Flavour physics at a hadron collider: part IV

- Lepton universality tests R_K and R_{K^*}.
- Effective field theories.
- Lepton universality tests in b—>clnu transitions.
- What does this all mean?

Patrick Owen

01/09/21

Reminder:Coherent pattern?

- If the P_5' discrepancy is due to NP, it would also cause the branching fractions to be lower than the SM.

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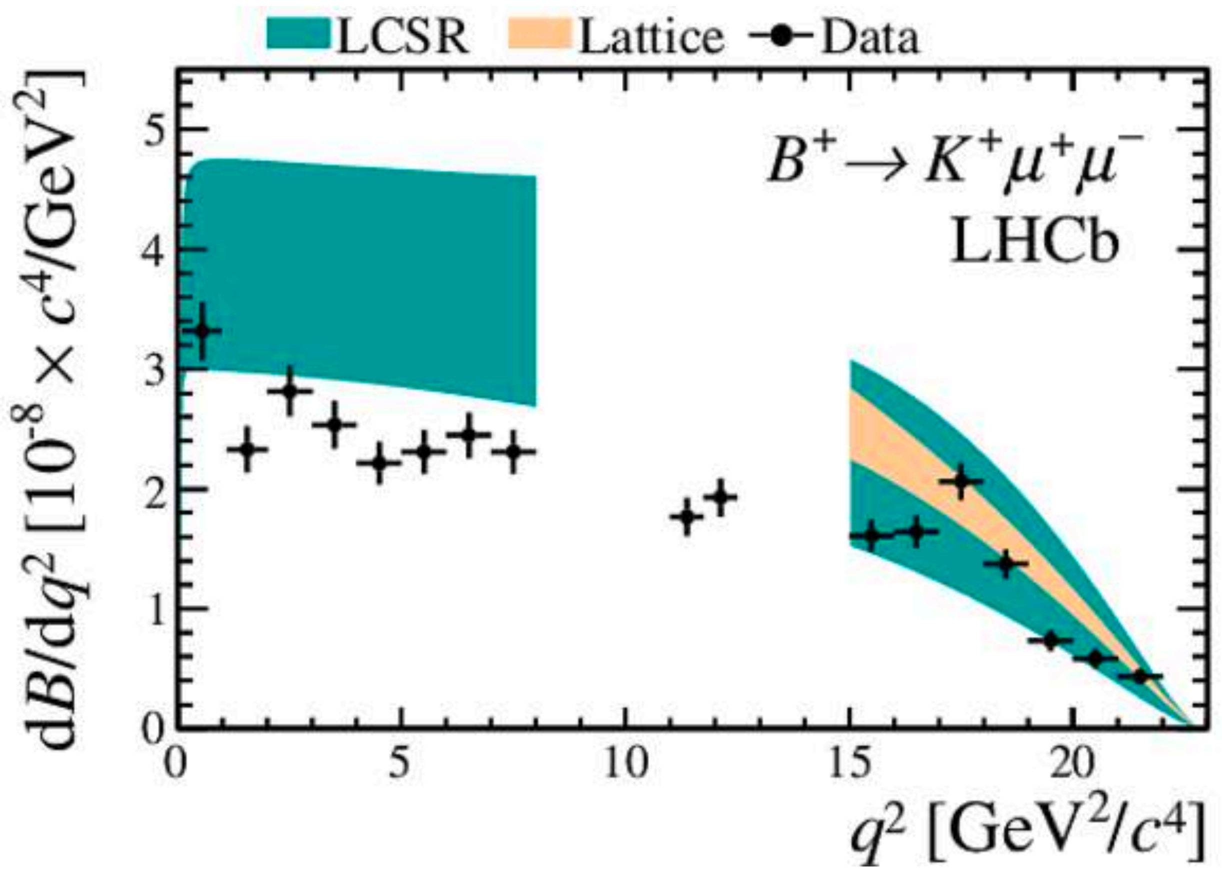

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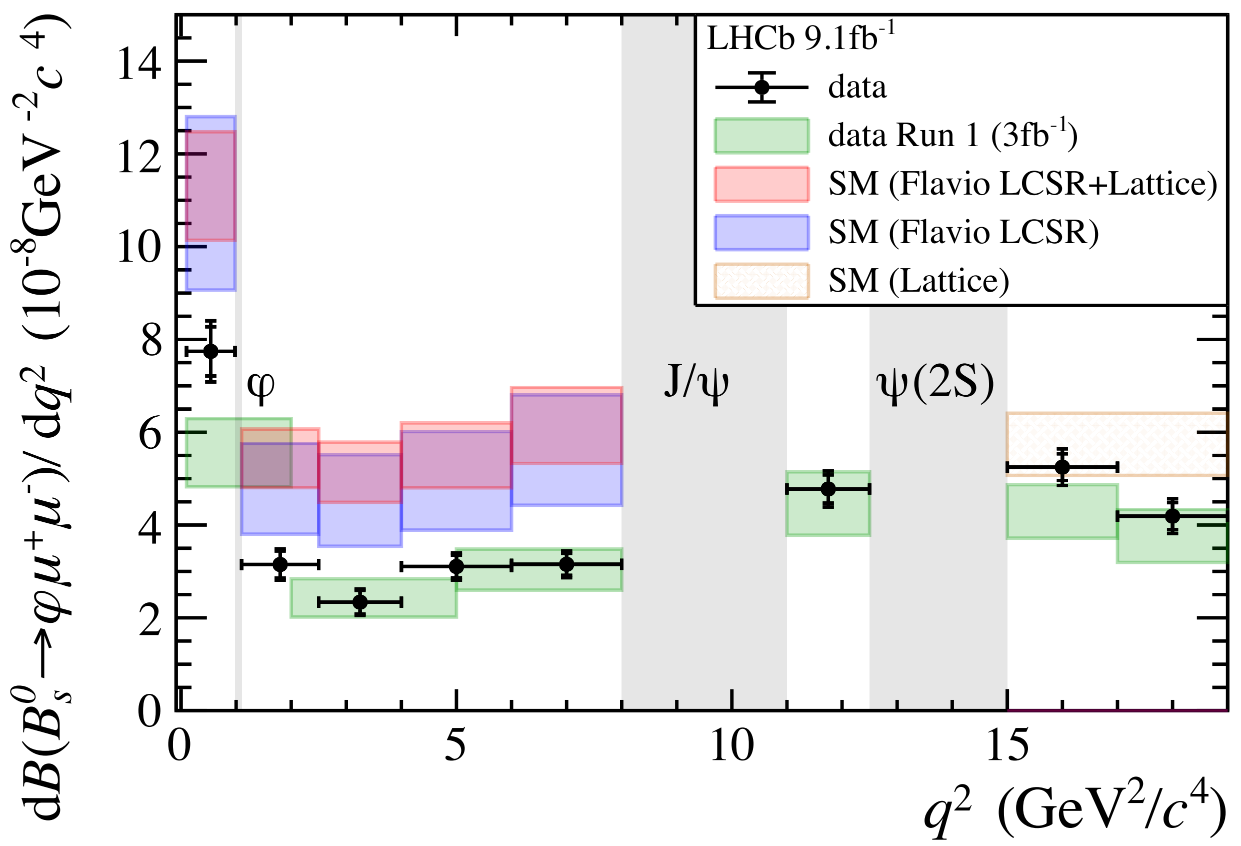
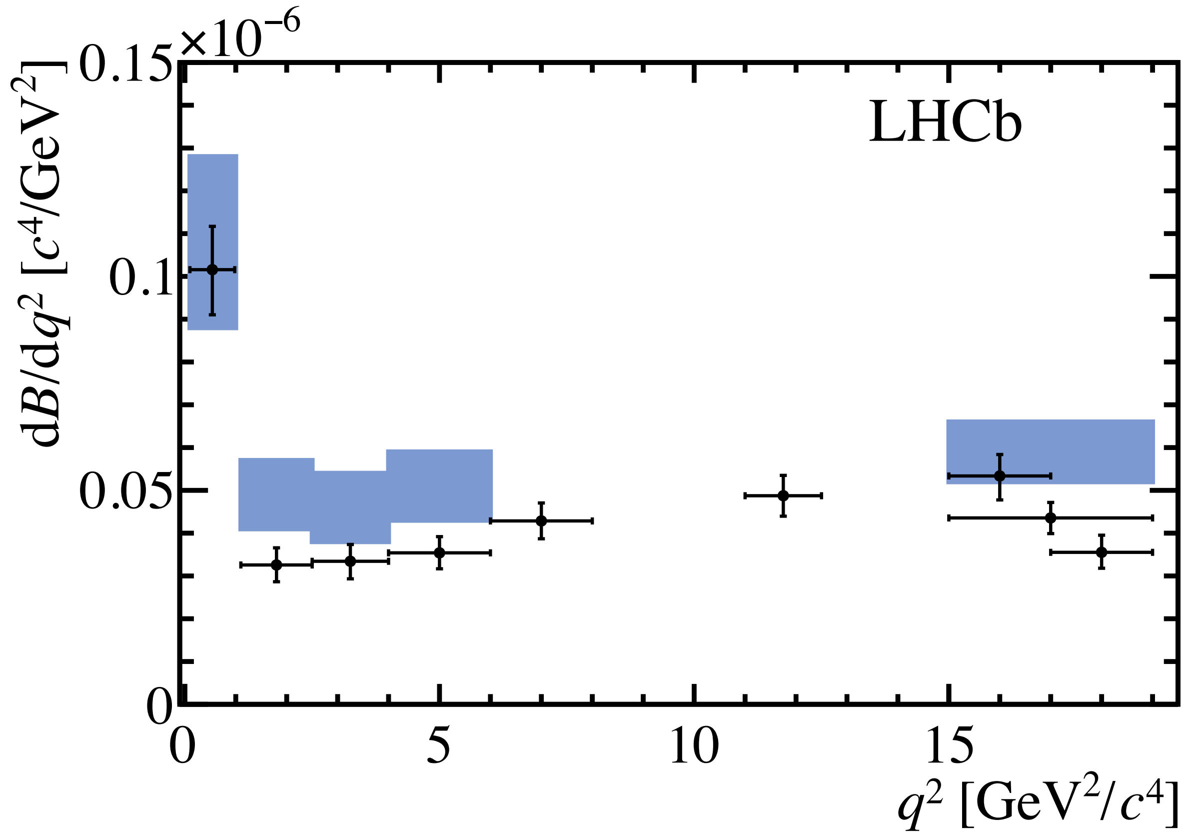
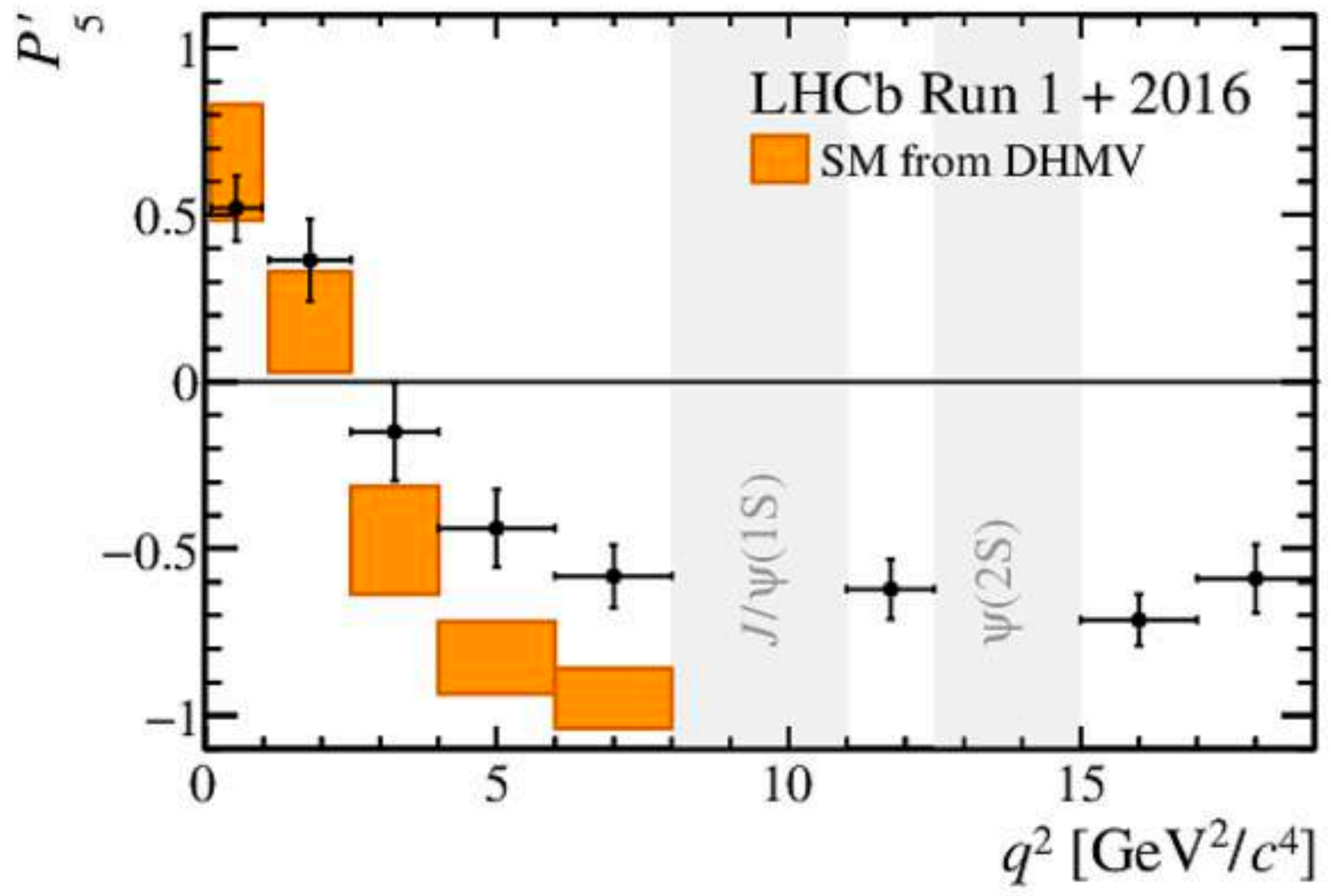






- Something appears to be negatively interfering with the SM b->sll decay amplitude, with a vector like coupling to the leptons.
- Cancel theoretical uncertainties via tests of lepton universality.

Accidental symmetries

- Noether's theorem: Symmetries translate to conservation laws.
  - Lorentz invariance: Conservation of four-momentum.
  - Global phase: Conservation of charge.
- Momentum/charge conservation are therefore **protected** by the fundamental symmetries of the theory.
- Let's look at the following processes to see which could be interesting for new physics:

$\mu^+ \to \pi^+ \bar{\nu_\mu}$

Violation of four-momentum: Protected by Lorentz invariance.

$\mu^+ \to e^- \bar{\nu_e} \bar{\nu_\mu}$

Violation of charge conservation: Protected by U(1) symmetry.

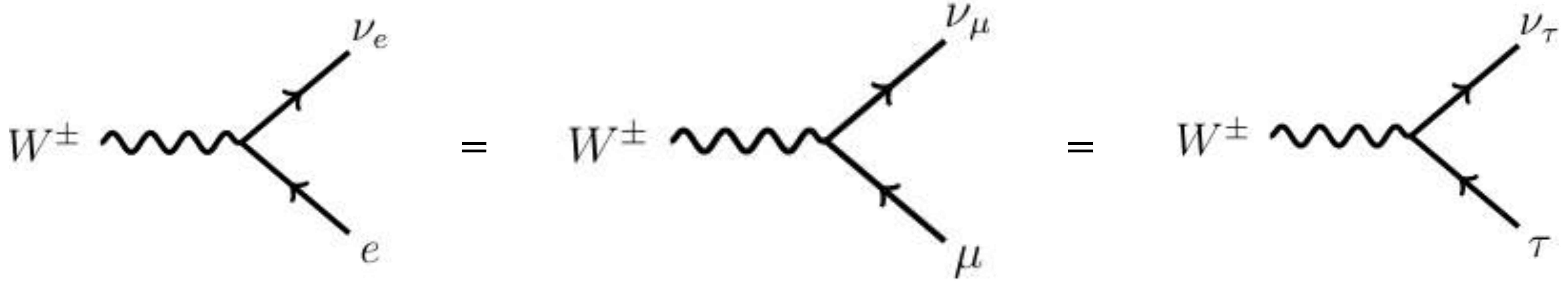
$\mu^+ \to e^+ e^- e^+$

Violation of lepton flavour violation: Protected by…. ????

- The lepton flavour symmetries in the Standard Model are **accidental.** Testing them is therefore a very sensitive to theories beyond the SM.
  - Some symmetries of interest: Lepton flavour, lepton universality (today) and lepton number.

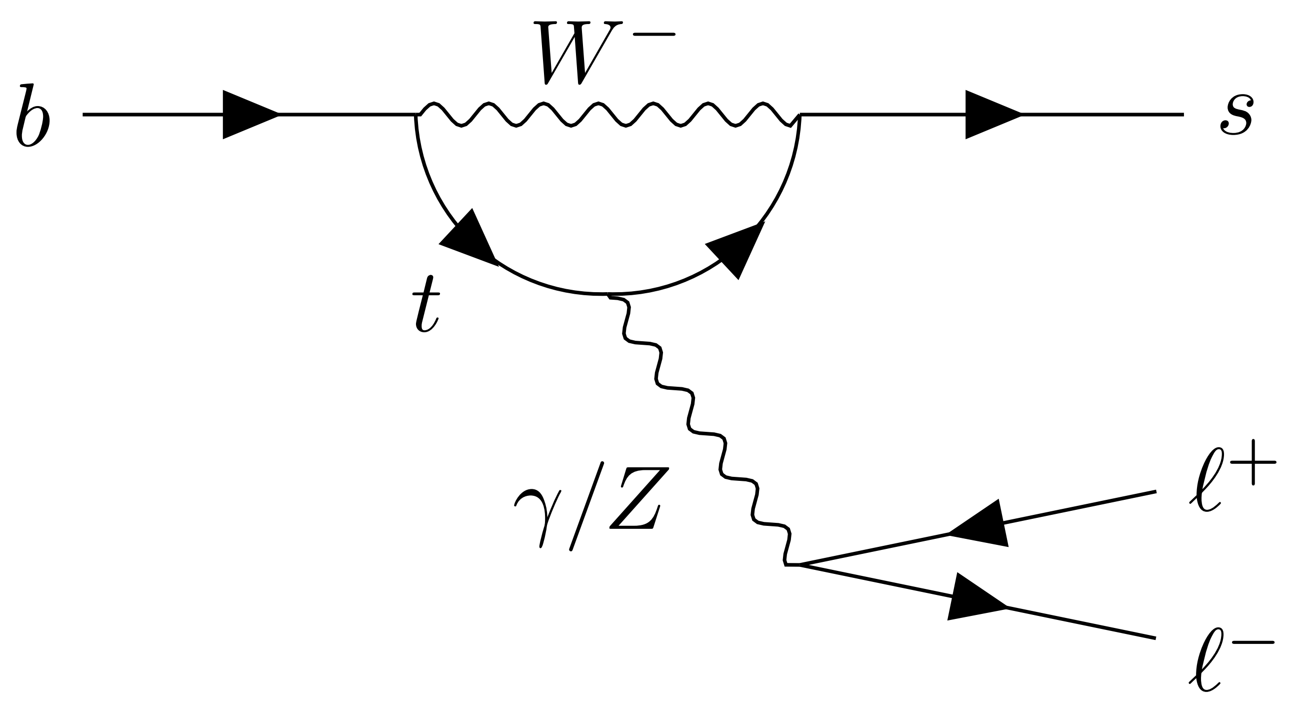
Lepton universality

- Lepton universality is an accidental symmetry in the Standard Model.

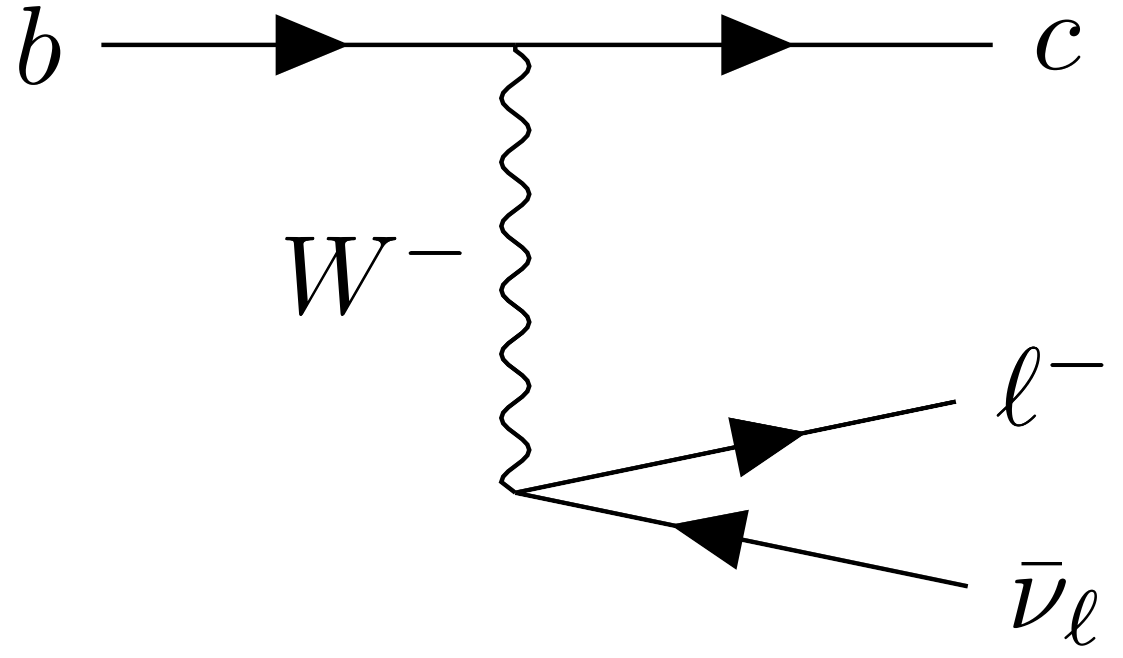


- We want to test it with so-called ‘semileptonic decays’.

