Anomalies in $b \to s l^+ l^-$ and $b \to c \tau \nu$

Recent results from LHCb

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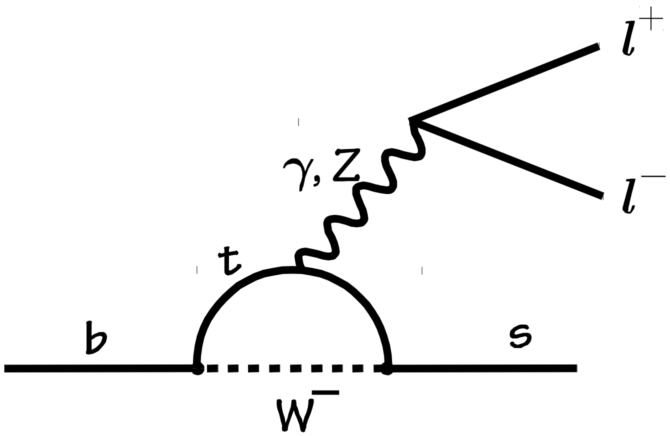
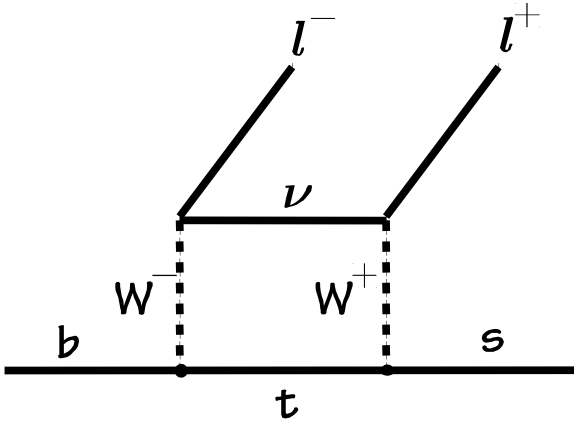
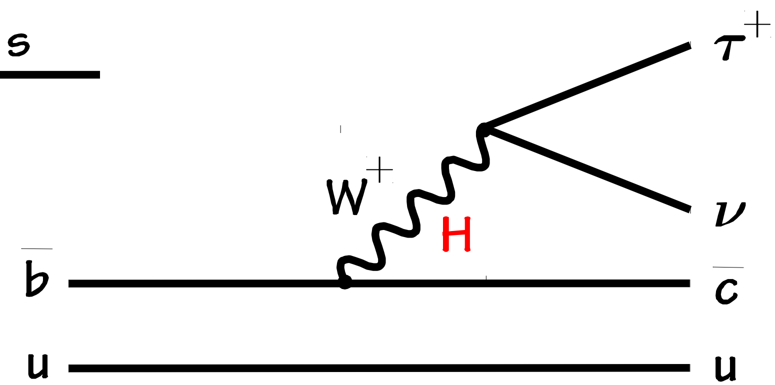
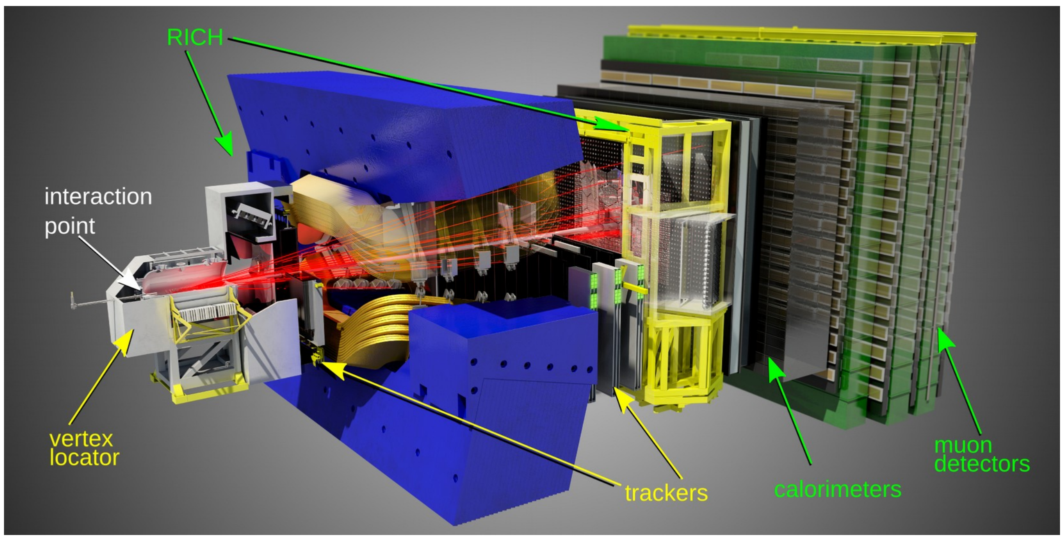


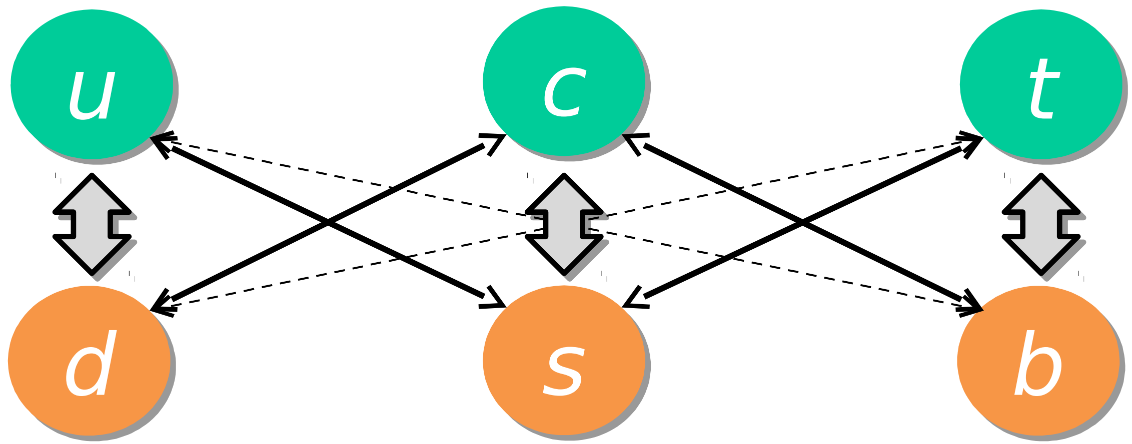




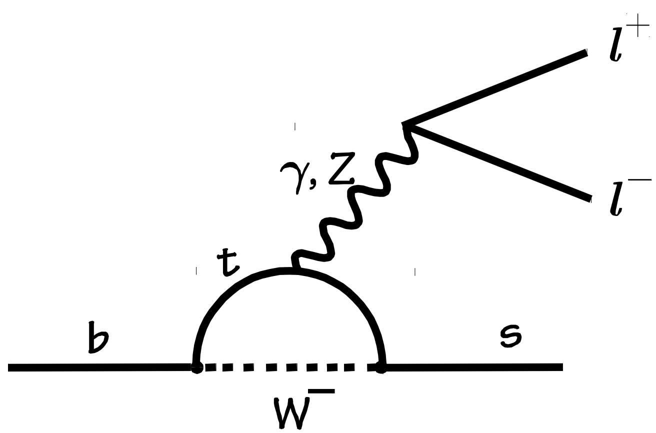


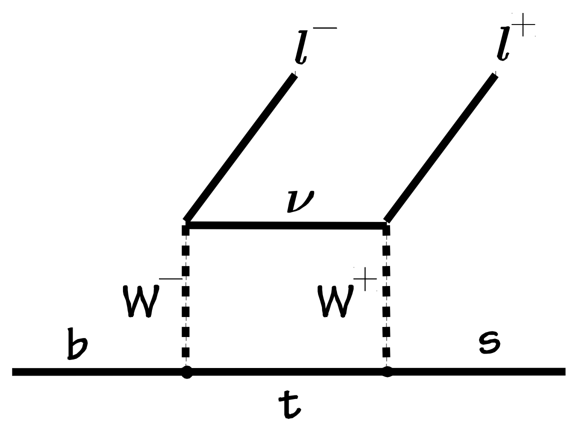
FPWS 2017, Oct 31st 2017

Rare B decays



- FCNC : Flavour Changing Neutral Current
- FCNC are strongly suppressed in the SM : only loops + GIM mechanism

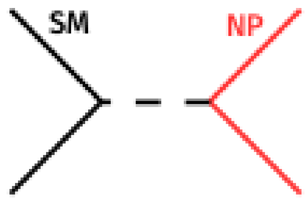




Rare B decays

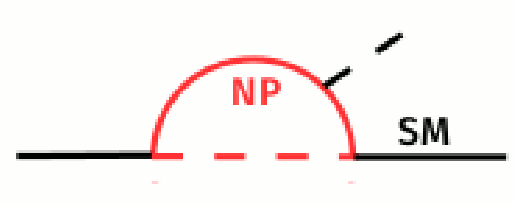
- FCNC are strongly suppressed in the SM: only loops + GIM mechanism
- Any new particle generating new diagrams can change the amplitudes

energy frontier



limited by beam energy

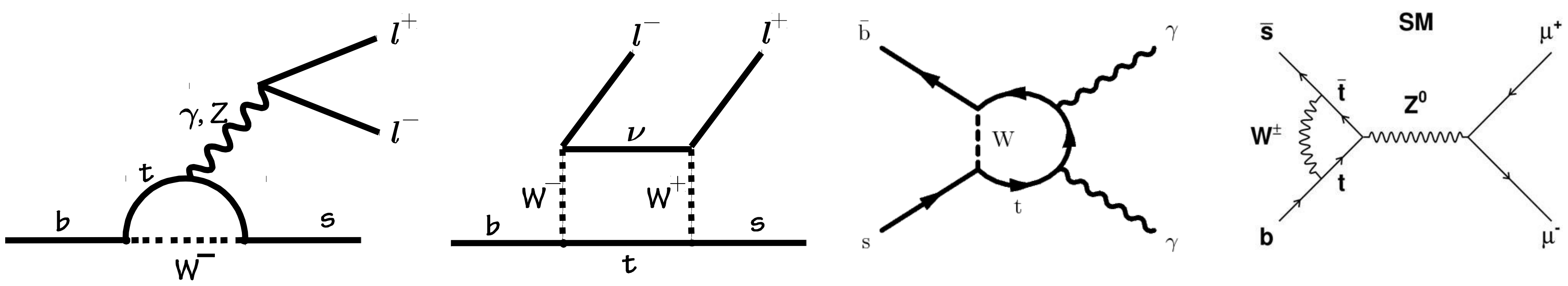
intensity frontier



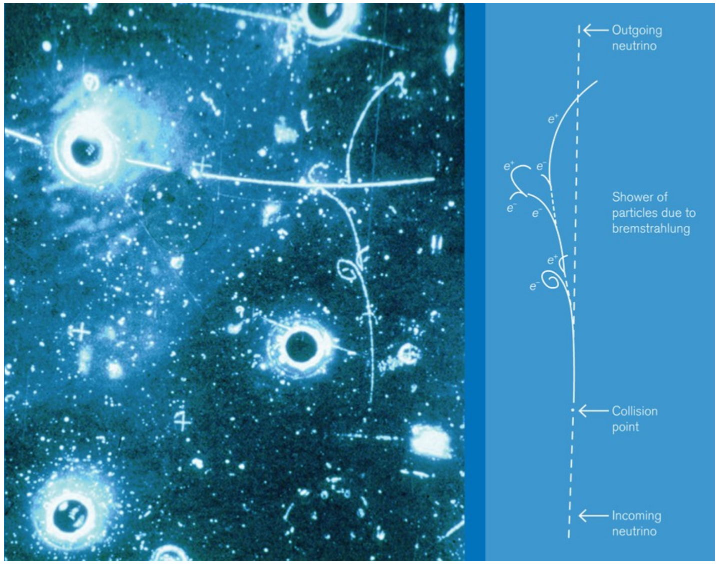
limited by statistics

→ **NP beyond the direct 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**

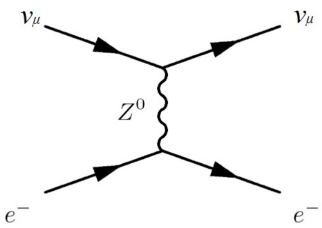


Indirect searches



Sensitive to New Physics effects

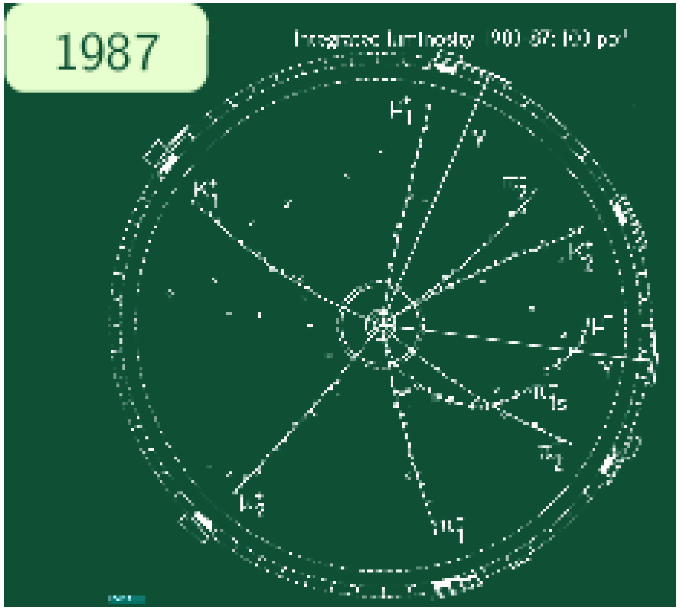
- When was the Z discovered ?
    - 1973 from N ν → N ν ?
    - 1983 at SpS ?



- c quark postulated by GIM, third family by KM

Estimate masses

- t quark from $B\bar{B}$ mixing



Get phases of couplings

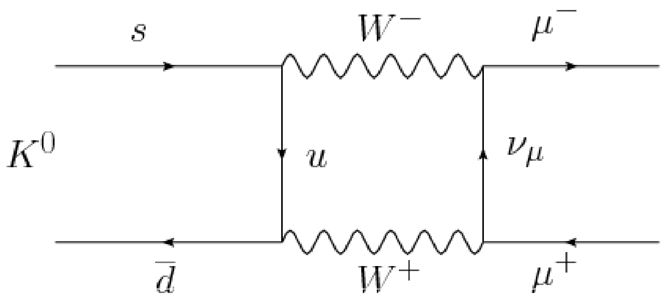
- Half of new parameters
- Needed for a full understanding

Look in lepton and **flavour** sectors

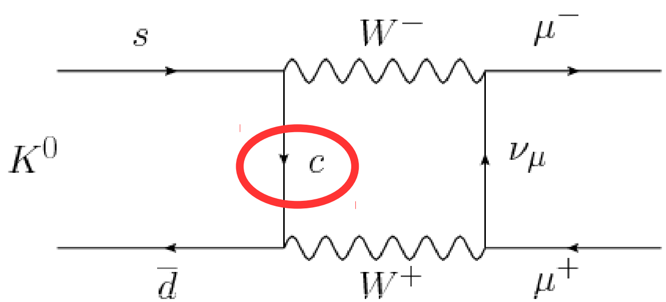
→ CP asymmetry in the Universe

indirect search: $K_L^0 \to \mu\mu$

$K_L \to \mu^+\mu^-$ decay can be generated by the box diagram:



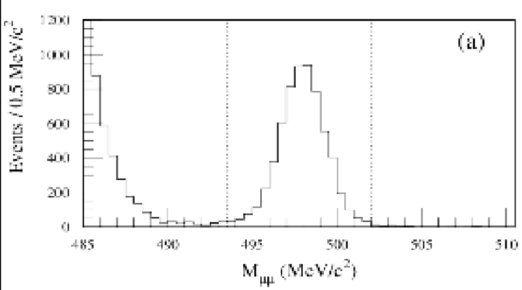
in a renormalisable gauge theory, is expected to give a branching ratio of $\mathbf{g^4 \sim \alpha^2 \sim 10^{-4}}$, with α the fine structure constant.



$K_L^0 \to \mu\mu$ was not observed though expected

Now BF is measured to be $(6.84 \pm 0.11)\,10^{-9}$

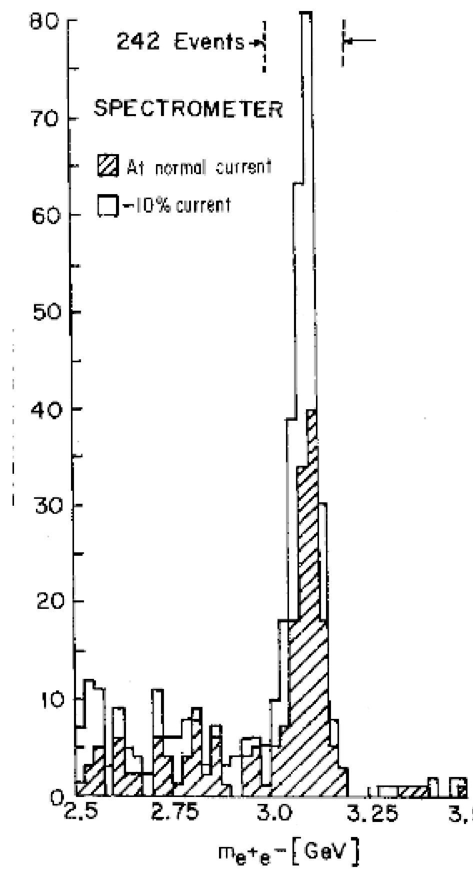
[Ambrose et al, 2000]

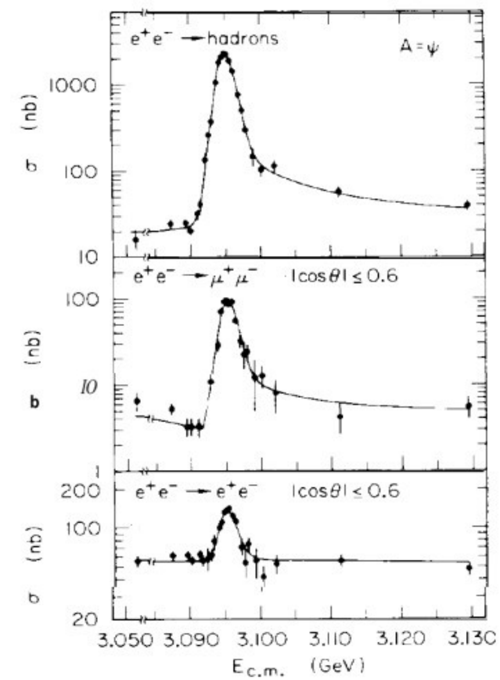


direct search: $J/\psi \to ee$

→ c quark eventually observed in 1974 [Ting], [Richter]

J/ψ

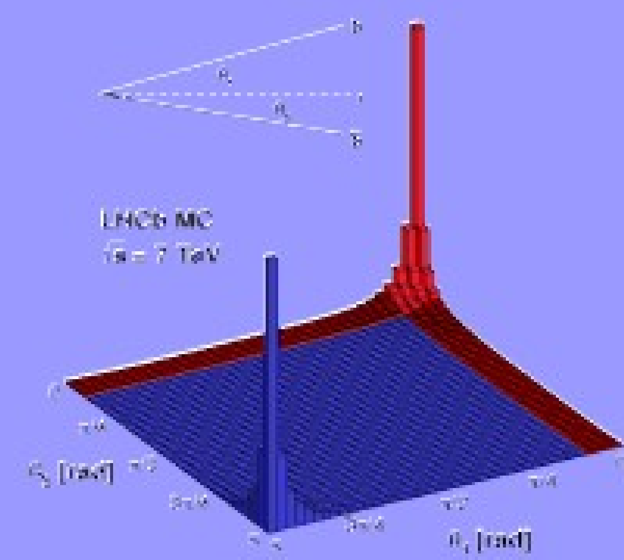


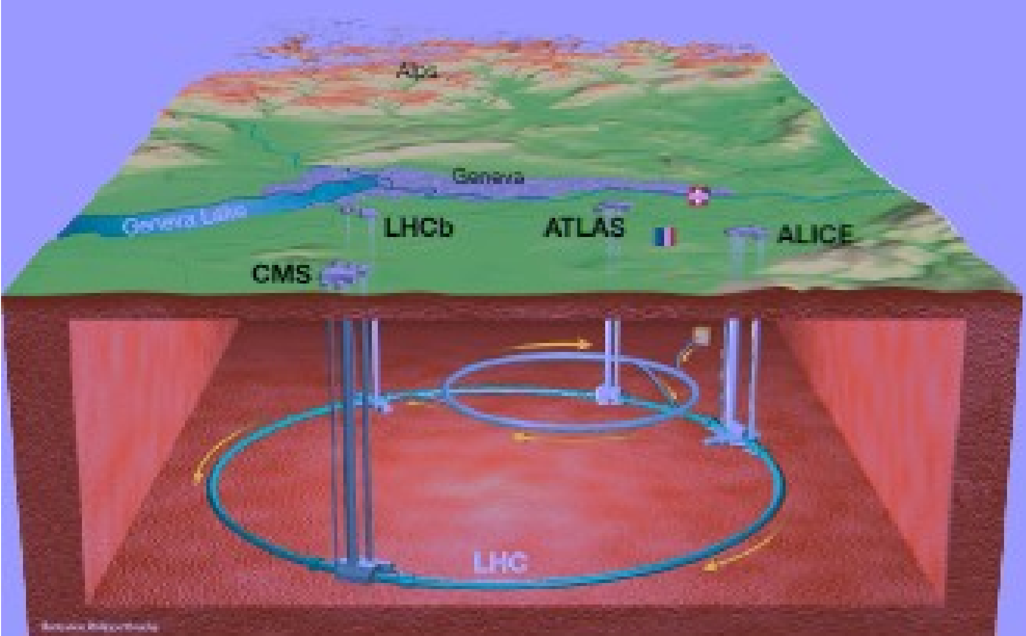


With the measured charm quark mass $m_c \sim 1.27$ GeV, the predicted rates are in agreement with observation.

LHCb is ...

