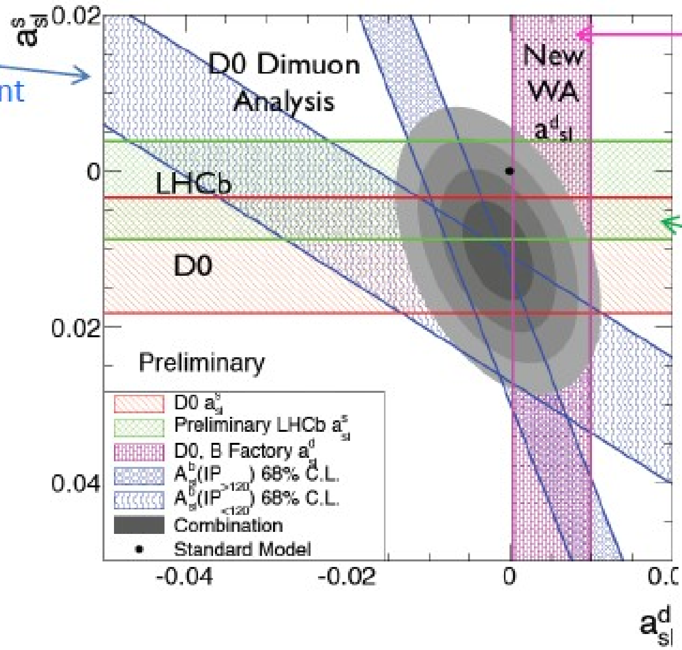
DØ experiment $(B^0 + B^0_s)$



DØ experiment + B-factories (B^0)

LHCb experiment (B^0_s)

LHCb result in agreement with SM

Needed more data for a conclusion

Why CP violation?

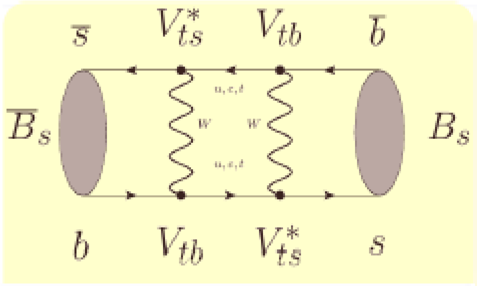
- New Physics models usually predict new heavy particles
  - these can enter in internal loops (Box diagrams and Penguins), lead to sizeable modification of CP phases
- the comparison of precise measurements of CP phases with precise predictions from Standard Model can therefore reveal the presence of New Physics
- these indirect searches for New Physics make use of the appearance of virtual particles in loop diagrams
- are therefore sensitive to higher mass scales than direct searches for new particles

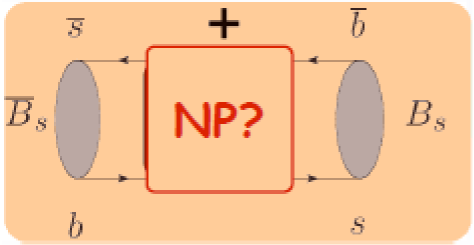
classic example: CP violation in $K^0\bar{K}^0$ (1964)

→ prediction of 3rd quark family (top direct discovery 1995)

- moreover, the pattern of observed deviations can hint at the structure of the New Physics at work

Sources of CP violation





<u>CP violation in mixing</u> ("indirect" CP violation)

- neutral meson systems ($K^0\overline{K}^0$, $D^0\overline{D}^0$, $B^0\overline{B}^0$, $B^0_s\overline{B}^0_s$): particle-antiparticle mixing due to box diagrams
- time evolution described by Schroedinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B^0_s \\ \overline{B}^0_s \end{pmatrix} = \begin{pmatrix} M^s_{11} - i\frac{\Gamma^s_{11}}{2} & M_{12} - i\frac{\Gamma^s_{12}}{2} \\ M^{s*}_{12} - i\frac{\Gamma^{s*}_{12}}{2} & M^s_{22} - i\frac{\Gamma^s_{22}}{2} \end{pmatrix} \cdot \begin{pmatrix} B^0_s \\ \overline{B}^0_s \end{pmatrix}$$

- solution yields mass eigenstates (= particles that propagate in vacuum):

$$|B_{s,L}\rangle = p\,|B^0_s\rangle + q\,|\overline{B}^0_s\rangle \qquad |B_{s,H}\rangle = p\,|B^0_s\rangle - q\,|\overline{B}^0_s\rangle$$

- CP violation due to interference of Γ_{12} and M_{12} if $\phi^s_M = \arg\left(-M^s_{12}/\Gamma^s_{12}\right) \neq 0$
  - results in $|q/p| \neq 1$: mass eigenstates are not CP eigenstates
  - different transition rates for $B^0_s \to \overline{B}^0_s$ and $\overline{B}^0_s \to B^0_s$
- New Physics can enter through heavy new particles in box and affect ϕ^s_M

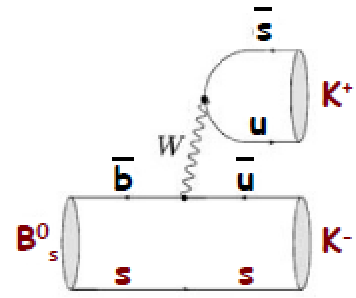
Sources of CP violation

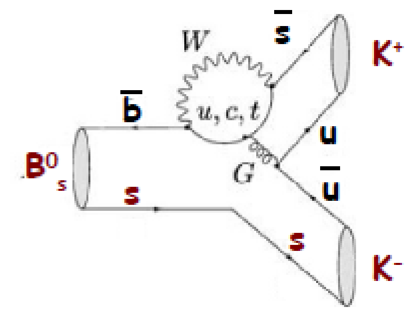
<u>CP violation in decay</u> ("direct" CP violation)

