Flavour Physics and CP violation

Lecture 2 of 3

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Contents

- Part 1
  - Why is flavour physics & CP violation interesting?
- Part 2
  - What do we know from the previous generation of experiments?
- Part 3
  - What do we hope to learn from current and future heavy flavour experiments?

What do we know about heavy quark flavour physics as of today?

CKM Matrix : parametrizations

- Many different possible choices of 4 parameters
- PDG: 3 mixing angles and 1 phase

PRL 53 (1984) 1802

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Apparent hierarchy: $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{13} \sim 0.004$
  - Wolfenstein parametrization (expansion parameter $\lambda \sim \sin\theta_c \sim 0.22$)

PRL 51 (1983) 1945

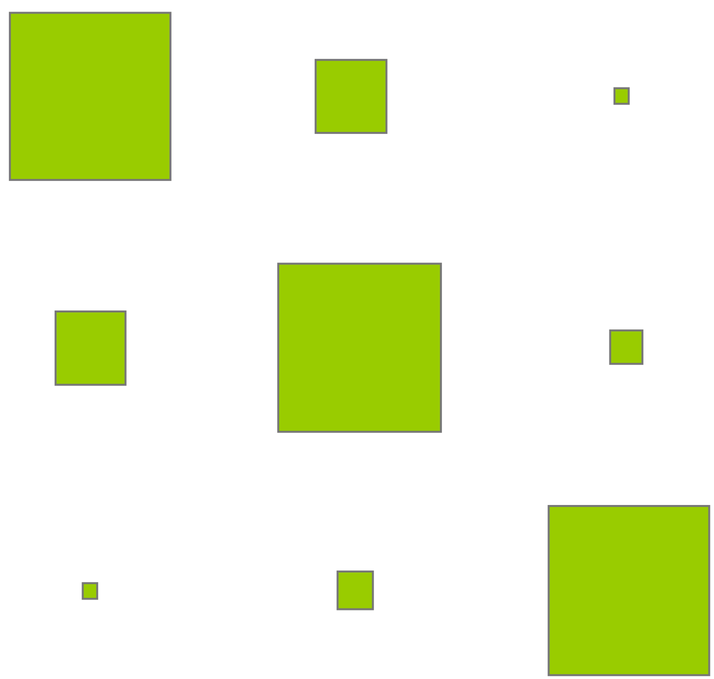
$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

- Other choices, eg. based on CP violating phases

PLB 680 (2009) 328

Hierarchy in quark mixing

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$



Very suggestive pattern

No known underlying reason

Situation for leptons (νs) is completely different

CKM matrix to O(λ^5)

$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

imaginary part at O(λ^3)

imaginary part at O(λ^4)

imaginary part at O(λ^5)

Remember – only *relative* phases are observable

Unitarity Tests

- The CKM matrix must be unitary

$$V^{+}_{CKM} V_{CKM} = V_{CKM} V^{+}_{CKM} = 1$$

- Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$V_{ud} V^{*}_{ub} + V_{cd} V^{*}_{cb} + V_{td} V^{*}_{tb} = 0$$

CKM Matrix – Magnitudes

PDG 2024

semileptonic / leptonic kaon decays
hadronic tau decays

superallowed $0^+ \rightarrow 0^+$ β decays

semileptonic / leptonic B decays

$$\begin{pmatrix} 0.97367 \pm 0.00032 & 0.22431 \pm 0.00085 & (3.82 \pm 0.20) \times 10^{-3} \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & (41.1 \pm 1.2) \times 10^{-3} \\ (8.6 \pm 0.2) \times 10^{-3} & (41.5 \pm 0.9) \times 10^{-3} & 1.010 \pm 0.027 \end{pmatrix}$$

semileptonic charm decays
charm production in neutrino beams

semileptonic B decays

semileptonic / leptonic charm decays

B_d oscillations

single top production

B_s oscillations

theory inputs (eg., lattice calculations) required

First row unitarity

- The eagle eyed may have spotted:

PDG 2024

superallowed $0^+ \to 0^+$ β decays

semileptonic / leptonic kaon decays
hadronic tau decays

semileptonic / leptonic B decays

$$\left(0.97367 \pm 0.00032 \quad 0.22431 \pm 0.00085 \quad (3.82 \pm 0.20) \times 10^{-3} \right)$$

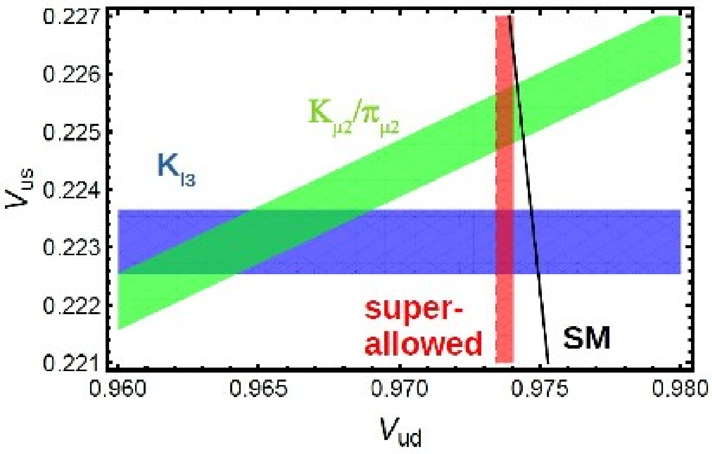
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9983(6)(4)$$

Uncertainty from $|V_{ud}|$

Uncertainty from $|V_{us}|$

(contribution from $|V_{ub}|$ negligible)

Figure from arXiv:2207.10492 (slightly different values to PDG2024)



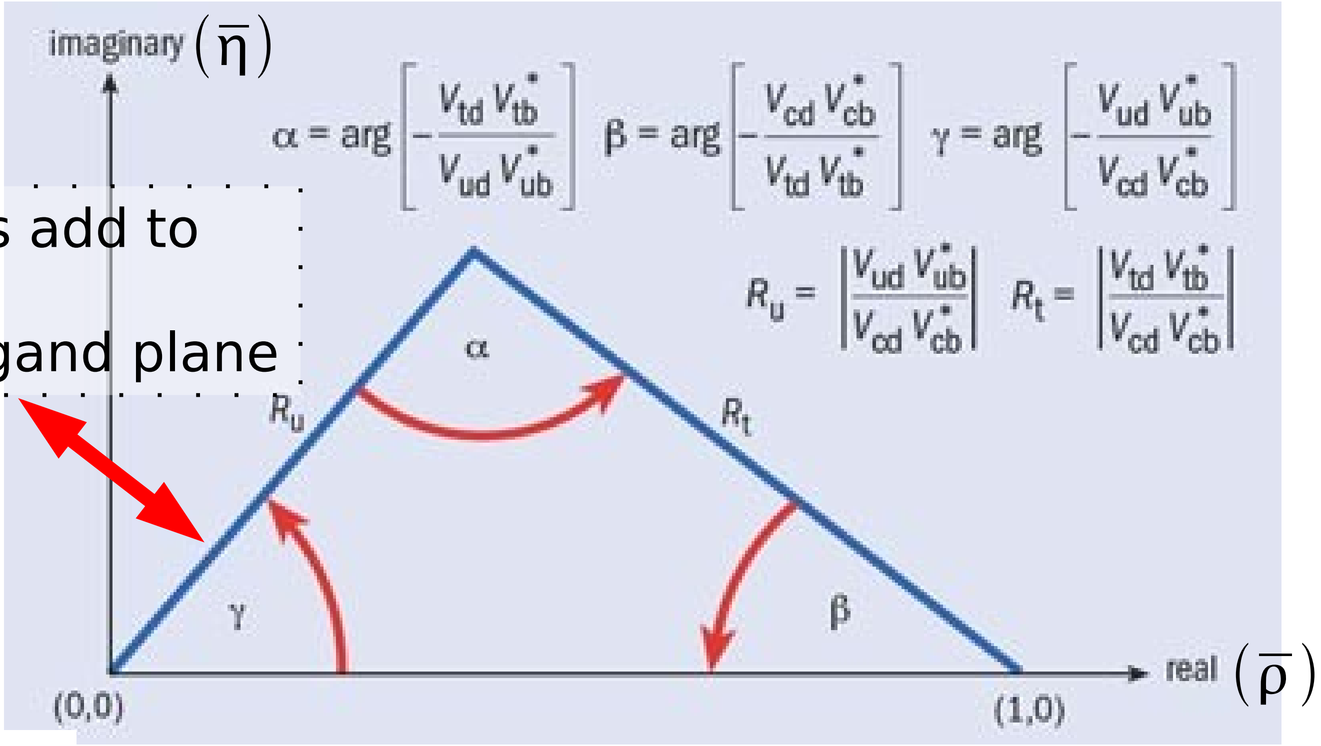
~2.5σ "tension"

Tim Gershon
Flavour physics
& CP violation

The Unitarity Triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Three complex numbers add to zero
⇒ triangle in Argand plane



Axes are ρ̅ and η̅ where

$$\overline{\rho} + i\overline{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$$\rho + i\eta = \frac{\sqrt{1 - A^2\lambda^4}(\overline{\rho} + i\overline{\eta})}{\sqrt{1 - \lambda^2}\left[1 - A^2\lambda^4(\overline{\rho} + i\overline{\eta})\right]}$$

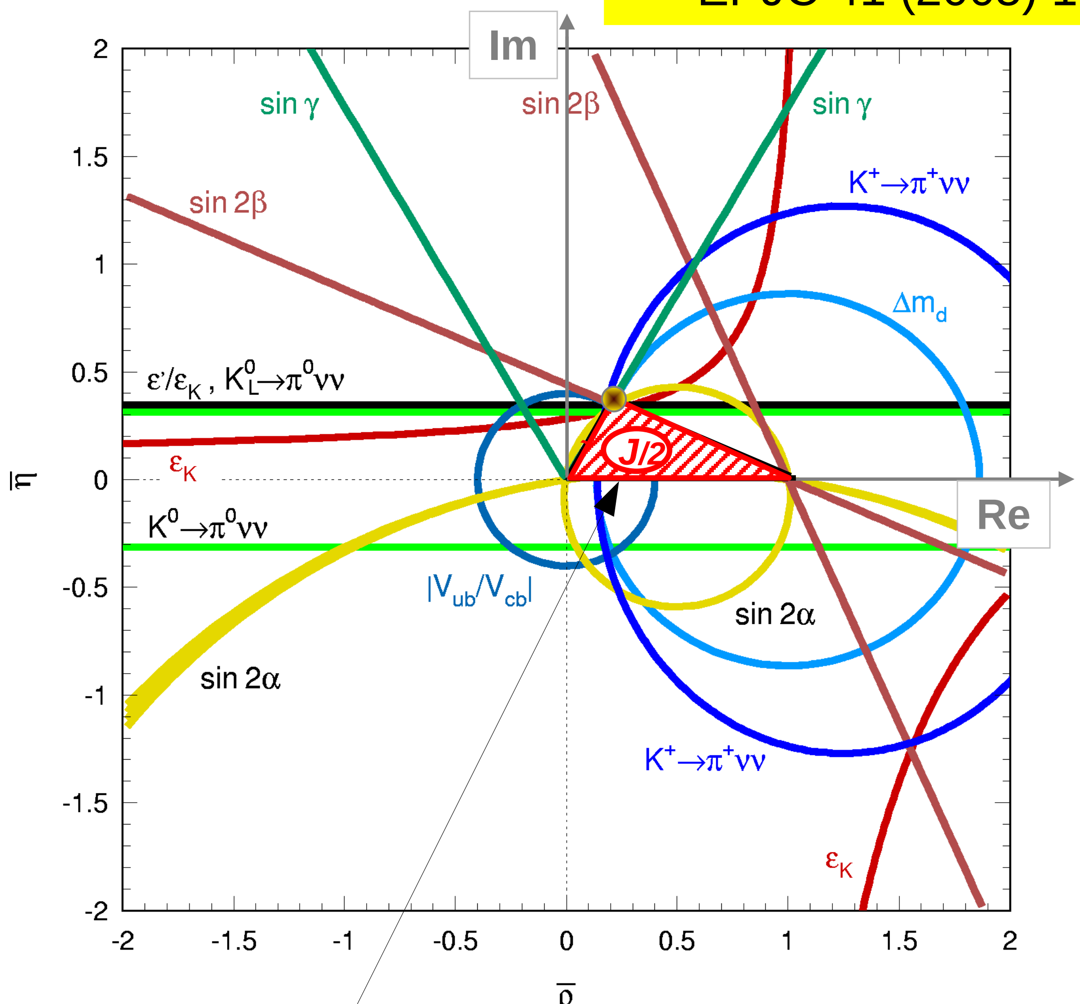
Predictive nature of KM mechanism

In the Standard Model the KM phase is the sole origin of CP violation

Hence:
all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)

EPJC 41 (2005) 1

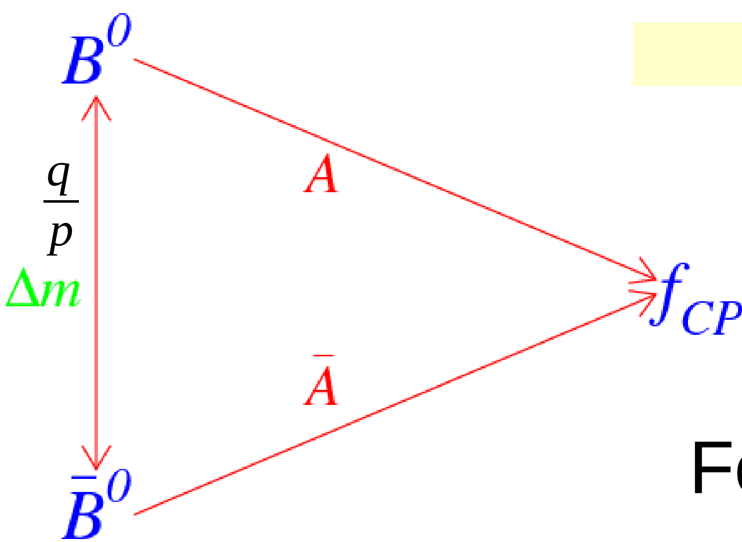


Area of (all of) the unrescaled Unitarity Triangle(s)
is given by the Jarlskog invariant

Time-Dependent CP Violation in the B^0–$\overline{B}^0$ System

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1 - \left(S\sin(\Delta m\, t) - C\cos(\Delta m\, t)\right)\right)$$
$$\Gamma\left(\overline{B}^0_{phys} \to f_{CP}(t)\right) \propto e^{-\Gamma t}\left(1 + \left(S\sin(\Delta m\, t) - C\cos(\Delta m\, t)\right)\right)$$



here assume ΔΓ negligible – will see full expressions later

$$S = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}^2|} \qquad C = \frac{1-|\lambda_{CP}^2|}{1+|\lambda_{CP}^2|} \qquad \lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

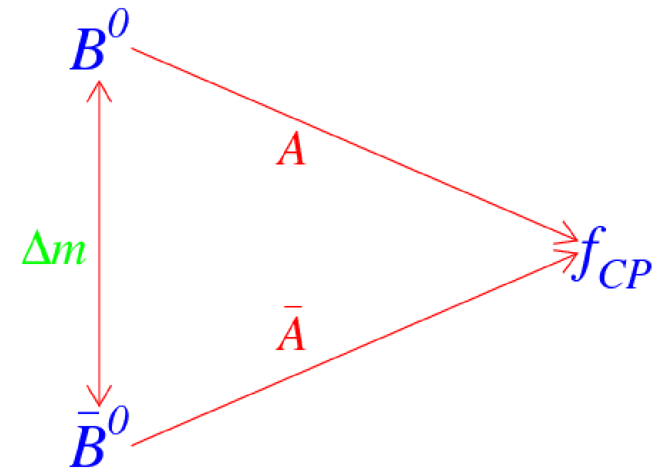
For $B^0 \to J/\psi K_S$, $S = \sin(2\beta)$, $C=0$

NPB 193 (1981) 85
I. Bigi and A. Sanda

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



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

CP violation in mixing

$$\left|\frac{\bar{A}}{A}\right| \neq 1$$

CP violation in decay

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

CP violation in interference between mixing and decay

Asymmetric B factory principle

To measure t require B meson to be moving

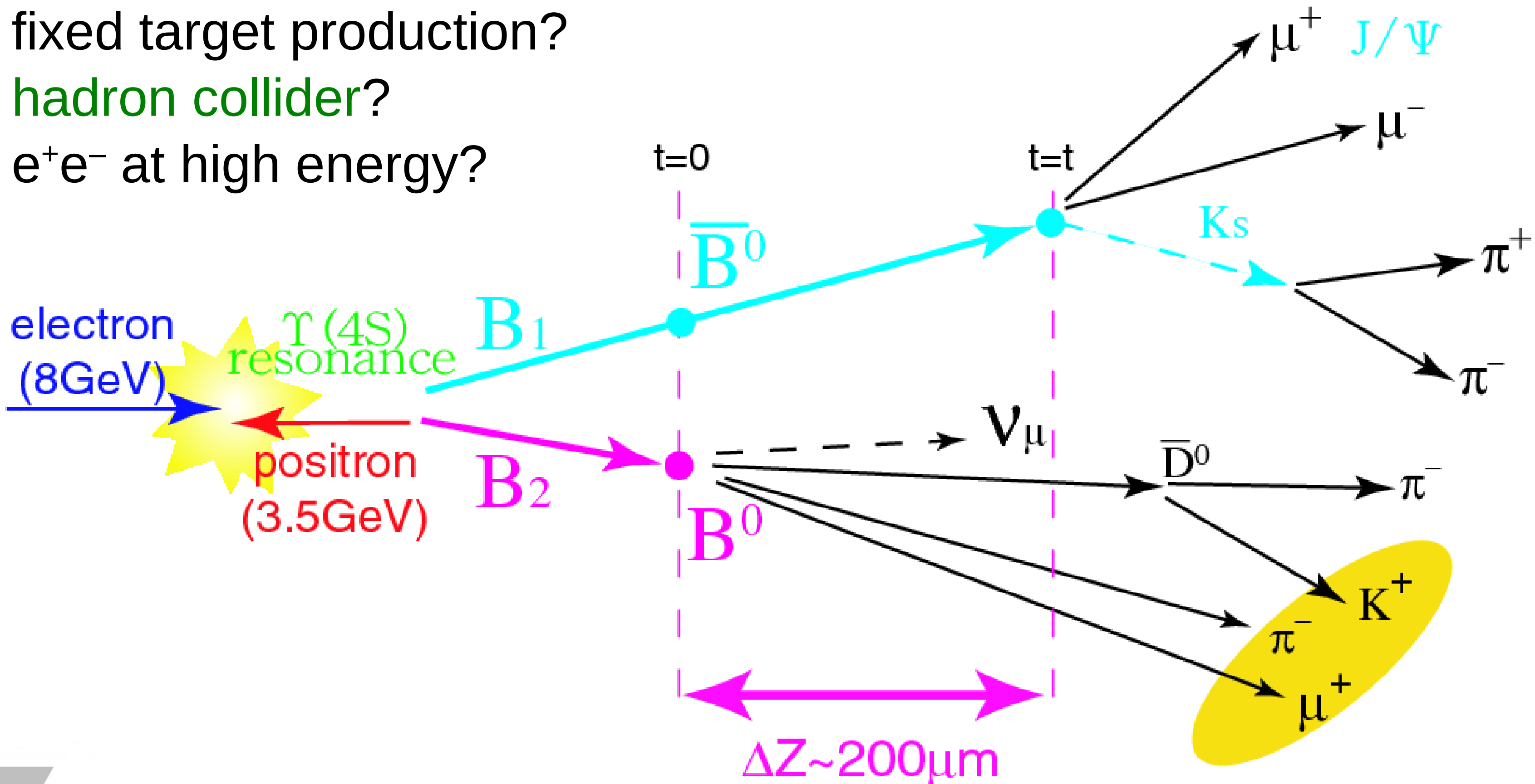
→ e^+e^- at threshold with asymmetric collisions (P. Oddone)

Other possibilities considered

→ fixed target production?

→ hadron collider?

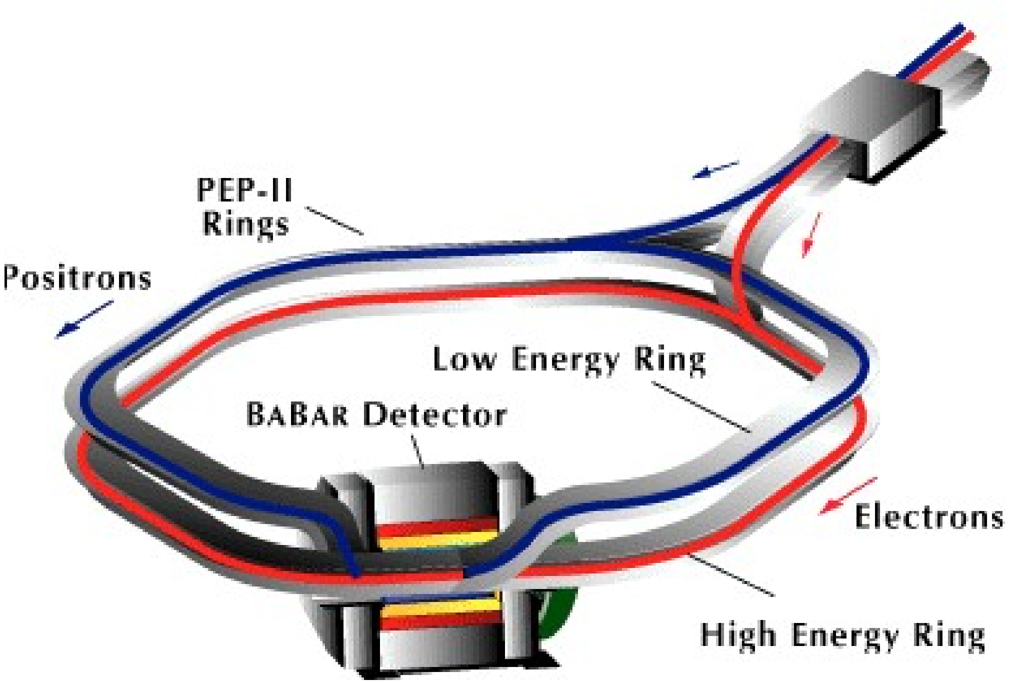
→ e^+e^- at high energy?