- 1075 members, from 68 institutes in 17 countries (September 2014)
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful*, *charming*, *strange* physics program



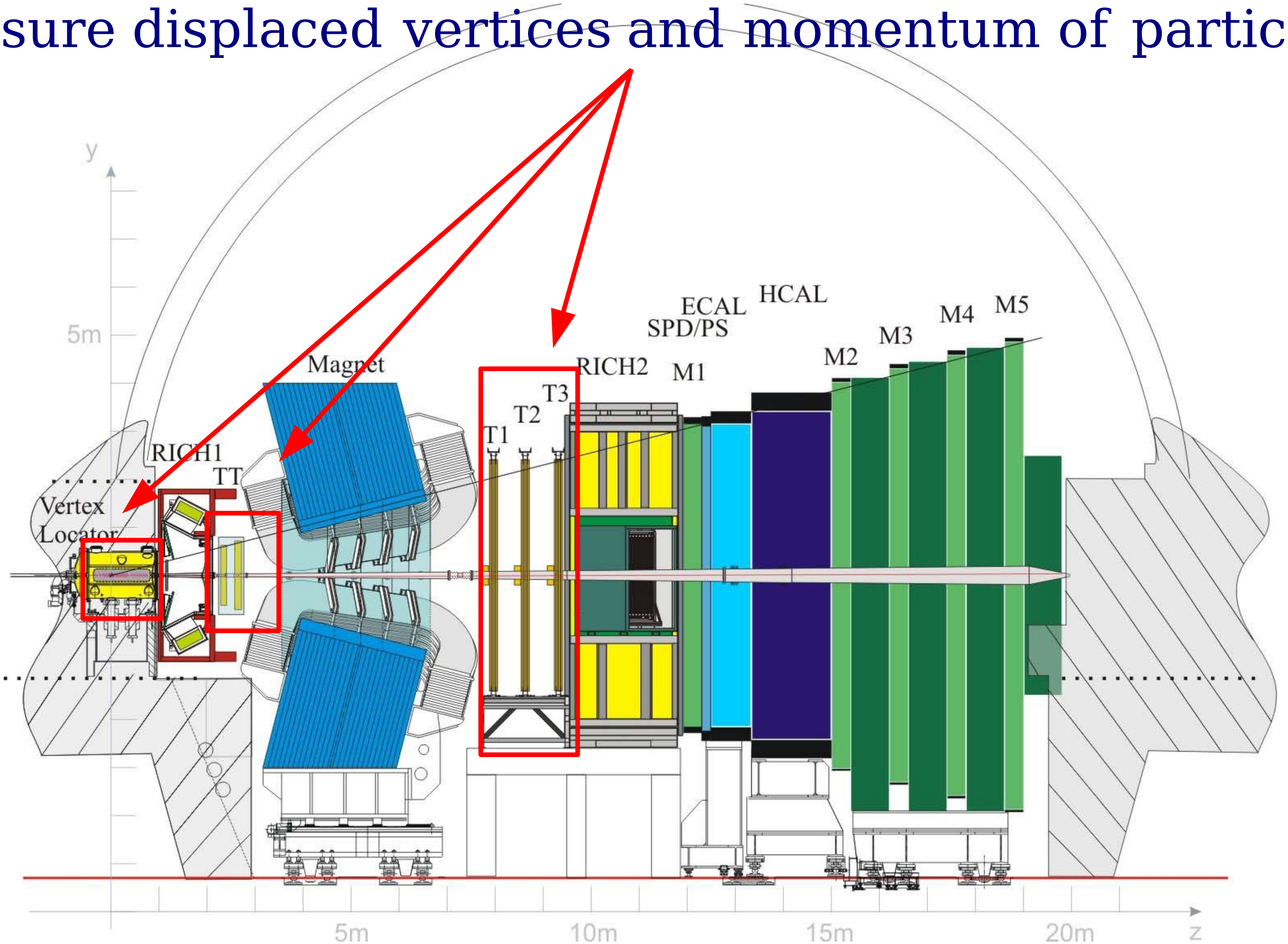


- pp collisions at $\sqrt{s} = 8(13)$ TeV in RunI (RunII)
- $b\bar{b}$ quark pairs produced correlated in the forward region
- Luminosity of $4 \times 10^{32} cm^{-2} s^{-1}$

LHCb

Tracking system

Measure displaced vertices and momentum of particles



Vertex and IP resolution

$\sigma(IP) \sim 24\,\mu m$ at $P_T = 2$ GeV/c

$\sigma_{BV} \sim 16\,\mu m$ in x, y

Momentum resolution

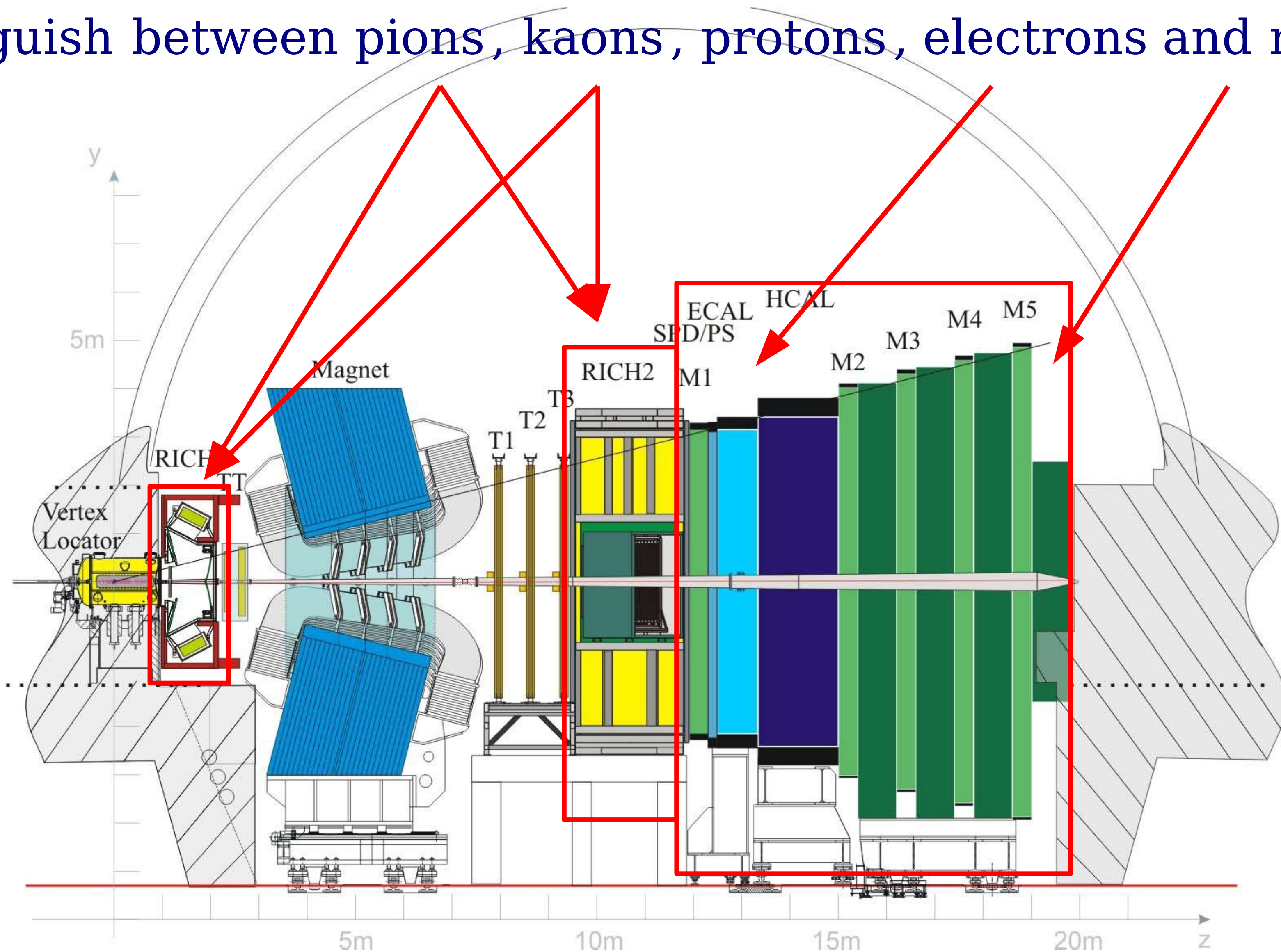
$\sigma(p)/p = 0.4\%$-0.6% for $p \in [0, 100]$ GeV/c

$\sigma(m_B) \sim 24$ MeV for two body decays

LHCb

Particle identification

Distinguish between pions, kaons, protons, electrons and muons



Kaon identification

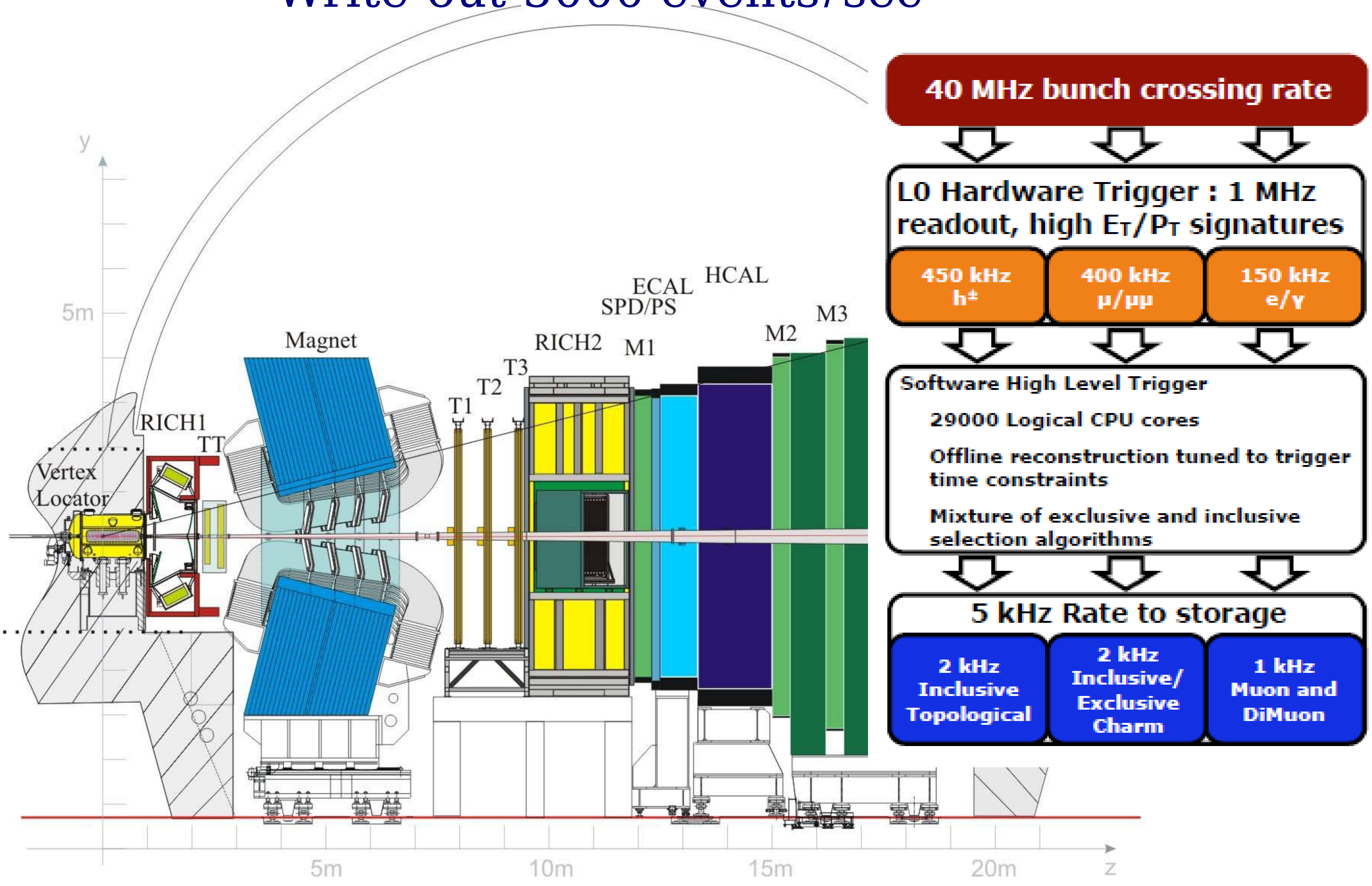
$\epsilon_K \sim 95\%$, $\epsilon_{\pi \to K}$ few%

Muon identification

$\epsilon_\mu = 98\%$, $\epsilon_{\pi \to \mu} = 0.6\%$

LHCb

Trigger system
Write out 5000 events/sec



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 ⇒ clean events

$\sigma_{b\bar{b}} \sim 1\,nb \Rightarrow 1\ fb^{-1}$ 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

⇒ 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 $\beta\gamma c\tau \sim 200\ \mu m$

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

data taking period(s)

[1999-2010] = 1 ab^{-1}

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

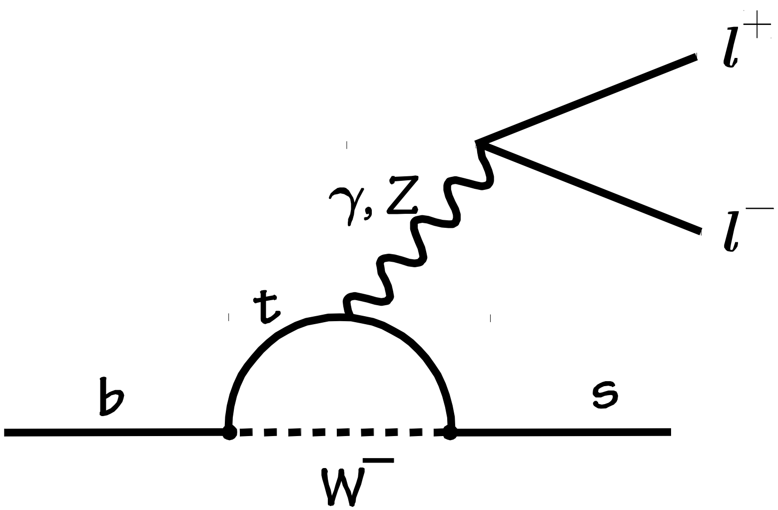
[run II: 2015-2018] = 2 fb^{-1} → 8 fb^{-1} ?

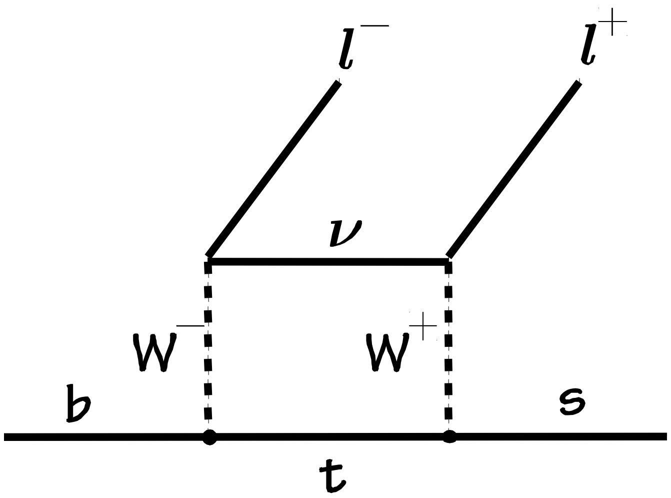
(near) future

[Belle II from 2018] → 50 ab^{-1}

[LHCb upgrade from 2020]

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





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

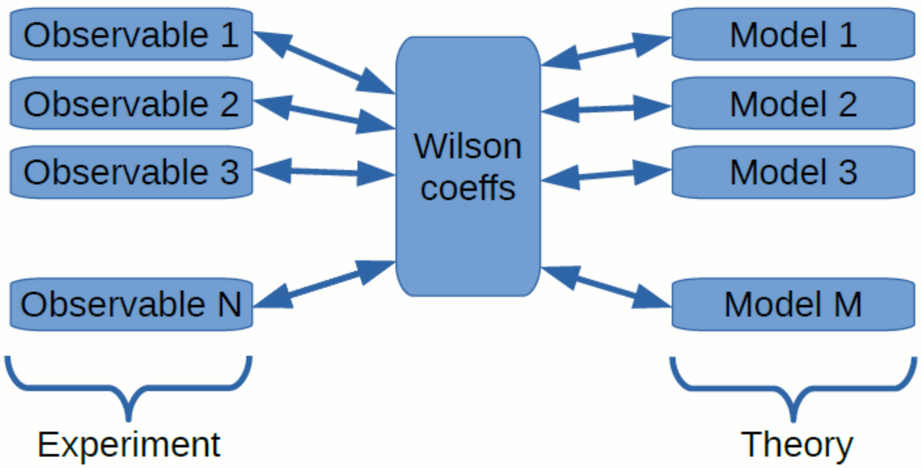
Amplitudes from
- electromagnetic penguin: C_7
- vector electroweak: C_9
- axial-vector electroweak: C_{10}

may interfere w/ contributions from NP

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

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

Sensitivity to new physics in rare B decays



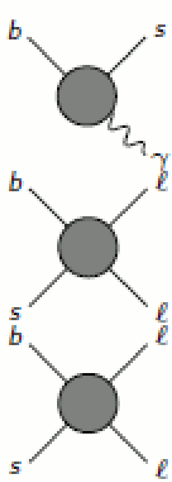
M.Ciuchini et al, arXiv:1512.07157
T.Hurth et al, arXiv:1603.00865
S.Descotes-Genon et al, arXiv:1510.04239...

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

- Model-independent description in effective field theory

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

- 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		✓	

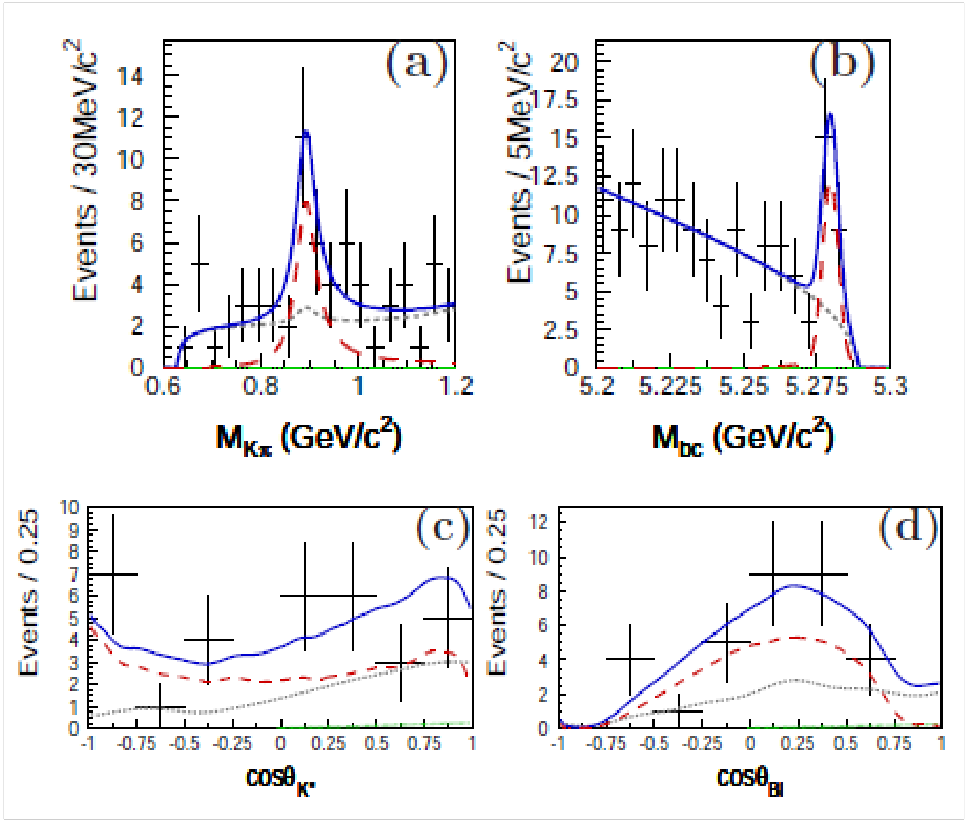
Situation pre-LHCb

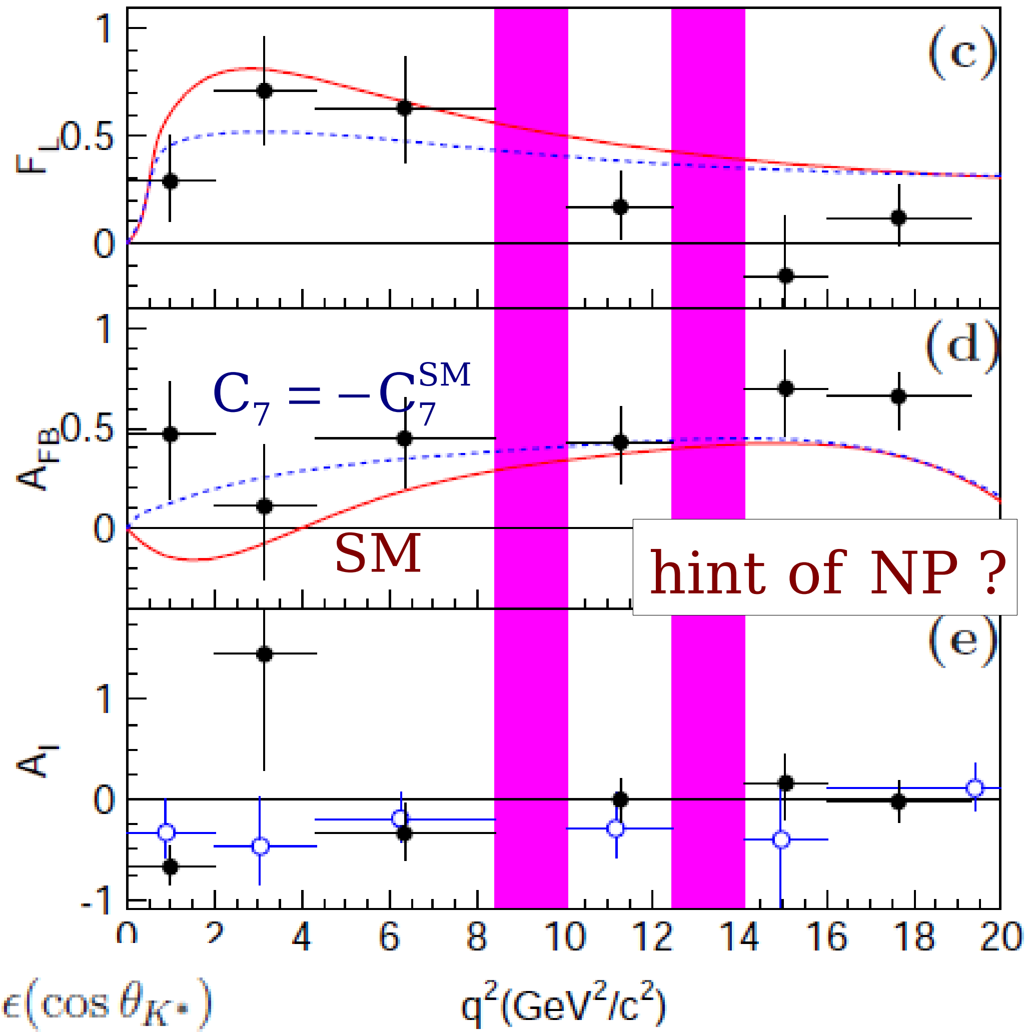
$B \to K^* l^+ l^-$ decays

[arXiv:0904.0770]

- Channels: $K^* \to K^+\pi^-$, $K^0_S\pi^+$, $K^+\pi^0$, $l = e$ or μ

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





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

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

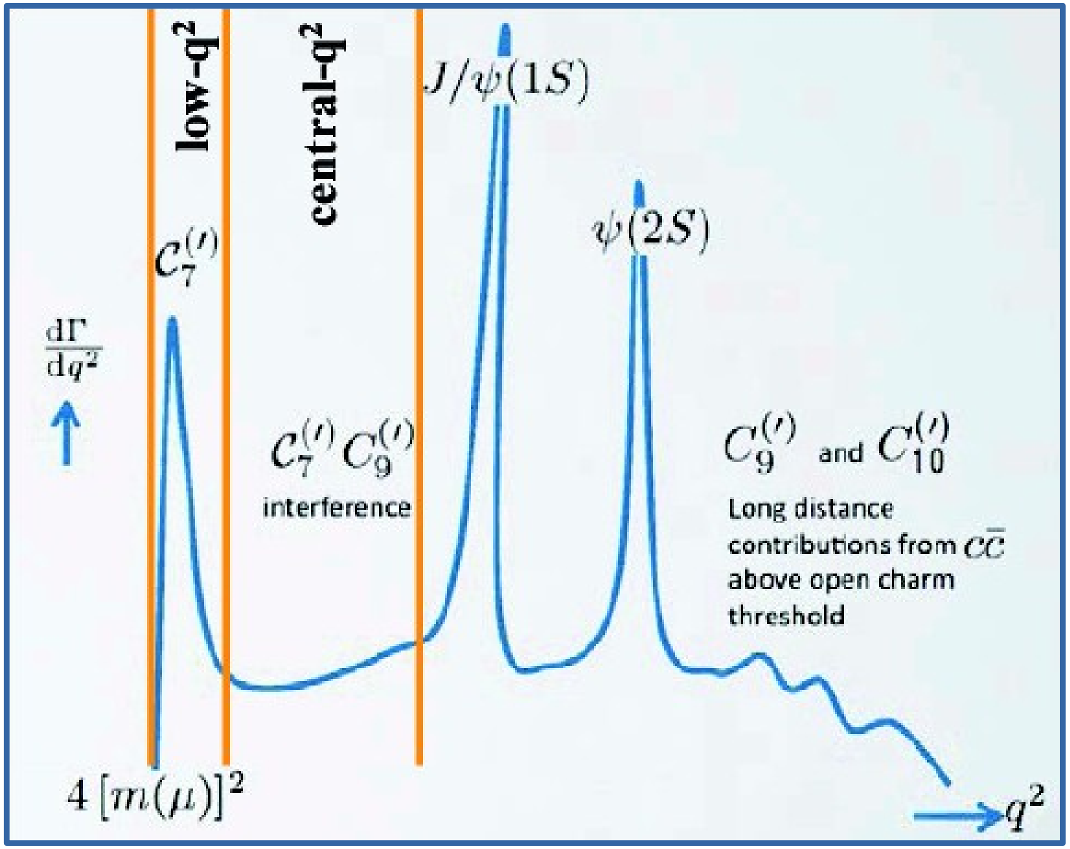
$R_{K^*} = 0.83 \pm 0.17 \pm 0.08$

$R_K = 1.03 \pm 0.19 \pm 0.06$

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

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

- **Selection as similar as possible between μμ and ee**
  - Pre-selection requirements on trigger and quality of the candidates
  - Cuts to remove the peaking backgrounds
  - Particle identification to further reduce the background
  - Multivariate classifier to reject the combinatorial background
  - Kinematic requirements to reduce the partially-reconstructed backgrounds
  - Multiple candidates randomly rejected (1-2%)

