B anomalies:
an experimental perspective

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15th December 2022

A Dickensian overview

1. B-anomalies past
   - continuation of flavour history
2. B-anomalies present
   - review of the measurements
3. B-anomalies future
   - LHC experiments
   - Belle II

Flavour physics – history of discovery

- Several aspects of the SM came about through flavour predictions
  - GIM mechanism to explain rate of

$$K_L^0(s\bar{d}) \rightarrow \mu^+\mu^-$$

  results in prediction of charm quark
  - Kobayashi-Maskawa extend to three generations to explain CP violation
  - B mixing $\Rightarrow$ heavy top
- **Common: low energy phenomena probing higher mass scales**

$$\begin{pmatrix} u & c \end{pmatrix} \begin{bmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{bmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Complementarity to direct searches

- Loop-mediated processes in quark and lepton flavour allow probes of higher masses scales
- Names of the game
  - Precise measurement
  - Rare process search
- Pattern of deviations from SM can point to toward what is next

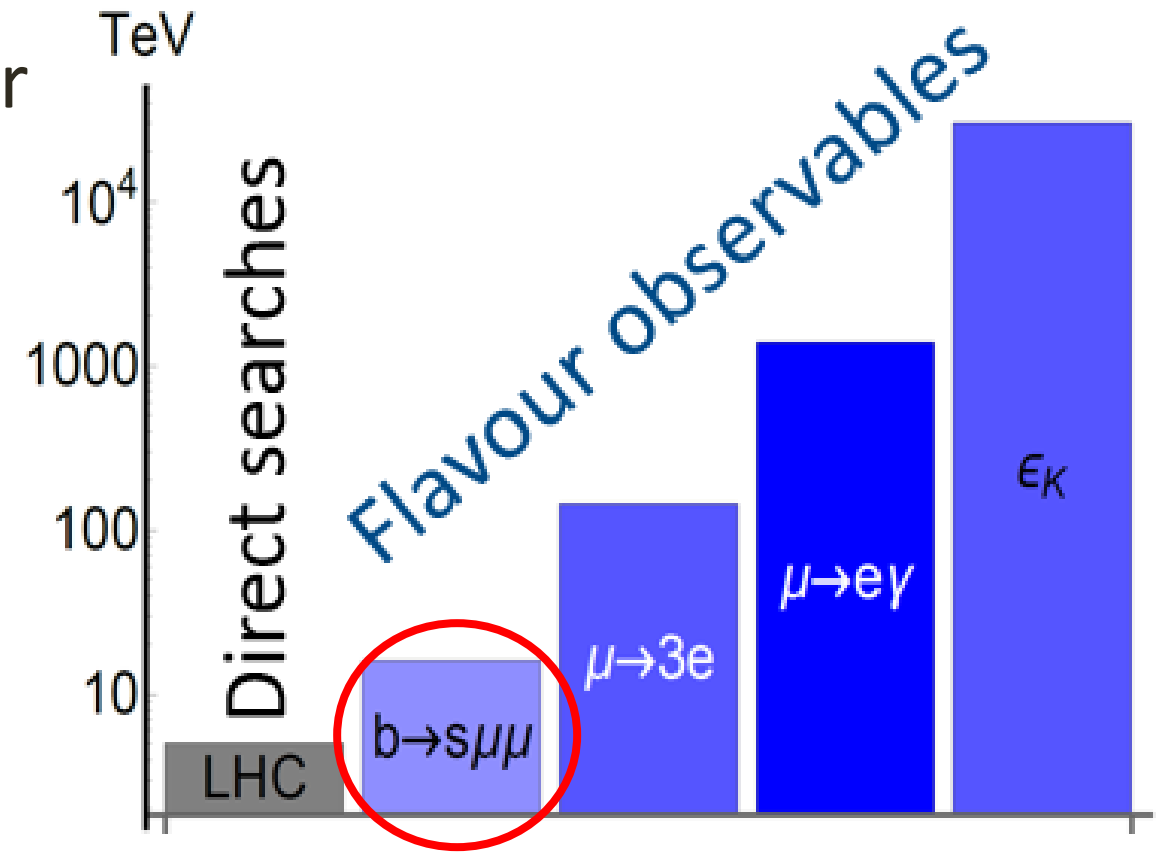


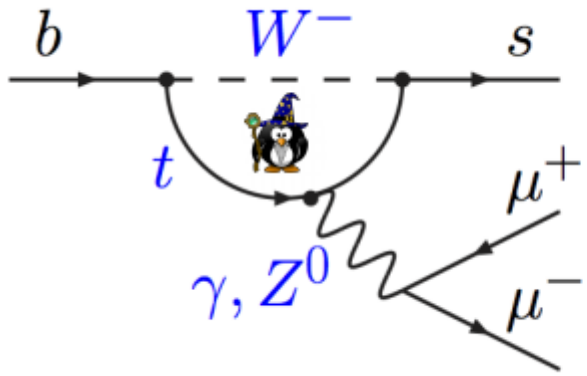
Figure from A. Crivellin talk to Belle II Summer Workshop

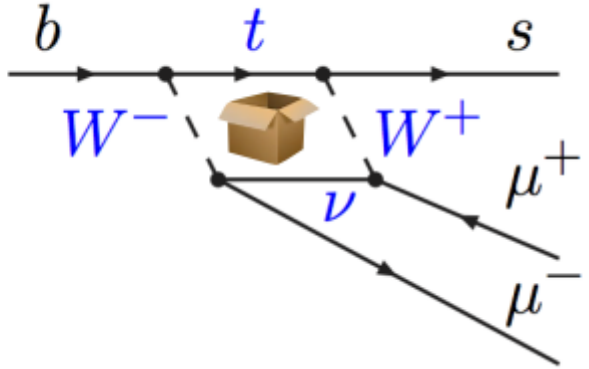
"There are ~~books~~ talks of which the ~~backs~~ conclusion and ~~covers~~ titles are by far the best parts", paraphrasing Dickens

B ANOMALIES PRESENT

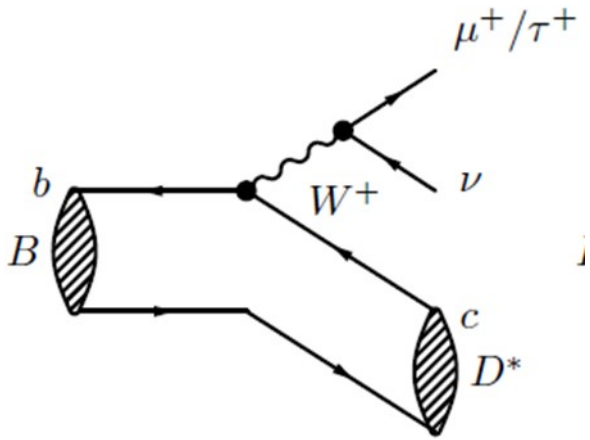
Overview of B modes with anomalies

- Flavour changing neutral current b→sll at loop level only





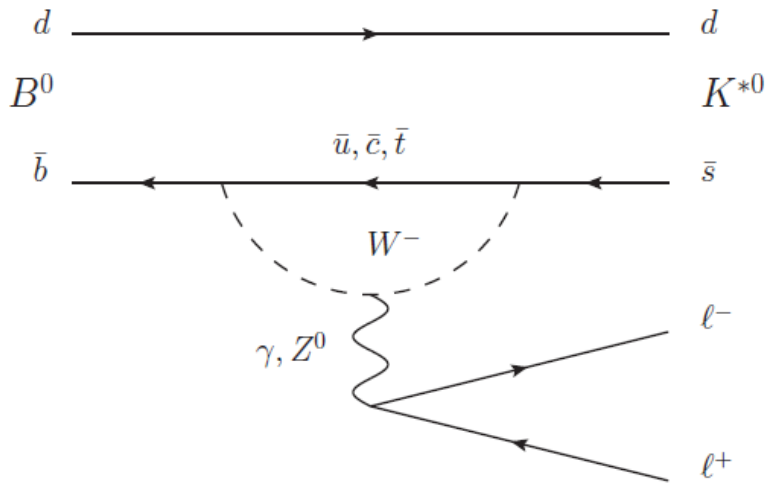
- Tree level b→cτν semileptonic

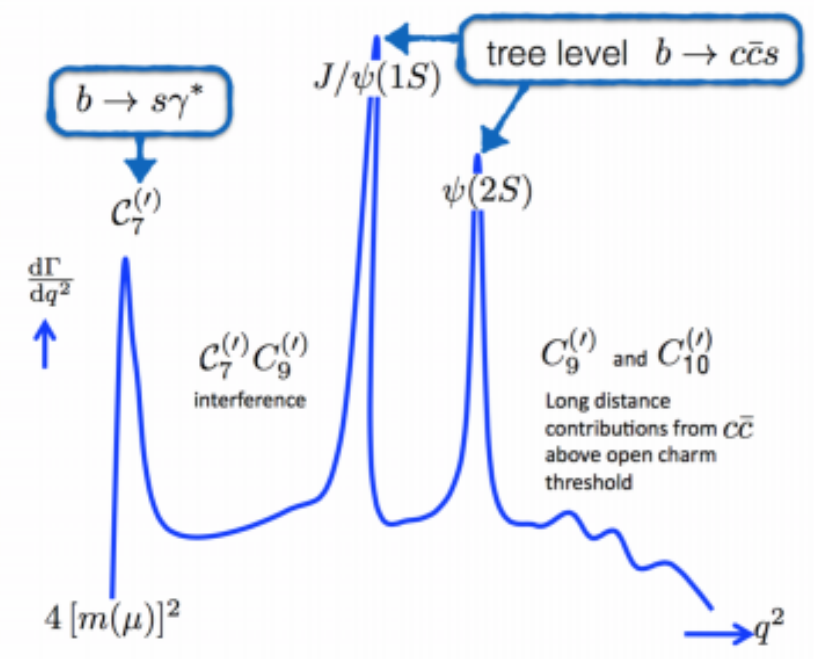


	Pro	Con
b→sll	New physics reach O(10 TeV)	One experiment
b→cτν	Three experiments	New physics near the EW scale

$B \to K^*(892) l^+ l^-$

- The K*→Kπ decay leads to four-body final state
- Allows differential distributions to be probed
  - Large new physics contributions possible as they appear via interference
  - **Textbook example forward-backward asymmetries in e^+e^-**
- Also variation with the invariant mass of the l^+l^- system - q^2





