LHCb status and selected, recent highlights

Monica Pepe Altarelli (CERN)

On behalf of LHCb

LISHEP2018, Salvador, Bahia

The LHCb collaboration

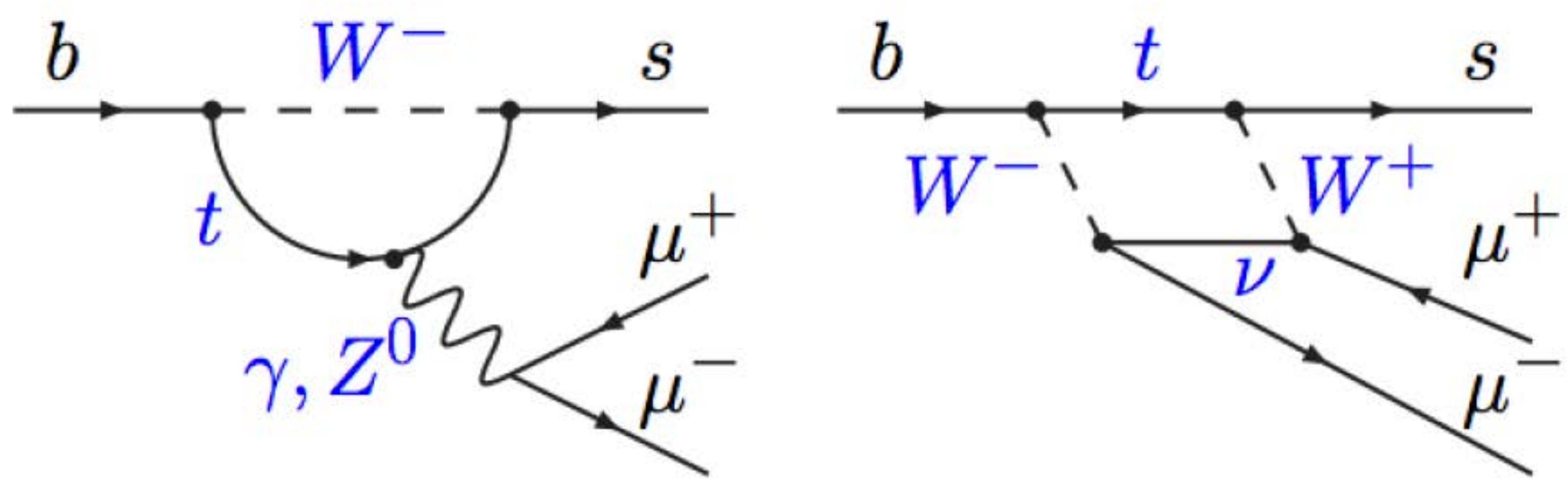
- ~850 authors from 78 institutes in 18 countries
- ~440 publications, some with very high impact
- Main focus on heavy flavour….but plenty of other physics in the forward direction

Why heavy (quark) flavour?

- A very rich field, and a vast laboratory to test the SM
- Heavy b mass → Easier to understand theoretically ($\alpha_s(m_b) \approx 0.2$, $\Lambda_{QCD}/m_b \approx 0.1$)
- b (and c) lifetimes long enough for experimental detection ($\tau_b \sim 1.5\ 10^{-12}$ s)
- Sizeable CP violation expected in many b decays
    - Large CPV effects expected in processes which involve quarks from all three generations
- Most TeV new physics contains new sources of CP and flavour violation
- The observed baryon asymmetry of the Universe requires CPV beyond the SM
    - Not necessarily in flavour changing processes, nor necessarily in quark sector, it could originate from lepton sector

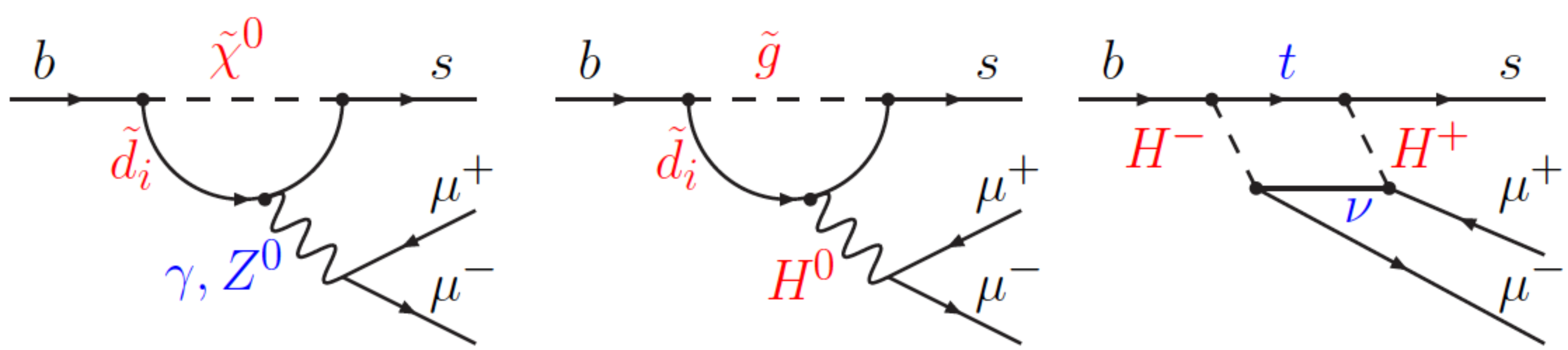
Why heavy (quark) flavour (II)?

- In the SM, some rare decays are forbidden at tree level and can only occur at loop level (penguin and box), e.g. $B_s \to \mu^+\mu^-$ (Talk by João Coelho)



No FCNCs

- A new particle, too heavy to be produced at the LHC, can give sizeable effects when exchanged in a loop (e.g. modify branching fractions, angular distributions,…)

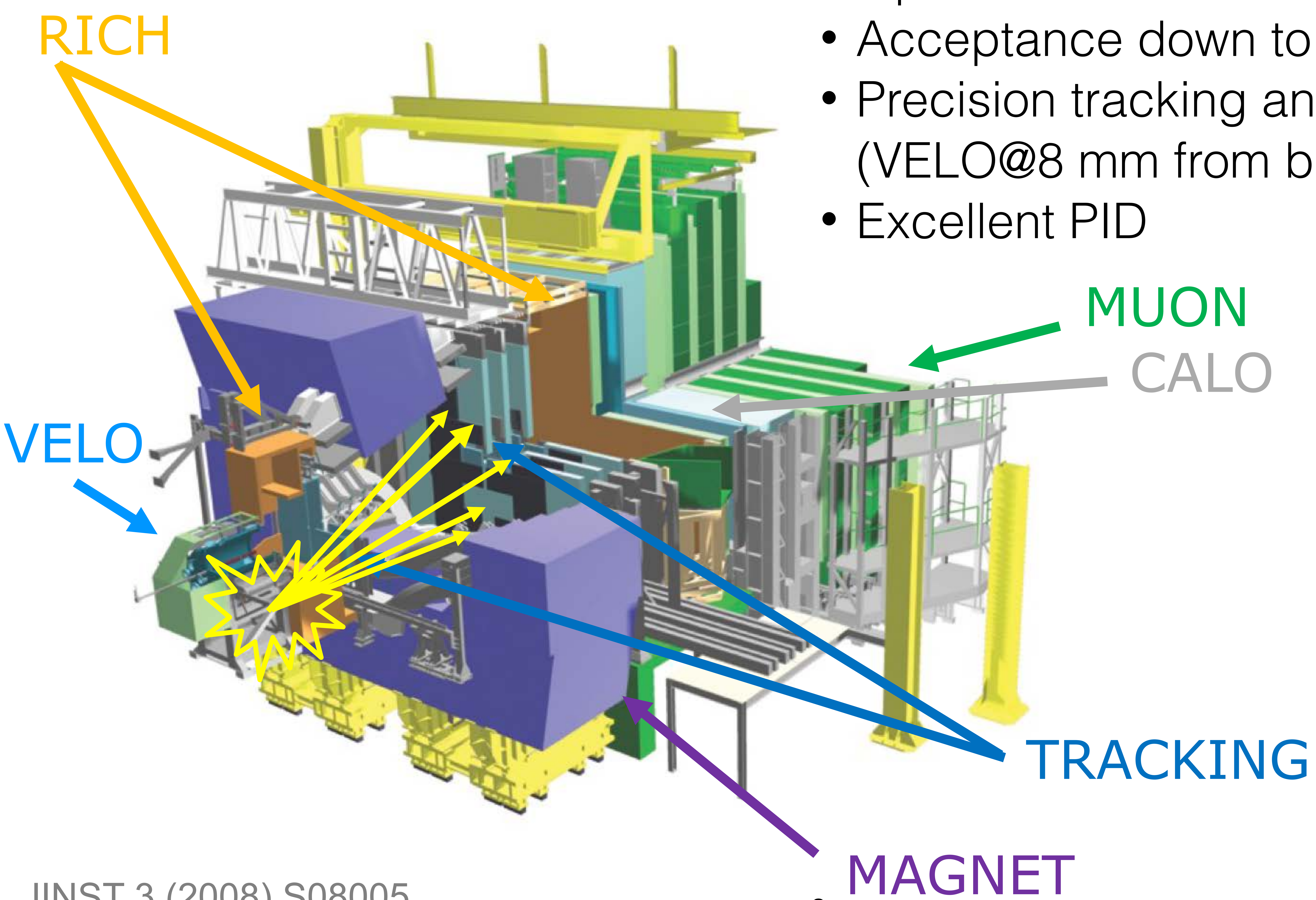


- Strategy: use well-predicted observables to look for deviations
- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS


A window on
NP at high
scales

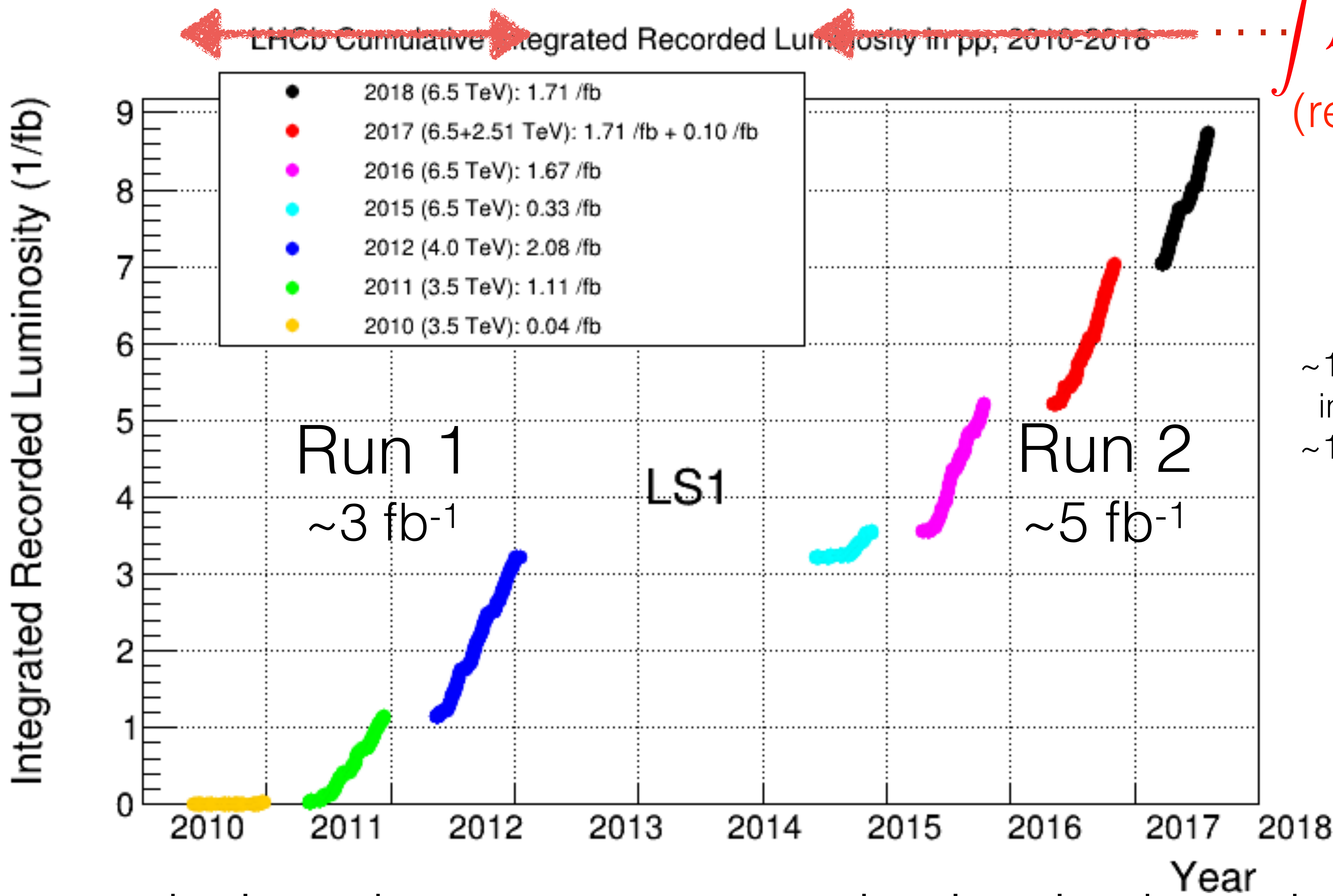
LHCb detector: the essentials

- Forward acceptance
- Efficient trigger for hadronic and leptonic modes
- Acceptance down to low p_T
- Precision tracking and vertexing (VELO@8 mm from beam)
- Excellent PID



JINST 3 (2008) S08005

Luminosity @ LHCb



$\int \mathcal{L}\,\mathrm{d}t \sim 9\,\mathrm{fb}^{-1}$

(reached ~8 fb^{-1})

~10^{11} $b\bar{b}$ decays/fb in acceptance

~10^{12} $c\bar{c}$ decays/fb

- Experiment designed to run at constant luminosity throughout fills
  - 4 x10^{32} cm^{-2} sec^{-1} (to be raised to 2 x10^{33} cm^{-2} sec^{-1} in Run 3)
  - mean number of interactions/bunch crossing ~1

Last year of LHCb as we know it!

- **LHCb is building its Upgrade I to be installed during Long Shutdown 2 (2019-20)→Factor 5 increase in Lumi: 2 x10^{33} cm^{-2} sec $^{-1}$**
- Possible LHCb detector consolidation and modest enhancements in LS3 (2025) - ATLAS/CMS Phase II upgrades also in LS3
- Major LHCb Upgrade II in LS4 (2030) →Factor 10 increase in instantaneous Lumi: 2 x10^{34} cm^{-2} sec $^{-1}$ (Expression of Interest in CERN-LHCC-2017-003 and physics document in CERN/LHCC 2018-027)

Last year of LHCb as we know it!

- **LHCb is building its Upgrade** **tdown 2 (2019-20)→Factor 5 increase**
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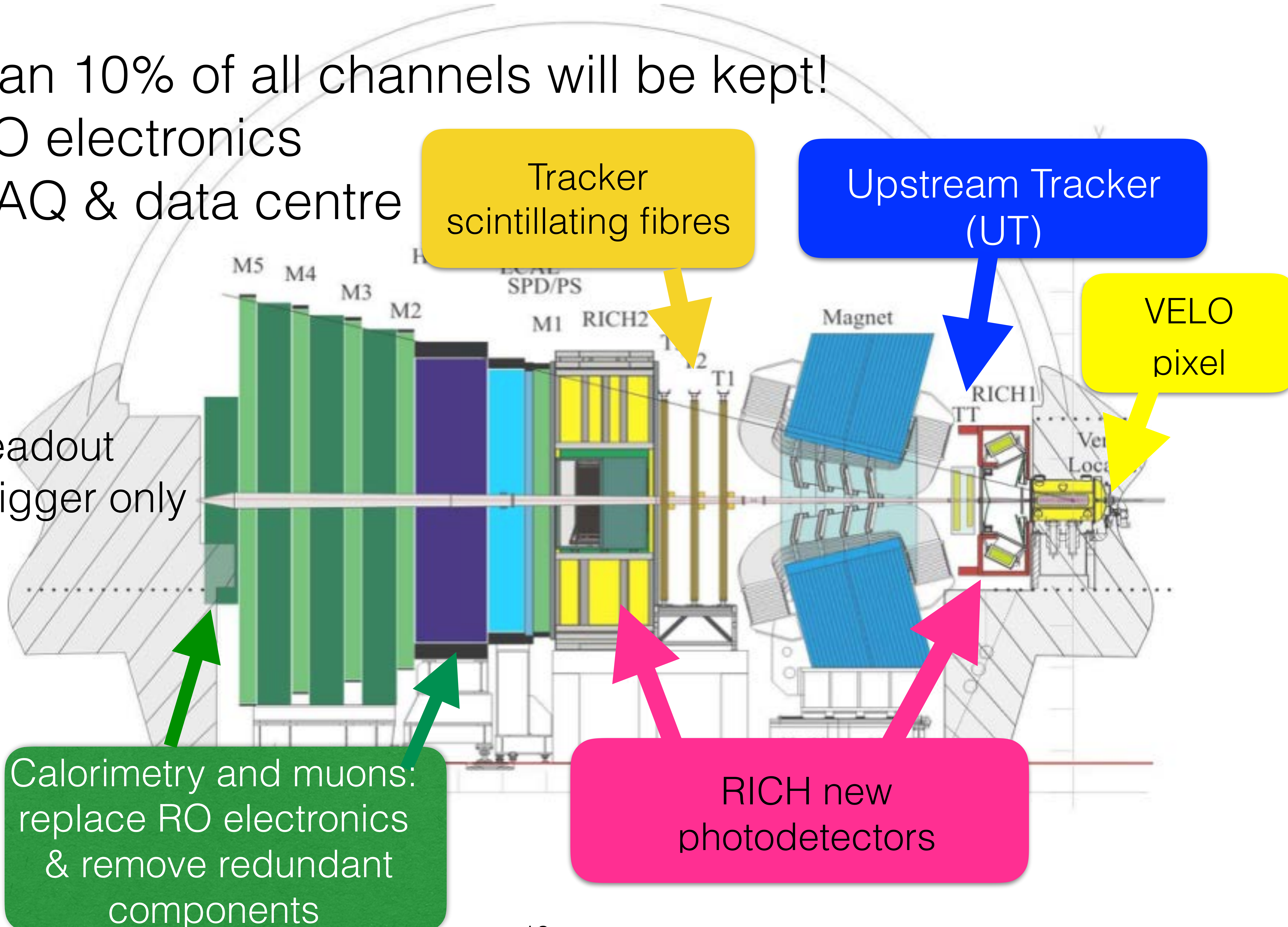
The upgraded detector

- Less than 10% of all channels will be kept!
- New RO electronics
- New DAQ & data centre

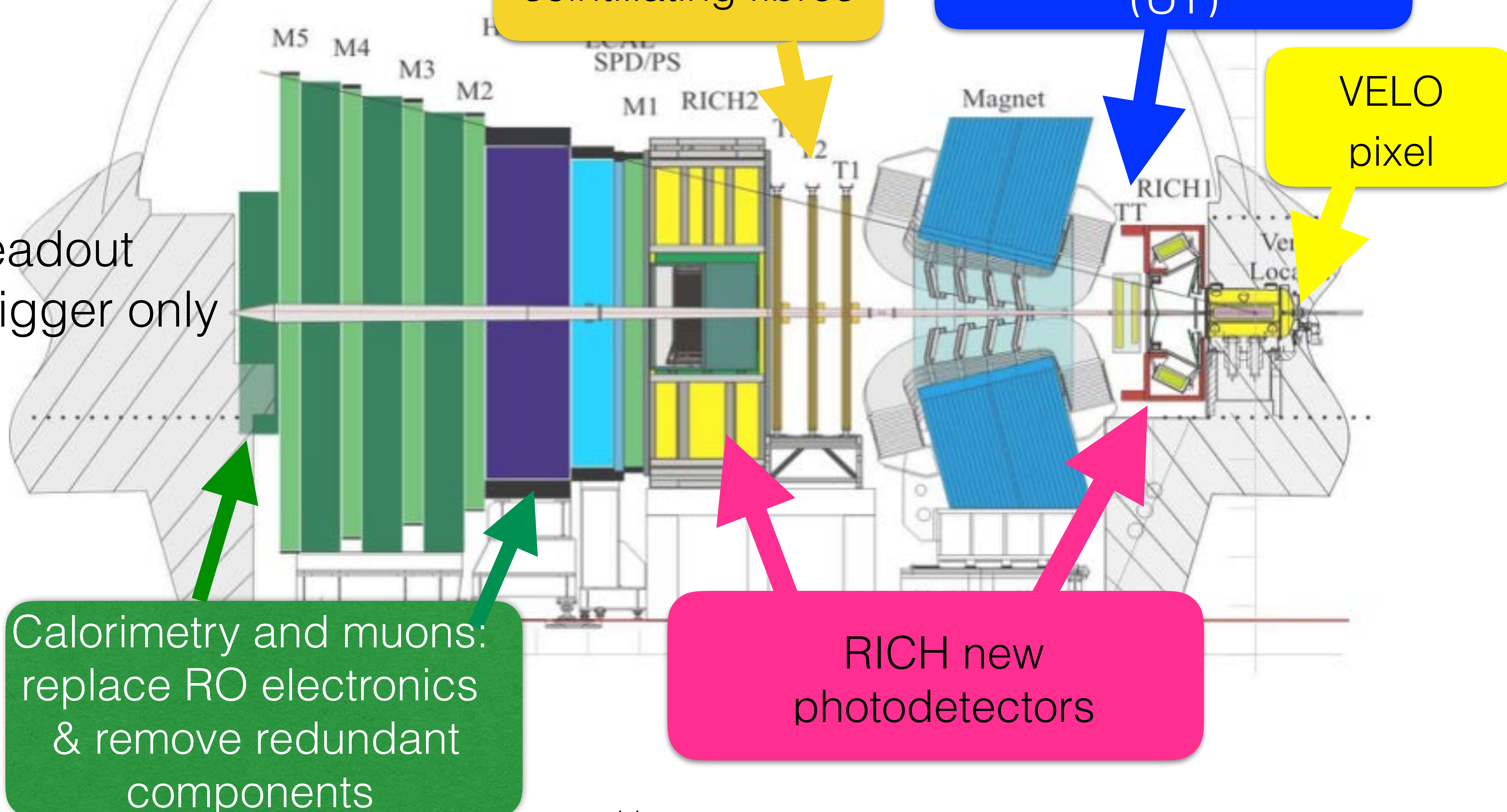
40 MHz Readout
Software trigger only



The **NEW** detector!

- Less than 10% of all channels will be kept!
- New RO electronics
- New DAQ & data centre

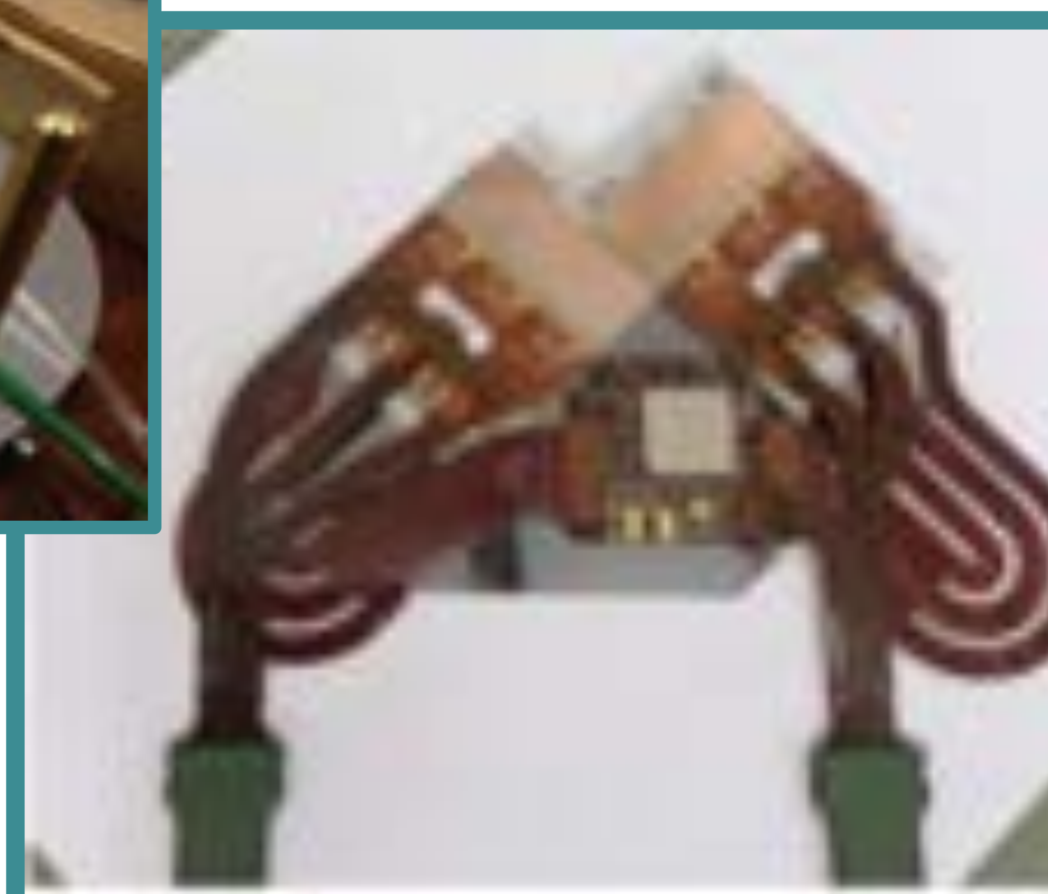
40 MHz Readout
Software trigger only



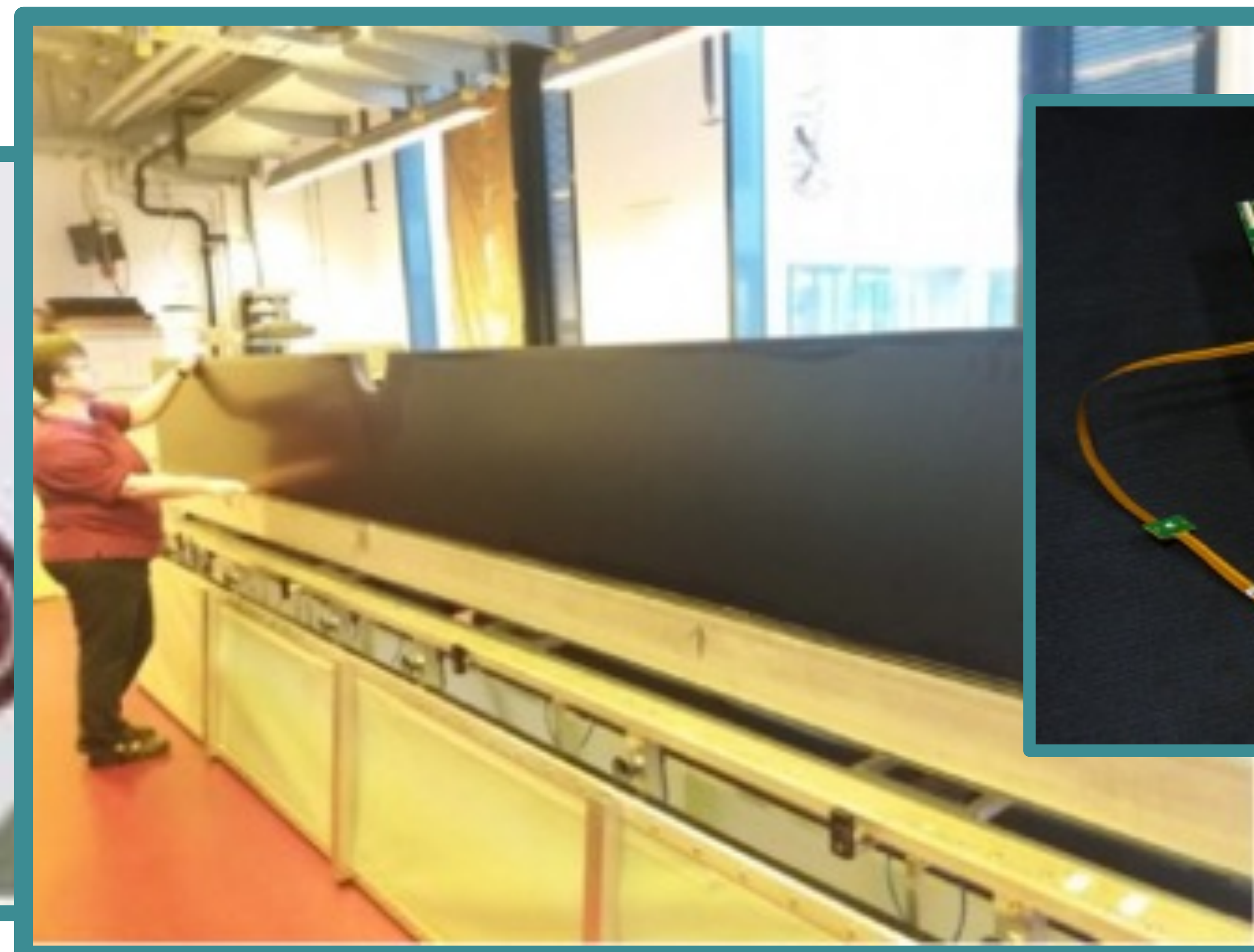
Installation starts in six months!