- **Efficiencies**
  - Determined using simulation, but tuned using data

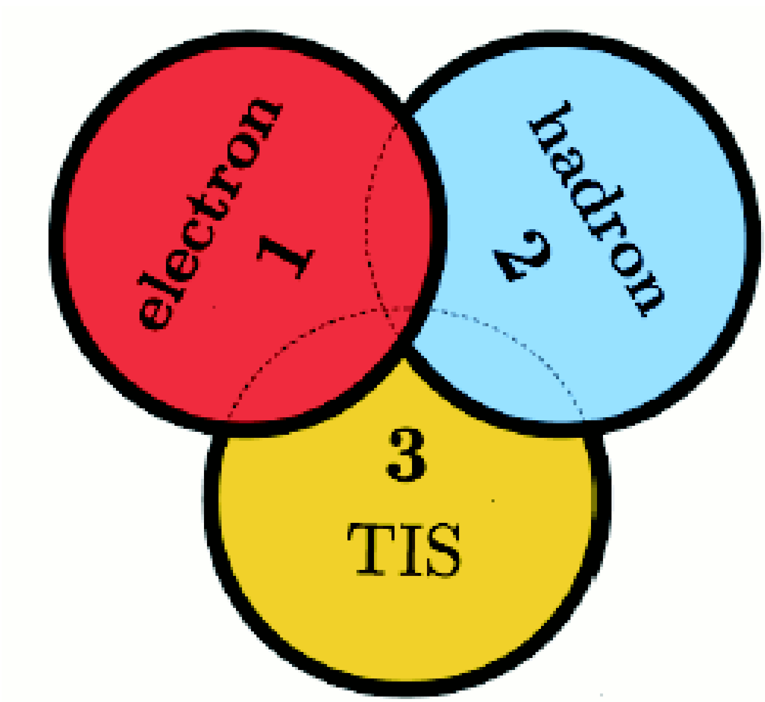
Strategy

- 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:

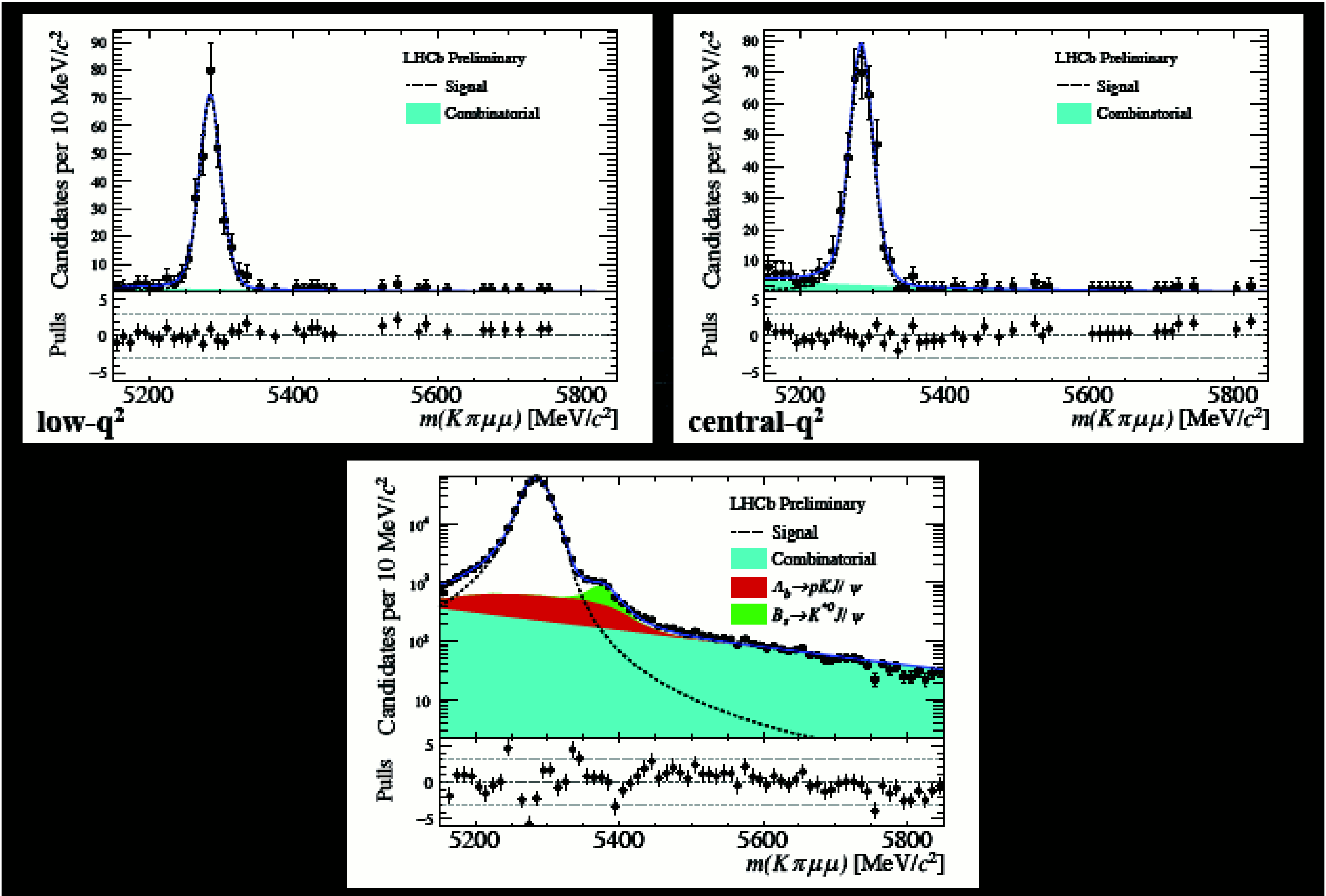
- L0 Electron: electron hardware trigger fired by clusters associated to at least one of the two electrons ($E_T > 2.5$ GeV)

- L0 Hadron: hadron hardware trigger fired by clusters associated to at least one of the K^{*0} decay products ($E_T > 2.5$ GeV)

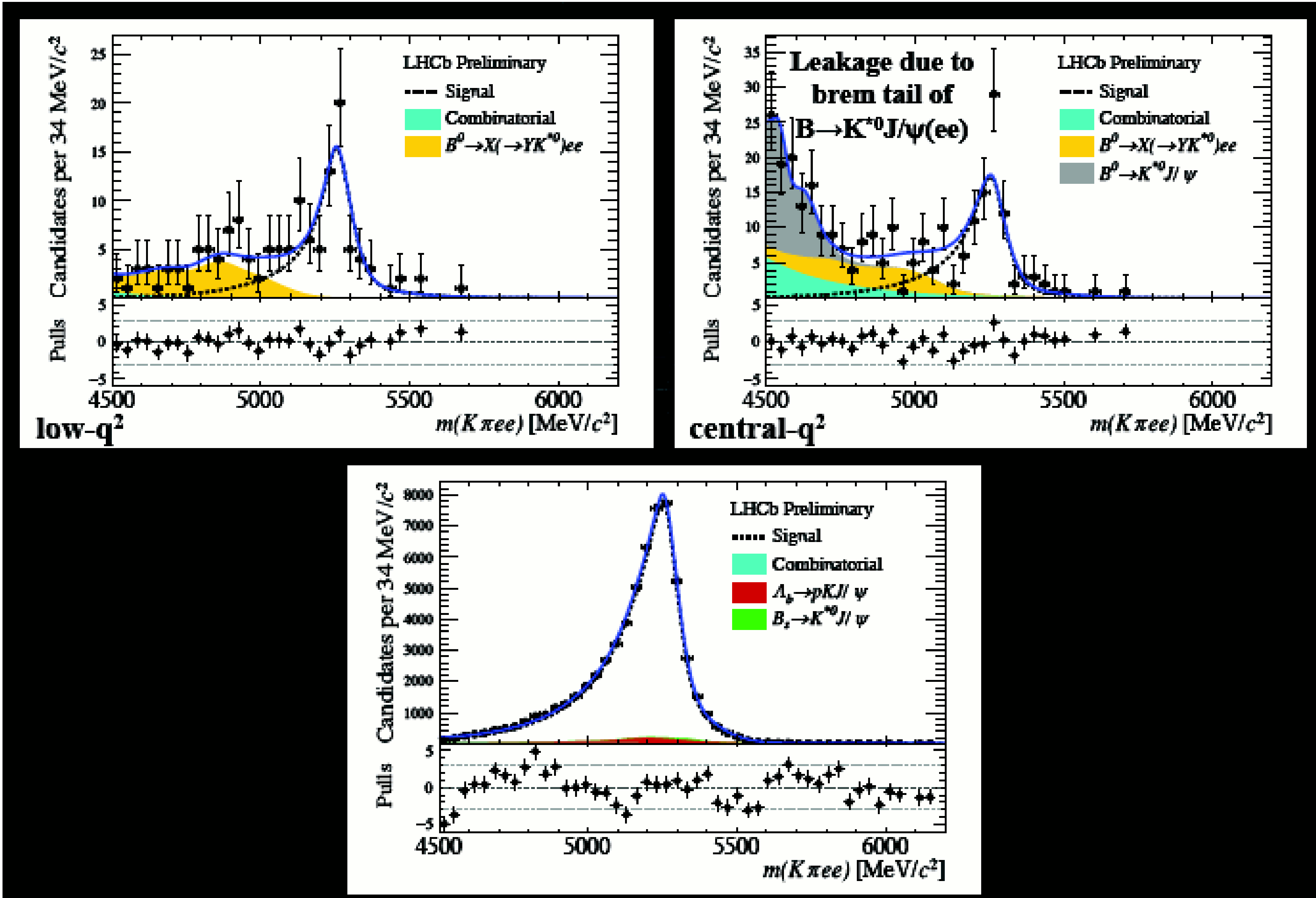
- L0 TIS(*): any hardware trigger fired by particles in the event not associated to the signal candidate

(*) TIS = Trigger Independent of Signal

Fit results – μμ



Fit results – ee



Yields

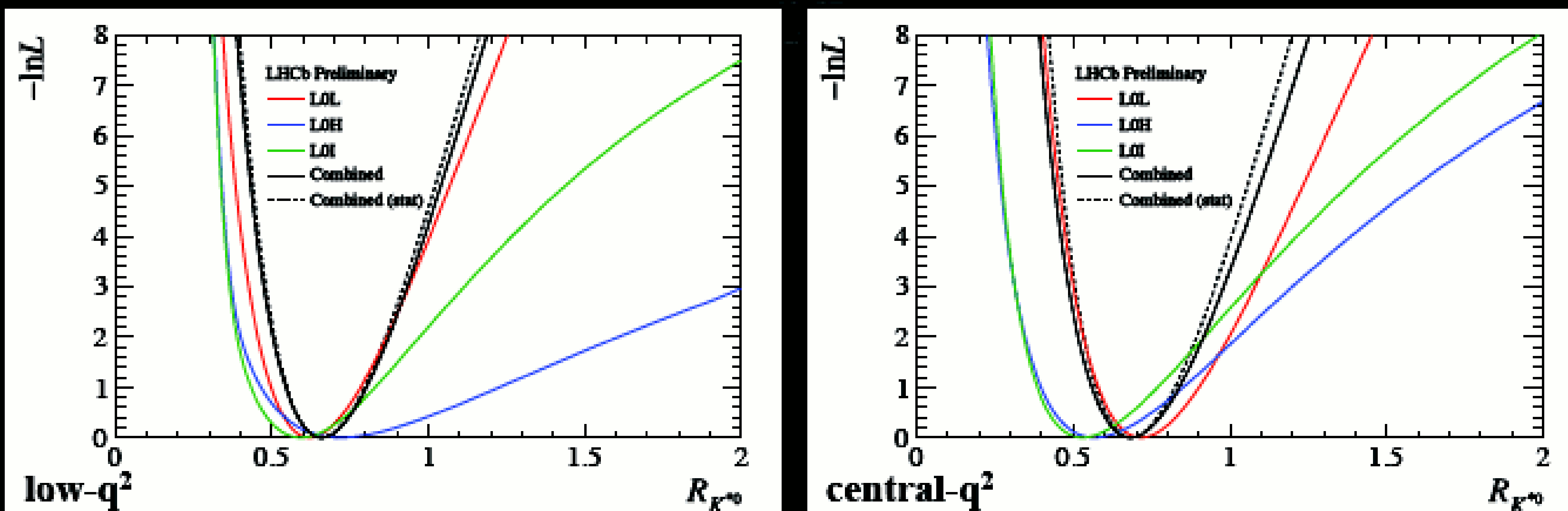
Precision of the measurement driven by the statistics of the electron samples

	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0}J/\psi(\to \ell^+\ell^-)$
	low-q^2	**central-q^2**	
$\mu^+\mu^-$	$285\,^{+\,18}_{-\,18}$	$353\,^{+\,21}_{-\,21}$	$274416\,^{+\,602}_{-\,654}$
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)	$21\,^{+\,5}_{-\,4}$	$25\,^{+\,7}_{-\,6}$	$11505\,^{+\,115}_{-\,114}$

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

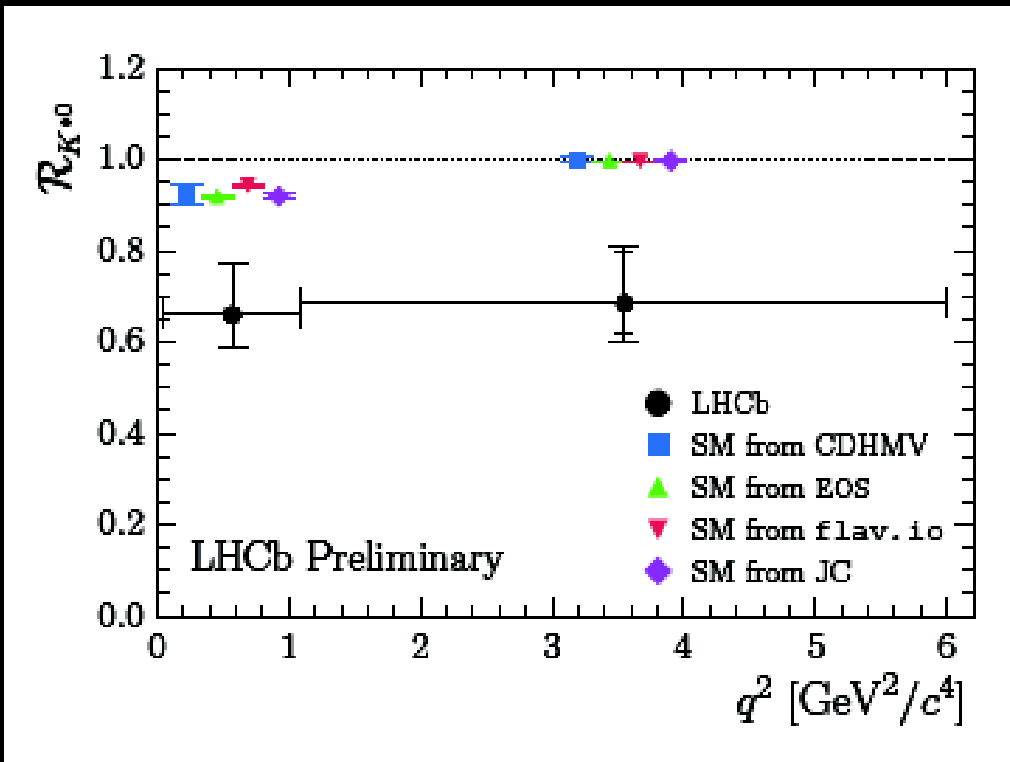
Results

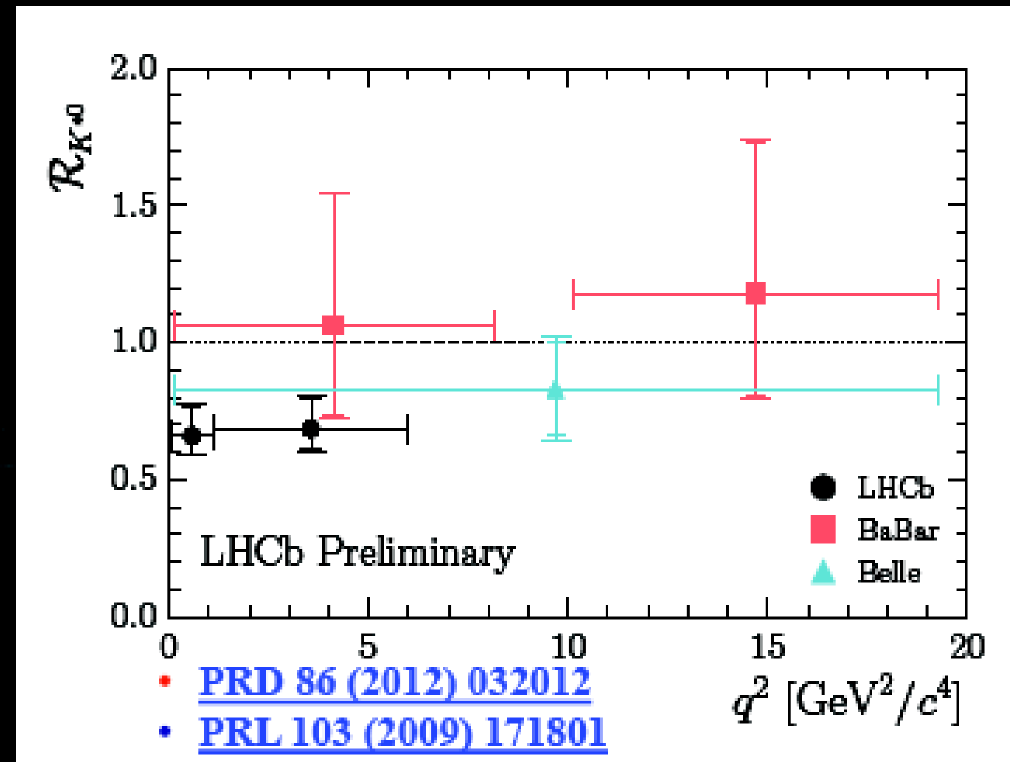
LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660\ ^{+\ 0.110}_{-\ 0.070} \pm 0.024$	$0.685\ ^{+\ 0.113}_{-\ 0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]



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

Results





- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

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

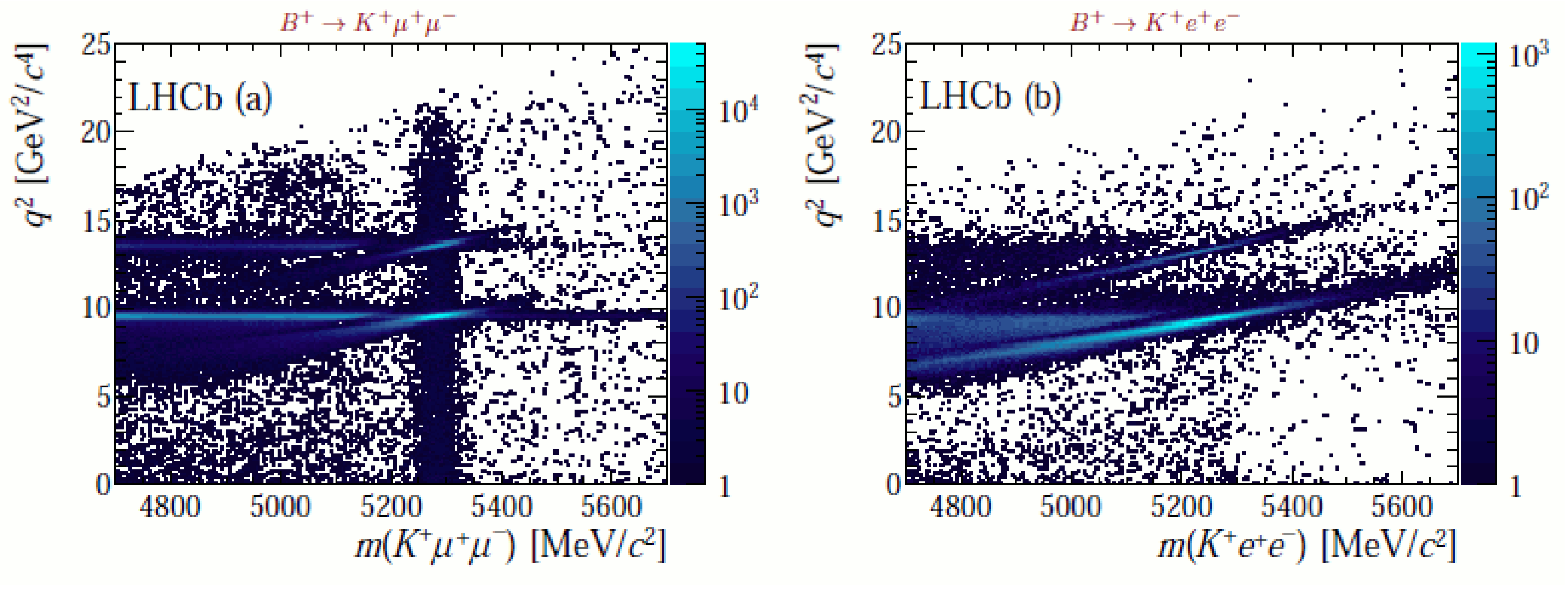
arXiv:1406.6482

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

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

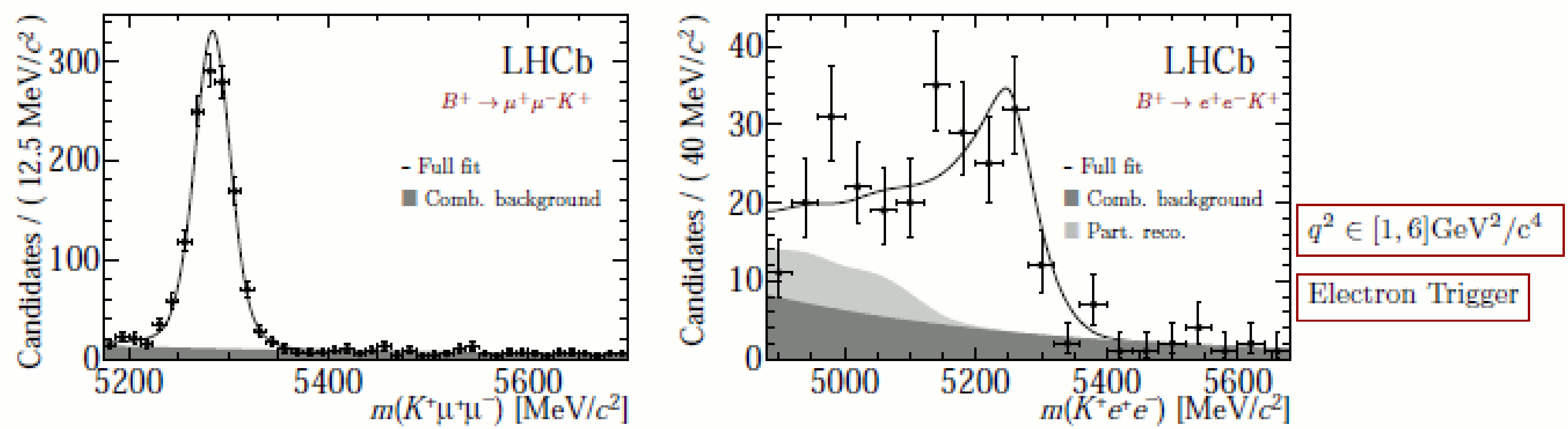
- SM prediction is $R_K = 1$ with an uncertainty of $O(10^{-3})$

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



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

[arXiv:1406.6482]



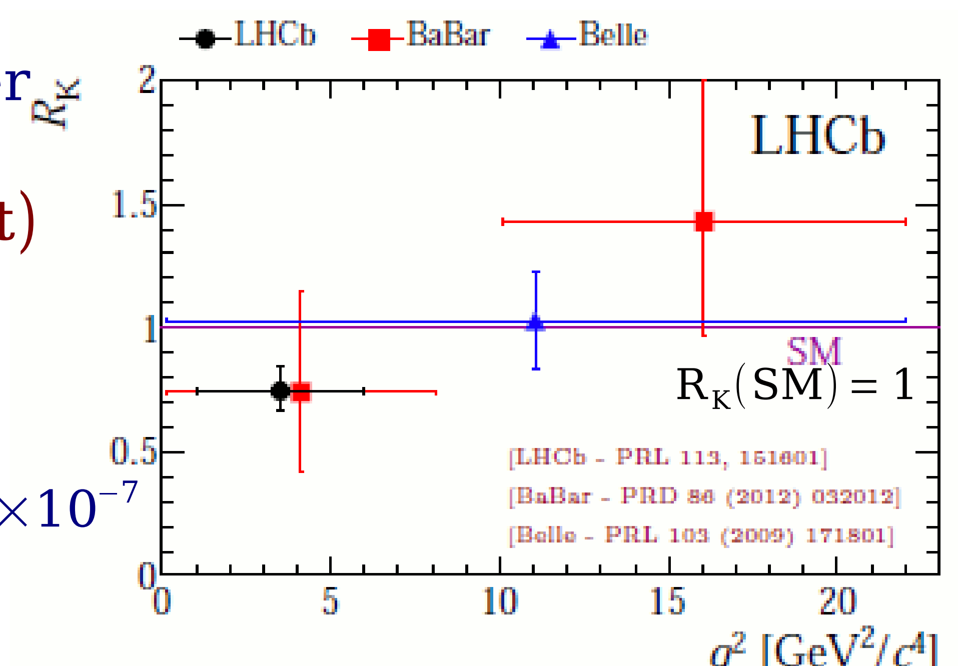
R_K: ratio of branching fractions for dilepton invariant mass squared range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

