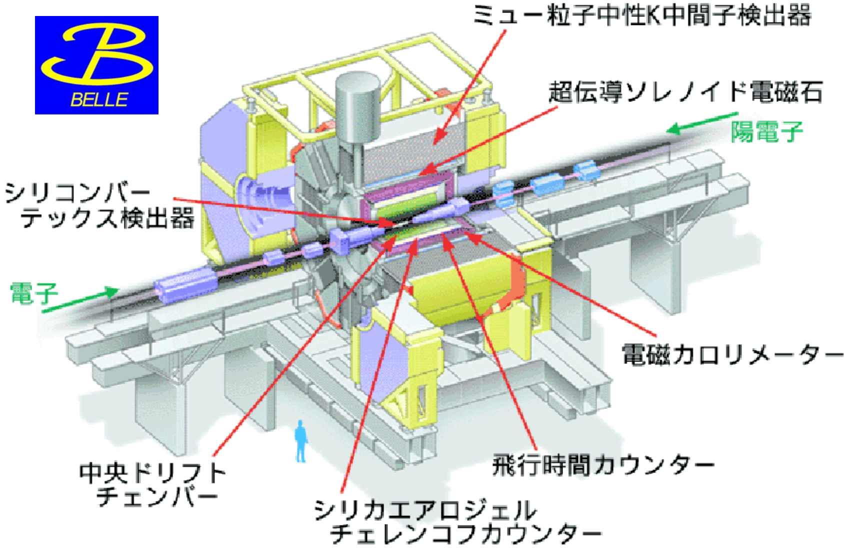
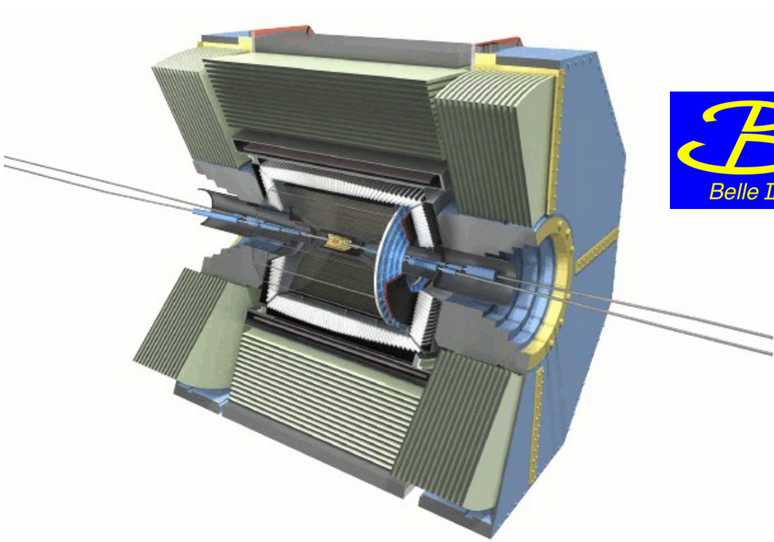
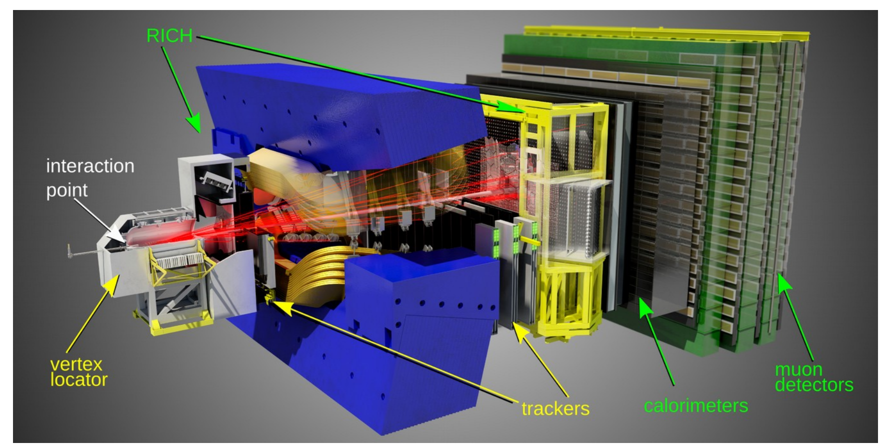
New Physics from Flavour (Experimental Highlights)

in the light of the recent anomalies





K.Trabelsi
karim.trabelsi@kek.jp



Gordon Research Conference, Hong-Kong, June 27, 2017

Belle(II), LHCb side by side

(in the context of B anomalies)

Belle (II)

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

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

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

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

but also a lot of other particles in the event

$\Rightarrow$ 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 $\Upsilon(4S)$

$\Rightarrow$ lower trigger efficiencies

B mesons live relativey long

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

mean decay length $\beta\gamma c\tau \sim 7$ mm

data taking period(s)

$[1999\text{-}2010] = 1\ \text{ab}^{-1}$

$[\text{run I: } 2010\text{-}2012] = 3\ \text{fb}^{-1}$,

$[\text{run II: } 2015\text{-}2018] = 2\ \text{fb}^{-1} \to 8\ \text{fb}^{-1}$?

(near) future

$[\text{Belle II from } 2018] \to 50\ \text{ab}^{-1}$

$[\text{LHCb upgrade from } 2020]$

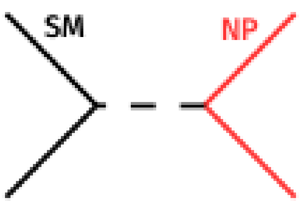
Motivation

In general, we search for NP indirectly in processes where SM contributions are suppressed, and so, small NP effects can become visible (or even dominant)

Phenomenologically, we can classify potential NP contributions as

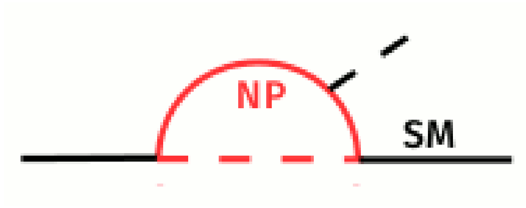
- **$\Delta F = 2$ (neutral B mixing)**
  - 2^{nd} order weak transition in SM, can be enhanced by NP
- **$\Delta F = 1$ (B decays)**
  - Loop suppression (NP can enter through trees, e.g. FCNC)
  - Helicity suppression (Vector-mediated SM transitions are small compared (pseudo) scalar-mediated NP)

energy frontier



limited by beam energy

intensity frontier



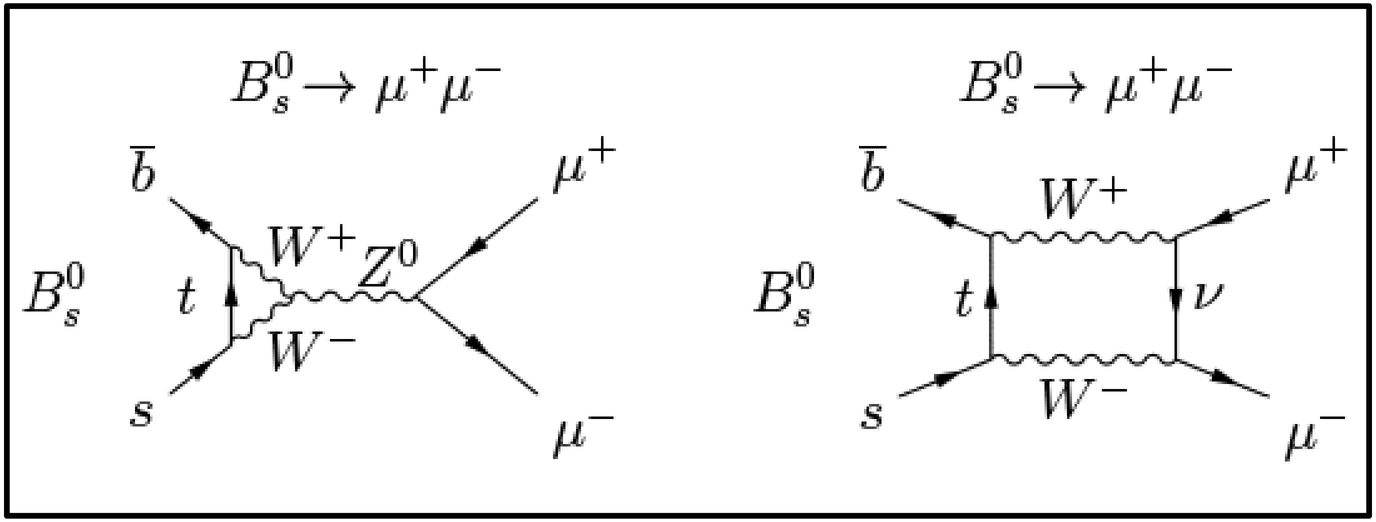
limited by statistics

➜ **NP beyond the <u>direct</u> reach of the LHC**

New particles can for example contribute to loop or tree level diagrams **by enhancing/suppressing decay rates, introducing new sources of CP violation or modifying the angular distribution of the final-state particles**

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

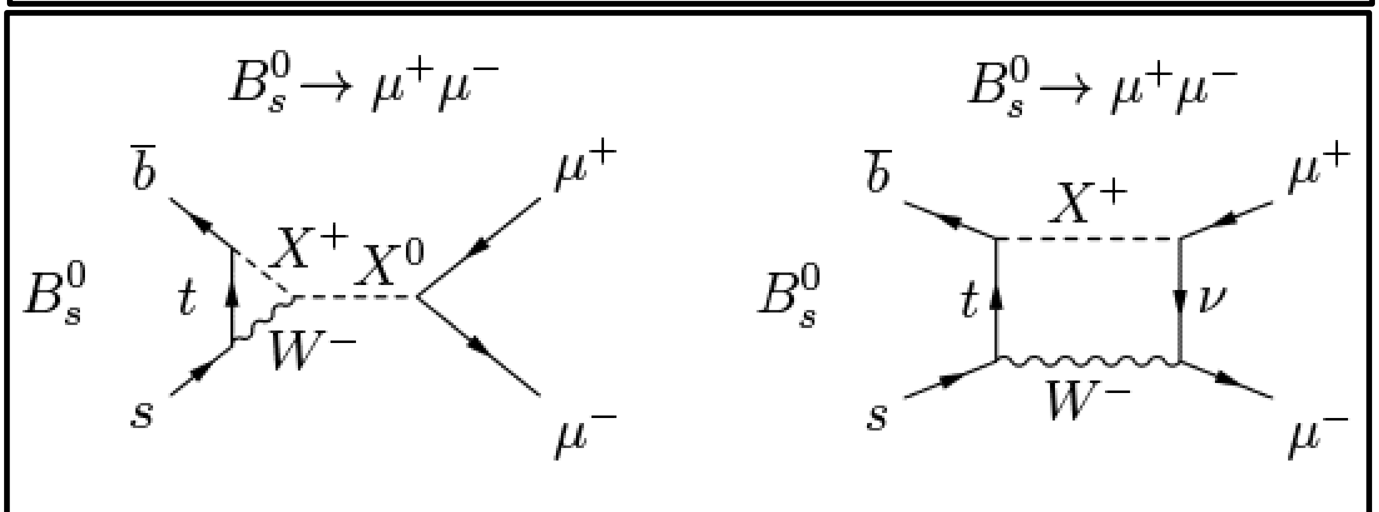
loop diagram + suppressed in SM + theoretically clean =
an excellent place to look for new physics



higher-order FCNC
allowed in SM

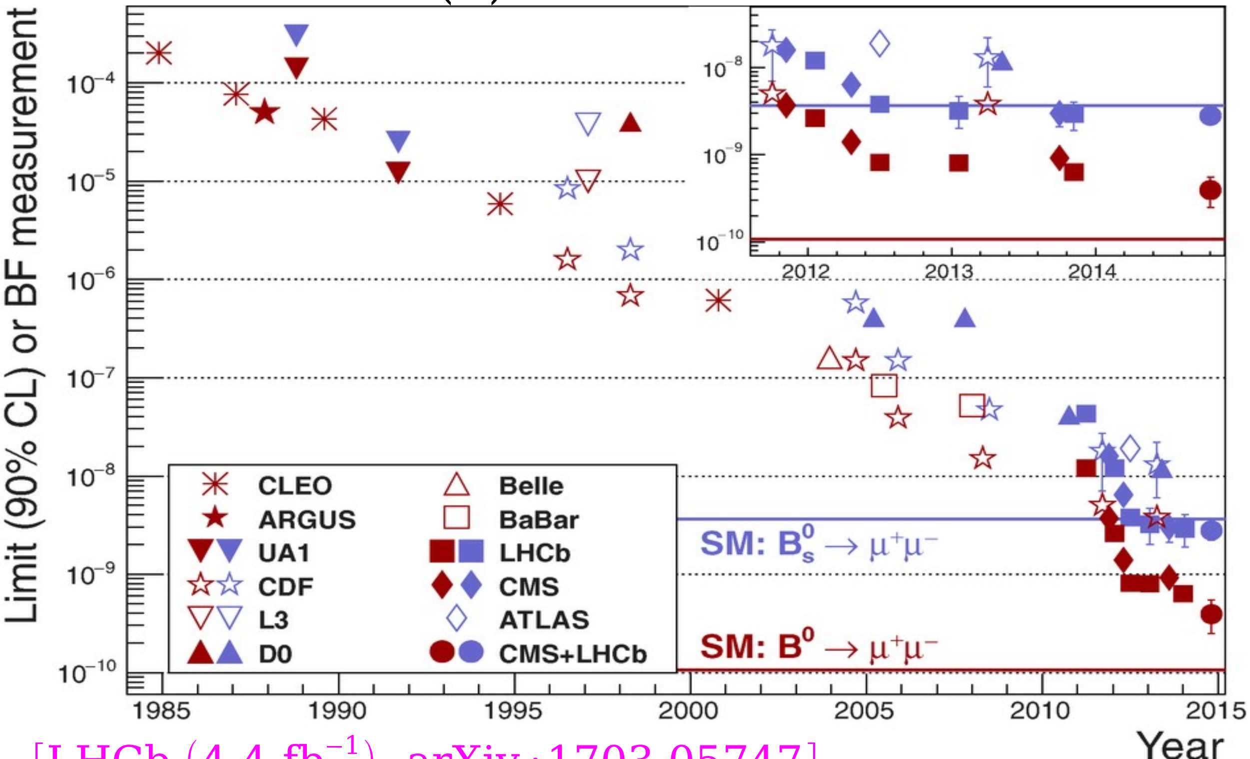
$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

[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)

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



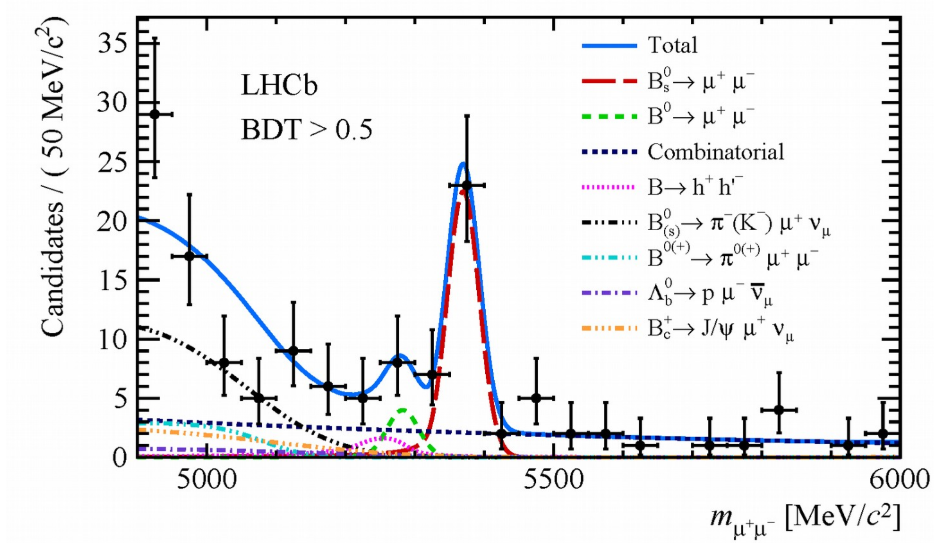
''I'm too old for limits,
I want to see signals''
(Francis Halzen, EPS 15)

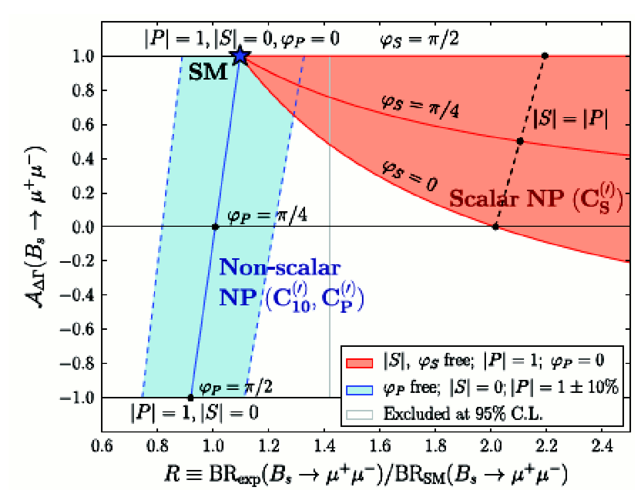
[LHCb (4.4 fb^{-1}), arXiv:1703.05747]

$B(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\ ^{+0.3}_{-0.2}) \times 10^{-9}$ (8σ significance)
$B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ @ 90% CL

SM: heavy state decays to $\mu^+\mu^-$

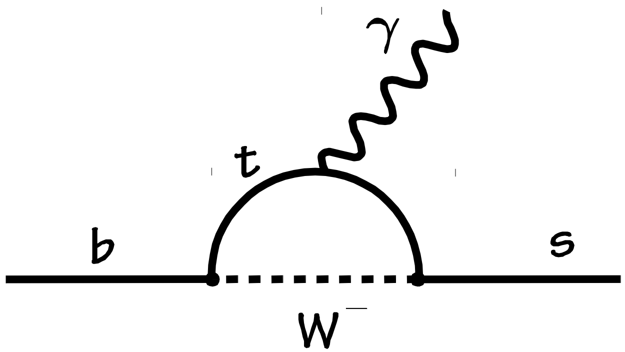
first lifetime measurement:
$\tau(B_s \to \mu^+\mu^\pm) = 2.04 \pm 0.44 \pm 0.05$ ps



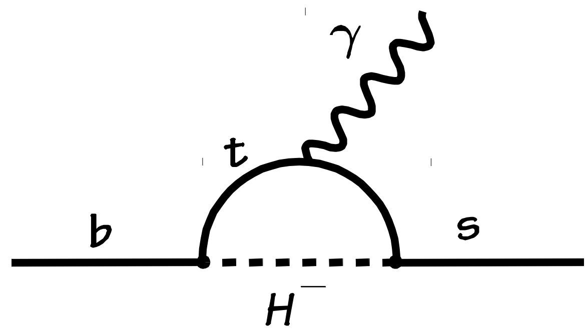


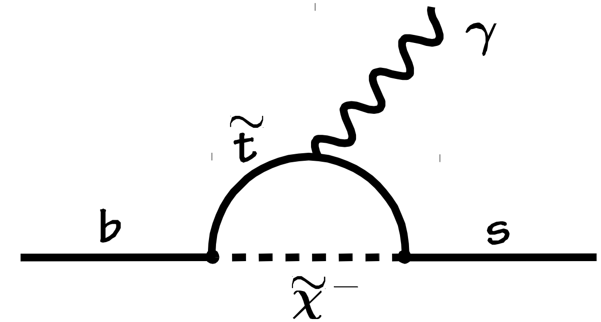
[De Bruyn et al., PRL 109, 041801 (2012)]

$B \to X_s \gamma$ as an illustration



Sensitive to NP





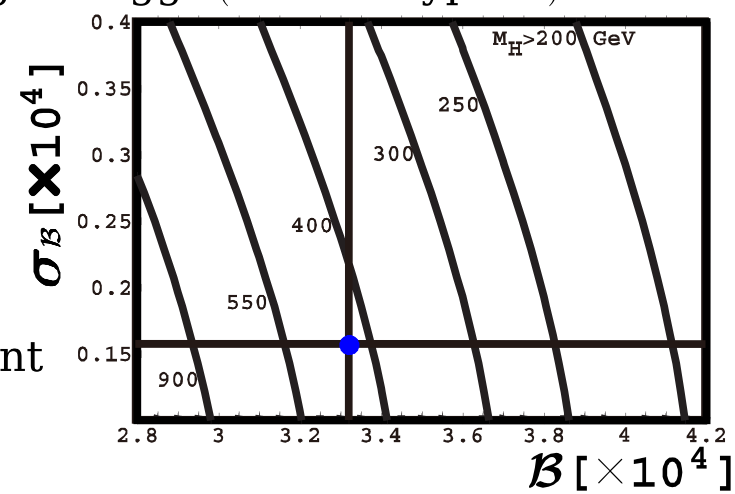
NNLO SM calculation:

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

(for $E_\gamma^* > 1.6$ GeV)

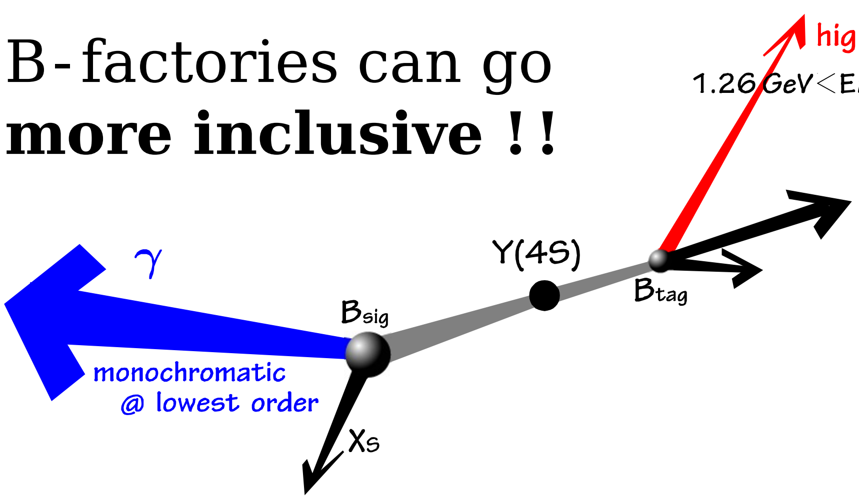
M. Misiak et al.
[arXiv:1503.01789]
PRL 98, 022002 (2007)

Charged Higgs (2HDM Type II) bound

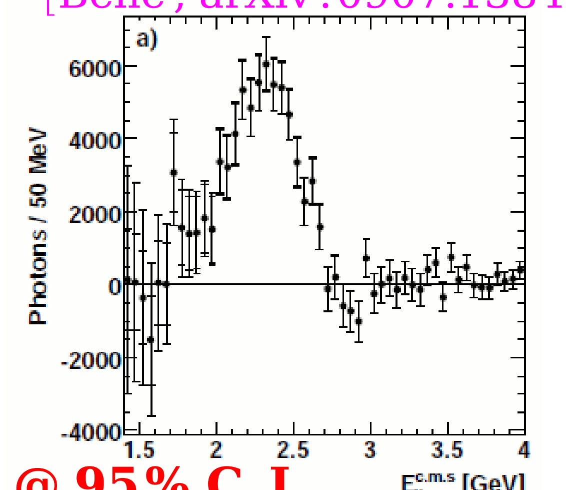


The lower γ energy threshold, the smaller the model uncertainties in SM but the larger background in measurement

B-factories can go
more inclusive !!



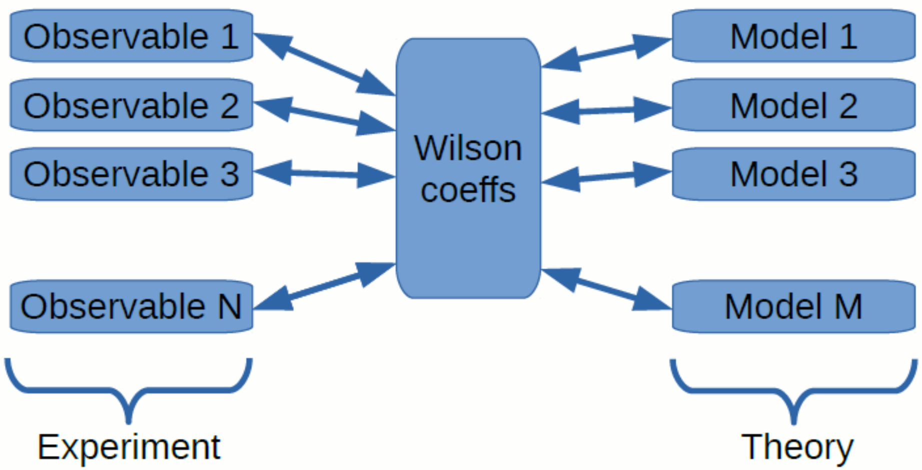
[Belle, arXiv:0907.1384]



WA: $B(B \to X_s \gamma) = (3.32 \pm 0.15) \times 10^{-4}$ (for $E_\gamma^* > 1.6$ GeV)

⇒ Charged Higgs bound (2HDM Type II): $M_{H^+} > 400$ GeV @ 95% C.L.

Sensitivity to new physics in rare B decays



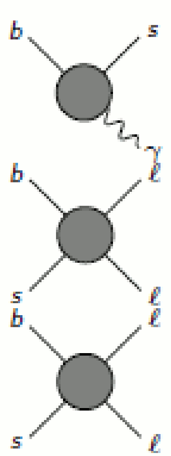
M.Ciuchini et al, arXiv:1512.07157
T.Hurth et al, arXiv:1603.00865
S.Descotes-Genon et al, arXiv:1510.04239...

NP changes short-distance C_i
and/or add new long-distance ops O'_i

- Model-independent description in effective field theory

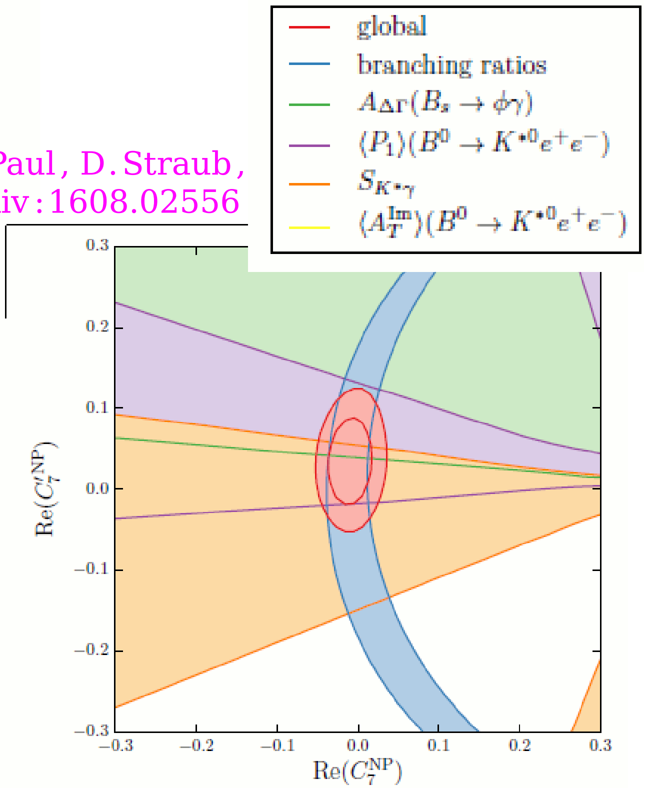
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm ts}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

- Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators



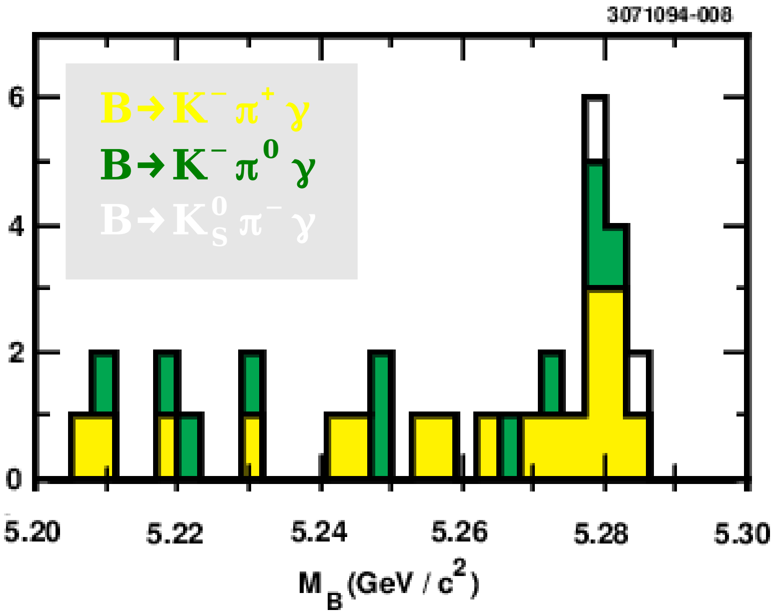
	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

A.Paul, D.Straub,
arXiv:1608.02556



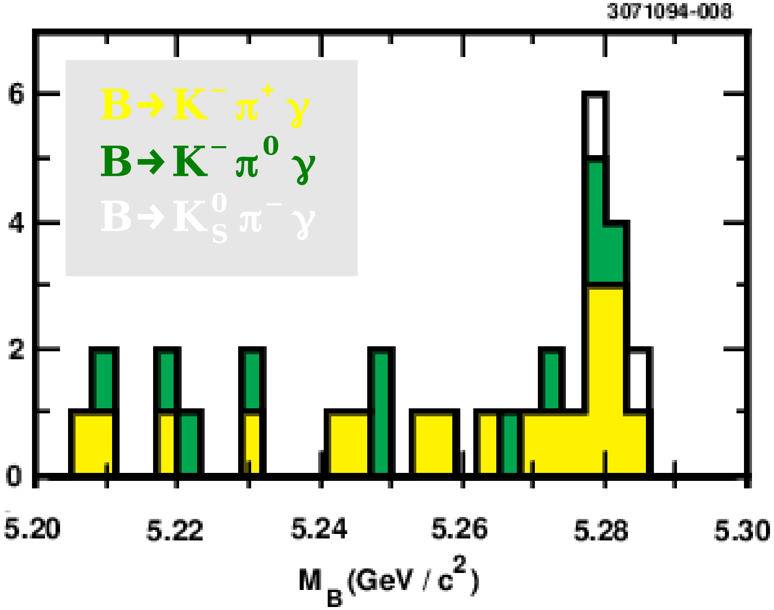
B→K*γ measurements

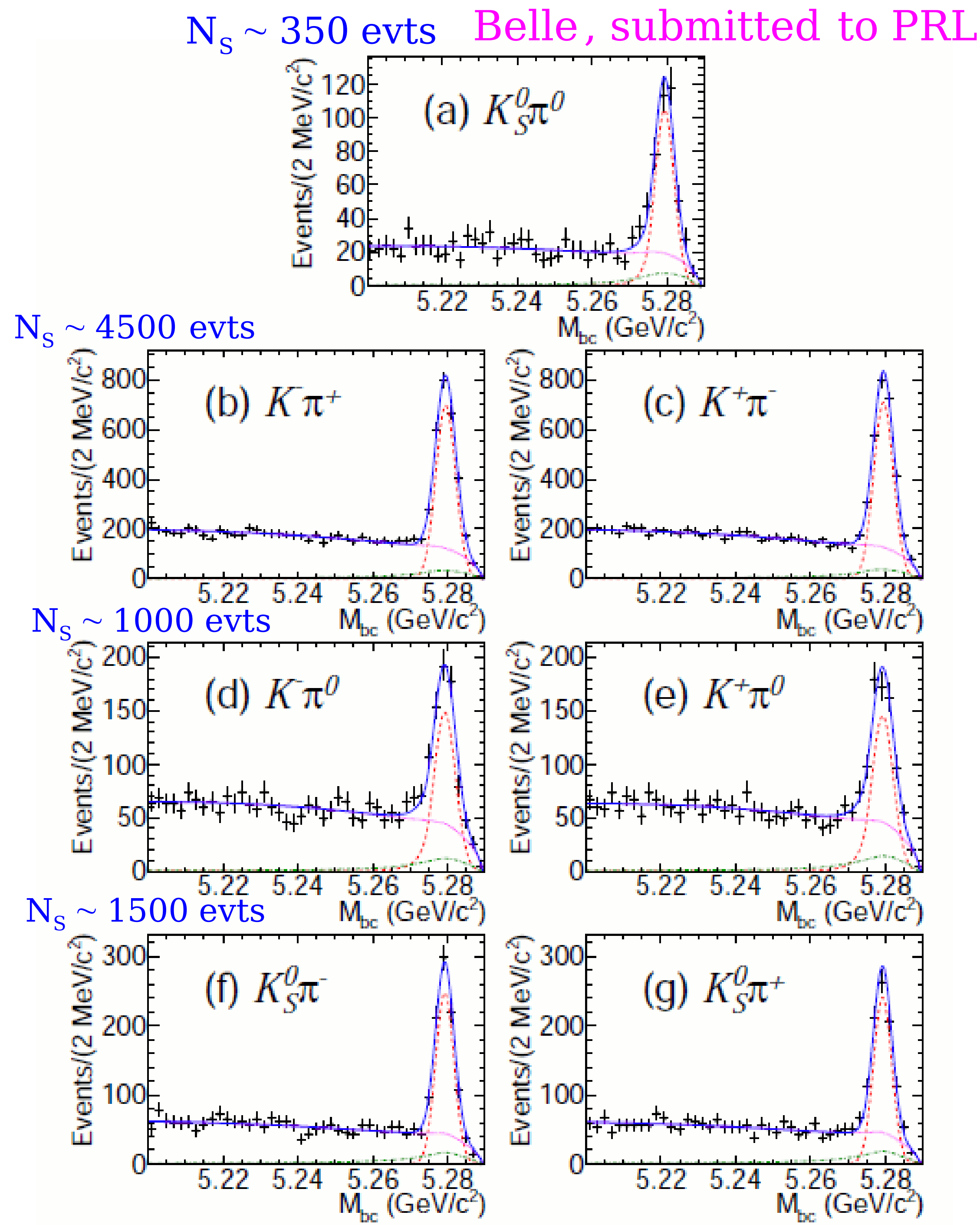
CLEO observation of B→K*γ [1993]



