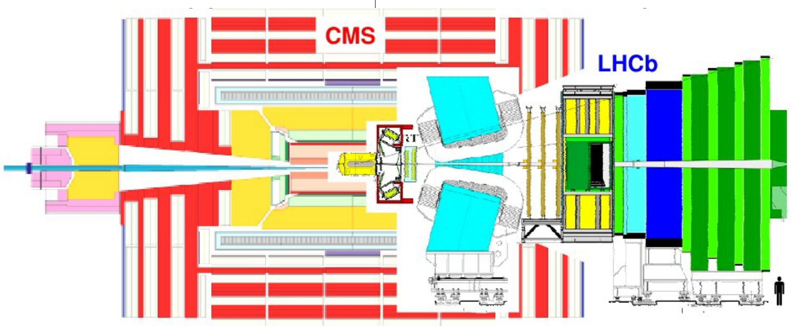
Beyond the Energy Frontier: Chasing the ghosts

Chris Parkes, Southampton, Halloween 2014

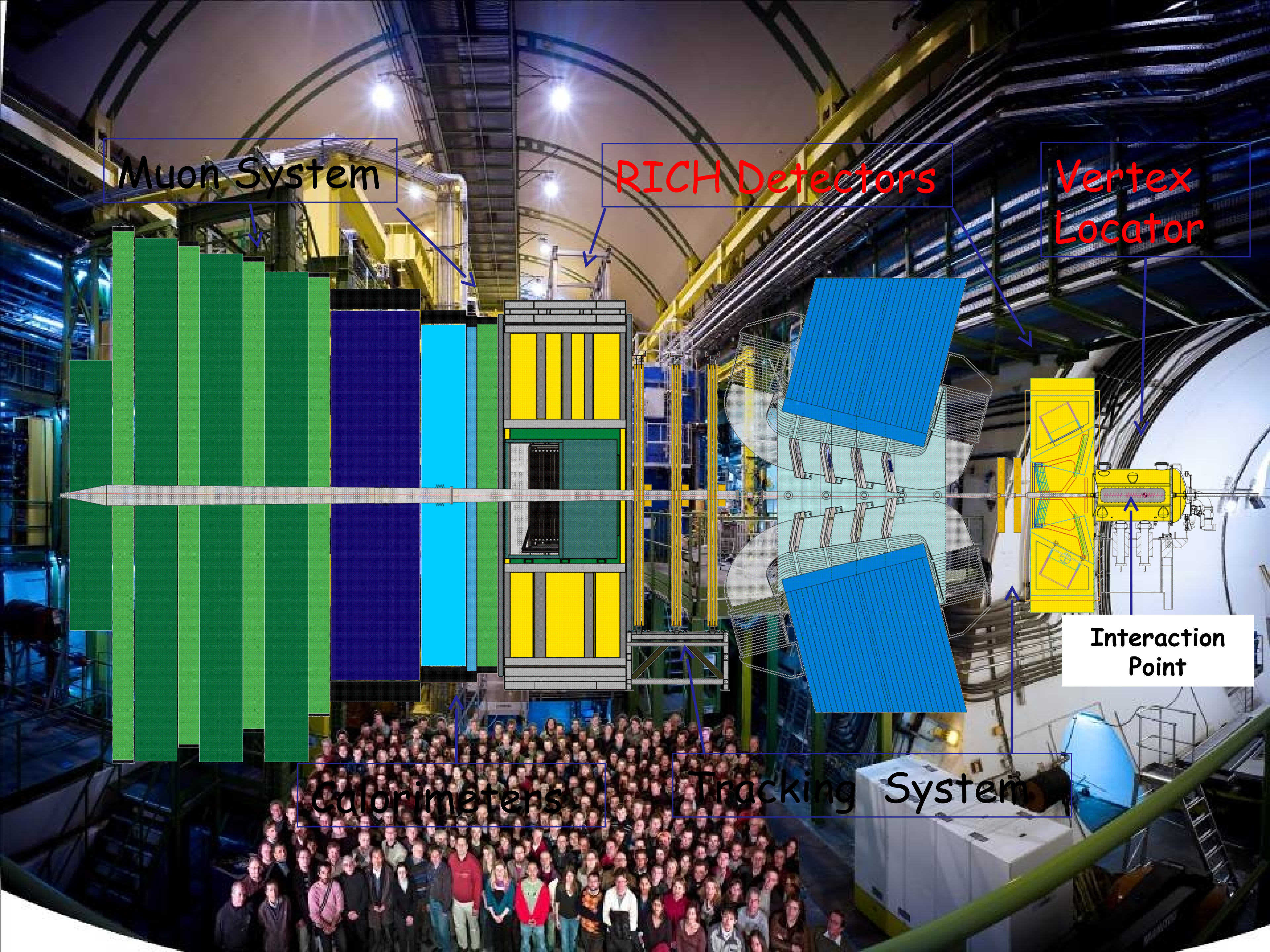
Beyond the Energy Frontier

- LHC Run I: Detector Performance
  Physics Highlights
  (>200 papers)
  - New Paper: $D \mp \pi^+\pi^-\pi^0$
  - Longer Term: Up



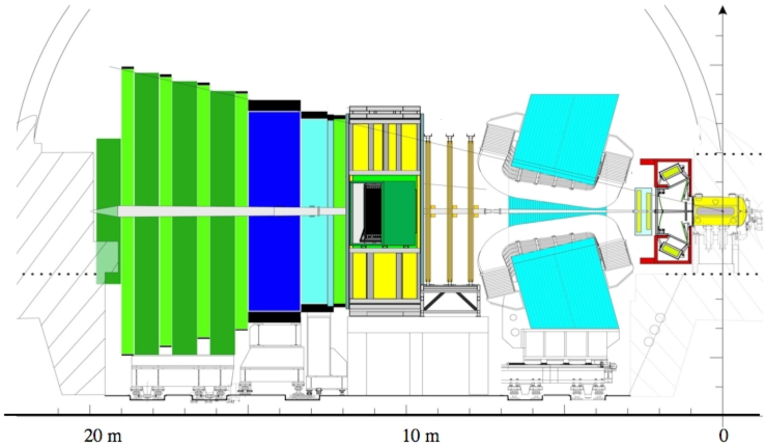
The Ghostbuster:
Introducing the experiment
& its physics highlights

- Mixing & Indirect CP
- Direct CP
- Rare decays


Muon System
RICH Detectors
Vertex Locator
Interaction Point
Calorimeters
Tracking System

Aims & Critical Compor

- LHCb:
  - study CP violation
  - rare B decays
    - New Physics



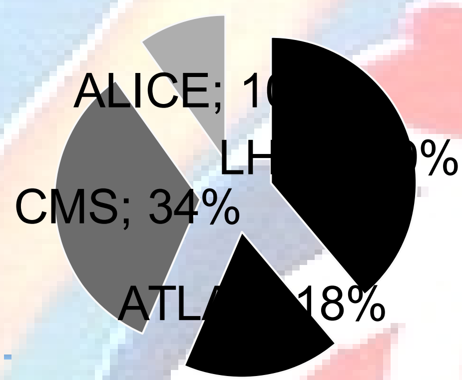
- Requirements:
  - efficient **trigger** on leptons and hadron channels
  - efficient **particle ID** for flavour tagging and background rejection
  - good **proper time resolution** for time dependent measurements of Bs decays
  - good **B mass reconstruction** for background rejection

- UK
  - "UK's LHC experiment": 18% of Collaboration
  - major contributors both key detectors (VELO/RICH)

Flag Waving

- Key Responsibilities
  - 2 Spokespersons
  - 2 Physics Co-ordinators
  - 2 RICH & 3 VELO Project Leaders
- Cost
  - £ Entire LHCb < Cost of ATLAS SCT
  - £ VELO R&D < Cost of ATLAS spare module boxes

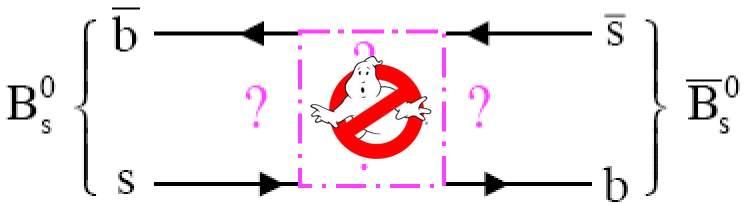
Physics Papers 2013



ALICE ~ 1000 authors
ATLAS~ 3000 authors
CMS ~ 3000 authors
LHCb ~ 600 authors

Papers published per year by LHC collaboration
(based on INSPIRE search for "cn [expt] and r cern-ph-ep-[year]-*)

LHCb:A New Era in Flavour Physics



B_s–$\bar{B}_s$ oscillations: "Box" diagram

Discovering New Physics through indirect effects: sensitive far beyond direct particle production reach

- Precision Measurements
  - Challenging forward region at hadron collider
  - Need events !
  - Need detailed understanding

  Of detector & systematics
- Compelling results

from initial operation

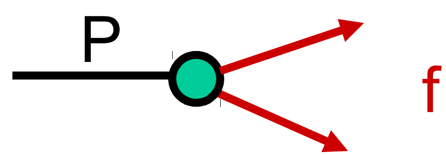
Key LHCb Attributes:
Cross-section,
Acceptance,
Trigger,
Vertex Resolution,
Momentum Resol.,
Particle ID

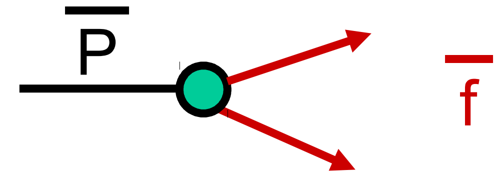
CP Violation Refresher

$$|P_1\rangle = p|P^o\rangle + q|\overline{P}^o\rangle \qquad A_f = \langle f|H|P\rangle$$

$$|P_2\rangle = p|P^o\rangle - q|\overline{P}^o\rangle \qquad \overline{A_{\bar{f}}} = \langle \bar{f}|H|\overline{P}\rangle$$

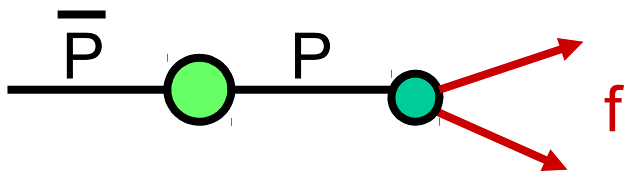
- ~~CP~~ in decay $\left|\frac{A_f}{\overline{A_{\bar{f}}}}\right| \neq 1$

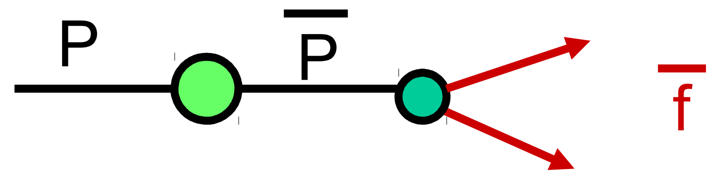




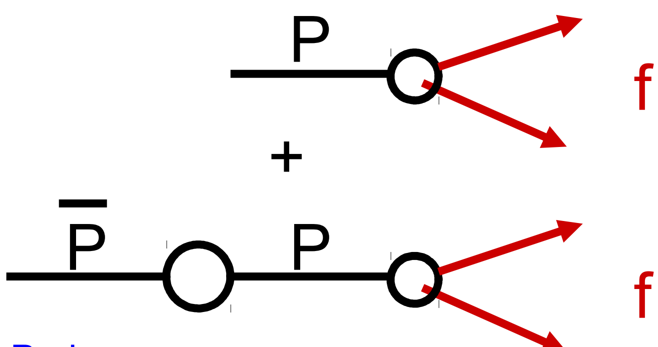
- ~~CP~~ in mixing

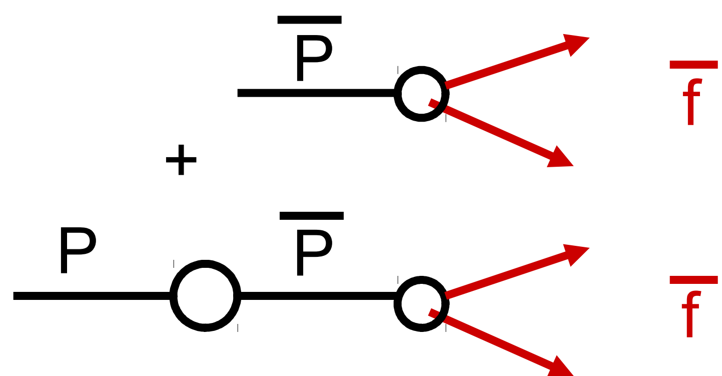
$$\left|\frac{q}{p}\right|^2 \neq 1$$





- ~~CP~~ in interference between mixing and decay $Im\left(\lambda = \frac{q}{p}\frac{\overline{A_{\bar{f}}}}{A_f}\right) \neq 1$

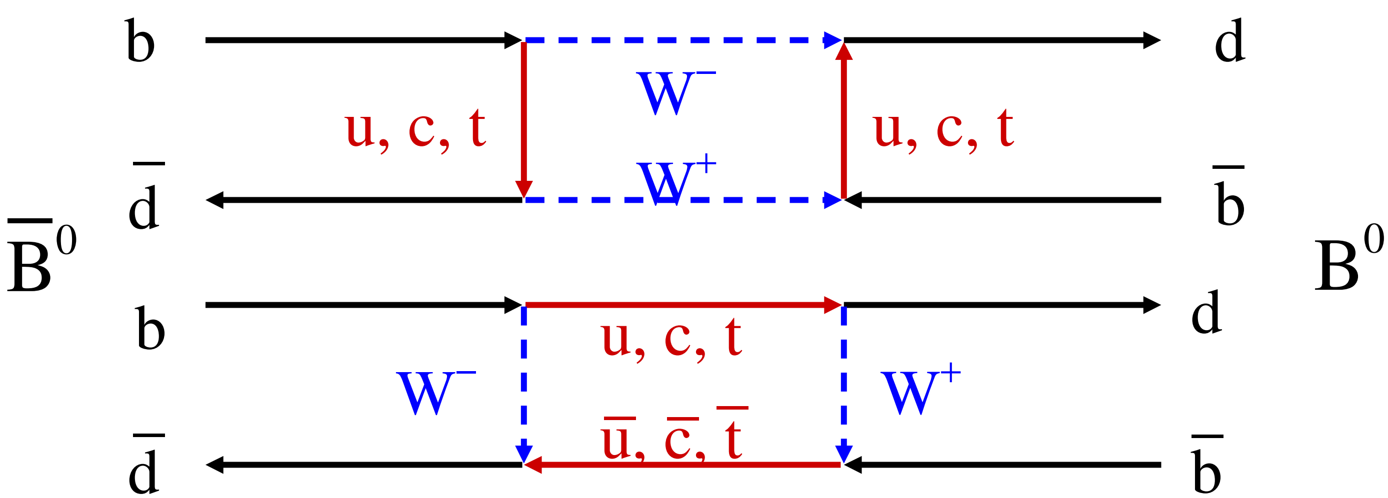




Oscillations
& Time-dependent (indirect) ~~CP~~
B / B_s system
D system

Neutral B-mesons mixing

- Feynman (box) diagrams for neutral B-meson mixing:



(and similarly for B_s)

- Dominated by top quark contribution :

$$\frac{q}{p} \approx \sqrt{\frac{M_{12}^*}{M_{12}}}$$

For B^0

$$\frac{q}{p} \approx \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$

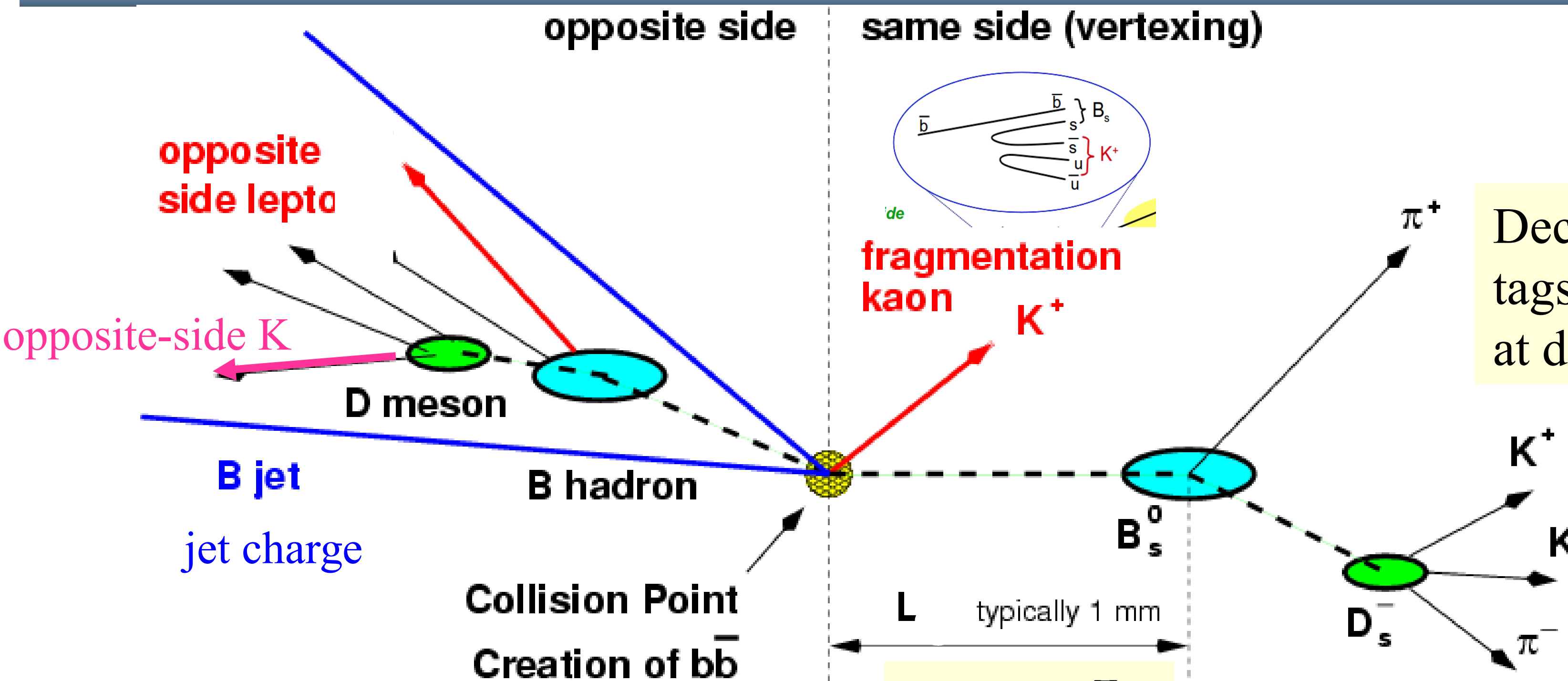
→ Sensitivity to a CKM triangle side and angle β

For B_s^0

$$\frac{q}{p} \approx \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}$$

→ Sensitivity to side and equivalent angle β_s

Measuring B_s mixing – tagging & decay time



Decay mode tags b flavor at decay

2nd B tags production flavor

negative lepton taggers (e^-, μ^-) from b-quark

positive leptons from $b \to c \to l$ cascade

opposite kaon tagger (K^-)

$$t = m\frac{L}{p}$$

Proper decay time from displacement (L) and momentum (p)

- Need to determine:
  - Flavour at production ⇔ tagging
  - Flavour at decay, from final state
  - B decay length

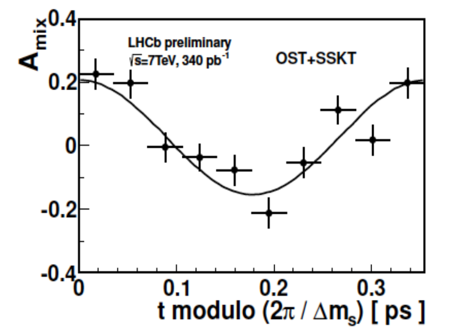
B_s Mixing Measurement

$$B_s^0 \to D_s^-(K^+K^-\pi^-)\pi^+$$

- CDF discovery 2006, LHCb measurement 2011

Most precise measurement of $|V_{td}/V_{ts}|$

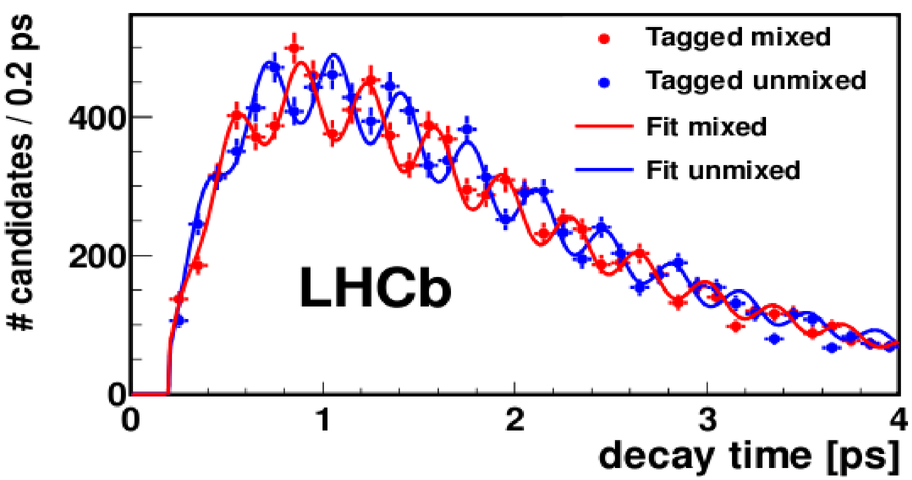
$$A_{\text{mix}}(t) = \frac{N(B_s^0; q=+1)(t) - N(B_s^0; q=-1)(t)}{N(B_s^0; q=+1)(t) + N(B_s^0; q=-1)(t)}$$

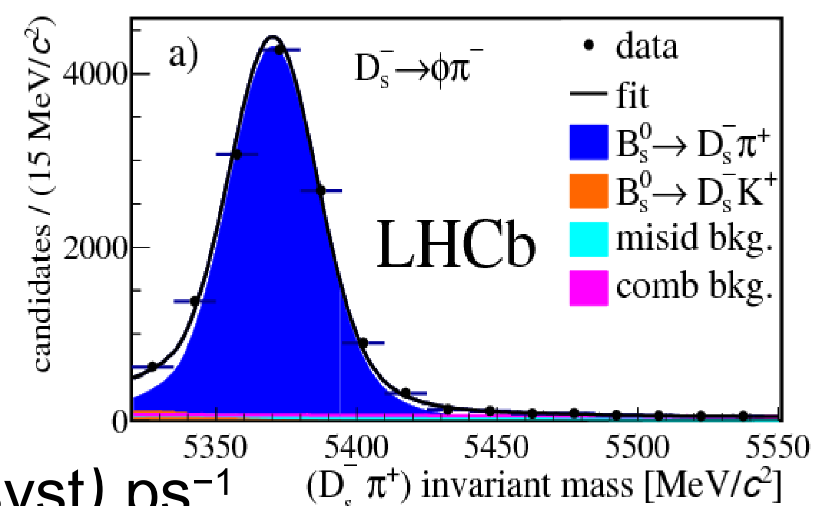


Oscillations occur at 3 trillion Hz !

