

CP VIOLATION AND CKM PHYSICS

(INCL. LHCb NEWS FROM RUN 2)

- The phases of New Physics
- First LHCb Run II data
- A tour of the unitarity triangle

On behalf of the LHCb collaboration
Including Babar, Belle, CMS and Atlas results

29/7/2015
EPS-HEP
Wien

Patrick Koppenburg



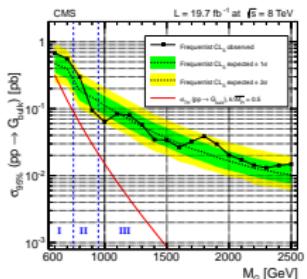
Patrick Koppenburg

CP Violation and CKM Physics

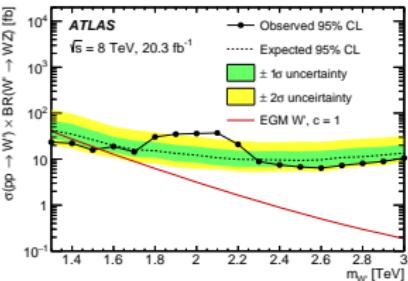


29/7/2015 — EPS-HEP [1 / 50]

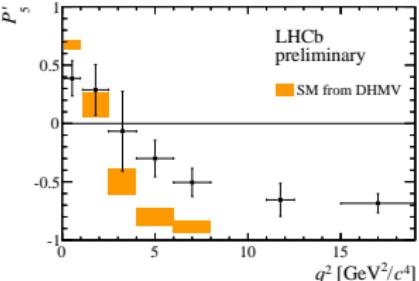
ARE WE ALREADY SEEING NEW PHYSICS?



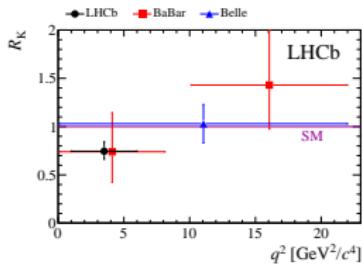
Excess at 2 TeV [CMS, JHEP 08 (2014) 174]



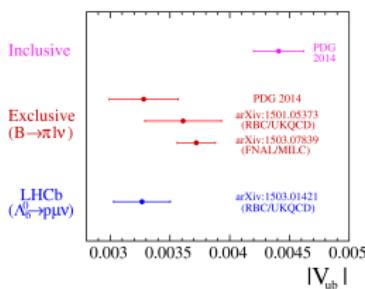
Excess at 2 TeV [Atlas, arXiv:1506.00962]



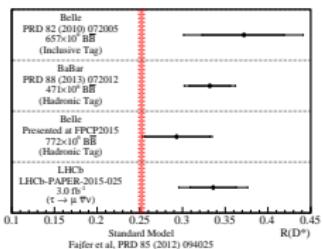
P_5 in $B \rightarrow K^* \mu^+ \mu^-$ [LHCb-CONF-2015-002]



Lepton universality [Phys. Rev. Lett. 113 (2014) 151601]



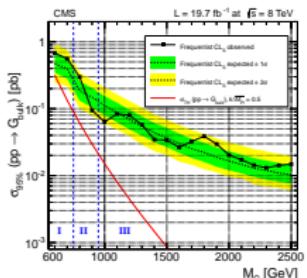
V_{ub} puzzle [Nature Physics 3415 (2015)]



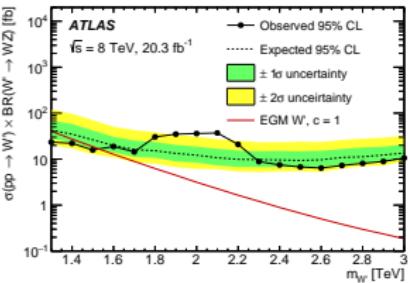
$B \rightarrow D^* \tau \nu$ [arXiv:1504.06339]

There's a handful of intriguing $3-4\sigma$ anomalies

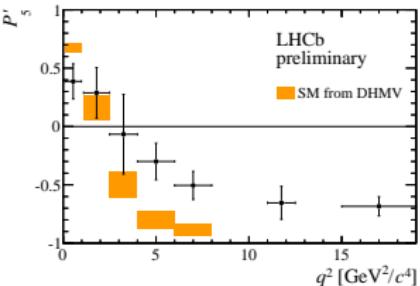
ARE WE ALREADY SEEING NEW PHYSICS?



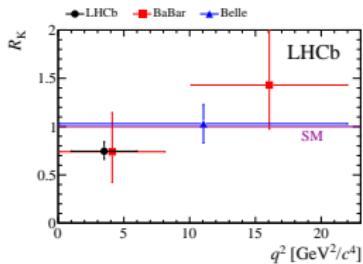
Excess at 2 TeV [CMS, JHEP 08 (2014) 174]



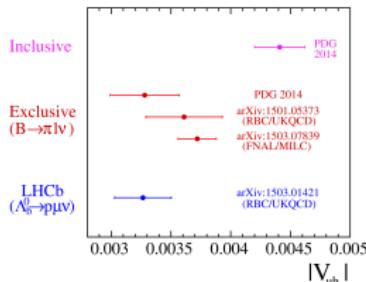
Excess at 2 TeV [Atlas, arXiv:1506.00962]



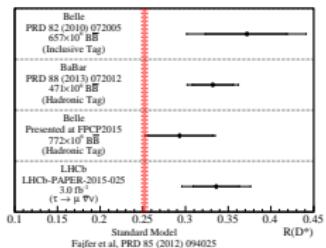
P_5 in $B \rightarrow K^* \mu^+ \mu^-$ [LHCb-CONF-2015-002]



Lepton universality [Phys. Rev. Lett. 113 (2014) 151601]



V_{ub} puzzle [Nature Physics 3415 (2015)]



$B \rightarrow D^* \tau \nu$ [arXiv:1504.06339]

→ Phases, phases, phases



CKM MATRIX

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation in $\lambda = 0.23 \sim \theta_c$ at order $\mathcal{O}(\lambda)$ (Cabibbo):

$$\begin{pmatrix} 1 & \lambda \\ -\lambda & 1 \end{pmatrix}$$

CKM MATRIX



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation in $\lambda = 0.23 \sim \theta_c$ at order $\mathcal{O}(\lambda^3)$:

$$\begin{pmatrix} 1 & -\frac{1}{2}\lambda^2 & \lambda \\ -\lambda & 1 & -\frac{1}{2}\lambda^2 \\ A\lambda^2 & -A\lambda^2 & 1 \end{pmatrix}$$

Labels in the matrix:
1
 $-\frac{1}{2}\lambda^2$
 λ
 $A\lambda^2(\rho - i\eta)$
 $A\lambda^2[1 - (\rho - i\eta)]$
 $-A\lambda^2$

CKM MATRIX



If η is the only CP -violating phase affecting quarks this picture should be consistent at all levels.

Wolfenstein

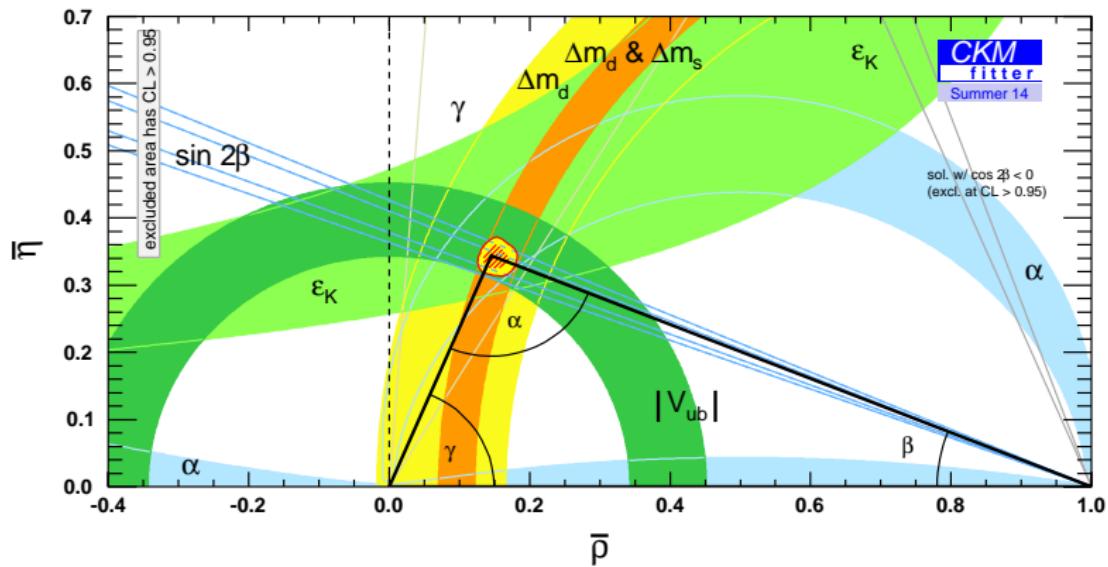
→ Let's check!

$$\left(\begin{array}{ccc} 1 & -\frac{1}{2}\lambda^2 & A\lambda^2(\rho - i\eta) \\ -\lambda & 1 & -A\lambda^2 \\ A\lambda^2[1 - (\rho - i\eta)] & -A\lambda^2 & 1 \end{array} \right)$$

UNITARITY TRIANGLE

“The” unitarity triangle exploits the relation

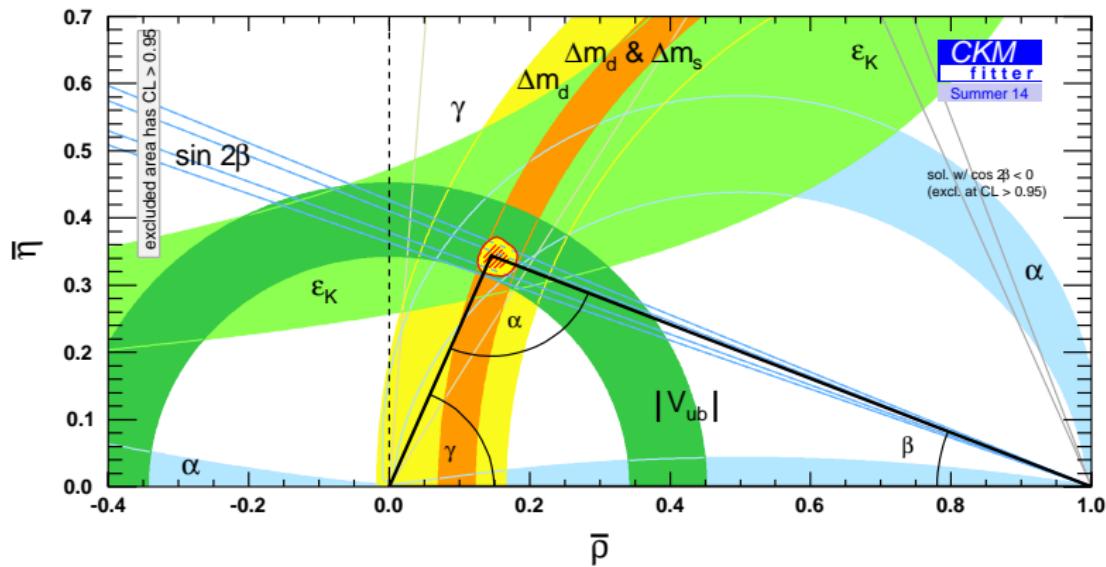
$$V_{ud} V_{ub}^* + V_{cb} V_{cb}^* + V_{td} V_{tb}^* = 0$$



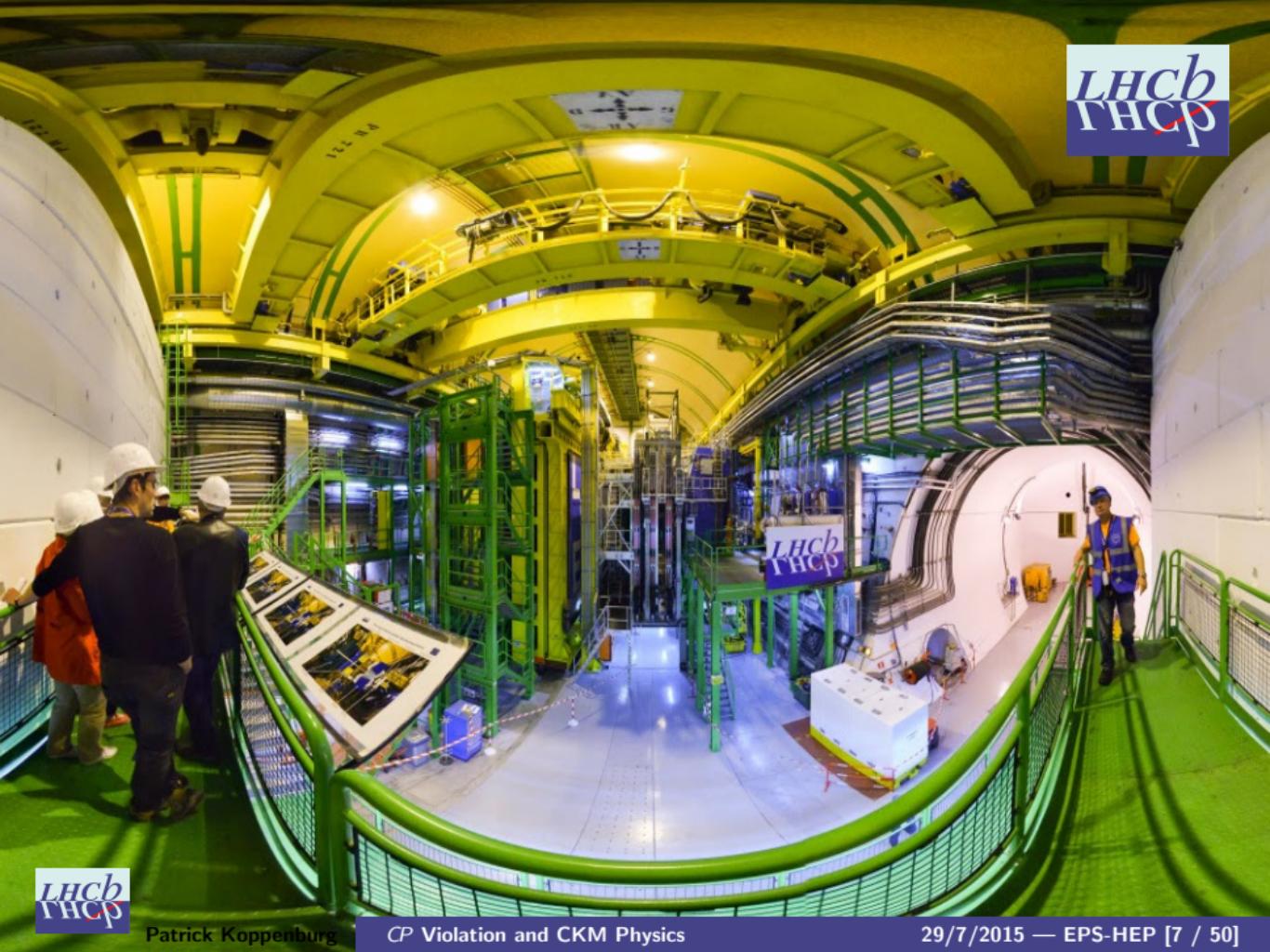
UNITARITY TRIANGLE

It all started with kaons.

Now the input from kaons needs theory input. See [Soni's talk]



We need more



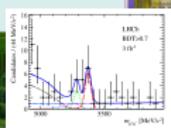
LHCb PHYSICS PROGRAMME



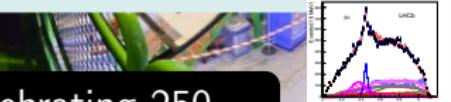
CKM and CP violation
with b and c hadrons



Rare decays of b hadrons
and c hadrons



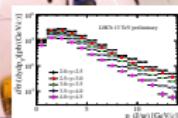
Spectroscopy in pp
interactions and B decays



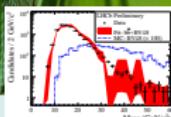
Celebrating 250
publications!



Electroweak and QCD
measurements in the
forward acceptance



Heavy quark production



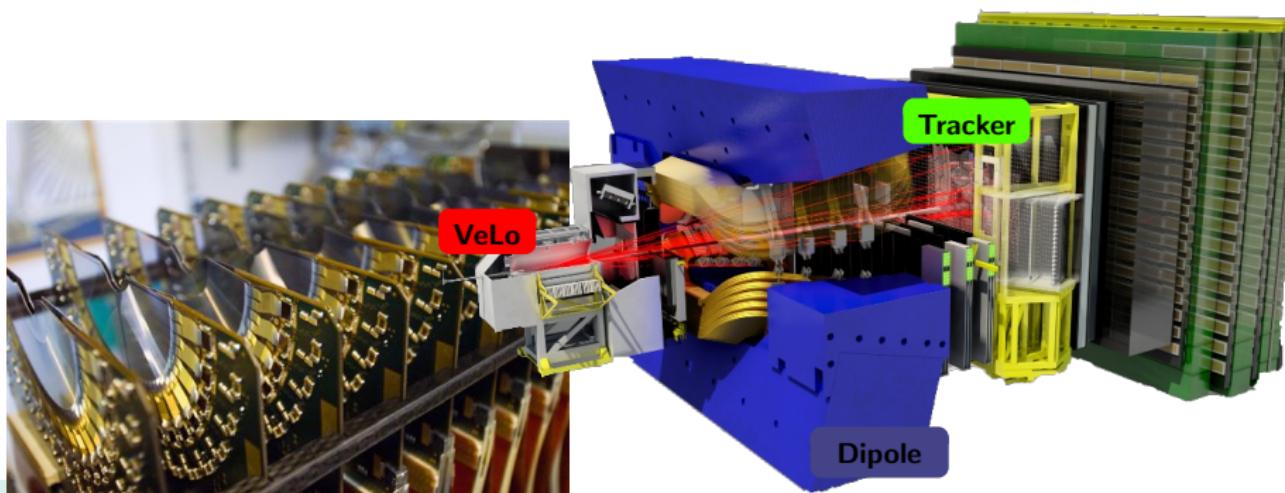
Exotica searches

LHCb DETECTOR



Forward detector (many b hadrons produced forward at LHC, $(75 \pm 5 \pm 13) \mu\text{b}$ in acceptance [Physics Letters B 698 (2011) 14, arXiv:1102.0348])

- Warm dipole magnet. Polarity can be reversed
- ✓ Good momentum and position resolution
 - Vertex detector gets 8mm to the beam

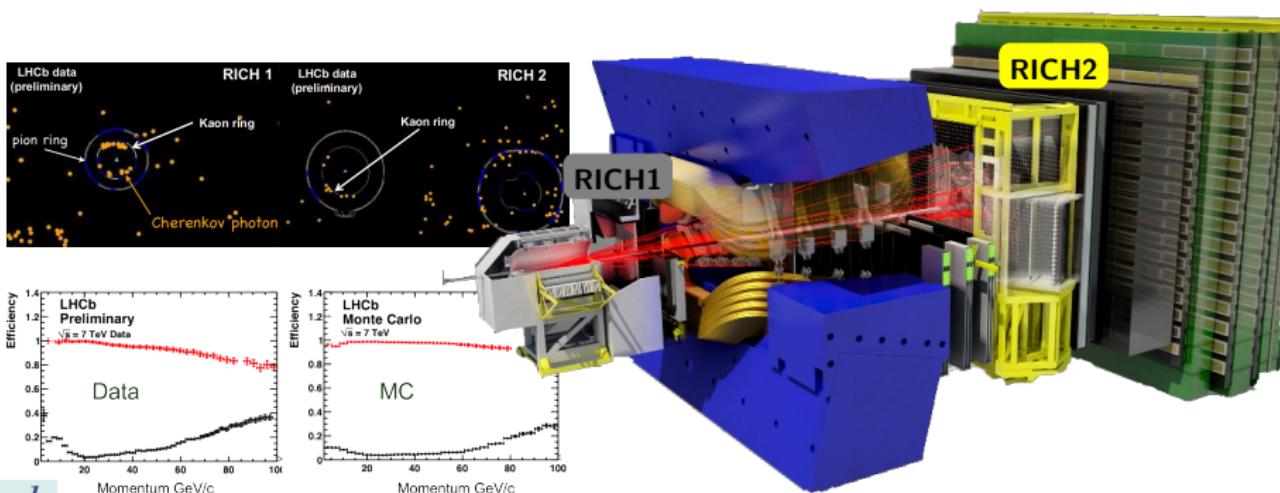


LHCb DETECTOR



Forward detector (many b hadrons produced forward at LHC, $(75 \pm 5 \pm 13) \mu\text{b}$ in acceptance [Physics Letters B 698 (2011) 14, arXiv:1102.0348])

- Warm dipole magnet. Polarity can be reversed
- ✓ Good momentum and position resolution, high efficiency
- ✓ Excellent Particle ID

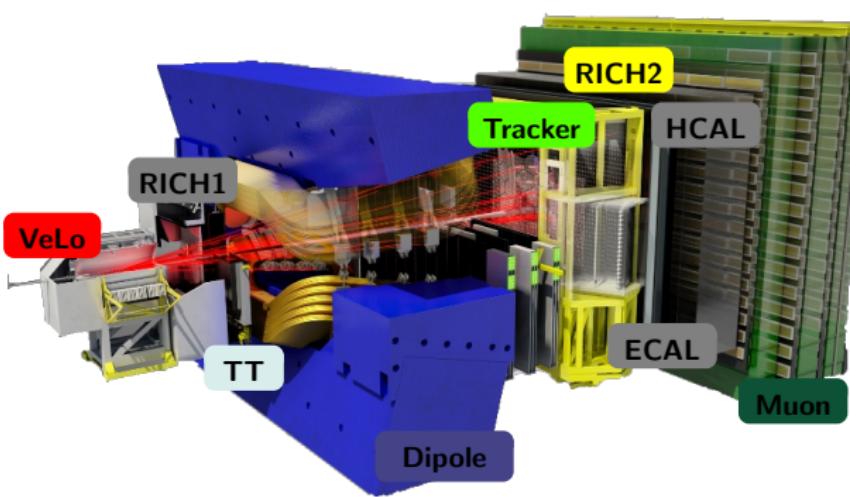
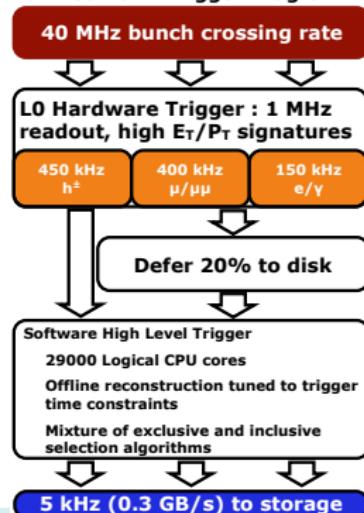


LHCb Trigger

Versatile two stage trigger

- Hardware-based L0 trigger: moderate p_T cuts → 1 MHz
- Whole data sent to trigger farm
- 3 kHz output rate (2011), 5 kHz in 2012 (some of it deferred)

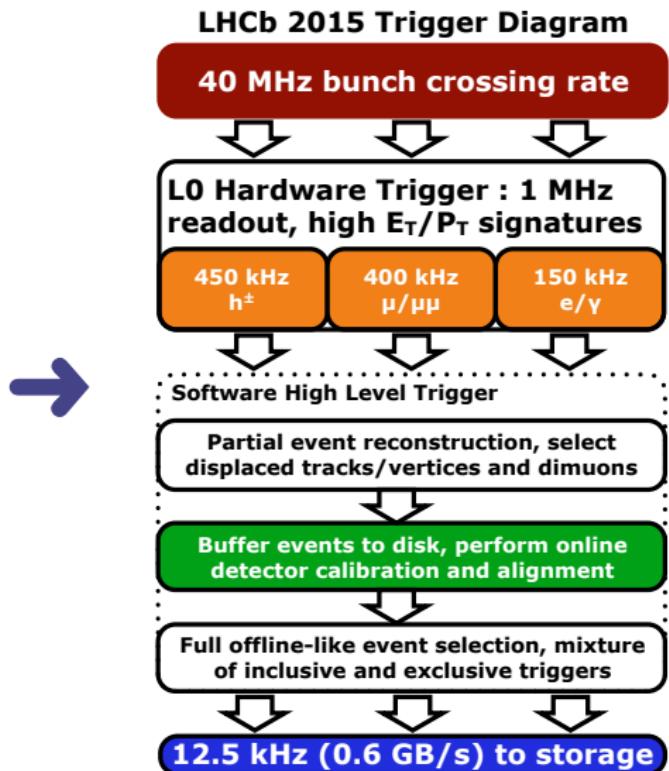
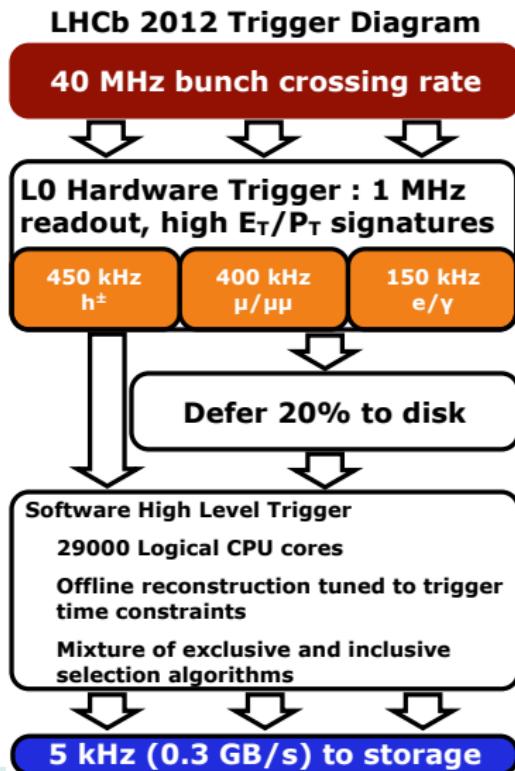
LHCb 2012 Trigger Diagram



Run II



LHCb Trigger in Run II



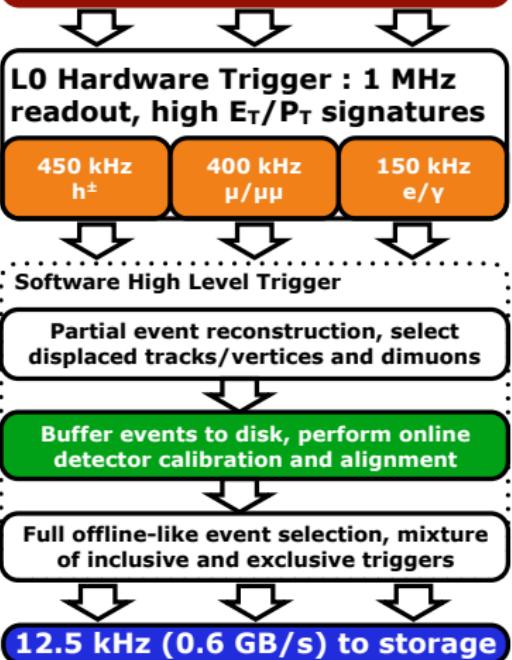
LHCb TRIGGER IN RUN II

New in 2015: Introducing the TURBO stream

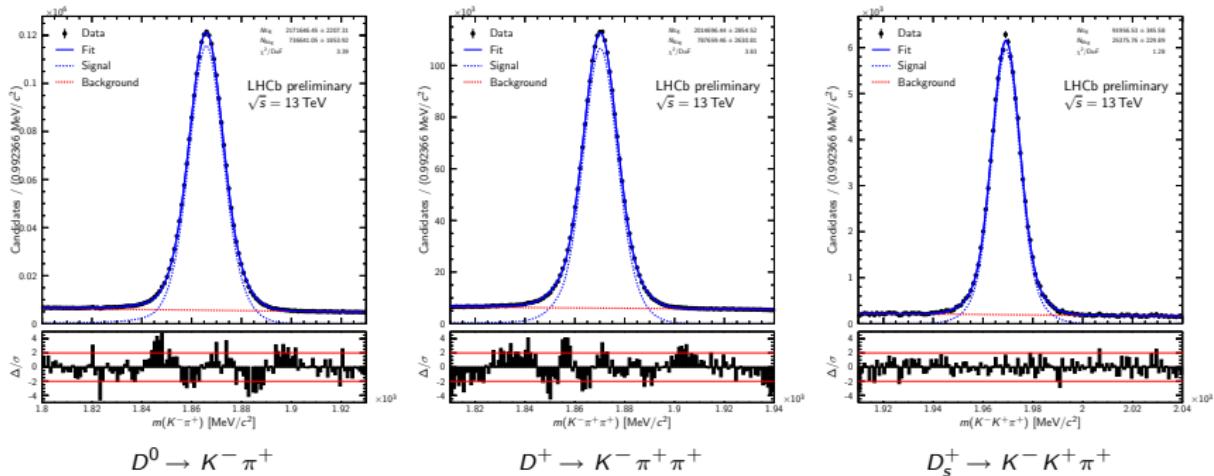
- 5 kHz of 12 kHz go to TURBO:
- Only trigger information is saved: tracks and vertices that caused the event to trigger
 - No raw event — no offline reconstruction
- ✓ Smaller events, faster analysis
- Used for high yield exclusive trigger lines : J/ψ , D^0 , D^+ ...

