Review of Unitarity Triangle and Spectroscopy Measurements with LHCb

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On behalf of the LHCb Collaboration

September 5th 2017

Outline

- General introduction
- The LHCb detector and running conditions
- A review of LHCb's measurements of the Unitarity Triangle parameters
  - The angle β
  - The triangle sides
  - The angle γ
- Recent measurements on spectroscopy
- Summary and outlook

The CKM matrix

- The CKM matrix is unitary, and reduces to three rotation angles and one phase.
- The Wolfenstein parameterisation is commonly used to expand in orders of λ, the sine of the Cabibbo angle: $\lambda \sim 0.22$
- The phase gives rise to CP violation in the SM

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(1-\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- Measured magnitudes:

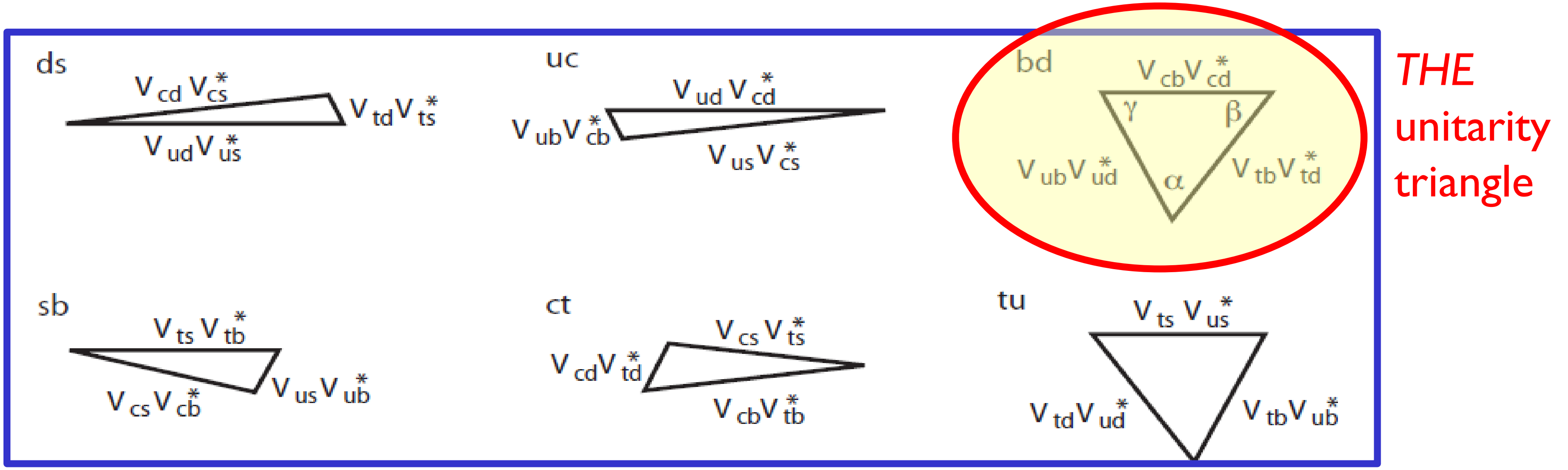
$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-ckm-matrix.pdf

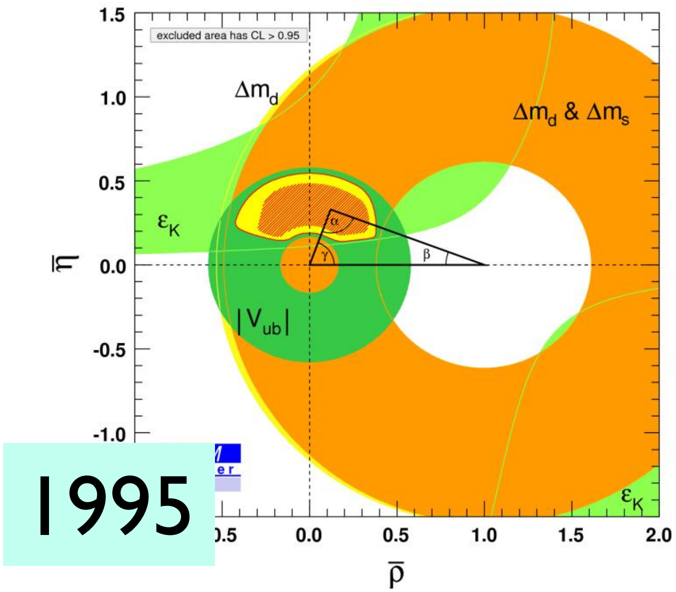
The Unitarity Triangle

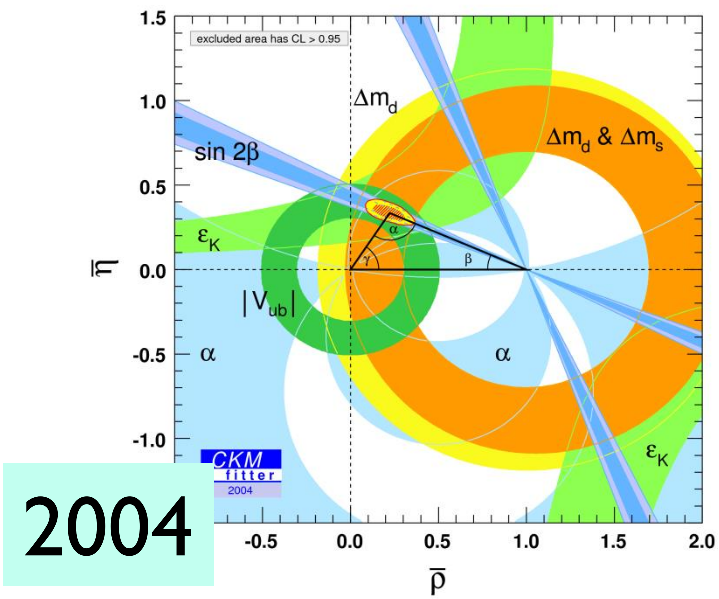
- 6 unitarity conditions of the CKM matrix
- Gives 6 triangles in the complex plane
- 2 of these triangles do not have a side much shorter than the other two:

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



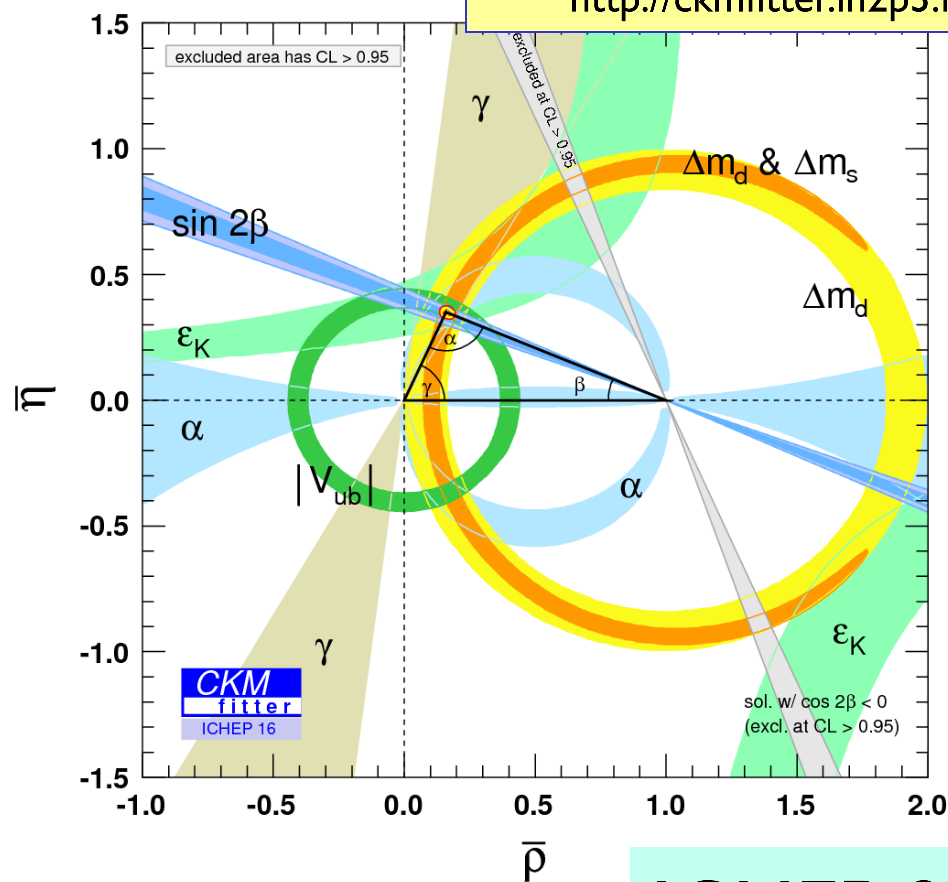
Unitarity triangle measurements





- Amazing progress in the last 20 years; the SM remains intact, but still a whole lot still to learn

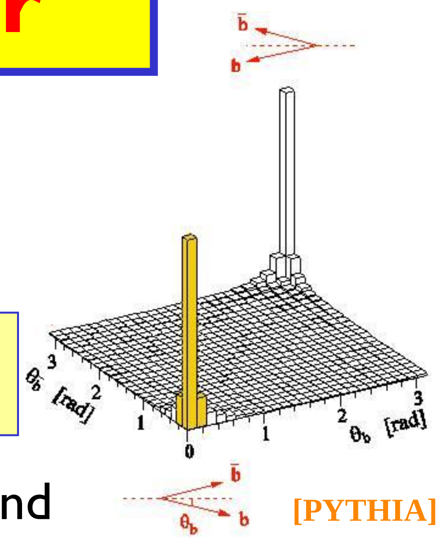
http://ckmfitter.in2p3.fr



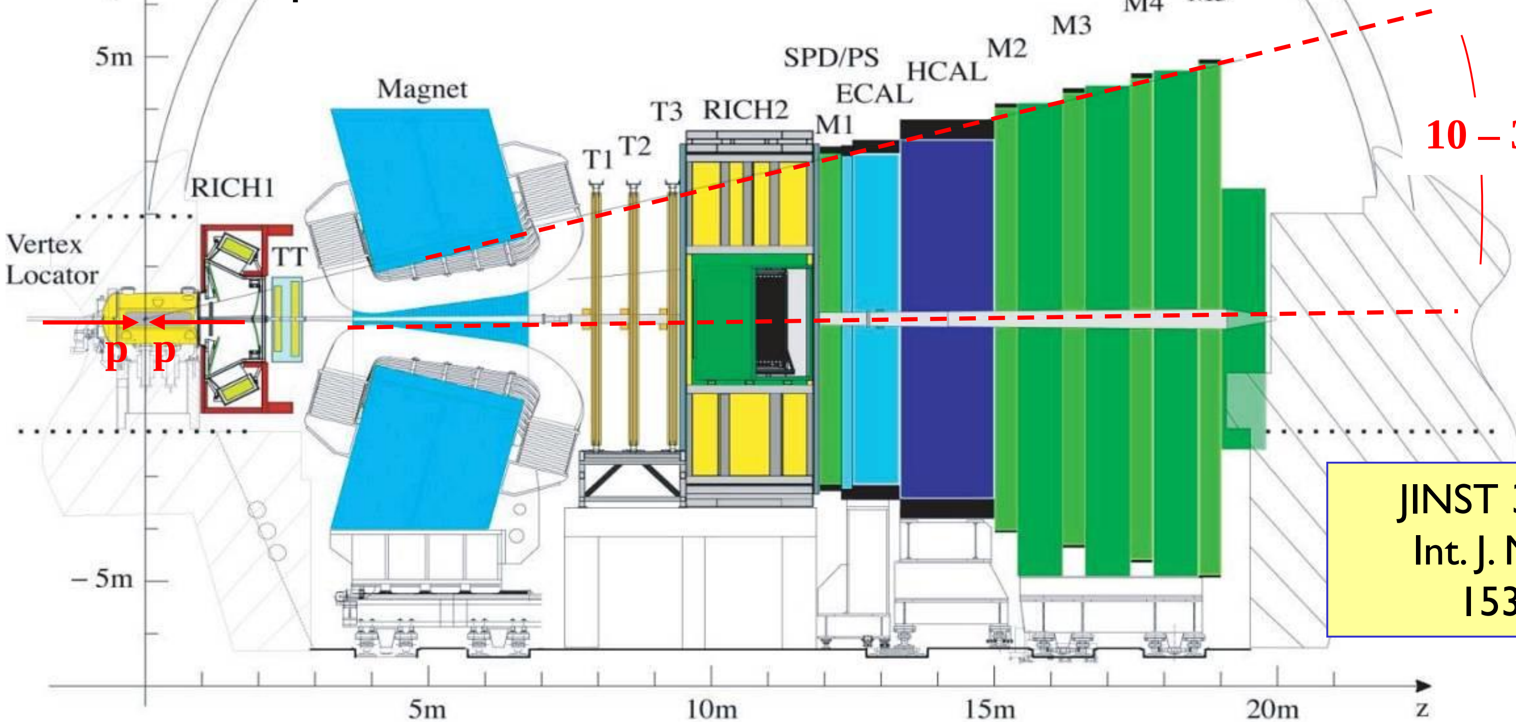
LHCb forward spectrometer

- Forward-peaked production → LHCb is a forward spectrometer (operating in LHC collider mode)
- $b\bar{b}$ cross-section = 72.0 ± 0.3 ± 6.8 μb at $\sqrt{s}$ = 7 TeV
  in the LHCb acceptance $2 < \eta < 5$
  At $\sqrt{s}$ = 13 TeV : 154.3 ± 1.5 ± 14.3 μb

PRL 118, 052002 (2017)



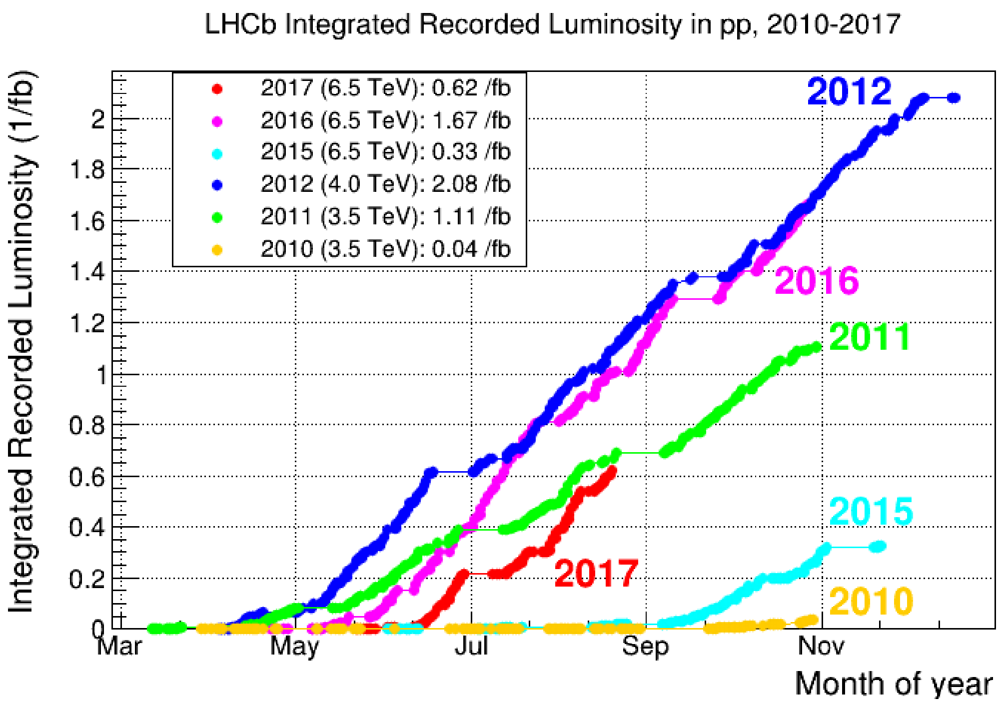
→ ~ 100,000 $b\bar{b}$ pairs produced/second (10^4 × B factories) and all species of B hadron



