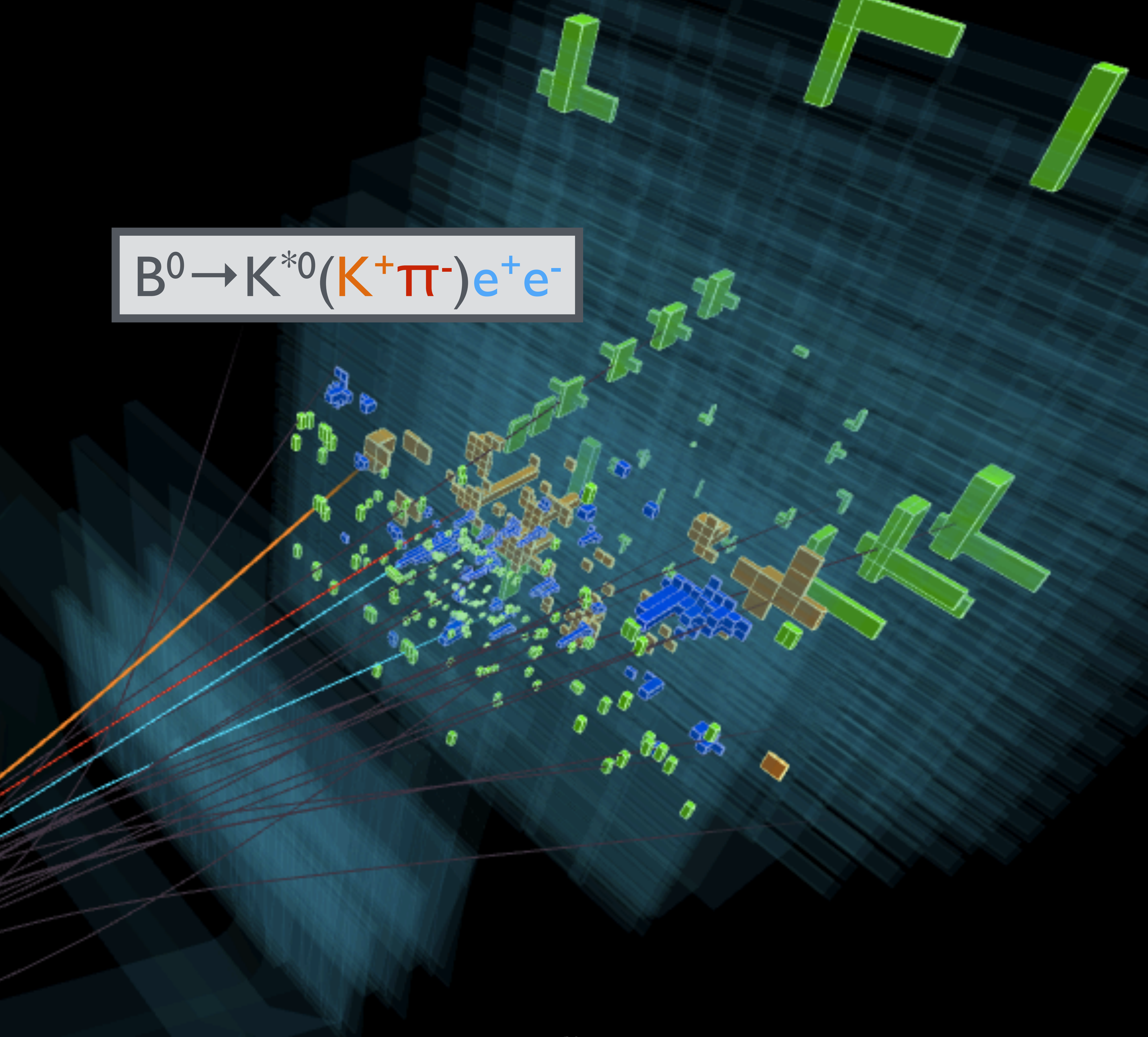


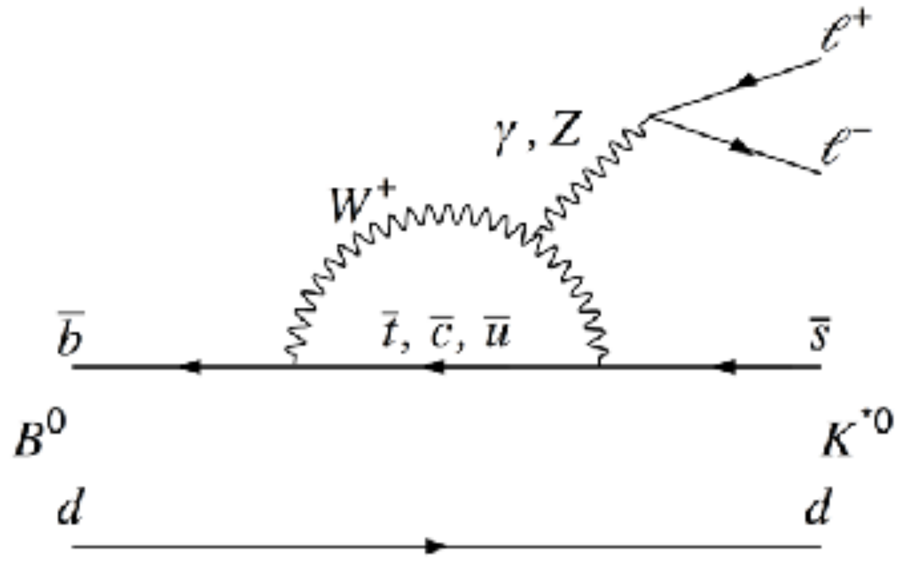
Testing lepton-flavour universality with the LHCb experiment

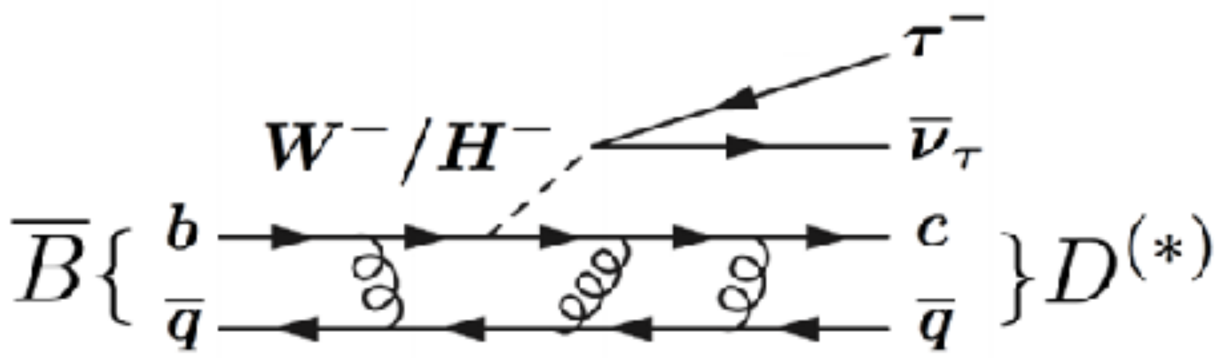
@GreigCowan
Edinburgh seminar
26th May 2017

Introduction: why LFU?

Recent data show intriguing hints of **L**epton **F**lavour **U**niversality violation.

- $b \rightarrow s$ neutral currents in e vs. μ (R_K, R_{K^*}, P_5' etc)
- $b \rightarrow c$ charged currents in τ vs. e, μ (R_D, R_{D^*})



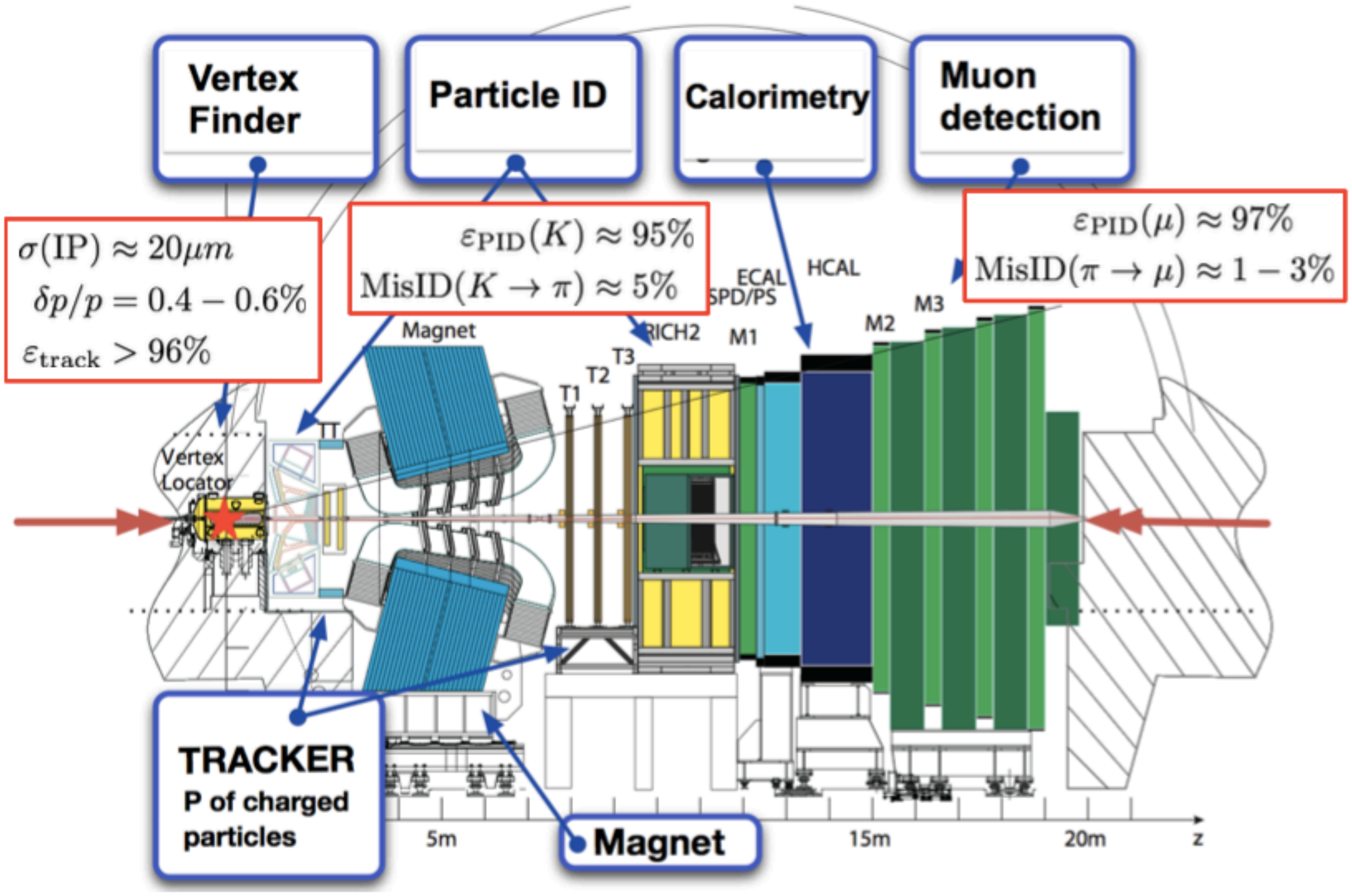


1. LFU is **not** a fundamental symmetry of the SM Lagrangian.

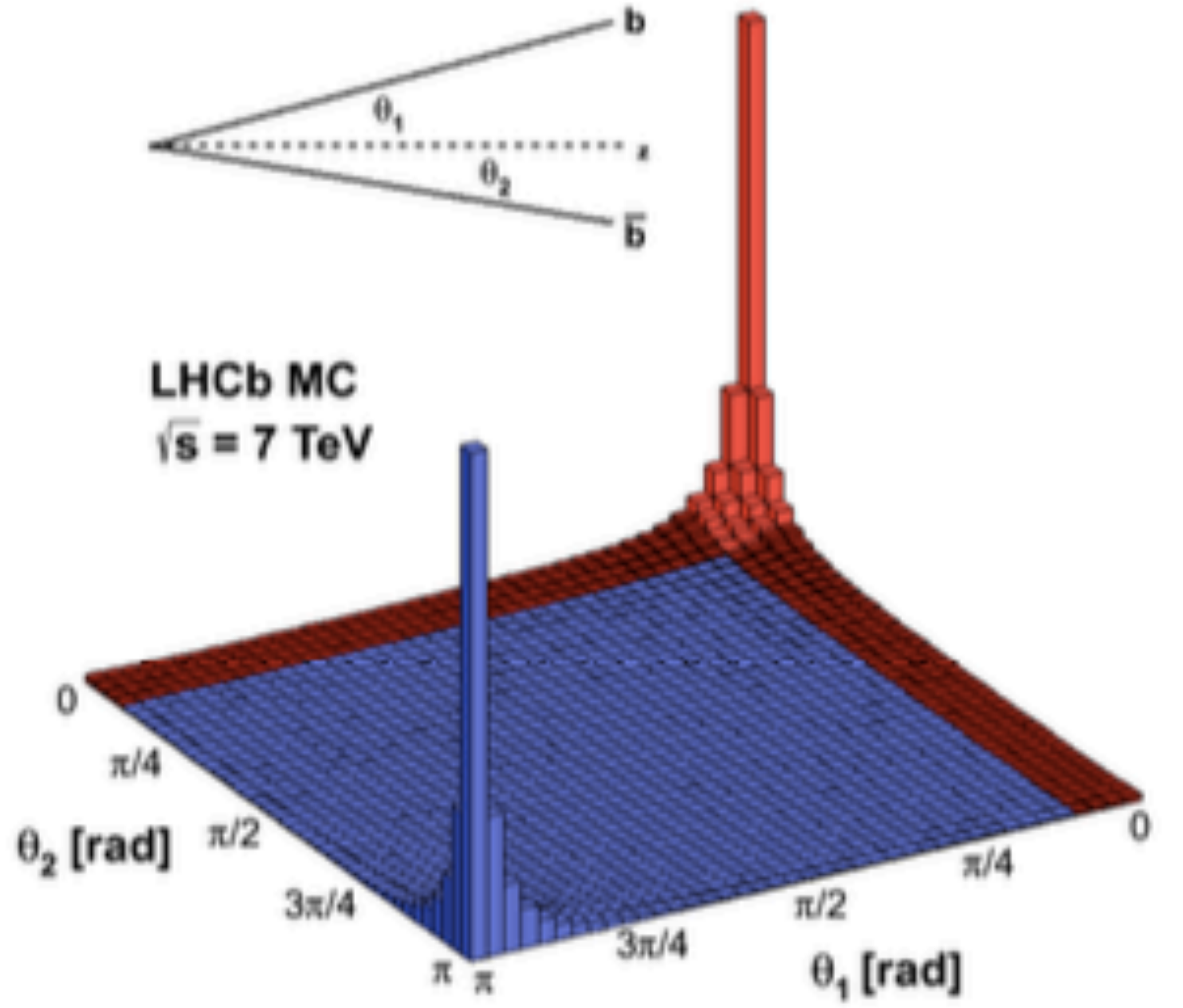
2. LFU tests do exist, but mostly constrain the **gauge sector** [LEP, Phys. Rept. 427 (2006) 257] or **1st and 2nd generation quarks and leptons** [PIENU collab., PRL 115, 071801 (2015)]

Could there be New Physics where LFU is violated more in processes involving 3rd generation quarks and leptons?

The LHCb experiment

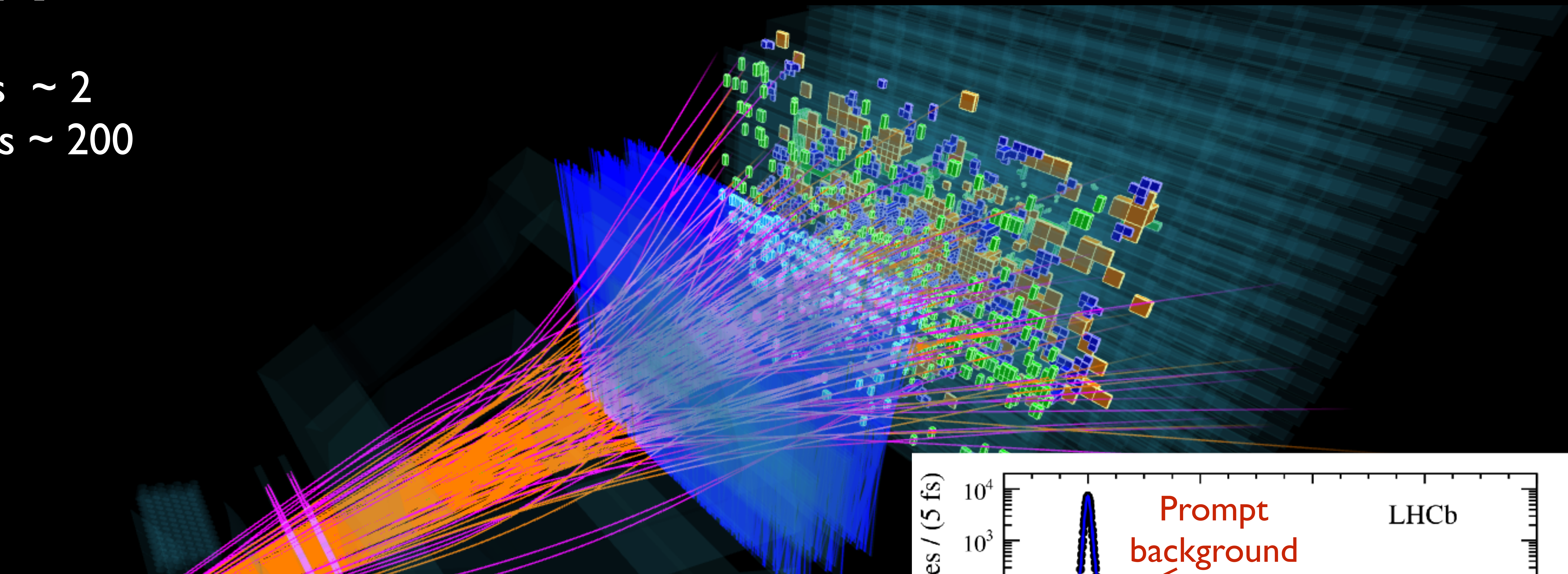


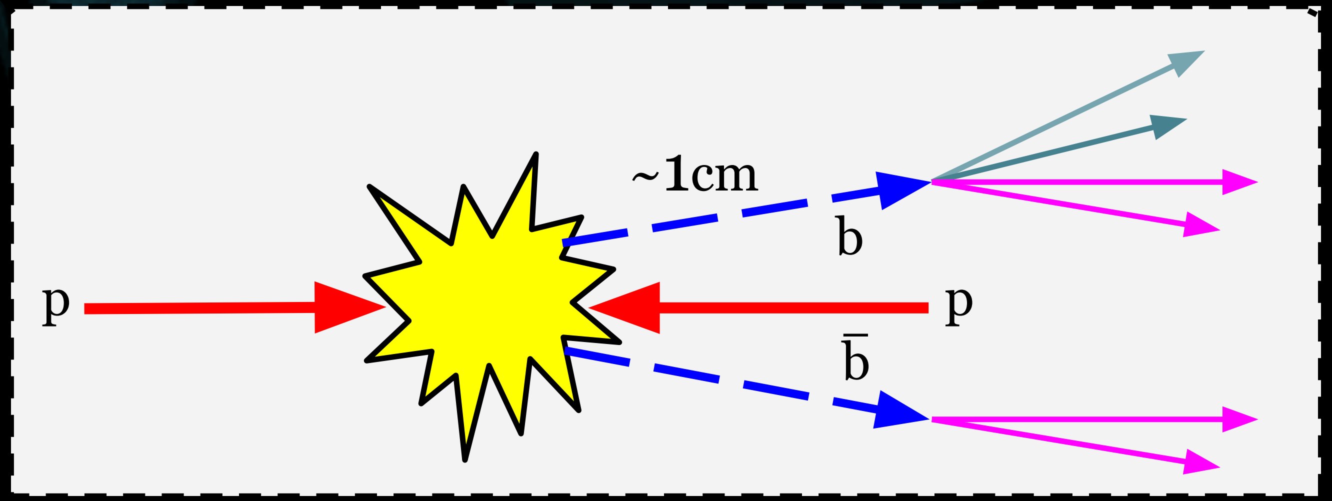
- Covers 4% of solid angle, but accepts 40% of heavy quark production cross section.

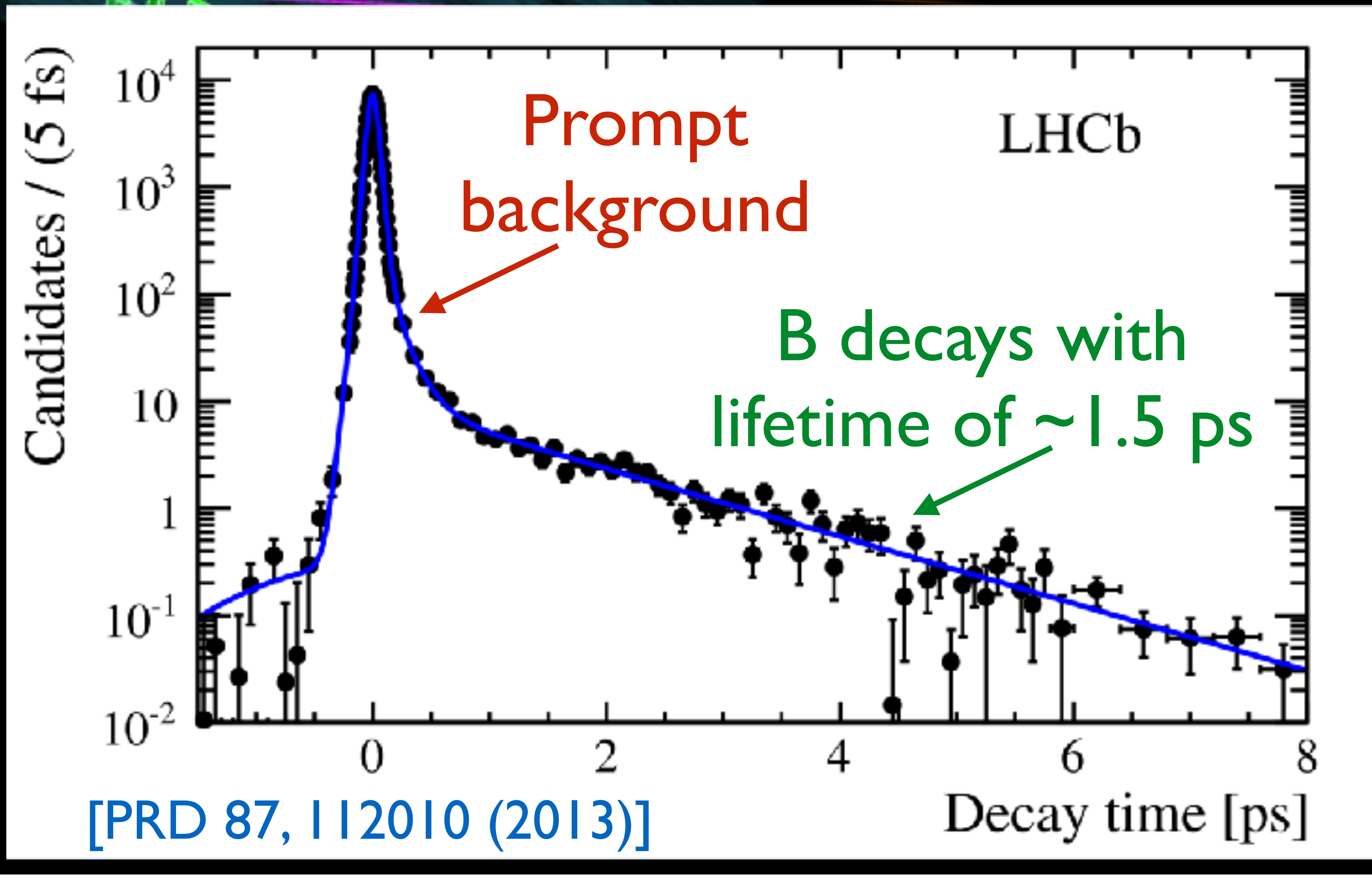


A typical LHCb event

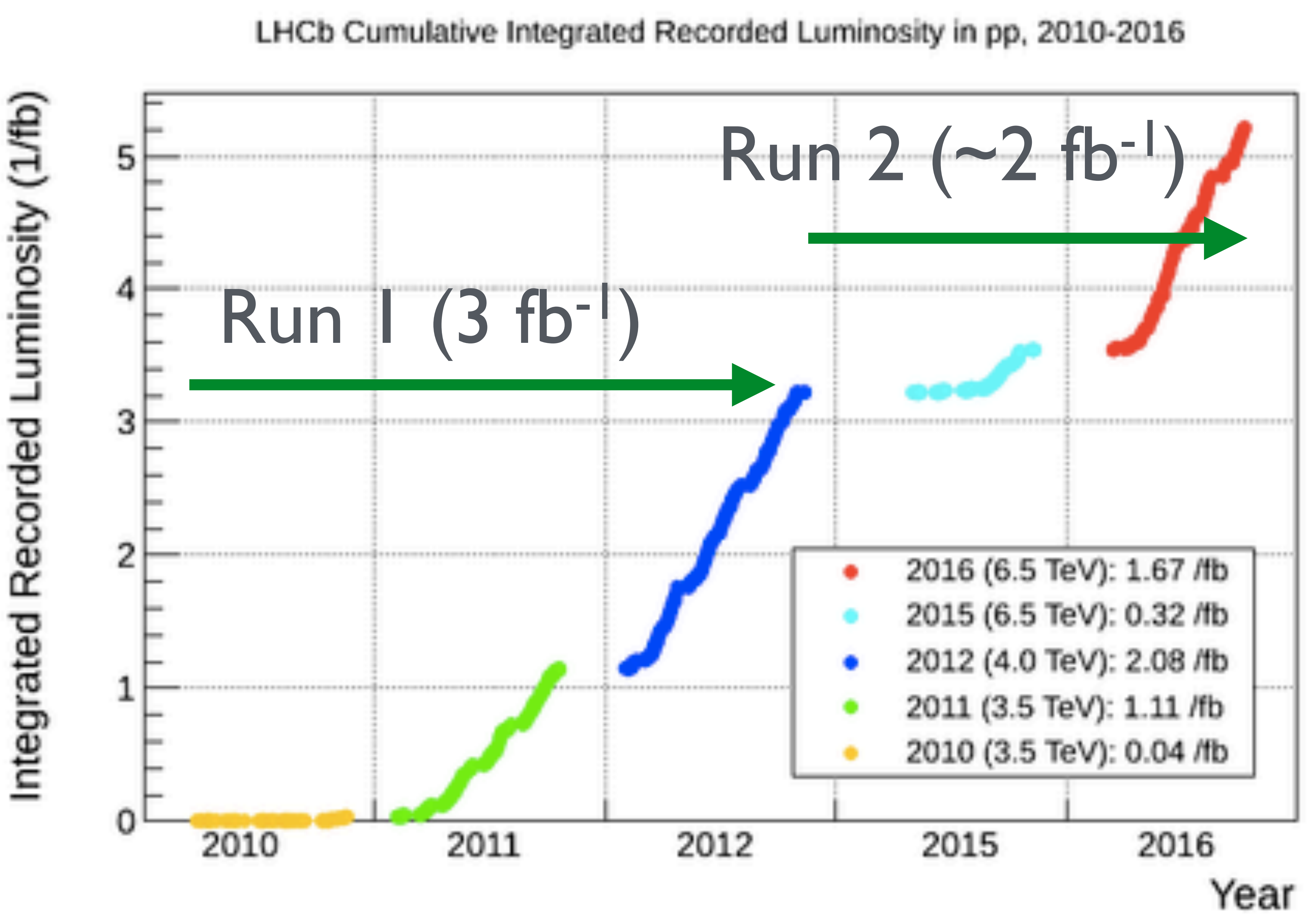
nPVs ~ 2
nTracks ~ 200



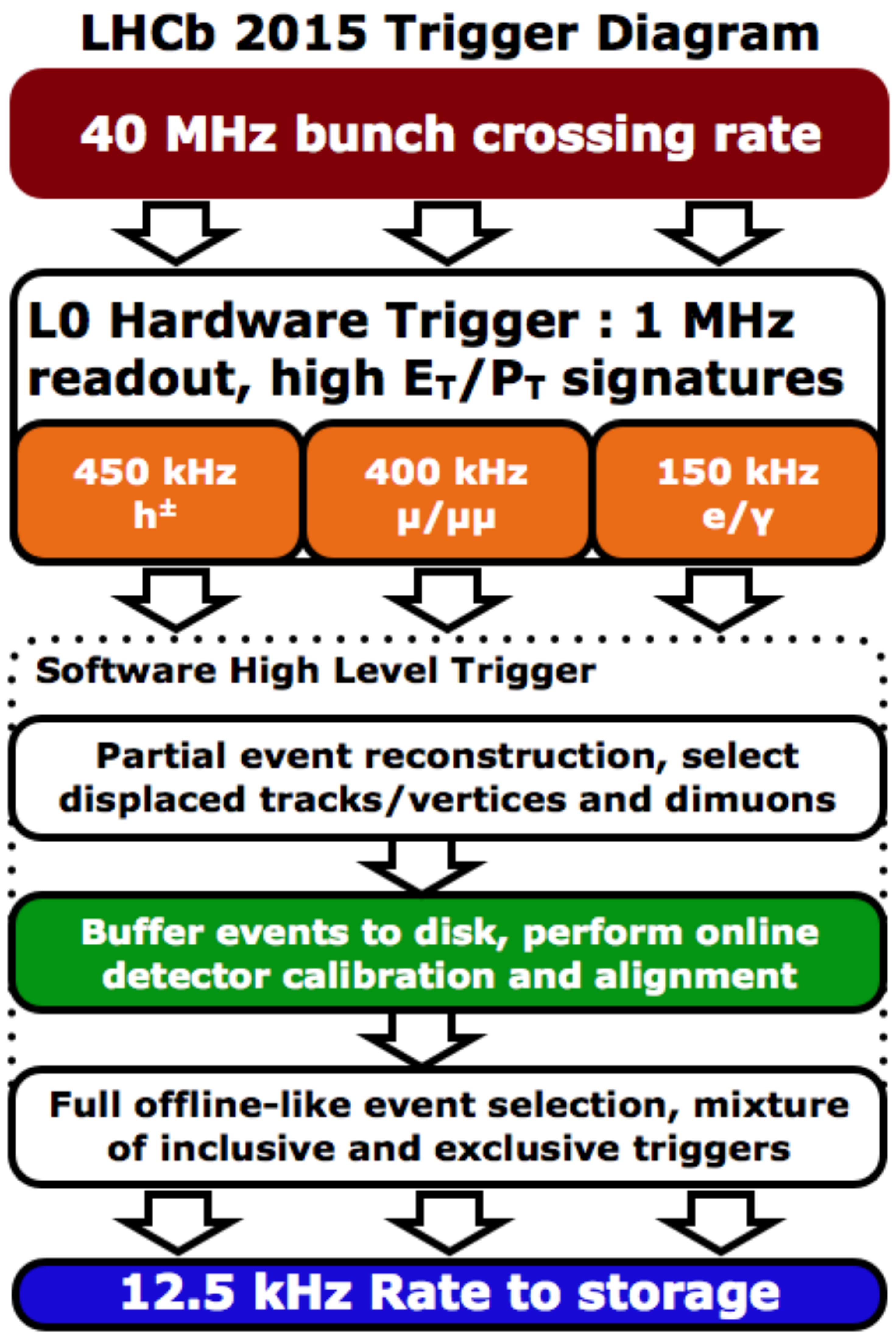




LHCb data sample

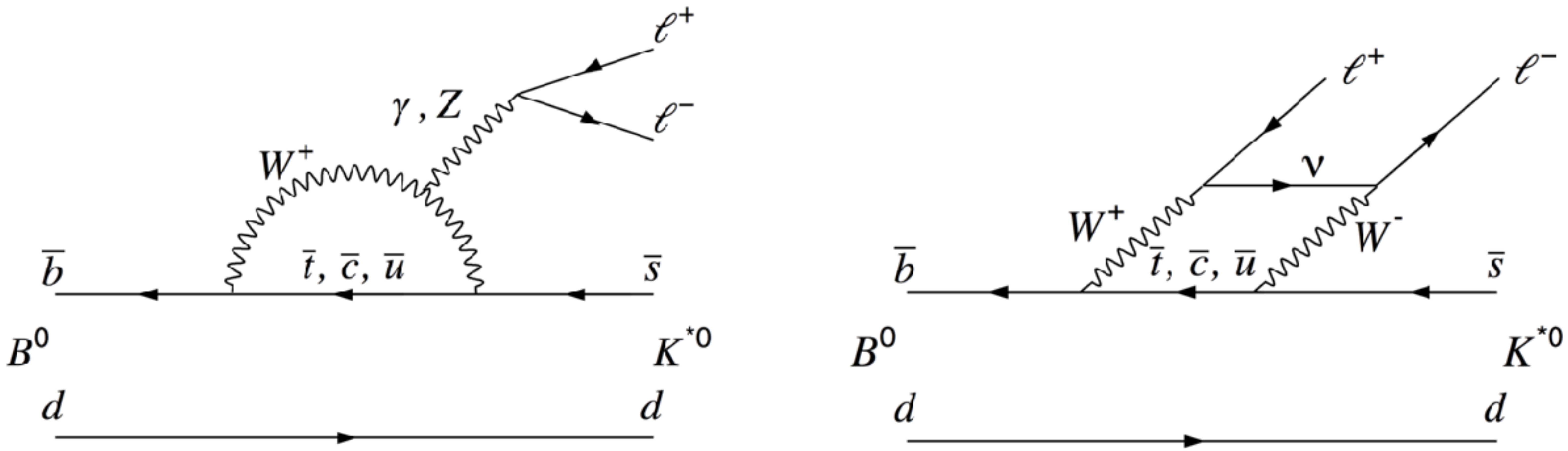


- $\langle\mathcal{L}\rangle_{2011} \sim 2.7 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\langle\mathcal{L}\rangle_{2012} \sim 4.0 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



b → s neutral currents

SM



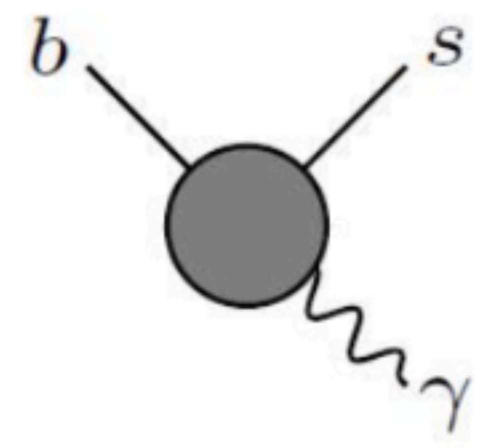
$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\, dq^2}$$

Theoretical framework

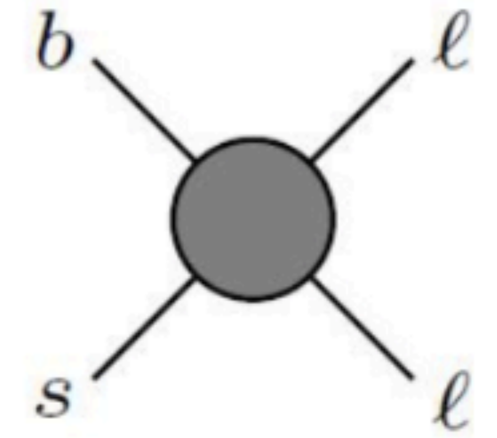
Use effective Hamiltonian to describe b → s transitions.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\text{right-handed part}}]$$

0 in the SM



i=7 photon penguin



i=9, 10, P, S

i = 1,2	Tree
i = 3 – 6,8	Gluon penguin
i = 7	Photon penguin
i = 9,10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

***C_i* Wilson coefficients**: short-distance physics (perturbative) couplings, μ = energy scale.

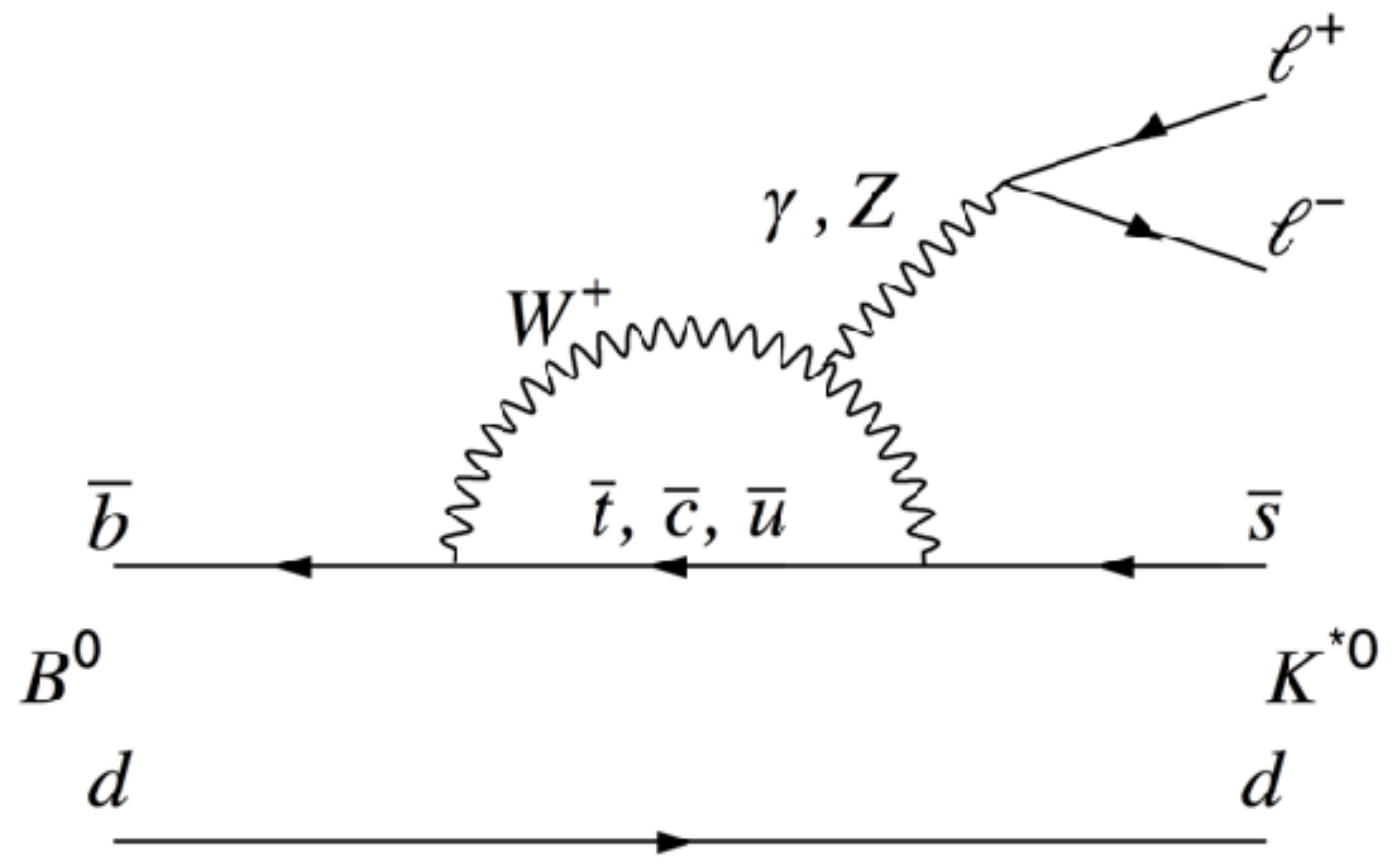
***O_i* operators**: long-distance (non perturbative) matrix elements, e.g. from lattice QCD.