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate



CHARM FROM FIRST JULY 2015 RUN



- Charm hadrons from TURBO stream
- Hardly any background
- The yields per pb are much larger than in Run I (and that's mostly the trigger)

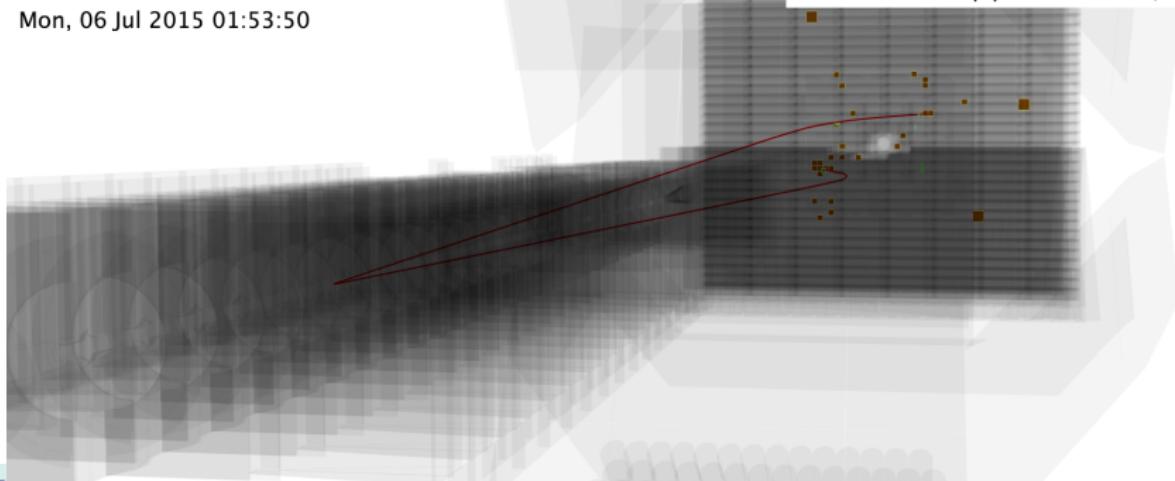
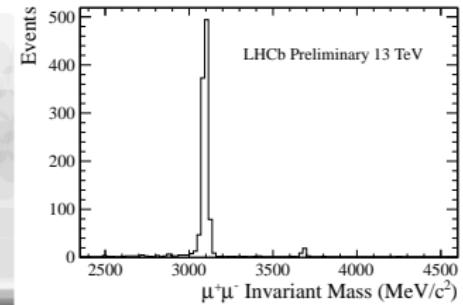
CENTRAL EXCLUSIVE $J/\psi \rightarrow \mu^+ \mu^-$



Event 92298607

Run 157027

Mon, 06 Jul 2015 01:53:50



J/ψ cross-section at 13 TeV



13 TeV LUMINOSITY



[The Onion]



airwater giveaway

AV CLUB

Courtesy: Google Maps

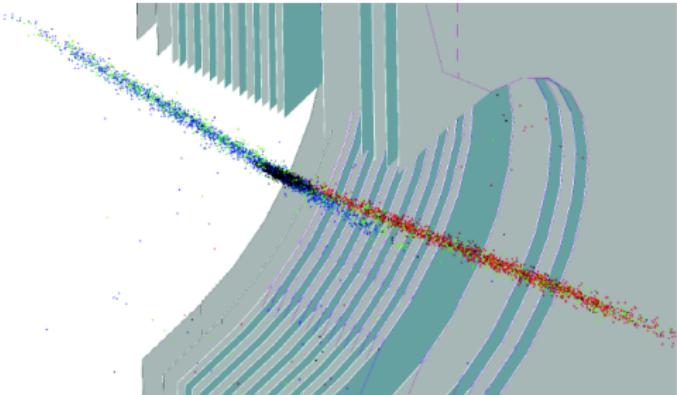
27 KILOMETER CIRCUMFERENCE

Tech Trends CERN: "THERE'S GOT TO BE SOMETHING ELSE TO DO WITH THIS HADRON COLLIDER" LIVE ON CNN

TOP NEWS NASA Says It's Only... SHARE by From Flying Mars Landing

0:26 / 1:53

Bored Scientists Now Just Sticking Random Things Into Large Hadron Collider 1:53

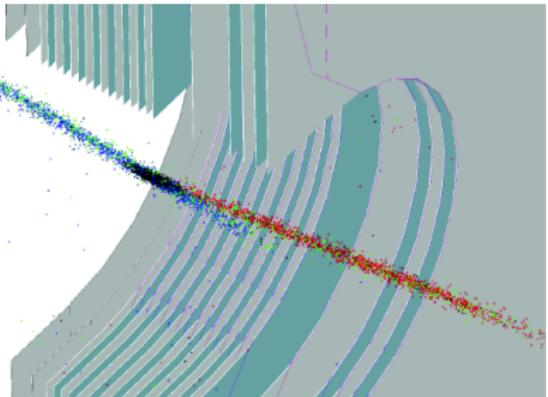


- The luminosity at 8 TeV was measured with two methods: Beam-gas imaging (BGI) and VdM scan [[JINST 9 \(2014\) P12005](#)]
- In the BGI method we use neon injected in the beam pipe to reconstruct the beams

13 TeV LUMINOSITY



$$\mu^{\text{ref}} = \sigma^{\text{ref}} \times \underbrace{N_1 N_2}_{\text{Bunch intensity}} \times \text{Overlap}$$

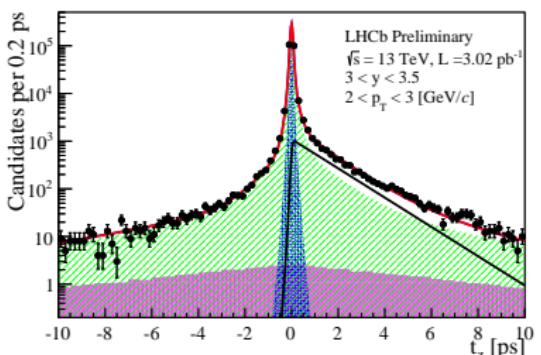
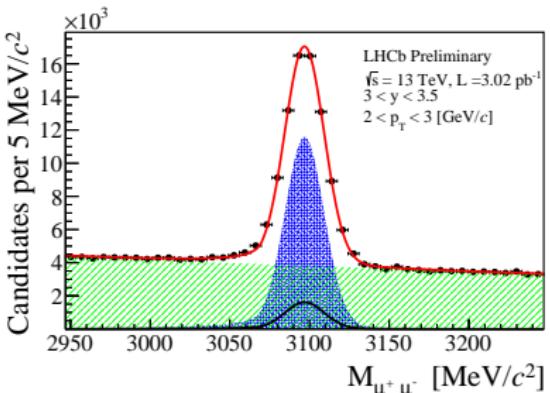


- μ^{ref} is the average number of interactions per crossing
- N_i are the bunch intensities from Direct Current Current Transformers (DCCT) and Fast Beam Current Transformer (FBCT)
- The Overlap is determined from beam gas imaging (BGI)

$$\sigma_{13 \text{ TeV}}^{\text{ref}} = 64.2 \pm 2.5 \text{ mb (3.9\%)} \text{ [LHCb preliminary]}$$

$$\sigma_{8 \text{ TeV}}^{\text{ref}} = 62.7 \pm 0.7 \text{ mb (1.1\%)} \text{ [JINST 9 (2014) P12005]}$$

J/ψ CROSS SECTION AT $\sqrt{s} = 13$ TeV

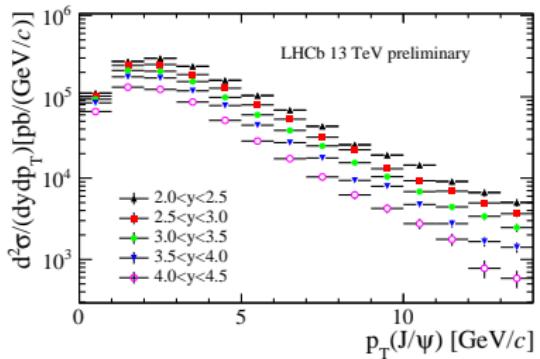
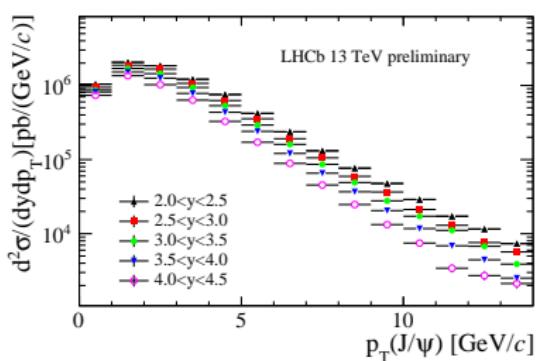


- The trigger found $10^6 J/\psi \rightarrow \mu^+ \mu^-$ in $3.02 \pm 0.12 \text{ pb}^{-1}$ with J/ψ $p_T < 14 \text{ GeV}/c$ and $2 < y < 4.5$
- Analysis based on trigger candidates — No offline processing
 - Mass resolution of $\sim 12 \text{ MeV}/c^2$, compatible with Run I data
- Data is binned in p_T and y and the pseudo decay time

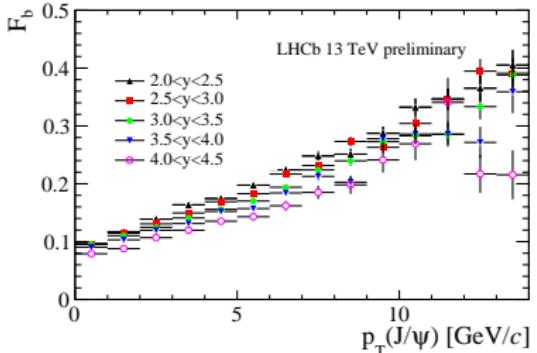
$$t_z = \frac{(z_{J/\psi} - z_{PV})M_{J/\psi}}{p_z}$$

is used to determine the fraction of J/ψ -from- b

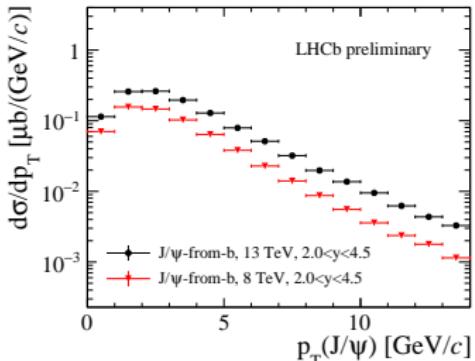
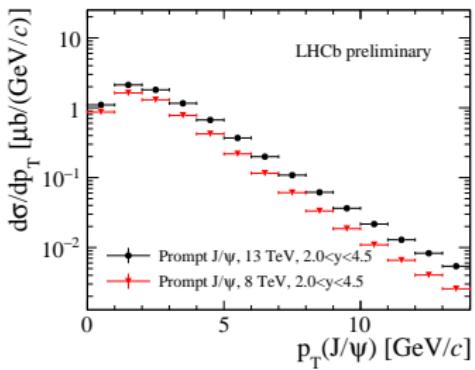
J/ψ CROSS SECTION AT $\sqrt{s} = 13$ TeV



Double-differential cross-sections are determined in J/ψ $p_T < 14$ GeV/c and $2 < y < 4.5$



J/ψ CROSS SECTION AT $\sqrt{s} = 13$ TeV

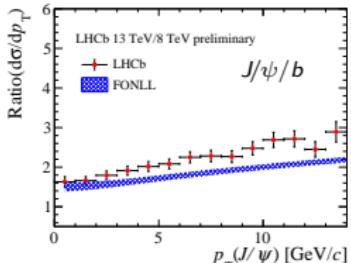
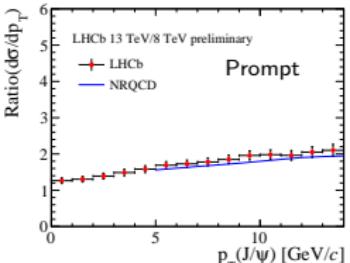


Double-differential cross-sections are determined in J/ψ $p_T < 14$ GeV/ c and $2 < y < 4.5$

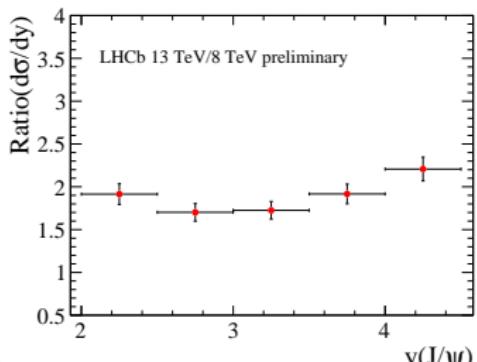
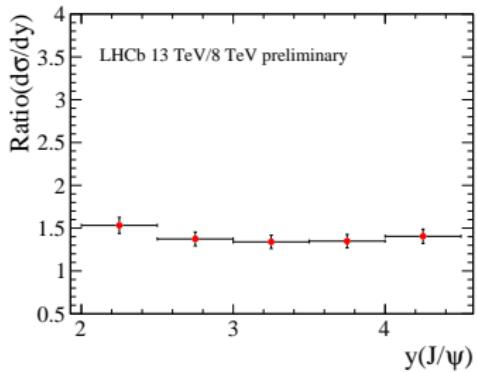
- which are integrated over y
- Ratios of 13 to 8 TeV cross-sections are determined

[Shao et al., JHEP05 (2015) 103, arXiv:1411.3300]

[Cacciari, Mangano, Nason, arXiv:1507.06197]



J/ψ CROSS SECTION AT $\sqrt{s} = 13$ TeV

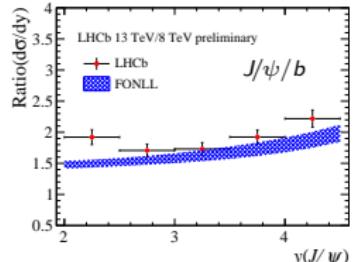
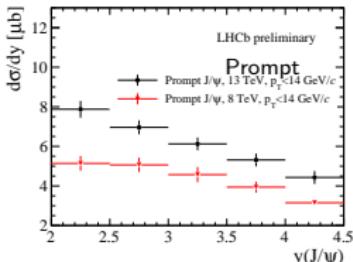


Double-differential cross-sections are determined in J/ψ $p_T < 14$ GeV/c and $2 < y < 4.5$

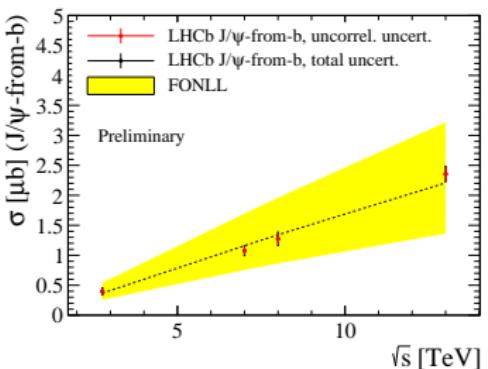
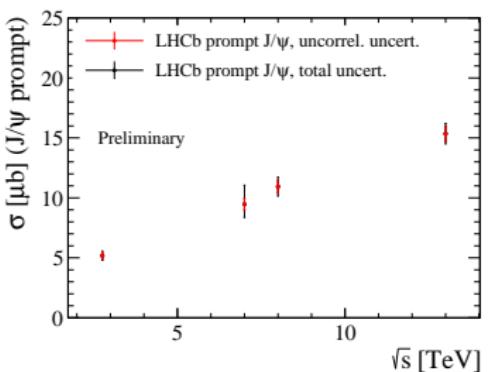
- which are integrated over y , or p_T
- Ratios of 13 to 8 TeV cross-sections are determined

[Shao et al., JHEP05 (2015) 103, arXiv:1411.3300]

[Cacciari, Mangano, Nason, arXiv:1507.06197]



J/ψ CROSS SECTION AT $\sqrt{s} = 13$ TeV



Double-differential cross-sections are determined in J/ψ $p_T < 14$ GeV/ c and $2 < y < 4.5$

Preliminary cross-sections :

$$\sigma_{J/\psi}(\text{LHCb}) = 15.35 \pm 0.03 \pm 0.85 \mu\text{b}$$

$$\sigma_{J/\psi/b}(\text{LHCb}) = 2.36 \pm 0.01 \pm 0.13 \mu\text{b}$$

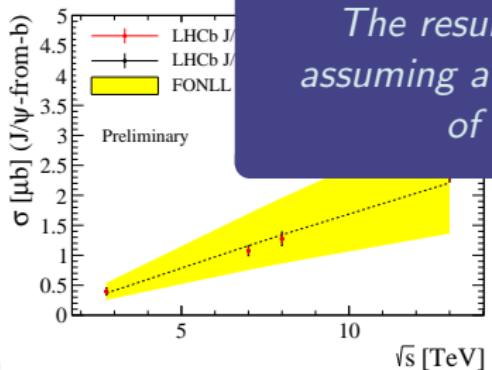
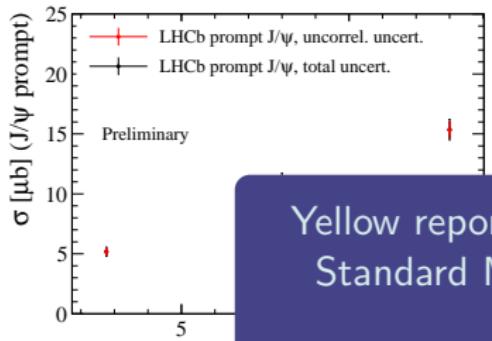
where the systematic uncertainty is dominated by the luminosity

Naively applying a factor 5.2 from Pythia:

$$\sigma_{b\bar{b}}(4\pi) = 518 \pm 2 \pm 53 \mu\text{b}$$

where there's no uncertainty for the extrapolation

J/ψ CROSS SECTION AT $\sqrt{s} = 13$ TeV



Double-differential cross-sections are determined in J/ψ $p_T < 14$ GeV/ c and $2 < y < 4.5$

Preliminary cross sections:

Yellow report of the 1999 workshop on Standard Model physics at the LHC

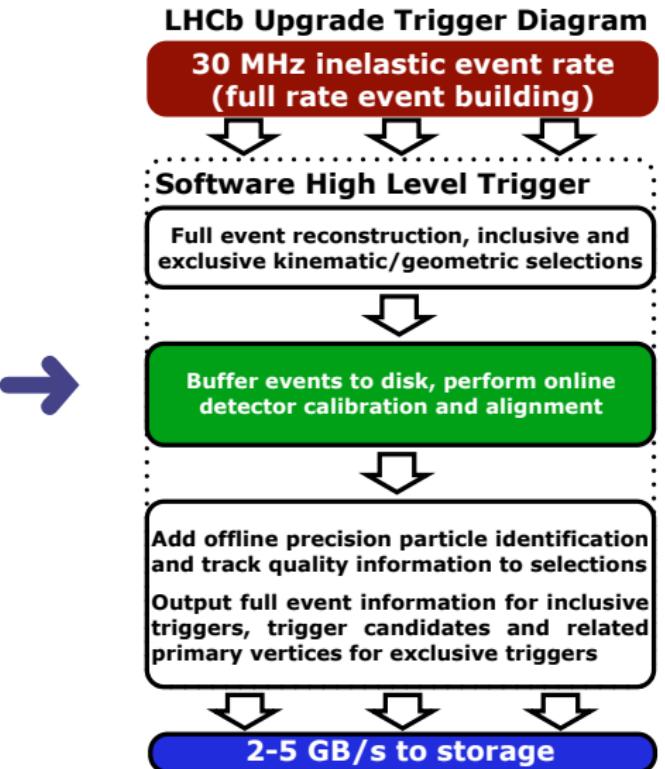
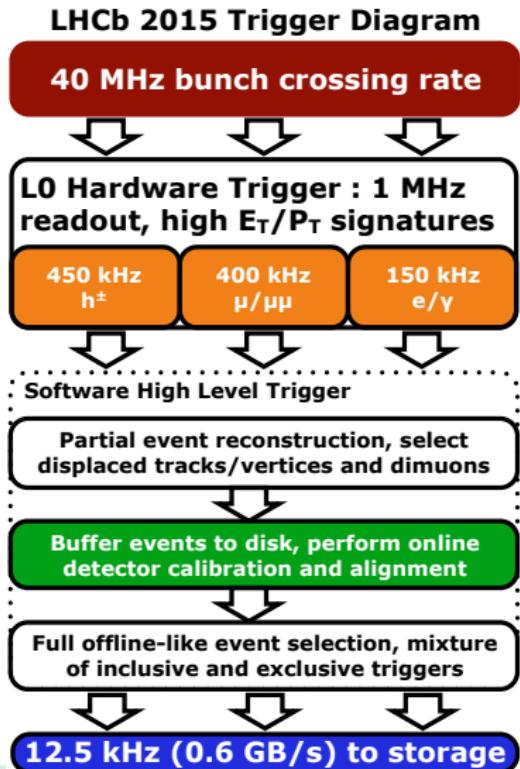
[arXiv:hep-ph/0003238]

The results have been normalised assuming a total [...] $b\bar{b}$ cross-section of 500 μb . (14 TeV)

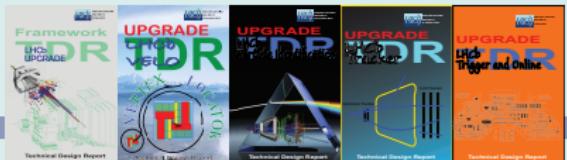
$$\sigma_{b\bar{b}}(4\pi) = 510 \pm 2 \pm 53 \mu b$$

where there's no uncertainty for the extrapolation

LHCb Trigger in Run III



LHCb UPGRADE

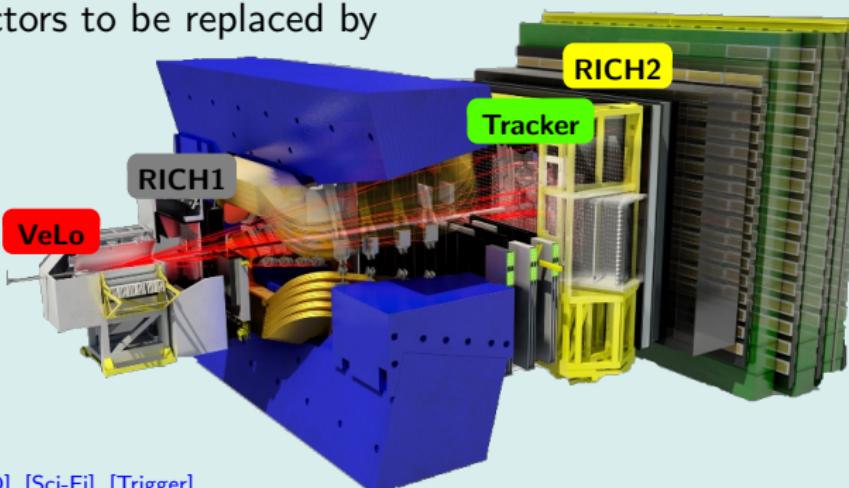


$\mathcal{L} = 2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ requires some new detectors and 40 MHz read-out clock new electronics

VELO: New pixel vertex detector

TRACKERS: New scintillating fibre tracker downstream the magnet.
The upstream tracker is also replaced.