VELO sensor tiles testing device

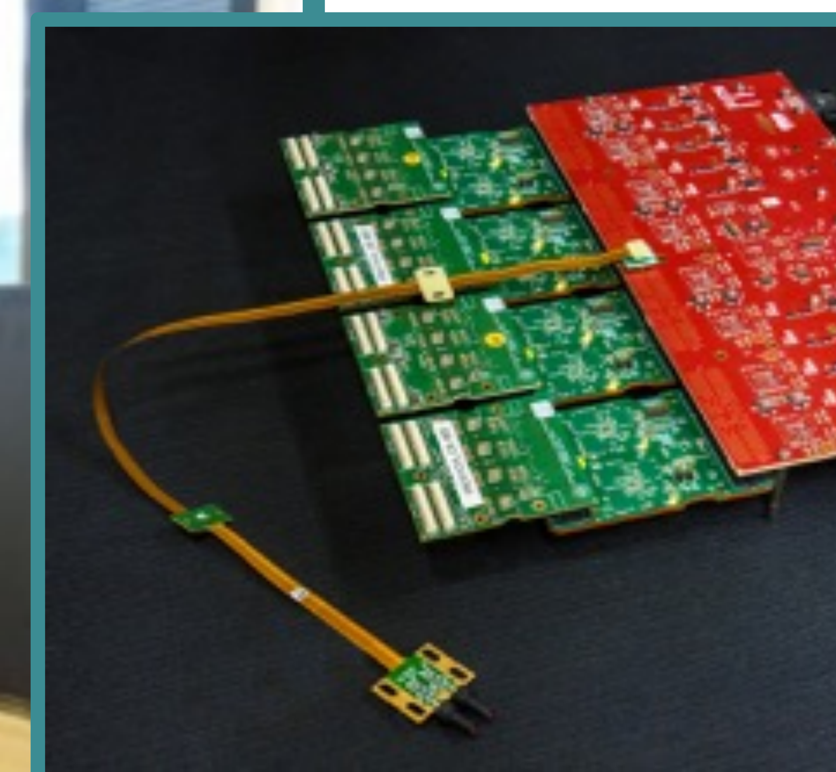
VELO module



SciFI module

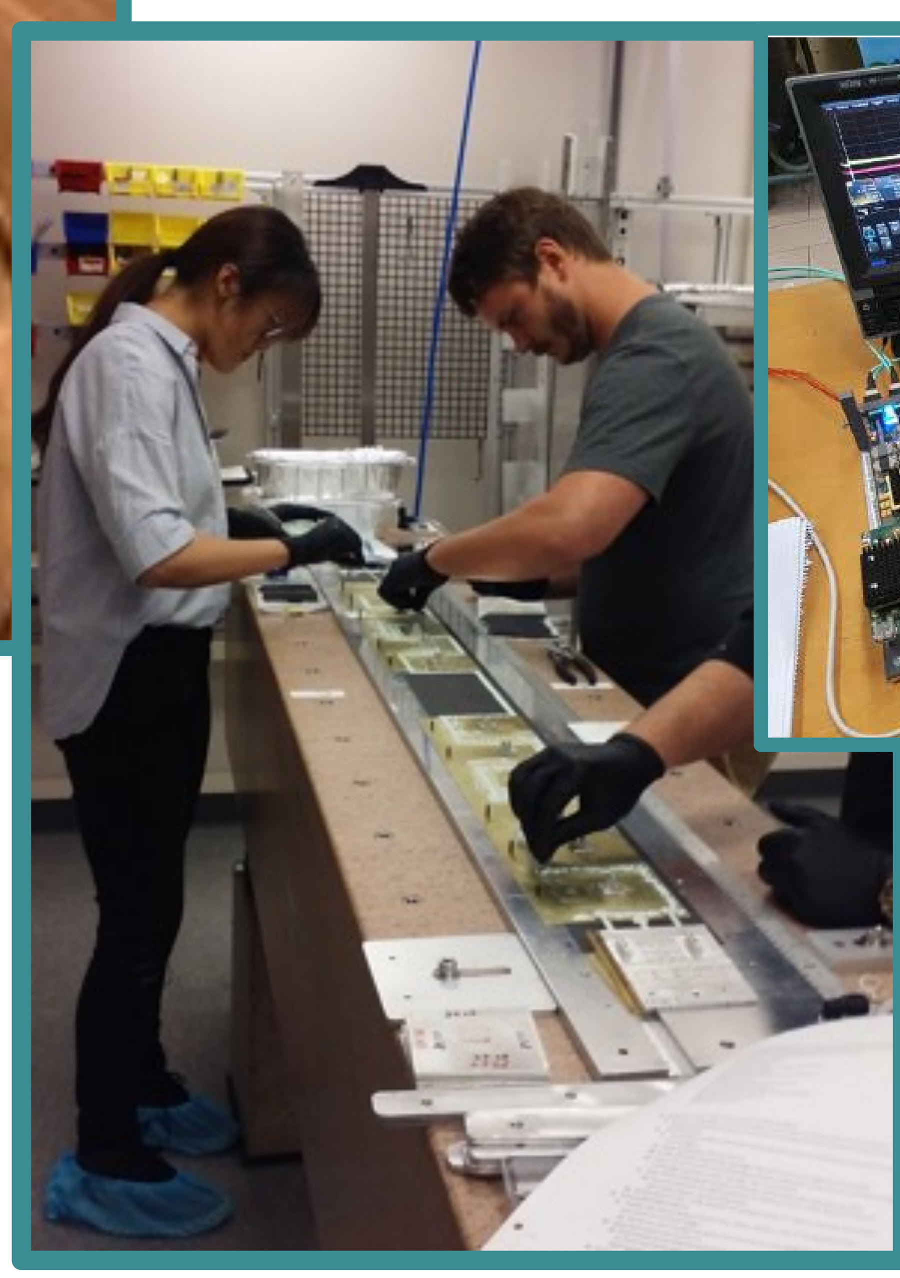


SciFI Readoout

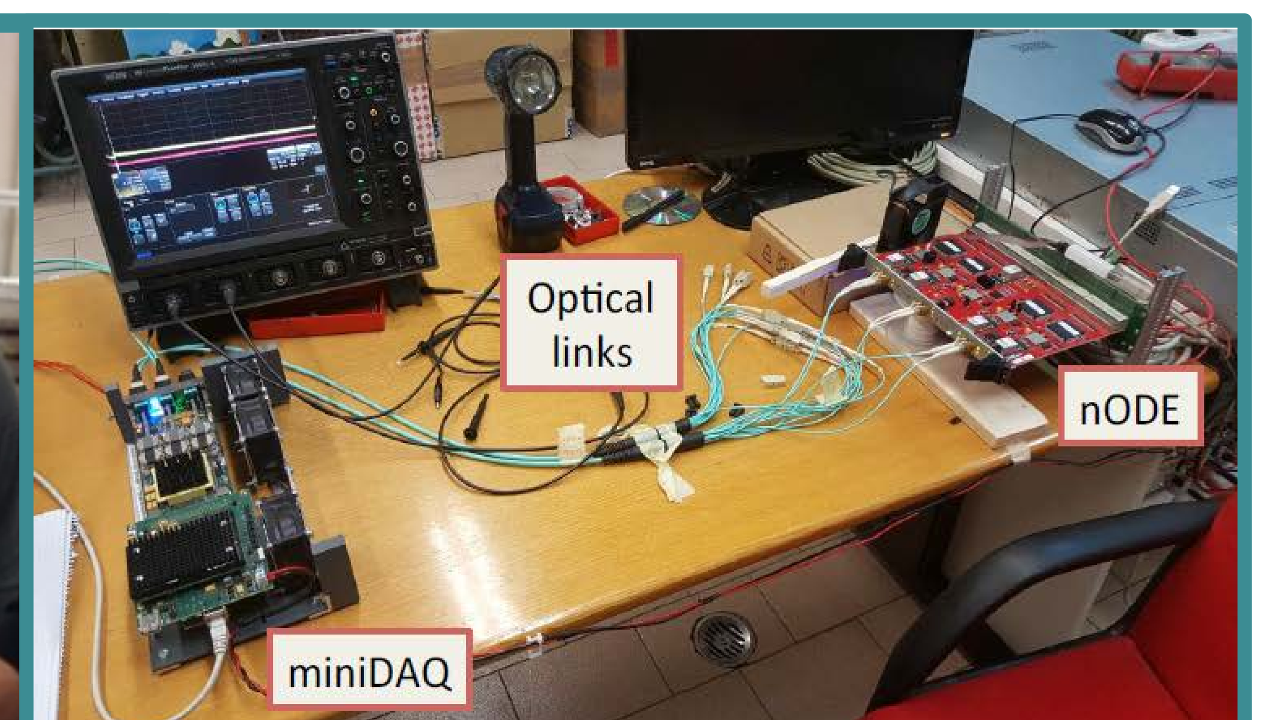


CALO electronics

UT sensor



UT staves construction



Test of MUON electronics

RICH MaPMTs under test

PCIe40 boards

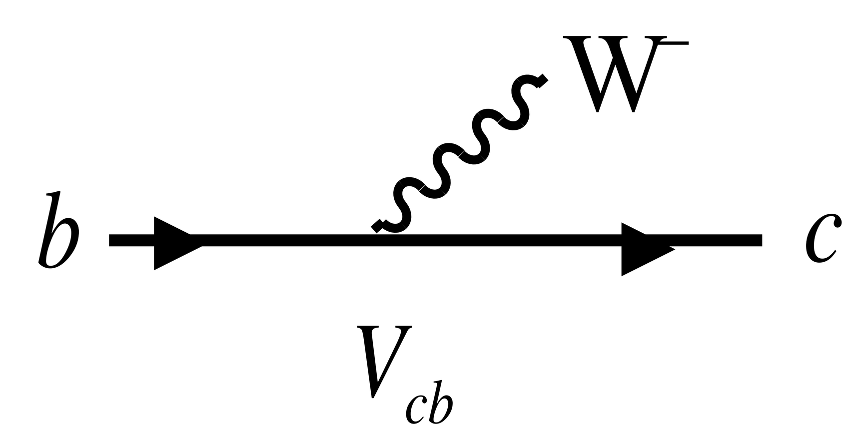
Measurement of the CKM parameters (γ)

More in the talk by
Fernando Ferreira Rodrigues

CKM Matrix

- The CKM matrix VCKM describes the decay of one quark to another by the emission of a W

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

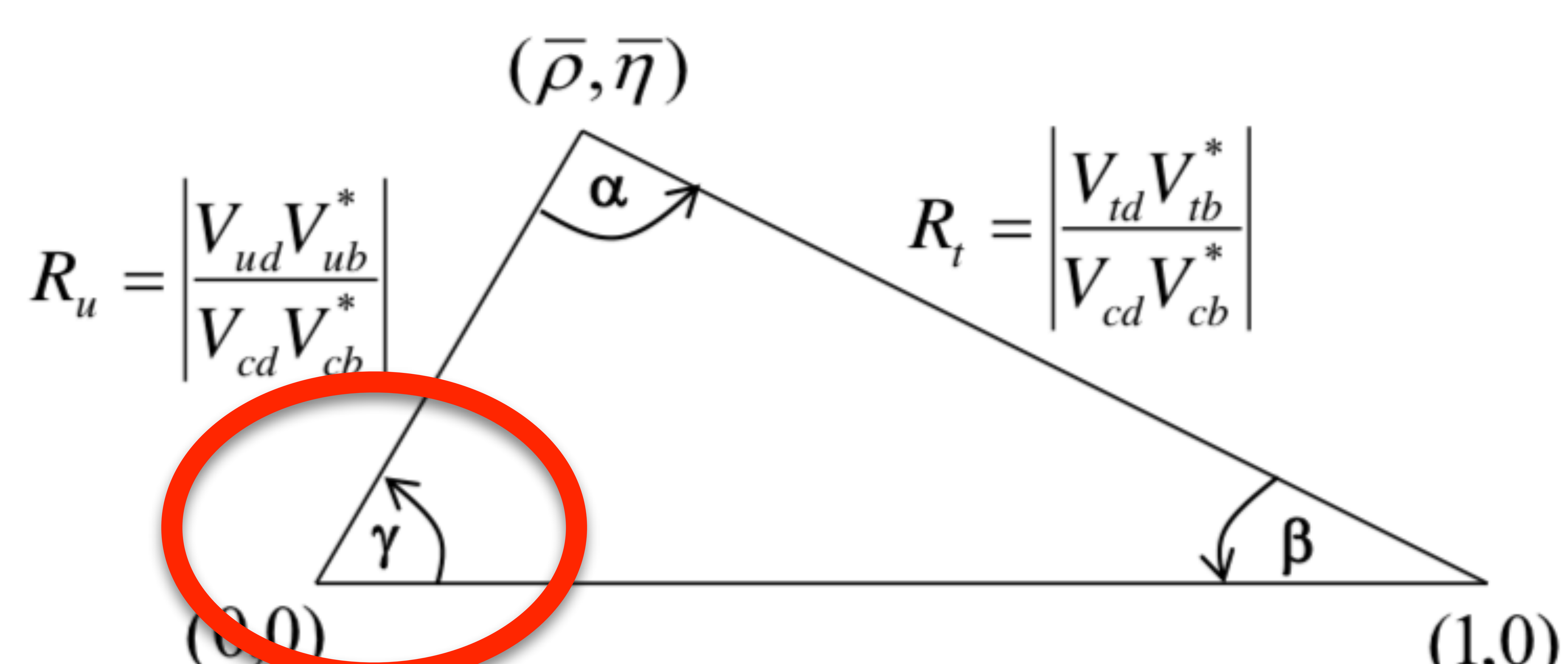


- The probability of the transition from flavour i to flavour j is ~ $|V_{ij}|^2$
- Probability of b to c decay ~ $|V_{cb}|^2$

- V_{CKM} depends on 3 mixing angles and 1 phase, which is the only source of CP violation in SM
- Phase only present with N≥3 generations (Nobel prize 2008)
    - With N=2, all phases can be removed→matrix real→no CPV
- These 4 parameters (3 angles, 1 phase) must be determined experimentally
- V_{CKM} unitary: unitarity constraints can be seen as sum of three complex numbers closing a triangle in complex plane

$$\sum_i V_{ij} V^*_{jk} = 0 \text{ for } j \neq k$$

- Check consistency of Unitary Triangles through precise measurements



Most open triangle: $j = d, k = b$

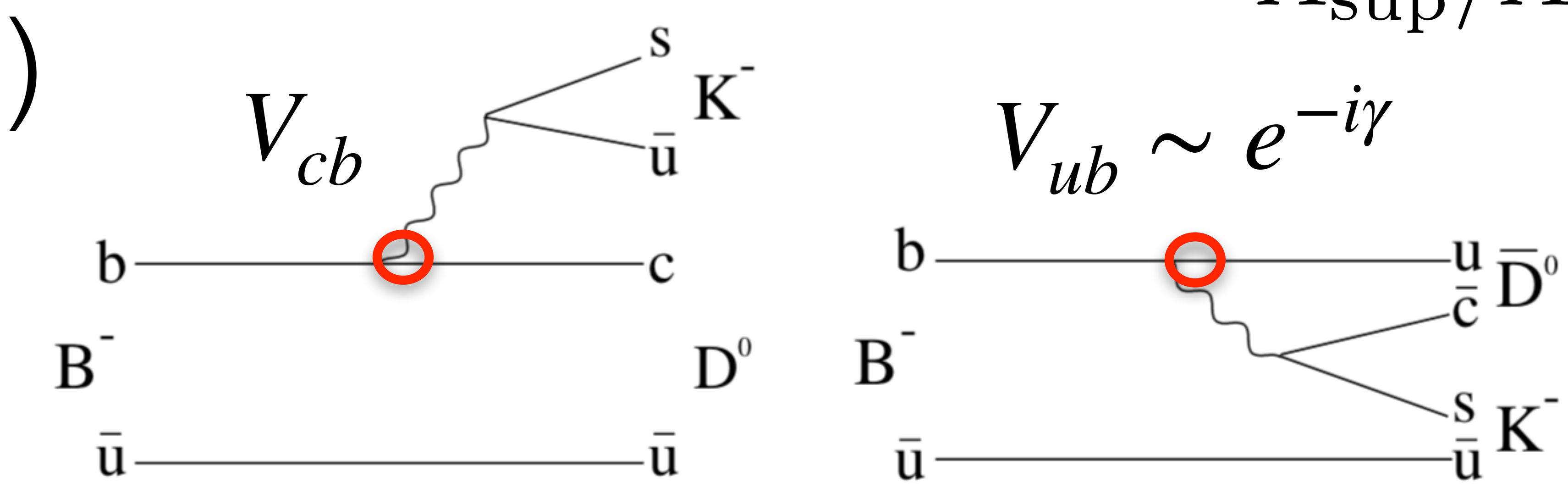
Measuring γ

- γ from tree-level processes is SM "standard candle"
  - theoretically very clean $\delta\gamma/\gamma_{th} \sim \mathcal{O}(10^{-7})$
  - yields results unpolluted by NP

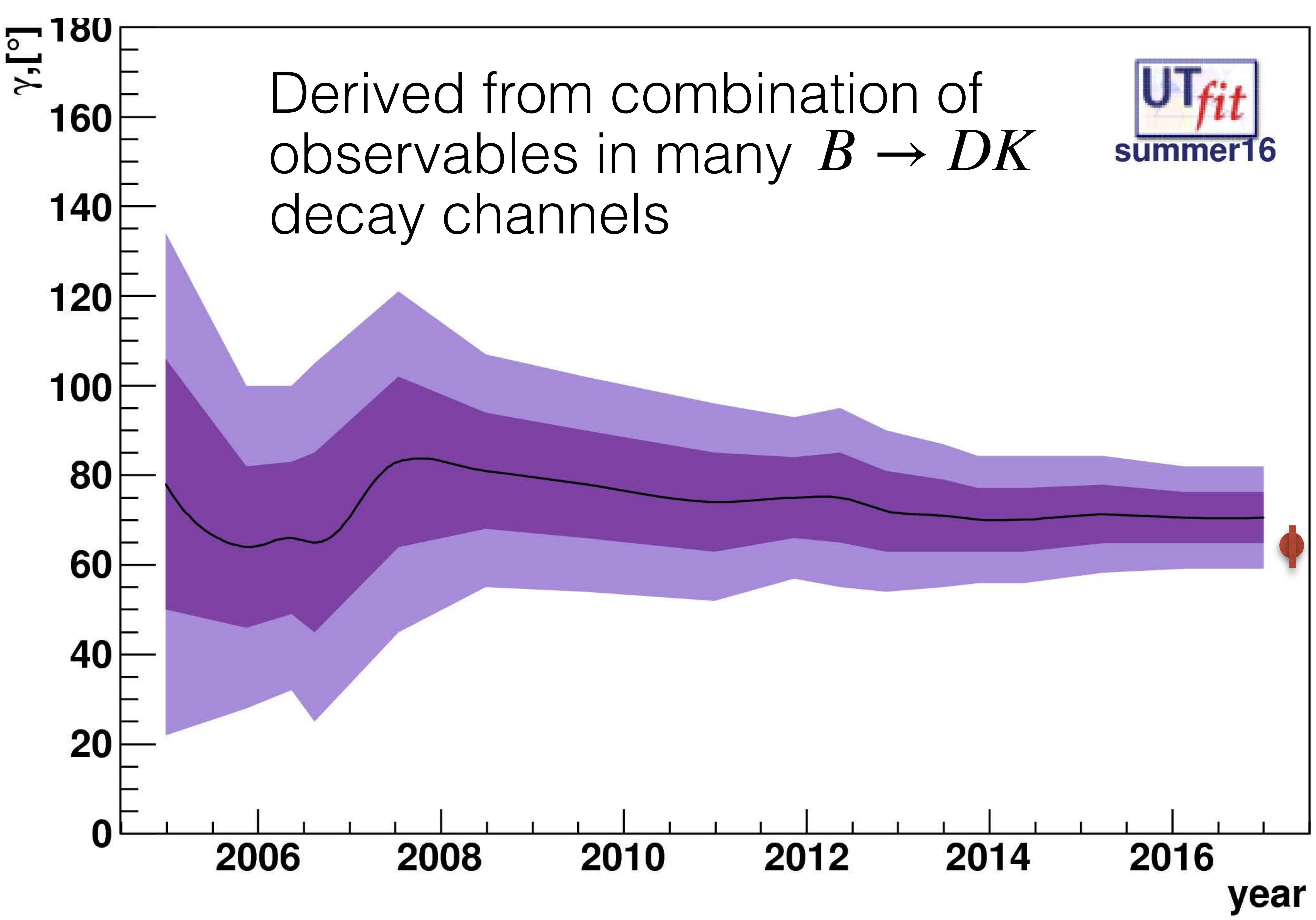
ratio of interfering B amplitudes ~0.10

$$A_{\rm sup}/A_{\rm fav} = r_B e^{i(\delta_B \pm \gamma)}$$

strong phase difference



- Golden mode $B^- \to DK^-$
  - Sensitivity from interference of $b \to c$ and $b \to u$ amplitudes through final states accessible to both D^0 and $\bar{D}^0$
  - Many different methods and decay modes $(K\pi, K3\pi, KK, K_s^0\pi\pi, \dots)$



- Uncertainty on world average ~5°, driven by LHCb
- Consistent with indirect precision but.. not as precise

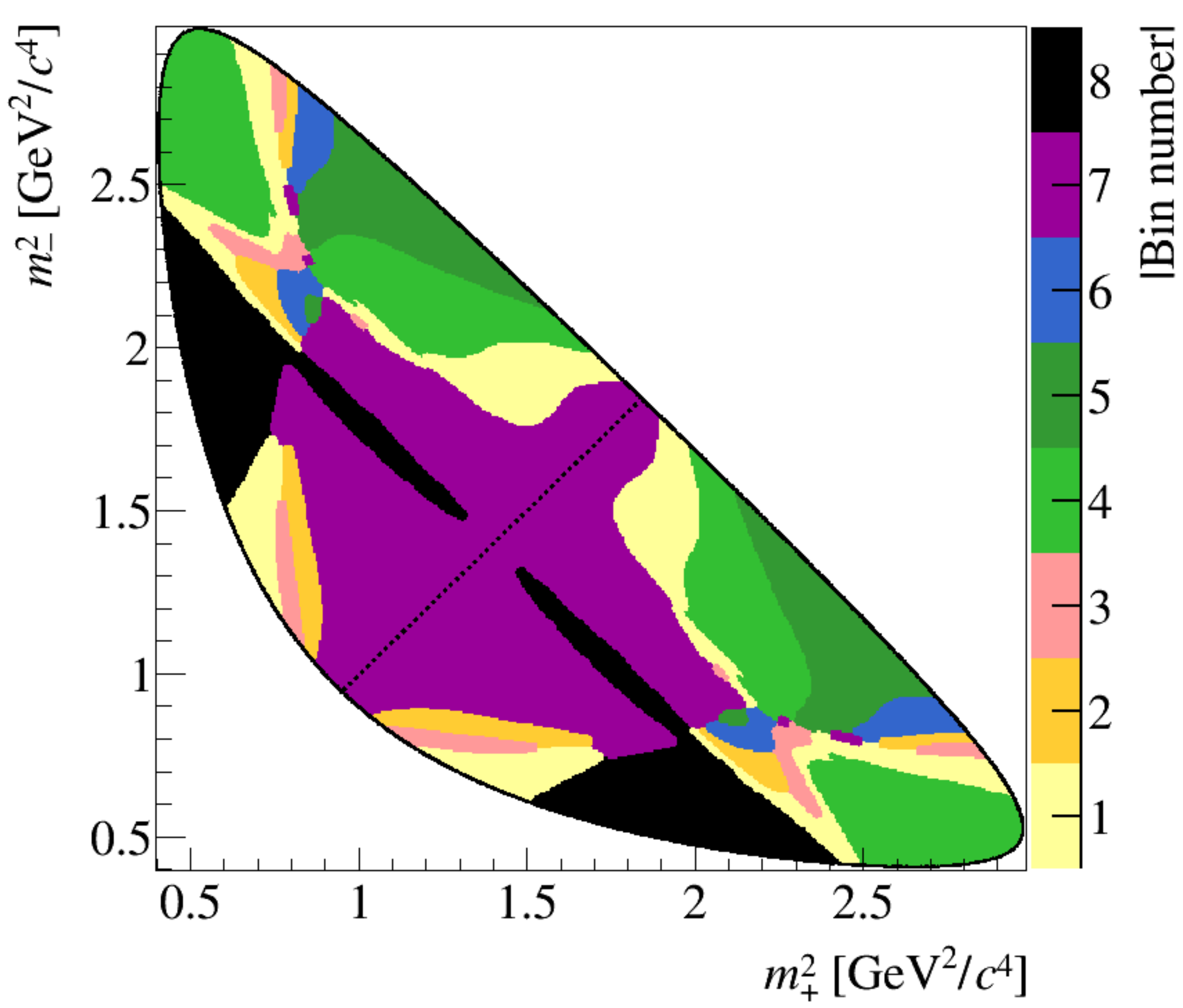
Indirect prediction from rest of triangle (~2° precision)

Measuring γ in *B*→*DK* decays with $D \to K_s^0\pi^+\pi^-,\, K_s^0K^+K^-$

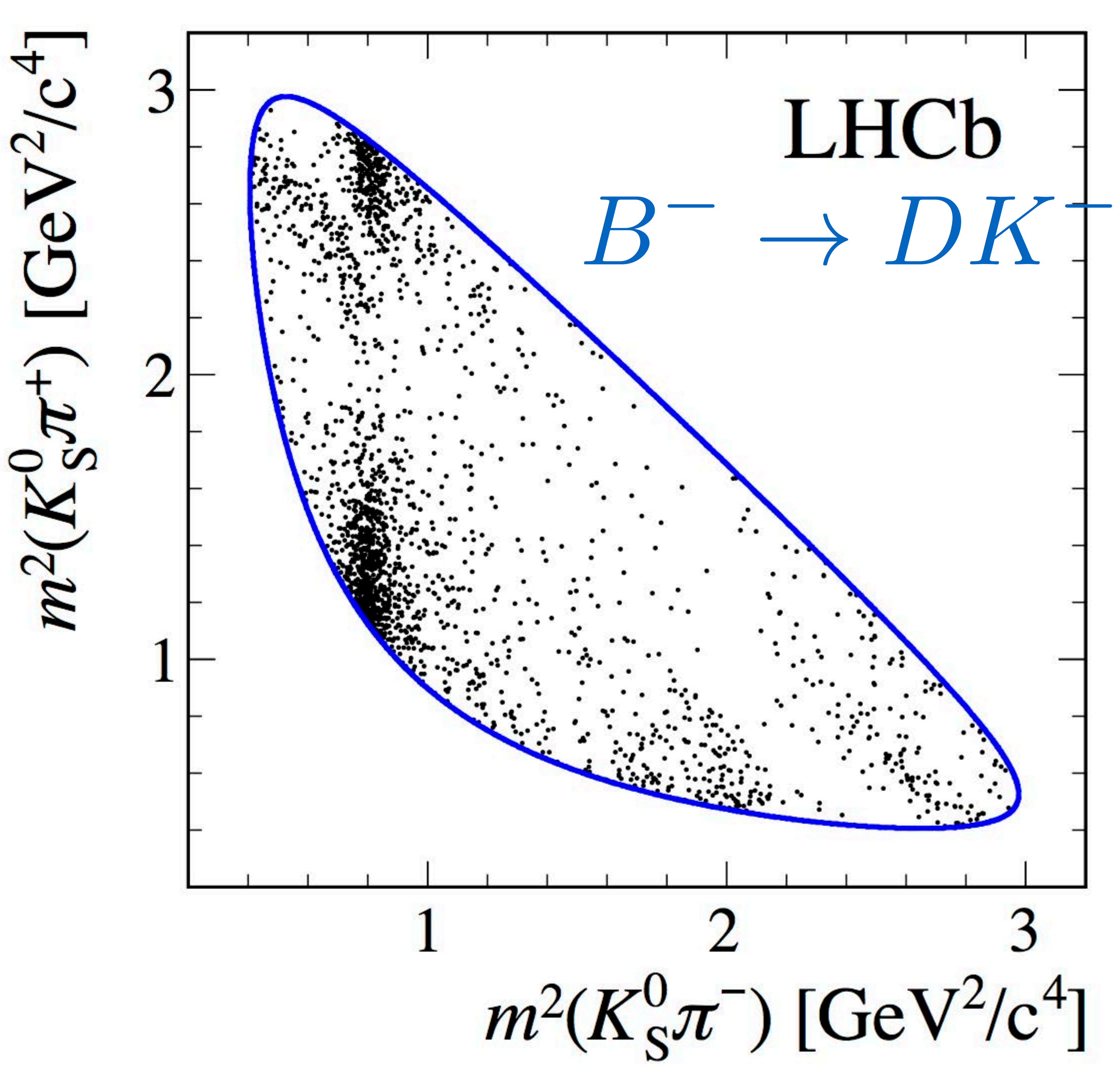
arXiv:1806.01202

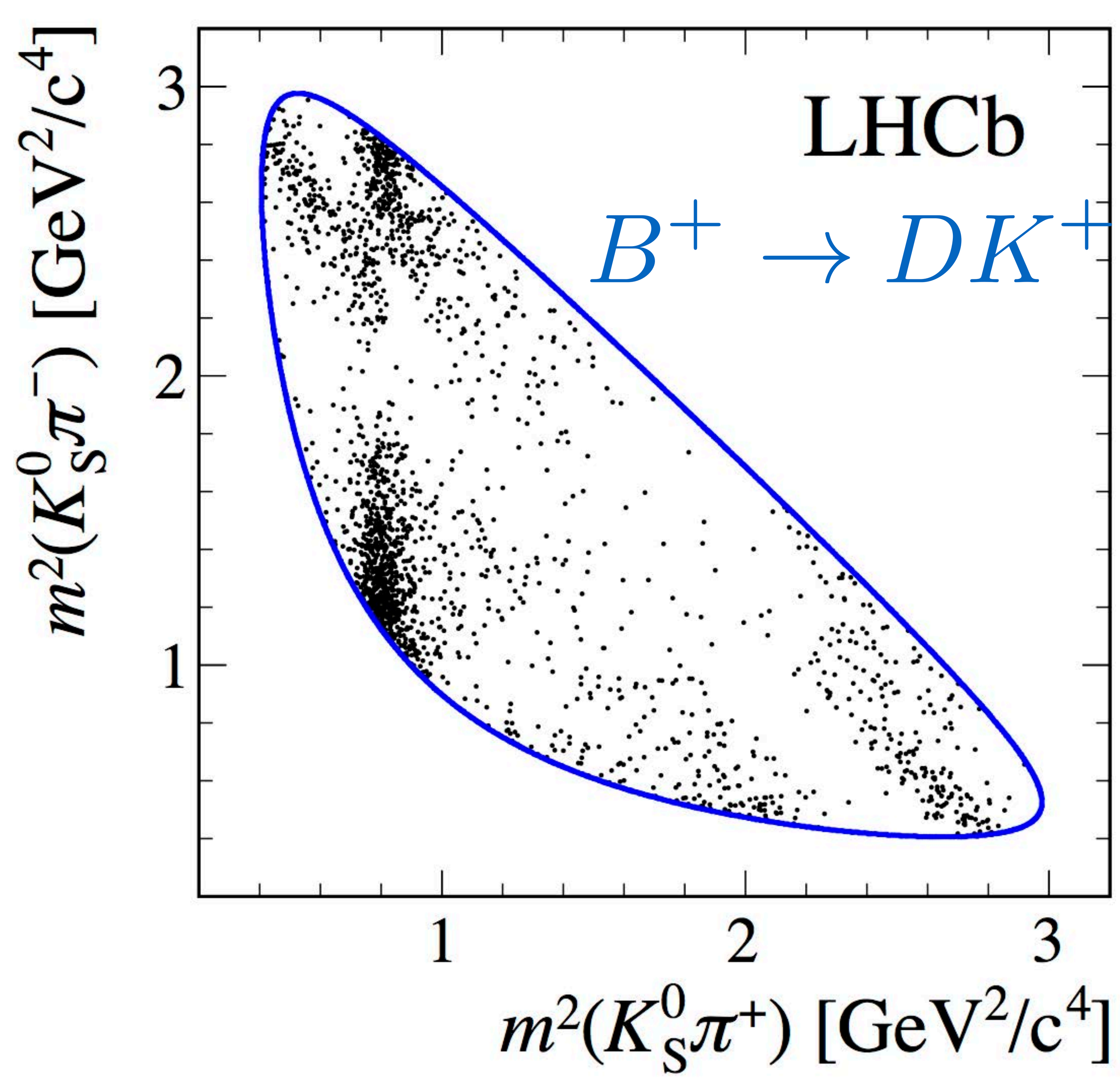
- D reconstructed using the three-body, self-conjugate final state
- Sensitivity to γ by comparing Dalitz plot distributions for B^+ and B^-
- Input on strong phase difference between $D^0, \overline{D}^0$ decay amplitudes across Dalitz plot taken from quantum correlation of $D^0\overline{D}^0$ pairs from ψ(3770) decays → model independent measurement [CLEO, PRD 82 (2010) 112006]
- Analysis of ~4500 decays from 2 fb^{-1} in Run 2

$D \to K_s^0\pi^+\pi^-$



Binning chosen to maximize γ sensitivity





Measuring γ in $B \to DK$ decays with $D \to K_s^0\pi^+\pi^-,\ K_s^0K^+K^-$

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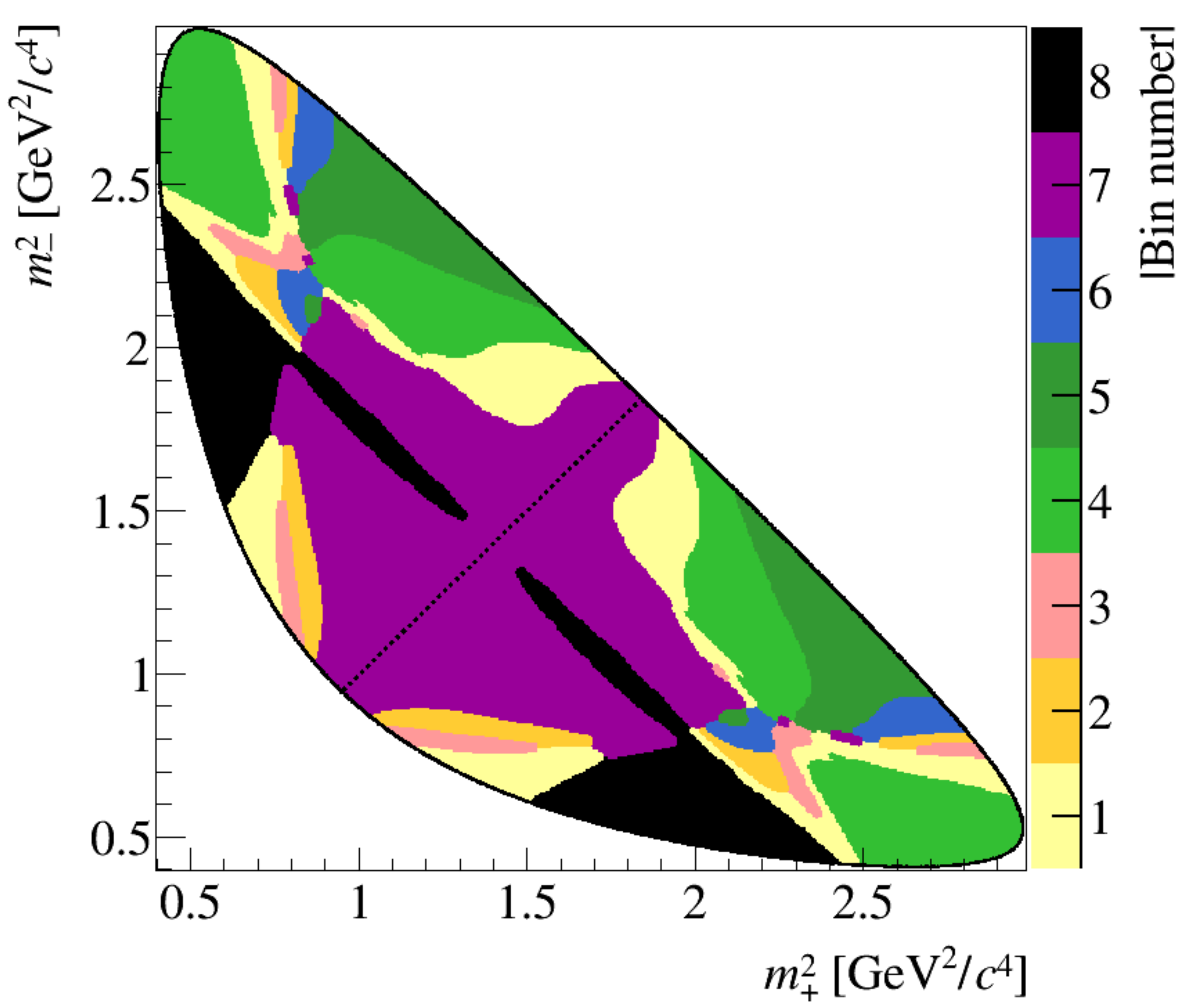