Observed amplitude is not 1 as smeared

- Mistag (B or B) of events
- Resolution on time





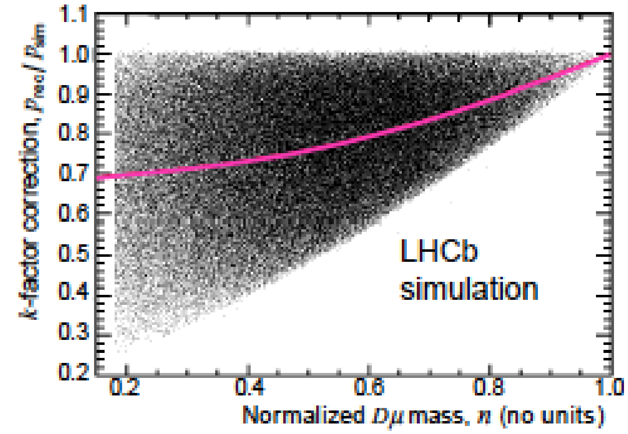
Line is fitted oscillations
Points are data

$\Delta m_s = 17.768 \pm 0.023\ (stat) \pm 0.006\ (syst)\ \text{ps}^{-1}$

Semi-leptonic B Mixing Measurement

Thomas Bird

- Aim to measure B mixing: Δm_s and Δm_d
- Use semi-leptonic B_d^0 and B_s^0 decays
- Difficult due to missing momentum



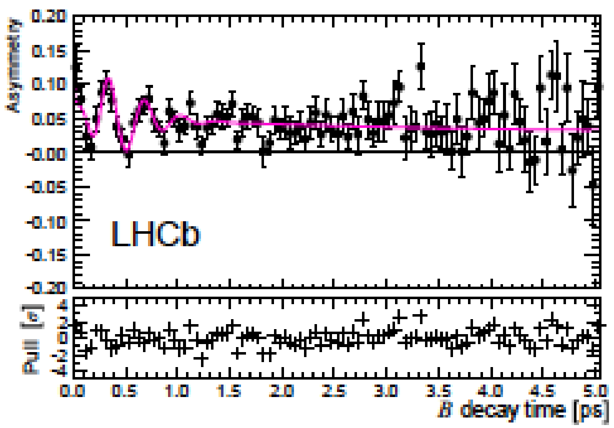
$$\Delta m_s = (17.93 \pm 0.22(\text{stat}) \pm 0.15(\text{syst}))\,\text{ps}^{-1}$$

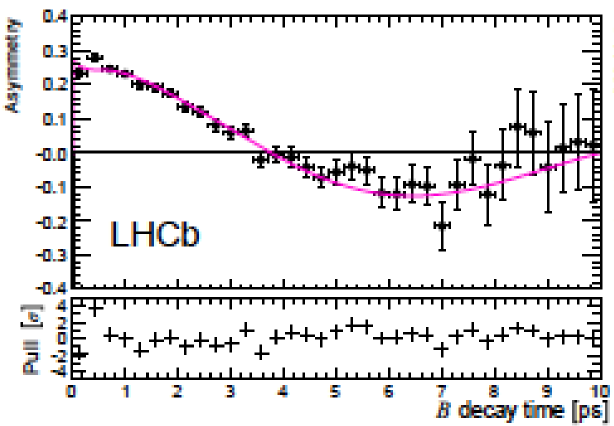
Reject null hypothesis of no mixing by 5.8σ

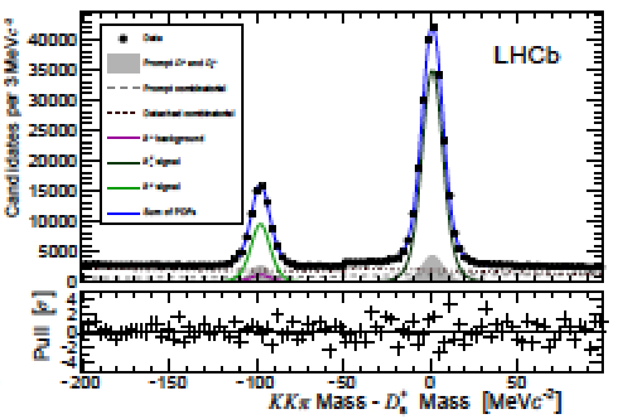
$$\Delta m_d = (0.503 \pm 0.011(\text{stat}) \pm 0.013(\text{syst}))\,\text{ps}^{-1}$$

Reject null hypothesis of no mixing by 13.0σ

[EPJC, 73 (12). p. 2655.]







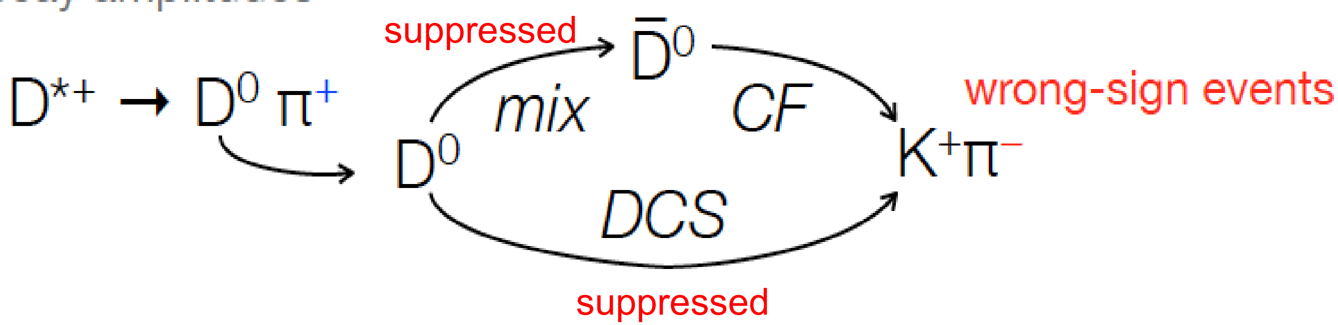
Listen to mixing !

Charm x-sec 20 times B x-sec

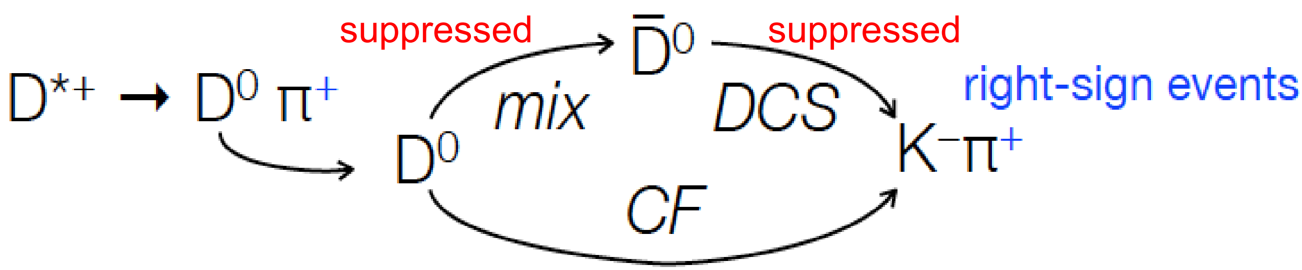
Charm mixing with $D^0 \to K^+\pi^-$

reminder x<<1 only small fraction of an oscillation before decay

- Exploit interference between mixing and doubly-Cabibbo-suppressed decay amplitudes



- Compare to RS events which are dominated by Cabibbo-favored amplitude



- Assuming |x|,|y|<<1 and no CPV

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\,y' t + \frac{x'^2 + y'^2}{4} t^2 \qquad \begin{aligned} x' &= x\cos\delta + y\sin\delta \\ y' &= y\cos\delta - x\sin\delta \end{aligned}$$

9

DCS interference mixing

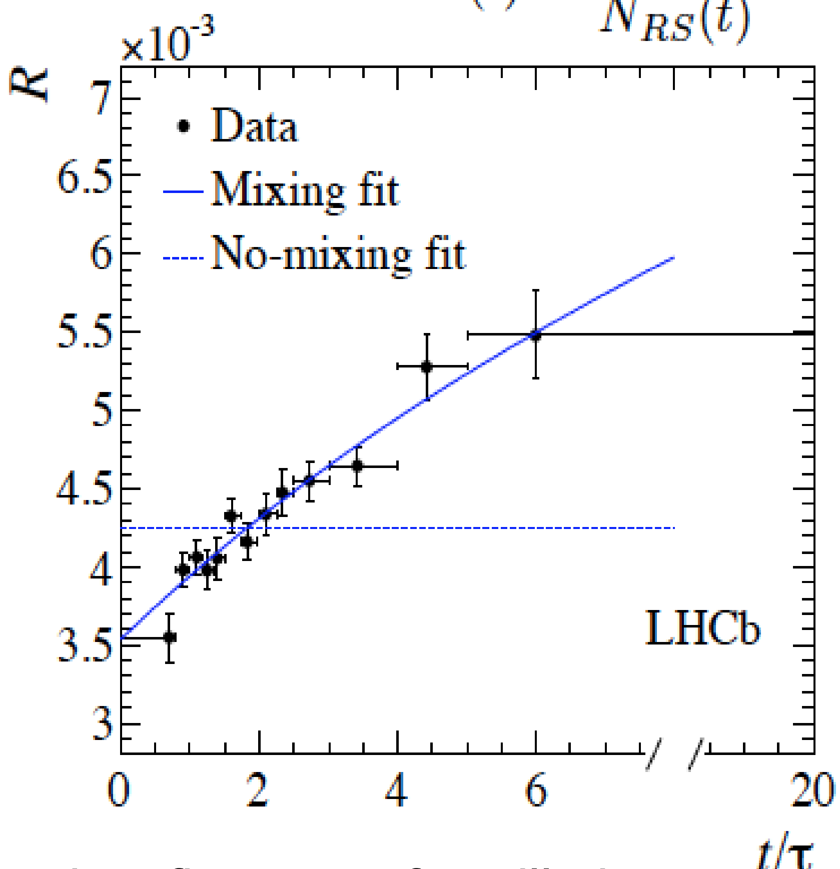
Key points on D mixing

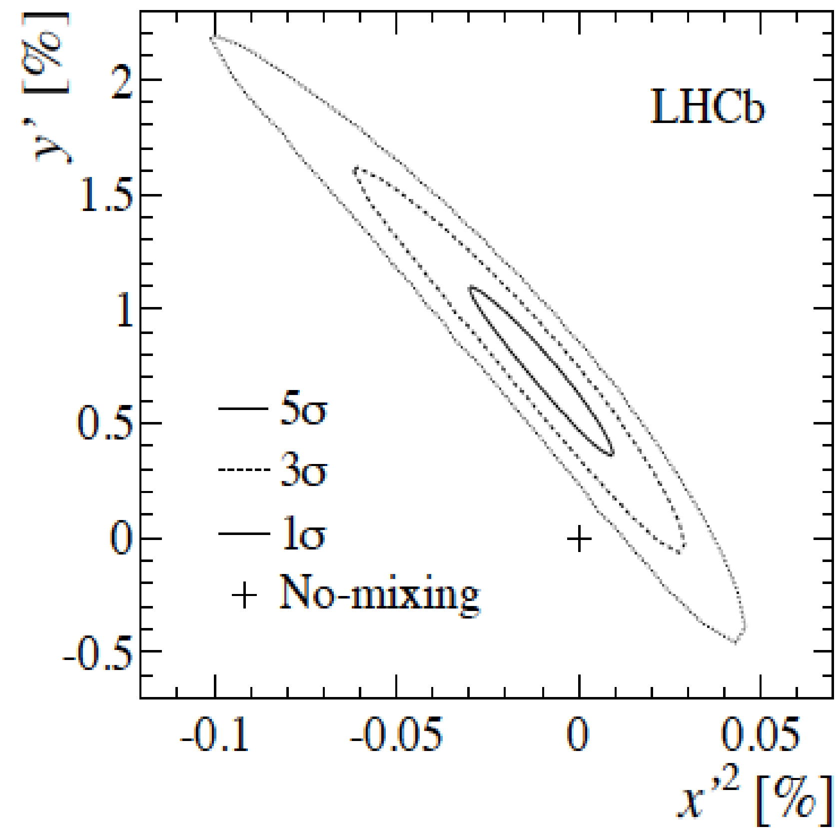
1. Wrong sign / right sign

$x = (0.48 \pm 0.14)\%$
$y = (0.76 \pm 0.10)\%$

Flat with time? no mixing, increases with time ? mixing

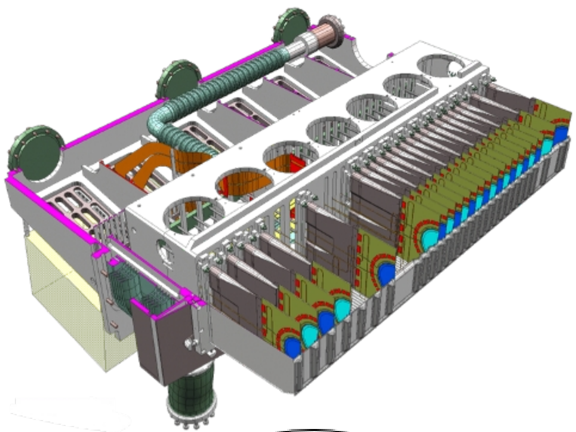
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t^2$$

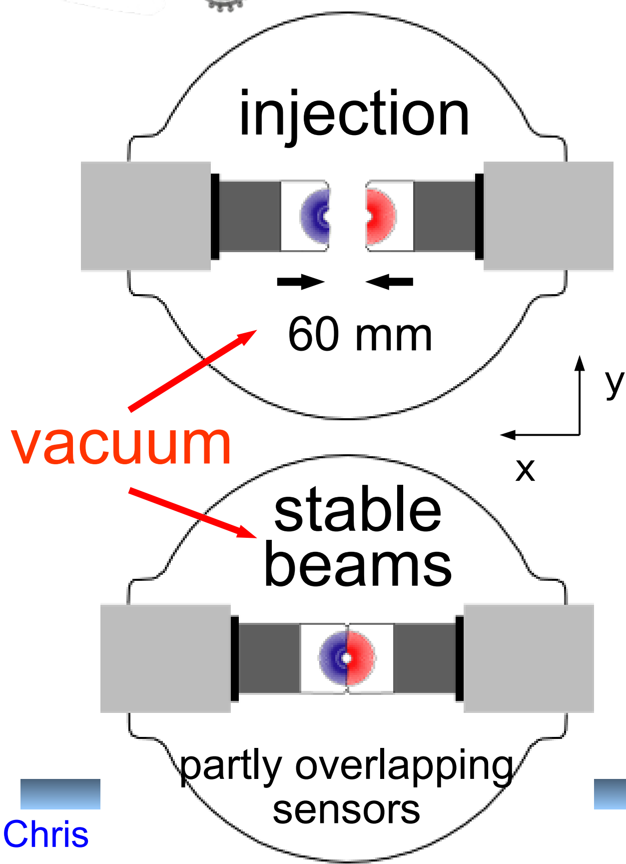


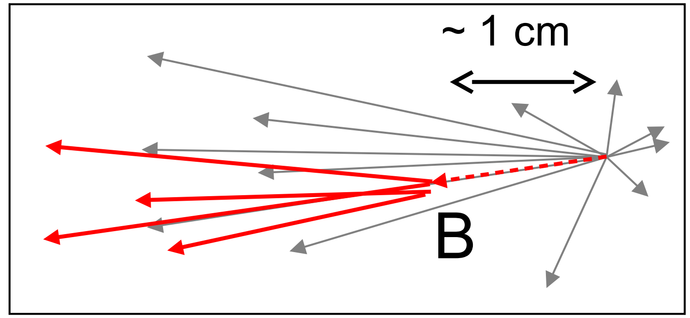


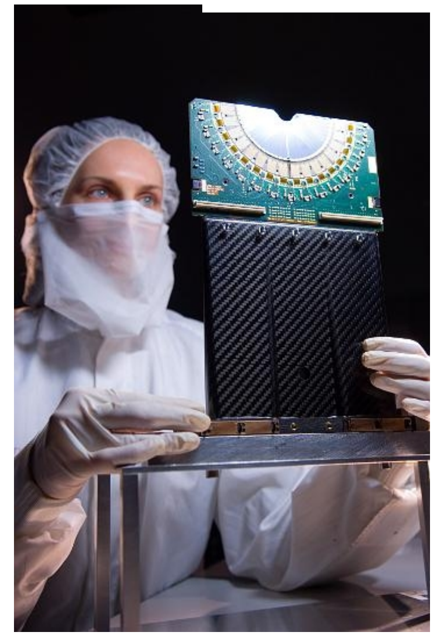
See just first part of oscillation curve

LHCb: Vertex LOcator





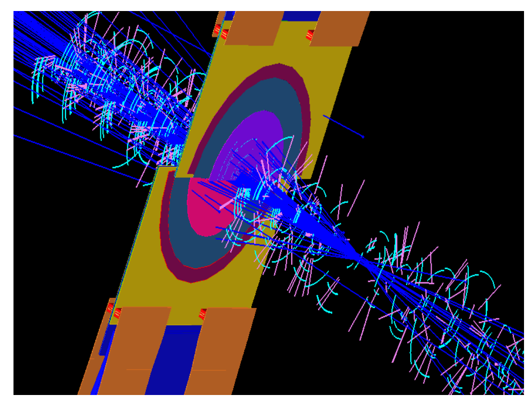




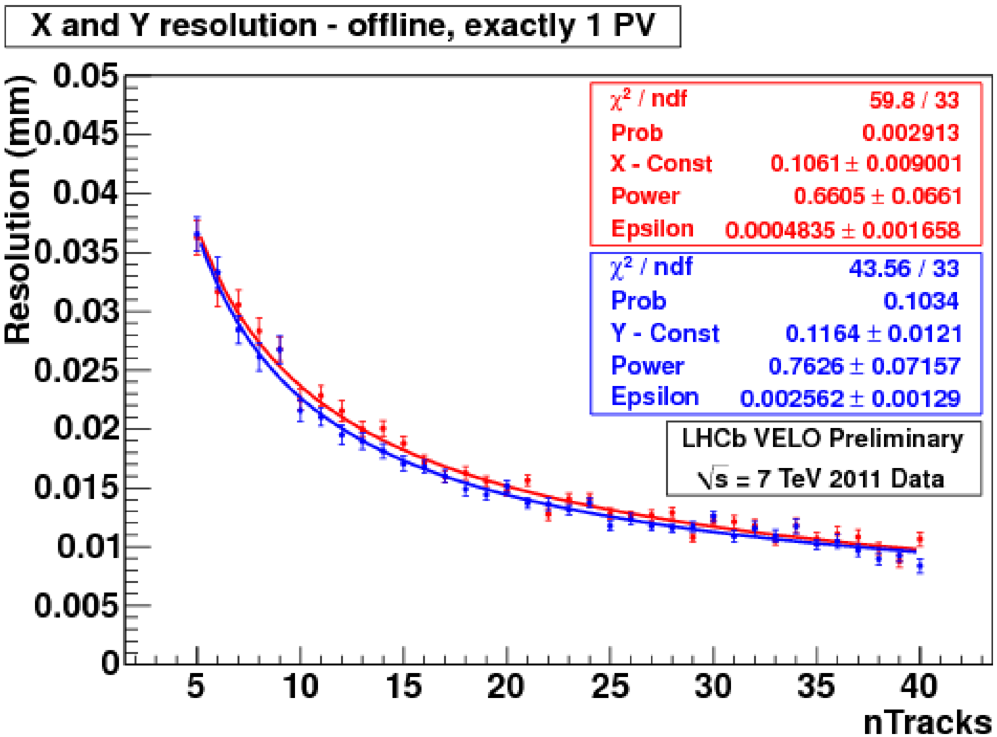
Beauty mesons live 10^{-12}s

Multiply by c and γ

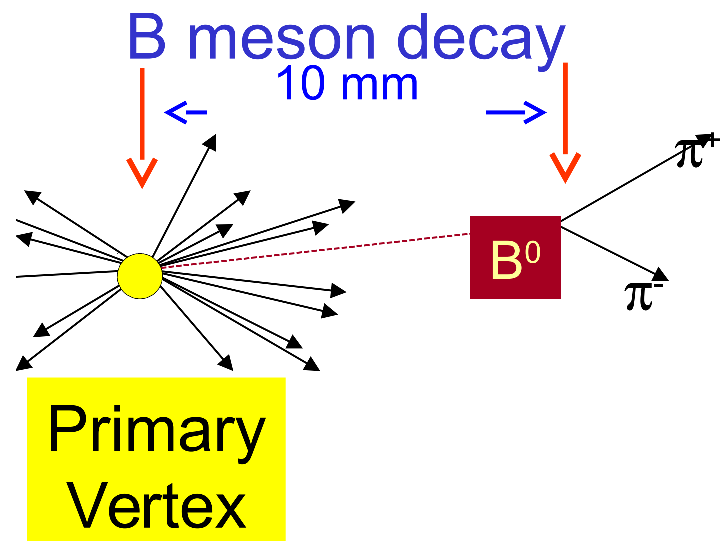
Travel few mm



Performance: Vertex Resolution



- Key Physics quantity in identifying long lived



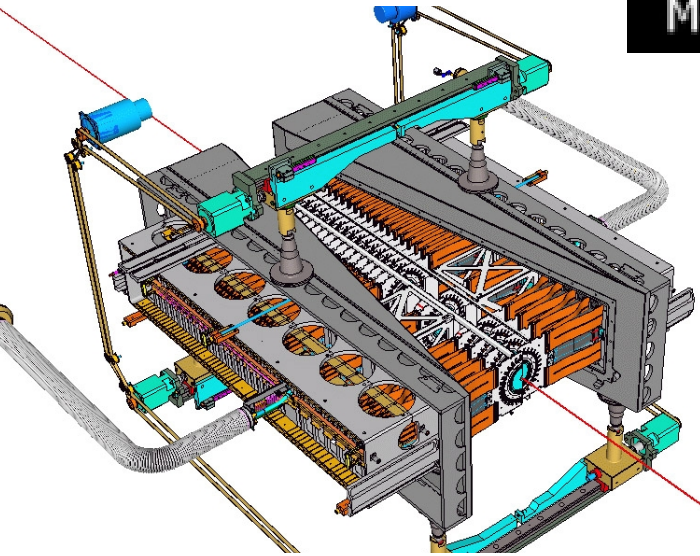
Vertex resolution

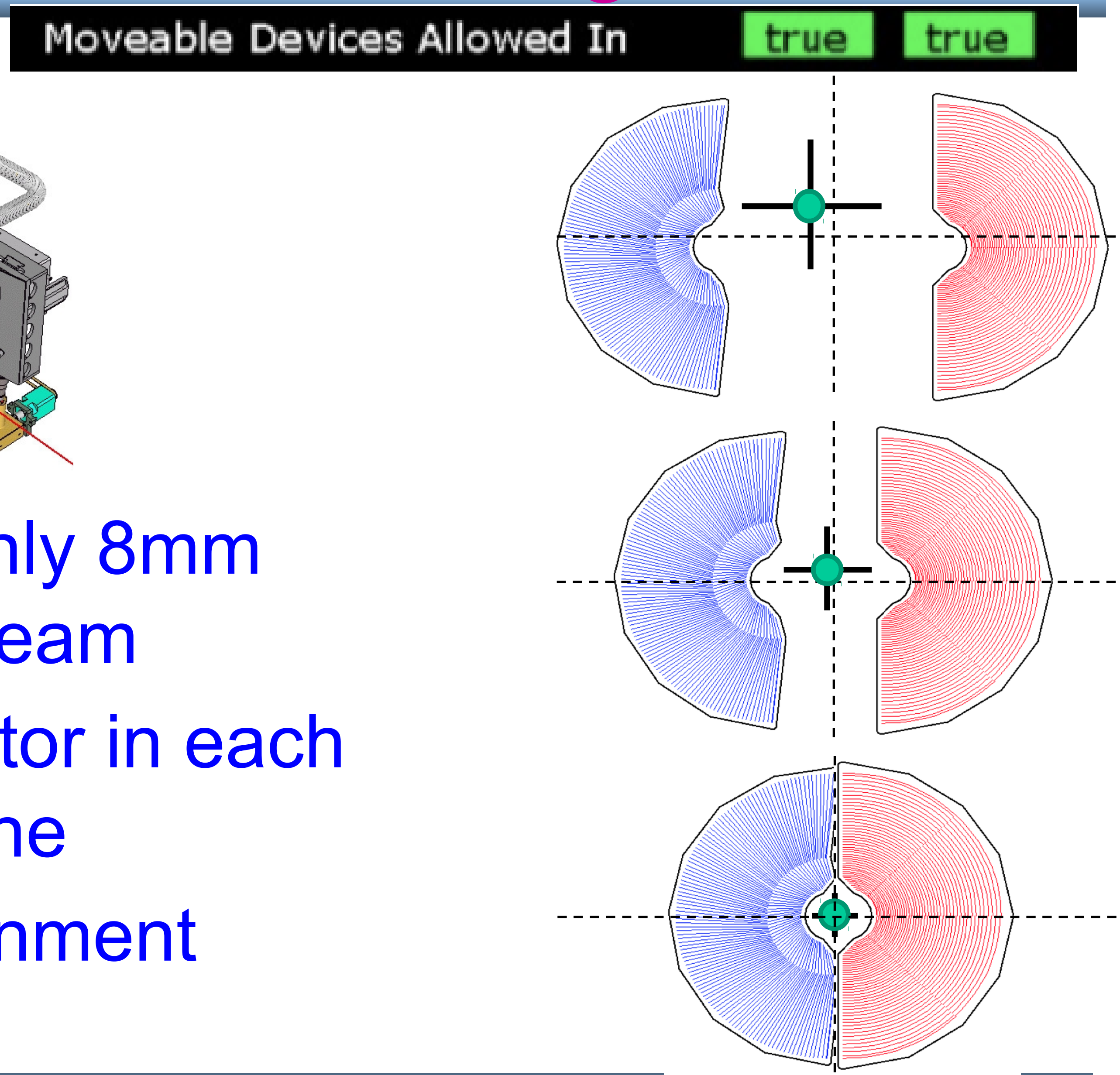
- 15μm in XY at 25 tracks
- 70μm in Z

propertime resolution

- ~50fs tracks

VELO Closing





- First strip only 8mm from LHC beam
- Move detector in each fill of machine
- Update alignment parameters