B

-
-
-
-

5.1 The process $e^+e^- \to \mu^+\mu^-$ 143

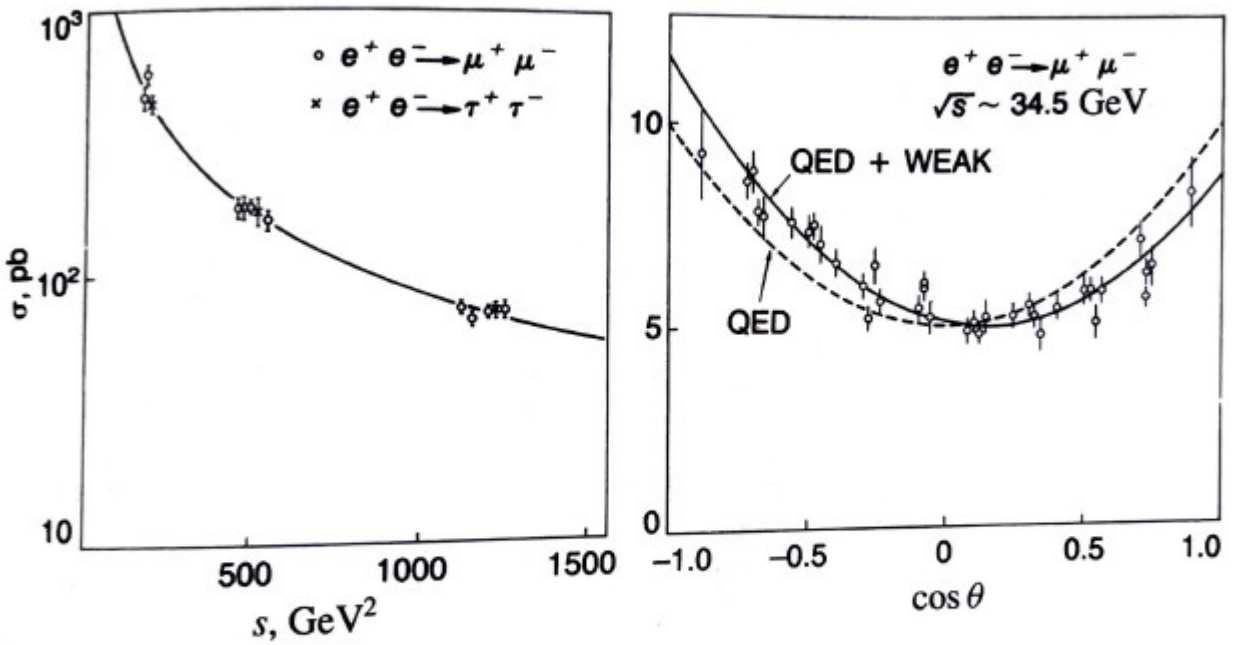
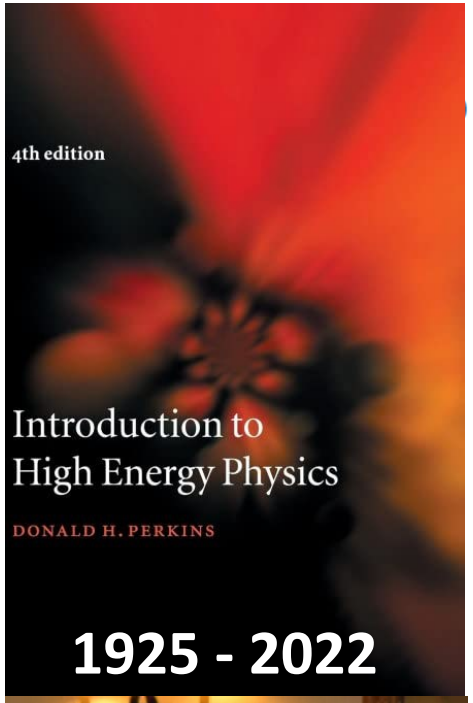
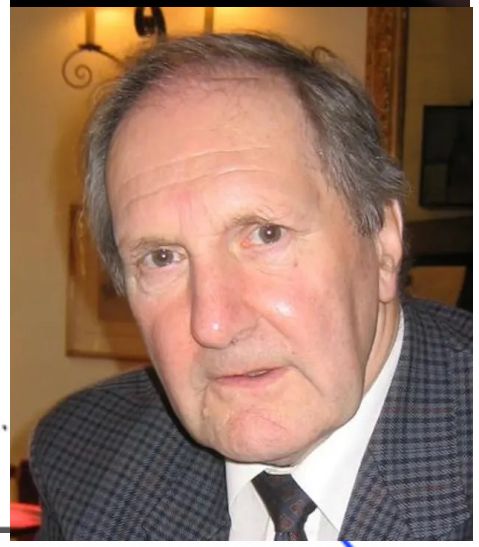


Fig. 5.2. Results on total and differential cross-sections for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ from the PETRA collider at DESY. The curve on the left shows the QED prediction for the total cross-section, on which neutral currents due to Z^0 exchange have small and unmeasurable effects. On the right is given the cms angular distribution. The broken curve shows the pure QED prediction (5.4), while the solid curve indicates the small forward–backward asymmetry expected from the combination of Z^0 and γ exchange.



1925 - 2022

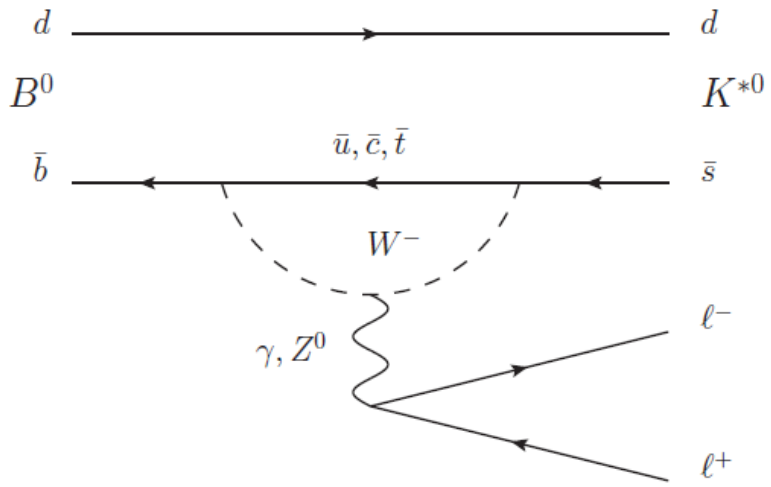


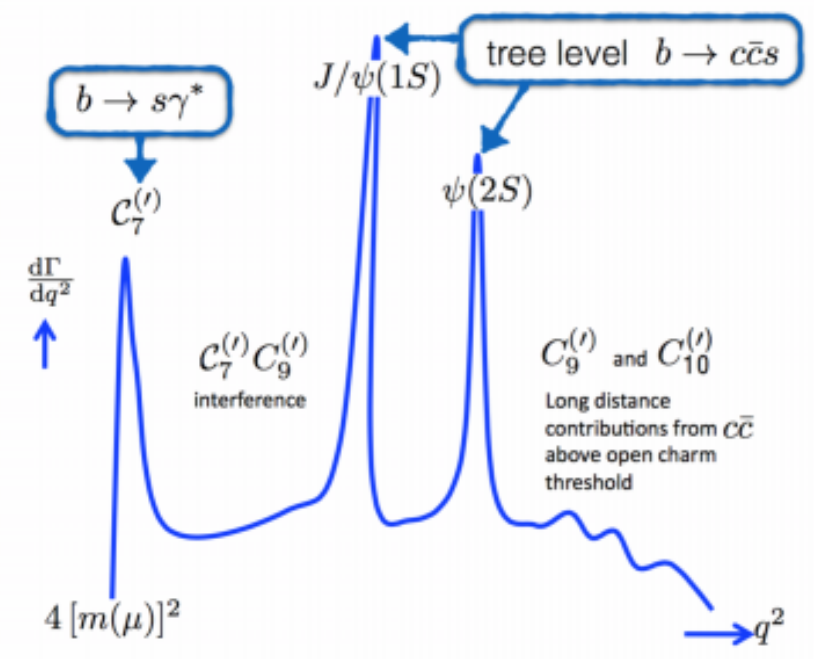
$4\,[m(\mu)]^2$

q^2

$B \to K^*(892) l^+ l^-$

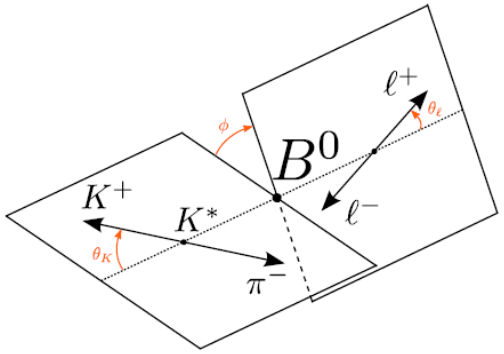
- The K*→Kπ decay leads to four-body final state
- Allows differential distributions to be probed
  - Large new physics contributions possible as they appear via interference
  - **Textbook example forward-backward asymmetries in e^+e^-**
- Also variation with the invariant mass of the l^+l^- system - q^2





$B \to K^*(892) l^+ l^-$ nomenclature

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_L\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K$$
$$+\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big]$$

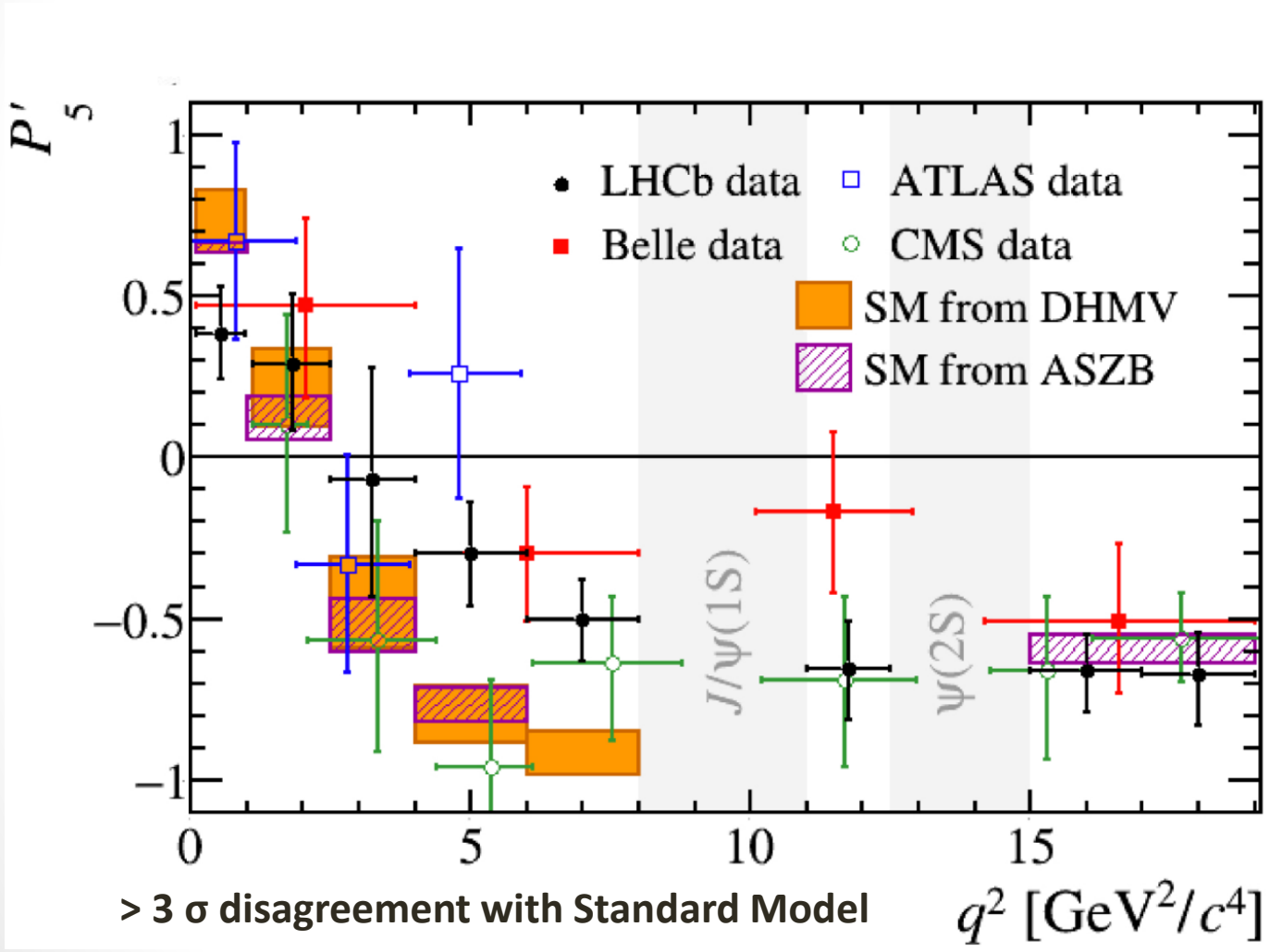


- Goal is to measure this 4D differential distribution and extract the coefficients from data to compare to the SM predictions
- Much work on defining observables with minimal theoretical uncertainties
- Let us focus on S_5 which get normalized as to minimize form factor uncertainties