Neutral current: BF ~ 10^{-6}



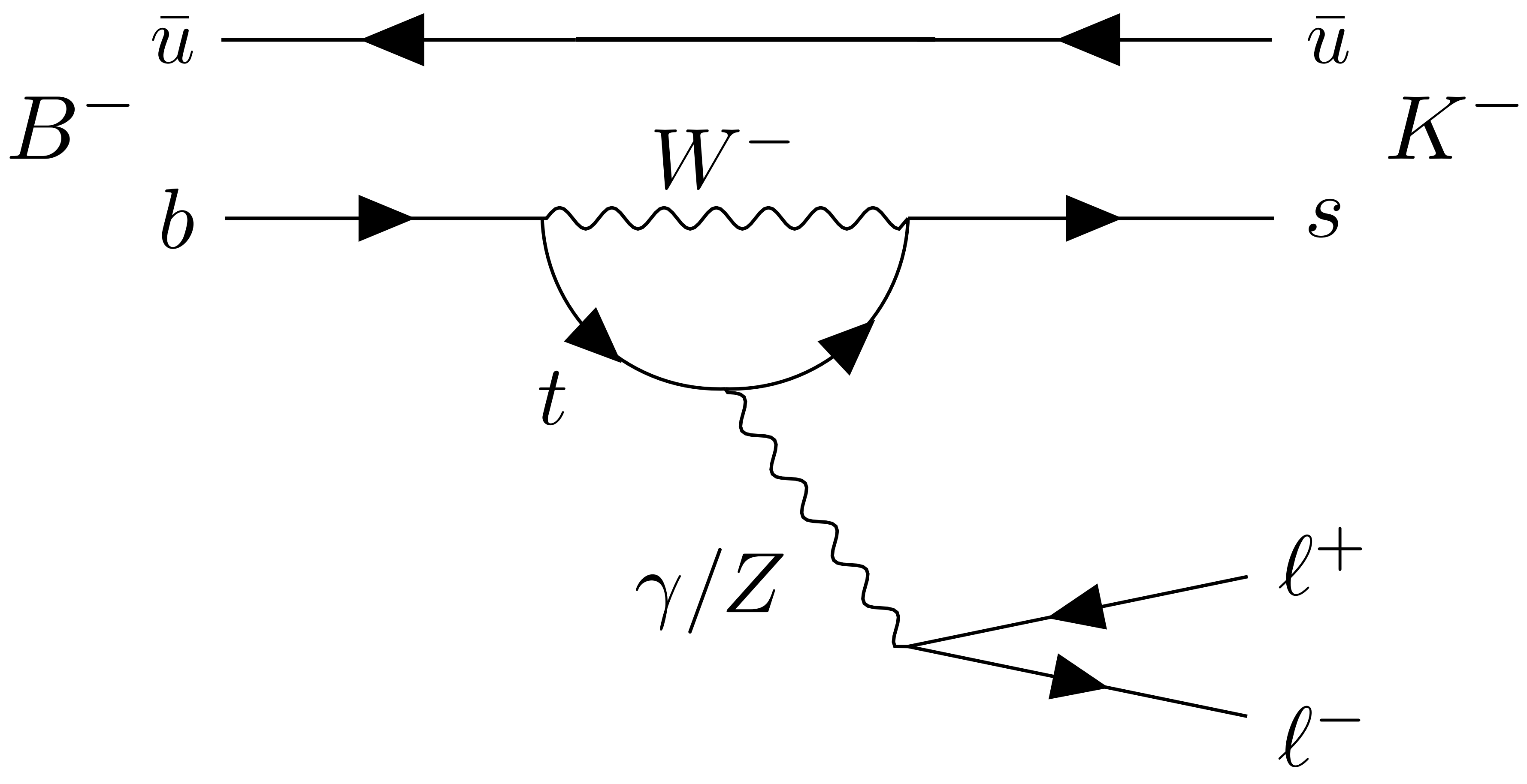
Charged current: BF ~ 10^{-2}

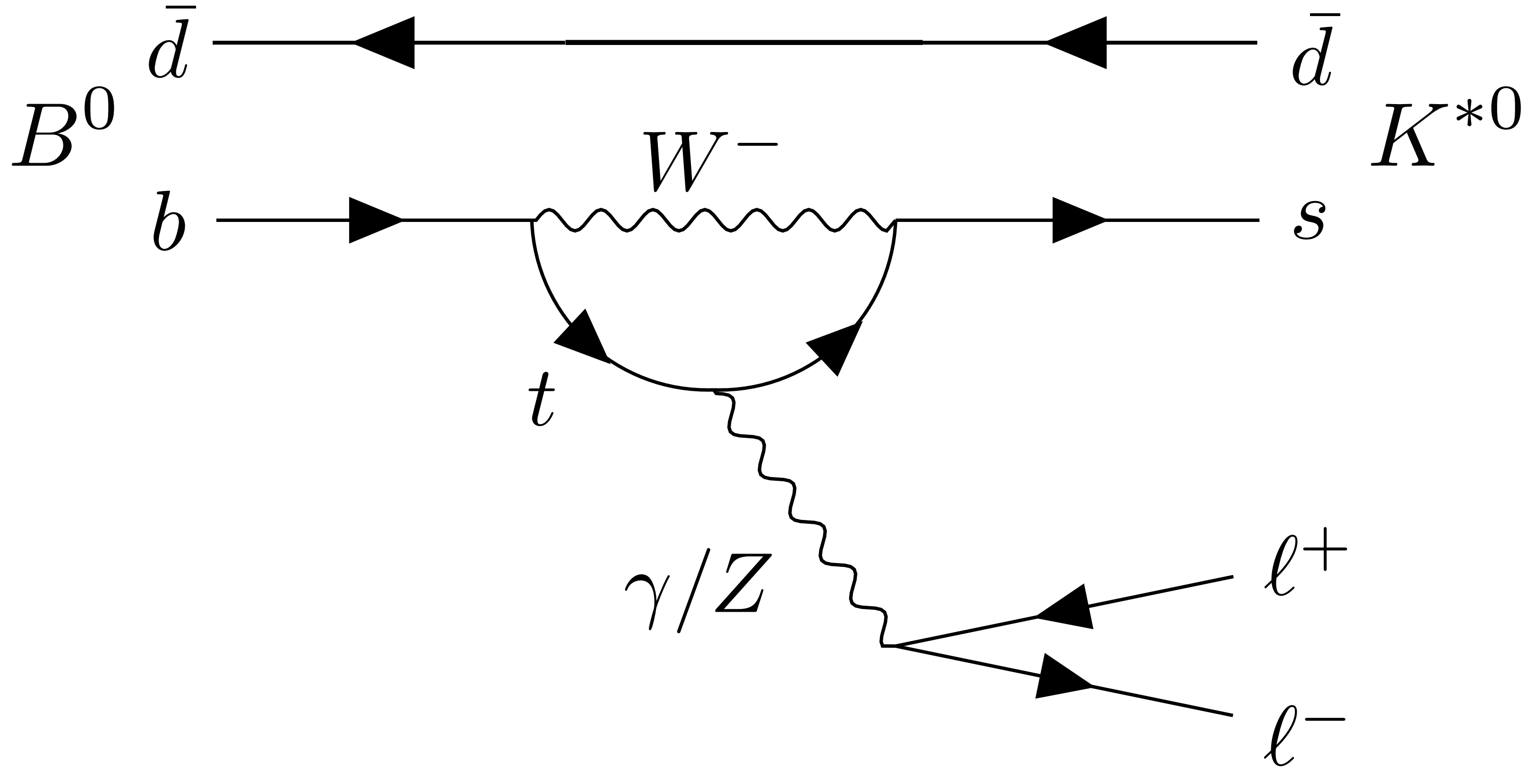


- Compare the decay probabilities (BF) involving different charged lepton types ℓ^-.

The lepton universality ratios $R_{K(*)}$

- Compare muons and electrons to see if the same discrepancies appear there.



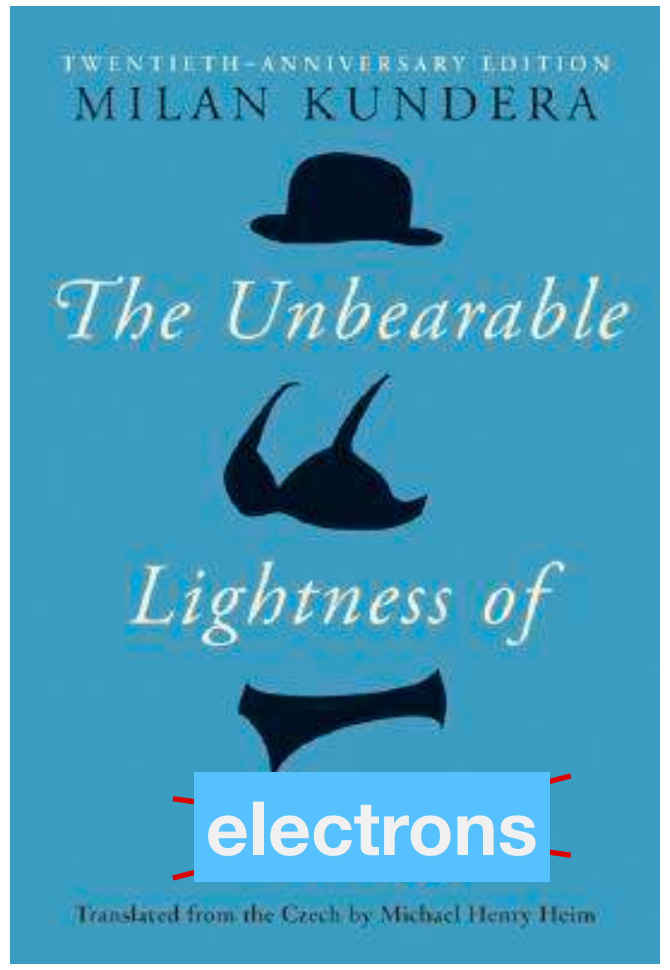


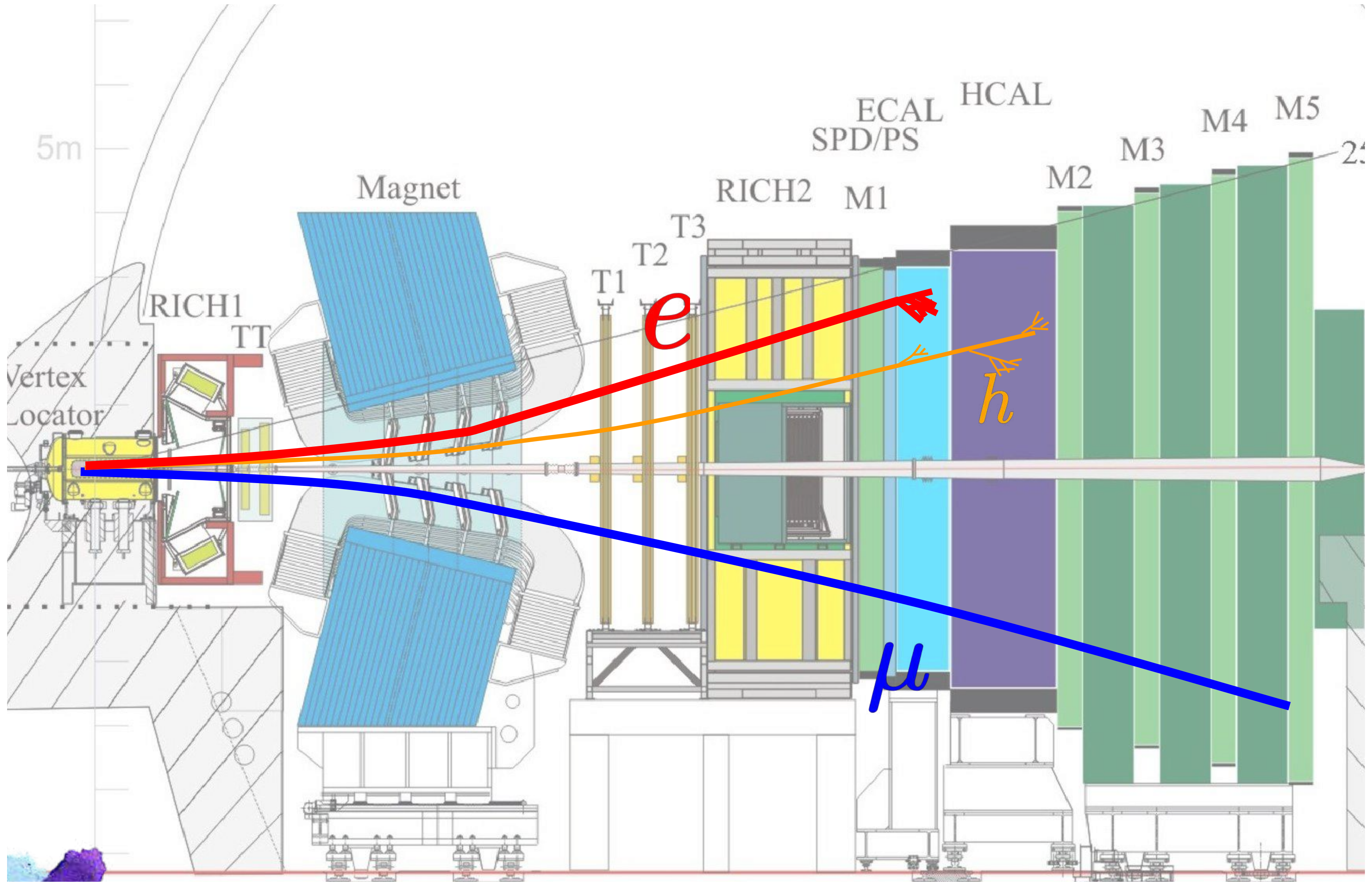
$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- Muon and electron masses small compared to b-quark: $R_{K(*)} \sim 1$

The unbearable lightness of electrons

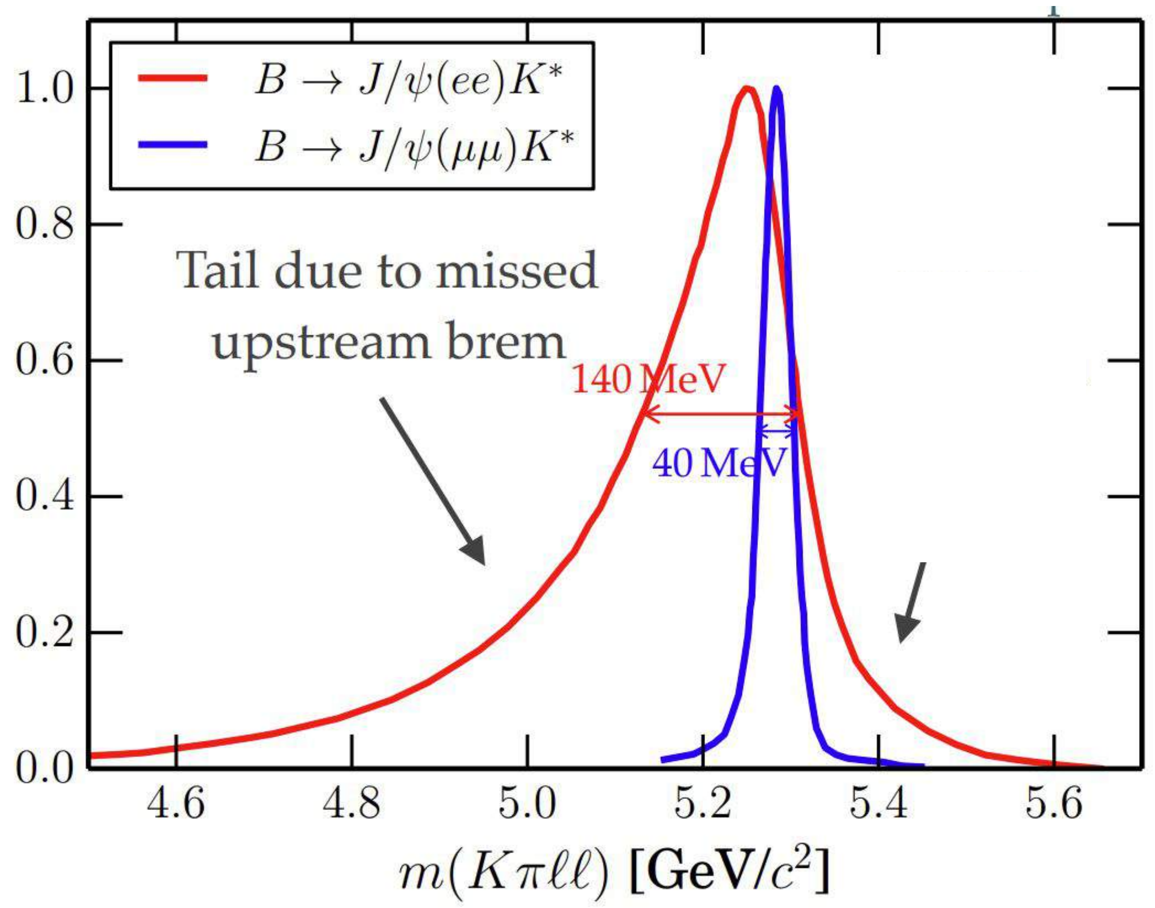
- Electrons are 200 times lighter than muons —> undergo bremsstrahlung more often.

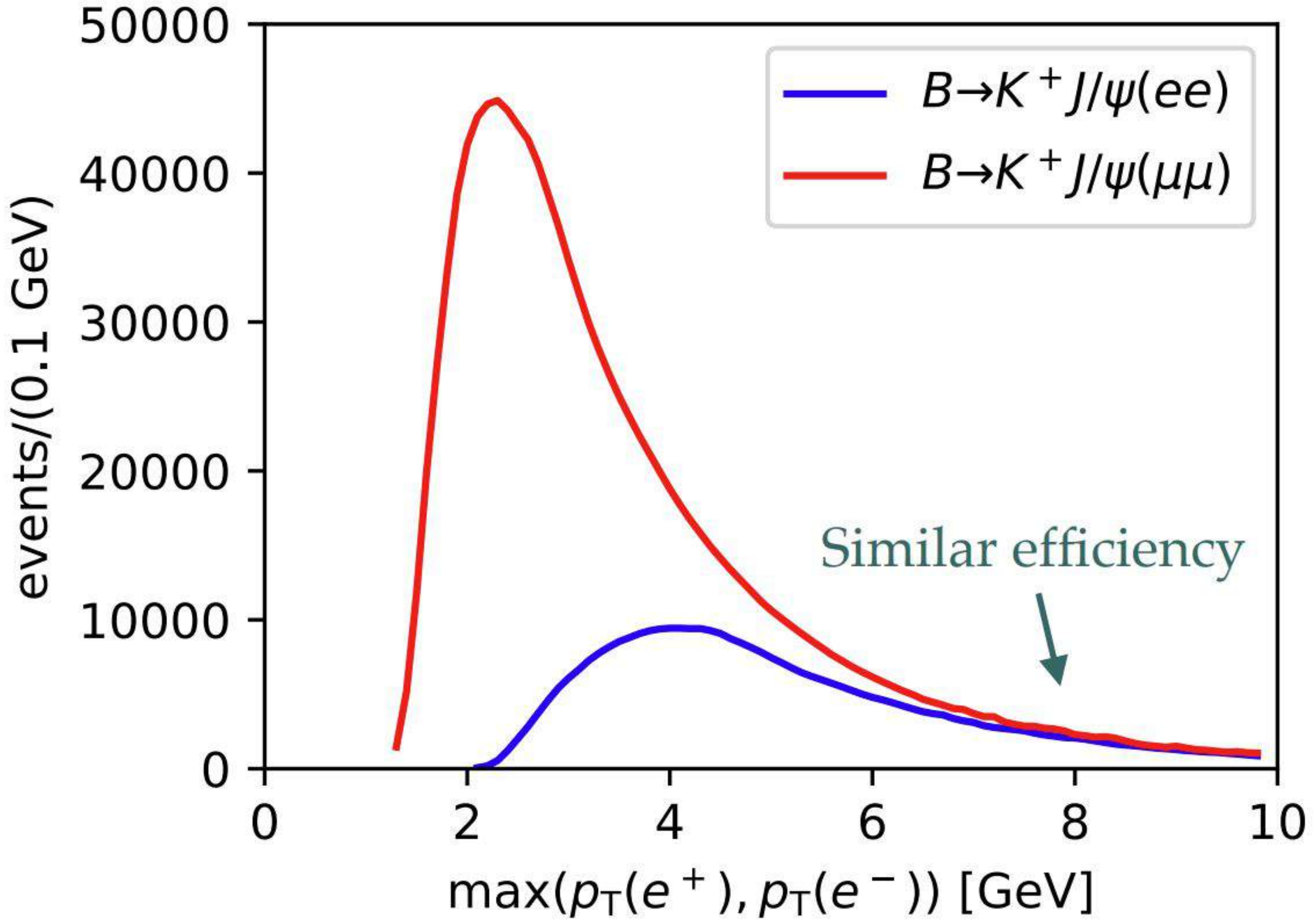




Credit: M. Atzeni

- Two effects from this:
  - Worse mass resolution for electrons.
  - Worse efficiency for electrons.





Bremsstrahlung issues

- Get background from the J/ψ and ψ(2S) leaking into signal region.

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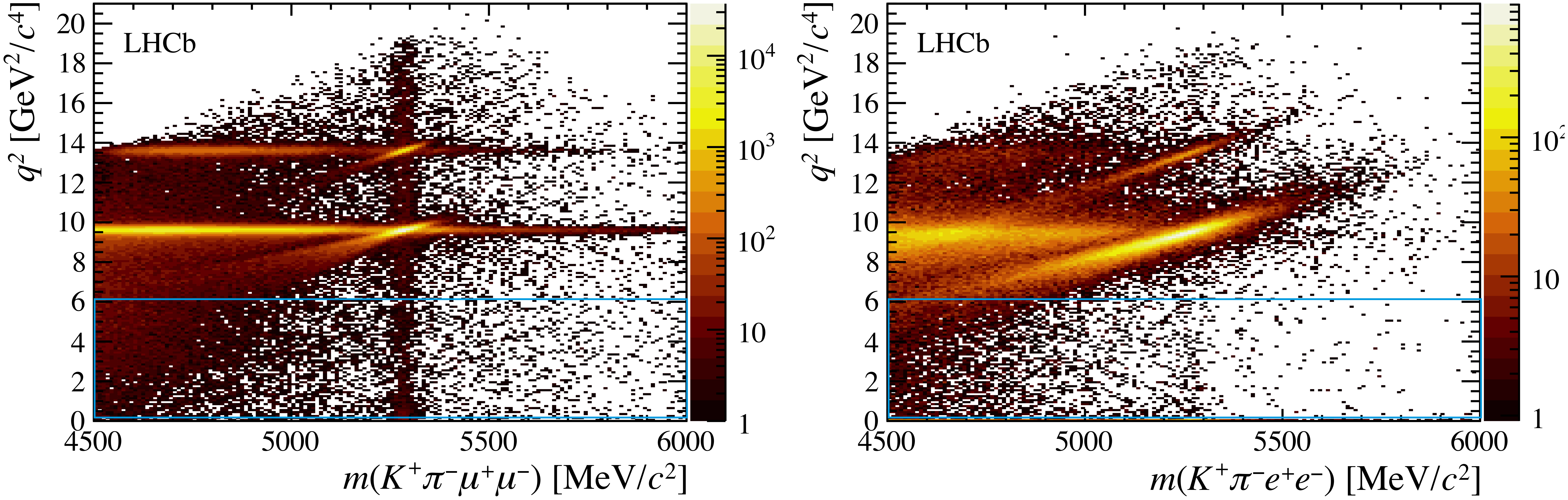
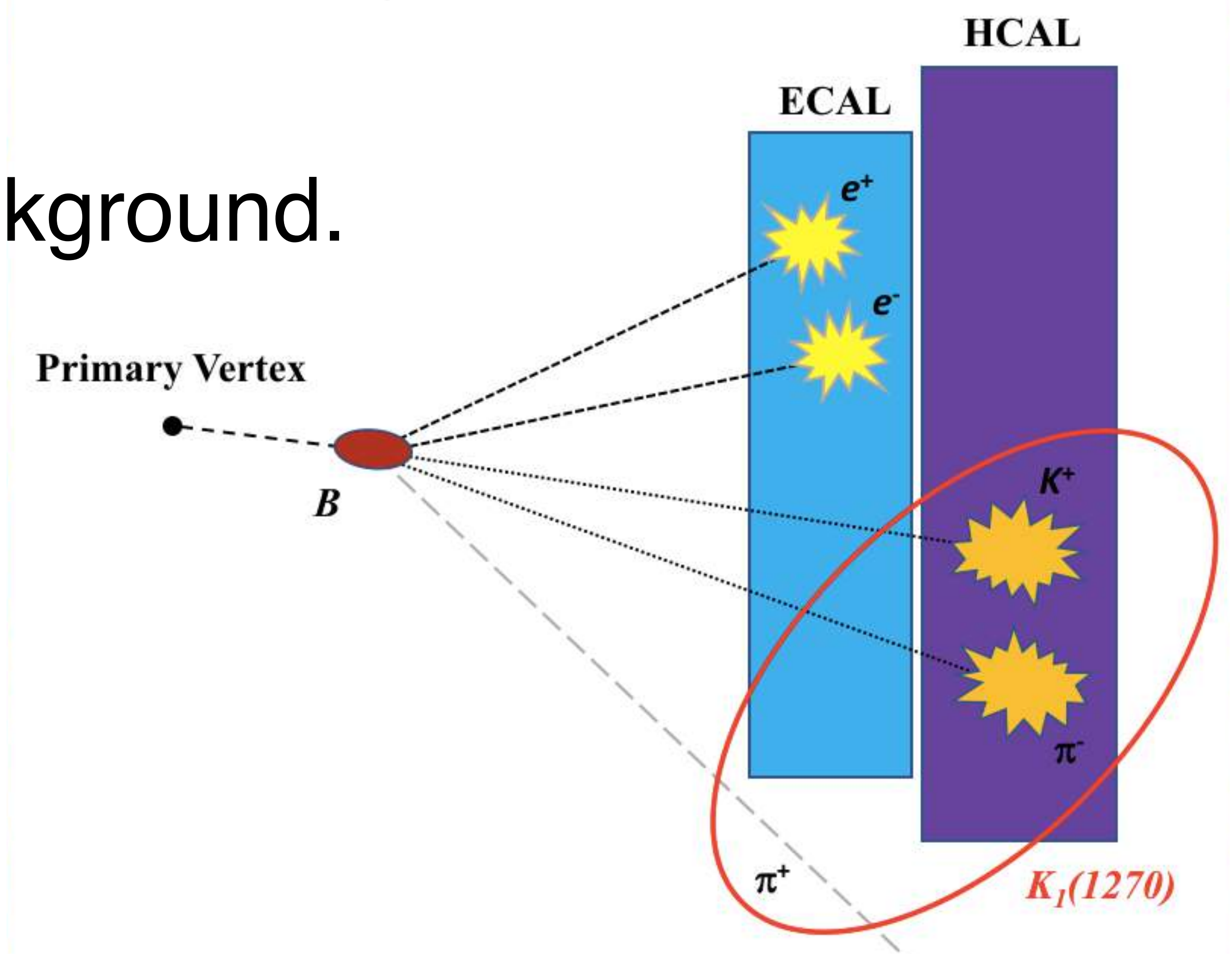


Bremsstrahlung issues

- Easier to confuse signal with ‘partially reconstructed’ background.