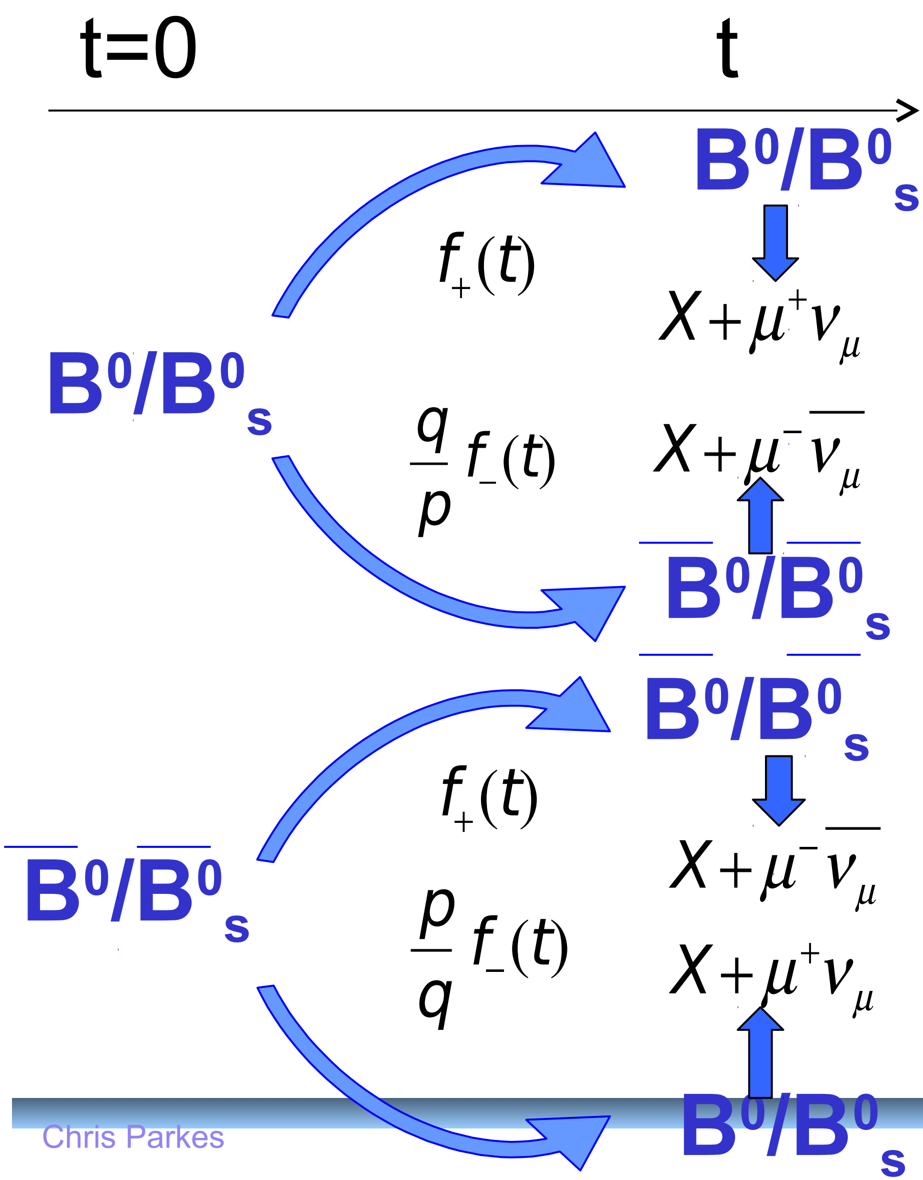
CP Violation in B mixing ?
Like-sign dimuon asymmetry

Like-sign dimuon asymmetry

D0 Collab.

PHYSICAL REVIEW D 84, 052007 (2011)

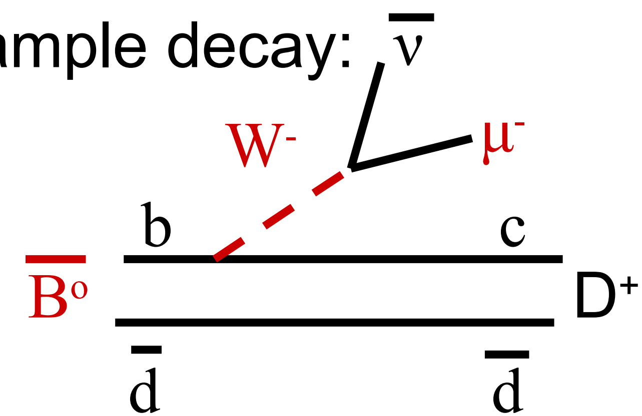
Measurement of the anomalous like-sign dimuon charge asymmetry with 9 fb^{-1} of $p\bar{p}$ collisions



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

- Produce $B\bar{B}$ pair (or B_s)
- If one oscillates before decaying get two like sign leptons (++ or --)
- If no CP Violation in mixing get $N^{++} = N^{--}$

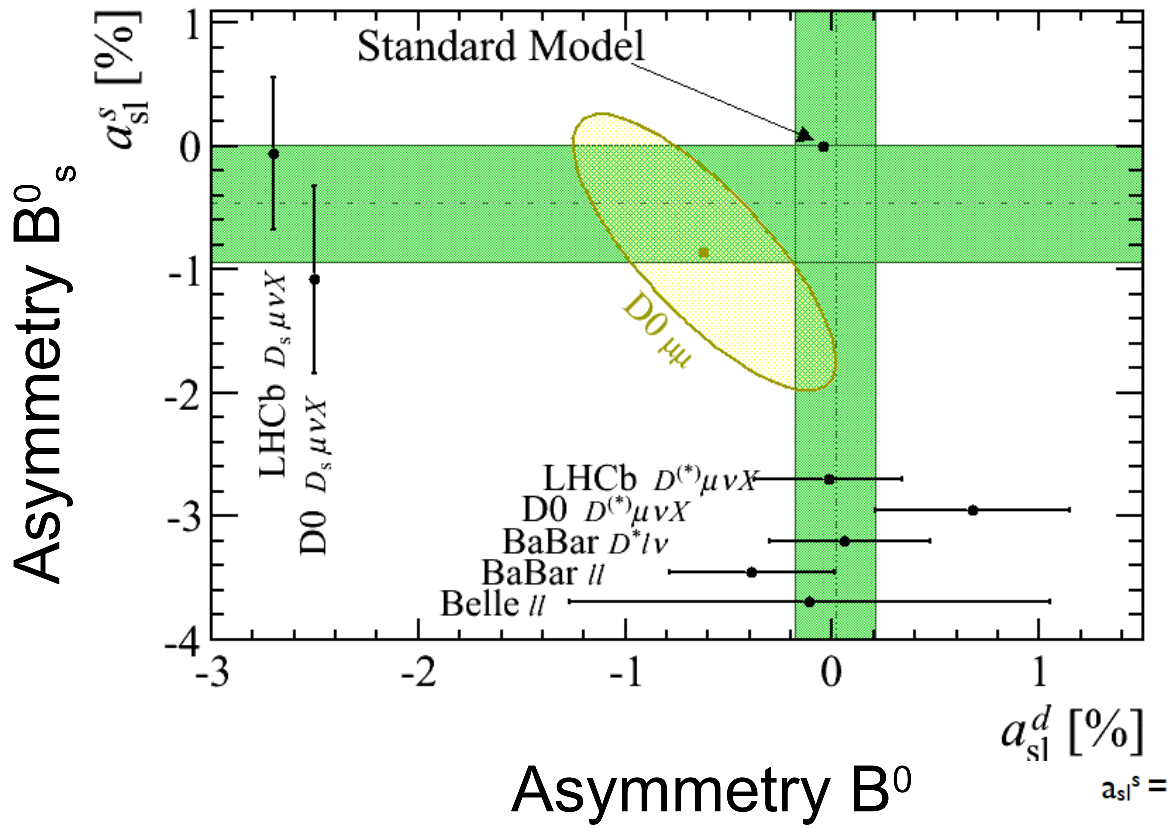
example decay:



Like sign dimuon asymmetry: current results

Tevatron: proton anti-proton – equal matter anti-matter

LHC: proton proton production asymmetry, makes analysis more tricky, but LHC statistics much higher



D0 – B and B_s decays inclusively (mainly)

LHCb – B_s / B_d only: first results compatible SM and D0 !

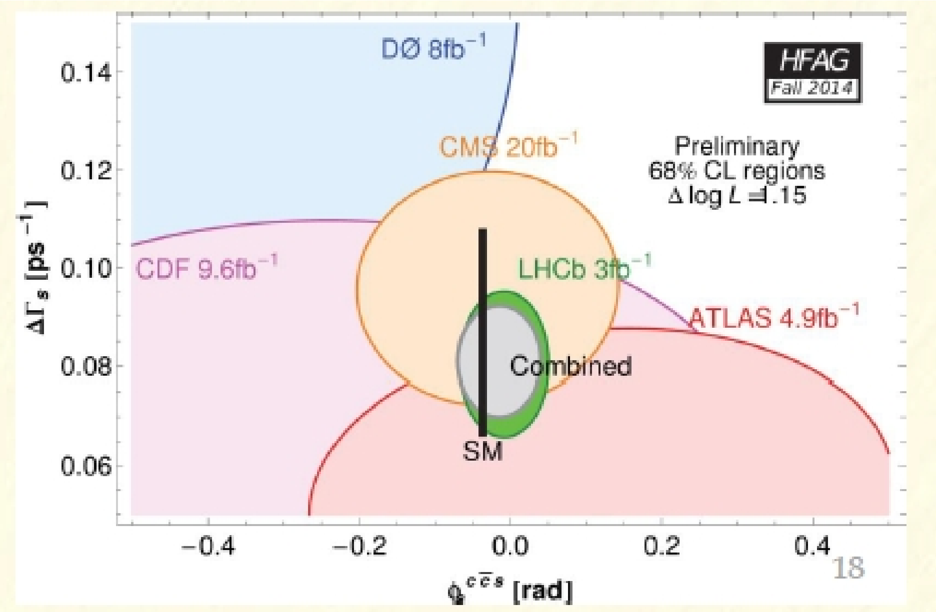
NEW ! a_{sl}^d

$a_{sl}^s = (-0.06 \pm 0.50_{stat} \pm 0.36_{syst})\%$ PLB 728C 607-615 (2014)

$a_{sl}^d = (-0.02 \pm 0.19_{stat} \pm 0.30_{syst})\%$ LHCb-PAPER-2014-053

New Physics ? Situation unclear –improved measurements needed

LHCb: Initial Highlights – Φ_s $B_s \to J/\psi\,\phi$



Observable	value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0033$

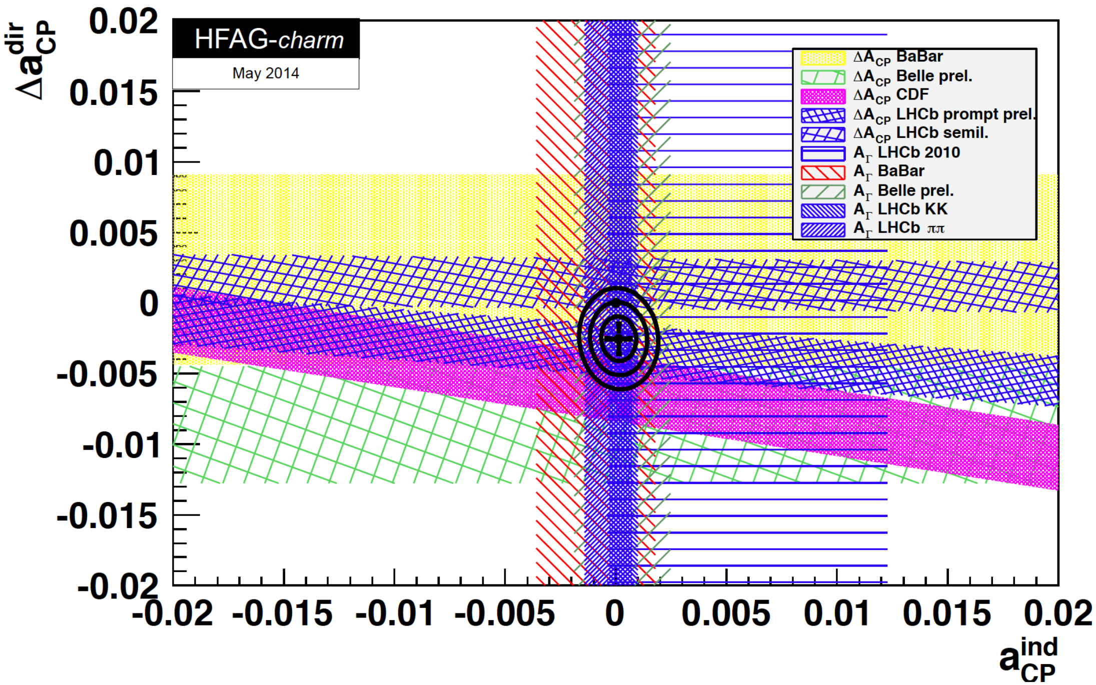
$$\phi_s = -0.010 \pm 0.040 \text{ rad}$$

NEW !

$$\sin(\phi_s) \equiv \sin\left(-arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)\right) \neq 0$$

- Φ_s: B_s mixing phase
  - Tagged, time dependent, angular analysis
  - TeVatron SM discrepancy resolved

LHCb: Initial Highlights – Charm



- Charm CP Violation

  $D^{*+} \to D^0(K^+K^-)\pi^+$ and $D^{*+} \to D^0(\pi^+\pi^-)\pi^+$

  – Direct CP Asymmetry

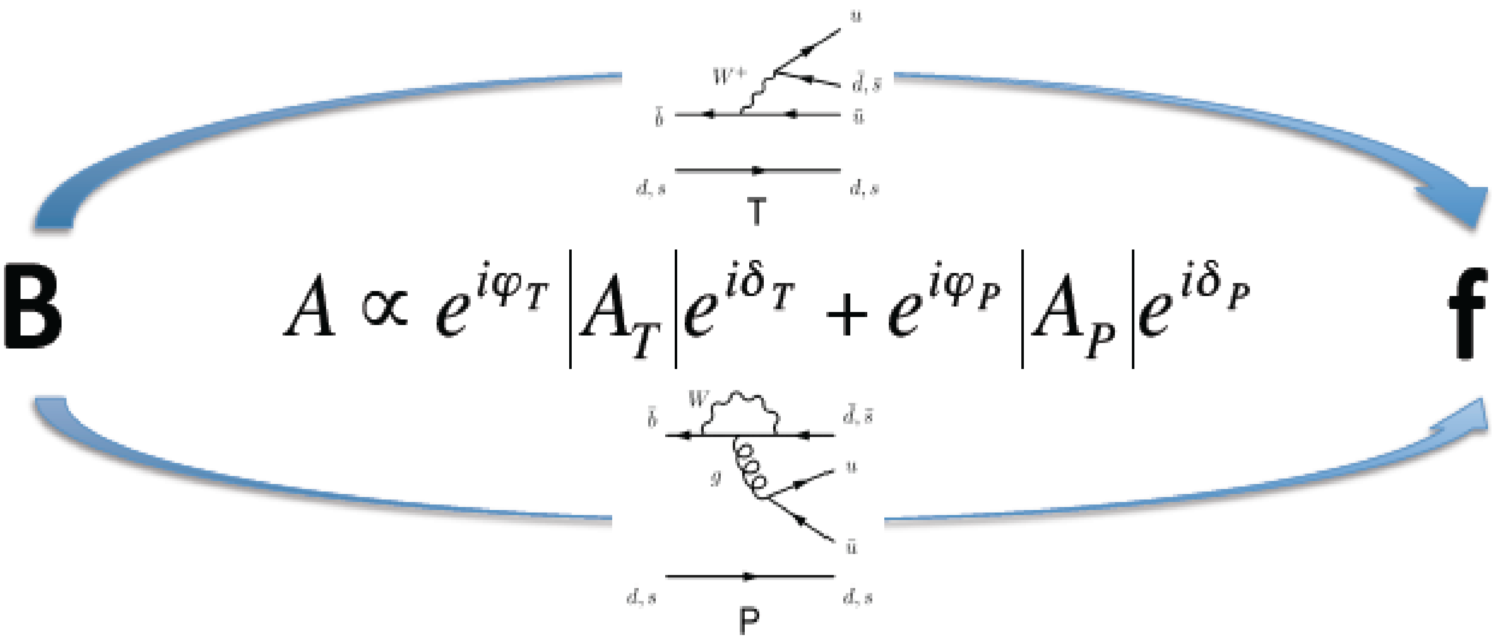
  – Indirect CP (A_Γ)

Direct / Time-integrated CP Violation including discovery of CP Violation in B_s system

Direct CP Violation: two-body B^0 & B_s decays

Time-integrated measurement: Direct CP Violation

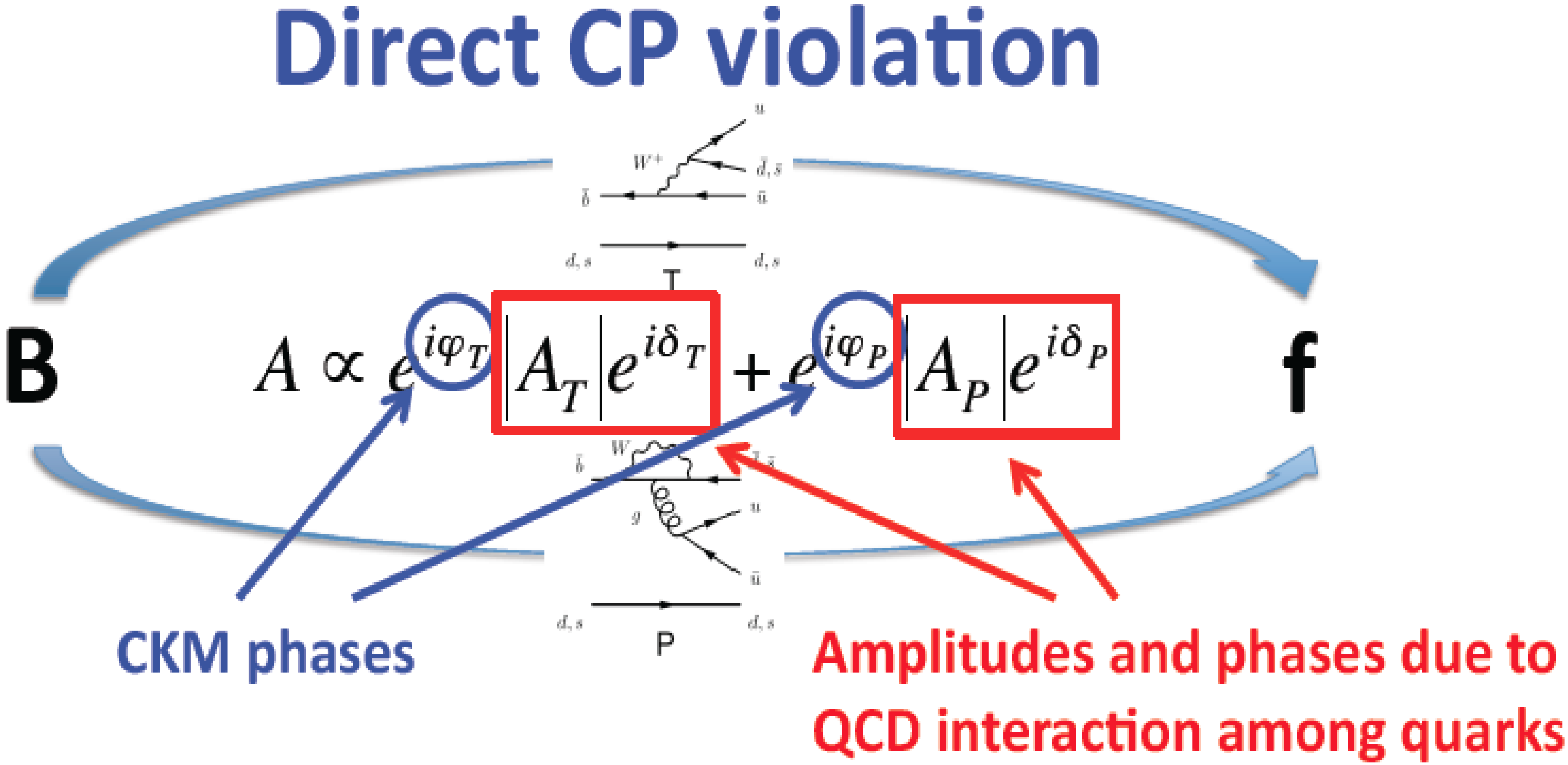
Direct CP violation



$$A \propto e^{i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

Direct CP Violation: two-body B^0 & B_s decays

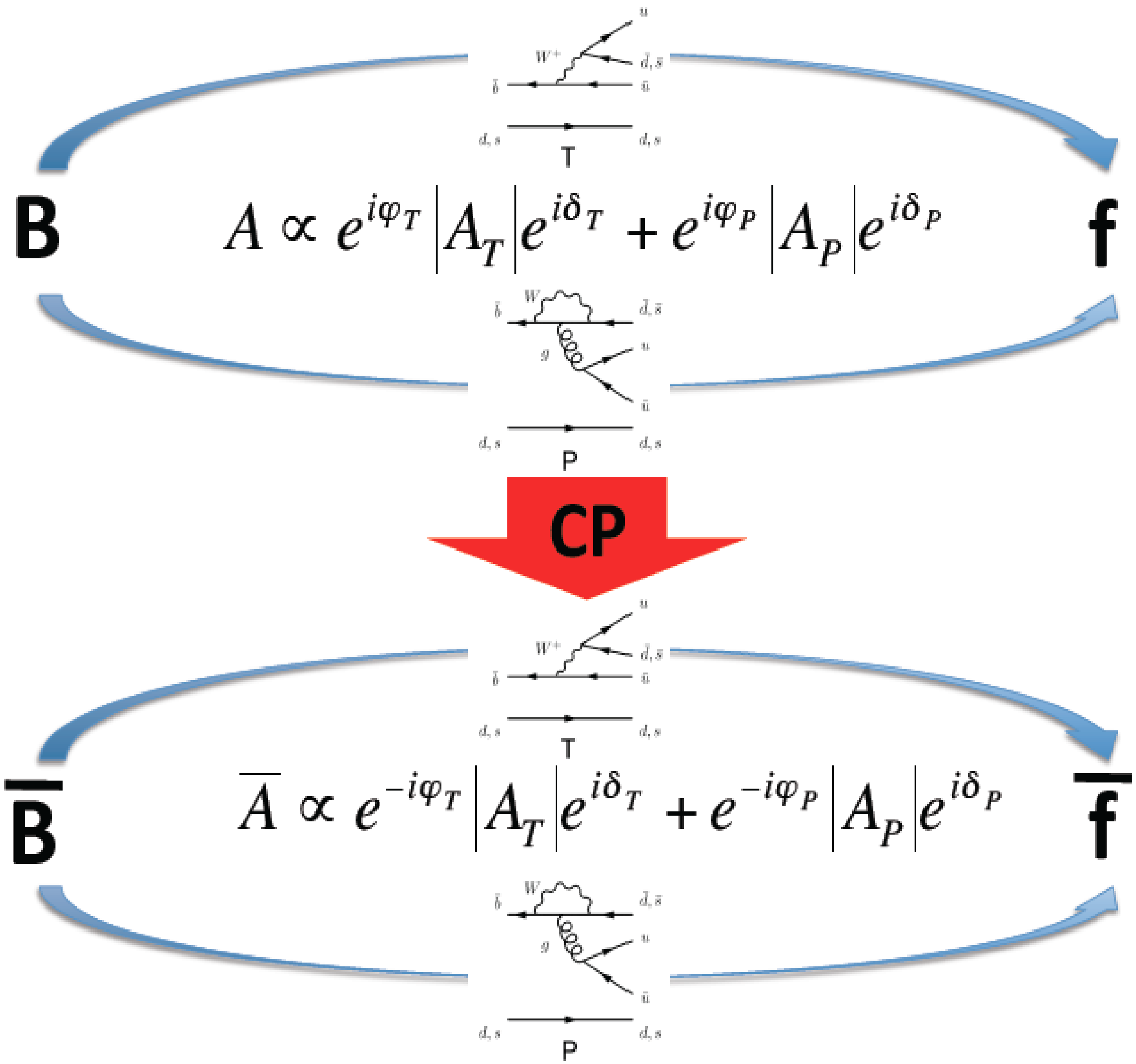
Time-integrated measurement: Direct CP Violation