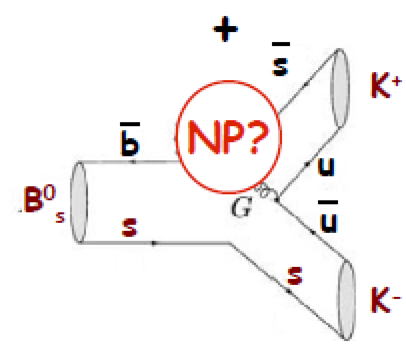
- due to interference of decay diagrams with different weak and strong phases
- causes different decay amplitudes for a process and its CP conjugate: $\left|\overline{A}_{\overline{f}}/A_f\right| \neq 1$
- measure time-integrated decay rate asymmetry

$$A_{\pm} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to \overline{f})}{\Gamma(B^- \to f) + \Gamma(B^+ \to \overline{f})} \neq 0$$

- interfering amplitudes usually involve Penguin diagrams
  - New Physics can then enter through new heavy particles in Penguin loops
- challenge: disentangle weak phase from strong phase



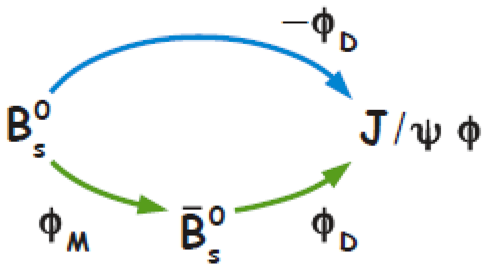




Sources of CP violation

CP violation due to the interferenc of mixing and decay

- if final state f accessible to both B^0_s and $\bar{B}^0_s$:
  CP violated due to interference between direct decay and decay after mixing if



$$\mathrm{Im}\left(\frac{\bar{A}_f}{A_f}\cdot\frac{q}{p}\right) \neq 0$$

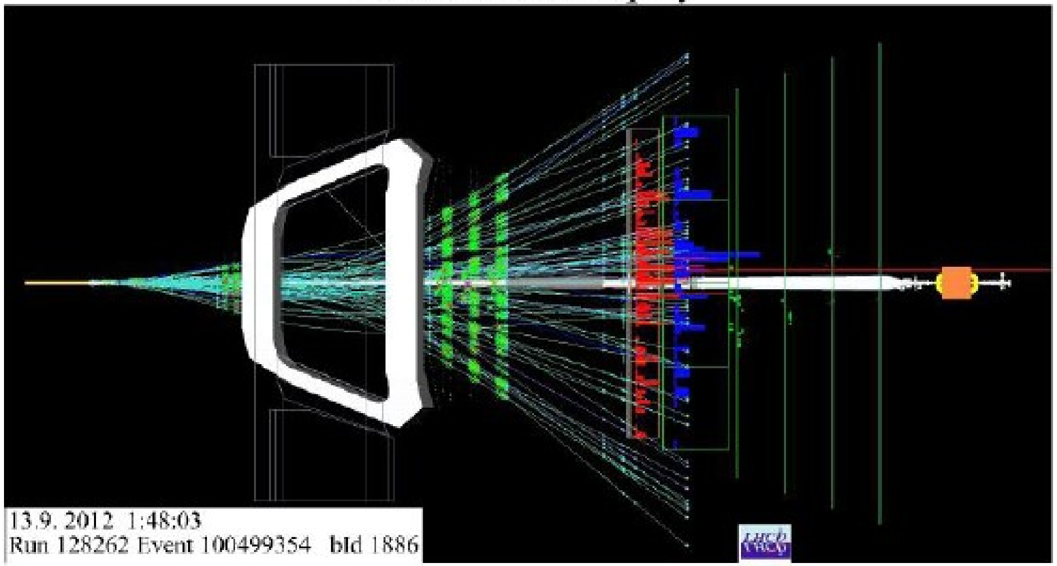
- measure time-dependent decay rate asymmetry:

$$A_{CP}(t) = \frac{\Gamma(B^0_s(t=0)\to f(t)) - \Gamma(\bar{B}^0_s(t=0)\to f(t))}{\Gamma(B^0_s(t=0)\to f(t)) + \Gamma(\bar{B}^0_s(t=0)\to f(t))} = \underbrace{S\sin(\Delta m_s t) + C\cos(\Delta m_s t)}_{\Delta m_s = m(B_{s,H}) - m(B_{s,L})}$$

- most prominent example pre-LHCb:
  measurement of CKM angle 2β in $B^0 \to J/\psi\ K^0_s$ by Babar and Belle
- NP can change phase of mixing (box diagram) and decay (if penguin)
- n.b. CP can be violated in this case even if $|q/p| = 1$ and $|\bar{A}_f/A_f| = 1$

First experience with ions

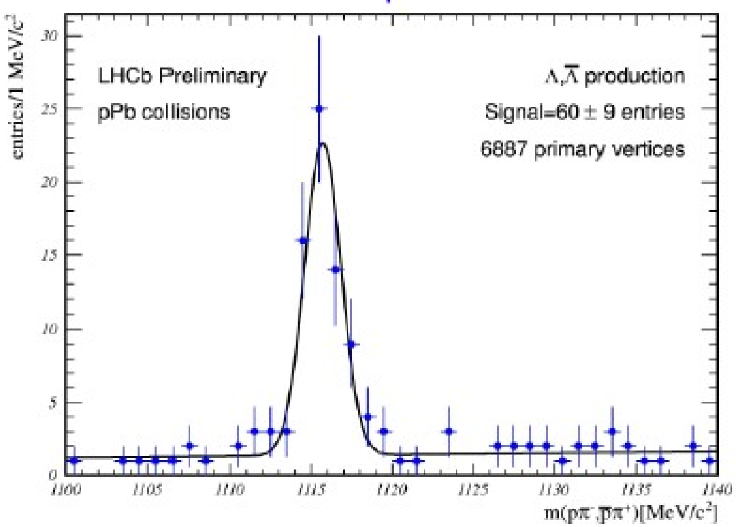
LHCb Event Display



First experience with pPb collisions in September:

