Recent results in flavour physics

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(CERN)

On behalf of (mainly) LHCb

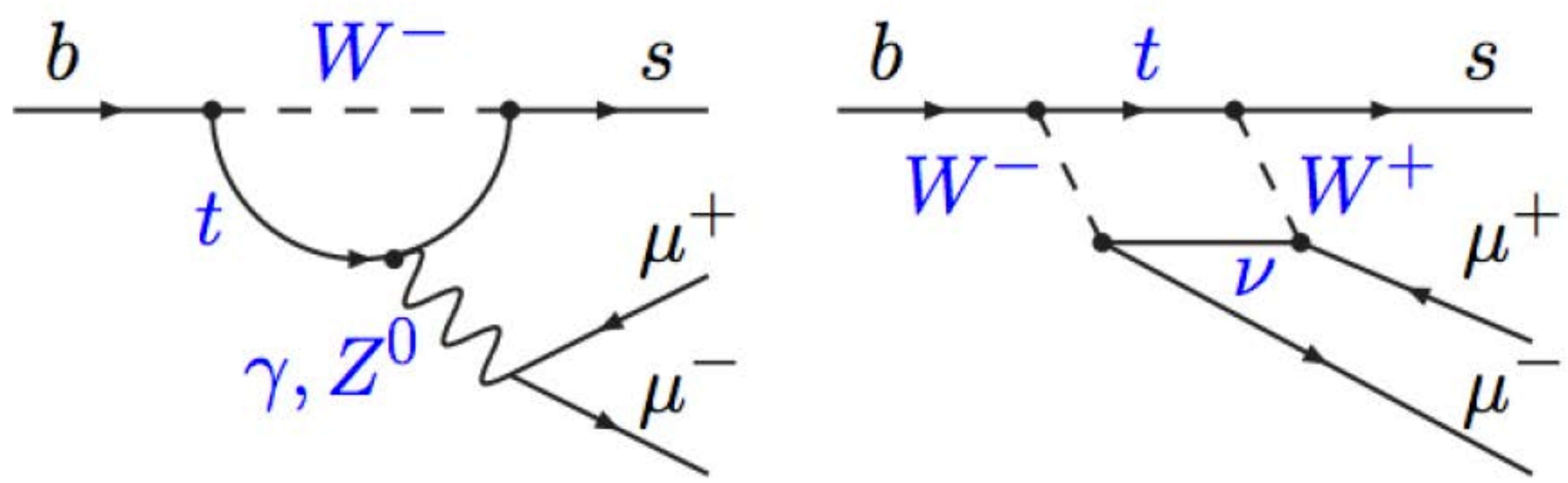
Annual Theory Meeting 2018, IPPP Durham

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 (τ_b~$1.5\ 10^{-12}$ 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

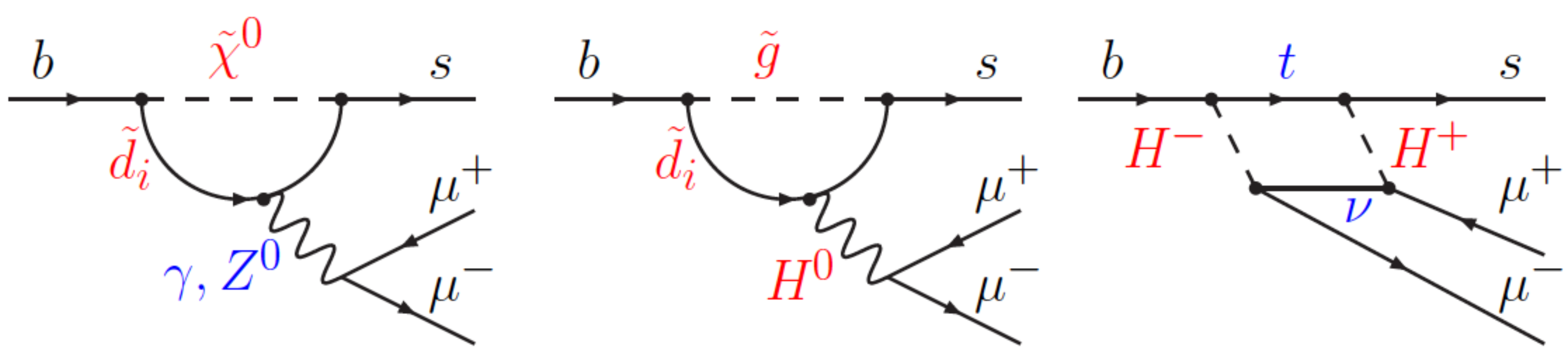
Flavour physics as a tool of discovery

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



No FCNCs

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



- Strategy: use well-predicted observables to look for deviations
- Indirect approach to New Physics searches, complementary to that of ATLAS/CMS and particularly relevant at this point!


A window on NP at high scales

The LHCb collaboration

- ~1250 members from 79 institutes in 18 countries
- ~450 publications, some with very high impact
- Main focus on heavy quark flavour…but plenty of other physics in the forward direction

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CKM & CPV

EW and QCD

Rare decays

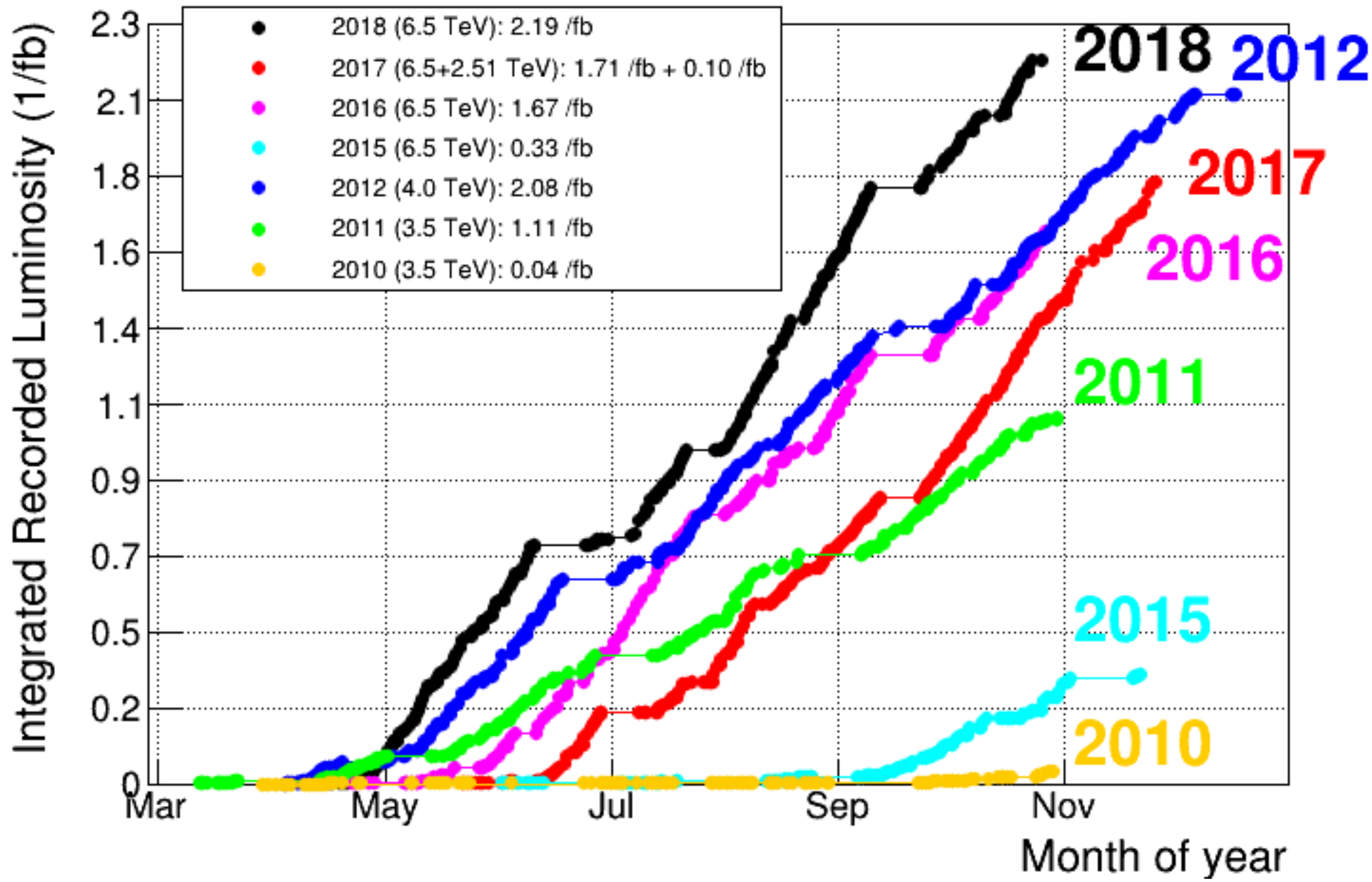
Spectroscopy

Semileptonic decays

Ions and fixed target

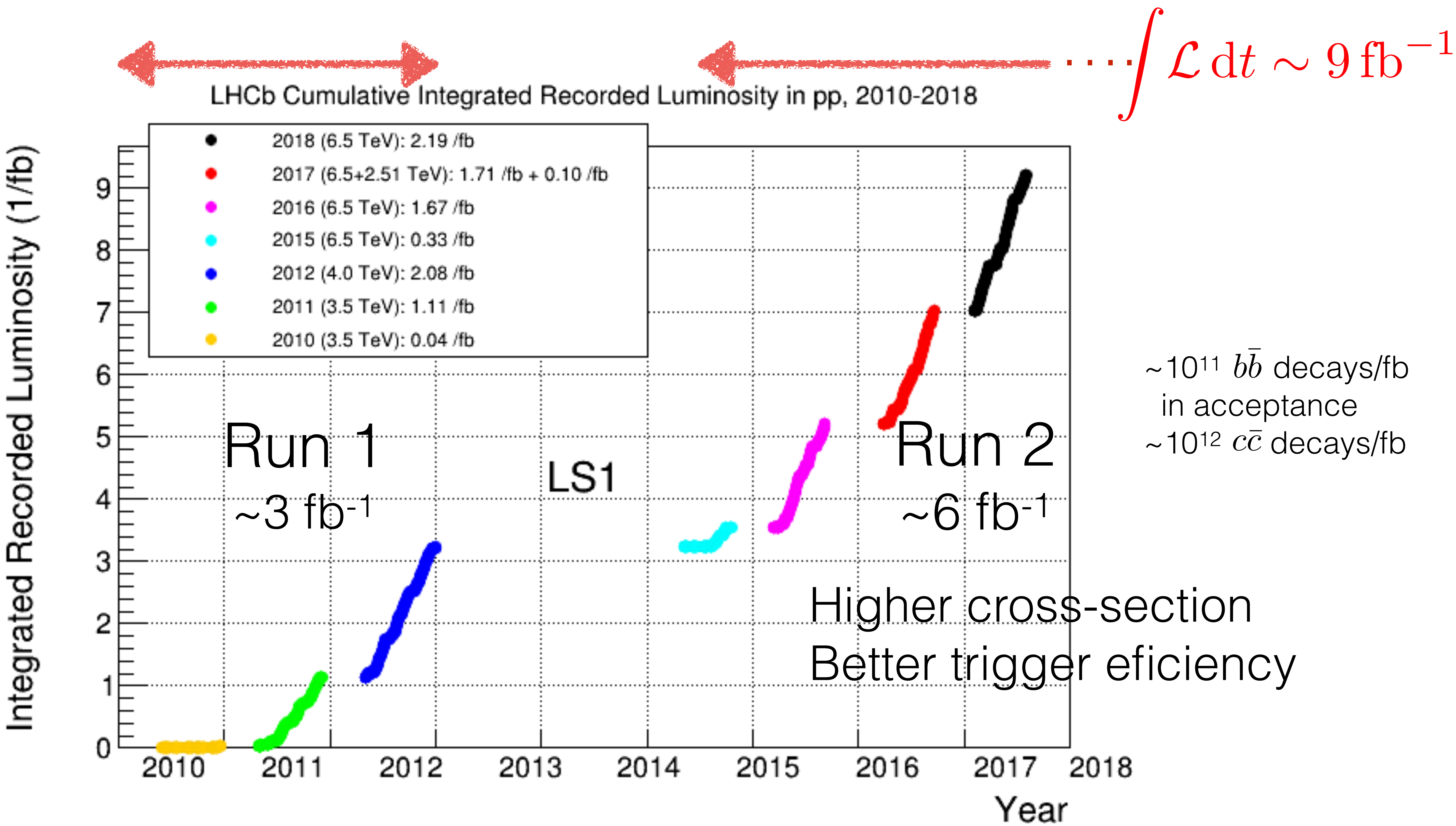
Exotica searches

Luminosity @ LHCb



- 2018: the best year!
- Record in delivered and recorded Luminosity
- Legacy Run 2 analyses: i.e. Run 1 (3/fb) +$(2x2/fb)_{2015/16}$ + $(2x1.8/fb)_{2017}$ + $(2x2.2/fb)_{2018}$ → total equivalent to ~5x Run 1 dataset

Luminosity @ LHCb



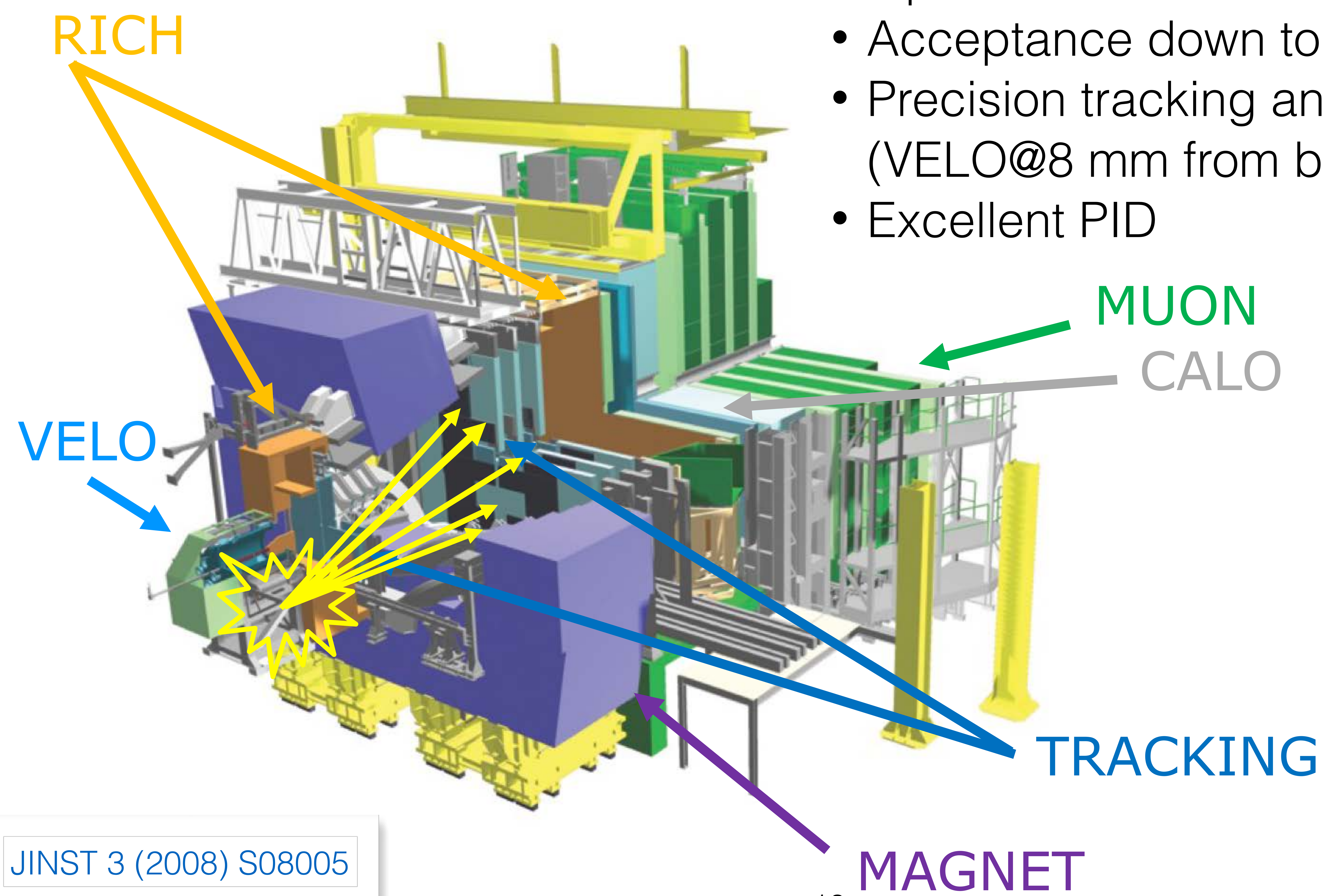
~10^{11} $b\bar{b}$ decays/fb in acceptance

~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
  - (Typical ’18 peak Lumi for ATLAS/CMS ~2 10^{34} cm^{-2} sec^{-1} , with ~37 interactions/bunch crossing, ~150/fb in Run 2)

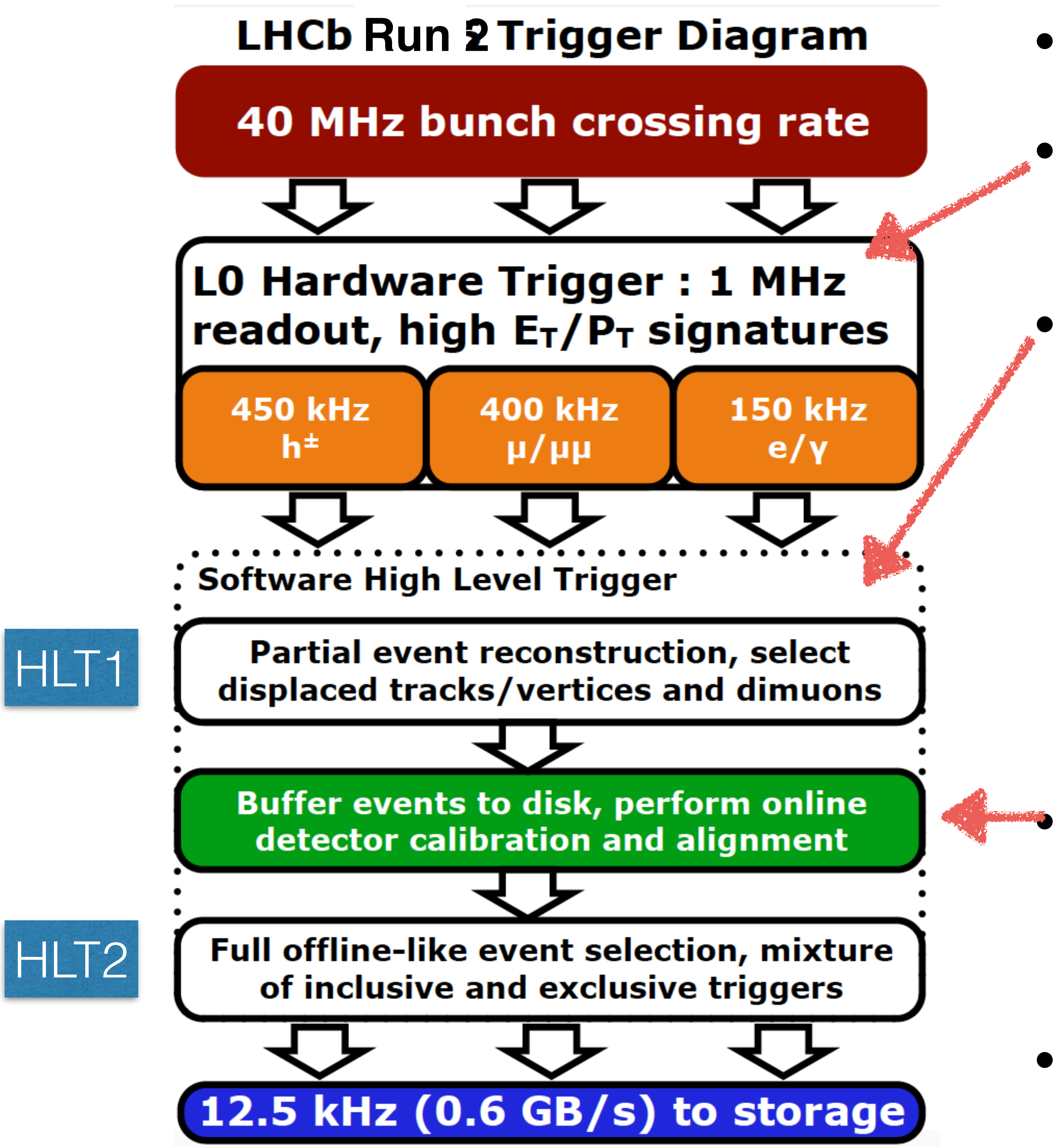
LHCb detector: the essentials

- 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

The LHCb trigger

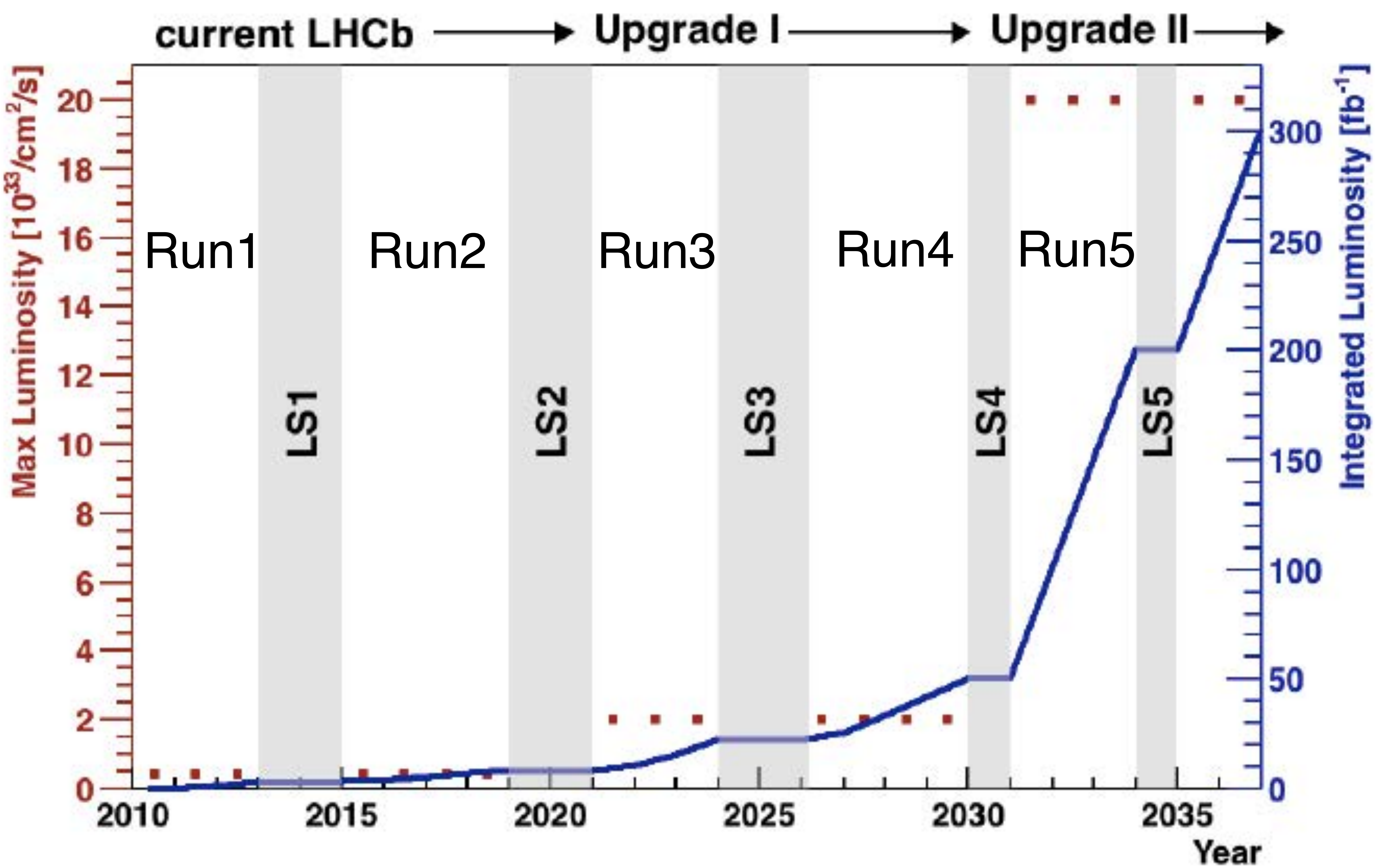


- Fully optimised for flavour physics
- At first stage (L0) a hardware trigger fires on single hadrons, leptons and photons
- High Level Trigger (HLT): software application designed to reduce event rate from 1 M to ~10 k events/s, executed on a large computing cluster. Flexible design that can adapt to changing machine conditions and evolving physics programme
- Split HLT in two steps: buffer events to disk after HLT1 to perform online calibration & alignment
- HLT2 uses offline-quality calibration → more discriminant trigger
- Offline-quality reconstruction up-front

2018: last year of LHCb as we know it!

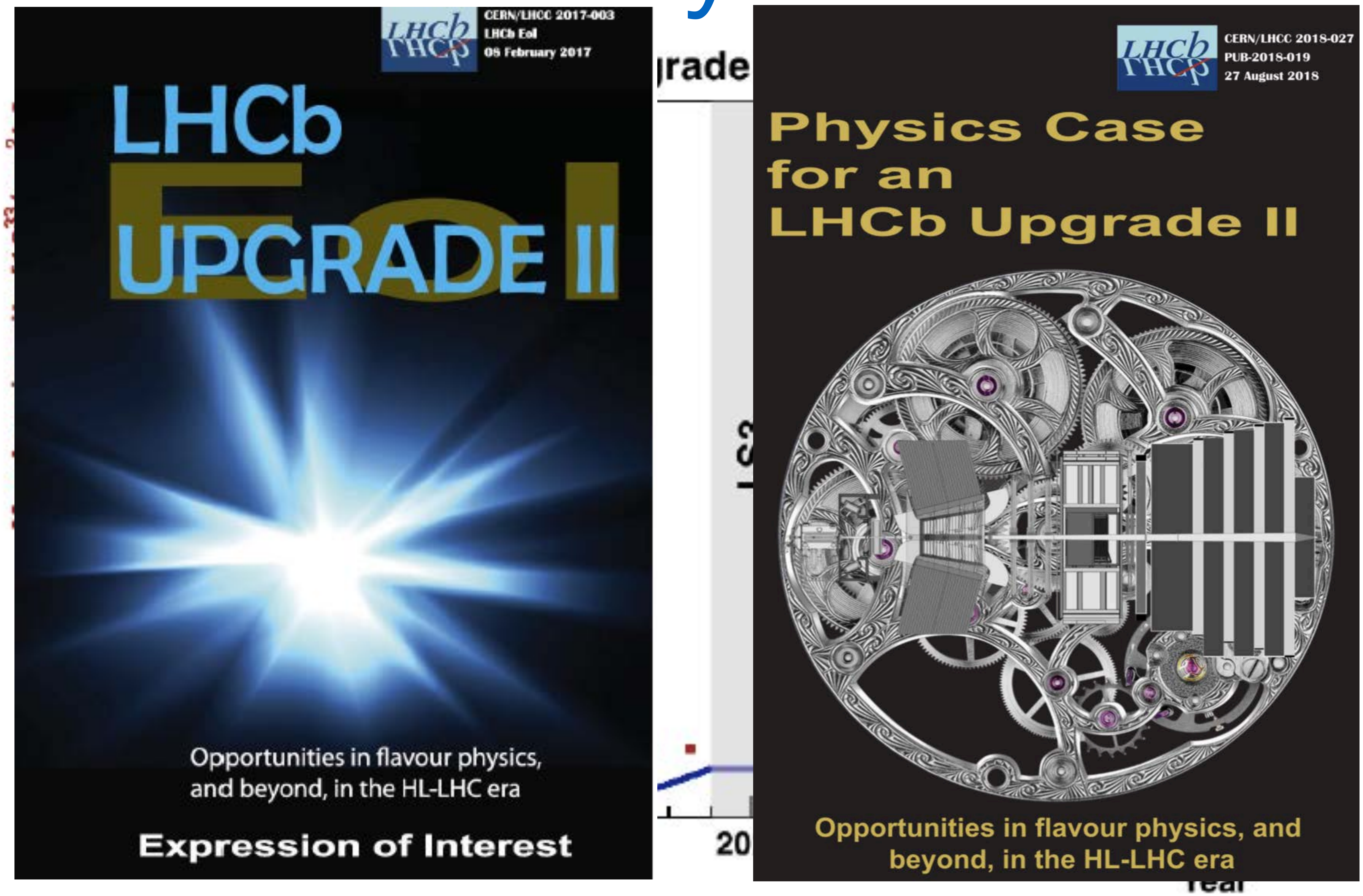
- **LHCb is building its Upgrade I to be installed during LS2 (2019-20)→**
  - **Higher Lumi: 4 x10^{32} →2 x10^{33} cm^{-2} sec^{-1}**
  - **more interactions per beam crossing: ~1→~5**
- Possible LHCb detector consolidation and modest enhancements in LS3 (2025) - ATLAS/CMS Phase II upgrades also in LS3
- Major LHCb Upgrade II in LS4 (2030) →Factor ~10 increase in $\mathcal{L}$: ~1.5 x10^{34} /cm^{2} /s

Luminosity evolution



- Expression of Interest for LHCb Upgrade II (CERN-LHCC-2017-003) and physics case (CERN/LHCC 2018-027) submitted to LHCC