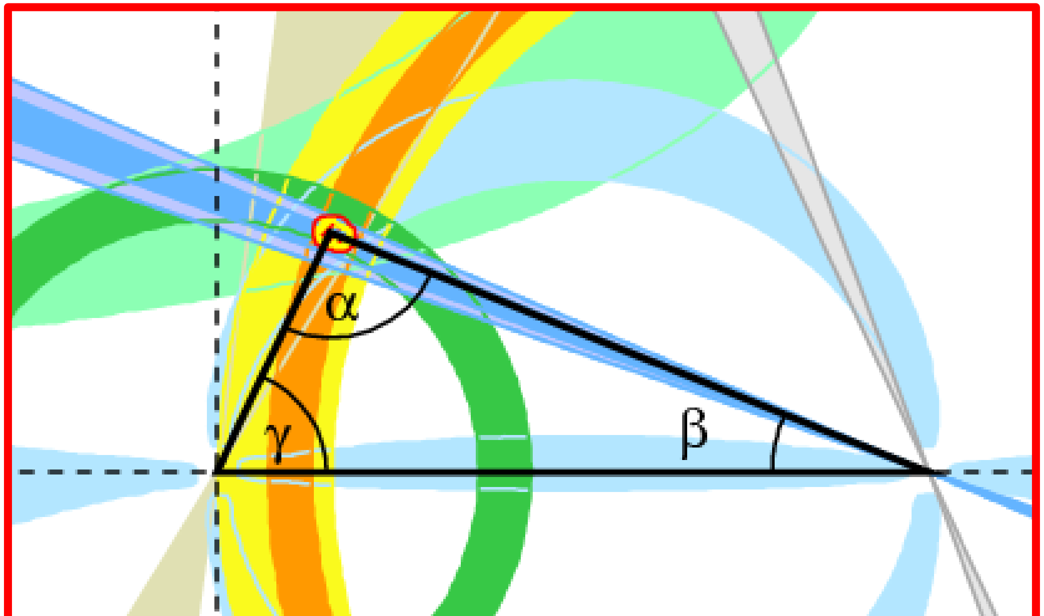
JINST 3:S08005 (2008), Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb data taking

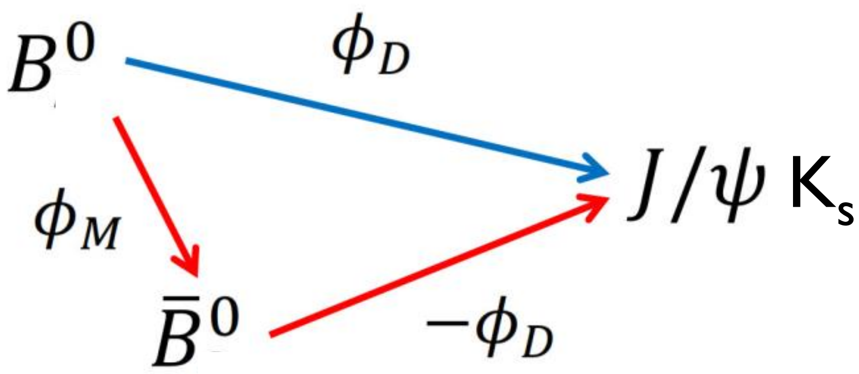
- Nominal luminosity = 2×10^{32} cm^{-2} s^{-1} (50 times less than ATLAS/CMS) : moreover, LHCb learned to run at >2 times this
  - 1 fb^{-1} @ 7 TeV in 2010-11
  - 2 fb^{-1} @ 8 TeV in 2012
  - 2.6 fb^{-1} @ 13 TeV in 2015-17



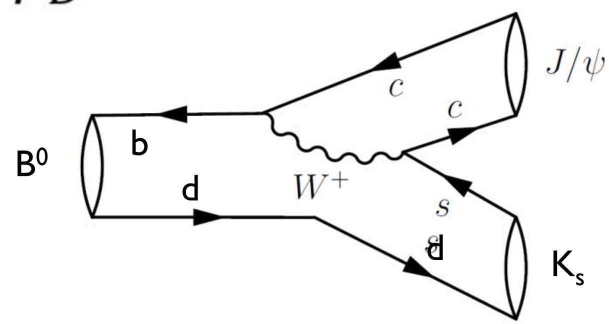
The angle β

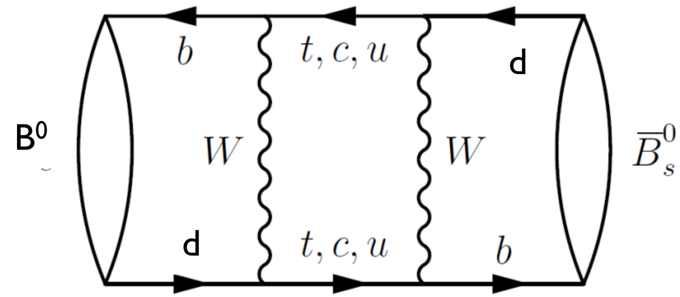


Measurement of angle β



$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$





- *Interference* between B^0 decay to J/ψK^0_S directly and via B^0 $\overline{\mathrm{B}}^0$ oscillation gives rise to a CP violating phase

$$\phi = \phi_{\mathrm{Mixing}} - 2\,\phi_{\mathrm{Decay}} = 2\beta$$

LHCb measurement of sin(2β)

Phys. Rev. Lett 115,031601 (2015)

sin(2β) from $B^0 \to J/\psi K^0_S$

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)}$$

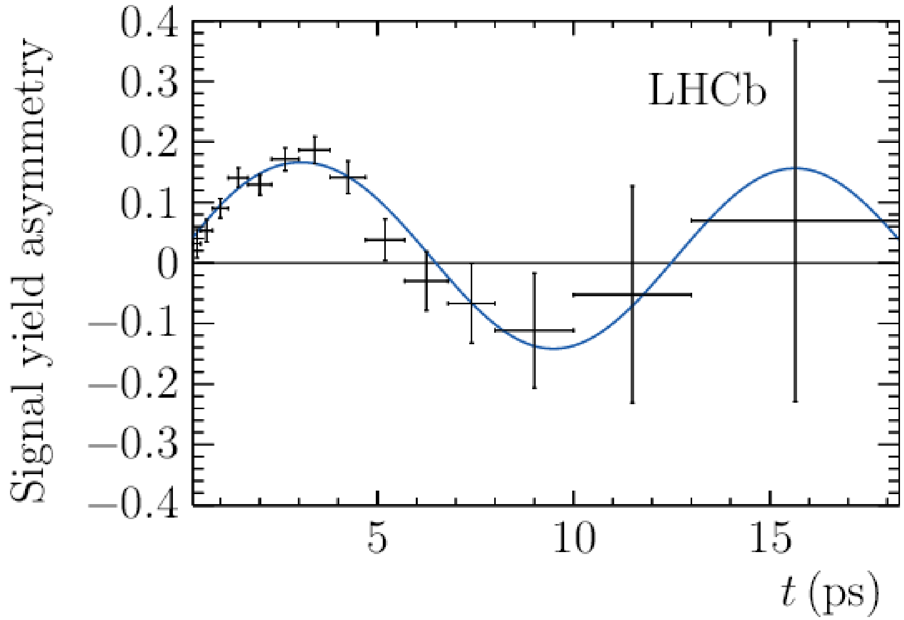
$$= S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t).$$

where $S_{J/\psi KS}$ = sin(2β) assuming $C_{J/\psi KS}$ (≡ penguin contribution) = 0

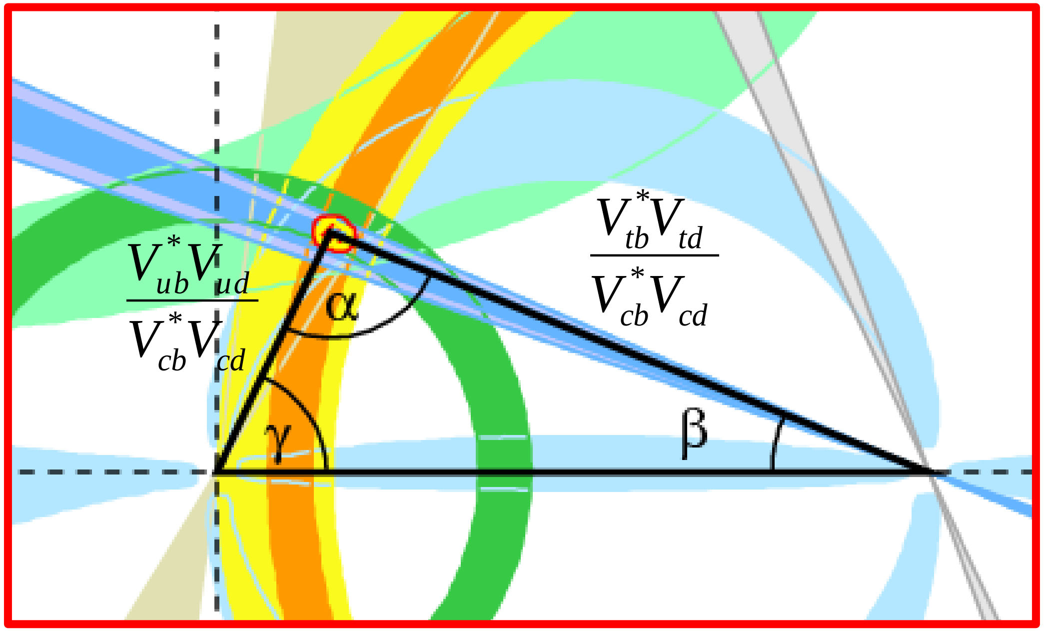
$S_{J/\psi Ks}$ = 0.731 ± 0.035 (stat) ± 0.020 (syst)

$C_{J/\psi Ks}$ = 0.0308 ± 0.032 (stat) ± 0.005 (syst)

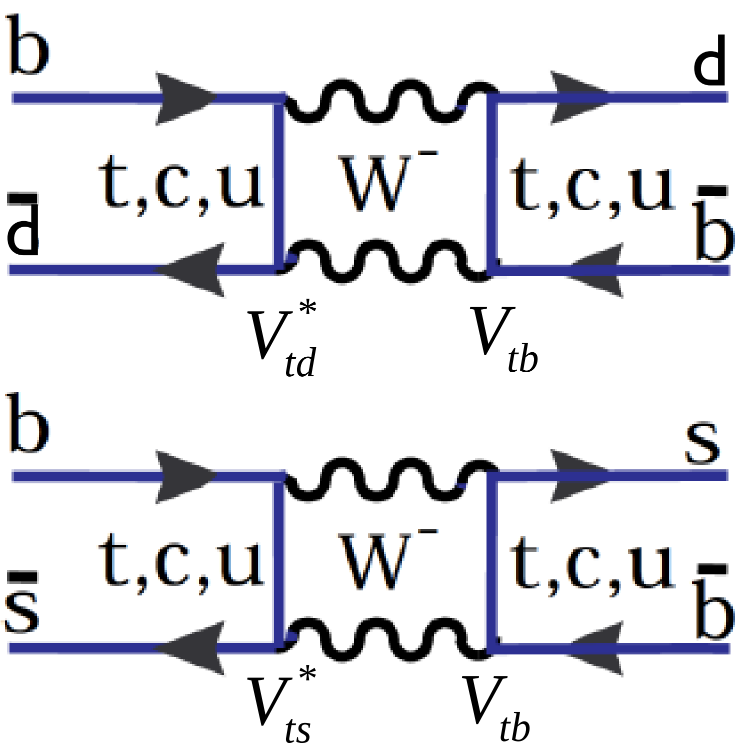
World average from all modes :
sin(2β) = 0.69 ± 0.02
(HFLAV EPS2016)

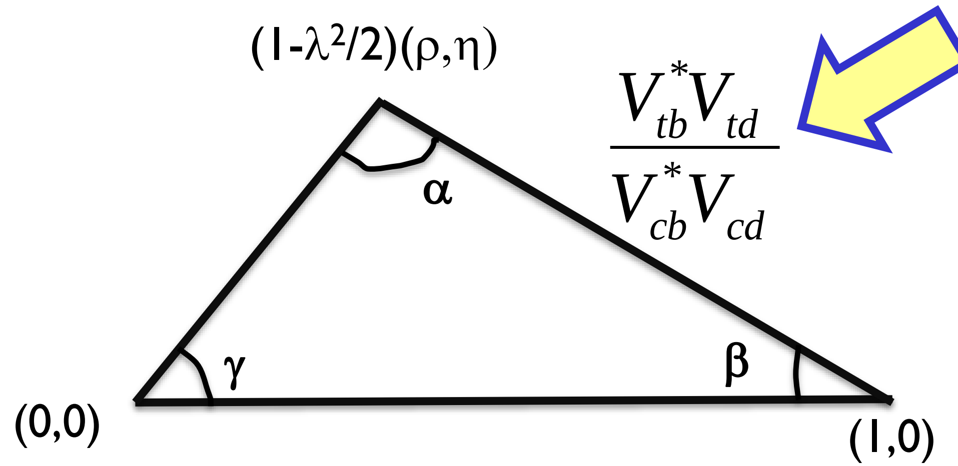


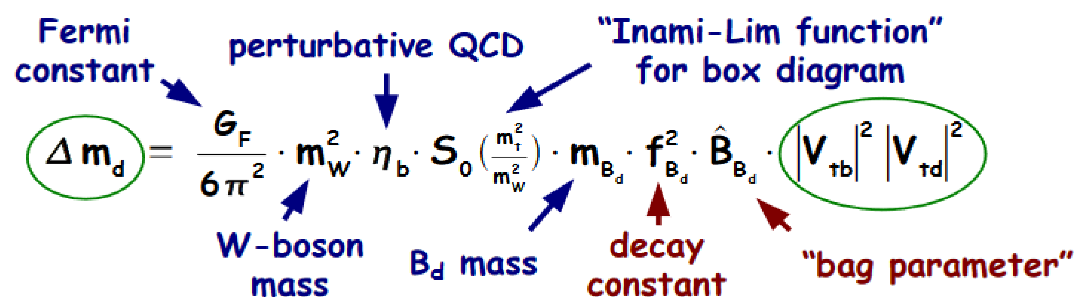
The sides of the triangle



$B_{(s)}$ mixing for side opposite to γ





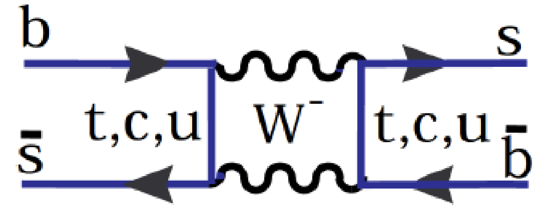


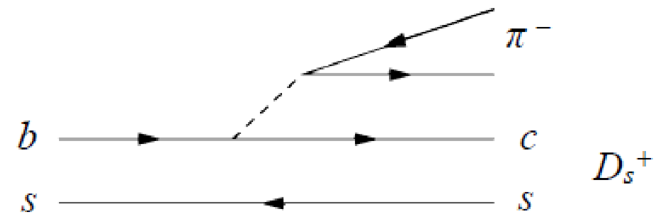
- Mixing loop dominated by the top
- Length of side from ratio of B_d and B_s : mixing frequencies extracted with input from lattice QCD (systematics cancel)

$$\left|\frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}}\right| \approx \frac{|V_{td}|}{|V_{ts}|} \times \frac{1}{|V_{cd}|}$$

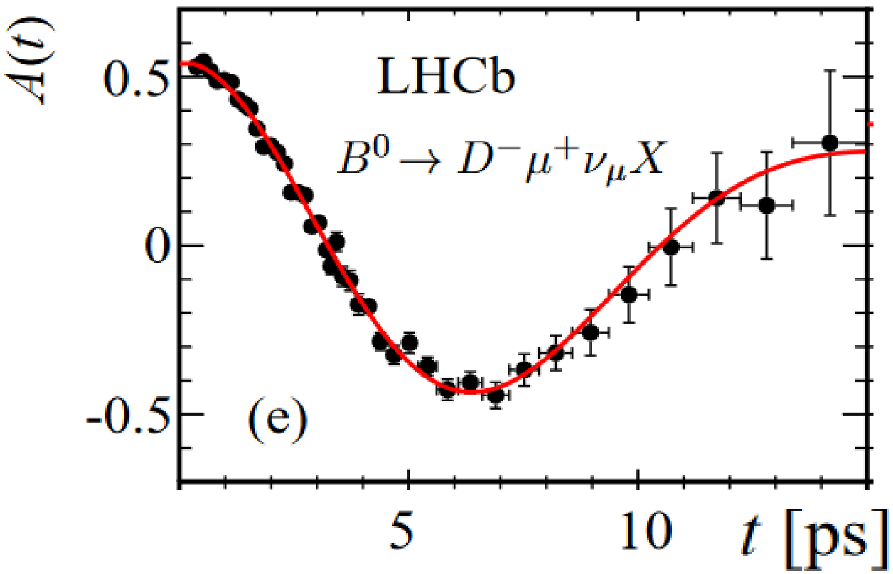
$$\frac{|V_{td}|}{|V_{ts}|} \sim \sqrt{\frac{\Delta m_d}{\Delta m_s}}$$