- Stable conditions
- Multiplicity in the detector compatible with pp collisions

Lambda production



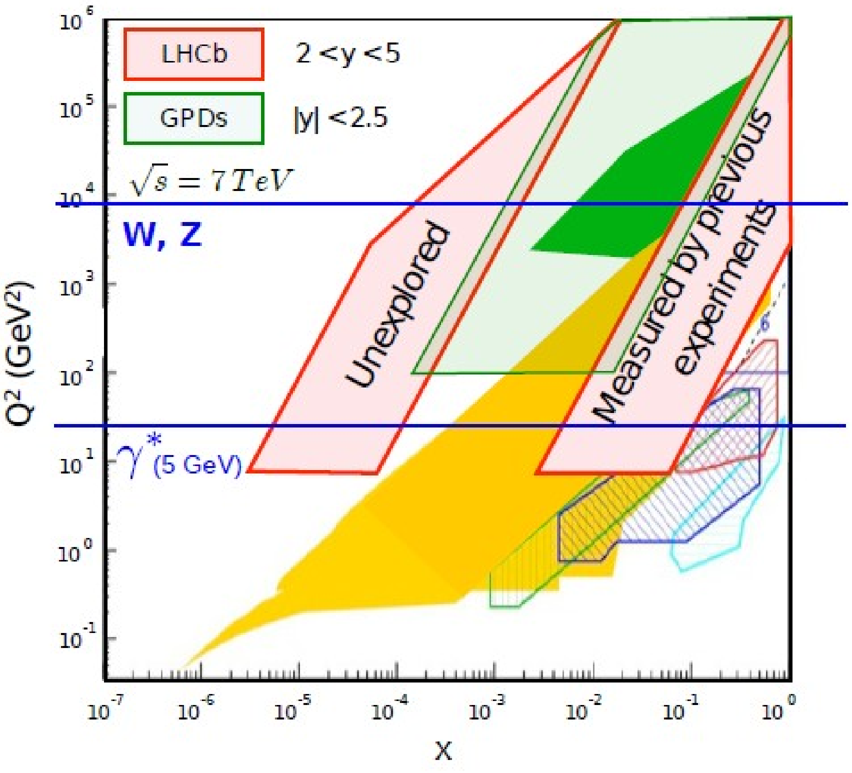
- Various resonances already reconstructed offline
- Ready for the pPb physics data taking early next year

Electroweak measurements at LHCb

$x_{a,b} = \frac{M}{\sqrt{s}} \cdot e^{\pm\eta}$ fraction of proton momentum carried by parton

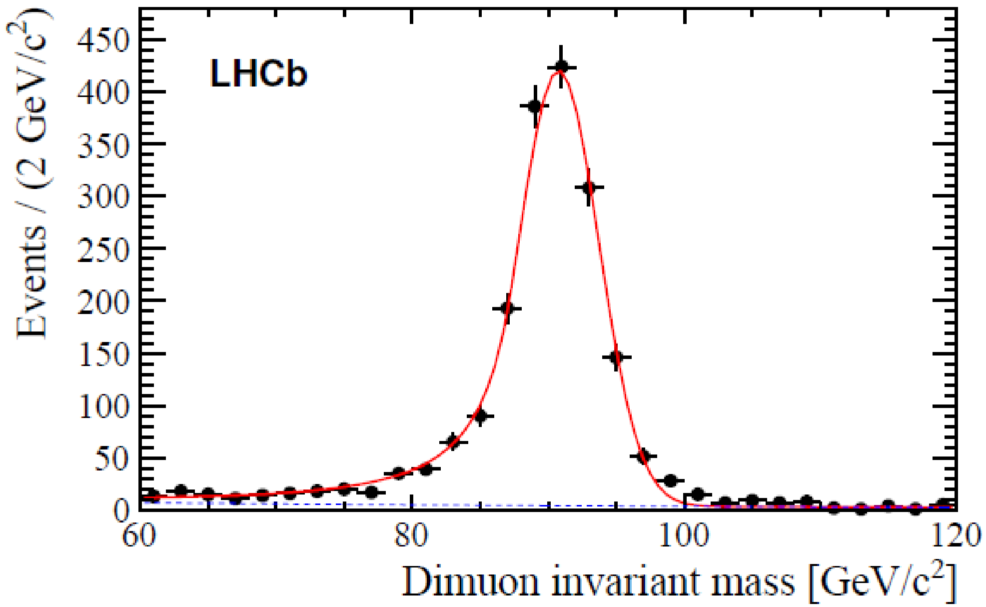
$Q^2 = M^2$ 4-momentum transfered

- LHCb probes two distinct regions in x/Q^2 plane
- unique region at low x down to $x = 8 \cdot 10^{-6}$



Electroweak measurements at LHCb

$Z \rightarrow \mu^+\mu^-$ (JHEP 2012, 6 (2012), 58)



Data

- 2010 dataset
  $\mathcal{L} = 37\,\text{pb}^{-1}$
- $60 < M_{\ell\ell} < 120\,\text{GeV}/c^2$
- $2 < \eta_\ell < 4.5$
- $p_T > 20\,\text{GeV}/c$

