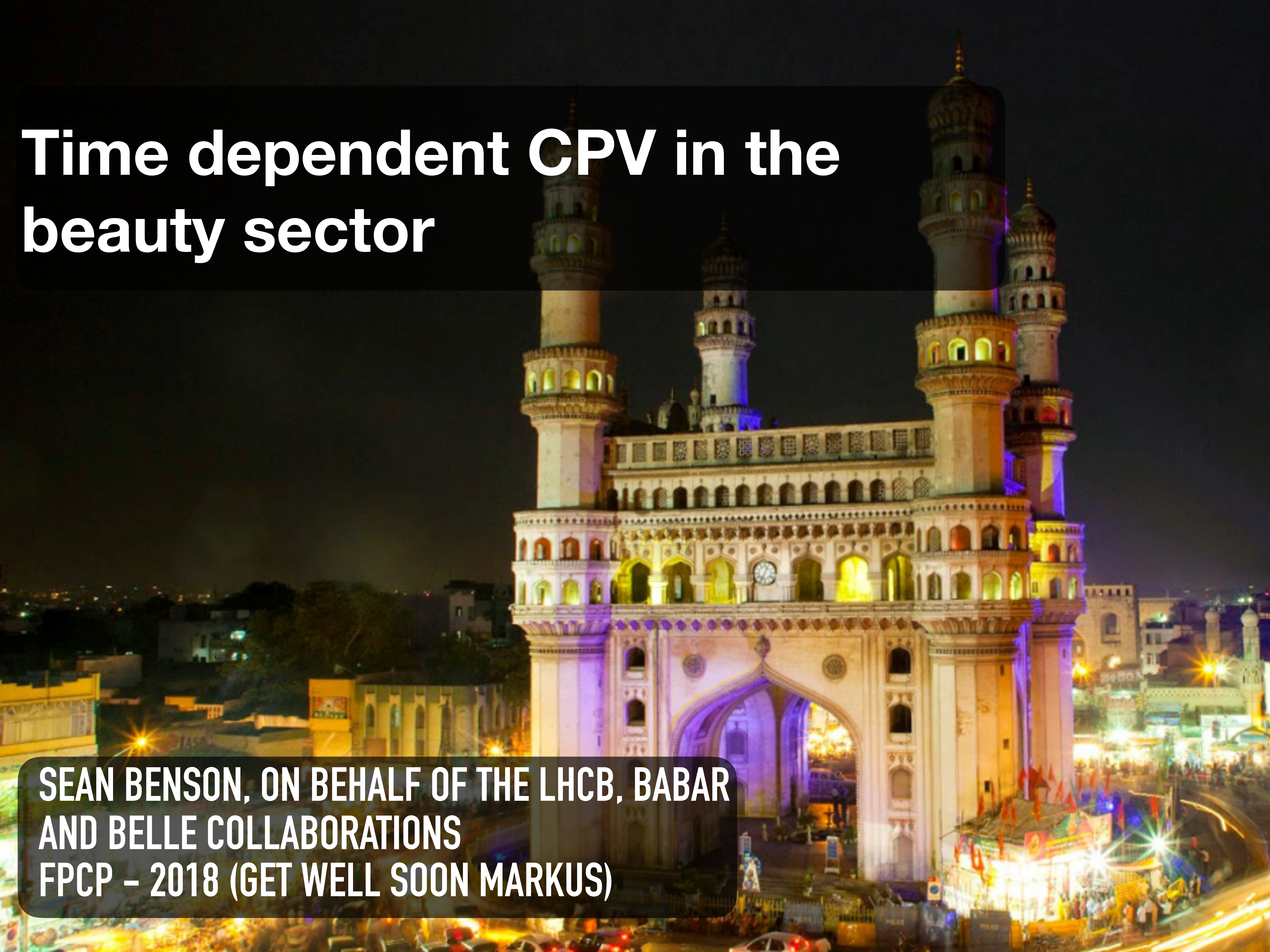


Time dependent CPV in the beauty sector

SEAN BENSON, ON BEHALF OF THE LHCB, BABAR AND BELLE COLLABORATIONS
FPCP - 2018 (GET WELL SOON MARKUS)

Introduction

CP asymmetry as a function of decay time for $B_{(s)}$ mesons decaying to a CP eigenstate f:

$$A_{CP}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f\cos(\Delta m_{d,s}t) + S_f\sin(\Delta m_{d,s}t)}{\cosh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_{d,s}}{2}t\right)},$$

$$C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}, \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1+|\lambda_f|^2}, \qquad \lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

where p, q relate the flavour and mass eigenstates of B mesons.

Assuming |p/q|~1:

- C_f measures direct CPV
- S_f measures indirect CPV

Why TD CPV?

$$\begin{tikzcd}
B_s \arrow[rr, "\phi_D"] \arrow[dr, "\phi_M"'] & & X^{CP} \\
& \bar{B}_s \arrow[ur, "-\phi_D"'] &
\end{tikzcd}$$

Allows access to measurement of the interference between mixing and decay diagrams.

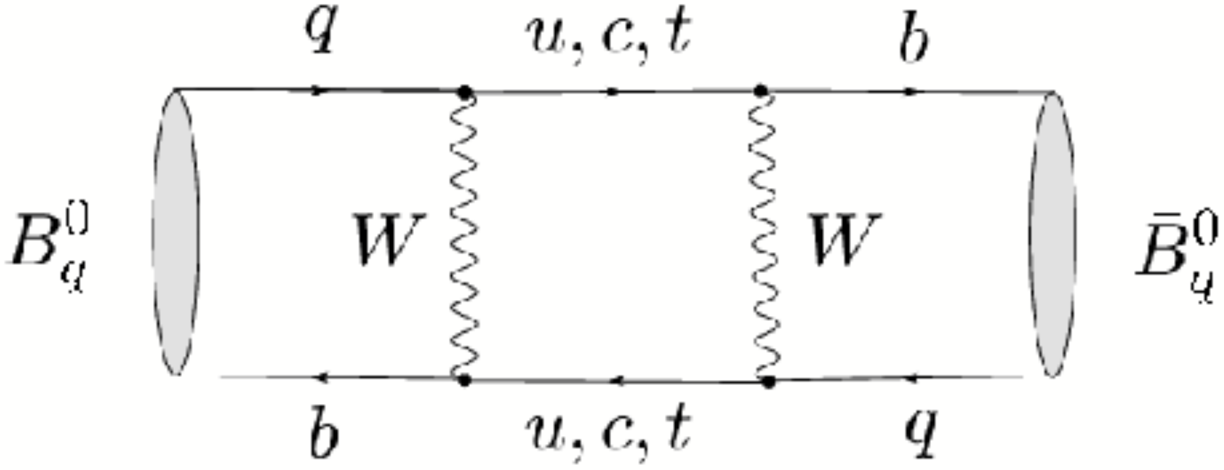
$$\phi_s = \phi_M - 2\phi_D$$

Neutral B meson mixing is an example of a FCNC interaction

=> Forbidden at tree level in the SM

Gives room for possible BSM contributions

Phys.Rev. D97 (2018) no.1, 015021



Why TD CPV (part 2)?

Talk from Arantza describes in detail anomalies from B->sll transitions
https://indico.cern.ch/event/698482/contributions/3063959/

Theories explaining anomalies have to deal with constraints from precision measurements in B_s mixing

Di Lucio, Kirk & Lenz -
Phys. Rev. D 97, 095035 (2018)

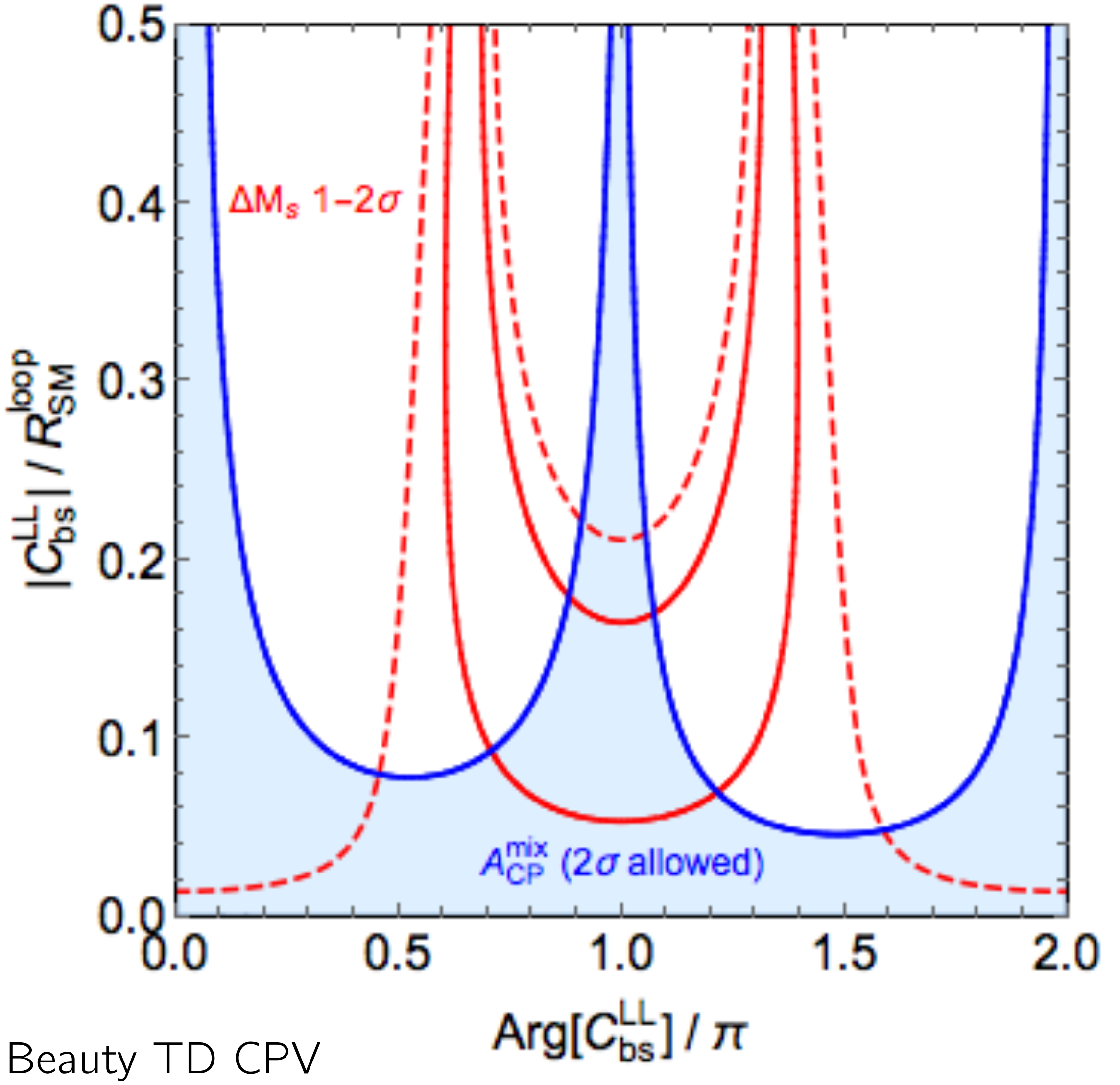
Example here for scalar leptoquark

$$\mathcal{L}_{S_3} = -M_{S_3}^2 |S_3^a|^2 + y_{i\alpha}^{QL} \overline{Q^c}^i (\epsilon\sigma^a) L^\alpha \, S_3^a + \text{h.c.}$$

Couplings also contribute to the mixing Lagrangian

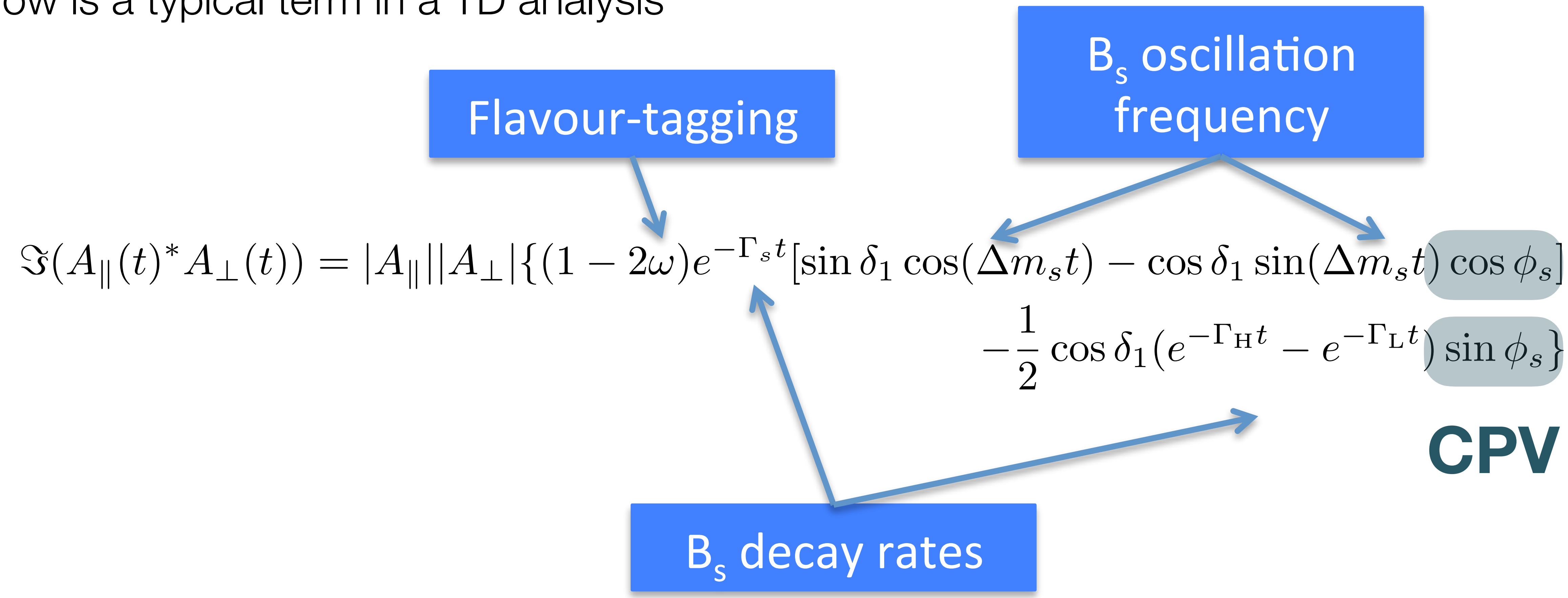
$$\mathcal{L}^{\text{NP}}_{\Delta B=2} = -\frac{4G_F}{\sqrt{2}} (V_{tb}V_{ts}^*)^2 \left[C_{bs}^{LL} \left(\bar{s}_L \gamma_\mu b_L\right)^2 + \text{h.c.}\right]$$

$$C_{bs}^{LL} = \frac{\eta^{LL}(M_{S_3})}{4\sqrt{2} G_F M_{S_3}^2} \frac{5}{64\pi^2} \left(\frac{y_{3\alpha}^{QL} y_{2\alpha}^{QL*}}{V_{tb}V_{ts}^*}\right)^2$$



Challenges of TD CPV

Below is a typical term in a TD analysis



Flavour-tagging

B_s oscillation frequency

$$\Im(A_{\parallel}(t)^* A_{\perp}(t)) = |A_{\parallel}||A_{\perp}|\{(1-2\omega)e^{-\Gamma_s t}[\sin\delta_1\cos(\Delta m_s t) - \cos\delta_1\sin(\Delta m_s t)\cos\phi_s] \\ - \frac{1}{2}\cos\delta_1(e^{-\Gamma_{\mathrm{H}} t} - e^{-\Gamma_{\mathrm{L}} t})\sin\phi_s\}$$