$B_{(s)}$ mixing at LHCb





$$\frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}$$

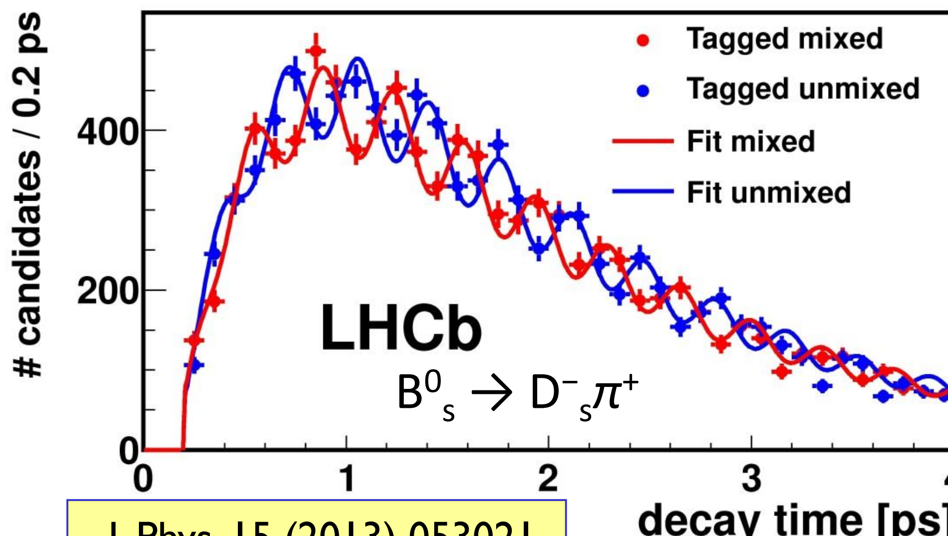


$$\Delta m_d = (505.0 \pm 2.1 \pm 1.0)\,\mathrm{ns}^{-1}$$

Eur. Phys. J. C76 (2016) 412

$$|V_{td}/V_{ts}| = 0.215 \pm 0.001 \pm 0.011$$

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-ckm-matrix.pdf

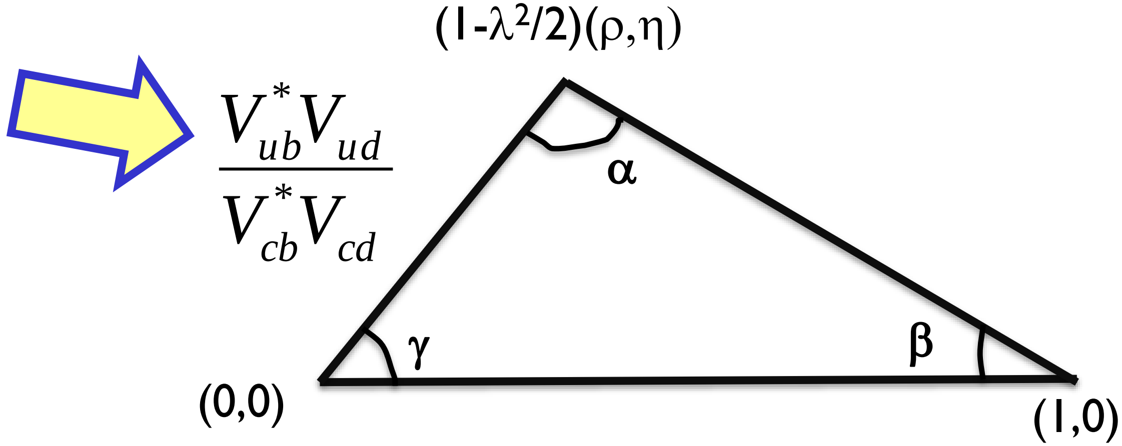


J. Phys. 15 (2013) 053021

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

Mixing measurements now dominated by LHCb (L-QCD systematics to be improved)

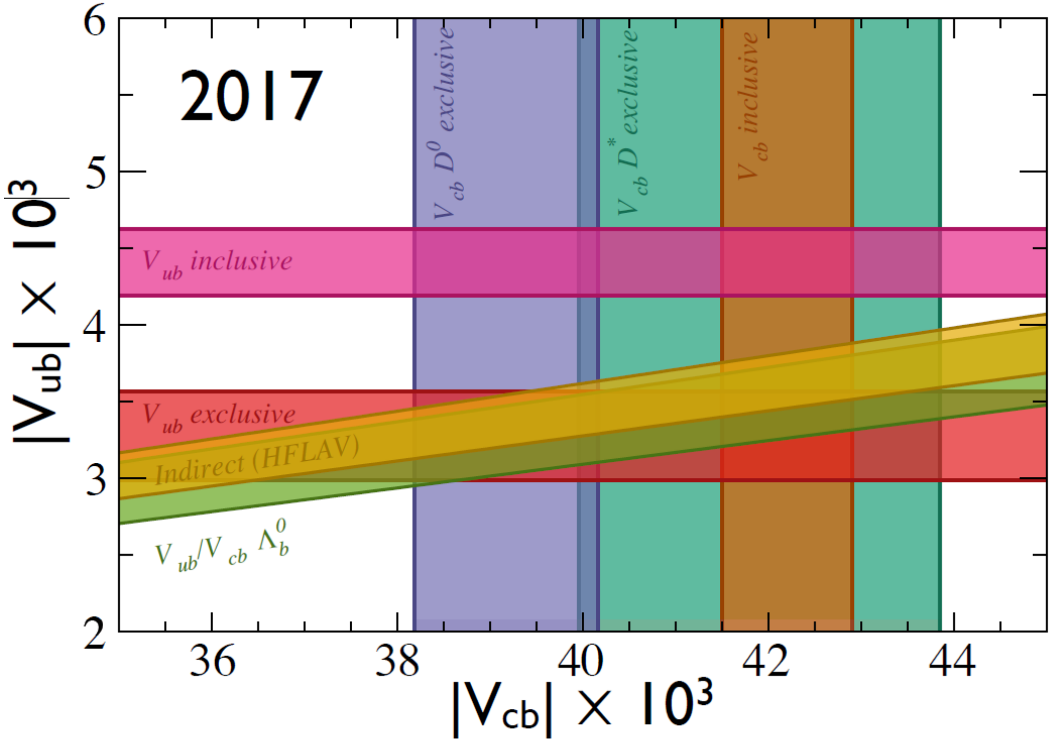
$|V_{ub}|$ measurement for side opposite to β



- Closure test of UT mainly limited by $|V_{ub}|$
- Side opposite to β proportional to $|V_{ub}| / |V_{cb}|$
- V_{ud} and V_{cd} very well known. $|V_{cb}|$ known to better than 3%
- $|V_{ub}|^2$ is directly proportional to the decay rate $B \rightarrow X_u l\nu$ and then calculated using HQET

Inclusive vs exclusive measurements of $|V_{ub}|$

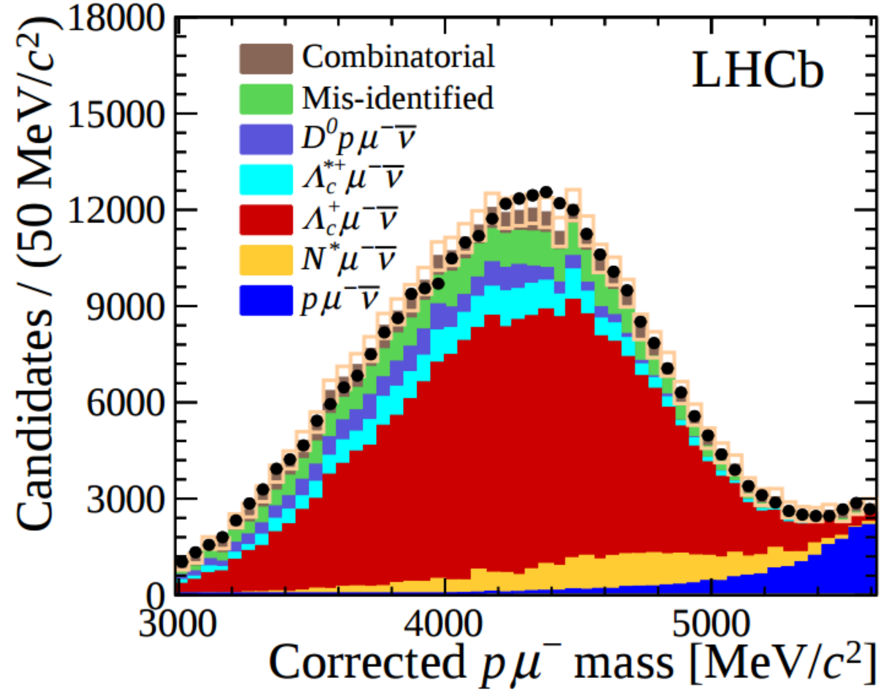
- Babar & Belle drive the current measurements of $|V_{ub}|$ which have an internal inconsistency between
  - Exclusive measurement: $B^0 \rightarrow \pi^- \mu^+ \nu$
  - Inclusive measurement : $B^0/B^+ \rightarrow X_u \mu^+ \nu$



Grinstein, Kobach, PLB771 (17) 359
Bigi, Gambino,Schacht, PLB 769 (17) 441

LHCb measurement of $|V_{ub}|$

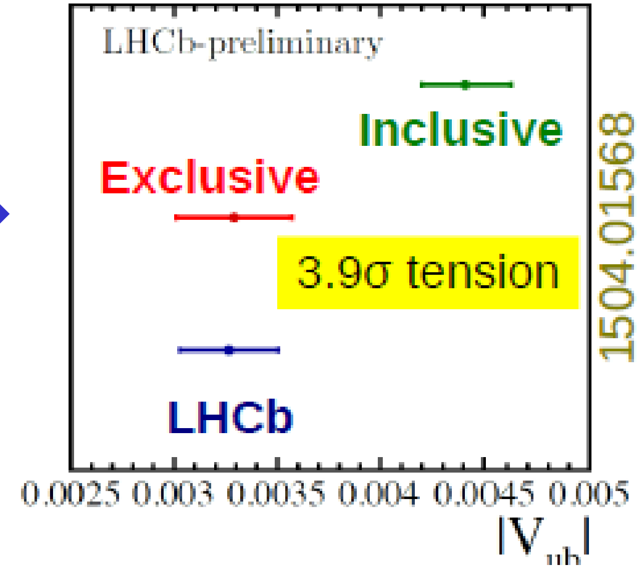
- $|V_{ub}| / |V_{cb}|$ difficult at hadron colliders due to presence of neutrino
- LHCb measures $\Lambda_b \rightarrow p\, \mu^- \nu$
- Measurement relies on $\Lambda_b \rightarrow p$ form factors from the lattice)

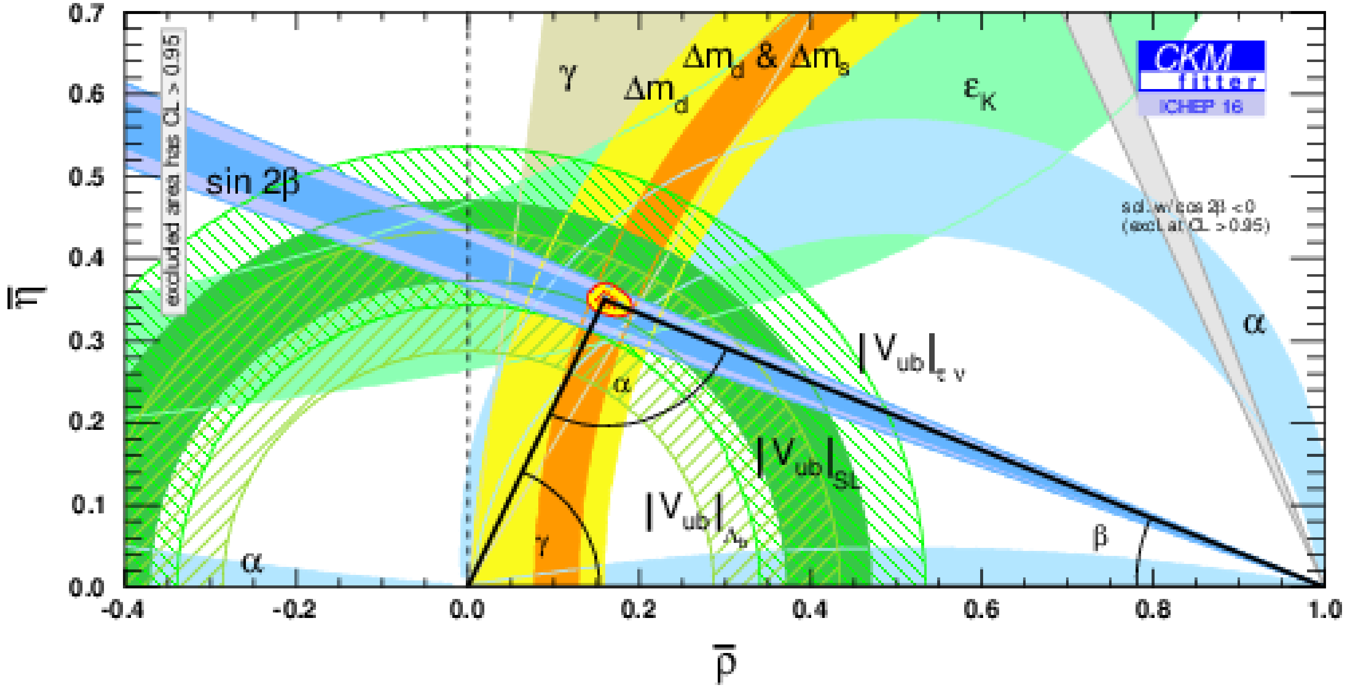


$$|V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06\ (|V_{cb}|) \times 10^{-3}$$

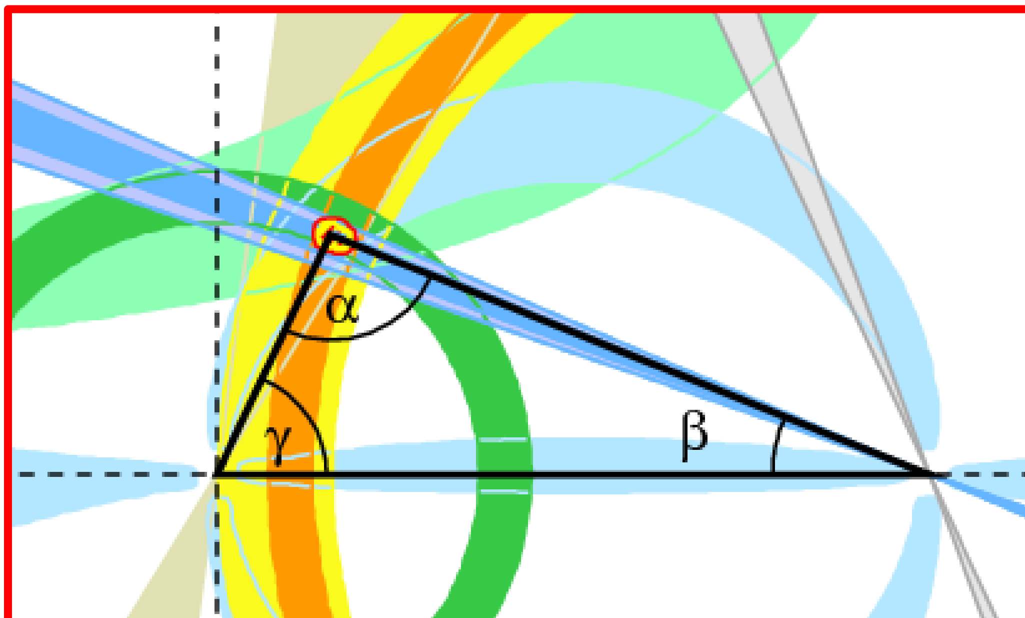
Nature Physics 10 (2015) 1038

Tension between inclusive and exclusive $|V_{ub}|$ persists : limits the precision on UT side