Direct CP Violation: two-body B^0 & B_s decays

Time-integrated measurement: Direct CP Violation

Direct CP violation



$$A \propto e^{i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

$$\overline{A} \propto e^{-i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{-i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

Use f

$B^0 \to \pi^- K^+$

$B_s \to K^- \pi^+$

$\overline{B^0} \to \pi^+ K^-$

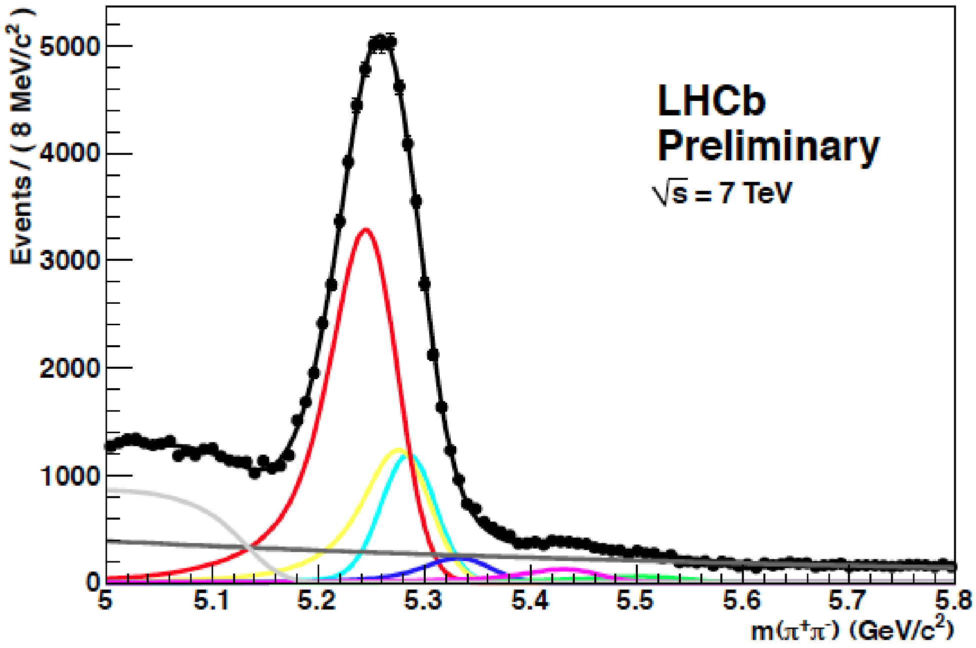
$\overline{B}_s \to K^+ \pi^-$

Direct CP Violation: two-body B^0 & B_s decays

However several different two-body B decays
Separate with Particle ID and mass for B^0/B_s

$B^0 \to \pi^- K^+$

$B_s \to K^- \pi^+$



$B_s^0 \to \pi K$

$B^0 \to \pi^+ \pi^-$

$B_s^0 \to K^+ K^-$

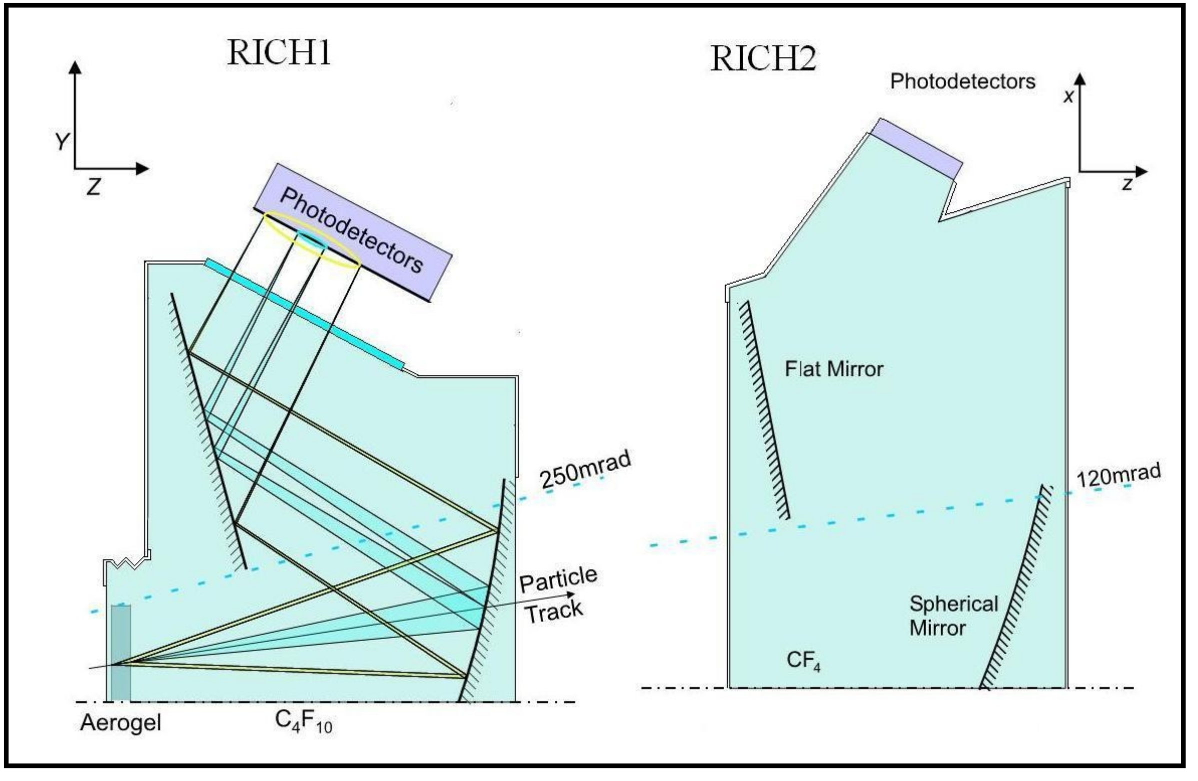
$B^0 \to K \pi$

(also Λ_b, 3-body backgrounds)

$B \to hh$, (h=K,π)

Ring Imaging Cherenkov (RICH)

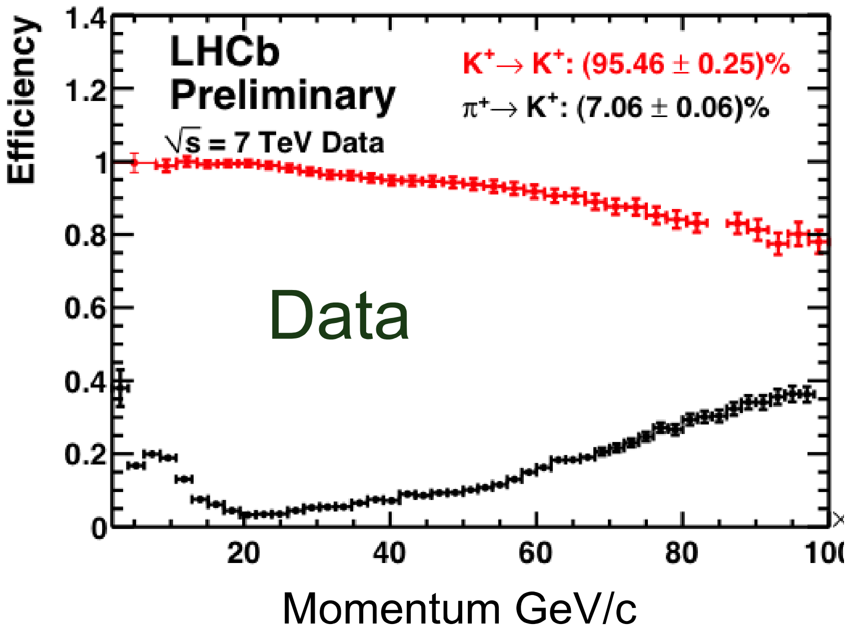
- Unique at LHC: π/K/p separation
  - Measure particle velocity through Cherenkov effect
- Two RICH detectors – lower / higher momentum



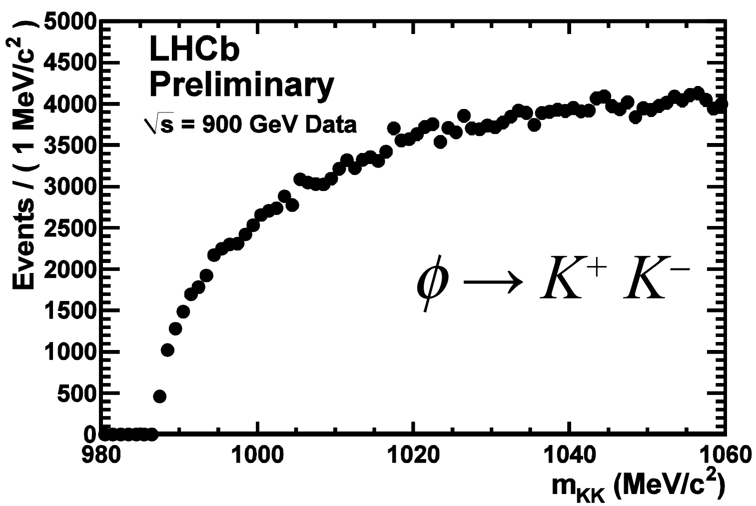
Gas enclosure and mirrors installed in LHCb pit

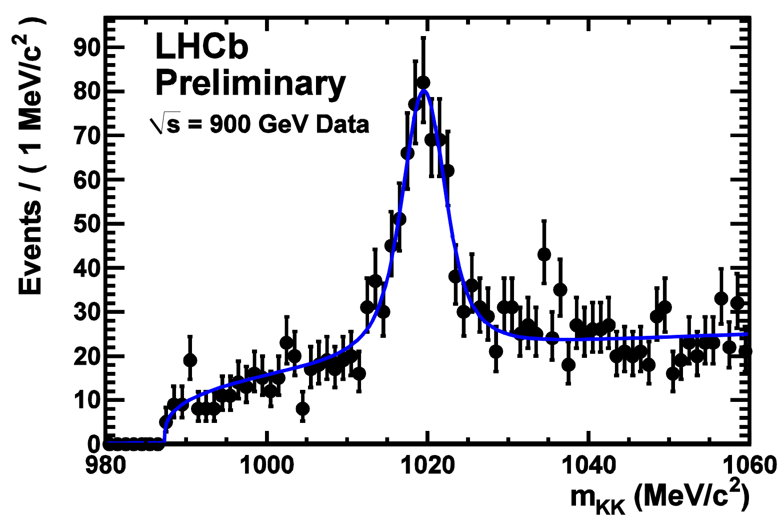
Particle Identification

RICH PID across wide momentum range



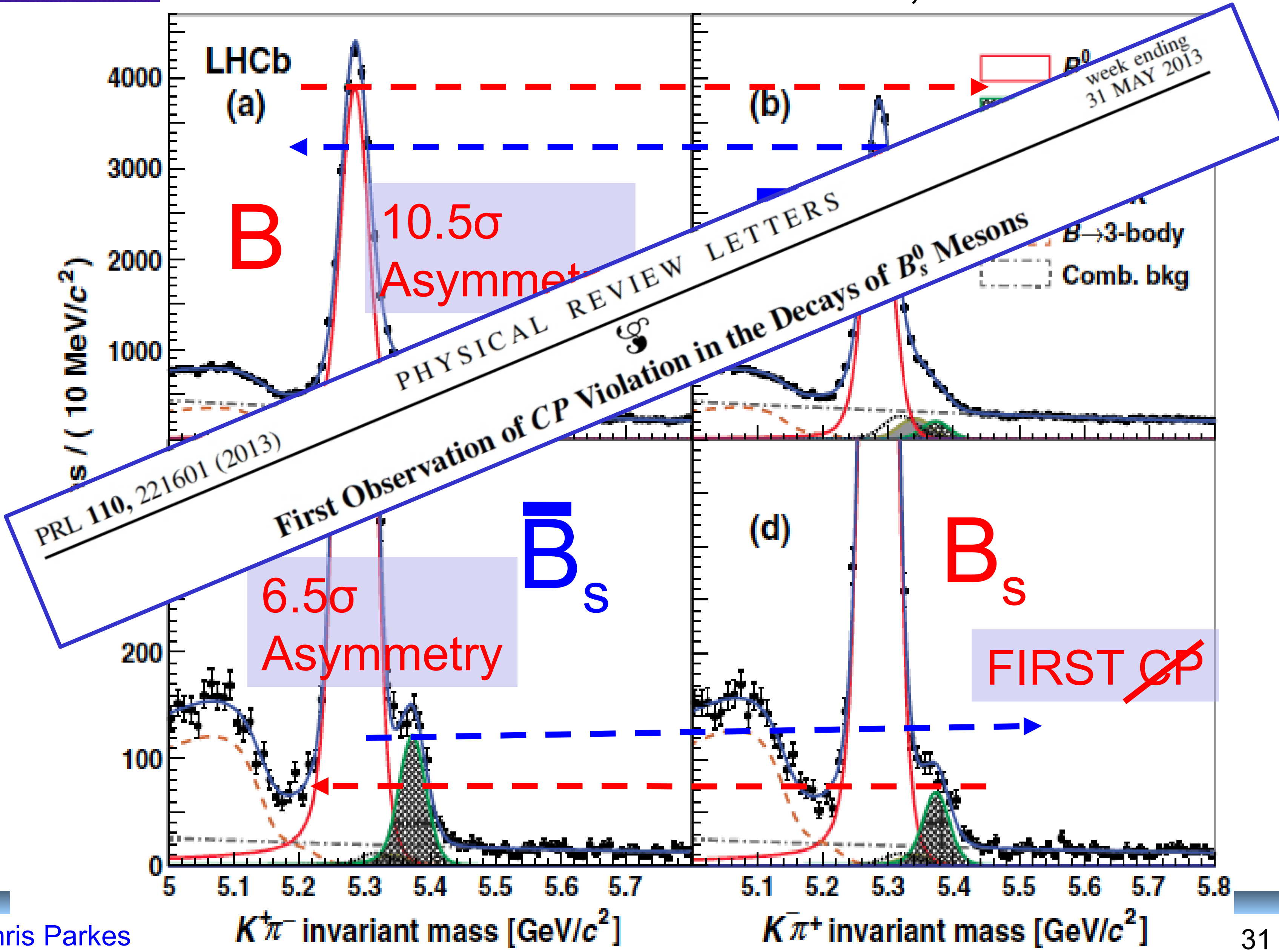
Clean reconstruction of hadronic decays critical to many physics results





Direct CP Violation: two-body B^0 & B_s decays

PRL110, 221601 2013



Dalitz Plots – three body decays

$B^+ \to h^+h^+h^-$

$D \to h^+h^+h^-$

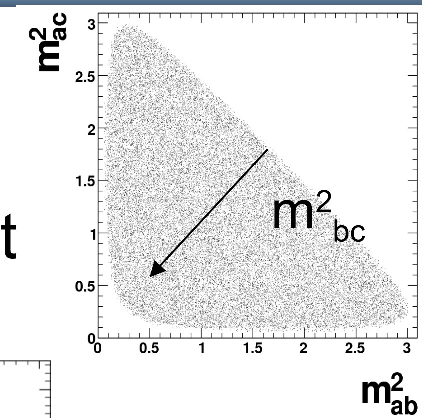
Dalitz Plot – Visualize three body decays

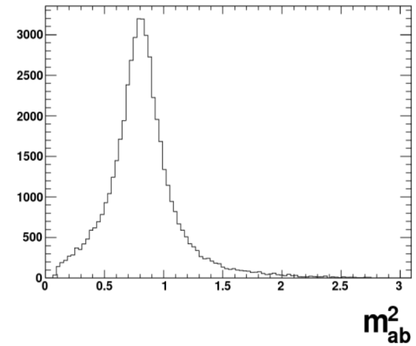
$$P \rightarrow ABC$$

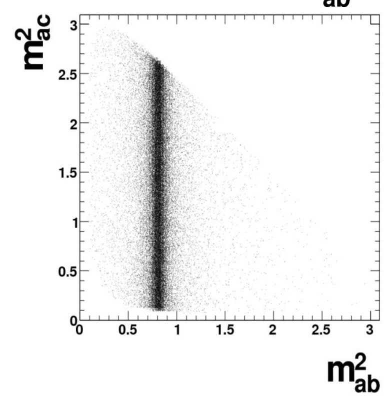
Dalitz Plot: Scatter plot in m_{ab}^2, m_{ac}^2

If no intermediate structure then uniformly populat

(inside kinematic bounds)







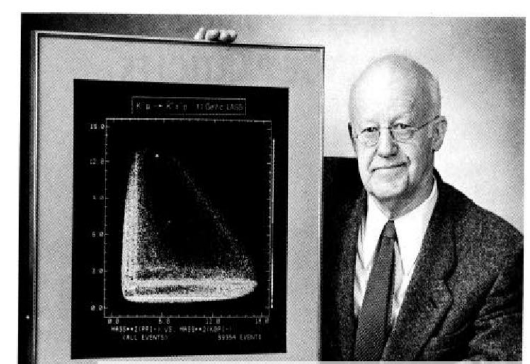
$$P \rightarrow rC, \quad r \rightarrow AB$$

If intermediate resonan

then plot will have internal structure

Shorter-lived resonances – larger widths

- Energy Conservation sets boundaries of plot
  - $Q = T_A + T_B + T_C$,
  - Q energy released in decay of P,
  - T_i K.E. of product i



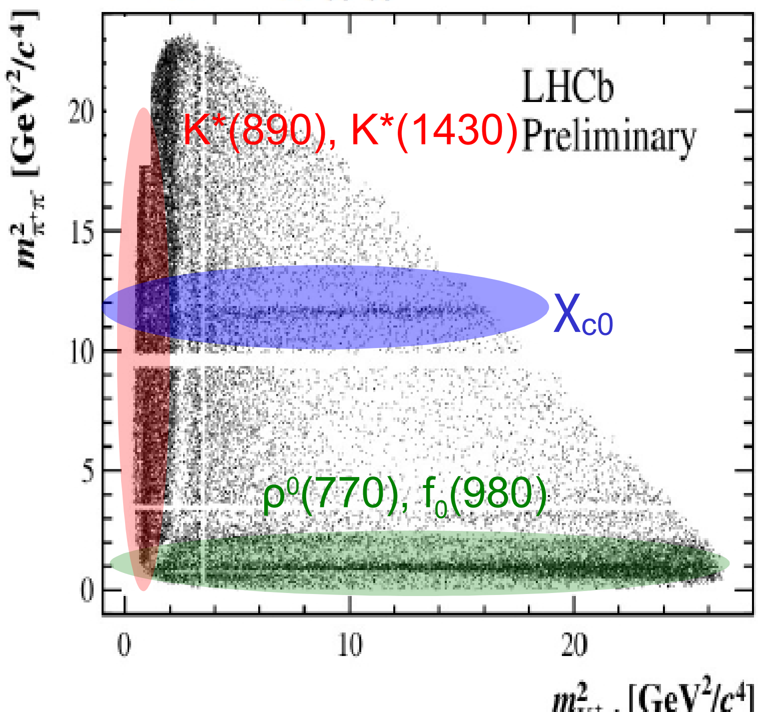
Richard Dalitz

CP Violation in $B^+ \to hhh$

arXiv:1408.5373v1

- $B^+ \to h^+h^+h^-$ (where h= K or π)
- Both tree & penguin diagrams contribute
- Any difference B^+/B^- is CP violation
  - Search for global
  - & local asymmetries

Dalitz Plot



$$A_{cp} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)}$$

$$\approx A_{CP} + A_{prod} + A^h_{det}$$

- A_{prod} is $B^\pm$ production asymmetry,
- A^h_{det} is h detection asymmetry.

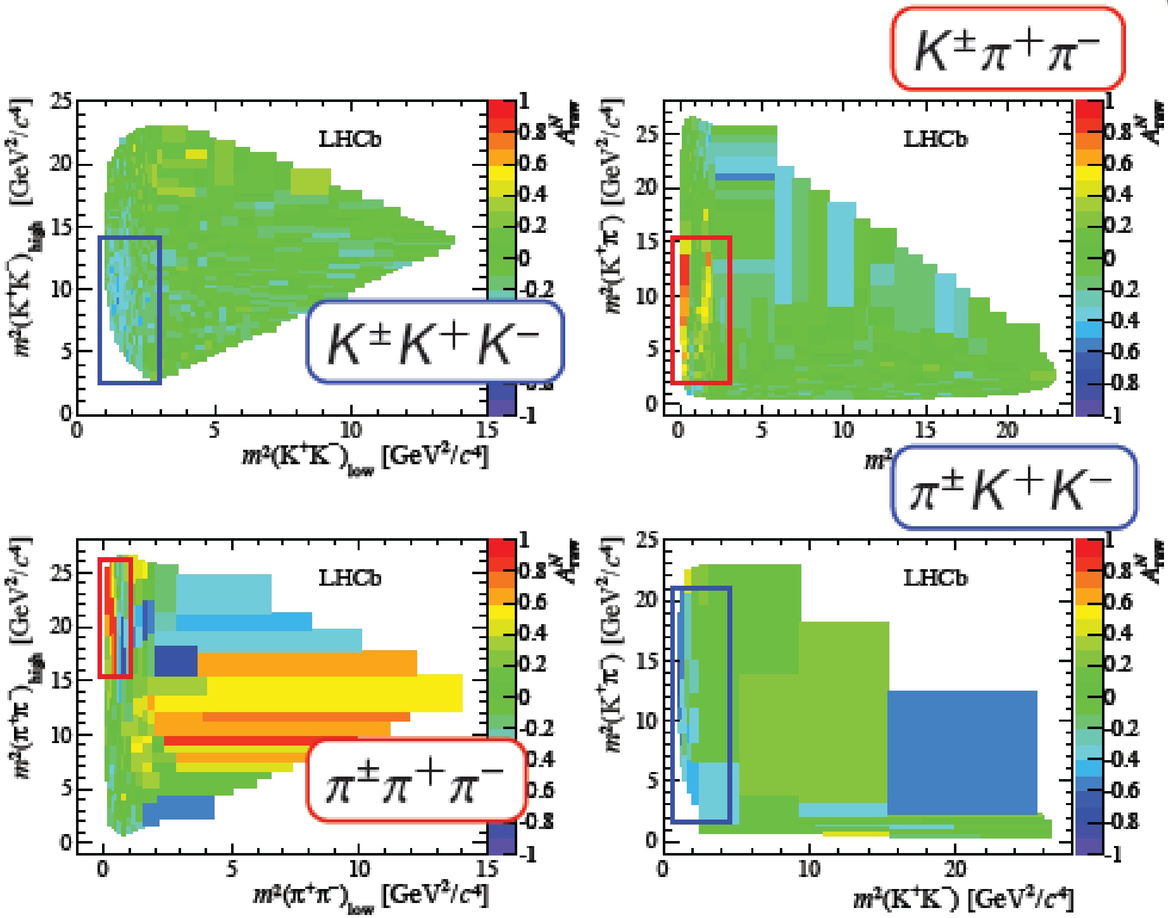
Control channel $B^\pm \to J/\psi K^\pm$ used to cancel production asymmetry.
$A^\pi_{det} = (0.00 \pm 0.25)\%$, $A^K_{det} = (-1.26 \pm 0.18)\%$ [PLB 713 (2012) 186].

CP Violation in $B^+ \to hhh$

PRL **111**, 101801 (2013)

- Make Dalitz plot for B^+,B^-
- Any difference is CP violation

$$A_{cp} = \frac{\Gamma(B^- \to f) - \Gamma(B^+ \to f)}{\Gamma(B^- \to f) + \Gamma(B^+ \to f)}$$



Positive for $h^\pm\pi^+\pi^-$, negative for $h^\pm K^+K^-$. Effects of $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering and interference between resonances. Full amplitude analysis will be invaluable.

