Flavour Physics at B-Factories and LHCb

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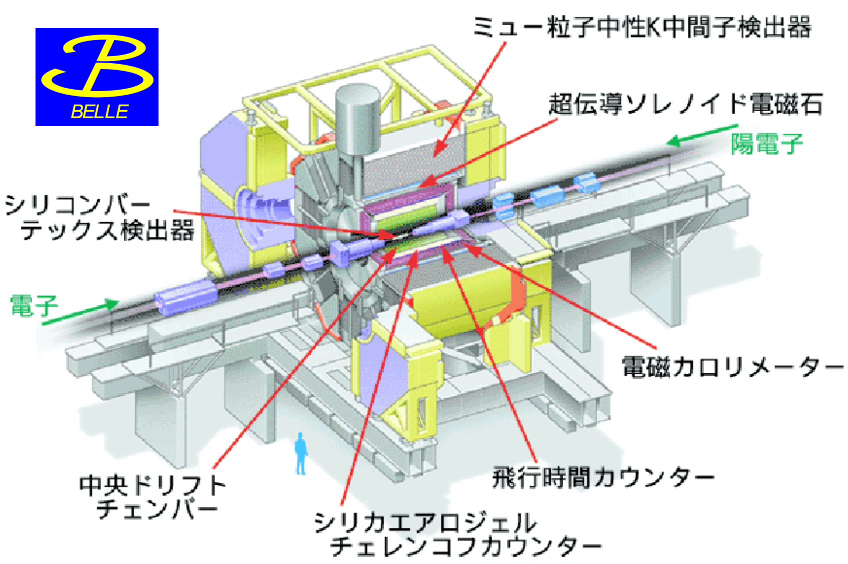
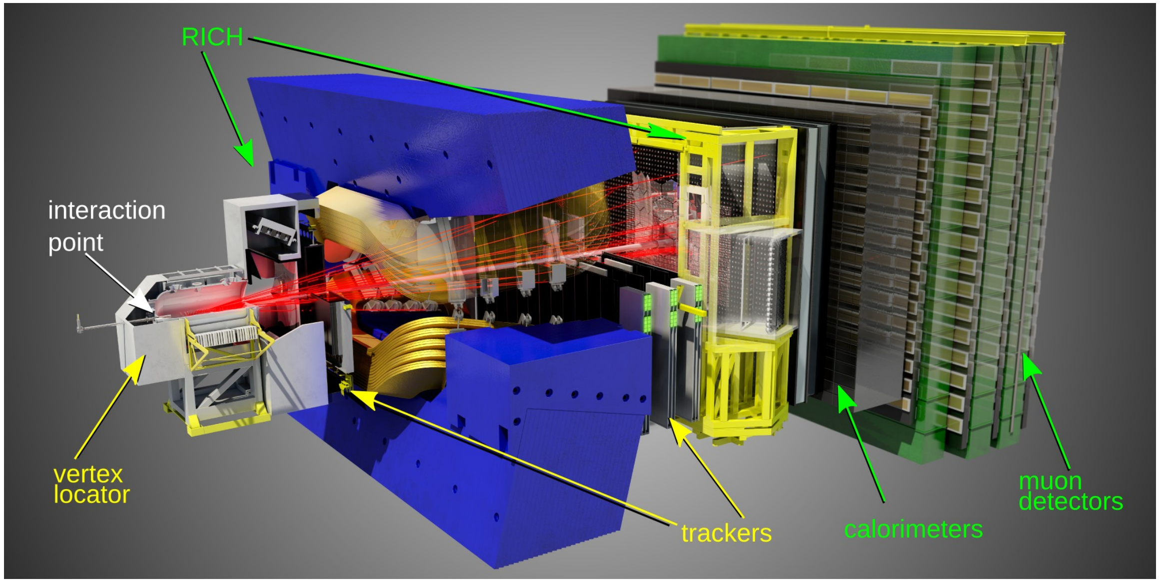




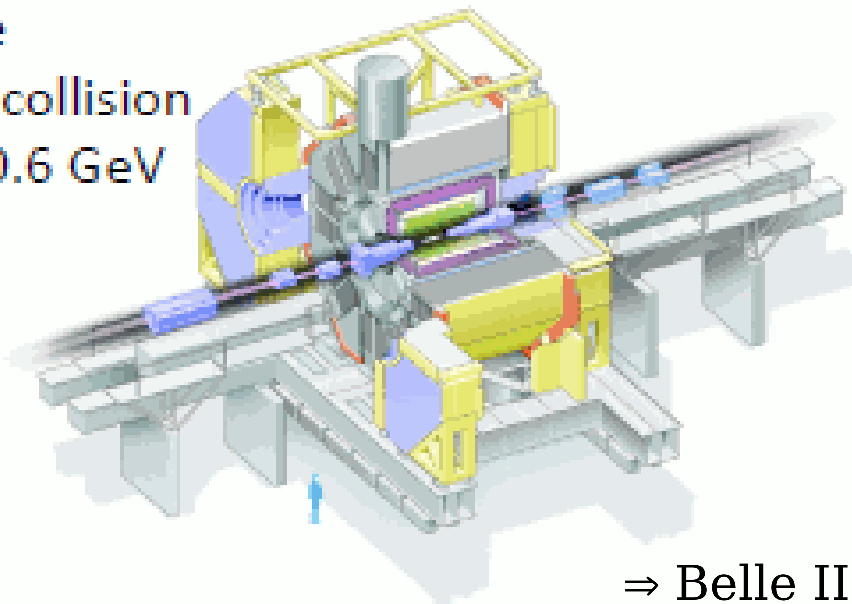
Seoul, May 19th 2016

A rich physics program...

- **Studies of CPV in B and B_s decays**
- **$b \to s$ transitions: probe for new sources of CPV and constraints from the $b \to s\gamma$ observables**
- **Forward-backward asymmetry and other observables in $b \to s l^+ l^-$**
- **Search for the charged Higgs in the rare decays $B \to \tau\nu$, $D^{(*)}\tau\nu$**
- Study of B_s, B_c, Λ_b decays
- Study of D^0-$\overline{D}^0$ mixing
- Search for CPV in D and D_s decays
- Studies of exotic charmonium, tetraquark, pentaquark states
- Studies of new bottomonium-like states
- Search for lepton flavor violation (LFV) in τ decays
- Search for CPV and study of hadronic τ decays
- Light Higgs searches, DM searches...
- ...

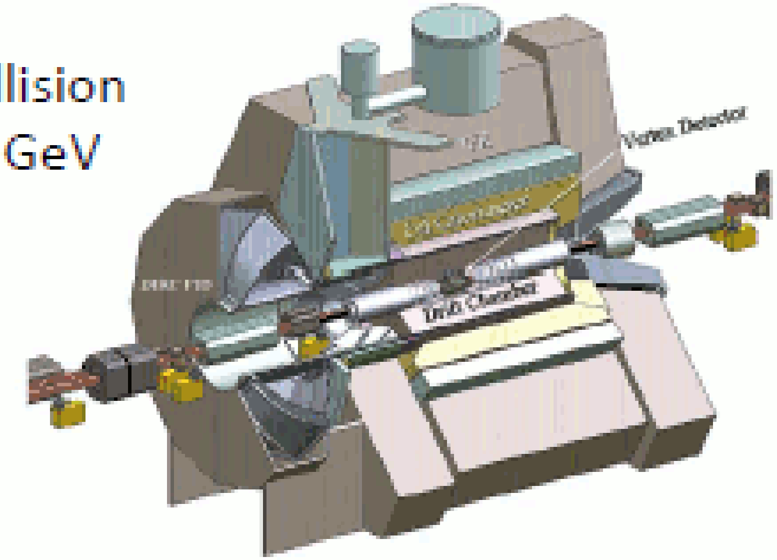
Main actors

Belle
e^+e^- collision
at 10.6 GeV

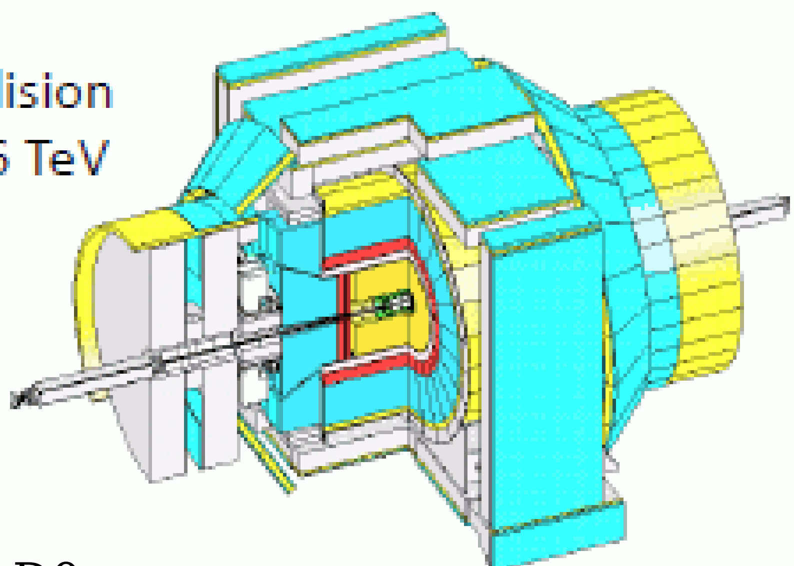


⇒ Belle II

BaBar
e^+e^- collision
at 10.6 GeV

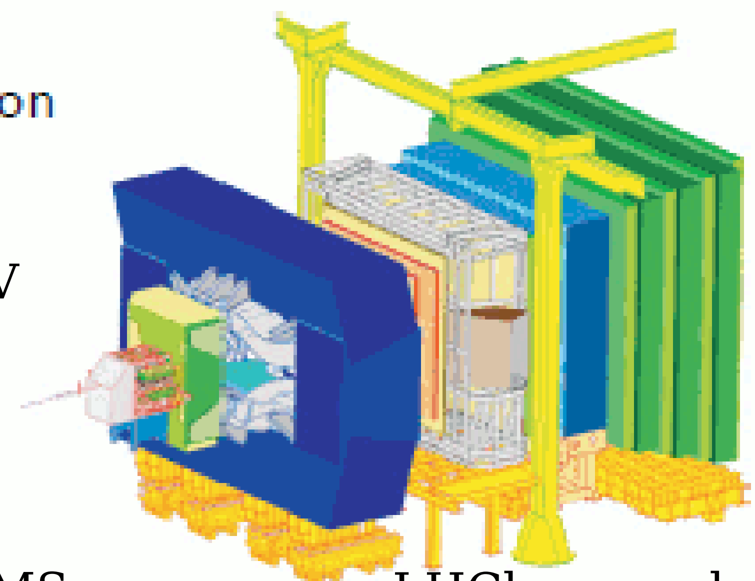


CDF
$p\bar{p}$ collision
at 1.96 TeV



... and D0

LHCb
pp collision
at 7 TeV
8 TeV
14 TeV



... and CMS

⇒ LHCb upgrade

Comparison B-factories/LHCb

B-factories

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow b\bar{b}$

at $\Upsilon(4S)$: 2 B's (B^0 or B^+) and nothing else ⇒ clean events

$\sigma_{b\bar{b}} \sim 1\,\text{nb} \Rightarrow 1\ \text{fb}^{-1}$ produces $10^6\,B\bar{B}$

$\sigma_{b\bar{b}}/\sigma_{total} \sim 1/4$

LHCb

$pp \rightarrow b\bar{b}X$

production of B^+, B^0, B_s, B_c, Λ_b...

but also a lot of other particles in the event

⇒ lower reconstruction efficiencies

$\sigma_{b\bar{b}}$ much higher than at the $\Upsilon(4S)$

	$\sqrt{s}$ [GeV]	$\sigma_{b\bar{b}}$ [nb]	$\sigma_{b\bar{b}}/\sigma_{tot}$
HERA pA	42 GeV	~30	~10^{-6}
Tevatron	2 TeV	5000	~10^{-3}
LHC	8 TeV	~3×10^5	~ 5×10^{-3}
	14 TeV	~6×10^5	~10^{-2}

$b\bar{b}$ production cross-section ~ 5× Tevatron, ~ 500,000 × BaBar/Belle !!

$\sigma_{b\bar{b}}/\sigma_{total}$ much lower than at the $\Upsilon(4S)$

⇒ lower trigger efficiencies

B mesons live relativey long

mean decay length $\beta\gamma c\tau \sim 200\,\mu\text{m}$

mean decay length $\beta\gamma c\tau \sim 7\,\text{mm}$

data taking period(s)

[1999-2010]

[run I: 2010-2012, run II: 2015-2018]

(near) future

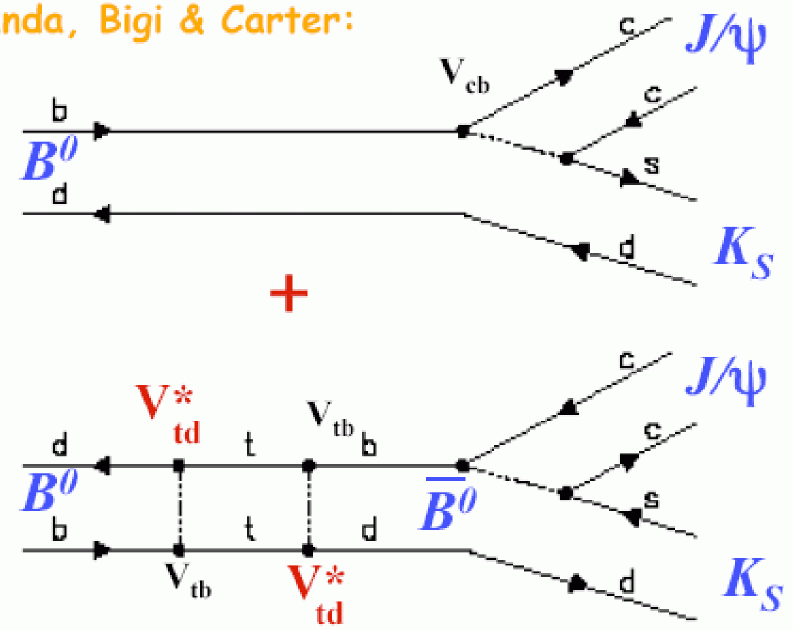
[Belle II from 2018]

[LHCb upgrade from 2020]

Time−dependent CP asymmetries in decays to CP eigenstates

$\sin 2\phi_1$ from $B \to f_{CP} + B \leftrightarrow \overline{B} \to f_{CP}$ interf.

Sanda, Bigi & Carter:



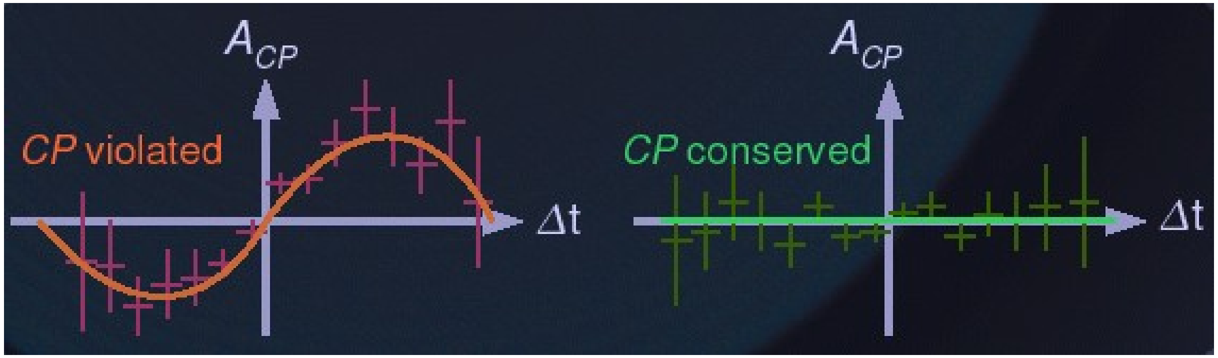
$$A_{CP}(f;t) = \frac{N(\overline{B}^0(t)\to f) - N(B^0(t)\to f)}{N(\overline{B}^0(t)\to f) + N(B^0(t)\to f)}$$

$$= \mathbf{S} \sin\Delta m_d t + \mathbf{A} \cos\Delta m_d t$$

$$= \frac{2\,\mathrm{Im}\,\lambda}{|\lambda|^2+1} \sin\Delta m_d t + \frac{|\lambda|^2-1}{|\lambda|^2+1} \cos\Delta m_d t$$

$$\lambda = \frac{q}{p}\,\frac{A(\overline{B}^0\to f)}{A(B^0\to f)} = e^{-i2\phi_i}\frac{\overline{A}_f}{A_f}$$

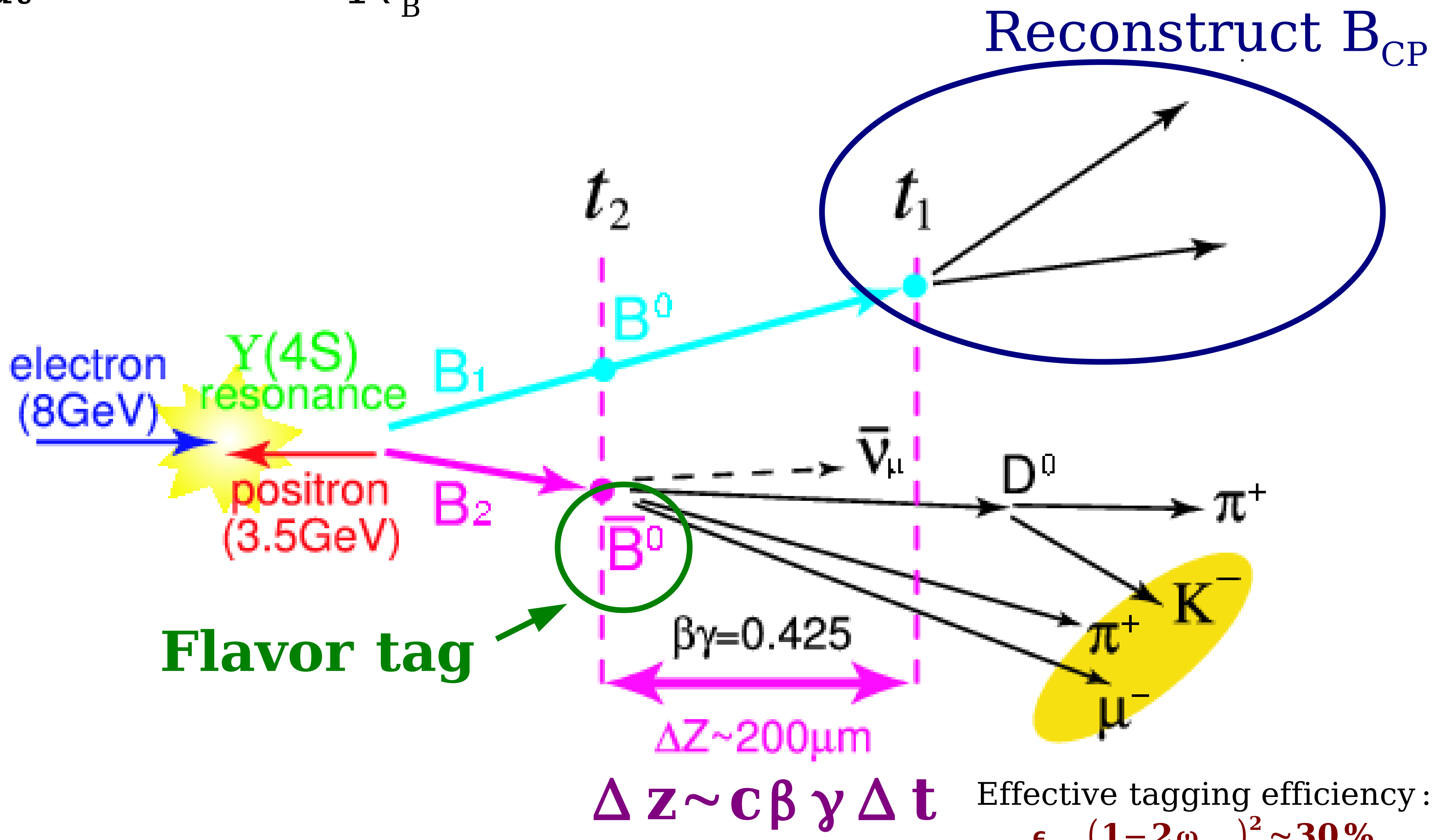
- $\mathbf{A} = 0$ and $\mathbf{S} = -\xi_f \sin 2\beta$ for $(c\bar{c})K_{S/L}$ $(\xi_f = \mp 1)$
- $\mathbf{A} = 0$ and $\mathbf{S} = \sin 2\alpha$ for $\pi^+\pi^-$ (if tree only)



C = − A

Measuring the CP parameters S and A

$$\frac{dP_{sig}}{dt}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left(1 + q\left(S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t)\right)\right)$$

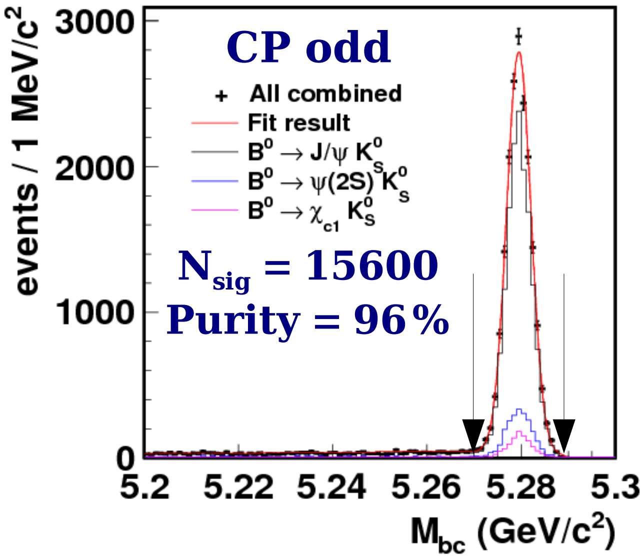


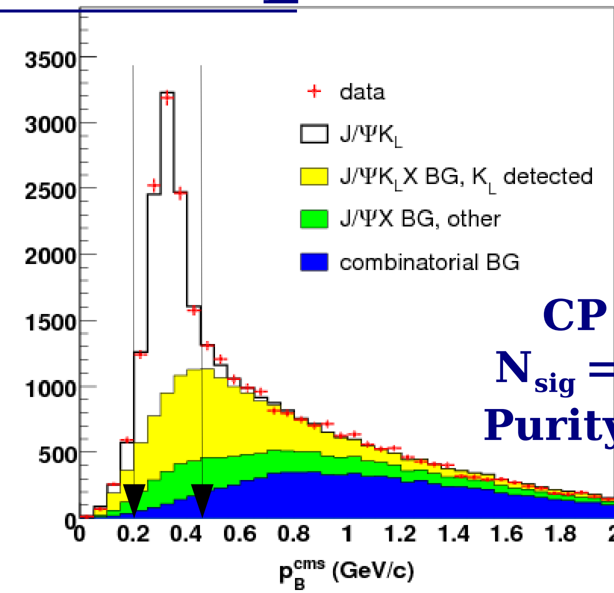
Effective tagging efficiency:
$\epsilon_{tag}(1-2\omega_{tag})^2 \sim 30\%$

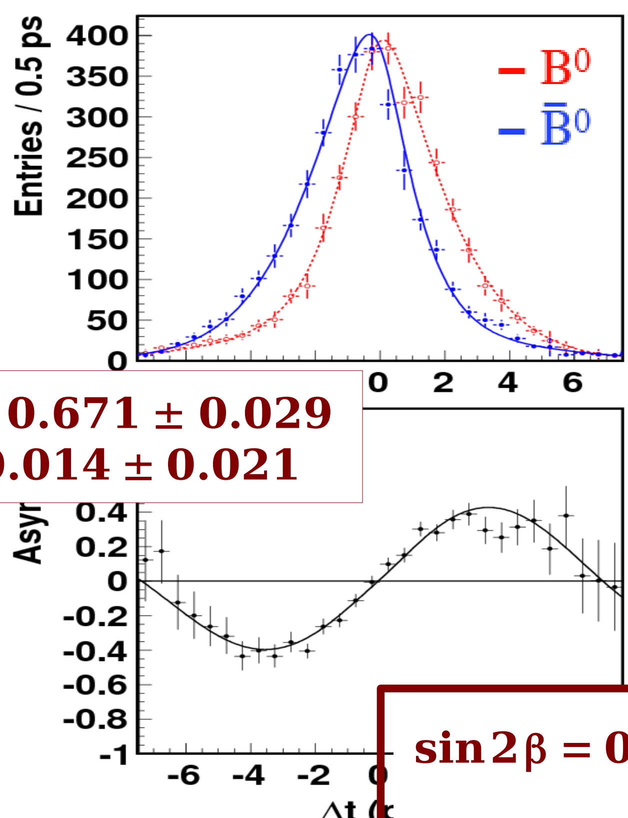
[see talks from FJPPL: FLAV_01 (I.Ripp-Baudot), FJPPL: A_RD_08 (P.Bambade)]

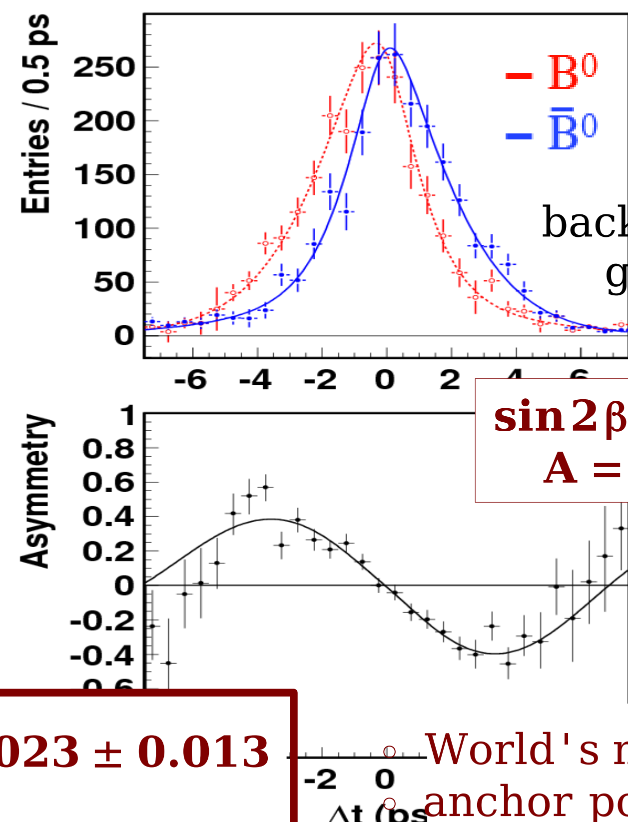
$c\bar{c}\,K_S$ and $J/\psi\,K_L$

$772\times10^{6}\ B\bar{B}$ pairs









background subtracted
good tagged only

$\sin 2\beta = 0.671 \pm 0.029$
$A = -0.014 \pm 0.021$

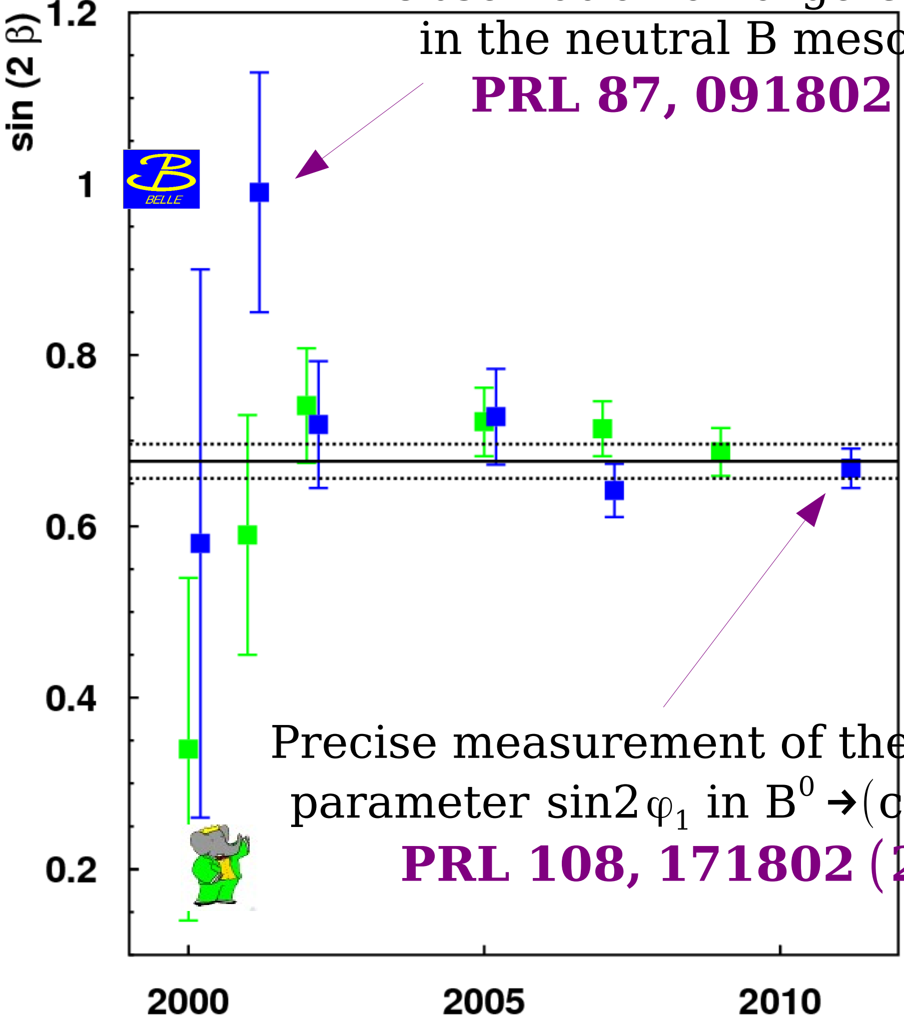
$\sin 2\beta = 0.641 \pm 0.047$
$A = 0.019 \pm 0.026$

$\sin 2\beta = 0.668 \pm 0.023 \pm 0.013$

$A = 0.007 \pm 0.016 \pm 0.013$

- World's most precise meas[t]
- anchor point of the SM
- still statistically limited !

$\sin 2\beta$ in $(c\bar{c})K^0$ ...