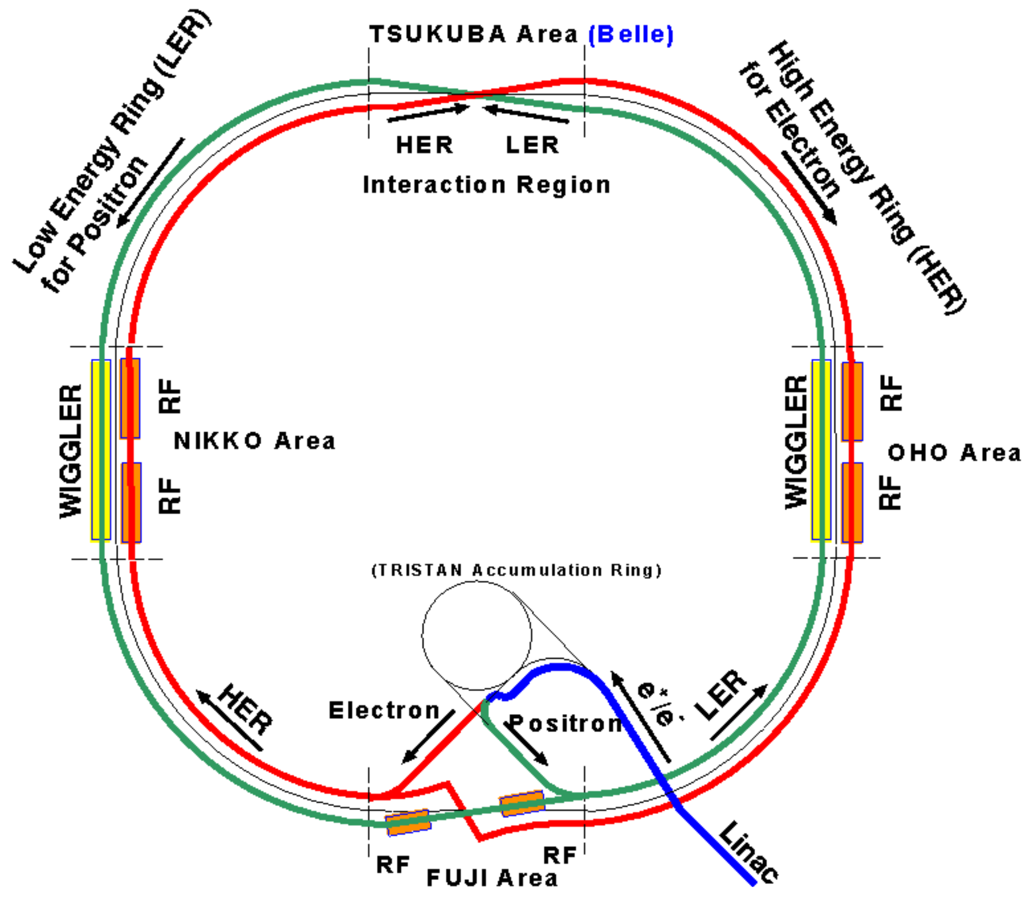


Asymmetric B Factories

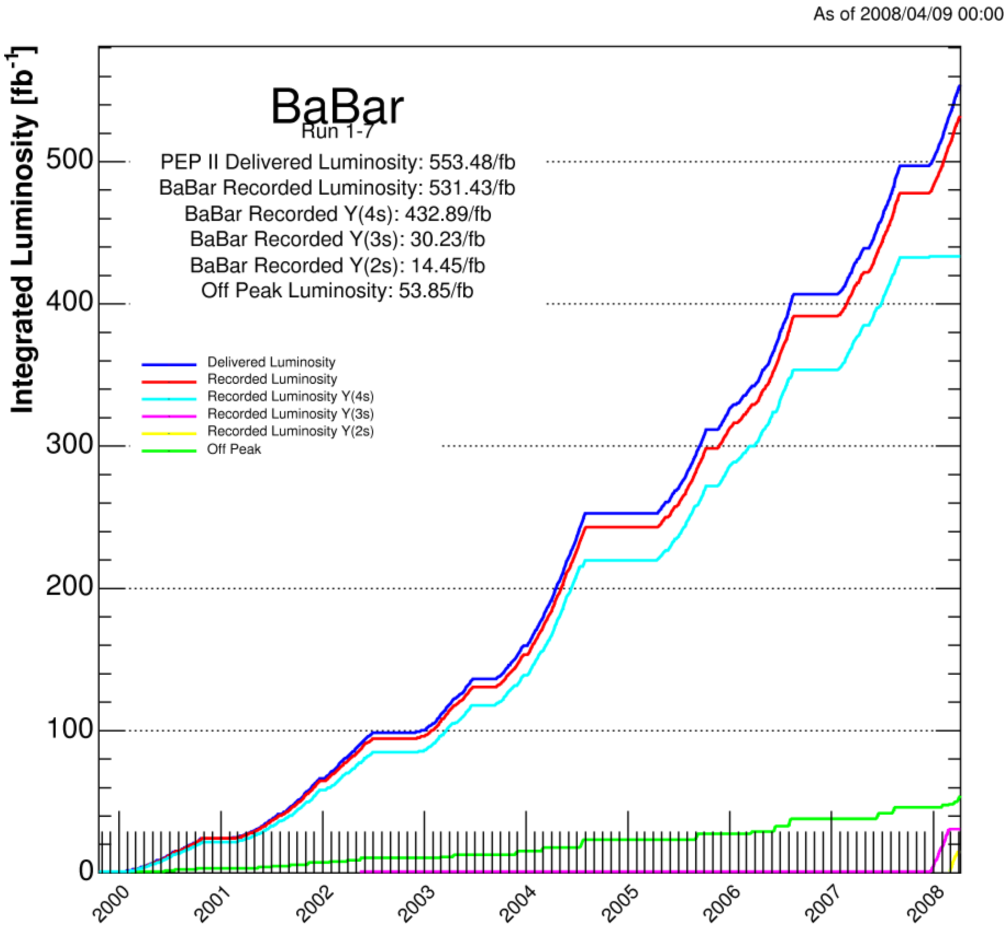
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

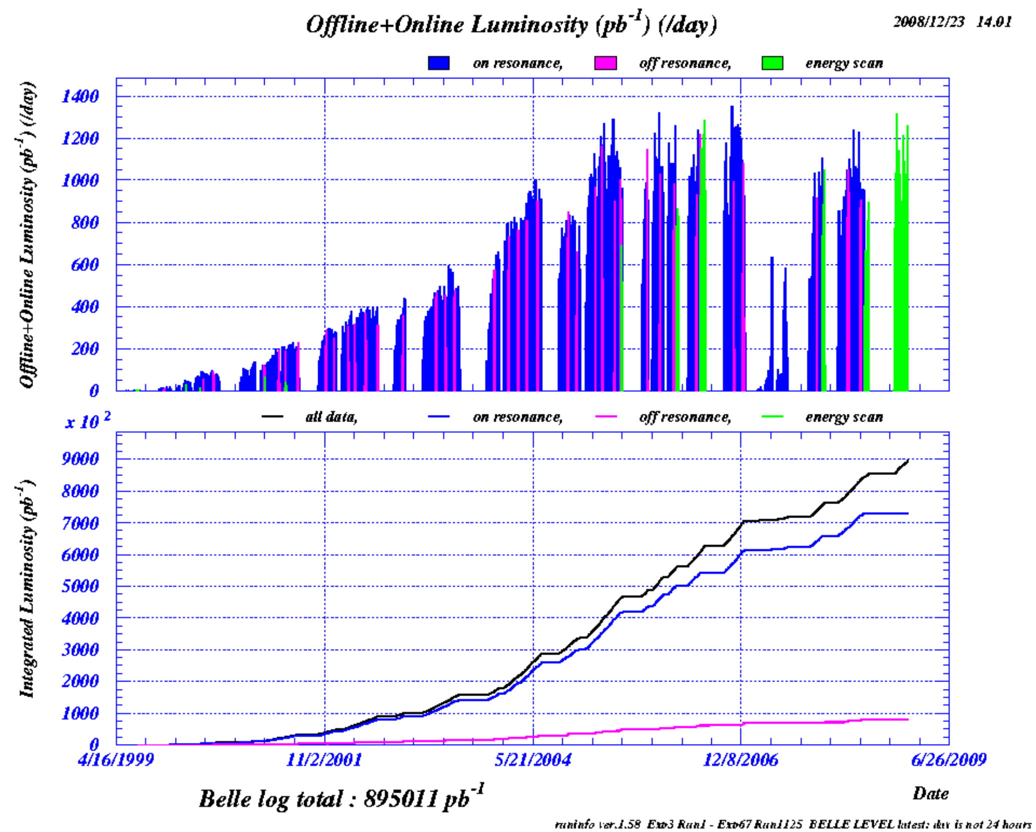
KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





B factories – world record luminosities





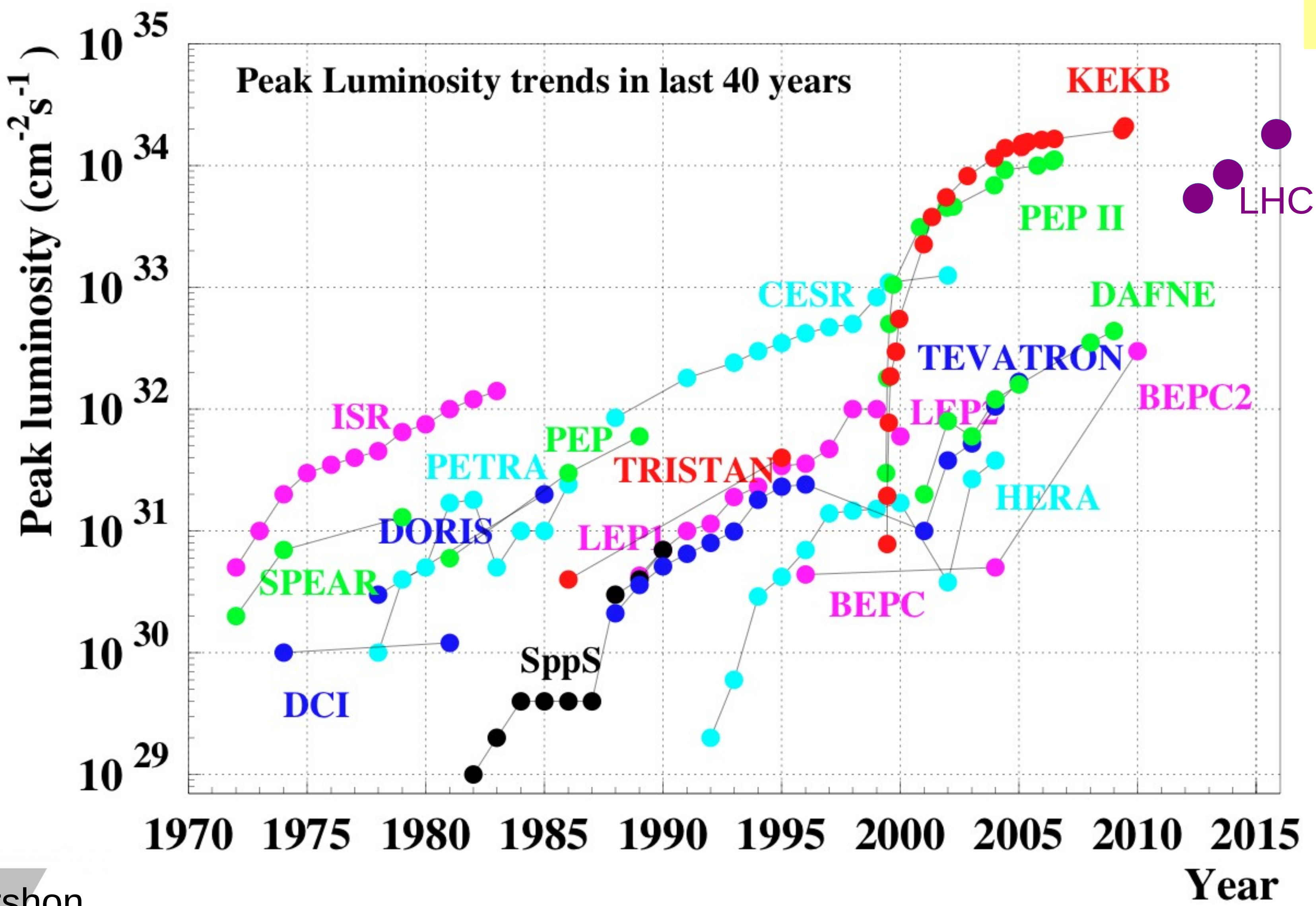
~ 433/fb on Y(4S)

~ 711/fb on Y(4S)

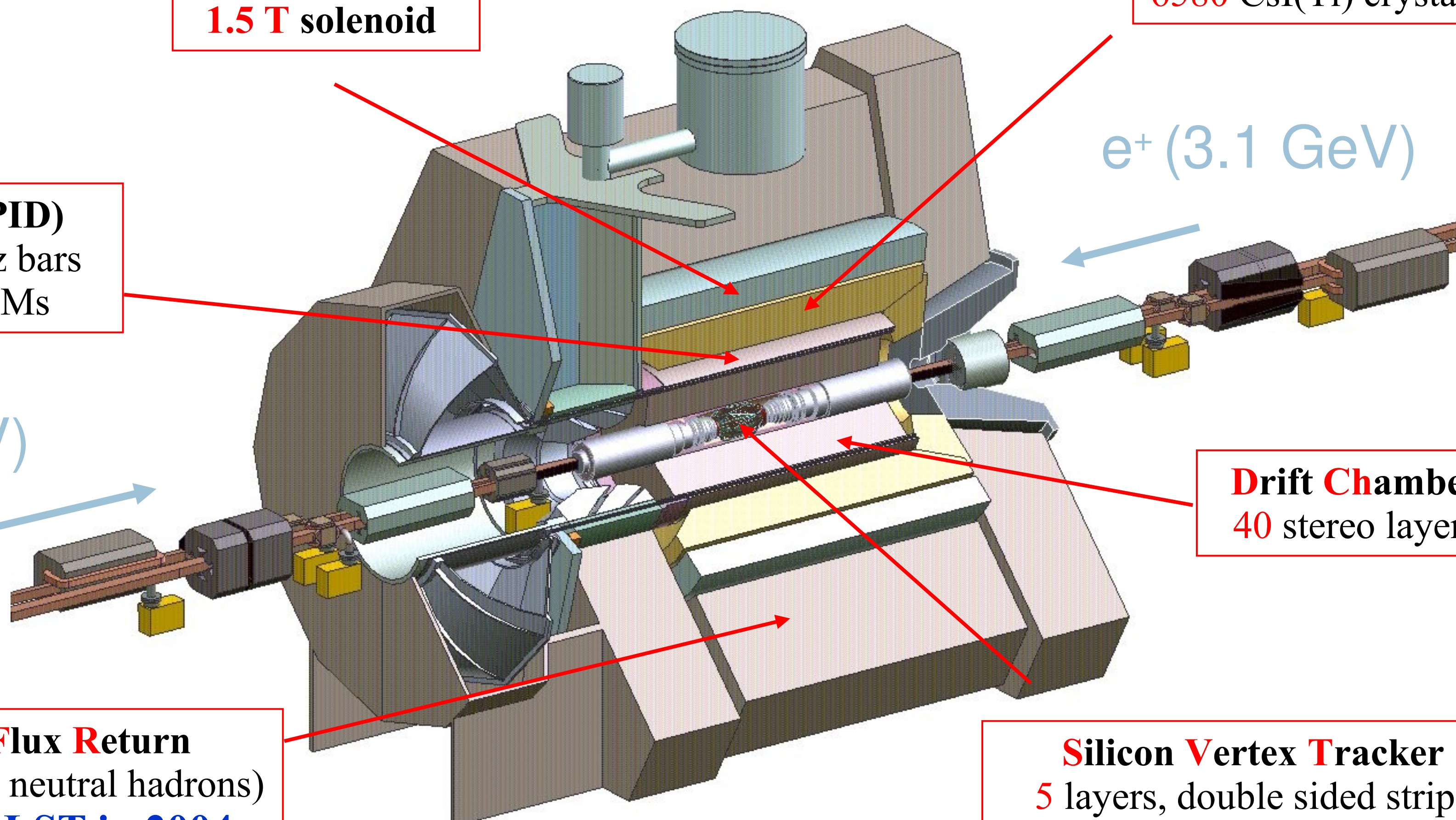
Total over 10^9 $B\overline{B}$ pairs recorded

World record luminosities (2)

