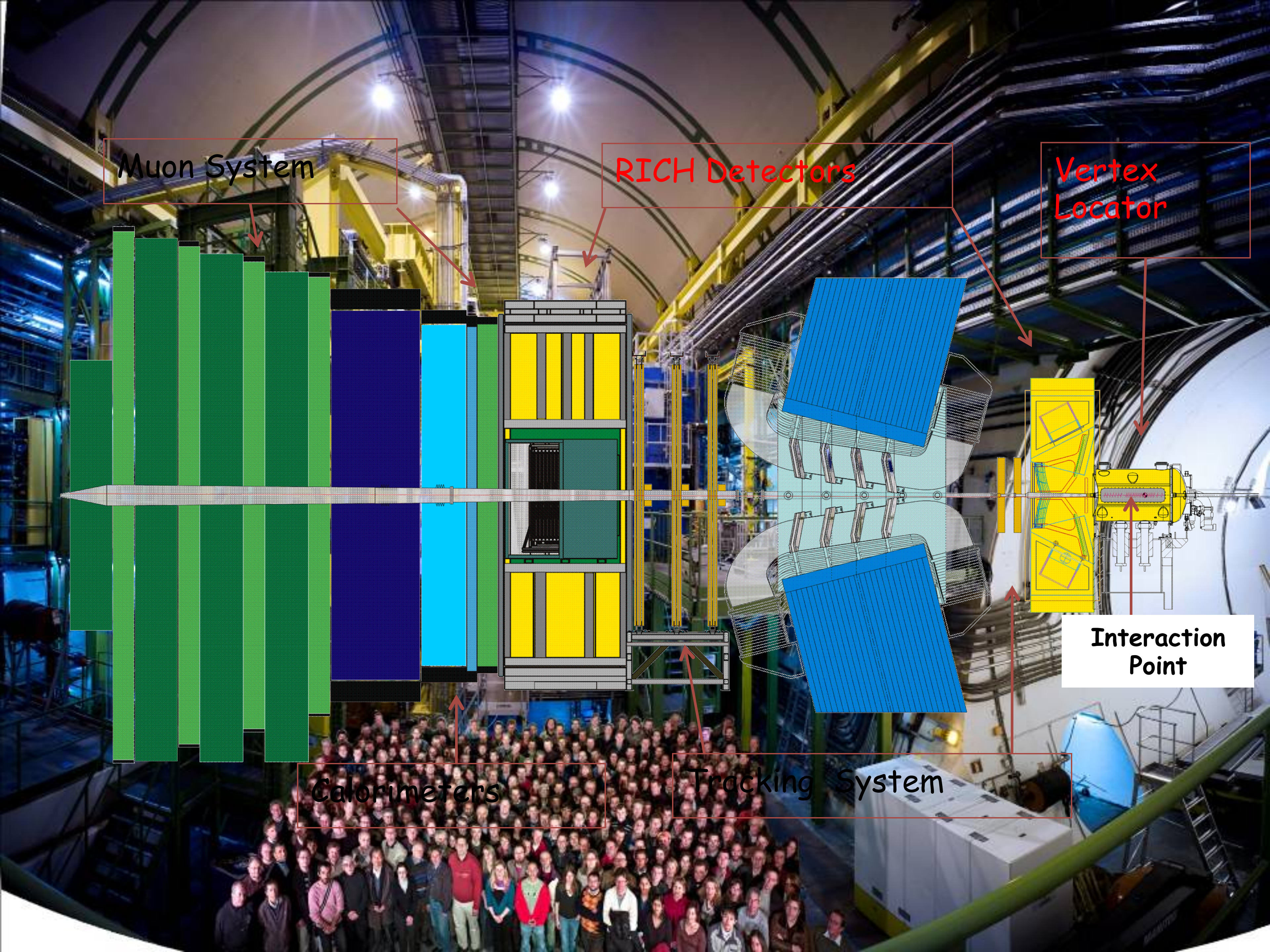
MANCHESTER 1824
The University of Manchester

LHCb

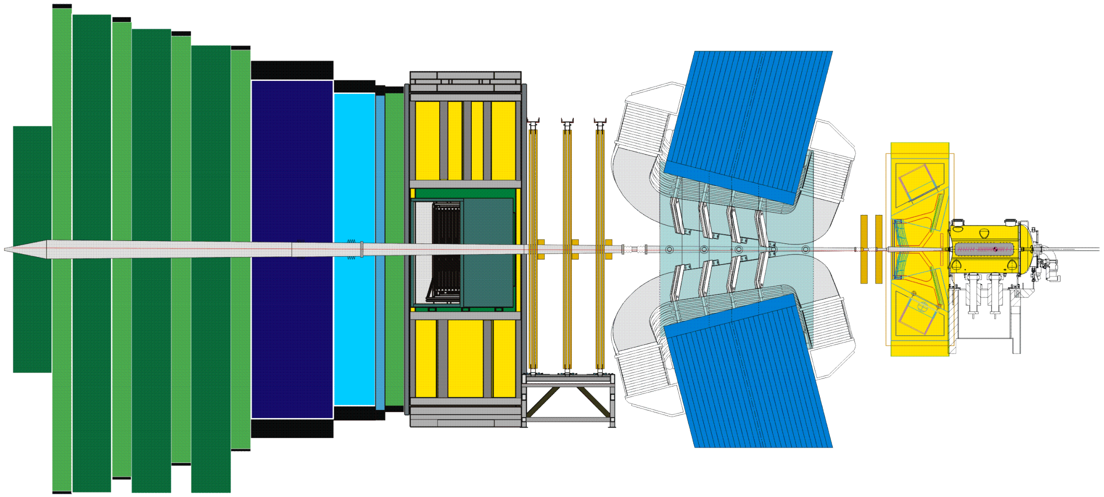
LHCb: Gifts from the wise Kings

1. LHCb Design
2. LHCb Physics: Motivation & Key Results
3. LHCb Future: Upgrade I & Upgrade II

LHCb Design


Muon System
RICH Detectors
Vertex
Locator
Interaction
Point
Calorimeters
Tracking System

Collaboration

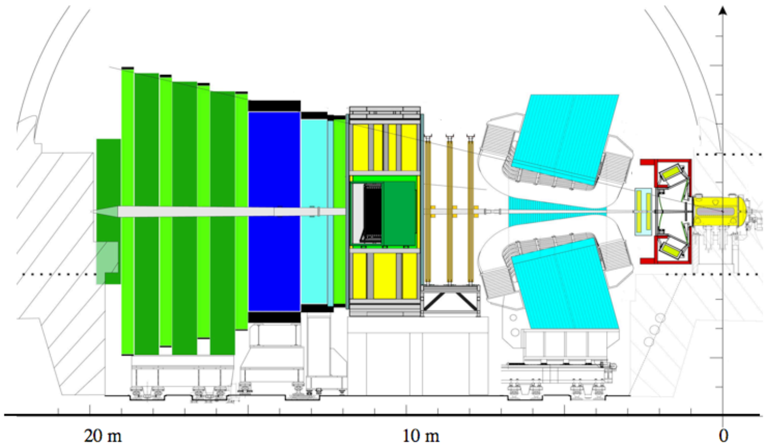


800	Authors
1500	Members
70	Institutes
16	Countries
11	UK Institutes (~20% Collab.)

Birmingham, Bristol, Cambridge, Edinburgh, Glasgow, Liverpool, Oxford, Imperial College, Manchester, RAL, Warwick

Aims & Critical Components

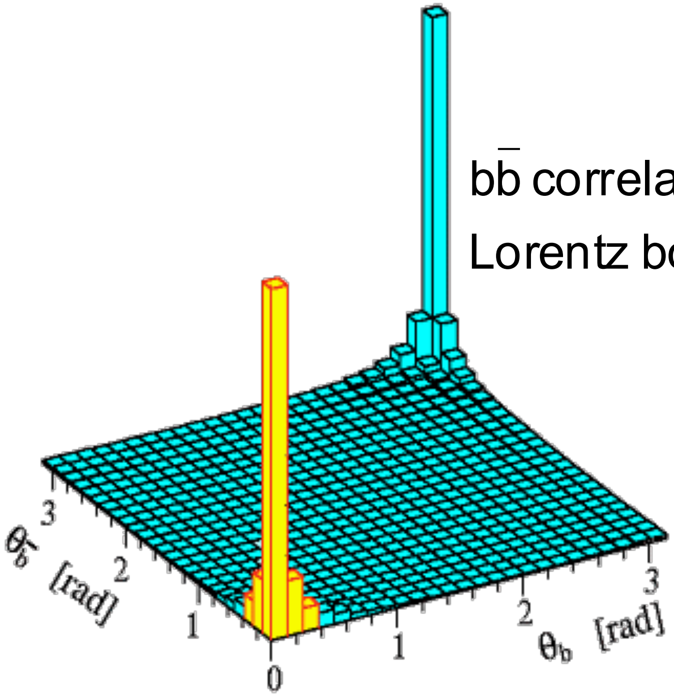
- LHCb:
  - study CP violation
  - rare B decays
    - →New Physics



- 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

B Production

- LHC: pp-collisions @ 7-13TeV
- ~2 fb^{-1} Nominal data taking year of 10^7s



$b\bar{b}$ correlated

Lorentz boost

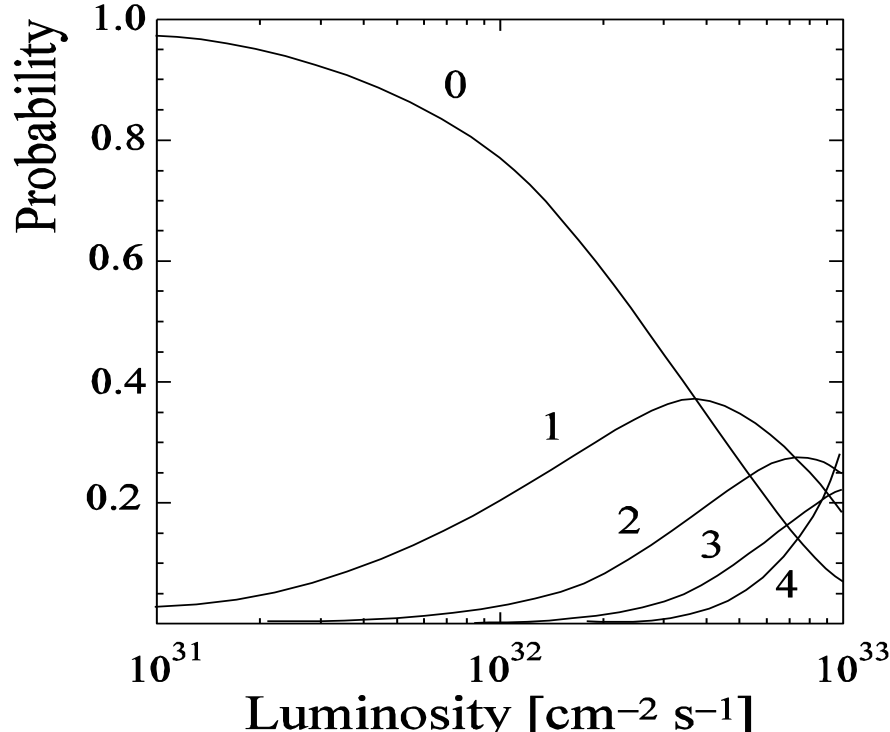
LHCb: forward spectrometer
15-250 mrad acceptance

- Pile-up at high luminosity
    - Choose $4x10^{32}$ cm^{-2} s^{-1}

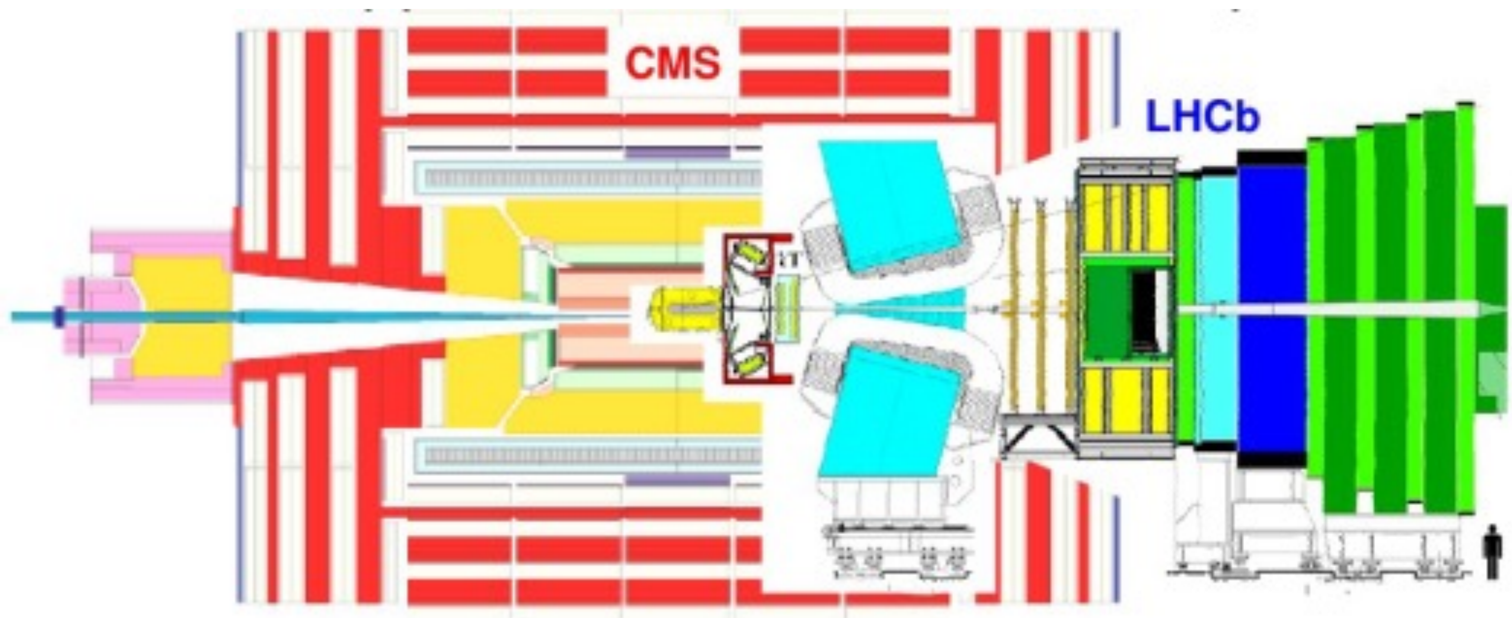
➔most events have single interactions

LHC reached early in run

Interactions/crossing



Complementarity of LHCb



- Angular acceptance of LHCb complementary to ATLAS/CMS
- LHCb Vertex Detector & Particle ID systems
  - Will describe later
- LHCb emphasis on individual particles measurements not jets

Has Santa Claus Brought New Physics ?

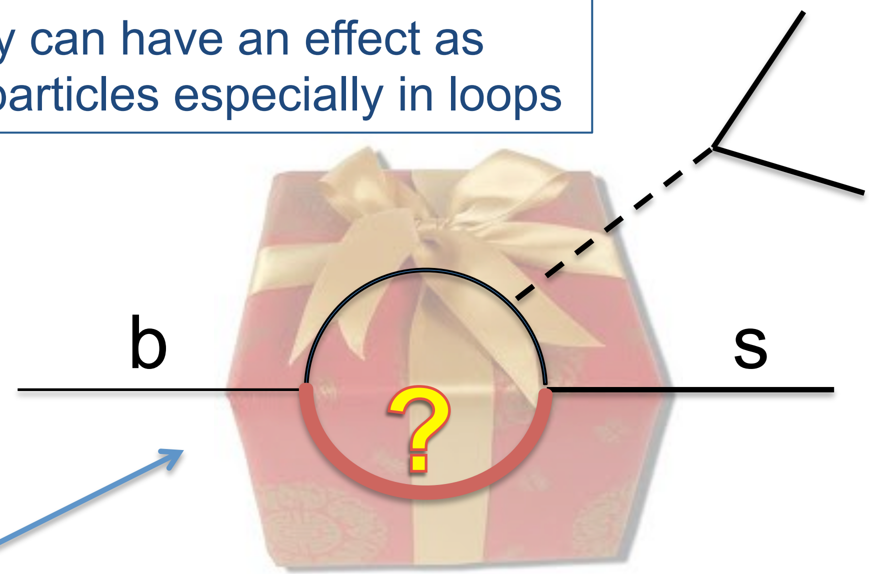
Two ways to find out

Direct Observation

Presents with $MC^2 > E$ cannot be produced directly

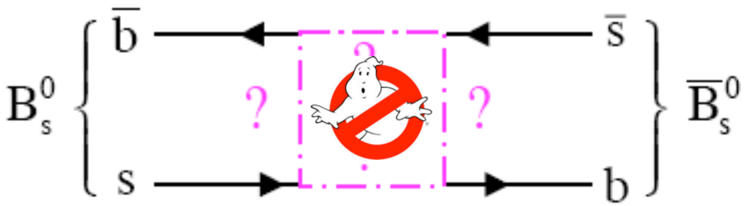
Indirect Effects

But they can have an effect as virtual particles especially in loops



This kind of approach is sensitive to particles far heavier than produced directly at a collider. It is what **flavour physics** is about it lets you see beyond the energy frontier.