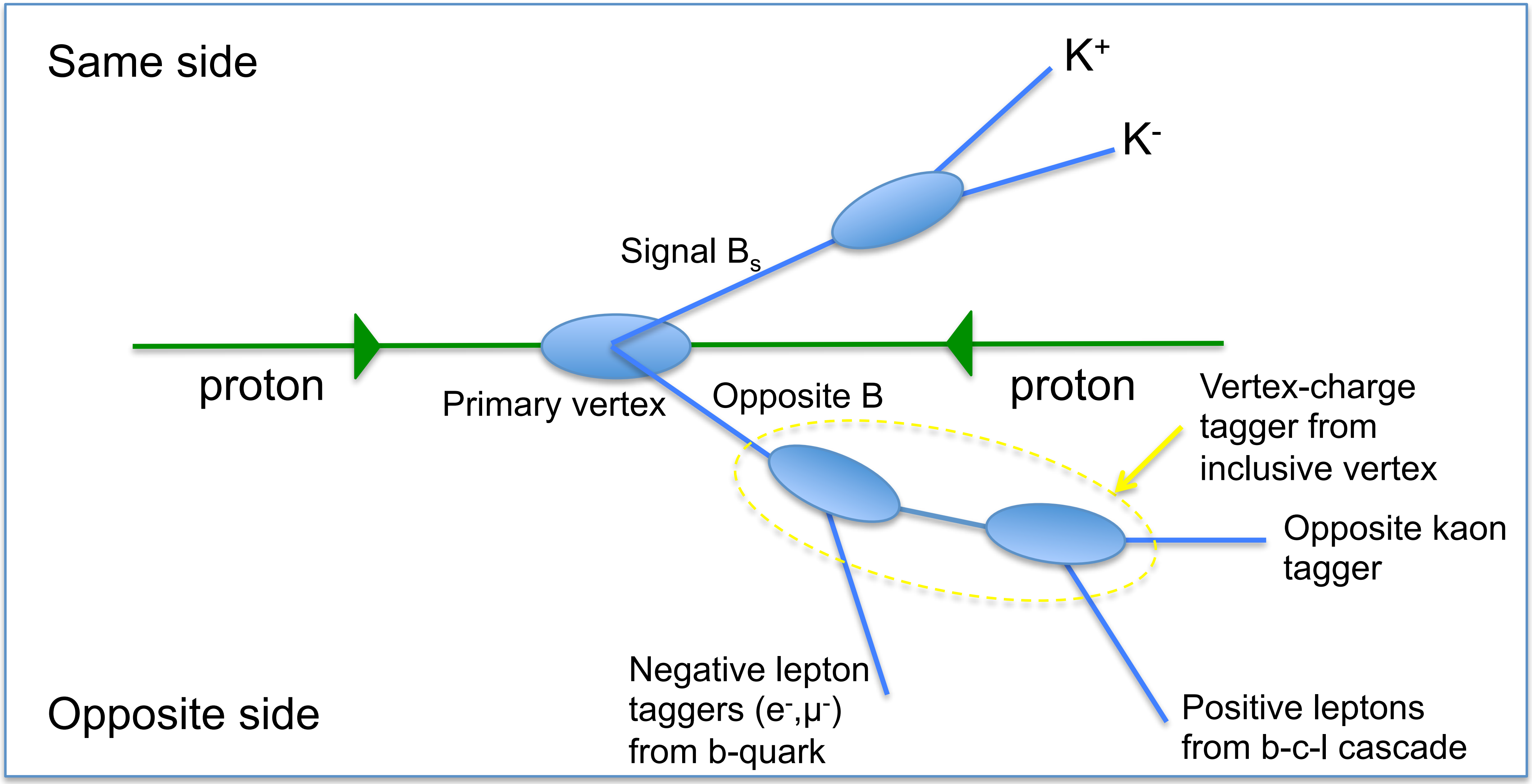
CPV

B_s decay rates

TD measurements require:

- Accurate decay time resolution
- Good understanding of acceptances
- Flavour tagging…

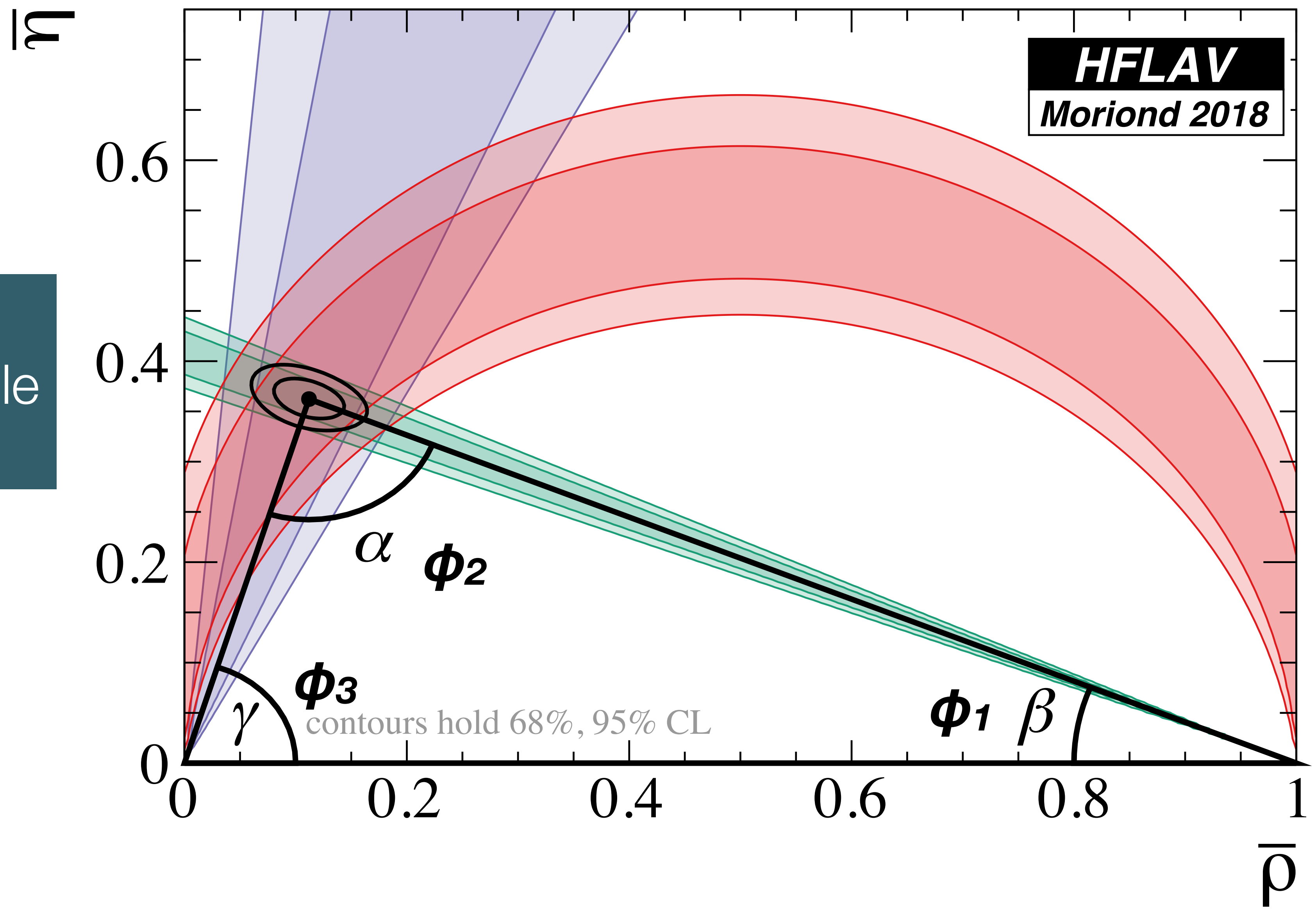
Challenges of flavour tagging



Requires reconstruction of other decays in the event.

- B factories ~30%
- LHCb ~4-6%

Note on conventions…



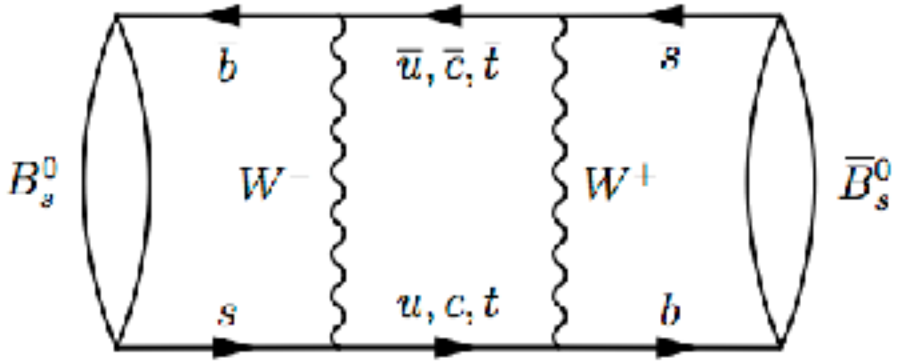
Difference between LHCb/BaBar and Belle angle names

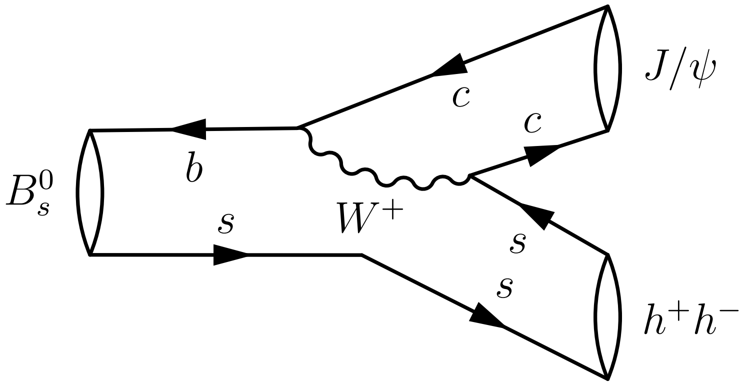
Note that for the case of FCNC Bs decays, the CP-violating phase is denoted as ϕ_s^{sqqbar} where *sqqbar* is the final state of the quark level transition.

B_s mixing

See talk of K. Gizdov

- An important measurement for LHCb is that of CP violation in B_s mixing, tested with tree-dominated $b \to c\bar{c}s$ decays.

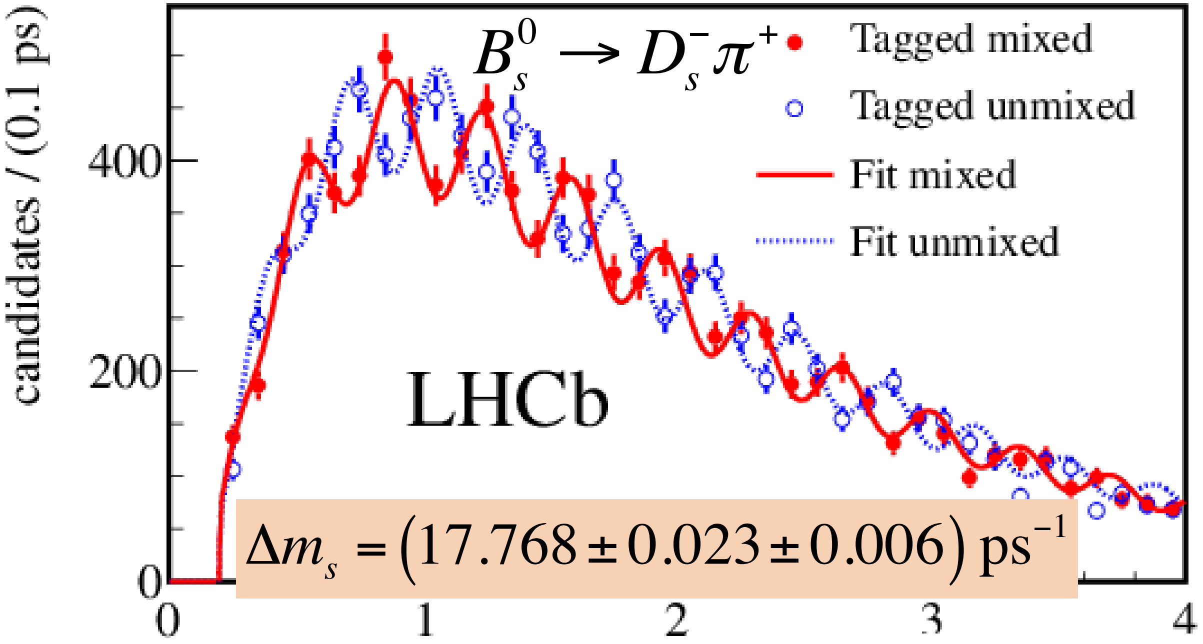




$$\phi_s \equiv -2\beta_s = -2\arg\left(-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right)$$

- Experimentally very complex due to mixture of CP eigenstates in the $B_s \to J/\psi KK$ transition
- CP eigenstates disentangled with an angular analysis
- Require excellent knowledge of the initial B meson flavour and B decay time resolution.

LHCb New J Phys 15 (2013) 053021

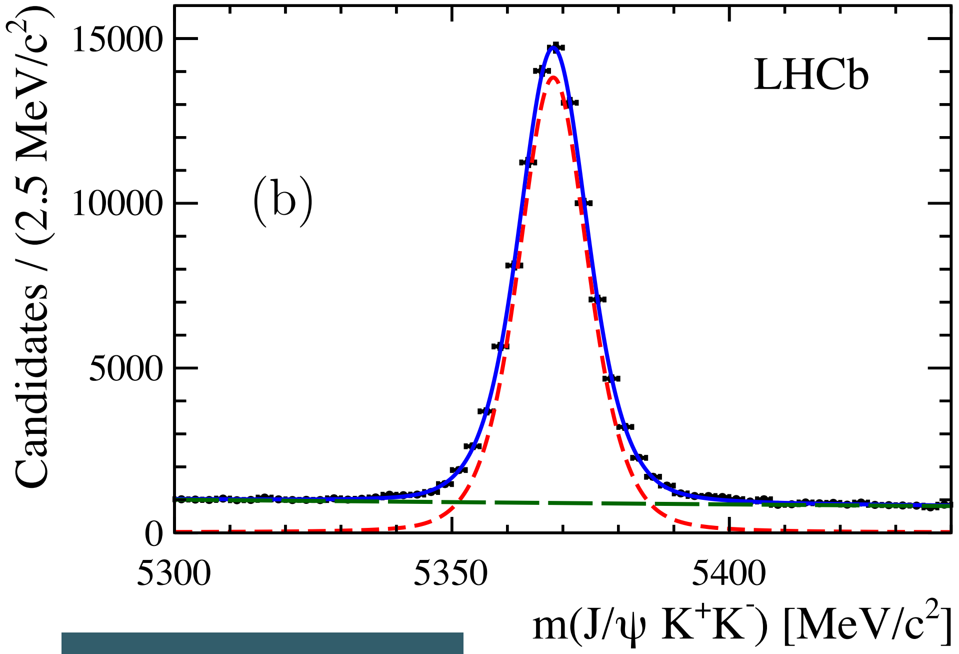


$$\Delta m_s = (17.768 \pm 0.023 \pm 0.006)\ \mathrm{ps}^{-1}$$

B_s mixing

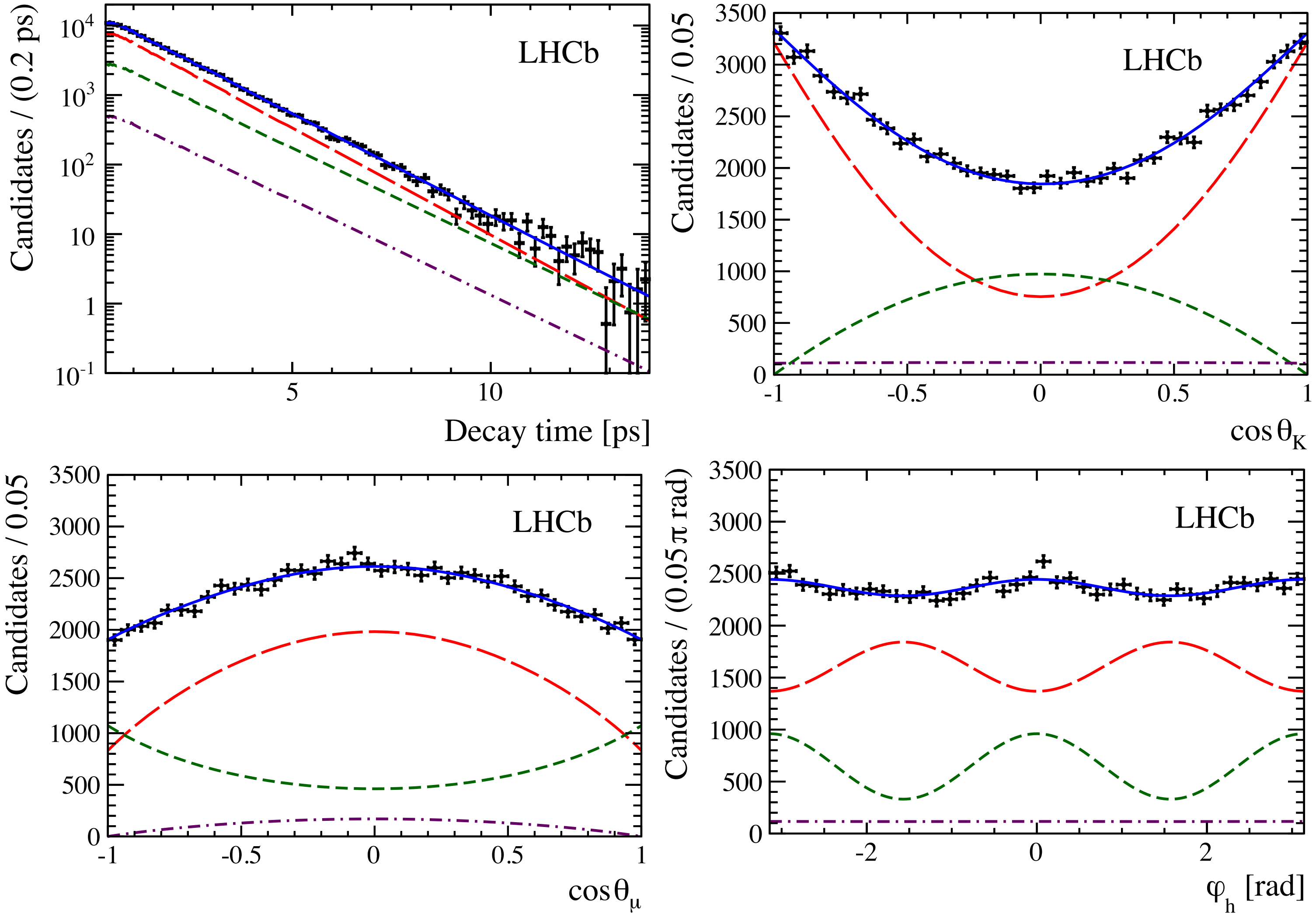
See talk of K. Gizdov

95k candidates



3fb^{-1} from Run I

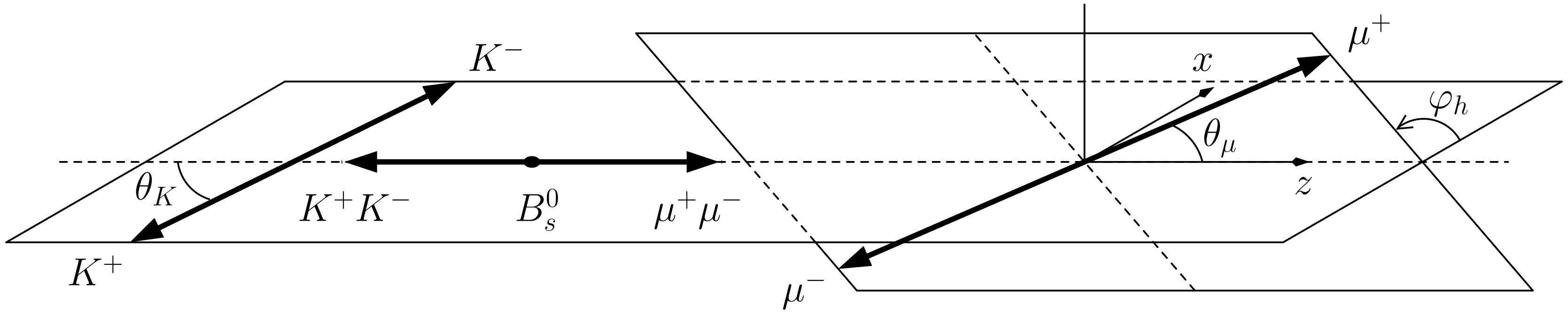
Phys. Rev. Lett. 114, 041801 (2015)