PID: Hybrid photodetectors to be replaced by multi-anode PMTs



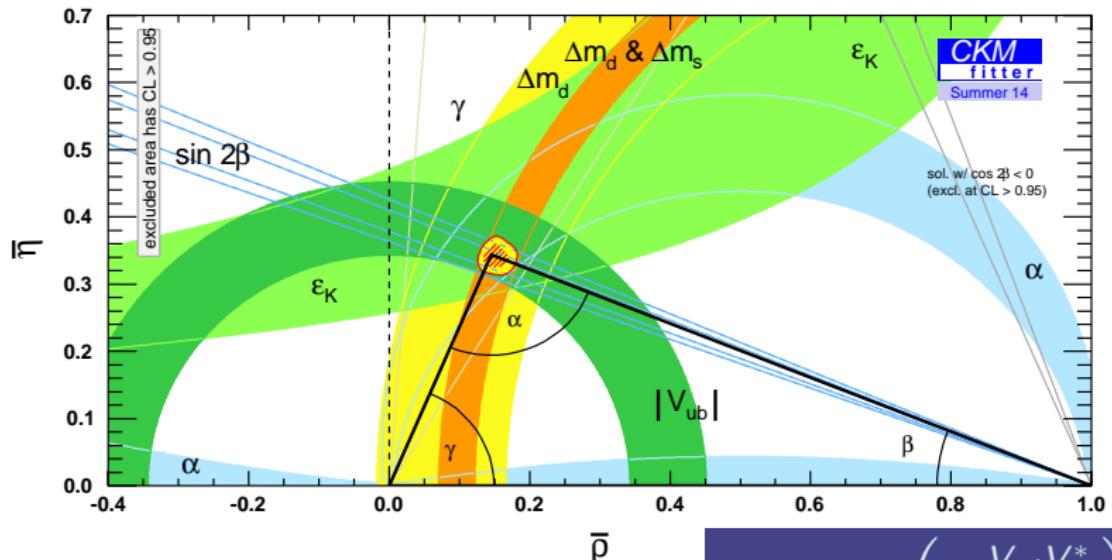
[Upgrade TDR] [Velo] [PID] [Sci-Fi] [Trigger]

β in B^0 mixing

UNITARITY TRIANGLE

“The” unitarity triangle exploits the relation

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

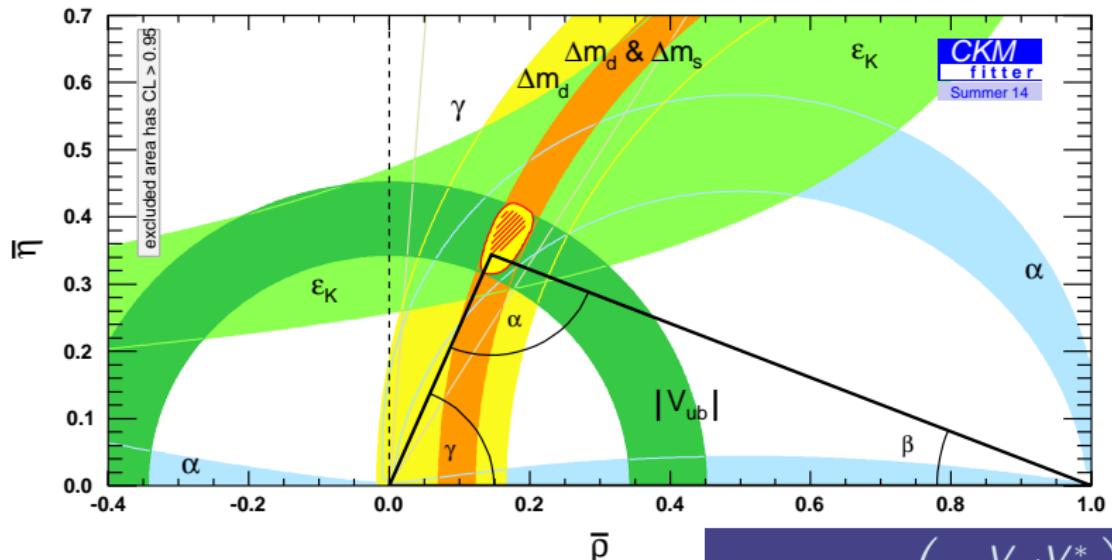


$$\beta = \arg \left(-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

UNITARITY TRIANGLE

We want to over-constrain it using several measurements.

This is the UT with all constraints but $\sin 2\beta$

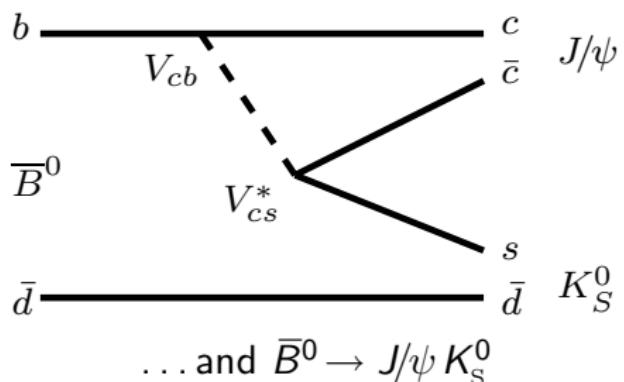
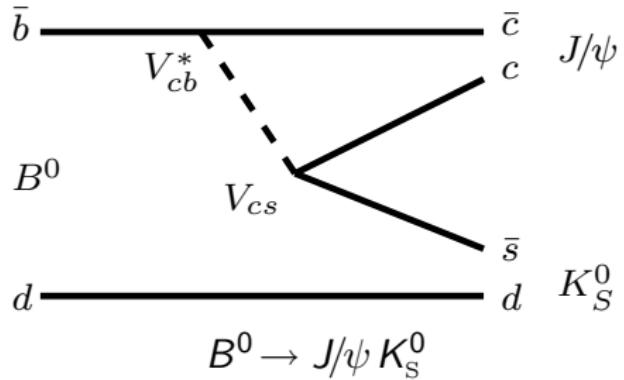
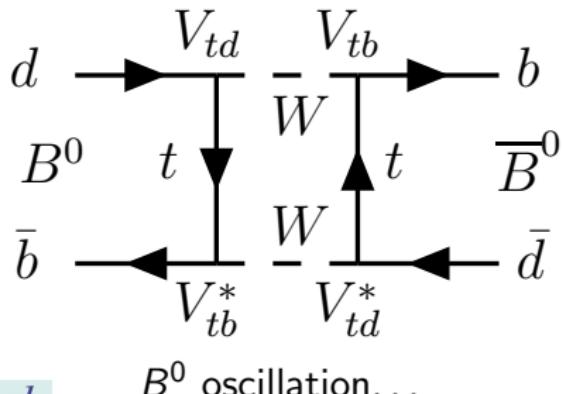


$$\beta = \arg \left(-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

$\sin 2\beta$ WITH $B^0 \rightarrow J/\psi K_S^0$

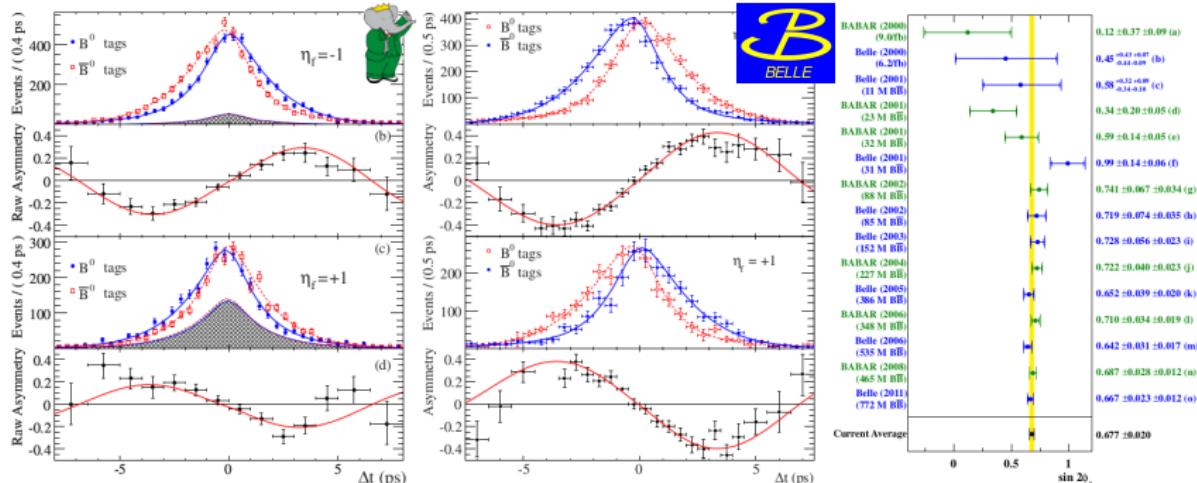
Golden mode for CP violation in B^0 decays, sensitive to

$$\beta = \arg \left(-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$





$\sin 2\beta$ AT THE B FACTORIES



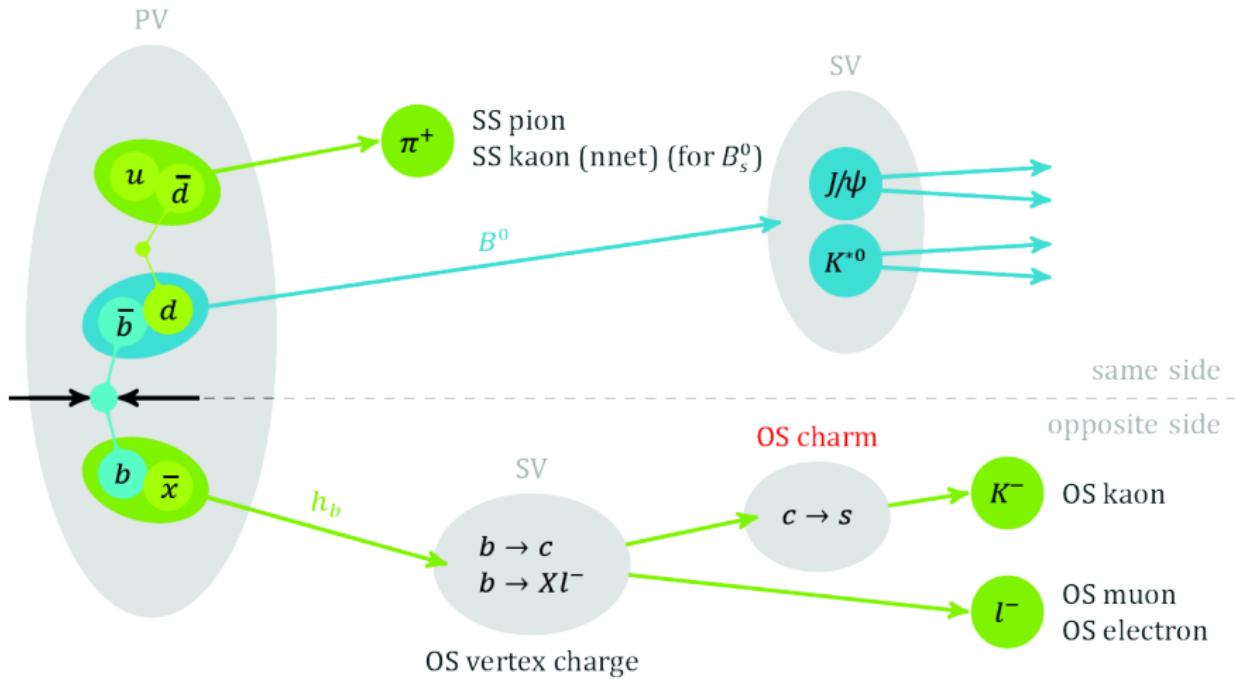
A long history of $\sin 2\beta$ measurements at the B factories

- Started in 1999,
- First observation in 2001

Now BaBar: $0.687 \pm 0.028 \pm 0.012$ [PRD 79, 072009 (2009)]

Belle: $0.667 \pm 0.023 \pm 0.012$ [PRL 108, 171802 (2012)]

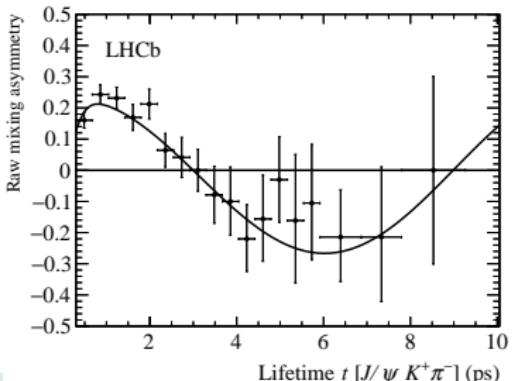
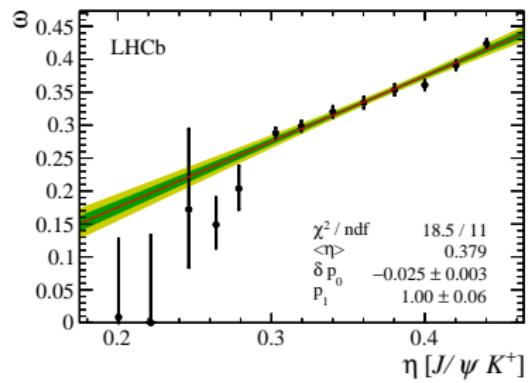
B FLAVOUR TAGGING AT THE LHC



OPPOSITE-SIDE CHARM TAGGER



NEW



- New opposite-side flavour tagging algorithm using exclusively reconstructed D decays from b hadrons.
- Complementary to vertex charge (uses PID) and to OS kaon (softer cuts on K , but requirements on other tracks)
- Low-ish $\epsilon_{\text{tag}} = 3\text{--}4\%$, good $\omega \sim 35\%$ $\rightarrow \epsilon_{\text{eff}} = 0.3\text{--}0.4\%$ depending on mode

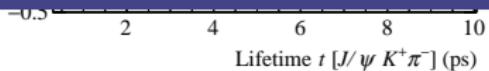
OPPOSITE-SIDE CHARM TAGGER



- New opposite-side flavour tagging

| Channel | $\epsilon_{\text{eff}} [\%]$ | | | Reference |
|---|------------------------------|-------|--------|--------------------------------------|
| | 2011 | Run I | Imprvt | |
| LHCb $B_s^0 \rightarrow \phi\phi$ | 3.29 | 5.38 | +64% | [Phys. Rev. D90 (2014) 052011] |
| LHCb $B_s^0 \rightarrow D_s^+ D_s^+$ | | 5.33 | | [Phys. Rev. Lett. 113 (2014) 211801] |
| LHCb $B_s^0 \rightarrow D_s^+ K^-$ | 5.07 | | | [JHEP 11 (2014) 060] |
| LHCb $B_s^0 \rightarrow J/\psi K^+ K^-$ | 3.13 | 3.73 | +19% | [Phys. Rev. Lett. 114 (2015) 041801] |
| LHCb $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ | 2.43 | 3.89 | +60% | [Phys. Lett. B736 (2014) 186] |
| LHCb $B_s^0 \rightarrow J/\psi K_S^0$ | 2.38 | 3.03 | +27% | [Phys. Rev. Lett. 115 (2015) 031601] |
| LHCb $B_s^0 \rightarrow J/\psi \phi$ | 1.45 | 1.49 | +3% | Preliminary |
| CMS $B_s^0 \rightarrow J/\psi \phi$ | 0.97 | 1.31 | +35% | [arXiv:1507.07527] |

Impressive improvements in tagging performance in the last 3 years



$\sin 2\beta$ WITH $B^0 \rightarrow J/\psi K_S^0$



Tagged time-dependent analysis

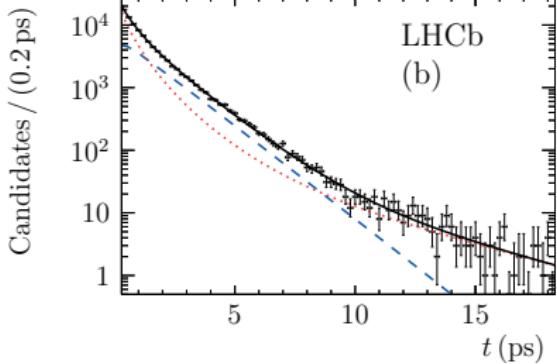
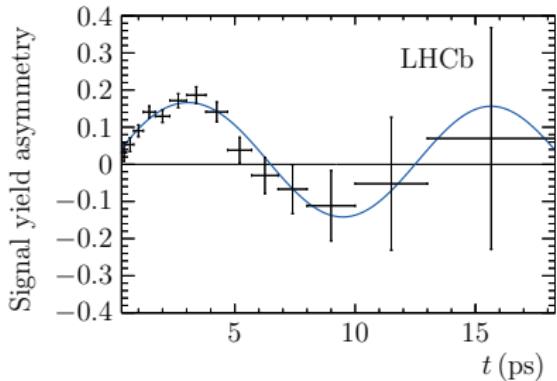
- Exploit OS and for first time SS π tag. $\epsilon D^2 = 2.99 \pm 0.03\%$
- Acceptance using splines for trigger (low times) and reco (high times) [LHCb, JHEP 04 (2014) 114, arXiv:1402.2554]
- Production asymmetry from [LHCb, Phys. Lett. B718 (2013) 902-909, arXiv:1210.4112]

$$S = 0.731 \pm 0.035 \pm 0.020$$

$$C = -0.038 \pm 0.032 \pm 0.005$$

$$\rho = 0.483$$

$$S_{C=0} = 0.746 \pm 0.030$$



$\sin 2\beta$ WITH $B^0 \rightarrow J/\psi K_S^0$



Golden mode for CP violation in B^0

- World average
 $\sin 2\beta^{\text{exp}} = 0.682 \pm 0.019$.
- Expectation from global fits
 $\sin 2\beta^{\text{SM}} = 0.771^{+0.017}_{-0.041}$.
[\[CKMFitter, arXiv:1501.05013\]](#)
- Systematic uncertainties mostly from data → will improve

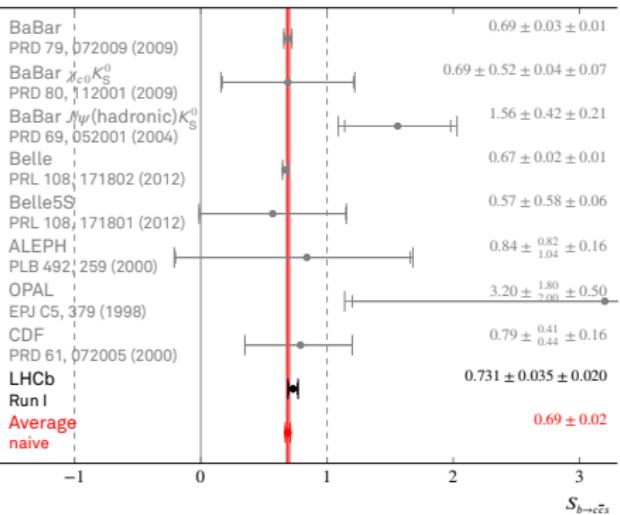
$$S = 0.731 \pm 0.035 \pm 0.020$$

$$S_{J/\psi K_S^0}^{\text{Belle}} = 0.670 \pm 0.029 \pm 0.013$$

$$S_{J/\psi K_S^0}^{\text{BaBar}} = 0.662 \pm 0.039 \pm 0.012$$

[Belle, Phys. Rev. Lett. 108, 171802 (2012), arXiv:1201.4643]

[Babar, Phys. Rev. D79 072009 (2009), arXiv:0902.1708]



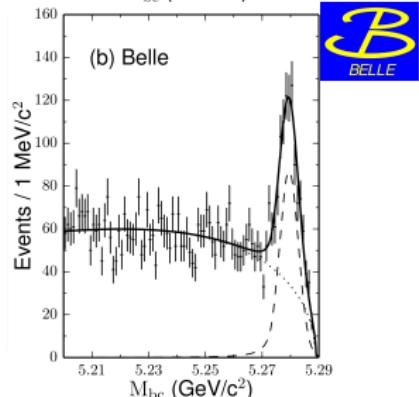
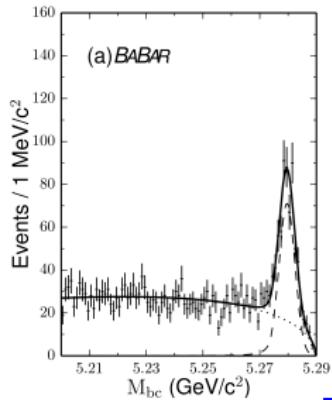
Now competitive
with B factories!

$\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$ WITH BABAR AND BELLE DATA

$\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$ dominated by $q \rightarrow c\bar{u}d$.

If D^0 decays to a CP eigenstate it interferes with the decay via oscillations. **Penguin-free!**

- Sensitive to $S \stackrel{\text{SM}}{=} \sin 2\beta$
- First combined fit of Babar and Belle data ($1.243 \times 10^9 B\bar{B}$ pairs)
- $\bar{B}^0 \rightarrow D\pi^0, D\eta, D\omega$ with $D^0 \rightarrow K_S^0\pi^0, K_S^0\omega$ (CP -even) and $D^0 \rightarrow K^+K^-$ or $D^{*0} \rightarrow D^0(K_S^0\pi^0)\pi^0$ (CP -odd)
- 508 ± 31 and 757 ± 44 decays for Babar and Belle



$\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$ WITH BABAR AND BELLE DATA

$\bar{B}^0 \rightarrow D_{CP}^{(*)} h^0$ dominated by $q \rightarrow c\bar{u}d$.

If D^0 decays to a CP eigenstate it interferes with the decay via oscillations. **Penguin-free!**

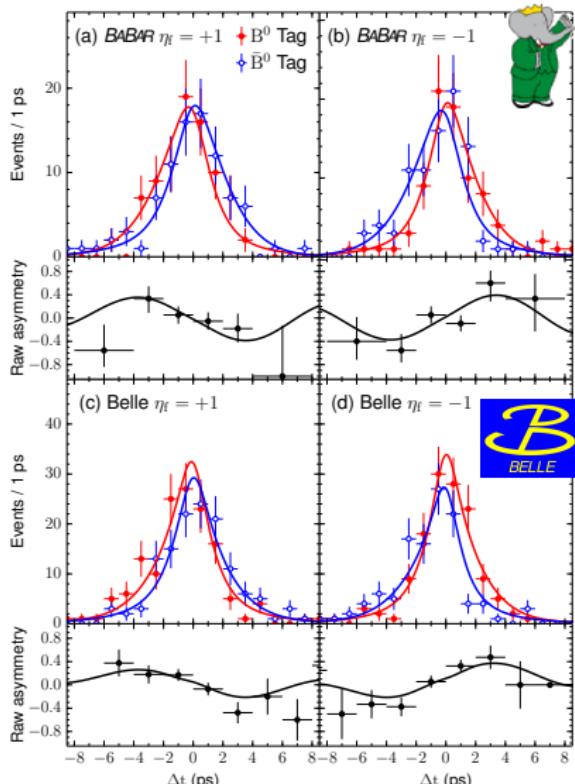
→ Sensitive to $S \stackrel{\text{SM}}{=} \sin 2\beta$

- First combined fit of Babar and Belle data ($1.243 \times 10^9 B\bar{B}$ pairs)

$$\eta_f S = +0.66 \pm 0.10 \pm 0.06$$

$$\mathcal{C} = -0.02 \pm 0.07 \pm 0.03$$

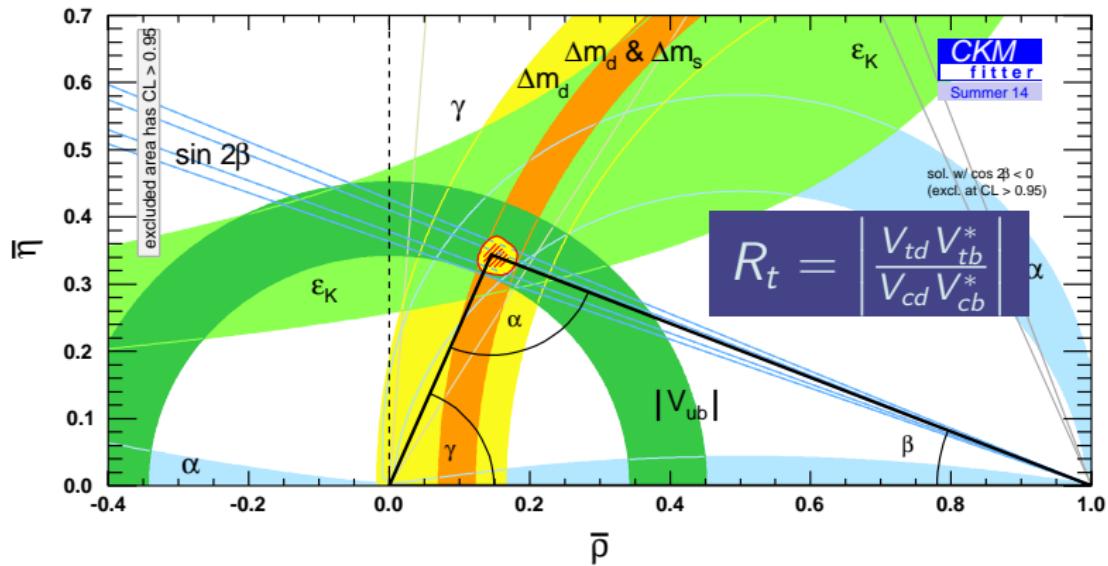
with $S = 0.52 \pm 0.15$ (Babar), 0.83 ± 0.15 (Belle), 0.52 ± 0.15 (CP -even), 0.80 ± 0.15 (CP -odd)