Nr. of Candidates 1966

Purity 99.7 %

Electroweak measurements at LHCb

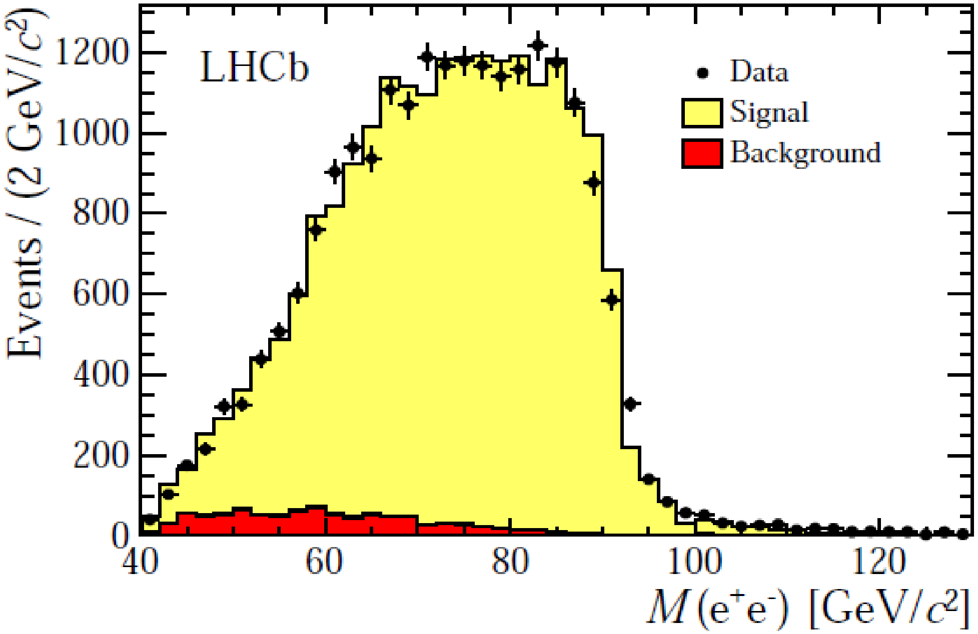
$Z \to e^+e^-$ (arXiv:1212.4620 [hep-ex])

Data

- 2011 dataset
  $\mathcal{L} = 945\,\mathrm{pb}^{-1}$

Challenges

- Energy measurement
  - saturation in calo
  - bremsstrahlung
- QCD background
  - use same-sign data



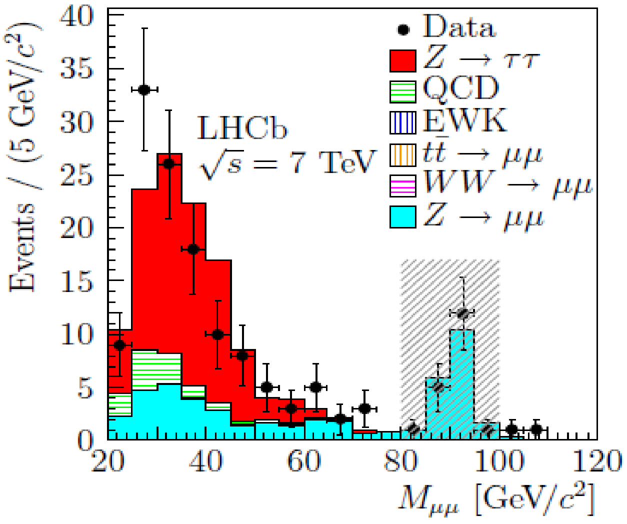
Nr. of Candidates	21 420
Purity	95.5 %

Electroweak measurements at LHCb

$Z \rightarrow \tau^+\tau^-$: Two Examples

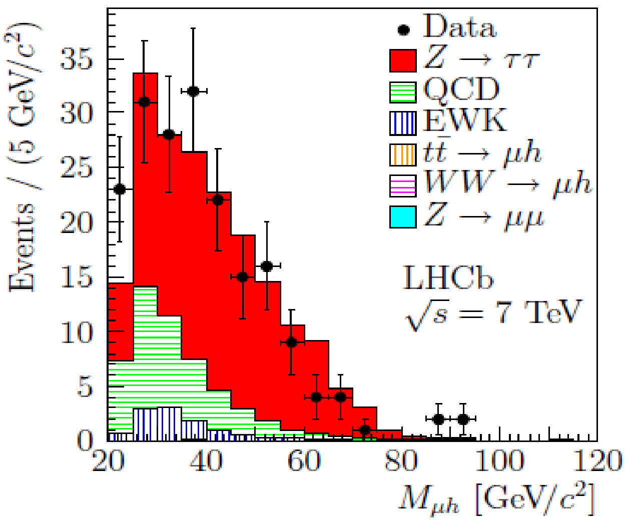
(arXiv:1210.6289 [hep-ex])