Luminosity evolution



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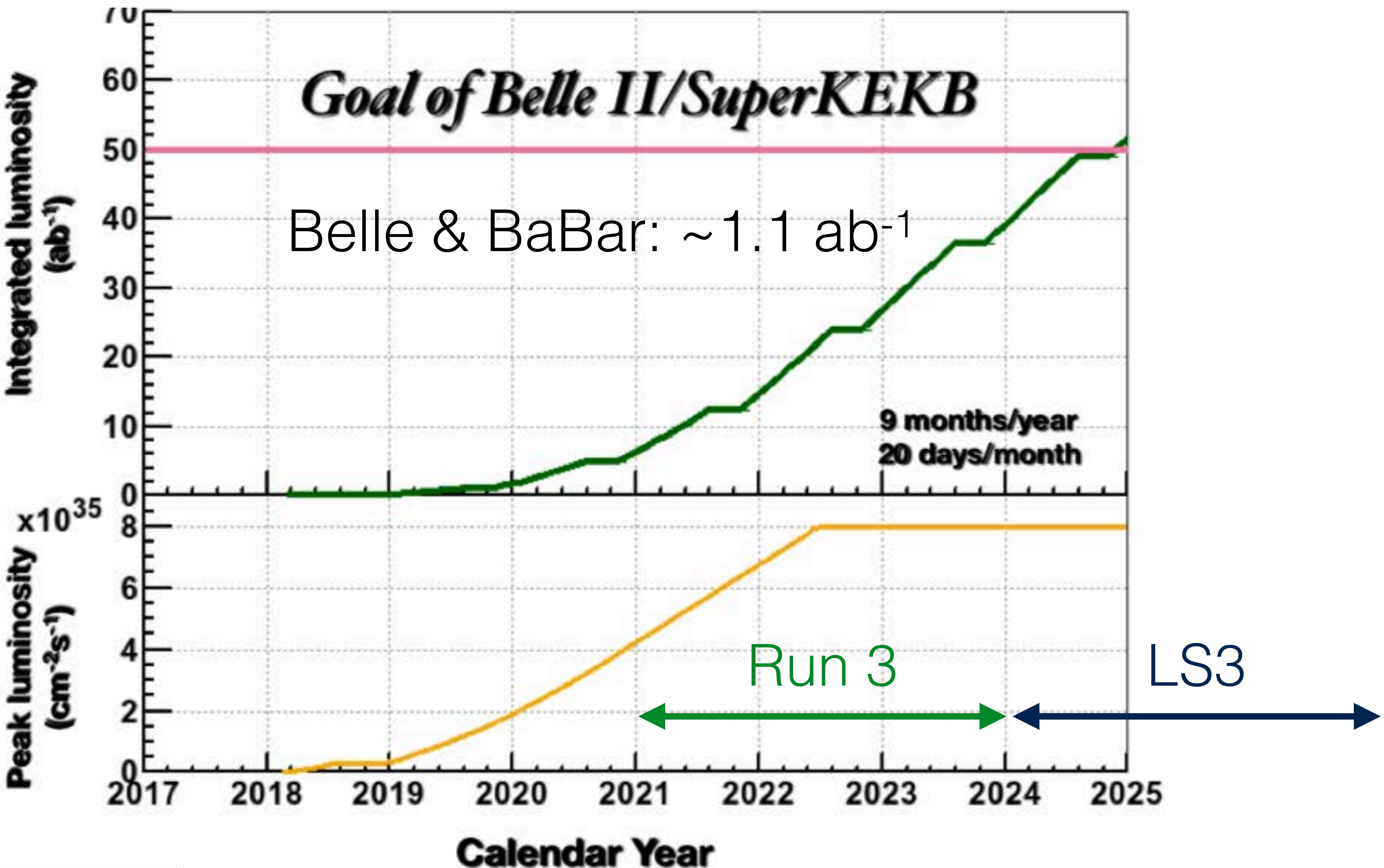
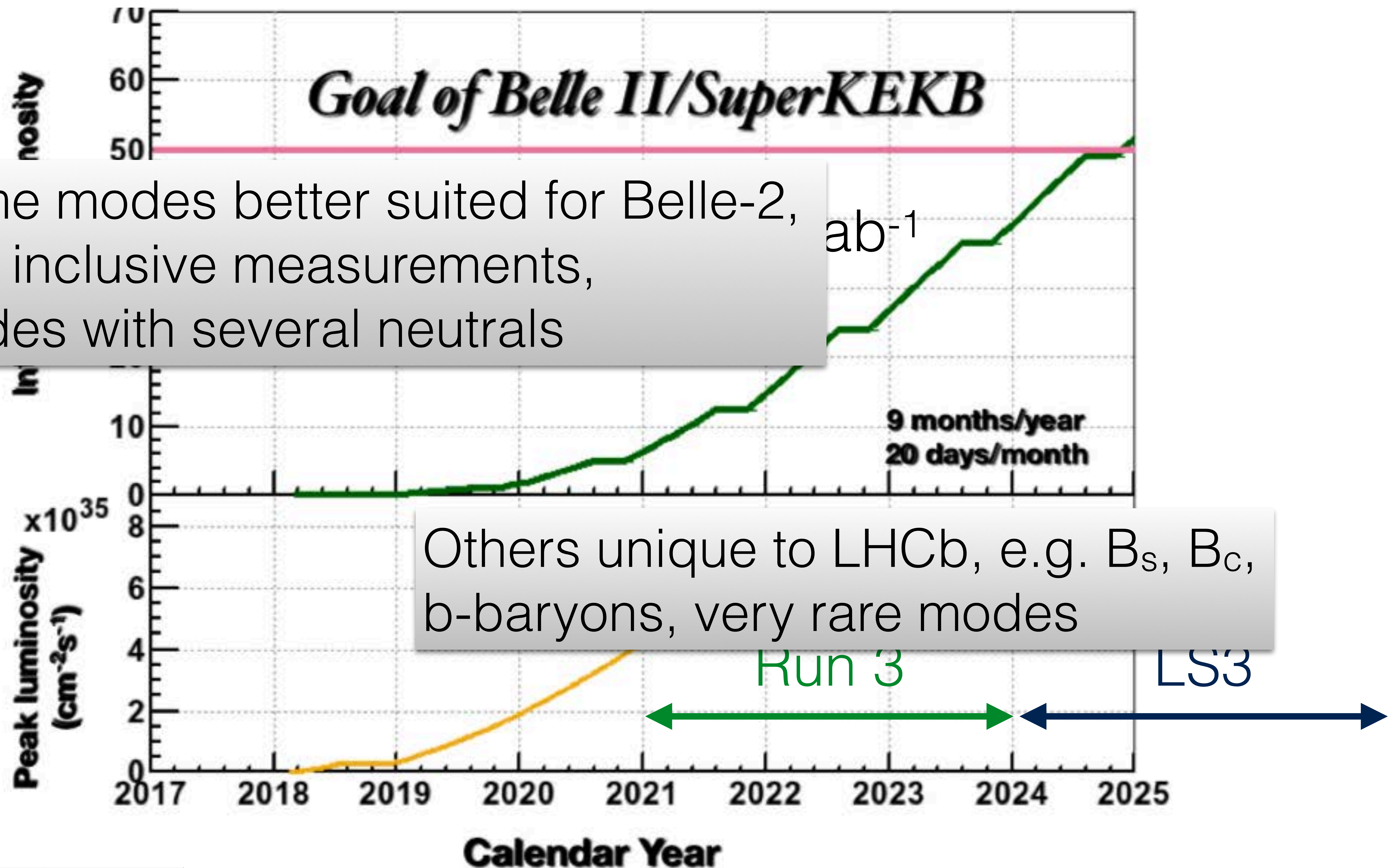
Belle II/SuperKEKB



arXiv:1808.10567

Belle II/SuperKEKB



Some modes better suited for Belle-2, e.g. inclusive measurements, modes with several neutrals

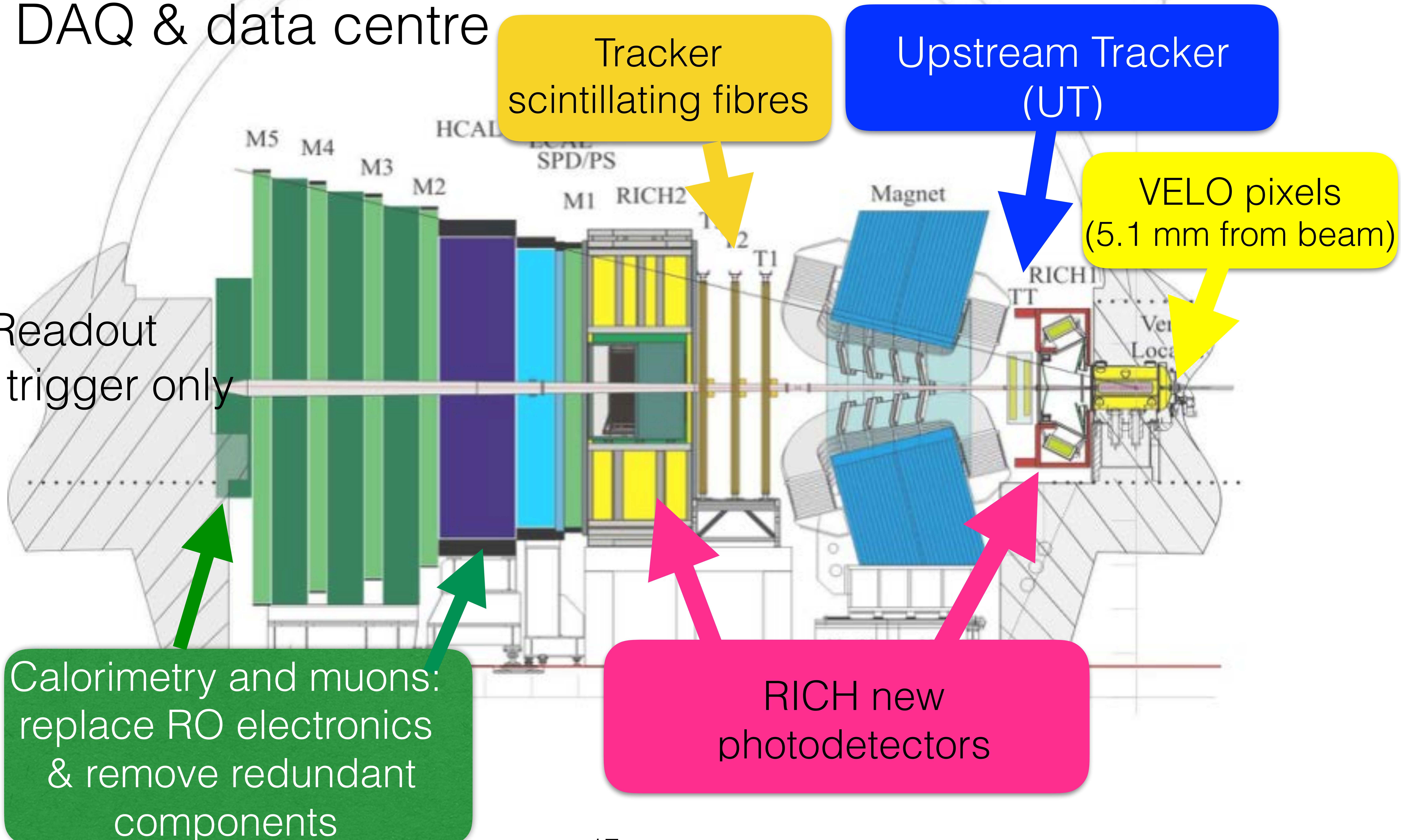
Others unique to LHCb, e.g. B_s, B_c, b-baryons, very rare modes

arXiv:1808.10567

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

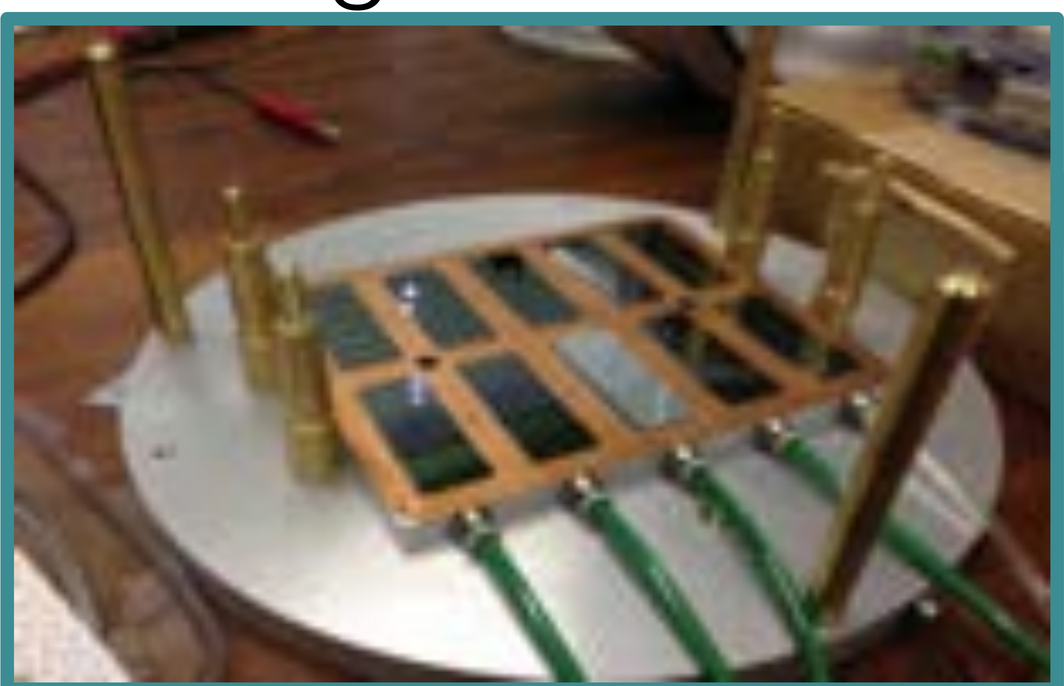


The **NEW** detector

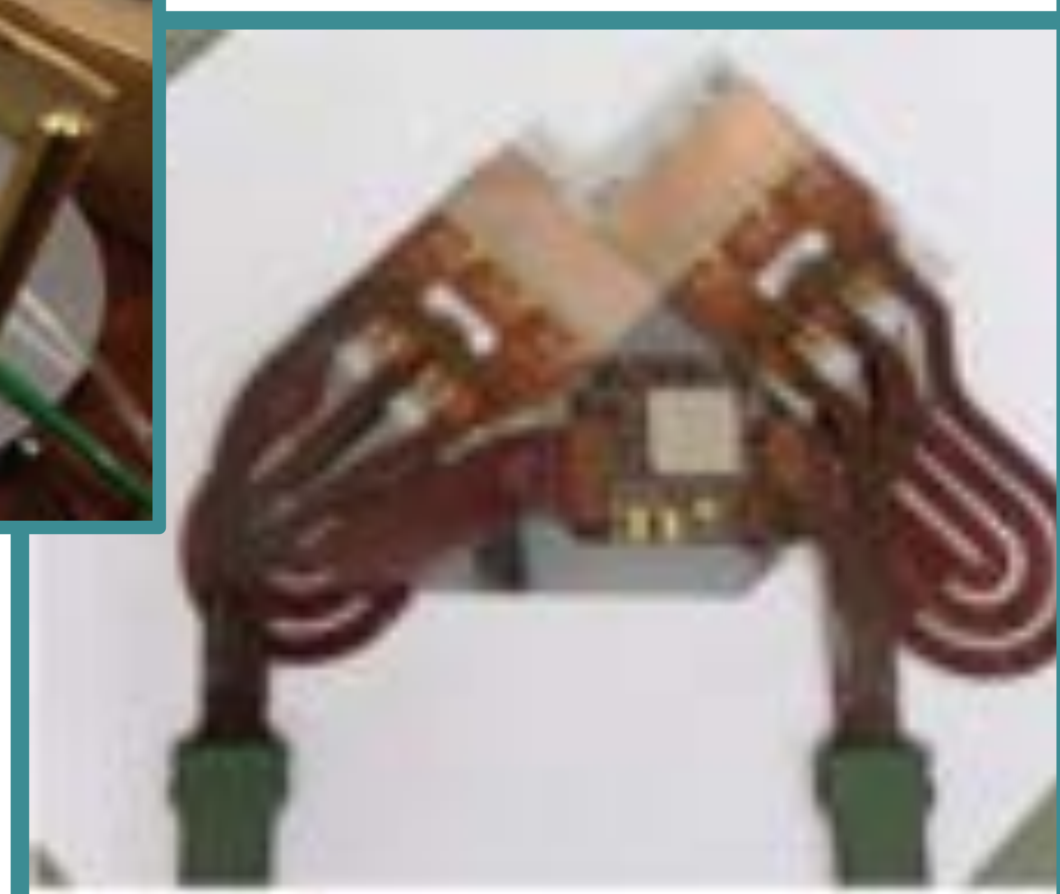
- Less than 10% of all channels will be kept!
- NEW RO electronics
- NEW DAQ & data centre

Dismantling and installation already started! Tight timescale!

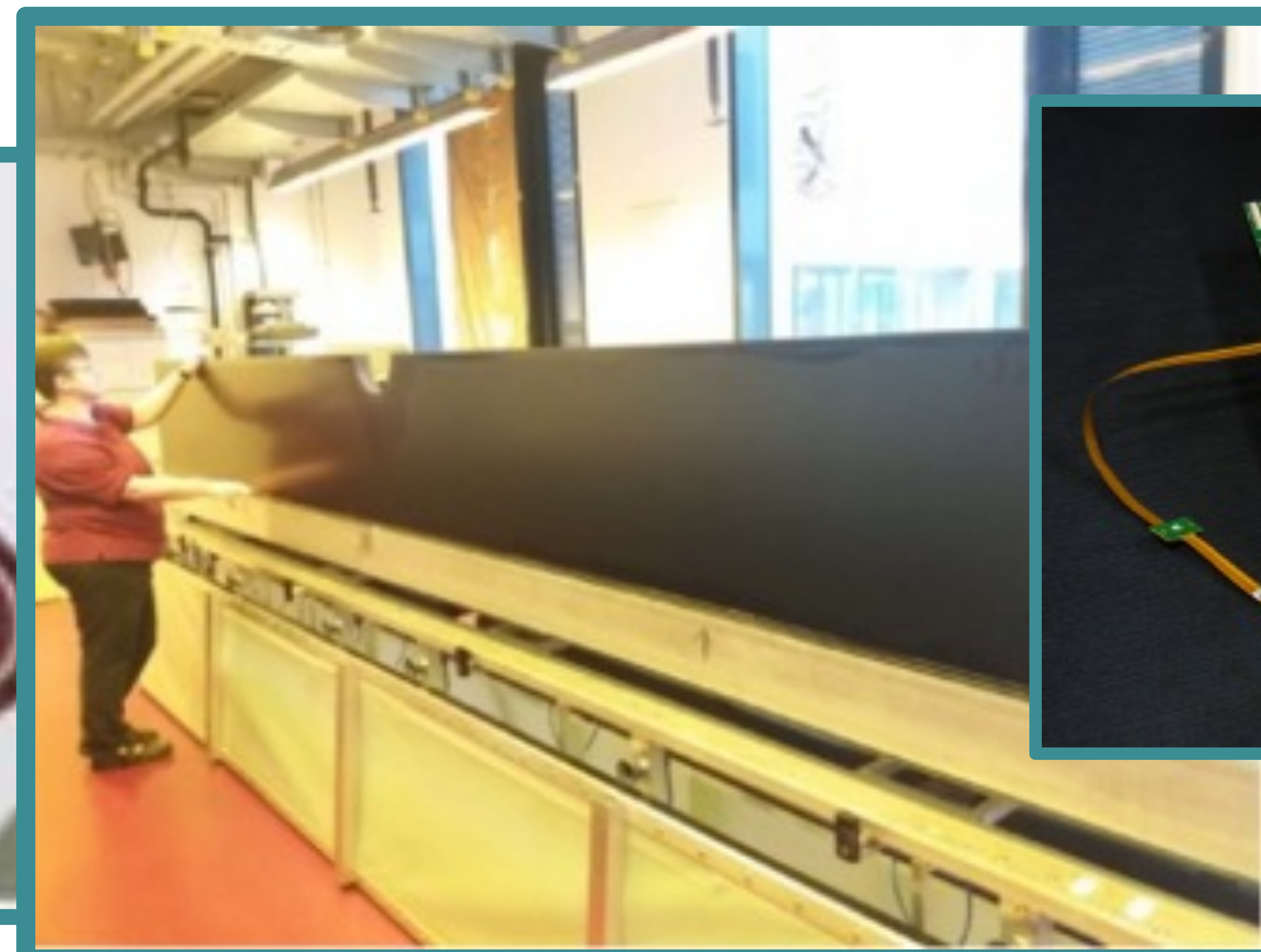
VELO sensor tiles testing device



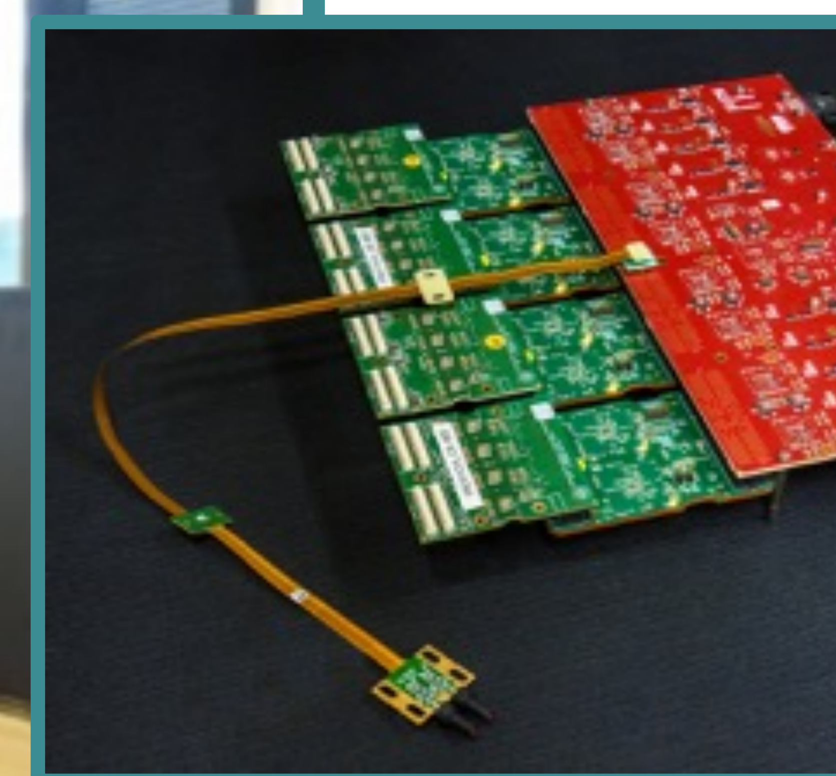
VELO module



SciFI module

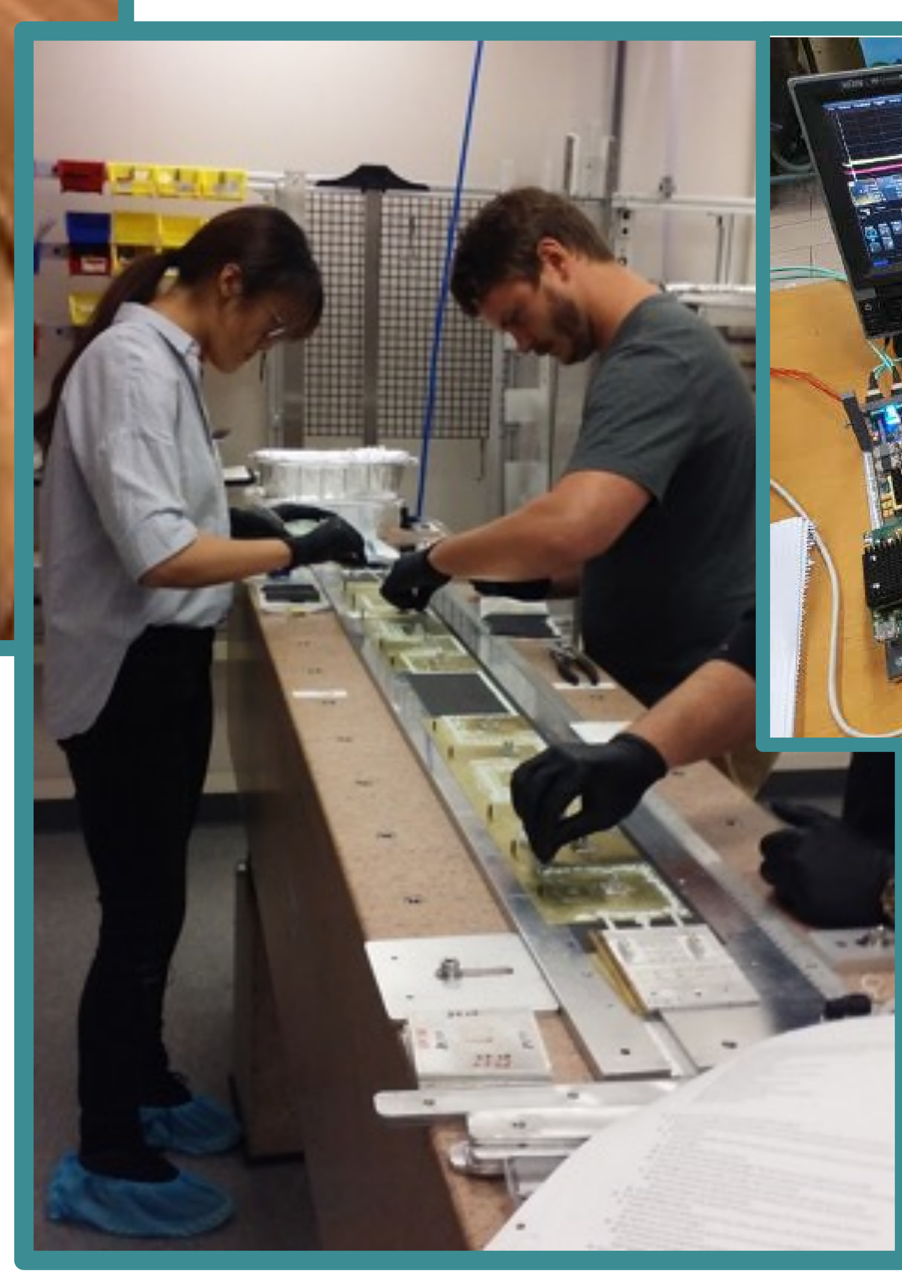


SciFI Readoout

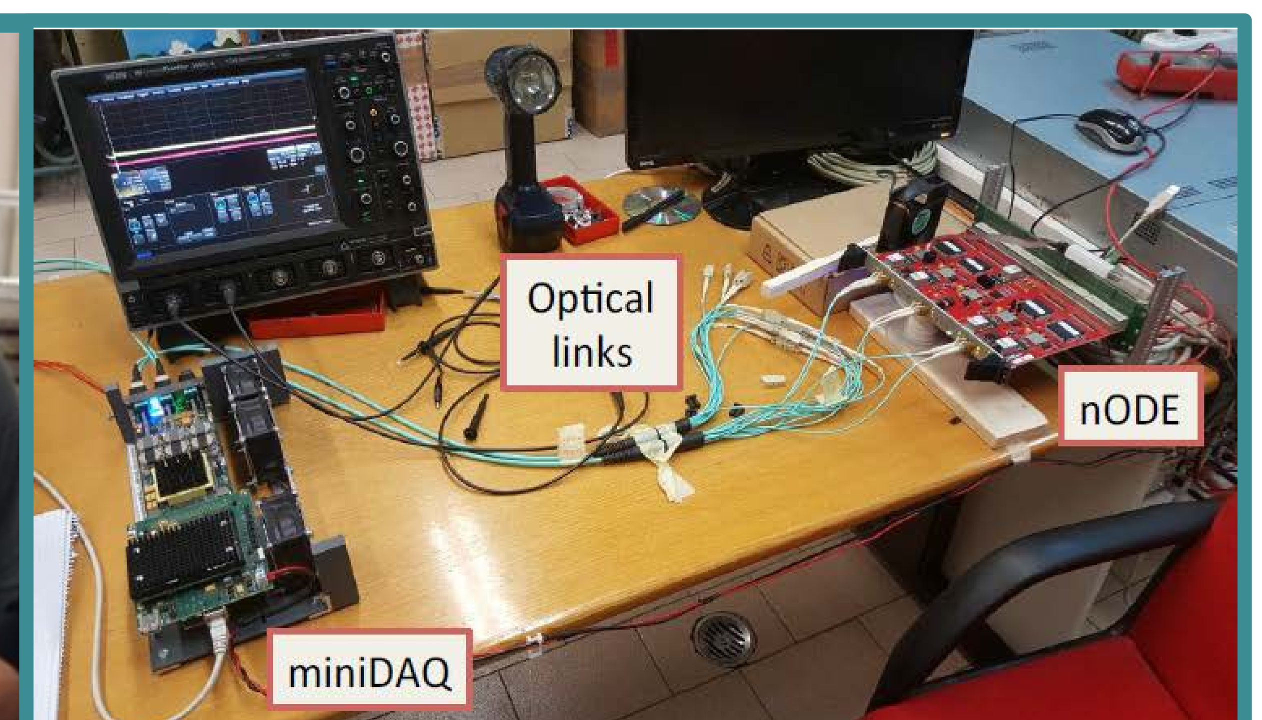


CALO electronics

UT sensor



UT staves construction



Test of MUON electronics

RICH MaPMTs under test

PCIe40 boards

Tatsuya Nakada @ End of LHCb Phase I Celebrations

Approval in 1998 was non-trivial

- Some of the things said were
  - B factory experiments would do everything. If not, Tevatron experiments would do the rest. Thus, nothing important would be left.
  - General purpose LHC experiments can do the same physics as well
  - Steal precious LHC luminosity from the general purpose experiments
  - Resources are already limited
  - etc…
- But, finally we got it!