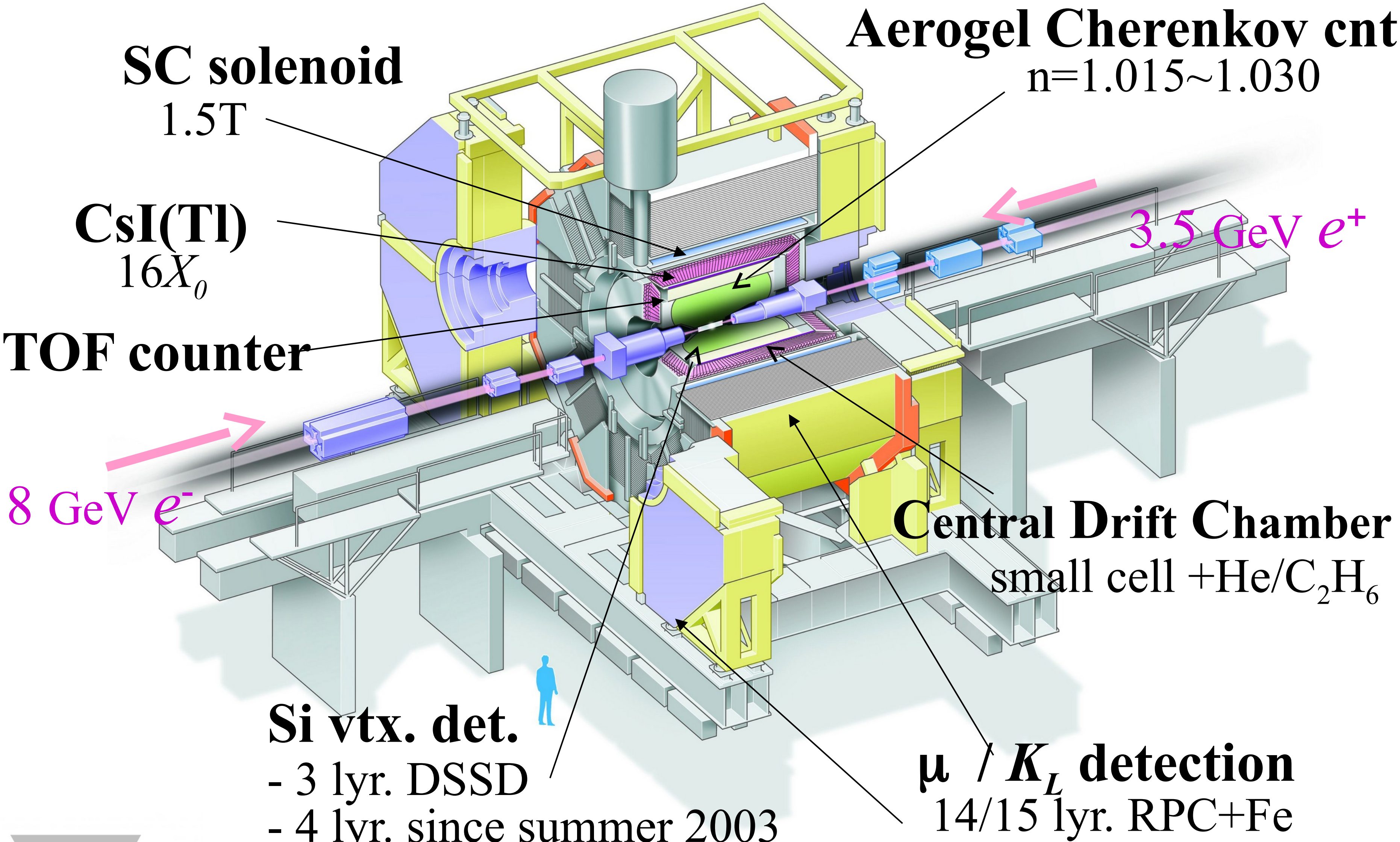
SuperKEKB & HL-LHC



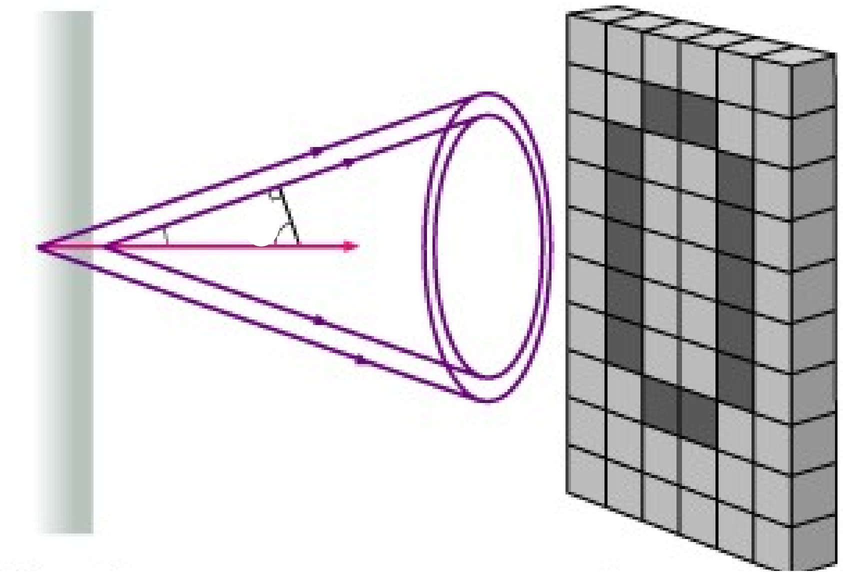
BaBar Detector



Belle Detector

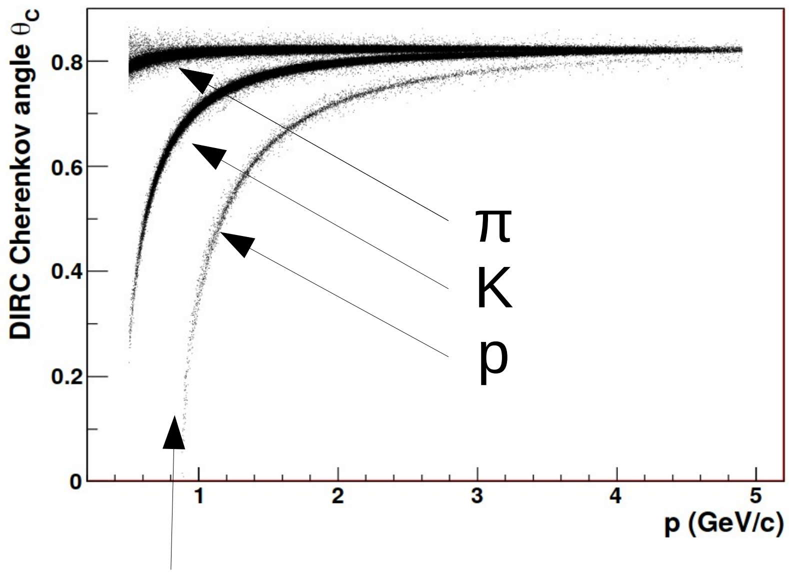


Particle ID with Cherenkov radiation



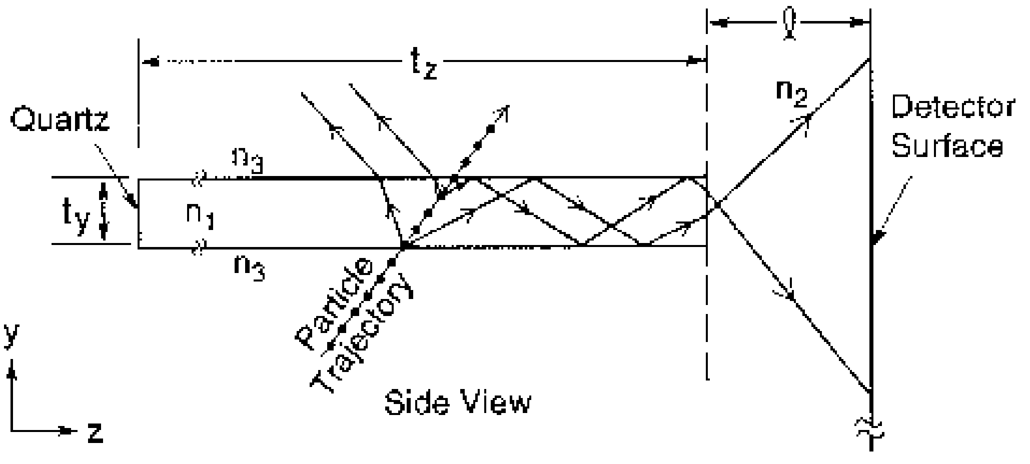
Particle travelling above speed of light in medium (with refractive index n) emits light in cone with opening angle given by
$\cos \theta_c = 1/(\beta n)$

BaBar DIRC: quartz radiator (n = 1.473)



Thresholds also provide separation

Particle ID with Cherenkov radiation



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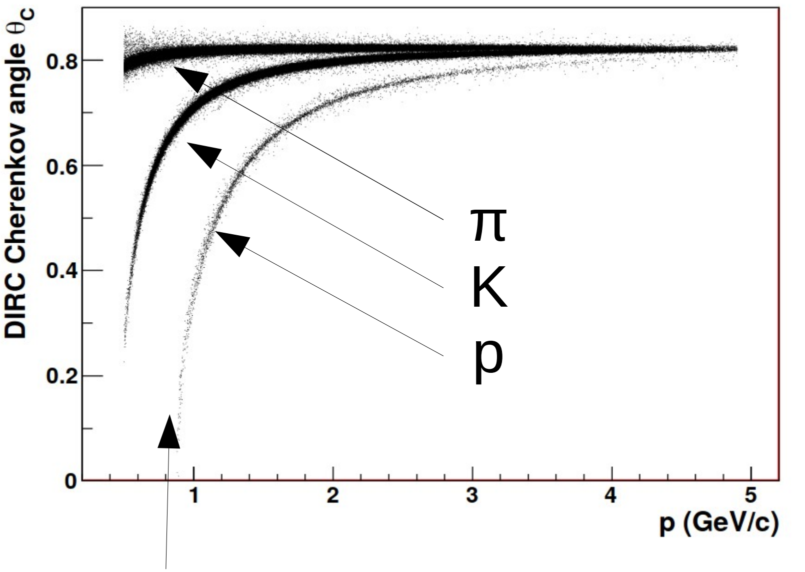


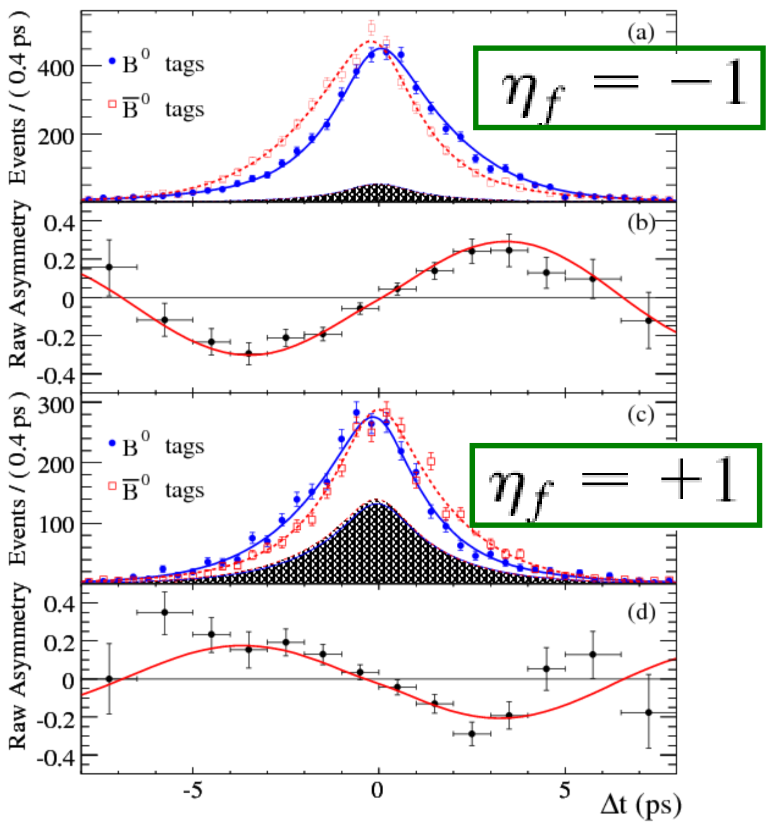
Thresholds also provide separation

Results for the golden mode

$$B^0 \to J/\psi K^0$$

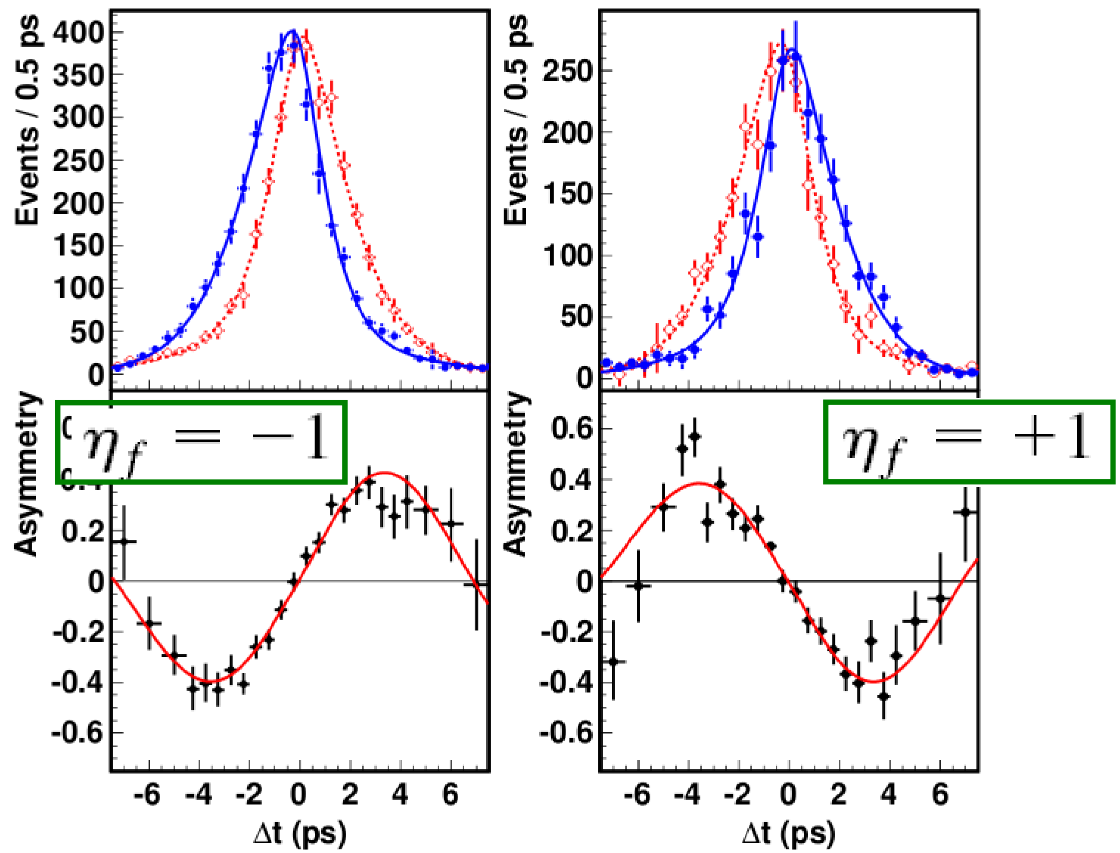
BABAR

PRD 79 (2009) 072009



BELLE

PRL 108 (2012) 171802



$$A_{CP}(t) = S\sin(\Delta m t) - C\cos(\Delta m t)$$

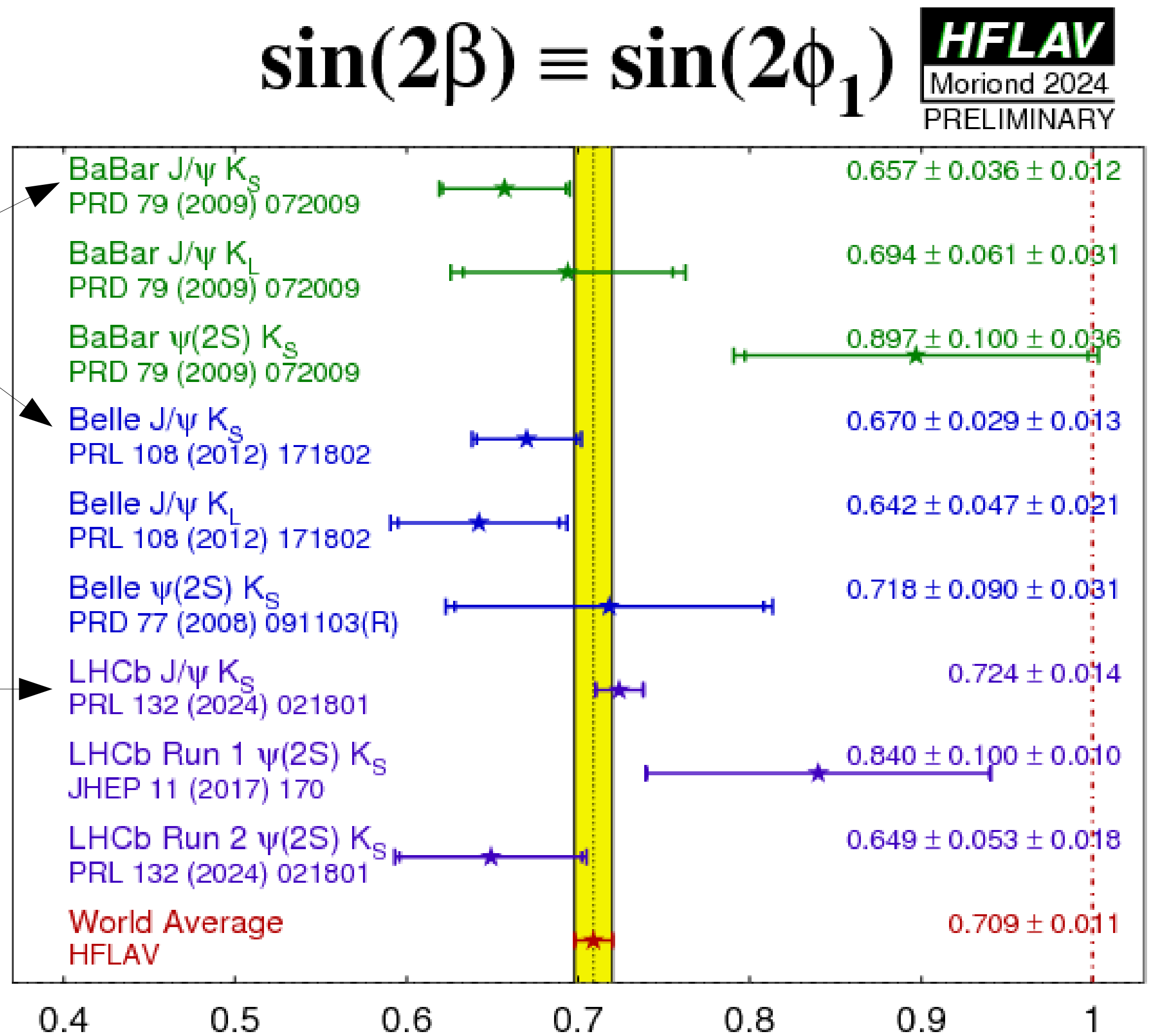
$$S = -\eta_f \sin(2\beta)\ ,\ C = 0$$

Experimentally, oscillations diluted by imperfect flavour tagging and resolution

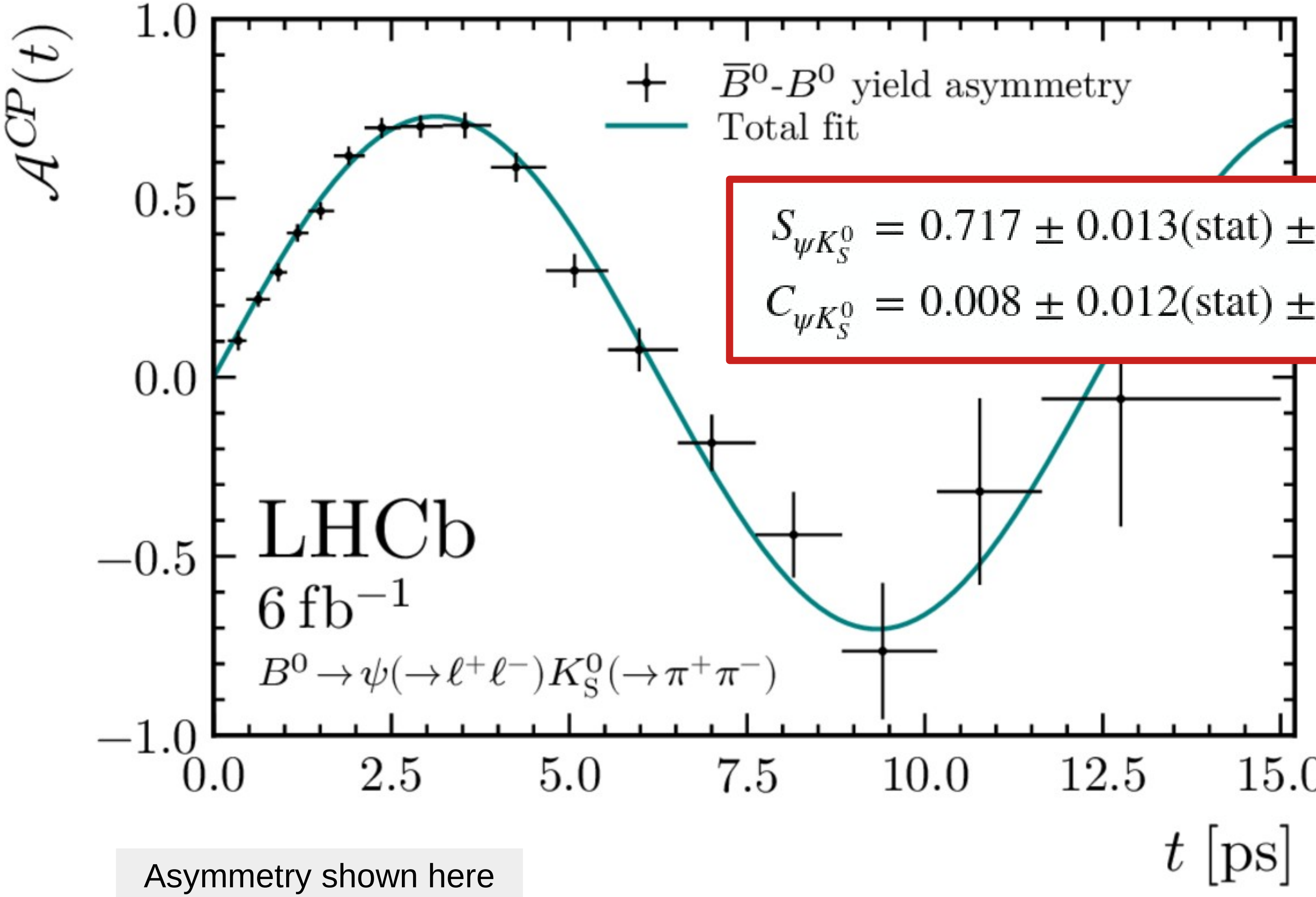
Compilation of results

Results on previous slide

Note LHCb now world-leading



LHCb results on sin(2β)



$$S_{\psi K^0_S} = 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst}),$$
$$C_{\psi K^0_S} = 0.008 \pm 0.012(\text{stat}) \pm 0.003(\text{syst}).$$

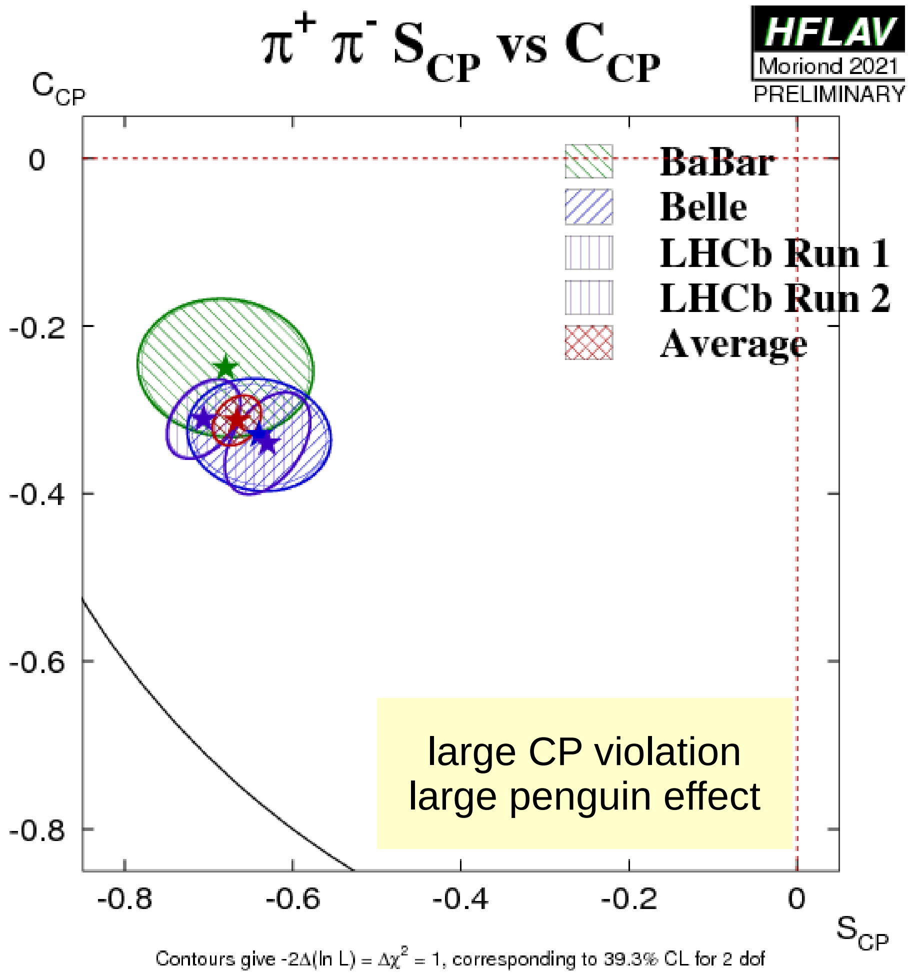
Asymmetry shown here corrected for imperfect flavour-tagging