$Z \rightarrow \tau^+\tau^- \rightarrow \mu^+\mu^-$



Nr. of Candidates 124
Purity 75 %

$Z \rightarrow \tau^+\tau^- \rightarrow \mu h$



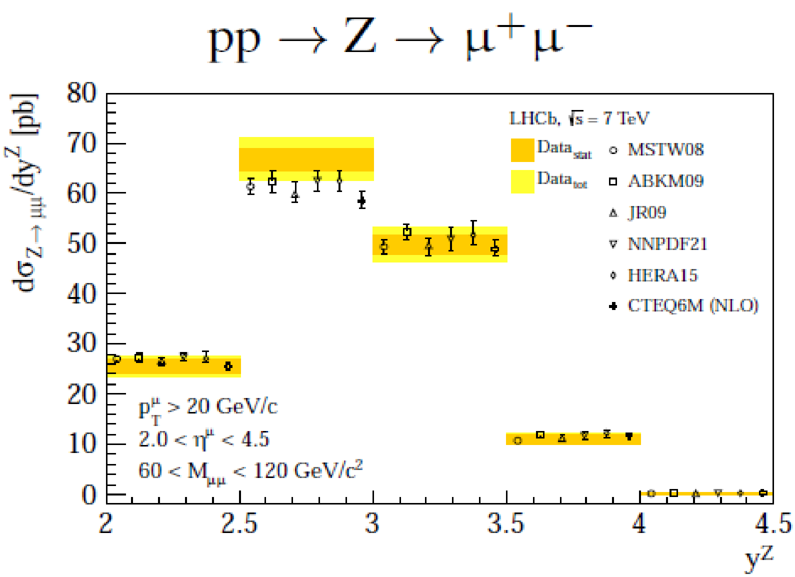
Nr. of Candidates 189
Purity 78 %

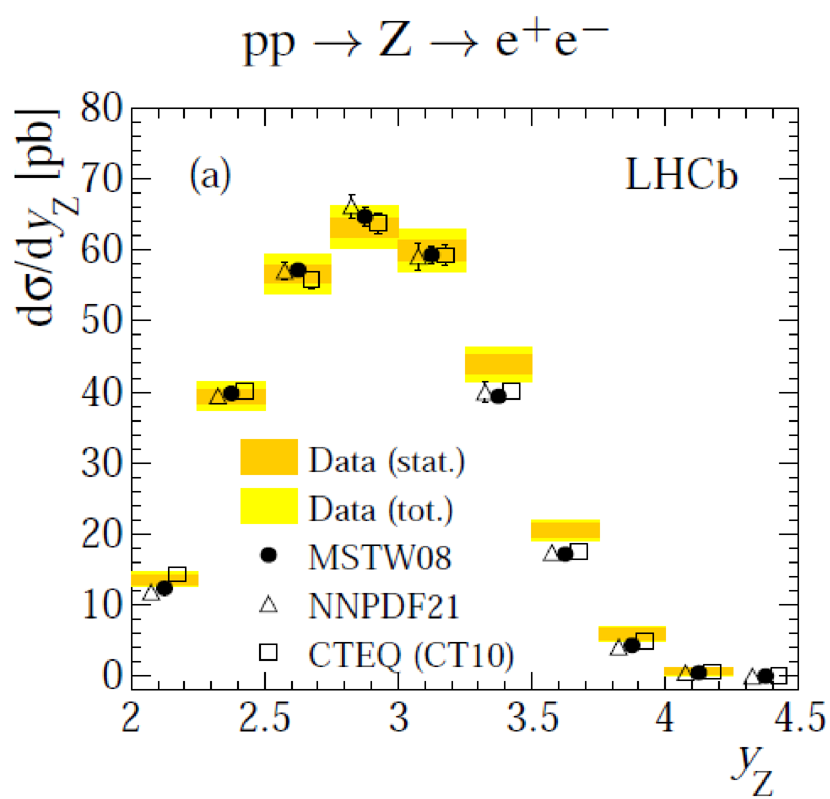
Total Nr. of Candidates 990

Electroweak measurements at LHCb

Differential Production Cross Sections

(JHEP 2012, 6 (2012), 58; arXiv:1212.4620 [hep-ex])



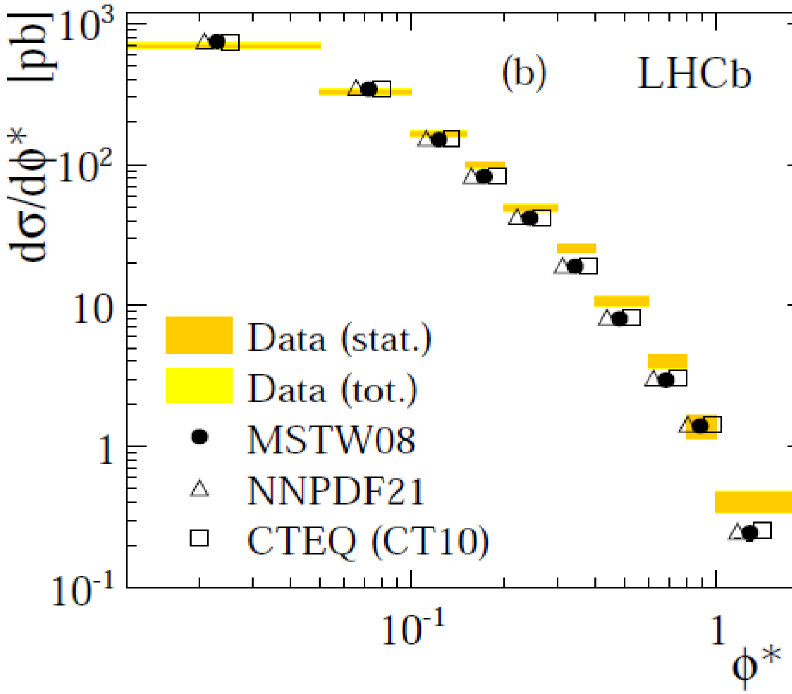


Compared to NNLO predictions (DYNNLO)

Electroweak measurements at LHCb

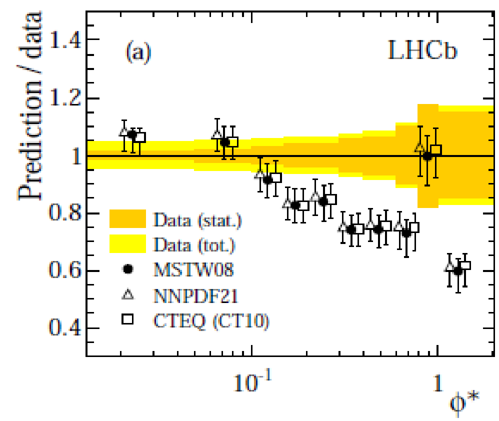
e^+e^- Angular Result

(arXiv:1212.4620 [hep-ex])

