Searching for New Physics in b-hadron decays

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on behalf of the LHCb experiment

including results from other experiments

27th August 2014

Overview

- Quark flavour physics state of the art
- Improving the precision
- A few anomalies appear
- New territory
- Conclusions

Introduction

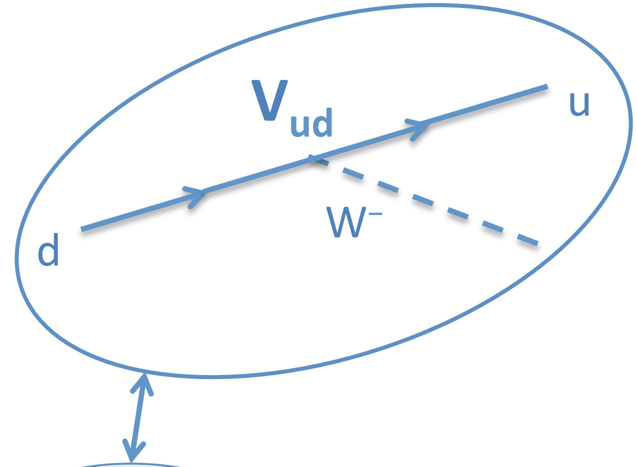
- Flavour physics is complementary approach to energy frontier searches in effort to uncover "New Physics"
  - This has been repeatedly demonstrated through the history of particle physics (e.g. CP violation pointing the way to the 3rd generation)
  - And is quite clear today (e.g. constraints on SUSY parameter space from branching fraction of $B_s \longrightarrow \mu^+\mu^-$)
- Many of the puzzles in the SM lie in the flavour realm:
  - CP violation (links to matter-antimatter asymmetry of universe and cosmology!)
  - Fermion mass hierarchy & number of generations
  - Values of CKM (and PMNS!) matrix parameters
- *B*-physics is an excellent laboratory to study these with great precision

B physics is a worldwide effort

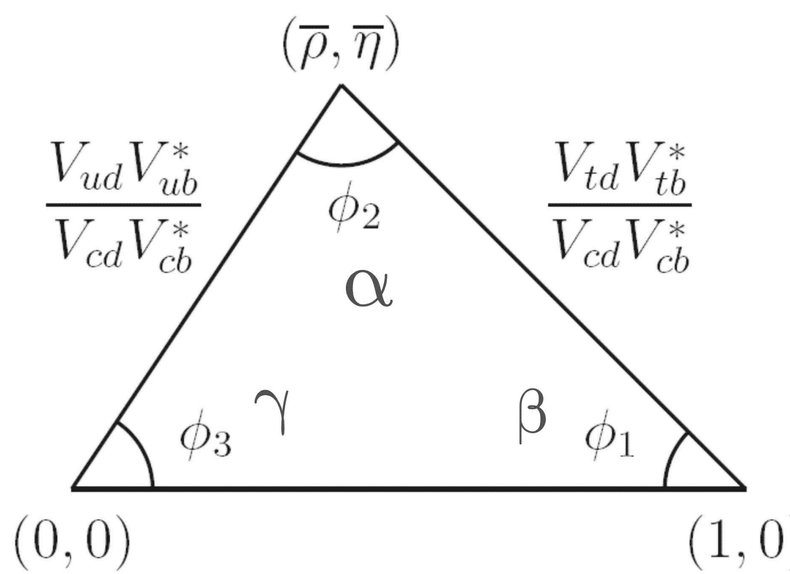
The state of the art

CKM mechanism

- Standard Model description of quark coupling to weak interaction
- CPV arises due to complex phase in the mixing matrix
- Convenient representation for *b*-hadron physics is the Unitarity Triangle
- Angles and side lengths can be measured through various *B*-decay processes

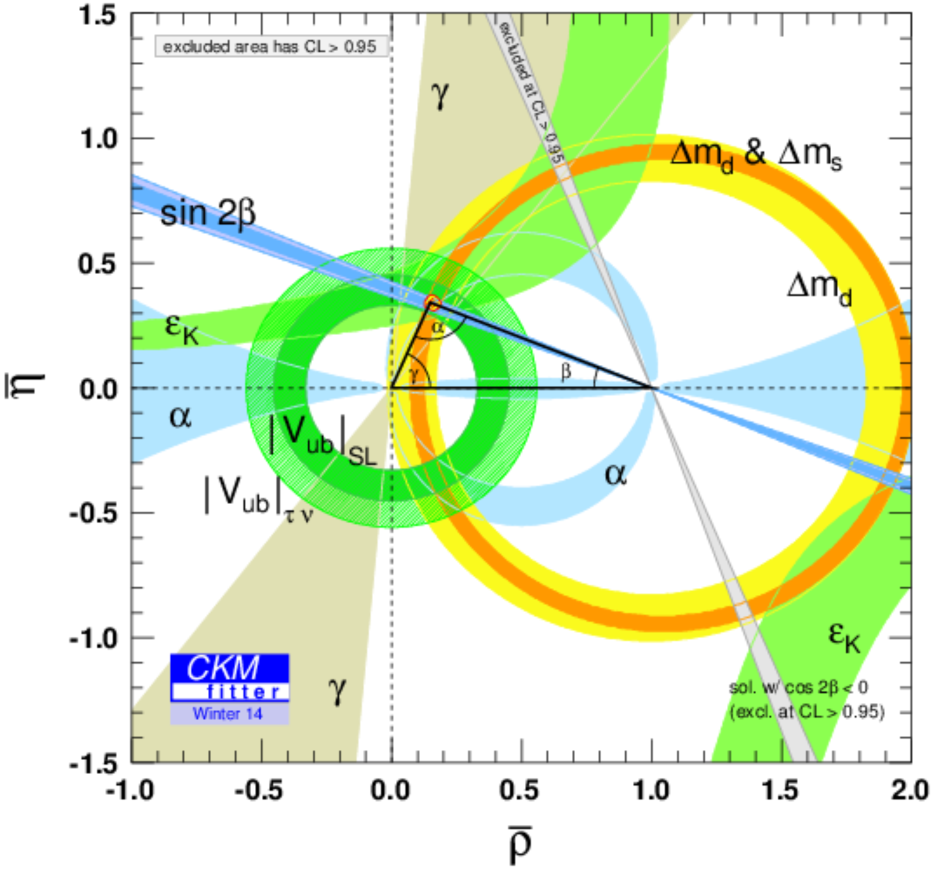


$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



Current status

- CKM mechanism agrees well with experiment
- But still room for new physics at ~10-20% level
- Vital to measure CP violating observables in as many different decay processes as possible
- Look for disagreements



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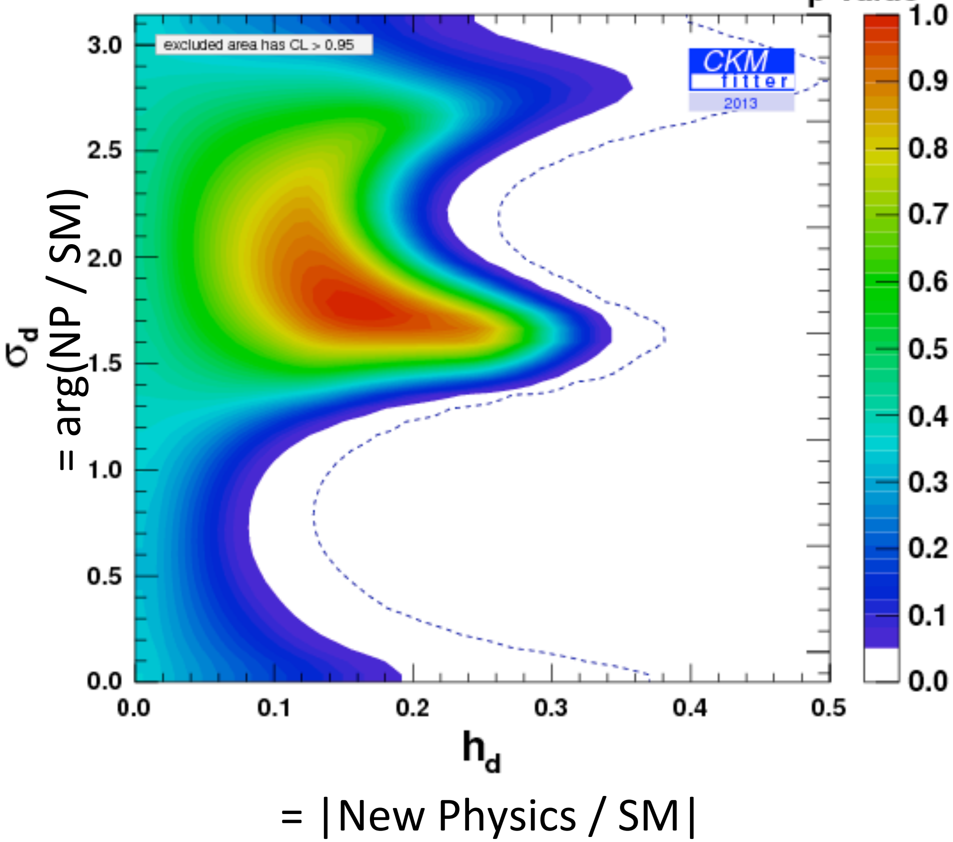
Allowed new physics contributions in B^0 mixing

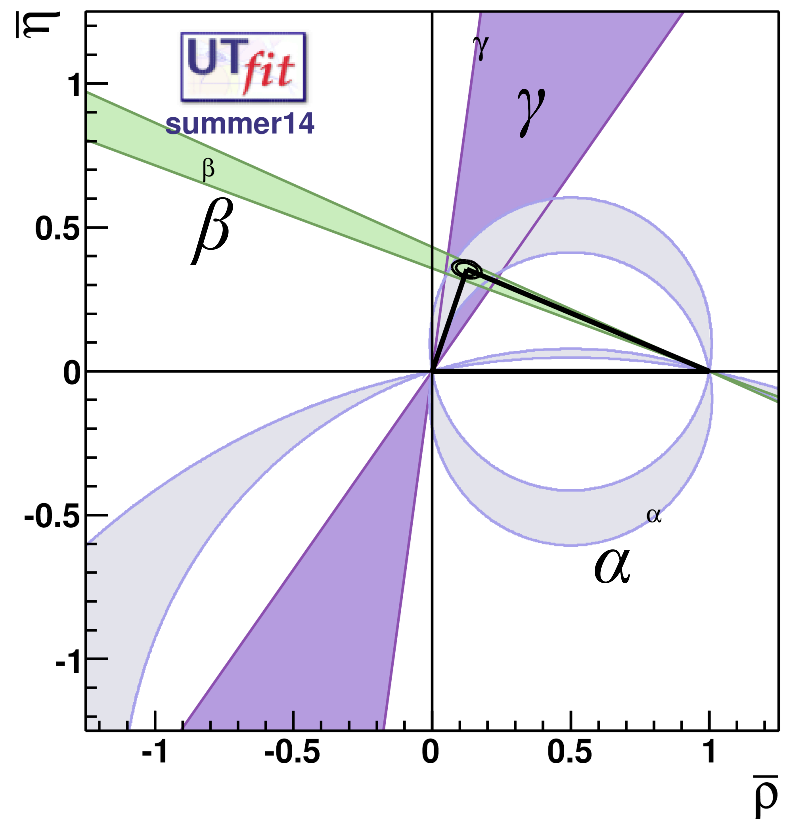


Increasing precision reveals the cracks?

UT angle γ

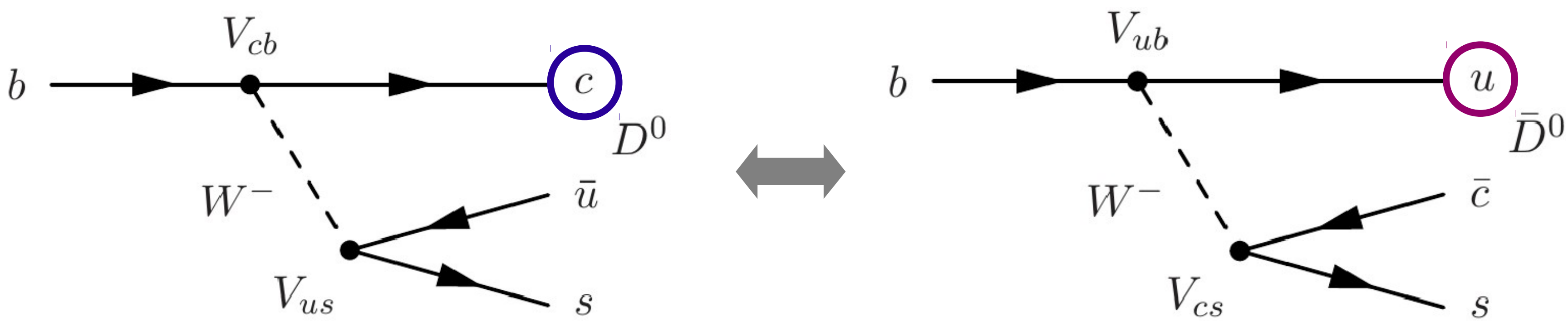
- Least well determined Unitarity Triangle angle:
  - BaBar: $(69\ ^{+17}_{-16})°$
    [Phys. Rev. D 87 (2013) 052015]
  - Belle: $(68\ ^{+15}_{-14})°$
    [arXiv:1301.2033]
  - LHCb: $(67 \pm 12)°$
    [LHCb-CONF-2013-006]
- Only angle that can be measured in pure tree-level processes
  - SM "standard candle"
  - Theoretically very clean
    $\delta\gamma/\gamma \leq O(10^{-7})$ [JHEP 01 (2014) 051]
- Need better precision

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



Methodology

- Measured through interference of two tree diagrams



$$A_{B^\pm} = A_D + e^{i(\delta_B \pm \gamma)} A_{\bar{D}}$$

- Hence *D* and $\bar{D}$ must decay to same final state
  - CP-eigenstate (e.g. K^+K^-): GLW method
  - Suppressed/favoured (e.g. $K^-\pi^+$ or $K3\pi$): ADS method
  - Multi-body flavour-conjugate state (e.g. $K_S\pi^+\pi^-$): GGSZ method

arXiv:1408.2748

LHCb GGSZ Analysis

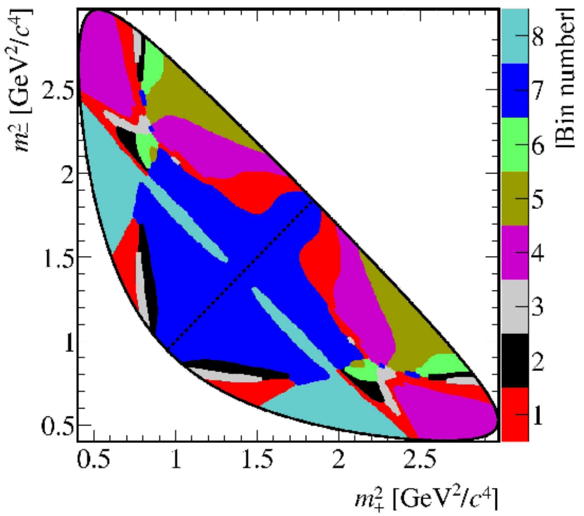
- Need to know strong phase variation over DP
  - Can use a model, e.g. from BaBar [PRL 105, 081803 (2010)]
  - Can use CLEO-c measurements in DP bins [PRD 82, 112006 (2010)]
    - As first done by Belle [PRD 85, 112014 (2012)]
- Show LHCb results from latter method using full Run1 dataset ($3fb^{-1}$)

$$N^{+}_{\pm i} = h_{B^+}\left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})\right]$$

- N^+ = # of D from B^+ events in bin ±i
- F_i = fraction of pure D^0 events in bin i – determined from $B^0 \to D^*(D^0\pi^+)\mu^-\nu$ LHCb data
- c and s are average cosine and sine of strong phase difference (δ_D) in bin i: CLEO-c inputs
- x and y are real and imaginary part of amplitude ratio:

$$x_\pm = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm = r_B \sin(\delta_B \pm \gamma)$$

- Simultaneous fit to B candidate invariant mass in all bins of DP to determine x and y



arXiv:1408.2748

LHCb GGSZ Results

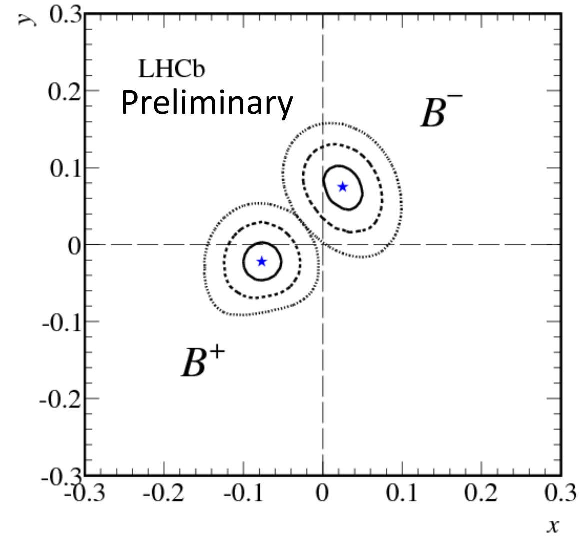
- Fit to both $K_S\pi\pi$ and K_SKK final states yields:

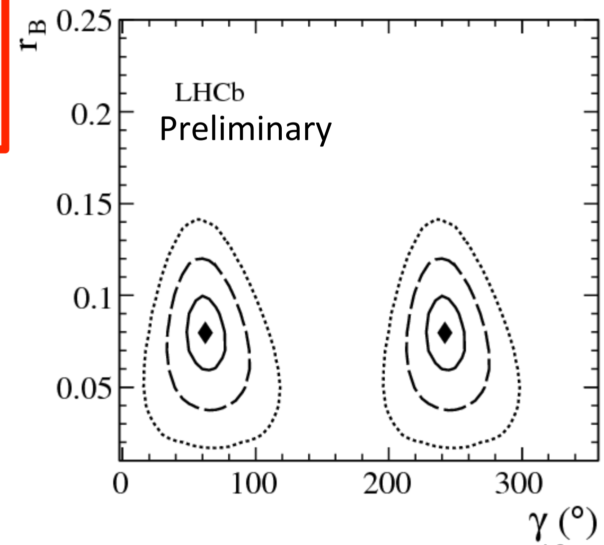
$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2},$$
$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2},$$
$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2},$$
$$y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2},$$

- Which gives the following results for the physical parameters:

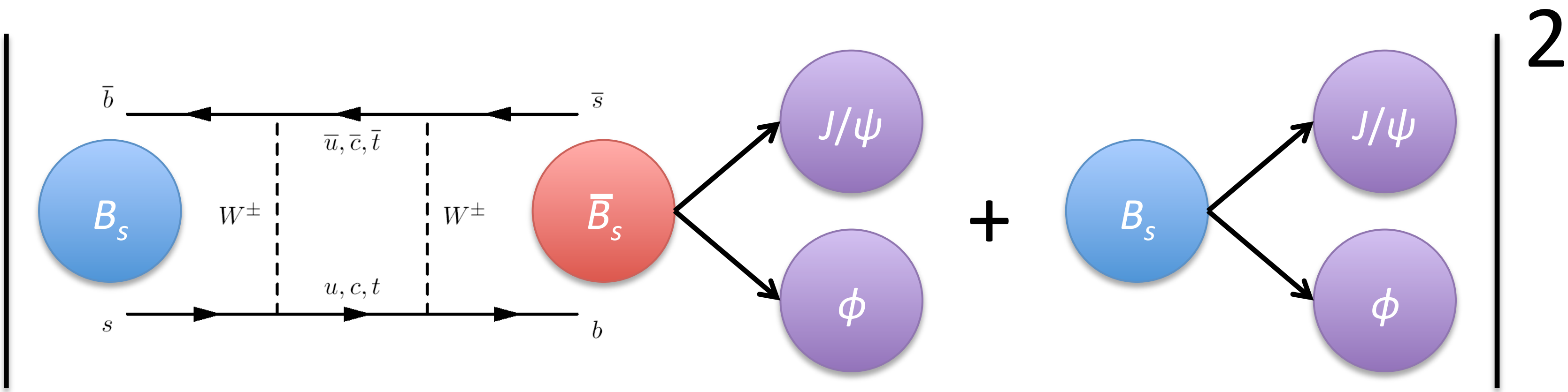
$$r_B = 0.080^{+0.019}_{-0.021}$$
$$\gamma = \left(62^{+15}_{-14}\right)^\circ$$
$$\delta_B = \left(134^{+14}_{-15}\right)^\circ$$

- Single most precise measurement of γ!
  - cf. $(66.4\ ^{+1.2}_{-3.3})^\circ$ from CKMfitter global fit (excluding direct measurements)
- Other LHCb analyses being updated to full data sample – expect new combination soon