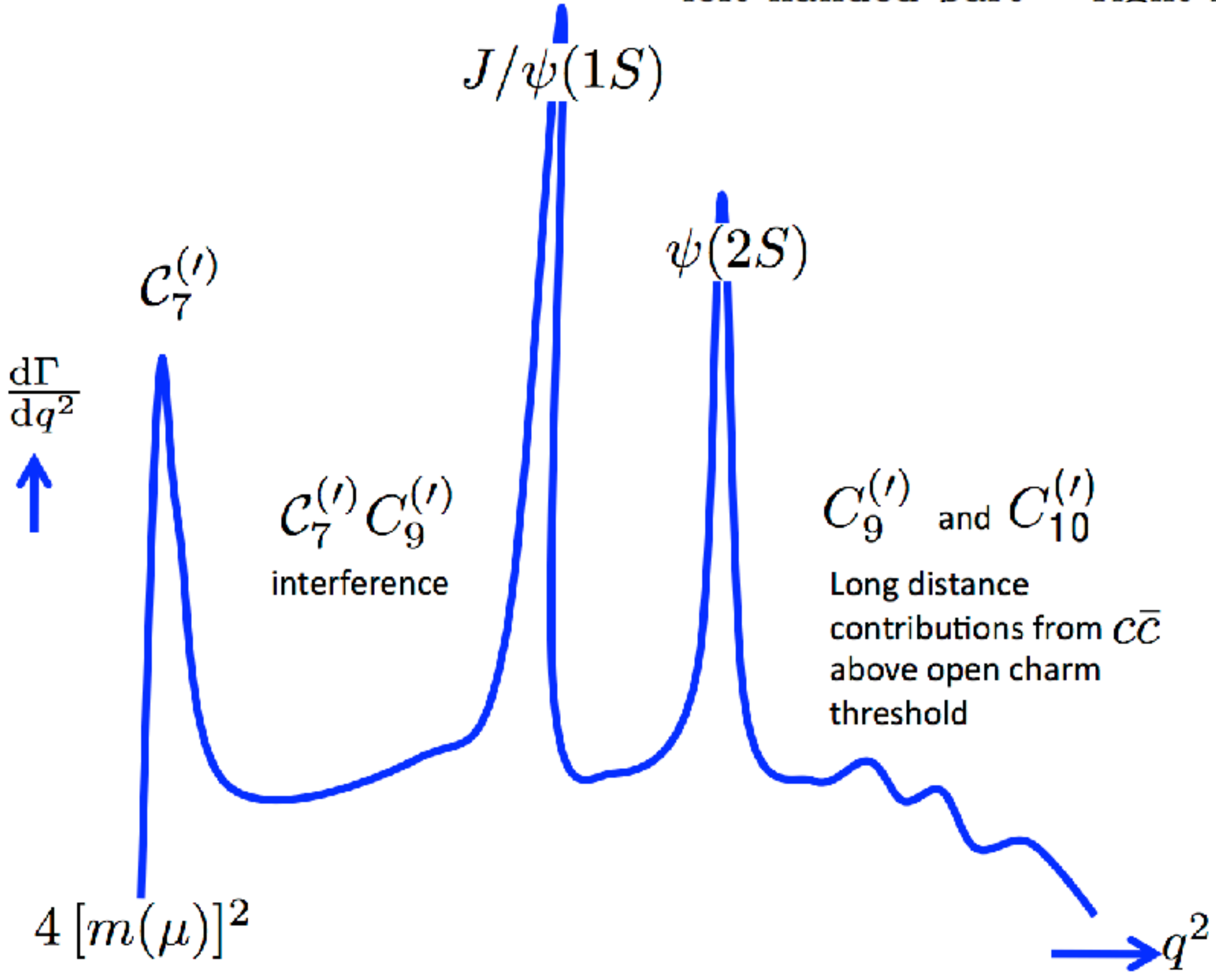
New physics can modify C_i Wilson coefficients and/or add new operators.

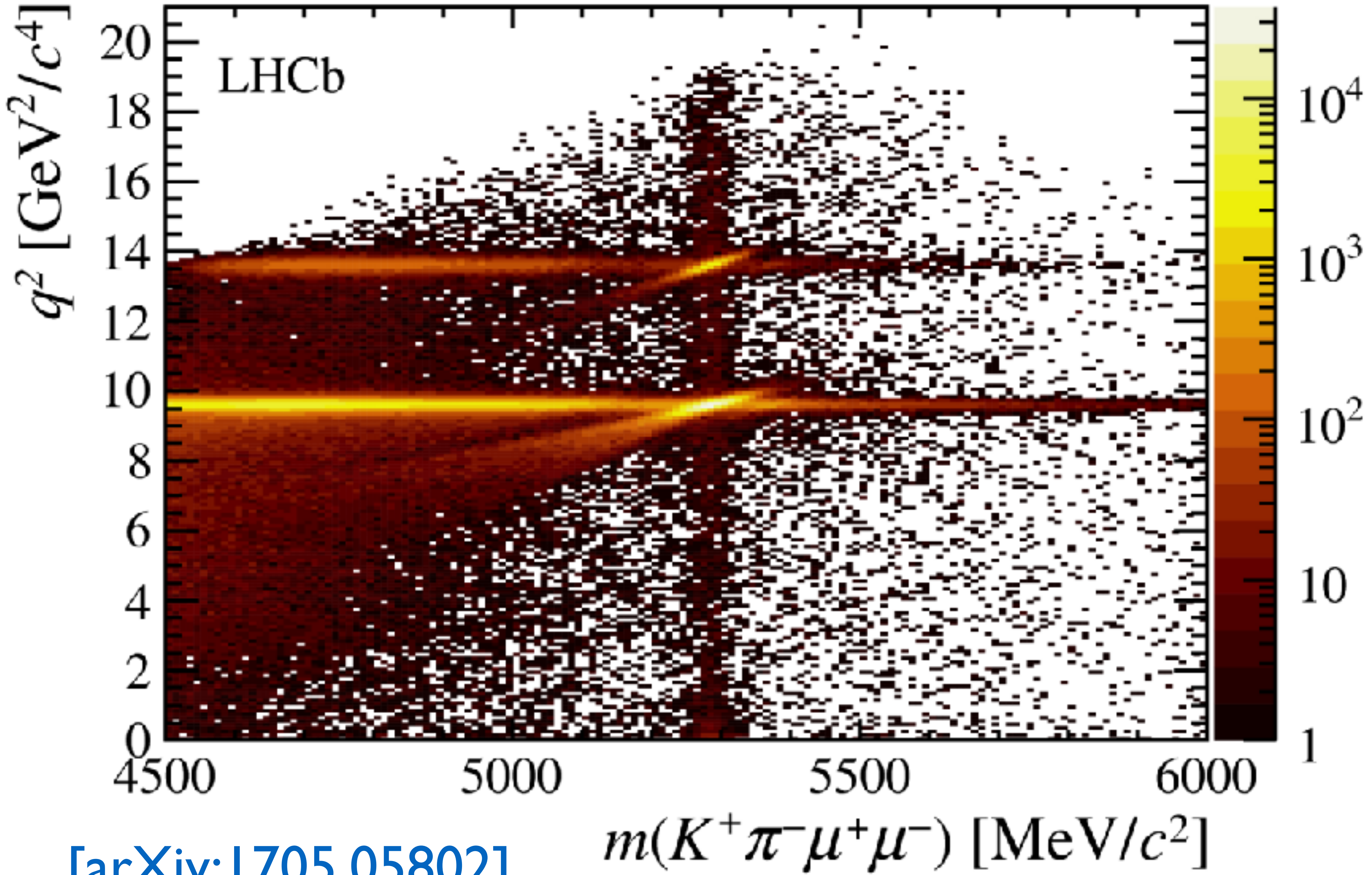
Theoretical framework

Use effective Hamiltonian to describe b → s transitions.

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \sum_i [\underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu)O_i'(\mu)}_{\text{right-handed part}}]$$







[arXiv:1705.05802]

Compare muons to electrons

Electrons emit large amount of **Bremsstrahlung** as they traverse LHCb; leads to **degraded** momentum and invariant mass resolutions; migration between q^2 regions.

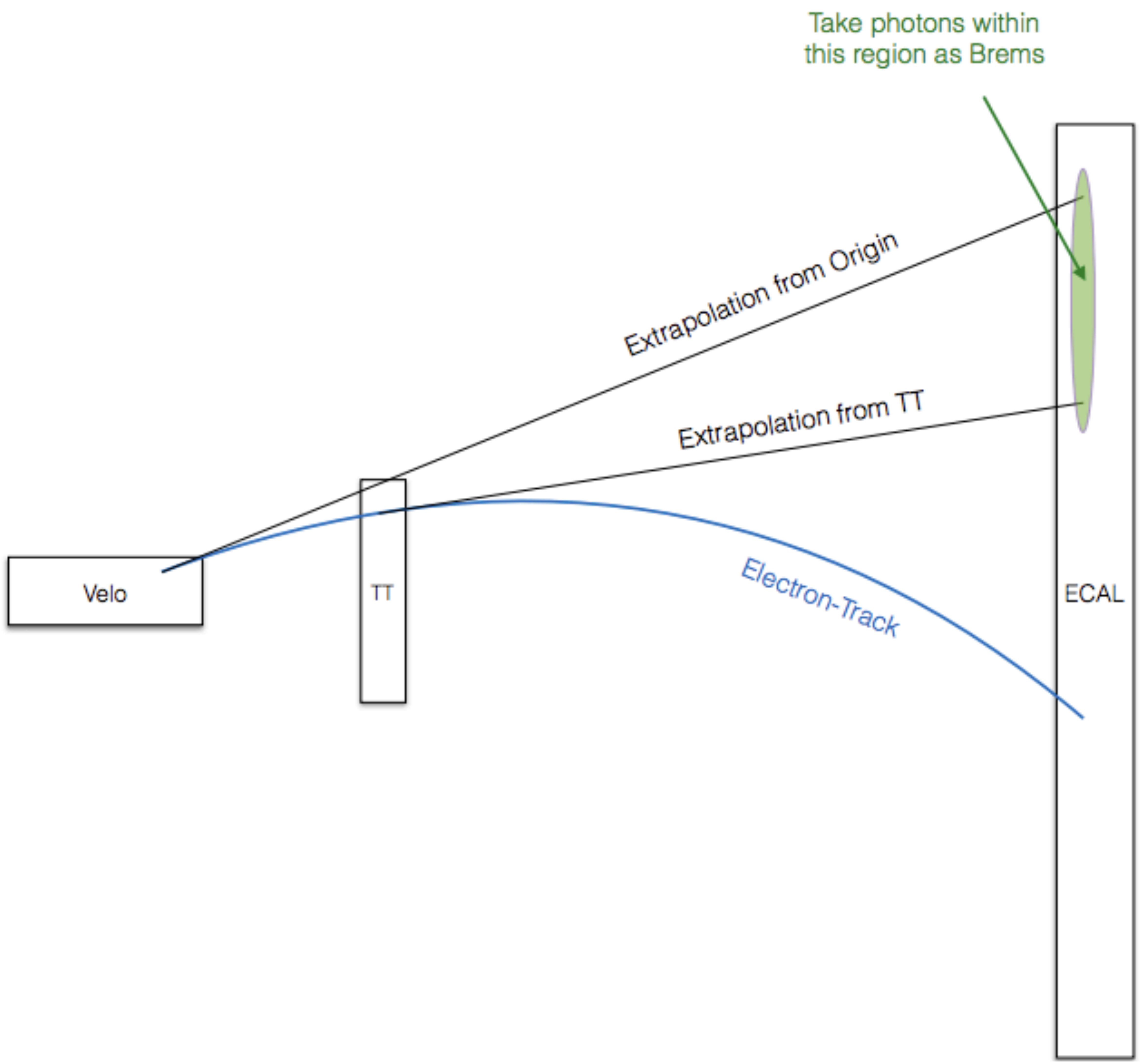
[arXiv:1705.05802]

Electron reconstruction @ LHCb

Bremsstrahlung photons emitted downstream of magnet will deposit energy in same ECAL cells as electron

Bremsstrahlung photons emitted upstream of magnet can be recovered during reconstruction.

4-momentum from photons deposited in ECAL is added to a matching electron track.



LHCb hardware trigger

Hardware trigger:

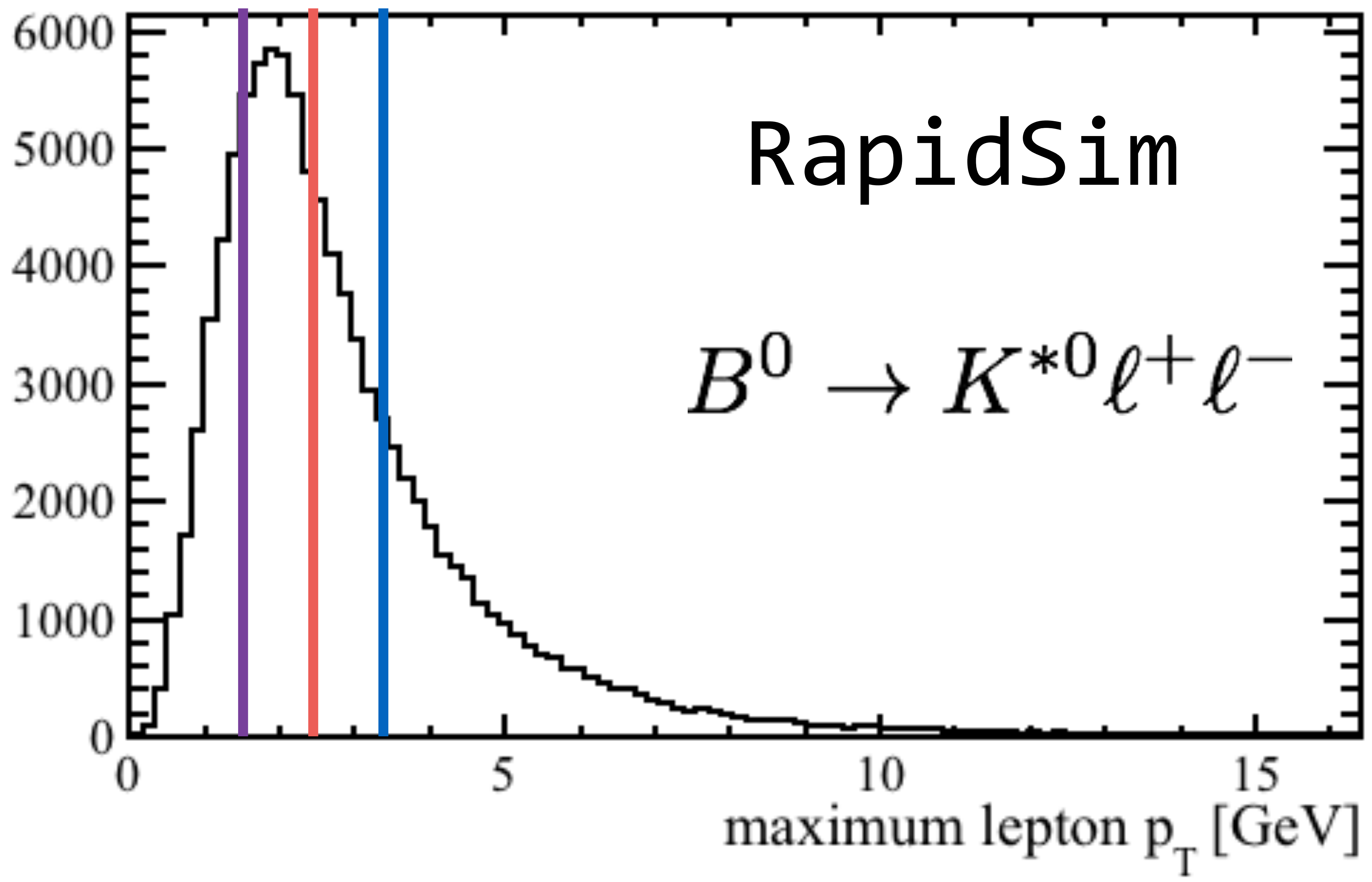
L0 Muon $p_T > 1.5 - 1.8$ GeV

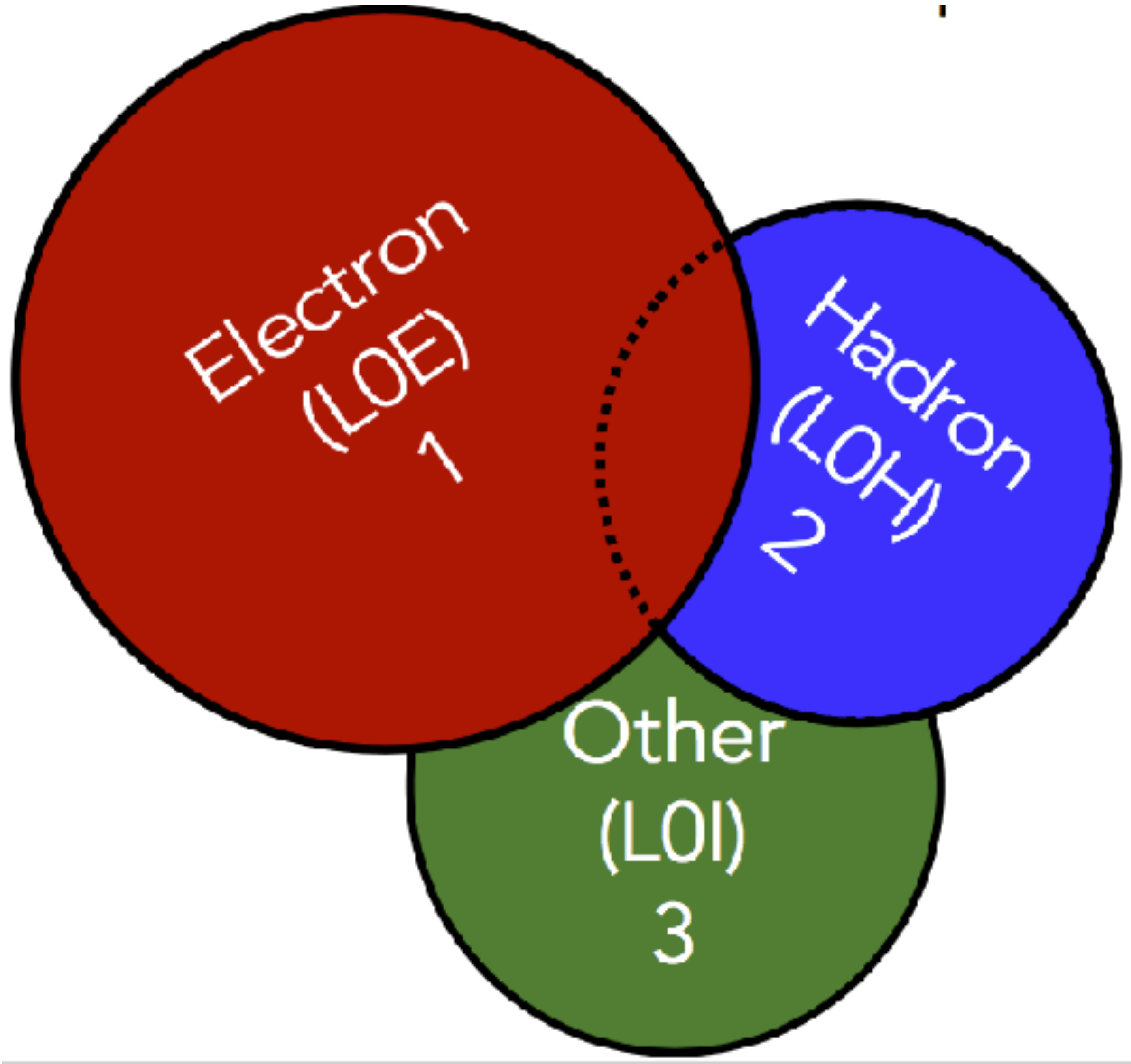
L0 Electron $E_T > 2.5 - 3.0$ GeV

L0 Hadron $E_T > 3.5$ GeV

Single category for muons

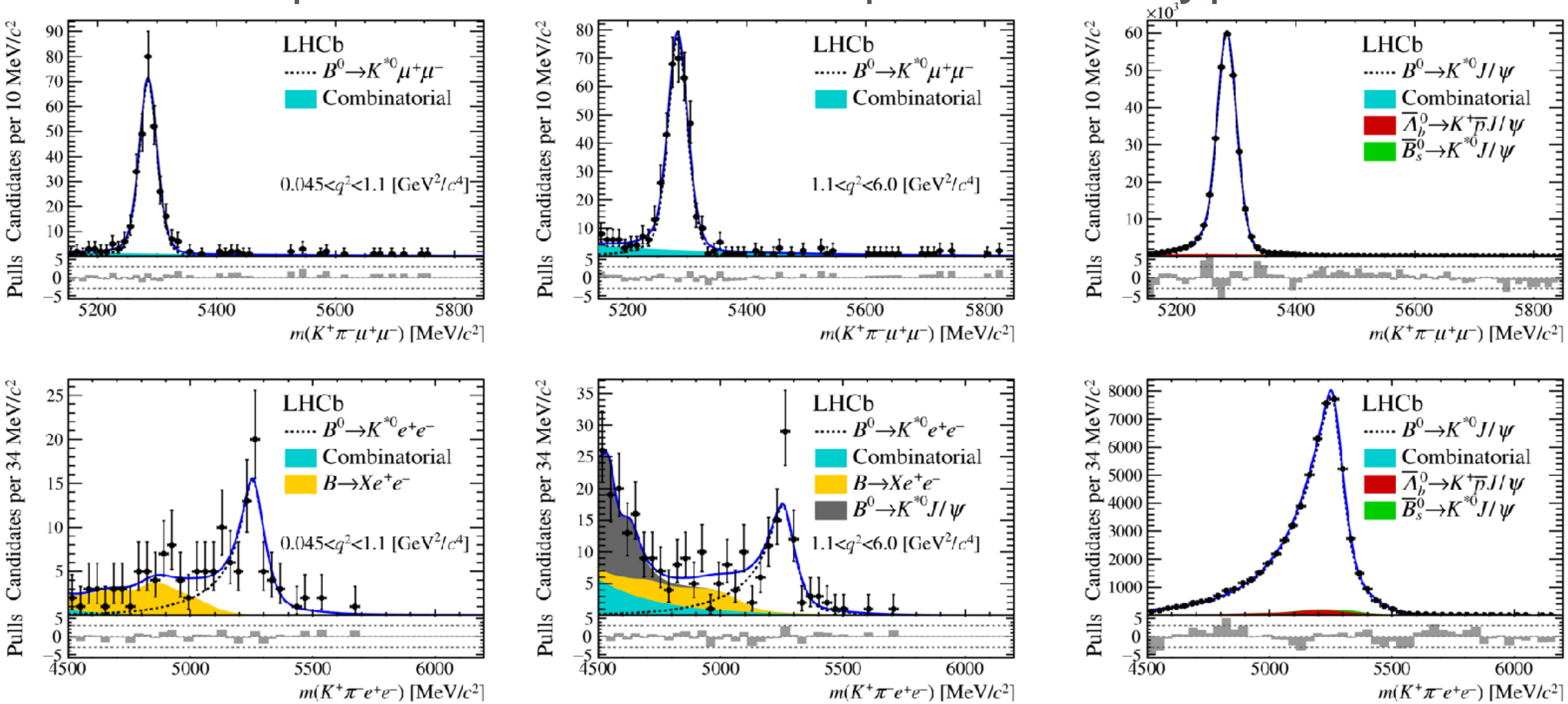
Three exclusive categories for electrons





R_{K^*}

low-q^2 | central-q^2 | J/psi control mode



$\mu^+\mu^-$

e^+e^-

Yields	low-q^2	central-q^2	J/psi
$\mu^+\mu^-$	285±18	353±21	274k
e^+e^-	89±11	111±14	58k

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

Cross-checks (1/2)

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

Measured to be ~independent of decay kinematics and event multiplicity.

$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ consistent with [LHCb arxiv:1606.04731]

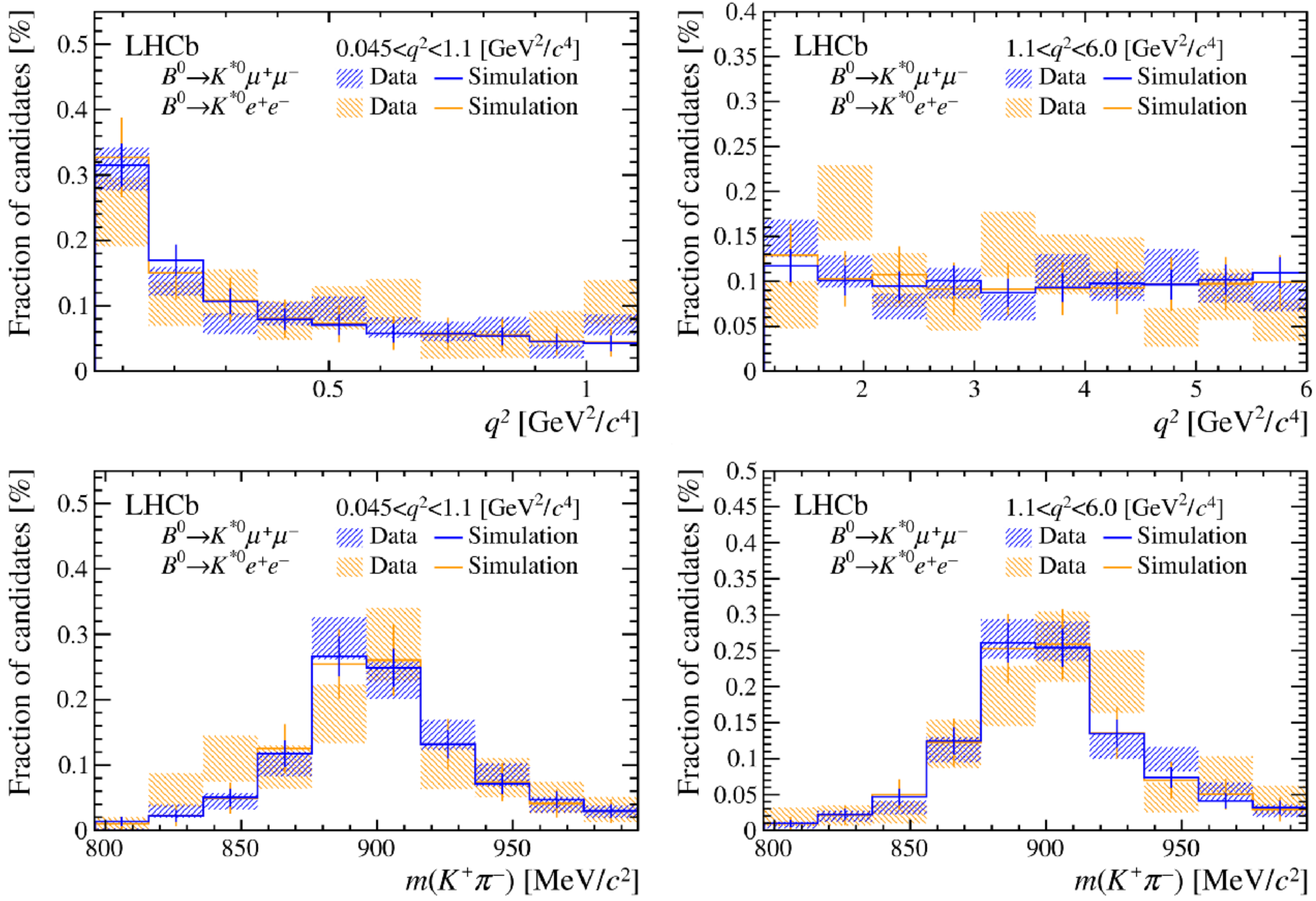
$$\mathcal{R}_{\psi(2S)} = \frac{r_{\psi(2S)}}{r_{J/\psi}} \qquad r_\gamma = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma)}{\mathcal{B}(B^0 \to K^{*0} J/\psi\,(\to e^+e^-))}$$

Compatible with expectations

If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus $R_{K^{*0}}$) **changes by less than 5%**

Cross-checks (2/2)

low-q^2 central-q^2



Compare background-subtracted data distributions with simulation.

Good agreement between electrons/muons and data/simulation.

Distributions normalised to same area.

Systematic uncertainties on R_{K*}

	$\Delta R_{K^{*0}}/R_{K^{*0}}$ [%]					
	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

Description of Brem tail in mass fits

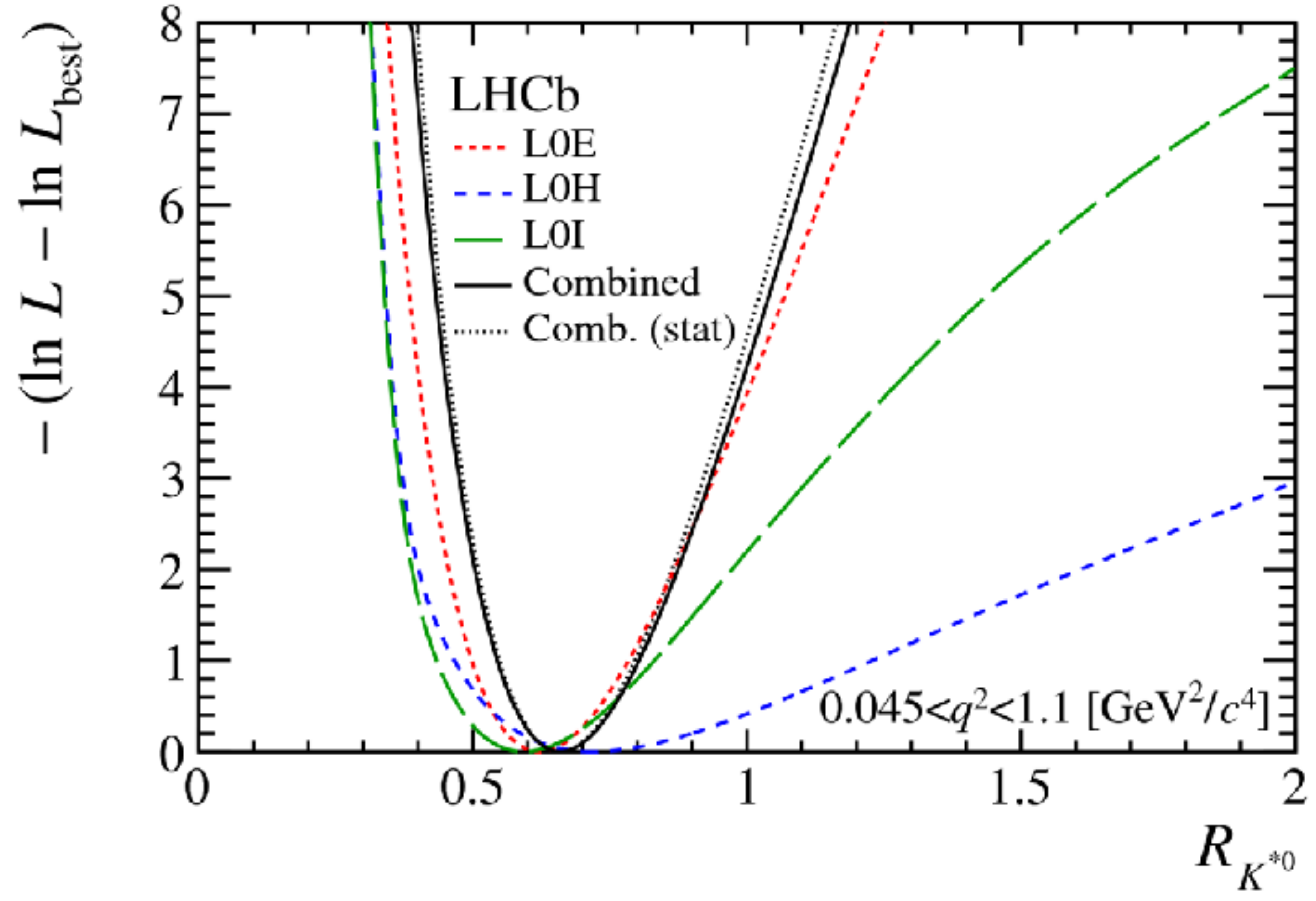
Residual background contamination due to $B\rightarrow K^{*0}J/\psi(ee)$ events with a $K\leftrightarrow e$ or $\pi\leftrightarrow e$ swap

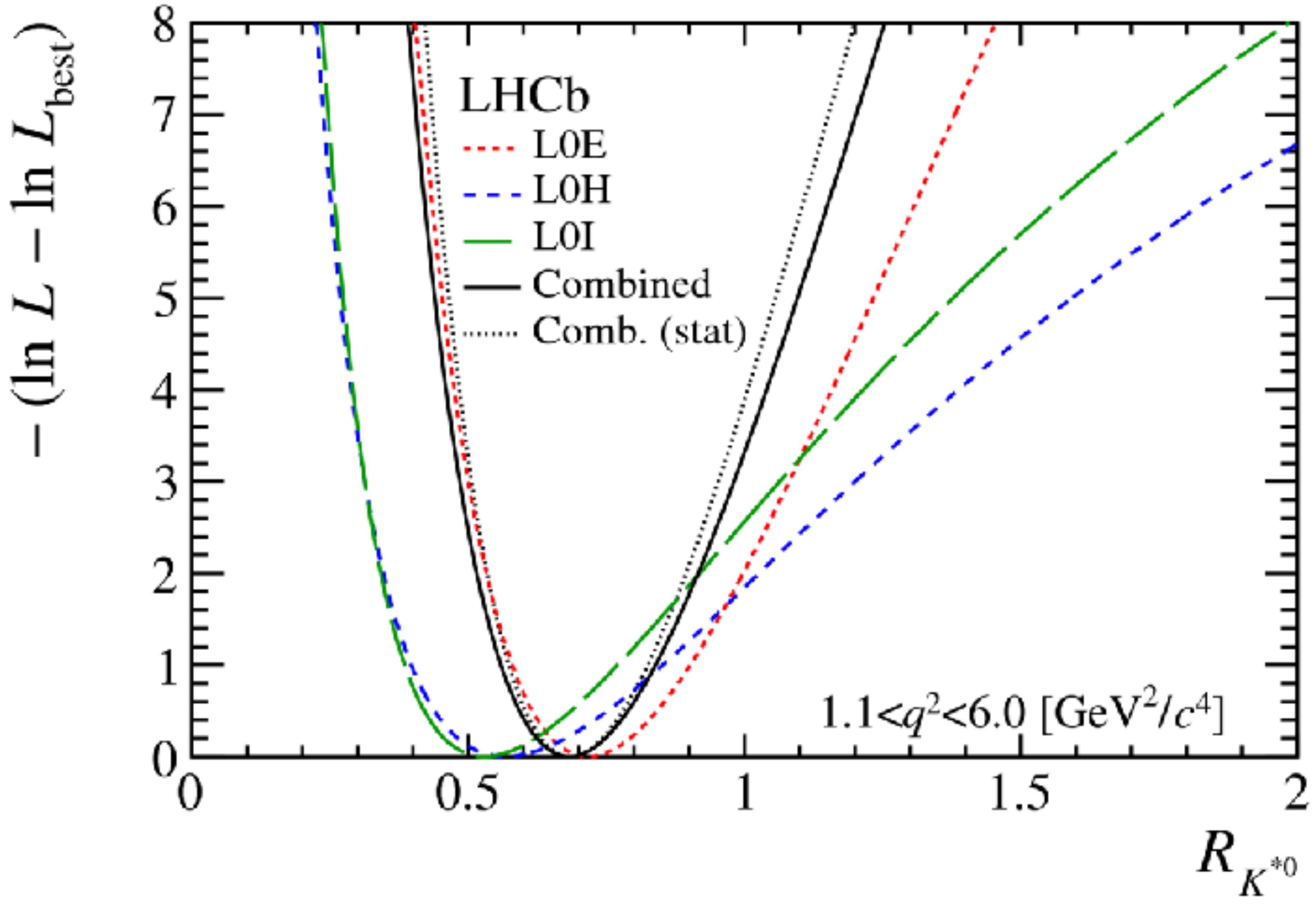
Double ratio means that many systematics cancel.

Statistical dominated (~15%) due to small yields in electron mode.