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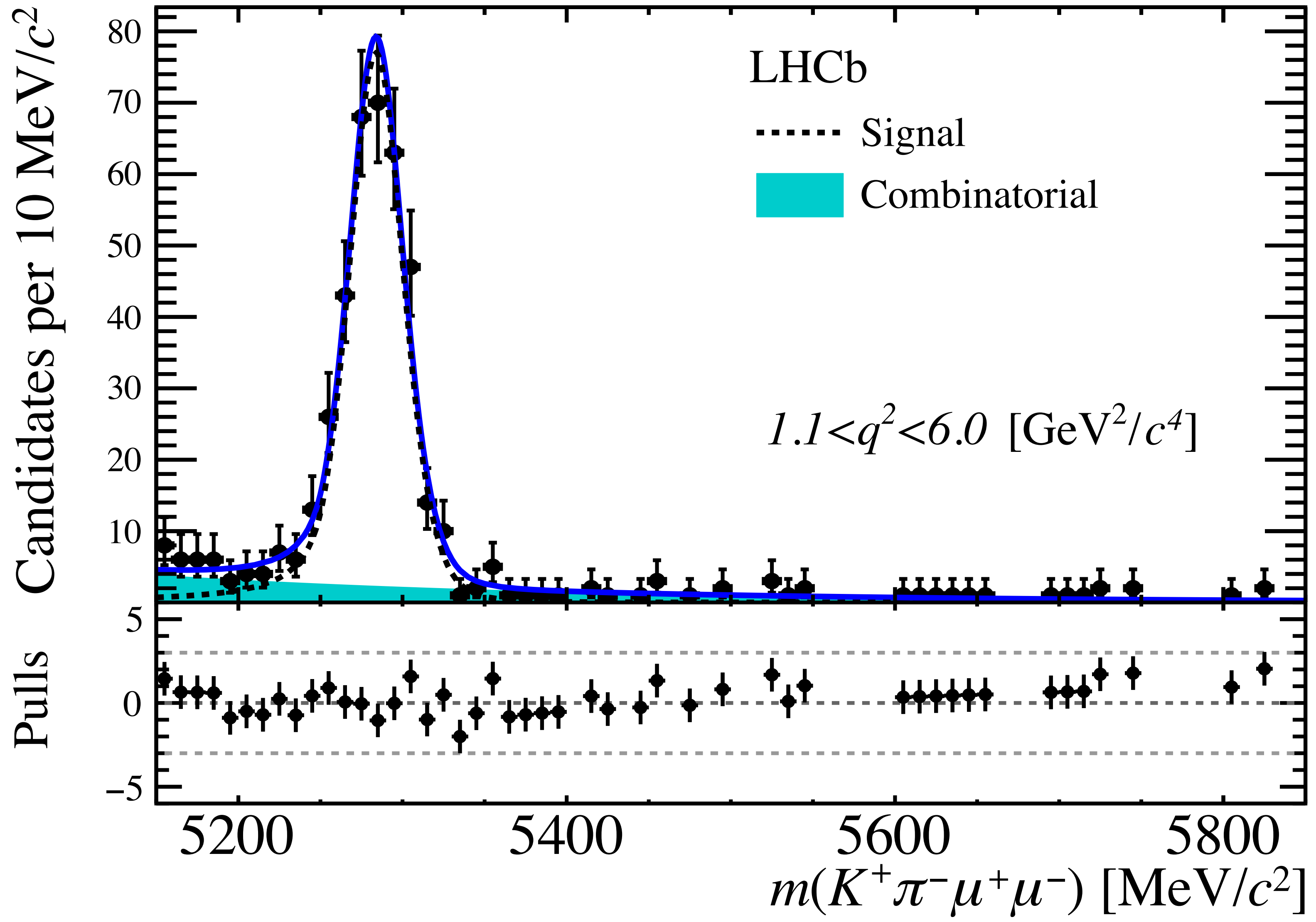
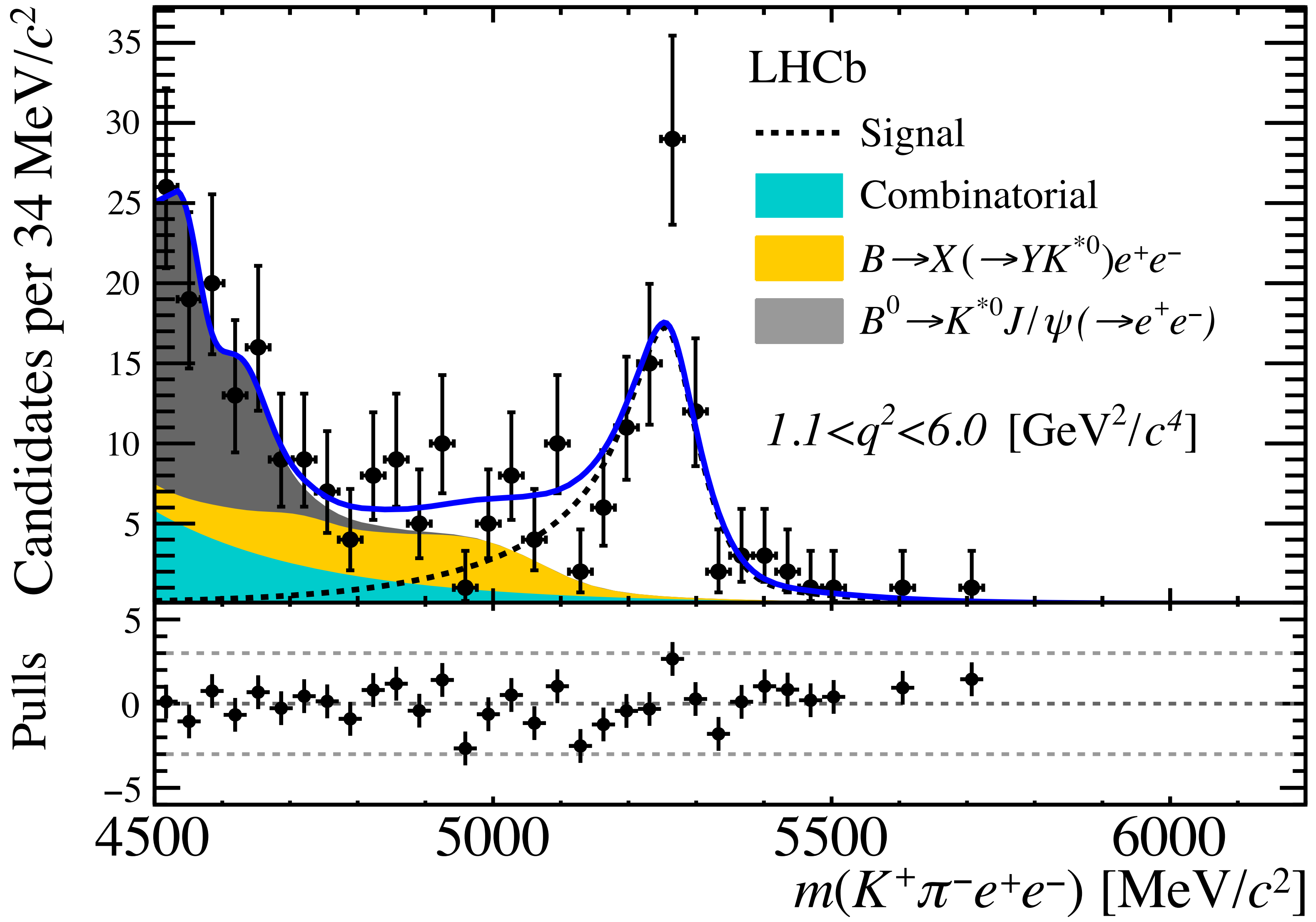
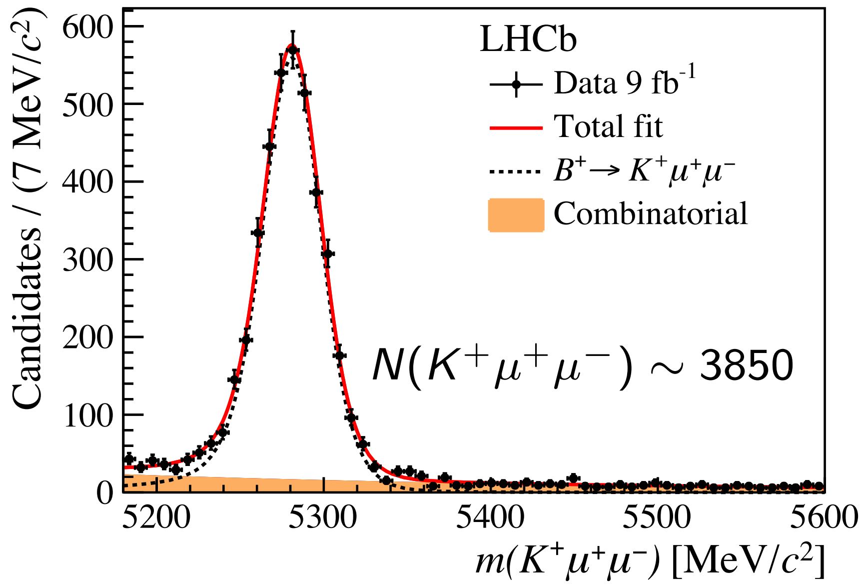




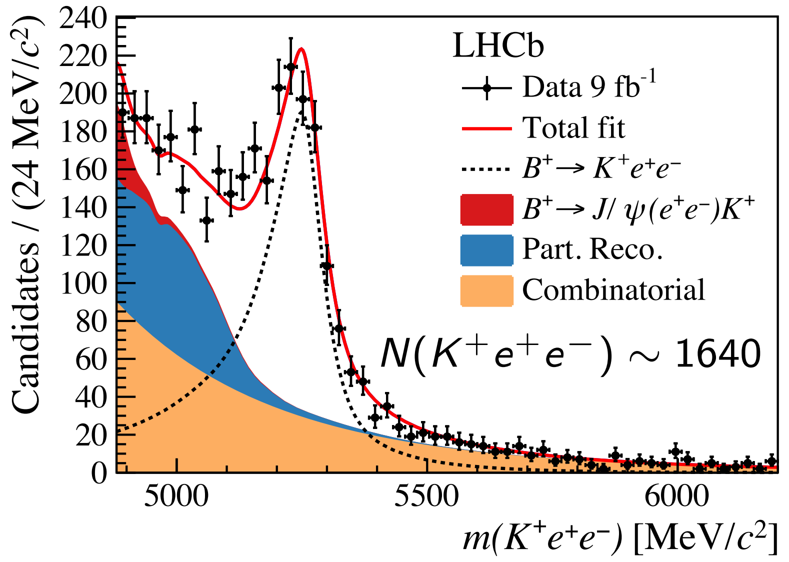
How to control this

$$R_K = \frac{\mathcal{B}(B^- \to K^-\mu^+\mu^-)}{\mathcal{B}(B^- \to K^-e^+e^-)} = \frac{N(B^- \to K^-\mu^+\mu^-)}{N(B^- \to K^-e^+e^-)}\,\frac{\epsilon_{e^+e^-}}{\epsilon_{\mu^+\mu^-}}$$

Muons



Electrons

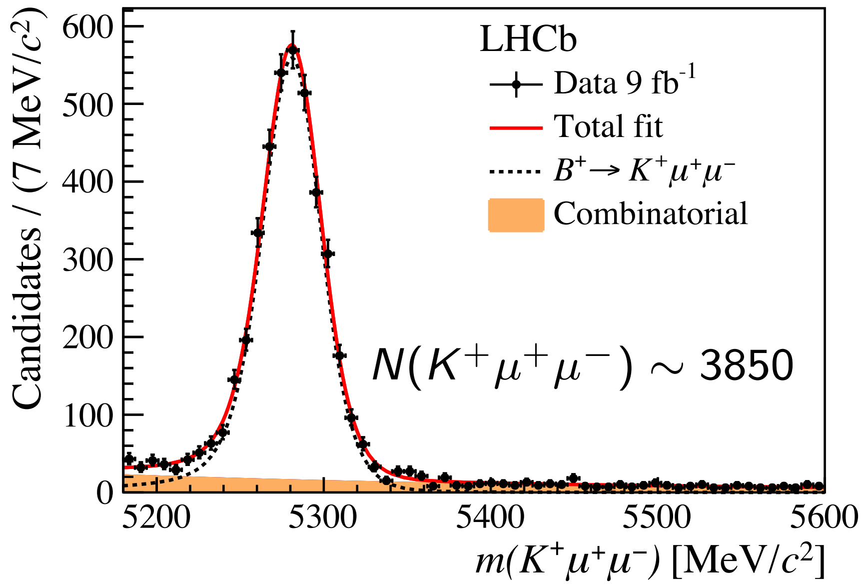


How to control this

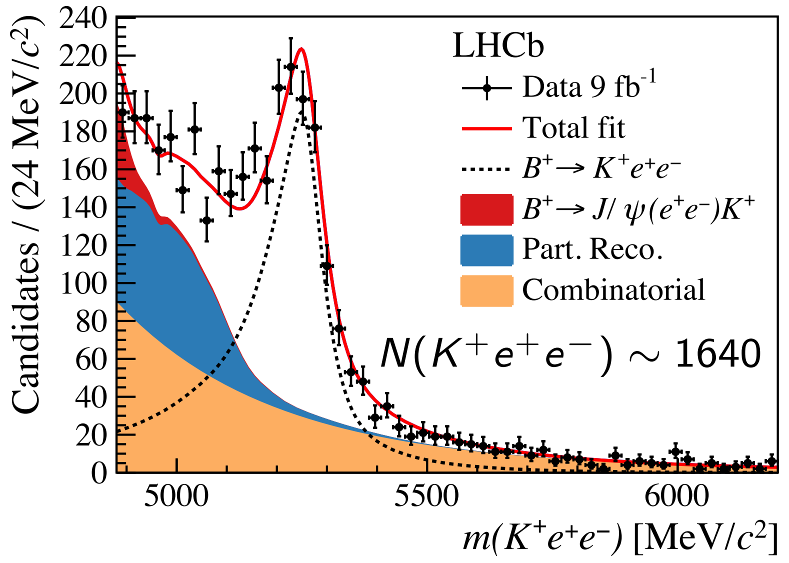
$$R_K = \frac{\mathcal{B}(B^- \to K^-\mu^+\mu^-)}{\mathcal{B}(B^- \to K^-e^+e^-)} = \frac{N(B^- \to K^-\mu^+\mu^-)}{N(B^- \to K^-e^+e^-)}\,\frac{\epsilon_{e^+e^-}}{\epsilon_{\mu^+\mu^-}}$$

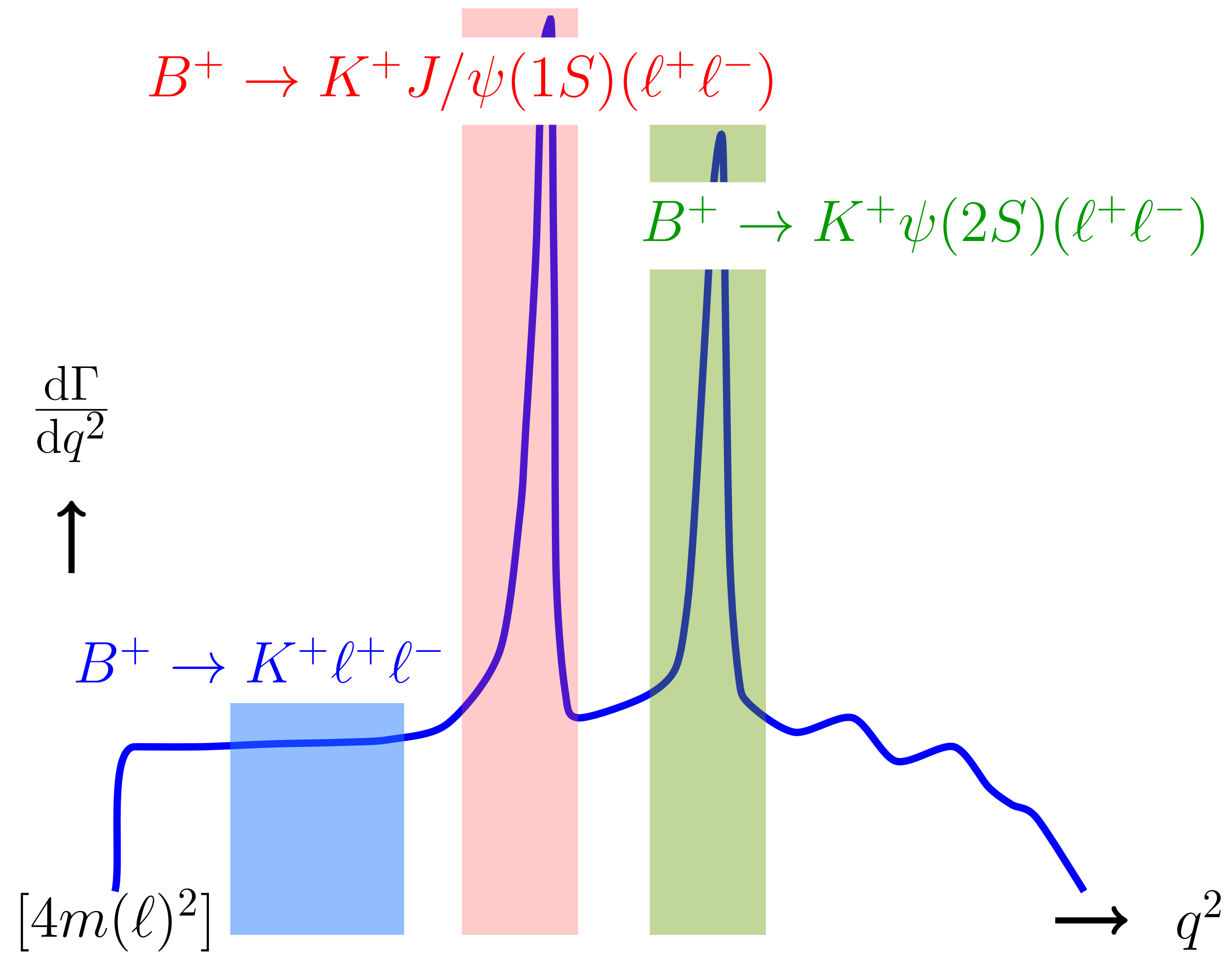
$$\frac{N(B^- \to K^-J/\psi(\mu^+\mu^-))}{N(B^- \to K^-J/\psi(e^+e^-))}\,\frac{\epsilon^{J/\psi}_{e^+e^-}}{\epsilon^{J/\psi}_{\mu^+\mu^-}}$$

Muons



Electrons

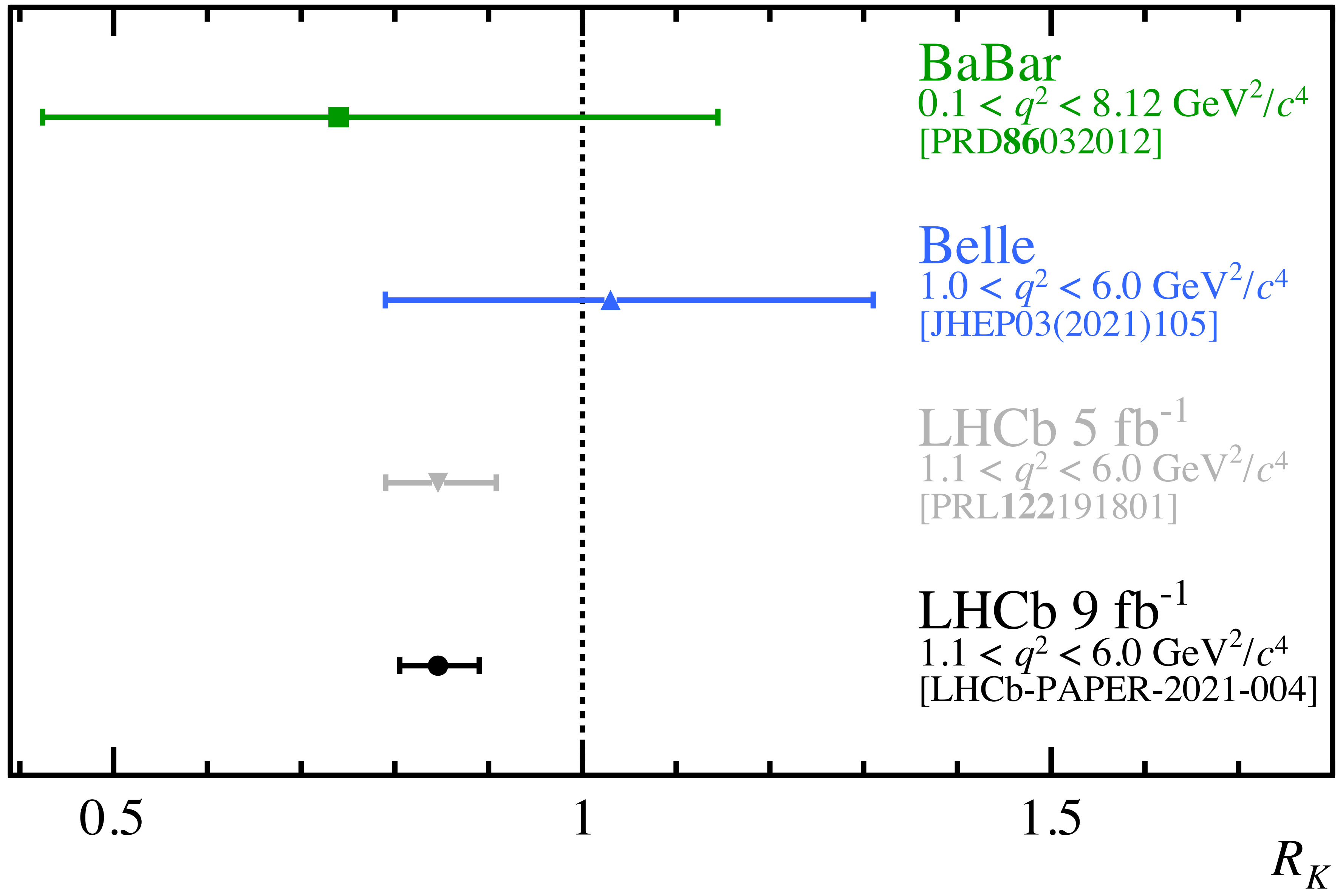




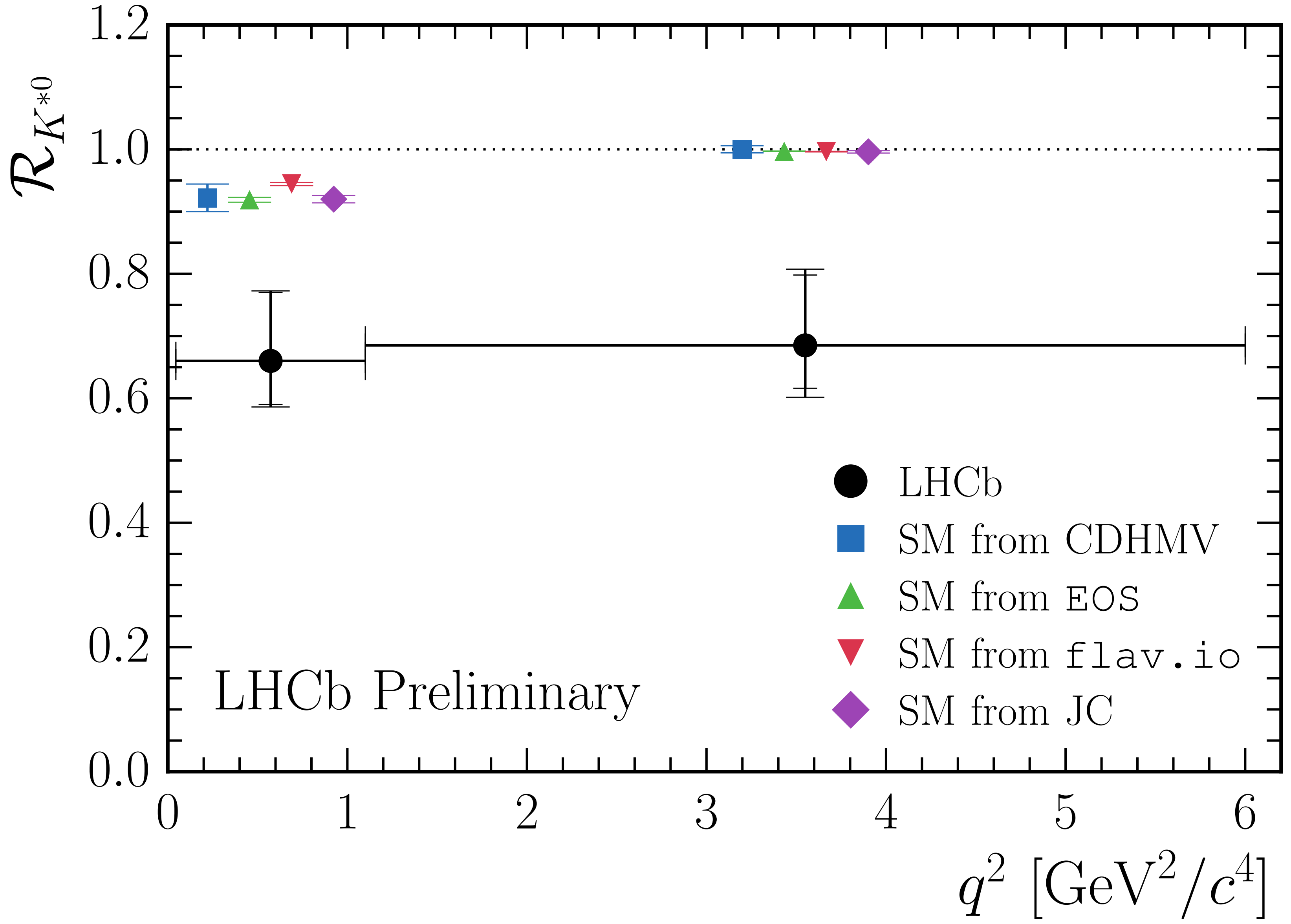
- Only the relative efficiency as a function of q² is needed.
- Stringent cross-check: $r_{J\psi} = \frac{N(B^- \to K^-J/\psi(\mu^+\mu^-))}{N(B^- \to K^-J/\psi(e^+e^-))}\,\frac{\epsilon^{J/\psi}_{e^+e^-}}{\epsilon^{J/\psi}_{\mu^+\mu^-}} = 0.981 \pm 0.020$

Latest results

- Recent update combines the full dataset collected so far by LHCb to measure R_K.
  - 3.1 standard deviations away from the SM prediction of unity.
- Also see deviations of around 2.2-2.4σ in the ratio R_{K^*} only using run 1 data so updates.