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

LHCb Physics

400 Physics papers to date

60 physics papers in 2017

- Direct CP Violation in B_s Decays
  - RICH detector
- Time Dependent CP Violation in B_s Decays
  - VELO detector
- Rare Decays: $B \rightarrow \mu\mu$
- Spectroscopy: Pentaquark Discovery
  - Greig Cowan tomorrow
- Lepton Universality – violation hints
  - Simone Bifani tomorrow

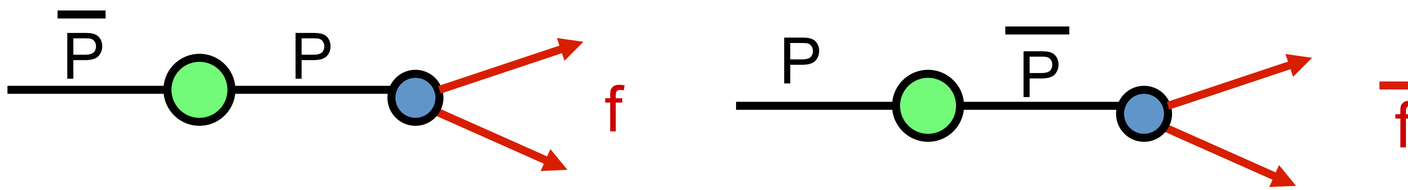
CP Violation Refresher

$$|P_1\rangle = p|P^o\rangle + q|\overline{P}^o\rangle$$
$$|P_2\rangle = p|P^o\rangle - q|\overline{P}^o\rangle$$

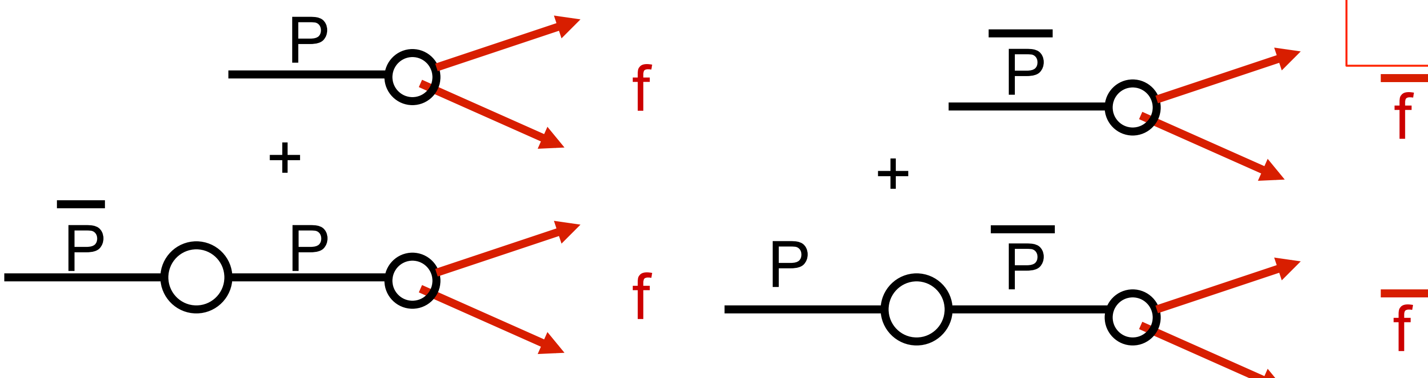
$$A_f = \langle f|H|P\rangle$$
$$\overline{A}_{\overline{f}} = \langle \overline{f}|H|\overline{P}\rangle$$

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

- ~~CP~~ in mixing $\left|\frac{q}{p}\right|^2 \neq 1$



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

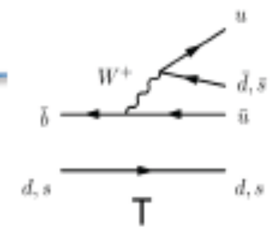


Direct / Time-integrated CP Violation including discovery of CP Violation in B_s system

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

Time-integrated measurement: Direct CP Violation

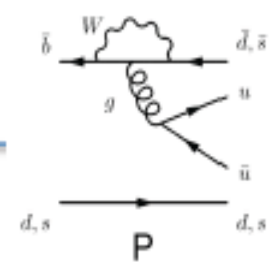
Direct CP violation



B

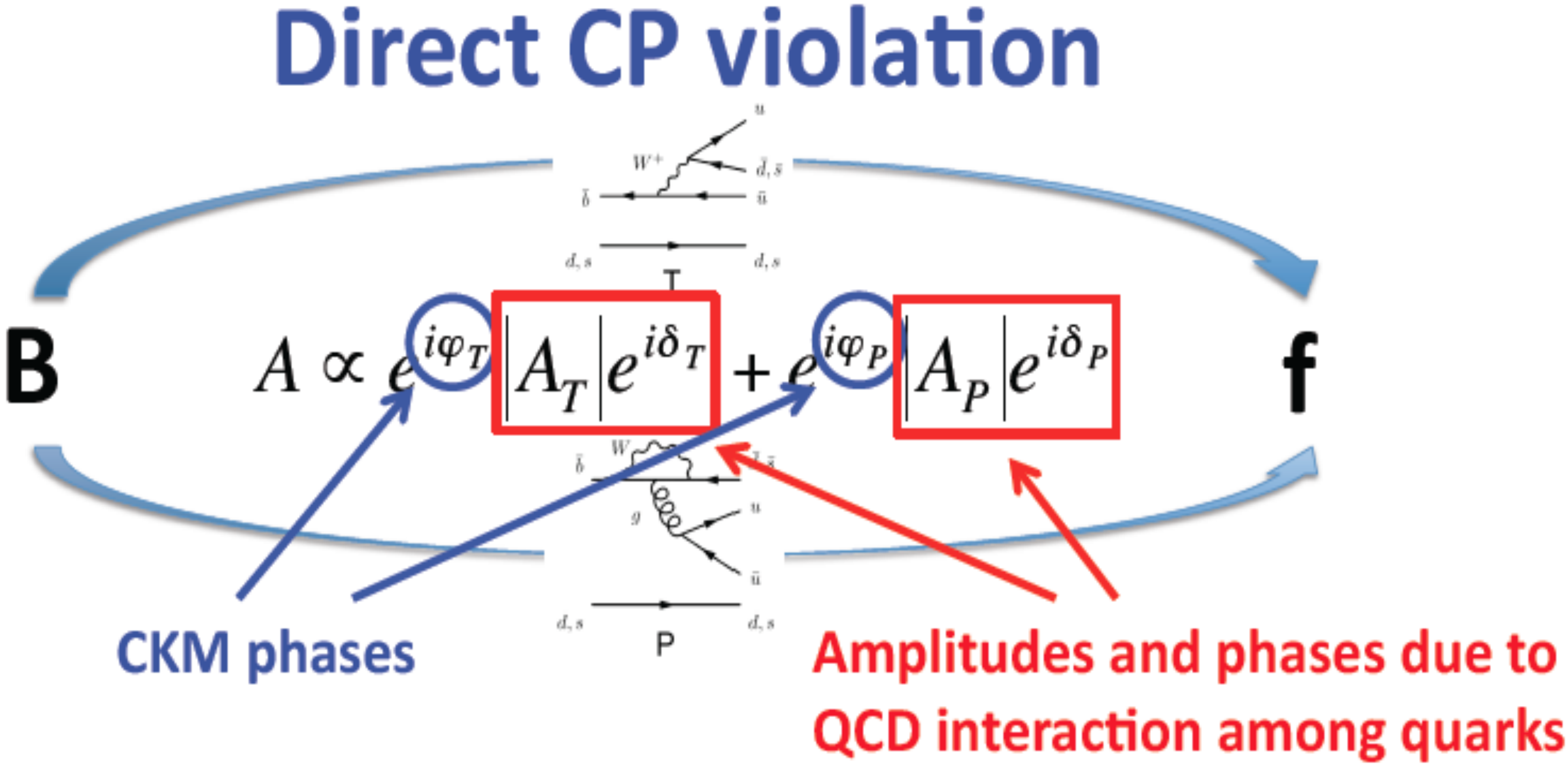
$$A \propto e^{i\varphi_T}\left|A_T\right|e^{i\delta_T} + e^{i\varphi_P}\left|A_P\right|e^{i\delta_P}$$

f



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

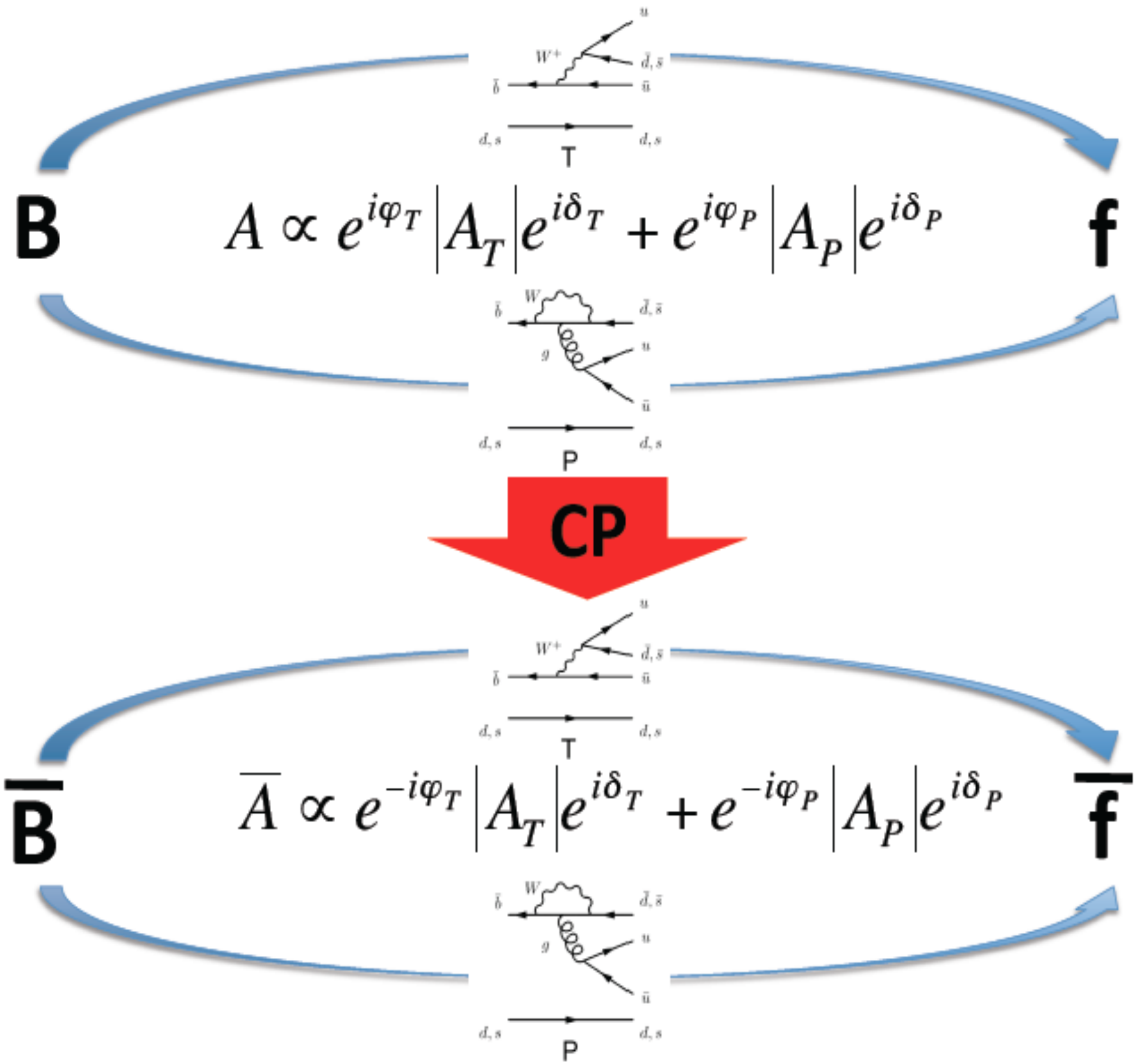
Time-integrated measurement: Direct CP Violation



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

Time-integrated measurement: Direct CP Violation

Direct CP violation



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

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

Use f

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

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

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

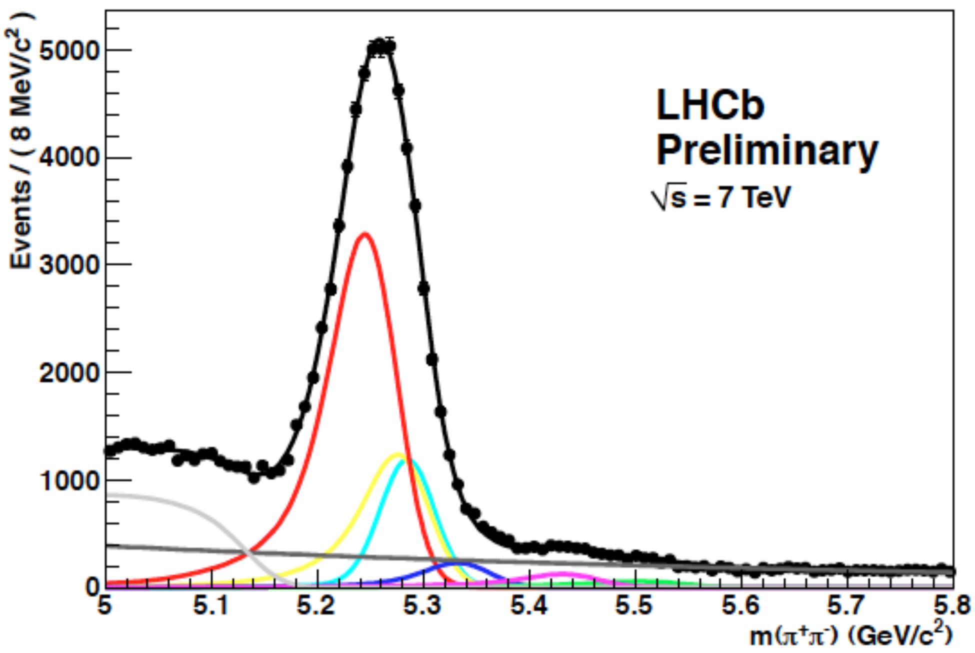
$\overline{B_s} \to K^+ \pi^-$

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

$$B^0 \rightarrow \pi^- K^+$$
$$B_s \rightarrow K^- \pi^+$$



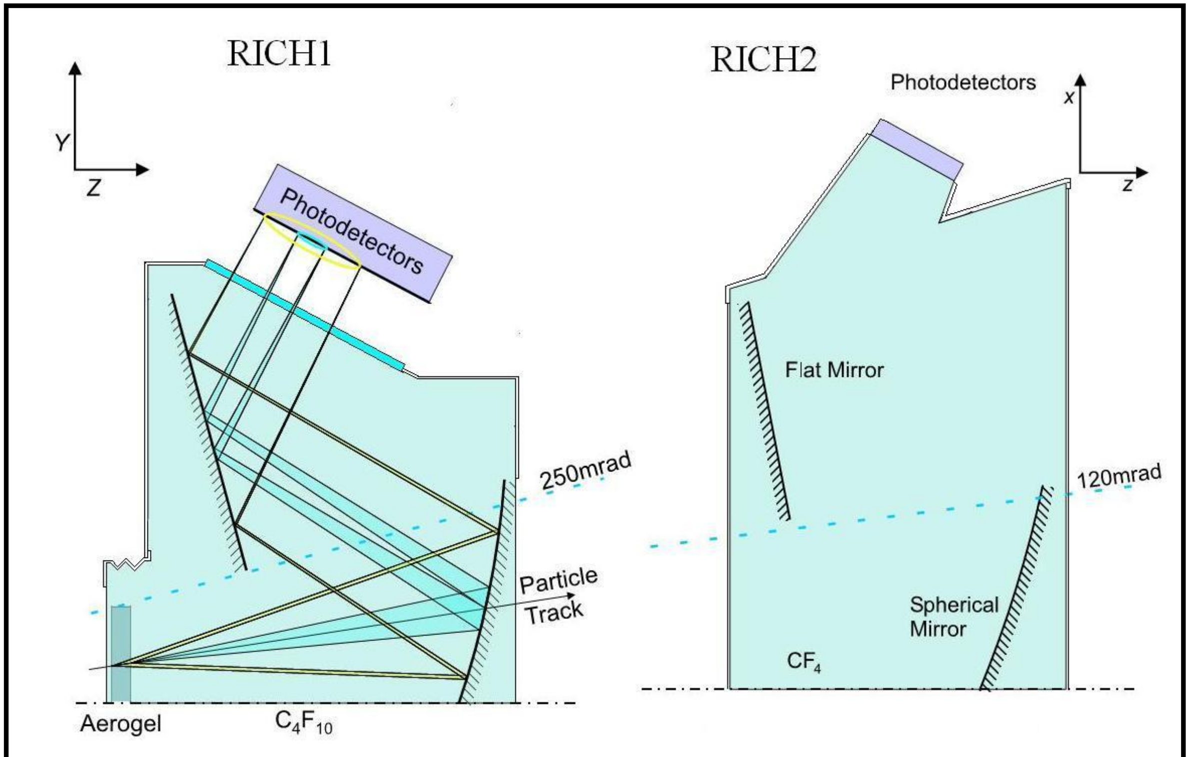
- red: $B_s^0 \rightarrow \pi K$
- light blue: $B^0 \rightarrow \pi^+ \pi^-$
- yellow: $B_s^0 \rightarrow K^+ K^-$
- blue: $B^0 \rightarrow K \pi$

(also Λ_b, 3-body backgrounds)

B➔hh, (h=K,π)

Ring Imaging Cherenkov (RICH)

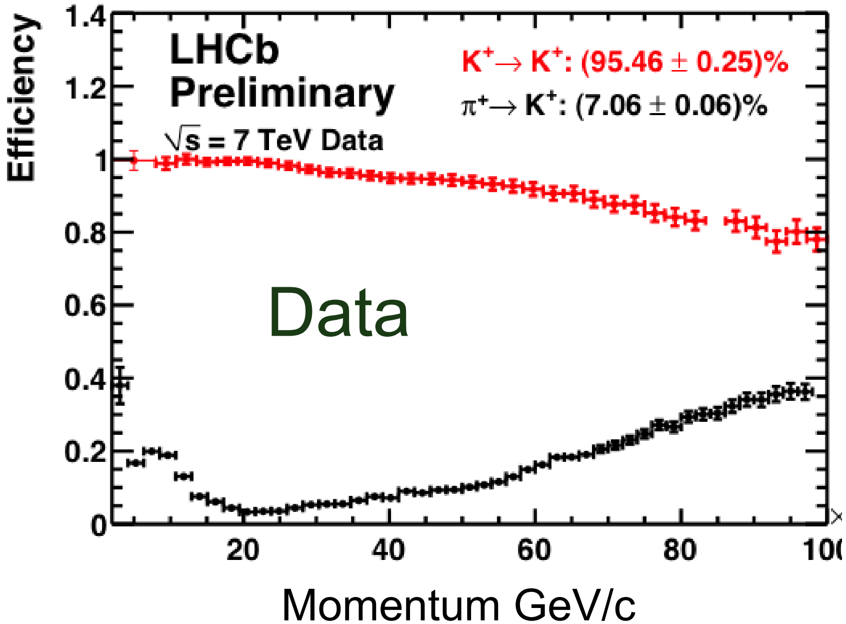
- Unique at LHC: π/K/p separation
  - Measure particle velocity through Cherenkov effect
- Two RICH detectors – lower / higher momentum



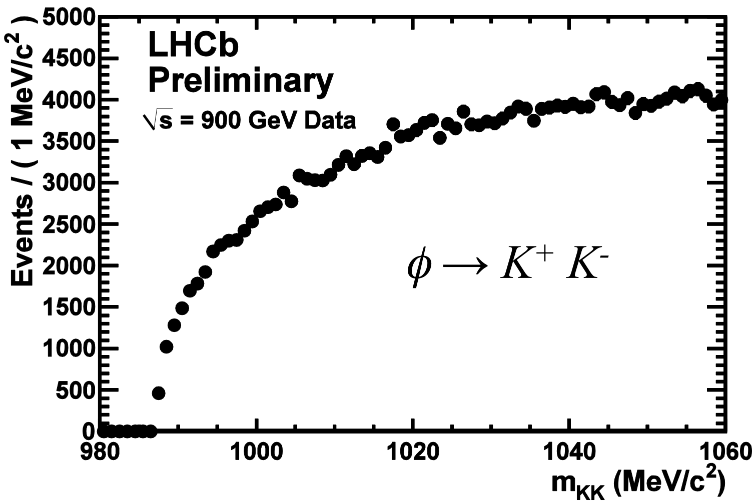
Gas enclosure and mirrors installed in LHCb pit