CP-even P-wave

CP-odd P-wave

S-wave



B_s mixing

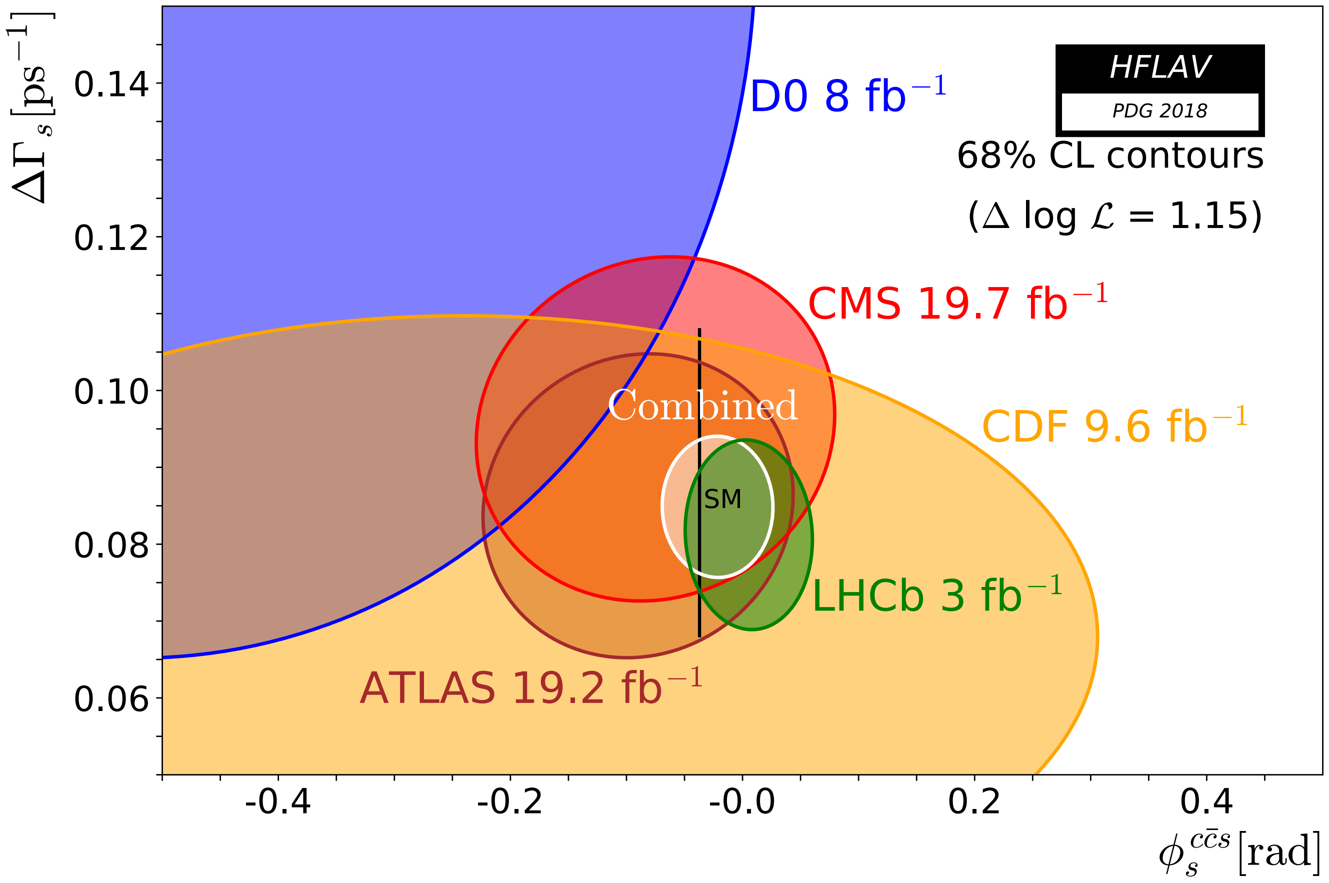
See talk of K. Gizdov

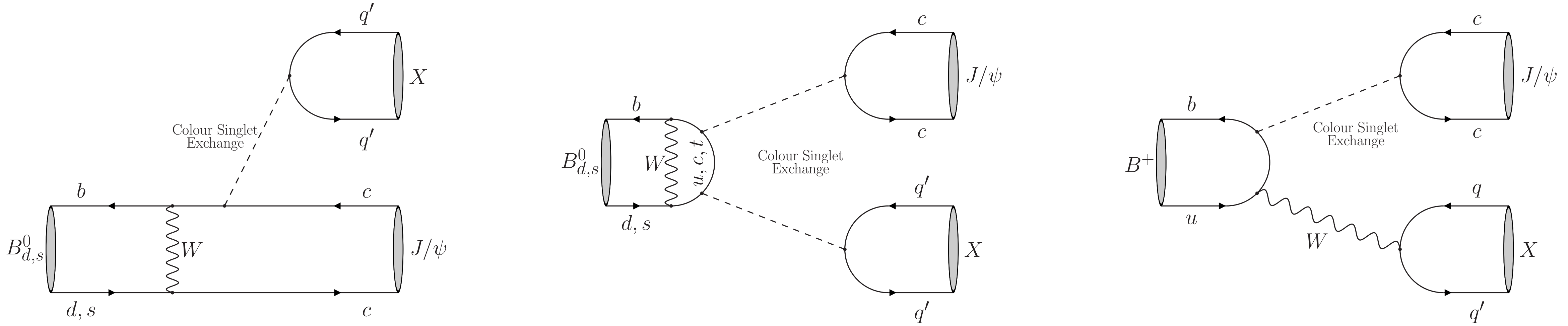
- LHCb measurement of -10±39 mrad dominates the global fit PRL 114 (2015) 04180
- Constraining power of the measurement will increase as LHC accumulates more data.
- Attention turns more to control of penguin pollution (and of course Run 2 data)…

$$\phi_{s,i} = -2\beta_s + \phi_s^{\mathrm{BSM}} + \Delta\phi_{s,i}^{J/\psi\,\phi}(a_i', \theta_i')$$

De Bruyn & Fleischer, arXiv:1412.6834

Global fit: -21±31 mrad

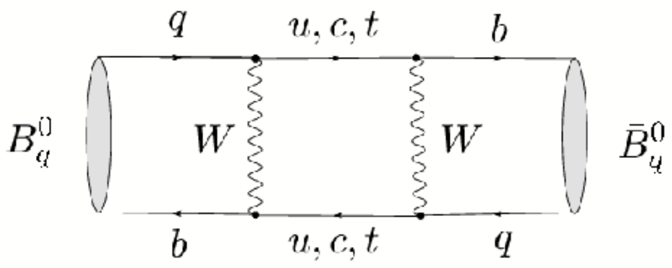




B_d mixing

- CP-violating phase in B_d mixing, defined as

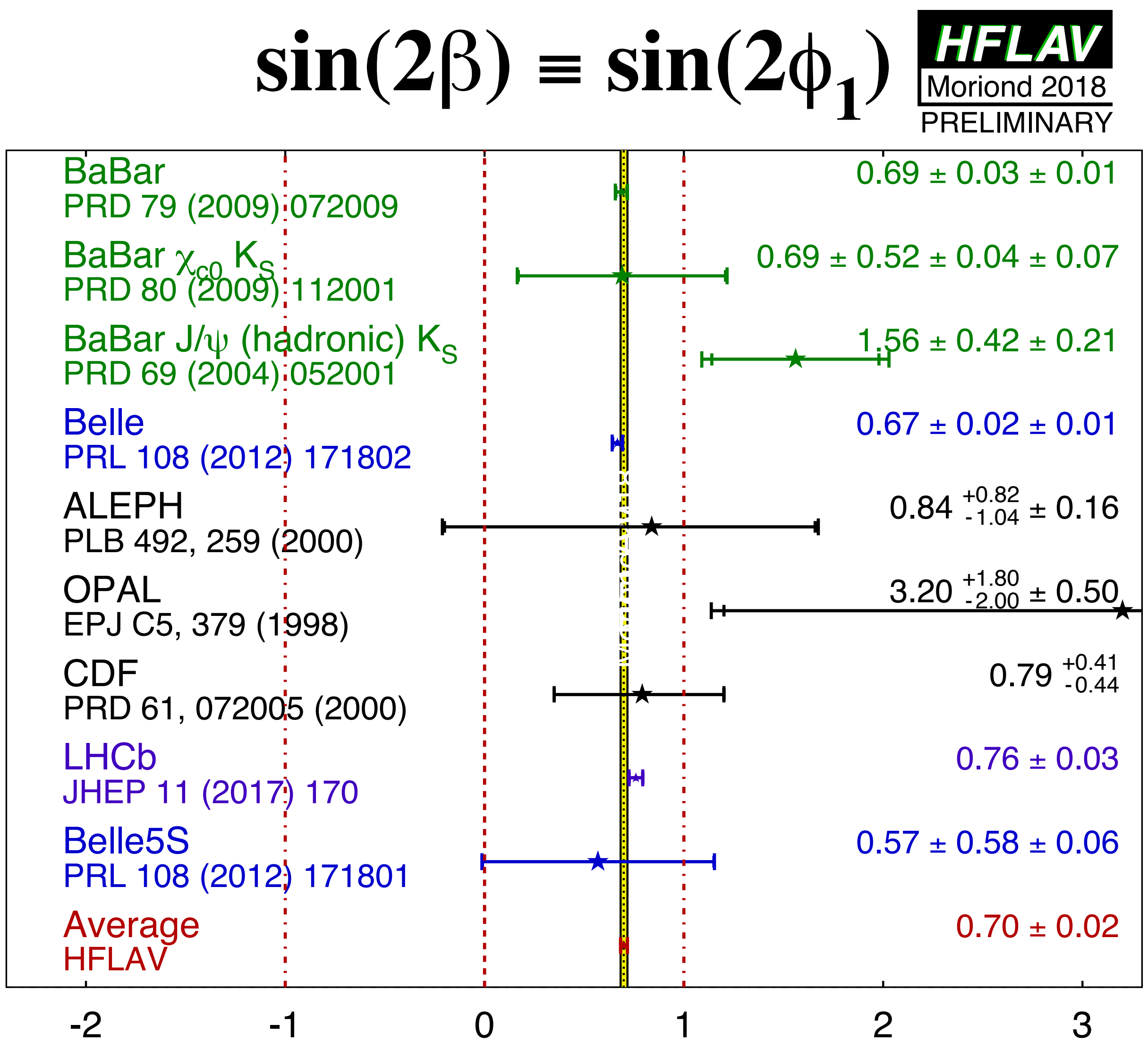
$$\phi_d \equiv 2\beta = 2\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

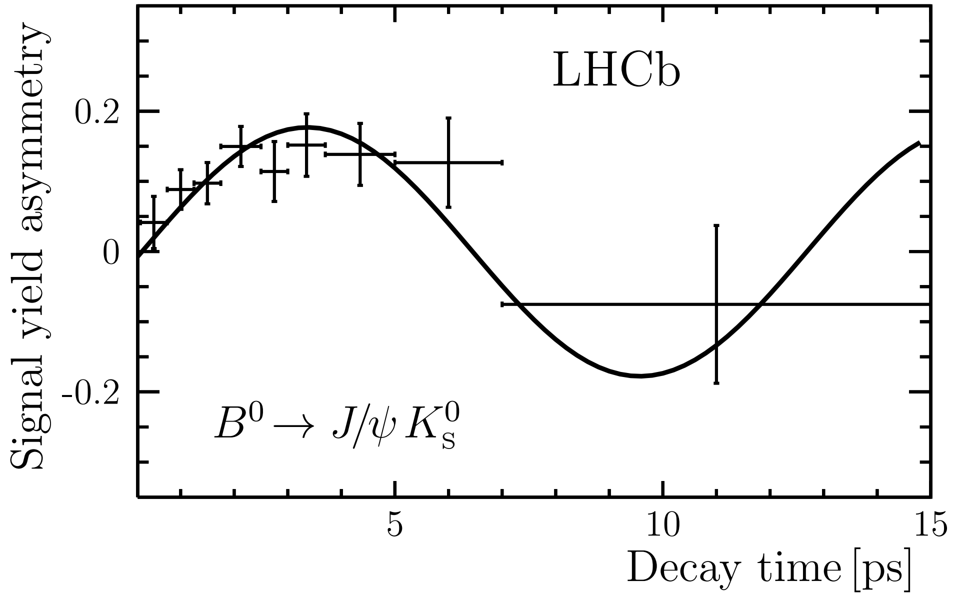


- Measured through $B_d \to K_S J/\psi$

LHCb: JHEP 11 (2017) 1701

- LHCb measurement of $S = \sin 2\beta = 0.760 \pm 0.034$ is approaching the precision of the B-factories





B->hh CPV

See talk of E. Bertholet

arXiv:1805.06759 (submitted to PRD)

3fb^{-1} from Run I

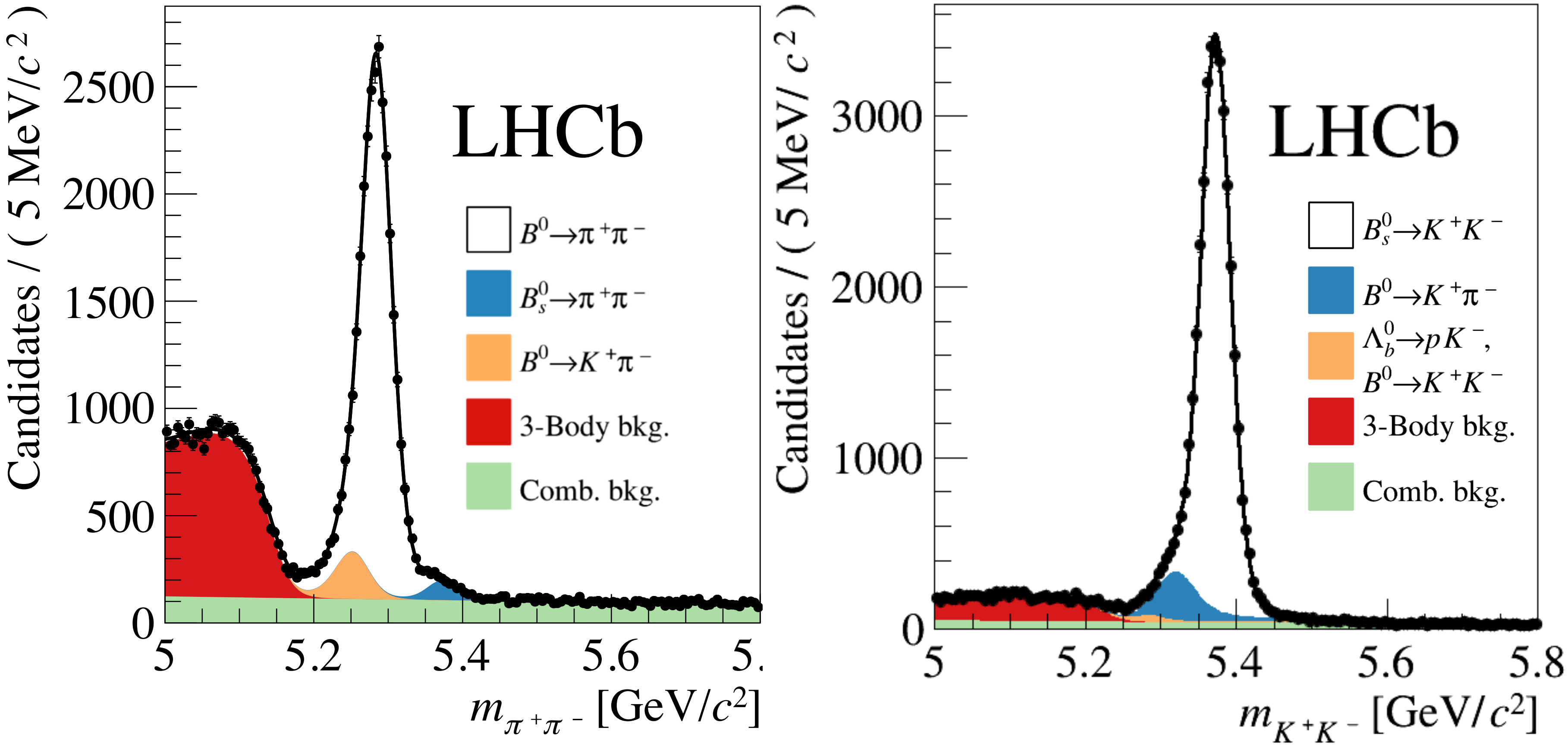
Signal yields

$$N(B^0 \to \pi^+\pi^-) = 28650 \pm 230$$

$$N(B_s^0 \to K^+K^-) = 36840 \pm 220$$

$$N(B^0 \to K^+\pi^-) = 94220 \pm 340$$

$$N(B_s^0 \to \pi^+K^-) = 7030 \pm 120$$



combinatorial reduced with BDT

- Trained with upper mass sideband
- Topological and kinematic information

cross feeds chosen with PID to be ~10% of signal yields

B->hh CPV

See talk of E. Bertholet

Fit observables

invariant mass m

decay time t

predicted decay time error δt

flavour tagging assignment ξ

predicted mistag probability η

final state (for Kπ) ψ

Fixed parameters (HFLAV values)