- 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, disagreement with SM at 2.6σ level

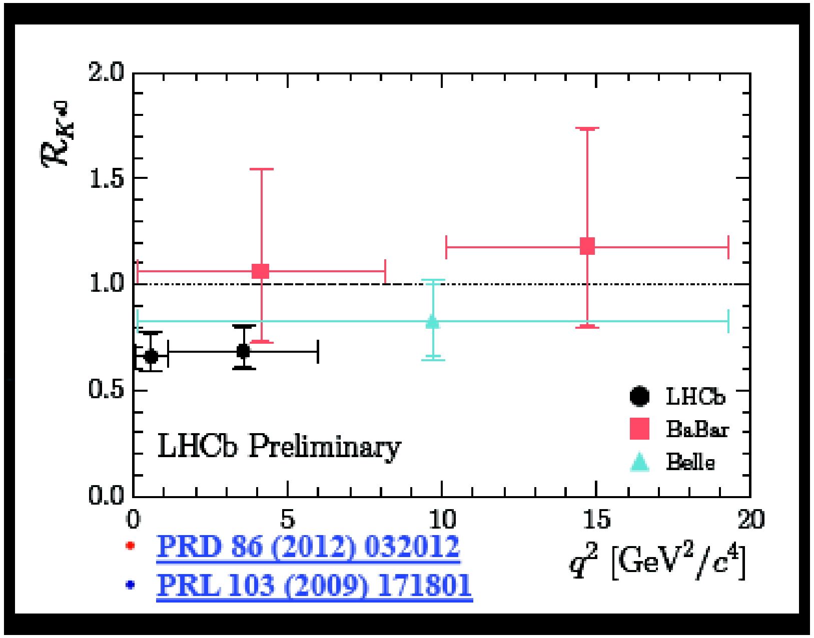
$\Rightarrow$ $B(B^+ \to e^+e^-K^+) = (1.56\,^{+0.19}_{-0.15}(\mathrm{stat})\,^{+0.06}_{-0.05}(\mathrm{syst})) \times 10^{-7}$ compatible with SM predictions

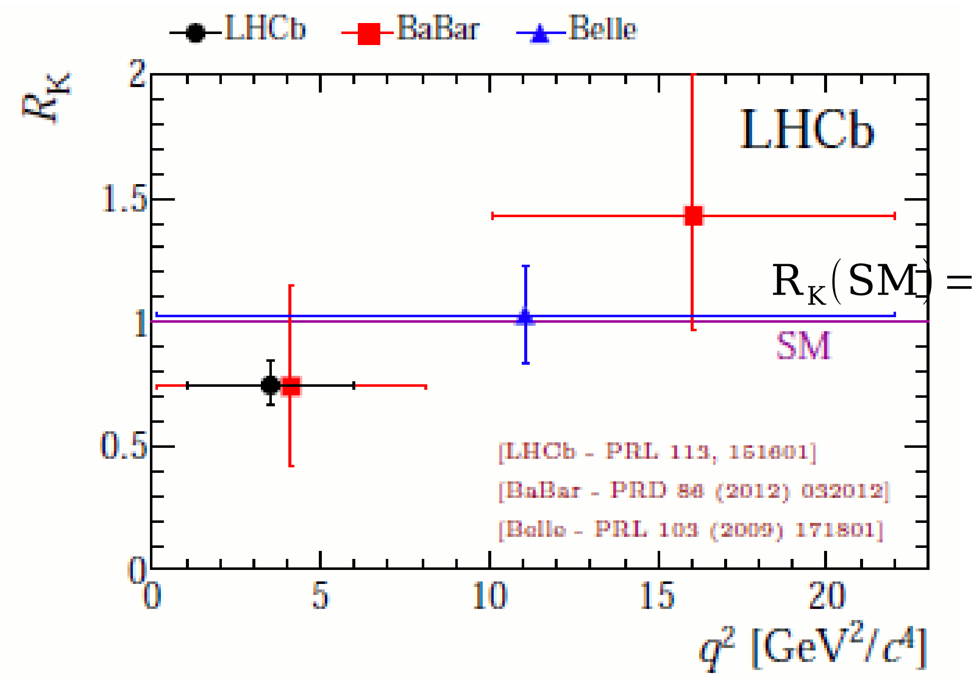


BSM LFNU and effect is in $\mu\mu$, not ee

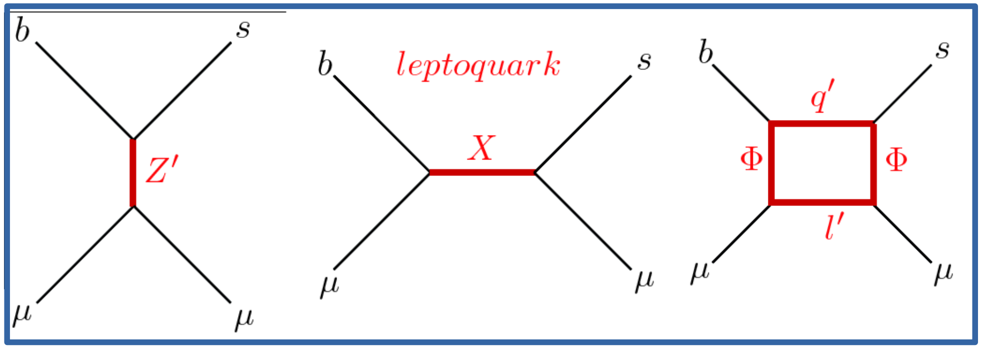
Looking forward for the coming measurement of R_{K^*} from LHCb!!

Test of lepton universality using $B^+ \to K^{(*)} l^+ l^-$ decays





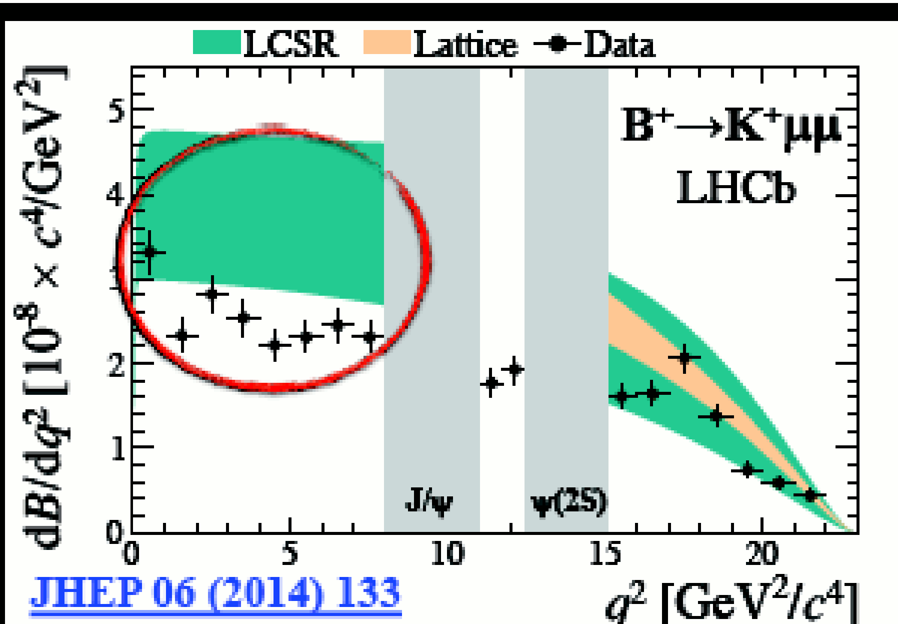
Model candidates

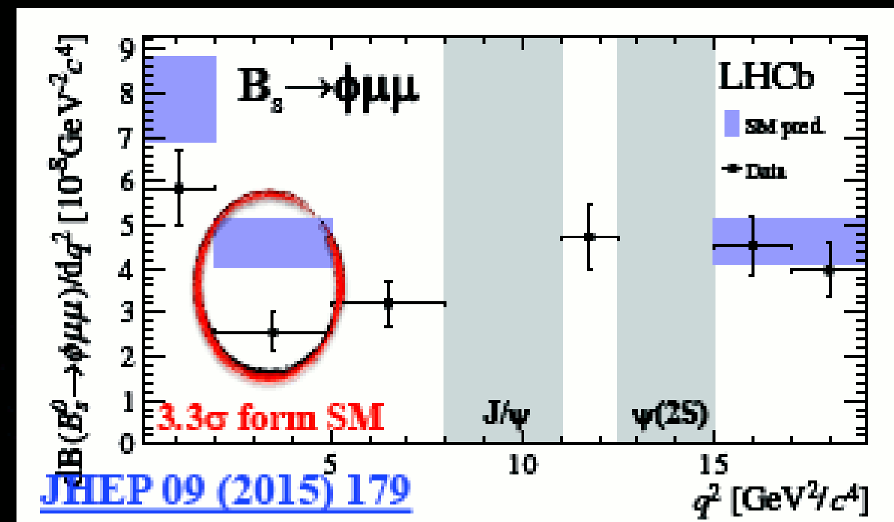


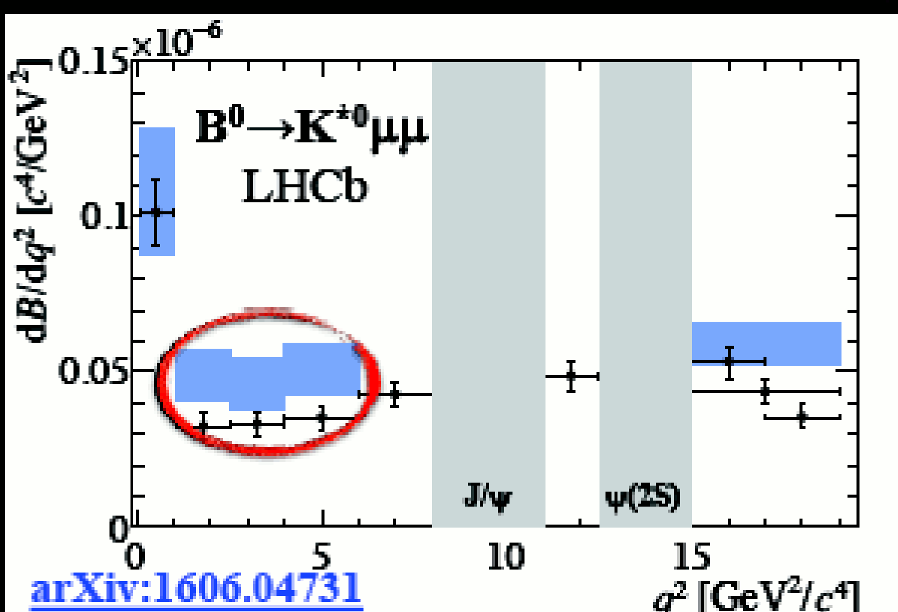
- ✧ **Model with extended gauge symmetry**
  - ✓ Effective operator from Z' exchange
  - ✓ Extra U(1) symmetry with flavor dependent charge
- ✧ **Models with leptoquarks**
  - ✓ Effective operator from LQ exchange
  - ✓ Yukawa interaction with LQs provide flavor violation
- ✧ **Models with loop induced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

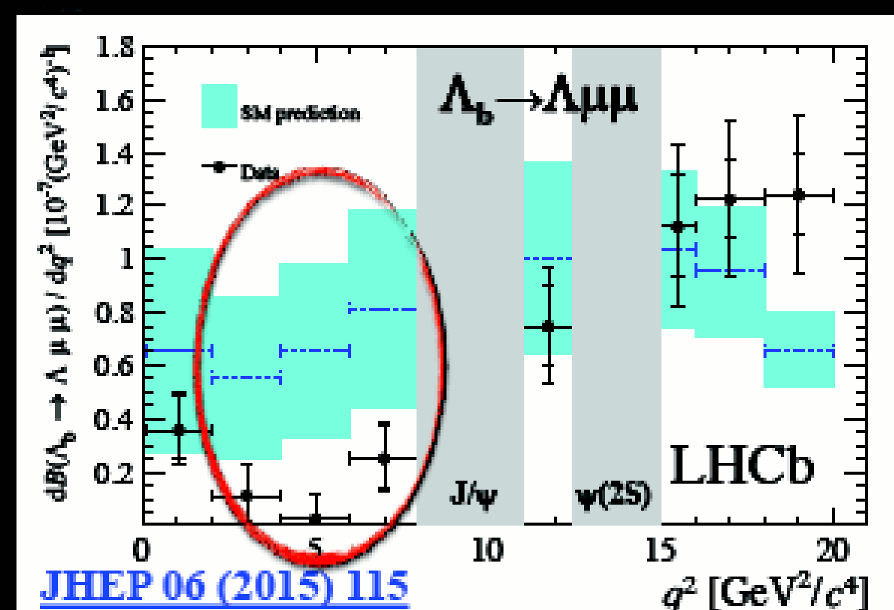
Differential Branching Fractions

Results consistently lower than SM predictions



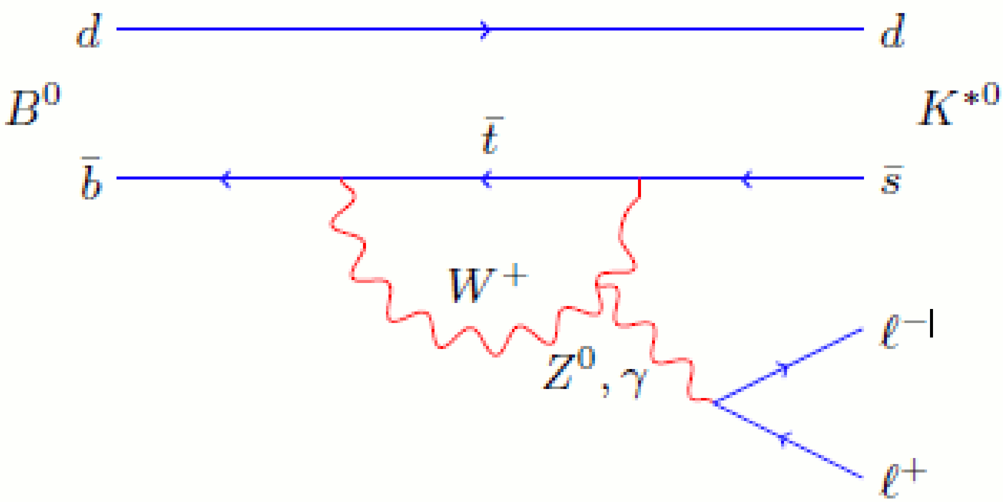


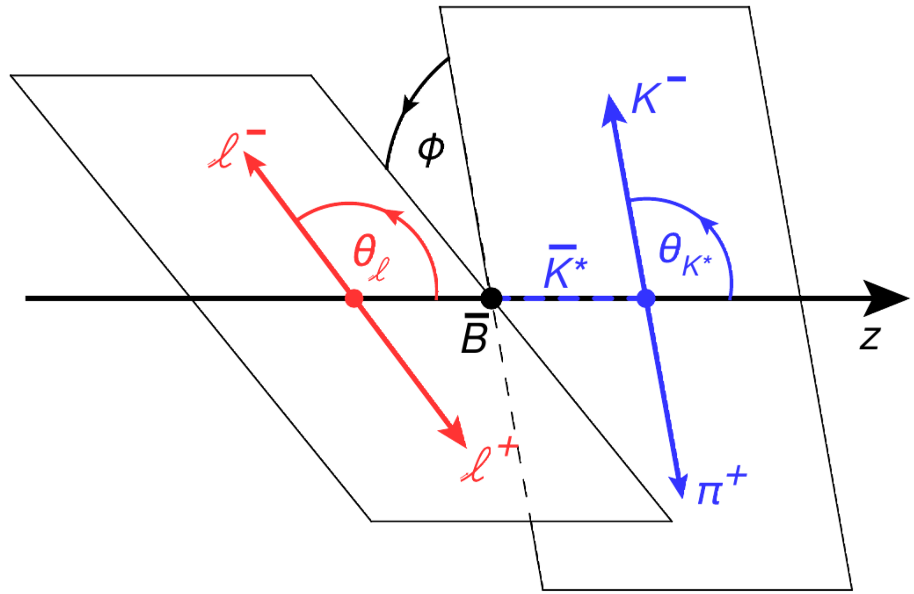




Angular analysis of $B_d^0 \to K^* l^+ l^-$ decays

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



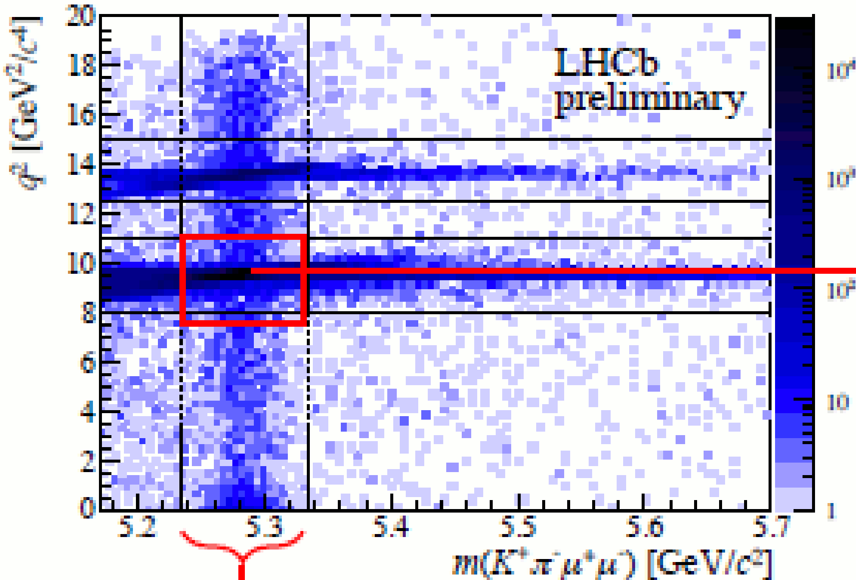


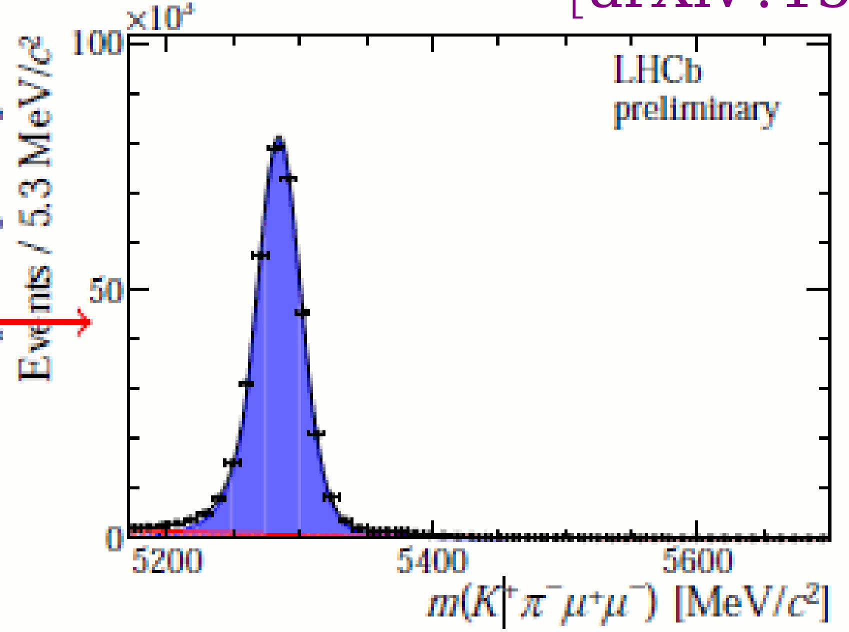
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos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

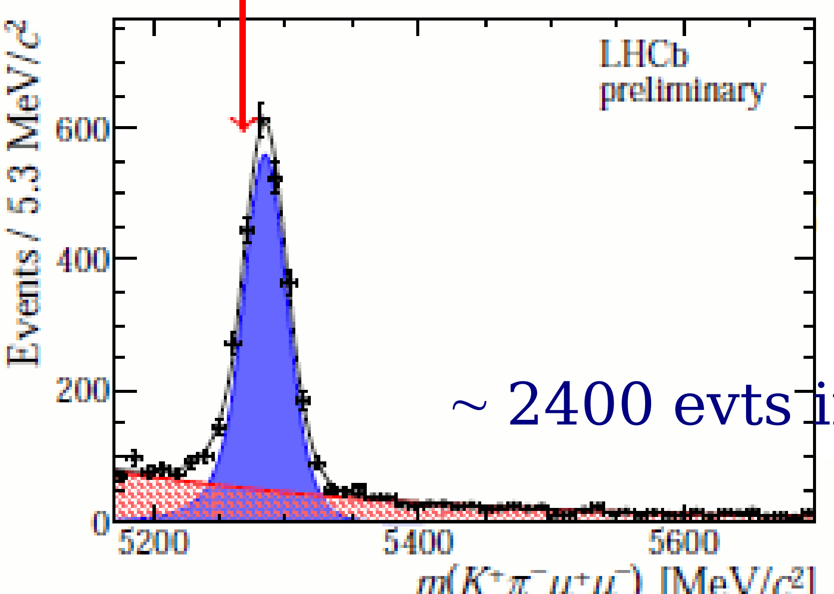
- F_L, A_{FB}, S_i sensitive to $C_7^{(')}$, $C_9^{(')}$, $C_{10}^{(')}$

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

- Channel: $B \to K^{*0} (\to K^+ \pi^-) \mu\mu$ [arXiv:1512.04442]







Selection:

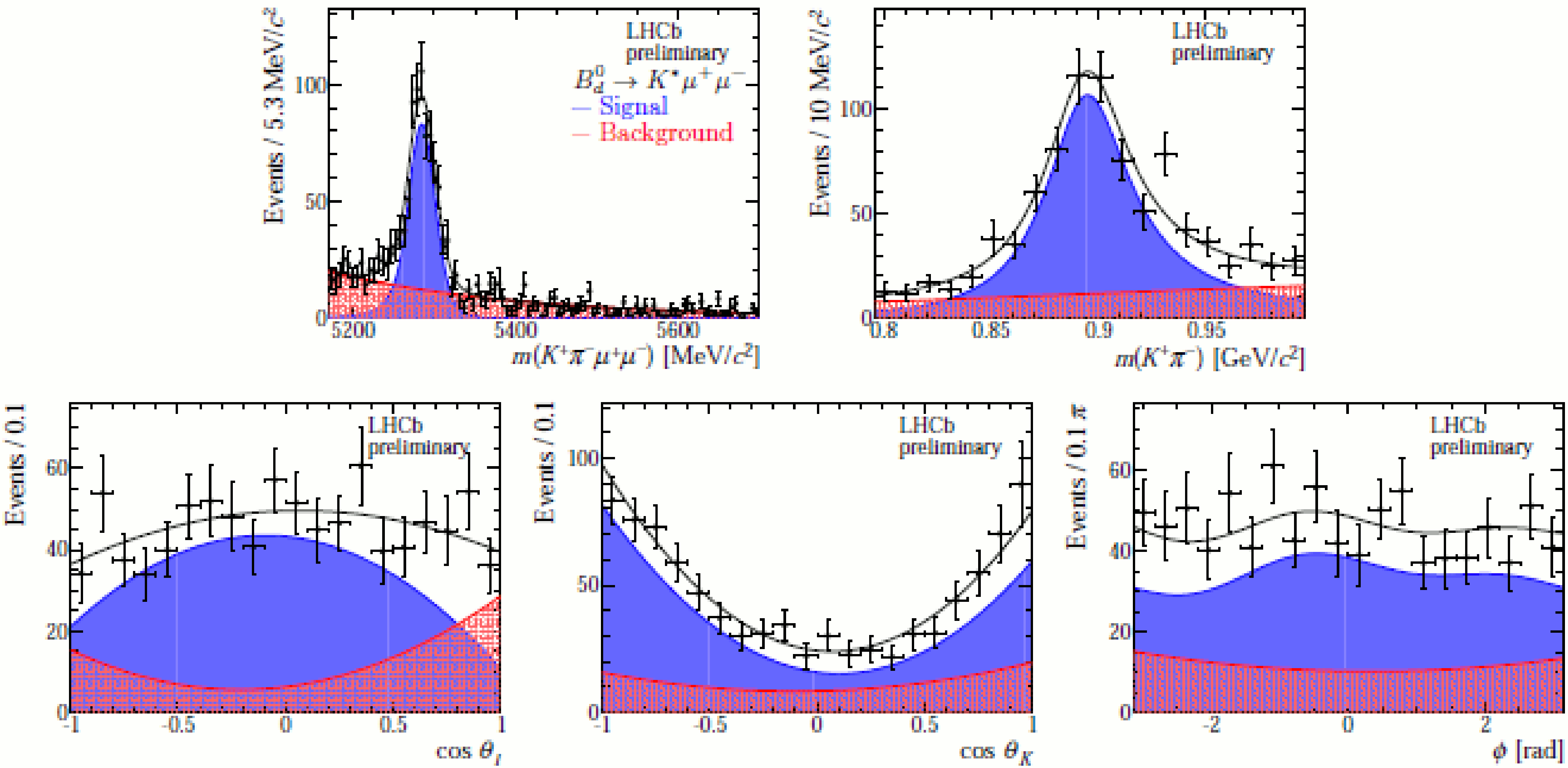
BDT to reject combinatorial background
Veto of resonant modes (control modes)