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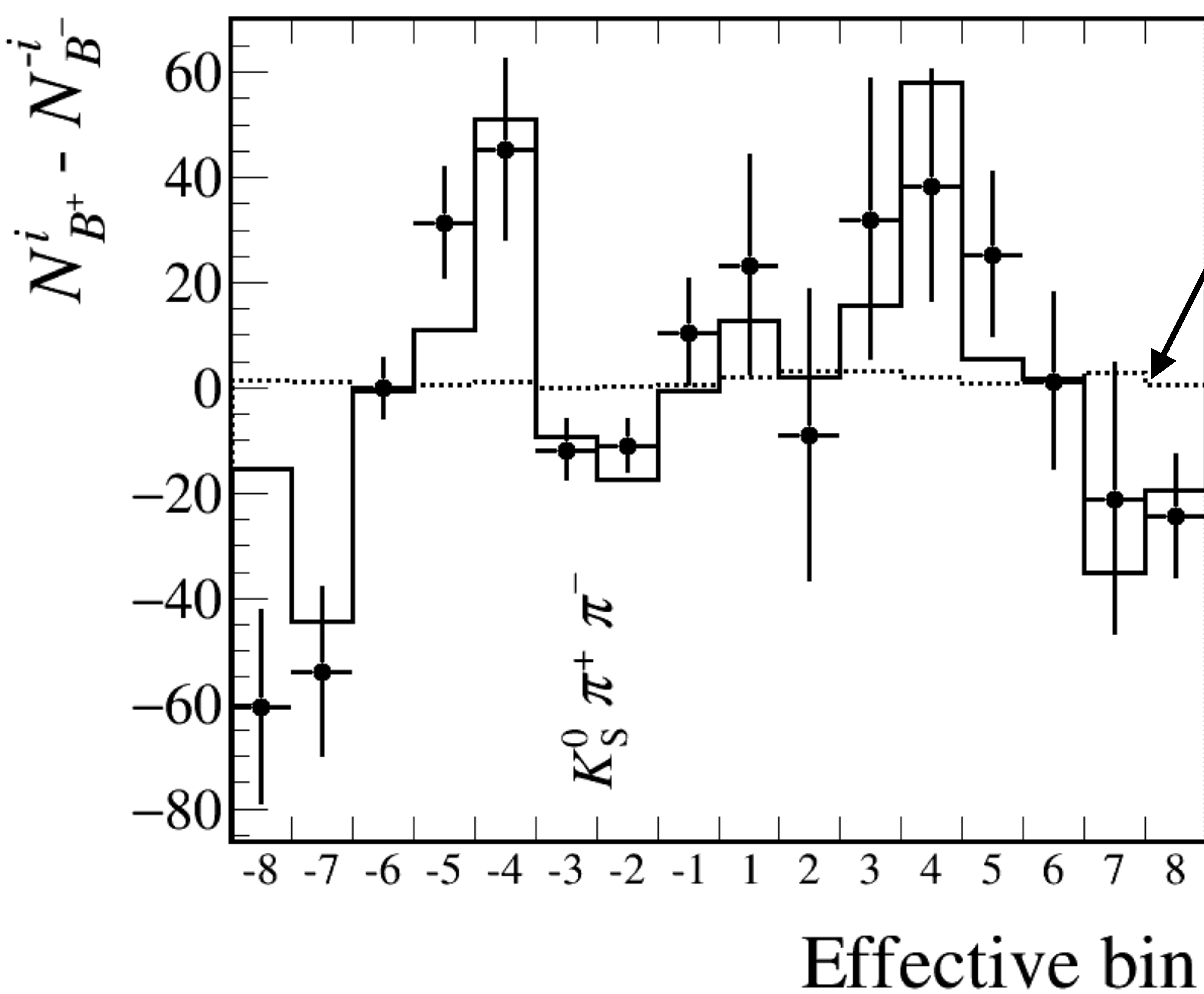
Assuming no CPV



B^+-B^- yields

Measuring γ in $B\to DK$ decays with $D \to K_s^0\pi^+\pi^-,\ K_s^0K^+K^-$

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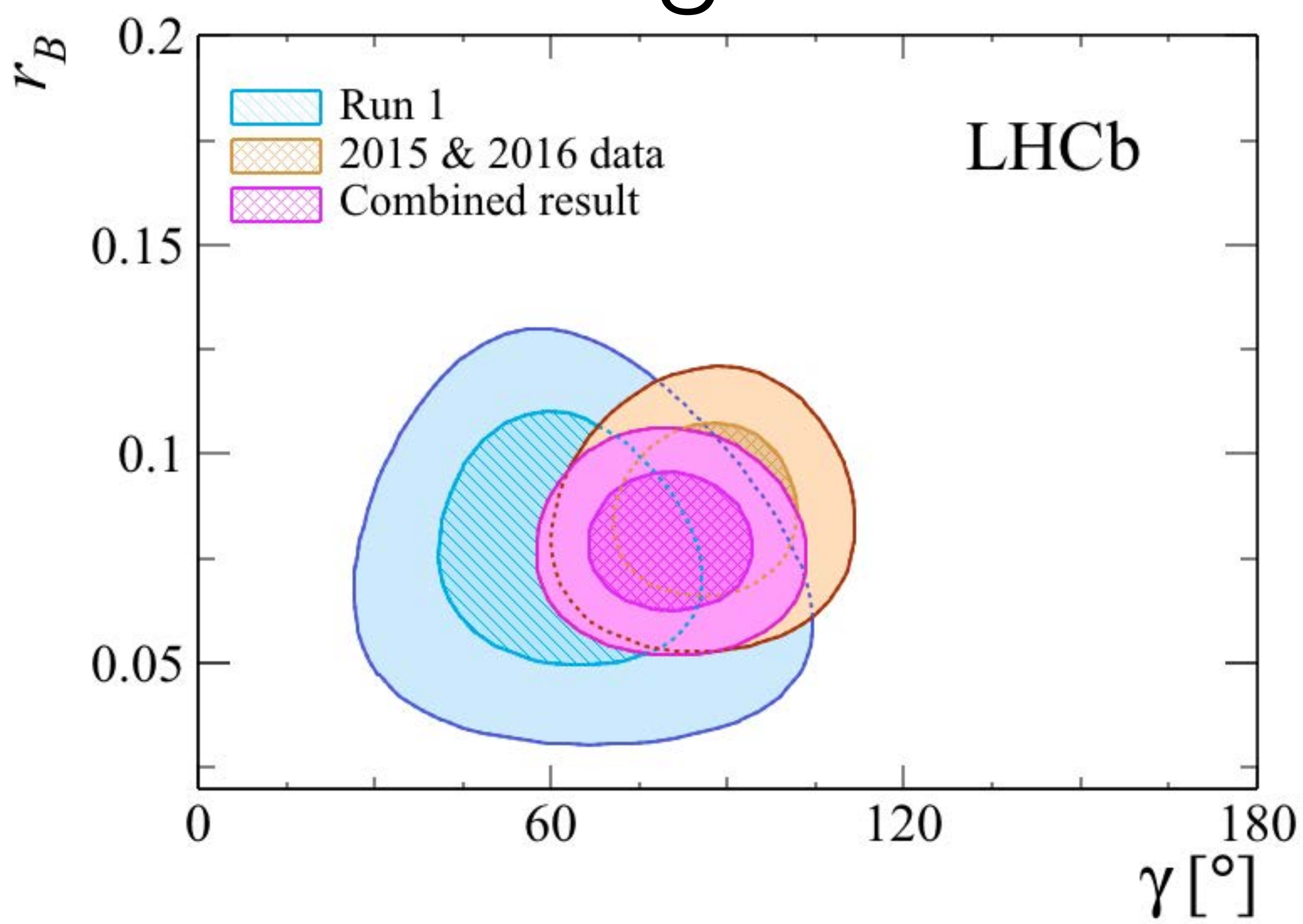
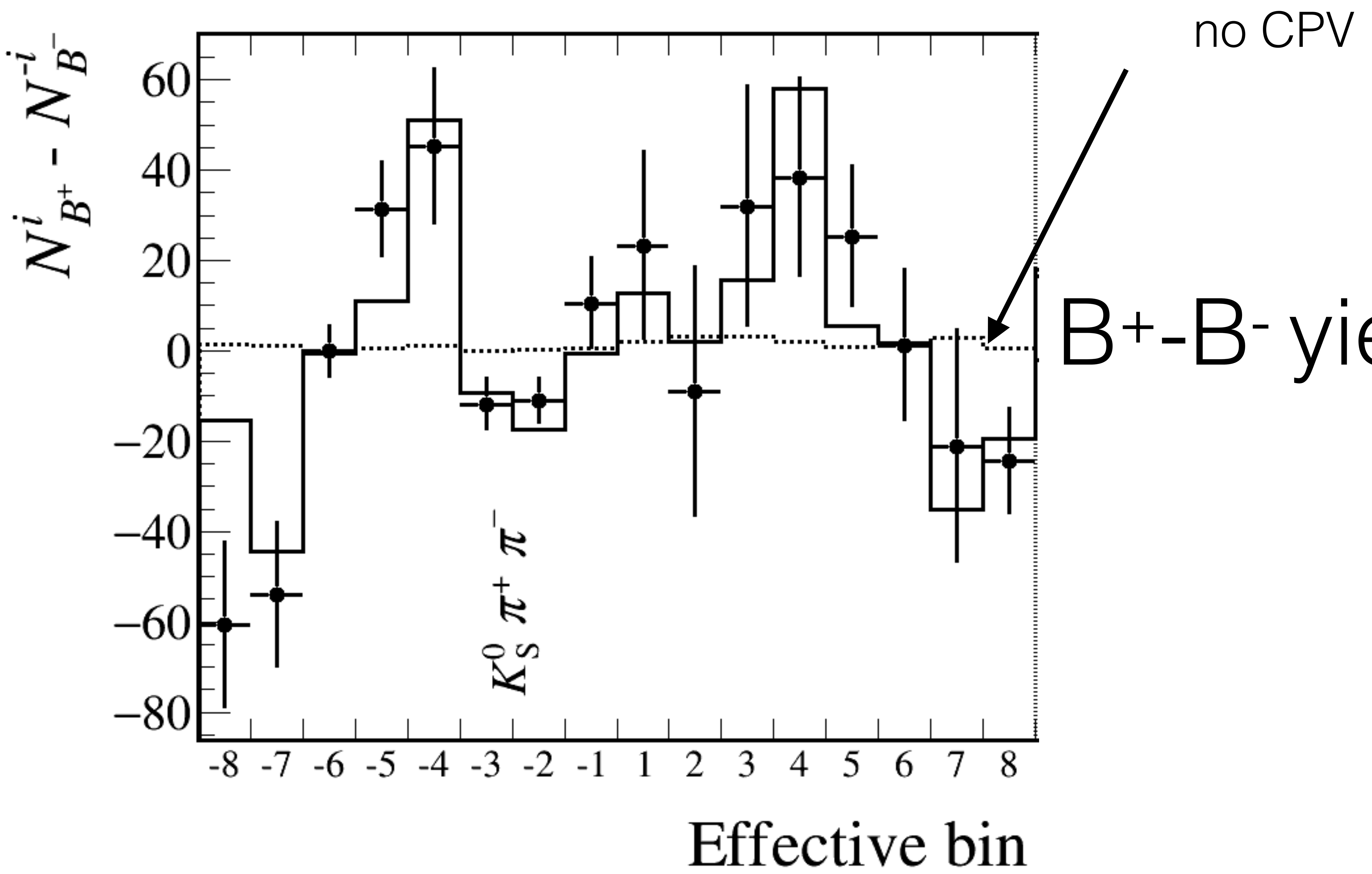
Combining with Run-1





B^+-B^- yields

Measuring γ in $B \to DK$ decays with $D \to K_s^0 \pi^+ \pi^-, K_s^0 K^+ K^-$

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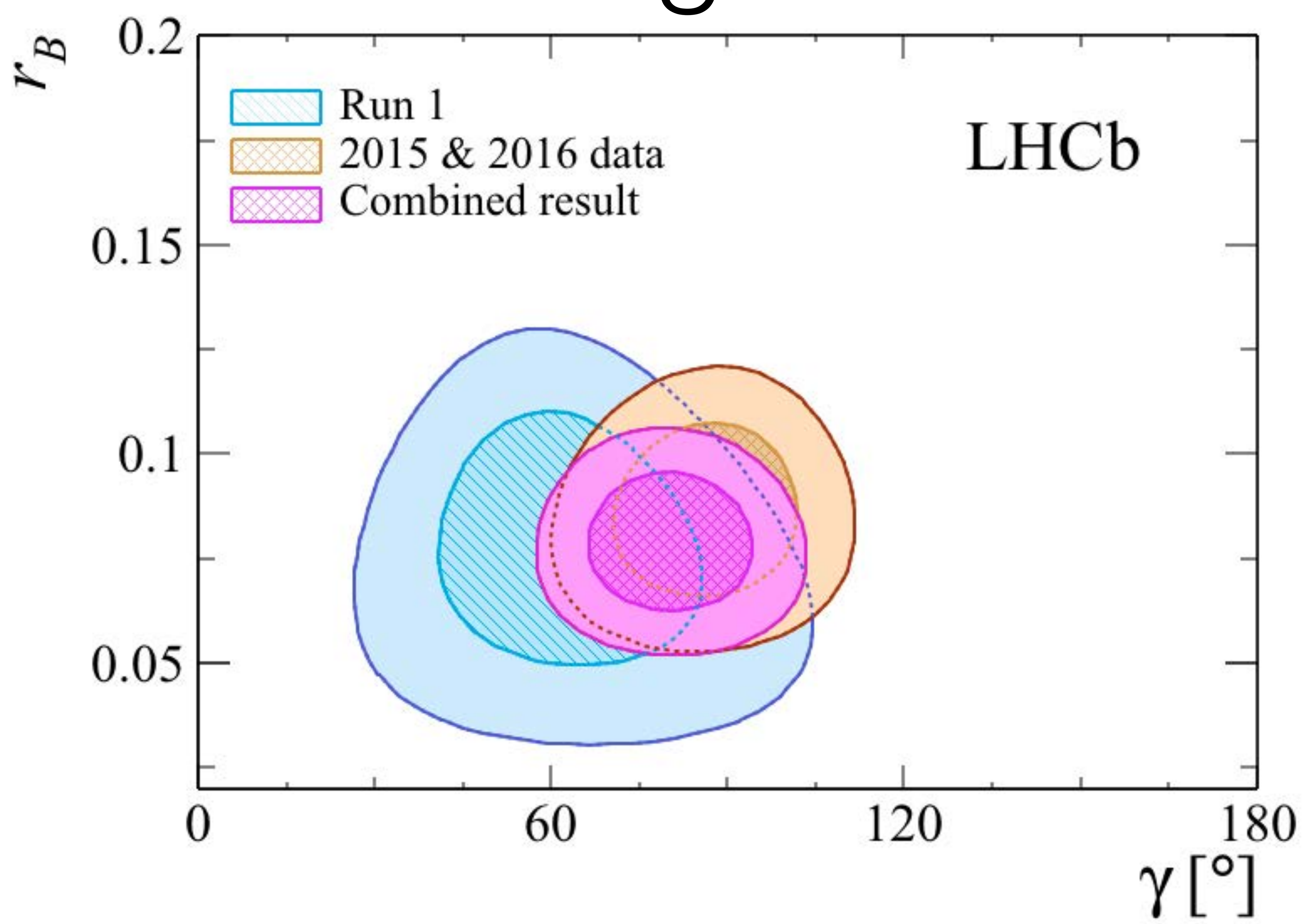


$$\gamma = (87^{+11}_{-12})^\circ$$

Most precise measurement from a single analysis (fixes a single, narrow solution)

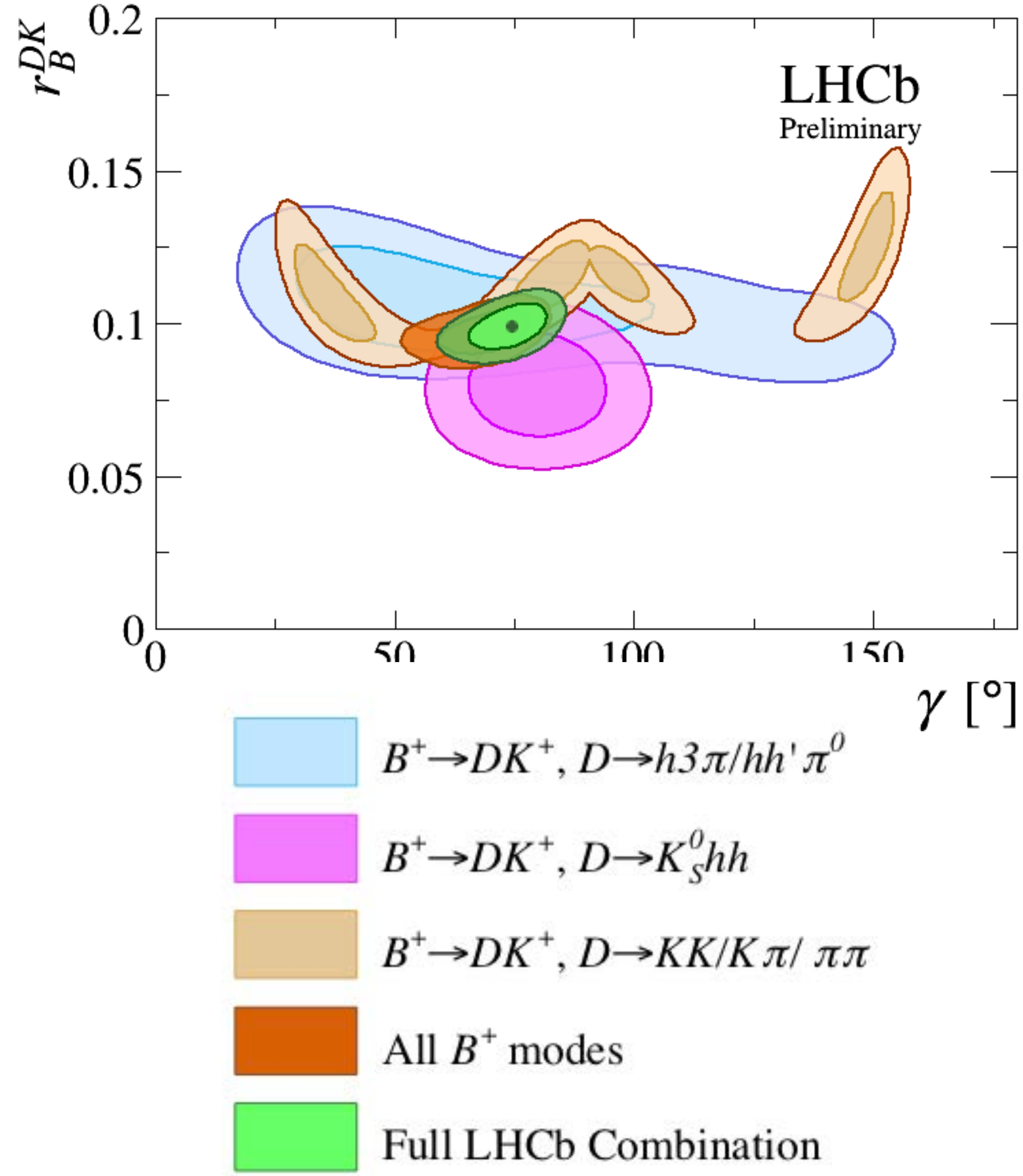
Updated LHCb γ combination

LHCb-CONF-2018-002

- Nice complementarity of the input methods, which vary in precision and number of solutions

	B decay	D decay	Method	Ref.	Dataset[†]
	$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
	$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
	$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
	$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
New	$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1
	$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2
	$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1
New	$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
	$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2
	$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2
	$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1
	$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1
	$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1
	$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1
New	$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	TD	[25]	Run 1
	$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1

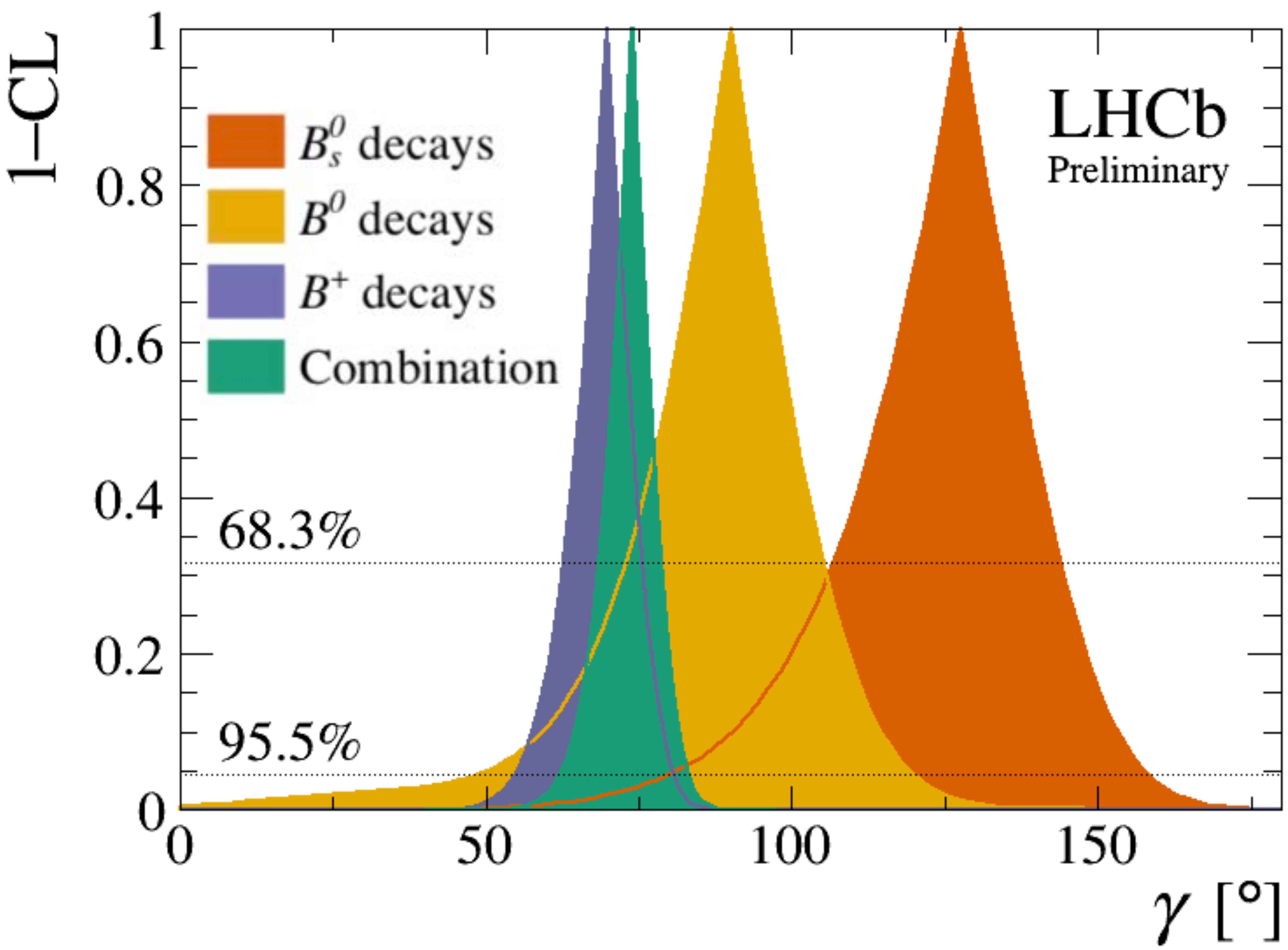
The power of the combination (B+)



Updated LHCb γ combination

LHCb-CONF-2018-002

- Breakdown by B meson type (results consistent at 2σ level)



$$\gamma = (74.0^{+5.0}_{-5.8})^\circ$$

Dominating the WA:

$\gamma = (73.5.0^{+4.2}_{-5.1})^\circ$ (HFLAV, winter '18)

$B^\pm, B^0, B_s$ combination is an LHCb triumph (Ph.Urquijo, ICHEP'18)

- Indirect constraints give $\gamma = (65.8 \pm 2.2)^\circ$ (UTfit, summer 2018, prel.)
  - Slight tension to be monitored as precision improves
  - Measurement statistically dominated (3° to 4° precision at the end of Run 2)

(Talk by Beatriz Garcia Plana)

Tests of Lepton Flavour Universality

Lepton Flavour Universality

- The property that the three charged leptons ($\mathbf{e}$, μ , τ) couple in a universal way to the SM gauge bosons

- In the SM the only flavour non-universal terms are the three lepton masses: m_τ /m_μ /m_e ↔ 3477 / 207/ 1

- If NP couples in a non-universal way to the three lepton families, then we can discover it by comparing classes of rare decays involving different lepton pairs (e.g. $\mathbf{e}/\mu$ or μ/τ)

The family of R ratios

- Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$ allows precise testing of lepton flavour universality

$$R_{\rm H}\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to H\mu^+\mu^-)}{{\rm d}q^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B\to He^+e^-)}{{\rm d}q^2}}\ , \quad q^2 = m^2(\ell\ell)$$

$$H = K, K^*, \phi, ...$$

- $b \to s\ell\ell$ flavour-changing neutral currents with amplitudes involving loop diagrams

- These ratios are clean probes of NP :

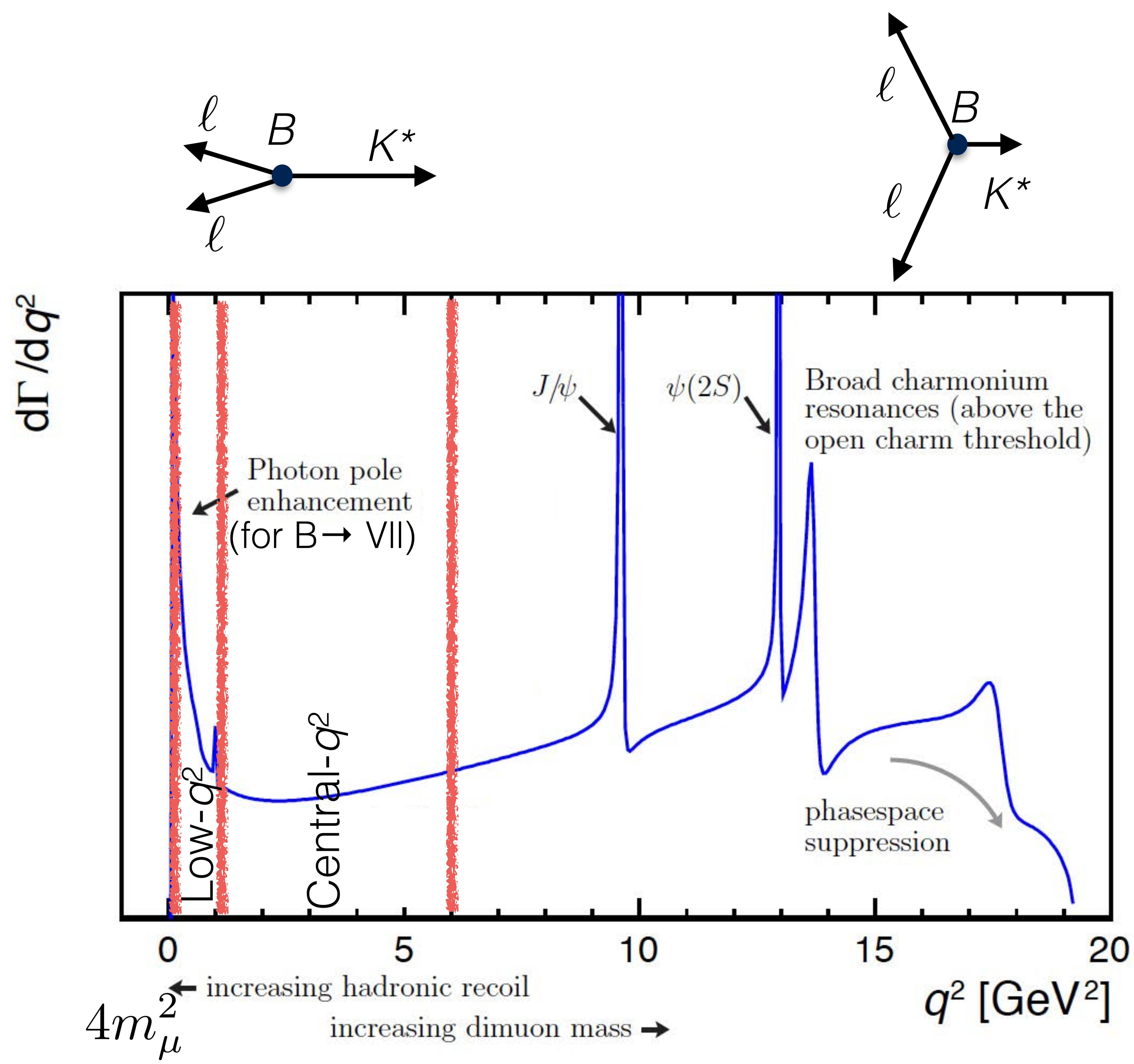
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons

  - Small theoretical uncertainties because hadronic uncertainties cancel: in SM, $R_{\rm H} = 1$ neglecting lepton masses, with QED corrections at ~% level

The R_{K^*} ratio

$$R_{\mathrm{K}^{*0}}\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0 \to K^{*0}\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0 \to K^{*0}e^+e^-)}{\mathrm{d}q^2}}, \quad K^*(892)^0 \to K^+\pi^-$$

- LHCb performed measurement in two q^2 bins:
    - Low-q^2 bin: [0.045,1.1] GeV^2
    - Central-q^2 bin: [1.1,6.0] GeV^2



A very challenging measurement!