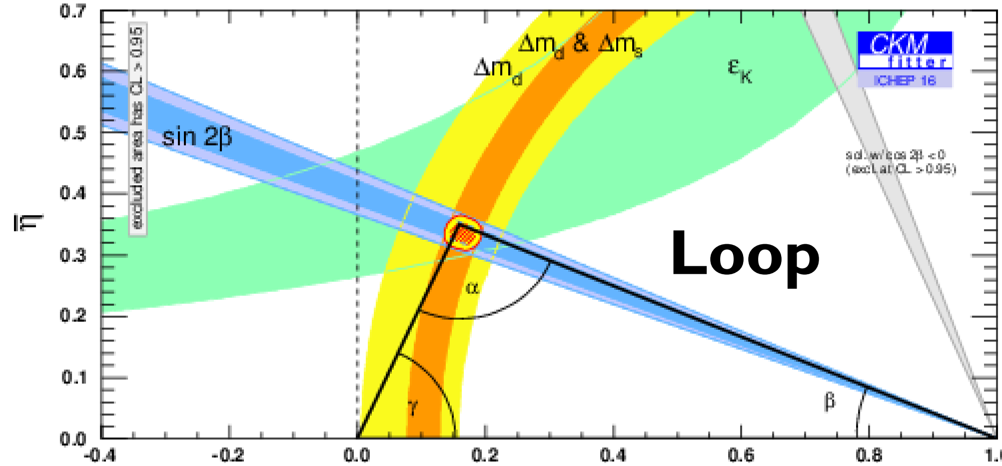
The angle γ

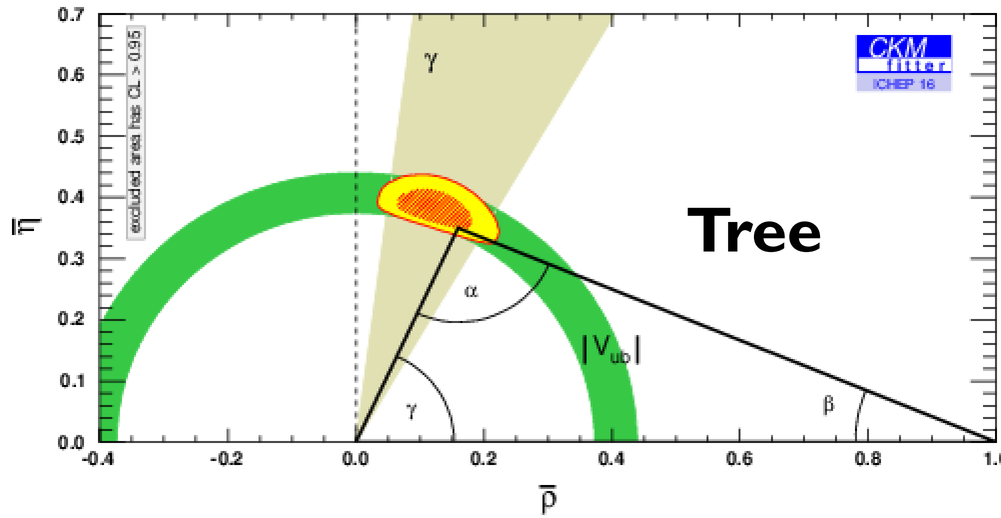


γ – why this is a key measurement

- Loop processes are very sensitive to the presence of New Physics
- Constraints on the triangle apex largely come from loop decay measurements
- Large uncertainty on γ, the only angle accessible at tree level : forms a SM benchmark*
- γ measurement theoretically very clean

JHEP 01 (2014) 051, PRD 92(3):033002 (2015)



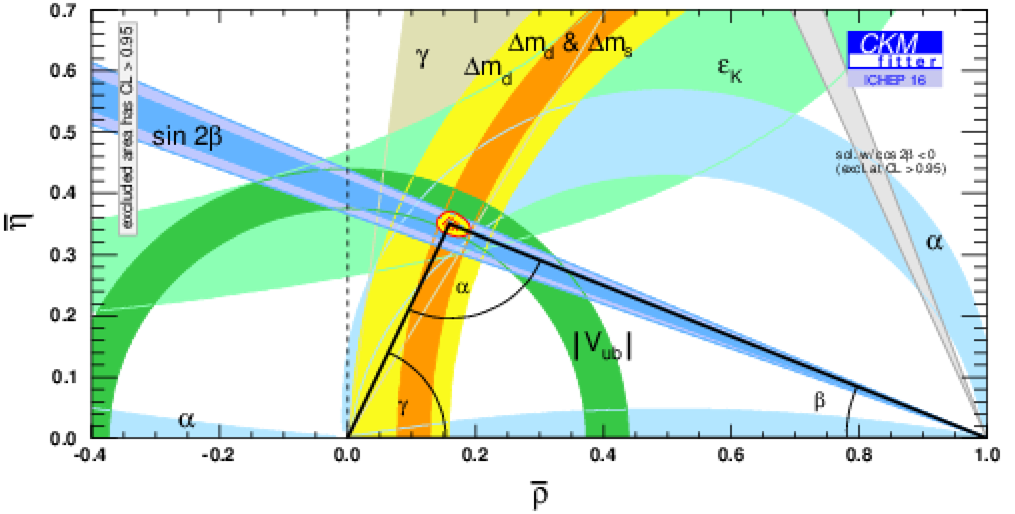


* assuming no significant New Physics in tree decays

http://ckmfitter.in2p3.fr

γ : Indirect vs direct determinations

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$



Combination of all direct measurements (summer 2016)

$$\gamma = (72.2^{+5.3}_{-5.8})^\circ$$

http://ckmfitter.in2p3.fr

Determination from CKM fit excluding all direct measurements of γ

$$\gamma = (65.3^{+1.0}_{-2.5})^\circ$$

EPJC (2016) 76 197

Reaching degree level precision from direct measurements is crucial

Uncertainties from LQCD, expect to reduce over the next decade

Several methods to measure γ

- $B^{\pm}$ (and $\overset{(-)}{B^0}$) decays : the "time-integrated", direct CP-violation modes $B^{\pm} \rightarrow \overset{(-)}{D^0} K^{\pm}$
  - GLW — Gronau & London, PLB 253 (1991) 483, Gronau & Wyler PLB 265 (1991) 172
  - ADS — Atwood, Dunietz & Soni PRL 78 (1997) 3257, Atwood, Dunietz & Soni PRD 63 (2001) 036005

  Focus on new measurements (GLW, ADS)

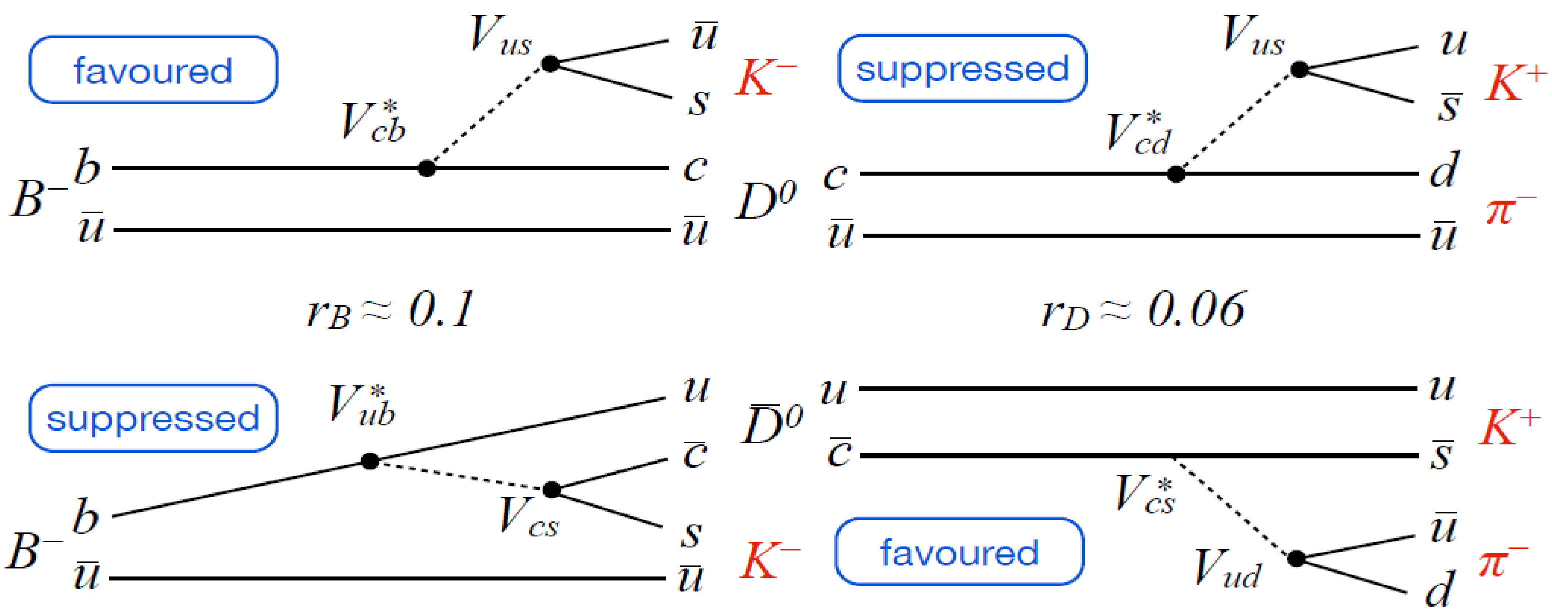
  - GGSZ — Giri, Gronau, Soffer & Zupan, PRD 68 (2003) 054018
- $B_s^0 \rightarrow D_s K$ time dependent analysis

  Dunietz & Sachs Phys. Rev. D37(1988) 3186,
  R. Aleksan, I. Dunietz & B. Kayser, Z. Phys. C54 (1992) 653

The time-integrated mode: $B^- \rightarrow D^0 K^-$

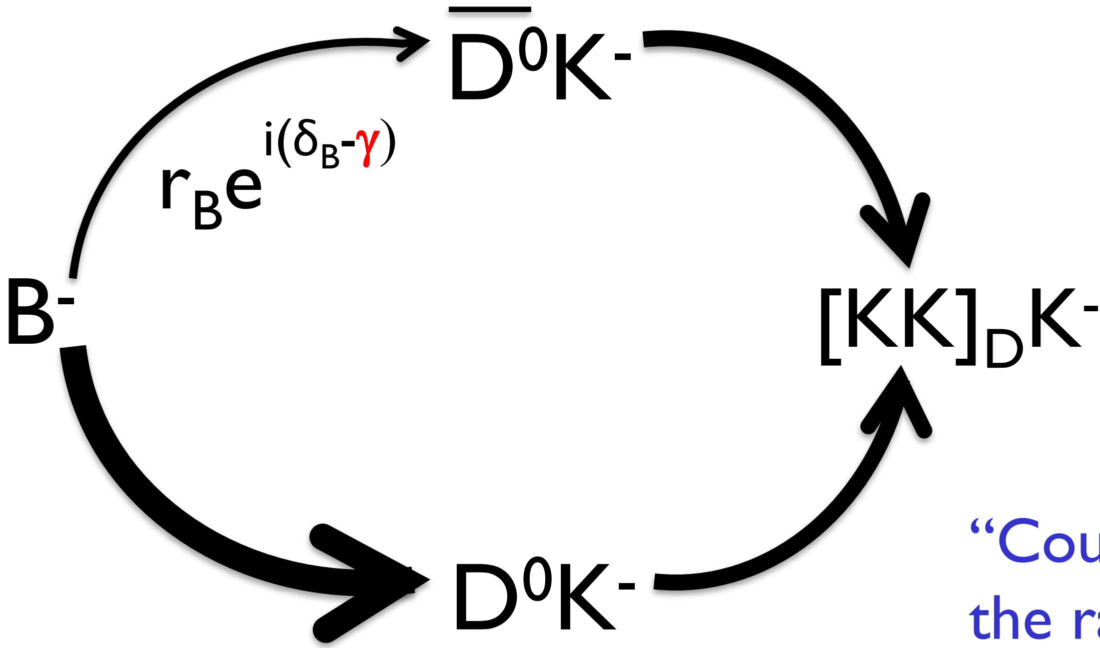
$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

(and charge conjugate mode $B^+ \rightarrow \bar{D}^0 K^+$)



- Interference possible if $\bar{D}^0$ and D^0 decay to same final state
- Branching fraction for favoured B decay ~10^{-4}
  - Measurements require high statistics

"GLW" method



- Method where D^0 and $\bar{D}^0$ decay to CP eigenstates
- Eigenstates are equally accessible to D^0 and $\bar{D}^0$
- r_B, δ_B hadronic parameters to be determined alongside γ ($r_B \sim 0.1$)

"Counting experiment" : observe the rate of B^- vs. B^+ decays

Weak phase changes sign for equiv B^+ diagram, thickness of arrows indicate relative strengths

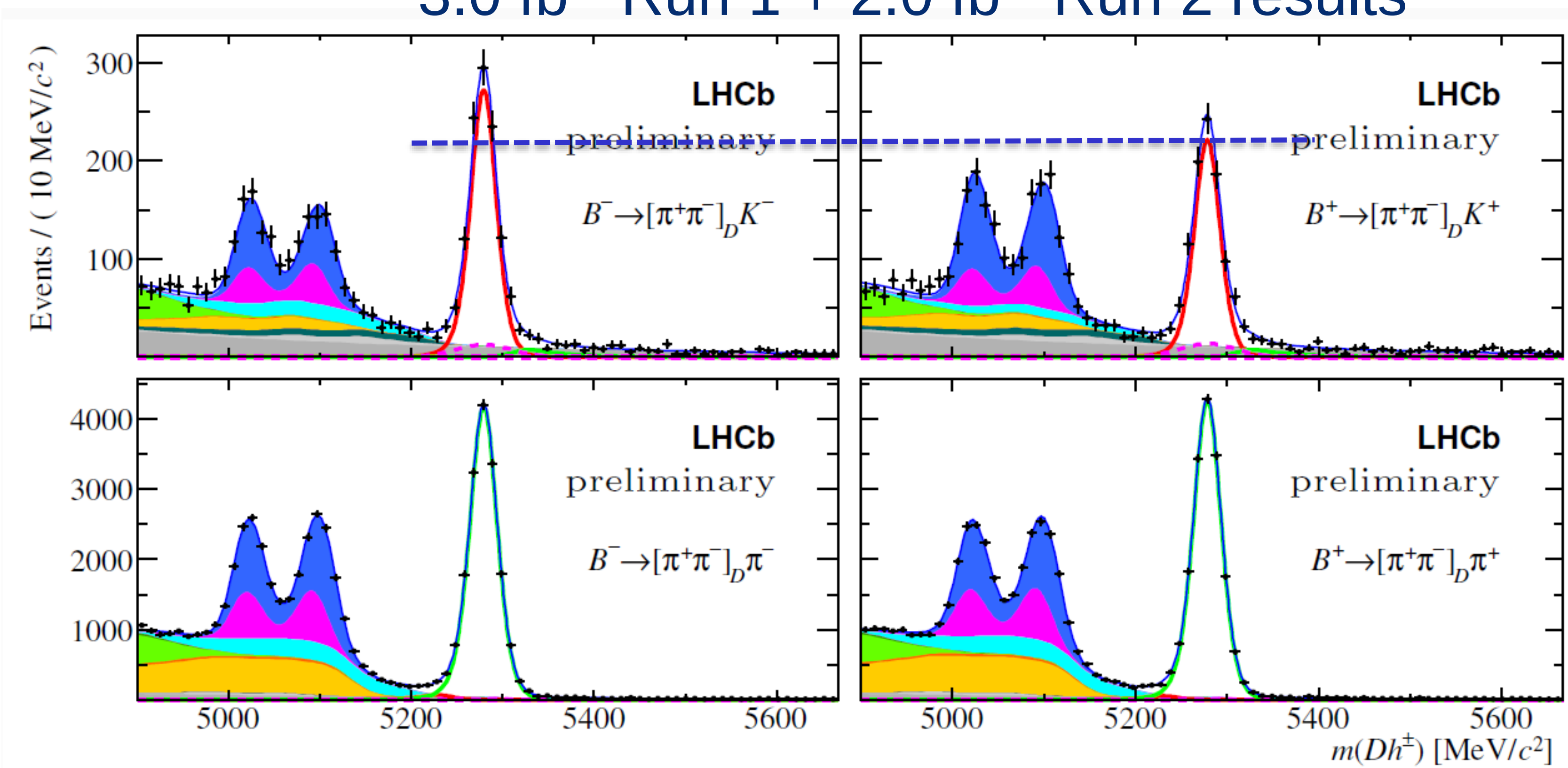
$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{CP+} = \frac{1}{R_{CP+}} 2r_B(2F_+ -1)\sin(\delta_B)\sin(\gamma)$$

$$\frac{N(B\to[KK]_D K)\times\Gamma(D\to K\pi)}{N(B\to[K\pi]_D K)\times\Gamma(D\to KK)} = R_{CP+} = 1 + r_B^2 + 2r_B(2F_+ -1)\cos(\delta_B)\cos(\gamma)$$

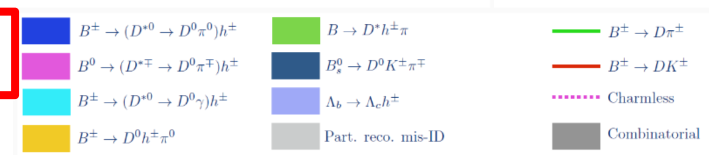
For CP+ eigenstates e.g KK, π π , $F_+ = 1$; For non CP eigenstates, F_+ measured at CLEO

$B \rightarrow D^{(*)}(\pi\,\pi)h$ (where h = K, π)