R_{K*} likelihood scans

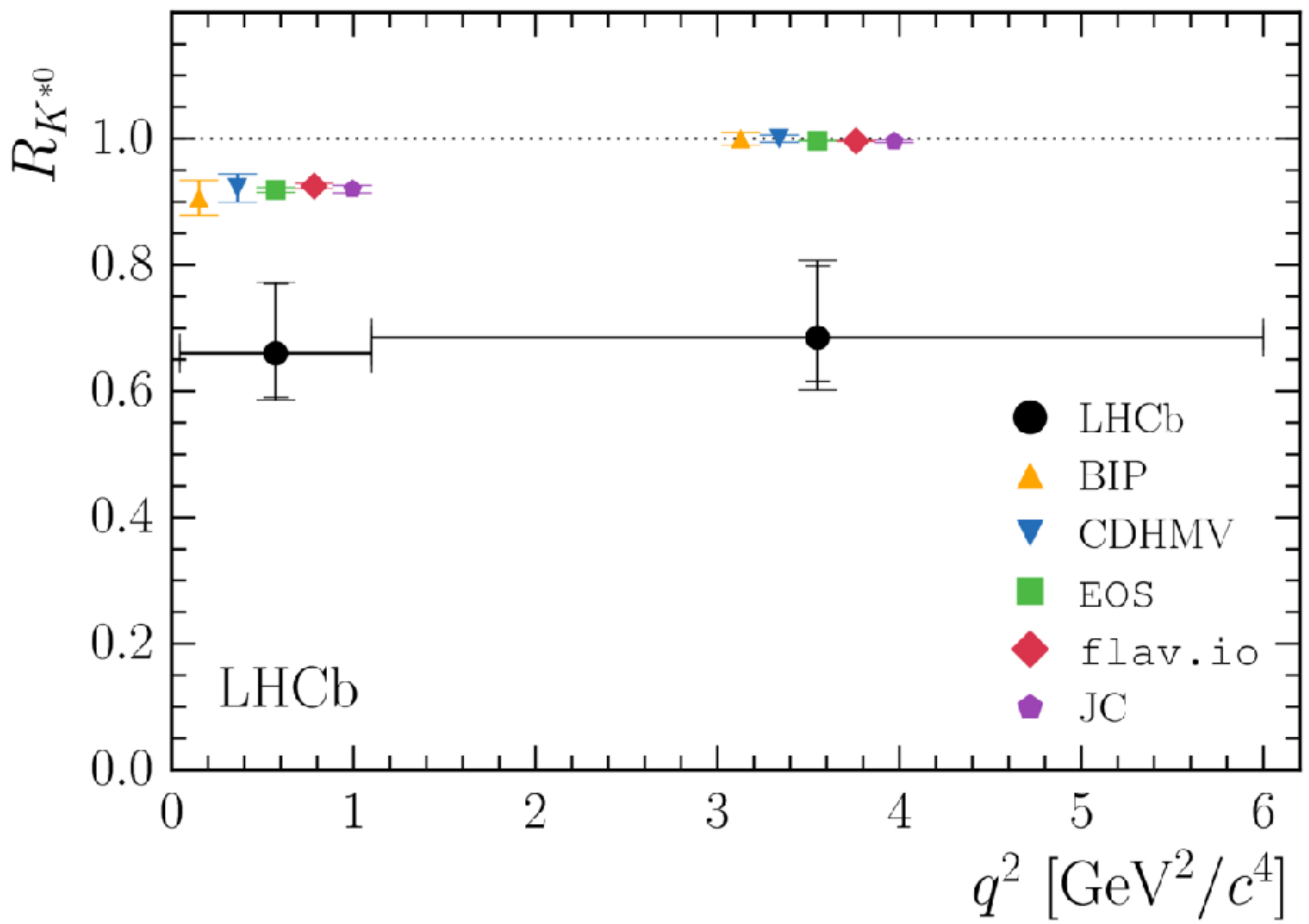
Good agreement between trigger categories

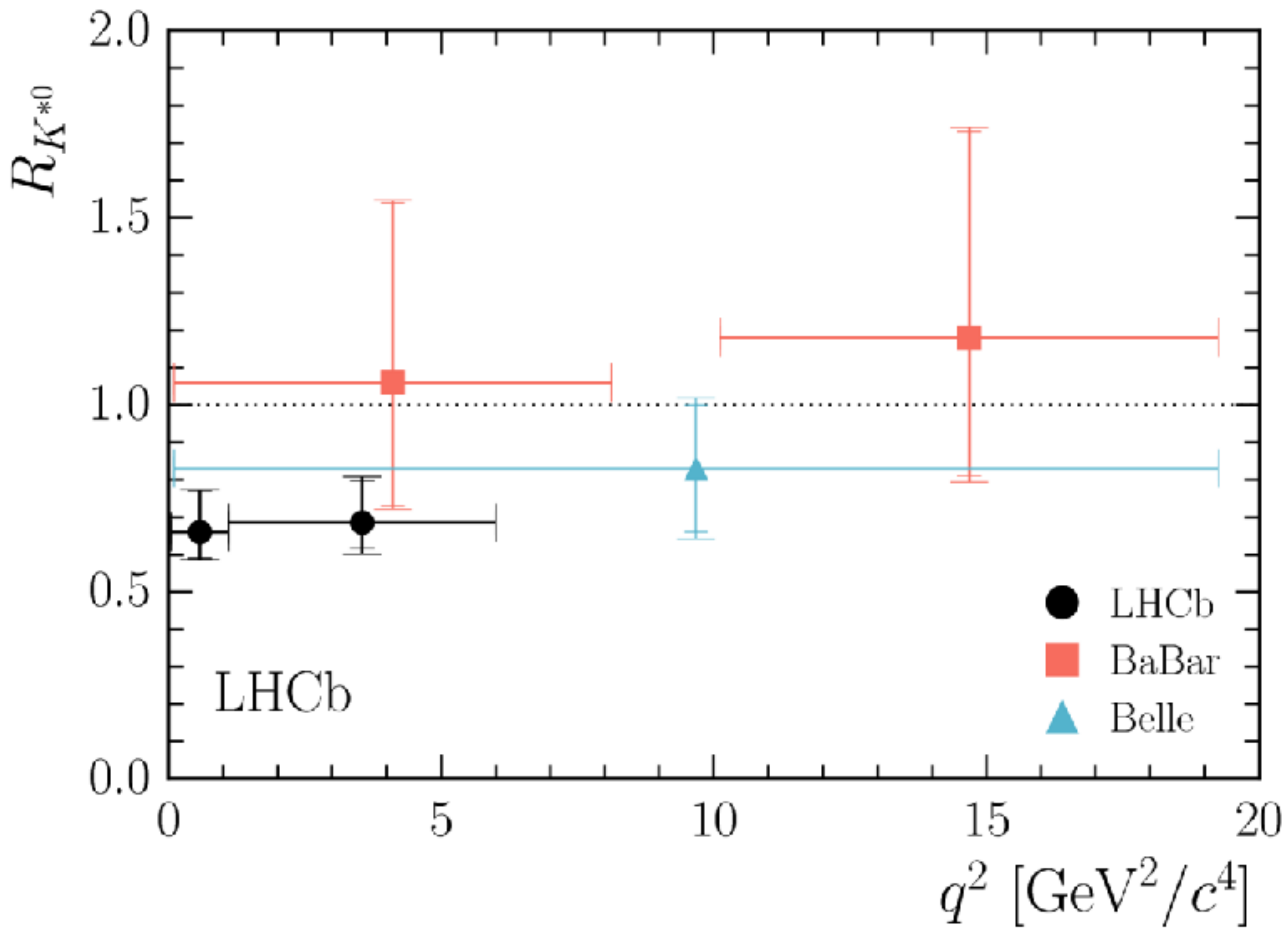




	low- q^2	central- q^2
$R_{K^{*0}}$	$0.66\ ^{+\ 0.11}_{-\ 0.07} \pm 0.03$	$0.69\ ^{+\ 0.11}_{-\ 0.07} \pm 0.05$
95.4% CL	[0.52, 0.89]	[0.53, 0.94]
99.7% CL	[0.45, 1.04]	[0.46, 1.10]

Comparison to theory and B-factories





PRD 86 (2012) 032012

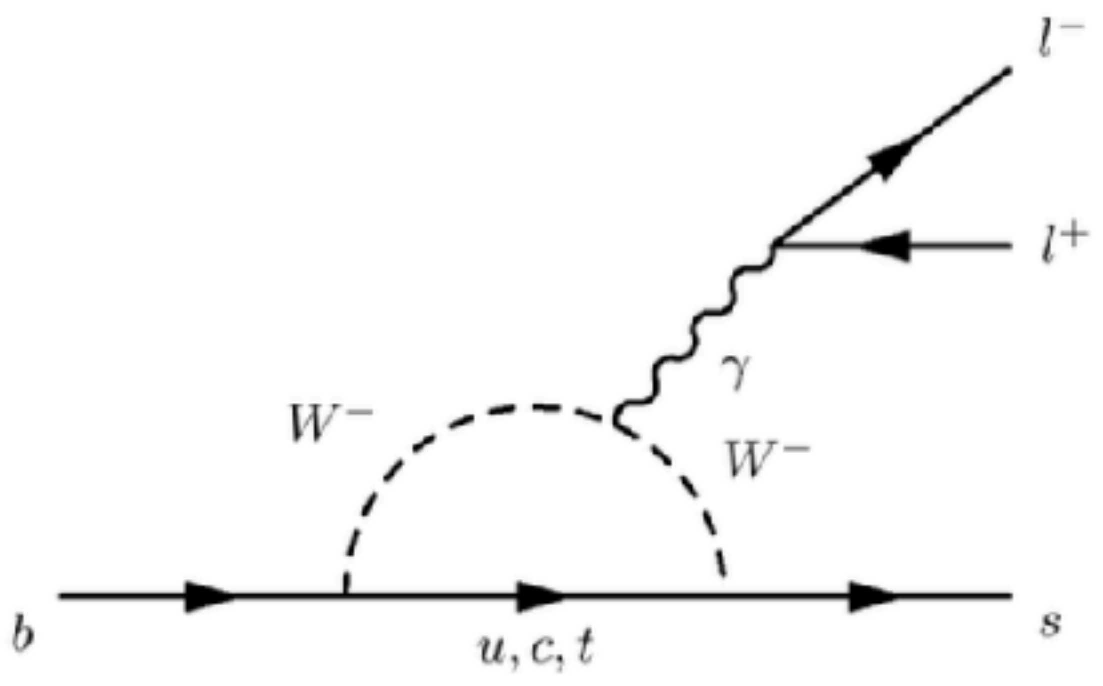
PRL 103 (2009) 171801

▲ BIP	[arXiv:1605.07633]
▼ CDHMV	[arXiv:1510.04239, 1605.03156, 1701.08672]
■ EOS	[arXiv:1610.08761, https://eos.github.io]
◆ flav.io	[arXiv:1503.05534, 1703.09189, flav-io/flavio]
⬟ JC	[arXiv:1412.3183]

O(1%) uncertainty on the SM predictions.

Compatibility with SM is 2.1-2.3σ (low-q^2) and 2.4-2.5σ (central-q^2)

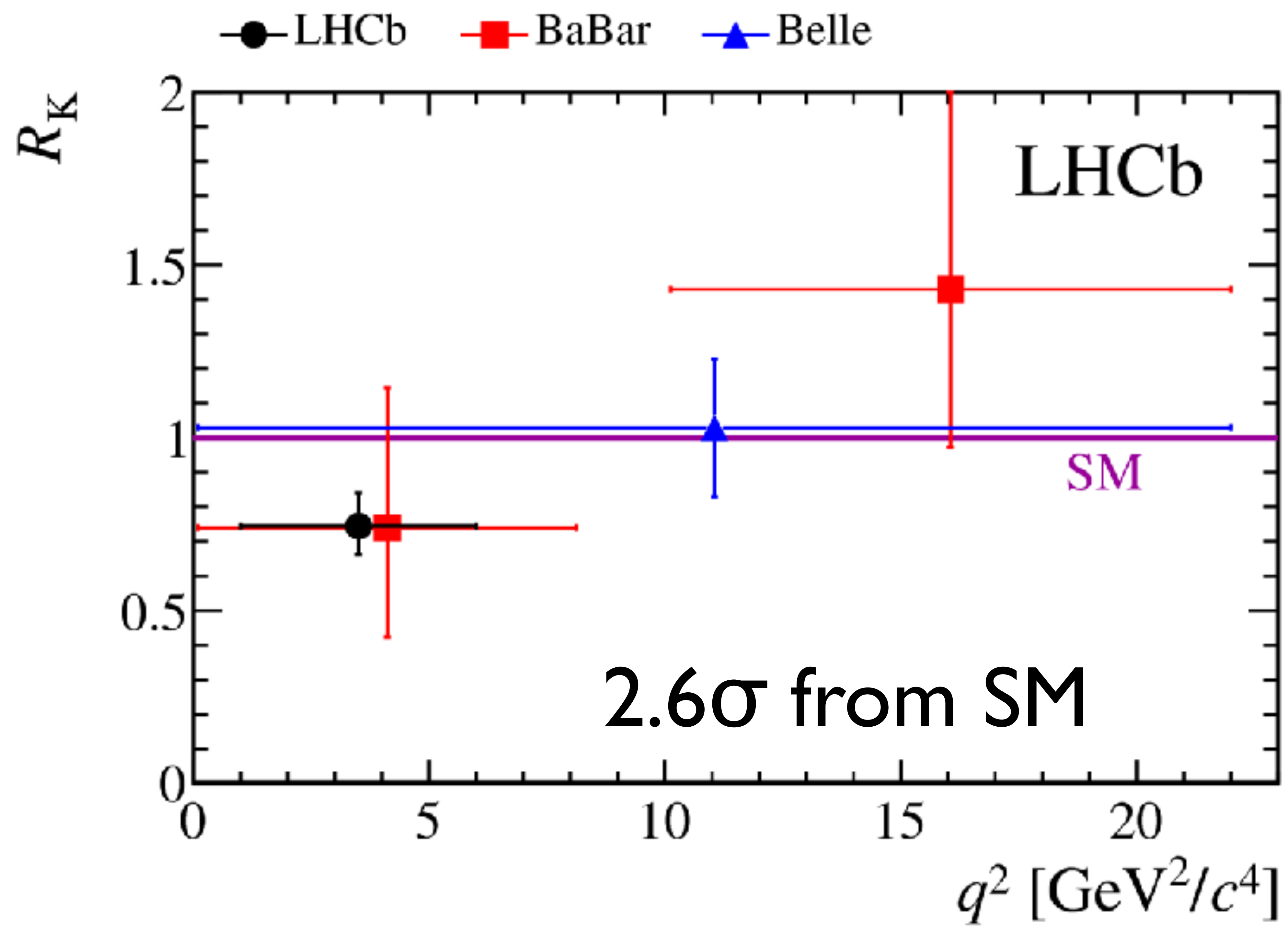
Another hint of LFUV: R_K

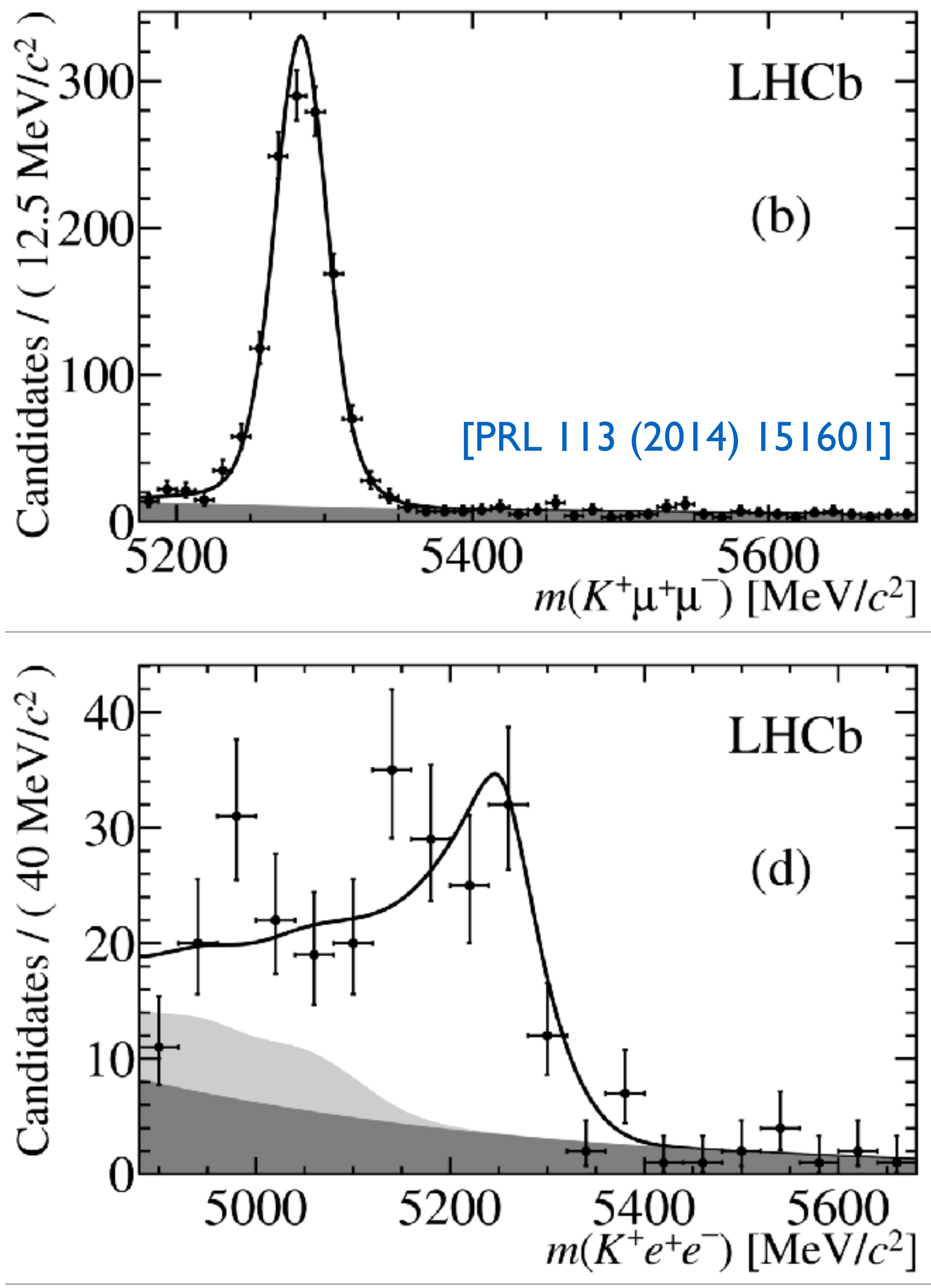


[Isidori et al., EPJC 76 (2016)]

$$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

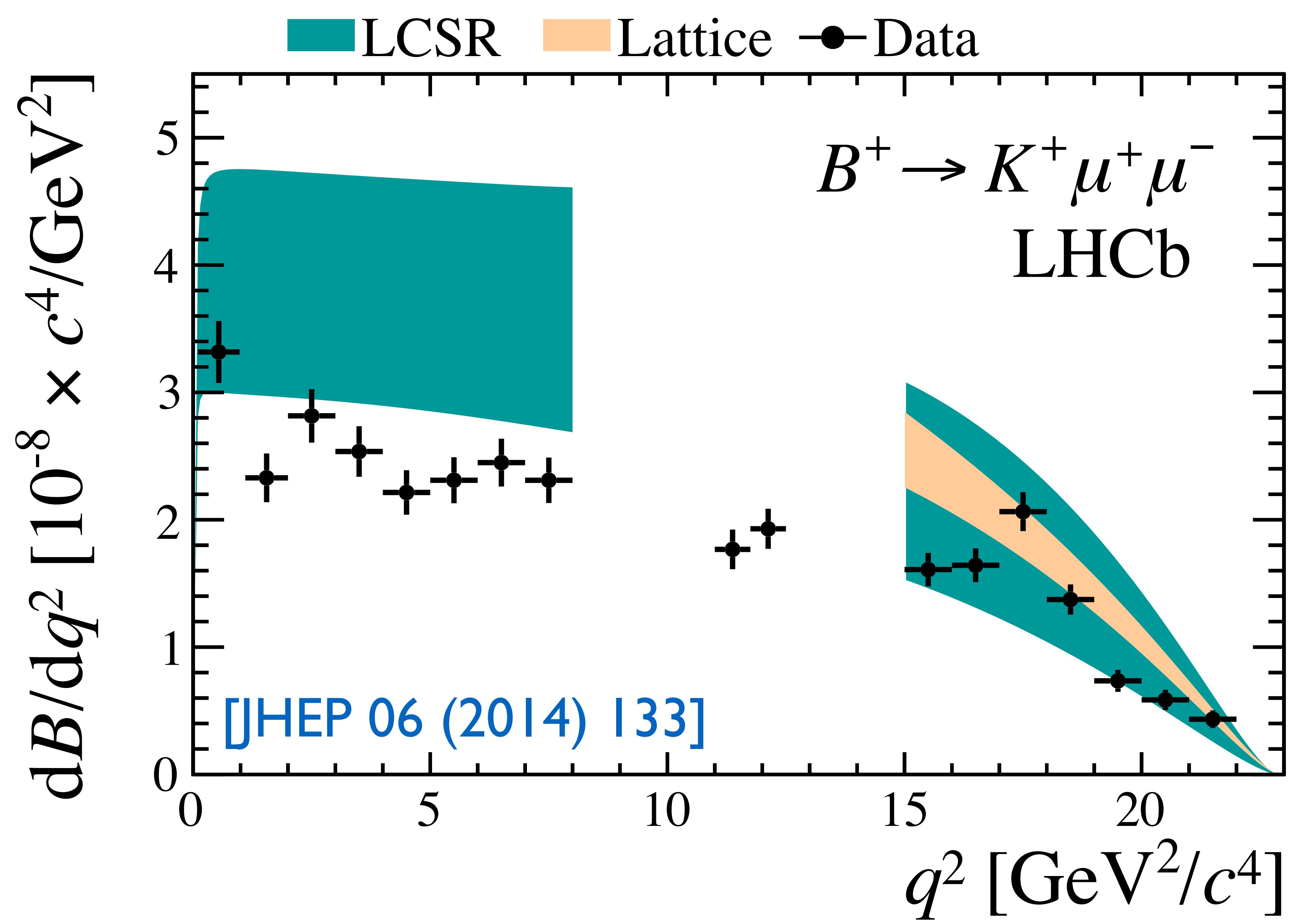
$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

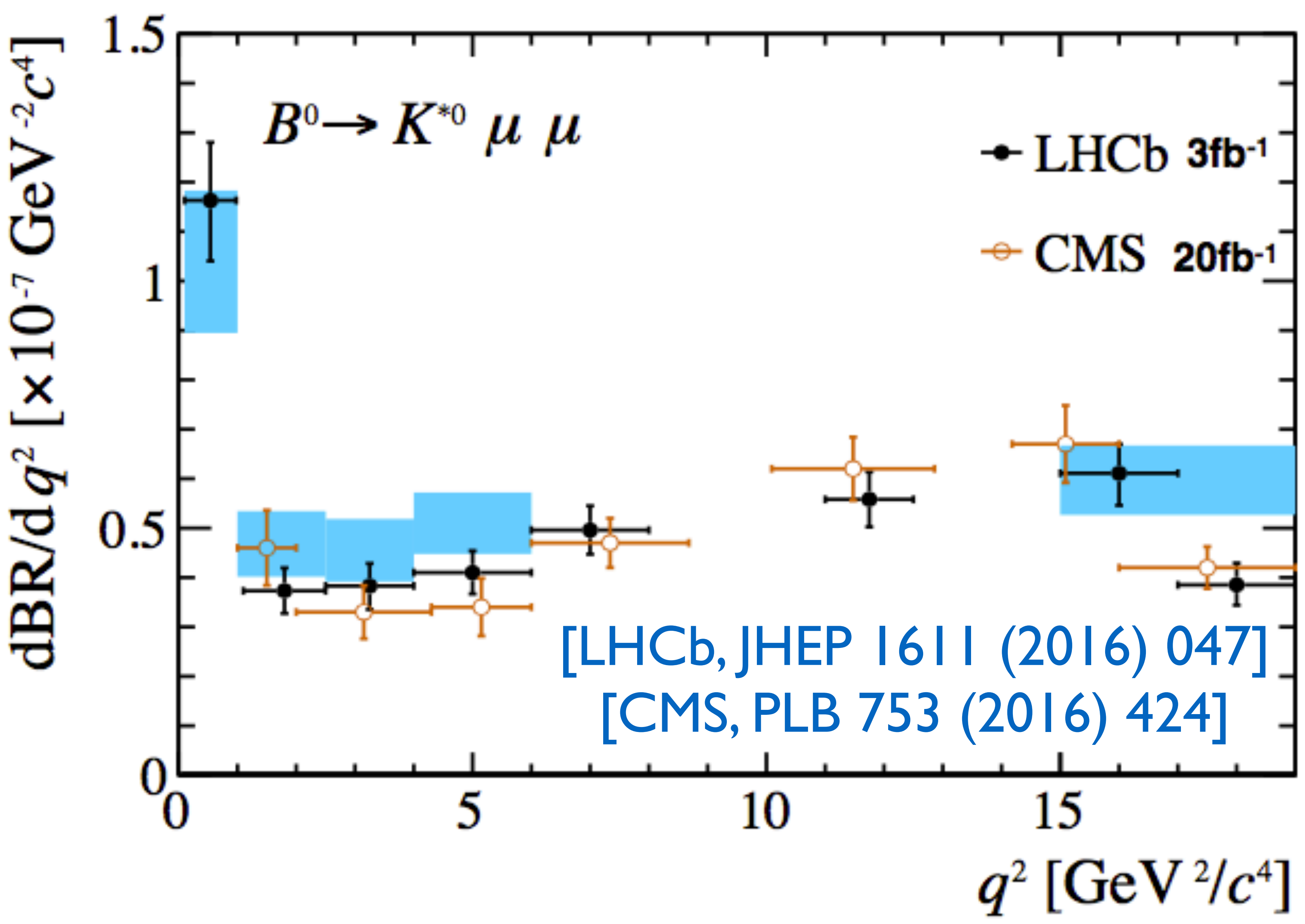


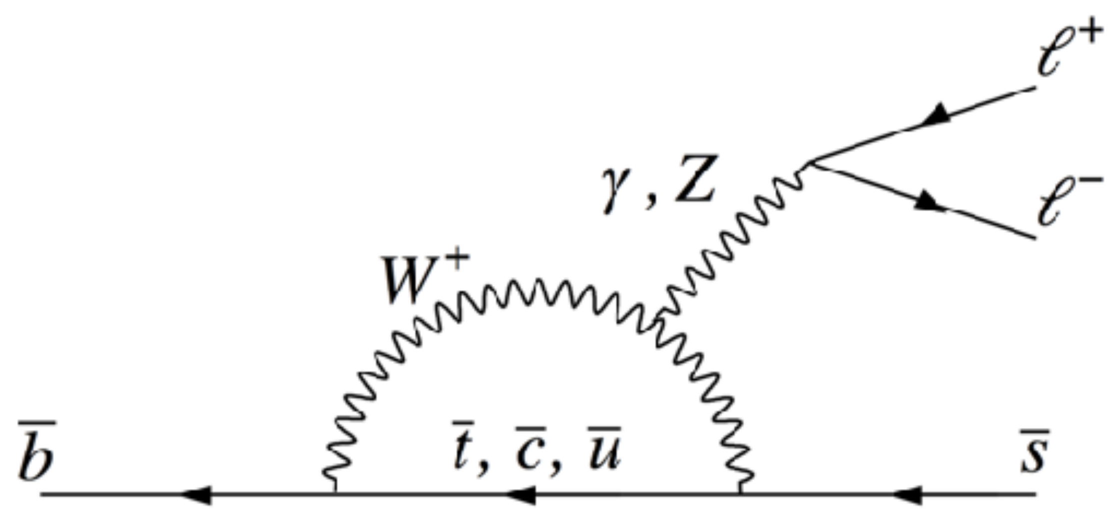


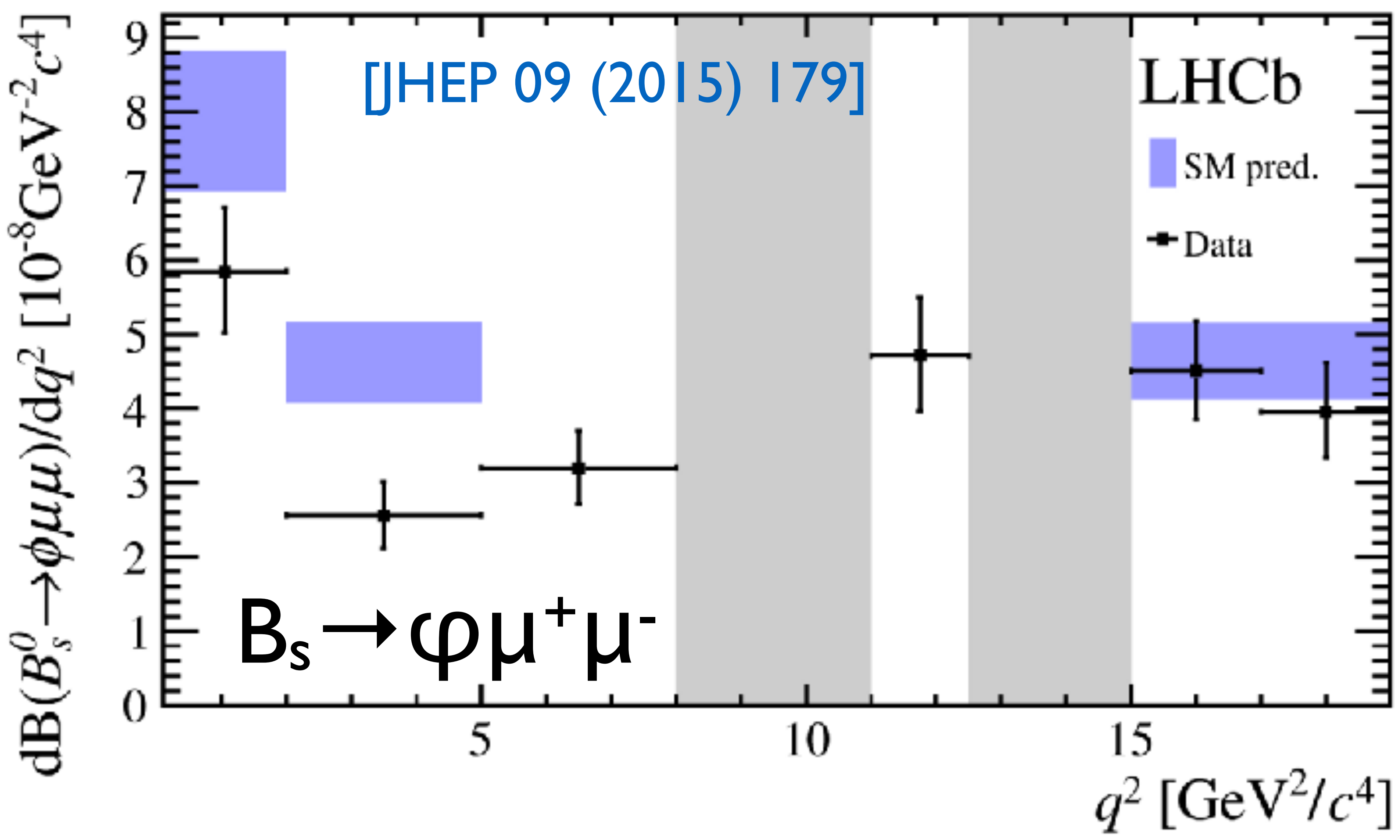
[PRL 113 (2014) 151601]

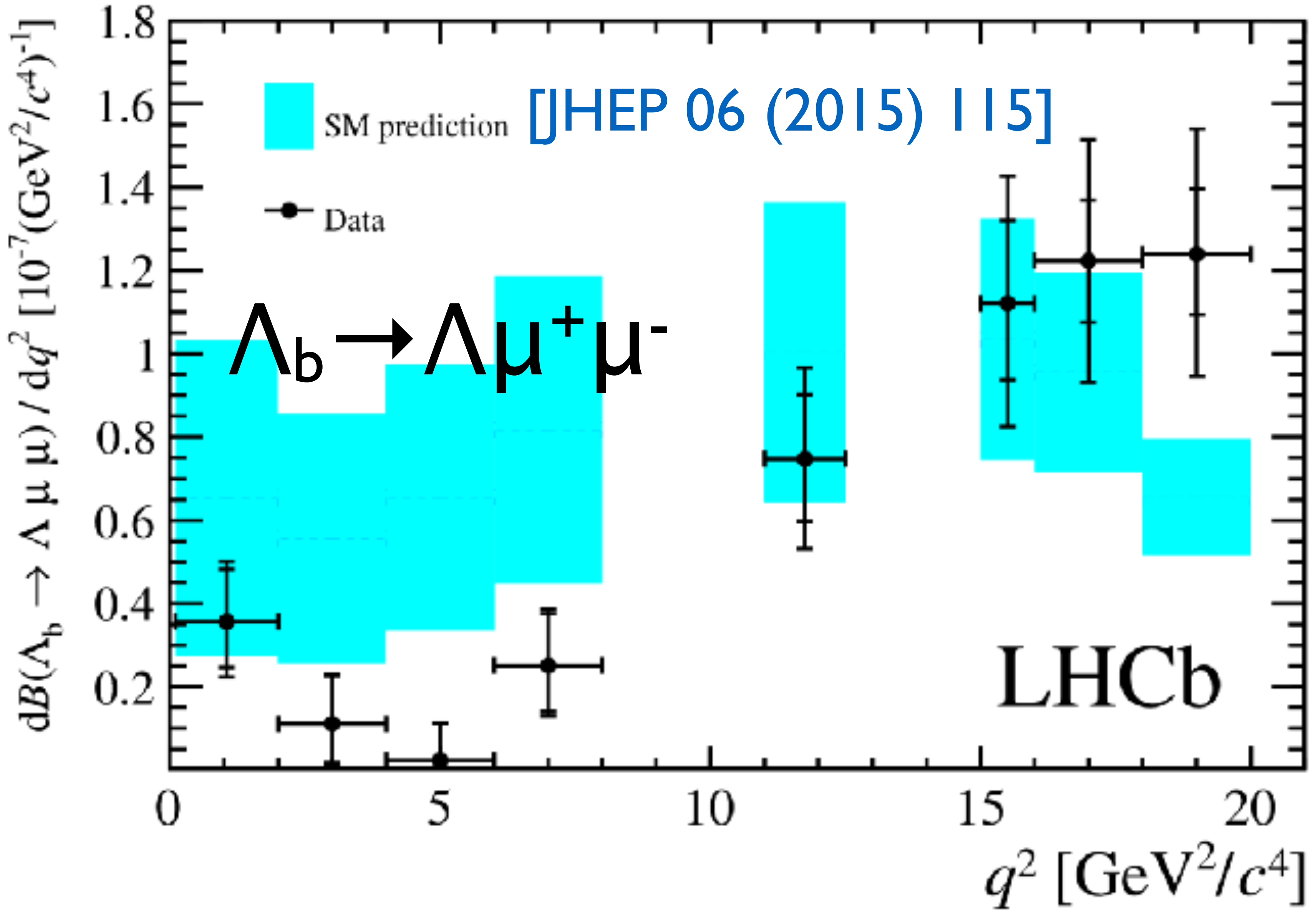
$b \to s\mu^+\mu^-$ branching fractions









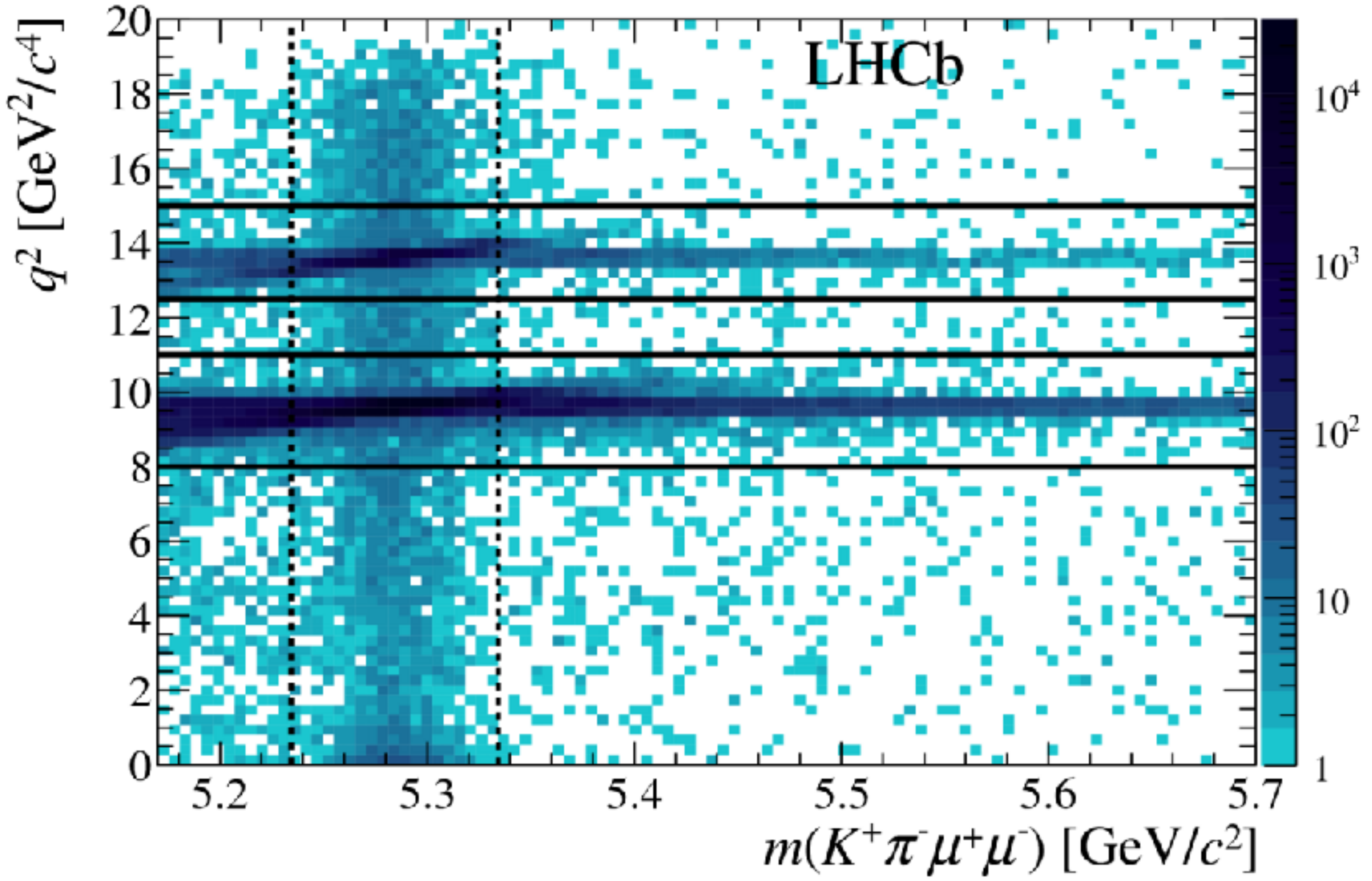


Many BR's of similar decay modes are **lower than predictions**.