$B \to K^* \gamma$ measurements

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





$B \to K^* \gamma$ measurements

Belle, submitted to PRL

simultaneous fit of 4 final states

$\Rightarrow$ extraction of BFs, Δ_{0+}, A_{CP}, ΔA_{CP}

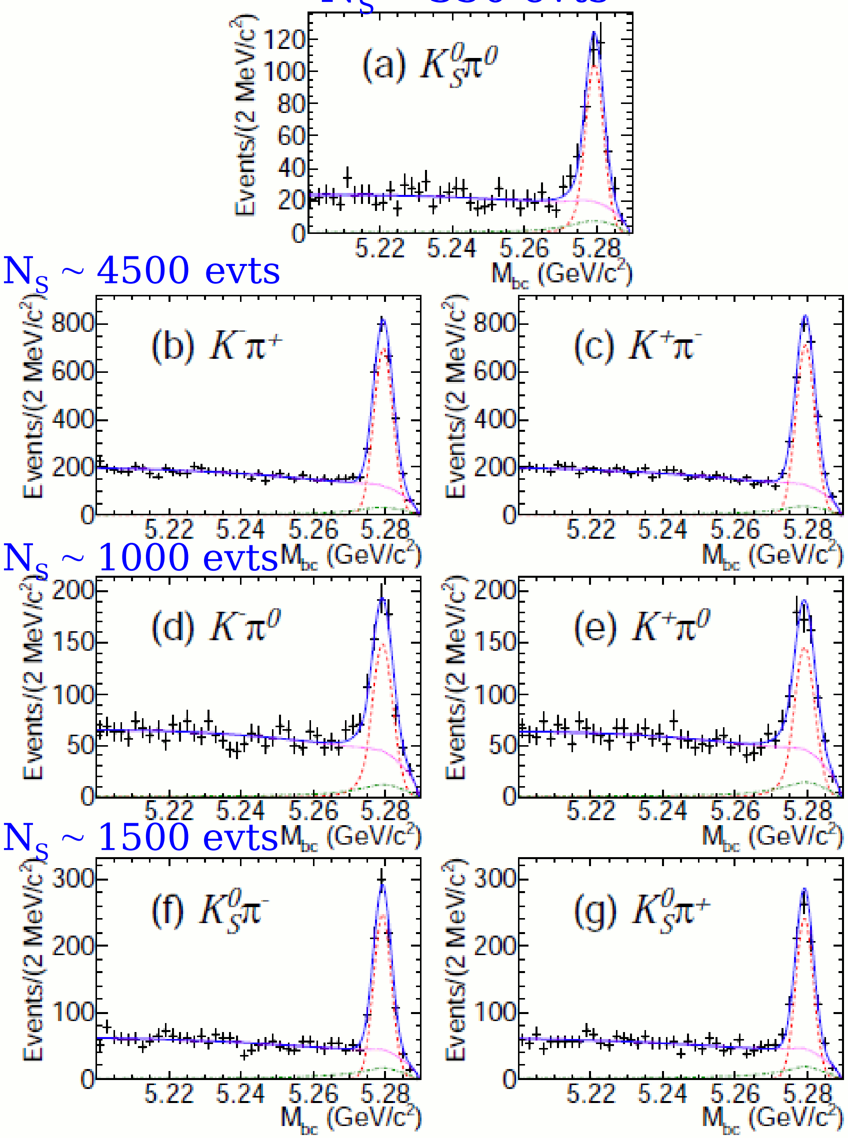
isospin asymmetry: $\Delta_{0+} = \dfrac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$

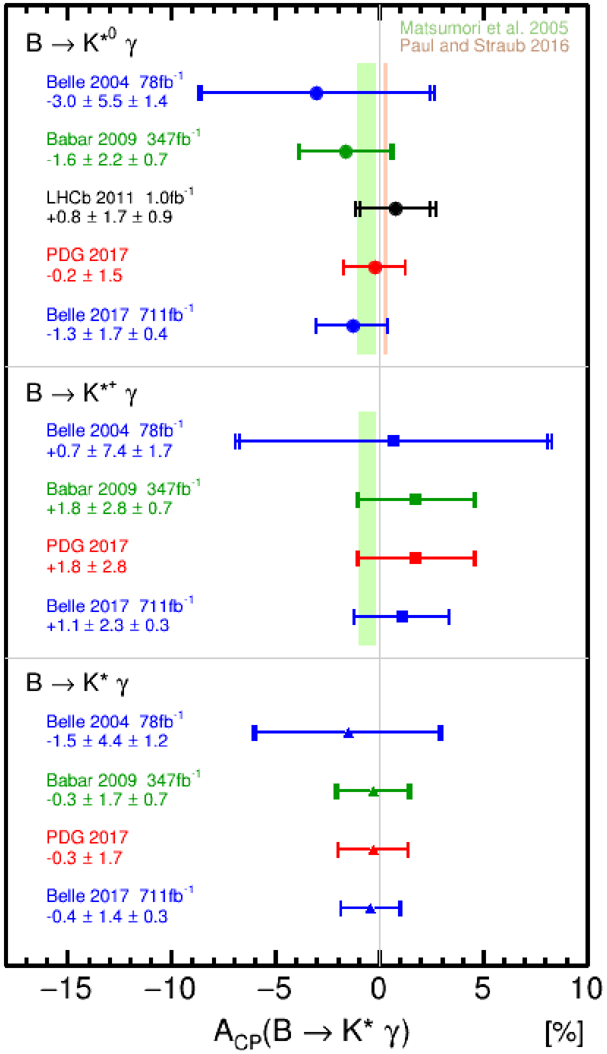
$N_S \sim 350$ evts

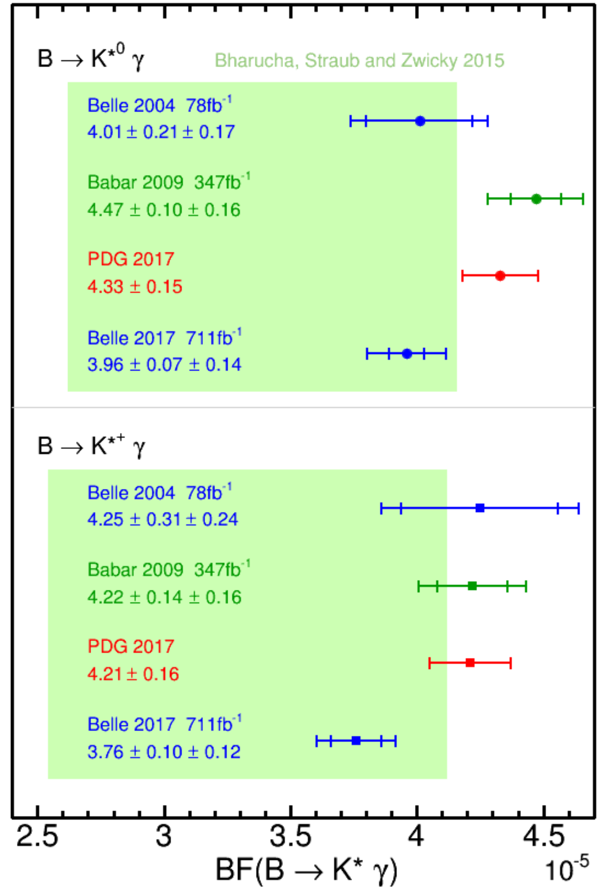
$N_S \sim 4500$ evts

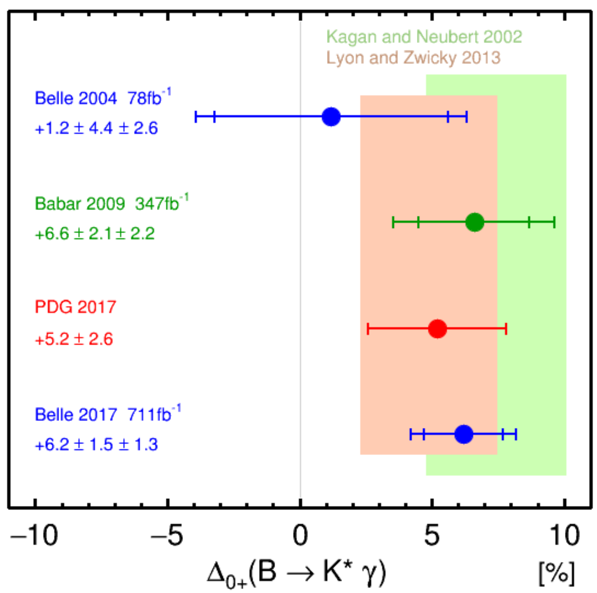
$N_S \sim 1000$ evts

$N_S \sim 1500$ evts



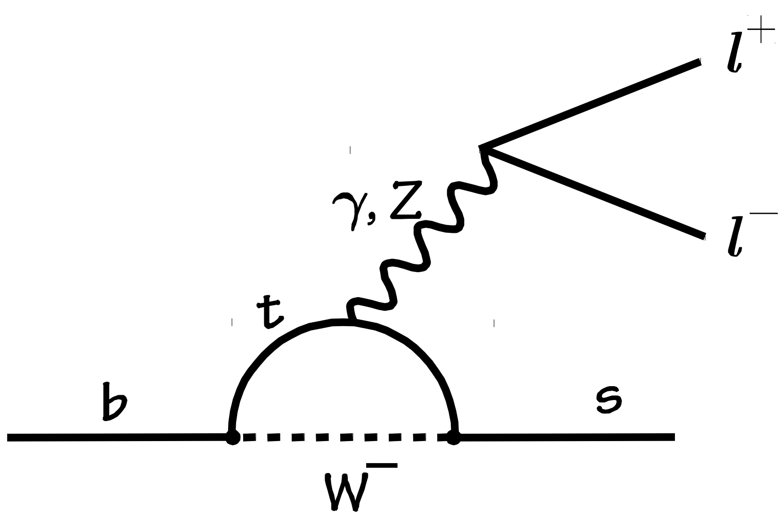


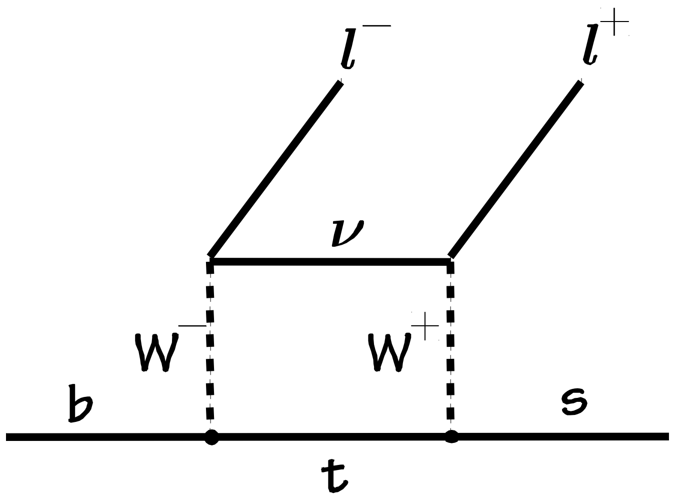




first evidence of isospin violation in $K^*\gamma$!

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





$\Rightarrow$ 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}

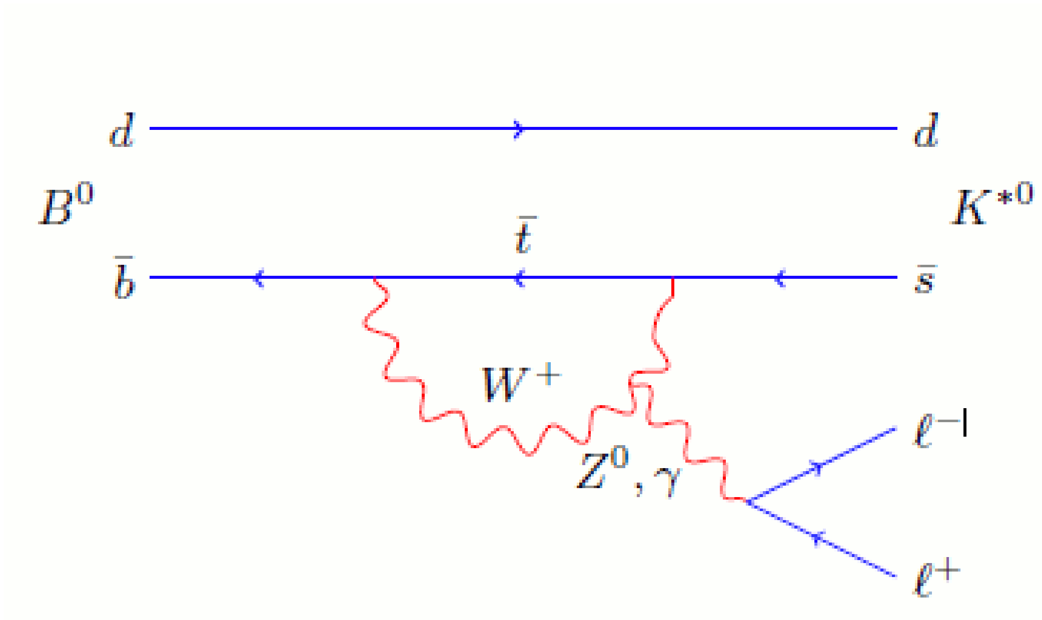
may interfere w/ contributions from NP

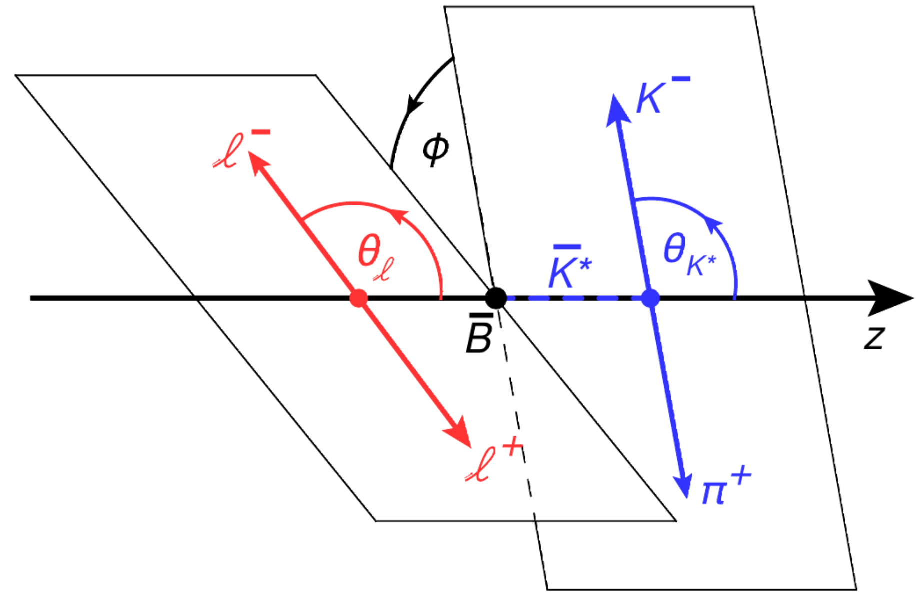
Many observables:
- Branching fractions
- Isospin asymmetry (A_I), Lepton forward-backward asymmetry (A_{FB}), CP asymmetry ...
- and much more...

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

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

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



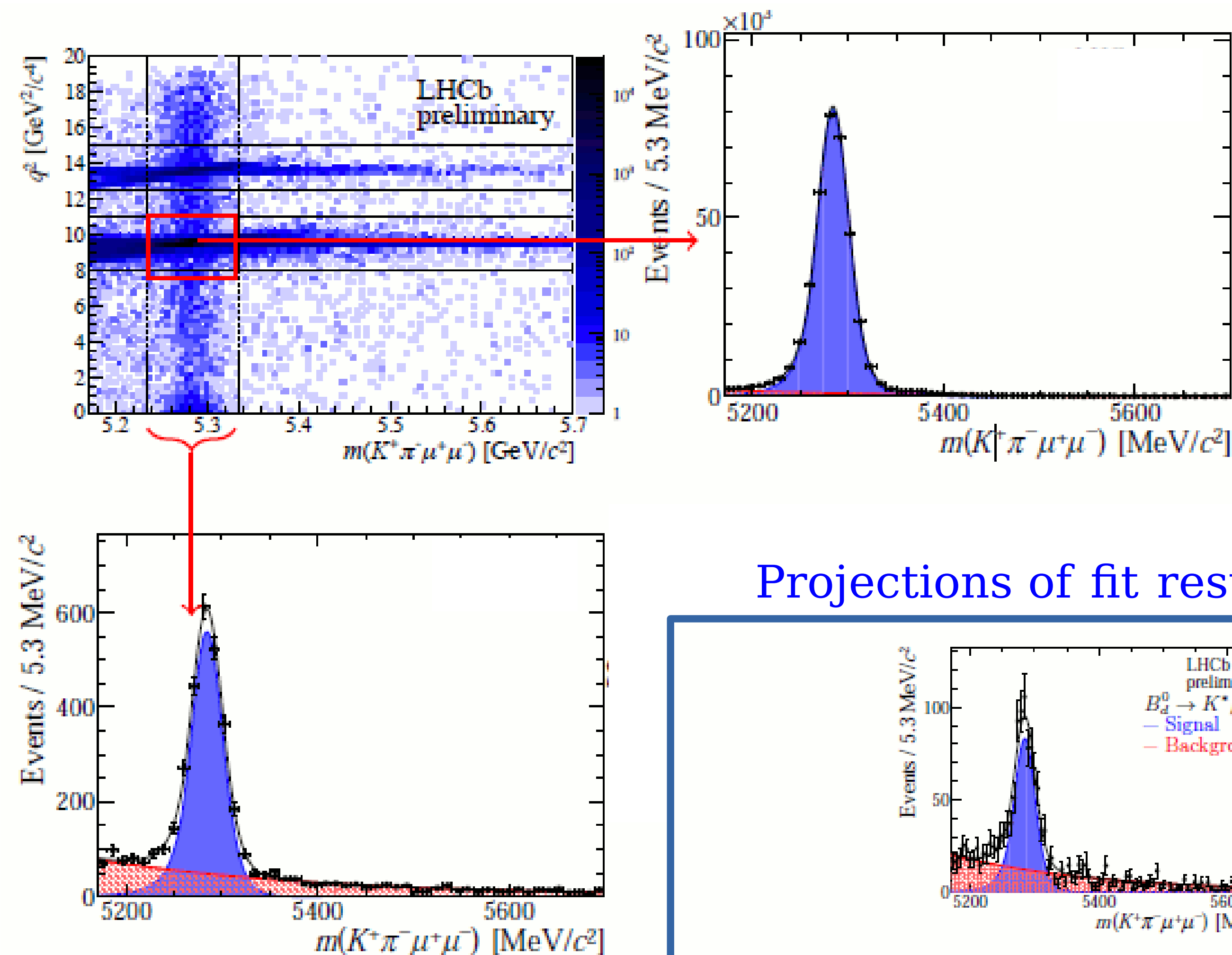


$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

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

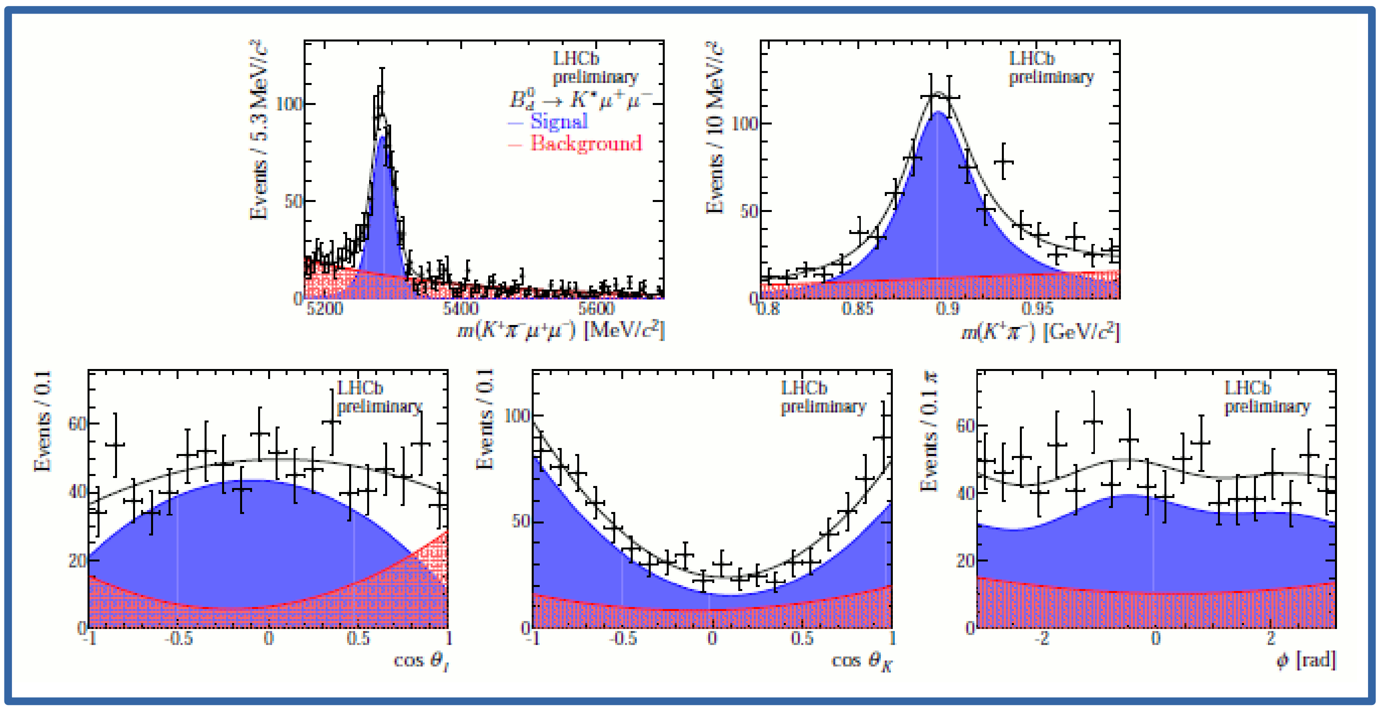
Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays [LHCb, arXiv:1512.04442]

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



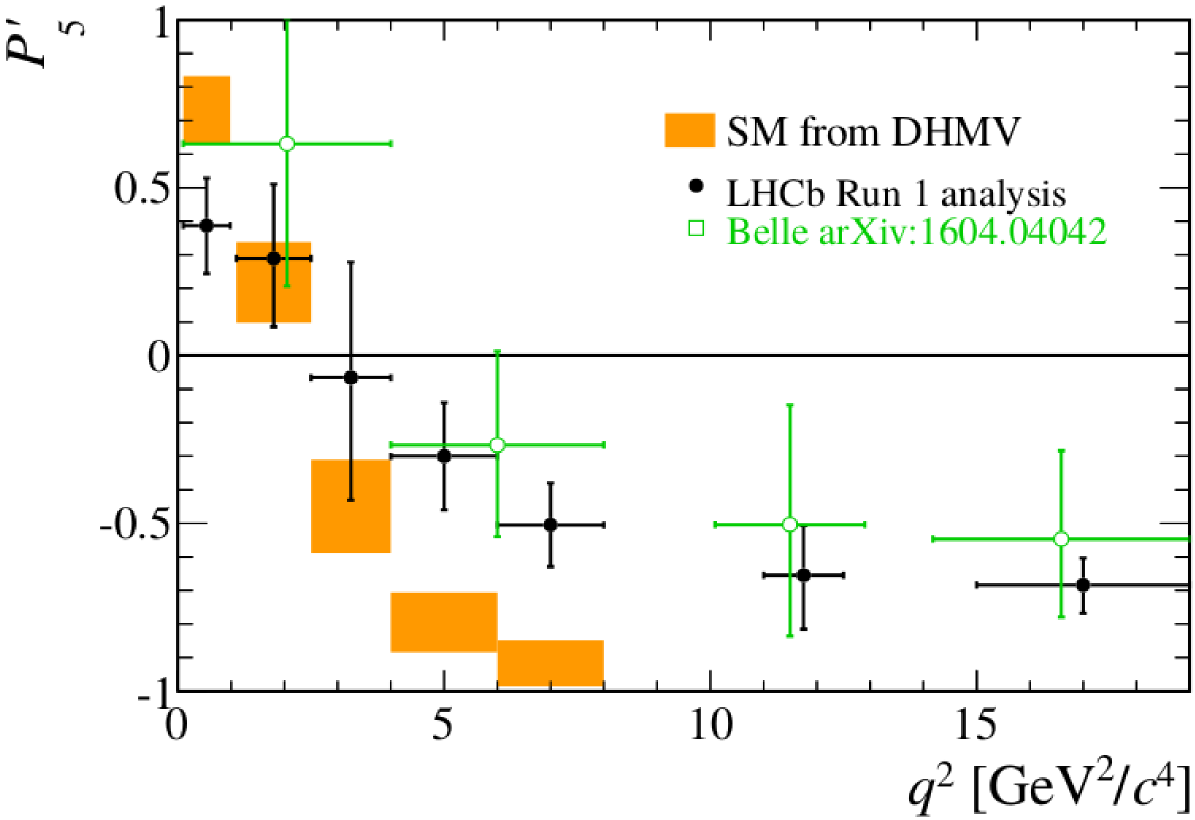
~ 2400 evts in full q^2 range

Projections of fit results for $q^2 \in [1.1, 6.0]$ GeV^2



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

- Form-factor less dependent observables $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$



[LHCb, arXiv:1512.04442]

- Tension in P_5' seen with $1\,\text{fb}^{-1}$ 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

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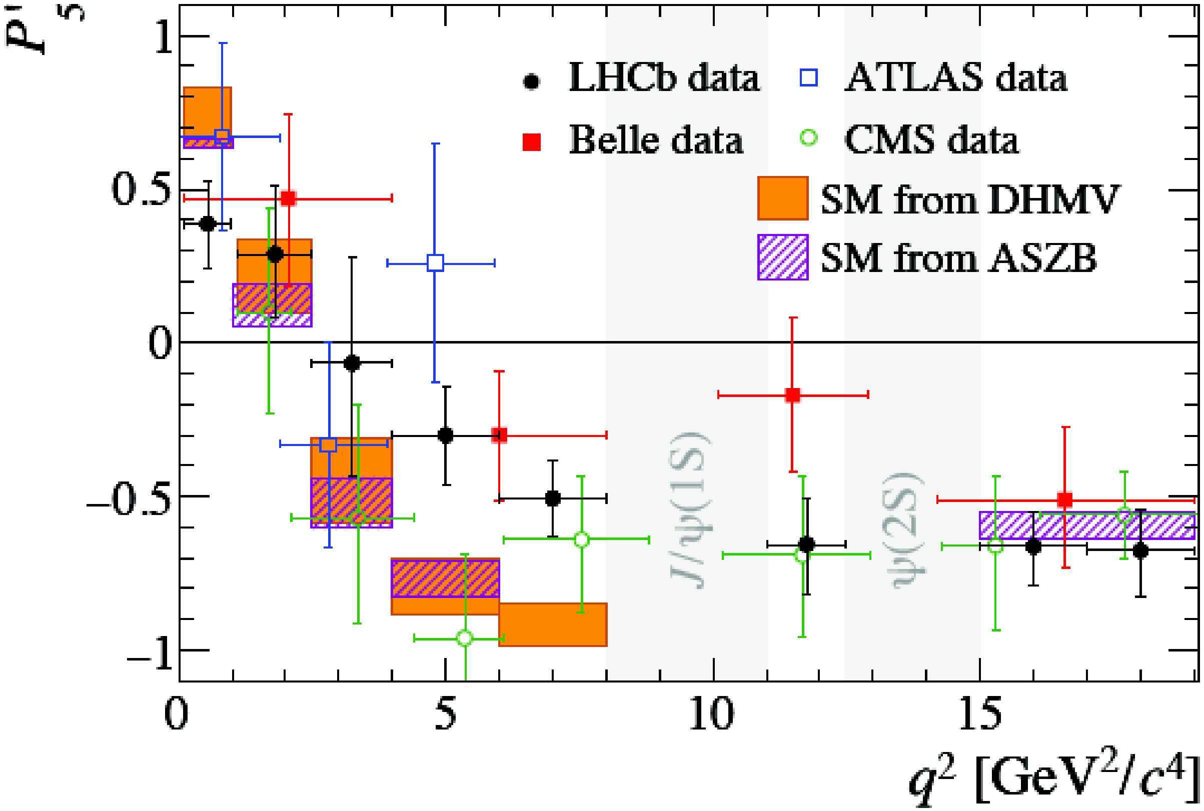