3.0 fb^{-1} Run 1 + 2.0 fb^{-1} Run 2 results



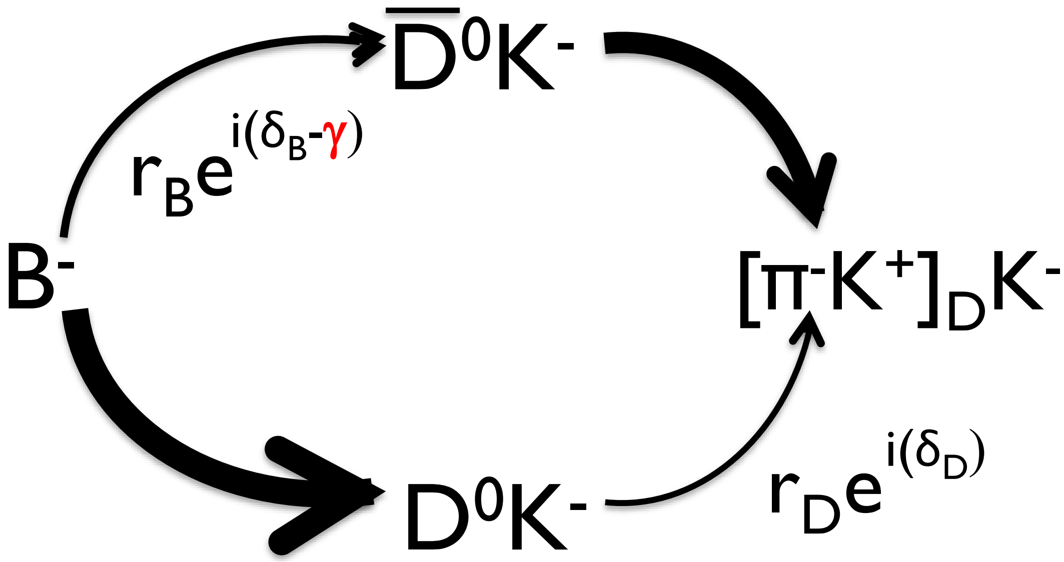
$$A_K^{\pi\pi} = +0.115 \pm 0.025\ (\text{stat}) \pm 0.007\ (\text{syst})$$



Phys Lett B 760 (2016) 117 & LHCb-PAPER-2017-021

Almost 5σ in single mode

"ADS" method



Weak phase changes sign for equivalent B^+ diagram

- Decay into flavour-specific final states
- Larger interference effects than for GLW as both amplitudes of similar sizes.
- r_B, δ_B hadronic parameters again to be determined alongside γ ($r_B \sim 0.1$)
- Additional two parameters r_D, δ_D . External inputs from charm mixing ($r_D \sim 0.06$)

$$\frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)} = A_{ADS} = \frac{1}{R_{ADS}} 2r_B r_D \sin(\delta_B+\delta_D)\sin(\gamma)$$

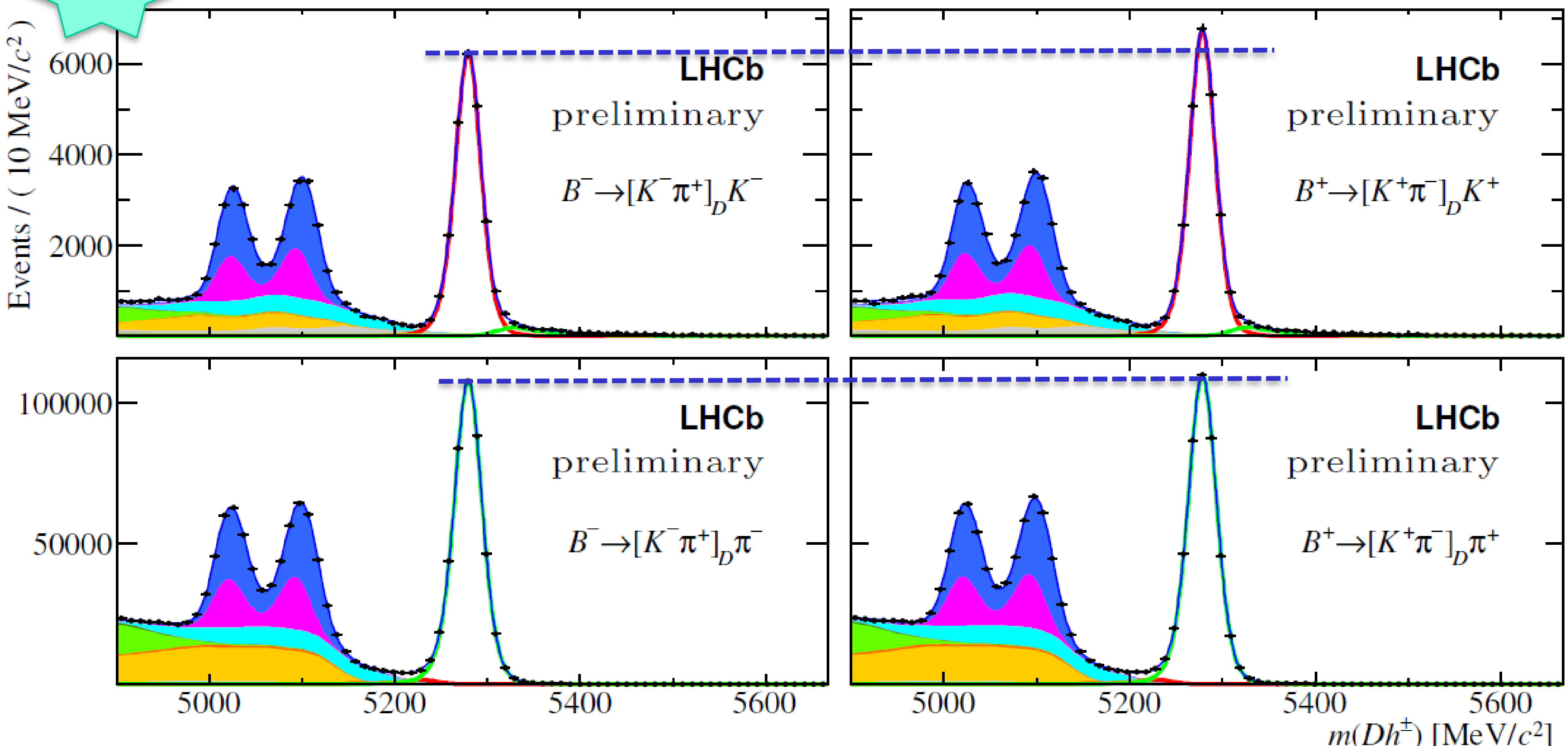
$$\frac{N(B^\pm \to [\pi^\pm K^\mp]_D K^\pm)}{N(B^\pm \to [K^\pm \pi^\mp]_D K^\pm)} = R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B+\delta_D)\cos(\gamma)$$

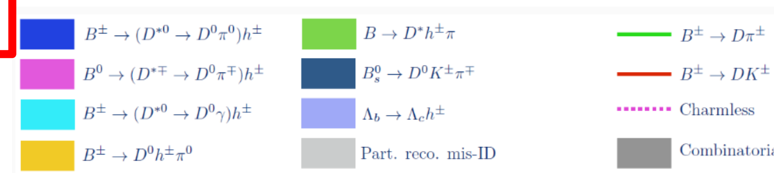
Again, a counting experiment : observing the rate of B^- vs. B^+ decays

$B \rightarrow D^{(*)}(K\pi)h$ (where h = K, π)

3.8σ

3.0 fb^{-1} Run 1 + 2.0 fb^{-1} Run 2 results





$$A_K^{K\pi} = -0.019 \pm 0.005\ (\text{stat}) \pm 0.002\ (\text{syst})$$

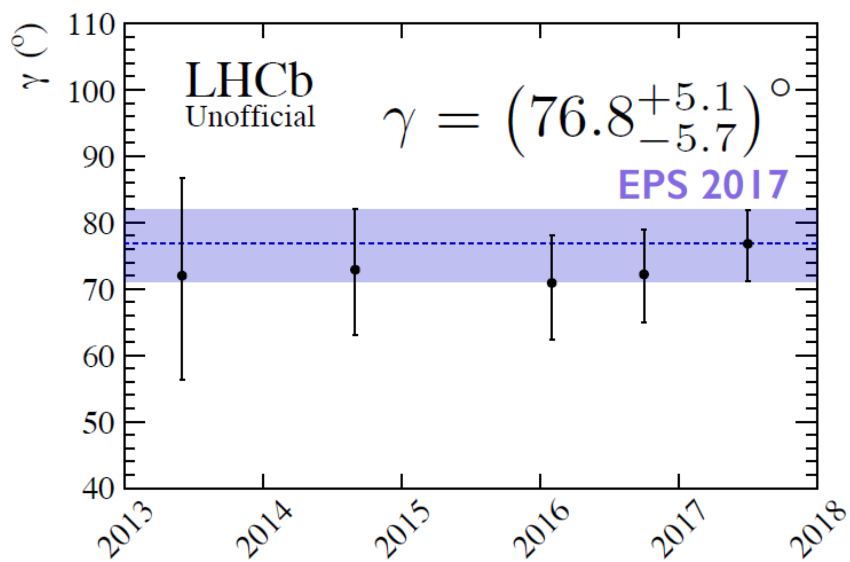
Phys Lett B 760 (2016) 117 & LHCb-PAPER-2017-021

Combination from different modes

- Includes the following updates since last combination:
  - $B^\pm \to D^0 K^{*\pm}$ ADS/GLW [LHCb-CONF-2016-014] NEW
  - $B^\pm \to D^{*0} K^{*\pm}$ ADS/GLW [LHCb-PAPER-2017-021] NEW
  - $B_s^0 \to D^{+-} K^{-+}$ TD [LHCb-CONF-2016-015] $1\ fb^{-1} \to 3\ fb^{-1}$
  - $B^\pm \to D^0 K^\pm$ GLW [LHCb-PAPER-2017-021] $3\ fb^{-1} \to 5\ fb^{-1}$

LHCb-CONF-2017-004

$$\gamma = (76.8^{+5.1}_{-5.7})^\circ \text{ (preliminary)}$$



Dominates HFLAV average $\gamma = (76.2^{+4.7}_{-5.0})^\circ$

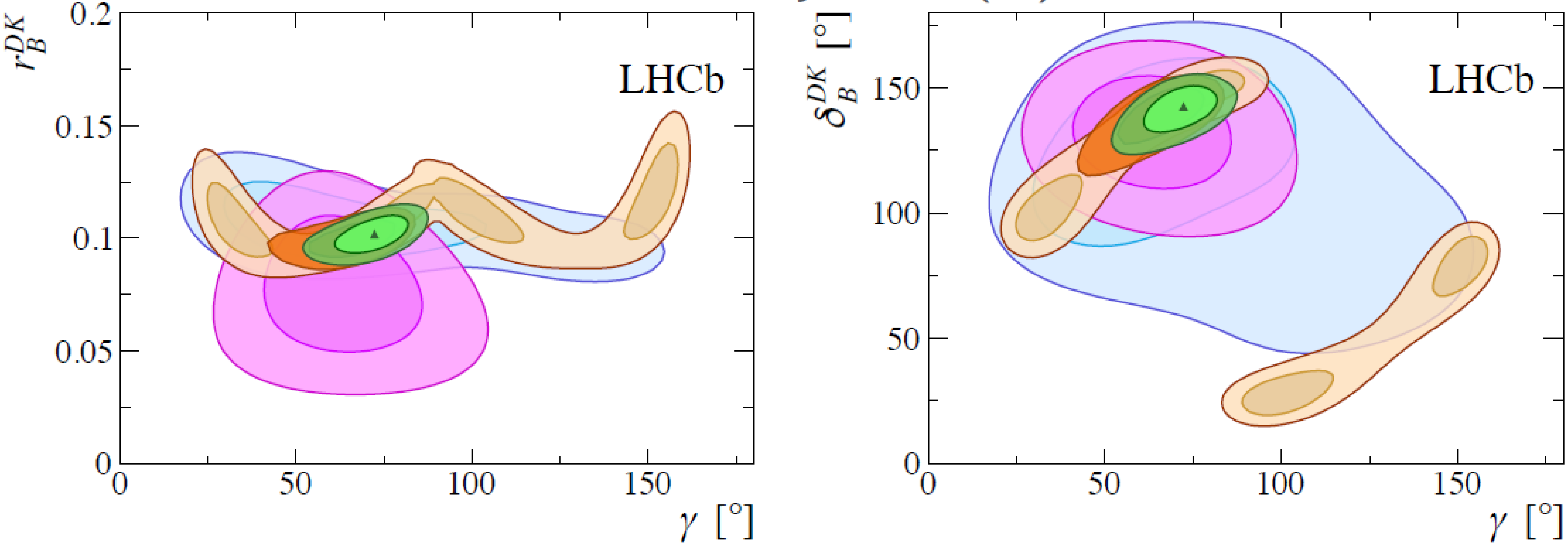
BaBar : $\gamma = (69^{+17}_{-16})^\circ$ PRD 87 (2013) 052015

Belle: $\gamma = (73^{+15}_{-14})^\circ$ arXiv:1301.2033

Combination of different modes

- It is necessary to pursue different B decays to provide crosschecks
- Current measurements are dominated by statistical uncertainties

Nov 2016 JHEP 12 (16) 087



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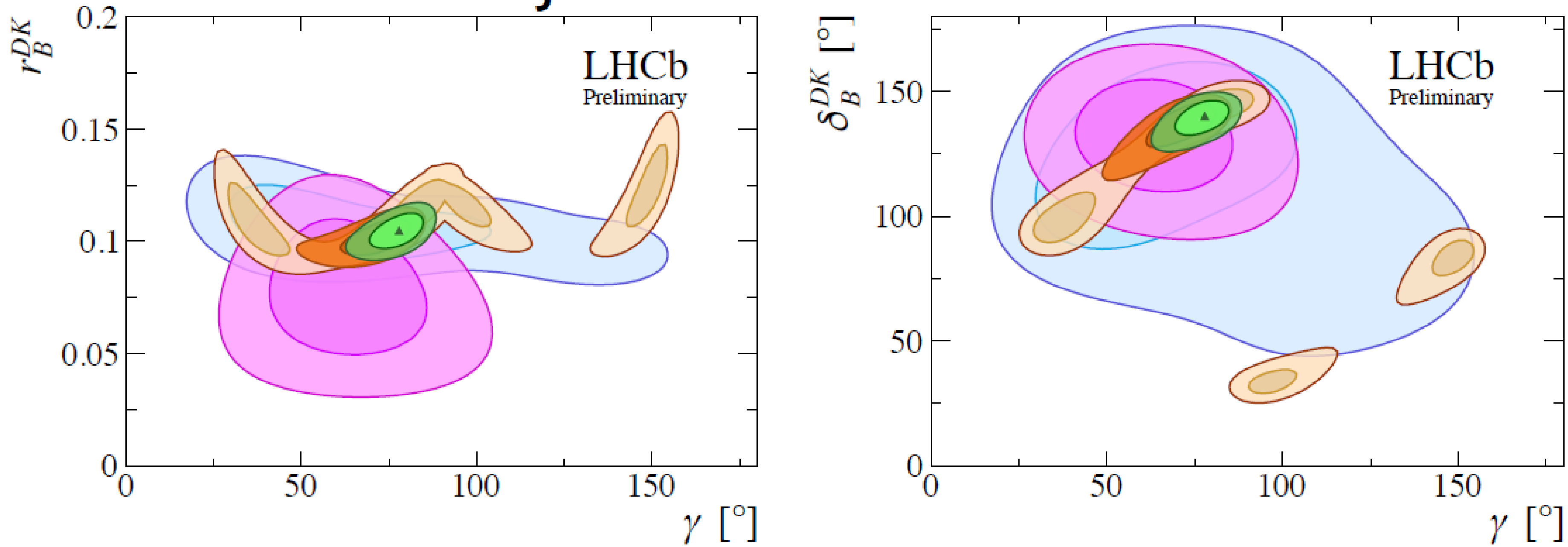
Jul 2017 CONF-2017-004