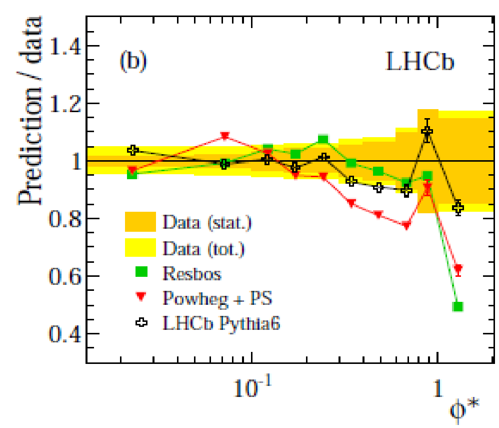


$$\phi^* \equiv \frac{\tan\left(\frac{\pi - |\Delta\phi|}{2}\right)}{\cosh\left(\frac{\Delta\eta}{2}\right)} \approx \frac{p_T}{Mc}$$

Fixed Order (no soft gluons)

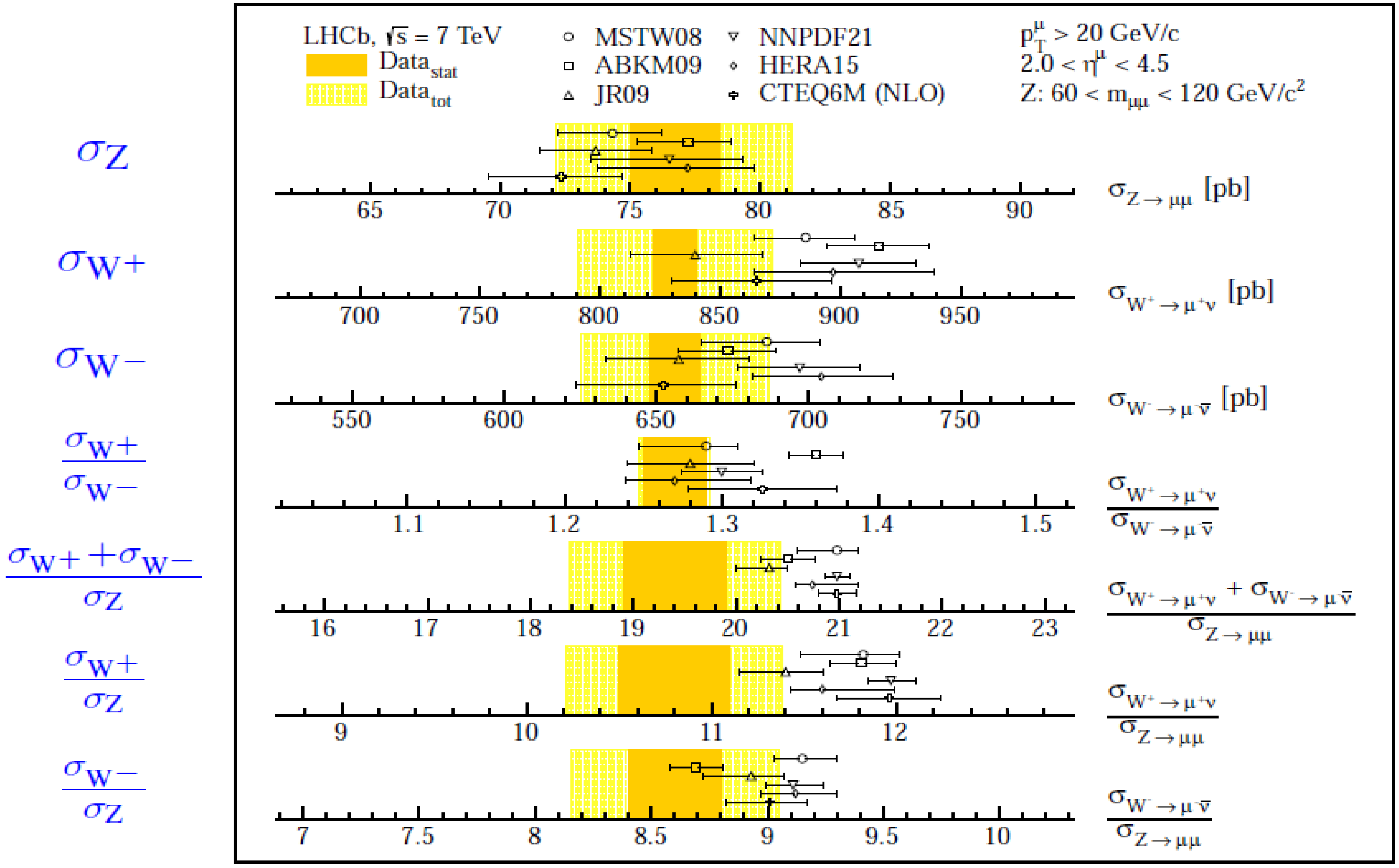


Resummation / Parton Shower



Electroweak measurements at LHCb

Production Cross Section and Ratios (JHEP 2012, 6 (2012), 58)