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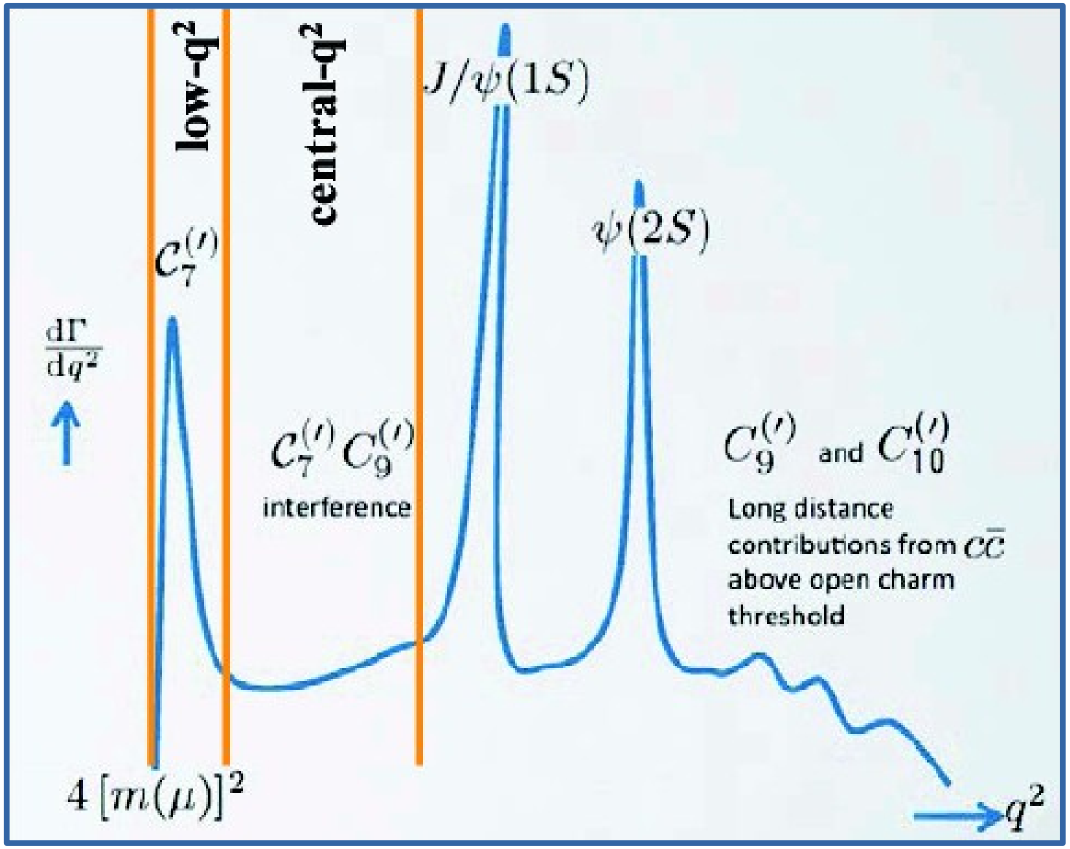
- LHCb, Belle and ATLAS show deviations in $4 < q^2 < 8$ GeV^2/c^4
- CMS shows better agreement

Test of LFU with $B \to K^{*0}\mu\mu$ and $B \to K^{*0}ee$, $R_{K^{*0}}$

Two regions of q^2

- Low [0.045-1.1] GeV^2/c^4
- Central [1.1-6.0] GeV^2/c^4



Different q^2 regions probe different processes in the OPE framework short distance contributions described by Wilson coefficients

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_e}{4\pi} \sum [C_i\mathcal{O}_i + C_i'\mathcal{O}_i']$$

- Measured relative to $B^0 \to K^{*0} J/\psi(ll)$ in order to reduce systematics
- Challenging:
  - due to significant differences in the way μ and e interact with detector
  - Bremsstrahlung
  - Trigger

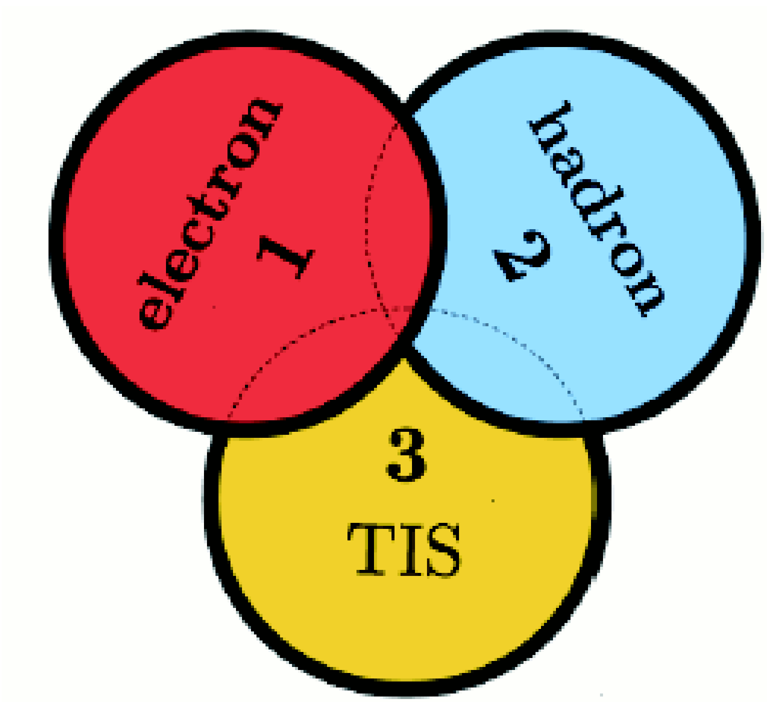
Strategy

- Measured relative to $B^0 \to K^{*0} J/\psi(ll)$ in order to reduce systematics

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

- High occupancy of calorimeters (compared to muon stations)

$\Rightarrow$ hardware thresholds on electron E_T higher than on muon p_T (L0 Muon, $p_T > 1.5$, 1.8 GeV)



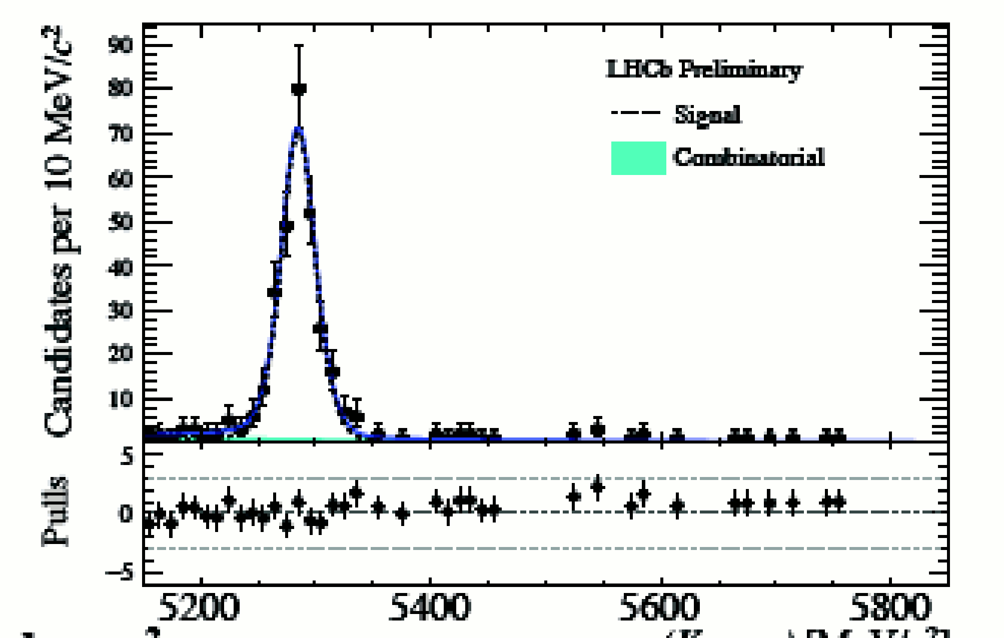
3 exclusive trigger categories:

- L0 Electron: electron hardware trigger fired by clusters associated to at least one of the two electrons ($E_T > 2.5$ GeV)
- L0 Hadron: hadron hardware trigger fired by clusters associated to at least one of the K^{*0} decay products ($E_T > 2.5$ GeV)
- L0 TIS(*): any hardware trigger fired by particles in the event not associated to the signal candidate

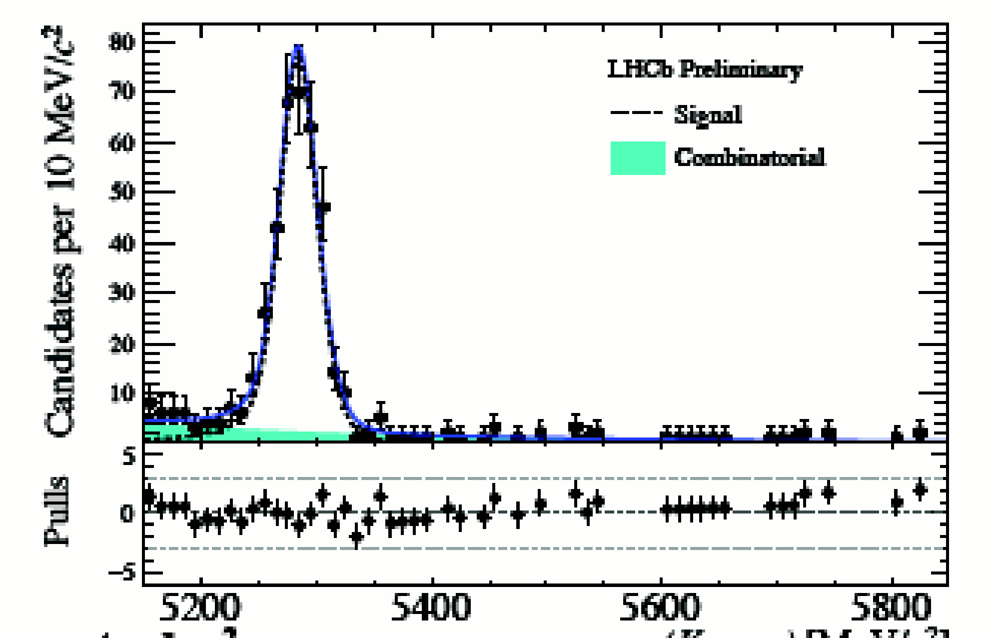
(*) TIS = Trigger Independent of Signal

Fit results – μμ

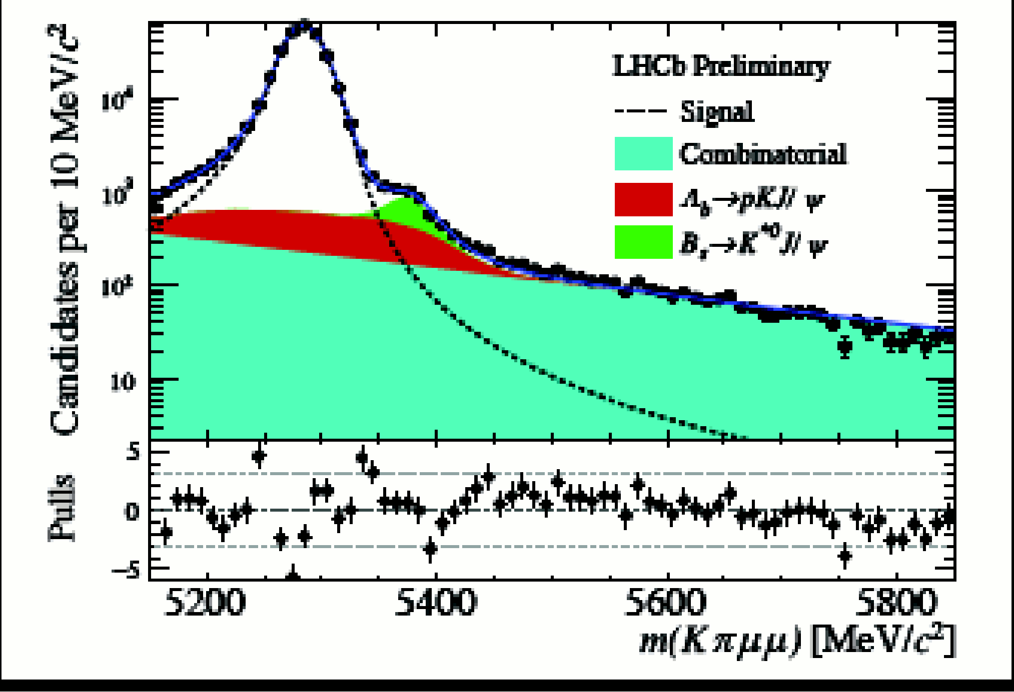
[LHCb, arXiv:1705.05802]



low-q^2

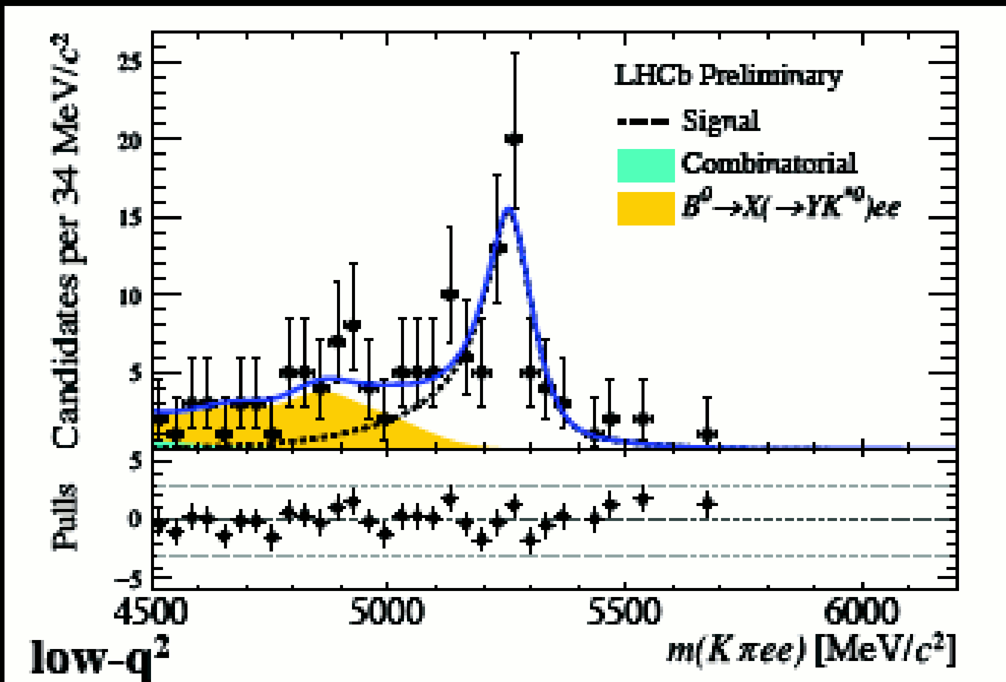


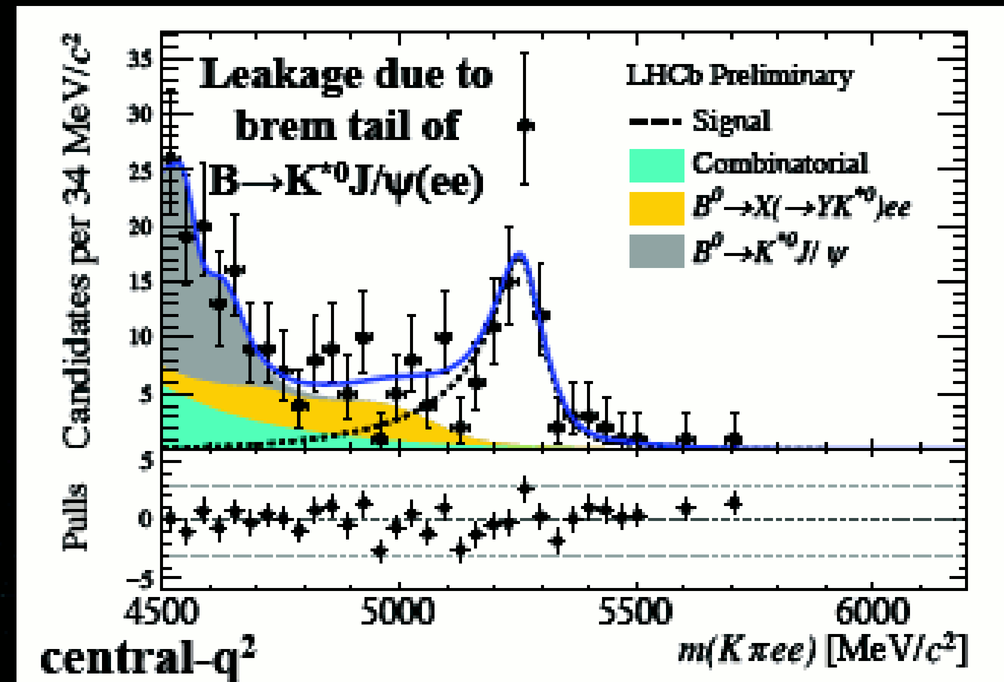
central-q^2

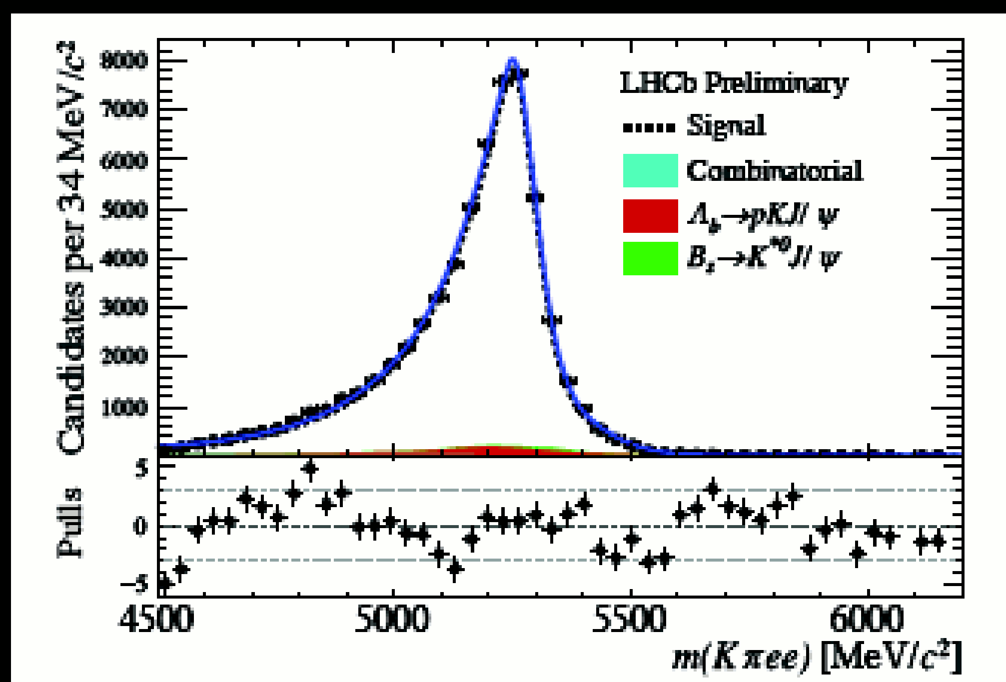


Fit results – ee

[LHCb, arXiv:1705.05802]







Results

[LHCb, arXiv:1705.05802]

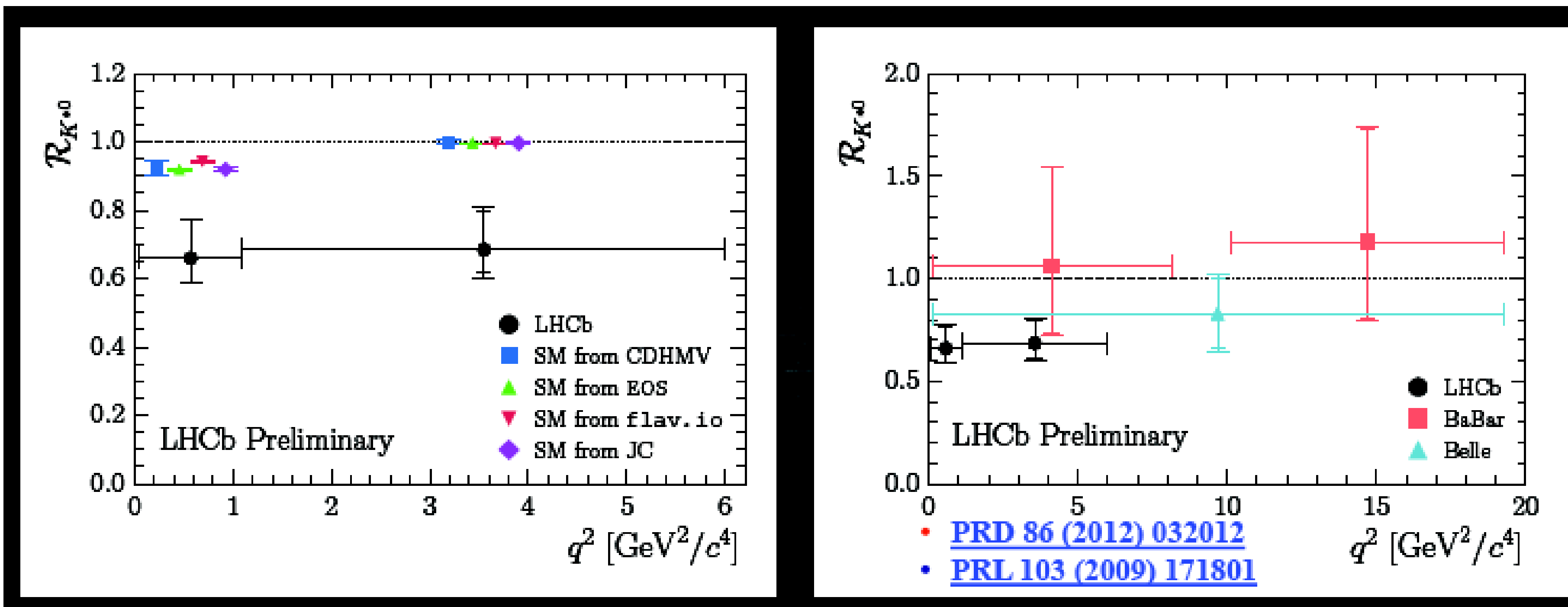
Precision of the measurement driven by the statistics of the electron samples

	$B^0 \to K^{*0}\ell^+\ell^-$ low-q^2	$B^0 \to K^{*0}\ell^+\ell^-$ central-q^2	$B^0 \to K^{*0}J/\psi(\to \ell^+\ell^-)$
$\mu^+\mu^-$	$285\ ^{+\ 18}_{-\ 18}$	$353\ ^{+\ 21}_{-\ 21}$	$274416\ ^{+\ 602}_{-\ 654}$
e^+e^- (L0E)	$55\ ^{+\ 9}_{-\ 8}$	$67\ ^{+\ 10}_{-\ 10}$	$43468\ ^{+\ 222}_{-\ 221}$
e^+e^- (L0H)	$13\ ^{+\ 5}_{-\ 5}$	$19\ ^{+\ 6}_{-\ 5}$	$3388\ ^{+\ 62}_{-\ 61}$
e^+e^- (L0I)	$21\ ^{+\ 5}_{-\ 4}$	$25\ ^{+\ 7}_{-\ 6}$	$11505\ ^{+\ 115}_{-\ 114}$

for $0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4$,
$R_{K^{*0}} = 0.66\ ^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$

for $1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$,
$R_{K^{*0}} = 0.69\ ^{+0.11}_{-0.07}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$

In total, about 90 and 110 $B^0 \to ee$ candidates at low- and central-q^2



- compatibility of result in the **low-q^2** with respect to SM is of **2.2-2.4** standard dev.
- compatibility of result in the **central-q^2** with respect to SM is of **2.4-2.5** standard dev.

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

[LHCb, arXiv:1406.6482]

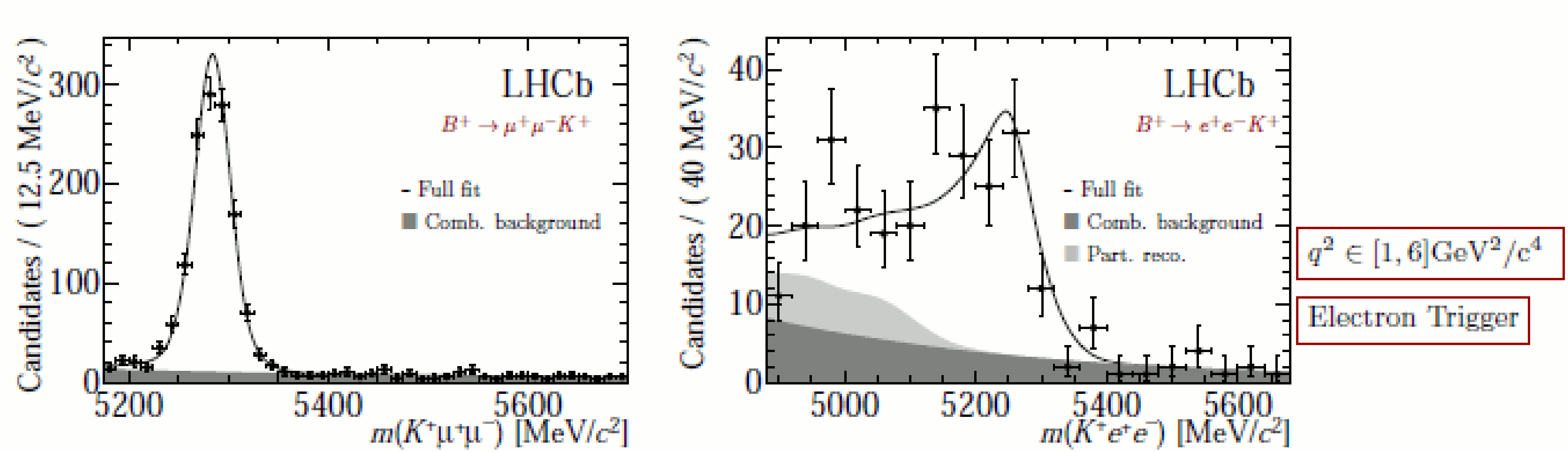
- Ratio of branching fractions of $B^+ \to K^+ e^+ e^-$ and $B^+ \to K^+ \mu^+ \mu^-$ sensitive to lepton universality

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)]}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[\mathcal{B}(B^+ \to K^+ e^+ e^-)]}{dq^2} dq^2} = \left(\frac{N_{K\mu\mu}}{N_{Kee}}\right) \left(\frac{N_{J/\psi(ee)K}}{N_{J/\psi(\mu\mu)K}}\right) \left(\frac{\varepsilon_{Kee}}{\varepsilon_{K\mu\mu}}\right) \left(\frac{\varepsilon_{J/\psi(ee)K}}{\varepsilon_{J/\psi(\mu\mu)K}}\right)$$

- SM prediction is $R_K = 1$ with an uncertainty of $O(10^{-2})$

[M.Bordone, G.Isodori, A.Pattori, arXiv:1605.07633]

- Measurement relative to resonant $B \to J/\psi K$ modes

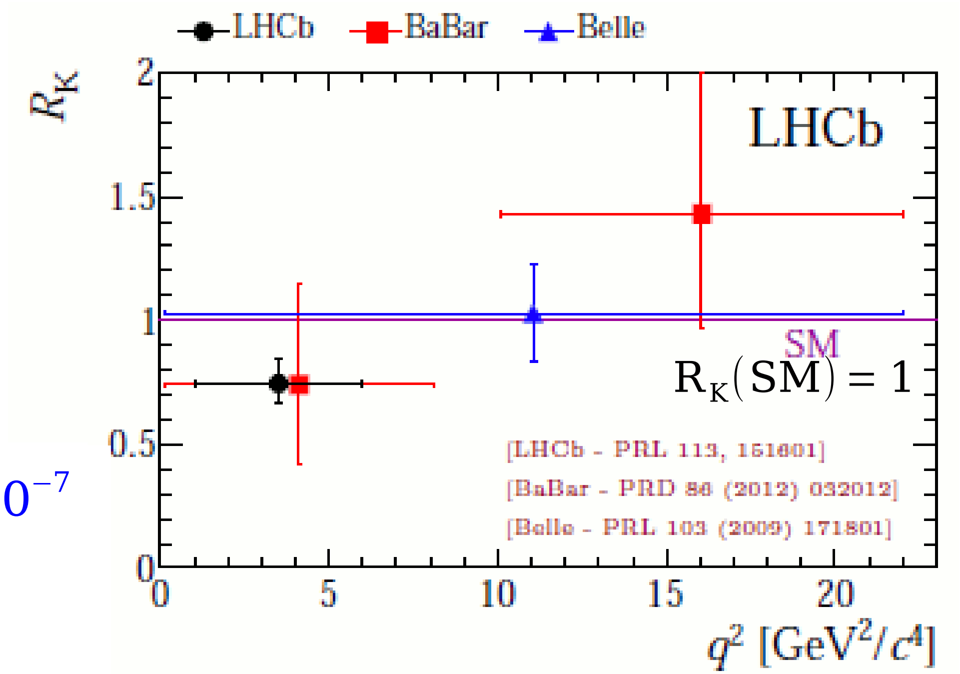


R_K: ratio of branching fractions for dilepton invariant mass squared range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

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

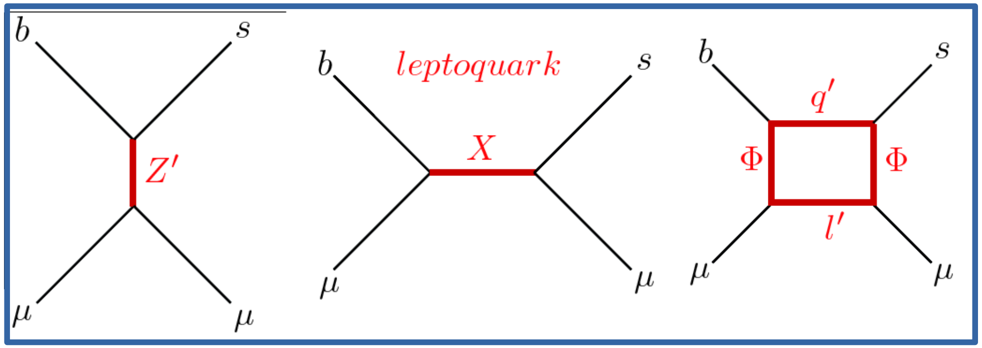
- The combination of the various trigger channels gives:
  $$R_K = 0.745\,^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$
- Most precise measurement to date, disagreement with SM at 2.6σ level

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



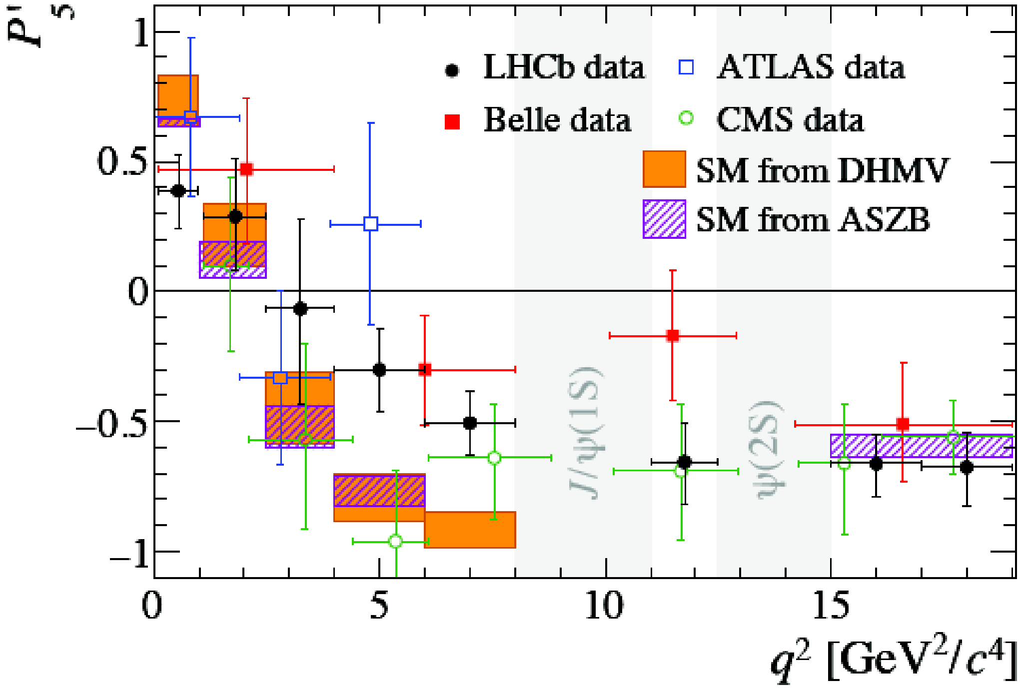
Model candidates

- ✧ **Model with extended gauge symmetry**
  - ✓ Effective operator from Z' exchange
  - ✓ Extra U(1) symmetry with flavor dependent charge
- ✧ **Models with leptoquarks**
  - ✓ Effective operator from LQ exchange
  - ✓ Yukawa interaction with LQs provide flavor violation
- ✧ **Models with loop induced effective operator**
  - ✓ With extended Higgs sector and/or vector like quarks/leptons
  - ✓ Flavor violation from new Yukawa interactions