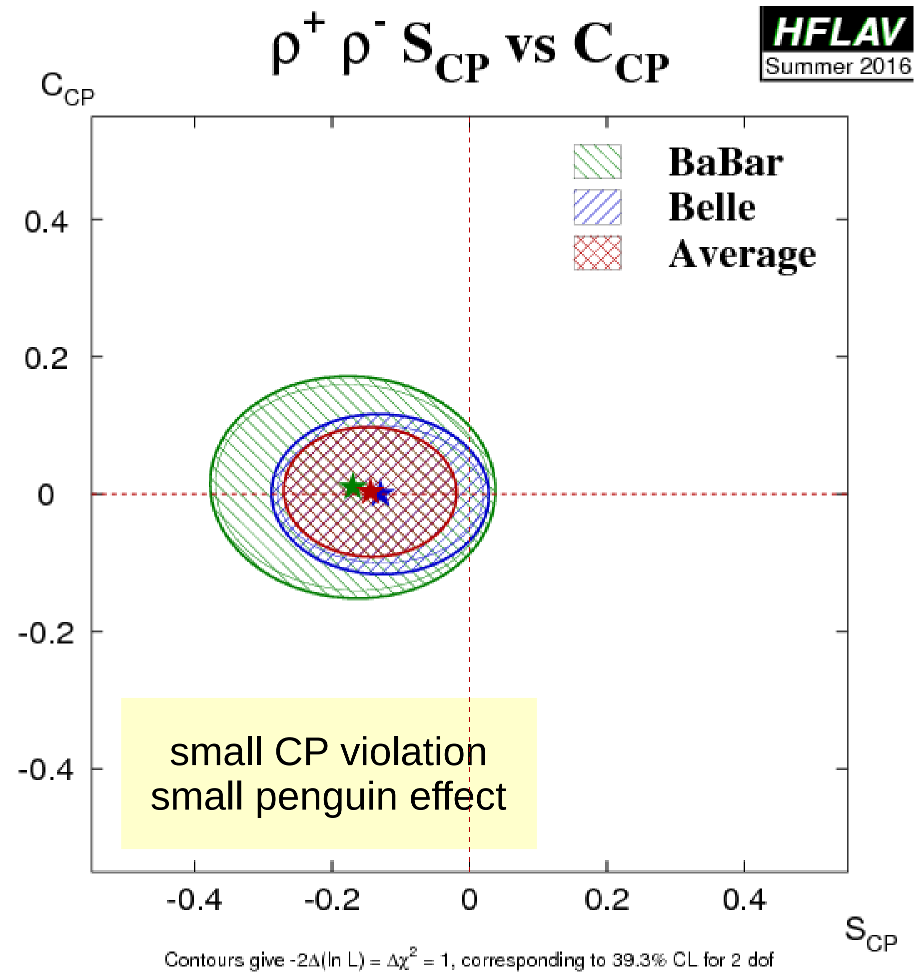
Measurement of α

- Similar analysis using $b \rightarrow u\bar{u}d$ decays (e.g. $B_d^0 \rightarrow \pi^+\pi^-$) probes $\pi-(\beta+\gamma) = \alpha$
  - but $b \rightarrow d u\bar{u}$ penguin transitions contribute to same final states ⇒ "penguin pollution"
  - $C \neq 0 \Leftrightarrow$ CP violation in decay can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$
- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

PRL 65 (1990) 3381

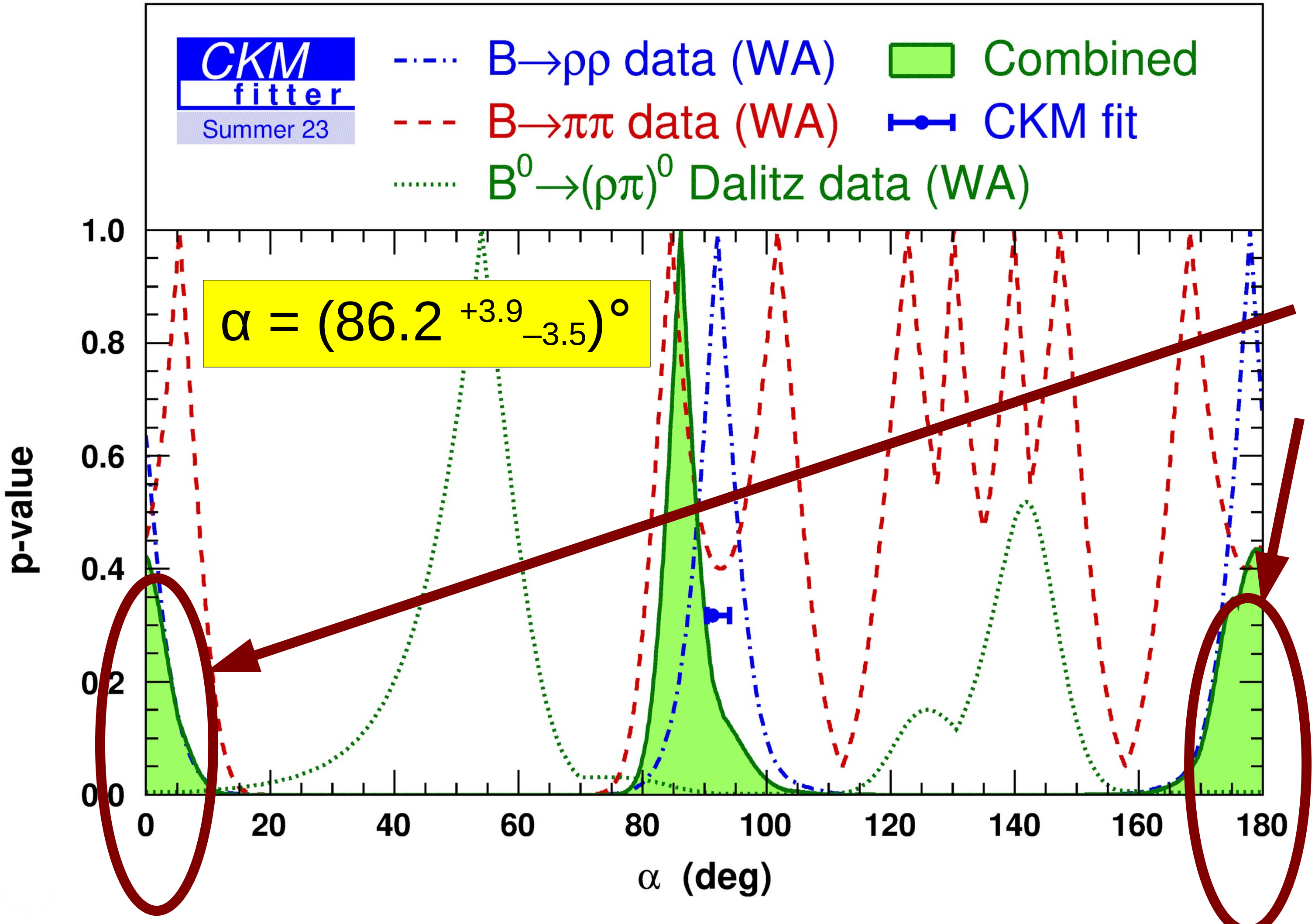
Experimental situation for α





improved measurements needed!

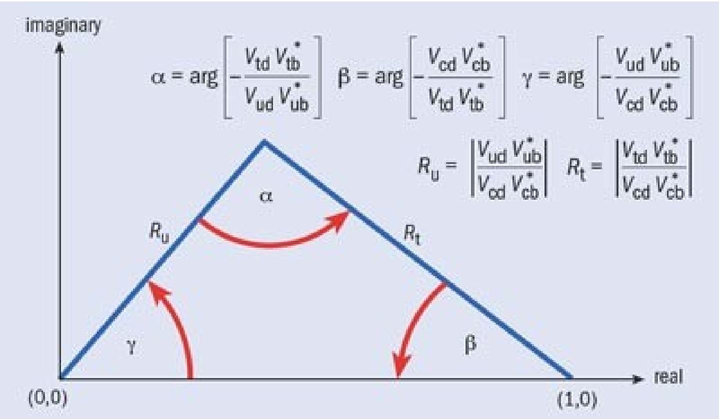
Measurement of α



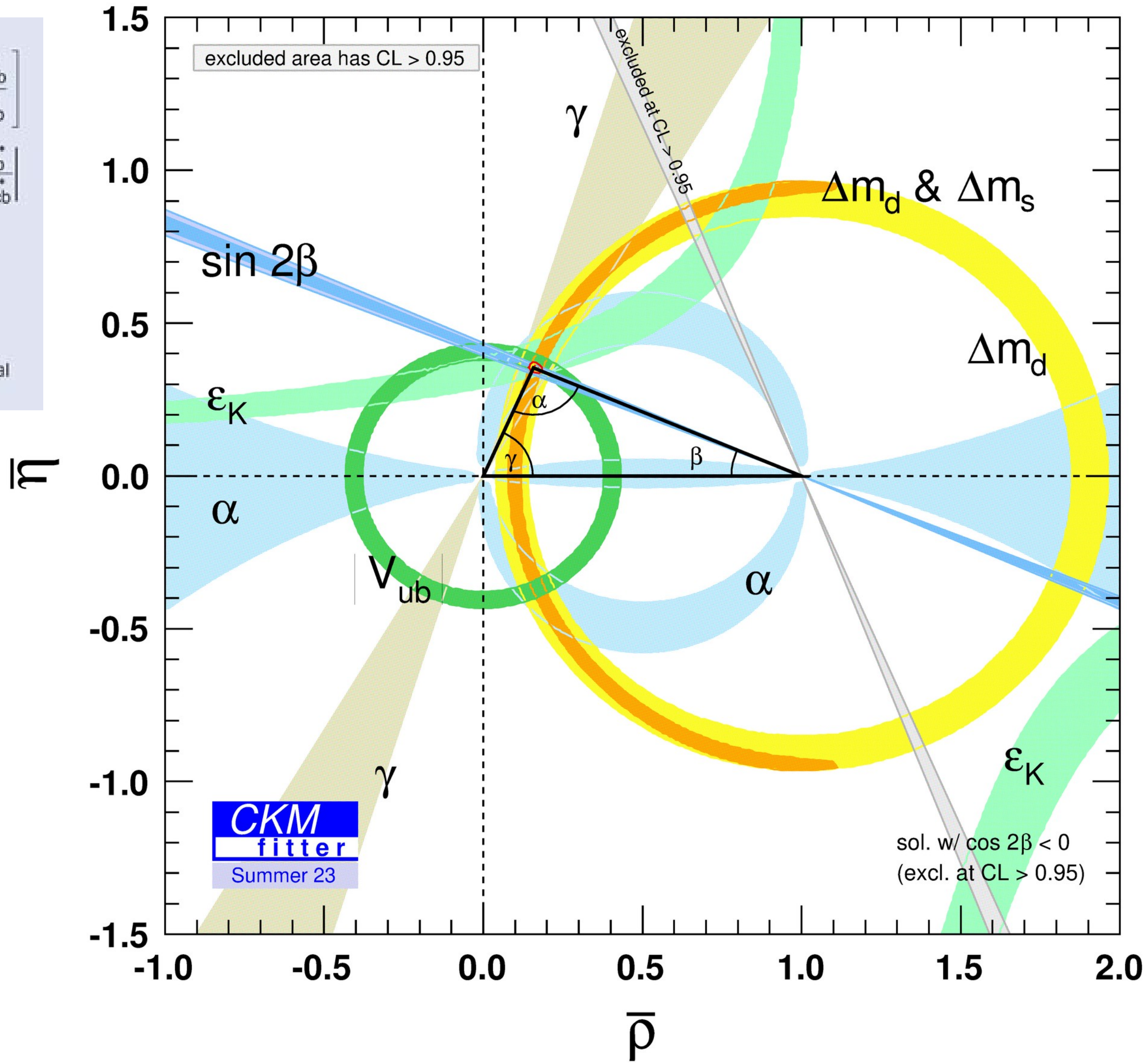
THESE SOLUTIONS RULED OUT BY OBSERVATION OF DIRECT CP VIOLATION IN $B^0 \to \pi^+\pi^-$

Is there any physical significance in the fact that α ≈ 90°?

The UT sides



imaginary
$\alpha = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$ $\beta = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$ $\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$
$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|$ $R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|$
α
R_u
R_t
γ
β
(0,0)
(1,0)
real

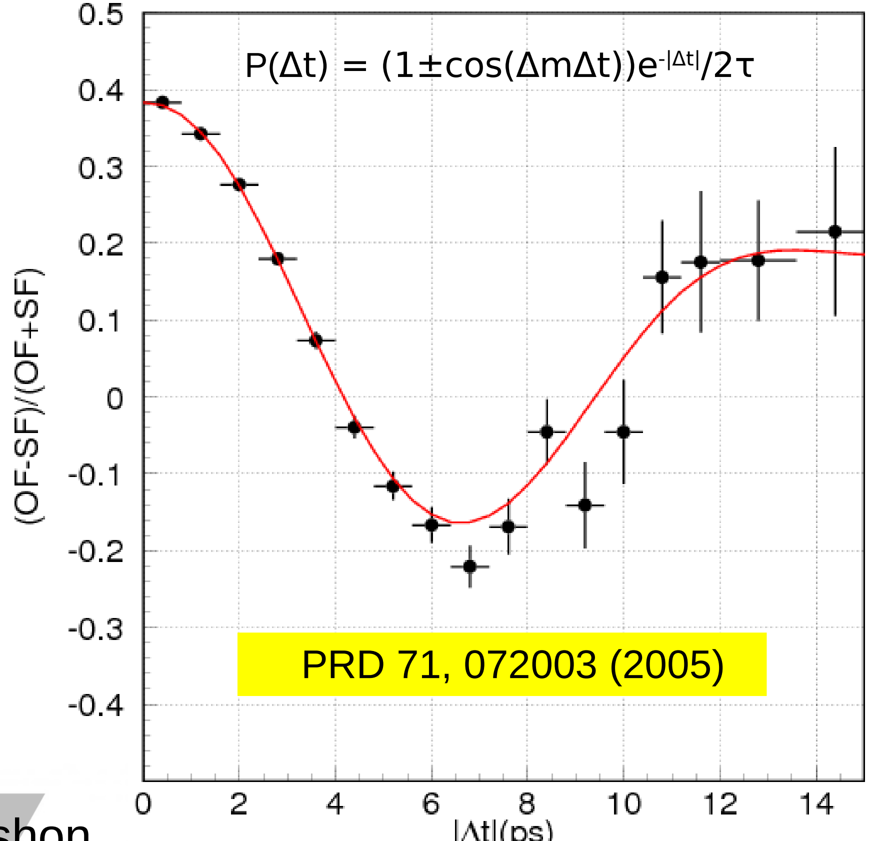


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
V_{ub}
α
γ
ε_K
CKM fitter
Summer 23
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0

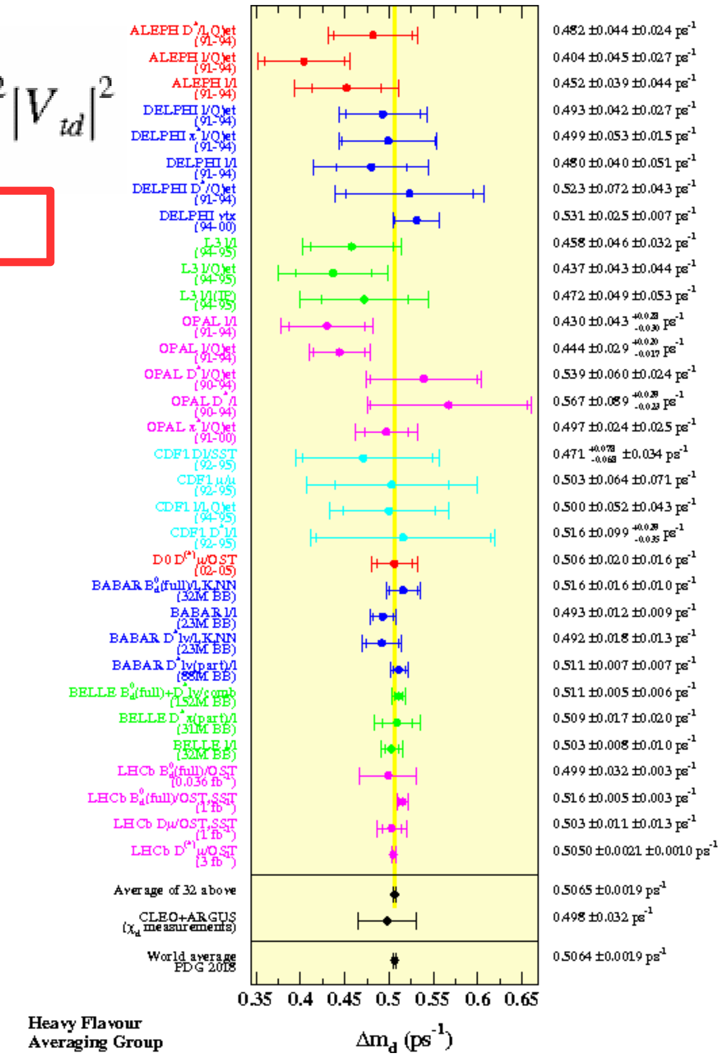
R_t side from B^0–$\overline{B}^0$ mixing

$$R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \quad \& \quad \Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2$$

sources of theory uncertainty



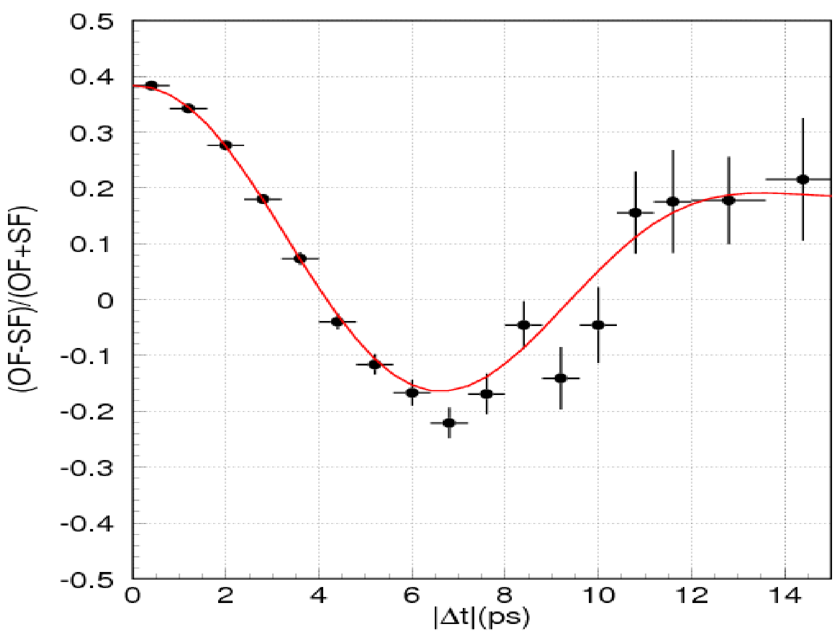
PRD 71, 072003 (2005)



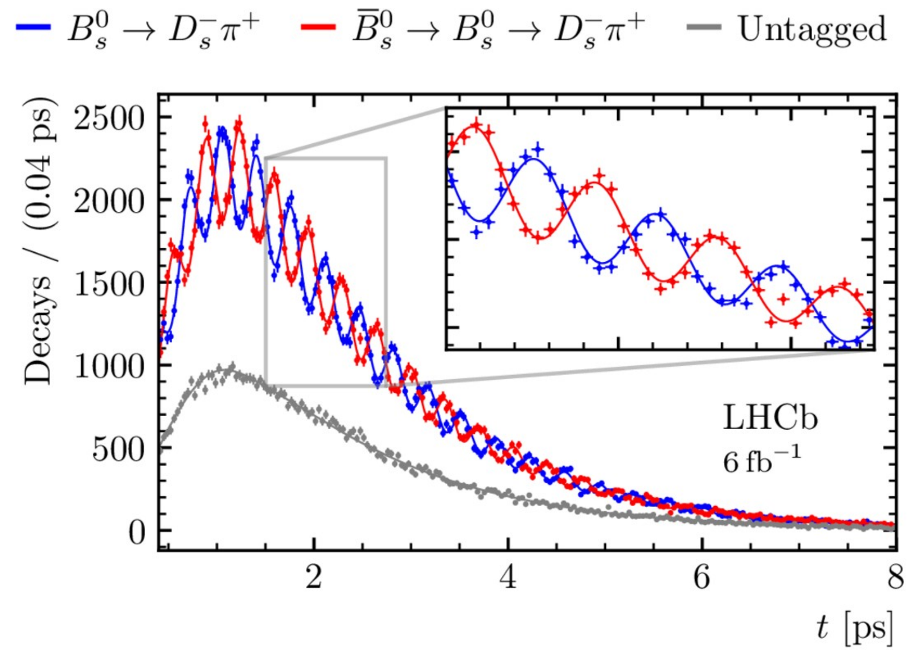
World average based on many measurements

R_t side from $B_{(s)}^0 – \overline{B}_{(s)}^0$ mixing

$$R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$



$\Delta m_d = (0.5064 \pm 0.0019)\ \mathrm{ps}^{-1}$



$\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032)\ \mathrm{ps}^{-1}$

Nature Physics 18 (2022) 1

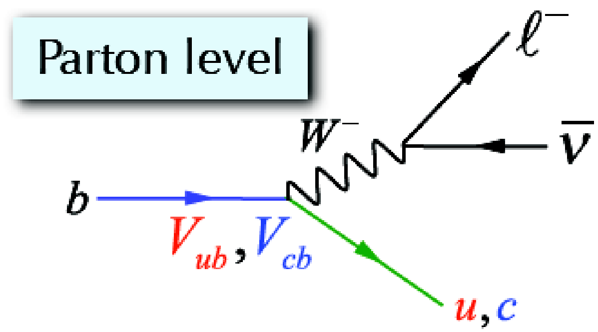
$$|V_{td}/V_{ts}| = 0.207 \pm 0.001 \pm 0.003$$