QCD effect, NP or some systematic?

Dominant systematic comes from BR of normalisation mode (typically measured by B factories)

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



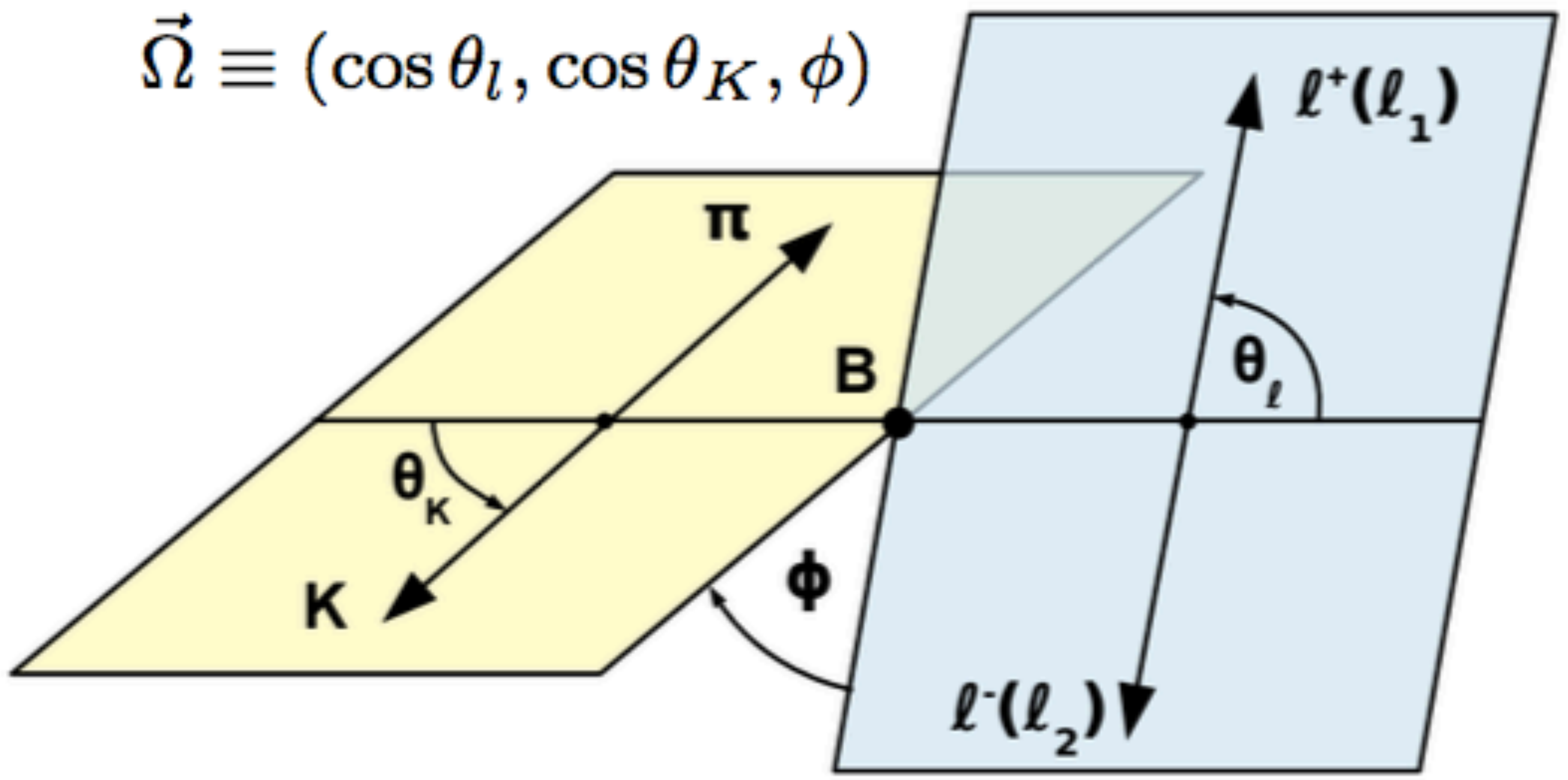
$$\frac{d^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi} \sum_{j=1}^{11} I_j(q^2) f_j(\vec{\Omega}), \quad I_j \to \bar{I}_j \text{ for } B^0$$

$$S_j = (I_j + \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right), \quad A_j = (I_j - \bar{I}_j) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

In the end we measure each S_j and A_j in each bin of q^2.

2398 ± 57 events, excluding the charmonia.

$\vec{\Omega} \equiv (\cos\theta_l, \cos\theta_K, \phi)$



Dimuon final state is experimentally clean, but BR ~10^{-7}

P->VV' decay, fully described by q^2 and 3 helicity angles.

Rich system of observables (rates, asymmetries) that are sensitive to NP

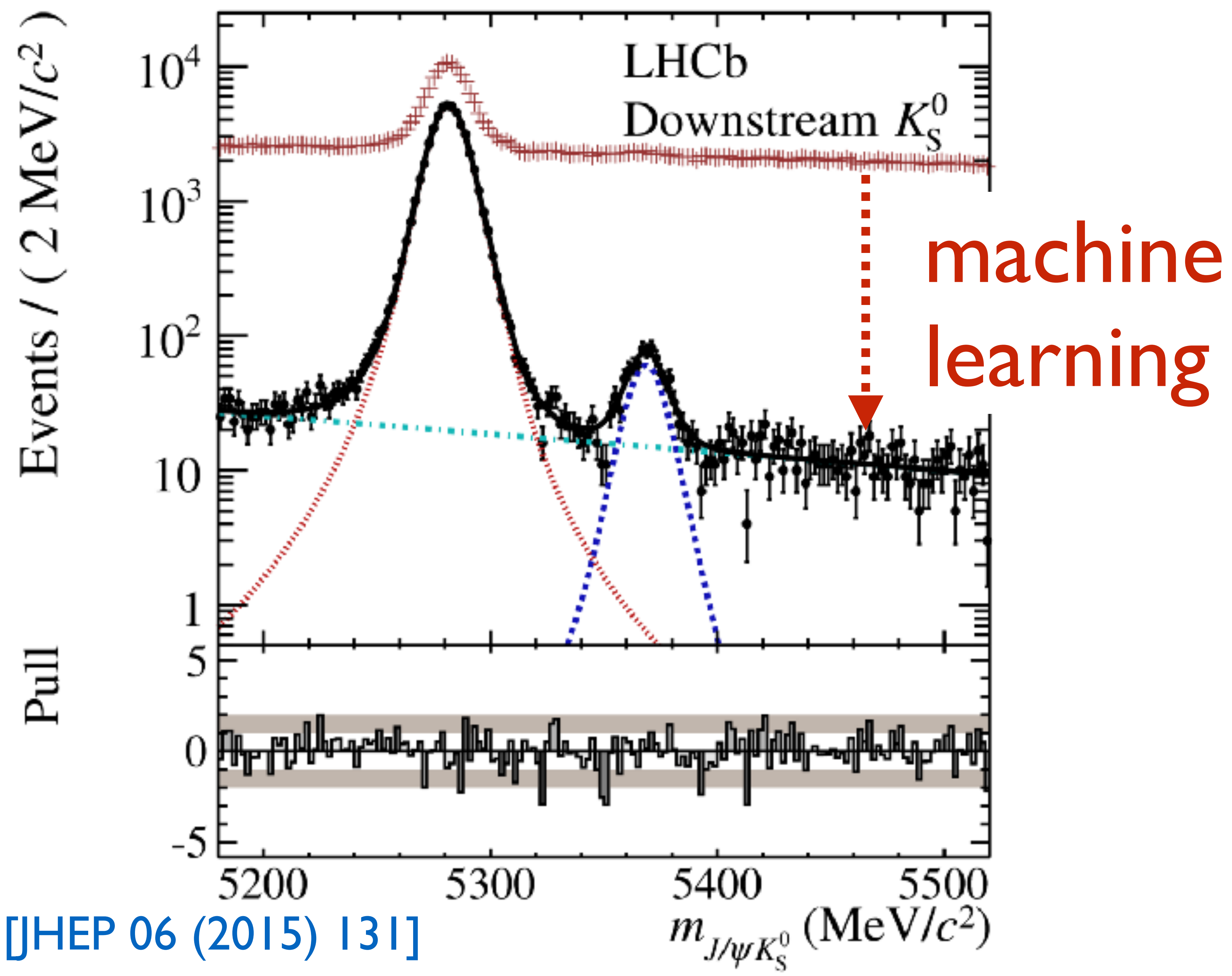
[JHEP 02 (2016) 104]

Experimental challenges

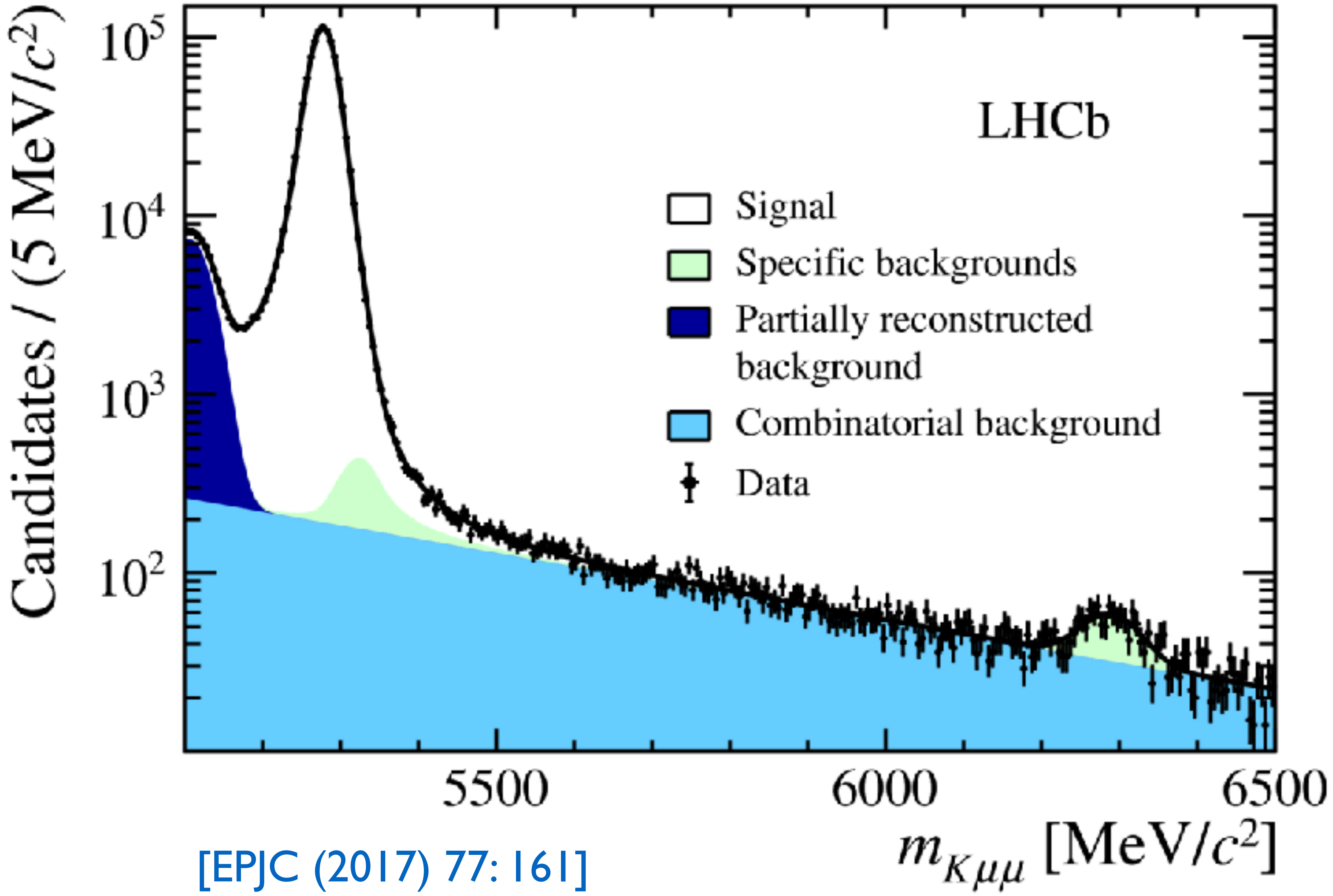
Isolate signal events from two backgrounds:

Combinatorial - use machine learning (BDTs etc) built from kinematic and topological information.

Peaking - use particle ID information from the LHCb RICH to suppress contributions from decays that look like signal when one or more particles mis-ID.



[JHEP 06 (2015) 131]

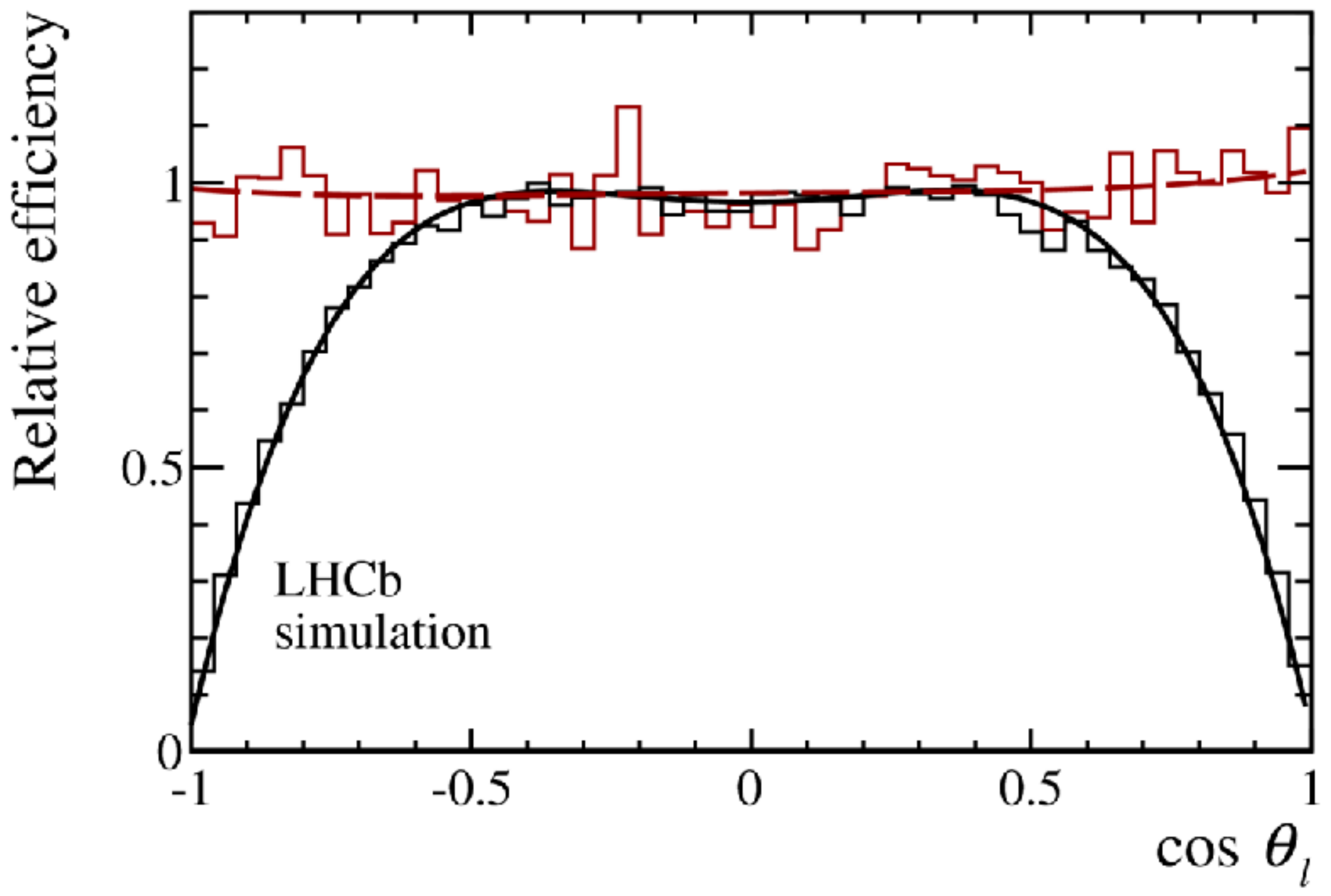


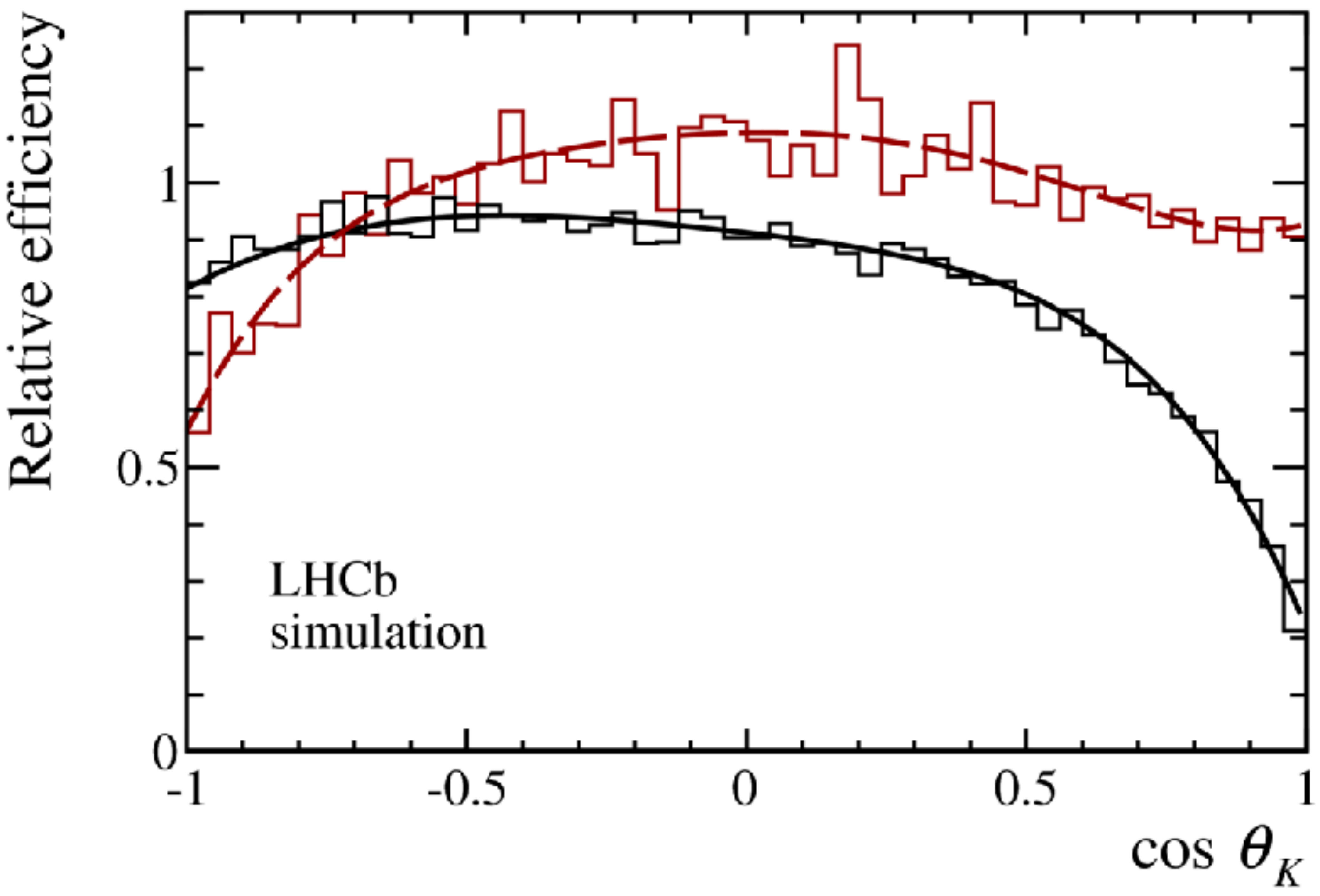
[EPJC (2017) 77: 161]

Experimental challenges

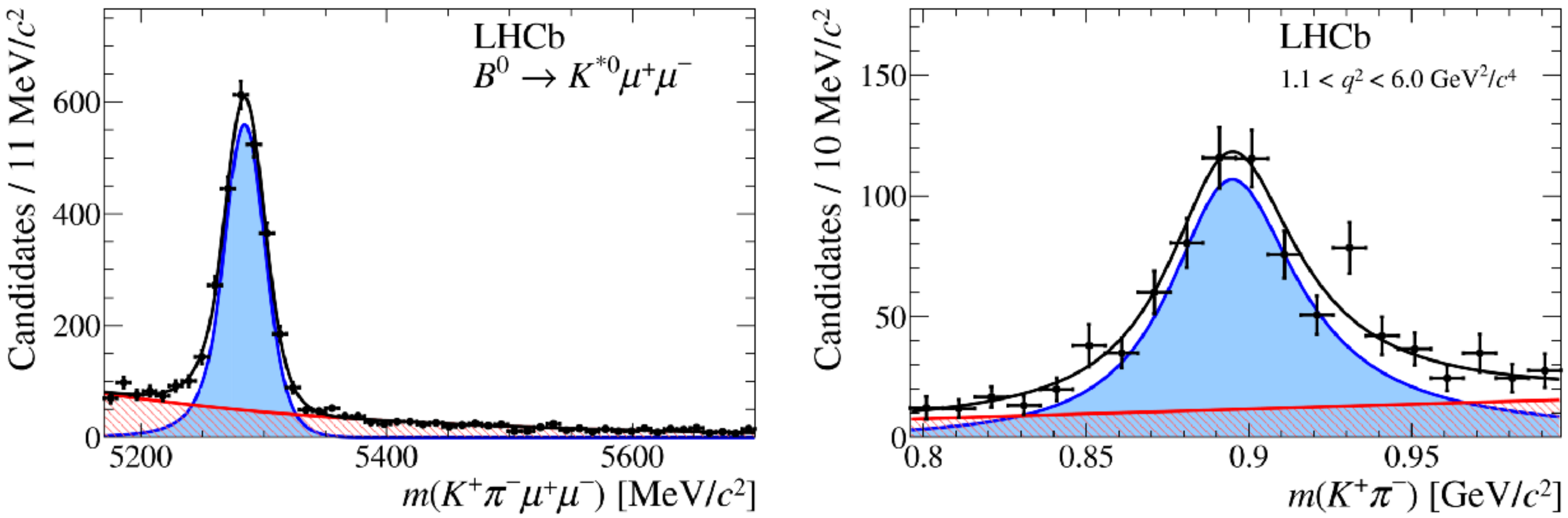
Angular and q^2-dependent **efficiencies**

Use simulation, corrected to look more like data in terms of detector occupancy, particle identification performance and production kinematics.

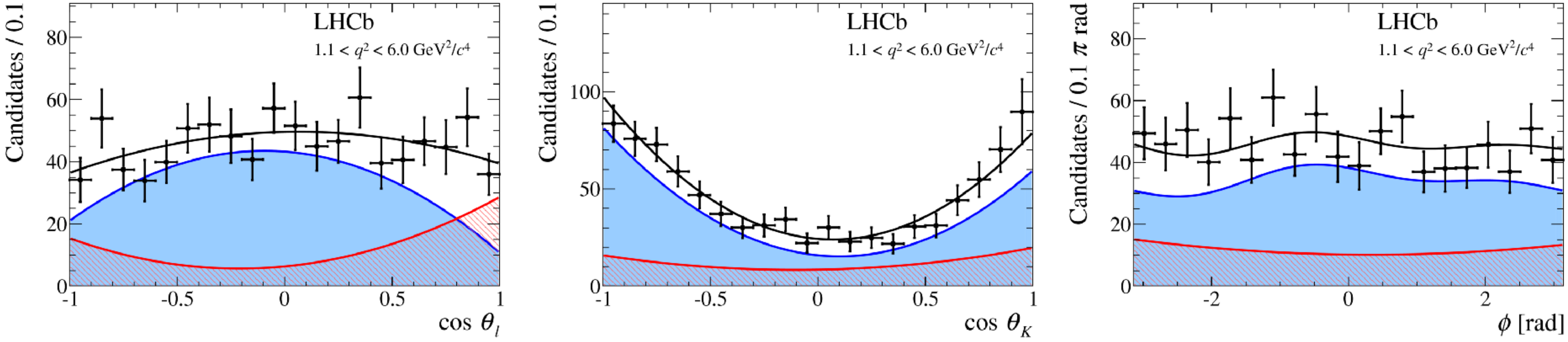




$B^0 \rightarrow K^{*0}(K^+\pi^-)\mu^+\mu^-$



S_i and A_i extracted using a maximum likelihood fit of the 3D angular distributions in bins of q^2



[JHEP 02 (2016) 104]

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

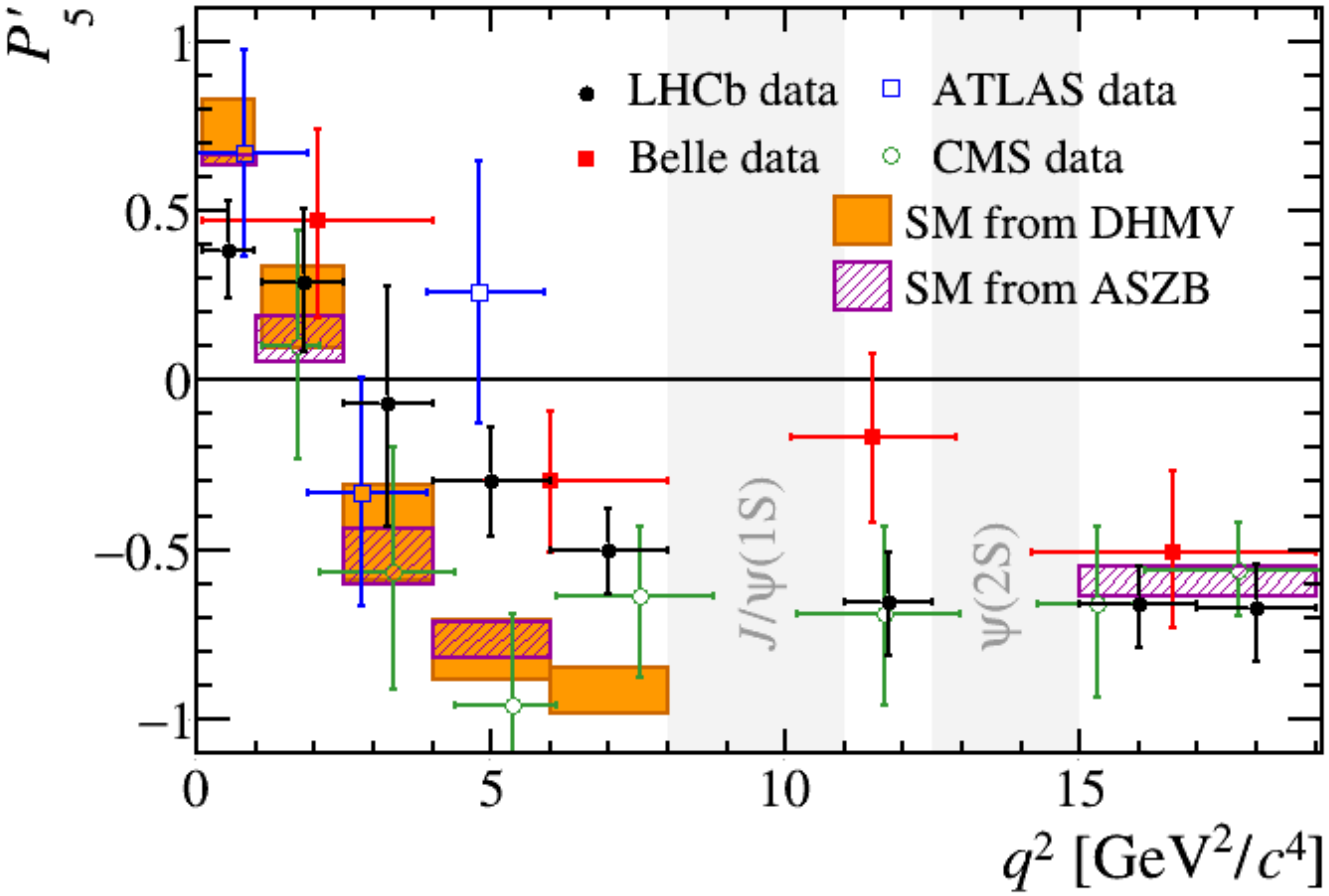
Measure the S_i observables, but build "**theoretically clean**" observables that divide-out the leading order form-factor uncertainties.

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

[Descotes-Genon et al., JHEP 05 (2013) 137]

[JHEP 02 (2016) 104]

New kids on the block

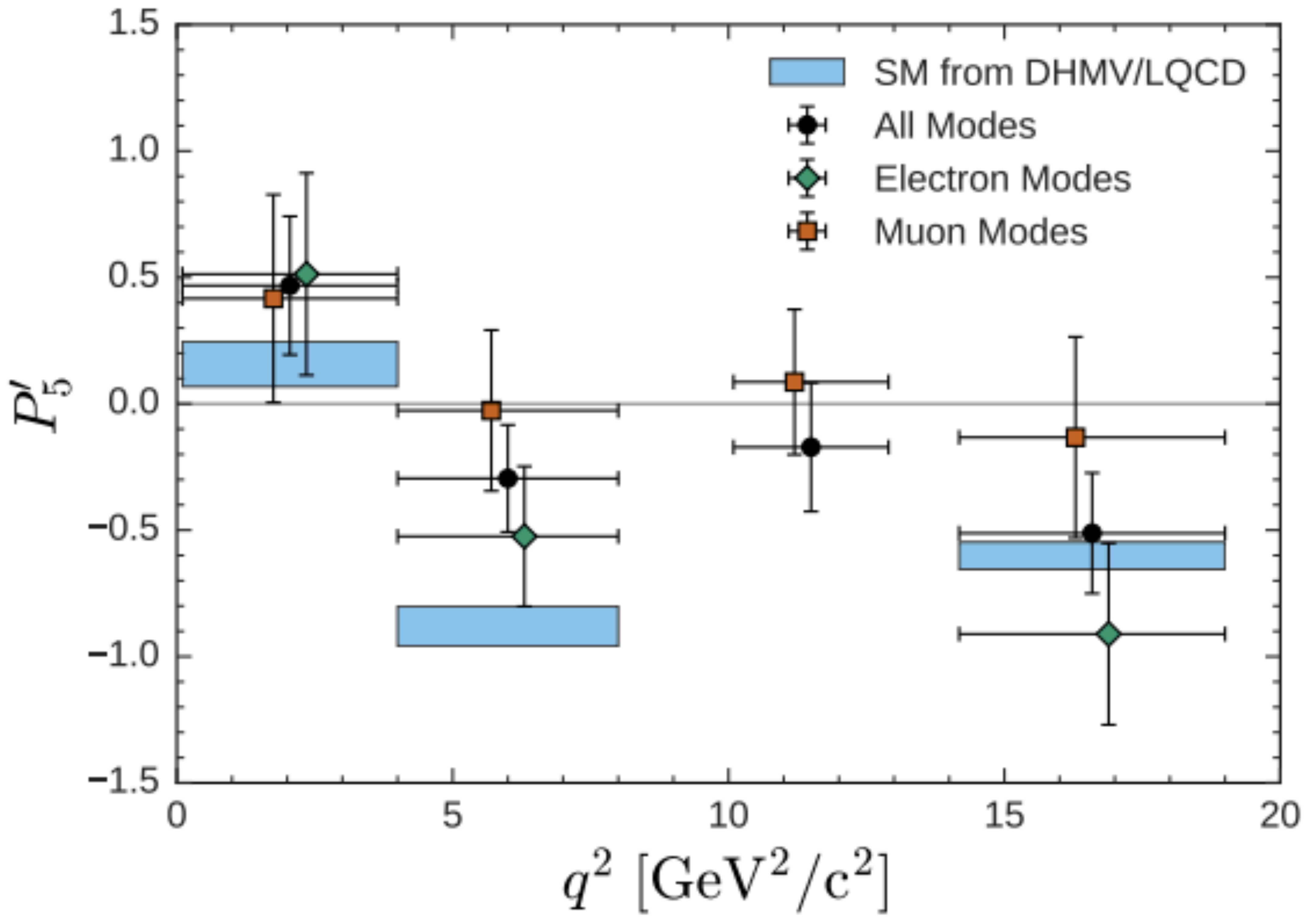


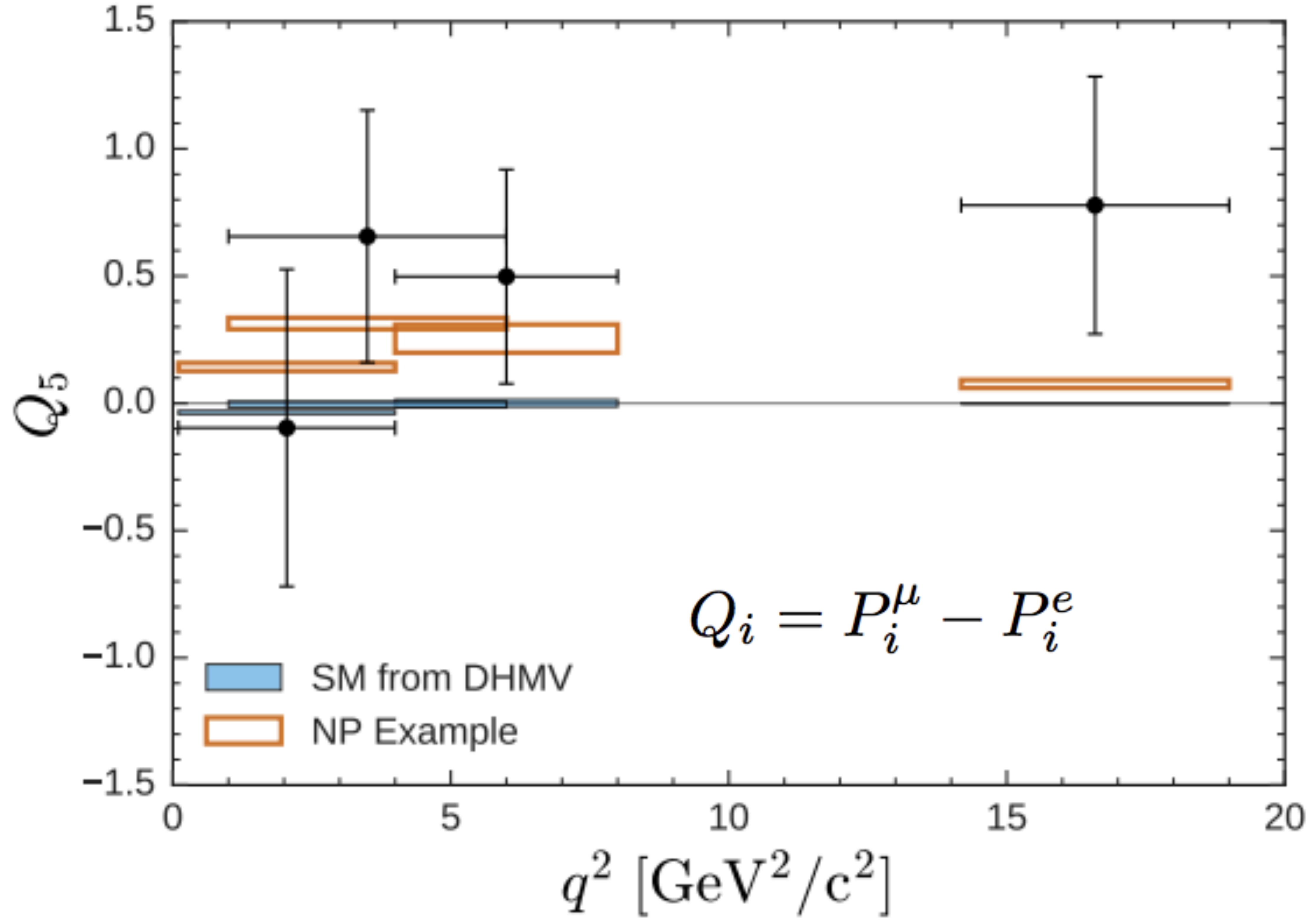
[LHCb-PAPER-2015-051, ATLAS-CONF-2017-023, CMS-PAS-BPH-15-008, Belle (PRL 118 (2017) no.11, 111801)]

New results from Belle on LFU

$B \to K^* \mu^+ \mu^-$ and $B \to K^* e^+ e^-$

[Belle, PRL 118 (2017) 111801]





Q_i != 0 would be indication of new physics.

Will likely hear more about these observables in the future (see later).