B_s mixing phase

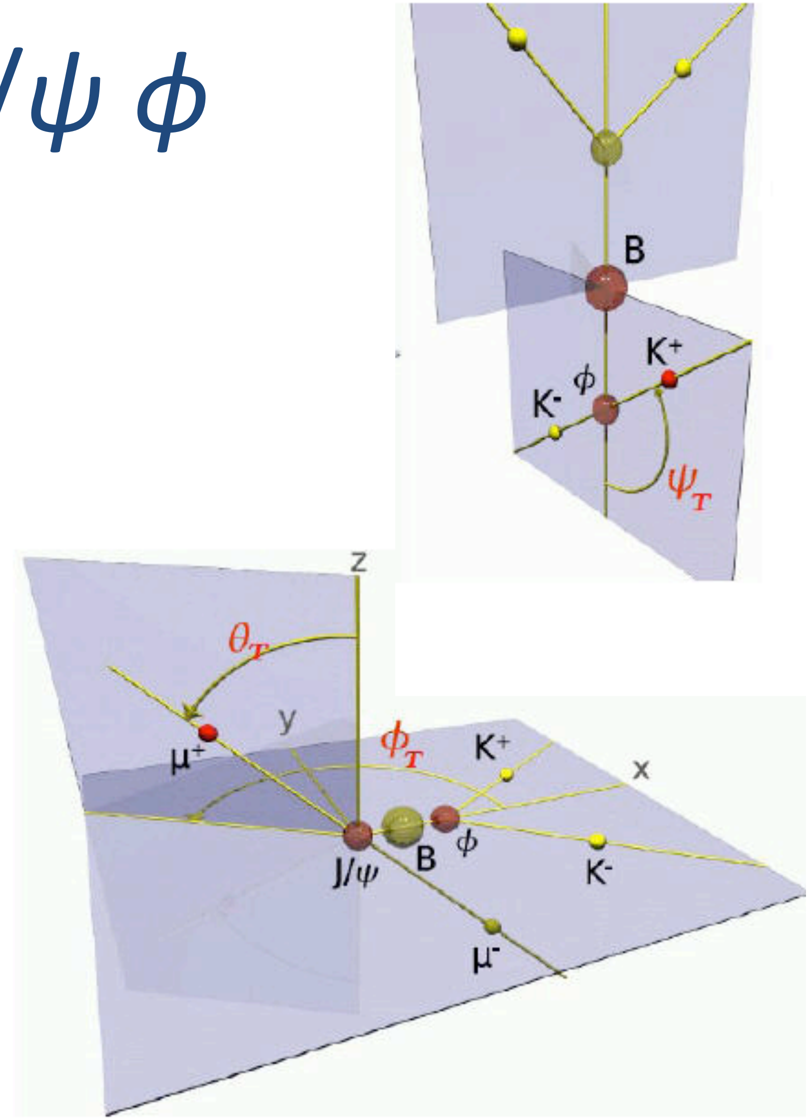


$$\phi_s \approx -2\beta_s = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

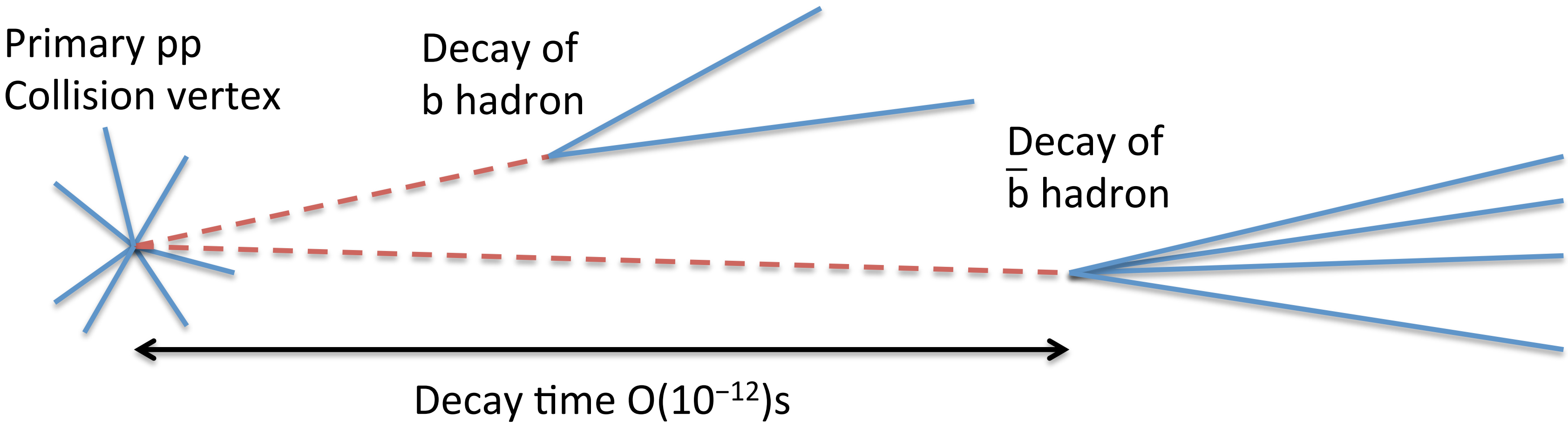
- Neutral *B* mesons exhibit mixing through box diagram
- Decays to CP eigenstates allow to probe the mixing phase ϕ_s through interference
- SM value is small $\phi_s \approx (-0.0363 \pm 0.0016)$ rad
- Many new physics models can enhance value

$B_s \to J/\psi\ \phi$

- Experimentally clean
- However, vector-vector final state is admixture of CP eigenstates
- Requires an angular analysis to disentangle CP-odd and CP-even components
  - Angles ϕ_T, θ_T, ψ_T defined in transversity basis
- Signal model sum of terms containing angular and time dependence
  - Sensitivity to mixing phase enters in sine and sinh terms in time dependence

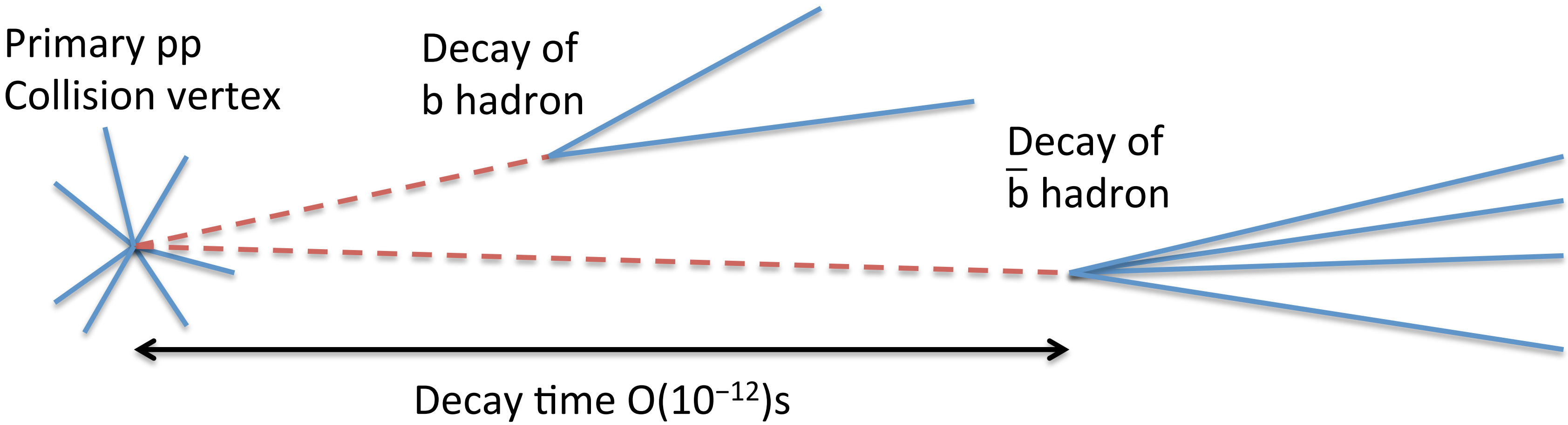


Experimental

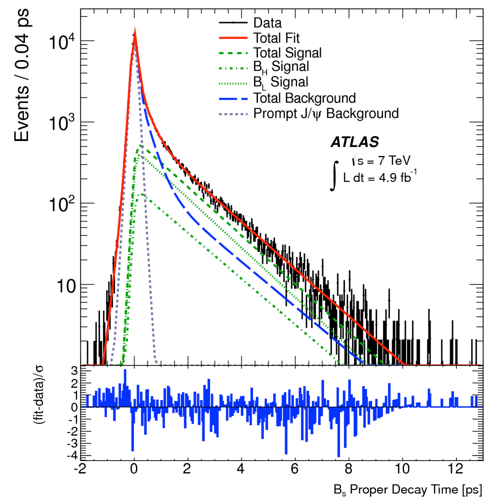


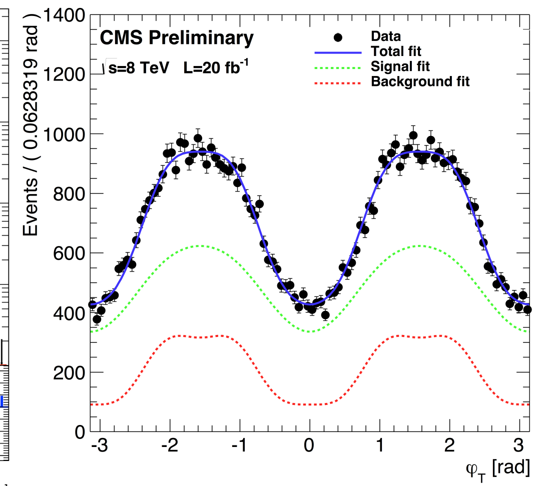
- Need to tag the flavour of the B_s at production
  - Can use flavour-specific decays of other *b*-hadron in event
  - Or use particles (e.g. charged kaons) associated with hadronisation of signal B_s

Experimental



- Also need to account for:
  - Efficiency as a function of angles and time
  - Resolution on angular and time measurements

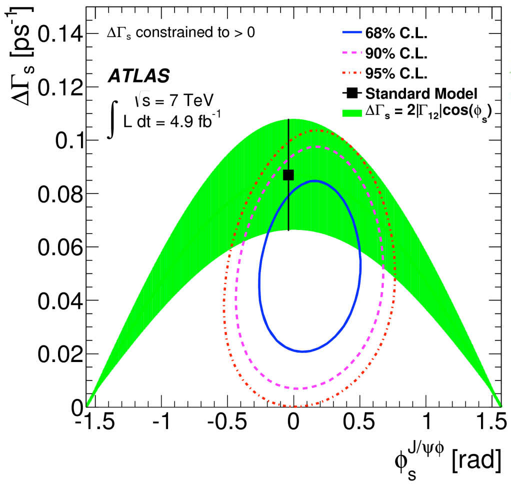




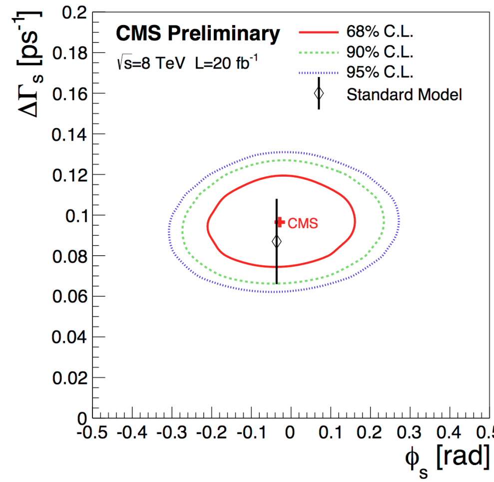
ATLAS, CMS & LHCb results

ATLAS
4.9 fb^{-1}

[arXiv:1407.1796]

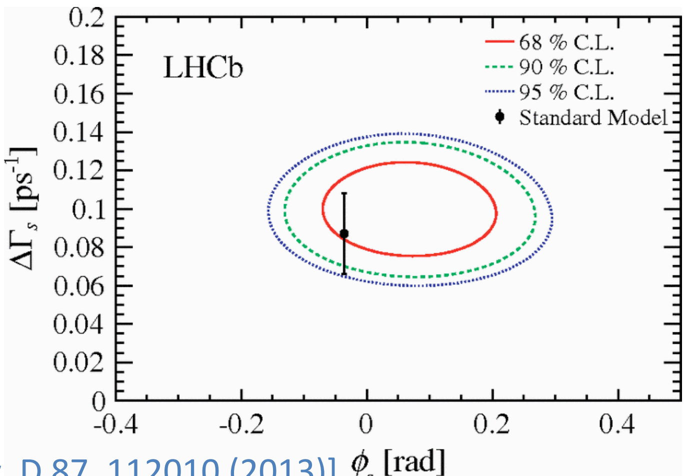


[CMS-PAS-BPH-13-012]



CMS
20 fb^{-1}

LHCb
1 fb^{-1}



[Phys. Rev. D 87, 112010 (2013)]

- ATLAS and CMS results from B_s decay to $J/\psi\ \phi$
- LHCb result shown is combination of $J/\psi\ K^+ K^-$ and $J/\psi\ \pi^+ \pi^-$ channels
- LHCb also have recent update of $J/\psi\ \pi^+ \pi^-$ with full Run 1 sample of 3fb^{-1}

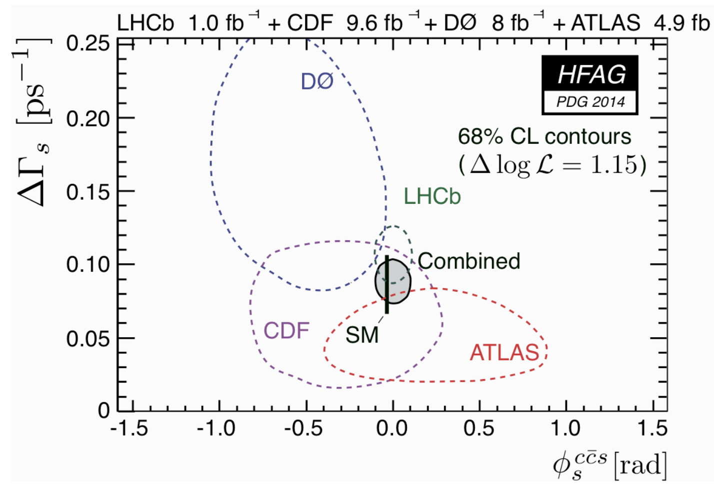
$$\phi_s = 70 \pm 68 \pm 8 \text{ mrad}$$

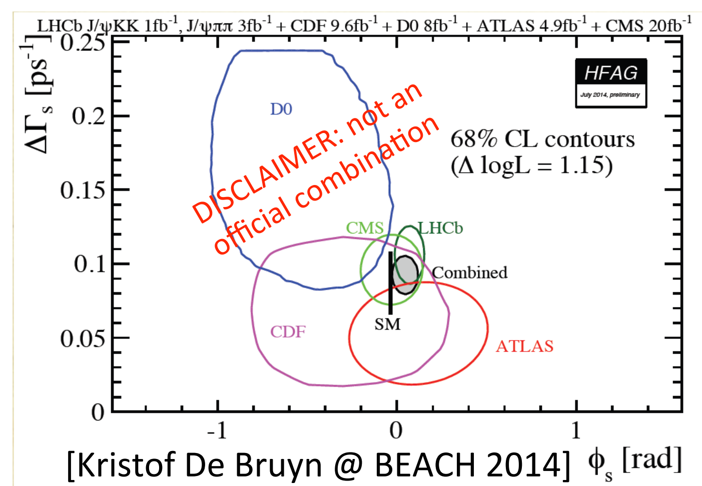
- Single most precise measurement!

[Phys. Lett. B736 (2014) 186]

World Average

- Official HFAG average (top plot) contains preliminary ATLAS result and does not yet include CMS result or LHCb update of $J/\psi\ \pi^+\ \pi^-$
- Bottom plot shows how these results are likely to improve the situation
- Everything still looks consistent with SM expectations
- Look forward to increasing precision from LHC experiments in the near future





[Kristof De Bruyn @ BEACH 2014]

V_{ub}/V_{cb}

- Some persistent puzzles in semi-leptonic *B* decays
  - Poor consistency between values of V_{xb} measured in inclusive and exclusive decays
  - Measurements of exclusive semi-leptonic *B* to charm decays are well short of inclusive rate

Adapted from Sascha Turczyk at CKM 2012 Workshop

charm state X_c	$\mathcal{B}(B \to X_c \ell \overline{\nu})$
D	$(2.29 \pm 0.09)\%$
D^*	$(5.43 \pm 0.17)\%$
$\sum D^{(*)}$	$(7.71 \pm 0.19)\%$
$D_0^* \to D\pi$	$(0.41 \pm 0.08)\%$
$D_1^* \to D^*\pi$	$(0.45 \pm 0.09)\%$
$D_1 \to D^*\pi$	$(0.43 \pm 0.03)\%$
$D_2^* \to D^{(*)}\pi$	$(0.41 \pm 0.03)\%$
$\sum D^{**} \to D^{(*)}\pi$	$(1.70 \pm 0.12)\%$
$D\pi$	$(0.66 \pm 0.08)\%$
$D^*\pi$	$(0.87 \pm 0.10)\%$
$\sum D^{(*)}\pi$	$(1.53 \pm 0.13)\%$
$\sum D^{(*)} + \sum D^{**} \to D^{(*)}\pi$	$(9.41 \pm 0.22)\%$
$\sum D^{(*)} + \sum D^{(*)}\pi$	$(9.24 \pm 0.23)\%$
inclusive X_c	$(10.98 \pm 0.14)\%$

inclusive – exclusive: (1.57 ± 0.26)%

PRL 109, 101802 (2012)
PRD 88, 072012 (2013)

$B \to D^{(*)} \tau \nu$

hep-ex/0910.4301
PRD 82, 072005 (2010)

- Measure ratios:

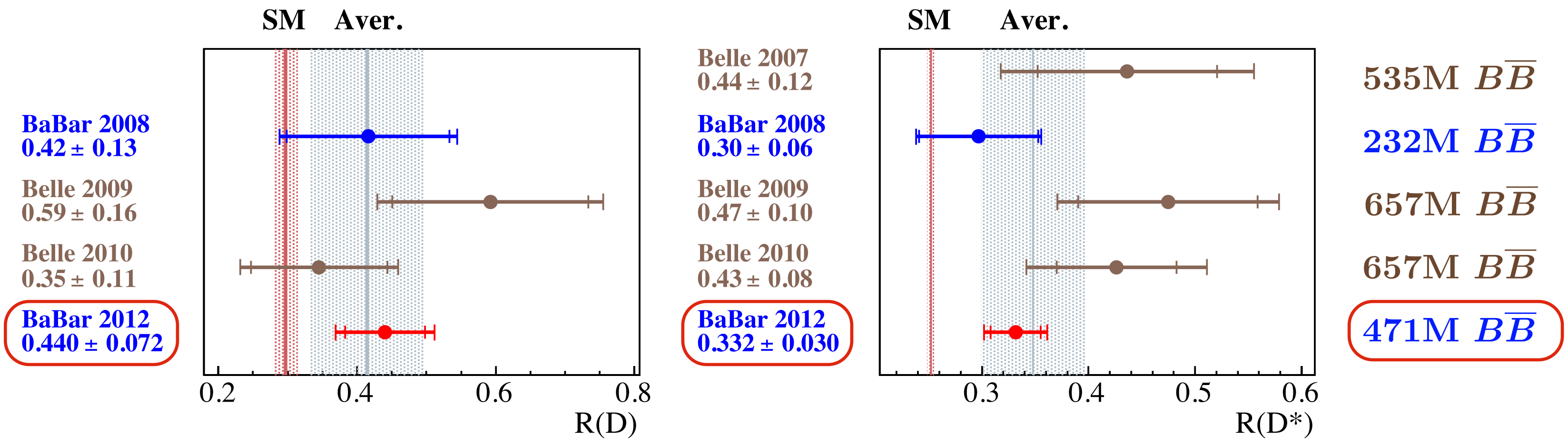
$$R\left(D^{(*)}\right)=\frac{BF\left(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{BF\left(\bar{B}\to D^{(*)}l^-\bar{\nu}_l\right)}=\frac{N_{\text{sig}}}{N_{\text{norm}}}\times\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}$$

$$R(D)=\begin{cases}0.440\pm0.072 & \text{BABAR}\\ 0.297\pm0.017 & \text{SM}\end{cases}\Bigg\}\ \mathbf{2.0\sigma}$$

$$R(D^*)=\begin{cases}0.332\pm0.030 & \text{BABAR}\\ 0.252\pm0.003 & \text{SM}\end{cases}\Bigg\}\ \mathbf{2.7\sigma}$$

Combined: $\mathbf{3.4\sigma}$

- BaBar sees deviation of 3.4σ from SM predictions
- Including Belle results takes this up to 4.8σ



BaBar 2012 not included in average shown

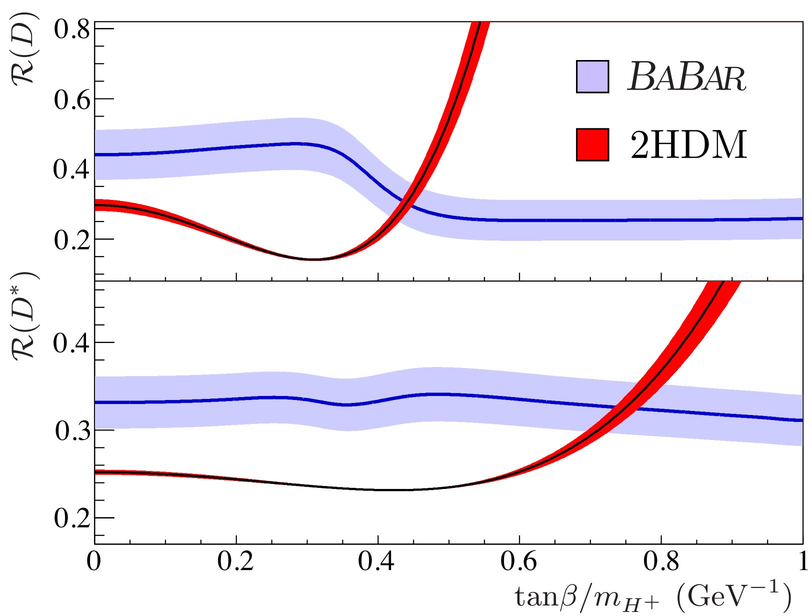
PRL 109, 101802 (2012)
PRD 88, 072012 (2013)

$B \to D^{(*)} \tau \nu$

hep-ex/0910.4301
PRD 82, 072005 (2010)

- Results are also incompatible (at 3.1σ) with Type-II 2 Higgs Doublet Models of charged Higgs
  - R(D) and R(D*) not in agreement in such models
  - Can be accommodated within Type-III 2HDM

- BaBar results can be improved with additional decay modes/tags
- Final results from full Belle dataset awaited with much anticipation!



