Universität Zürich[UZH]

Physik-Institut

Flavour anomalies in B-physics

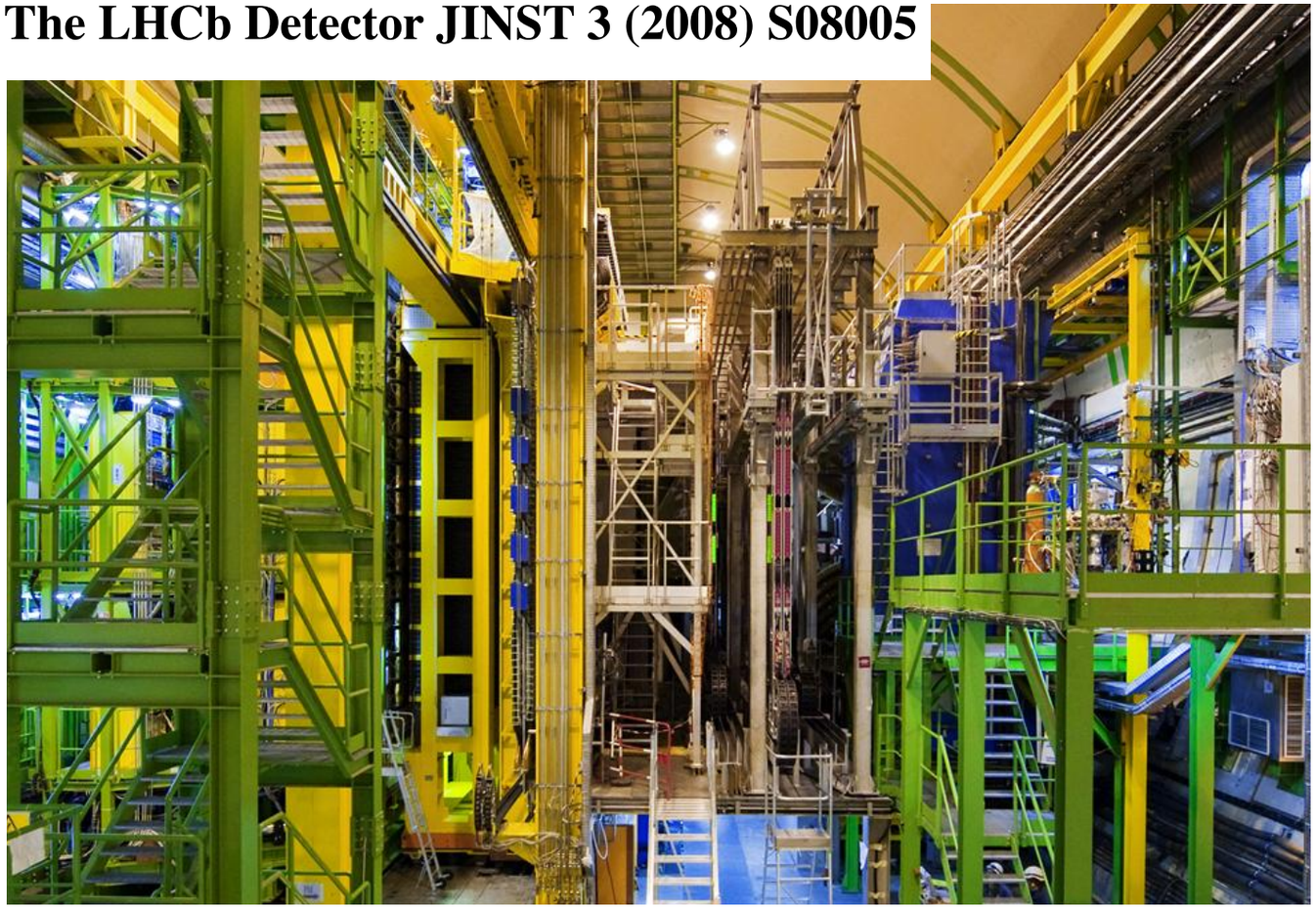
Nico Serra (Universität Zürich)
on behalf of the LHCb collaboration

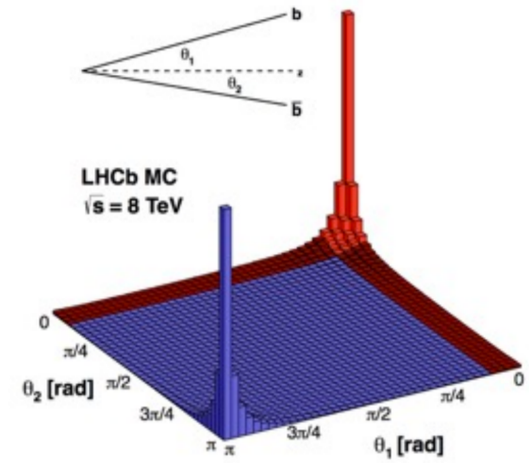
Phenomenology Symposium 2019

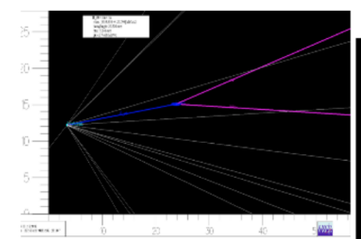
University of Pittsburg 6-8th May

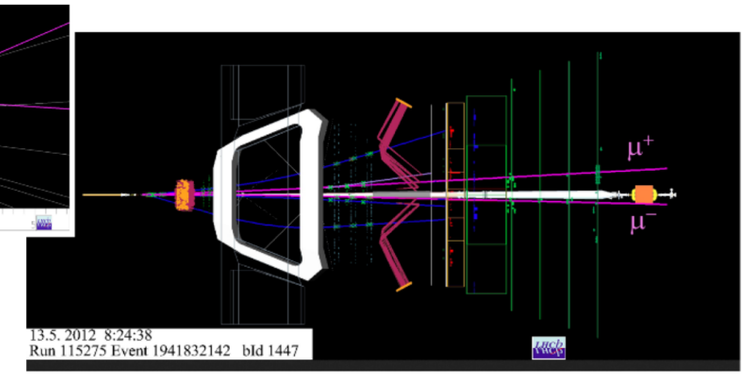
LHCb Experiment

The LHCb Detector JINST 3 (2008) S08005





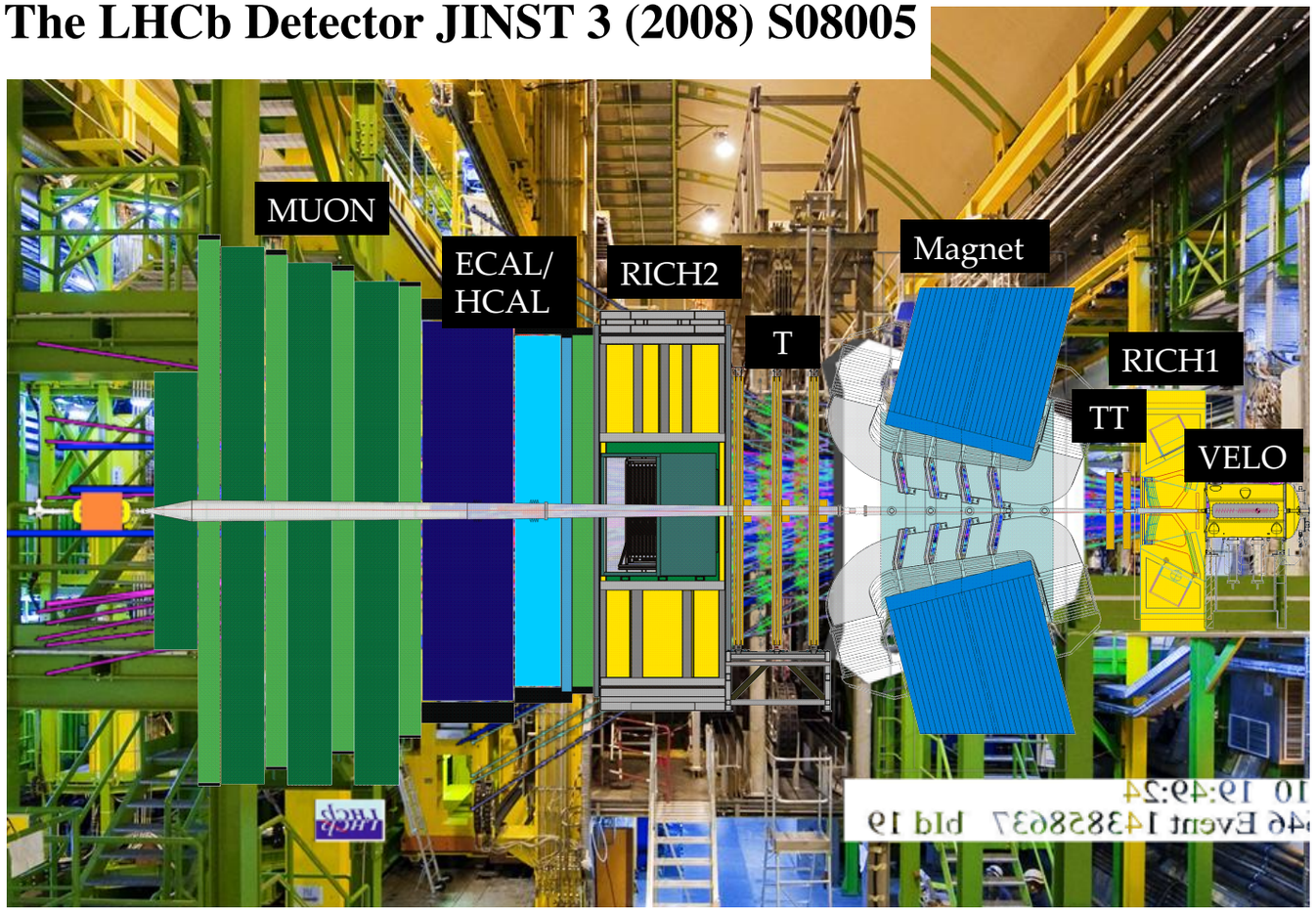


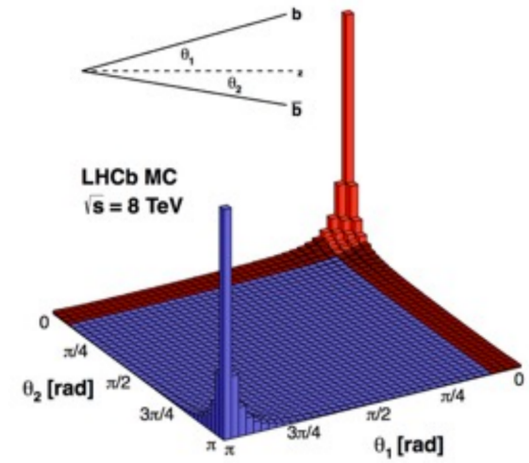


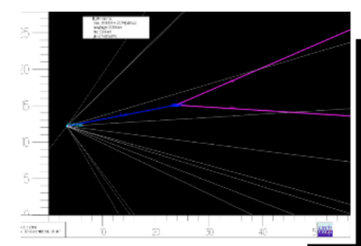
- $b\bar{b}$ produced predominantly forward and backward
- Displacement between primary (PV) and secondary (SV) vertexes one of the main discriminating variable
- Run 1 LHCb collected 1+2 fb^{-1} of data in 2011+2012
- Run 2 LHCb collected 6 fb^{-1} of data between 2015 and 2018 (roughly twice b-meson per fb^{-1} due to increased $\sqrt{s}$)

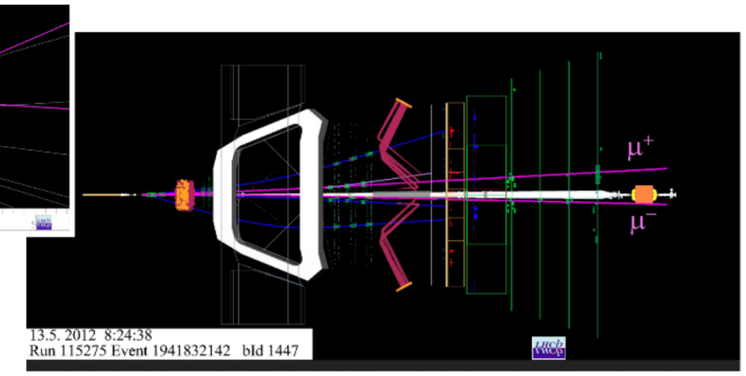
LHCb Experiment

The LHCb Detector JINST 3 (2008) S08005









- $b\bar{b}$ produced predominantly forward and backward
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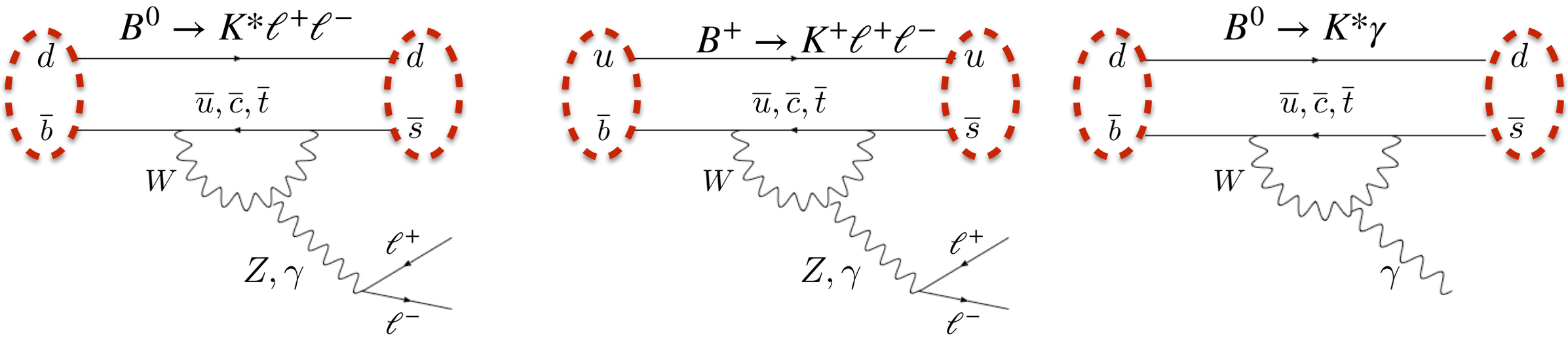
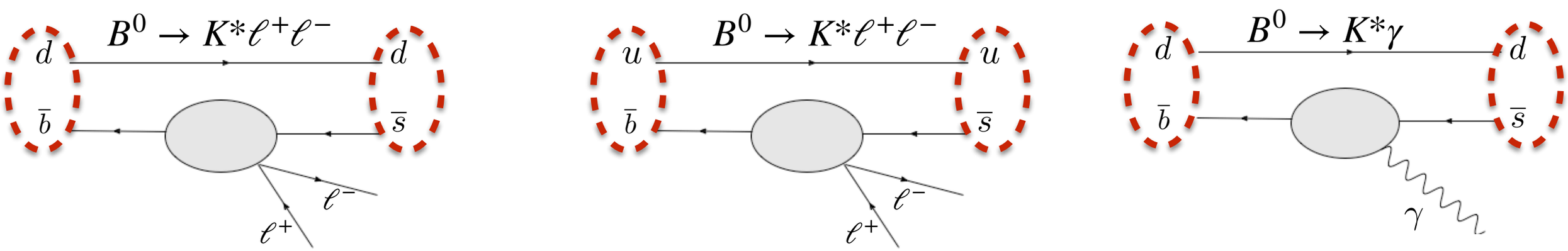
Effective Hamiltonian



Use an effective operator approach, similar to Fermi theory of weak interaction



$$\mathscr{A}(i \to f) = \langle f | \mathscr{H}_{eff} | i \rangle$$

Effective Hamiltonian

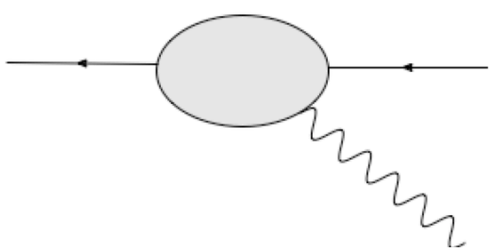
$$\mathscr{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathscr{C}_i^{(')} \mathcal{O}_i^{(')}$$

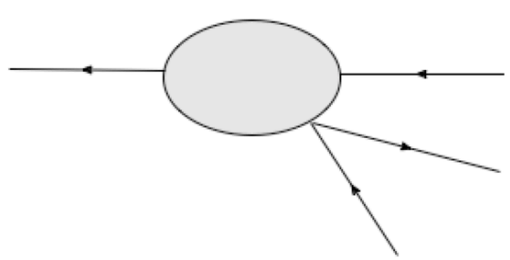
Wilson Coefficients
Effective coupling

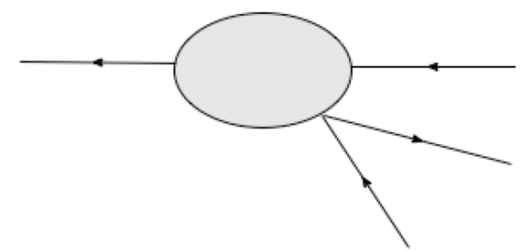
Local operators

$\langle f | O_i | i \rangle$ Long distance QCD

New Physics can contribute to different WCs depending on its Lorentz structure







$$\mathcal{O}_9^{(')} \propto \left(\bar{s}\gamma_\mu P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\mathcal{O}_S^{(')} \propto \left(\bar{s} P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\mathcal{O}_7^{(')} \propto \left(\bar{s}\sigma_{\mu\nu} P_{R(L)} b\right) F_{\mu\nu}$$

$$\mathcal{O}_{10}^{(')} \propto \left(\bar{s}\gamma_\mu P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

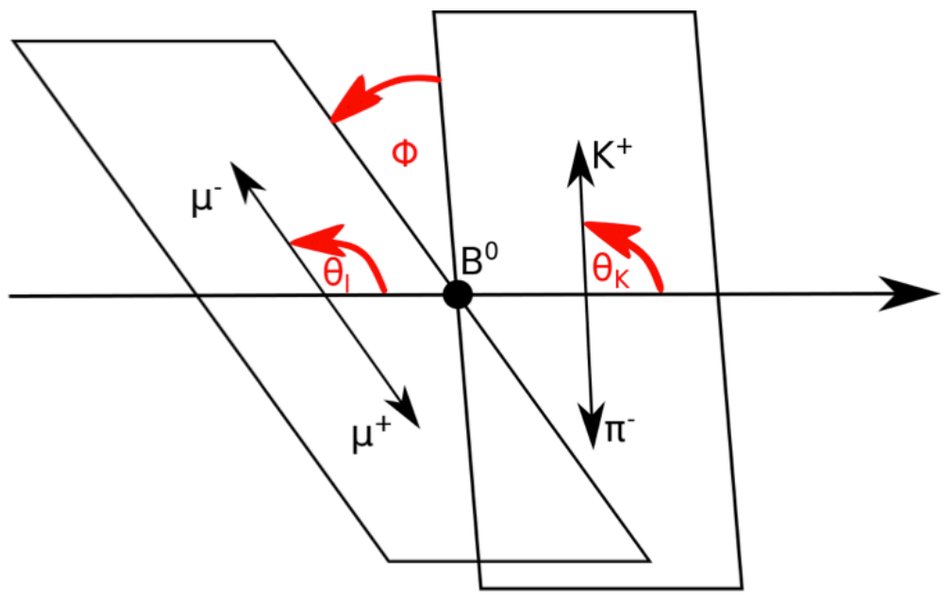
$$\mathcal{O}_P^{(')} \propto \left(\bar{s} P_{R(L)} b\right)\left(\bar{\ell}\gamma^\mu \gamma_5 \ell\right)$$

$b \to s\gamma$

$b \to s\ell\ell$

$B_{(s)}^0 \to \ell^+\ell^-$

$B^0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$

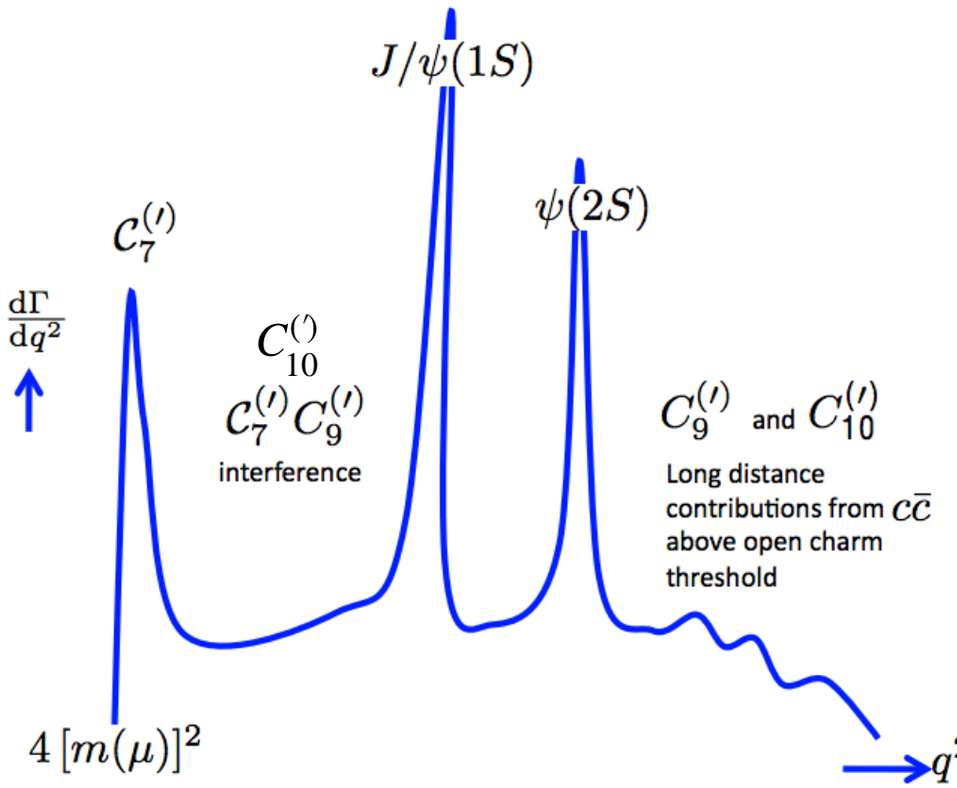


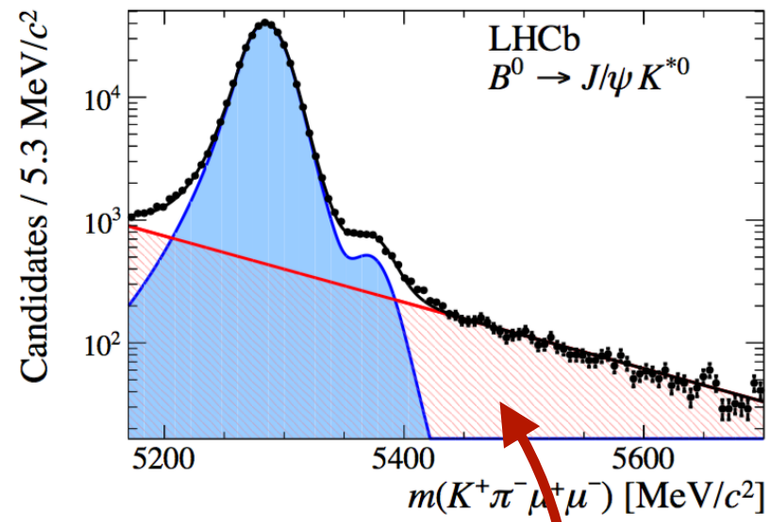
This decay is described by 3 angles (**θ_l ,θ_K ,ϕ**) and the di-muon invariant mass squared (q^2)

This is analogous to the orbitals in atoms, i.e. the spectroscopy allows you to infer about atomic potential

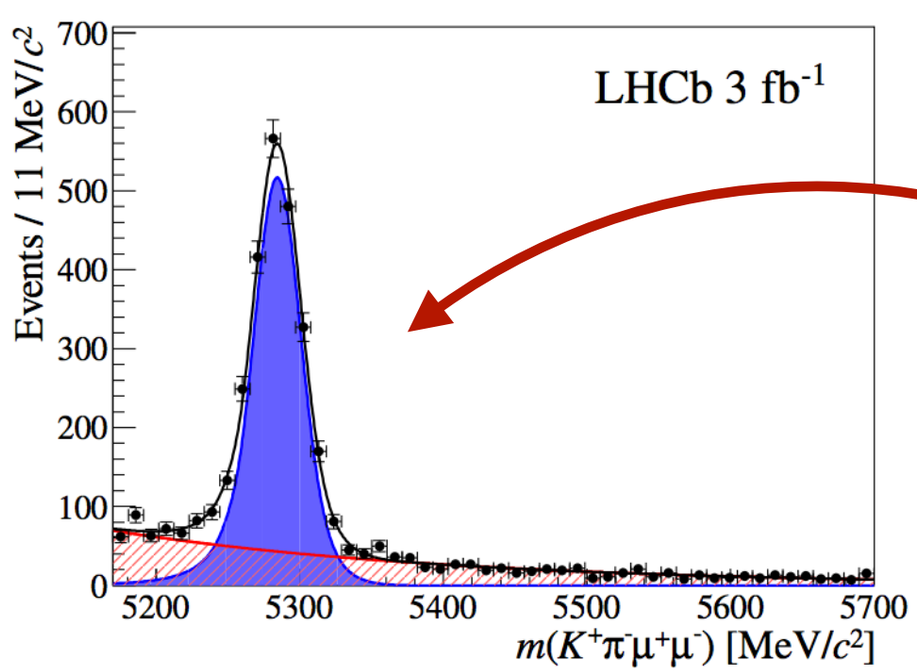
$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$\sqrt{F_L(1-F_L)}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

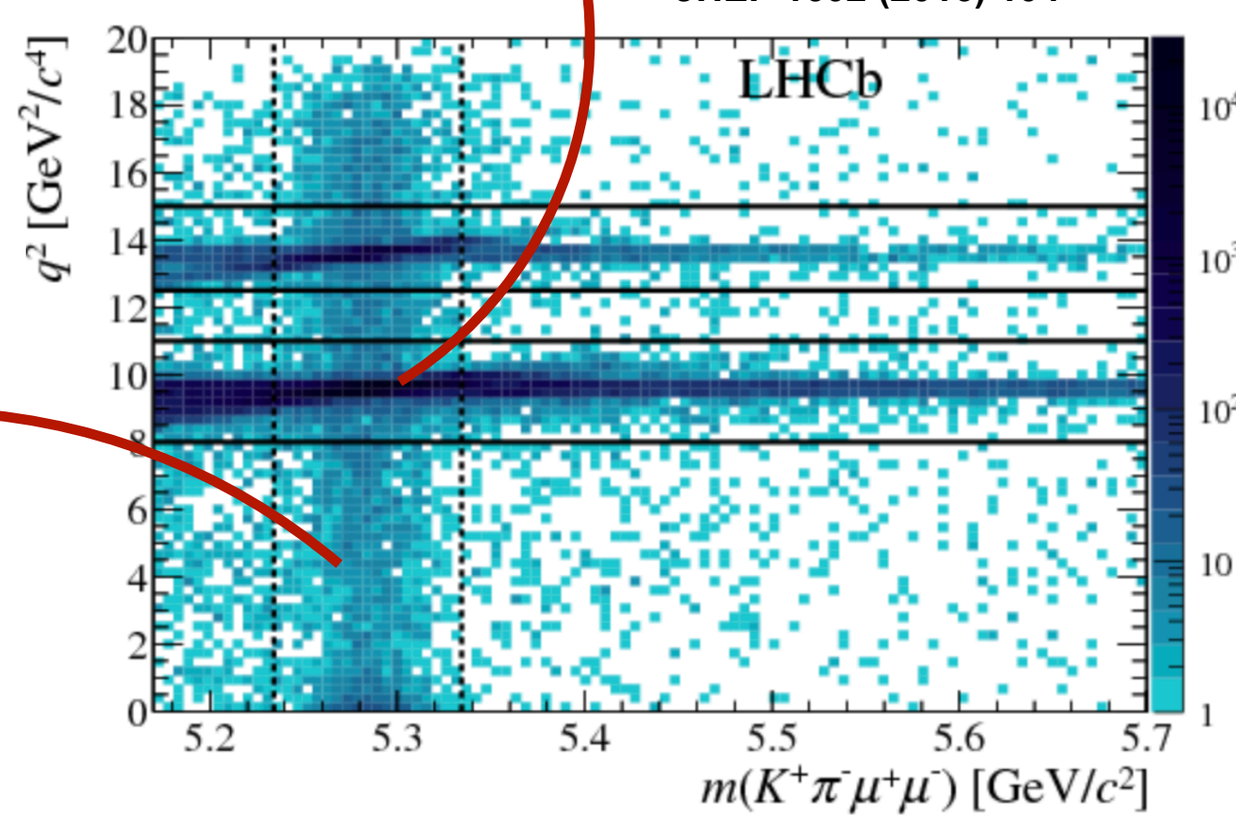
$B^0 \to K^*(\to K^+\pi^-)\mu^+\mu^-$





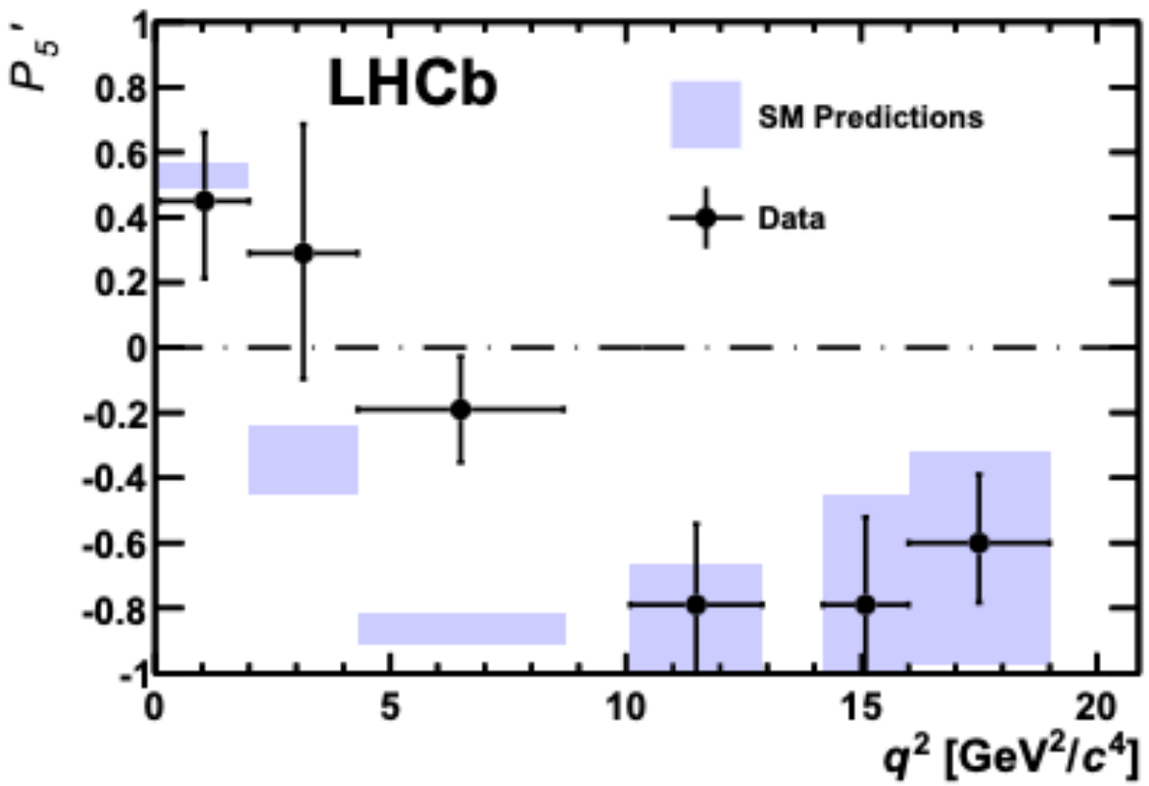
JHEP 1602 (2016) 104



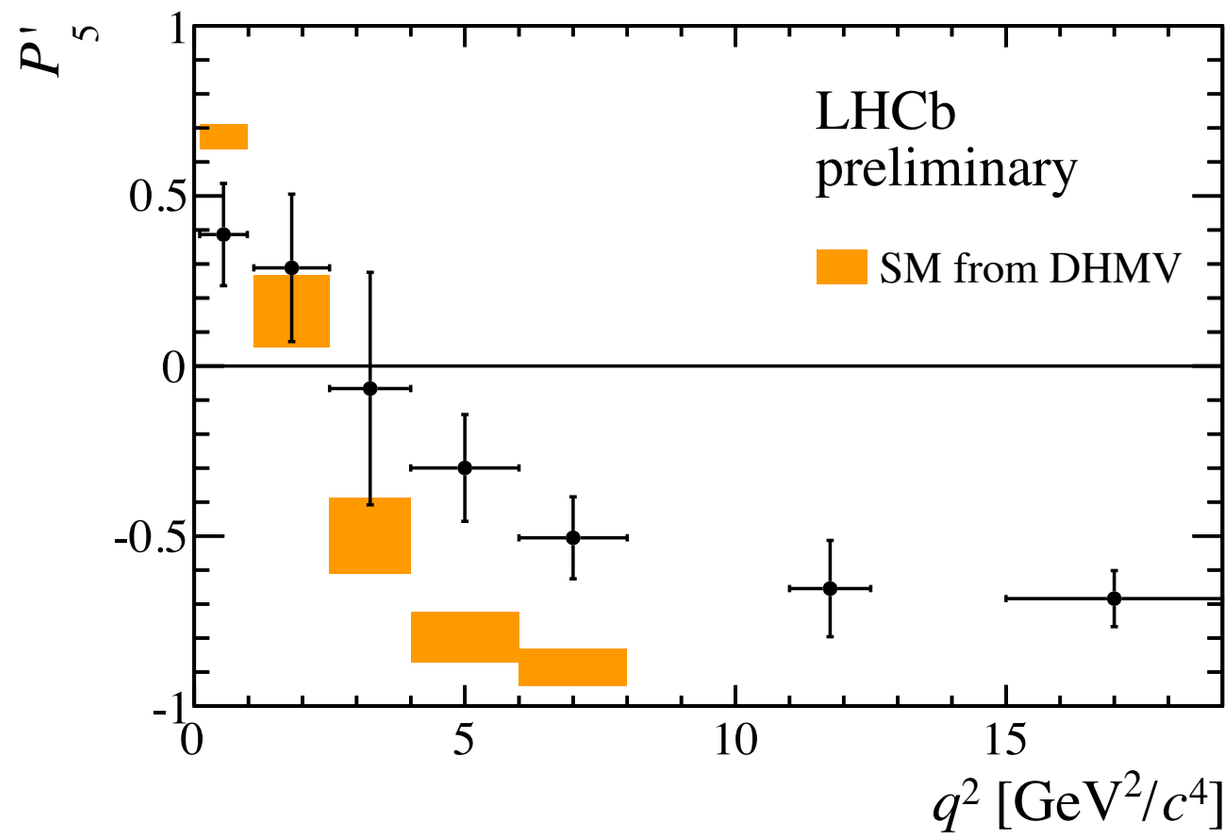


Measurement of P_5'

Phys. Rev. Lett. 111, 191801 (2013)



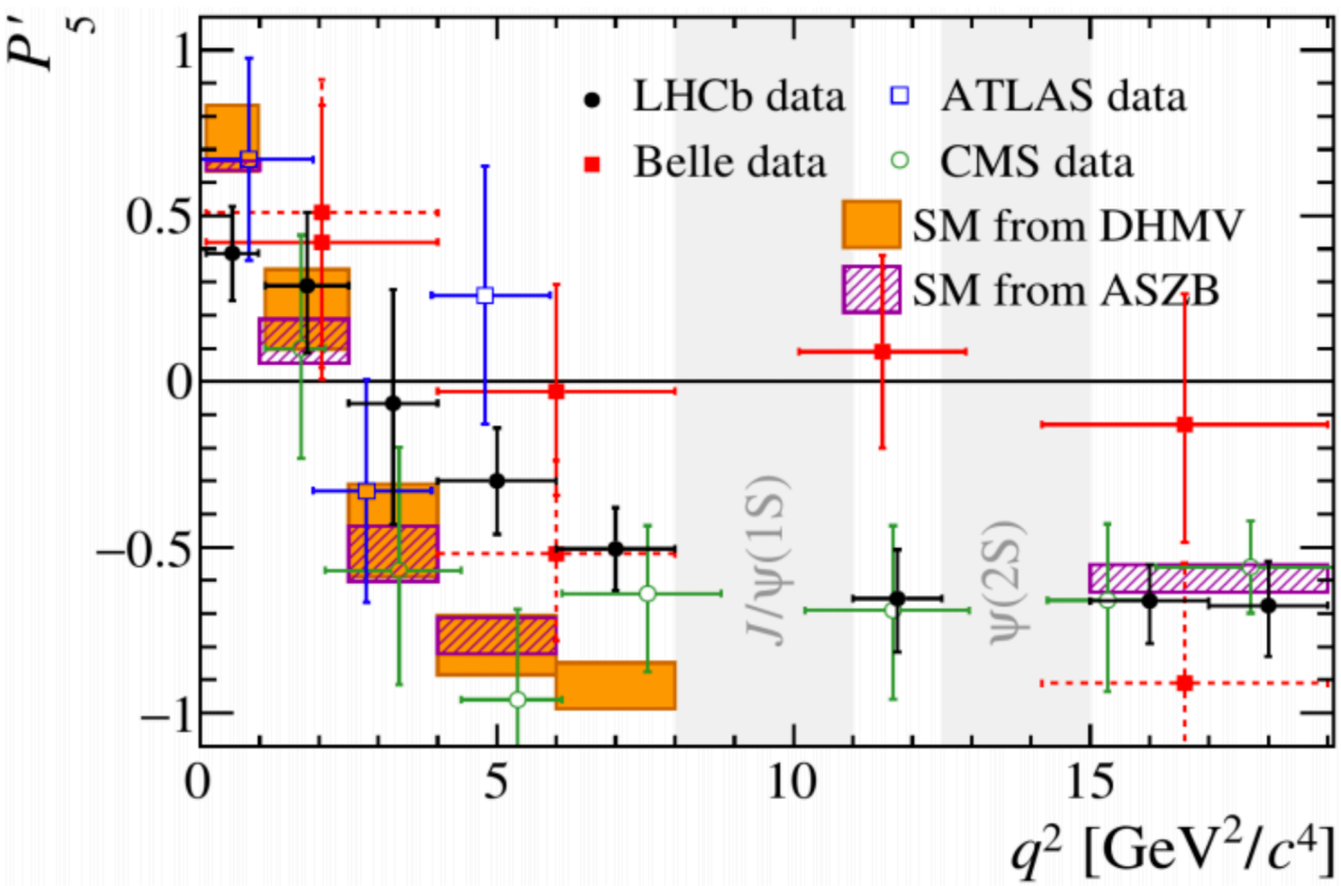
JHEP 1602 (2016) 104



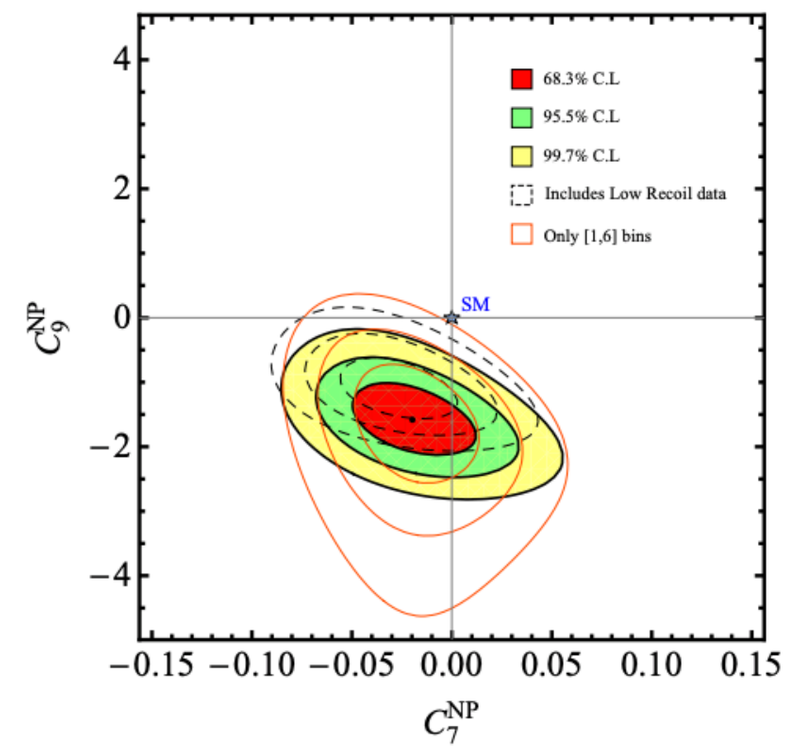
- Discrepancy first observed in 2013 with 1fb^{-1}
- Confirmed consistent result in 2016 with 3fb^{-1}
- Analysis with Run 2 dataset ongoing

Measurement of P_5'

ATLAS: arXiv:1805.04000
CMS: CMS-PAS-BPH-15-008
Belle: PRL 118 (2017) 111801
LHCb: JHEP 02 (2016) 104



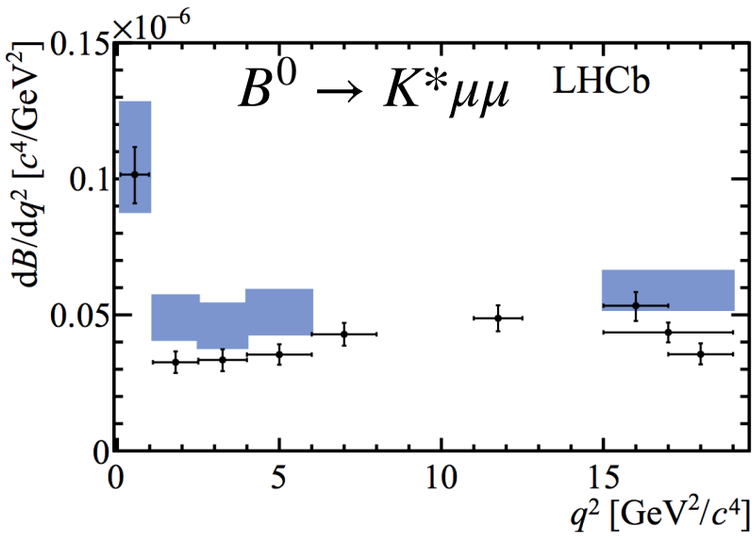
Descotes-Genon, Matias, Virto
Phys. Rev. D 88, 074002 (2013



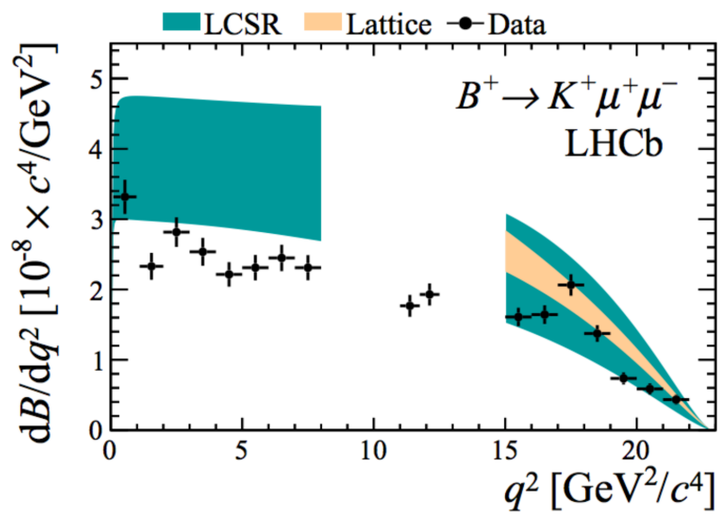
- ATLAS, CMS and Belle also measured this quantity
- The discrepancy in P_5' wrt SM can be interpreted as NP in either C_9 or $C_{9/10}$ simultaneously

A Coherent Pattern?

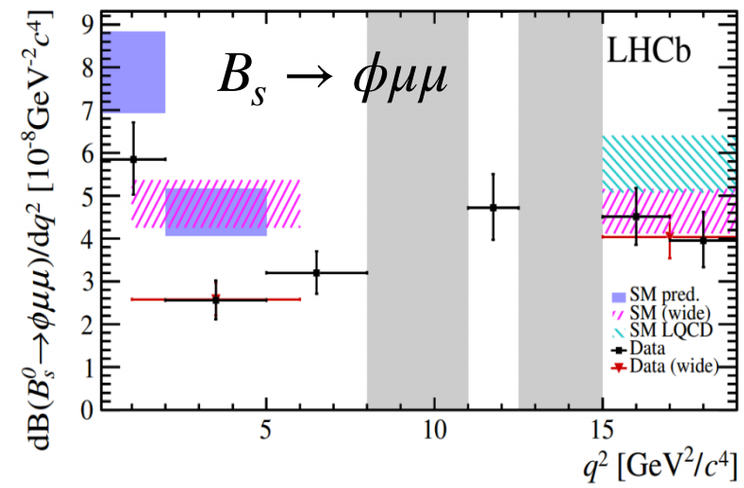
JHEP 11 (2016) 047



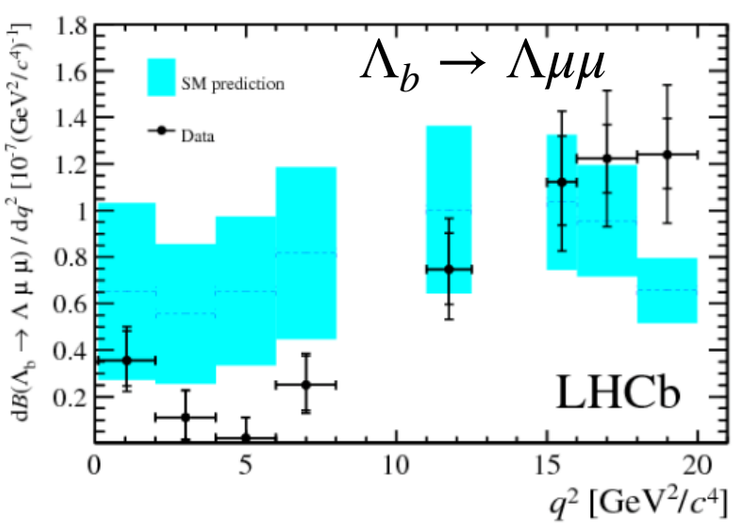
JHEP 06 (2014) 133



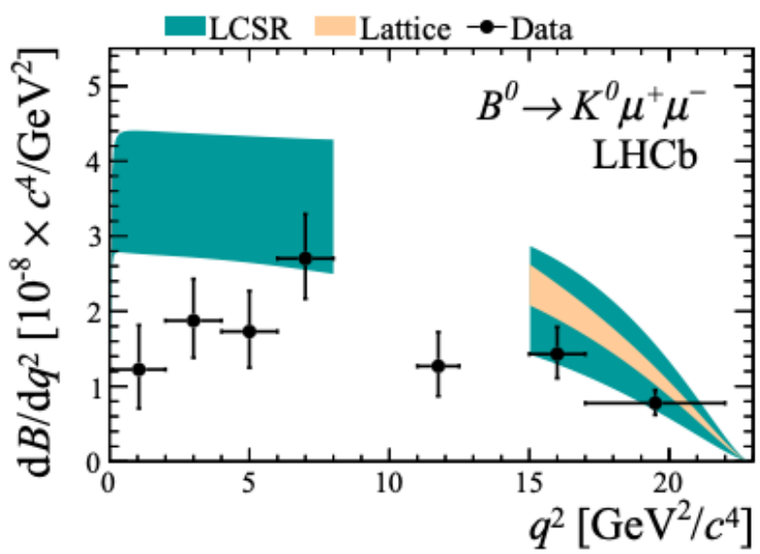
JHEP 09 (2015) 179



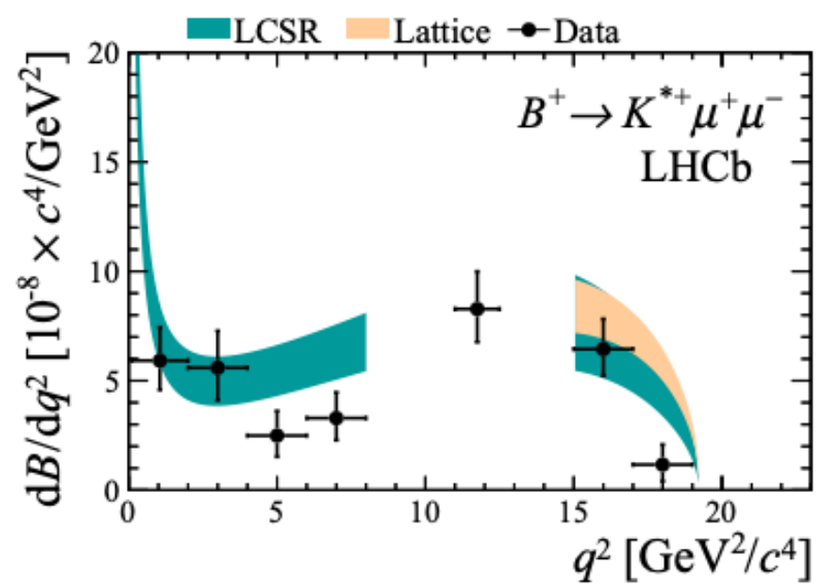
JHEP 06 (2015) 115



JHEP 06 (2014) 133



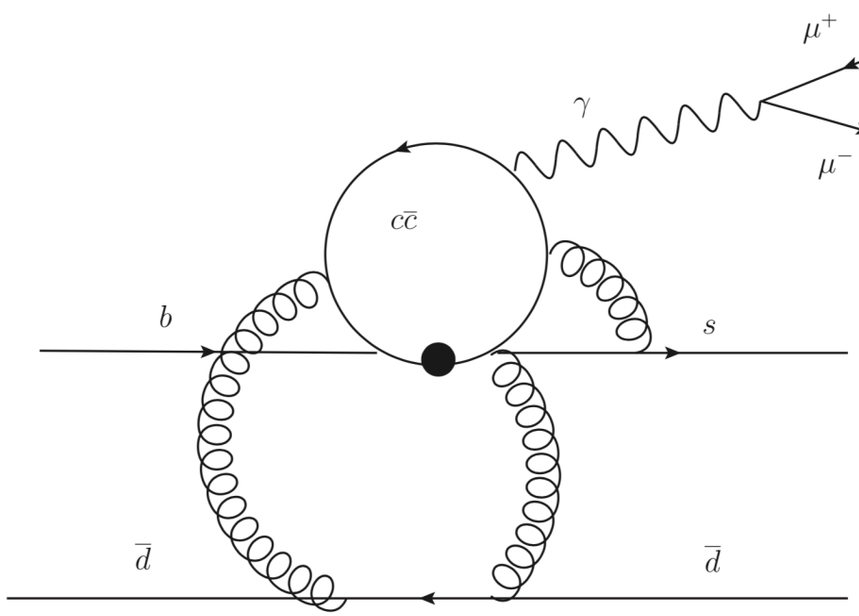
JHEP 06 (2014) 133

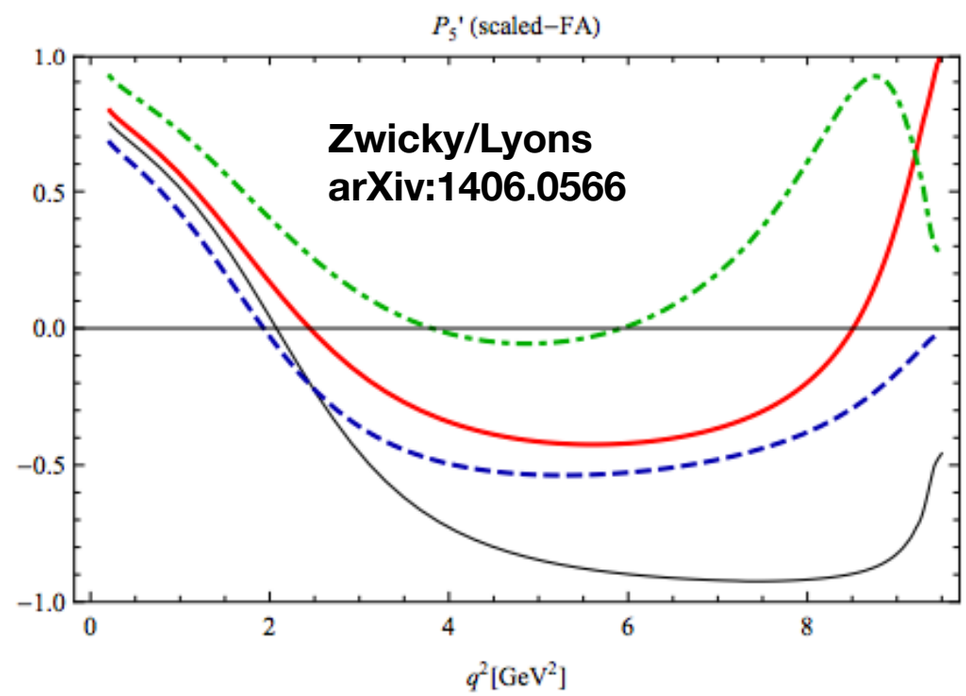


- Data consistently below SM predictions
- Large theory uncertainty due to form factors

Theory Uncertainty

- Both P_5' and the branching ratios discrepancy can be explain with the same shift in C_9 or $C_{9/10}$
- Charm loop contribution is essentially a correction to C_9 not possible to compute this contribution reliably

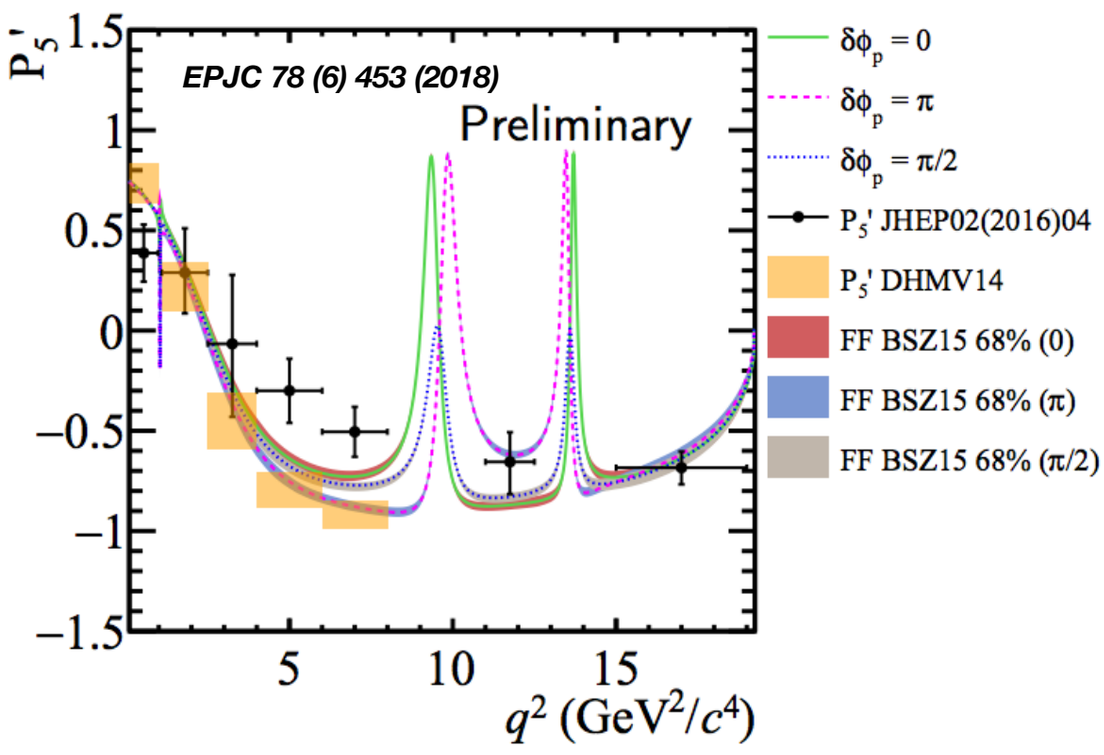


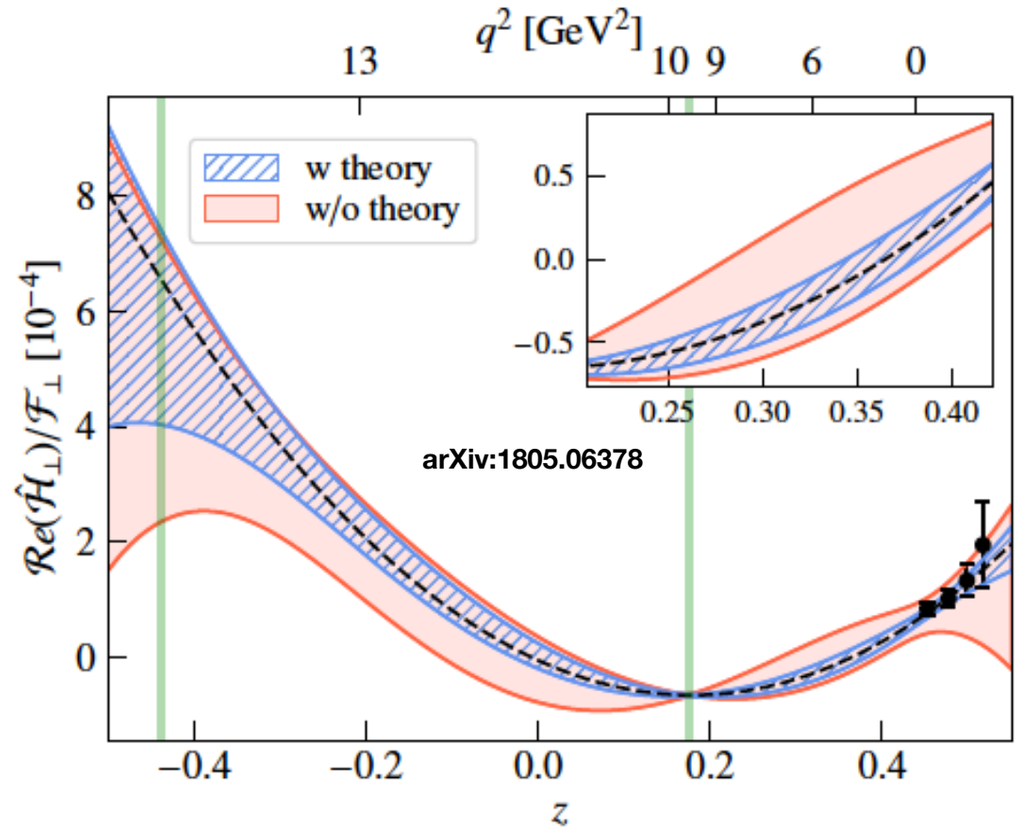


- Long debate on the community if the relatively large effect we see is NP or can be attributed to charm loop
- Charm loop can be considered as the sum of the tails of all resonances + open charm