- 3rd Year u/g Lab experiment in

MANCHESTER 1824
The University of Manchester

- Local regions of large CP violation

Slides: Shanzhen Chen

New !

Direct CP Violation Search

$D \to \pi^+\pi^-\pi^0$

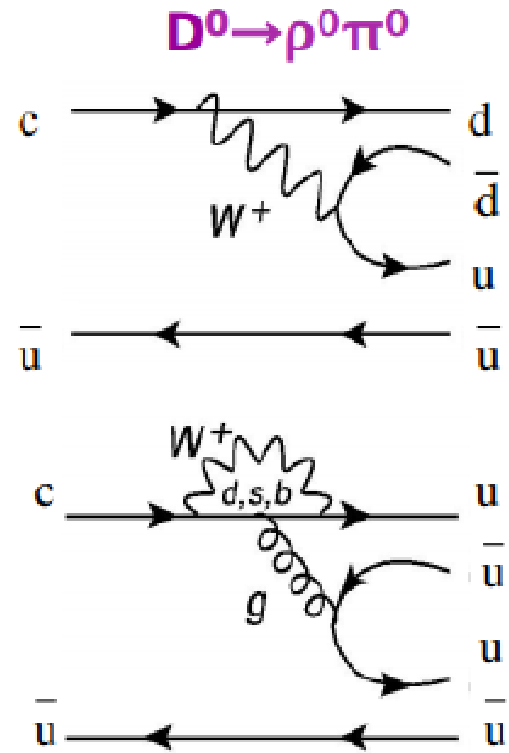
- First LHCb CPV result with π^0
- First use of Energy Test

Introduction to $D^0 \to \pi^-\pi^+\pi^0$

Singly Cabibbo suppressed decay:

Tree + Penguin

- CP asymmetry $< 10^{-3} \sim 10^{-2}$ within SM
- New Physics can increase CPV
- Phase space dominated by three interfering $\rho\pi$ resonances



First time use full LHCb π^0 reconstruction:

- Two separated photon clusters (resolved π^0)
- Two overlapping photon clusters (merged π^0)

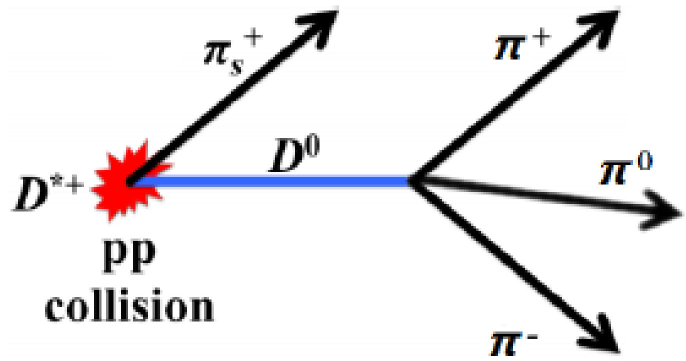
Previous studies:

BaBar: PRD78, 051102 (2008) Belle: PLB662, 102-110 (2008)

CPV effects of several % excluded

$D^0 \to \pi^-\pi^+\pi^0$ data

Prompt: $D^{*+} \to D^0\pi_s^+$, flavor tagged by slow pion (π_s^+)

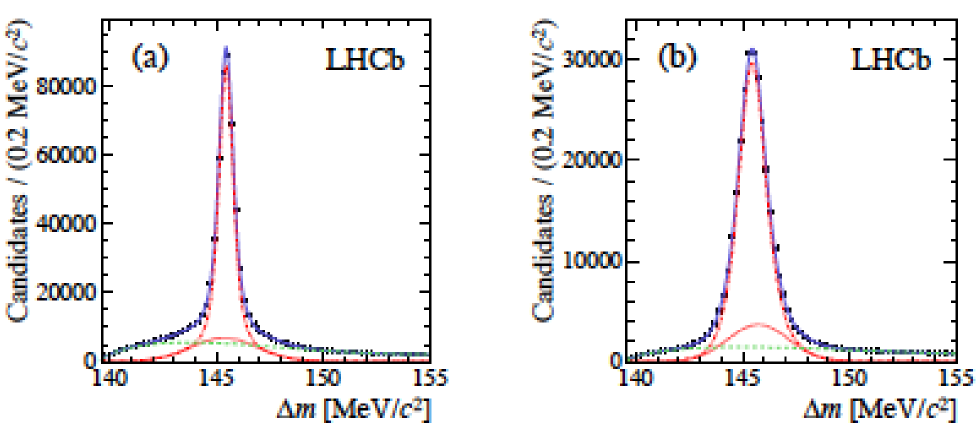


2012 data, integrated luminosity 2fb^{-1}

Selected candidates:

(a) Resolved π^0s, 416×10^3 candidates, purity 82%

(b) Merged π^0s, 247×10^3 candidates, purity 91%

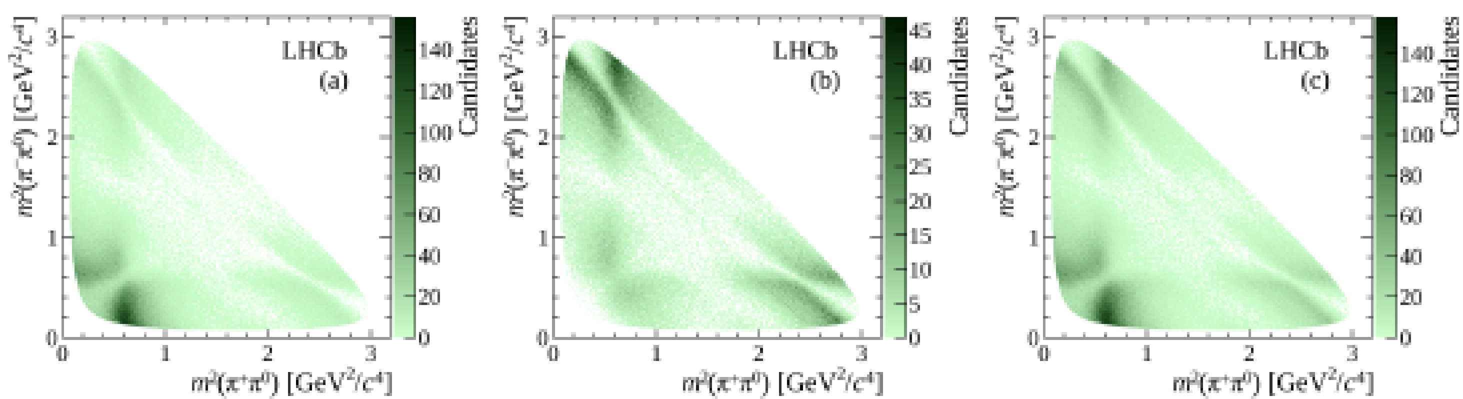


arXiv:1410.4170

Resolved and merged π^0

- π^0 has low momentum $\rightarrow$ two separated photon clusters in *ECAL* $\rightarrow$ resolved π^0
- π^0 has high momentum $\rightarrow$ one merged photon cluster in *ECAL* $\rightarrow$ merged π^0

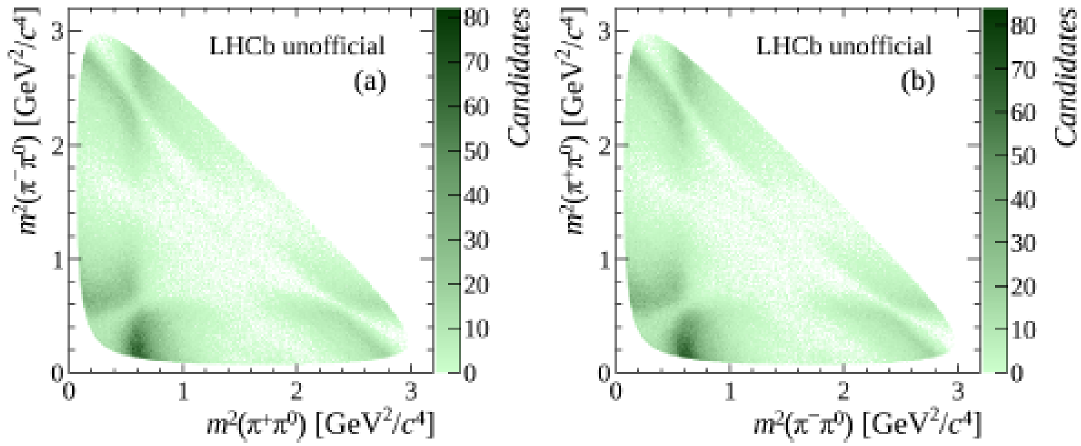
arXiv:1410.4170



(a) Resolved π^0 (b) Merged π^0 (c) Combined sample

A model independent unbinned method: Energy test

- Looking for asymmetries on Dalitz plot
- Compare D^0 and $\bar{D}^0$ decays statistically



- Test statistic:

$$T = \underbrace{\frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(d_{ij})}_{\text{average } \psi \text{ of } D^0 \text{ set}} + \underbrace{\frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(d_{ij})}_{\text{average } \psi \text{ of } \bar{D}^0 \text{ set}} - \underbrace{\frac{1}{n\bar{n}} \sum_{i,j}^{n,\bar{n}} \psi(d_{ij})}_{\text{average } \psi \text{ of } D^0 \text{ to } \bar{D}^0}$$

with $\psi(d_{ij}) = e^{-d_{ij}^2/2\sigma^2}$, $d_{ij} = |\,(m_{12}^{2,j} - m_{12}^{2,i}, m_{23}^{2,j} - m_{23}^{2,i}, m_{13}^{2,j} - m_{13}^{2,i})\,|$

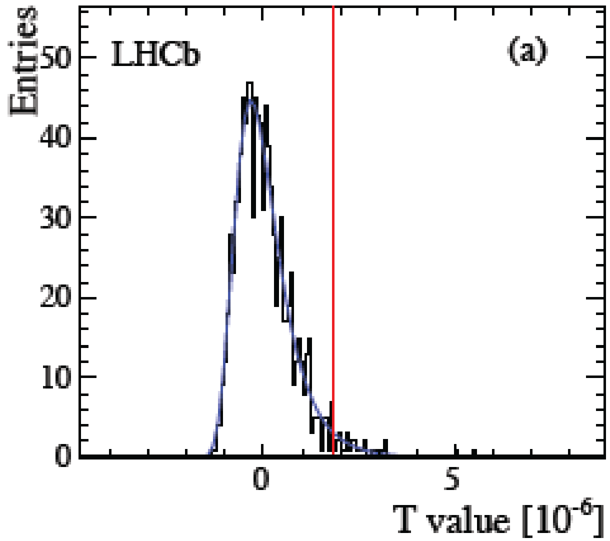
Results

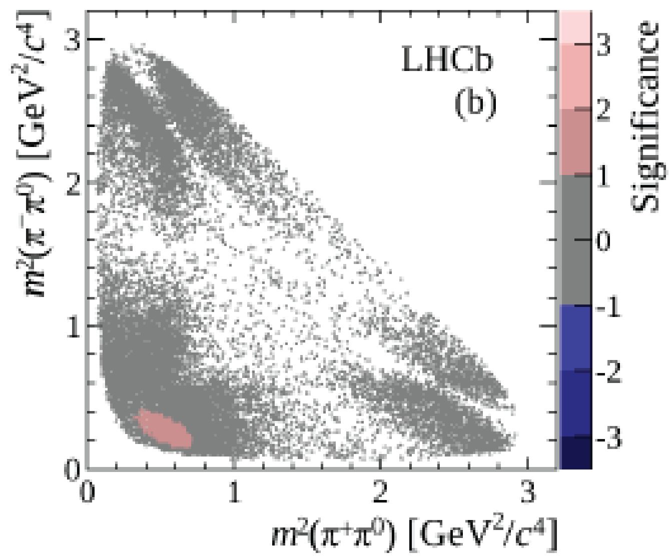
arXiv:1410.4170

- With 1000 permutations
- For no-CPV hypothesis:
  p-value $= (2.6 \pm 0.5)\%$
  Result consistent with no CPV hypothesis
- Other metric parameters:

Table 2: Results for various metric parameter values. The p-values are obtained with the counting method.

σ [GeV^2/c^4]	p-value
0.2	$(4.6 \pm 0.6) \times 10^{-2}$
0.3	$(2.6 \pm 0.5) \times 10^{-2}$
0.4	$(1.7 \pm 0.4) \times 10^{-2}$
0.5	$(2.1 \pm 0.5) \times 10^{-2}$





Rare B decays

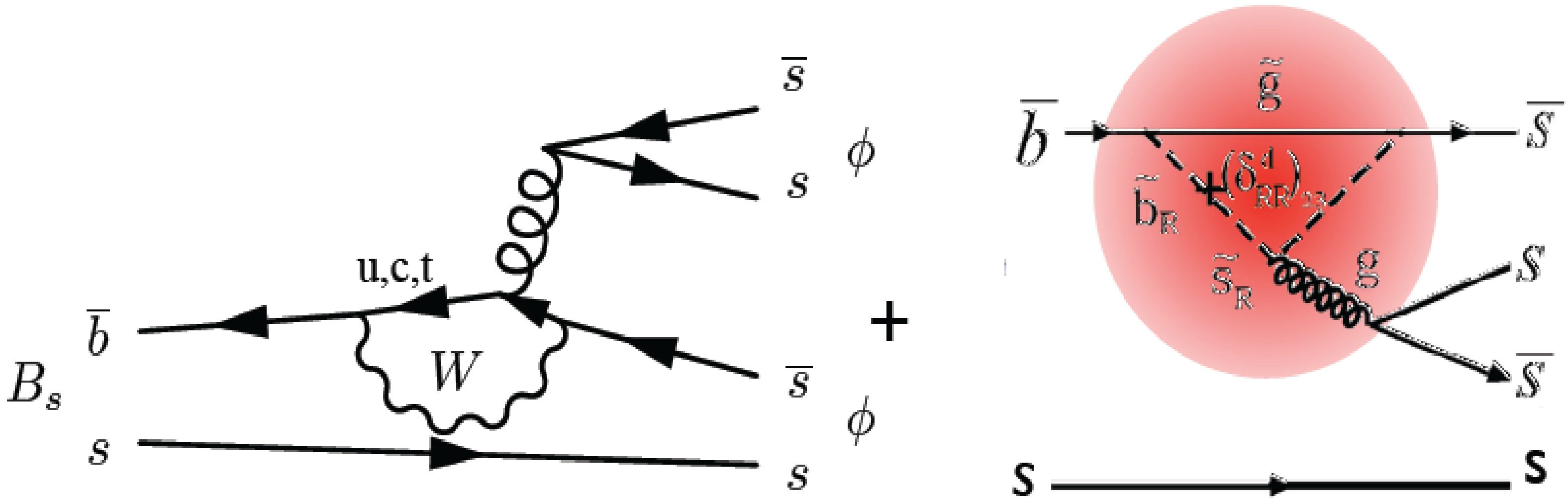
$B_{(s)} \to \mu^+\mu^-$

$B^0 \to K^*\mu^+\mu^-$

Rare Decay Loops

Why are loop dominated decay processes very perceptible to 'new' particles?

- You can simply replace an 'internal quark line' (the circle) with 'new' particles without affecting the initial and final state of the decay

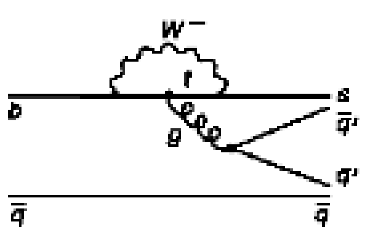


- Momentum flowing through loop should be integrated to "infinity"
  → Potential high masses of virtual particles don't kill their contribution…

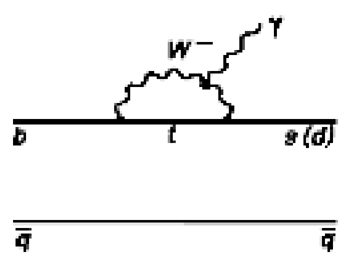
- No tree-level diagrams: less competition/pollution from (boring) Standard Model amplitudes..

Rare B decays – All active research topics at LHCb

DECAY	TYPE	B.R. (approx.)
$B^0 \to K^{*0} \gamma$ $B_s \to \phi \gamma$ $B^0 \to \omega \gamma$	Radiative penguin	4.0×10^{-5} 2.1×10^{-5} 4.6×10^{-7}
$B^0 \to K^{*0} \mu^+ \mu^-$	Electroweak penguin	1.2×10^{-6}
$B_s \to \phi \phi$ $B^0 \to \phi K_S$	Gluonic penguin	1.3×10^{-6} 1.4×10^{-6}
$B_s \to \mu^+ \mu^-$	Rare box diagram	3.5×10^{-9}

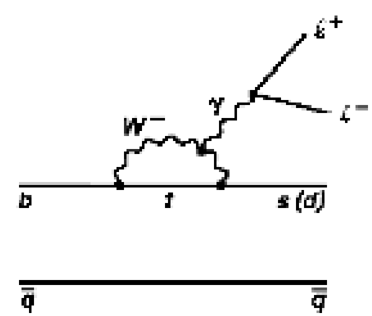


(e) Gluonic penguin



(f) EM penguin

Radiative penguin

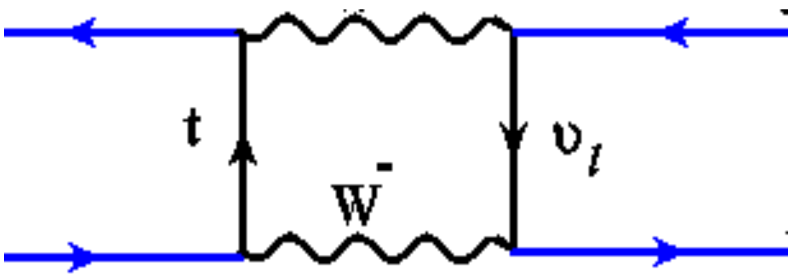


(g) EM penguin

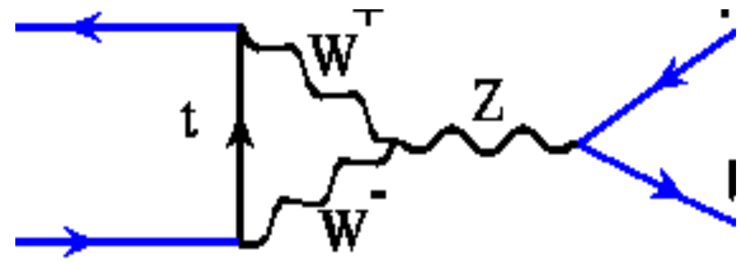
The $B_{(s)} \to \mu^+\mu^-$ decay (1/2)

- Unique Experimental signature
  - Easy to identify / trigger – good for ATLAS/CMS as well

- Really really rare! But well predicted in SM



SM box

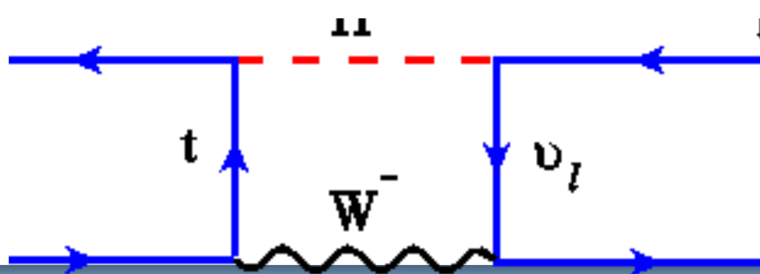


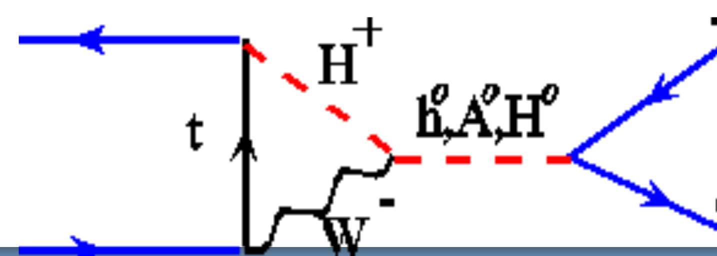
SM Penguin

- Sensitive to New Physics

$B(B_s \to \mu\mu)$ in SUSY models

$$\sim 5 \times 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{300GeV}{M_A}\right)^4$$





First evidence of the $B_s^0 \to \mu^+\mu^-$ decay

LHCb collaboration

Phys.Rev.Lett. 108 (2012) 231801

DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 87-111
September 1987

B MESON DECAYS INTO CHARMONIUM STATES

25 year long search

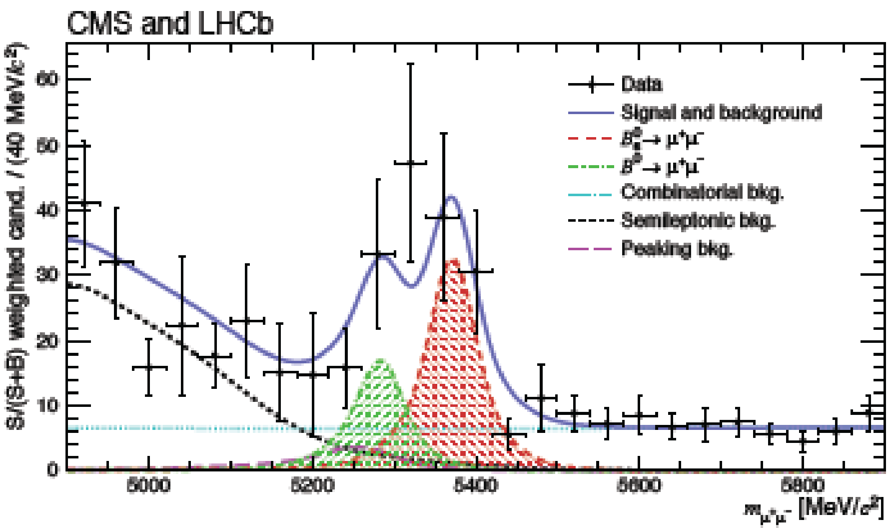
ted exclusive events the masses of the B^0 and B^+ mesons are determined to be $(5279.5 \pm 1.6 \pm 3.0)$ MeV/c^2 and $(5278.5 \pm 1.8 \pm 3.0)$ MeV/c^2 respectively. Branching ratios are determined from five events of the type $B^0 \to J/\psi K^{*0}$ and three of $B^+ \to J/\psi K^+$. In the same data sample a search for $B^0 \to e^+e^-$, $\mu^+\mu^-$ and $\mu^\pm e^\mp$ leads to upper limits for such decays.