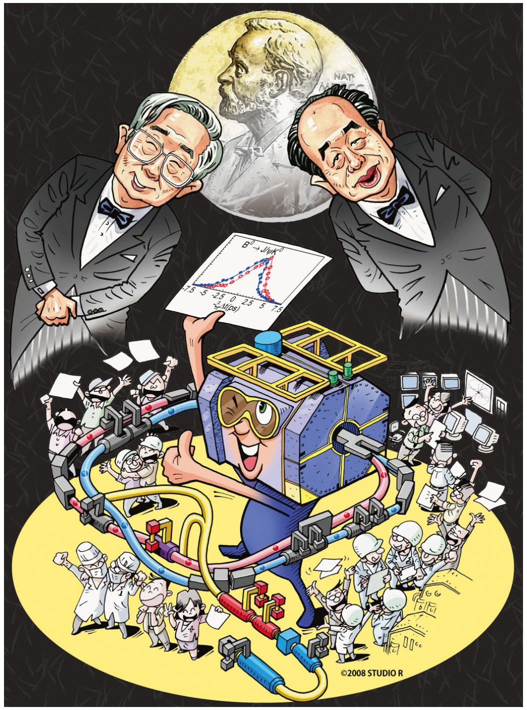
Observation of large CP violation in the neutral B meson system
PRL 87, 091802 (2001)

Precise measurement of the CP violation parameter $\sin 2\varphi_1$ in $B^0 \rightarrow (c\bar{c})K^0$ decays
PRL 108, 171802 (2012)

$$\beta = (21.4 \pm 0.8)^\circ$$

Critical role of the B factories in the verification of the KM hypothesis

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's



Measurement of CPV in $B \to J/\psi K^0_S$ at LHCb

$3\ fb^{-1}$, arXiv:1503.07089

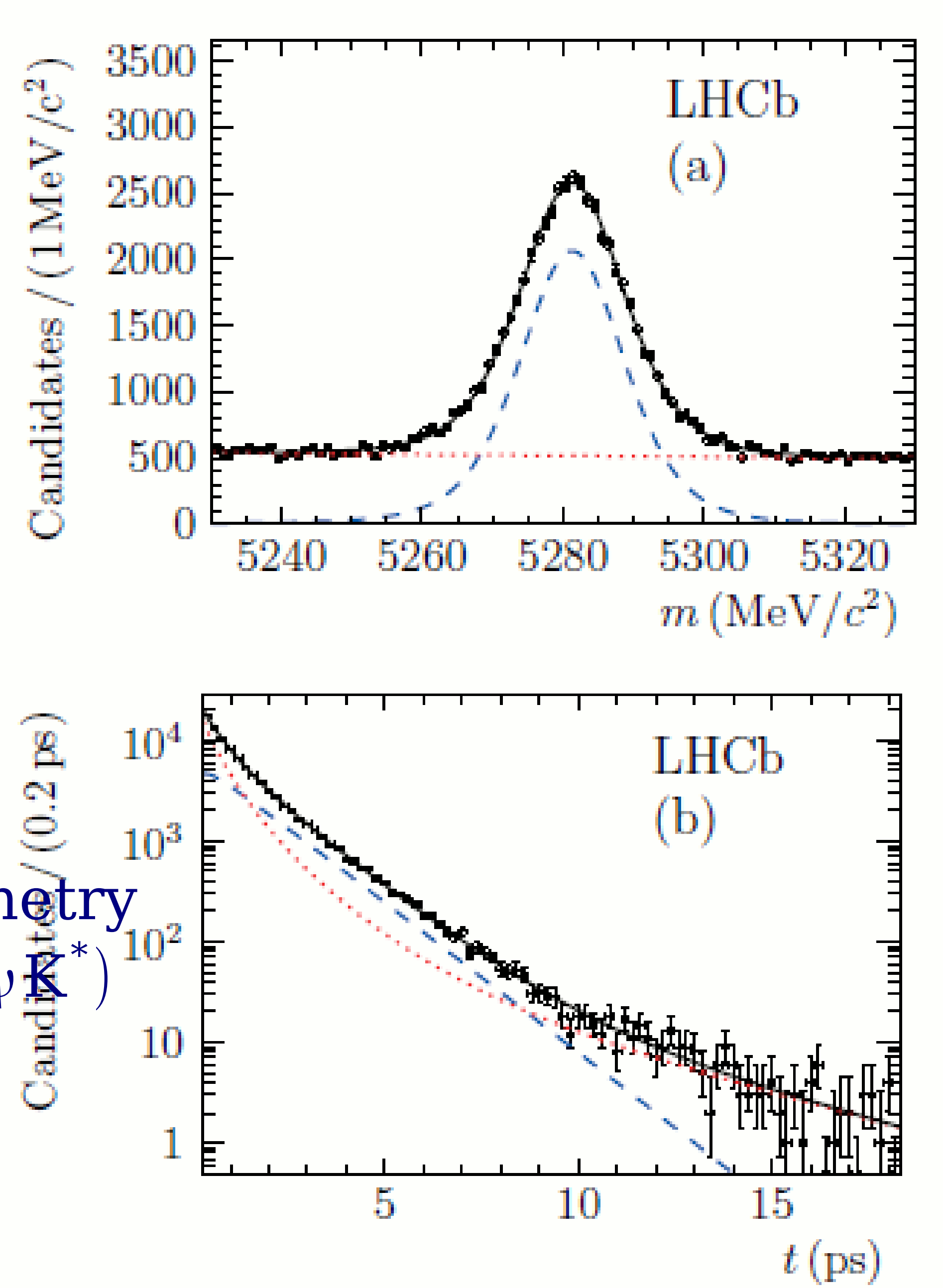
Reconstruct 41560 ± 720 tagged $B \to J/\psi K_S$ events with $J/\psi \to \mu\mu$ and $K_S \to \pi^+\pi^-$ in $3\ fb^{-1}$ (2011-2012 data)

Opposite side flavour-tagging mostly

Magnet polarity reversed periodically to help control detector asymmetries

Need to correct for production asymmetry at p-p collider (measured with $B_d \to J/\psi K^*$)

$$A_P = \frac{[\sigma(\overline{B}^0) - \sigma(B^0)]}{[\sigma(\overline{B}^0) + \sigma(B^0)]}$$



Flavour-Tagging at LHCb

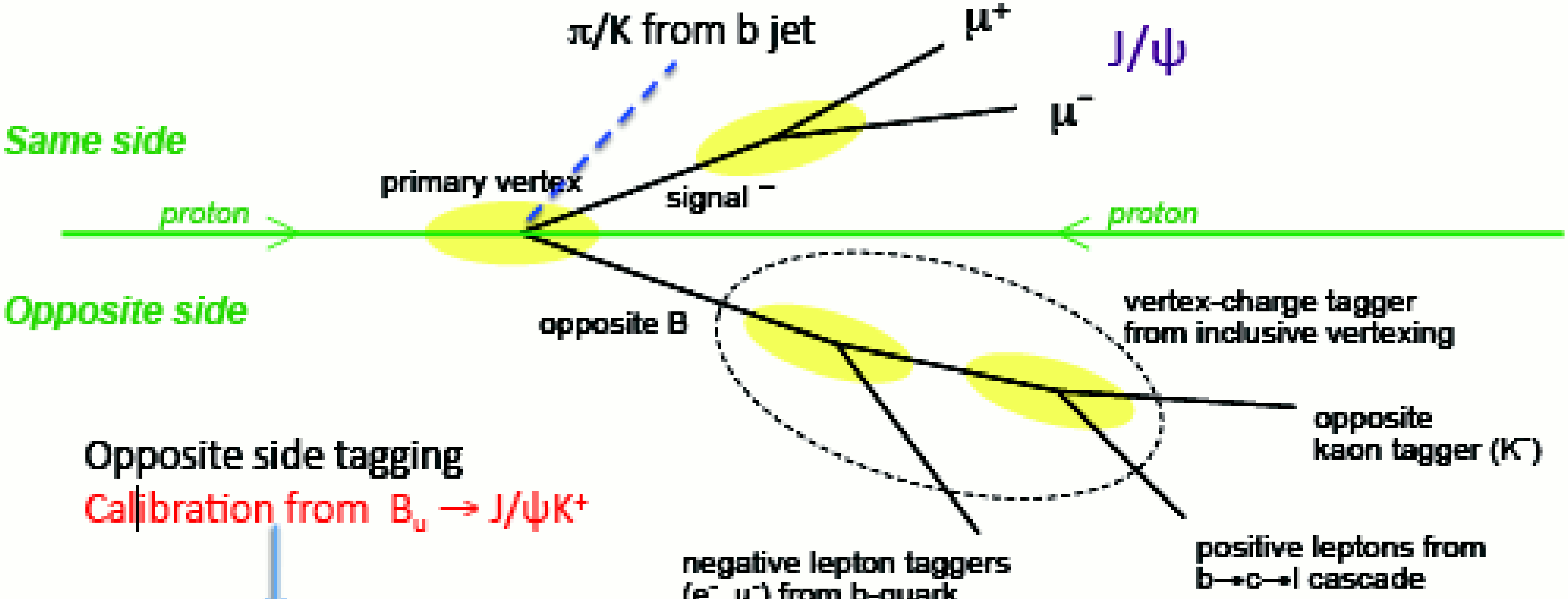
tagging efficiency ε_{tag} ~ 50%

effective mistag ω_{tag} ~ 39%

effective tagging power $\varepsilon_{tag}(1-2\omega_{tag})^2$ ~ 2.4%

Same side Kaon tagging

Calibration from $B_s \rightarrow D_s\pi$



Opposite side tagging

Calibration from $B_u \rightarrow J/\psi K^+$

tagging efficiency ε_{tag} ~ 65%

effective mistag ω_{tag} ~ 39%

effective tagging power $\varepsilon_{tag}(1-2\omega_{tag})^2$ ~ 3.0%

Analyses can either use average or per event tagging information

Flavour-Tagging at LHCb

tagging efficiency ε_{tag} ~ 50%

effective mistag ω_{tag} ~ 39%

Same side Kaon tagging

Calibration from $B_s \to D_s\pi$

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

Impressive improvements in tagging performance in the last 3 years

tagging efficiency ε_{tag} ~ 85%

effective mistag ω_{tag} ~ 39%

effective tagging power $\varepsilon_{tag}(1-2\omega_{tag})^2$ ~ 3.0%

Analyses can either use average or per event tagging information

Measurement of CPV in $B \to J/\psi K^0_S$ at LHCb

$$A(t) = \frac{\Gamma(\bar{B}) - \Gamma(B)}{\Gamma(\bar{B}) + \Gamma(B)}$$

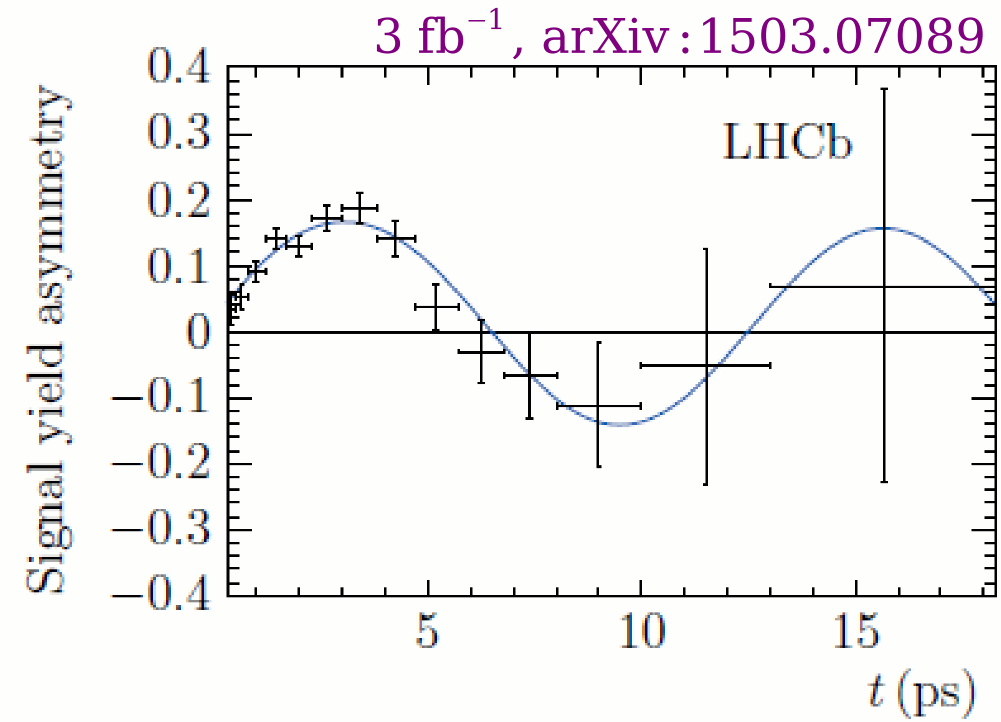
$$S = \sin 2\beta$$

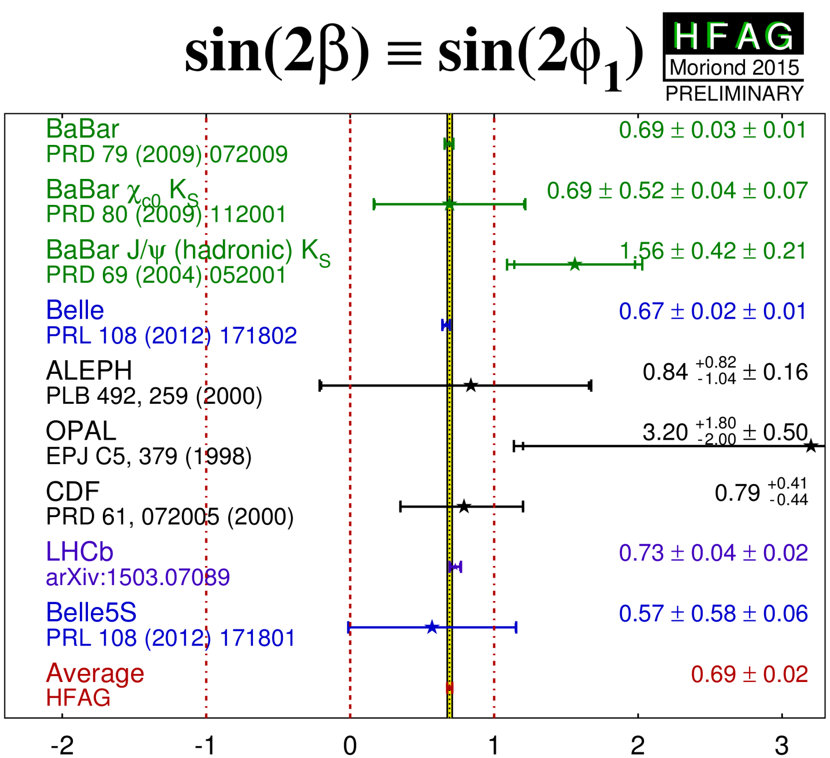
$$C = 0$$

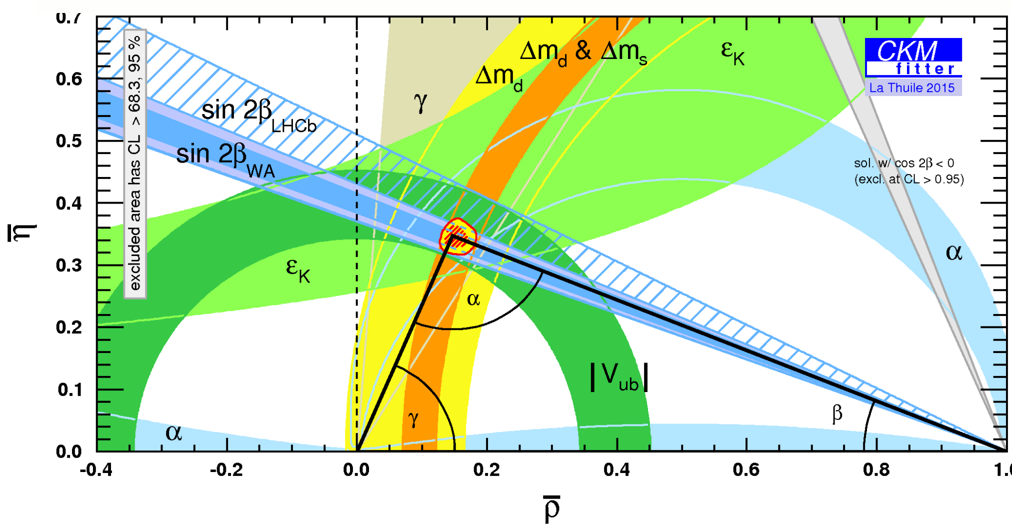
$$A(t) = S \sin(\Delta m_d t) - C \cos(\Delta m_d t)$$

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

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





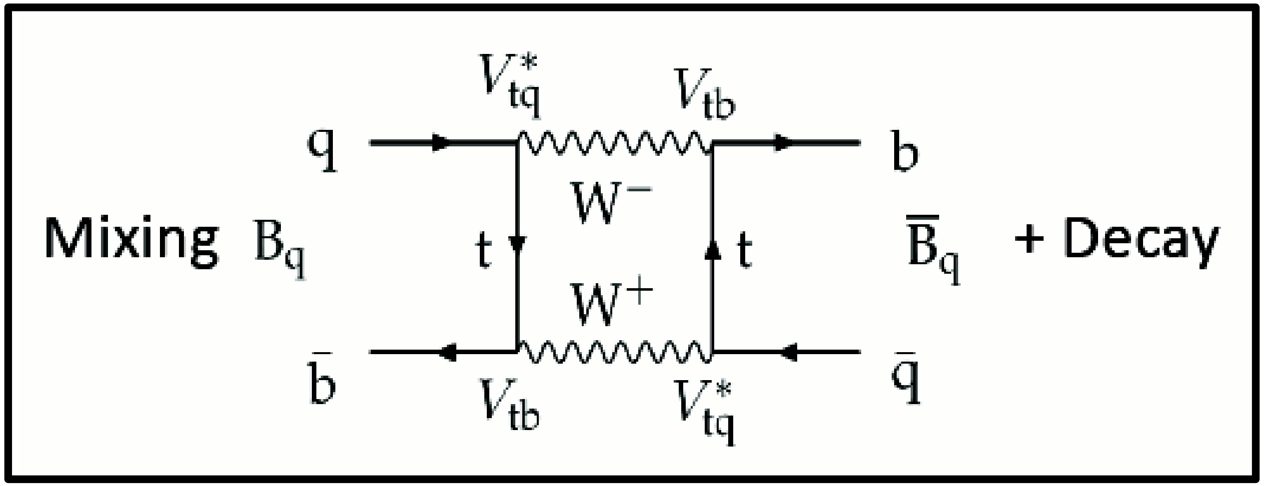


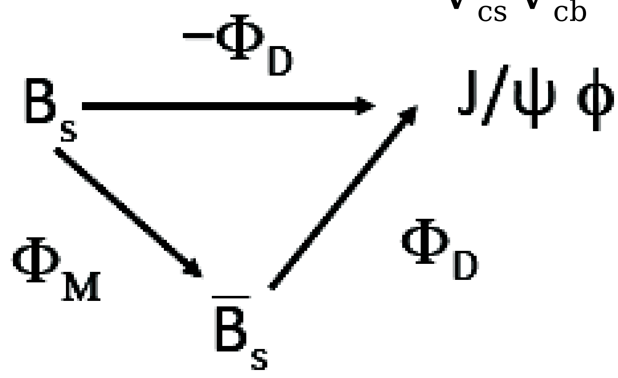
$$\beta = (21.9 \pm 0.7)^\circ$$

WA 2015

CPV in $B_s \to J/\psi\varphi$ at LHCb

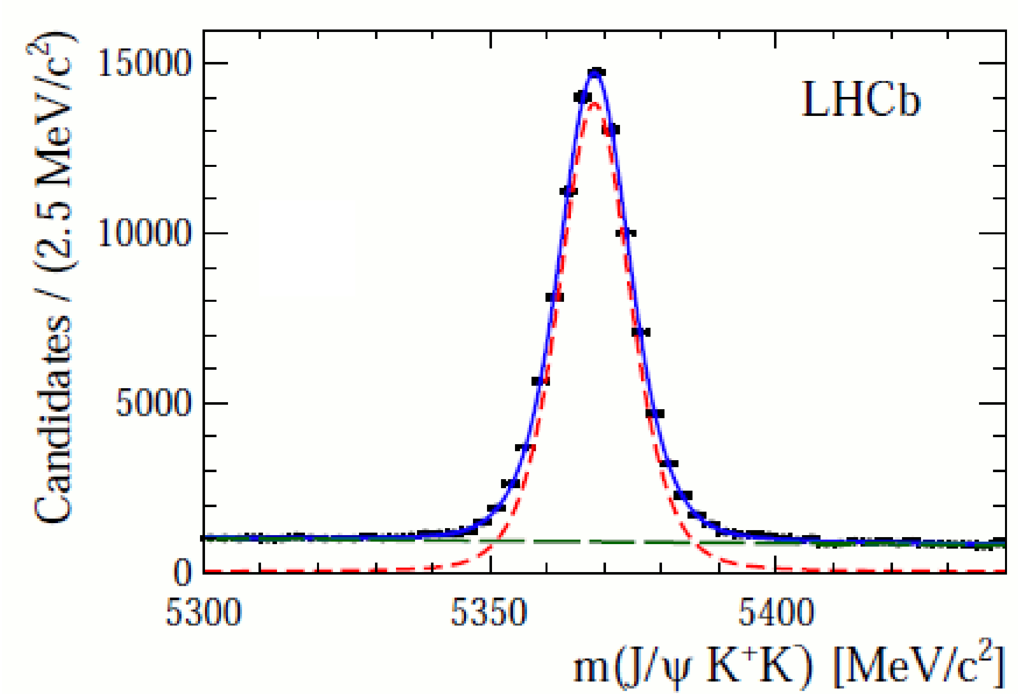
$$-2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

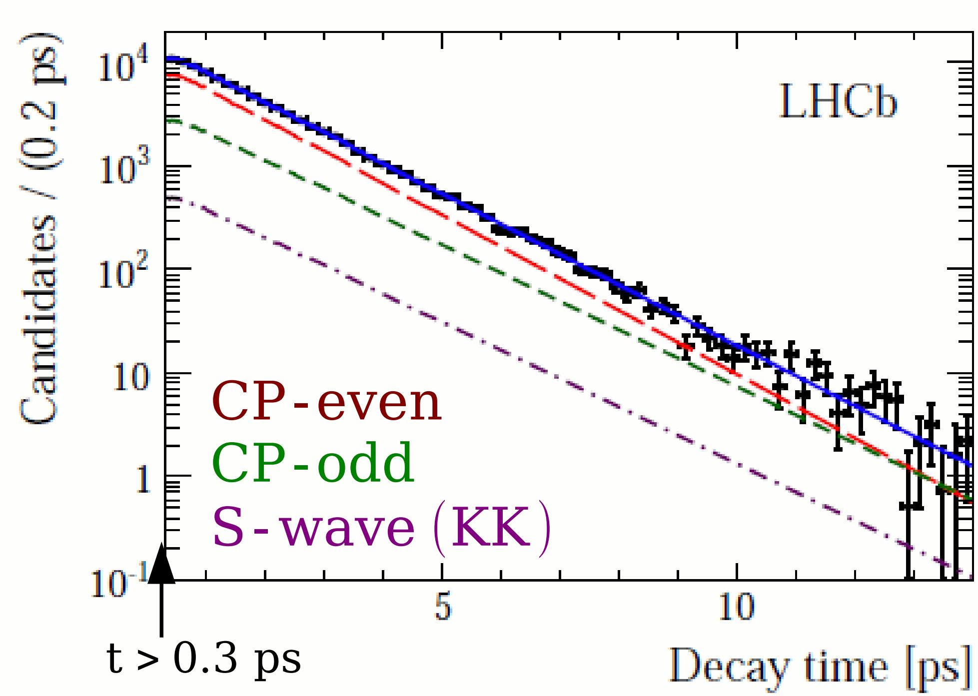




In SM, CPV phase is small $\varphi_s \sim -0.04$ rd

3 fb^{-1}, arXiv:1411.3104





Reconstruct 95690 ± 350 tagged $B_s \to J/\psi\varphi$ evts with $J/\psi \to \mu\mu$ and $\varphi \to K^+K^-$ in 3 fb^{-1} (2011-2012)

$\Gamma_s = \Gamma_H + \Gamma_L/2$
$= 0.6603 \pm 0.0027 \pm 0.0015\ ps^{-1}$
consistent with previous measurements

Results for $B_s \to J/\psi\, h^+ h^-$ at LHCb

CP violating phase [$3\ fb^{-1}$, arXiv:1411.3104]

$$\varphi_s = -0.058 \pm 0.049 \pm 0.006$$

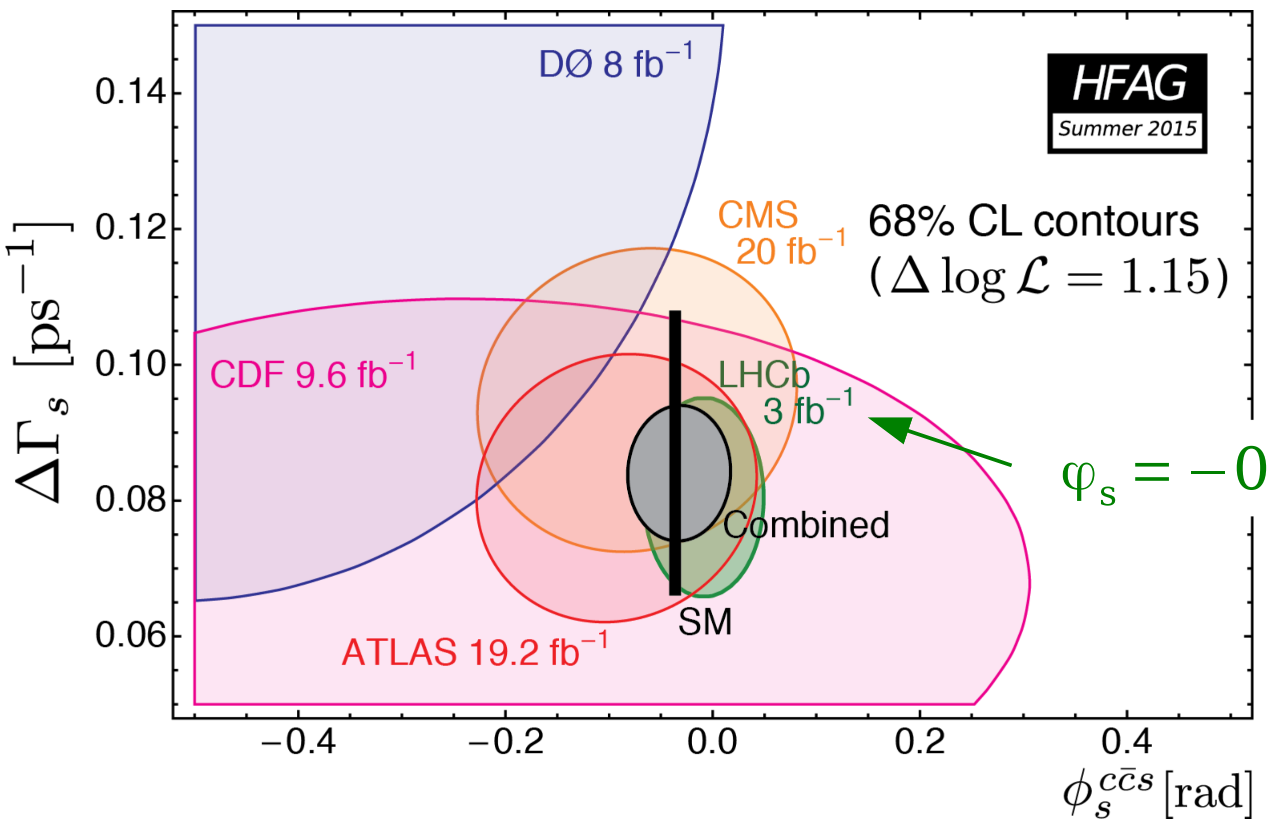
CP violating in mixing or direct decay (no CPV: $|\lambda| = 1$)

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

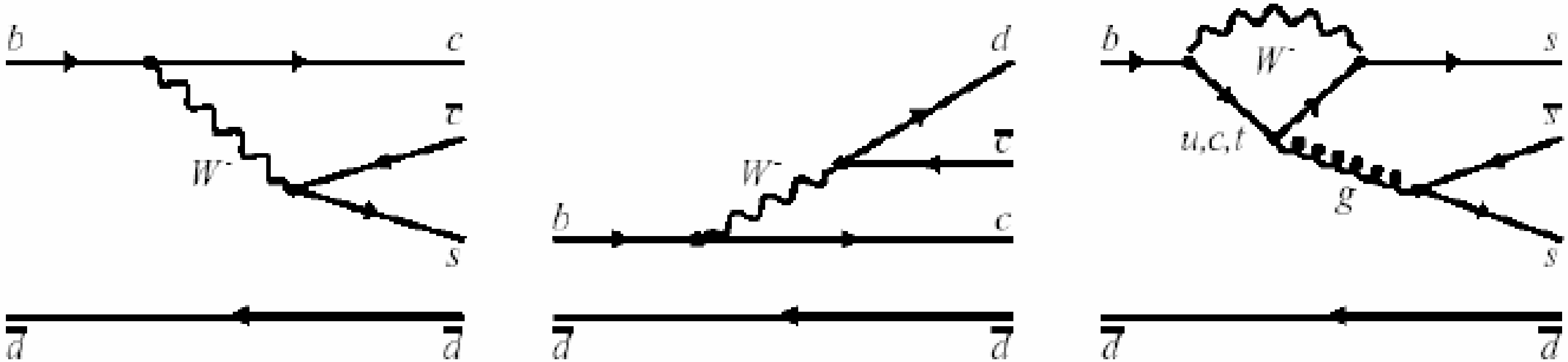
Decay width difference $\Delta\Gamma_s = (\Gamma_L - \Gamma_H) = 0.0805 \pm 0.0091 \pm 0.0032\ ps^{-1}$

$\Delta\Gamma_s(SM) = 0.087 \pm 0.021\ ps^{-1}$

$\varphi_s(SM) = -0.0363\ ^{+0.0012}_{-0.0014}$ rad



$\varphi_s = -0.010 \pm 0.039$ rad
[combined with $J/\psi\pi\pi$]



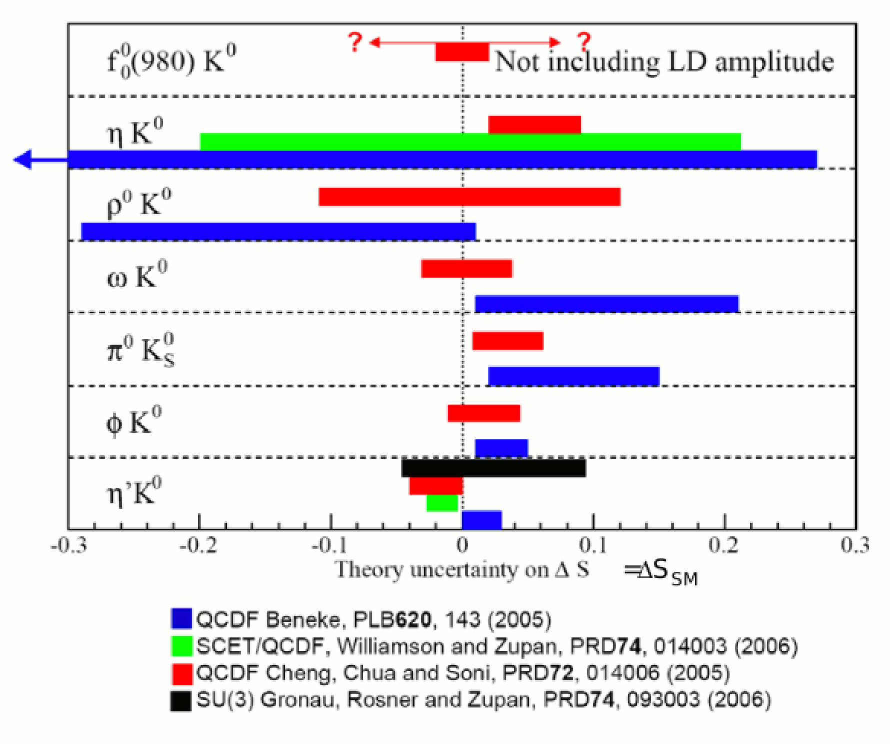
$J/\psi K_S^0, \psi(2S)K_S^0, \chi_{c1}K_S^0,$ $\eta_c K_S^0, J/\psi K_L^0,$ $J/\psi K^{*0}(K^{*0} \rightarrow K_S^0\pi^0)$	$D^{*+}D^-, D^+D^-$ $J/\psi\pi^0, D^{*+}D^{*-}$	$\phi K^0, K^+K^-K_S^0,$ $K_S^0K_S^0K_S^0, \eta' K^0, K_S^0\pi^0,$ $\omega K_S^0, f_0(980)K_S^0$

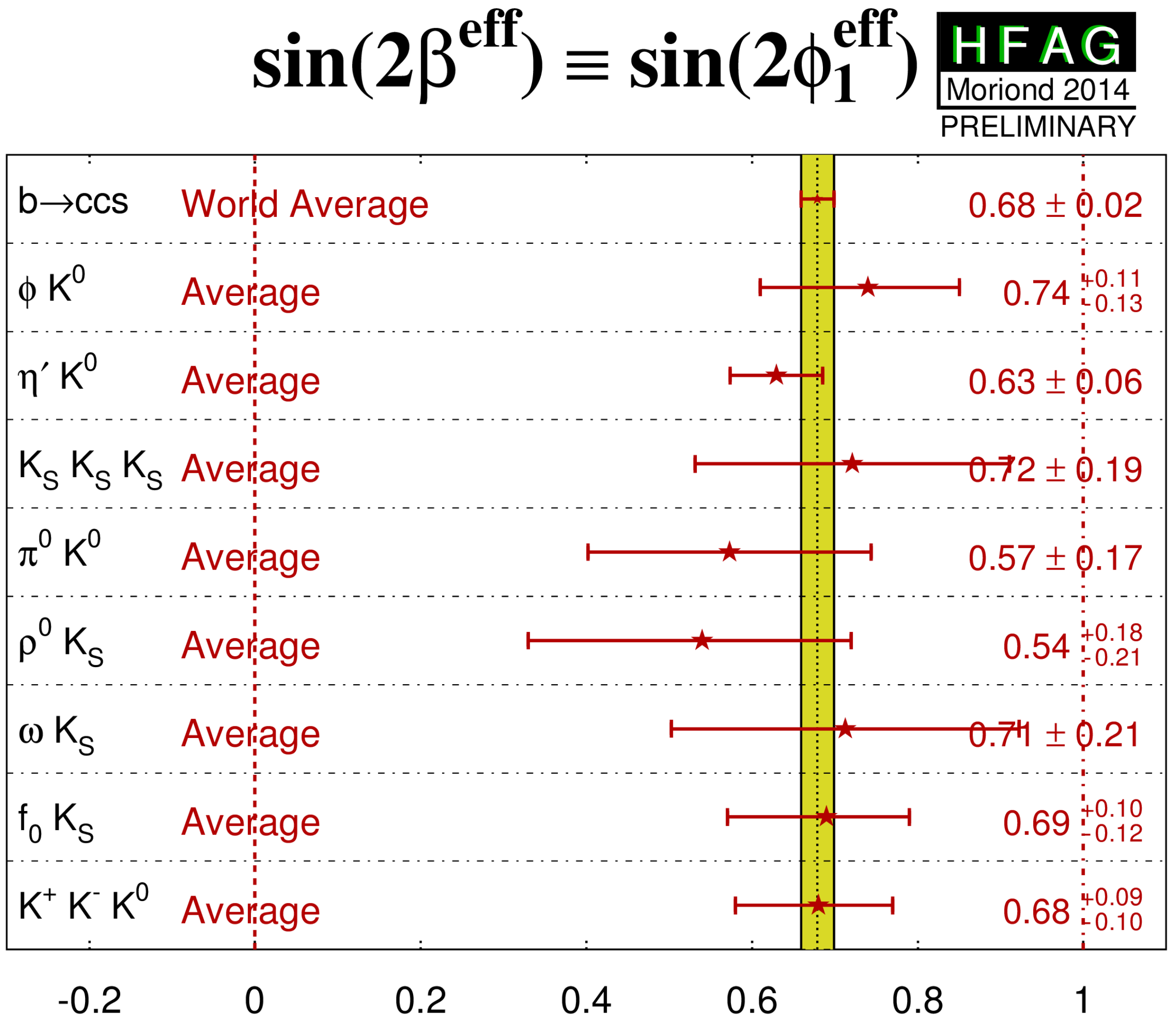
increasing tree diagram amplitude ←

increasing sensitivity to new physics →

$\sin 2\beta$ with $b \to s$ penguins

dominated by B-factories

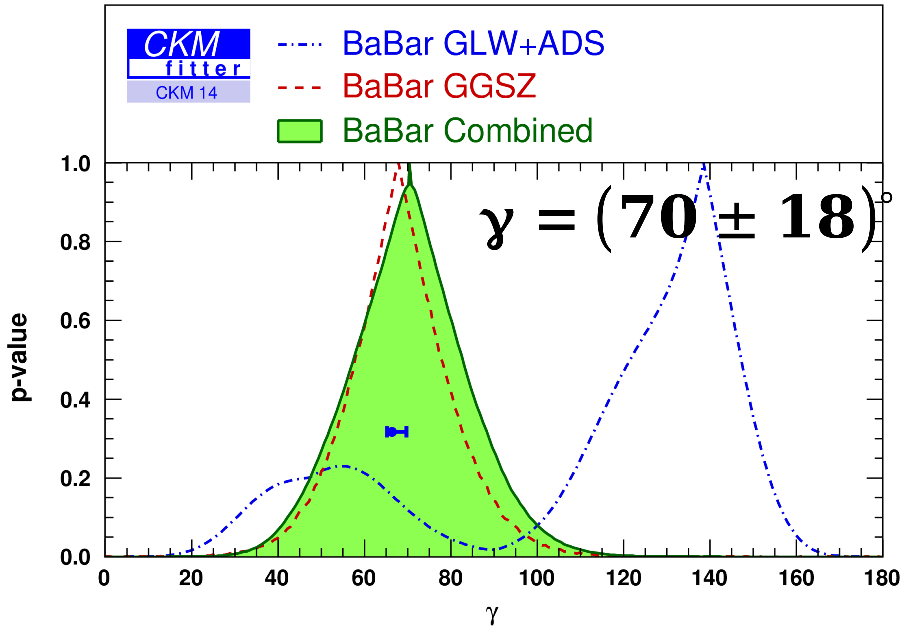


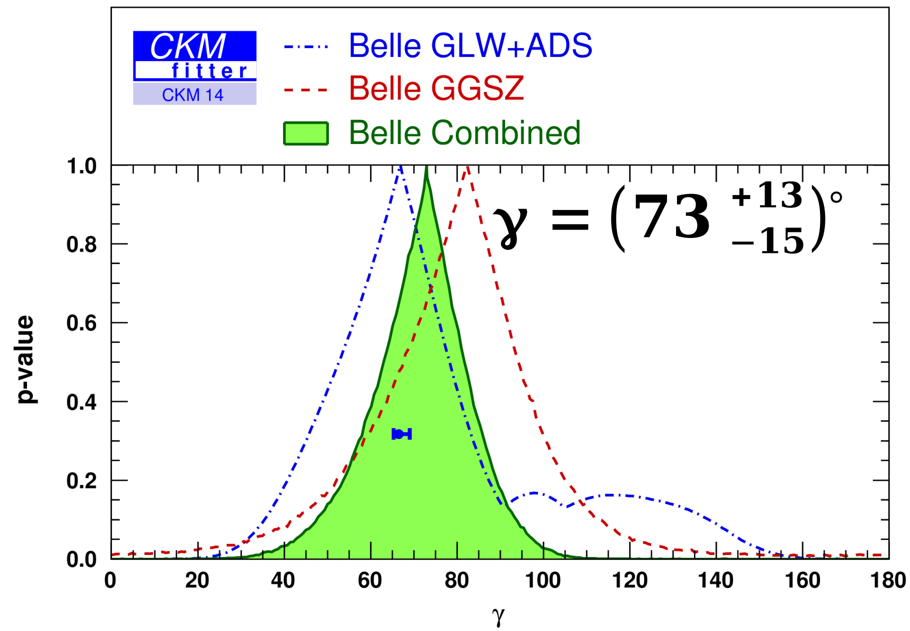


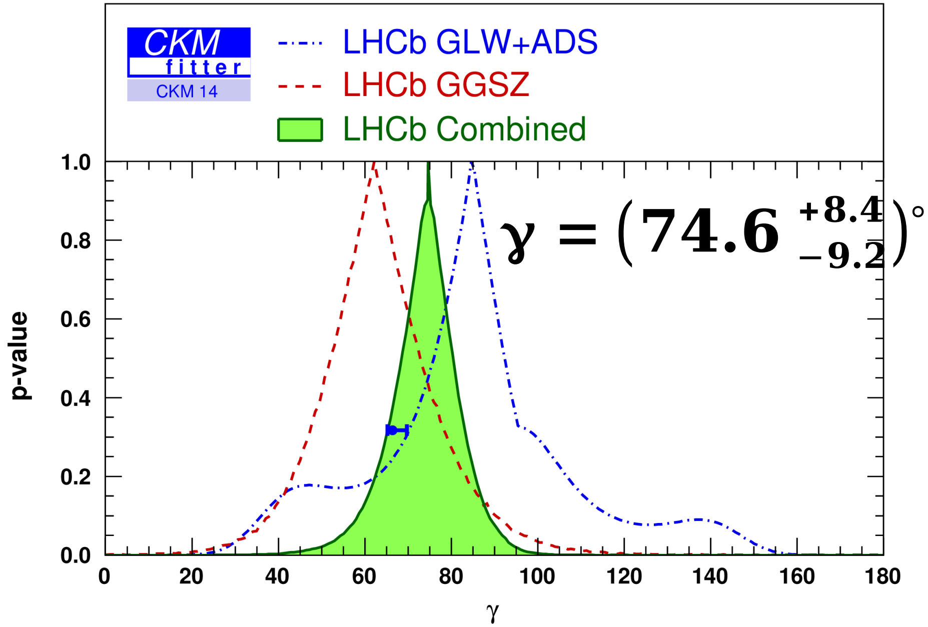
More statistics crucial for mode-by-mode studies