- Lepton identification is anything but universal!
  - Electrons emit a large amount of bremsstrahlung, degrading mass resolution → need to recover energy using clusters in the calorimeter
  - Due to higher occupancy of calorimeters, trigger thresholds are higher for electrons (~2.5 to 3.0 GeV) than for muons (~1.5 to 1.8 GeV) → decays with electrons also selected using hadron trigger either fired by K^* products or by any other particle in the event not associated with signal

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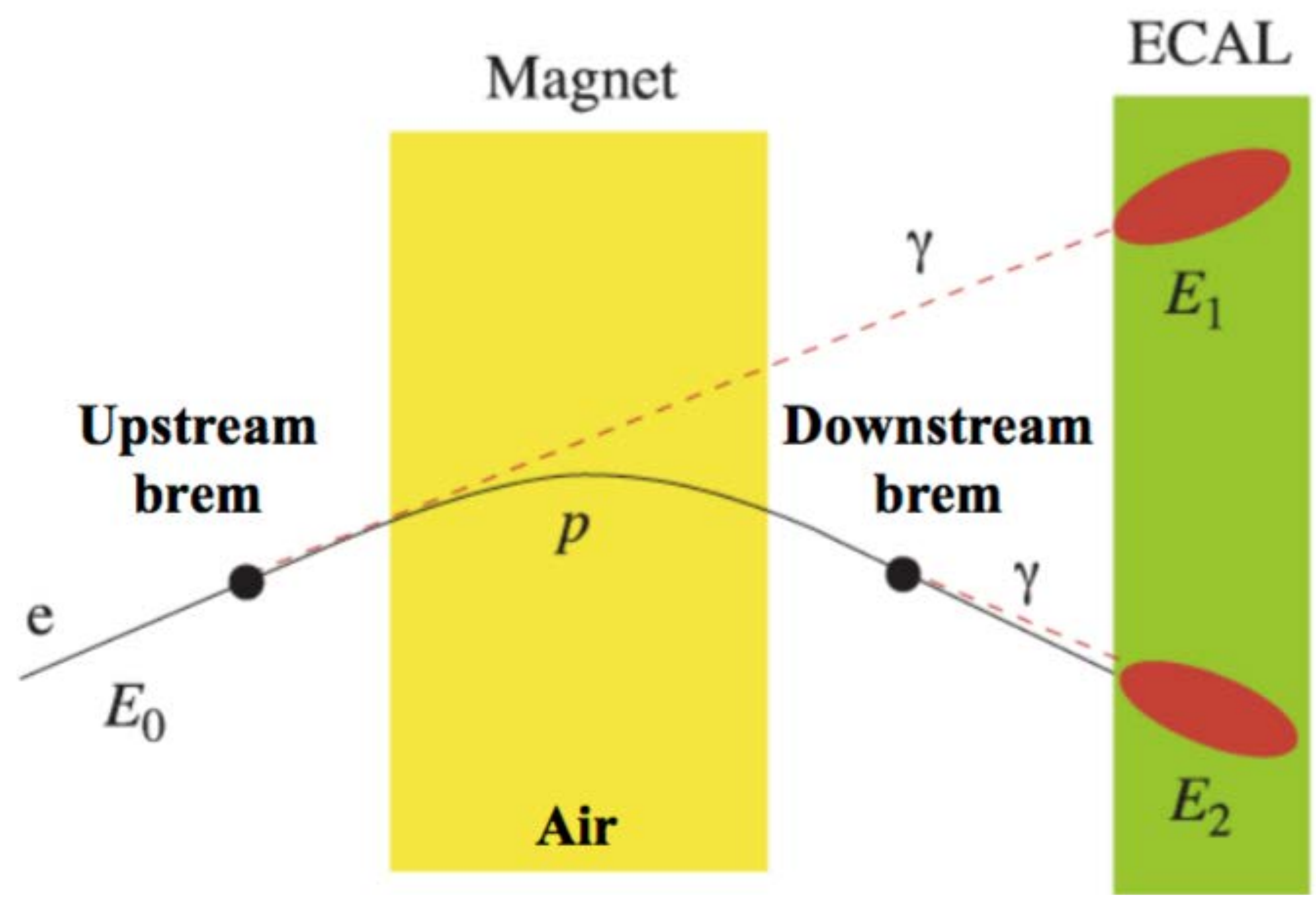
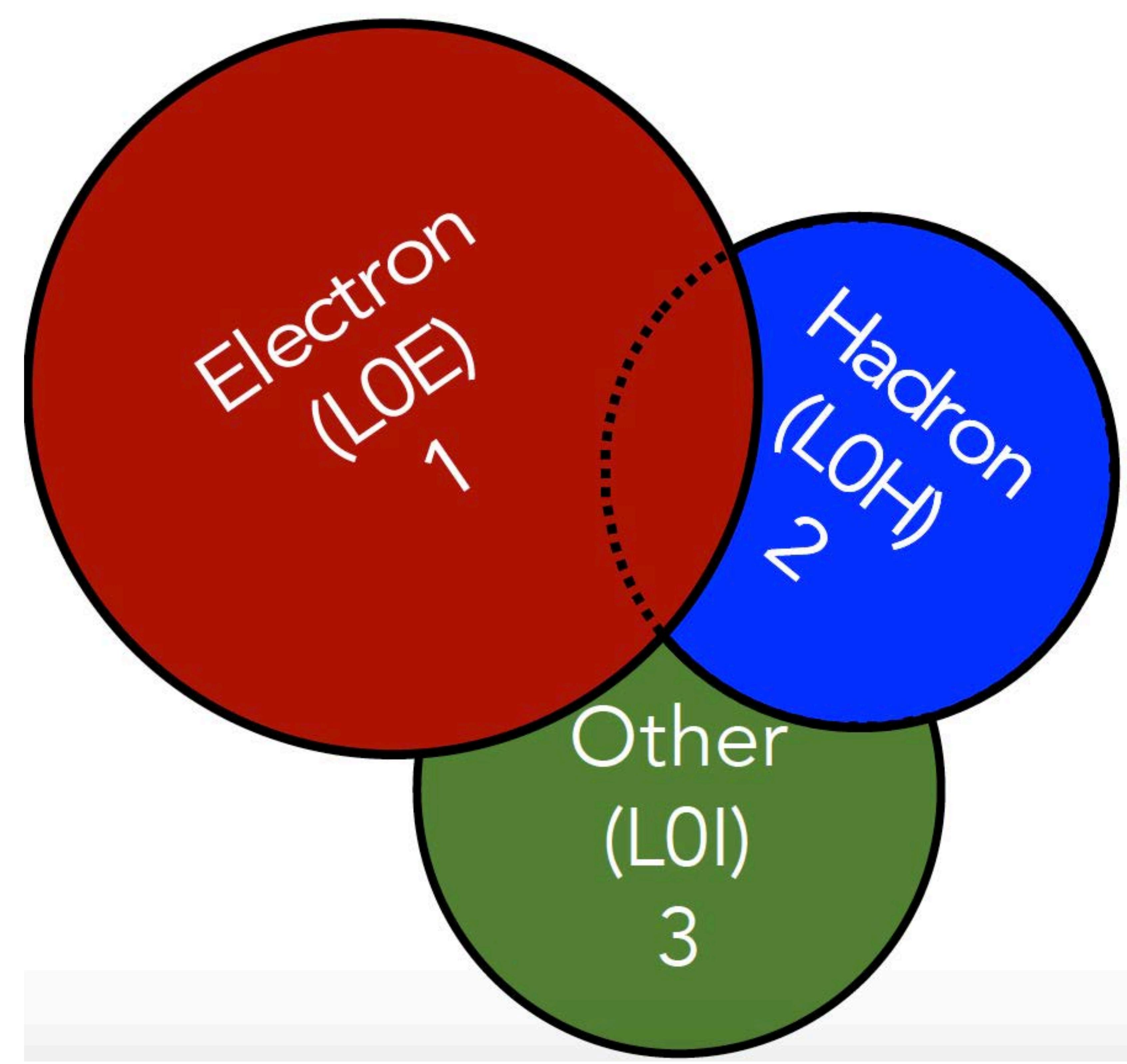




Measure as a double ratio

- To mitigate muon and electron differences due to bremsstrahlung and trigger, measurement performed as a double ratio with “resonant” control modes $B^0 \to J/\psi K^*$ which are not expected to be affected by NP:

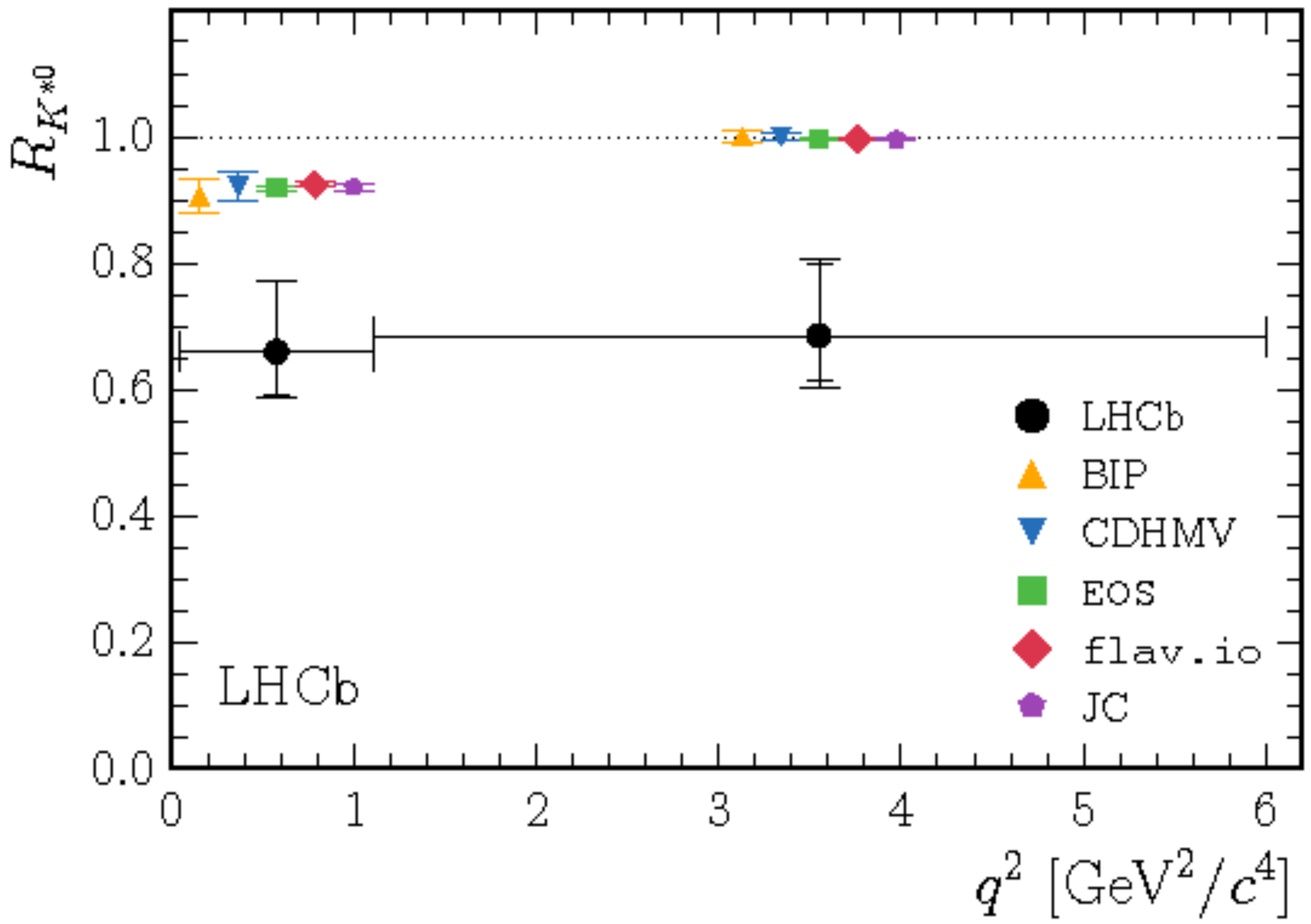
$$R_{\mathrm{K}^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

→ Relevant experimental quantities: yields & efficiencies for the four decays

- Similarities between the experimental efficiencies of the non resonant and resonant modes ensure a substantial reduction of systematic uncertainties in the double ratio

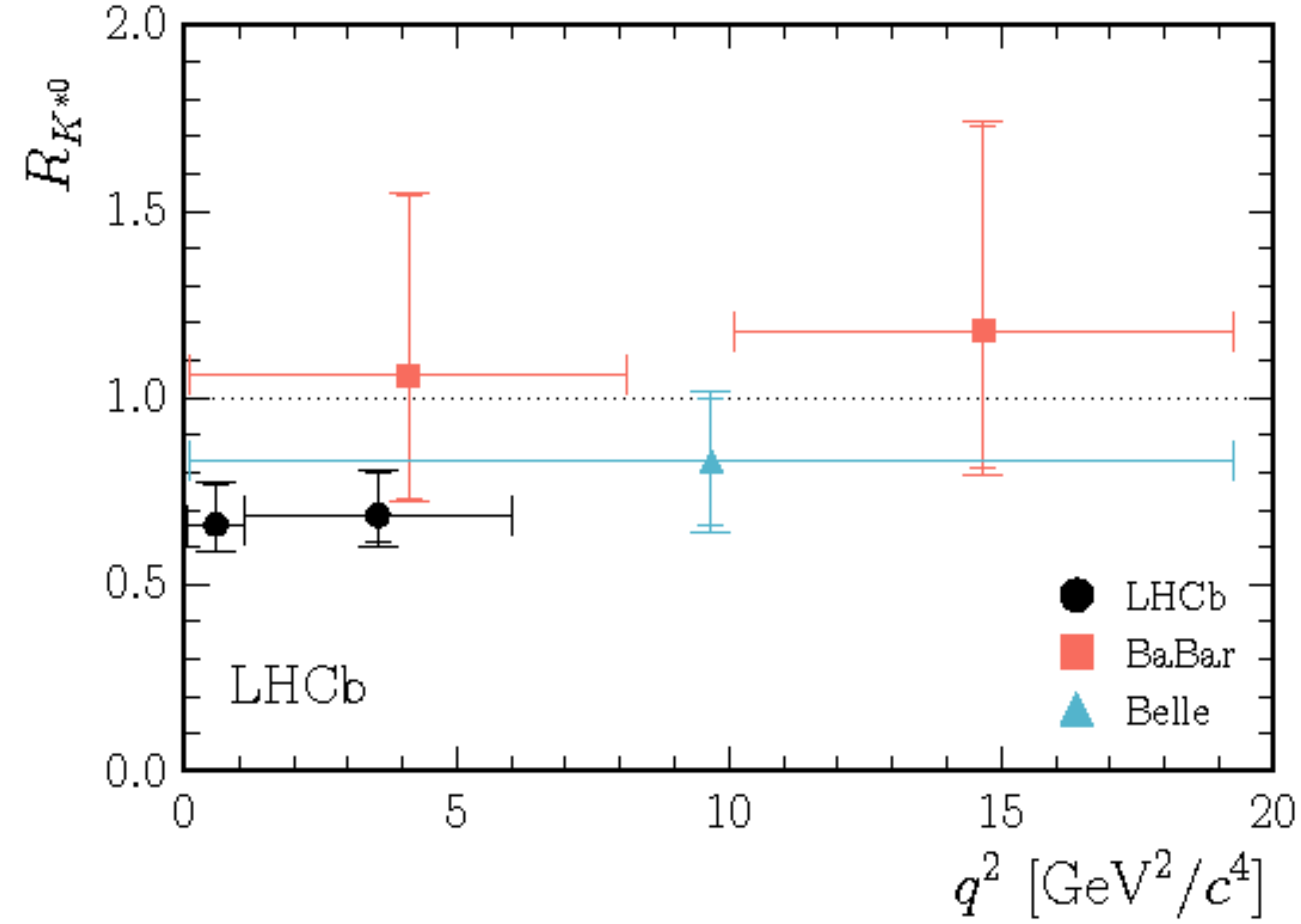
Results

Comparison with SM predictions



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

Comparison with BaBar & Belle



BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

LHCb: JHEP 08 (2017) 055

$\int \mathcal{L}\, dt \sim 3\, \text{fb}^{-1}$

$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2 \end{cases}$$

2.1 - 2.3 σ
2.4 - 2.5 σ

Crosschecks

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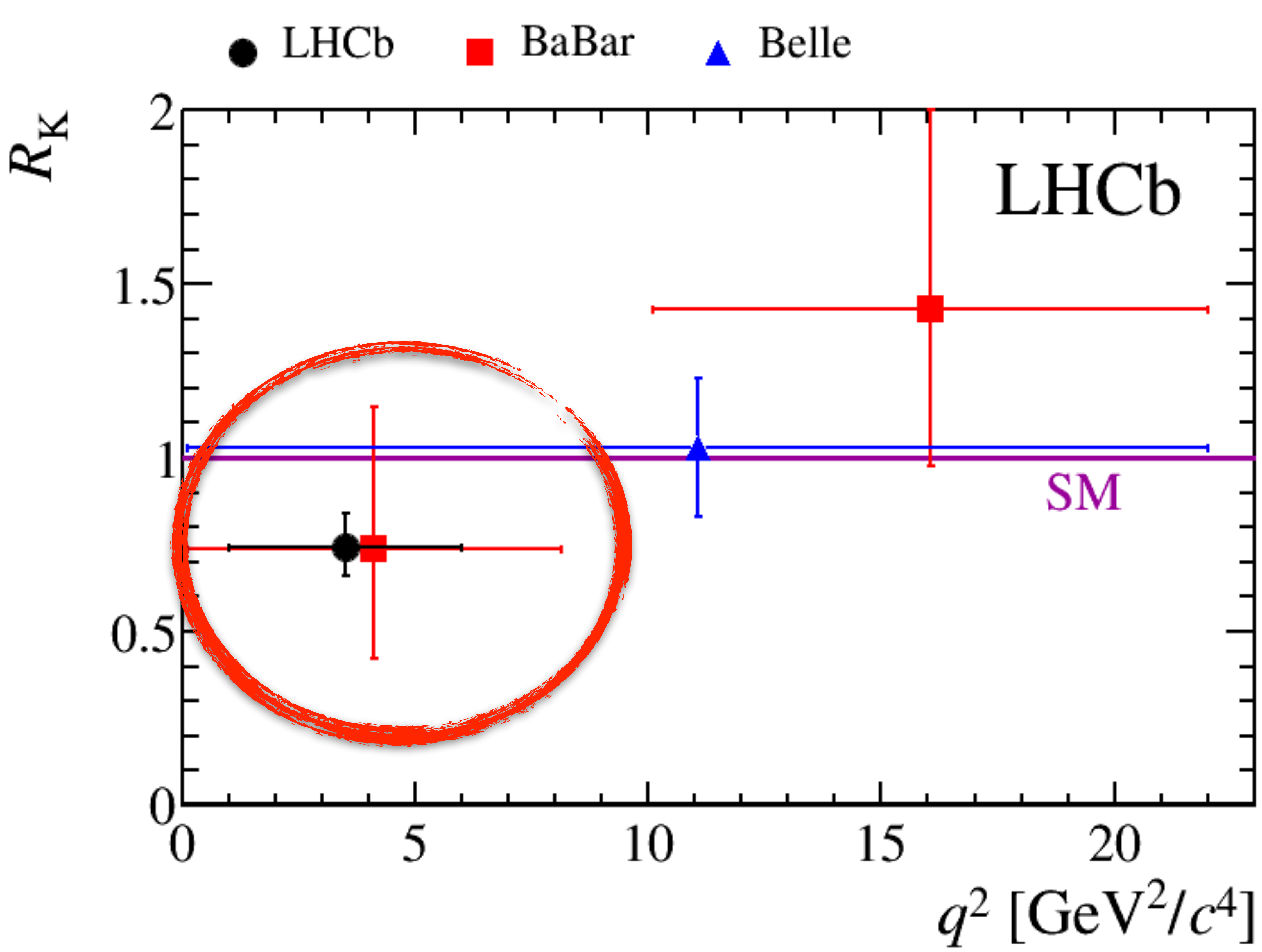
- $r_{J/\psi} = \dfrac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$
  - very stringent test of absolute scale of efficiencies that does not benefit from the cancellation of the experimental systematics from the double ratio
  - compatible with being independent of decay kinematics (p_{T}, η of the B^0 candidate) and track multiplicity
- $R_{\psi(2S)} = \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Big/ \dfrac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$ → compatible with expectation
- $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$ in agreement with JHEP 04 (2017) 142
- $\mathcal{B}(B^0 \to K^{*0}\gamma)$ compatible with expectations
- If corrections to simulation are not accounted for, the ratio of the efficiencies (and thus R_{K^*}) changes by less than 5%

A reminder: R_K

- LHCb published an analysis of R_K based on Run 1 ($\int \mathcal{L}\,\mathrm{d}t \sim 3\mathrm{fb}^{-1}$)

$$R_K\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^+\to K+e^+e^-)}{\mathrm{d}q^2}}, \quad 1 < q^2 < 6\,\mathrm{GeV}^2$$

- Also measured as a double ratio wrt $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$



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

LHCb: PRL 113 (2014) 151601

BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

What happens next?

Short term

- Work very advanced on R_K update with additional Run 2 data (5 fb^{-1} in total) with much improved sensitivity (rel. uncertainty reduced by ~40%)
- Run 2 update of R_{K^*}
- Can make analogous measurement with $R_\phi(B_s \to \phi\ell^+\ell^-)$ and other similar modes

Long term

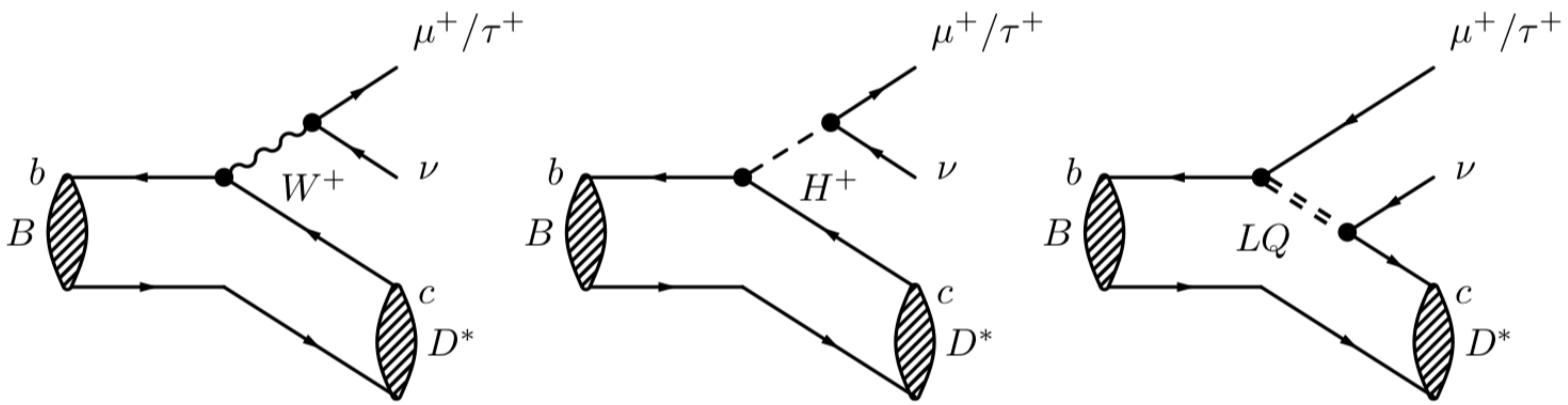
The Belle II Physics Book (in preparation)
LHCb: LHCb-PUB-2018-009 (in preparation)

Observable	Current LHCb	Run 2	LHCb 2025	Belle II	Upgrade II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1	0.05	0.022	0.036	0.006
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2 c^4)$	0.1	0.06	0.029	0.032	0.008
R_ϕ, R_{pK}, R_π			0.07, 0.04, 0.11	–	0.02, 0.01, 0.03

- ATLAS/CMS also getting more interested, e.g. CMS has in place a new trigger strategy wrt flavour with sizeable fraction of trigger bandwidth dedicated to flavour physics since beginning of this year

Another puzzling result in tree-level b → c transitions

LFU studies in $B \to D^{(*)}\tau\nu$ decays



- Different class of decays (tree-level charged current with V_{cb} suppression)
- Not at all rare: $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\%$, problem is the background
- Lepton-universality ratio R(D*) : $R(D^*) = \dfrac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\tau)}$
  - sensitive to any NP model coupling preferentially to third generation leptons
- Predicted theoretically at ~1%, e.g.

$$R(D)_{\mathrm{SM}} = 0.299 \pm 0.003$$
$$R(D^*)_{\mathrm{SM}} = 0.227 \pm 0.003$$

Berlochner et al
arXiv:1703.05330

[R(D*) ~4%, according to Bigi et al, arXiv:1707.09509]

- Studied by Belle, BaBar and LHCb

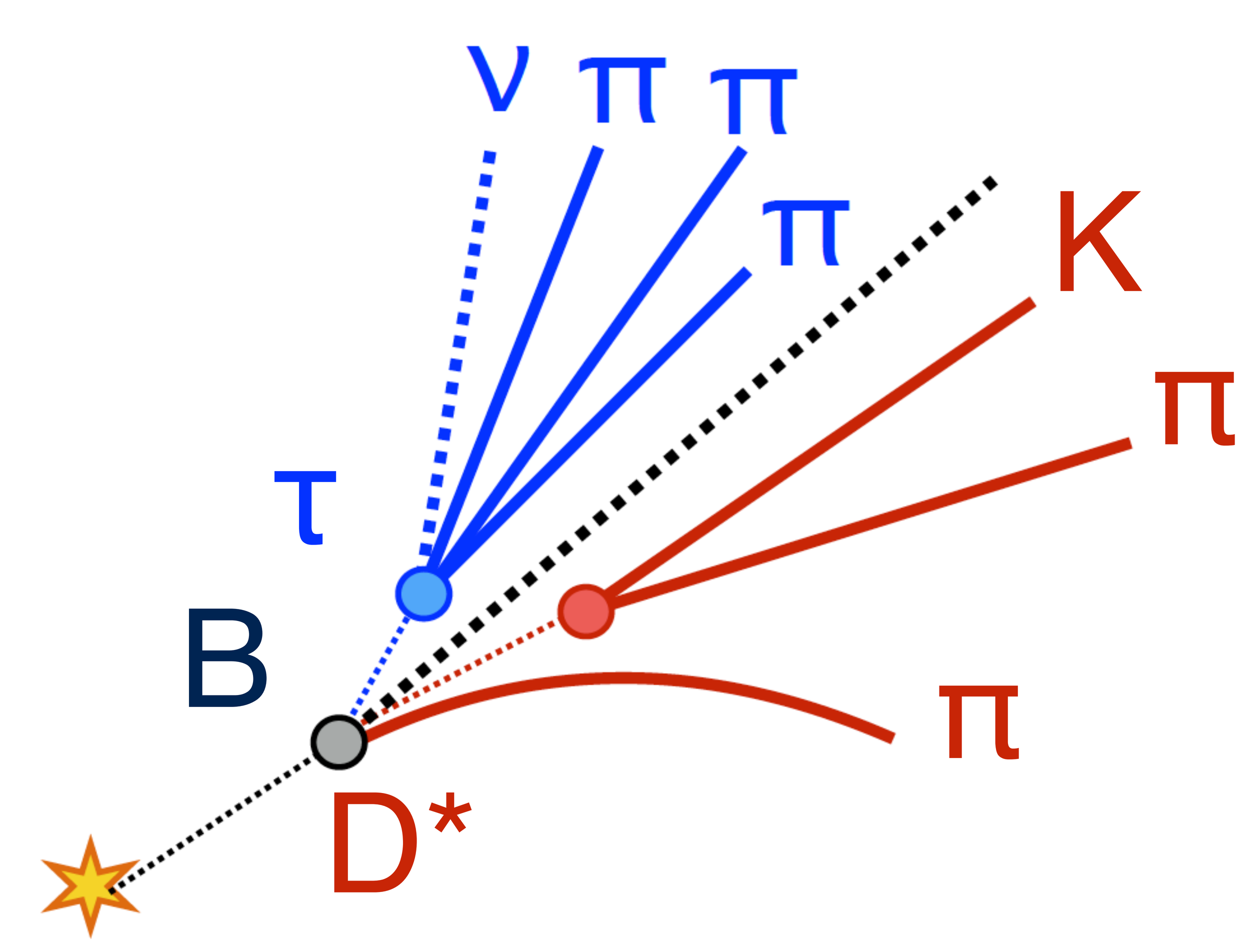
Experimental challenges

- At least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$)

- At the LHC, as opposed to B factories, the rest of the event does not provide any useful kinematic constraint. However, profit from large boost and huge B production

- Latest LHCb measurement:

$$\begin{cases} \tau^+ & \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau \\ D^{*-} & \to \overline{D}^0(\to K^+\pi^-)\pi^- \end{cases}$$



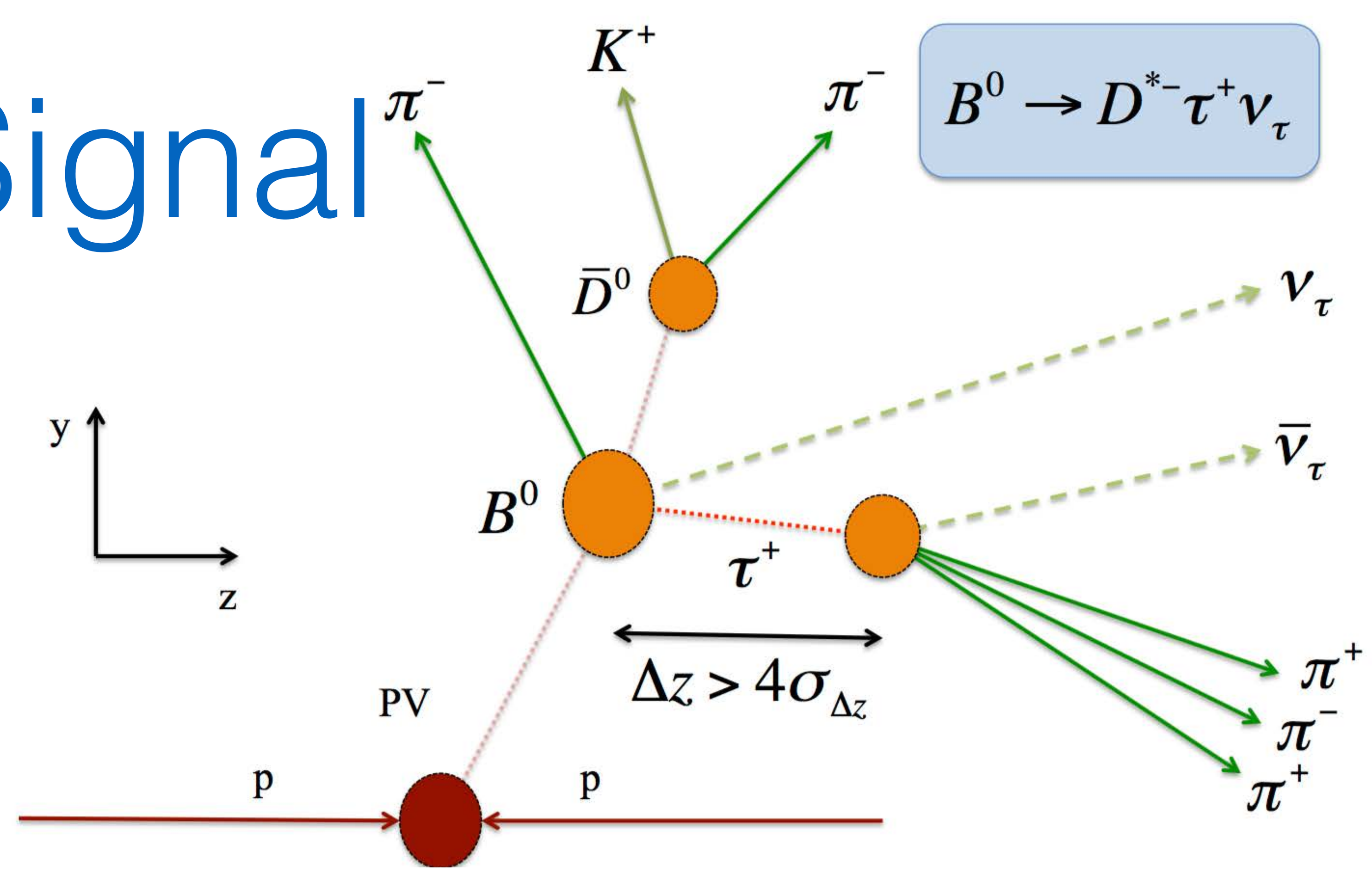
Three-prong mode used for the first time!