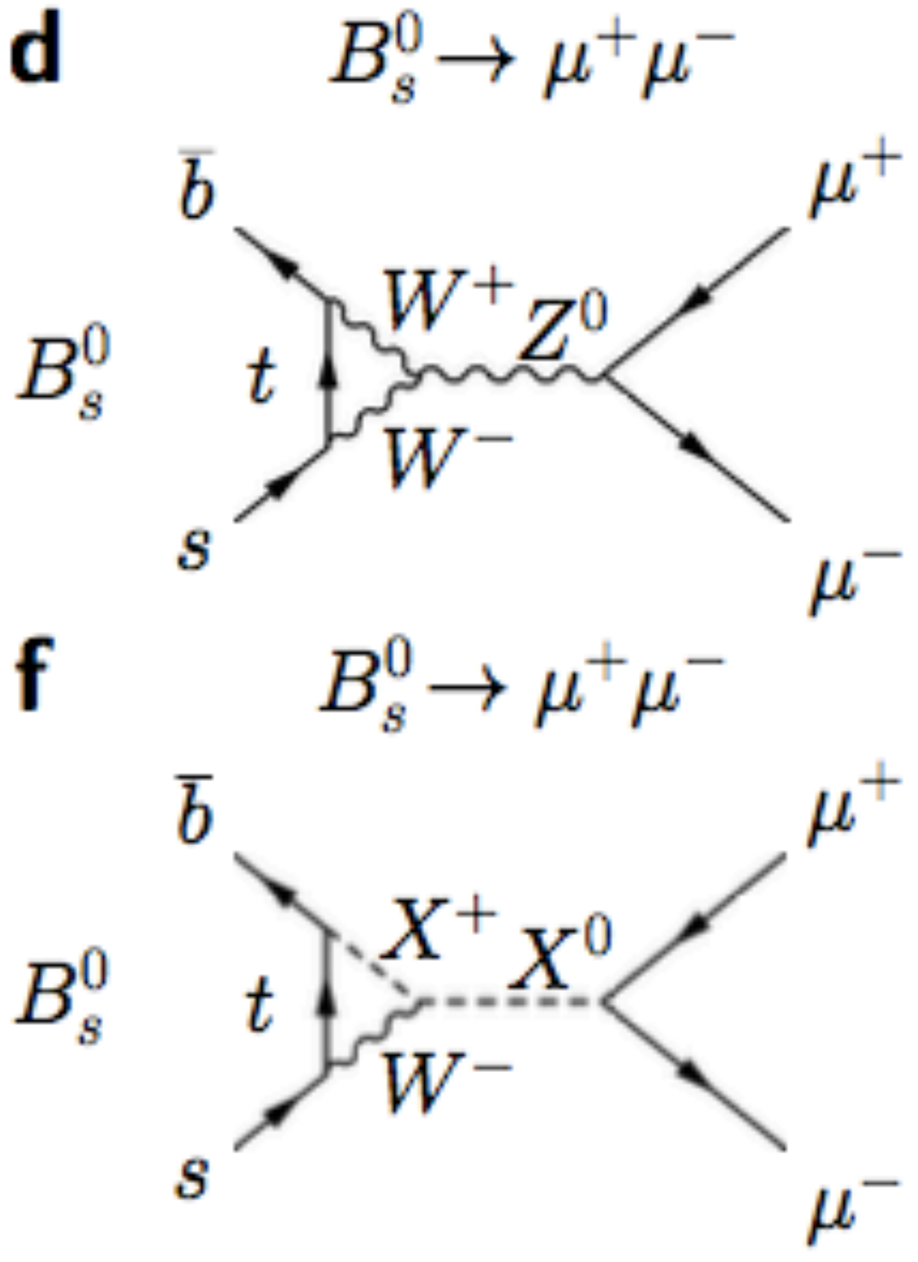
Observation of $B^0_s \to \mu^+\mu^-$

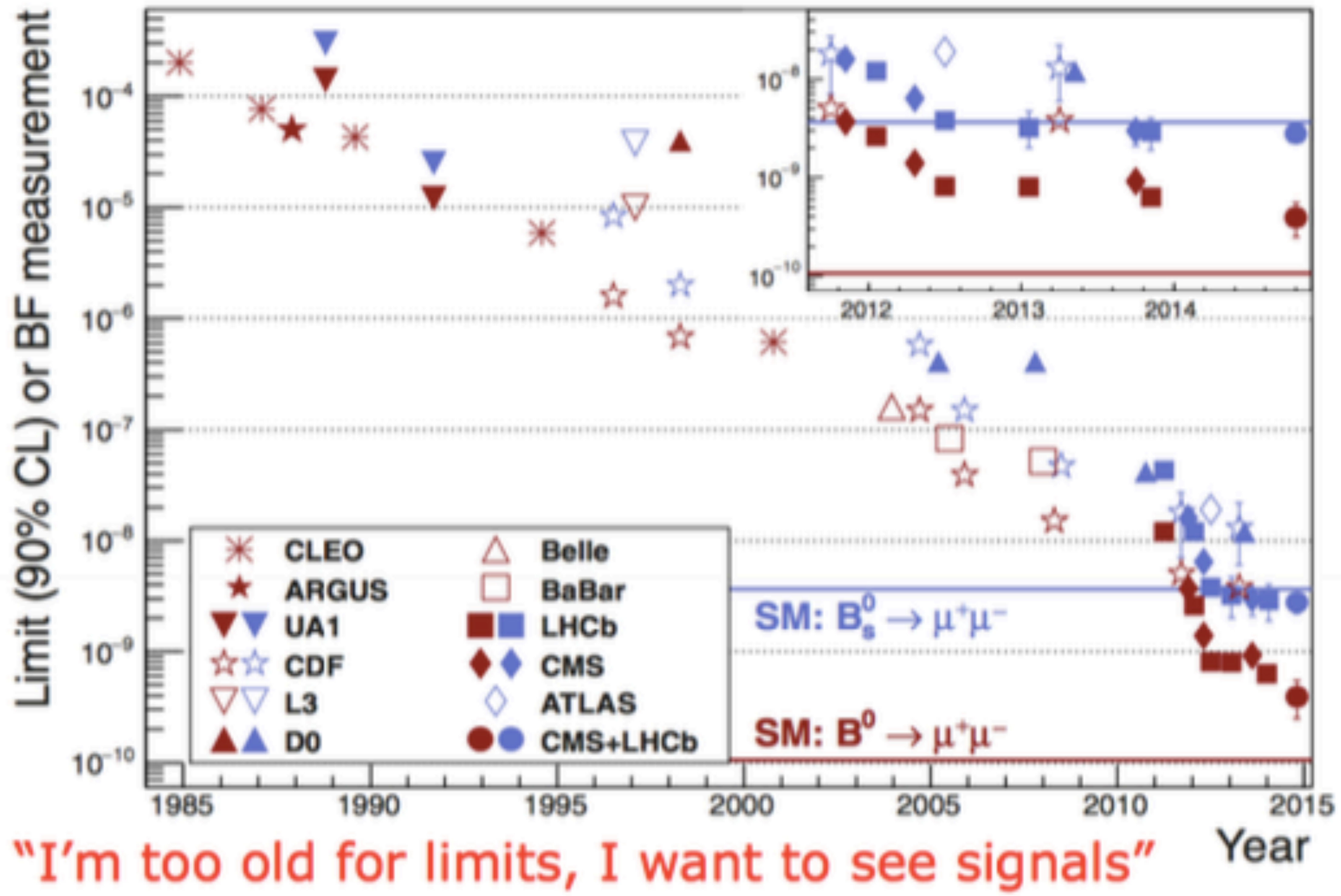
- CKM, loop and helicity suppressed ($(m_\mu/m_B)^2$).
  - $\mathcal{B}(B^0_s \to \mu\mu)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu\mu)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$
  - [PRL 112, 101801 (2014)]

$$\mathcal{B}(B_q \to \ell^+\ell^-)_{SM} = \tau_{B_q} \frac{G_F^2 \alpha_{EM}^2}{16\pi^2} f_{B_q}^2 m_l^2 m_{B_q} \sqrt{1 - \frac{4m_\ell^2}{m_{B_q}^2}} |V_{tb}V_{tq}|^2 |C_{10}^{SM}|^2$$

30 years of effort!

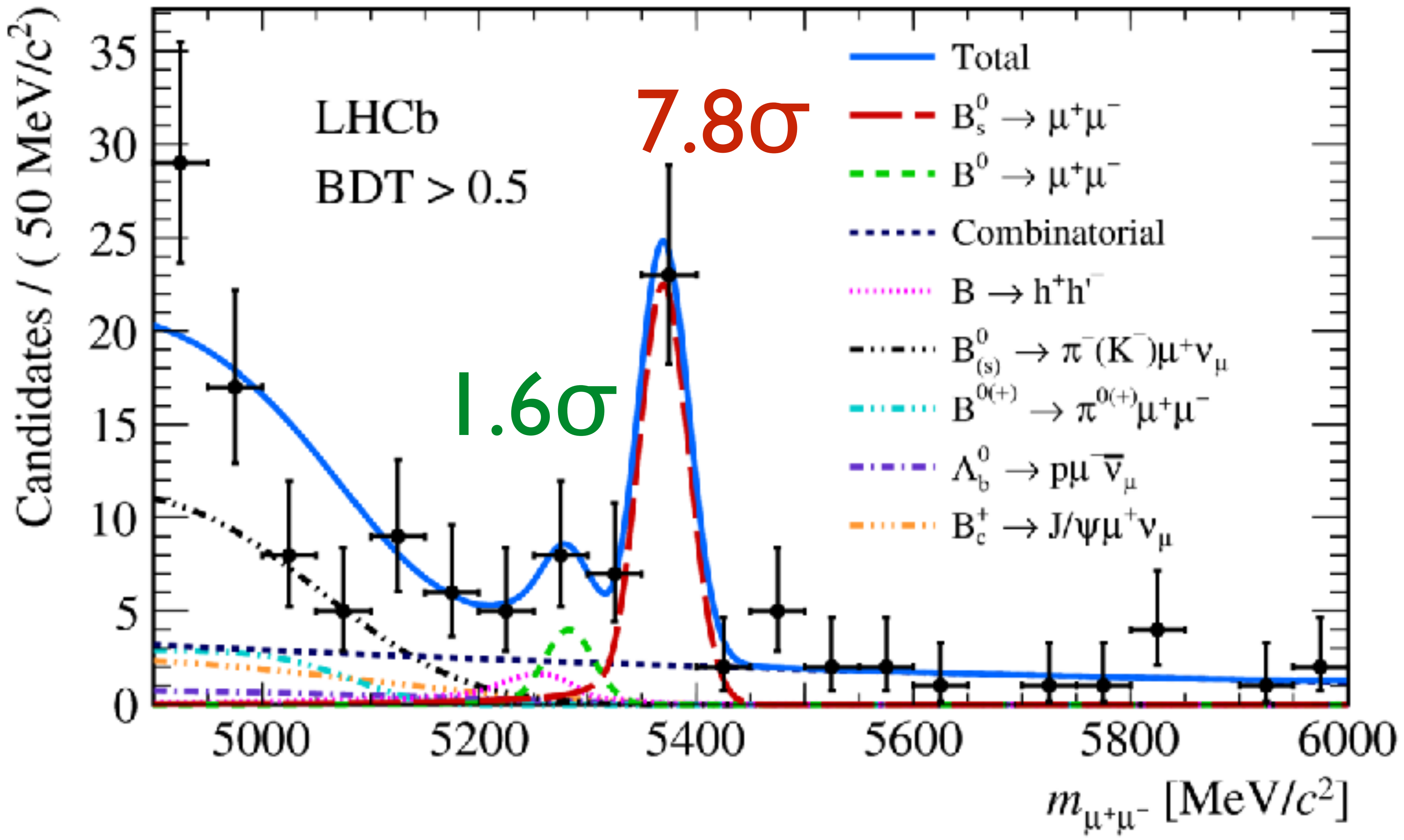
- Sensitive to scalar and pseudoscalar NP couplings, e.g., in MSSM $\mathcal{B} \propto (\tan\beta)^6$

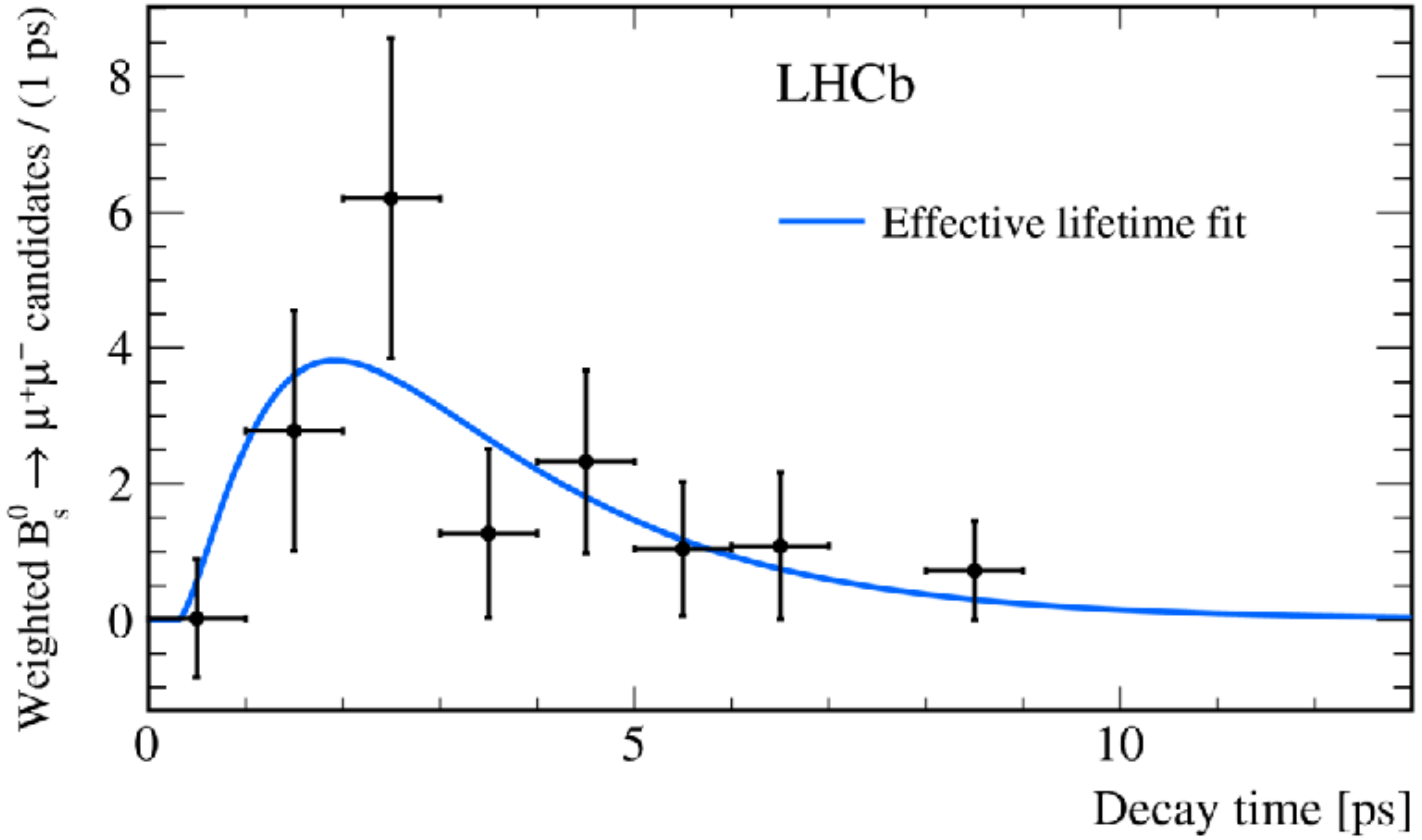


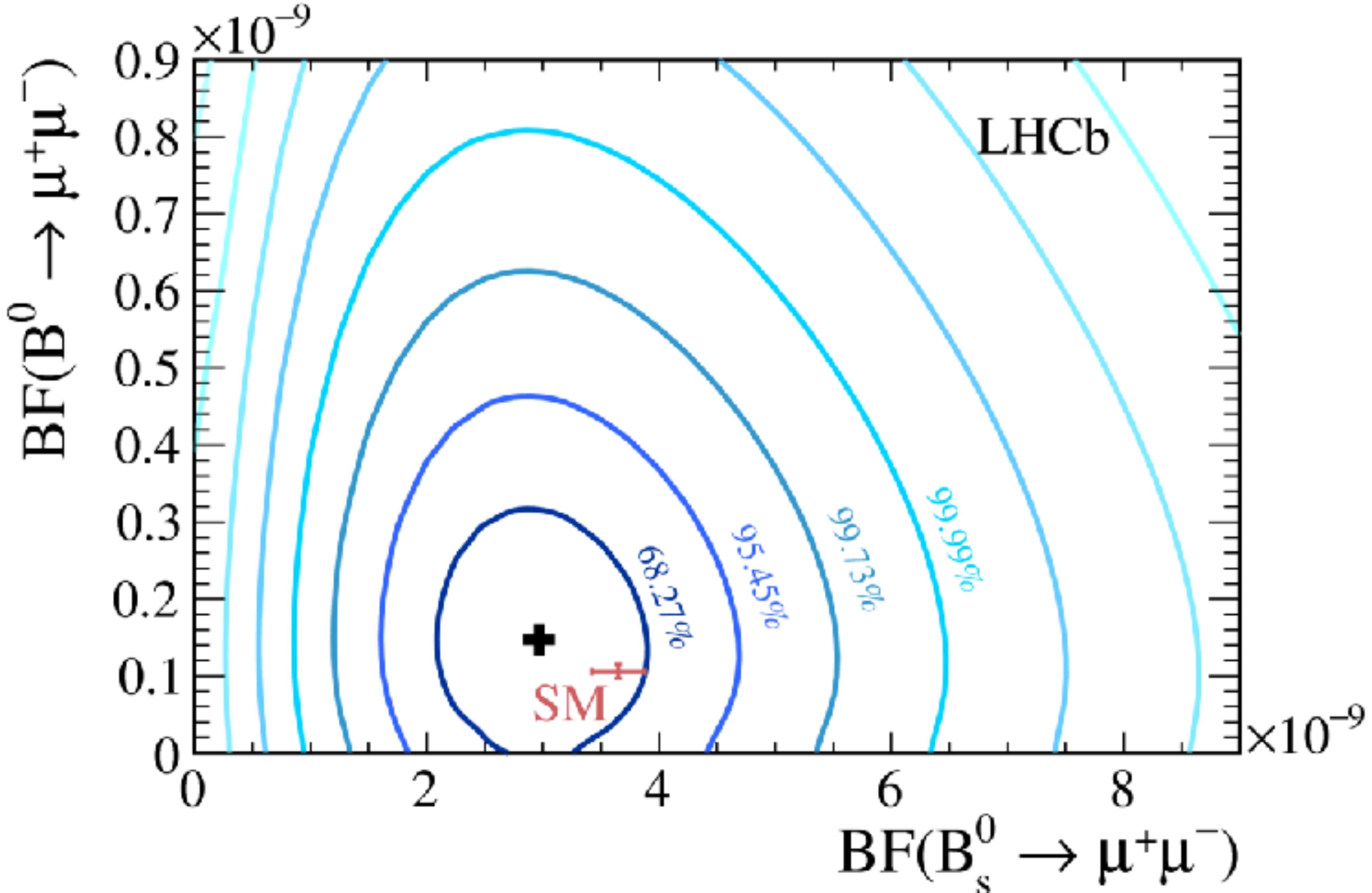


"I'm too old for limits, I want to see signals"
Francis Halzen (EPS '15)

$B^0_s \to \mu^+\mu^-$ using Run 1+2







[PRL 118, 191801 (2017)]

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.0 \pm 0.6\,^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

$$\tau(B^0_s \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05\,\mathrm{ps}$$

[ATLAS EPJC 76 (2016) 513]
[CMS+LHCb Nature 522, 68-72 (2015)]

Anomalies in b→s transitions

Observable	Experiment	Standard Model	Pull (σ)
$\langle P_5' \rangle_{[4,6]}$	-0.30 ± 0.16	-0.82 ± 0.08	-2.9
$\langle P_5' \rangle_{[6,8]}$	-0.51 ± 0.12	-0.94 ± 0.08	-2.9
$R_K^{[1,6]}$	$0.745^{+0.097}_{-0.082}$	1.00 ± 0.01	$+2.6$
$R_{K*}^{[0.045,1.1]}$	$0.66^{+0.113}_{-0.074}$	0.92 ± 0.02	$+2.3$
$R_{K*}^{[1.1,6]}$	$0.685^{+0.122}_{-0.083}$	1.00 ± 0.01	$+2.6$
$\mathcal{B}^{[2,5]}_{B_s \to \phi \mu^+ \mu^-}$	0.77 ± 0.14	1.55 ± 0.33	$+2.2$
$\mathcal{B}^{[5,8]}_{B_s \to \phi \mu^+ \mu^-}$	0.96 ± 0.15	1.88 ± 0.39	$+2.2$

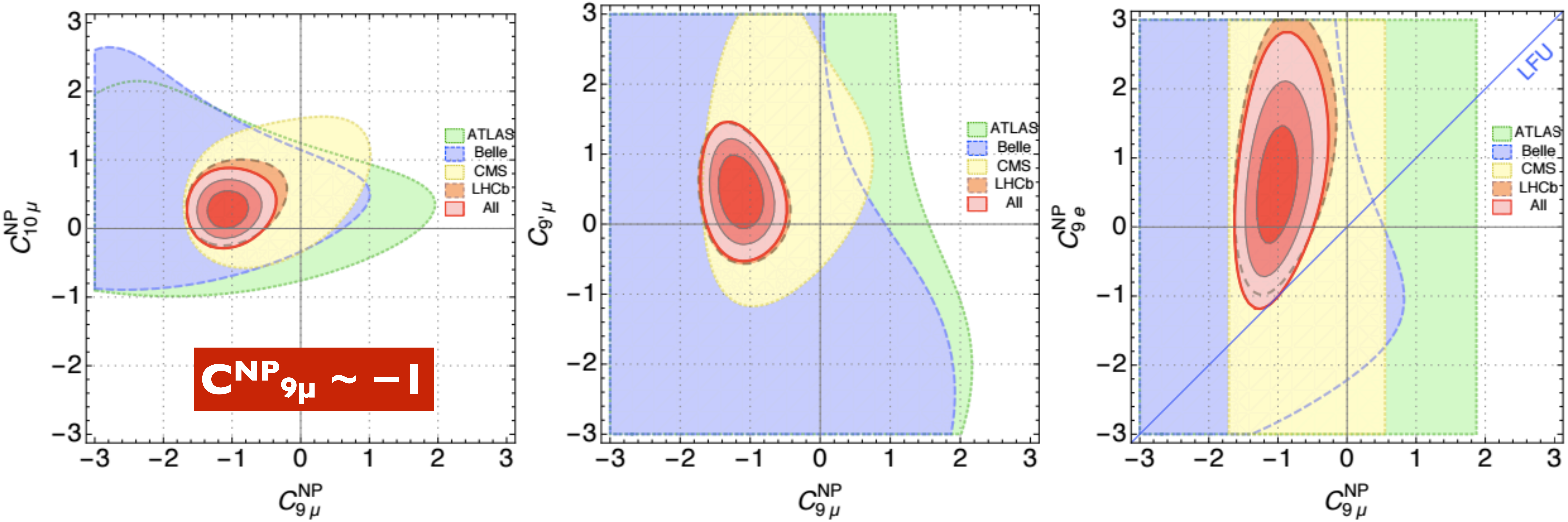
[J.Virto, Instant workshop @ CERN]

Most prominent out of ~170 observables

Are these just statistical fluctuations? If not, do they make sense and what can we learn?

A smörgåsbord of global fits

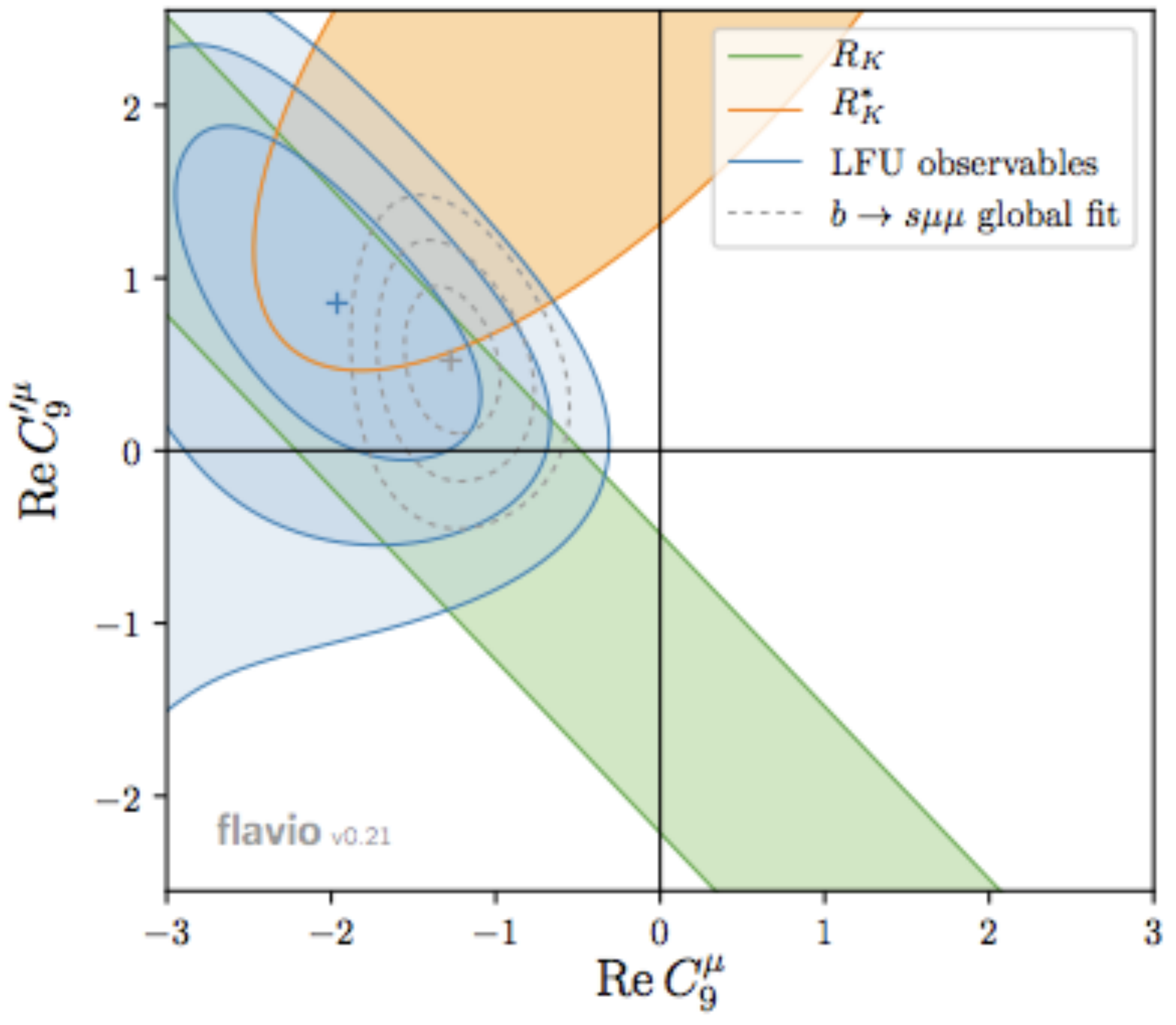
[Capdevilla et al., arXiv:1704.05340]

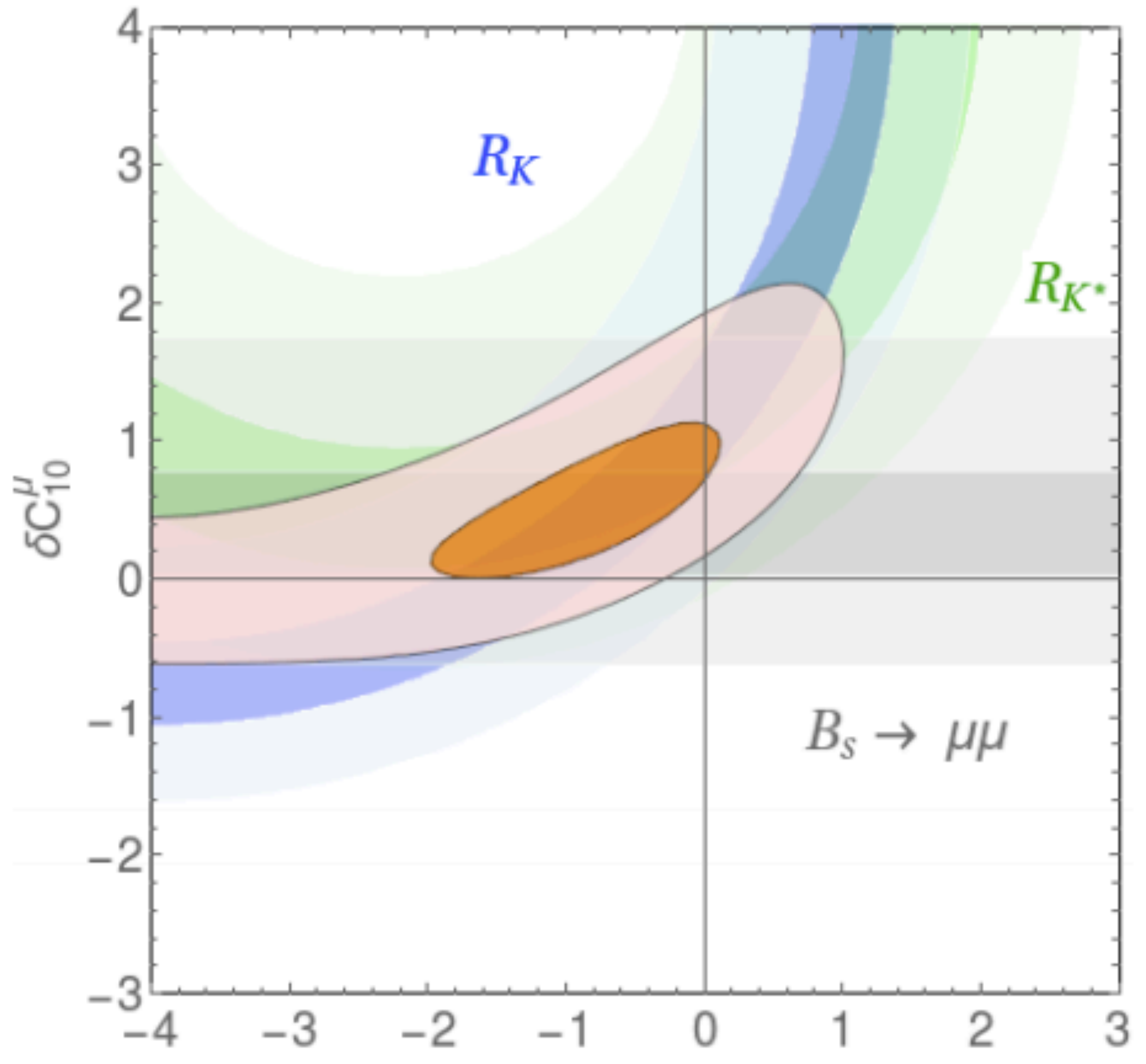


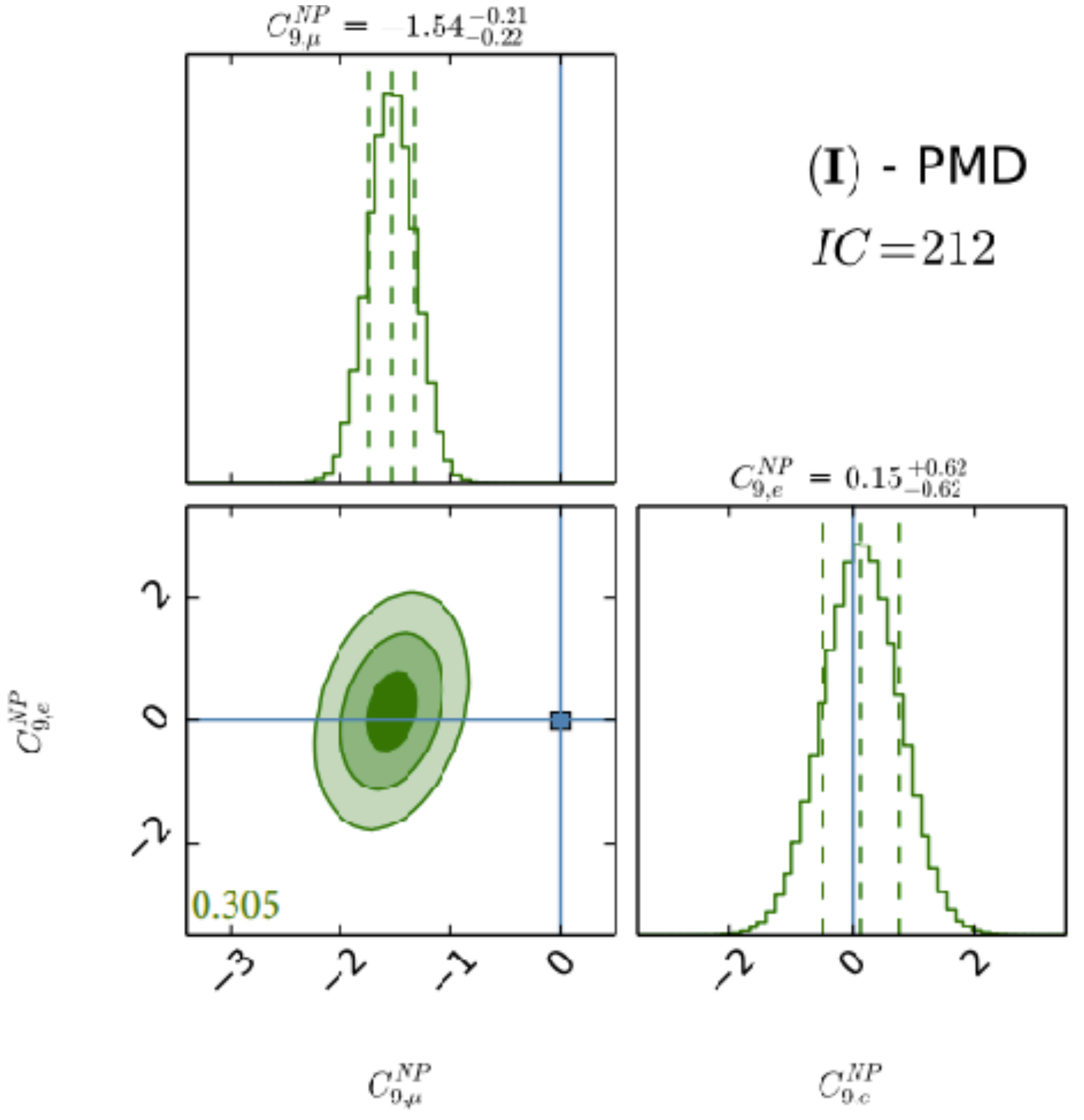
NP in $C^{NP}_{9\mu}$ **only** OR
$\mathbf{C^{NP}_{9\mu} = -C^{NP}_{10\mu}}$ OR
$\mathbf{C^{NP}_{9\mu} = -C^{NP\prime}_{9\mu}}$

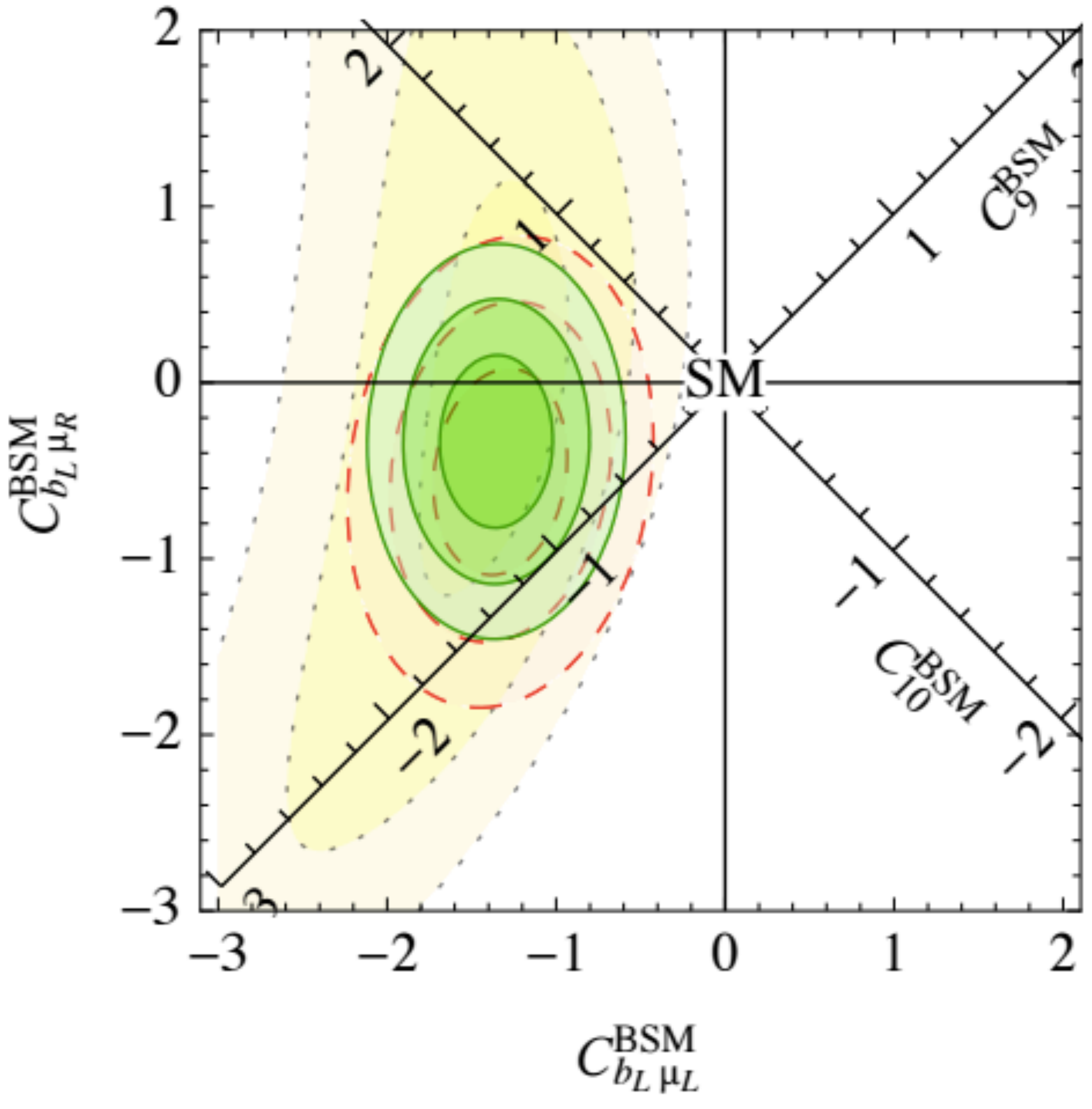
	All		
2D Hyp.	Best fit	Pull_{SM}	p-value
$(\mathcal{C}^{NP}_{9\mu}, \mathcal{C}^{NP}_{10\mu})$	(-1.17,0.15)	5.5	74
$(\mathcal{C}^{NP}_{9\mu}, \mathcal{C}'_{7})$	(-1.05,0.02)	5.5	73
$(\mathcal{C}^{NP}_{9\mu}, \mathcal{C}_{9'\mu})$	(-1.09,0.45)	5.6	75
$(\mathcal{C}^{NP}_{9\mu}, \mathcal{C}_{10'\mu})$	(-1.10,-0.19)	5.6	76
$(\mathcal{C}^{NP}_{9\mu}, \mathcal{C}^{NP}_{9e})$	(-0.97,0.50)	5.4	72

A smörgåsbord of global fits









Different fitting groups exist, using different assumptions (e.g., form-factor parameterisations)

Pattern is the same: better fits obtained with new contributions to C_9 and/or C_{10}, mainly for muons.