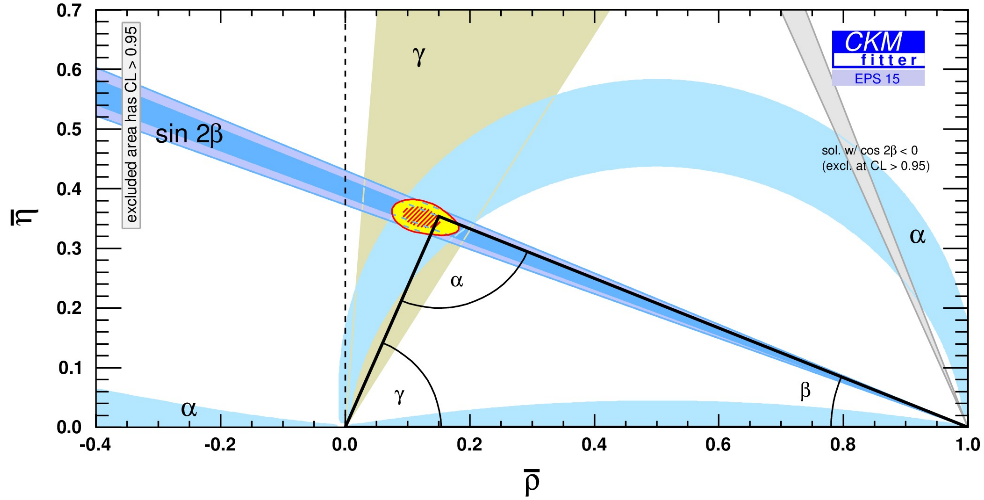
γ angle in the global fit

measurements from B → DK

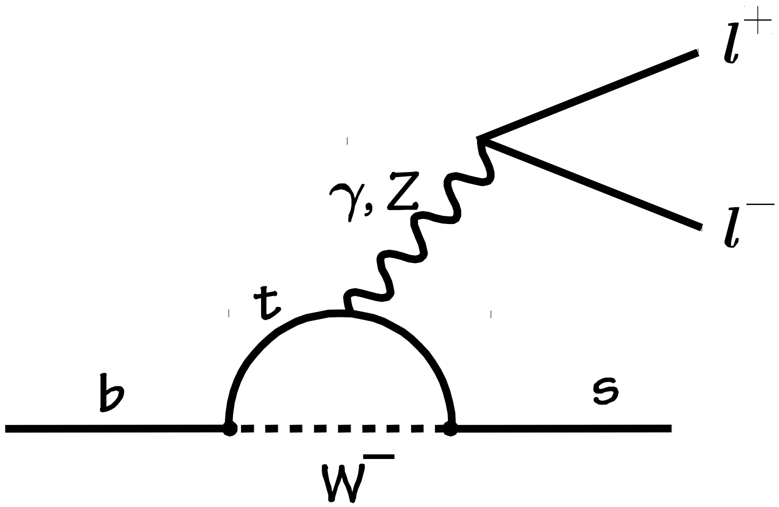


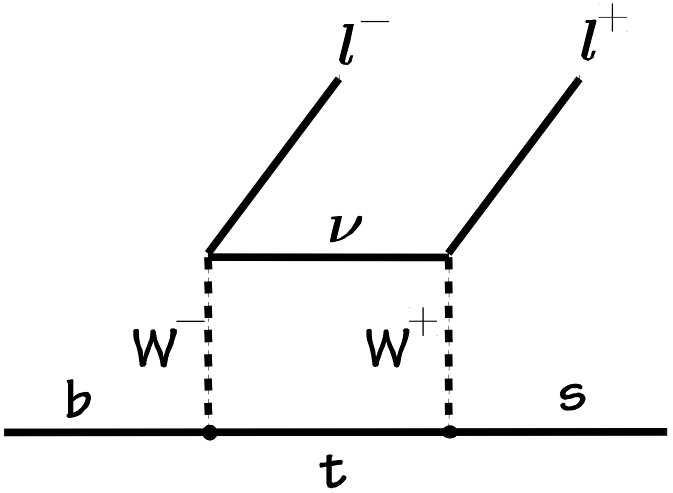






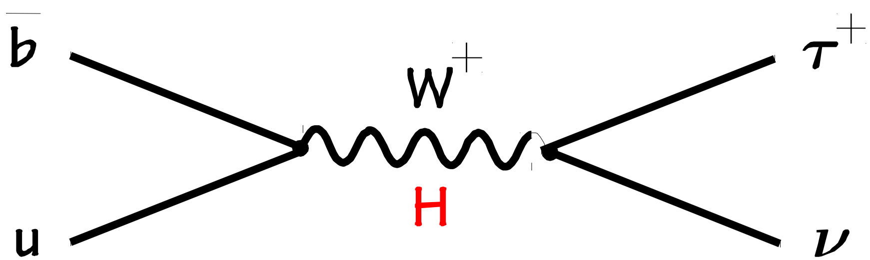
long way to go … (→ $\sigma_\gamma = 1^\circ$ or less)

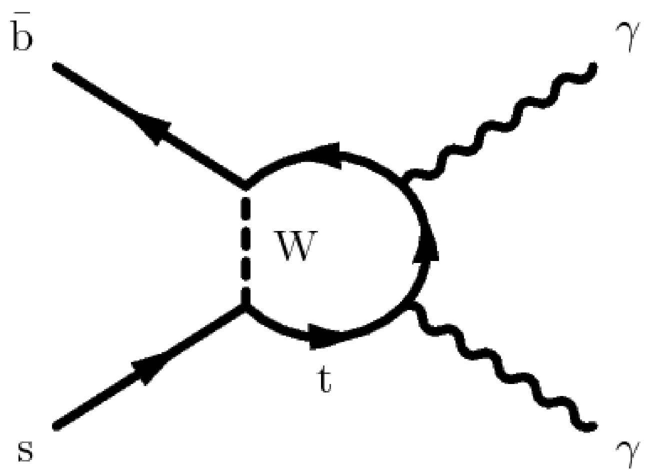


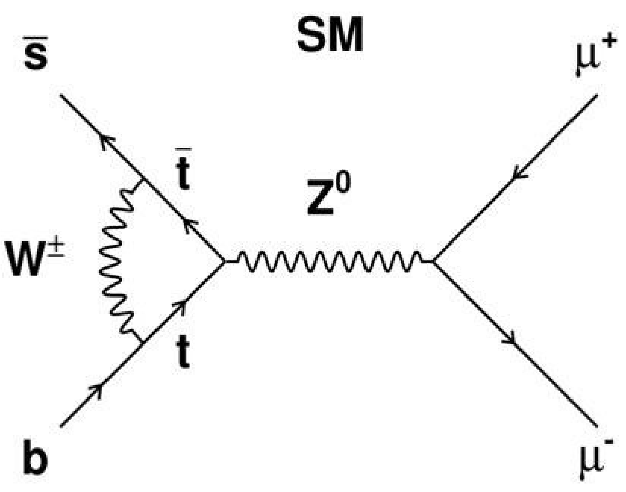


Rare B decays

- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

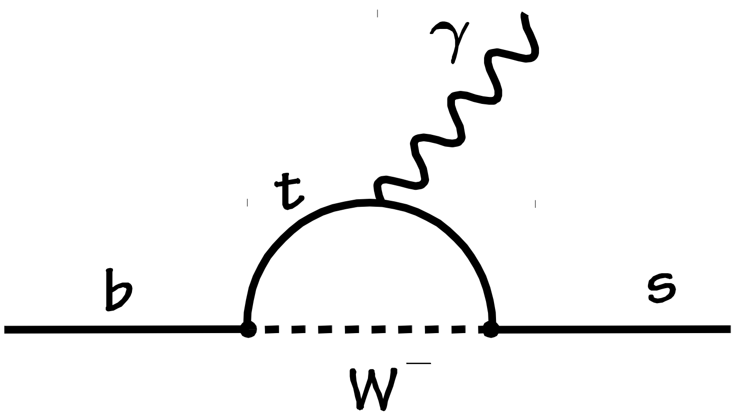




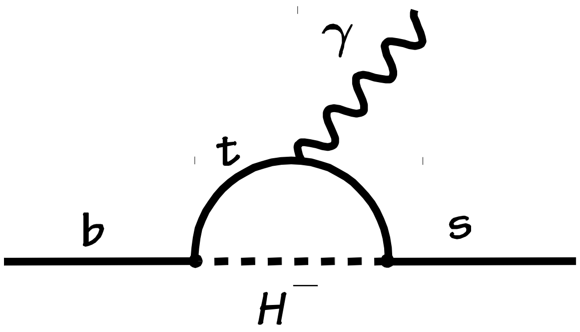


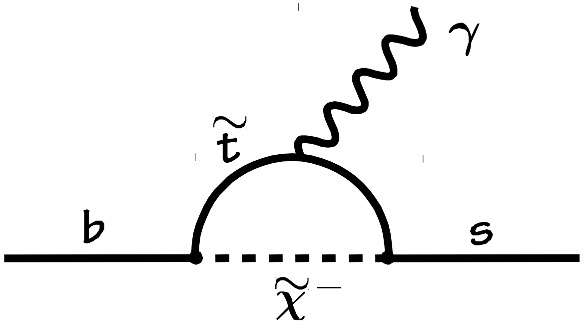
[see talk from FJPPL: FLAV_02 (K.Hara)]

$B \to X_s \gamma$



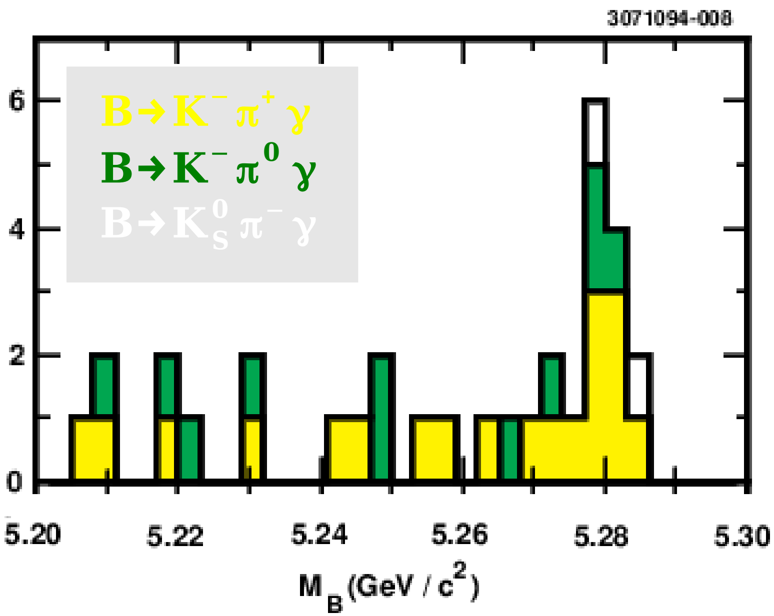
Sensitive to NP



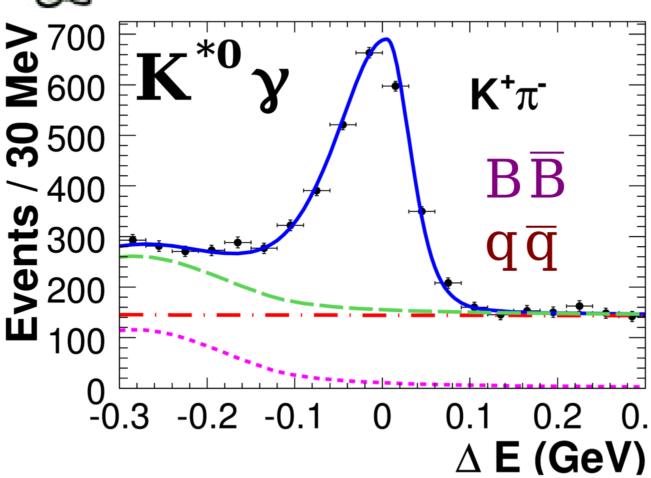


rare ? not that rare...

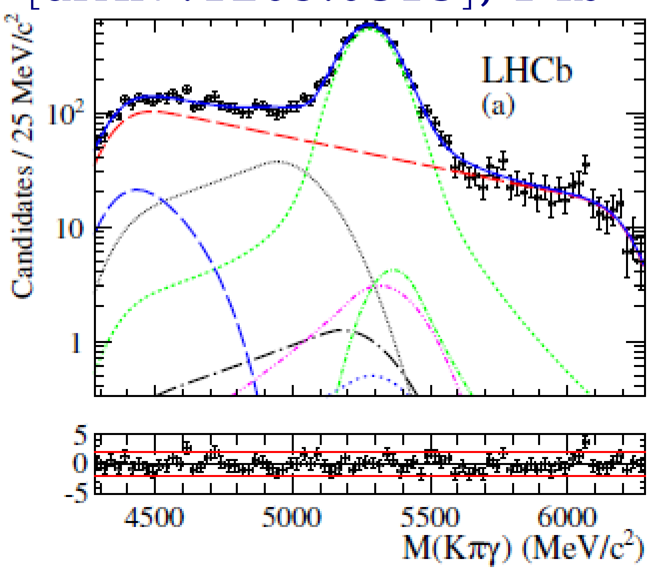
CLEO observation of $B \to K^* \gamma$ [1993]



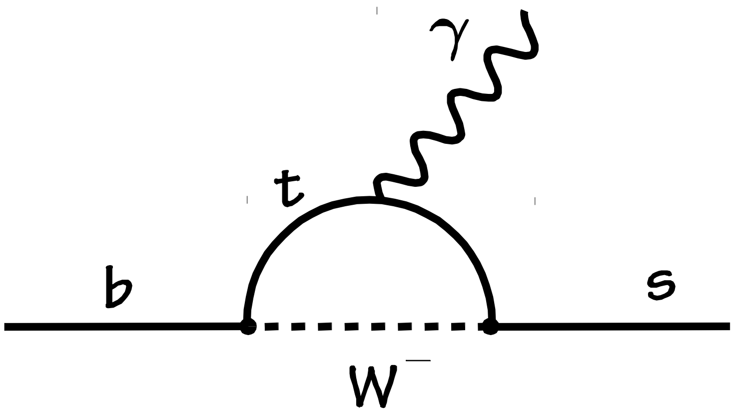
[383 MBB]
[arXiv:0906.2177]



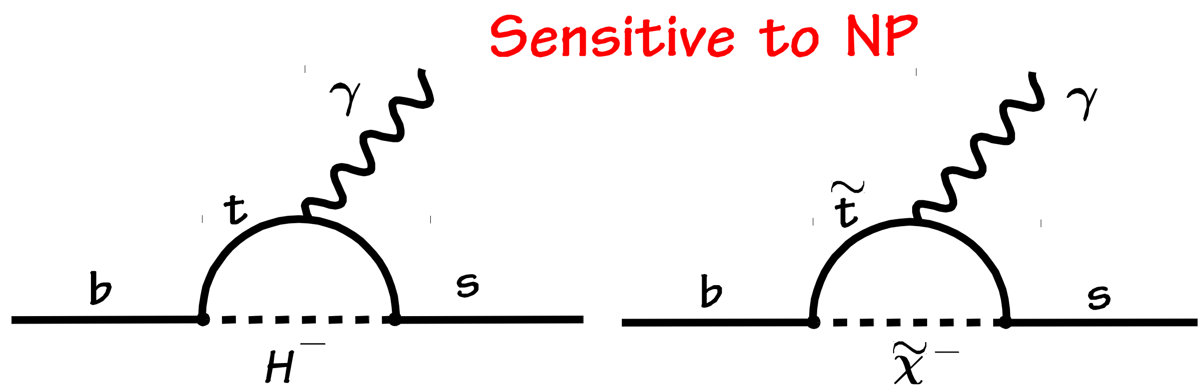
[arXiv:1209.0313], 1 fb^{-1}



$B \to X_s \gamma$



Sensitive to NP



NNLO SM calculation:

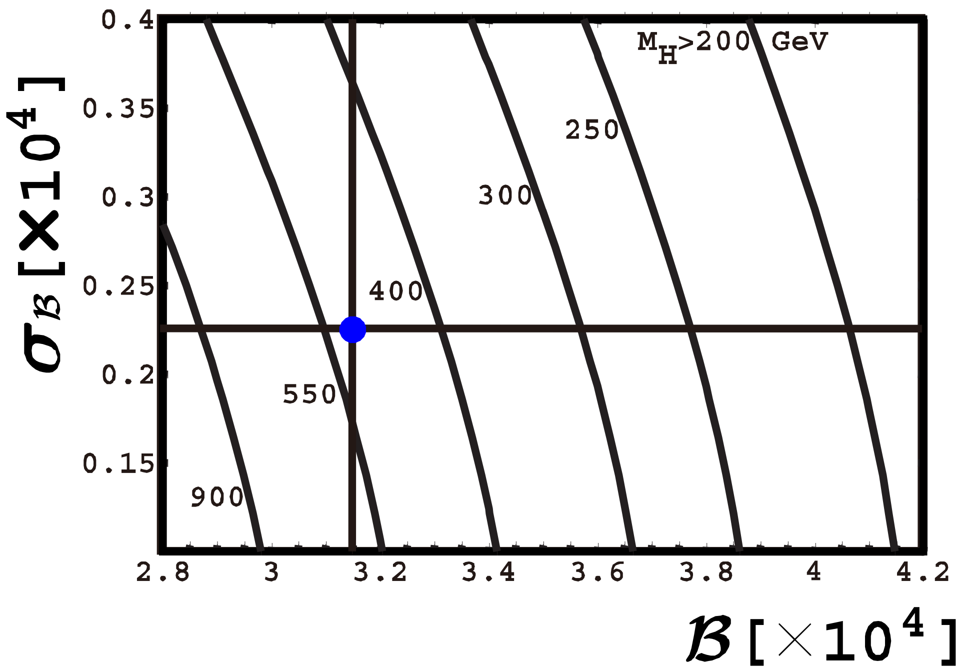
$$B_{SM}(B \to X_s \gamma) = (3.36 \pm 0.23) \times 10^{-4}$$

(for $E_\gamma > 1.6$ GeV)

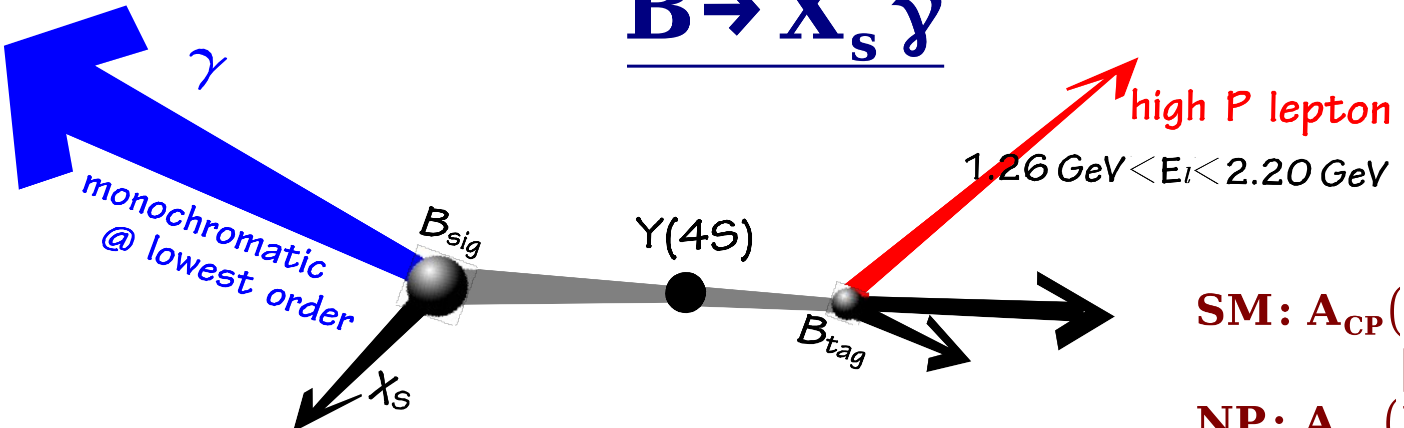
M.Misiak et al.
[arXiv:1503.01789]
(central value increased by 6.4% compared to 2007 value)
PRL 98, 022002 (2007)

The lower γ energy threshold, the smaller the model uncertainties in SM, but the larger background in measurement

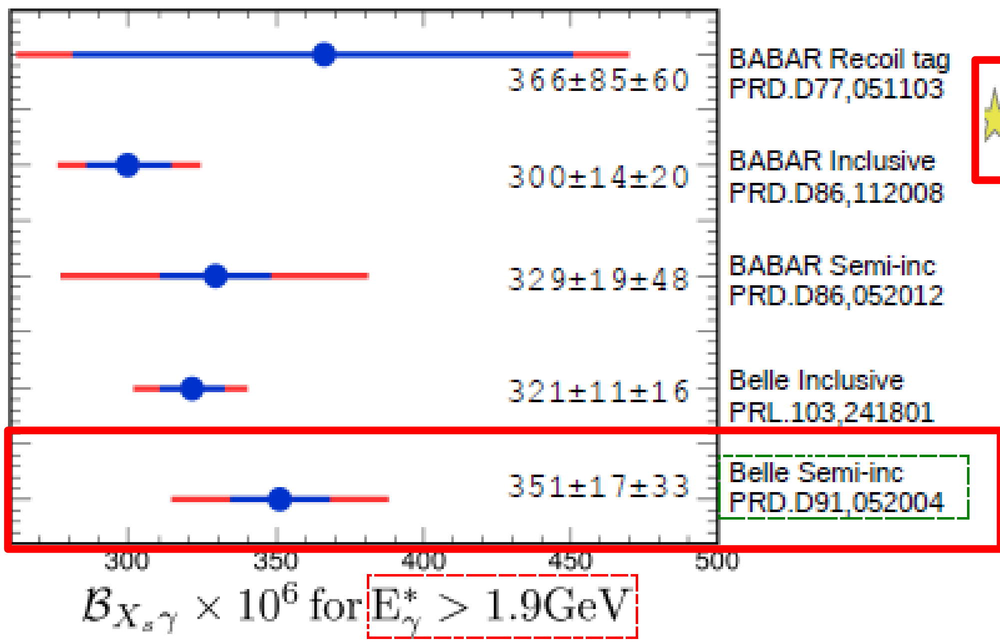
Charged Higgs (2HDM Type II) bound

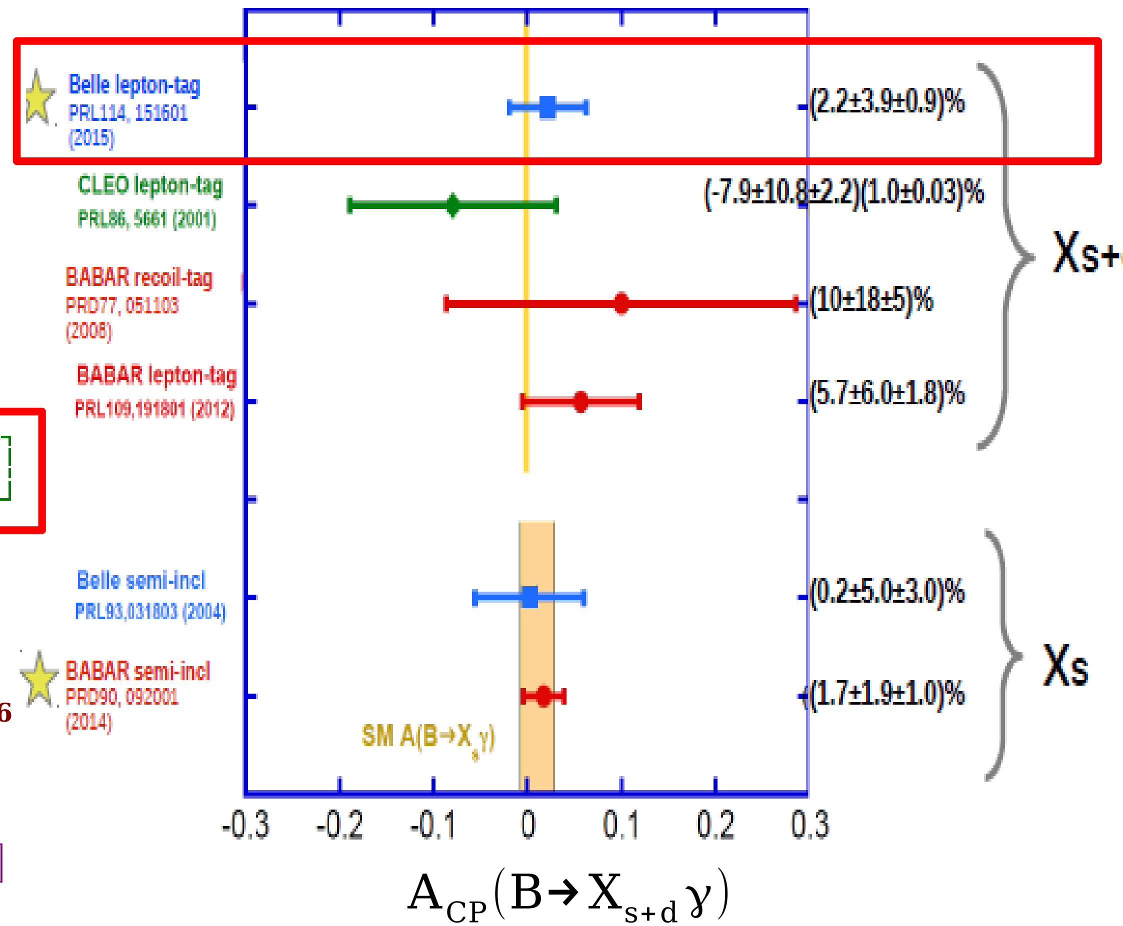


$B \to X_s \gamma$



SM: $A_{CP}(B \to X_{s+d}\gamma) = 0$ to order 10^{-6}
[Hurth and Mannel, 2001]
NP: $A_{CP}(B \to X_{s+d}\gamma)$ as large as 10%





at $E_\gamma > 1.6$ GeV:

$$\boldsymbol{\mathcal{B}(B \to X_s\gamma) = (341 \pm 15 \pm 4\ (\text{extrap})) \times 10^{-6}}$$

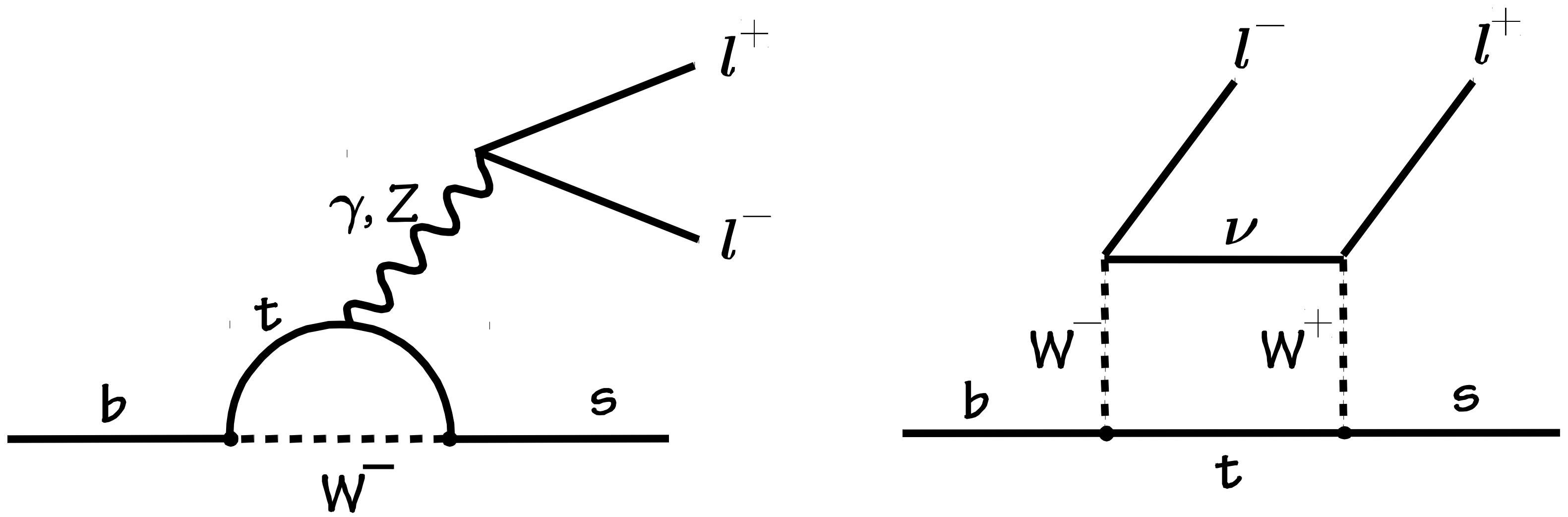
$$B_{SM}(B \to X_s\gamma) = (336 \pm 23) \times 10^{-6}$$

[Misiak et al, arXiv:1503.01789]

For charged Higgs in 2HDM Type II
$M(H^-) > 540$ GeV at 95% CL

⇒ limited by statistics: Belle II...