$\tan\beta/m_{H^+} =$
$0.44 \pm 0.02\ \text{GeV}^{-1}$

$\tan\beta/m_{H^+} =$
$0.75 \pm 0.04\ \text{GeV}^{-1}$

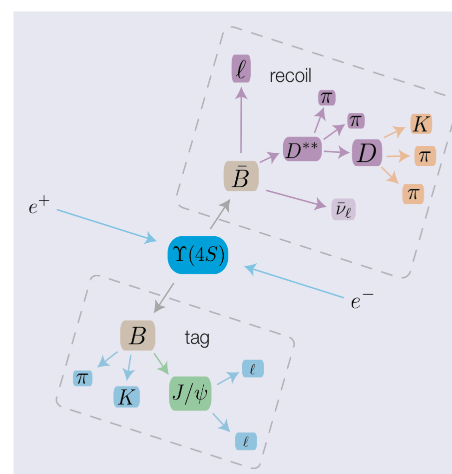
BaBar and Belle results for $B \to \tau \nu$ also favour different regions!

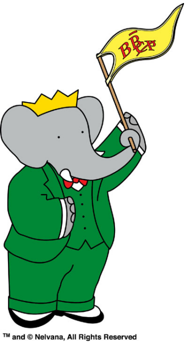
$B \longrightarrow D^{(*)}\pi^{\pm}(\pi^{\mp})l\nu$

- Largest uncertainty in $B \longrightarrow D^{(*)}\, \tau\, \nu$ analysis is from D^{**} backgrounds
- Good to have (better) measurements of these
- Can hopefully also help with "gap" in inclusive-exclusive BFs
- Use full reconstruction of "tag" B to constrain kinematics of signal B

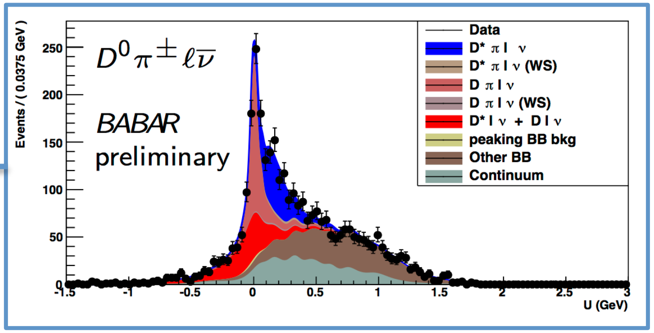
Systematic uncertainties in B -> $D^{(*)}\ \tau\ \nu$

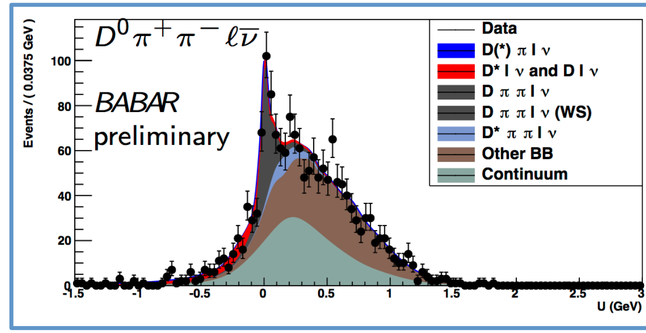
Source	Uncertainty (%) $R(D)$	Uncertainty (%) $R(D^*)$	ρ
$D^{**}\ell\nu$ background	5.8	3.7	0.62
MC statistics	5.0	2.5	-0.48
Cont. and $B\overline{B}$ bkg.	4.9	2.7	-0.30
$\varepsilon_{sig}/\varepsilon_{norm}$	2.6	1.6	0.22
Systematic uncertainty	9.5	5.3	0.05
Statistical uncertainty	13.1	7.1	-0.45
Total uncertainty	**16.2**	**9.0**	**-0.27**





$B \to D^{(*)}\pi^{\pm}(\pi^{\mp})l\nu$ Results





$$U = E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$

BABAR preliminary

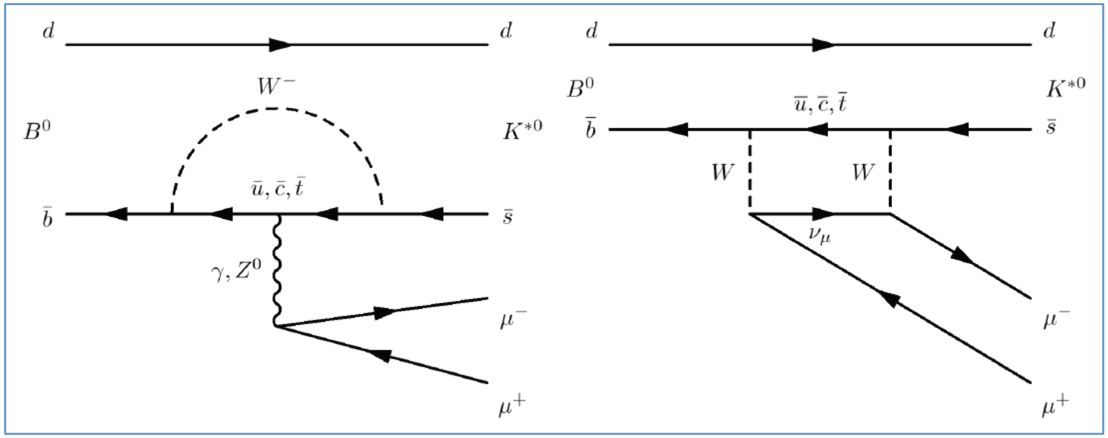
signal	norm.	R [%]	$\mathcal{B}$ [%]
$D^0\pi^+$	D^+	18.89 ± 1.73 ± 1.13	0.412 ± 0.038 ± 0.025 ± 0.023
$D^+\pi^-$	D^0	18.02 ± 1.31 ± 1.32	0.402 ± 0.029 ± 0.029 ± 0.022
$D^{*0}\pi^+$	D^{*+}	12.80 ± 0.87 ± 0.84	0.631 ± 0.043 ± 0.042 ± 0.014
$D^{*+}\pi^-$	D^{*0}	10.64 ± 0.59 ± 1.16	0.607 ± 0.034 ± 0.066 ± 0.020
$D^0\pi^+\pi^-$	D^0	9.56 ± 2.04 ± 1.24	0.213 ± 0.045 ± 0.028 ± 0.012
$D^+\pi^+\pi^-$	D^+	5.25 ± 1.90 ± 1.21	0.114 ± 0.041 ± 0.026 ± 0.006
$D^{*0}\pi^+\pi^-$	D^{*0}	1.61 ± 0.78 ± 0.35	0.092 ± 0.044 ± 0.020 ± 0.003
$D^{*+}\pi^+\pi^-$	D^{*+}	2.69 ± 0.92 ± 0.49	0.132 ± 0.045 ± 0.024 ± 0.003
$D\pi^{\pm}$	D	18.41 ± 1.06 ± 0.85	0.421 ± 0.024 ± 0.019 ± 0.016
$D^*\pi^{\pm}$	D^*	11.79 ± 0.54 ± 0.59	0.641 ± 0.029 ± 0.032 ± 0.021
$D\pi^+\pi^-$	D	7.28 ± 1.39 ± 0.89	0.166 ± 0.032 ± 0.020 ± 0.006
$D^*\pi^+\pi^-$	D^*	2.04 ± 0.60 ± 0.30	0.111 ± 0.033 ± 0.016 ± 0.004

$B \longrightarrow D^{(*)}\pi^{\pm}(\pi^{\mp})l\nu$

- First measurements of $B \longrightarrow D^{(*)}\pi^{+}\pi^{-}l\nu$ decays
  - $D\pi^{+}\pi^{-}l\nu$: combined significance = 5.1σ
  - $D^{*}\pi^{+}\pi^{-}l\nu$: combined significance = 3.5σ
- Results for $B \longrightarrow D^{(*)}\pi^{\pm}l\nu$ decays are more precise than previous measurements
- The inclusive–exclusive gap is reduced by ~60% (significance drops from ~7σ to ~3σ)
- Should help to reduce systematic uncertainties on future $B \longrightarrow D^{(*)}\tau\nu$ analyses

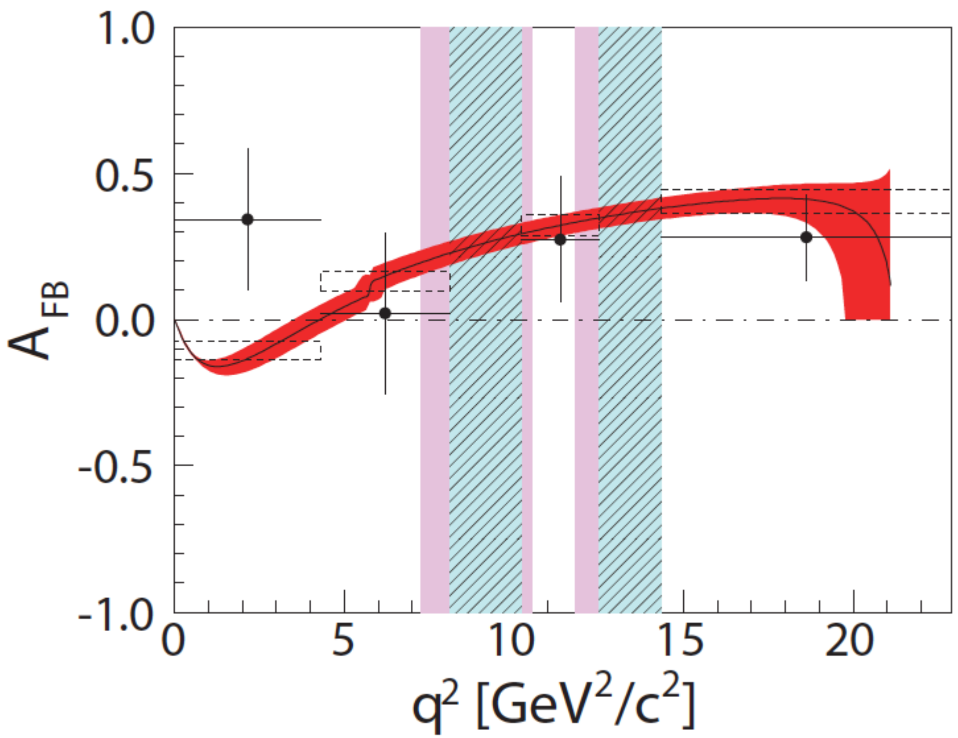
$b \longrightarrow s\, l^{+}\, l^{-}$

- Such rare decays proceed through penguin and box diagrams in SM
- Wilson coefficients encode strength of short-distance interactions:
  - C_7: EM ($b \longrightarrow s\gamma$, $b \longrightarrow sll$)
  - C_9: semi-leptonic vector ($b \longrightarrow sll$)
  - C_{10}: s-l axial vector ($b \longrightarrow sll$, $B^0_s \longrightarrow \mu^+\mu^-$)



- Many New Physics models predict additional contributions to decay amplitude at similar level to SM
- Observables (branching fractions, angular moments, CP asymmetries, etc.) depend on q^2 (4-momentum transferred to dimuon system)

Inclusive $B \to X_s l^+ l^-$



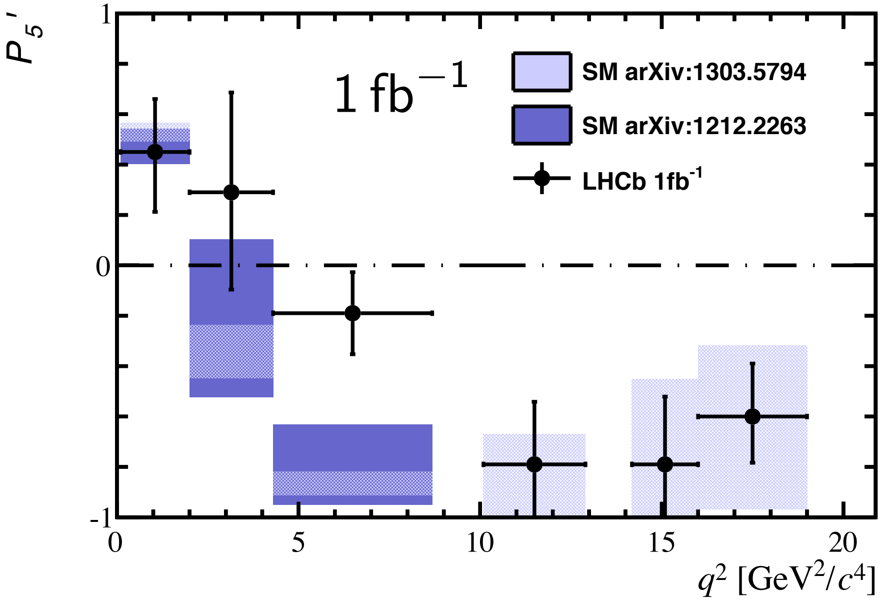
Red band is SM prediction

- Belle have made first measurement of forward-backward asymmetry for inclusive $B \to X_s l^+ l^-$
- Use sum of 10 exclusive final states (both B^0 and B^+)
- Data sample of 772×10^6 B meson pairs
- $A_{FB} < 0$ excluded at 2.3σ in region above 10.2 (GeV/c)^2
- Deviation from SM of 1.8σ in first bin (< 4.3 (GeV/c)^2)

Phys. Rev. Lett. 111, 191801

$B^0 \longrightarrow K^{*0}\mu^+\mu^-$

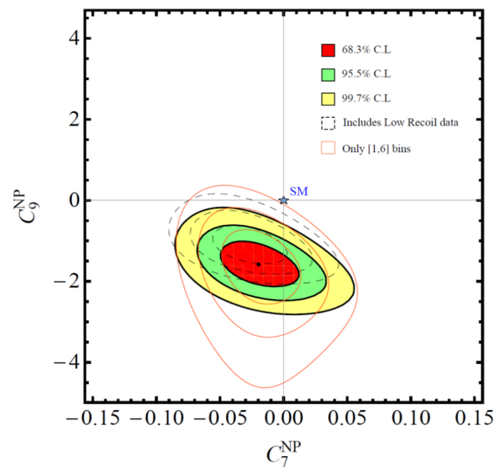
- LHCb now making high precision measurements in this sector
- A few anomalies starting to appear
- Analysis of "optimised" angular observables [JHEP 1204 (2012) 104] using 1fb^{-1} data sample
- Large (3.7σ) local deviation found in one bin of P_5'
  - Global p-value is 0.5%



- Uncertainties on residual form factor dependence a hot topic in theory community

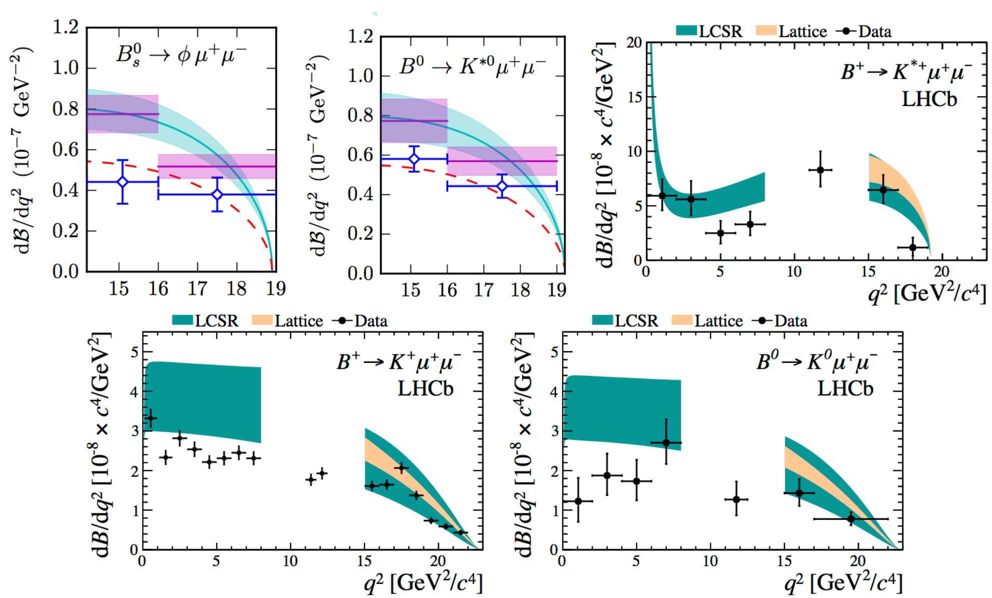
JHEP 1308 (2013) 131
JHEP 1307 (2013) 084
JHEP 1406 (2014) 133

$B^0 \longrightarrow K^{*0}\mu^+\mu^-$



[Phys.Rev. D88 (2013) 074002]

- Global fits suggest reduced value of C_9 coefficient
  (e.g. [Phys.Rev. D88 (2013) 074002], [Eur.Phys.J. C73 (2013) 2646] and [Eur.Phys.J. C74 (2014) 2897])
- If so, would expect BFs to also be low
- LHCb has measured BFs for $B \longrightarrow K^{(*)}\mu^+\mu^-$ & $B_s \longrightarrow \phi\mu^+\mu^-$
- Indeed they are low wrt predictions from Lattice (arXiv:1310.3207 [hep-ph], Phys.Rev.Lett. 112 (2014) 212003) and LCSR (JHEP 1201 (2012) 107, JHEP 1107 (2011) 067)



arXiv:1406.6482

NEW!