LHCb-PAPER-2017-013

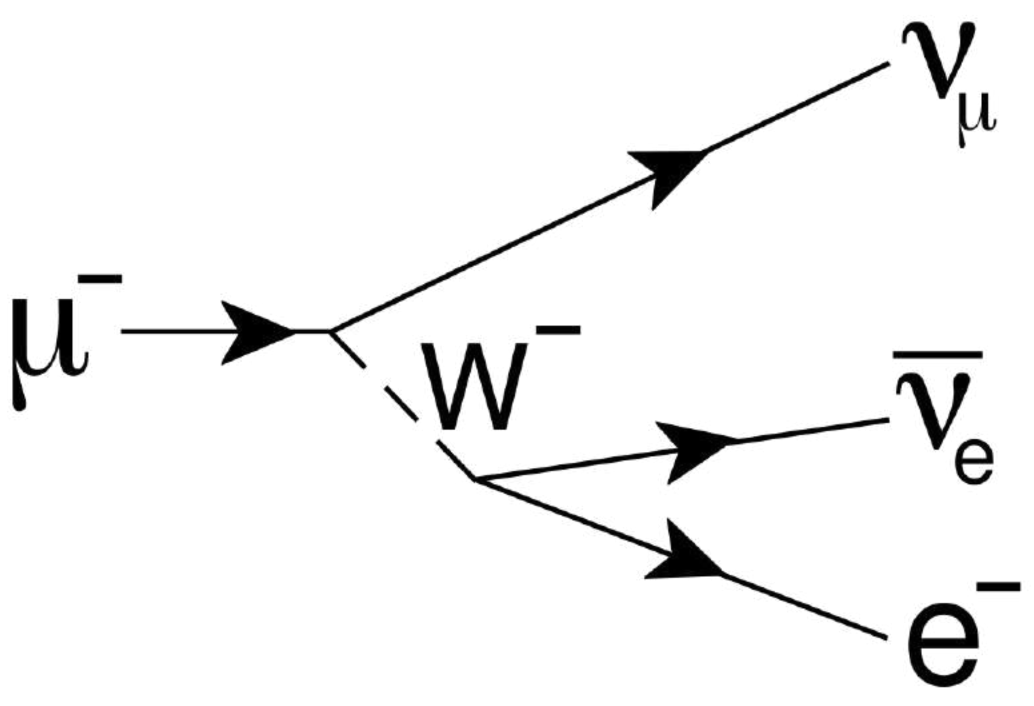


- Are these deviations consistent with the other anomalies and what is the combined significance?

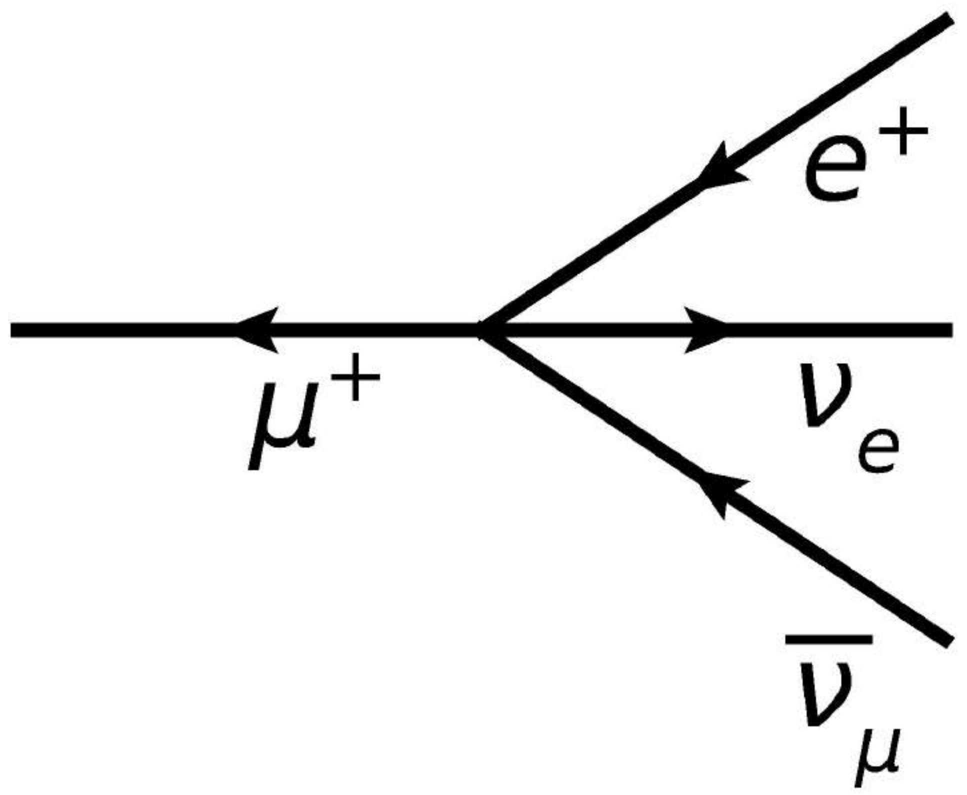
Effective field theories

- We have a general way to connect our observables together via Effective Field Theories (EFTs).
- The idea is a generalisation of Fermi's theory of weak decays:

Full theory



Effective (Fermi) theory



$$\mathcal{M} = \frac{g_L^2}{2}\bar{x}(k_3)\bar{\sigma}_\rho x(p)\frac{1}{q^2 - m_W^2}\bar{x}(k_1)\bar{\sigma}_\rho y(k_2)$$

$$\mathcal{M} \approx -\frac{g_L^2}{2m_W^2}[\bar{x}(k_3)\bar{\sigma}_\rho x(p)][\bar{x}(k_1)\bar{\sigma}_\rho y(k_2)]\left[1 + \mathcal{O}(q^2/m_W^2)\right]$$

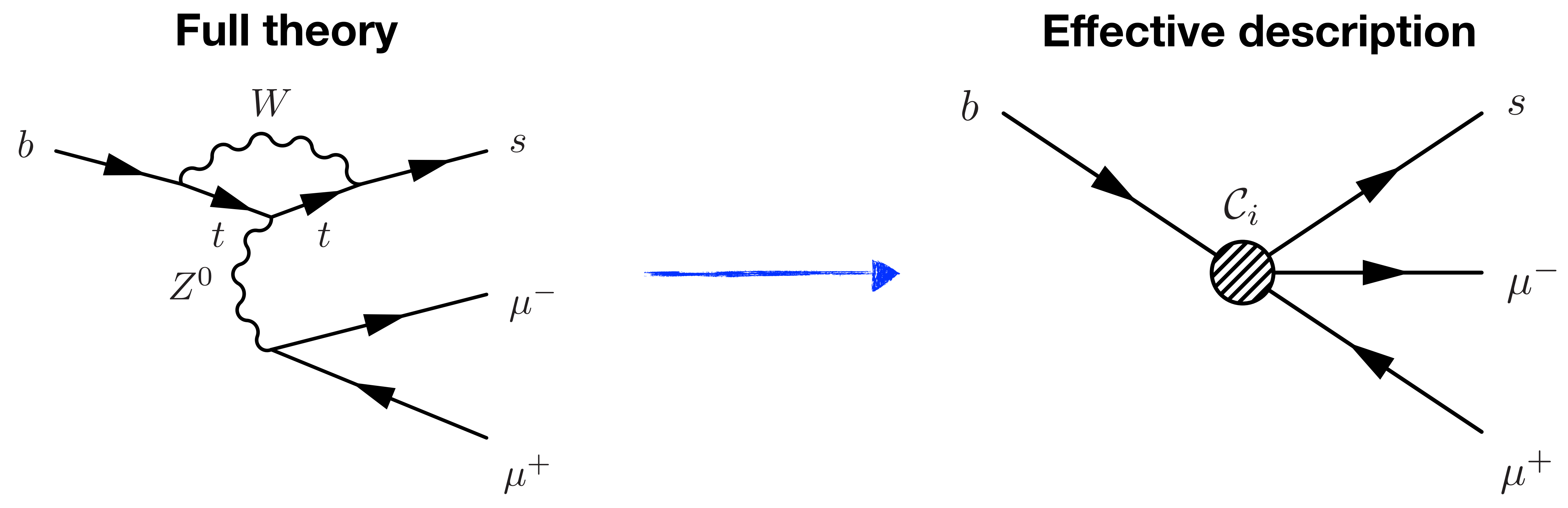
- This results in an effective hamiltonian, written as a combination of Wilson Coefficients and operators.

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\sum_i V_{CKM}^i C_i(\lambda)\mathcal{O}_i(\lambda)$$

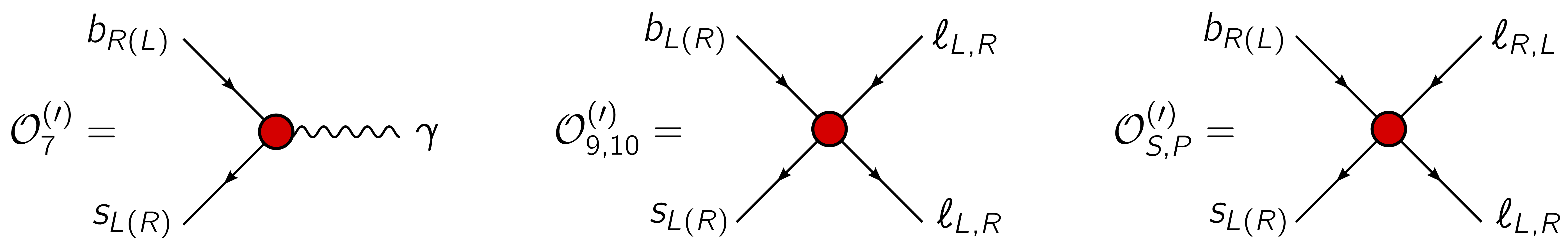
- Wilson coefficients (short-distance): evaluated in perturbation theory
- Local operators (long-distance): the corresponding form factor is computed with, e.g., lattice QCD

EFTs in heavy flavour physics

- The EFT we use in heavy flavour physics assumes that NP much heavier than the b mass scale.



- Familiar operators:



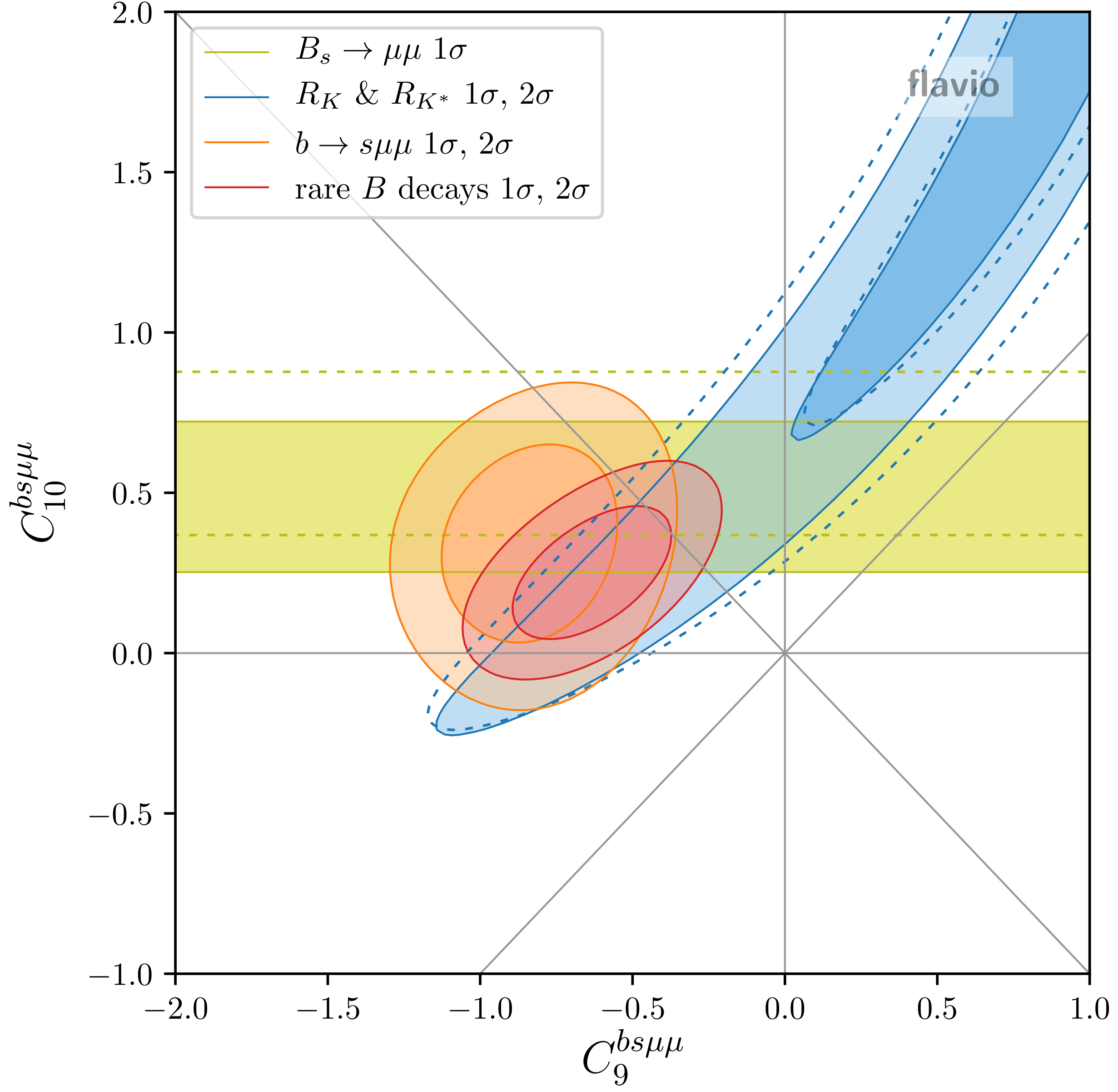
- O_7 gives a long distance contribution to b—>sll via the photon.
- $O_{9,10,S,P}$ can be different for different lepton flavours.

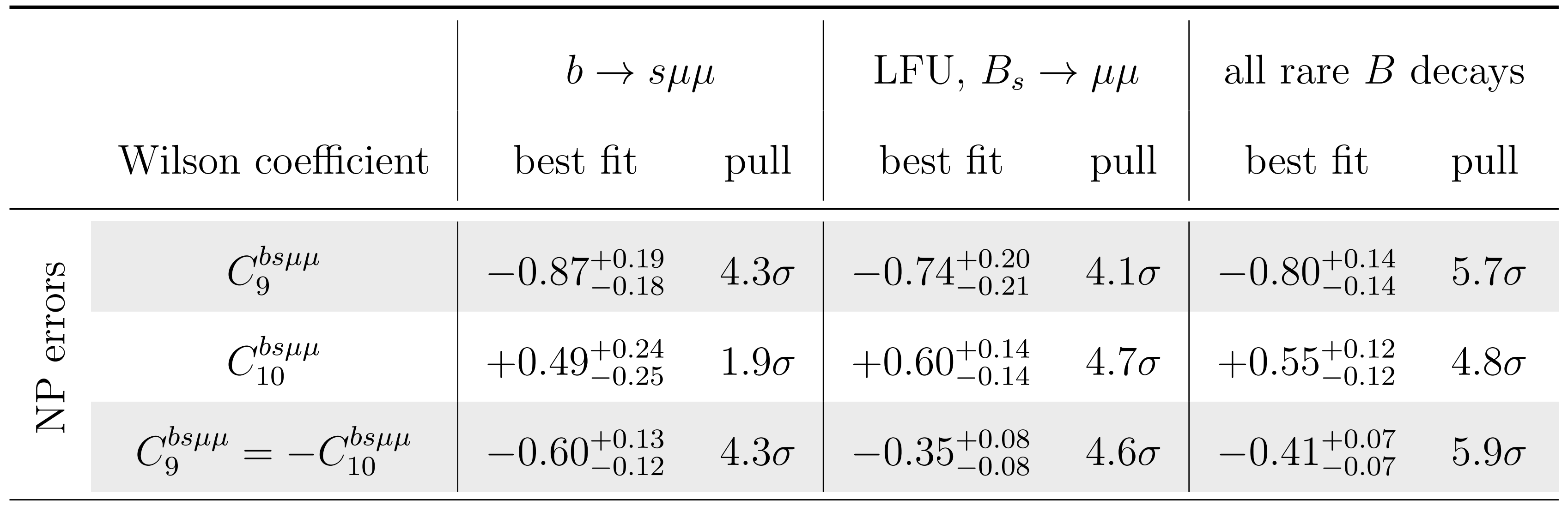
- Common to define C_L=C_9-C_{10}, left handed coupling to leptons: Dominant SM semileptonic contribution.
- Primed coefficients are right-handed coupling to the quarks: Suppressed by m_s/m_b in the SM (null tests).

Global $b \to s\ell^+\ell^-$ fits

- Global b—>sll fits show that all discrepancies are in consistent within the EFT approach, with significances easily exceeding the conventional 5σ threshold.

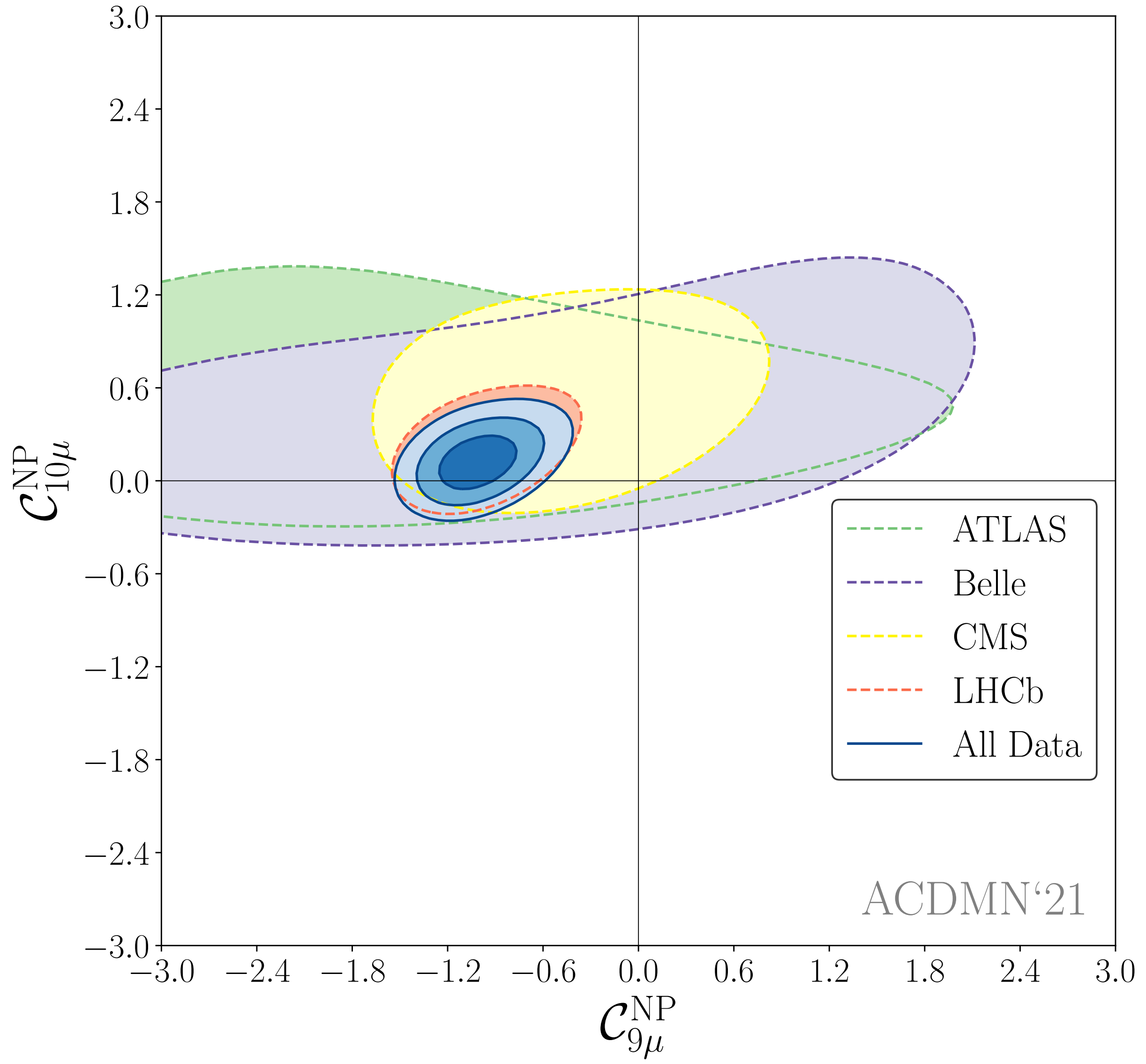
W. Altmannshofer, P. Stangl

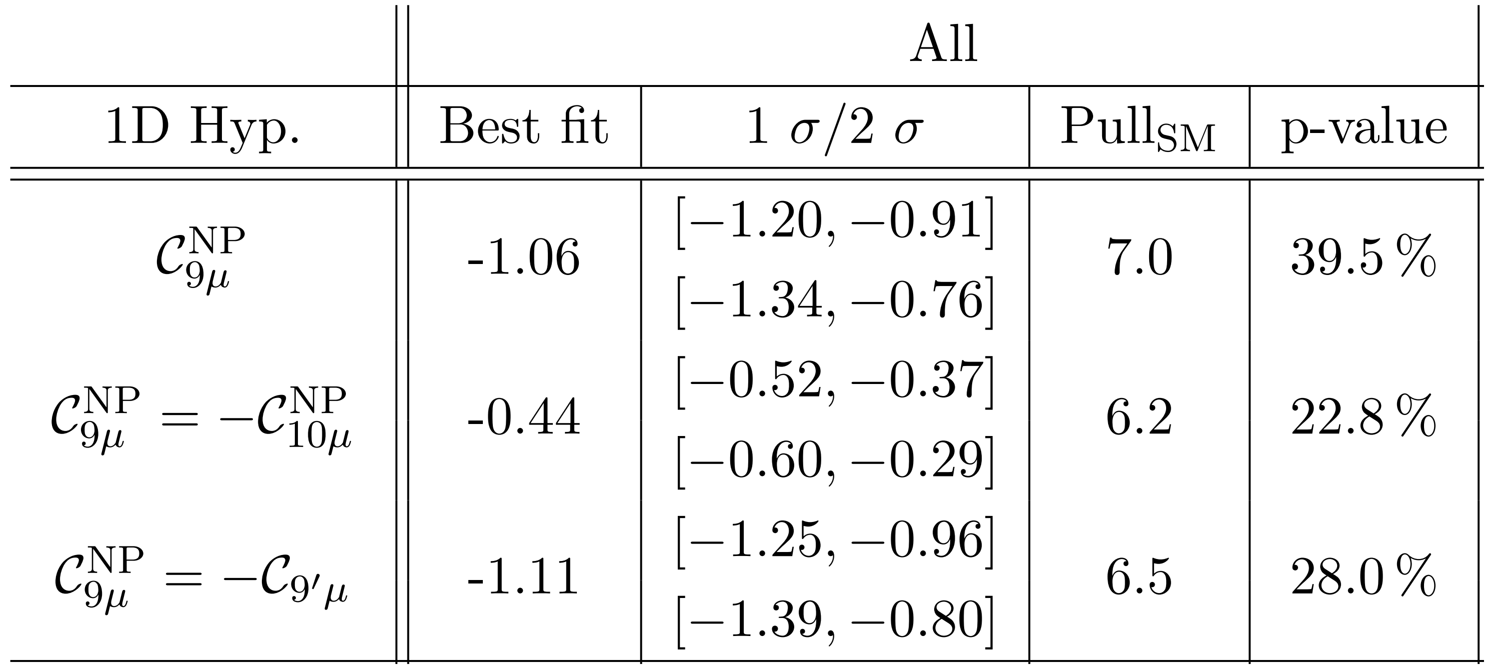




		$b \to s\mu\mu$		LFU, $B_s \to \mu\mu$		all rare B decays	
	Wilson coefficient	best fit	pull	best fit	pull	best fit	pull
NP errors	$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
	$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