$b \to s\, l^+ l^-$



⇒ 2 orders of magnitude smaller than $b \to s\gamma$ but rich NP search potential

Amplitudes from
- electromagnetic penguin: C_7
- vector electroweak: C_9
- axial-vector electroweak: C_{10}

may interfere w/ contributions from NP

Many observables:
- Branching fractions
- Isospin asymmetry (A_I)
- Lepton forward-backward asymmetry (A_{FB})

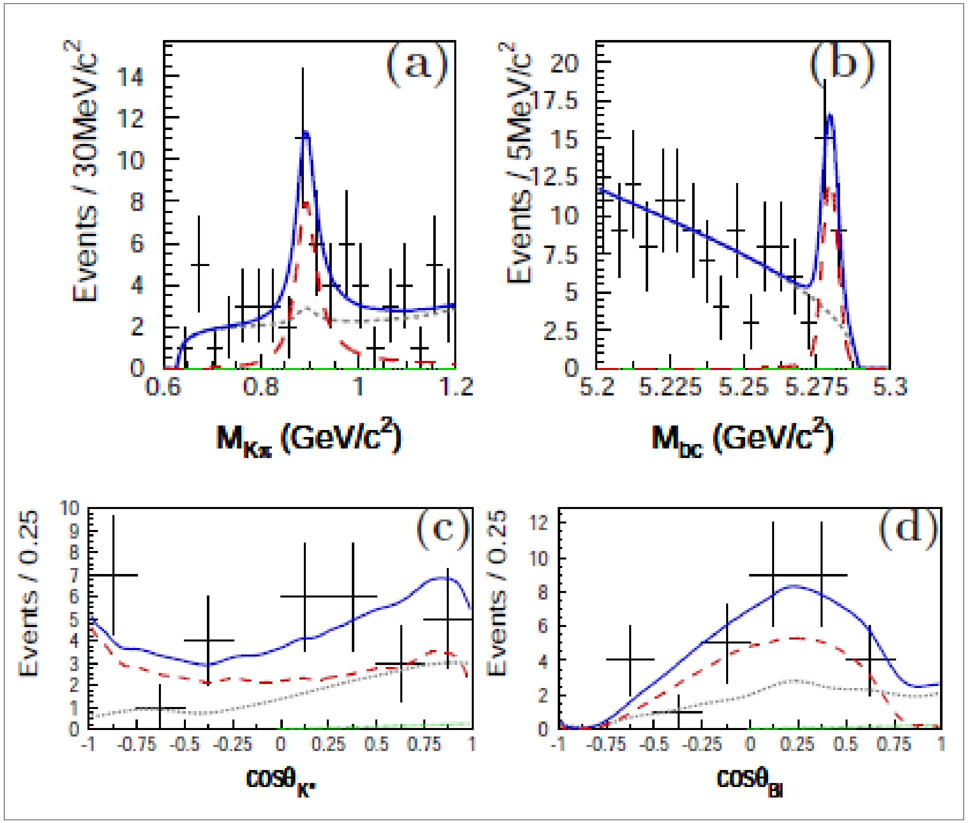
⇒ Exclusive ($B \to K^{(*)} l^+ l^-$), Inclusive ($B \to X_s\, l^+ l^-$)

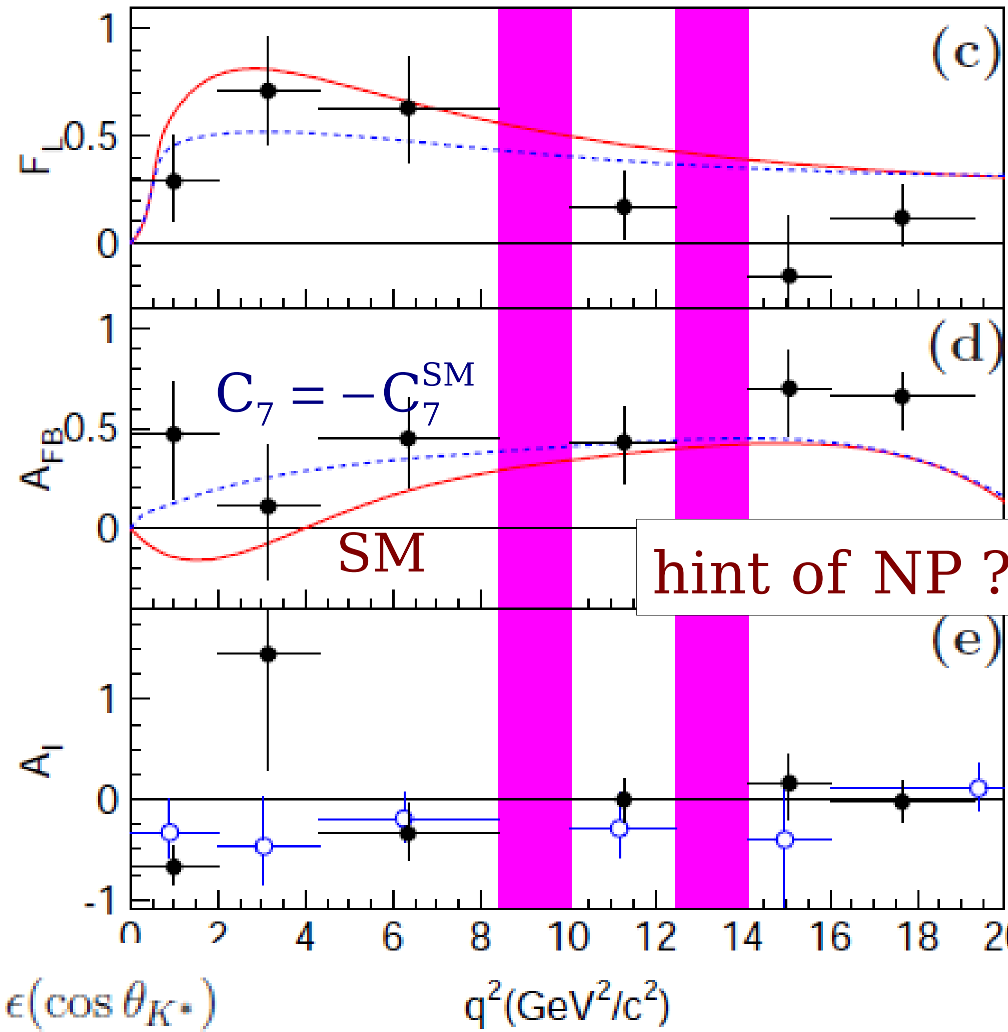
$B \to K^{*} l^{+} l^{-}$ decays

- Channels: $K^{*} \to K^{+}\pi^{-}$, $K^{0}_{S}\pi^{+}$, $K^{+}\pi^{0}$, $l = e$ or μ

[arXiv:0904.0770]

illustration: $q^2 \in [0.0,\ 2,0]\ \mathrm{GeV}^2$





$$\left[\ \tfrac{3}{2}F_L\cos^2\theta_{K^*} + \tfrac{3}{4}(1-F_L)(1-\cos^2\theta_{K^*})\ \right]\ \times \epsilon(\cos\theta_{K^*})$$

$$\left[\ \tfrac{3}{4}F_L(1-\cos^2\theta_{B\ell}) + \tfrac{3}{8}(1-F_L)(1+\cos^2\theta_{B\ell}) + A_{FB}\cos\theta_{B\ell}\ \right] \times \epsilon(\cos\theta_{B\ell})\ ,$$

$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$

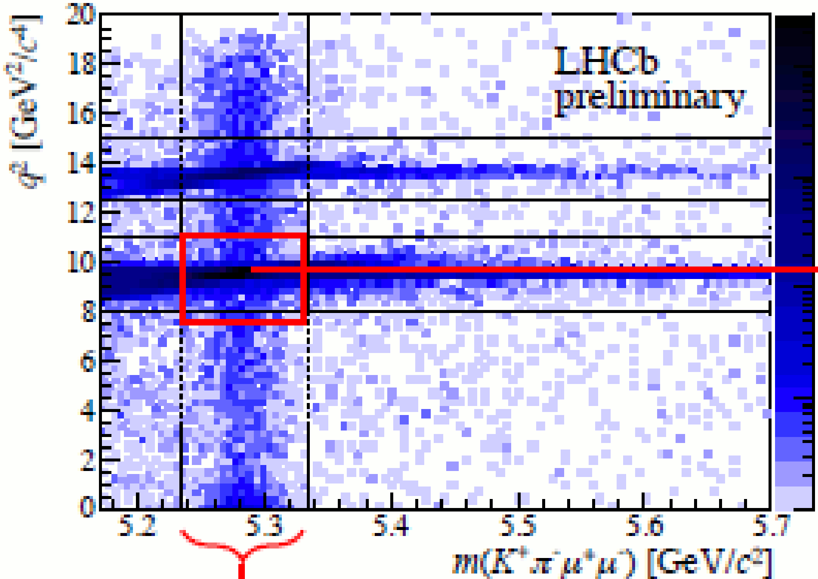
$R_K = 1.03 \pm 0.19 \pm 0.06$

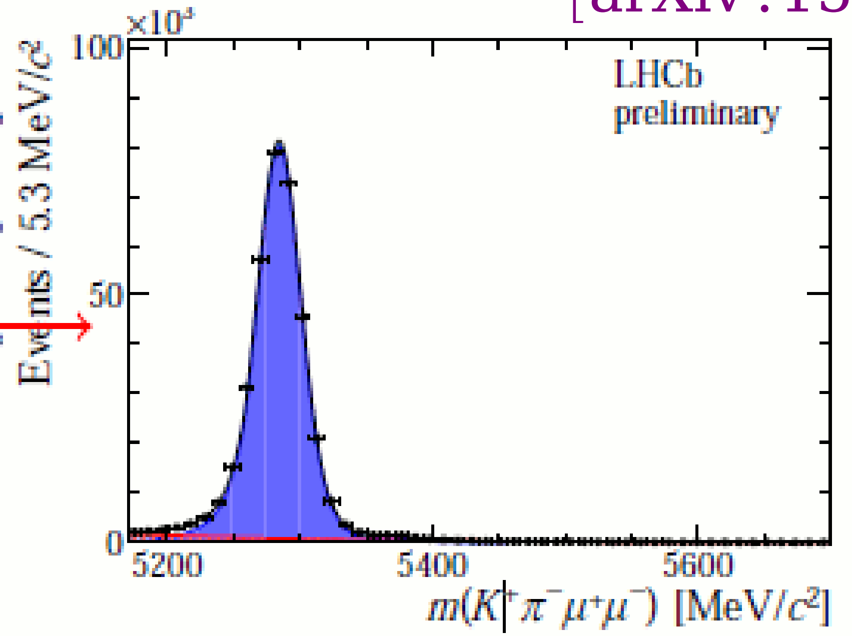
$R_K^{SM} = 1$, $R_{K^*}^{SM} = 0.75$ (photon pole !)

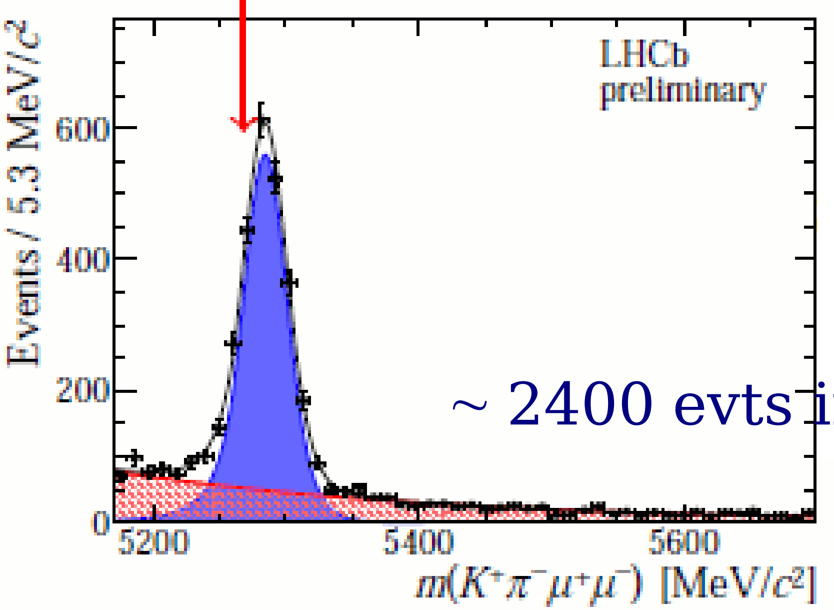
Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

- Channel: $B \to K^{*0}(\to K^+ \pi^-)\mu\mu$

[arXiv:1512.04442]







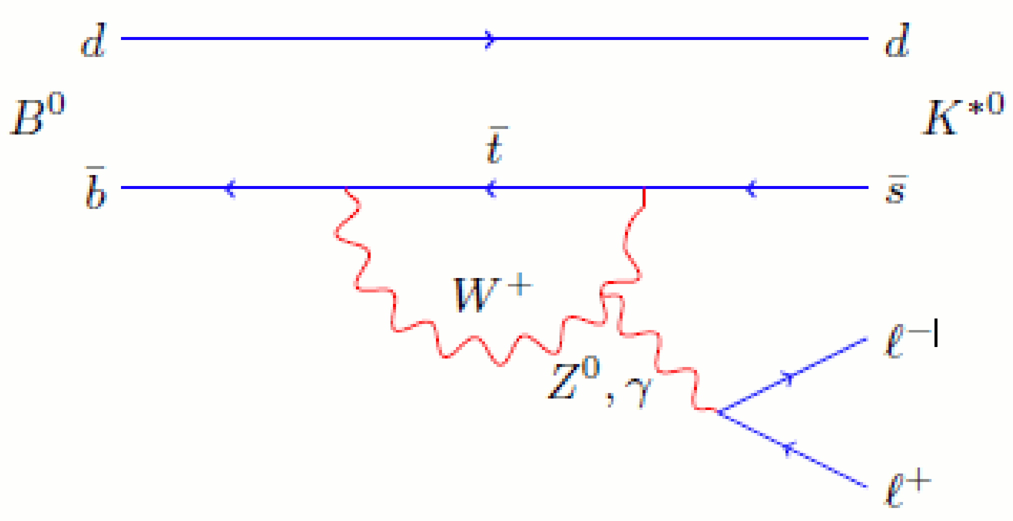
Selection:

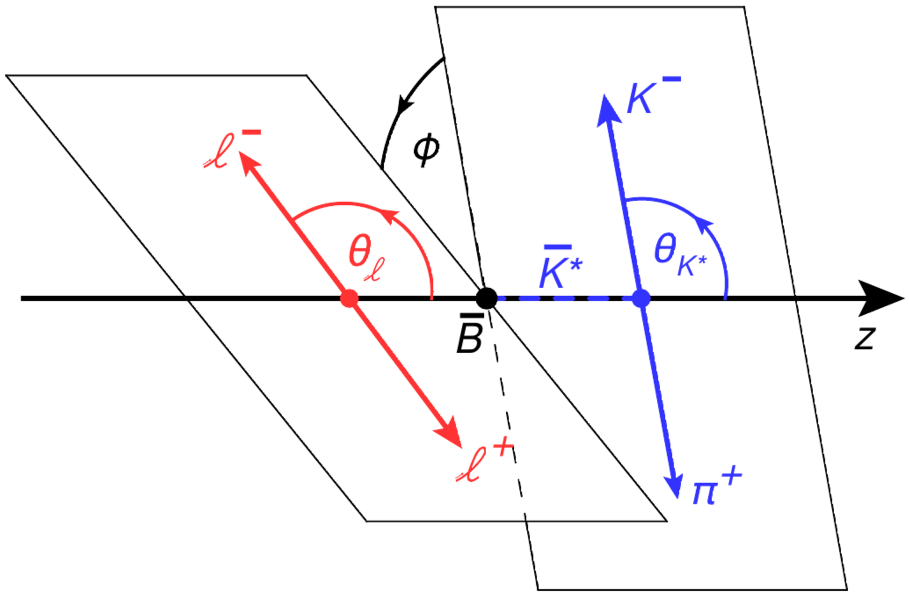
BDT to reject combinatorial background
Veto of resonant modes (control modes)

~ 2400 evts in the full q^2 range

Angular analysis of $B_d^0 \to K^* l^+ l^-$ decays

- Final state described by $q^2 = m_{ll}^2$ and three angles $\Omega = (\theta_l, \theta_K, \varphi)$





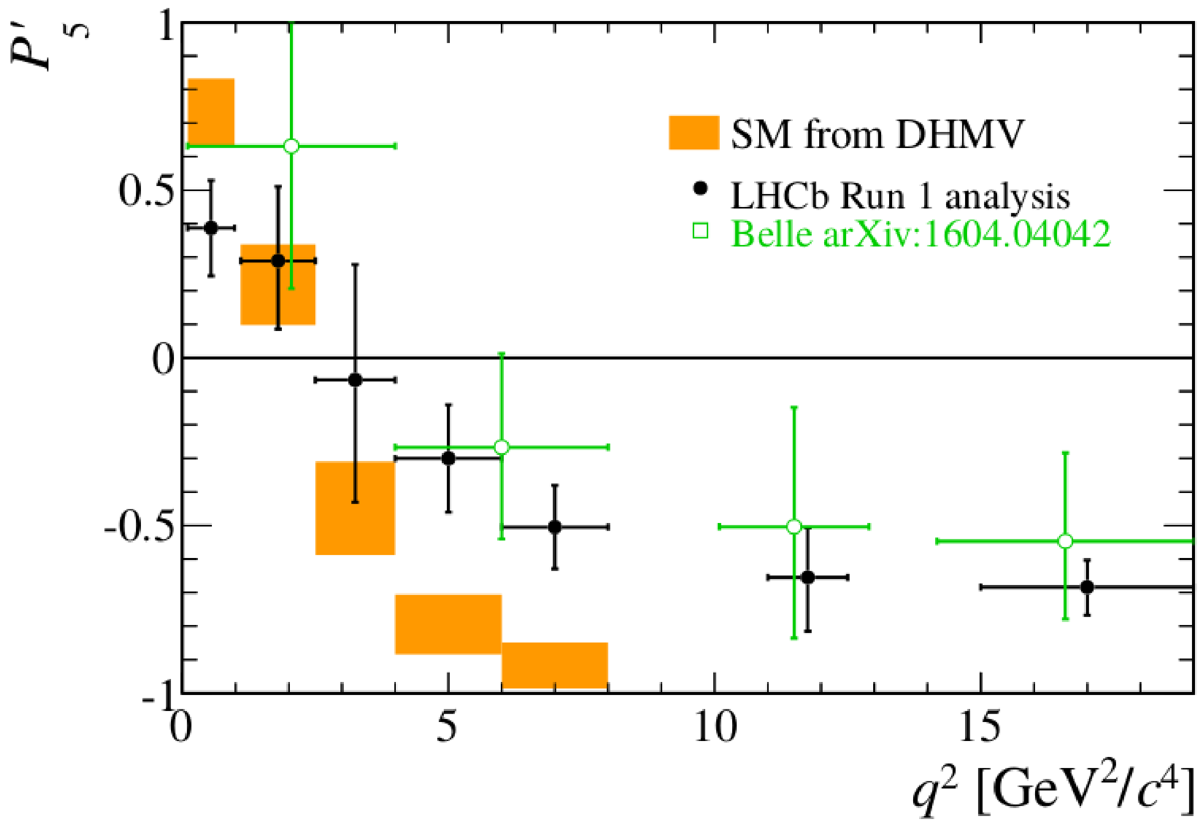
$$\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^3(\Gamma+\bar{\Gamma})}{d\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \tfrac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- F_L, A_{FB}, S_i sensitive to $C_7^{(')}$, $C_9^{(')}$, $C_{10}^{(')}$

Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

[arXiv:1512.04442]

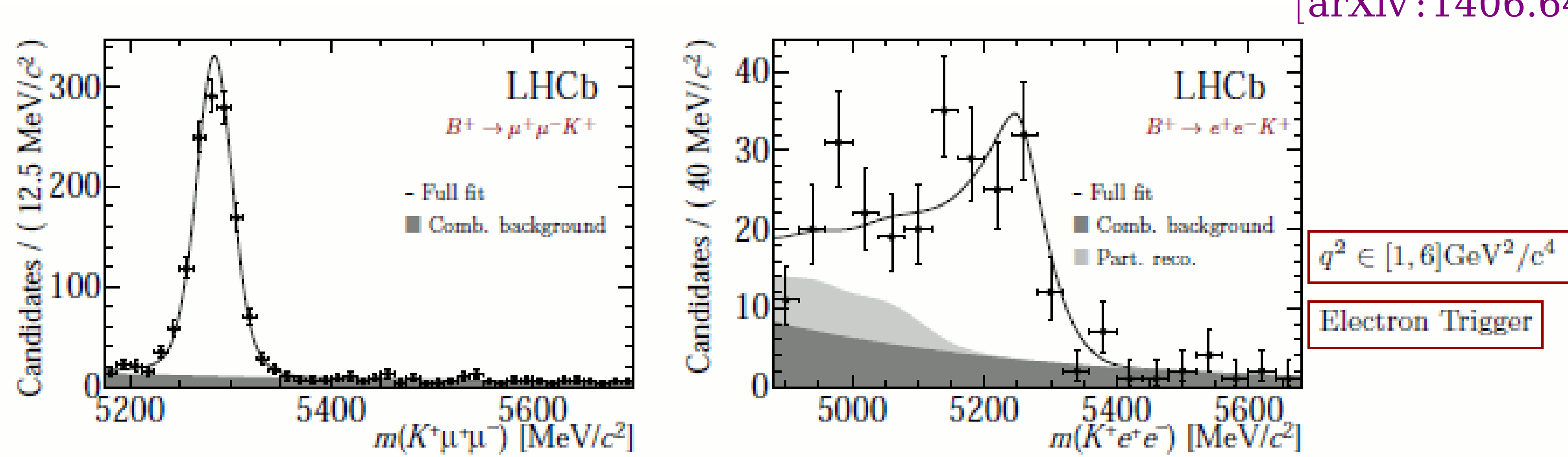
- no deviation for A_{FB} but...
- Form-factor independent observable $P_5' = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$



- Tension in P_5' seen with $1\,fb^{-1}$ is confirmed
- Local deviations of 2.9σ and 3.0σ for $q^2 \in [4.0, 6.0]$ and $[6.0, 8.0]$ GeV^2
- Naive combination of the two gives local significance of 3.7σ

Test of lepton universality using $B^+ \to K^+ l^+ l^-$ decays

[arXiv:1406.6482]

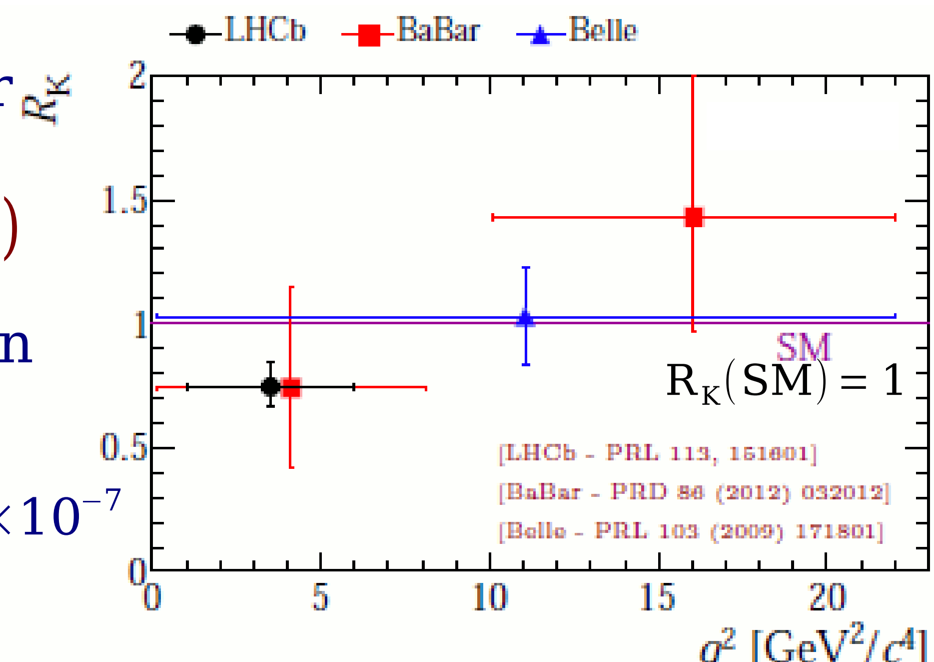


R_K: ratio of branching fractions for dilepton invariant mass squared range $1<q^2<6\,\mathrm{GeV}^2/c^4$

- The combination of the various trigger channels gives:

  $$\mathbf{R_K = 0.745\,^{+0.090}_{-0.074}(stat) \pm 0.036(syst)}$$

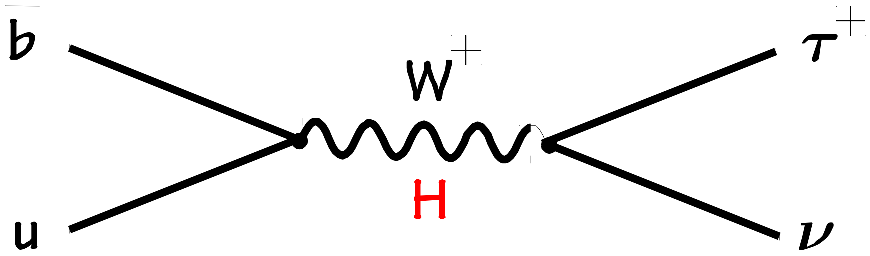
- Most precise measurement to date is in disagreement with SM at 2.6σ level

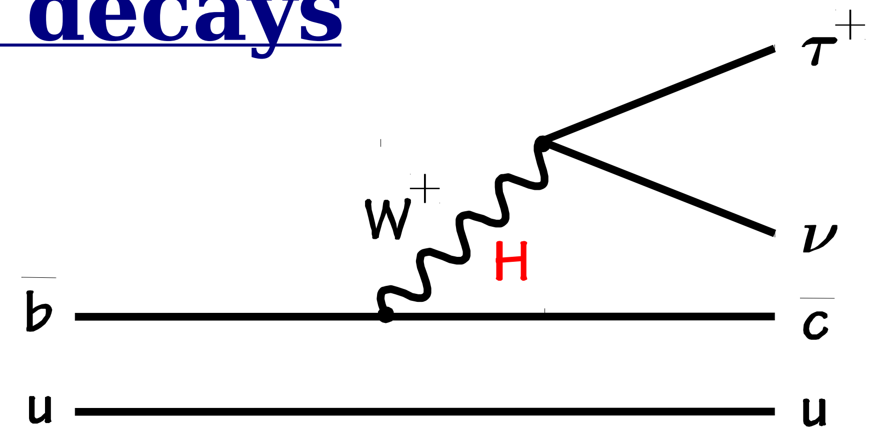


$\Rightarrow$ $B(B^+ \to e^+e^-K^+) = (1.56\,^{+0.19}_{-0.15}(\mathrm{stat})\,^{+0.06}_{-0.05}(\mathrm{syst}))\times 10^{-7}$ compatible with SM predictions

Lepton Flavor Non-Universality ? effect is in $\mu\mu$, not ee

Tauonic B decays





$B \to \tau \nu$

$$\mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

$$\text{2HDM (type II)}: \mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B
and other CKM uncertainties by combining with precise Δm_d

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

$$\text{2HDM (type II)}: \mathcal{B}(B \to D \tau^+ \nu) = G_F^2 \tau_B |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

uncertainties from form factors F_V and F_S can be studied
with $B \to D l \nu$ (more form factors in $B \to D^* \tau \nu$)

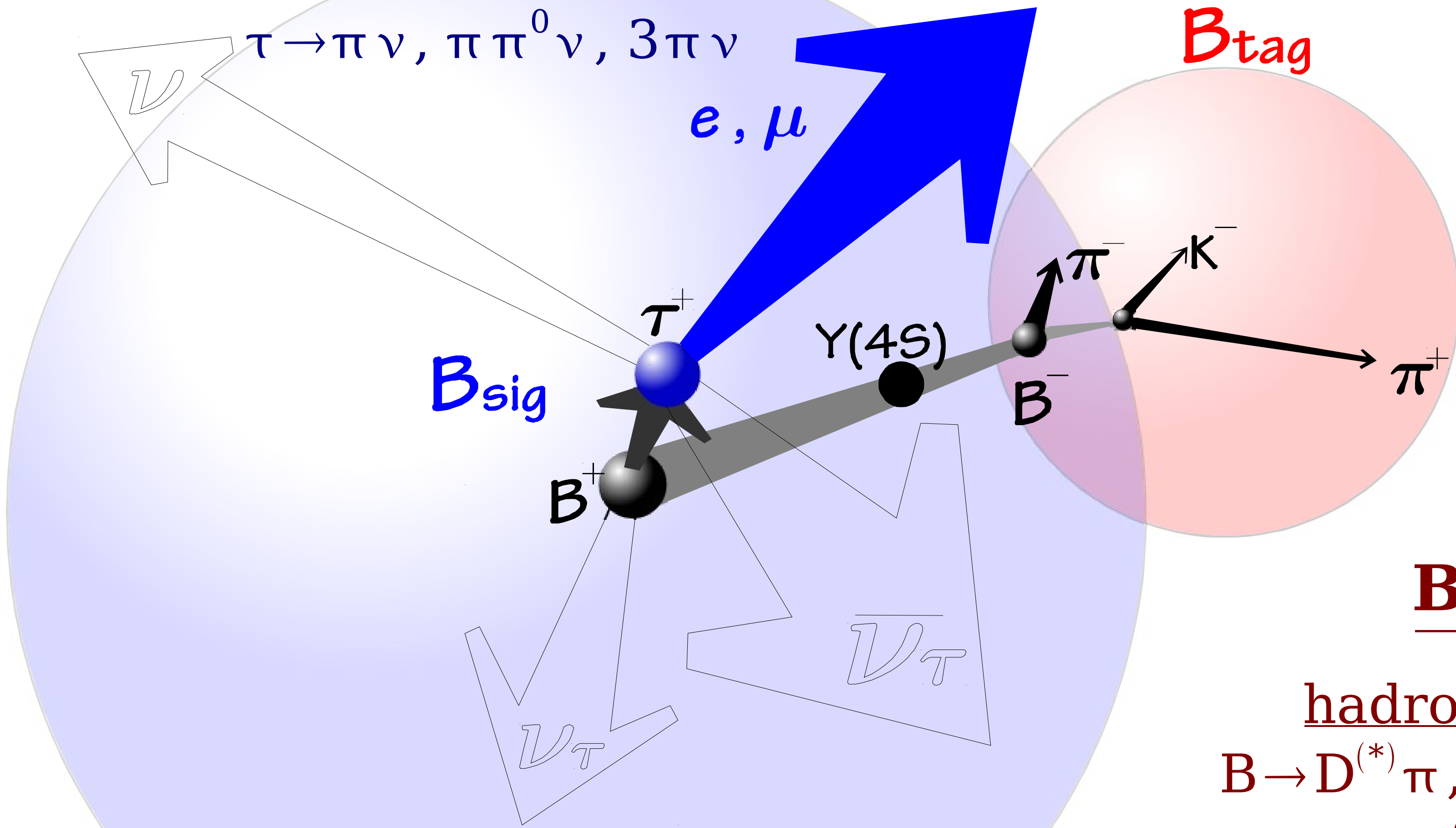
Event reconstruction in B→τ ν

B_{sig}→τ ν

(70 % of all τ decays)

τ→e ν ν , μ ν ν ,

τ→π ν , π π^{0}ν , 3π ν



Require no particle
and no energy left
after removing B_{tag}
and visible particles of B_{sig}

B_{tag}

hadronic tag

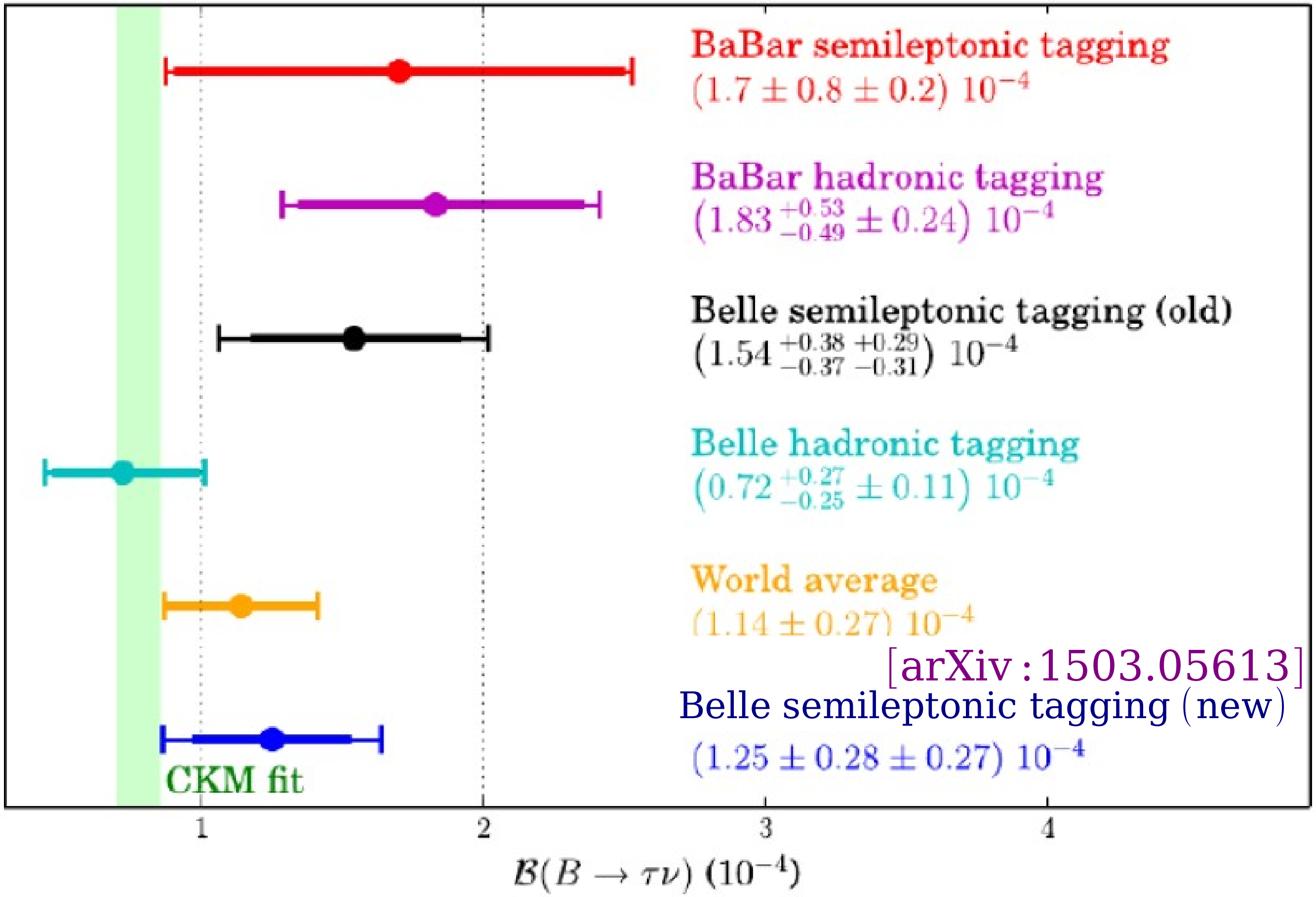
B→D$^{(*)}$π , D$^{(*)}$rho....