~ 2400 evts in the full q^2 range

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

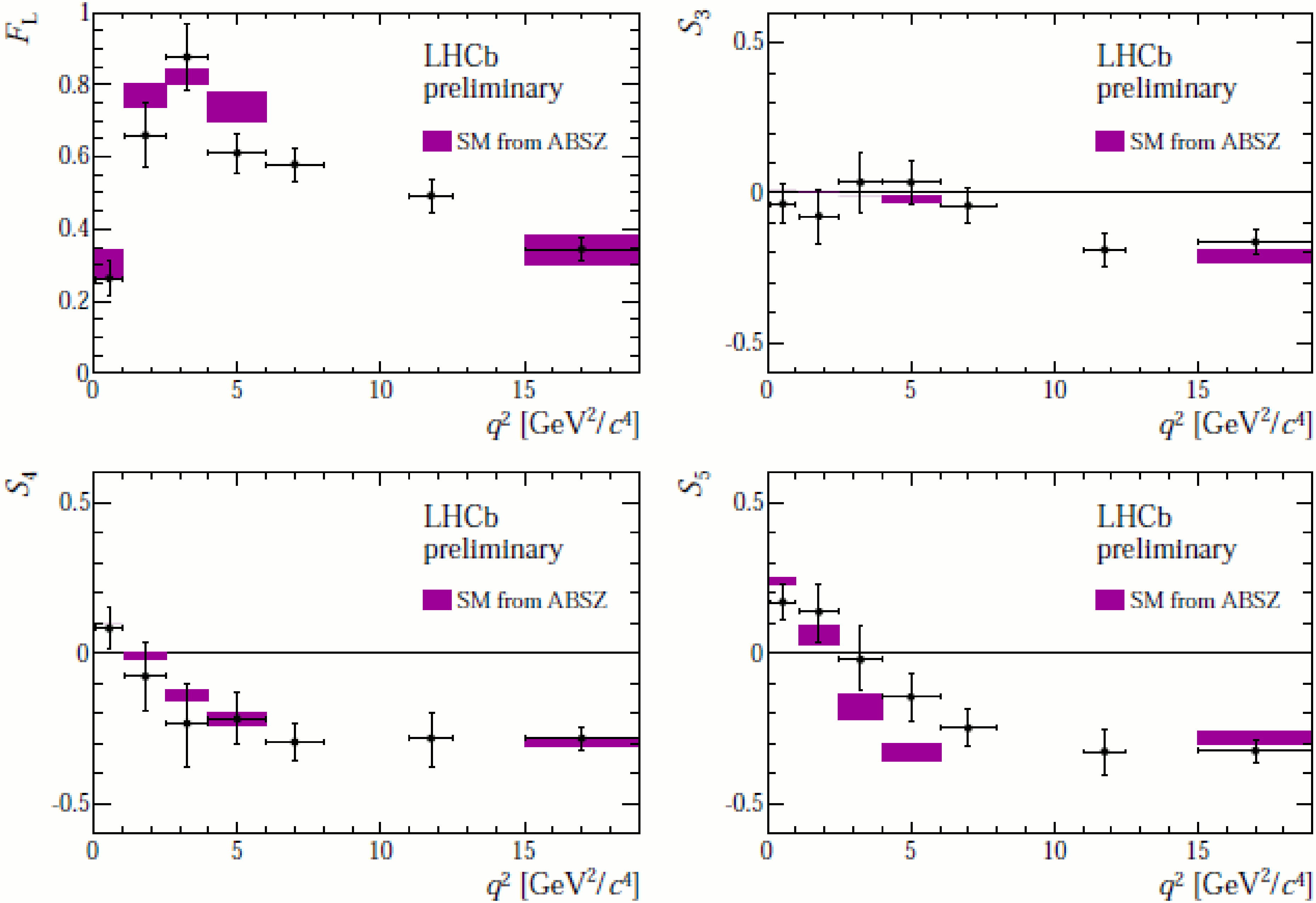
[arXiv:1512.04442]

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



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

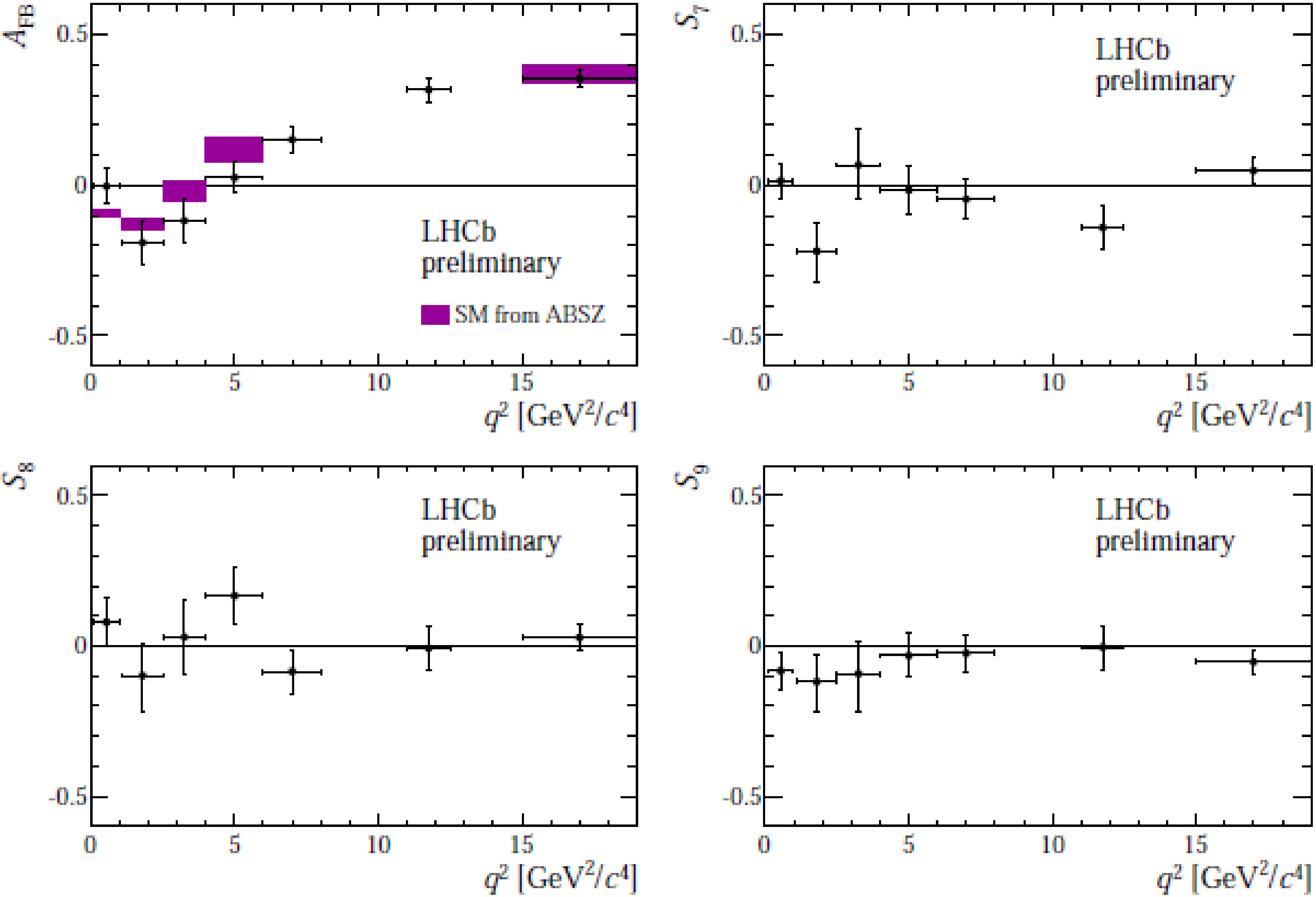
[arXiv:1512.04442]



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

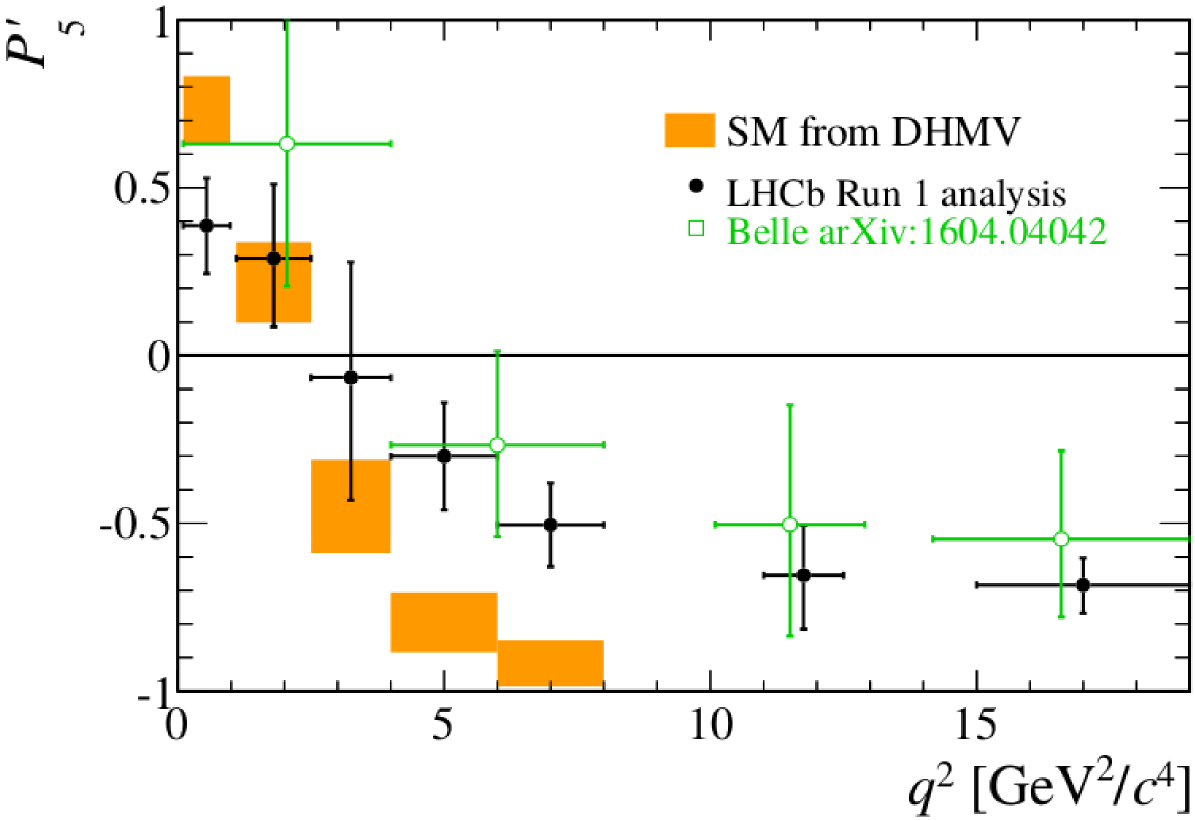
data points systematically lower than SM

[arXiv:1512.04442]



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

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

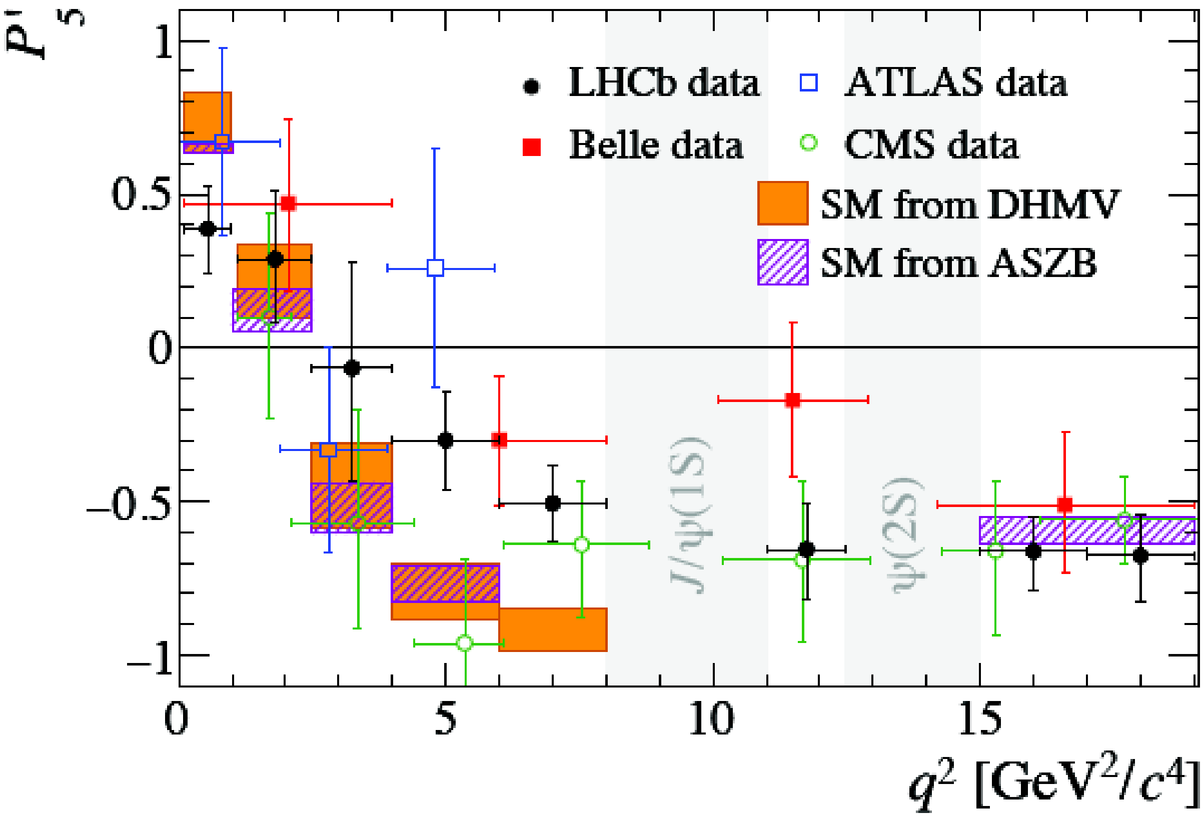


[LHCb, arXiv:1512.04442]

- Tension in P'_5 seen with 1 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

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 $1\,\mathrm{fb}^{-1}$ 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

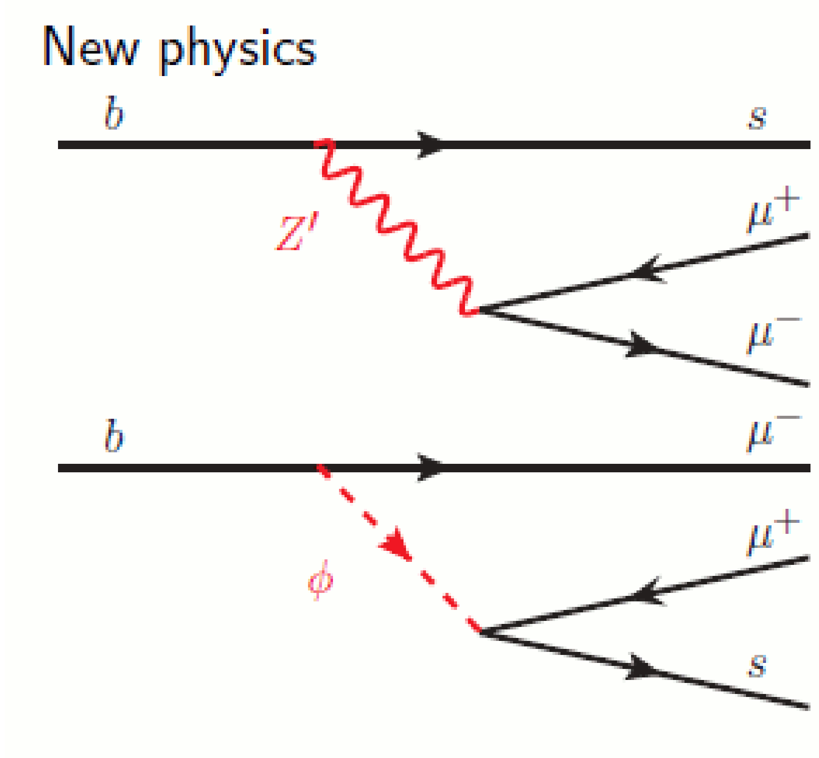
- LHCb, Belle and ATLAS show deviations in $4 < q^2 < 8$ GeV^2/c^4
- CMS shows better agreement

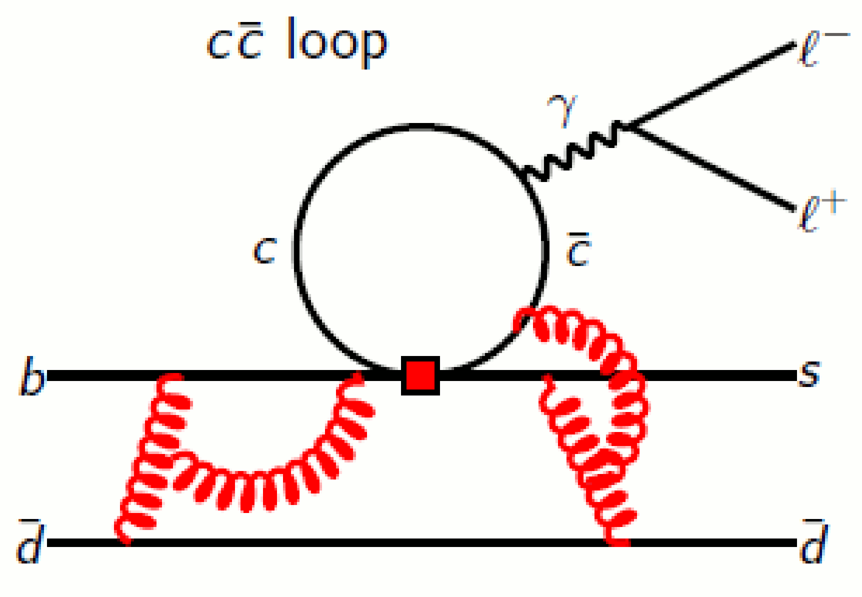
NP or hadronic effect ?

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**

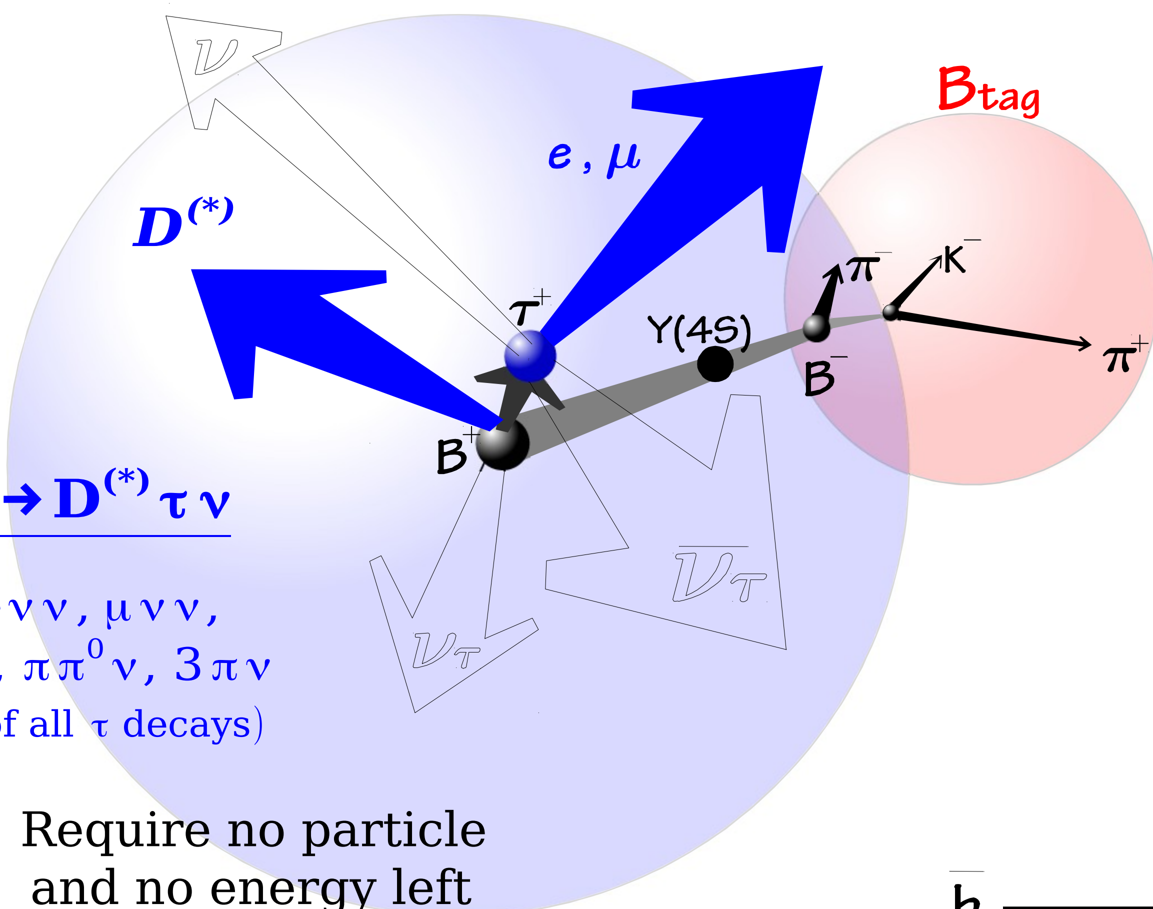




NP e.g. Z', leptoquarks

hadronic charm loop contributions

Event reconstruction in $B \to D^{(*)} \tau \nu$ at B factories



B_{tag}

hadronic tag

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

$\epsilon \sim 0.2\%$

semileptonic tag

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

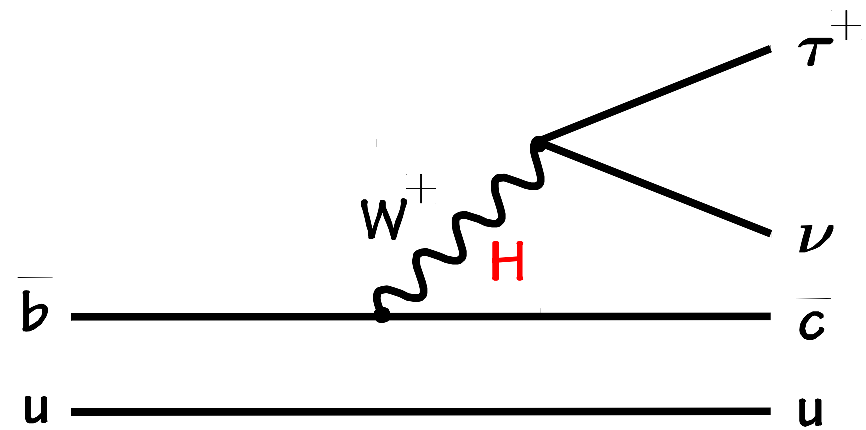
$B_{sig} \to D^{(*)} \tau \nu$

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

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

(70 % of all τ decays)