$B^+ \rightarrow K^+ l^+ l^-$

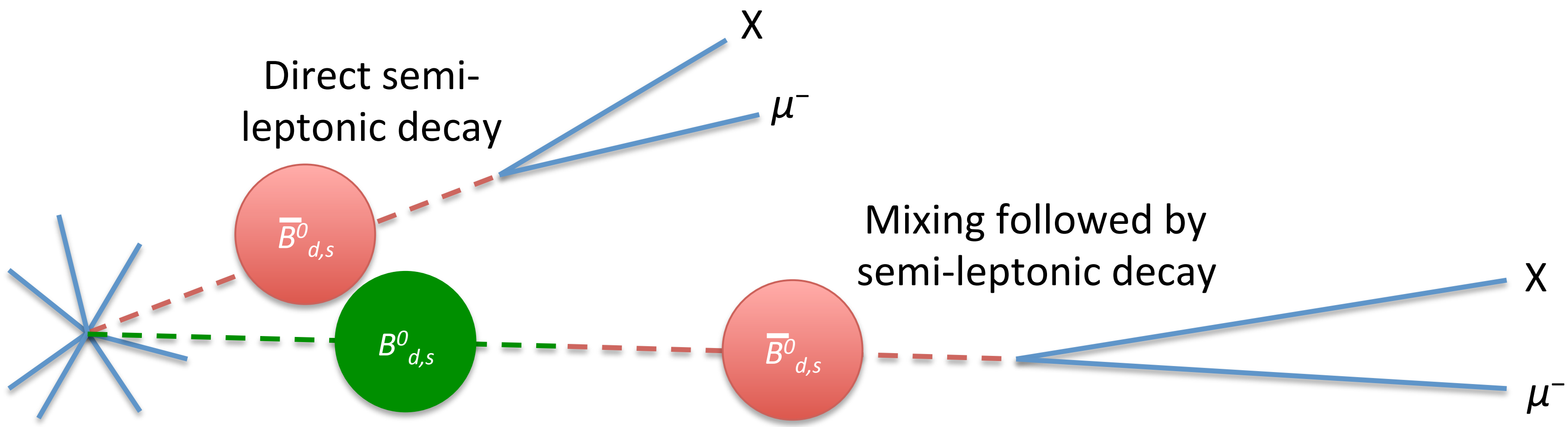
- Possible explanation for low C_9 from Z' particle (e.g. [arXiv: 1310.1082])
- Some Z' models favour muon coupling over electron (e.g. [arXiv:1403.1269])
- Predict BF($B^+ \rightarrow K^+\mu^+\mu^-$) lower than BF($B^+ \rightarrow K^+e^+e^-$)
- LHCb has preliminary measurement of ratio using full Run1 sample of $3fb^{-1}$
- Deviates from SM (unity) by 2.6σ

$$R_K = \frac{BF(B^+ \rightarrow K^+\mu^+\mu^-)}{BF(B^+ \rightarrow K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

- Much still to be understood however!
- Importance of $c\bar{c}$ resonances at high q^2
- Update measurements with full data sample
- Look at other modes, e.g. $\Lambda b \rightarrow \Lambda\mu^+\mu^-$ and $B^+ \rightarrow K^+\pi^+\pi^- l^+ l^-$

Phys. Rev. D 89, 012002 (2014)

Dimuon charge asymmetry



- CP violation in mixing => $\Gamma\left(B^0_{(s)} \to \bar{B}^0_{(s)} \to \mu^- X\right) \neq \Gamma\left(\bar{B}^0_{(s)} \to B^0_{(s)} \to \mu^+ X\right)$
- Asymmetry is combination of semi-leptonic charge asymmetries of B_d^0 and B_s^0

$$A_{sl} = \frac{N\left(\mu^+\mu^+\right) - N\left(\mu^-\mu^-\right)}{N\left(\mu^+\mu^+\right) + N\left(\mu^-\mu^-\right)}$$

$$= C_d a^d_{sl} + C_s a^s_{sl} + C\frac{\Delta\Gamma_d}{\Gamma_d}$$

$$a^q_{sl} = \frac{\Gamma\left(\bar{B} \to \mu^+ X\right) - \Gamma\left(B \to \mu^- X\right)}{\Gamma\left(\bar{B} \to \mu^+ X\right) + \Gamma\left(B \to \mu^- X\right)}$$

- Corrected for backgrounds – use single muon asymmetry to help reduce systematic uncertainties
- Also correct for CP violation from interference between mixing and decay

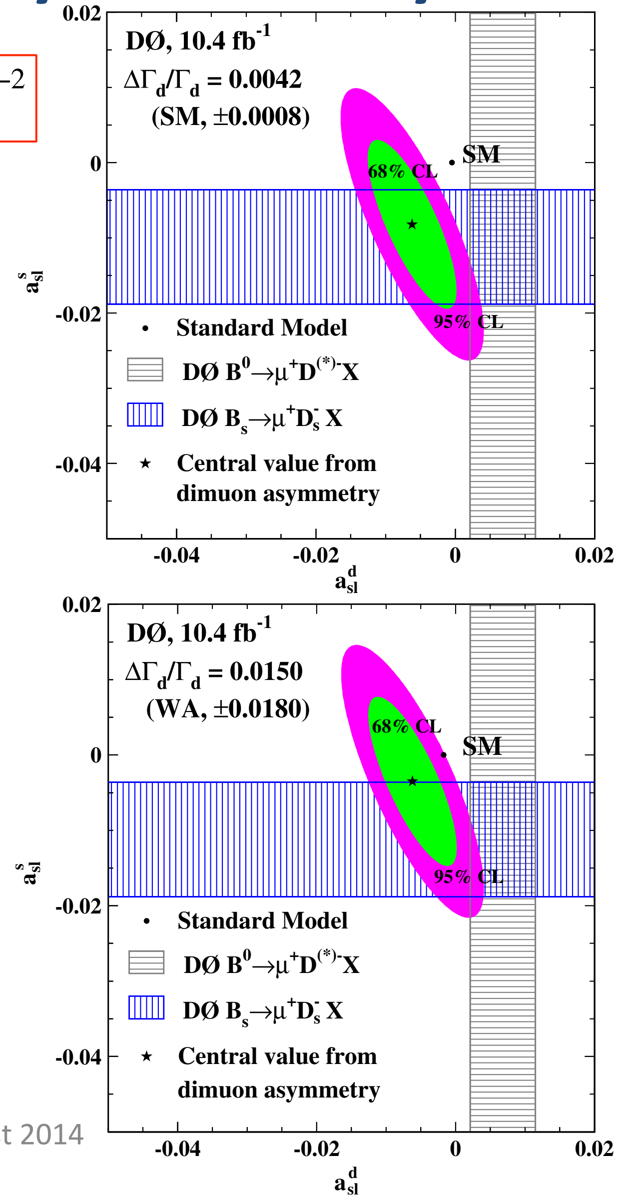
Phys. Rev. D 89, 012002 (2014)

Dimuon charge asymmetry

- D0 find: $A_{sl} = (-0.496 \pm 0.153 \pm 0.072) \times 10^{-2}$
- cf. SM prediction:

$$A_{sl}^{SM} = (-0.023 \pm 0.004) \times 10^{-2}$$

- Interpretation in terms of a^d_{sl} and a^s_{sl} depends strongly on value of $\Delta\Gamma_d/\Gamma_d$
- Plots shows contours for two scenarios:
  - $\Delta\Gamma_d/\Gamma_d$ fixed to SM expectation
  - $\Delta\Gamma_d/\Gamma_d$ fixed to world average experimental value
- Discrepancy with SM point is 3.4σ or 1.9σ, respectively
- Allowing $\Delta\Gamma_d/\Gamma_d$ to float results in 3.0σ deviation
- Important to improve the precision of $\Delta\Gamma_d/\Gamma_d$ in the future
  - Recent measurement from LHCb:
    −0.044 ± 0.025 ± 0.011 [JHEP 1404 (2014) 114]



Large A_{CP} in charmless *B* decays

- LHCb analysis of $B^{\pm} \longrightarrow h^{+}h^{-}h'^{\pm}$ decays using full Run1 data sample
- CP asymmetries seen in inclusive measurements

Preliminary

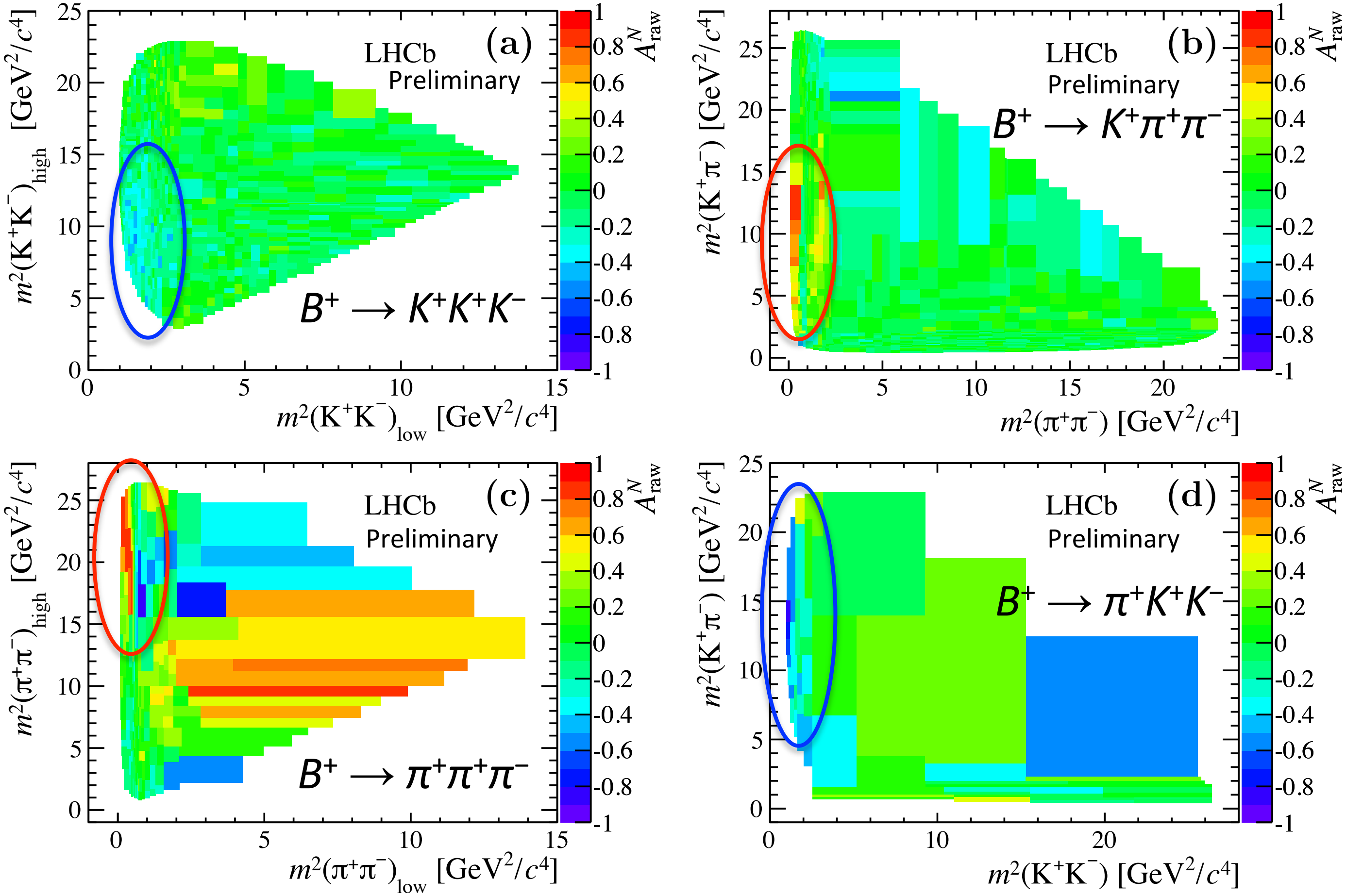
$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad \mathbf{2.8\sigma}$$
$$A_{CP}(B^{\pm} \to K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004\,(\text{stat}) \pm 0.002\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad \mathbf{4.3\sigma}$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008\,(\text{stat}) \pm 0.009\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad \mathbf{4.2\sigma}$$
$$A_{CP}(B^{\pm} \to \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017\,(\text{stat}) \pm 0.012\,(\text{syst}) \pm 0.007(J/\psi\, K^{\pm}) \quad \mathbf{5.6\sigma}$$

- Asymmetries in some regions of the phase space are even more pronounced

Large A_{CP} in charmless B decays

Large positive asymmetries at low $m^2_{\pi\pi}$

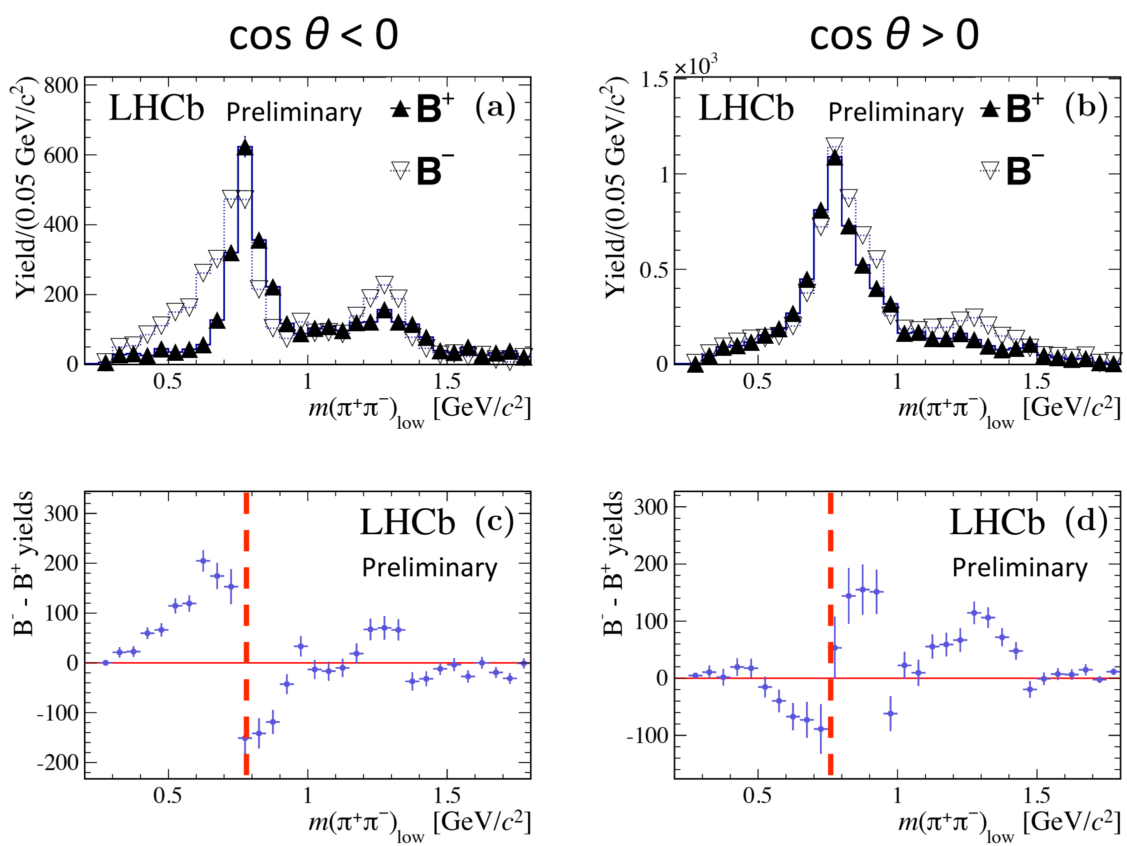
Large negative asymmetries at low m^2_{KK}

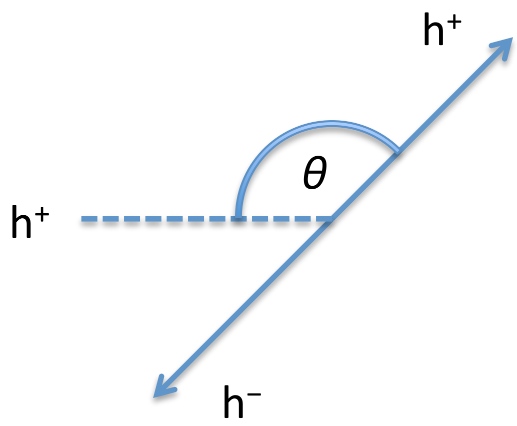


LHCb-PAPER-2014-044

Large A_{CP} in charmless *B* decays

- Larger data samples allow more detail to be extracted than previous analyses: [PRL 111, 101801 (2013)] [PRL 112, 011801 (2014)]
- Want to understand the origin of the strong-phase difference
- Examine dependence of asymmetry as function of invariant mass and helicity angle in regions around resonances, e.g. for $\pi^+\pi^+\pi^-$



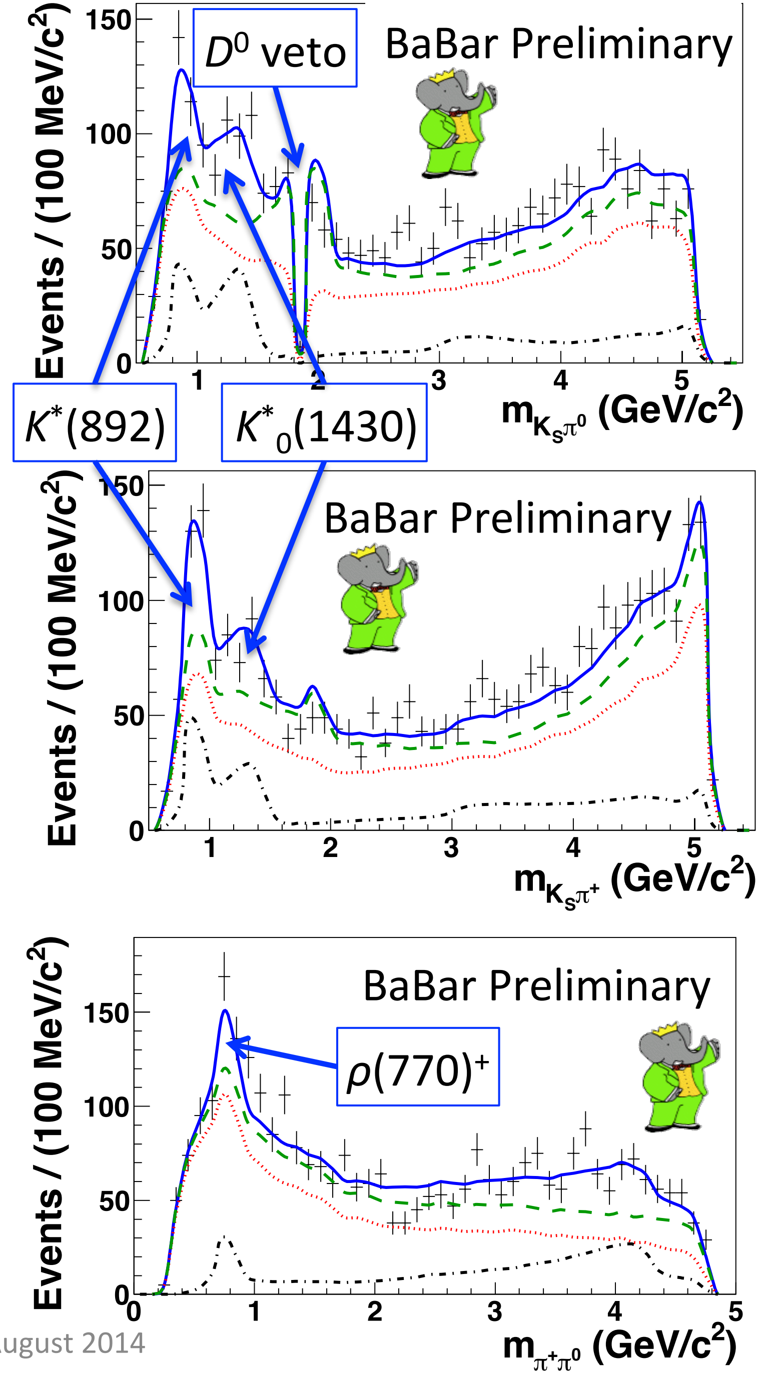


- Asymmetries as large as 60% in some regions!!
- Flips of sign indicate interference between S- and P-wave is important
- Rescattering may also play a role in region between 1 and 1.5 GeV
- Need amplitude analyses

DP analysis of $B^+ \longrightarrow K_S\, \pi^+\, \pi^0$

NEW!