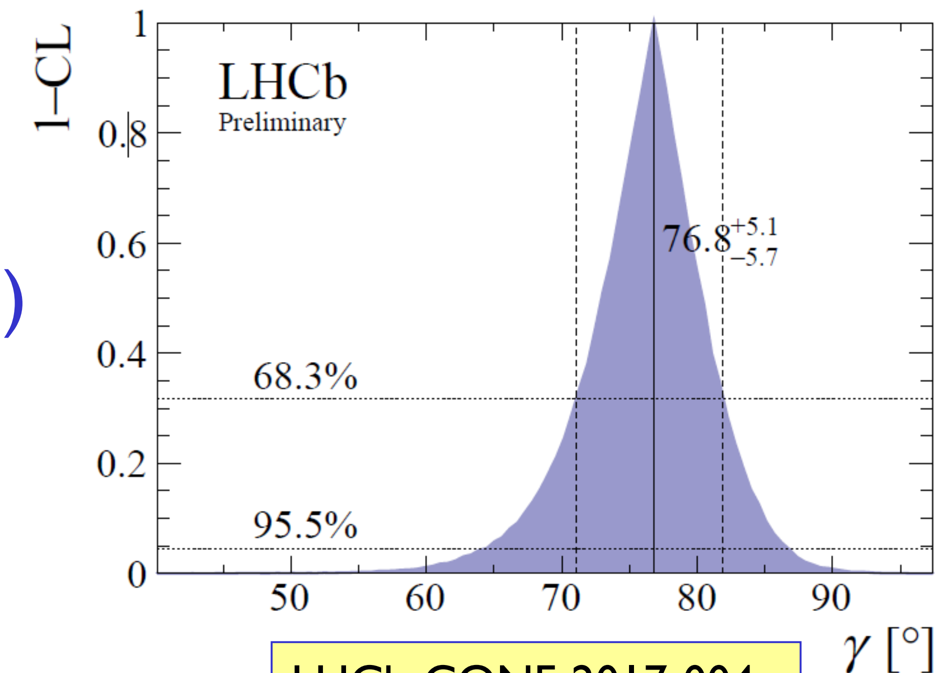


γ prospects : Run 1 → Run 2 → upgrade

- Run 1 target of 8° attained : (analyses now mostly complete)
- Run 2 data incoming
- Run 2 : target 4° (7-8 fb^{-1})
- LHCb Upgrade : target 0.9° (~50 fb^{-1})

EPJC (2013) 73:2373

$$\gamma = (76.8^{+5.1}_{-5.7})^\circ \text{ (preliminary)}$$

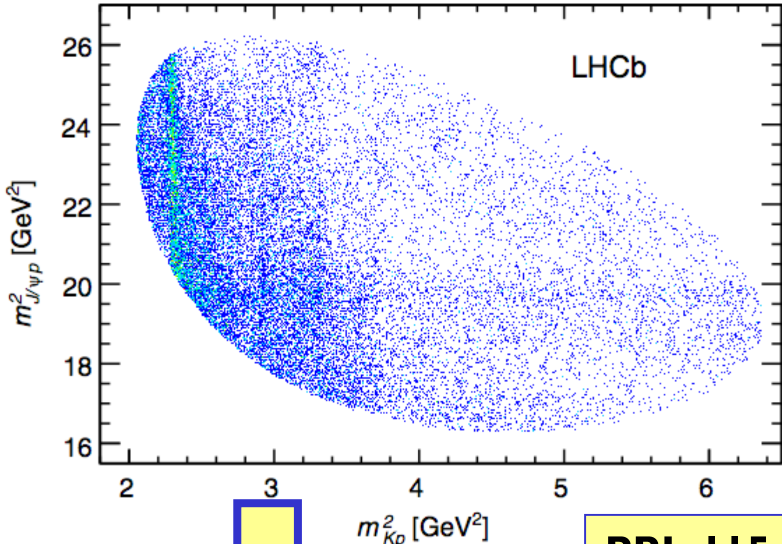


LHCb-CONF-2017-004

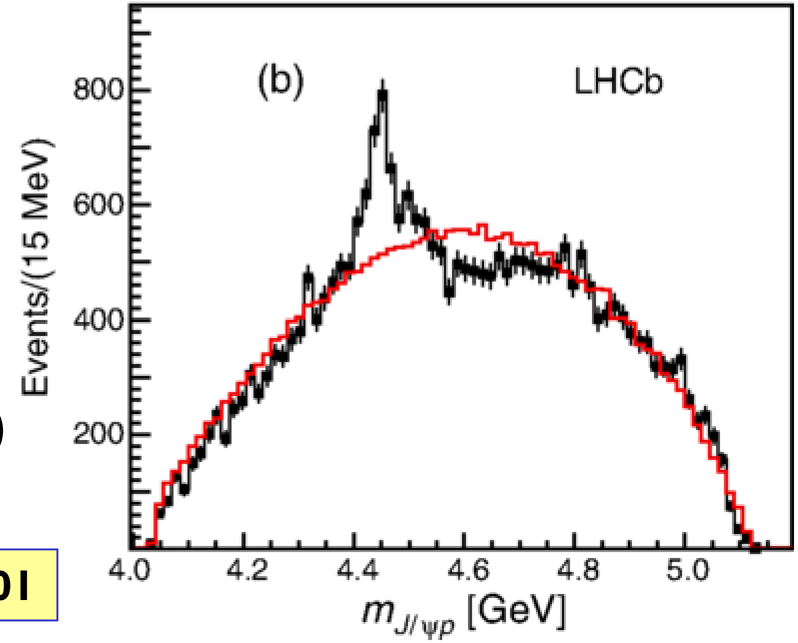
Spectroscopy highlights

Pentaquarks

Observed in 2015→ LHC Run 1 data : 3 fb^{-1}

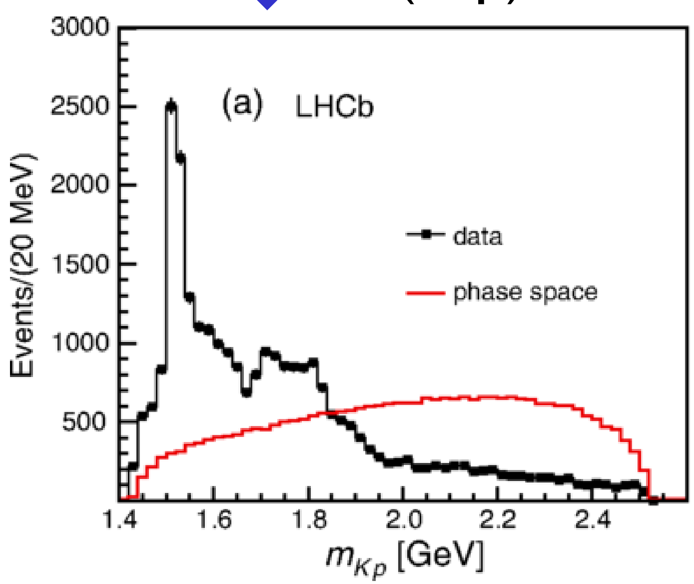


m(J/ψ p)



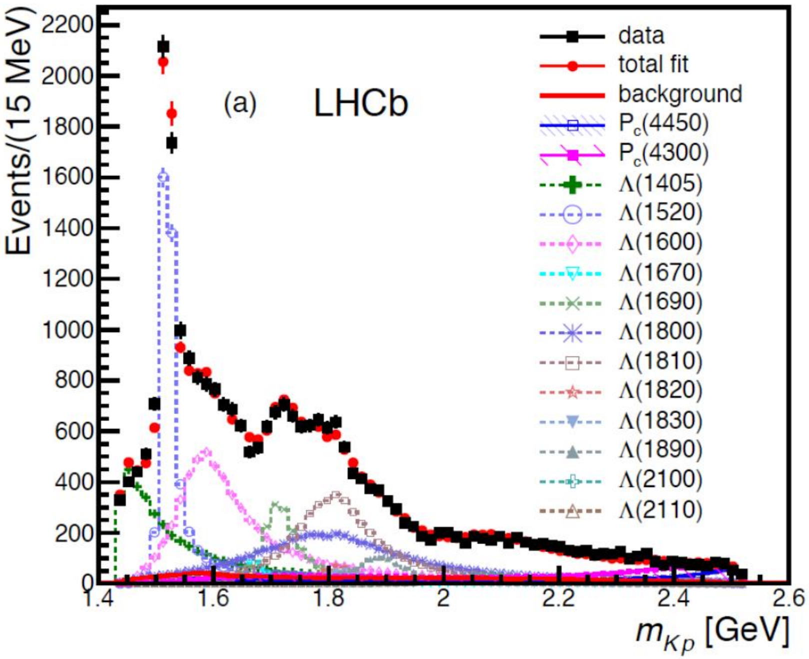
m(K p)

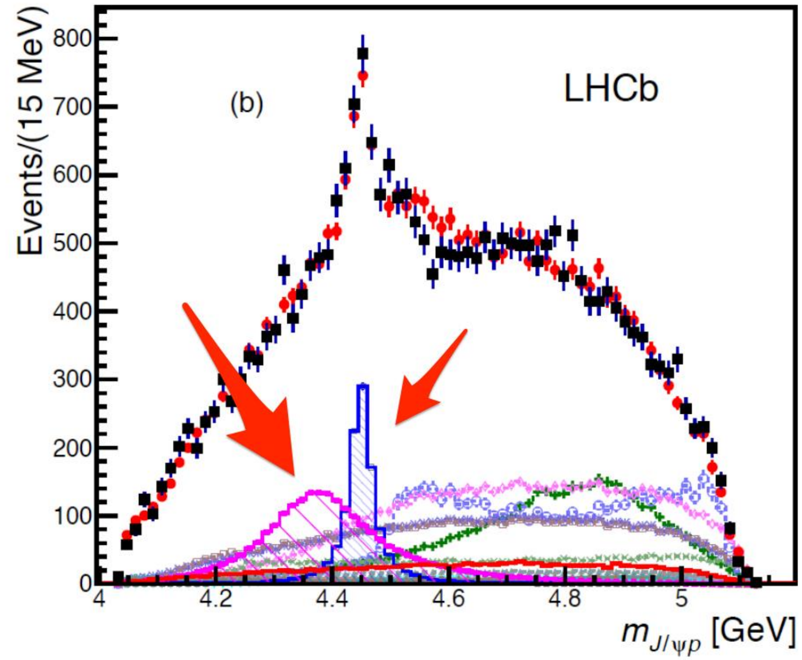
PRL 115 (2015) 072001

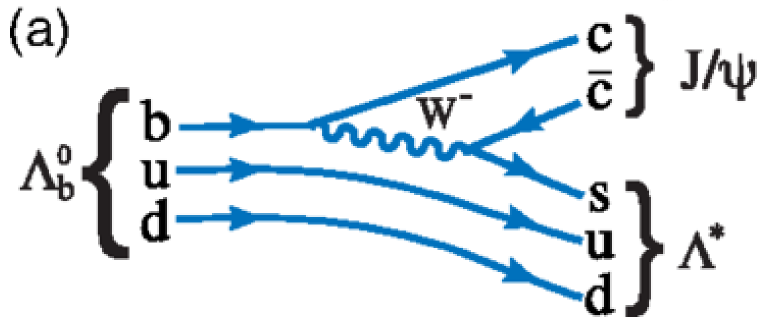


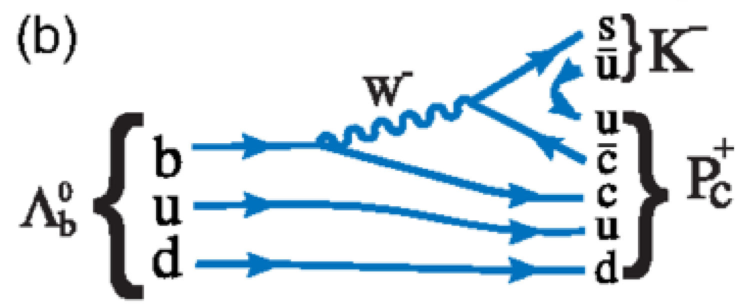
- Observation of unexpected narrow resonance in mass spectrum of (J/ψ p) where $\Lambda_b \rightarrow$ (J/ψ p) K$^-$
- Consistent with pentaquarks: allowed by QCD, but not observed after 50 years of searching.

Pentaquarks – full amplitude analysis







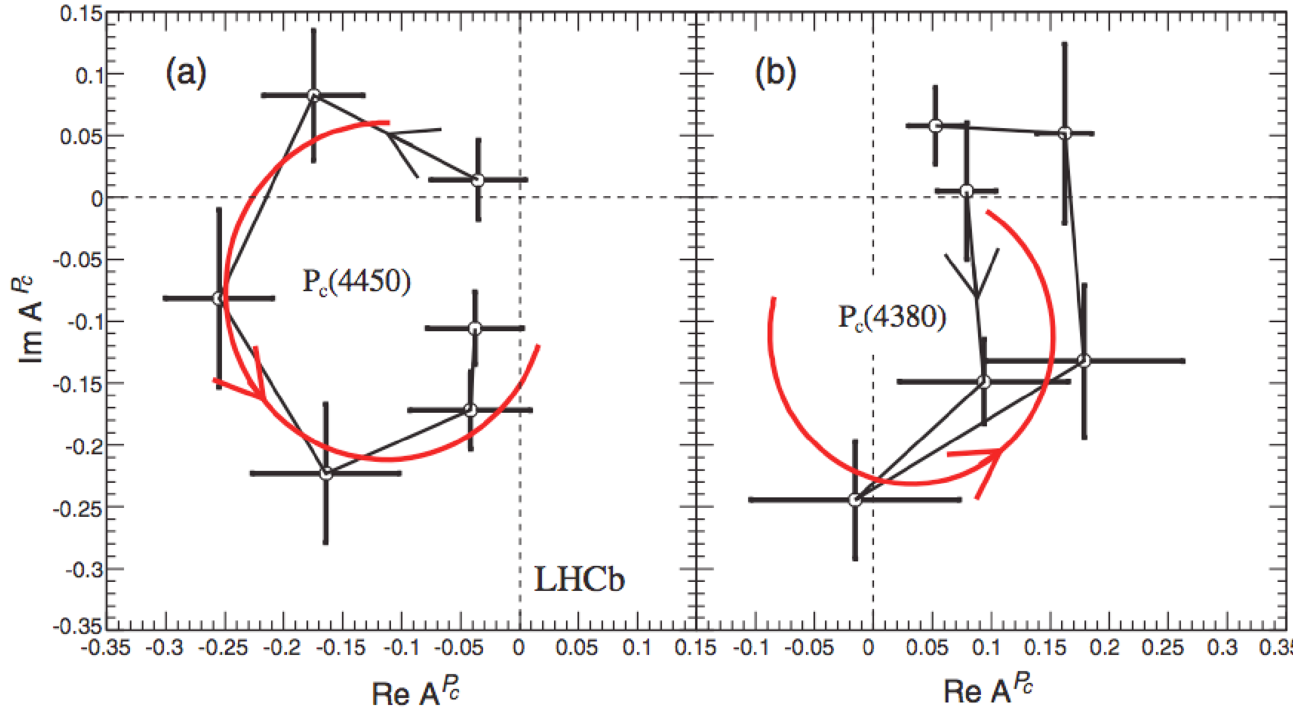


$P_c^+(4380)$: M = 4380±8±29 MeV , Γ = 205±18±86 MeV — **9 σ**

$P_c^+(4450)$: M = 4449.8±1.7±2.5 MeV , Γ = 39±5±19 MeV — **12 σ**

Pentaquarks J^P assignments

Argand diagram



- The preferred J^P assignments are of opposite parity, with $P_c^+(4380)$ having $3/2^-$ and the $P_c^+(4450)$ having $5/2^+$
- Good evidence for the resonant character of $P_c^+(4450)$ Too large errors for $P_c^+(4380)$: hard to make a definitive conclusion

PRL 115 (2015) 072001

Pentaquarks in $\Lambda_b \to (J/\psi\ p)\ K^-$

- Search for additional Pentaquark candidates in other production channels
- $\Lambda_b \to (J/\psi\ p)\ \pi^-$ (Cabbibo suppressed ≈ 15 times smaller statistics)
- Contributions from:

  $N^* \to p\pi^-$

  $P_c(4380)^+ \to J/\psi\ p$

  $P_c(4450)^+ \to J/\psi\ p$

  $Z_c(4200)^- \to J/\psi\ \pi^-$

- Fit with 2 pentaquarks + $Z_c(4200)$ tetraquark : favoured by 3σ compared to no exotic contributions