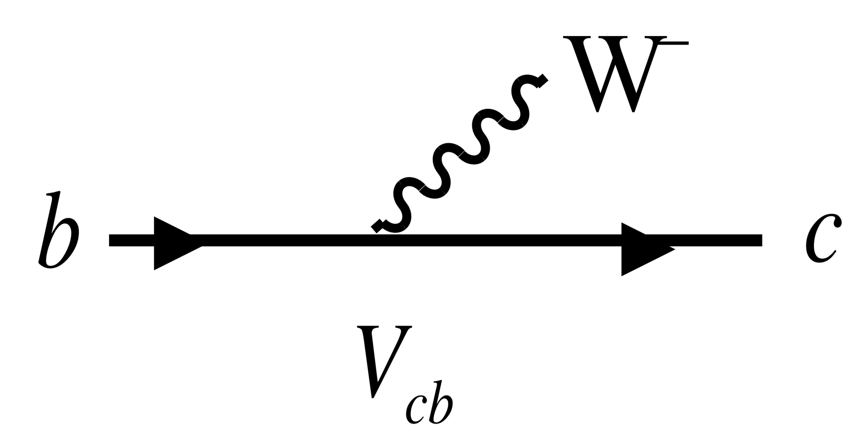
6 December 2018 End of LHCb Phase 1

CPV in beauty and charm

CKM Matrix and γ

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

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

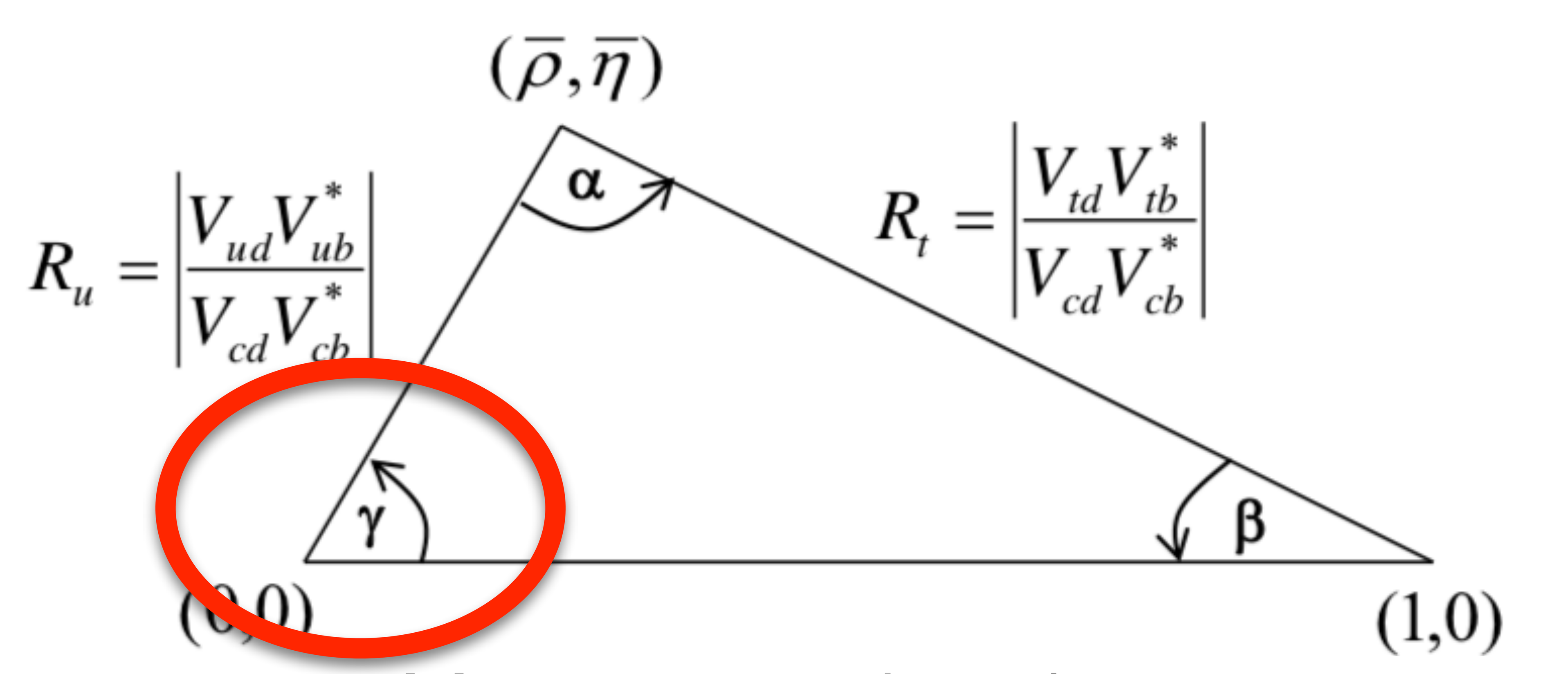


- The probability of the transition from flavour i to flavour j is ~ $|V_{ij}|^2$
- Probability of b to c decay ~ $|V_{cb}|^2$

- 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: $j = d, k = b$

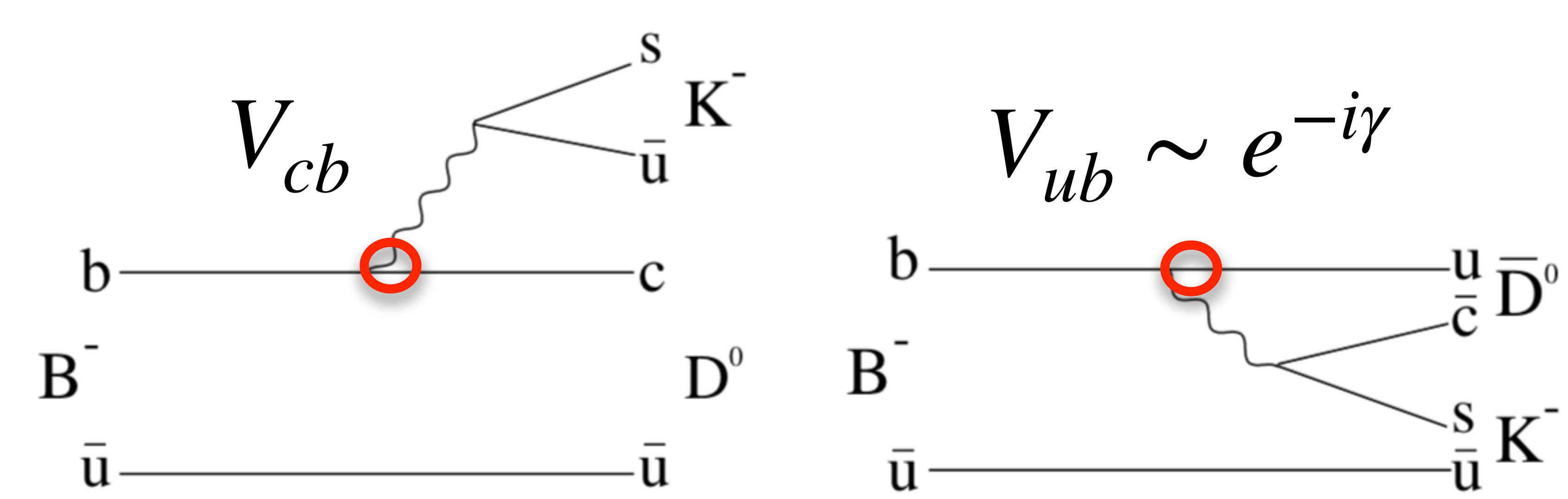
Measuring γ

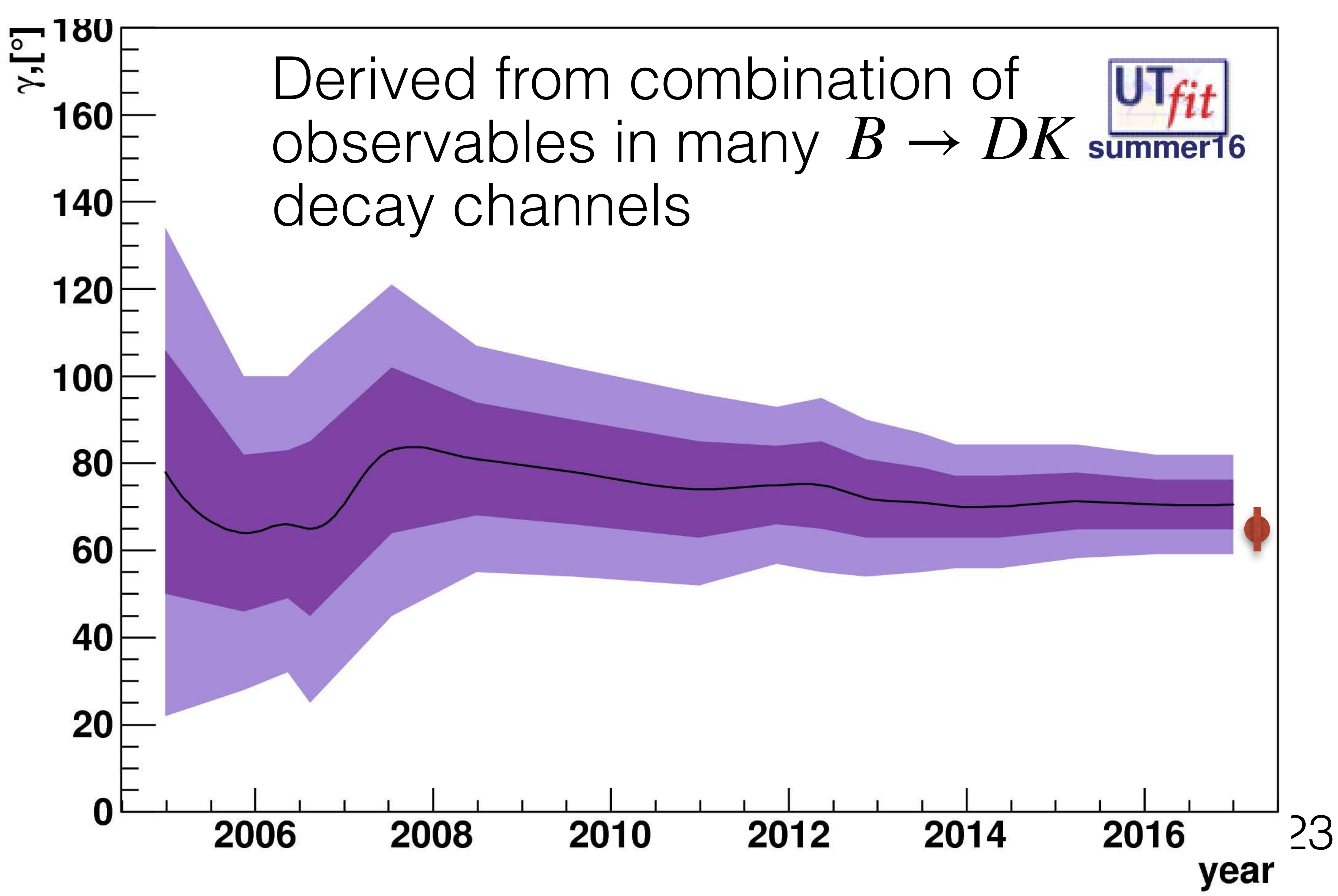
- γ easily accessible from tree-level processes
  - theoretically very clean $\delta\gamma/\gamma_{th} \sim \mathcal{O}(10^{-7})$
  - yields results unpolluted by NP
  - “SM Standard Candle”
- Golden mode $B^- \rightarrow DK^-$
  - Sensitivity from interference of $b \rightarrow c$ and $b \rightarrow u$ amplitudes through final states accessible to both D^0 and $\bar{D}^0$
  - Many different methods and decay modes $(K\pi, K3\pi, KK, K_s^0\pi\pi, \ldots)$

ratio of interfering B amplitudes ~0.10

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

strong phase difference





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

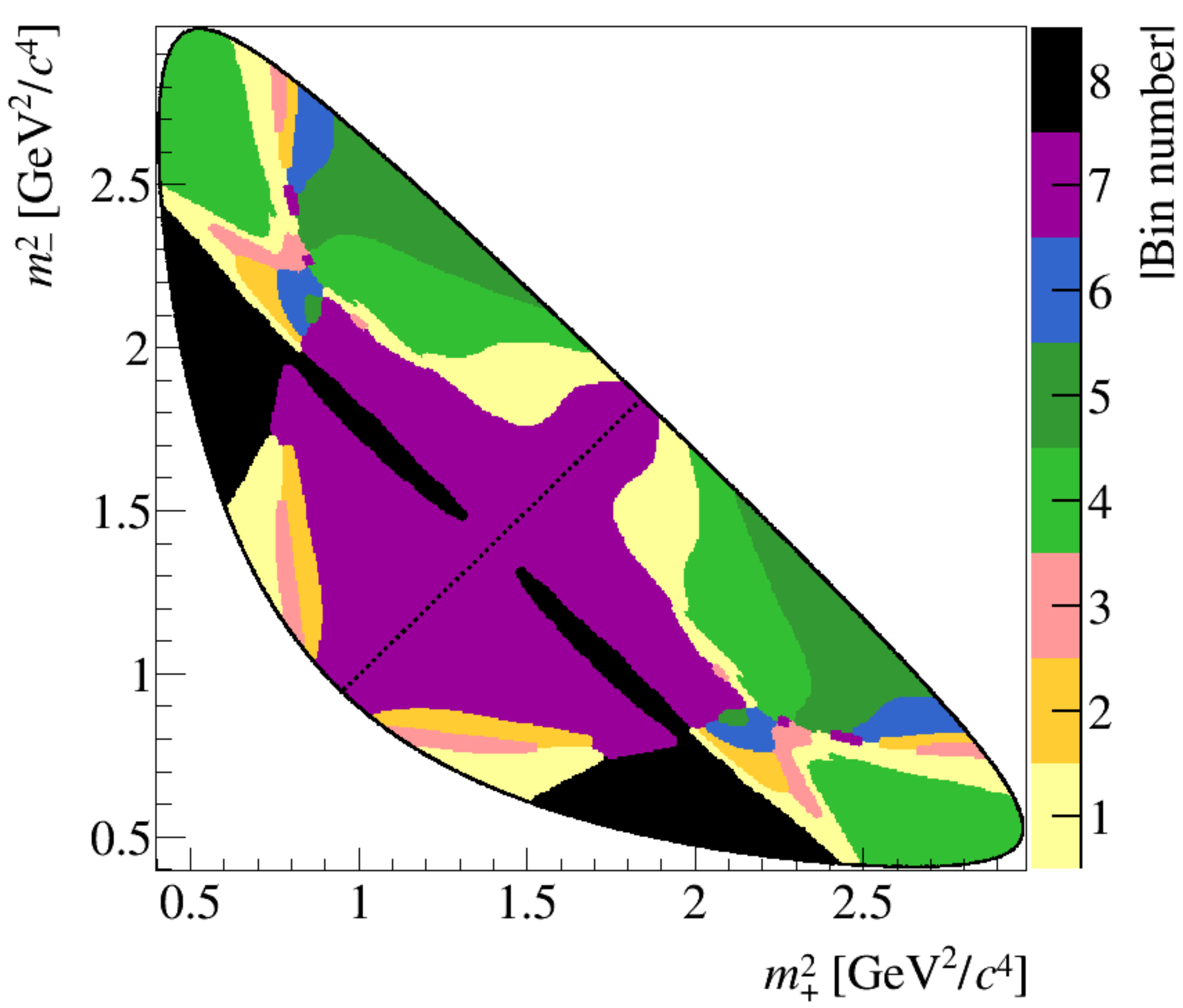
Indirect prediction from rest of triangle (~2° precision)

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

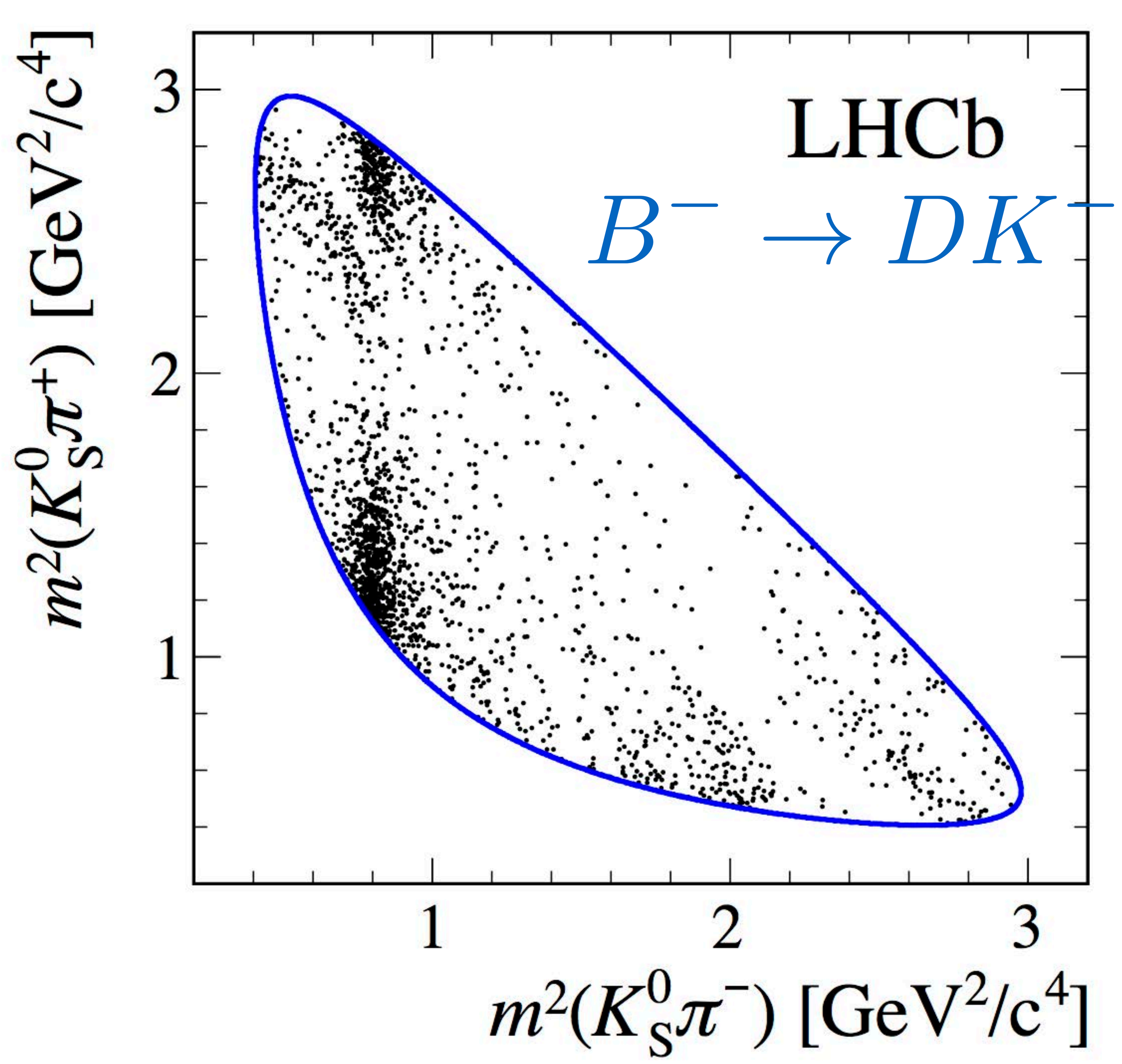
[arXiv:1806.01202]

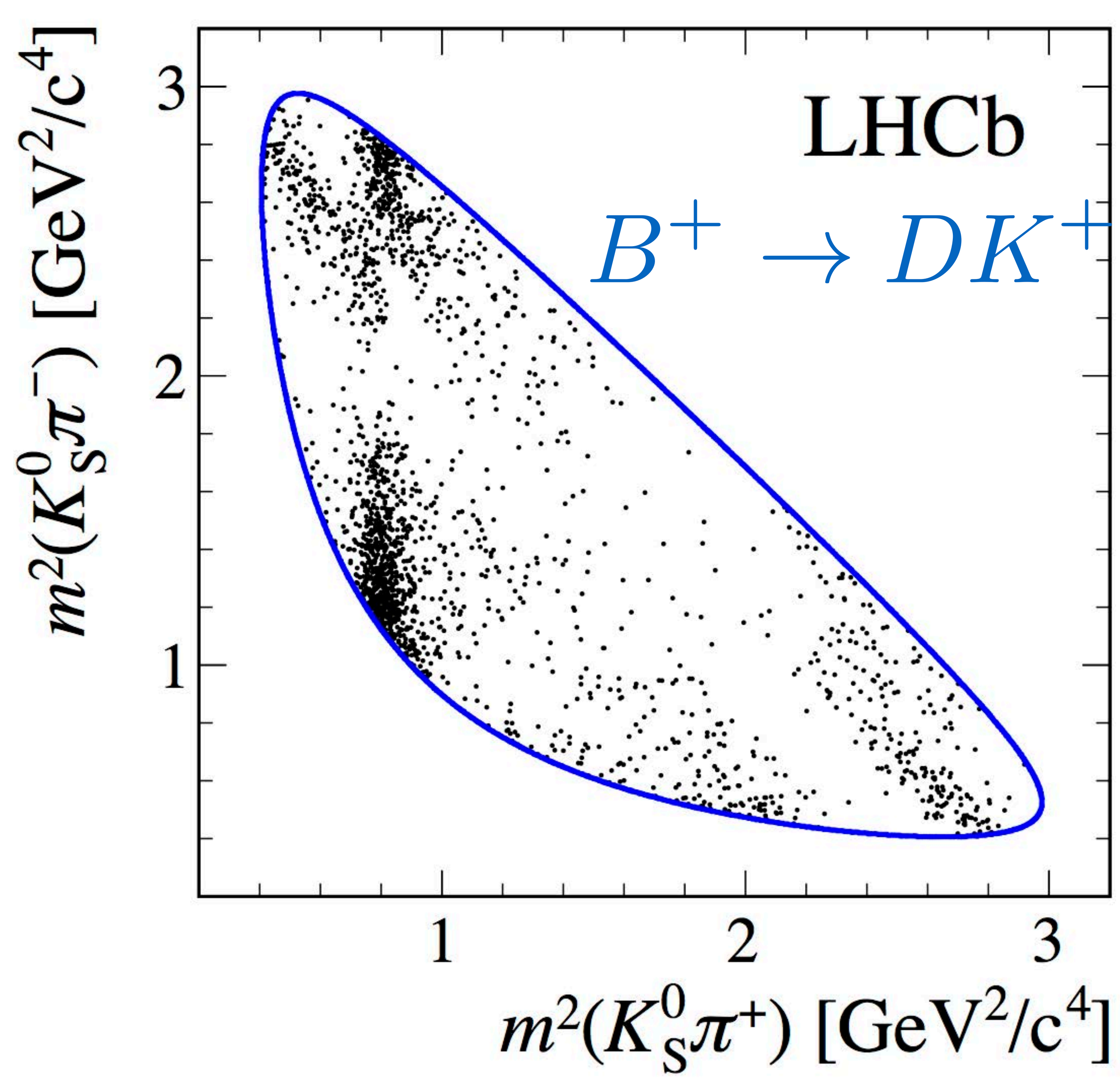
- D reconstructed using the three-body, self-conjugate final state
- Sensitivity to γ by comparing Dalitz plot distributions for B^+ and B^-
- Input on strong phase difference between $D^0, \overline{D}^0$ decay amplitudes across Dalitz plot taken from quantum correlation of $D^0\overline{D}^0$ pairs 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 $D \to K_s^0 \pi^+ \pi^-, K_s^0 K^+ K^-$

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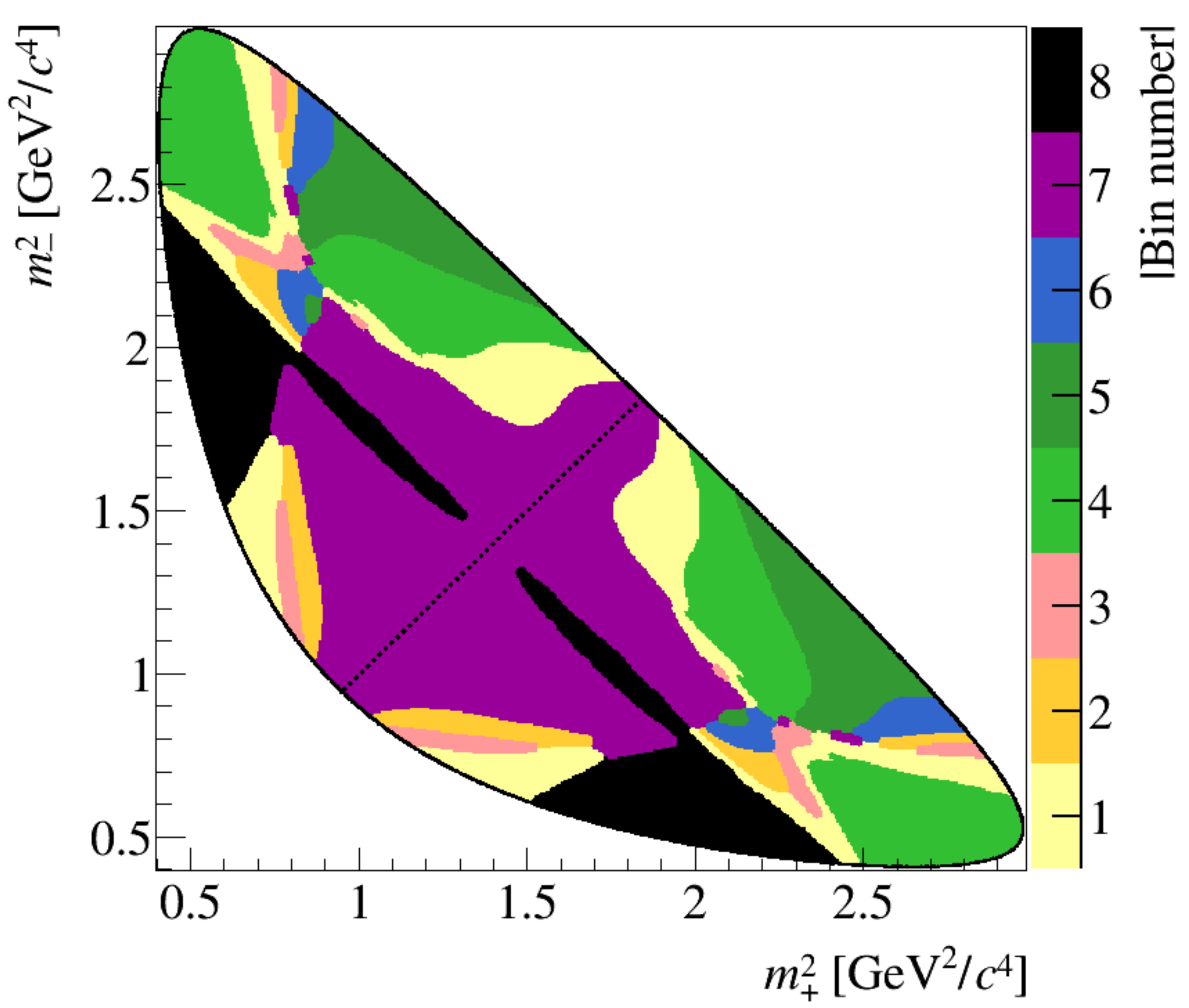

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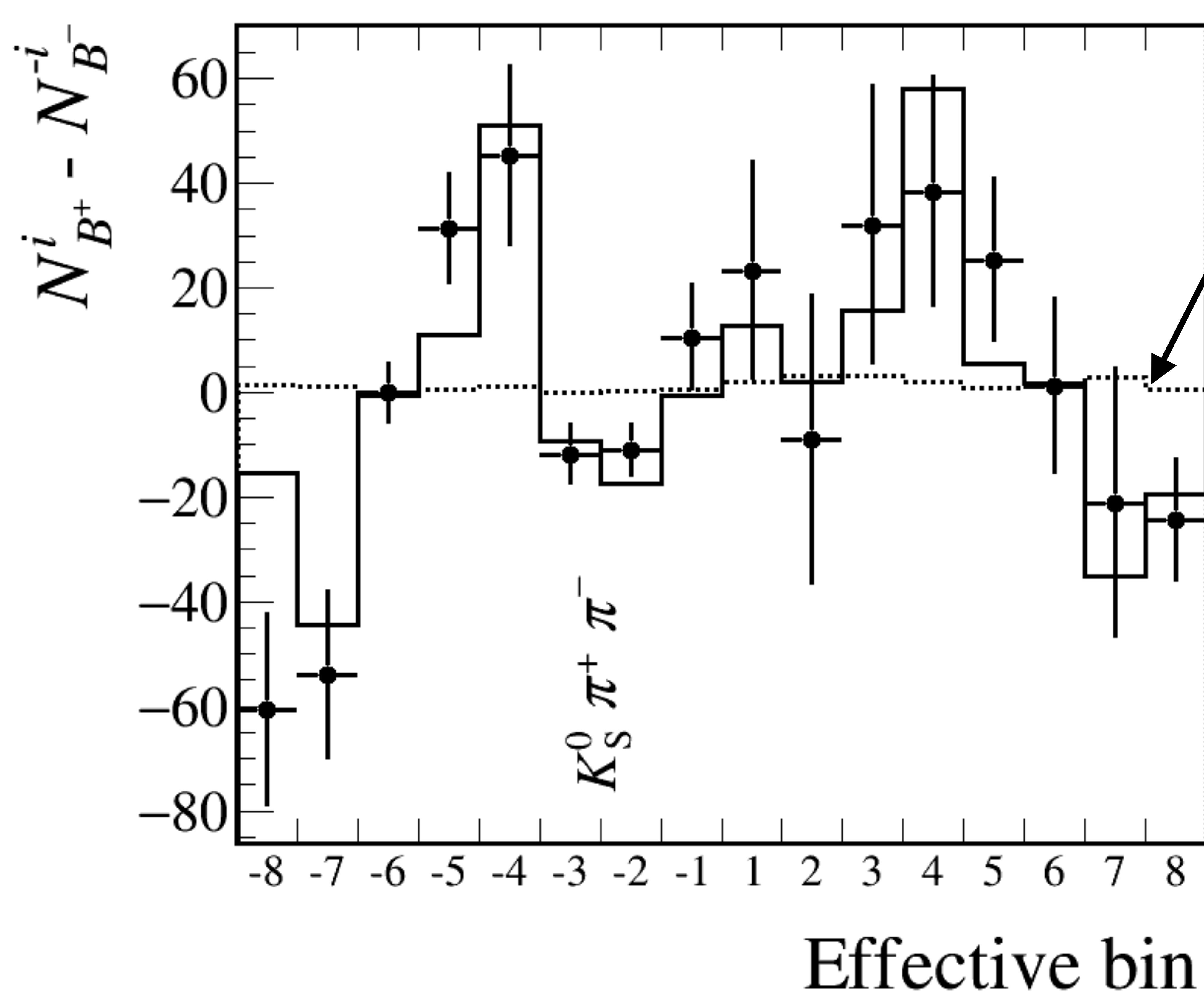