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



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

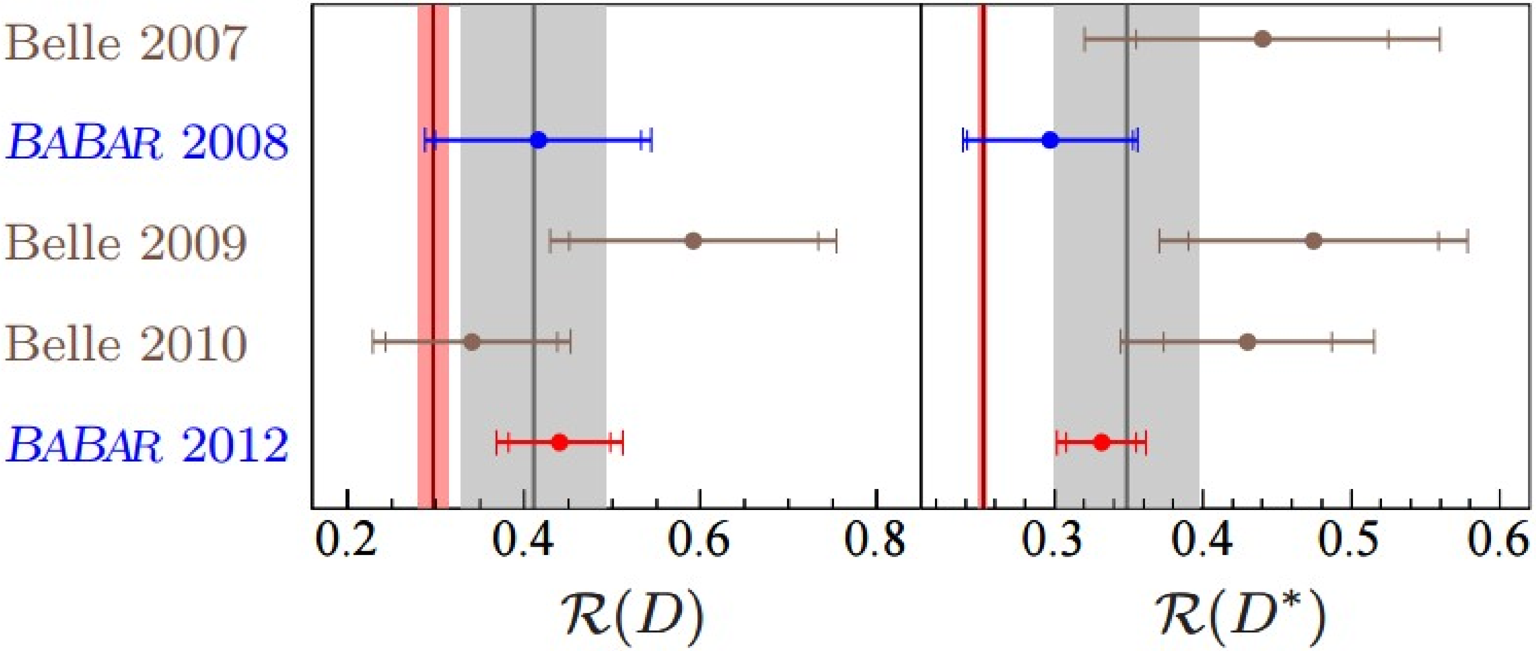
uncertainties from form factors F_V and F_S can be studied with $B \to D l \nu$ (more form factors in $B \to D^* \tau \nu$)

Situation pre-LHCb

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

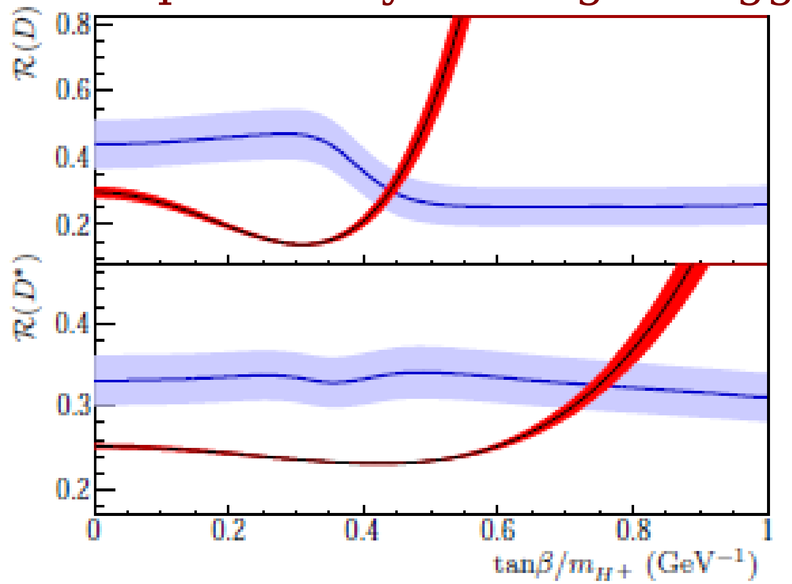
$$R(D^{(*)}) = \frac{B \to D^{(*)} \tau \nu}{B \to D^{(*)} l \nu}$$

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 ''

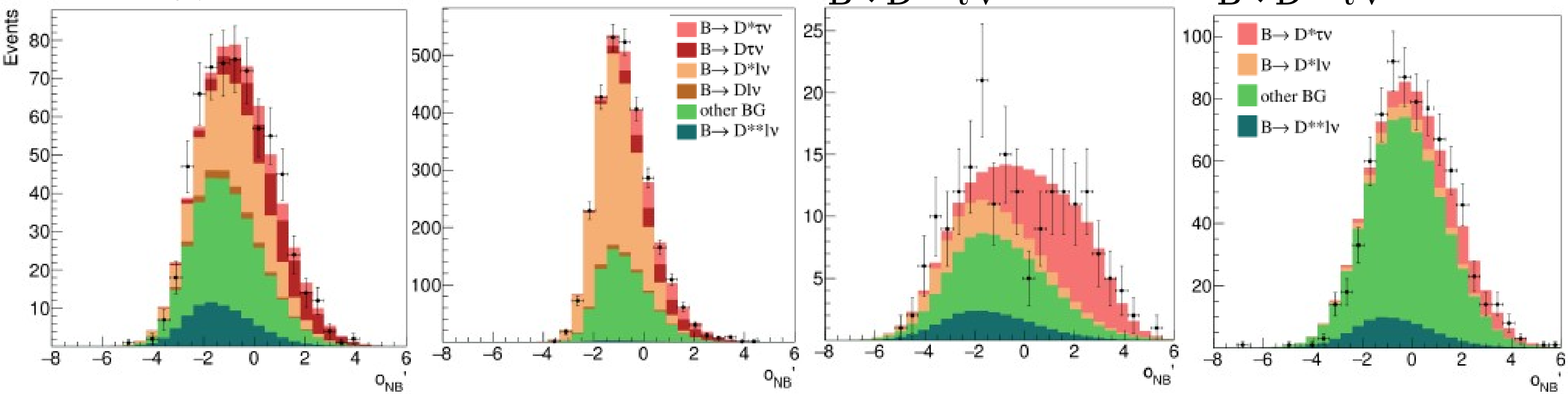


$B \to D^{(*)} \tau \nu$ at Belle

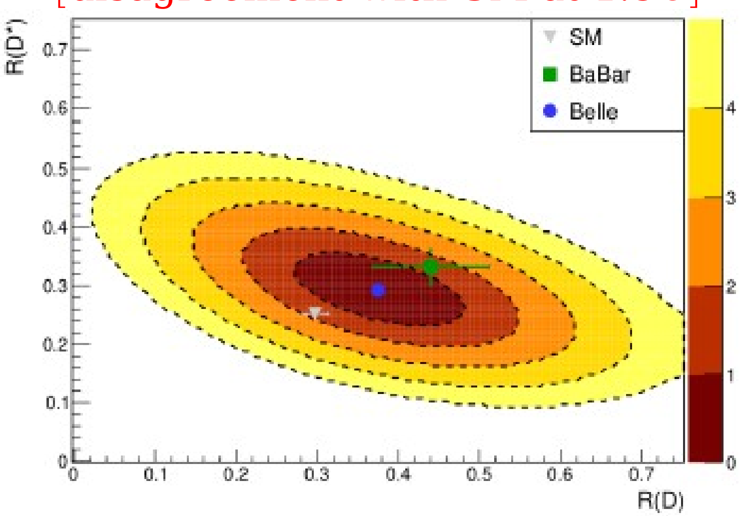
[arXiv:1507.03233]

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

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



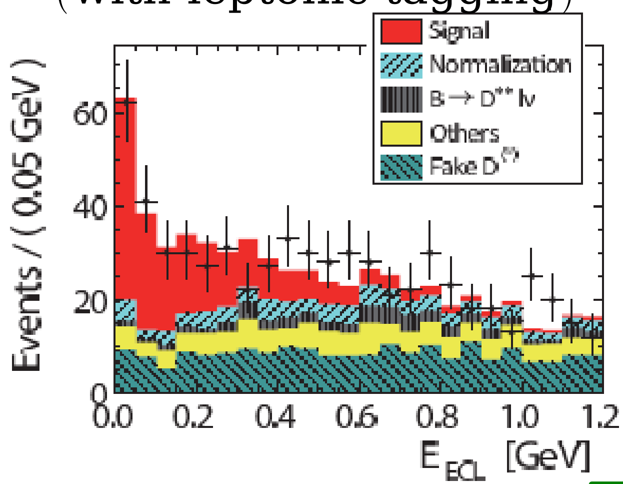
[disagreement with SM at 1.5σ]

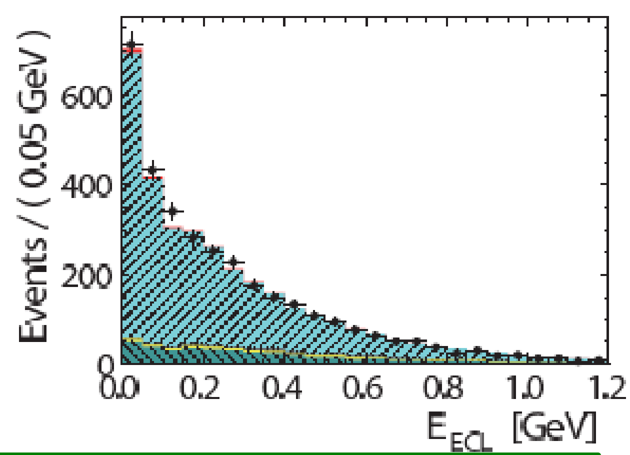


$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

(with leptonic tagging)

[arXiv:1607.07923]





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

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

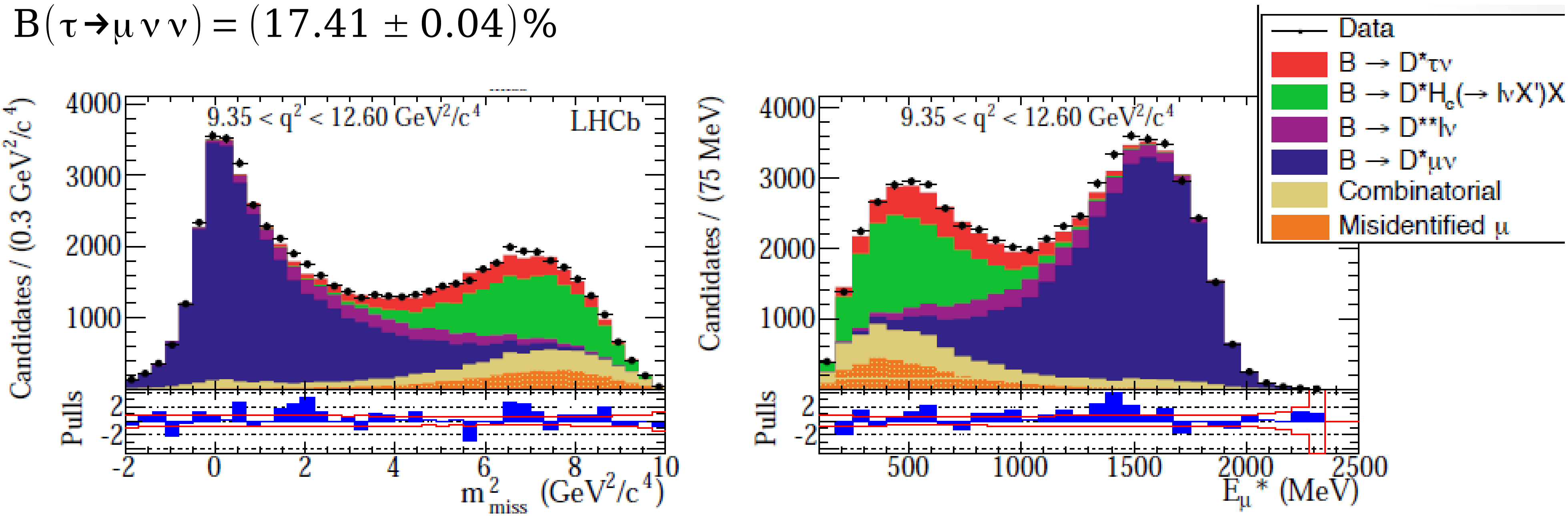
[arXiv:1506.08614]

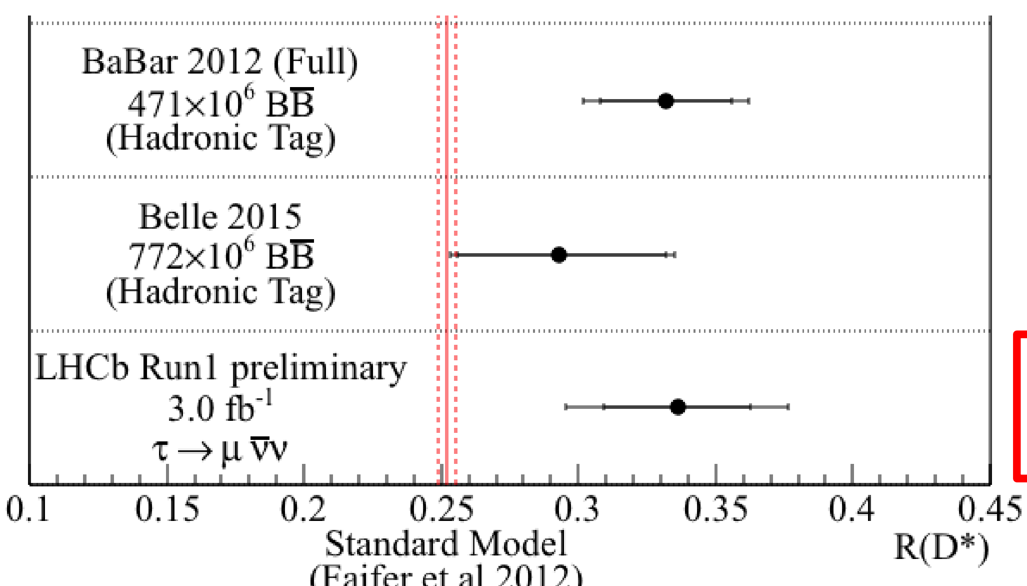
$$R(D^*) \equiv \frac{\mathcal{B}\left(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\bar{\nu}_\mu\nu_\tau)\bar{\nu}_\tau\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu\right)}$$

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

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

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





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

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

[Belle, arXiv:1507.03233]

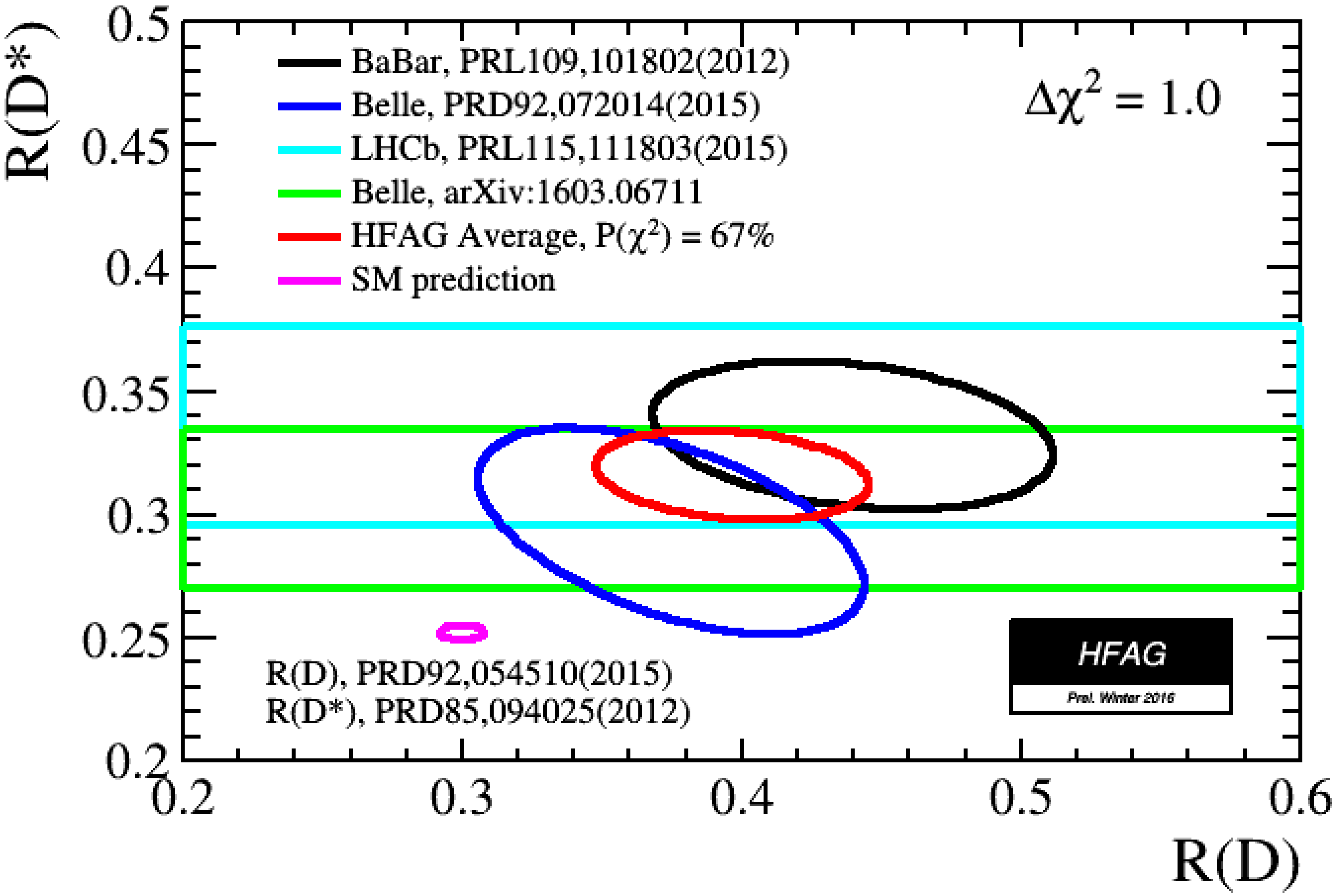
$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

[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

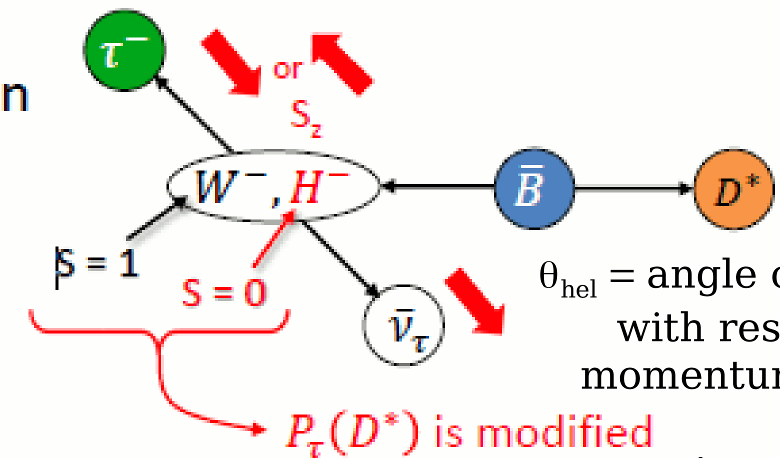
New result using:
- hadronic decays of $\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$
- hadronic tagging

$\tau^- \to \pi^- \nu_\tau, \rho^- \nu_\tau$ 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)

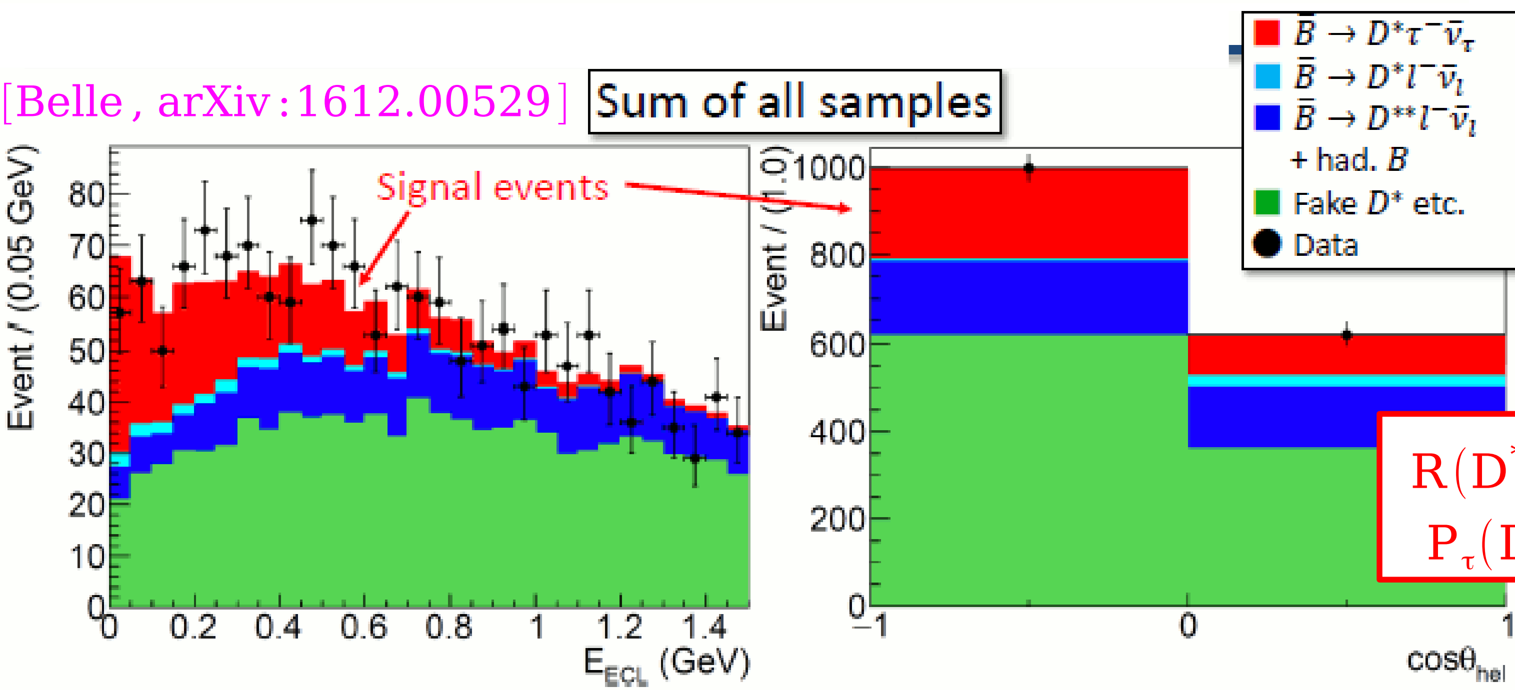


θ_{hel} = angle of τ daughter meson momentum with respect to direction opposite to momentum of $\tau\nu$ system in τ rest frame

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

τ polarization is a variable sensitive to NP

[Belle, arXiv:1612.00529]