Parameter	Value
Δm_d	$0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$
Γ_d	$0.6579 \pm 0.0017\,\mathrm{ps}^{-1}$
$\Delta\Gamma_d$	0
Δm_s	$17.757 \pm 0.021\ \ \mathrm{ps}^{-1}$
Γ_s	$0.6654 \pm 0.0022\,\mathrm{ps}^{-1}$
$\Delta\Gamma_s$	$0.083 \pm 0.007\ \ \mathrm{ps}^{-1}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	-0.292

$$\begin{aligned}
A_{CP}^{B^0} &= -0.084 \pm 0.004 \pm 0.003 \\
A_{CP}^{B_S^0} &= 0.213 \pm 0.015 \pm 0.007 \\
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01 \\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01 \\
C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02 \\
S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02 \\
A_{K^+K^-}^{\Delta\Gamma} &= -0.79 \pm 0.07 \pm 0.10
\end{aligned}$$

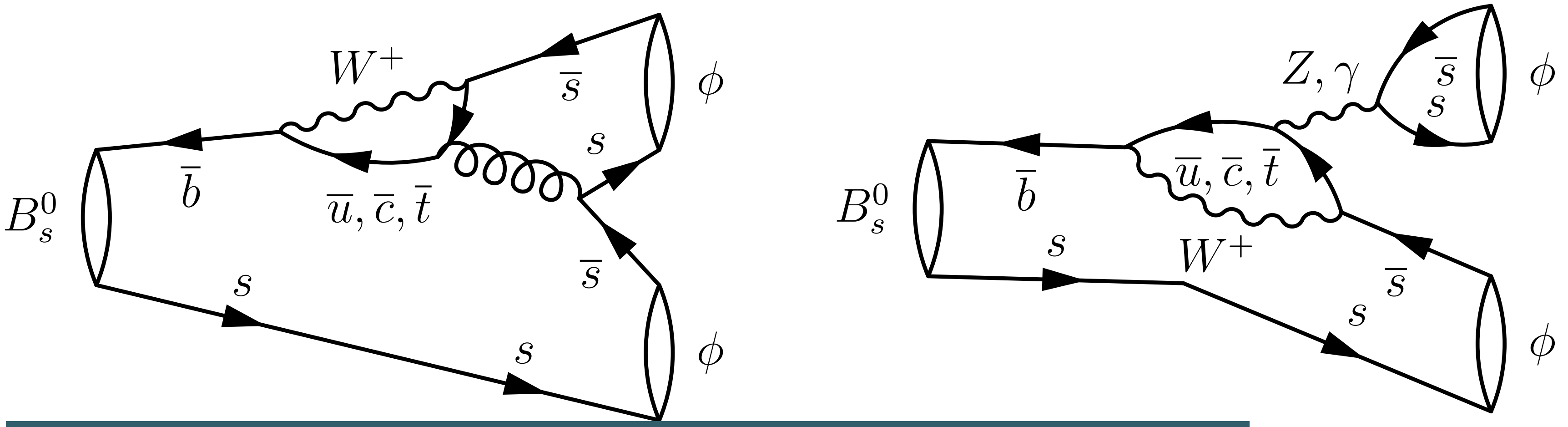
Most accurate measurement from a single experiment

1st measurement

B_s->$\phi\phi$ CPV

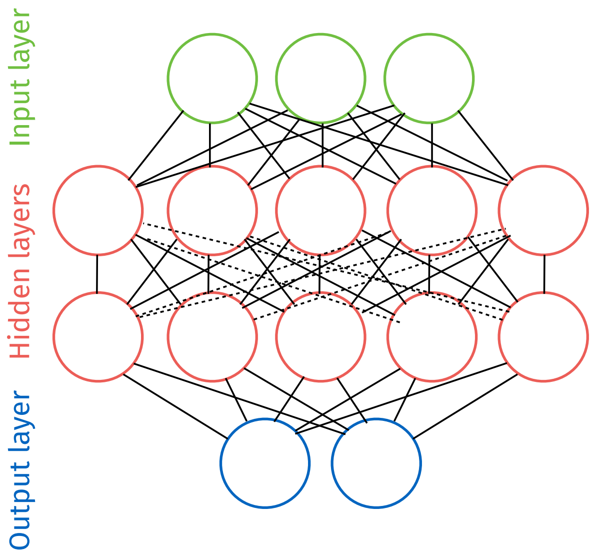
See talk of T. Schmelzer

LHCb-CONF-2018-001



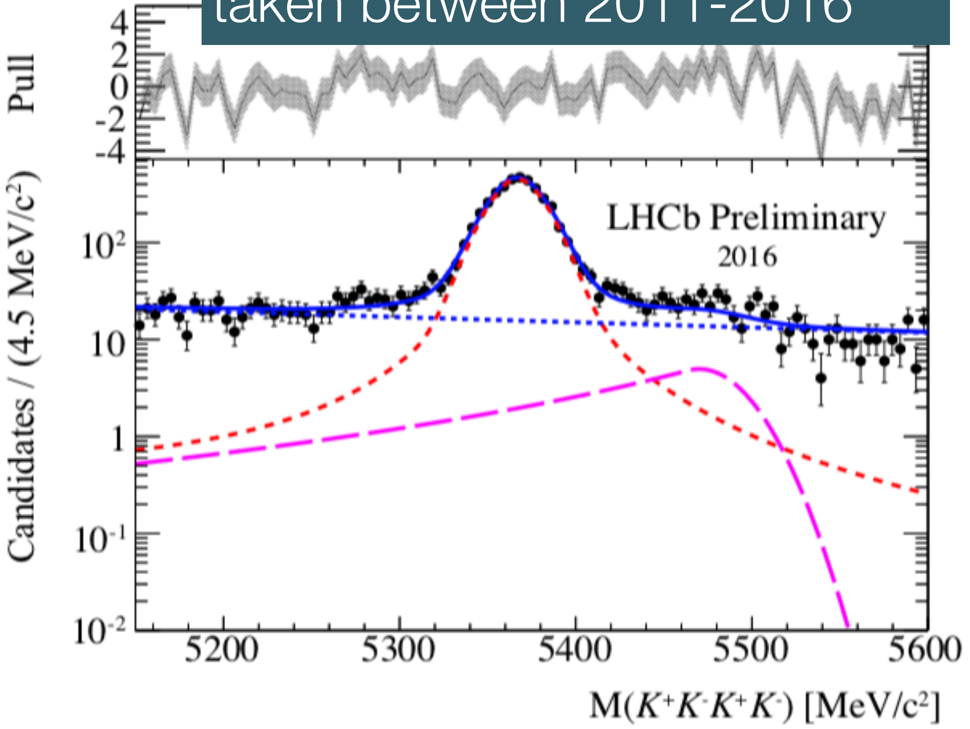
Electroweak and gluons penguin contributions (gluonic expected to dominate)

~8500 candidates from 5fb-1 taken between 2011-2016



MLP used to separate signal from background

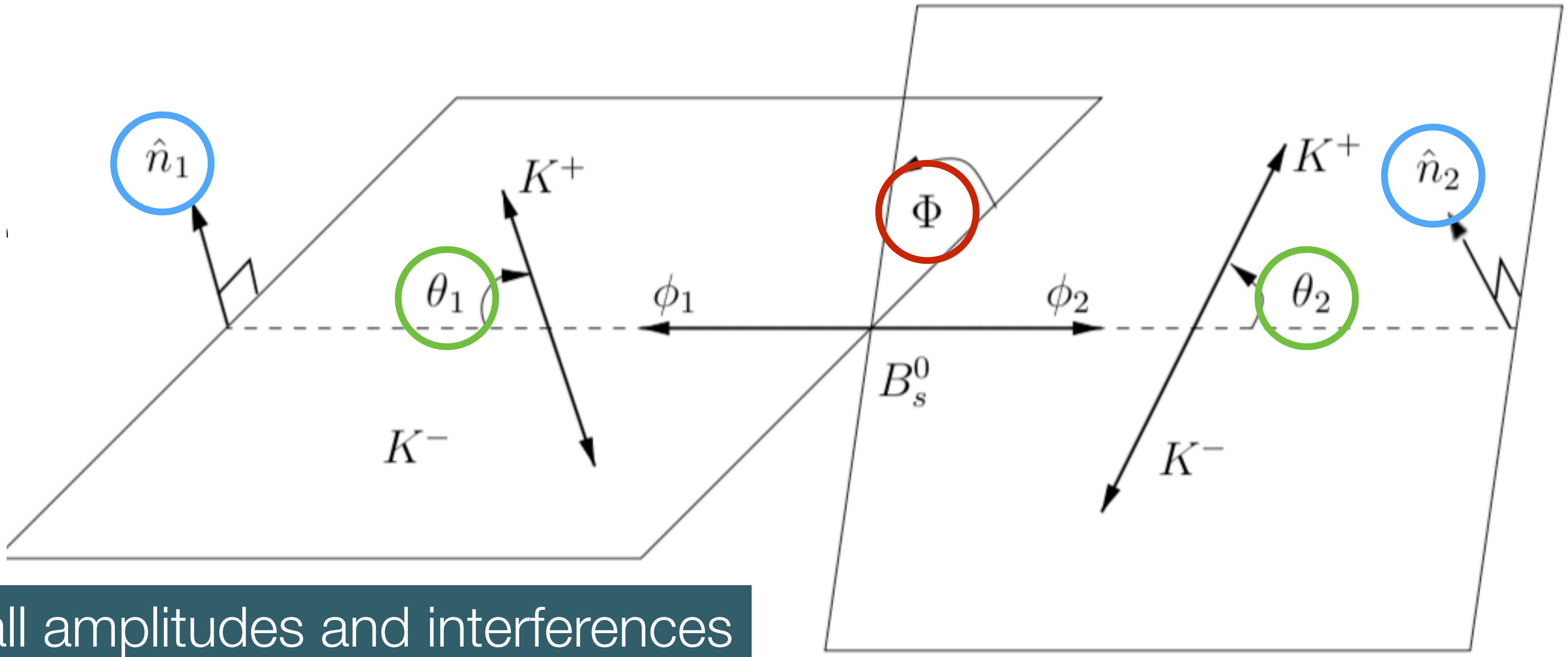
- trained using B sidebands and MC
- Kinematic + topological information



B_s->$\phi\phi$ CPV

See talk of T. Schmelzer

$$\mathcal{A}(t,\theta_1,\theta_2,\Phi) = A_0(t)\cos\theta_1\cos\theta_2 + \frac{A_{\parallel}(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\Phi + i\frac{A_{\perp}(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\Phi + \frac{A_S(t)}{\sqrt{3}}(\cos\theta_1+\cos\theta_2) + \frac{A_{SS}(t)}{3}$$



15 angular terms to fit all amplitudes and interferences

- 3 P-wave Bs->ϕϕ terms
- Single spin-0 kaon pair (A_S)
- Double spin-0 pair (A_{SS})

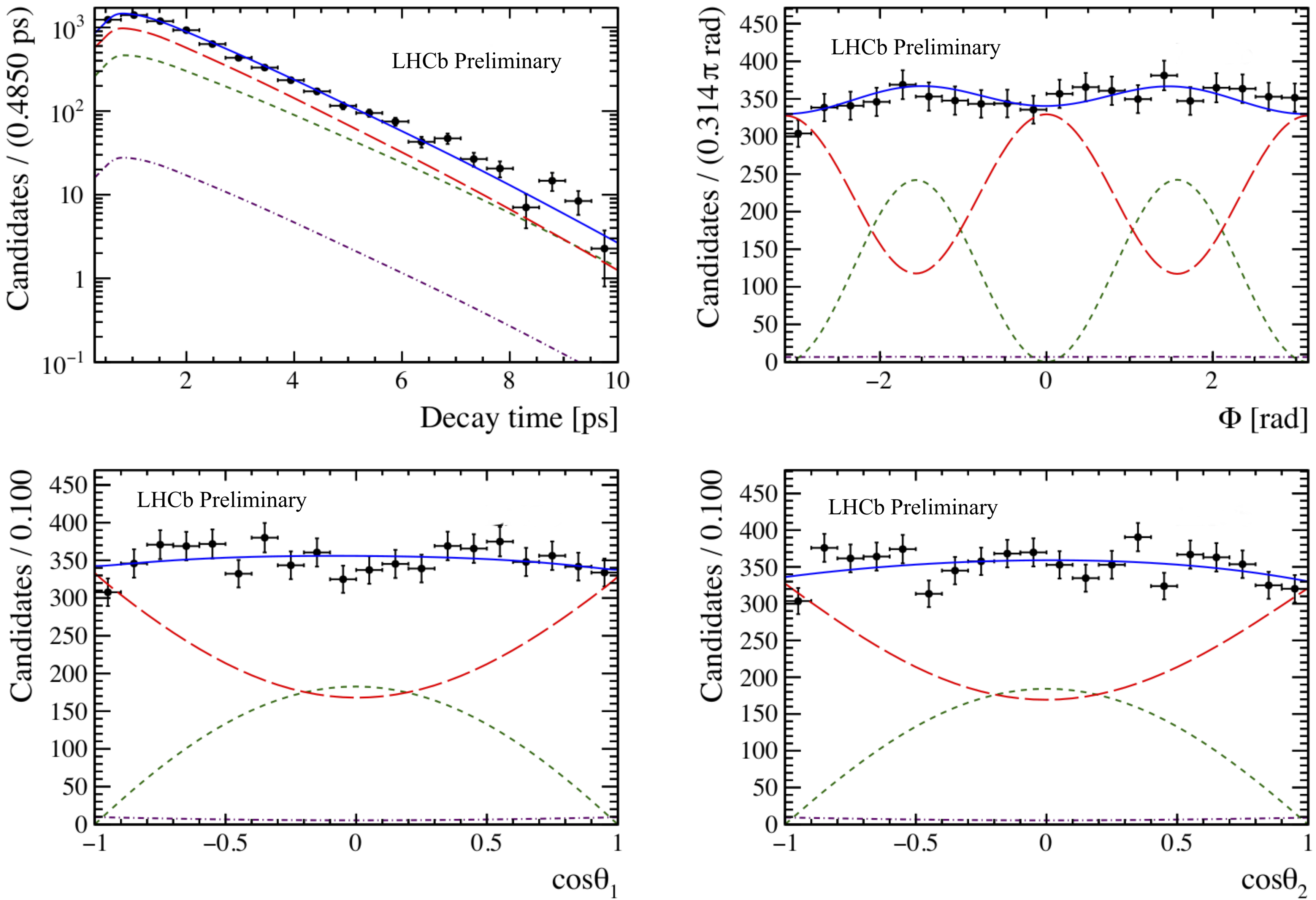
B_s->$\phi\phi$ CPV

See talk of T. Schmelzer

$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13\,(\text{stat}) \pm 0.03\,(\text{syst})\ \text{rad}$$

$$|\lambda| = 1.02 \pm 0.05\,(\text{stat}) \pm 0.03\,(\text{syst})\,.$$

$$\begin{aligned}
|A_0|^2 &= 0.382 \pm 0.008\,(\text{stat}) \pm 0.011\,(\text{syst})\,,\\
|A_\perp|^2 &= 0.287 \pm 0.008\,(\text{stat}) \pm 0.005\,(\text{syst})\,,\\
\delta_\perp &= 2.81 \pm 0.21\,(\text{stat}) \pm 0.10\,(\text{syst})\ \text{rad}\\
\delta_\parallel &= 2.52 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})\ \text{rad}
\end{aligned}$$