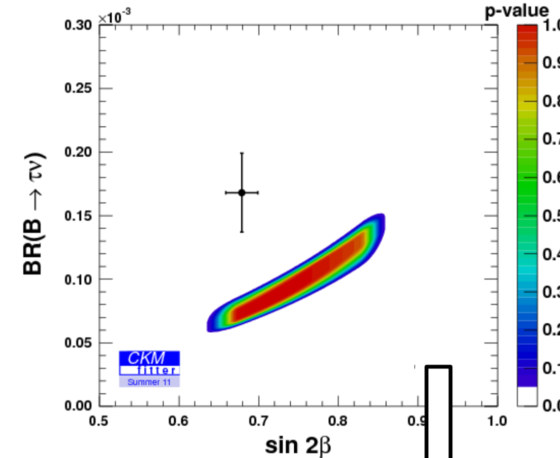
ϵ ~ 0.2 %

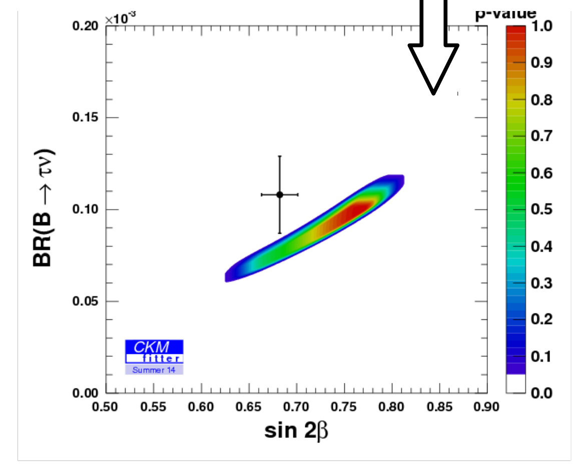
semileptonic tag

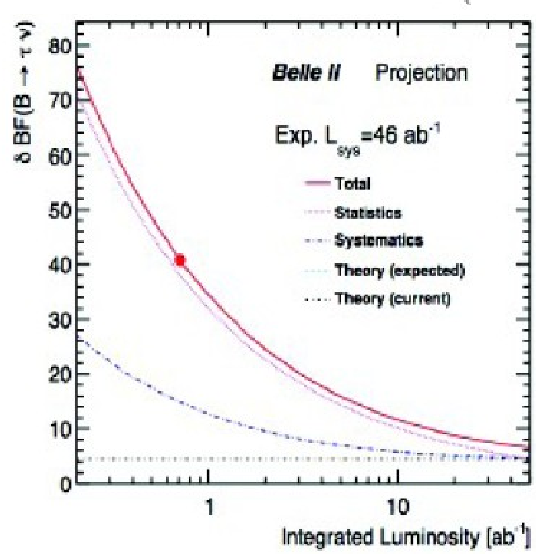
B→D$^{(*)}$l ν X

B→τν status







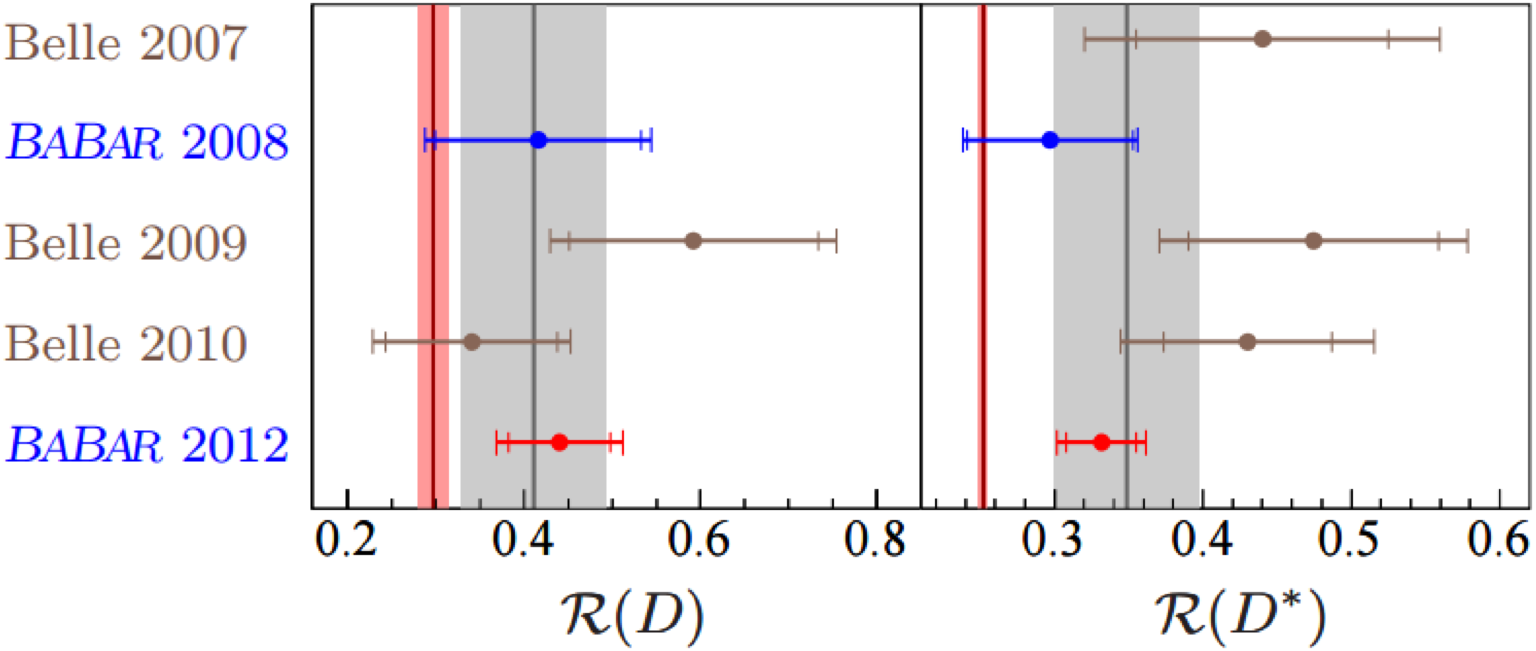


Belle II	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	19.0	(7.1, 2.2)	20.4	2.5	20.5
5 ab^{-1}	7.2	(2.7, 2.2)	7.9	1.5	8.1
50 ab^{-1}	2.3	(0.8, 2.2)	3.2	1.0	3.4
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
605 fb^{-1}	12.4	$(9.0, ^{+3.0}_{-4.8})$	$^{+15.6}_{-16.1}$	2.5	$^{+15.8}_{-16.2}$
5 ab^{-1}	4.3	$(3.1, ^{+3.0}_{-4.8})$	$^{+6.1}_{-7.2}$	1.5	$^{+6.3}_{-7.3}$
50 ab^{-1}	1.4	$(1.0, ^{+3.0}_{-4.8})$	$^{+3.4}_{-5.1}$	1.0	$^{+3.6}_{-5.2}$

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

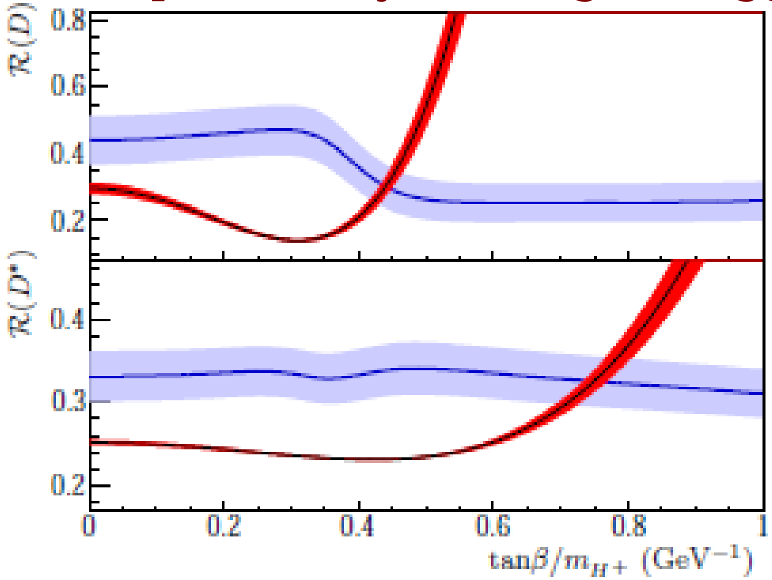
$$R(D^{(*)}) = \frac{B \to D^{(*)} \tau \nu}{B \to D^{(*)} l \nu}$$

Babar and Belle measurements hint to deviation from SM



BaBar (arXiv:1303.0571) observes a 3.4σ excess over SM expectation

''This excess cannot be explained by a charged Higgs boson in the 2HDM type II''



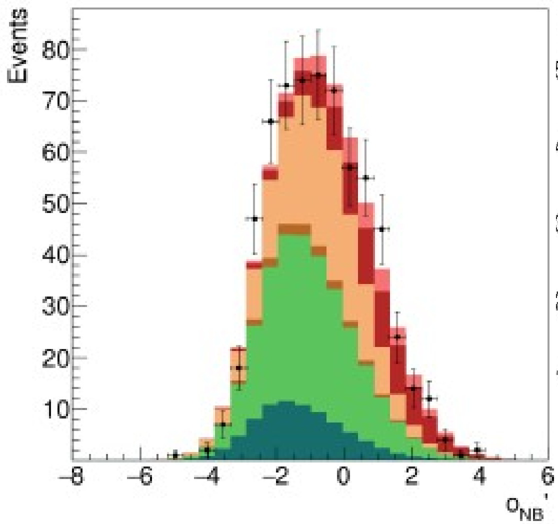
$B \to D^{(*)} \tau \nu$ at Belle

[arXiv:1507.03233]

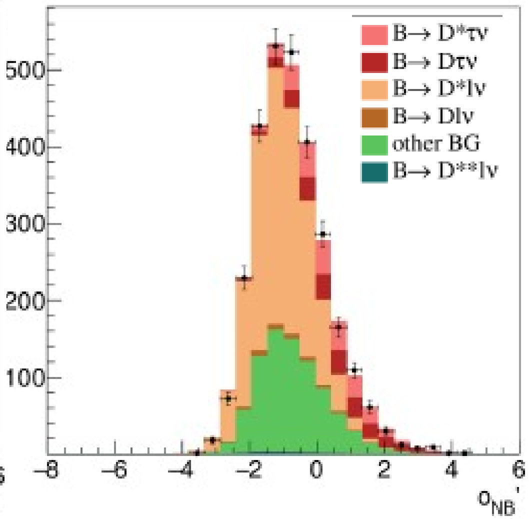
(with hadronic tagging)

projections for large M^2_{miss} region, $N(D\tau\nu) \sim 300$, $N(D^*\tau\nu) \sim 500$

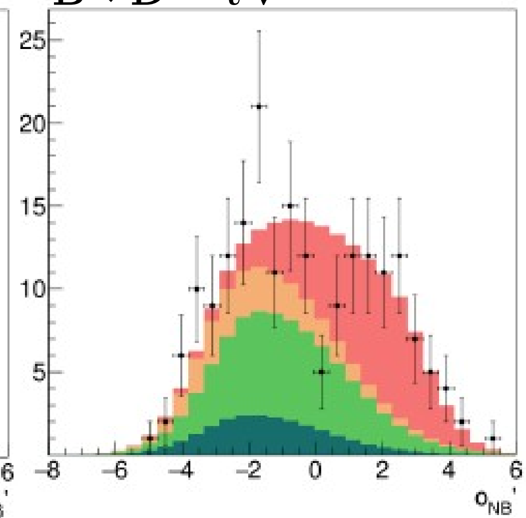
$B \to D^+ \tau \nu$



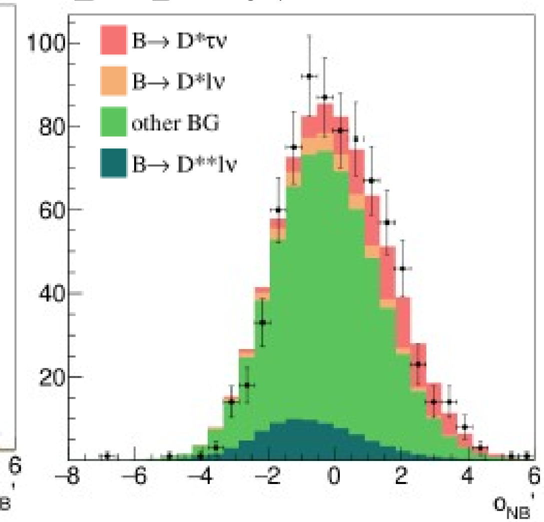
$B \to D^0 \tau \nu$



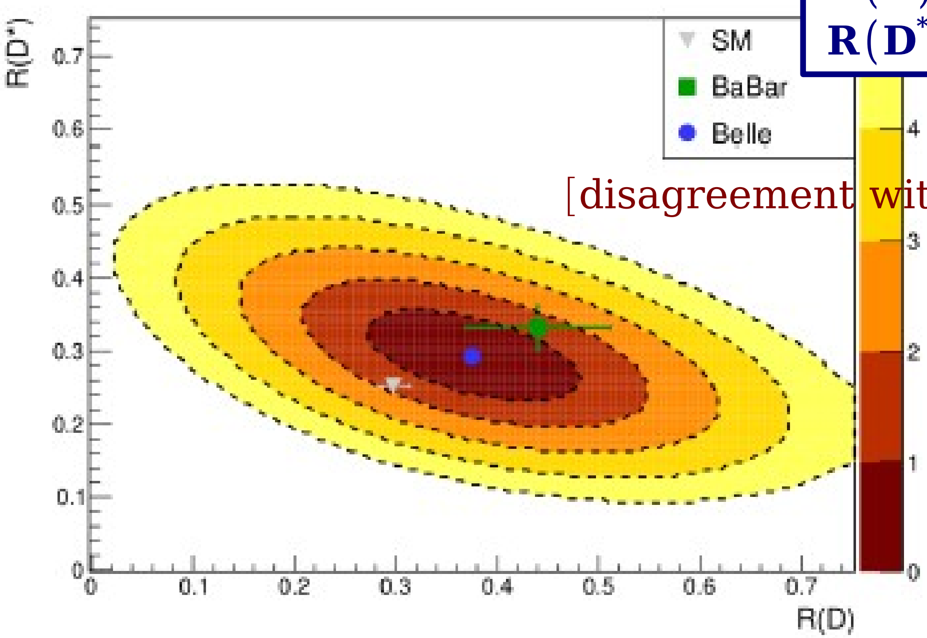
$B \to D^{*+} \tau \nu$



$B \to D^{*0} \tau \nu$



$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

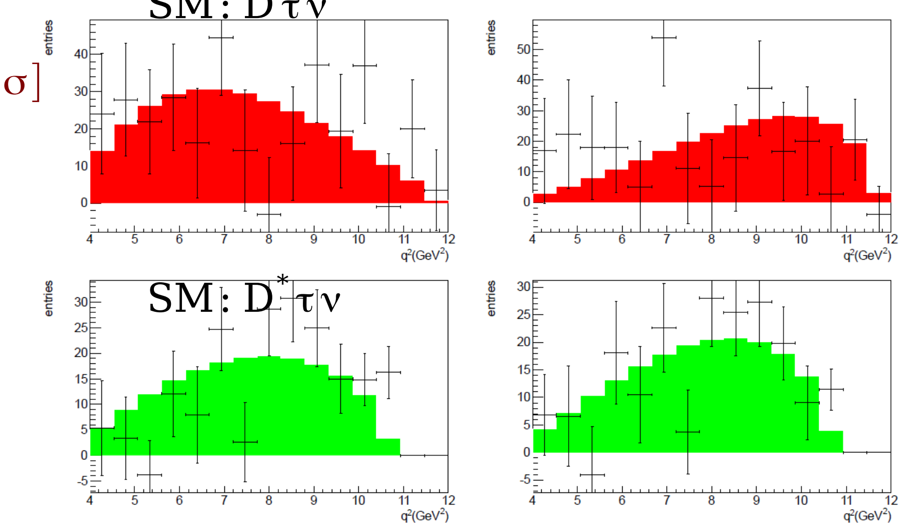


[disagreement with SM at 1.5σ]

stat error only !

SM: $D\tau\nu$

SM: $D^*\tau\nu$



$B \to D^{*+} \tau \nu$ at LHCb

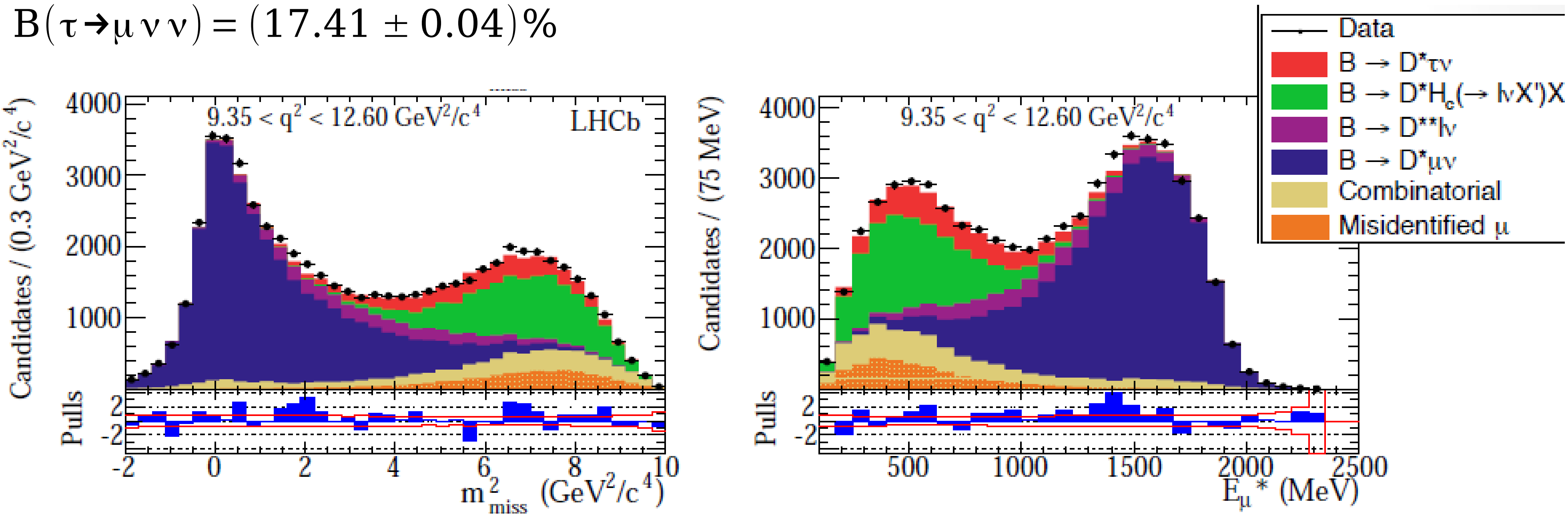
[arXiv:1506.08614]

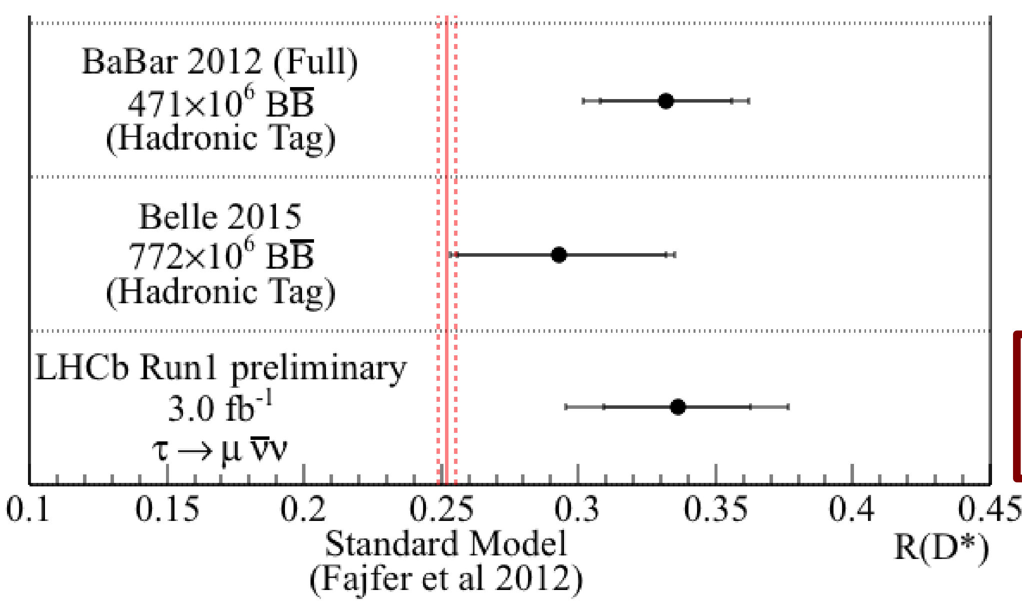
$$R(D^*) \equiv \frac{\mathcal{B}\left(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu\right)}$$

363,000 ± 1,600 events in $D^*\mu\nu$ sample

$N(D^*\tau\nu)/N(D^*\mu\nu) = (4.54 \pm 0.46)\%$

$B(\tau \to \mu\nu\nu) = (17.41 \pm 0.04)\%$





$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

[arXiv:1507.03233]

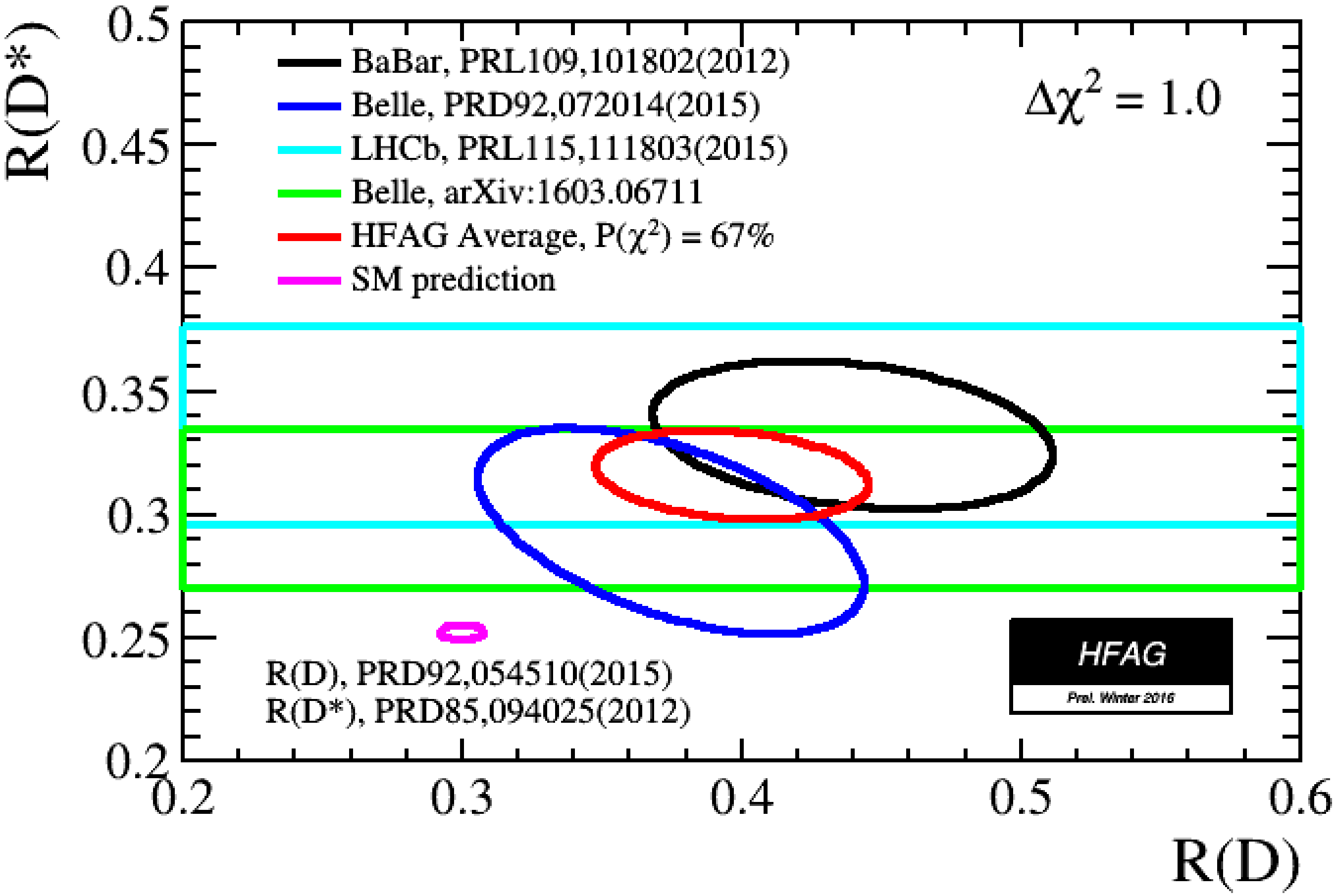
$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

[disagreement with SM at 2.1 σ]

[arXiv:1506.08614]

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

$$\Rightarrow \quad R(D^{(*)}) = \frac{BF(B \to D \tau \nu_\tau)}{BF(B \to D l \nu_l)}$$



BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

LHCb

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

$R(D) = 0.397 \pm 0.040 \pm 0.028$
$R(D^*) = 0.316 \pm 0.016 \pm 0.010$

difference with SM predictions is at **4.0** σ level

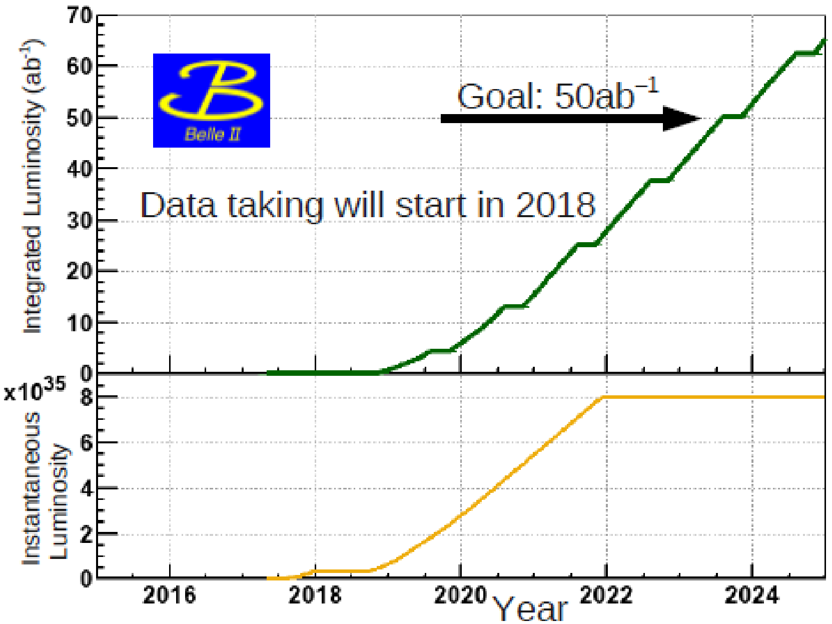
$\Rightarrow$ more measurements to come, more observables (τ polarization...)

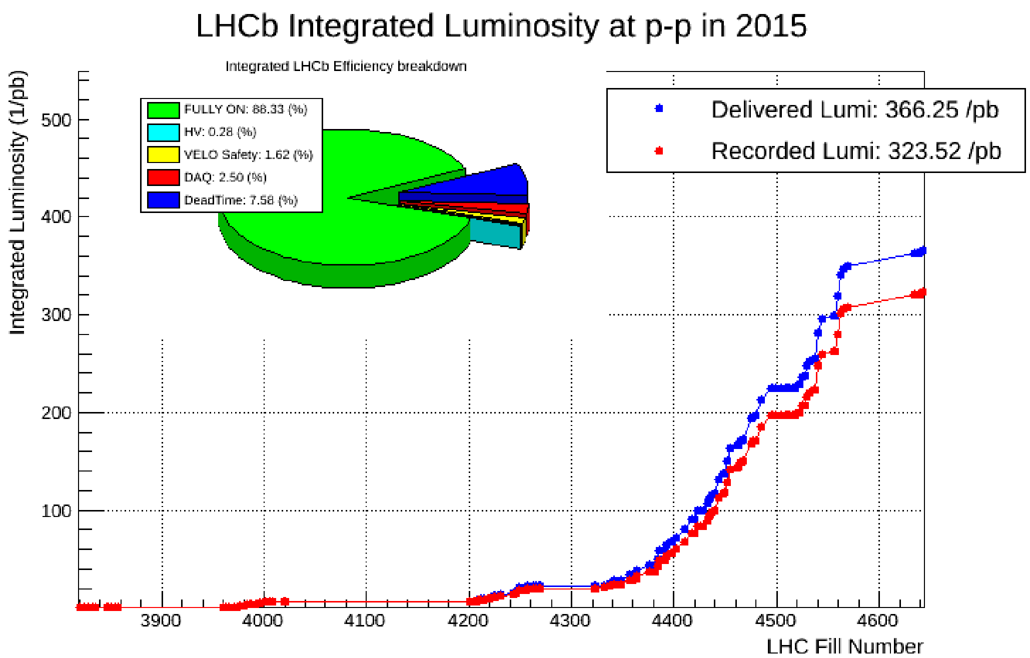
Summary

- Few results on CP violation and rare decays in B sector covered in this talk... but much more in B decays, also in charm, charmonium, bottomonium, light Higgs, τ, kaon sectors...

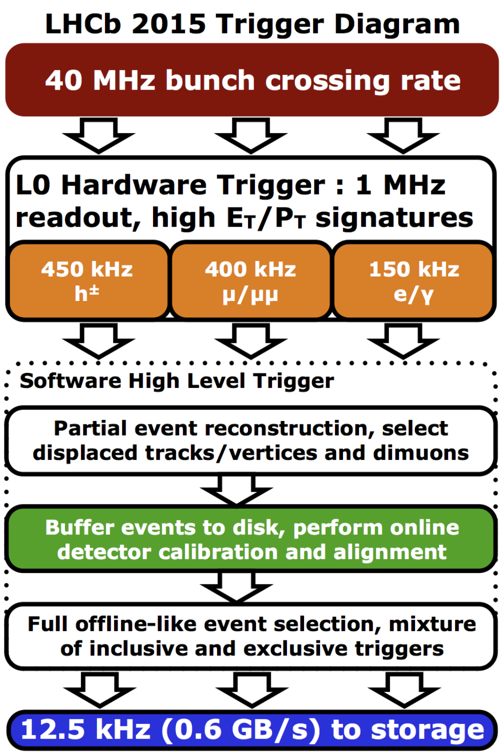
- Definitely not only complementary, but stimulating competition between (super) B-factories and LHCb (upgrade):
  - for the expected: results on $B_{(s)} \to \mu\mu$, $B \to K^* \mu\mu$, $B_s \to J/\psi \varphi$, γ angle...
  - for the less expected: results on $|V_{ub}|$, $D^* \tau \nu$...

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}





LHCb Integrated Luminosity at p-p in 2015
Integrated LHCb Efficiency breakdown
FULLY ON: 88.33 (%)
HV: 0.28 (%)
VELO Safety: 1.62 (%)
DAQ: 2.50 (%)
DeadTime: 7.58 (%)
Delivered Lumi: 366.25 /pb
Recorded Lumi: 323.52 /pb
Integrated Luminosity (1/pb)
LHC Fill Number



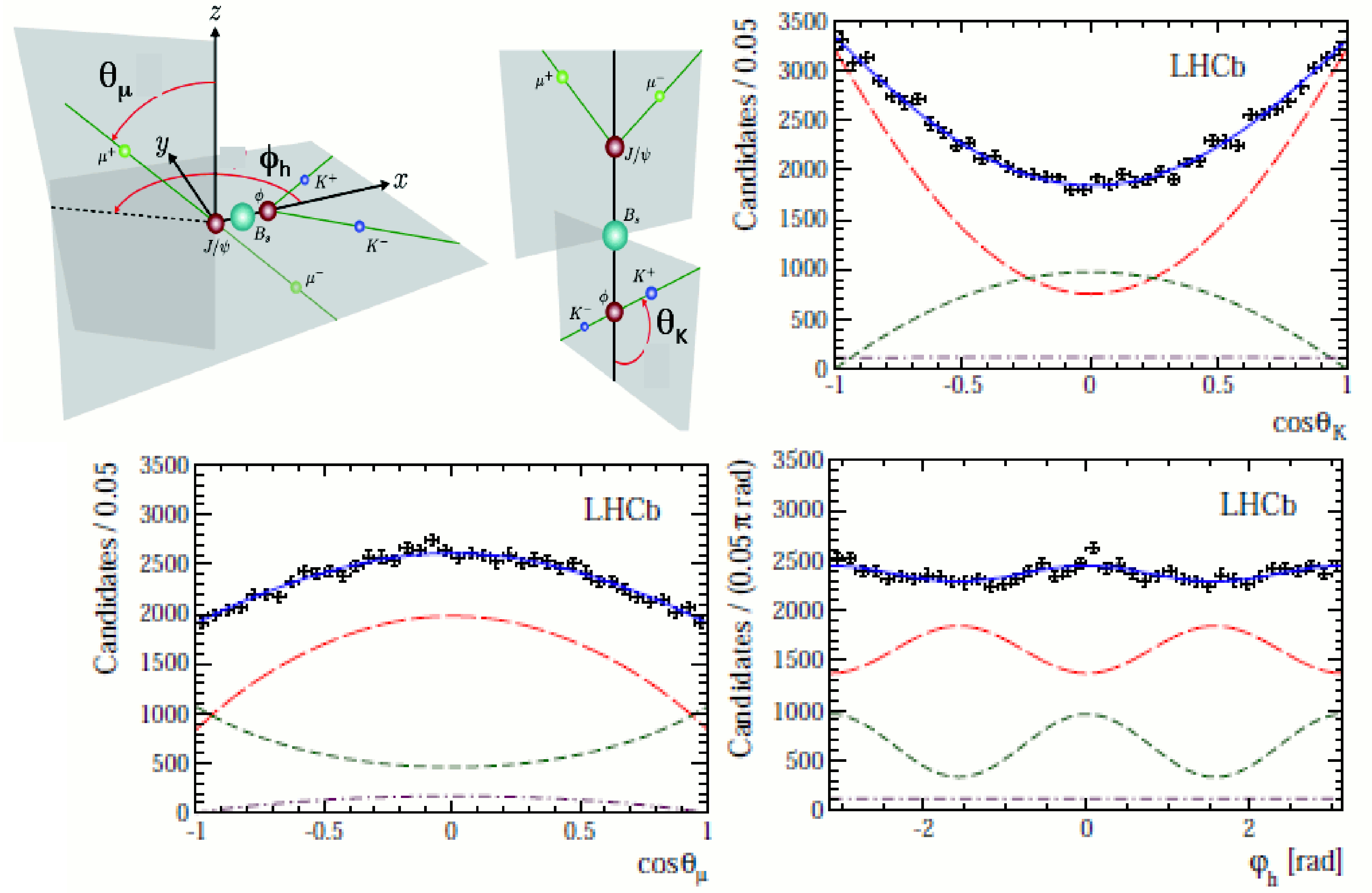
LHCb 2015 Trigger Diagram
40 MHz bunch crossing rate
L0 Hardware Trigger : 1 MHz readout, high ET/PT signatures
450 kHz h±
400 kHz μ/μμ
150 kHz e/γ
Software High Level Trigger
Partial event reconstruction, select displaced tracks/vertices and dimuons
Buffer events to disk, perform online detector calibration and alignment
Full offline-like event selection, mixture of inclusive and exclusive triggers
12.5 kHz (0.6 GB/s) to storage

CPV in $B_s \to J/\psi\varphi$ at LHCb

[3 fb^{-1}, arXiv:1411.3104]

CP-even
CP-odd
S-wave (KK)