- A semileptonic decay with no (charged) lepton in final state (one *K*, five π) ➞ Zero background from $B^0 \to D^{*-}\mu^+\nu_\mu X$
- However, signal to noise ratio less than 1% ➞ need at least 10^3 rejection!
- Large background, notably from $B \to D^{*-}3\pi X$ (BF~100 x signal) and $B \to D^{*-}D_s^+(X)$ (BF~10 x signal, same vertex topology)

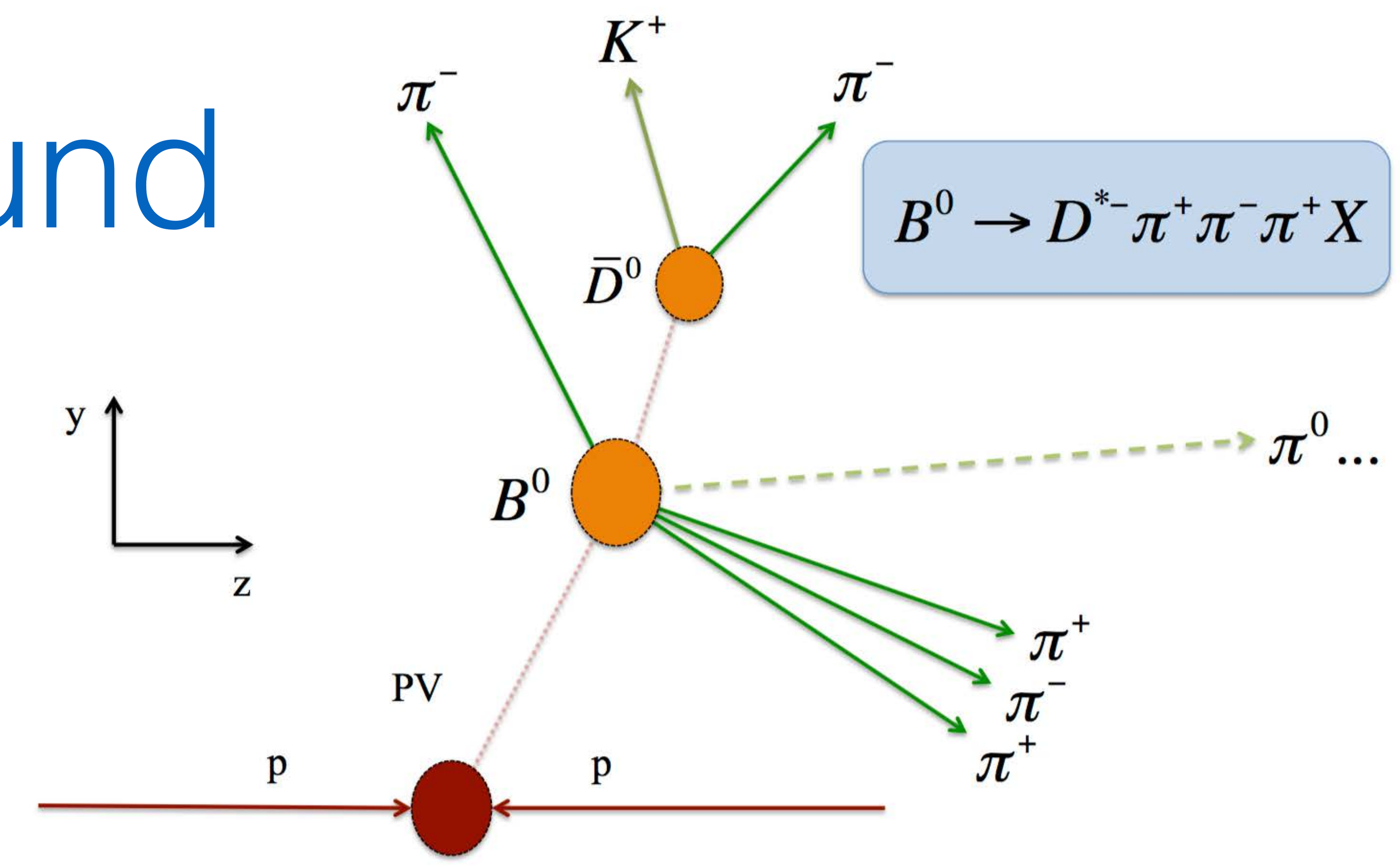
Background reduction

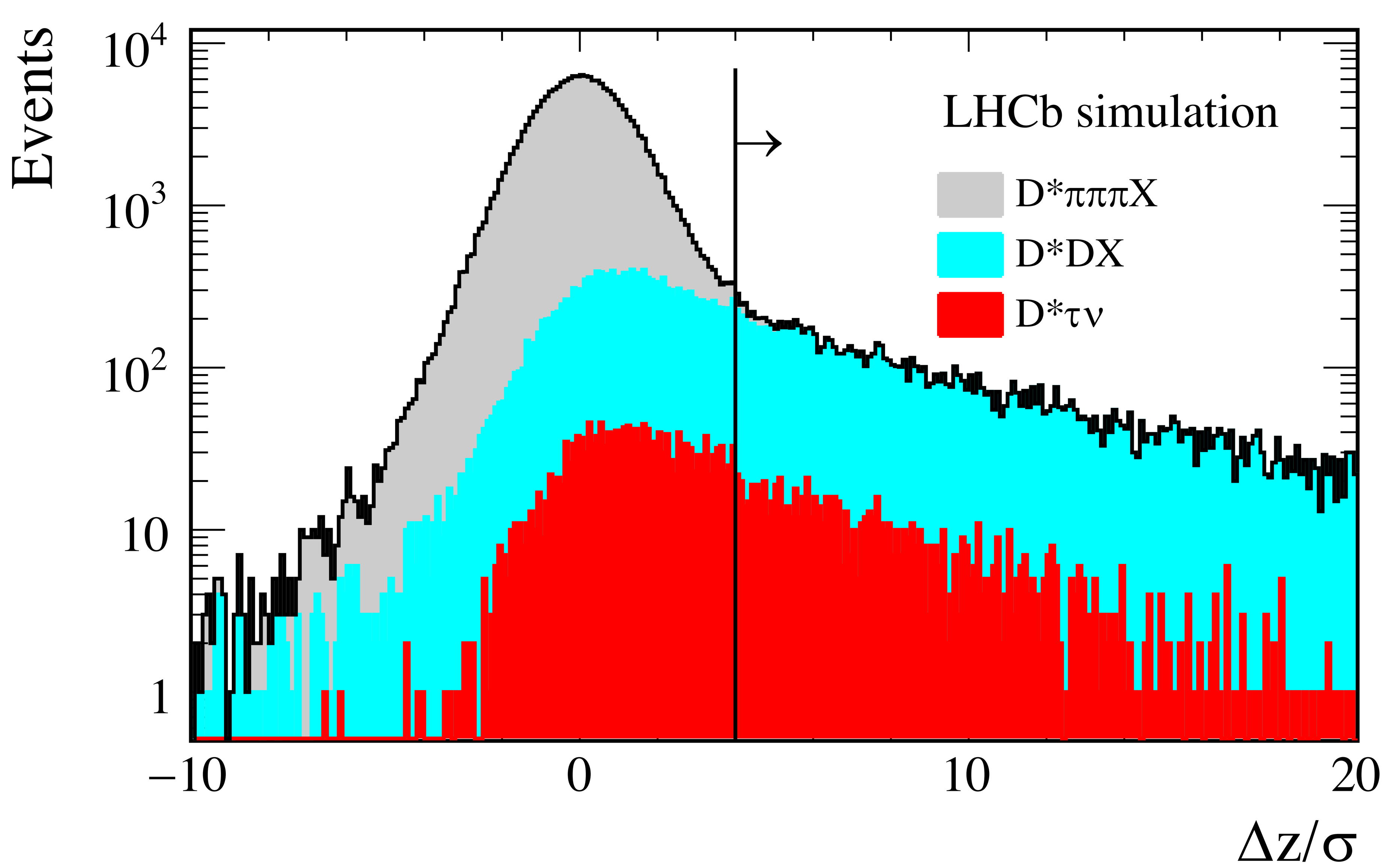
- Separation between B and 3π vertices ($\Delta z > 4\sigma_{\Delta z}$) crucial to obtain the required rejection of $B \to D^{*} 3\pi X$

Signal



Background





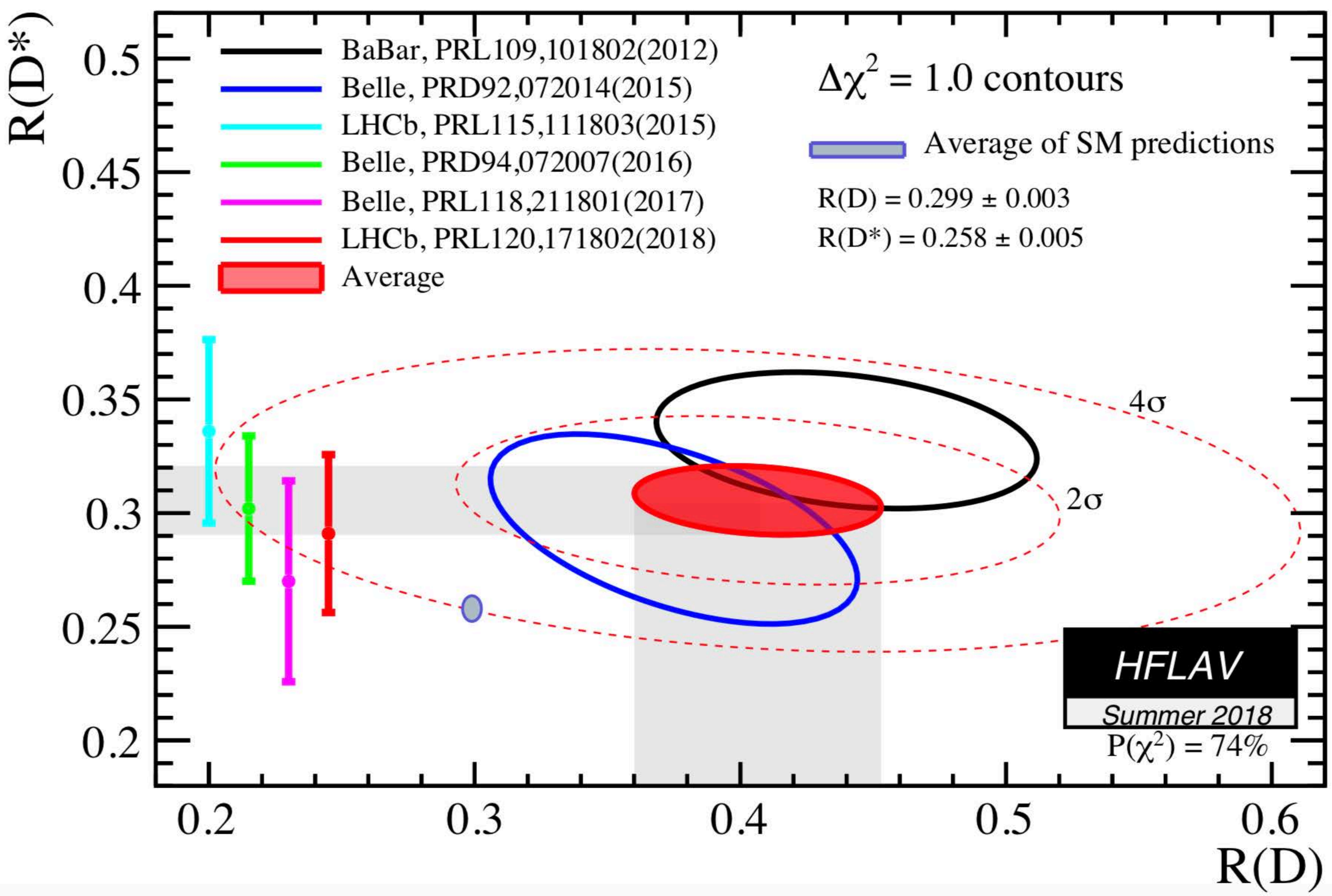
- Remaining double-charm background ($D^*D_{(s)}X$) suppressed by employing a multivariate classifier
- Signal normalised to $B \to D^{*-} 3\pi$ to minimize experimental systematics

PRL120 (2018) 171802
PRD 97 (2018) 072013

$$R(D^{*-}) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext})$$

~1.1σ > SM

$R(D)$ vs $R(D^*)$



LHCb Prospects

- Extend to full Run2 statistics
  - from ~1300 to ~6000 events
  - goal is to be competitive with world average
- A whole programme of semi-tauonic measurements, e.g.

$$\text{fit to} \quad R(D)\,\&\,R(D^*)$$

$$R(D_s^{(*)}) : B_s^0 \to D_s^{(*)}\tau^+\nu_\tau$$

$$R(\Lambda_b) : \Lambda_b \to \Lambda_c^{(*)}\tau^+\nu_\tau$$

Waiting for Belle II

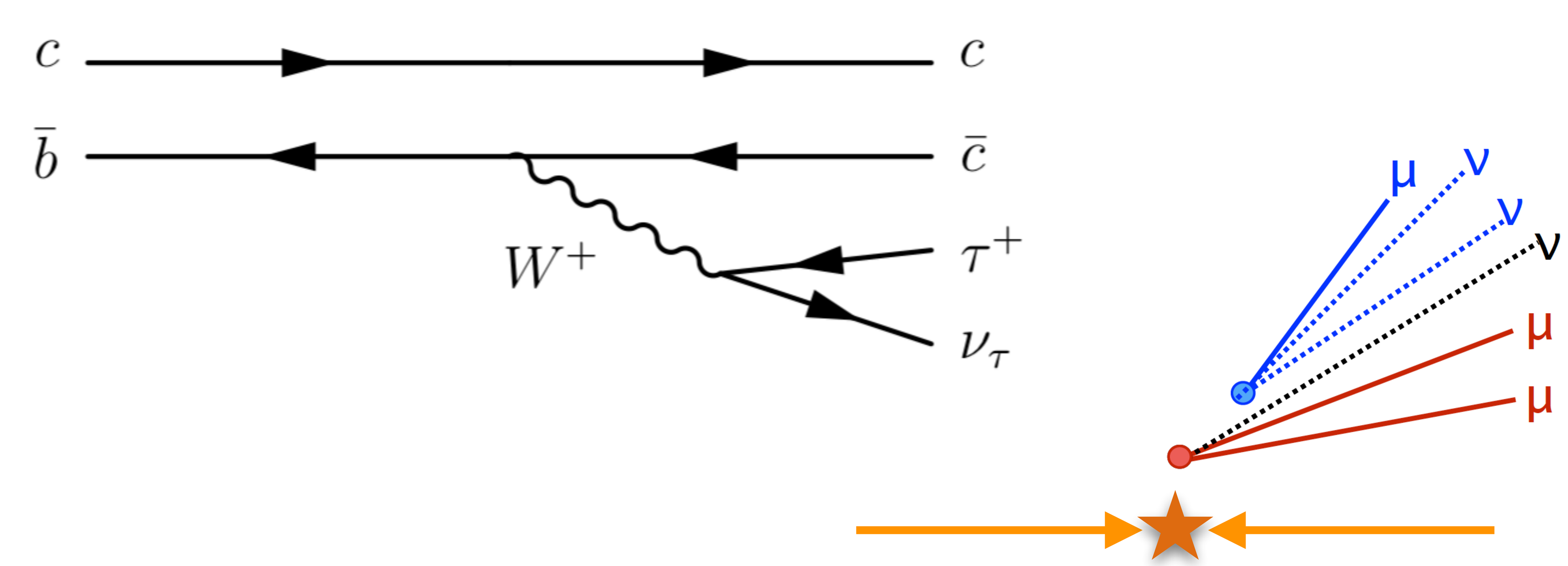
- ~1.5% projected sensitivity on R(D*) with 5 ab^{-1}

- All experiments see an excess wrt SM predictions
- Tension at ~3.8 σ level (according to Bigi et al, arXiv:1707.09509) INTRIGUING!
- ~20% effect on R(D*)

Testing LFU with B_c decays

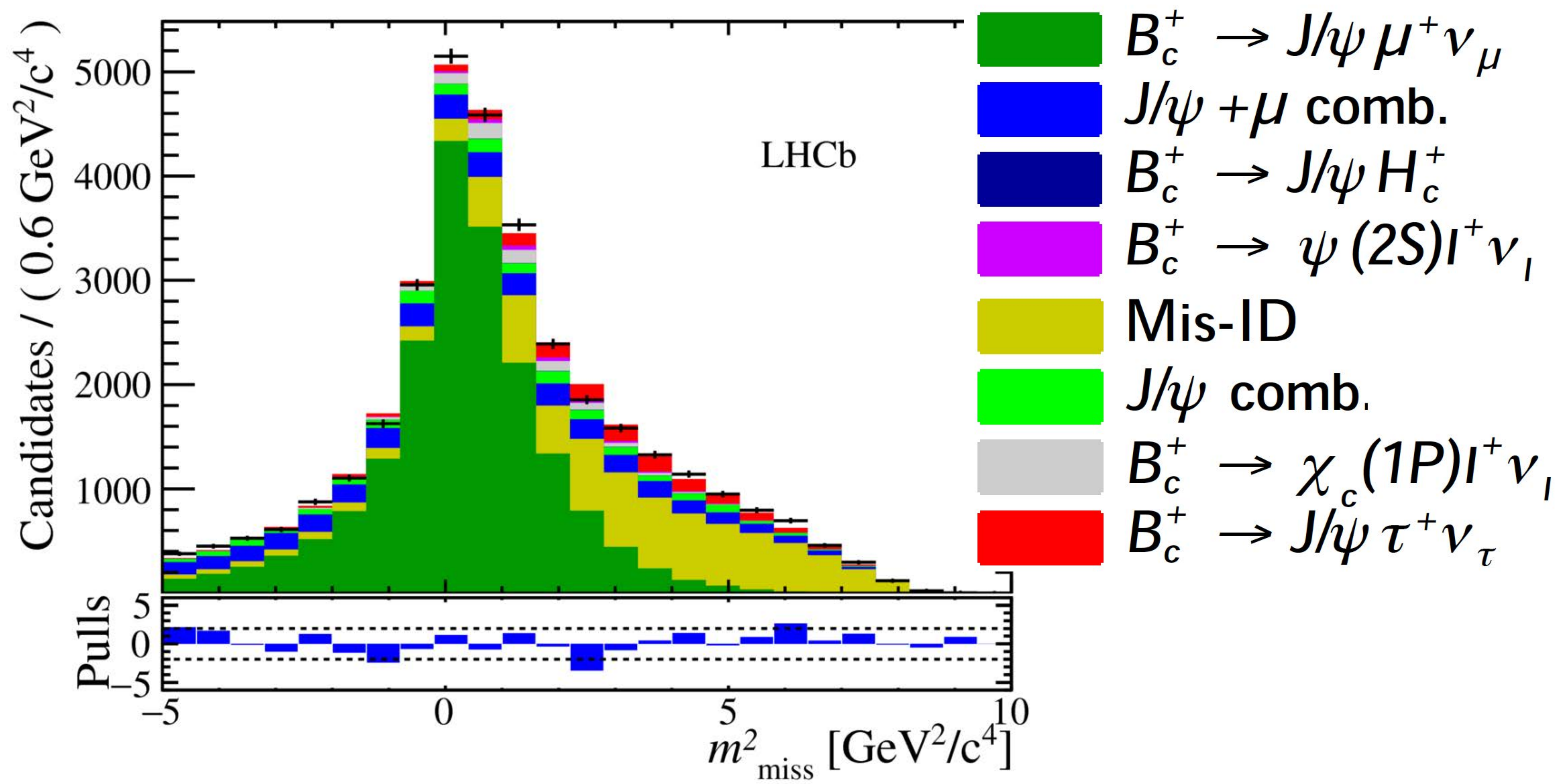
- Generalization of R(D*) to B_c :

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$



- Signal reconstructed using τ→μνν, $B_c^+ \to J/\psi\mu^+\nu_\mu$ as normalisation

- Largest background from light b hadrons to J/ψ with a π or K misidentified as μ

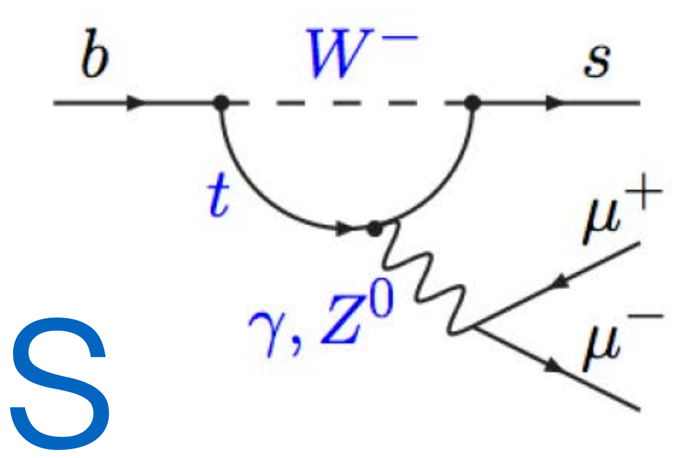


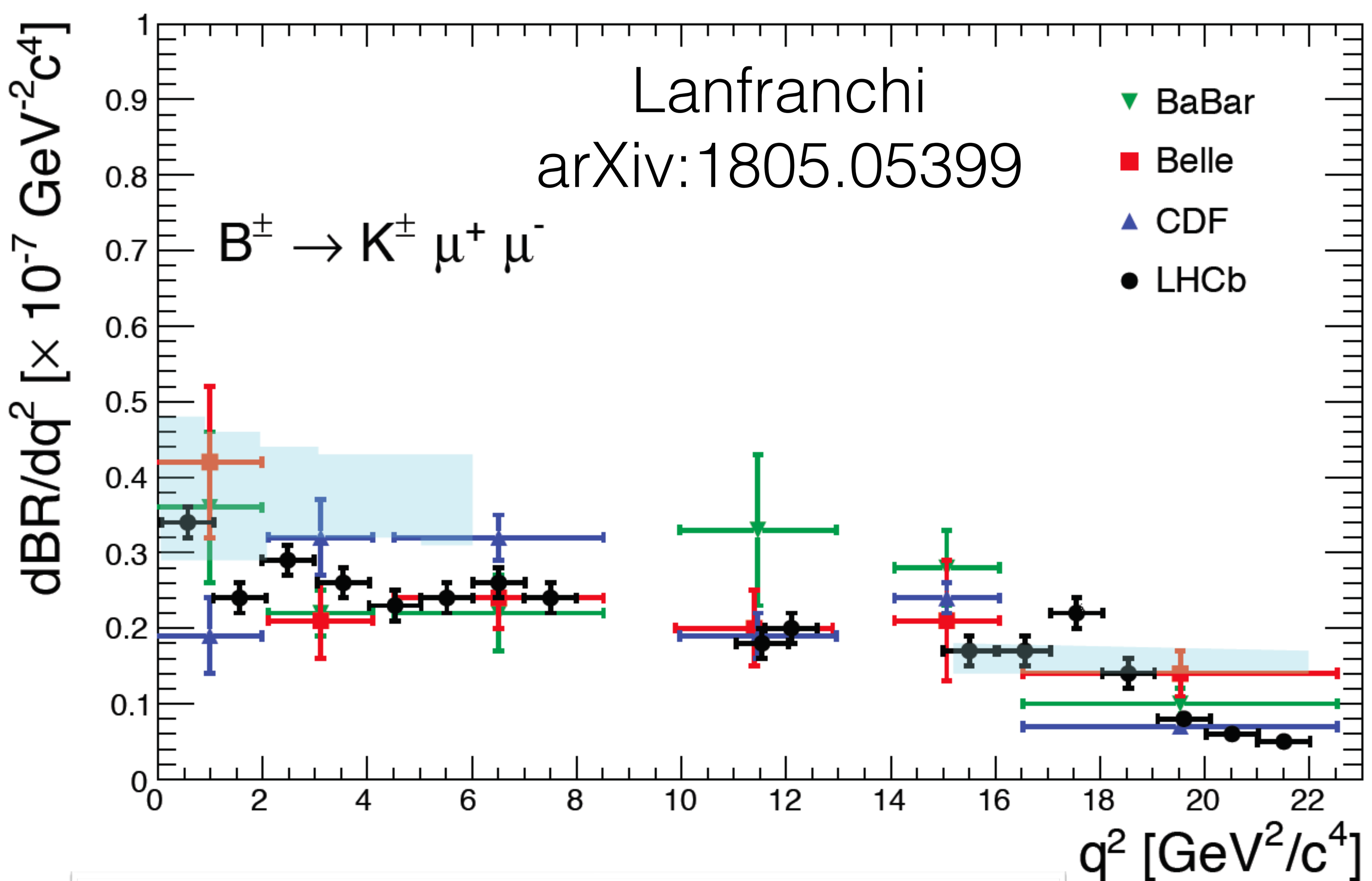
PRL120 (2018) 121801

$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

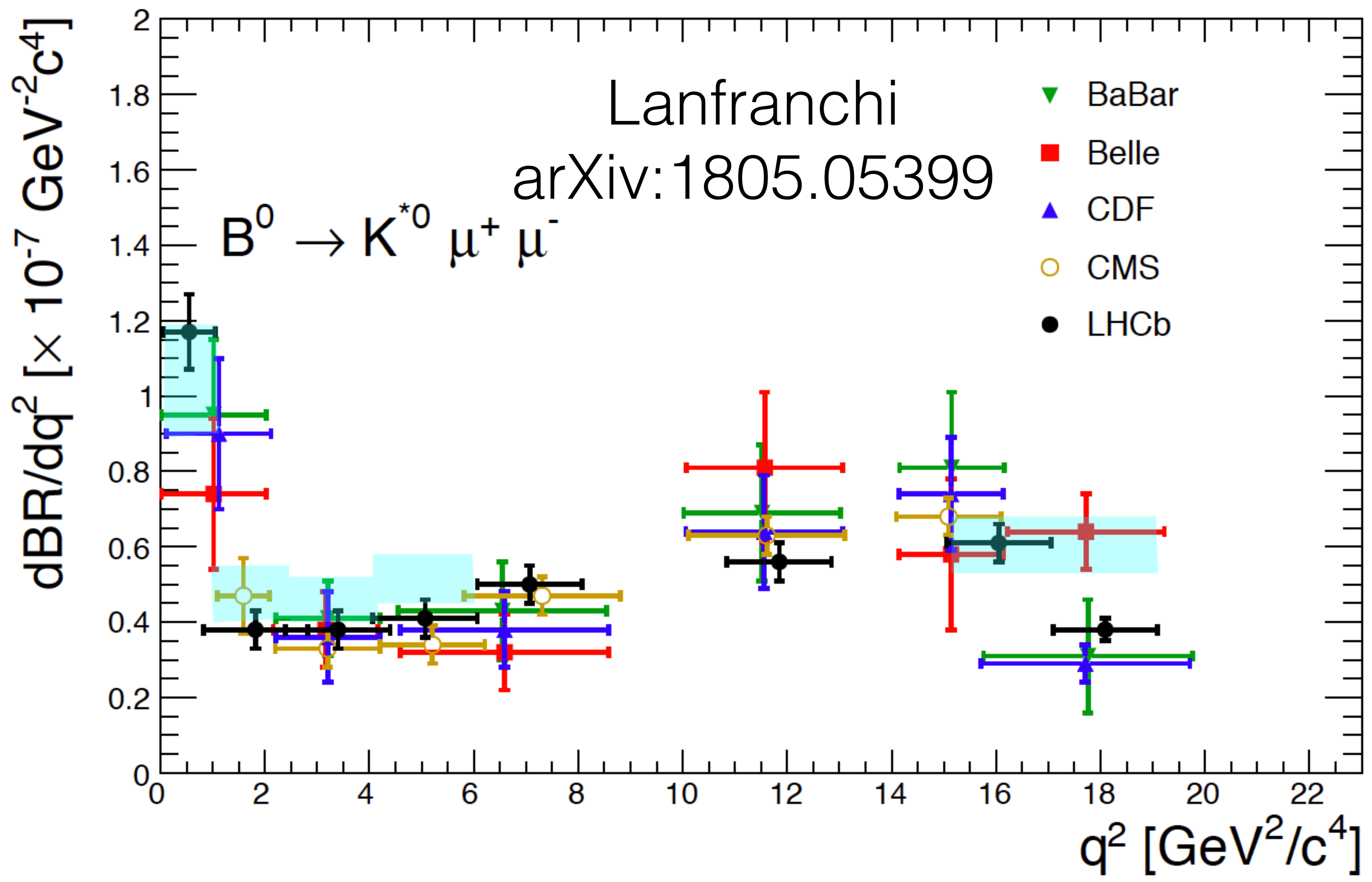
Higher by 2σ than SM prediction (0.25-0.28)

Intriguing set of results in differential branching fractions for b→sμμ transitions

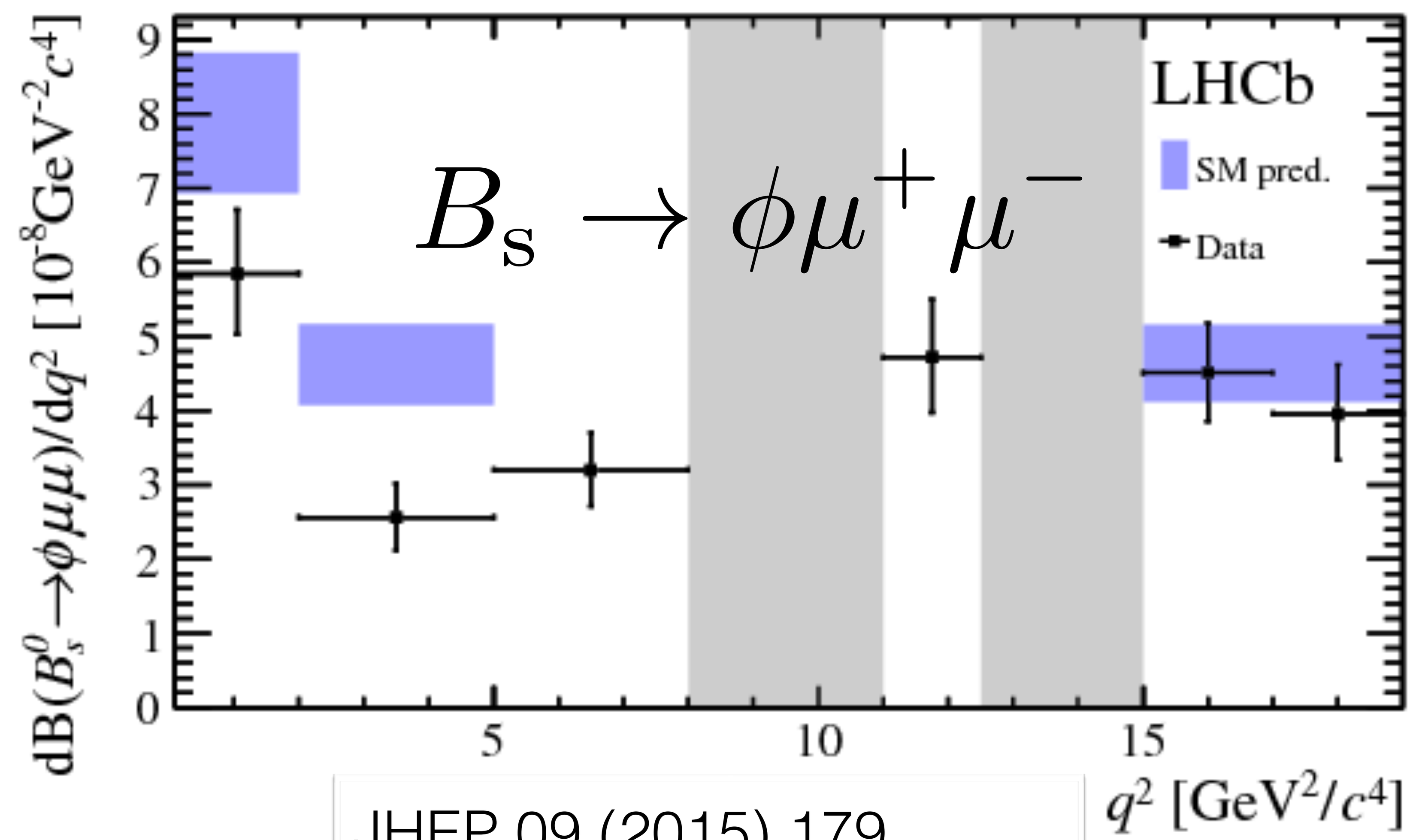




LHCb: JHEP 06 (2014) 133
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802

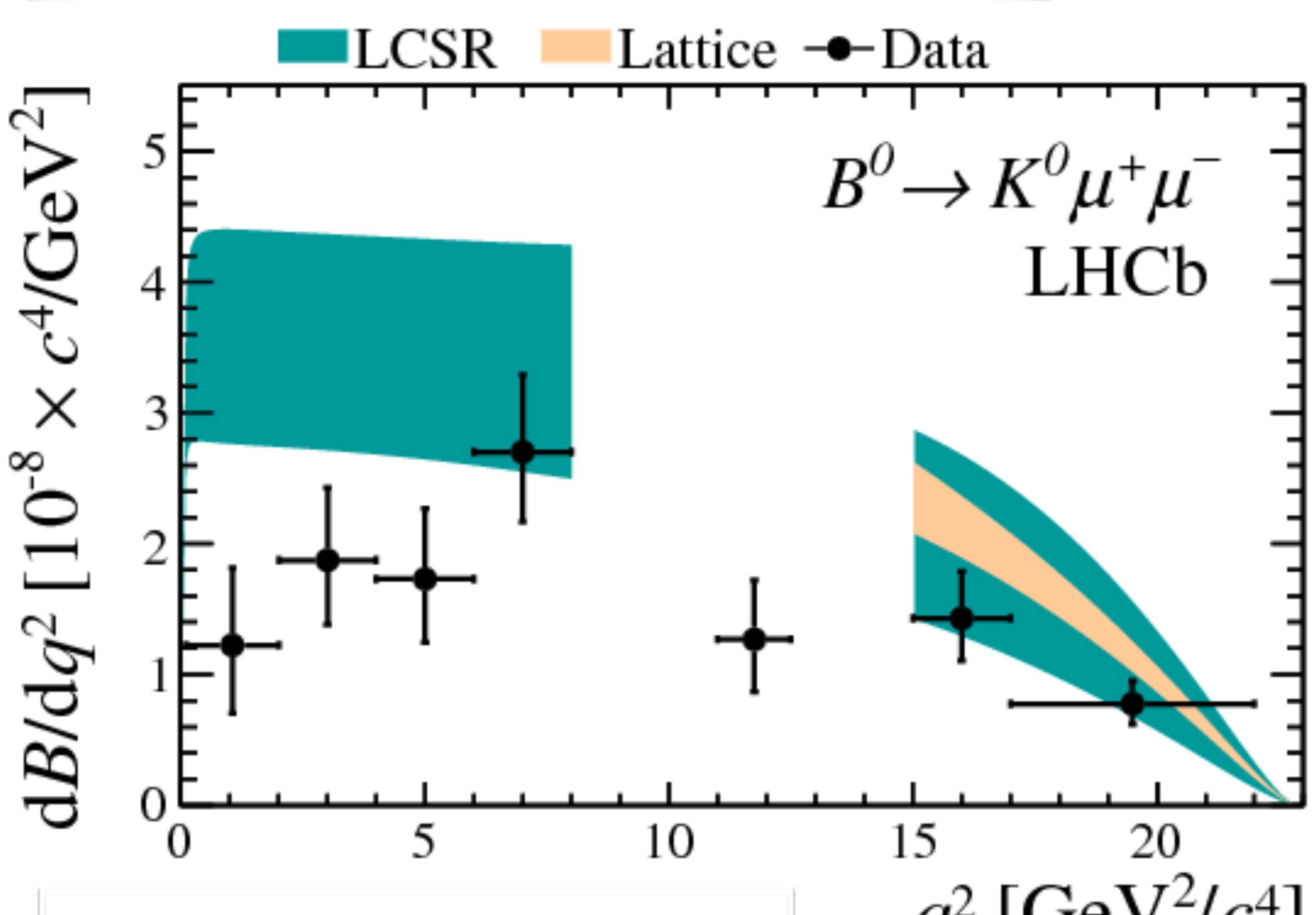


CMS: PLB 753 (2016) 424
LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802