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

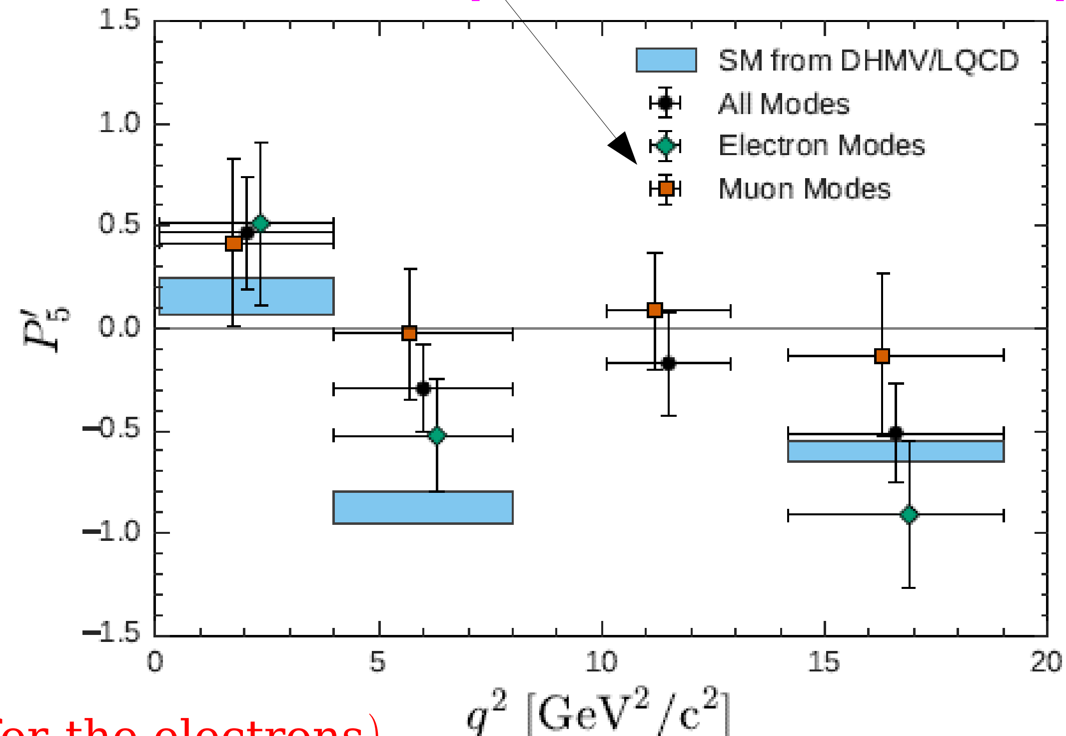
- Form-factor less dependent observables $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$



- LHCb, Belle and ATLAS show deviations in $4 < q^2 < 8$ GeV^2/c^4
- CMS shows better agreement

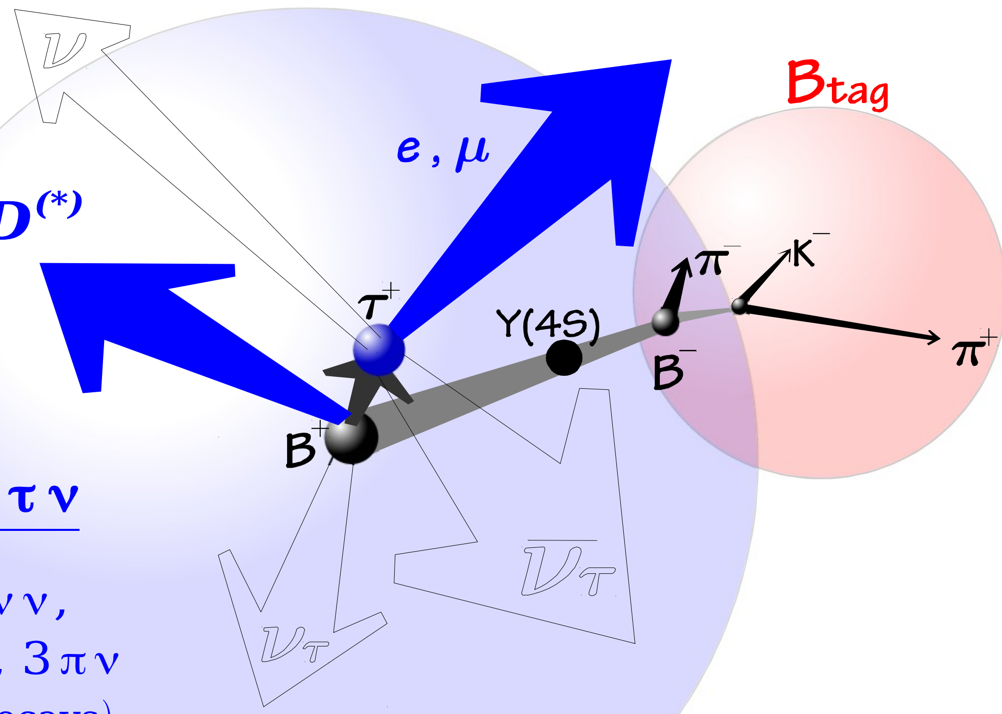
not only use K^{*0}, also K^{*+} ($\to K_S\pi^+$, $K^+\pi^0$)

[Belle, arXiv:1612.05014]



- LFU test, measurement of $Q^i = P^i_\mu - P^i_e$
- 2.6σ in P'_5 for the muons channels (1.3σ for the electrons)

Event reconstruction in $B \to \tau\nu$ at B factories



B_{tag}

hadronic tag

$B \to D^{(*)}\pi,\ D^{(*)}\rho \ldots$

$\epsilon \sim 0.2\,\%$

semileptonic tag

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

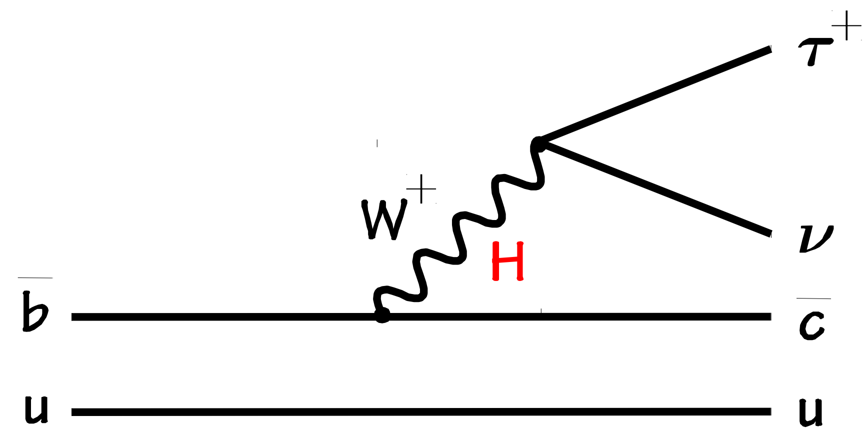
$B_{sig} \to D^{(*)}\tau\nu$

$\tau \to e\nu\nu,\ \mu\nu\nu,$

$\tau \to \pi\nu,\ \pi\pi^{0}\nu,\ 3\pi\nu$

(70 % of all τ decays)

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



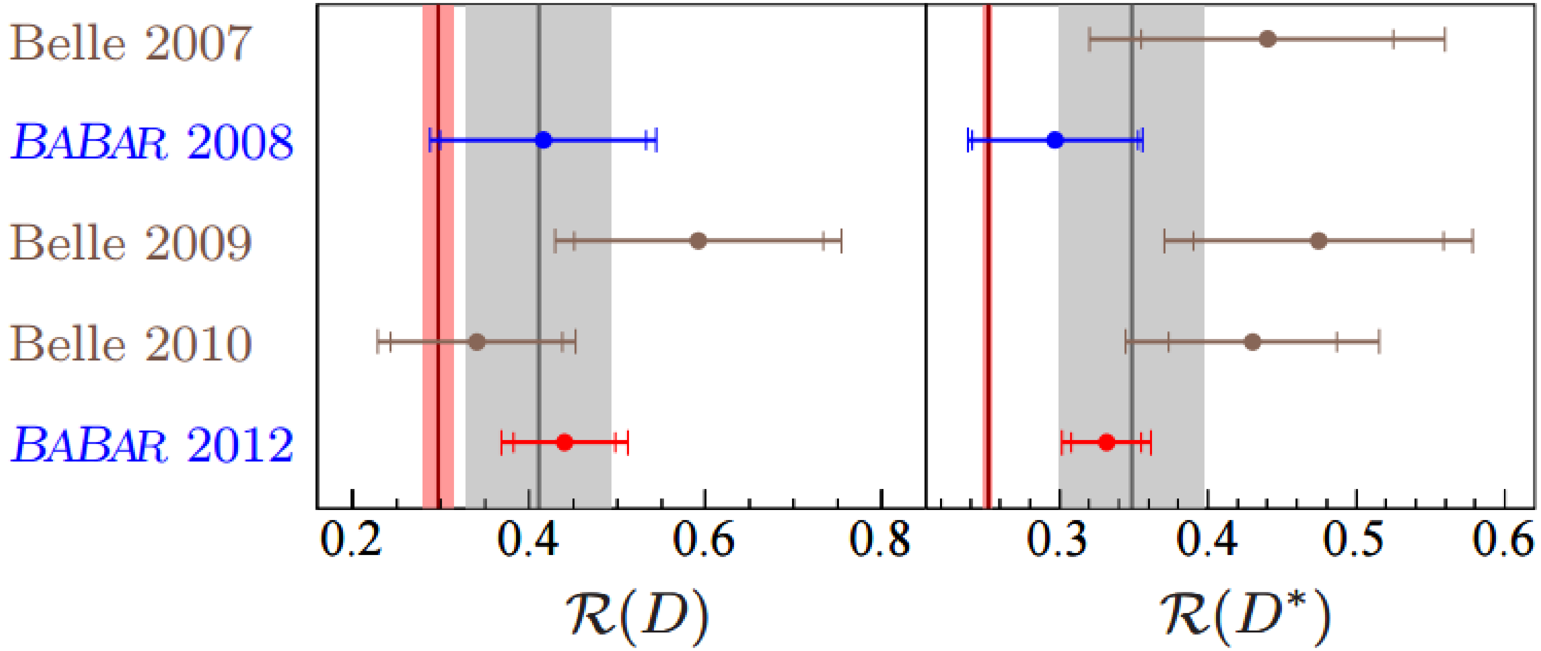
$$\text{2HDM (type II)}: \mathcal{B}(B \to D\tau^{+}\nu) = G_F^2\,\tau_B\,|V_{cb}|^2\, f\left(F_V,\, F_S,\, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

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

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

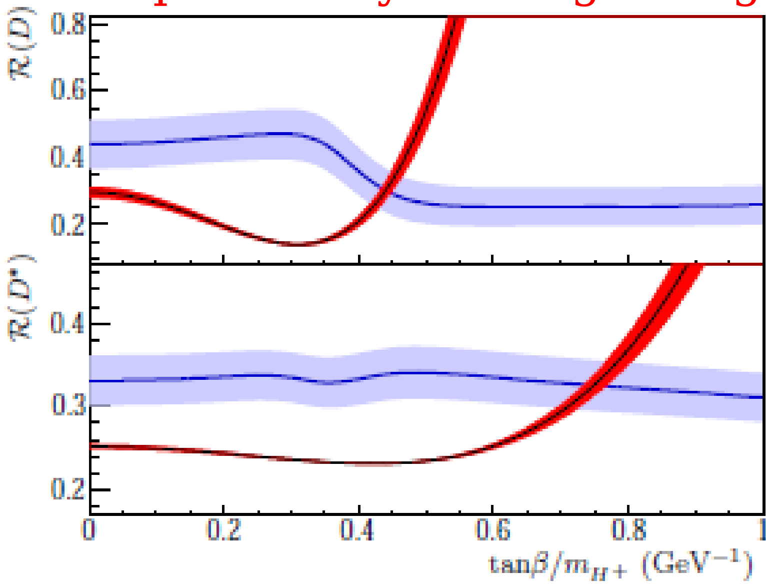
$$R(D^{(*)}) = \frac{B(B \to D^{(*)} \tau \nu)}{B(B \to D^{(*)} l \nu)}$$

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"

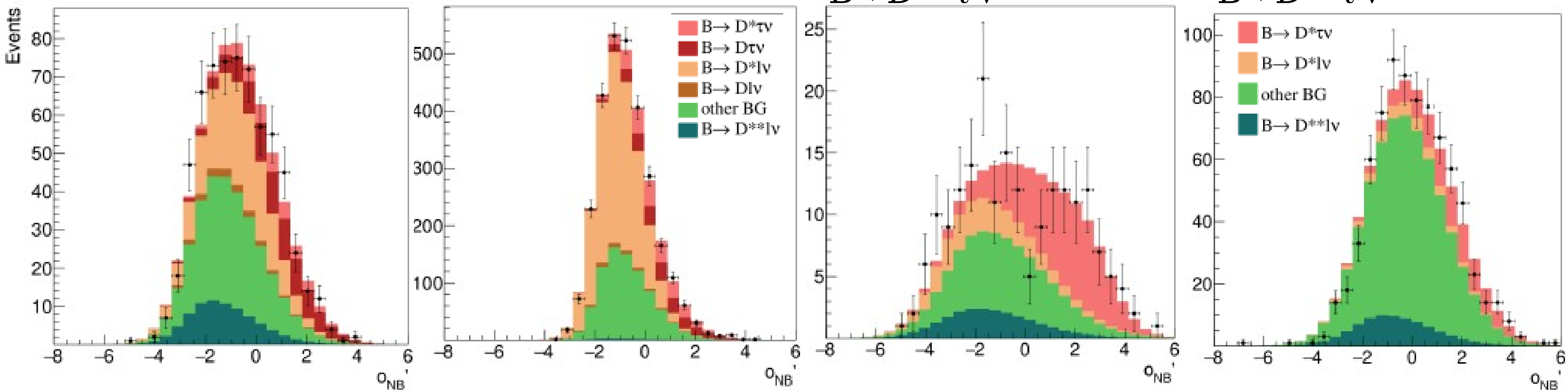


$B \to D^{(*)} \tau \nu$ at Belle

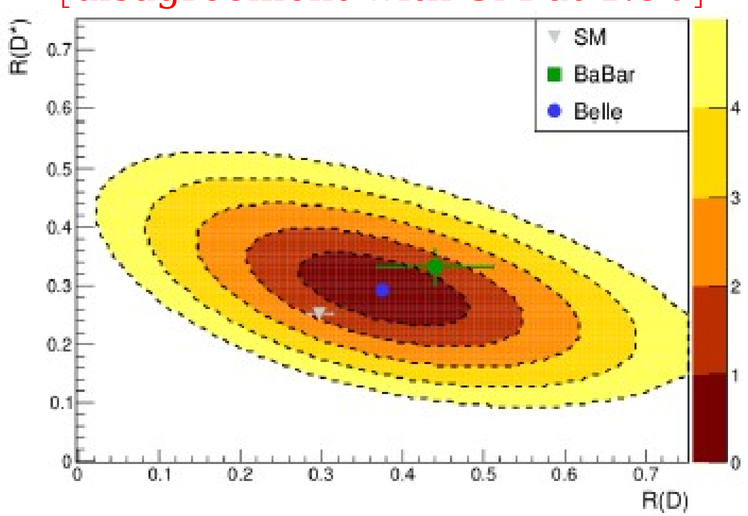
[arXiv:1507.03233]

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

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



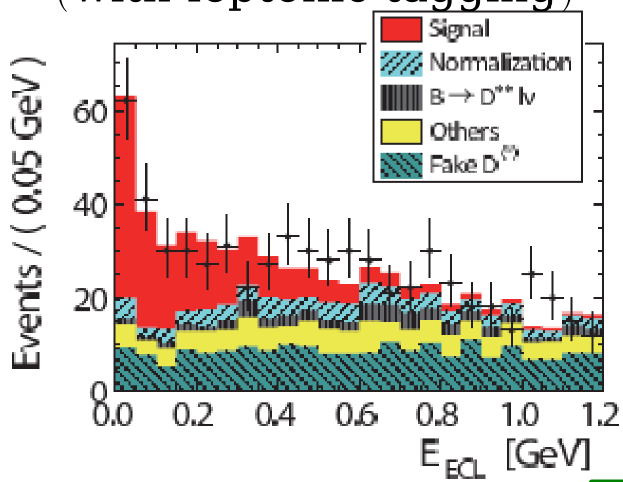
[disagreement with SM at 1.5σ]

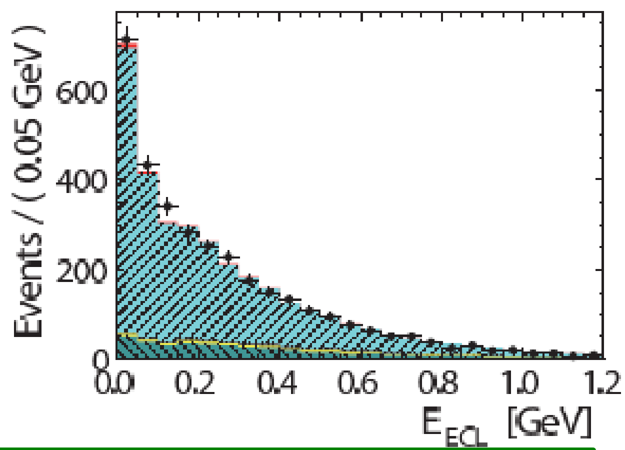


$\mathbf{R(D) = 0.375 \pm 0.064 \pm 0.026}$
$\mathbf{R(D^*) = 0.293 \pm 0.038 \pm 0.015}$

(with leptonic tagging)

[arXiv:1607.07923]





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

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

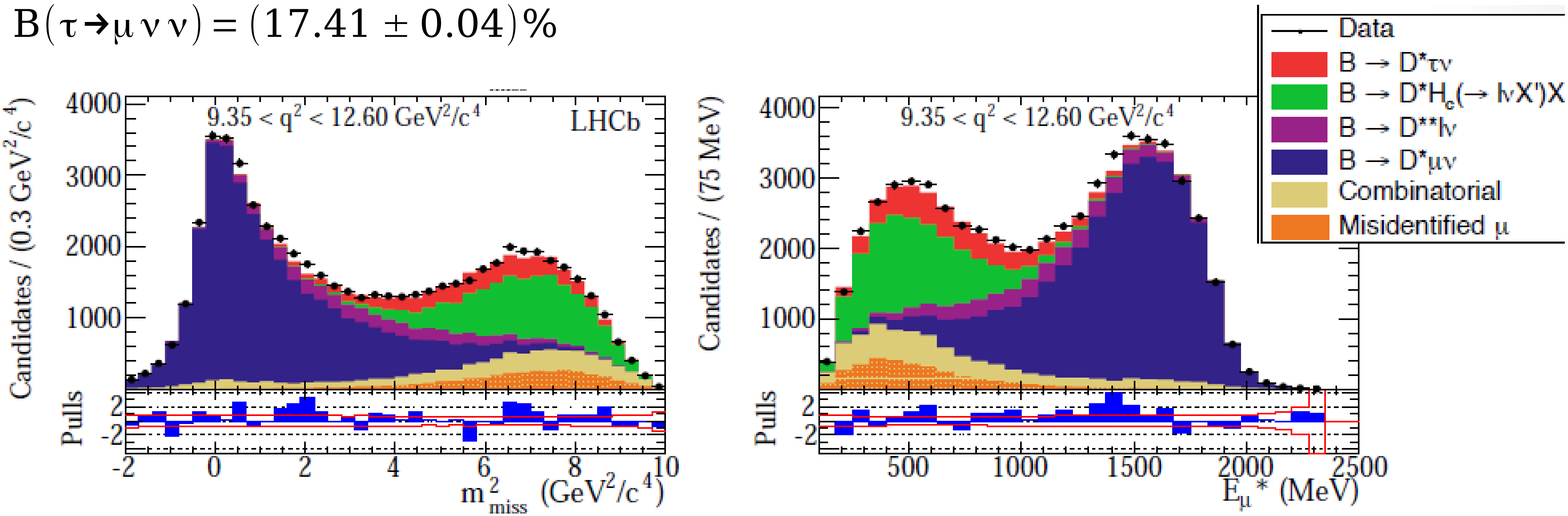
[arXiv:1506.08614]

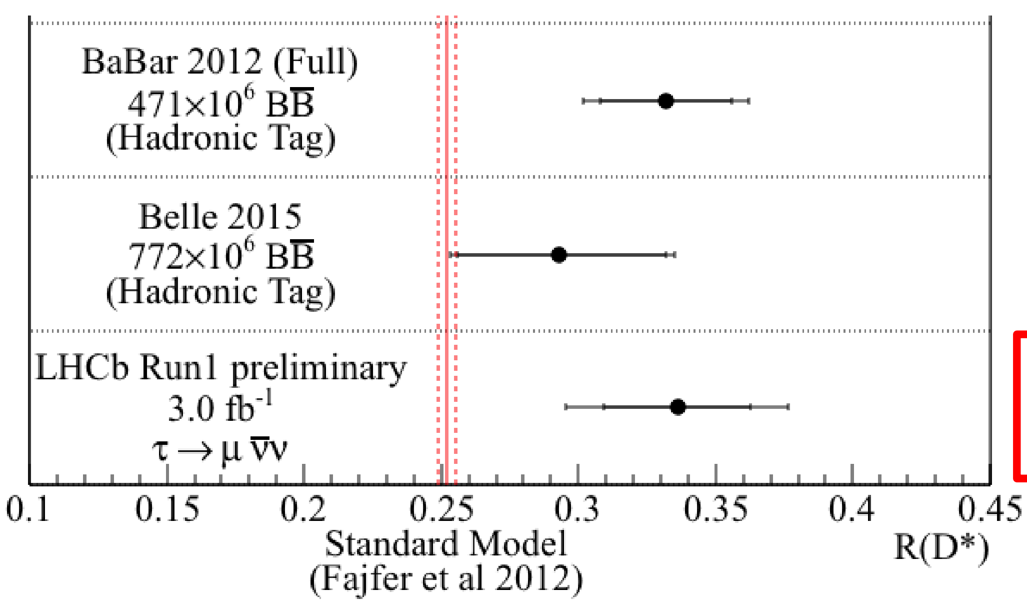
$$R(D^*) \equiv \frac{\mathcal{B}\left(\bar{B}^0 \rightarrow D^{*+}\tau^-(\mu^-\bar{\nu}_\mu \nu_\tau)\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu\right)}$$

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

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

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





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

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

[Belle, arXiv:1507.03233]

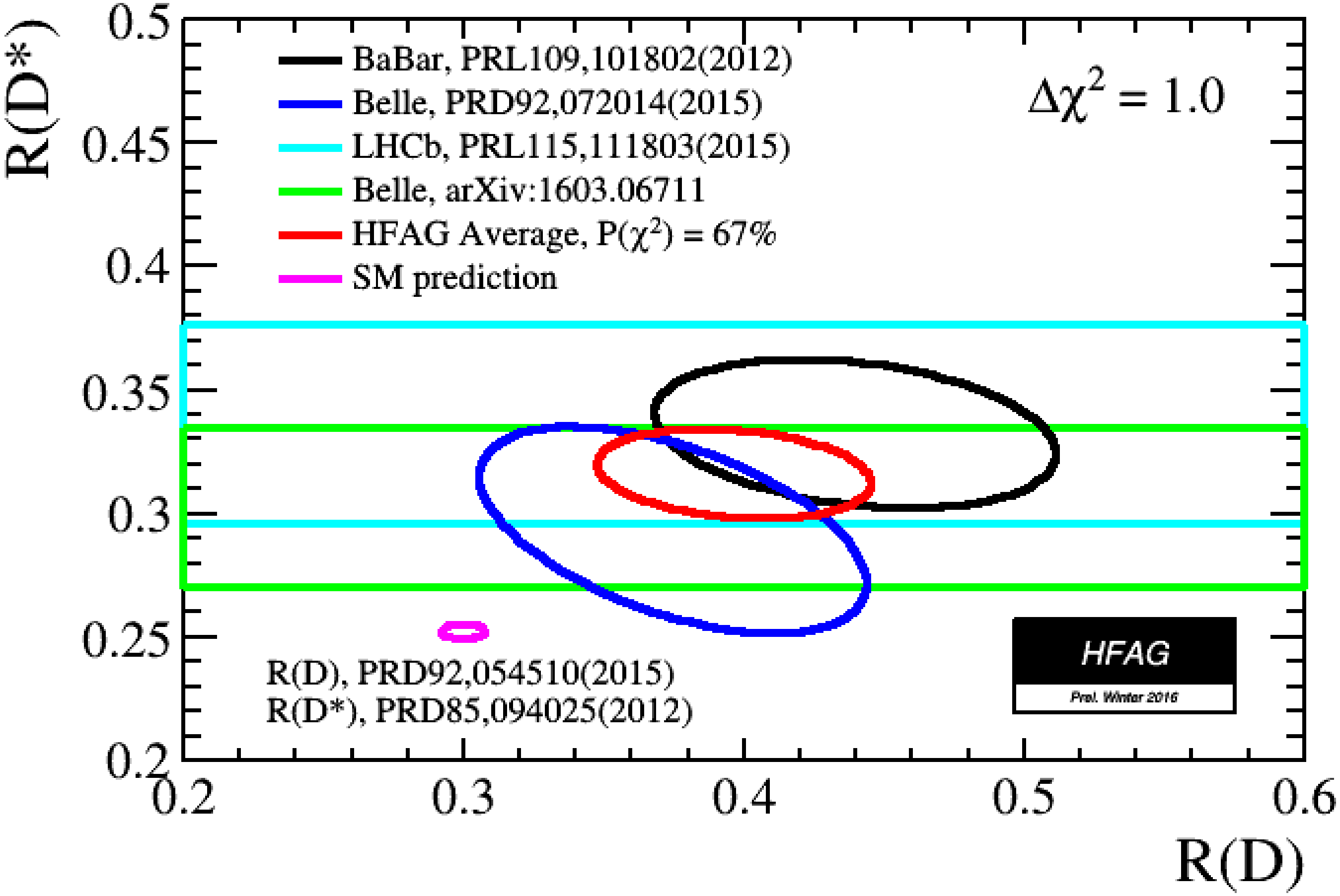
$\mathbf{R(D^*) = 0.336 \pm 0.027 \pm 0.030}$

[disagreement with SM at 2.1 σ]

[LHCb, arXiv:1506.08614]

Summary for $B \to D^{(*)} \tau \nu$ in 2016

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



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 **4.0σ** level

$B \to D^* \tau \nu$ at Belle

$D^{(*)}$ leptonic with hadronic tagging, arXiv:1507.03233
D^* with leptonic tagging, arXiv:1607.07923

New result using:
- hadronic decays of $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$
- hadronic tagging

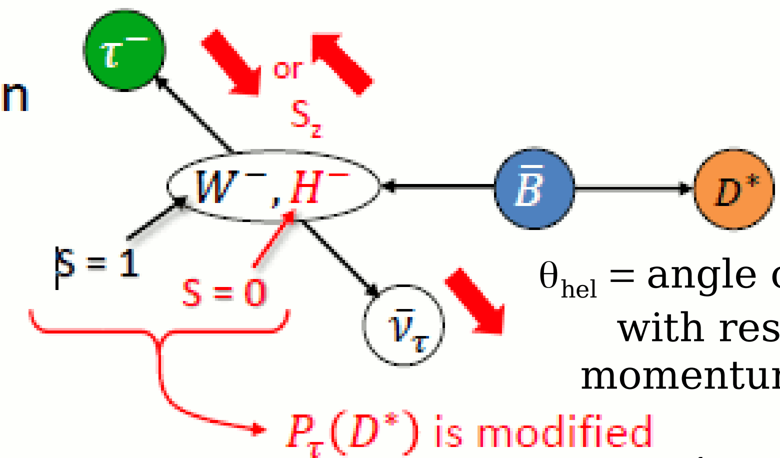
$\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$ are good polarimeter for τ polarization

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$\Gamma^{+(-)}$ for right-(left-)handed τ

$P_\tau(D^*)_{SM} = -0.497 \pm 0.013$

M. Tanaka and R. Watanabe, Phys. Rev. D 87, 034028 (2013)

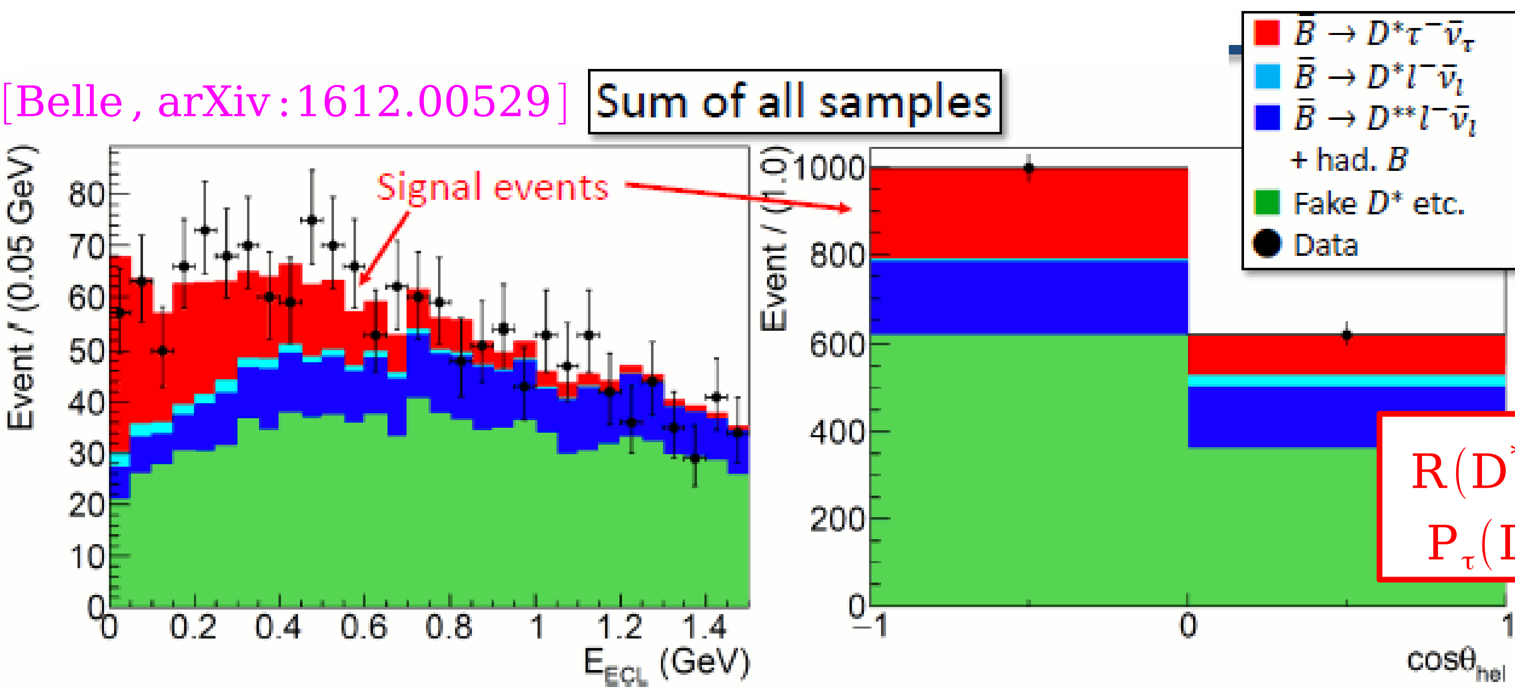


τ polarization is a variable sensitive to NP

θ_{hel} = angle of τ daughter meson momentum with respect to direction opposite to momentum of $\tau\nu$ system in τ rest frame

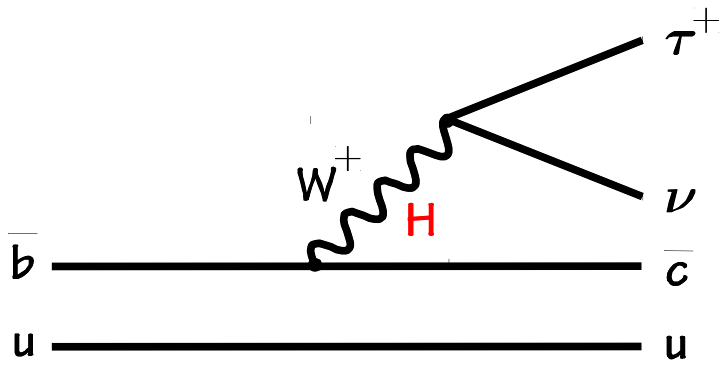
$$\frac{1}{\Gamma(D^*)}\frac{d\Gamma(D^*)}{d\cos\theta_{hel}} = \frac{1}{2}[1\,\alpha P_\tau(D^*)\cos\theta_{hel}]$$

[Belle, arXiv:1612.00529]

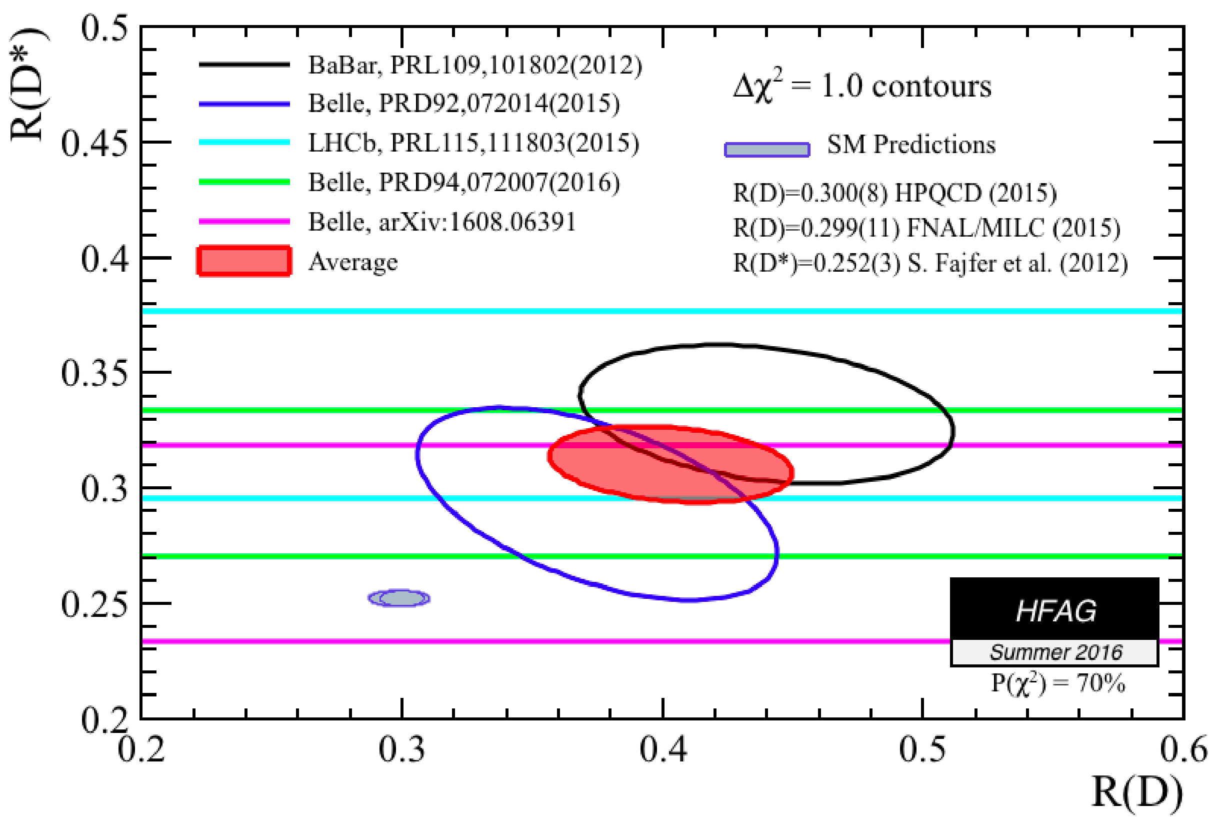


$R(D^*) = 0.270 \pm 0.035\,^{+0.028}_{-0.025}$
$P_\tau(D^*) = -0.38 \pm 0.51\,^{+0.21}_{-0.16}$

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



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



BaBar

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

Belle

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

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

$\mathbf{R(D^*) = 0.276 \pm 0.034 \,^{+0.029}_{-0.026}}$

LHCb

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

average

$\mathbf{R(D) = 0.403 \pm 0.040 \pm 0.024}$
$\mathbf{R(D^*) = 0.310 \pm 0.015 \pm 0.008}$

difference with SM predictions is at **3.9** σ level

$\Rightarrow$ more precise measurements needed, more observables (τ polarization ...)