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

P_5' anomaly: the first in $b \to s l^+ l^-$

- Constructed in such a way that the form factor dependence is minimized

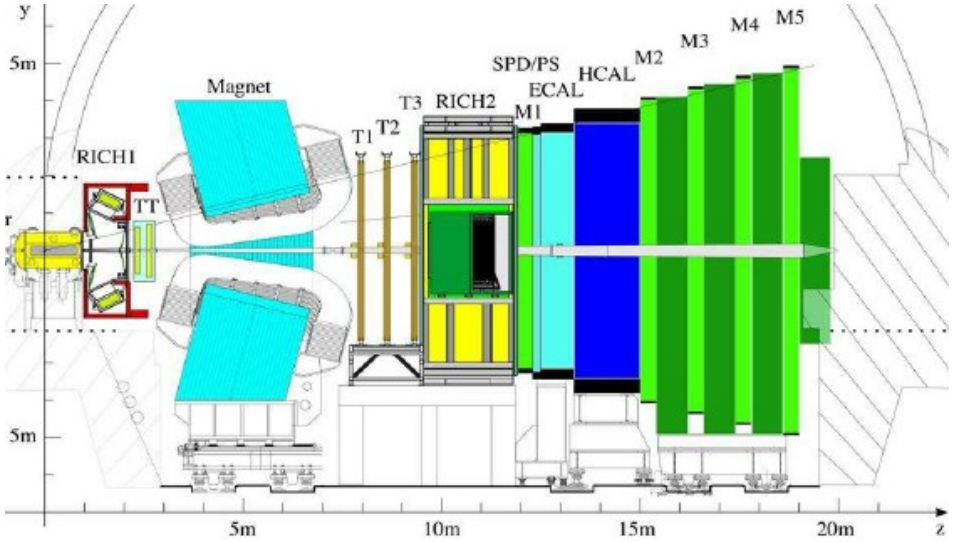


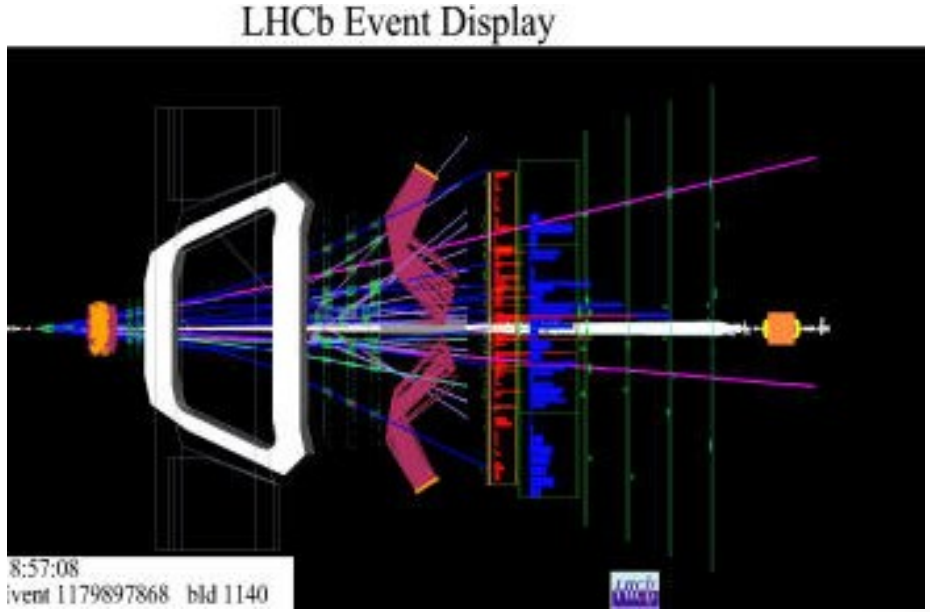
Note this is just for $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$ - time to talk about LHCb

PRL **125**, 011802 (2020)
PLB **781**, 517 (2018)
JHEP **10** (2018) 047
PRL **118**, 111801 (2017)
JHEP 12 (2014) 125
JHEP 09 (2010) 089

LHCb in a slide

- 13 TeV pp collisions
  - trillion bb/2 fb^{-1}
  - 6 fb^{-1} @ 13 TeV
  - + 3 fb^{-1} @ 7/8 TeV
- Forward geometry gets both b quarks in acceptance and boosted – exploit b lifetime to separate background
- RICHes for π/K separation
- Full trigger bandwidth for B physics





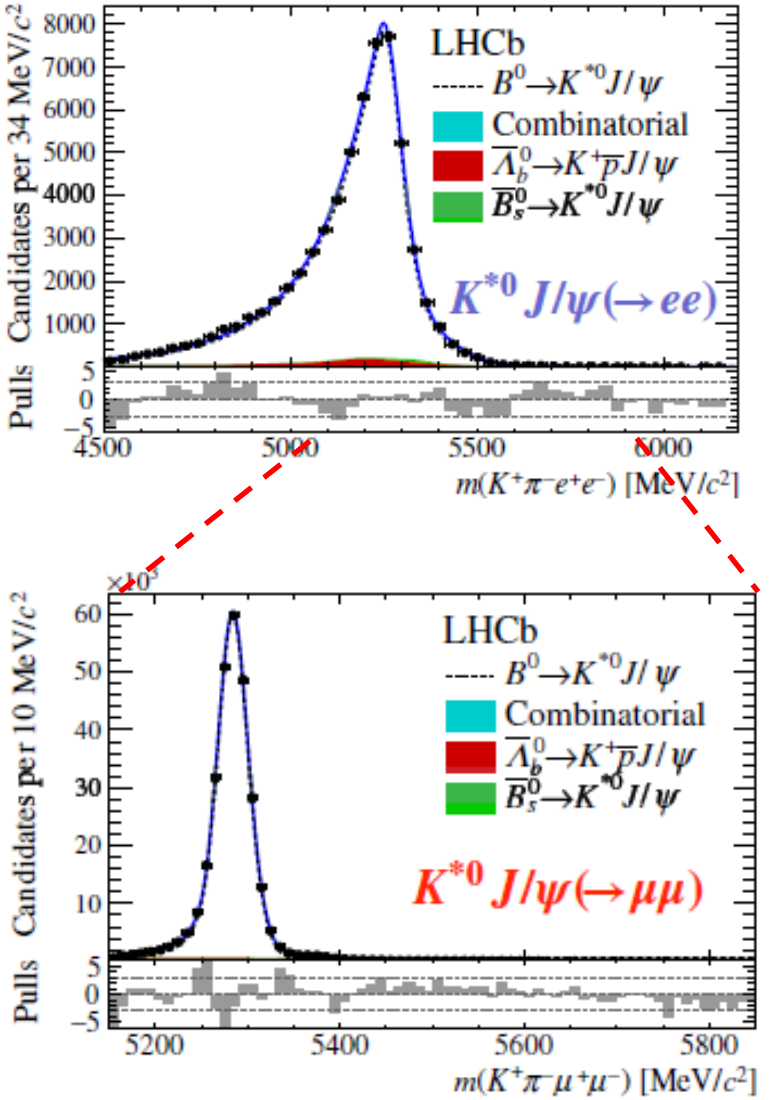
Tests of Lepton Universality Violation (LUV)

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

H=K or K*

- Standard Model prediction ~1 to a few %
  - limited theoretical uncertainties
- $B\to K^{(*)}J/\psi(l^+l^-)$ bountiful control channel

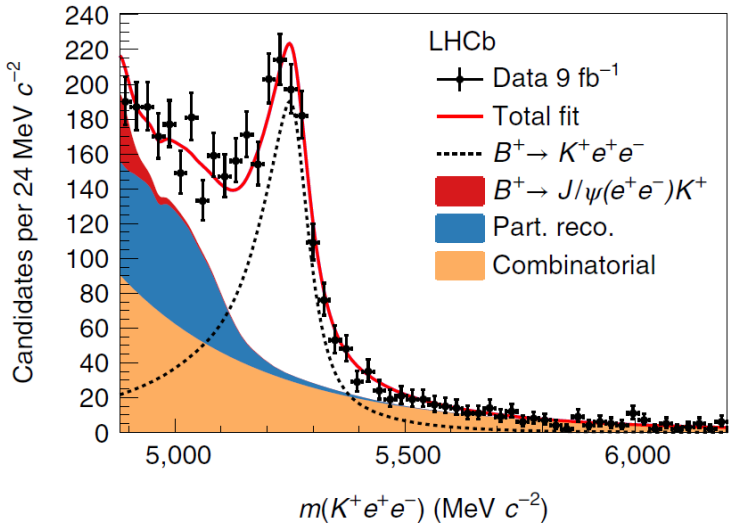
JHEP **08** (2017) 055

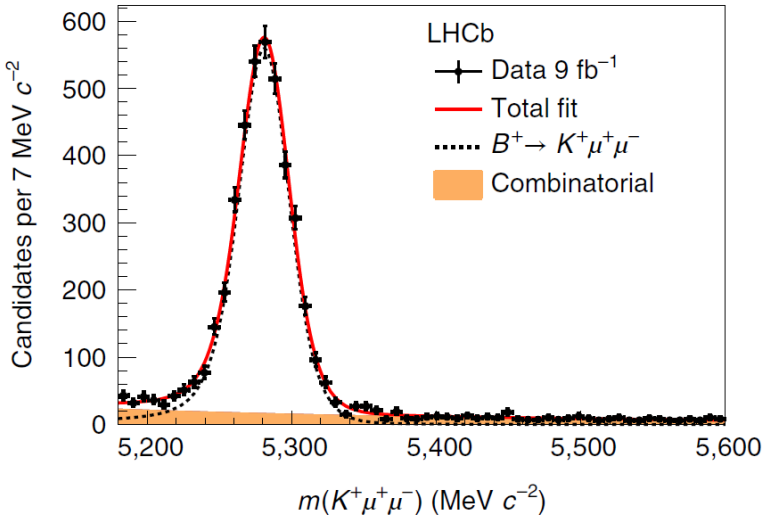


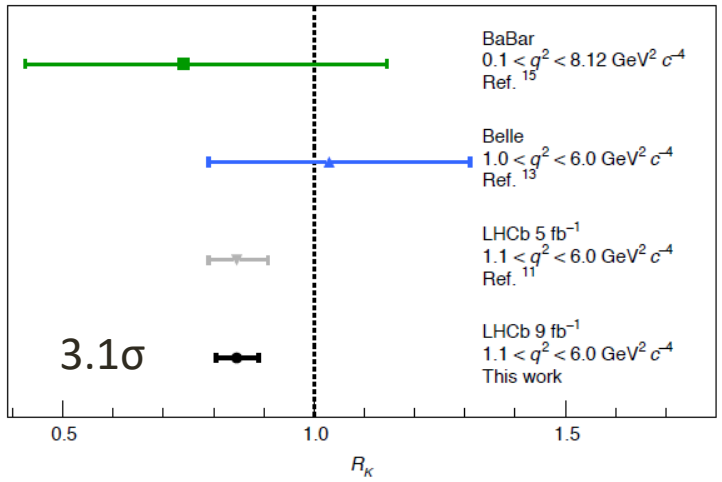
The results: muons low

Consistent picture in other modes (backup)

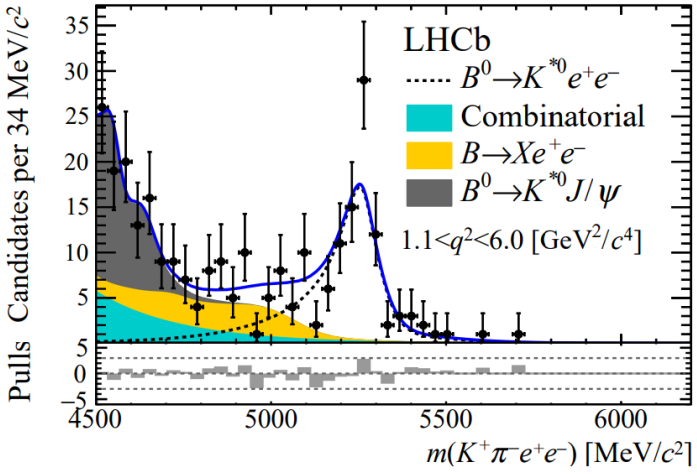
B→K*l+l− PRL Nature Physics 18 (2022) 277 – Run 1 + 2