CP-even P-wave

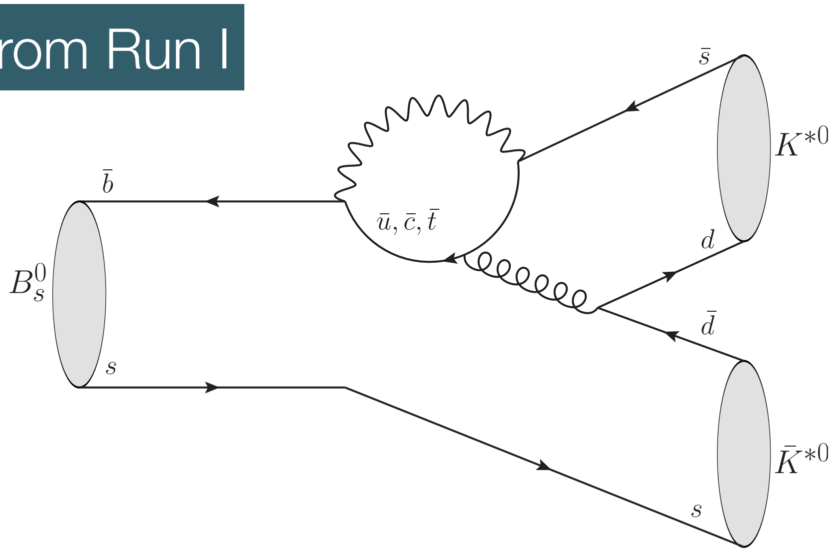
CP-odd P-wave

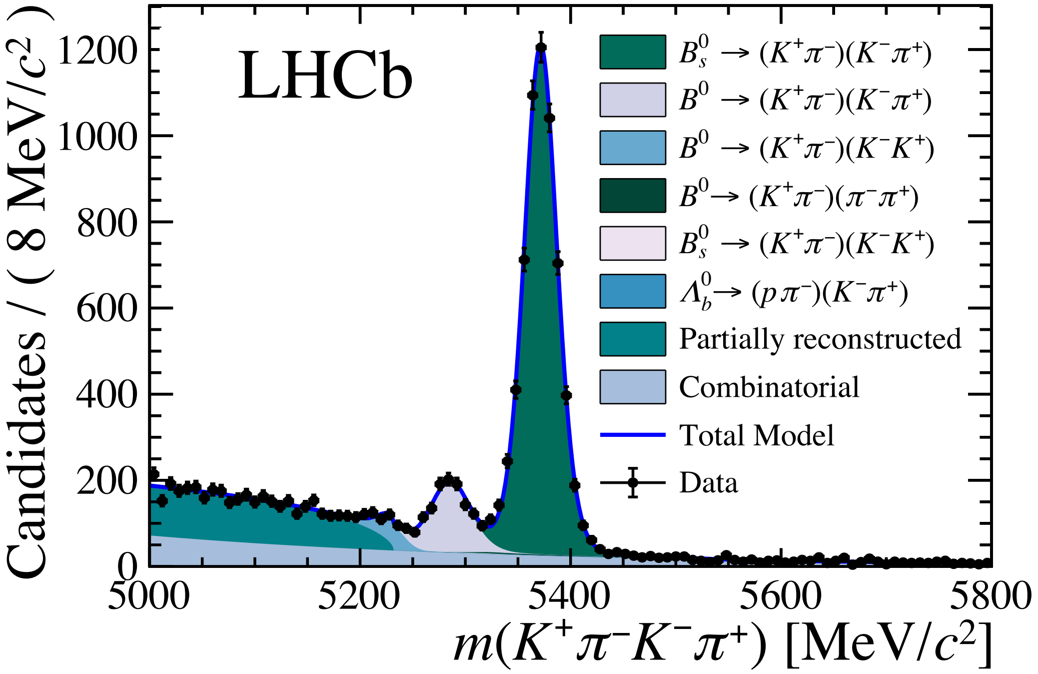
S-wave

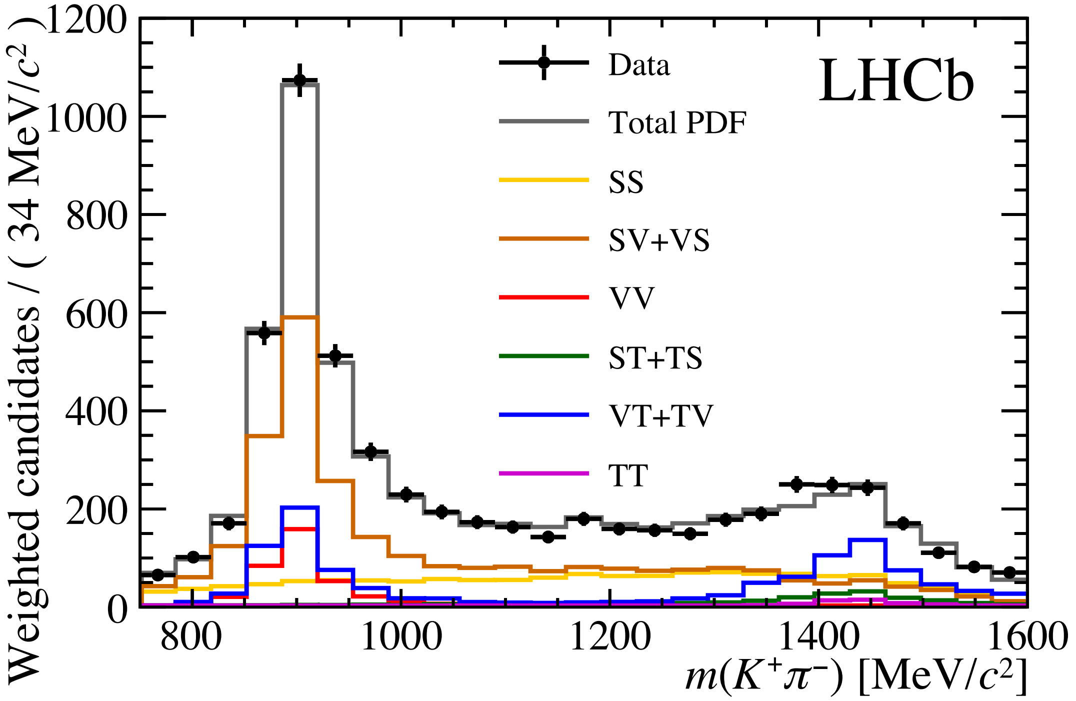
B_s -> KπKπ - pure penguins

3fb^{-1} from Run I

JHEP 03 (2018) 140





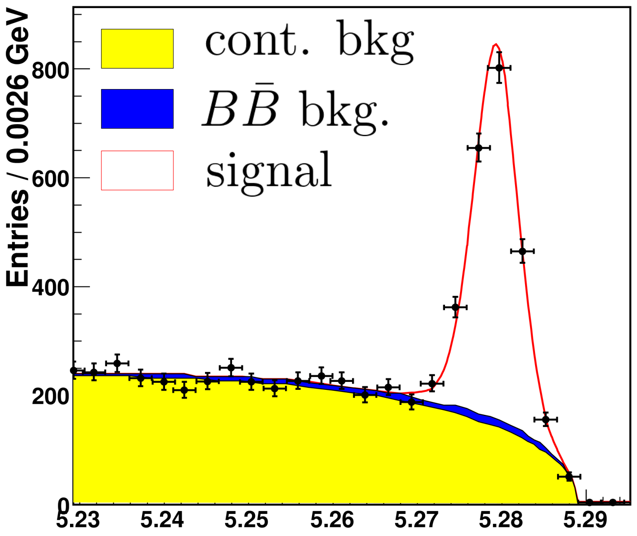


$$
\begin{array}{c|l}
\phi_s^{d\bar{d}}\ [\mathrm{rad}] & -0.10 \quad \pm 0.13 \quad \pm 0.14 \\
|\lambda| & \quad 1.035 \pm 0.034 \pm 0.089
\end{array}
$$

Very complex analyses, Run II updates will shed more light

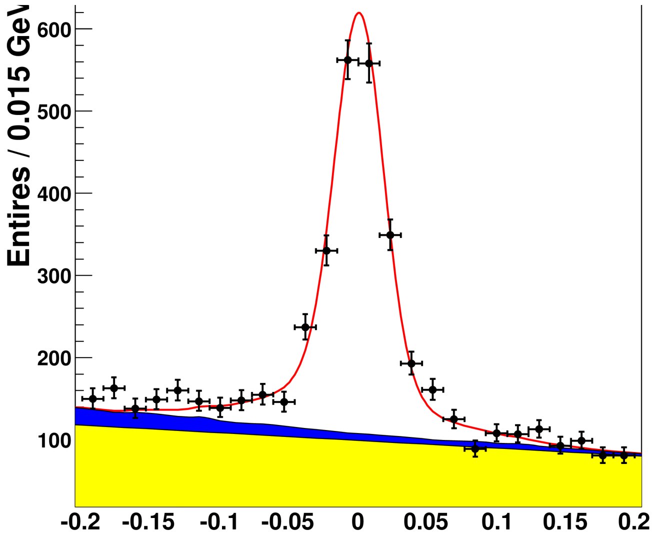
Background rejection at the B factories

Extra variables available from an electron-positron collider - well known collision energy



Beam constraint mass:

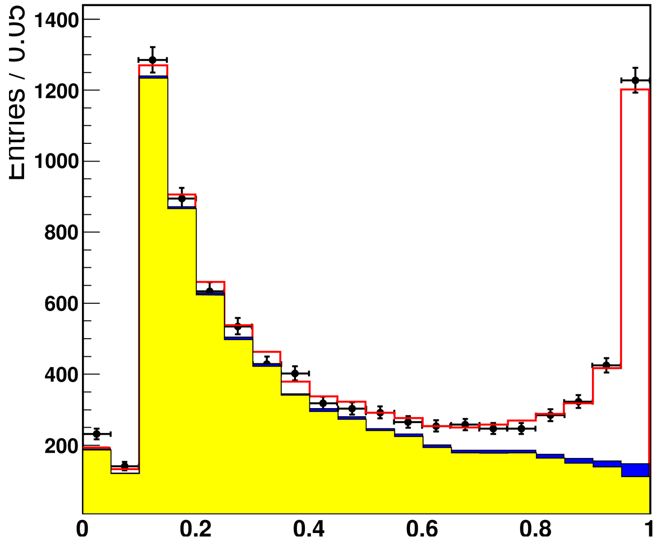
$$M_{bc} = \sqrt{(E_{beam}/2)^2 - p_{rec}^2}$$



Eenergy difference:

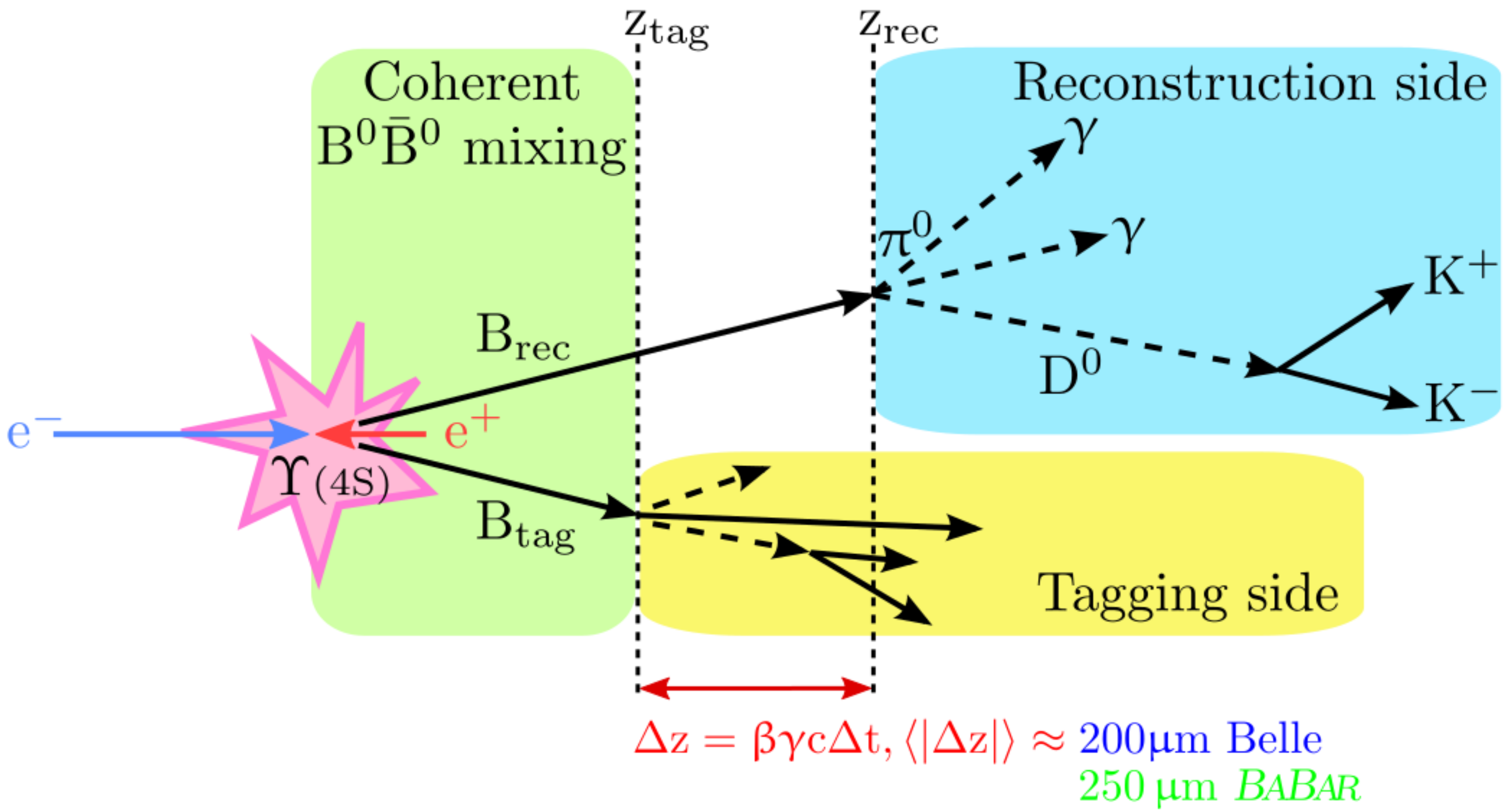
$$\Delta E = E_{rec}^{CM} - E_{beam}/2$$

Fox-Wolfram moments: $\Sigma|p_i||p_j|P(\cos(\theta_{ij}))$ used to separate qq topologies from BB



qq suppression (Likelihood)

Time dependent measurements at the B factories



General time dependent form then becomes:

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 + q\,[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]\}$$

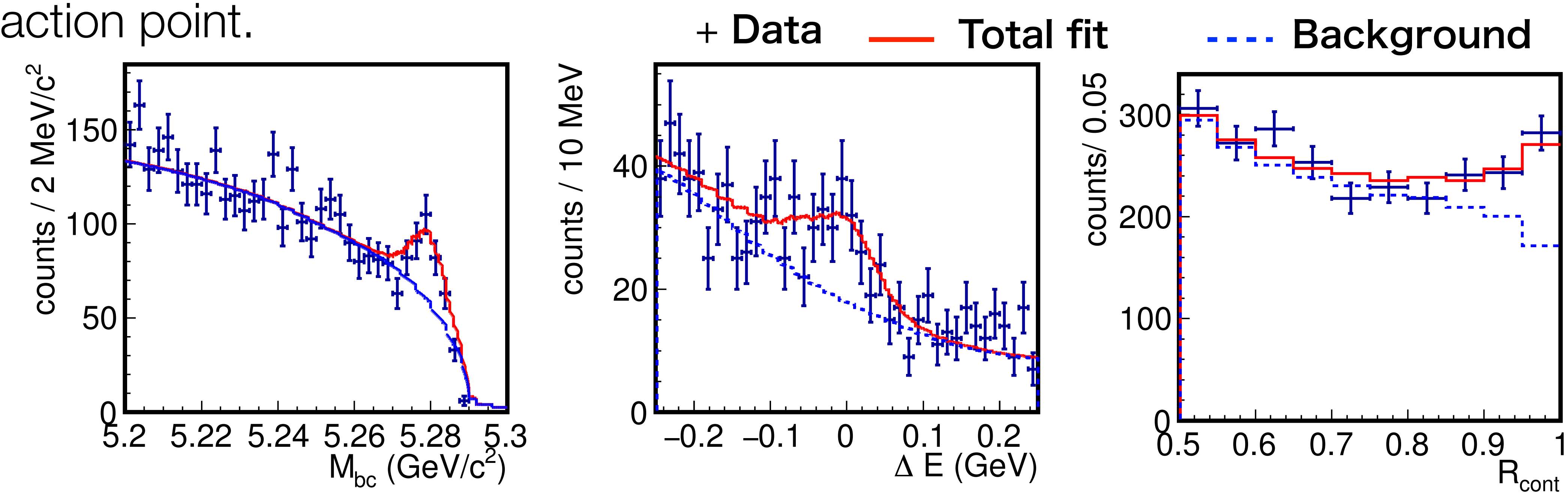
$\phi_1^{\rm eff}$ measurement using B->$\pi^0\pi^0K_S$

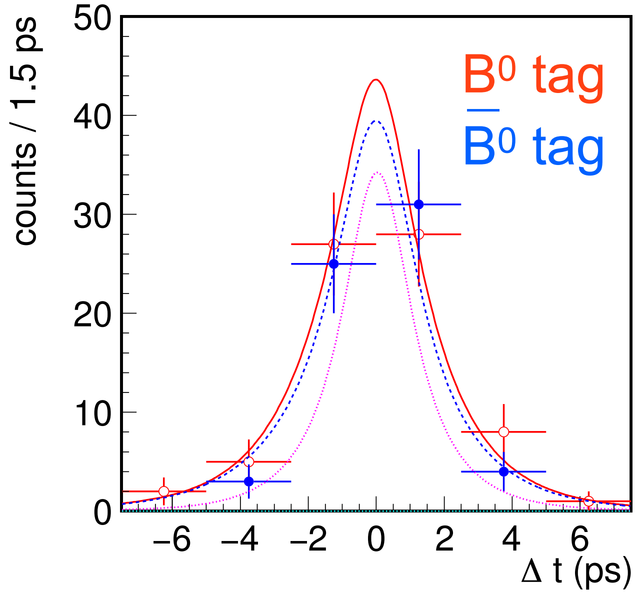
Preliminary - arXiv will appear soon

K_S decays a point apart from the B decay vertex and π^0 is reconstructed from the photon hit in the ECL

-> Reconstruct signal side vertex using flight direction of K^0 with constraint of e^+e^- interaction point.