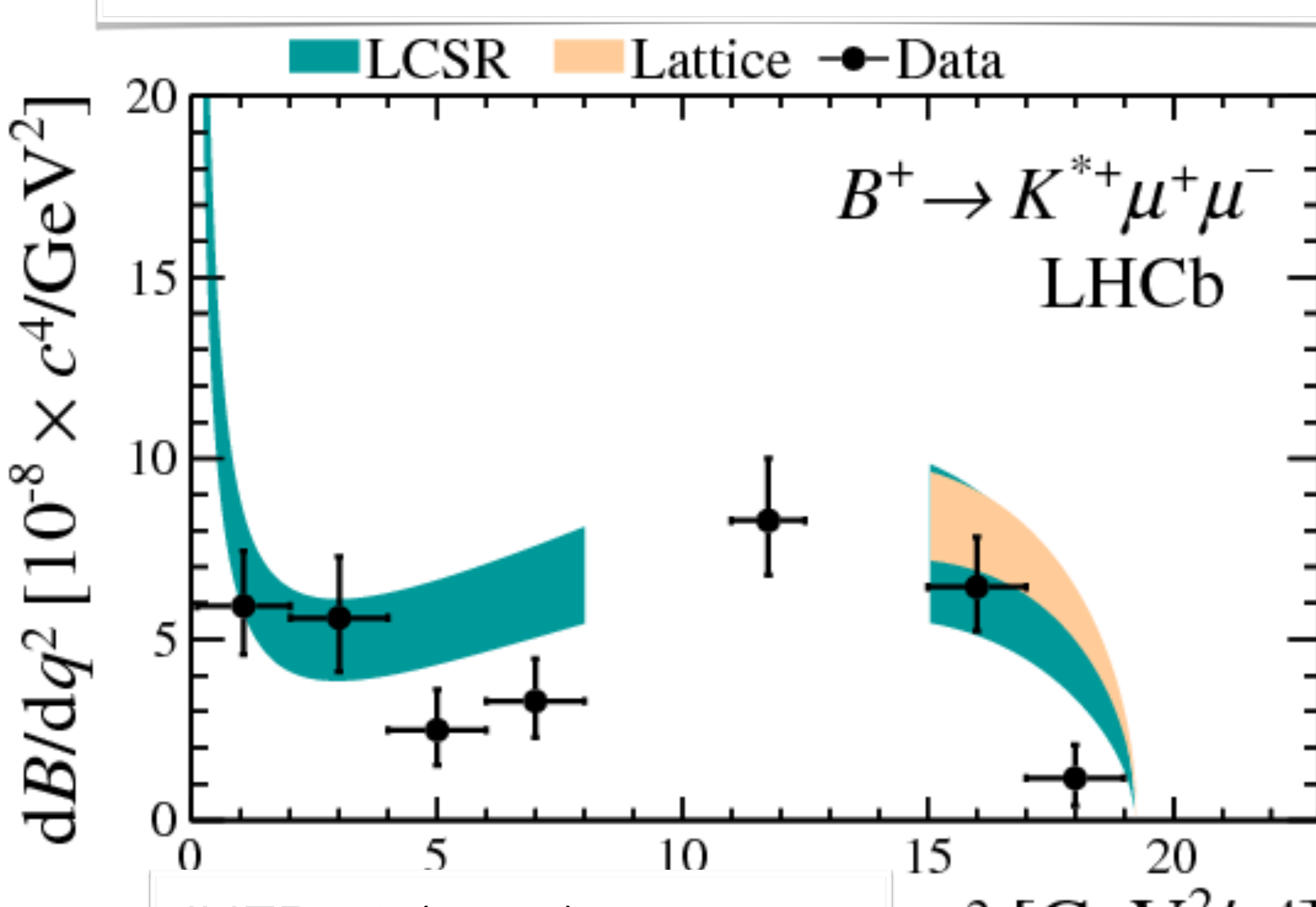


JHEP 09 (2015) 179

$$q^2 = m^2_{\mu^+\mu^-}$$

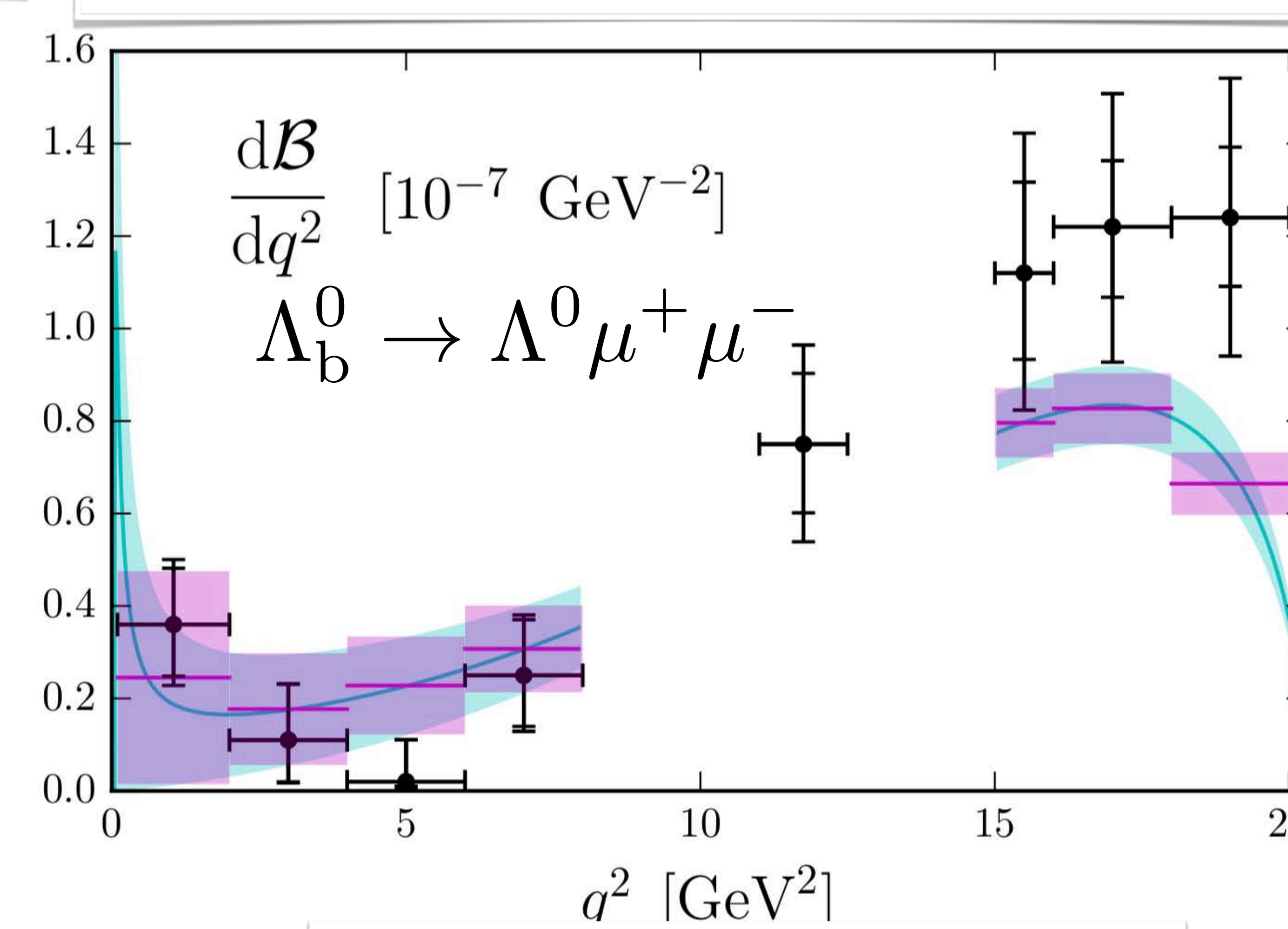


JHEP 06 (2014) 133



JHEP 06 (2014) 133

Detmold and Meinel, PRD93 074501 (2016)



JHEP 06 (2015) 115

- In general, data tend to be lower than theory predictions at low q^2
- Comparison limited by theoretical knowledge of form factors

Possible explanations of the anomalies

- **Statistical fluctuations:** unlikely given the number and pattern of the effects?
- **Experimental artefacts**: these are difficult measurements; have the systematic errors been correctly estimated?
- **Theoretical uncertainties**: large theoretical uncertainties from hadronic form factors on but LFU tests should be robust?
- A cocktail of the above?

- **New Physics** once all the above have been excluded...
- Many NP models proposed (leptoquarks,…), see for example: "B-physics anomalies: a guide to combined explanations" D. Buttazzo et al., JHEP 1711 (2017) 044, arXiv:1706.07808
  - "the case of an $SU(2)_L$-singlet vector leptoquark emerges as a particularly simple and successful framework."
- The large amount of data still to be analysed by LHCb and high-p_T LHC experiments, as well as from future Belle II, will certainly shed more light on the origin of the B-physics anomalies


Much more than flavour!
Spectroscopy
Talk byAntonio Augusto Alves Junior


JORNAL DO BRASIL
Segunda-feira, 30 de outubro de 2017
Ciência e Tecnologia
Cern anuncia descoberta de partícula da matéria
physicsworld.com
WIRED
the japan times
NEWS
The New York Times
CULTURA & SPETTACOLI
BBC
NEWS
Science & Environment
LHC double heavy particle t
Science Springs
THE HINDU
NATIONAL
Scientists discov
Press Trust of India
c ha trova
Scoperta al Cern la particella Xi, inseguita da anni
IlFattoQuotidiano.it / Scienza
Scoperta dal Cern la particella Xi: "È come un sistema planetario in miniatura"
WJLA
Physicists find new particle with a
ong force
El CERN observa una nueva partícula en el Gran Acelerador de Hadrones
From LHCb at CERN: " Observation of an exceptionally charming particle"
HAARETZ
L'expérience LHCb est charmée
ALLA CONFERENZA DELLA SOCIETÀ EUROPEA DI FISICA A VENEZIA
Cern, scoperta la particella Xi: aiuterà a capire cosa tiene unita la materia
Charming New Particle Xi-cc++ Discovered at CERN
swissinfo.ch
New Subatomic P
Israeli Scientist D
Physicists find new particle with a double dose of
Doubly cha
found at Geneva atom smasher
SPIEGEL ONLINE
WISSENSCHAFT
of Doubly Cha
Jul 6, 2017 by News Staff / Source
Kernforschung
Forsche
elPeriódico
SOCIEDAD
Últimas noticias sobre Puigdemont y la independencia de Catalunya
El CERN observa una nueva partícula con
The Himalayan Times
LHCb实验首次发现双粲重子
EXPRESS
CERN scientists one step to unlocking key to Univ after LHC breakthrough
Physicists Find New Particle With a Double Dose of Charm
Physicists find ne
人民网
scientists found a new par
Cern: scoperta la particella Xi. Servirà
RT QUESTION MORE
TRALIAN
Newsweek
POTSDAMER NEUESTE NACHRICHTEN
TEILCHENPHYSIK
Xicc++, ein neues Partikel
'New frontier' in physics: Sub 'charm' discovered
TECH & SCI
By Gong Zhe
Cern-Wissenschafter haben ein n Teilchen entdeckt
HC: CHARMING PARTICLE XI-CC++ DISCOVERED AT CERN FITS WITH STANDARD MODEL AND OPENS NEW WINDOW ON THE UNIVERSE
Ξ_{cc}^{++} [ccu]

New results on Ξ_{cc}^{++} $[ccu]$

- Observed for the first time in the decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ but lifetime left for later studies

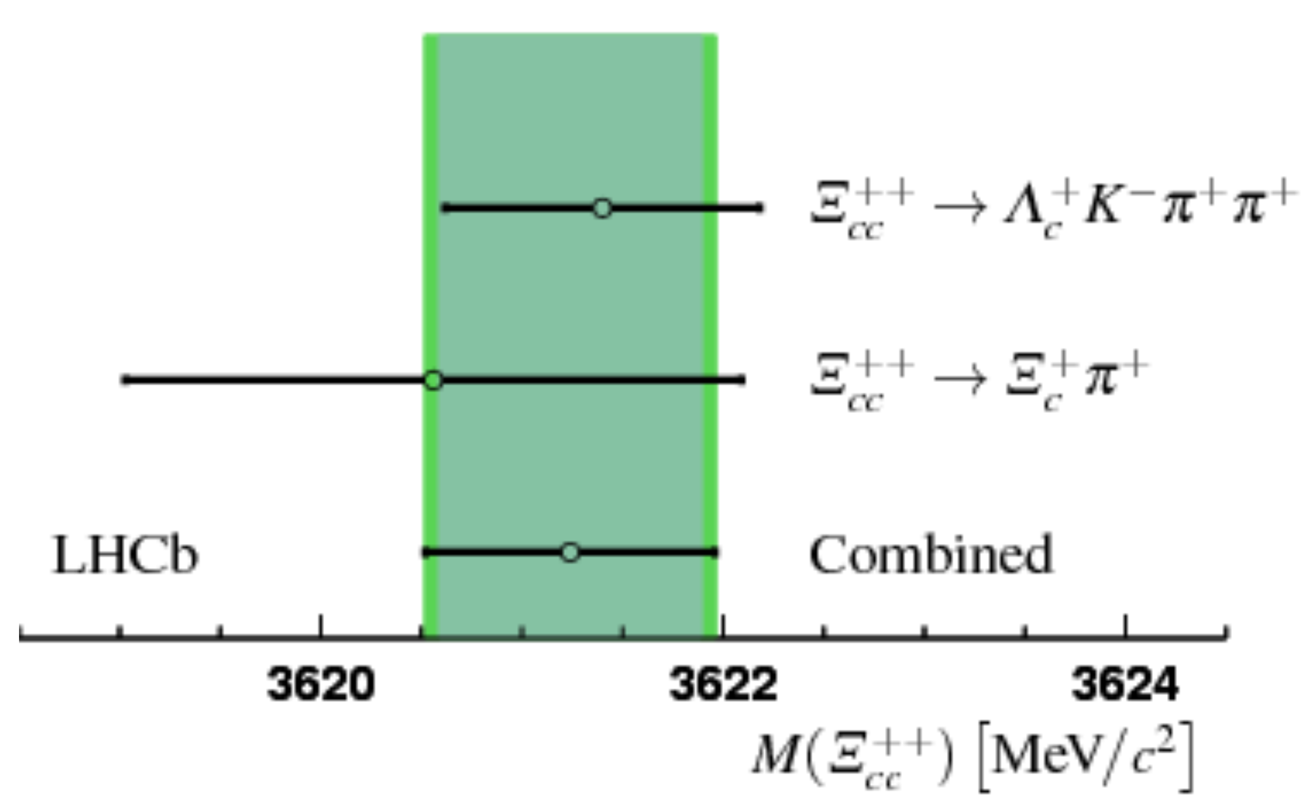
PRL 119 (2017) 112001

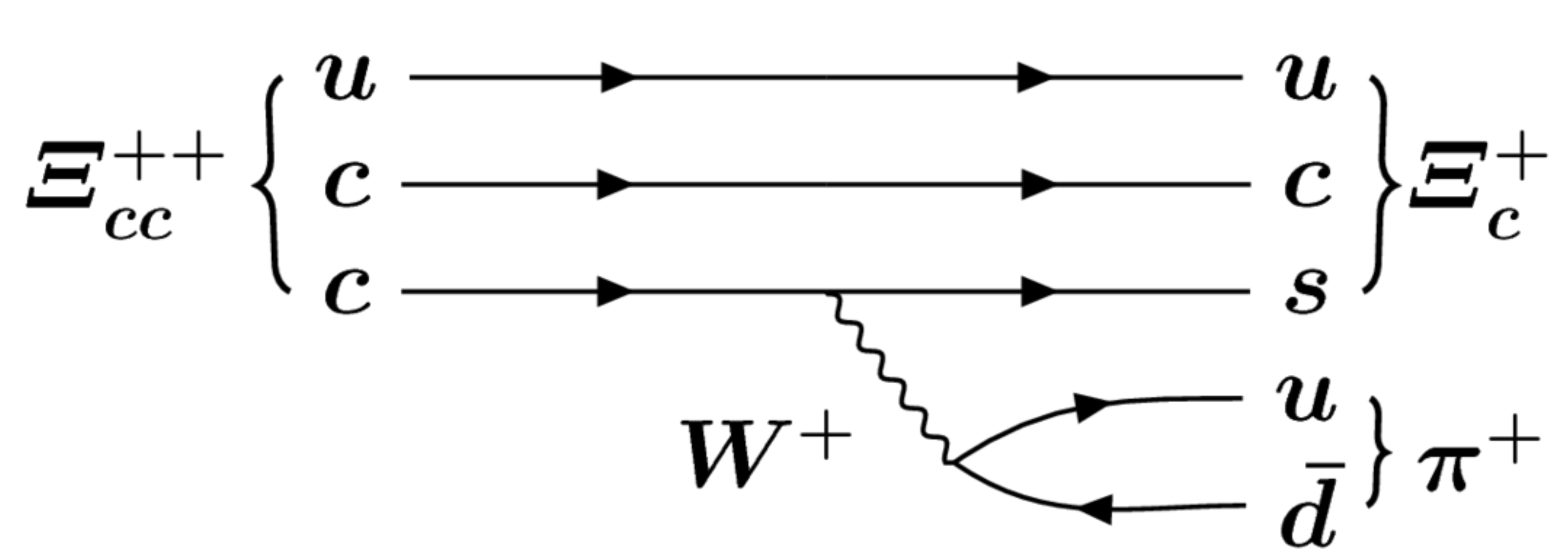
- Now measured relative to $\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^- \pi^+$ [1.7 fb^{-1} in Run 2], consistent with expectations from weak decay

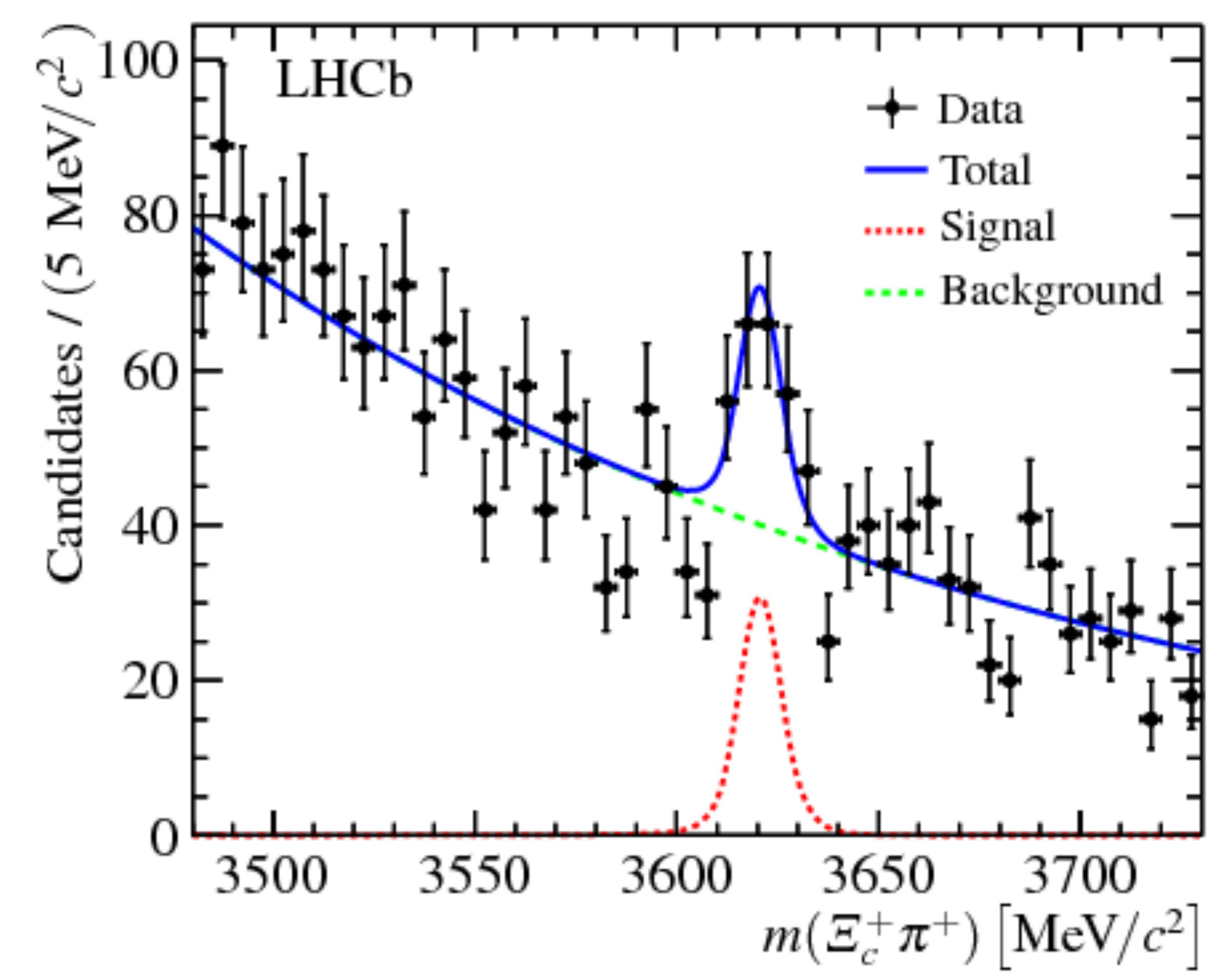
PRL 121 (2018) 052002

$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022} \pm 0.014\,\mathrm{ps}$$

- Recently re-observed in $\Xi_{cc}^{++} \to \Xi_{cc}^{+} \pi^+$ [1.7 fb^{-1} in Run 2]







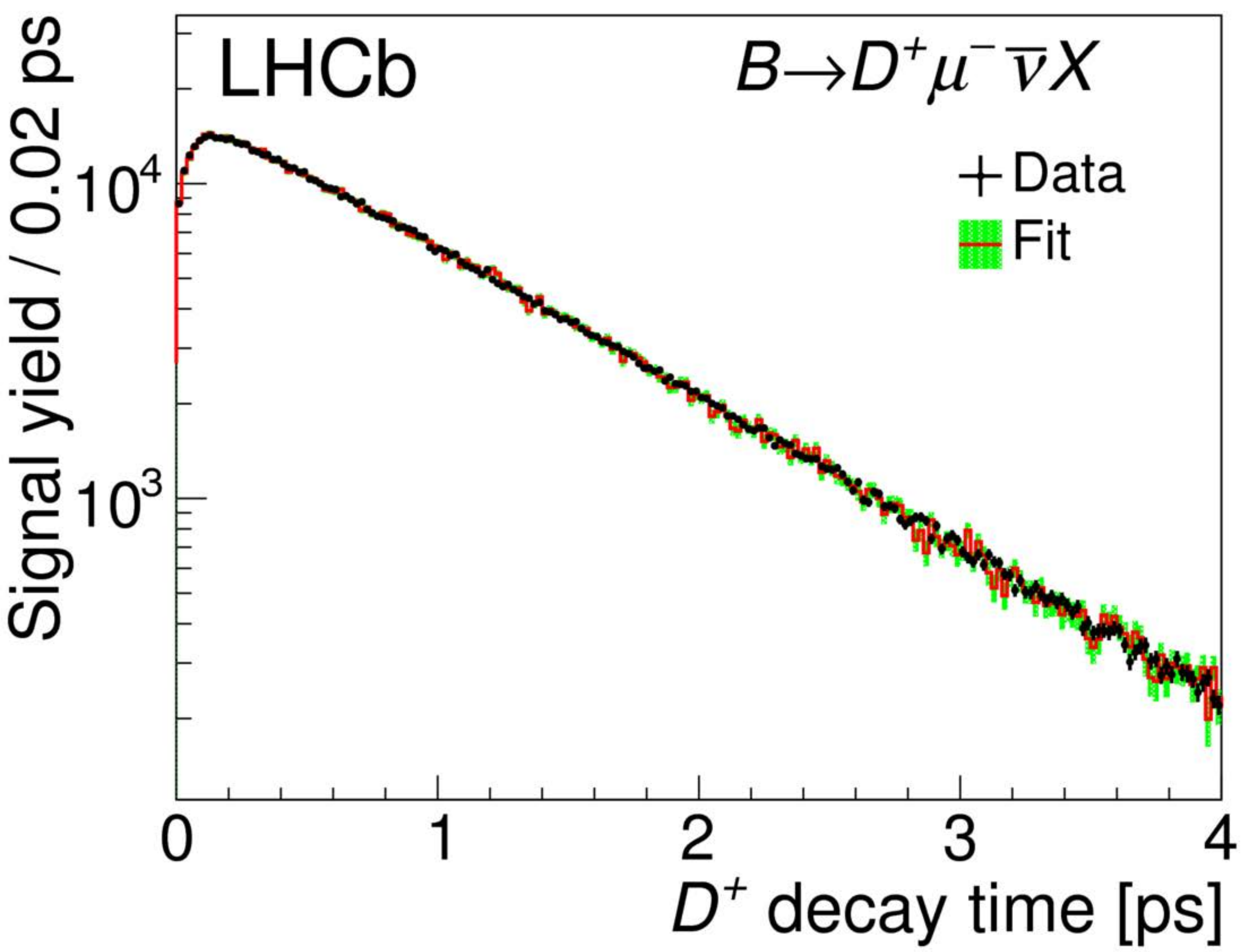
- Combined mass:

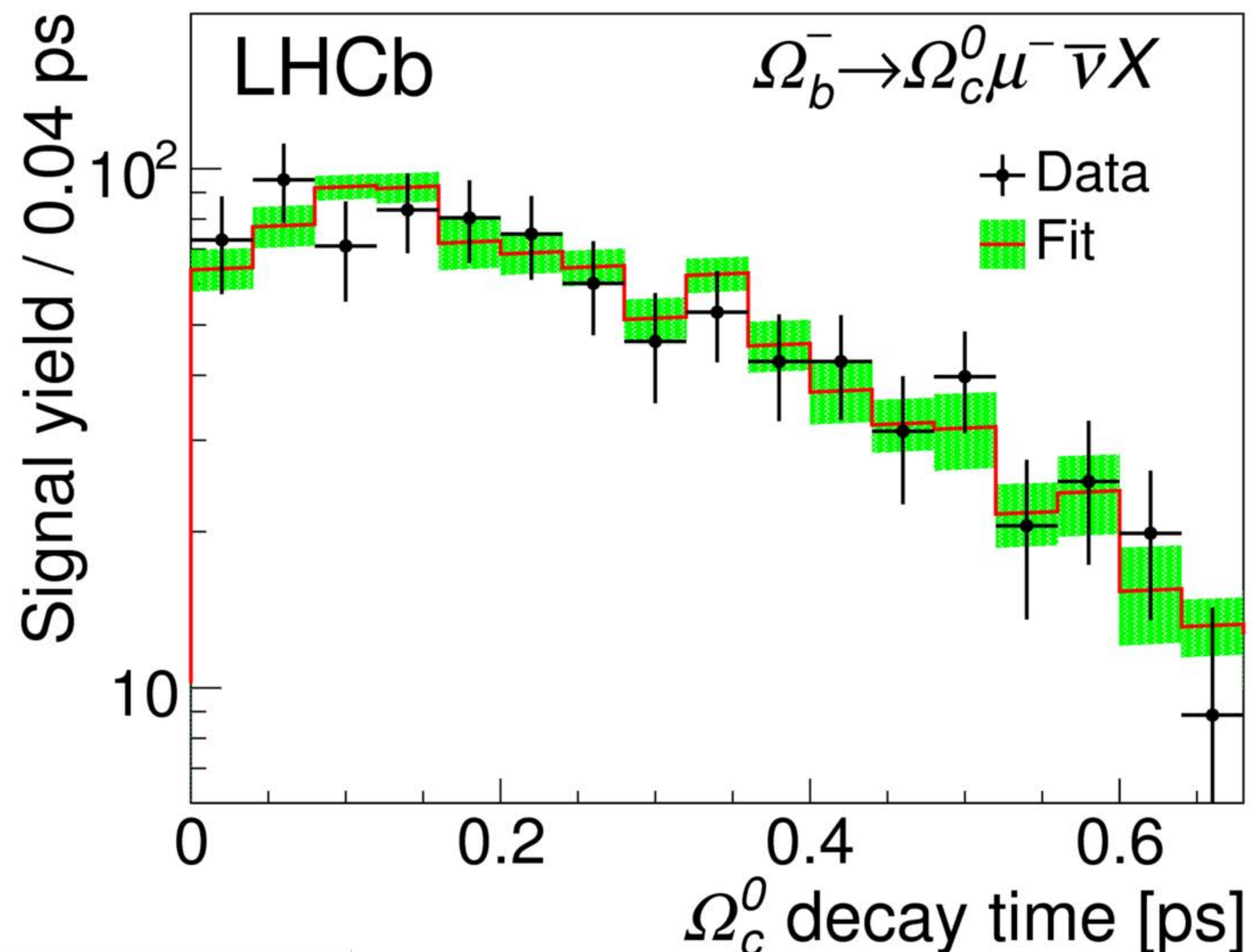
arXiv:1707.01919

$$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65\,(\mathrm{stat}) \pm 0.31\,(\mathrm{syst})\,\mathrm{MeV}/c^2$$

Ω_c^0 lifetime

- Least well measured charmed baryon lifetime
- ~1000 decays $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X,\ \Omega_c^0 \to p K^- K^- \pi^+$
- Measured relative to $D^+ \to K^- \pi^+ \pi^+$ with D^+ from semileptonic B





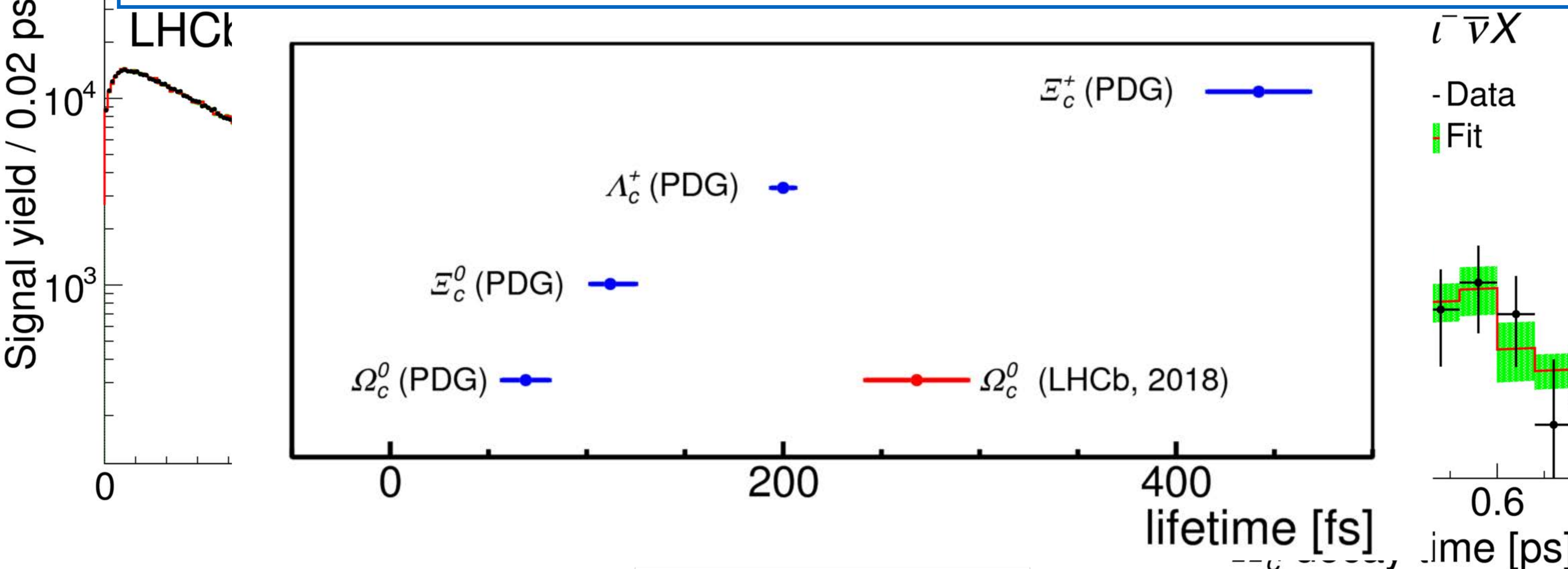
arXiv:1807.02024

$$\tau(\Omega_c^0) = 268 \pm 24\,(\mathrm{stat}) \pm 10\,(\mathrm{syst}) \pm 2(\mathrm{D}^+)\ \mathrm{fs}$$