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

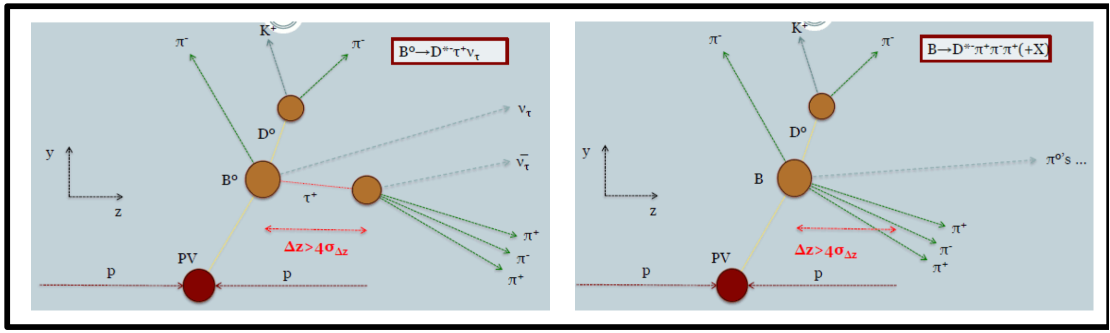
$\tau \to 3\pi(\pi^0)$

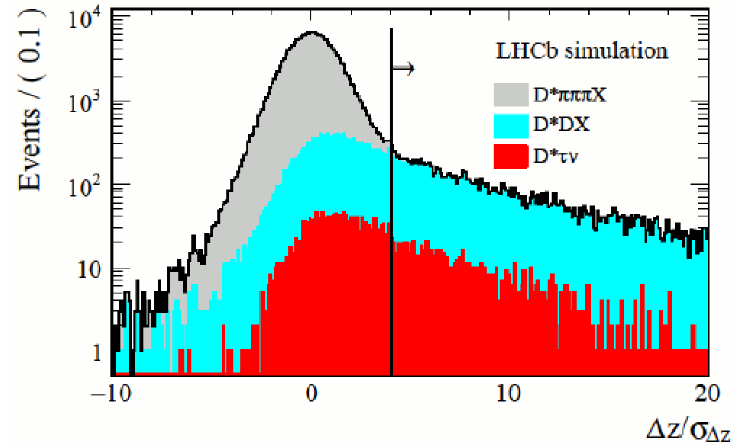
[LHCb-PAPER-2017-017]

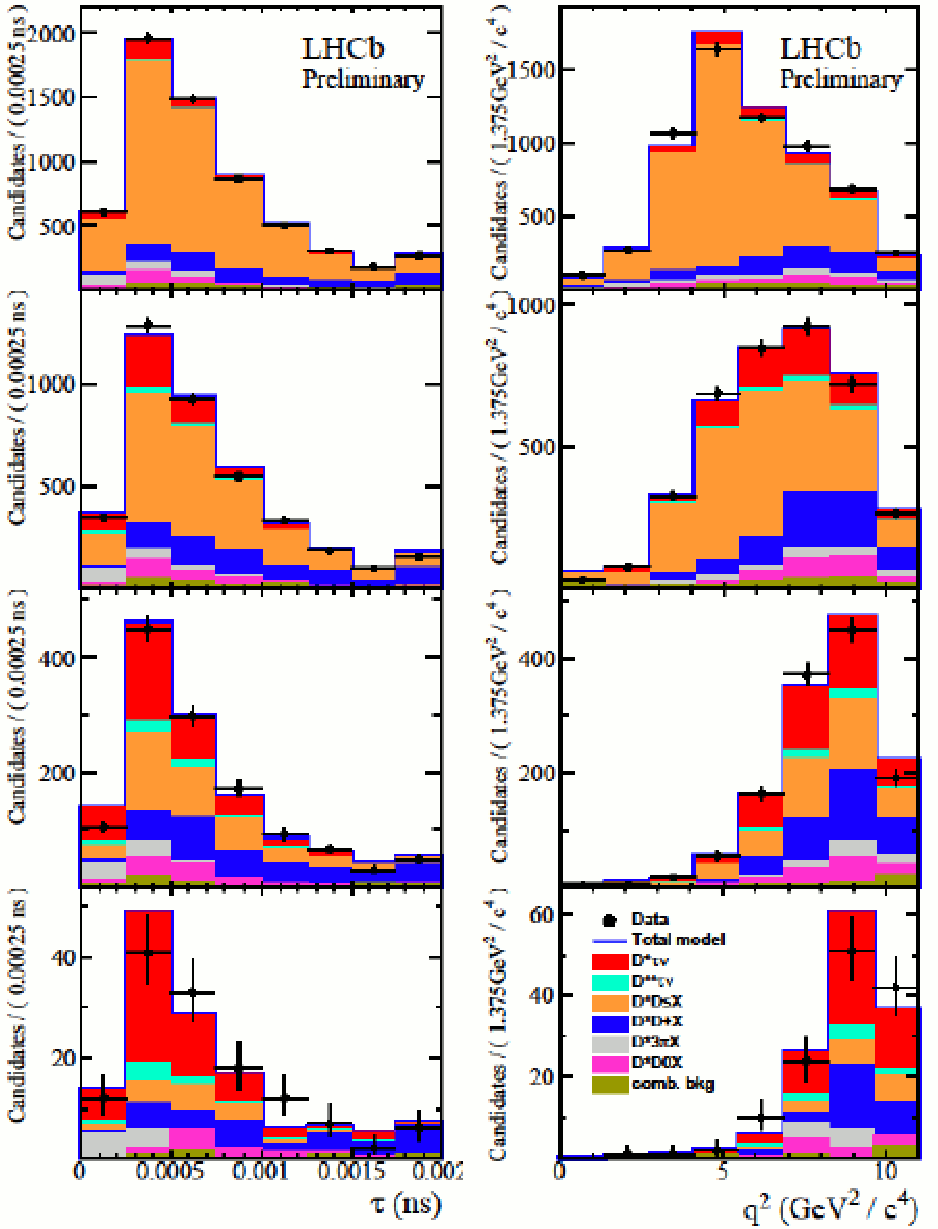
need a strong background suppression:

$\mathcal{B}(B^0 \to D^* 3\pi + X)/\mathcal{B}(B^0 \to D^* \tau\nu;\ \tau \to 3\pi)_{SM} \sim 100$

$\Rightarrow$ detached vertex method







components of 3D fit (q^2, 3π decay time, BDT):

anti-D_s

$\tau \to \pi^-\pi^+\pi^-\nu_\tau,\ \pi^-\pi^+\pi^-\pi^0\nu_\tau$

$X_b \to D^{**}\tau\nu_\tau$

$\left.\begin{array}{l} B \to D D_{s(J)} X \\ X_b \to D D X \end{array}\right\}$ (relative) yields constrained from control samples

$\mathcal{B}(B^0 \to D^*\tau\nu)/\mathcal{B}(B^0 \to D^* 3\pi) = (1.93 \pm 0.13 \pm 0.17)$

$\Rightarrow$ **$R(D^*) = 0.285 \pm 0.019 \pm 0.025 \pm 0.014$**

$R(D)$, $R(D^*)$ still at 4σ away from SM

Summary

- Few tantalizing results on rare decays in B sector covered in this talk… but much more in B decays: LFV searches, $B\to K^{(*)}\nu\bar{\nu}$, $B\to\tau\nu$, $\mu\nu$…

  also in charm, charmonium, bottomonium, light Higgs, τ, DS, kaon sectors…

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

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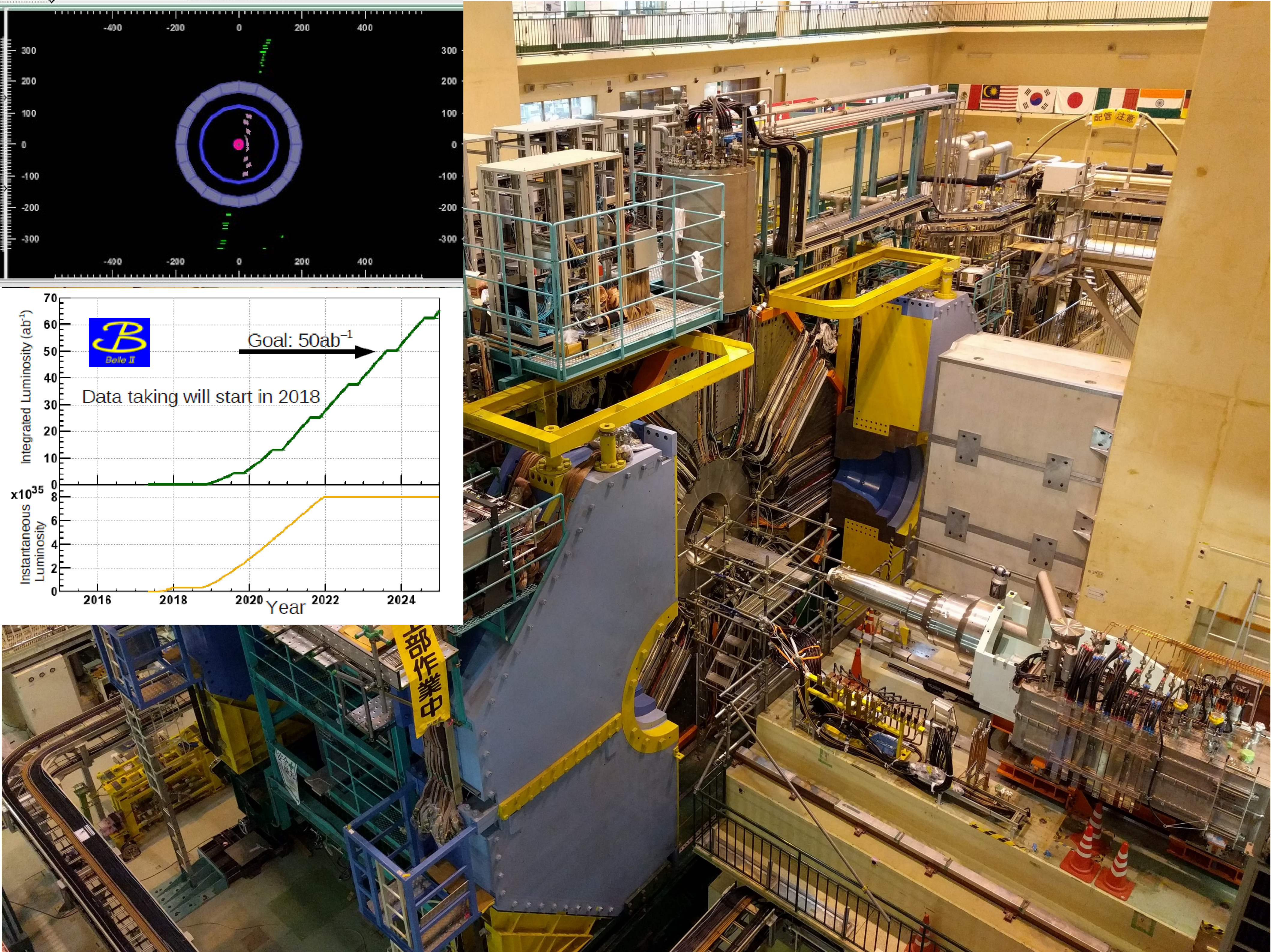
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}



Integrated Luminosity (ab^{-1})
Goal: 50ab^{-1}
Belle II
Data taking will start in 2018
x10^{35}
Instantaneous Luminosity
2016
2018
2020
2022
2024
Year
配管 注意
部作業中

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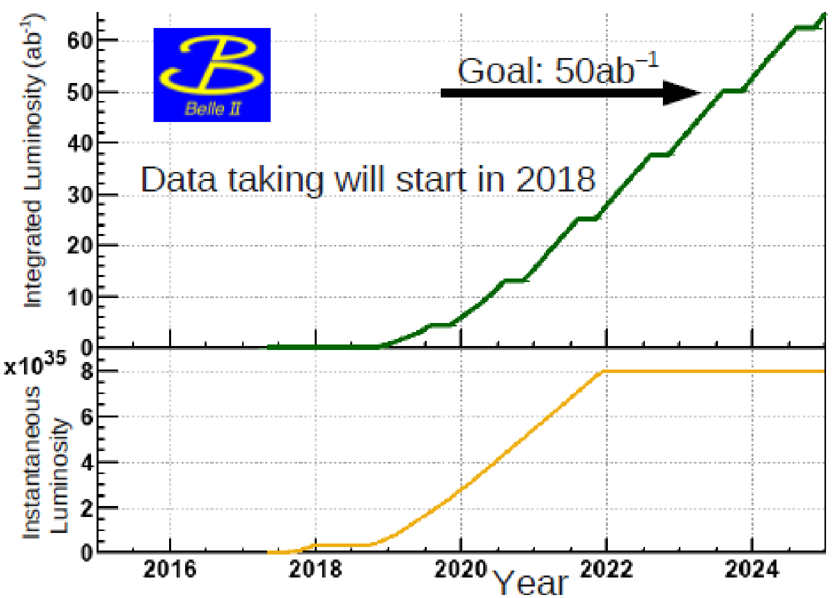
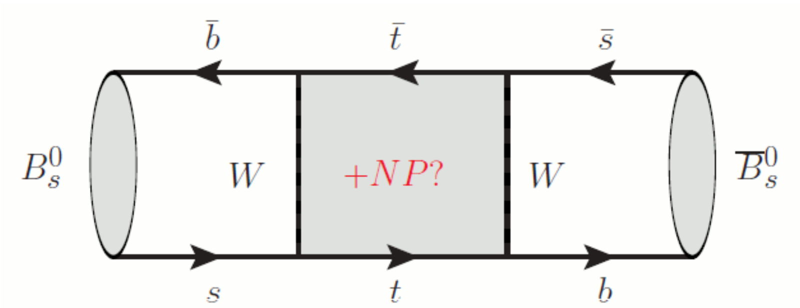


$\Delta F = 2$: New Physics



Evolution of $B^0_{(s)}$ system is described by $H = M - i\Gamma/2$
Off-diagonal terms M_{12}, Γ_{12} responsible for oscillations

- M_{12} dominated by (virtual) top boxes
  [affected by NP, e.g. if heavy new particles in the box]
- Γ_{12} dominated by tree decays into (real) charm states
  [affected by NP if changes in (constrained) tree-level decays]
- Tree level (4 diff flavours) processes not affected by NP

Model-independent parametrisation under the assumption only changes modulus and phase of M^d_{12} and M^s_{12}

$$\mathbf{M^q_{12} = (M^q_{12})_{SM} \times \Delta_q \qquad \Delta_q = |\Delta_q| e^{i\phi^\Delta_q} = (1 + h_q\, e^{2i\sigma_q})}$$

affects Δm_q ($\Leftrightarrow |\Delta_q|$), a^q_{SL} ($\Leftrightarrow \Delta_q$), $\Delta\Gamma_q$ and ϕ_{B_q} ($\Leftrightarrow \phi^\Delta_q$)

Δm_d, Δm_s, β, ϕ_s, a^d_{SL}, a^s_{SL}, $\Delta\Gamma_s$ to constrain Δ_d and Δ_s

$\Delta F = 2$: CKM projections

[CKMfitter, arXiv:1501.05013]

Observables not affected by NP, used to fix CKM:
$|V_{ud}|$, $|V_{us}|$, $|\mathbf{V_{ub}}|$, $|V_{cb}|$, $\boldsymbol{\gamma}$ and $\gamma(\alpha) \equiv \pi - \alpha - \beta$ (ϕ_{B_d} cancels)

Stage I
7 fb^{-1} LHCb
+ 5 ab^{-1} Belle II

Stage II
50 fb^{-1} LHCb
+ 50 ab^{-1} Belle II

	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ ($K_{\ell 3}$)	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert \epsilon_K \rvert$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3$ ($b \to c\ell\bar{\nu}$)	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\lvert V_{ub}\rvert \times 10^3$ ($b \to u\ell\bar{\nu}$)	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	[17]
$\sin 2\beta$	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A^d_{SL} \times 10^4$	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{SL} \times 10^4$	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]

$\Delta F = 2$: NP fit

[CKMfitter, arXiv:1501.05013]

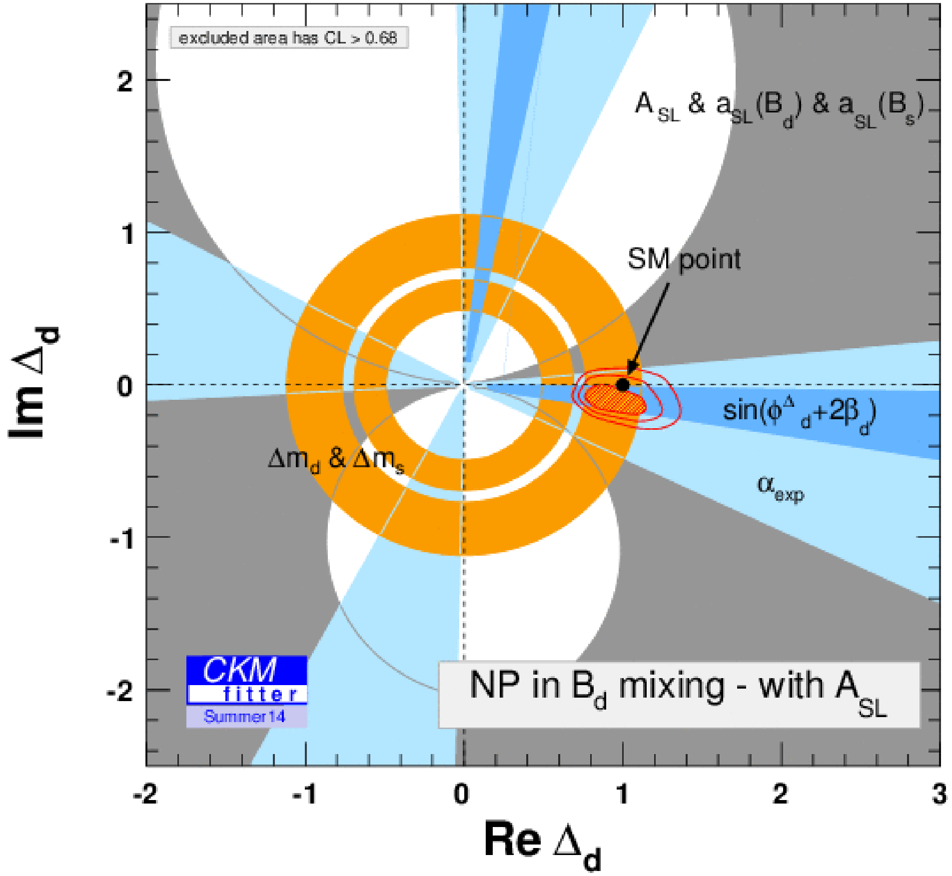
Δm_d, Δm_s, β, ϕ_s, a_{SL}^d, a_{SL}^s, $\Delta\Gamma_s$ to constrain Δ_d and Δ_s

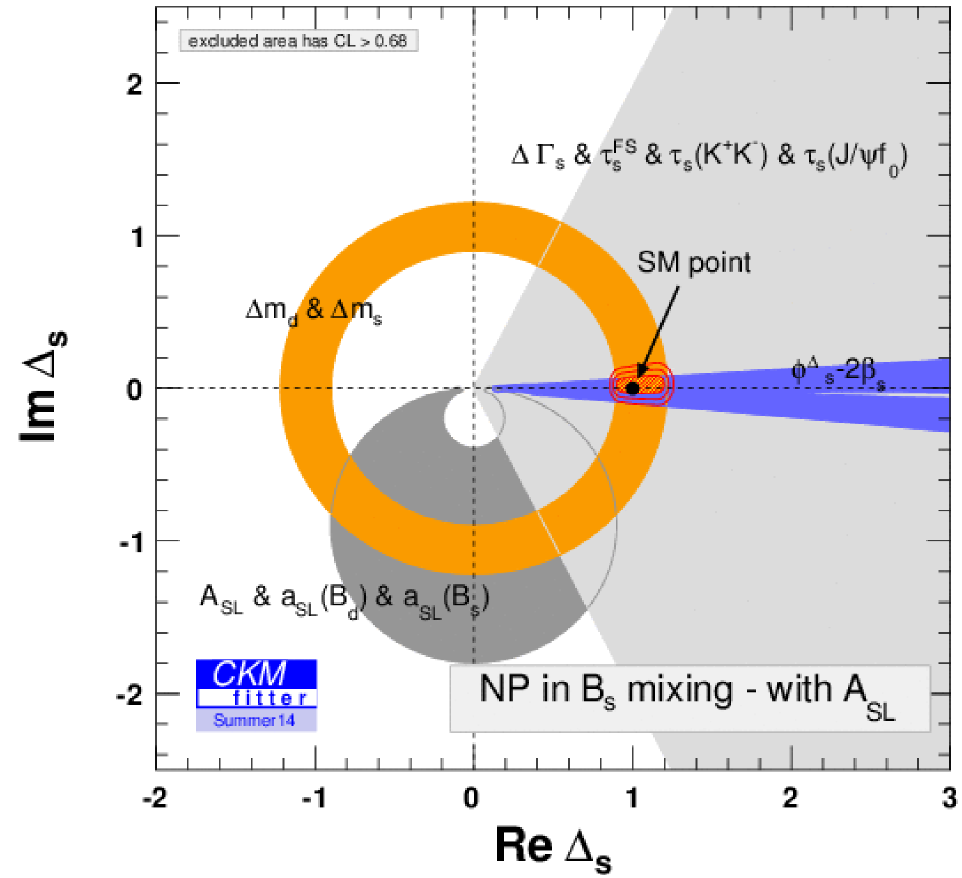
		Stage I 7 fb^{-1} LHCb + 5 ab^{-1} Belle II		**Stage II** 50 fb^{-1} LHCb + 50 ab^{-1} Belle II	
	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ ($K_{\ell 3}$)	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert\epsilon_K\rvert$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3$ ($b \to c\ell\bar{\nu}$)	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\lvert V_{ub}\rvert \times 10^3$ ($b \to u\ell\bar{\nu}$)	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	[17]
$\sin 2\beta$	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A_{SL}^d \times 10^4$	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A_{SL}^s \times 10^4$	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]

$\Delta F = 2$: Current constraints

[CKMfitter, arXiv:1501.05013]

$$M_{12} = M_{12} . \Delta,\ \Delta = |\Delta| e^{i\phi^\Delta}$$





$$\Delta_d = 0.88^{+0.22}_{-0.10} + i\left(-0.11^{+0.07}_{-0.05}\right) \qquad \Delta_s = 1.01^{+0.17}_{-0.09} + i\left(+0.02 \pm 0.04\right)$$

Bounds/prospects for New Physics at:

- Stage I: 7 fb^{-1} LHCb + 5 ab^{-1} Belle II
- Stage II: 50 fb^{-1} LHCb + 50 ab^{-1} Belle II

$\Delta F = 2$: Inputs

[CKMfitter, arXiv:1501.05013]

	2003	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert \epsilon_K\rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar{\nu})$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\lvert V_{ub}\rvert \times 10^3$ $(b \to u\ell\bar{\nu})$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	[17]
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	—	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A^d_{\rm SL} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{\rm SL} \times 10^4$	—	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]
$\bar{m}_c$	$1.2 \pm 0 \pm 0.2$	$1.286 \pm 0.013 \pm 0.040$	1.286 ± 0.020		1.286 ± 0.010	
$\bar{m}_t$	167.0 ± 5.0	$165.8 \pm 0.54 \pm 0.72$	id		id	
$\alpha_s(m_Z)$	$0.1172 \pm 0 \pm 0.0020$	$0.1184 \pm 0 \pm 0.0007$	id		id	
B_K	$0.86 \pm 0.06 \pm 0.14$	$0.7615 \pm 0.0026 \pm 0.0137$	0.774 ± 0.007	[19, 20]	0.774 ± 0.004	[19, 20]
f_{B_s} [GeV]	$0.217 \pm 0.012 \pm 0.011$	$0.2256 \pm 0.0012 \pm 0.0054$	0.232 ± 0.002	[19, 20]	0.232 ± 0.001	[19, 20]
B_{B_s}	1.37 ± 0.14	$1.326 \pm 0.016 \pm 0.040$	1.214 ± 0.060	[19, 20]	1.214 ± 0.010	[19, 20]
f_{B_s}/f_{B_d}	$1.21 \pm 0.05 \pm 0.01$	$1.198 \pm 0.008 \pm 0.025$	1.205 ± 0.010	[19, 20]	1.205 ± 0.005	[19, 20]
B_{B_s}/B_{B_d}	1.00 ± 0.02	$1.036 \pm 0.013 \pm 0.023$	1.055 ± 0.010	[19, 20]	1.055 ± 0.005	[19, 20]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	—	$1.01 \pm 0 \pm 0.03$	1.03 ± 0.02		id	
$\tilde{B}_{B_s}$	—	$0.91 \pm 0.03 \pm 0.12$	0.87 ± 0.06		id	

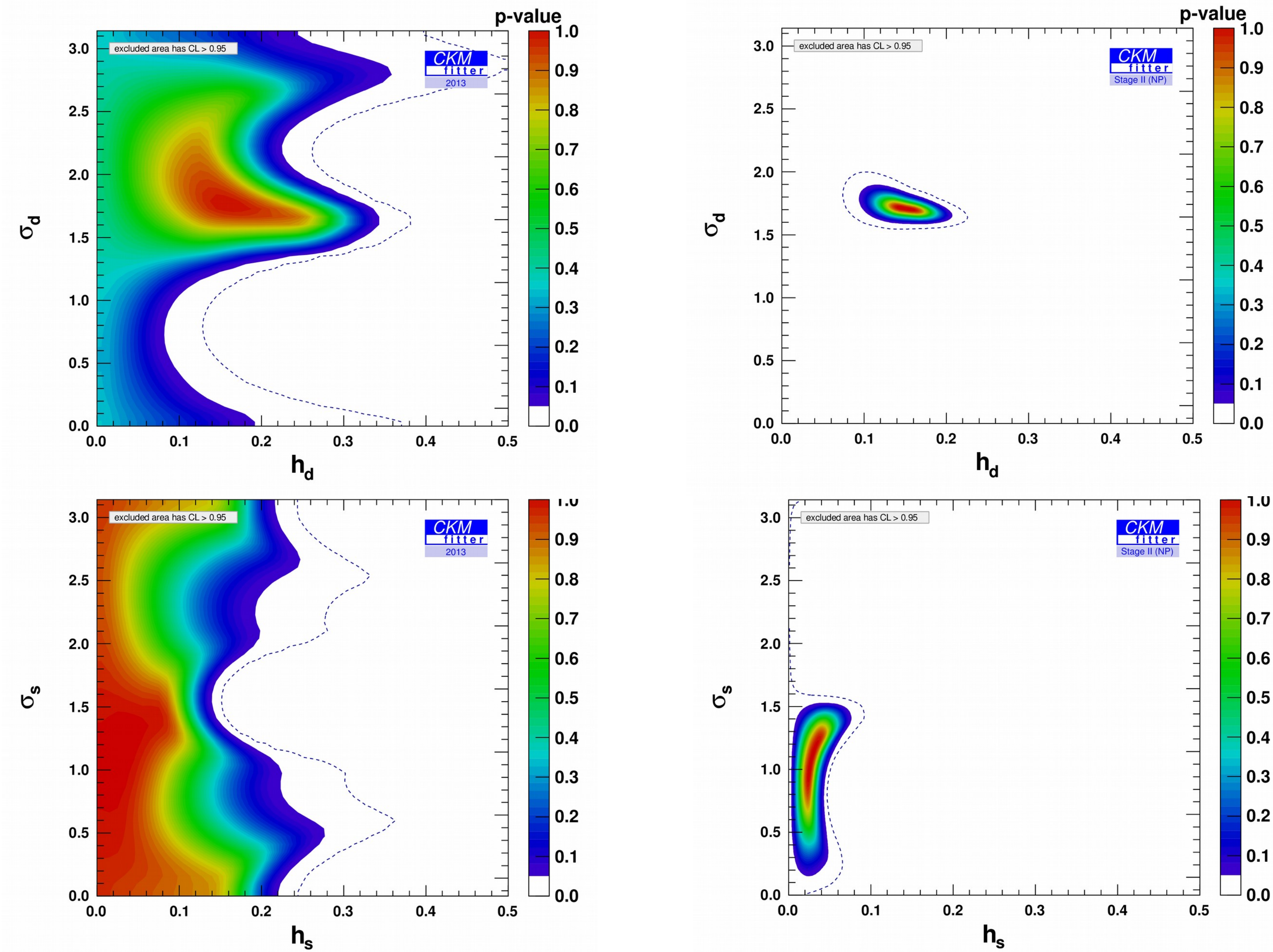
NB: No D0 $A_{\rm SL}$ input

$\Delta F = 2$: NP !! ideal scenario...