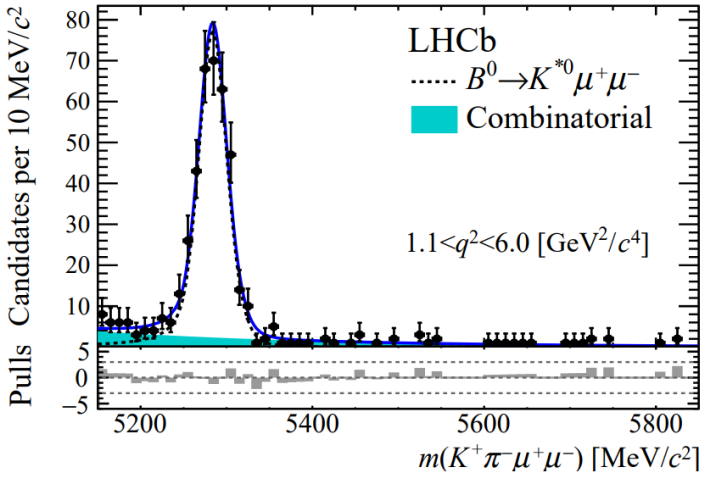


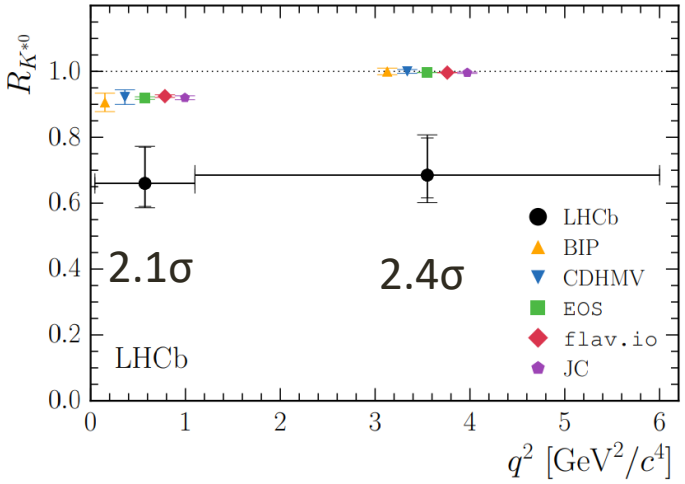




B→K*l+l− JHEP 08 (2017) 055 – Run 1 (25% data)







LHC Seminar

Measurements of $R(K)$ and $R(K^*)$ with the full LHCb Run 1 and 2 data

by Renato Quagliani (EPFL - Ecole Polytechnique Federale Lausanne (CH))

Tuesday Dec 20, 2022, 11:00 AM → 12:00 PM Europe/Zurich

500/1-001 - Main Auditorium (CERN)

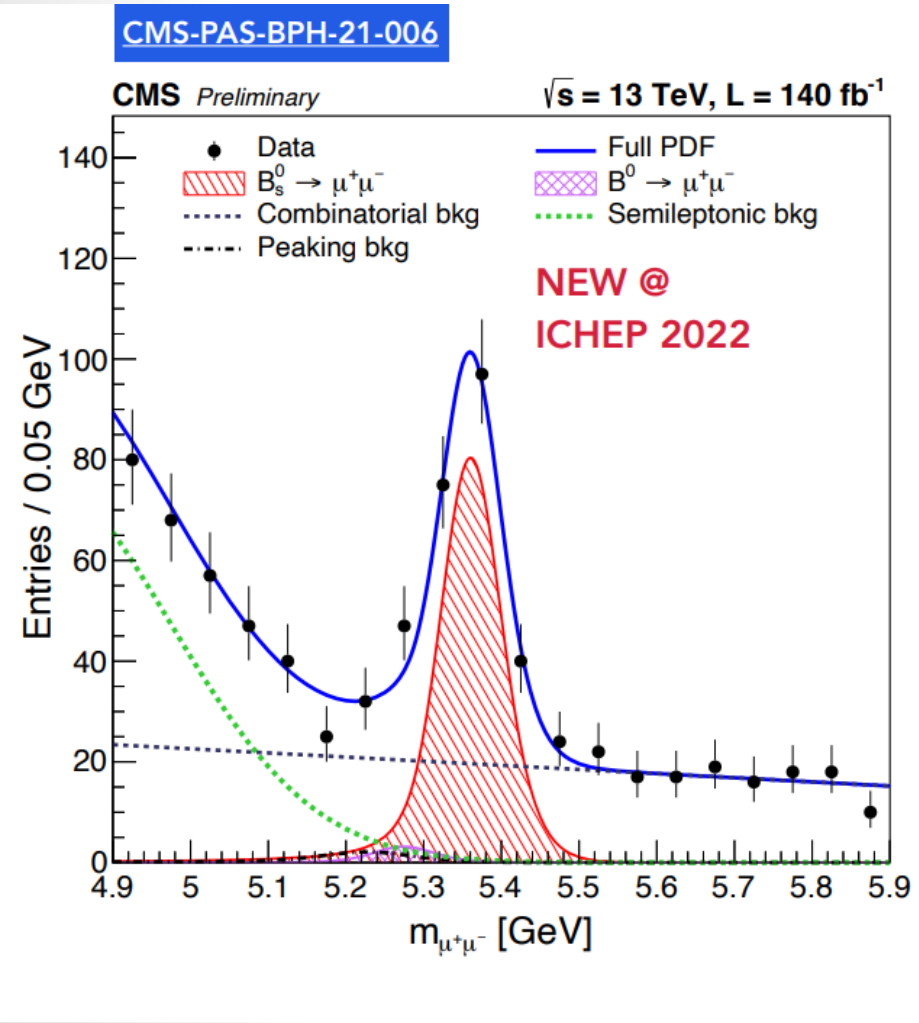
Description In this seminar we present the first simultaneous test of muon-electron universality in $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ decays, known as $R(K)$ and $R(K^*)$, in two regions of di-lepton invariant mass squared.
The analysis operates at a higher signal purity compared with previous analyses and implements a data-driven treatment of residual hadronic backgrounds. The analysis uses the full LHCb Run 1 and 2 data recorded in 2011-2012 and 2015-2018, corresponding to an integrated luminosity of 9 fb^{-1}. This analysis is the most sensitive lepton universality test in rare b-decays and the results obtained supersede the previous LHCb measurements of $R(K)$ and $R(K^{*0})$.

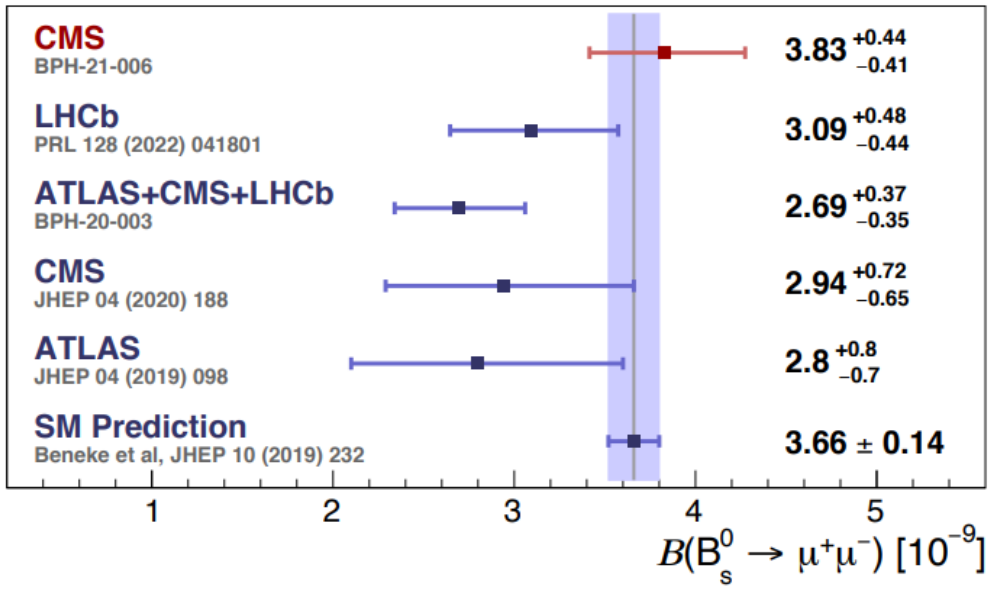
Organized by Michelangelo Mangano, Jan Fiete Grosse-Oetringhaus and Pedro Silva.....Refreshments will be served at 10h30

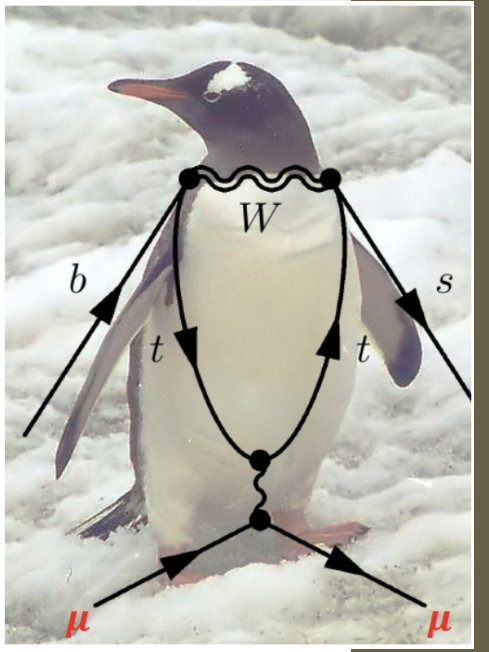
Videoconference LHC seminar - 20 December - LHCb — Join

Webcast There is a live webcast for this event — Watch

Anomaly related: $B_{(s)} \to \mu^+\mu^-$





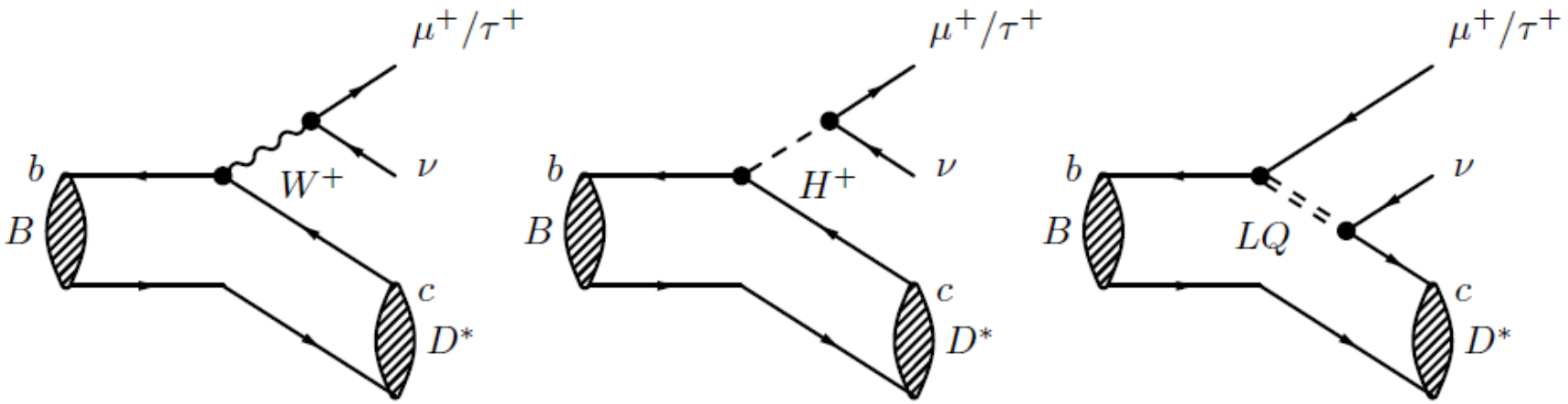


- Highly suppressed in the SM
- Therefore, readily enhanced by non-SM contributions
- Clean experimental signature
- Theoretically clean: decay constant vs form factors

“PLEASE SIR, I WANT SOME MORE”