Assuming no CPV

B^+-B^- yields

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

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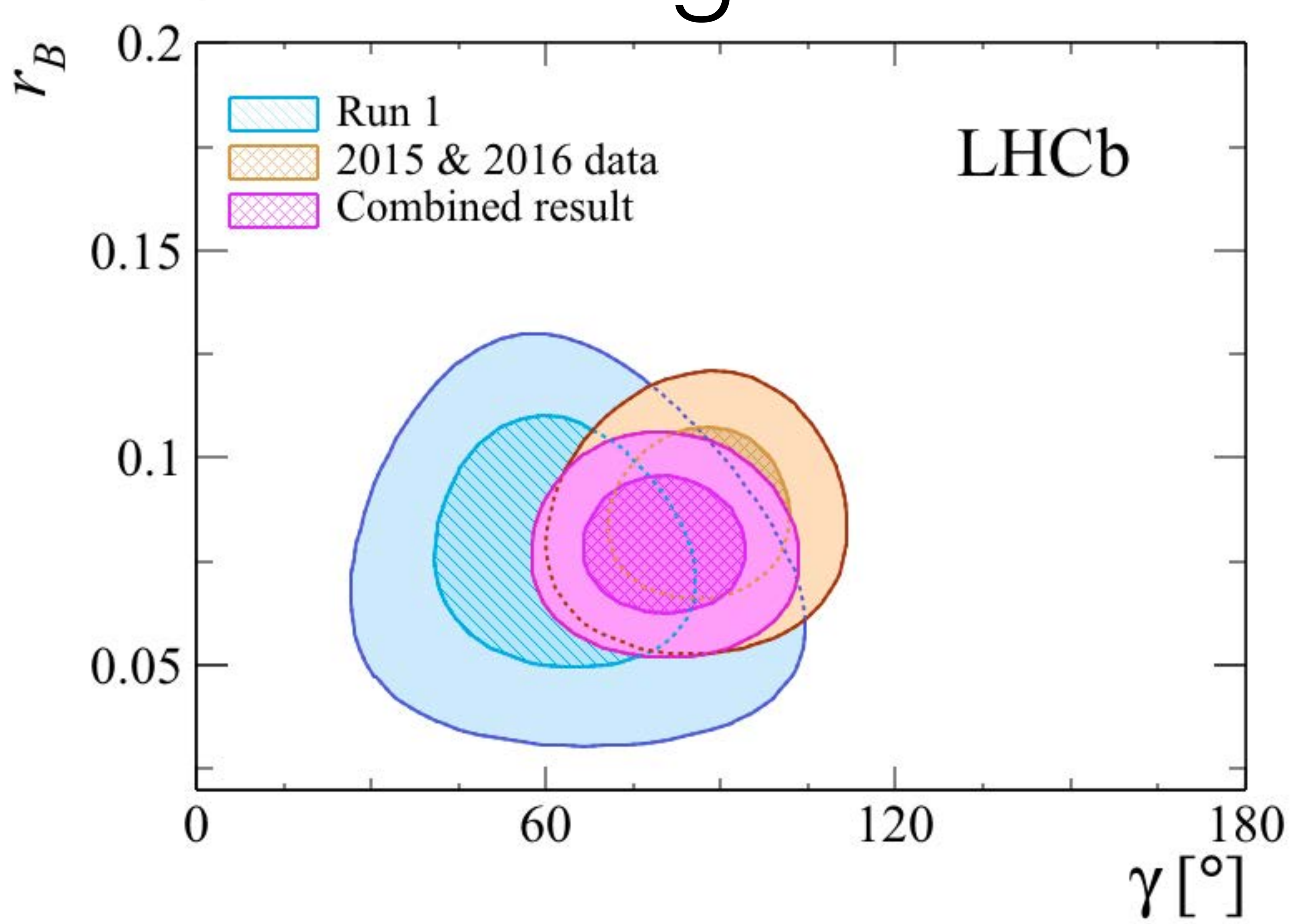
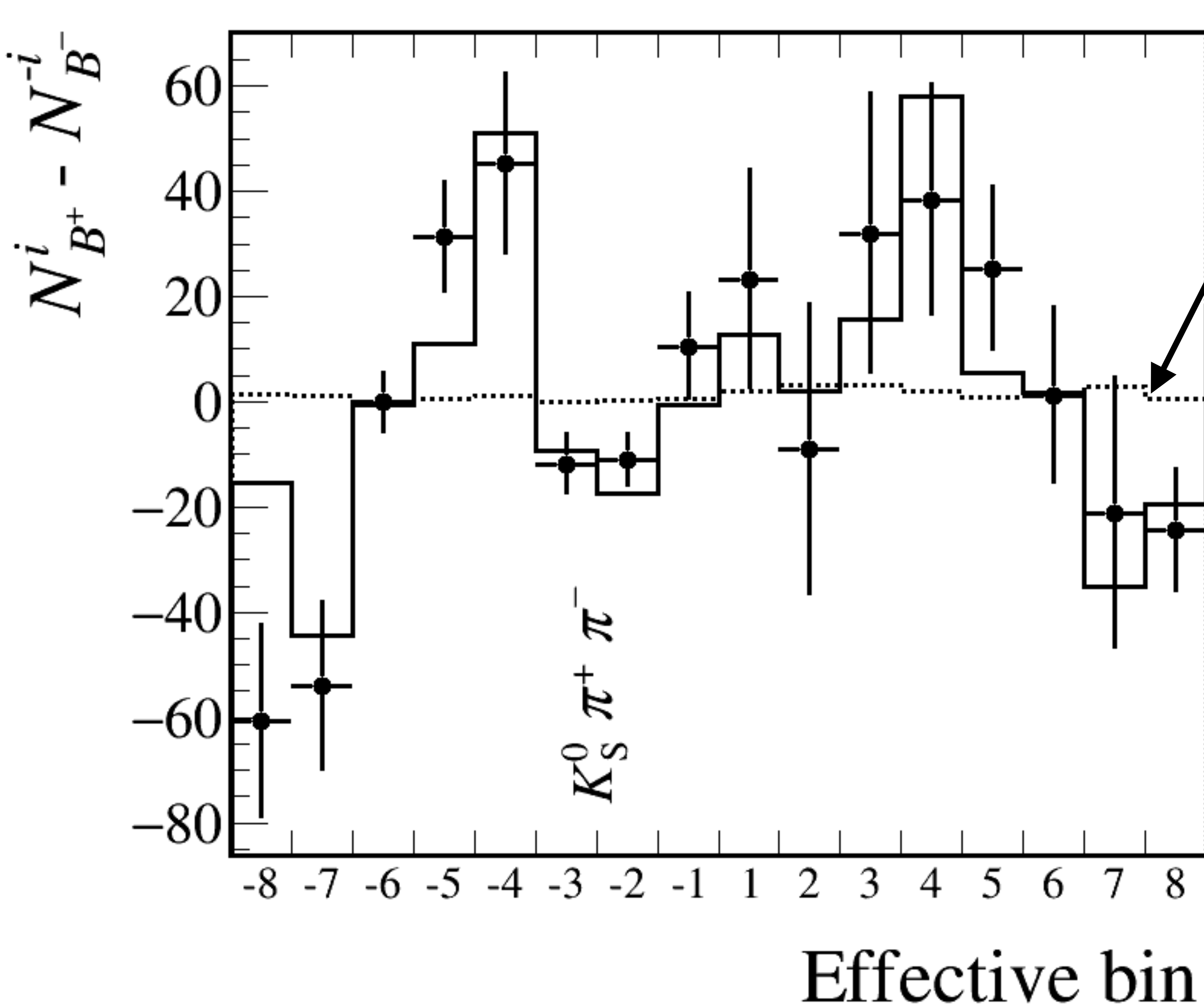
Combining with Run1



Assuming no CPV



B+-B- yields

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
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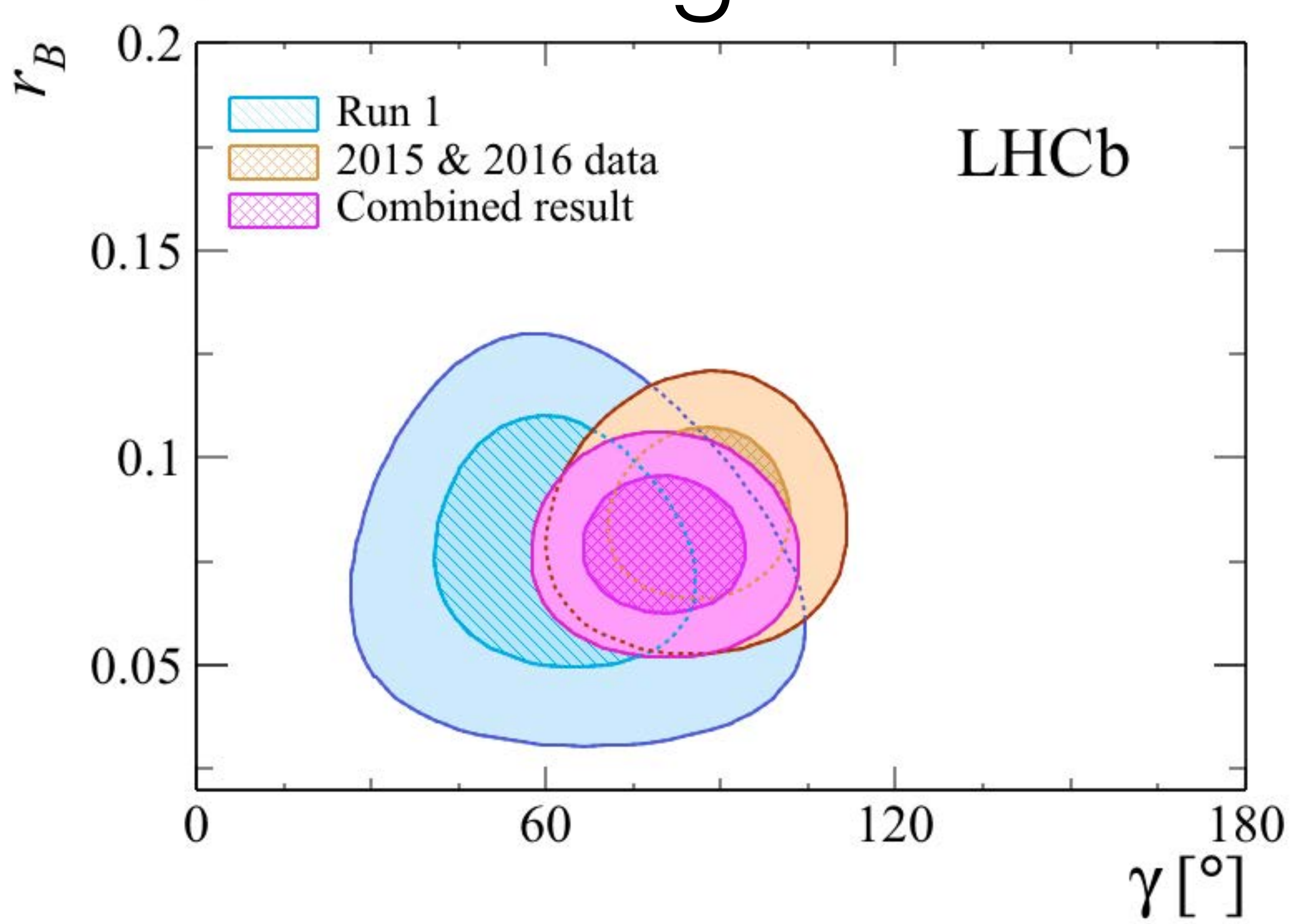
Combining with Run1



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

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

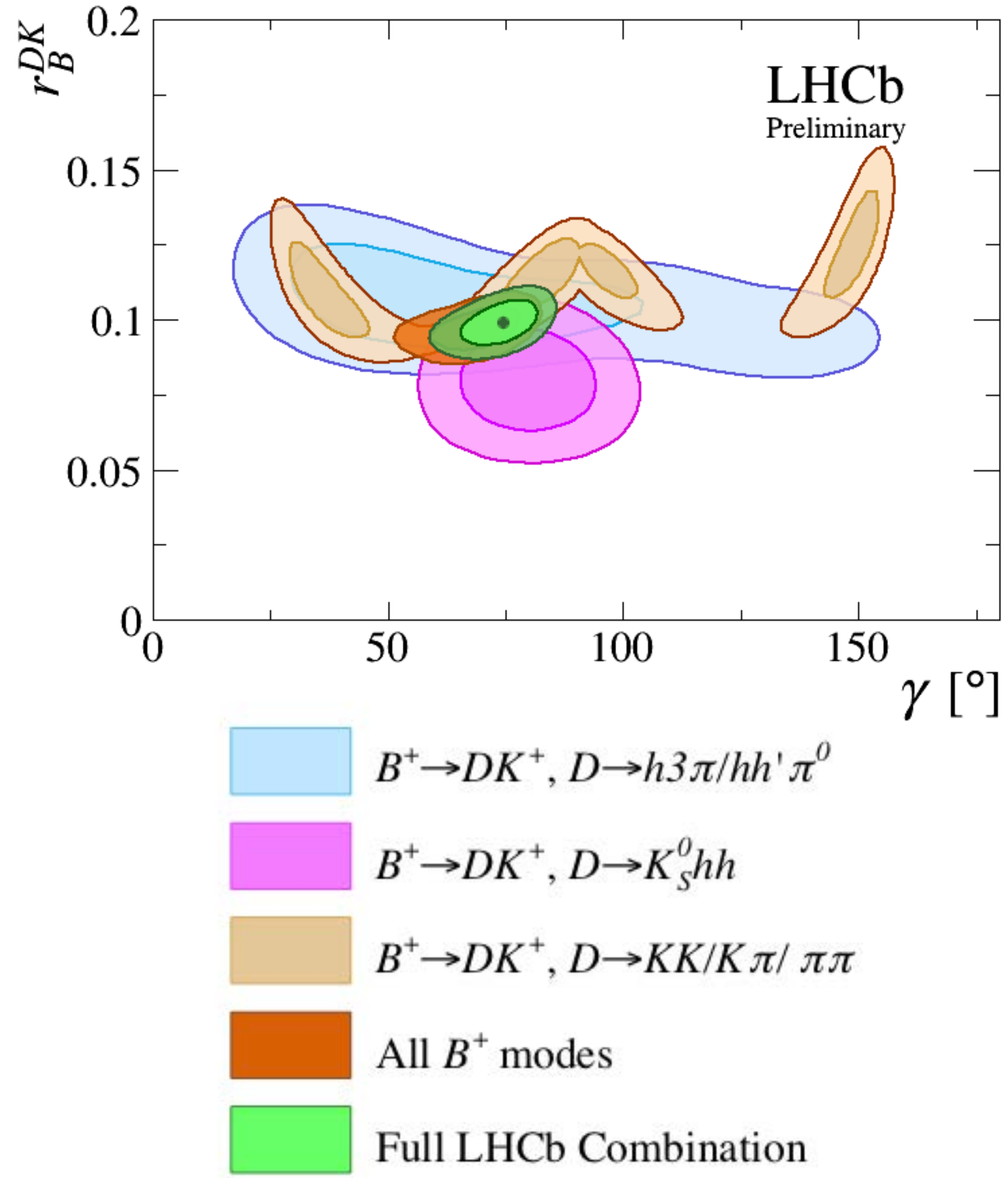
Updated LHCb γ combination

LHCb-CONF-2018-002

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

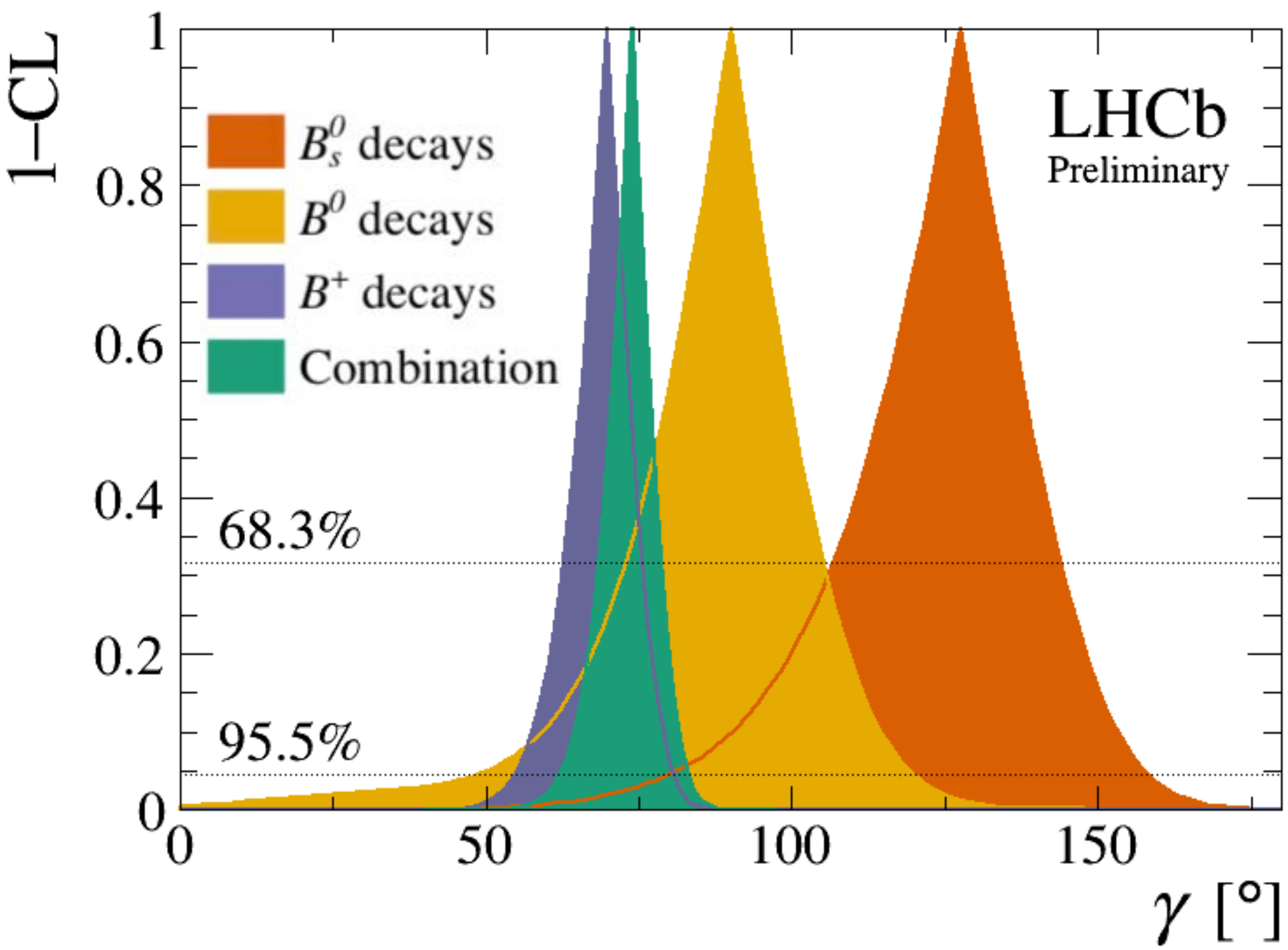
	B decay	D decay	Method	Ref.	Dataset[†]
	$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2
	$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1
	$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1
	$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1
New	$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	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

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



LHCb-CONF-2018-002

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

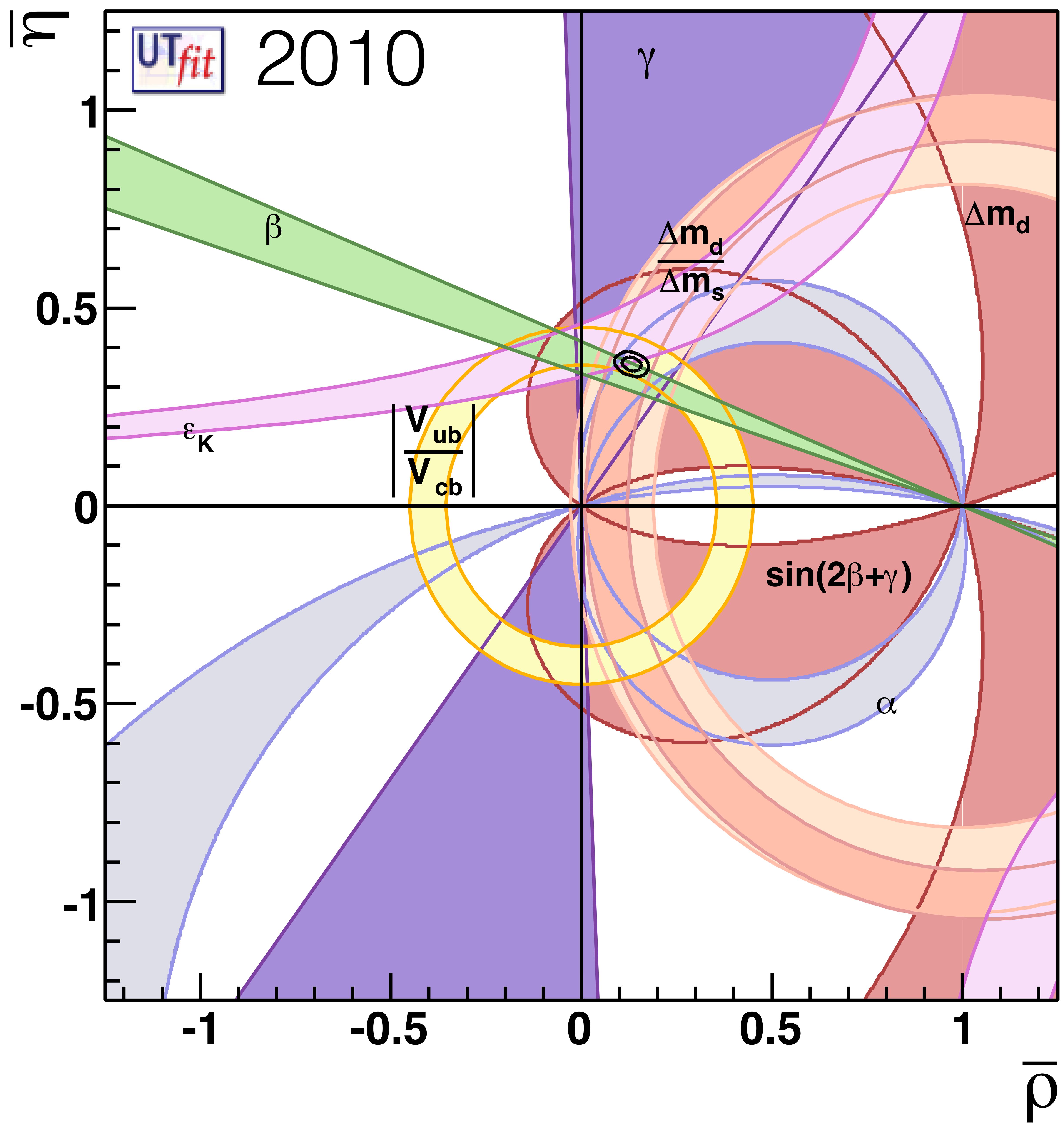
Dominating the WA:

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

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

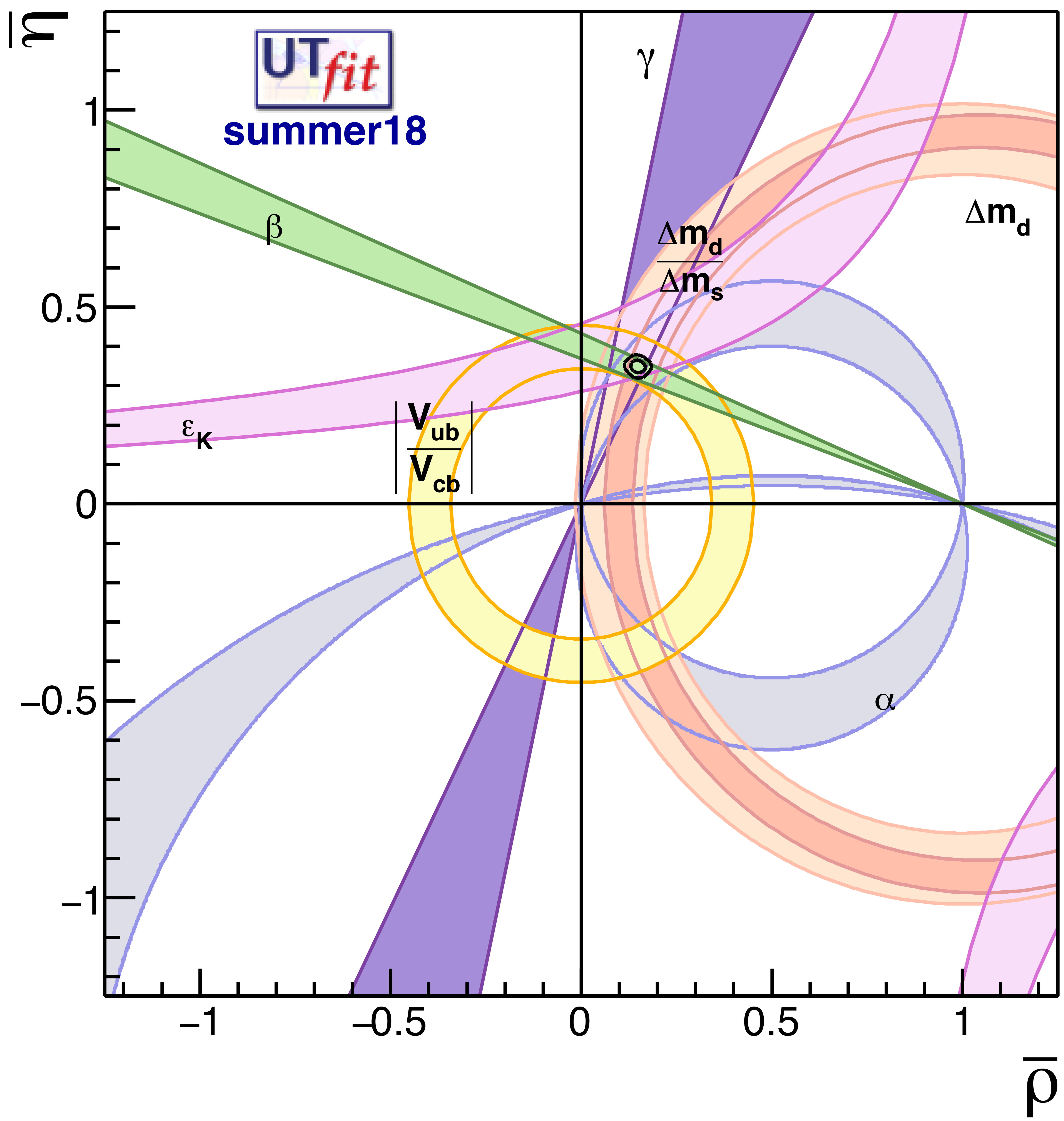
- Indirect constraints give $\gamma = (65.8 \pm 2.2)^\circ$ (UTfit, summer 2018, prel.)
  - Slight tension to be monitored as precision improves
  - Measurement statistically dominated (3° to 4° precision at the end of Run 2)

Evolving constraints



Evolving constraints

- Major impact of LHCb



What about charm?