Hypothetical Stage II fits for NP, assuming that all future experimental results correspond to the current best-fit values of $\bar{\rho}$, $\bar{\eta}$, $h_{d,s}$, $\sigma_{d,s}$

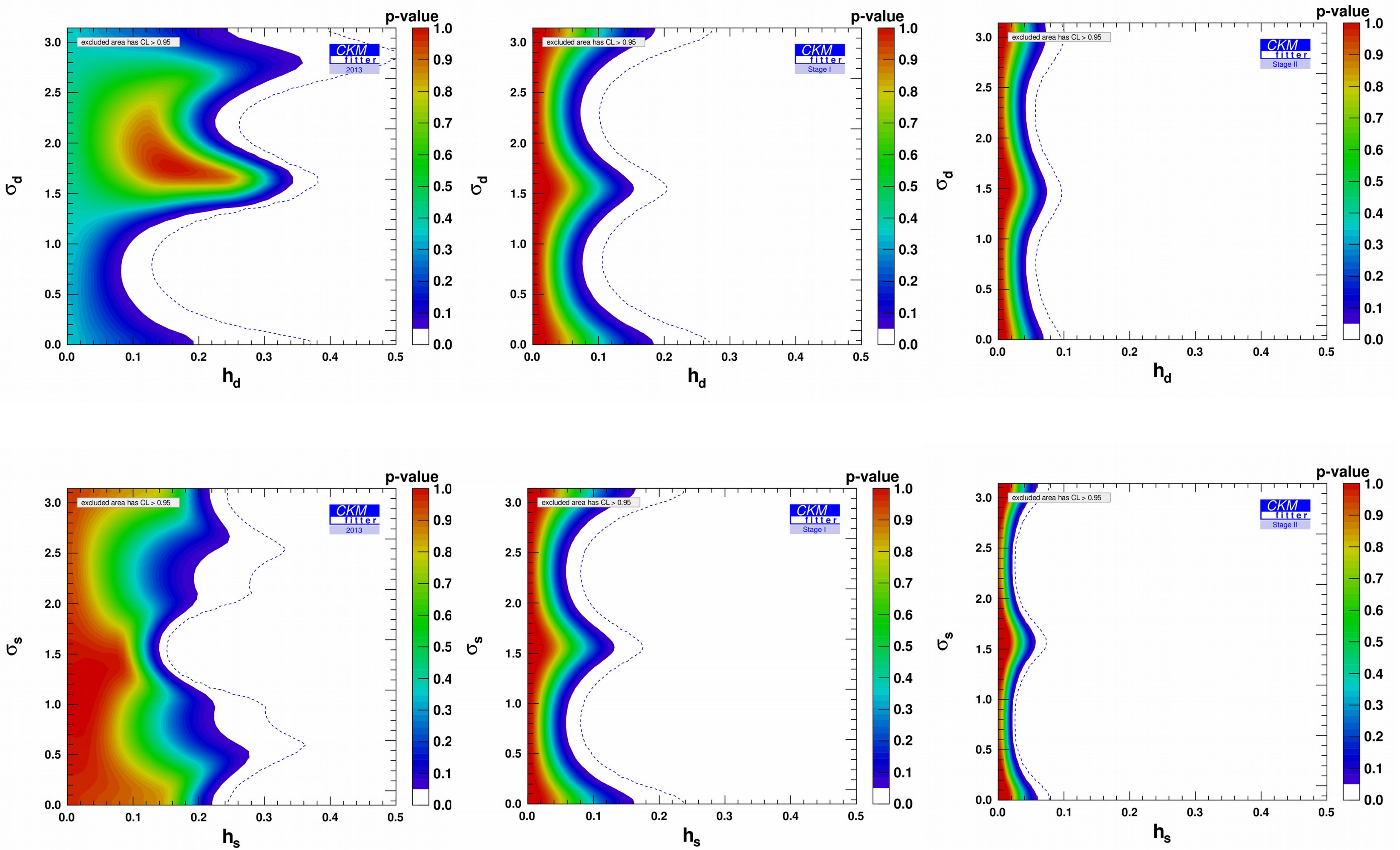
σ_d vs h_d

σ_s vs h_s



2013 **Stage II**

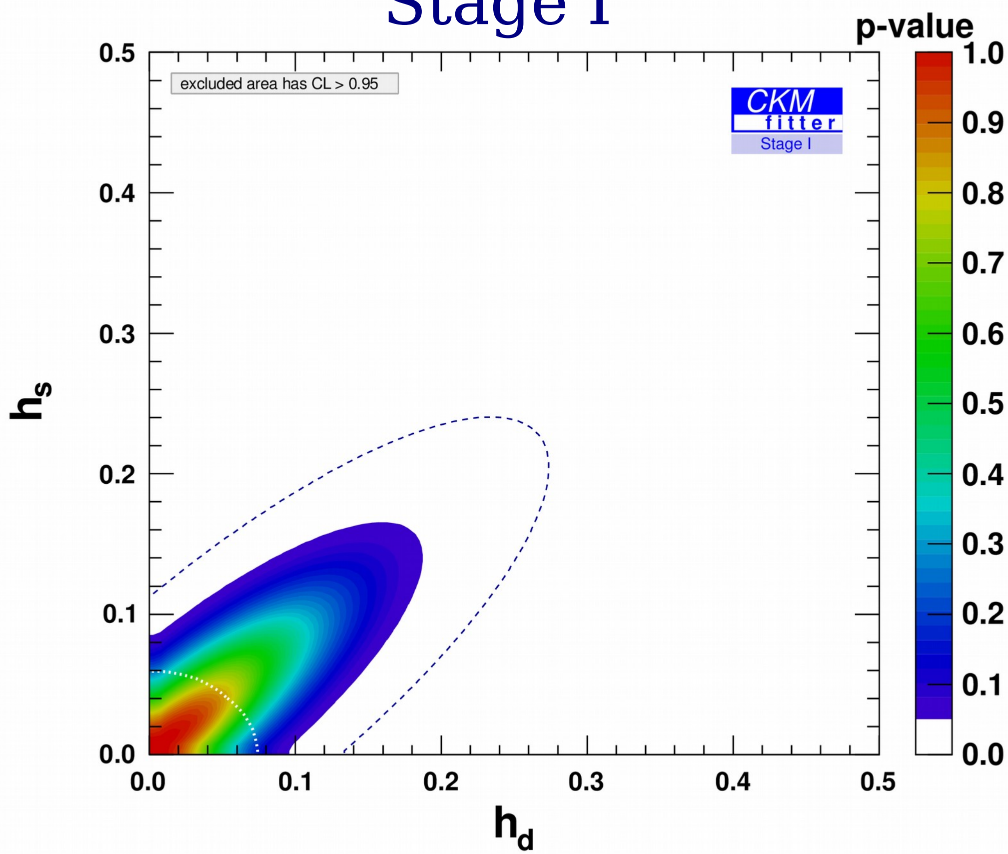
$\Delta F = 2$: bounds for $B_{d,s}$ mixings



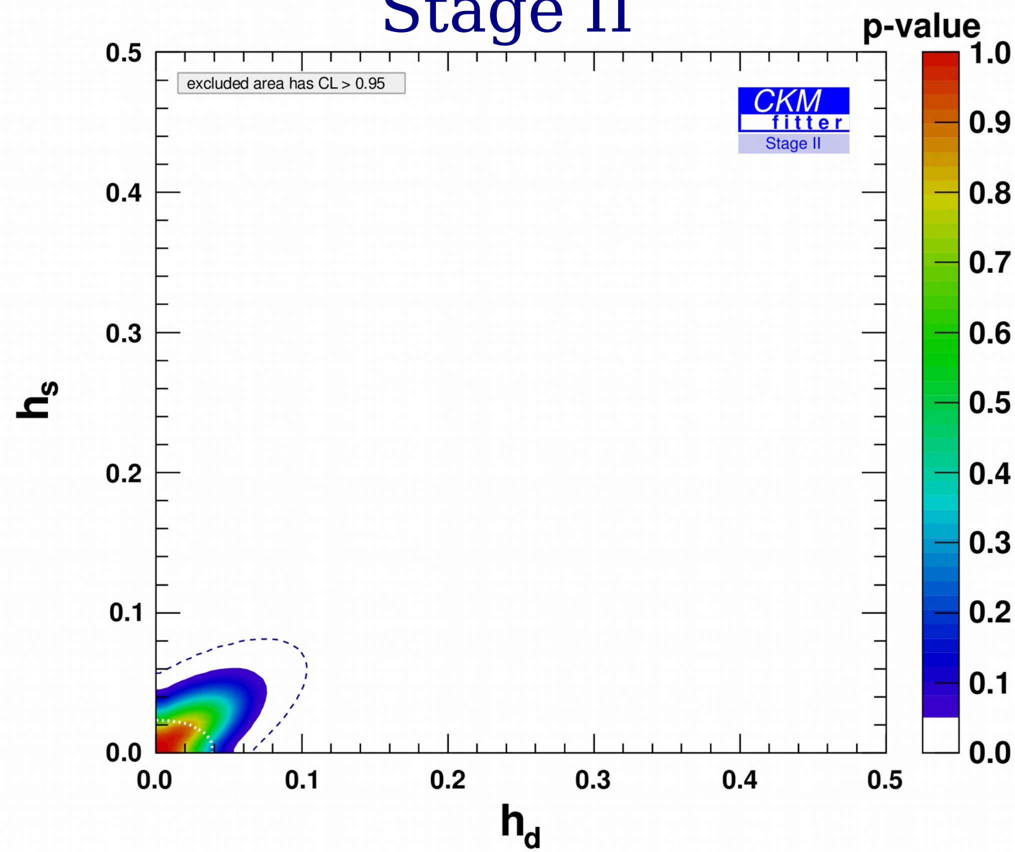
2013 **Stage I** **Stage II**

ΔF = 2: bounds on energy scale

Stage I



Stage II



NP contribution to the mixing

from $\dfrac{C_{ij}^2}{\Lambda^2}\,(\bar{b}_L \gamma^\mu q_{j,L})^2$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|V_{ti}V_{tj}|^2}\frac{(4\pi)^2}{G_F\Lambda^2} \simeq \frac{|C_{ij}|^2}{|V_{ti}V_{tj}|^2}\left(\frac{4.5\ \text{TeV}}{\Lambda}\right)^2$$

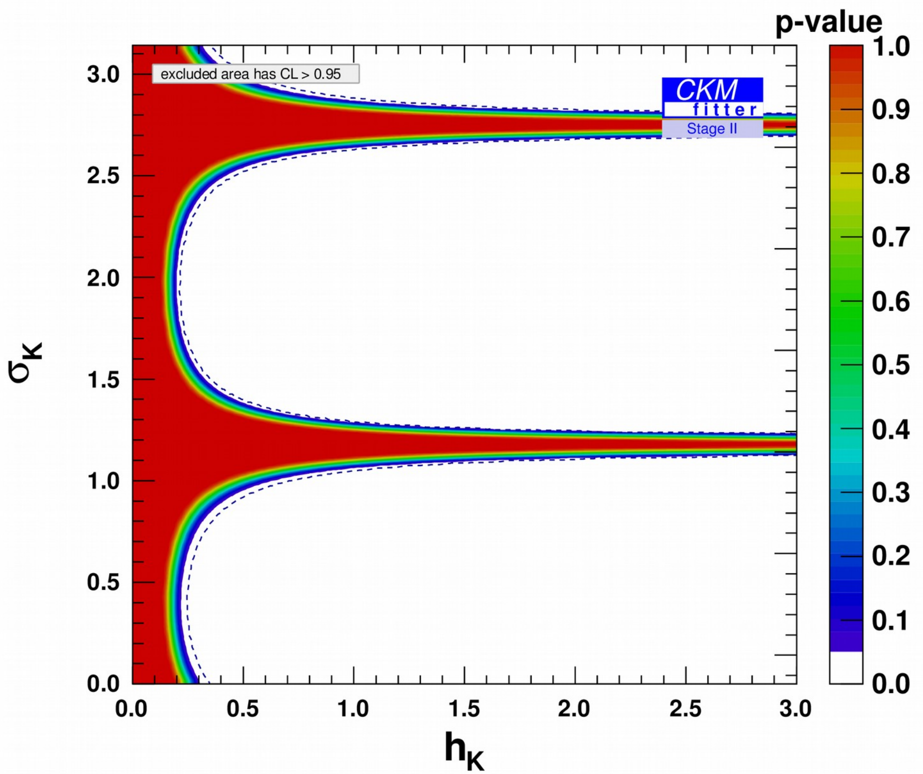
Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

probe new particles with CKM-like couplings with masses, M, in the 10-20 TeV range if contribute at tree level ($\Lambda \sim M$), in 1-2 TeV range if enter with a loop suppression ($\Lambda \sim 4\pi M$)

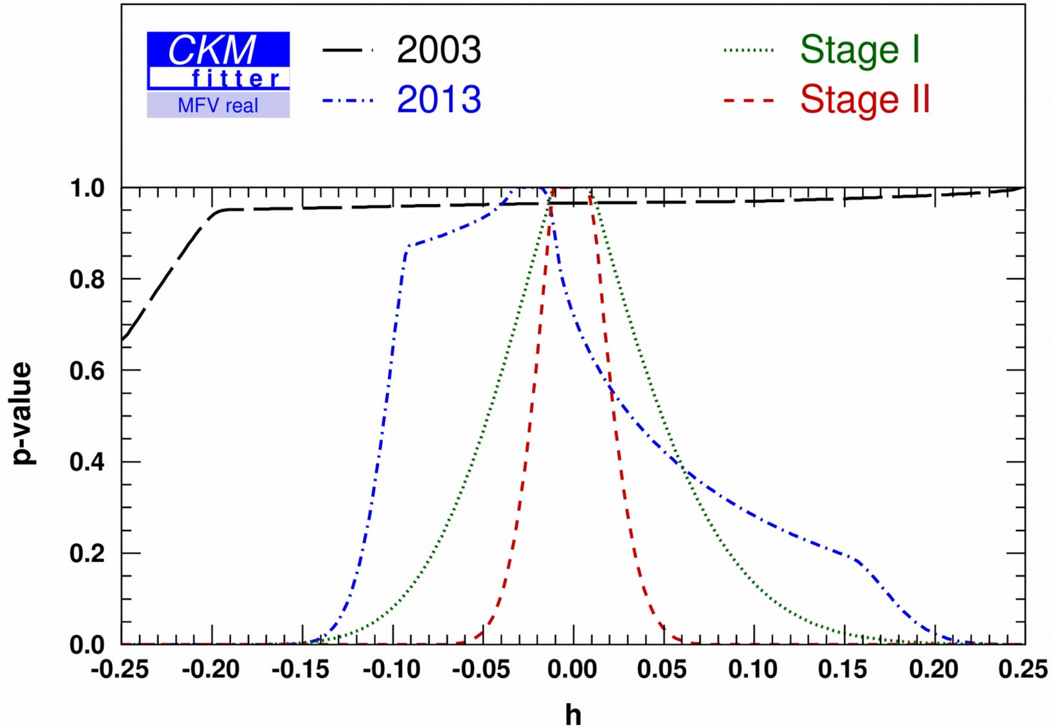
NP in K mixing, $\Delta F = 2$: ϵ_K

- K, B_d and B_s mixings in general not related
- ϵ_K not enough to bound NP in K mixing, even if NP only in tt box
- but in the case of MFV, possible to exploit all neutral mesons

$$h = h_d\, e^{2i\sigma_d} = h_s\, e^{2i\sigma_s} = h_K\, e^{2i\sigma_K} \text{ with } \sigma_i = 0 \; (\text{mod } \pi/2)$$



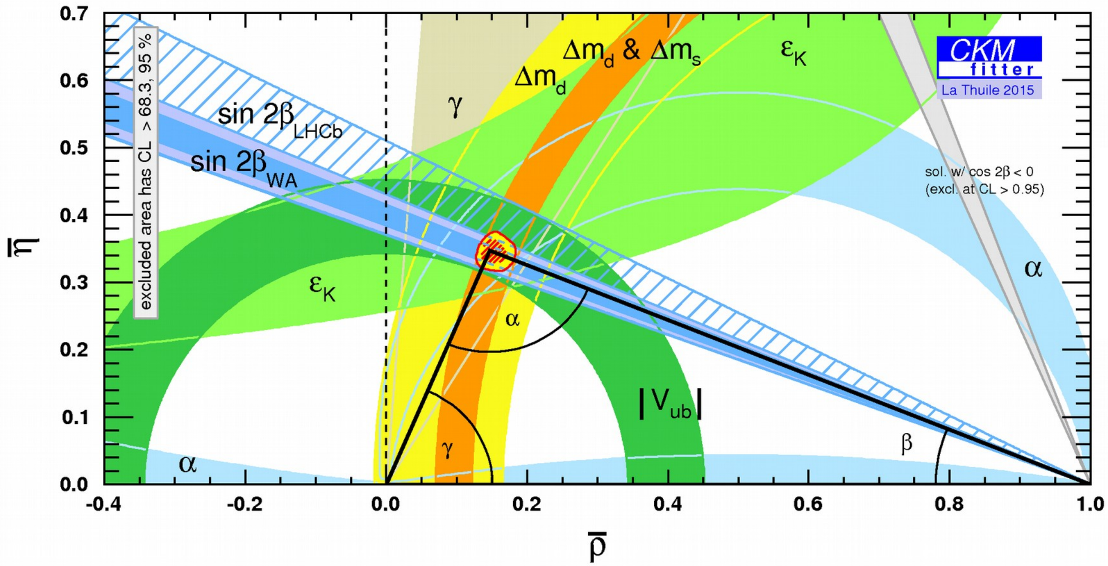
Arbitrary NP in tt K boxes - Stage II



MFV case

Precision , precision , precision …

50 ab^{-1} $\Rightarrow$ major updates for $|V_{ub}|$, $\sin 2\beta$, α, γ



sin 2β at Belle (II)

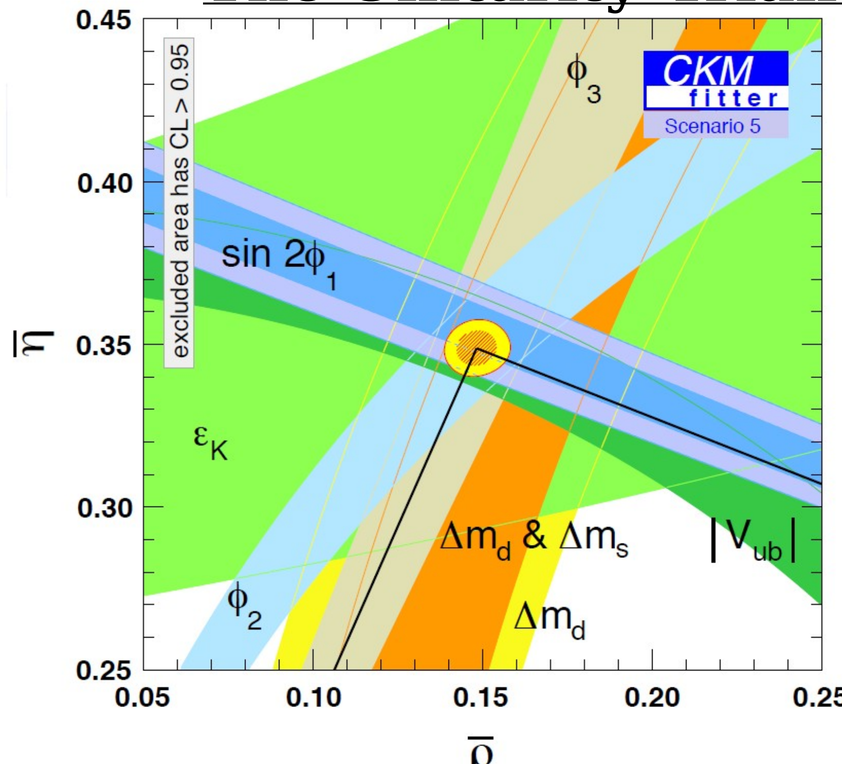
anchor of SM

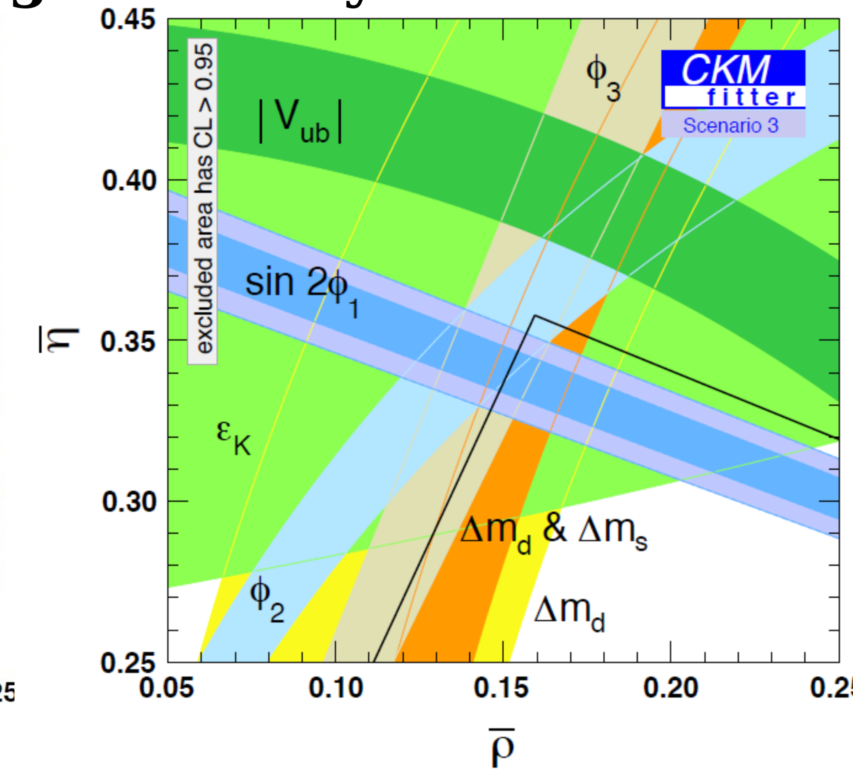
	Belle	Belle II (50 ab^{-1})
S	0.667 ± 0.023 ± 0.012	x.xxxx ± 0.0027 ± 0.0044
A	0.006 ± 0.016 ± 0.012	x.xxxx ± 0.0033 ± 0.0037

dominated by systematic uncertainties

WA 2016: $\beta = (21.9 \pm 0.7)^\circ$

The Unitarity Triangle in the year 2025

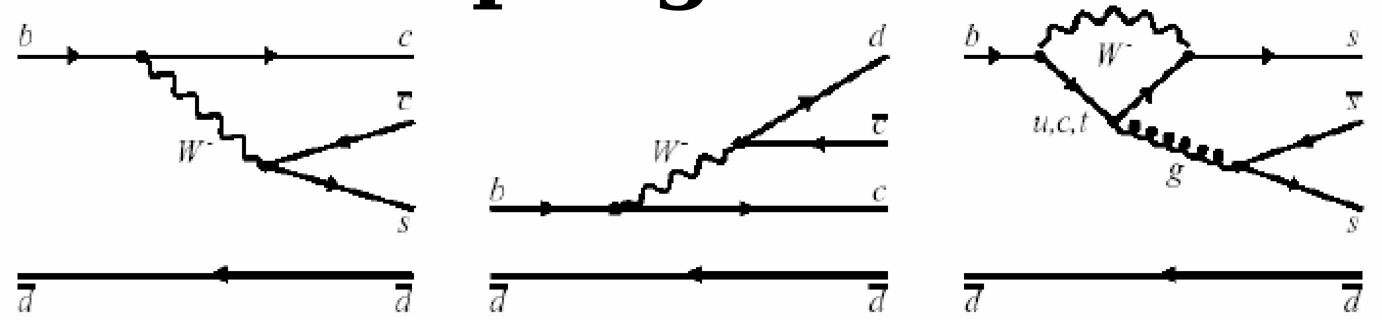




sin 2β with b→s penguins

dominated by B-factories

sin 2β



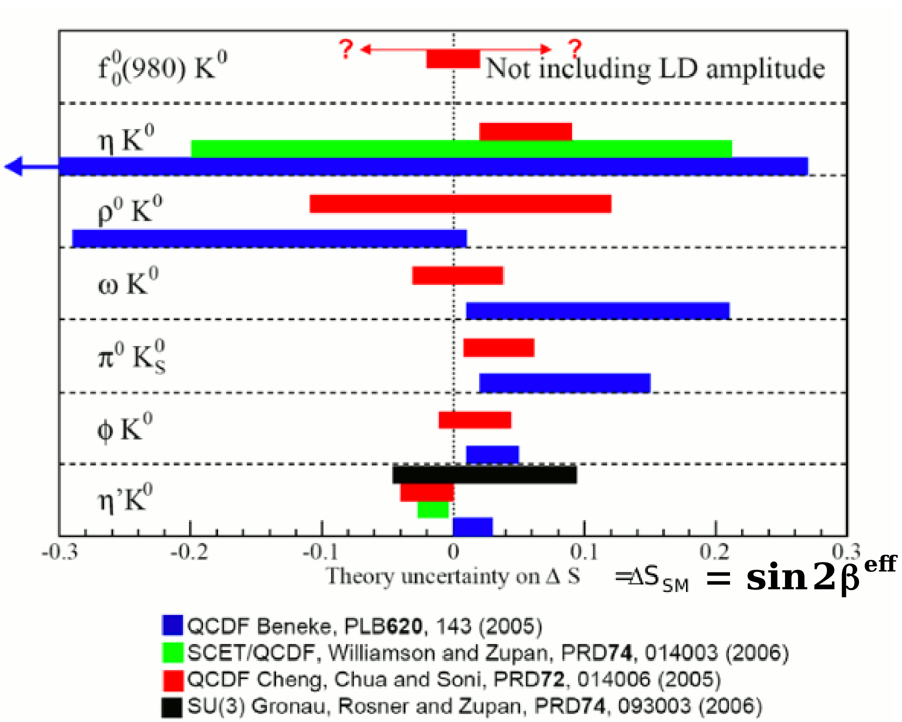
$\sin 2\beta^{\mathrm{eff}}$

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

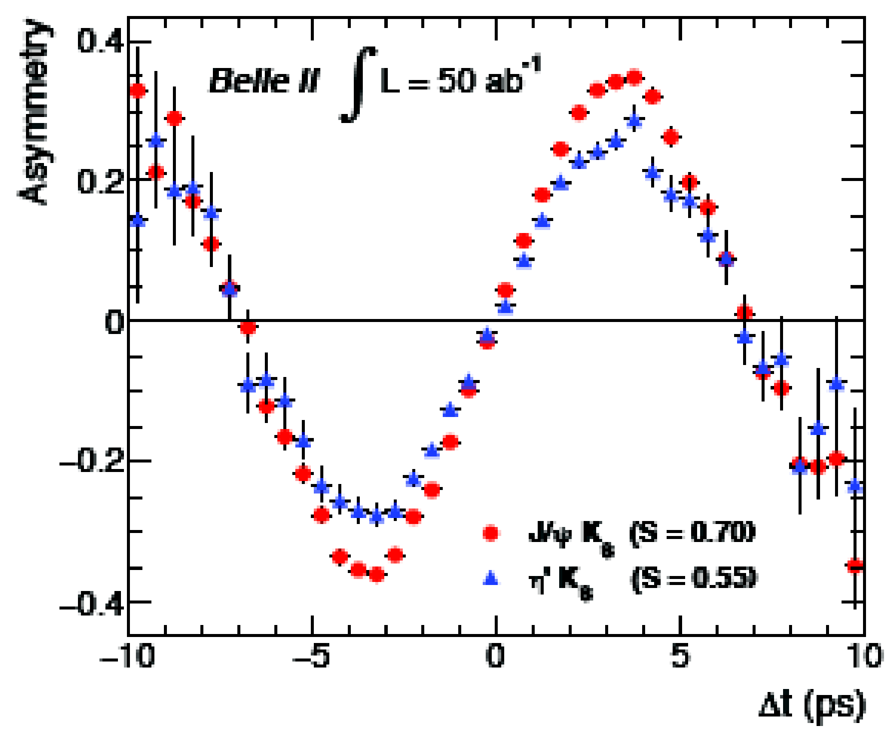
increasing tree diagram amplitude ←

increasing sensitivity to new physics →

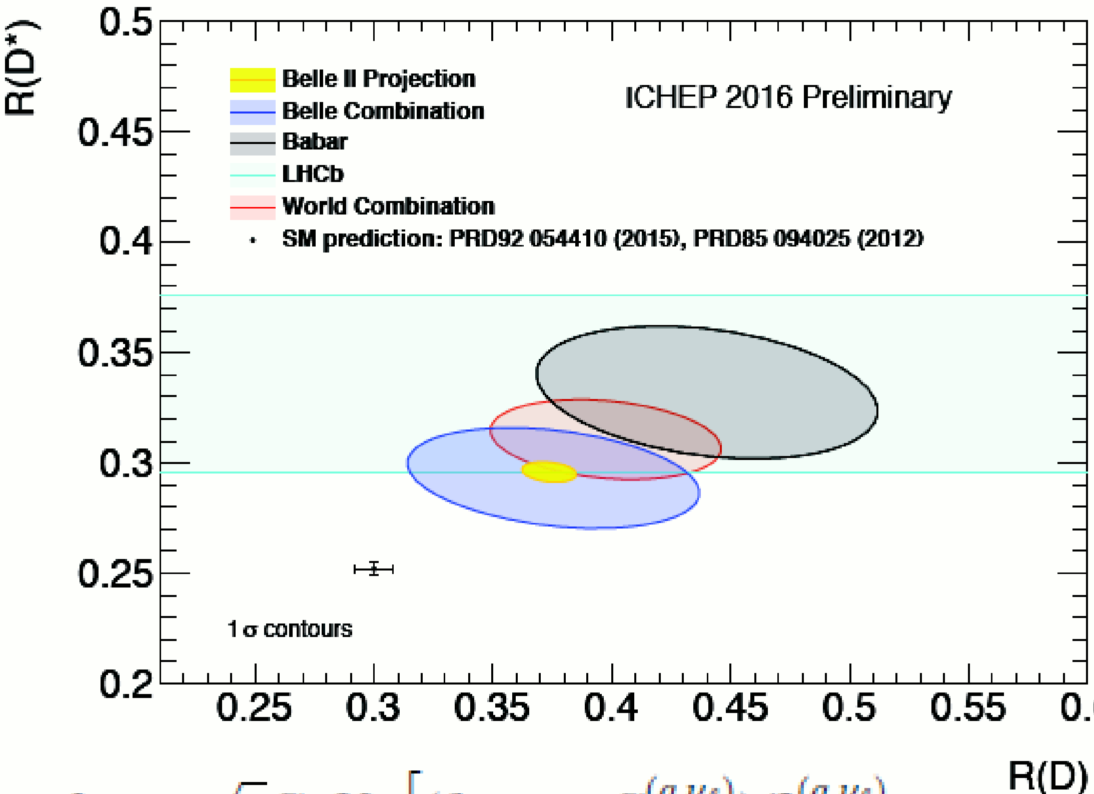
Statistics crucial for mode-by-mode studies