Way Forward

- It is difficult to disentangle short distance and long distance contributions
- A few attempts:
  - Parametrizing the charmonia resonance as BW (including tails away from resonances) ***EPJC 78 (6) 453 (2018)***
  - Parametrizing the charmonia resonances as polynomials **(JHEP 11 (2017) 176, arXiv:1805.06378, arXiv:1707.07305)**

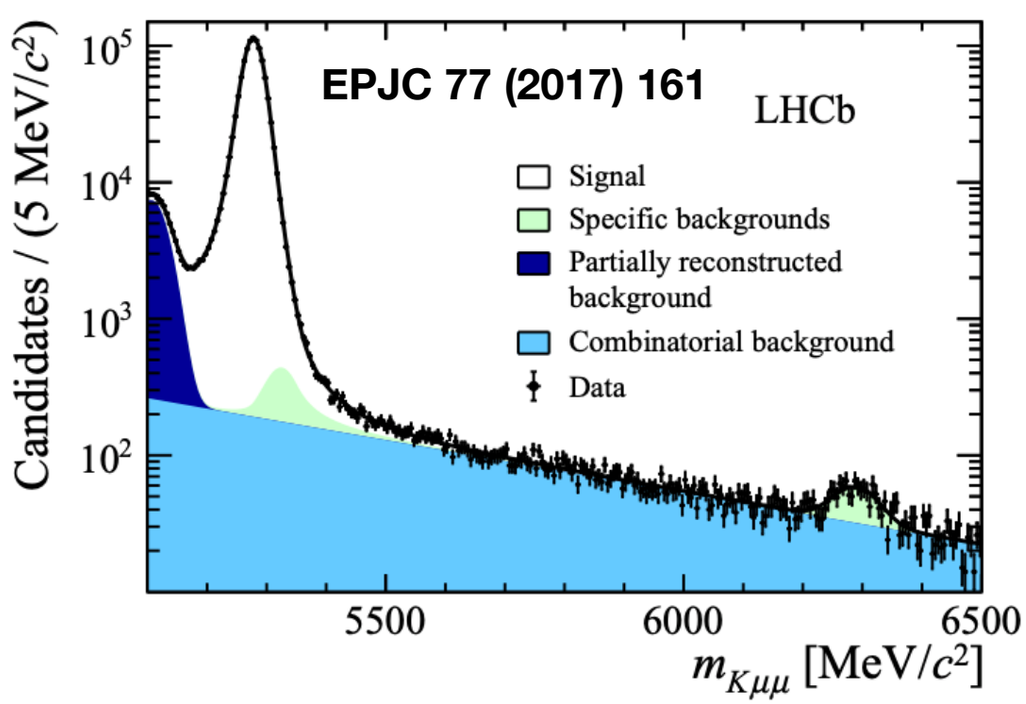


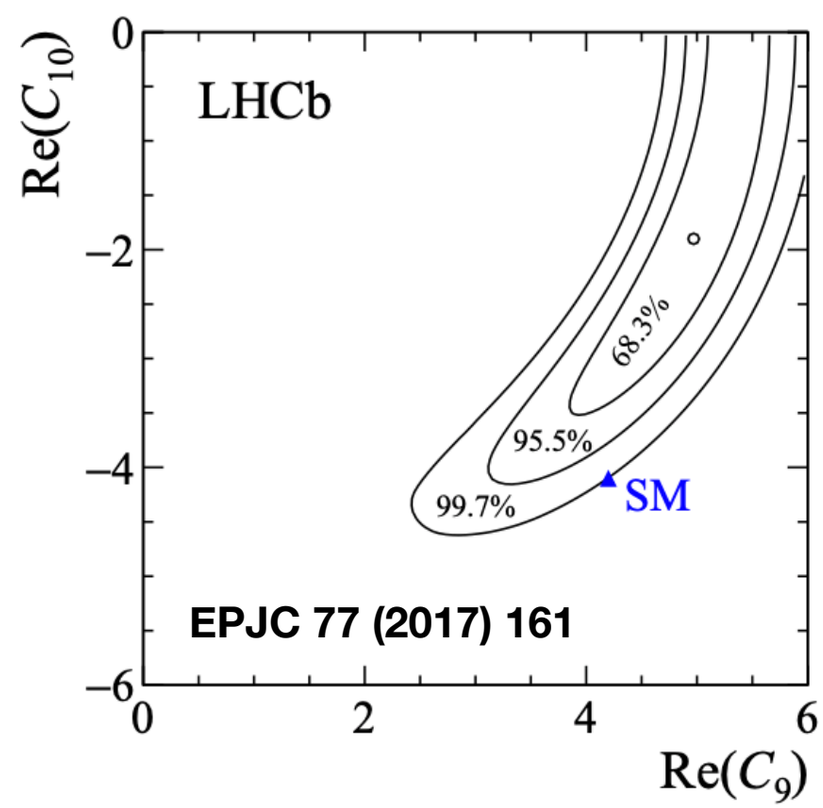


Phase Difference with Charmonia

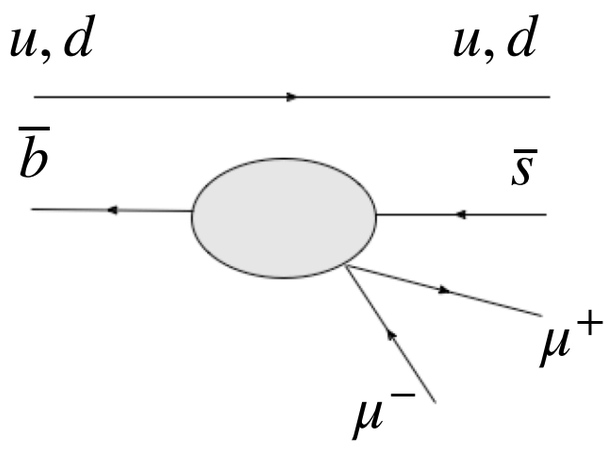
- Fit of the q^2 spectrum, parametrising the resonances as relativistic BW

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{128\pi^5}|\boldsymbol{k}|\beta\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta^2\left|\mathcal{C}_{10}f_+(q^2)\right|^2 + \frac{4m_\mu^2(m_B^2-m_K^2)^2}{q^2m_B^2}\left|\mathcal{C}_{10}f_0(q^2)\right|^2 + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta^2\right]\left|\mathcal{C}_9 f_+(q^2) + 2\mathcal{C}_7\frac{m_b+m_s}{m_B+m_K}f_T(q^2)\right|^2\right\}$$



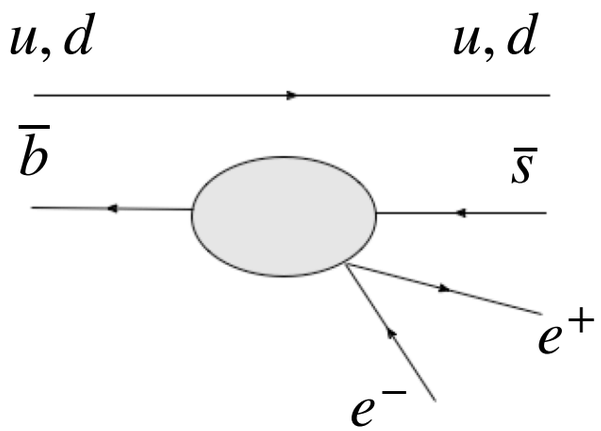


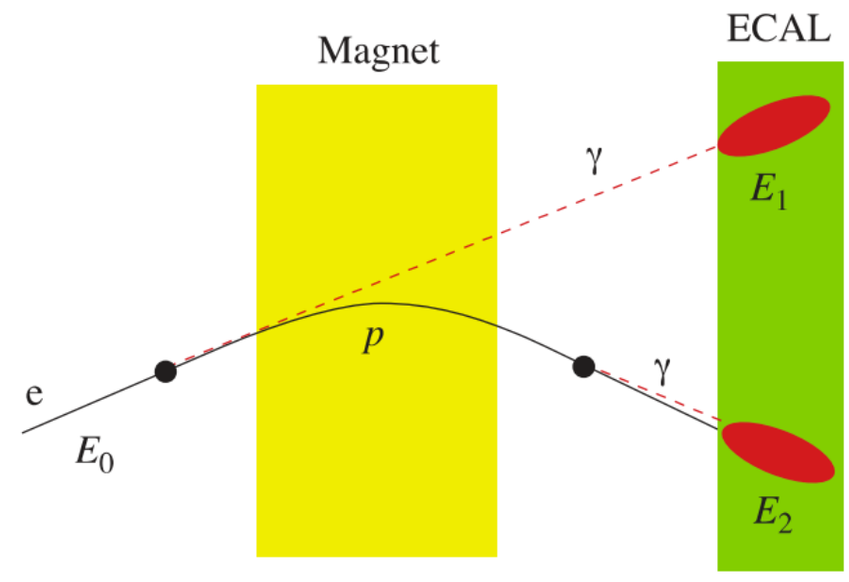
LFU in Rare Decays

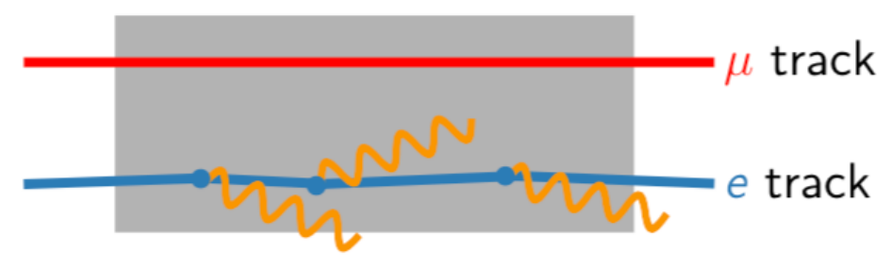


EPJC 76 (2016) 8, 440

$$= 1.0 \pm 0.1$$



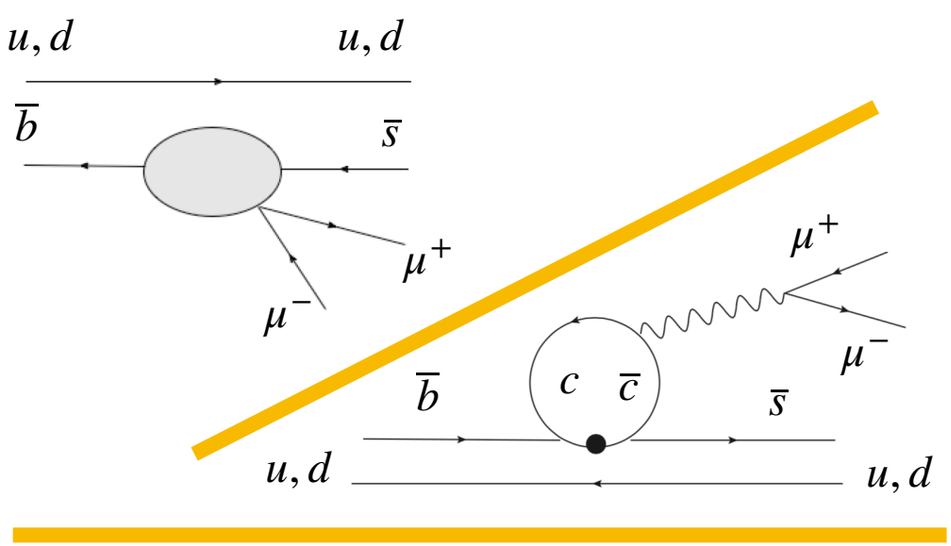




Electron emit bremsstrahlung photons spoiling q^2, invariant mass and momentum resolutions:

- More complicate and difficult J/ψ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons

LFU in Rare Decays



EPJC 76 (2016) 8, 440

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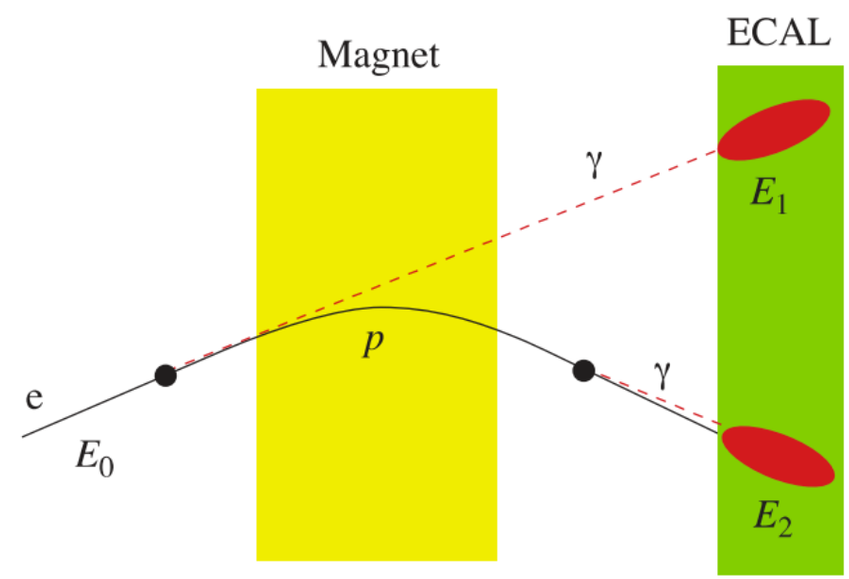
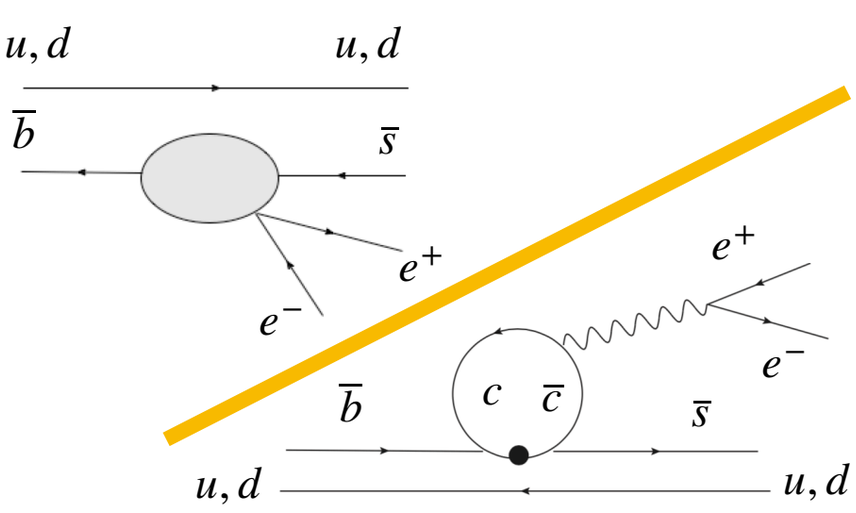
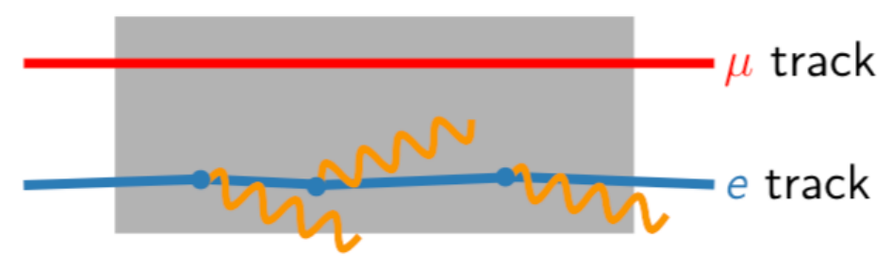






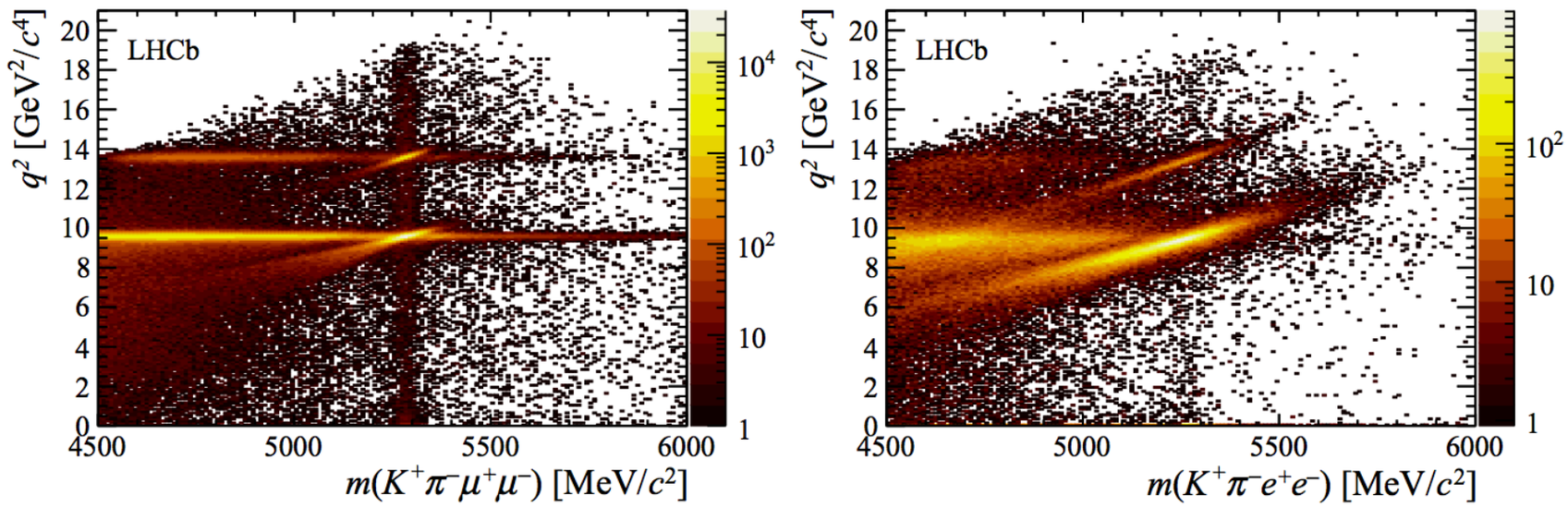
Electron emit bremsstrahlung photons spoiling q^2, invariant mass and momentum resolutions:

- More complicate and difficult J/ψ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons
- Critical aspect in these analyses is the double ratio with the corresponding J/ψ modes

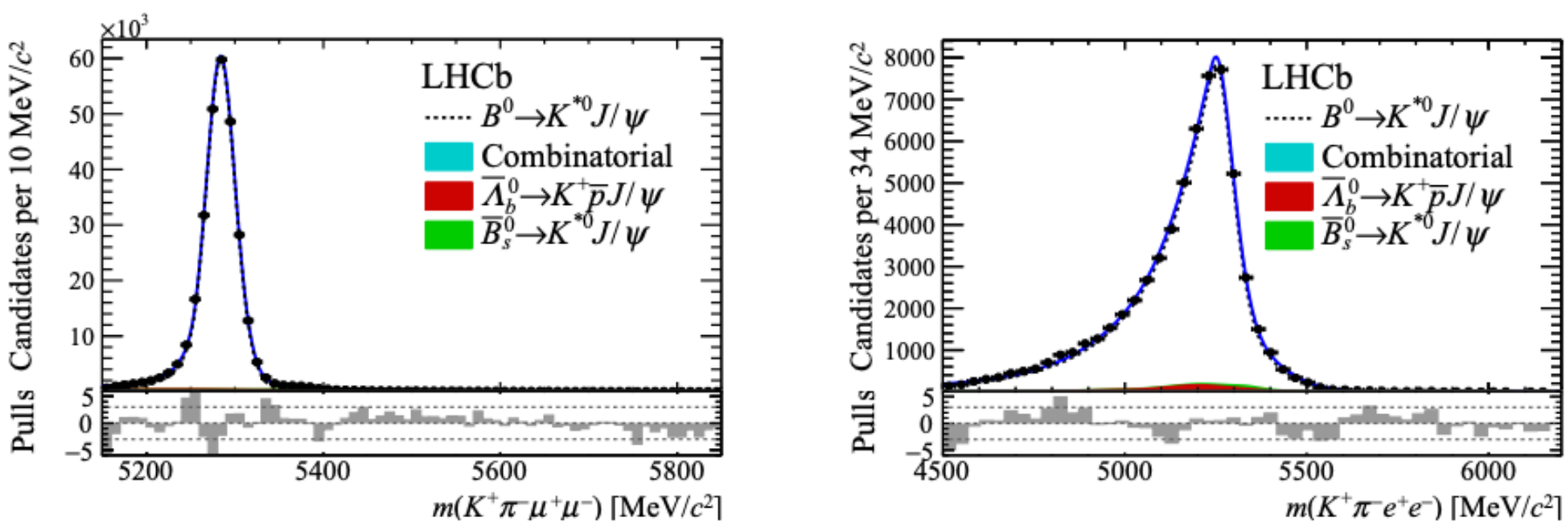
LFU in Rare Decays

JHEP 1708 (2017) 055

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



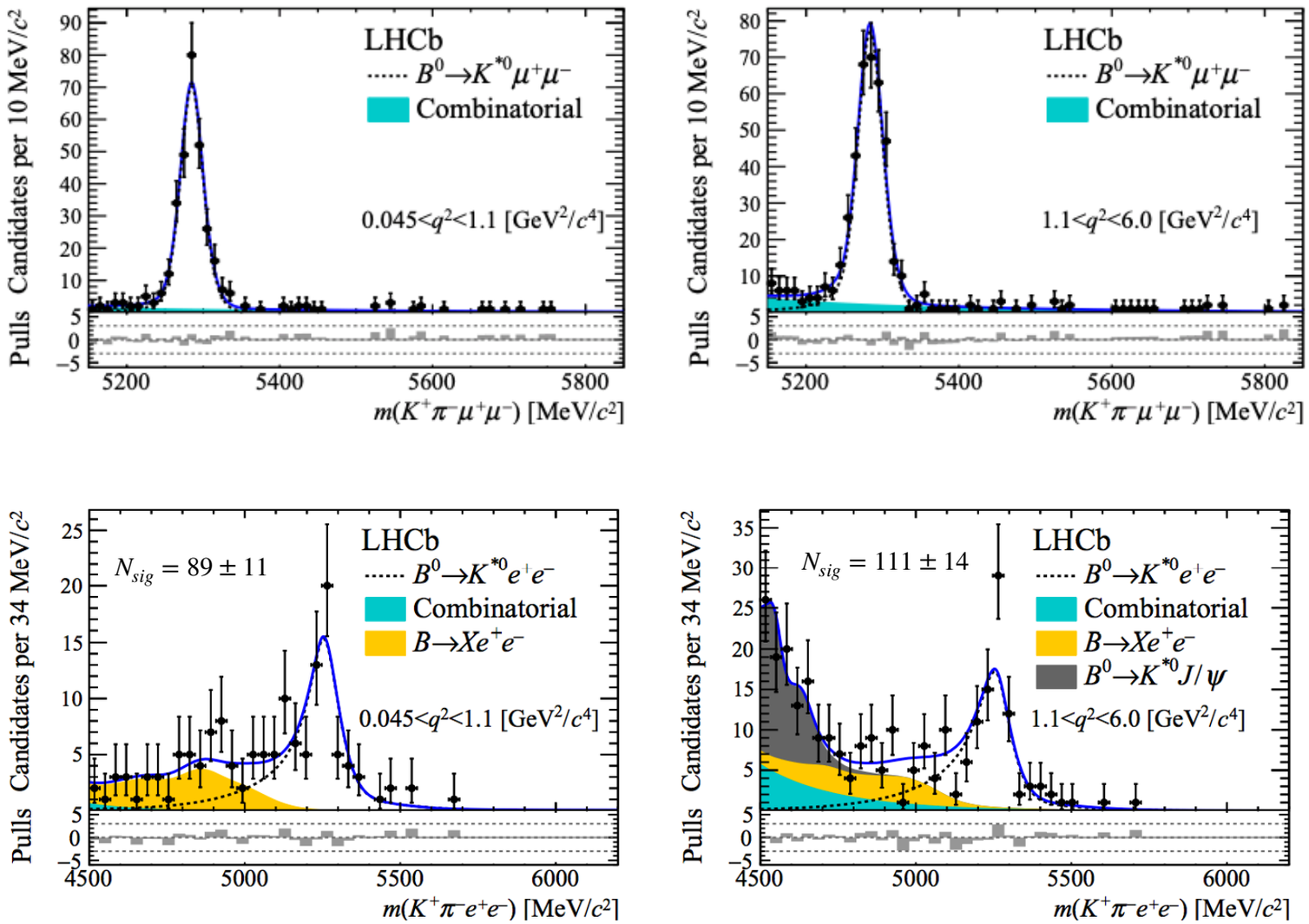
$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$



LFU in Rare Decays

JHEP 1708 (2017) 055

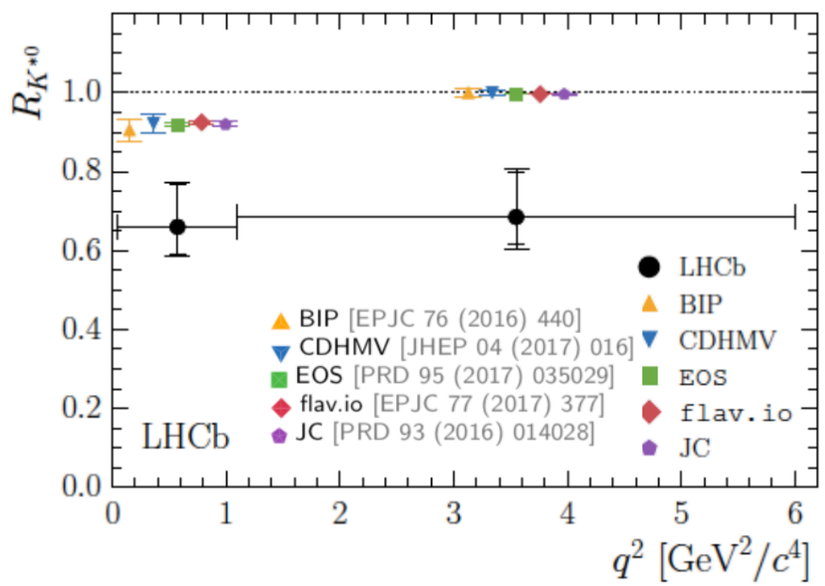
$$R(K^*) = \frac{\mathscr{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathscr{B}(B^0 \to K^{*0}e^+e^-)} \frac{\mathscr{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}{\mathscr{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}$$



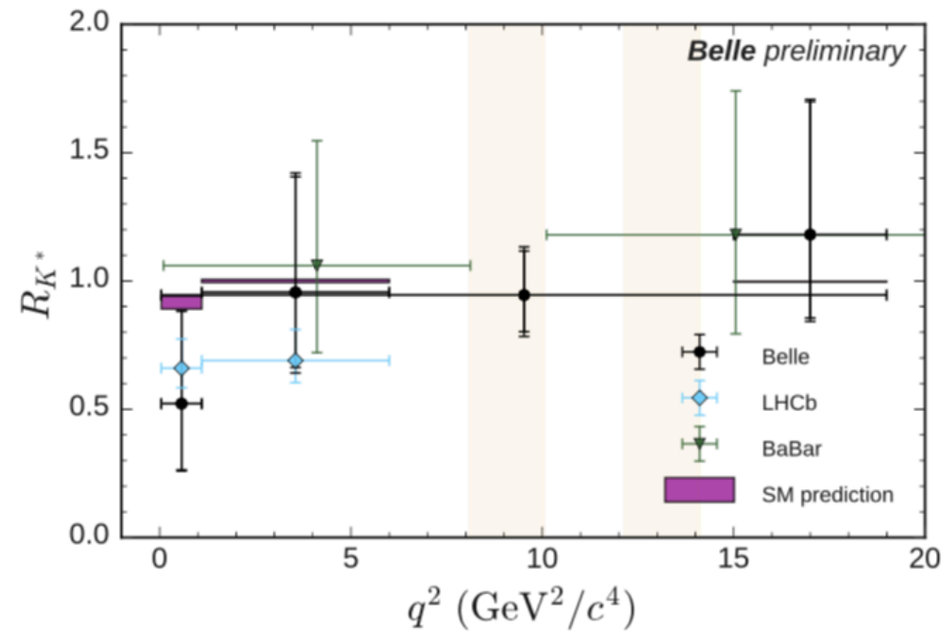
- Mass fit model taken from the fit to $B^0 \to J/\psi K^*$
- Specific bkg taken from MC after data/MC corrections

LFU in Rare Decays

LHCb Coll. JHEP 1708 (2017) 055



Markus Prim (Belle), Moriond EW 2019

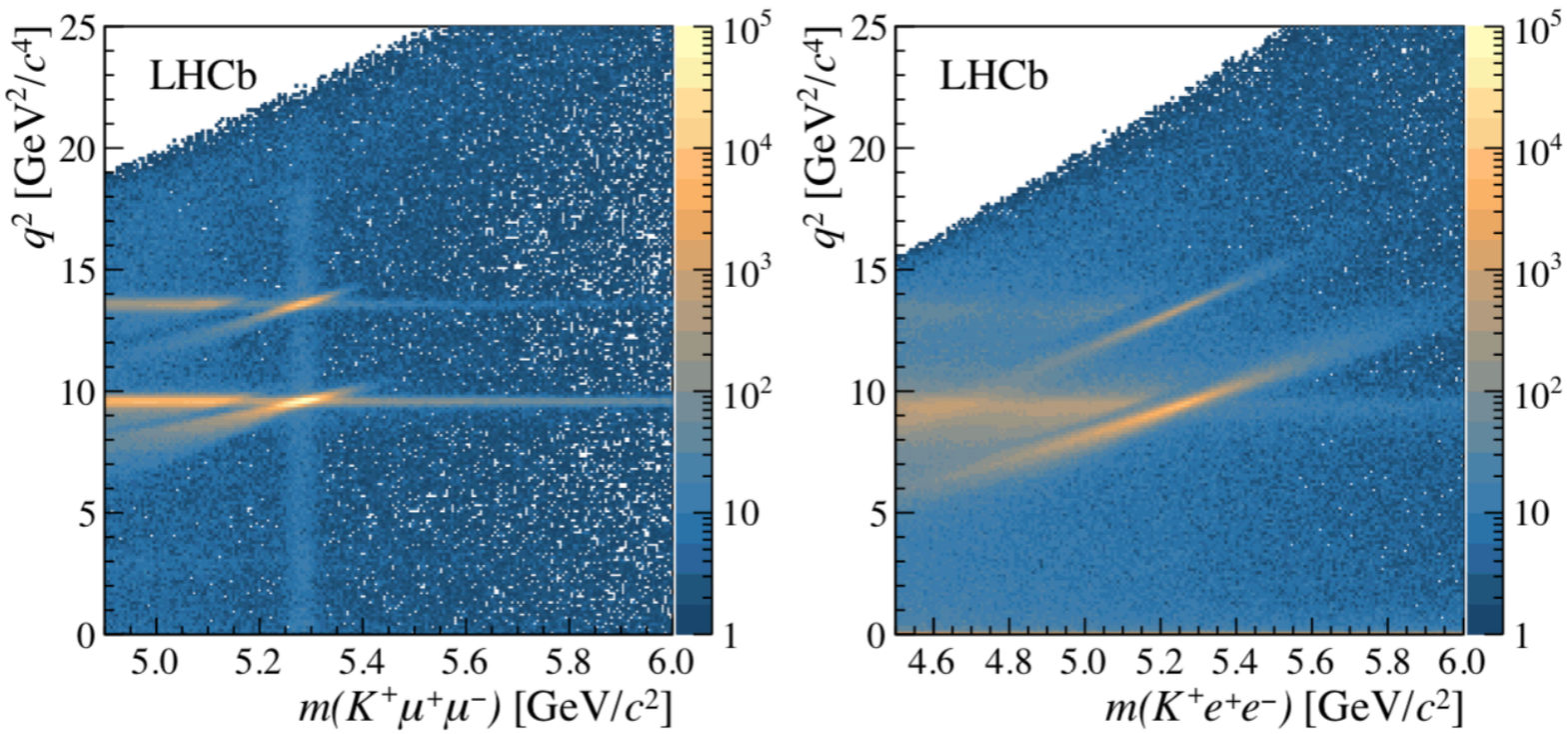


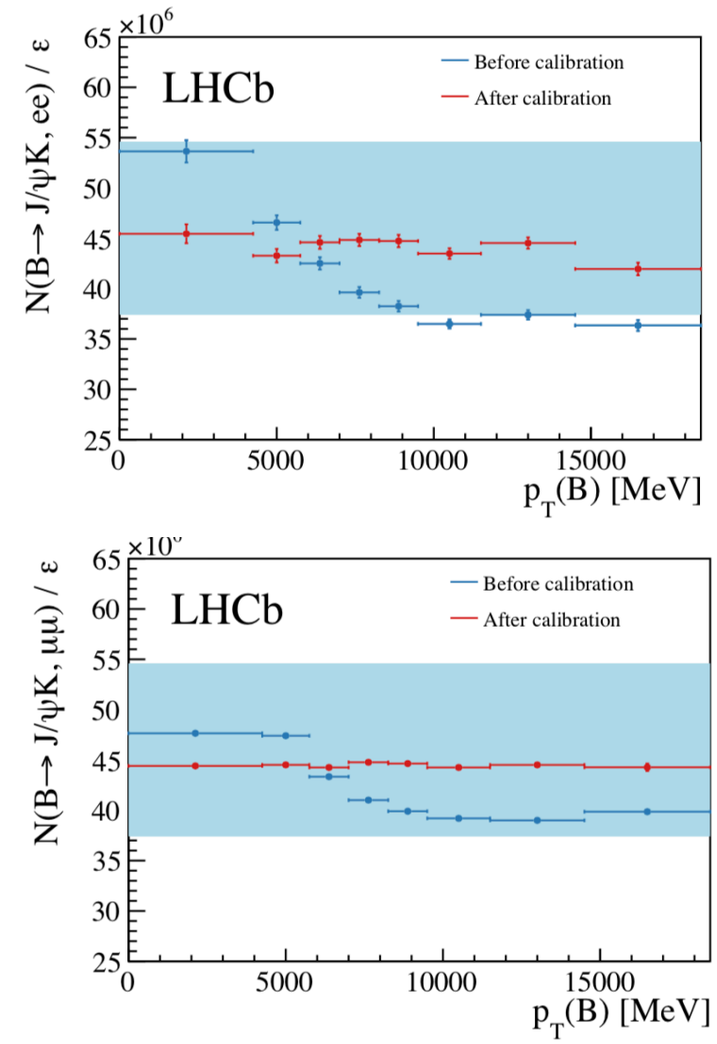
- Discrepancy with respect to the SM, numerically consistent with the $b \to s\mu\mu$
- Surprising result at low q^2, would expect this part to be dominated by the photon contribution, but large statistical error still
- Compatibility with SM 2.2-2.4σ (low-q^2) 2.4-2.5σ (central-q^2)
- Only 3fb^{-1} of Run1 (6 fb^{-1} of Run2 available) used for this analysis

LFU in Rare Decays

LHCb-PAPER-2019-009

$$R(K^+) = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)} \frac{\mathscr{B}(B^+ \to K^+J/\psi(\to e^+e^-))}{\mathscr{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}$$



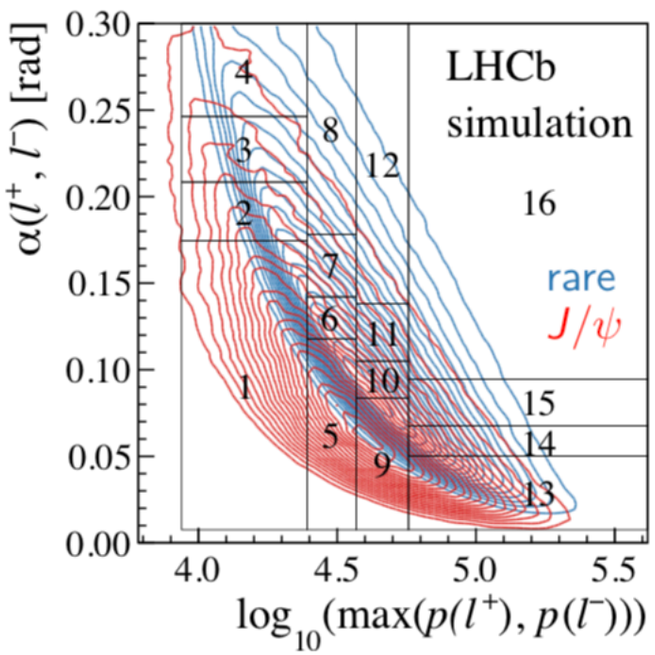


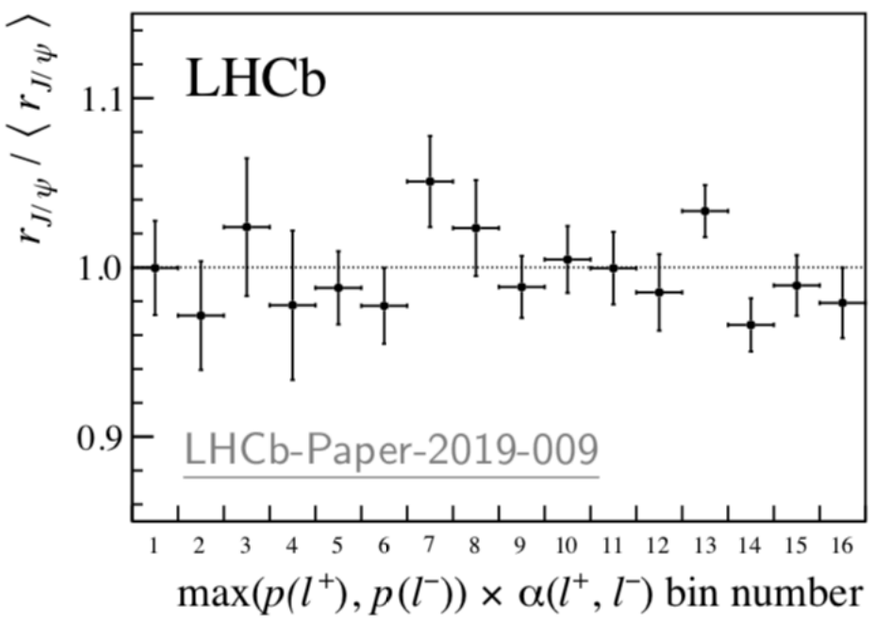
Ratio of efficiency determined with simulation using control channels:

- B-momentum kinematics, Tracking Efficiency,
- Particle Identification **EPJ T&I(2019)6:1**
- Trigger calibration
- Calibration of q^2 distribution and invariant mass

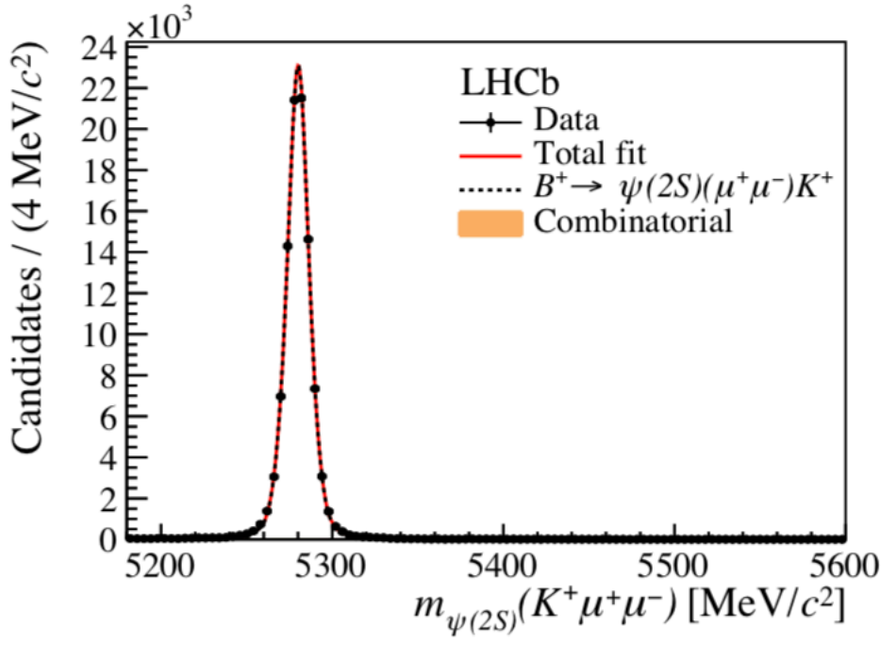
LFU in Rare Decays

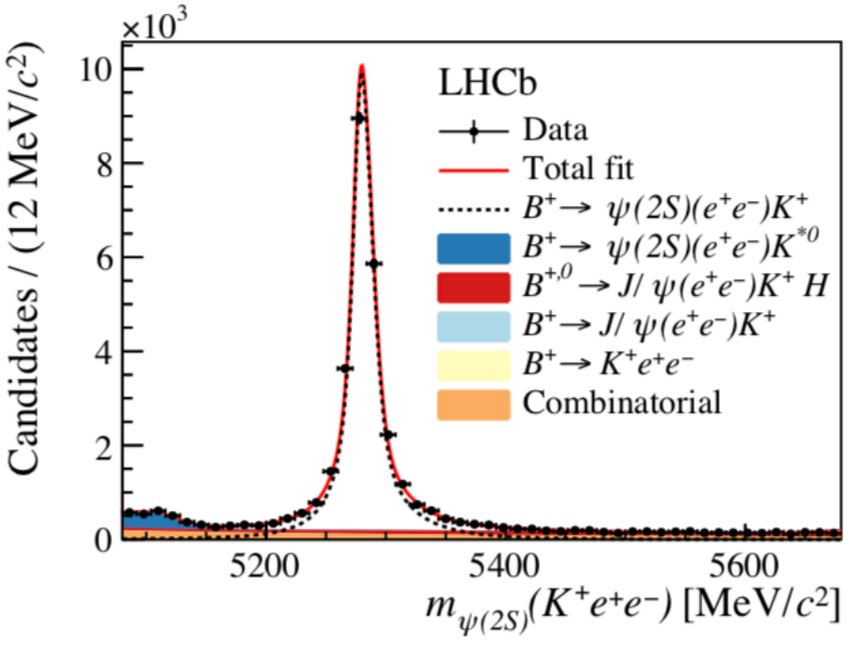
LHCb-PAPER-2019-009





$$r_{J/\psi} = 1.014 \pm 0.035 \text{ (stat. + syst.)}$$



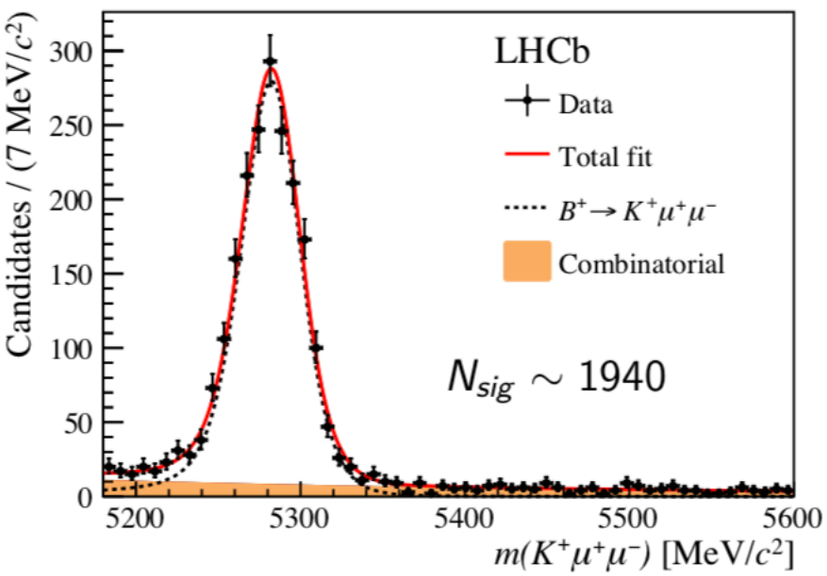


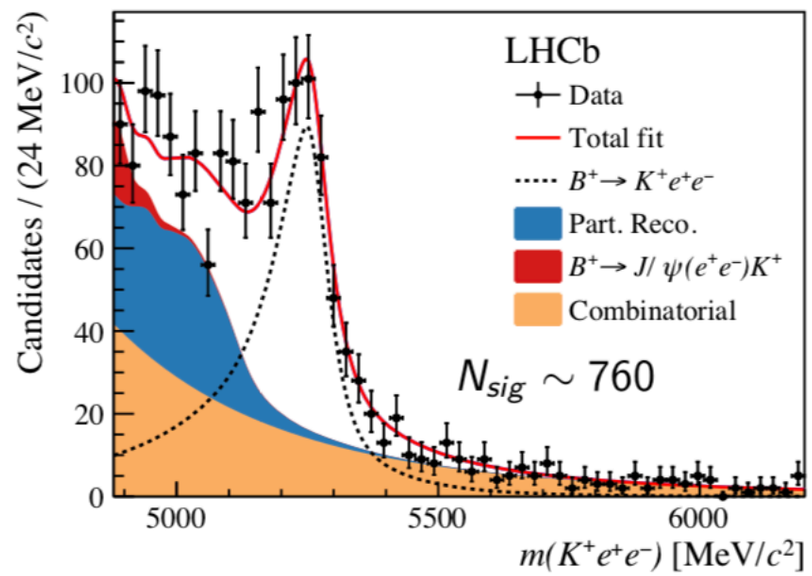
$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = 0.986 \pm 0.013 \text{ (stat + syst)}$$

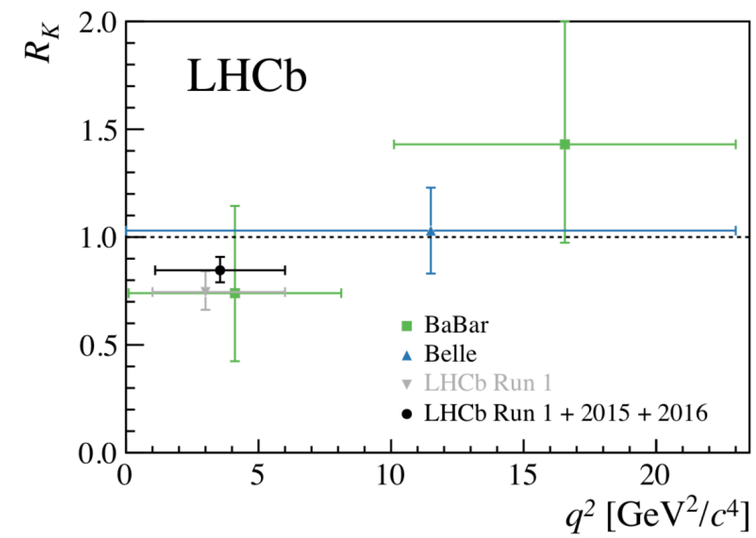
LFU in Rare Decays

LHCb-PAPER-2019-009

$$R(K^+) = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)} \frac{\mathscr{B}(B^+ \to K^+J/\psi(\to e^+e^-))}{\mathscr{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} = \frac{\int_{1.1GeV^2}^{6.0GeV^2} \frac{d\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{1.1GeV^2}^{6.0GeV^2} \frac{d\mathscr{B}(B^+ \to K^+e^+e^-)}{dq^2} dq^2} = 0.846^{+0.060}_{-0.054}(stat)^{+0.016}_{-0.014}(syst)$$







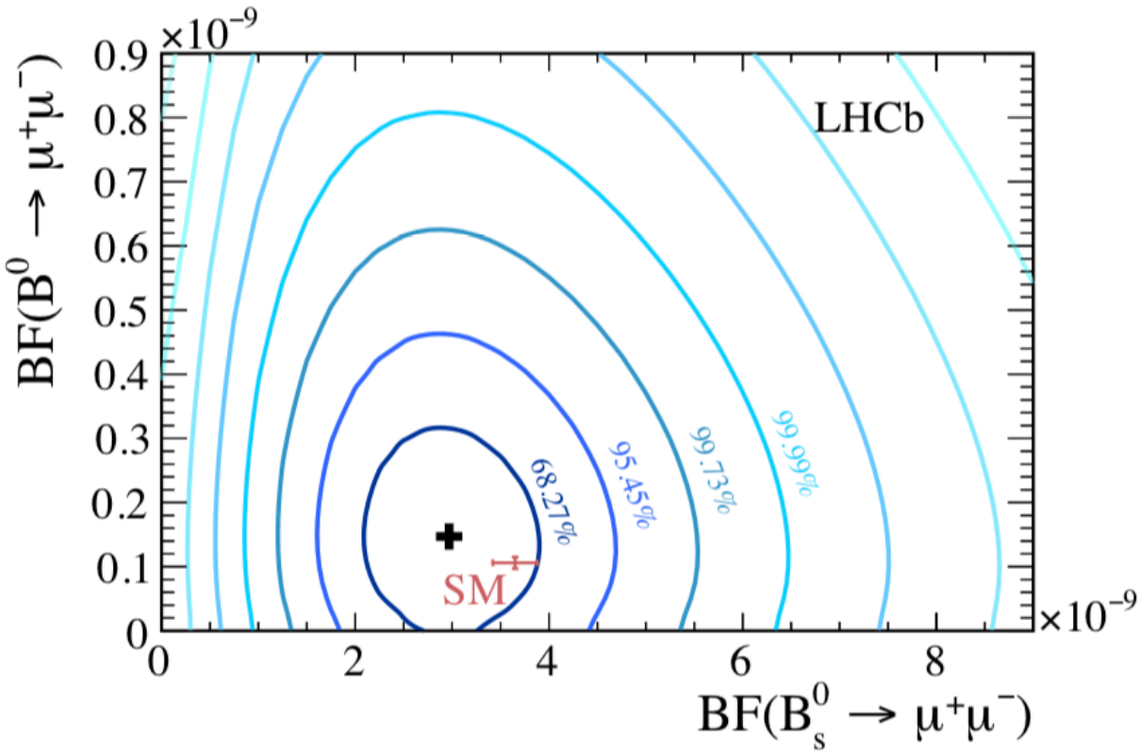
- 1.9 sigmas compatibility between Run1 and Run2
- Combined dataset 2.5 sigmas from SM predictions

Run1 + 2fb^{-1} (out of 6fb^{-1}) of Run2 (2015/2016)

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083+0.017}_{-0.071-0.016}, \qquad R_{K\ \mathrm{Run\ 2}} = 0.928^{+0.089+0.020}_{-0.076-0.017},$$

$$R_{K\ \mathrm{Run\ 1}}^{\mathrm{old}} = 0.745^{+0.090}_{-0.074} \pm 0.036 \quad (\mathrm{PRL113(2014)151601}),$$

$B_{s,d} \to \mu^+\mu^-$



- $B_{s,d} \to \mu^+\mu^-$ branching ratio sensitive to scalar and pseudo-scalar contributions, which lift helicity suppression
- No large enhancement, but still precise measurement of this decay sensitive to $C_{10}^{(')}$

$$BR(B_s \to \mu^+\mu^-) \propto |C_{10} - C'_{10}|^2$$

- Precise SM prediction

C. Bobeth et al. PRL 112, 101801 (2014)

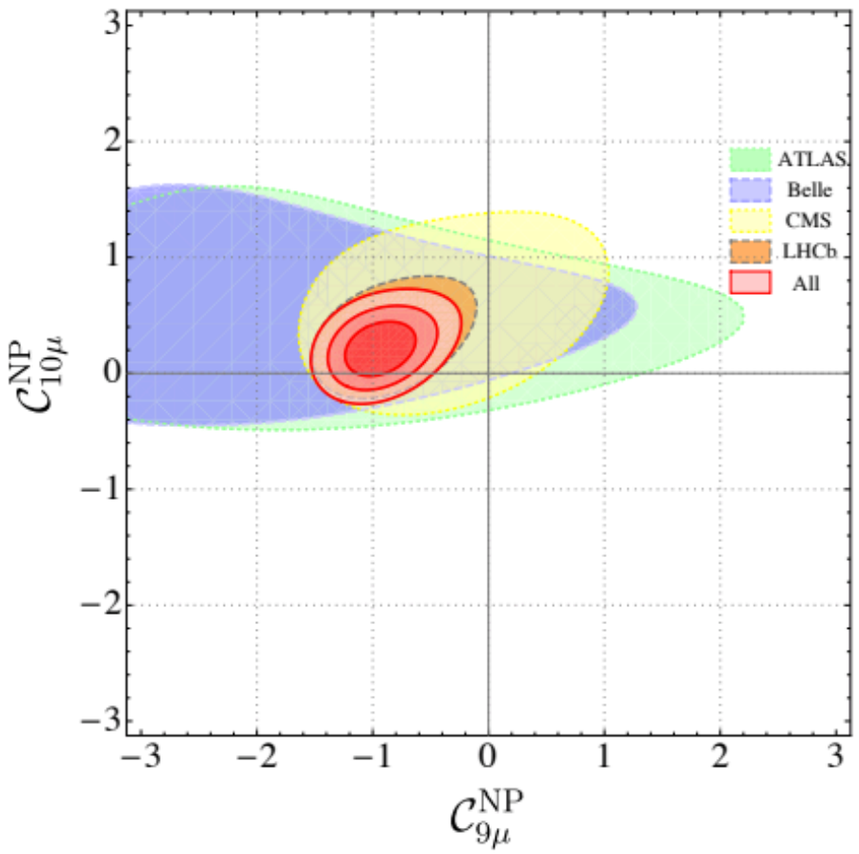
$$BR(B_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} \qquad BR(B^0 \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$$