- Extremely small level of CPV expected in charm mixing and decays offers the opportunity for very sensitive null tests of the CKM picture

- Recent LHCb measurement of charm-mixing parameter y_{CP}

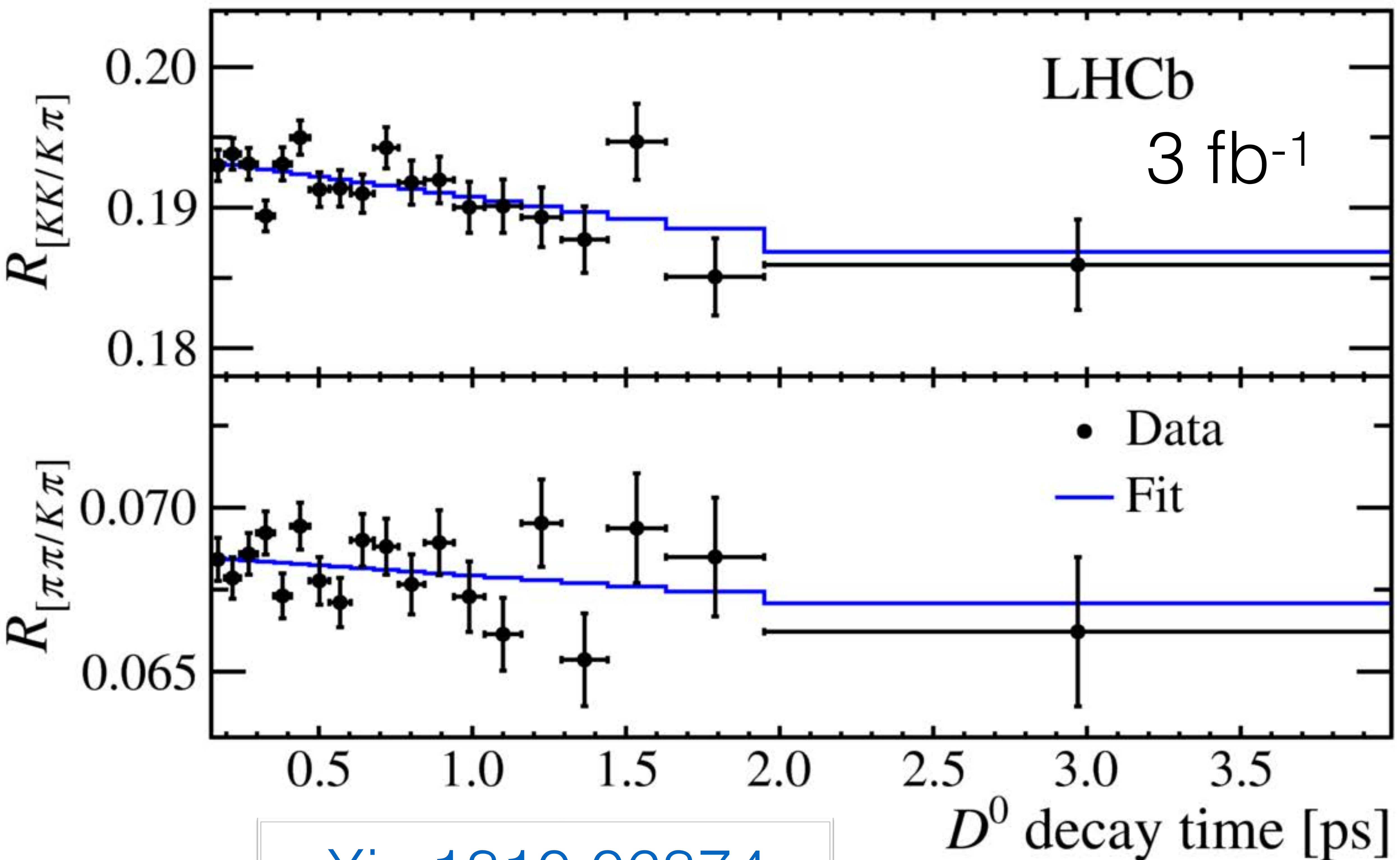
- Compare decay width Γ_{CP} from decays to CP-even eigenstates $(D^0 \to K^+K^-, D^0 \to \pi^+\pi^-)$ with decay width Γ to CP-mixed states $(D^0 \to K^-\pi^+)$

$$y_{CP} \equiv \frac{\Gamma_{CP}}{\Gamma} - 1$$

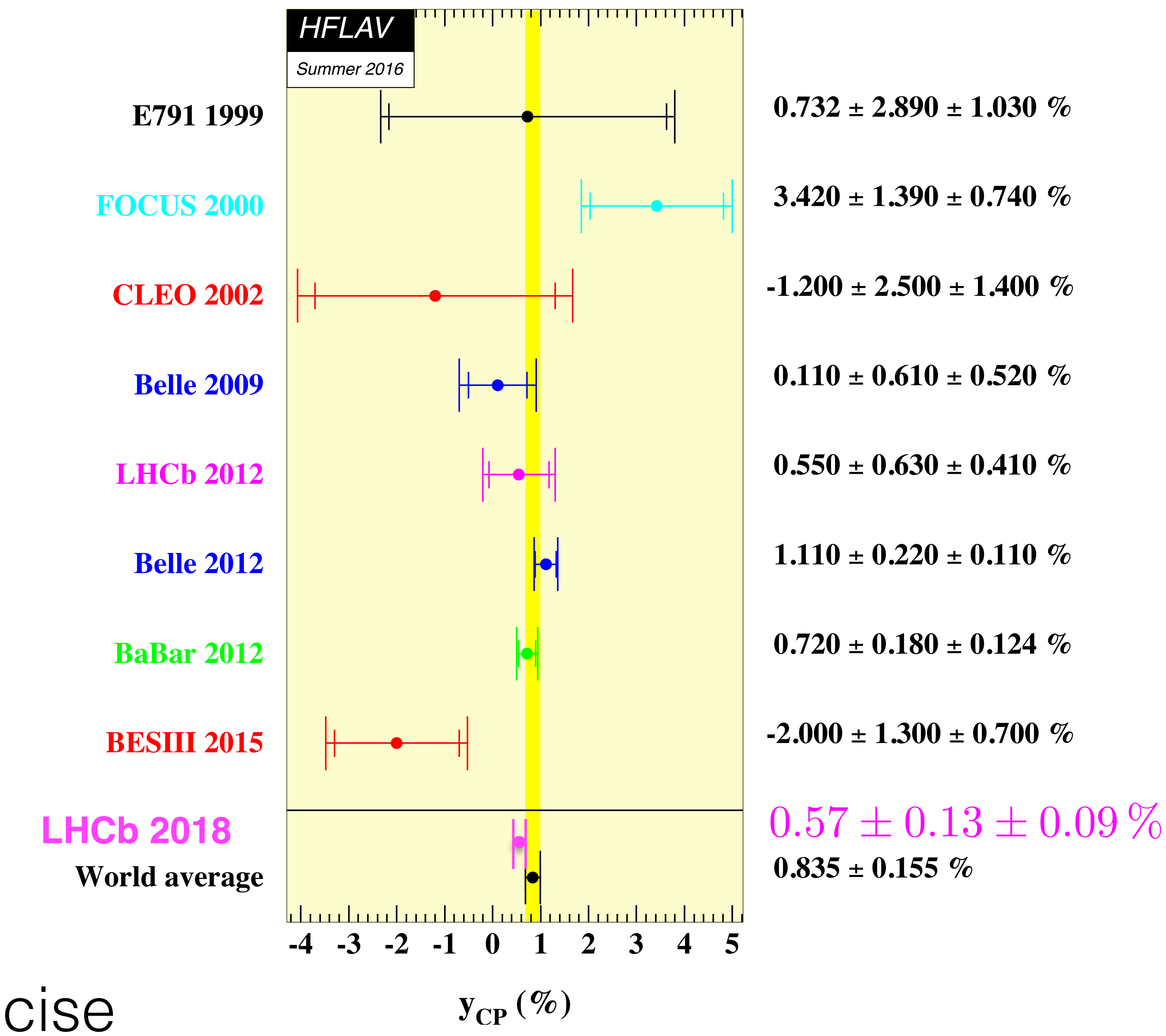
- y_{CP} differs from zero because of mixing
- y_{CP} differs from $y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$ in presence of CPV (with Γ_1, Γ_2 decay widths of CP-even (odd) eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$)
- Reconstruct D^0s from semi-muonic B decays $B^-(B^0) \to D^0\mu^-\overline{\nu}_\mu X$

arXiv:1810.06874

Measurement of the charm mixing parameter y_{CP}



arXiv:1810.06874



- Measurement of y_{CP} from K^+K^- mode most precise from single experiment
- Combination consistent and as precise as current world average
- Also consistent with known value of mixing parameter y (0.62±0.07) %

No evidence of CPV in $D^0 - \overline{D}^0$ mixing

Tests of Lepton Flavour Universality

Lepton Flavour Universality

- The property that the three charged leptons (**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: $m_\tau / m_\mu / m_e \leftrightarrow 3477 / 207 / 1$

- 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. **e**/μ 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

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

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

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

- These ratios are clean probes of NP :

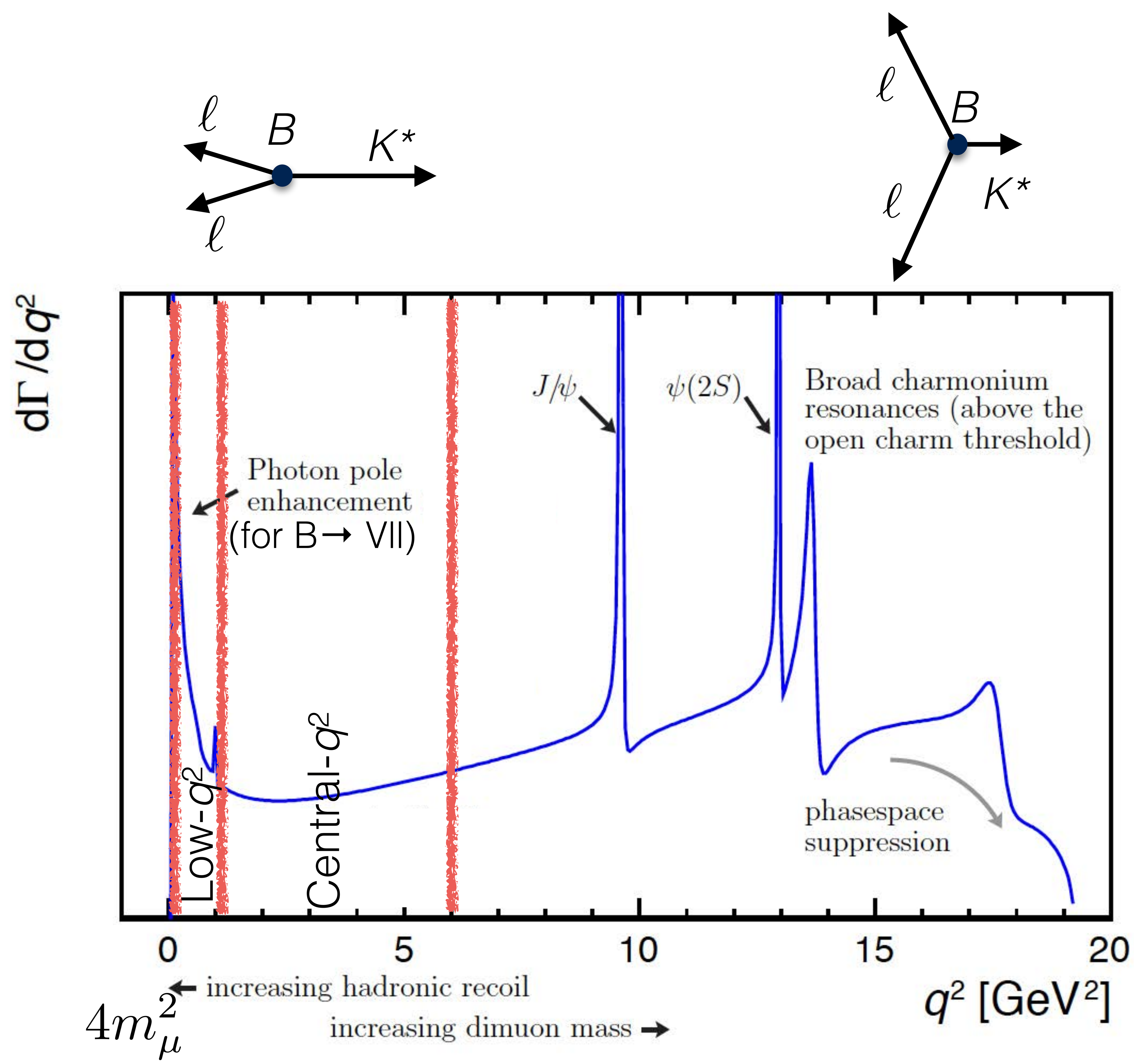
  - Sensitive to possible new interactions that couple in a non-universal way to electrons and muons

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

The R_{K^*} ratio

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

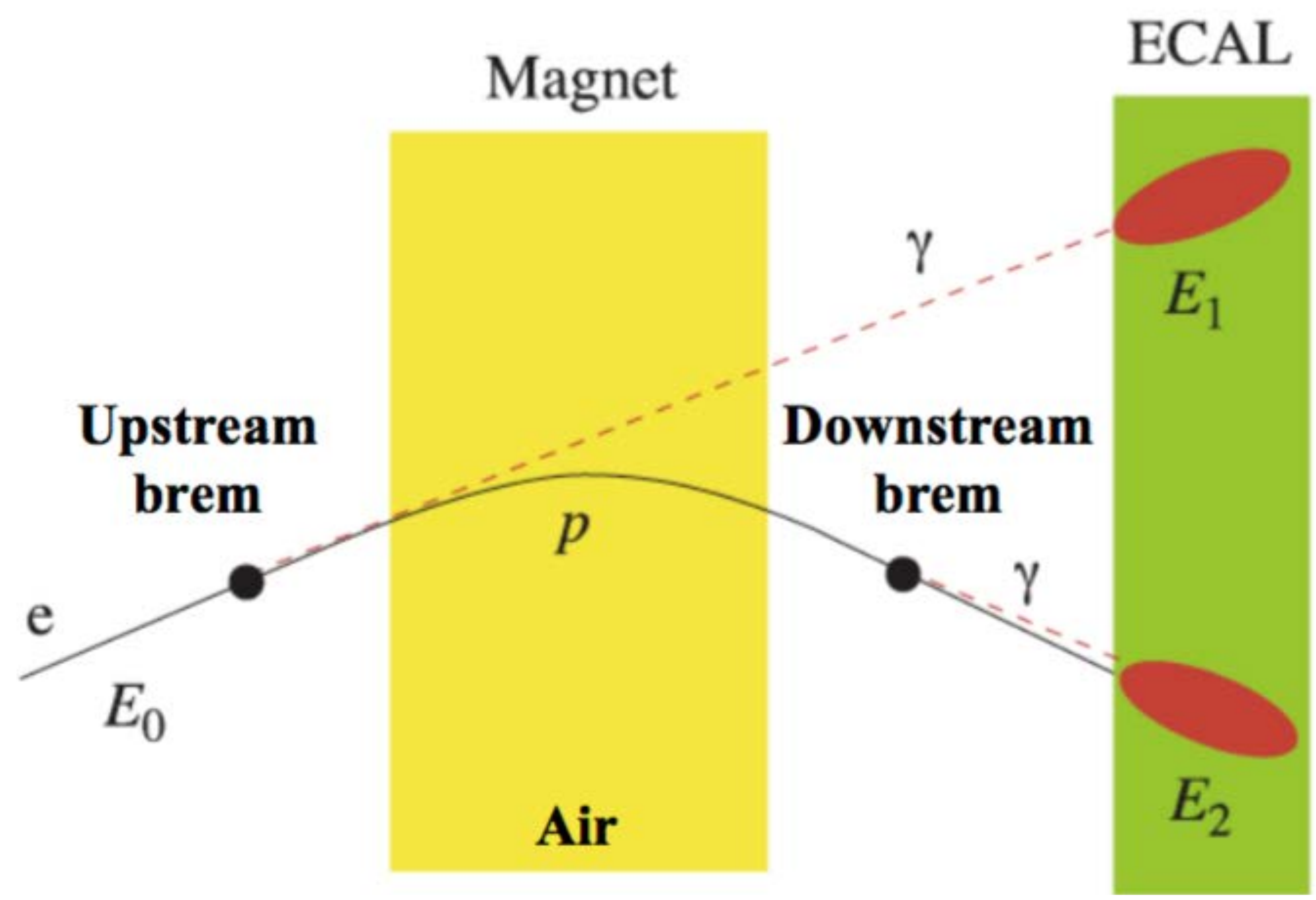
- LHCb performed measurement in two q^2 bins:
  - Low-q^2 bin: [0.045,1.1] GeV^2
  - Central-q^2 bin: [1.1,6.0] GeV^2

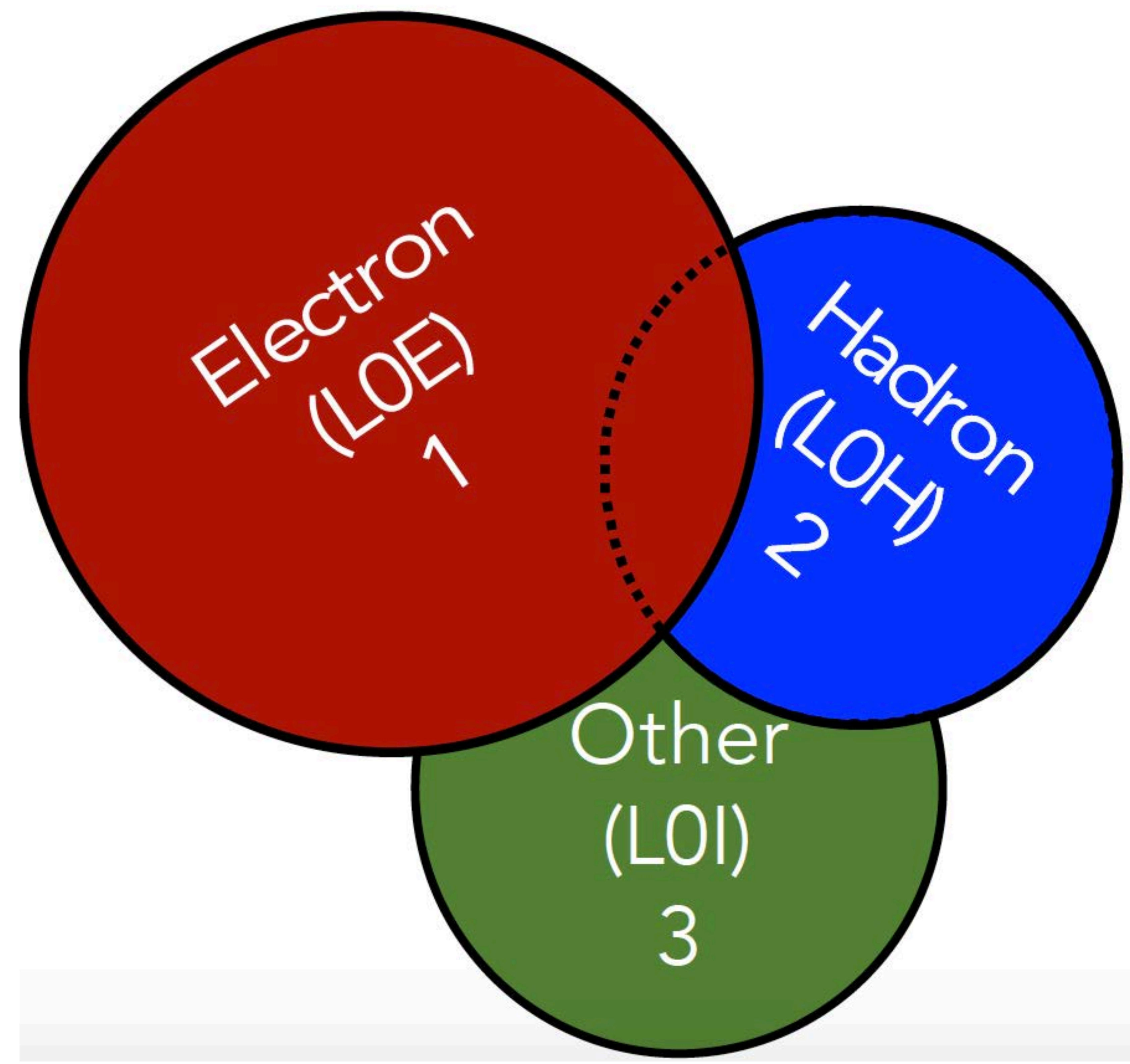


A very challenging measurement!

JHEP 08 (2017) 055

- 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





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:

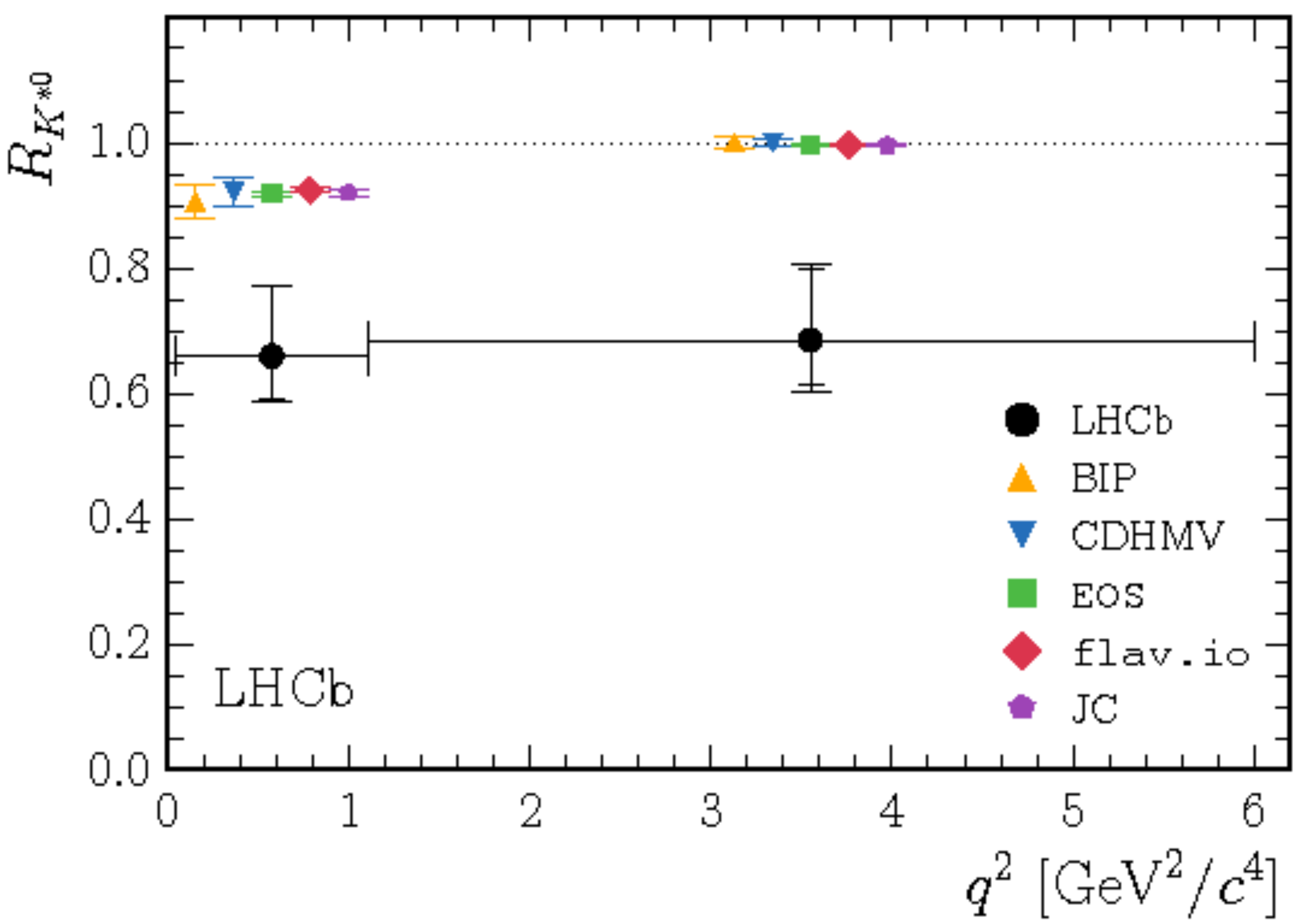
$$R_{\mathrm{K}^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

→ 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 (absolute size of e.g. tracking, PID or trigger efficiencies do not need to be known exactly, only ratios between rare mode and control mode matter)

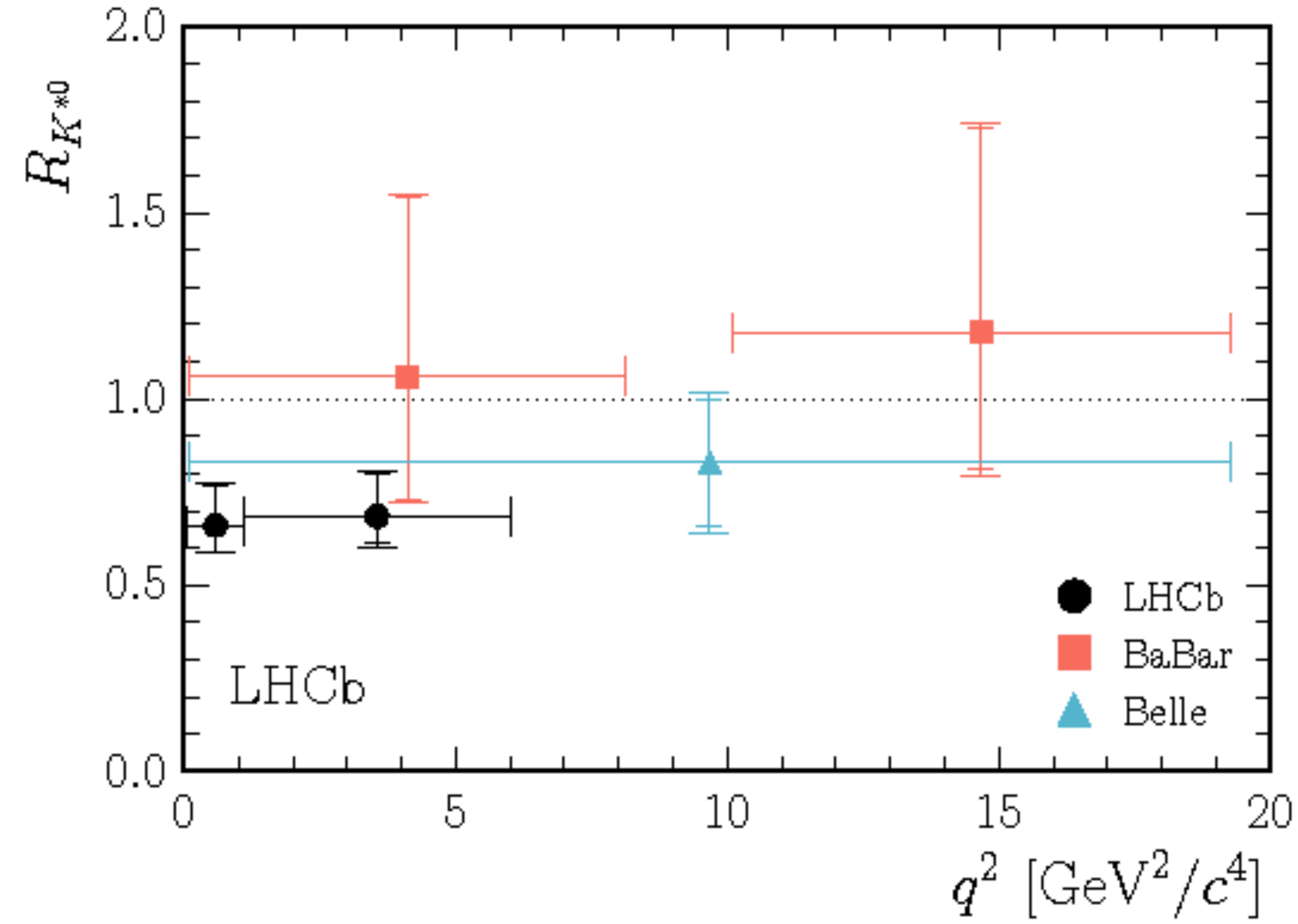
Results

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

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

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

2.1 - 2.3 σ
2.4 - 2.5 σ

Cross-checks

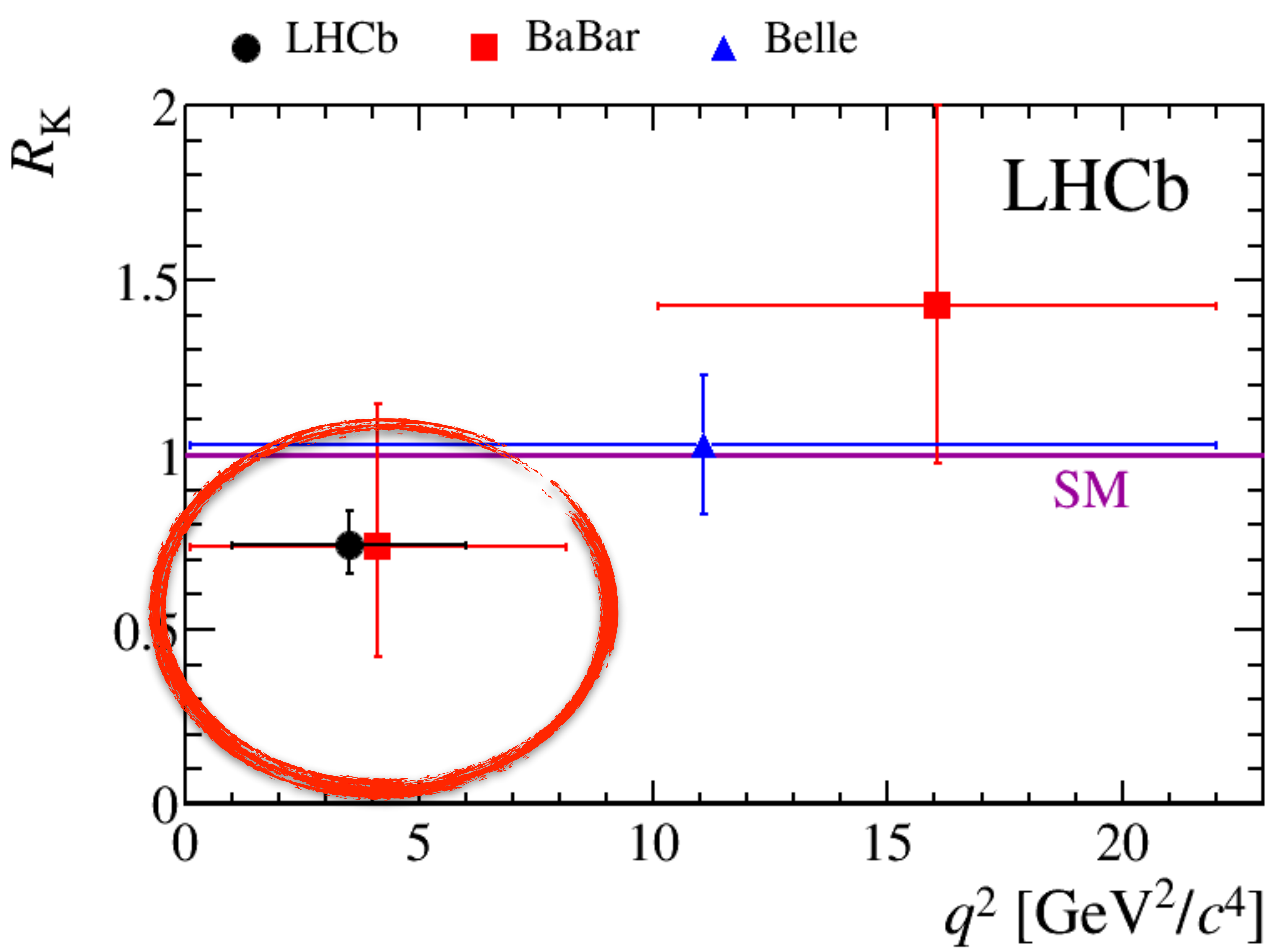
- $$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$ JHEP 08 (2017) 055
  - very stringent test of absolute scale of efficiencies that does not benefit from the cancellation of the experimental systematics from the double ratio, also has small statistical uncertainty
  - compatible with being independent of decay kinematics (p_T, η of the B^0 candidate) and track multiplicity
- $$R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$ → 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 expectation
- 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 ($\int \mathcal{L}\, dt \sim 3 fb^{-1}$)

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

- Also measured as a double ratio wrt $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$
- ~250 $B^+ \to K^+e^+e^-$ candidates (~1200 dimuon candidates)



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

(~12% precision)

LHCb: PRL 113 (2014) 151601

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

What happens next?