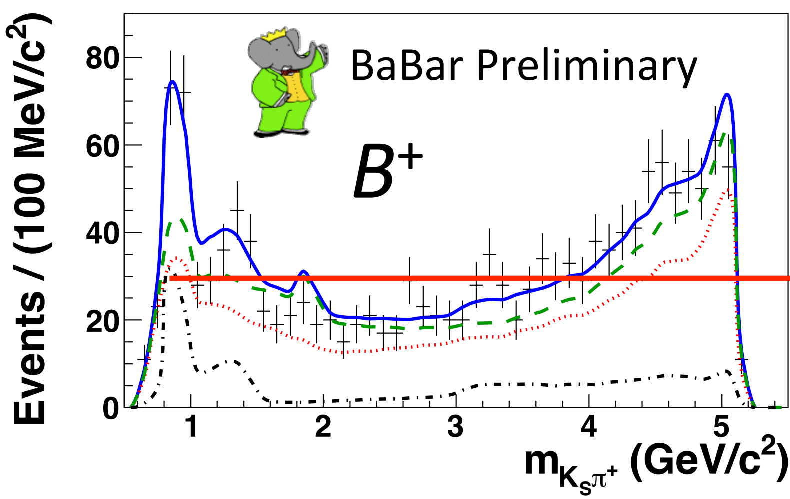
- Model contains $K^*(892)$, $K\pi$ S-wave and $\rho(770)$ contributions
- Both charged and neutral K^*'s included
- $K\pi$ S-wave modelled using LASS parameterisation (coherent sum of $K^*_0(1430)$ resonance and effective range nonresonant terms) [Nucl. Phys. **B296**, 493 (1988)]

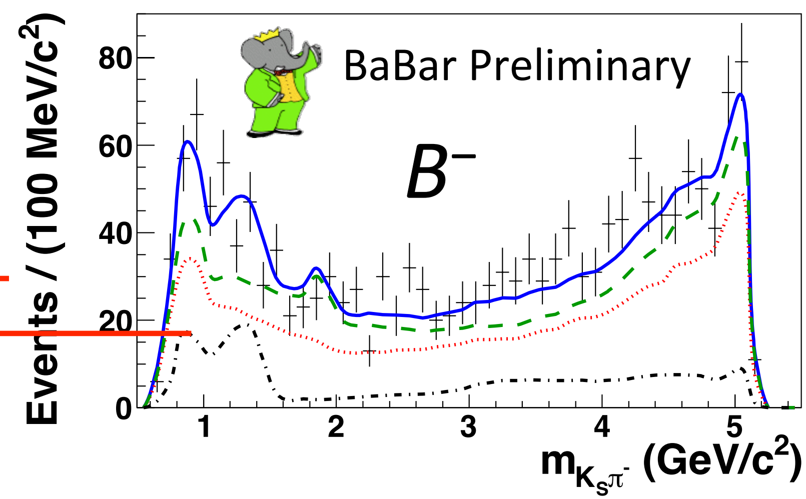


Direct CP Violation

- First evidence of direct CP violation in $B^+ \to K^{*+}\pi^0$
- 3.4σ significance estimated including statistical, systematic and model uncertainties
- A_{CP} for $B^+ \to K^{*0}\pi^+$ consistent with zero (as expected)

Decay channel	A_{CP}
$K^0\pi^+\pi^0$	$0.07 \pm 0.05 \pm 0.03 \pm 0.04$
$K^{*0}(892)\pi^+$	$-0.12 \pm 0.21 \pm 0.08 \pm 0.11$
$K^{*+}(892)\pi^0$	$-0.52 \pm 0.14 \pm 0.04 \pm 0.04$
$K_0^{*0}(1430)\pi^+$	$0.14 \pm 0.10 \pm 0.04 \pm 0.14$
$K_0^{*+}(1430)\pi^0$	$0.26 \pm 0.12 \pm 0.08 \pm 0.12$
$\rho^+(770)K^0$	$0.21 \pm 0.19 \pm 0.07 \pm 0.30$

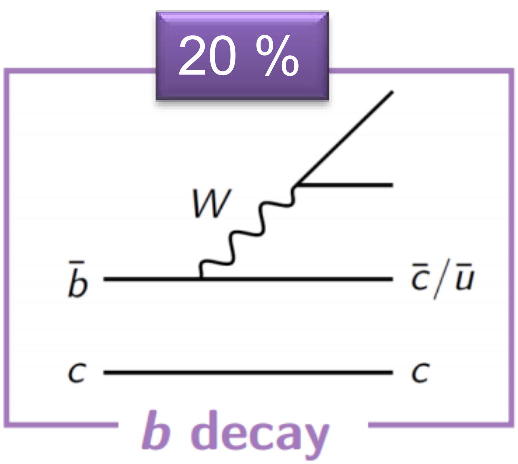


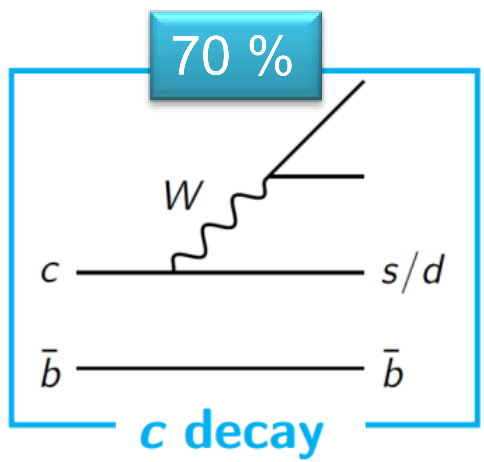


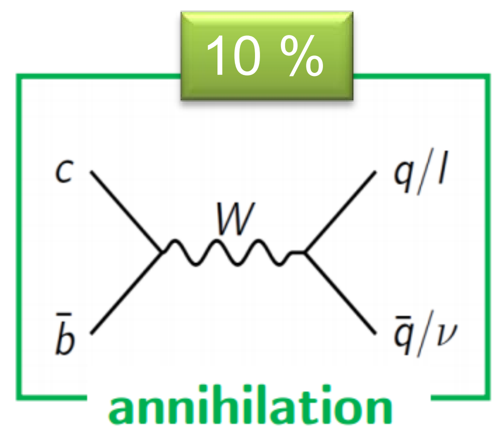
New territory

B_c mesons

- Only meson composed of heavy quarks with different flavours
- Largely unexplored territory
  - Production fraction in pp collisions unknown
  - Need better precision on lifetime, mass, etc.
- Very few decay modes observed – only 1 c-decay ($B_c \rightarrow B_s\pi$ by LHCb [Phys.Rev.Lett. 111 (2013) 181801]), the rest b-decay modes
- Will show a couple of recent developments in this rapidly changing field







[Phys.Atom.Nucl. 67 (2004) 1559]

CDF Note 11083

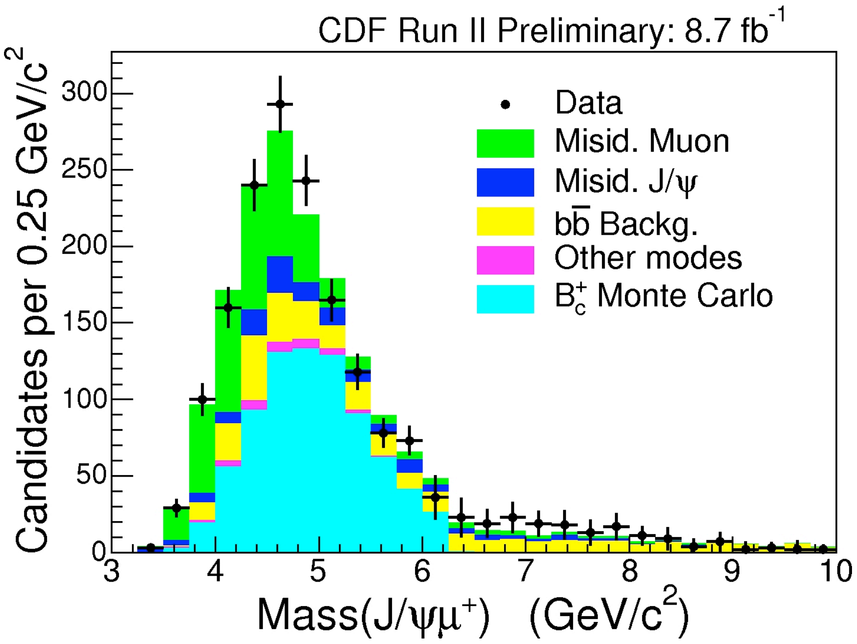
NEW!

$B_c^+ \rightarrow J/\psi\mu^+\nu$ relative cross section

- Measure ratio of $B_{(c)}^+$ production cross section times BF

$$R = \frac{\sigma(B_c^+)\times BF(B_c^+ \rightarrow J/\psi\mu^+\nu_\mu)}{\sigma(B^+)\times BF(B^+ \rightarrow J/\psi K^+)} = \frac{N(B_c^+)}{N(B^+)} \times \varepsilon_{\mathrm{rel}}$$
$$= 0.211 \pm 0.012^{+0.021}_{-0.020}$$

- Compare invariant mass distributions
- Can be compared with LHCb measurements to determine ratio of production fractions at Tevatron and LHC



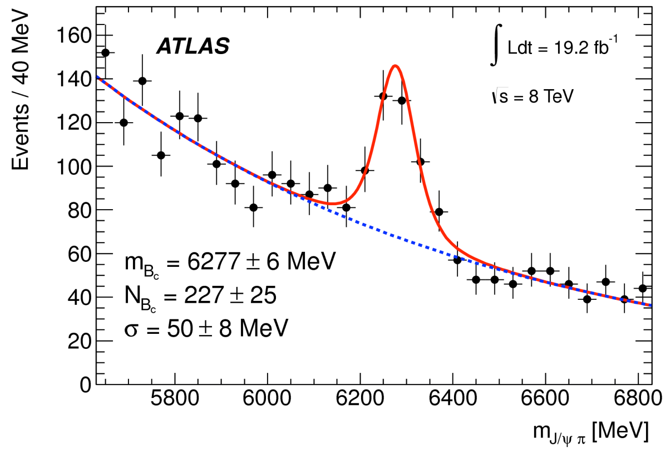
ATLAS EXPERIMENT

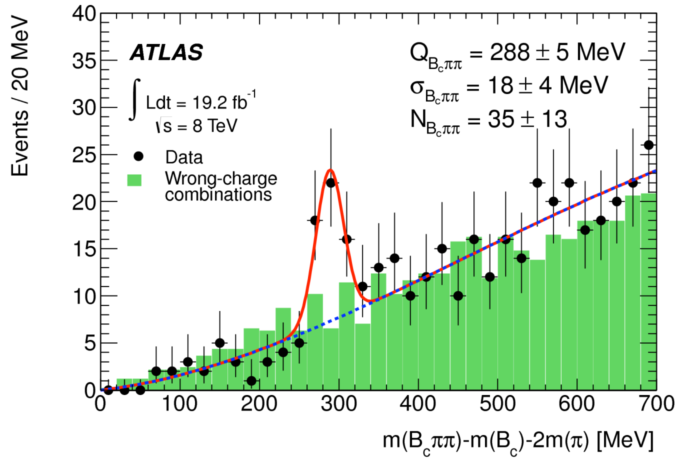
arXiv:1407.1032

Observation of an excited B_c meson

NEW!

- Search for excited B_c mesons in decay chain: $B_c(2S) \to B_c\pi\pi$; $B_c \to J/\psi\, \pi$
- Analysis uses 4.9 fb^{-1} of 7 TeV and 19.2 fb^{-1} of 8 TeV data
- Results consistent within the two data samples
- Combined significance of 5.2σ
- Mass: 6842 ± 4 ± 5 MeV
- Awaits confirmation from CMS and LHCb

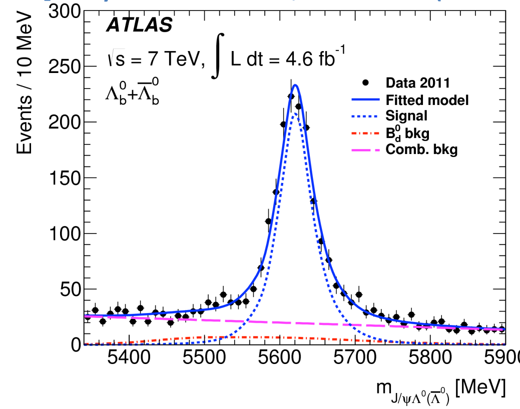




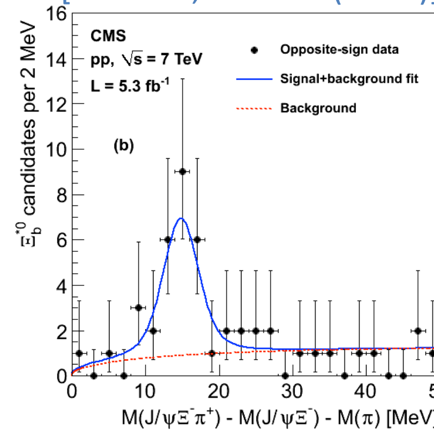
b-baryons

- Largely unexplored territory
- No mixing, so potentially simpler for disentangling some CP effects
- Lots of progress made in last couple of years with lifetime measurements, new decay modes being observed (including some charmless/ rare decays!)
- Will be a very rich field in the coming years
- Need improved theory predictions as well as experimental results

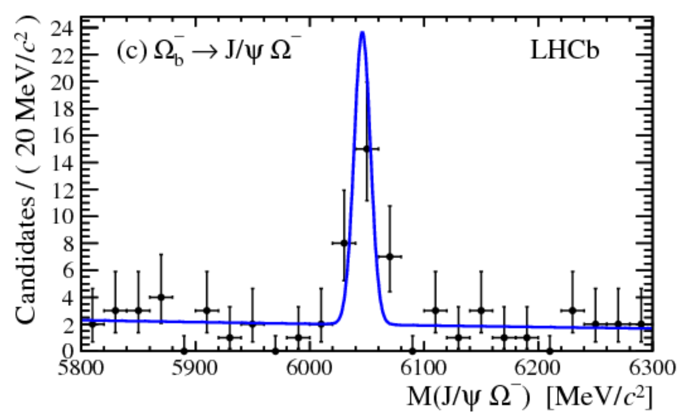
[Phys. Rev. D 89, 092009 (2014)]



[PRL 108, 252002 (2012)]



[PRL 110, 182001 (2013)]

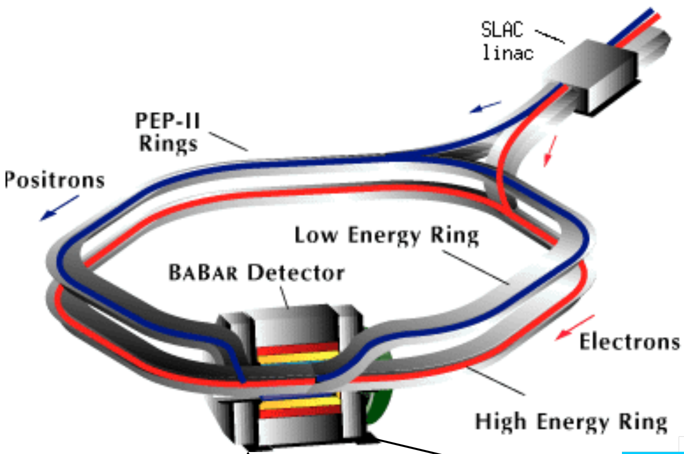


Summary

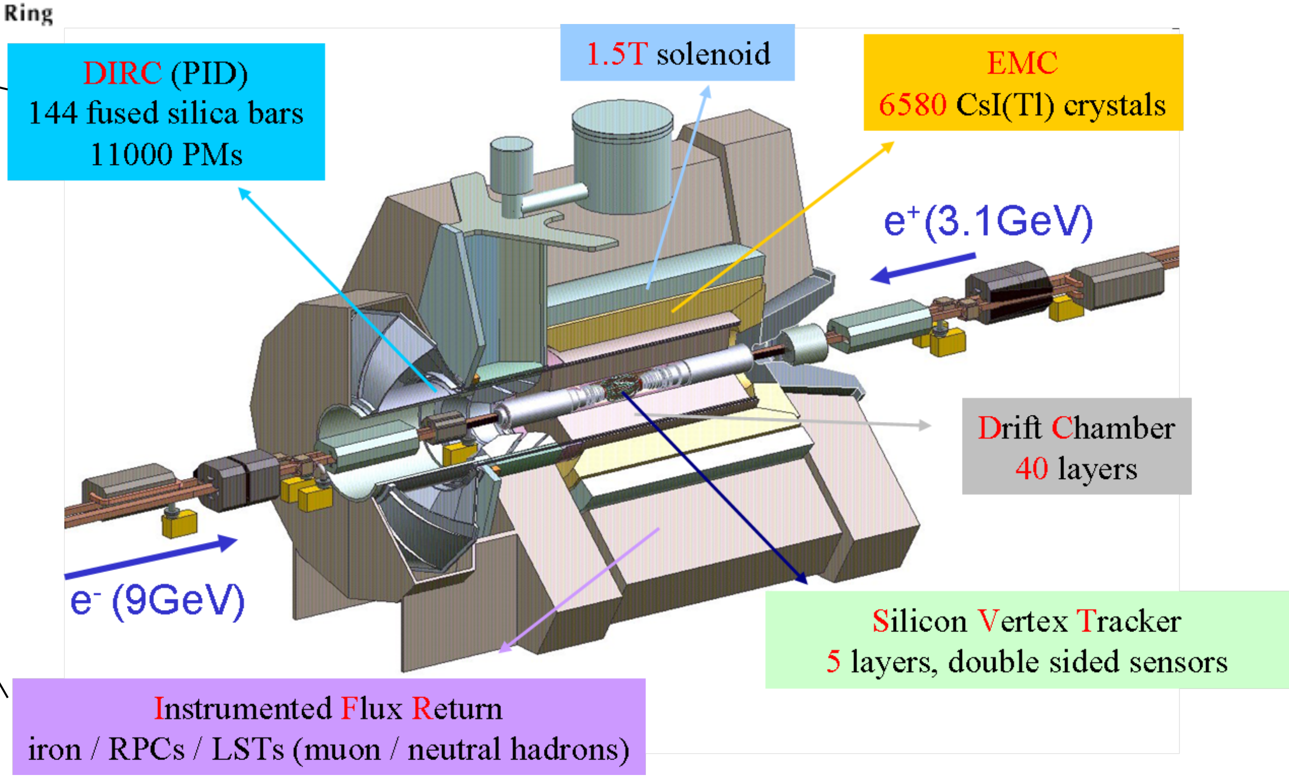
- With increasingly precise and sophisticated measurements, some anomalies have appeared in the realm of *b*-hadron physics
- Are they hints that we are on the threshold of uncovering New Physics? Hopefully!!
- The coming years will be exciting times as LHC Run 1 data is fully exploited and the data samples from LHC Run 2 are collected and analysed
- Look forward also to the unprecedented precision that will come with the start of Belle II and the LHCb upgrade