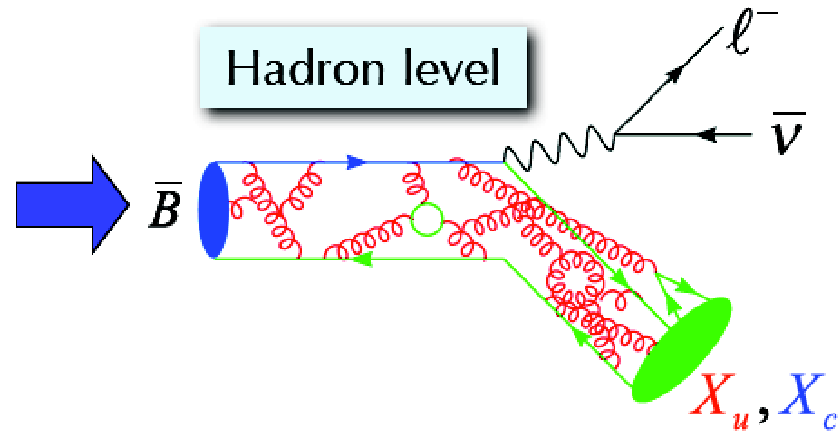
experimental uncertainty

theoretical uncertainty

R_u side from semileptonic decays

$$R_u = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right|$$





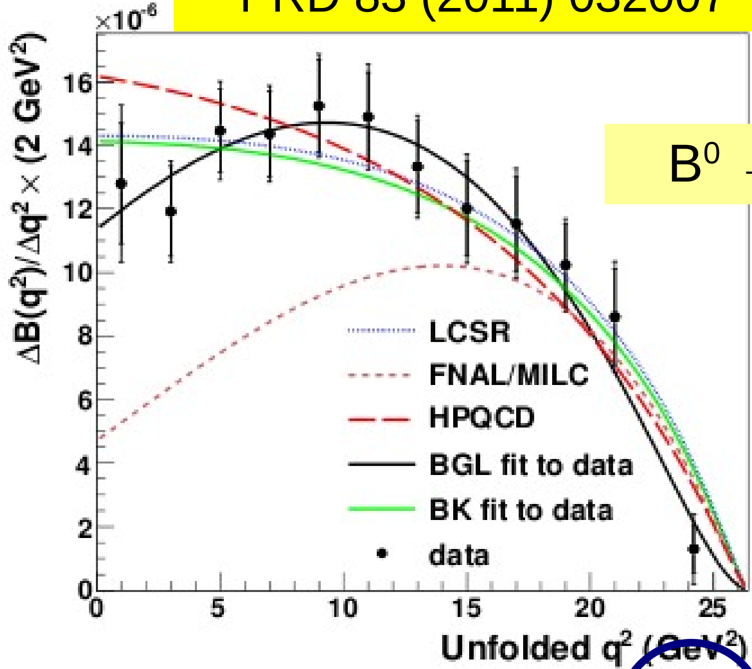
- Approaches:
  - exclusive semileptonic B decays, eg. $B^0 \rightarrow \pi^- e^+ \nu$
    - require knowledge of form factors
      - can be calculated in lattice QCD at kinematical limit
  - inclusive semileptonic B decays, eg. $B \rightarrow X_u e^+ \nu$
    - clean theory, based on Operator Product Expansion
    - experimentally challenging:
      - need to reject $b \rightarrow c$ background
      - cuts re-introduce theoretical uncertainties

$|V_{ub}|$ from exclusive semileptonic decays

Current best measurements use $B^0 \rightarrow \pi^- l^+ \nu$

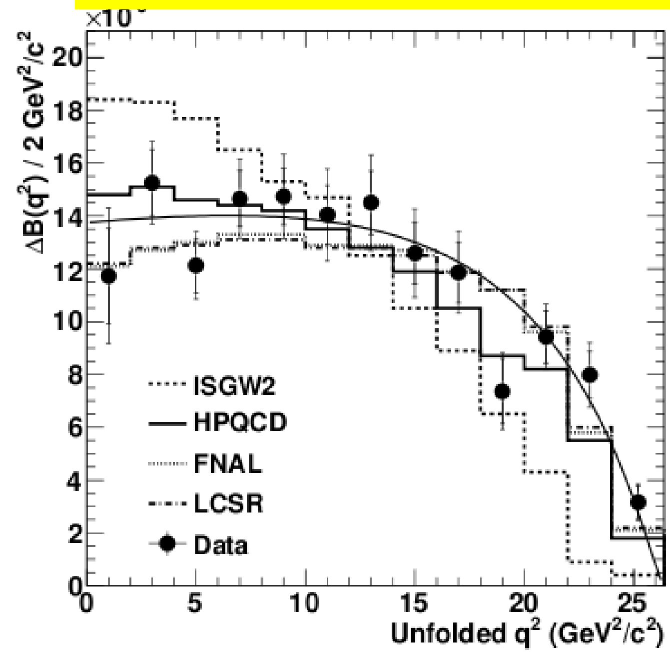
(recent competitive measurement from LHCb with $\Lambda_b \rightarrow p\mu\nu$)

BaBar experiment
PRD 83 (2011) 052011
PRD 83 (2011) 032007



$B^0 \rightarrow \pi^- l \nu$

Belle experiment
PRD 83 (2011) 071101(R)

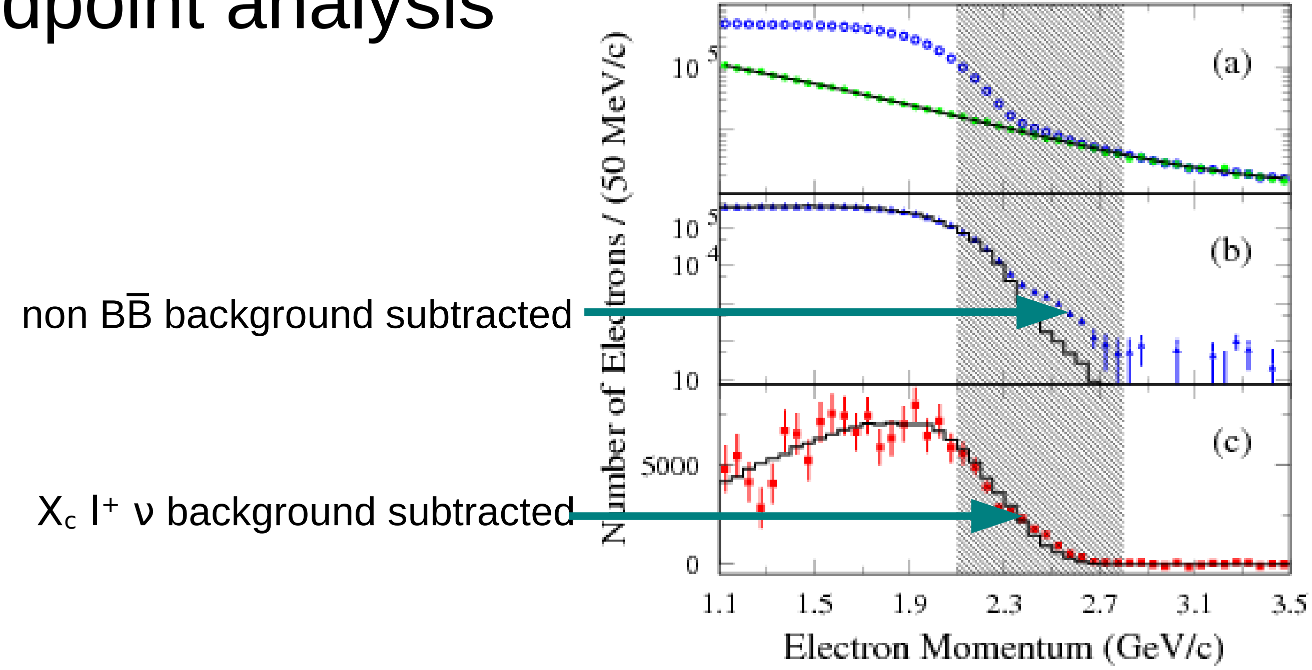


$$(3.09 \pm 0.08 \pm 0.12 {}^{+0.35}_{-0.29}) \times 10^{-3} \qquad |V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$

lattice uncertainty

$|V_{ub}|$ from inclusive semileptonic decays

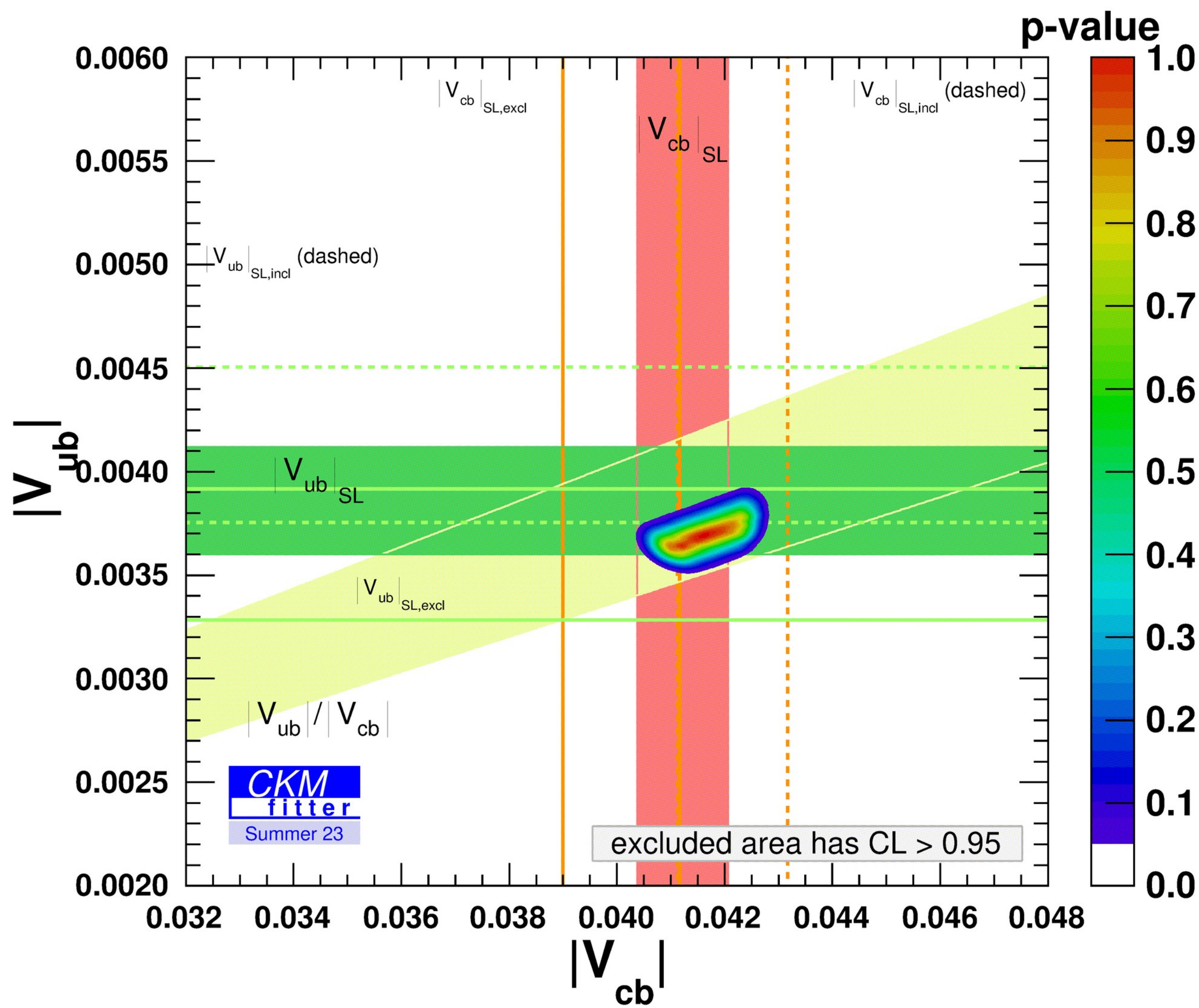
- Main difficulty to measure inclusive $B \to X_u l^+ \nu$
  - background from $B \to X_c l^+ \nu$
- Approaches
  - cut on E_l (lepton endpoint), q^2 ($l\nu$ invariant mass squared), $M(X_u)$, or some combination thereof
- Example: endpoint analysis



$|V_{ub}|$ average

- Averages on $|V_{ub}|$ from both exclusive and inclusive approaches
  - exclusive: $|V_{ub}| = (3.67 \pm 0.09 \pm 0.12) \times 10^{-3}$
  - inclusive: $|V_{ub}| = (4.13 \pm 0.12\ ^{+0.13}_{-0.14} \pm 0.18) \times 10^{-3}$
  - slight tension between these results
  - in both cases theoretical errors are dominant
    - but some "theory" errors can be improved with more data
  - PDG2014 does naïve average rescaling due to inconsistency to obtain $|V_{ub}| = (3.82 \pm 0.20) \times 10^{-3}$

Inclusive vs. exclusive : $|V_{ub}|$ and $|V_{cb}|$



Discrepancies need to be understood!

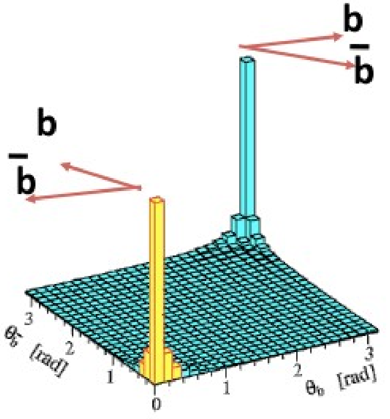
Flavour physics at hadron colliders

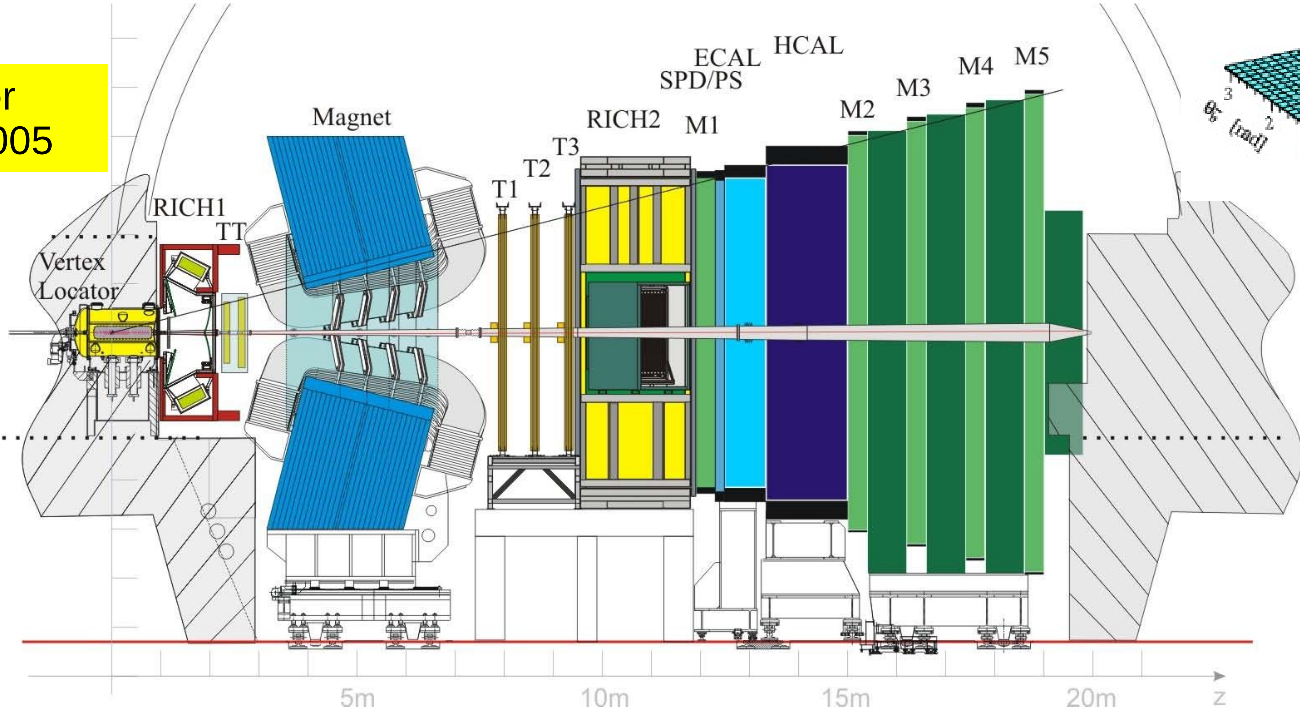
	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\text{TeV}$) LHC
Production cross-section	1 nb	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\text{kHz}$	$\sim 500\,\text{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B^0_s (10%), Λ^0_b (10%), others ($< 1\%$)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\epsilon D^2 \sim 30\%$	$\epsilon D^2 \sim 5\%$	

Huge production rate: can we exploit it?

Geometry

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer



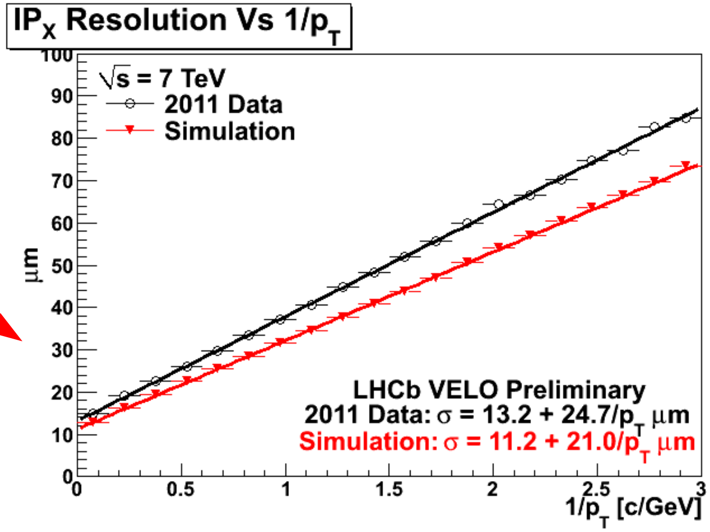


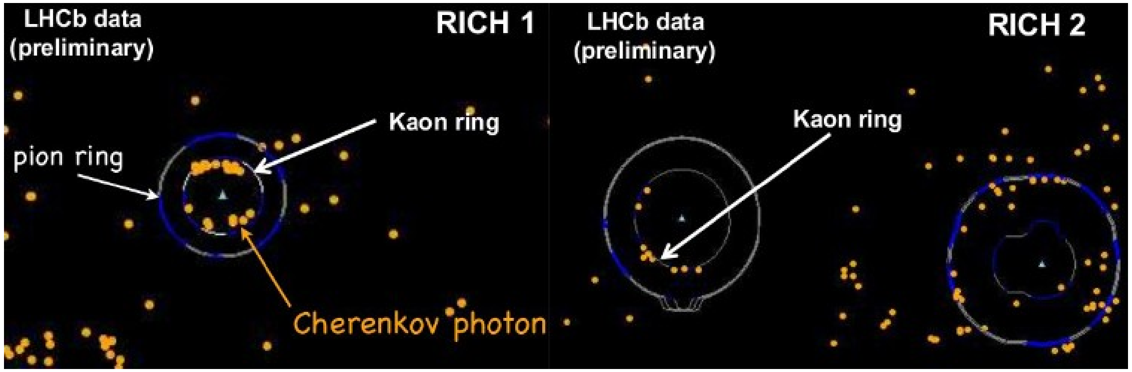
The LHCb Detector
JINST 3 (2008) S08005

Here discussing the detector used in Runs 1+2. Upgrades will be discussed tomorrow

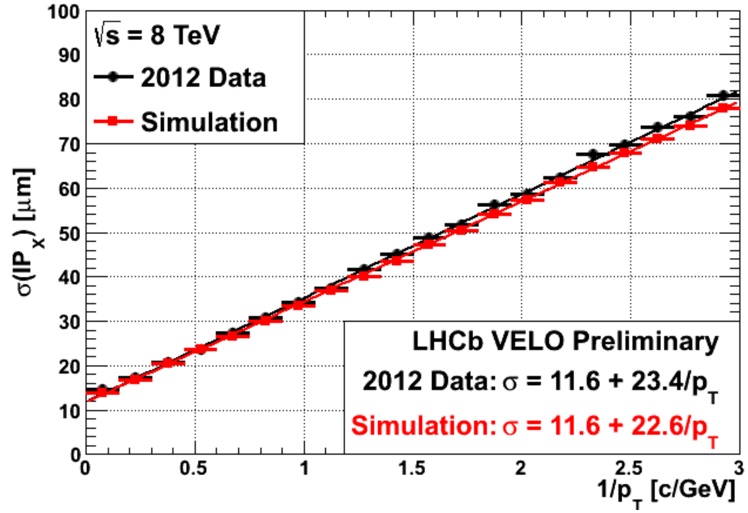
LHCb detector features

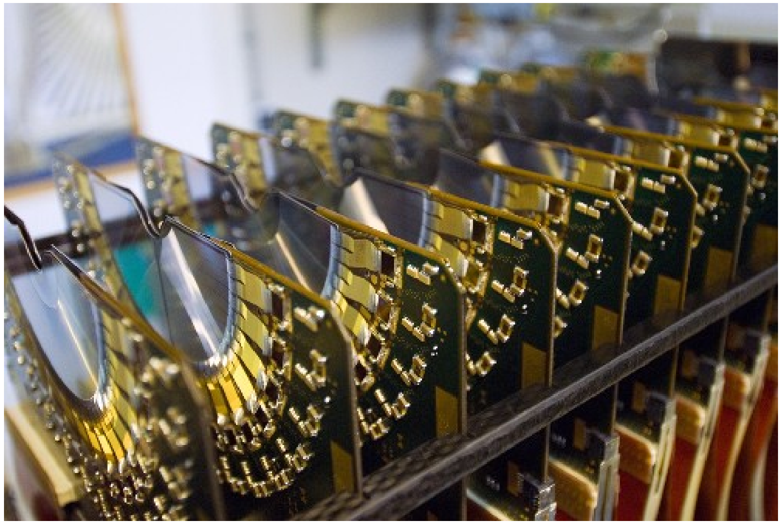
- Tracking and calorimetry
  - basic essentials of any collider experiment!
  - muon chambers
- VELO
  - reconstruct displaced vertices
- RICH
  - particle ID (K/π separation)
- Trigger
  - fast and efficient