Short term

- R_K analysis to be updated soon with much improved sensitivity
  - Improvements to offline processing
  - Adding part of Run 2 data (2015,16) gives ~2 fb^{-1} but with nearly twice cross-section and better trigger
  - ~250 →~900 $B^+ \to K^+e^+e^-$ candidates
  - Expected previous uncertainty of ~12% to shrink to ~7%
  - In main trigger category, systematic effects controlled at 2-3% level
- R^*_K update with Run 2 data - still expect it to be statistically limited
- Can make analogous measurement with $R_\phi(B_s \to \phi\ell^+\ell^-)$ and other similar modes

(Very) Long term

Belle II Physics Book: arXiv:1808.10567
LHCb: CERN/LHCC 2018-027

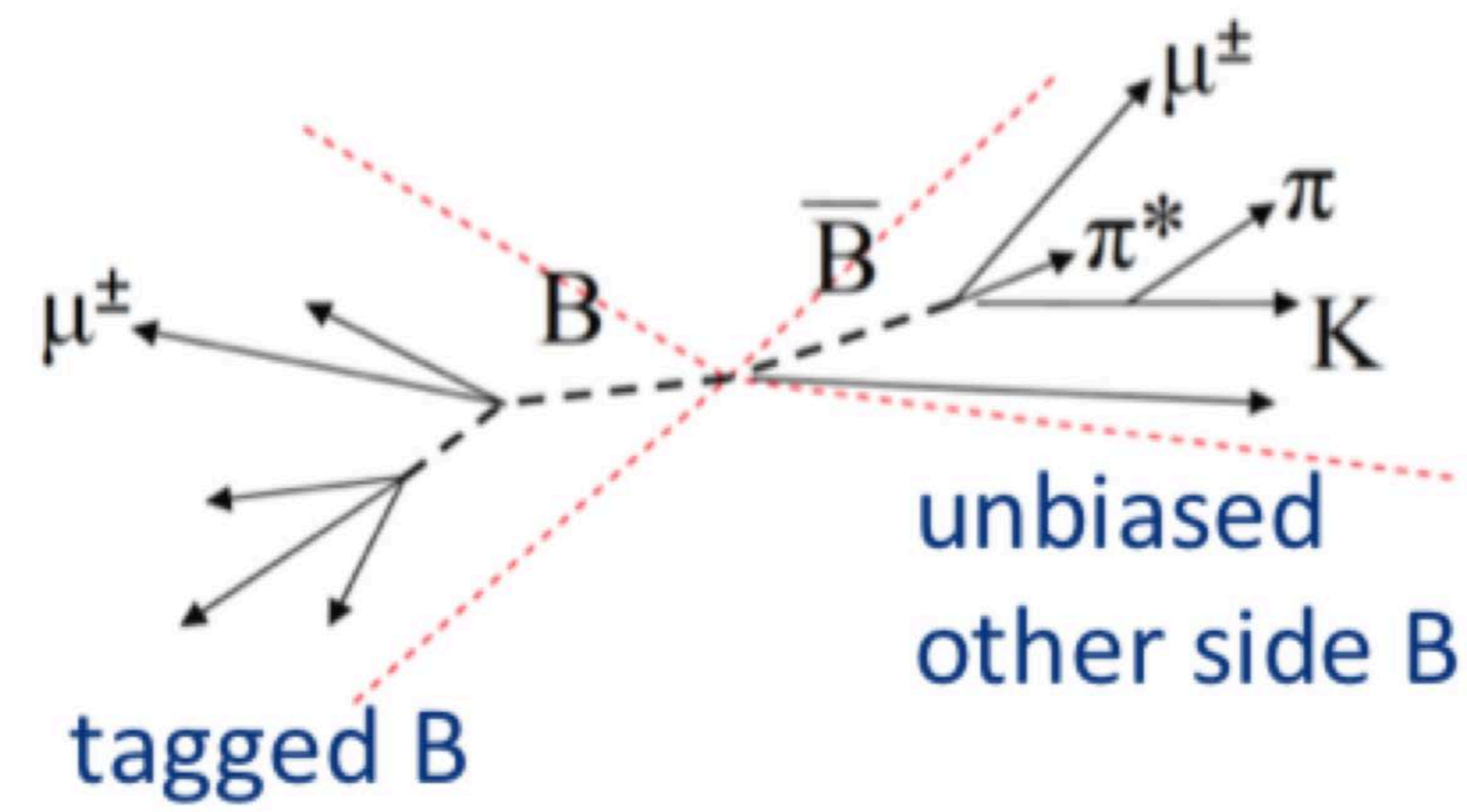
Run 2

Observable	Current LHCb	Run 2	LHCb 2025	Belle II	Upgrade II
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	~0.05	0.025	0.036	0.007
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1	~0.05	0.031	0.032	0.008
R_ϕ, R_{pK}, R_π			0.08, 0.06, 0.18	–	0.02, 0.02, 0.05

Other experimental inputs

- In 2018 CMS have put in place a new trigger strategy in which a sizeable fraction of the trigger bandwidth is dedicated to flavour physics

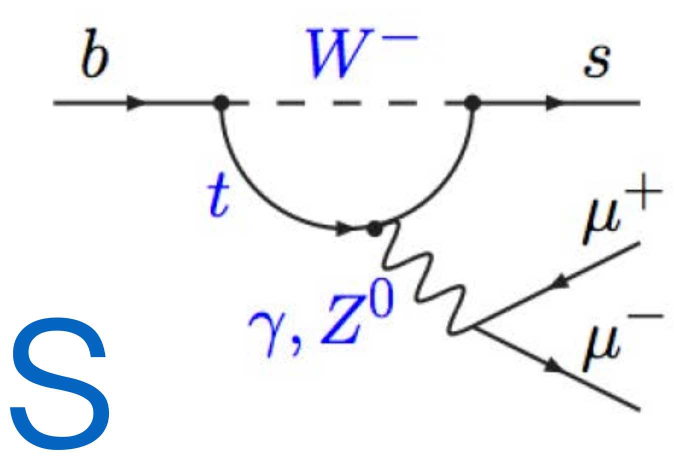
- They have on tape **an unbiased sample of ~10^{10} B hadrons** (tag on B-tag side by requiring muons with significant impact parameter, no requirement on the other side)

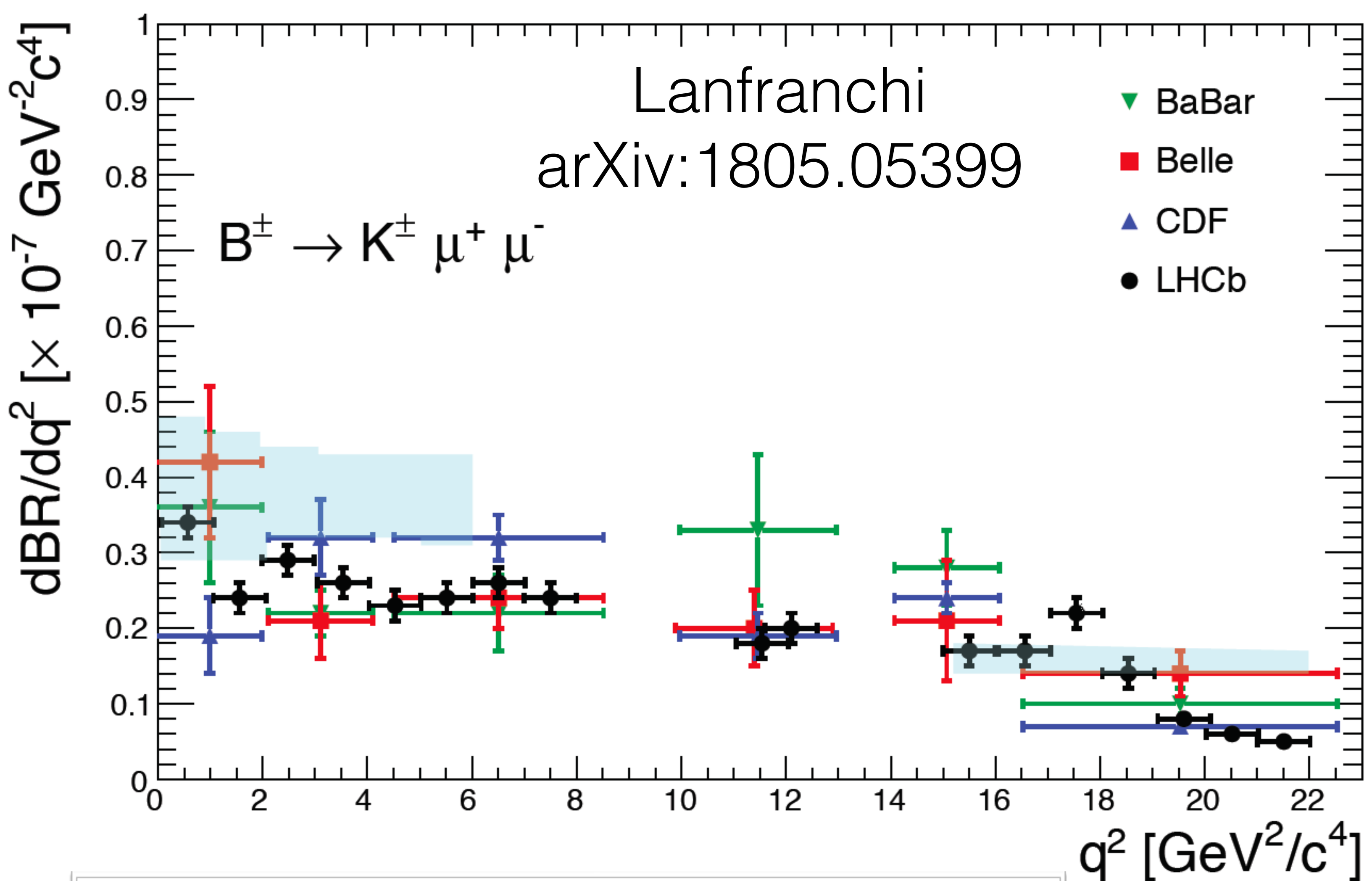


- Rate exceeds 5 kHz near the end of the fill, when pileup is low, not to exceed buffer capacity

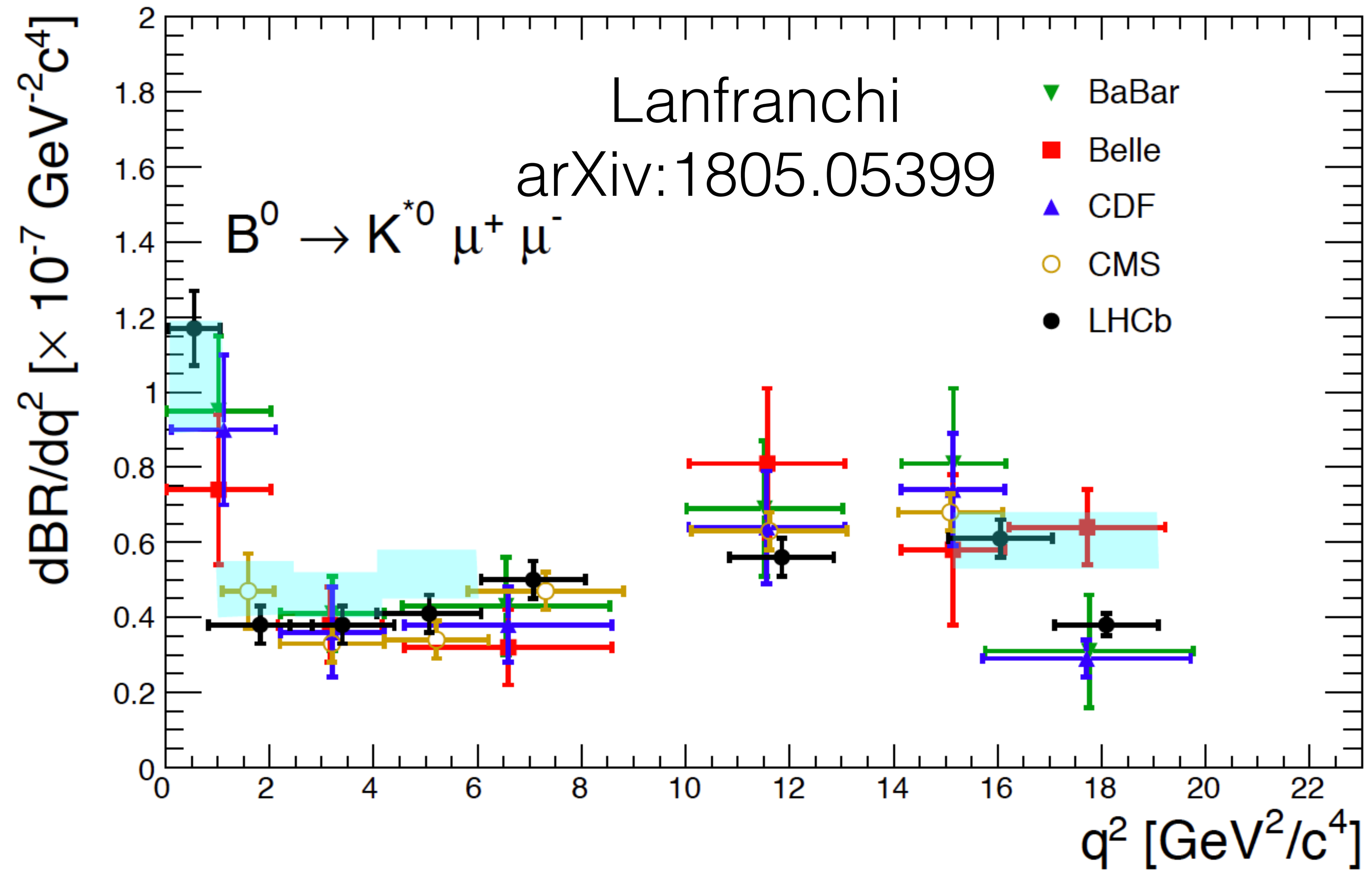
- **Data are parked** (→ no prompt reconstruction, opportunistic reconstruction during LS2, but over 1billion events already processed for monitoring and trigger optimisation)

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

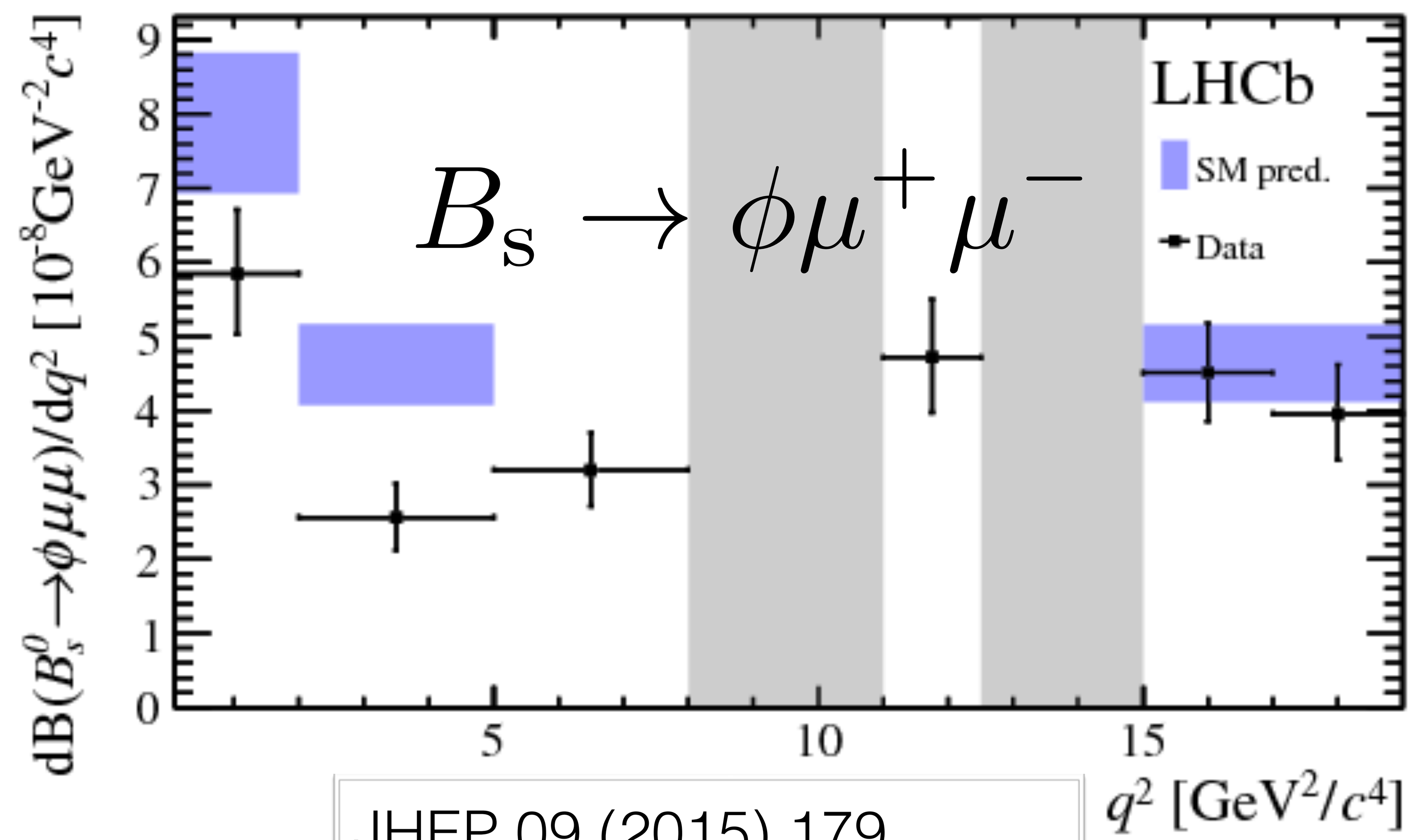




LHCb: JHEP 06 (2014) 133
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802

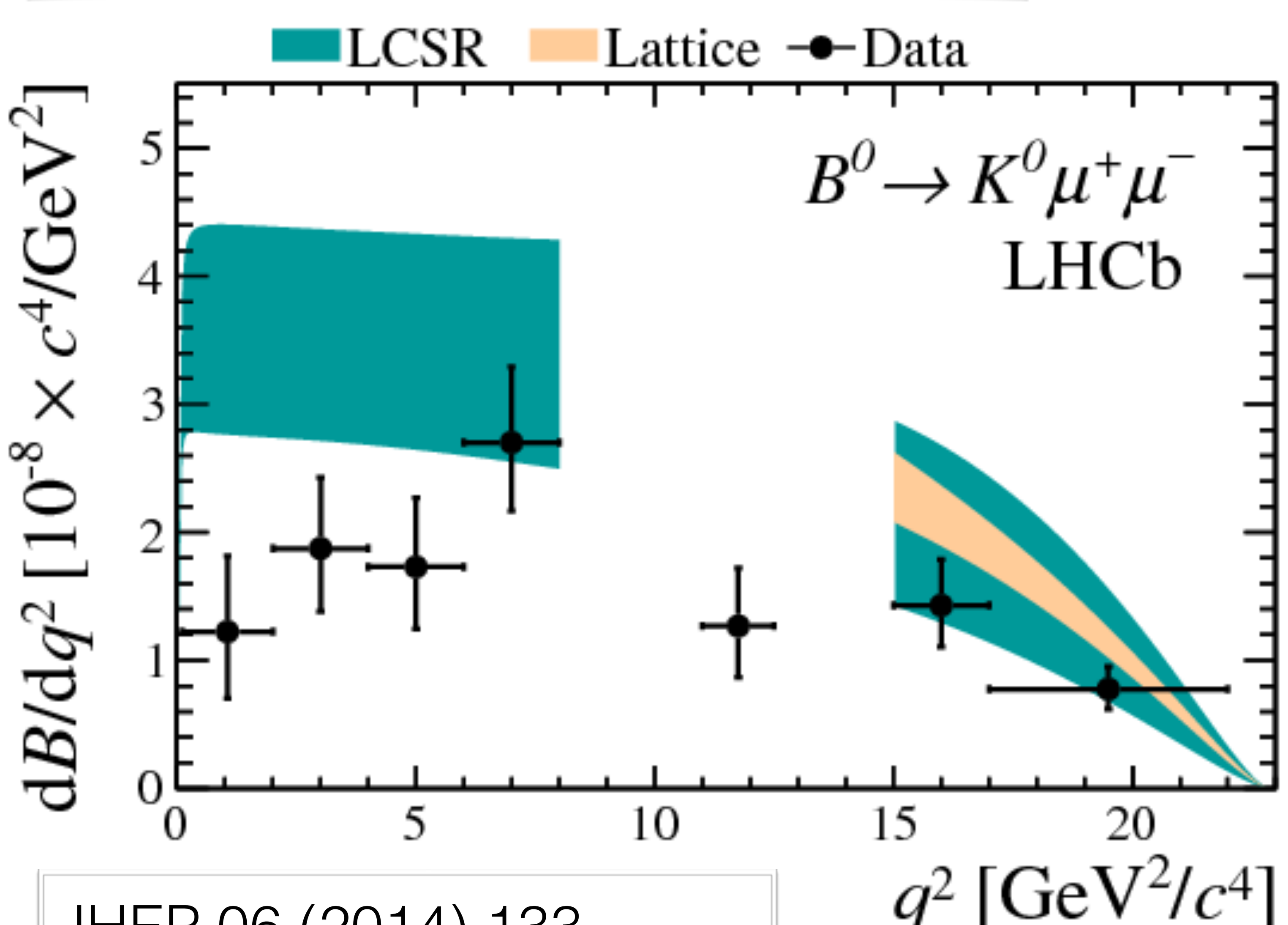


CMS: PLB 753 (2016) 424
LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801
CDF: PRL 107 (2011) 201802

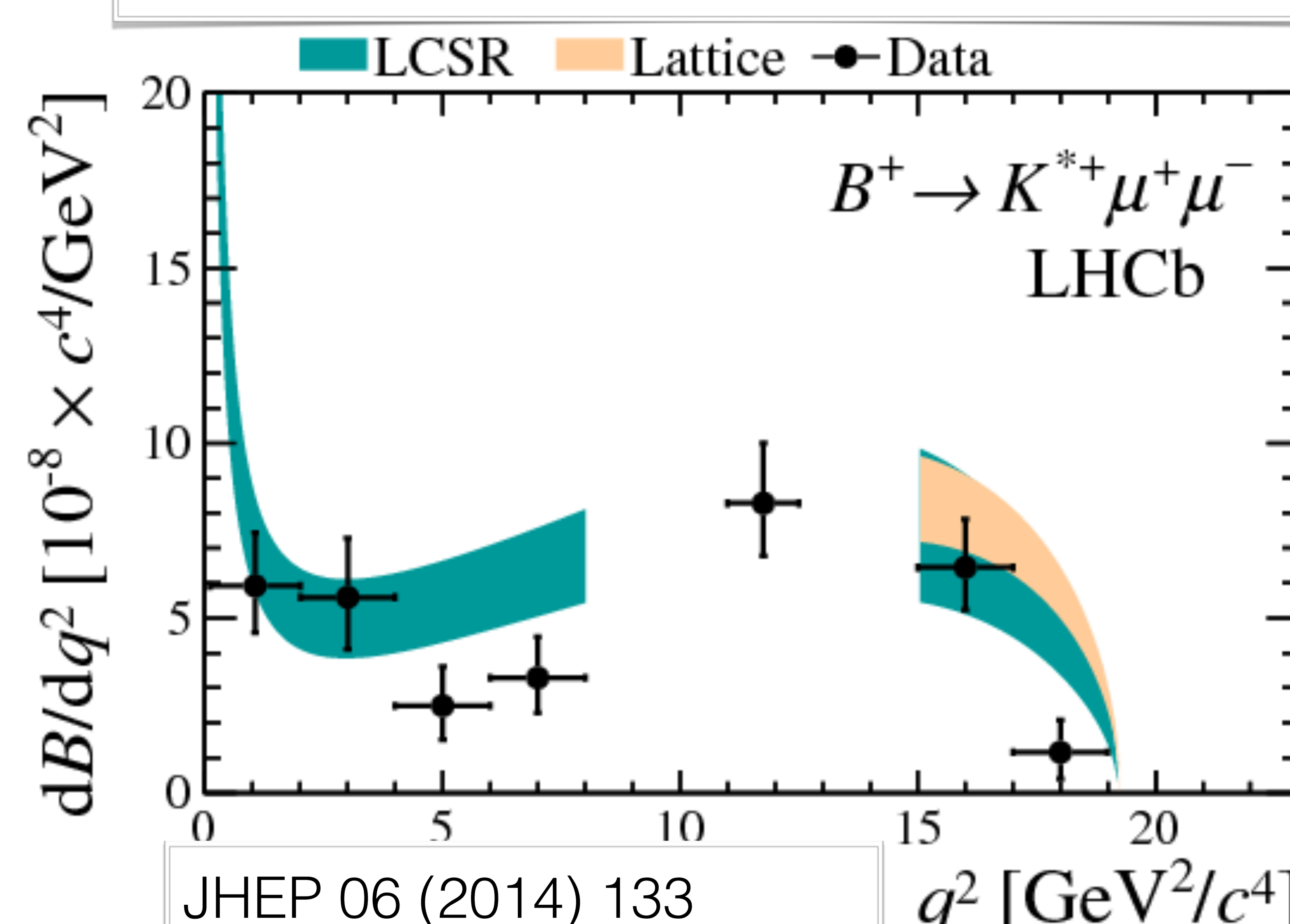


JHEP 09 (2015) 179

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

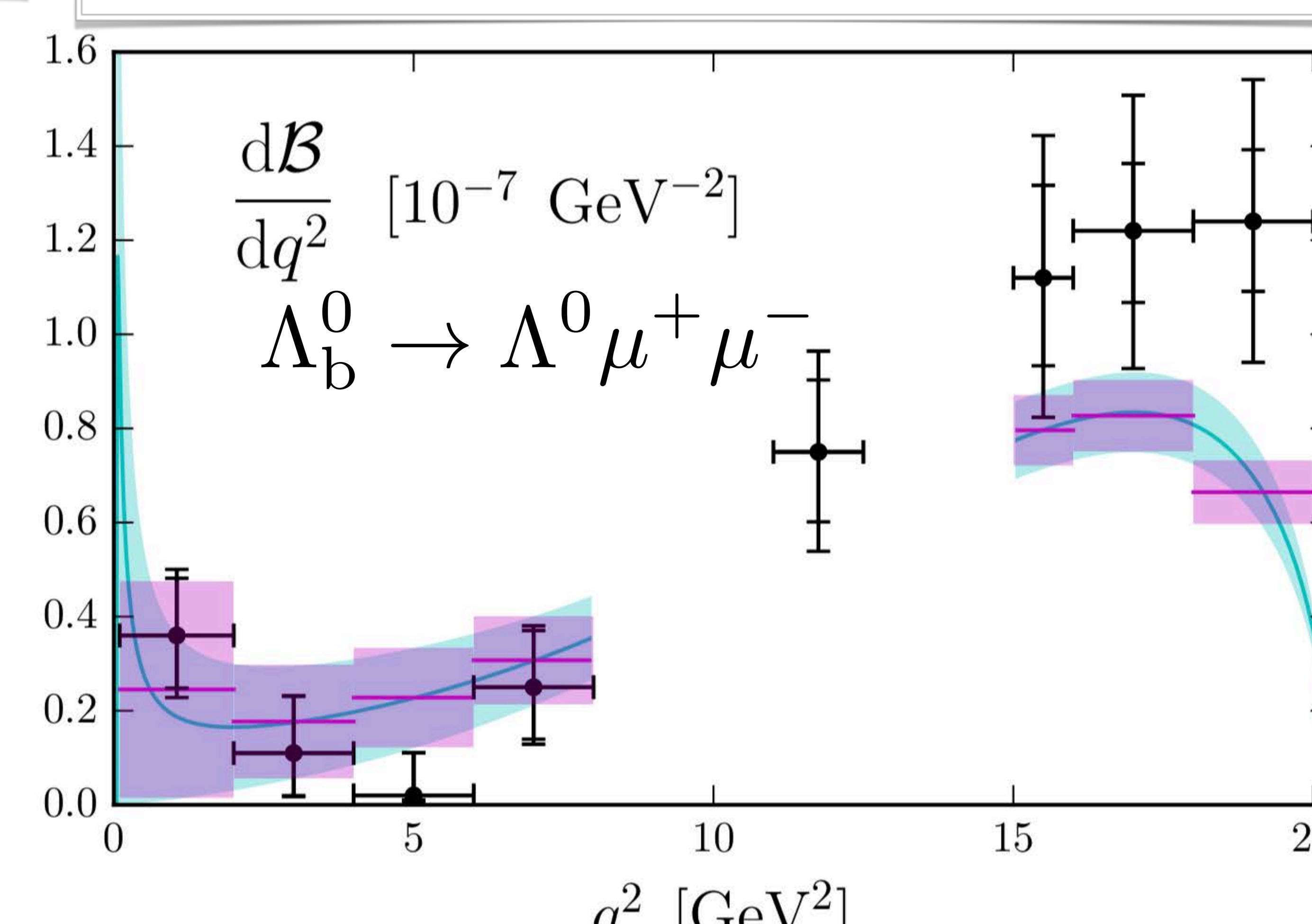


JHEP 06 (2014) 133



JHEP 06 (2014) 133

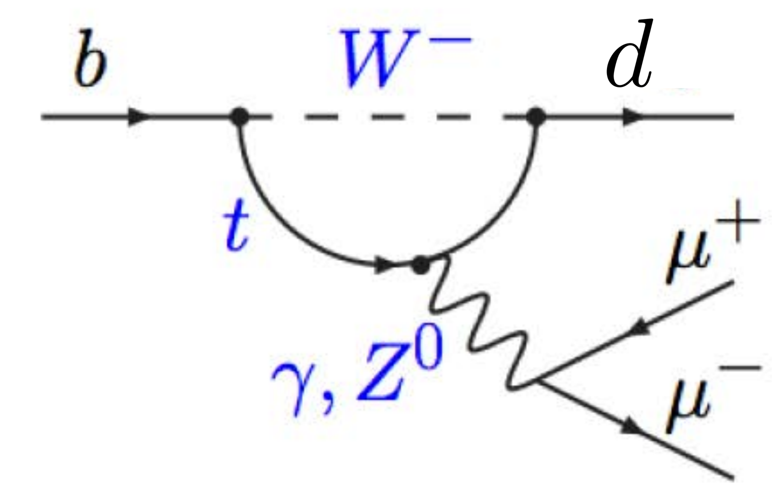
Detmold and Meinel, PRD93 074501 (2016)