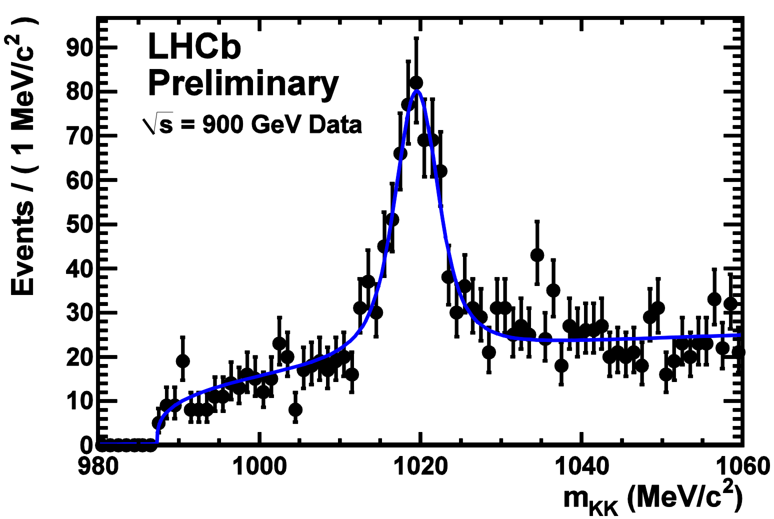
Particle Identification

RICH PID across wide momentum range



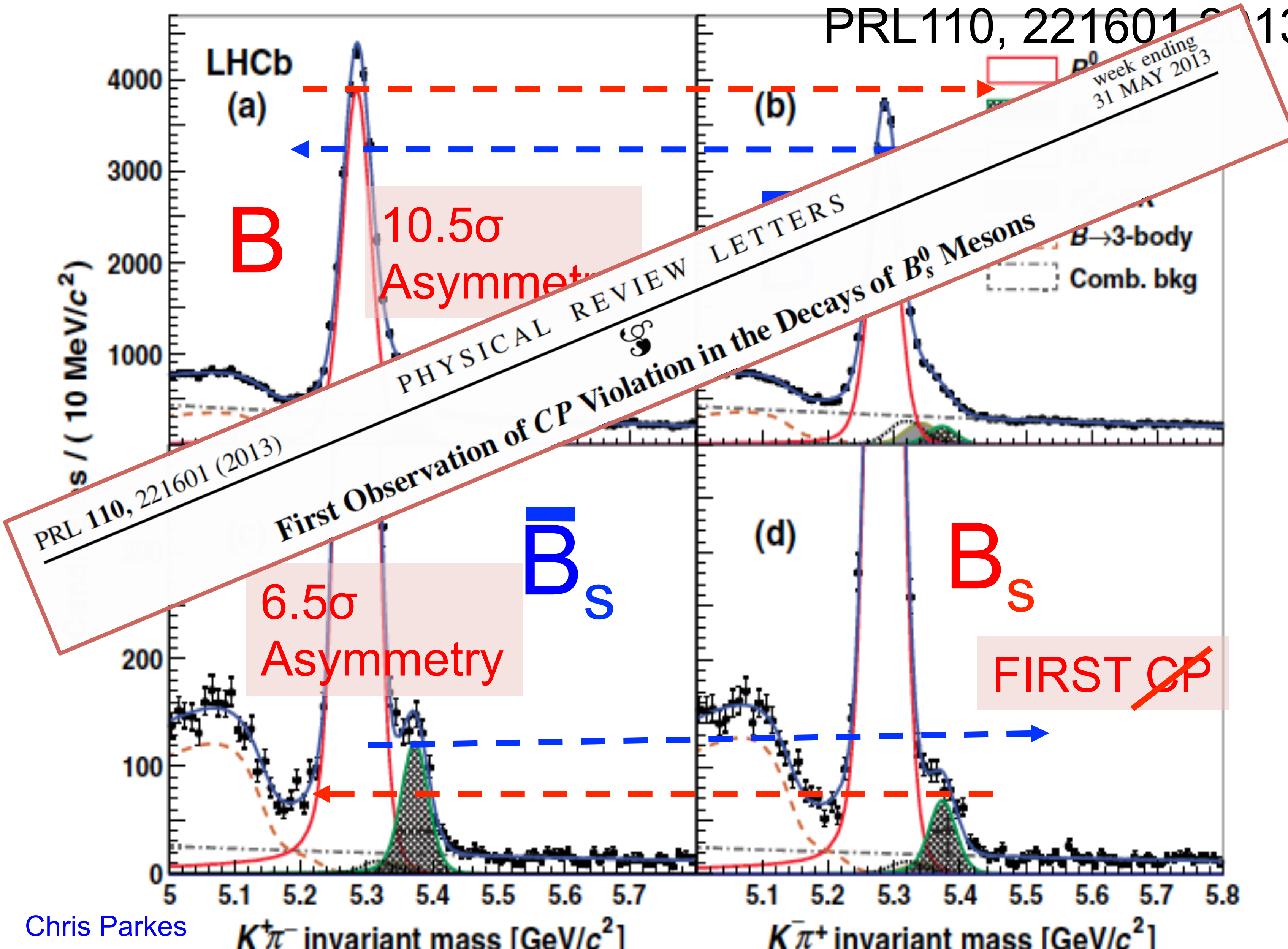
Clean reconstruction of hadronic decays critical to **many** physics results





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

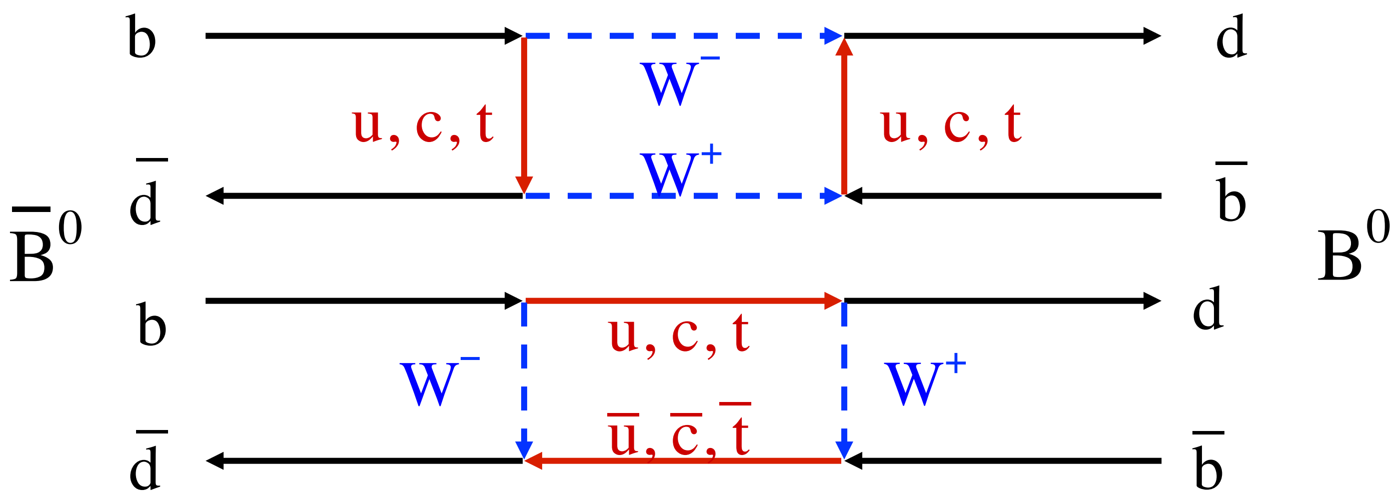
PRL110, 221601 2013



Indirect / Time-dependent CP Violation Including constraining CP Violation in B_s system (ϕ_s)

Neutral B-mesons mixing

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



(and similarly for B_s)

- Dominated by top quark contribution :

$$t-\bar{t}: \quad \propto m_t^2 \left| V_{tb} V_{td}^* \right|^2 \quad \propto m_t^2 \lambda^6$$

$$c-\bar{c}: \quad \propto m_c^2 \left| V_{cb} V_{cd}^* \right|^2 \quad \propto m_c^2 \lambda^6$$

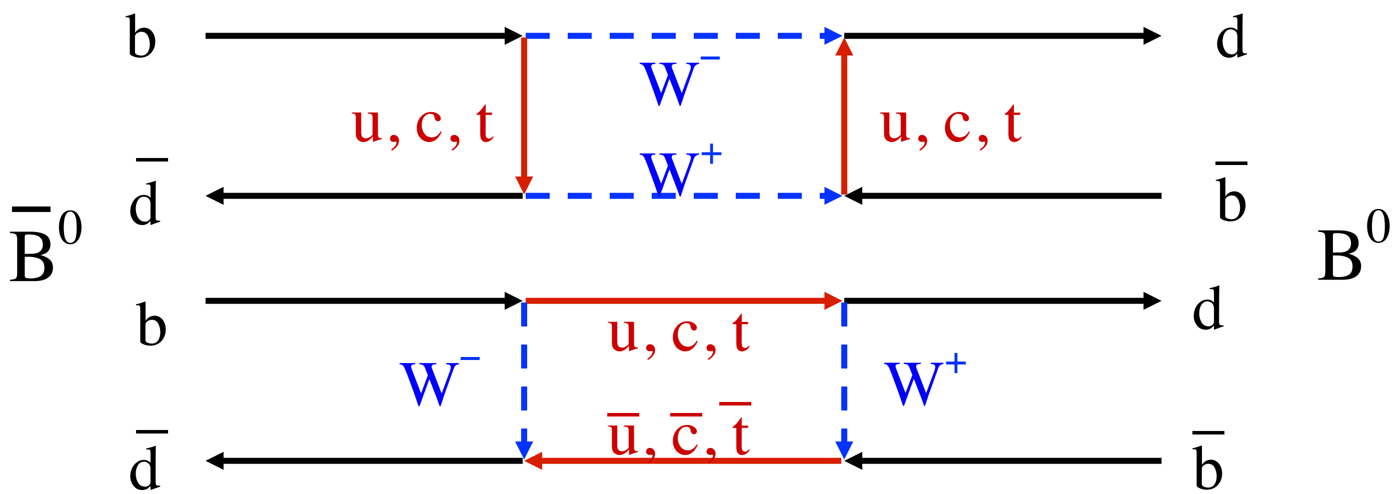
$$c-\bar{t}, \bar{c}-t: \quad \propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^* \propto m_c m_t \lambda^6$$

GIM (=V_{CKM} unitarity):
if u,c,t same mass, everything cancels *by construction*!

$$\Delta m_d \propto m_t^2 \left| V_{td} \right|^2$$

Neutral B-mesons mixing

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



- Dominated by top quark contribution :

(and similarly for B_s)

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

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

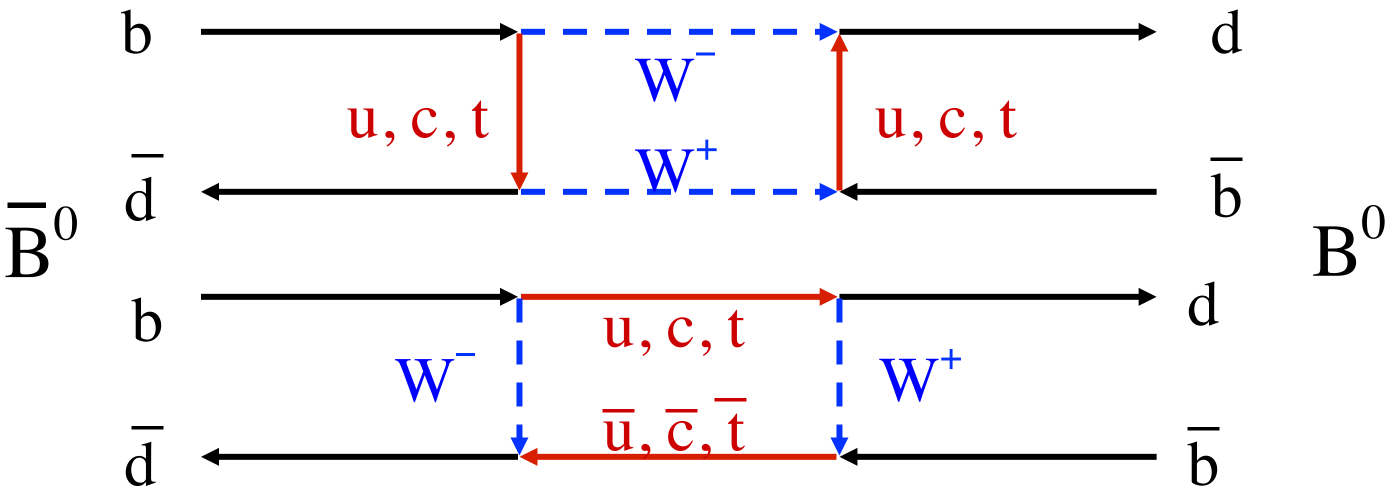
For B_s^0

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

→ Sensitivity to side and equivalent angle β_s

Neutral B-mesons mixing

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



(and similarly for B_s)

- Dominated by top quark contribution :

most important difference with B^0:
replace $V_{td} \rightarrow V_{ts}$

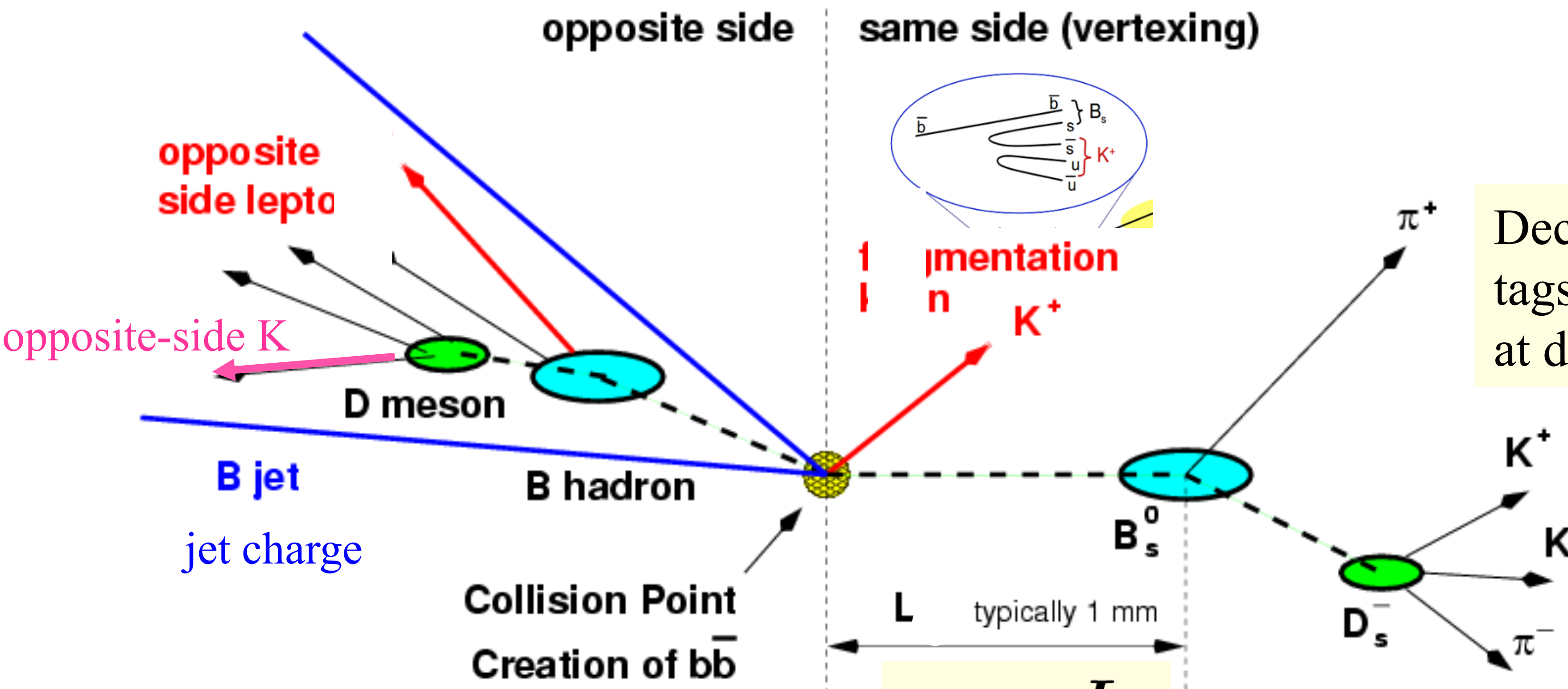
$$\frac{\Delta m_d}{\Delta m_s} \approx \frac{|V_{td}|^2}{|V_{ts}|^2} \approx \frac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04$$

$$\Delta m_d = 0.502 \pm 0.006\ \mathrm{ps}^{-1}$$

$$\Rightarrow \Delta m_s \approx 12\ \mathrm{ps}^{-1}$$

A more complete calculation leads to the SM expectation of ~18/ps

Tagging & Decay Time



Decay mode tags b flavor at decay

2nd B tags production flavor

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

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

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

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

opposite kaon tagger (K^-)

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

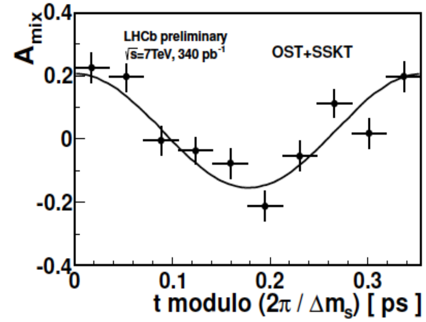
B_s Mixing Measurement

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

CDF discovery 2006, LHCb measurement 2011

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

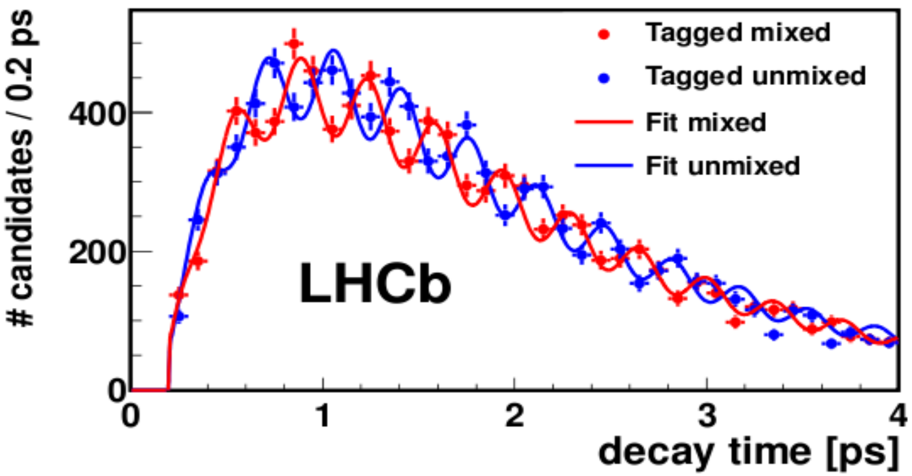
$$A_{\mathrm{mix}}(t) = \frac{N(B_s^0; q=+1)(t) - N(B_s^0; q=-1)(t)}{N(B_s^0; q=+1)(t) + N(B_s^0; q=-1)(t)}$$



Oscillations occur at 3 trillion Hz !