M. Algueró et al

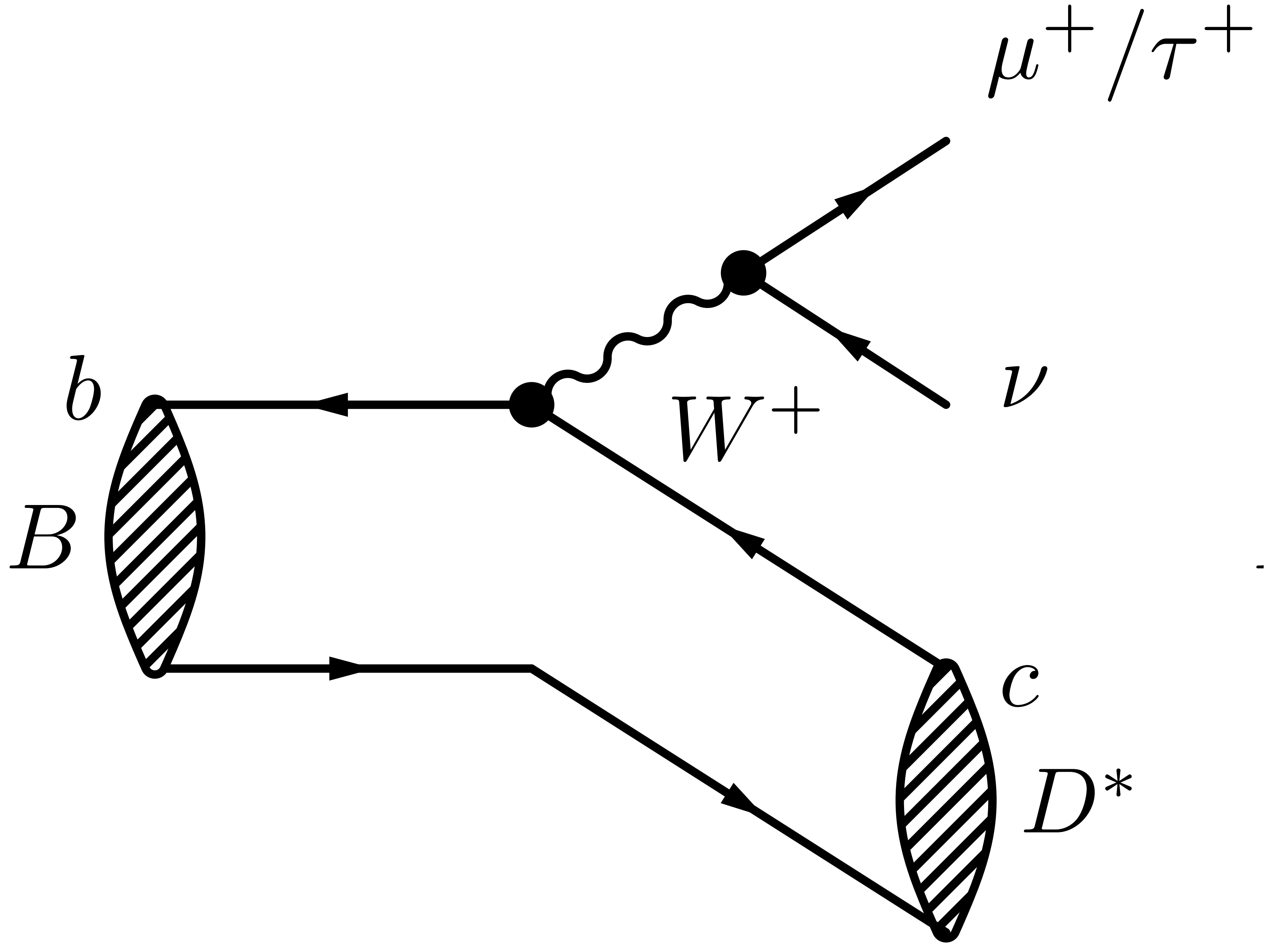




	All			
1D Hyp.	Best fit	1 σ/2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.06	$[-1.20,-0.91]$ $[-1.34,-0.76]$	7.0	39.5 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.44	$[-0.52,-0.37]$ $[-0.60,-0.29]$	6.2	22.8 %
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	-1.11	$[-1.25,-0.96]$ $[-1.39,-0.80]$	6.5	28.0 %

- Of course some measurements rely on hadronic uncertainties - most conservative approach possible results in significance of around 4σ. D. Lancierini, G. Isidori, PO, N. Serra

Tree-level $b \to c\ell\nu$ transitions



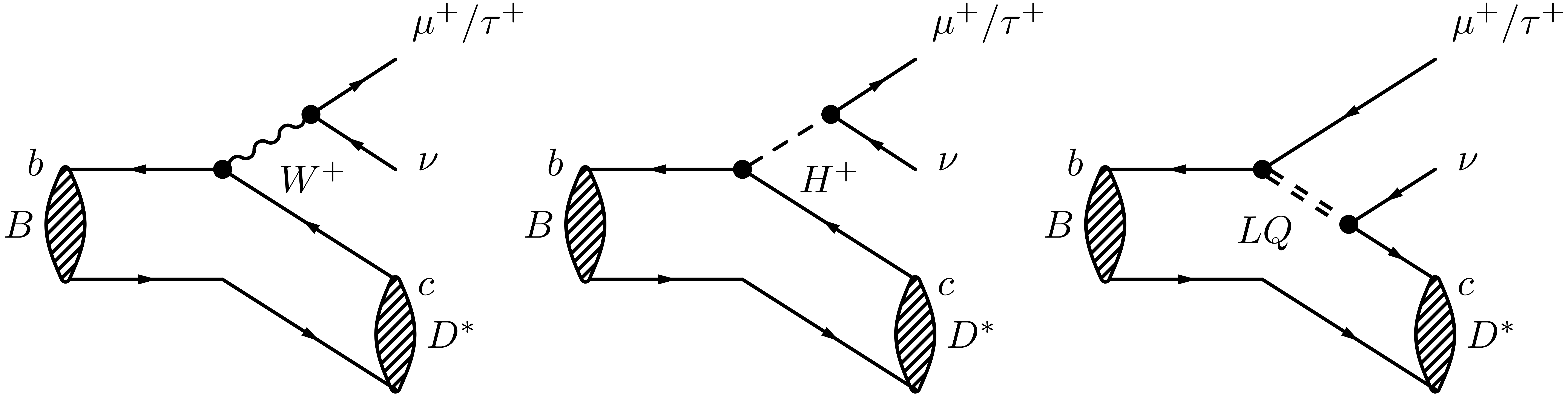
R(D*)

- Large rate of charged current decays allow for measurement in semi-tauonic decays.

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

- Form ratio of decays with tau and lighter generations.
- Cancel QCD/expt uncertainties (90% of R(D*), 50% of R(D)).

- R(D*) sensitive to any physics model favouring 3rd generation leptons (e.g. charged Higgs).



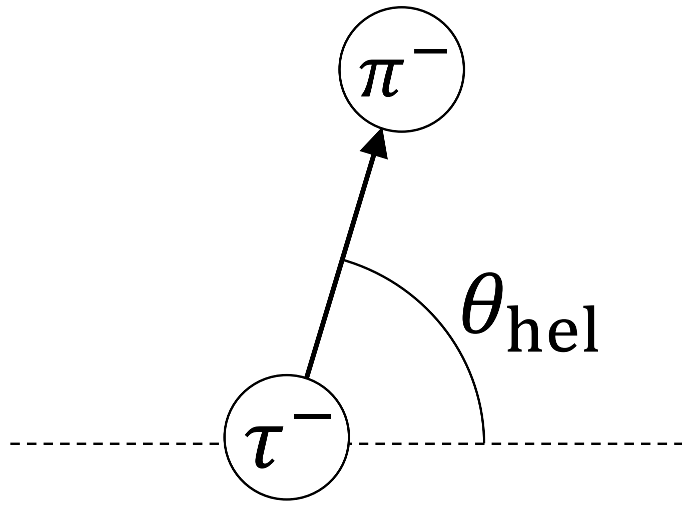
Who has made measurements

- Three experiments have made measurements

	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \rightarrow B\bar{B}$	$\Upsilon(4S) \rightarrow B\bar{B}$	$pp \rightarrow gg \rightarrow b\bar{b}$
Publications	Phys.Rev.Lett 109, 101802 (2012) Phys. Rev. D 88, 072012 (2013)	Phys.Rev.D 92, 072014 (2015) Phys. Rev. D 94, 072007 (2016) Phys. Rev. D 97, 012004 (2018)	Phys.Rev.Lett.115, 111803 (2015) Phys. Rev. Lett. 120, 171802 (2018)

* during run 1 of the LHC

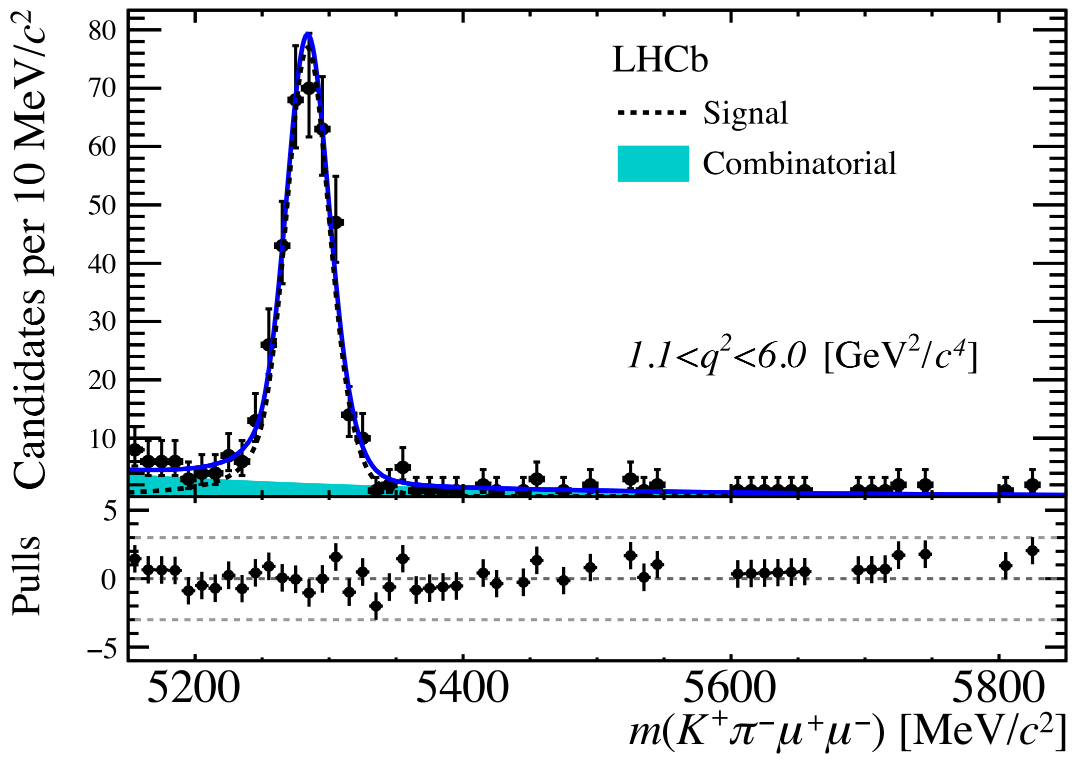
Tau decays

$\tau \to \mu\nu\nu$	$\tau \to 3\pi\nu$	$\tau \to \pi\nu$
Large statistics	More kinematic information	Good polarimeter
Efficiency largely cancels with muonic mode $B \to D^*(\tau \to \mu\nu\nu)\nu$ vs $B \to D^*\mu\nu$	Precise tau flight information	
Tau decay well understood	No background from muonic modes	Tau decay well understood

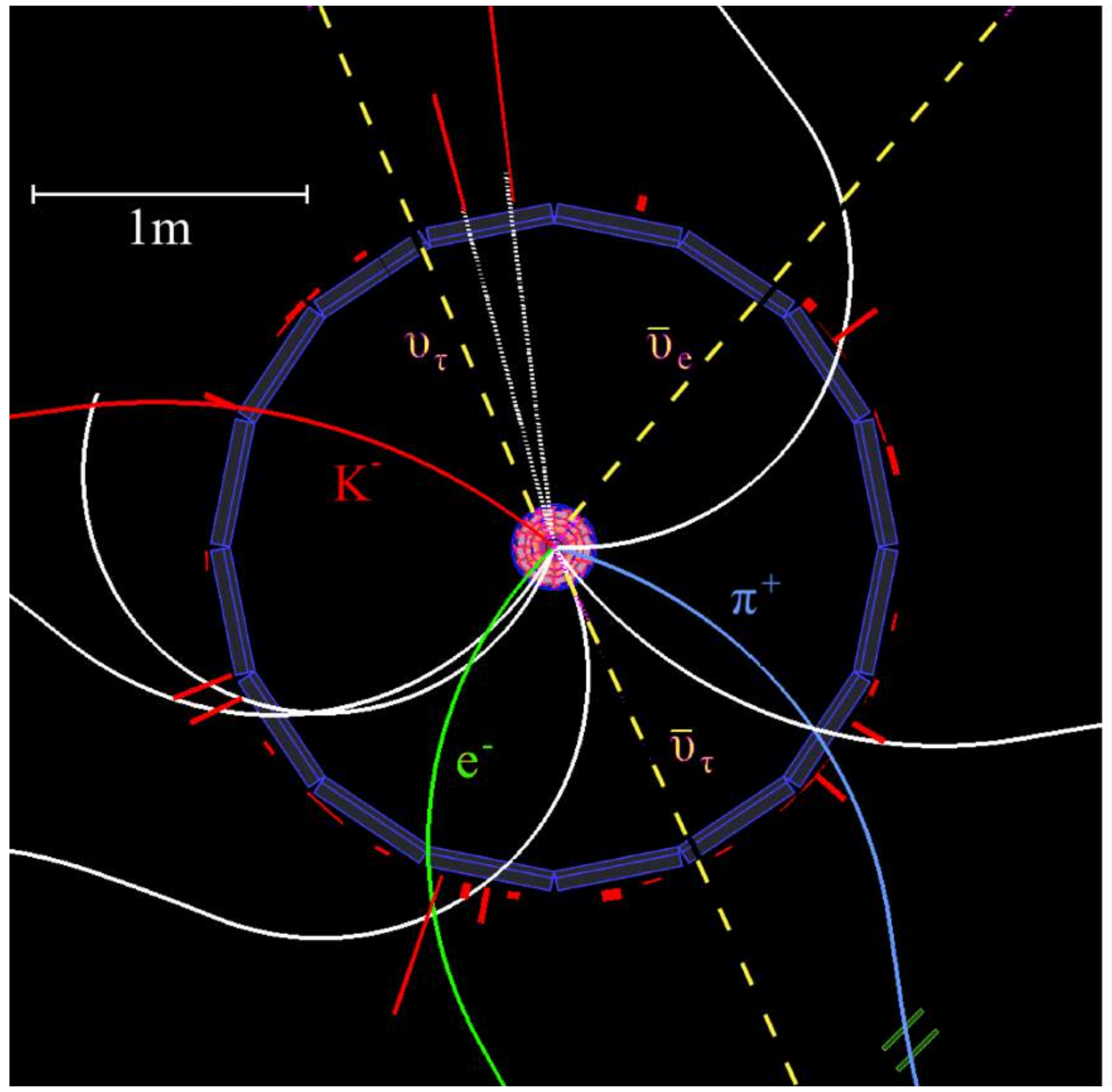
I will start with the measurements using $\tau \to \mu\nu\nu$

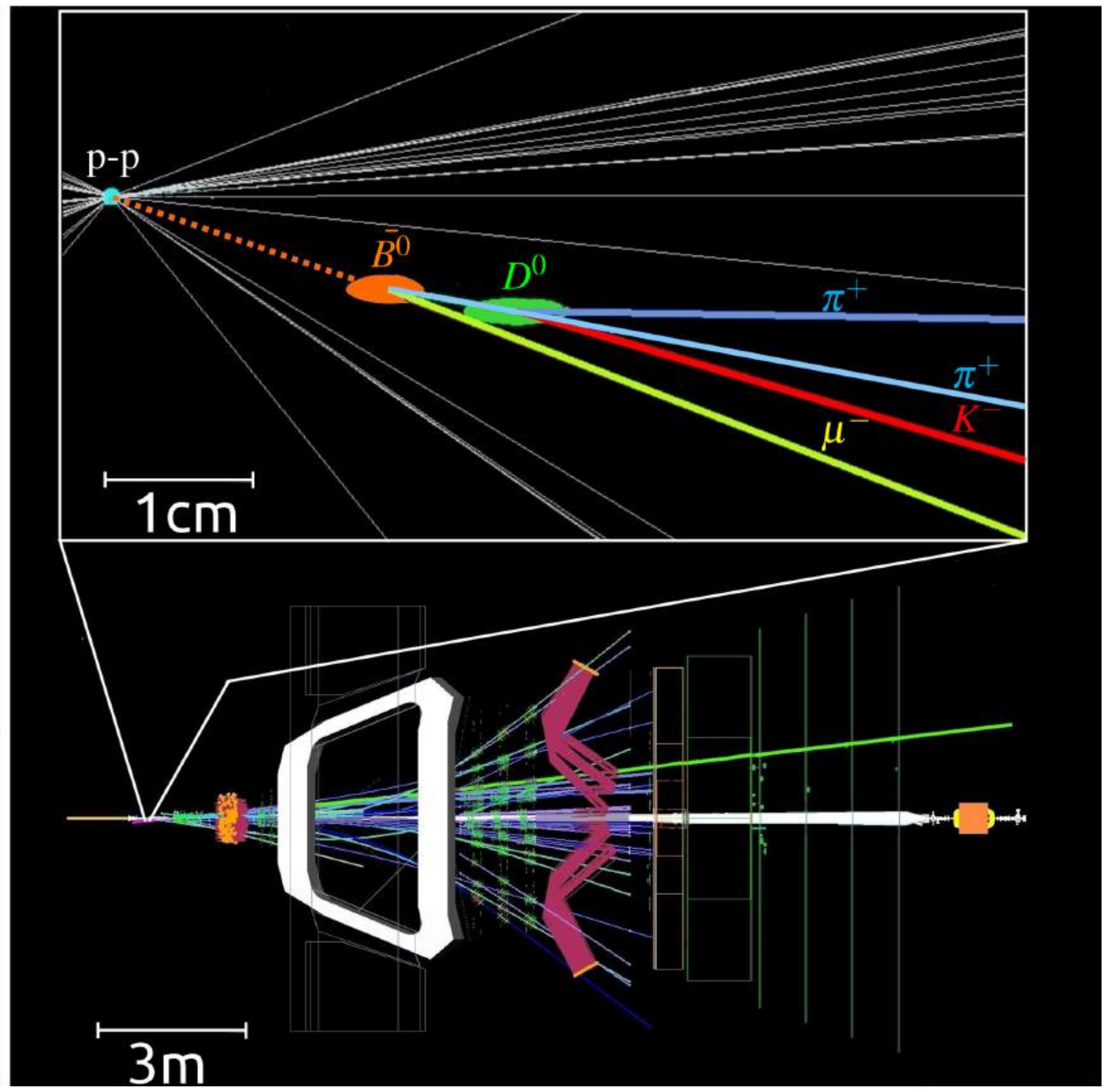
The problem with neutrinos

- At least two neutrinos in the final state (three if using $\tau \to \mu\nu\nu$).
  - No sharp peak to fit in any distribution:



- Difficult to reconstruct B rest frame (used to discriminate signal and backgrounds).



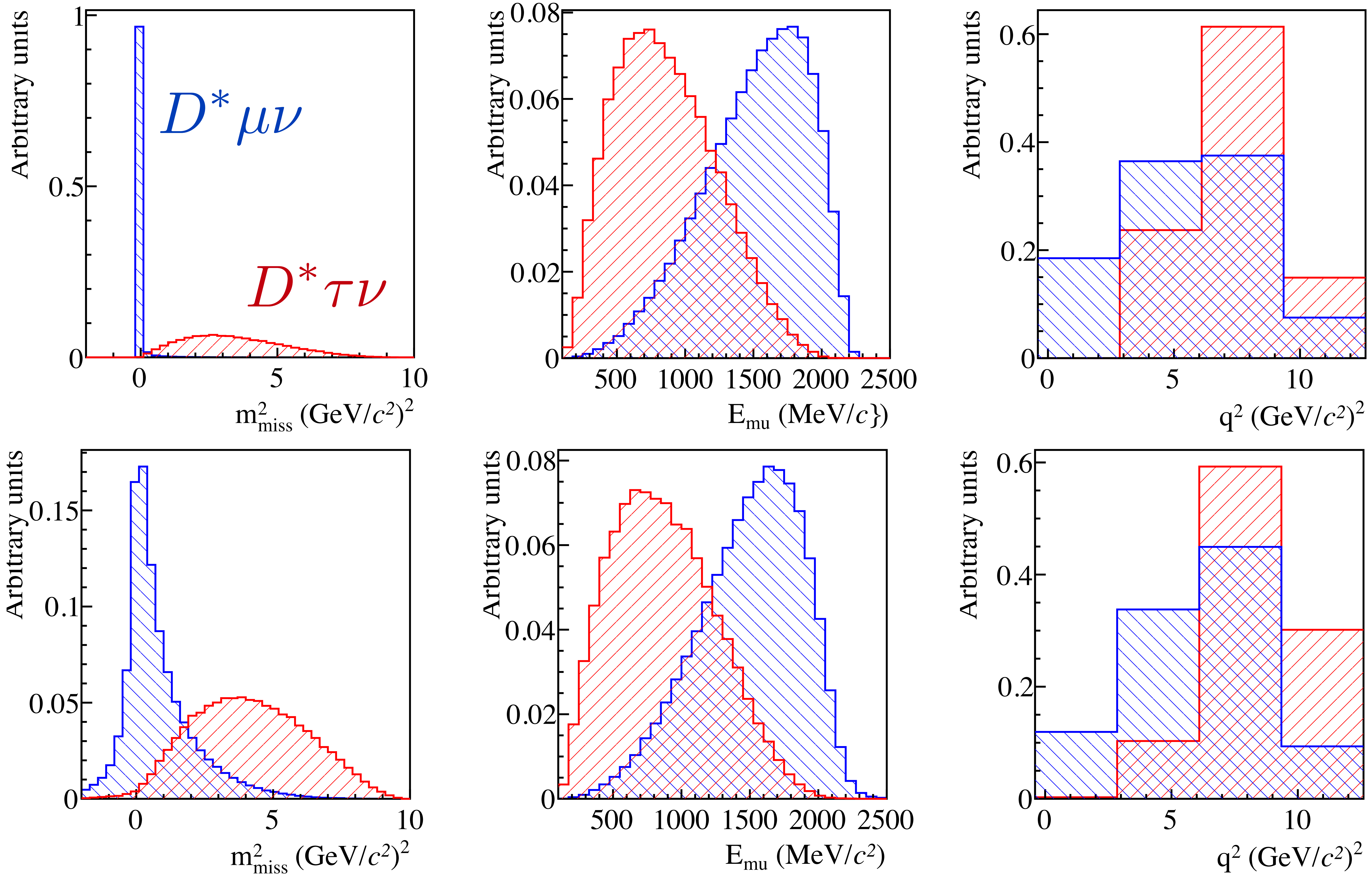


Nature volume 546, pages 227–233

Things don’t get much worse

Perfect resolution

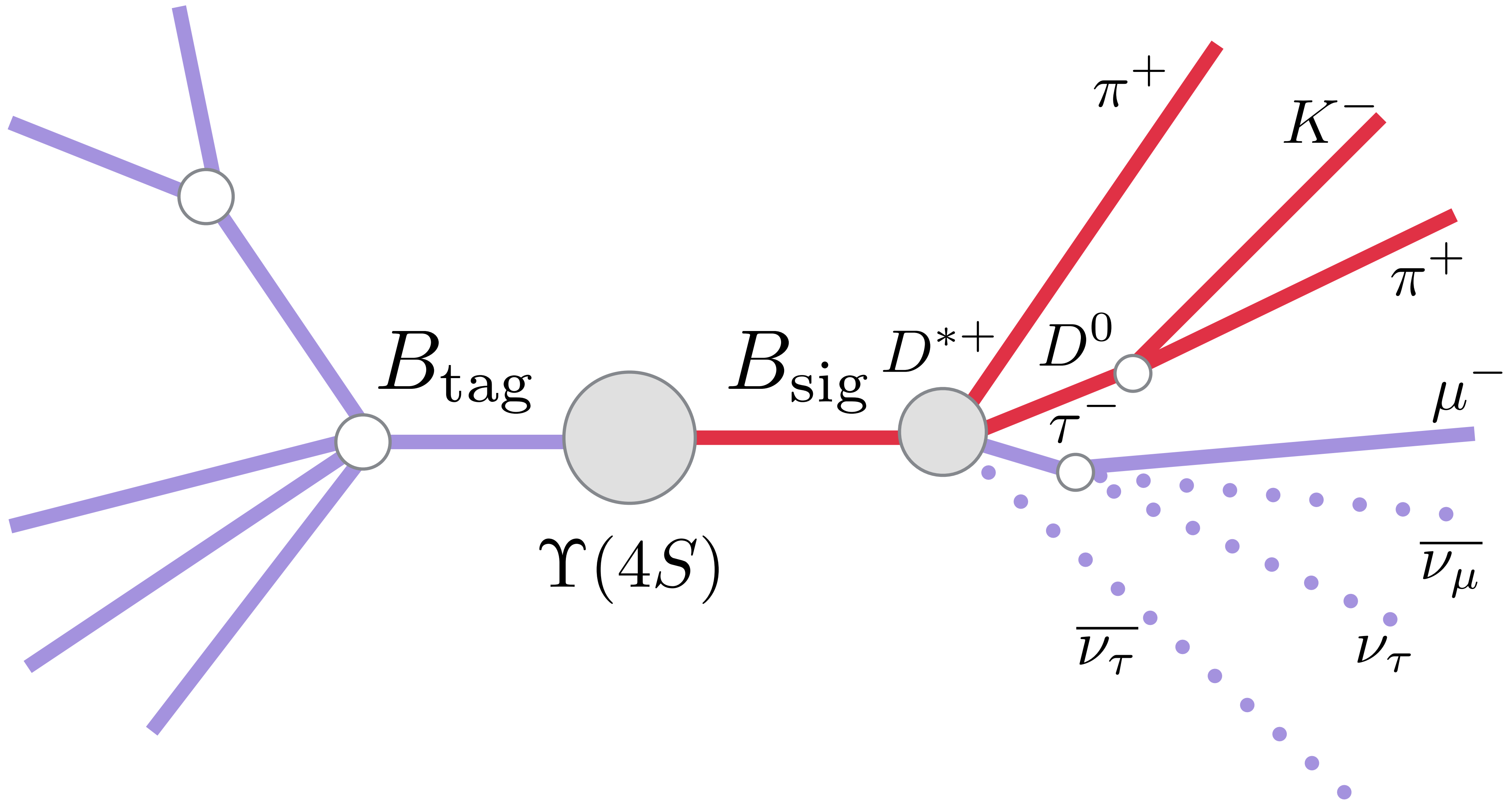
LHCb resolution



In the end $B \to D^{(*)}\mu\nu$ is not such a problem.