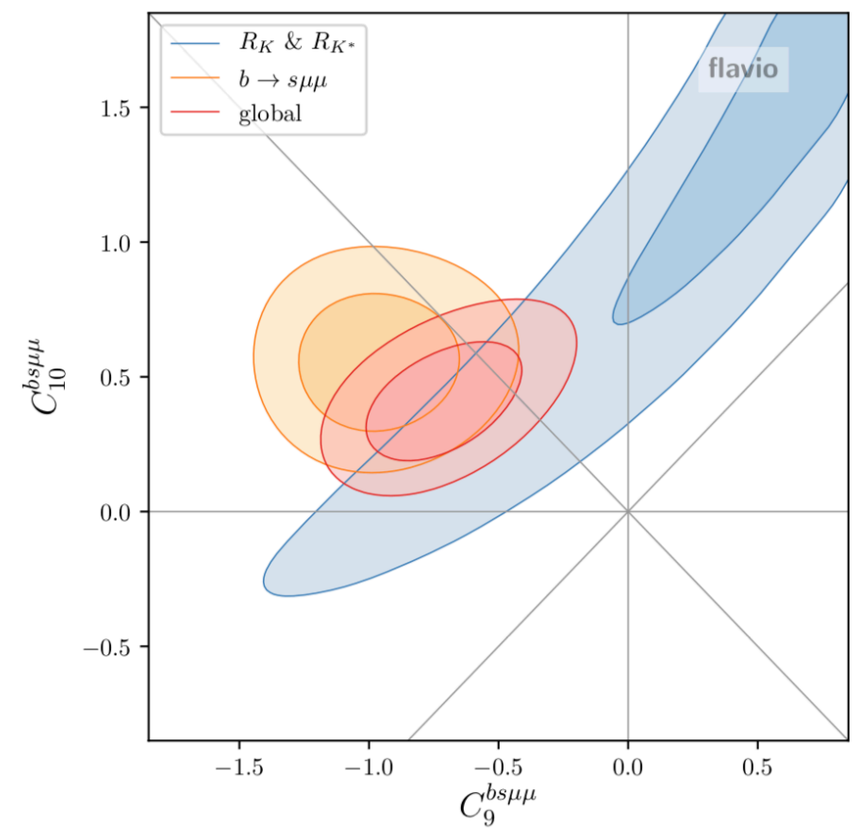
- First observation (7.8σ) by a single experiment experiment:

PRL 118 (2017) 191801

$$BR(B_s \to \mu^+\mu^-)_{LHCb} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \qquad BR(B^0 \to \mu^+\mu^-)_{LHCb} = (1.5^{+1.2+0.2}_{-1.0-0.1}) \times 10^{-10}$$

Wilson Coefficient Fits





Scenario		Best-fit point	1 σ	2 σ	Pull_{SM}	p-value
Scenario 5	$\mathcal{C}_{9\mu}^{\rm V}$	−0.34	[−0.93, +0.19]	[−1.57, +0.70]	5.5	71.6 %
	$\mathcal{C}_{10\mu}^{\rm V}$	+0.69	[+0.21, +1.12]	[−0.33, +1.52]		
	$\mathcal{C}_9^{\rm U} = \mathcal{C}_{10}^{\rm U}$	−0.50	[−0.92, +0.02]	[−1.26, +0.59]		
Scenario 6	$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$	−0.52	[−0.64, −0.41]	[−0.75, −0.31]	5.8	71.5 %
	$\mathcal{C}_9^{\rm U} = \mathcal{C}_{10}^{\rm U}$	−0.37	[−0.52, −0.22]	[−0.64, −0.06]		
Scenario 7	$\mathcal{C}_{9\mu}^{\rm V}$	−0.91	[−1.25, −0.58]	[−1.57, −0.26]	5.5	65.3 %
	$\mathcal{C}_9^{\rm U}$	−0.08	[−0.46, +0.31]	[−0.82, +0.71]		
Scenario 8	$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$	−0.33	[−0.45, −0.22]	[−0.56, −0.12]	5.9	74.1 %
	$\mathcal{C}_9^{\rm U}$	−0.72	[−0.93, −0.47]	[−1.12, −0.22]		
Scenario 9	$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$	−0.63	[−0.79, −0.47]	[−0.94, −0.33]	5.3	73.4 %
	$\mathcal{C}_{10}^{\rm U}$	−0.39	[−0.65, −0.13]	[−0.89, +0.13]		

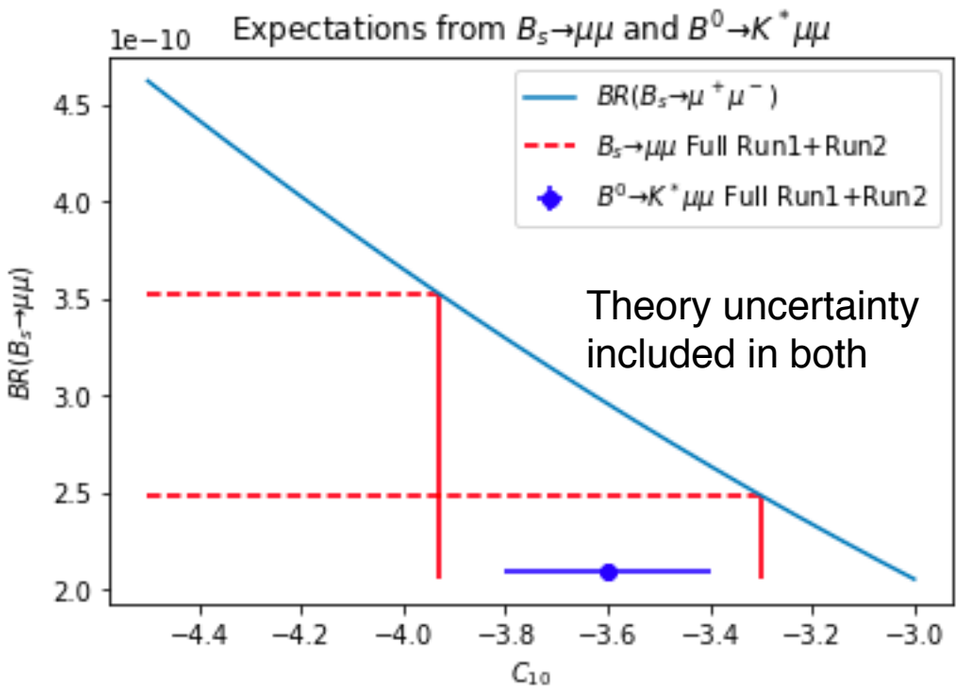
J Matias et al., Portoz 2019 & 1903.09578

Coeff.	Dirac structure	best fit	1σ	pull
$C_9^{bs\mu\mu}$	$L \otimes V$	−0.95	[−1.10, −0.79]	5.8σ
$C_9'^{bs\mu\mu}$	$R \otimes V$	+0.09	[−0.07, +0.24]	0.5σ
$C_{10}^{bs\mu\mu}$	$L \otimes A$	+0.73	[+0.59, +0.87]	5.6σ
$C_{10}'^{bs\mu\mu}$	$R \otimes A$	−0.19	[−0.30, −0.07]	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	+0.20	[+0.05, +0.35]	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$L \otimes L$	−0.53	[−0.62, −0.45]	6.5σ

D. Straub Moriond EW 2019 & 1903.10434

Near Future

- The decay $B^0 \to K^*\mu^+\mu^-$ allows also to probe C_{10}



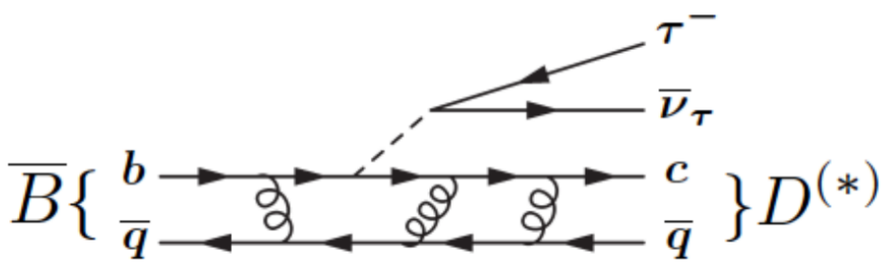
My own extrapolation from current experimental results and using arXiv:1805.06378

- R(K*) measurement with full Run1+Run2 (only Run1)
- R(K) measurement with full Run1+Run2 (only Run1 + 2015-2016)
- Measurement of other related decays R(ϕ), R(Kππ), R($\Lambda^{(*)}$)
- Measurement of non-LFU angular asymmetries in $B^0 \to K^*\ell^+\ell^-$ such as ΔP_5'
- Measurement of $C_9^{\mu\mu}$ - C_9^{ee} and $C_{10}^{\mu\mu}$ - C_{10}^{ee} **Phys. Rev. D 99, 013007 (2019)**

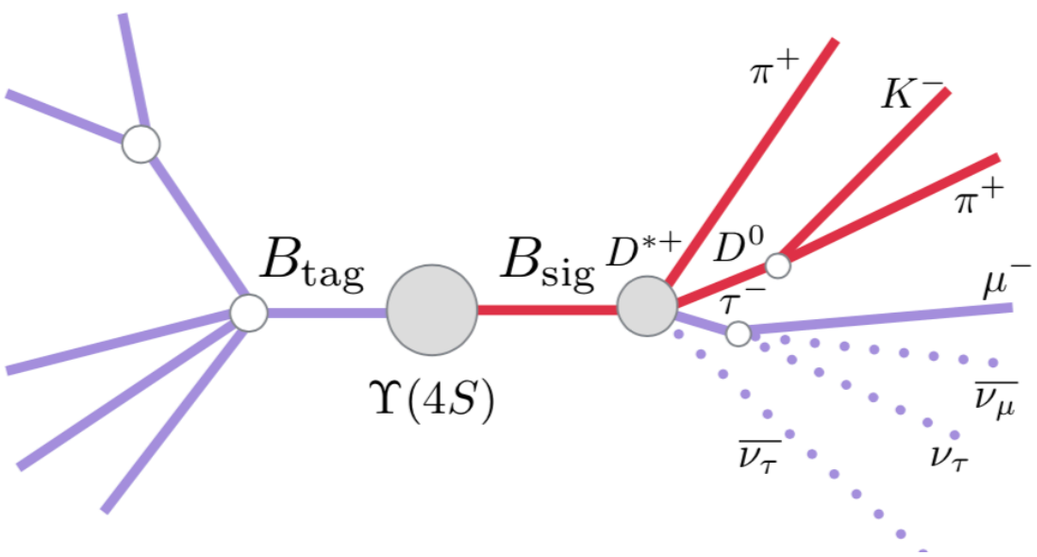
Semileptonic

	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \to B\bar{B}$	$\Upsilon(4S) \to B\bar{B}$	$pp \to gg \to b\bar{b}$

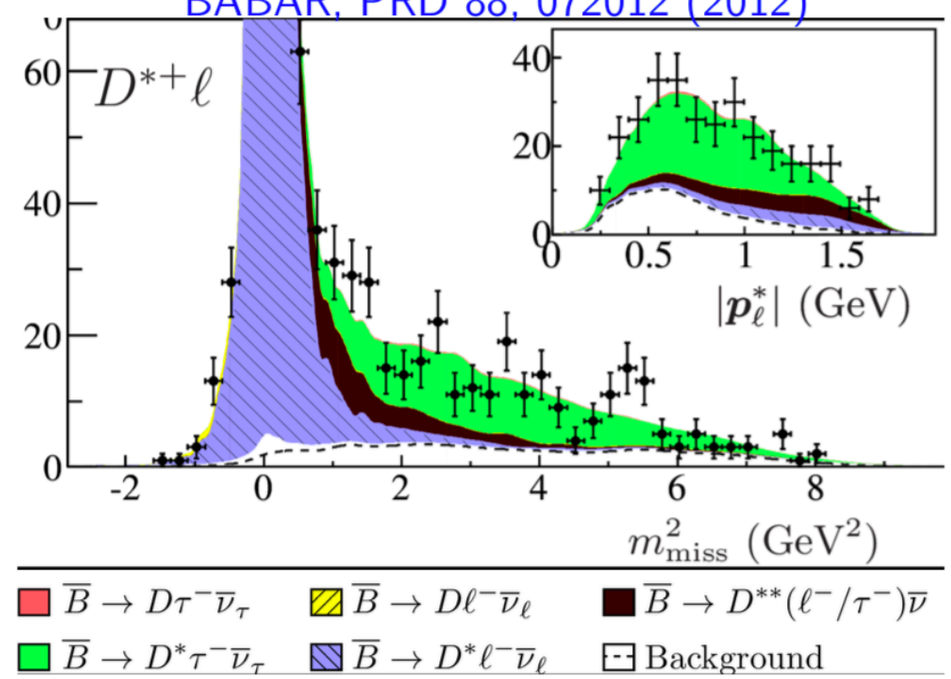
LFU with Semileptonic



$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)} = \frac{Signal}{Normalization}$$

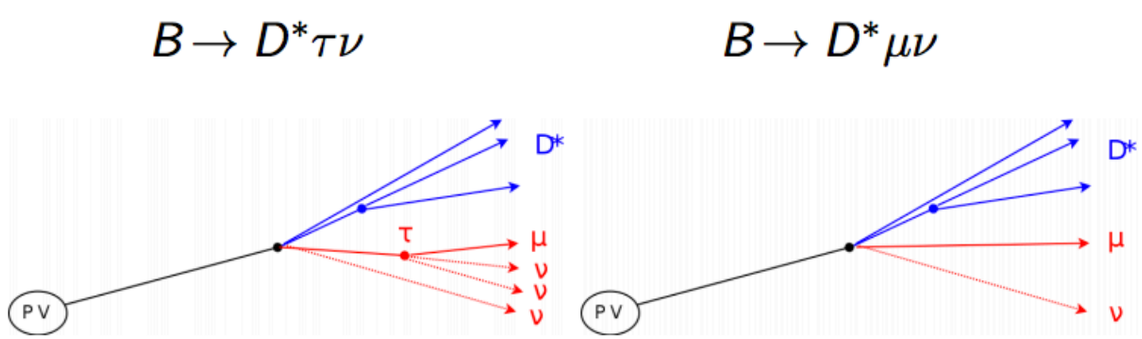


BABAR, PRD 88, 072012 (2012)



- B-factories exploit the fact that B_{sig} momentum
- B-factories use the electron, muon and hadronic modes
- LHCb only uses $\tau \to \mu 2\nu$ and $\tau \to 3\pi\nu$
- B-factories have cleaner events, while LHCb larger statistics

LFU with Semileptonic

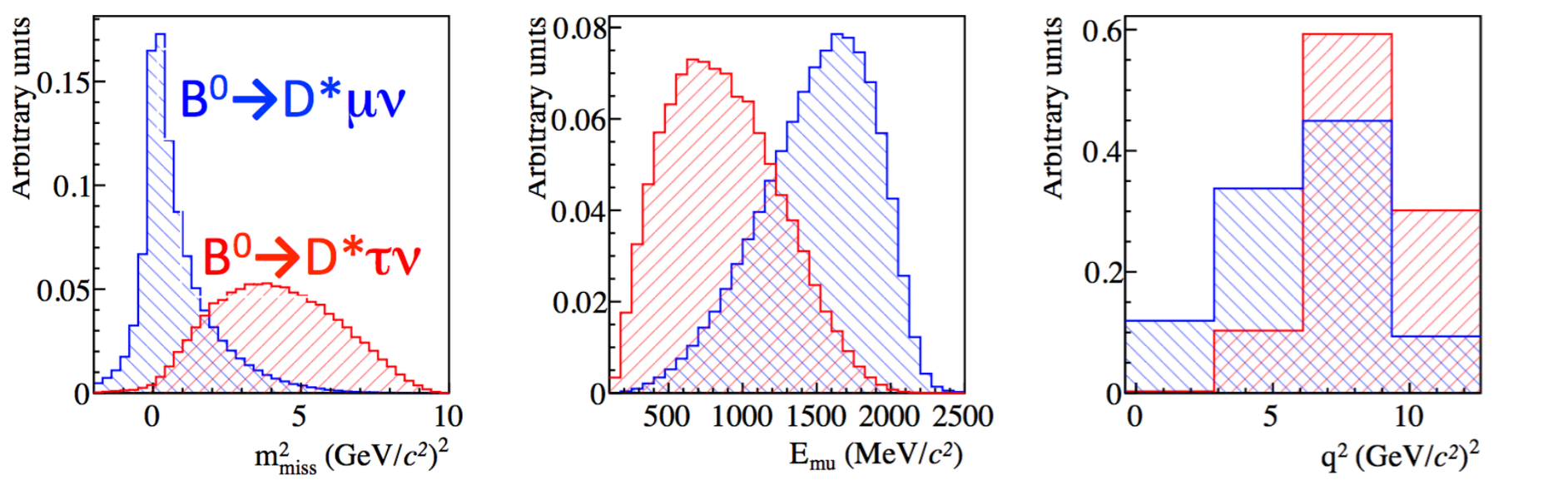


$$(\gamma\beta_{\hat{z}})_B \simeq (\gamma\beta_{\hat{z}})_{D^*\mu} \Rightarrow (p_{\hat{z}})_B = \frac{m_B}{m(D^*\mu)}(p_{\hat{z}})_{D^*\mu}$$

- Fit of E* and missing mass using template from the simulation tuned with data
- Background from $B \to D^* D_{(s)}$ and from $B \to D^{**}\ell\nu$ taken from control regions

LHCb simulation

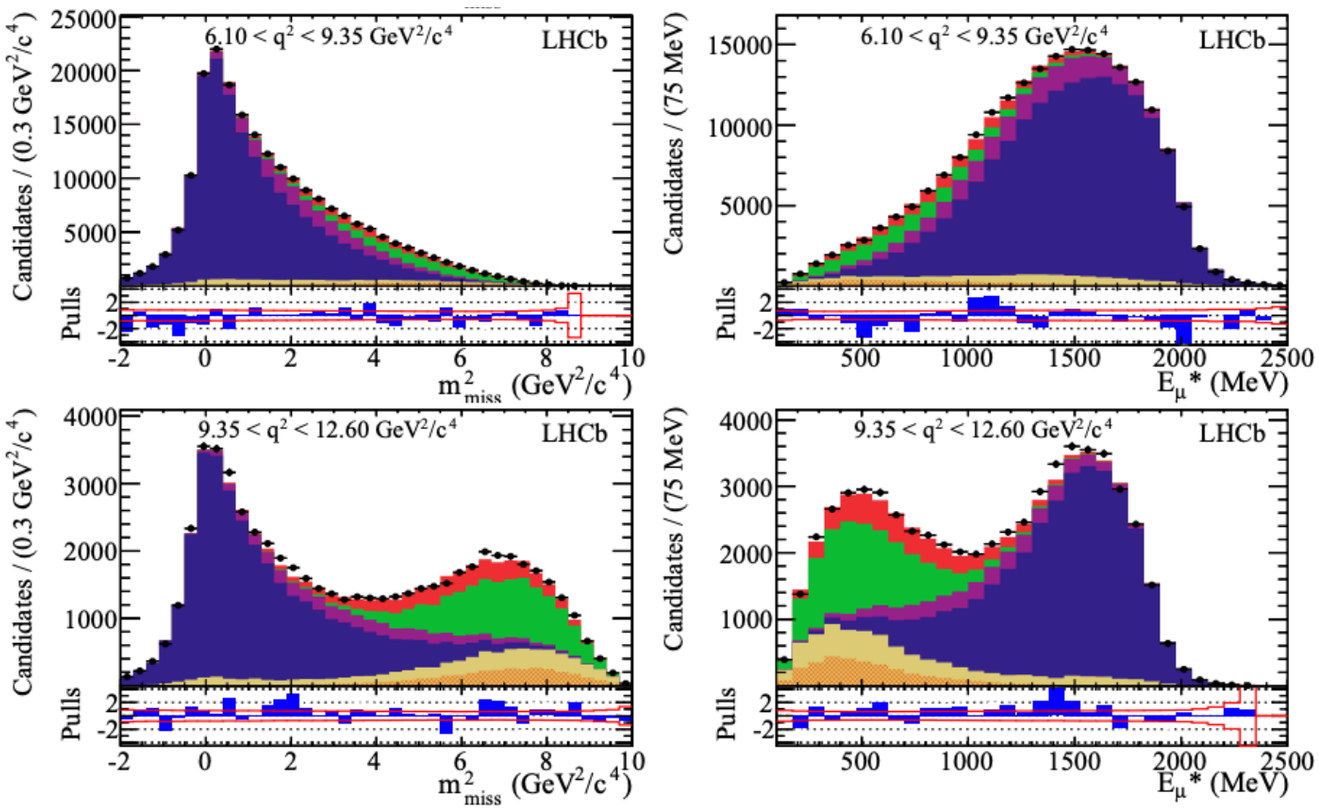
Supplementary material PRL115(2015)111803



LFU with Semileptonic

$\tau \to \mu 2\nu$

LHCb Coll., Phys.Rev.Lett. 115 (2015) no.11, 111803



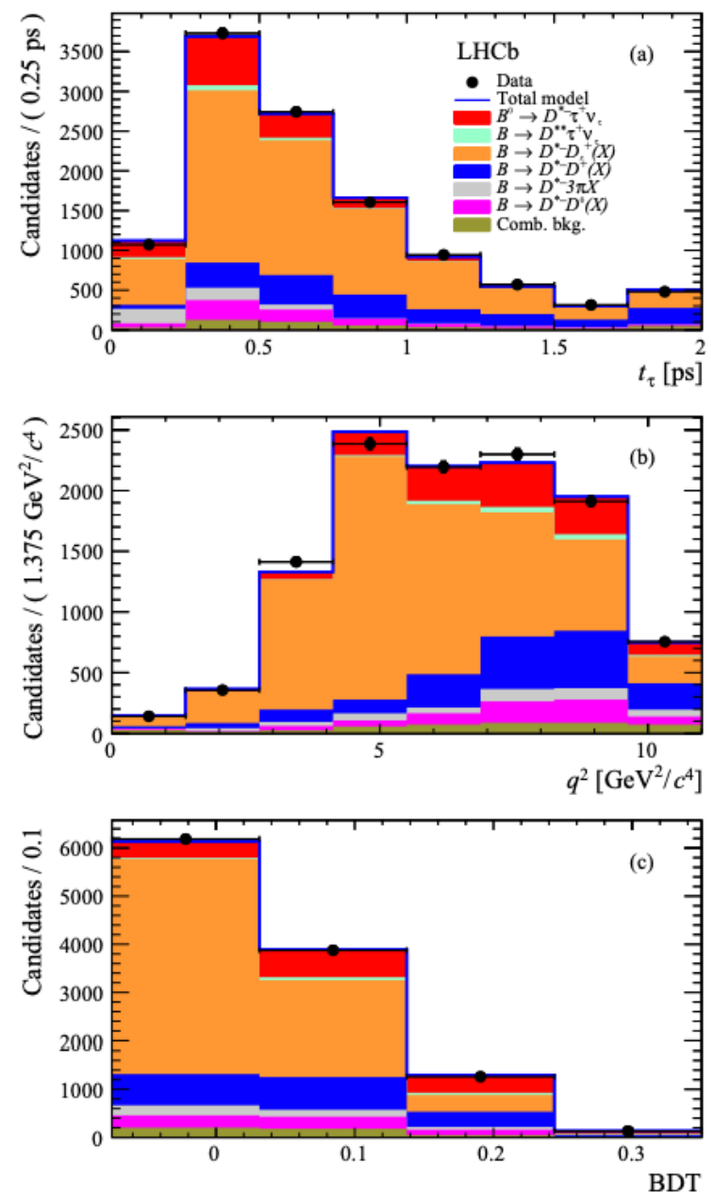
$$R(D^*)_{\tau\to\mu 2\nu} = 0.336 \pm 0.027 \pm 0.030$$

SM Prediction

$R(D^*)_{SM} = 0.252 \pm 0.003$ (S. Fajfer et al. 2012)

$\tau \to 3\pi\nu$

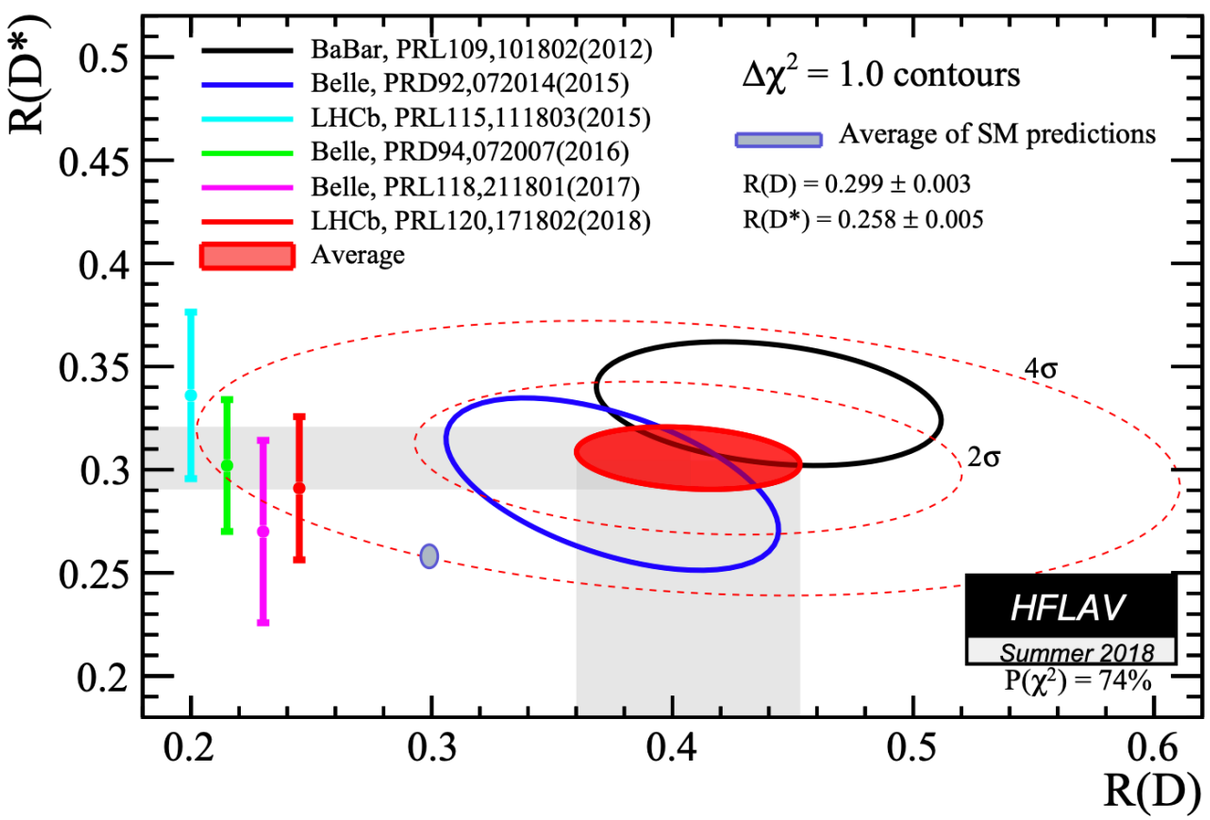
LHCb Coll., Phys. Rev. D 97, 072013 (2018)

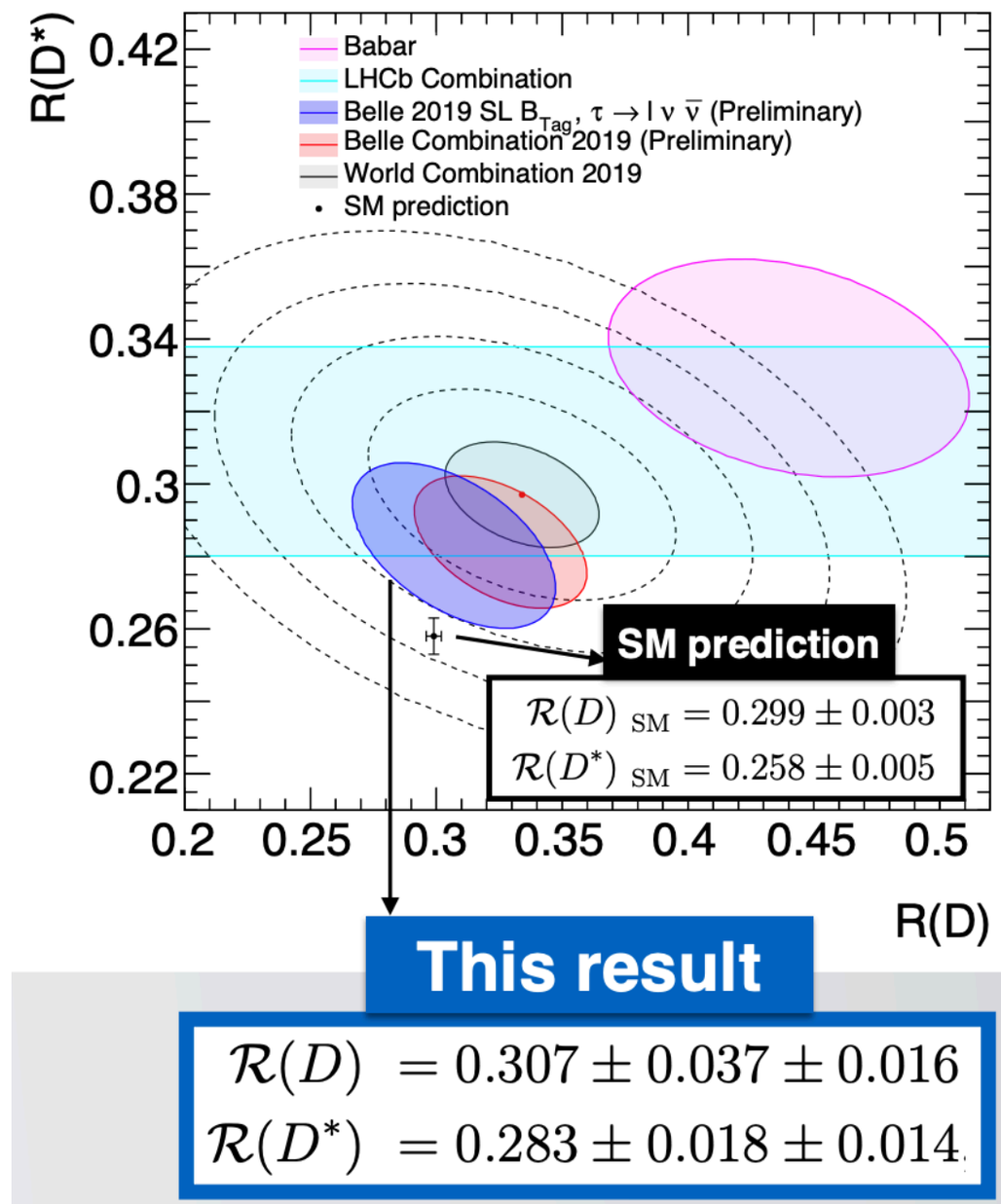


$$R(D^*)_{\tau\to 3\pi\nu} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

Combination

HFLAV 2018





- Tension wrt SM predictions goes from 3.8σ (pre-Moriond 2019) to 3.1σ (post-Moriond 2019)

G. Caria, Moriond EW, March 2019

Near Future

- Measurement of $R(D^*)$ from LHCb still with Run1, but much better trigger efficiency for Run2

- Several measurements in the pipeline:

  - Simultaneous measurement of $R(D^*)$ and $R(D^0)$ with Run1 + Run2
  - Measurement of $R(D_s)$ with Run2
  - Measurement of $R(D^+)$ and $R(D^*)$with Run2
  - Measurement of $R(\Lambda_c)$ with Run2

Less feed-down background

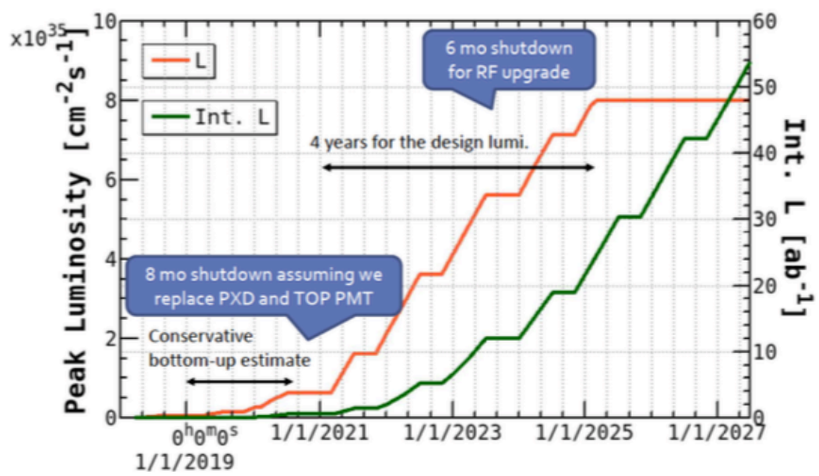
Belle II

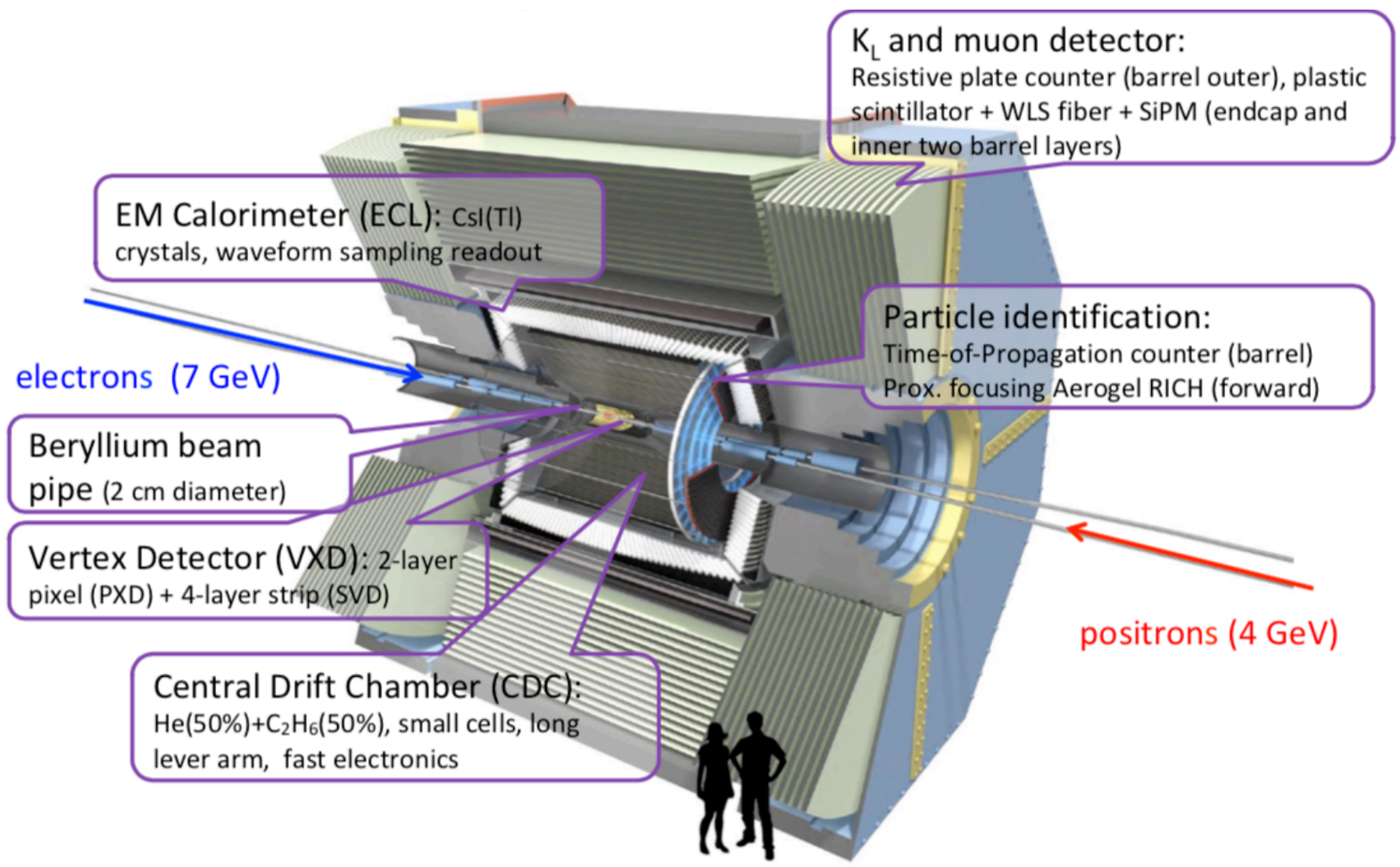
Belle II experiment at SuperKEK:

Belle II TDR, arXiv:1011.0352

- Target Luminosity

$$\mathscr{L} = 8 \times 10^{35} cm^{-2} s^{-1} \Rightarrow 10^{10} B\overline{B}, \tau^+\tau^-, c\overline{c} \text{ pairs} \qquad \int \mathscr{L} dt > 50 ab^{-1}$$



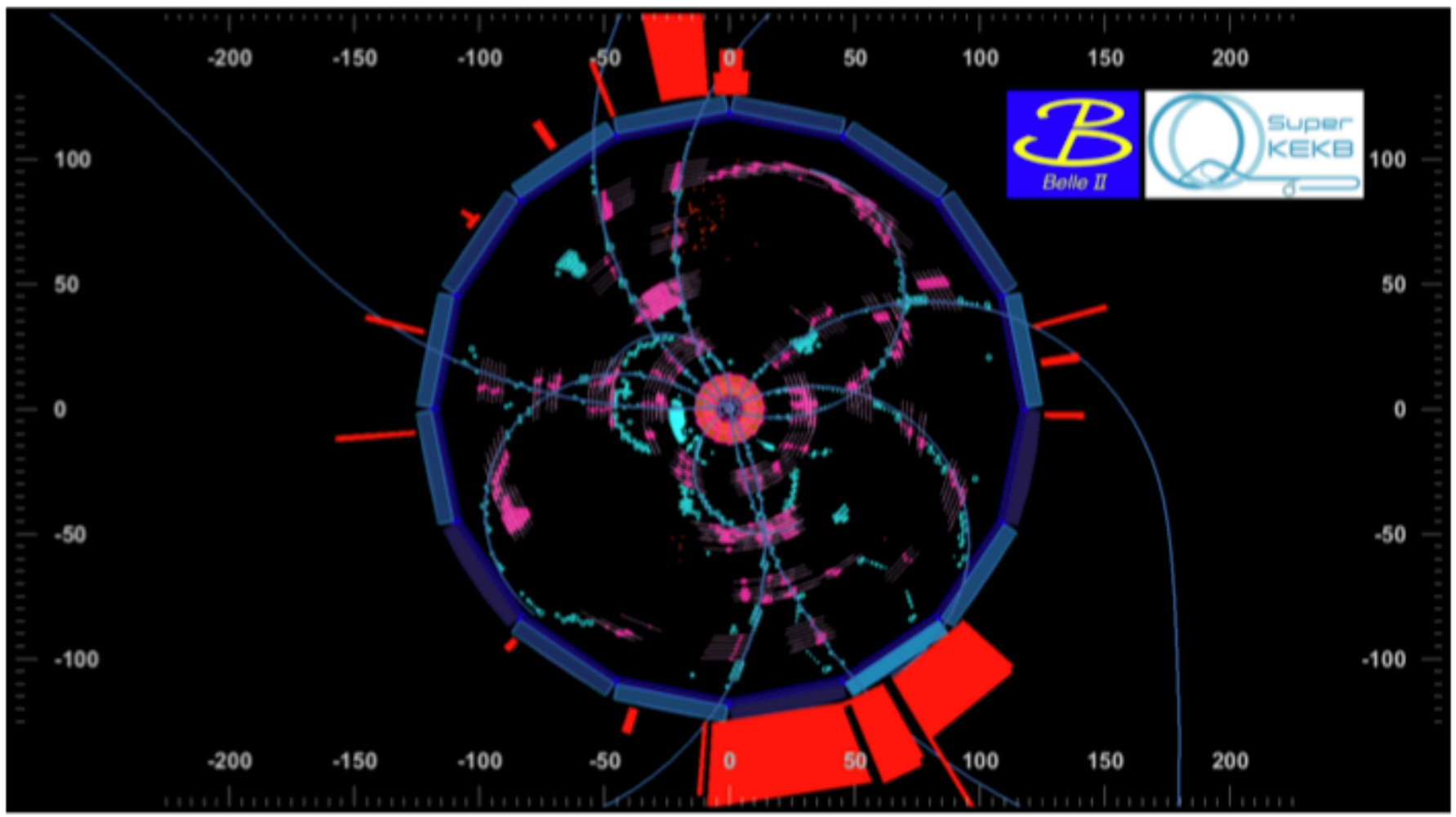


Improvements wrt Belle:

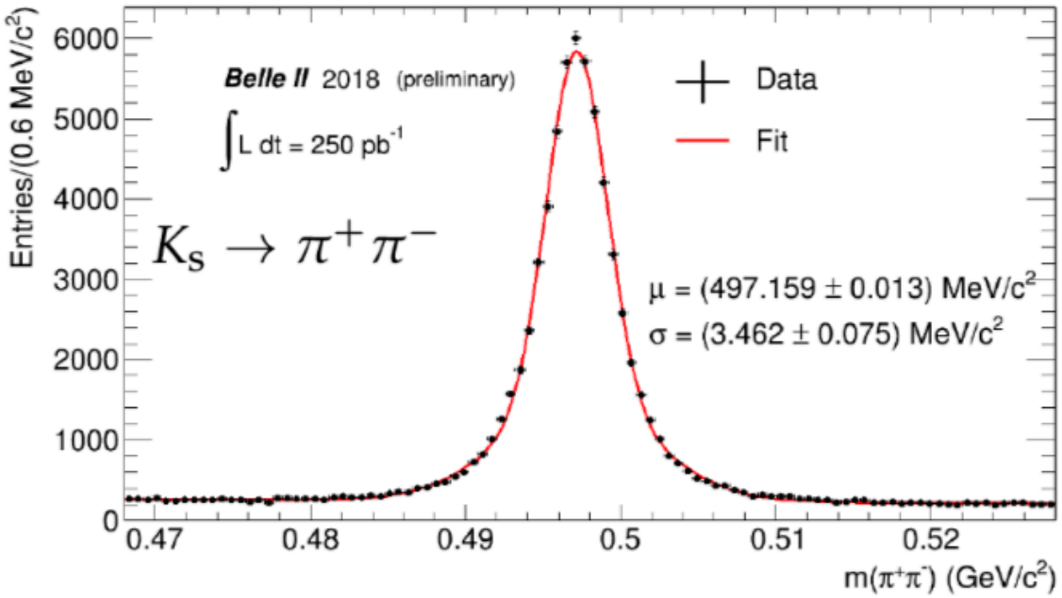
- Capability to deal with higher bkg, radiation damage, occupancy
- Higher trigger efficiency
- Improved performances and hermeticity

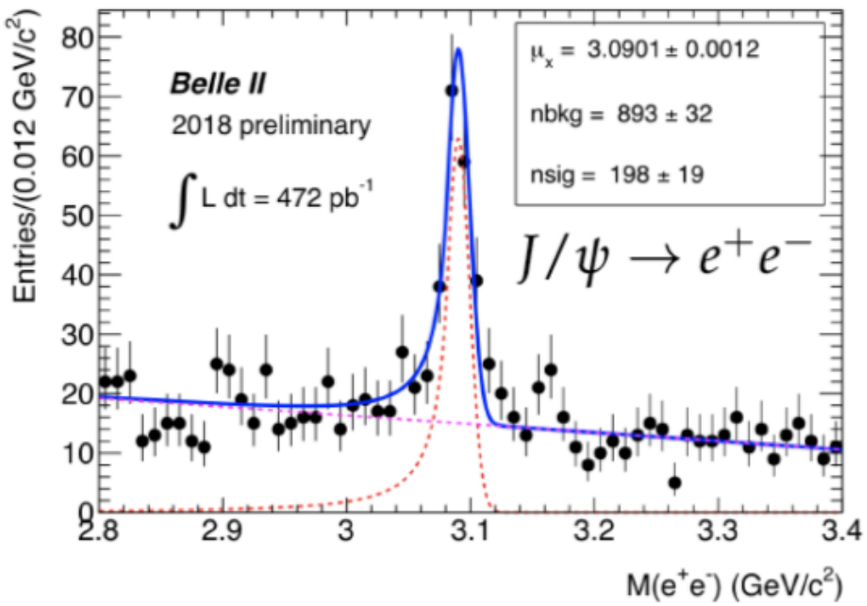
Belle II

First $B\bar{B}$ event seen in Belle II detector



Belle II





❑ Charged tracks reconstructed using info mostly from the CDC are available since the beginning of collisions

❑ Mass resolutions of known particles in data in agreement with simulations (B field measured well and sub-detectors also aligned)

Gagan Mohanty, Moriond EW 2019

- Physics run of Belle2 started:
  - First results envisaged for LP2019
- – Significant luminosity ~2022

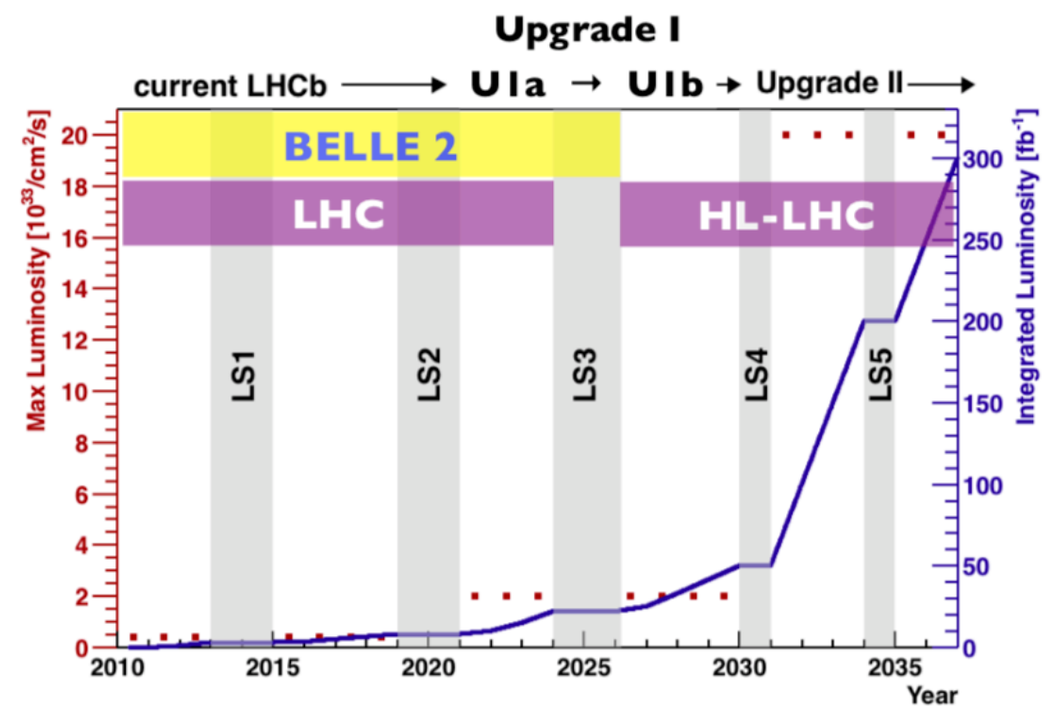
Belle II Physics Book

arXiv:1808.10567

LHCb Upgrades

[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]

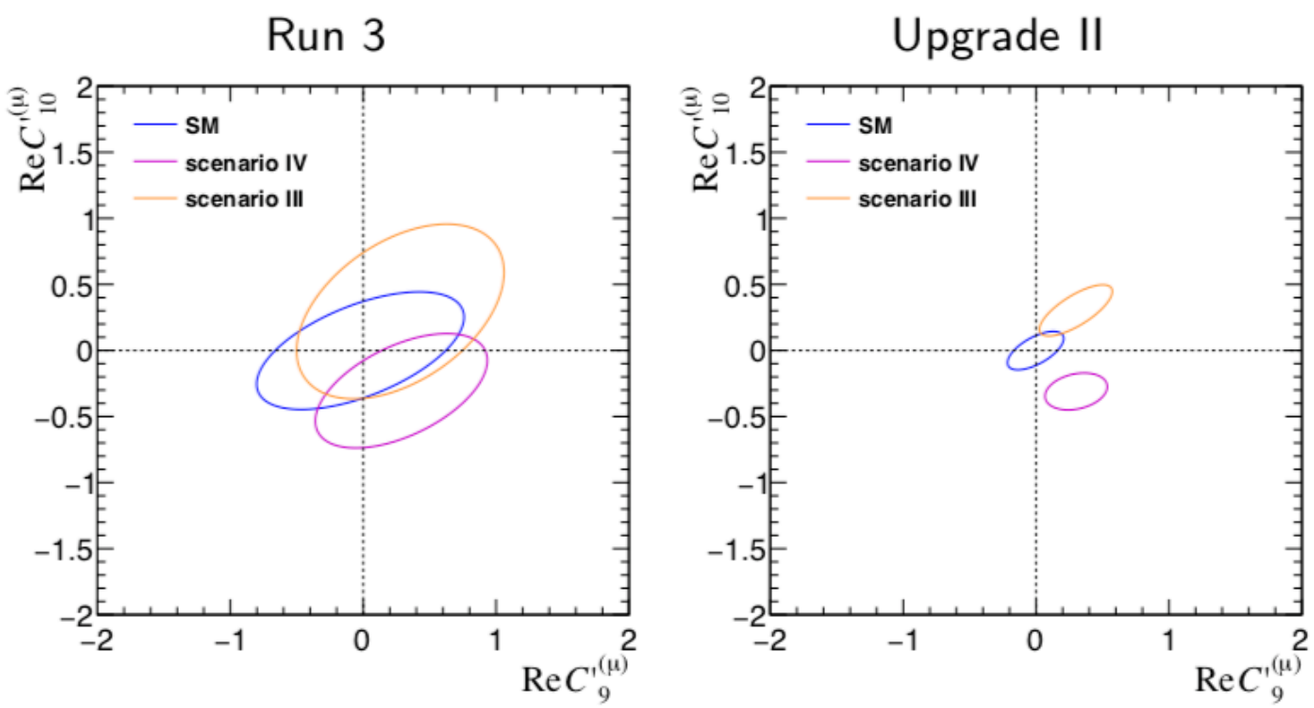
- Upgrade of the LHCb detector during LHC LS2 (2019-20):
  - Change subdetector electronics to 40 MHz readout
  - All trigger decision software
  - Start data taking in 2021
  - Upgrade detector qualified to accumulate $50fb^{-1}$



In order to exploit the full potential of the LHC, it is natural to have a further major LHCb upgrade during LS4

The Upgrade II will allow to increase data sample from $50fb^{-1}$ to $300fb^{-1}$

LHCb Upgrades

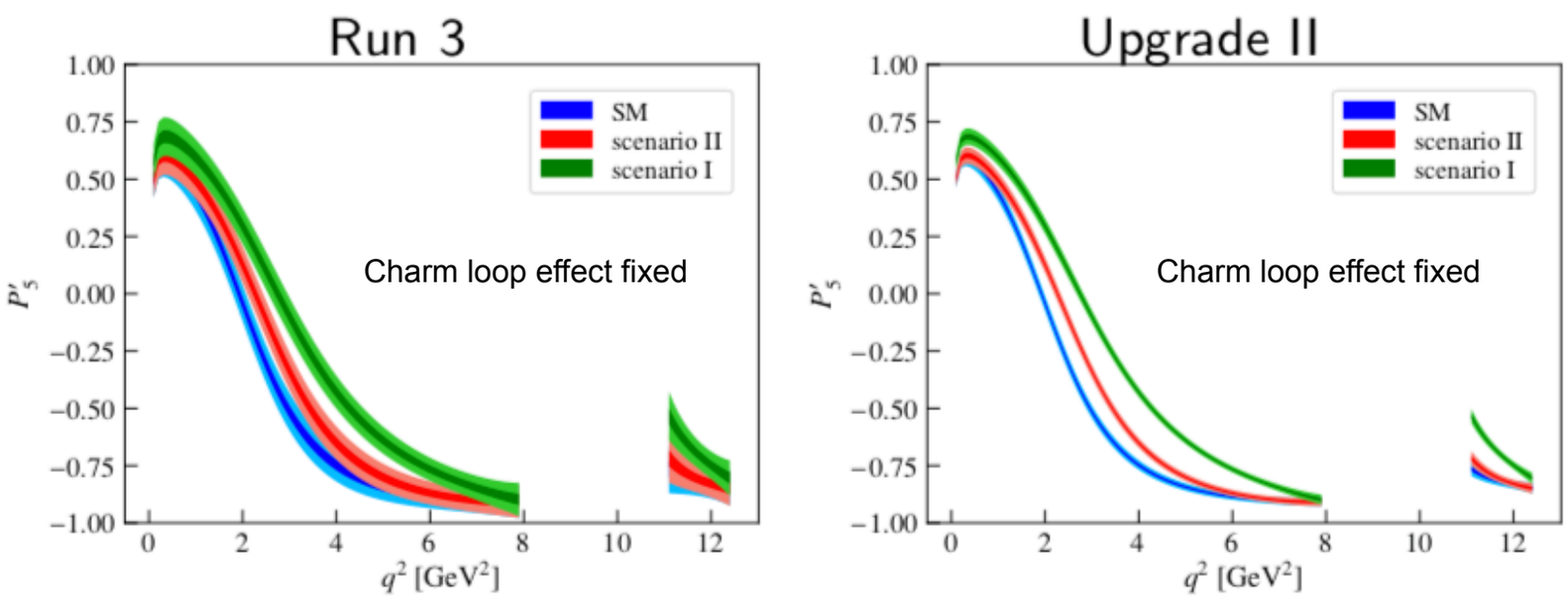


[CERN-LHCC-2017-003]

[CERN-LHCC-2018-027]

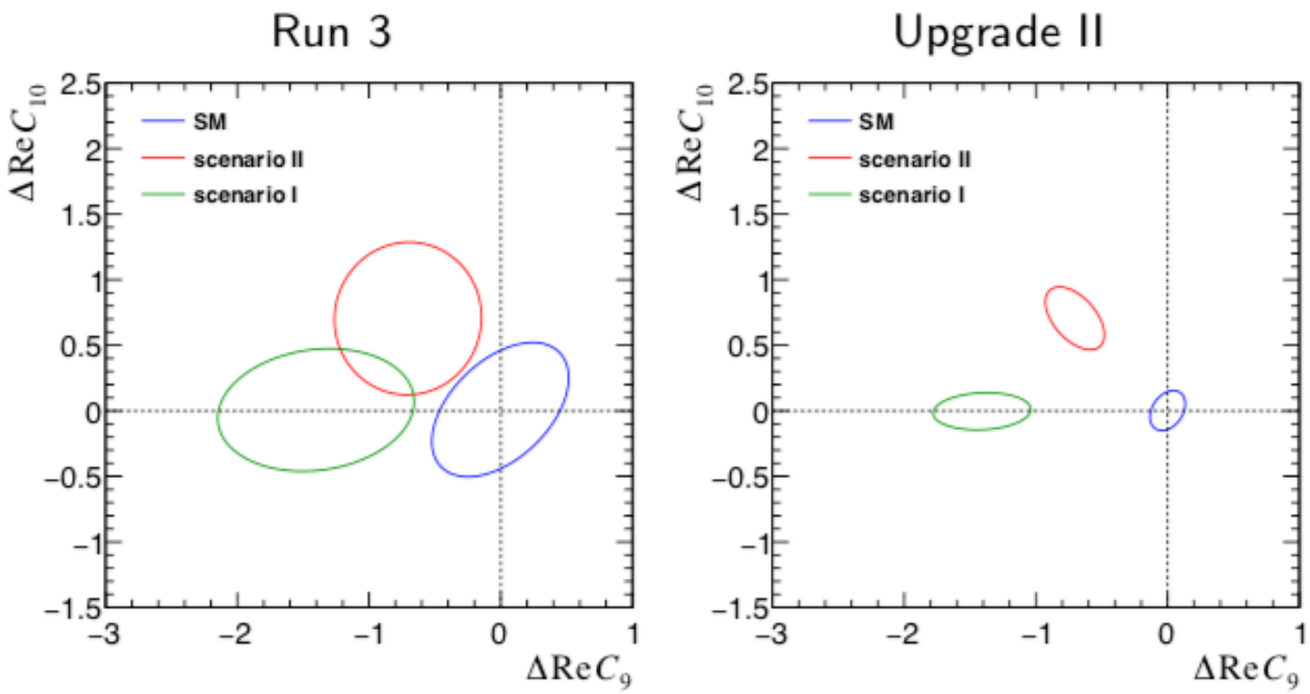
Physics of the HL-LHC, WG 4 Flavour [arxiv:1812.07638]

Scenario	$\Delta\mathcal{C}_9$	$\Delta\mathcal{C}_{10}$
SM	0	0
I	-1.4	0
II	-0.7	+0.7