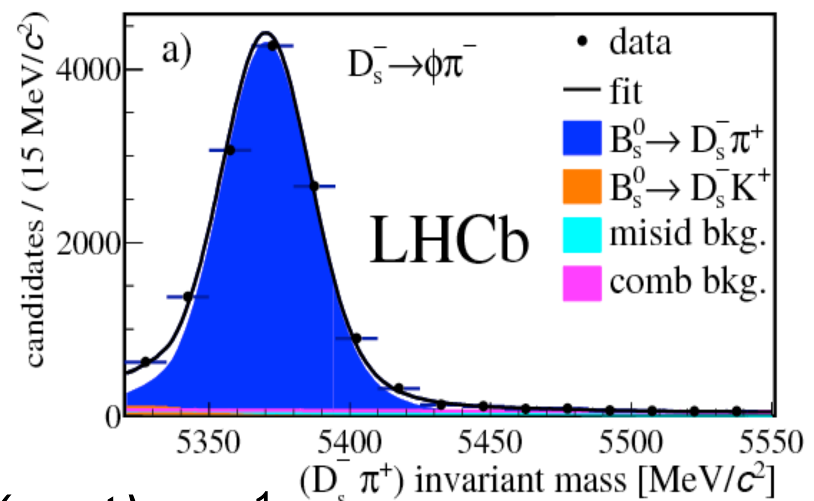
Observed amplitude is not 1 as smeared

- Mistag (B or $\bar{B}$) of events
- Resolution on time



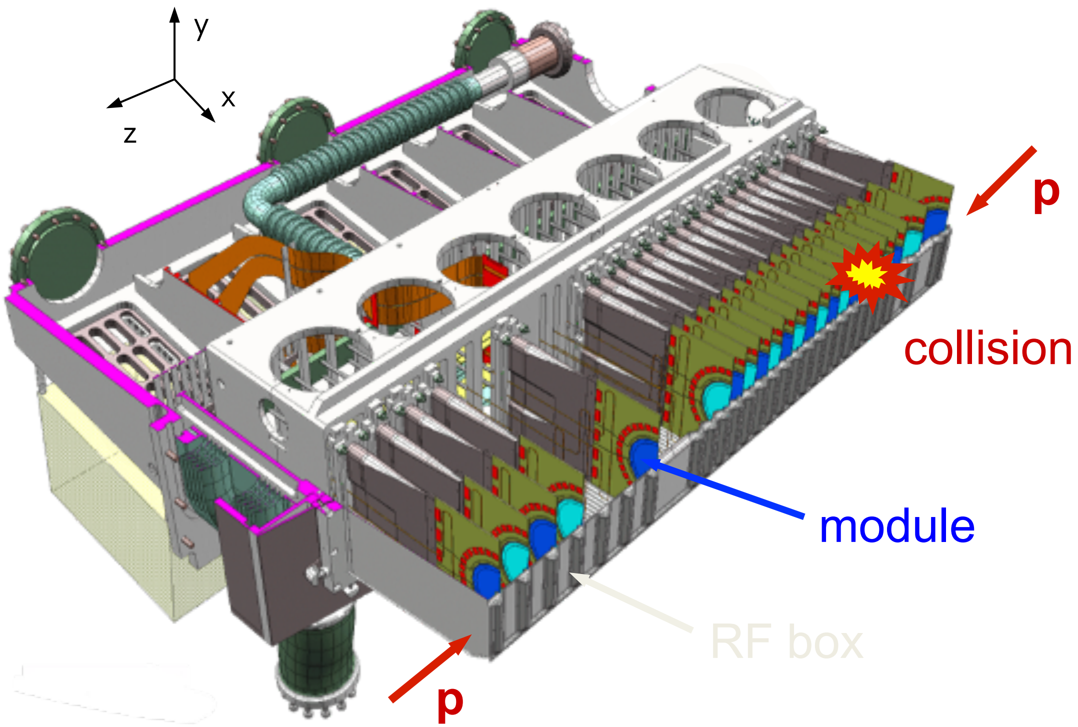
Line is fitted oscillations

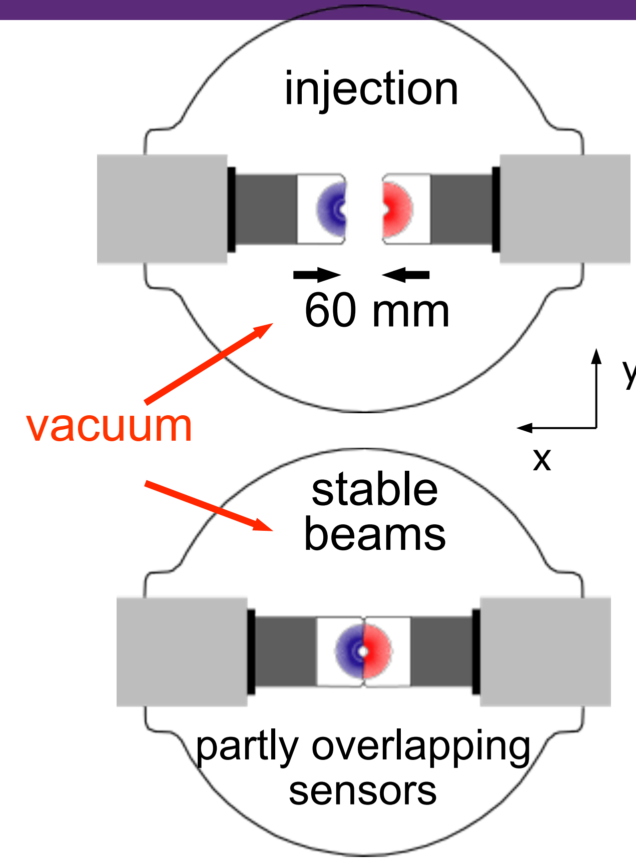
Points are data



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

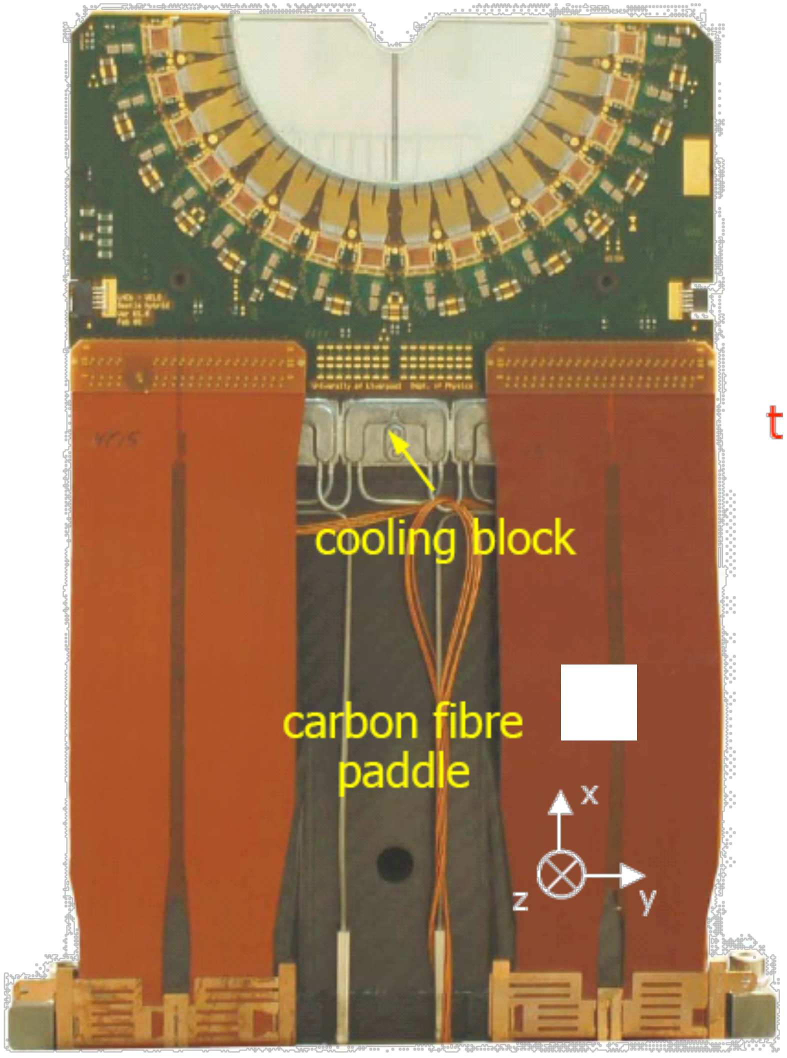
VELO Layout





- 2 retractable detector halves
- 21 stations per half with an R and ϕ sensor
- Operates in secondary vacuum
- 300 μm foil separates detector from beam vacuum
- 8 mm from LHC beam

Velo Roles



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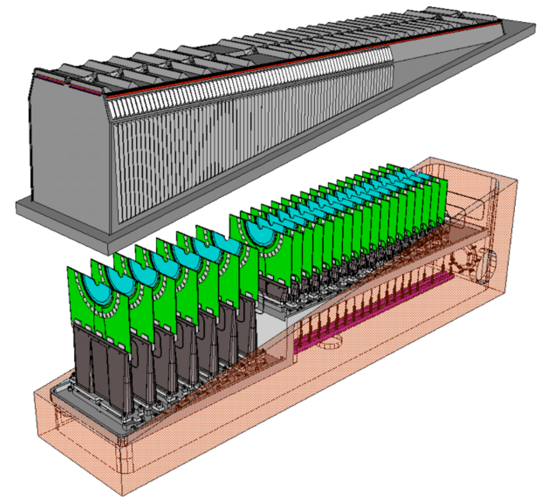
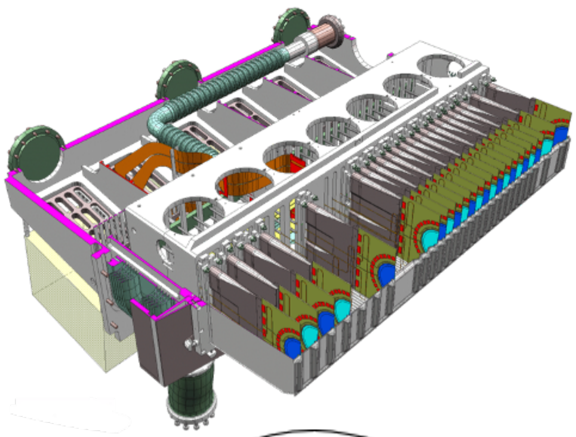
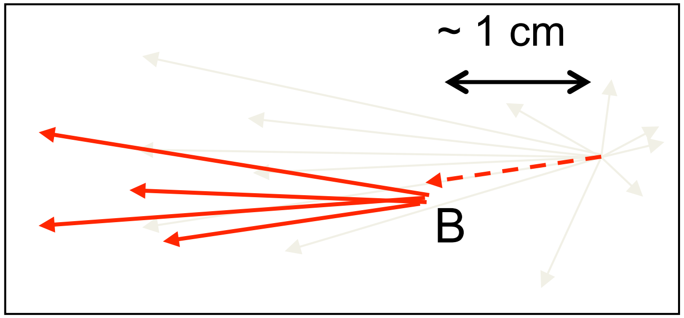


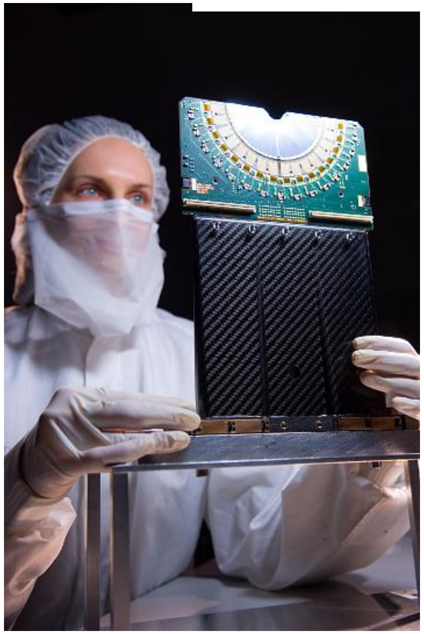
Velo Modules

- n-*on*-n & 1 n-*on*-p
- Two semi-circular designs
  - R-measuring
  - Phi-measuring
- double metal layer readout
- 2048 strips, 40-100 μm pitch
- .25 μm Analogue Readout
- TPG core Hybrid, CF paddles

LHCb: Vertex LOcator



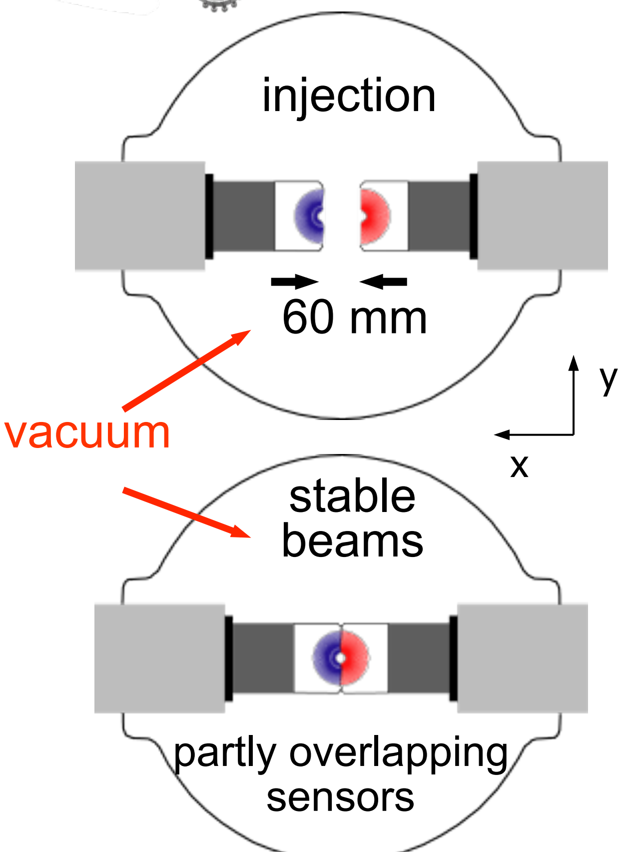


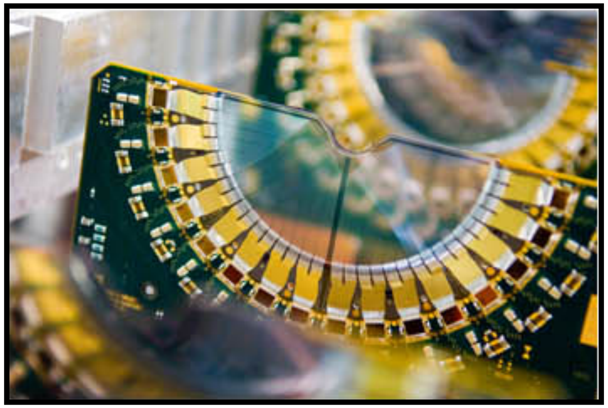


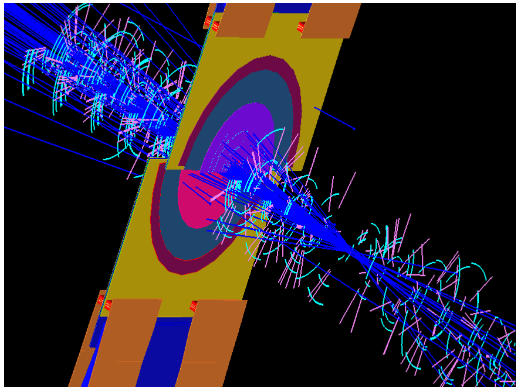
Beauty mesons live 10^{-12}s

Multiply by c and γ

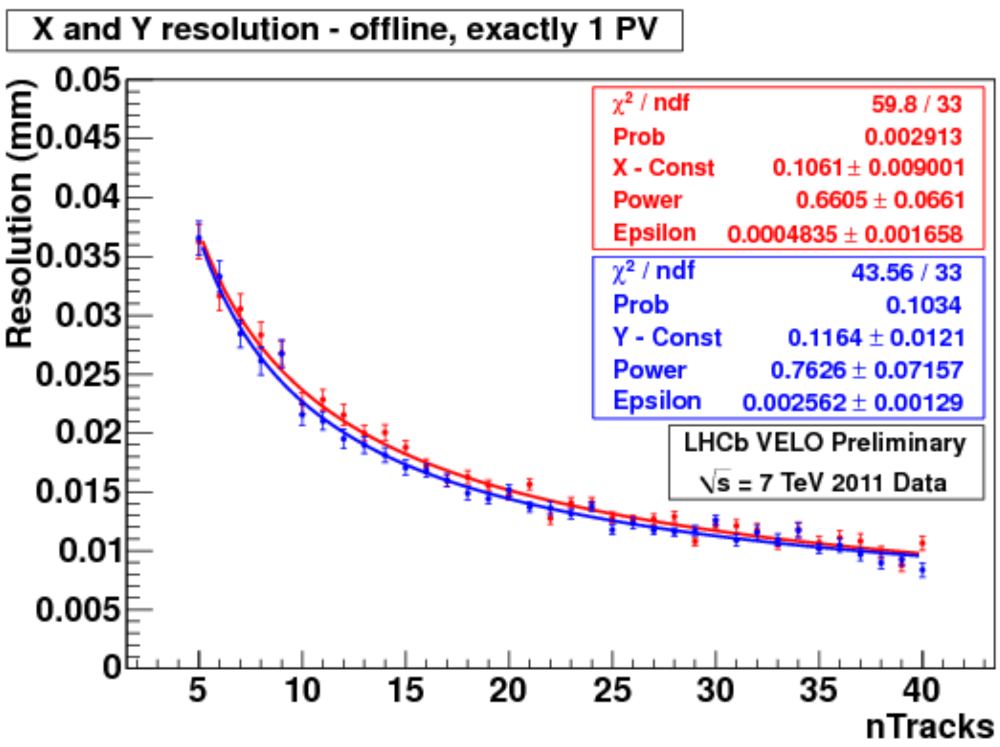
Travel few mm



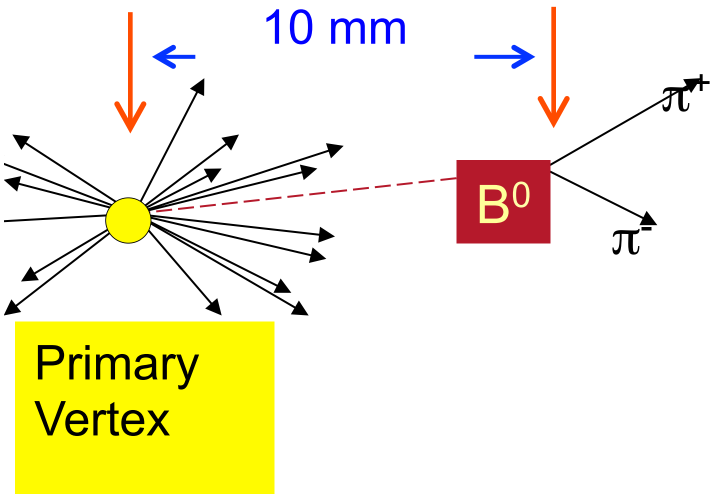




Performance: Vertex Resolution



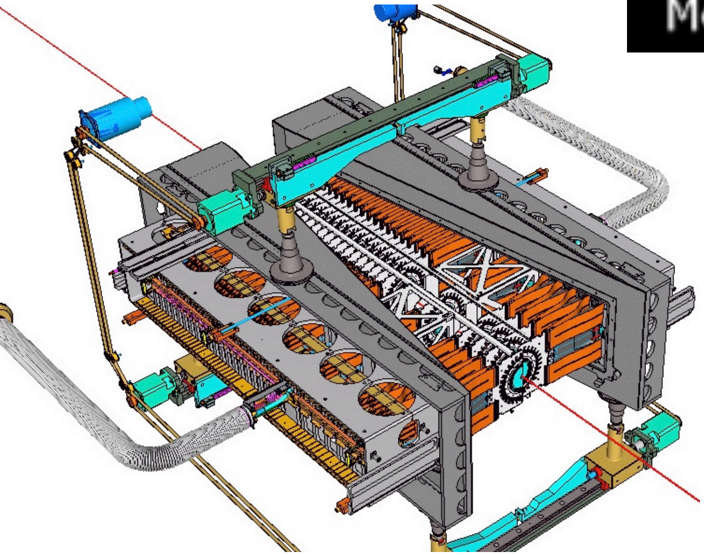
- Key Physics quantity in identifying long lived B meson decay