$= \Delta S_{SM} = \sin 2\beta^{\mathrm{eff}} - \sin 2\beta$



$B \to D^{(*)}\tau\nu$ and much more observables at Belle II

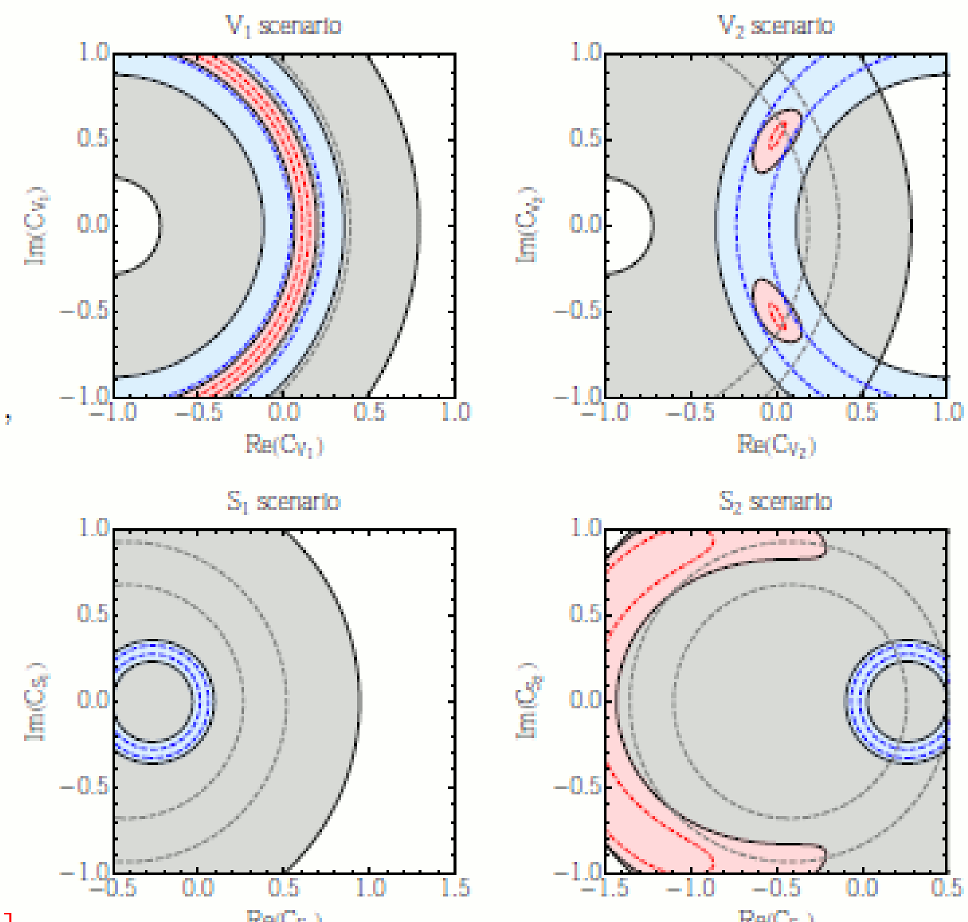


$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)}l\nu)}, \text{ in red}$$

$$R_{ps} = \frac{\tau_{B^0}}{\tau_{B^-}} \frac{B(B \to \tau^-\nu)}{B(B \to \pi^+ l^- \nu)}, \text{ in blue}$$

$$R(\pi) = \frac{B(B \to \pi\tau\nu)}{B(B \to \pi l \nu)}, \text{ in grey}$$

Dashed : Belle II



$$-\mathcal{L}_{\rm eff} = 2\sqrt{2} G_F V_{qb} \Big[(\delta_{\nu_\tau,\nu_\ell} + C_{V_1}^{(q,\nu_\ell)}) \mathcal{O}_{V_1}^{(q,\nu_\ell)} + \sum_{X=}^{V_2,S_1,S_2,T} C_X^{(q,\nu_\ell)} \mathcal{O}_X^{(q,\nu_\ell)} \Big],$$

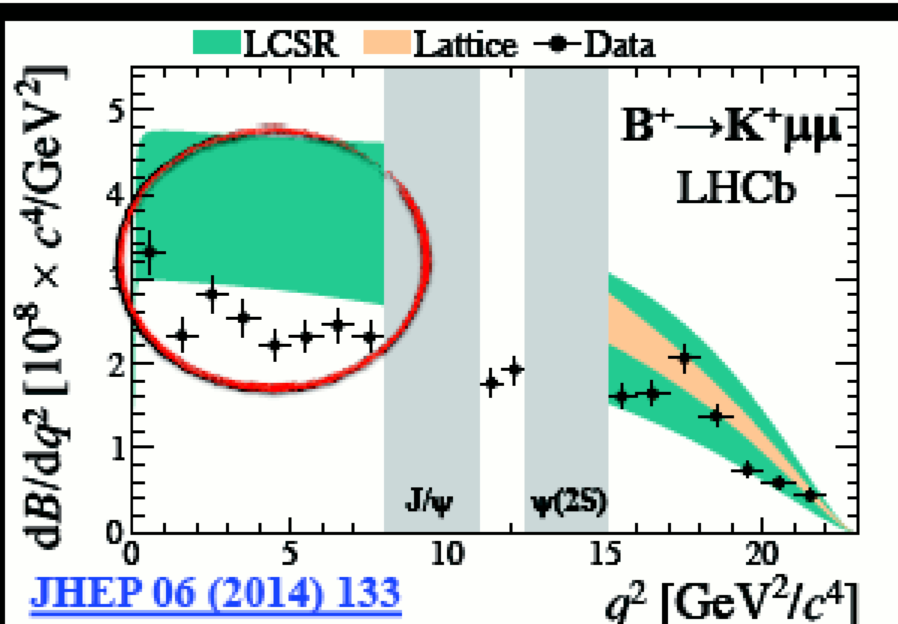
where the four-Fermi operators:

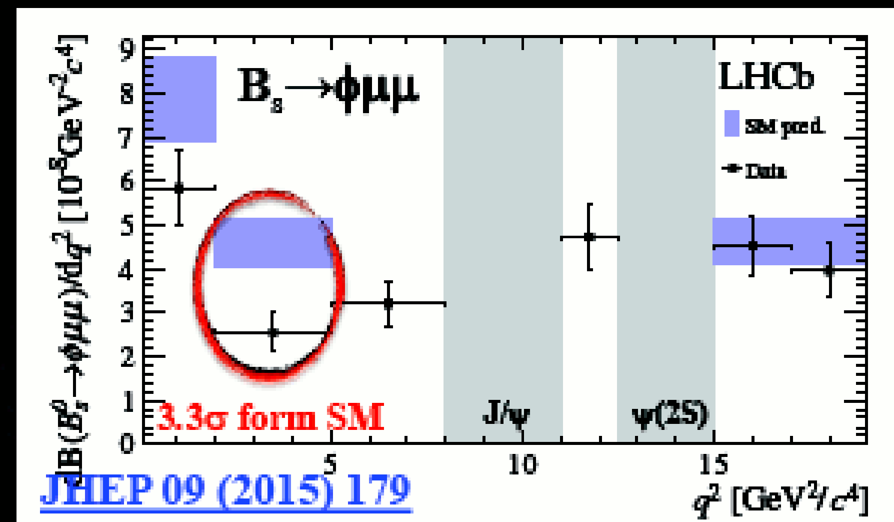
$$\mathcal{O}_{V_1}^{(q,\nu_\ell)} = (\bar{q}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\ell),$$
$$\mathcal{O}_{V_2}^{(q,\nu_\ell)} = (\bar{q}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\ell),$$
$$\mathcal{O}_{S_1}^{(q,\nu_\ell)} = (\bar{q} P_R b)(\bar{\tau} P_L \nu_\ell),$$
$$\mathcal{O}_{S_2}^{(q,\nu_\ell)} = (\bar{q} P_L b)(\bar{\tau} P_L \nu_\ell),$$
$$\mathcal{O}_T^{(q,\nu_\ell)} = (\bar{q}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\ell)$$

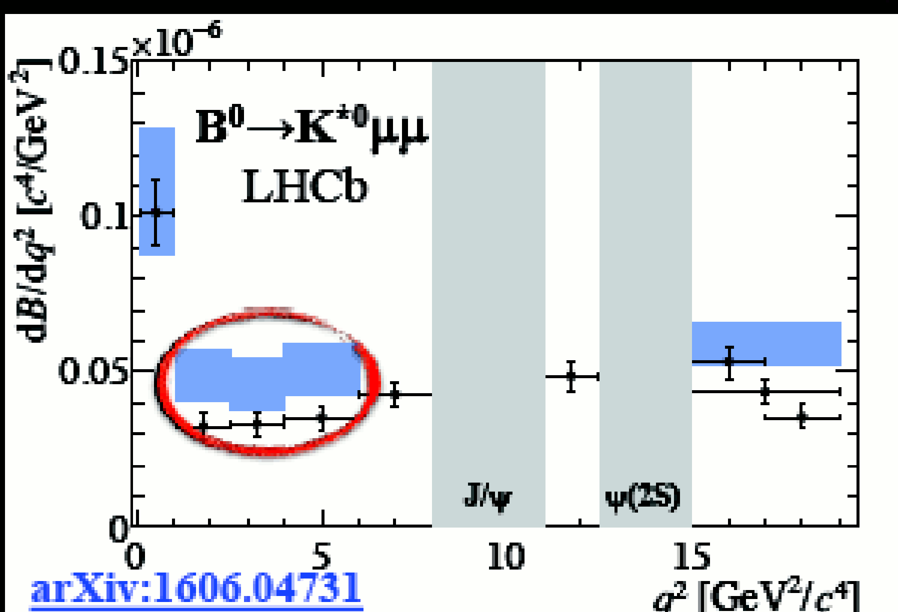
[Details in Watanabe et al, B2TiP theory]

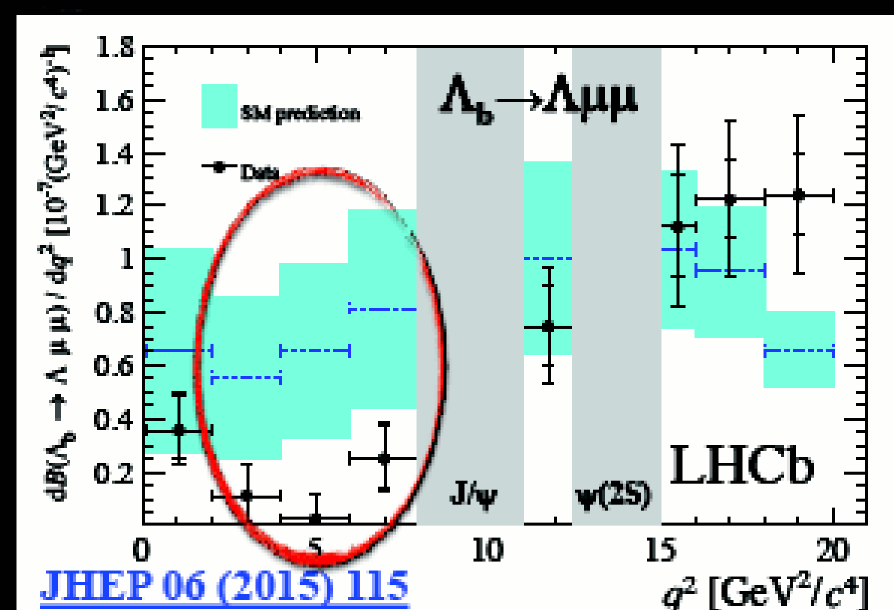
Differential Branching Fractions

Results consistently lower than SM predictions



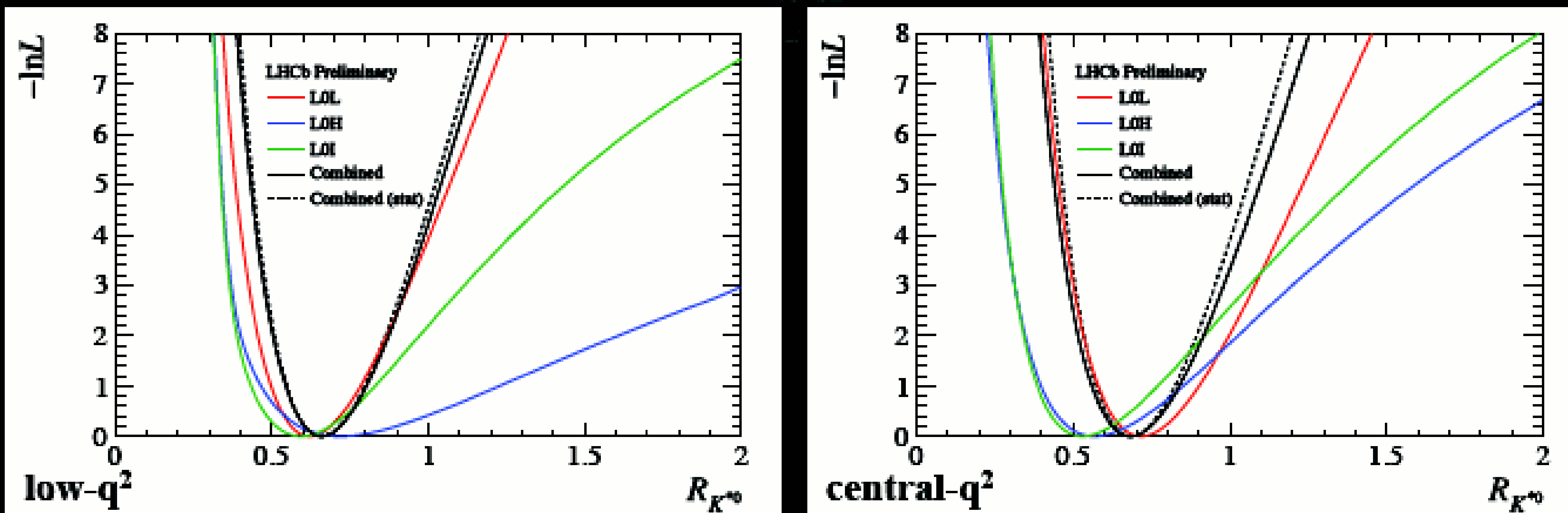






Results

LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\,0.110}_{-\,0.070} \pm 0.024$	$0.685\ ^{+\,0.113}_{-\,0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]



The measured values of $R_{K^{*0}}$ are found to be in good agreement among the three trigger categories in both q^2 regions

Cross-checks

- **Control of the absolute scale of the efficiencies** via the ratio

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

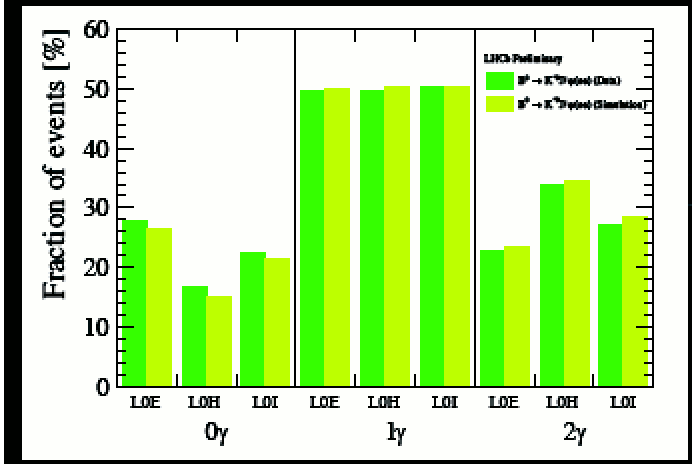
which is expected to be unity and measured to be

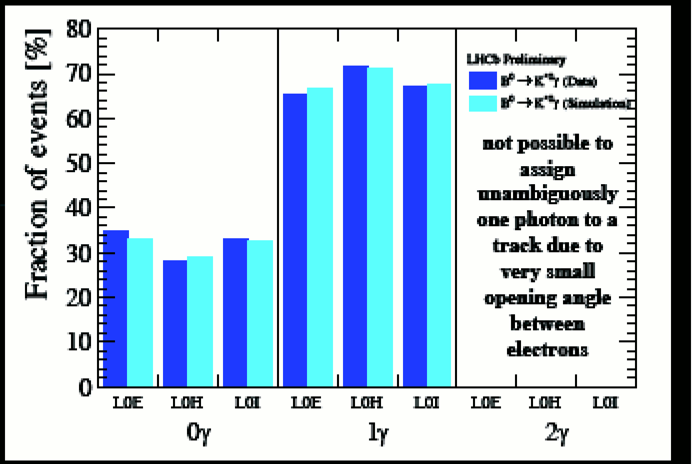
$$1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

- Result observed to be reasonably flat as a function of the decay kinematics and event multiplicity

- Extremely stringent test, which does not benefit from the cancellation of the experimental systematics provided by the double ratio

- Relative population of **bremsstrahlung categories** compared between data and simulation using $B^0 \to K^{*0} J/\psi(ee)$ and $B^0 \to K^{*0}\gamma(ee)$ events





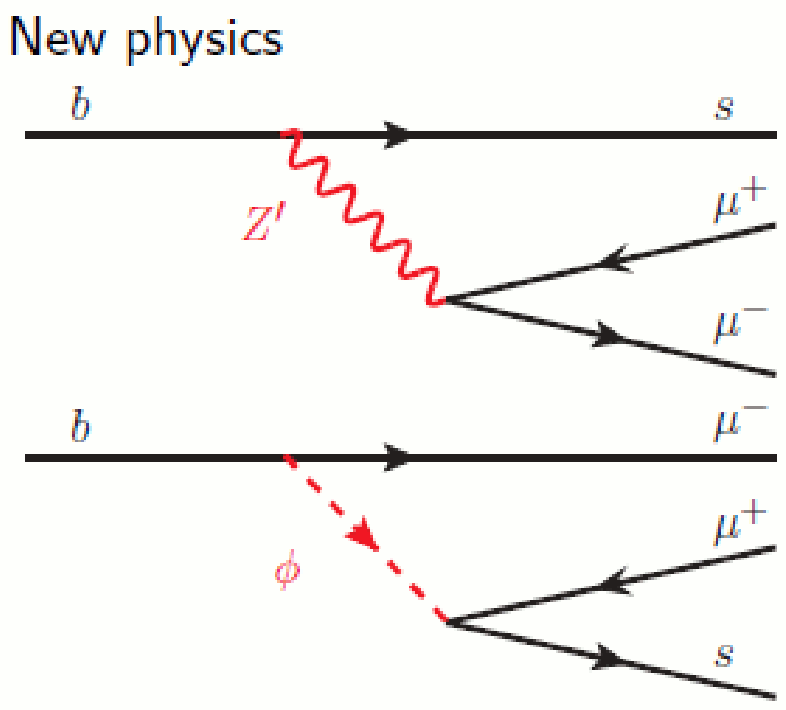
NP or hadronic effect ?

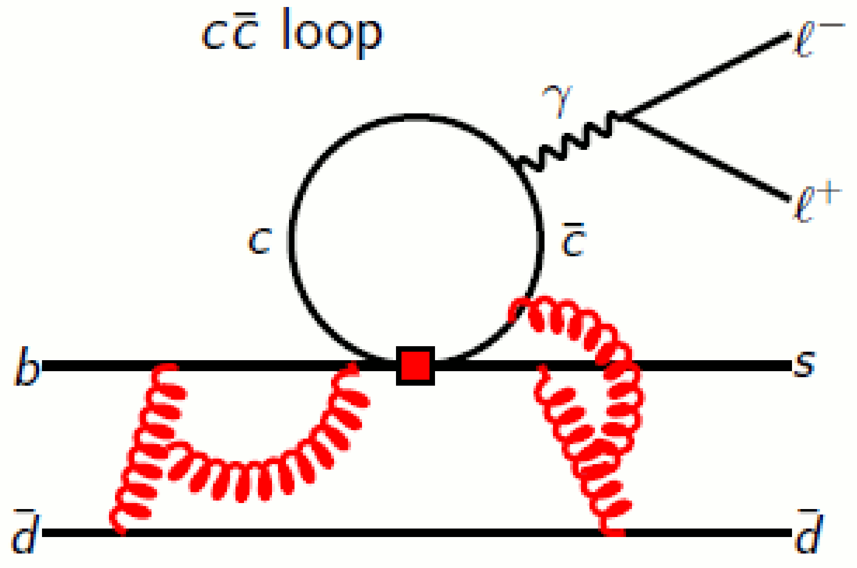
Possible explanations for shift in C_9:

a potential new physics contribution C_9^{NP} enters amplitudes always with

a charm-loop contribution $C_9^{c\bar{c}\,i}(q^2)$

⇒ **spoiling an unambiguous interpretation of the fit result in terms of NP**





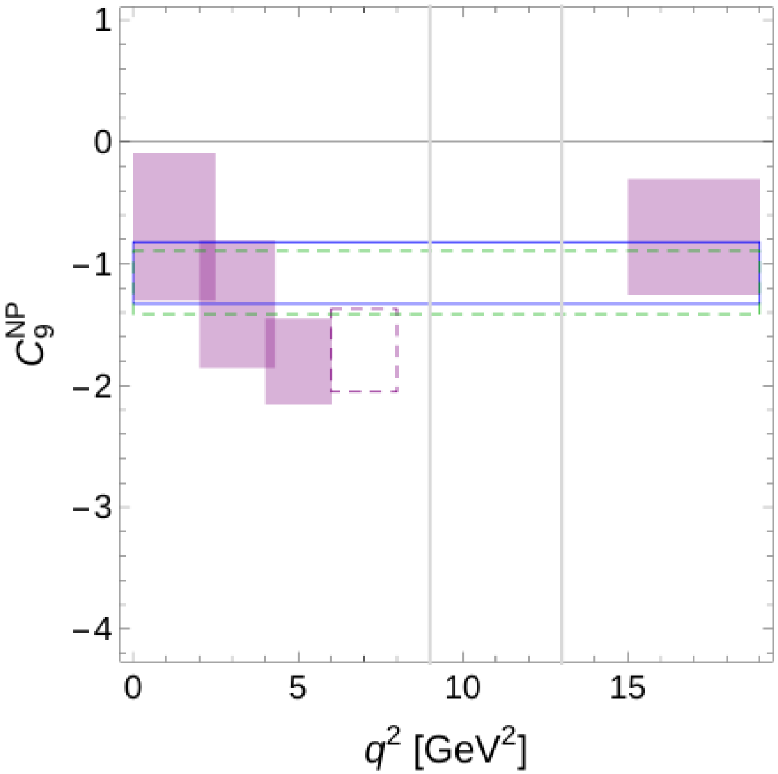
NP e.g. Z', leptoquarks

hadronic charm loop contributions

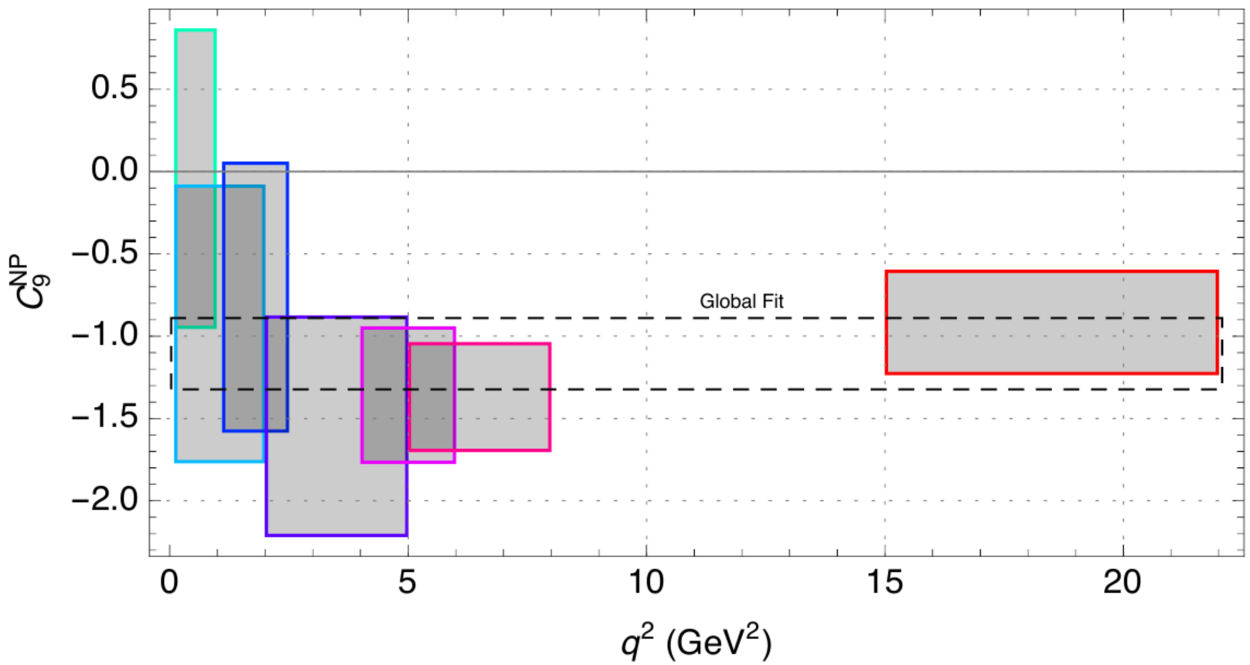
NP or hadronic effect ?

Bin-by-bin fit of the one-parameter scenario with a single coefficient $\mathbf{C_9^{NP}}$

[W.Altmannshofer et al, arXiv:1503.06199]



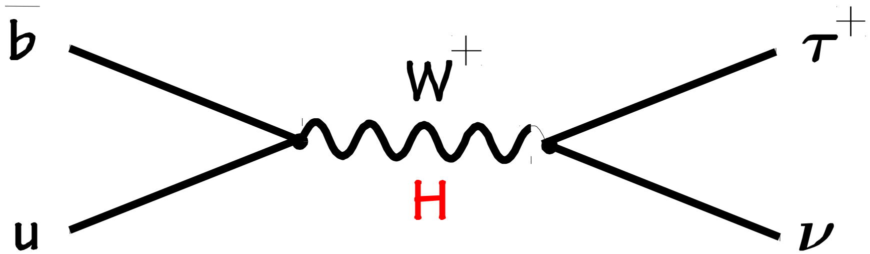
[S.Descotes-Genon et al, arXiv:1510.04239]

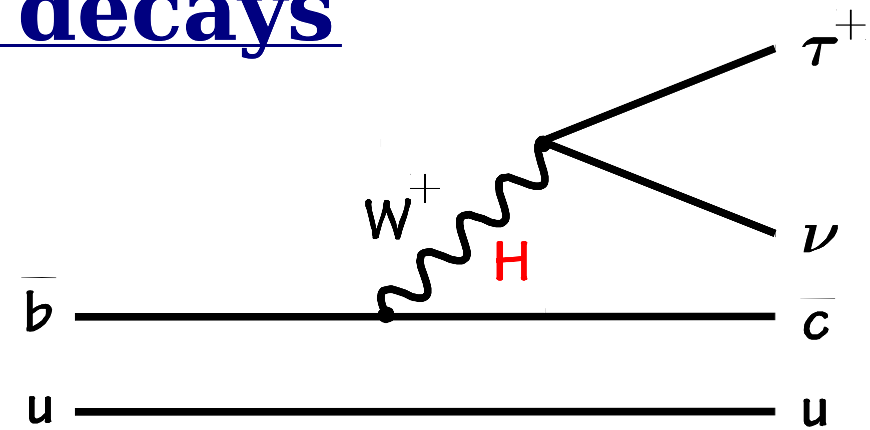


C_9^{NP} doesn't depend on q^2,
$C_9^{c\bar{c}\,i}(q^2)$ expected to exhibit a non-trivial q^2 dependence

⇒ definitely need more stat.