Reconstruction at the B-factories

- At B-factories, gain a lot information using a ‘tagging’ technique.



- Cleanest is to fully reconstruct hadronic decays: ε ~ 0.1%.
  - Over 2000 final states are reconstructed.
- Can also use semileptonic decays: ε ~ 0.2%.
  - Better efficiency but information is lost.

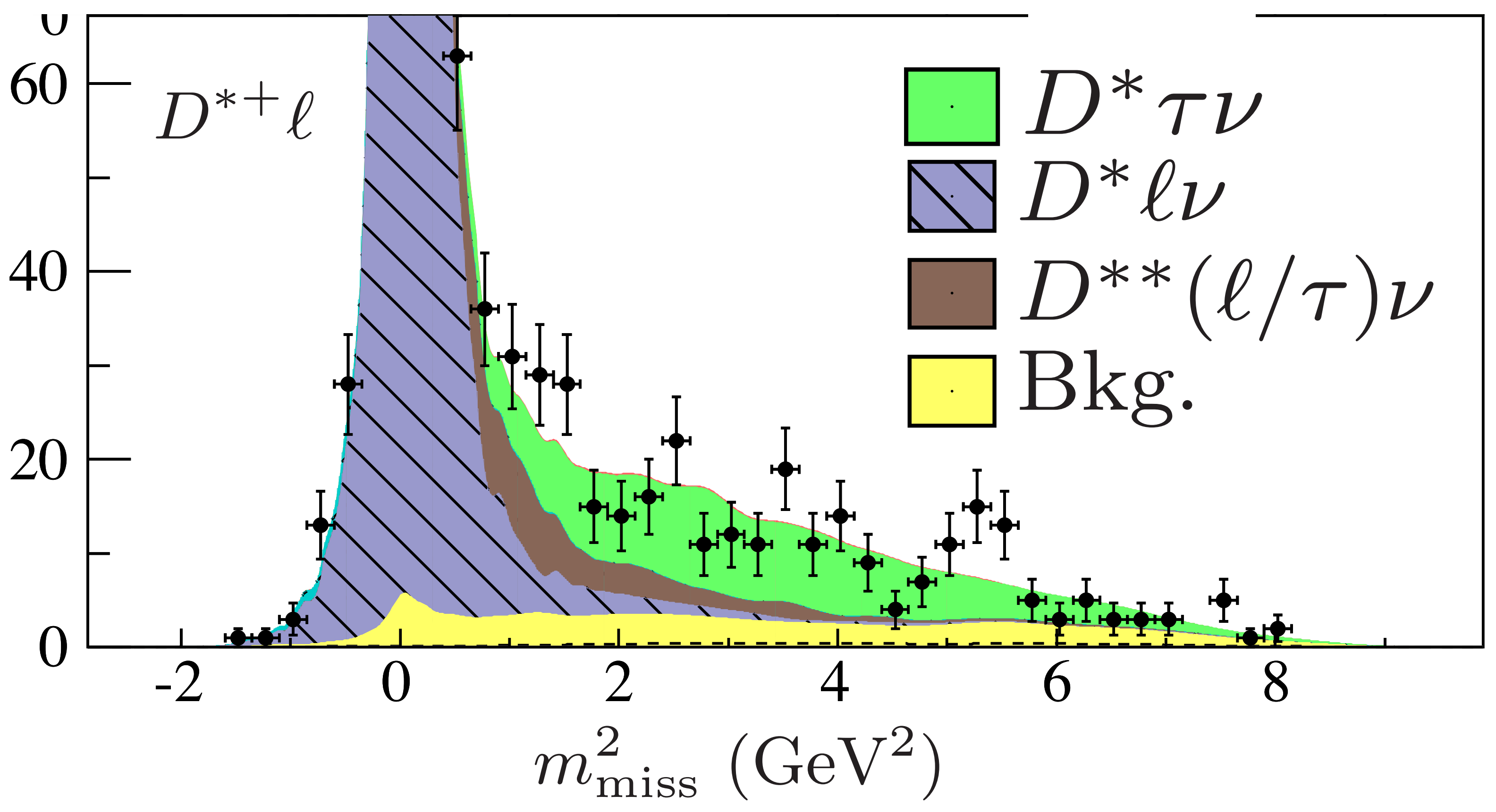
Belle II’s new algorithm improves things by a factor over a factor 2.

Signal fits

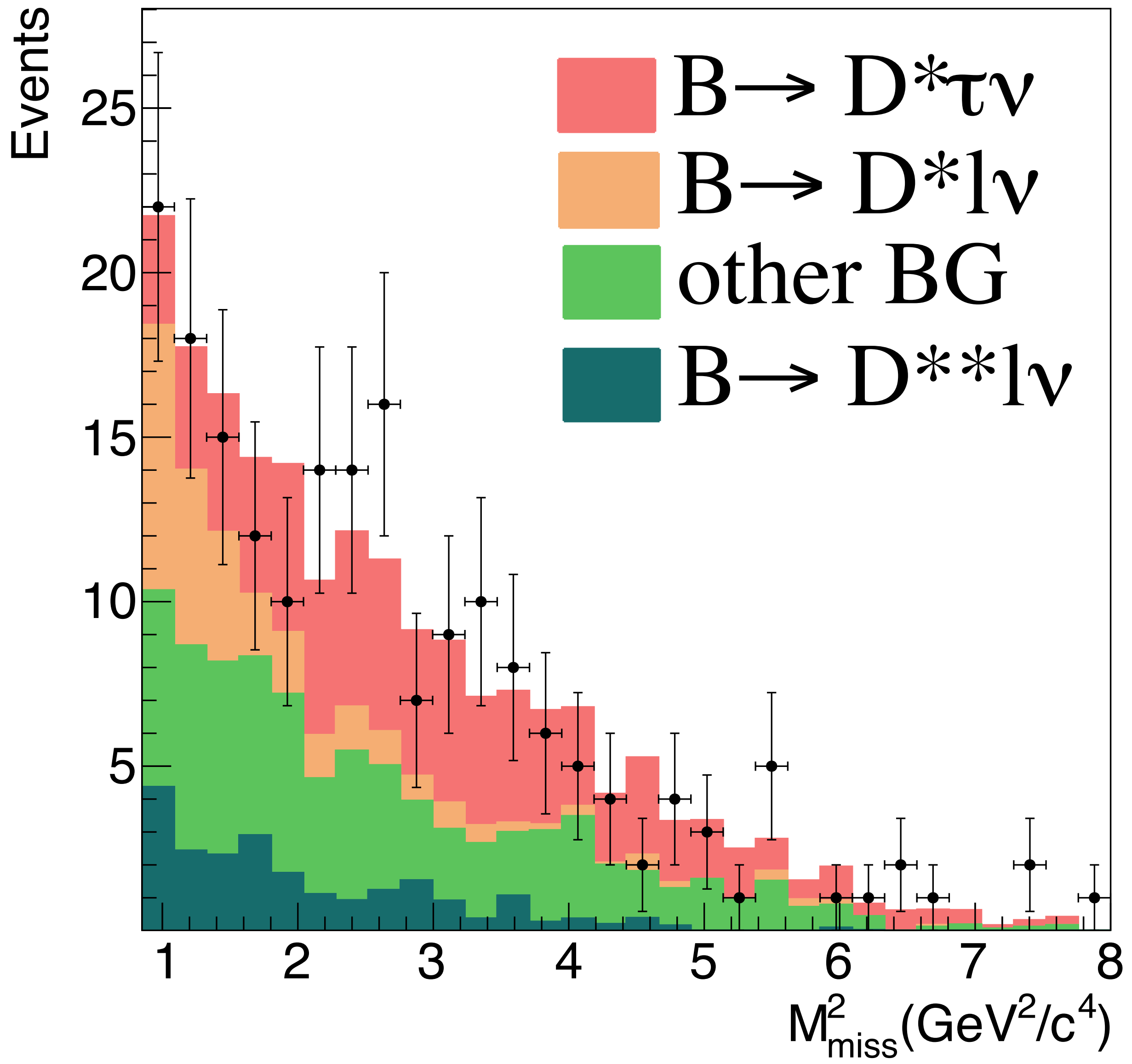
- Three main backgrounds:

$$B \to D^* \ell \nu$$
$$B \to D^{**} \ell \nu$$
$$B \to D^* D X$$

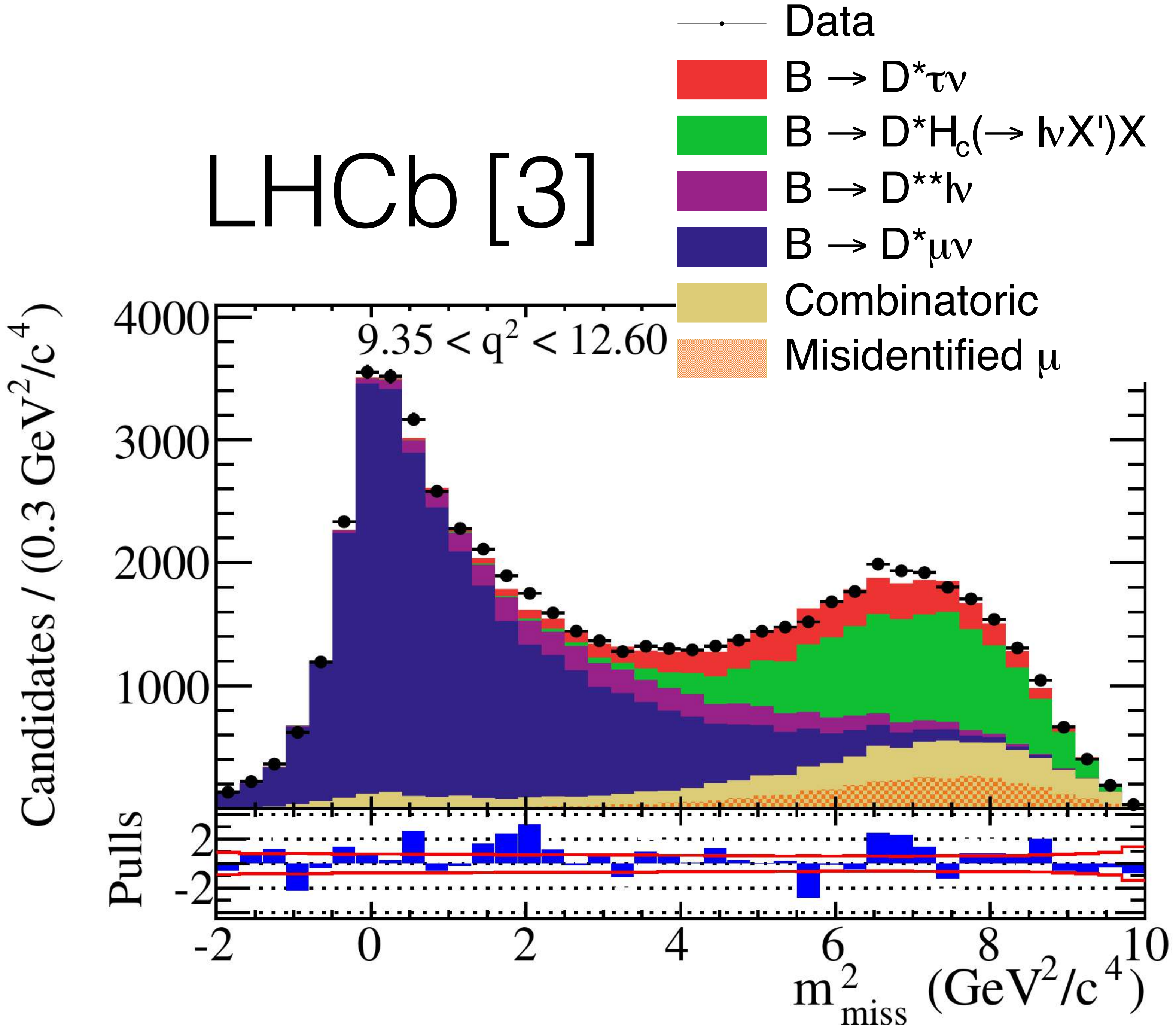
BaBar [1]



Belle [2]



LHCb [3]



- Fit variables which discriminate between muon and tauonic mode.

- LHCb fit is 3D also to lepton energy and q^2.

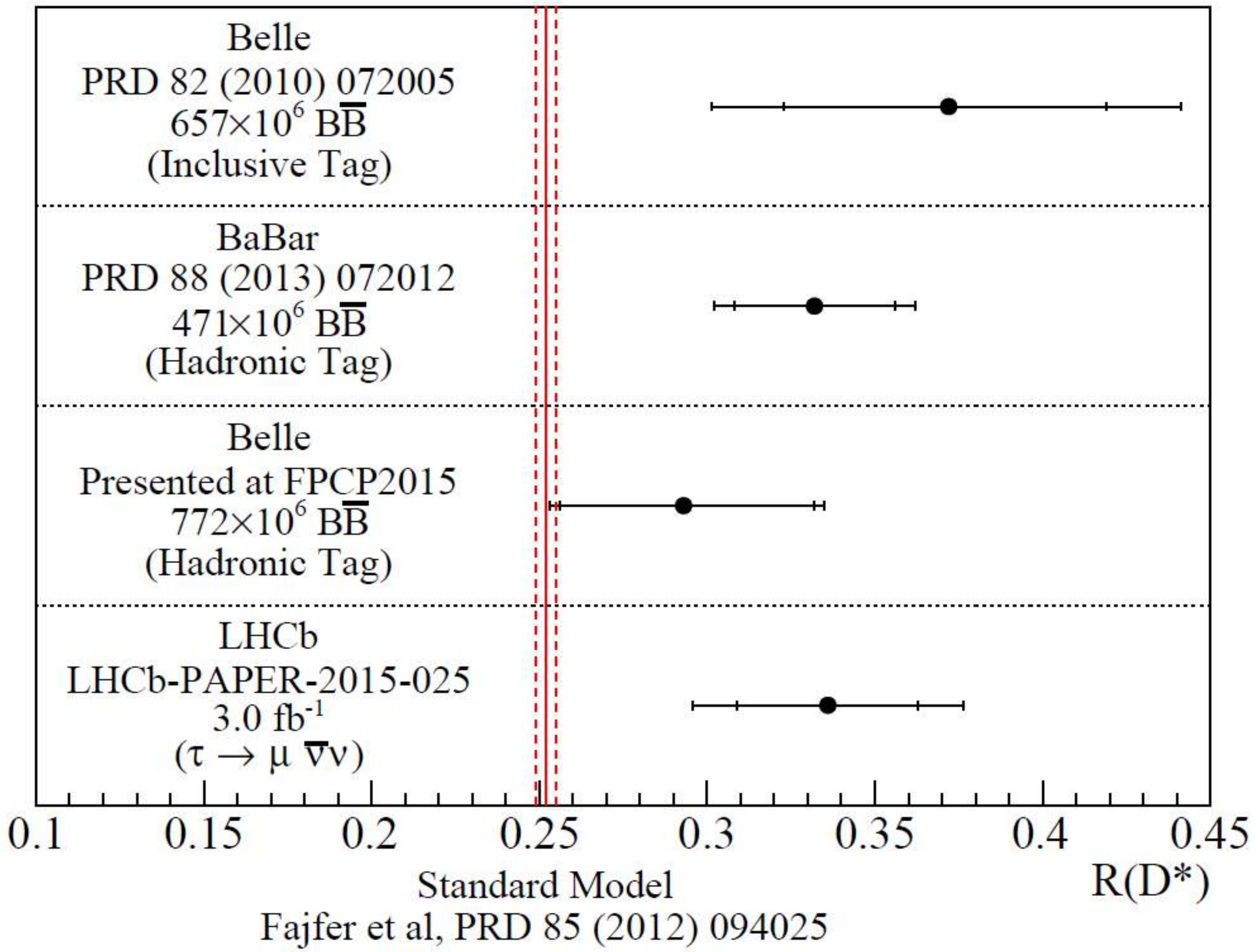
[1] Phys. Rev. D 88, 072012 (2013)

[2] Phys.Rev.D 92, 072014 (2015)

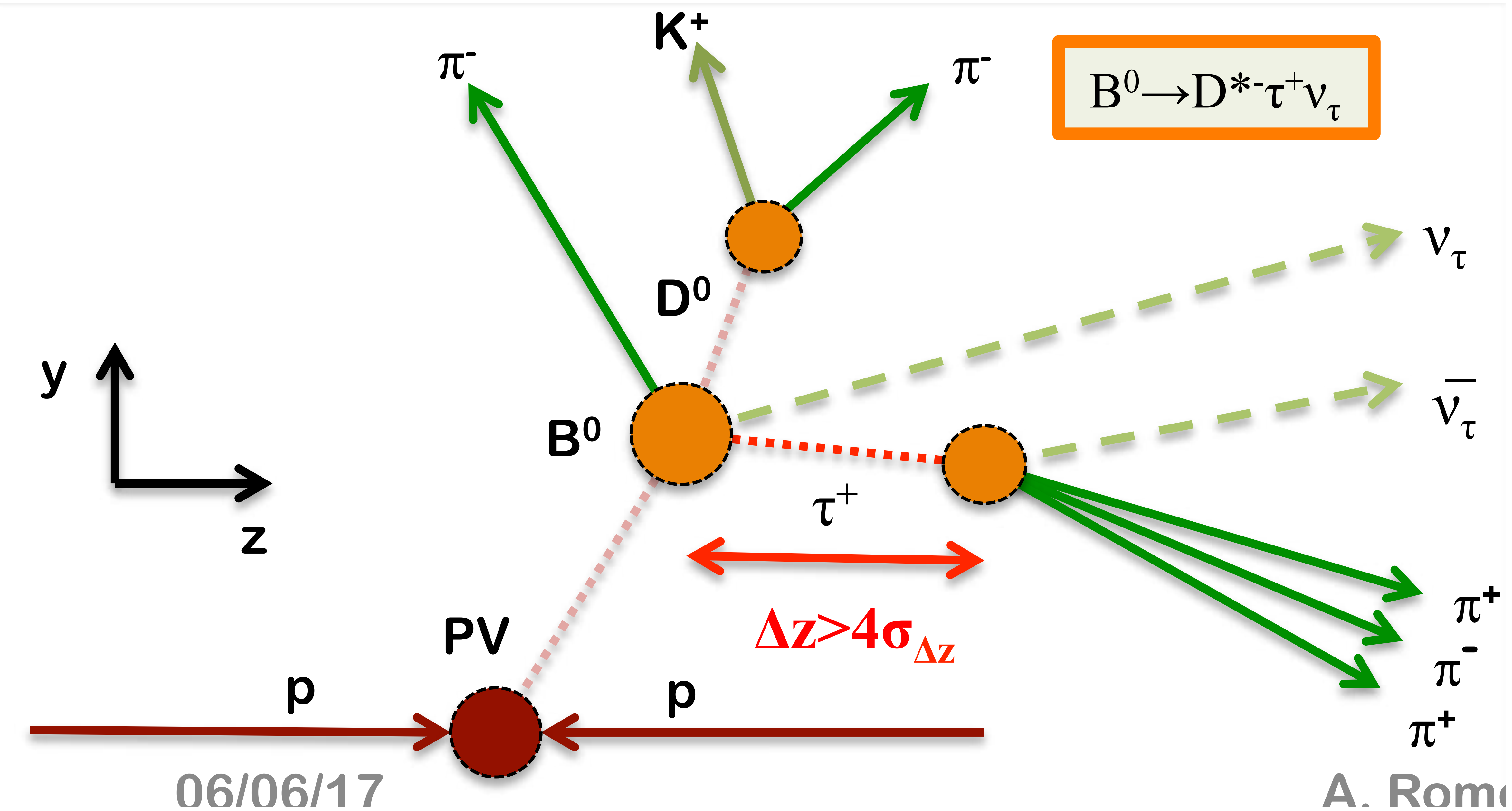
[3] Phys.Rev.Lett.115, 111803 (2015)

Hints of an excess?

- All experiments see an excess in the number of $B \to D^* \tau \nu$ candidates.