Backup Slides

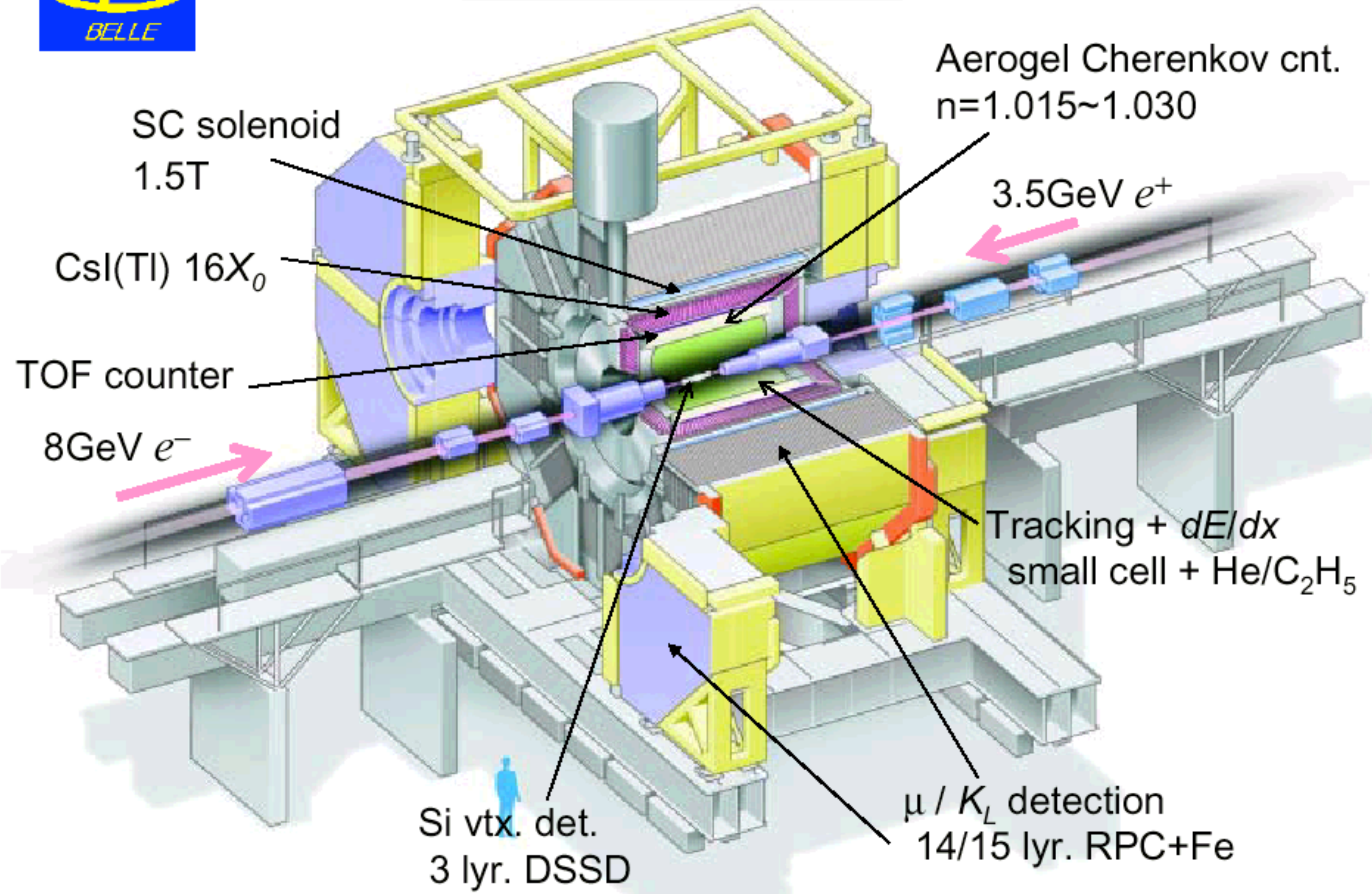
PEP-II and BaBar



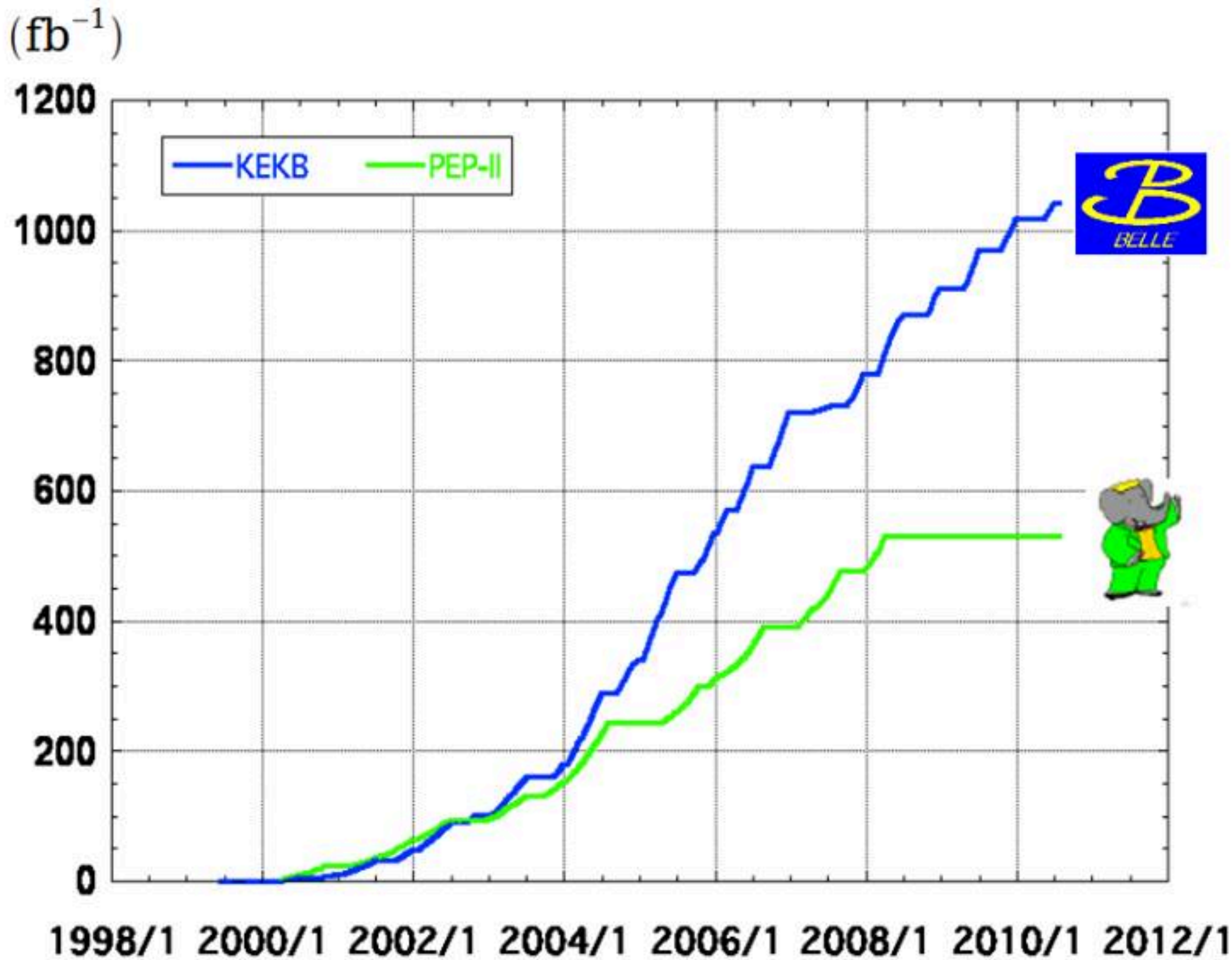
- PEP II/BaBar *B*-Factory located at SLAC National Accelerator Laboratory
- Collided beams of electrons and positrons with asymmetric energies



Belle Detector



Integrated luminosity of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

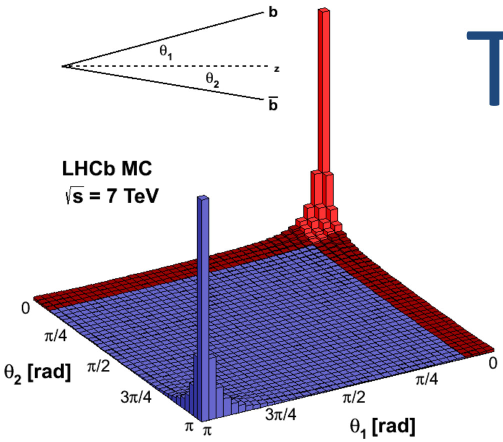
$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

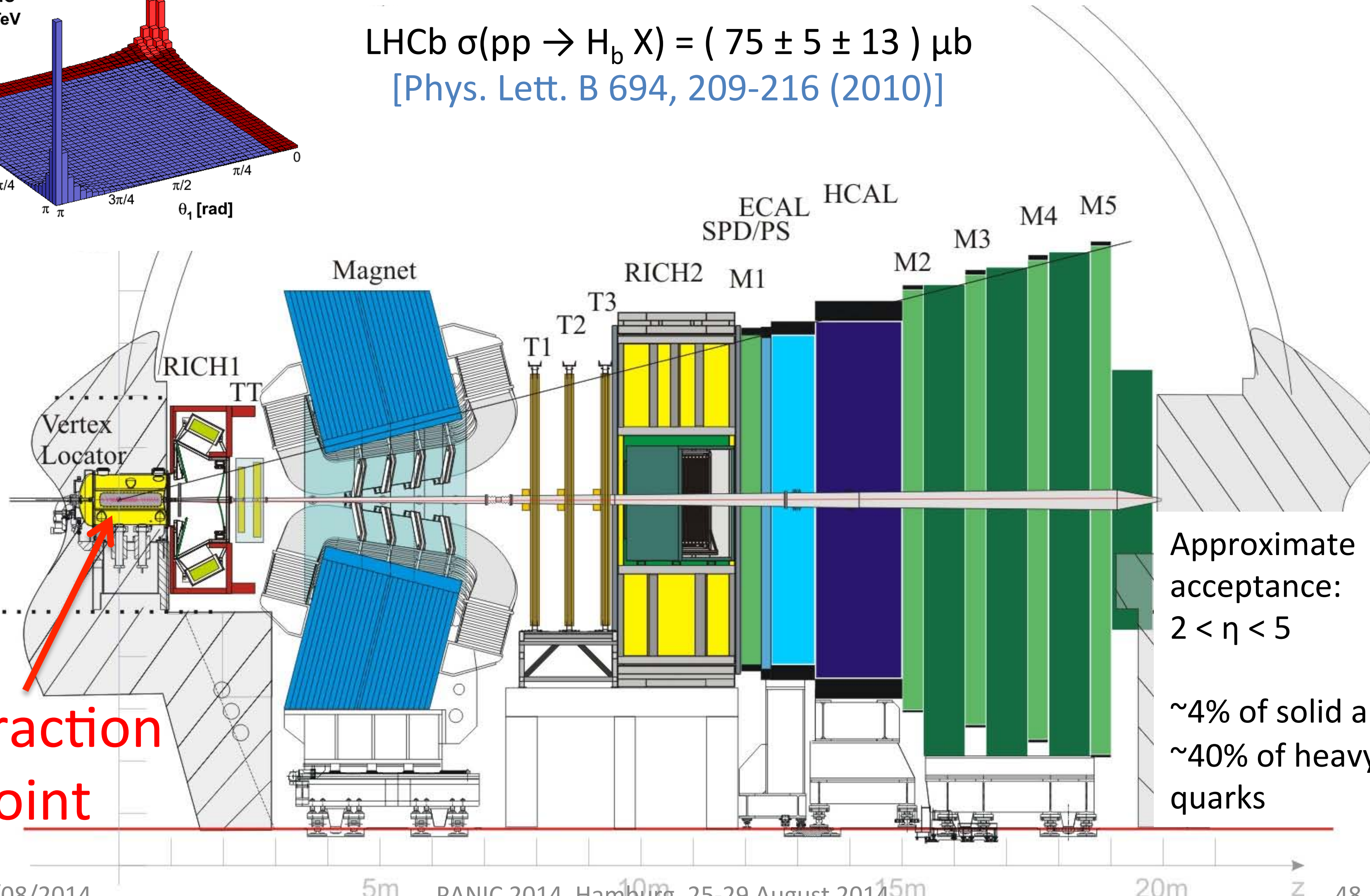
Off resonance:

~ 54 fb^{-1}

The LHCb detector



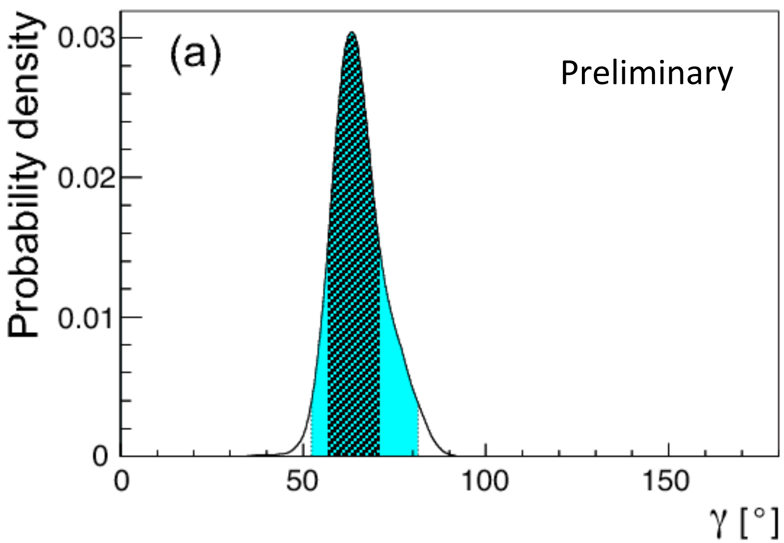
LHCb $\sigma(pp \rightarrow H_b X)$ = (75 ± 5 ± 13) μb
[Phys. Lett. B 694, 209-216 (2010)]



Approximate acceptance:
$2 < \eta < 5$

~4% of solid angle
~40% of heavy quarks

γ from loop-dominated decays

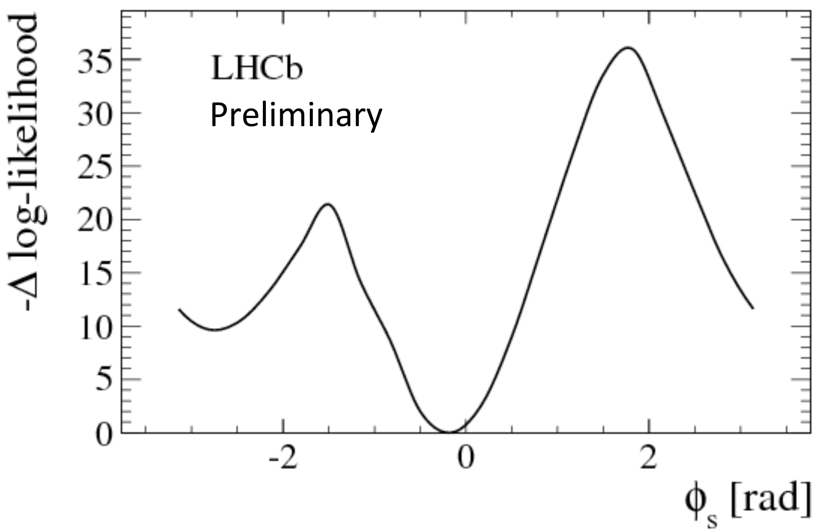


- Preliminary results using latest LHCb results on time-dependent CP violation in $B_s^0 \longrightarrow K^+K^-$ and U-spin symmetry relation with $B^0 \longrightarrow \pi^+\pi^-$
- Also include isospin information from *B*-factories on $\pi\pi$ system
- Find:

$$\gamma = \left(63.5\,^{+7.2}_{-6.7}\right)^\circ$$

arXiv:1407.2222

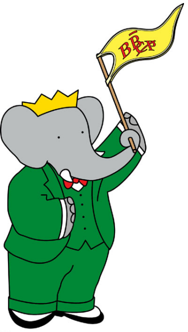
ϕ_s from loop-dominated decays



- Use decay $B_s \to \phi\phi$
- Perform time-dependent angular analysis
- Find

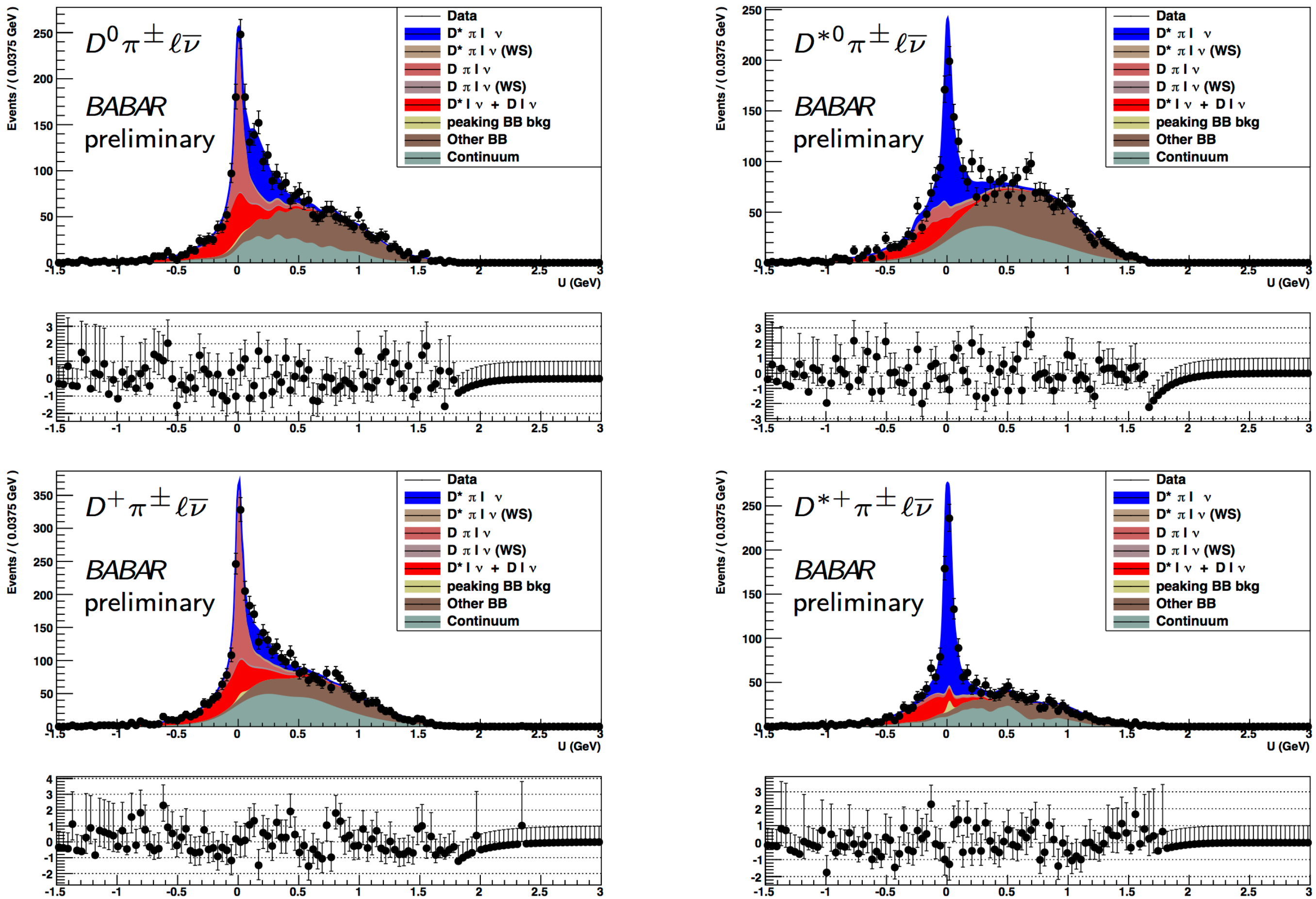
$$\phi_s = -0.17 \pm 0.15 \pm 0.03 \text{ rad.}$$

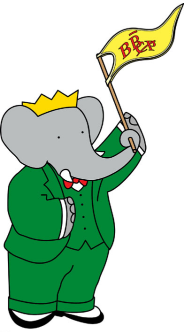
- Consistent with results from $B_s \to J/\psi h^+ h^-$



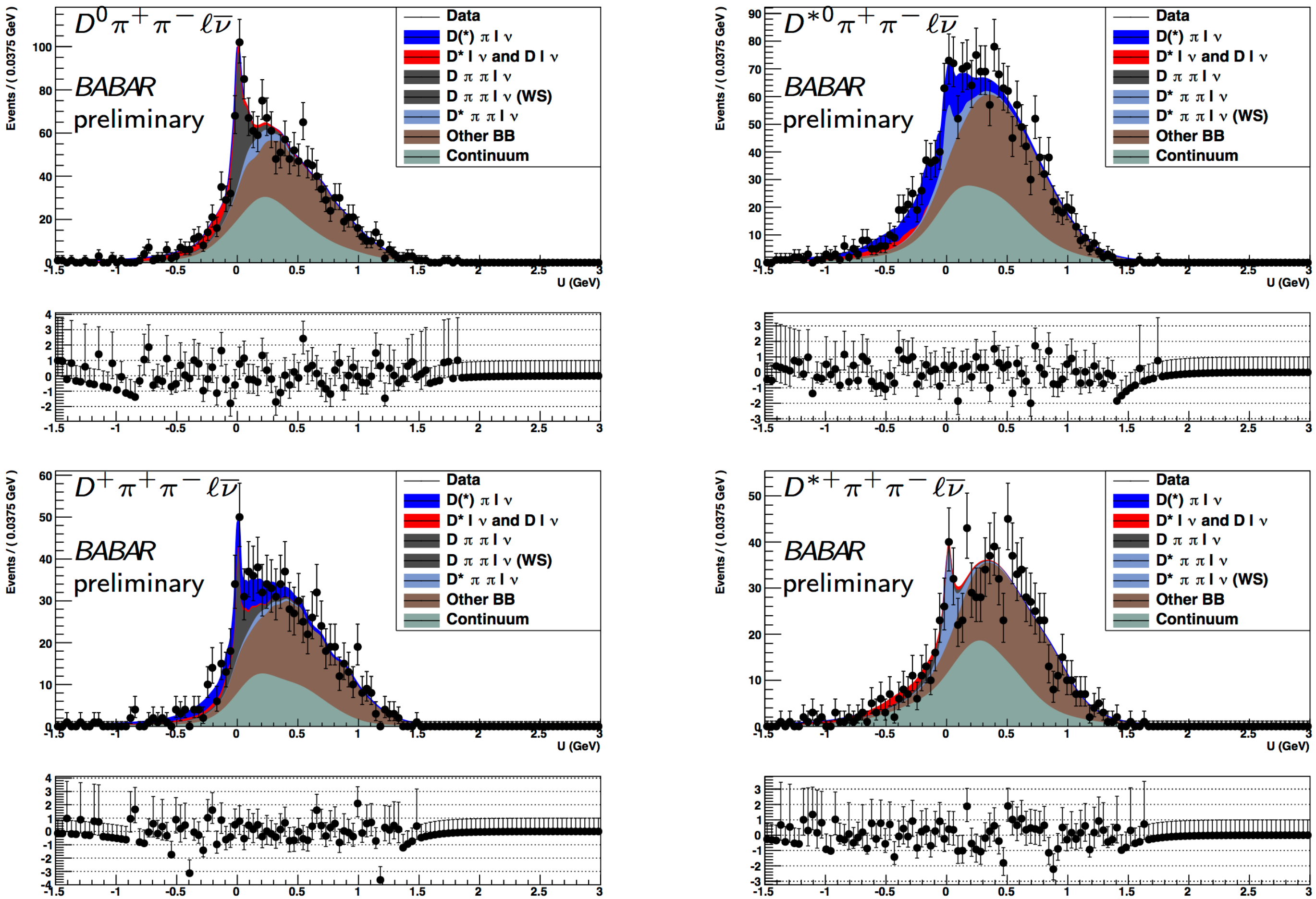
$B \to D^{(*)}\pi^{\pm}l\nu$ Results

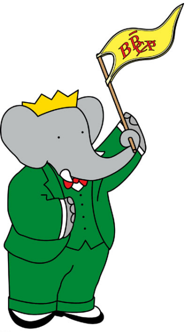
NEW!