147 signal candidates





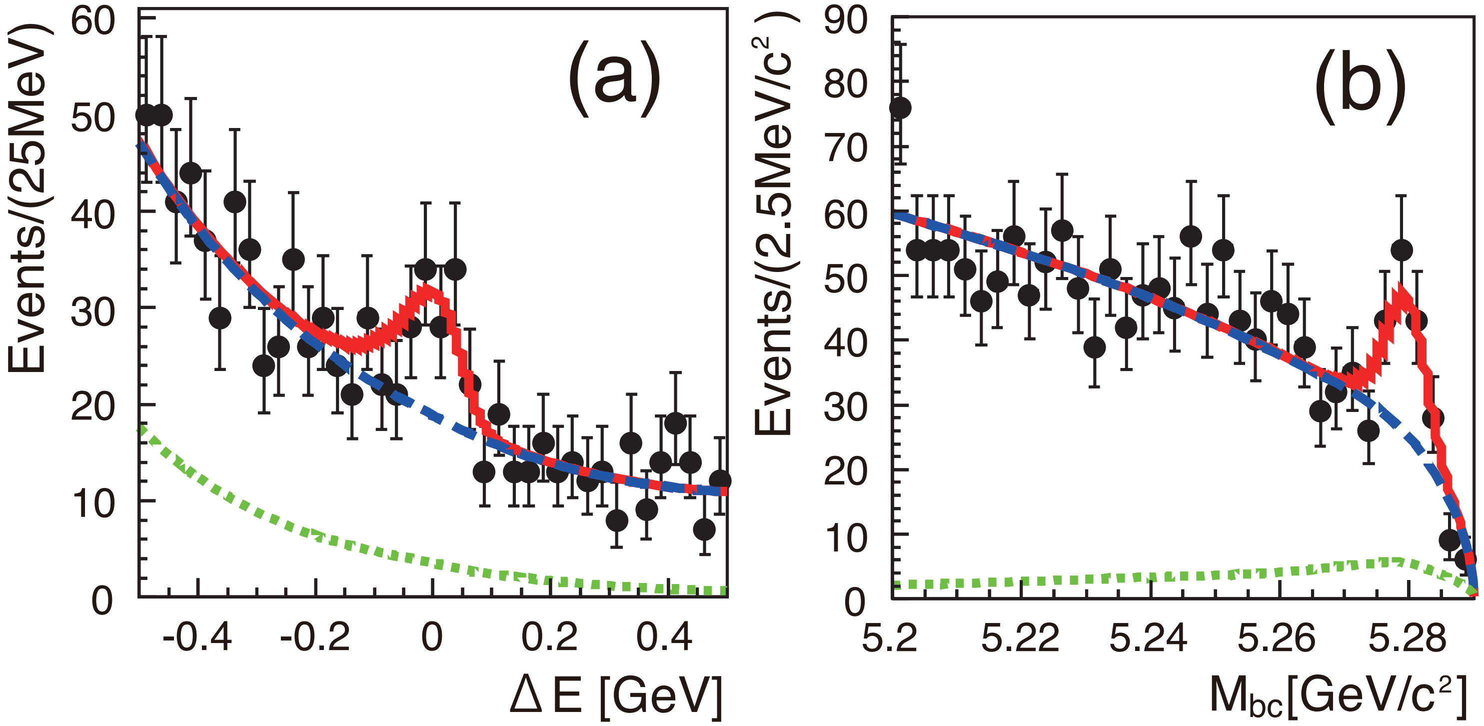
$$\sin 2\phi_1^{\rm eff} = 0.92^{+0.27}_{-0.31}\ ({\rm stat.})\ ^{+0.10}_{-0.11}\ ({\rm syst.})$$

$$\mathcal{A} = 0.28 \pm 0.21\ ({\rm stat.})\ \pm 0.04\ ({\rm syst.})$$

TD CPV in B->KSηγ

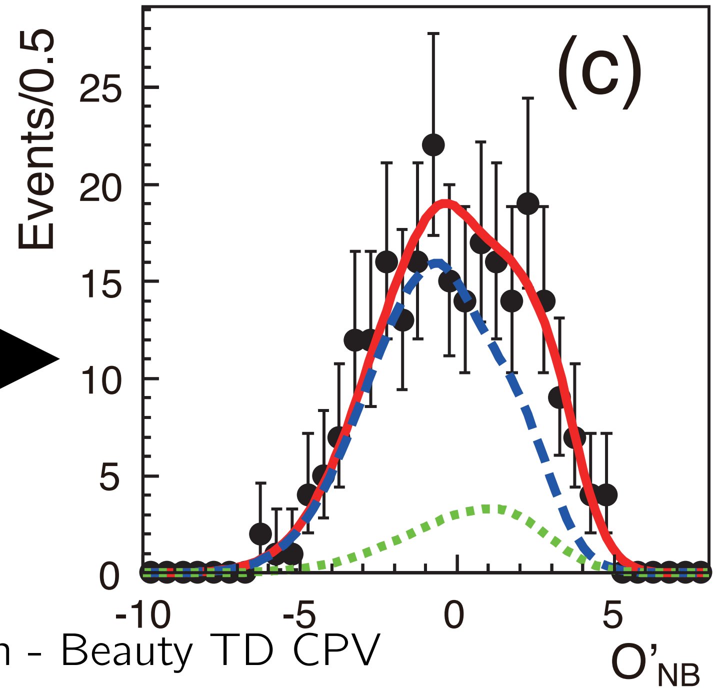
Phys.Rev. D97 (2018) no.9, 092003

Total of ~90 signal events (combining 2 decay modes of the η)



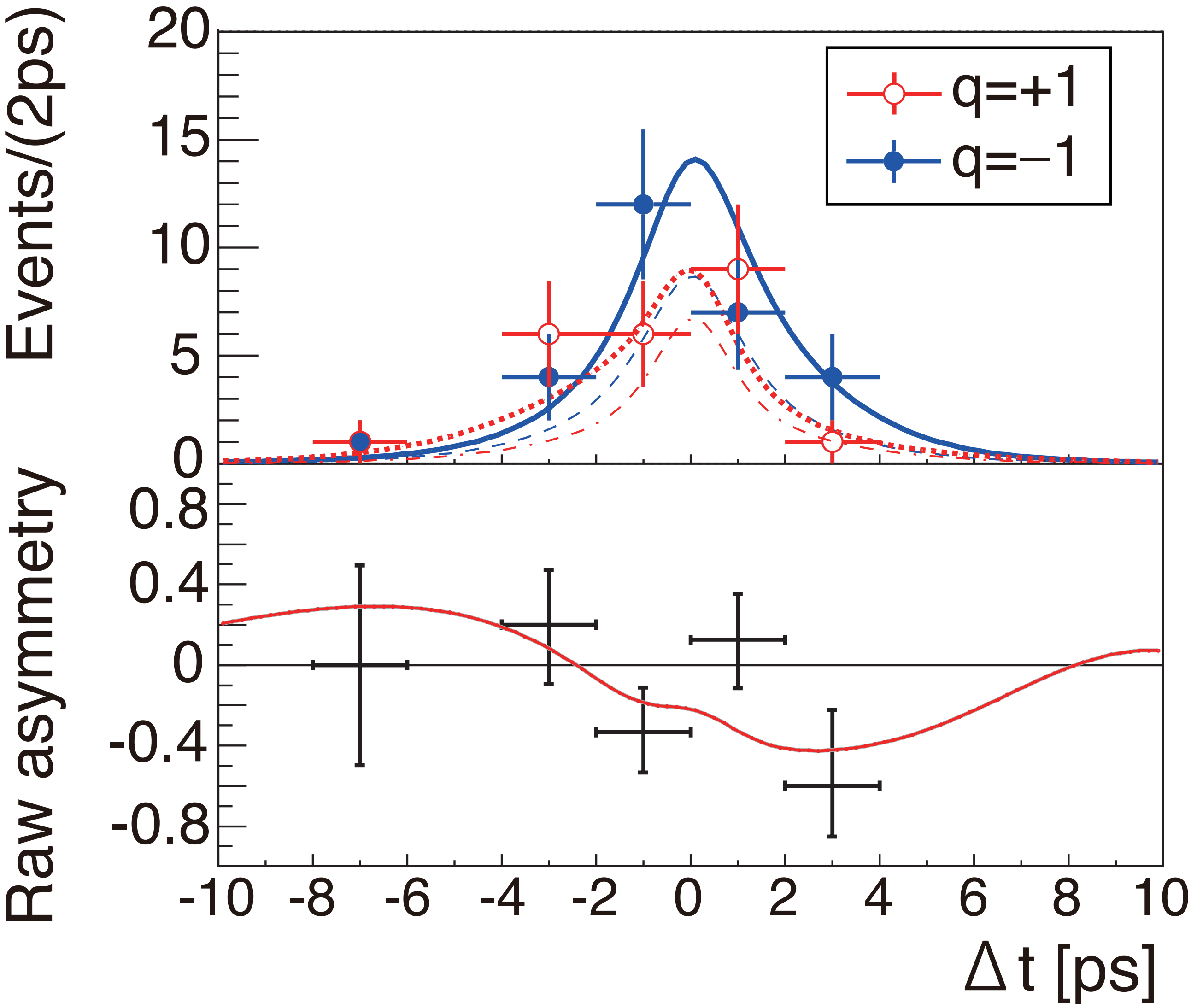
Transformed output of neural network:

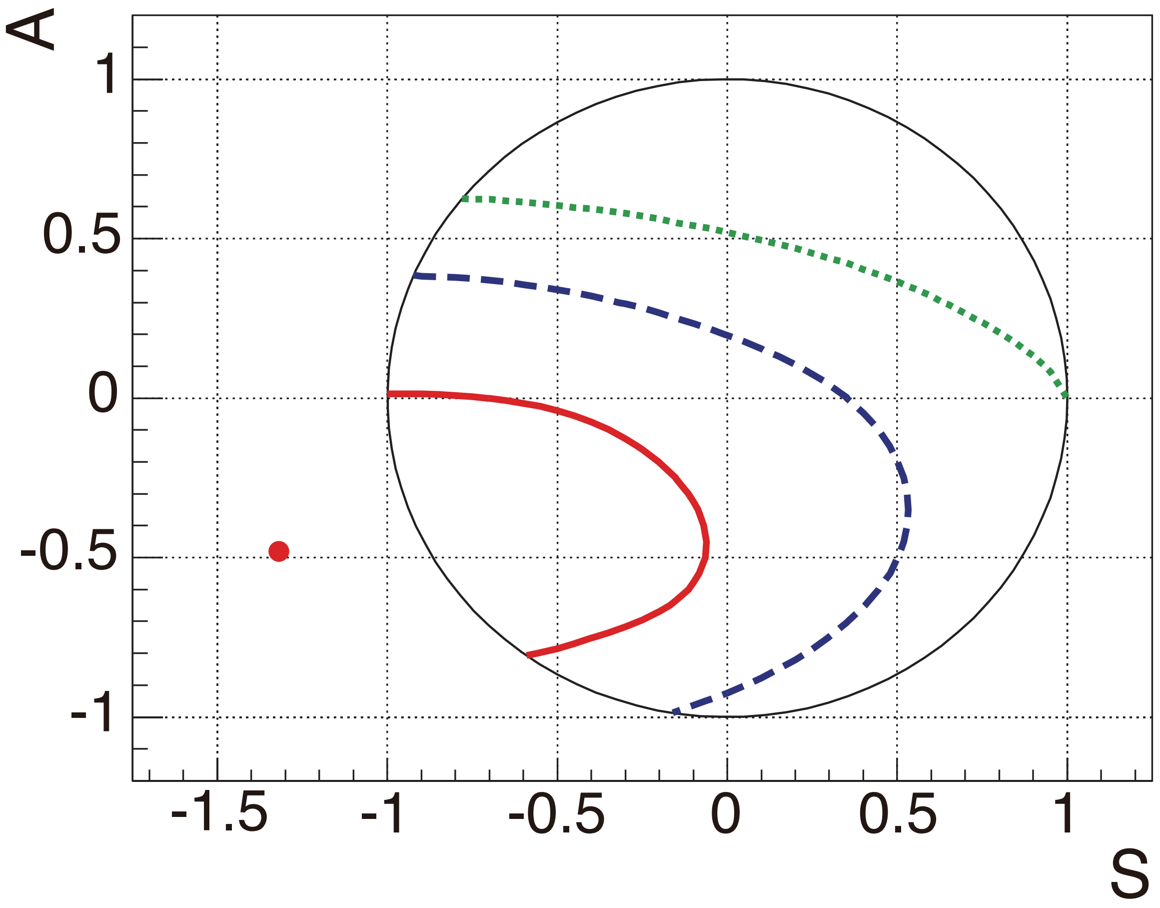
- Trained on MC
- Uses:
  - qq suppression (see earlier)
  - B momentum
  - Angles wrt sphericity axes



$$\mathcal{O}'_{\rm NB} = \ln \frac{\mathcal{O}_{\rm NB} - \mathcal{O}^{\rm min}_{\rm NB}}{\mathcal{O}^{\rm max}_{\rm NB} - \mathcal{O}_{\rm NB}}$$

TD CPV in B->$K_S\eta\gamma$



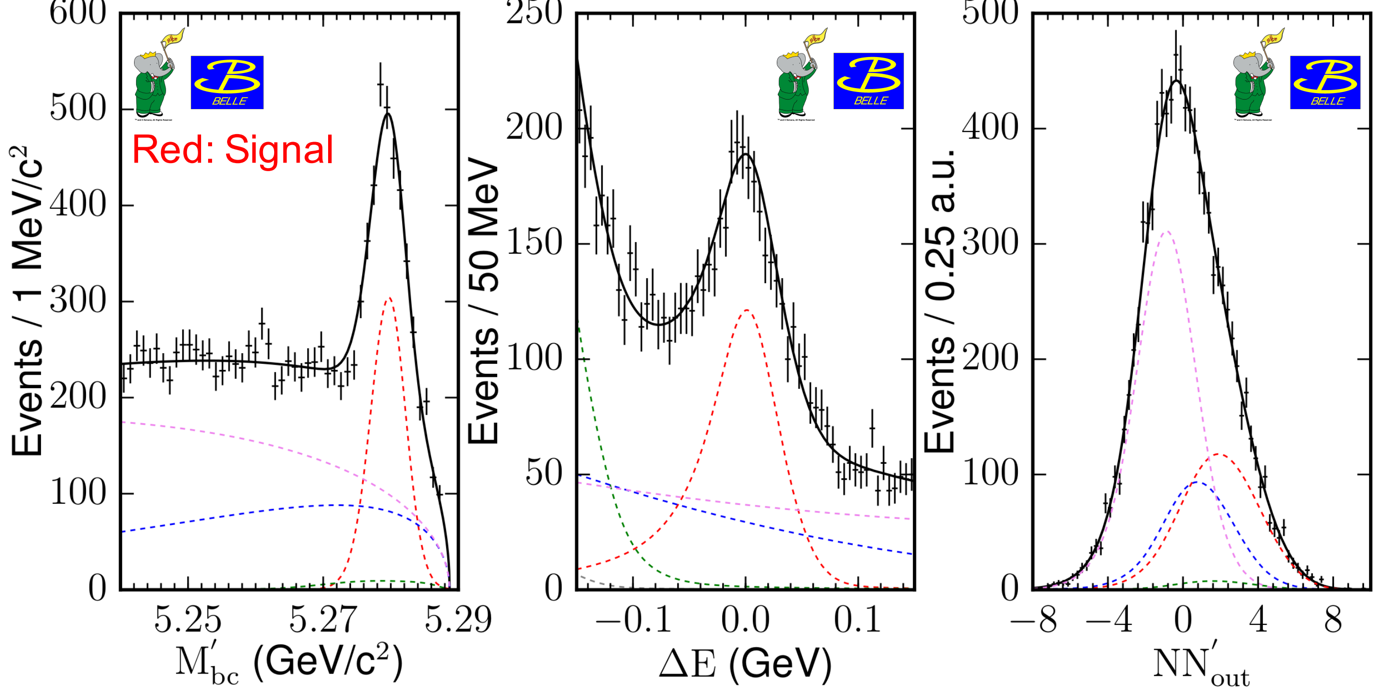


$$\mathcal{S} = -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.}),$$
$$\mathcal{A} = -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})$$

cos(2β) measurement using B->D$^{(*)}$h^0

arXiv:1804.06152, arXiv:1804.06153

Extract signal by 3D fit of beam-constrained mass M'bc, energy-difference ΔE, and NN'out.