Scenario	$\mathcal{C}_9'$	$\mathcal{C}_{10}'$
SM	0	0
III	+0.3	+0.3
IV	+0.3	-0.3

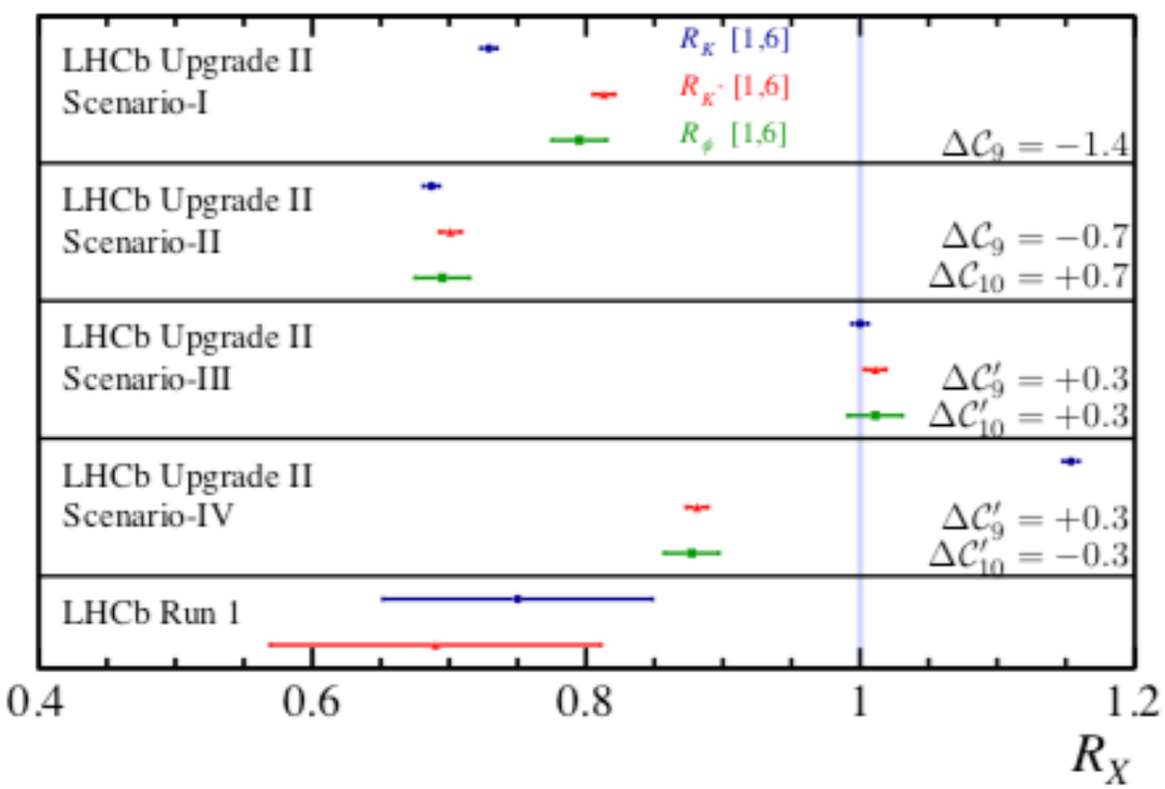
LHCb Upgrades



Scenario	ΔC_9	ΔC_{10}
SM	0	0
I	-1.4	0
II	-0.7	+0.7

[Upgrade II Physics case] [Physics of the HL-LHC WG 4]

Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	300 fb^{-1}
$B^+ \to K^+ e^+ e^-$	254 ± 29	1120	3300	46000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14	490	1400	20000
$B_s^0 \to \phi e^+ e^-$	–	80	230	3300
$\Lambda_b^0 \to p K e^+ e^-$	–	120	360	5000
$B^+ \to \pi^+ e^+ e^-$	–	20	70	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$	0.043	0.025	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$	0.052	0.031	0.008
R_ϕ	–	0.130	0.076	0.020
R_{pK}	–	0.105	0.061	0.016
R_π	–	0.302	0.176	0.047



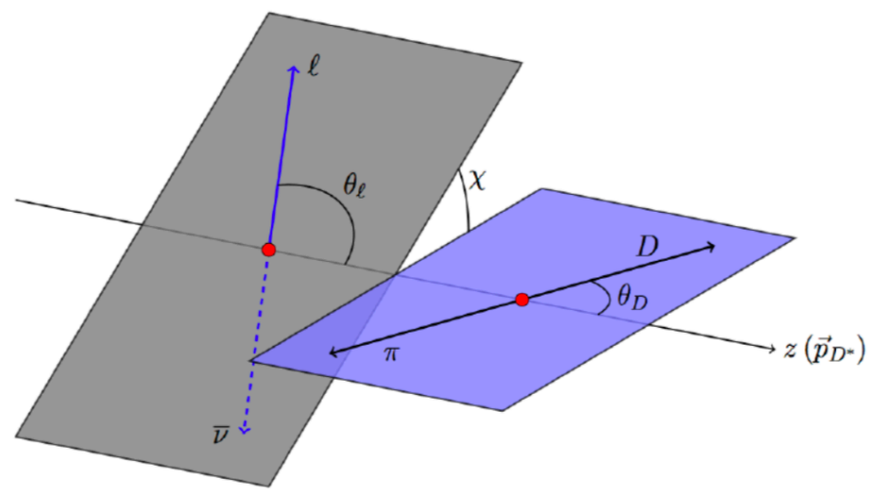
[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]

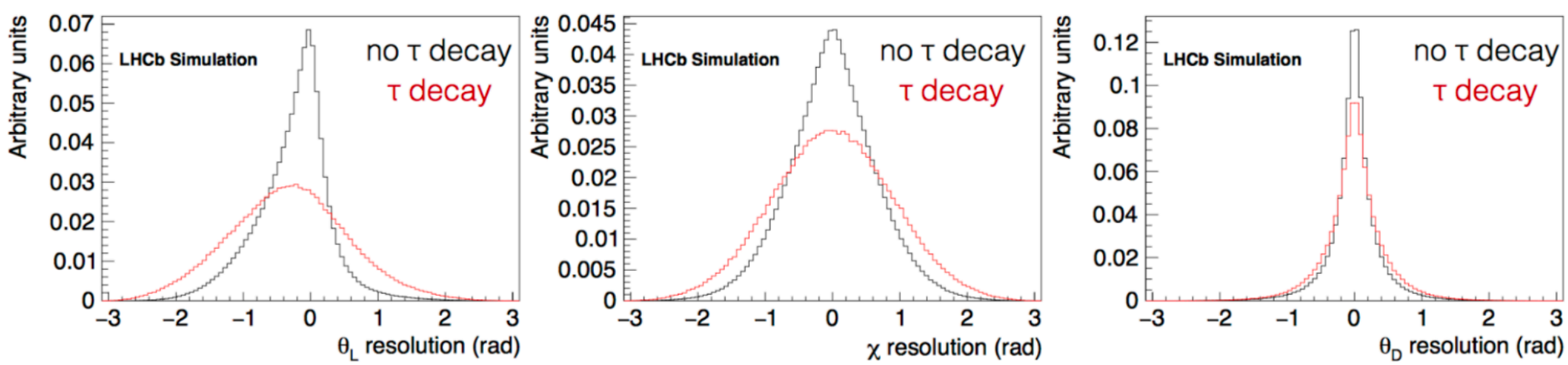
Physics of the HL-LHC, WG 4
Flavour [arxiv:1812.07638]

LHCb Upgrades

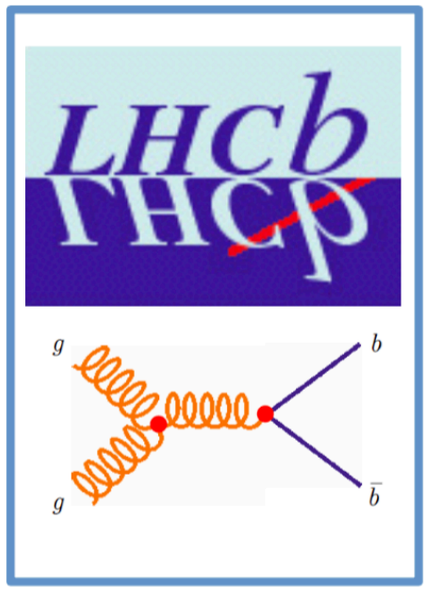
Expected LHCb sensitivity with Upgrade II: $\frac{\sigma(R(D^*))}{R(D^*)} \sim 1\,\%$

Angular analysis of semi-tauonic decays allow to determine spin structure of potential NP contribution

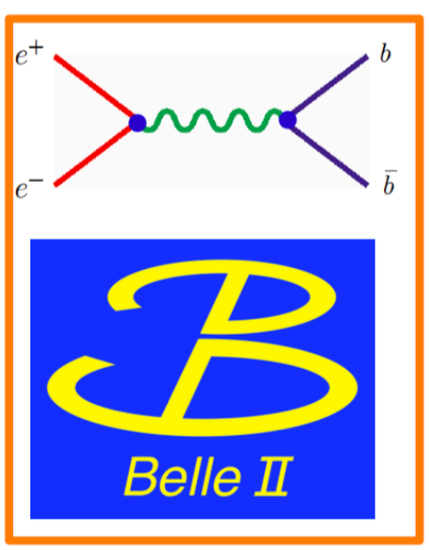




Belle II and LHCb Upgrades



- Time dependent B_s physics
  - CPV in $B_s \to J/\psi\, \phi$, $B_s \to \phi\phi$
- $B_s \to \mu^+\mu^-$
- CKM angle γ
- CPV in B_d
- $B \to X_s\, \ell^+\ell^-$ (exclusive) → **LFU**
- $B \to X_s\, \gamma$ (exclusive)
- Charm physics
- Semileptonic B decays
- $B \to D\, \tau^- \nu$, $B \to D^*\, \tau^- \nu$
- Dark matter
- τ − physics: LFV
- $B \to \tau^- \nu$, $B \to \mu^- \nu$
- $B \to K^*\, \nu\nu$, $B \to \nu\nu$
- $B \to X_s\, \ell^+\ell^-$ (inclusive)
- $B \to X_s\, \gamma$ (inclusive)



"B_s & charged tracks"

Important overlap: sporty competition!

"inclusive & neutrals "

J. Albrecht Portoroz 2019

Conclusions

- Intriguing patter of anomalies in rare and semi-leptonic decays, measured by LHCb, BaBar and Belle

- Still need much larger statistics to understand if these anomalies are a genuine sign of PBSM

- More results will come from LHCb Run2 analyses for both anomalies

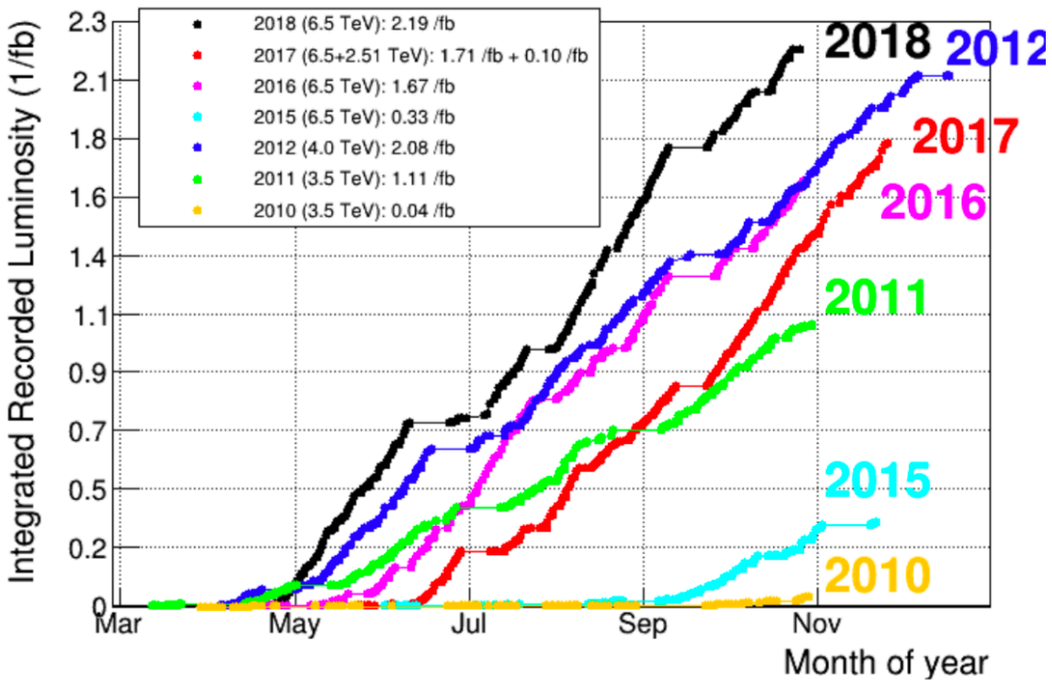
- Belle II and LHCb Upgrades will allow to further clarify the situation and if these anomalies are due to NP to disentangle between different scenarios

Let’s hope this story doesn’t have a disappointing finale

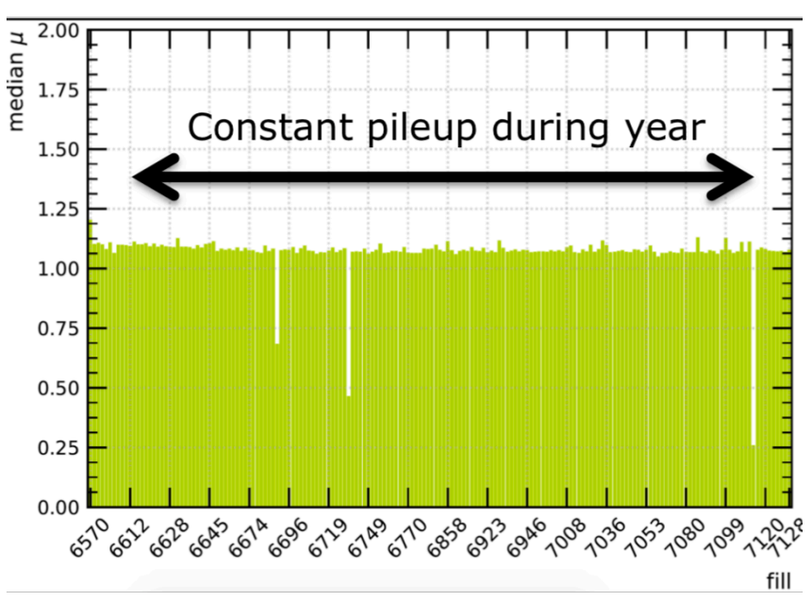
Backup Slides

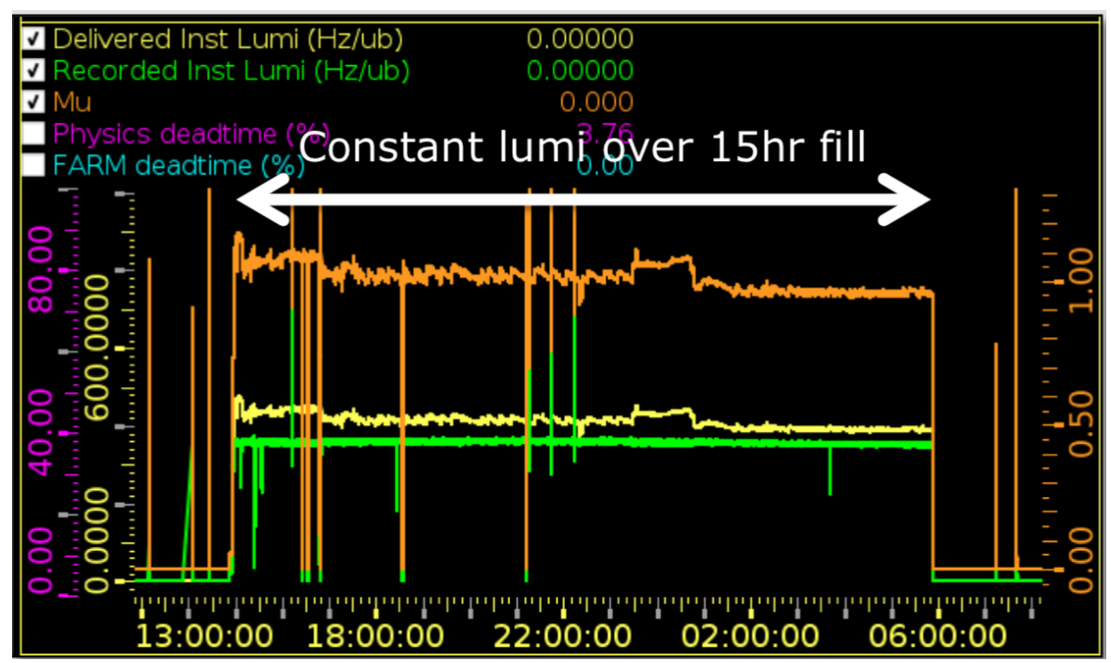
LHCb Experiment

LHCb Experiment

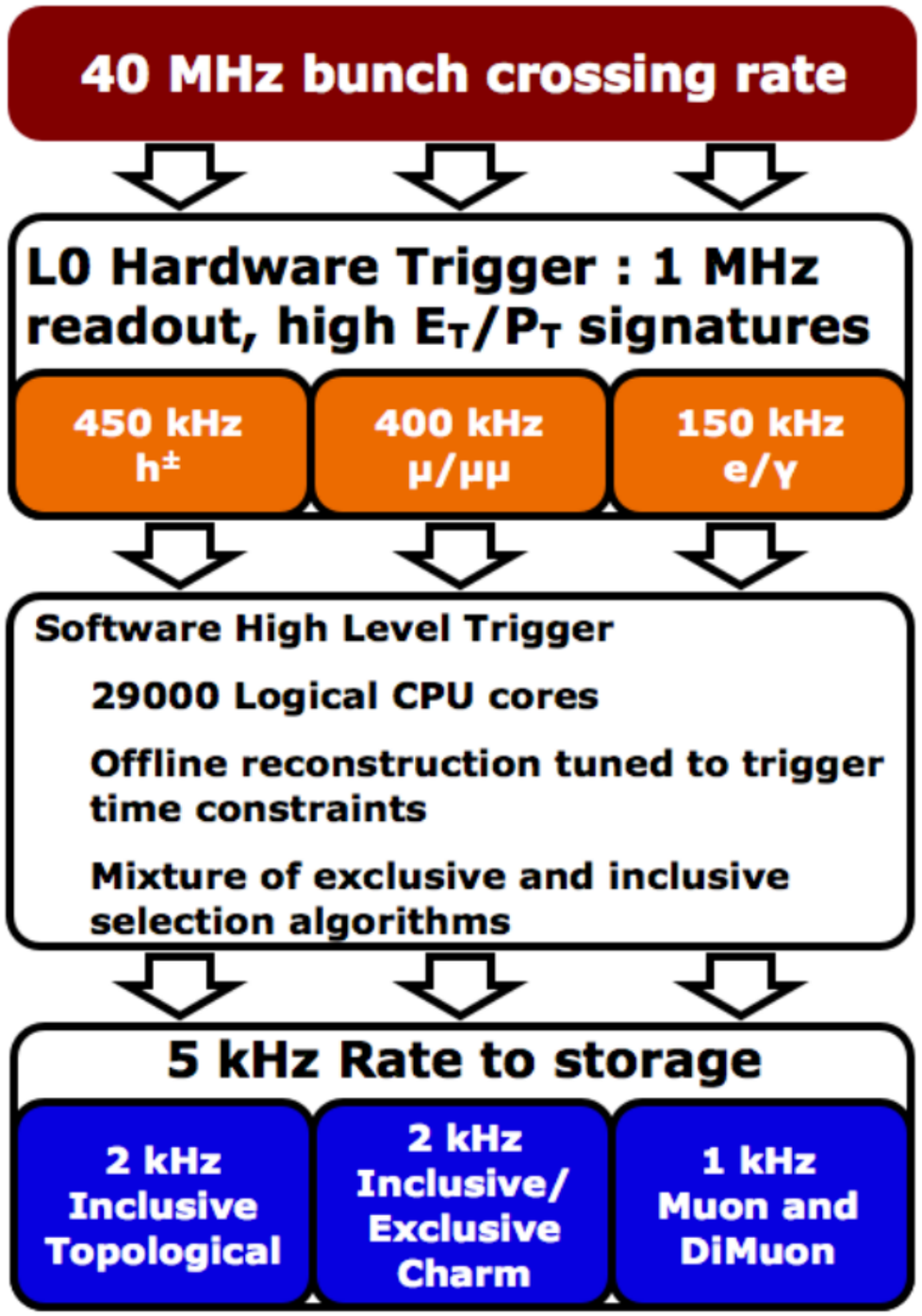


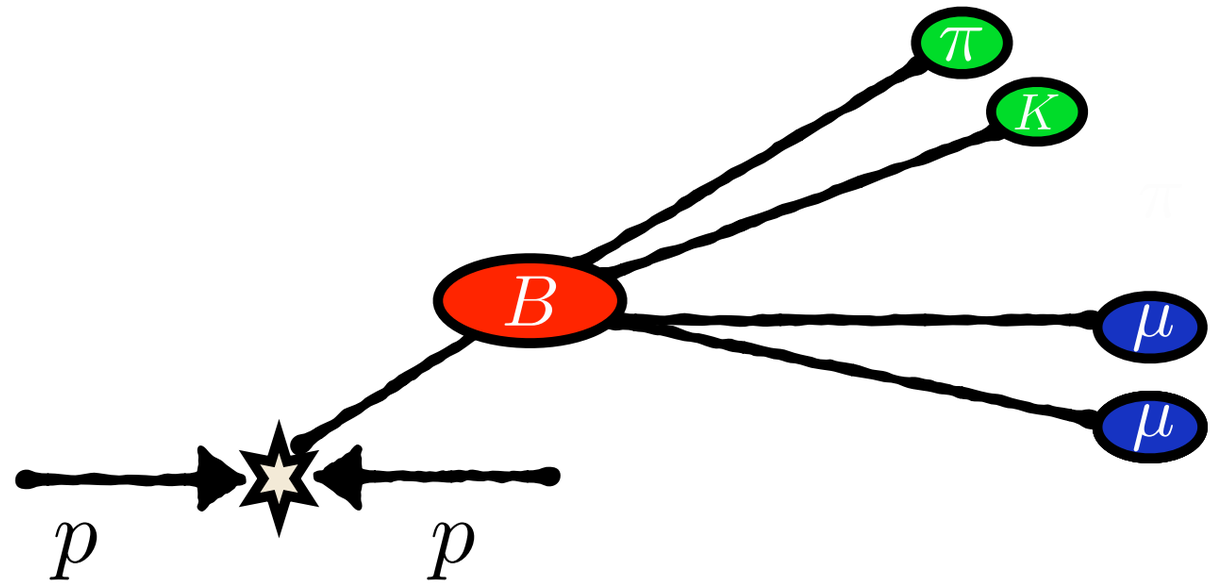
- LHCb operates at a constant levelled optimal luminosity (lower wrt GPD)
- Best compromise between clean events and high luminosity





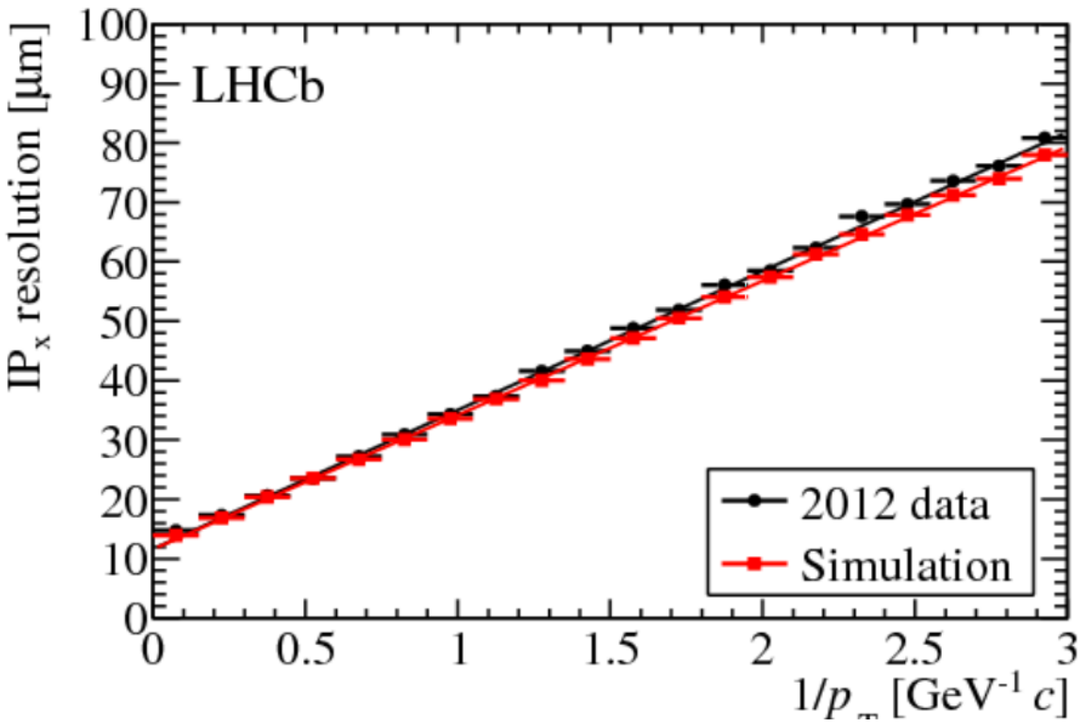
LHCb experiment



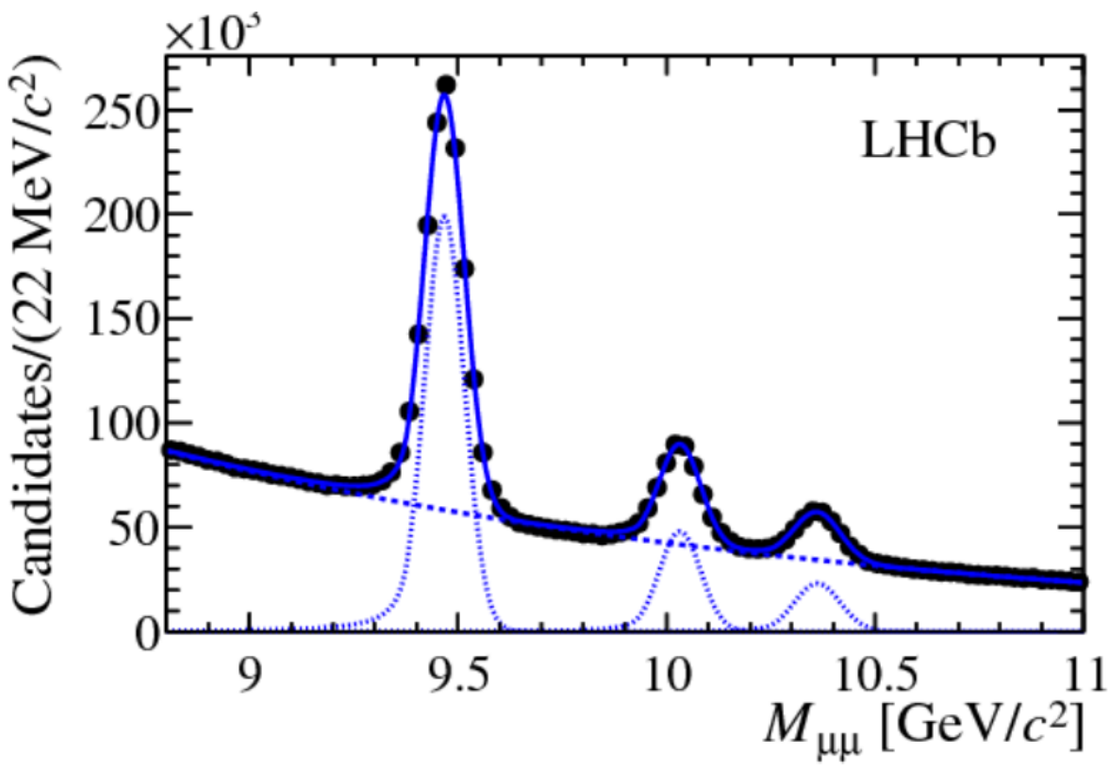


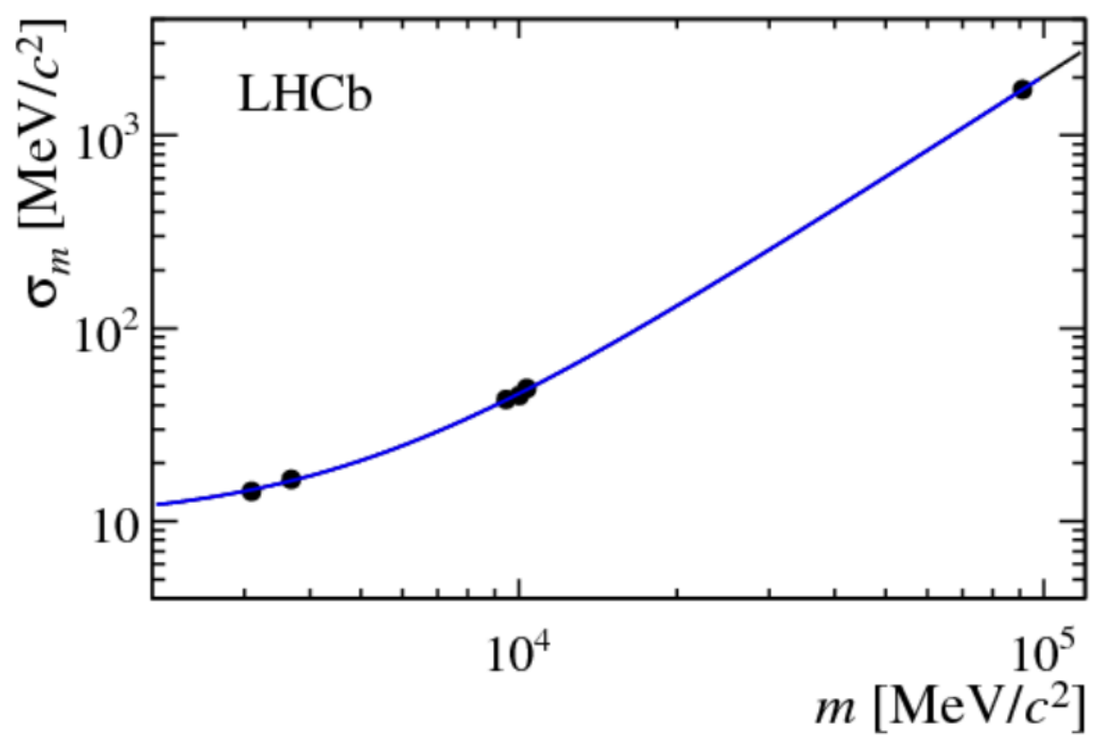
- Single arm forward spectrometer $2.0 < y < 5.0$
- Levelled luminosity $2 \times 10^{32} cm^{-2} s^{-1}$
- Good particle identification (e.g. $\pi \to \mu \sim 0.5\%$)
- Excellent momentum resolution ($\delta p/p \sim 0.5\%$)

LHCb Performances

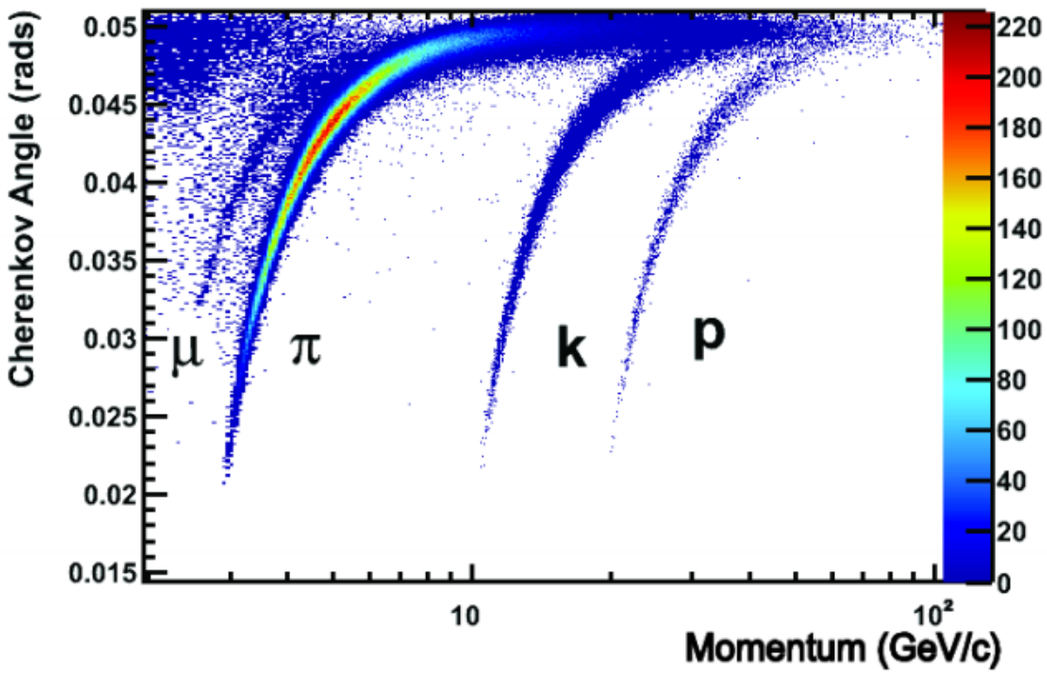


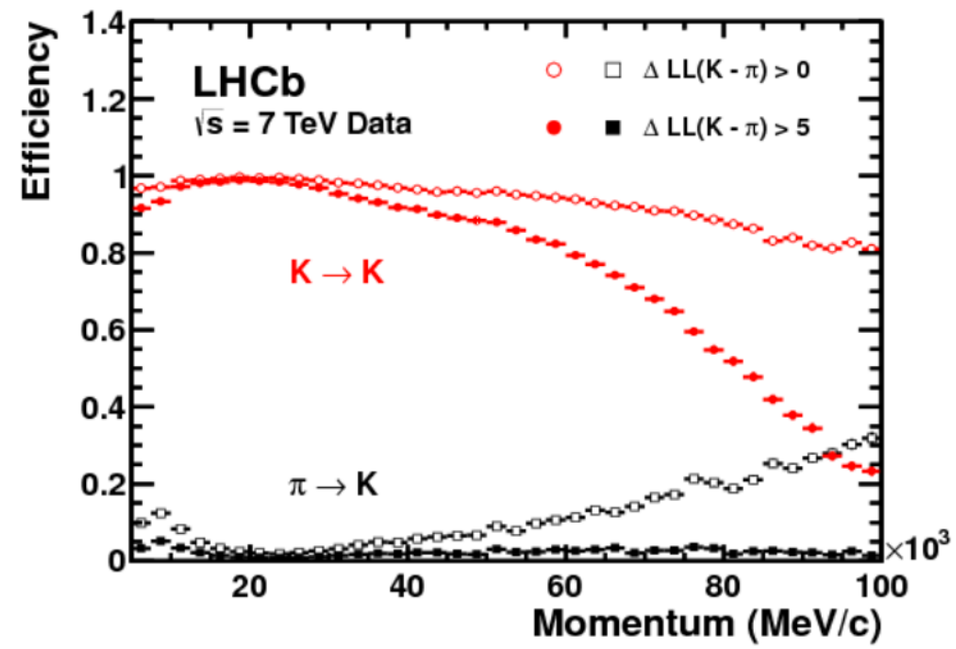
Resonance	Mass resolution (MeV/c^2)
J/ψ	14.3 ± 0.1
$\psi(2S)$	16.5 ± 0.4
$\Upsilon(1S)$	42.8 ± 0.1
$\Upsilon(2S)$	44.8 ± 0.1
$\Upsilon(3S)$	48.8 ± 0.2
Z^0	1727 ± 64

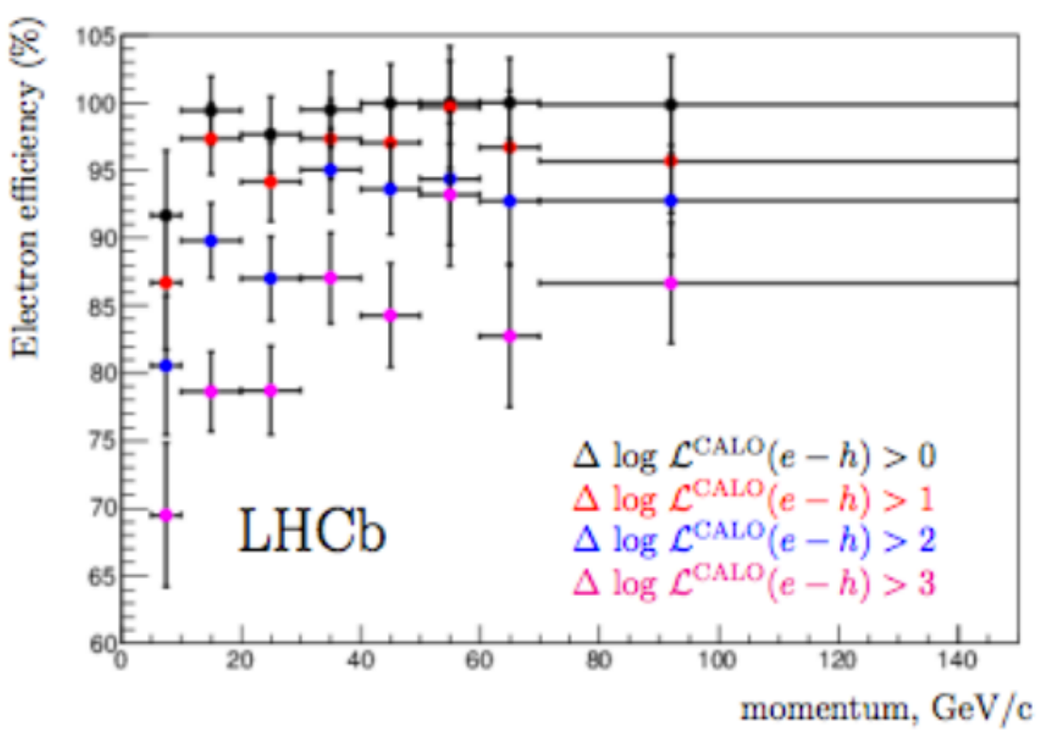


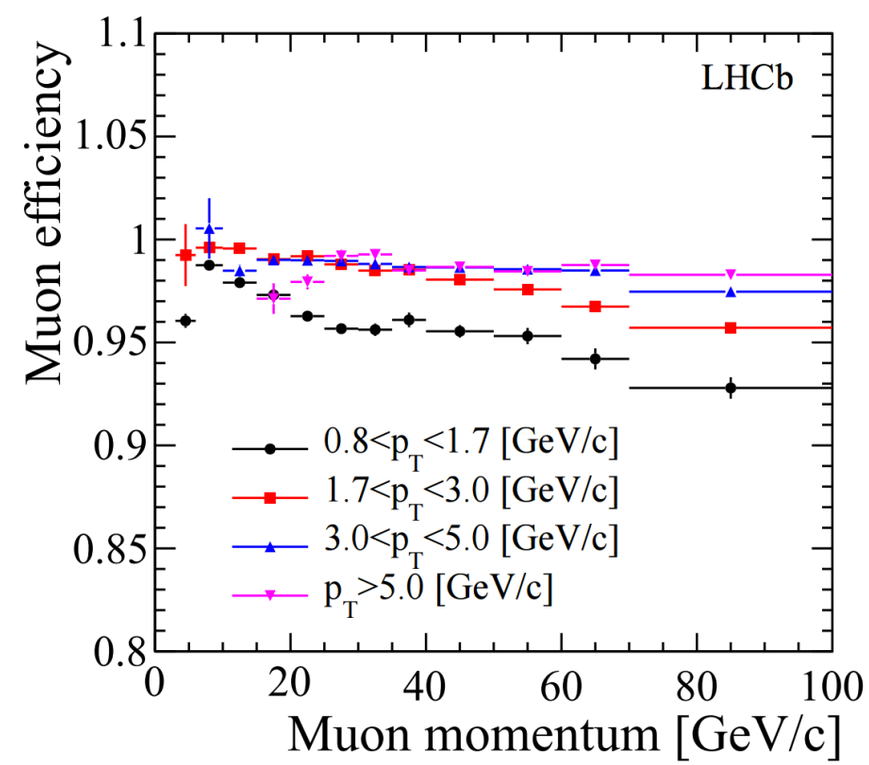


LHCb Performances









Amplitude B—>K*mm

Amplitudes

- The decay is described by six complex amplitudes $A^{L,R}_{0,\parallel,\perp}$
- Correspond to different transversity state of the K^*
- and different (left- and right-handed) chiralities of the dimuon system

$$F_L = \frac{A_0^2}{A_\parallel^2 + A_\perp^2 + A_0^2} = 1 - F_T$$

$$S_3 = \frac{1}{2}\frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R$$

$$S_4 = \frac{1}{\sqrt{2}}\frac{\Re(A_0^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R$$

$$S_5 = \sqrt{2}\frac{\Re(A_0^{L*}A_\perp^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} - L \to R$$

$$A_{FB} = \frac{8}{3}\frac{\Re(A_\perp^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} - L \to R$$

$$S_7 = \sqrt{2}\frac{\Im(A_0^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R$$

$$S_8 = \frac{1}{\sqrt{2}}\frac{\Im(A_0^{L*}A_\perp^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} + L \to R$$

$$S_9 = \frac{\Im(A_\perp^{L*}A_\parallel^L)}{A_\parallel^2 + A_\perp^2 + A_0^2} - L \to R$$

$$A_0^{L,R} \propto \left[C^+_{9\mp10}A_{12} + C^+_7 T_{23}\right]$$

$$A_\parallel^{L,R} \propto \left[C^-_{9\mp10}A_1 + C^-_7 T_2\right]$$

$$A_\perp^{L,R} \propto \left[C^-_{9\mp10}V + C^-_7 T_1\right]$$

$$R_1 = \frac{T_1}{V} \sim 1$$

$$R_2 = \frac{T_2}{A_1} \sim 1$$

$$R_3 = \frac{T_{23}}{A_{12}} \sim \frac{q^2}{m_B^2}$$

$$A_\perp^{L,R} = \sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\rm eff} + \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\rm eff} + \mathcal{C}_7^{\rm eff\prime})\right]\xi_\perp(E_{K^*})$$

$$A_\parallel^{L,R} = -\sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime})\right]\xi_\perp(E_{K^*})$$

$$A_0^{L,R} = -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}'_{10}) + 2\hat{m}_b(\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime})\right]\xi_\parallel(E_{K^*})$$

Amplitudes

$$A_0^{L,R} \propto \left[C_{9\mp10}^{+}A_{12} + C_7^{+}T_{23}\right]$$
$$A_{\parallel}^{L,R} \propto \left[C_{9\mp10}^{-}A_{1} + C_7^{-}T_{2}\right]$$
$$A_{\perp}^{L,R} \propto \left[C_{9\mp10}^{-}V + C_7^{-}T_{1}\right]$$

$$R_1 = \frac{T_1}{V} \sim 1$$
$$R_2 = \frac{T_2}{A_1} \sim 1$$
$$R_3 = \frac{T_{23}}{A_{12}} \sim \frac{q^2}{m_B^2}$$

$$A_{\perp}^{L,R} = \sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\rm eff}+\mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10}+\mathcal{C}_{10}') + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\rm eff}+\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\perp}(E_{K^*})$$

$$A_{\parallel}^{L,R} = -\sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10}-\mathcal{C}_{10}') + \frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\perp}(E_{K^*})$$

$$A_0^{L,R} = -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10}-\mathcal{C}_{10}') + 2\hat{m}_b(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\parallel}(E_{K^*})$$

We now build ratios such that the same combination of FF appears in the numerator and in the denominator

$$P_5' \propto \frac{\Re(A_0 A_\perp)}{\sqrt{|A_0|^2 \times |A_\perp|^2}}$$

Observables

- The number of degrees of freedom are 3x2x2 = 12
- However there are 4 symmetries of the angular distributions, so there are 8 independent observables
- The maximum number of “clean” observables is 6

$$P_1 = A_T^{(2)} = \frac{2S_3}{(1-F_L)} = \frac{A_\perp^{L2} - A_\parallel^{L2}}{A_\parallel^2 + A_\perp^2} + L \to R$$

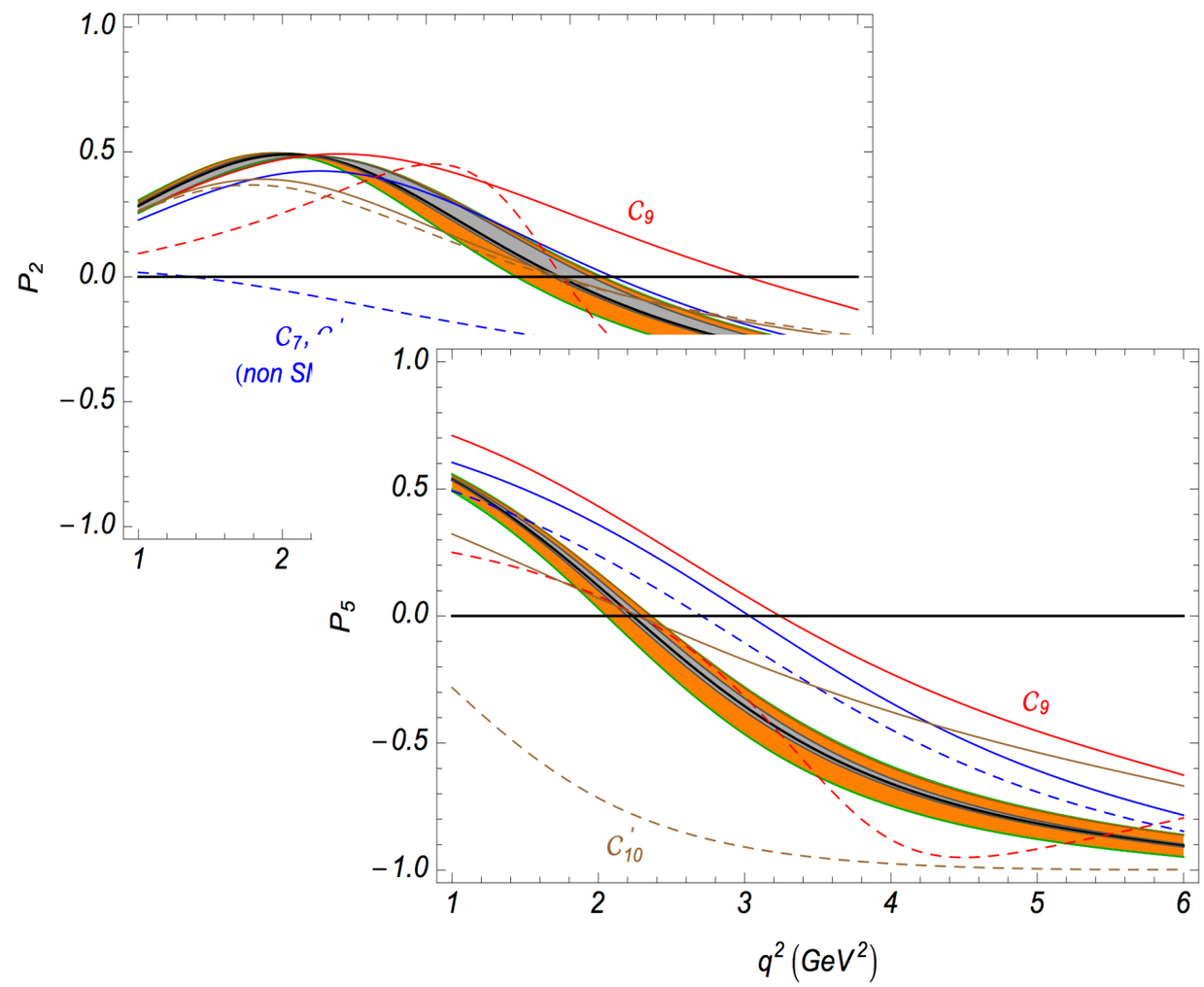
$$P_2 = 2A_T^{Re} = \frac{2A_{FB}}{3(1-F_L)} \propto \frac{\Re(A_\perp^{L*} A_\parallel^L)}{A_\parallel^2 + A_\perp^2} - L \to R$$

$$P_3 = \frac{S_9}{(1-F_L)} = \frac{\Im(A_\perp^{L*} A_\parallel^L)}{A_\parallel^2 + A_\perp^2} - L \to R$$

$$P_4' = \frac{S_4}{\sqrt{F_L(1-F_L)}} \propto \frac{\Re(A_0^{L*} A_\parallel^L)}{\sqrt{|A_0|^2 |A_\parallel|^2}} + L \to R$$

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}} \propto \frac{\Re(A_0^{L*} A_\perp^L)}{\sqrt{|A_\perp|^2 |A_0|^2}} - L \to R$$

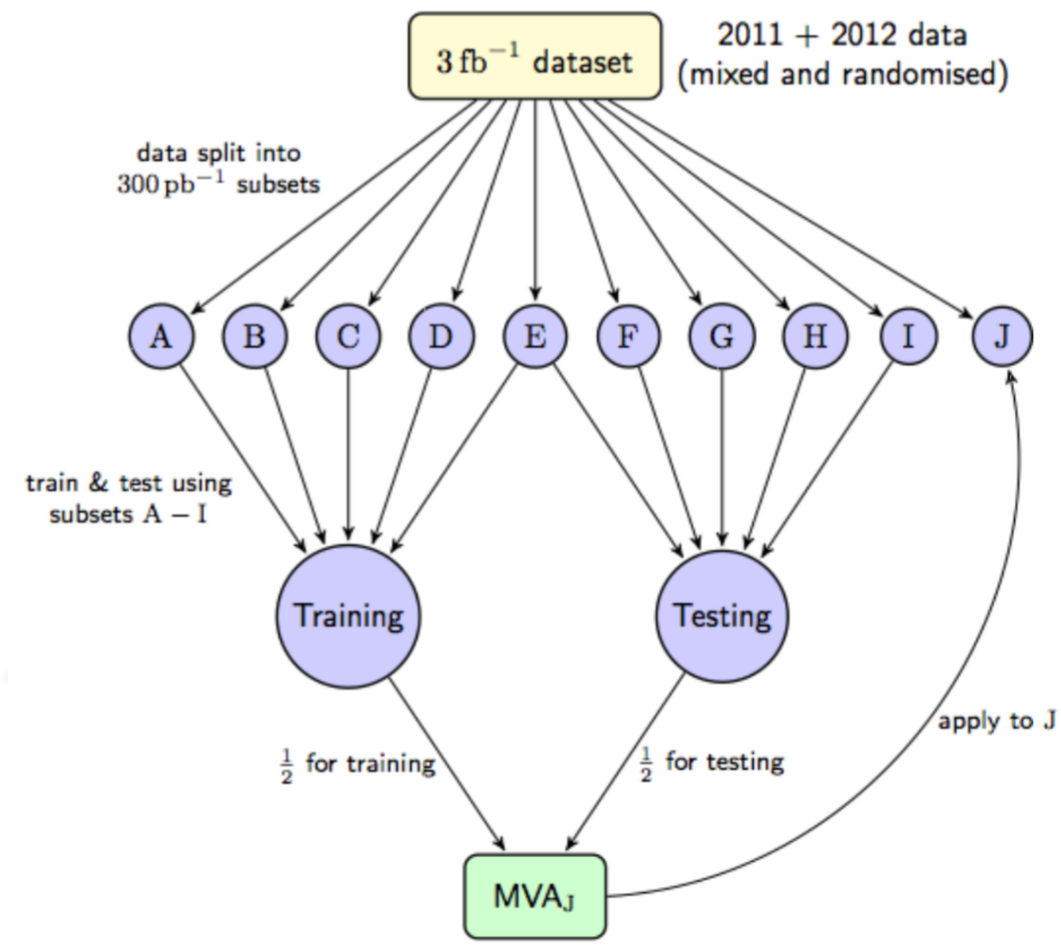
$$P_6' = \frac{S_7}{\sqrt{F_L(1-F_L)}} \propto \frac{\Im(A_0^{L*} A_\parallel^L)}{\sqrt{|A_\parallel|^2 |A_0|^2}} + L \to R$$



Analysis B—>K*mm

Selection

- JHEP 1602 (2016) 104
- PID, kinematics and isolation variables used in a Boosted Decision Tree (BDT) to reject background.
- Reject the regions of J/ψ and $\psi(2S)$.
- Specific vetos for backgrounds: $\Lambda_b \to pK\mu\mu$, $B_s^0 \to \phi\mu\mu$, etc.
- Using k-Fold technique and signal proxy $B \to J/\psi K^*$ for training the BDT.
- Improved selection allowed for finer binning than the $1\mathrm{fb}^{-1}$ analysis.



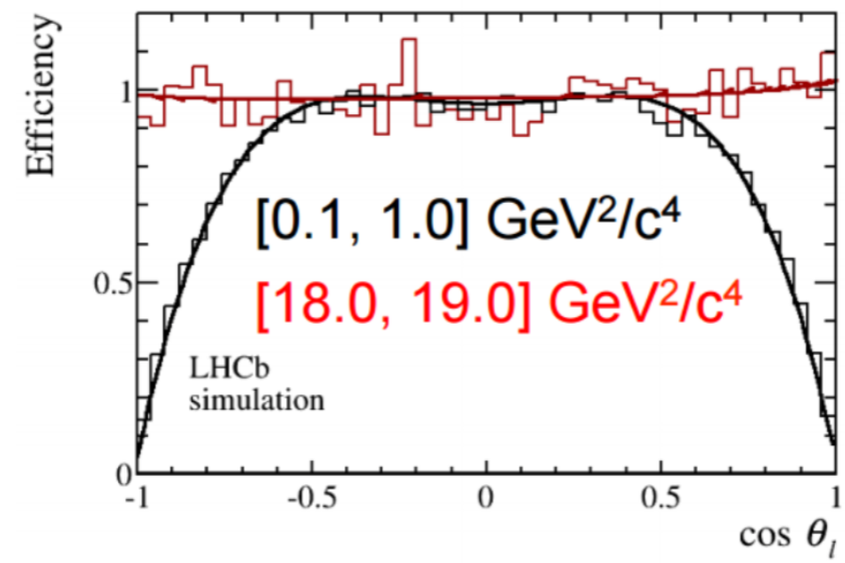
Acceptance

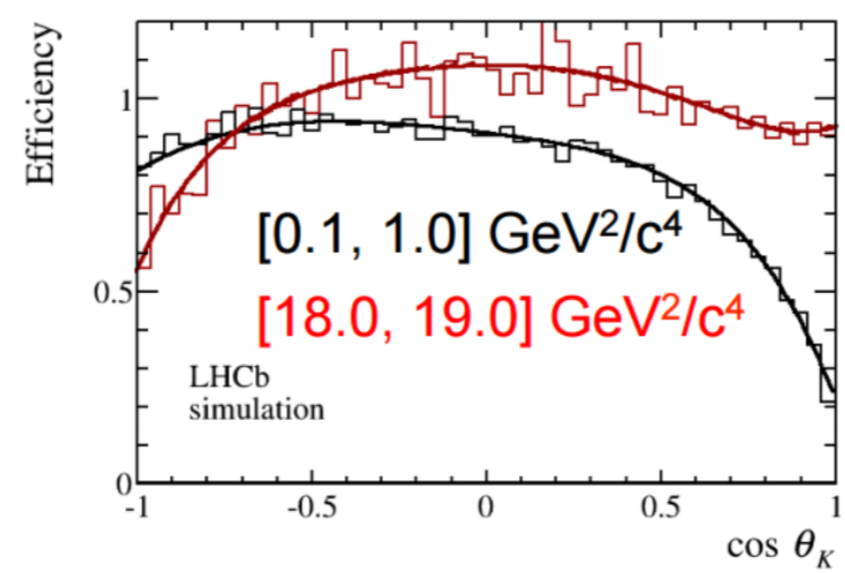
- Detector distorts our angular distribution.
- We need to model this effect.
- 4D function is used:

$$\epsilon(\cos\theta_l, \cos\theta_k, \phi, q^2) = \sum_{ijkl} P_i(\cos\theta_l) P_j(\cos\theta_k) P_k(\phi) P_l(q^2),$$

where P_i is the Legendre polynomial of order i.

- We use up to $4^{th}, 5^{th}, 6^{th}, 5^{th}$ order for the $\cos\theta_l, \cos\theta_k, \phi, q^2$.
- The coefficients were determined using Method of Moments, with a huge simulation sample.
- The simulation was done assuming a flat phase space and reweighing the q^2 distribution to make is flat.





Methods

1. Maximum likelihood fit:
   - The most standard way of obtaining the parameters.
   - Can have problem with low statistics.
2. Method of moments:
   - Less precise then the likelihood estimator ($10 - 15\%$ larger uncertainties).
   - Does not suffer from the problems of likelihood fit.
3. Amplitude fit:
   - Incorporates all the physical symmetries inside the amplitudes! The most precise estimator.
   - Has theoretical assumptions inside!