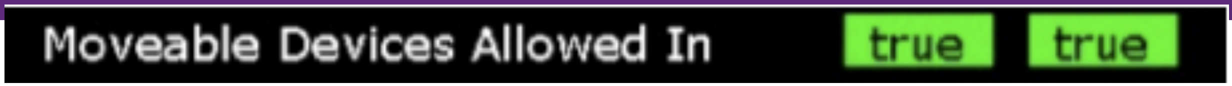


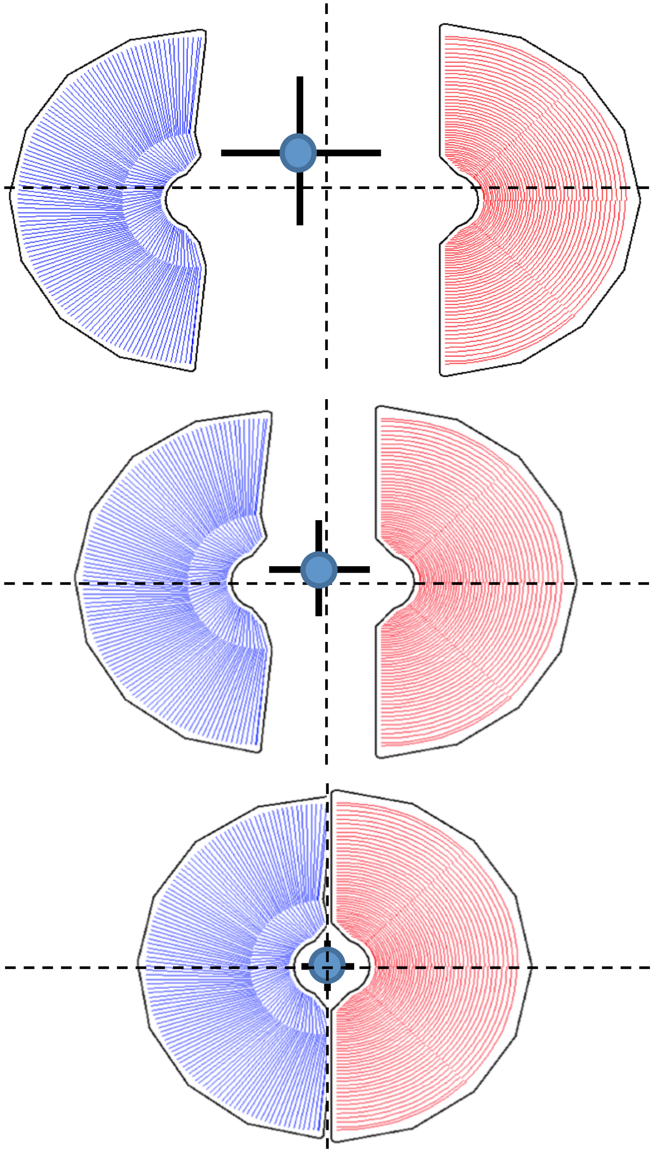
Vertex resolution
- 15μm in XY at 25 tracks
- 70μm in Z

propertime resolution
- ~50fs tracks

VELO Closing

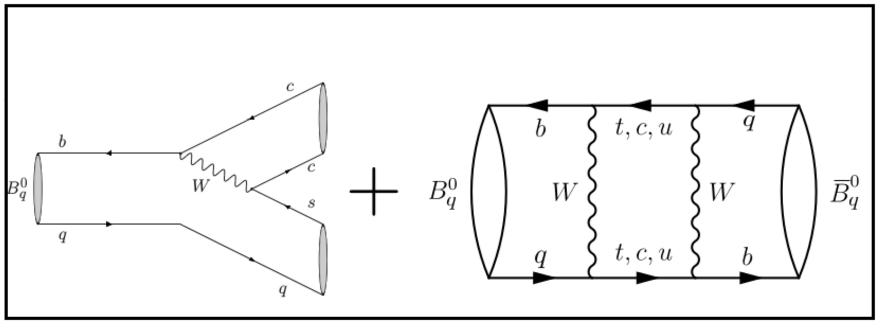






- First strip only 8mm from LHC beam
- Move detector in each fill of machine
- Update alignment parameters

CP violation in interference between mixing and decay



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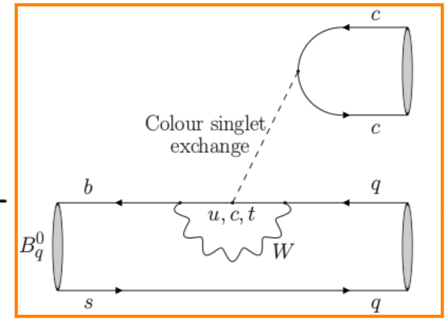

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Dominant SM "tree" contribution

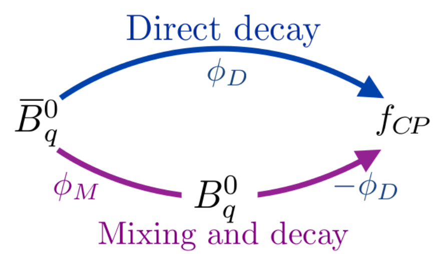
Higher order "penguin" contributions from non-perturbative hadronic effects

NP could be difficult to distinguish from penguins...

- $\phi_q = \phi_M - 2\phi_D = -2\beta_q + \Delta\phi_q + \delta_q^{NP}$,
  $\beta_q = \arg\left(\frac{V_{tq}V_{tb*}}{V_{cq}V_{cb}^*}\right)$

ϕ_s and ϕ_d determined via global fit to experimental results ignoring contributions from penguin diagrams:

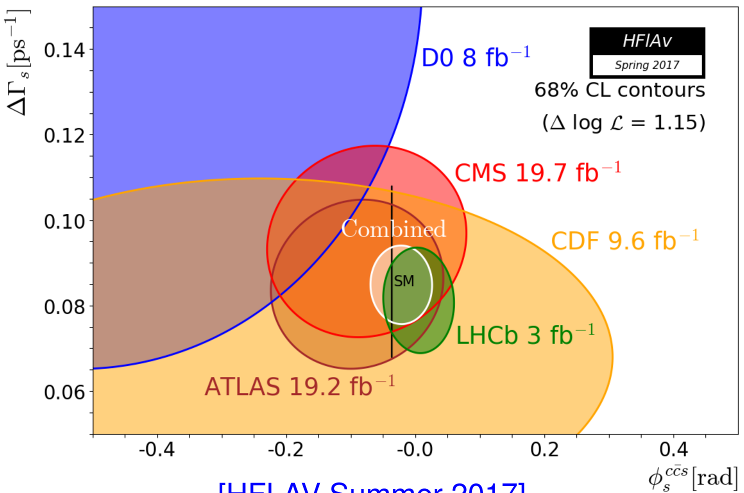
- $\phi_s^{\mathrm{SM}} \equiv -2\arg\left(-\frac{V_{ts}V_{tb*}}{V_{cs}V_{cb}^*}\right) = -37.6^{+0.7}_{-0.8}$ mrad
  [CKM Fitter]
- $\sin 2\beta^{\mathrm{SM}} \equiv \sin 2\arg\left(-\frac{V_{cd}V_{cb*}}{V_{td}V_{tb}^*}\right) = 0.740^{+0.020}_{-0.025}$
  [CKM Fitter]



Predictions are very precise!

State of art of ϕ_s

Extensively studied in LHCb, CMS, ATLAS with Run I.
Although there has been impressive progress since the initial measurements at CDF/D0, **the uncertainty needs to be further reduced:**



[HFLAV Summer 2017]

LHCb:

- $J/\psi\phi$ [PRL114, 041801 (2015)]
- $J/\psi K^+K^-$ [arXiv:1704.08217 (2017)]
- $J/\psi\pi^+\pi^-$ [Phys. Lett. B736, (2014) 186]
- $\psi(2S)\phi$ [Phys. Lett. B762 (2016) 253-262]
- $D_s^+D_s^-$ [PRL113, 211801 (2014)]

CMS:

- $J/\psi\phi$ [Phys. Lett. B 757 (2016) 97]

ATLAS:

- $J/\psi\phi$ [JHEP 08 (2016) 147]

$$\phi_s = -21 \pm 31 \text{ mrad}$$

[HFLAV Summer 2017]

$$\phi_s^{SM} = -37.6^{+0.7}_{-0.8} \text{ mrad}$$

[CKM Fitter]

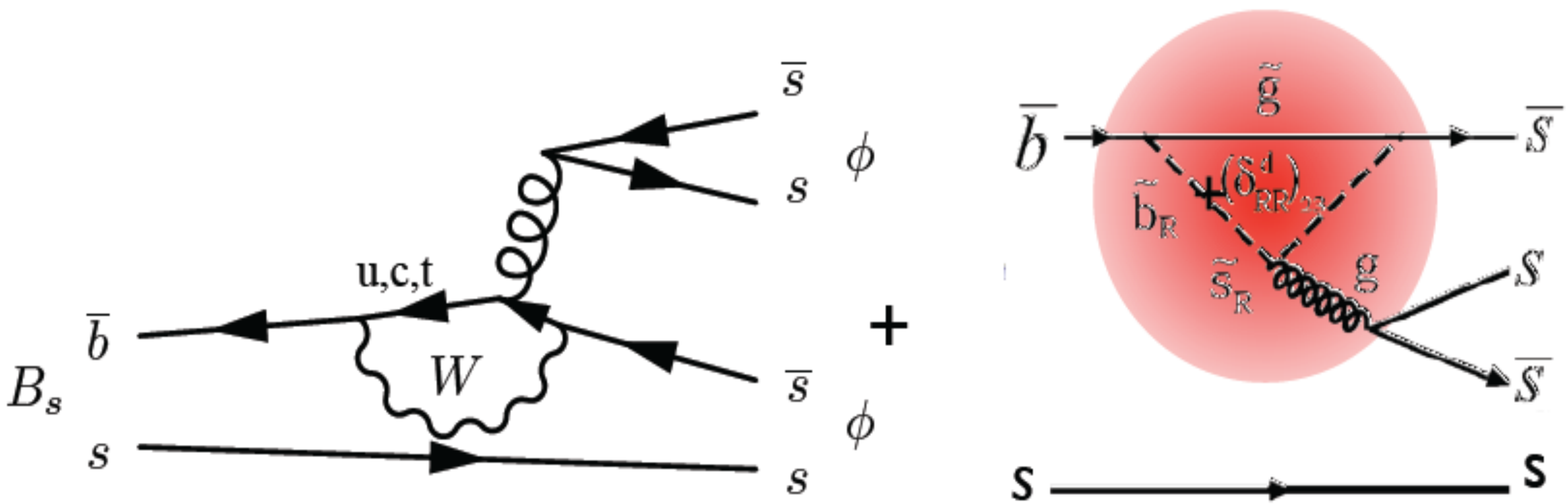
- World average consistent with SM prediction;
- Exp. uncertainty almost a factor of 30 larger than predictions.

Rare Decays including discovery of $B_s \rightarrow \mu\mu$

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

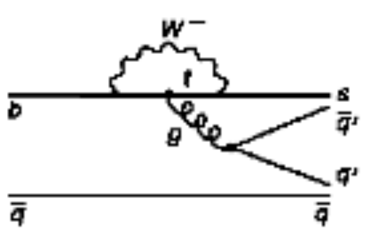


- Momentum flowing through loop should be integrated to "infinity"
  → Potential high masses of virtual particles don't kill their contribution…

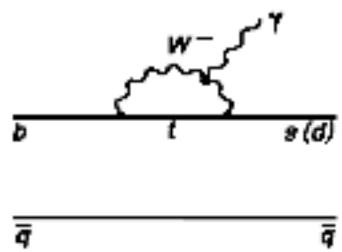
- No tree-level diagrams: less competition/pollution from (boring) Standard Model amplitudes..

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}

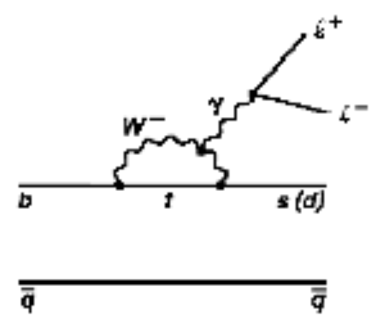


(e) Gluonic penguin



(f) EM penguin

Radiative penguin

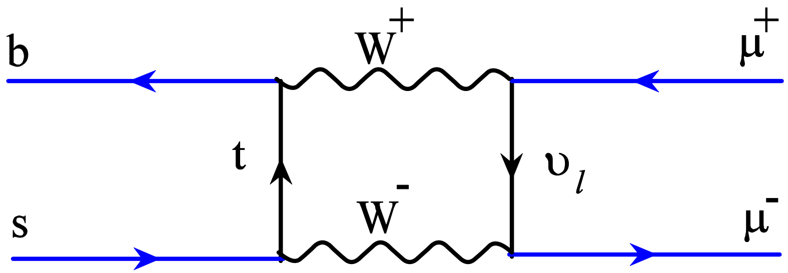


(g) EM penguin

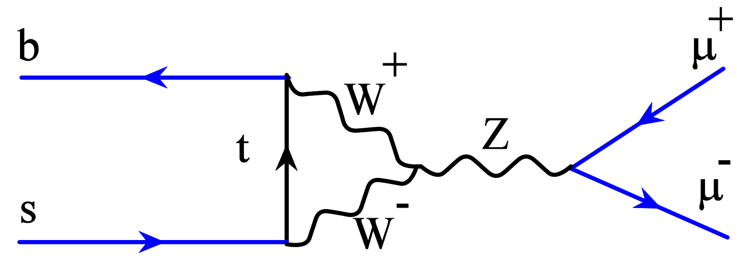
The $B_{(s)} \to \mu^+\mu^-$ decay (1/2)

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

- Really really rare! But well predicted in SM



SM box

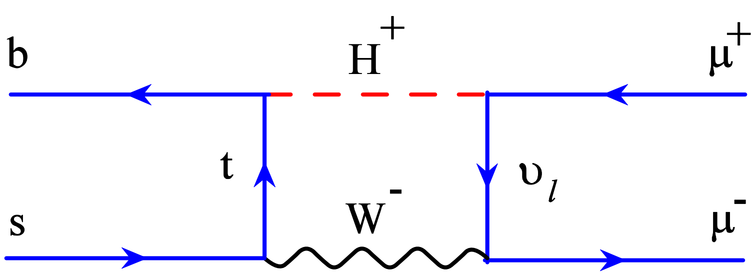


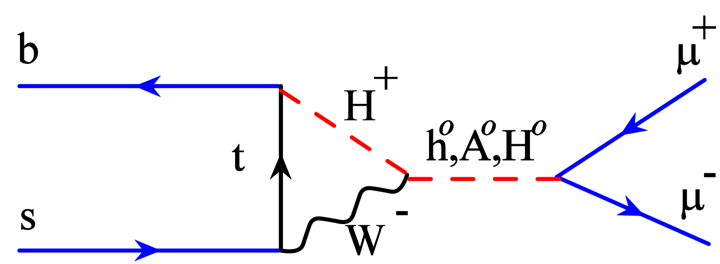
SM Penguin

- 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 2012

2017

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.

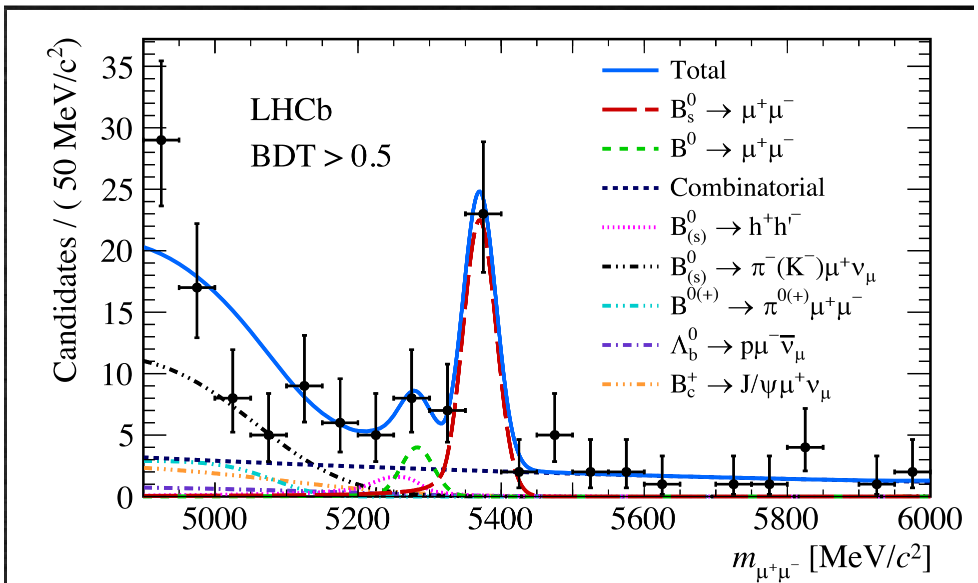
Table 2 Upper limits for exclusive dilepton decays.

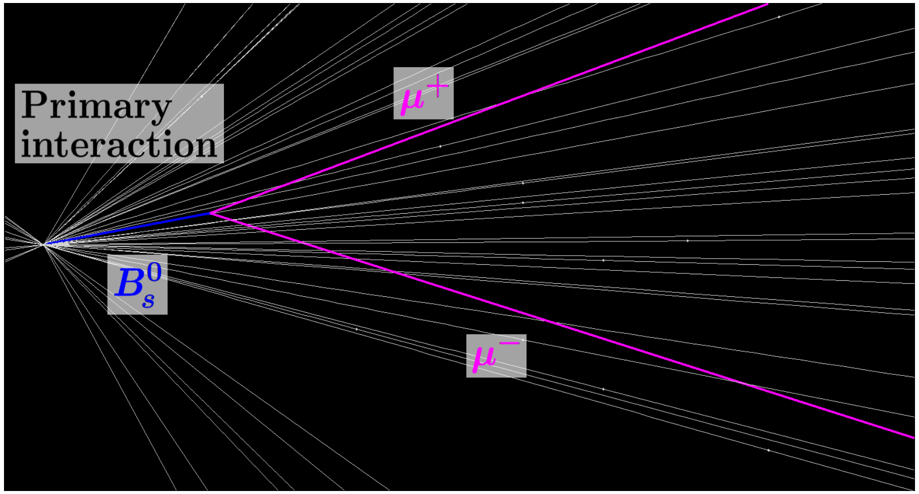
decay channel	upper limit with 90% CL
$B^0 \to e^+e^-$	$8.5 \cdot 10^{-5}$
$B^0 \to \mu^+\mu^-$	$5.0 \cdot 10^{-5}$
$B^0 \to e^\pm\mu^\mp$	$5.0 \cdot 10^{-5}$

Now 7.8σ LHCb alone

LHCb Measurement $3.0 \pm 0.6 \pm 0.3\ 10^{-9}$

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





Powerful constraint on SUSY

Lepton Flavour Universality

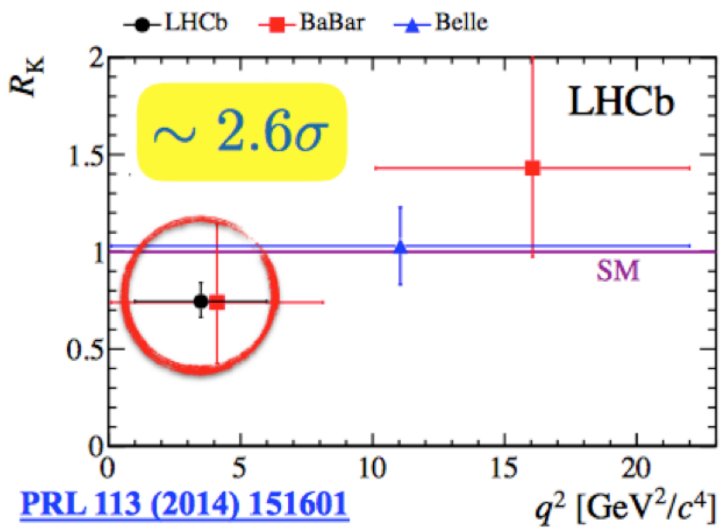
- We know that Lepton Flavour Number is not conserved from neutrino oscillations

- Is electon/muon/tau behaviour universal ?