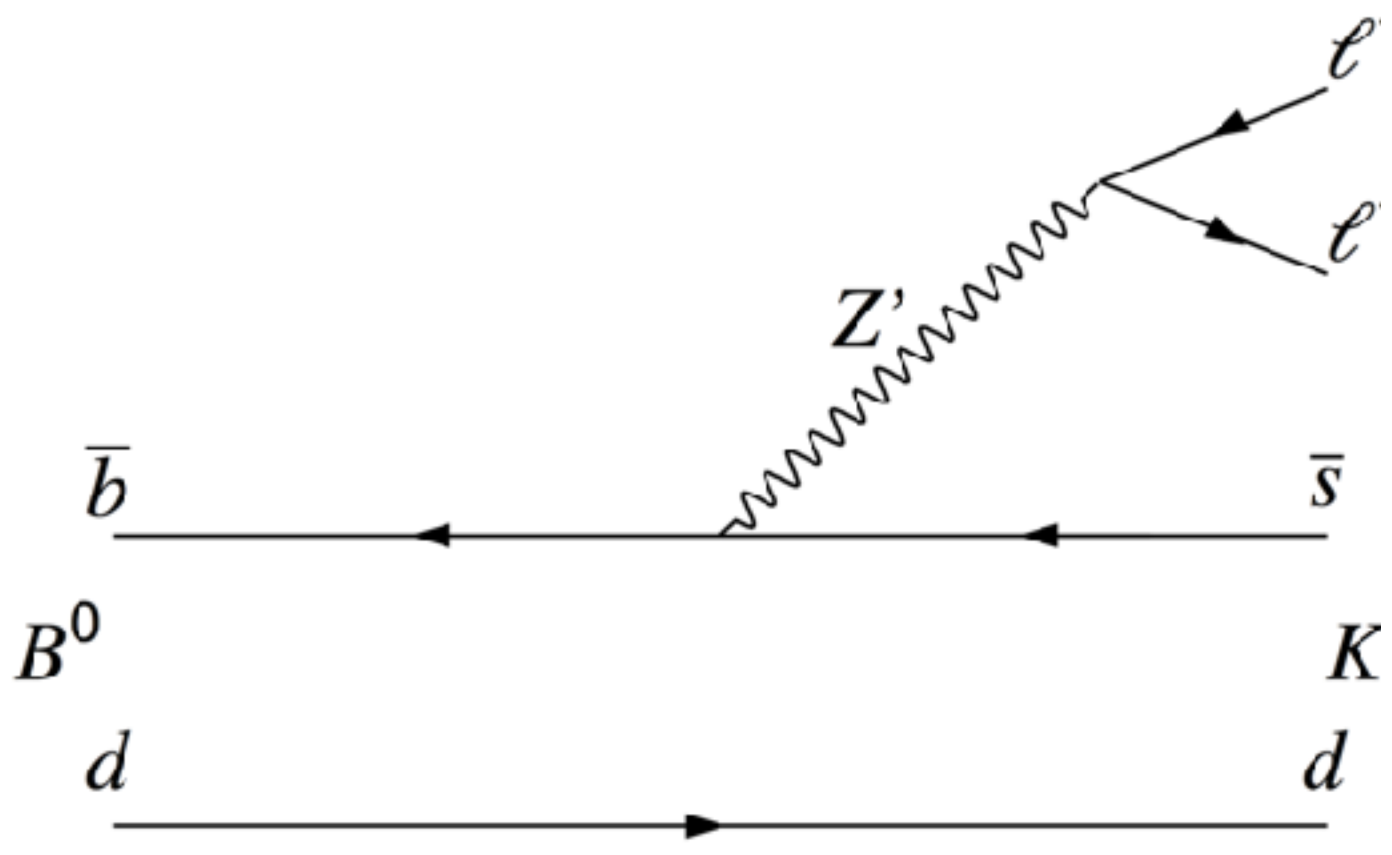
[Altmannshofer et al., arXiv:1704.05435]
[Ciuchini et al., arXiv:1704.05447]
[Geng et al., arXiv:1704.05446]
[…]

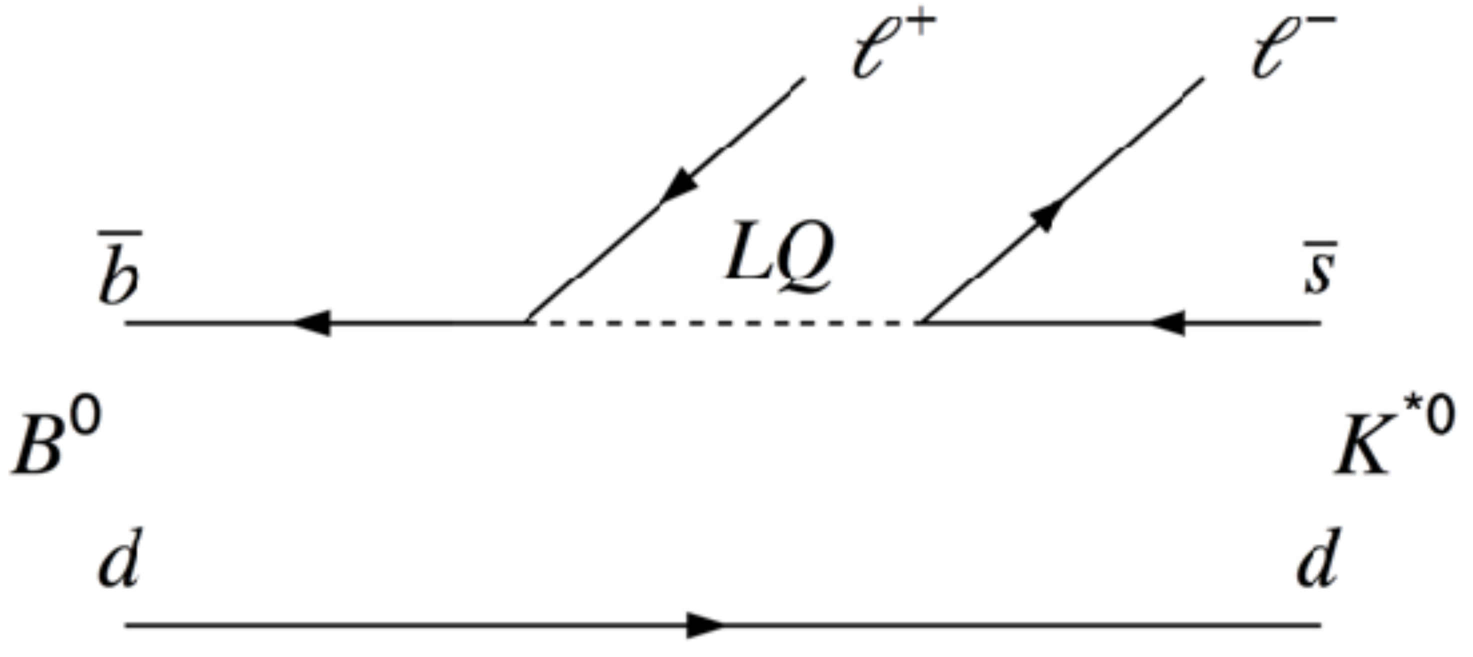
New physics interpretations

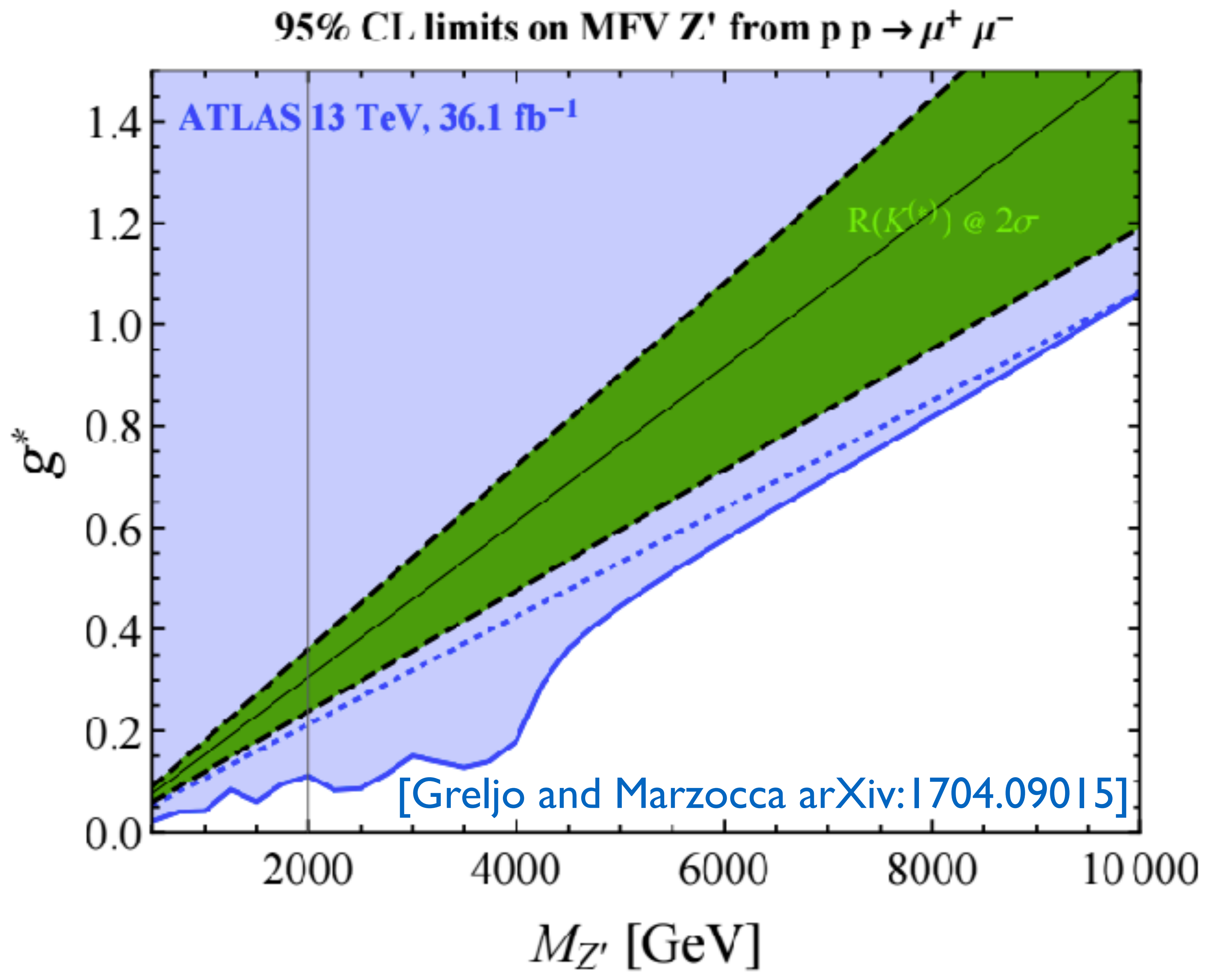
Instant workshop on B meson anomalies
https://indico.cern.ch/event/633880/

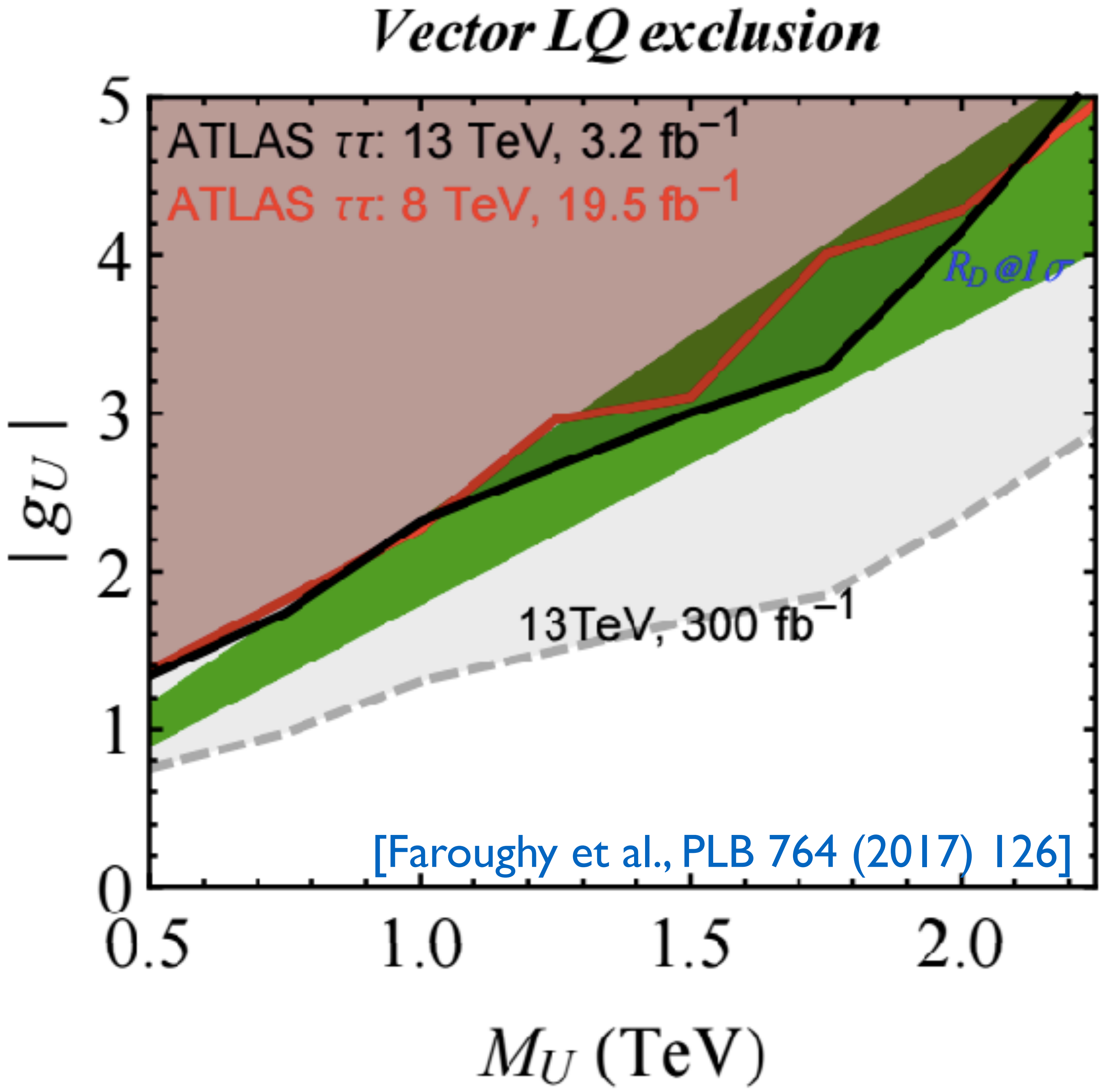
Z' and lepto-quarks lead the way

[Buttazzo et al., JHEP 1608 (2016) 035], [Bauer et al., PRL 116 (2016) 141802],
[Crivellin et al., PRL 114 (2015) 151801], [Altmannshofer et al., PRD 89 (2014) 095033]
[Diptomoy et al., PRD 89 (2014) 071501], [Descotes-Genon et al., PRD 88 (2013) 074002]…









Limits from direct searches providing complementary information to b meson decays.

But may be able to escape bounds with more elaborate models or fine tuning [Crivellin et al., arXiv:1703.09226]

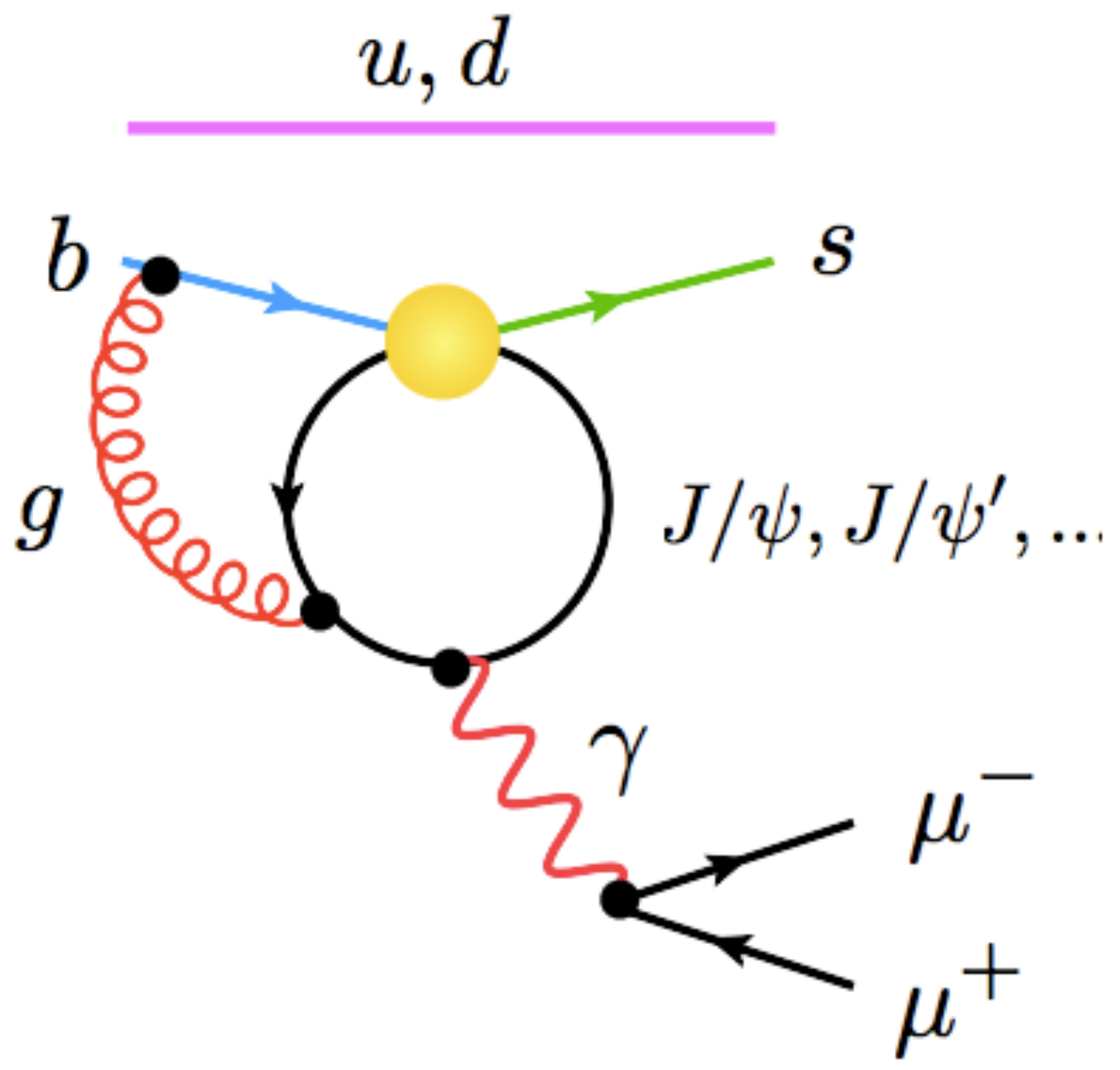
Or is it QCD?

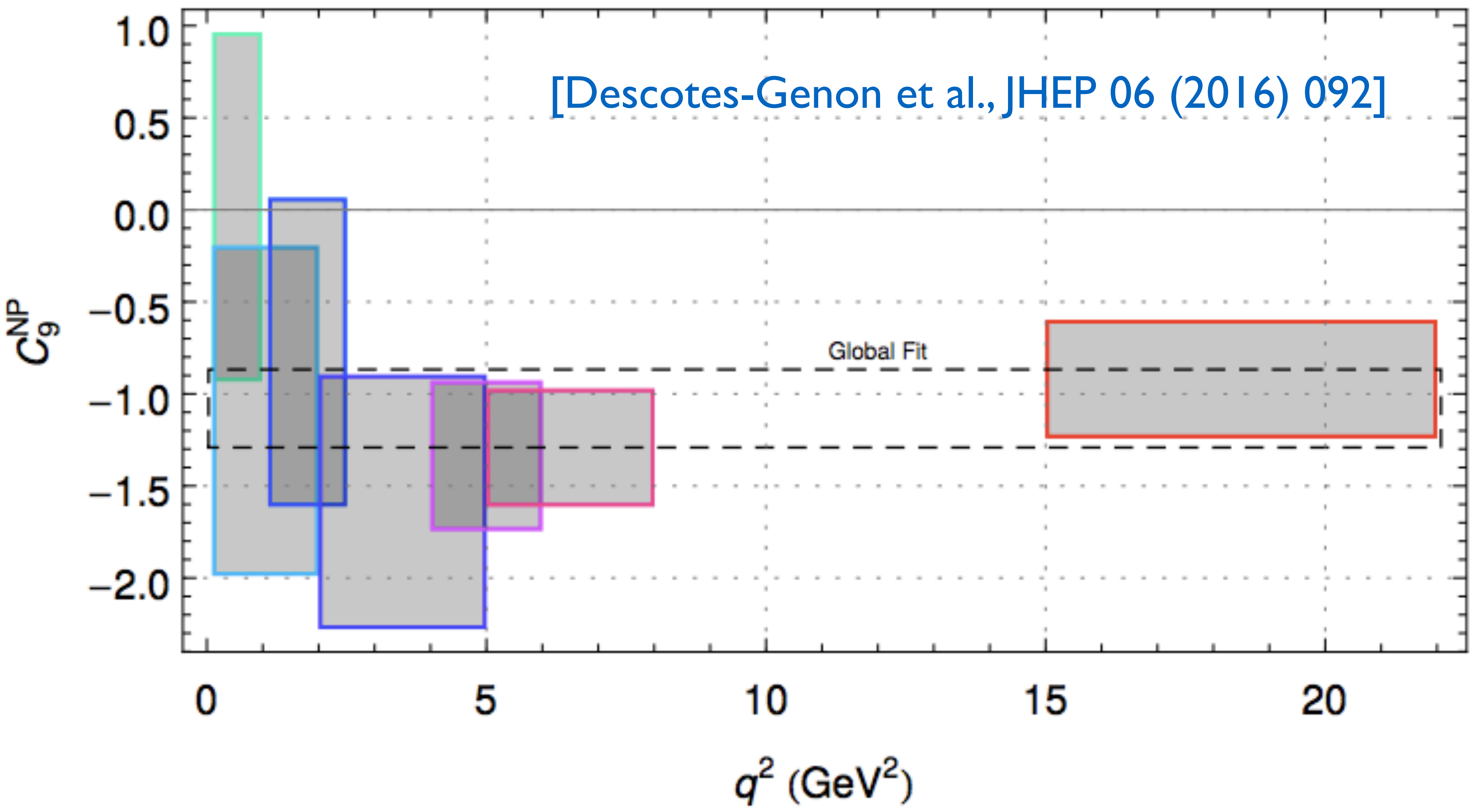
Potential problem with our understanding of contributions from B → $[c\bar{c}](\to\mu^+\mu^-)$ K

[Lyon and Zwicky, arXiv:1406.0566],[Altmannshofer and Straub arXiv:1503.06199], [Ciuchini et al., arXiv:1512.07157], but:

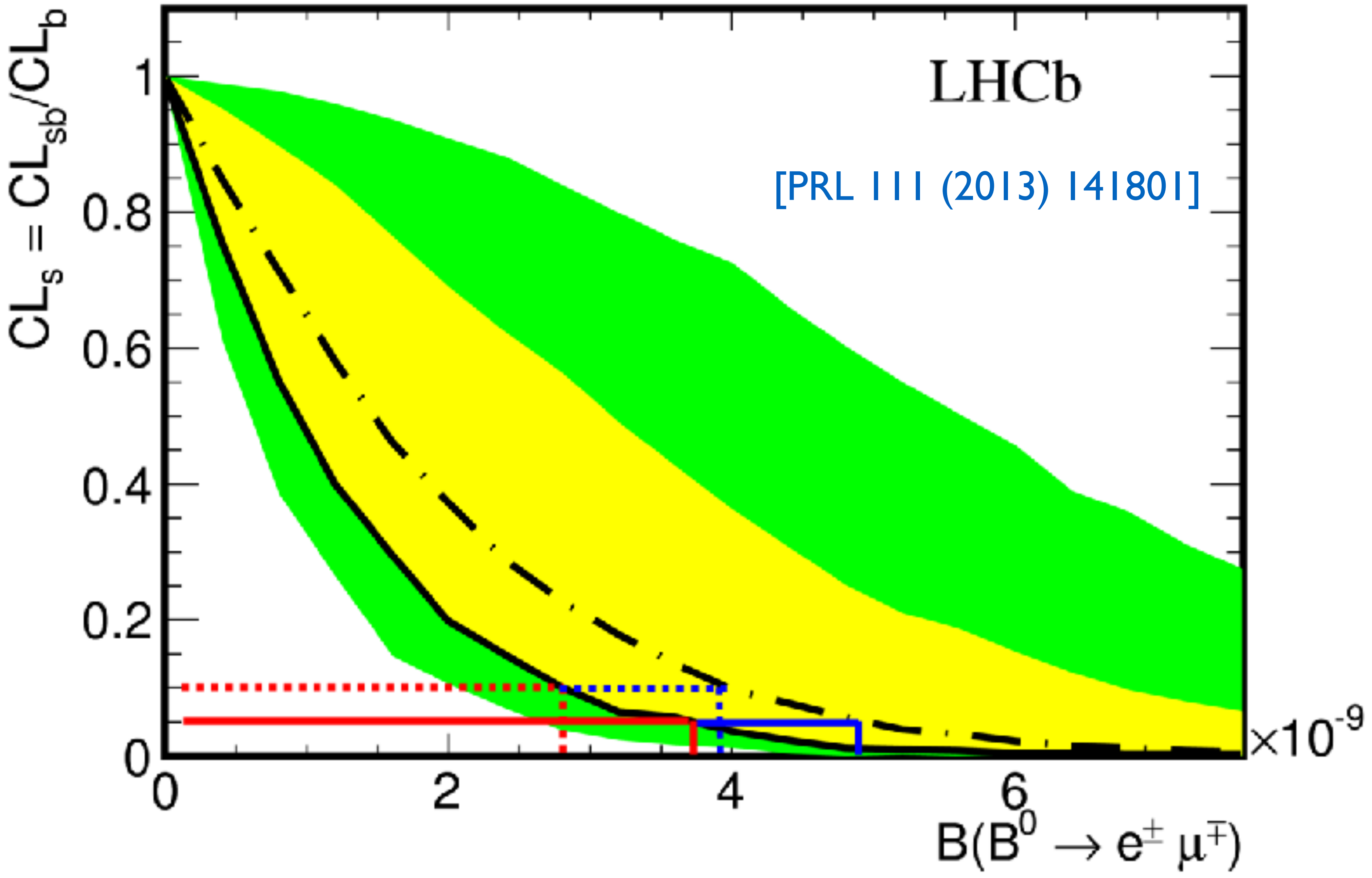
1. LHCb measurements of these effects in $B^+\to K^+\mu^+\mu^-$ indicate this is not the explanation
   [EPJC (2017) 77:161]

2. Global fits in bins of q^2 indicate no dependence



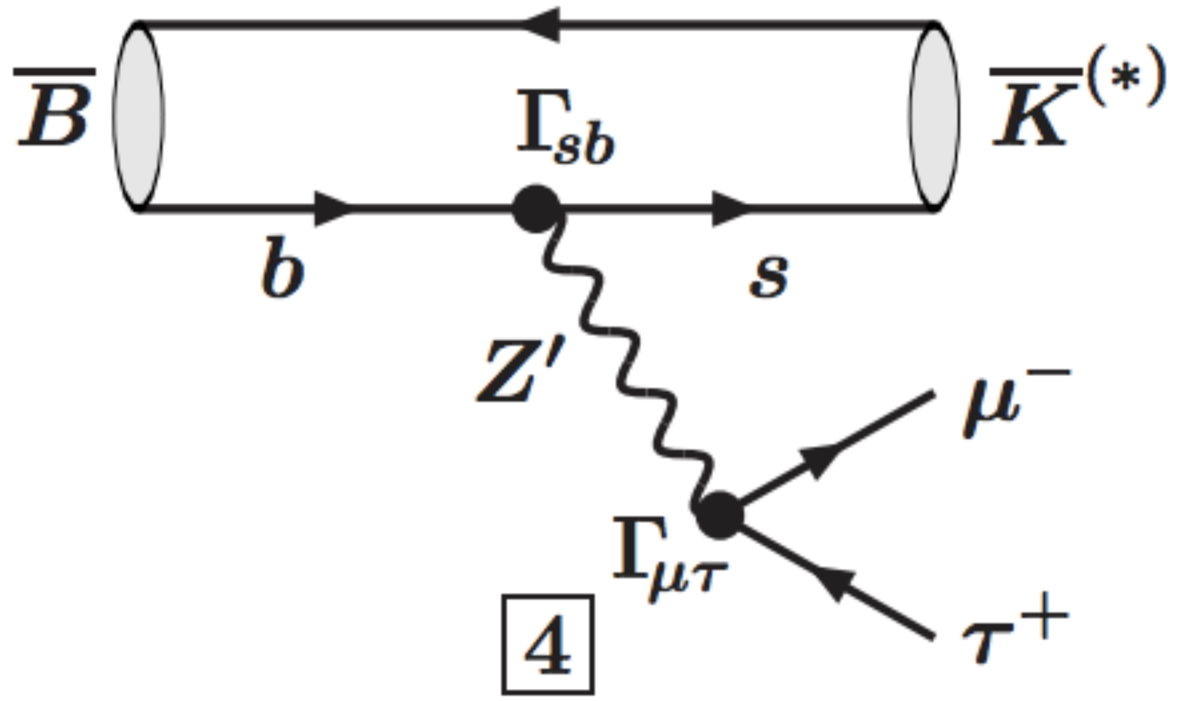


Lepton-flavour violation



$B(B^0 \to e\mu) < 2.8 \times 10^{-9}$ @ 90%

Can translate into limits on lepto-quark masses

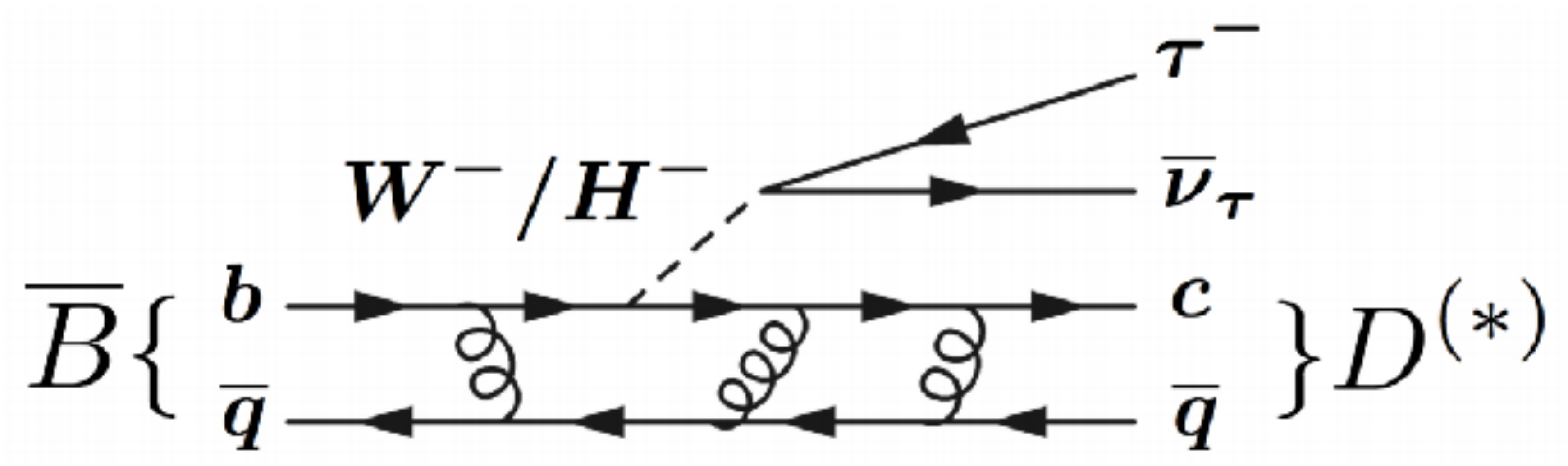


Future: study decays with tau-leptons in the final state since less constrained by existing data [BaBar PRD 86, 012004 (2012)] and often enhanced in NP models.

e.g., $B^+ \to K^+\mu\tau$ predicted to be 10^{-6}

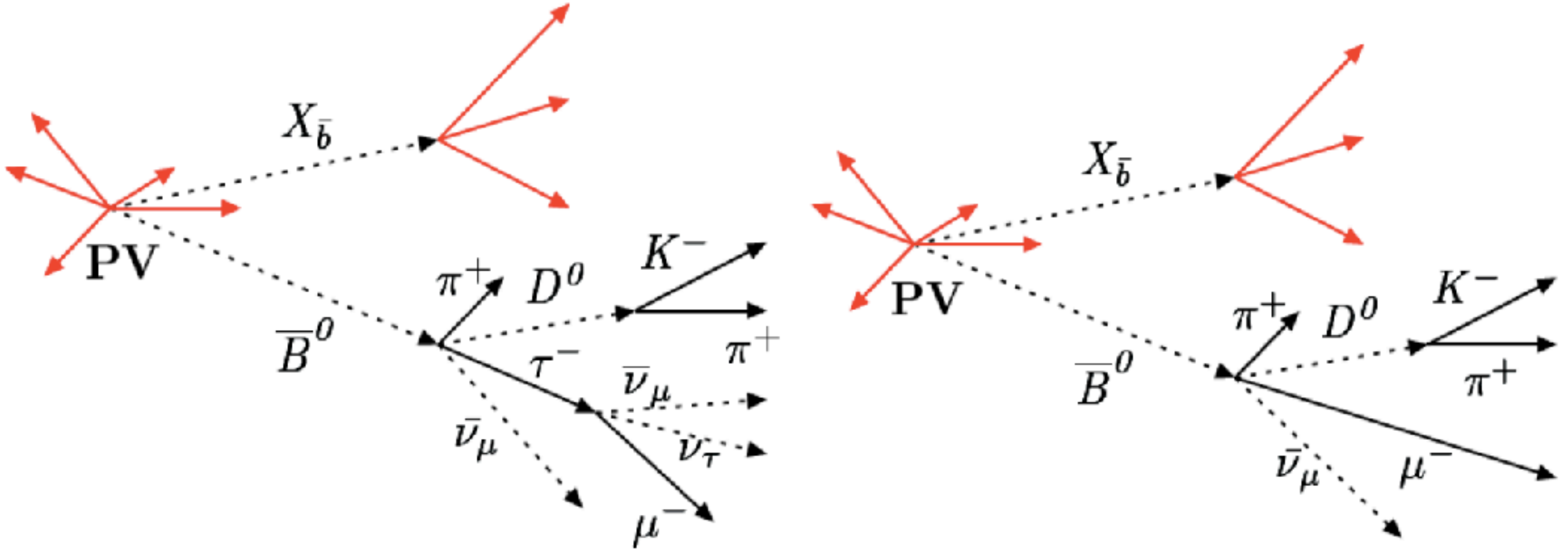
[Glashow et al., Phys. Rev. Lett. 114 (2015) 091801]
[Crivellin et al., Phys. Rev. D 92 (2015) 054013]
[Guadagnoli and Lane PLB 751 (2015) 54]

b → c charged currents



R(D*)

$$R(D^*) \equiv \frac{\mathcal{B}(\overline{B^0} \to D^{*+}\tau\nu_\tau)}{\mathcal{B}(\overline{B^0} \to D^{*+}\mu\nu_\mu)}$$