Semi-tauonic decays

- Tree level in the SM but allows lepton universality tests

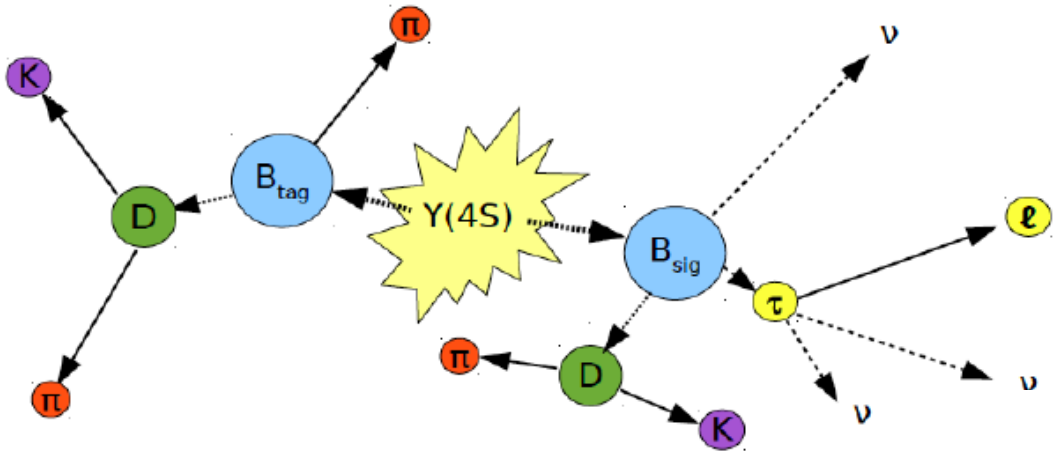


- Measure ratios to reduce theoretical and experimental uncertainties

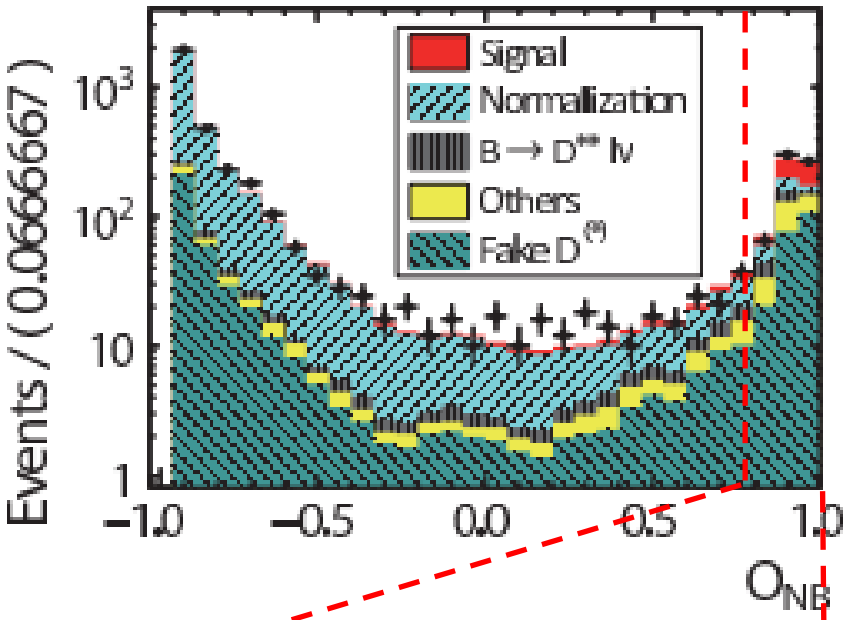
$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

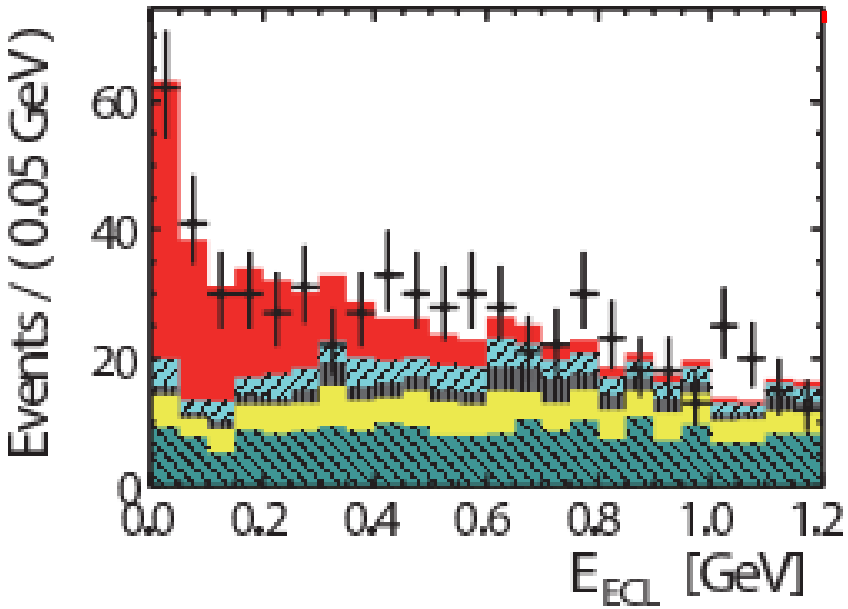
- BaBar reported an anomalous result PRL 109, 101802 (2012) much activity since

Belle results

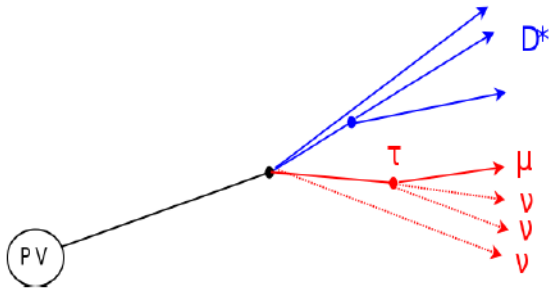


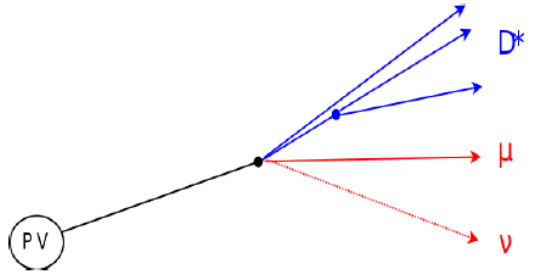
- Tag signal by fully reconstructing or identifying a semileptonic (SL) decay of the other B
- Then use residual energy in ECL, missing mass, multivariates and/or lepton momentum to separate signal
- Example: Phys. Rev. D **94**, 072007 (2016)
  - Semileptonic tag



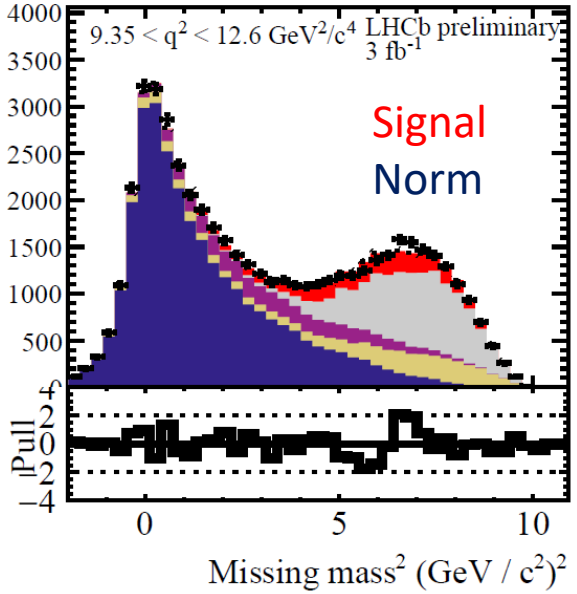


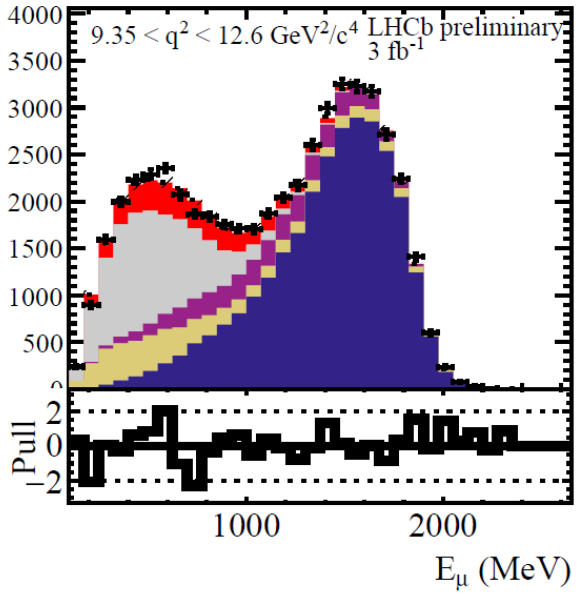
- LHCb also in the game using their vertexing prowess – Run 1 data only 3 fb^{-1}

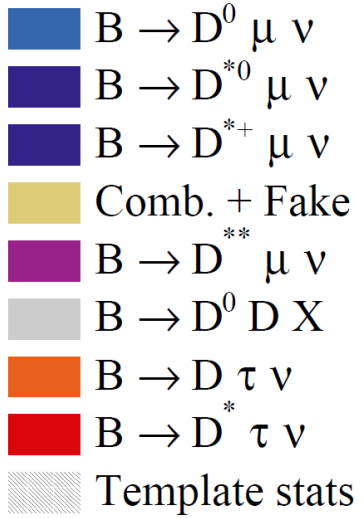




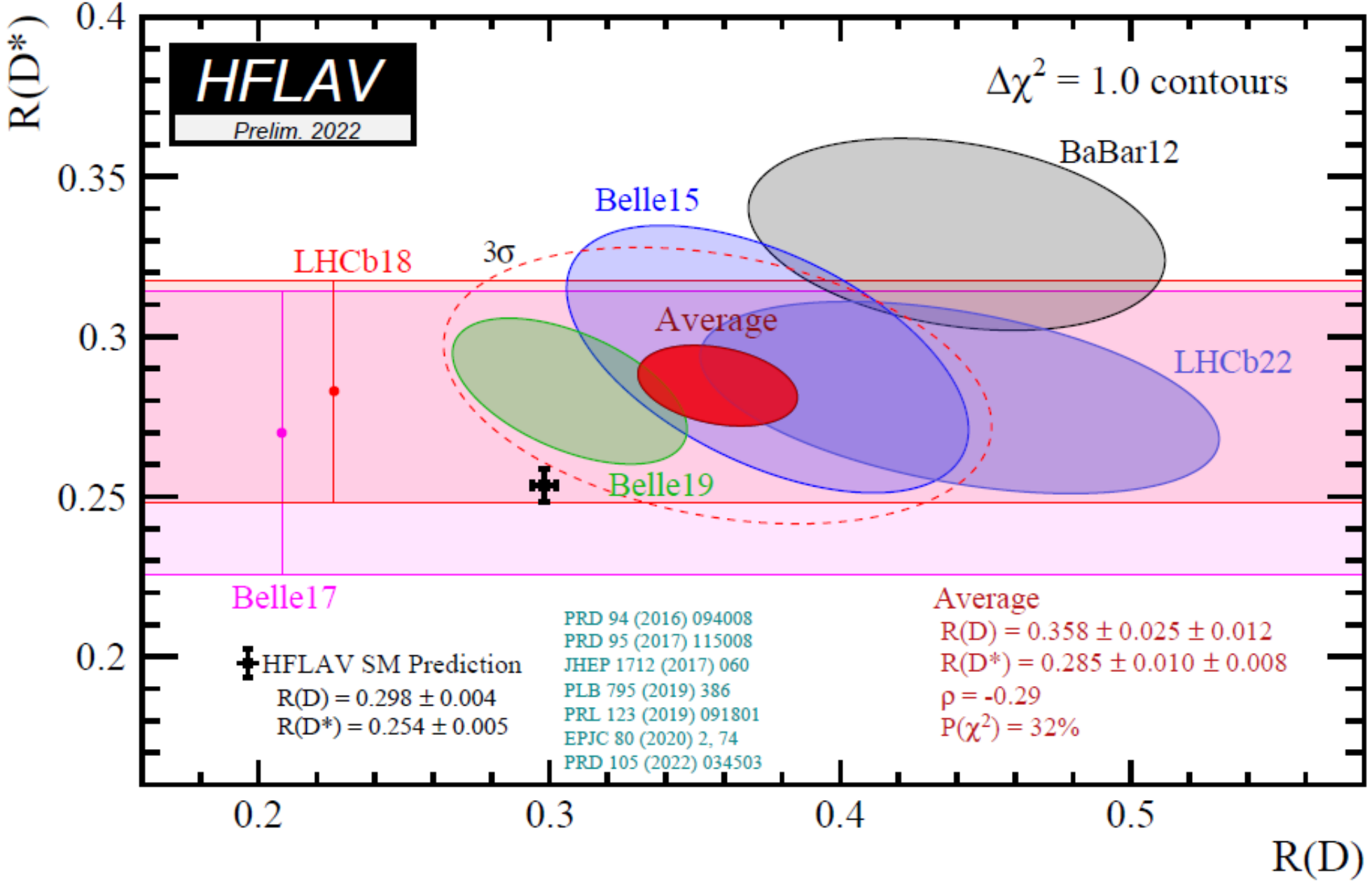
- Use B flight for transverse momentum and approximate full longitudinal boost to measured component → 20% B momentum resolution
- Template fit in bins of q^2, E_μ and missing-mass square in B's frame
  - **New: simultaneously fit to D and D* signal + control samples**