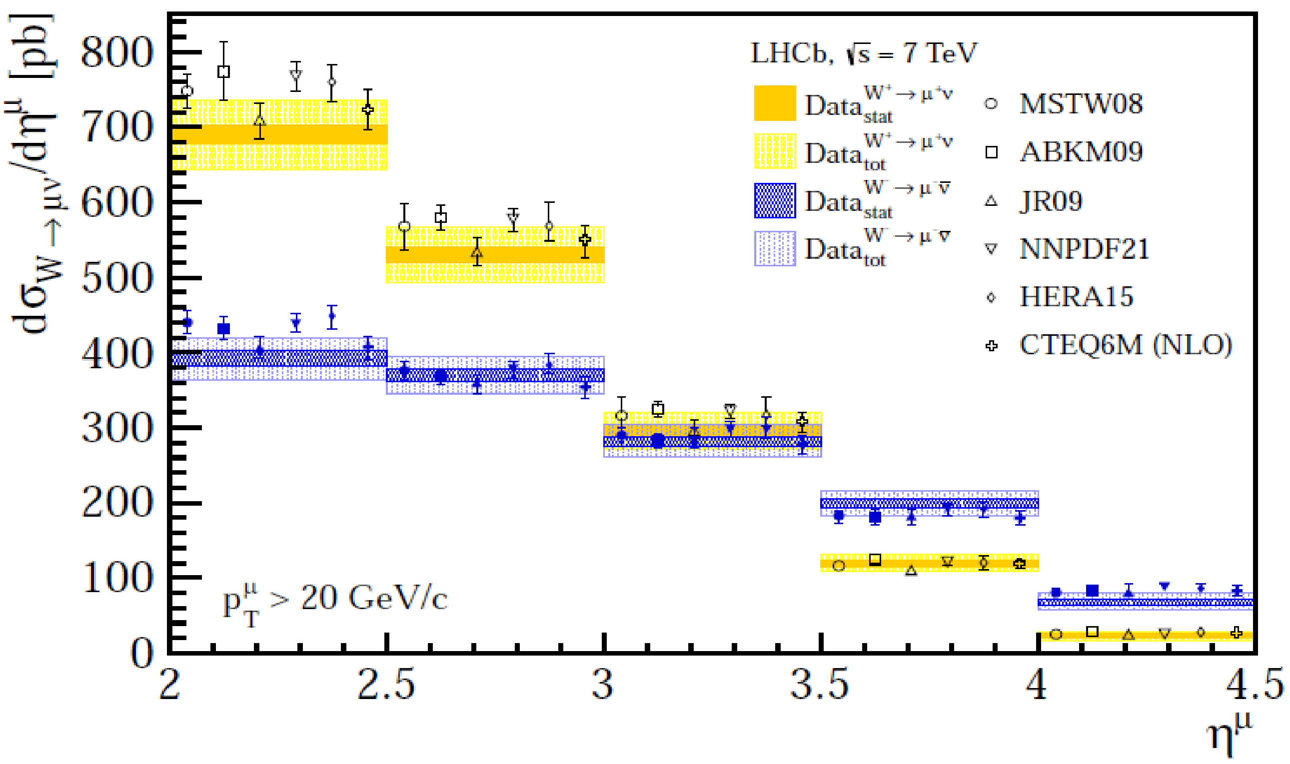


Compared to NNLO predictions (DYNNLO)

Electroweak measurements at LHCb

Differential W Cross Section

(JHEP 2012, 6 (2012), 58)



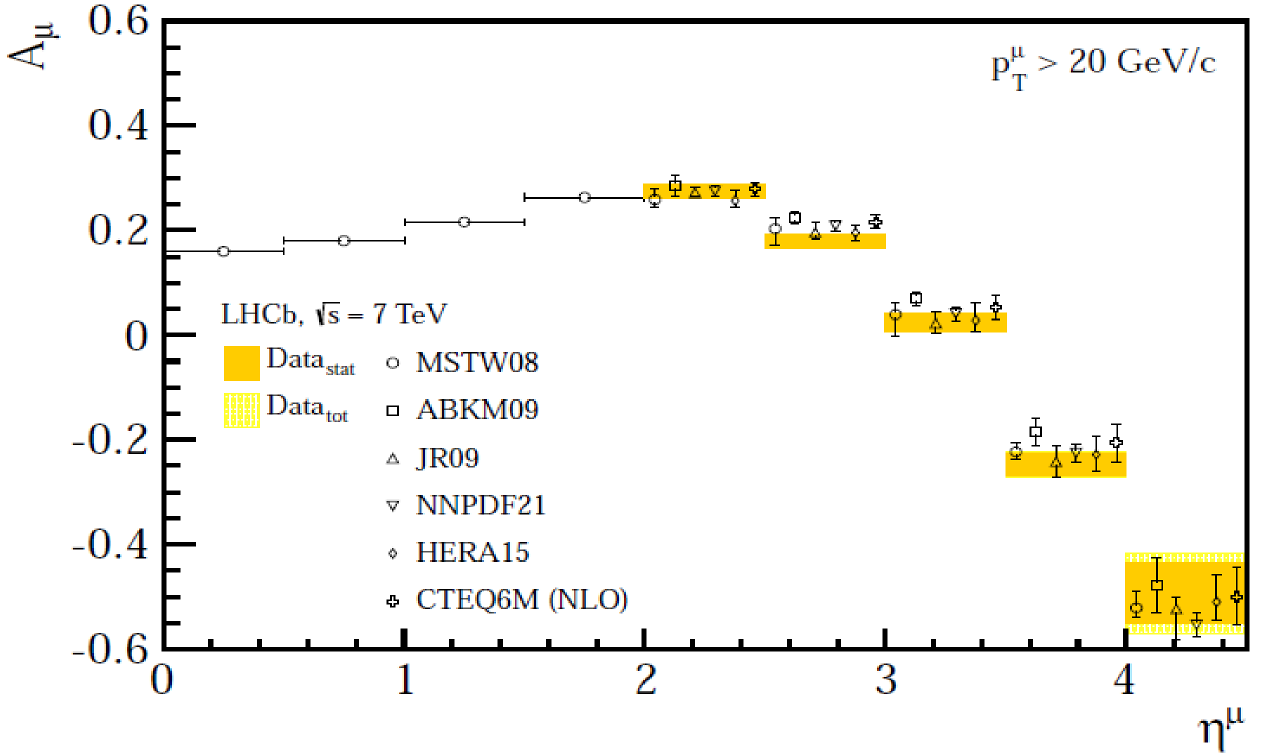
As expected W^- production higher than W^+ in forward region