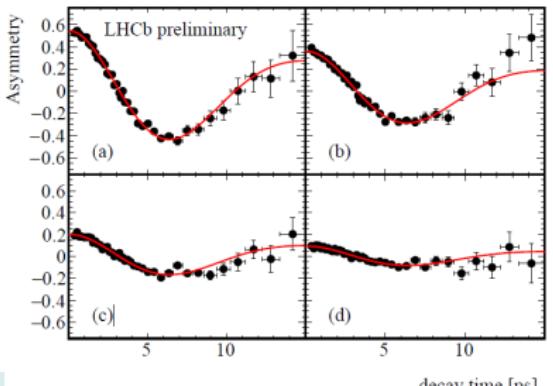
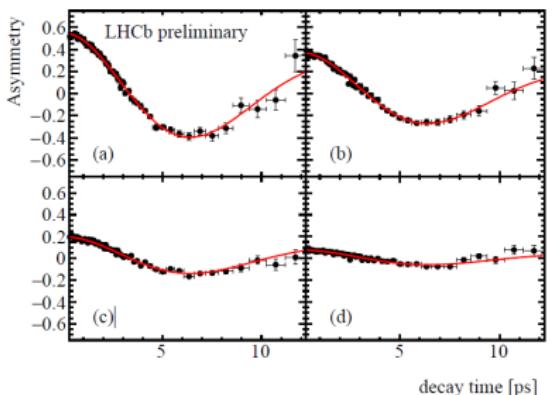
UNITARITY TRIANGLE

“The” unitarity triangle exploits the relation

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



Δm_d WITH SEMILEPTONIC B^0 DECAYS



- Use $B^0 \rightarrow D^{(*)-} \mu^+ \nu_\mu X$ with $2.2 \times 10^6 D^- \rightarrow K^+ \pi^+ \pi^+$ and $8.2 \times 10^5 D^{*-} \rightarrow \bar{D}^0 (K^+ \pi^-) \pi^-$
- Tagging power 2.32–2.55% **NEW** depending on mode and year

Preliminary result:

$$\Delta m_d = (503.6 \pm 2.0 \pm 1.3) \text{ ns}^{-1}$$

We are still working on the systematics
→ expect them to decrease

World average [\[HFAG\]](#)

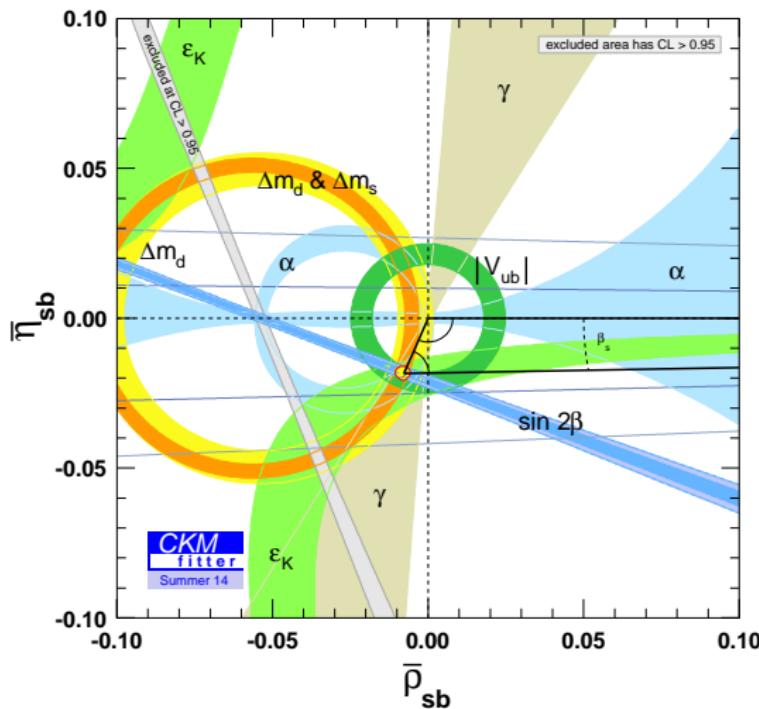
$$\Delta m_d = (510 \pm 3) \text{ ns}^{-1} \text{ (without this)}$$

$$\Delta m_d = (505.5 \pm 2.0) \text{ ns}^{-1} \text{ (with this)}$$

ϕ_s in B_s^0 mixing



B_s^0 UNITARITY TRIANGLE



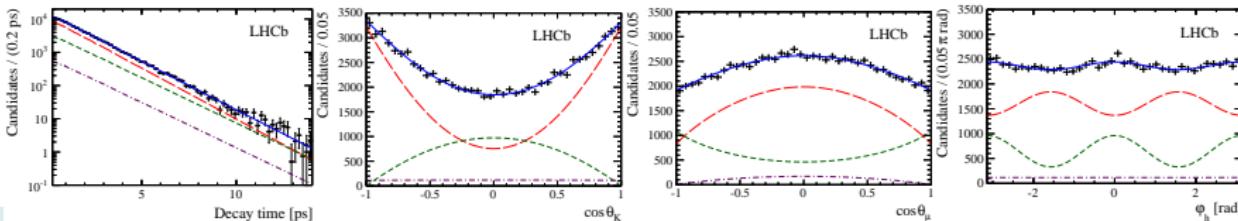
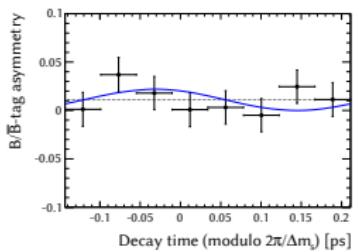
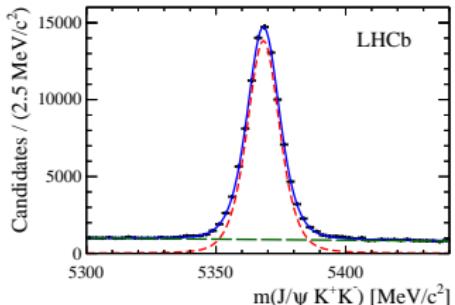
This is another CKM UT triangle, where the phase of B_s^0 mixing ϕ_s , appears.

External constraints fix it very precisely to
$$\phi_s = -2\arg\left(\frac{-V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right) = -0.0363^{+0.0014}_{-0.0012}$$

✓ Good potential for NP searches

[CKMfitter 09/14]

CP VIOLATION IN $B_s^0 \rightarrow J/\psi K^+ K^-$



- Measuring the CP -violating phase $\varphi_s^{c\bar{c}s}$:
 $-2\beta_s \equiv -2 \arg(-V_{ts} V_{tb}^*/V_{cs} V_{cb}^*) = -0.0363 \pm 0.0013$ in SM

- Angular analysis needed to disentangle polarisation states

$$\varphi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad},$$

$$|\lambda| = 0.964 \pm 0.019 \pm 0.007,$$

$$\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1},$$

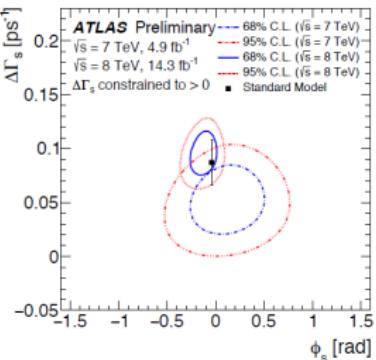
$$\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0033 \text{ ps}^{-1}$$



φ_s AND $\Delta\Gamma_s$ AT ATLAS

Atlas analysis of $B_s^0 \rightarrow J/\psi \phi$ with 2012 dataset

- Tagged time-dependent angular analysis
- Total effective tagging power $1.49 \pm 0.02\%$
 - Retuned wrt 2011 and added electrons
 - Size of $B^+ \rightarrow J/\psi K^+$ control sample main source of systematic uncertainty on φ_s
- Statistically combine 2011 and 2012 data



| | 2011 (5 fb^{-1}) [PRD 90, 052007, arXiv:1407.1796] | 2012 (20 fb^{-1}) [ATLAS preliminary] | Run I |
|---------------------------------|---|--|------------------------------|
| $B_s^0 \rightarrow J/\psi \phi$ | 22670 ± 150 | | |
| ϕ_s [rad] | $0.12 \pm 0.25 \pm 0.05$ | $-0.119 \pm 0.088 \pm 0.036$ | $-0.094 \pm 0.083 \pm 0.033$ |
| $\Delta\Gamma_s$ [ps $^{-1}$] | $0.053 \pm 0.021 \pm 0.001$ | $0.096 \pm 0.013 \pm 0.007$ | $0.082 \pm 0.011 \pm 0.007$ |
| Γ_s [ps $^{-1}$] | $0.677 \pm 0.007 \pm 0.004$ | | $0.677 \pm 0.003 \pm 0.003$ |

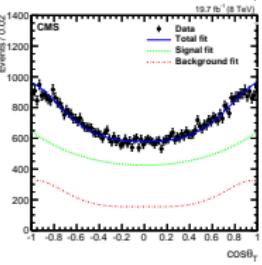
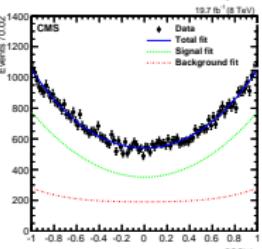
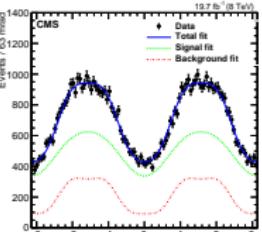
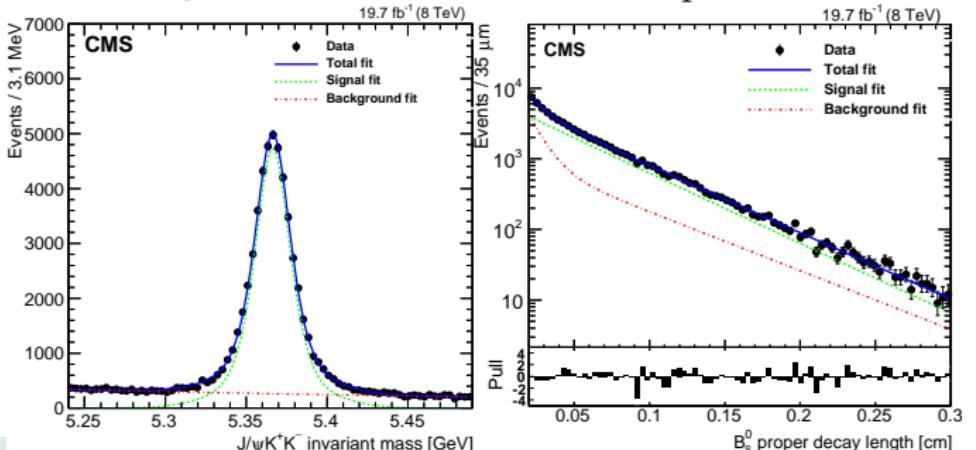


φ_s AND $\Delta\Gamma_s$ AT CMS

- 49000 $B_s^0 \rightarrow J/\psi \phi$ decays
- Tagged angular analysis
 - Total effective tagging power
 $(1.307 \pm 0.031 \pm 0.007)\%$

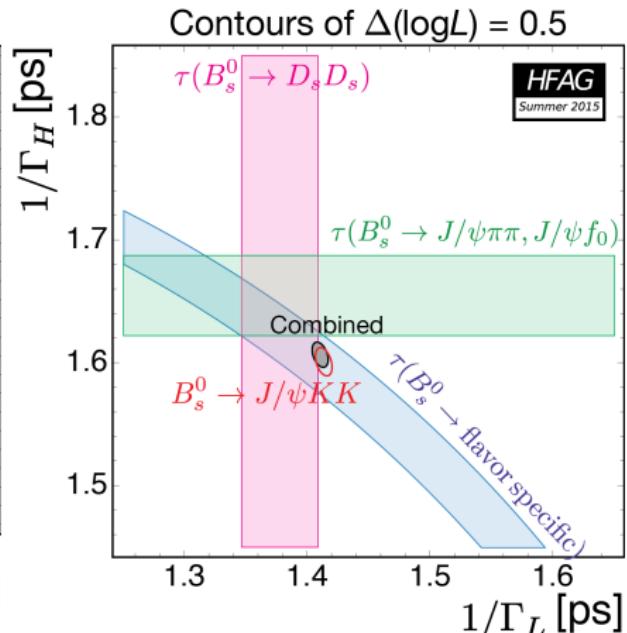
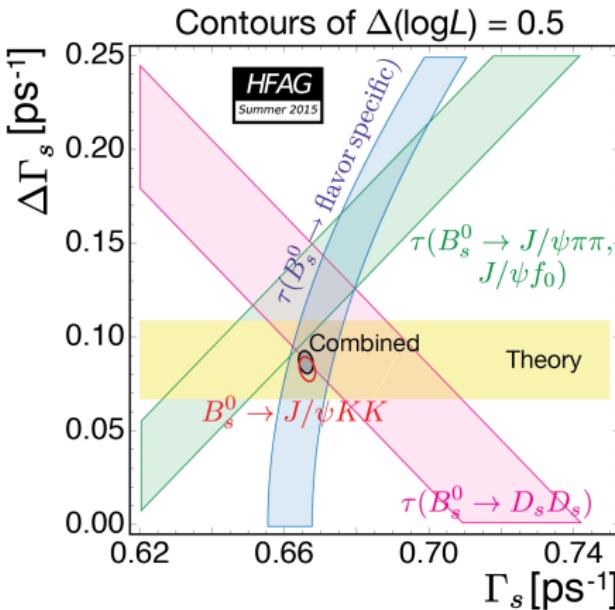
$$\phi_s = -0.075 \pm 0.097 \pm 0.031 \text{ rad}$$

$$\Delta\Gamma_s = 0.095 \pm 0.013 \pm 0.007 \text{ ps}^{-1}$$



$\Delta\Gamma_s$ VERSUS Γ_s IN SUMMER 2015

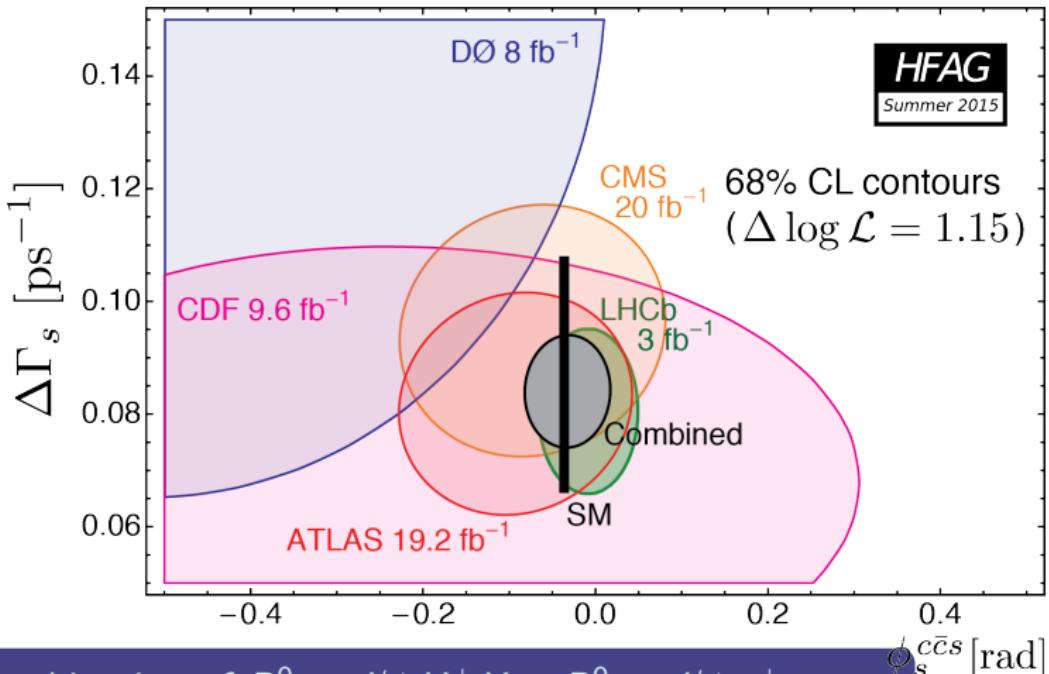
NEW



- These measurements set constraints on φ_s , the decay width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and Γ_s
- Here are the lifetime plots. Note the large $\Delta\Gamma_s$. $B_s^0 \sim K^0!$

$\Delta\Gamma_s$ VERSUS φ_s IN SUMMER 2015

NEW



Combination of $B_s^0 \rightarrow J/\psi K^+ K^-$, $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$
and $B_s^0 \rightarrow D_s^+ D_s^-$: $\varphi_s = -0.034 \pm 0.033 \text{ rad}$

PENGUINS



Patrick Koppenburg

CP Violation and CKM Physics

29/7/2015 — EPS-HEP [36 / 50]

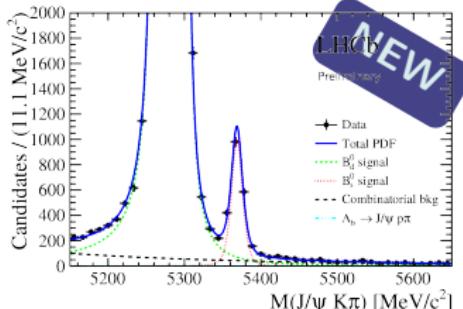
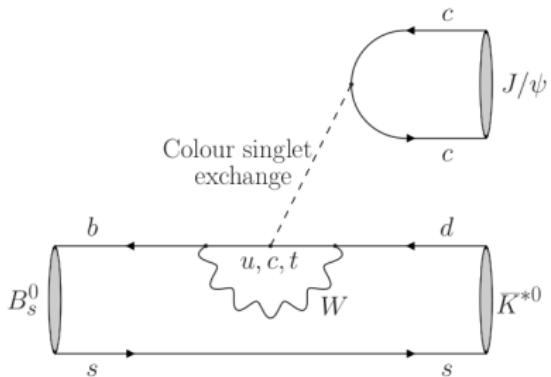
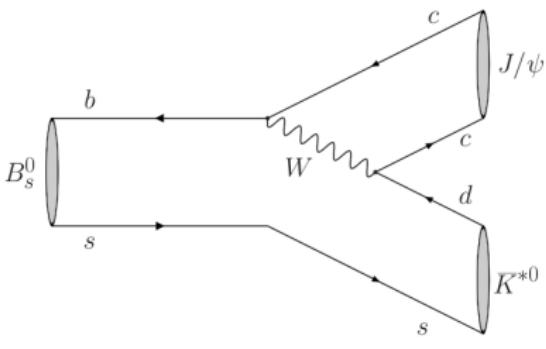
[Pictures from here]

ANGULAR ANALYSIS OF $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$



The predictions of φ_s and $\sin 2\beta$ assume these are measured in $b \rightarrow c\bar{c}s$ transitions.

- Size of penguin topologies?
 - ✗ Effects \simeq exp. sensitivity
- Measure it in decays where these are enhanced relative to the tree



Following [De Bruyn, Fleischer, JHEP 1503 (2015) 145], [Faller et al., PRD79 014005]. See [backup]

ANGULAR ANALYSIS OF $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$



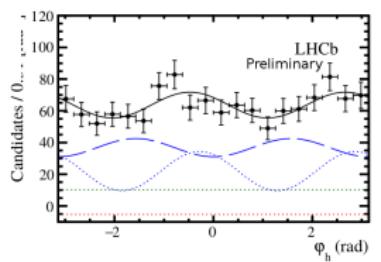
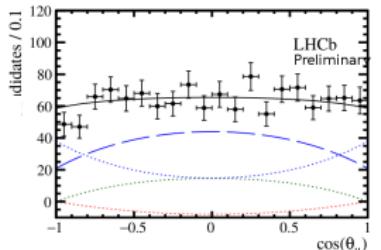
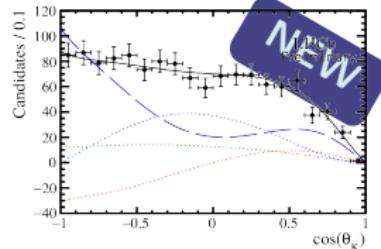
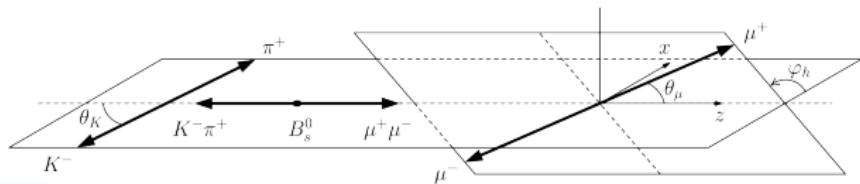
Angular analysis in helicity frame

- 208700 ± 500 B^0 and 1800 ± 60 B_s^0 decays
- Correction for production and detection asymmetries [Phys. Rev. Lett. 114 (2015) 041601] [Phys. Lett. B739 (2014) 218] [JHEP 07 (2014) 041]

Preliminary results:

$$\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = (4.13 \pm 0.16(\text{stat}) \pm 0.25(\text{syst}) \pm 0.24(f_d/f_s)) \times 10^{-5}$$

$$\begin{aligned} f_0 &= 0.497 \pm 0.025 \text{ (stat)} \pm 0.025 \text{ (syst)} \\ f_{\parallel} &= 0.179 \pm 0.027 \text{ (stat)} \pm 0.013 \text{ (syst)} \\ A_0^{CP}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) &= -0.048 \pm 0.057 \text{ (stat)} \pm 0.020 \text{ (syst)} \\ A_{\parallel}^{CP}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) &= 0.171 \pm 0.152 \text{ (stat)} \pm 0.028 \text{ (syst)} \\ A_{\perp}^{CP}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) &= -0.049 \pm 0.096 \text{ (stat)} \pm 0.025 \text{ (syst)} \end{aligned}$$



ANGULAR ANALYSIS OF $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$



$$A(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = -\lambda \mathcal{A}_i \left[1 - a_i e^{i\theta_i} e^{i\gamma} \right], i = 0, \parallel, \perp$$

$$A(B_s^0 \rightarrow J/\psi \phi) = \left(1 - \frac{\lambda^2}{2} \right) \mathcal{A}'_i \left[1 - \epsilon a'_i e^{i\theta'_i} e^{i\gamma} \right]$$

with $\epsilon = 0.054$, $\gamma = 74 \pm 7^\circ$ (CKM) and $a_i = a'_i$, $\theta_i = \theta'_i$ (SU(3)) \rightarrow

$$\begin{aligned} a_0 &= 0.03^{+0.97}_{-0.03}, & \theta_0 &= (64^{+116}_{-244})^\circ, \\ a_\parallel &= 0.32^{+0.58}_{-0.32}, & \theta_\parallel &= -(15^{+150}_{-14})^\circ, \\ a_\perp &= 0.45^{+0.21}_{-0.27}, & \theta_\perp &= (175 \pm 10)^\circ, \end{aligned}$$

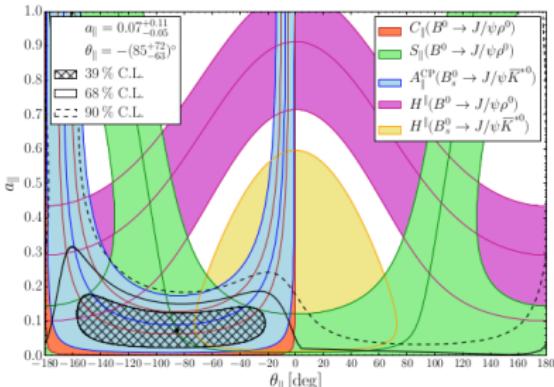
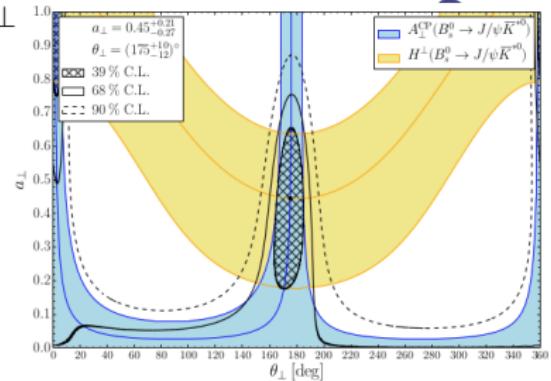
Combine with $B^0 \rightarrow J/\psi \rho^0$ [Phys. Lett. B742 (2015) 38]

$$\frac{\mathcal{A}'_i}{\mathcal{A}_i} \equiv \left| \frac{\mathcal{A}'_i(B_s^0 \rightarrow J/\psi \phi)}{\mathcal{A}_i(B_s^0 \rightarrow J/\psi \bar{K}^{*0})} \right| = \left| \frac{\mathcal{A}'_i(B_s^0 \rightarrow J/\psi \phi)}{\mathcal{A}_i(B^0 \rightarrow J/\psi \rho^0)} \right|$$

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011} \text{ (stat)}^{+0.004}_{-0.009} \text{ (syst)},$$

$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014} \text{ (stat)}^{+0.007}_{-0.008} \text{ (syst)},$$

$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014} \text{ (stat)}^{+0.007}_{-0.008} \text{ (syst)}.$$