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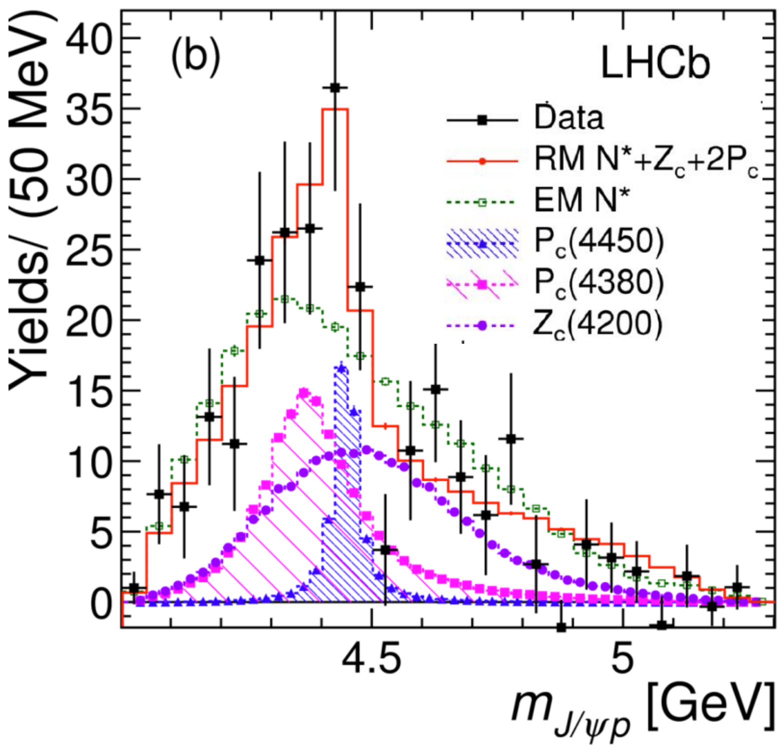
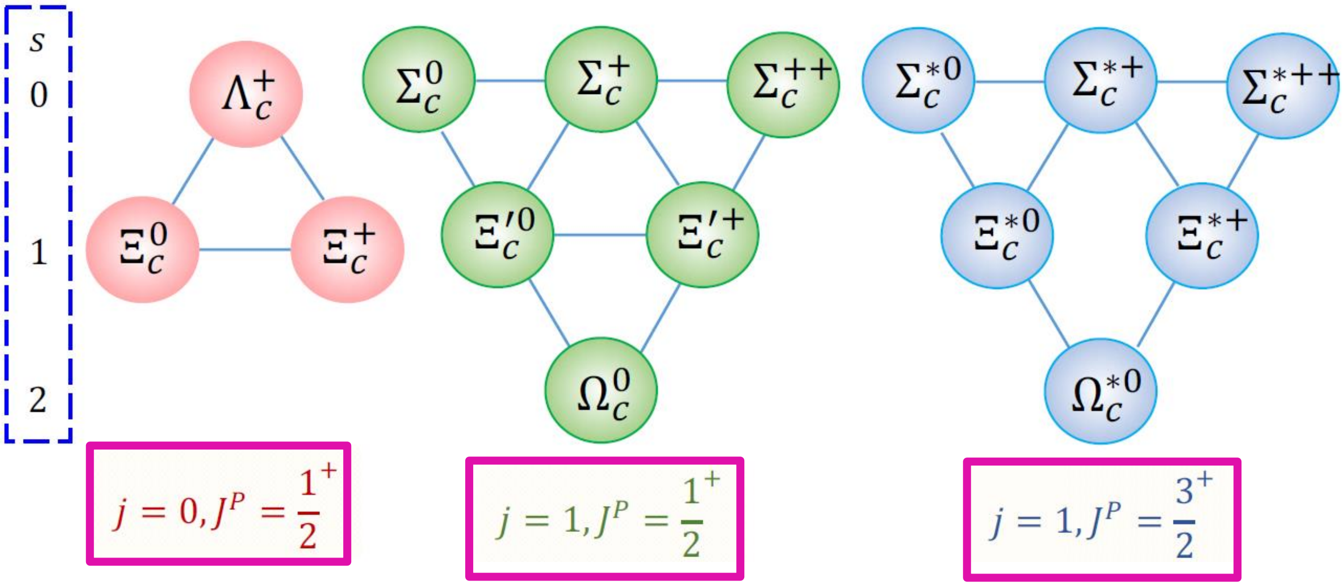


Observation of Ω_c excited states

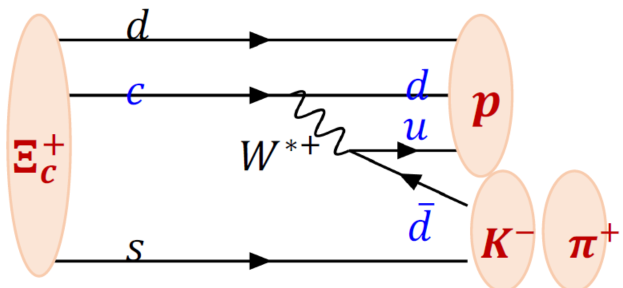
- Single charmed baryons predicted to form SU(3) baryon multiplets: $3 \otimes 3 = \bar{3} \oplus 6$ (Jaffe, Phys. Rep. 409 (2005) 1)
- All ground states have been observed, as have excited states Λ_c, Σ_c and Ξ_c

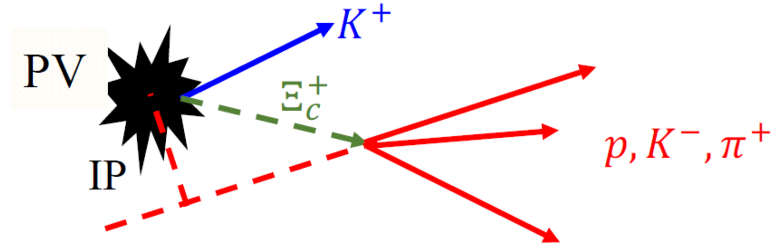


- LHCb: 3 fb^{-1} Run I + 0.3 fb^{-1} Run II pp collisions data

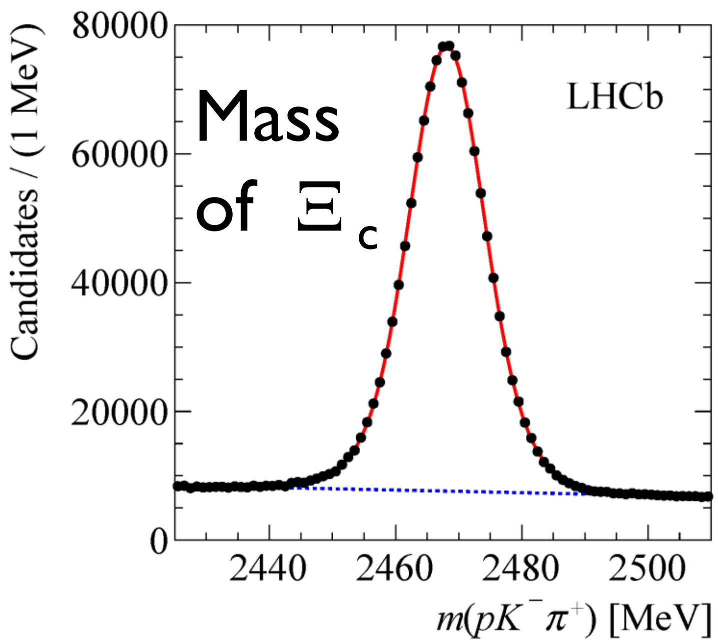
Observation of five new narrow Ω_c^0 excited states

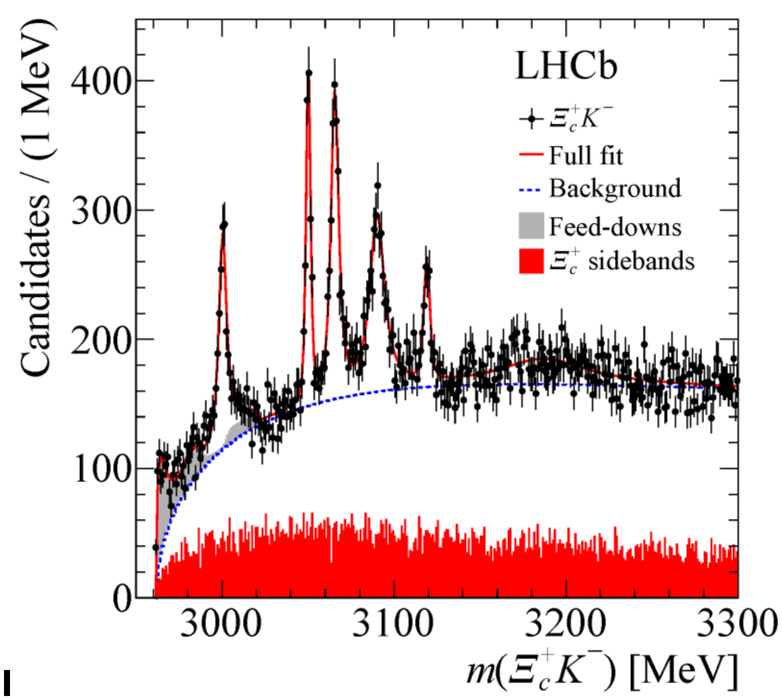
- Decay : Ω_c^{0*} (css) $\rightarrow \Xi_c^+$ (csu) K^- ; Ξ_c^+ (csu) $\rightarrow pK^-\pi^+$





- Decay well separated from primary vertex $\tau(\Xi_c) \approx 45$ ps





LHCb, PRL 118 (2017) 182001

Masses and widths

LHCb, PRL 118 (2017) 182001

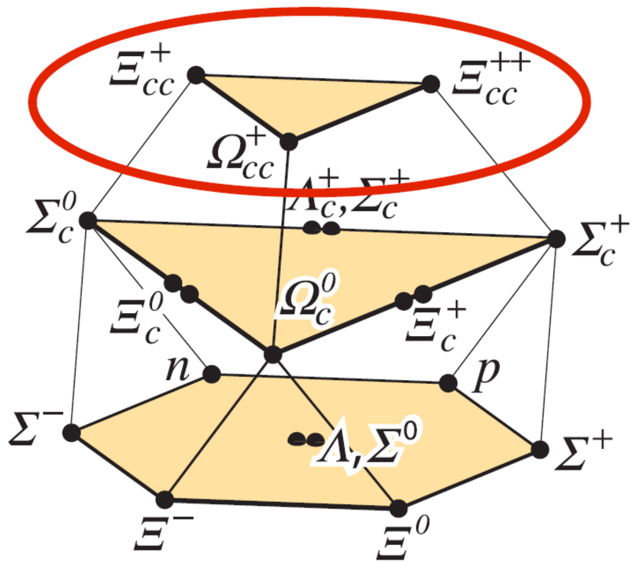
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		$< 1.2\,\text{MeV}, 95\%$ CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		$< 2.6\,\text{MeV}, 95\%$ CL
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

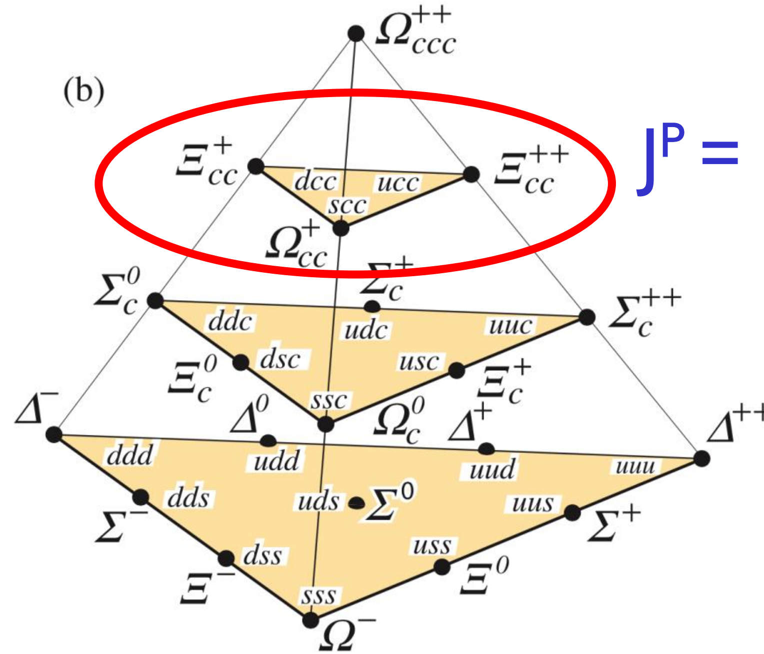
- 5 narrow states & evidence for 6th broader state at high mass
- Assignment of J^P states in the quark model (see backup slides)
  (M. Karliner, J.L. Rosner, PR D95, 114012 (2017))
- Suggestion the 2 narrowest states might be pentaquarks ?
  (Michał Praszałowicz et al Phys.Rev. D96 (2017) 014009)
- Confirmation of states awaits spin-parity assignments

Search for the doubly charmed baryon Ξ_{cc}^{++}

- The quark model predicts three weakly decaying $C = 2$ $J^P = ½^+$ states: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, and $\Omega_{cc}^{+}(ccs)$
- $J^P = ½^+$ states decay weakly with a c quark to lighter quarks
- $J^P = {}^3/_2{}^+$ states expected to decay to $½^+$ states via strong or EM interaction

$J^P = {}^1/_2{}^+$

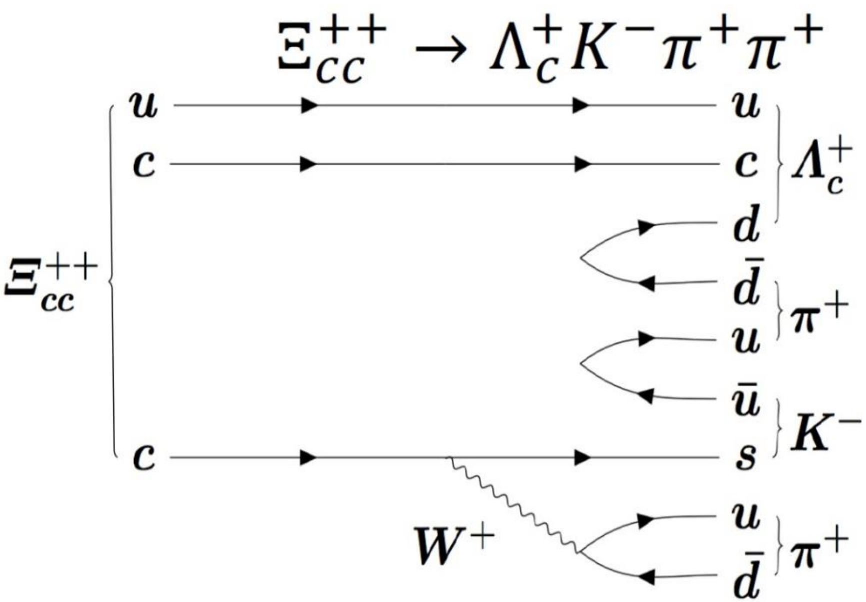


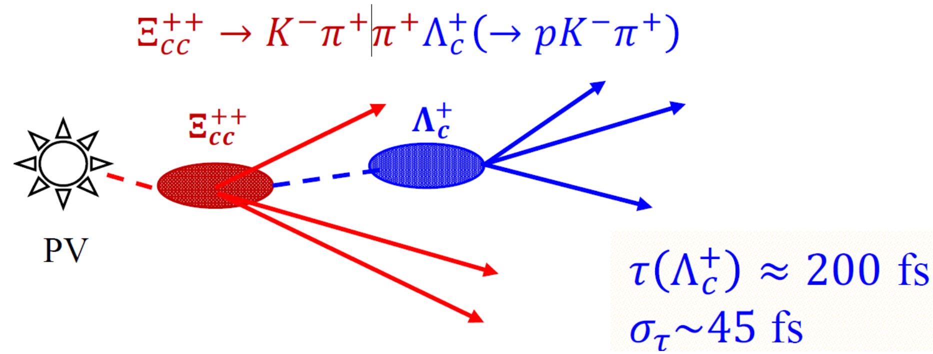


$J^P = {}^3/_2{}^+$

Decay mode of Ξ_{cc}^{++}

- Search in decay mode : $\Xi_{cc}^{++} \rightarrow \Lambda_c K^- \pi^+ \pi^+$ Branching fraction can be significant (10%) (Yu et al., arXiv:1703.09086)
- Run 2 data sample: $\sqrt{s}$=13 TeV, ~1.7 fb^{-1}