Electroweak measurements at LHCb

Lepton Charge Asymmetry

(JHEP 2012, 6 (2012), 58)

$$A_\mu = \frac{\sigma_{W^+ \to \mu^+ \nu} - \sigma_{W^- \to \mu^- \bar{\nu}}}{\sigma_{W^+ \to \mu^+ \nu} + \sigma_{W^- \to \mu^- \bar{\nu}}}$$

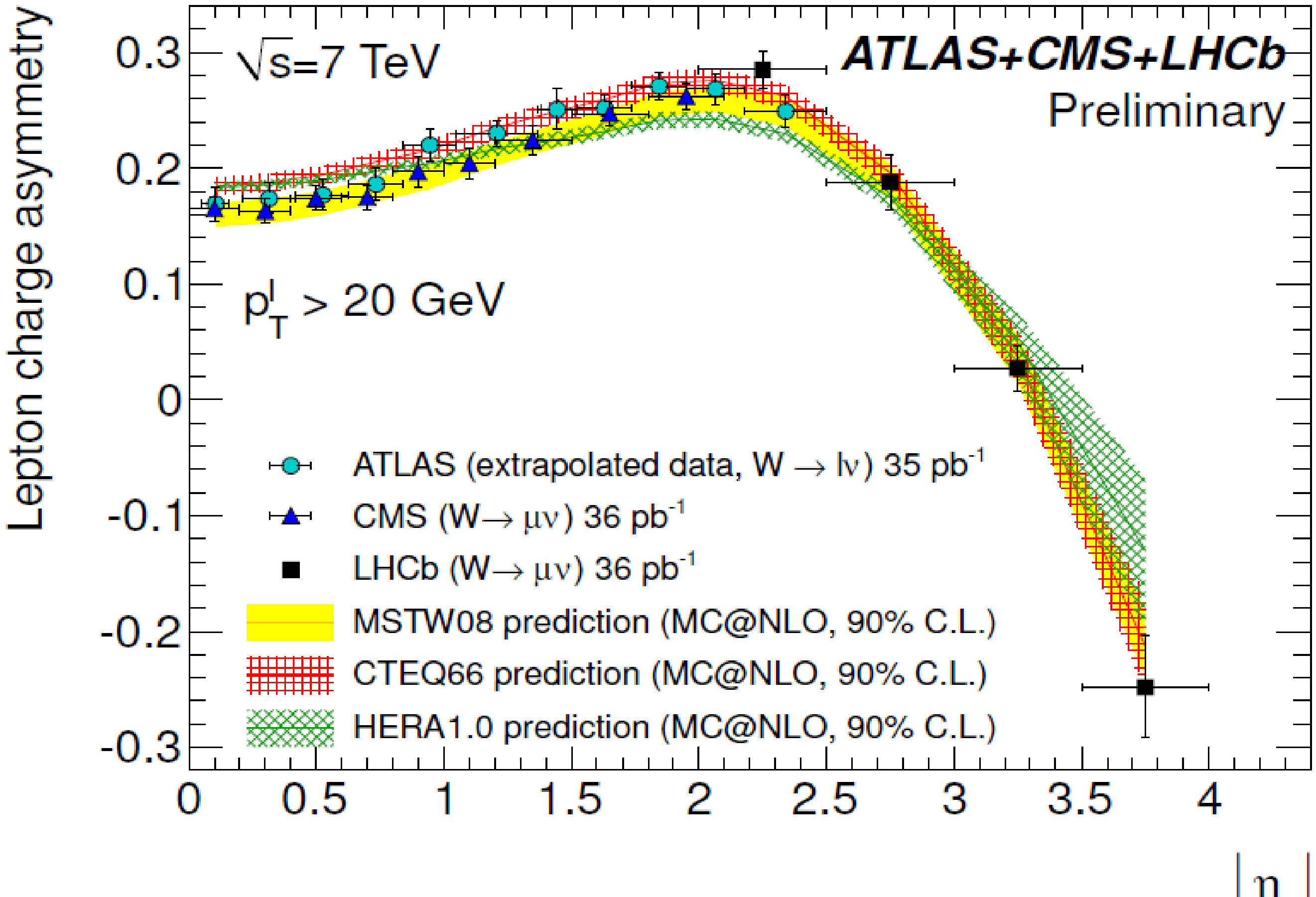


Precise measurement in good agreement with predictions

Electroweak measurements at LHCb

LHC Combination

(ATLAS-CONF-2011-129)



Summary

- LHCb at LHC is making precise measurements
→ hints for strong signs of NP from other experiments are not confirmed, LHCb results are in agreement with the SM prediction,
LHCb is an “anomaly killer”
- but … there are a few new interesting observations, interesting SM features?, signs for New Physics?
- most results published used 2011 data; LHCb data sample more than tripled since then.
→ Excellent prospects for excellent results at Moriond 2013

LHCb upgrade

- LHC and LHCb are a spectacular success
- so is the Standard Model

  … still

- current precision of measurements still leaves lots of room for sub-dominant contributions from New Physics
- almost all LHCb results are completely dominated by statistical uncertainties
- leading systematic uncertainties will also decrease with increasing statistics

NEED MORE STATISTICS

⇒

THE LHCb UPGRADE !

2010	0.037 fb^{-1} @ 7 TeV
2011	1 fb^{-1} @ 7 TeV
2012	2 fb^{-1} @ 8 TeV
2013	LHC LS1
2014	
2015	5 fb^{-1} @ 13 TeV
2016	
2017	
2018	LHC LS2, LHCb upgrade
2019	
2020	5 fb^{-1} per year
2021	
2022	