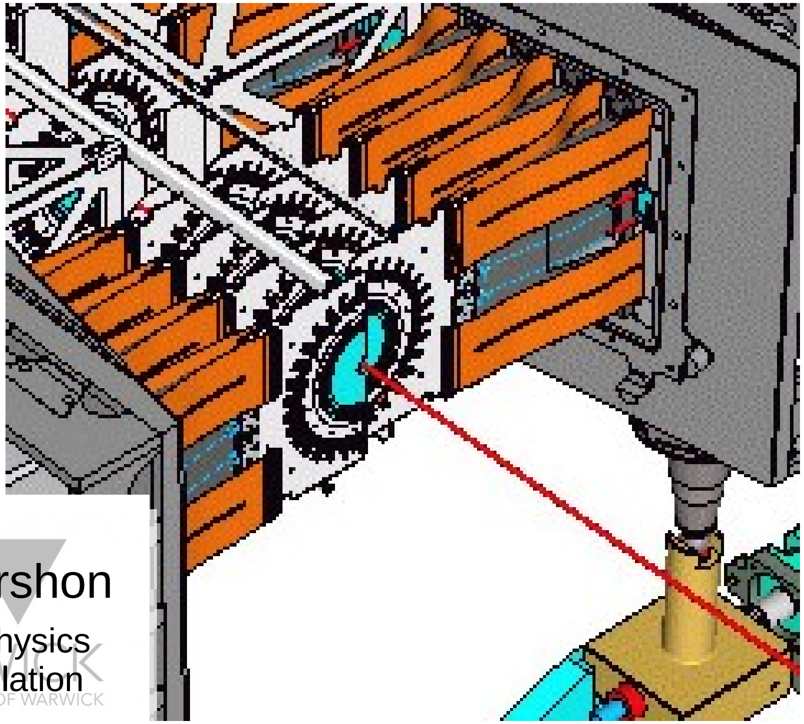




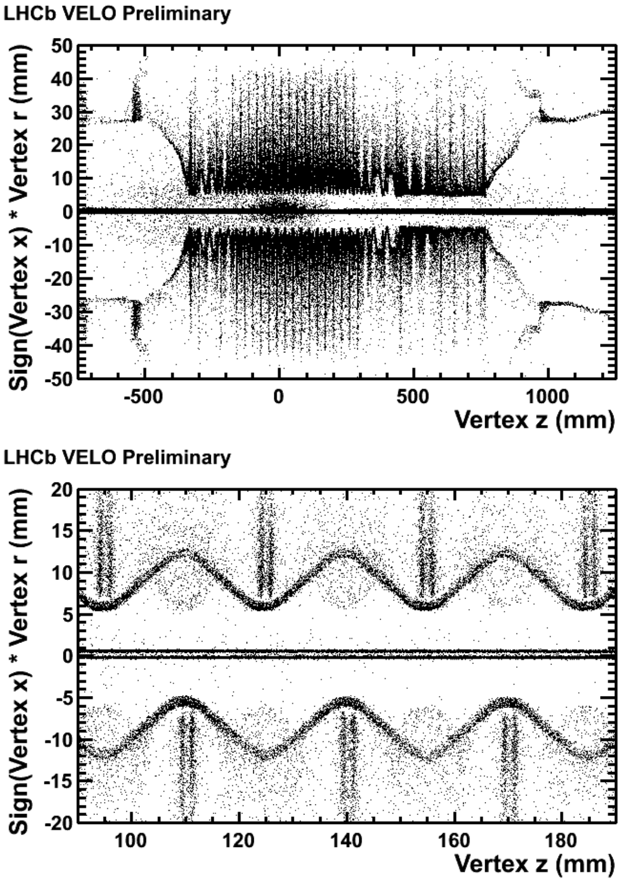
VELO







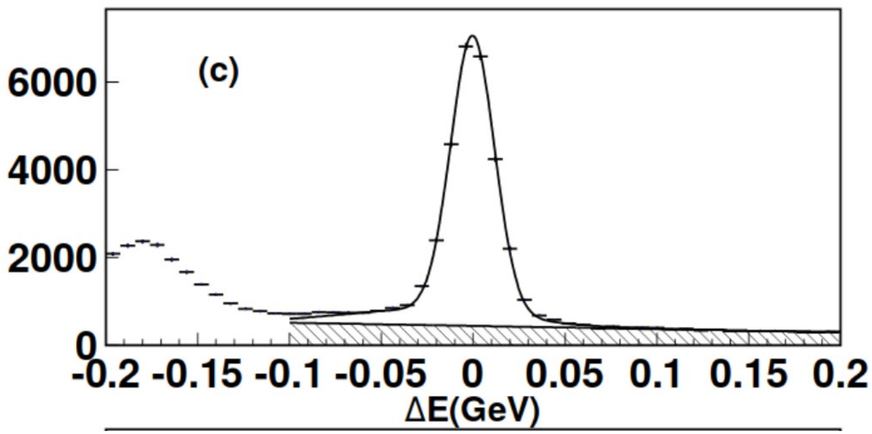
Material imaged used beam gas collisions

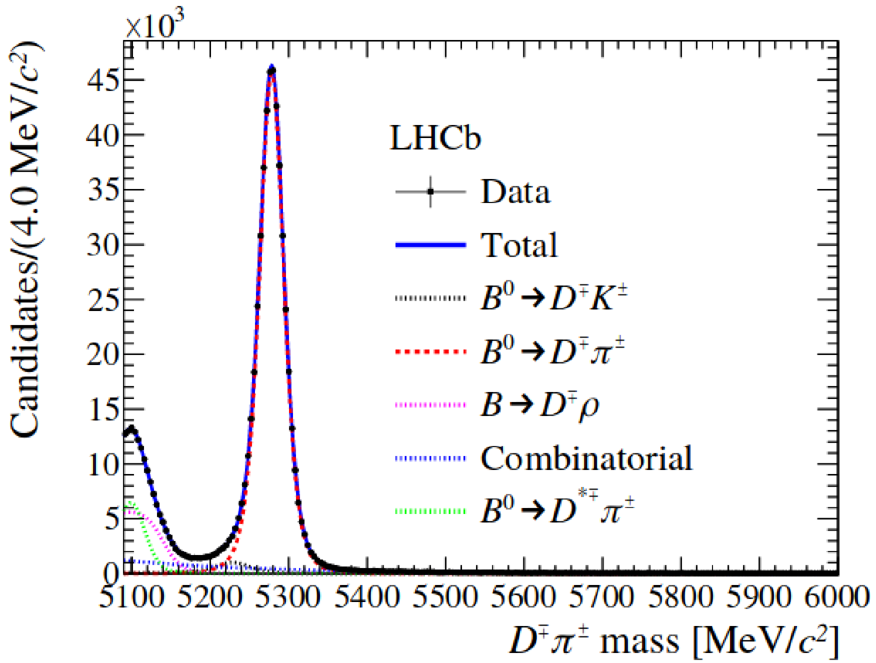


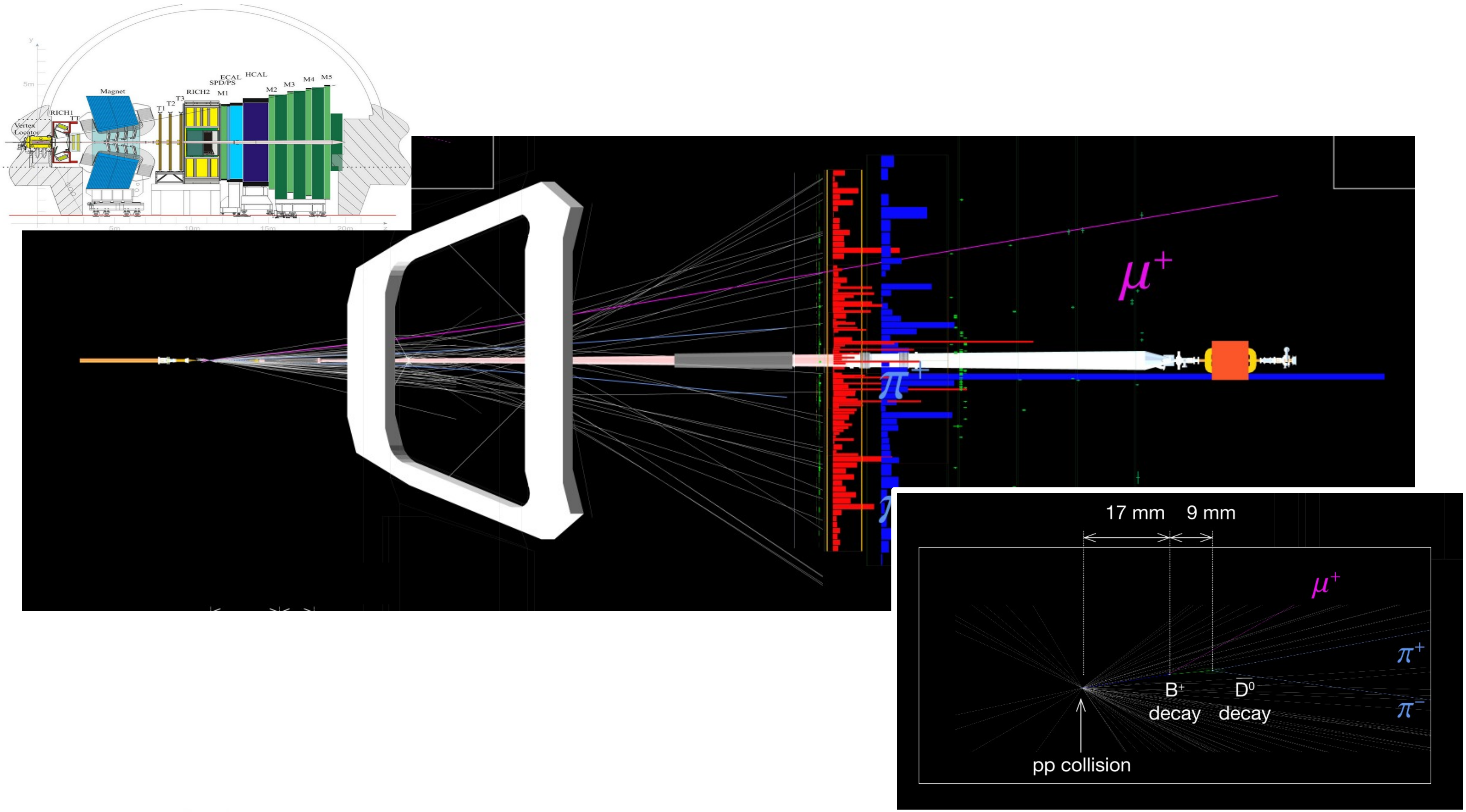
Tim Gershon
Flavour physics & CP violation

Vertexing kills background

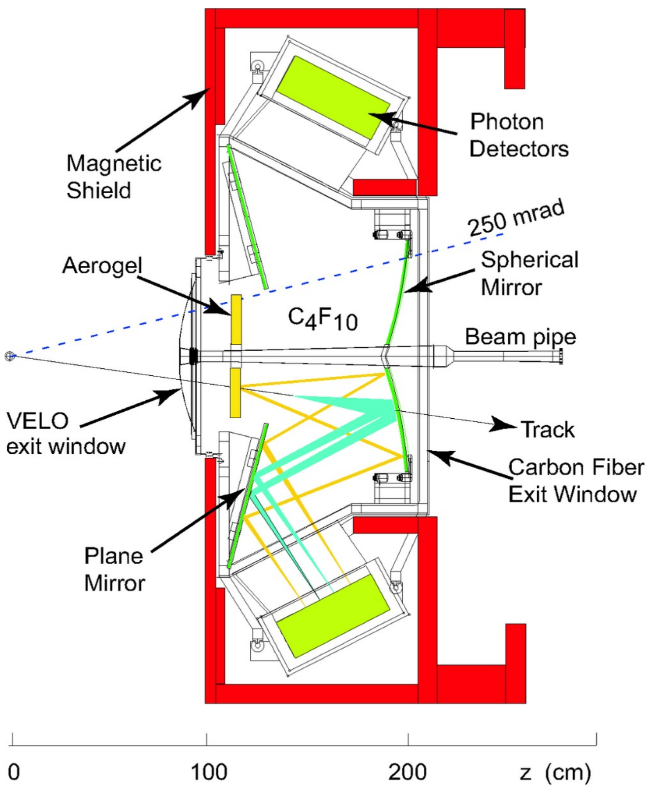
Comparison of (left) Belle and (right) LHCb signals for $B^0 \to D^-\pi^+$
Which is the “low background” environment?

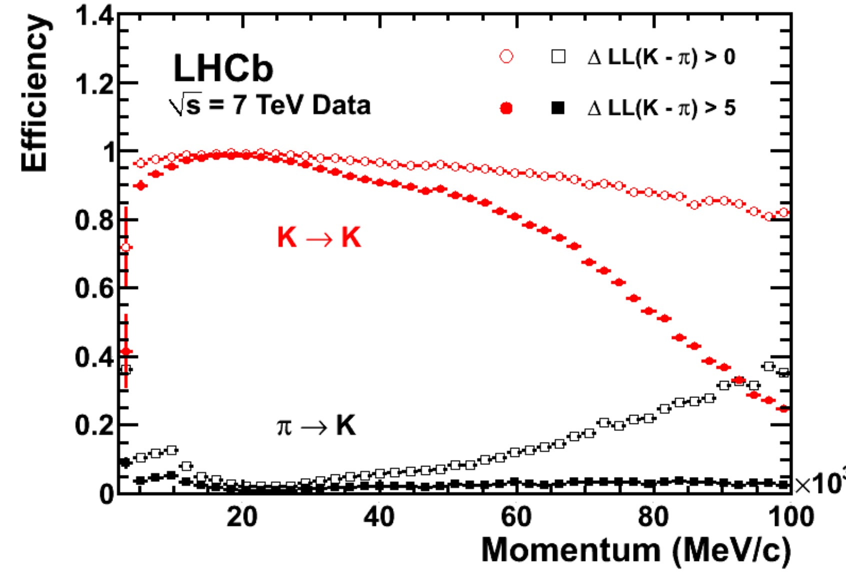


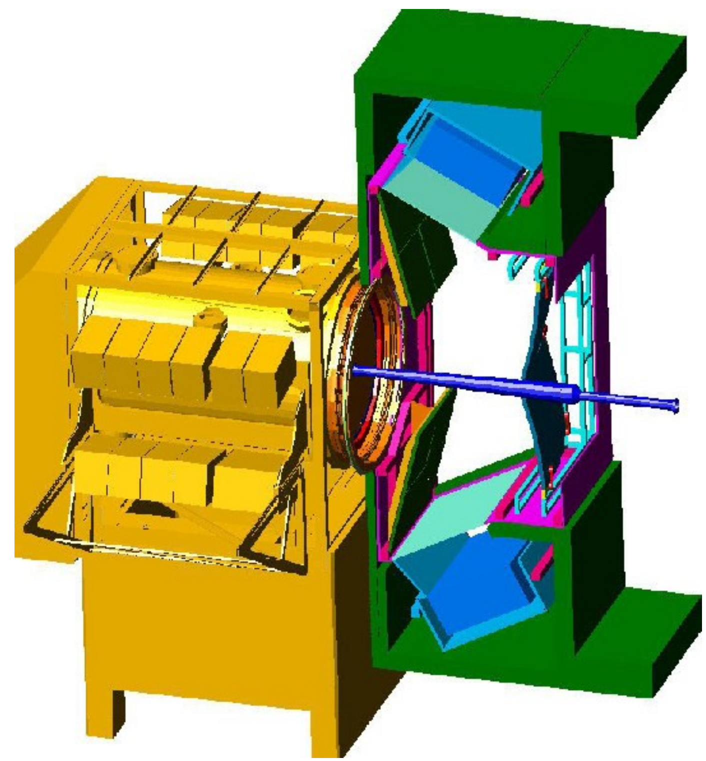



Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
μ^+
π^+
17 mm
9 mm
μ^+
π^+
B^+ decay
$\overline{D}^0$ decay
π^-
pp collision

RICH

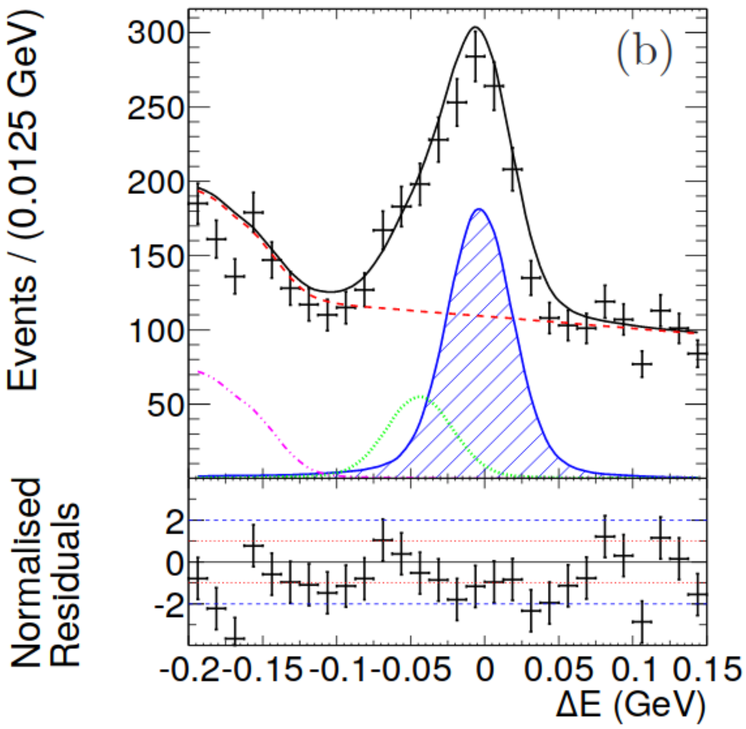

Magnetic Shield
Photon Detectors
250 mrad
Aerogel
Spherical Mirror
C_4F_{10}
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror
0
100
200
z (cm)

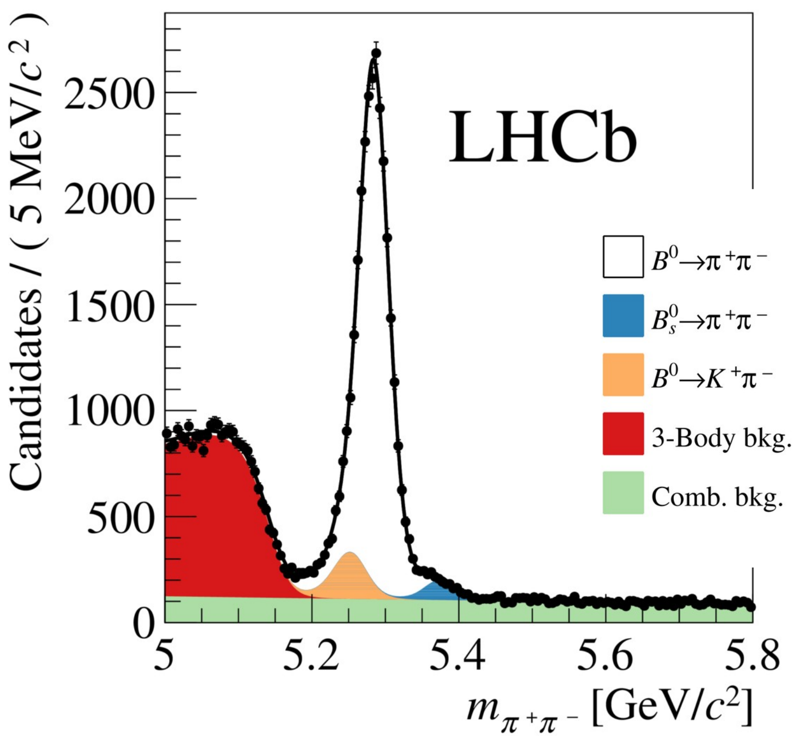

Efficiency
LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
Momentum (MeV/c)
$\times 10^3$