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

- Four dimensional fit of B-mass, angles (ϕ, θ_ℓ, θ_K) and simultaneous fit of $m(K\pi)$ (background fraction shared)

$$\log\mathcal{L} = \sum_i \log\Big[\epsilon(\vec{\Omega}, q^2) f_{\rm sig}\mathcal{P}_{\rm sig}(\vec{\Omega})\mathcal{P}_{\rm sig}(m_{K\pi\mu\mu}) + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\vec{\Omega})\mathcal{P}_{\rm bkg}(m_{K\pi\mu\mu})\Big] + \sum_i \log\Big[f_{\rm sig}\mathcal{P}_{\rm sig}(m_{K\pi}) + (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(m_{K\pi})\Big]$$

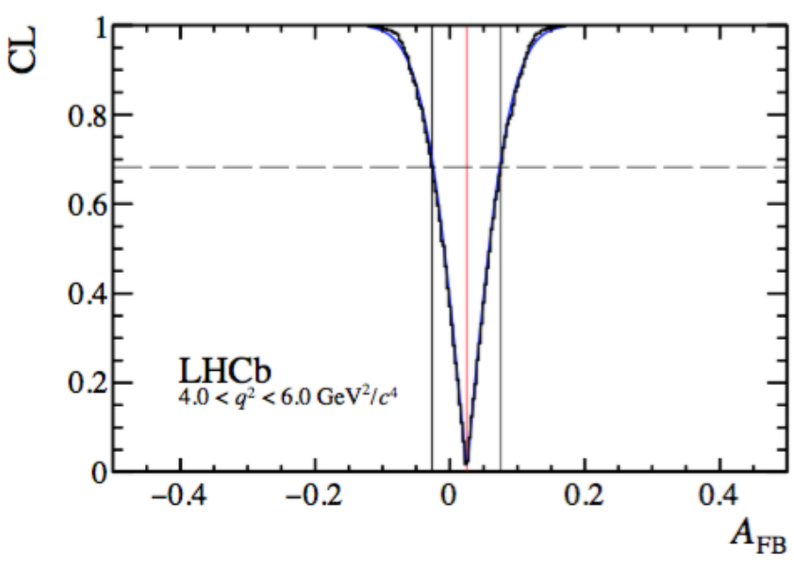
- $\mathcal{P}_{sig}(\Omega) = \frac{d^3\Gamma}{d\cos\theta_\ell d\cos\theta_K d\phi}$ and $\epsilon(\Omega, q^2)$ is the signal efficiency
- $\mathcal{P}_{bkg}(\Omega)$ is modelled with three second order Chebychel polynomial and extracted from the sidebands
- $\mathcal{P}_{bkg}(m_{K\pi\mu\mu})$ is an esponential

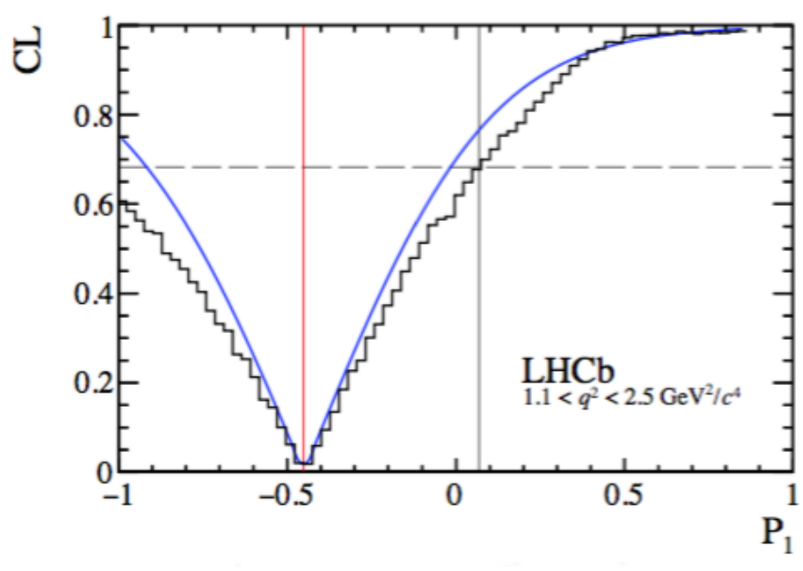
Likelihood

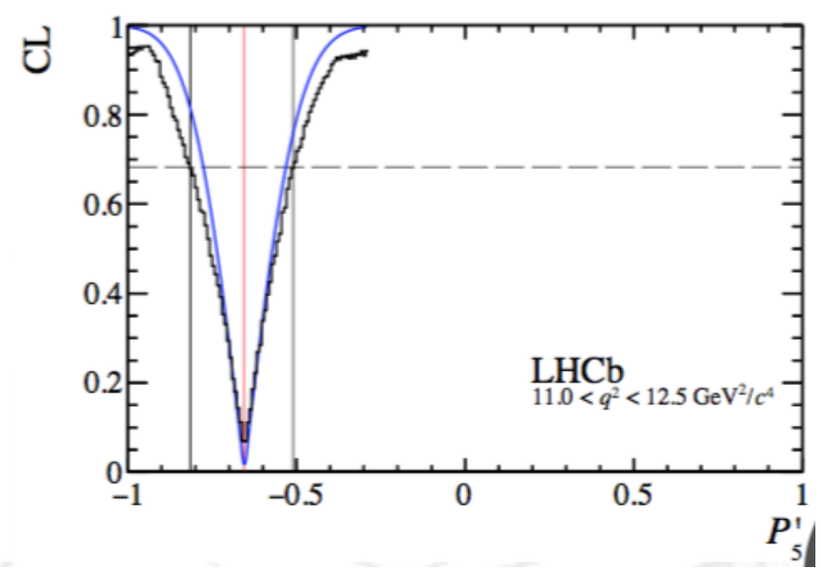
- In the maximum likelihood fit one could weight the events accordingly to the $\frac{1}{\varepsilon(\cos\theta_l, \cos\theta_k, \phi, q^2)}$
- Better alternative is to put the efficiency into the maximum likelihood fit itself:

$$\mathcal{L} = \prod_{i=1}^{N} \epsilon_i(\Omega_i, q_i^2)\mathcal{P}(\Omega_i, q_i^2) / \int \epsilon(\Omega, q^2)\mathcal{P}(\Omega, q^2) d\Omega dq^2$$

- Only the relative weights matters!
- The Procedure was commissioned with TOY MC study.
- Use Feldmann-Cousins to determine the uncertainties.
- Angular background component is modelled with 2nd order Chebyshev polynomials, which was tested on the side-bands.
- S-wave component treated as nuisance parameter.







Method of Moments

Use orthogonality of spherical harmonics to determine the coefficients

$$\int f_i(\vec{\Omega}) f_j(\vec{\Omega}) \mathrm{d}\vec{\Omega} = \delta_{ij}$$

$$M_i = \int \left(\frac{1}{\mathrm{d}(\Gamma + \bar{\Gamma})/\mathrm{d}q^2} \right) \frac{\mathrm{d}^3(\Gamma + \bar{\Gamma})}{\mathrm{d}\vec{\Omega}} f_i(\vec{\Omega}) \mathrm{d}\vec{\Omega}$$

We sample the angular distribution with our data, so the integral becomes a sum over data

$$\widehat{M_i} = \frac{1}{\sum_e w_e} \sum_e w_e f_i(\vec{\Omega}_e)$$

The weights w_e accounts for the efficiency

Amplitude Fit

⇛ Fit for amplitudes as (continuous) functions of q^2 in the region: $q^2 \in [1.1.6.0]\ \mathrm{GeV}^2/\mathrm{c}^4$.

⇛ Needs some Ansatz:

$$A(q^2) = \alpha + \beta q^2 + \frac{\gamma}{q^2}$$

⇛ The assumption is tested extensively with toys.

⇛ Set of 3 complex parameters α, β, γ per vector amplitude:

- $L,\ R,\ 0,\ \|,\ \perp,\ \Re,\ \Im \rightarrowtail\ 3 \times 2 \times 3 \times 2 = 36$ DoF.
- Scalar amplitudes: $+4$ DoF.
- Symmetries of the amplitudes reduces the total budget to: 28.

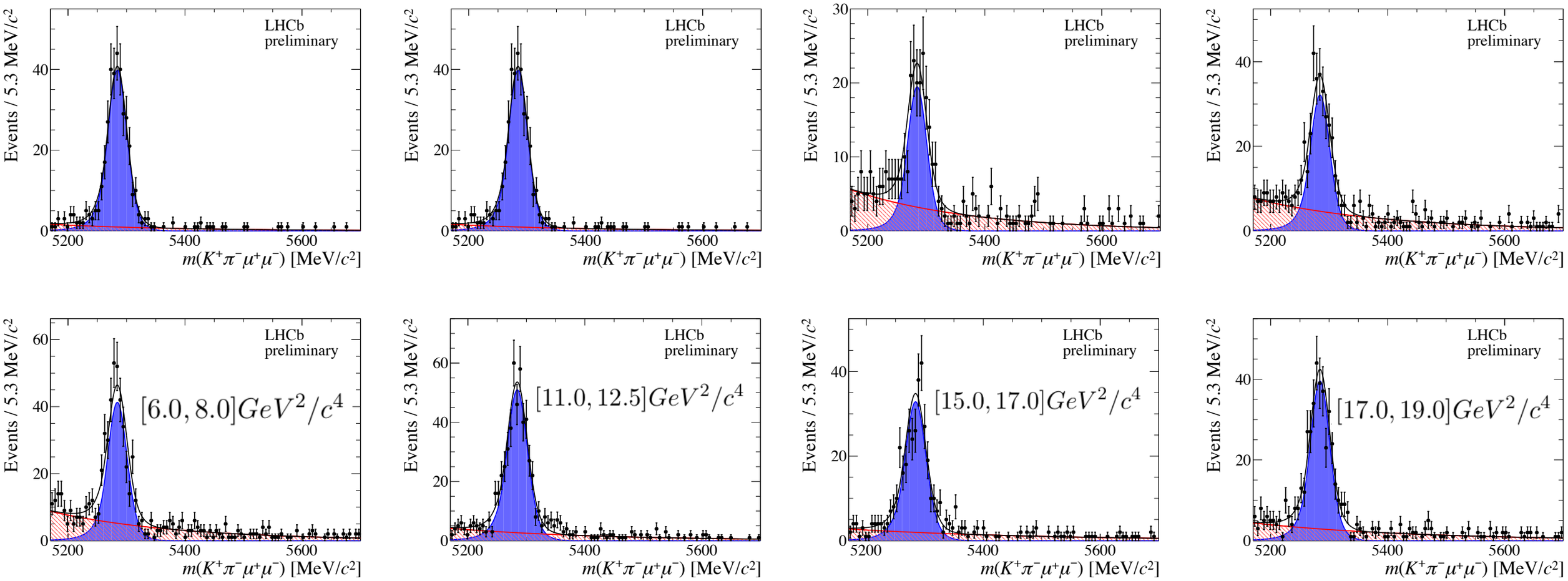
⇛ The technique is described in JHEP06(2015)084, U. Egede, M. Patel, K.A. Petridis.

⇛ Allows to build the observables as continuous functions of q^2:

- At current point the method is limited by statistics.
- In the future the power of this method will increase.

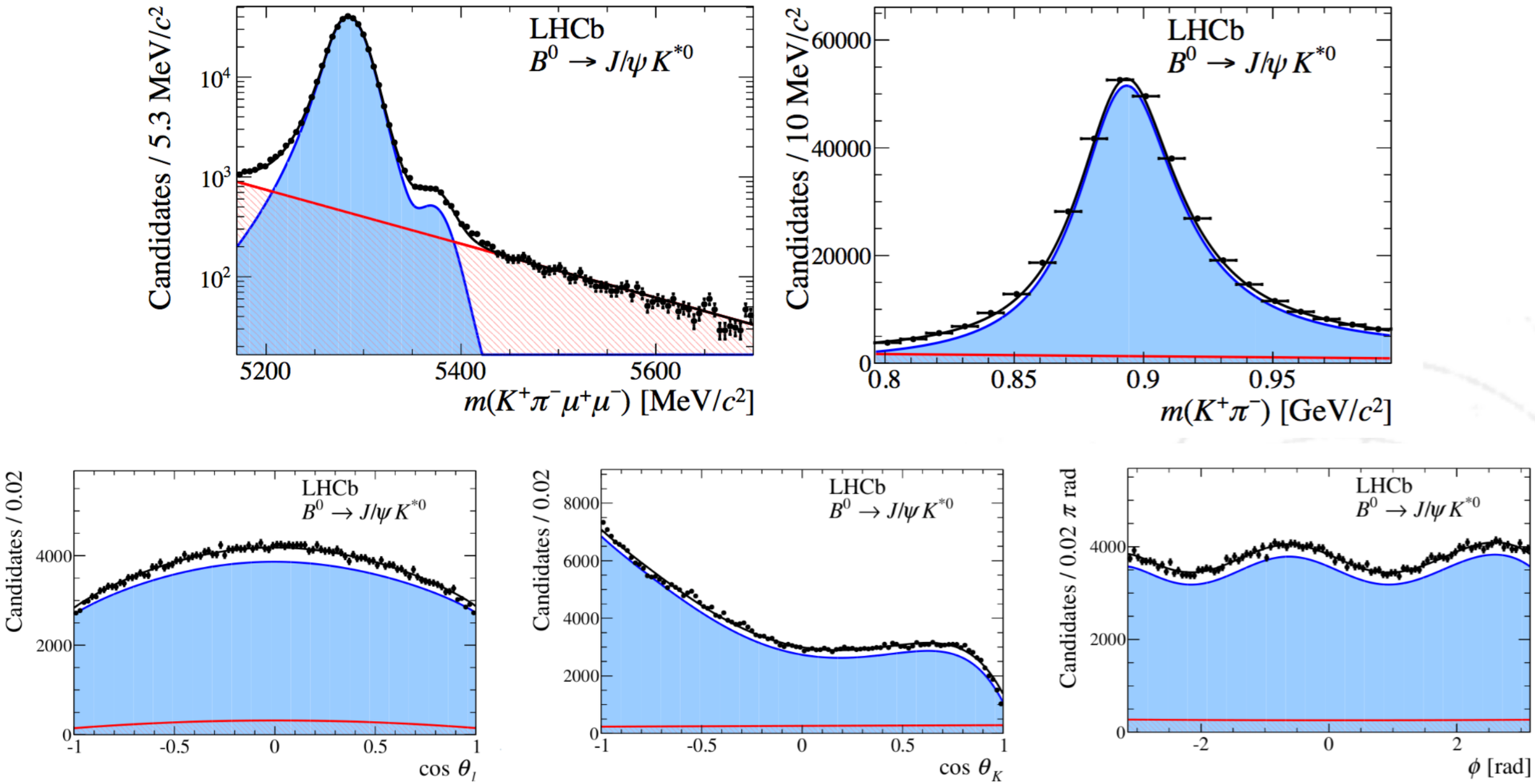
⇛ Allows to measure the zero-crossing points for free and with smaller errors than previous methods.

Signal



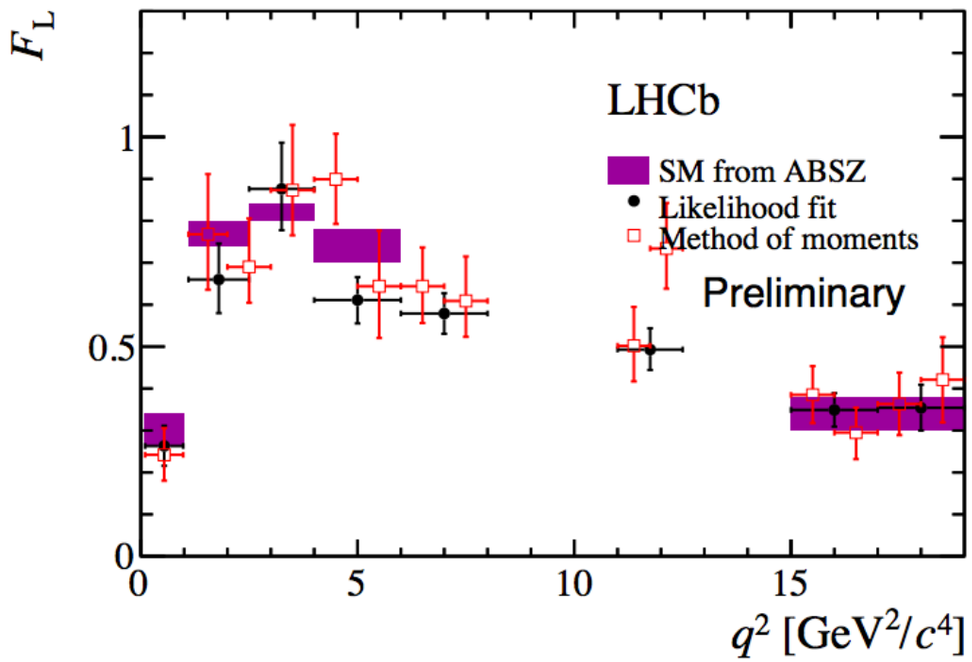
- Total signal yield integrated in q^2: 2398 ± 58 events
- Angular analysis performed in small q^2 bins is more sensitive to NP contributions
- High significance of the signal in all bins
- Independent angular and mass fits in each bins

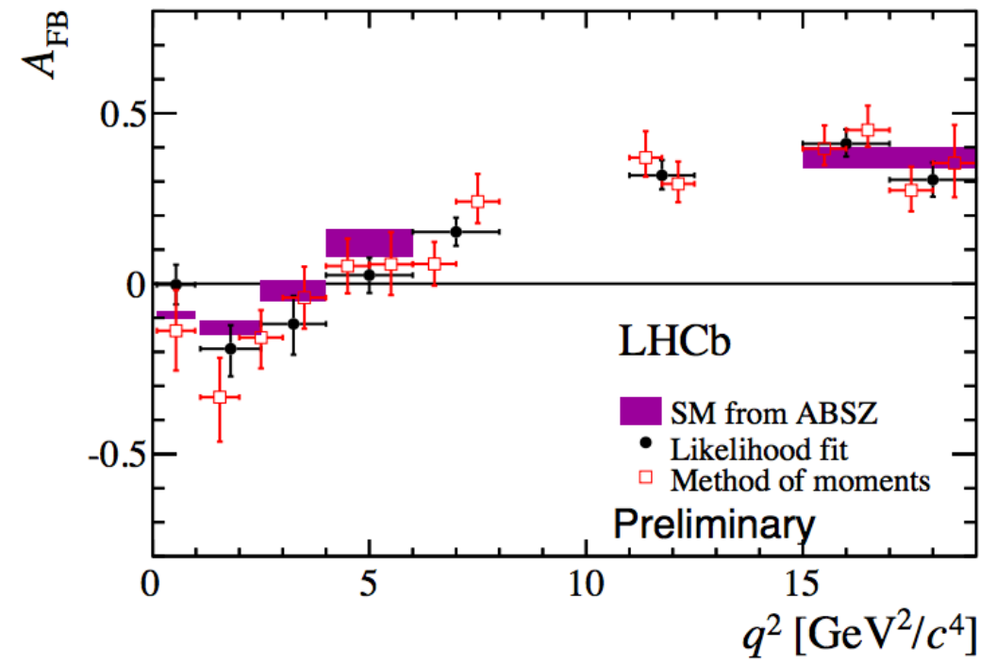
Control Channel

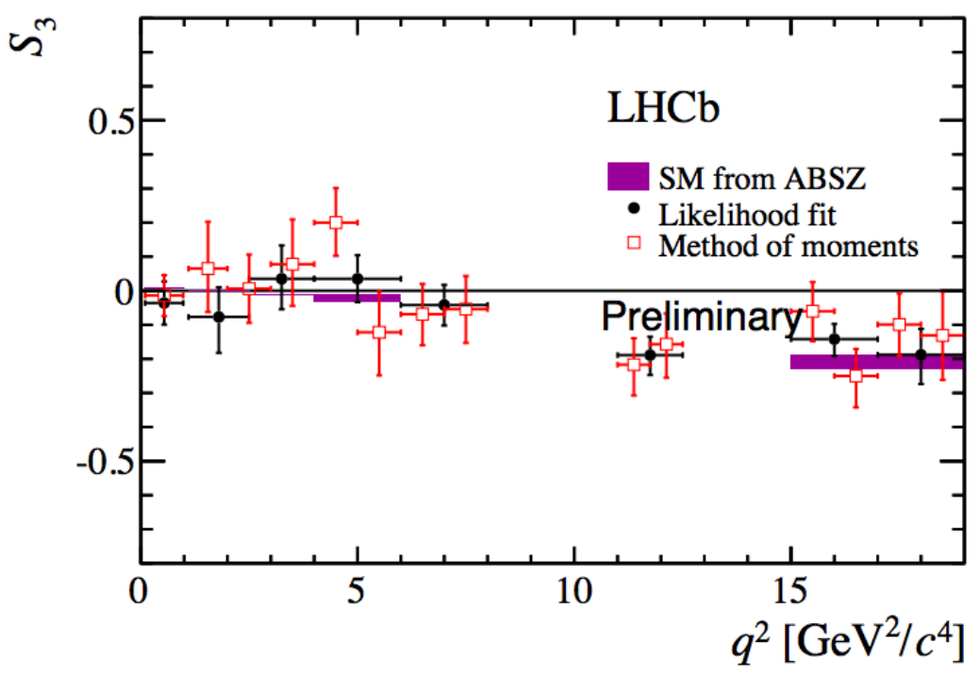


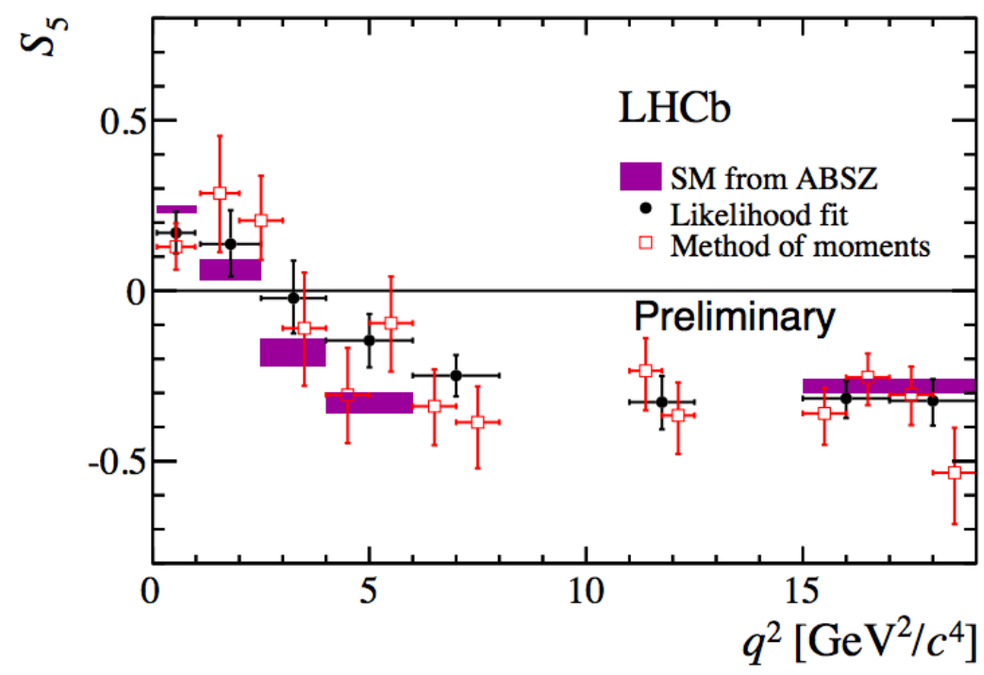
- Very good agreement with the expected angular distributions in the control channel

Results

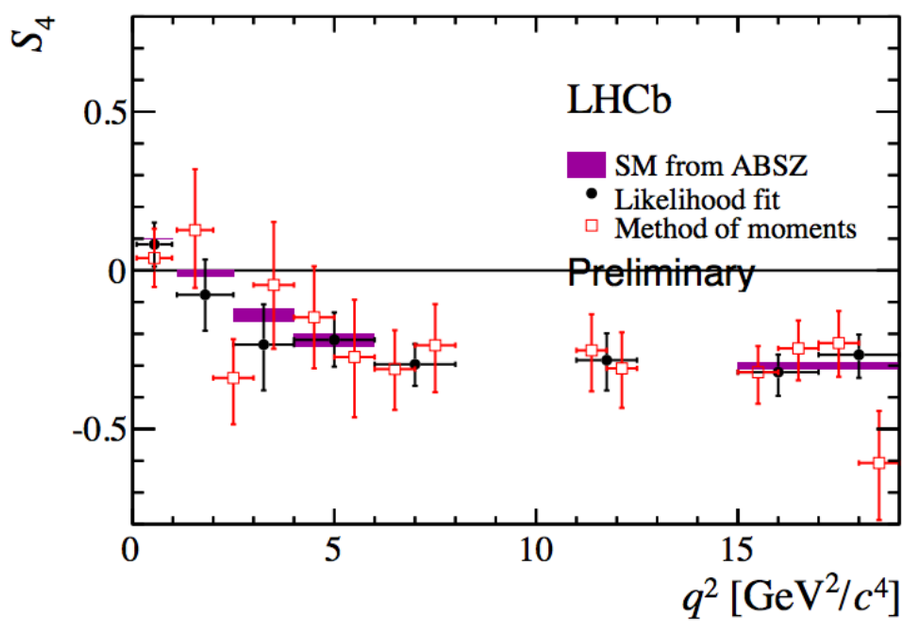

F_L
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]

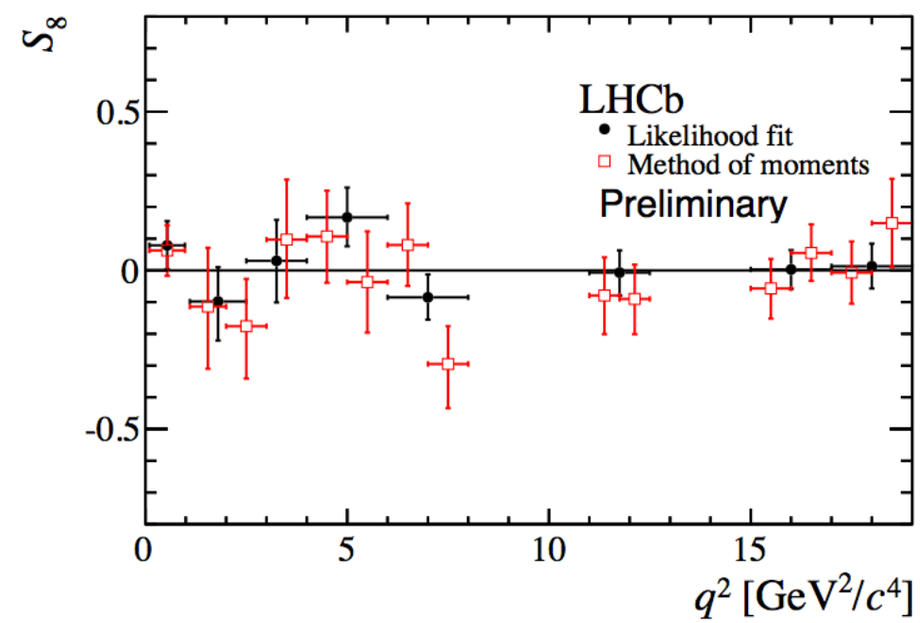

A_{FB}
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]

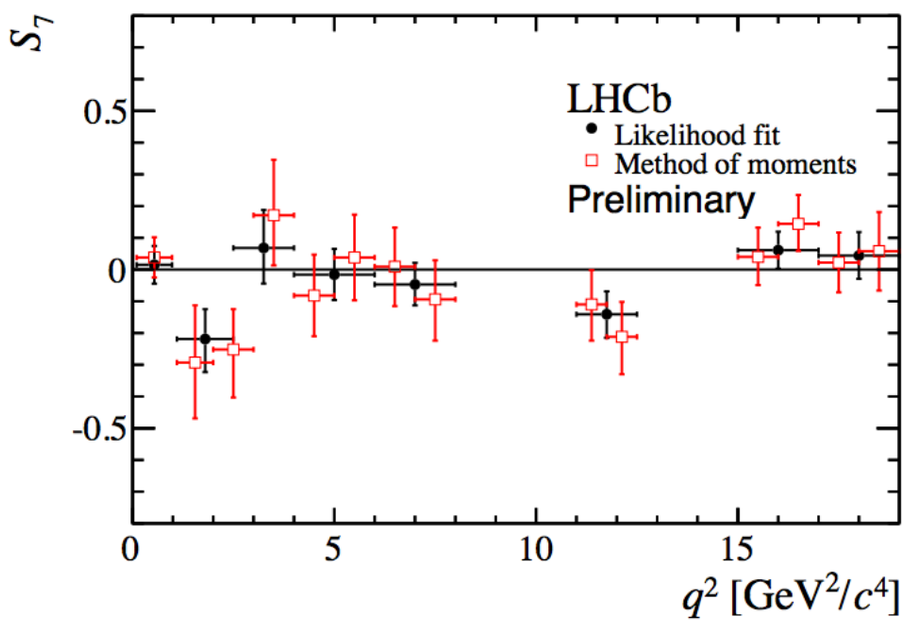

S_3
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]

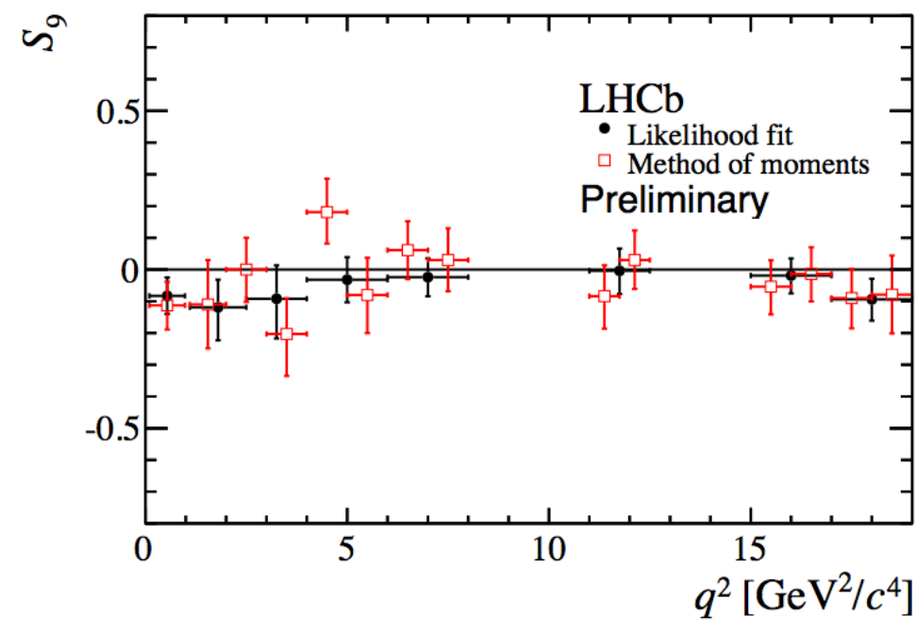

S_5
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
q^2 [GeV^2/c^4]

Results

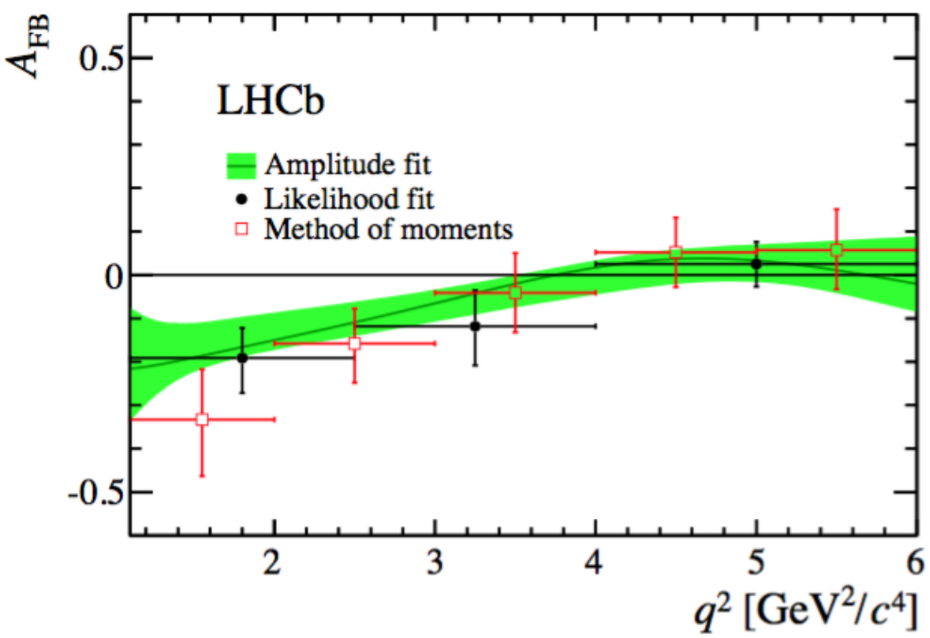

S_4
LHCb
SM from ABSZ
Likelihood fit
Method of moments
Preliminary
0.5
0
-0.5
0
5
10
15
q^2 [GeV^2/c^4]

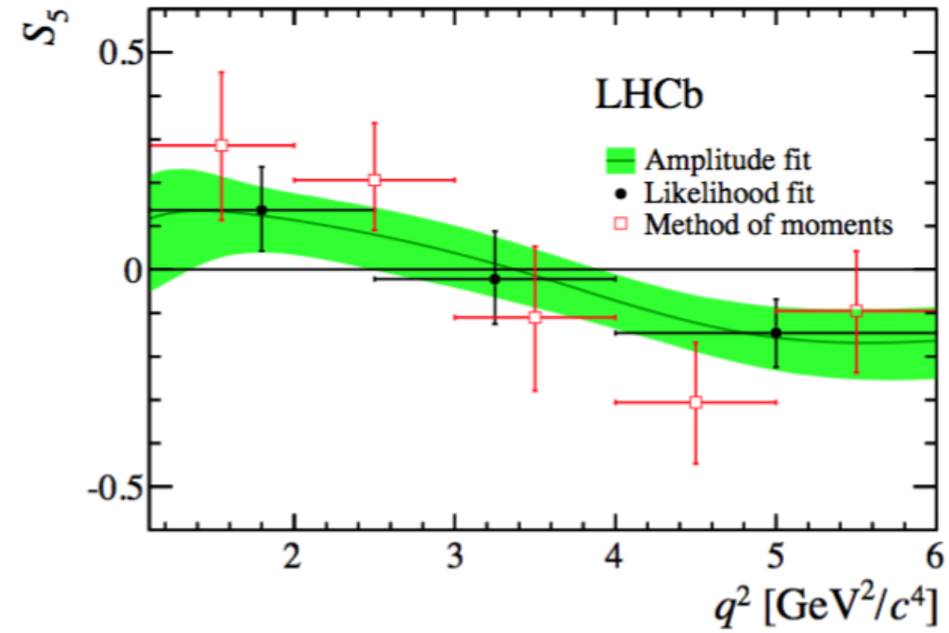

S_8
LHCb
Likelihood fit
Method of moments
Preliminary
0.5
0
-0.5
0
5
10
15
q^2 [GeV^2/c^4]

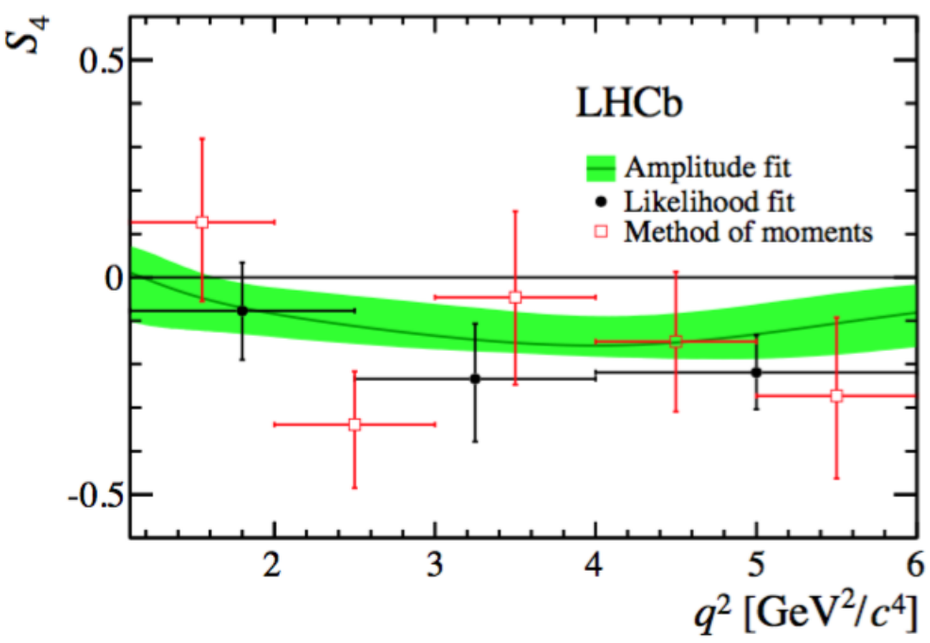

S_7
LHCb
Likelihood fit
Method of moments
Preliminary
0.5
0
-0.5
0
5
10
15
q^2 [GeV^2/c^4]


S_9
LHCb
Likelihood fit
Method of moments
Preliminary
0.5
0
-0.5
0
5
10
15
q^2 [GeV^2/c^4]

Method Comparison







Zero crossing points:

$$q_0(S_4) < 2.65 \quad \text{at } 95\%\ CL$$
$$q_0(S_5) \in [2.49, 3.95] \quad \text{at } 68\%\ CL$$
$$q_0(A_{FB}) \in [3.40, 4.87] \quad \text{at } 68\%\ CL$$

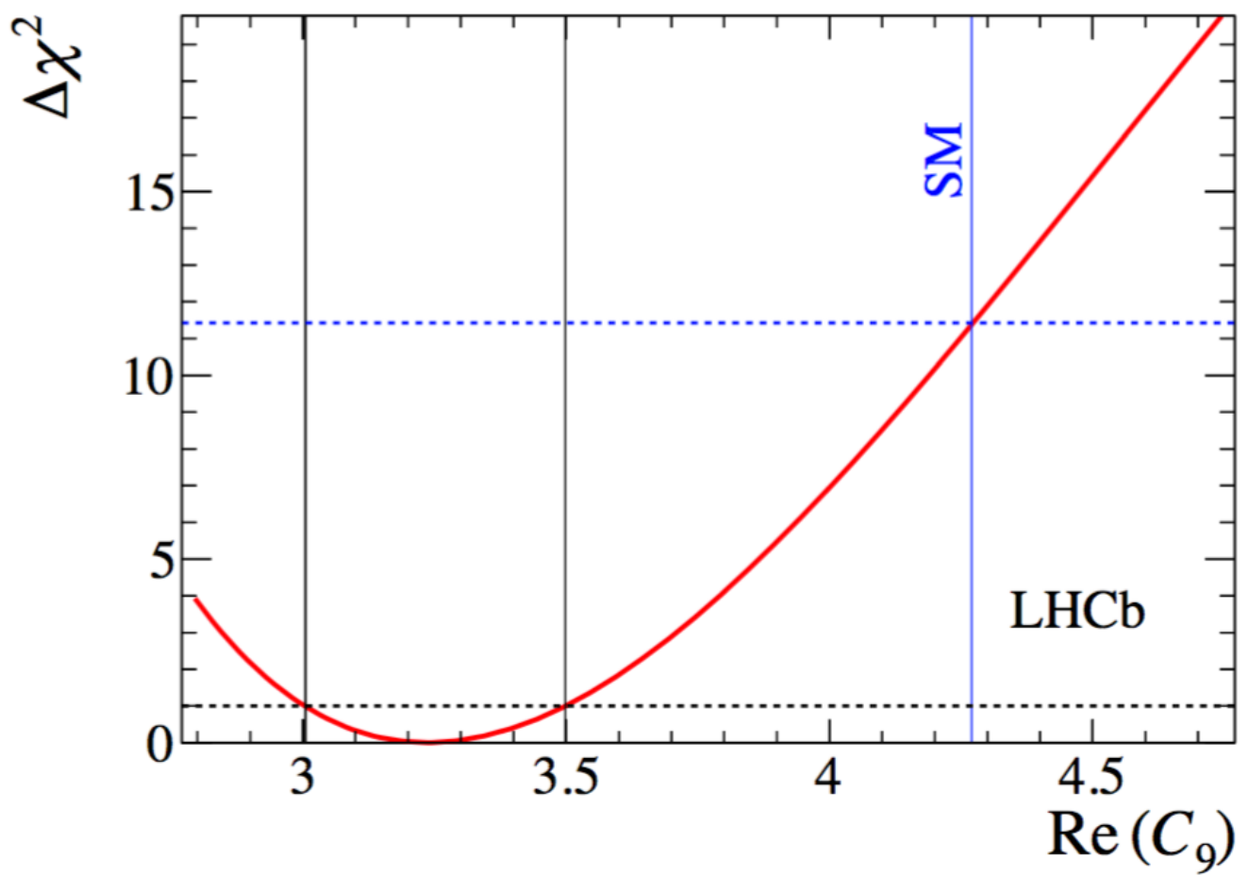
EOS Fit (LHCb)

⇛ Use EOS software package to test compatibility with SM.
⇛ Perform the χ^2 fit to the measured:

$$F_L, A_{FB}, S_{3,\ldots,9}.$$

⇛ Float a vector coupling: $\Re(C_9)$.
⇛ Best fit is found to be $3.4\ \sigma$ away from the SM.

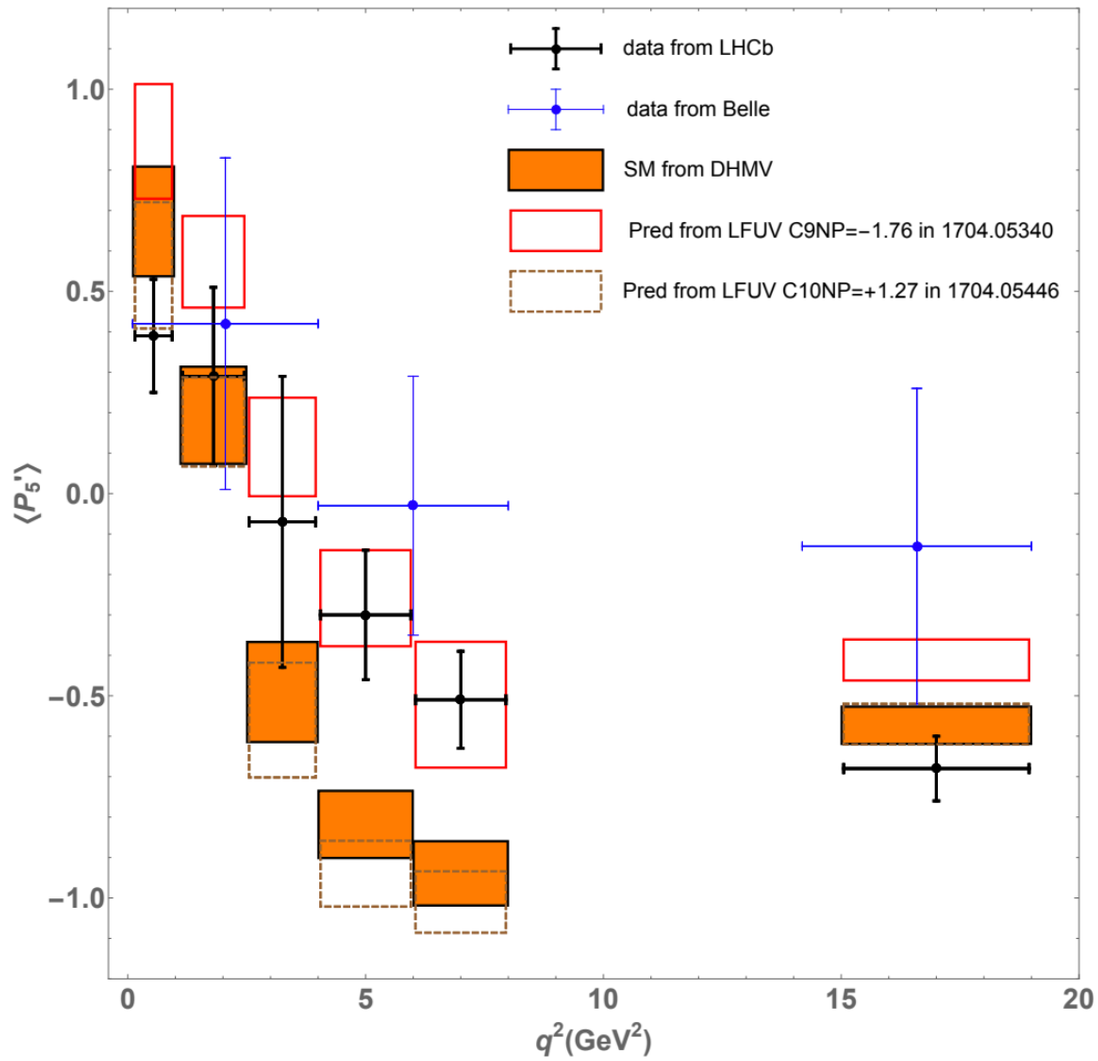
$$\Delta\Re(C_9) \equiv \Re(C_9)^{\text{fit}} - \Re(C_9)^{\text{SM}} = -1.03$$



Interpretation B—>K/K*mm

A coherent pattern?

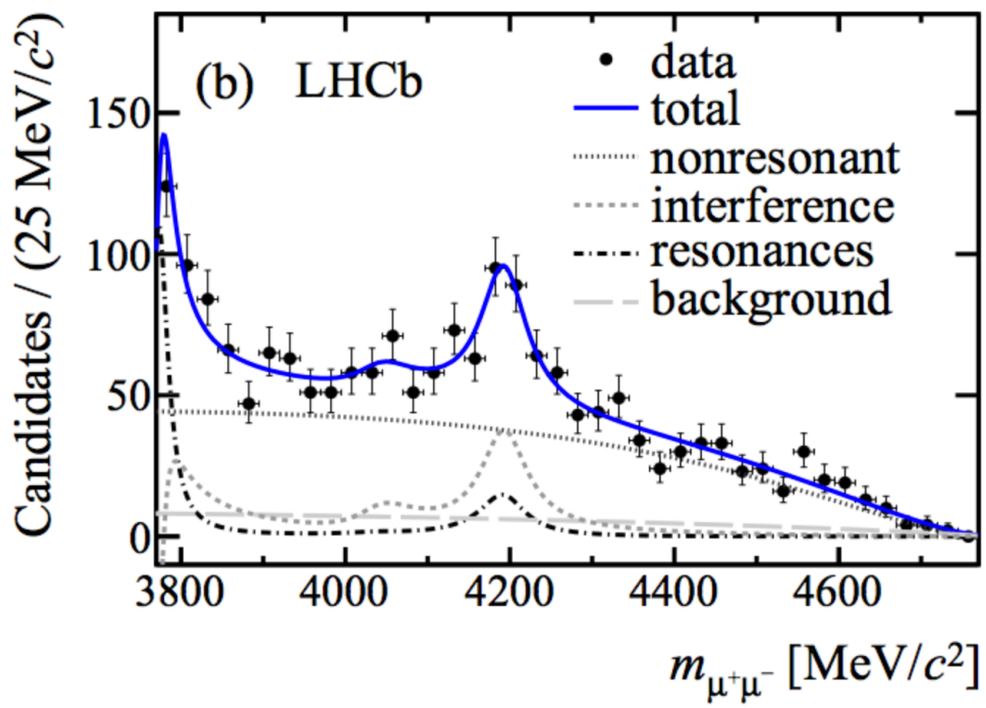
From J. Matias - Zurich Phenomenology Workshop 2018



- Missing newest data from R_K, not as coherent as before
- However, more effects have to be considered, including NFC from b—>sττ

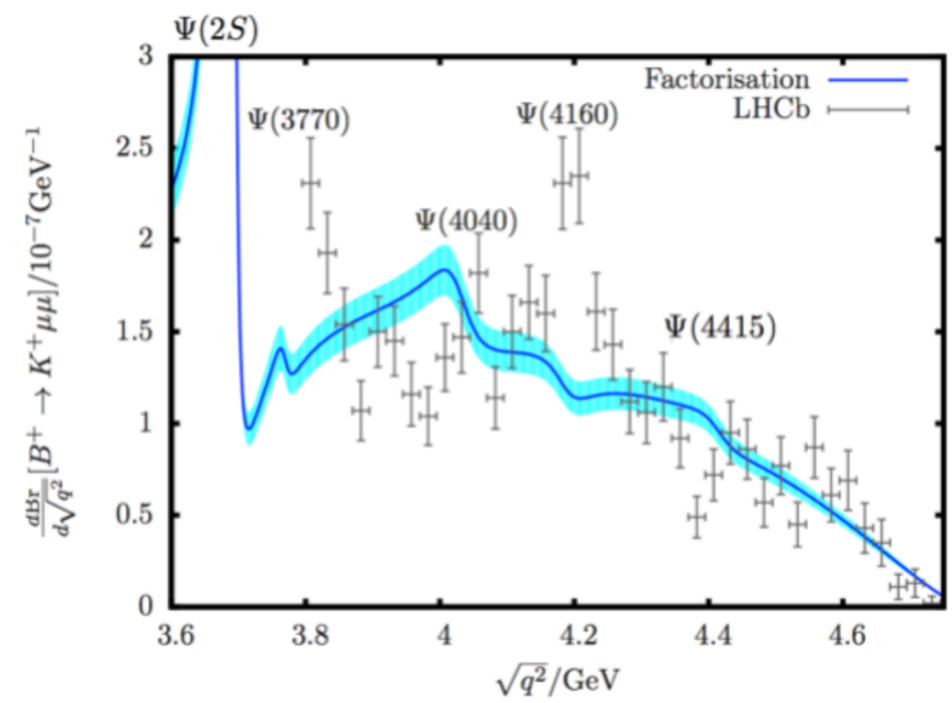
High q^2 region

- LHCb has evidence of resonance structures in the high q^2 region of $B^+ \to K^+\mu^+\mu^-$
- First observation of $B^+ \to K^+\psi(4160)(\to \mu^+\mu^-)$



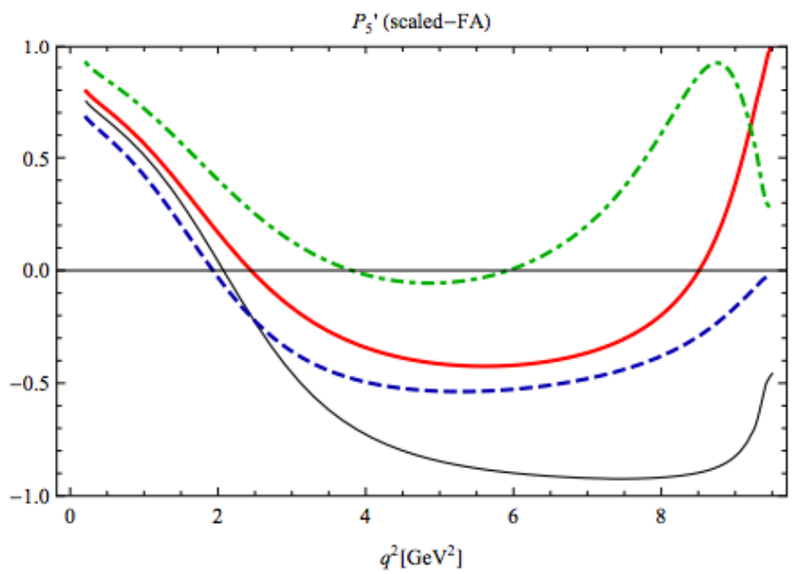
Lyons and Zwicky arXiv:1406.0566

Extrapolation from BESII assuming QCD factorisation



Resonance structure at high q^2 failure of factorisation

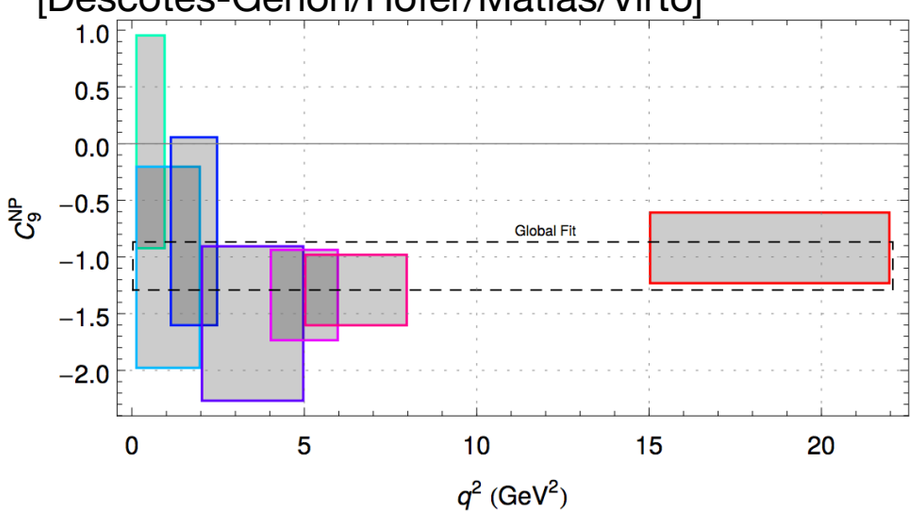
A New Particle?

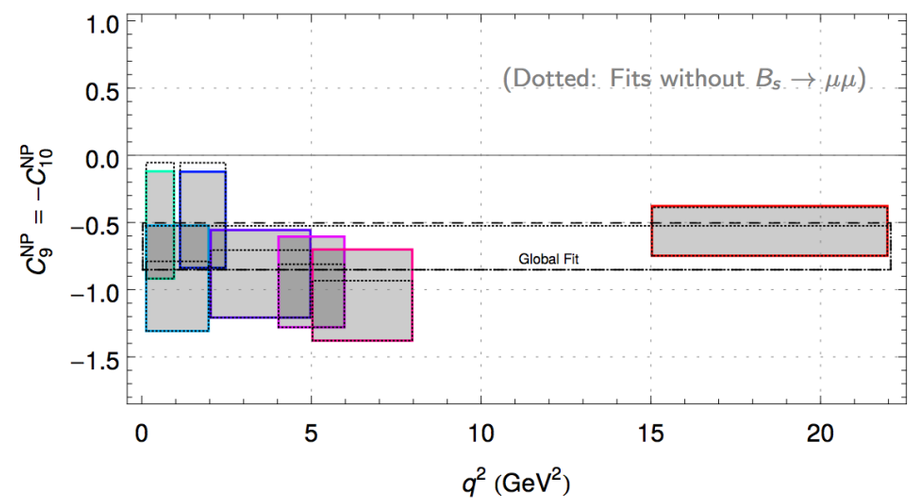


- Different contributions from charm loop (parameterized as the interference with the J/ψ) can change the behaviour of P_5'

- New Physics must be a flat contribution in the Wilson coefficient(s) as a function of q^2

[Descotes-Genon/Hofer/Matias/Virto]





- Up to now consistent with flat, but more statistics needed
- We are developing a method to determine the non-flat hadronic contribution directly from data!

Unbinned B—>K*mm

Charm Loop

lepton mass term

phase-space

form factors

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{2^7\pi^5} |\boldsymbol{k}|\beta_+ \left\{ \frac{2}{3}|\boldsymbol{k}|^2\beta_+^2 \left|C_{10}^{\text{eff}} f_+(q^2)\right|^2 + \frac{m_\ell^2 (M_B^2 - M_K^2)^2}{q^2 M_B^2} \left|C_{10}^{\text{eff}} f_0(q^2)\right|^2 \right.$$
$$\left. + |\boldsymbol{k}|^2 \left[1 - \frac{1}{3}\beta_+^2\right] \left| C_9^{\text{eff}} f_+(q^2) + 2C_7^{\text{eff}} \frac{m_b + m_s}{M_B + M_K} f_T(q^2) \right|^2 \right\}, \qquad (2.10)$$

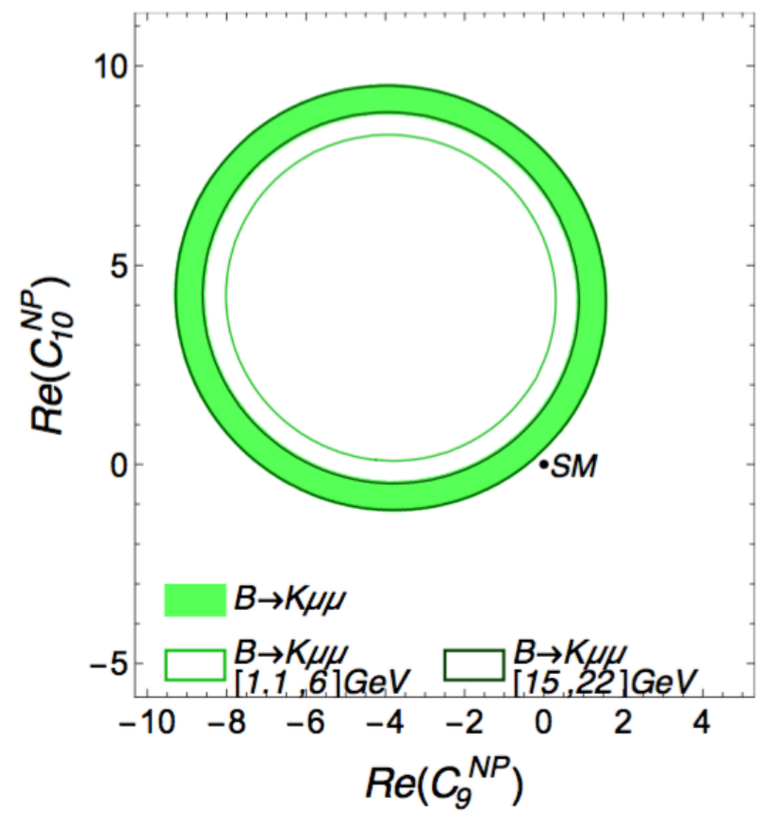
Add resonances here.