BABAR:
1129 ± 48 signal events

Belle:
1567 ± 56 signal events

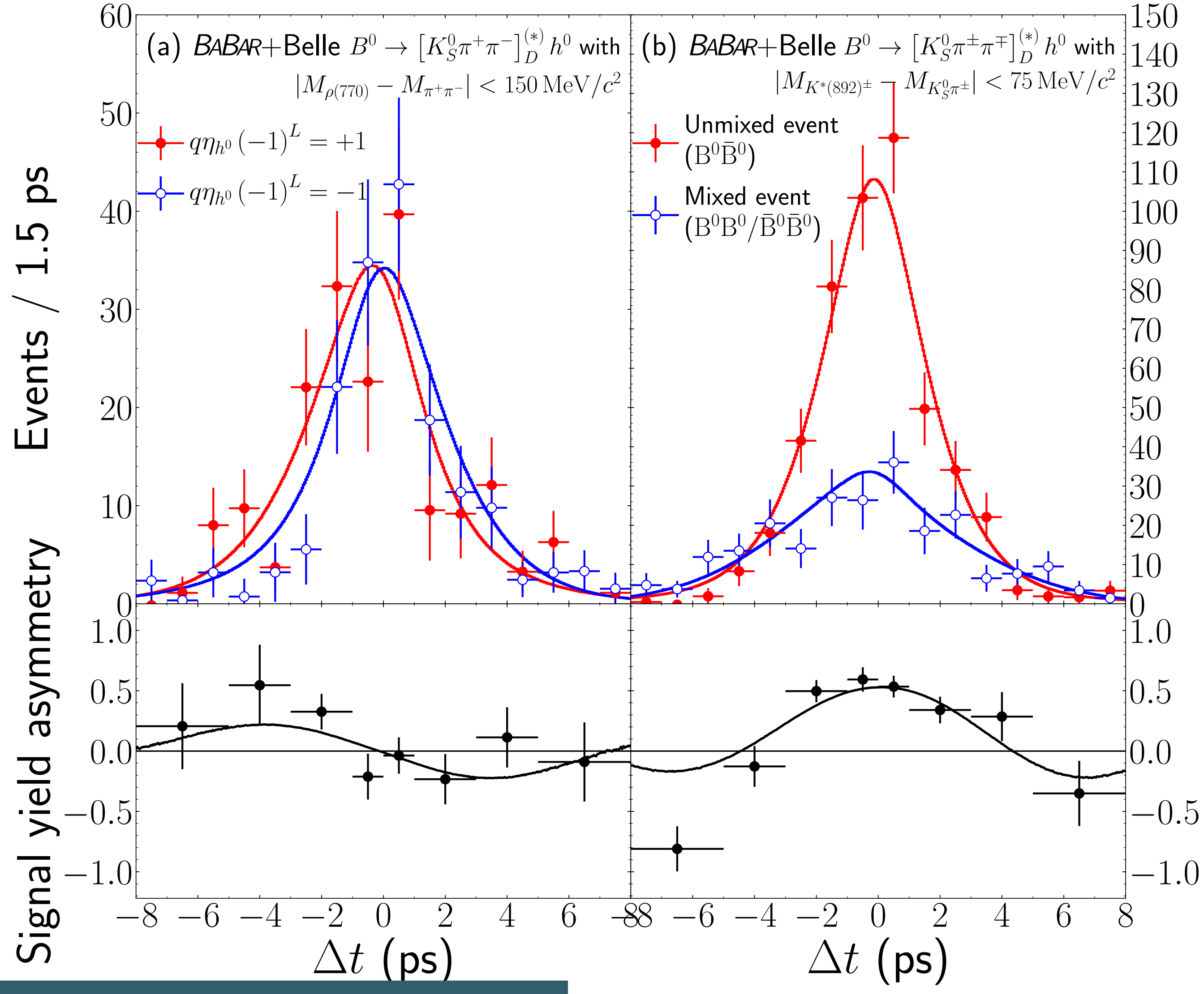
Perform measurement by maximising the combined log-likelihood function
Physics PDFs are convoluted with specific resolution functions:
Apply BaBar and Belle specific resolution models and flavour tagging algorithms

$$
\begin{aligned}
\mathrm{P}_{\mathrm{sig}}(\Delta \mathrm{t}) \propto & \left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2\right] \\
& \mp \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2\right) \cos(\Delta m \Delta t) \\
& \pm 2\eta_{h^0} \left(-1\right)^L \left[\mathrm{Im}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\cos(2\beta) - \mathrm{Re}\left(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0}\right)\sin(2\beta)\right]\sin(\Delta m \Delta t)
\end{aligned}
$$

common signal model

cos(2β) measurement using B->D$^{(*)}$h^0

CP eigenstate final states



Flavour specific final states

BaBar + Belle 1.1ab^{-1}

First evidence that cos(2β)>0 (3.7σ)

$$\sin(2\beta) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$

$$\cos(2\beta) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$

$$\beta = (22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model}))^\circ$$

Prospects for the future

All LHCb results presented here can be updated with more Run 2 data

Mode	Presented σ	Projected σ end Run 2
$B_s \to J/\psi\varphi$	0.05 rad	0.03 rad
$B_s \to \varphi\varphi$	0.13 rad	0.10 rad
$B_s \to K^*K^*$	0.11 rad	0.07 rad
$B_s \to KK$	0.06	0.04

And after this the future gets even brighter…

The LHCb Upgrade

See talk of T. Szumlak

The LHCb Upgrade

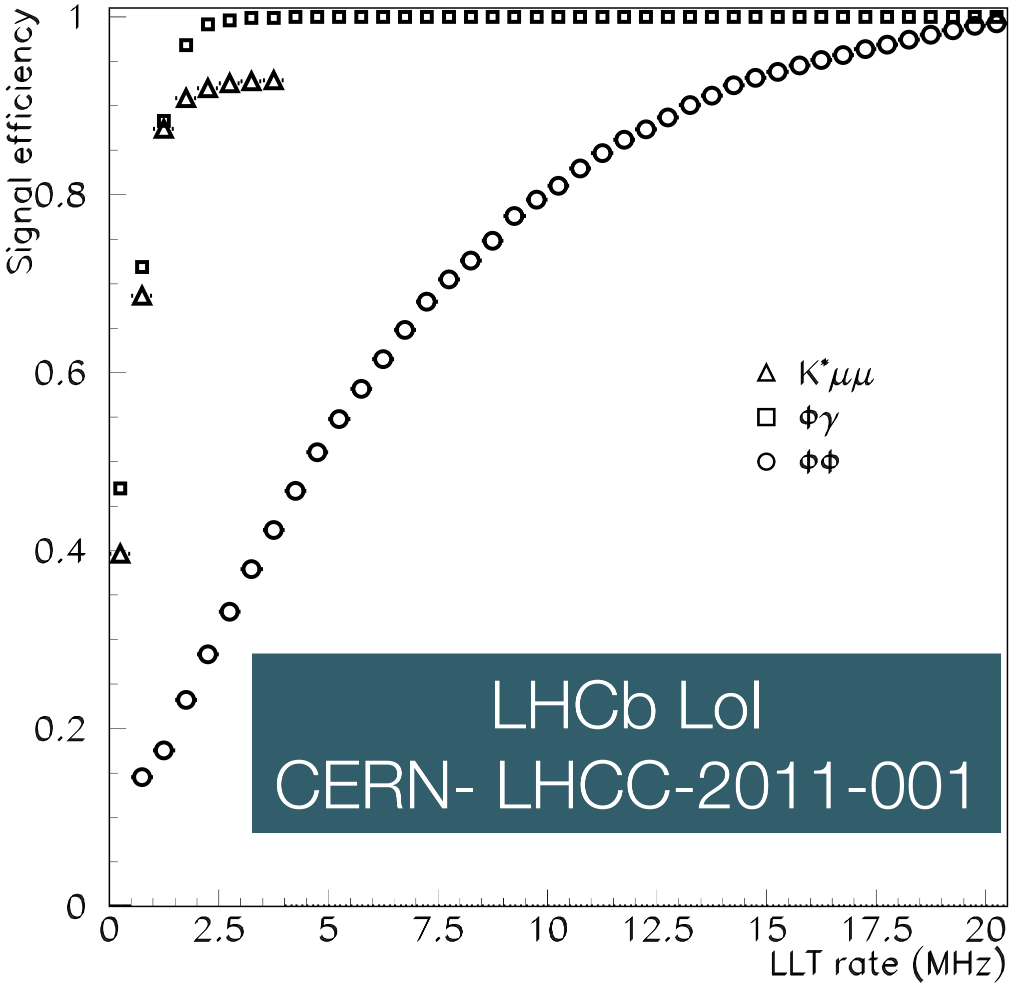
1) Full software trigger

- Allows effective operation at higher luminosity
- Improved efficiency in hadronic modes

2) Raise operational luminosity to 2 x 10^{33} cm^{-2} s^{-1}

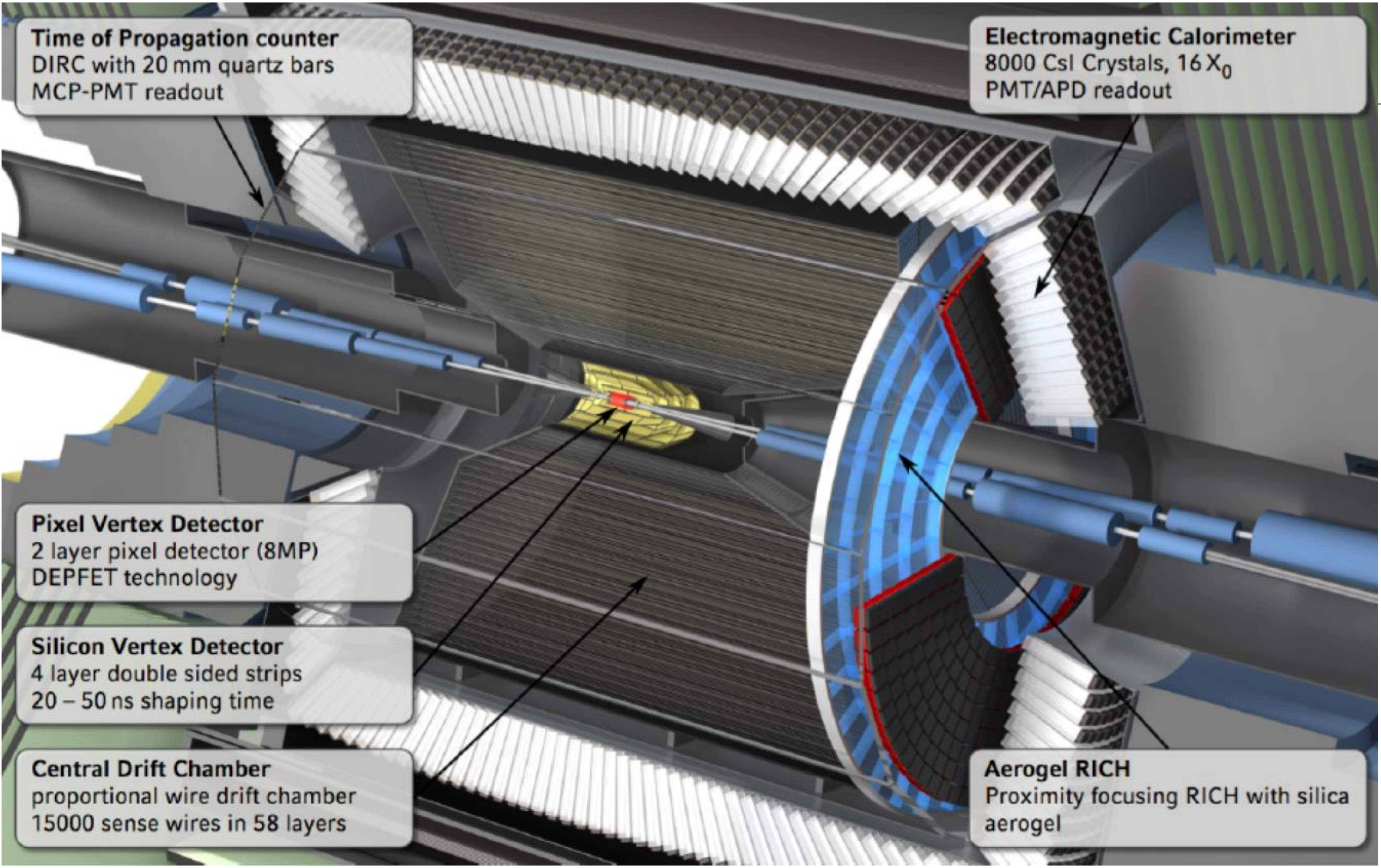
- Necessitates redesign of several sub-detectors
- overhaul of readout

Upgrade + run 2 yield in hadronic modes ~ 60x that of run 1



LHCb LoI
CERN- LHCC-2011-001

Belle II



Time of Propagation counter
DIRC with 20 mm quartz bars
MCP-PMT readout

Electromagnetic Calorimeter
8000 CsI Crystals, 16 X_0
PMT/APD readout

Pixel Vertex Detector
2 layer pixel detector (8MP)
DEPFET technology

Silicon Vertex Detector
4 layer double sided strips
20 – 50 ns shaping time

Central Drift Chamber
proportional wire drift chamber
15000 sense wires in 58 layers

Aerogel RICH
Proximity focusing RICH with silica aerogel

Improvements wrt Belle I: K_S/π^0 efficiency, IP and vertex efficiency, K/π separation, Hadron & muon ID in endcaps

Future physics improvements

Key take-away facts:

Belle II:

~50x more than BaBar + Belle, plus benefit from several detector improvements.

LHCb Upgrade (+ run 2):

~60x more than LHCb run 1 in hadronic modes ~30x more than LHCb run 1 in muonic modes,

where the difference is driven by the use of a full software trigger. Order of magnitude improvement in precision expected

Summary

- I have been privileged to give a review of TD CPV in B decays on behalf of LHCb, BaBar, and Belle.

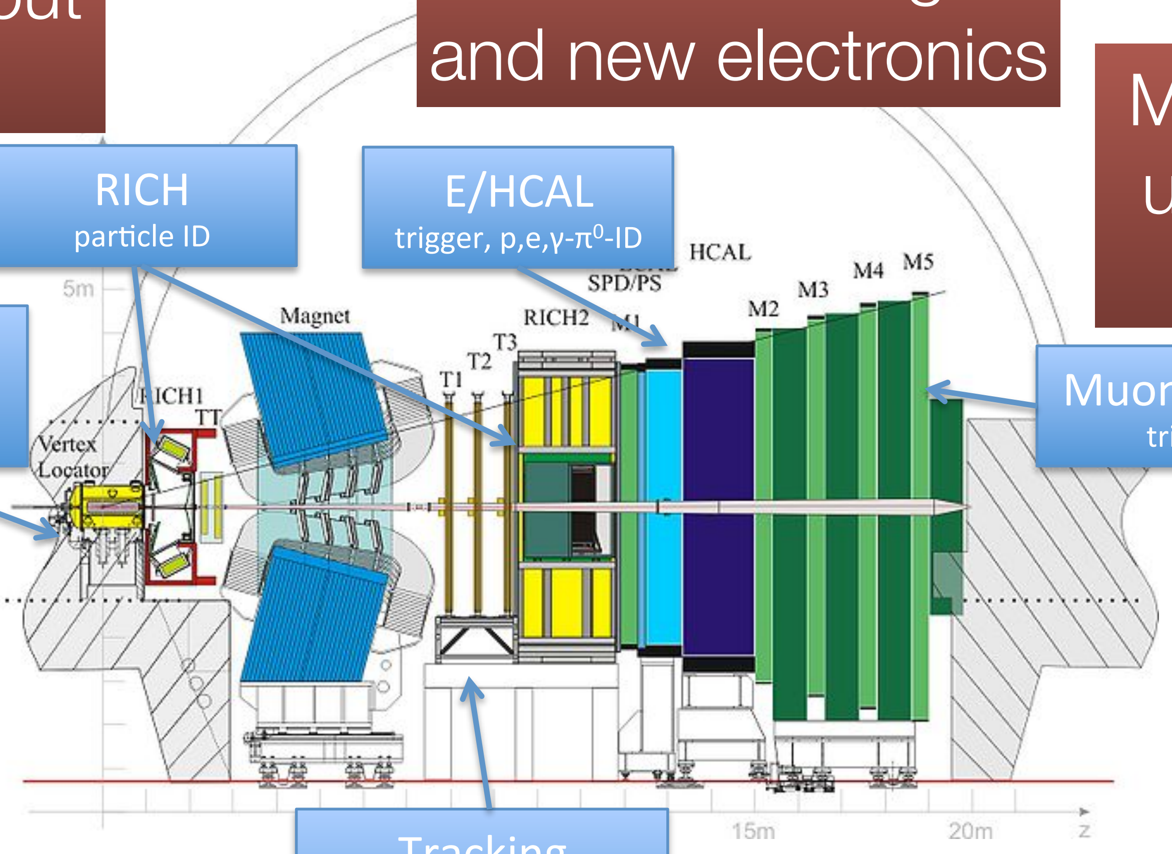
- TD CPV in B decays is important as it places strong constraints on BSM models describing, in addition to potentially revealing BSM physics when going to high precision.