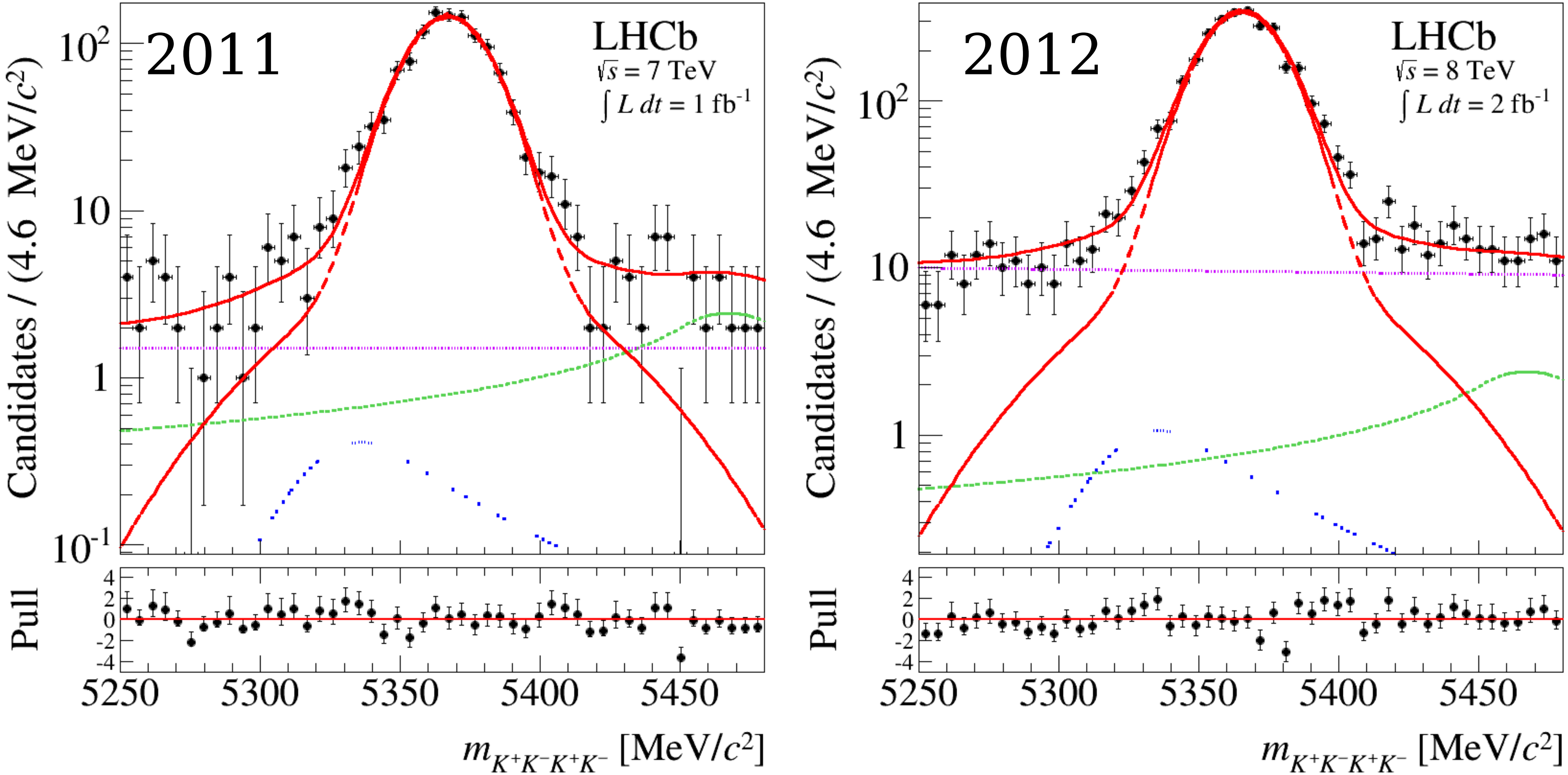
mixture of CP eigenstates ⇒ angular analysis in helicity basis



$B_s \to \varphi\varphi$

[arXiv:1407.2222]

$\bar{b} \to \bar{s} s \bar{s}$ loop process



- 4000 signal events
- Combinatorial background is flat and small
- Very small contributions from mis-ID of $B_d \to \varphi K^{*0}$ and $\Lambda_b \to \varphi p K$
- mixture of CP eigenstates ⇒ angular analysis in helicity basis

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

$\varphi_s(c\bar{c}s) \sim -0.01 \pm 0.04$ rad

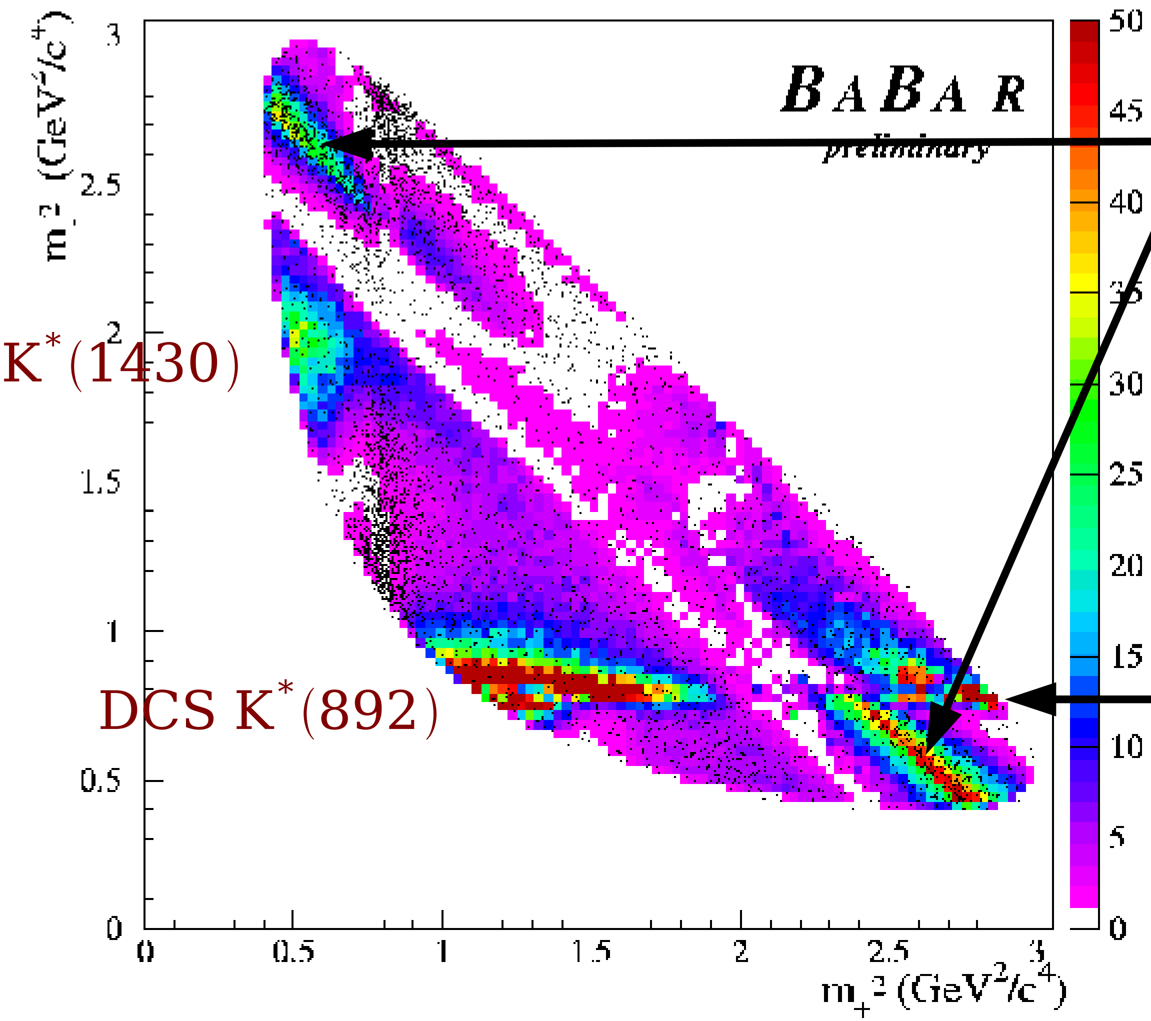
$\varphi_s(\mathrm{SM}) = -0.0363\,^{+0.0012}_{-0.0014}$

Sensitivity to γ in $B \to D(K_S \pi\pi)K$ mode

sensitivity to γ/ϕ_3 varies across the Dalitz plot

$\gamma=75^\circ$, $\delta=180^\circ$, $r_B=0.125$

$w=1/(d^2L/d\gamma^2)$



DCS $K^*(1430)$

DCS $K^*(892)$

GLW like

Interference of

$B^- \to D^0 K^-$, $D^0 \to K_S^0 \rho^0$

with

$B^- \to \overline{D}^0 K^-$, $\overline{D}^0 \to K_S^0 \rho^0$

ADS like

Interference of

$B^- \to D^0 K^-$, $D^0 \to K^{*+} \pi^-$

with

$B^- \to \overline{D}^0 K^-$, $\overline{D}^0 \to K^{*+} \pi^-$

$B \to D^{(*)} K^{(*)}$ Dalitz analysis

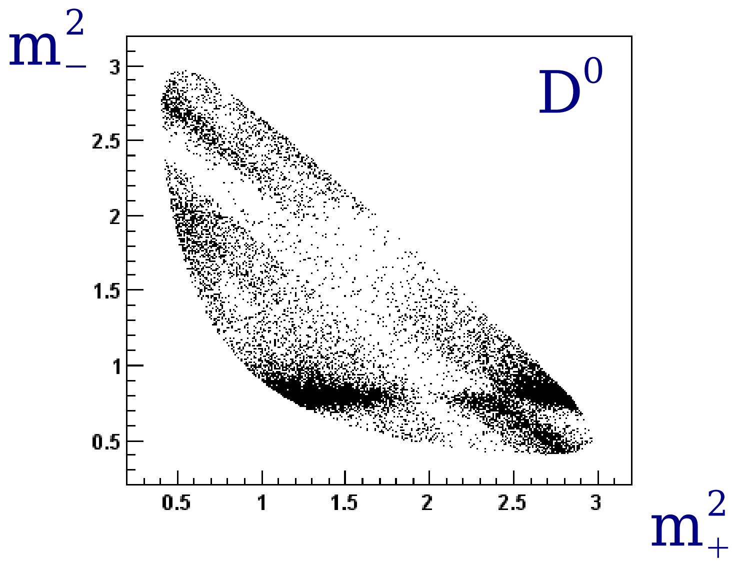
Reconstruction of three-body final states $D^0, \overline{D}^0 \to K_S \pi^+ \pi^-$

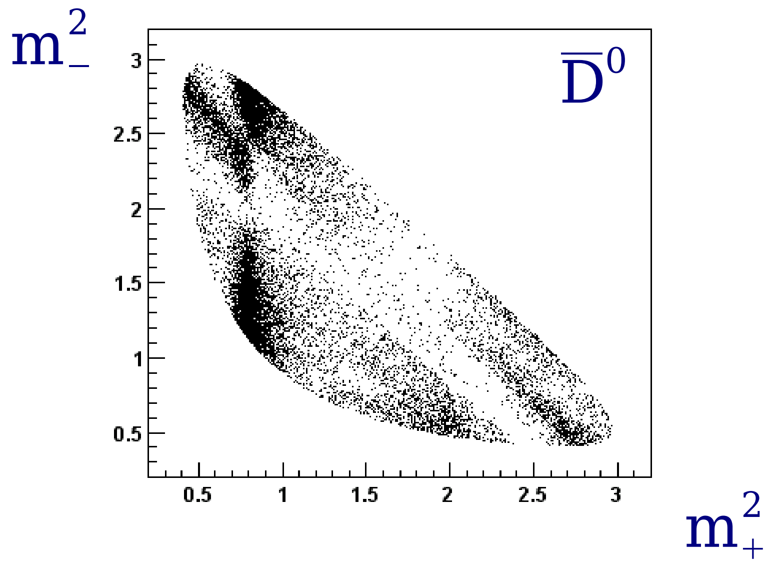
Amplitude for each Dalitz point is described as:

$$\overline{D}^0 \to K_S \pi^+ \pi^- \sim f(m_+^2, m_-^2)$$
$$D^0 \to K_S \pi^+ \pi^- \sim f(m_-^2, m_+^2)$$

$$B^+ \to (K_S \pi^+ \pi^-)_D K^+ : f(m_+^2, m_-^2) + r_B e^{i(\delta_B + \gamma)} f(m_-^2, m_+^2)$$

$m_- = M(K_S \pi^-)$
$m_+ = M(K_S \pi^+)$



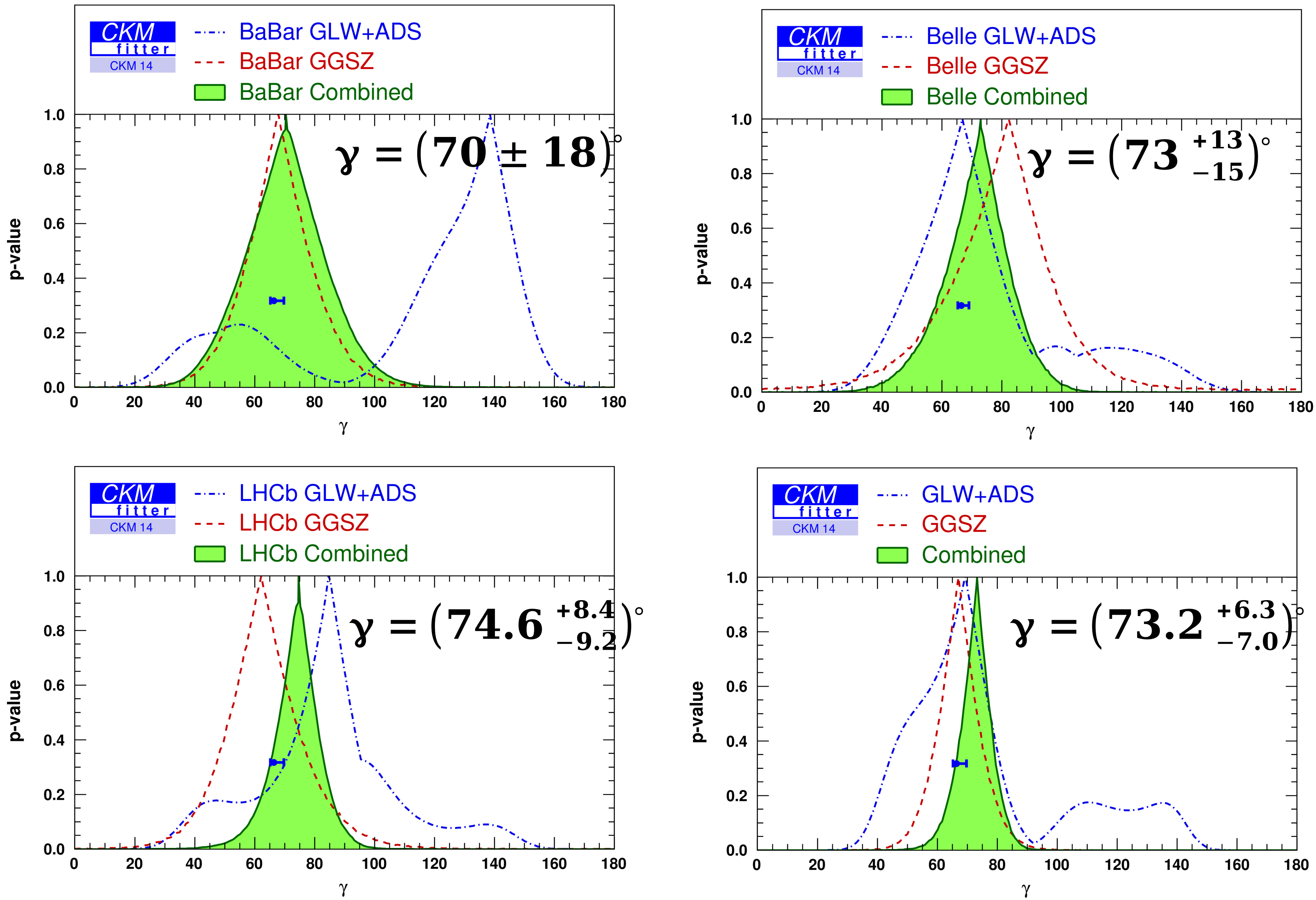


$$B^- \to (K_S \pi^+ \pi^-)_D K^- : f(m_-^2, m_+^2) + r_B e^{i(\delta - \gamma)} f(m_+^2, m_-^2)$$

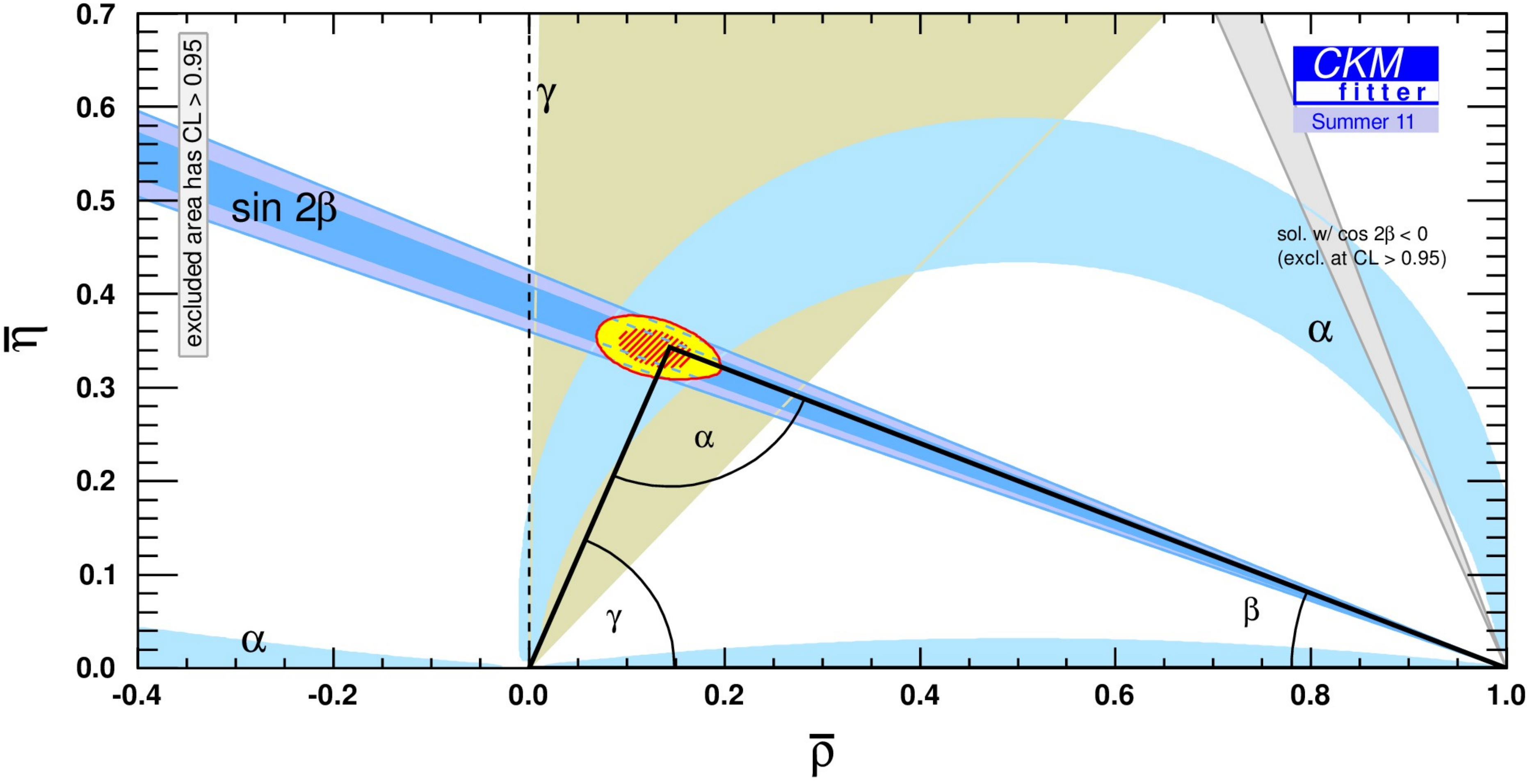
Simultaneous fit of B^+ and B^- to extract parameters r_B, γ and δ_B

Note: 2 fold ambiguity on γ: $(\gamma, \delta_B) \to (\gamma + \pi, \delta_B + \pi)$

Experiment by experiment

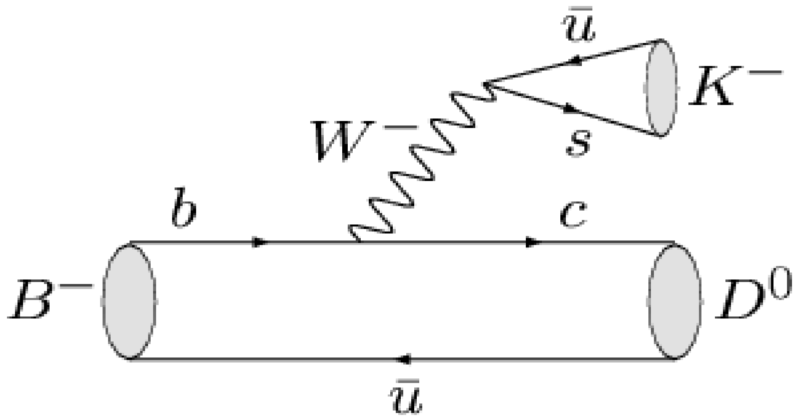


γ angle in the global fit

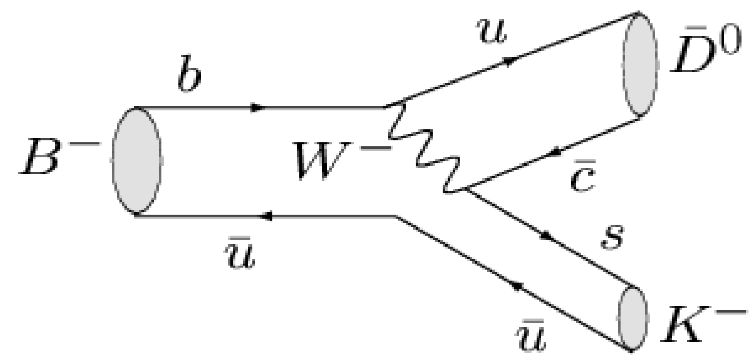


γ measurements from $B^{\pm} \rightarrow DK^{\pm}$

- Theoretically pristine $B \rightarrow DK$ approach
- Access γ via interference between $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \bar{D}^0 K^-$



color allowed
$B^- \rightarrow D^0 K^- \sim V_{cb} V_{us}^*$
$\sim A\lambda^3$



color suppressed
$B^- \rightarrow \bar{D}^0 K^- \sim V_{ub} V_{cs}^*$
$\sim A\lambda^3(\rho + i\eta)$

relative magnitude of suppressed amplitude is r_B

$$r_B = \frac{|A_{suppressed}|}{|A_{favoured}|} \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times [\text{color supp}] = 0.1\text{-}0.2$$

relative weak phase is γ, relative strong phase is δ_B

γ measurements from $B^{\pm} \to DK^{\pm}$

- Reconstruct D in final states accessible to both D^0 and $\overline{D}^0$
  - $D = D_{CP}$, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$

    GLW method (Gronau-London-Wyler)
  - $D = D_{sup}$, Doubly-Cabbibo suppressed decays as $K\pi$

    ADS method (Atwood-Dunietz-Soni)
  - Three-body decays as $D \to K_S\pi^+\pi^-$, $K_S K^+ K^-$

    GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

- Largest effects due to
  - charm mixing
  - charm CP violation

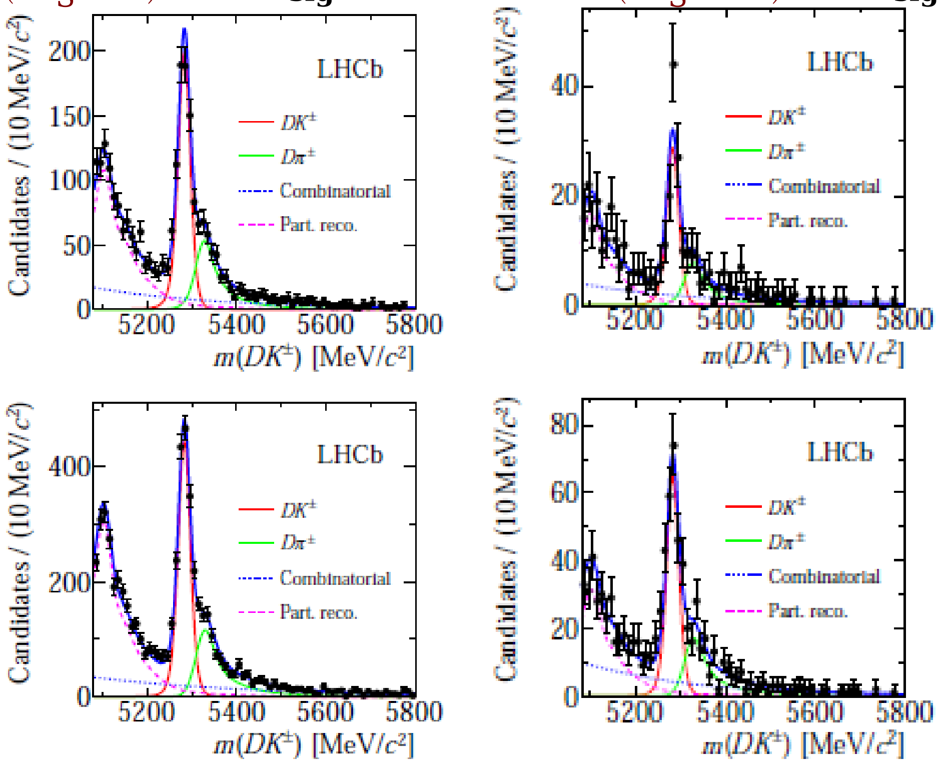
  } small, can be included

  Y.Grossman, A.Soffer, J.Zupan [PRD 72, 031501 (2005)]

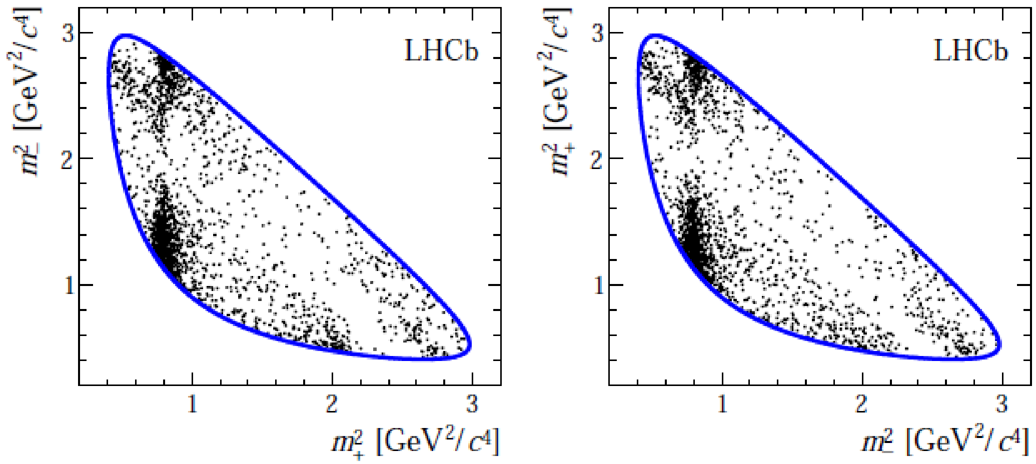
- Different B decays (DK, D^*K, DK^*)
  - different hadronic factors (r_B, δ_B) for each

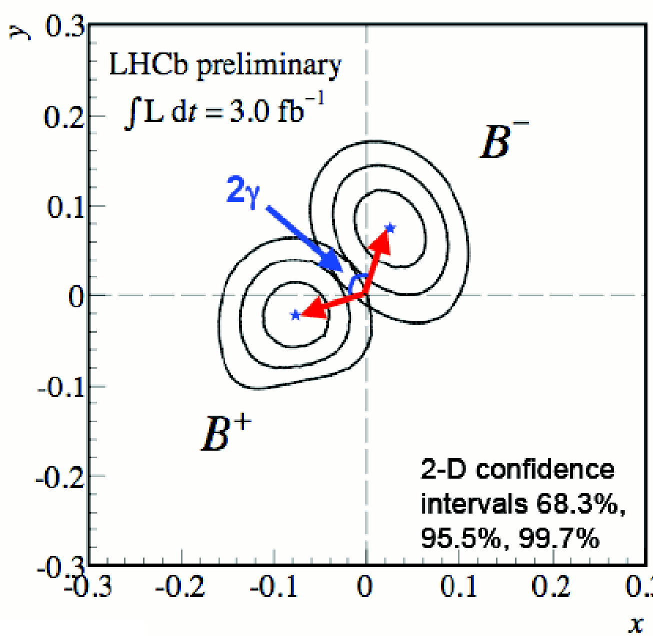
GGSZ LHCb Results [arXiv:1408.2748]

$D(K_S\pi\pi)K$ $N_{sig} \sim 2260$ $D(K_S KK)K$ $N_{sig} \sim 324$



$D(K_S\pi\pi)K$





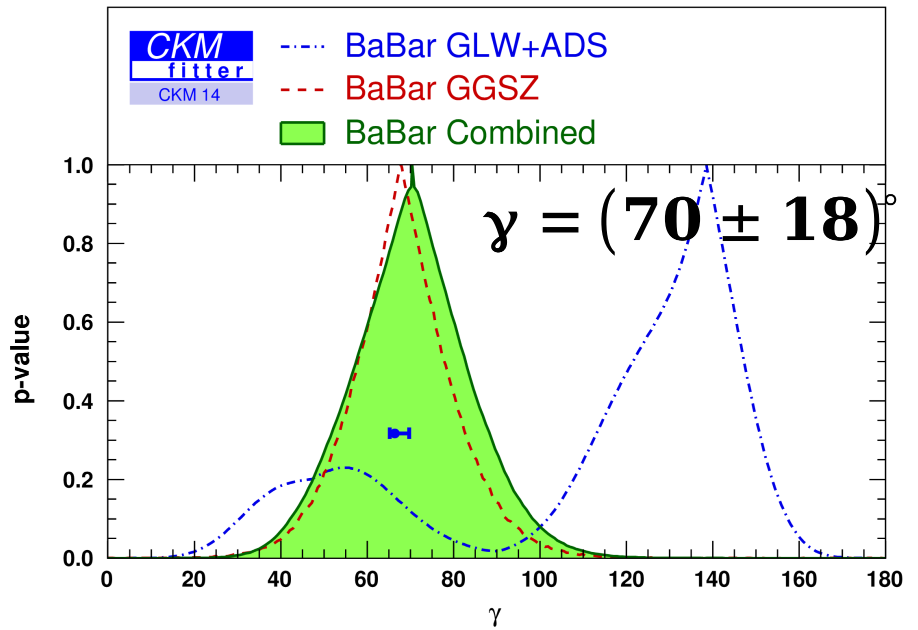
cartesian coordinates

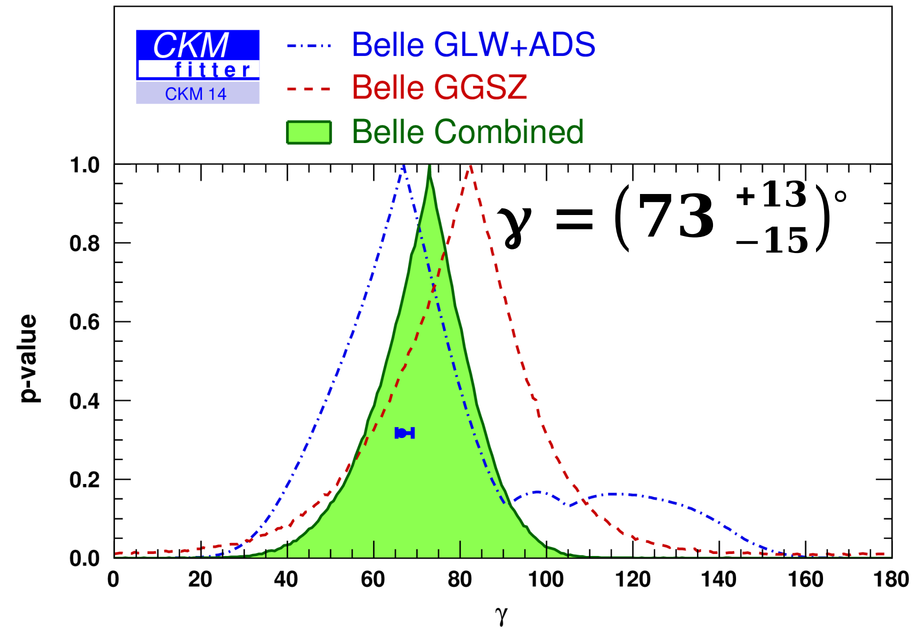
$$x^{\pm} = r_B \cos(\delta_B \pm \gamma)$$
$$y^{\pm} = r_B \sin(\delta_B \pm \gamma)$$

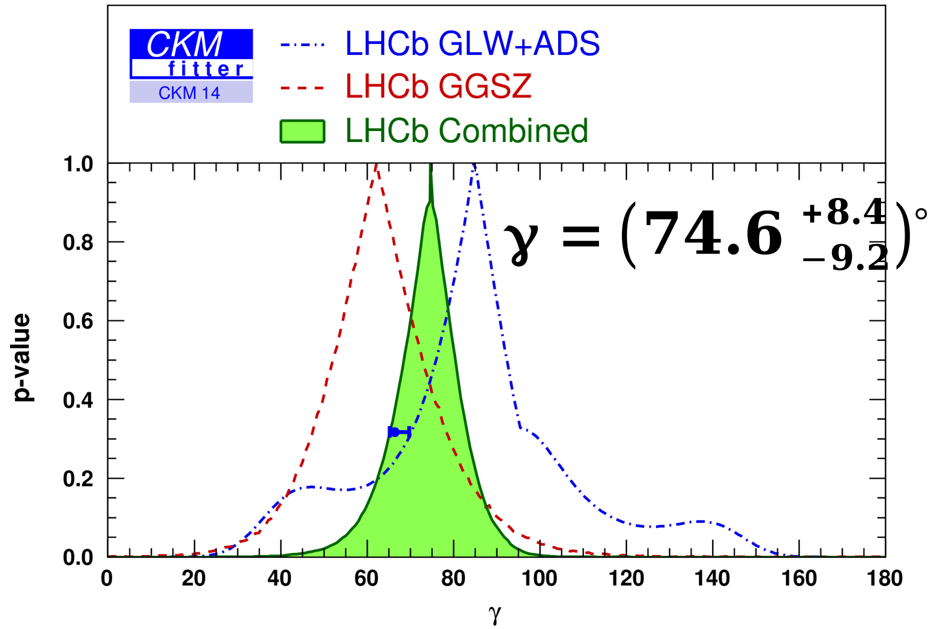
$\Rightarrow$

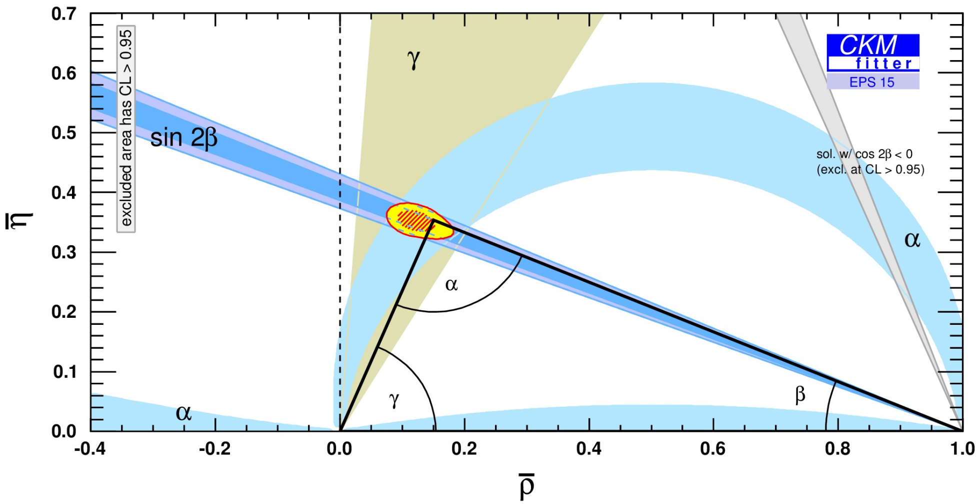
$$\gamma = (62^{+15}_{-14})^{\circ}$$
$$r_B = (8.0^{+1.9}_{-2.1}) \times 10^{-2}$$
$$\delta_B = (134^{+14}_{-15})^{\circ}$$

Experiment by experiment









long way to go … ($\rightarrow \sigma_\gamma = 1^\circ$ or less)

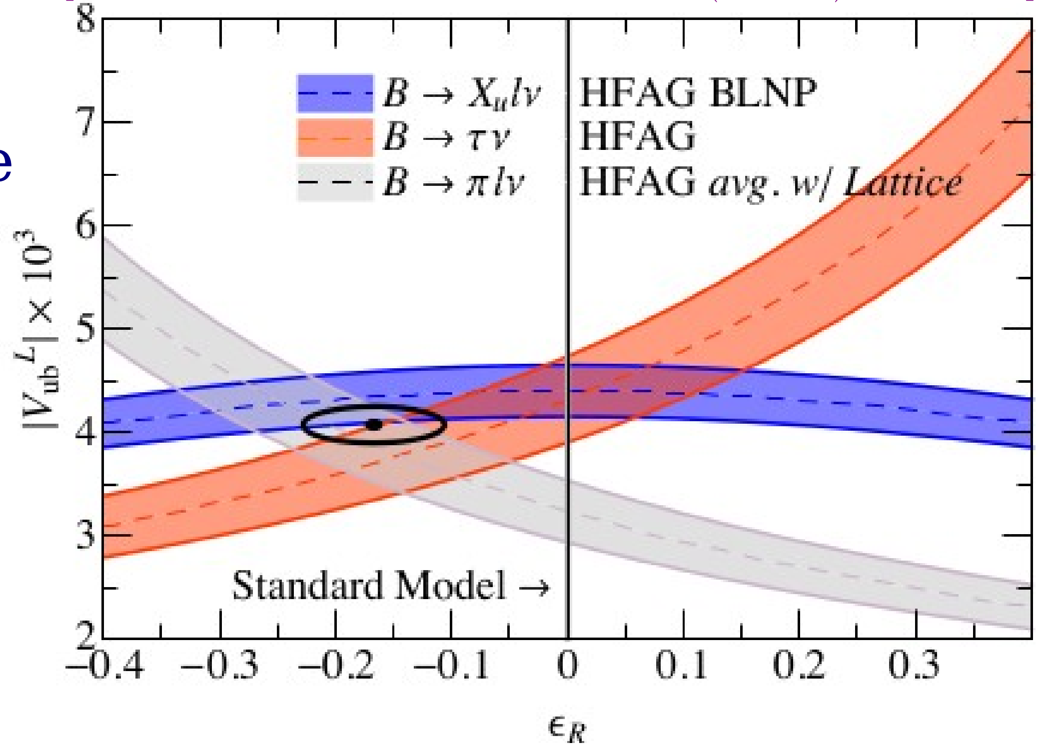
Could it be due to new physics ?