We do not include any Y(q2) term in C_9^{eff}.

Charm Loop

- Sensitive to $|C_9|^2 + |C_{10}|^2$.
- Can break degeneracy using e.g. BF(B_s->μμ).

Fermilab Lattice and MILC, Phys. Rev. D 93, 034005 (2016)

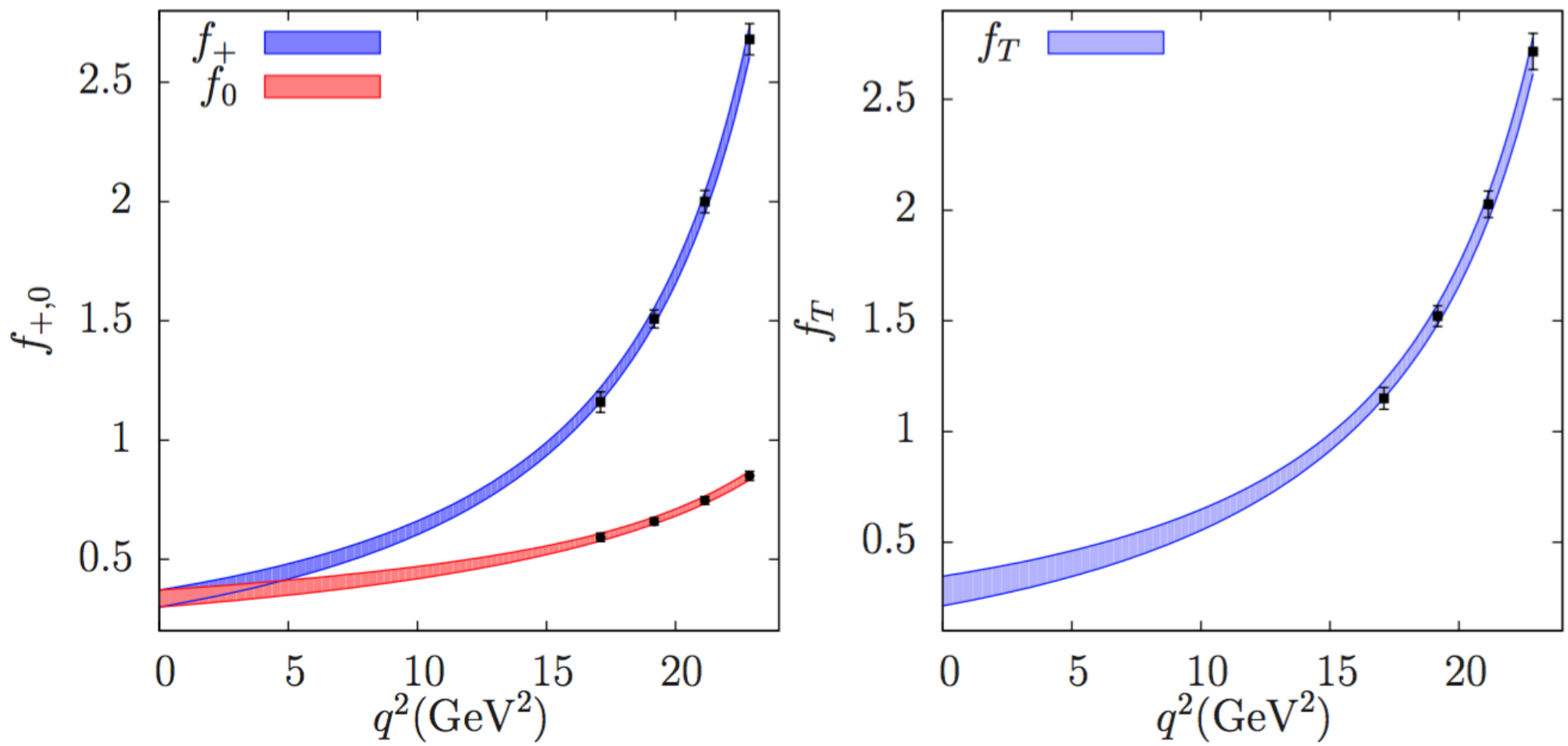


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{2^7\pi^5}|\boldsymbol{k}|\beta_+\left\{\frac{2}{3}|\boldsymbol{k}|^2\beta_+^2\left|C_{10}^{\rm eff}f_+(q^2)\right|^2 + \frac{m_l^2(M_B^2-M_K^2)^2}{q^2M_B^2}\left|C_{10}^{\rm eff}f_0(q^2)\right|^2\right.$$
$$\left. + |\boldsymbol{k}|^2\left[1-\frac{1}{3}\beta_+^2\right]\left|C_9^{\rm eff}f_+(q^2) + 2C_7^{\rm eff}\frac{m_b+m_s}{M_B+M_K}f_T(q^2)\right|^2\right\}, \qquad (2.10)$$

Equation from Fermilab Lattice and MILC, Phys. Rev. D 93, 025026

Charm Loop

- Use latest Fermilab/MILC form factor calculations:



Fermilab Lattice and MILC, Phys. Rev. D 93, 025026

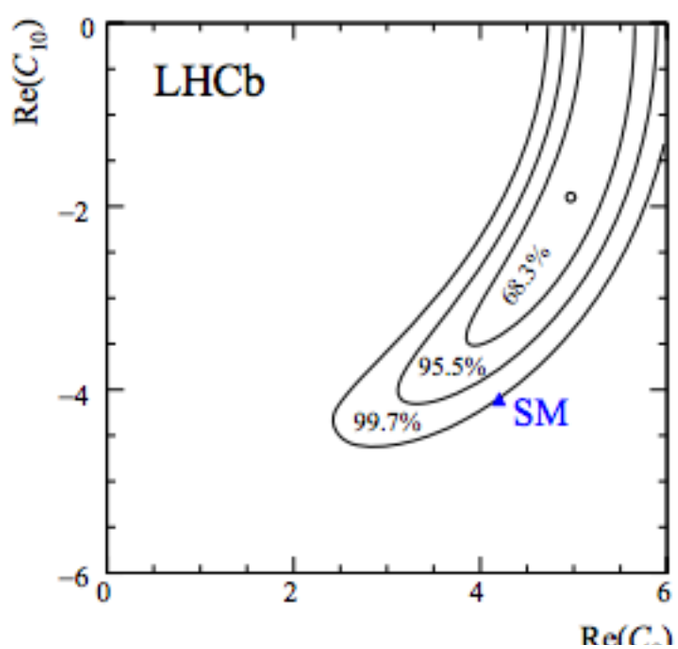
- z-expansion coefficients allowed to float within uncertainties.

Charm Loop

- Results show minimal interference with J/ψ and $\psi(2S)$ resonances

  $\rightarrow$ Given this model, the J/ψ and $\psi(2S)$ resonances play sub-dominant role below their pole mass
- Phases of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ in good agreement with Lyon Zwicky [1406.0566]

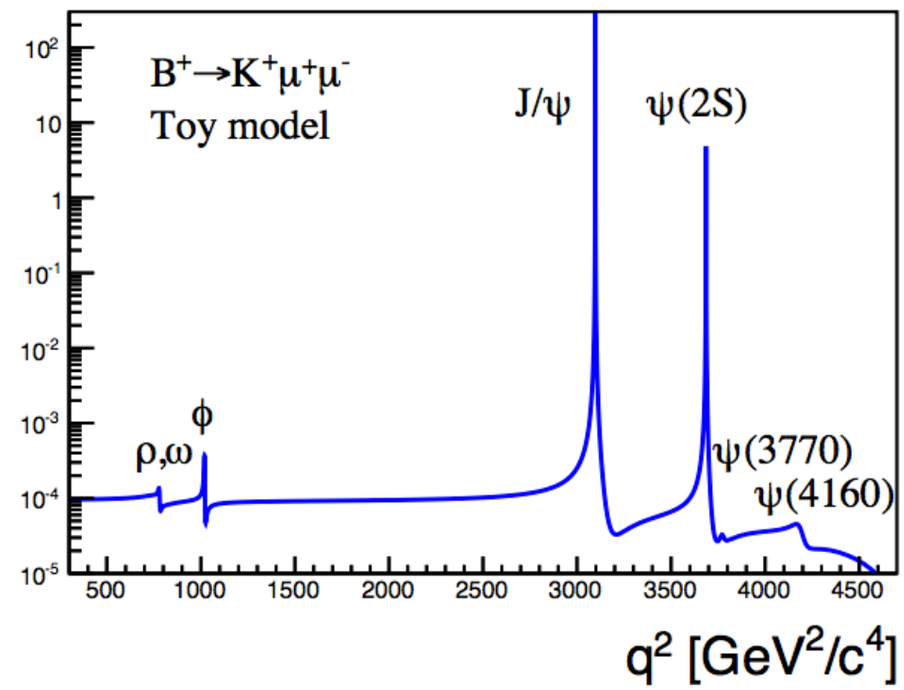
Resonance	J/ψ negative/$\psi(2S)$ negative	
	Phase [rad]	Branching fraction
$\rho(770)$	-0.35 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$
$\omega(782)$	0.26 ± 0.39	$(4.93 \pm 0.59) \times 10^{-10}$
$\phi(1020)$	0.47 ± 0.39	$(2.53 \pm 0.26) \times 10^{-9}$
J/ψ	-1.66 ± 0.05	–
$\psi(2S)$	-1.93 ± 0.10	$(4.64 \pm 0.20) \times 10^{-6}$
$\psi(3770)$	-2.13 ± 0.42	$(1.38 \pm 0.54) \times 10^{-9}$
$\psi(4040)$	-2.52 ± 0.66	$(4.17 \pm 2.72) \times 10^{-10}$
$\psi(4160)$	-1.90 ± 0.64	$(2.61 \pm 0.84) \times 10^{-9}$
$\psi(4415)$	-2.52 ± 0.36	$(6.04 \pm 3.93) \times 10^{-10}$



- Constrains on C_9 and C_{10} in agreement with other global analyses
- Interference with resonances exclude $C_9 = 0$ at more than 5σ!
- Significantly improve precision on b_1^+ and b_2^+

Charm Loop

Decay	% of $B^+ \to K^+\mu^+\mu^-$
Penguin	0.6 %
$B^+ \to \rho K^+$	0.0003 %
$B^+ \to \omega K^+$	0.0006 %
$B^+ \to \phi K^+$	0.003 %
$B^+ \to J/\psi K^+$	92 %
$B^+ \to \psi(2S) K^+$	7.3 %
$B^+ \to \psi(3770) K^+$	0.007 %
$B^+ \to \psi(4040) K^+$	~ 0 %
$B^+ \to \psi(4160) K^+$	0.005 %
$B^+ \to \psi(4415) K^+$	~ 0 %



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{2^7\pi^5} |\boldsymbol{k}| \beta_+ \left\{ \frac{2}{3} |\boldsymbol{k}|^2 \beta_+^2 \left| C_{10}^{\text{eff}} f_+(q^2) \right|^2 + \frac{m_l^2 (M_B^2 - M_K^2)^2}{q^2 M_B^2} \left| C_{10}^{\text{eff}} f_0(q^2) \right|^2 \right.$$
$$\left. + |\boldsymbol{k}|^2 \left[1 - \frac{1}{3}\beta_+^2 \right] \left| C_9^{\text{eff}} f_+(q^2) + 2C_7^{\text{eff}} \frac{m_b + m_s}{M_B + M_K} f_T(q^2) \right|^2 \right\}$$

Charm Loop

$$\mathcal{A}_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

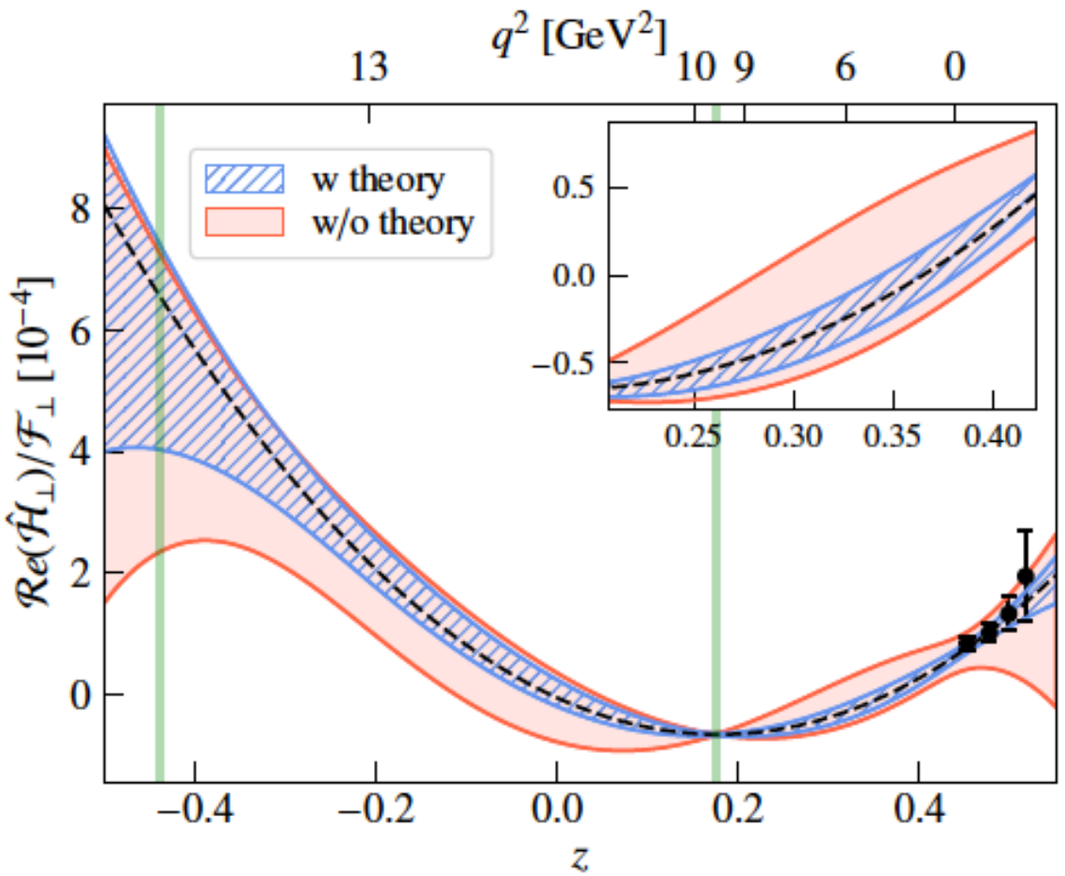
- Wilson coefficients
- Form factors
- Non-local hadronic matrix elements

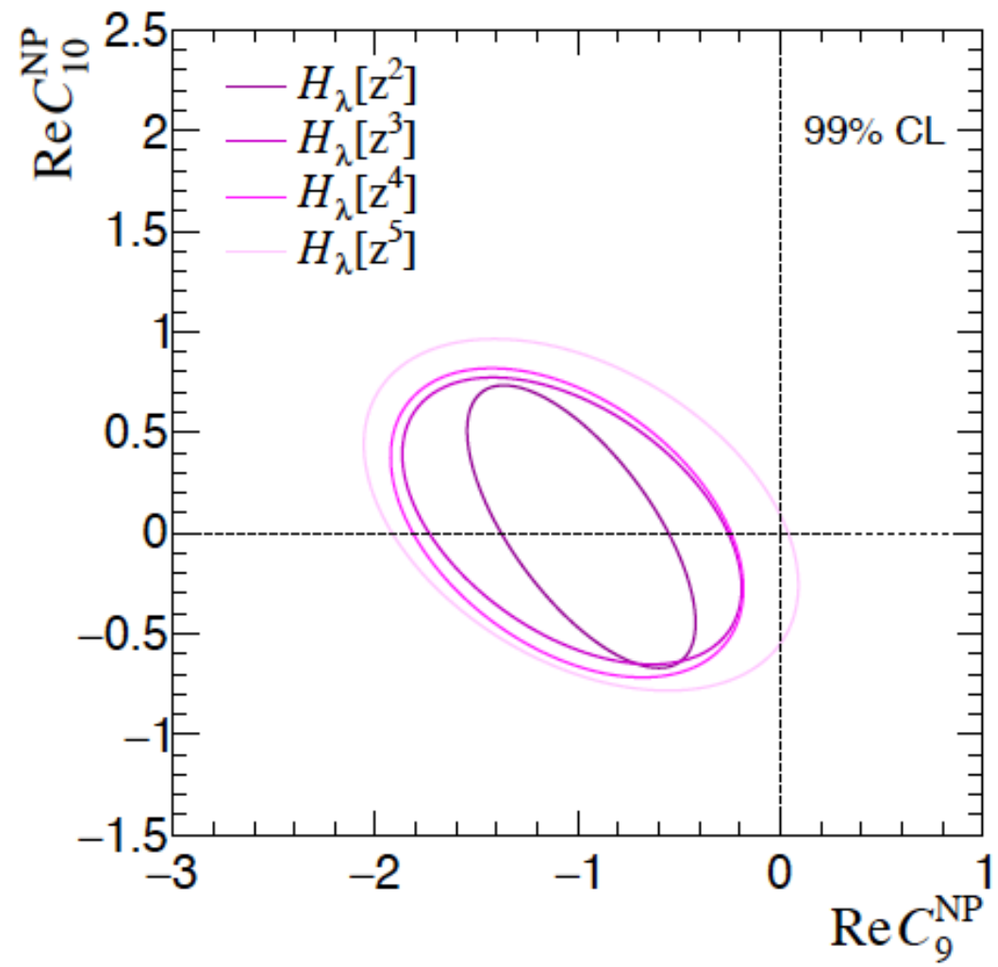
Mapping $q^2 \to z(q^2)$

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z) \xrightarrow[\text{expansion}]{\text{polynomial}} \hat{\mathcal{H}}_\lambda(z) = \left[\sum_k \alpha_k^{(\lambda)} z^k \right] \mathcal{F}_\lambda(z)$$

- analytic within $|z| = 1$
- expansion used up to $z \sim 0.4$
- cut-off of the series introduce a model bias

Charm Loop





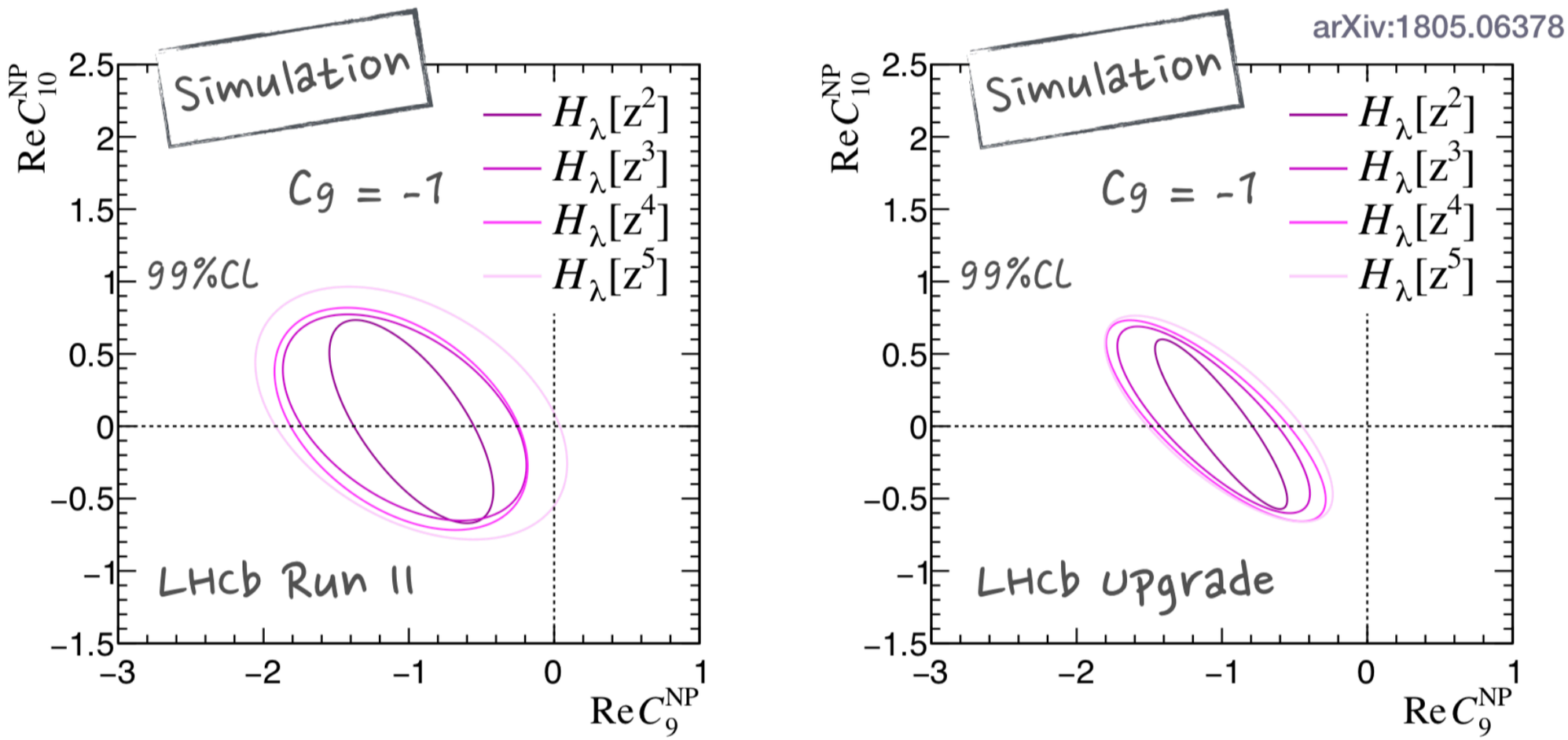
Mauri/Chrzaszcz/NS/vanDyk/Silva arXiv:1805.06378

- Extension of the parametrisation of the model in arXiv:1709.03921, including points at negative q^2
- Fit much more stable with the theory points, but not yet a rigorous procedure to evaluate systematics

LHCb Experiment

- Studying the **order of the polynomial** allows to inspect charm-loop effects

arXiv:1805.06378



- Uncertainty (slightly) **increase** with the order of the polynomial
- Modeling of the charm-loop → main **systematic**
- Statistical uncertainty on the Wilson coefficients saturates already after Run II due to **form factor uncertainties**

LHCb Experiment

***classic* angular analysis**

2 steps procedure:

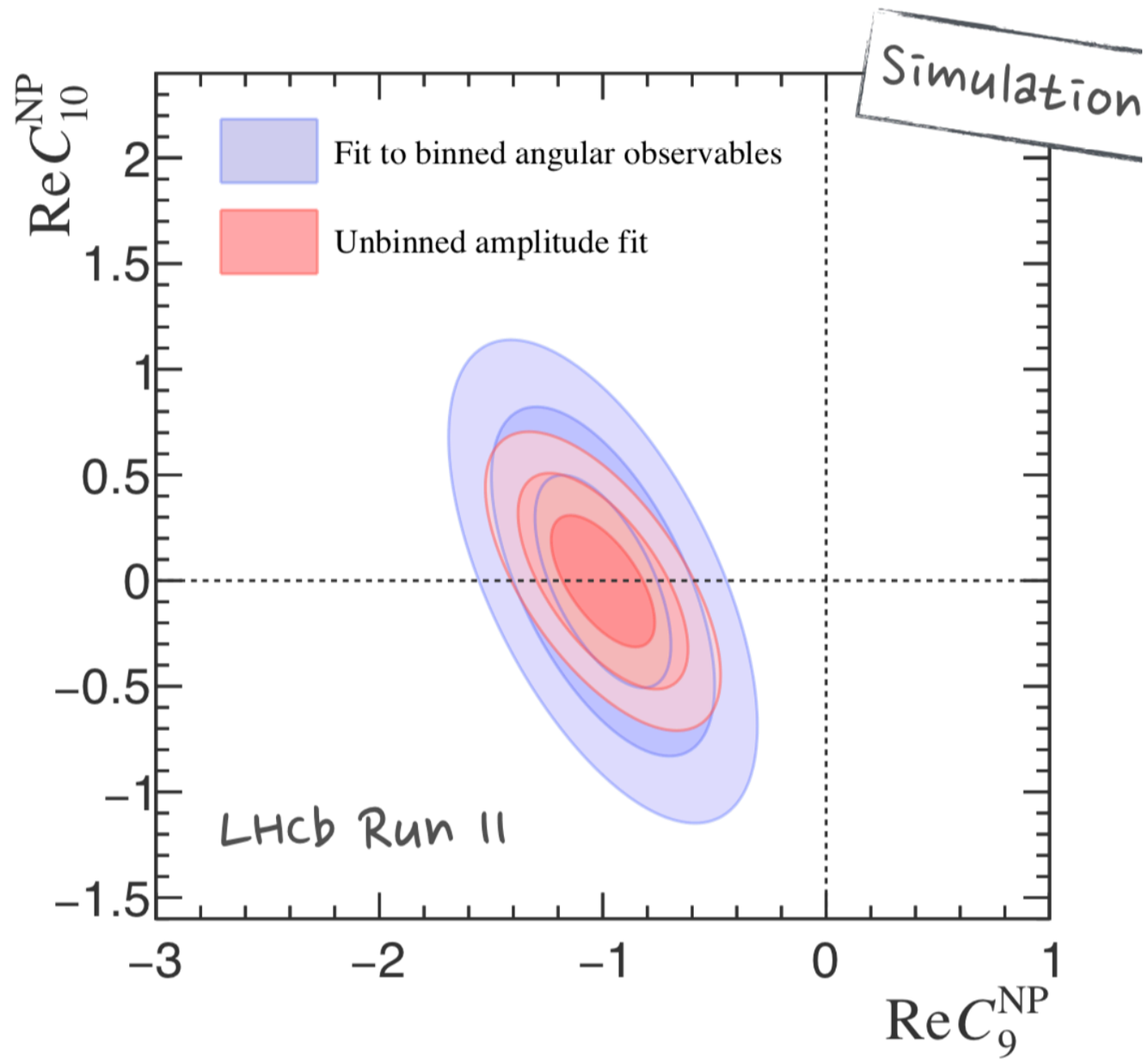
- fit for angular observables S_i
- fit for Wilson coeff. (using same model for charm-loop)

VS

amplitude fit

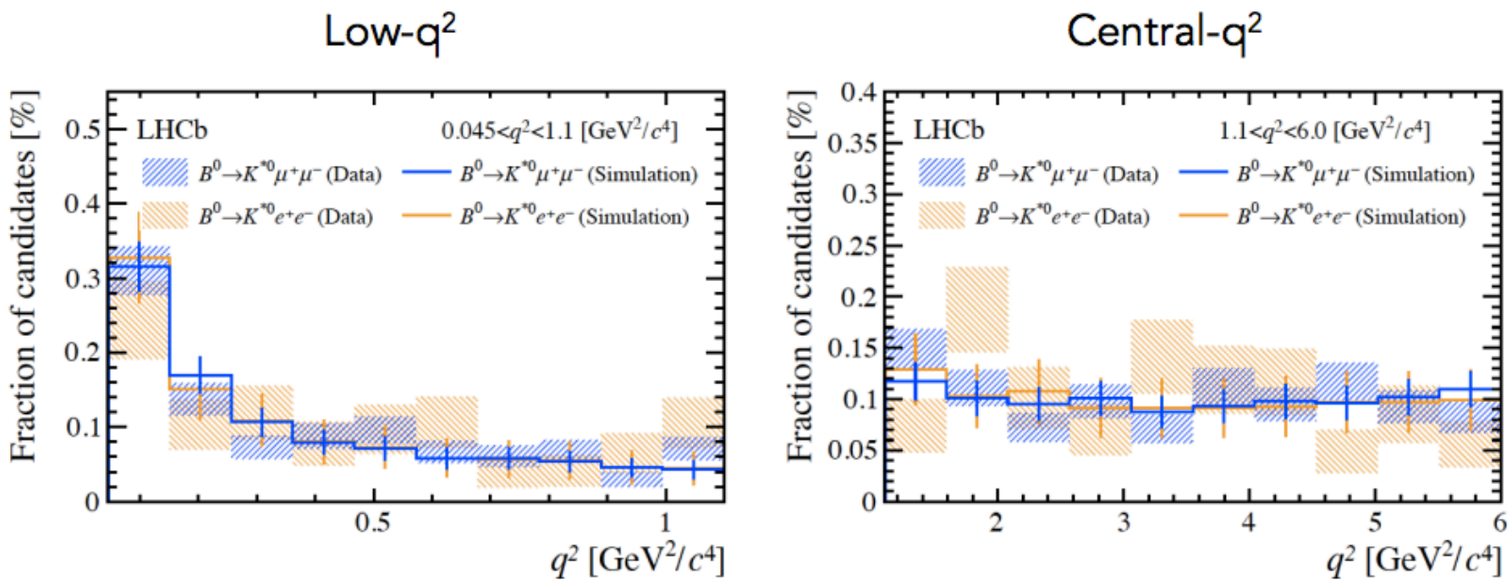
direct determination of Wilson coeff.

(include branching ratio information via an extended ML fit to signal yield)



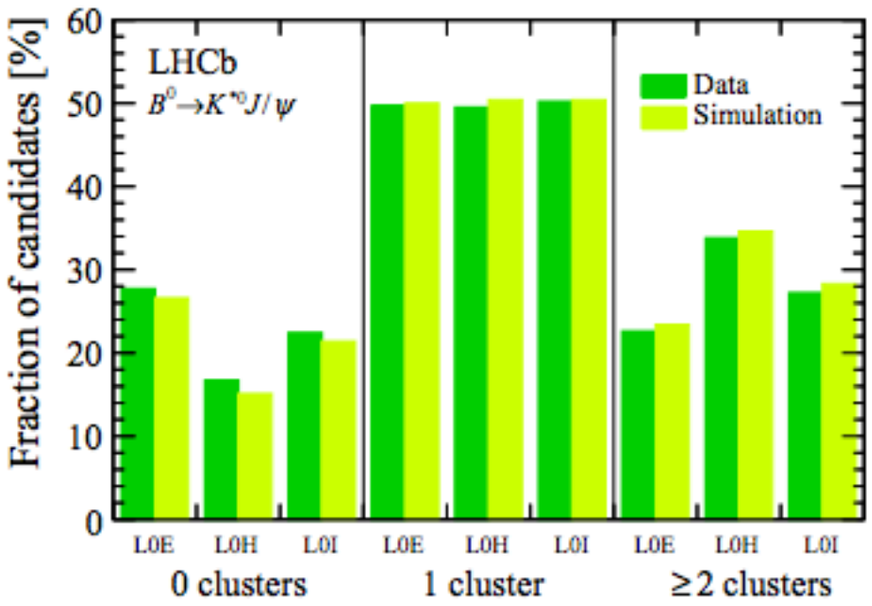
RK*

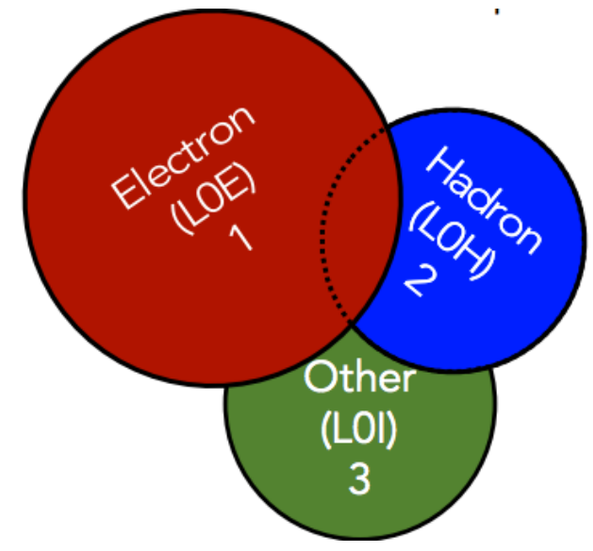
R_{K^*} Analysis



- Fit MC in different trigger and bremsstrahlung categories to extract initial parameters (separately for all modes)
- Combine bremsstrahlung PDFs into one signal model per each trigger category (bremsstrahlung fractions fixed from MC) ee
- Fit the data in trigger categories allowing (some) parameters to vary
- **Signal**
  - 0γ (1γ and 2γ) — Crystal-Ball (Crystal-Ball and Gaussian)
  - Free parameters — mass shift and width scale
- **Backgrounds**
  - Combinatorial — exponential
  - Λ_b — simulation & data, yield constrained using muons
  - B_s — same as signal but shifted by m_{Bs}-m_{B0}, yield constrained using muons
  - Leakage — simulation, yield constrained using data
  - Part-Reco — simulation & data

R_{K^*} Analysis





Yield

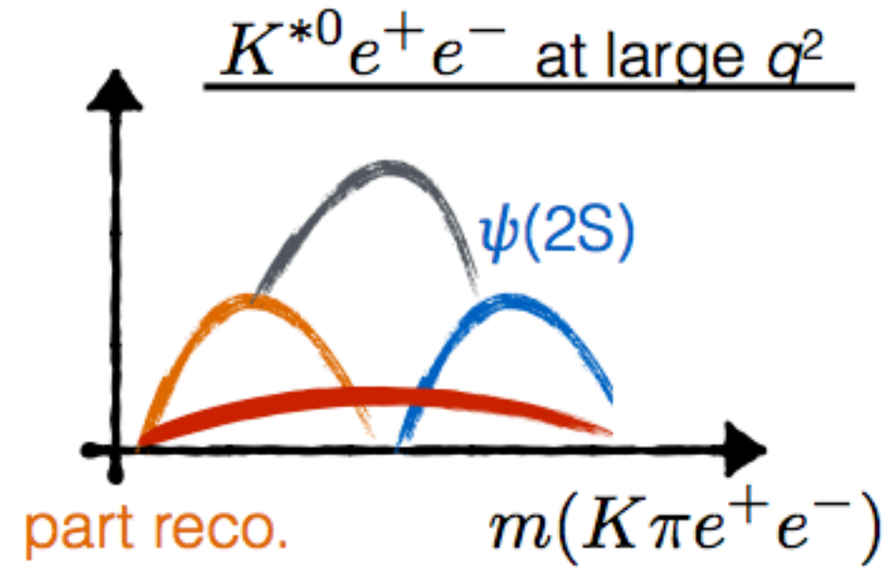
	$B^0 \to K^{*0}\ell^+\ell^-$		$B^0 \to K^{*0} J/\psi(\to \ell^+\ell^-)$
	low-q^2	central-q^2	
$\mu^+\mu^-$	285^{+18}_{-18}	353^{+21}_{-21}	274416^{+602}_{-654}
e^+e^- (L0E)	55^{+9}_{-8}	67^{+10}_{-10}	43468^{+222}_{-221}
e^+e^- (L0H)	13^{+5}_{-5}	19^{+6}_{-5}	3388^{+62}_{-61}
e^+e^- (L0I)	21^{+5}_{-4}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

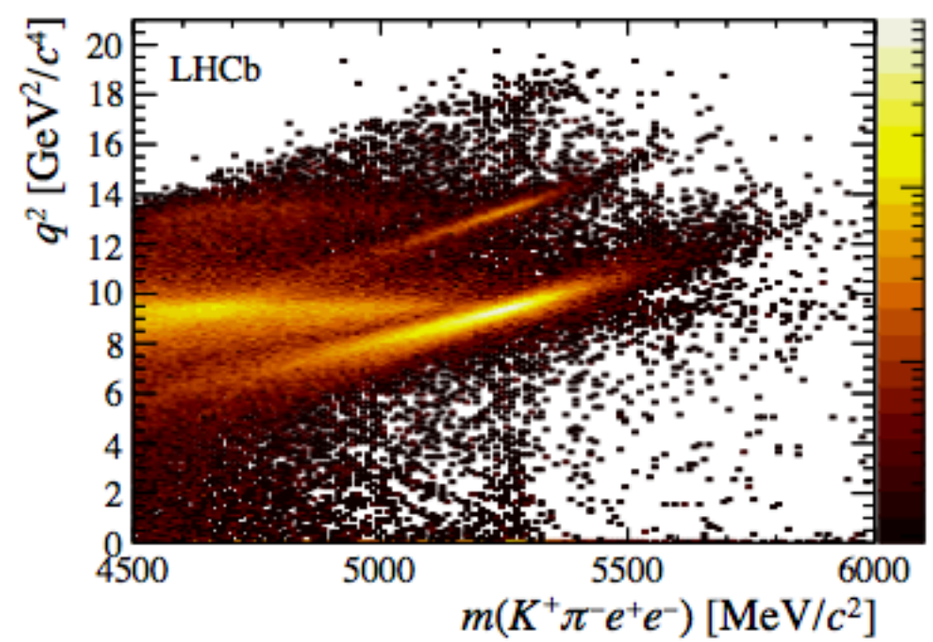
Systematics

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ ratio	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

R_{K^*} High q^2

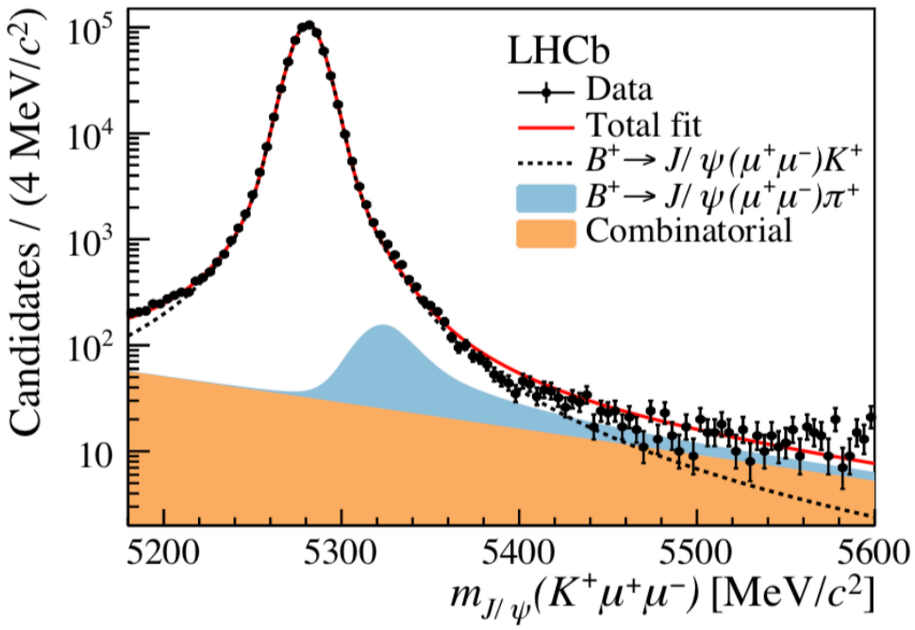
- Very little rate for q^2<1.0 GeV^2 (no photon pole)
- Working to add high q^2 bin – difficulty same for R_K and $R_K{}^*$
  - Rare decays with higher K* resonances can leak into signal region from below
  - ψ(2S)K* decays can leak into signal region on the upper side
  - Signal sandwiched between these and hence difficult to fit reliably

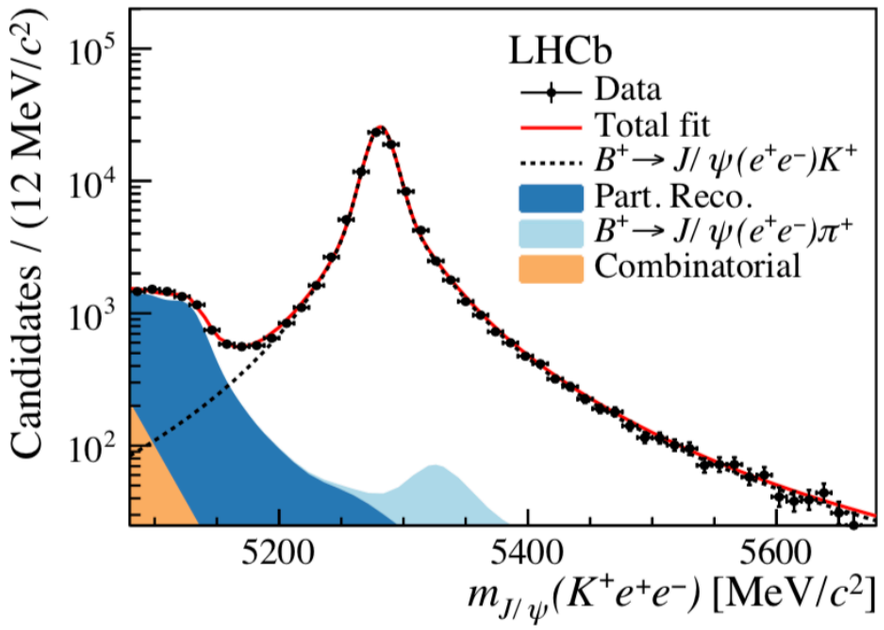


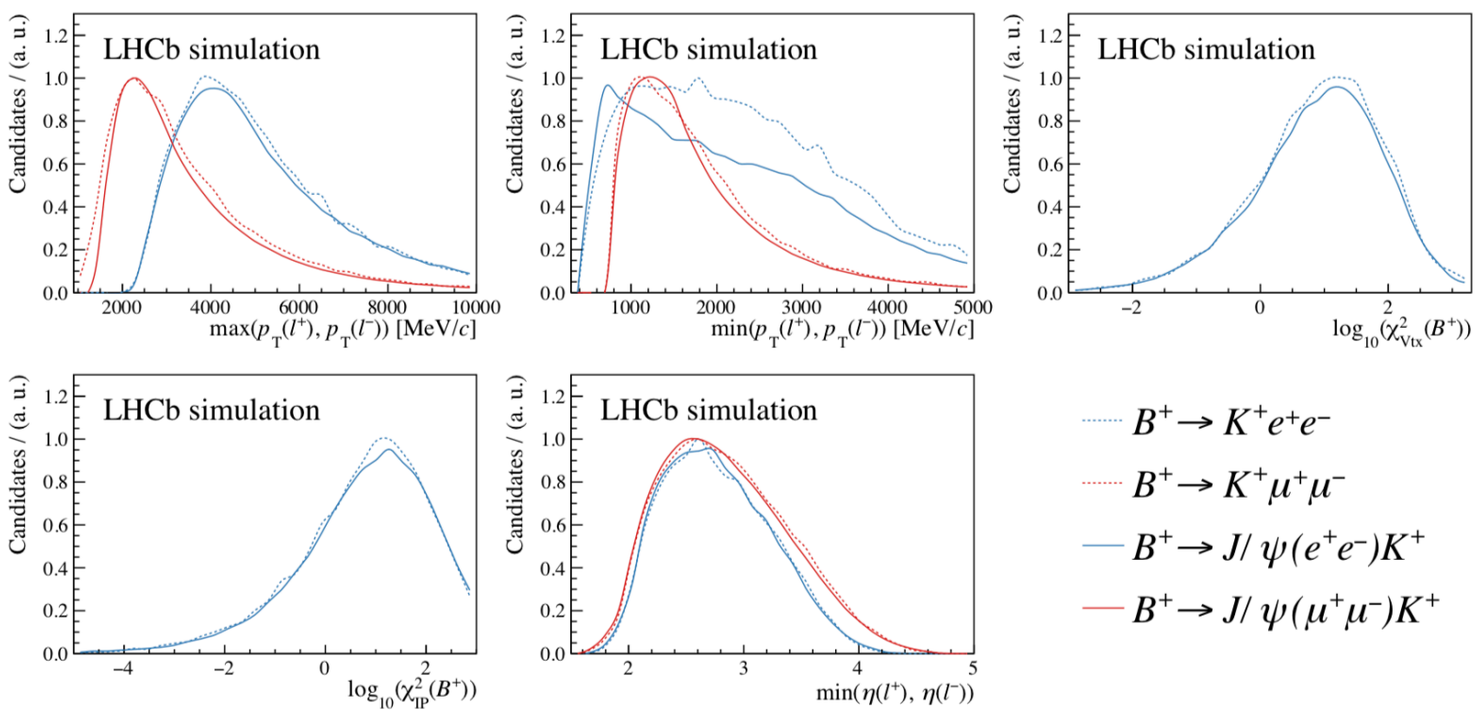


RK

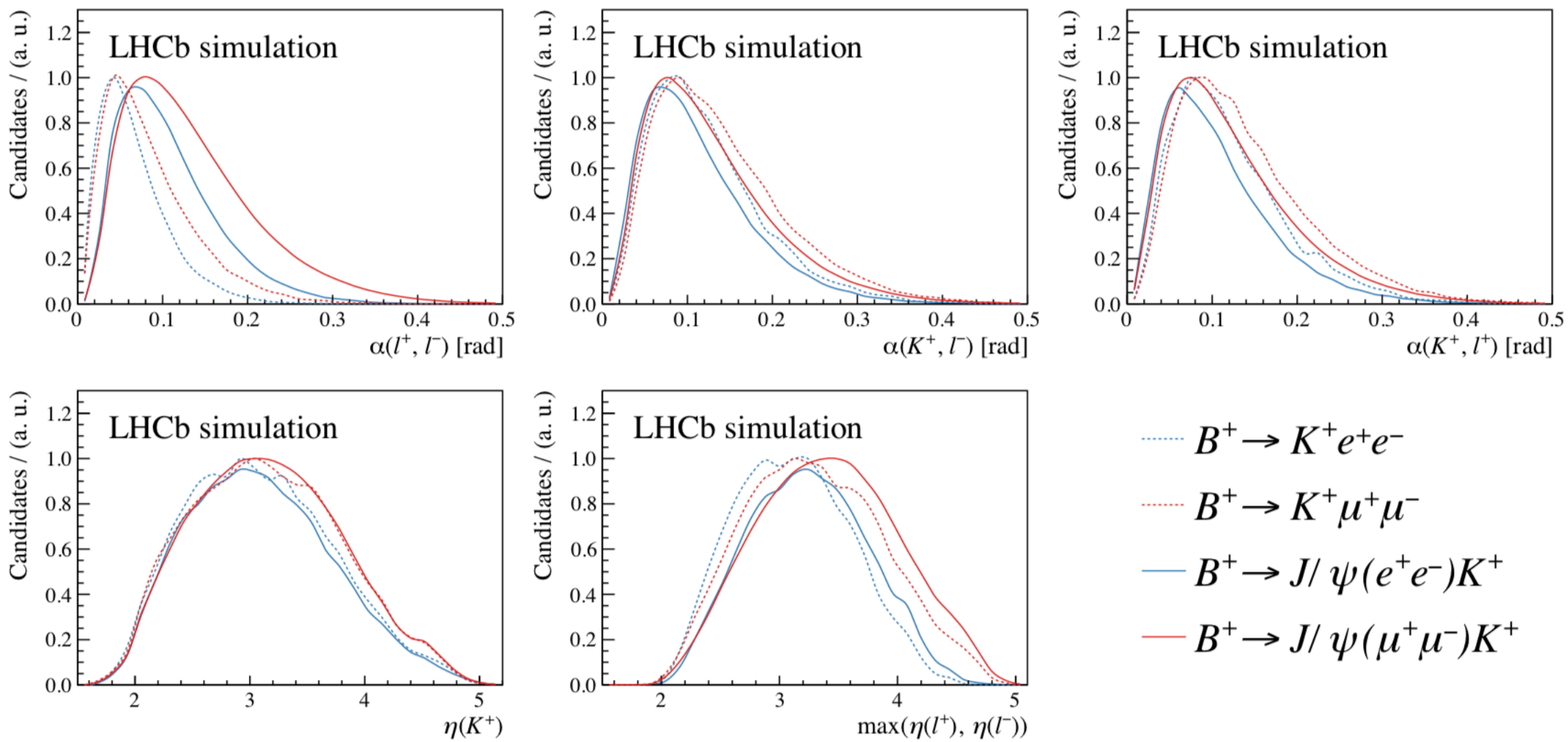
RK


LHCb
Data
Total fit
$B^+ \to J/\psi(\mu^+\mu^-)K^+$
$B^+ \to J/\psi(\mu^+\mu^-)\pi^+$
Combinatorial
Candidates / (4 MeV/c^2)
$m_{J/\psi}(K^+\mu^+\mu^-)$ [MeV/c^2]

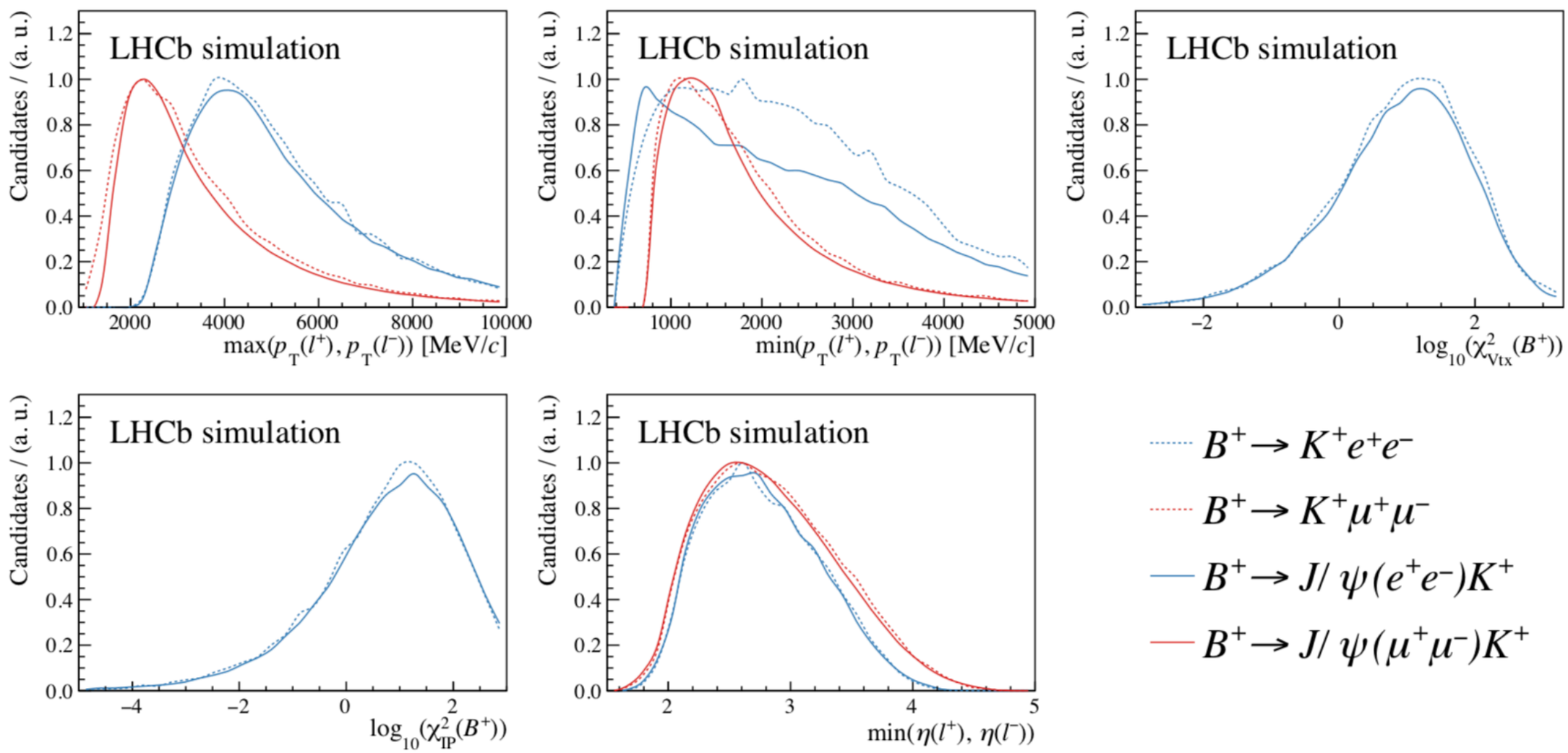

LHCb
Data
Total fit
$B^+ \to J/\psi(e^+e^-)K^+$
Part. Reco.
$B^+ \to J/\psi(e^+e^-)\pi^+$
Combinatorial
Candidates / (12 MeV/c^2)
$m_{J/\psi}(K^+e^+e^-)$ [MeV/c^2]


LHCb simulation
Candidates / (a. u.)
$\max(p_T(l^+), p_T(l^-))$ [MeV/c]
$\min(p_T(l^+), p_T(l^-))$ [MeV/c]
$\log_{10}(\chi^2_{Vtx}(B^+))$
$\log_{10}(\chi^2_{IP}(B^+))$
$\min(\eta(l^+), \eta(l^-))$
$B^+ \to K^+e^+e^-$
$B^+ \to K^+\mu^+\mu^-$
$B^+ \to J/\psi(e^+e^-)K^+$
$B^+ \to J/\psi(\mu^+\mu^-)K^+$

RK

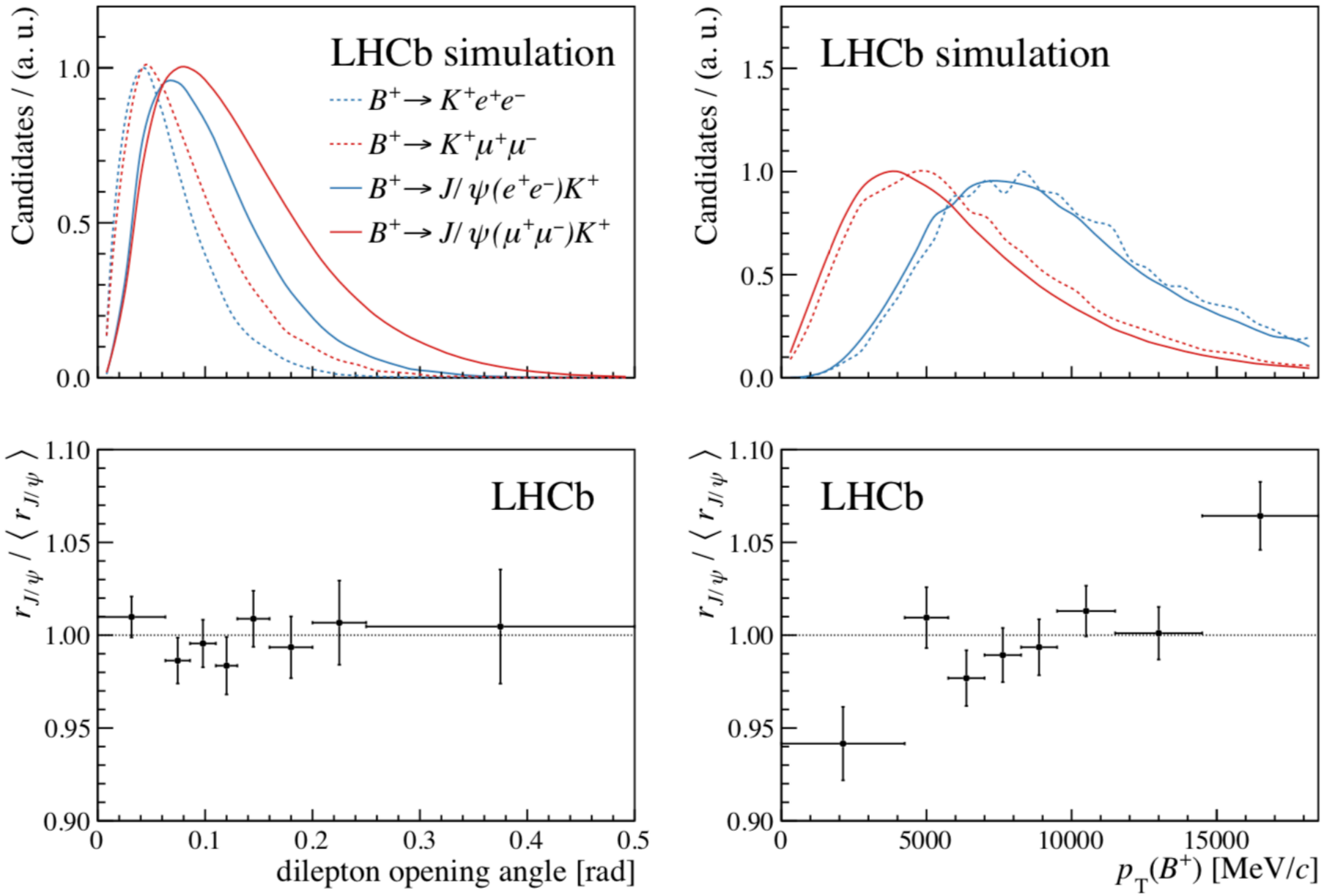

LHCb simulation
Candidates / (a. u.)
α(l⁺, l⁻) [rad]
α(K⁺, l⁻) [rad]
α(K⁺, l⁺) [rad]
η(K⁺)
max(η(l⁺), η(l⁻))
B⁺ → K⁺e⁺e⁻
B⁺ → K⁺μ⁺μ⁻
B⁺ → J/ψ(e⁺e⁻)K⁺
B⁺ → J/ψ(μ⁺μ⁻)K⁺