3.2σ deviation w.r.t. SM

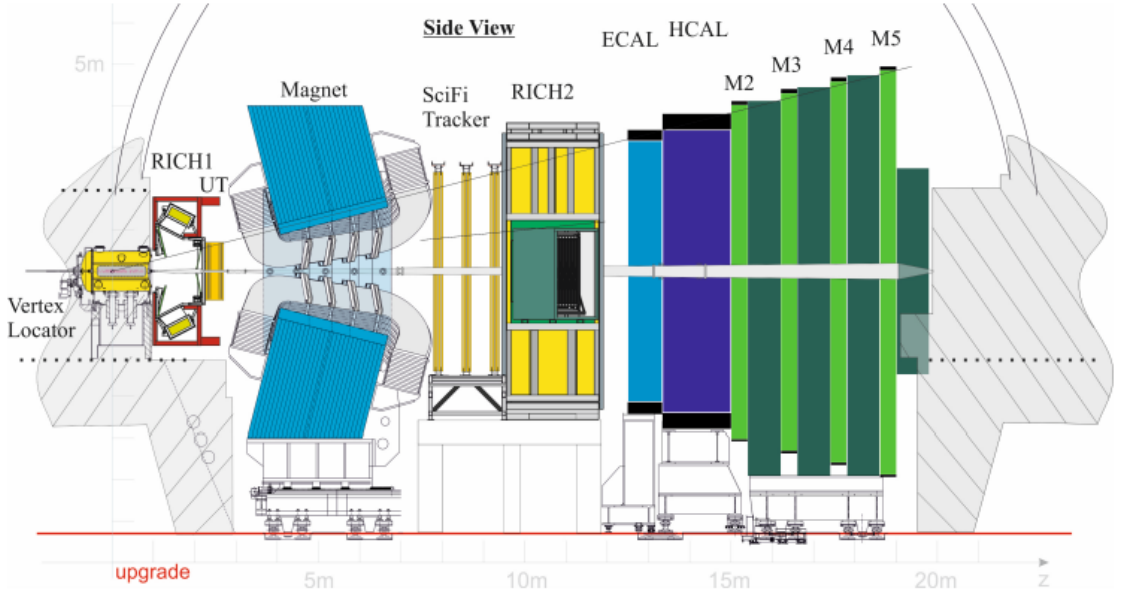


‘Something will turn up’,
Mr. Micawber (David Copperfield)

B ANOMALIES: THE FUTURE

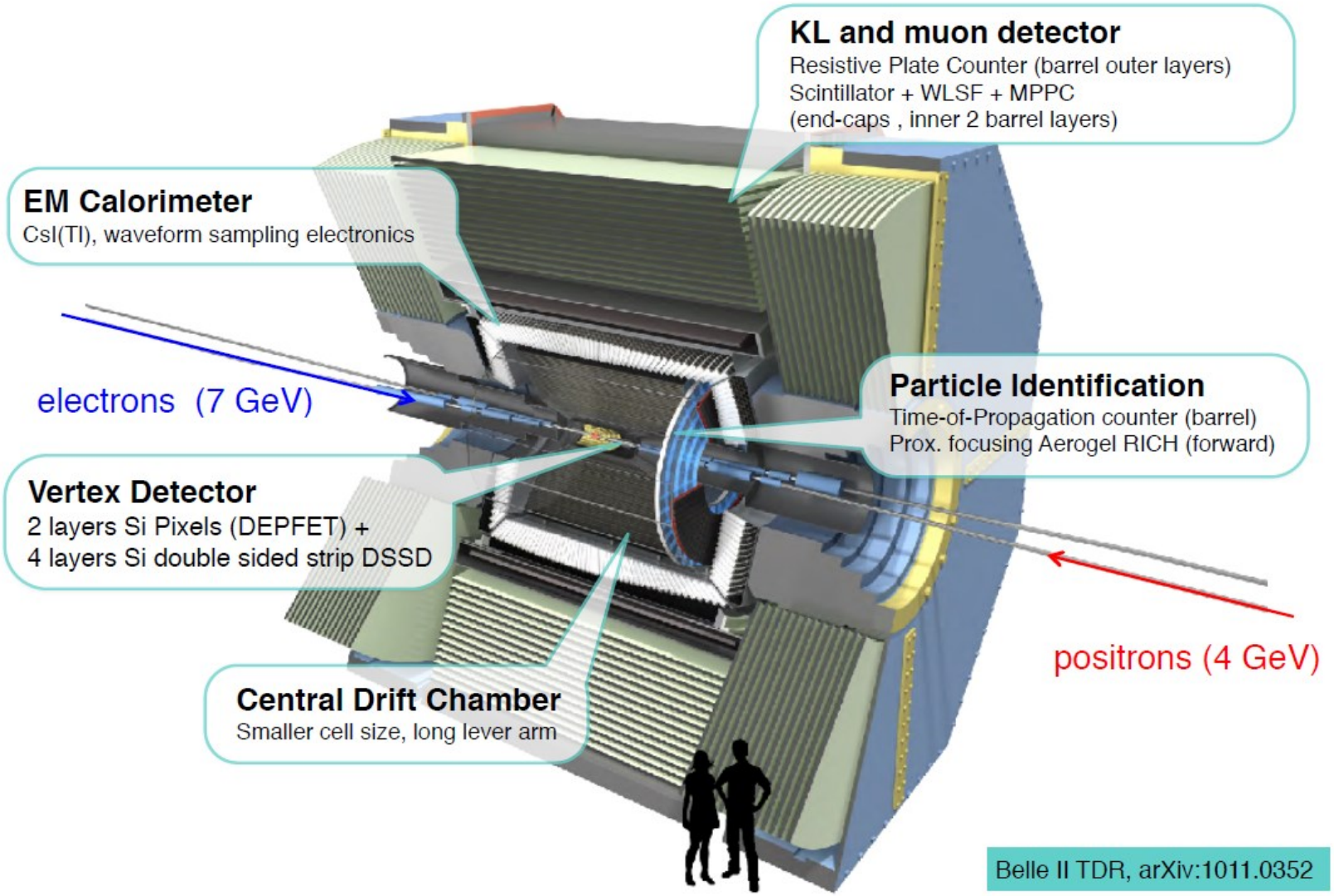
LHCb status

- New silicon vertex, tracker and SciFi tracker
- 40 MHz readout – factor 2-4 more in the trigger efficiency for hadrons (not so important for anomalies)
- **LHCb will continue to have a big impact**
- **CMS and ATLAS also focusing more on B-physics in the future**