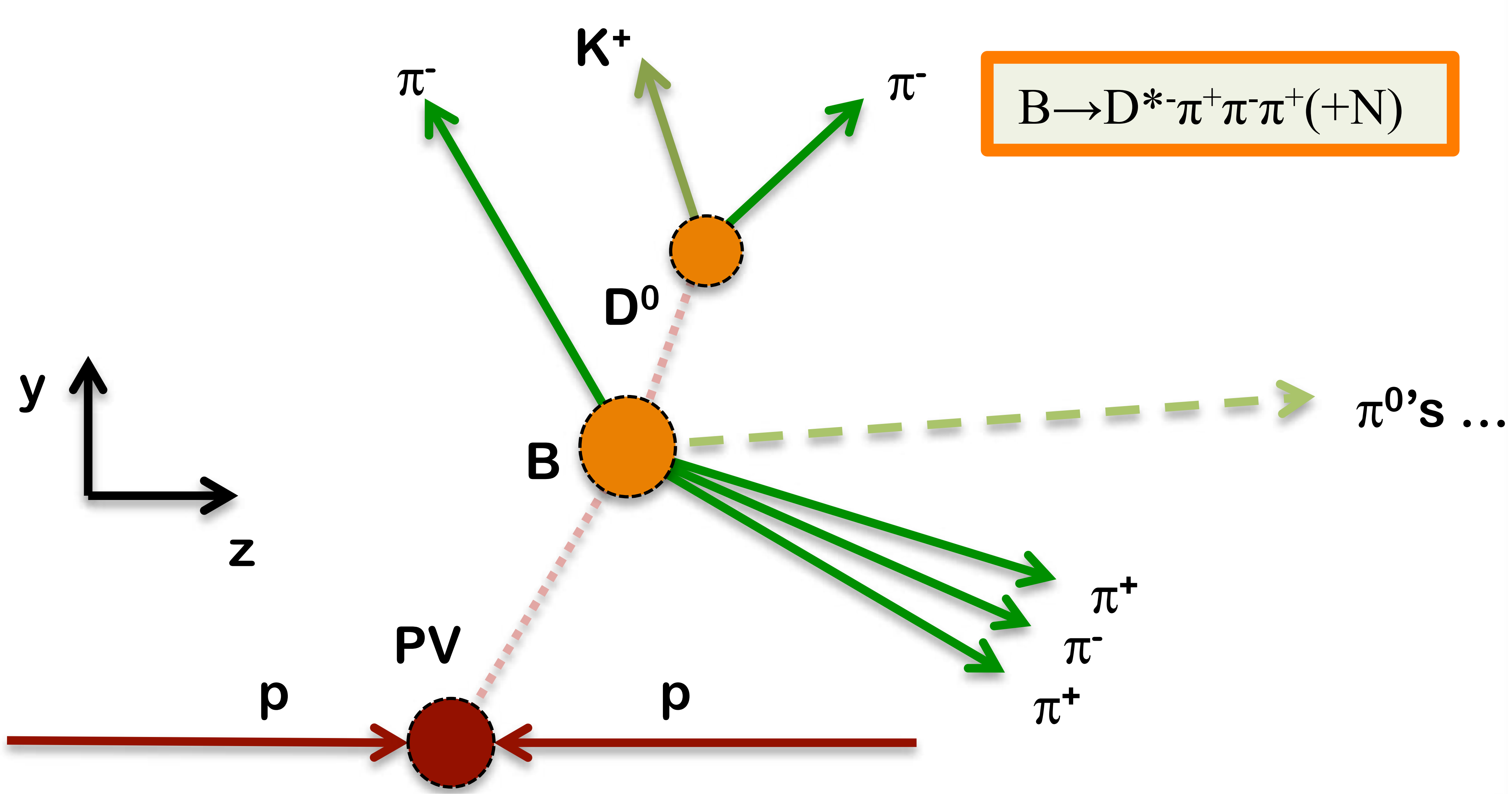
$\tau \to 3\pi\nu$

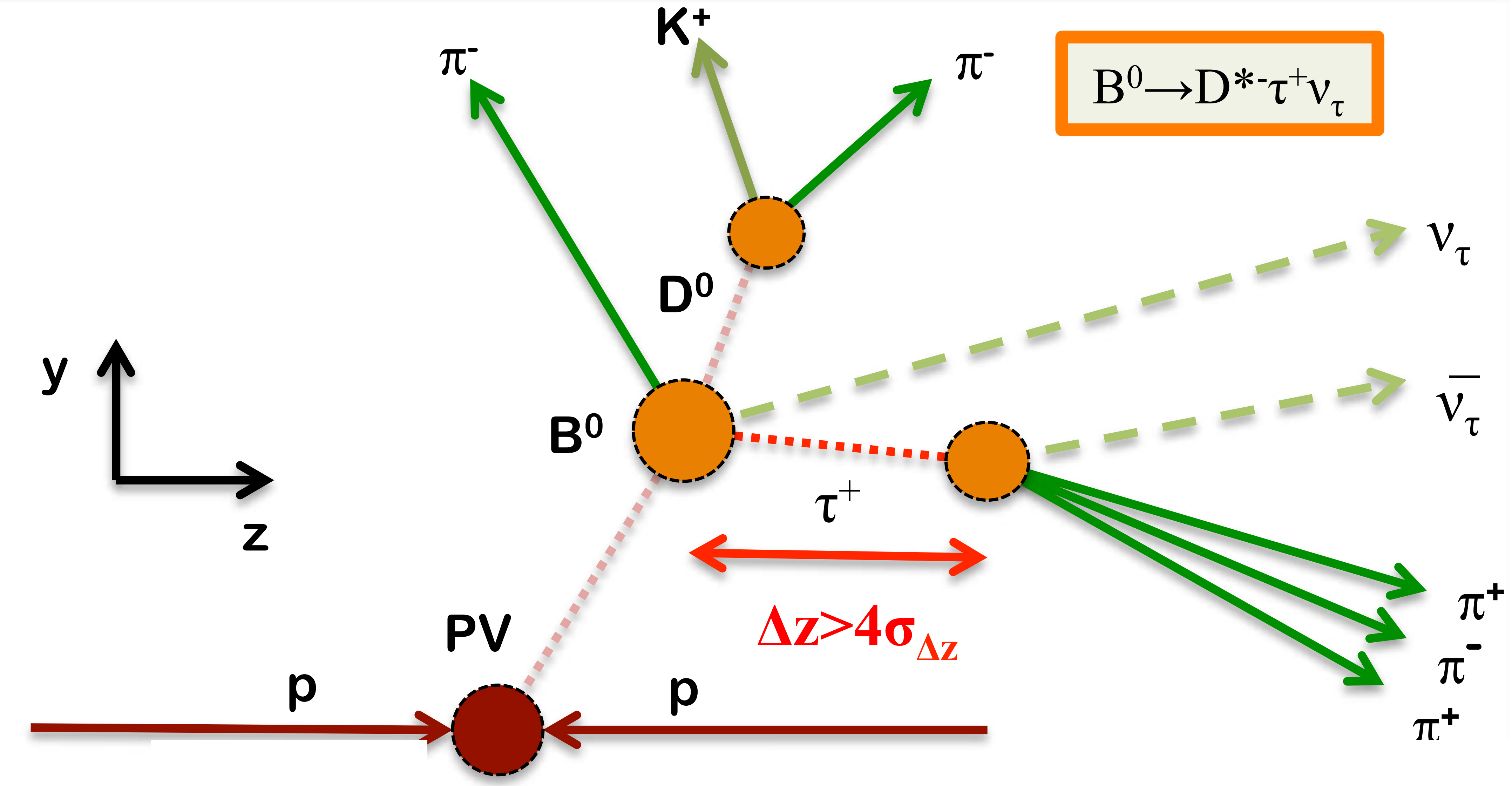

π^-
K^+
π^-
$B^0 \to D^{*-}\tau^+\nu_\tau$
ν_τ
D^0
y
B^0
$\bar{\nu}_\tau$
z
τ^+
$\Delta z > 4\sigma_{\Delta z}$
π^+
π^-
π^+
PV
p
p
06/06/17
A. Rom

Flight distance cut

- Huge background from $B \to D^{(**)} 3\pi X$
- Reduced by requiring a flight significance > 4σ.

Phys. Rev. Lett. 120, 171802 (2018)

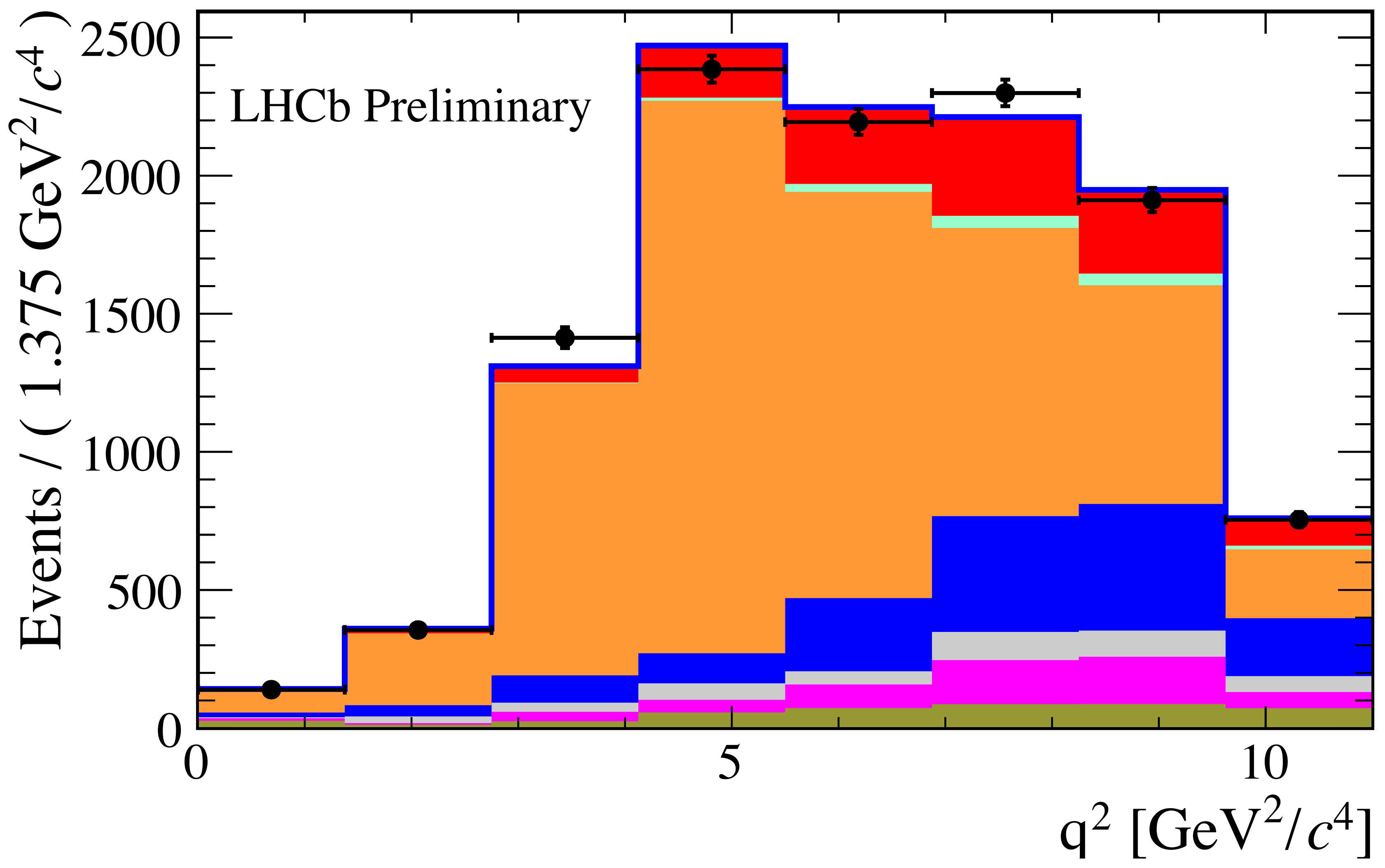


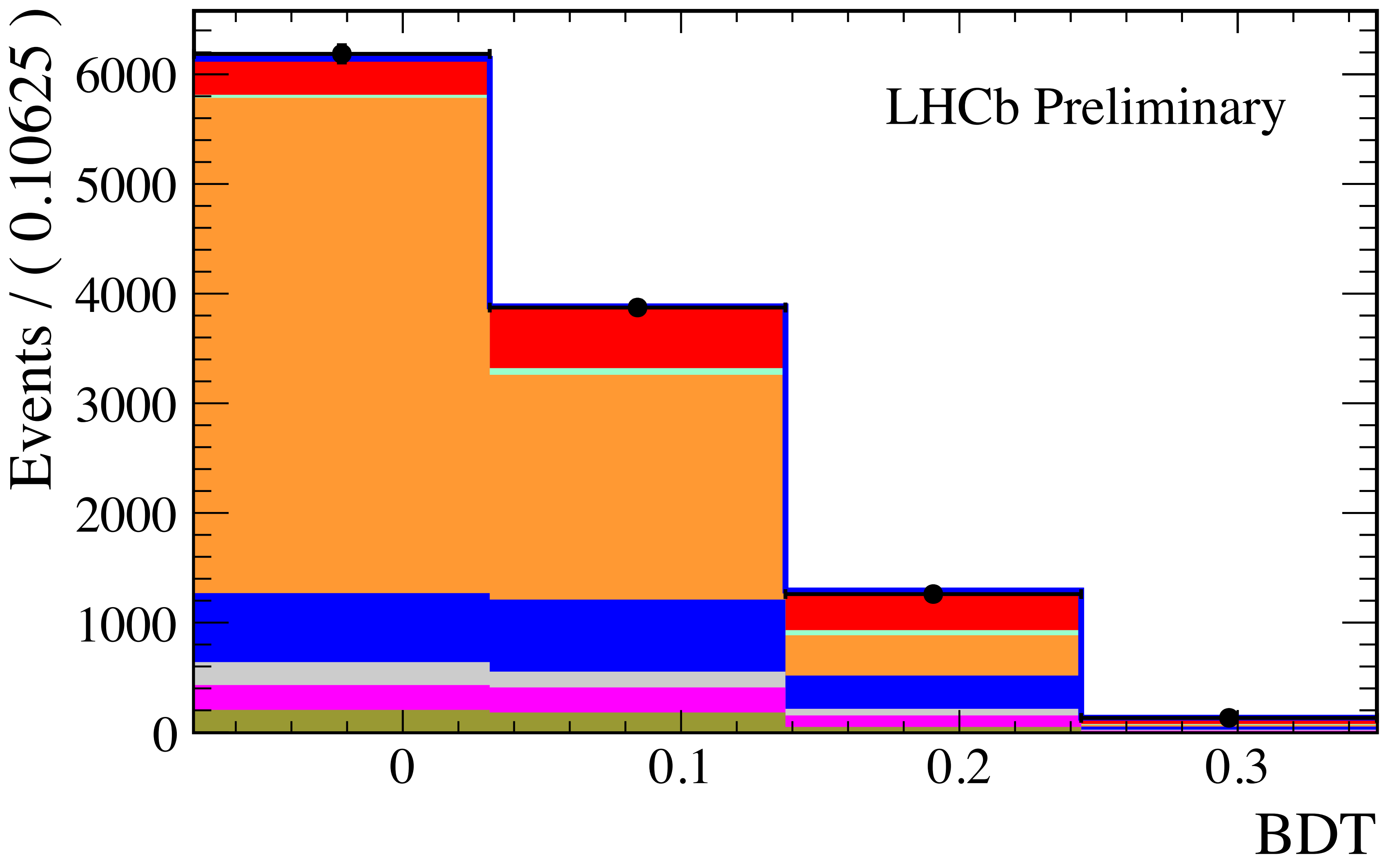


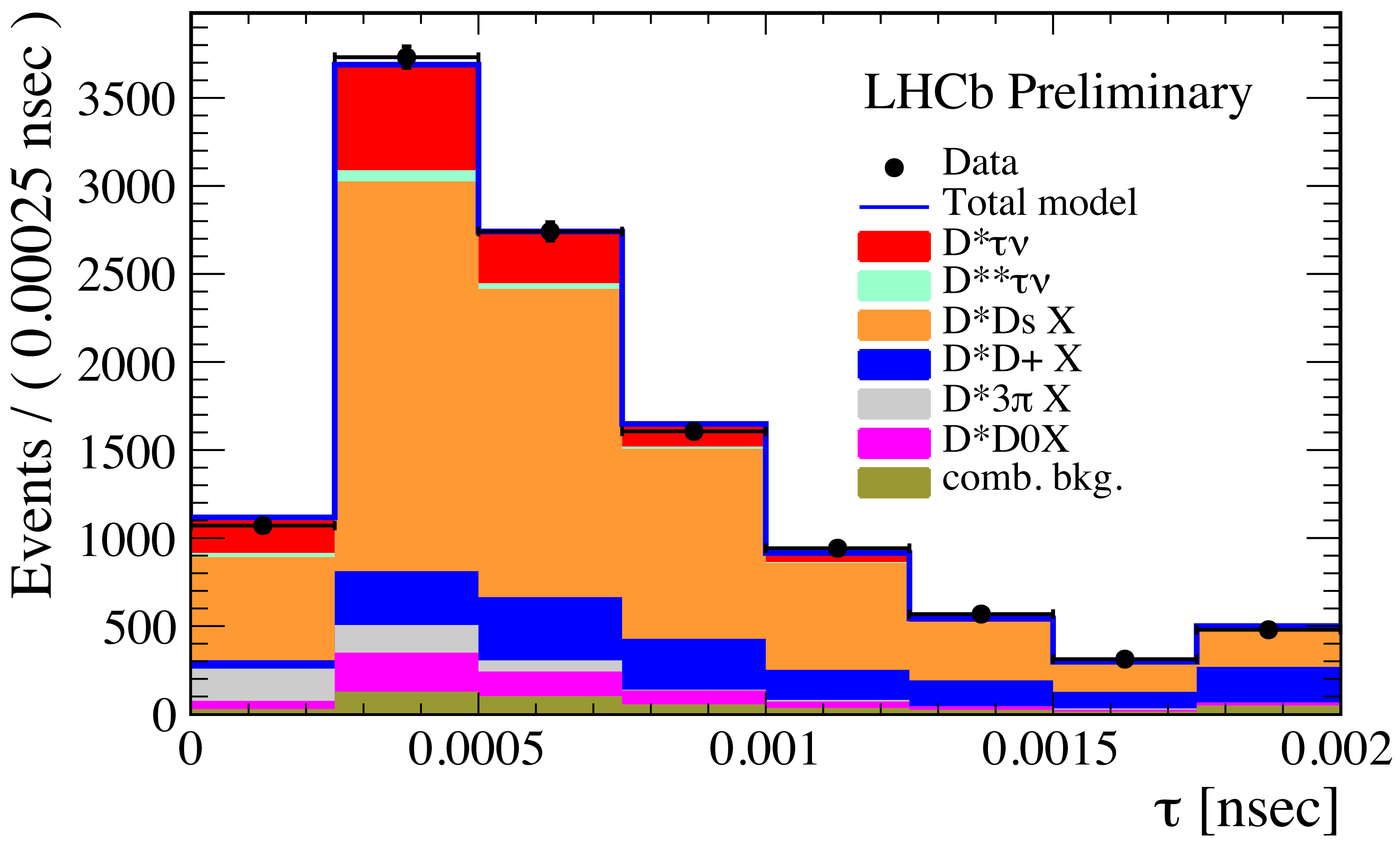
Signal fit

- Perform 3D template fit to determine signal yield.

Phys. Rev. Lett. 120, 171802 (2018)







Results

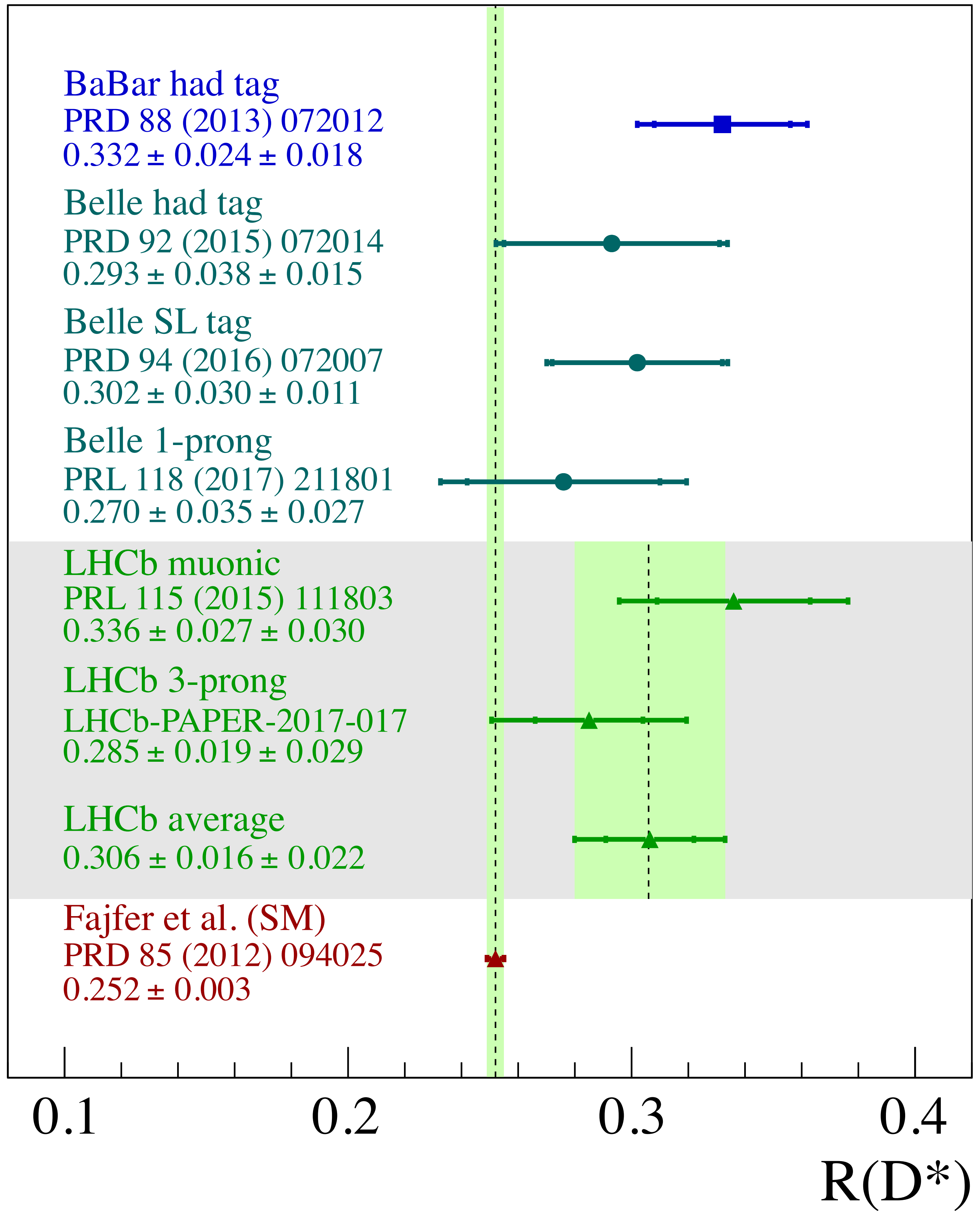
Phys. Rev. Lett. 120, 171802 (2018)

- Combine signal yield, efficiencies and external info to determine $R(D^*)$.

$$K_{had}(D^*) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

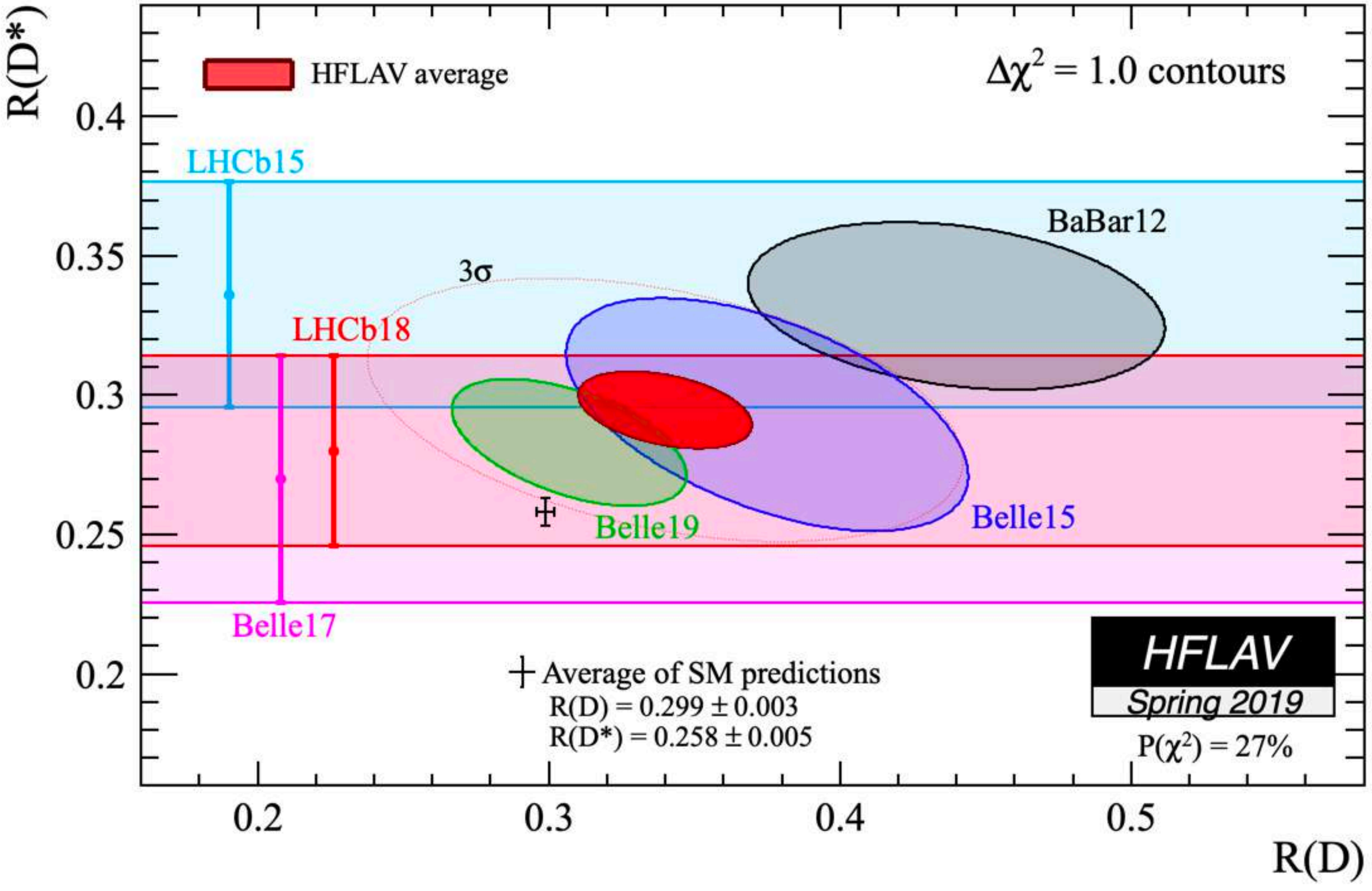
$$R(D^*) = K_{had}(D^*) \times \frac{BR(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- Dominant systematics from external BFs, efficiency corrections and background shapes.