Lepton Flavour Univerality

See Simone Bifani's Talk tomorrow

- Individually "small" excesses
- But "coherent" set of BSM effects…generating much interest



PRL 113 (2014) 151601

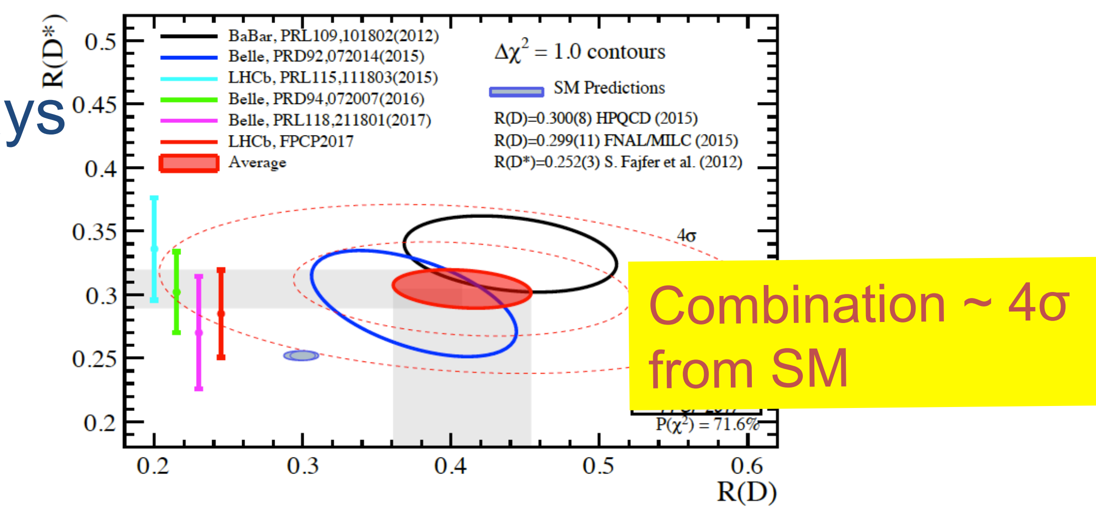
$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2}$$

and similar effects in two bins in

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

…and in semileptonic decays

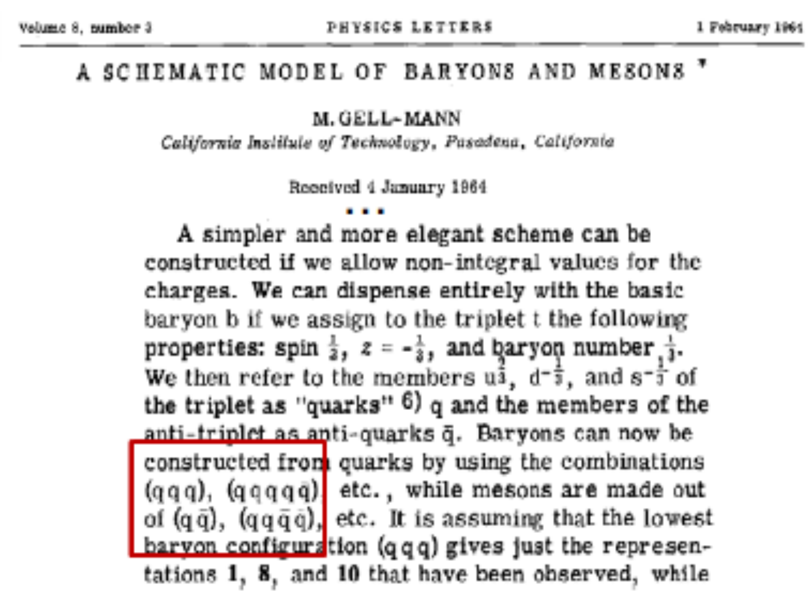
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$



Spectroscopy: Exotic States

Spectroscopy: Exotic States

See Greig Cowan's Talk tomorrow



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

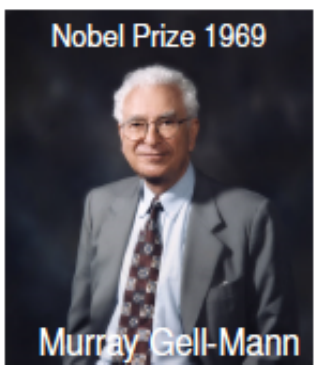
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

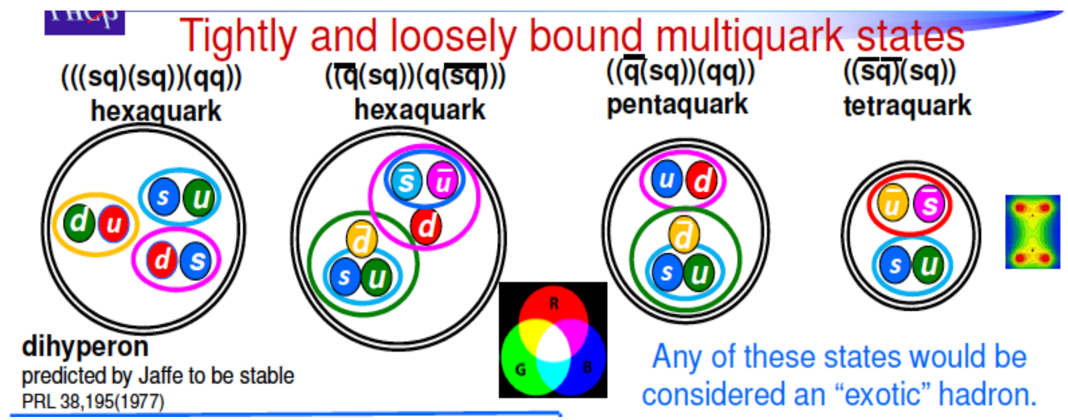
. . .

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



Mesons: quark, anti-quark
Baryons: 3 quarks
50 year history of searching for 'exotic' states

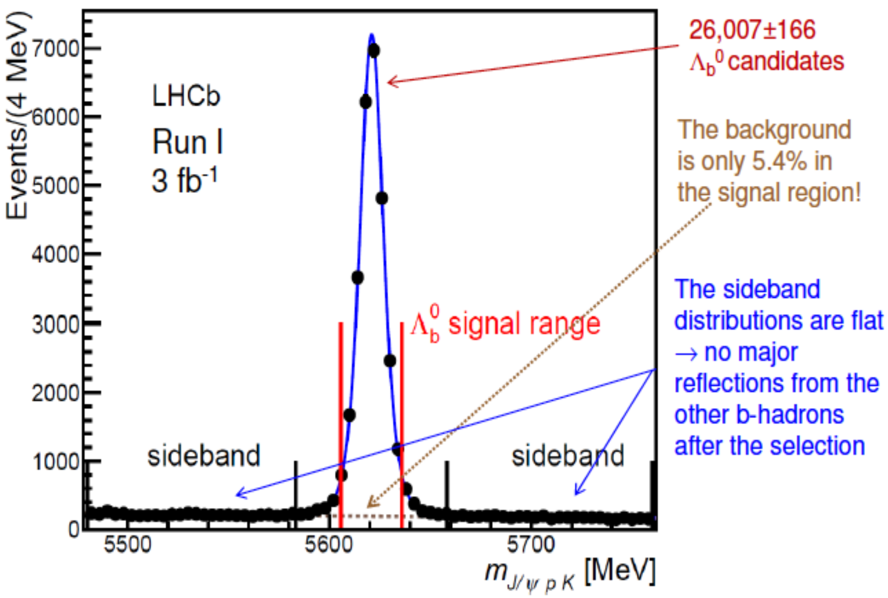
For example:

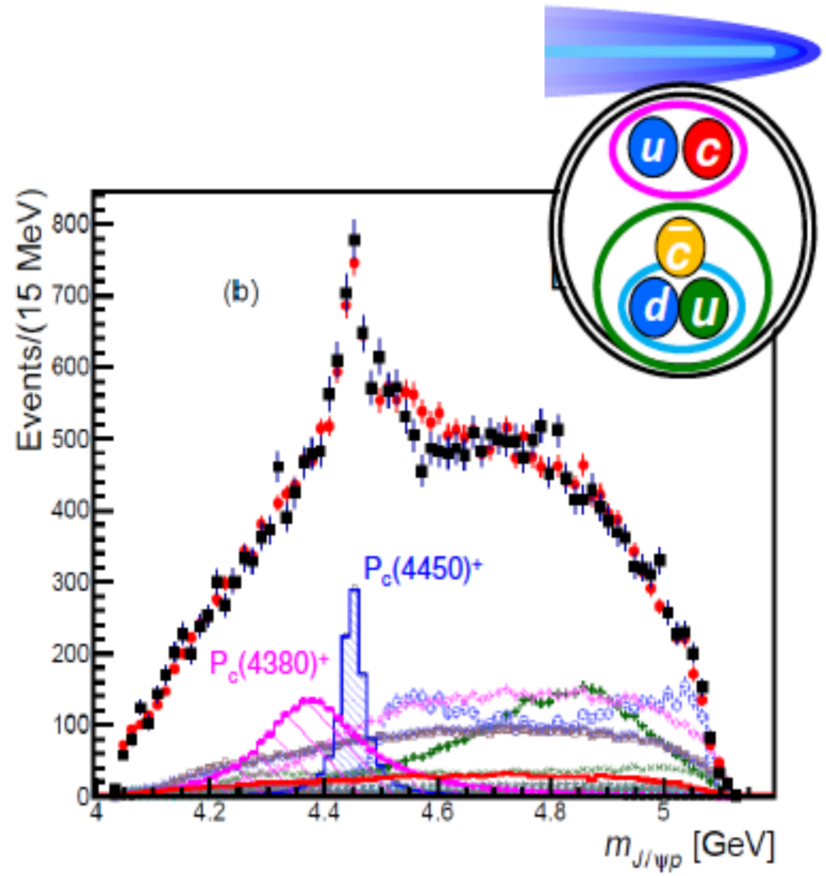


Pentaquark States

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

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201





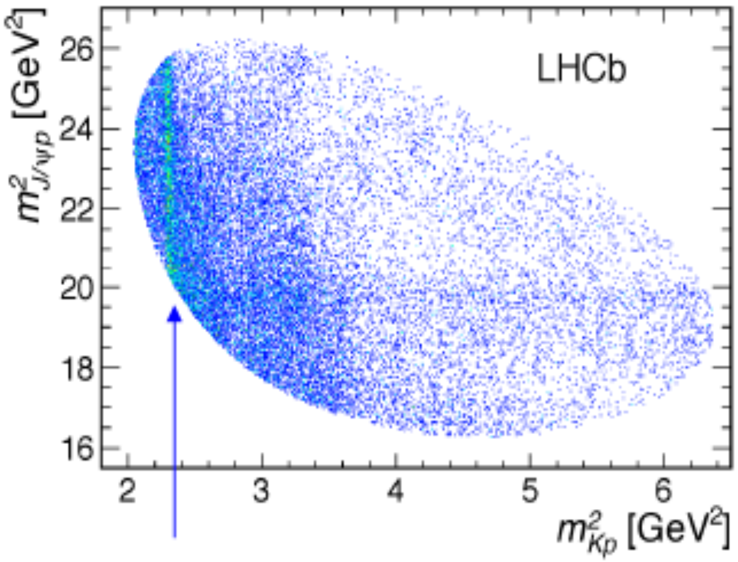
Invariant mass calculation using $E^2 = p^2 + m^2$
with measured momenta
known J/Ψ, p, K masses
E, **p**, conservation
Clean selection – low background
Λ_b quark content (udb)

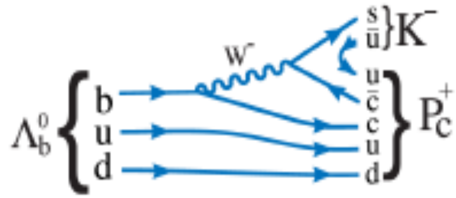
- Study two-body mass combinations

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

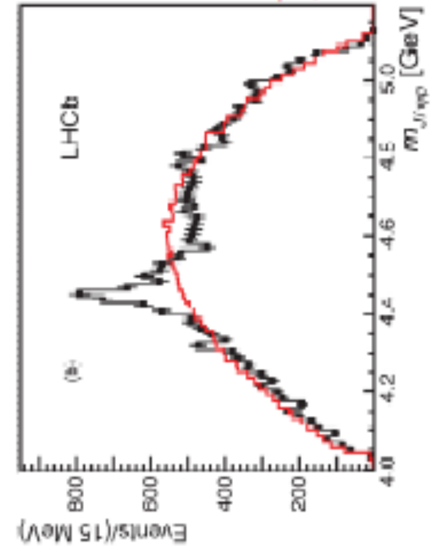
Quark content J/Ψ ($c\bar{c}$), p (uud)

$\Lambda_b^0 \to J/\psi p K^-$: unexpected structure in $m_{J/\psi\, p}$





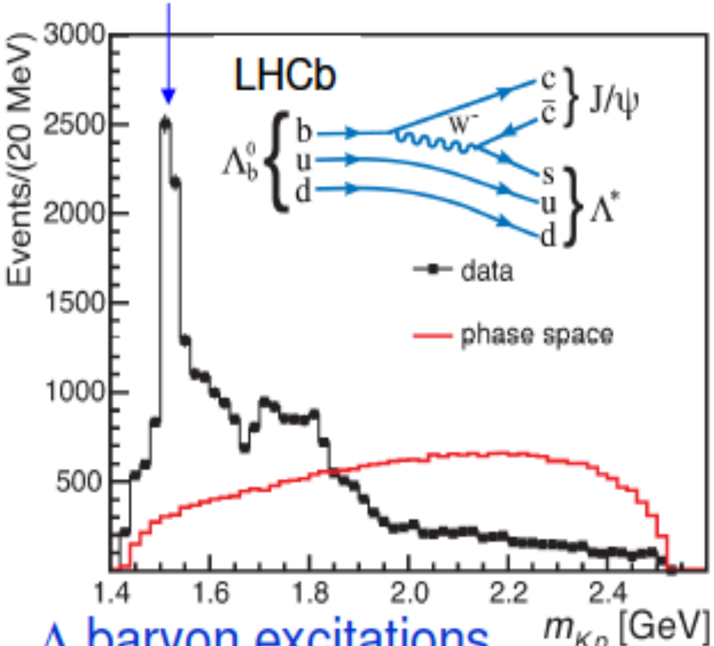
$\longleftarrow$ $P_c^+ \to J/\psi\, p$ $\longrightarrow$
?



Exotic pentaquark

$\Lambda(1520)$ and other Λ^*'s $\to p K^-$

- Unexpected, narrow peak in $m_{J/\psi\, p}$



Λ baryon excitations

Full analysis – with all known contributions to Dalitz plots included in model – shows two new states needed

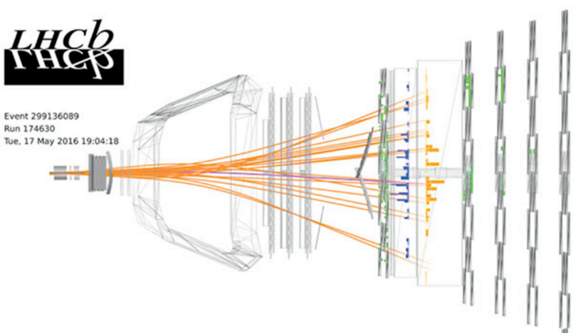
Pentaquarks !

Lots More Areas !

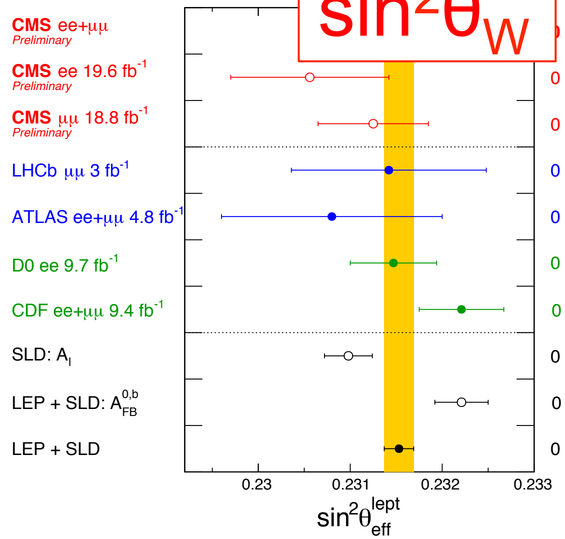
LHCb designed as heavy flavour experiment but unique design leads to…

Fixed Target

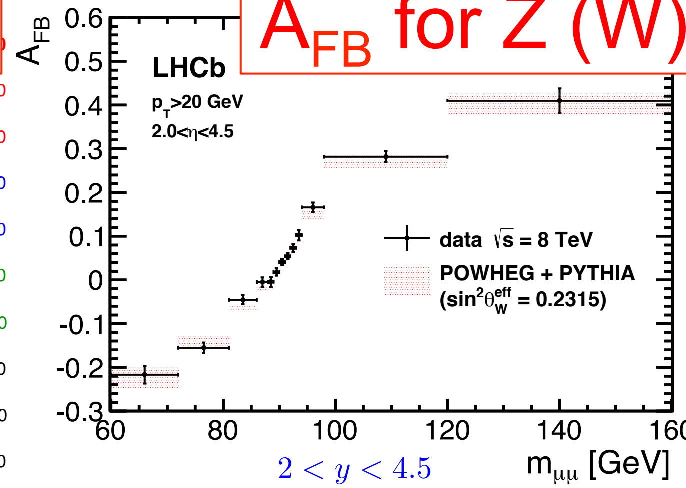
Gas injection



$\sin^2\theta_W$

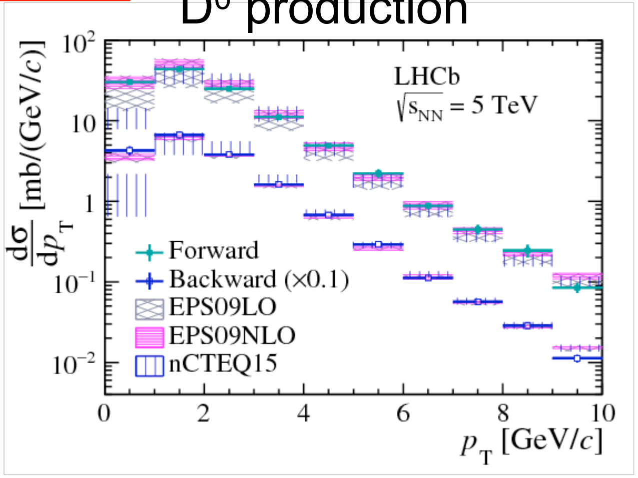


A_{FB} for Z (W)

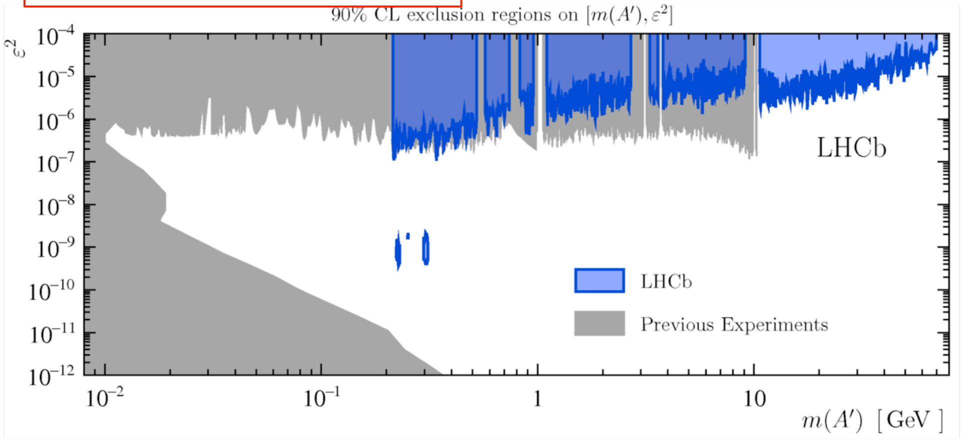


Ions

D^0 production

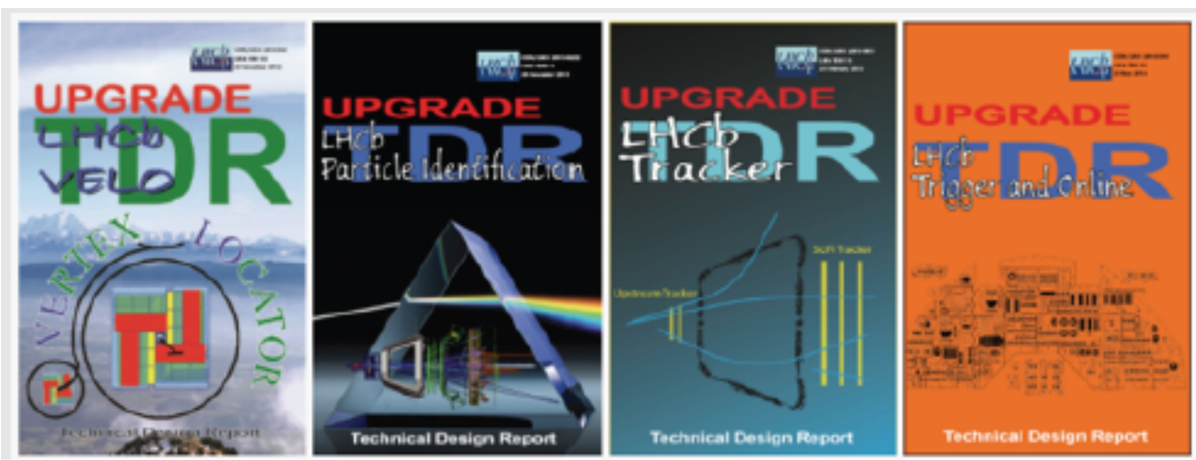


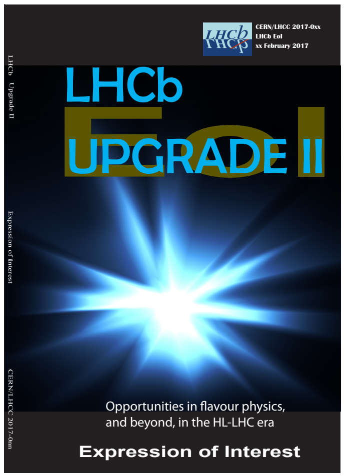
Dark Sector



General purpose experiment for the forward region

LHCb Future


UPGRADE
TDR
LHCb
VELO
VERTEX LOCATOR
UPGRADE
TDR
LHCb
Particle Identification
Technical Design Report
UPGRADE
TDR
LHCb
Tracker
Technical Design Report
UPGRADE
TDR
LHCb
Trigger and Online
Technical Design Report