Ω_c^0 lifetime

- Least well measured charmed baryon lifetime
- ~1000 decays $\Omega_b^- \to \Omega_c^0 \mu^- \bar{\nu}_\mu X,\ \Omega_c^0 \to p K^- K^- \pi^+$
- Mea … ic *B*

~ four times larger than, and inconsistent with, the current world-average value of 69 ± 12 fs



arXiv:1807.02024

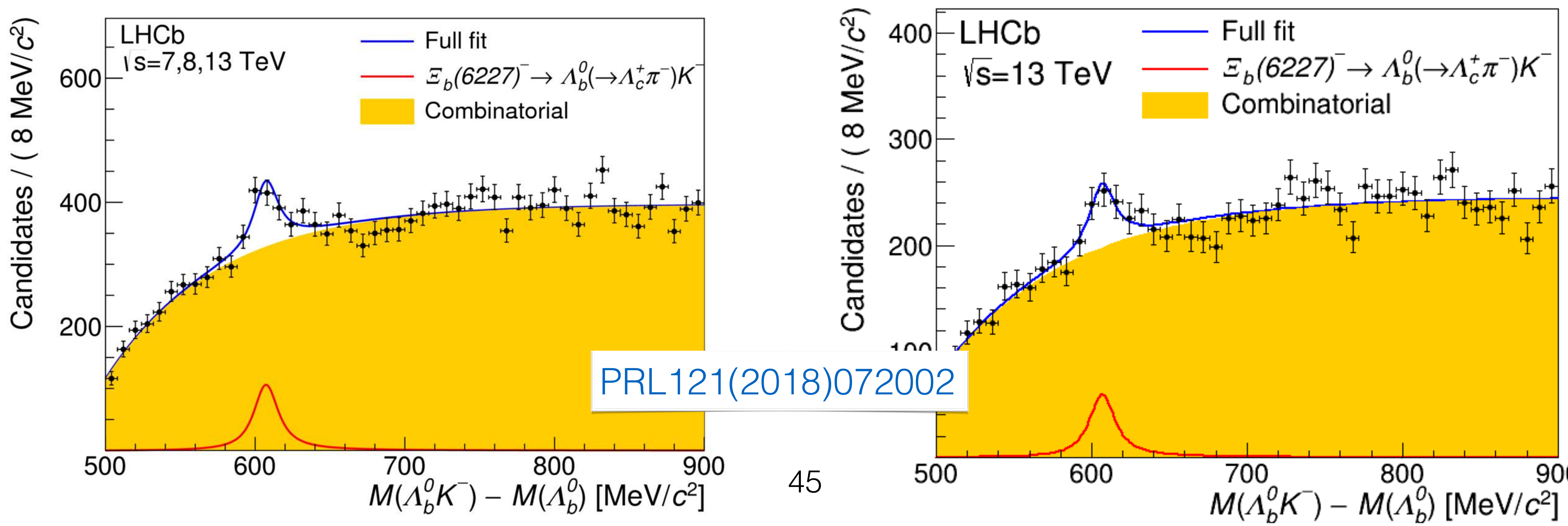
$$\tau(\Omega_c^0) = 268 \pm 24\,(\mathrm{stat}) \pm 10\,(\mathrm{syst}) \pm 2(\mathrm{D}^+)\ \mathrm{fs}$$

Observation of a new Ξ_b^- resonance

- In the quark model, radially and orbitally excited Ξ_b^- resonances are expected $[b, d, s]$
- First observation of a new state decaying into $\Lambda_b^0 K^-$ and $\Xi_b^0\pi^-$ in both fully hadronic (Λ_b) and semileptonic (Λ_b, Ξ_b) decays
- Mass and width from fully hadronic channel (no J^P analysis yet)

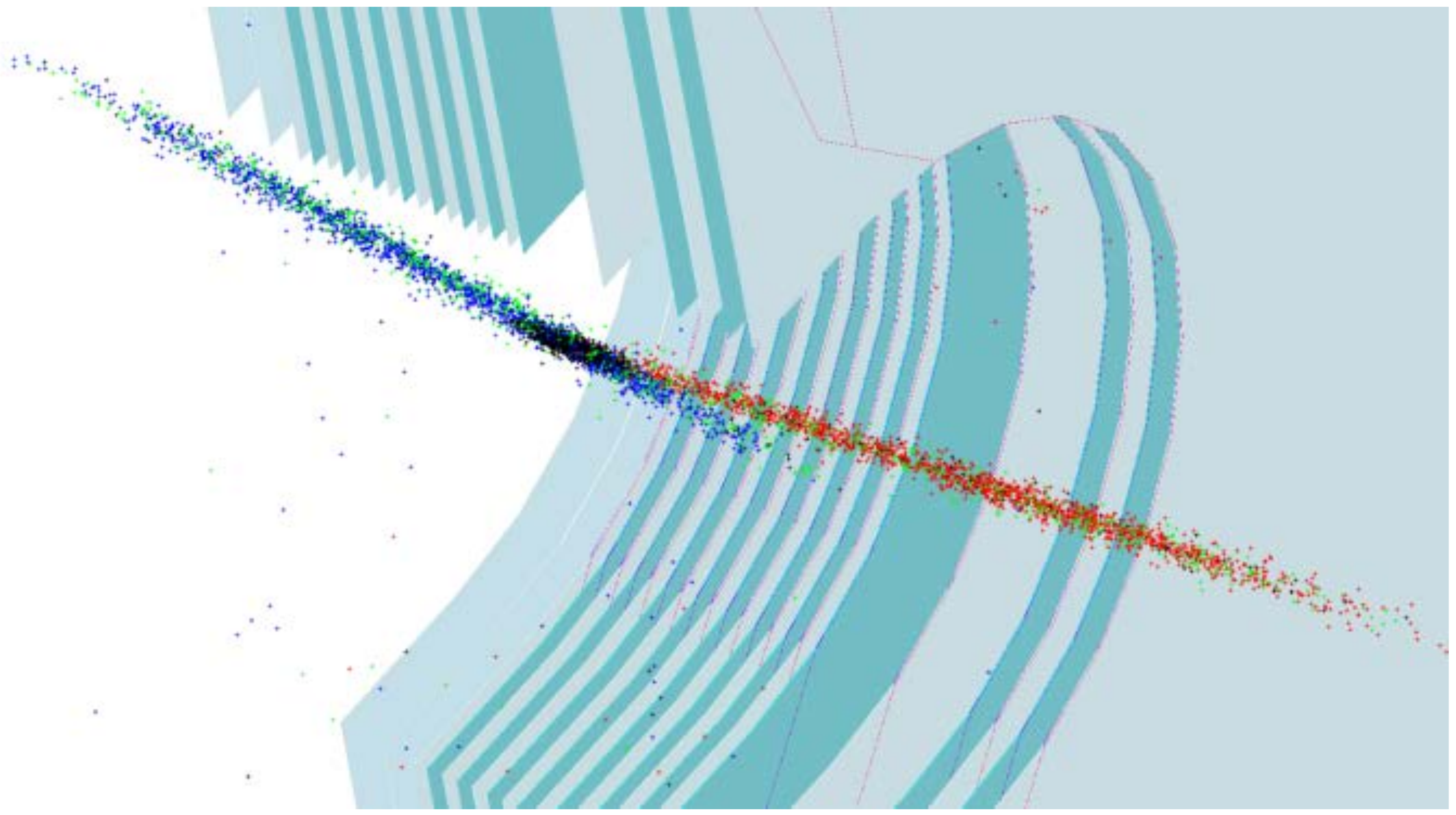
$$m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0(\mathrm{stat}) \pm 0.3(\mathrm{syst}) \pm 0.2(\Lambda_b^0)\,\mathrm{MeV/c^2}$$

$$\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4(\mathrm{stat}) \pm 1.8(\mathrm{syst})\,\mathrm{MeV/c^2}$$



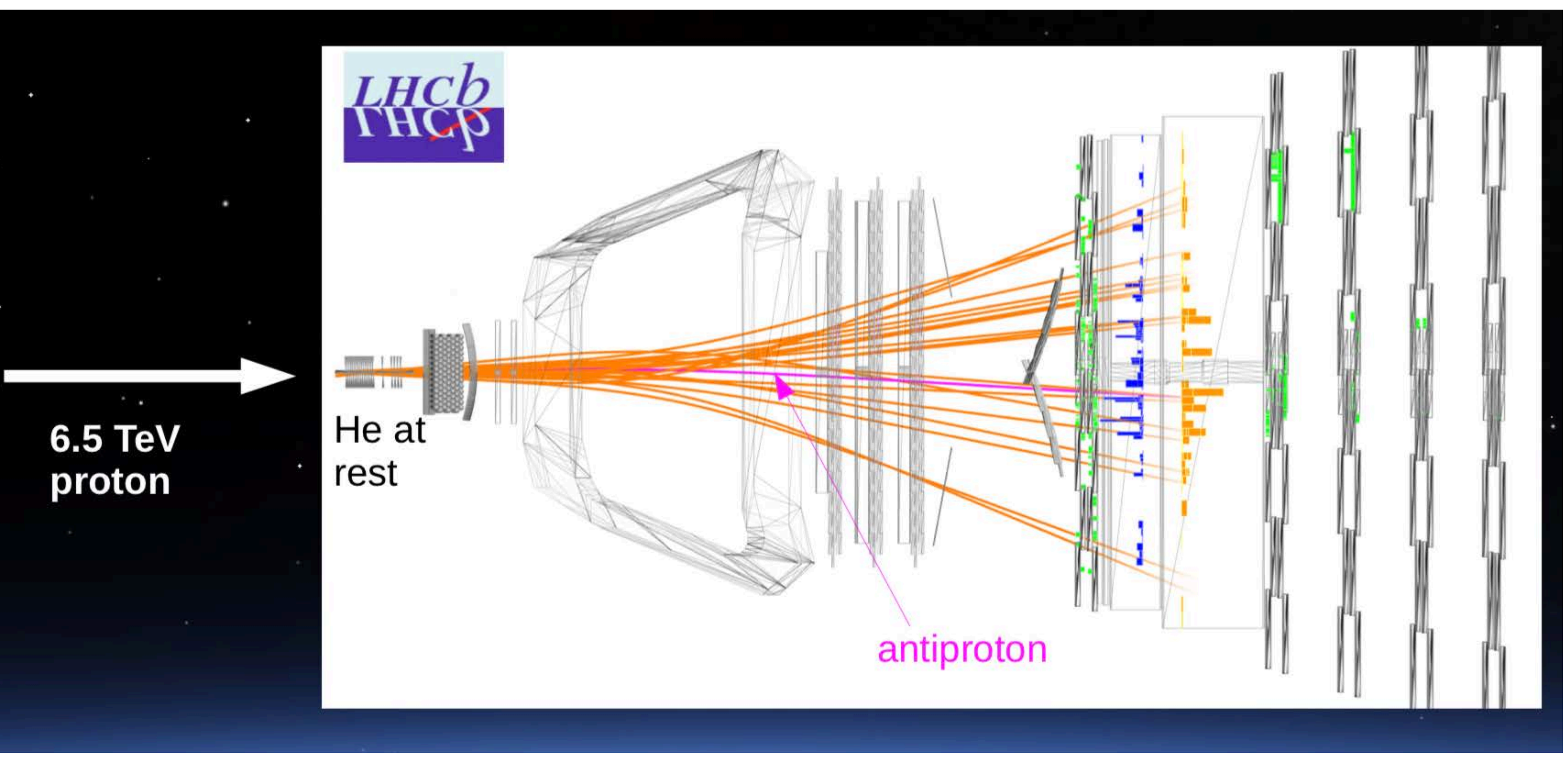
PRL121(2018)072002

“Fixed-target like” geometry very well suited for. . . fixed-target physics!



- With SMOG (**S**ystem for **M**easuring **O**verlap with **G**as) a small amount of noble gas is injected in beam pipe around (~ ±20 m) the collision region

Turns LHCb into a fixed-target experiment!

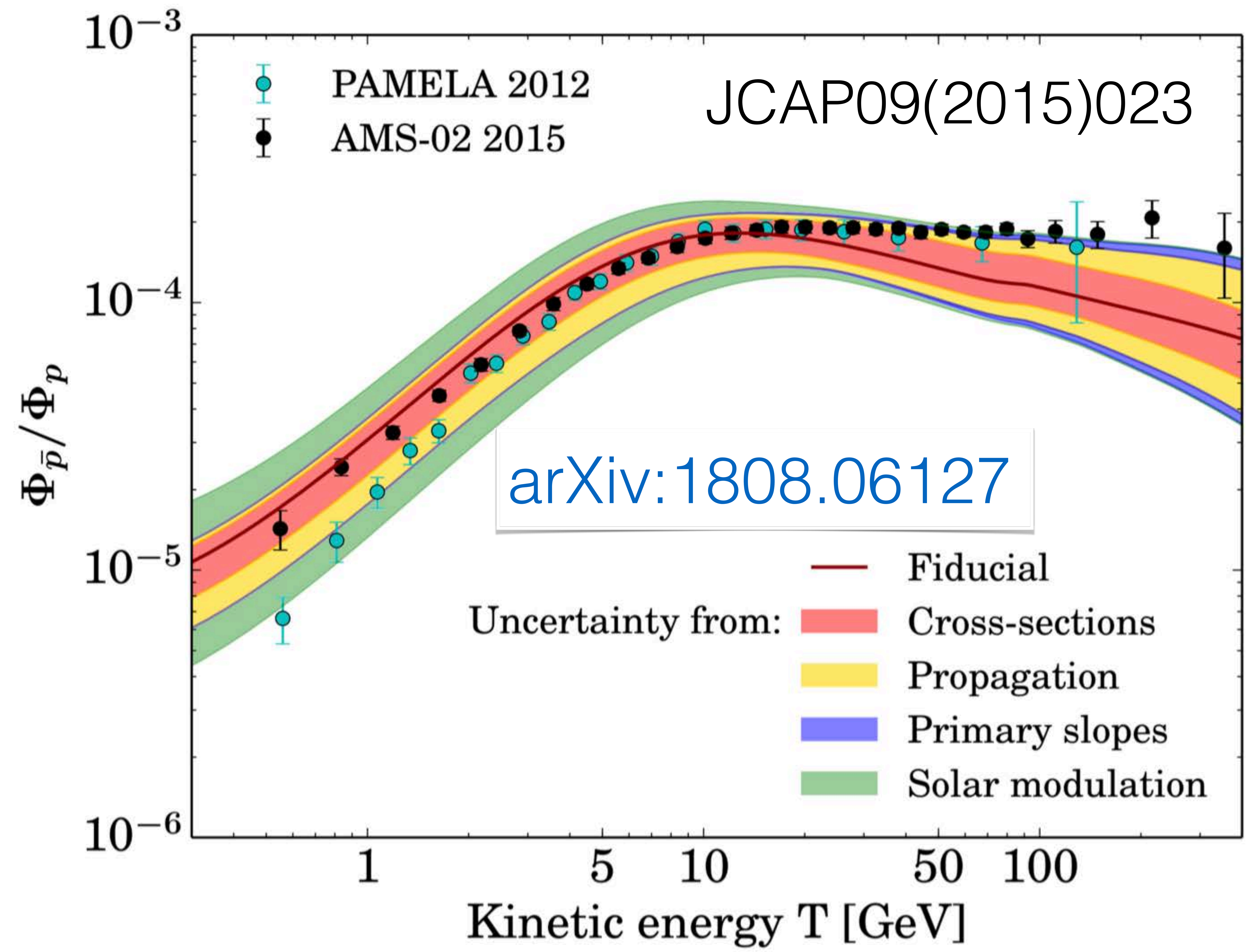


- Possible targets: He, Ne, Ar,….
- Gas pressure ~10^{-7}mb, ~2 orders of magnitude larger than vacuum pressure (only local temporary degradation of LHC vacuum)

Link with cosmic ray physics

- Cosmic-ray flux of antiprotons is measured with high precision by AMS-02 and PAMELA

- Its interpretation requires a correct description of the dominant production process for antiprotons, i.e. the interaction of cosmic-ray protons with the interstellar medium (H, He)



- LHCb performed first measurement of cross-section for $p + He \to \overline{p} + X$ at $\sqrt{s_{\rm NN}} \sim 100\,\mathrm{GeV}$

- Results cover $12 < p < 110\,\mathrm{GeV}/c,\ p_T > 0.4\,\mathrm{GeV}/c$

- Precision well below the spread among models for $\overline{p}$ production

Conclusions

- Lots of measurements from LHCb in flavour and beyond, only a few of which were highlighted here, e.g. nothing on charm (covered by Mike Sokoloff), heavy ions, EW, exotic searches…
- Dramatic improvements to the already impressive knowledge accumulated by the B-factories and Tevatron. Healthy competition from Belle II, ATLAS & CMS very welcome!
- Precise measurements of flavour observables provide a powerful way to probe for NP effects beyond the SM, complementing direct searches for NP
- Most of these results show good compatibility with the SM, but some signs of tension are emerging
- Need more data to test these hints. These data are arriving in Run 2!
- Working hard to prepare for the future: getting ready to instal the LHCb upgraded detector in ’19-20 and also thinking about a possible Upgrade II for the the ultimate exploitation of the LHC for flavour physics in the HL-LHC era

A few extra slides

Projected sensitivities

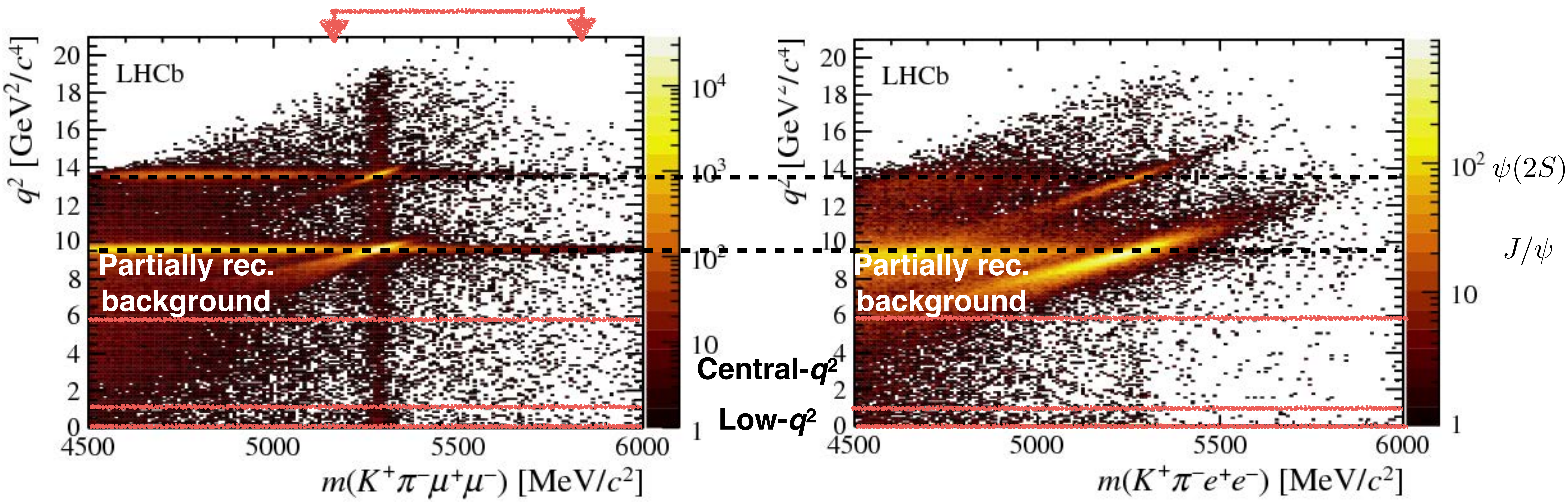
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [273]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [272]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [134]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [163]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [601]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [42]	14 mrad	–	4 mrad	22 mrad [602]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [47]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	150 mrad [603]	60 mrad	–	17 mrad	Under study [604]
a_{sl}^s	33×10^{-4} [208]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [198]	3%	1%	1%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [262]	34%	–	10%	21% [605]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [262]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **LUV studies**					
$R(D^*)$	9% [213, 218]	3%	2%	1%	–
$R(J/\psi)$	25% [218]	8%	–	2%	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [606]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [238]	4.3×10^{-5}	3.5×10^{-5}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [226]	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}	–

A very challenging measurement

Number of candidates for $B^0 \to K^{*0}\mu^+\mu^-$

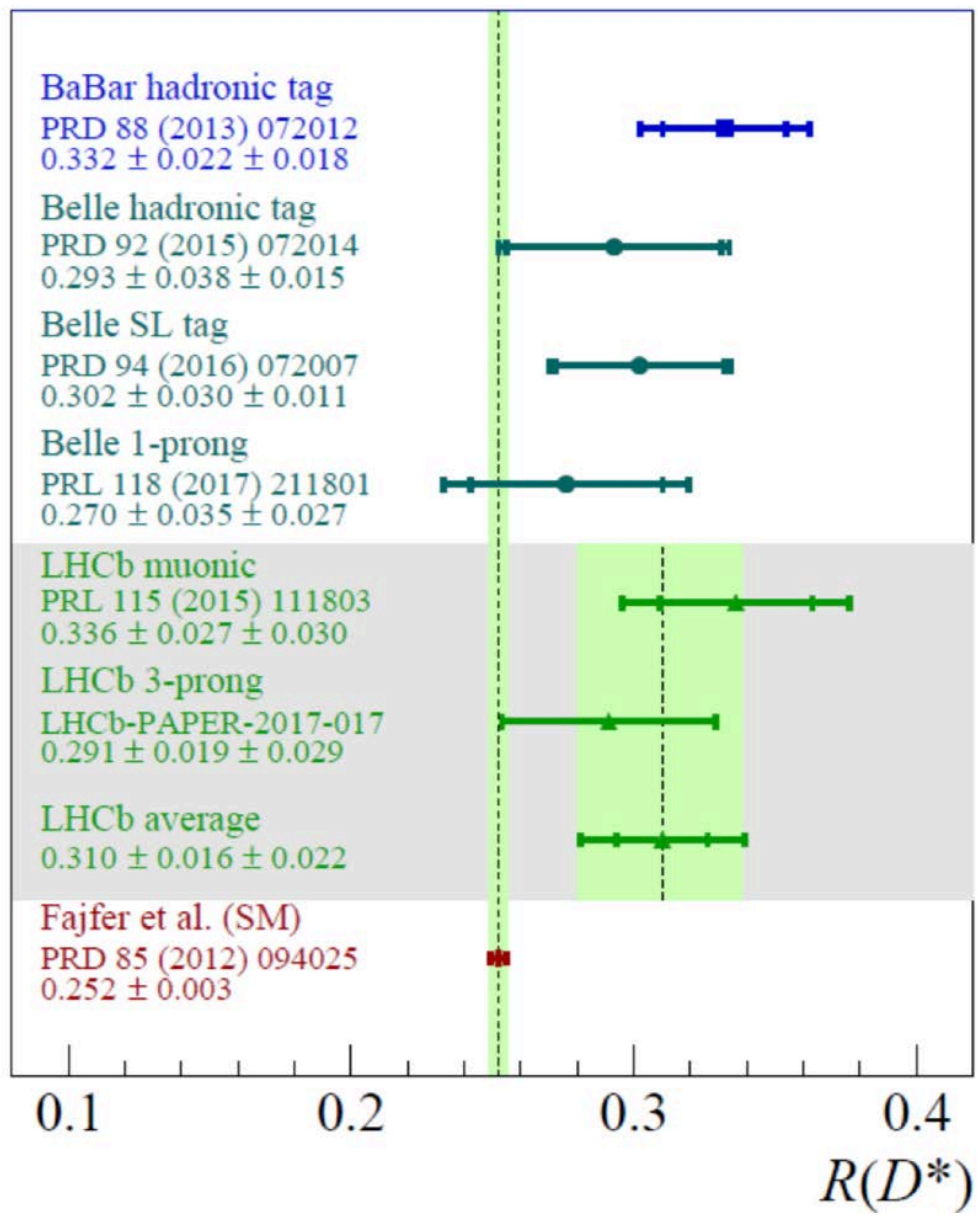
Number of candidates for $B^0 \to K^{*0}e^+e^-$

JHEP 08 (2017) 055



- Due to bremsstrahlung the reconstructed B mass is shifted towards lower values and events leak into the central-q² bins

Results R(D*)

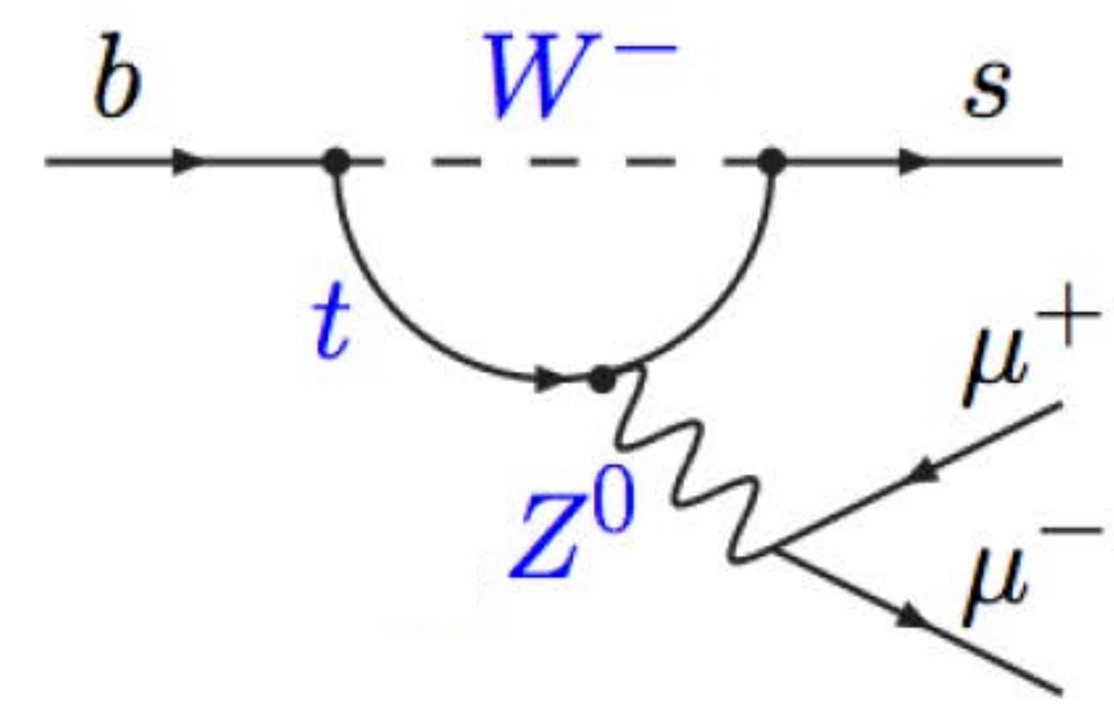


New world average:

$$R(D^{*-}) = 0.304 \pm 0.013\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst})$$

One of the milestones of flavour programme $B_{(s)} \to \mu^+\mu^-$

- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for B_s) and helicity $\sim \left(\frac{m_\mu}{M_B}\right)^2$



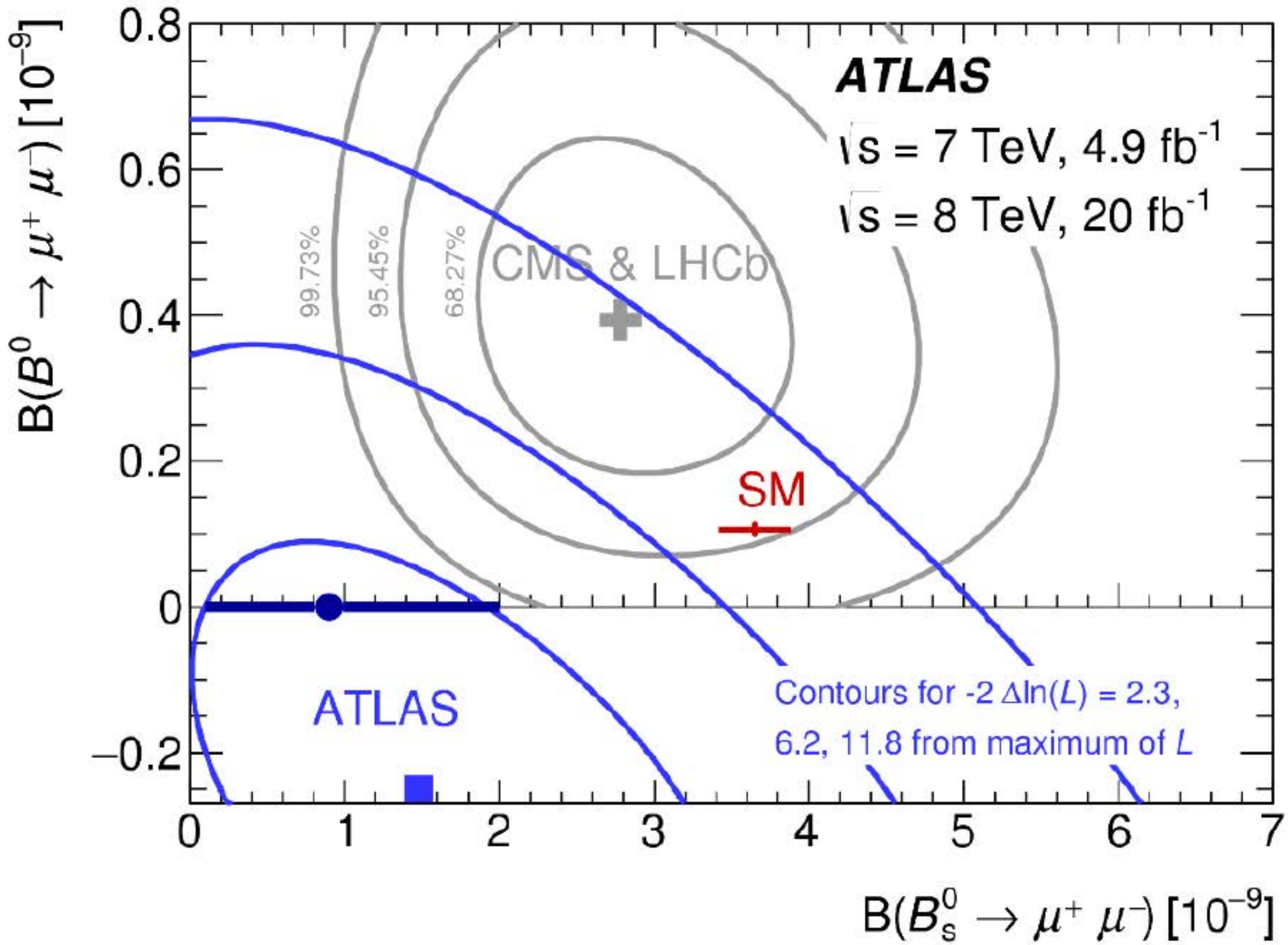
- Theoretically “clean” → precisely predicted

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9} \quad (\sim 6\%)$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.
PRL 112 (2014) 101801