$B \rightarrow D^{(*)}\pi^{+}\pi^{-}l\nu$ Results





$B \rightarrow D^{(*)}\pi^{\pm}(\pi^{\mp})l\nu$ Results

Comparison with previous results for $D^{(*)}\pi^{\pm}\ell\overline{\nu}$ branching fractions:

BABAR preliminary

	this result[%]	prev. *BABAR* [a] [%]	HFAG [b] [%]
$\mathcal{B}(B^0 \rightarrow D^0\pi^-\ell^+\overline{\nu})$	$0.41 \pm 0.04 \pm 0.03$	$0.43 \pm 0.08 \pm 0.03$	0.43 ± 0.06
$\mathcal{B}(B^+ \rightarrow D^+\pi^-\ell^+\overline{\nu})$	$0.40 \pm 0.03 \pm 0.04$	$0.42 \pm 0.06 \pm 0.03$	0.42 ± 0.05
$\mathcal{B}(B^0 \rightarrow D^{*0}\pi^-\ell^+\overline{\nu})$	$0.63 \pm 0.04 \pm 0.04$	$0.48 \pm 0.08 \pm 0.04$	0.49 ± 0.08
$\mathcal{B}(B^+ \rightarrow D^{*+}\pi^-\ell^+\overline{\nu})$	$0.61 \pm 0.03 \pm 0.07$	$0.59 \pm 0.05 \pm 0.04$	0.61 ± 0.05

- Note, previous *BABAR* / HFAG values use inclusive $B \rightarrow X_c\ell\overline{\nu}$ as normalization
- more precise except for $B^+ \rightarrow D^{*+}\pi^-\ell^+\overline{\nu}$
- some tensions for $B^0 \rightarrow D^{*0}\pi^-\ell^+\overline{\nu}$

[a] Phys. Rev. Lett. 100, 151802, (2008)
[b] Heavy Flavor Averaging Group

Slide from Thomas Lück (ICHEP 2014)

$D^0 \to \pi^- e^+ \nu$ and implications for V_{ub}

- Measurement of the $D^0 \to \pi^- e^+ \nu$ form factor and branching fraction at BaBar, competitive and in agreement with CLEO-c and BELLE.

$$|V_{cd}| f_{+,D}^{\pi}(0) = 0.1374 \pm 0.0038_{\mathrm{stat.}} \pm 0.0022_{\mathrm{syst.}} \pm 0.0009_{\mathrm{ext.}}$$

$$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (2.770 \pm 0.068 \pm 0.092 \pm 0.037) \times 10^{-3}$$

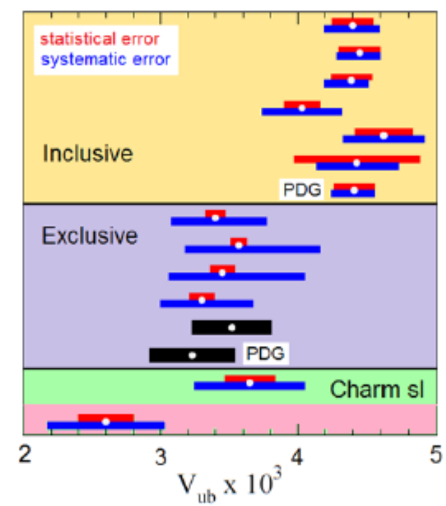
- Physics interpretation of the form factor: [Bečirević *et al*, arXiv:1407.1019 [hep-ph]]
  - The form factor cannot be explained by the D* and $D^{*\prime}_1$ contributions.
  - Description in terms of a "three" poles model, being the 3rd pole effective, agrees well with data.

- V_{ub} has been extracted using the information of charm sl data:

→Using a constant form factor ratio from Lattice.

→Using the "three" poles model.

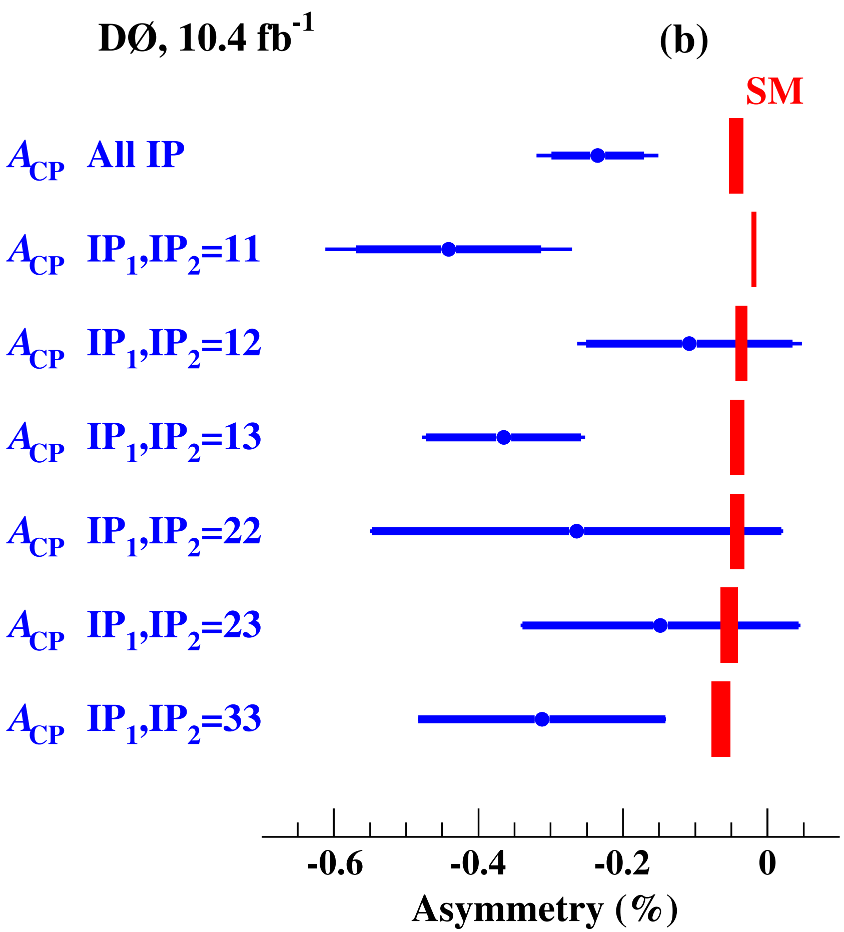
- Systematics of different origin, hope to be reduced in future by Lattice calculations



ICHEP 2014, Valencia

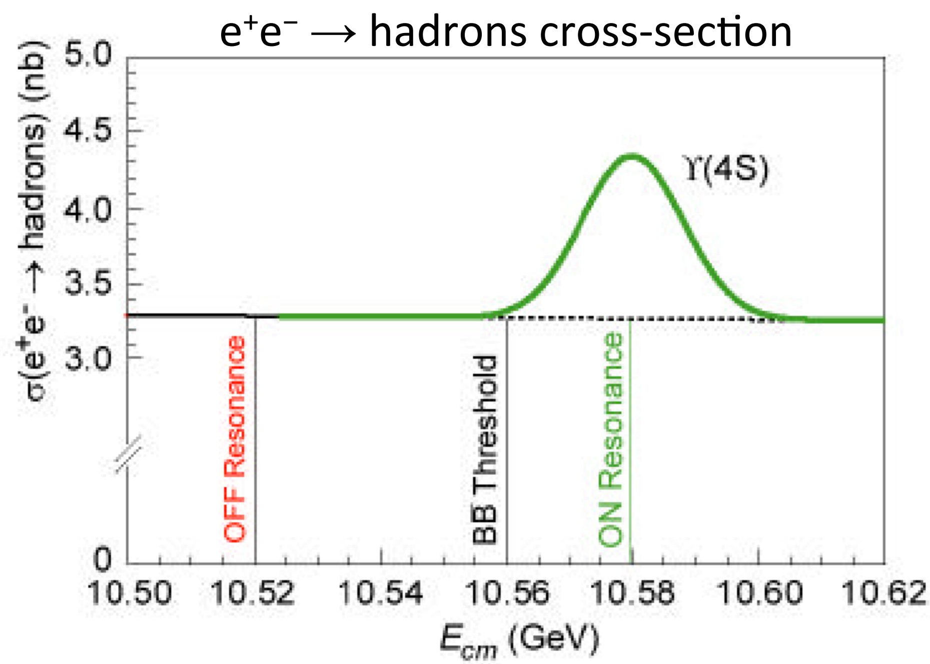
Arantza Oyanguren

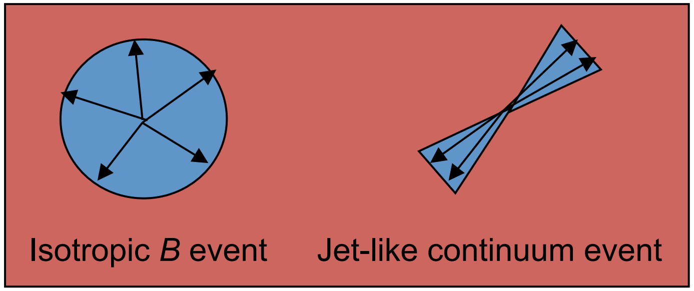
Dimuon charge asymmetry



B-factory Analysis Variables – Topological

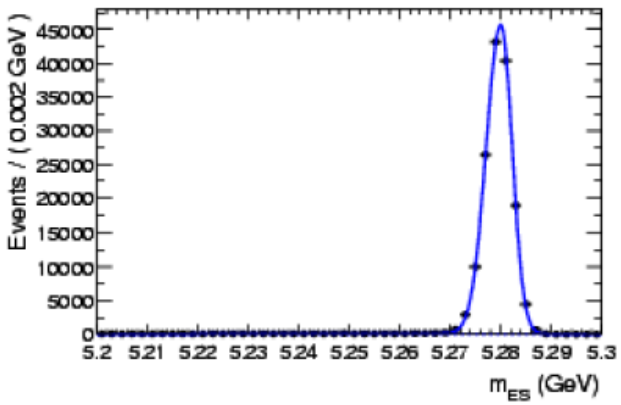
- Light quark continuum cross section ~3x $\sigma\left(b\bar{b}\right)$
- *B* mesons produced almost at rest since just above threshold
- Use event topology to discriminate
- Combine variables in an MVA, e.g. Fisher, Neural Network or Decision Tree



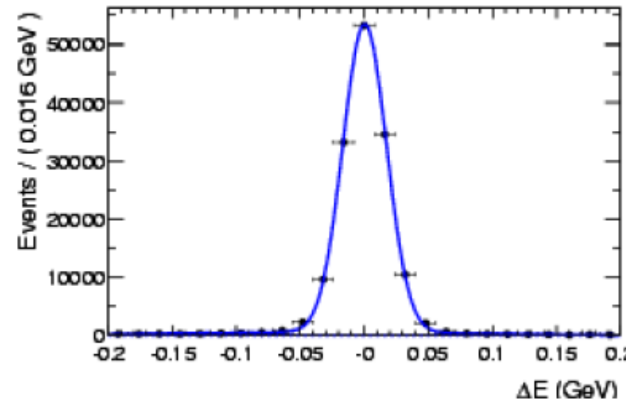


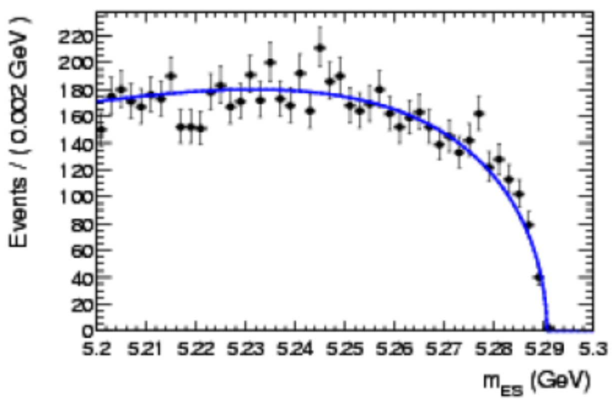
B-factory Analysis Variables – Kinematic

Make use of precision kinematic information from the beams.

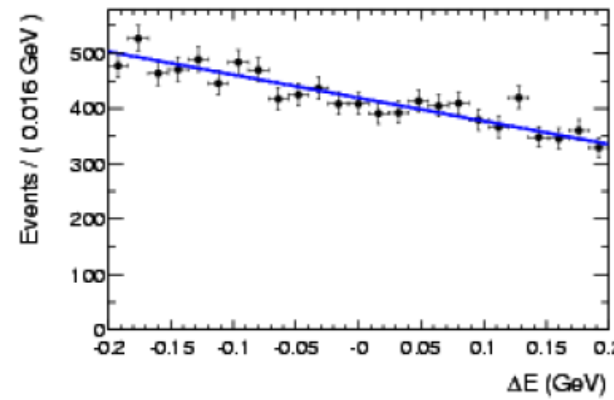


Characteristic Signal Distributions





Characteristic Continuum Distributions

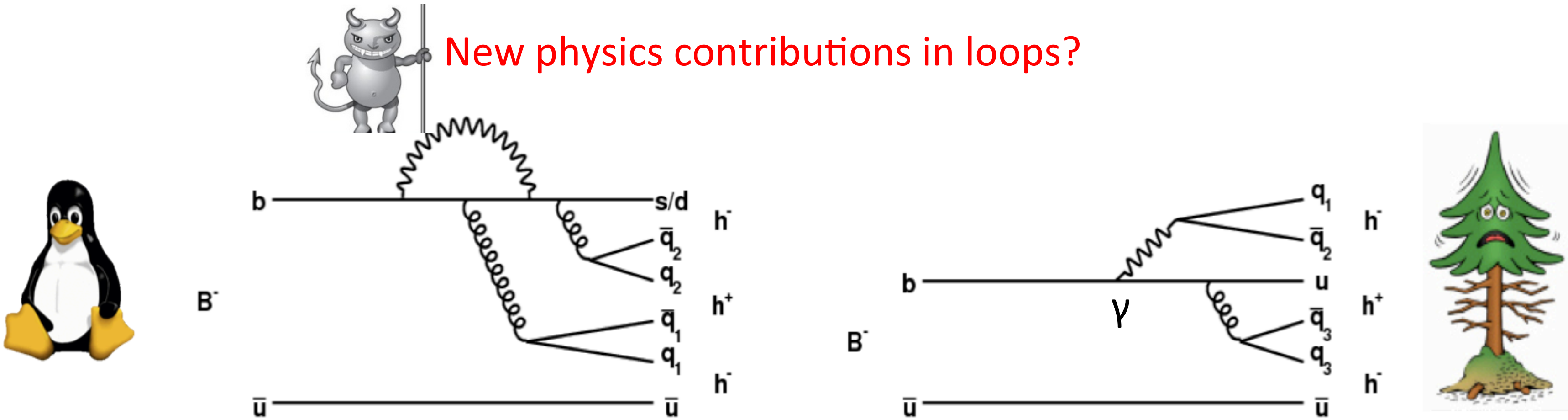


$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

Plots show simulation

$$\Delta E = E_B^* - E_{beam}^*$$

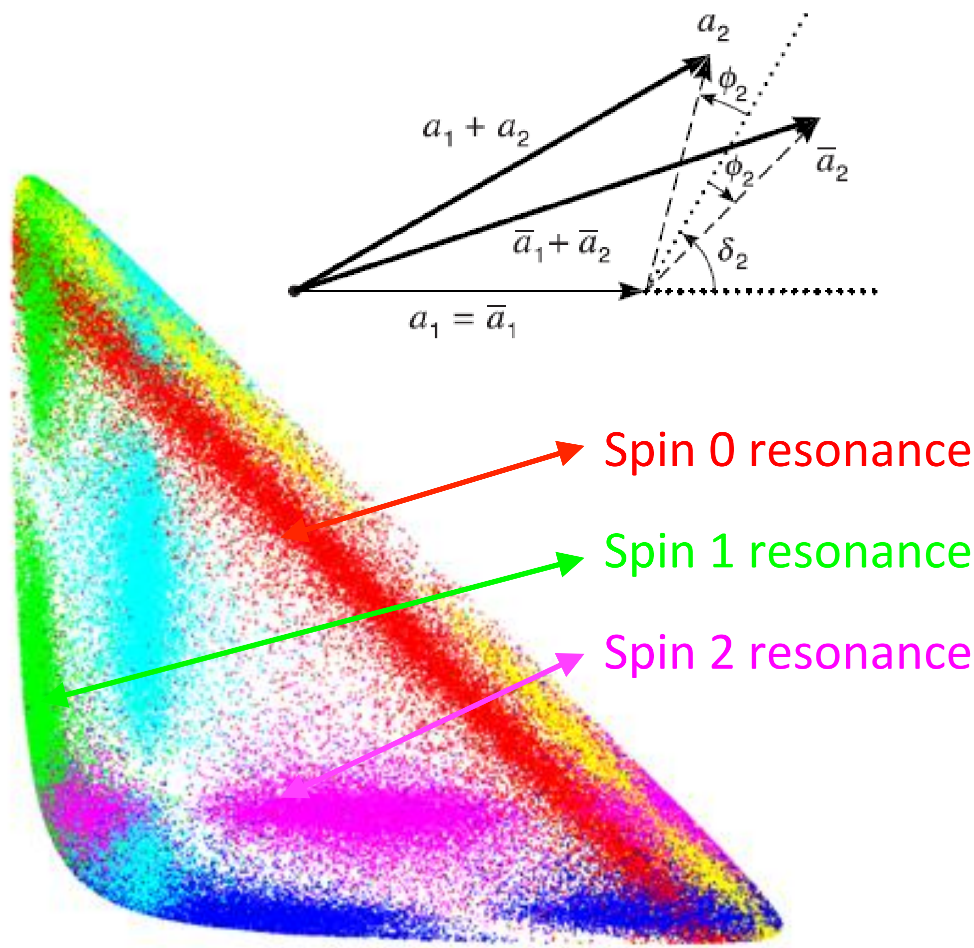
Charmless *B* decays



- Contributions from both loop (penguin) and tree decay diagrams
- These diagrams have a relative weak phase (= γ in SM)
- Interference can therefore give rise to CP violation in decay
- In neutral *B* decays can make time-dependent measurements, allowing measurements of mixing-induced CP asymmetries
- These can be compared with measurements from, e.g. $B^0 \to J/\psi\, K_S$, to search for signs of new physics

Dalitz plot analysis

- Intermediate resonances appear as structures in Dalitz plot, characterised by their mass, width and spin
- Overlapping resonant contributions lead to interference effects
- Hence the sensitivity to relative phases



Simulated data

$B^+ \to K_S\pi^+\pi^0$ Motivation

- Only upper limit exists on inclusive branching fraction, from CLEO collaboration

$$\mathcal{B}\left(B^+ \to K^0\pi^+\pi^0\right) < 66 \times 10^{-6}$$

Phys. Rev. Lett. **89**, 251801 (2002)

- Improved measurements of direct CP violation in $B^+ \to K^{*+}\pi^0$ can shed light onto equivalent of "$K\pi$ puzzle" in $K^*\pi$ system [Phys. Rev. **D81**, 094011 (2010)]
- ΔA_{CP} predicted to be zero

$$\Delta A_{\rm CP} = A_{\rm CP}(K^{*+}\pi^0) - A_{\rm CP}(K^{*+}\pi^-)$$

- $A_{CP}(K^{*+}\pi^-)$ quite precisely measured by BaBar & Belle

$$A_{\rm CP}(B^0 \to K^{*+}\pi^-) = -0.23 \pm 0.06$$

HFAG Average

- Only previous measurement of $A_{CP}(K^{*+}\pi^0)$ by BaBar, using final state $B^+ \to K^+\pi^0\pi^0$

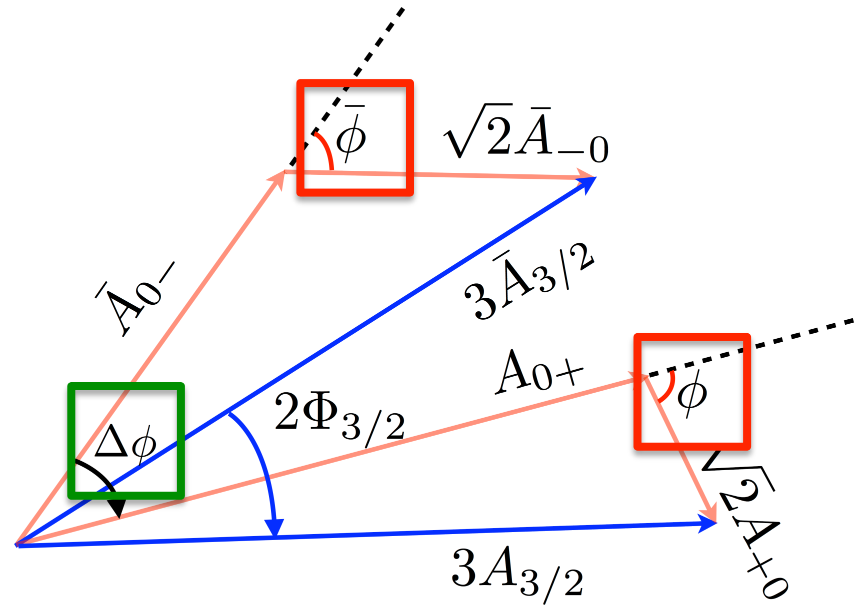
$$A_{\rm CP}(B^+ \to K^{*+}\pi^0) = -0.06 \pm 0.24$$

Phys. Rev. **D84**, 092007 (2011)