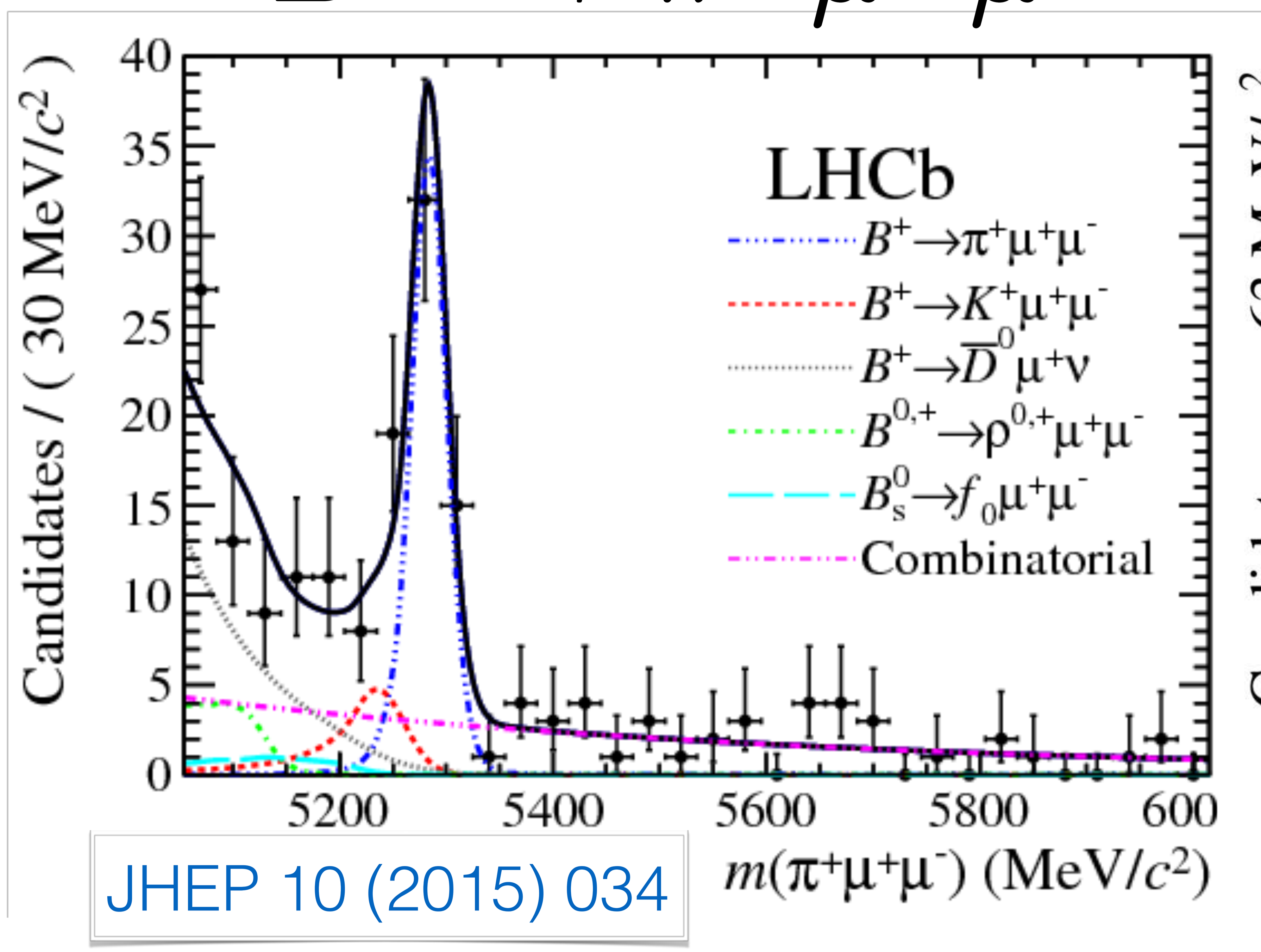
JHEP 06 (2015) 115

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

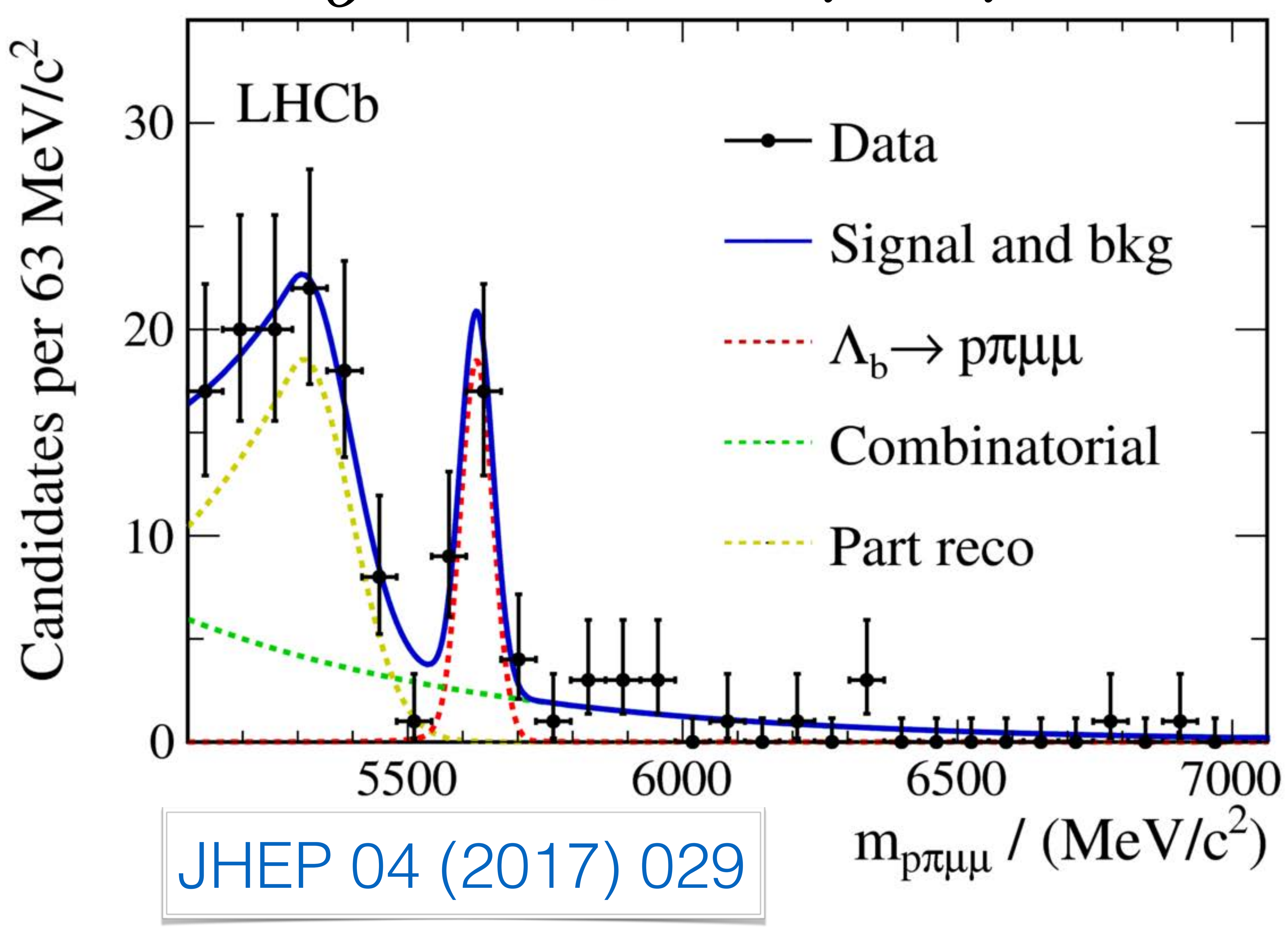
$b \to d\,\ell^+\ell^-$ transitions



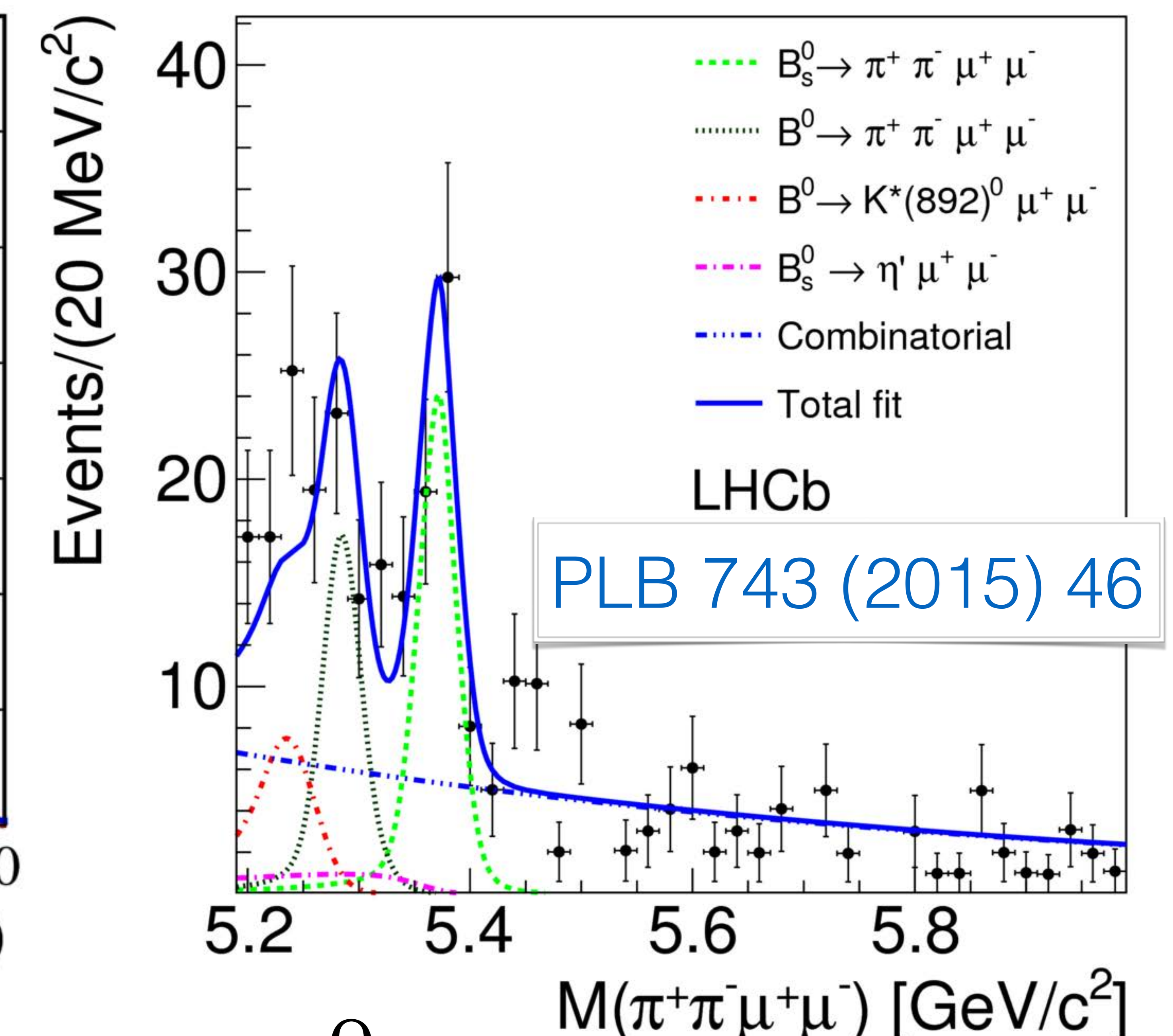
$B^+ \to \pi^+\mu^+\mu^-$



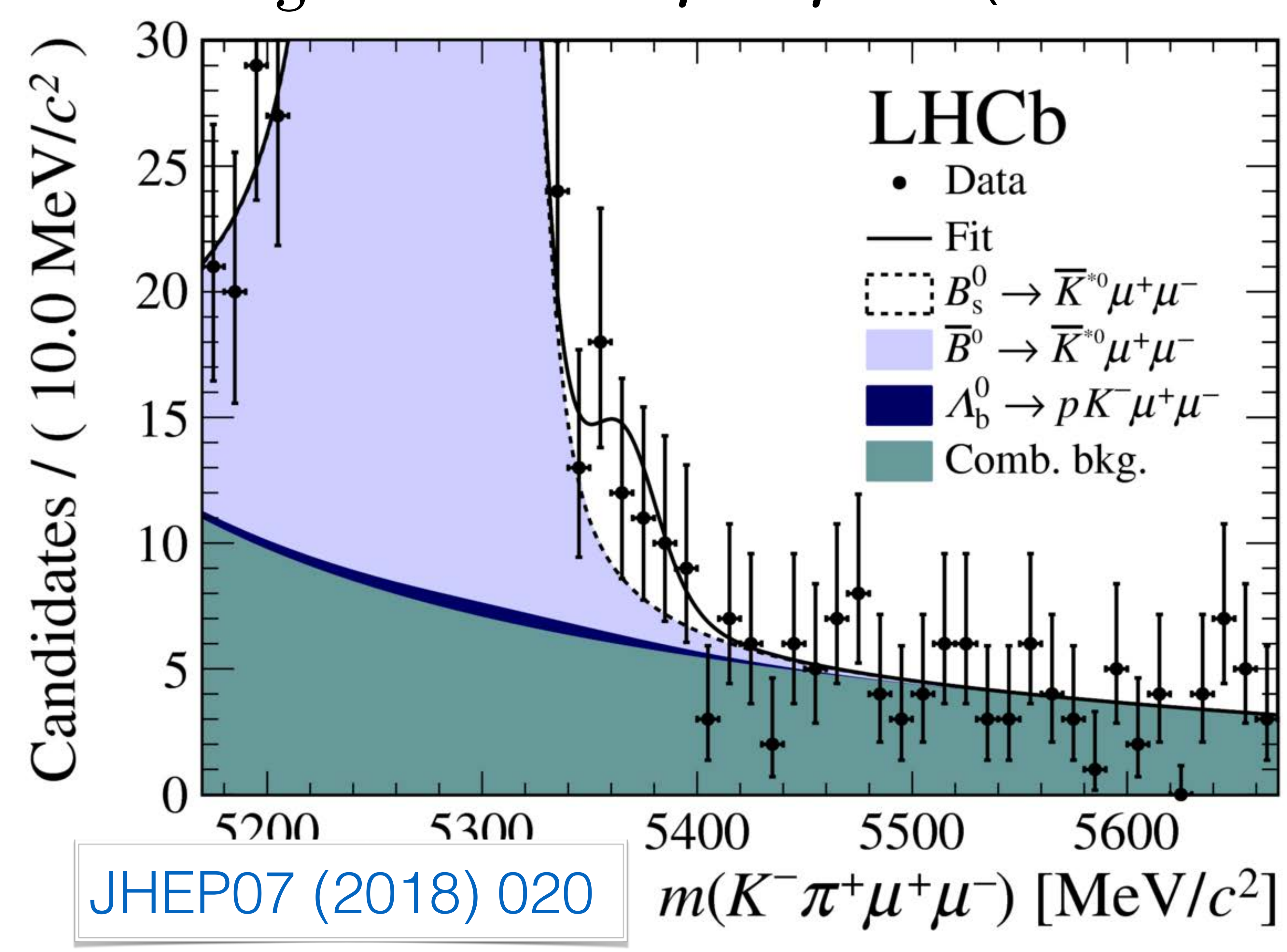
$\Lambda_b^0 \to p\pi^-\mu^+\mu^-$



$B^0 \to \pi^+\pi^-\mu^+\mu^-$



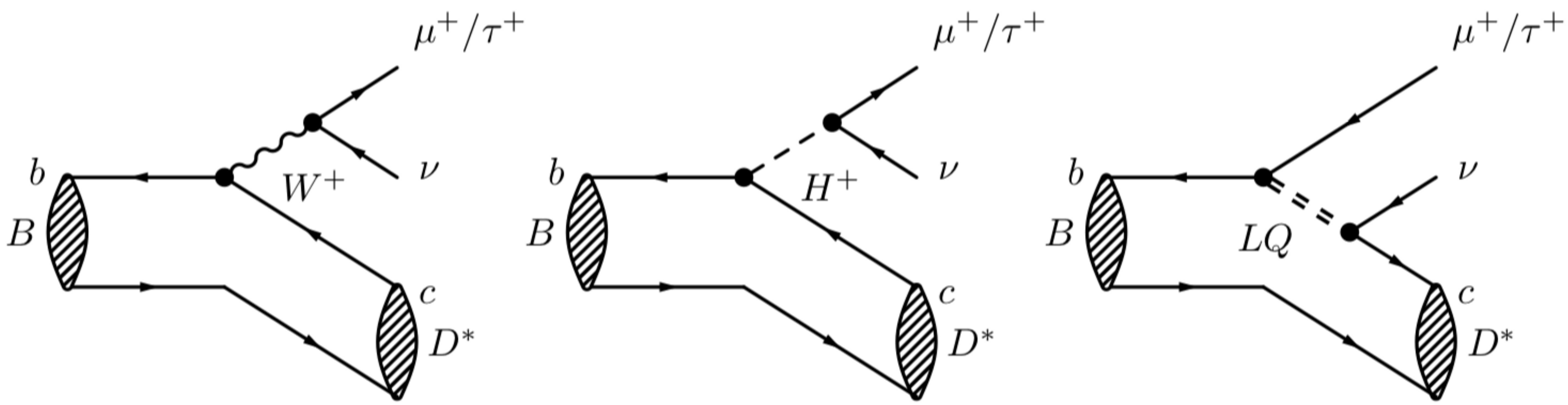
$B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$ (3+1.6/fb)



- First observation of $B^+ \to \pi^+\mu^+\mu^-$ and $\Lambda_b^0 \to p\pi^-\mu^+\mu^-$ and first evidence for $B^0 \to \pi^+\pi^-\mu^+\mu^-$ and $B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$
- Decays with BF $\mathcal{O}(10^{-8})$
- Ratios of rates for $b \to d\ell^+\ell^-$, $b \to s\ell^+\ell^-$ give access to $|V_{td}|/|V_{ts}|$

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*) : $R(D^*) = \dfrac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$
  - sensitive to any NP model coupling preferentially to third generation leptons
- Predicted theoretically at ~1-2%:

$$R(D)_{SM} = 0.299 \pm 0.003$$
$$R(D^*)_{SM} = 0.258 \pm 0.005$$

HFLAV 2018

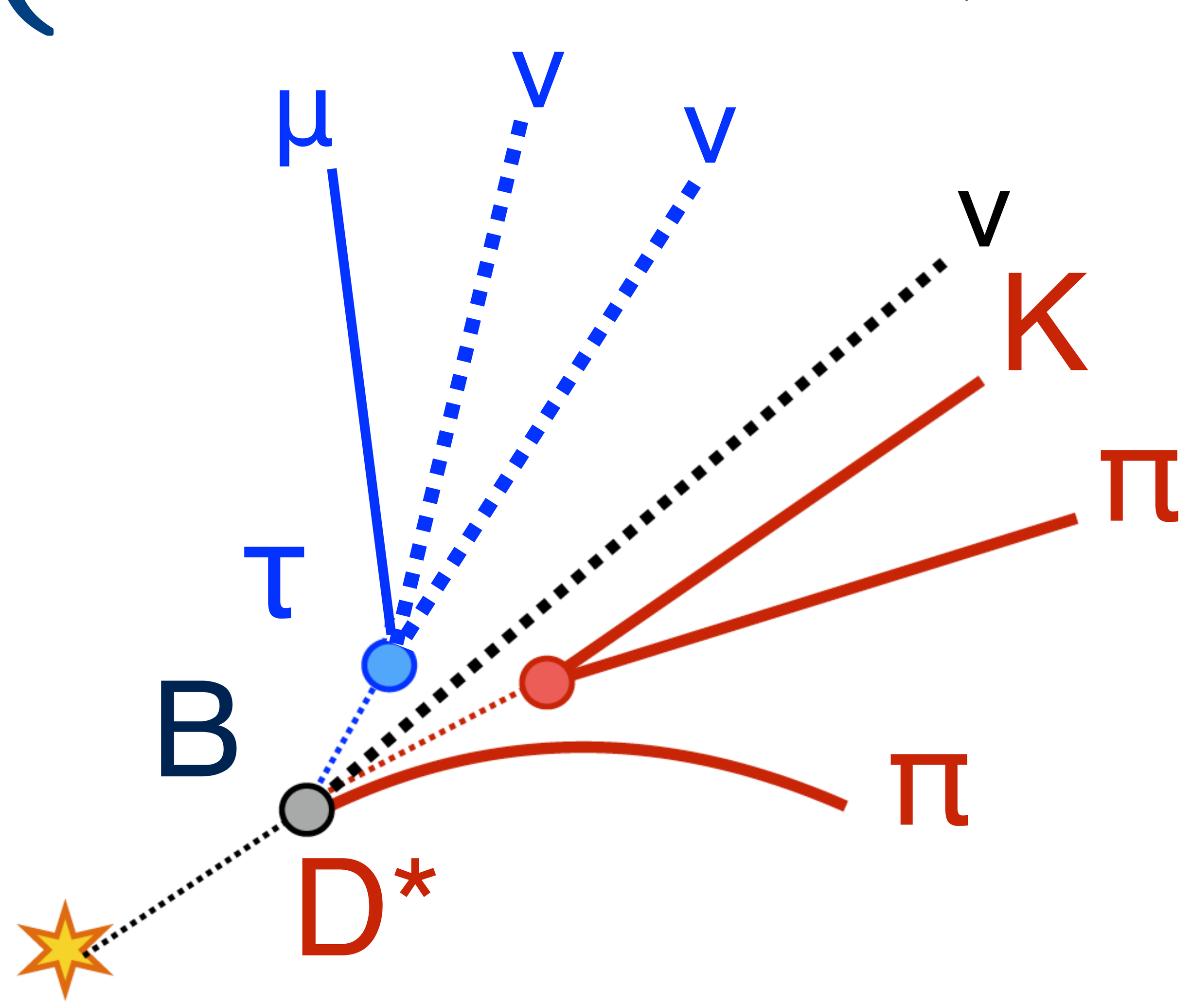
[R(D*) ~4%, according to Bigi et al, arXiv:1707.09509]

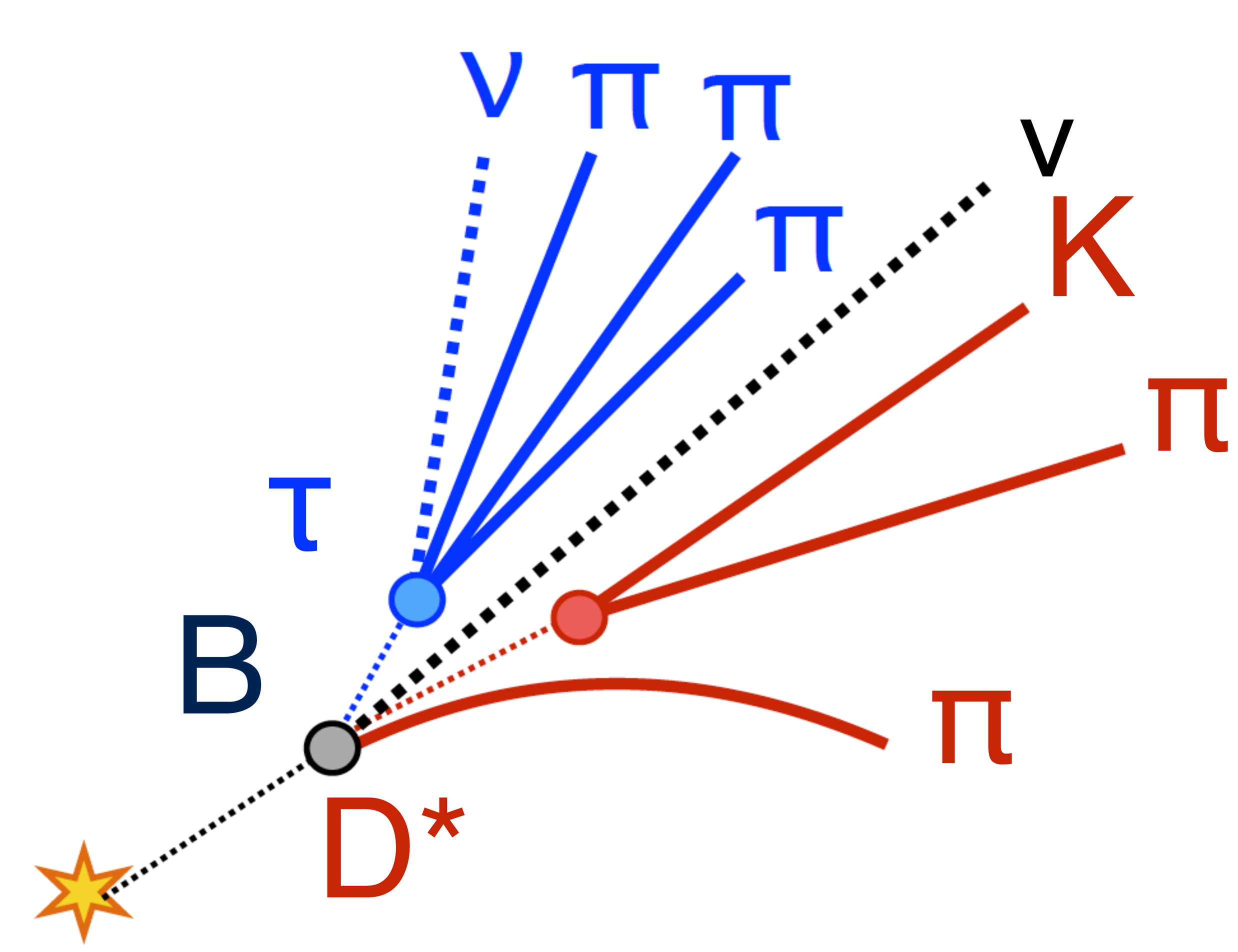
- Studied by Belle, BaBar and LHCb

$R(D^*)$: Experimental challenges

- Experimentally very difficult al the LHC (considered unfeasible)
- 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.)
- At least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$)
- Two LHCb measurements, in muonic and hadronic τ decays:

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





- Three-prong mode used for the first time!
- A semileptonic decay with no (charged) lepton in final state (one *K*, five π)

$R(D^*)$ with $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$

- Fit in $m^2_{miss} = (P^\mu_B - P^\mu_D - P^\mu_\mu)^2$, $q^2 = (P^\mu_B - P^\mu_D)^2$, E_μ
- $R(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$ ~2 σ > SM

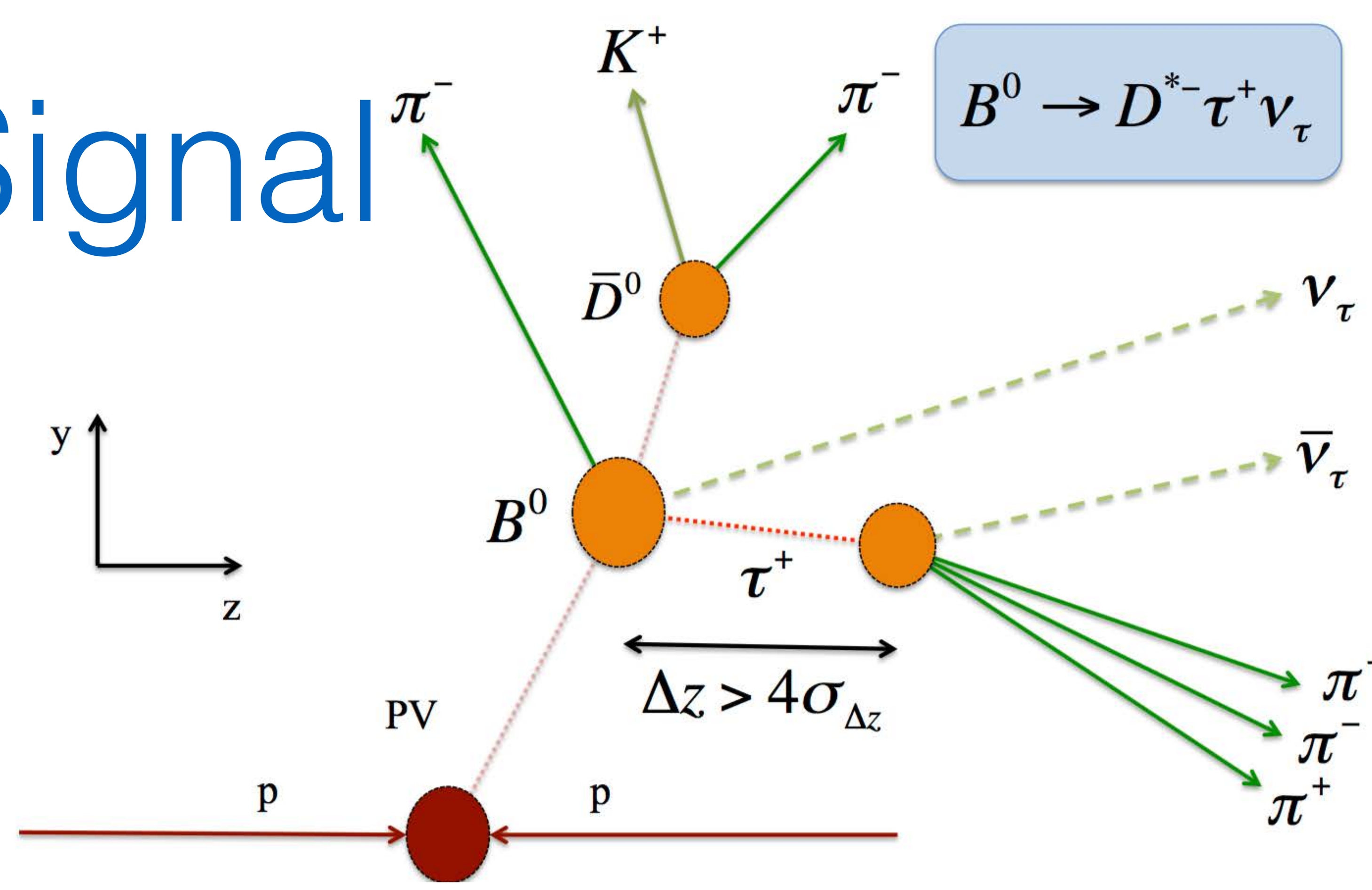
$$\int \mathcal{L}\,\mathrm{dt} \sim 3\,\mathrm{fb}^{-1}$$