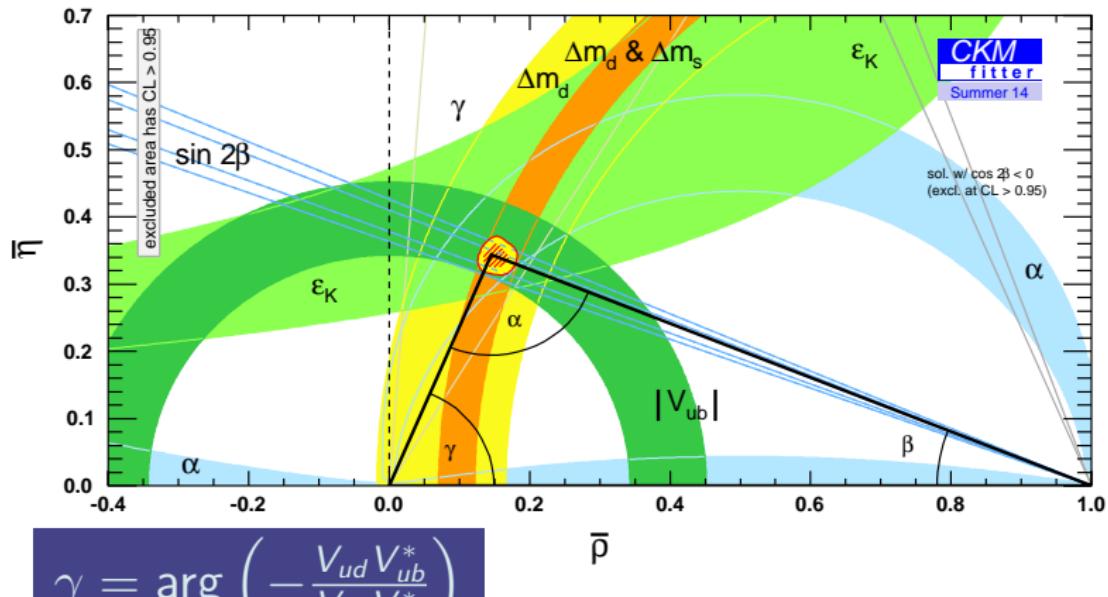




UNITARITY TRIANGLE

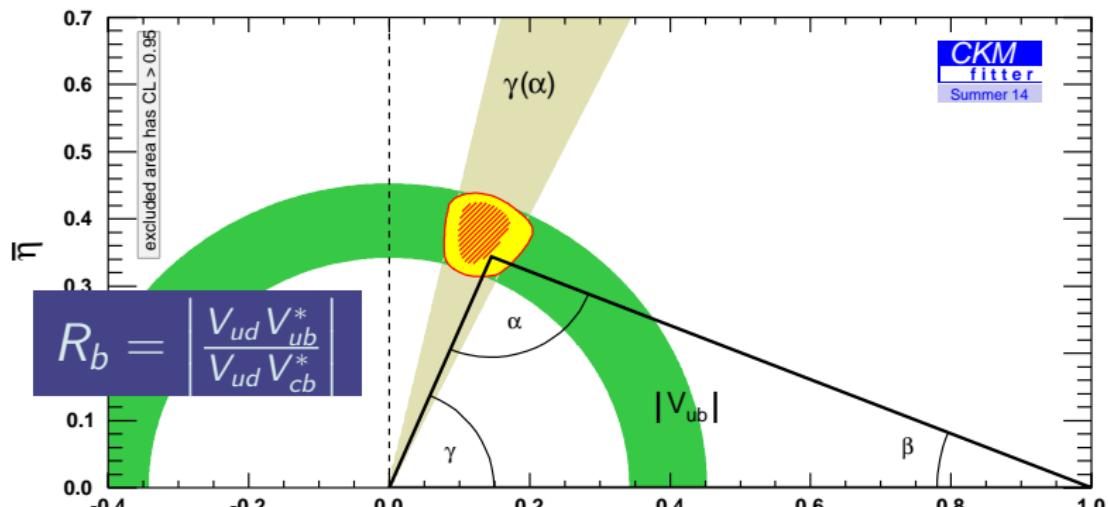
“The” unitarity triangle exploits the relation

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



UNITARITY TRIANGLE

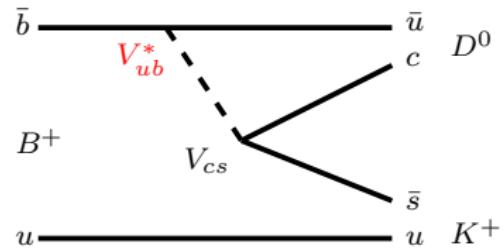
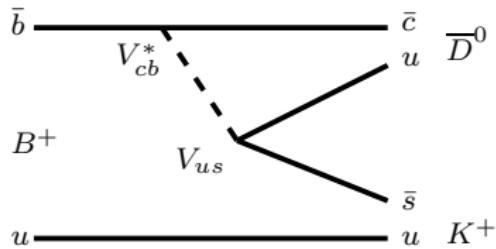
The unitarity triangle with only constraints from tree decays



γ FROM $B^+ \rightarrow DK^+$ WITH $D \rightarrow K_S^0 hh$



- Can access γ through interference of $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow \bar{D}^0 K^+$ with $D \rightarrow K_S^0 \pi^+ \pi^-$ or $K_S^0 K^+ K^-$



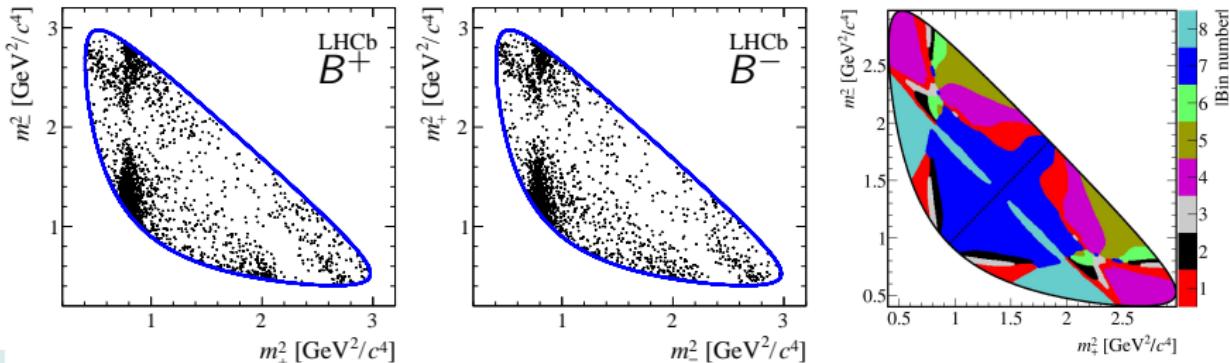
GGZS method [Phys.Rev. D68 (2003) 054018]

- Interference of $b \rightarrow c$ and $b \rightarrow u$, $\gamma \equiv \arg(-V_{ud} V_{ub}^*/V_{cb} V_{cd}^*)$
- We also need a strong phase difference δ_B and a ratio of amplitudes r_B

γ FROM $B^+ \rightarrow DK^+$ WITH $D \rightarrow K_S^0 hh$



- Can access γ through interference of $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow \bar{D}^0 K^+$ with $D \rightarrow K_S^0 \pi^+ \pi^-$ or $K_S^0 K^+ K^-$
- But needs strong phase of $D \rightarrow K_S^0 hh$: Use CLEO-c data
 - Shown here for $D \rightarrow K_S^0 \pi^+ \pi^-$



γ FROM $B^+ \rightarrow DK^+$ WITH $D \rightarrow K_s^0 hh$



$$x_+ = r_B \cos(\delta_B + \gamma) = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4)\%$$

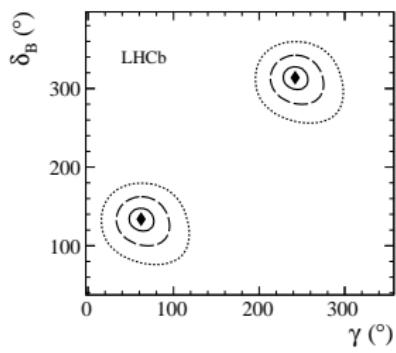
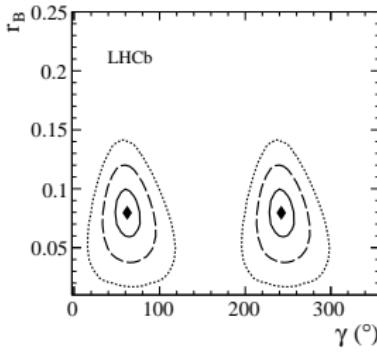
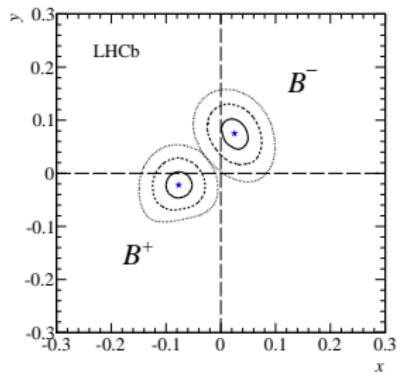
$$y_+ = r_B \sin(\delta_B + \gamma) = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0)\%$$

$$x_- = r_B \cos(\delta_B - \gamma) = (+2.5 \pm 2.5 \pm 1.0 \pm 0.5)\%$$

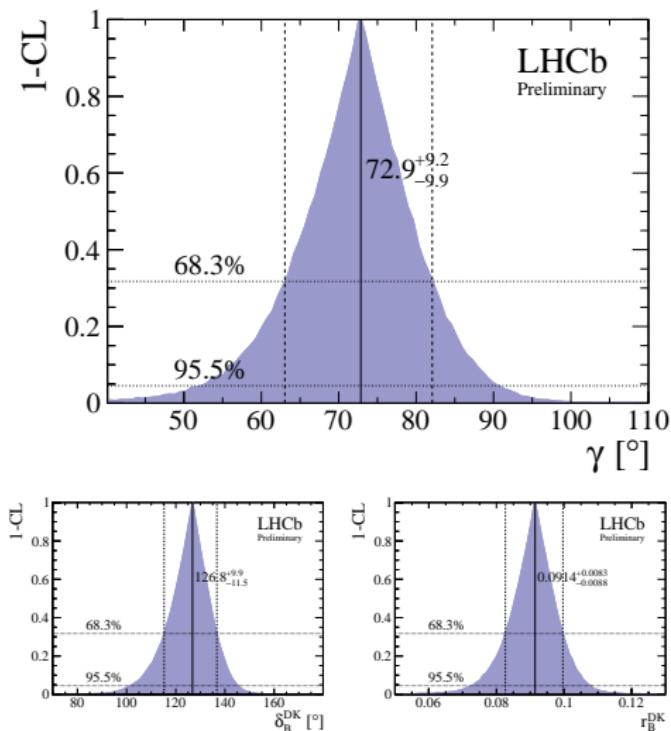
$$y_- = r_B \sin(\delta_B - \gamma) = (+7.5 \pm 2.9 \pm 0.5 \pm 1.4)\%$$

$$r_B = 0.080^{+0.019}_{-0.012} \quad \delta_B = (134^{+14}_{-15})^\circ \quad \gamma = (62^{+15}_{-14})^\circ$$

These are the most precise measurements from a single experiment



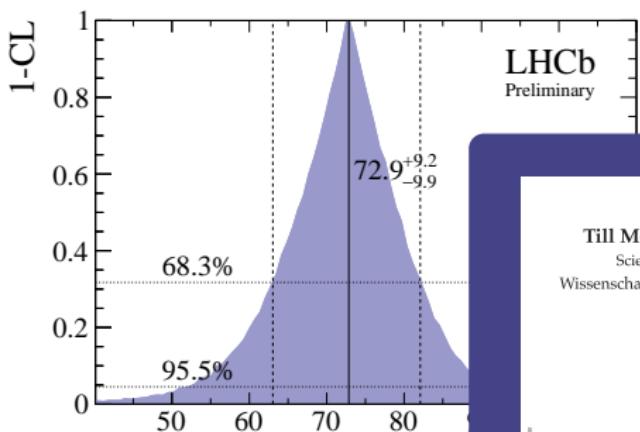
γ COMBINATION FOR CKM



- Using only $B \rightarrow DK$ gets
 $\gamma = (73^{+9}_{-10})^\circ$
- More precise than B factory combination

New results sensitive to γ
came out in the meantime
 $B^+ \rightarrow D(h^\pm h^\mp \pi^0)h^+$ [Phys.
Rev. D91 (2015) 112014]
 $B^+ \rightarrow Dh^+\pi^+\pi^-$
[\[arXiv:1505.07044\]](https://arxiv.org/abs/1505.07044) and more will
come soon.

γ COMBINATION FOR CKM



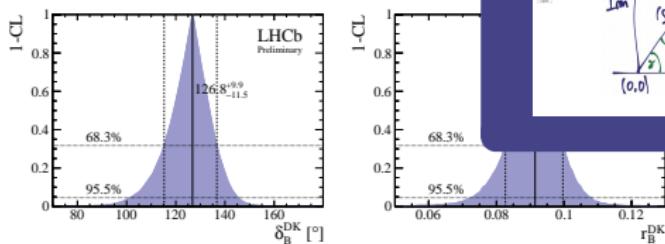
- Using only $B \rightarrow DK$ gets
 $\gamma = (73^{+9}_{-10})^\circ$

→ More precise than $B_s \rightarrow D_s K$

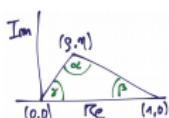
Till Moritz
Karbach

(1979–2015)

[LHCb-PUB-2015-010]



Till Moritz Karbach
Scientific Legacy
Wissenschaftliches Vermächtnis



[arXiv:1505.07044] and more will
come soon.

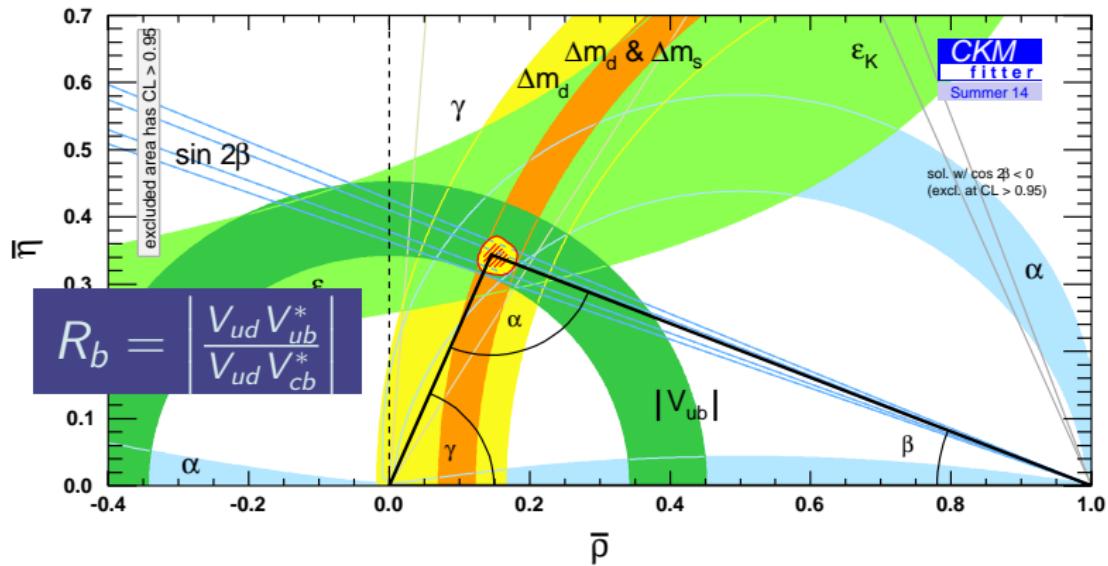
V_{ub}



UNITARITY TRIANGLE

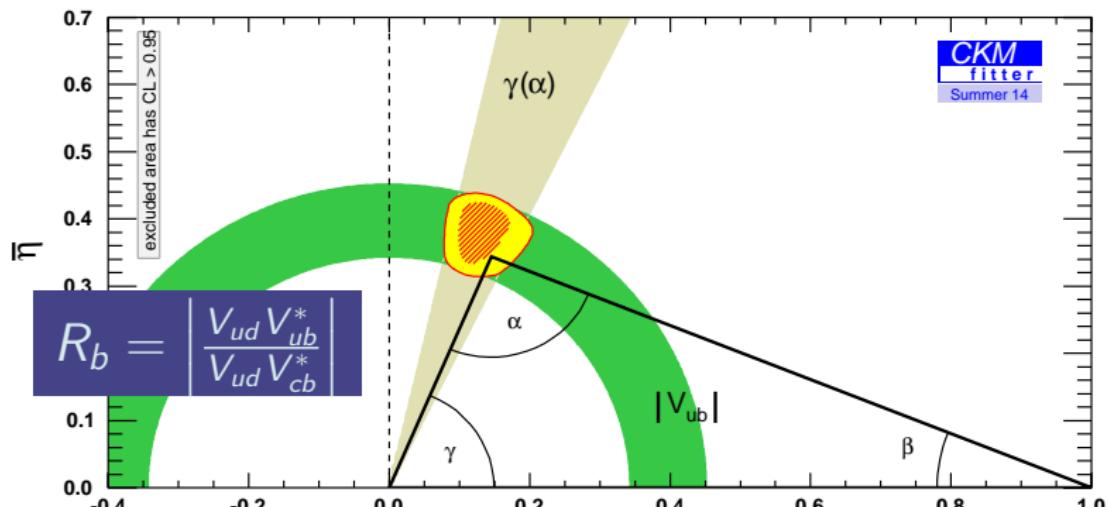
“The” unitarity triangle exploits the relation

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



UNITARITY TRIANGLE

The unitarity triangle with only constraints from tree decays



$$\gamma = \arg \left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

V_{ub} HISTORY

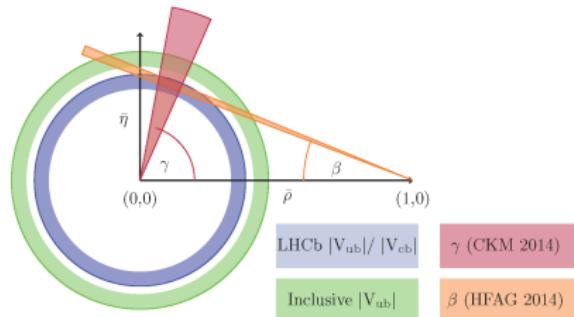
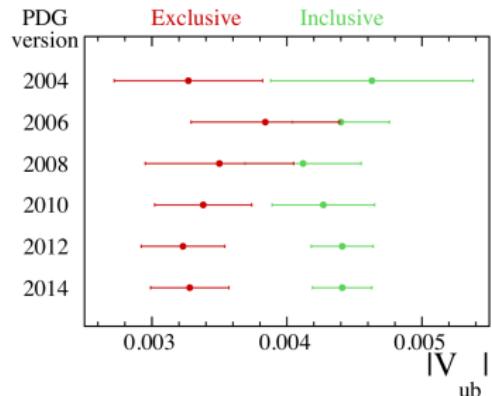
- There has been a long standing discrepancy between the value of $|V_{ub}|$ determined from exclusive $B \rightarrow \pi \ell \nu$ and inclusive $b \rightarrow u \ell \nu$ decays.
- PDG 2014 reports

$$\text{Inclusive} : (4.41 \pm 0.15^{+0.15}_{-0.10}) \times 10^{-3}$$

$$\text{Exclusive} : (3.28 \pm 0.29) \times 10^{-3}$$

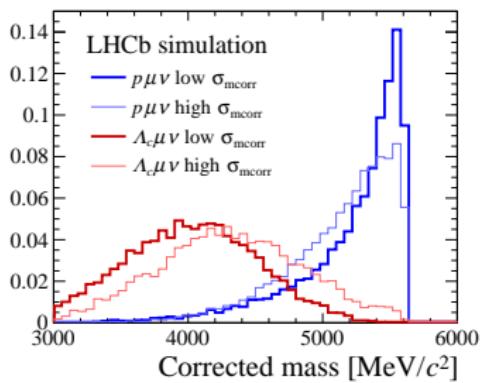
$$\text{Average} : (4.13 \pm 0.49) \times 10^{-3}$$

- CKMFitter uses $3.55^{+0.17}_{-0.15} \times 10^{-3}$,
- UTfit $3.75 \pm 0.46 \times 10^{-3}$



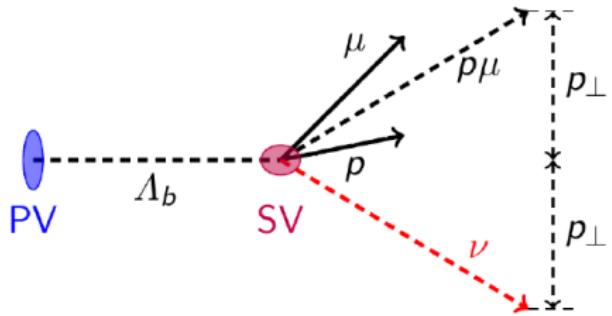
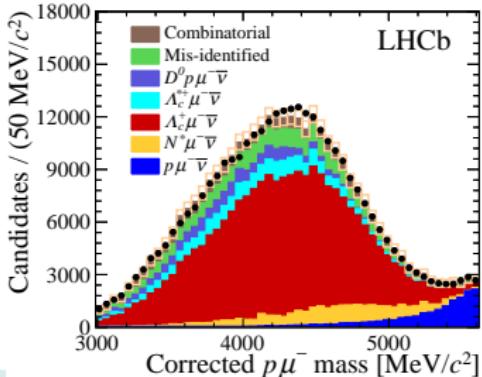


$|V_{ub}|/|V_{cb}|$ FROM $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$

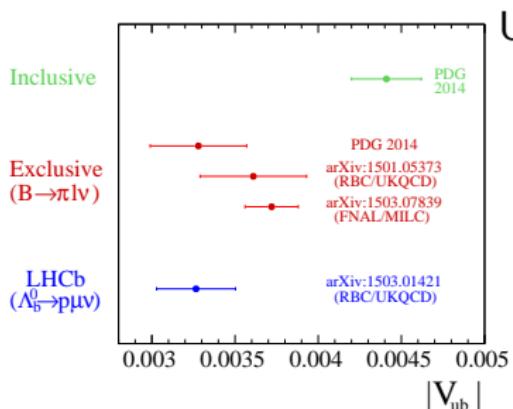


The LHC is a Λ_b^0 factory: $B^0:B_s^0:\Lambda_b^0 \sim 4:1:2$ in LHCb acceptance.

- Key to finding $\Lambda_b^0 \rightarrow p\mu\nu$ is the corrected mass
 $m_{\text{corr}} = \sqrt{m^2 + p_\perp^2} + p_\perp$, the minimal b -hadron mass compatible with its direction of flight.
- ✓ First observation of $\Lambda_b^0 \rightarrow p\mu\nu$



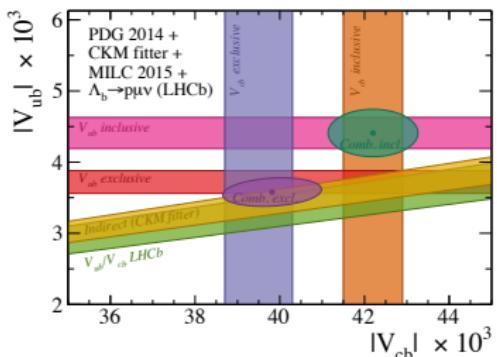
$|V_{ub}|/|V_{cb}|$ FROM $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$



Using 2 fb^{-1} (2012) we measure

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\nu)_{q^2 > 15 \text{ GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu\nu)_{q^2 > 7 \text{ GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

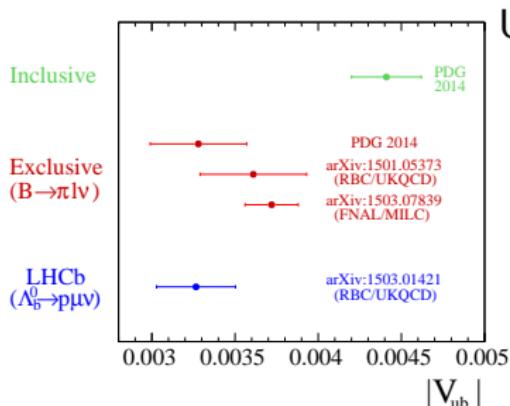
- The result is $|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-5}$ where the uncertainties are statistical, experimental and from lattice.



- We measure $|V_{ub}|/|V_{cb}|$, while the B factories measure $|V_{ub}|$ and $|V_{cb}|$ separately

→ The puzzle is still alive

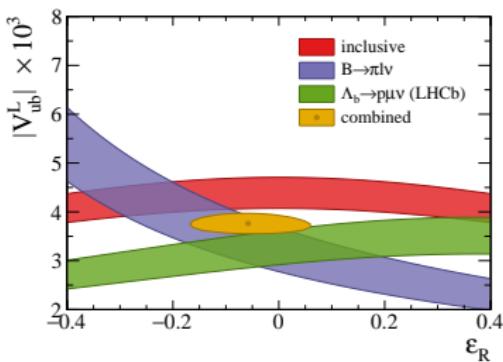
$|V_{ub}|/|V_{cb}|$ FROM $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$



Using 2 fb^{-1} (2012) we measure

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu\nu)_{q^2 > 15 \text{ GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu\nu)_{q^2 > 7 \text{ GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$

- The result is $|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-5}$ where the uncertainties are statistical, experimental and from lattice.
 - We measure $|V_{ub}|/|V_{cb}|$, while the B factories measure $|V_{ub}|$ and $|V_{cb}|$ separately
→ The puzzle is still alive
 - It was proposed that a NP right-handed coupling ϵ_R could explain the discrepancy [Bernlochner et al.,

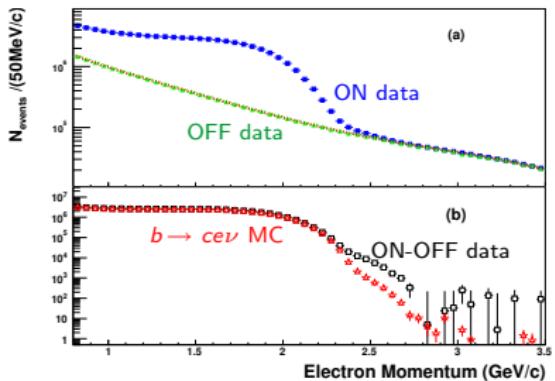
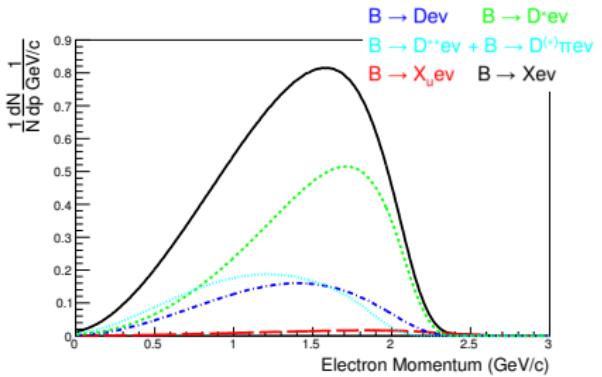




V_{ub} INCLUSIVE

Inclusive $b \rightarrow ue\nu$ result by Babar.

- Full reco tag on other B
- OFF $\gamma(4S)$ data subtracted from ON data
 - Excess of electrons beyond $b \rightarrow ce\nu$ kinematical endpoint (2.3 GeV).





V_{ub} INCLUSIVE

Inclusive $b \rightarrow ue\nu$ result by Babar.

- Full reco tag on other B
- OFF $\Upsilon(4S)$ data subtracted from ON data
 - Excess of electrons beyond $b \rightarrow ce\nu$ kinematical endpoint (2.3 GeV).