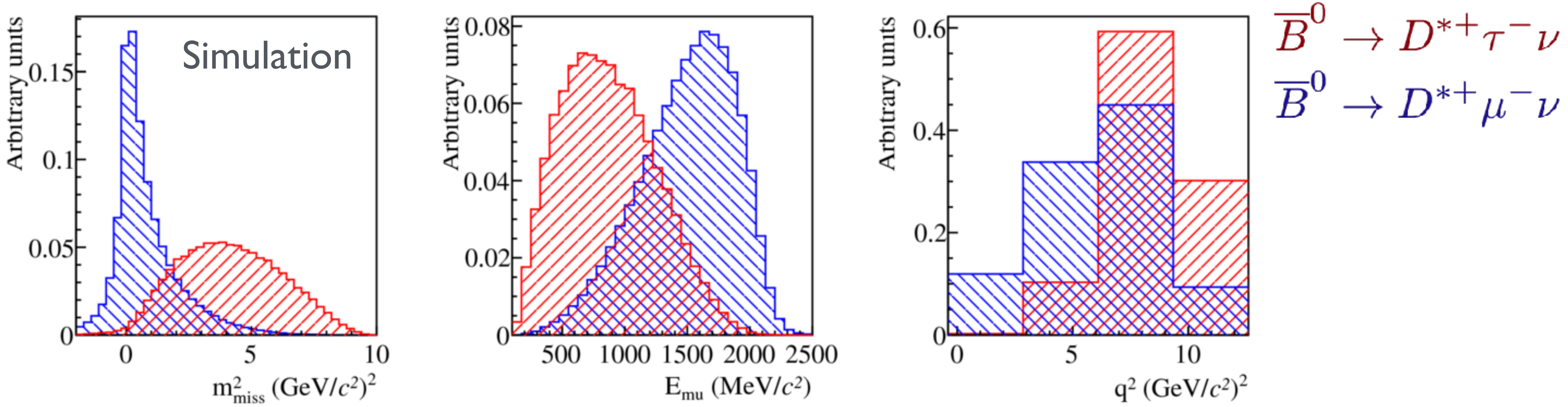
Experimental challenges at LHCb:

Missing neutrino, so no narrow peak to fit

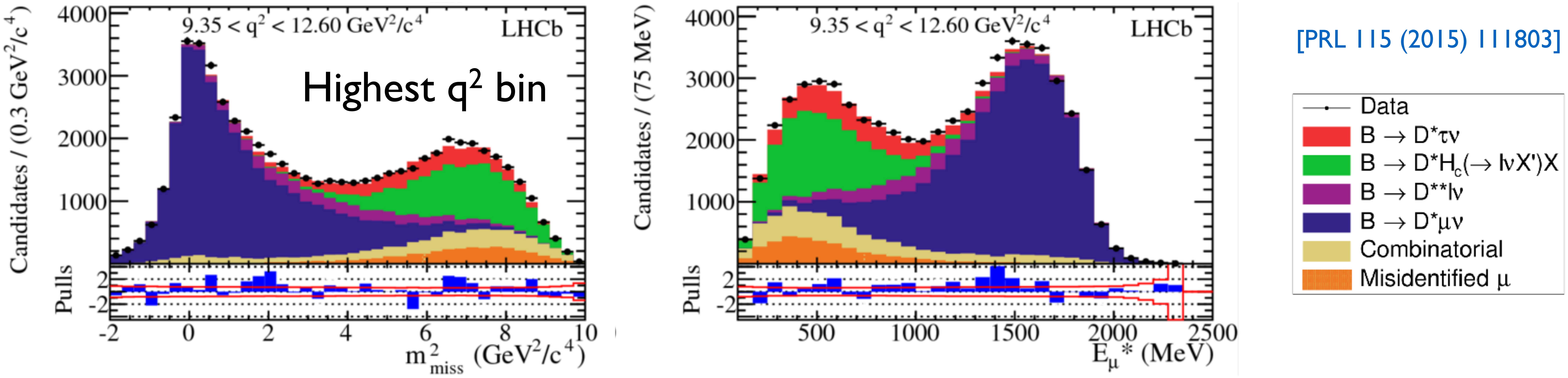
Signal and normalisation mode have identical final state

Background from partially reconstructed decays

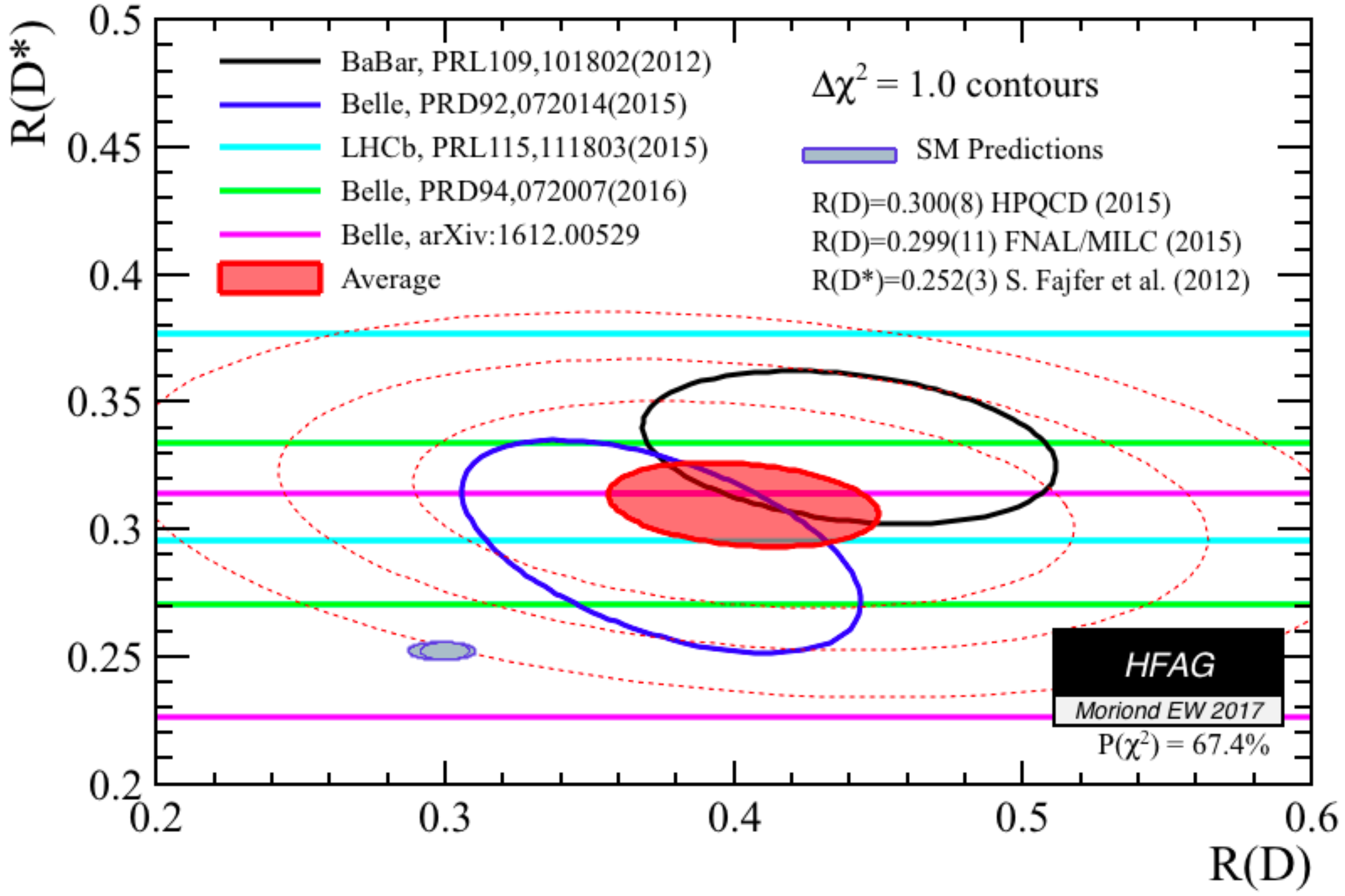
$$\mathcal{B}(\tau \to \mu\nu_\mu\nu_\tau) = (17.41 \pm 0.04)\%$$



R(D*), R(D)



[PRL 115 (2015) 111803]



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

Systematically limited (size of simulation samples for templates)

HFAG global average ~4σ from precise SM prediction

Many other "R" measurements ongoing (D^*, D^0, D^+, D_s, Λ_c, J/Ψ).

Looking to the future

R_K

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Use available Run 2 data (~2.0 fb^{-1}) to update result.

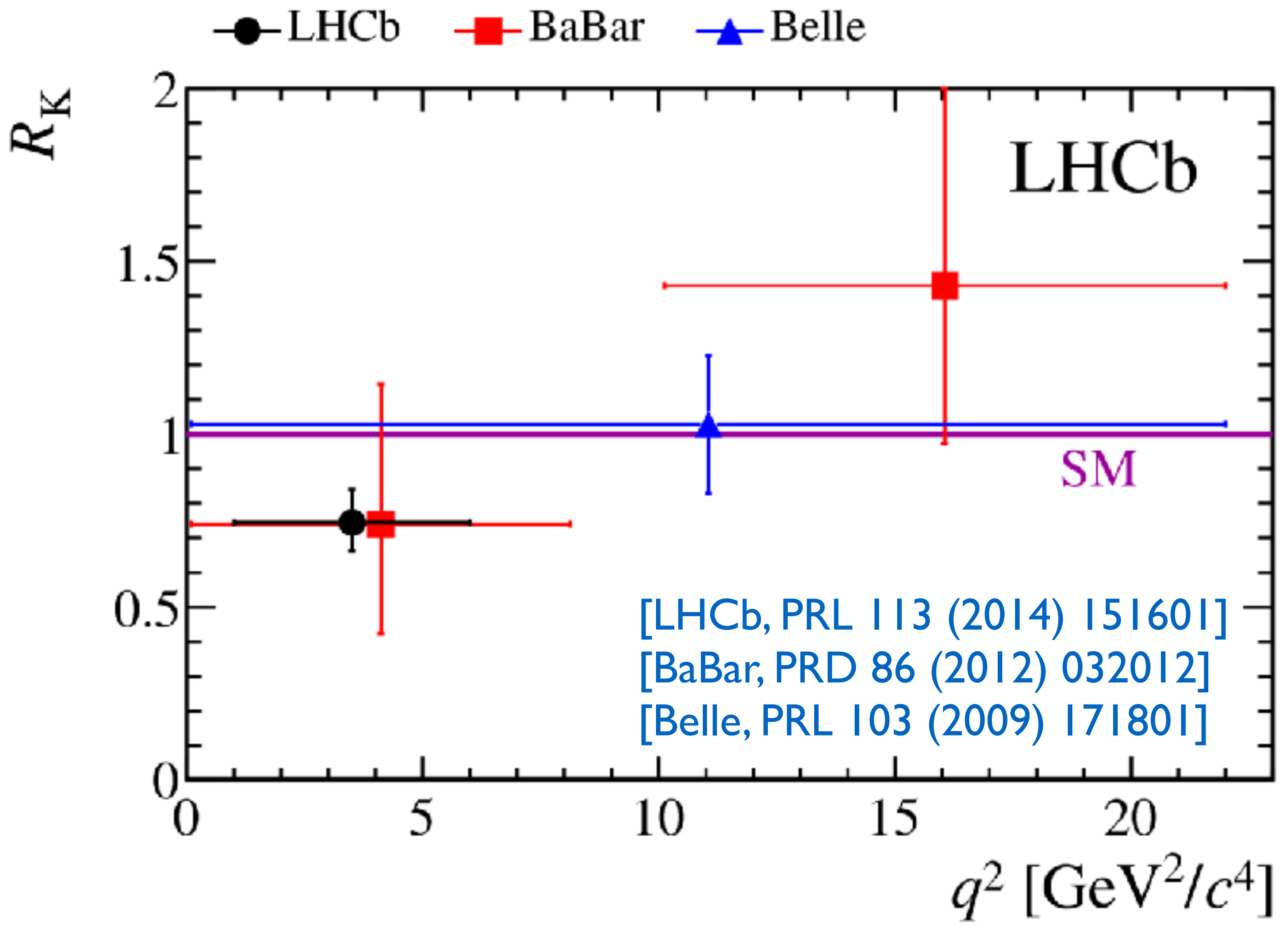
Improvements in offline processing and increased cross-section at 13 TeV.

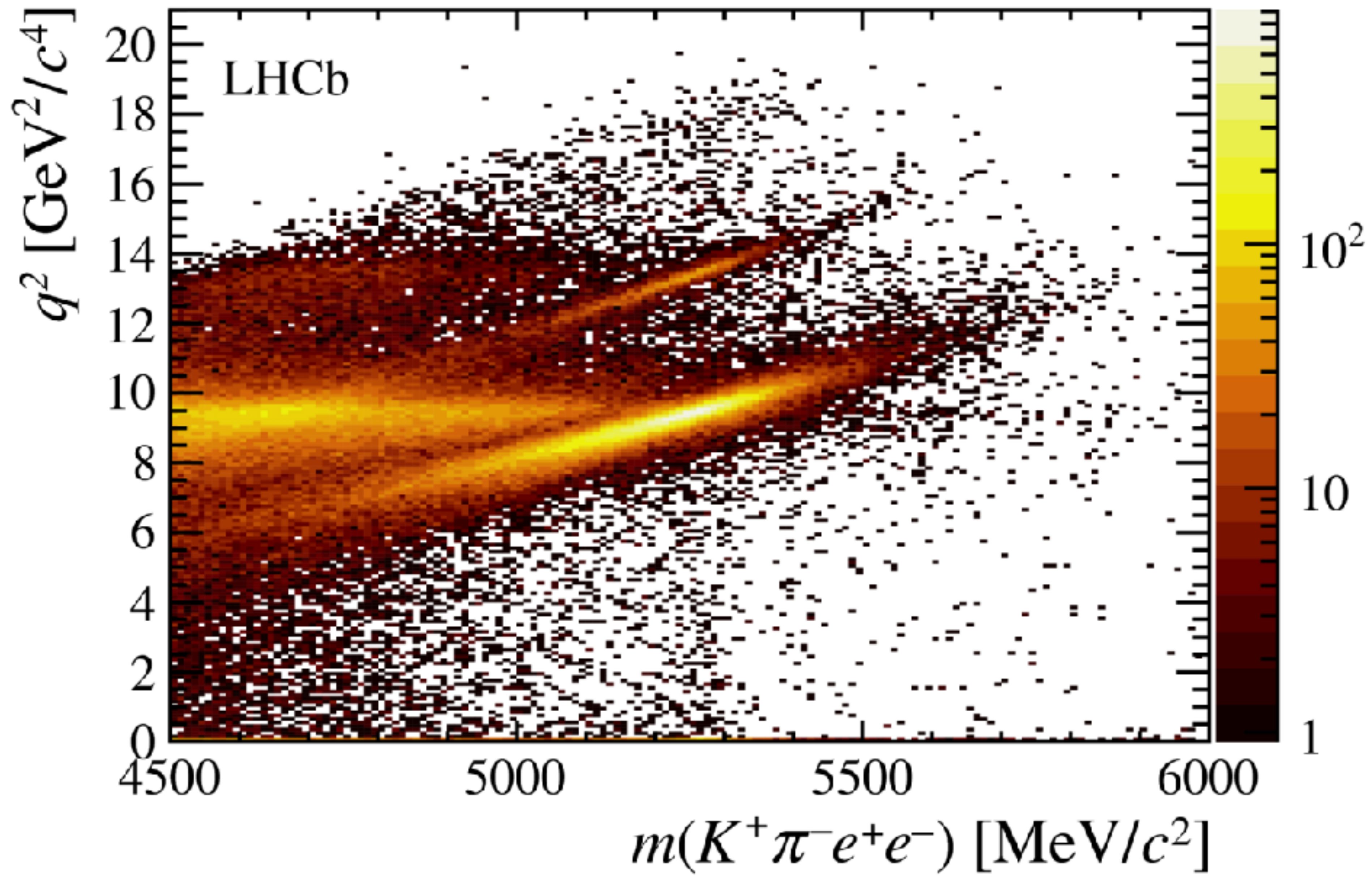
~250 → ~800 $B^+ \to K^+e^+e^-$ candidates.

R_K uncertainty decreases by factor ~1.8.

Systematics should be data-driven.

Add high-q^2 region, but difficult due to part-reco backgrounds from higher K* resonances and ψ(2S) leakage.





R_φ, R_X and other measurements

R_φ is analogous, but using $B_s \to \varphi l^+ l^-$ decays.

$$R_\phi = \frac{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \phi e^+e^-)}$$

Signal suppressed by fs/fd ~ 0.25 and BR($\varphi \to K^+K^-$) = 0.5 but has experimental advantages (narrow φ).

NB: the electron yields will be of the order of 10's of events.

Effort starting on (K,K*,φ)eμ searches; even some effort on μτ and ττ modes.

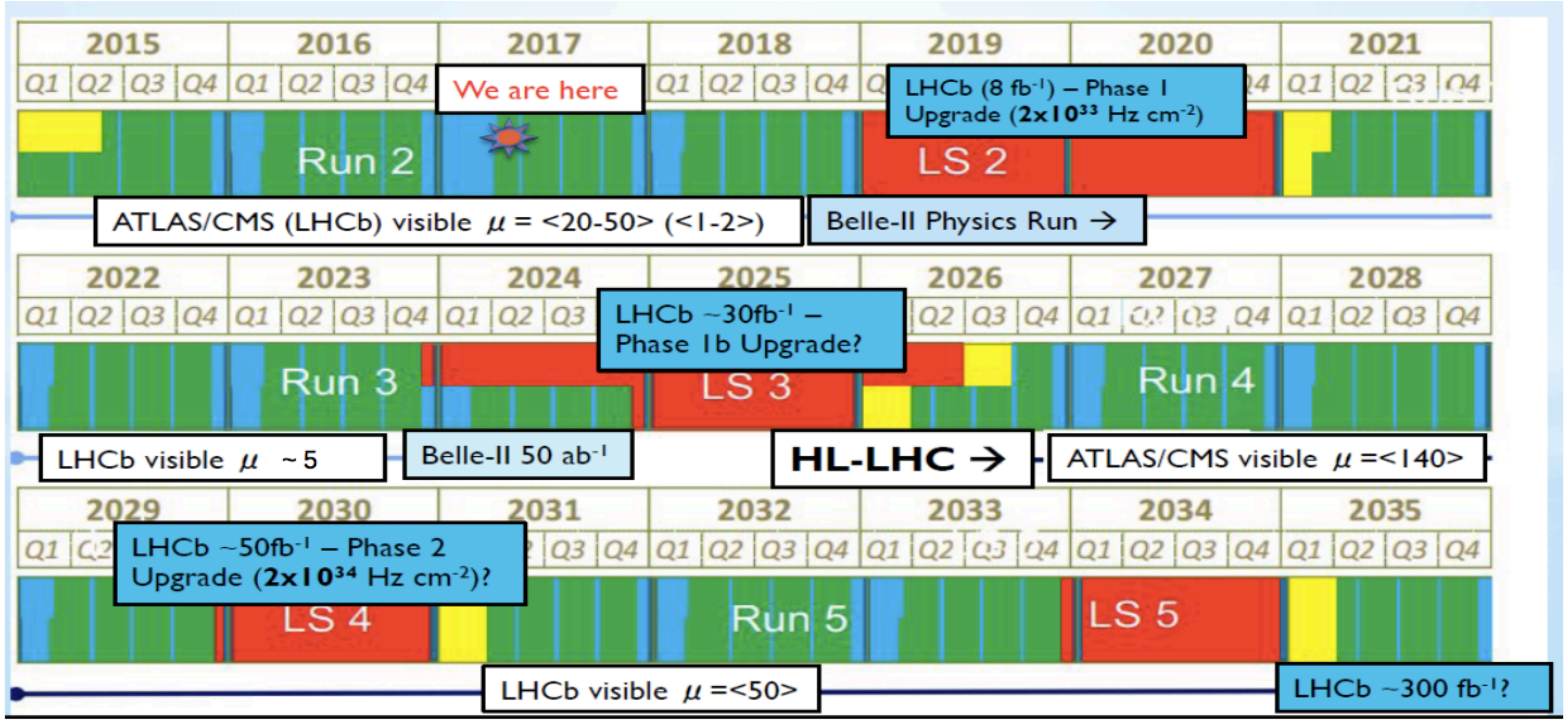
Angular analyses will be important.

[Gratrex, Zwicky PRD 93 (2016) 054008]

Run 1 yields in muon modes

Kμμ ~1200
K*μμ ~600
φμμ ~100
pKμμ ~600
Kππμμ ~360
K^{**}μμ ~230
K_Sμμ ~30
K^{*+}μμ ~40

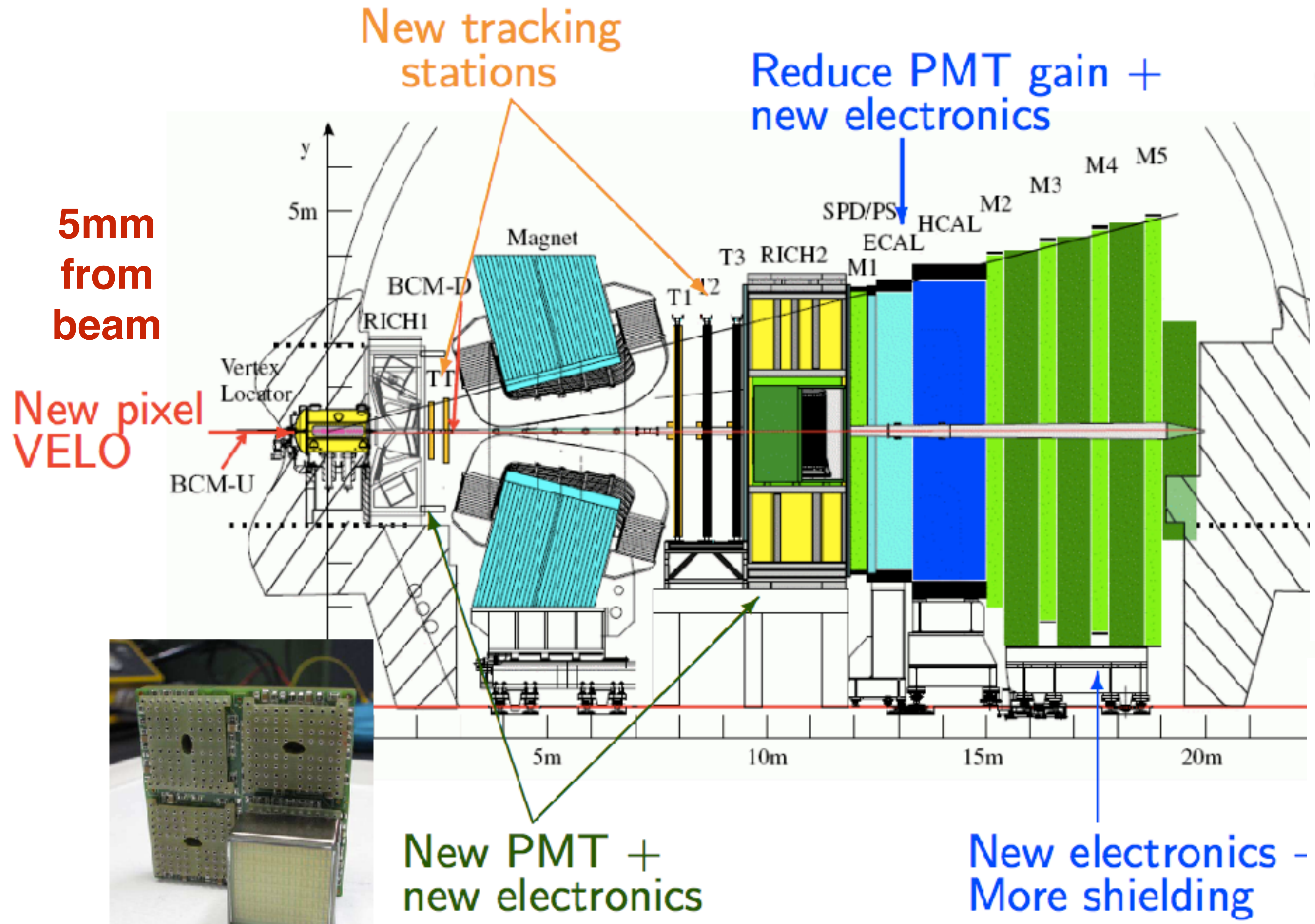
LHCb upgrade

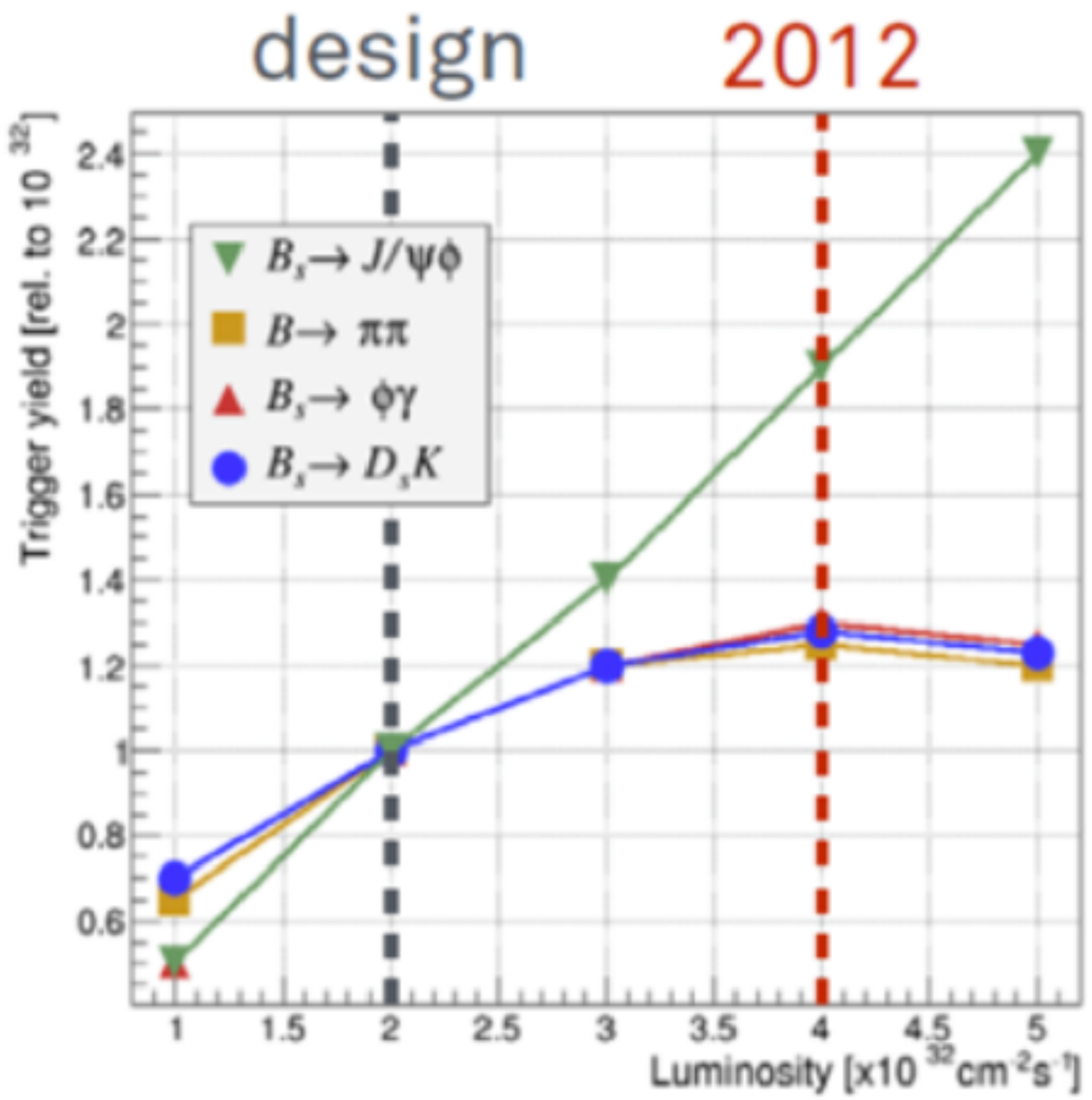


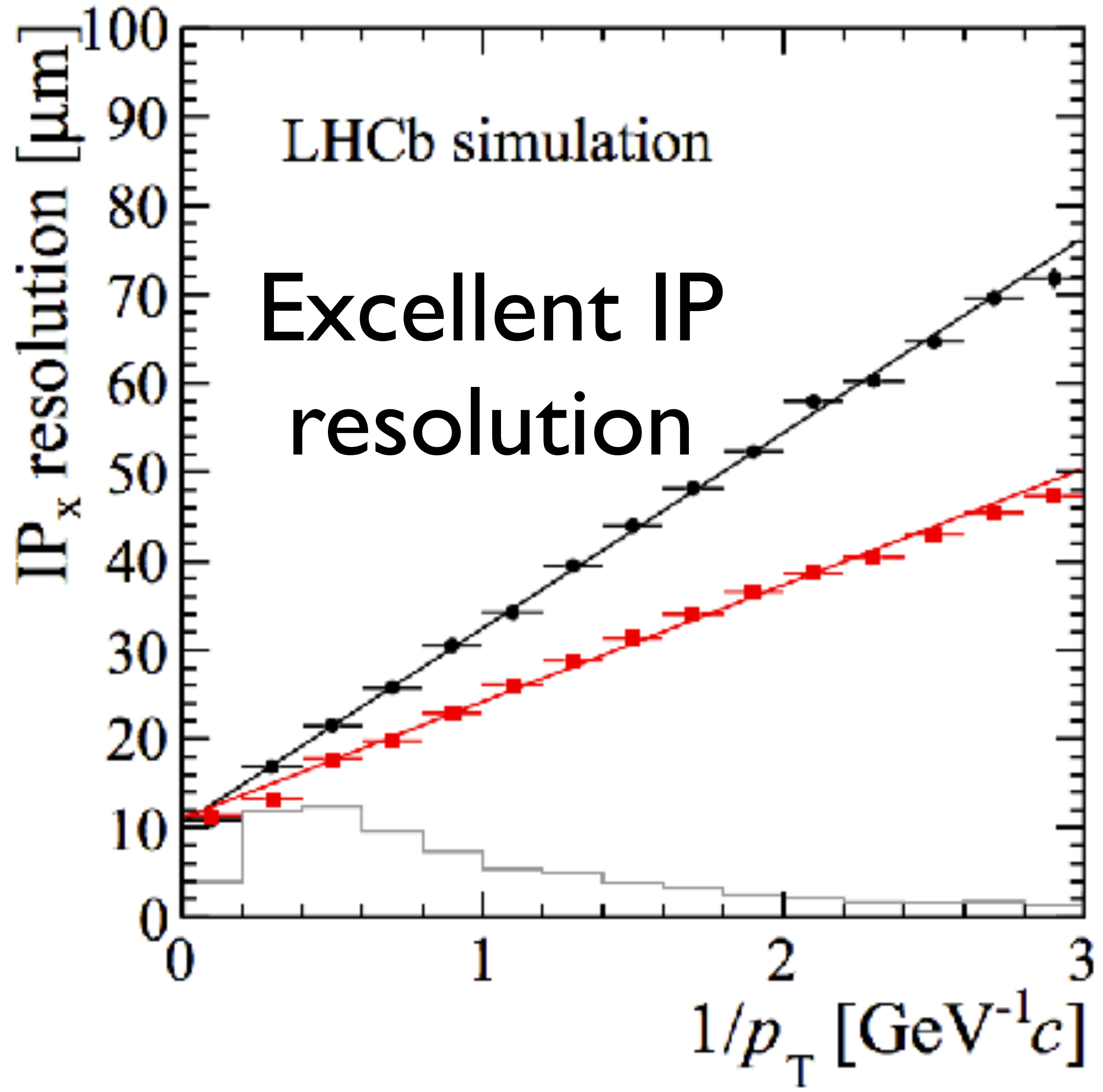
Full Run-I+Run-II dataset will effectively have 5x statistics of Run-I

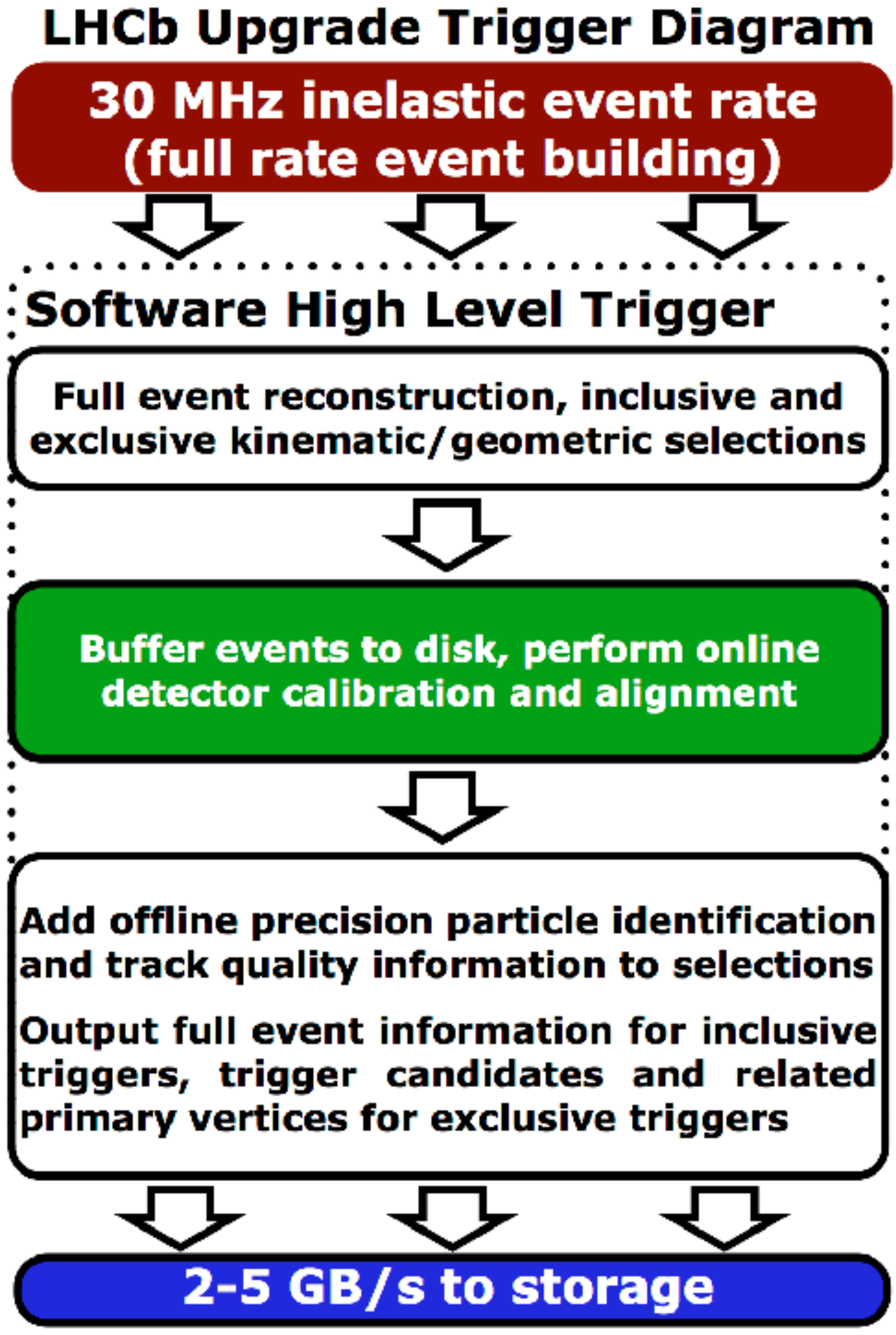
LHCb-upgrade (phase 1) will be installed in LS2 and operate during Run-3

LHCb upgrade (phase 1)





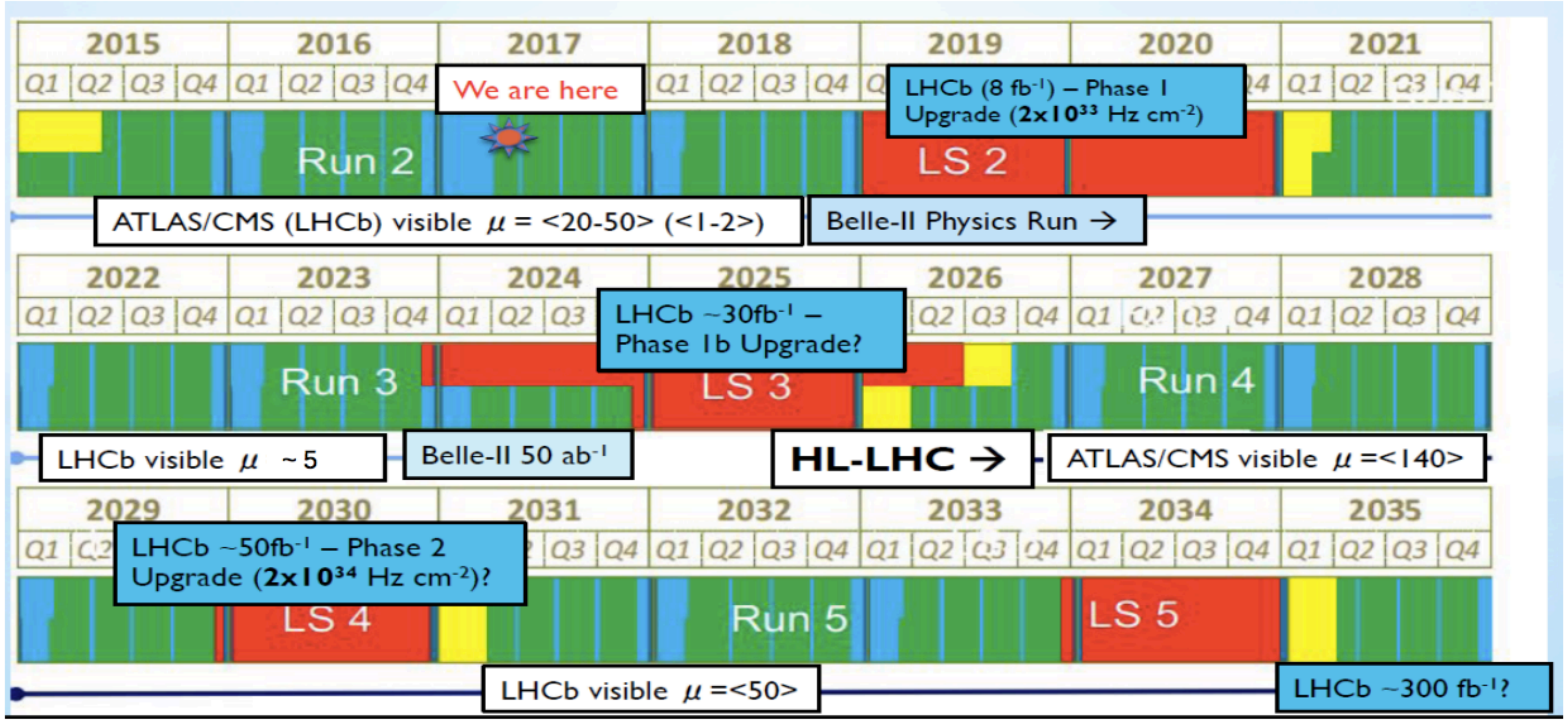


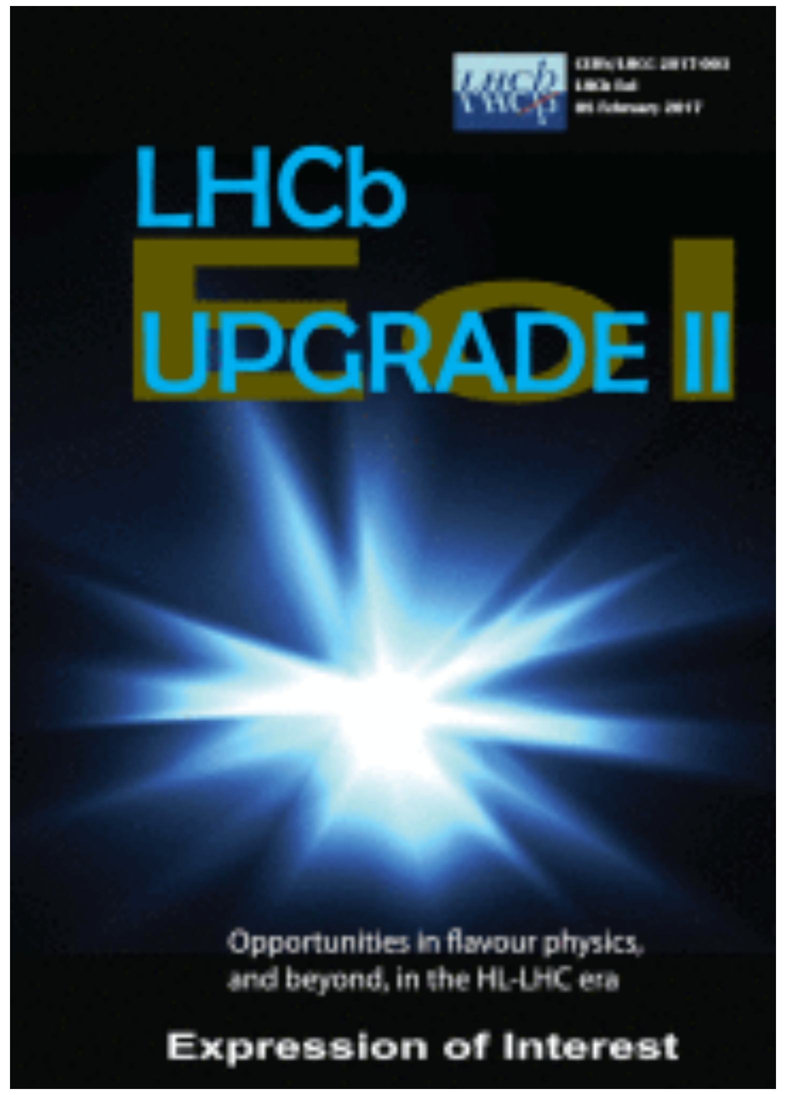


Many LHCb measurements will be statistically limited after Run 1+2.