CERN/LHCC 2017-0xx
LHCb EoI
xx February 2017
LHCb
EoI
UPGRADE II
Opportunities in flavour physics,
and beyond, in the HL-LHC era
Expression of Interest


Myrrh
Anointing Oil
Myrrh

Physics Programme

Limited by Detector

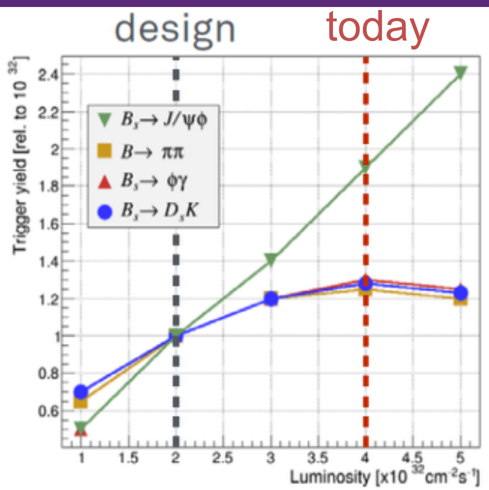
But **NOT** Limited by LHC

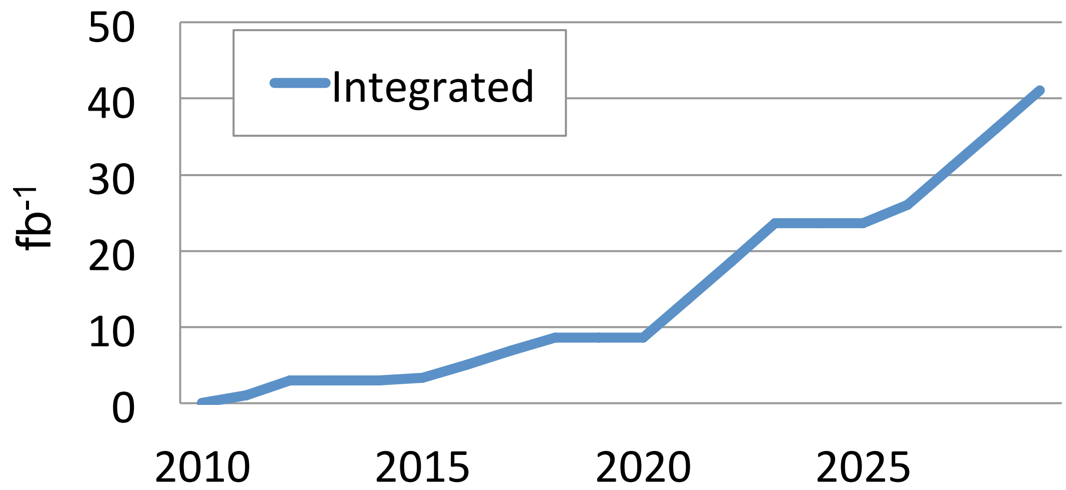
- Upgrade to extend Physics reach
  - Exploit advances in detector technology
    - Fully Software Trigger, **40MHz readout**
  - Better utilise LHC capabilities
- Upgrade I(a/b) Collect >50 fb^{-1} data
  - L ~ $2x10^{33}$ cm^{-2} s^{-1}
- Upgrade II Collect > 300 fb^{-1} data
  - L ~ 1-$2x10^{34}$ cm^{-2} s^{-1}

Upgrade I
•HL-LHC not needed
•But compatible
With HL-LHC phase

Upgrade II
• Utilise HL-LHC
phase luminosities

Upgrade I – Beyond the Energy Frontier





- Hardware 1st Level Trigger ➔ Fully Software Trigger
- Increase Lumi to $2{\times}10^{33}$ cm^{-2}s^{-1} to collect 50 fb^{-1}
- General purpose detector in forward region

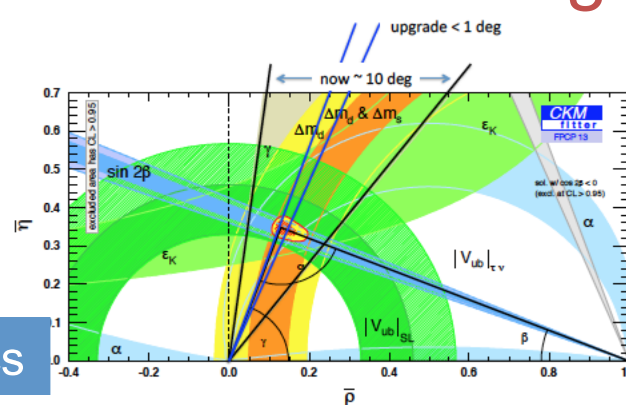
New Physics in Rare Decays

New Physics in CP Violation

New Physics in Charm

Electroweak & QCD Physics

Long Lived Stable Particle Searches, Dark Photon Searches



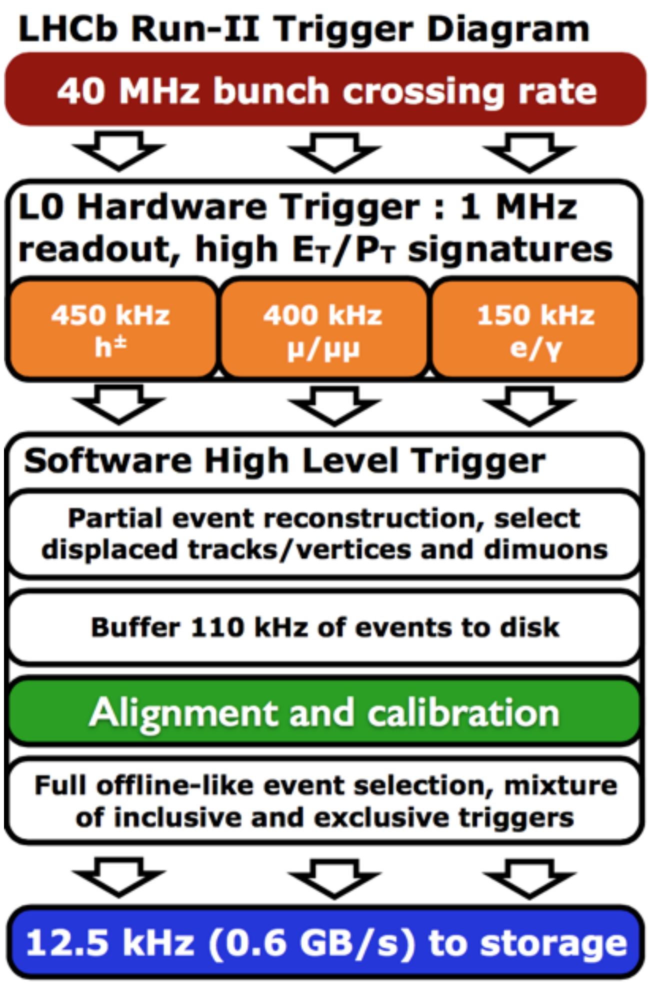
Probe 100 TeV for tree-level couplings

Eur. Phys. J. C (2013) 73:2373

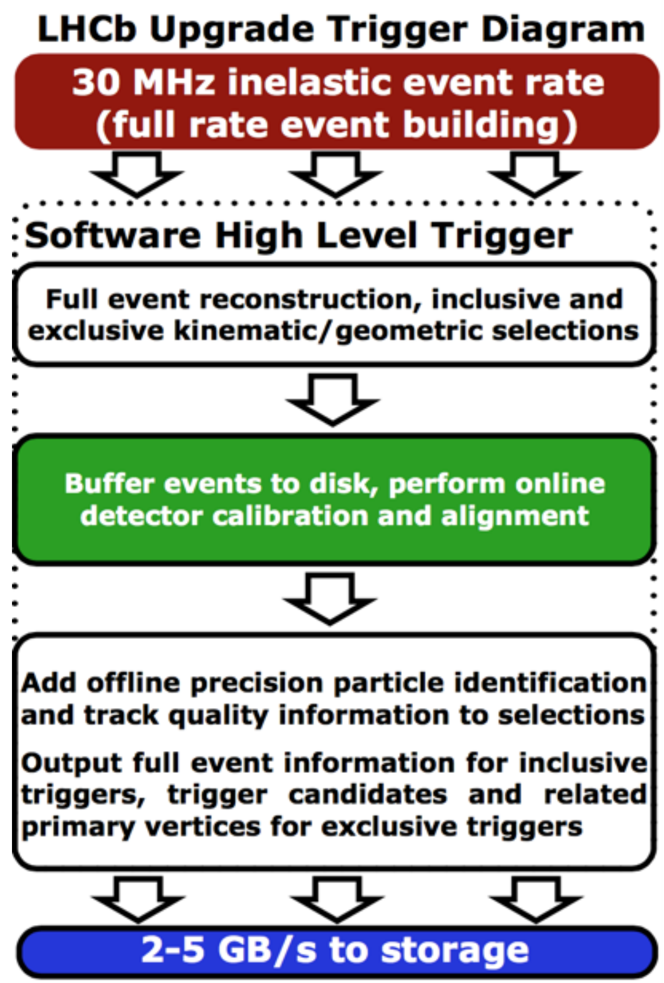
Trigger Evolution – Upgrade I

- Flexibility of Fully Software Trigger

Run II

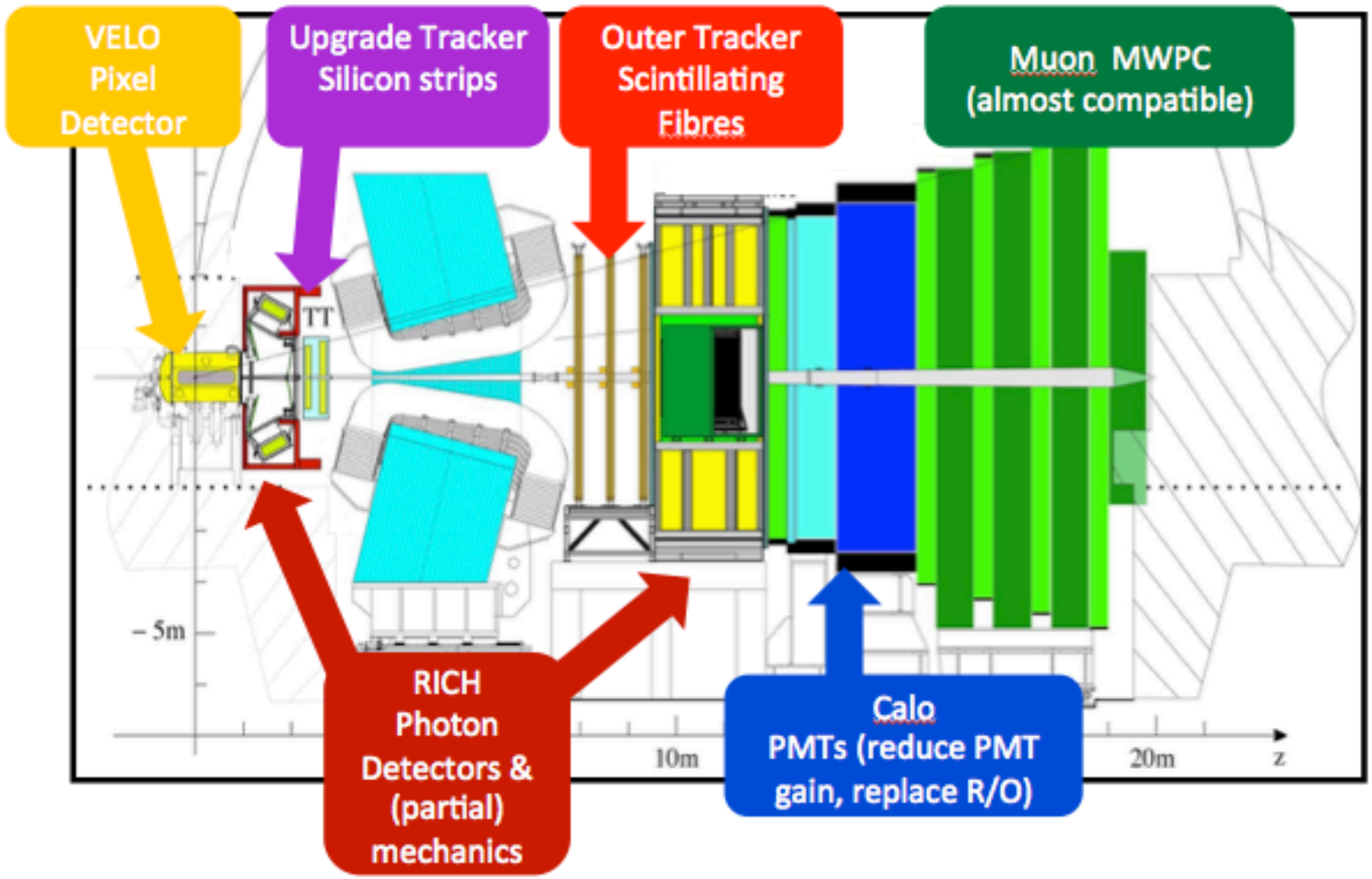


Upgrade I



LHCb Upgrade I for LS2 (2021)
25ns readout, software only triggering

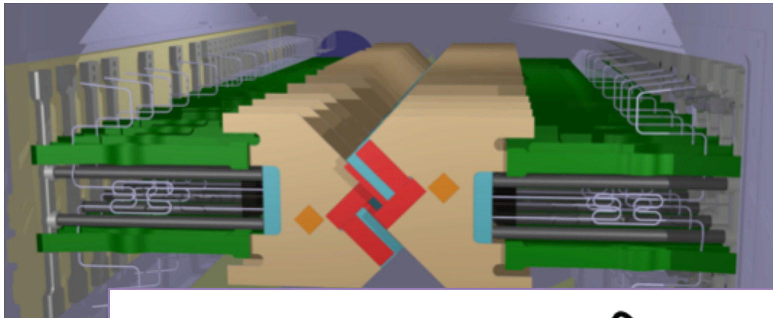
- Major UK construction project
  - B'ham, Bristol, Cambridge, Edinburgh, Glasgow, ICL, Liverpool, Manchester, Oxford, RAL, Warwick



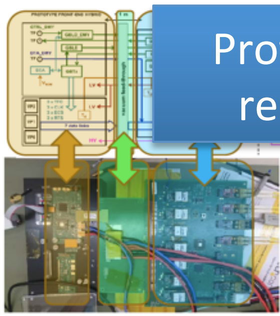
- Collect 50 fb^{-1} during 2020s (Run 3 and 4)

LHCb Upgrade I: Vertex Locator

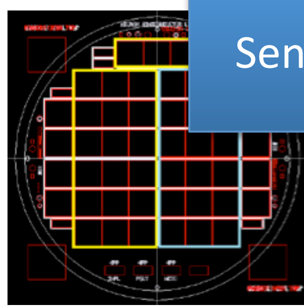
- Pixel Detector
  - 55×55 μm pixels
  - In vacuum



ASIC (VeloPix) final version

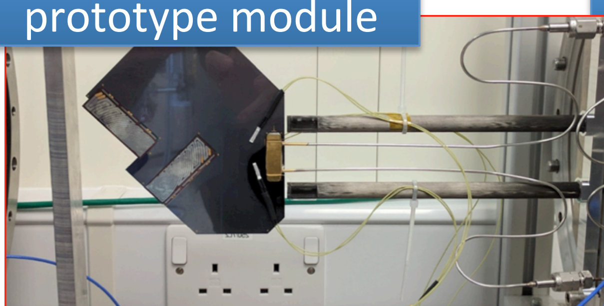


Prototoypes full readout chain

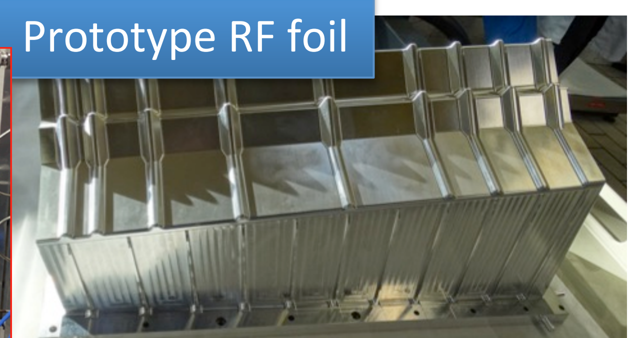


Sensors produced

- 5mm from beam
  - $10^{16}\ n_{eq}/cm^2$
  - Retracted for filling
- Bi-phase CO_2 cooling
- Si Microchannel



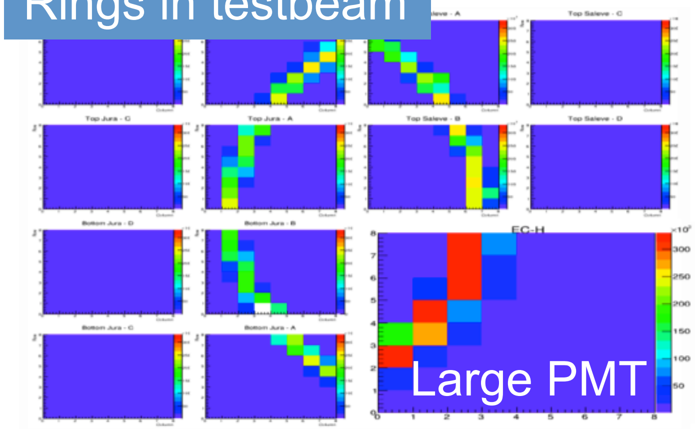
Mechanical prototype module



Prototype RF foil

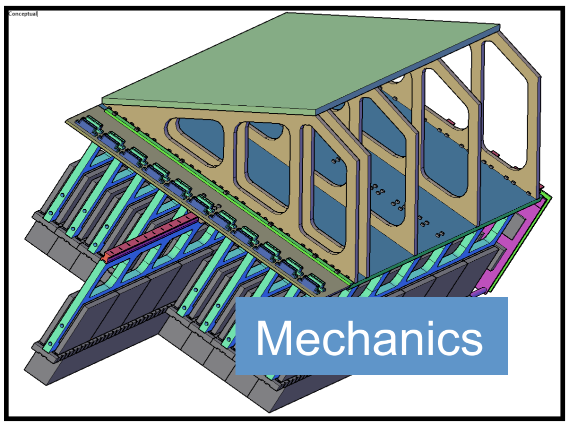
LHCb Upgrade I : RICH 1&2

- π/K separation critical to physics
- Most MaPMTs received and qualified

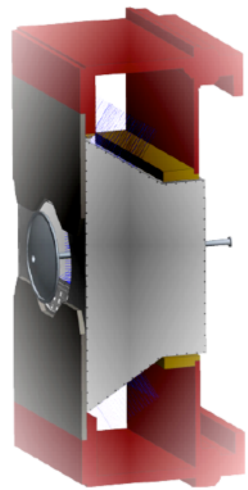


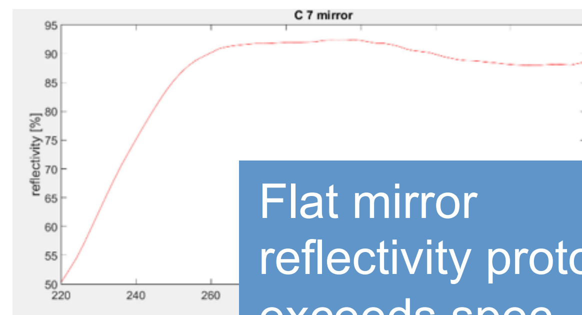
Rings in testbeam

Large PMT



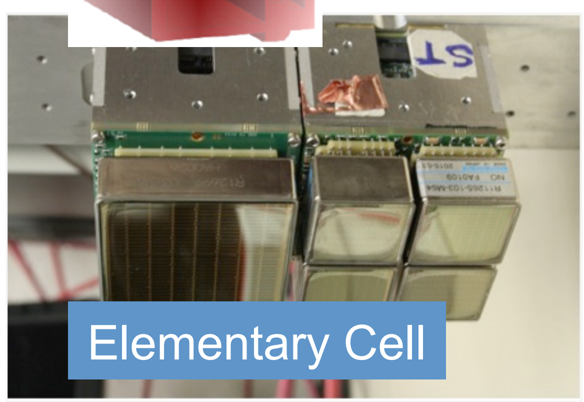
Mechanics





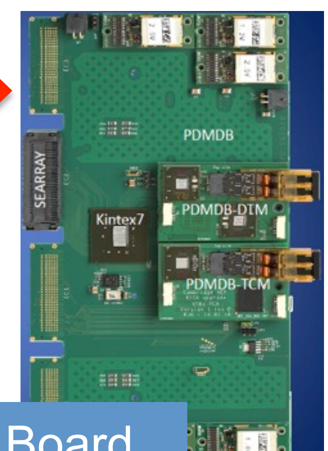
Flat mirror reflectivity prototype exceeds spec.