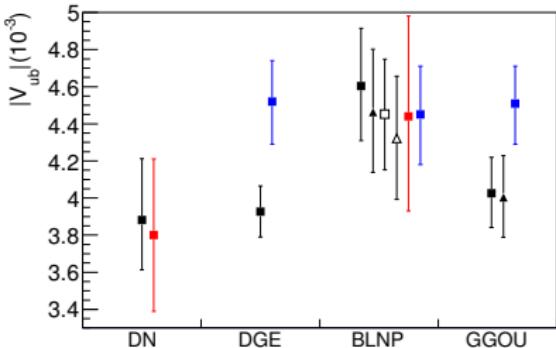
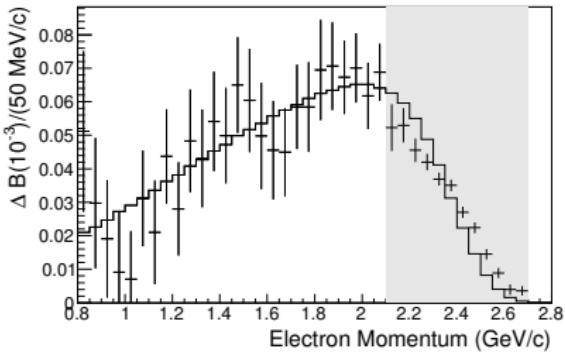
- Result depends on model.
Babar favour GGOU model

[JHEP 908 10, 058 (2007)]

→ $|V_{ub}| = (4.0 \pm 0.2) \times 10^{-3}$,
closer to the mean of
exclusive and inclusive

Also new exclusive V_{ub} using D decays to constrain form factors [PRD91]

052022 (2015), arXiv:1412.5502].





V_{ub} INCLUSIVE

Inclusive $b \rightarrow ue\nu$ result by Babar.

- Full reco tag on other B
- OFF $\Upsilon(4S)$ data subtracted from ON data

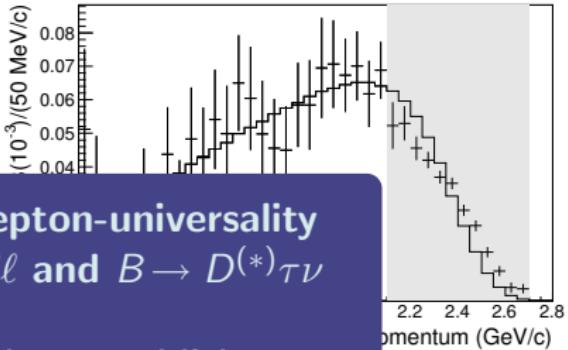
→ Except
 $b \rightarrow$
endpoints

- Result dependent on Babar fav

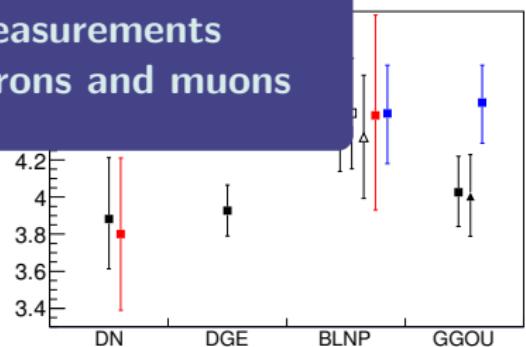
[JHEP 908 10,

→ $|V_{ub}|$ closer to the mean of
exclusive and inclusive

Also new exclusive V_{ub} using D decays to constrain form factors [PRD91



B -factories: please publish semileptonic measurements separately for electrons and muons

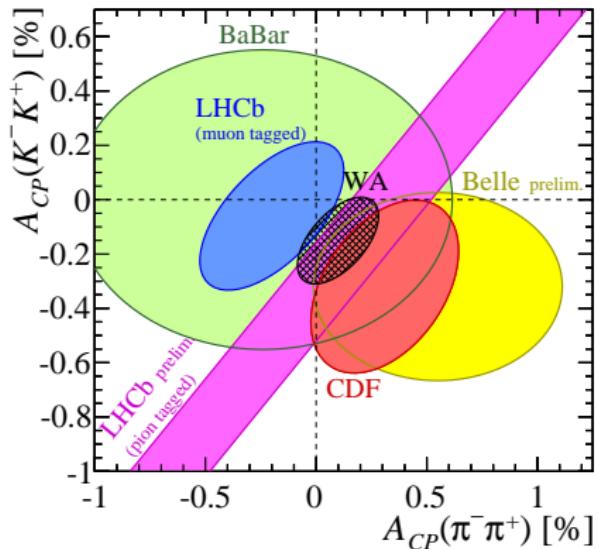
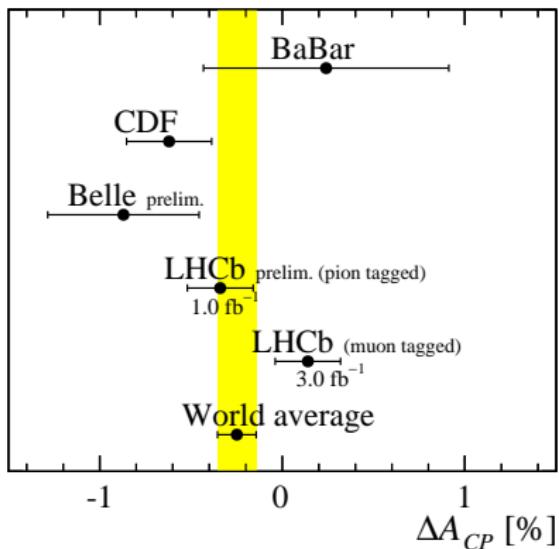


052022 (2015), arXiv:1412.5502].

Charm: Looking for anything but zero



ΔA_{CP} OF $D^0 \rightarrow K^+K^-$ AND $D^0 \rightarrow \pi^+\pi^-$



$$A_{CP}(K^+K^-) = (-0.016 \pm 0.012)\%$$

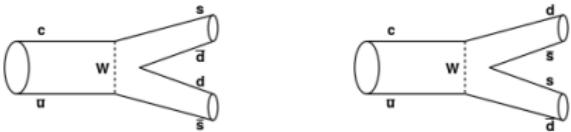
$$A_{CP}(\pi^+\pi^-) = (-0.05 \pm 0.15)\%$$

$$\Delta A_{CP} = (-0.253 \pm 0.104)\% \quad [\text{HFAG 2/15}]$$

CP ASYMMETRY IN $D^0 \rightarrow K_S^0 K_S^0$



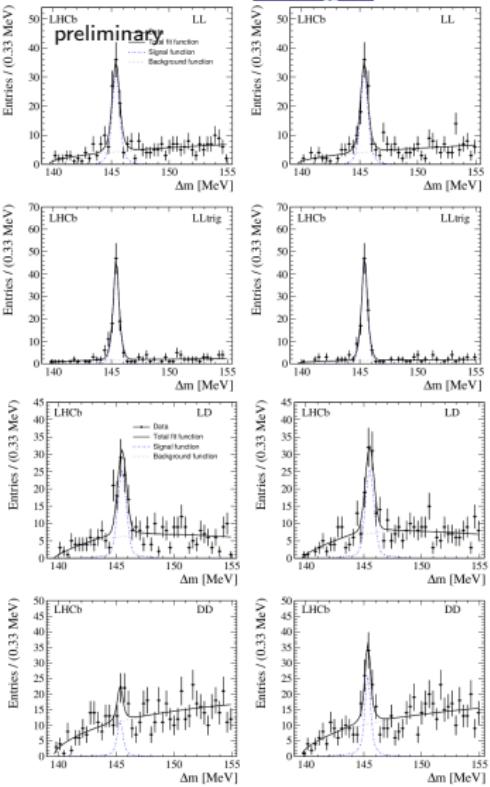
- $D^0 \rightarrow K_S^0 K_S^0$ proceeds via two annihilation diagrams → in SM phases should cancel



- Can only trigger on cases where both K_S^0 decay in Velo ("LLtrig")
- Three other categories with 0 (DD), 1 (LD) or 2 (LL, but not triggered) K_S^0 in Velo
→ 600 decays, tagged by D^* charge

$$A_{CP} = -(2.9 \pm 5.2 \pm 2.2)\% \text{ (Prelim.)}$$

Compatible with CP symmetry



Conclusion

- LHCb had a very good start in Run II
 - We are commissioning the trigger and processing of the future
 - ✓ First $b\bar{b}$ cross-section
- CP asymmetry measurements consistent with SM
 - Precision and penguin control improving
 - ✓ Expect all uncertainties to go down with LHC & Belle II
 - There's something going on with V_{ub}
- CKM matrix elements are crucial input to rare decays
 - See Karim's talk

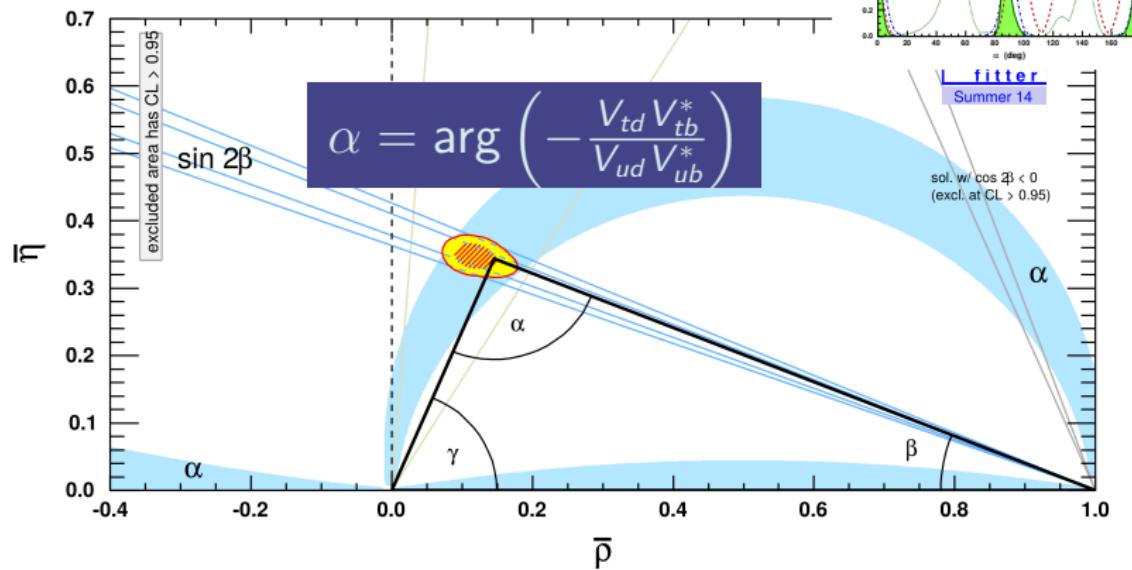


Backup



UNITARITY TRIANGLE

The unitarity triangle with only constraints from angles

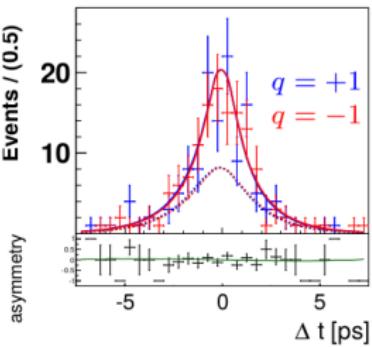
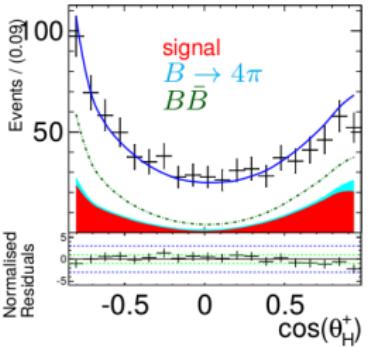
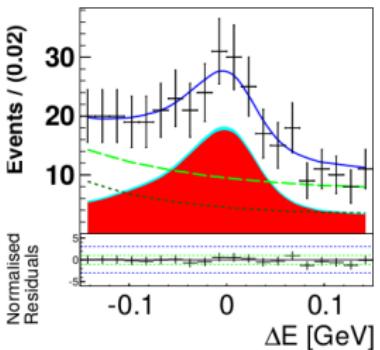
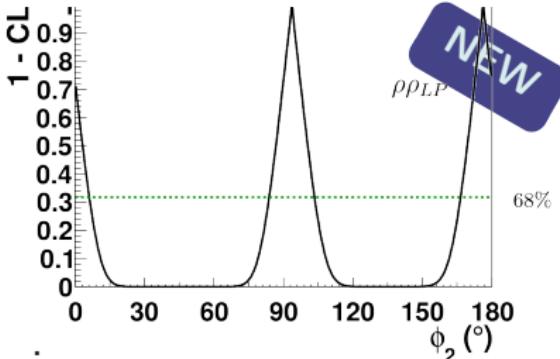


$$B^0 \rightarrow \rho^+ \rho^-$$

Belle performs a tagged time-dependent angular analysis using their full dataset

$$\begin{aligned} \mathcal{B}(B^0 \rightarrow \rho^+ \rho^-) &= (28.3 \pm 1.5 \text{ (stat)} \pm 1.4 \text{ (syst)}) \times 10^{-6}, \\ f_L &= 0.988 \pm 0.012 \text{ (stat)} \pm 0.023 \text{ (syst)}, \\ \mathcal{S}_{CP} &= -0.13 \pm 0.15 \text{ (stat)} \pm 0.05 \text{ (syst)}, \\ \mathcal{A}_{CP} &= 0.00 \pm 0.10 \text{ (stat)} \pm 0.06 \text{ (syst)} \end{aligned}$$

→ $\alpha = (93.7 \pm 10.6)^\circ$ from isospin analysis



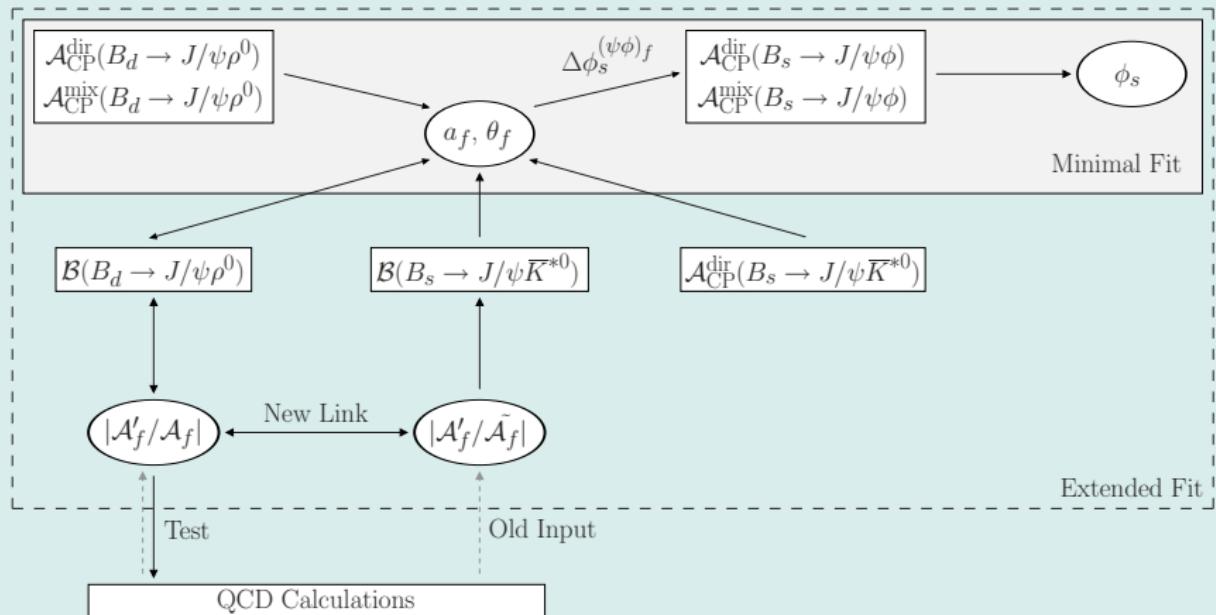
INTERPLAY OF CKM AND RARE DECAYS

CKM matrix elements uncertainties dominate in many “clean” measurements

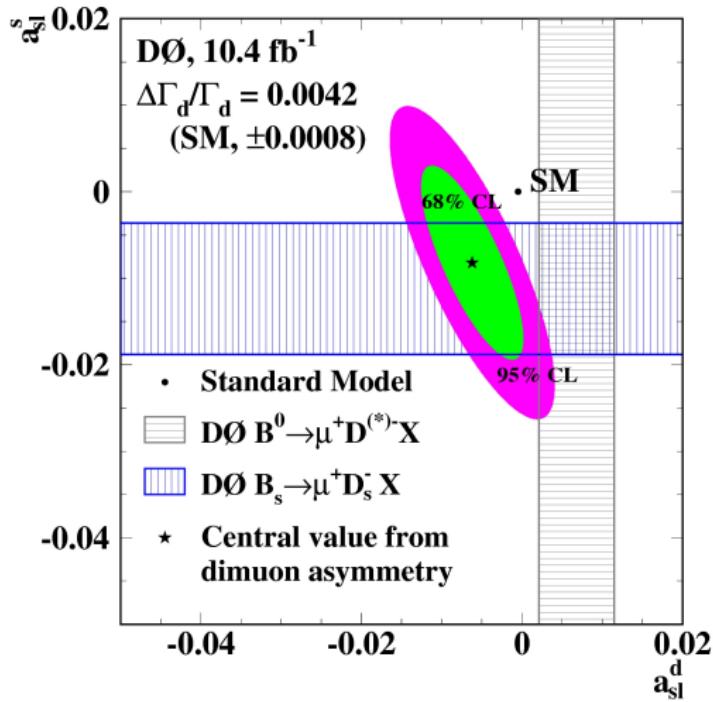
- SM BF uncertainties on $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ dominated by CKM uncertainties
- Wilson coefficient extraction from $b \rightarrow s l \bar{l}$ affected by form factors and CKM elements.
- $B^0 \rightarrow \mu^+ \mu^-$: 6.9 of 8.5% theory uncertainty comes from CKM elements

We are entering a regime where an improved knowledge of the CKM matrix will help constraining new physics in rare decays.

PENGUINS ROADMAP



DIMUON ASYMMETRY AT D0



- D0 measure the inclusive single muon charge asymmetry and the like-sign dimuon charge asymmetry
- Interpreted as semileptonic charge asymmetries as

$$A_{sl}^d = (-0.62 \pm 0.43)\%$$

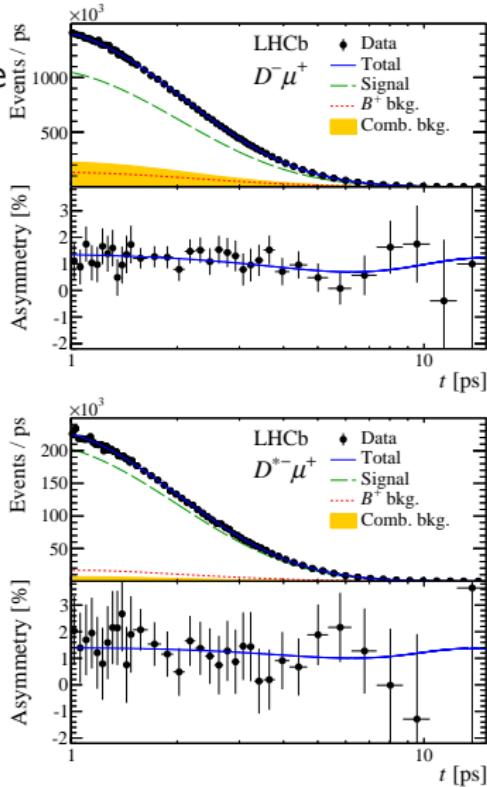
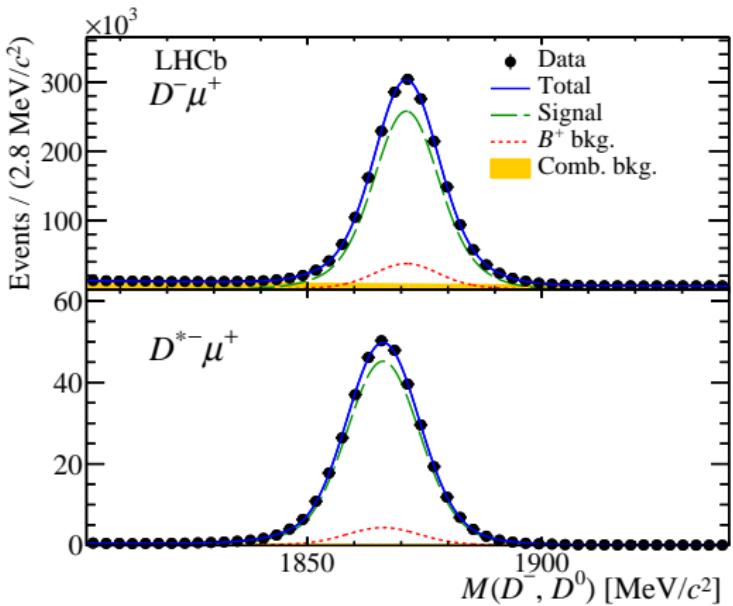
$$A_{sl}^s = (-0.82 \pm 0.99)\%$$

- 3σ deviation from the SM

SEMILEPTONIC B^0 ASYMMETRY A_{sl}^d



- Use 1.8M $B^0 \rightarrow D^- \mu^+ \nu_\mu X$ and 340k $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu X$ and measure charge asymmetry versus decay time



SEMILEPTONIC B^0 ASYMMETRY A_{sl}^d



- Use 1.8M $B^0 \rightarrow D^- \mu^+ \nu_\mu X$ and 340k $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu X$ and measure charge asymmetry versus decay time
- Time distribution ($\zeta = \pm 1$ for f, \bar{f})

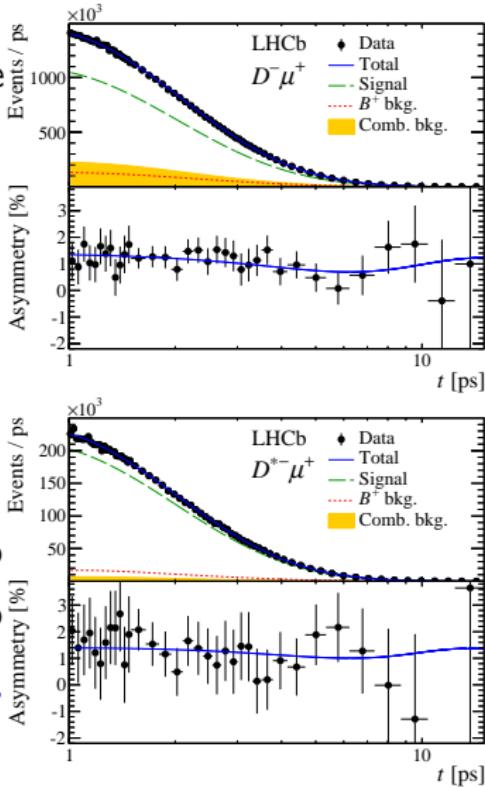
$$N(t) \propto e^{-\Gamma_d t} \left[1 + \zeta A_D + \zeta \frac{1}{2} a_{\text{sl}}^d - \zeta \left(A_P + \frac{1}{2} a_{\text{sl}}^d \right) \cos \Delta m_d t \right]$$

allows extraction of

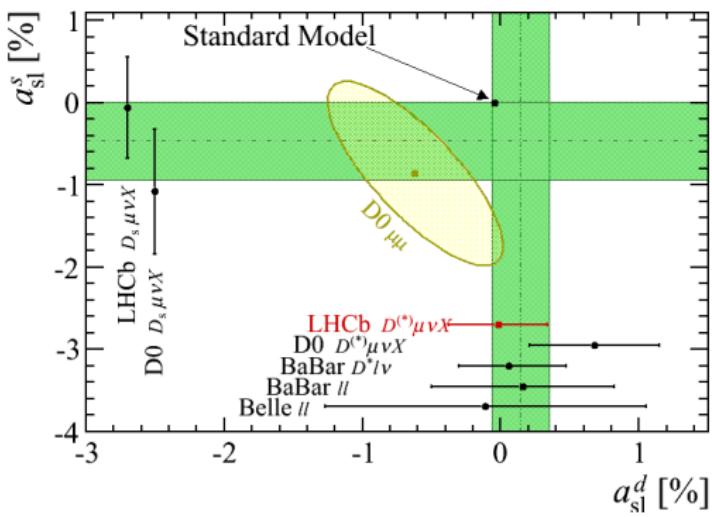
$$A_P(7 \text{ TeV}) = (-0.66 \pm 0.26 \pm 0.22)\%$$

$$A_P(8 \text{ TeV}) = (-0.48 \pm 0.15 \pm 0.17)\%$$

- Consistent with [LHCb, Phys. Lett. B739 (2014) 218, arXiv:1408.0275] (gives p_T, η dependence)



SEMILEPTONIC B^0 ASYMMETRY A_{sl}^d



- Surprising deviation from SM expectation in $(a_{\text{sl}}^d, a_{\text{sl}}^s)$ plane from D0 results [Phys. Rev. D 89, 012002 (2014), arXiv:1310.0447]
- LHCb measured a_{sl}^s with 1 fb^{-1} [Phys. Lett. B728 (2014) 607]
- New LHCb result of a_{sl}^d with 3 fb^{-1}
- The a_{sl}^s update will come soon

$$a_{\text{sl}}^d = (-0.02 \pm 0.19 \pm 0.30)\%$$

b FRAGMENTATION FRACTION f_s/f_d



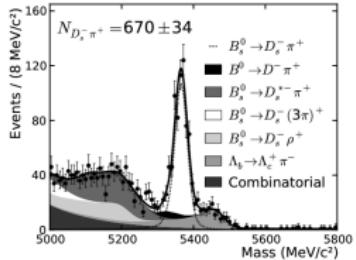
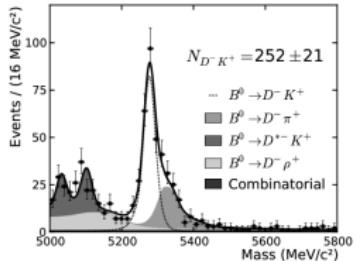
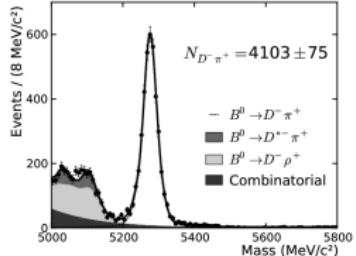
Fraction f_s of $b \rightarrow B_s^0 X$ is an essential ingredient for $B_s^0 \rightarrow \mu^+ \mu^-$ and other rare decays