- Sensitive to NP
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

Era of precision measurements of $B_{(s)} \to \mu^+\mu^-$



ATLAS, EPJC 76 (2016) 513
CMS & LHCb, Nature 522 (2015) 68

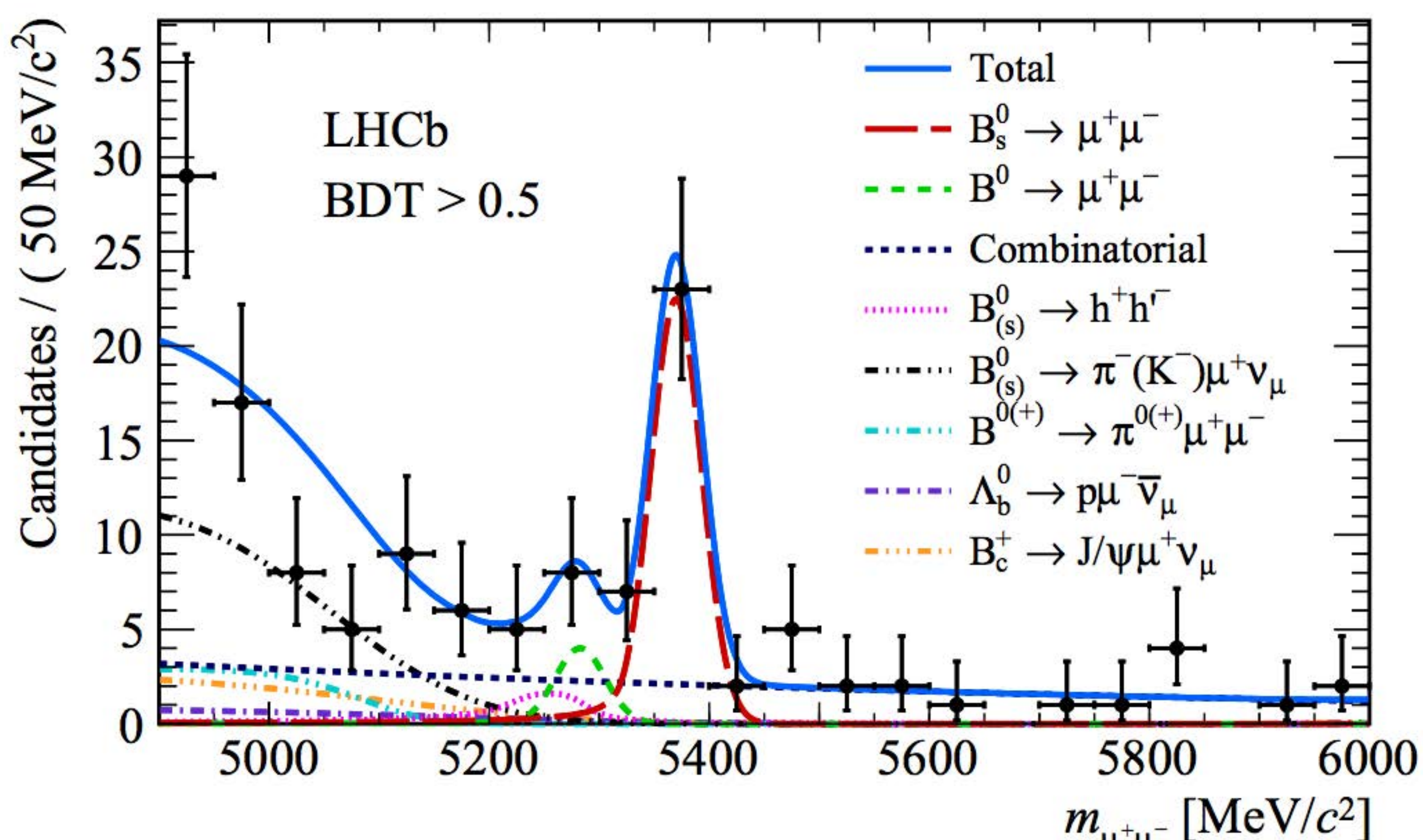
LHCb update with Run 2 data

- LHCb analysis based on Run 1 and Run 2 data (3+1.4 fb^{-1})
- First observation from a single experiment with a significance of 7.8 σ

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad (\;20\%) \qquad \mathcal{B}_{\rm SM} = (3.65 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

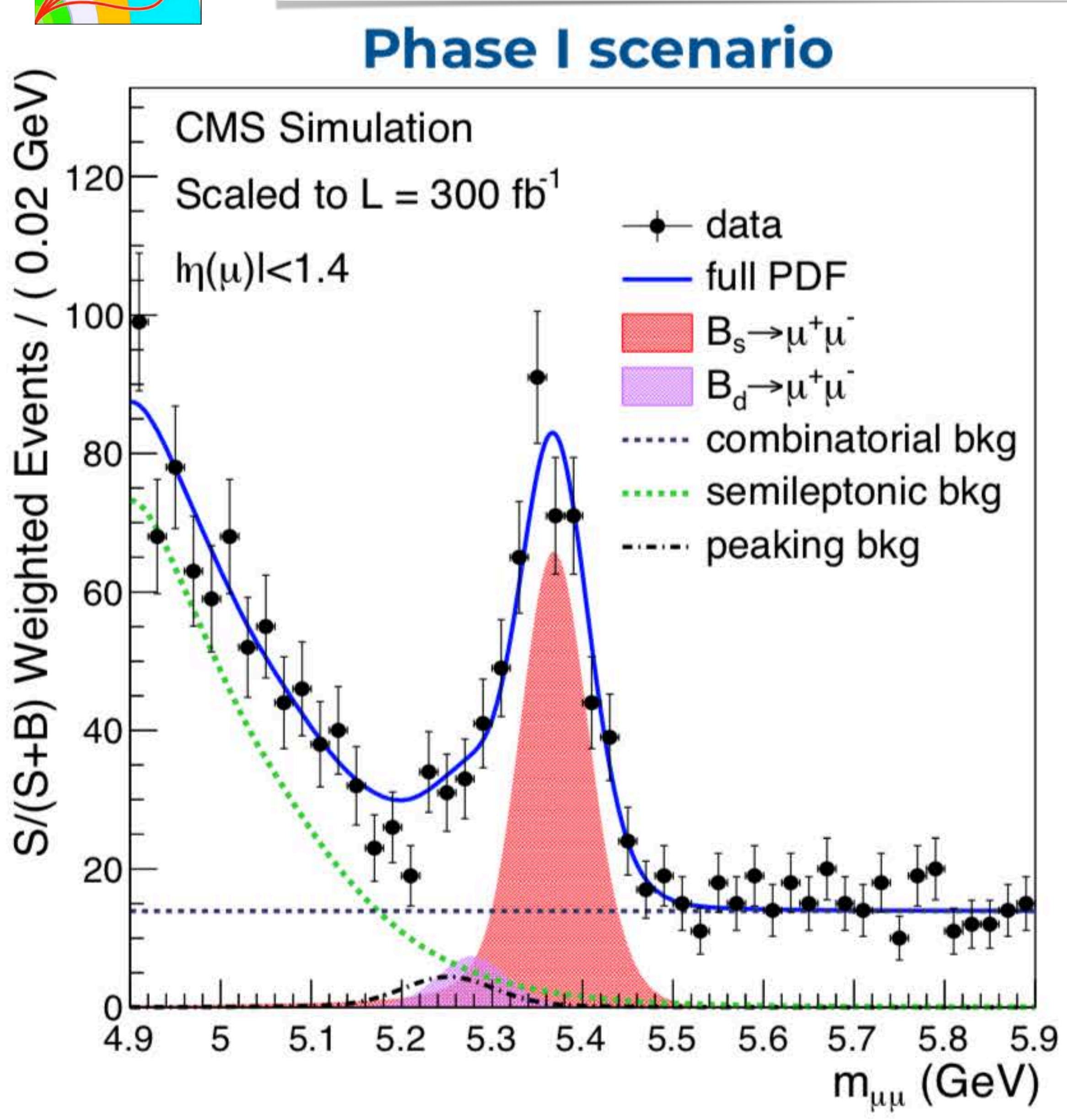
- Consistent with SM expectation at current level of precision

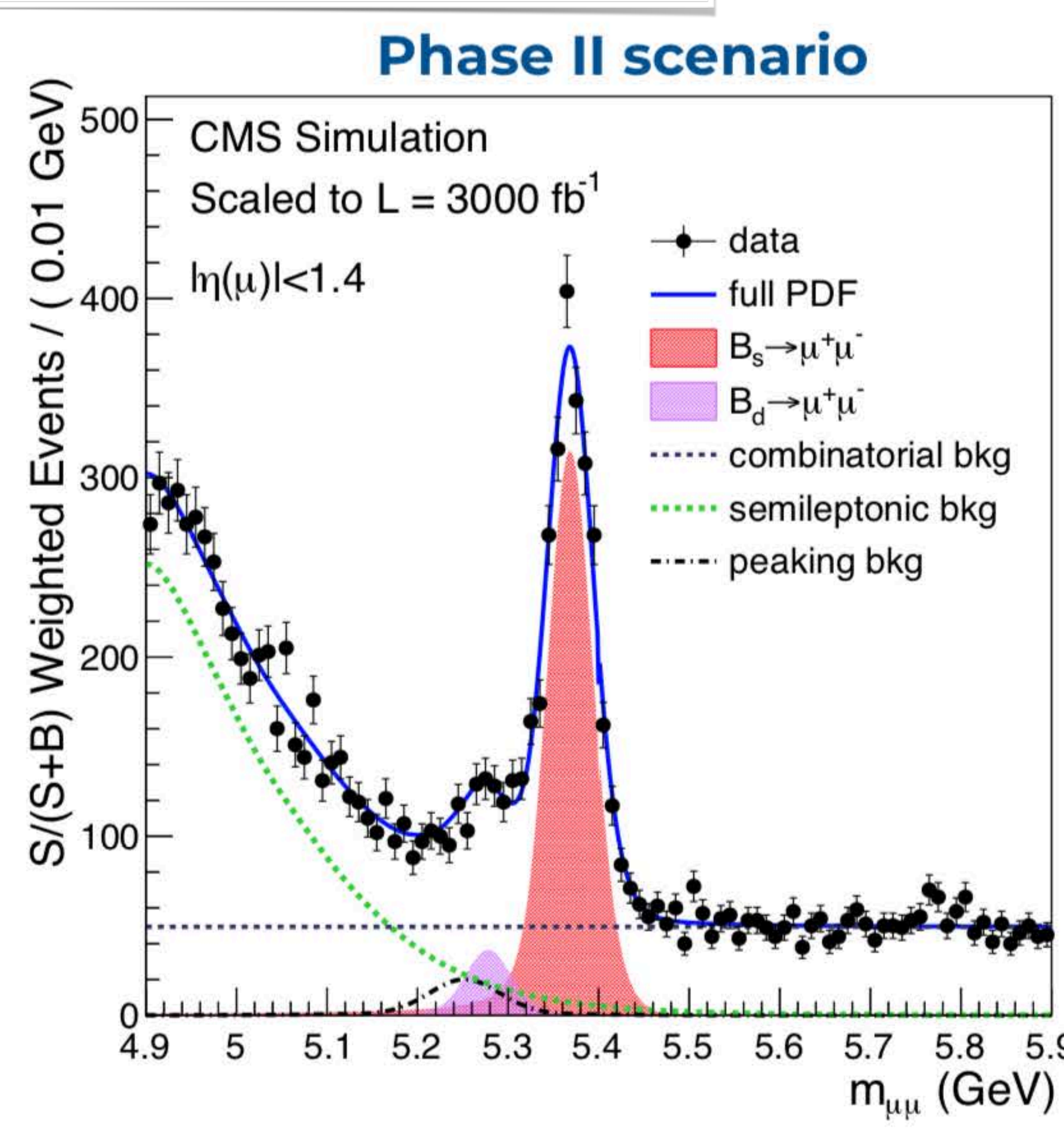


PRL 118 (2017) 191801

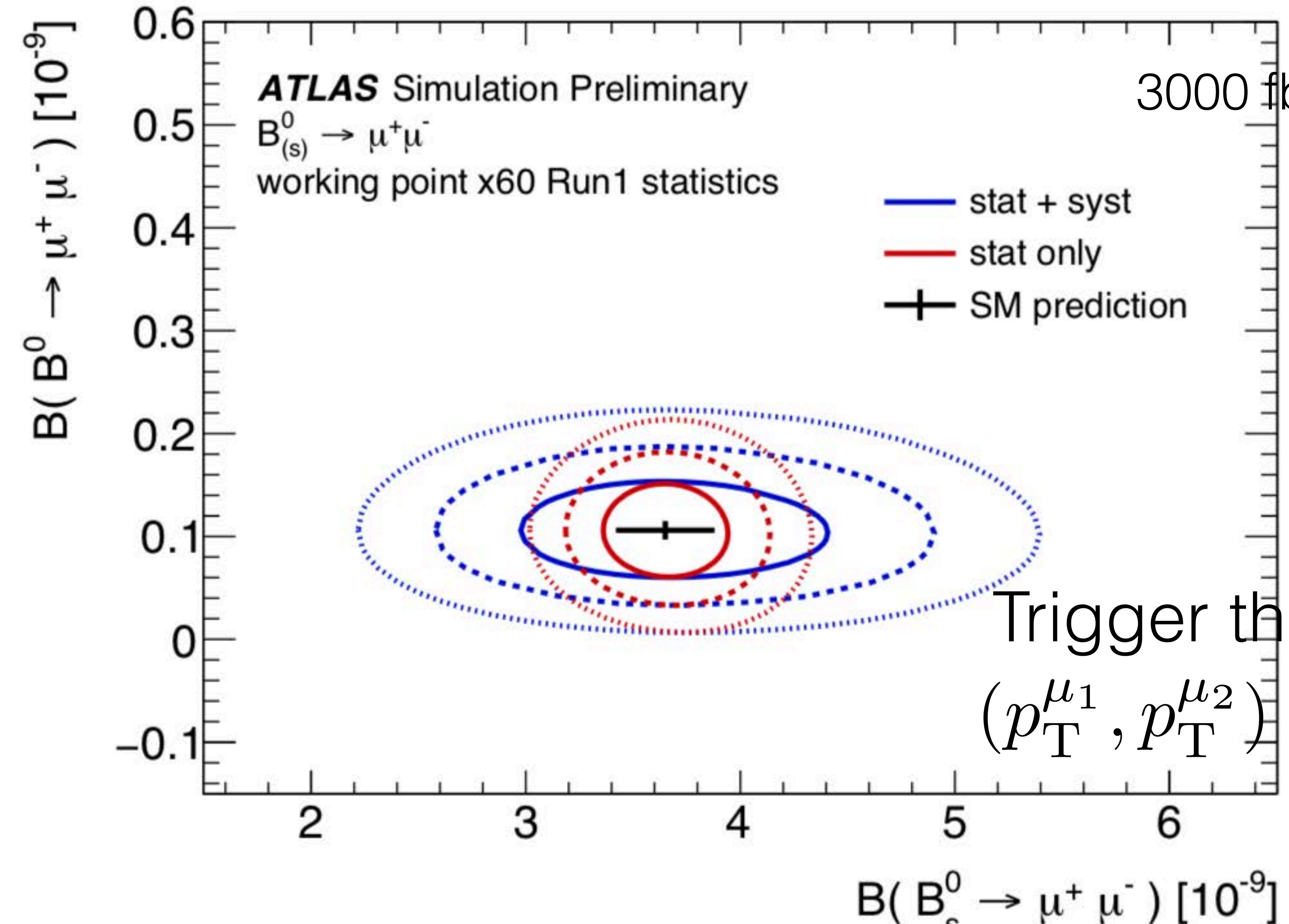
$B_{(s)} \to \mu^+\mu^-$ projections

CMS PAS FTR-14-015





ATLAS-PHYS-PUB-2018-005



Trigger thresholds: $(p_T^{\mu_1}, p_T^{\mu_2})$: (6 GeV, 10 GeV)

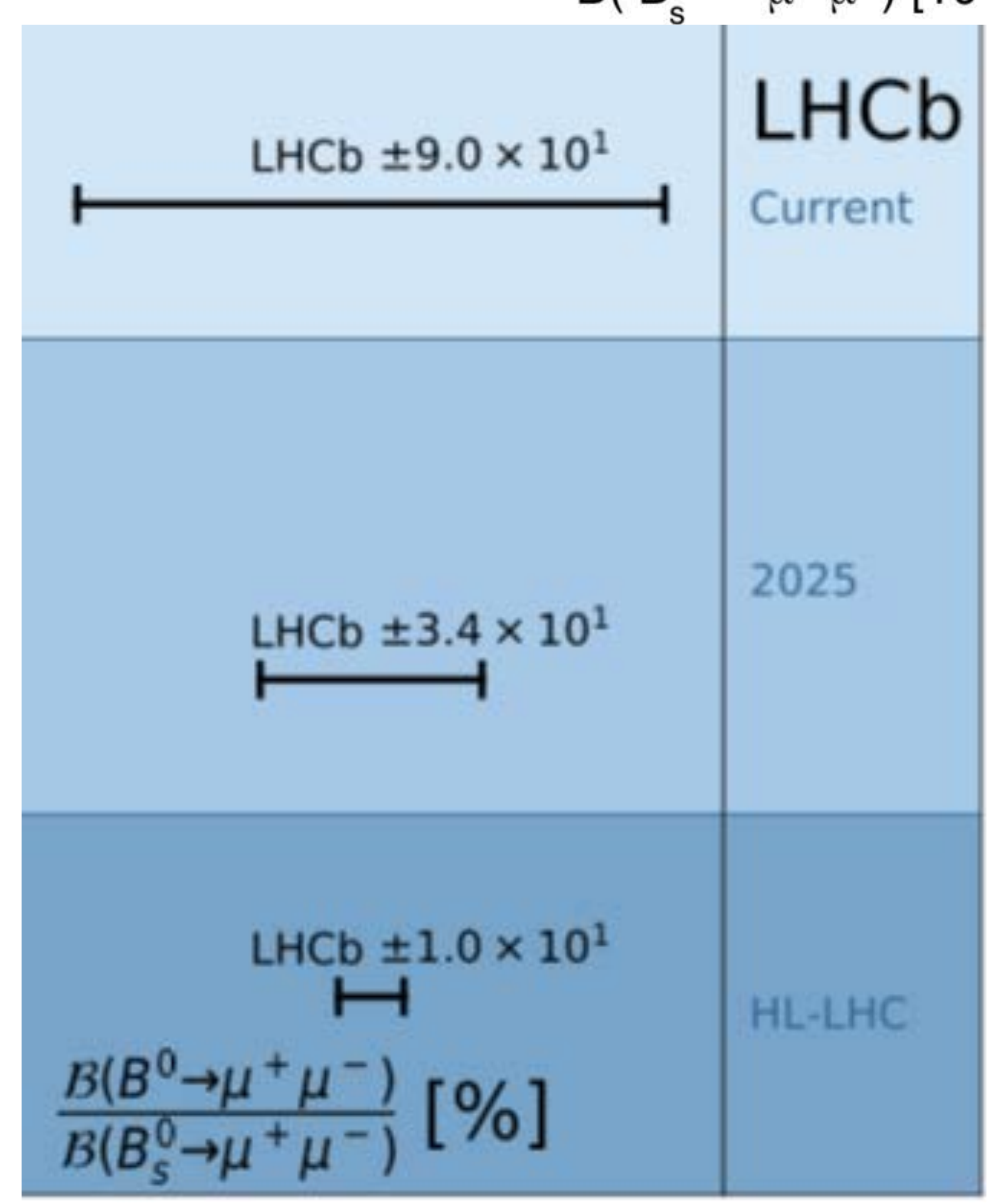
CMS PAS FTR-14-015

$\mathcal{L}$ (fb^{-1})	$N(B^0_s)$	$N(B^0)$	$\delta \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_S \to \mu^+\mu^-)}$
20	18.2	2.2	$>100\%$
100	159	19	66%
300	478	57	43%
300 (barrel)	346	42	50%
3000 (barrel)	2250	271	21%

LHCb (23/300 fb^{-1})

~34 %

~10 %



$\tau_{\rm eff}$

~8 %

~2 %

LHCb: Physics case for an LHCb Upgrade II (in preparation)

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

- In the SM, larger BF due to larger τ mass (m_τ^2/M_B^2)

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) = (7.73 \pm 0.49) \times 10^{-7}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) = (2.22 \pm 0.19) \times 10^{-8}$$

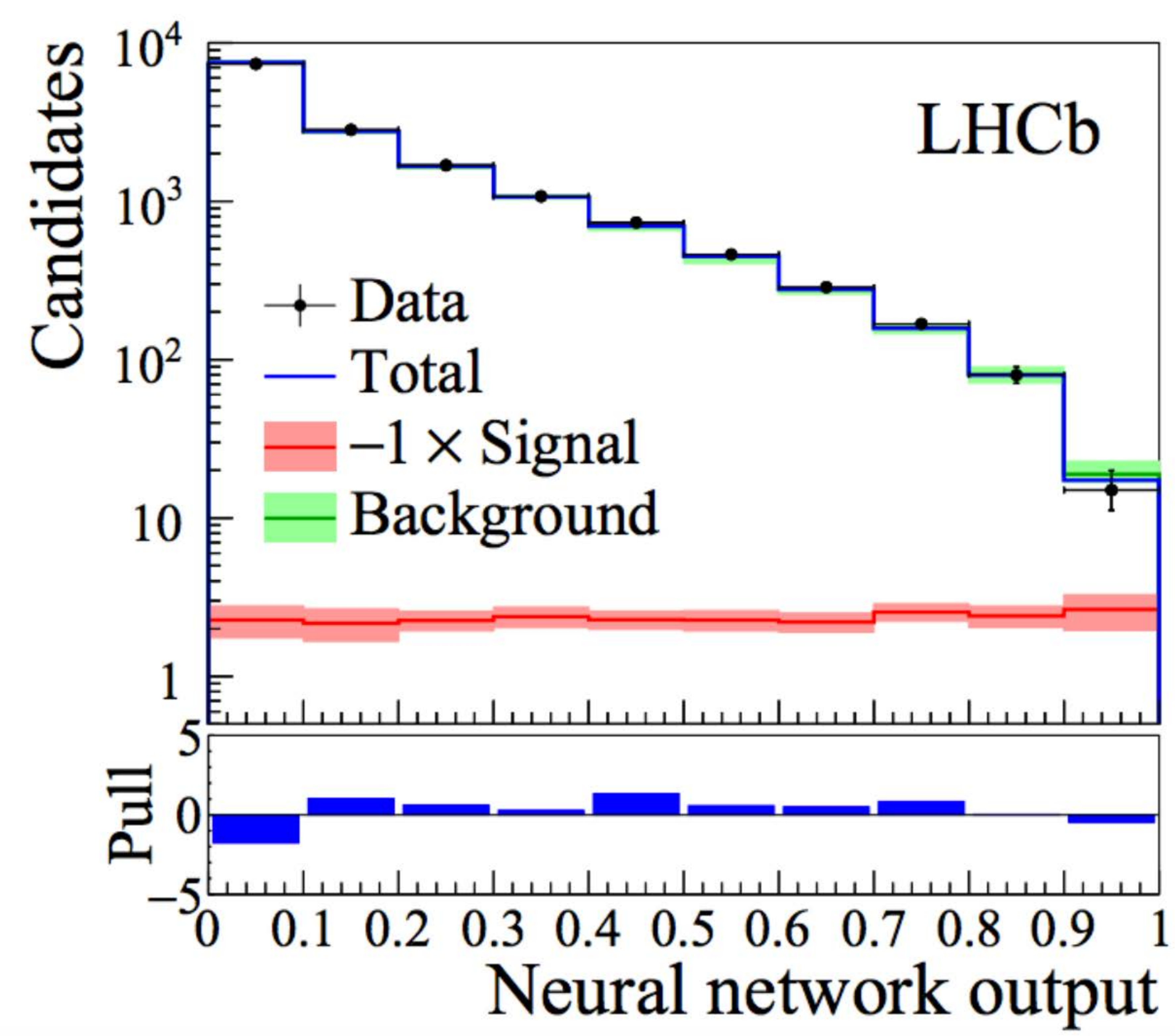
Bobeth et al.
PRL 112 (2014) 101801

- Experimentally challenging due to undetected neutrinos in final state

- Searched by LHCb through the decay
$$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$$

- $B_{s,d}$ unresolvable in mass → analysis optimised for B_s

- Exploit intermediate $\rho(770)^0$ resonance to define signal/control regions of $m_{\pi^-\pi^+}$, then fit MVA



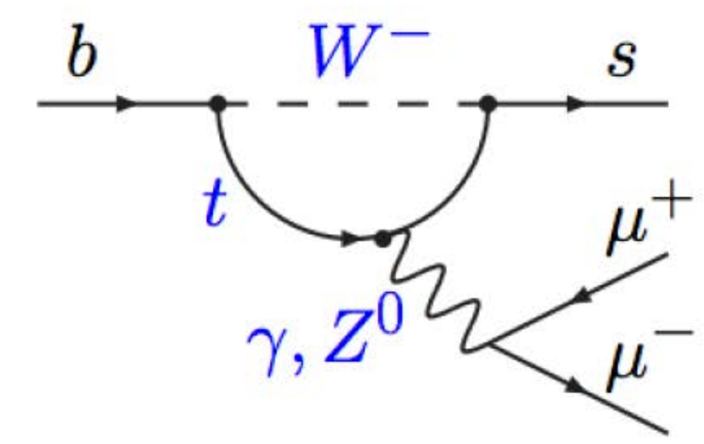
- Limits set:

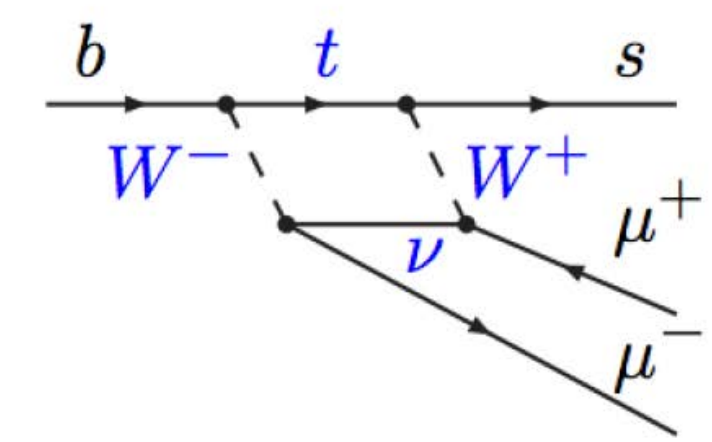
PRL 118 (2017) 251802

$$\mathcal{B}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$ → first direct limit
$$\mathcal{B}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ at } 95\% \text{ C.L.}$$ → best limit

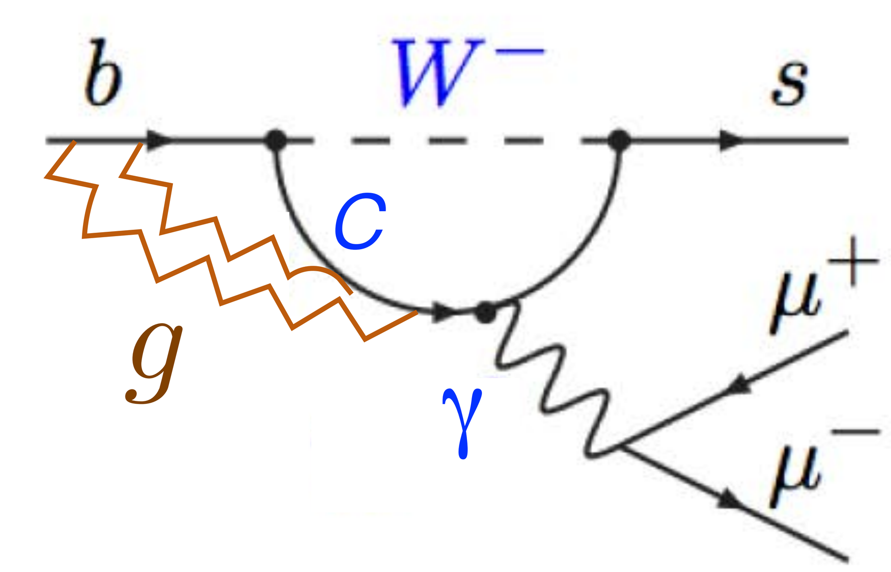
Another interesting rare decay: $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

- A b →s transition that can only proceed via loop diagrams
- NP can be competitive with SM processes





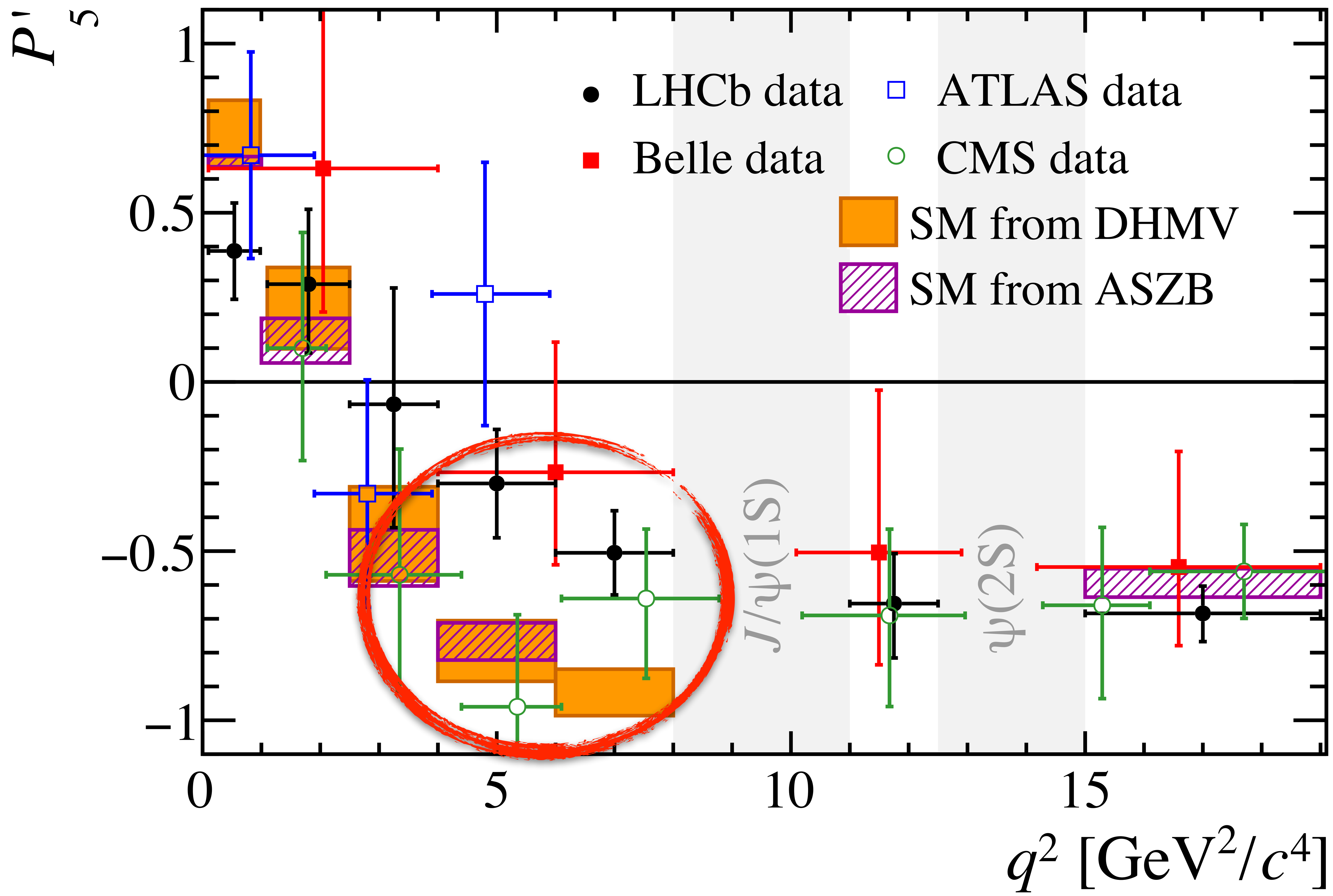
- Four final state particles with rich phenomenology, plethora of observables, which can be built from the measured amplitudes
- Rates, angular distributions and asymmetries sensitive to NP
- A lot of phenomenological work invested in defining observables with “clean” theoretical predictions.
  - Observables form-factor free at leading order
  - Still susceptible to non-factorisable corrections



- Question: how clean?

The curious case of P_5'

- One such observable is so-called P'_5, not intuitive, but constructed from angular observables to be robust from 'form-factor uncertainties'



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

- Is the SM prediction less precise than what is claimed?

Fit to the invariant masses

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Low-q^2 | Central-q^2 | $B^0 \to K^* J/\psi(\to \ell^+\ell^-)$

- Precision of measurement driven by statistics of electron sample : ~90 and 110 signal candidates in low-q² and central-q², muon sample 3-5 times larger