ASIC (CLARO)



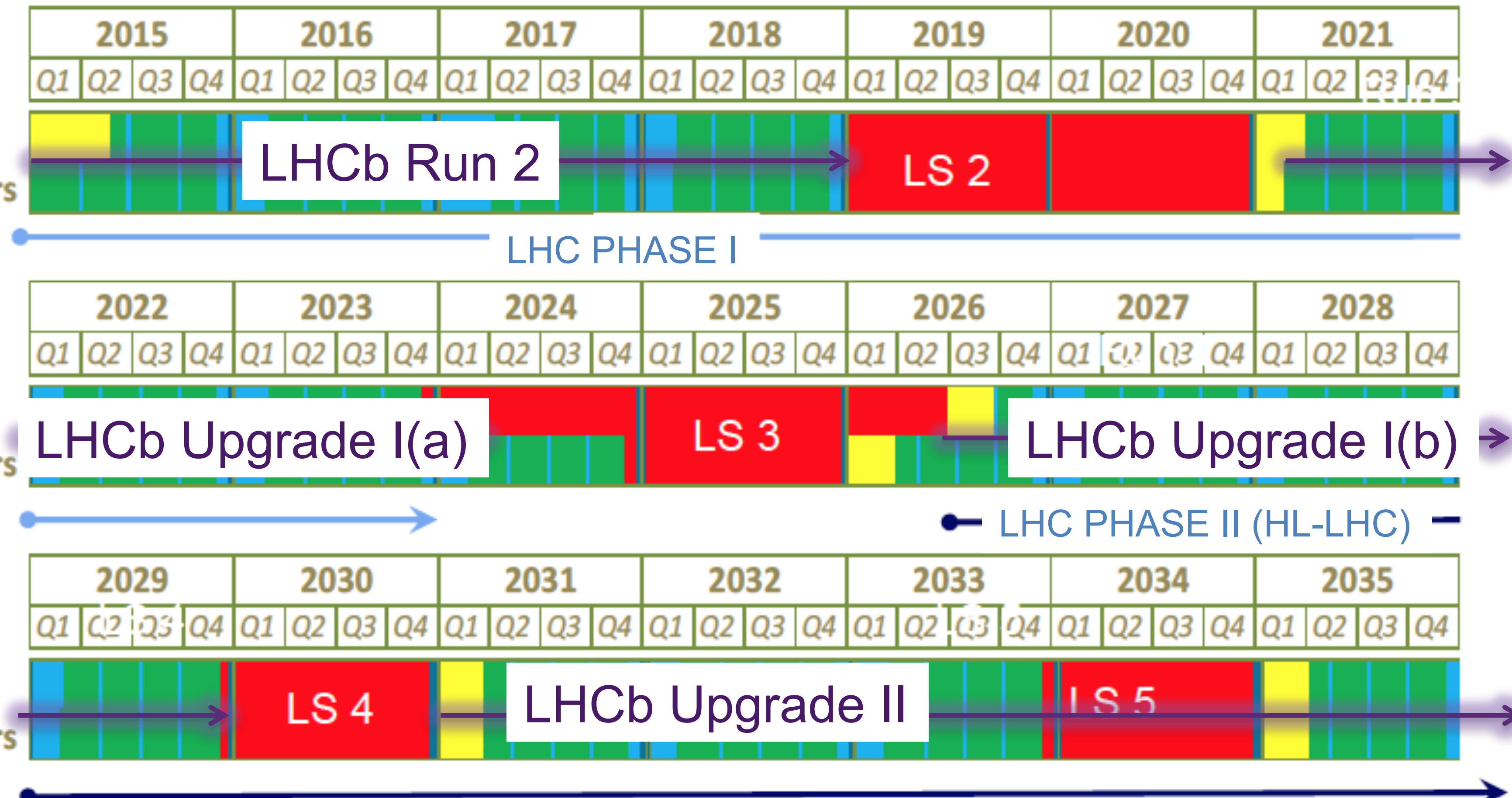
Elementary Cell

4x EC



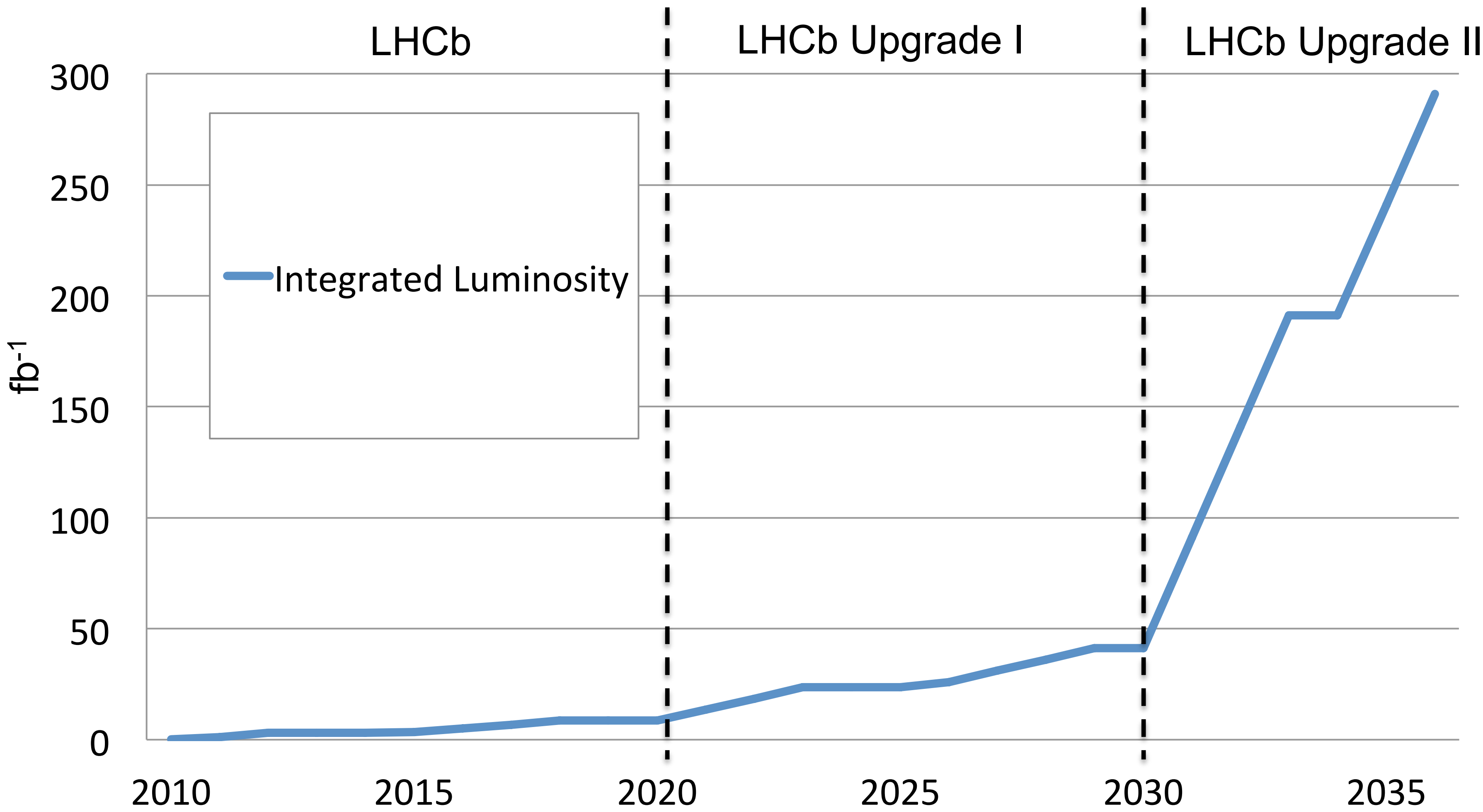
Digital Board

LHC Schedule & LHCb

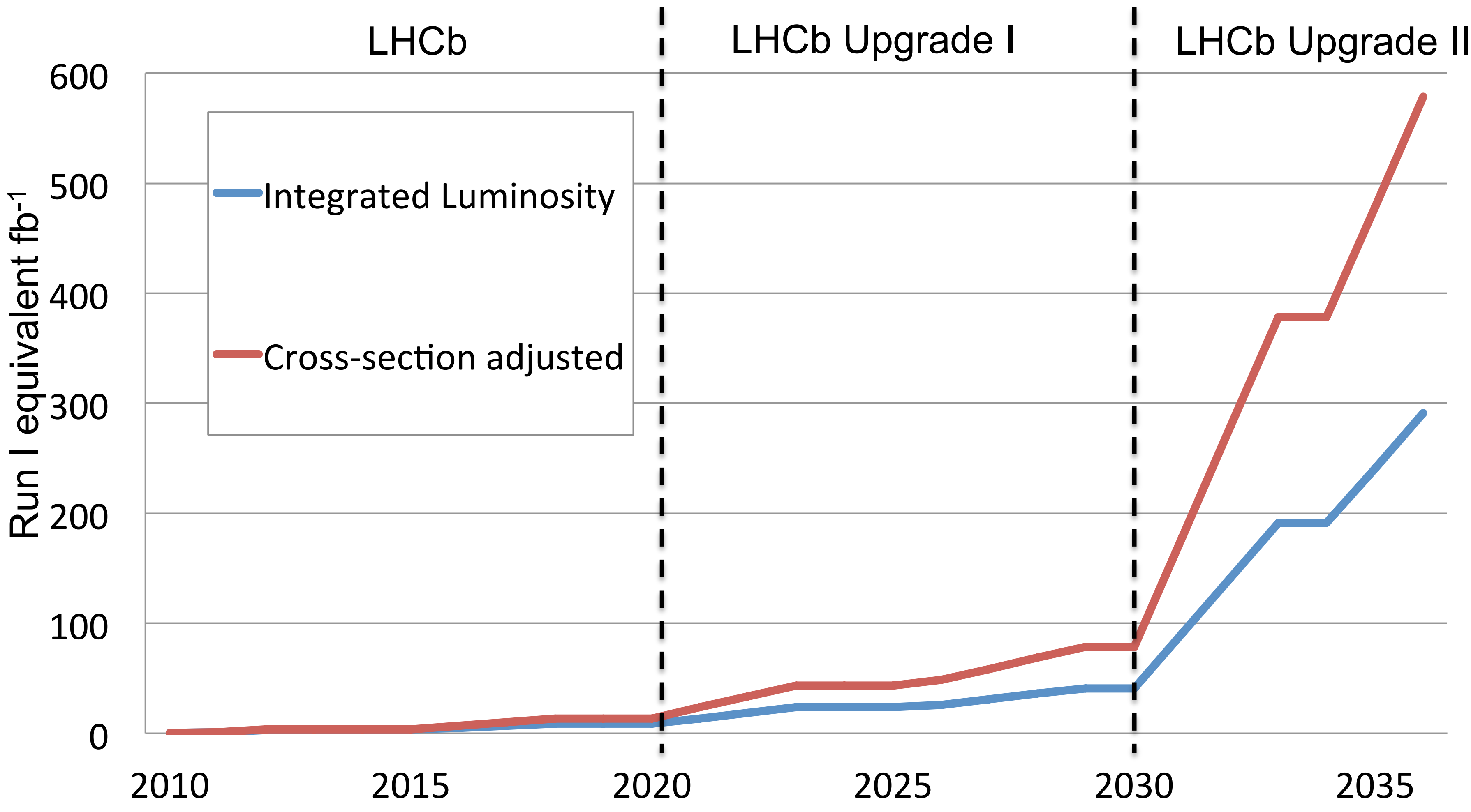


- Schedule till 2020 firm
- GPD main upgrades (phase II) scheduled for LS3
- HL-LHC upgrade in LS3
- **Belle II finishes ~ 2025**

LHCb Statistics- Timeline

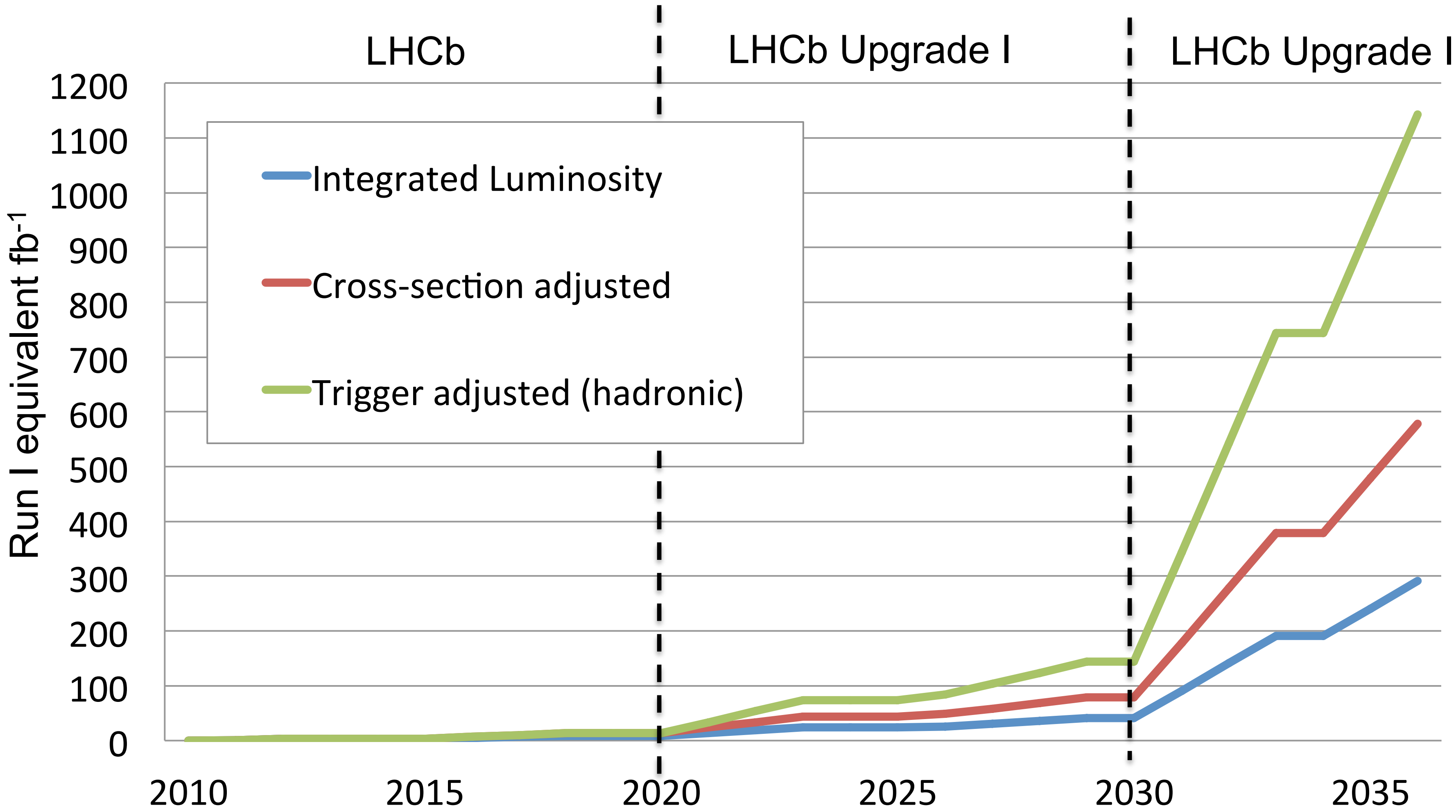


LHCb Statistics- Timeline



- Adjustment for 7/813/14 TeV cross-sections

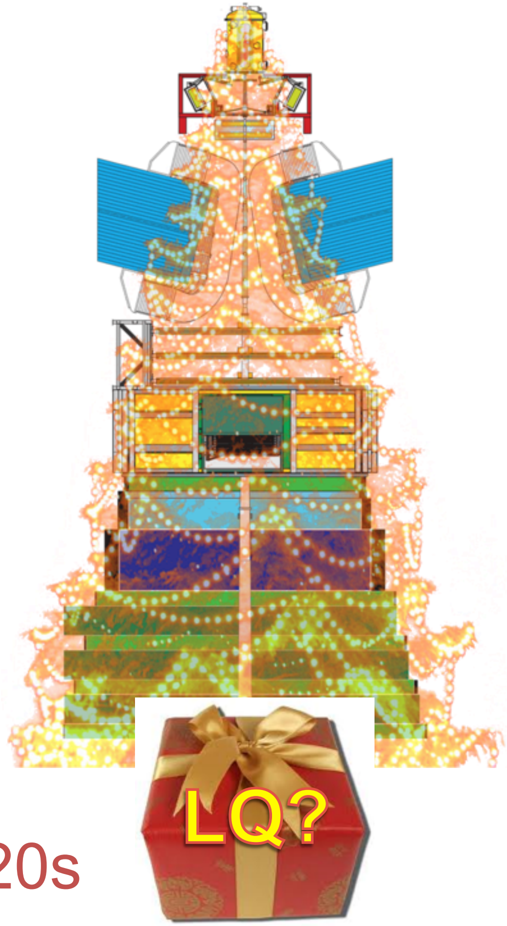
LHCb Statistics- Timeline



- Assumptions made on relative trigger efficiencies have significant uncertainty

Summary

- Unique Design at LHC
  - Acceptance, Vertex Detector, RICH
  - Originally for CPV and rare decays
  - …but physics in many other areas also
- Major "textbook" Physics Results
  - Searches for New Physics in CPV
  - Rare decay observations
  - Spectroscopy results (7 new particles in 2017)
- Future Plans
  - 2018 is final year of current experiment
  - Upgrade I: Under construction, operate 2020s
  - Upgrade II: early studies, operate 2030s



3rd annual workshop on LHCb Future in Annecy 21-23 March. Theory & experiment. Open to all.