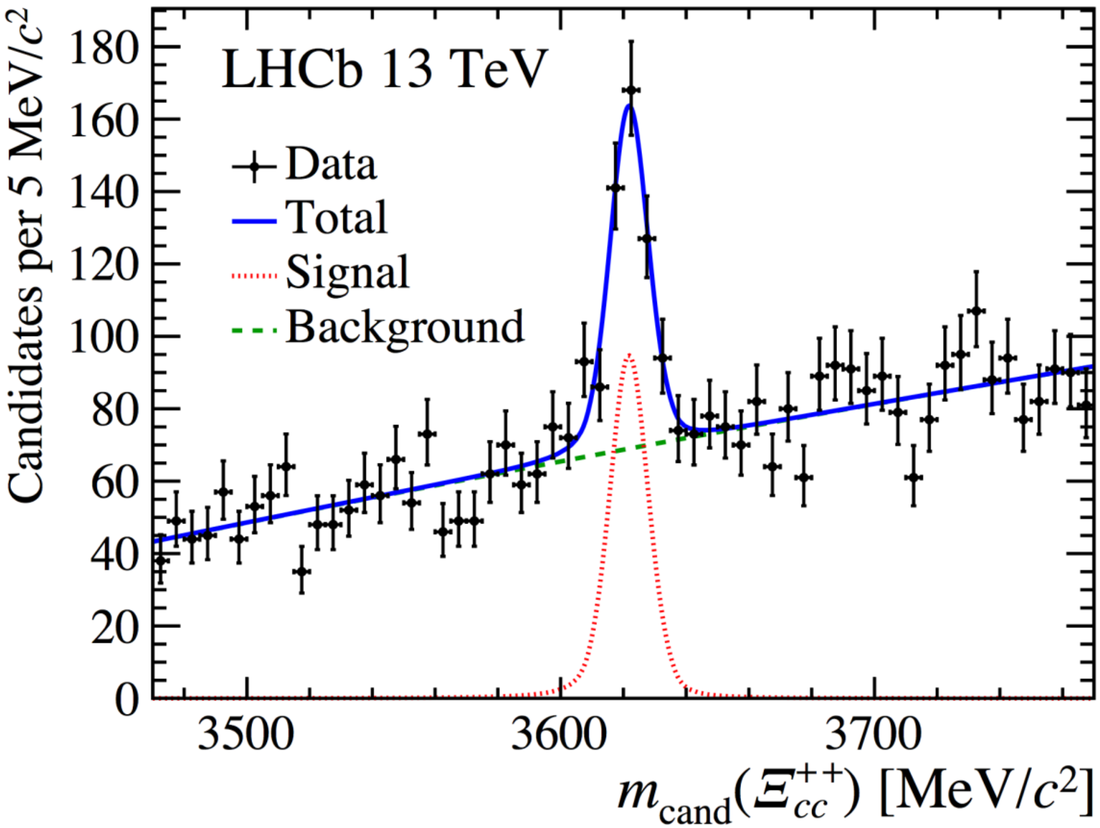
Observation of Ξ_{cc}^{++}

LHCb-PAPER-2017-018

- Ξ^{++} is Λ_c-mass corrected :

$$m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$$

- Signal yield: 313 ± 33 events
- Width 6.6±0.8 MeV, consistent with resolution
- Local significance > 12σ
- Peaking structure remains significant (> 12σ) after requiring minimum decay time, $t > 5\sigma_t \rightarrow$ weak decay



$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV

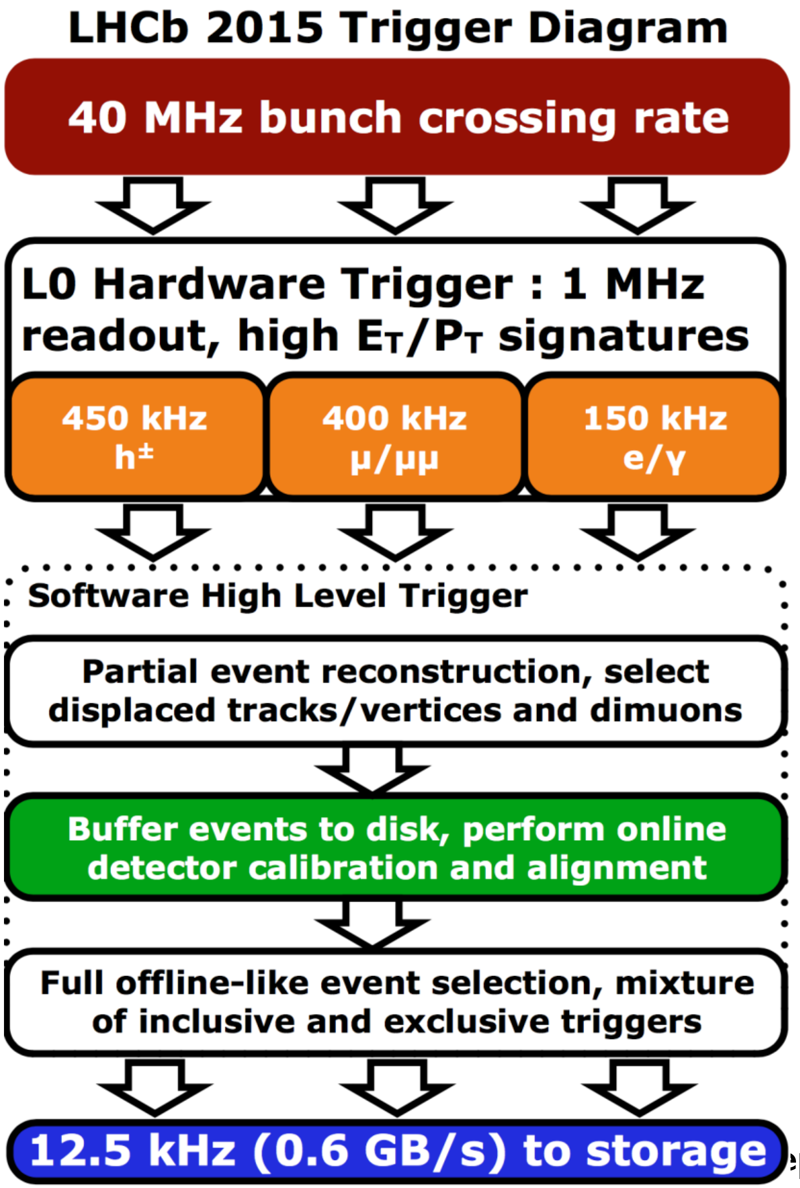
$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})$ MeV

Summary and Outlook

- The LHCb experiment is performing spectacularly well
- So far all UT measurements are in good agreement with the Standard Model
  $\longrightarrow$ new physics is becoming constrained in the flavour sector
- LHCb is a fantastic platform for spectroscopy measurements: charm baryonic resonance formation was not even in LHCb's original physics portfolio.
- Up to 2018 we expect 7-8 fb^{-1} of data, much of this will be at $\sqrt{s}$ =13 TeV at ~twice the 8 TeV heavy-flavour production cross-section
- Still much room for new physics, but higher precision required
  $\longrightarrow$ preparing for LHCb Upgrade beyond 2020 !

Spare Slides

LHCb Run 2 trigger



- After LHCb's hardware trigger, events are buffered.
- LHCb's automated real-time alignment and calibration runs :
  - Full detector alignment and calibration in minutes.
- Full event reconstruction in software trigger
  - Exclusive decay modes and calibration modes fully reconstructed,
  - Results stored and used as basis for analysis.
- See LHCb-PROC-2015-011

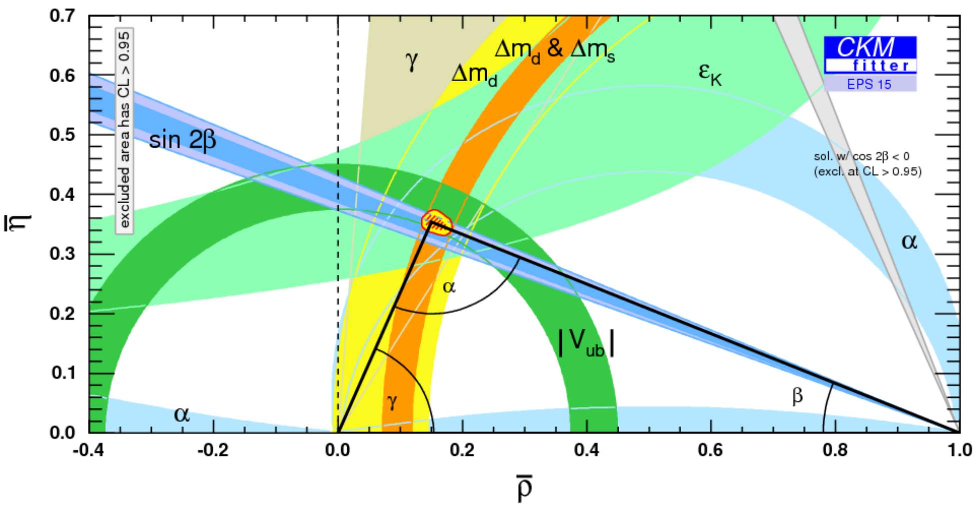
Measurement of α

- Constraints on α from B→π π, ρπ and ρρ (Babar and Belle)
- $\alpha = (87.6\ ^{+3.5}_{-3.3})^\circ$ world average measurement
- Compared to the prediction from the global CKM fit (not including the α -related measurements)
  $\alpha = (90.6\ ^{+3.9}_{-1.1})^\circ$

http://ckmfitter.in2p3.fr

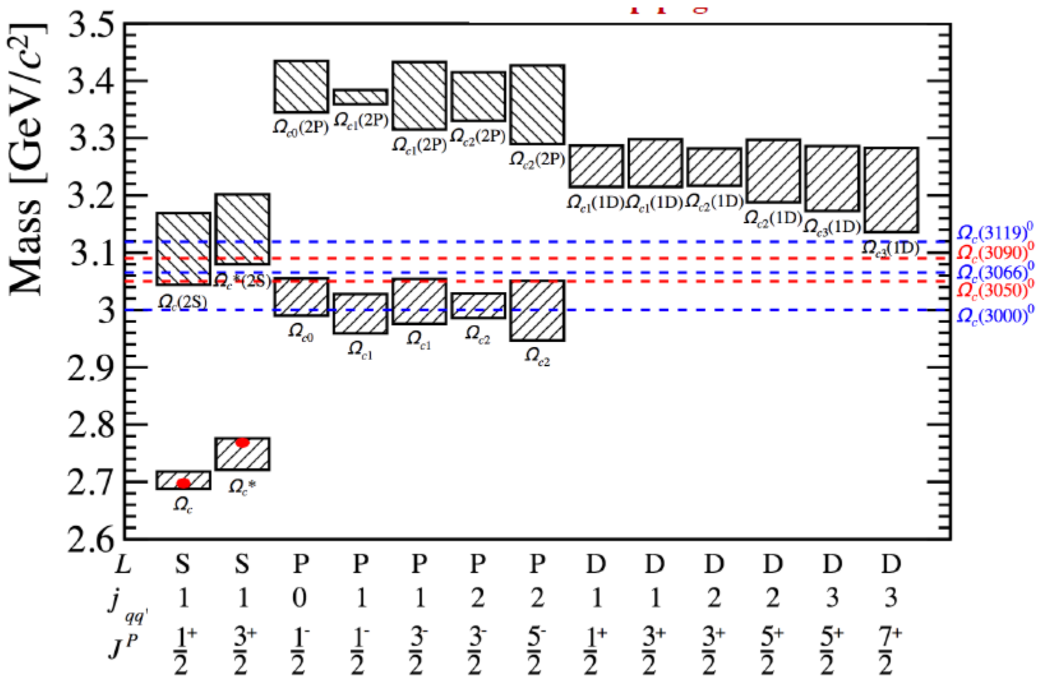
$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$

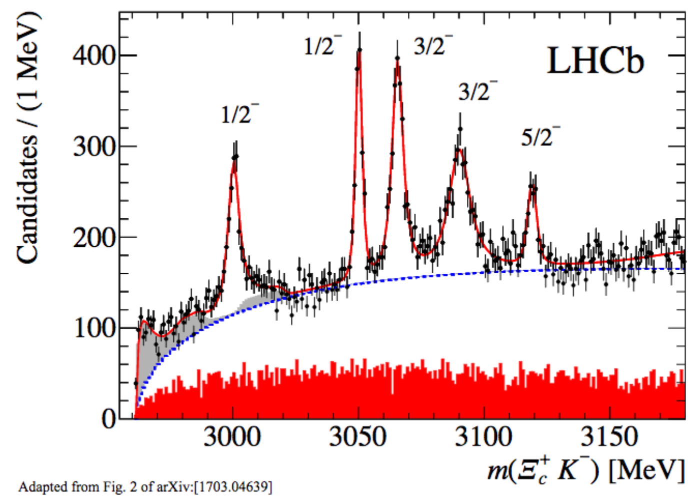
- As yet there has been no LHCb 'standalone' measurement of α
- LHCb can provide useful input to B-factories measurements to constrain alpha.



Possible assignment of excited Ω_c states

- Matching between observed peaks and predictions requires spin-parity information

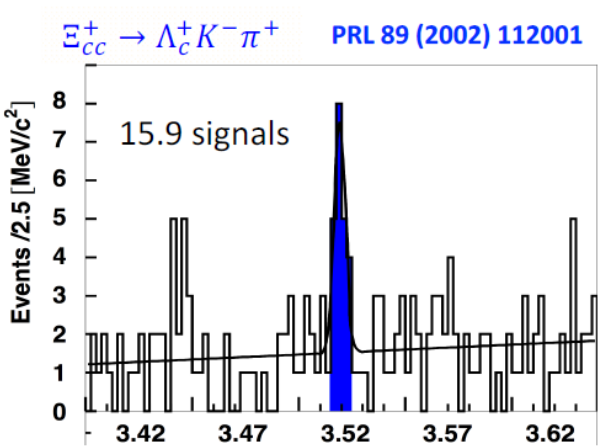


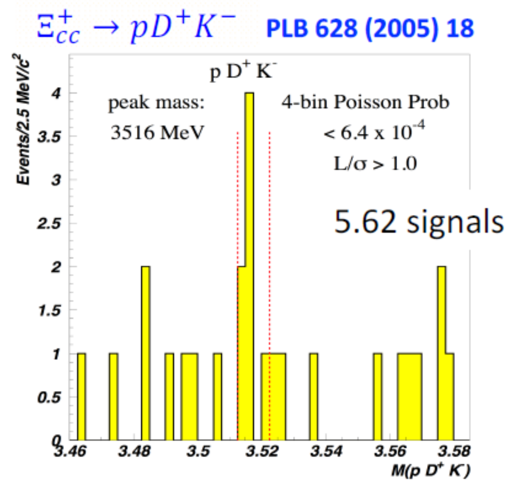


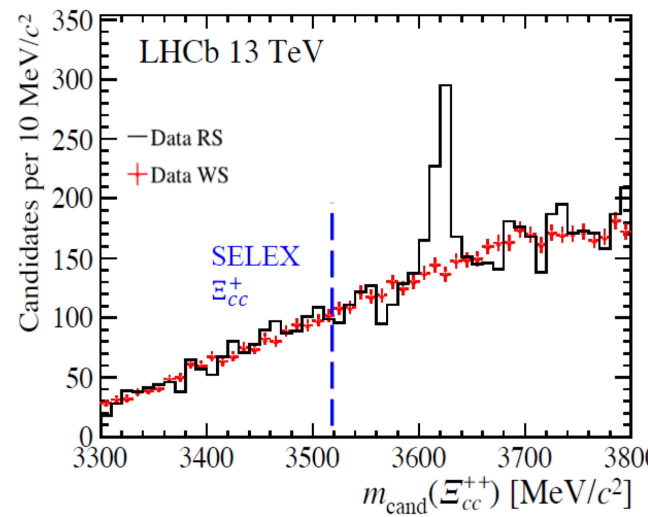
M. Karliner, J.L. Rosner, PR D95, 114012 (2017)

Comparisons with SELEX

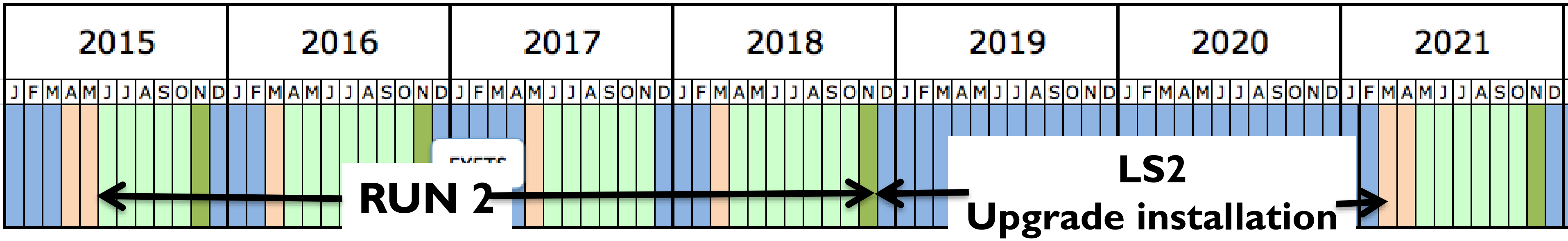
- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to pD^+K^-$ decays
- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^+)_{\text{SELEX}} = 103 \pm 2$ MeV







LHCb Upgrade : timescale



- Full upgrade in LS2
- Run at higher luminosity from 2021 onwards
  ($\sim 4 \times 10^{32}$ cm^{-2}s^{-1} $\rightarrow$ 2×10^{33} cm^{-2}s^{-1})
- L0 hardware trigger → software trigger
  - Increase efficiency for hadronic modes
- External inputs will benefit from BES-III data

LHCb upgrade projection (50 fb^{-1}) for γ is 0.9°

EPJC (2013) 73:2373

This precision will pin down all UT parameters : and hopefully New Physics