PRL 115 (2015) 111803

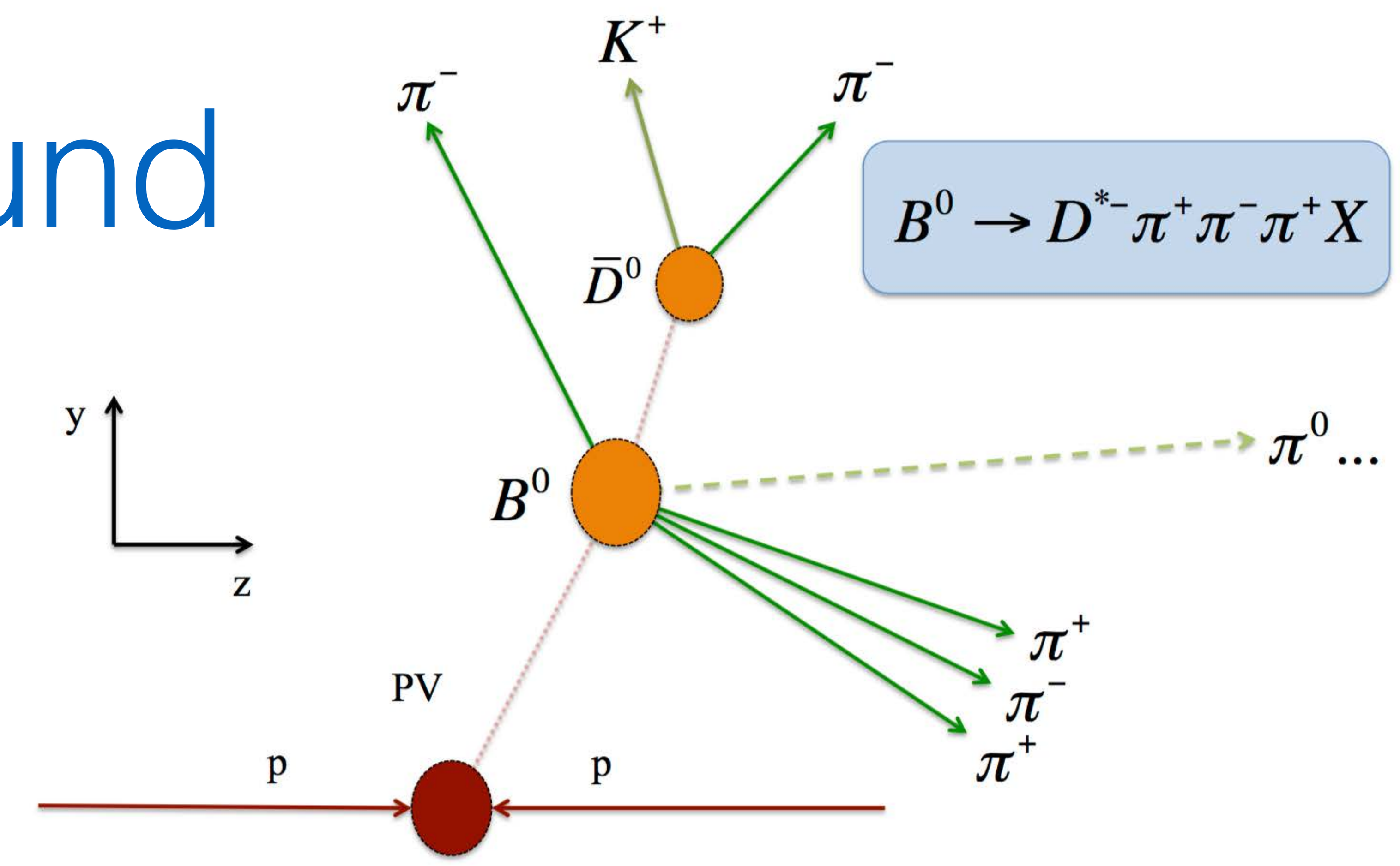
$R(D^*)$ with $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$

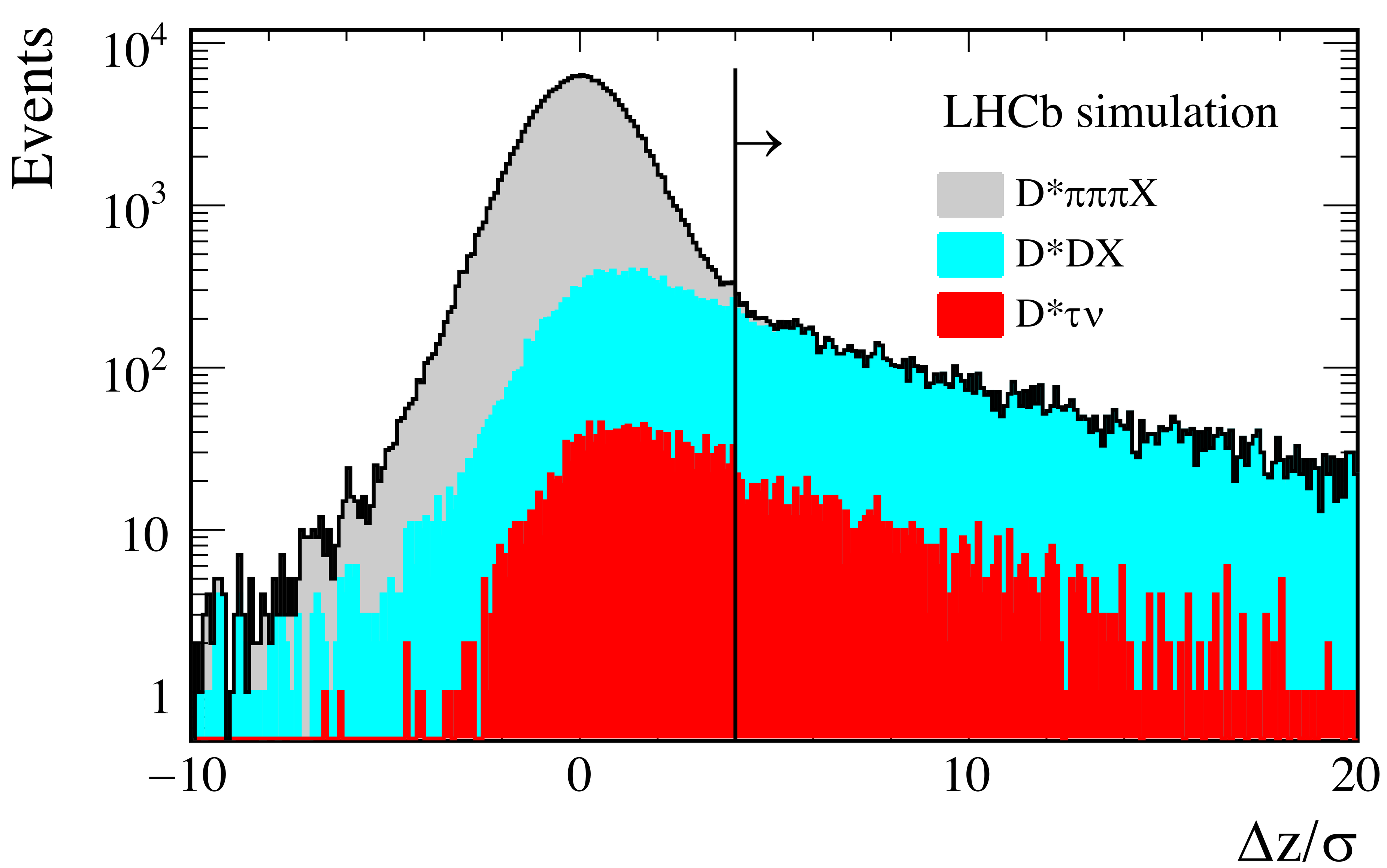
- Separation between B and 3π vertices ($\Delta z > 4\sigma_{\Delta z}$) crucial to obtain the required rejection of $B \to D^* 3\pi X$ (BF~100 x signal)

Signal



Background





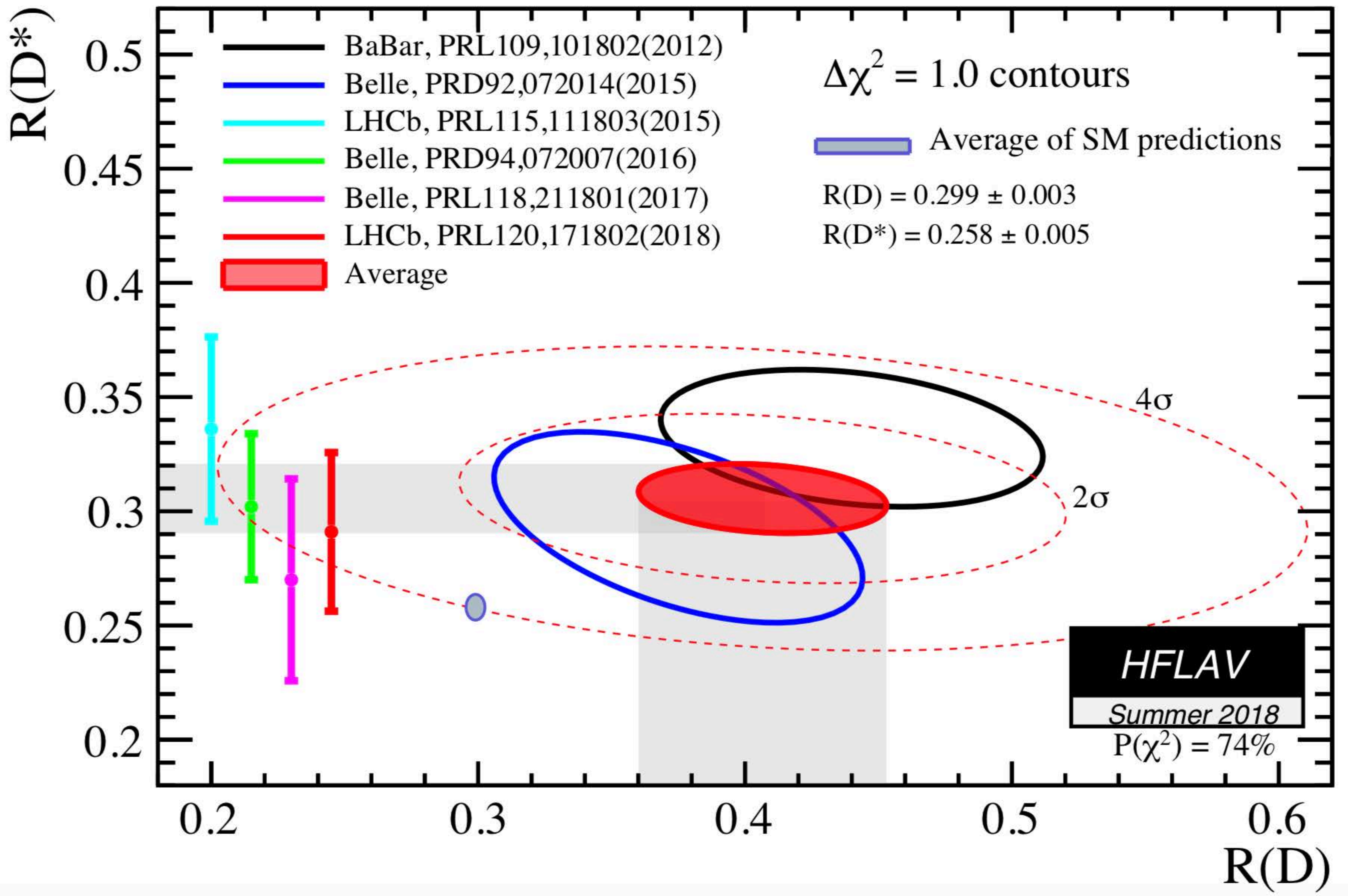
- Remaining double-charm background ($D^*D_{(s)}X$, (BF~10 x signal, same vertex topology) suppressed by employing a multivariate classifier

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 σ > SM

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

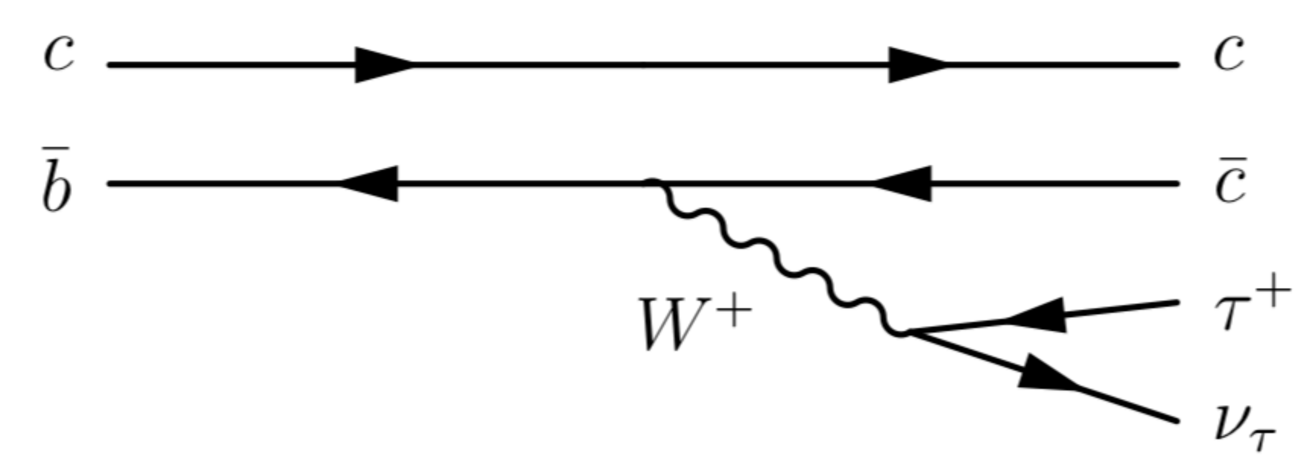


- All experiments see an excess wrt SM predictions
- Tension at ~3.8 σ level (Bigi et al, arXiv:1707.09509) INTRIGUING!
- ~20% effect on R(D*) (more precise, larger BF and less feed-down)

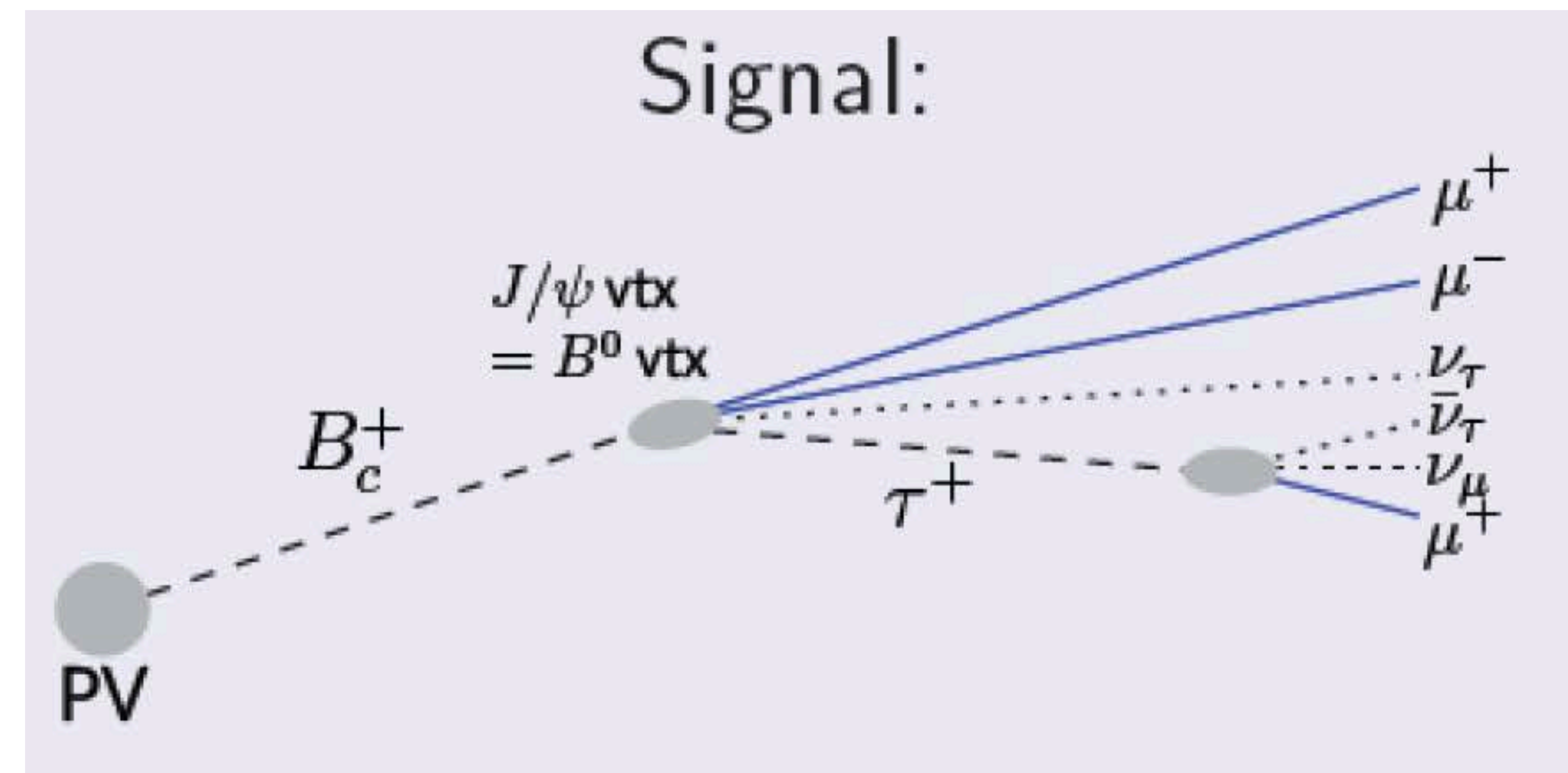
Testing LFU with B_c decays

- Generalization of R(D*) to B_c :

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

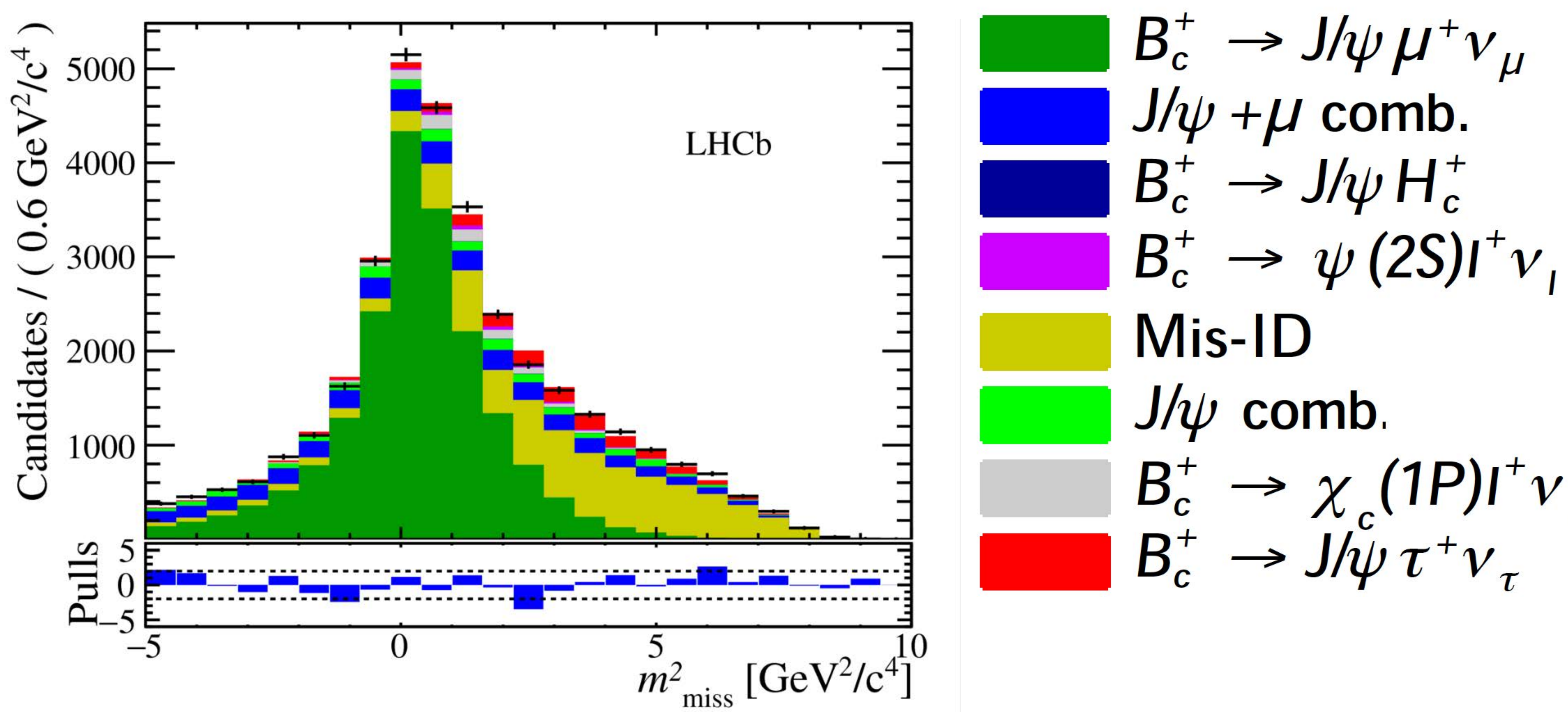


- Signal reconstructed using τ→μνν, with $B_c^+ \to J/\psi \mu^+ \nu_\mu$ as norm.



- 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)

What happens next?

- Extend analyses to full Run2 statistics (will take time!)
  - from ~1300 to ~6000 events in hadronic mode
  - goal is to be competitive with world average
- A whole programme of semi-tauonic measurements, e.g.

$$\begin{cases} R(D) : B^+ \to D^0\tau^+\nu_\tau \\ R(D^*) : B^0 \to D^{*-}\tau^+\nu_\tau \end{cases}$$

← First expected result, simultaneous fit to $D^0\mu^+$ & $D^{*-}\mu^+$ (Still Run 1- based)

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

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

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

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 uncertainties been correctly estimated?
- **Theoretical uncertainties?**: large theoretical uncertainties from hadronic form factors, but LFU tests should be robust
- A cocktail of the above?

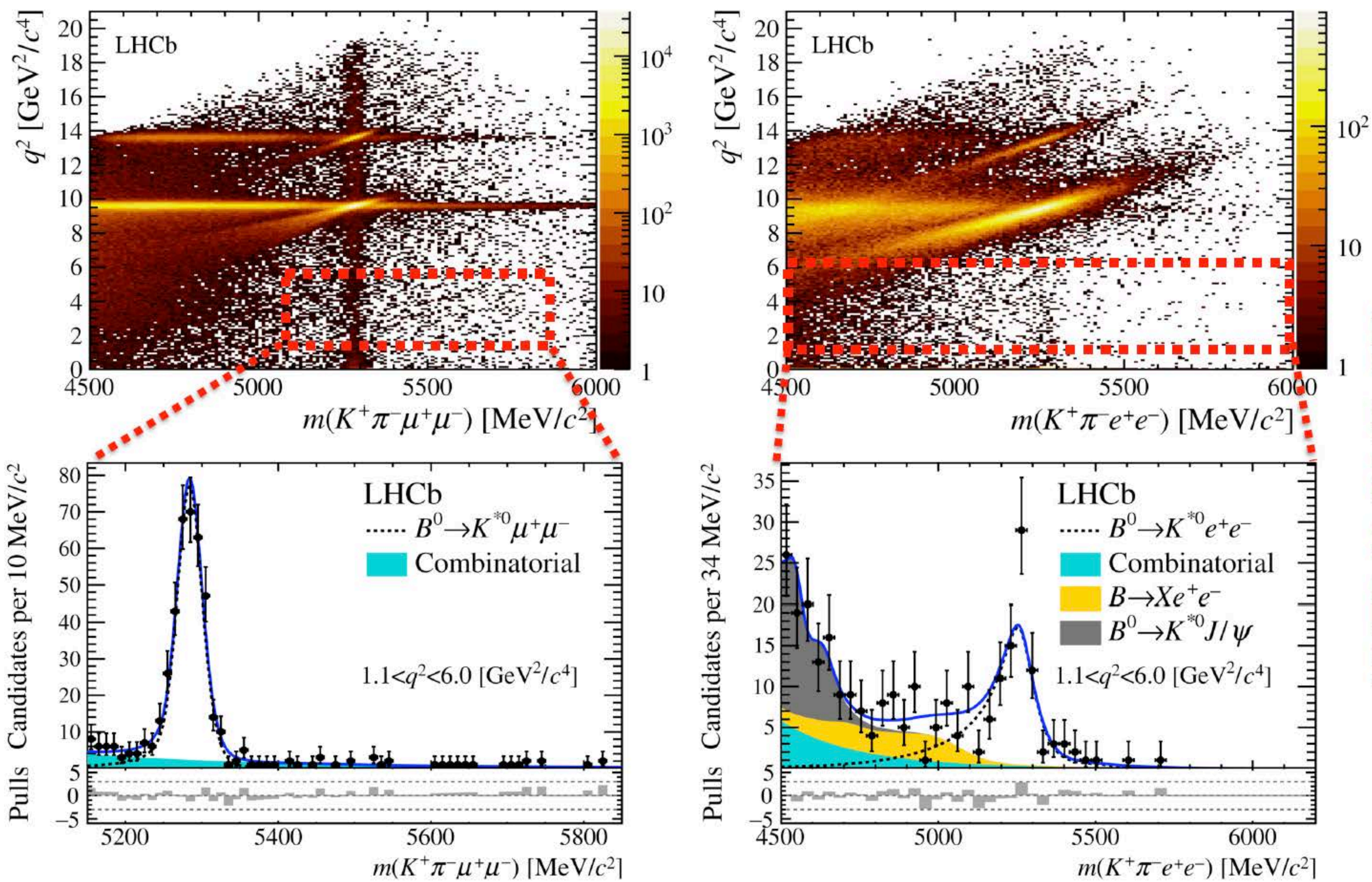
- **New Physics only once all the above have been excluded...**
- Many NP models proposed (leptoquarks,…), see for example: “B-physics anomalies: a guide to combined explanations” D. Buttazzo et al., JHEP 1711 (2017) 044, arXiv:1706.07808
  - “the case of an $SU(2)_L$-singlet vector leptoquark emerges 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 these effects

Conclusions

- Lots of measurements in flavour only a few of which were highlighted here
- 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 to analyse Run 2 to test these hints
- In LHCb we are working hard to prepare for the future: ready to instal 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
- Belle II and the LHCb Upgrade(s) will open up a new frontier in precision

A few extra slides

R_X – experimental challenges



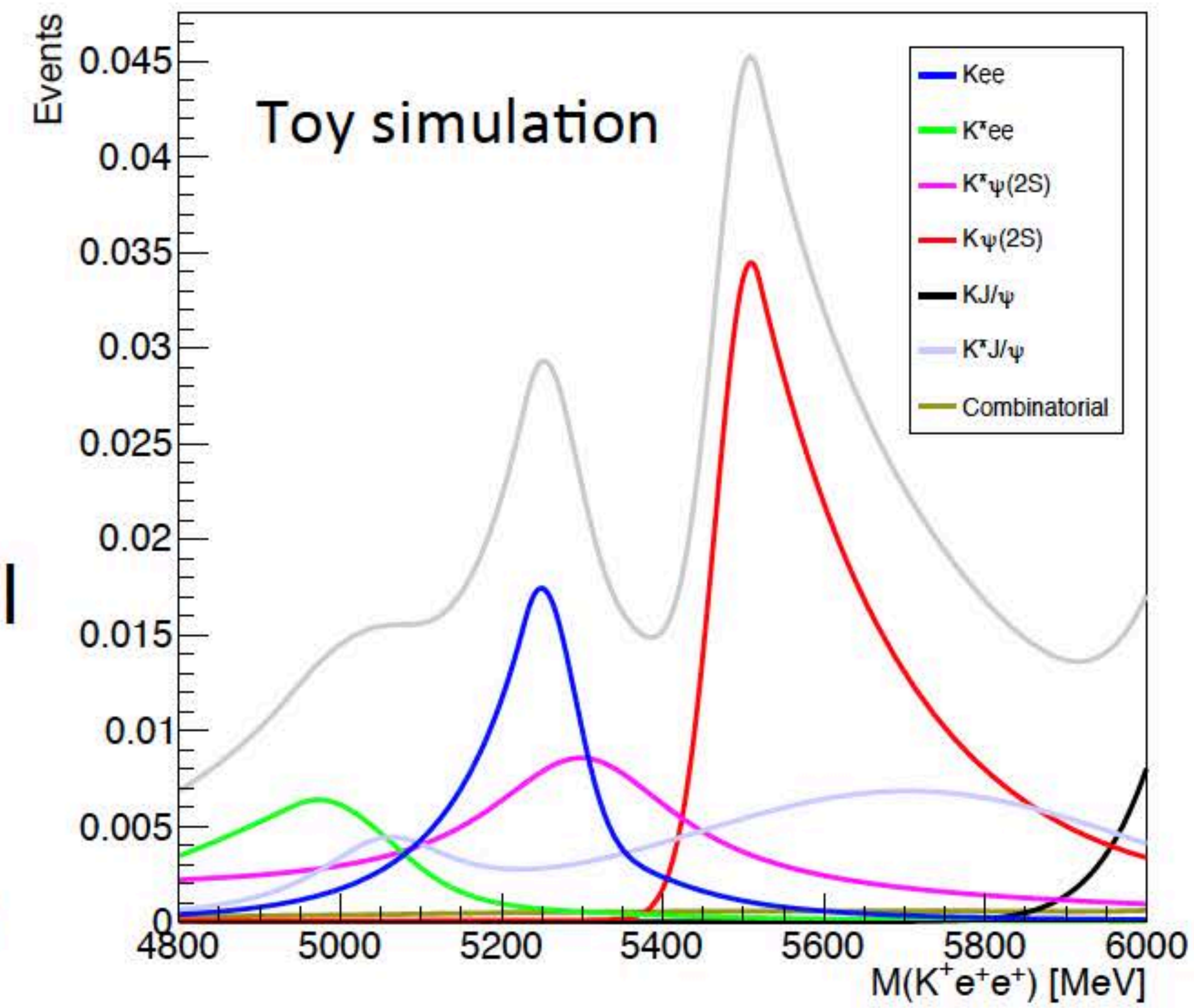
[JHEP 08 (2017) 055]

7

R_K update – other q^2 regions

- (In SM) little $B^+ \rightarrow K^+e^+e^-$ signal with $q^2<1.0$ GeV^2

- Can 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 in m_{Kee}
  - ψ(2S)K* decays can leak into signal region on the upper side
  - Signal sandwiched between these and hence difficult to fit reliably



Mitesh Patel

1808.08865

Physics highlights

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

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%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **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}	–