$B^+ \to K_S\pi^+\pi^0$ Motivation

- Relative phases between the two $K^*\pi$ intermediate states can be used to measure CKM angle γ
- Uses the fact that $K^{*0}\pi^+$ is a pure penguin decay
  - Hence $\Delta\phi$ is approximately zero
- In absence of EW penguins $\Phi_{3/2} = \gamma$

Isospin relations



Phys. Rev. D74, 051301 (2006)
Phys. Rev. D75, 014002 (2007)

Dalitz plot analysis formalism

- Resonance parameterisation (isobar model):

$$\overset{(-)}{\mathrm{A}} = \sum \overset{(-)}{\mathrm{A}}_i = \sum \overset{(-)}{\mathrm{c}}_i F\left(m^2_{K_S\pi^+}, m^2_{\pi^0\pi^+}\right)$$

Complex coefficients

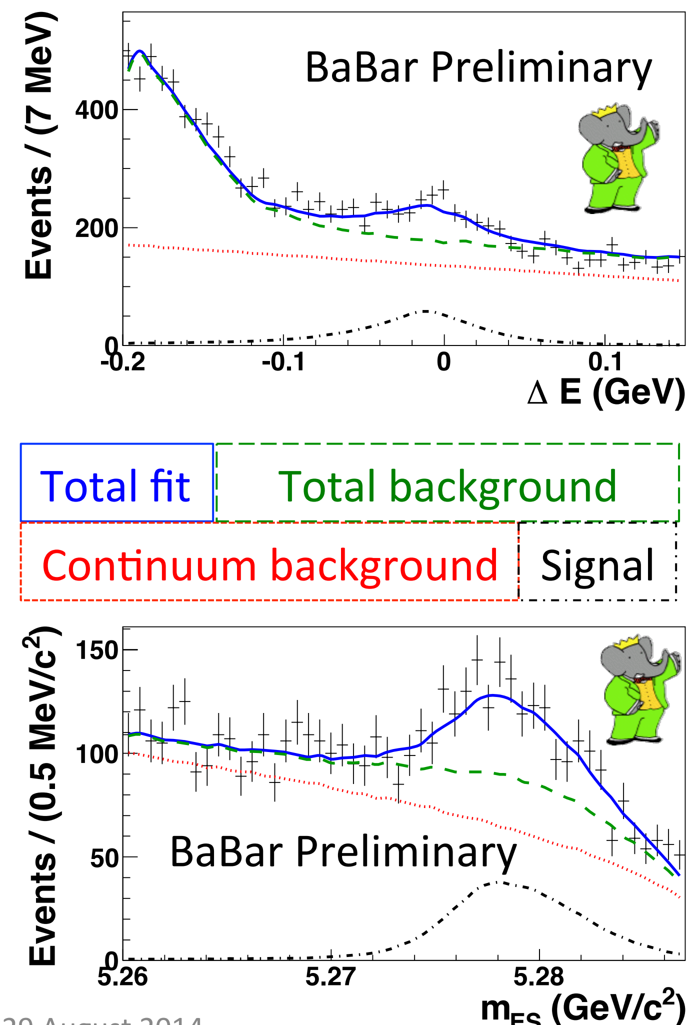
Decay dynamics

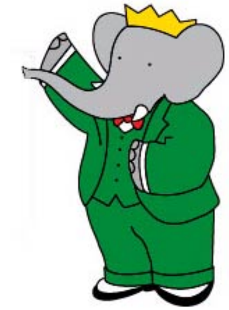
- Directly extracted parameters: Re(c_i) & Im(c_i)
- Other quantities (relative phases, BF, A_{CP}) are derived from these

$B^+ \to K_S\pi^+\pi^0$ Selection and fit

- K_S candidates reconstructed in decay to $\pi^+\pi^-$
- Largest B backgrounds removed by vetoing $D^0 \to K_S\pi^0$
- Approx. 32,000 candidates after all selection

- Maximum likelihood fit to m_{ES}, ΔE, Boosted Decision Tree (event topology) and DP
- Large correlations between DP position and kinematic variables
- Signal PDFs parameterised as function of DP position
- Signal yield of 1014 ± 63 (statistical uncertainty only)





$B^+ \to K_S\pi^+\pi^0$ BFs and Phases

Decay channel	$\mathcal{B}\,(10^{-6})$
$K^0\pi^+\pi^0$	$45.9 \pm 2.6 \pm 3.0 \pm 8.6$
$K^{*0}(892)\pi^+$	$14.6 \pm 2.4 \pm 1.3 \pm 0.5$
$K^{*+}(892)\pi^0$	$9.2 \pm 1.3 \pm 0.6 \pm 0.5$
$K_0^{*0}(1430)\pi^+$	$50.0 \pm 4.8 \pm 6.0 \pm 4.0$
$K_0^{*+}(1430)\pi^0$	$17.2 \pm 2.4 \pm 1.5 \pm 1.8$
$\rho^+(770)K^0$	$9.4 \pm 1.6 \pm 1.0 \pm 2.6$

- First measurement of inclusive $K^0\pi^+\pi^0$ and $K^{*+}_0(1430)\pi^0$ BFs
- First uncertainty is statistical, second systematic, and third due to the signal model
- Sensitivity to relative phases depends strongly on overlap in DP and effects of mis-reconstruction in the corners
- Smaller uncertainties for pairs of parallel resonances

Reference amplitude \ Resonances	Relative phases (°)				
	$K^{*0}(892)\pi^+$	$K^{*+}(892)\pi^0$	$(K\pi)_0^{*0}\pi^+$	$(K\pi)_0^{*+}\pi^0$	$\rho^+(770)K_S^0$
$B^+ \to K^{*0}(892)\pi^+$	0	-96 ± 44	174 ± 11	-91 ± 43	-122 ± 38
$B^+ \to K^{*+}(892)\pi^0$	–	0	-90 ± 42	6 ± 10	-27 ± 26
$B^+ \to (K\pi)_0^{*0}\pi^+$	–	–	0	95 ± 42	64 ± 37
$B^+ \to (K\pi)_0^{*+}\pi^0$	–	–	–	0	-32 ± 25
$B^+ \to \rho^+(770)K_S^0$	–	–	–	–	0

$B^+ \to K_S\pi^+\pi^0$ BFs and Phases

Decay channel	$\mathcal{B}\,(10^{-6})$
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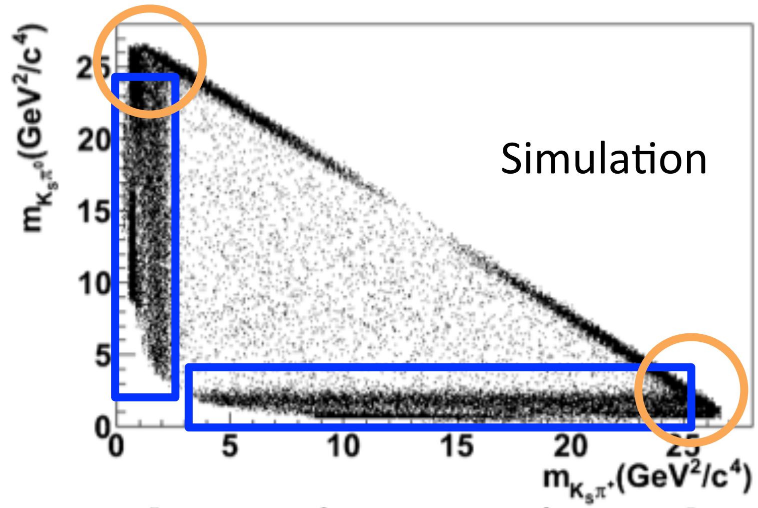

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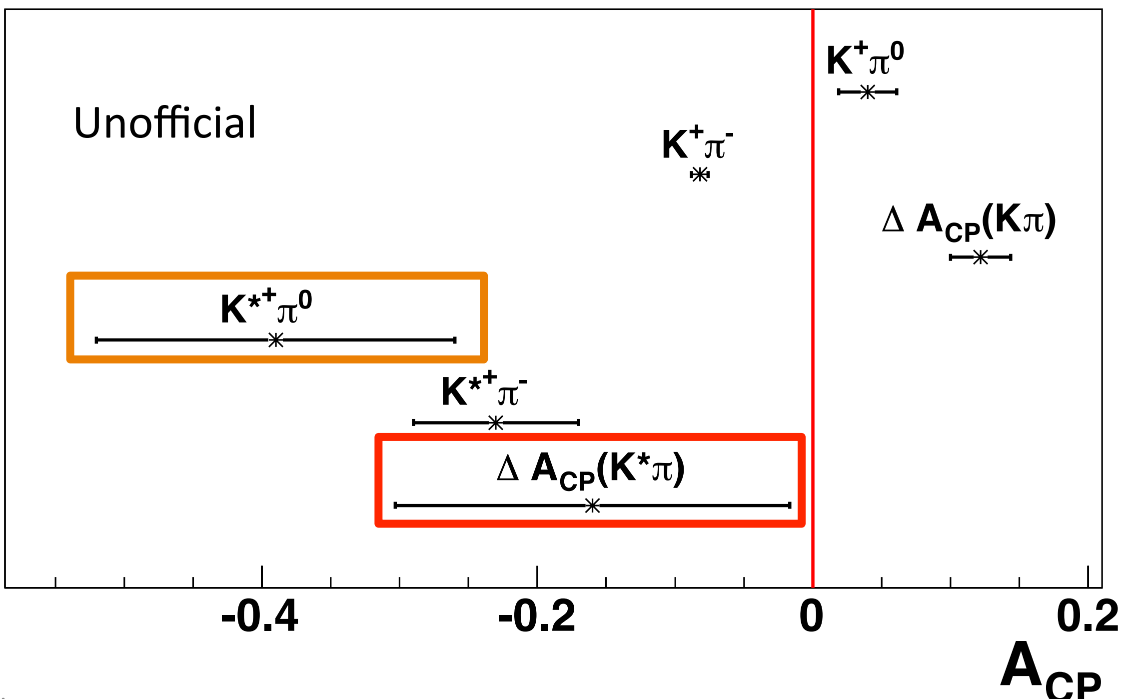
$B^+ \to \rho^+(770)K_S^0$	–	–	–	–	0

Effect on $K^{(*)}\pi$ puzzle

NEW!

- Plot uses world average values for $K\pi$ and $K^{*+}\pi^-$ asymmetries and personal average of the two BaBar results for $K^{*+}\pi^0$
- Gives $\Delta A_{CP}(K^*\pi) \equiv A_{CP}(K^{*+}\pi^0) - A_{CP}(K^{*+}\pi^-) = -0.16 \pm 0.14$
  - Consistent with zero
- Uncertainty much improved but still too large to be conclusive



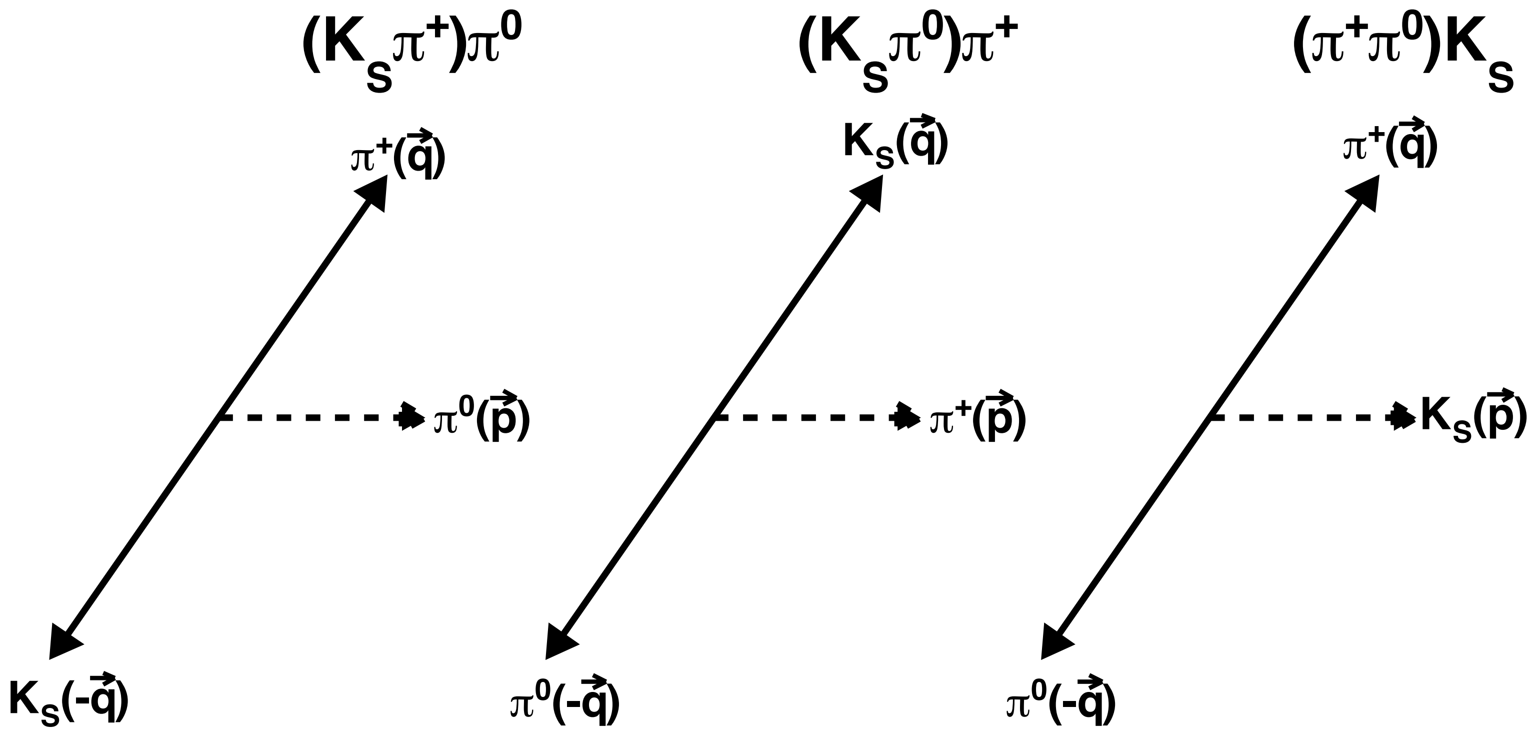
BaBar, Belle

BaBar, Belle, CDF, LHCb

BaBar only!

BaBar, Belle

$B^+ \to K_S\pi^+\pi^0$ Phase convention



LASS parameterisation

- Parametrising the $J^P = 0^+$ component of the $K\pi$ spectrum with LASS parametrisation
- Integrating separately for the different contributions in the parametrisation gives:
  - 88% resonance $K^{*0/+}{}_0(1430)$
  - 49% effective range nonresonant component (describes slowly increasing phase as a function of $K\pi$ mass)
  - extra 37% from destructive interference
- Effective range part of the amplitude has a cut-off at 1800 MeV/c^2

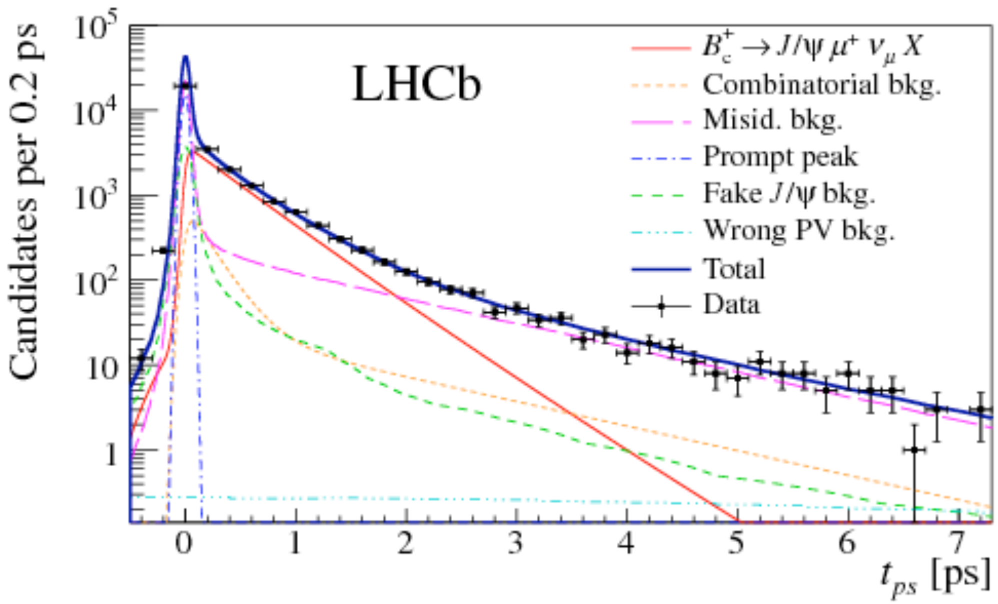
$$R_j^{\text{LASS}} = \frac{m}{q\cot\delta_B - iq} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{(m_0^2 - m^2) - im_0\Gamma_0\frac{qm_0}{mq_0}}$$

B_c meson lifetime

- Uses 2fb^{-1} of data from 2012 (8 TeV)
- Using decay modes:

  $B_c^+ \rightarrow J/\psi\, \mu^+\, \nu_\mu\, X$
- Lifetime measured to be:

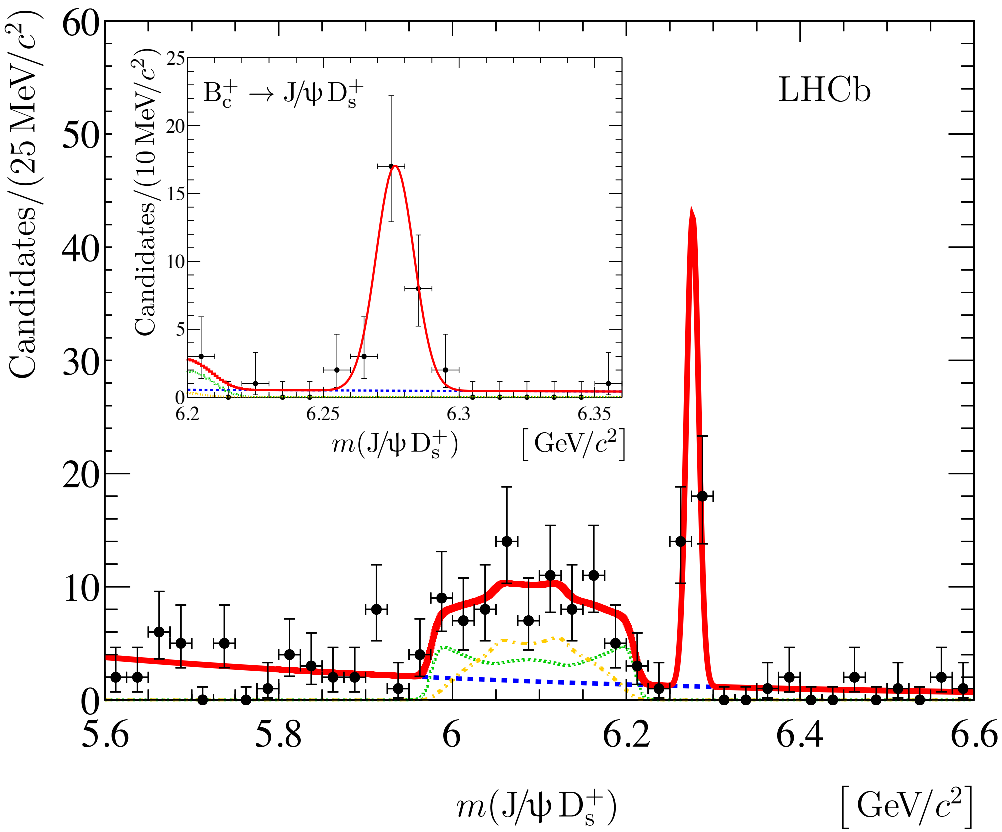
  $\tau(B_c) = 509 \pm 8 \pm 12$ fs



Mass of the B_c meson

- Properties of B_c meson are still rather poorly determined
- Lifetime is rather shorter than other B mesons
  - Indicates importance of charm quark in the weak decay
  - See also recent LHCb observation of $B_c \longrightarrow B_s \pi$

  [Phys. Rev. Lett. 111 (2013) 181801]
- Recent observation of B_c decays to $J/\psi\ D_s$ provide a way to reduce the systematic uncertainty on the mass measurement
- Obtains a yield of 29 signal events



Phys. Rev. D87 (2013) 112012

Mass of the B_c meson

- Mass determination makes use of recent improvement in D_s mass measurement (also from LHCb)
- Also helped by low Q-value for the decay
- Dominant systematics from knowledge of momentum scale and detector material
- Mass determined to be:

$$m(B_c) = 6276.28 \pm 1.44 \pm 0.36\ \mathrm{MeV}/c^2$$

- Uncertainties on momentum scale and D_s mass largely cancel in the mass difference:

$$m(B_c) - m(D_s) = 4307.97 \pm 1.44 \pm 0.20\ \mathrm{MeV}/c^2$$