- $B \to \pi l \nu$ is a purely vector current, whereas $B \to X_u l \nu$ is V−A
- Adding right-handed current (V+A), increases vector current but decreases axial-vector current

A negative right-handed current can reduce tension between those two results

Decay	$\lvert V_{ub}\rvert \times 10^3$	ϵ_R dependence
$B \to \pi \ell \bar{\nu}$	3.23 ± 0.30	$1 + \epsilon_R$
$B \to X_u \ell \bar{\nu}$	4.39 ± 0.21	$\sqrt{1 + \epsilon_R^2}$
$B \to \tau \bar{\nu}_\tau$	4.32 ± 0.42	$1 - \epsilon_R$

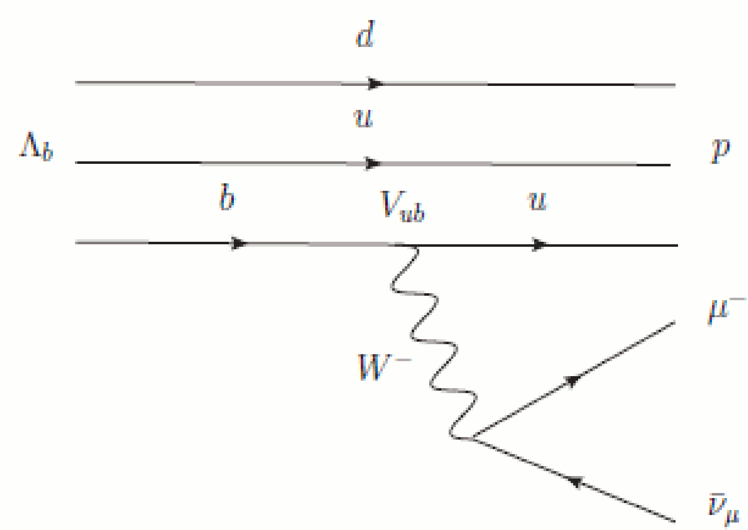
[F.Bernlochner et al, PRD 90 (2014) 094003]

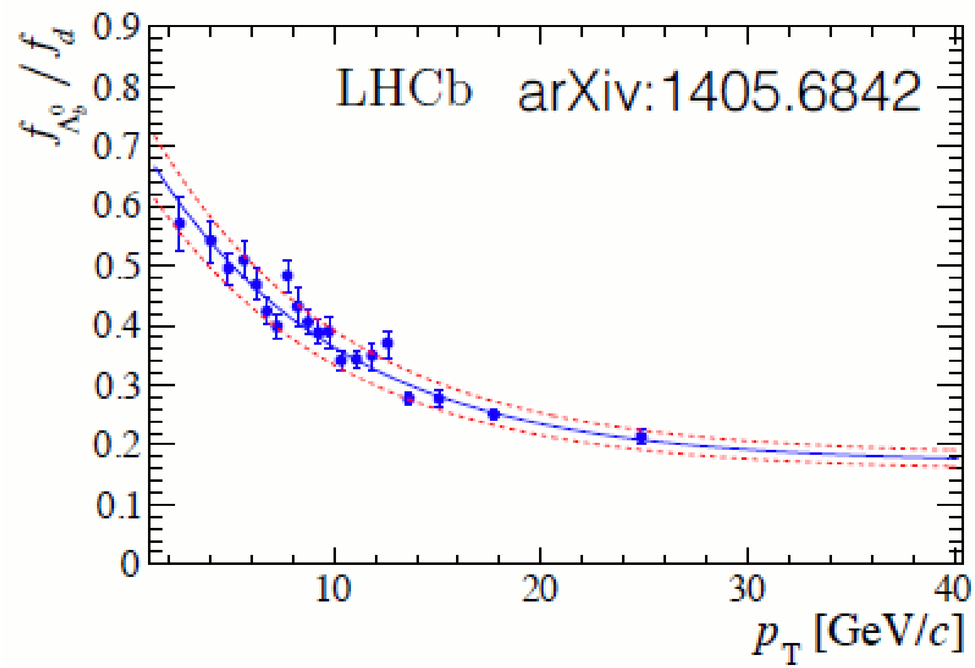


New measurements neeeded, with different approaches also

The decay $\Lambda_b^0 \to p \mu \nu$

- The decay $\Lambda_b^0 \to p \mu \nu$ is the baryonic version of $B \to \pi l \nu$
- Cleaner at LHCb as protons are rarer than kaons/pions
- Λ_b^0 baryons not produced at BaBar or Belle experiments but at the LHC produced 1/4 as often as B mesons





$\Rightarrow$ Signature in detector: displaced muon-proton vertex

Analysis strategy

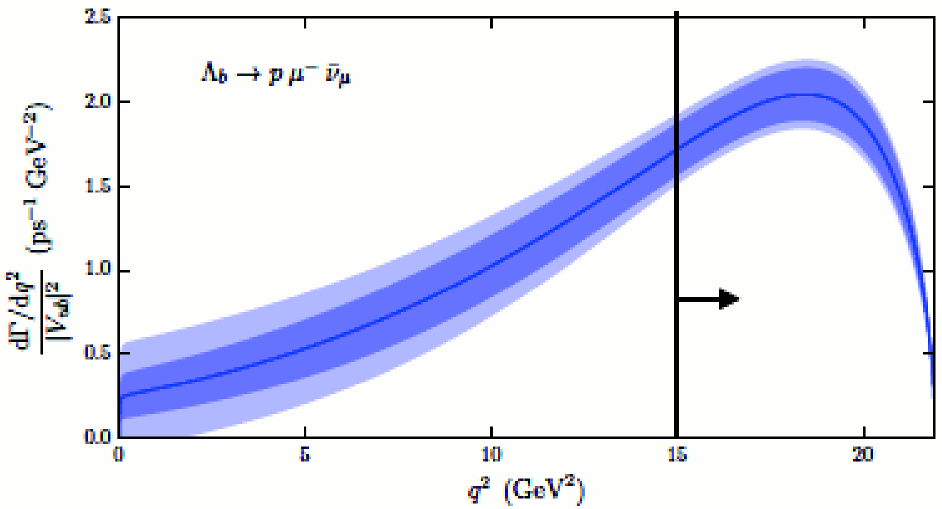
arXiv:1504.01568

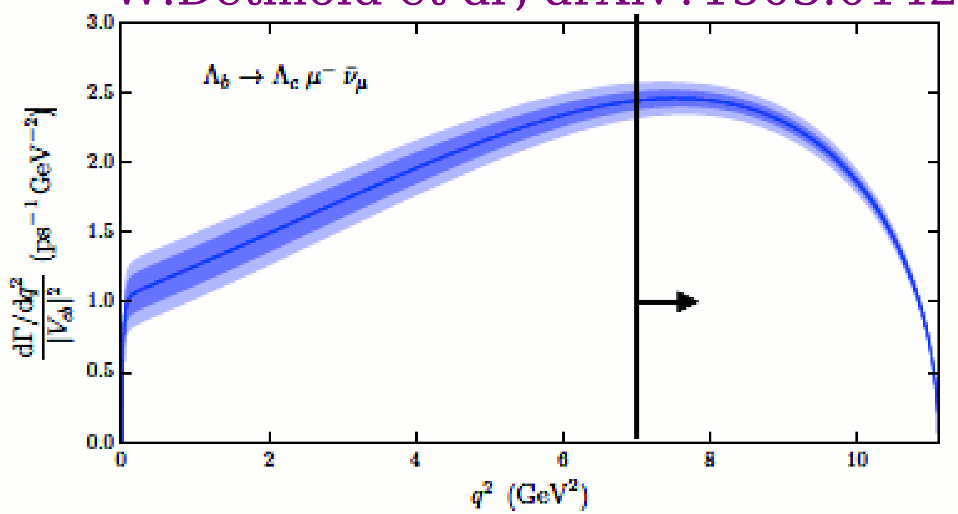
- Normalize signal yield to V_{cb} decay, $\Lambda_b^0 \to \Lambda_c \mu \nu$

  $\Rightarrow$ Cancel many systematic uncertainties (including the production rate of Λ_b baryons

- Calculate the branching fraction ratio at high q^2

W.Detmold et al, arXiv:1503.01421





$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu\nu)_{q^2>7\,\mathrm{GeV}^2}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}}{N(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2}} \times \frac{\epsilon(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu)_{q^2>7\,\mathrm{GeV}^2}}{\epsilon(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2}} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$$

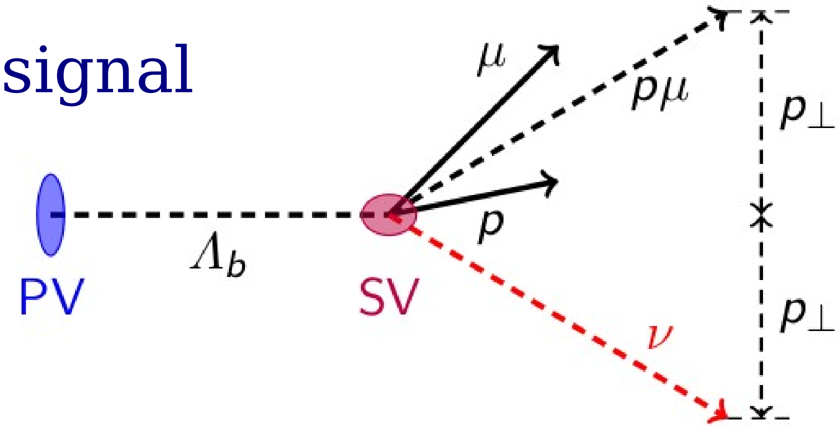
measured precisely by Belle !

Signal fit

arXiv:1504.01568

Corrected mass used to extract the signal

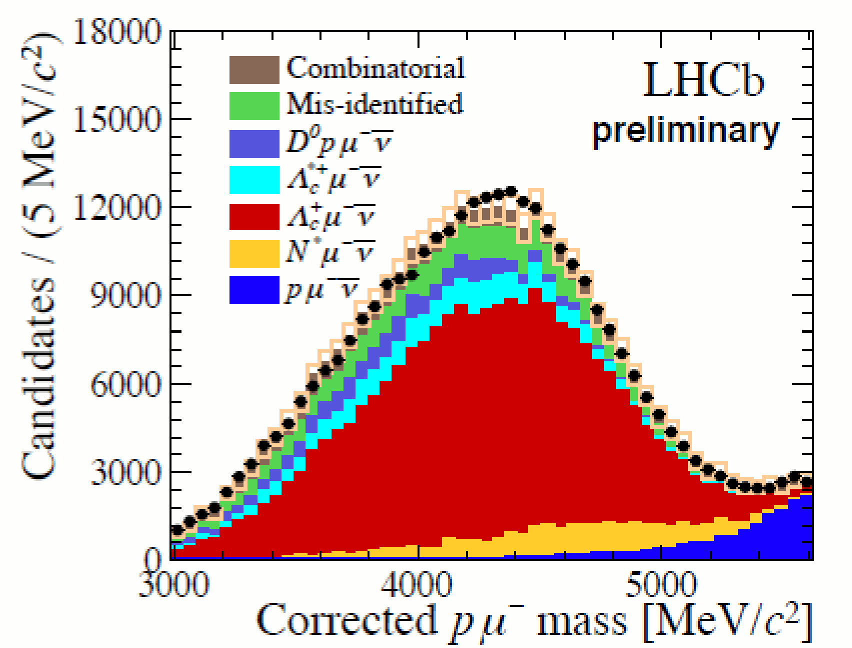
$$M_{corr} = \sqrt{p_{\perp}^2 + M_{p\mu}^2} + p_{\perp}$$

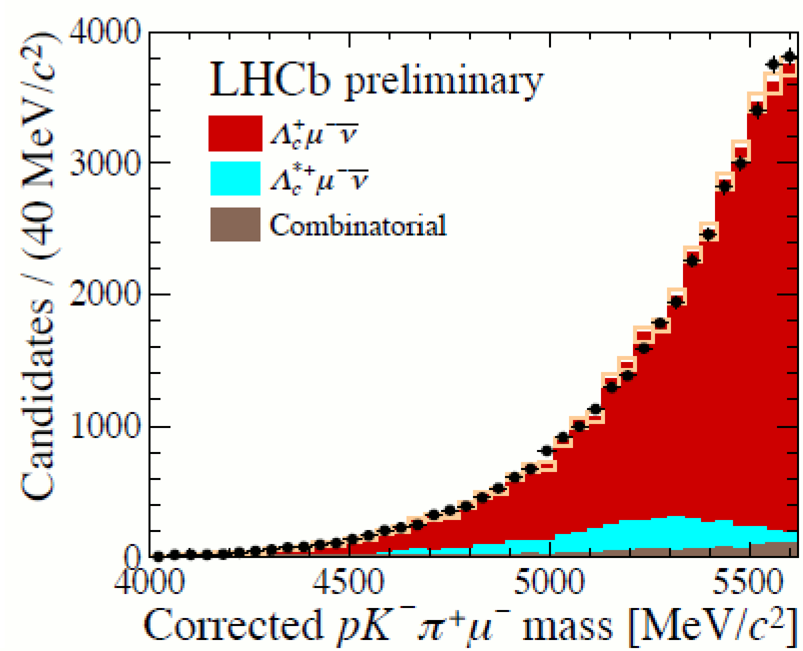


$N(\Lambda_b^0 \rightarrow p \mu \nu) = 17{,}687 \pm 733$

First observation of this decay

$N(\Lambda_b^0 \rightarrow \Lambda_c(pK) \mu \nu) = 34{,}255 \pm 571$





$$\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c \mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

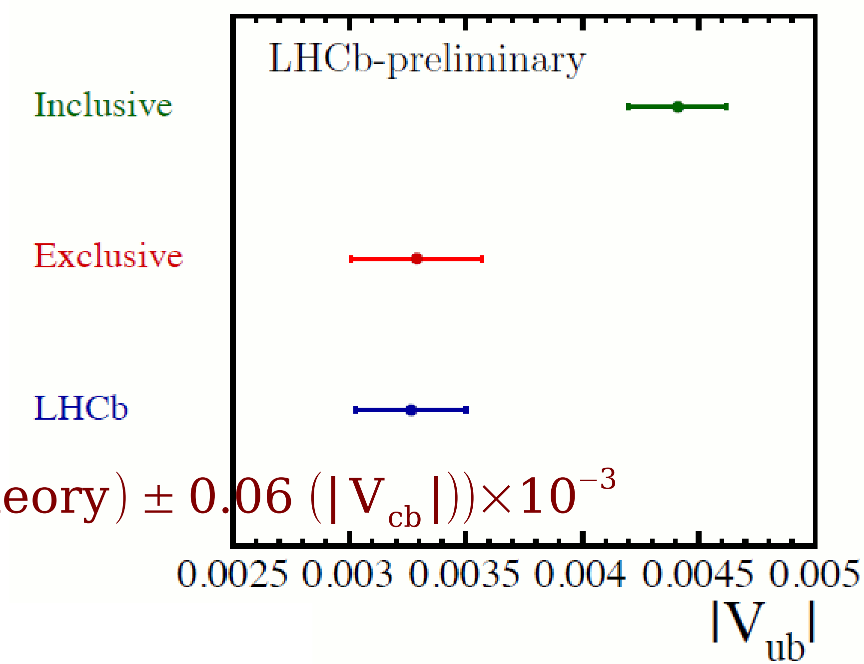
Determining $|V_{ub}|/|V_{cb}|$ arXiv:1504.01568

- Use ratio of differential rates from lattice calculations to calculate the ratio of CKM elements squared:

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\int_{15\ \mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{\mathrm{d}\Gamma(\Lambda_b \to p\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{7\ \mathrm{GeV}^2}^{q^2_{\mathrm{max}}} \frac{\mathrm{d}\Gamma(\Lambda_b \to \Lambda_c\,\mu^-\bar{\nu}_\mu)}{\mathrm{d}q^2}\mathrm{d}q^2}(0.68 \pm 0.07)$$

- leads to: W.Detmold et al, arXiv:1503.01421

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004\,(\mathrm{exp}) \pm 0.004\,(\mathrm{LQCD})$$

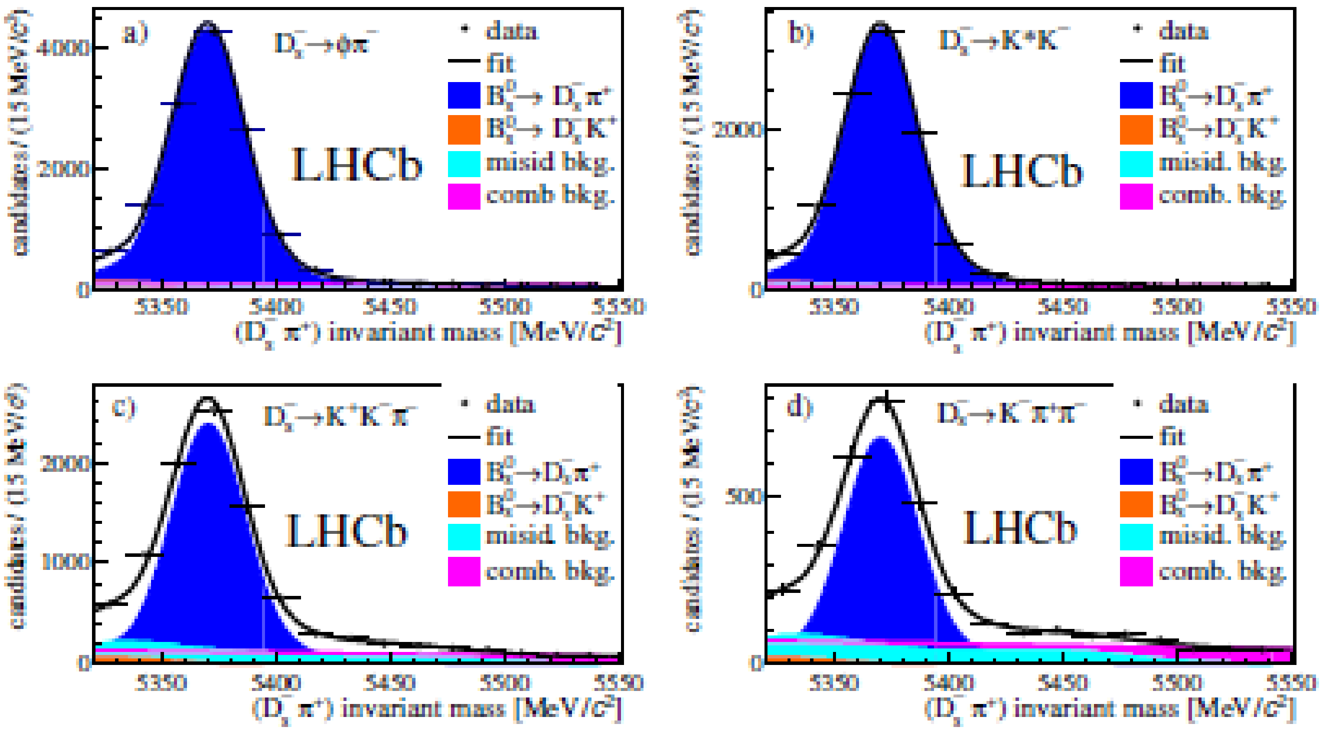


$$|V_{cb}| = (3.27 \pm 0.15\,(\mathrm{exp}) \pm 0.17\,(\mathrm{theory}) \pm 0.06\,(|V_{cb}|)) \times 10^{-3}$$

Measurement of Δm_s

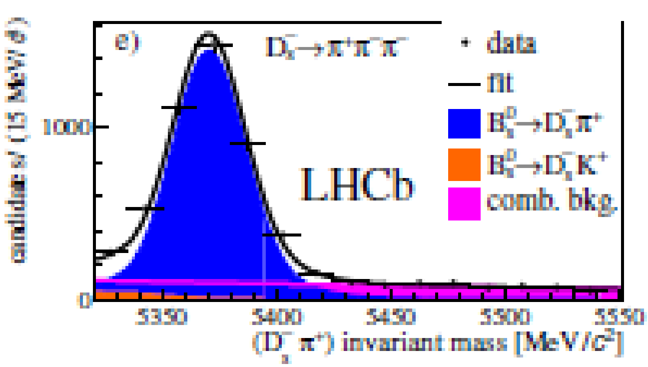
- Observation for the first time in 2006 by CDF
- Precise measurement of B_s^0-$\overline{B}_s^0$ oscillation frequency with $B_s^0 \rightarrow D_s^- \pi^+$

[arXiv:1304.4741]



34,000 $B_s \rightarrow D_s \pi$

=



Decay mode	$(D_s^- \pi^+)$ candidates
$D_s^- \to \phi(K^+K^-)\pi^-$	14691
$D_s^- \to K^{*0}(K^+\pi^-)K^-$	10866
$D_s^- \to K^+K^-\pi^-$ nonresonant	11262
$D_s^- \to K^-\pi^+\pi^-$	4288
$D_s^- \to \pi^-\pi^+\pi^-$	6674
Total	47781

Measurement of Δm_s

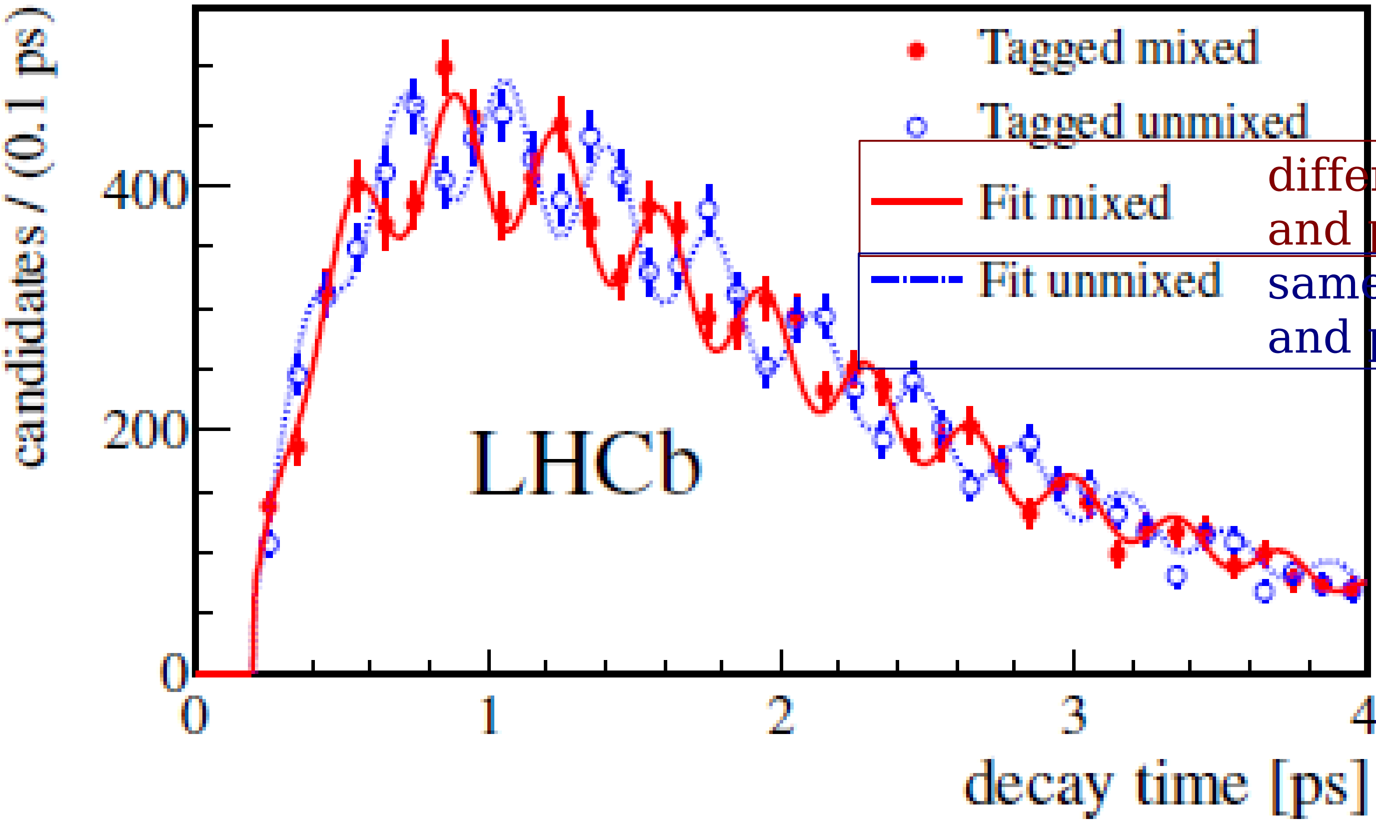
[arXiv:1304.4741]

- Precise measurement of B_s^0-$\overline{B}_s^0$ oscillation frequency with $B_s^0 \to D_s^- \pi^+$

$$\mathcal{P}_t(t|\sigma_t) \propto \left\{ \Gamma_s e^{-\Gamma_s t} \frac{1}{2} \left[\cosh\left(\frac{\Delta\Gamma_s}{2} t\right) + q\left[1 - 2\omega(\eta_{\rm OST}, \eta_{\rm SST})\right] \cos(\Delta m_s t) \right] \theta(t) \right\} \otimes G(t, S_{\sigma_t}\sigma_t)\, \mathcal{E}_t(t)\, \epsilon,$$

34,000 $B_s \to D_s \pi$

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

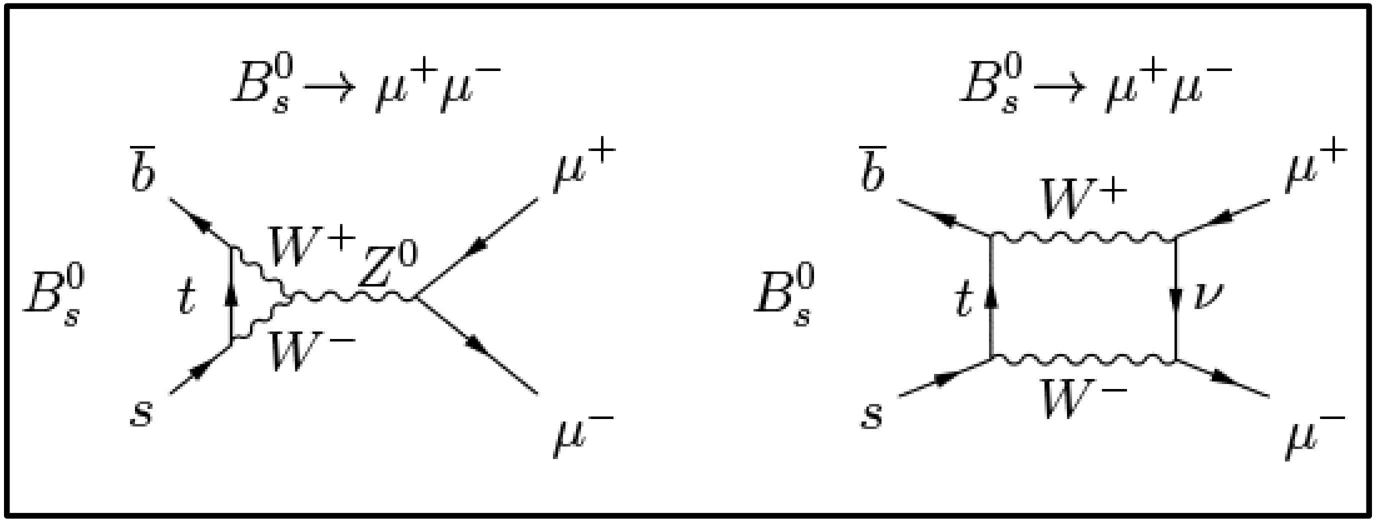


different flavour at decay and production

same flavour at decay and production

$B_{(s)} \to \mu\mu$: ultra rare processes...

loop diagram + suppressed in SM + theoretically clean =
an excellent place to look for new physics

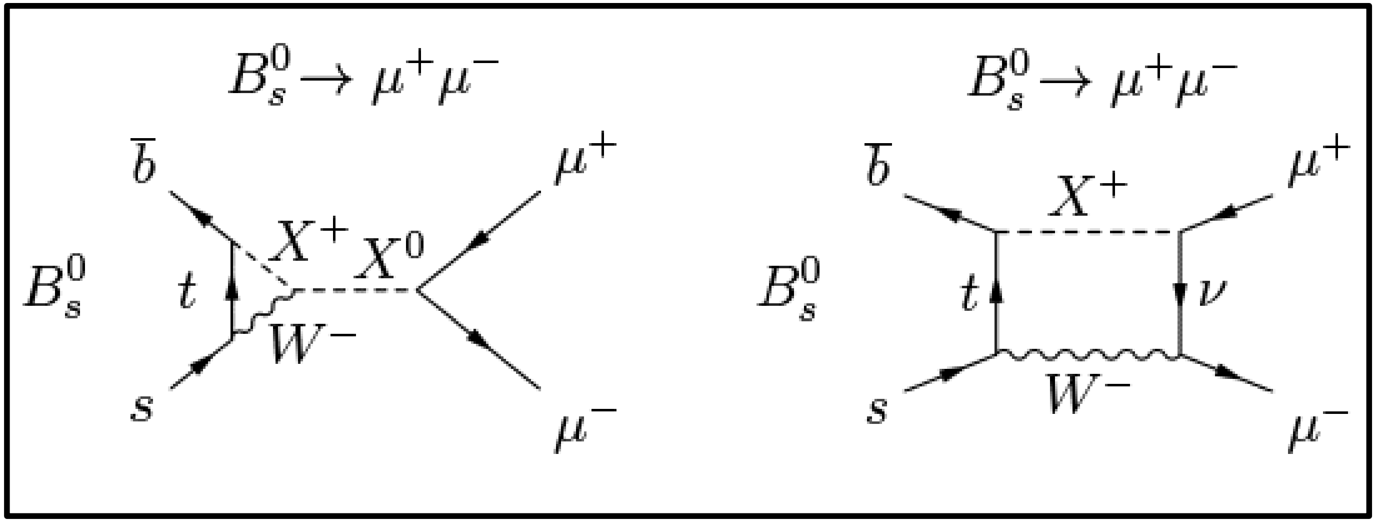


higher-order FCNC allowed in SM

$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

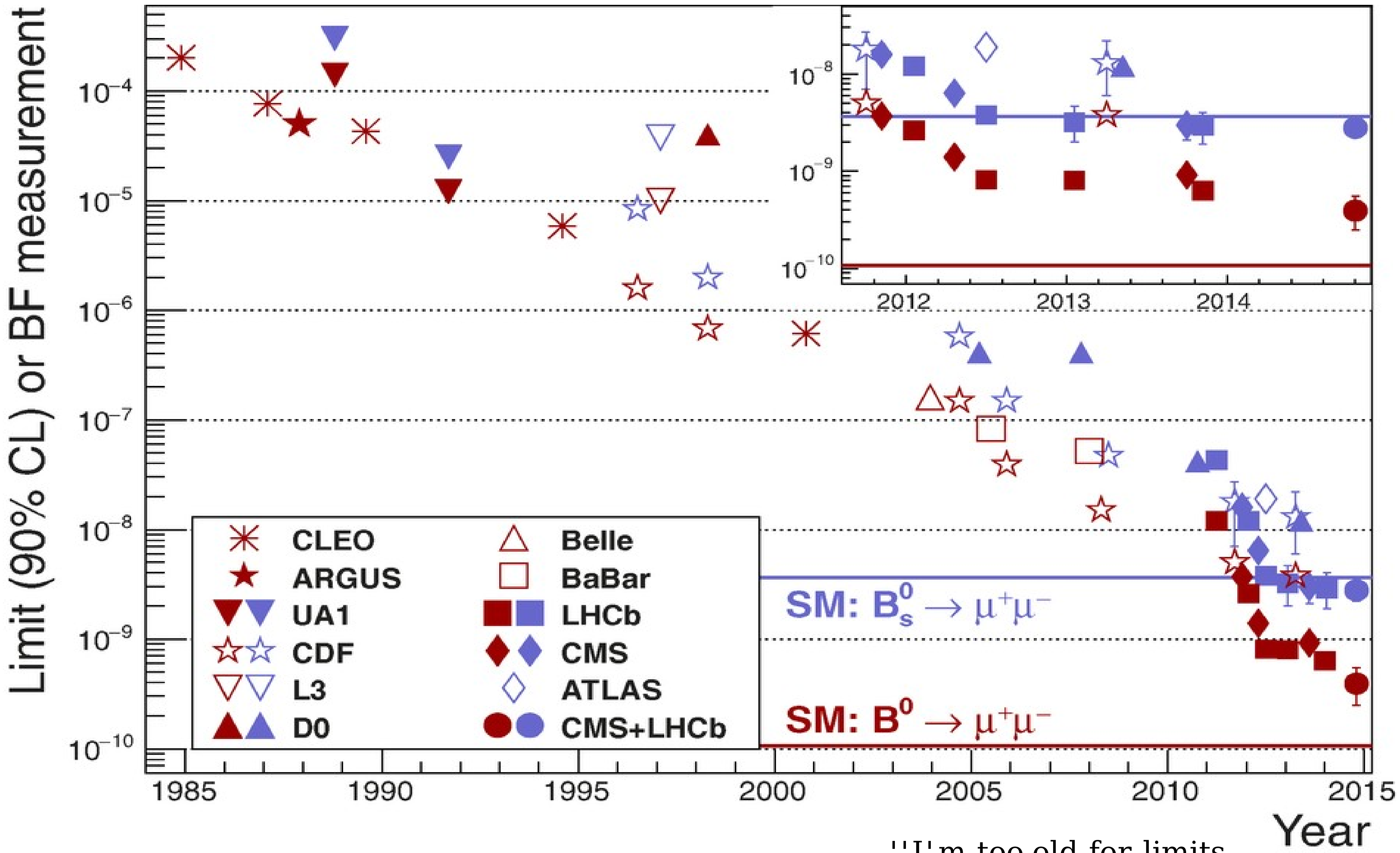
$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[Bobeth et al, PRL 112 (2014) 101801]



same decay in theories extending the SM (some of NP scenarios may boost the $B \to \mu\mu$ decay rates)

$B_{(s)} \rightarrow \mu\mu$: ultra rare processes...