Belle II

See K. Trabelsi plenary



Key advantages for anomaly measurements

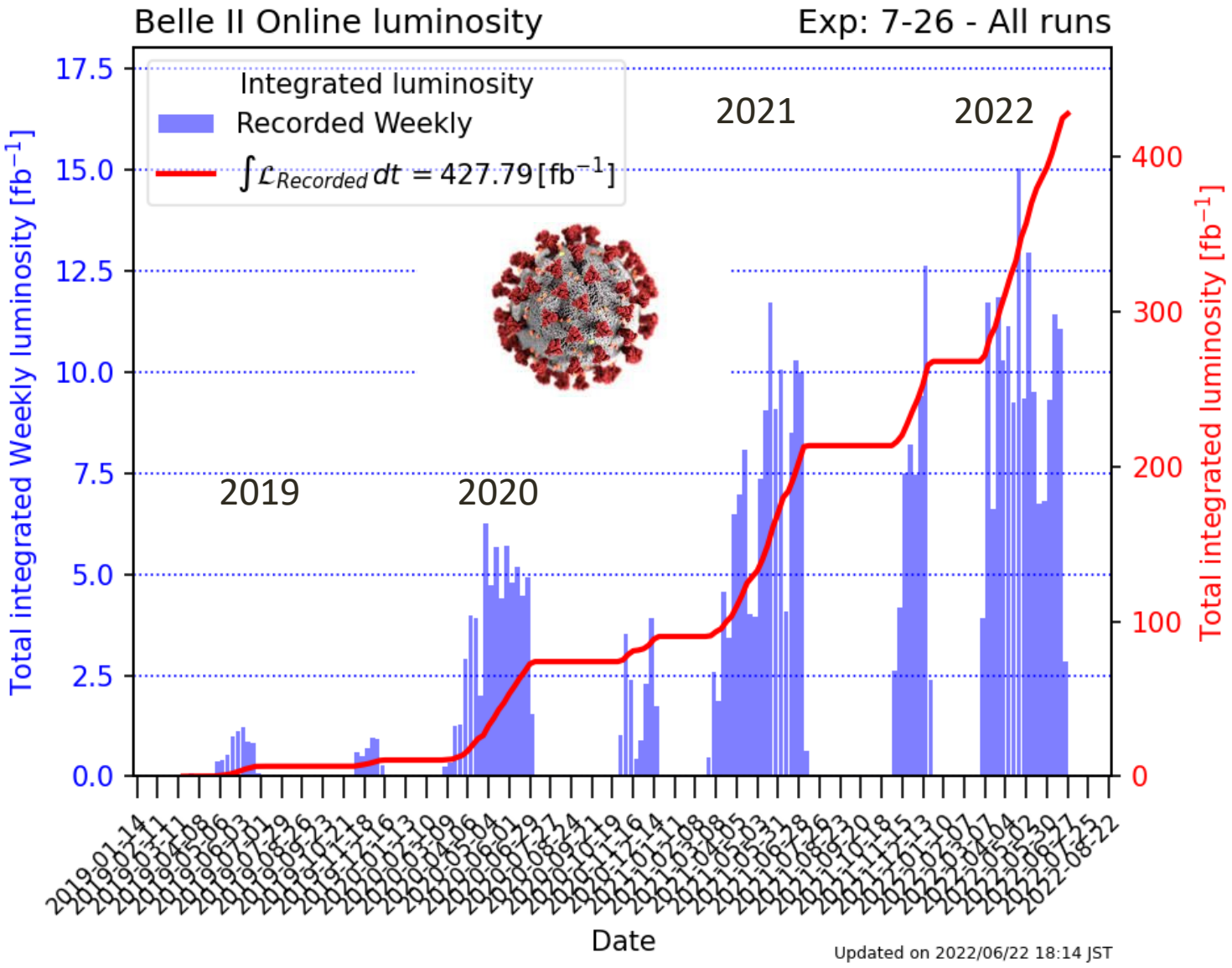
Hermiticity

Known initial state kinematics, i.e., good missing momentum resolution

Similar electron and muon identification efficiencies

Disadvantage: sample size

Integrated luminosity so far

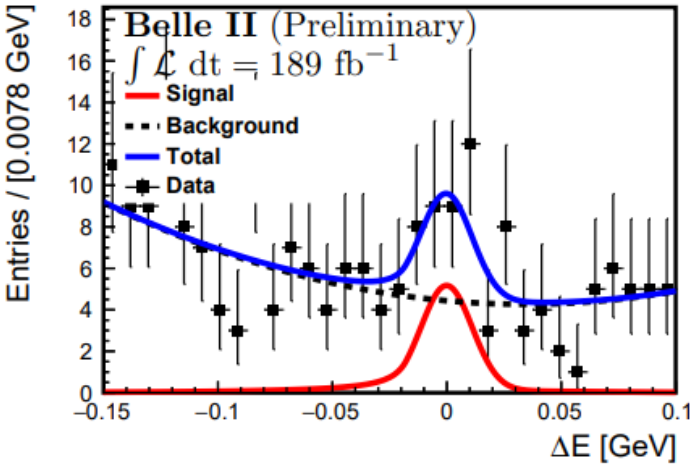


b → sll related results from Belle II

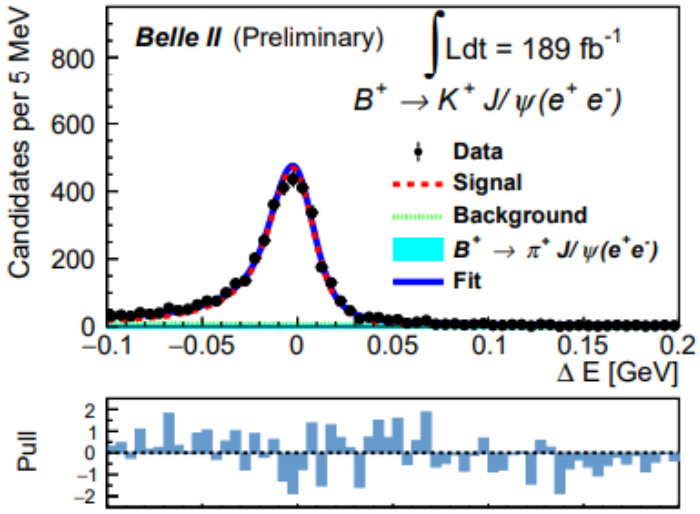
- B→K*ll (charged and neutral) studied

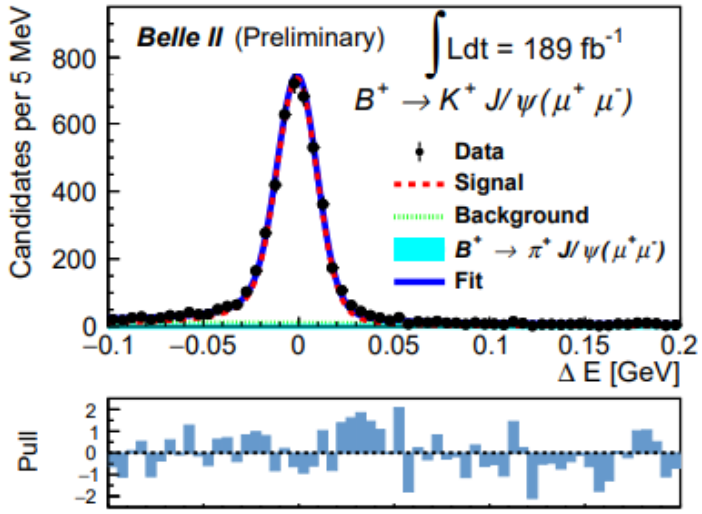
$$\mathcal{B}(B \to K^* \mu^+ \mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^* e^+ e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$

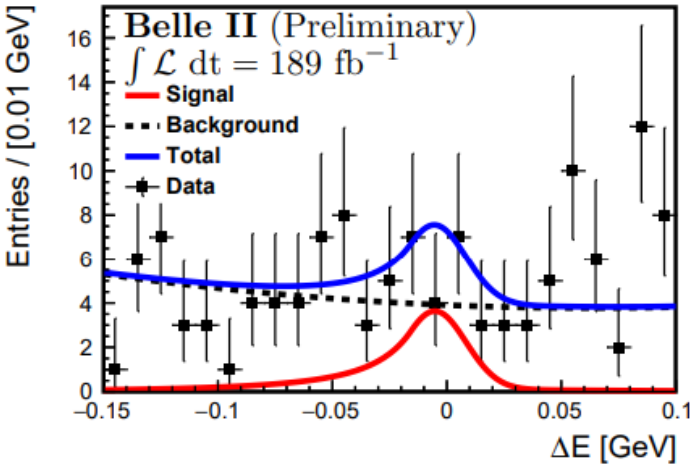
  - Similar efficiency for e and μ
  - Absolute measurement possible
  - arXiv:2206.05946 **[hep-ex]**



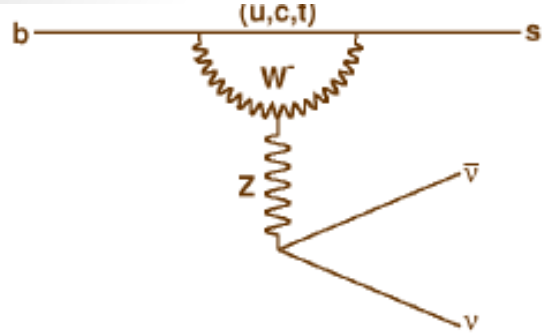
- B→J/ψK also studied - arXiv:2207.11275 **[hep-ex]**





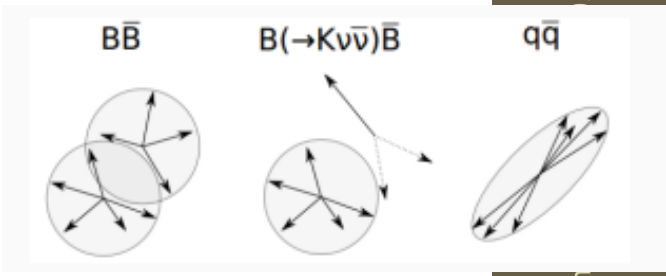


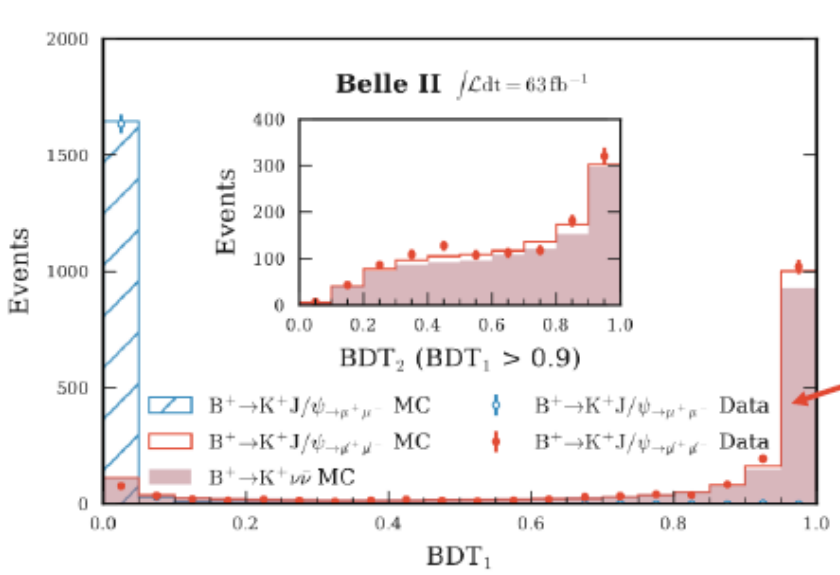
$b \to s\nu\nu$ - PRL **127**, 181802 (2021)



- Transition mediates by a virtual Z-boson.
- SM prediction for the $BF[B \to K^+\nu\nu]_{SM}$ is $(4.6 \pm 0.5) \times 10^{-6}$ **[B2TIP, PTEP 2019, 123C01].**

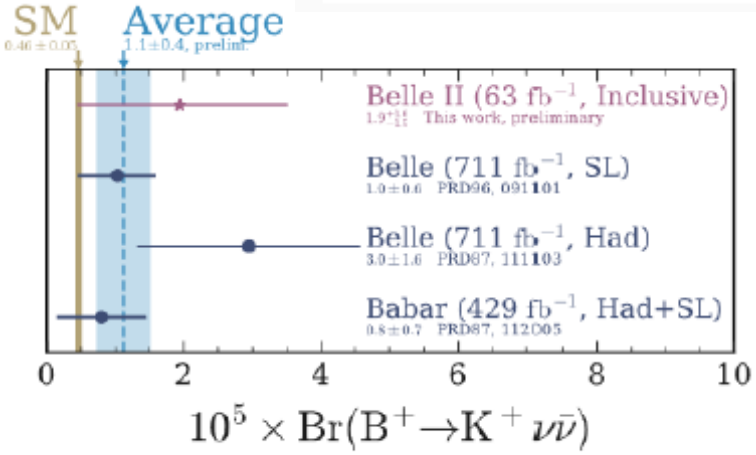
- **Inclusive tagging approach** : nested statistical-learning discriminators exploits efficiently topology allowing for sizeable signal (4%) while controlling large backgrounds.





- Validate with $B^+ \to K^+ J/\psi\,[\to \mu^+\mu^-]$

- $\mu^+\mu^-$ ignored
- K^+ momentum modified
  2-body → 3 body



Sensitivity with just 63 fb^{-1} data is already close to previous searches with significantly large data-set.

Semileptonic LUV results from Belle II

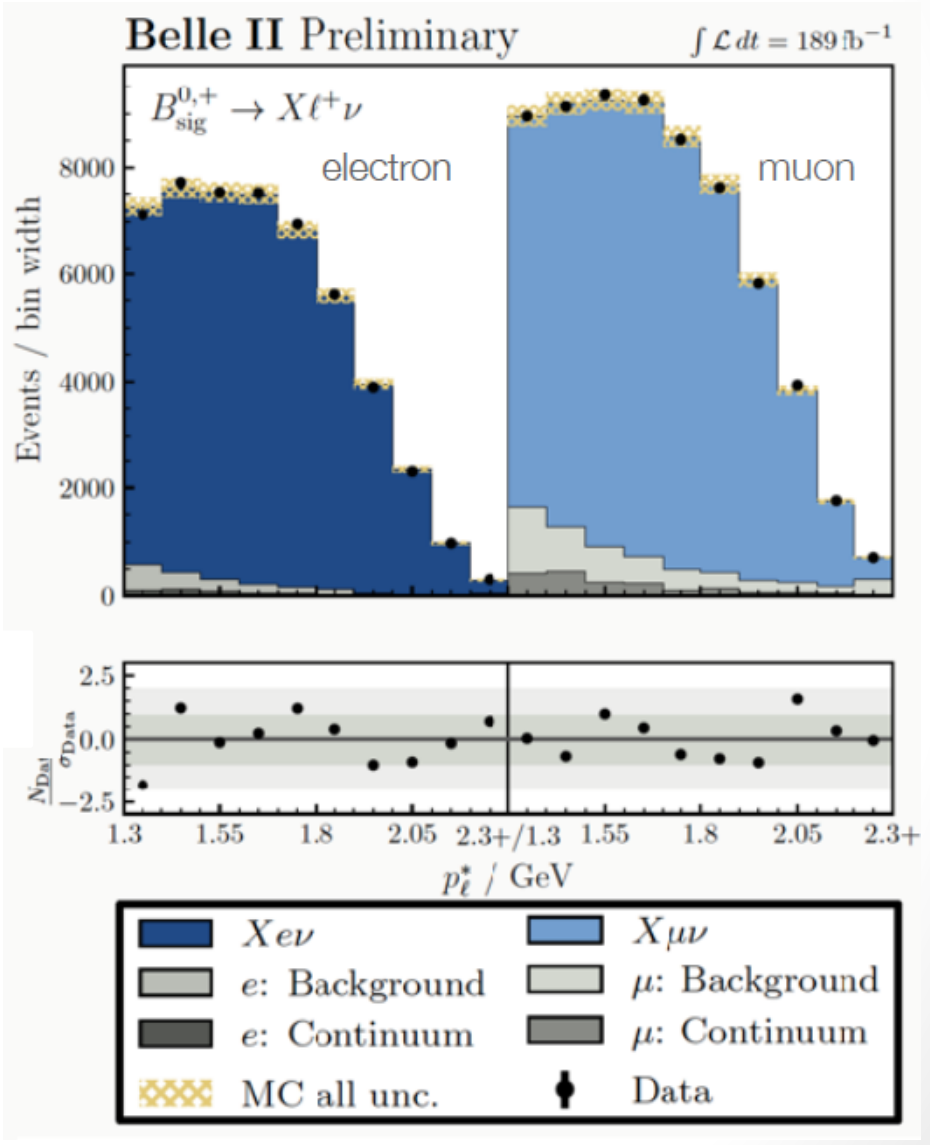
- Test of LUV with inclusive semileptonic decays

$$R(X_{e/\mu}) = \frac{B(B \to Xe\nu)}{B(B \to X\mu\nu)}$$

- Full reconstruction of one hadronic B decay then look at lepton spectrum from rest of the event
- Fit CM frame lepton momentum while constraining background with wrong-sign lepton control sample

$$R(X_{e/\mu}) = 1.033 \pm 0.010\,(\text{stat}) \pm 0.020\,(\text{syst})$$

- Most precise measurement of LUV in semileptonic decay
- Key step toward $R(X_{\tau/\mu})$
- Paper in preparation