RK

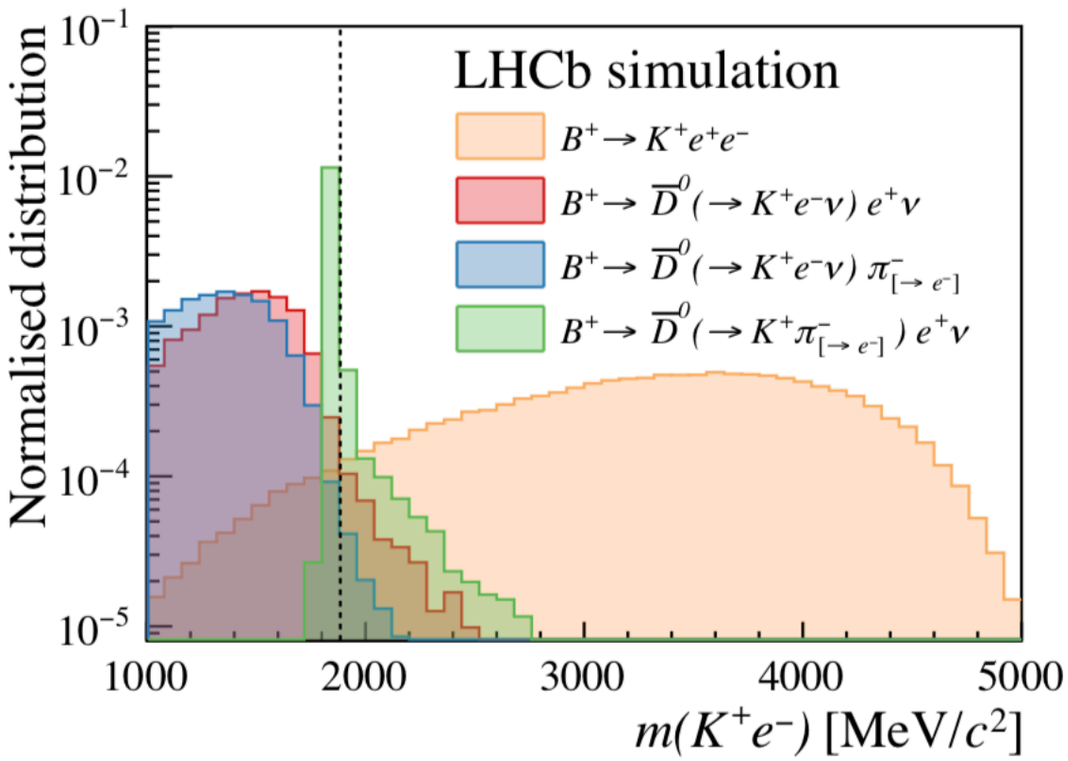

LHCb simulation
Candidates / (a. u.)
max($p_T(l^+), p_T(l^-)$) [MeV/c]
min($p_T(l^+), p_T(l^-)$) [MeV/c]
$\log_{10}(\chi^2_{Vtx}(B^+))$
$\log_{10}(\chi^2_{IP}(B^+))$
min($\eta(l^+)$, $\eta(l^-)$)
$B^+ \to K^+e^+e^-$
$B^+ \to K^+\mu^+\mu^-$
$B^+ \to J/\psi(e^+e^-)K^+$
$B^+ \to J/\psi(\mu^+\mu^-)K^+$

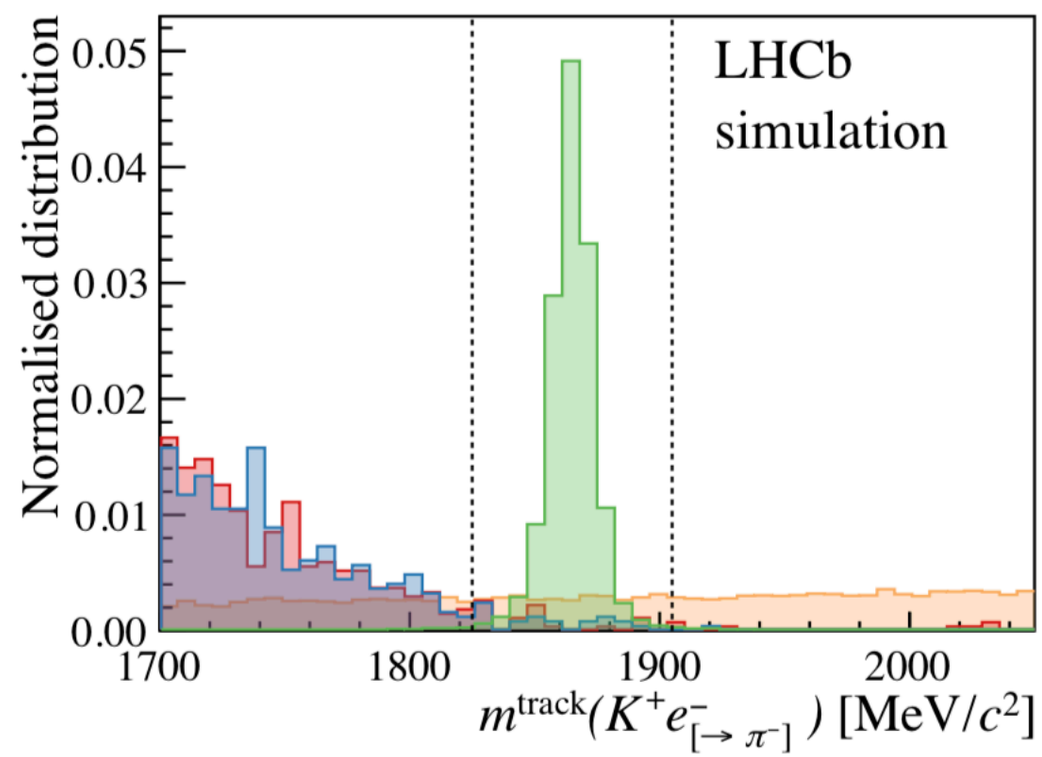
RK

Supplementary $r_{J/\psi}$ 1D

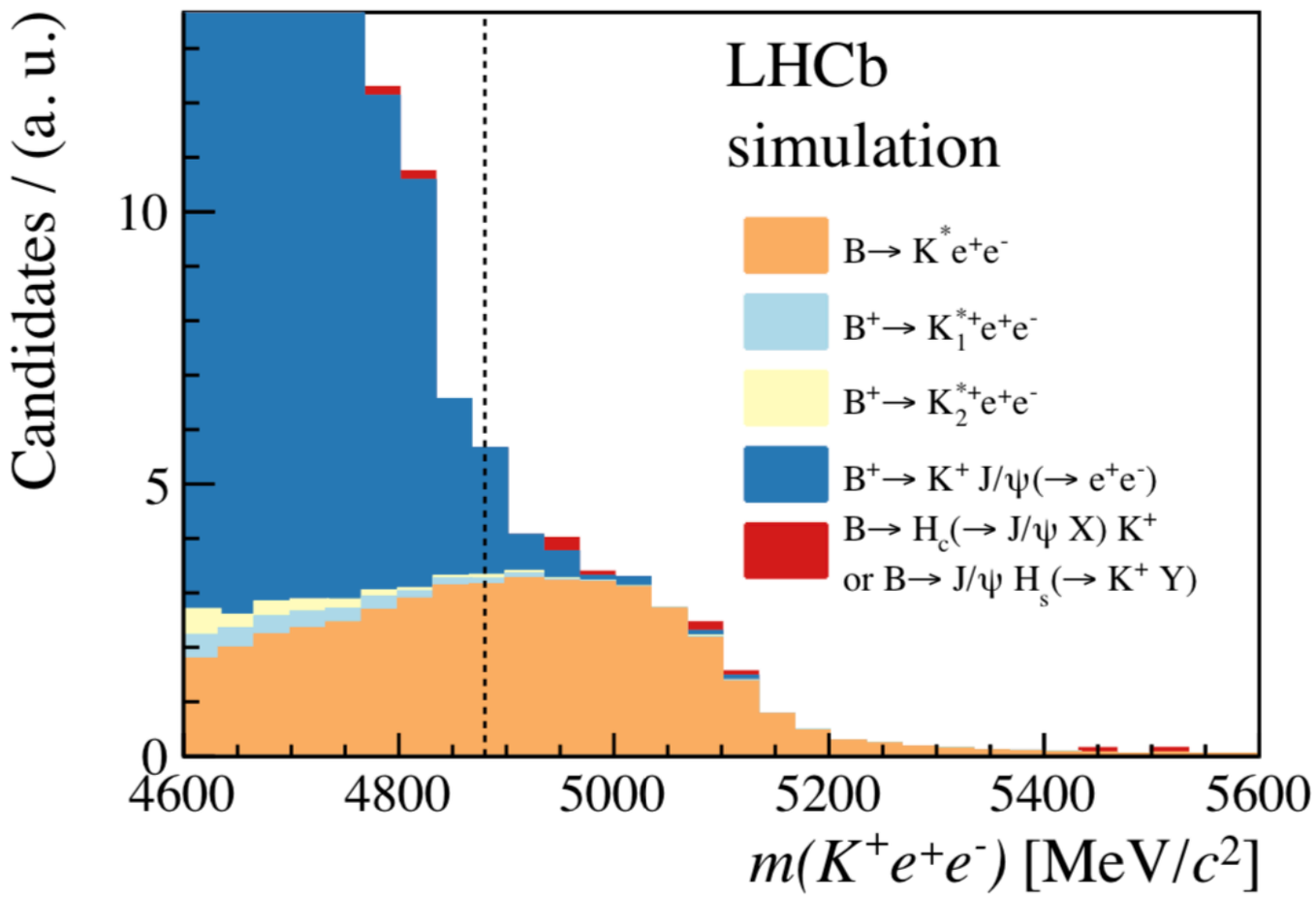


Cascade Vetos in RK





RK Part Reco

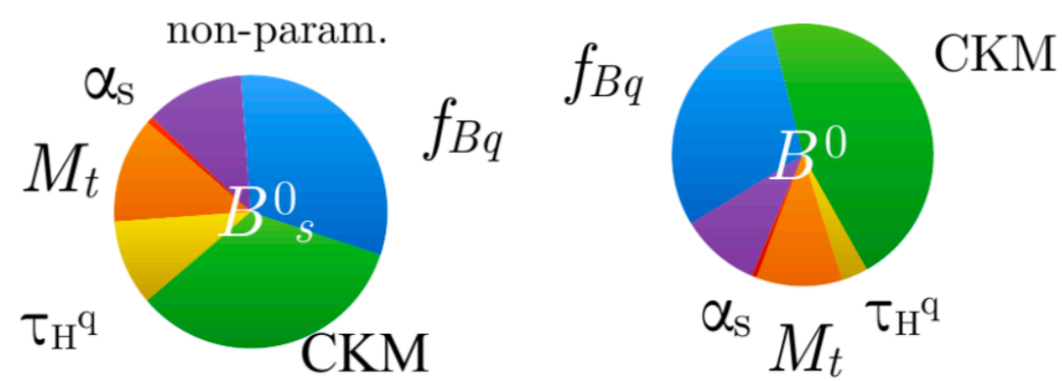

LHCb
simulation
B→ K* e+e-
B+→ K1*+e+e-
B+→ K2*+e+e-
B+→ K+ J/ψ(→ e+e-)
B→ Hc(→ J/ψ X) K+
or B→ J/ψ Hs(→ K+ Y)
Candidates / (a. u.)
0
5
10
4600
4800
5000
5200
5400
5600
m(K+e+e-) [MeV/c2]

Bs—>mm

Bs—>mm

Current Experimental Systematics	
Source	size
Hadronisation fraction f_s/f_d	5.8%
Normalisation modes	3%
Particle identification	2%
Track reconstruction	2%

Current Theory Systematics

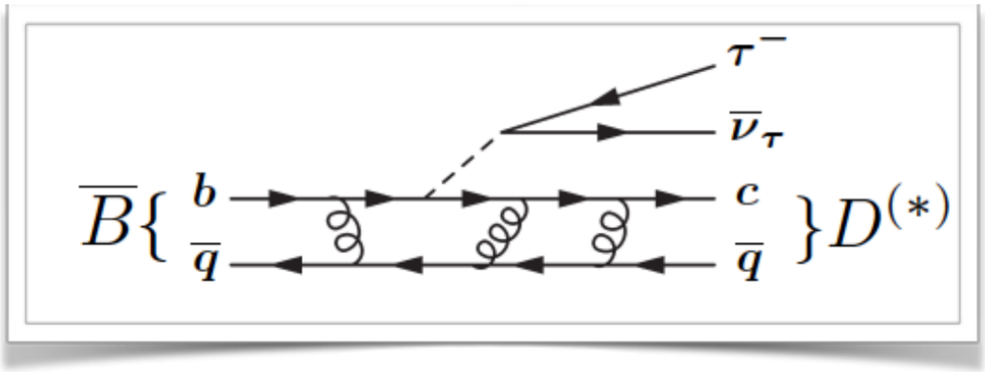


- Bs—>mm will stay statistically dominated till LHCb Upgrade II

	now	$23\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
absolute uncertainty $B^0_s \to \mu^+\mu^-$ $[10^{-9}]$	0.67	0.30	0.16
rel. uncertainty $B^0 \to \mu^+\mu^- / B^0_s \to \mu^+\mu^-$ [%]	90%	34%	10%

Semileptonic LHCb

Semileptonic



$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B} \to D^{(*)}\ell\nu)} = \frac{\text{signal}}{\text{normalization}} \quad (\ell = e, \mu)$$

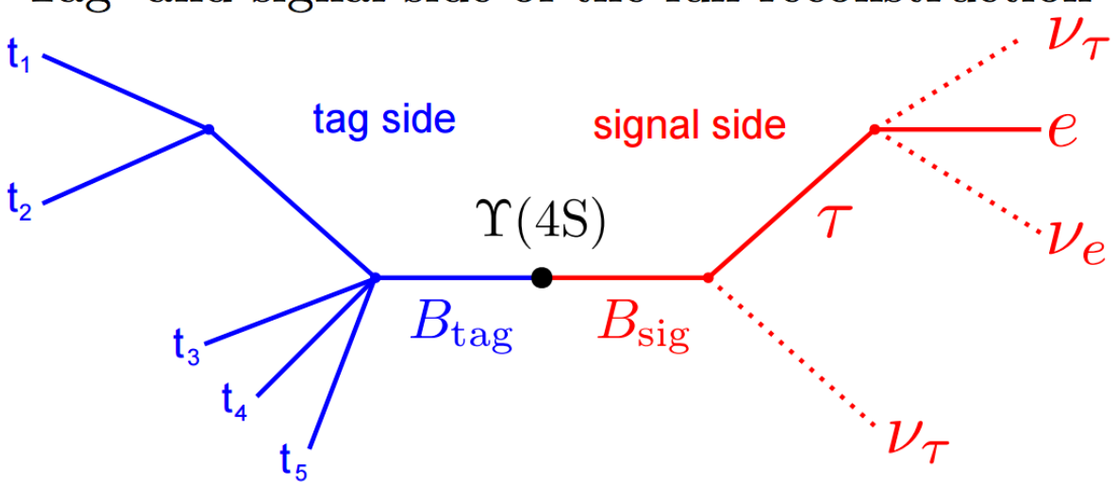
- B-factories measure tau->e,mu 2v
- LHCb measures tau->mu 2v

$$\frac{\mathrm{d}\Gamma_\tau}{\mathrm{d}q^2} = \frac{G_F^2\,|V_{cb}|^2\,|\boldsymbol{p}^*_{D^{(*)}}|\,q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\Big[(|H_+|^2+|H_-|^2 + |H_0|^2)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_s|^2\Big]$$

- Since the D-meson is a scalar $H_{+,-}$ vanish
- Amplitudes depend on 4 universal FFs extracted from data
- Four free parameters in the fit
- In the case of the e/mu H_S is suppressed by the mass, so this is only present in the channel with the tau (from HQET)

Semileptonic

Tag- and signal-side of the full reconstruction



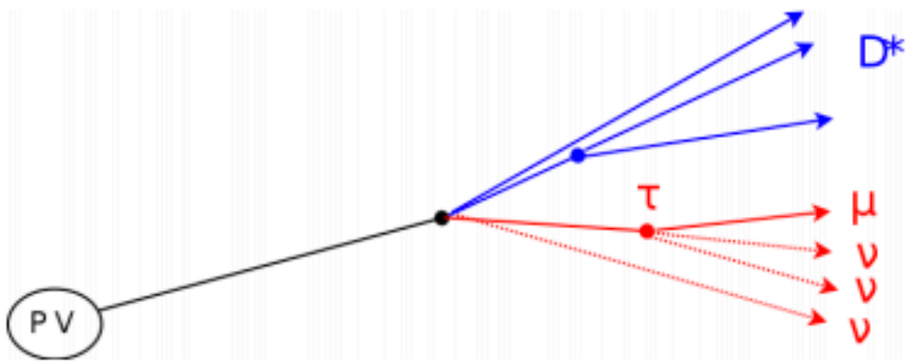
$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} = \frac{\int_{m_\tau^2}^{q^2_{\rm max}} \frac{{\rm d}\Gamma_\tau}{{\rm d}q^2}\,{\rm d}q^2}{\int_{m_\ell^2}^{q^2_{\rm max}} \frac{{\rm d}\Gamma_\ell}{{\rm d}q^2}\,{\rm d}q^2}$$

- Hadronic tag analyses:
  - Reconstruct tag B meson in all hadronic mode
  - Precise knowledge of kinematic of missing system
  - Kill background, but efficiency about 10^{-3}

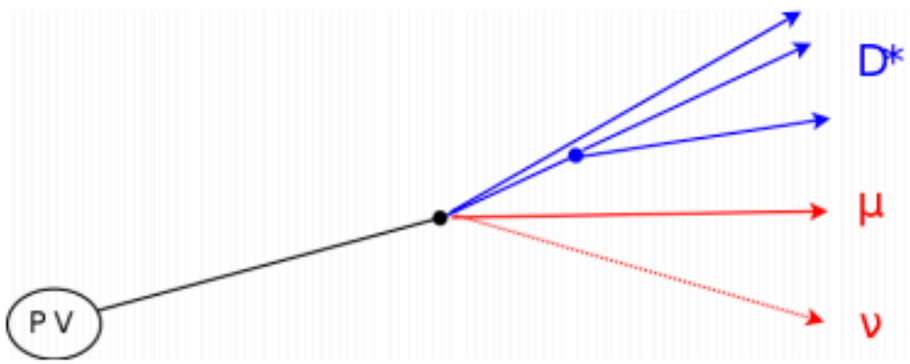
- Semileptonic analyses:
  - Tag B-meson in semileptonic channel
  - Selection: E_T, missing mass and angle between D^*l and B

Semileptonic

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

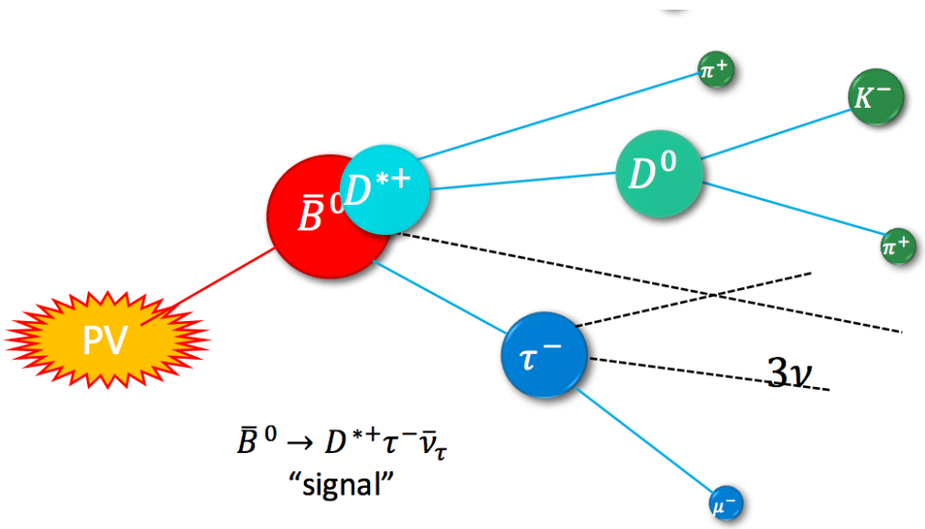


$B \to D^* \mu \nu$



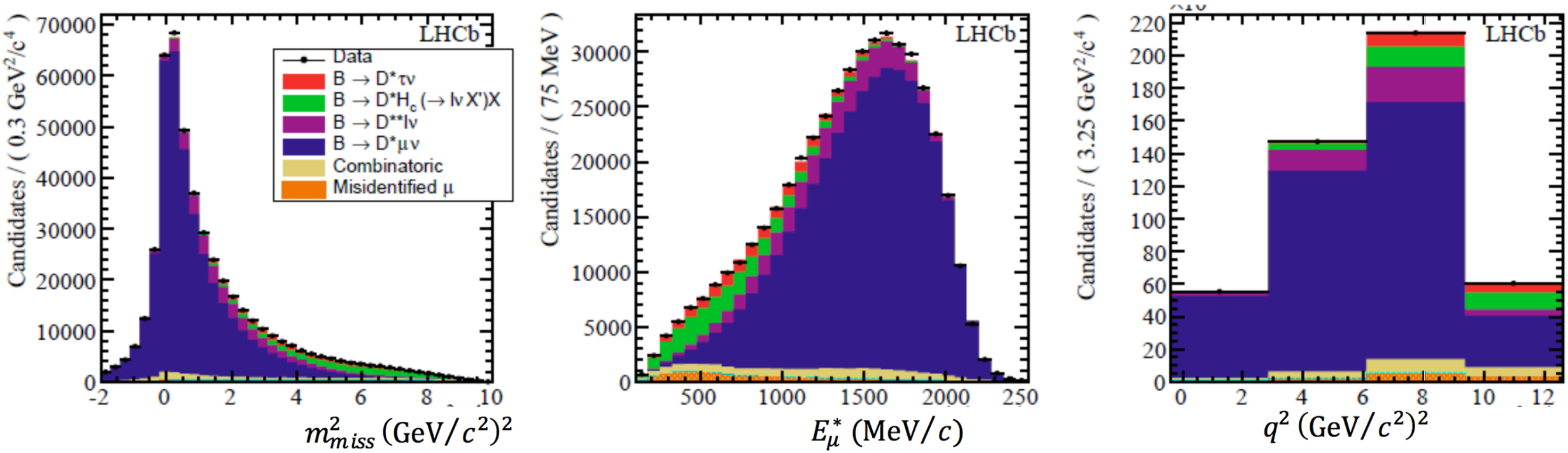
- Difficulty: neutrinos - 2 for $(\tau \to \pi\pi\pi\nu)\nu$, 3 for $(\tau \to \mu\nu\nu)\nu$
  - No narrow peak to fit (in any distribution)
- Main backgrounds: partially reconstructed B decays
  - $B \to D^* \mu\nu$,$B \to D^{**} \mu\nu$, $B \to D^* D(\to \mu X)X$ ...
  - $B \to D^* \pi\pi\pi X$, $B \to D^* D(\to \pi\pi\pi X)X$ ...
- Also combinatorial, misidentified background

Semileptonic

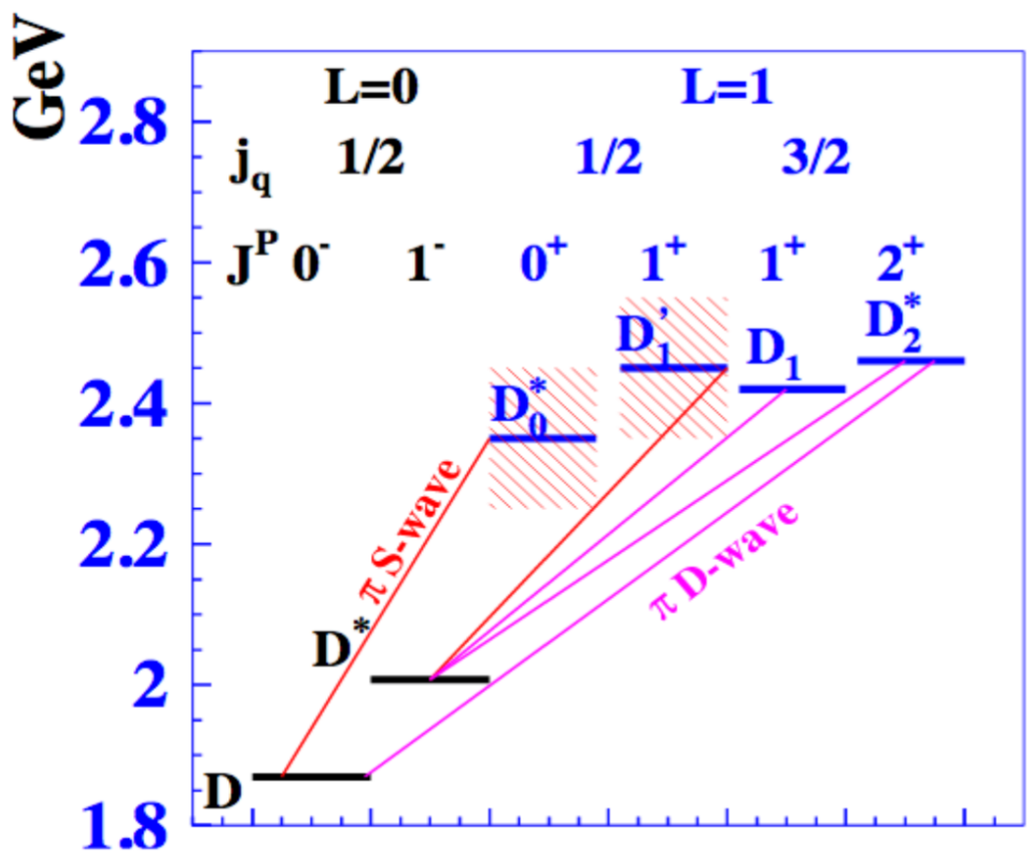


$$(\gamma\beta_z)_{\bar{B}} = (\gamma\beta_z)_{D^*\mu} \quad \Rightarrow \quad (p_z)_{\bar{B}} = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$

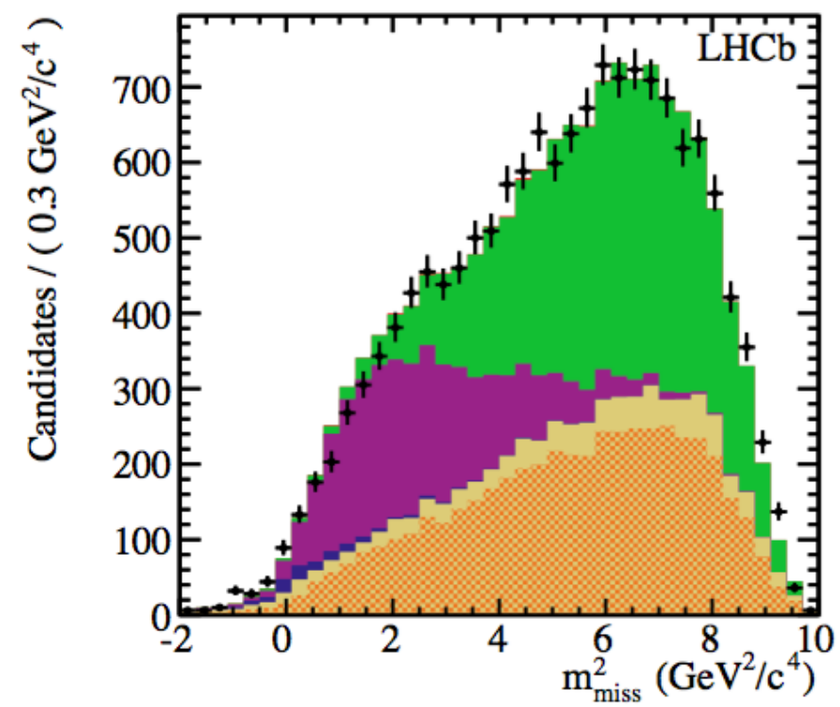
- B-direction given by PV-SV
- Full fit of the MM, E^*, q^2
- Muon, tau modes and bkg fit simultaneously



Semileptonic

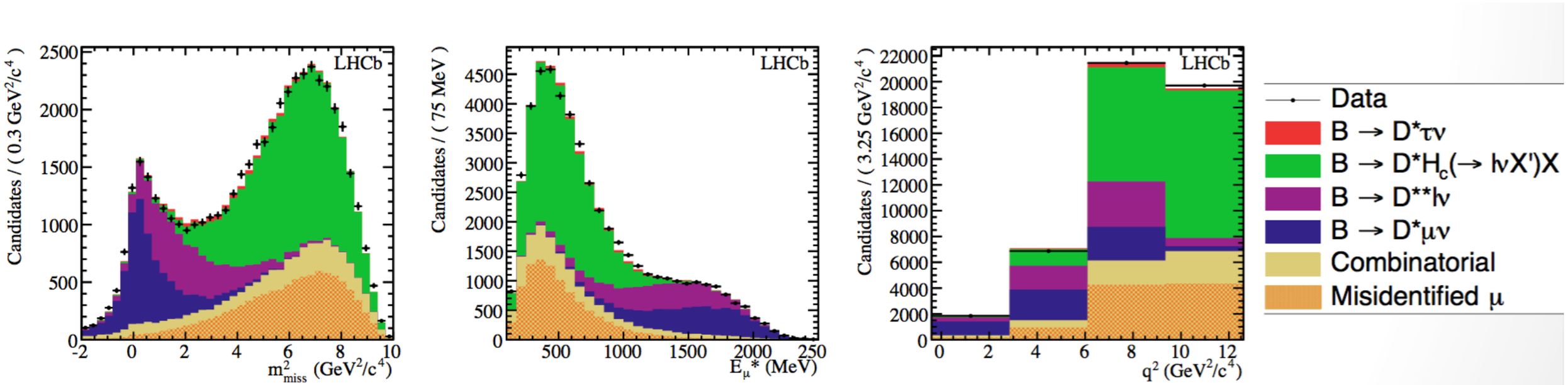


example B->D*pipi lv



- Large contribution from excited D** states
- Narrow states ($D_1^{(\prime)}$ and D_2^*) fit directly from data B->D*pi lv used as a control sample
- Higher D** excited states also fit from data and B->D pipi lv used as a control channel

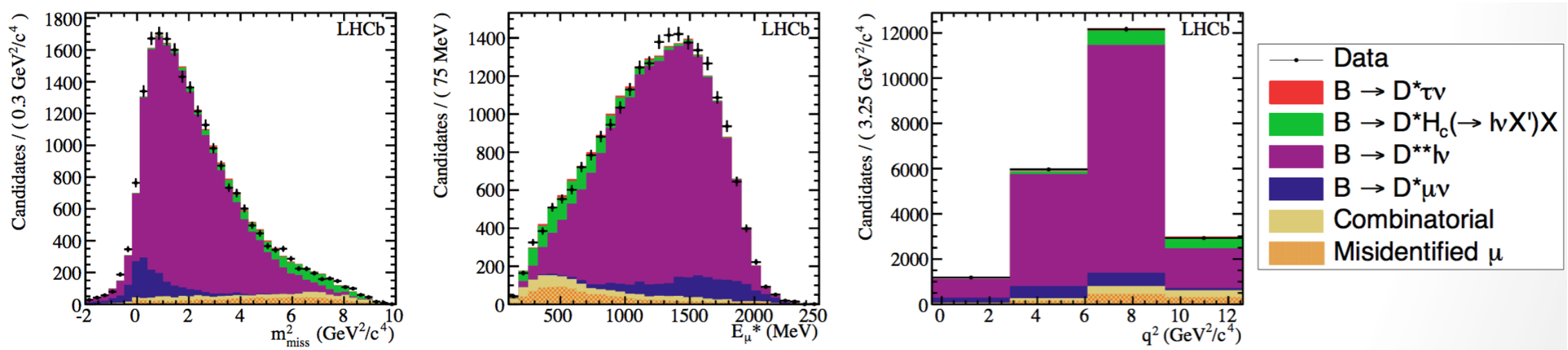
Semileptonic



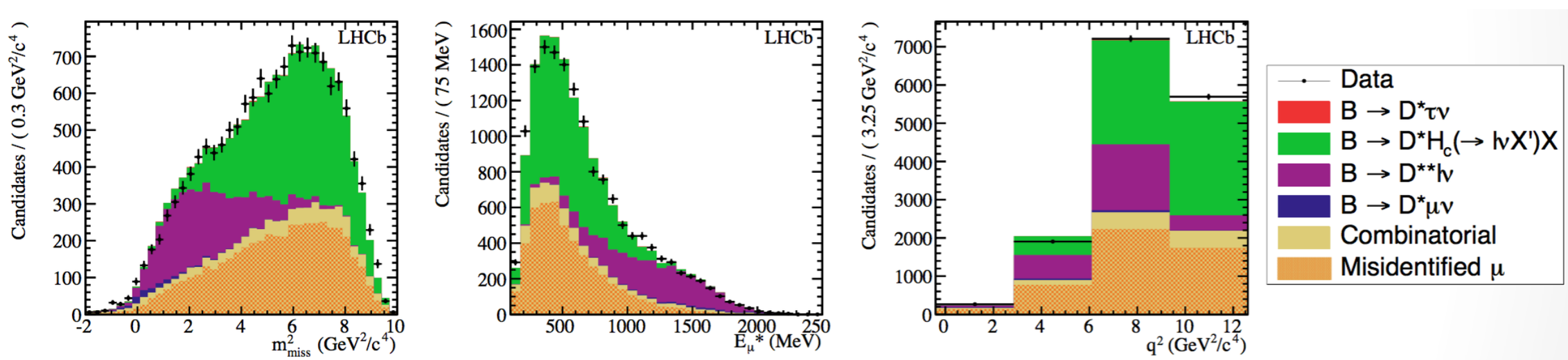
- As usual charm is a background for tau
- Bkg from D_s->tau nu, D ->K lv fit directly from data
- Control sample obtained reconstructing B->D* K lv

Semileptonic

- Fit to the control sample “D*pi l”

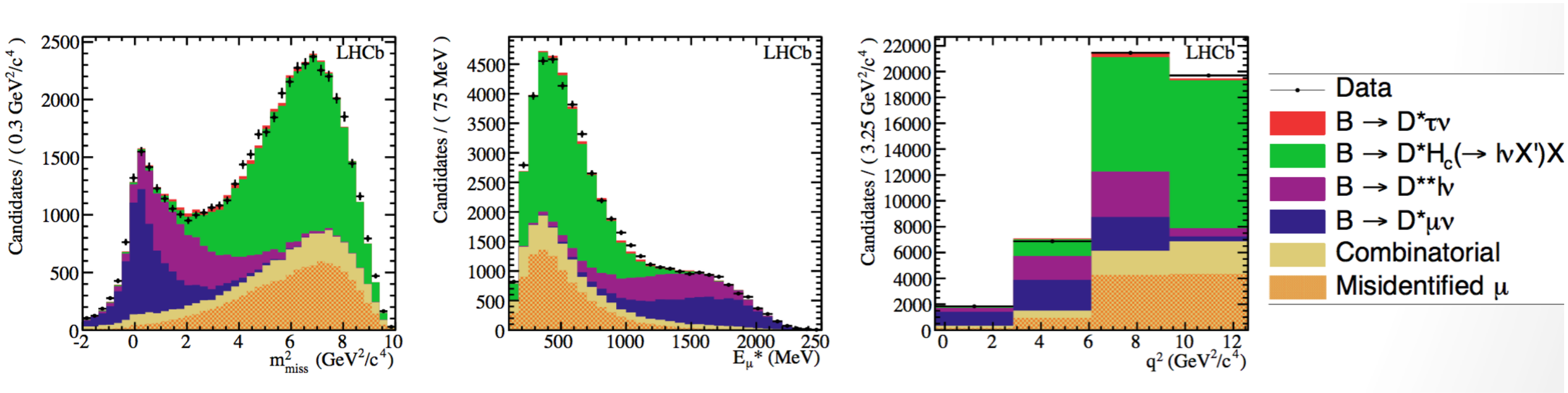


- Fit to the control sample “D*pipi l”



Semileptonic

- Fit to the control sample “D*K l”



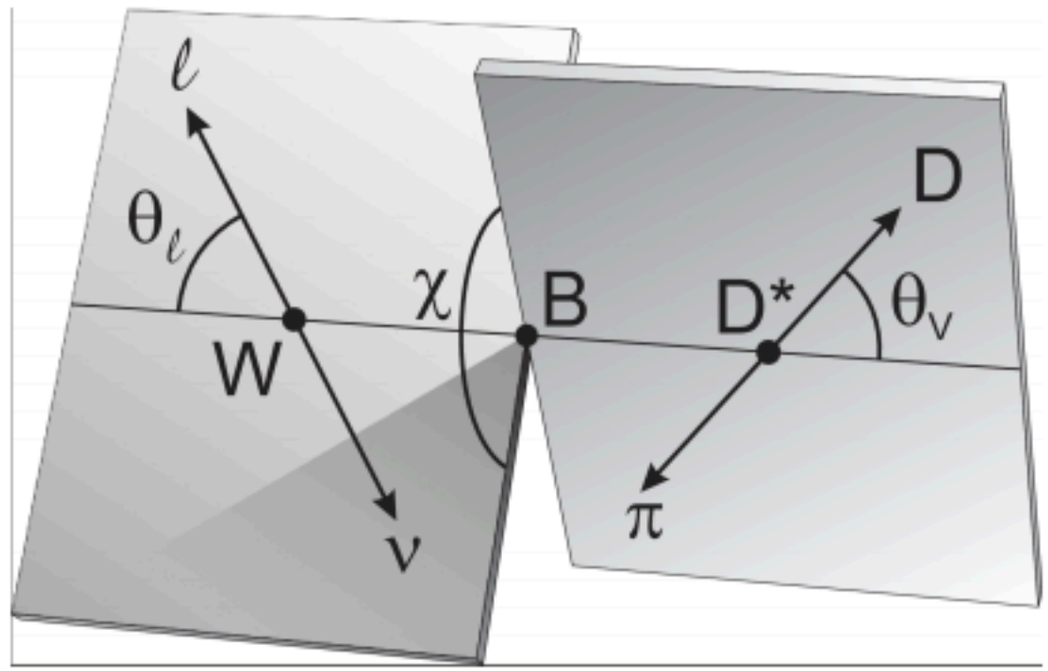
- Similar simulated sample for B->DD$_s$ with D$_s$->tau v

Semileptonic

Systematics uncertainty for R(D*) in LHCb

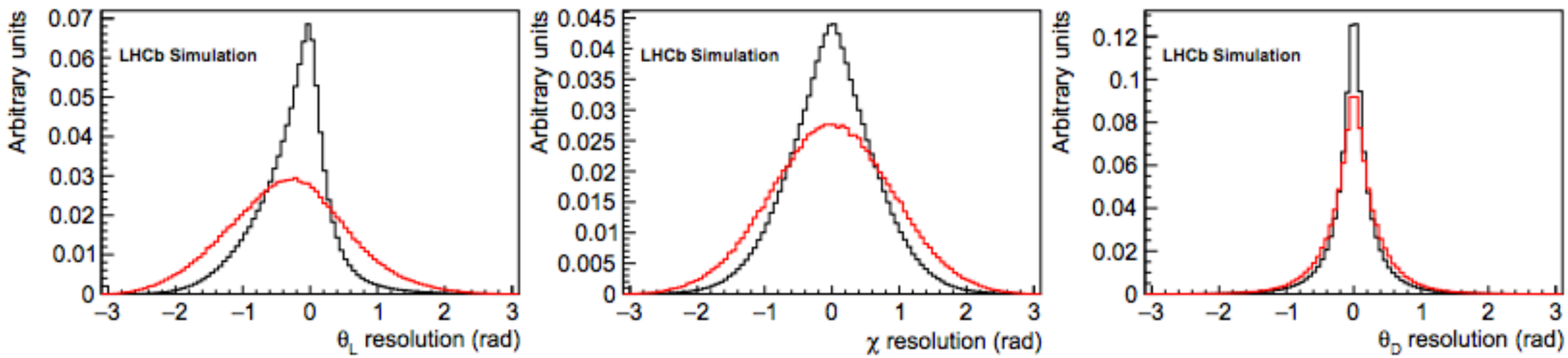
Model uncertainties		Absolute size ($\times 10^{-2}$)
Simulated sample size		2.0
Misidentified μ template shape		1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors		0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	Background	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	modelling;	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	depends	0.4
Corrections to simulation	on control	0.4
Combinatorial background shape	sample size	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors		0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction		0.1
Total model uncertainty		**2.8**
Normalization uncertainties		**Absolute size ($\times 10^{-2}$)**
Simulated sample size		0.6
Hardware trigger efficiency		0.6
Particle identification efficiencies		0.3
Form-factors		0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$		< 0.1
Total normalization uncertainty		**0.9**
Total systematic uncertainty		**3.0**

Semileptonic



- Ratios of branching fractions are only the first observable
  - q^2, angles, τ/D^* polarisation have different sensitivity to new physics
- Variables fitted in $\tau \to \mu\nu\nu$ analyses already have some sensitivity to this
  - For now, measurements assume SM distributions (+ uncertainties)

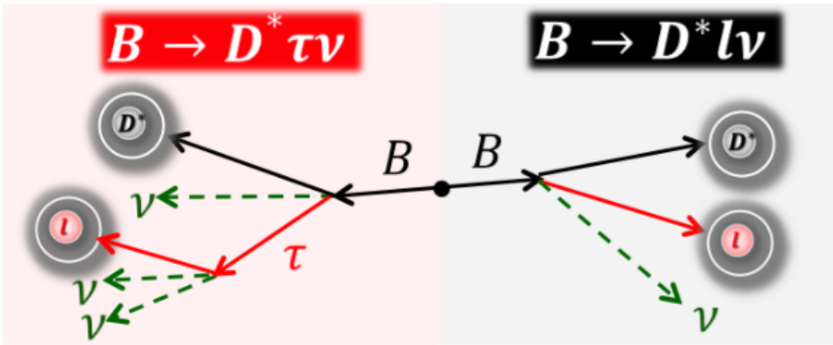
Semileptonic



- Angular resolution for $B \to D^* \mu\nu$ (black) and $B \to D^* \tau\nu$ (red)
- Tau decay results in degredation of resolution
- Pretty wide, but have something to work with
  - Interesting mesurements also possible in muonic modes
- Ideas for how to exploit this, some tools already exist
- Sensitivity not yet known, may need larger samples to really pin things down..

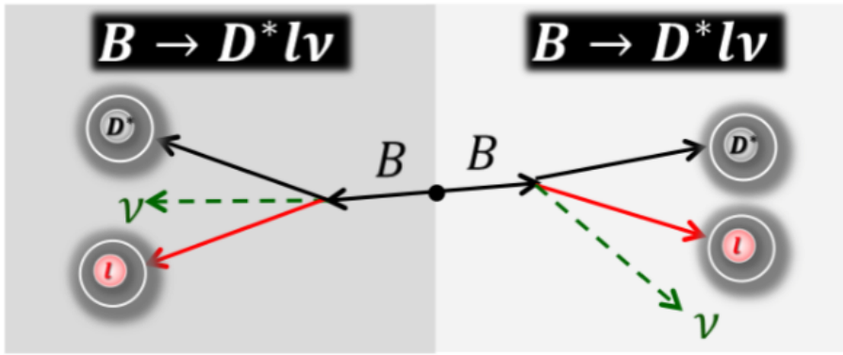
Semileptonic

Semitauonic signal-side decay and semileptonic tag-side.



Numerator in $\mathcal{R}(D^*)$

Normalization events are double semileptonic decays.



Denominator in $\mathcal{R}(D^*)$

D^* reconstruction:

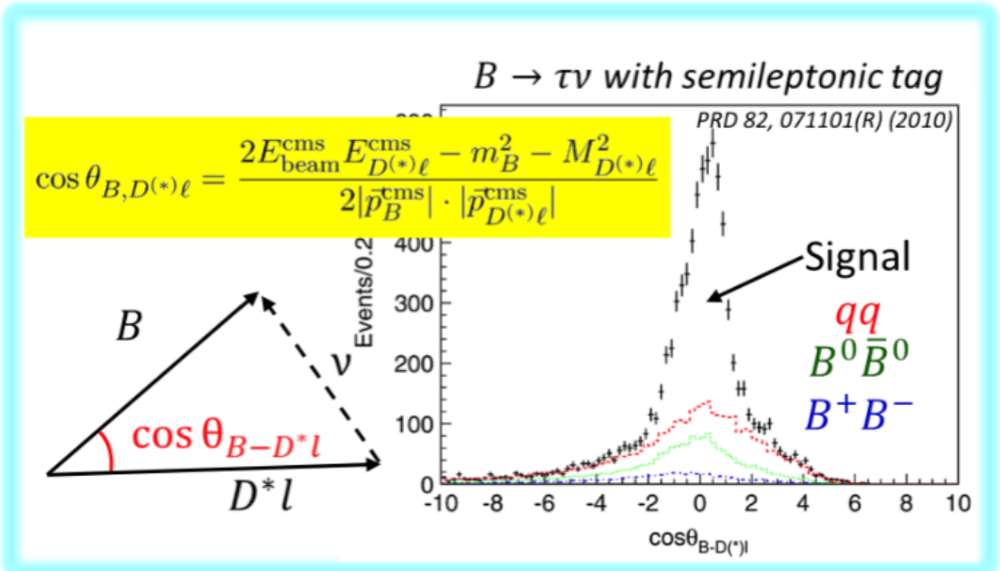
- $D^{*+} \to D^0\pi^+, D^+\pi^0$ ($\sim 100\%$)

  D^0: 10 modes ($\sim 37\%$)

  D^+: 5 modes ($\sim 22\%$)

Tag semileptonic B-decay: Combine D^{*+} and oppositely-charged lepton candidates and calculate the cosine of the angle between the B momentum and the D^*l in the $\Upsilon(4S)$ frame.

$\Rightarrow$

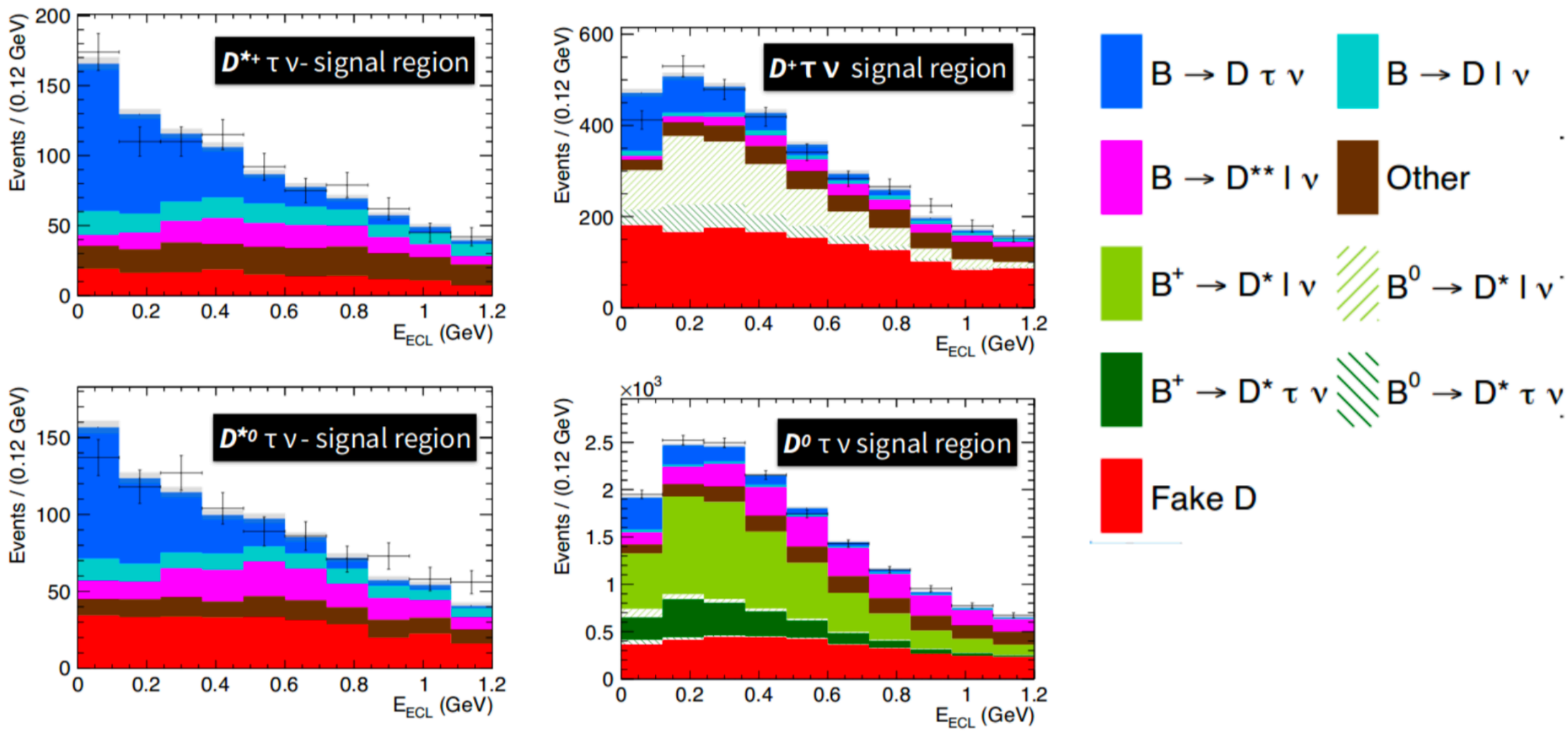


✓ **tag candidates: $\cos\theta_{B\text{-}D^*\ell} \in [-1, 1]$**

Image credits: Y. Sato (Nagoya)

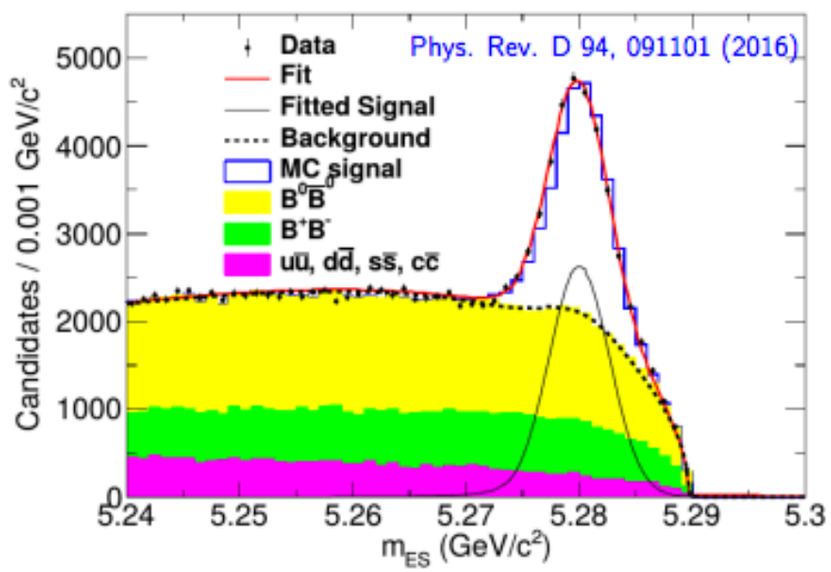
New Belle R(D(*))

- Semileptonic tag using full event information
- Statistically independent from previous analyses based on hadronic tags
- Yields determined from 2D fit to to extra calorimeter energy and BDT classifier



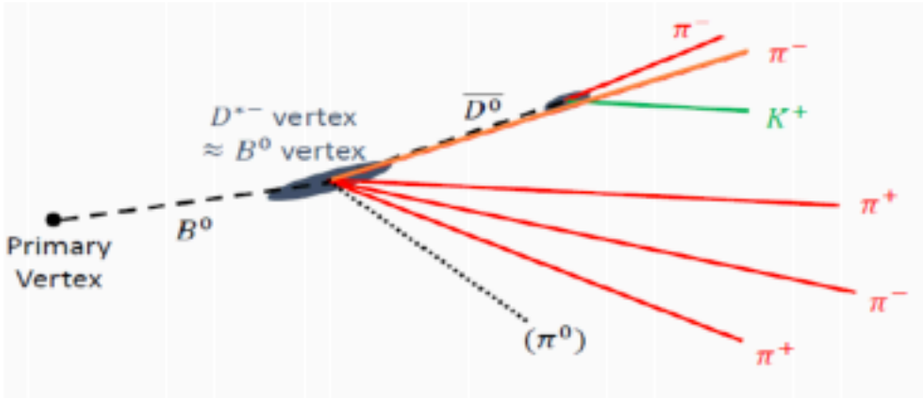
Semileptonic

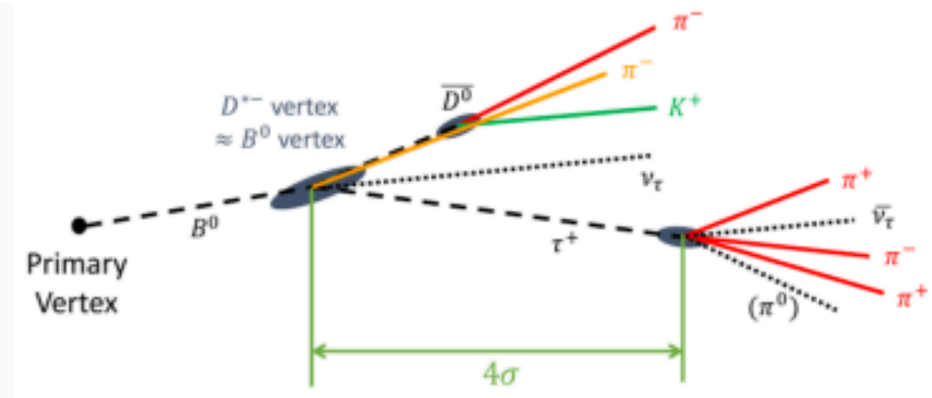
$\mathcal{R}(D^*)$ with $\tau \to \pi\pi\pi\nu$



- Measurement of $\mathcal{B}(B \to D^*\tau\nu)$ also near completion using $\tau \to \pi\pi\pi\nu$
- Different sets of backgrounds:
  - Large $B \to D^*\mu\nu$, $B \to D^{**}\mu^+\nu$ backgrounds absent
  - Additional $B \to D^*\pi\pi\pi X$ backgrounds
  - $B \to D^*DX$ with $D \to \pi\pi\pi X$
- Control experimental efficiencies by measuring rate relative to $B \to D^*\pi\pi\pi$
  - Recent measurement from Babar for this purpose $\to$ 4.4% uncertainty