- LHCb has measured it in two ways
 - Ratio of $b \rightarrow D_s^+ \mu X$ to $b \rightarrow D^+ \mu X$ modes
[\[LHCb, Phys. Rev. D85 \(2012\) 032008, arXiv:1111.2357\]](#)
 - Ratio of $B^0 \rightarrow DK$ and $B_s^0 \rightarrow D_s^+ \pi^-$ modes
[\[LHCb, Phys. Rev. Lett. 107 \(2011\) 211801, arXiv:1106.4435\]](#)

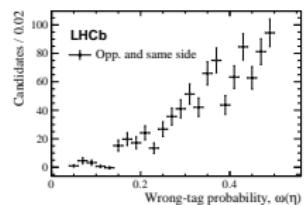
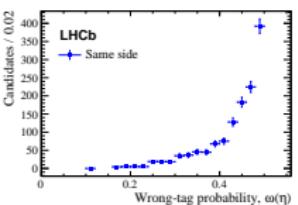
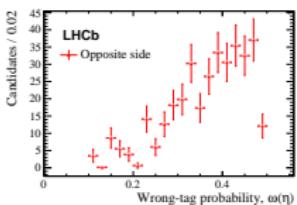
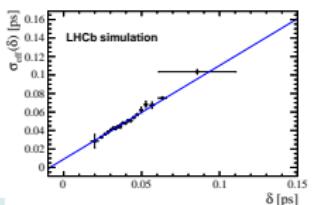
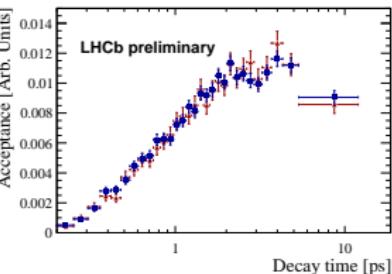
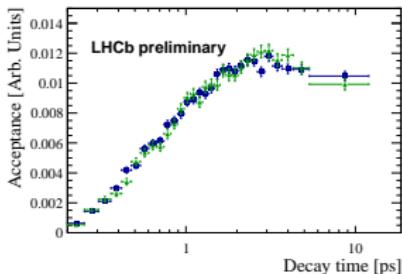
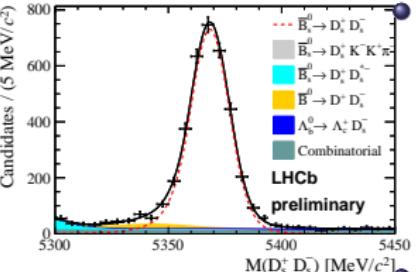
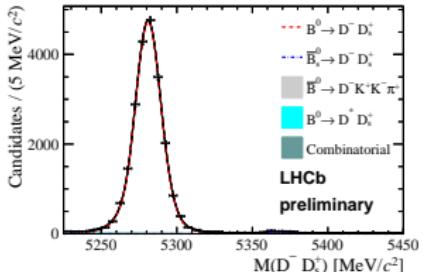
→ Combination [\[LHCb, LHCb-CONF-2013-011\]](#)

$$\left(\frac{f_s}{f_d}\right)_{\text{LHCb}} = 0.259 \pm 0.015$$

- Similar to LEP, and below Tevatron result
- Quite ironic it's known better than at the $\Upsilon(5S)$
 - B_s^0 BFs better measures at the LHC



ϕ_s FROM $B_s^0 \rightarrow D_s^+ D_s^-$

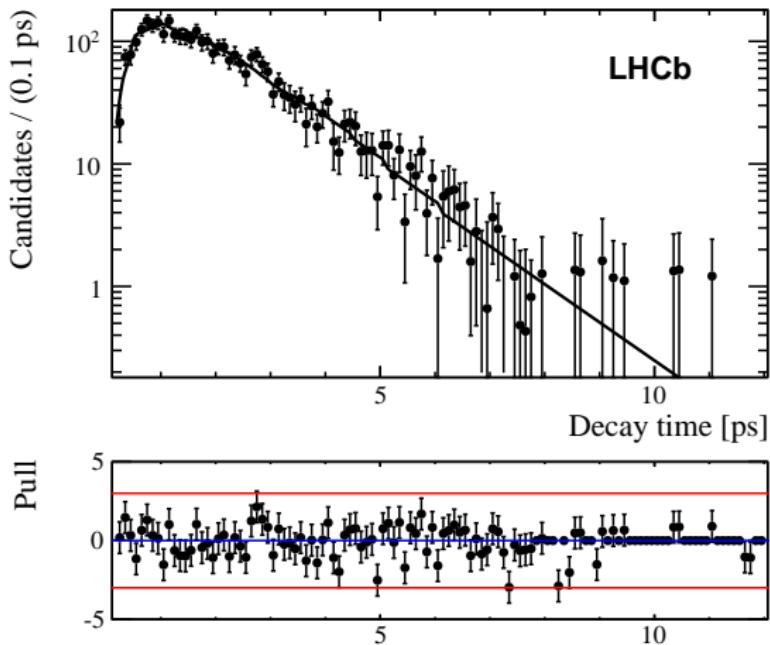


- Time dependent CP analysis of $B_s^0 \rightarrow D_s^+ D_s^-$ with $B^0 \rightarrow D^- D_s^+$ as control.

- Time acceptance from data and resolution from MC

- Excellent tagging power of 5.3%

ϕ_s FROM $B_s^0 \rightarrow D_s^+ D_s^-$



- Time dependent CP analysis of $B_s^0 \rightarrow D_s^+ D_s^-$ with $B^0 \rightarrow D^- D_s^+$ as control.
- Time acceptance from data and resolution from MC
- Excellent tagging power of 5.3%

$$\phi_s = 0.02 \pm 0.17 \pm 0.02 \text{ rad}$$

(or $\phi_s = 0.02 \pm 0.17 \pm 0.02 \text{ rad}$ with $CPV |\lambda| = 0.91^{+0.18}_{-0.15} \pm 0.02$)

γ WITH $B^- \rightarrow DK^-\pi^+\pi^-$ AND $B^- \rightarrow D\pi^-\pi^+$



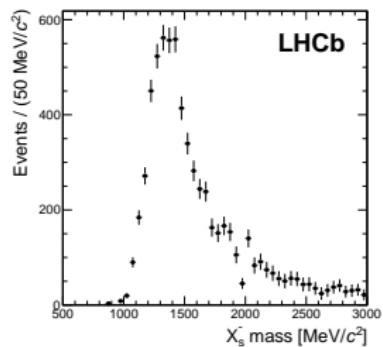
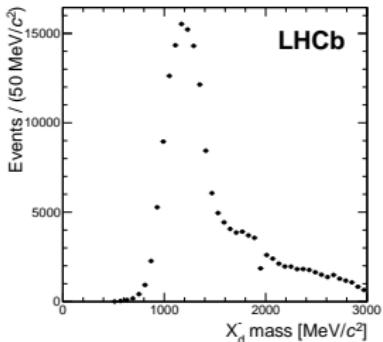
- The CKM angle γ is the least constrained angle of the unitarity triangle,

$$\gamma = (73^{+9}_{-10})^\circ \quad [\text{LHCb, LHCb-CONF-2014-004}]$$

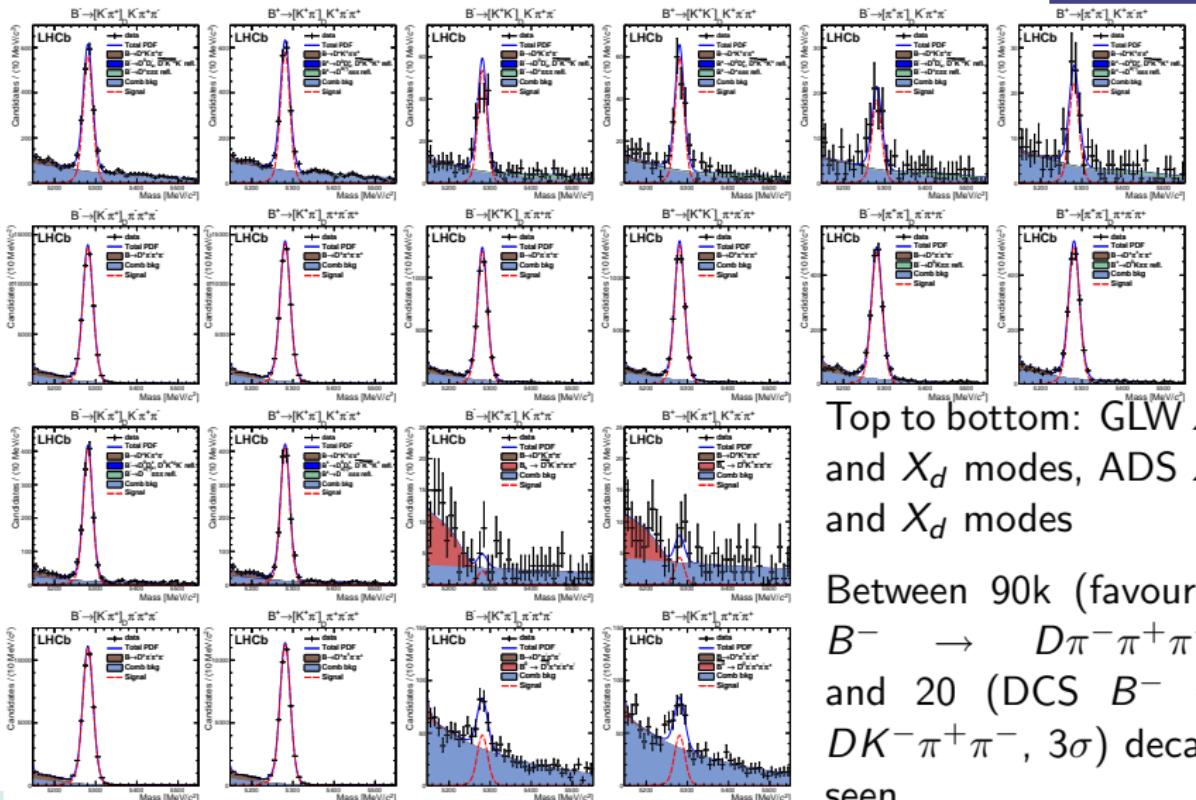
- $B^\pm \rightarrow D(hh\pi^0)h^\pm$ [Phys. Rev. D91 (2015) 112014],
 - $B^0 \rightarrow DK^*$ [Phys. Rev. D90 (2014) 112002],
 - $B_s^0 \rightarrow D_s^\mp K^\pm$ [JHEP 11 (2014) 060],
 - $B^\pm \rightarrow D(K_s^0\pi^+\pi^-)h^\pm$ [JHEP 10 (2014) 097],
 - [Nucl. Phys. B888 (2014) 169],
 - $B^\pm \rightarrow D(K_s^0K\pi)h^\pm$ [Phys. Lett. B733 (2014) 36]

...

- But it can be determined in tree decays to unlimited precision [Brod, Zupan, JHEP 1401 (2014) 051]
- Here look for $B^- \rightarrow DK^-\pi^+\pi^-$ and $B^- \rightarrow D\pi^-\pi^+\pi^-$ with $D \rightarrow K^\mp\pi^\pm$ (ADS) and $D \rightarrow h^+h^- h = \pi, K$ (GLW)



γ WITH $B^- \rightarrow DK^-\pi^+\pi^-$ AND $B^- \rightarrow D\pi^-\pi^+$



Top to bottom: GLW X_s and X_d modes, ADS X_s and X_d modes

Between 90k (favoured $B^- \rightarrow D\pi^-\pi^+\pi^-$) and 20 (DCS $B^- \rightarrow DK^-\pi^+\pi^-$, 3σ) decays seen

γ WITH $B^- \rightarrow DK^-\pi^+\pi^-$ AND $B^- \rightarrow D\pi^-\pi^+$



A combined fit to all CP observables gets
 $\gamma = (74^{+20}_{-18})^\circ$ and $r_B^{DX_s} = 0.08 \pm 0.03$ at
68% CL. At 95% there are no constraints yet.

$$R_{CP+}^{K^+K^-} = 1.043 \pm 0.069 \pm 0.034,$$

$$R_{CP+}^{\pi^+\pi^-} = 1.035 \pm 0.108 \pm 0.038,$$

$$\mathcal{A}_{X_d}^{K^+K^-} = -0.019 \pm 0.011 \pm 0.010,$$

$$\mathcal{A}_{X_d}^{\pi^+\pi^-} = -0.013 \pm 0.016 \pm 0.010,$$

$$\mathcal{A}_{X_d}^{K^-\pi^+} = -0.002 \pm 0.003 \pm 0.011,$$

$$R^{X_d^+} = (42.8 \pm 5.3 \pm 2.1) \times 10^{-4},$$

$$R^{X_d^-} = (42.5 \pm 5.3 \pm 2.1) \times 10^{-4},$$

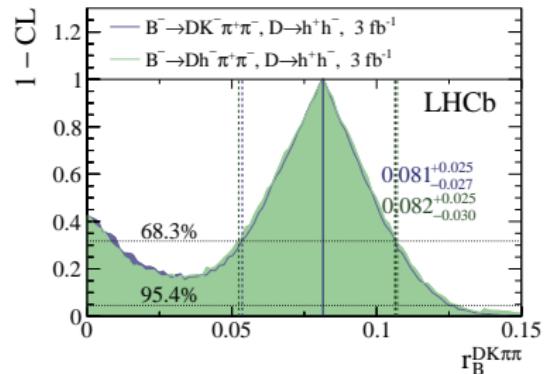
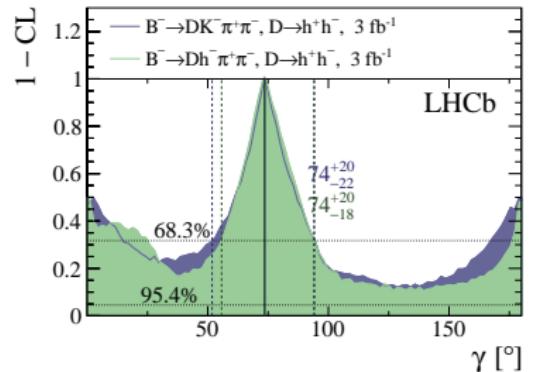
$$\mathcal{A}_{X_s}^{K^+K^-} = -0.045 \pm 0.064 \pm 0.011,$$

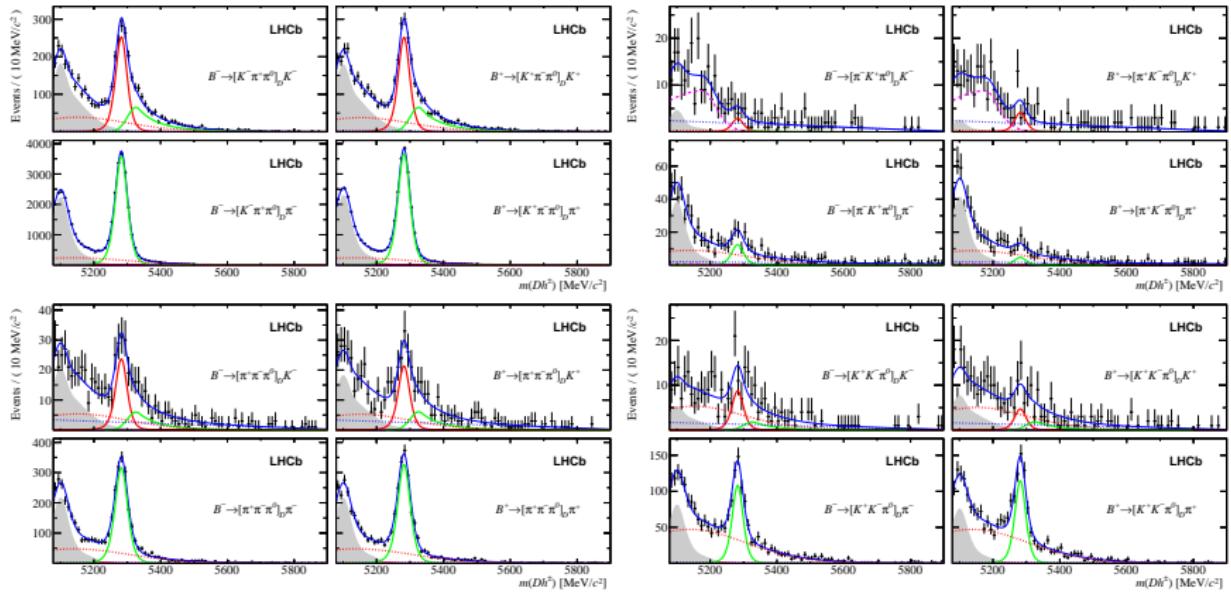
$$\mathcal{A}_{X_s}^{\pi^+\pi^-} = -0.054 \pm 0.101 \pm 0.011,$$

$$\mathcal{A}_{X_s}^{K^-\pi^+} = 0.013 \pm 0.019 \pm 0.013,$$

$$R^{X_s^+} = (105^{+60}_{-44} \pm 11) \times 10^{-4} \quad [< 0.018 \text{ at 95\% CL }],$$

$$R^{X_s^-} = (54^{+45}_{-42} \pm 6) \times 10^{-4} \quad [< 0.012 \text{ at 95\% CL }].$$



γ WITH $B^+ \rightarrow D(h^+ h^- \pi^0) K^+$ (ADS/GLW)


$B^- \rightarrow D(h^\pm h^\mp \pi^0) h^-$ with π^0 in the final state:

37k $D(K^- \pi^+ \pi^0) \pi^-$, 3k $D(K^- \pi^+ \pi^0) K^-$, 88 ± 20 $D(K^+ \pi^- \pi^0) \pi^-$ (FO),
 40 \pm 13 $D(K^+ \pi^- \pi^0) K^-$, 3k $D(\pi^- \pi^+ \pi^0) \pi^-$, 164 ± 27 $D(\pi^- \pi^+ \pi^0) K^-$,
 1k $D(K^+ K^- \pi^0) \pi^-$, 76 ± 17 $D(K^+ K^- \pi^0) \pi^-$ (FO).

γ WITH $B^+ \rightarrow D(h^+ h^- \pi^0) K^+$ (ADS/GLW)



- Ratios R of suppressed to favoured modes and asymmetries A of B^- and B^+ are determined following ADS [PRD63 036005] and GLW prescriptions [PLB265 172].
 - $h^+ h^- \pi^0$ is almost a CP eigenstate (quasi-GLW).
 - Systematics dominated by mass PDF and instrumental symmetry for kaons
- Bounds on γ , r_B and δ_B . Consistent with average [LHCb-CONF-2014-001].

$$A_{\text{ADS}(K)}^{K\pi\pi^0} = -0.20 \pm 0.27 \pm 0.04$$

$$A_{\text{ADS}(\pi)}^{K\pi\pi^0} = 0.438 \pm 0.190 \pm 0.011$$

$$A_{\text{qGLW}(K)}^{KK\pi^0} = 0.30 \pm 0.20 \pm 0.02$$

$$A_{\text{qGLW}(\pi)}^{\pi\pi\pi^0} = 0.054 \pm 0.091 \pm 0.011$$

$$A_{\text{qGLW}(\pi)}^{KK\pi^0} = -0.030 \pm 0.040 \pm 0.005$$

$$A_{\text{qGLW}(\pi)}^{\pi\pi\pi^0} = -0.016 \pm 0.020 \pm 0.004$$

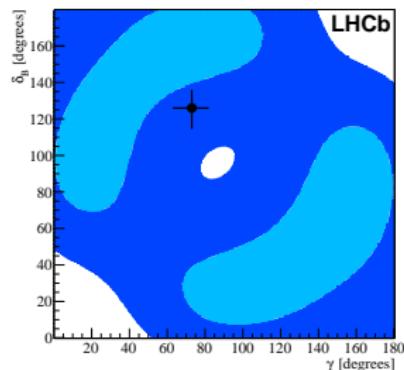
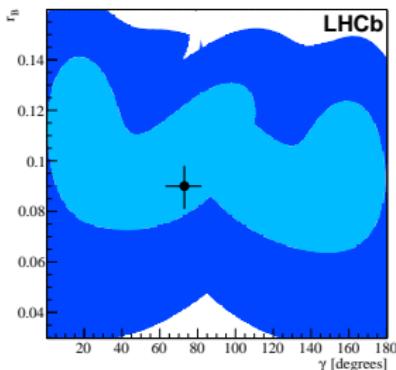
$$A_K^{K\pi\pi^0} = 0.010 \pm 0.026 \pm 0.005$$

$$R_{\text{ADS}(K)}^{K\pi\pi^0} = 0.0140 \pm 0.0047 \pm 0.0021$$

$$R_{\text{ADS}(\pi)}^{K\pi\pi^0} = 0.00235 \pm 0.00049 \pm 0.00006$$

$$R_{\text{qGLW}}^{KK\pi^0} = 0.95 \pm 0.22 \pm 0.05$$

$$R_{\text{qGLW}}^{\pi\pi\pi^0} = 0.98 \pm 0.11 \pm 0.05$$



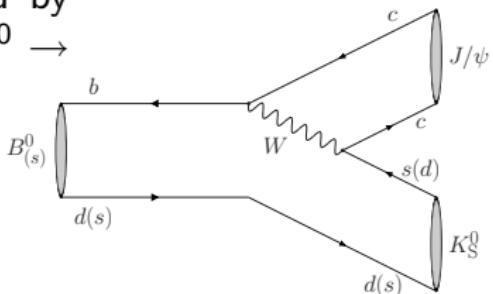
CPV IN $B_s^0 \rightarrow J/\psi K_s^0$



In $B_s^0 \rightarrow J/\psi K_s^0$ the penguin is enhanced by a factor 20 wrt the tree, compared to $B^0 \rightarrow J/\psi K_s^0$

→ Penguin control for $B^0 \rightarrow J/\psi K_s^0$

✗ Cabibbo-suppressed



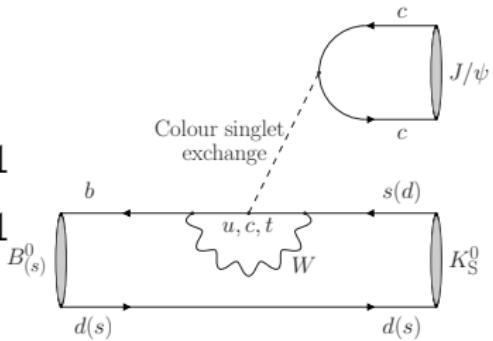
$$\Gamma \equiv \mathcal{N}_f e^{it/\tau_{B_s^0}} [\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s t/2) - S_{\text{mix}} \sin(\Delta m_s t) + C_{\text{dir}} \cos(\Delta m_s t)] ,$$

SM predictions: [De Bruyn et al., arXiv:1412.6834]

$$\mathcal{A}_{\Delta\Gamma}(B_s^0 \rightarrow J/\psi K_s^0) = 0.957 \pm 0.061$$

$$C_{\text{dir}}(B_s^0 \rightarrow J/\psi K_s^0) = 0.003 \pm 0.021$$

$$S_{\text{mix}}(B_s^0 \rightarrow J/\psi K_s^0) = 0.29 \pm 0.20$$



CPV IN $B_s^0 \rightarrow J/\psi K_s^0$



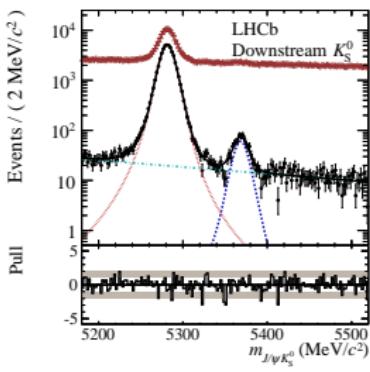
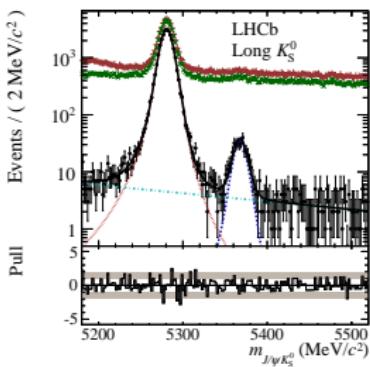
In $B_s^0 \rightarrow J/\psi K_s^0$ the penguin is enhanced by a factor 20 wrt the tree, compared to $B^0 \rightarrow J/\psi K_s^0$

→ Penguin control for $B^0 \rightarrow J/\psi K_s^0$

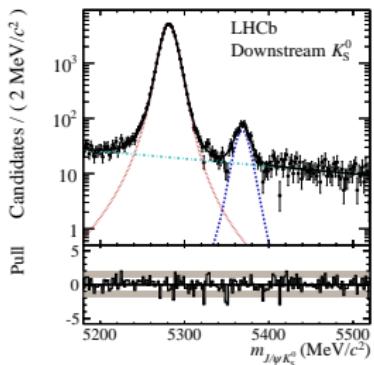
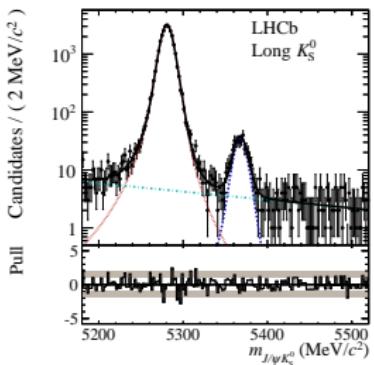
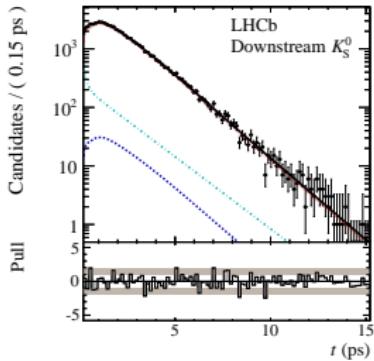
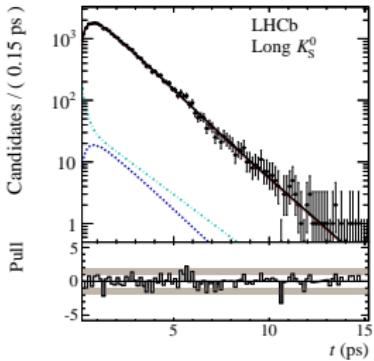
✗ Cabibbo-suppressed