Tauonic B decays





$B \to \tau\nu$

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

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

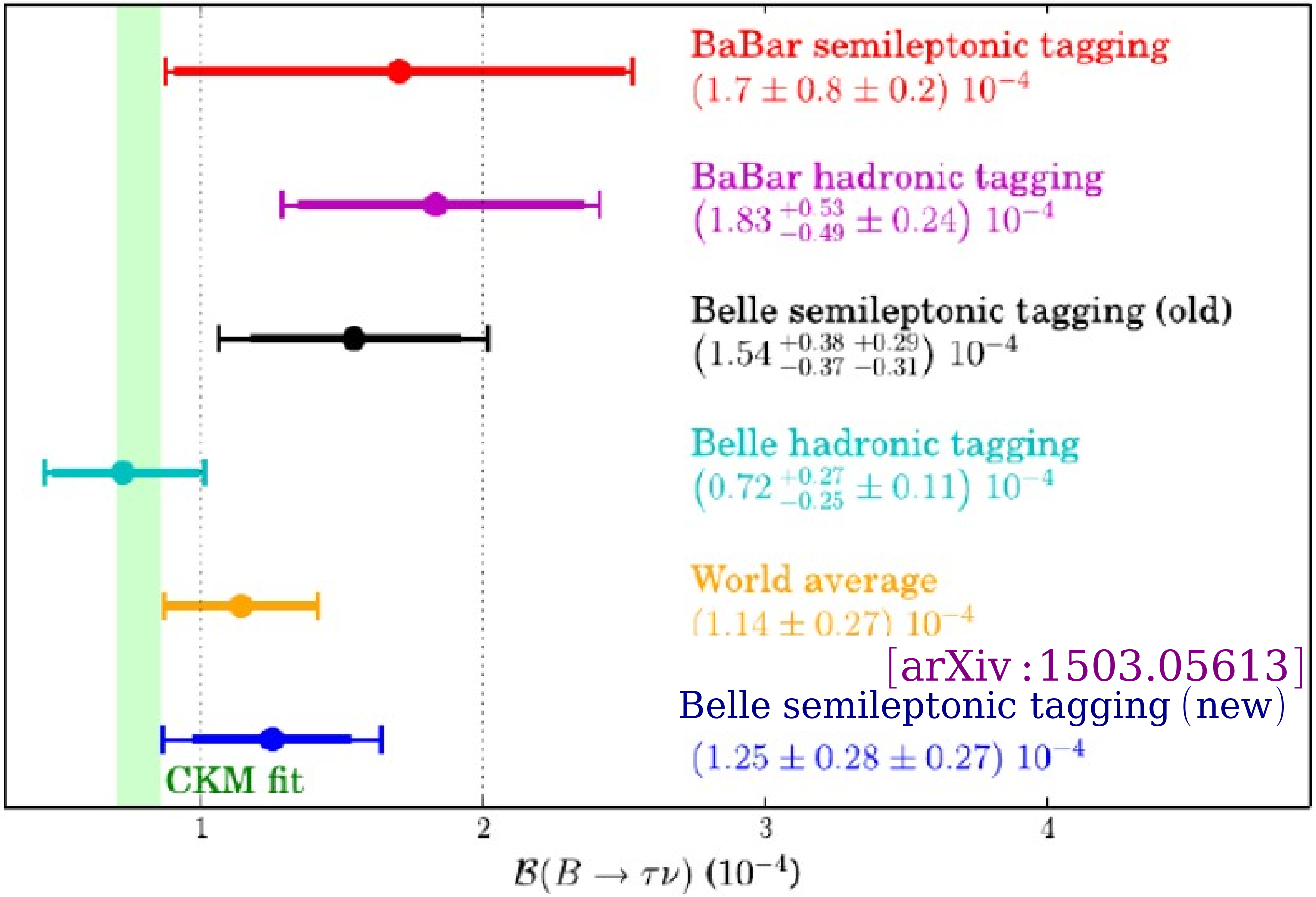
uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B
and other CKM uncertainties by combining with precise Δm_d

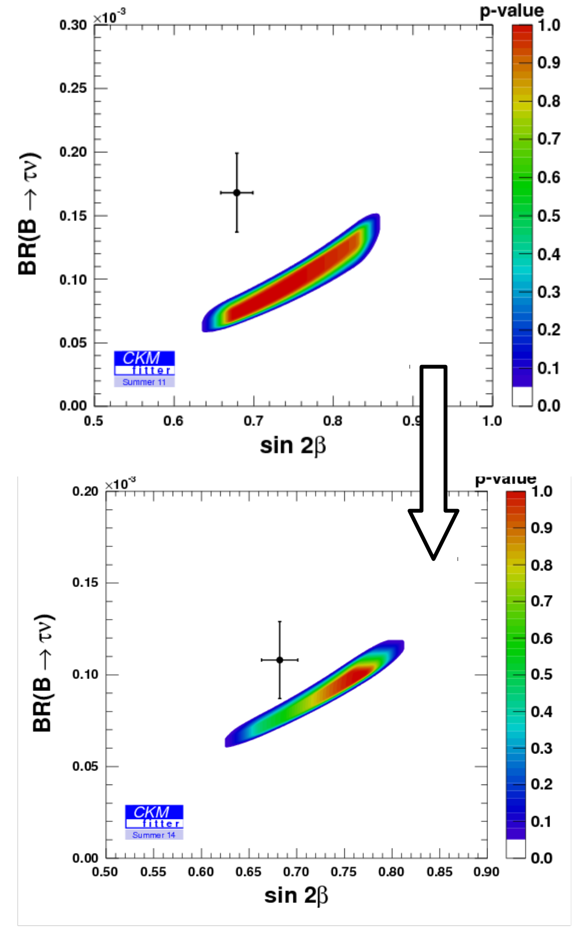
$B \to D^{(*)}\tau\nu$

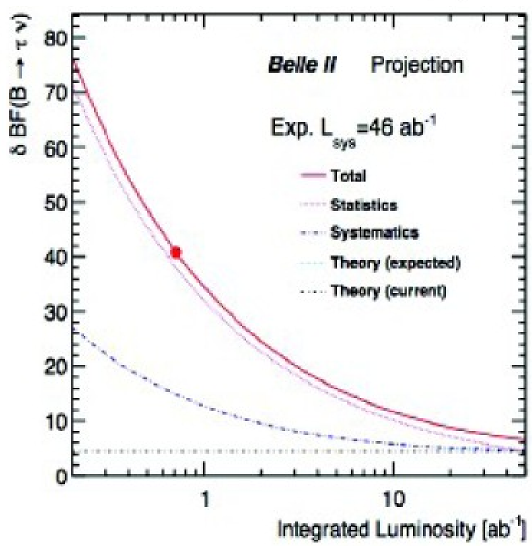
$$\text{2HDM (type II)}: \mathcal{B}(B \to D\tau^+\nu) = G_F^2 \tau_B |V_{cb}|^2 f\left(F_V, F_S, \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)$$

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

B→τν status





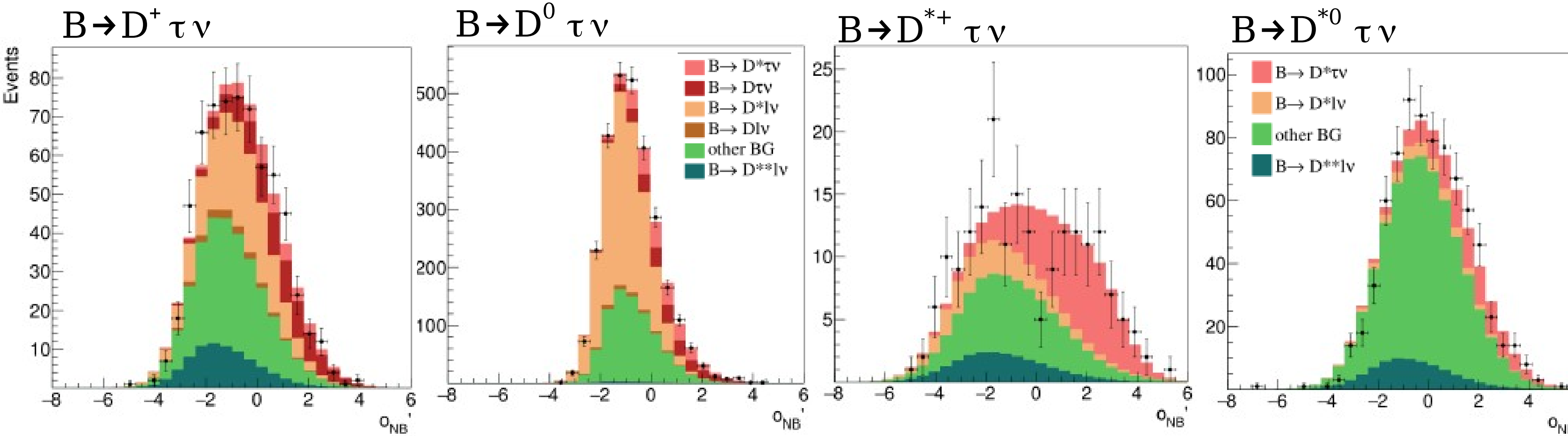


Belle II	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	19.0	(7.1, 2.2)	20.4	2.5	20.5
5 ab^{-1}	7.2	(2.7, 2.2)	7.9	1.5	8.1
50 ab^{-1}	2.3	(0.8, 2.2)	3.2	1.0	3.4
$\lvert V_{ub}\rvert$ $B \to \tau\nu$ (SL tagged)					
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	$^{+3.6}_{-5.2}$

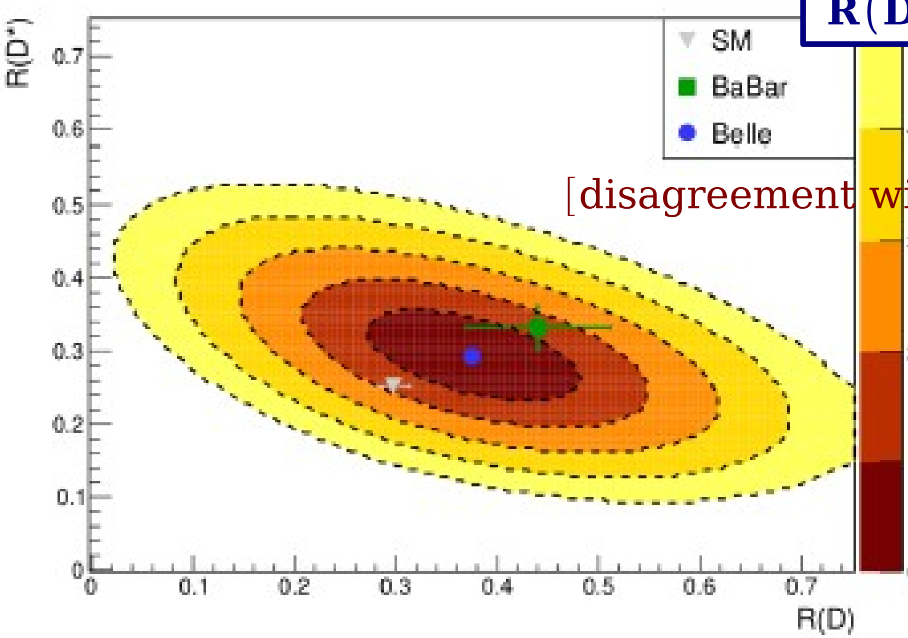
$B \to D^{(*)}\tau\nu$ at Belle

$D^{(*)}$ with hadronic tagging: arXiv: 1507.03233

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

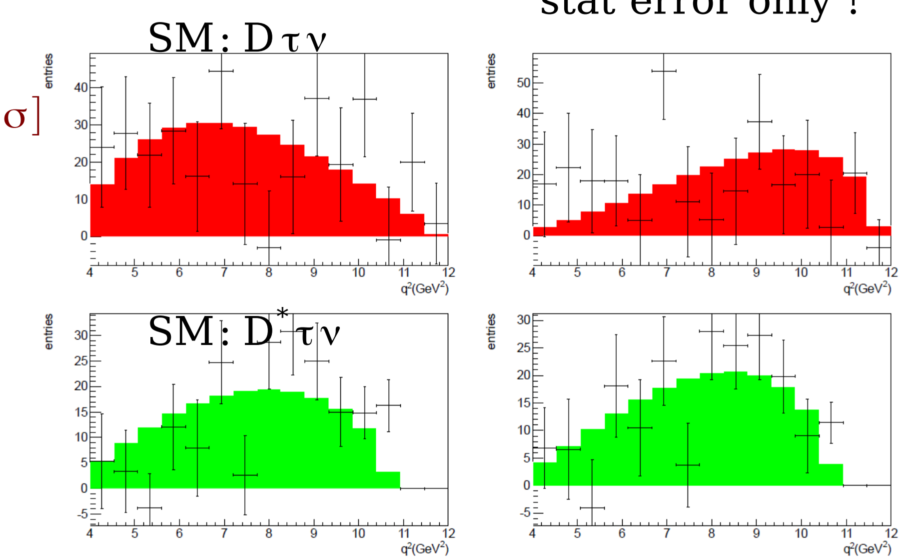


$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$



[disagreement with SM at 1.5σ]

stat error only !

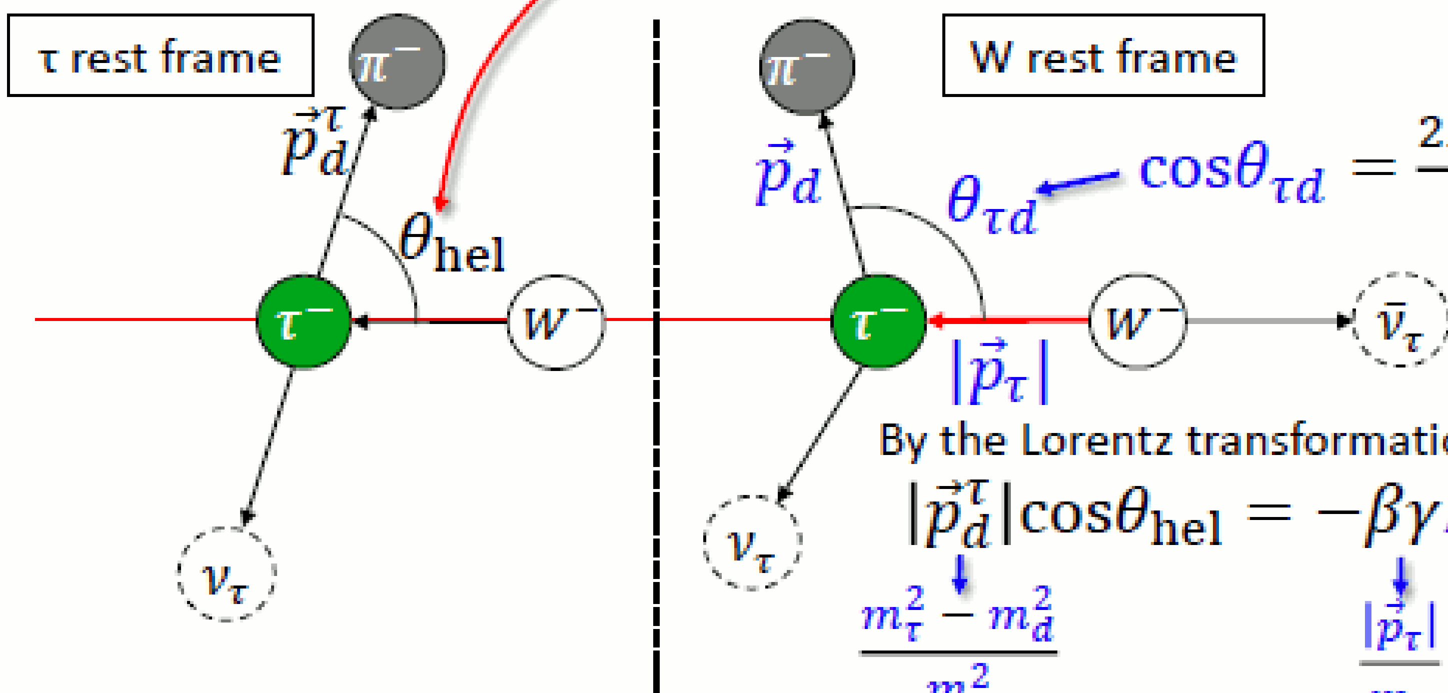


Belle Collaboration, Phys. Rev. Lett. 118, 211801 (2017)

■ $P_\tau(D^*)$ Measurement Method

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\mathrm{hel}}} = \frac{1}{2}\left(1 + \alpha P_\tau(D^*)\cos\theta_{\mathrm{hel}}\right)$$

$$\alpha = \begin{cases} 1 & \text{for } \tau^- \to \pi^-\nu_\tau \\ \sim 0.45 & \text{for } \tau^- \to \rho^-\nu_\tau \end{cases}$$



$$\cos\theta_{\tau d} = \frac{2E_\tau E_d - m_\tau^2 - m_d^2}{2|\boldsymbol{p}_\tau||\boldsymbol{p}_d|}$$

By the Lorentz transformation,

$$\underbrace{|\vec{p}_d^{\,\tau}|}_{\frac{m_\tau^2 - m_d^2}{m_\tau^2}}\cos\theta_{\mathrm{hel}} = -\underbrace{\beta\gamma}_{\frac{|\vec{p}_\tau|}{m_\tau}} E_d + \underbrace{\gamma}_{\frac{E_\tau}{m_\tau}}|\vec{p}_d|\cos\theta_{\tau d}$$

Solving the equation, $\cos\theta_{\mathrm{hel}}$ is obtained

cLFV : beyond the Standard Model

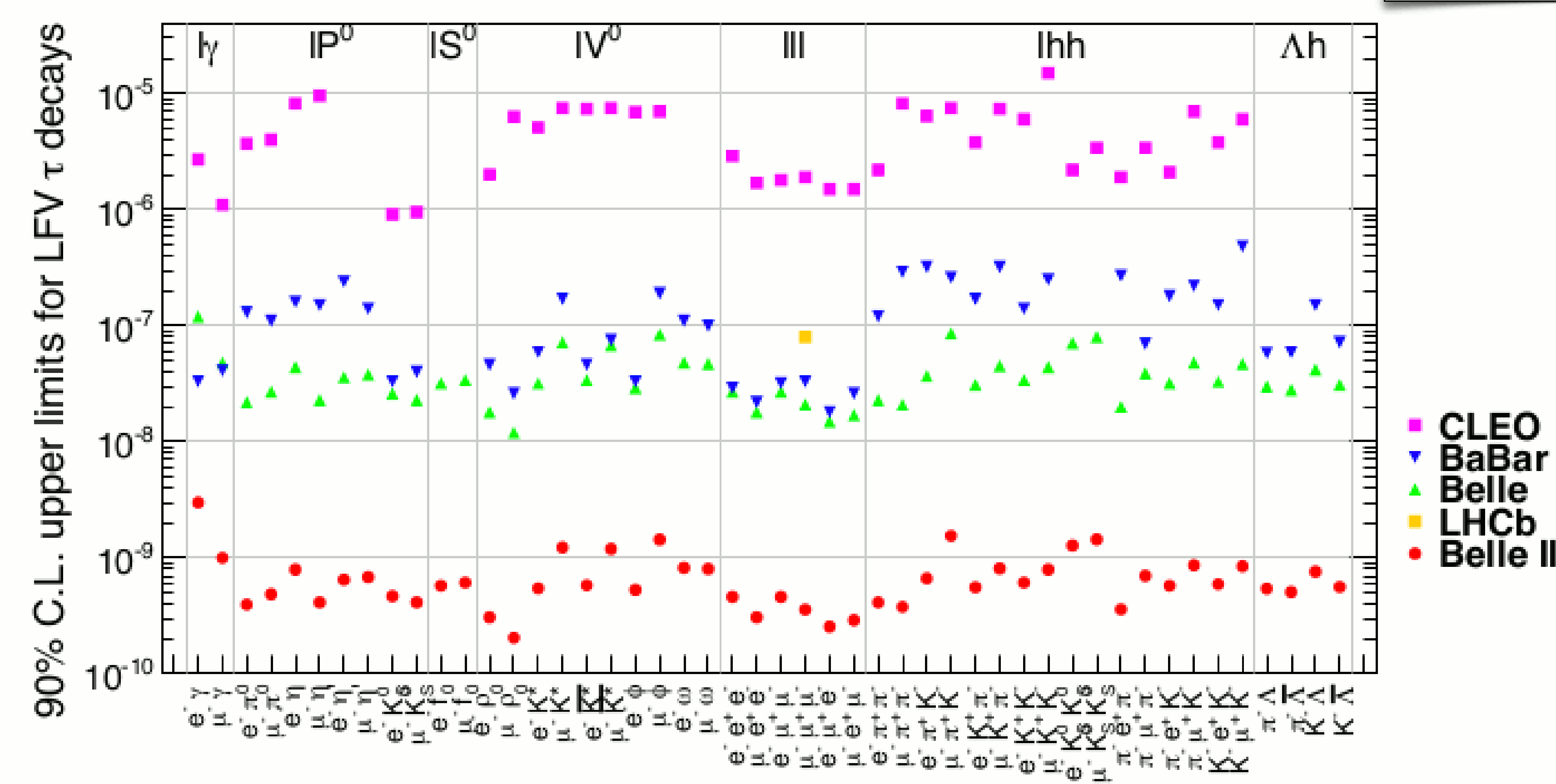
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left| U^*_{\tau i} U_{\mu i} \frac{\Delta m^2_{3i}}{m^2_W} \right|^2 < 10^{-40}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \dots$$

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

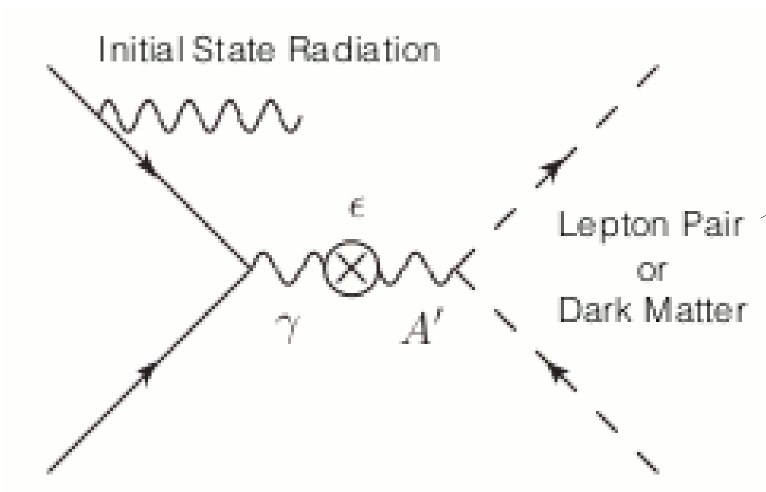
		$\tau \to 3\mu$	$\tau \to \mu\gamma$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
4-lepton	$O^{4\ell}_{S,V}$	✓	–	–	–	–	–
dipole	O_D	✓	✓	✓	✓	–	–
lepton-quark	O^q_V	–	–	✓ (I=1)	✓(I=0,1)	–	–
lepton-quark	O^q_S	–	–	✓ (I=0)	✓(I=0,1)	–	–
lepton-gluon	O_{GG}	–	–	✓	✓	–	–
lepton-quark	O^q_A	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-quark	O^q_P	–	–	–	–	✓ (I=1)	✓ (I=0)
lepton-gluon	$O_{G\tilde{G}}$	–	–	–	–	–	✓

Celis, Cirigliano, Passemar (2014)

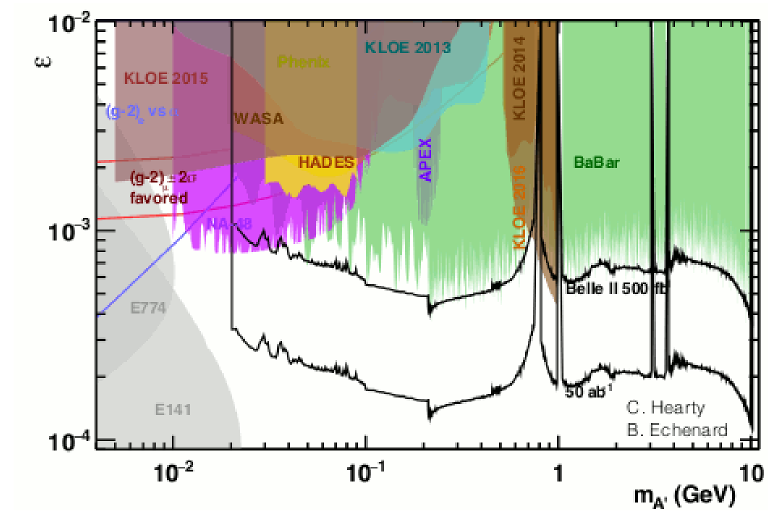


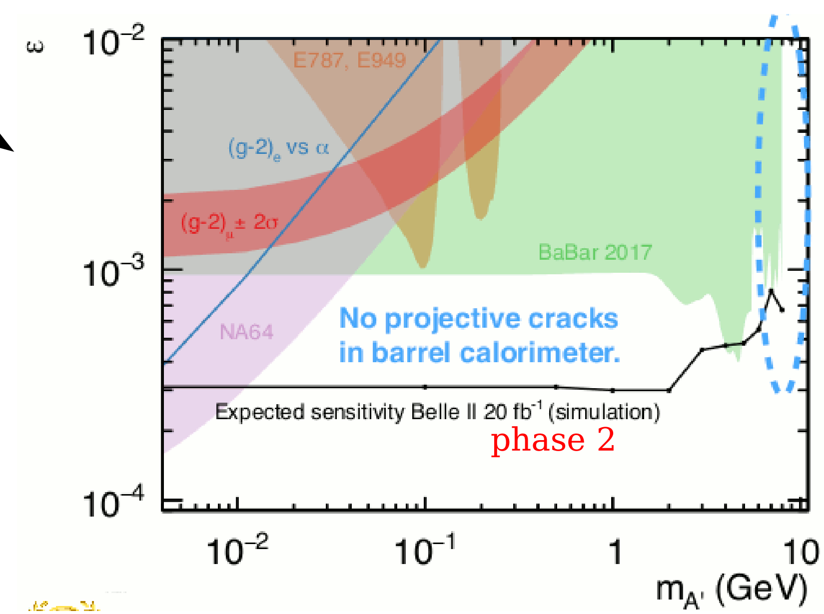
Dark Sector Physics

exploit the clean e^+e^- environment to probe the existence of exotic hadrons, dark photons/Higgs, light Dark Matter particles, ...



dark photon A' mixes with SM photon γ with strength ϵ

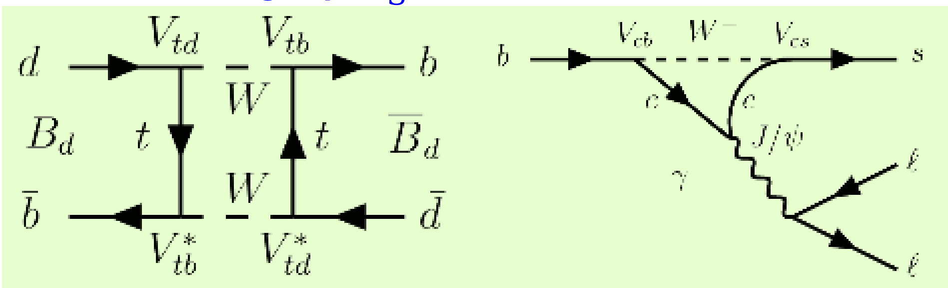




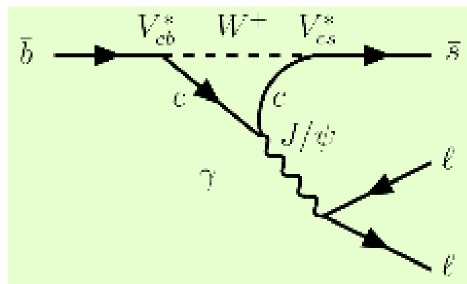
search for a dark photon decaying invisibly, and the search for an axion-like particle may be possible even in "Phase 2"

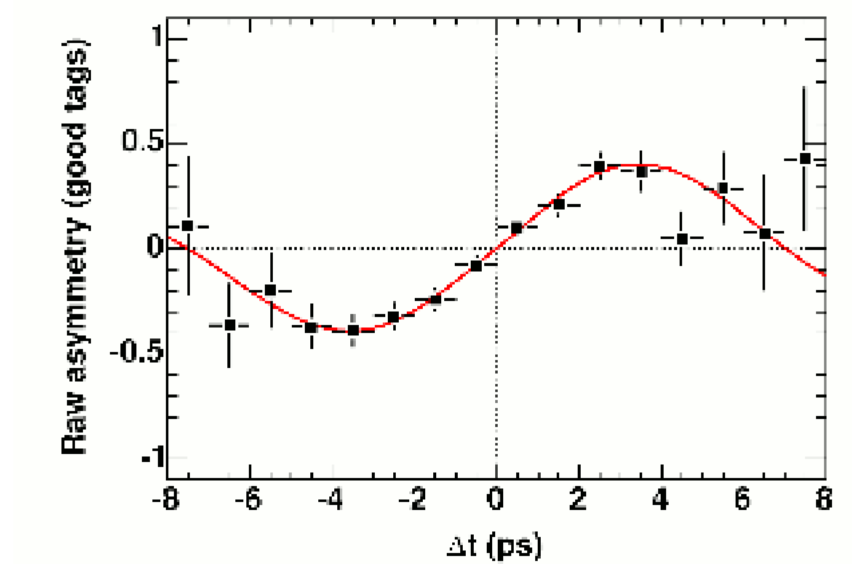
Mixing-induced CP violation

Remember $B^0 \to J/\psi K_S^0$:

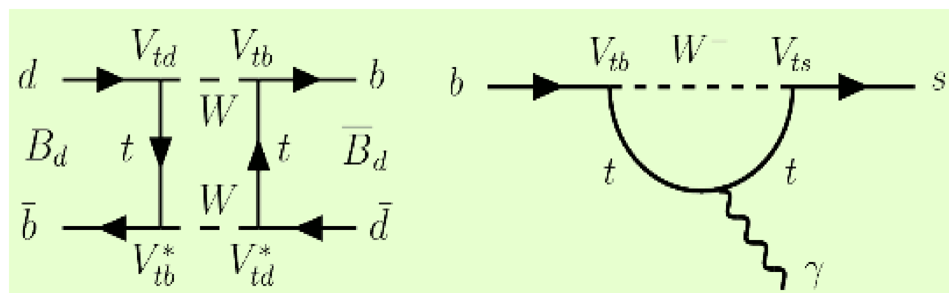


interferes with

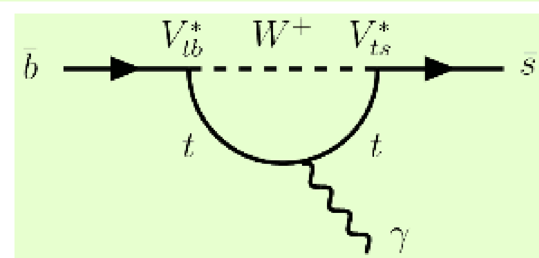




What about $B^0 \to \gamma K_S^0 \pi^0$?



interferes with right-handed component of



In SM mainly $B^0 \to K_S^0 \pi^0 \gamma_R$ and $\overline{B}^0 \to K_S^0 \pi^0 \gamma_L$: $K_S^0 \pi^0 \gamma$ behaves like an effective flavor eigenstate,

$\Rightarrow$ **mixing-induced CP violation is expected to be small $S \sim -2(m_s/m_b)\sin(2\phi_1)$**

Constraints on NP from radiative B decays

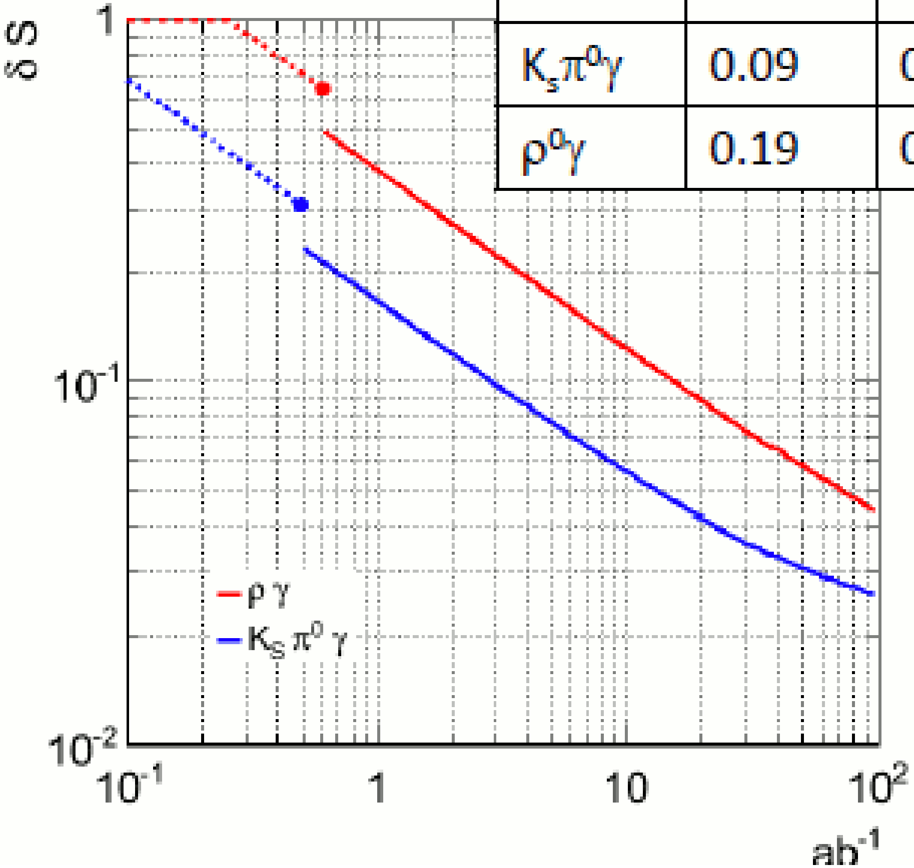
At Belle II, expect significant improvement in the determination of $A_{CP}(t)$ in $K_S^0 \pi^0 \gamma$

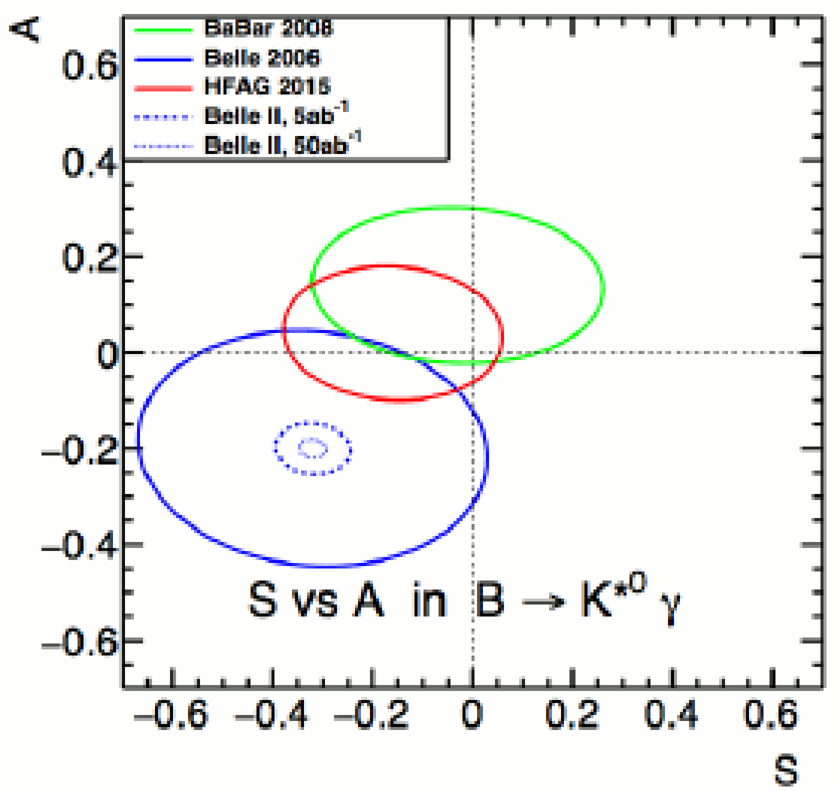
- **Belle II SVD larger than Belle (6 → 11.5 cm)**

 $\Rightarrow$ 30% more K_S with vertex hits available, effective tagging eff. 13% better

- Expected errors for ***S*** measurements of $K_s\pi^0\gamma$ and $\rho^0\gamma$.

Mode	5 ab^{-1}	50 ab^{-1}
$K_s\pi^0\gamma$	0.09	0.030
$\rho^0\gamma$	0.19	0.064





16σ deviation with 50 ab^{-1}.