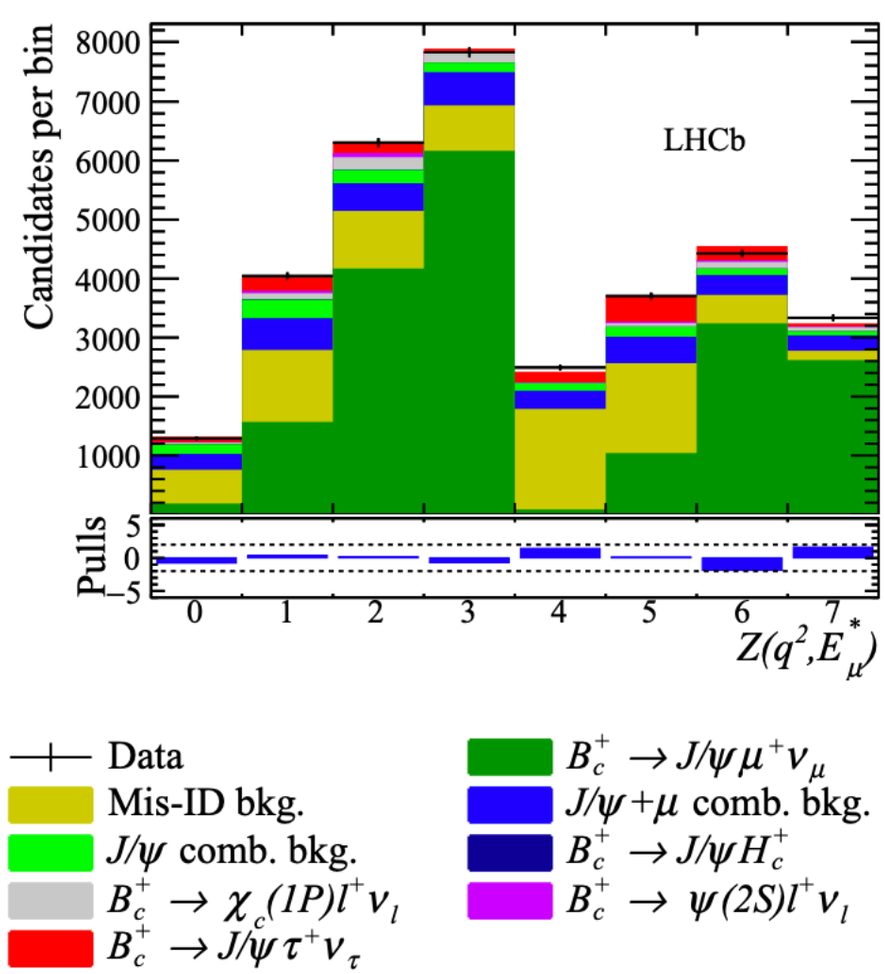
Semileptonic

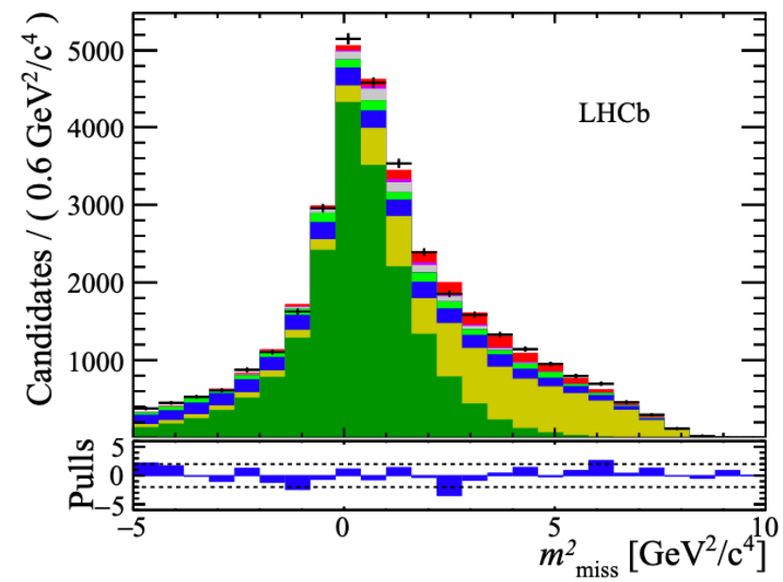


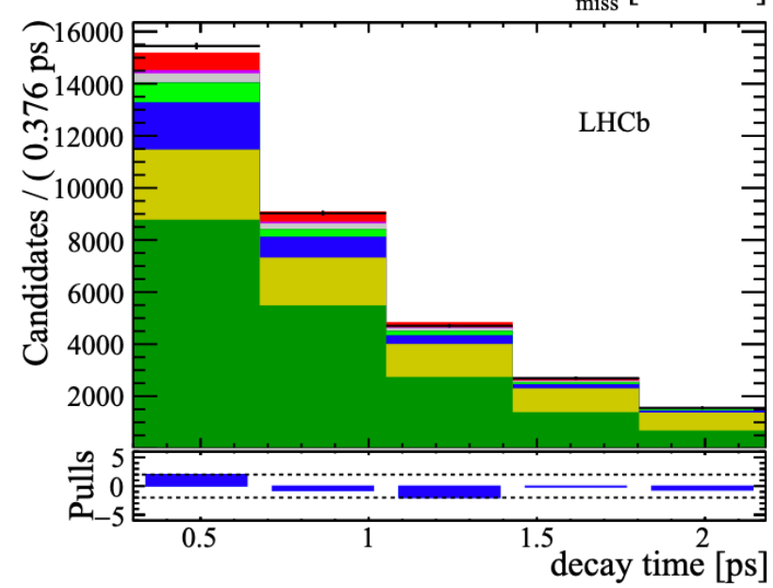


- Can use decay topology to remove direct $B \to D^*\pi\pi\pi X$ decays:
- If the $\pi\pi\pi$ vertex is displaced from the B vertex, cannot be direct $B \to D^*\pi\pi\pi X$
- Can remove a large, poorly measured background
  - And control the remainder
- $B \to D^* DX$ major physics background remaining

Semileptonic



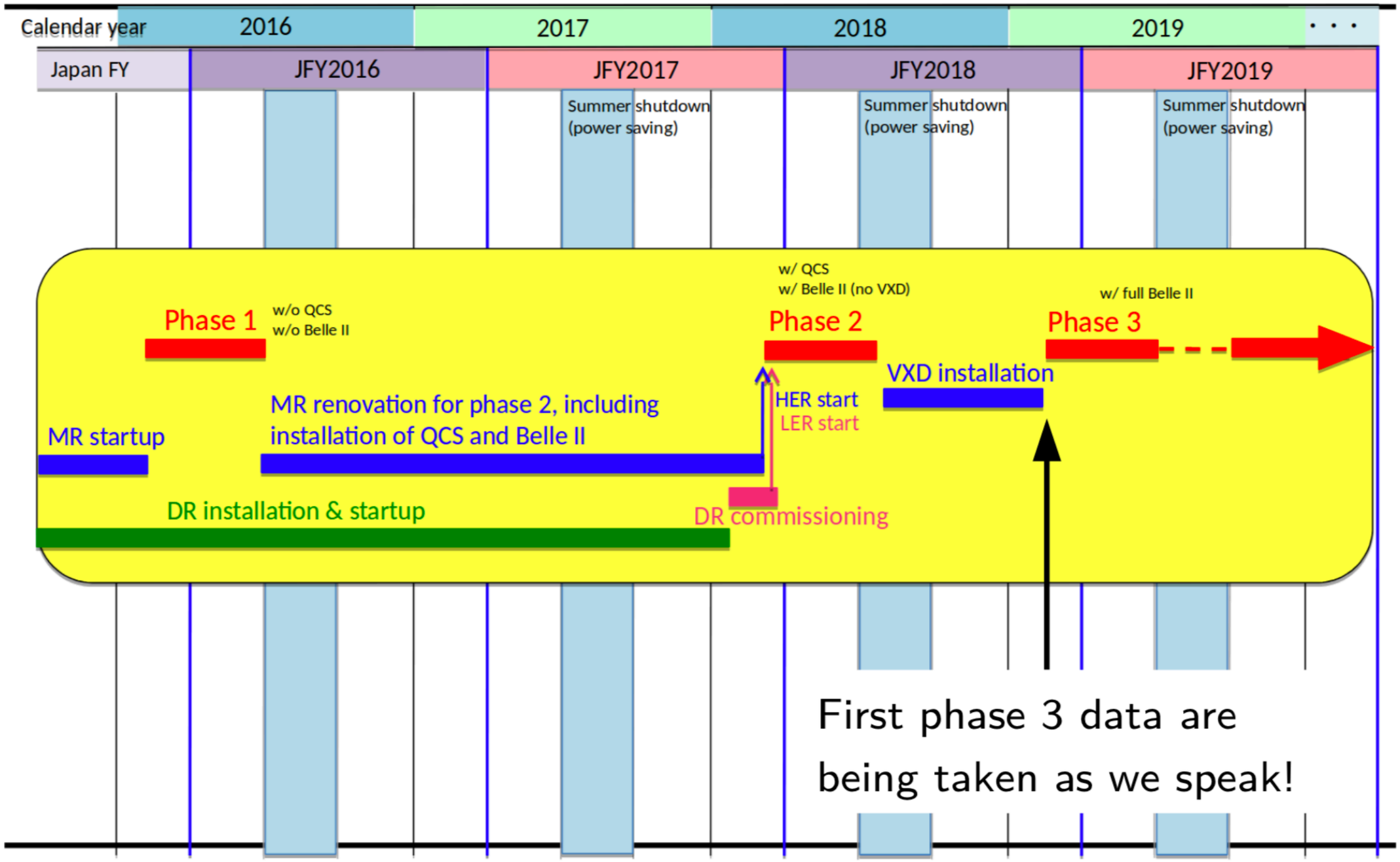




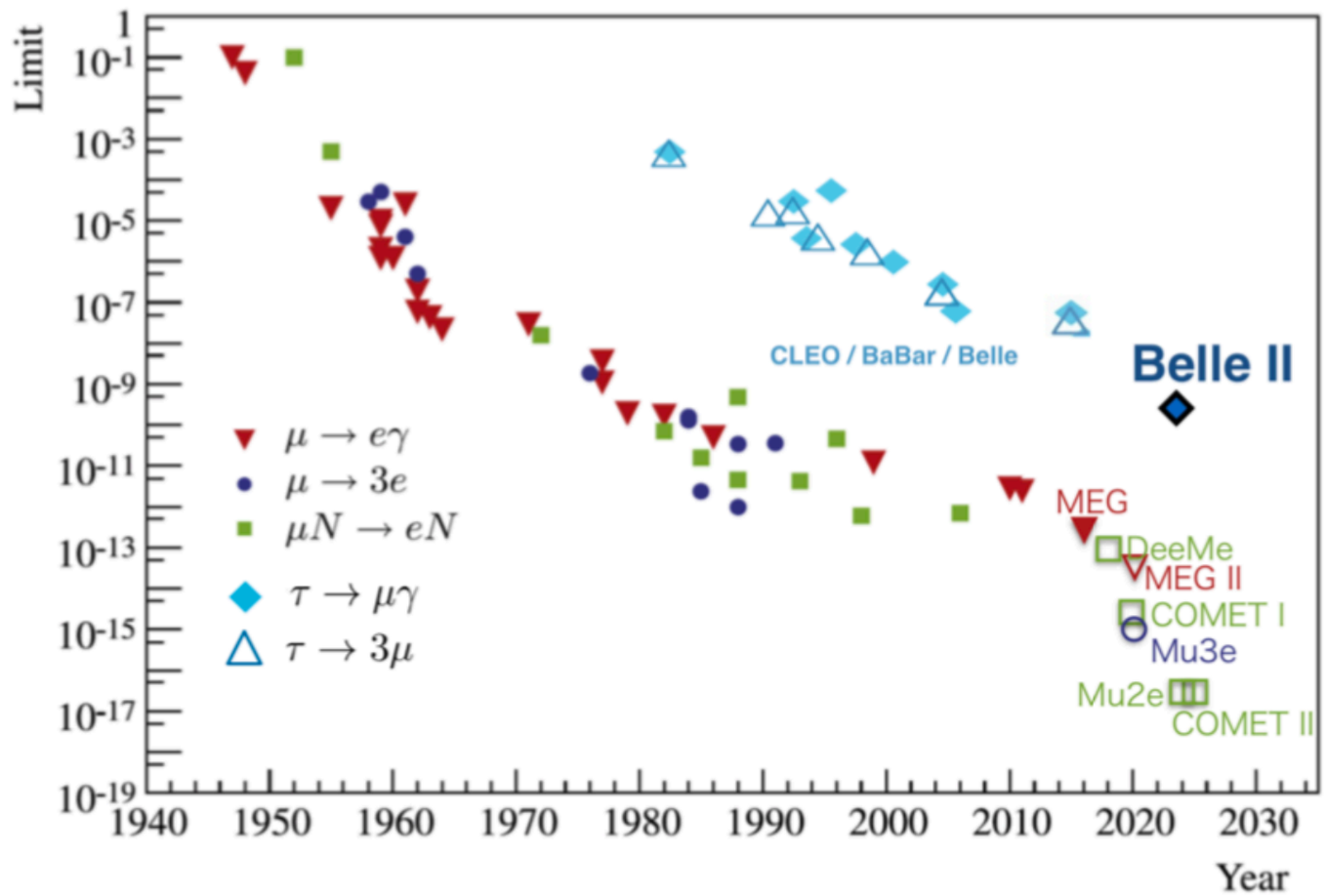
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

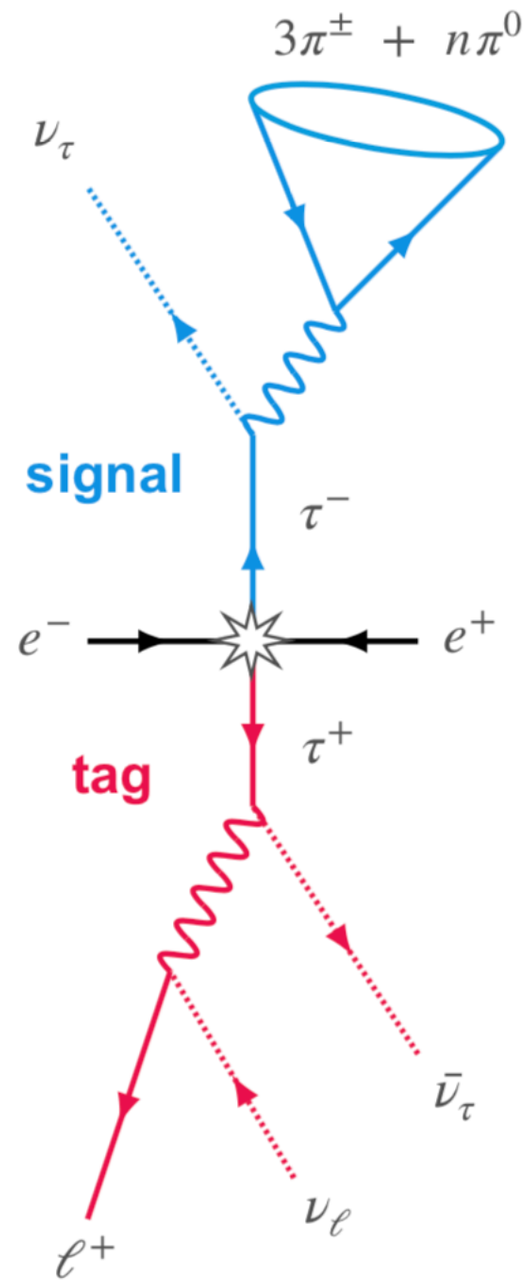
Belle II

BelleII

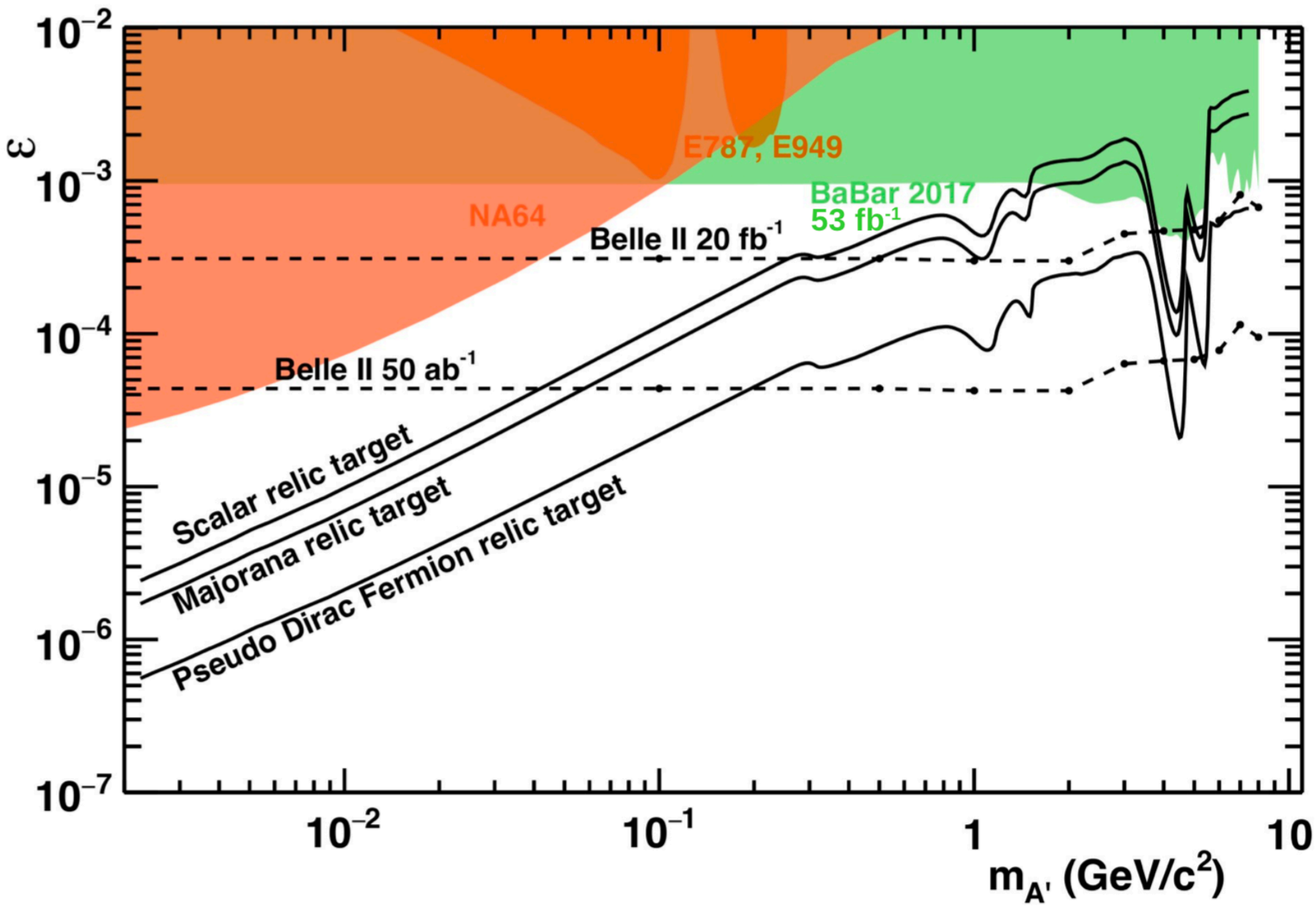

Calendar year
2016
2017
2018
2019
Japan FY
JFY2016
JFY2017
JFY2018
JFY2019
Summer shutdown (power saving)
Summer shutdown (power saving)
Summer shutdown (power saving)
Phase 1
w/o QCS
w/o Belle II
w/ QCS
w/ Belle II (no VXD)
Phase 2
w/ full Belle II
Phase 3
VXD installation
HER start
LER start
MR startup
MR renovation for phase 2, including installation of QCS and Belle II
DR installation & startup
DR commissioning
First phase 3 data are being taken as we speak!

BelleII tau

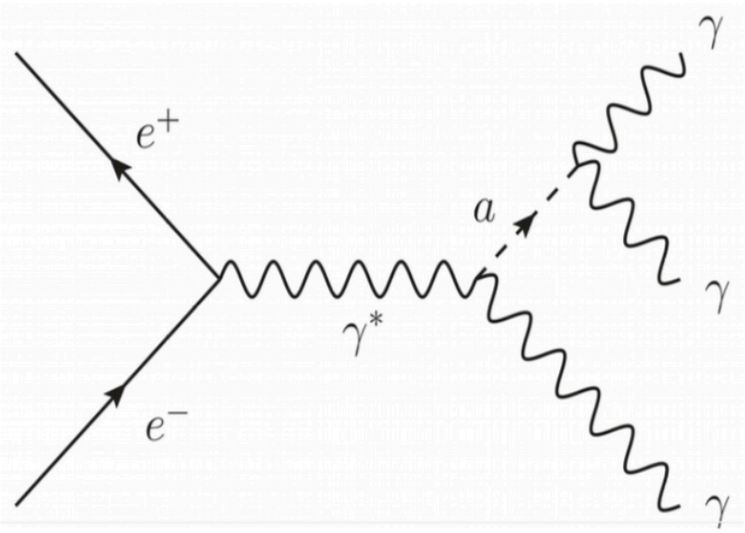

Limit
1
10-1
10-3
10-5
10-7
10-9
10-11
10-13
10-15
10-17
10-19
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
Year
μ → eγ
μ → 3e
μN → eN
τ → μγ
τ → 3μ
CLEO / BaBar / Belle
Belle II
MEG
DeeMe
MEG II
COMET I
Mu3e
Mu2e
COMET II

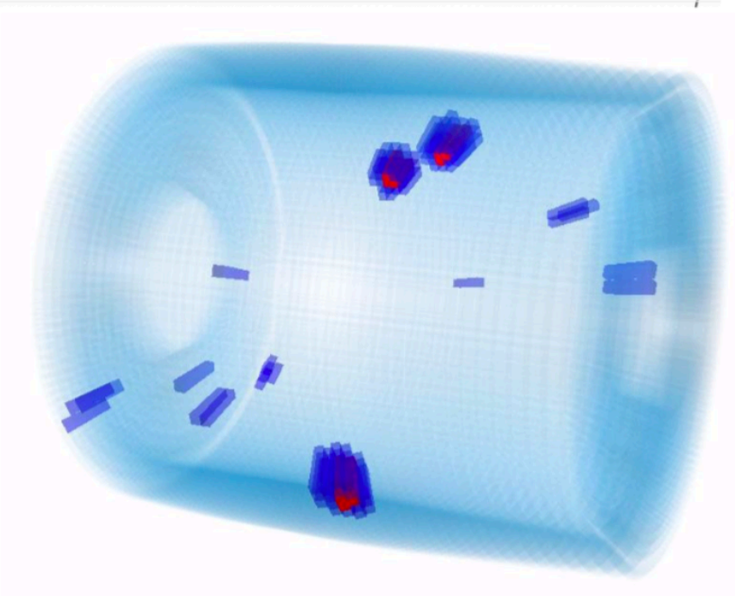

$3\pi^{\pm} + n\pi^{0}$
ν_τ
signal
τ^-
e^-
e^+
τ^+
tag
$\bar{\nu}_\tau$
ν_ℓ
ℓ^+

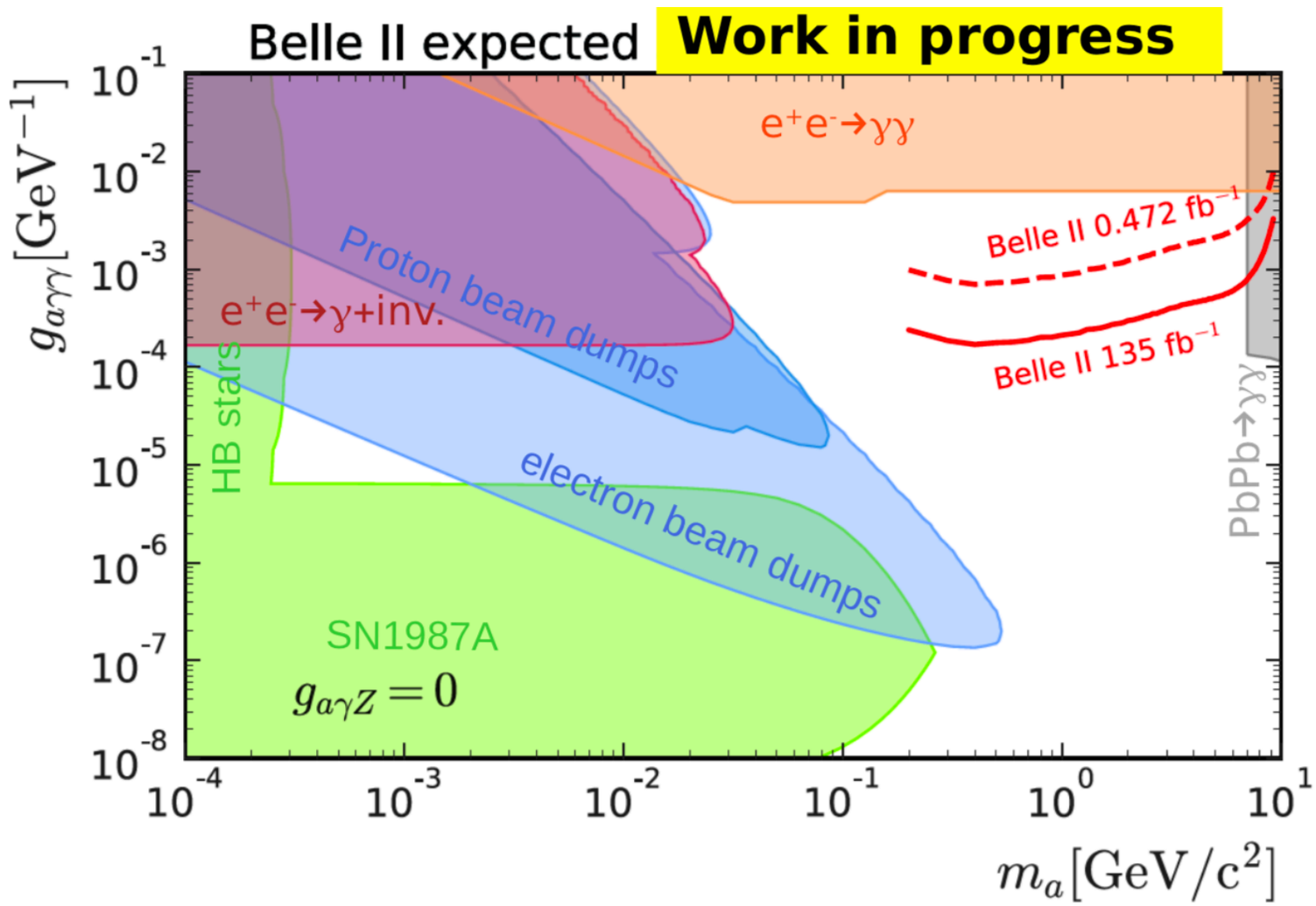
BelleII LDM


E787, E949
NA64
BaBar 2017
53 fb-1
Belle II 20 fb-1
Belle II 50 ab-1
Scalar relic target
Majorana relic target
Pseudo Dirac Fermion relic target
ε
10−2
10−3
10−4
10−5
10−6
10−7
10−2
10−1
1
10
mA' (GeV/c2)

BelleII DP

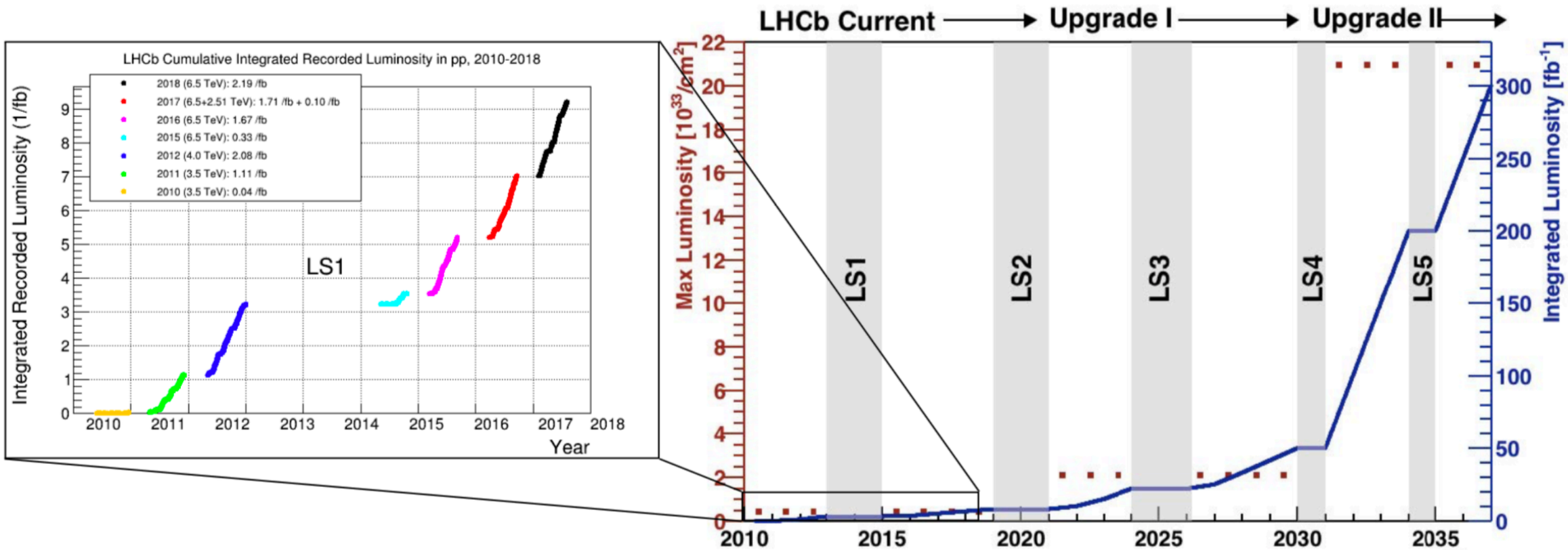

e^+
e^-
γ^*
a
γ
γ
γ



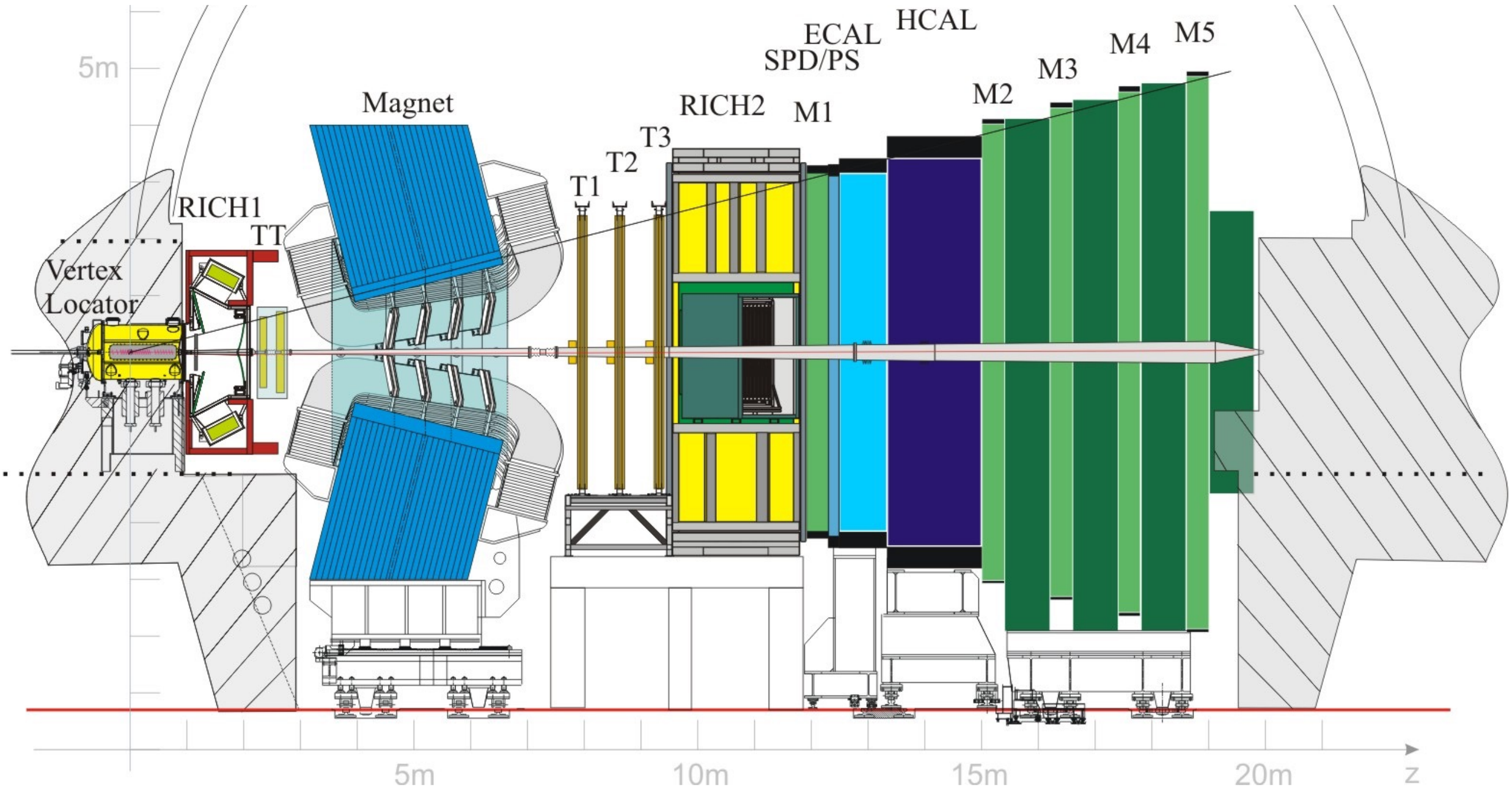

Belle II expected
Work in progress
$g_{a\gamma\gamma}[\mathrm{GeV}^{-1}]$
$m_a[\mathrm{GeV/c^2}]$
$e^+e^-\to\gamma\gamma$
Belle II 0.472 fb^{-1}
Belle II 135 fb^{-1}
Proton beam dumps
$e^+e^-\to\gamma$+inv.
HB stars
electron beam dumps
SN1987A
$g_{a\gamma Z}=0$
PbPb→$\gamma\gamma$

LHCb Upgrades

LHCb Upgrades



The LHCb upgrade



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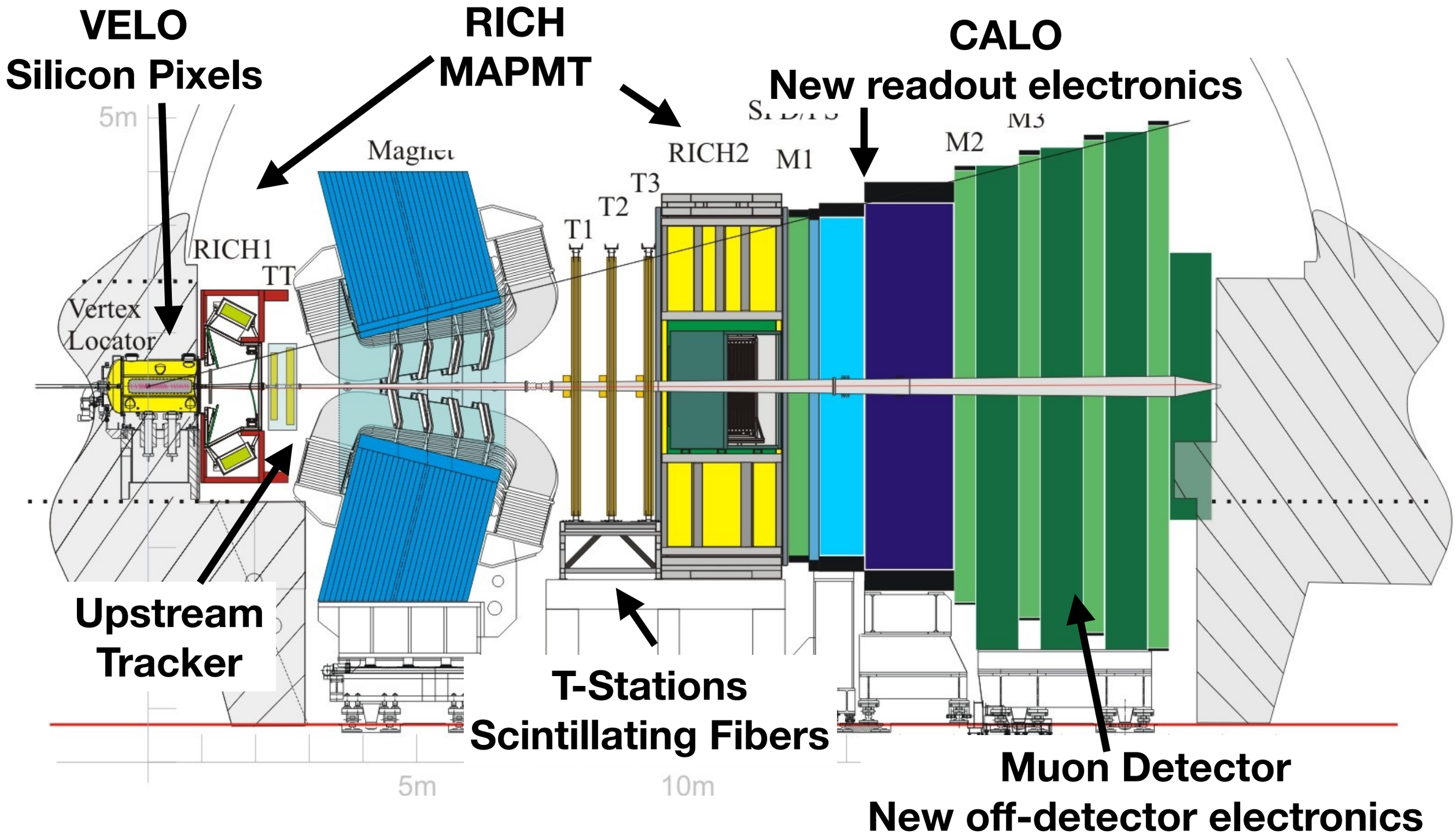
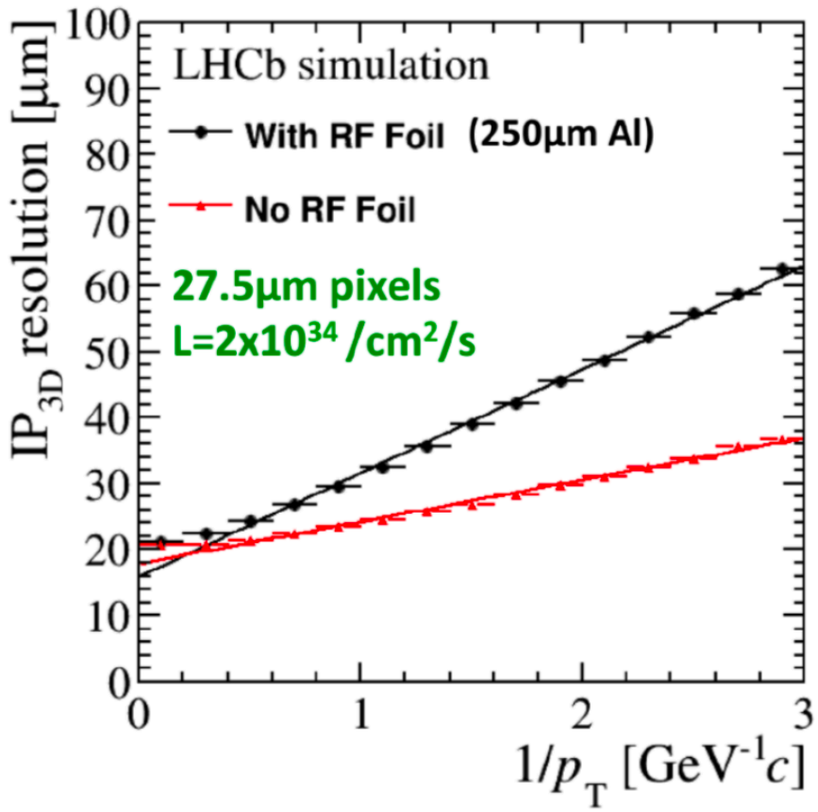
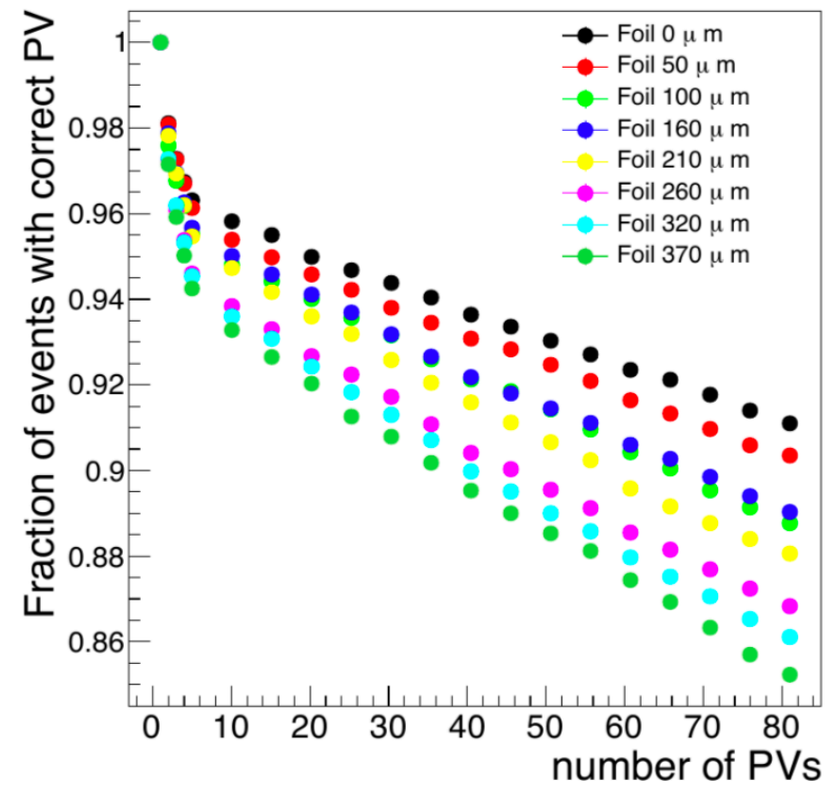
The LHCb upgrade



LHCb Experiment





- RF foil removal will drastically improve vertexing performance
  - IP resolution at low pT nearly doubles, better bkg. suppression
  - Fraction of wrong PV association reduced by 30%
- More precise determination of m^2_{miss}, q^2, E_l^*
- Expected trigger efficiency improvement of ~ 1.5

LHCb Upgrade

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\mathrm{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\mathrm{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

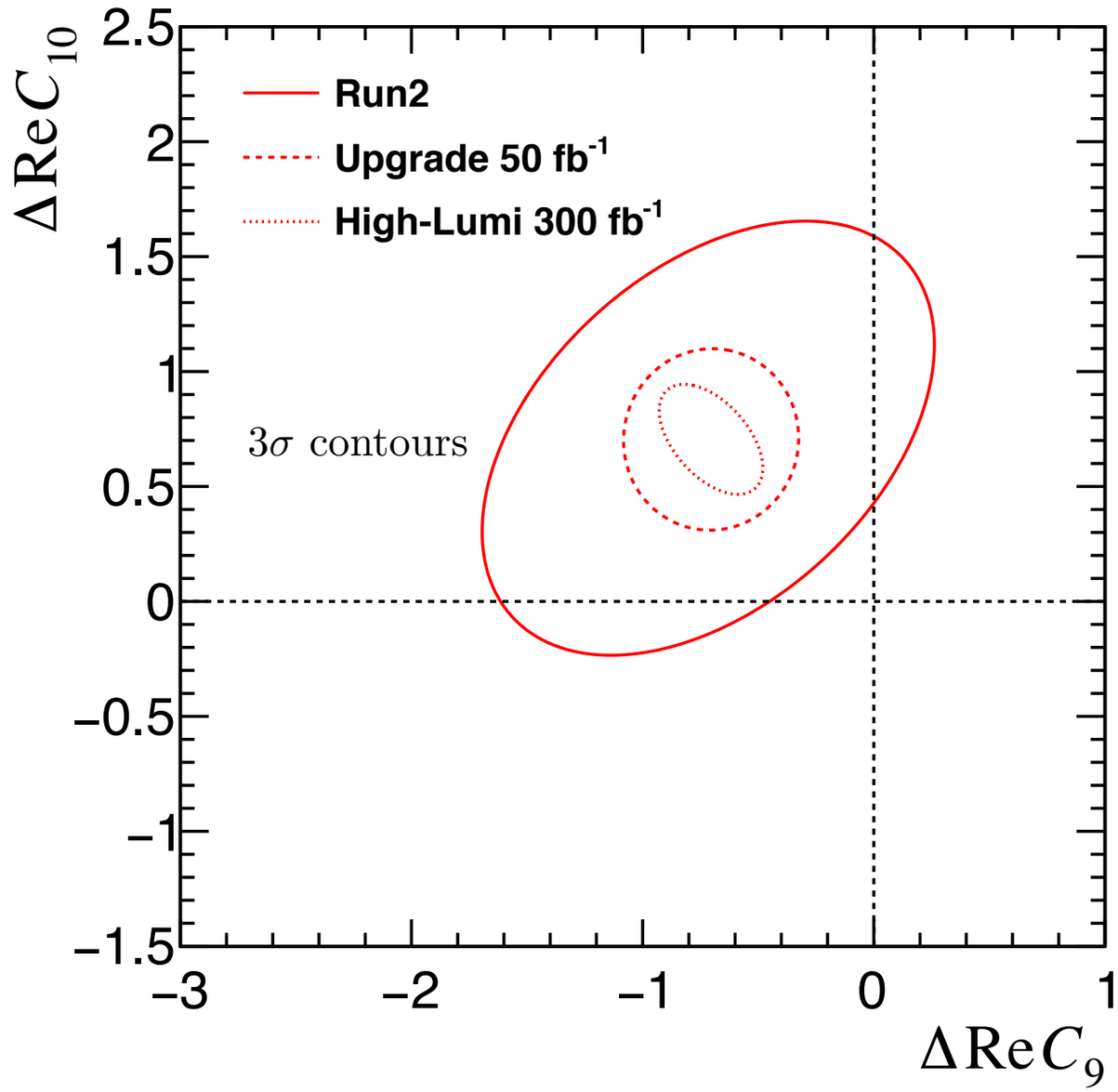
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm CP violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

LHCb Upgrade II

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215] [217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

WC Fit

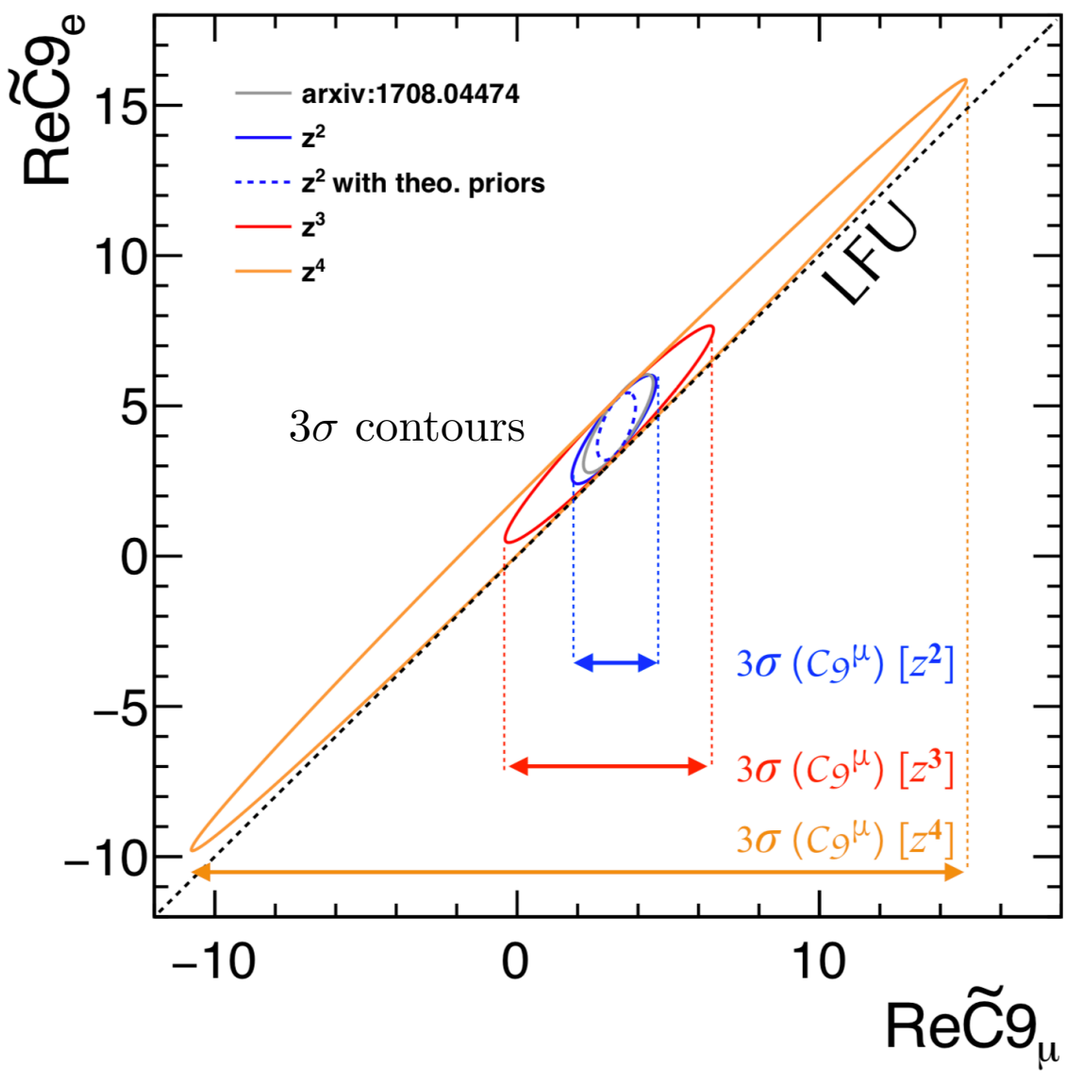
Prospect for LHCb Upgrades

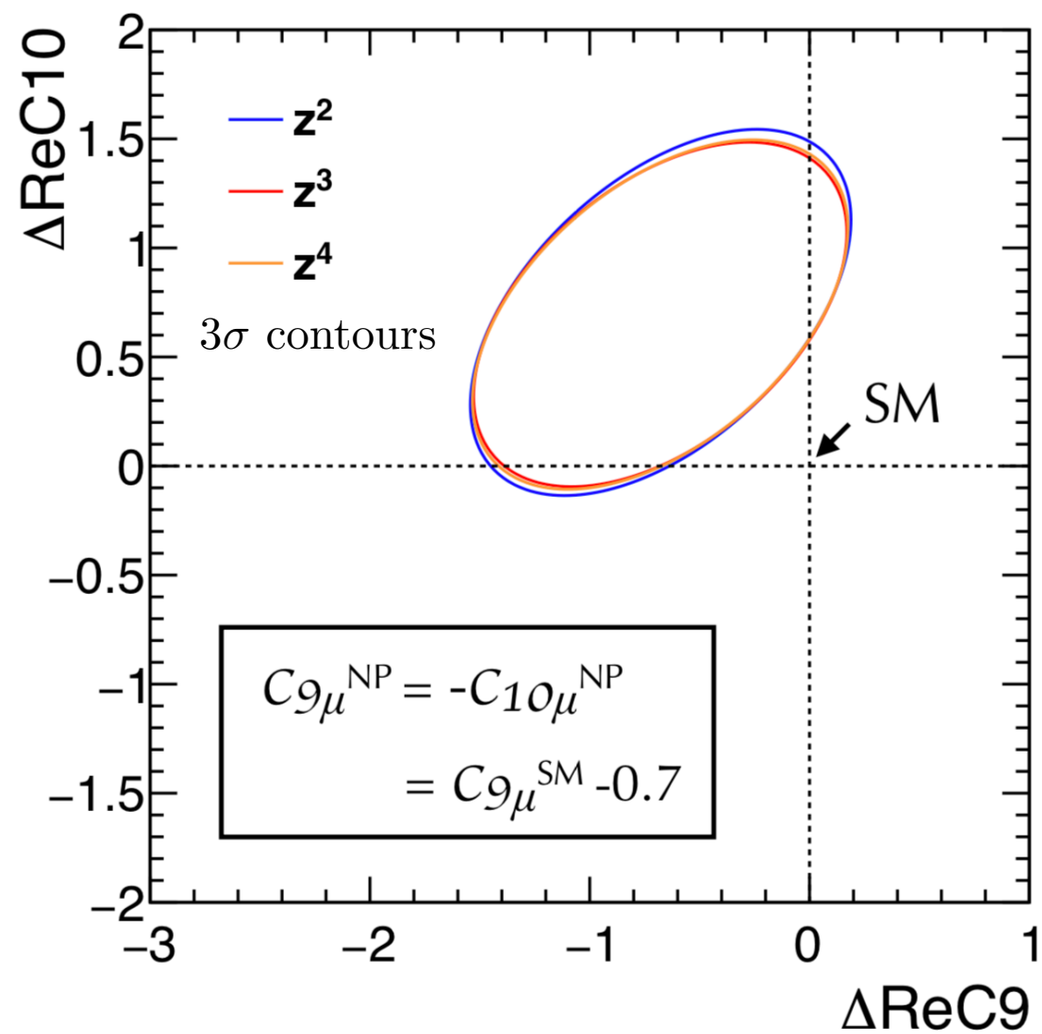


Fit to $B \to K^* \ell\ell$ toy data, assuming the scenario $\Delta C_9 = -\Delta C_{10} = 0.7$

$B^0 \to K^* \ell^+ \ell^-$ simultaneous fit

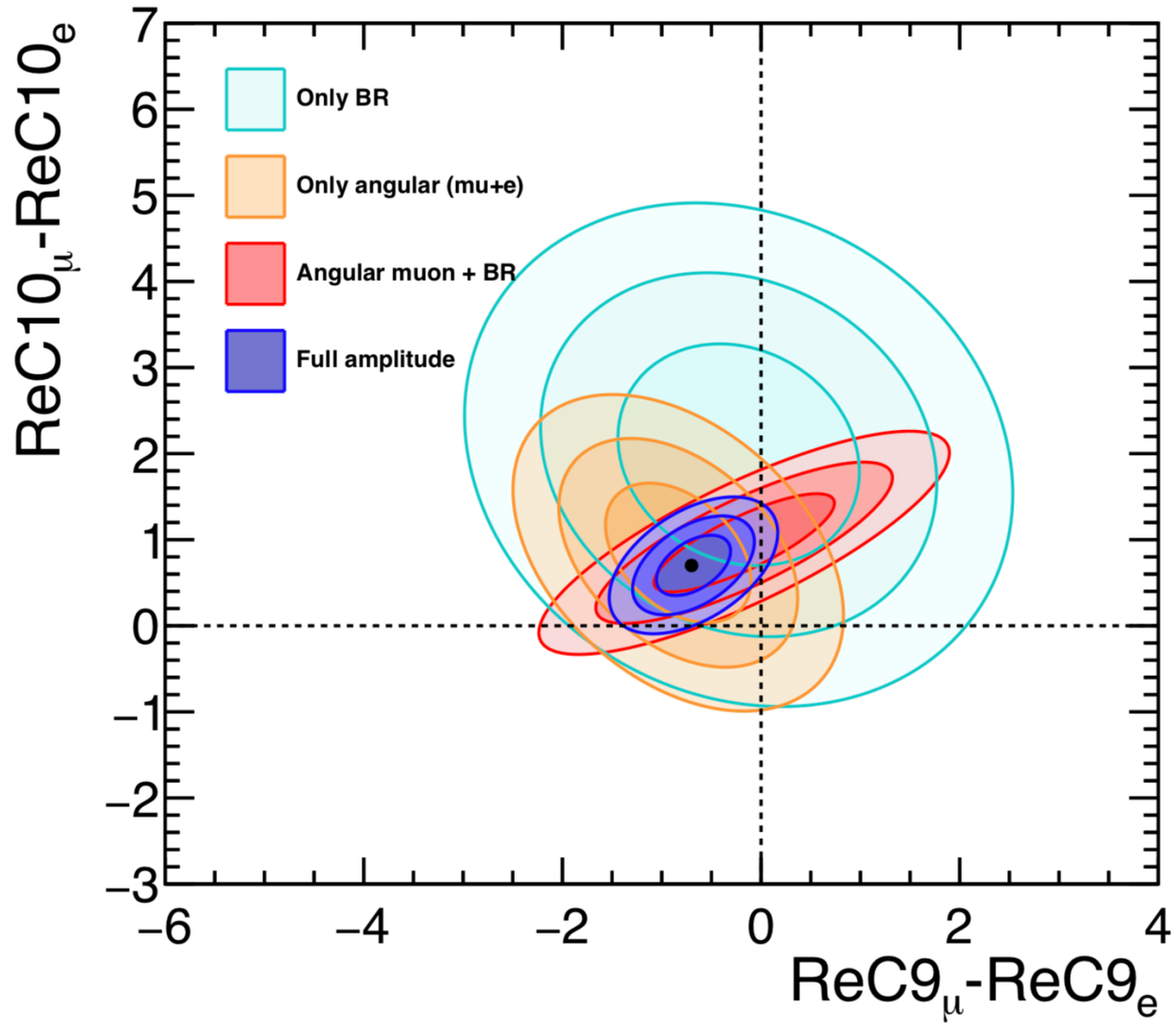
Mauri/NS/Silva





- Simultaneous fit of electron and muons allows to cancel theory uncertainty
- Robust experimental procedure since most of the parameters are “fixed” from the high statistics muons —> only two free parameters in the electron sample (in addition to few nuisance parameters)

$B^0 \to K^* \ell^+ \ell^-$ simultaneous fit



- The Amplitude it of $B \to K^* \ell\ell$ includes <u>all information</u> of angular observables and $R(K^*)$
- It is insensitive on theory parameters