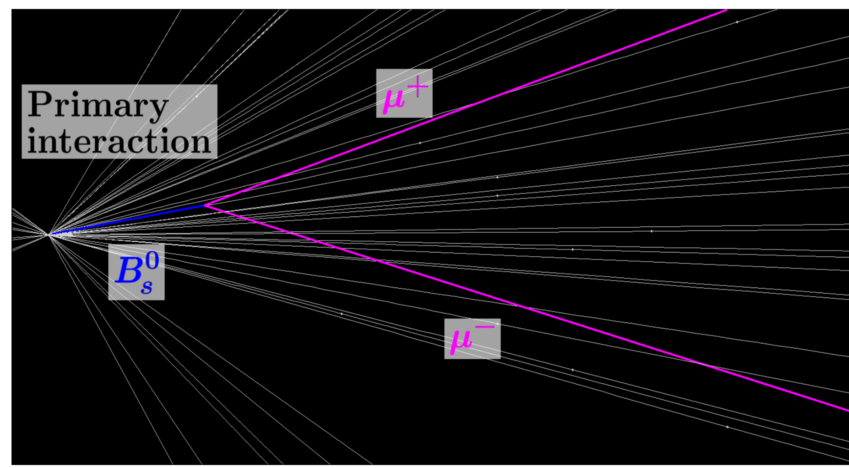
Table 2 Upper limits for exclusive dilepton decays.

decay channel	upper limit with 90% CL
$B^0 \to e^+e^-$	$8.5 \cdot 10^{-5}$
$B^0 \to \mu^+\mu^-$	$5.0 \cdot 10^{-5}$
$B^0 \to e^\pm\mu^\mp$	$5.0 \cdot 10^{-5}$

$$BR(B_s \to \mu^+\mu^-) = (3.17^{+1.47}_{-1.20}) \times 10^{-9}$$

SM theory $3.23 \pm 0.27\ 10^{-9}$





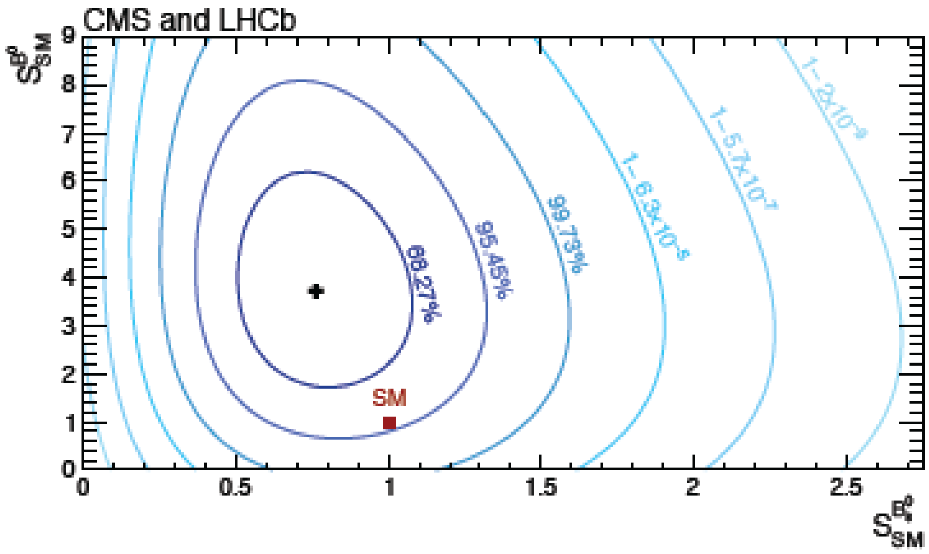
Powerful constraint on SUSY

$B_{d,s} \to \mu^+\mu^-$: LHCb and CMS combination

[LHCb-PAPER-2014-049]

2D likelihood of $\mathcal{B}(B_d^0 \to \mu^+\mu^-)$ vs $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$:

NEW !



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9} \qquad 6.2\sigma$$

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10} \qquad 3.2\sigma$$

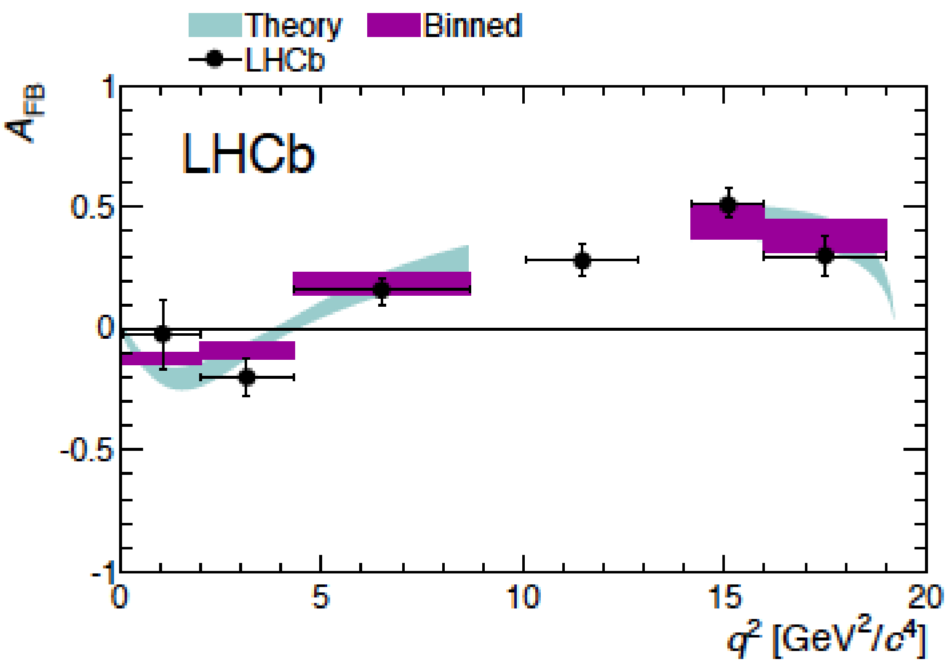
Both compatible with SM predictions.

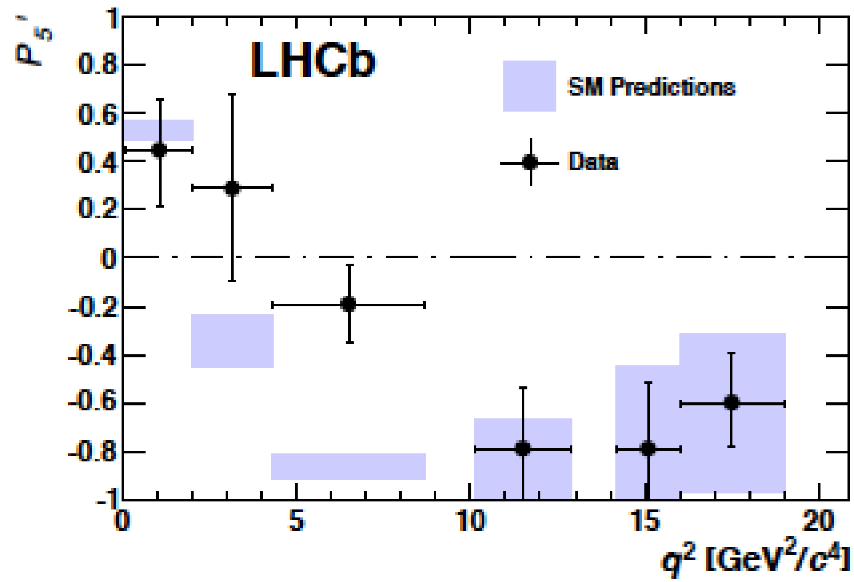
$\mathcal{B}(B_d^0 \to \mu^+\mu^-)$ compatible with SM at 2.2σ.

Paper submitted to Nature.

LHCb: Initial Highlights– $B^0 \to K^* \mu^+ \mu^-$

- $B^0 \to K^* \mu^+ \mu^-$: NP in loops
  - Rare decays are not so rare now !



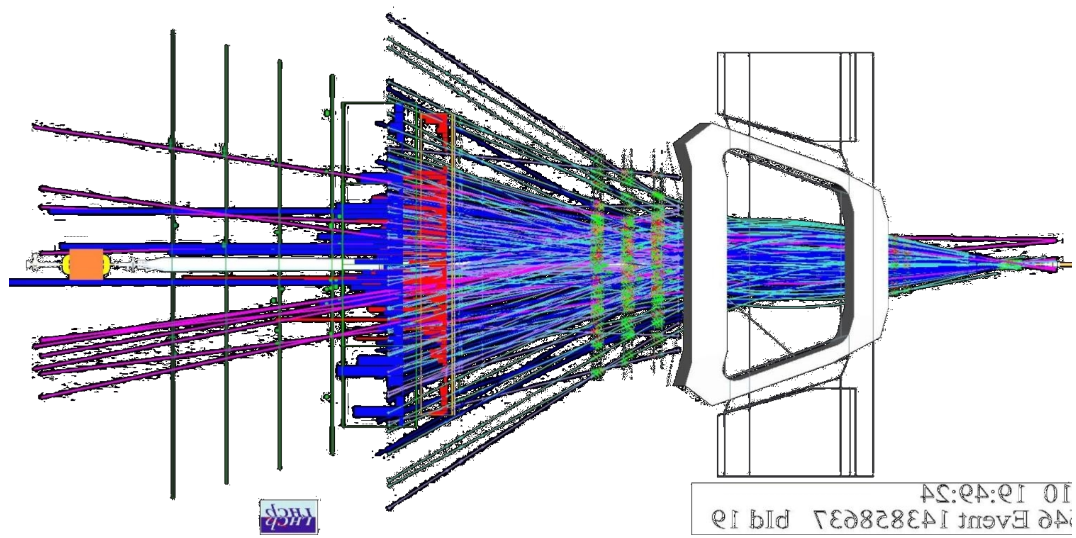


► Large (3.7σ) local deviation in P_5' (measure of $L \leftrightarrow R$ asymmetry of interference between A_0 and $A_\perp$ [Descote-Genon et al. JHEP 1305(2013)137])

Beyond the Energy Frontier

New ! Recommended for approval by STFC

- Upgrade



Physics Programme

Limited by Detector

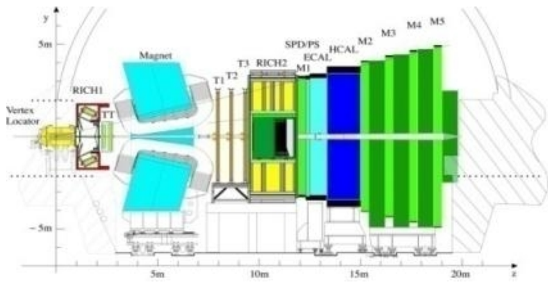
But **NOT** Limited by LHC

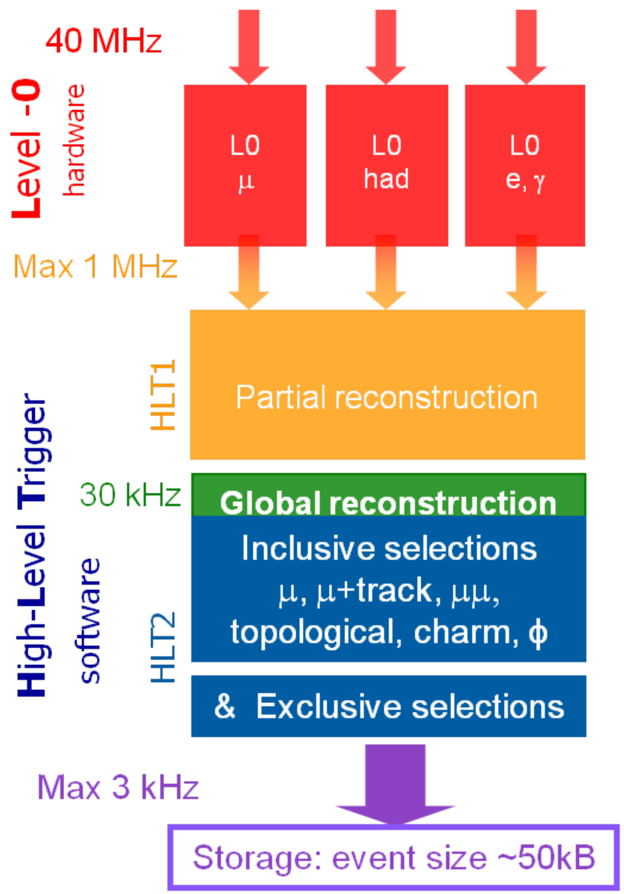
- Upgrade to extend Physics reach
  - Exploit advances in detector technology
    - Displaced Vertex Trigger, 40MHz readout
    - Radiation Hard Vertex Detector
  - Better utilise LHC capabilities
- Timescale, 2018-2020
- Collect >50 fb^{-1} data
- Modest cost compared with existing accelerator infrastructure

Independent of LHC upgrade

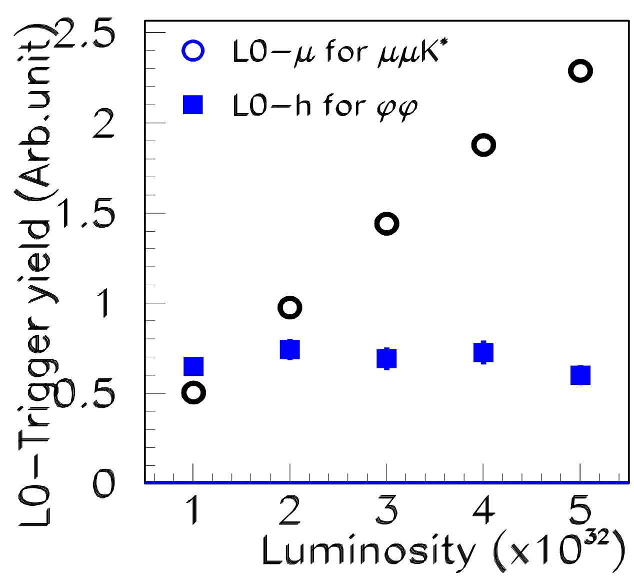
- HL-LHC not needed
- But compatible With HL-LHC phase

LHCb Trigger: the key to higher Lumi



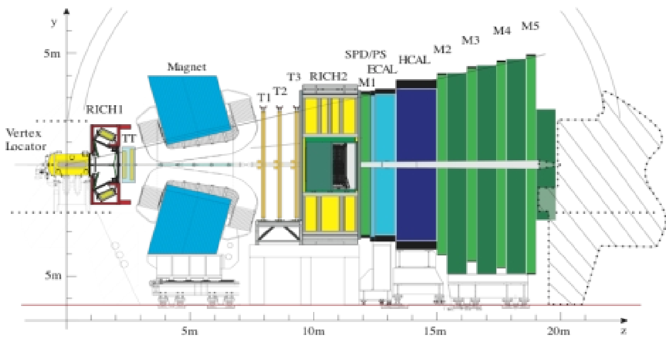


Current First Trigger Level:
Hardware Muon/ECAL/HCAL
1.1 MHz readout



Performance:
Muon channels scale
Hadronic channels saturate bandwidth

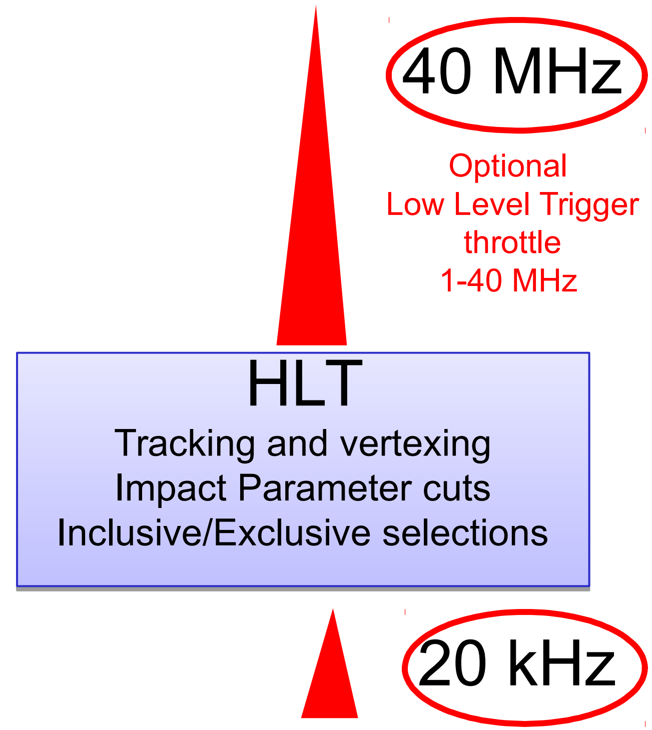
Solution: Upgrade detector to 40MHz readout



Upgrade Trigger fully software based
Runs in stageable Event Filter Farm
Up to **40 MHz input rate**
20 kHz output rate
Trigger has access to all event information

Run at L > 10^{33} cm^{-2} s^{-1}
~ Gain of 2 in signal rates for hadronic dependent on farm size

Efficiency	Farm Size = 5 x 2011	Farm Size = 10 x 2011
$B_s \rightarrow \phi\phi$	29%	50%
$B^0 \rightarrow K^*\mu\mu$	75%	85%
$B_s \rightarrow \phi\gamma$	43%	53%

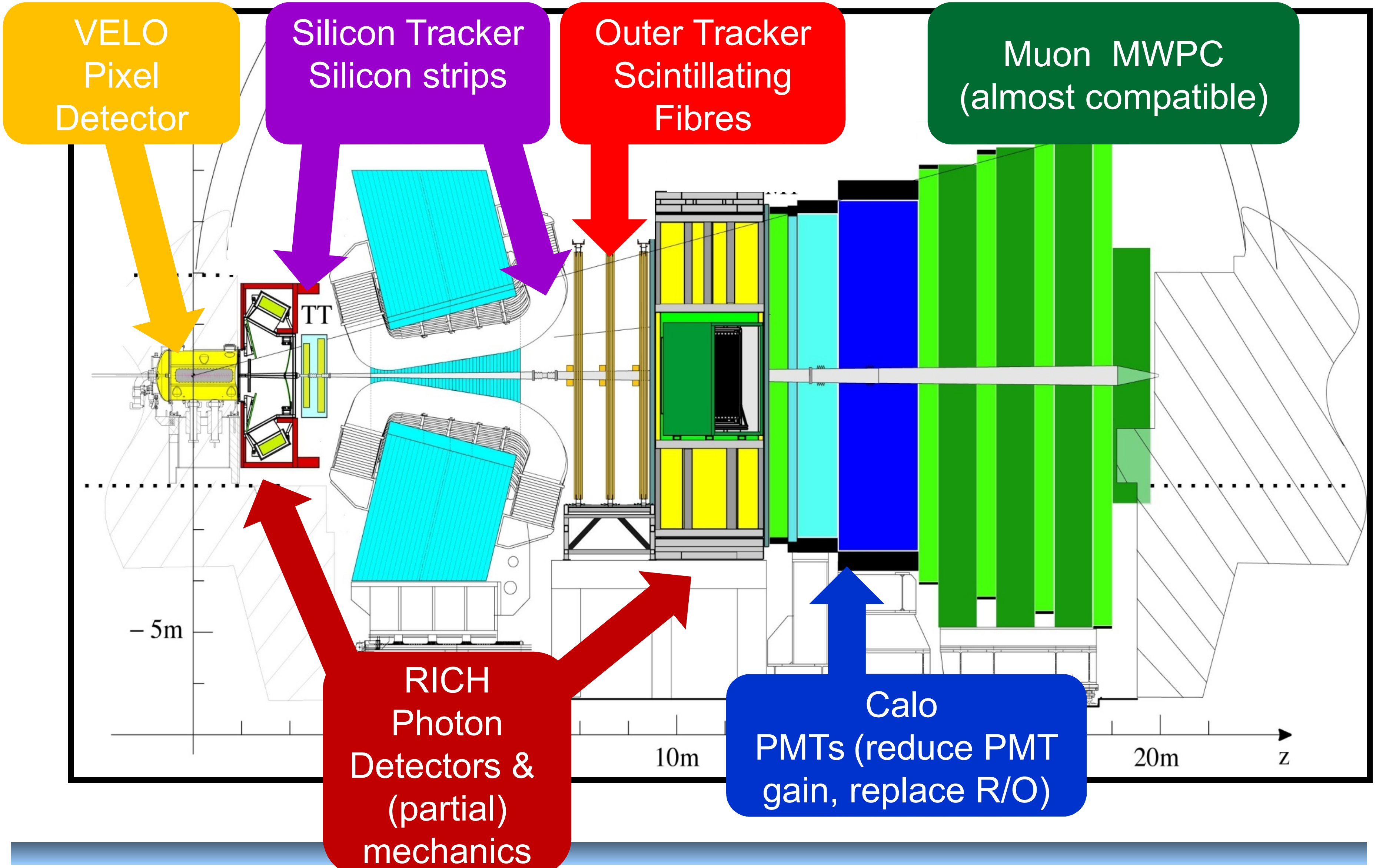


LHCb Upgrade Overview

- 40 MHz Readout of all subdetectors
  - Flexible Trigger: General purpose experiment in forward region

  Retain key LHCb advantages:
  - Vertex Resolution, Momentum resolution, Particle ID
- Installation 2018
- LOI submitted March 2011
- Approved by LHCC June 2011
  - “compelling physics case”
- Funding effectively in place October 2014

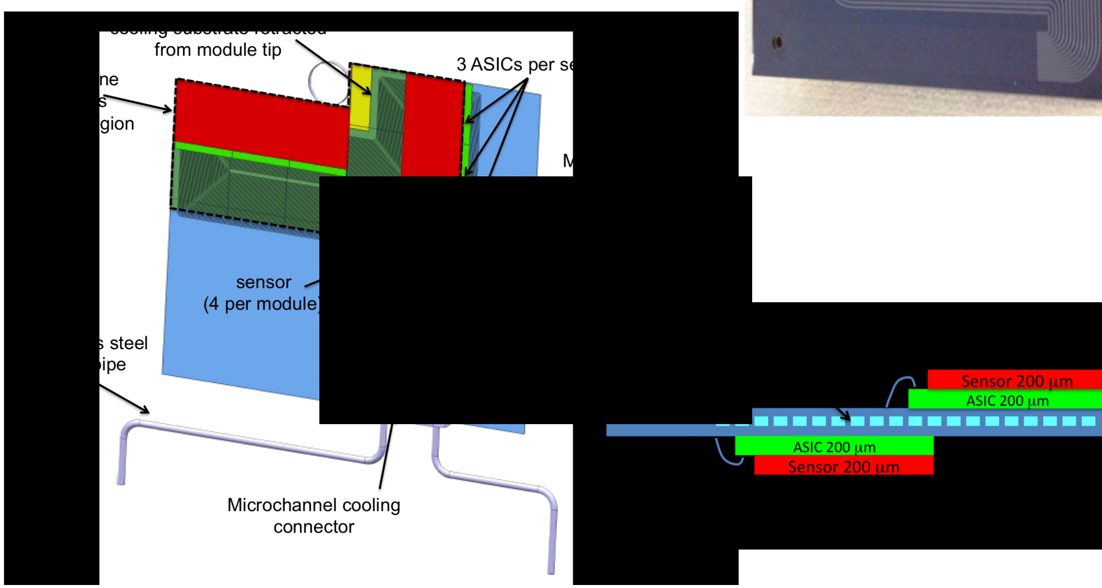
LHCb Upgrade to 40 MHz



VELO Design

Thomas Bird

- New VELO sensors need optimal placement
- Right: Sensor position effects IP resolution
- Below: Final sensor placement
  - Upgrade VELO
  - Current VELO



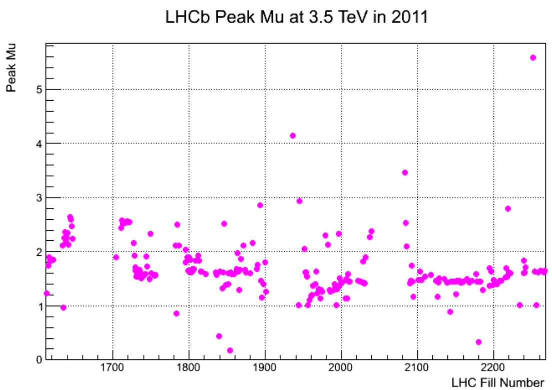
Summary

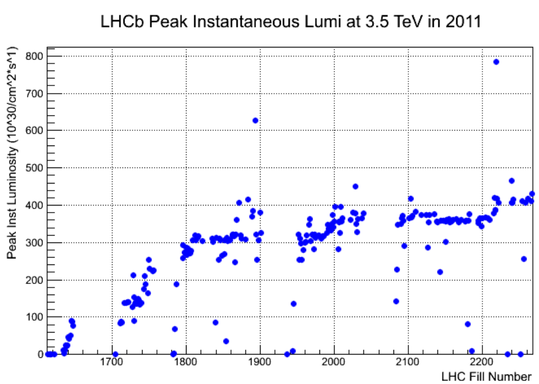
- Physics Highlights
  - New Physics searches at mass scales beyond direct production
  - CP Violation, Rare Decays
  - $D \to \pi^+\pi^-\pi^0$
- LHCb Upgrade
  - 40 MHz Readout of all subdetectors
    - trigger flexibility
  - Installation 2018-2020