- Results shown at this conference demonstrate we are on the way there.
  - Indeed the new analyses with BaBar and Belle datasets show the immense value of such data.

- Upgrades of experiments will prove very valuable.

Backup

The LHCb Upgrade



New PMTs & readout electronics

Reduced PMT gain and new electronics

More shielding and upgraded readout electronics

RICH
particle ID

E/HCAL
trigger, p,e,γ-π^0-ID

VELO
primary and secondary vertices

Muon chambers
trigger, μ-ID

New pixel VELO detector

Tracking stations
momentum resolution

New stations based on SciFi technology

will take data at luminosity of $2\mathrm{x}10^{33}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
although LHCb currently runs at 2x the design luminosity anyway…

Why a B factory?

B physics at the Y(4S) presents several advantages over the hadronic environment at the LHC

- Can reconstruct full event, which is beneficial for missing energy modes and also inclusive measurements (lower theory uncertainties).

- Low multiplicity environment permits excellent performance for final states with π^0s, η's, photons. Also, good efficiency for long-lived particles K_S and K_L.

- Coherent B^0B^0bar production at Y(4S) makes flavour tagging easier and compensates for lower sample sizes in time-dependent CP measurements
  - B factories had a x5 better FT power than LHCb

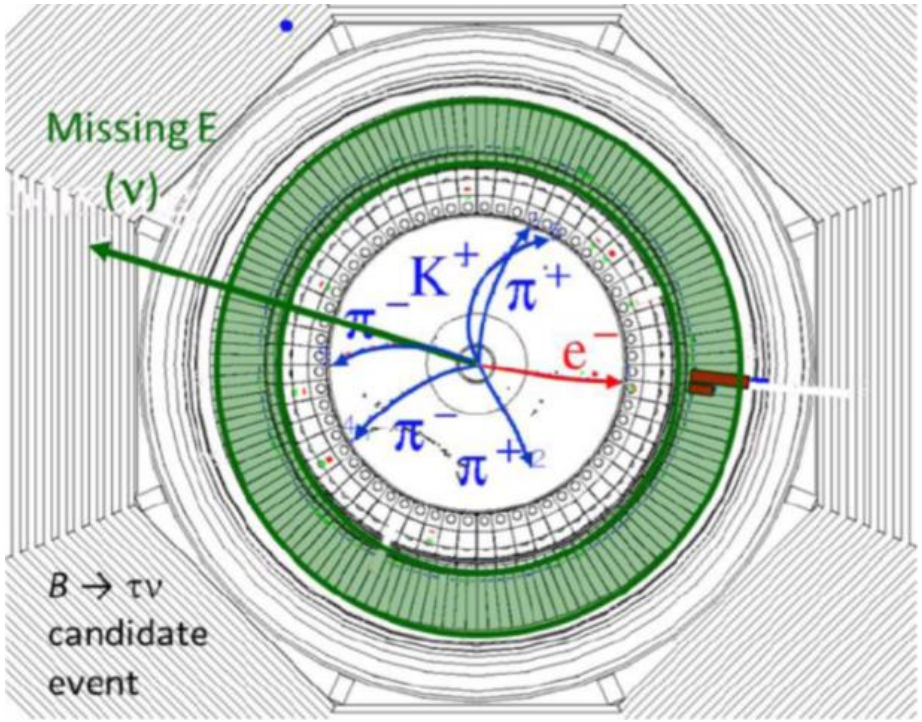
e.g. in sin2β measurement with $B^0 \rightarrow J/\psi K_S$

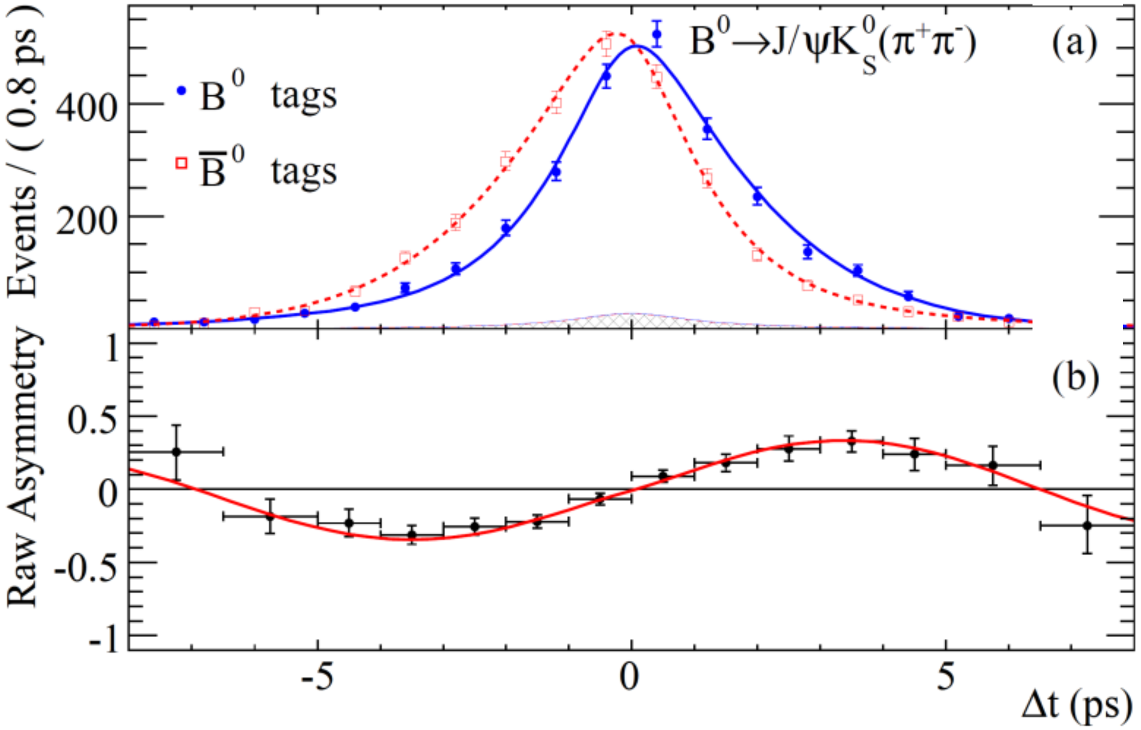
ε (tag effective) BaBar ~ 31 % [PRD 79 (2009) 072009]

ε (tag effective) LHCb ~ 3 % [PRL 115 (2015) 031601]

e.g.

$B \rightarrow \tau\nu$

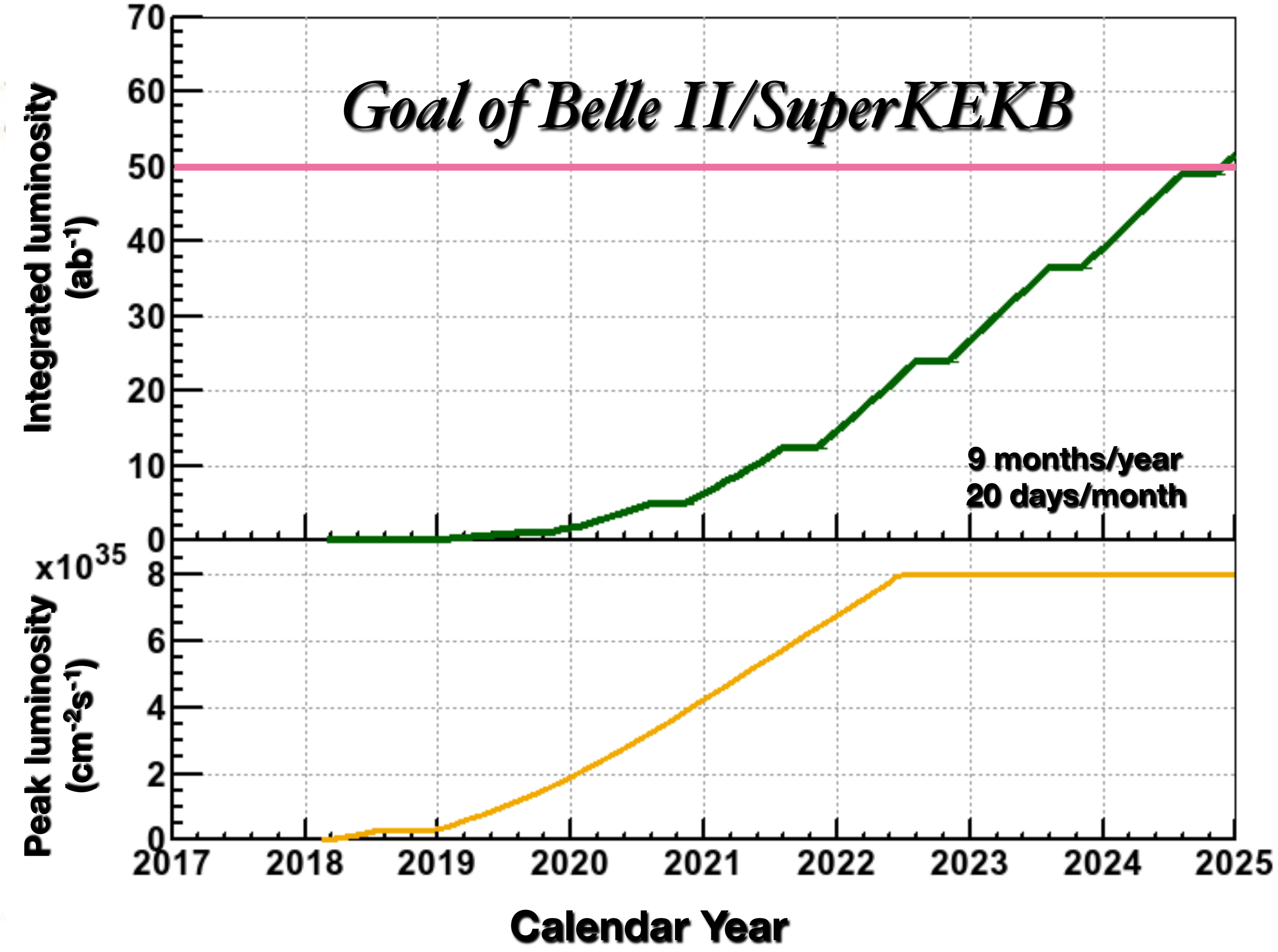


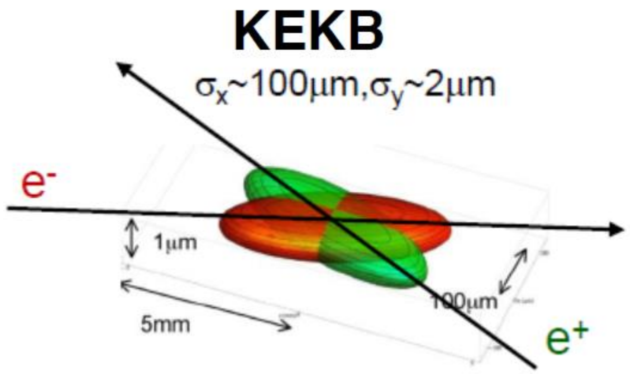


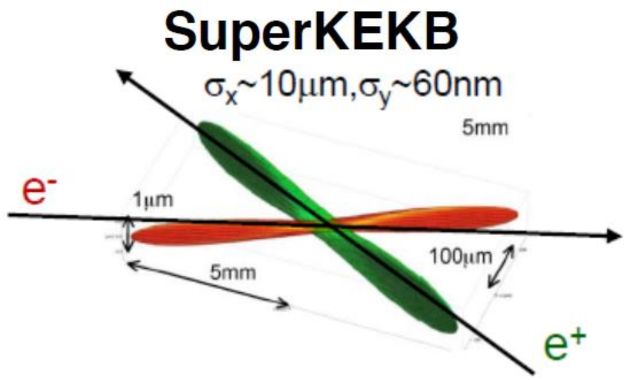
SuperKEKB

Timeline:
Now: beams circulating
2018: First collisions
2019: Target collisions with full detector
2024: luminosity of 8 x 10^{35} $cm^{-2}s^{-1}$ and 50 ab^{-1}

40x increase on KEKB
1/20 beam size
2x beam current



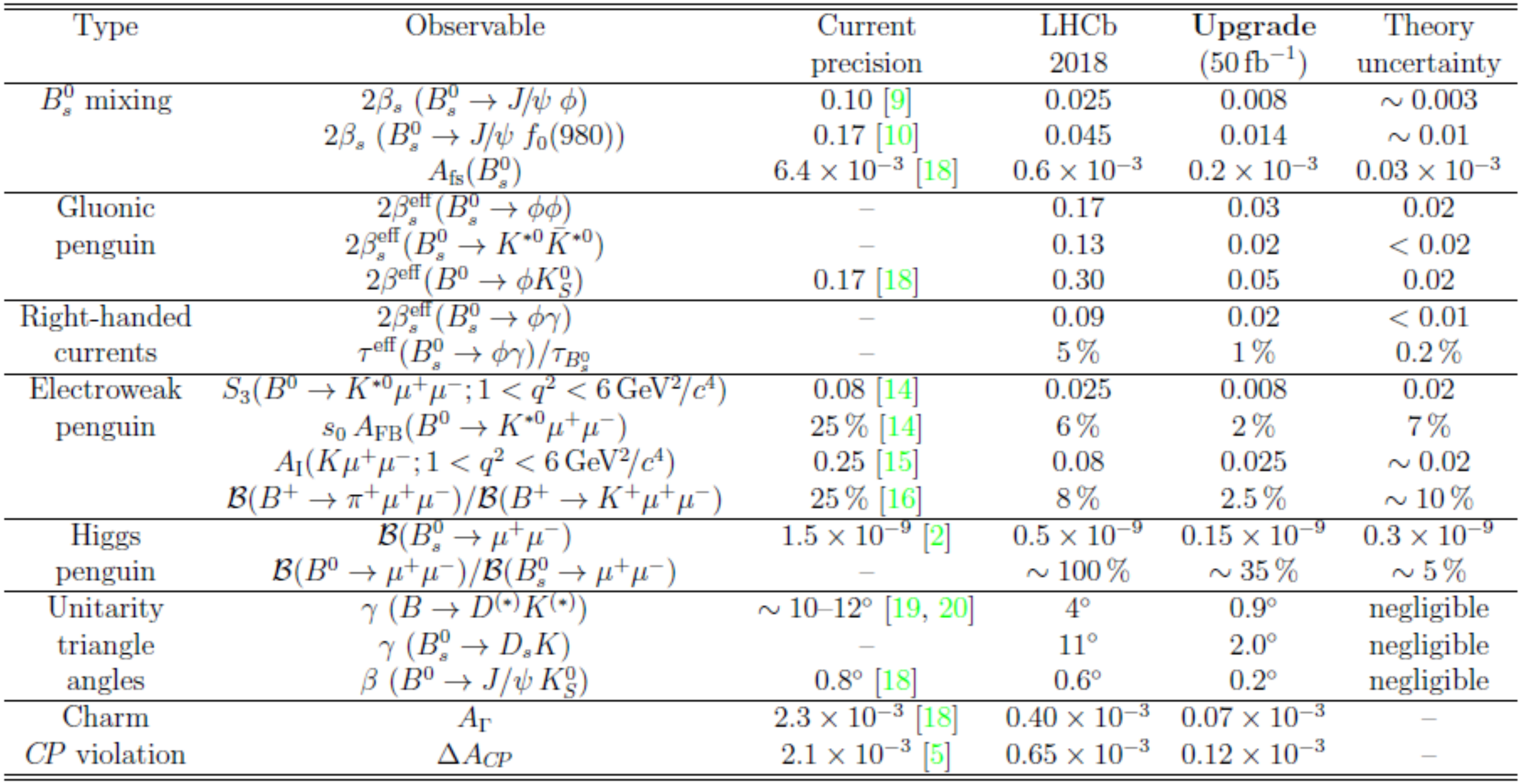




Future physics improvements

Predictions exist for the expected accuracy in the form of the implications workshop document

[‘old’ table from EPJ C 73 (2013) 2373; arXiv:1208.3355.if re-made with current numbers the argument would remain]



Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\,A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	$\sim 10\,\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	$\sim 100\,\%$	$\sim 35\,\%$	$\sim 5\,\%$
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\,K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–