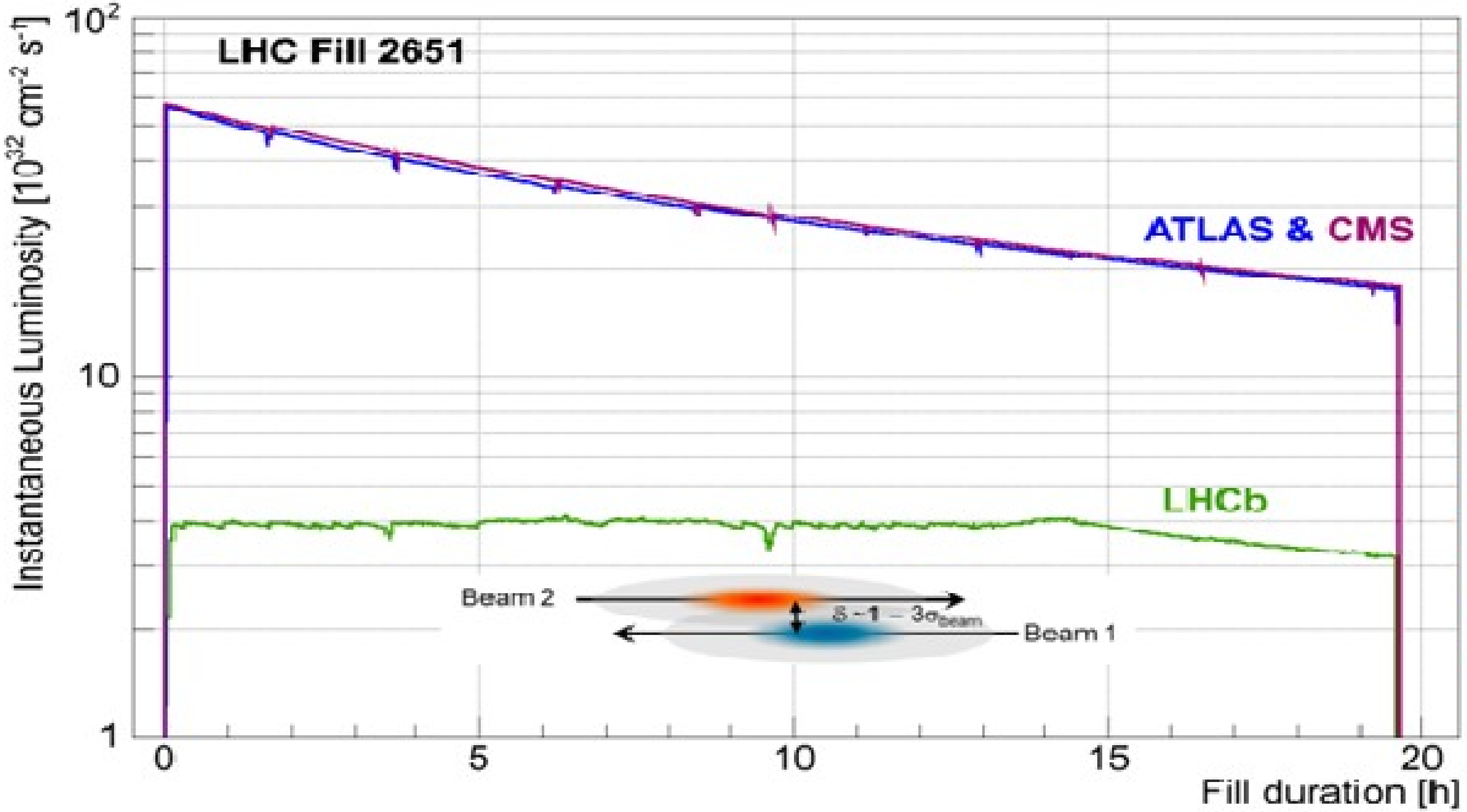
Particle ID kills other backgrounds

Comparison of (left) Belle and (right) LHCb signals for $B^0 \to \pi^- \pi^+$





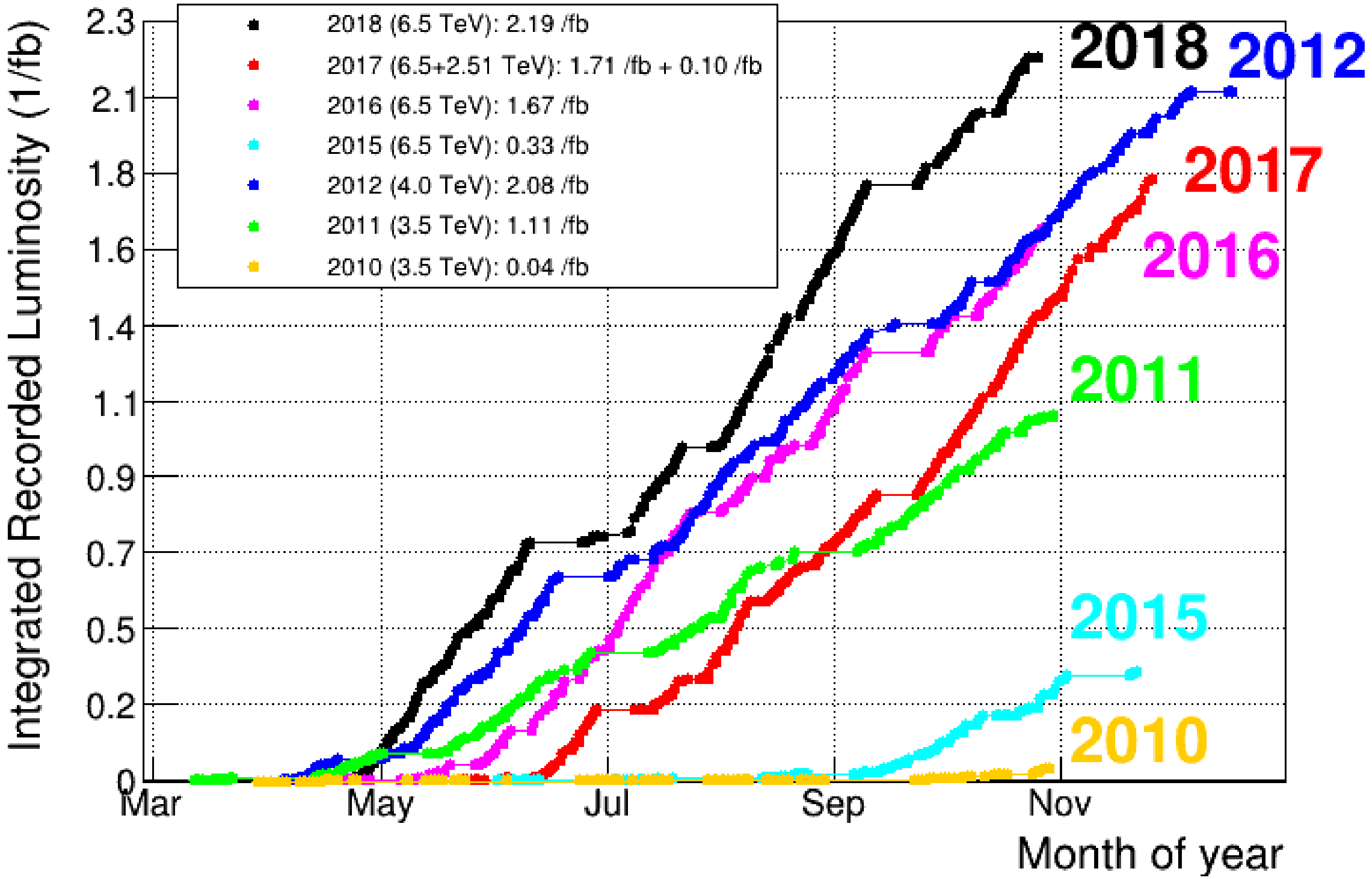
Luminosity levelling in LHCb



luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation (with tilted crossing angle)

from C. Gaspar, via. F. Zimmerman

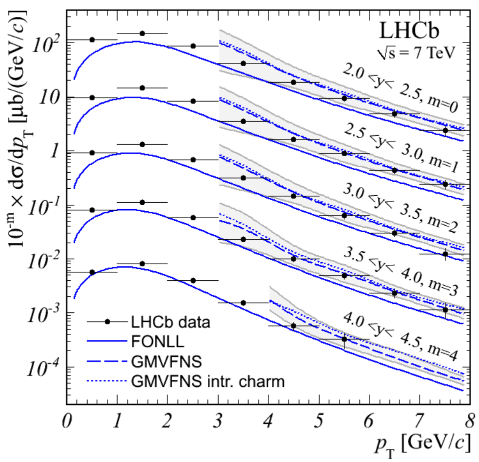
Run 1+2 data taking



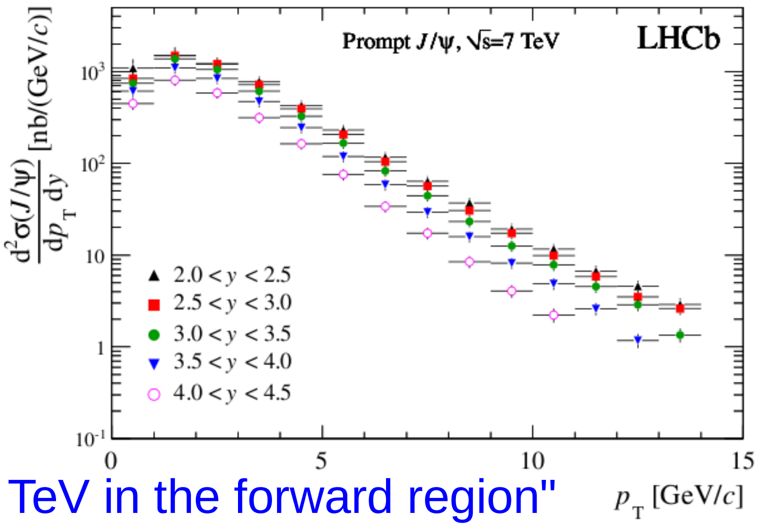
1 fb^{-1} @ $\sqrt{s}$ = 7 TeV, 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV, 6 fb^{-1} @ $\sqrt{s}$ = 13 TeV
(considering pp collisions only)

Heavy flavour production @ LHCb

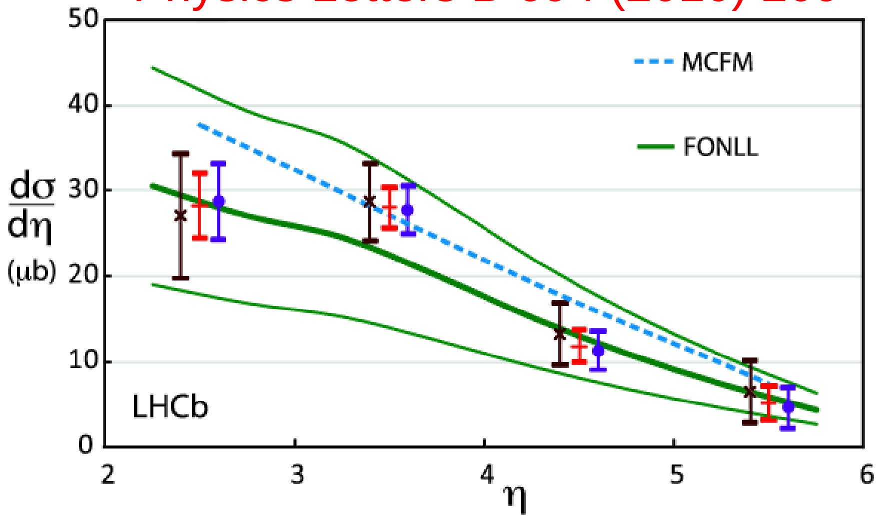
"Prompt charm production in pp collisions at √s = 7 TeV"
Nucl. Phys. B 871 (2013) 1



"Measurement of J/ψ production in pp collisions at √s = 7 TeV"
Eur. Phys. J. C 71 (2011) 1645



"Measurement of σ(pp→$b\bar{b}$X) at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



Tim Gershon
Flavour physics & CP violation

What does $\int L\,dt = 1\ \text{fb}^{-1}$ mean?

- Measured cross-section, in LHCb acceptance (for $\sqrt{s}$ = 7 TeV)

$$\sigma(pp \to b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced in 1 fb^{-1}

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- “B factories” BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample(*)

- p.s.: for charm, $\sigma(pp \to c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

(*) ATLAS+CMS have larger numbers produced, but tend to have lower efficiencies

The all important trigger

JINST 8 (2013) P04022

Challenge is

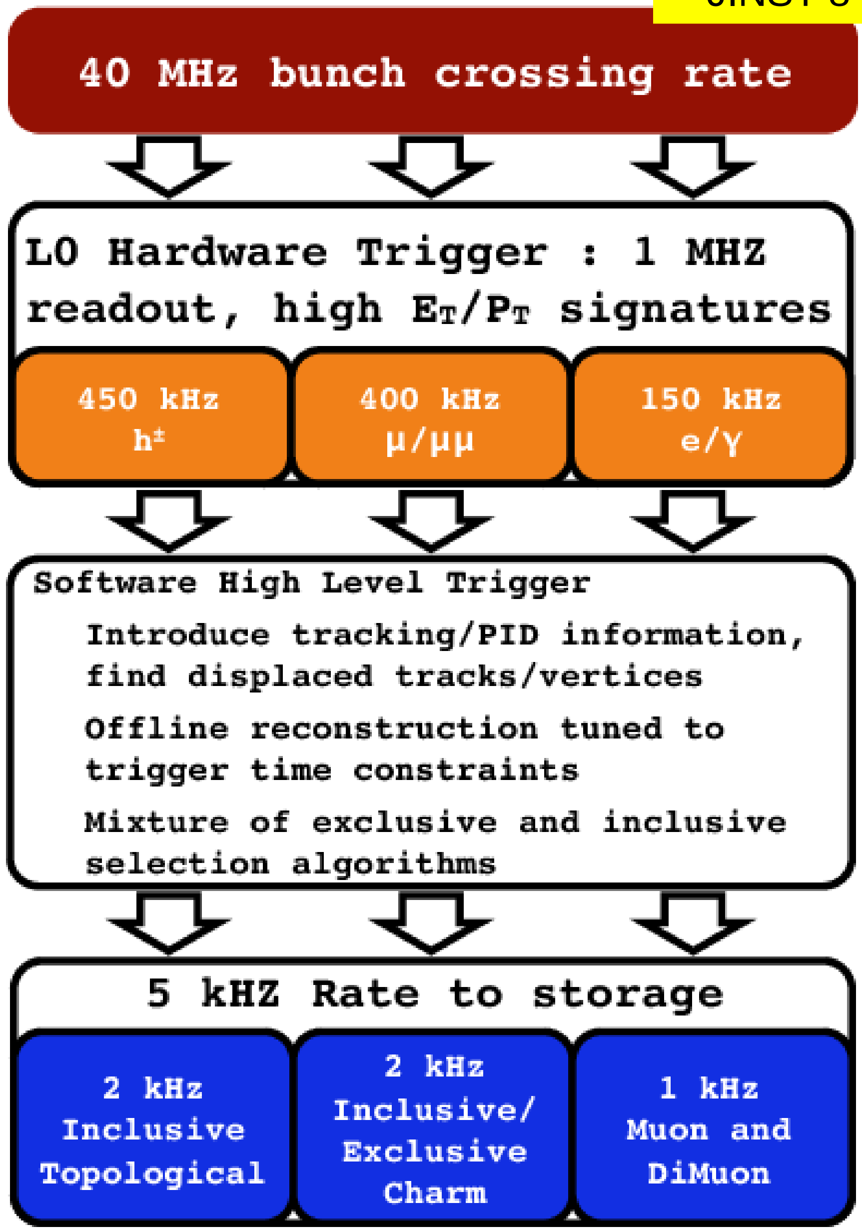
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- "minimum bias" inelastic pp scattering
- other charm and beauty decays

Handles

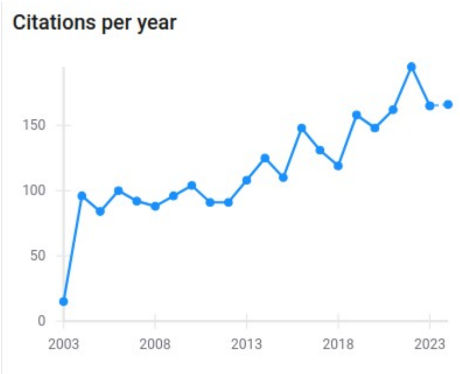
- high p_T signals (muons)
- displaced vertices

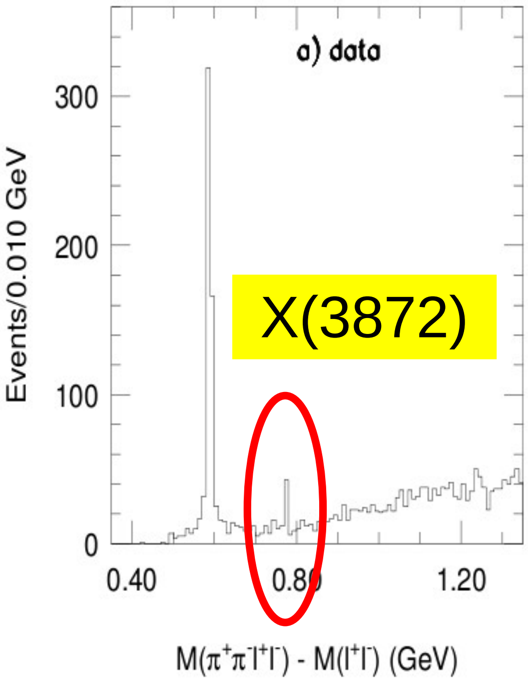


Spectroscopy

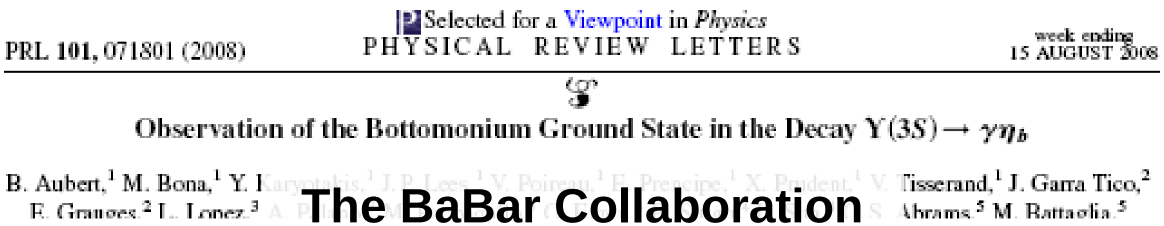
- I've talked about the headline items of flavour physics
  - CP violation, searches for new physics
  - what we tell the funding agencies, and the press
- But, much of the physics performed by flavour experiments is the study of properties of hadronic states
  - lifetimes, masses, decay channels, quantum numbers
  - and the discoveries of new ones

PRL 91 (2003) 262001
Most highly cited paper (>2500 citations)
from BaBar or Belle





Discovery of the lightest $b\bar{b}$ state – 2008

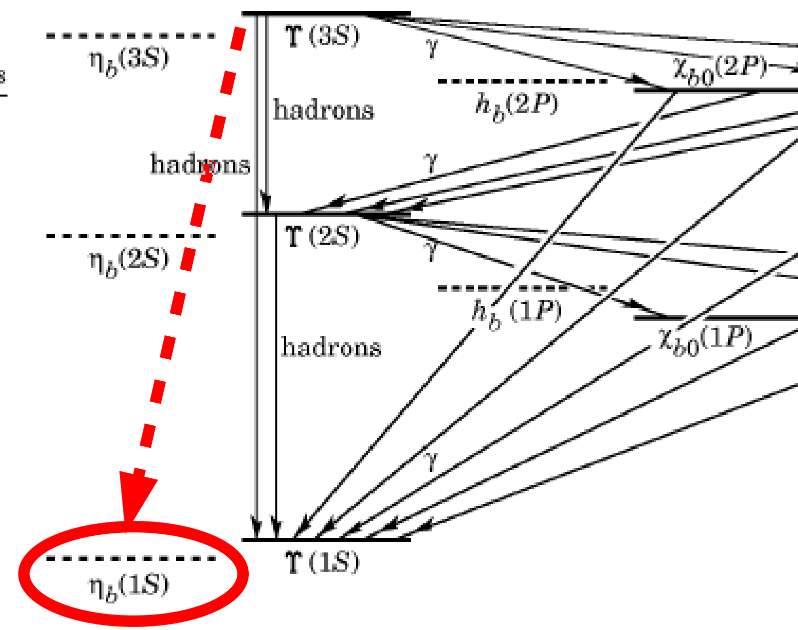

Selected for a Viewpoint in *Physics*
PRL 101, 071801 (2008) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2008

Observation of the Bottomonium Ground State in the Decay $\Upsilon(3S) \to \gamma\eta_b$

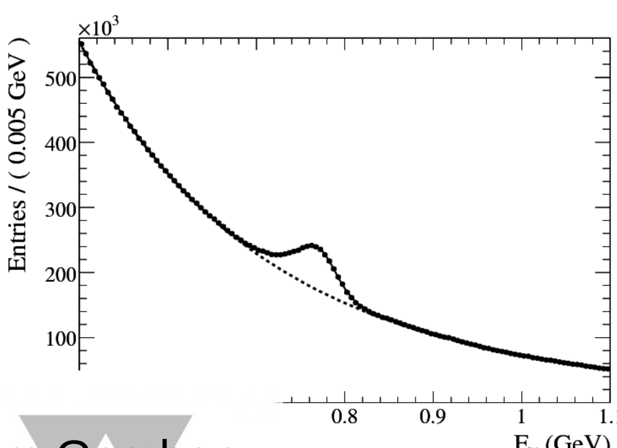
B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2] E. Grauges,[2] L. Lopez,[3] A. Palano,[3] M. ... S. Abrams,[5] M. Battaglia,[5]

The BaBar Collaboration

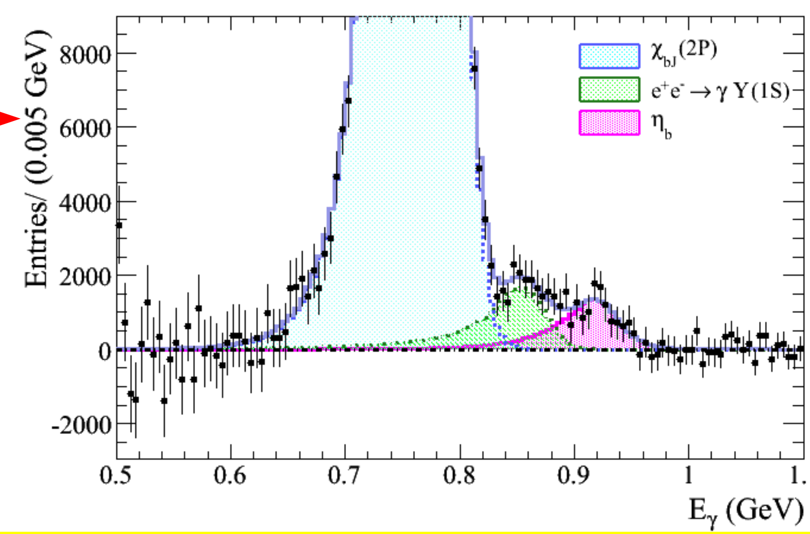
Only recoil γ is reconstructed



$$m(\eta_b(1S)) = (9388.9\,^{+3.1}_{-2.3} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$m(\Upsilon(1S)) - m(\eta_b(1S)) = (71.4\,^{+2.3}_{-3.1} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$B(\Upsilon(3S) \to \gamma\,\eta_b(1S)) = (4.8 \pm 0.5 \pm 1.2) \times 10^{-4}$$



subtract smoothly varying background



Signal confirmed in ϒ(2S) transitions by BaBar, and by CLEO

Why wasn't the η_b discovered at a hadronic experiment?