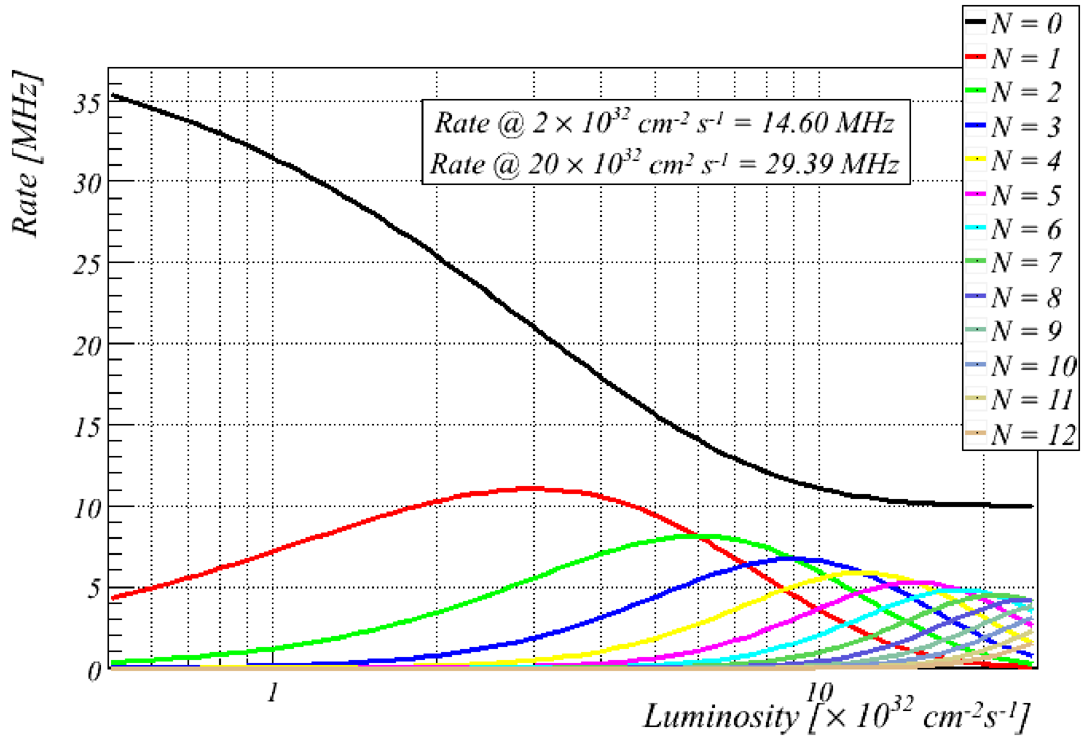
Backup

Luminosity and Pile-Up

- **LHCb design:** L ~ 2×10^{32} cm^{-2} s^{-1} with 25 ns BX
  - interactions / beam crossing = 0.4
- **LHCb operations in run I**: L up to 4×10^{32} cm^{-2} s^{-1} with 50 ns BX
  - interactions / beam crossing = 2
- **LHCb Upgrade:** L > 1×10^{33} cm^{-2} s^{-1} with 25 ns BX
  - interactions / beam crossing = 2

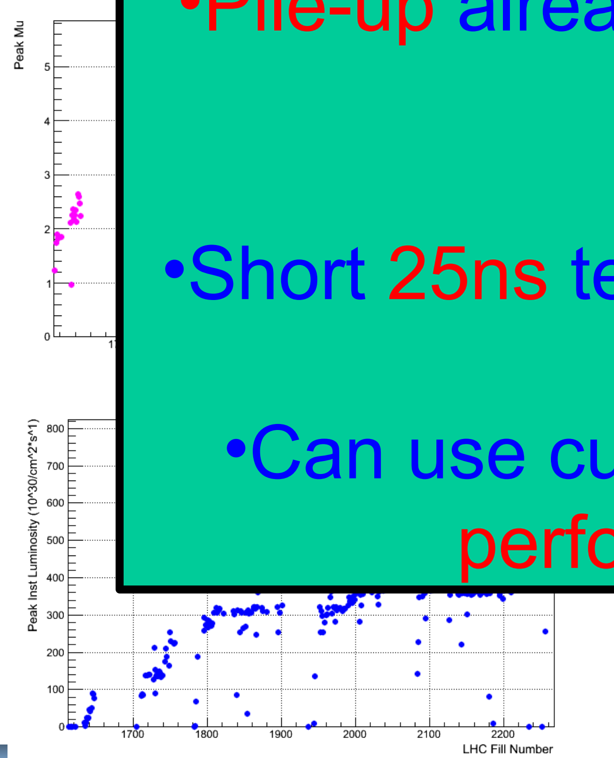






Luminosity and Pile-Up

- **LHCb design:** L ~ 2×10^{32} $cm^{-2} s^{-1}$ with 25 ns BX
  - interactions / beam crossing = 0.4
- **LHCb**
  - inte
- **LHCb**
  - inter

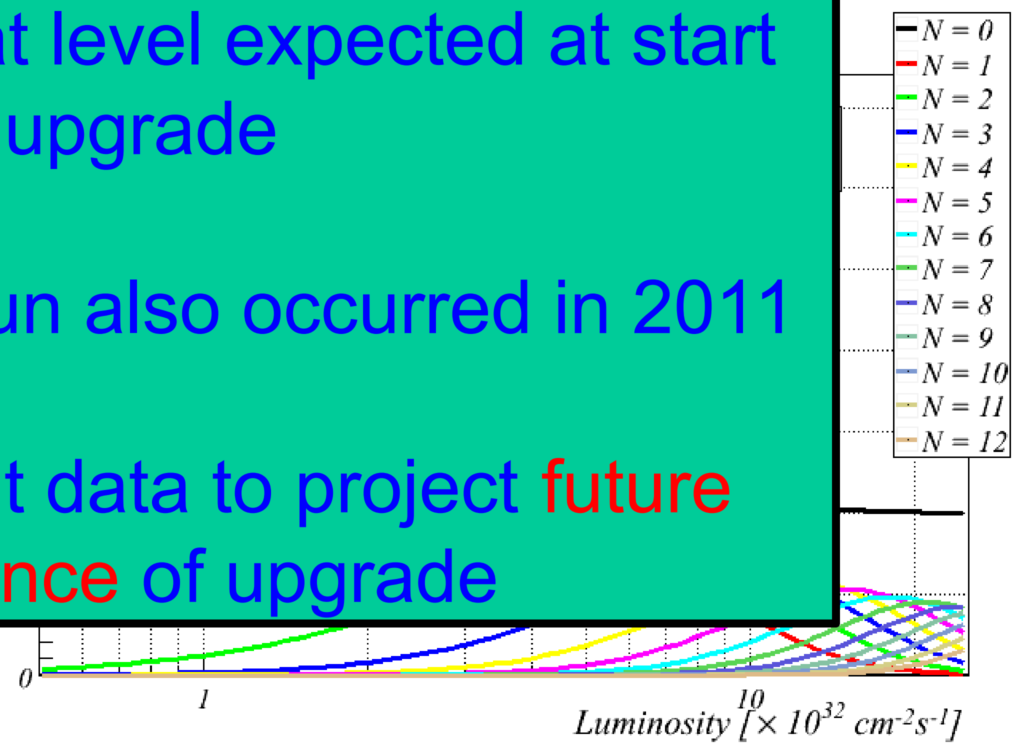


•LHCb already running at twice design luminosity

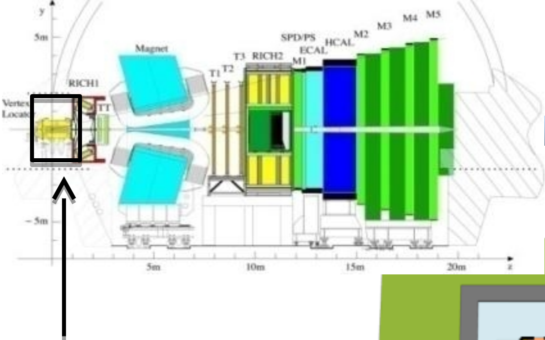
•Pile-up already at level expected at start of upgrade

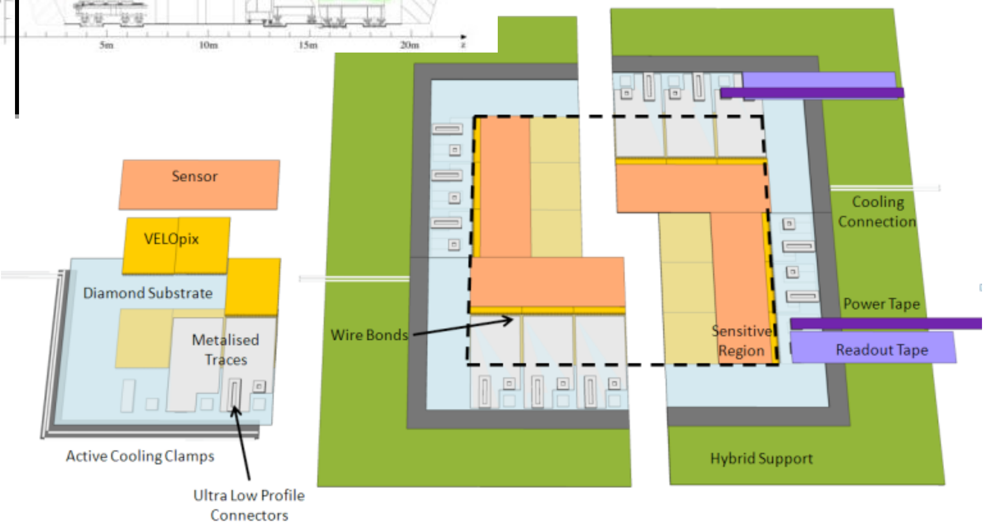
•Short 25ns test run also occurred in 2011

•Can use current data to project future performance of upgrade



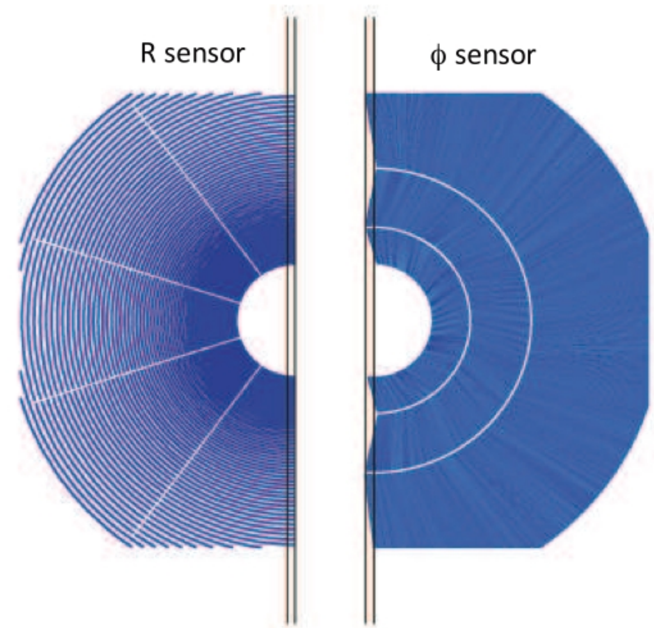
Velo Upgrade



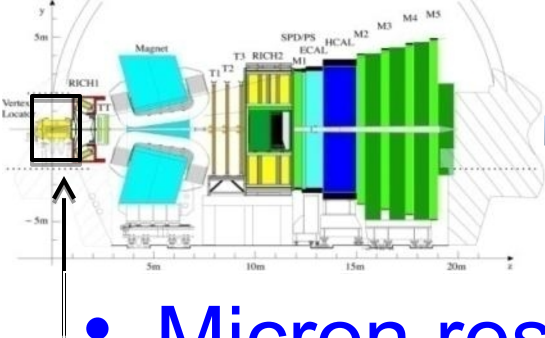


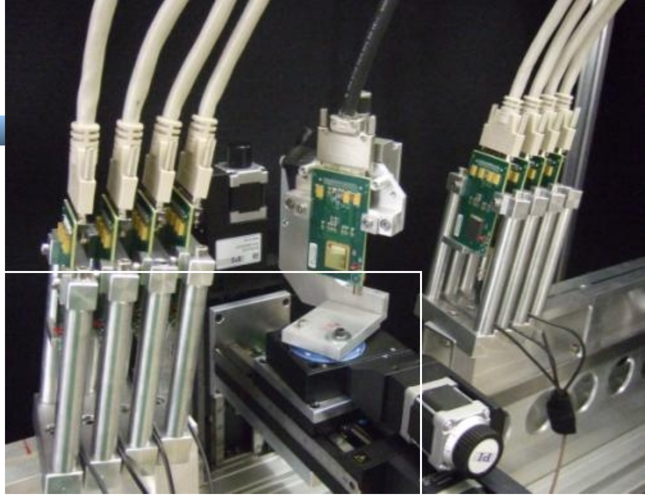
- New Velo @40 MHz readout
  - Pixel detector: VELOPIX based on Timepix chip
    - 55 μm x 55 μm pixel size
  - Strip detector
    - New chip

- R&D programme
  - Module structure (X_0)
  - Sensor options
    - Planar Si, Diamond, 3D
  - CO_2 cooling
  - Electronics
  - RF-foil of vacuum box



Velo R&D



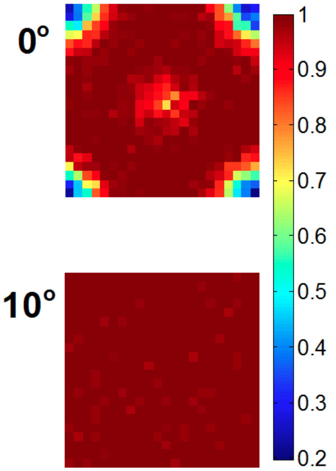


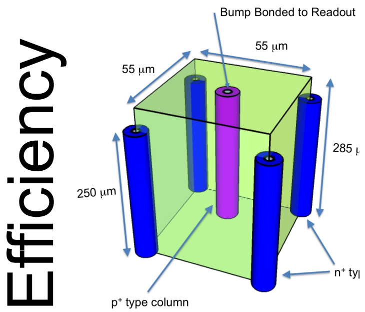
- Micron resolution, high rate telescope based on TimePix

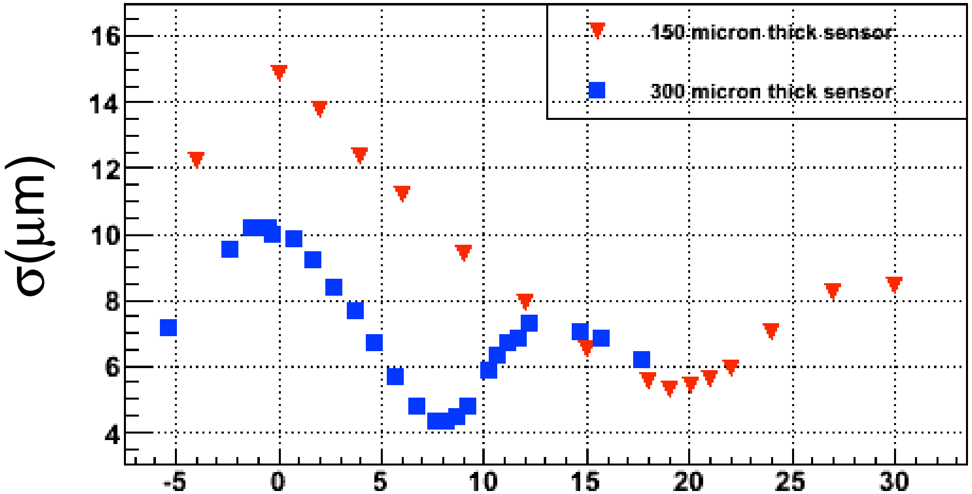
3D Sensor Studies

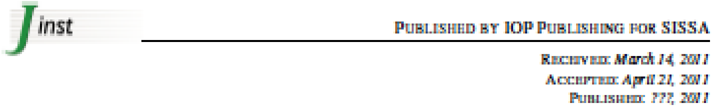
Nucl. Instrum. Meth. A Volume 661, Issue 1, 1 January 2012, Pages 31-49

Planar Sensor Studies







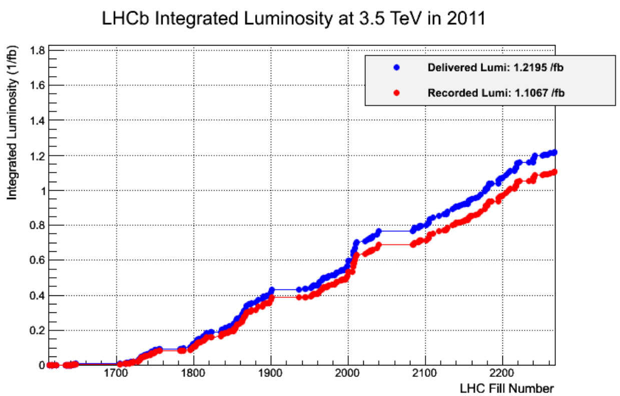


JINST 6 P05002 (2011)

Precision scans of the Pixel cell response of double sided 3D Pixel detectors to pion and X-ray beams

~Timescales: LHCb & Accelerator

- 2011: 1.2 fb^{-1}



- Doubling time for statistics requires upgrade ~ 2018

2010 - 2012
Start of LHCb physics programme
7-8 TeV

Long shutdown
Splice repairs

2015-2017
14 TeV
LHCb > 5 fb^{-1}

LHCb upgrade installed

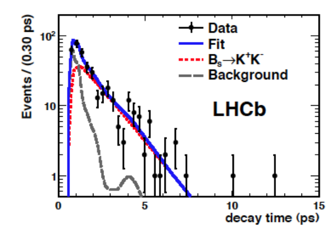
Injector and LHC Phase I GPD upgrades

2018-2022
Start of LHCb upgrade physics programme

Towards High Luminosity LHC

CP Violation: Upgrade Examples

- Core familiar physics – two examples:
- ϕ_s : Mixing induced CPV in B_s
  - Phase I: Observe NP in ϕ_s if larger than 3xSM
    - arXiv:1112.3183; arXiv:1112.3056
  - Upgrade: Beyond SM precision measurement: $\sigma \approx 0.006$
- Rare penguin decay topologies sensitive to NP: Charmless hadronic B-decays

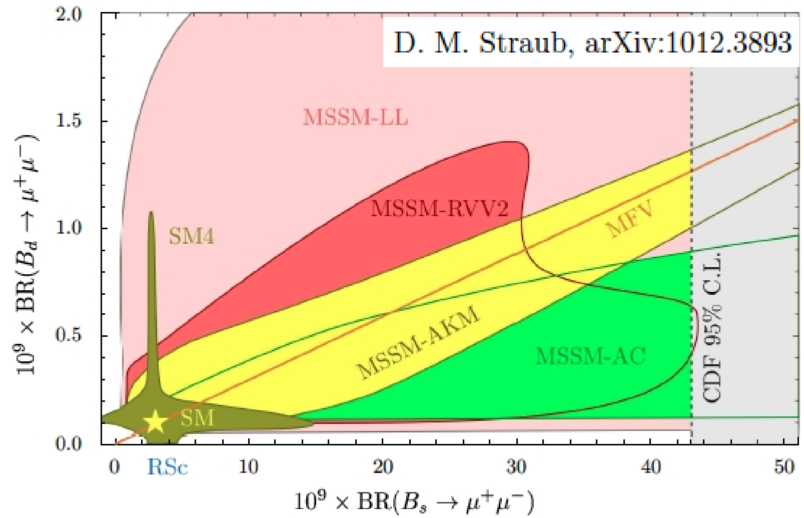


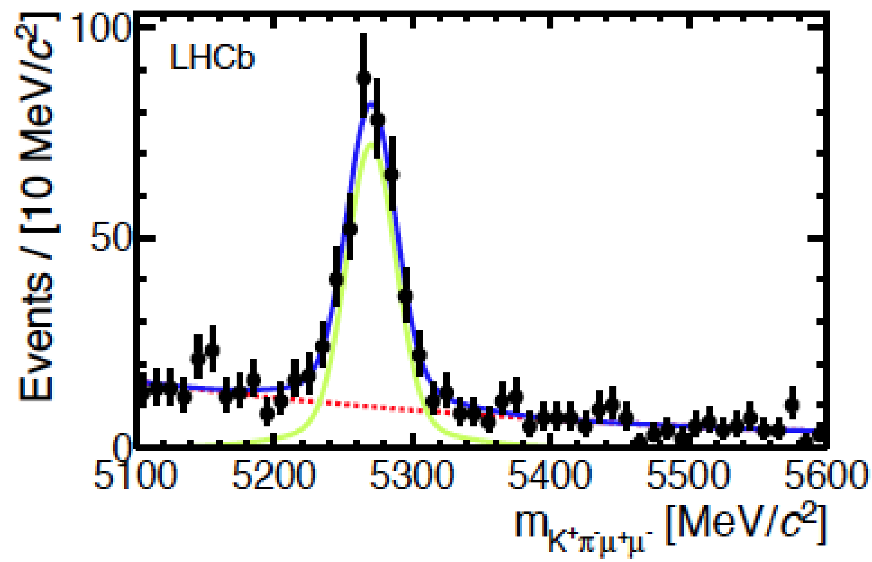
  - Phase I: Direct CP violation in B_s and $\Lambda_{b,}$
    Time dependent CPV in $B_s \rightarrow K^+K^-$ (arXiv:1111.0521)
  - Upgrade: Precision time dependent CPV in penguin dominated $B_s \rightarrow K^{*0}K^{*0}$ (arXiv:1111.4183), $B_s \rightarrow \phi\phi$: $\sigma \sim 0.02$
- A_{fs} - probing D0 result soon; CKM angle γ….

Rare Decays

- $B_{s,d} \to \mu^+\mu^-$
  - Phase I: Search for NP in $B_s \to \mu^+\mu^-$ (arXiv:1112.1600, arXiv:1103.2465)
  - Upgrade: Correlation $B_s \to \mu^+\mu^-$ vs $B_d \to \mu^+\mu^-$
- $B^0 \to K^{*0}\mu^+\mu^-$
  - Phase I: measure AFB and other observables (arXiv:1112.3515)
  - Upgrade: precision full angular analysis
- Radiative decays: $b \to s\, \gamma$: $B_s \to \phi\, \gamma$, photon polarisation (flexible trigger)

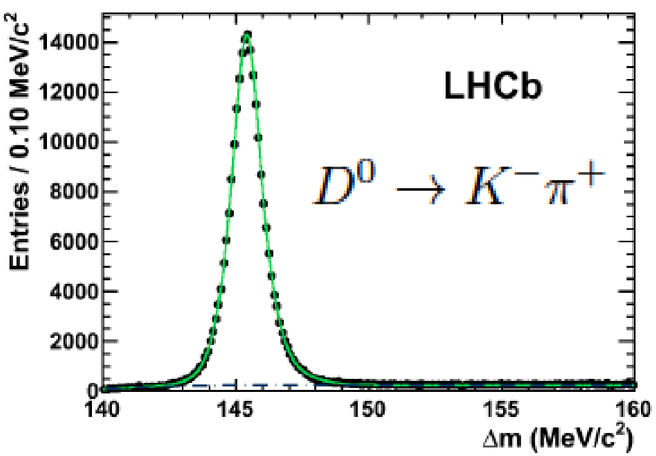
Probing MFV Scenarios





Charm

- LHCb is world's foremost charm factory
  - Evidence direct CP violation (arXiv:1112.0938)
  - Probing oscillations (y_{CP})
  - CP violation in mixing* (A_Γ) (arXiv:1112.4698)
    - Upgrade D sample approx 1000 X B factories and time dependent measurements benefit from excellent resolution
  - Rare decay measurements e.g. $D^0 \to \mu^+\mu^-$
    - where limit currently 10^6 X larger than SM
  - Dalitz Analyses e.g.
    $D^+ \to K^+K^-\pi^+$
  - Time dep. CP violation in
    $D^0 \to K^0_S h^+h^-$



* mostly, see arXiv:1111.6515

Sensitivities to key flavour channels

Type	Observable	Current precision	LHCb ($5\ \mathrm{fb}^{-1}$)	Upgrade ($50\ \mathrm{fb}^{-1}$)	Theory uncertainty
Gluonic penguin	$S(B_s \to \phi\phi)$	-	0.08	0.02	0.02
	$S(B_s \to K^{*0}\bar{K}^{*0})$	-	0.07	0.02	< 0.02
	$S(B^0 \to \phi K_S^0)$	0.17	0.15	0.03	0.02
B_s mixing	$2\beta_s\ (B_s \to J/\psi\phi)$	0.35	0.019	0.006	~ 0.003
Right-handed currents	$S(B_s \to \phi\gamma)$	-	0.07	0.02	< 0.01
	$\mathcal{A}^{\Delta\Gamma_s}(B_s \to \phi\gamma)$	-	0.14	0.03	0.02
E/W penguin	$A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-)$	-	0.14	0.04	0.05
	$s_0\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	-	4%	1%	7%
Higgs penguin	$\mathcal{B}(B_s \to \mu^+\mu^-)$	-	30%	8%	$< 10\%$
	$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B_s\to\mu^+\mu^-)}$	-	-	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	$\sim 20°$	$\sim 4°$	0.9°	negligible
	$\gamma\ (B_s \to D_s K)$	-	$\sim 7°$	1.5°	negligible
	$\beta\ (B^0 \to J/\psi\, K^0)$	1°	0.5°	0.2°	negligible
Charm CPV	A_Γ	2.5×10^{-3}	2×10^{-4}	4×10^{-5}	-
	$A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi)$	4.3×10^{-3}	4×10^{-4}	8×10^{-5}	-

- Unique potential B_s / b baryon sector
- Charged particle final states far in excess of other facilities

Lepton Flavour Violation

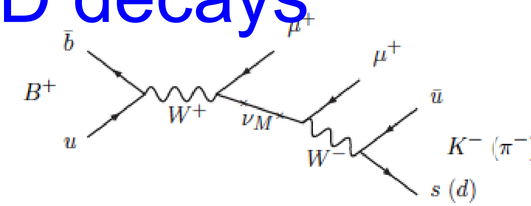
- Neutrino oscillations established

T. Asaka and M. Shaposhnikov, Phys. Lett. **B 620** (2005) 17; T. Asaka, S. Blanchet and M. Shaposhnikov, Phys. Lett. **B 631** (2005) 151; F. Bezrukov, D. Gorbunov, JHEP **1005** (2010) 010. [arXiv:0912.0390 [hep-ph]]; A. Roy, M. Shaposhnikov, Phys. Rev. **D82** (2010) 056014. [arXiv:1006.4008 [hep-ph]].