Increase luminosity from $\sim 4\text{x}10^{32}$ to $\sim 2\text{x}10^{33}$

LHCb upgrade (phase 1b and 2)





- EoI for LHCb-upgrade(s) in LS3 and LS4 so that it can operate in Run-4,5.
  - Stations in the magnet (to improve reconstruction of multi-body final states).
  - Improvements to PID via time-of-flight (TORCH project)
- Increase luminosity to 10^{34}.

https://cds.cern.ch/record/2244311?ln=en

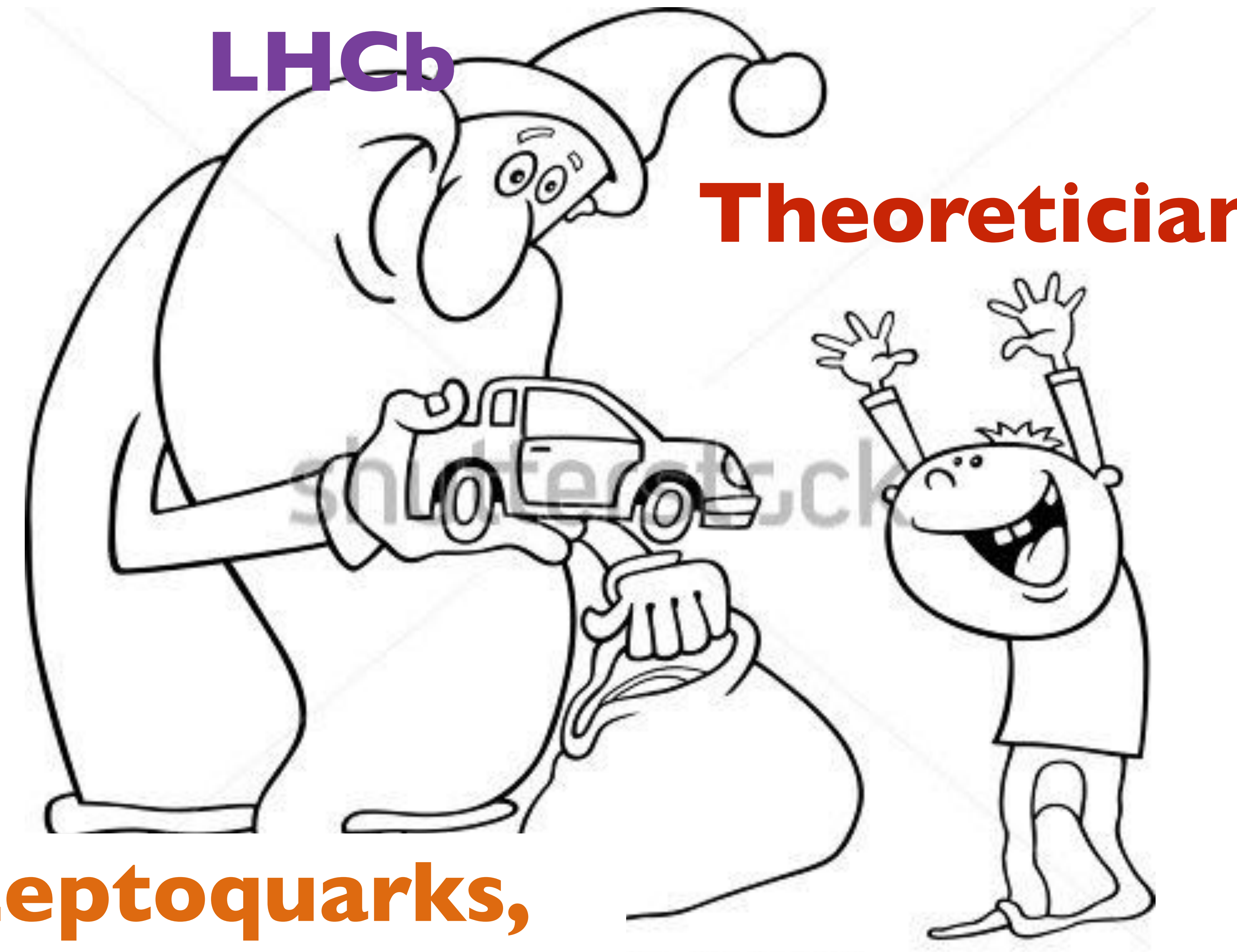
Summary

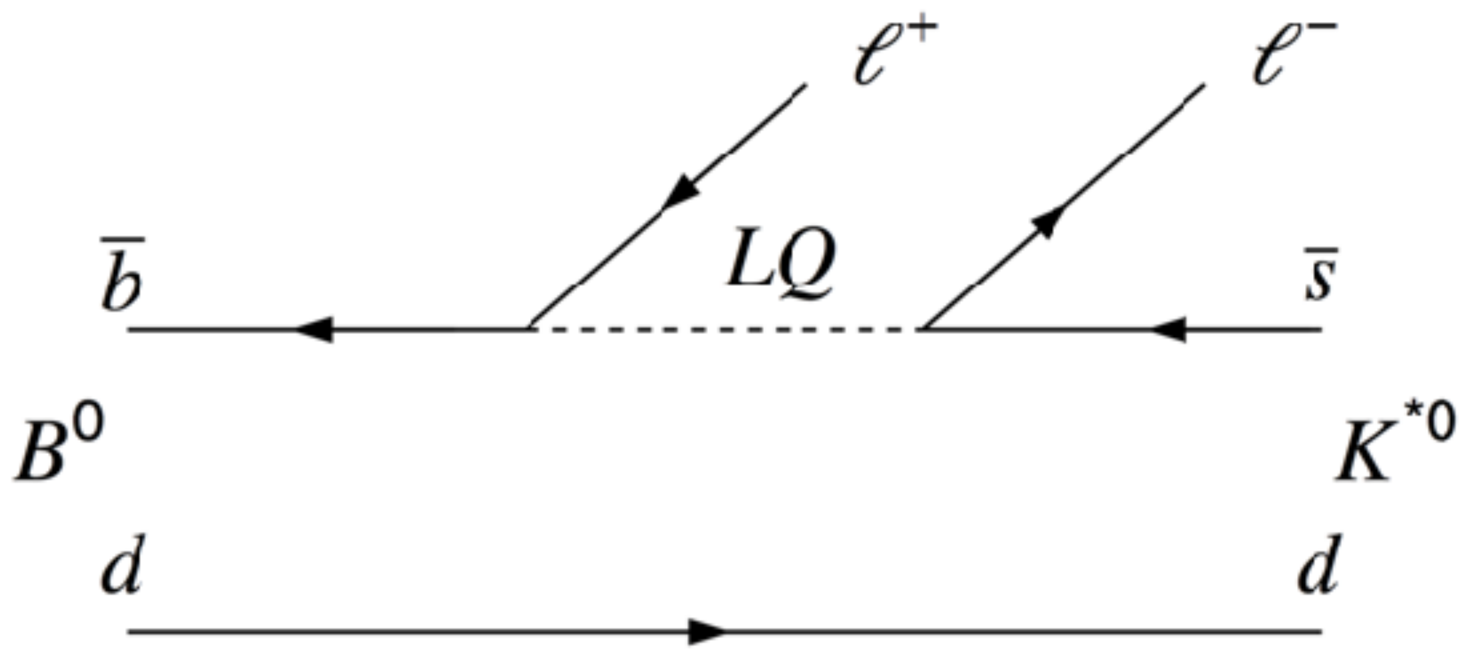
Recent data show hints of **LFU** violation.

- b → s neutral currents in e vs. μ (R_K, R_{K^*}, P_5' etc)
- b → c charged currents in τ vs. e, μ (R_D, R_{D^*})

More measurements (with more data) on the way.

Starting to plan for phase-1b and phase-2 upgrades to extend programme into HL-LHC era (~2035).



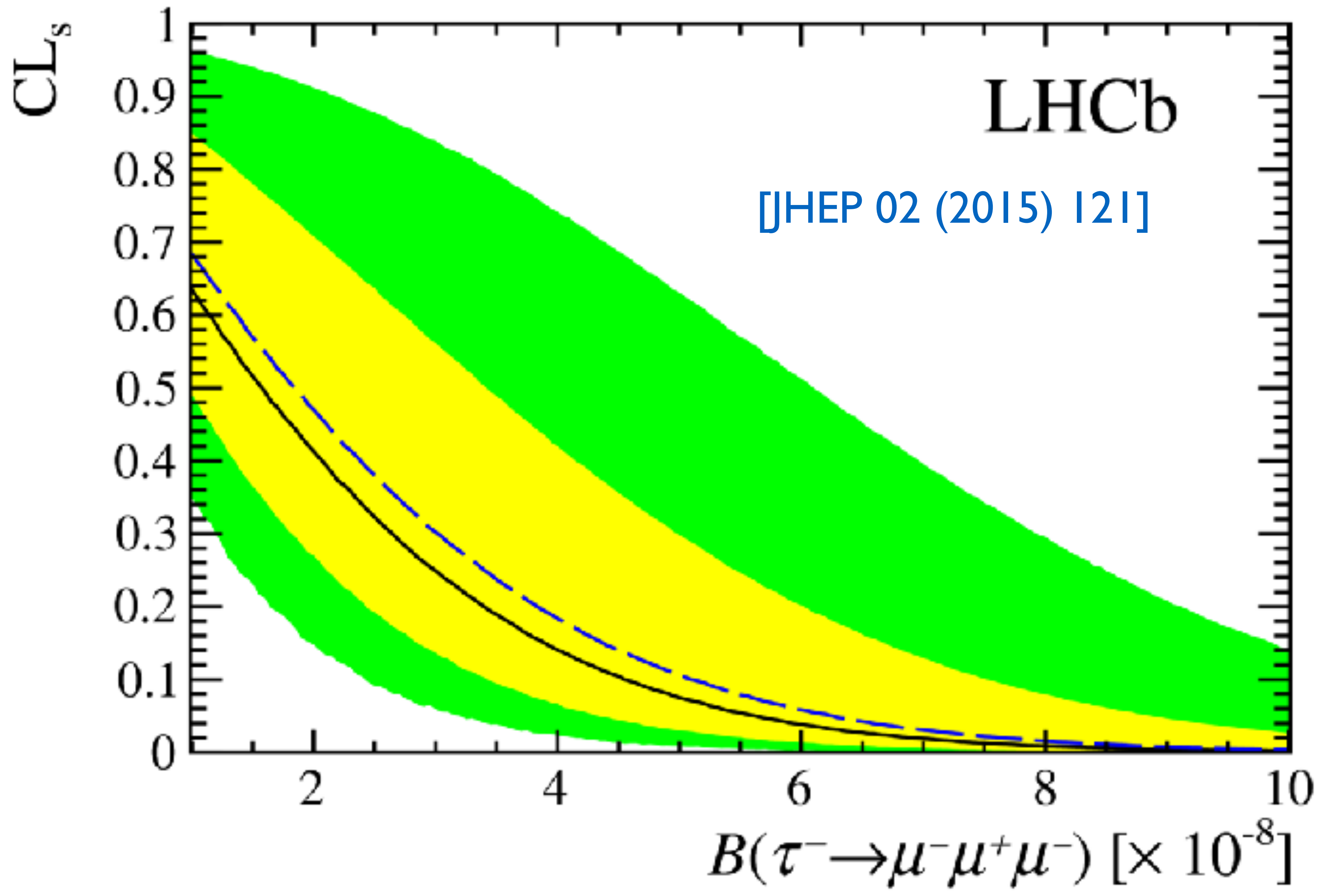


LHCb upgrade (phase 1)

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	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
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	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°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	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	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

LFV in lepton decays

B(tau -> 3mu) < 4.6 x 10^-8 @ 90%



10^{-40} in the SM

Low-q^2 region and hadronic resonances

In the low-q^2 bin there are hadronic resonances (φ,ρ,ω,η) that decay to di-lepton final states.

$BR(B \to K^*(\varphi,\rho,\omega,\eta)) \sim 2\text{-}30 \times 10^{-10}$ (compared to 10^{-7} for the signal modes).

In this region, the electrons and muons are similar in the detector.

We do not subtract these. They should actually contribute to increase R_{K^*}.

Also can have $\eta \to l^+ l^- \gamma$ (BR's ~ $0.3\text{-}7 \times 10^{-3}$) but where we miss a photon, leading to the partially reconstructed background.

Electron-muon universality test

[PIENU collaboration, PRL 115, 071801 (2015)]

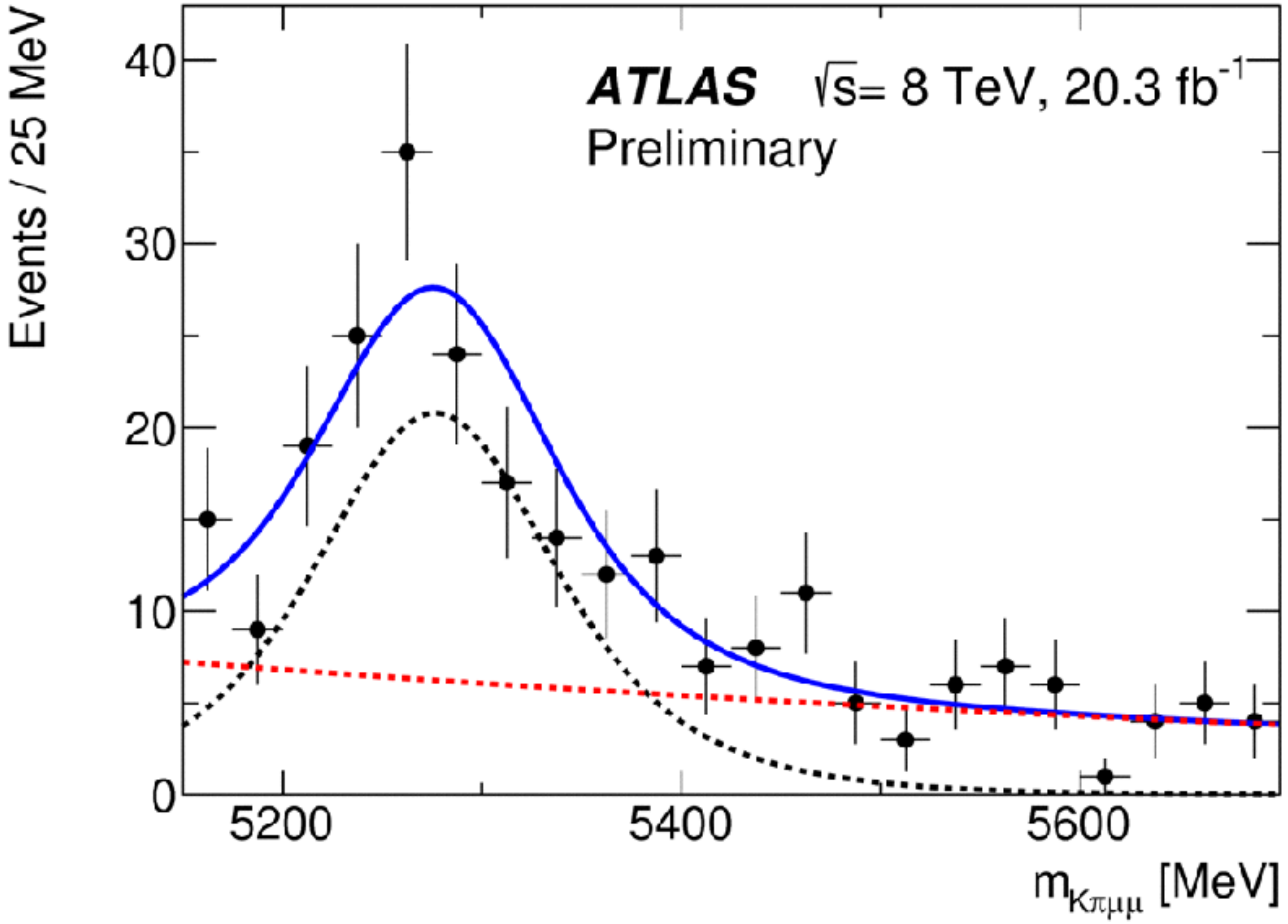
$$R_{e/\mu} = \Gamma[(\pi \to e\nu(\gamma)]/\Gamma[(\pi \to \mu\nu(\gamma)]$$

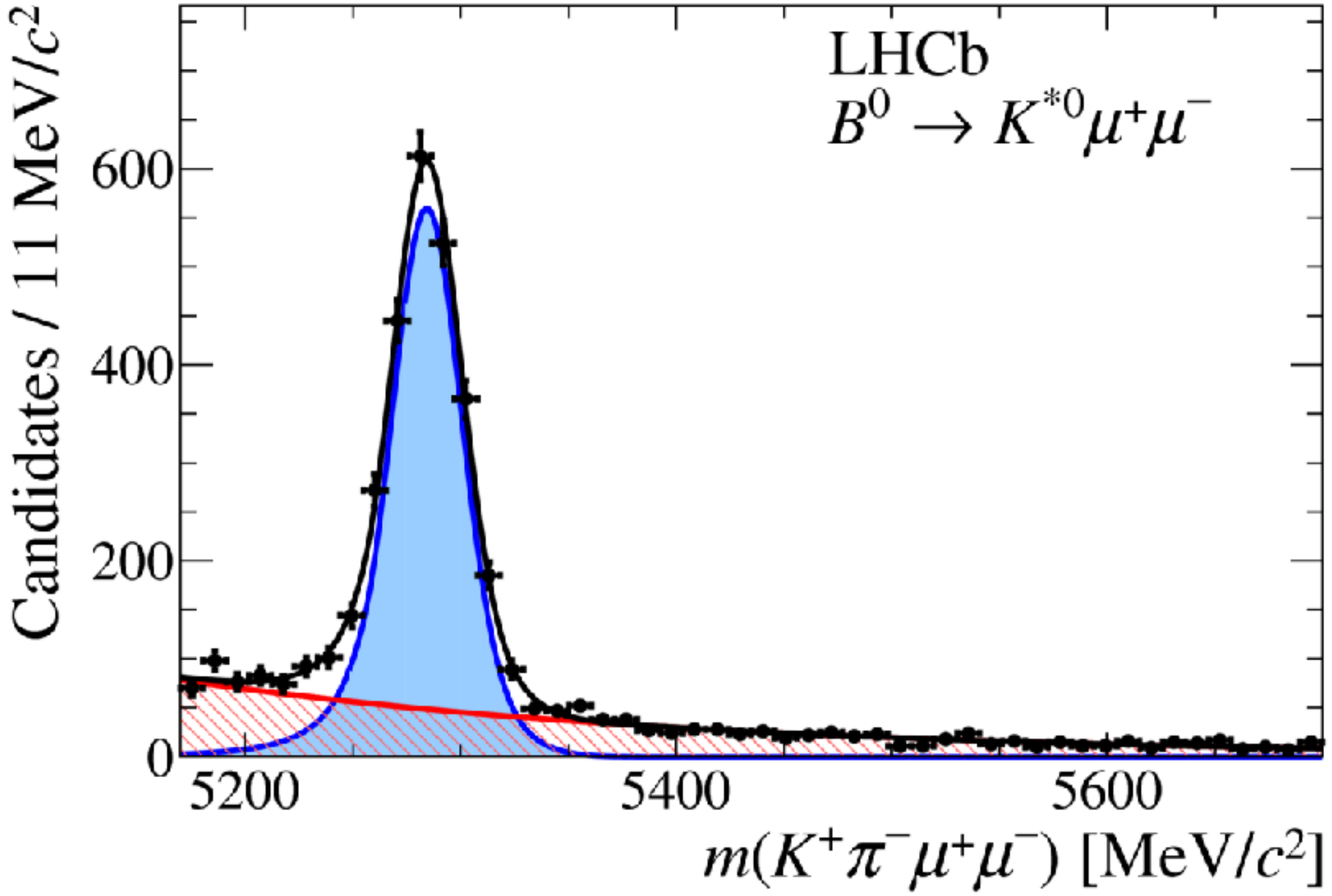
$$R^{\rm SM}_{e/\mu} = (1.2352 \pm 0.0002) \times 10^{-4}$$

$$R^{\rm exp}_{e/\mu} = [1.2344 \pm 0.0023({\rm stat}) \pm 0.0019({\rm syst})] \times 10^{-4}$$

Gives sensitivity to new physics beyond the SM > O(500) TeV

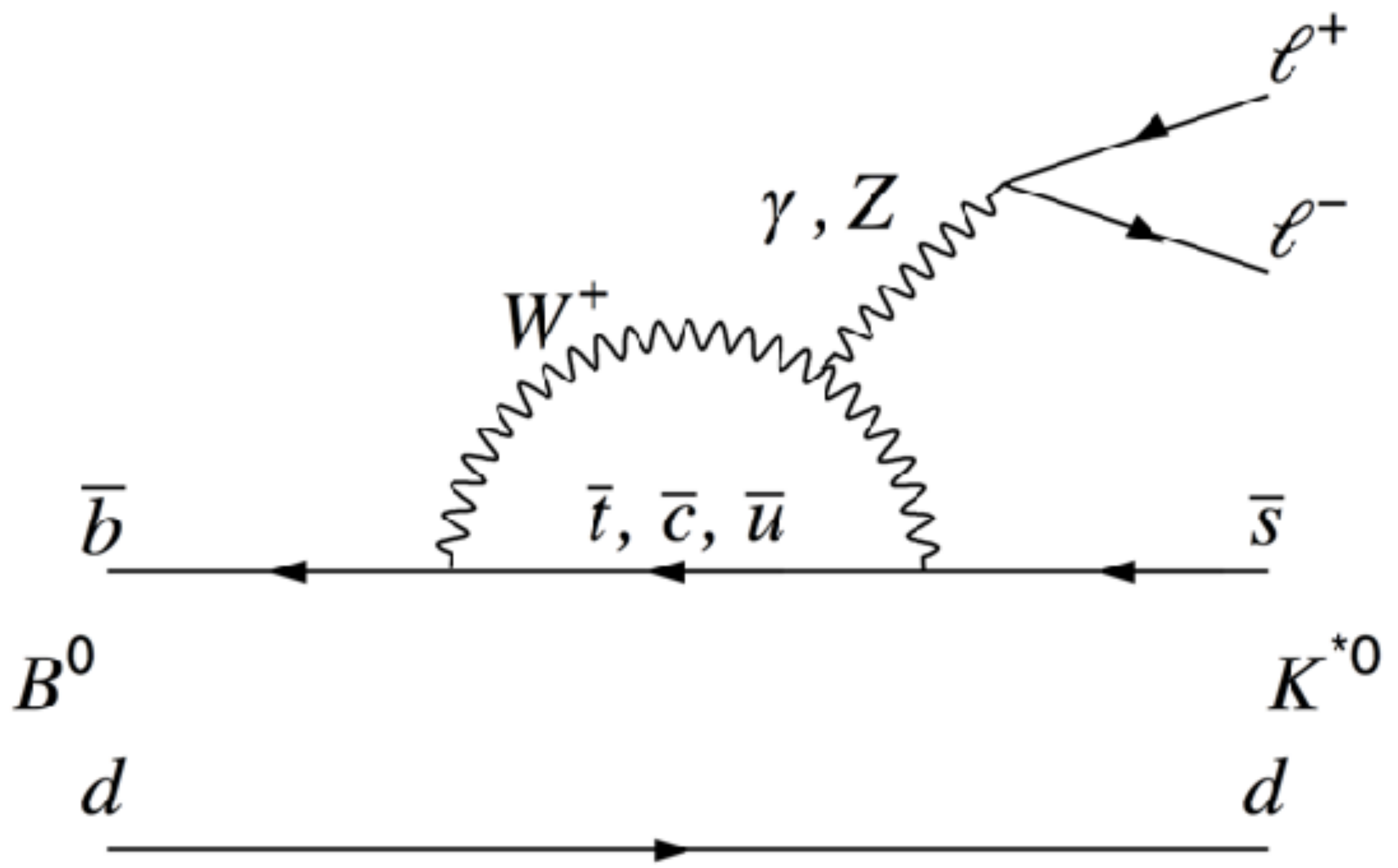
Comparison between experiments

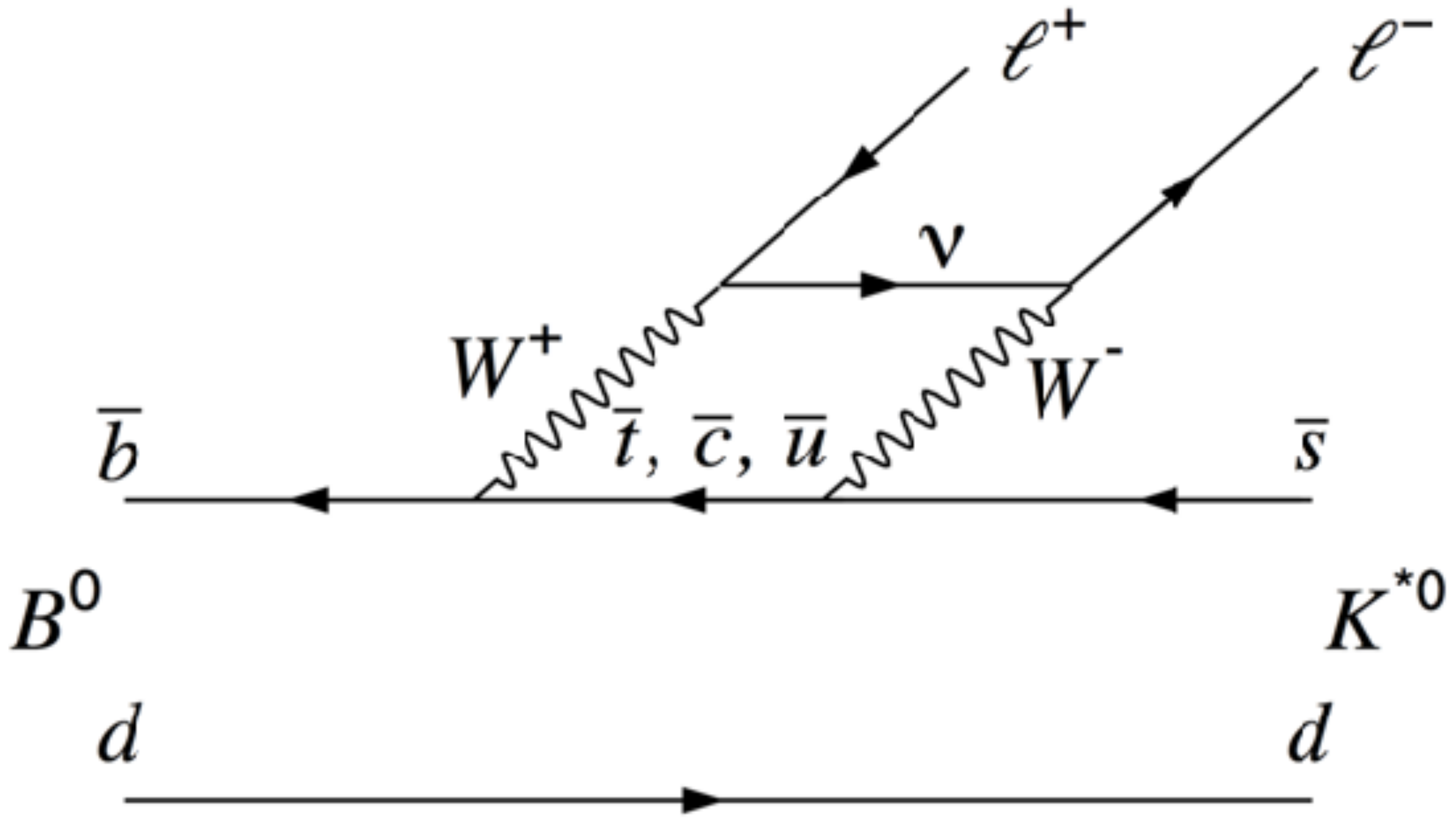




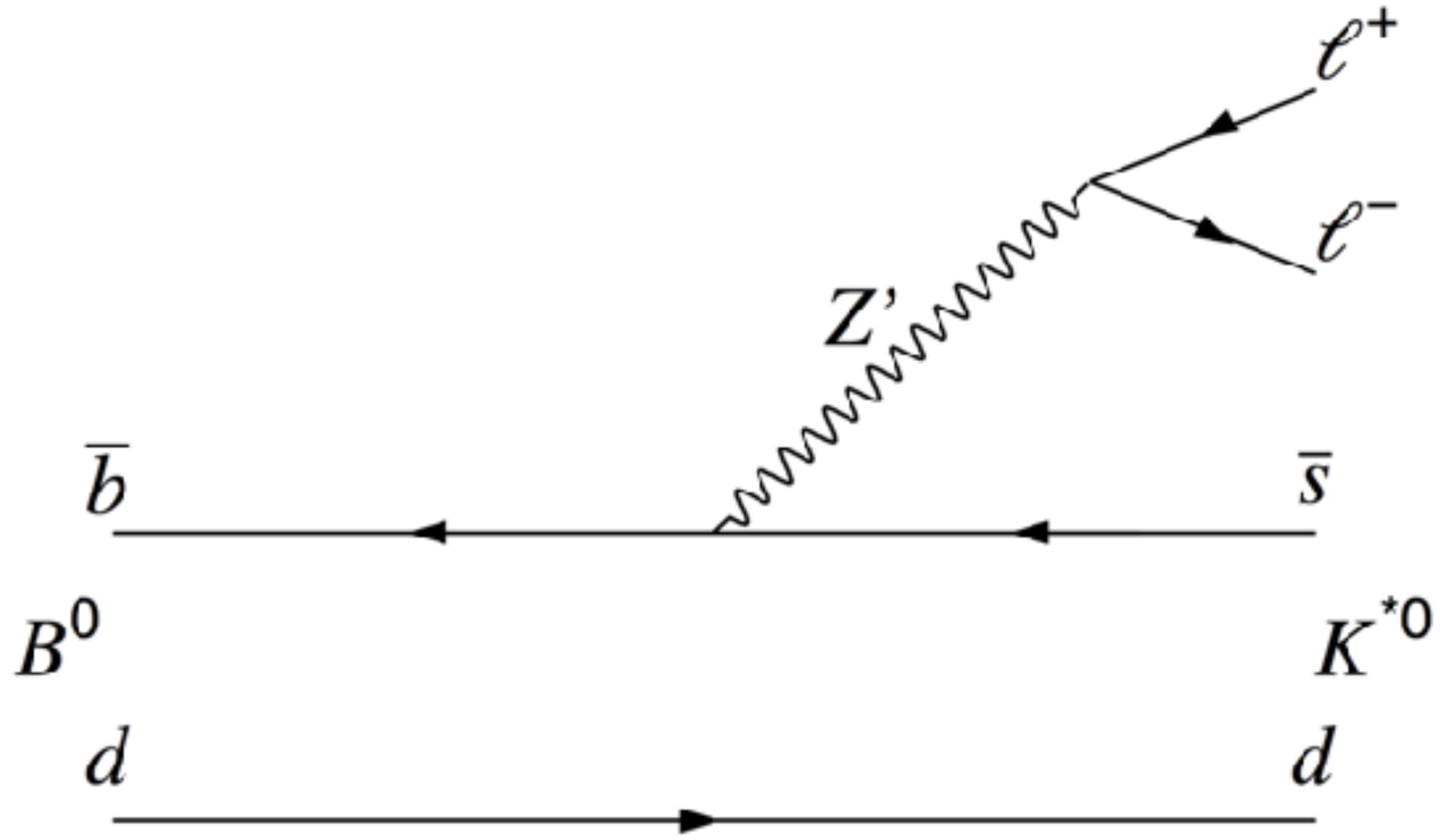
b → s neutral currents

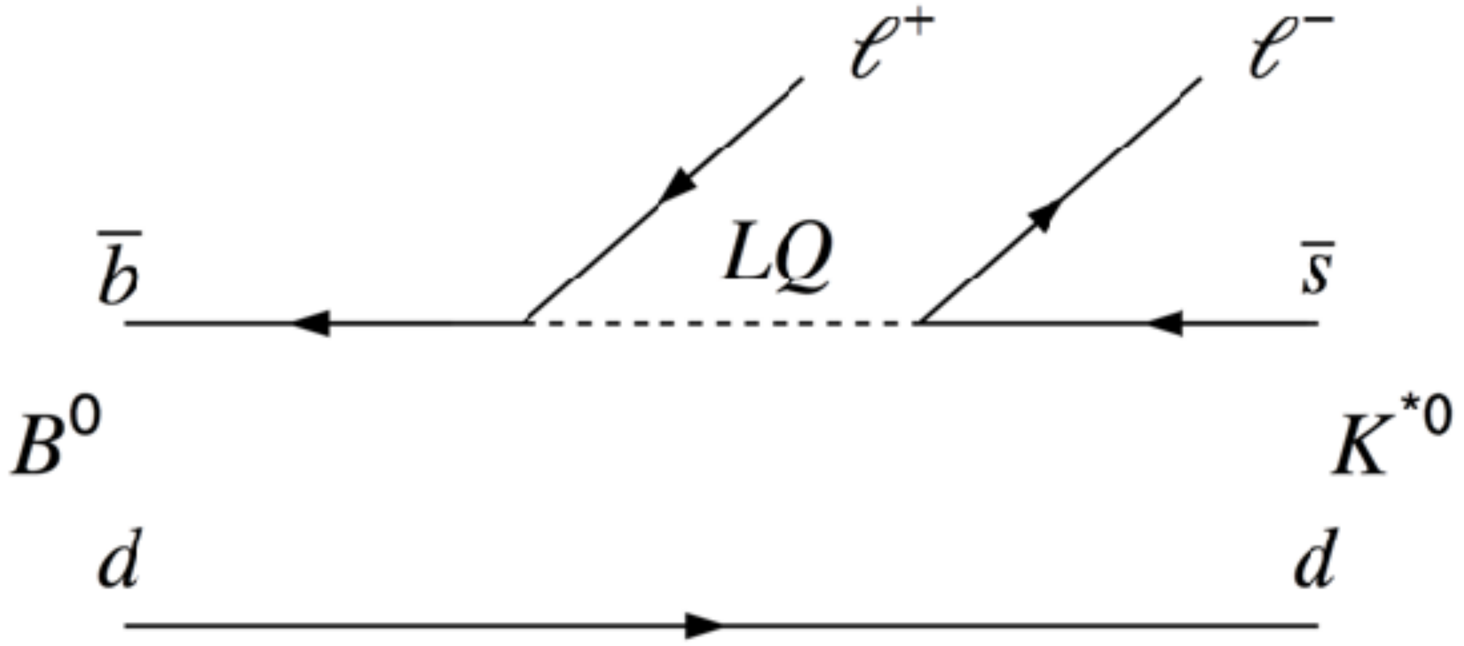
SM





NP





Hadronic uncertainties

[Capdevilla et al., arXiv:1704.05340]

Coloured bands represent different NP scenarios

Size of band indicates size of hadronic uncertainty

In models with LFUV this gets larger as there is no long a cancellation for e/mu