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

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

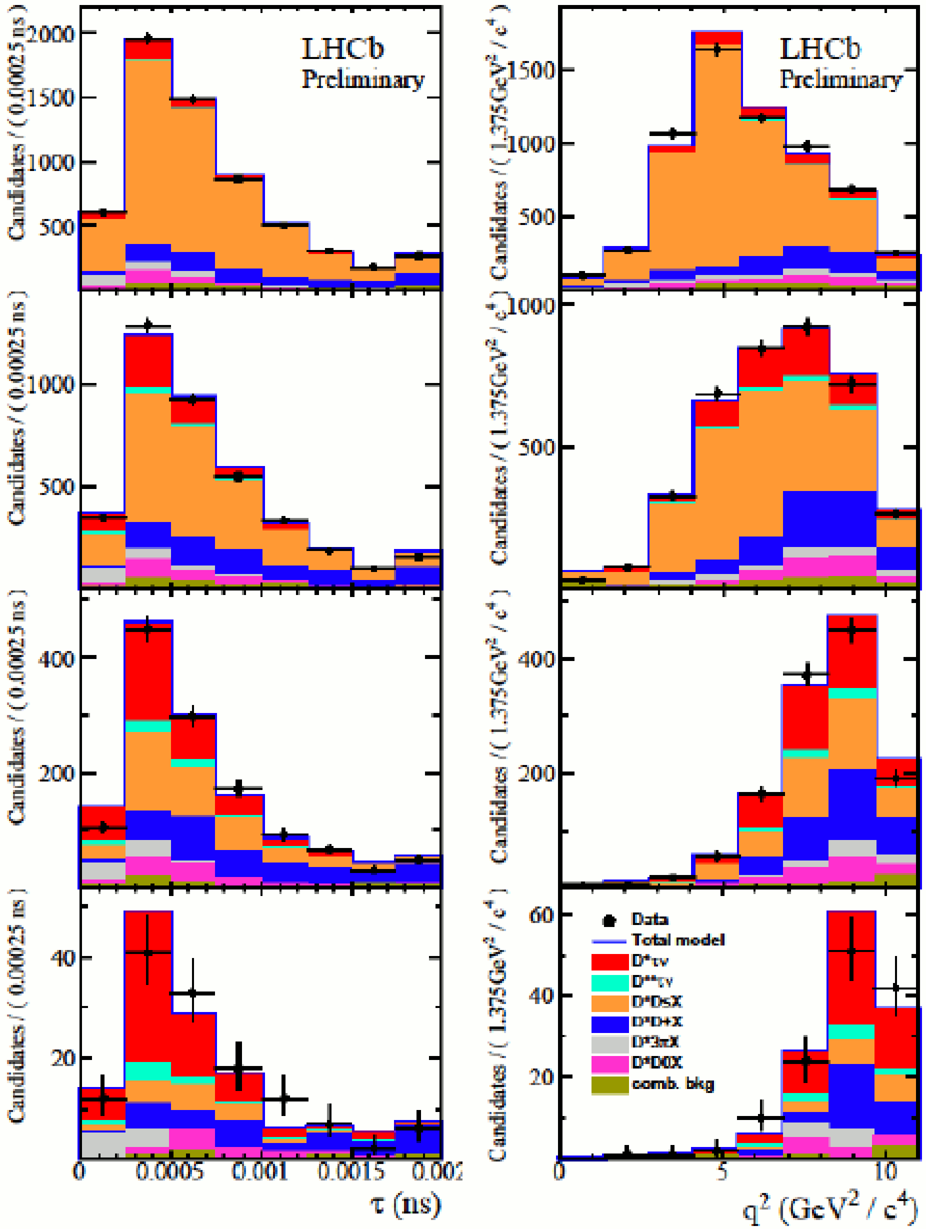
$\tau \to 3\pi(\pi^0)$

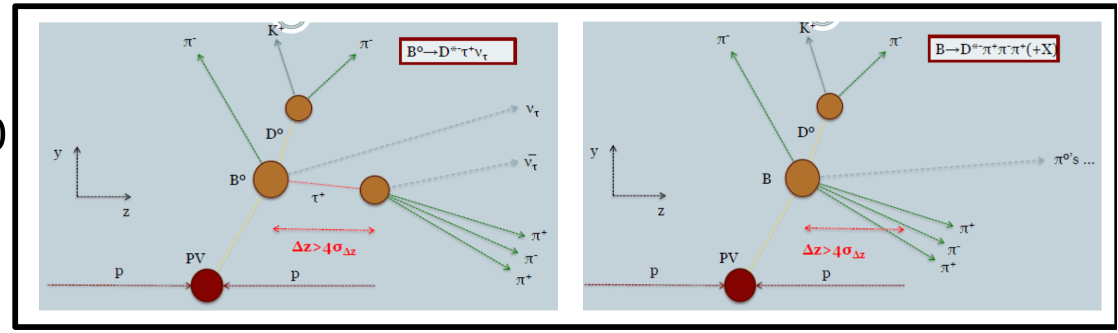
[LHCb-PAPER-2017-017]

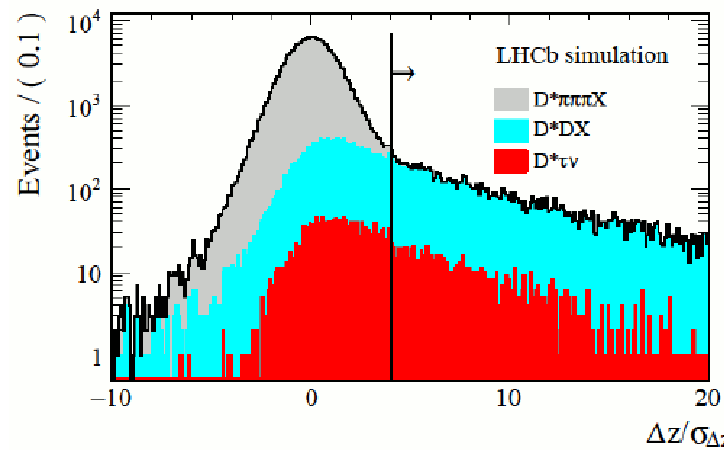
need a strong background suppression:

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

$\Rightarrow$ detached vertex method







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

anti-D_s

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

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

$B \to D D_{s(J)} X$

$X_b \to D D X$

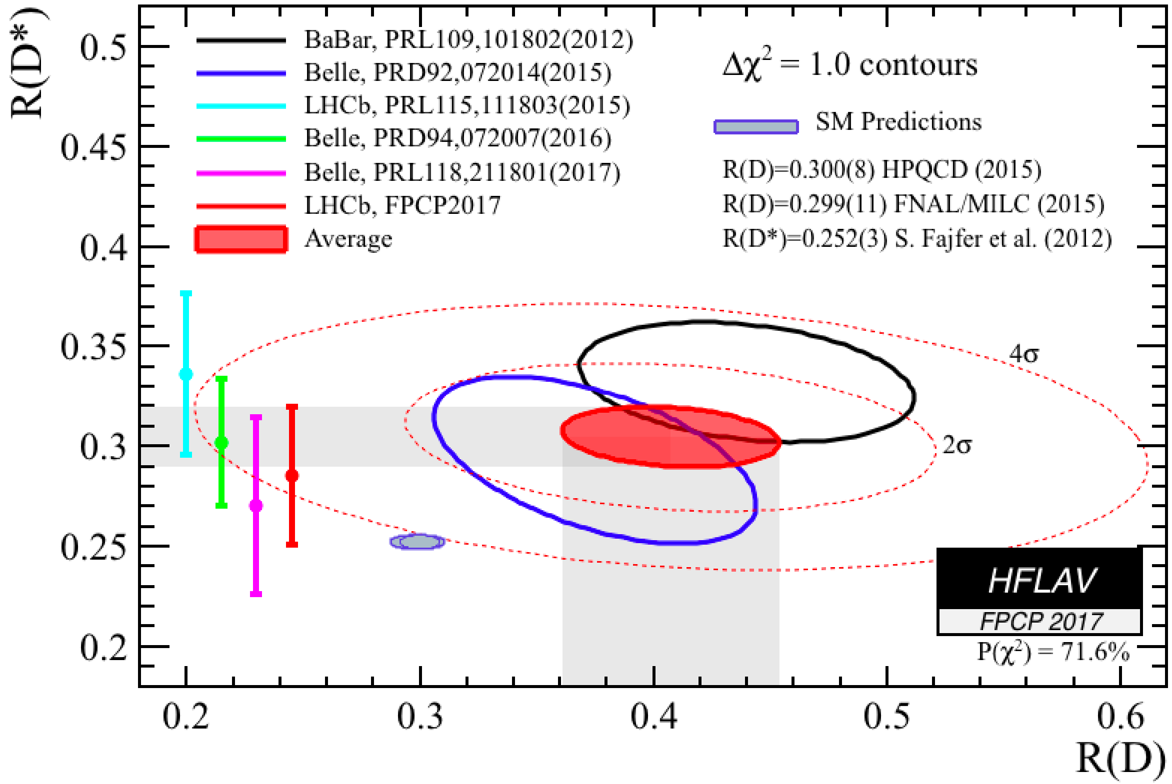
(relative) yields constrained from control samples

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

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

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

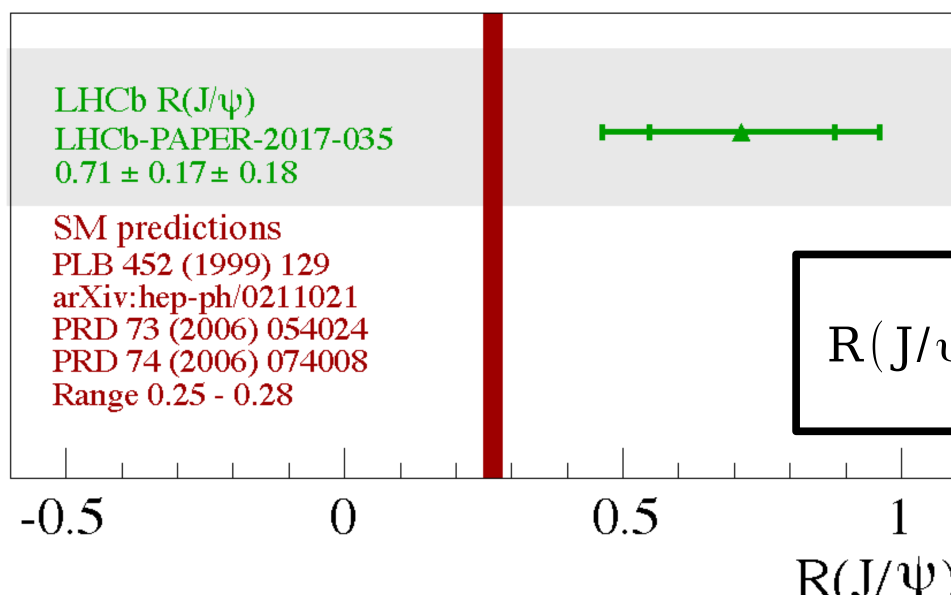
$B \to D^{(*)} \tau \nu$



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

$R(D) = 0.407 \pm 0.039 \pm 0.024$
$R(D^*) = 0.304 \pm 0.013 \pm 0.007$
difference with SM predictions is at **4.1σ** level

$B_c \to J/\psi \tau \nu$



$$R(J/\psi) = \frac{BF(B_c \to J/\psi \tau \nu_\tau)}{BF(B_c \to J/\psi l \nu_l)}$$

Summary

- Using the full Run 1 data set the $R_{K^{*0}}$ ratio has been measured by LHCb with the best precision to date in two q^2 bins
- The compatibility of the result with respect to the SM prediction(s) is of 2.2-2.5 standard deviations in each q^2 bin
- The result is particularly interesting given a similar behaviour in R_K
- Rare decays will largely benefit from the increase of energy (cross-section) and collected data (~5 fb^{-1} expected in LHCb) in Run2
- LHCb has a wide programme of LU tests based on similar ratios
- Unexpectedly provide some of the most precise results for $B \to D^* \tau \nu$
- Many improvements and new results to come..

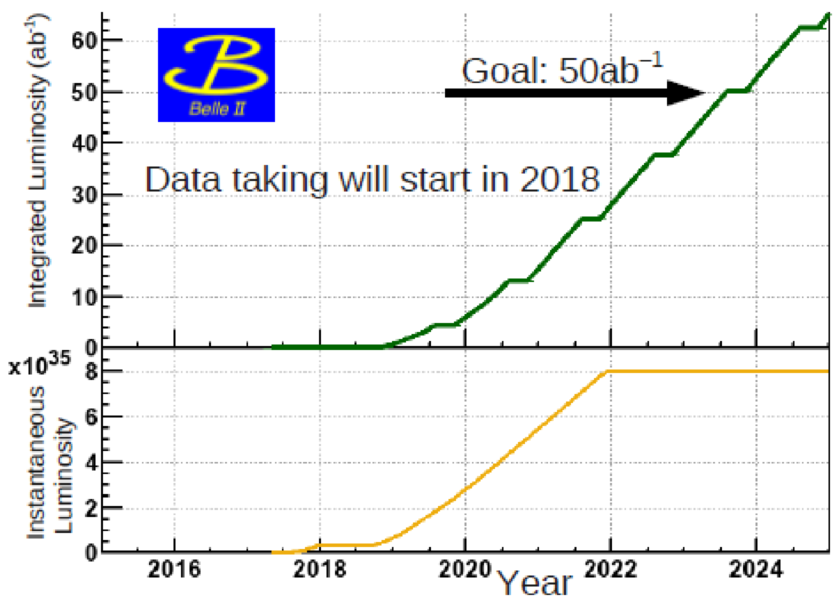
Outlook

- 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…

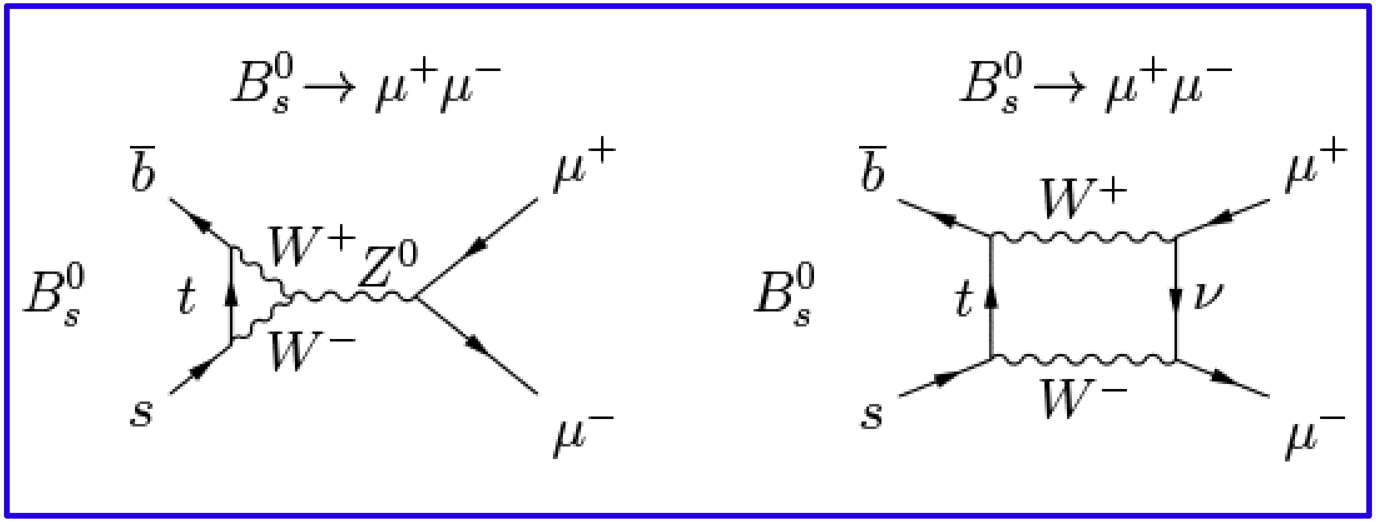
- Definitely not only complementary, but stimulating competition between (super) B-factories and LHCb (upgrade):
  - for the expected: results on $B_{(s)} \to \mu\mu$, $B \to K^* \mu\mu$, $B_s \to J/\psi \phi$, γ angle…
  - for the less expected: results on $|V_{ub}|$, $D^* \tau \nu$…

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}



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

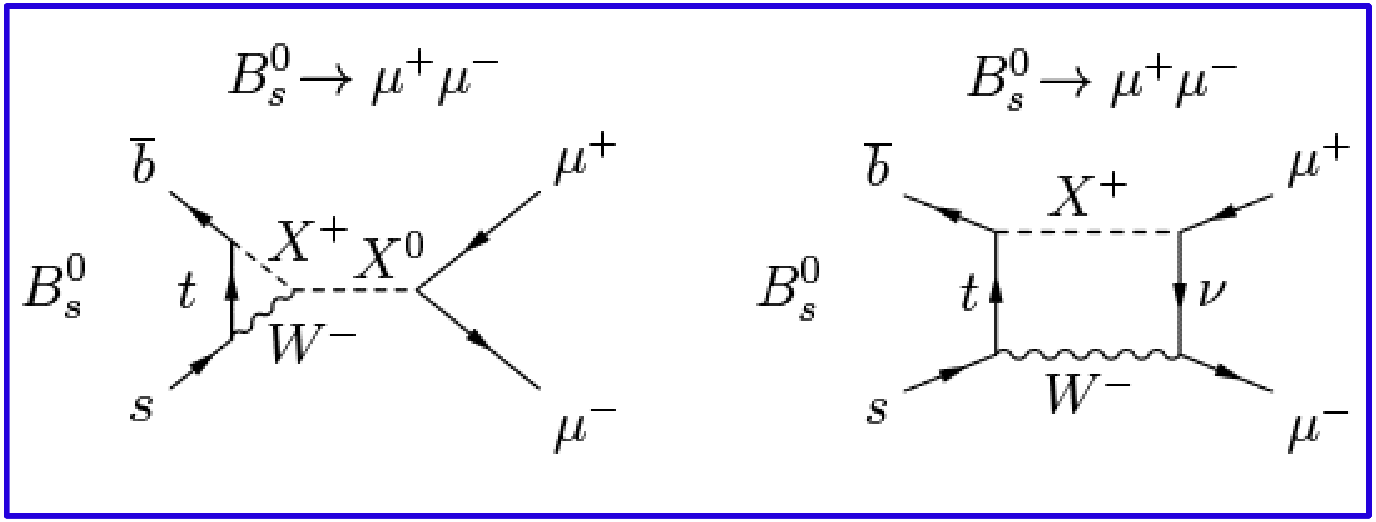
loop diagram + suppressed in SM + theoretically clean =
an excellent place to look for new physics



higher-order FCNC
allowed in SM

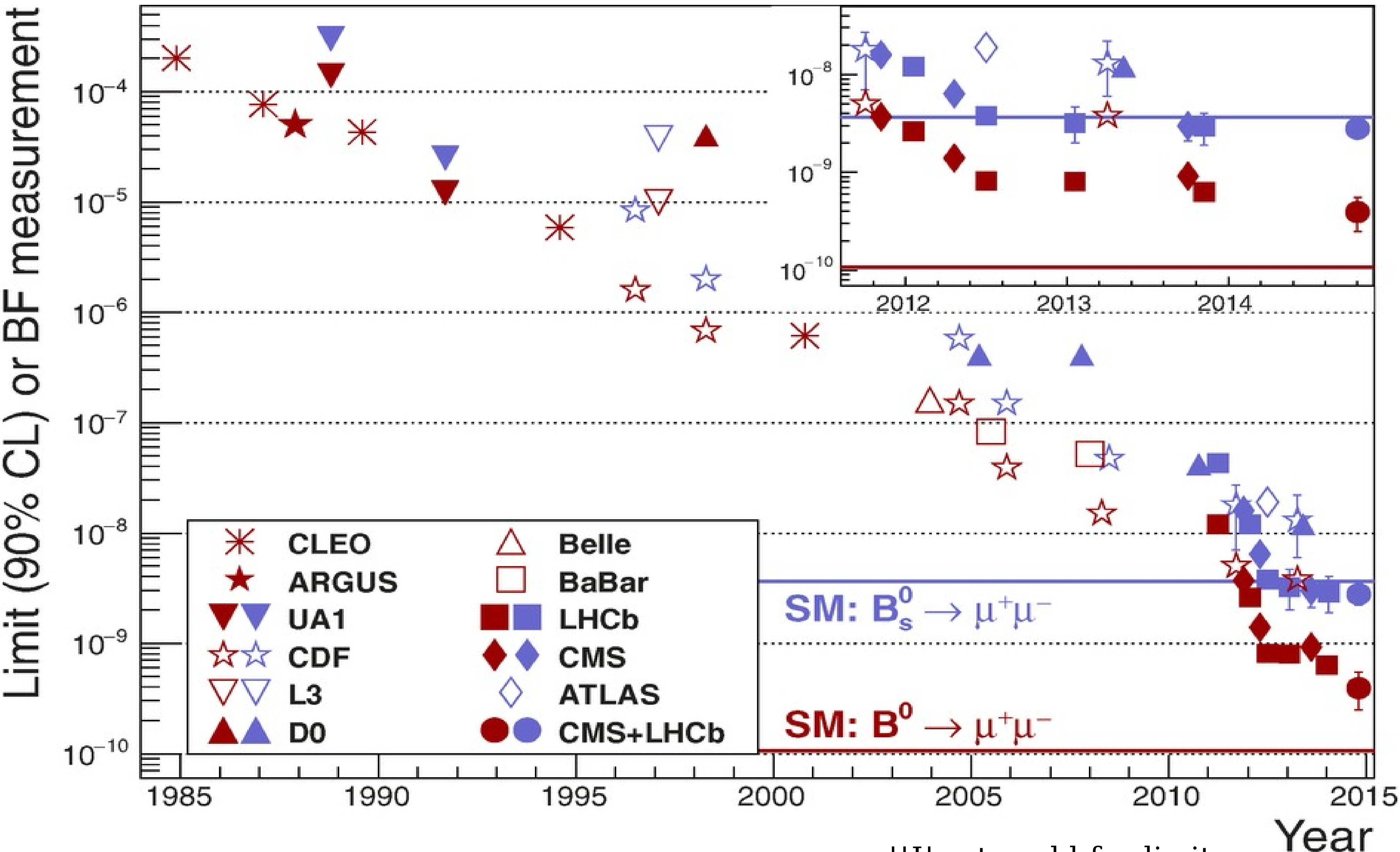
$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

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



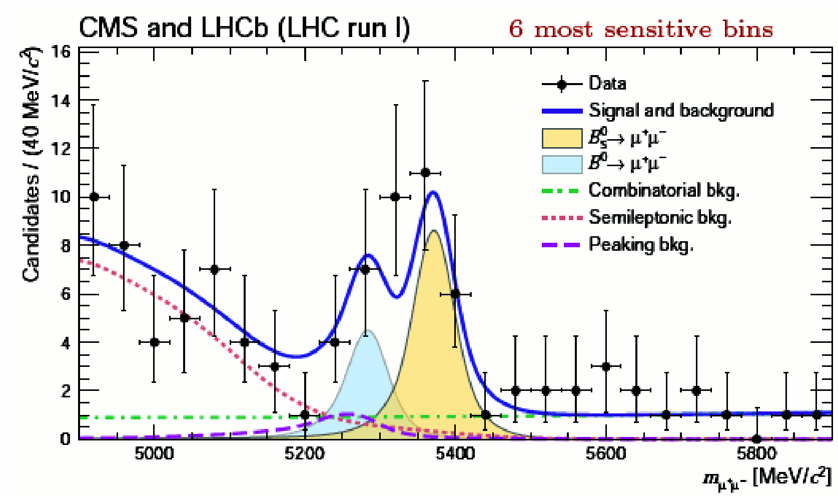
same decay in theories
extending the SM
(some of NP scenarios
may boost the $B \to \mu\mu$
decay rates)

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



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

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



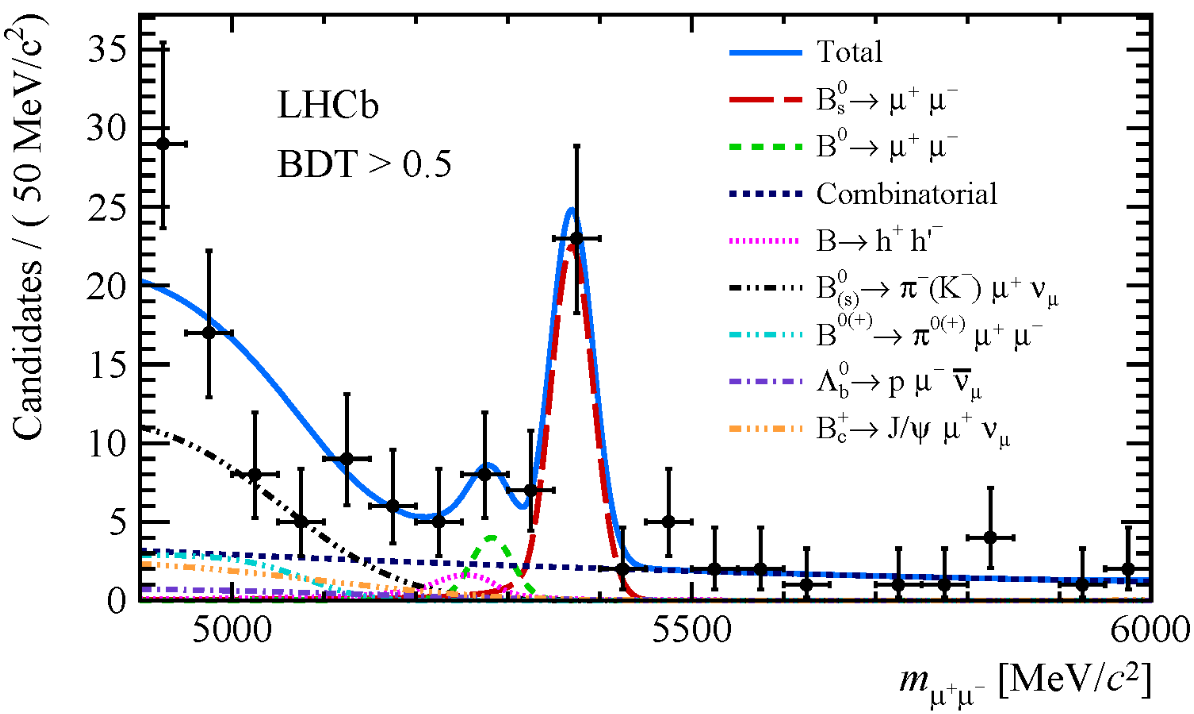
$$B(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

first observation: 6.2σ significance

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

first evidence: 3.0σ significance

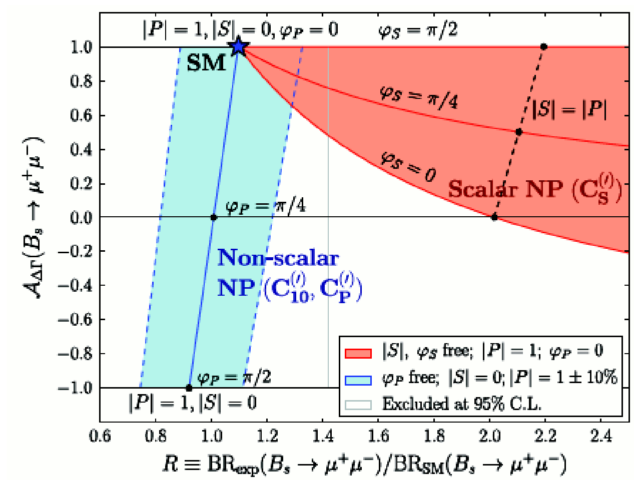
[arXiv:1703.05747]