- Selection in three steps:

- ➊ Preselection, identical to $B^0 \rightarrow J/\psi K_s^0$
- ➋ NN to suppress $B^0 \rightarrow J/\psi K^*$ background (LL)
- ➌ NN to suppress background

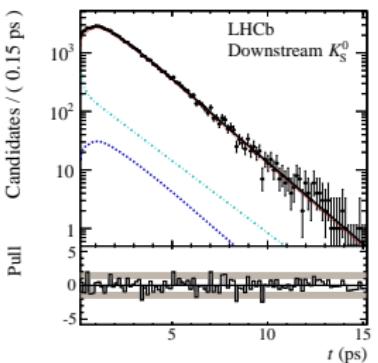
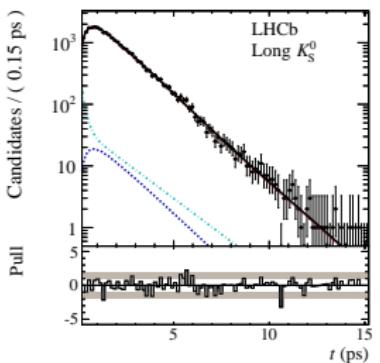


CPV IN $B_s^0 \rightarrow J/\psi K_S^0$



- Time-dependent tagged fit
- Identical to $B^0 \rightarrow J/\psi K_S^0$, except for same-side kaon
- That has some efficiency on the B^0 , when its decision is reversed

CPV IN $B_s^0 \rightarrow J/\psi K_S^0$



With 3 fb^{-1} we can make a measurement but are not sensitive to penguins yet

$$\mathcal{A}_{\Delta\Gamma}(B_s^0 \rightarrow J/\psi K_S^0) = 0.49^{+0.77}_{-0.65} (\text{stat}) \pm 0.06 (\text{syst}),$$

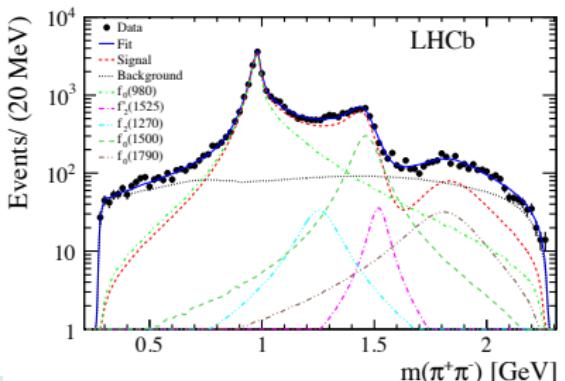
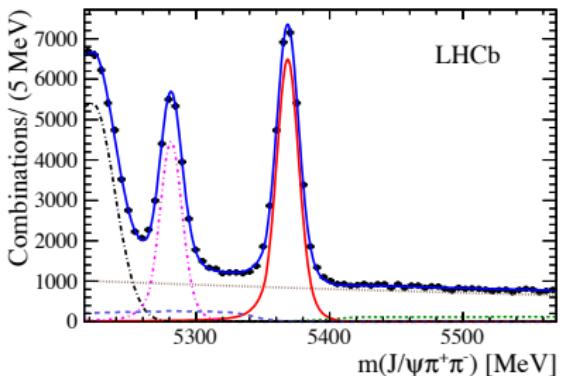
$$C_{\text{dir}}(B_s^0 \rightarrow J/\psi K_S^0) = -0.28 \pm 0.41 (\text{stat}) \pm 0.08 (\text{syst}),$$

$$S_{\text{mix}}(B_s^0 \rightarrow J/\psi K_S^0) = -0.08 \pm 0.40 (\text{stat}) \pm 0.08 (\text{syst}).$$

$$\frac{\mathcal{B}(B_s^0 \rightarrow J/\psi K_S^0)}{\mathcal{B}(B^0 \rightarrow J/\psi K_S^0)} = 0.0431 \pm 0.0017 (\text{stat}) \pm 0.0012 (\text{syst})$$

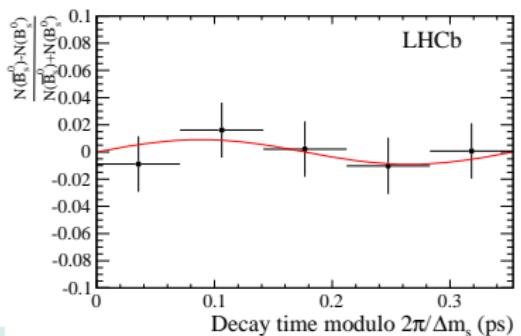
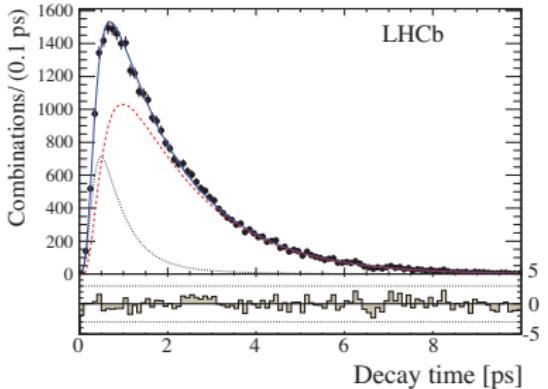
$$\pm 0.0025 (f_s/f_d)$$

ϕ_s IN $B_s^0 \rightarrow J/\psi \pi^- \pi^+$



- Follow-up of CP -components in $B_s^0 \rightarrow J/\psi \pi^- \pi^+$ [Phys. Rev. D89 (2014) 092006, arXiv:1402.6248] → > 97% CP -odd
- Tagged time-dependent angular analysis
 - Use opposite and same-side taggers
 - Effective power $3.89 \pm 0.25\%$

ϕ_s IN $B_s^0 \rightarrow J/\psi \pi^- \pi^+$



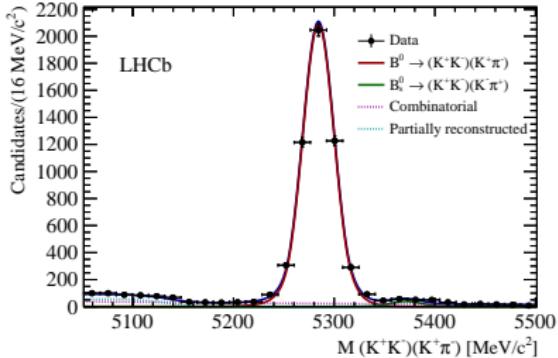
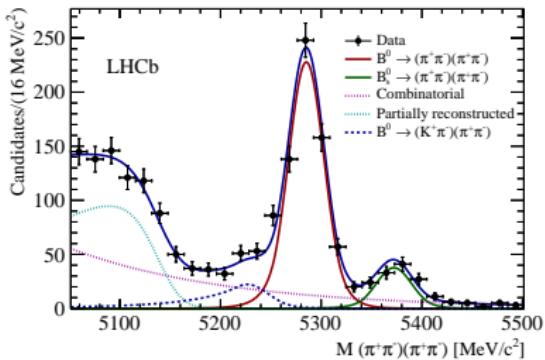
- Follow-up of CP -components in $B_s^0 \rightarrow J/\psi \pi^- \pi^+$ [Phys. Rev. D89 (2014) 092006, arXiv:1402.6248] → > 97% CP -odd
- Tagged time-dependent angular analysis
 - Use opposite and same-side taggers
 - Effective power $3.89 \pm 0.25\%$
- Result: $\phi_s = 75 \pm 67 \pm 8$ mrad
 - $\phi_s = 70 \pm 68 \pm 8$ mrad and $|\lambda| = \left| \frac{q}{p} \frac{\bar{A}}{A} \right| = 0.89 \pm 0.05 \pm 0.01$ if CPV allowed
- Consistent with SM
 $\phi_s = -36.3 \pm 1.6$ mrad and
 $B_s^0 \rightarrow J/\psi KK$: $\phi_s = 70 \pm 90 \pm 10$
[Phys. Rev. D 87, 112010 (2013), arXiv:1304.2600]

AMPLITUDE ANALYSIS OF $B^0 \rightarrow \rho^0 \rho^0$

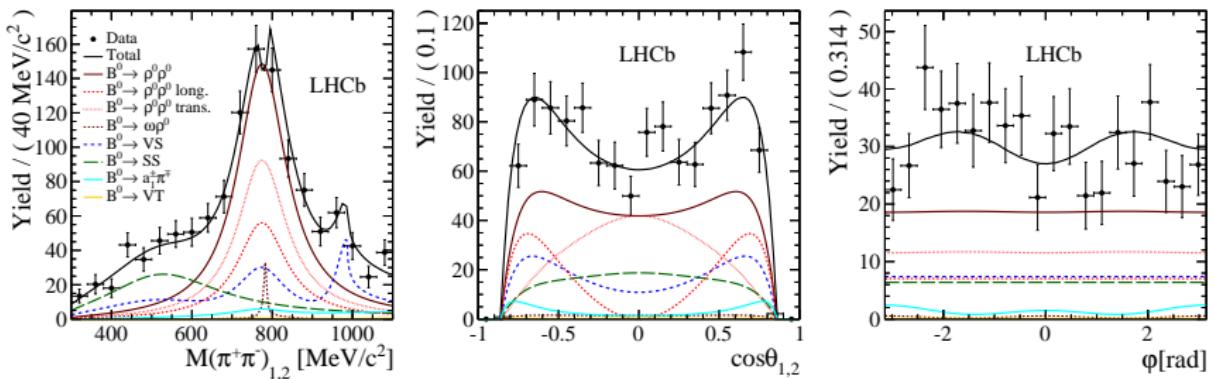


$B \rightarrow \rho\rho$ sensitive to α but size of penguin must be determined via isospin analysis of charged and neutral modes.

- Discrepancy in polarisation of $B^0 \rightarrow \rho^0 \rho^0$: $f_L = 0.12^{+0.22}_{-0.26}$ at Belle [PRD89, 072008, arXiv:1212.4015] and $f_L = 0.75^{+0.12}_{-0.15}$ at BaBar [PRD78, 071104, arXiv:0807.4977]
- Select $B^0 \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)$ with $300 < m_{\pi^+\pi^-} < 1100$ MeV/c² (no charge ambiguities)
 - 634 ± 29 decays
 - $B^0 \rightarrow \phi K^*$ used as normalisation channel

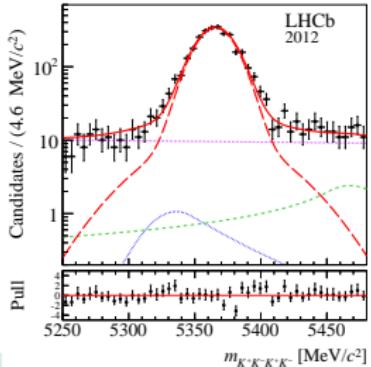
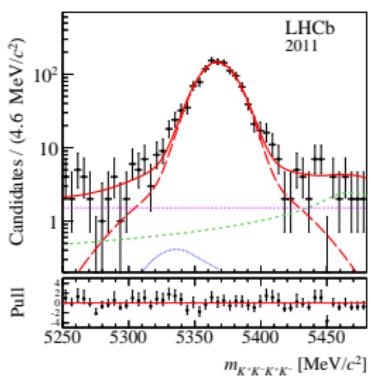


AMPLITUDE ANALYSIS OF $B^0 \rightarrow \rho^0 \rho^0$



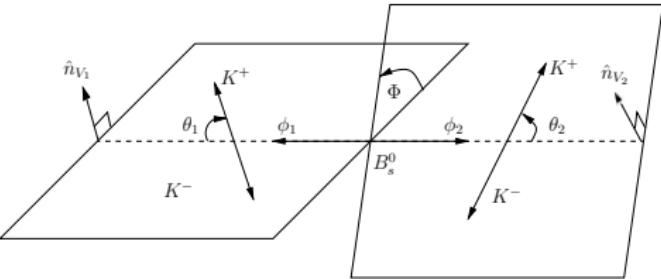
- Amplitude analysis used to determine the VV ($\rho^0 \rho^0$ and $\rho^0 \omega$), VS ($\rho^0 f_0$ and $\rho^0 \pi^+ \pi^-$) and VT ($\rho^0 f_2(1270)$).
- $F_L = 0.745^{+0.048}_{-0.058} \pm 0.034$ (same as BaBar, more precise)
- BFs normalised to $B^0 \rightarrow \phi K^*$:
 $\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) = (0.94 \pm 0.17 \pm 0.09 \pm 0.06) \times 10^{-6}$ and
 $\mathcal{B}(B^0 \rightarrow \rho^0 f_0(980)) \times \mathcal{B}(f_0 \rightarrow \pi^+ \pi^-) < 0.82 \times 10^{-6}$

CP VIOLATION IN $B_s^0 \rightarrow \phi\phi$

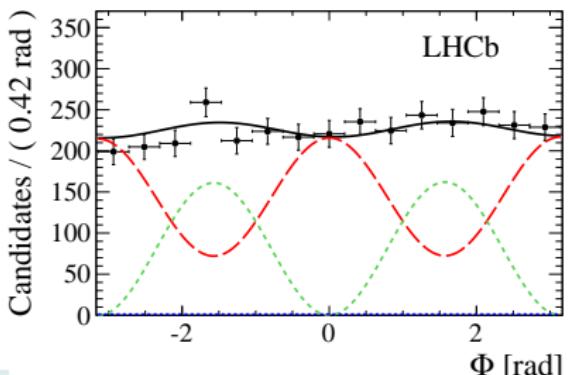
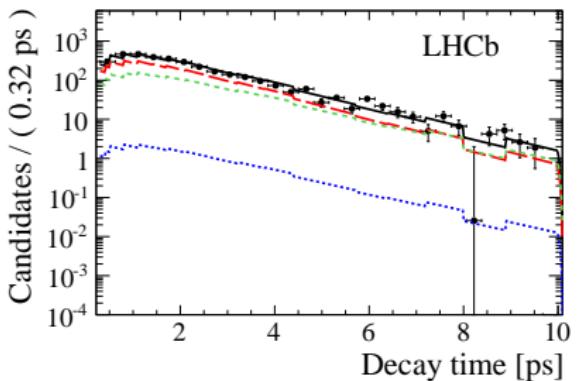


- $B_s^0 \rightarrow \phi\phi$ is a QCD penguin induced decay. Allows to measure the phase of interference of mixing and decay. SM prediction is $\phi_s = 0$.
- Select almost 4000 decays and do a time-dependent tagged angular analysis

$$\rightarrow \epsilon \mathcal{D}^2 \simeq 3.1\%$$

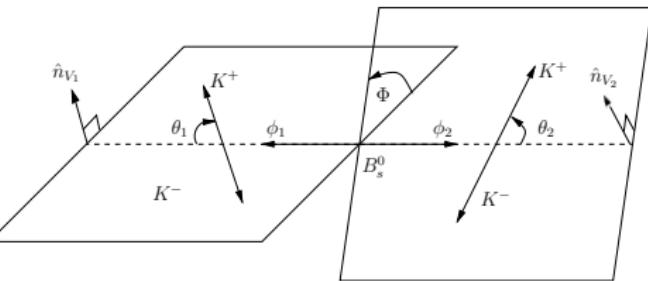


CP VIOLATION IN $B_s^0 \rightarrow \phi\phi$

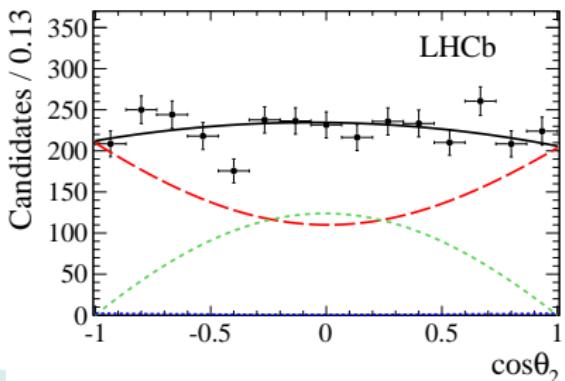
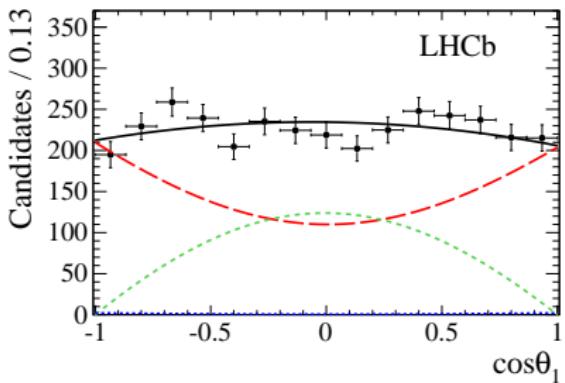


- $B_s^0 \rightarrow \phi\phi$ is a QCD penguin induced decay. Allows to measure the phase of interference of mixing and decay. SM prediction is $\phi_s = 0$.
- Select almost 4000 decays and do a time-dependent tagged angular analysis

$$\rightarrow \epsilon \mathcal{D}^2 \simeq 3.1\%$$



CP VIOLATION IN $B_s^0 \rightarrow \phi\phi$



- $B_s^0 \rightarrow \phi\phi$ is a QCD penguin induced decay. Allows to measure the phase of interference of mixing and decay. SM prediction is $\phi_s = 0$.
- Select almost 4000 decays and do a time-dependent tagged angular analysis
→ $\epsilon\mathcal{D}^2 \simeq 3.1\%$
- $\phi_s = -0.17 \pm 0.15 \pm 0.03$
 $(\lambda = 1.04 \pm 0.07 \pm 0.03)$
- T-odd triple product asymmetries:

$$A_U = -0.003 \pm 0.017 \pm 0.006$$

$$A_V = -0.017 \pm 0.017 \pm 0.006$$

$D^0 \rightarrow hh$ A_Γ WITH SEMILEPTONICS



Measurement of time-dependent CP violation

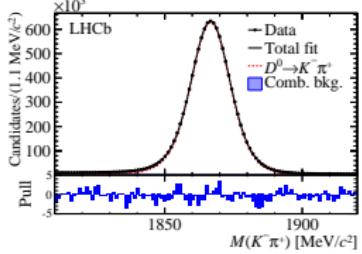
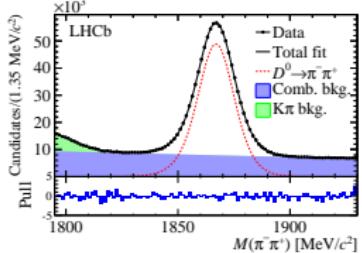
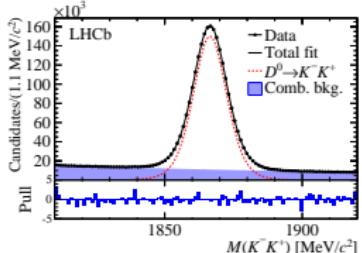
$$A_{CP}(t) \simeq A_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau}$$

where A_Γ is the asymmetry of effective lifetimes of D^0 and \bar{D}^0 .

In terms of mixing parameters x and y :

$$A_\Gamma \simeq \left(\frac{1}{2} A_{CP}^{\text{mix}} - A_{CP}^{\text{dir}} \right) y \cos \phi - x \sin \phi$$

- This is measured for $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$ in semileptonic B decays



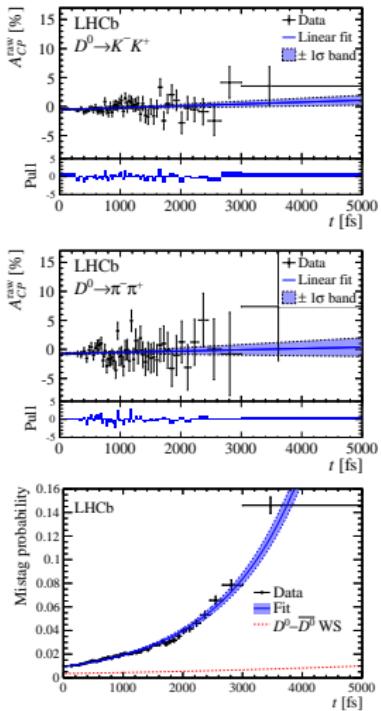
$D^0 \rightarrow hh A_\Gamma$ WITH SEMILEPTONICS



Measurement of time-dependent CP violation

$$A_{CP}(t) \simeq A_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau}$$

- This is measured for $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$ in semileptonic B decays
- Lifetime obtained from $D^0 \mu$ to $D^0 \rightarrow hh$ vertices
- Mistag asymmetry is the largest systematic uncertainty
 - Mistag larger for larger lifetimes. Checked with $D^0 \rightarrow K^- \pi^+$



$D^0 \rightarrow hh$ A_Γ WITH SEMILEPTONICS



Measurement of time-dependent CP violation

$$A_{CP}(t) \simeq A_{CP}^{\text{dir}} - A_\Gamma \frac{t}{\tau}$$

where A_Γ is the asymmetry of effective lifetimes of D^0 and \bar{D}^0 .

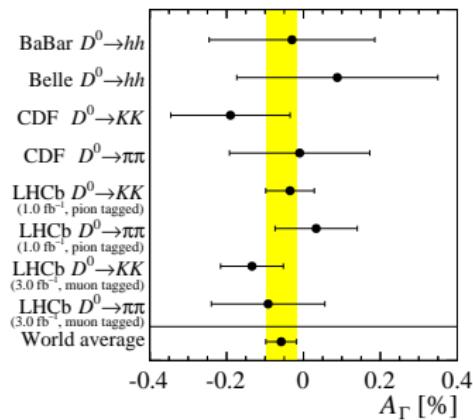
In terms of mixing parameters x and y :

$$A_\Gamma \simeq \left(\frac{1}{2} A_{CP}^{\text{mix}} - A_{CP}^{\text{dir}} \right) y \cos \phi - x \sin \phi$$

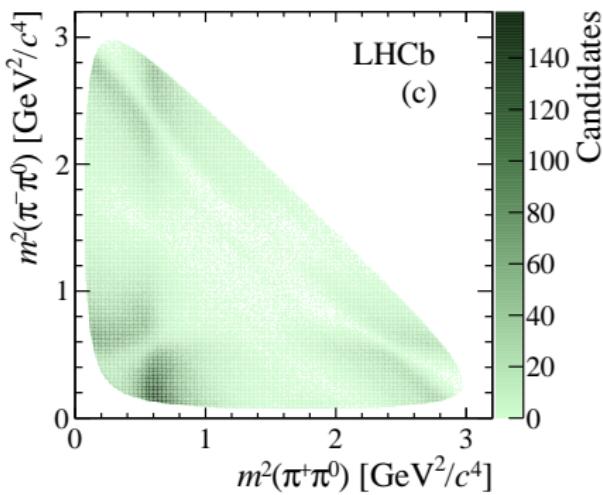
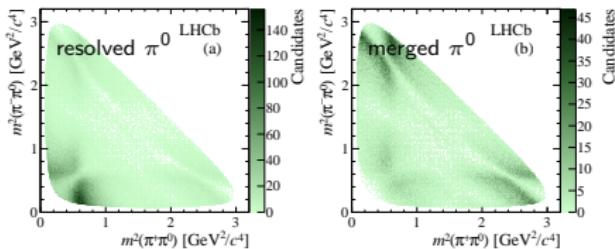
We measure:

$$A_\Gamma(K^+K^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%,$$

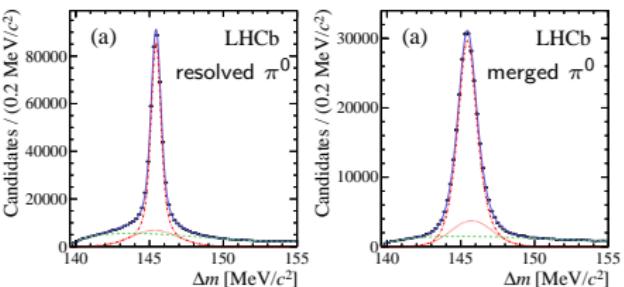
$$A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$$

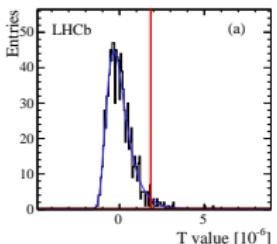
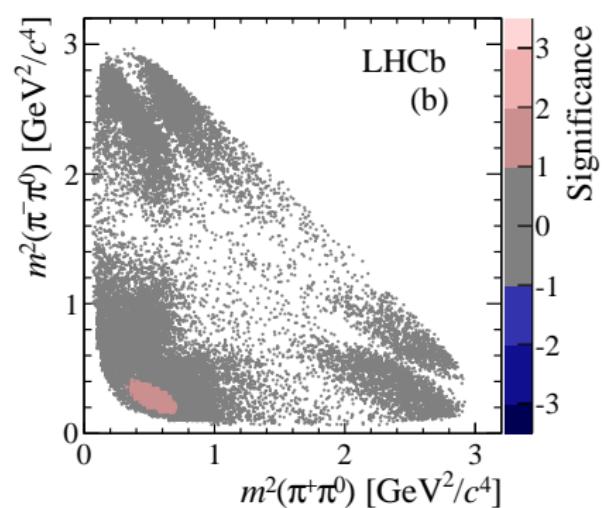


3 fb^{-1} Prompt still to come

CPV IN $D^0 \rightarrow \pi^+ \pi^- \pi^0$ WITH ENERGY TEST

- Model-independent search for local CP asymmetry in tagged $D^0 \rightarrow \pi^+ \pi^- \pi^0$ decays.
 - Use resolved (both γ seen) and merged π^0
 - 2 fb^{-1} at 8 TeV



CPV IN $D^0 \rightarrow \pi^+\pi^-\pi^0$ WITH ENERGY TEST

- Model-independent search for local CP asymmetry in tagged $D^0 \rightarrow \pi^+\pi^-\pi^0$ decays.
 - Use resolved (both γ seen) and merged π^0
 - 2 fb^{-1} at 8 TeV
- Energy test: Unbinned test of compatibility between D^0 and \bar{D}^0 Dalitz distributions
 - Based on distance in phase-space of events
- The data are found to be consistent with the hypothesis of CP symmetry with a p-value of (2.6 ± 0.5) .