- Remember: Υ(1S) discovered at FNAL in 1977
  - fixed target experiment: p on Be

PRL 39 (1977) 252

- η_b is lighter
- e^+e^- collisions produce only vector mesons
  - i.e. $J^{PC} = 1^{--}$, same as γ*
- but pp or $p\bar{p}$ collisions produce hadrons with all quantum numbers
- So why couldn't the η_b be discovered, e.g., at the Tevatron?

Why wasn't the η_b discovered at a hadronic experiment?

- Remember: Υ(1S) discovered at FNAL in 1977
  - fixed target experiment: p on Be

PRL 39 (1977) 252

- η_b is lighter
- So why couldn't the η_b be discovered, e.g., at the Tevatron?
- It's all about the trigger! (Although it's also about the detection capability)
  - need clean signature for trigger and reconstruction
  - CDF search used $\eta_b \to J/\psi J/\psi$ decay, with predicted BF ~ 0!

CDF note 8448

The ingredients for precision flavour

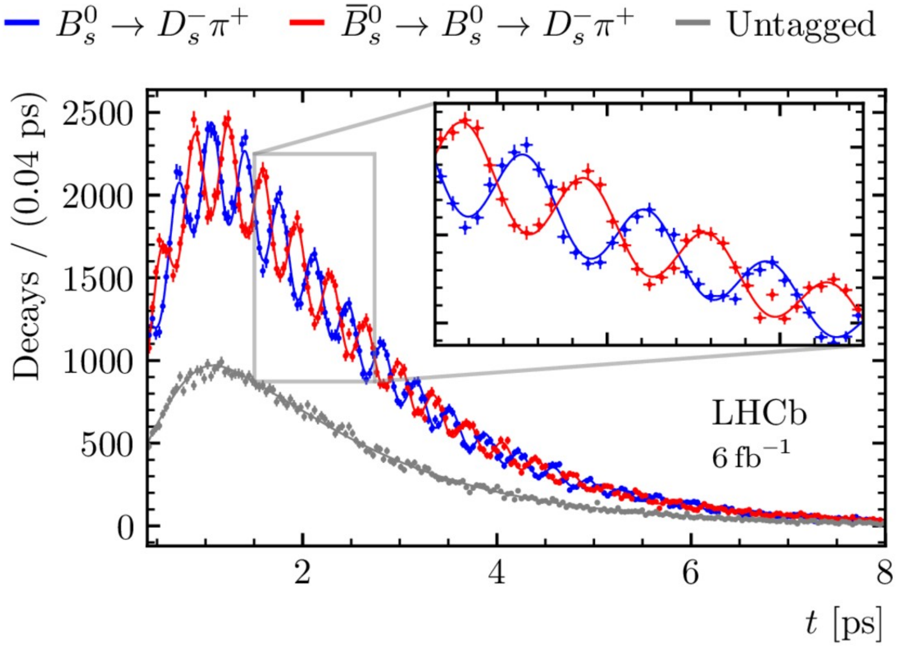
Enormous production cross-section of beauty and charm

Large boost

Ability to identify displaced vertices …
with capability to exploit this online

Detection and separation of different final state particles

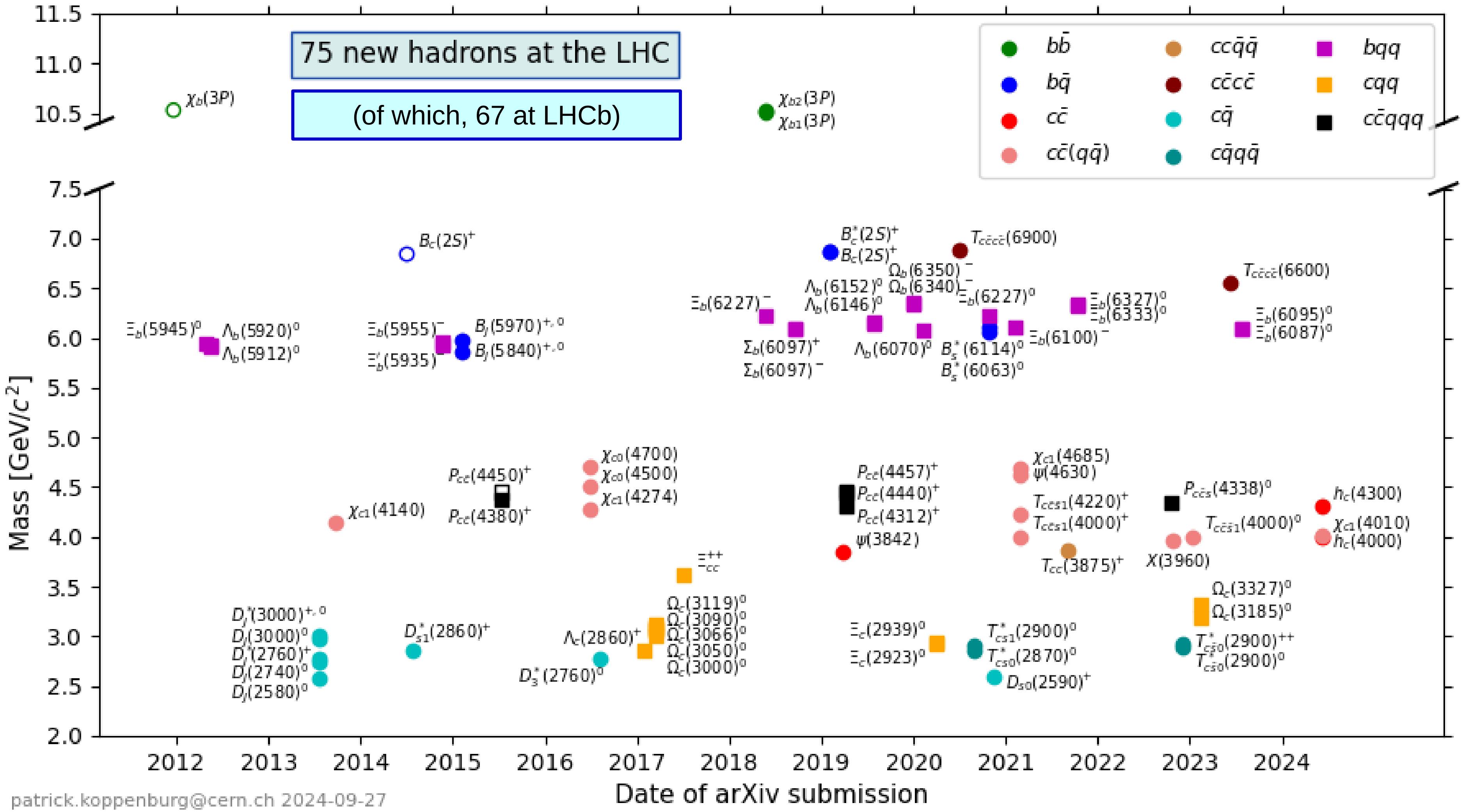
- charged: e, π, μ, K, p
- neutral: γ, π^0 [challenging]
- missing: ν, K_L, n [challenging^2]



Δm_s = (17.7683 ± 0.0051 ± 0.0032) ps^{-1}

Nature Physics 18 (2022) 1

Same ingredients enable spectroscopy

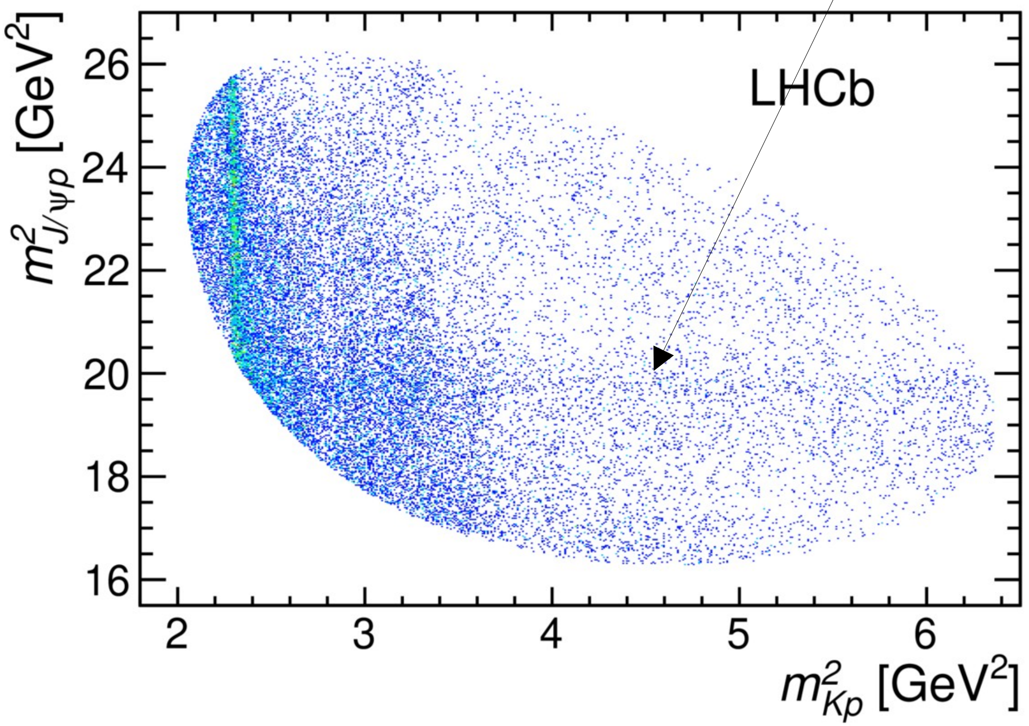


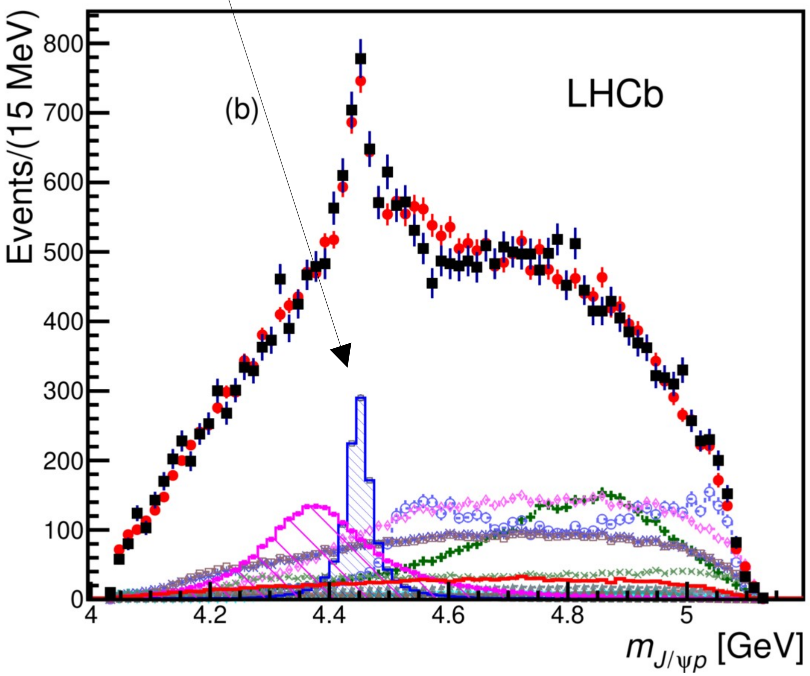
One example: charmonium pentaquark

PRL 115 (2015) 072001

(LHCb's most cited paper)

Reconstruct $\Lambda_b \rightarrow J/\psi p K^-$ decays
Clear exotic $J/\psi p$ structure seen in Dalitz plot and invariant mass projection





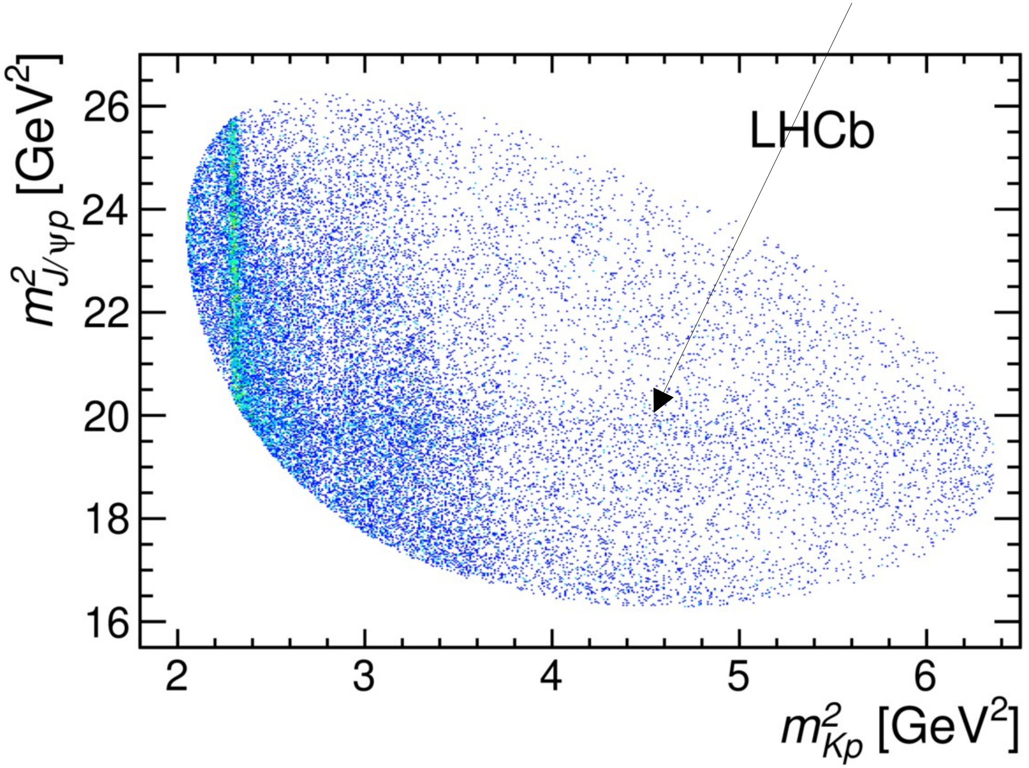
A resonance in $J/\psi p$ has minimal quark content $c\bar{c}uud$
Not a conventional 3 quark baryon – "pentaquark"

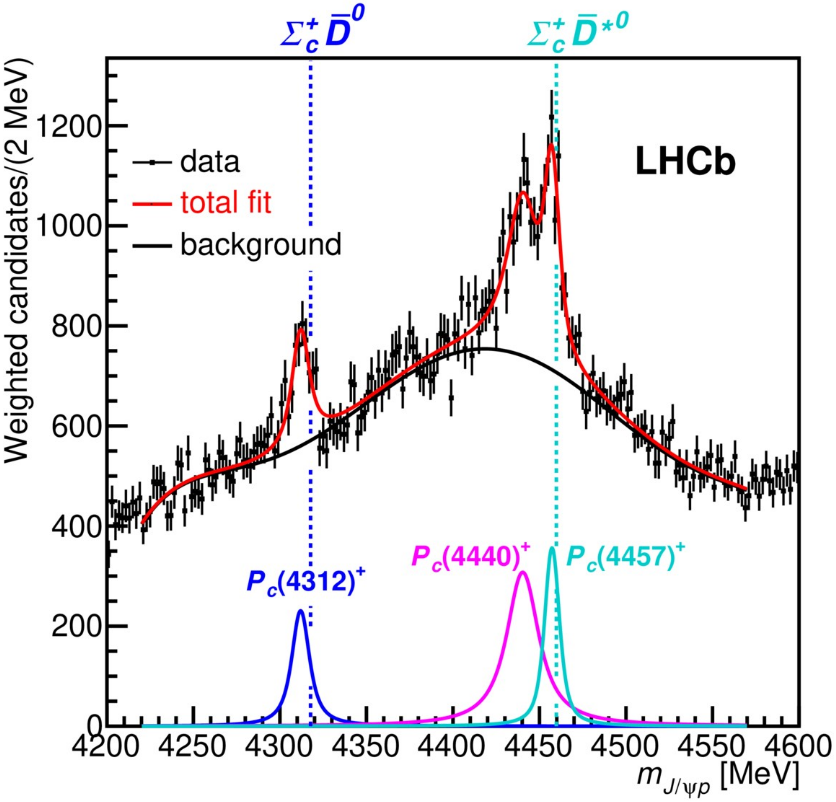
One example: charmonium pentaquark

PRL 115 (2015) 072001

(LHCb's most cited paper)

Reconstruct $\Lambda_b \to J/\psi p K^-$ decays
Clear exotic $J/\psi p$ structure seen in Dalitz plot and invariant mass projection



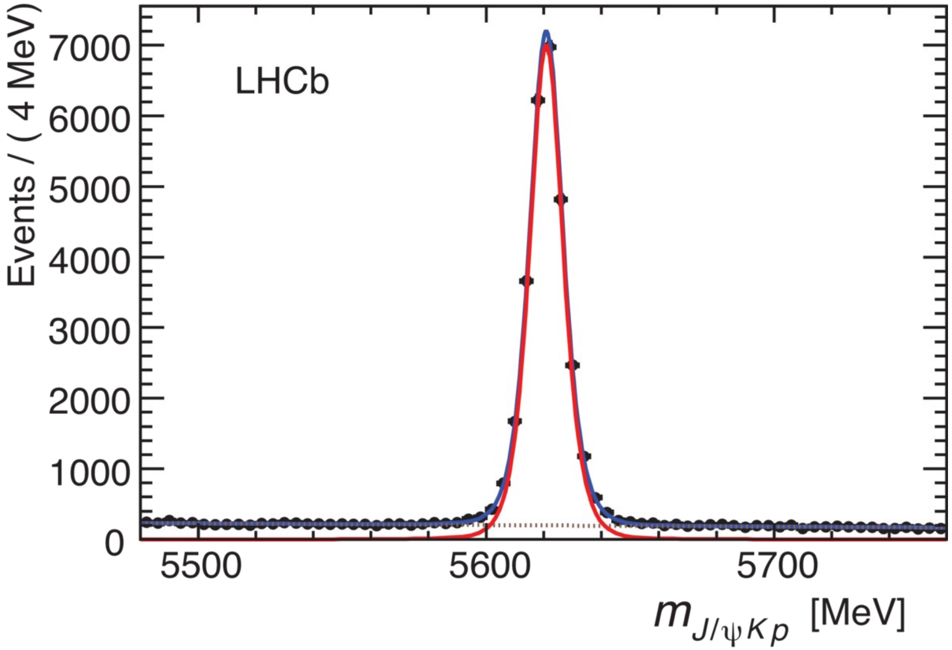


With more data, later resolved into multiple resonances

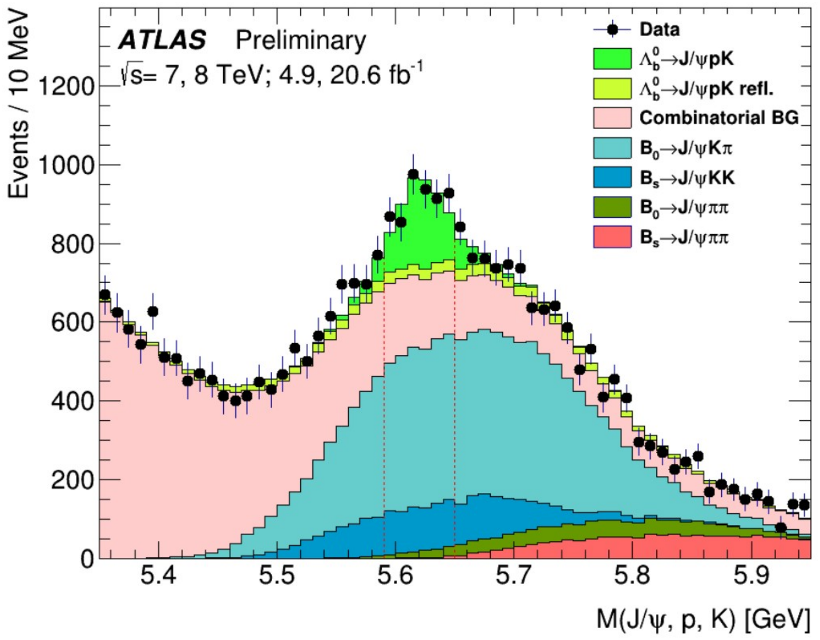
PRL 122 (2019) 222001

In case you forget importance of vertexing and particle identification

PRL 115 (2015) 072001



ATLAS-CONF-2019-048



Tomorrow

- More key observables
  - CP violation in decay: the CKM angle γ
  - CP violation in the B_s and D systems
  - Rare decays: $B_{(s)} \to \mu^+\mu^-$, $B \to K^{(*)}l^+l^-$, $B \to K^{(*)}\nu\bar{\nu}$
- Future flavour physics experiments
  - Belle II
  - LHCb upgrades