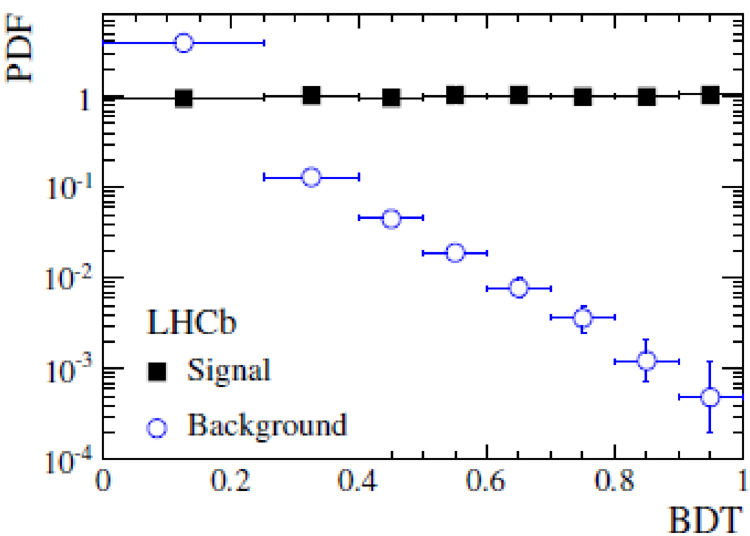
"I'm too old for limits,
I want to see signals"
(Francis Halzen)

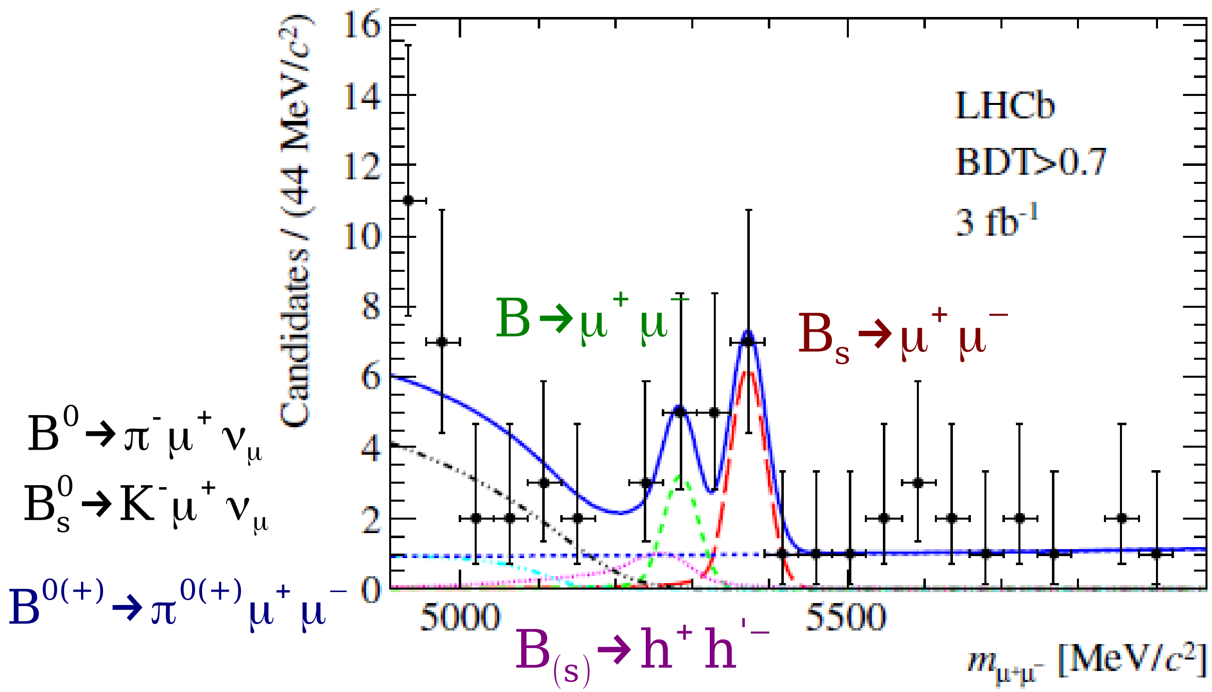
$B_s \to \mu^+ \mu^-$ results

[arXiv:1307.5024]

- after trigger and loose selection, $B_{(s)} \to \mu^+ \mu^-$ candidates classified according to $M(\mu\mu)$ and BDT output
- separate $B_s \to \mu^+ \mu^-$ (signal) and $b\bar{b} \to \mu^+ \mu^- X$ events (background)

  BDT combining B candidate decay time, IP and p_T, minimum χ^2_{IP} of the 2 muons, distance of closest approach btw 2 muons etc...

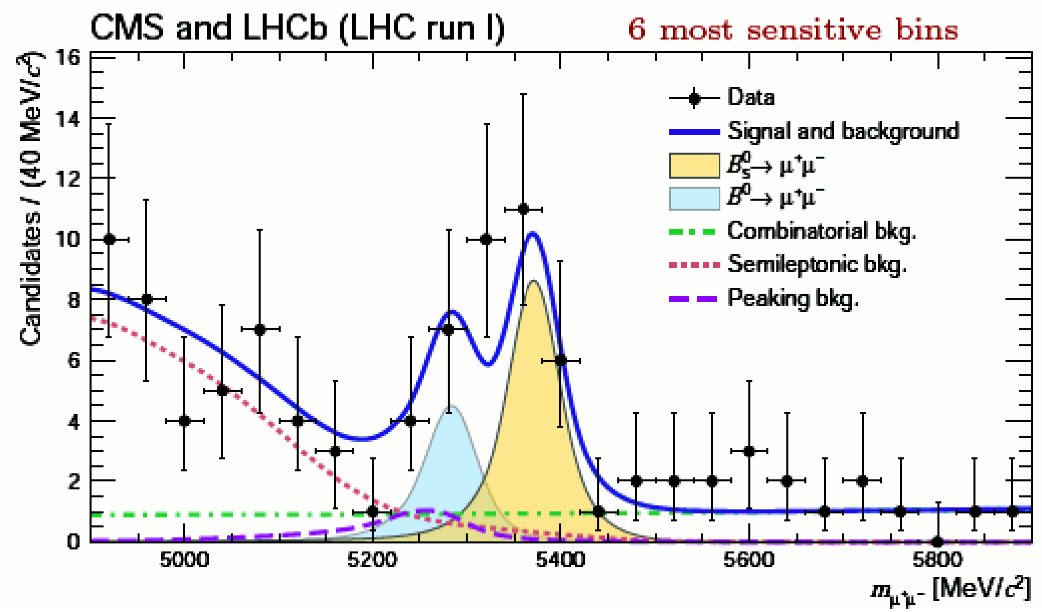




$$B(B_s^0 \to \mu^+ \mu^-) = (2.9\ ^{+1.1}_{-1.0}\ ^{+0.3}_{-0.1}) \times 10^{-9}\ (4.0\sigma \text{ significance})$$

$$B(B^0 \to \mu^+ \mu^-) = (3.7\ ^{+2.4}_{-2.1}\ ^{+0.6}_{-0.4}) \times 10^{-10}\ (2.0\sigma \text{ significance})$$

Combination results $B_{(s)} \to \mu^+\mu^-$ [arXiv:1411.4413] published in Nature

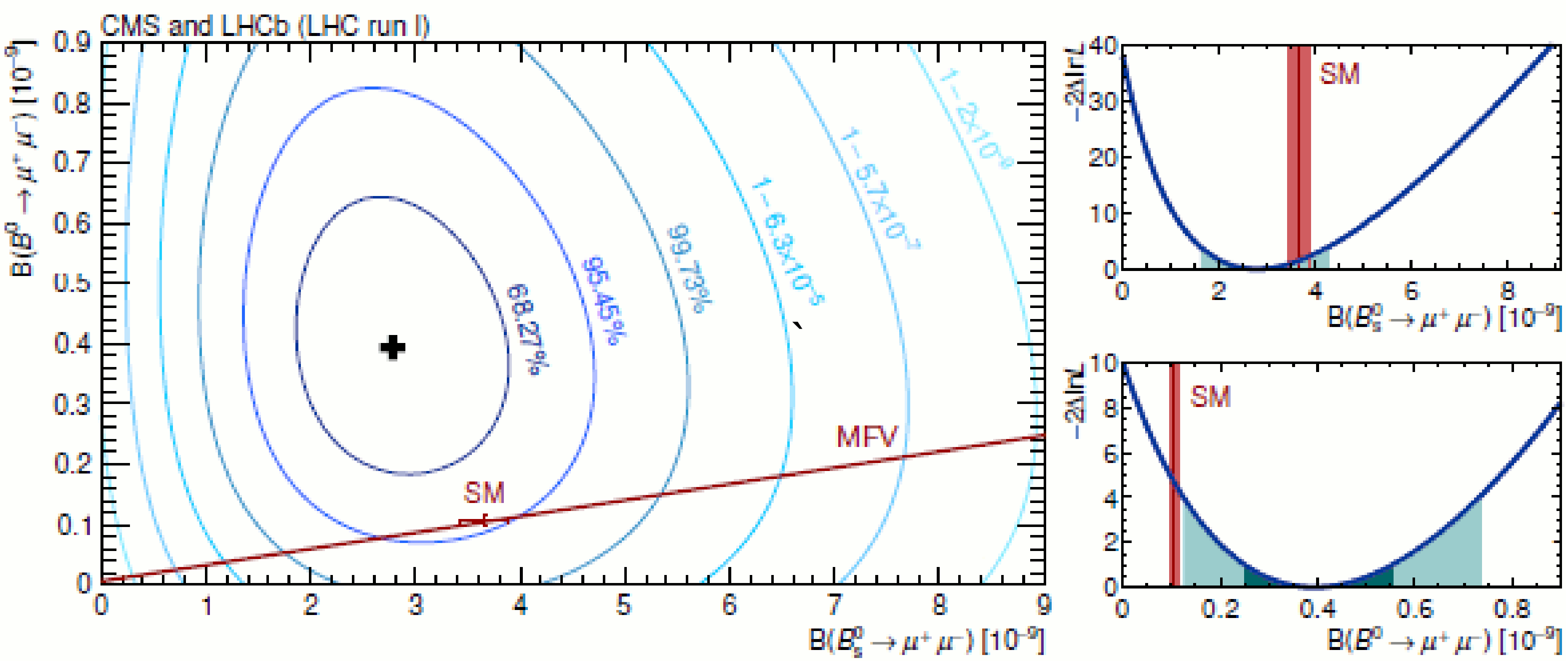


$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$

first observation: 6.2σ significance

$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$

first evidence: 3.0σ significance



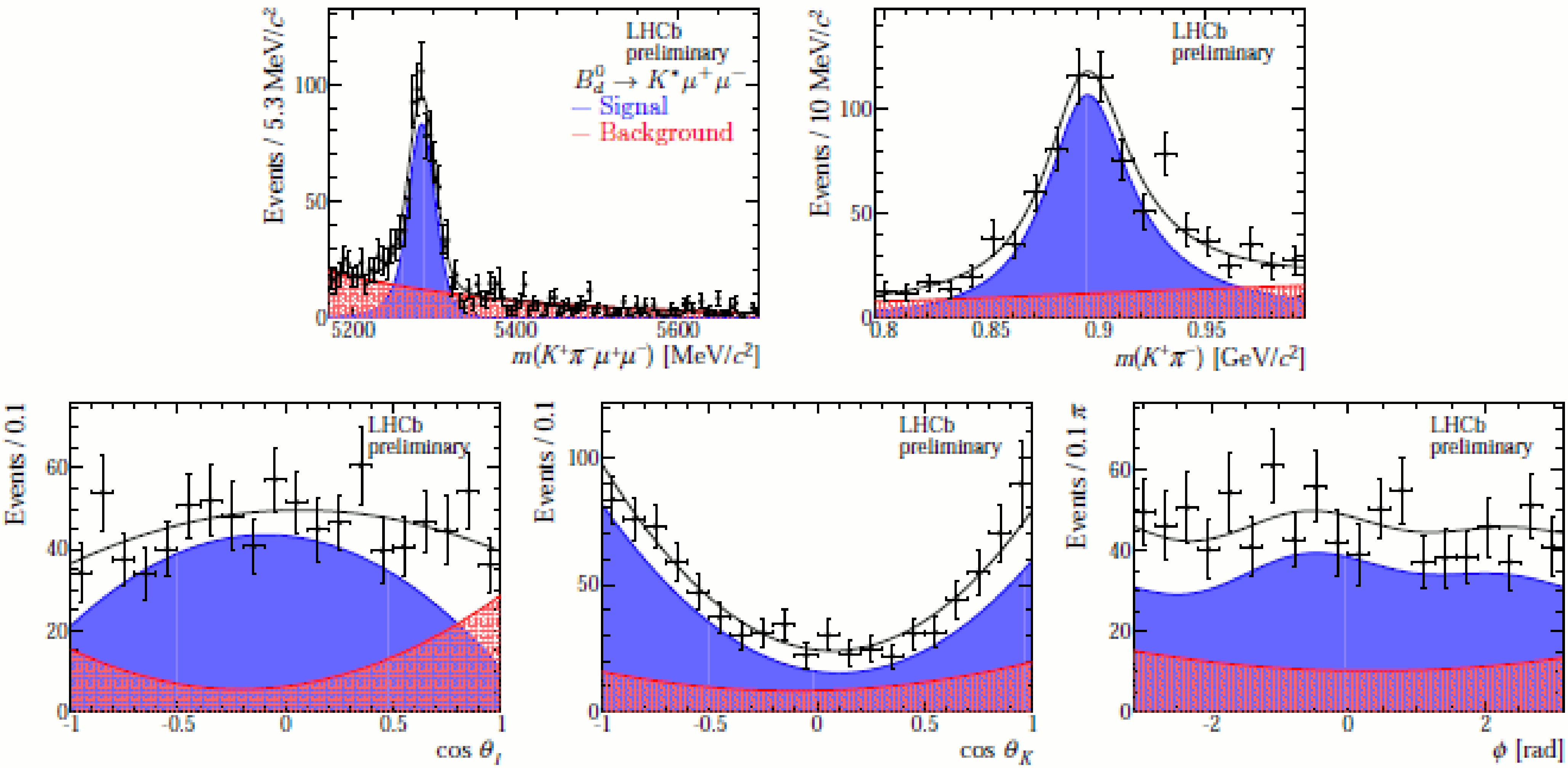
and more to come...

[Talk by Kai-Feng Chen for CMS, arXiv:1208.3355 for LHCb]

Angular analysis of $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays

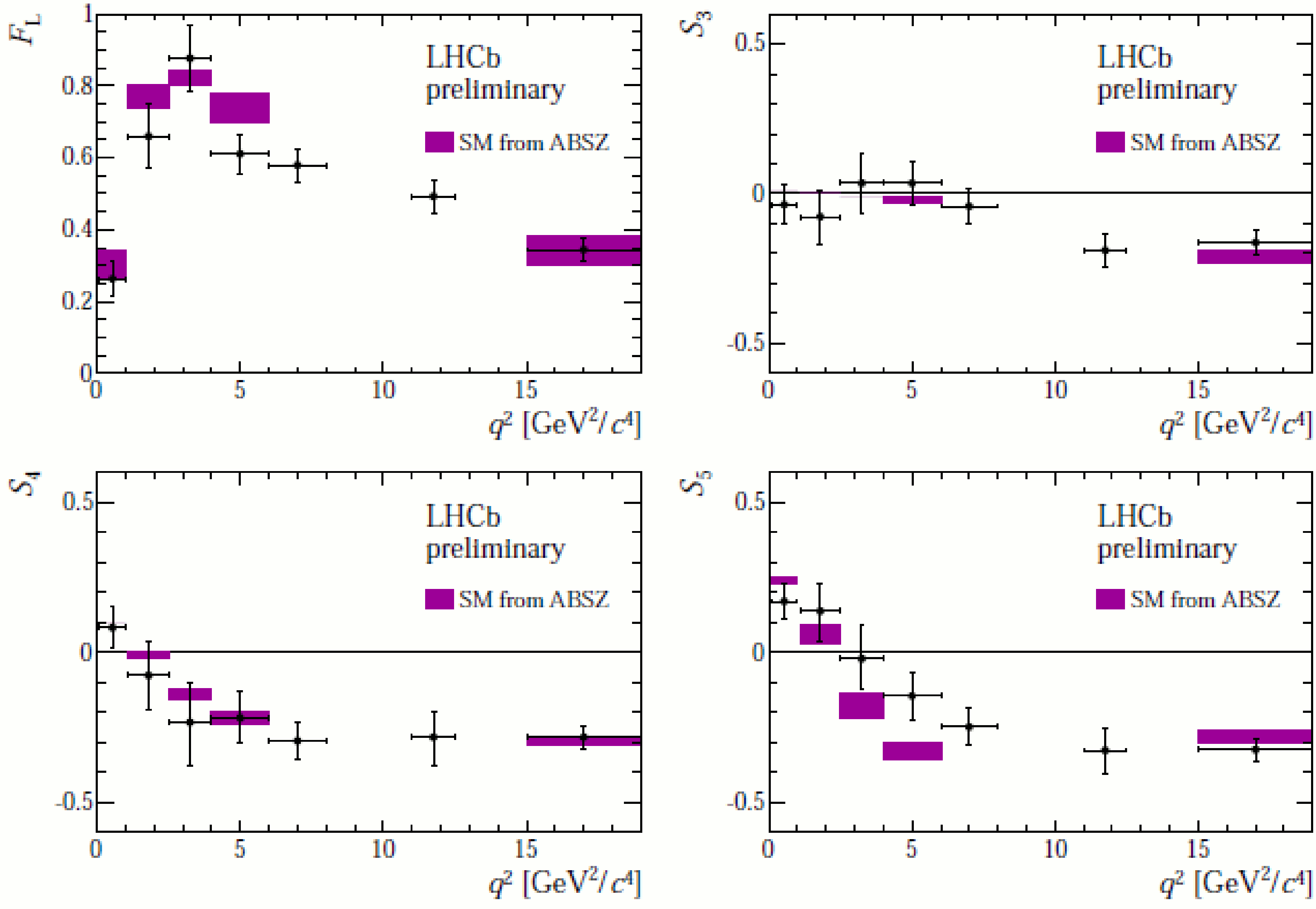
[arXiv:1512.04442]

- Projections of fit results for $q^2 \in [1.1, 6.0]$ GeV^2
- Good agreement of PDF projections with data in every bin of q^2



Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

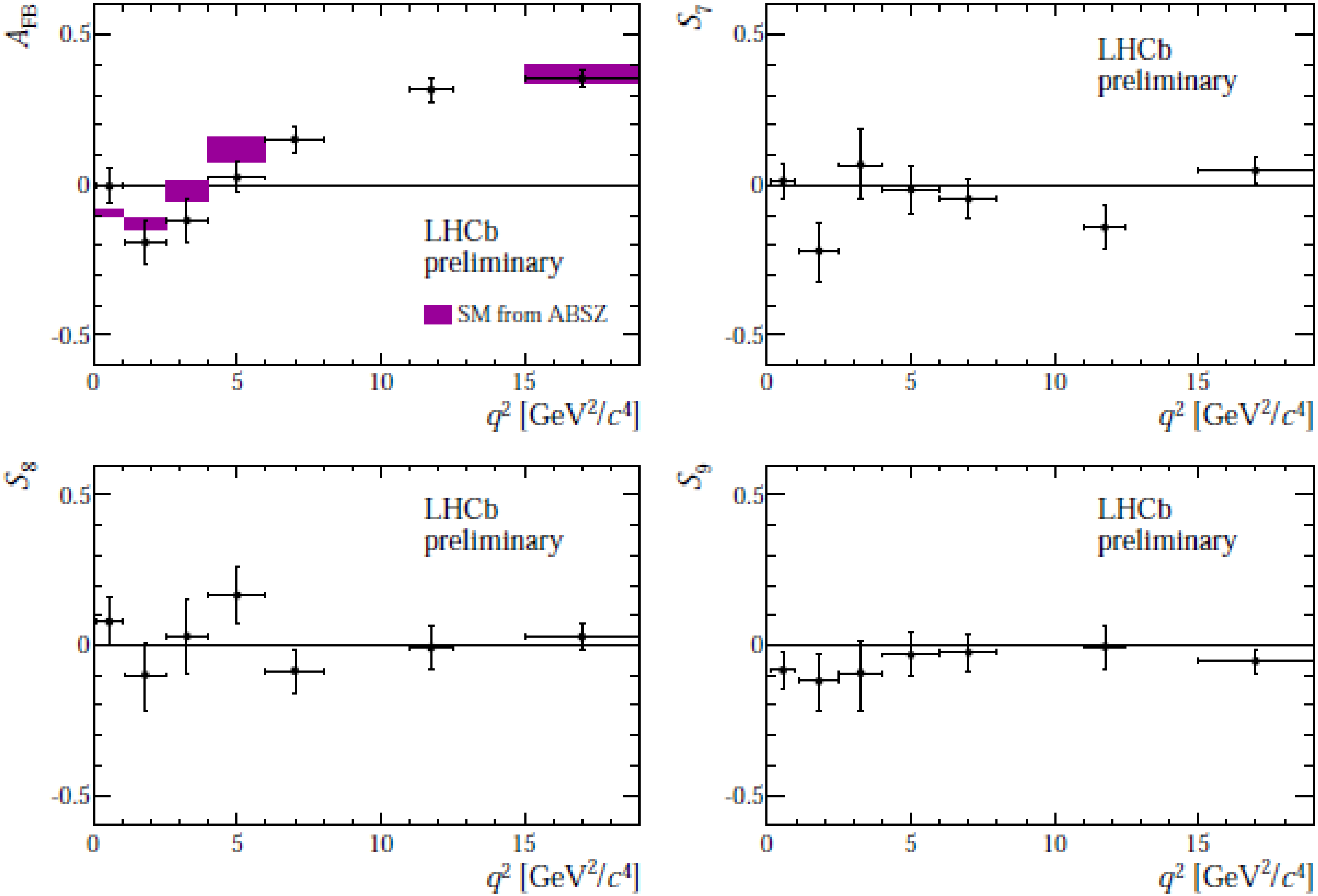
[arXiv:1512.04442]



Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

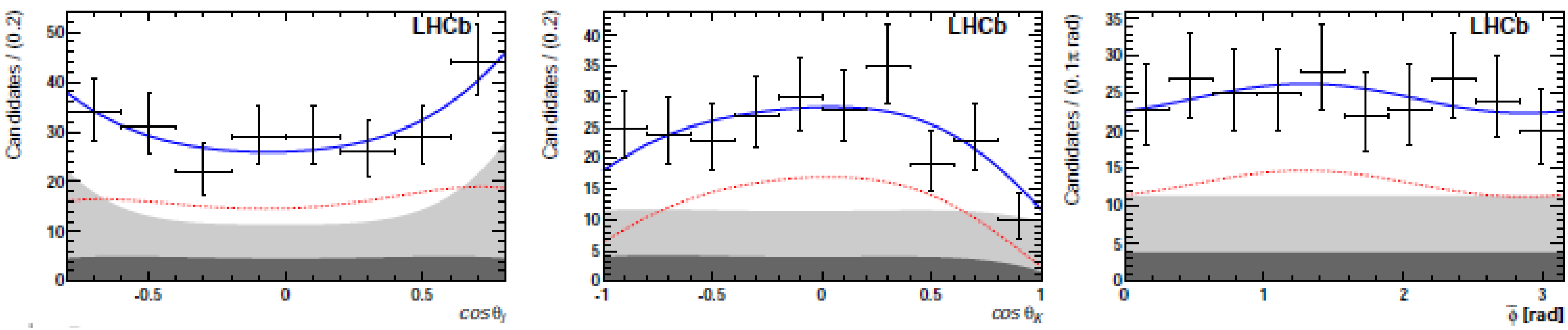
data points systematically lower than SM

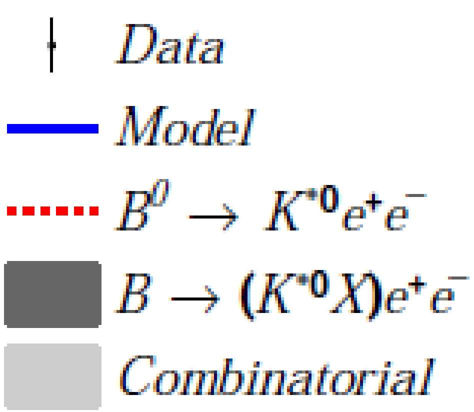
[arXiv:1512.04442]



Angular analysis of $B_d^0 \to K^* e^+ e^-$ decays

[arXiv:1501.03038]





Observable	Measurement	SM prediction†
F_{L}	$+0.16 \pm 0.06 \pm 0.03$	$+0.10^{+0.11}_{-0.05}$
$A_{\mathrm{T}}^{(2)}$	$-0.23 \pm 0.23 \pm 0.05$	$0.03^{+0.05}_{-0.04}$
$A_{\mathrm{T}}^{\mathrm{Re}}$	$+0.10 \pm 0.18 \pm 0.05$	$-0.15^{+0.04}_{-0.03}$
$A_{\mathrm{T}}^{\mathrm{Im}}$	$+0.14 \pm 0.22 \pm 0.05$	$(-0.2^{+1.2}_{-1.2}) \times 10^{-4}$

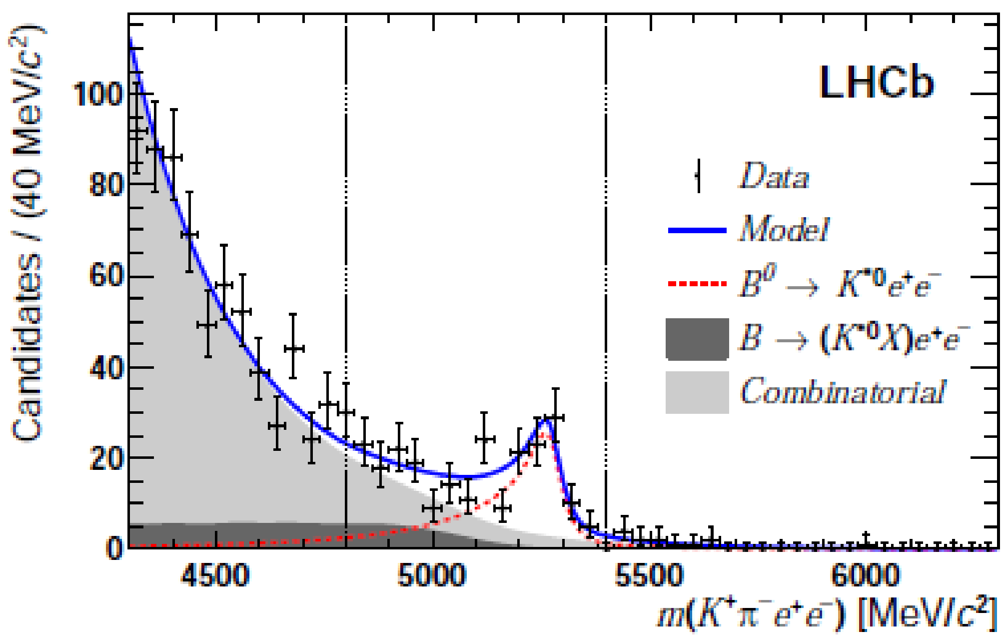
S.Jager, J.M.Camalich [arXiv:1412.3283]

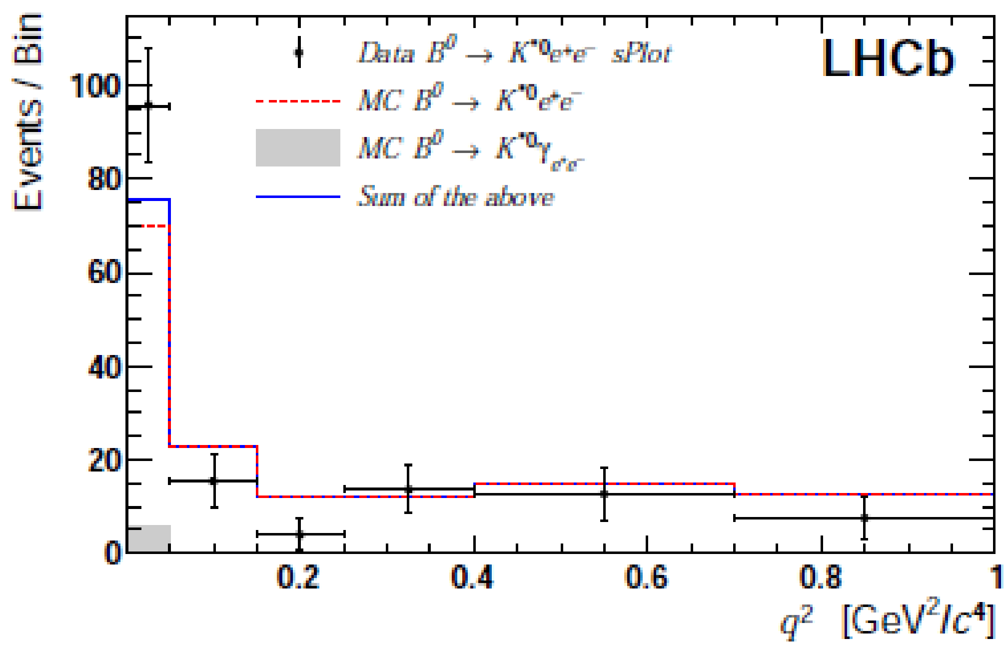
- Measurements well in agreement with SM predictions
- Constraints on $C_7^{'}$ in complementary with radiative decays

Angular analysis of $B_d^0 \to K^* e^+ e^-$ decays

[arXiv:1501.03038]

- Angular analysis of $B_d^0 \to K^* e^+ e^-$ at very low q^2 ($\in [0.002, 1.120]$ GeV^2)
- Folded angular observables ($\varphi = \varphi + \pi$ if $\varphi < 0$)
- Measurement of F_L, $A_T^{(2)}$, $A_T^{(Im)}$, $A_T^{(Re)}$, sensitive to C_7' as $q^2 \to 0$





$$A_T^{(Re)} = \frac{4}{3} A_{FB} / (1 - F_L), \quad A_T^{(2)} = \frac{1}{2} S_3 / (1 - F_L) \text{ and } A_T = \frac{1}{2} S_9 / (1 - F_L)$$

The LHCb / LHCb upgrade timeline

LHCb future (2012 + end 2014 - 2017)

- $\mathcal{L} \geq 4 * 10^{32}$ cm^{-2} s^{-1}
- $L_{int} > 8$ fb^{-1} by the end of 2017
  $\rightarrow$ Factor-4 in statiscal power wrt 1 fb^{-1}

Upgraded LHCb (2019 -)

- Full readout @ 40 MHz with full software trigger $\rightarrow$ trigger efficiency enhanced by a factor-2 for hadronic modes!
- Increase the luminosity by a factor-5
  $\rightarrow \mathcal{L} \geq (1-2) * 10^{33}$ cm^{-2} s^{-1}
  $\rightarrow$ 25 ns bunch spacing $\rightarrow \mu = 2$
  $\rightarrow \sqrt{s} =$ 13-14 TeV
  $\rightarrow$ +100% $b\bar{b}$ x-section wrt $\sqrt{s} = 7$ TeV
  $\rightarrow \geq 5$ fb^{-1}/year
- Run for 10 years
  $\rightarrow L_{int} > 50$ fb^{-1}
  $\rightarrow$ > Factor-10 in stat. power wrt 1 fb^{-1}