Hints of an excess

- Three different experiments see an excess in the number of semitauonic candidates.

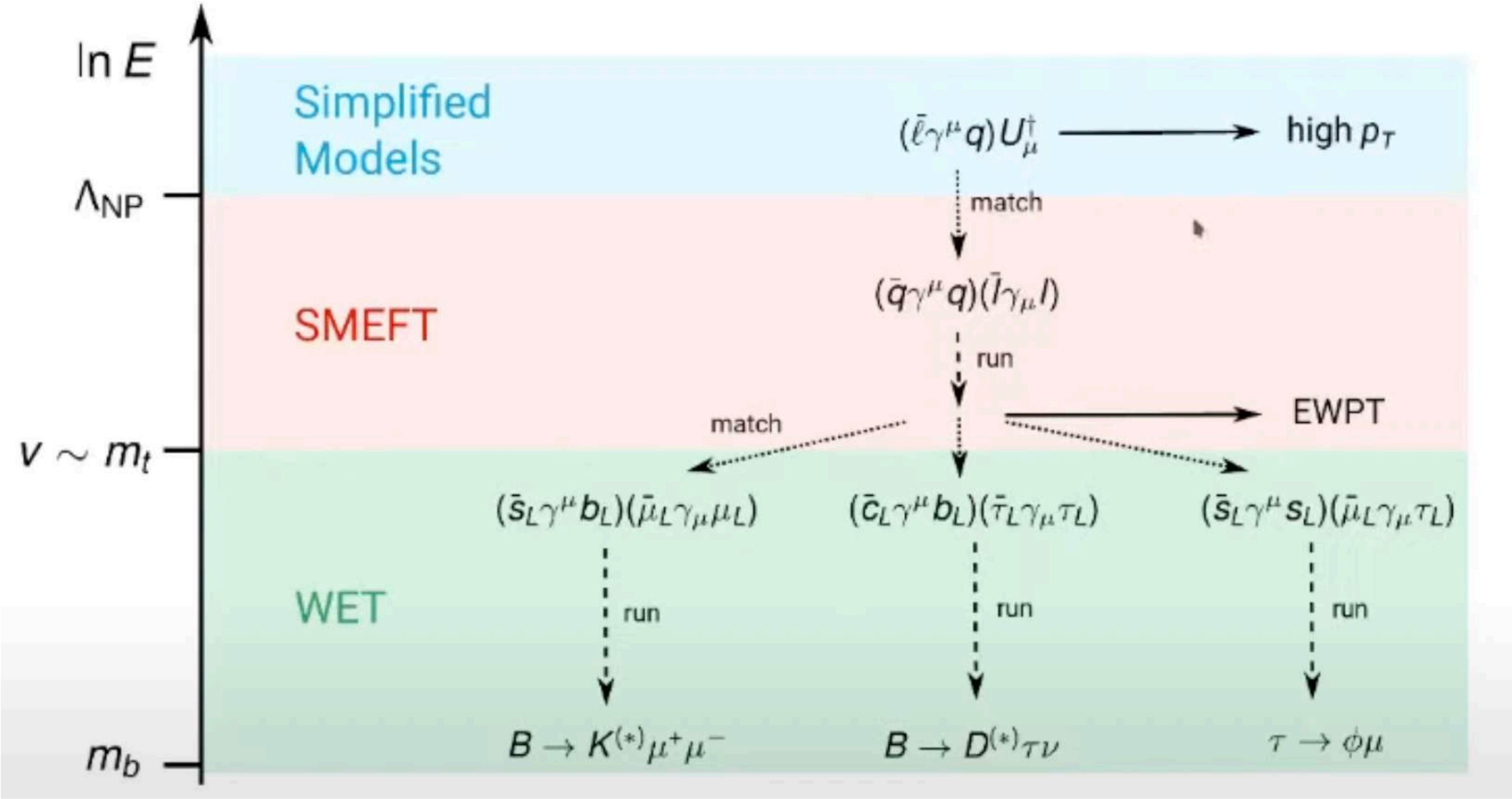


- Combined deviation around 3 σ.

- Is there any connect between these anomalies and the R_{K^*} ones?

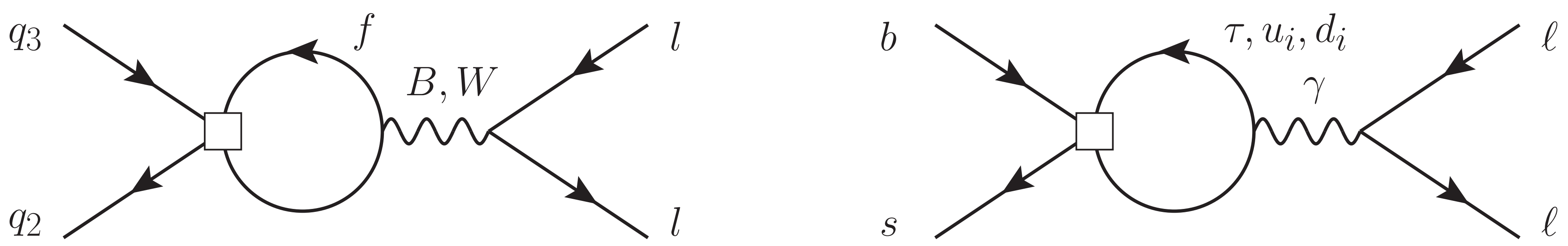
Different flavours of EFTs

- We are used to integrating out everything above the B/D mass.



D. Straub

SMEFT diagrams contributing to C_9.



- WET/LEFT: Integrate W/Z/top out.
- SMEFT/HEFT: Integrate everything above SM scale.

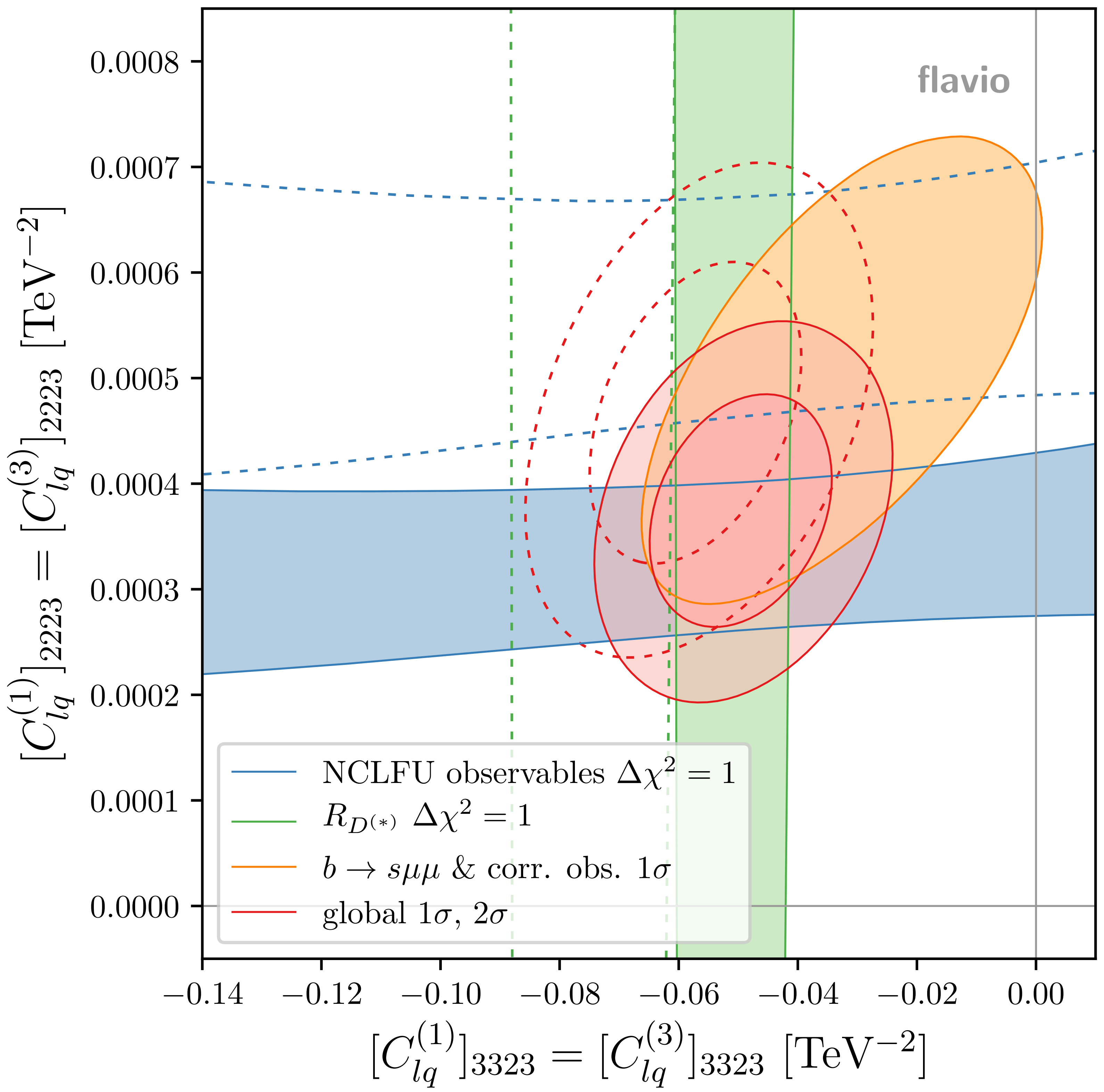
The flavour anomalies in in SMEFT

- The C_9 and C_{10} in WET can be matched to SMEFT operators.

$$2\mathcal{N}\, C_9^{bs\ell_i\ell_i} = [C_{qe}]_{23ii} + [C_{lq}^{(1)}]_{ii23} + [C_{lq}^{(3)}]_{ii23} - \zeta c_Z\,,$$
$$2\mathcal{N}\, C_{10}^{bs\ell_i\ell_i} = [C_{qe}]_{23ii} - [C_{lq}^{(1)}]_{ii23} - [C_{lq}^{(3)}]_{ii23} + c_Z\,,$$

- Can then relate the R_D and R_{K^*} anomalies.

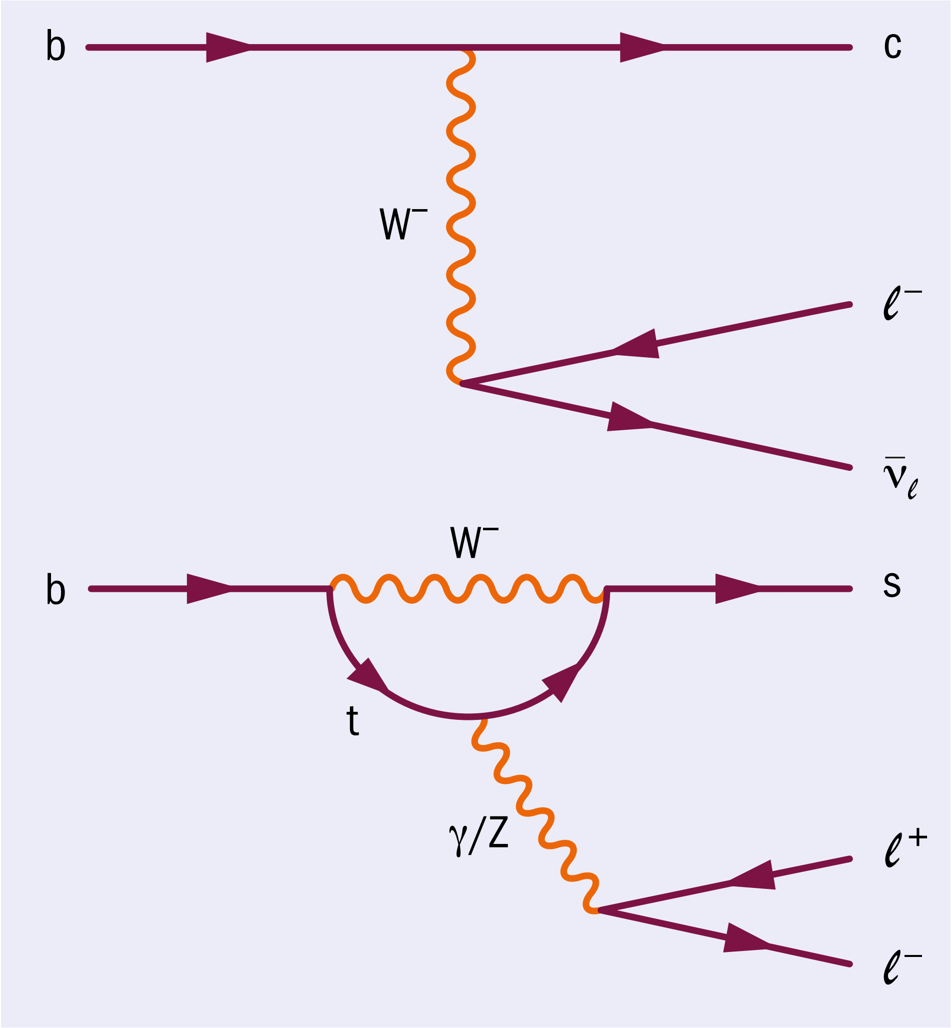
https://arxiv.org/pdf/1903.10434.pdf



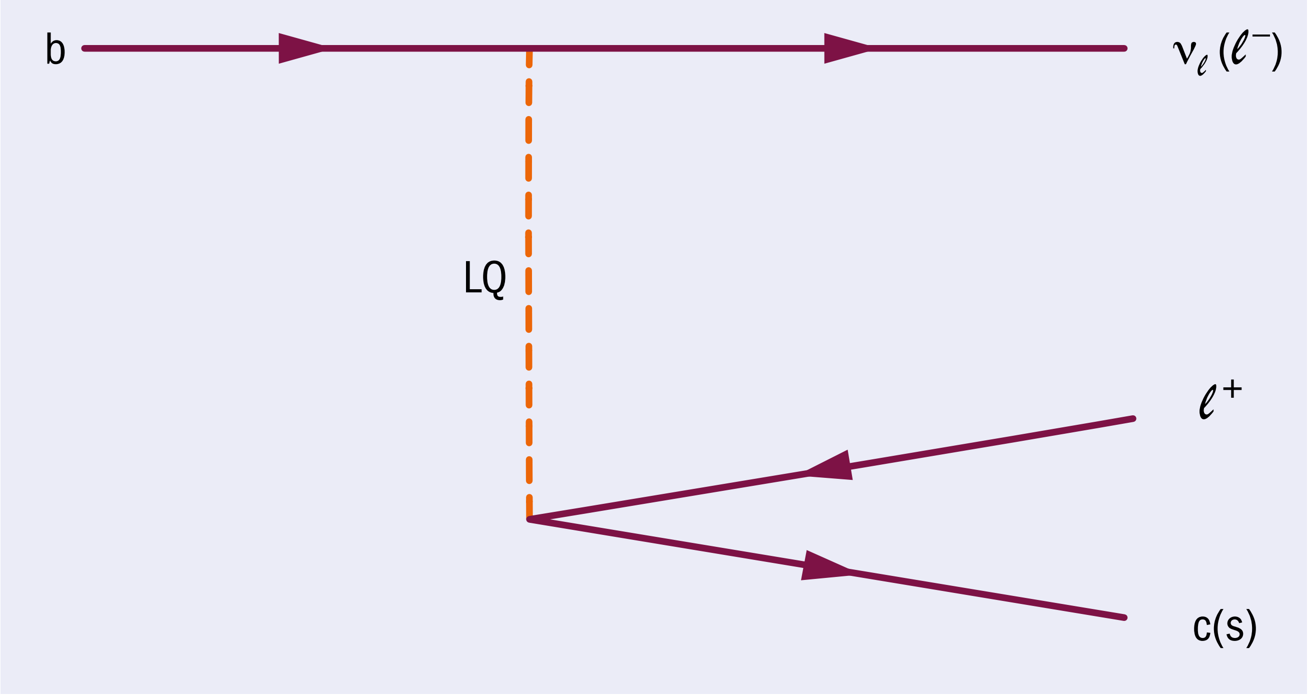
What could this all mean?

- We have two sets of anomalies in charged and neatral current semileptonic B decays.
- They both point towards a violation of lepton universality.
- Possible to explain both anomalies with a single new particle (leptoquark) of around 2TeV mass.

SM diagrams



New physics diagram



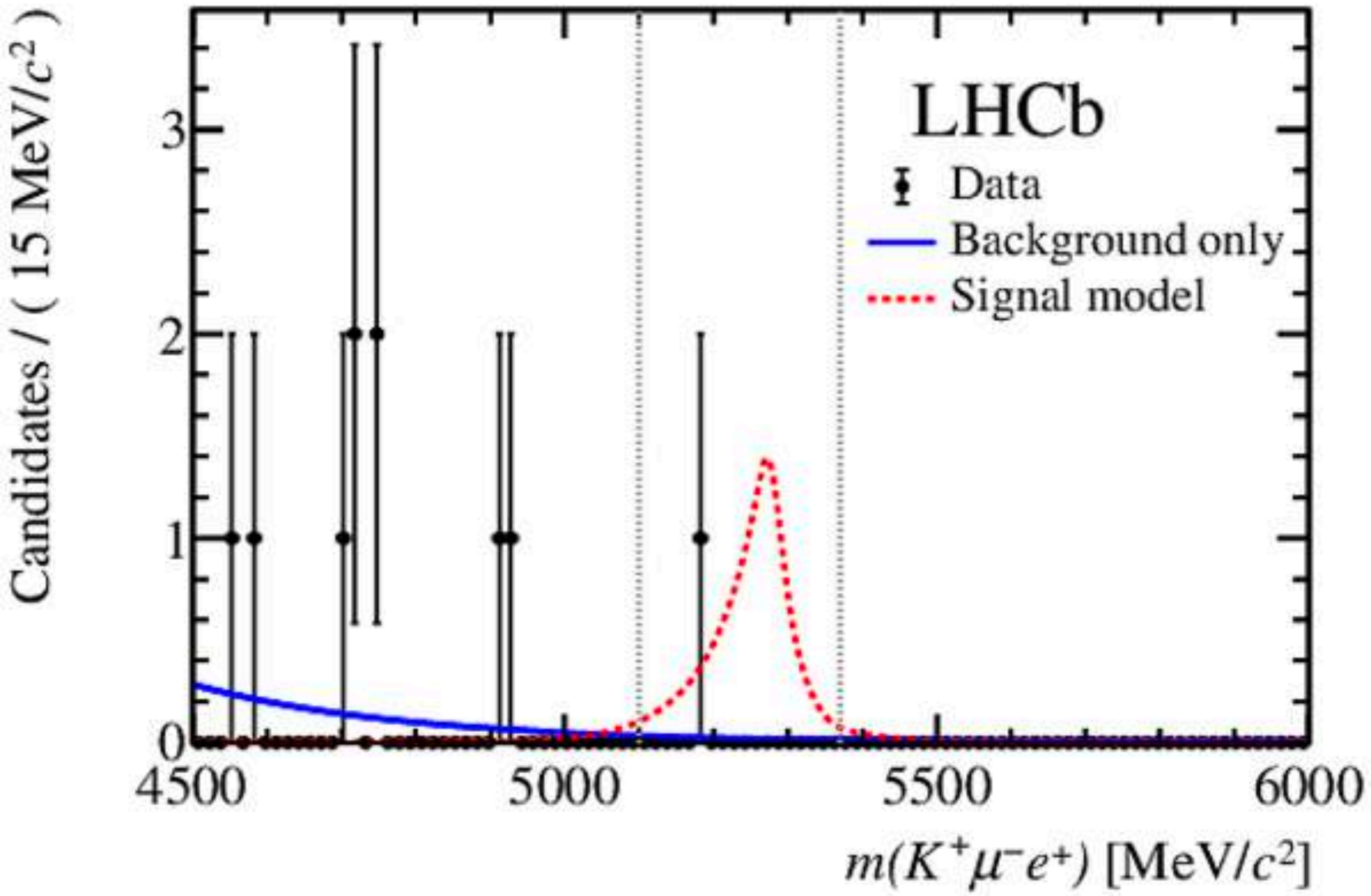
- Huge consequences! Motivation for more measurements is clear.

Lepton flavour violation

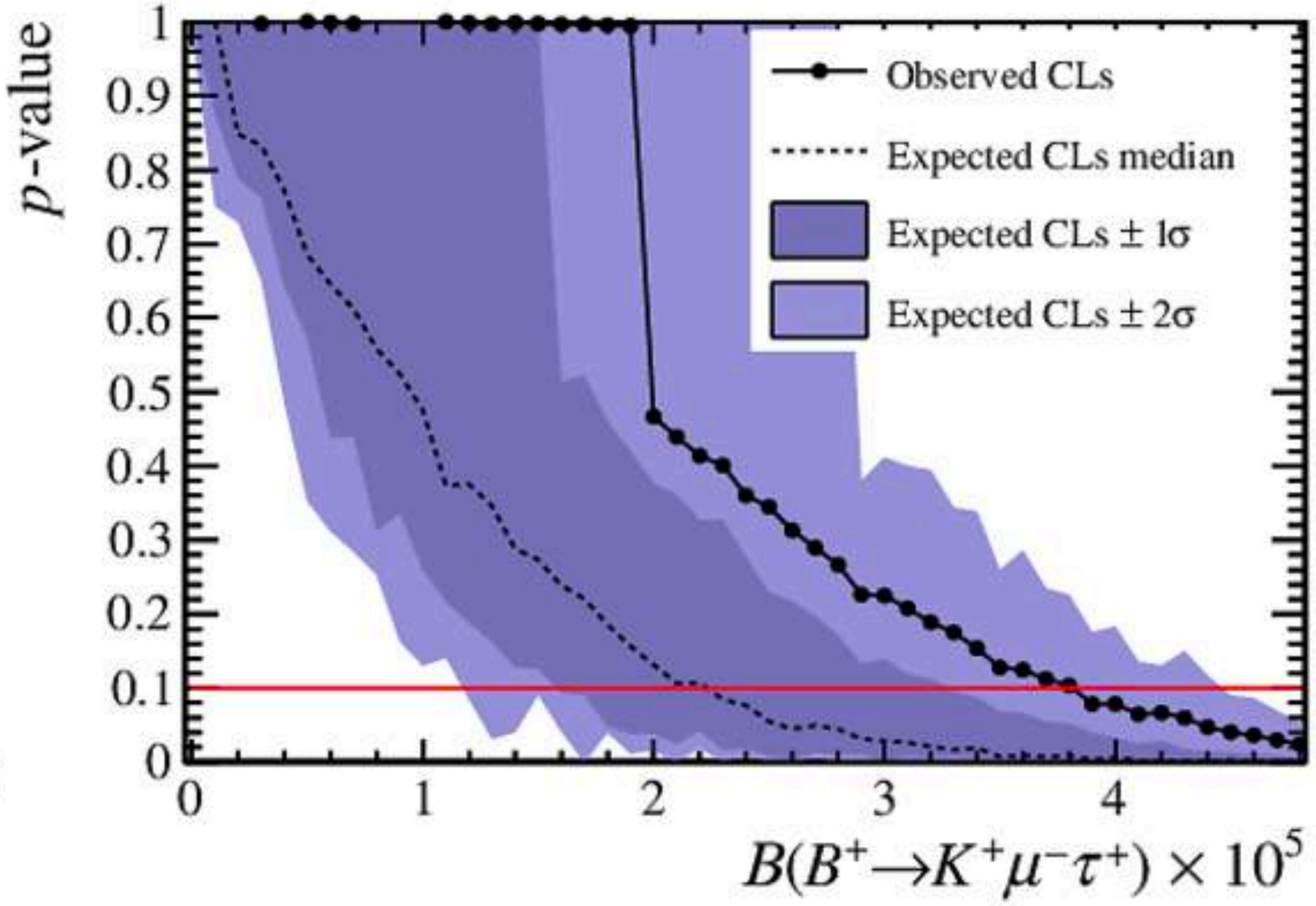
Sheldon L. Glashow, Diego Guadagnoli, Kenneth Lane

- Lepton universality violation naturally implies lepton flavour violation.
- If the anomalies are true, eventually expect to see decays such as $B^+ \rightarrow K^+ e^\pm \mu^\pm$ and $B^+ \rightarrow K^+ \tau^\pm \mu^\pm$.

LHCB-PAPER-2019-022



LHCB-PAPER-2019-043



- Getting close to expected sensitivity for well motivated models (particularly with the τ)..

What’s next?

- We have not yet fully exhausted the current dataset at LHCb. Upcoming measurements:
  - Update of R_{K^*} with the full run II dataset.
  - Measurement of $R_{K^{(*)}}$ in the high q^2 region.
  - Measurement of new R ratios with different hadron species ($R_{K\pi}$,$R_{K\pi\pi}$,R_{ϕ},R_{D},$R_{J/\psi}$)
  - Angular analysis of $B^0 \rightarrow K^{*0}e^+e^-$ decays.
  - Lepton universality tests with baryons (Λ_b baryons).
  - Searches for $b \to s\tau^+\tau^-$
  - \+ many more ..
- Exciting times to be on LHCb!

STAY TUNED!