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)]

$$\mathbf{B(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}\ (7.8\sigma\ significance)}$$

$$\mathbf{B(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}\ @\ 90\%\ CL}$$

Cross-checks

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

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

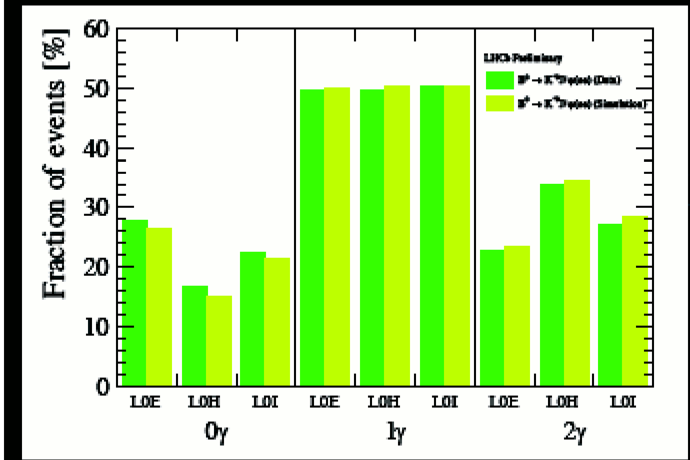
which is expected to be unity and measured to be

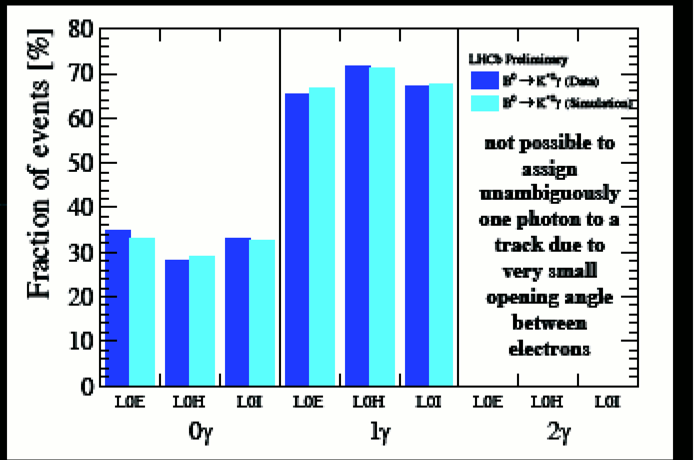
$$1.043 \pm 0.006\,(\mathrm{stat}) \pm 0.045\,(\mathrm{syst})$$

- 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

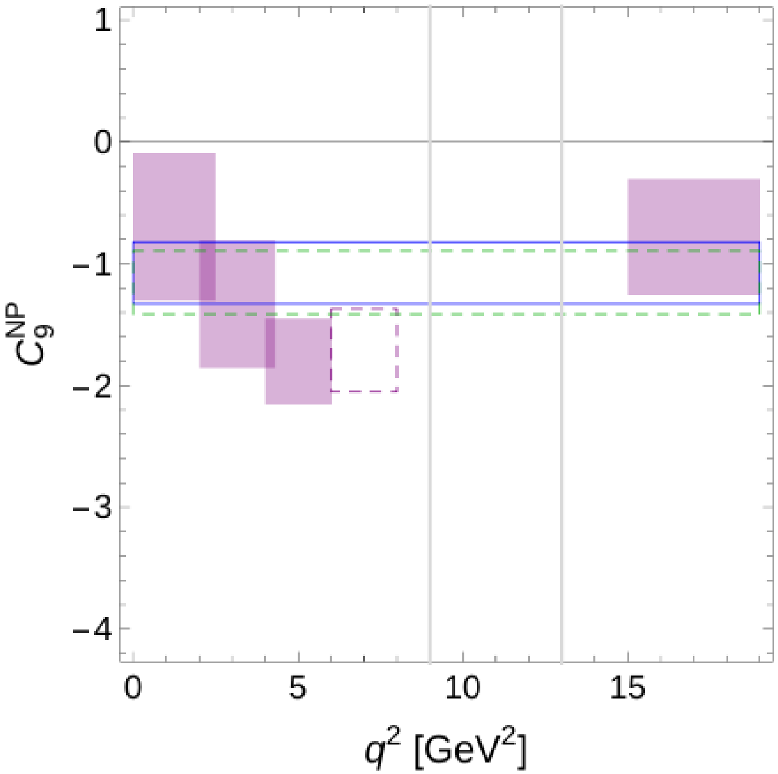




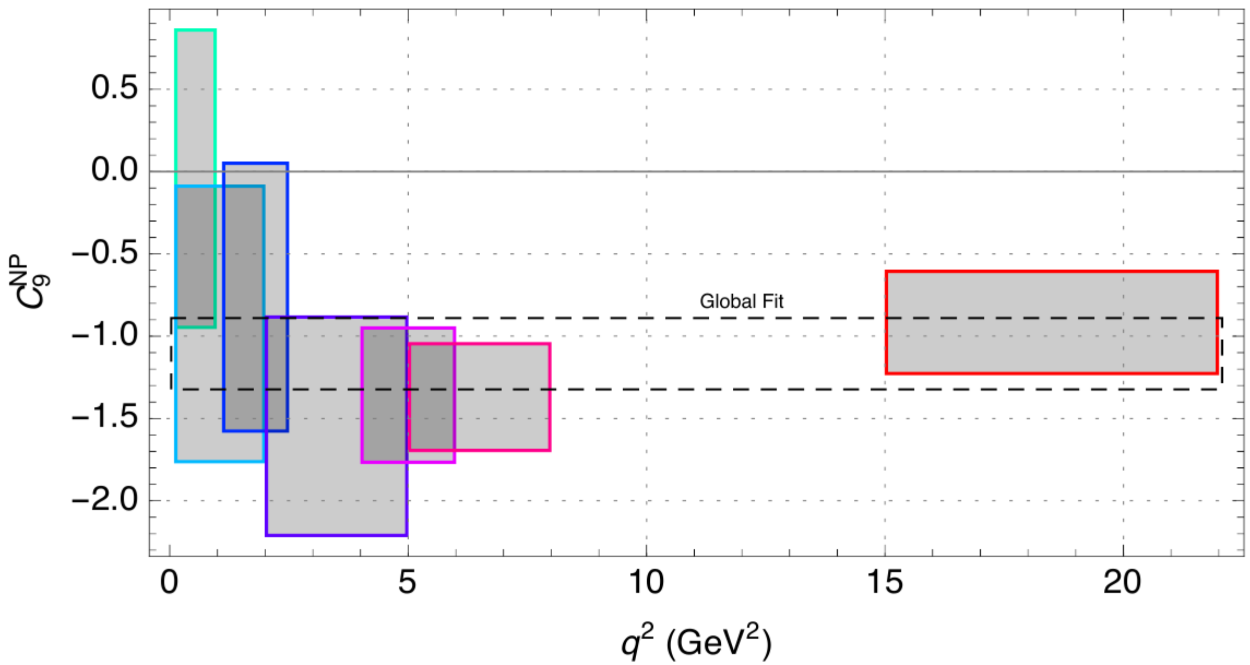
NP or hadronic effect ?

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]



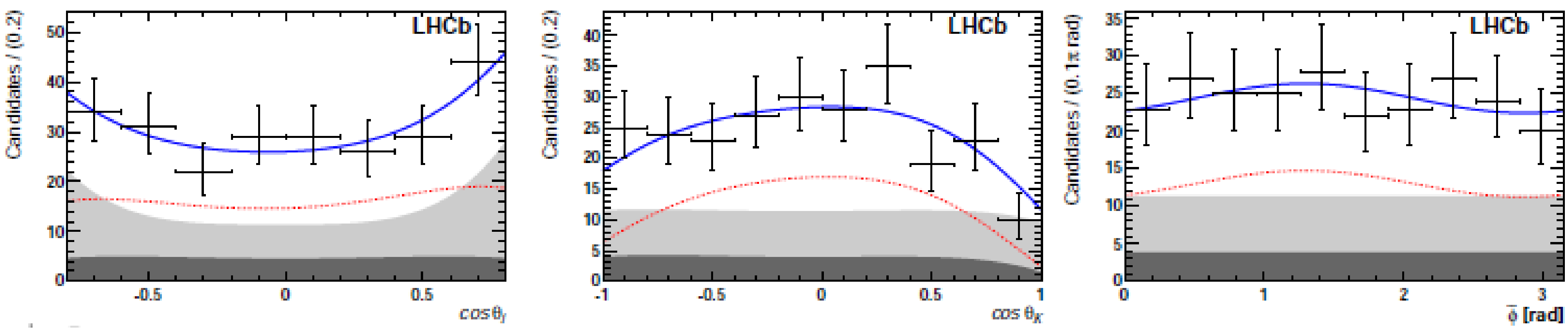
$\mathbf{C_9^{NP}}$ doesn't depend on $\mathbf{q^2}$,

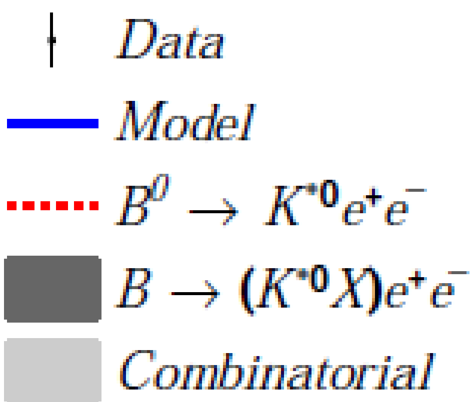
$\mathbf{C_9^{c\bar{c}\,i}(q^2)}$ expected to exhibit a non-trivial $\mathbf{q^2}$ dependence

⇒ definitely need more stat.

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

[arXiv:1501.03038]





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

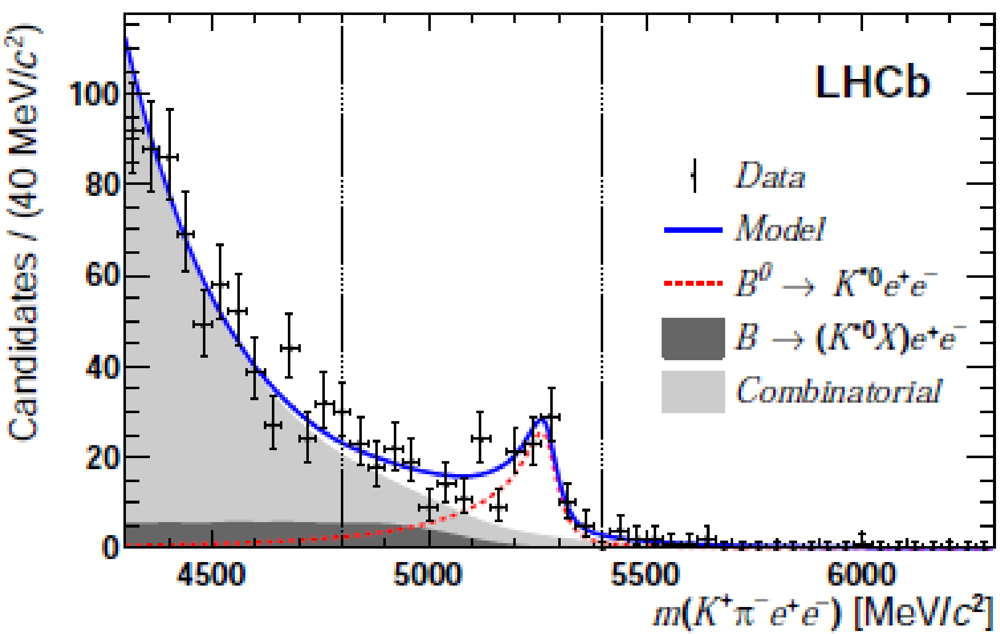
S.Jager , J.M.Camalich [arXiv:1412.3283]

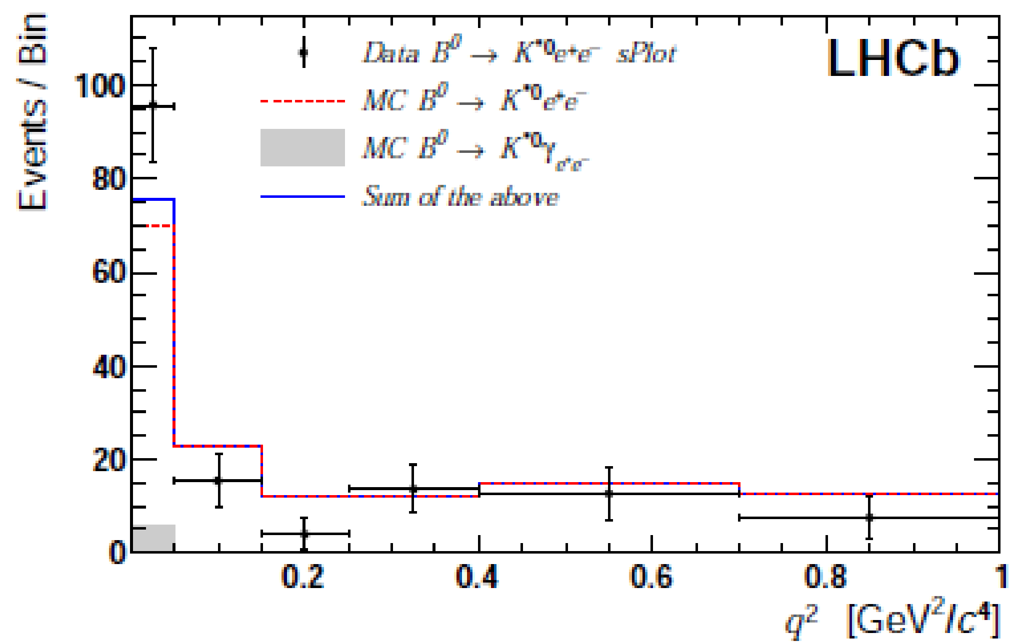
- Measurements well in agreement with SM predictions
- Constraints on C_7' in complementary with radiative decays

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 ($\phi = \phi + \pi$ if $\phi < 0$)
- 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

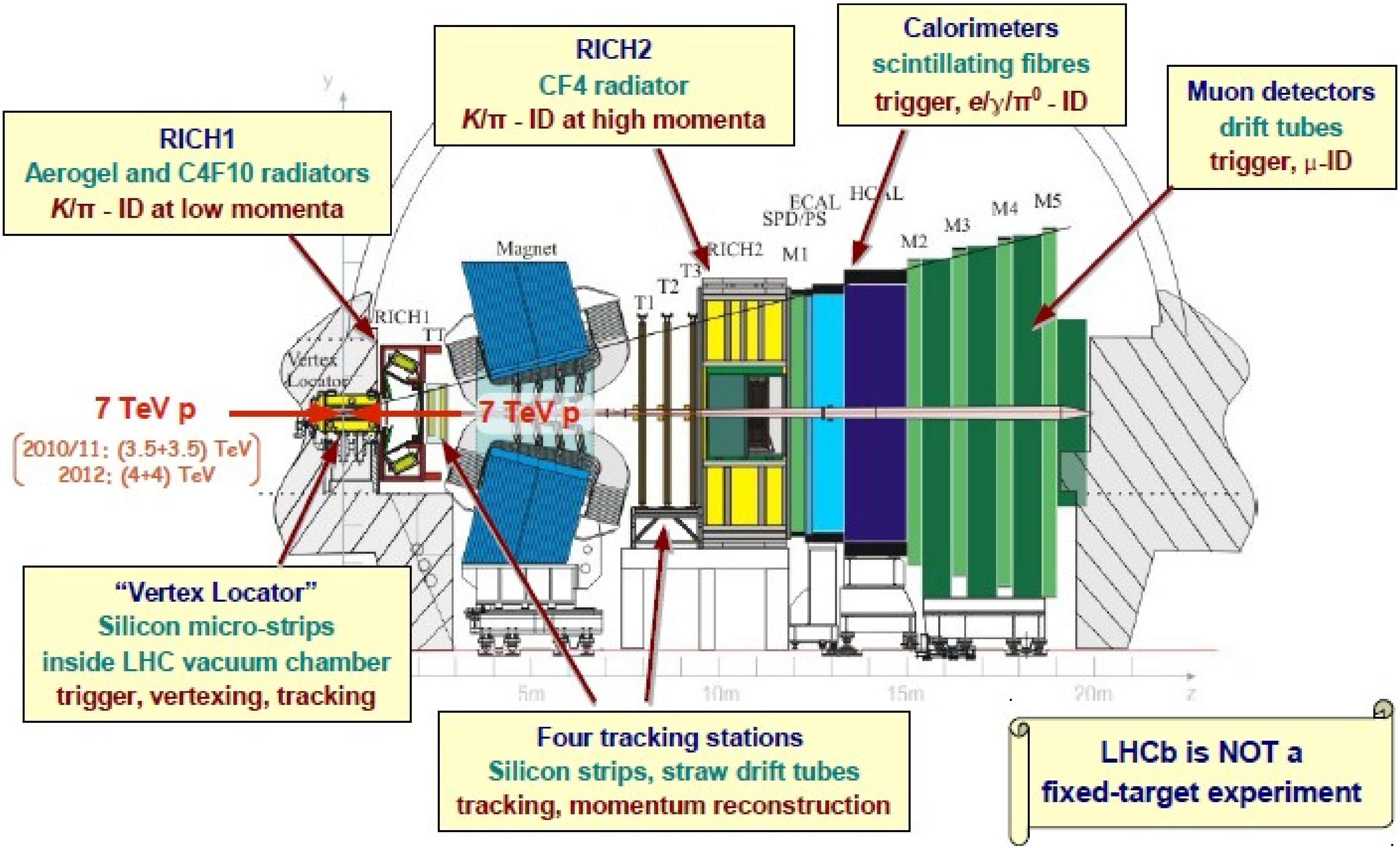
LHCb future (2012 + end 2014 - 2017)

- $\mathcal{L} \geq 4 * 10^{32}$ 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 -)

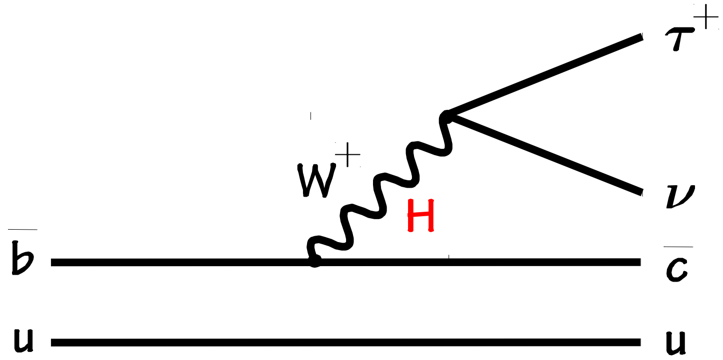
- Full readout @ 40 MHz with full software trigger $\rightarrow$ trigger efficiency enhanced by a factor-2 for hadronic modes!
- Increase the luminosity by a factor-5
  $\rightarrow \mathcal{L} \geq (1-2) * 10^{33}$ cm^{-2} s^{-1}
  $\rightarrow$ 25 ns bunch spacing $\rightarrow \mu = 2$
  $\rightarrow \sqrt{s} =$ 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}

LHCb



RICH1
Aerogel and C4F10 radiators
K/π - ID at low momenta
RICH2
CF4 radiator
K/π - ID at high momenta
Calorimeters
scintillating fibres
trigger, e/γ/π⁰ - ID
Muon detectors
drift tubes
trigger, μ-ID
7 TeV p
(2010/11: (3.5+3.5) TeV
2012: (4+4) TeV)
7 TeV p
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z
y
"Vertex Locator"
Silicon micro-strips
inside LHC vacuum chamber
trigger, vertexing, tracking
Four tracking stations
Silicon strips, straw drift tubes
tracking, momentum reconstruction
LHCb is NOT a
fixed-target experiment

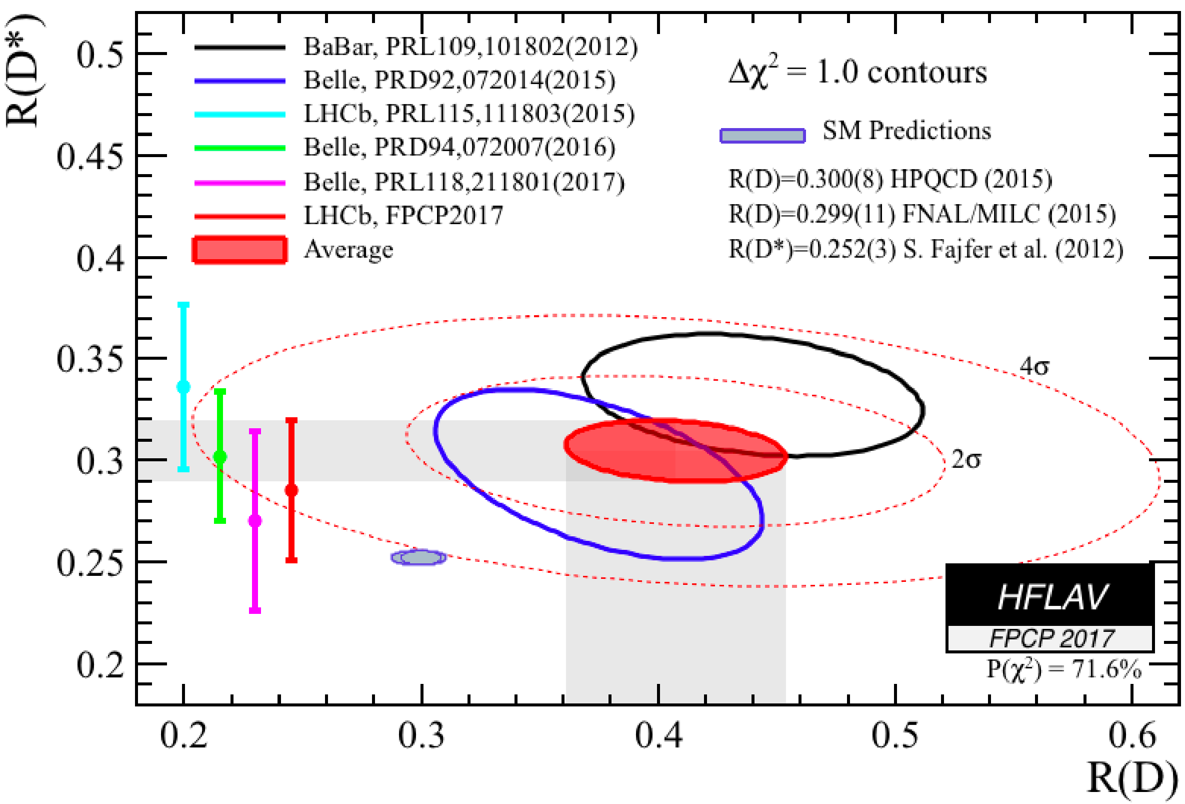
$B \to D^{(*)} \tau \nu$



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

BaBar

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



Belle

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

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

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

LHCb

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

$R(D^*) = 0.285 \pm 0.019 \pm 0.029$

average

$R(D) = 0.407 \pm 0.039 \pm 0.024$
$R(D^*) = 0.304 \pm 0.013 \pm 0.007$

difference with SM predictions is at **4.1** σ level