  - but low neutrino mass scale to be understood
  - Heavy Majorana neutrinos in many NP models
    - e.g. νMSM (dark matter, baryon asymmetry)
  - Direct Search: long lived from B& D decays

Search for the lepton number violating decays $B^+ \to \pi^-\mu^+\mu^+$ and $B^+ \to K^-\mu^+\mu^+$

(arXiv:1110.0730)



  - Indirect: lepton violating e.g.

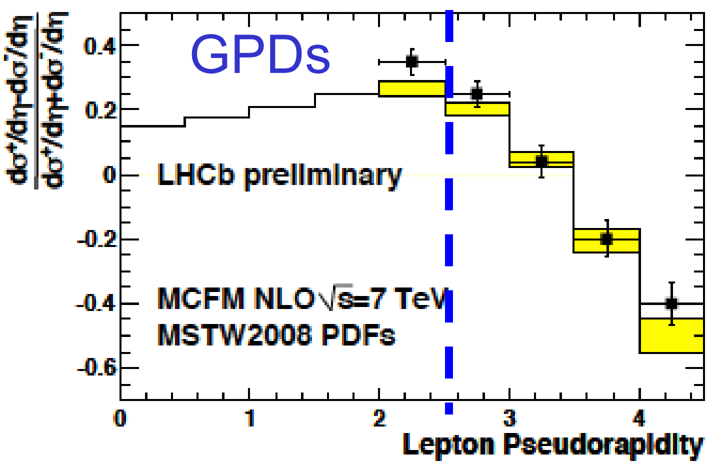
$D_s^\pm \to \pi^\mp\ell^\pm\ell^\pm$ or $B^\pm \to \pi^\mp\ell^\pm\ell^\pm$

Lepton Flavour violating τ-decays

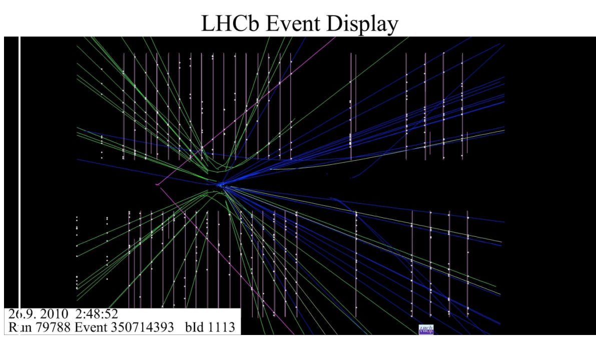
- – Vanishingly small in SM with mixing
- LHC mainly produces τ's from B and D_s decays
  - – LHCb : τ → 3μ
    - Phase-1: aim to match B-factories with few years
    - Upgrade: 10^{-9} level

Electroweak & QCD

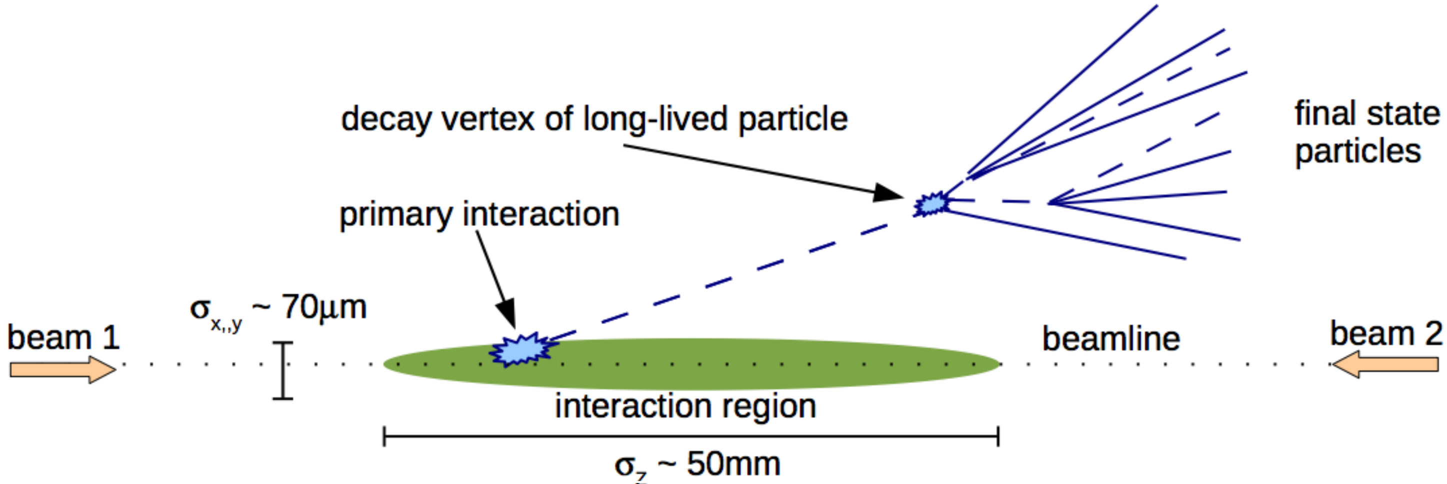
- Boson follows quark direction in forward
  - Hence asymmetry measurements at LHCb
  - – $\sin^2 \theta_{eff}^{lept}$: measure A_{FB} of leptons in Z-decays
    - raw A_{FB} asymmetry factor 5 larger than @ LEP
  - Top quark forward-backward asymmetry
- Constraining pdfs, e.g. W Charge Asymmetry
  - – changes **sign** in LHCb region: constraints on the **low x quark content of the** protons at **high q²**
- Central Exclusive Production



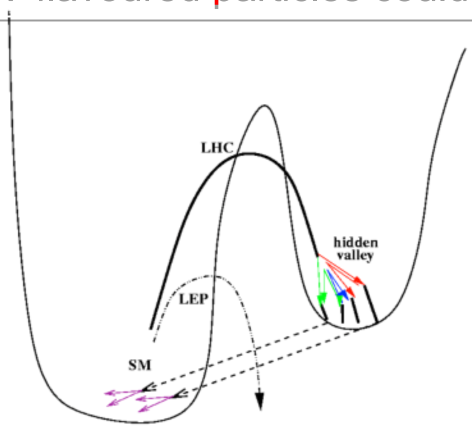
- pp ▭ p + X + p with rapidity gap:
  - – Photon or pomeron exchange



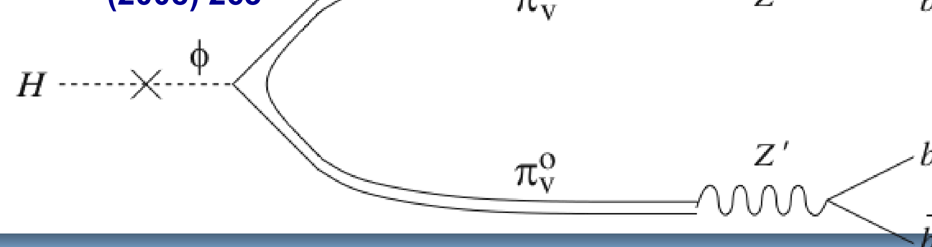
Exotics



- Hierarchy problem: why is Higgs mass not at Planck scale?
  - Many models (Susy, Xtra dimensions, Technicolour, Little Higgs) predict new states at TeV scale: Z', 4th generation, leptoquarks, Hidden Valley particles
- Hidden Valley particles carry "v" quantum number and can be low mass
  - Lightest v-particle is a dark matter candidate
  - V-neutral particles might have long lifetime and decay, e.g. to b bbar
  - V flavoured particles could be produced by Higgs



M.J. Strasser and K.M. Zurek, Phys. Lett. B 661 (2008) 263



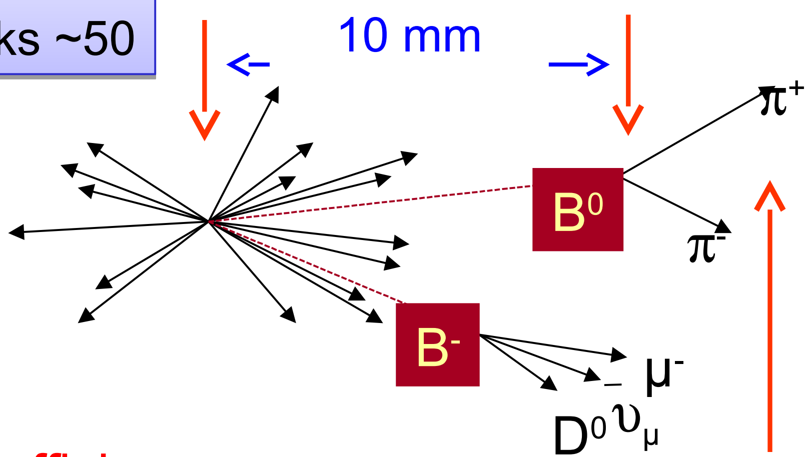
Introducing LHCb

LHCb is a dedicated experiment to study flavour physics at the LHC

- Search for New Physics in quantum loop processes
- CP violation and rare decays allowing to probe beyond the LHC energy frontier

Primary vertex: many tracks ~50

B decay vertices: a few tracks



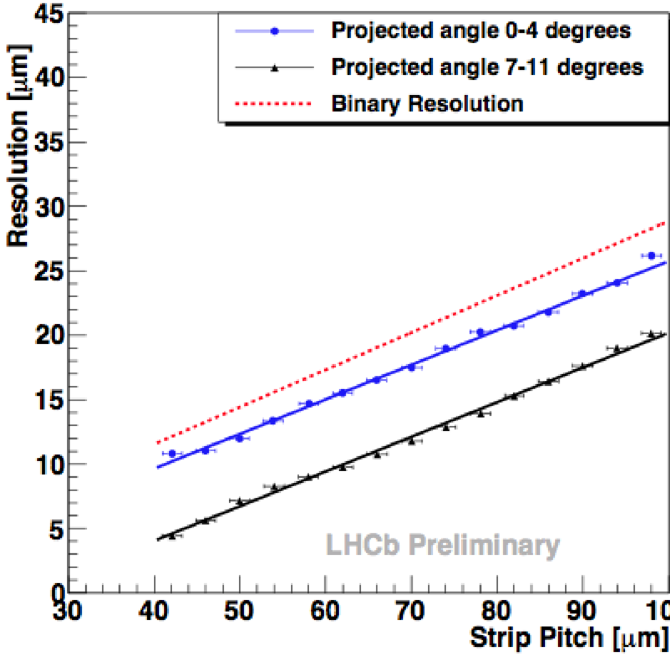
K/π separation

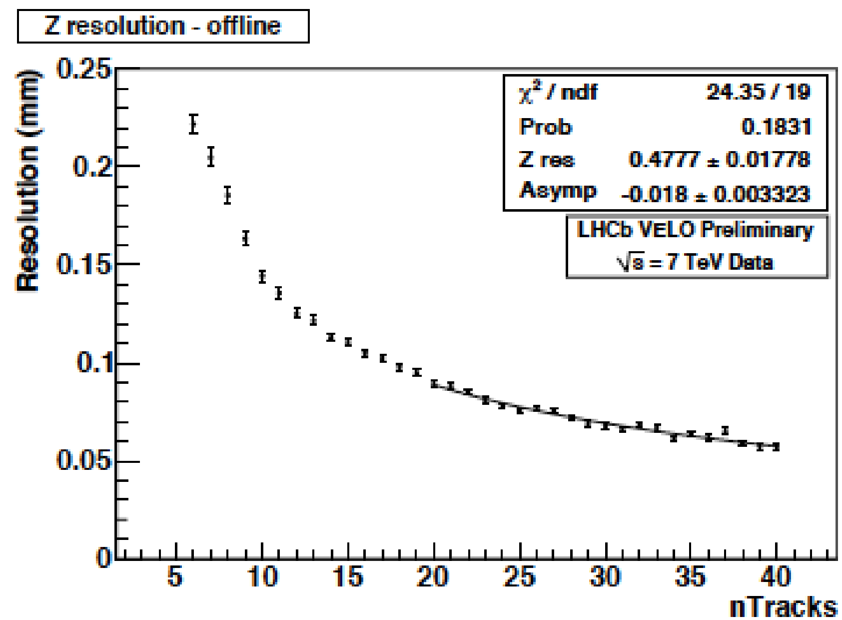
Detector requirements

- Efficient trigger for both leptonic and hadronic final states
- Excellent vertex finding and tracking efficiency
- Outstanding particle identification

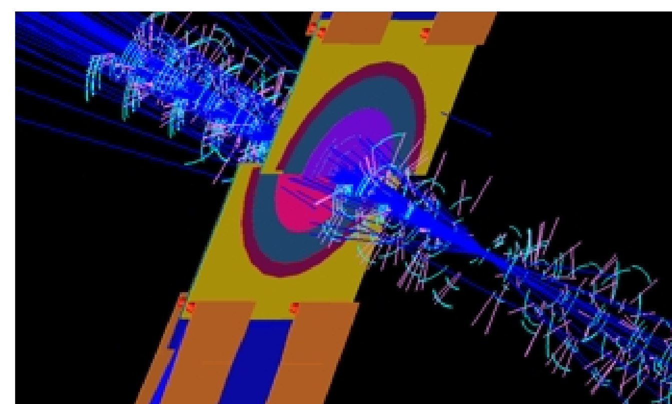
Vertex Resolution

VELO - Highest Resolution Vertex Detector at LHC



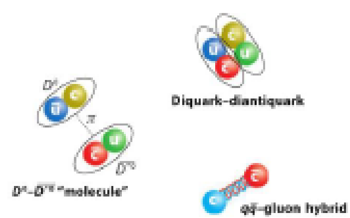


Identification of beauty and charm from displaced vertices critical to LHCb physics

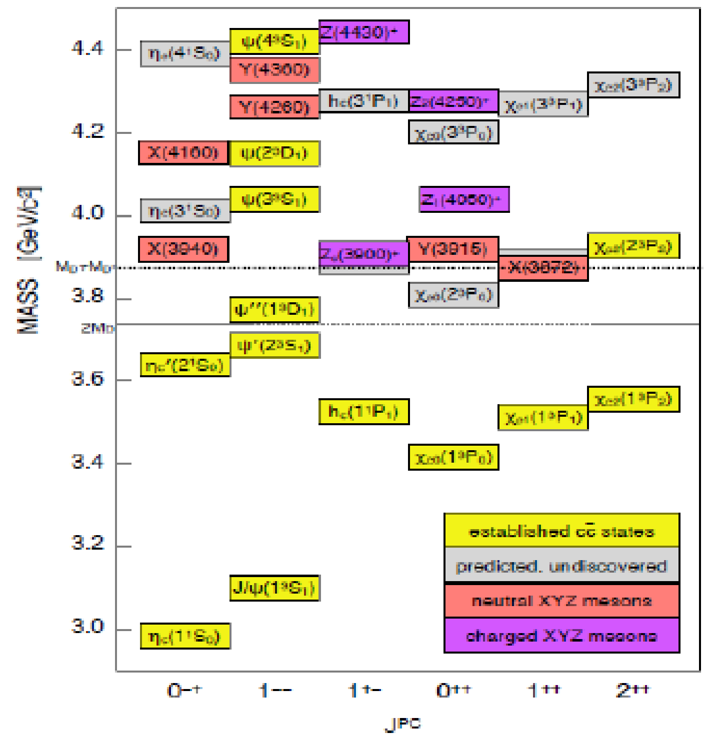


Heavy hadrons spectroscopy

- Many predicted states still not observed
- New XYZ states observed at the B factories
  - Their properties do not fit with the expectations for quarkonia
- Many theoretical interpretations
  - Tetraquarks
  - Meson molecules
  - qqg hybrids
  - glueballs,…



Example : charmonium



More experimental input needed !

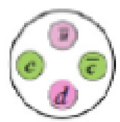
12

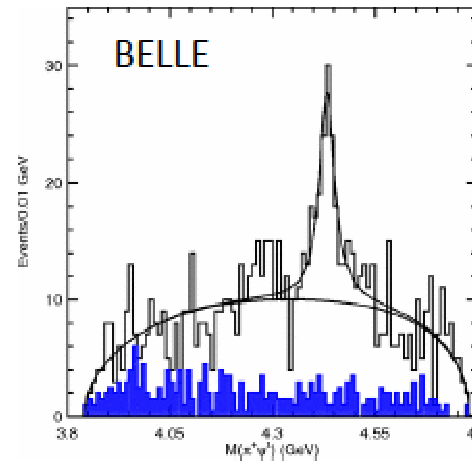
Exotic spectroscopy: the Z(4430)$^-$

- History:
  - Structure seen by Belle in $\psi'\pi^-$ mass distribution (2007)
  - not confirmed by Babar (explained by reflexions)

  Charged $\Rightarrow$ minimal quark content = $c\bar{c}\bar{u}d$

  $\Rightarrow$ Exotic state : tetraquark, $D^*\bar{D}^*$ molecule?



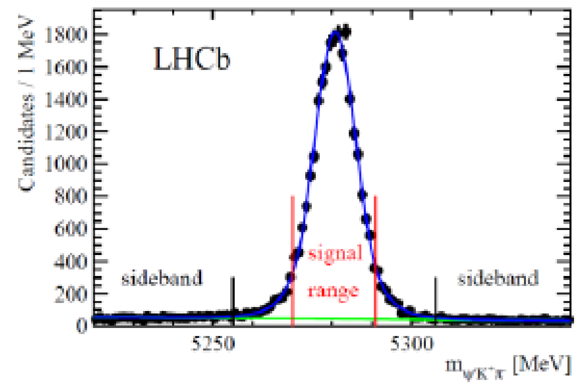


PRL100, 142001

- LHCb analysis: PRL 112,222002(2014)
  - Uses $B \to \psi'\pi^- K^+$

    Z^- K^* resonances

    and interferences

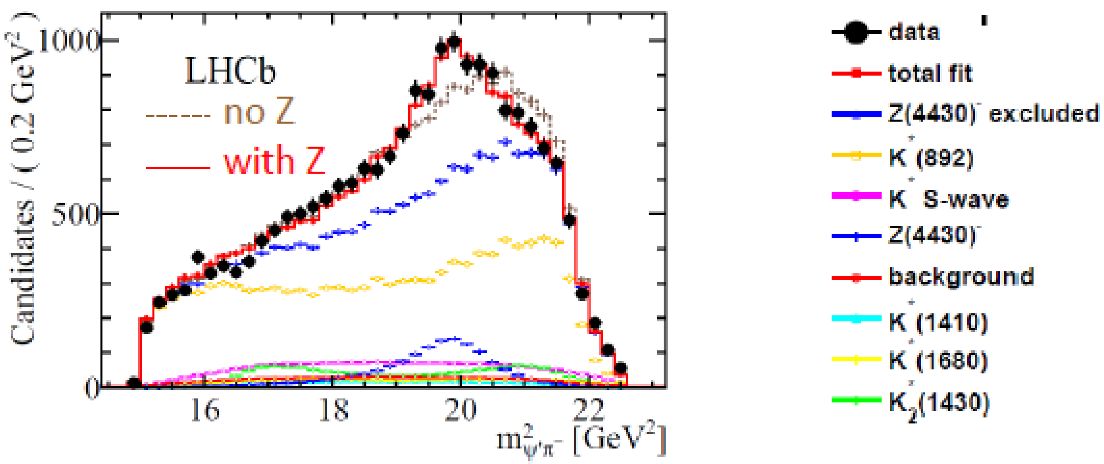


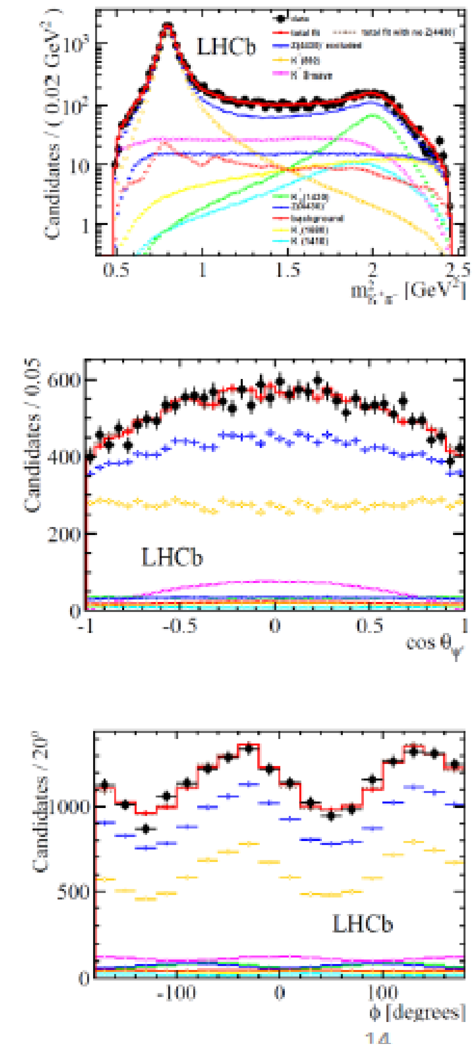
  - 10 times more data than at B-factories

  $\Rightarrow$ 4D amplitude analysis

Z(4430)$^-$

- 4-D fit with known K* resonances + a Z$^-$ + interferences
  - Resonances described with relativistic Breit-Wigners



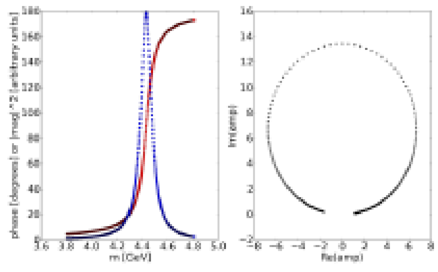


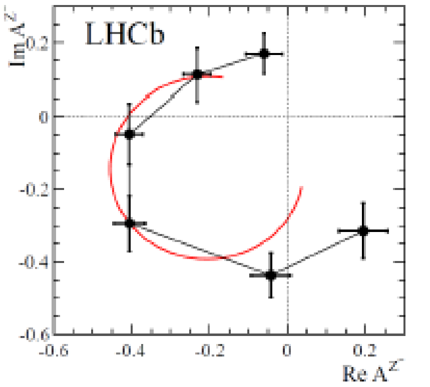
The presence of the Z(4430)$^-$ is well established!

$M(Z)$	$4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma(Z)$	$172 \pm 13^{+37}_{-34}$ MeV
f_Z	$5.9 \pm 0.9^{+1.5}_{-3.3}$ %
f_Z^I	$16.7 \pm 1.6^{+2.6}_{-5.2}$ %
Significance	$> 13.9\sigma$

Nature of the Z(4430)$^-$

- Measure the Z(4430)$^-$ amplitude in 6 bins of mass:
  - If this is a resonance ⇒ circle in the Argand plane





Resonance behaviour is clear!

- Spin determination : testing J^P=0$^-$,1$^-$,1$^+$,2$^-$,2$^+$ possibilities

  Z(4430)$^-$ is a 1$^+$ state with more than 9σ significance over other possibilities

  ⇒ Rules out the D*D* molecule interpretation (J^P=0$^-$,1$^-$,2$^-$)

  ⇒ The Z(4430)$^-$ is a good tetraquark candidate!