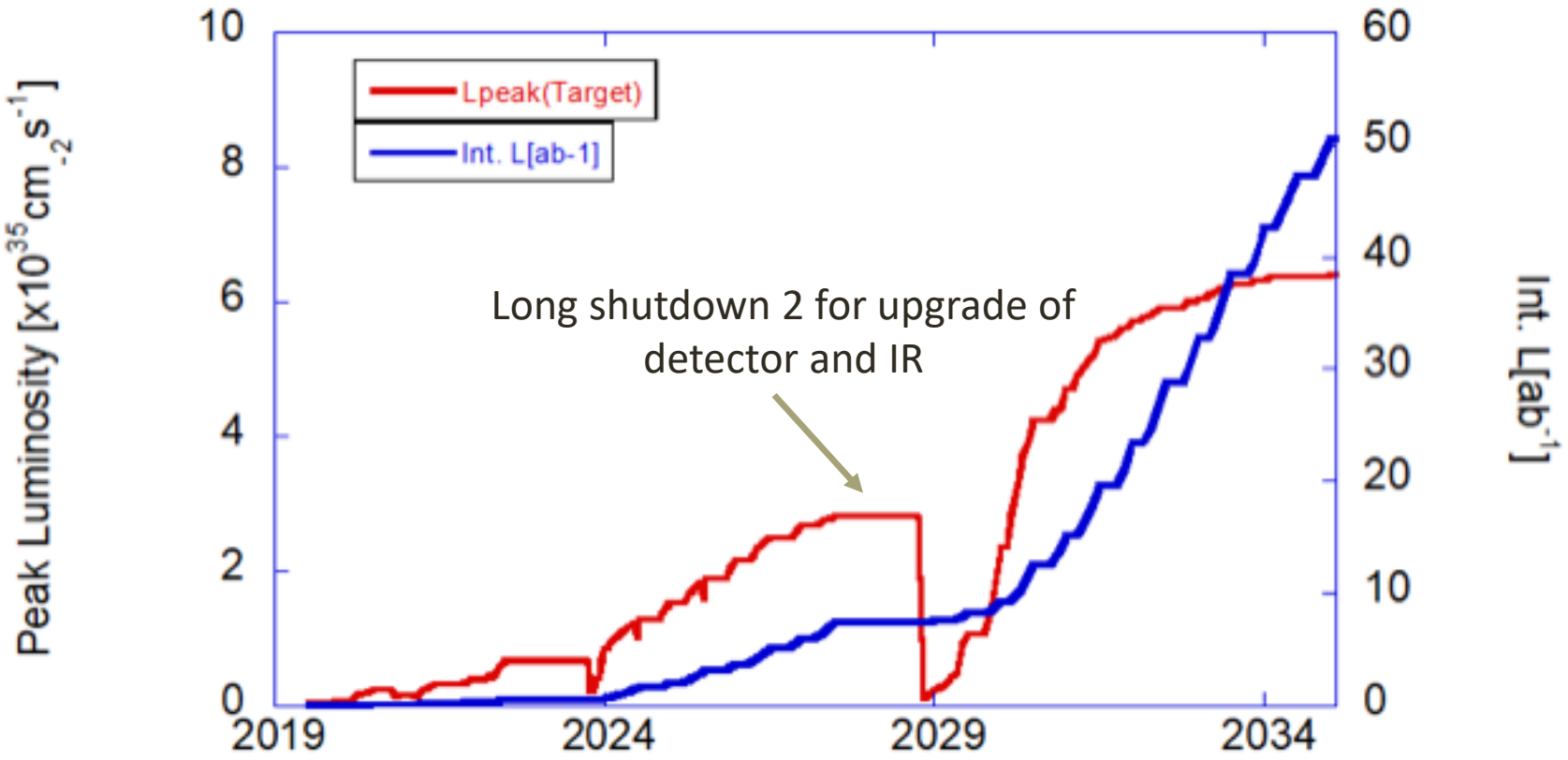
Belle II data-taking plan

High backgrounds from the beams have made stable running at high luminosity difficult

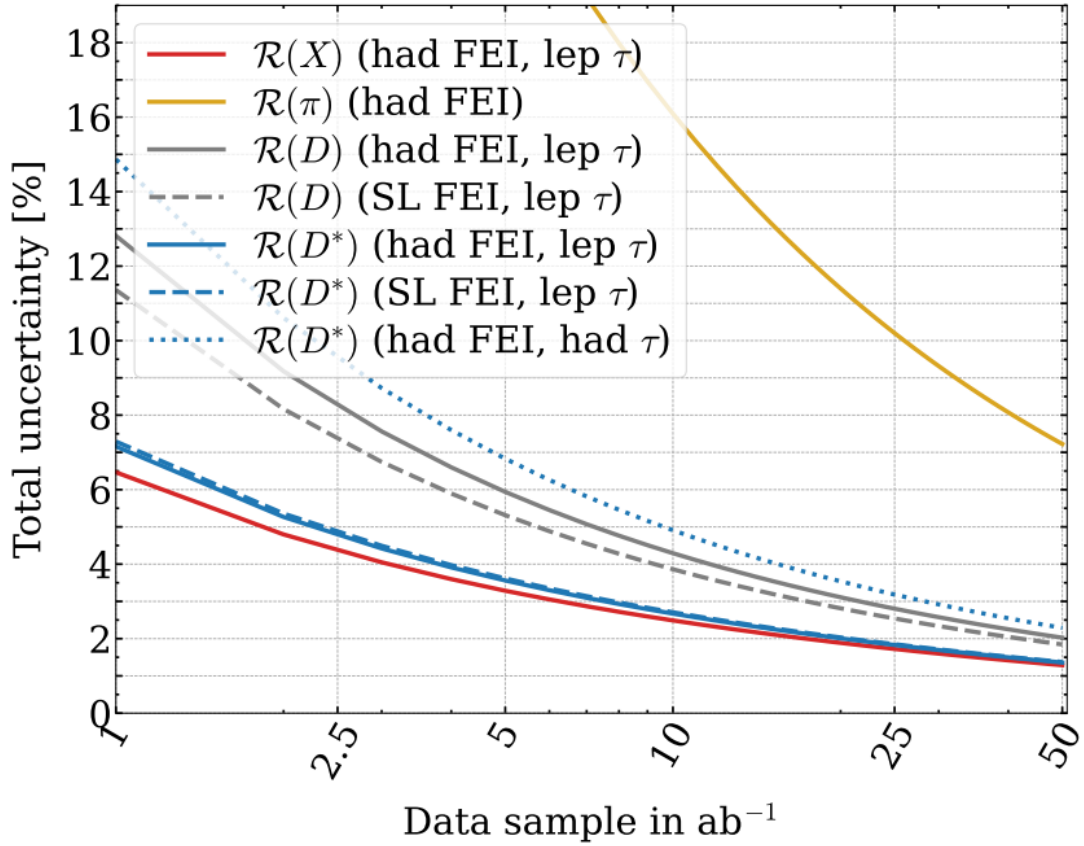
We have not accumulated data at the rate anticipated

Long shutdown ongoing: accelerator and detector improvements

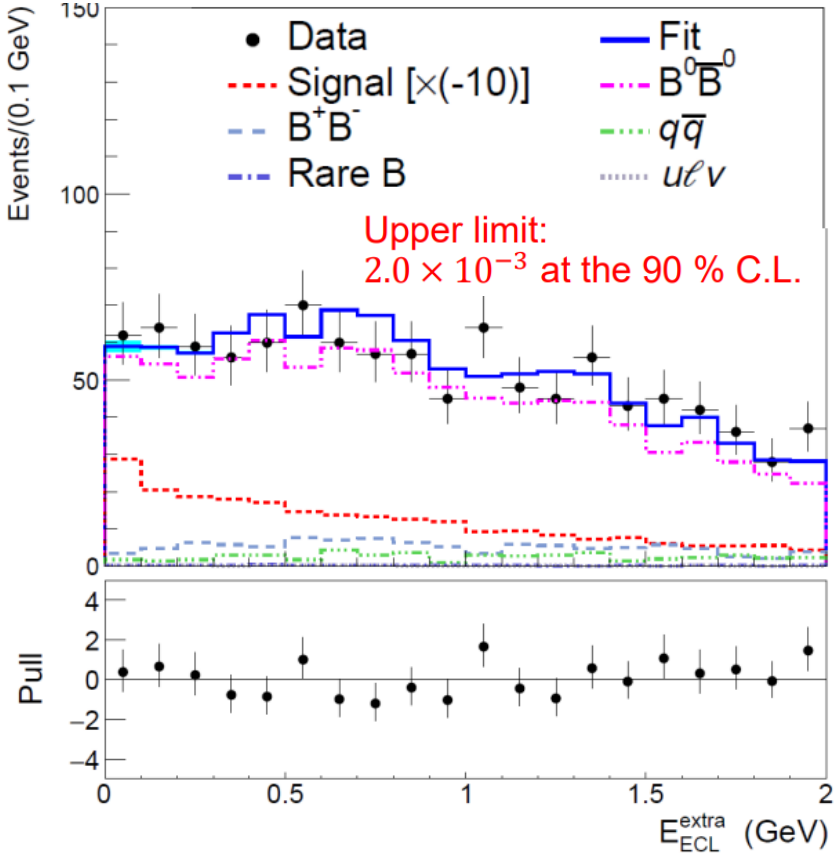
Path to 2 x 10^{35} $cm^{-2}s^{-1}$ but thereafter more work required



Some Belle II prospects



arXiv:2110.03871



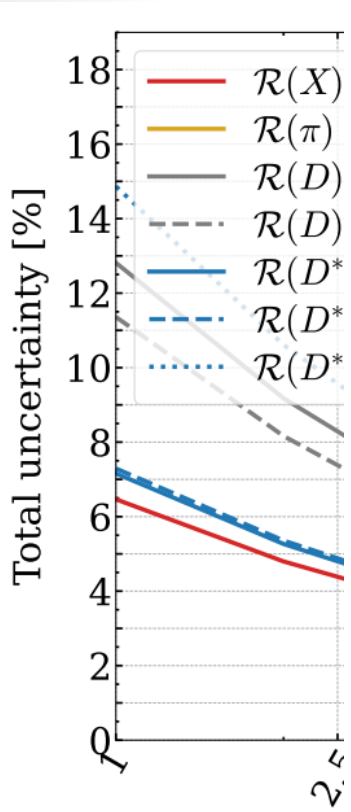
	$\mathcal{B}(B^0 \to K^{*0}\tau\tau)$ (had tag)	
ab^{-1}	"Baseline" scenario	"Improved" scenario
1	$< 3.2 \times 10^{-3}$	$< 1.2 \times 10^{-3}$
5	$< 2.0 \times 10^{-3}$	$< 6.8 \times 10^{-4}$
10	$< 1.8 \times 10^{-3}$	$< 6.5 \times 10^{-4}$
50	$< 1.6 \times 10^{-3}$	$< 5.3 \times 10^{-4}$

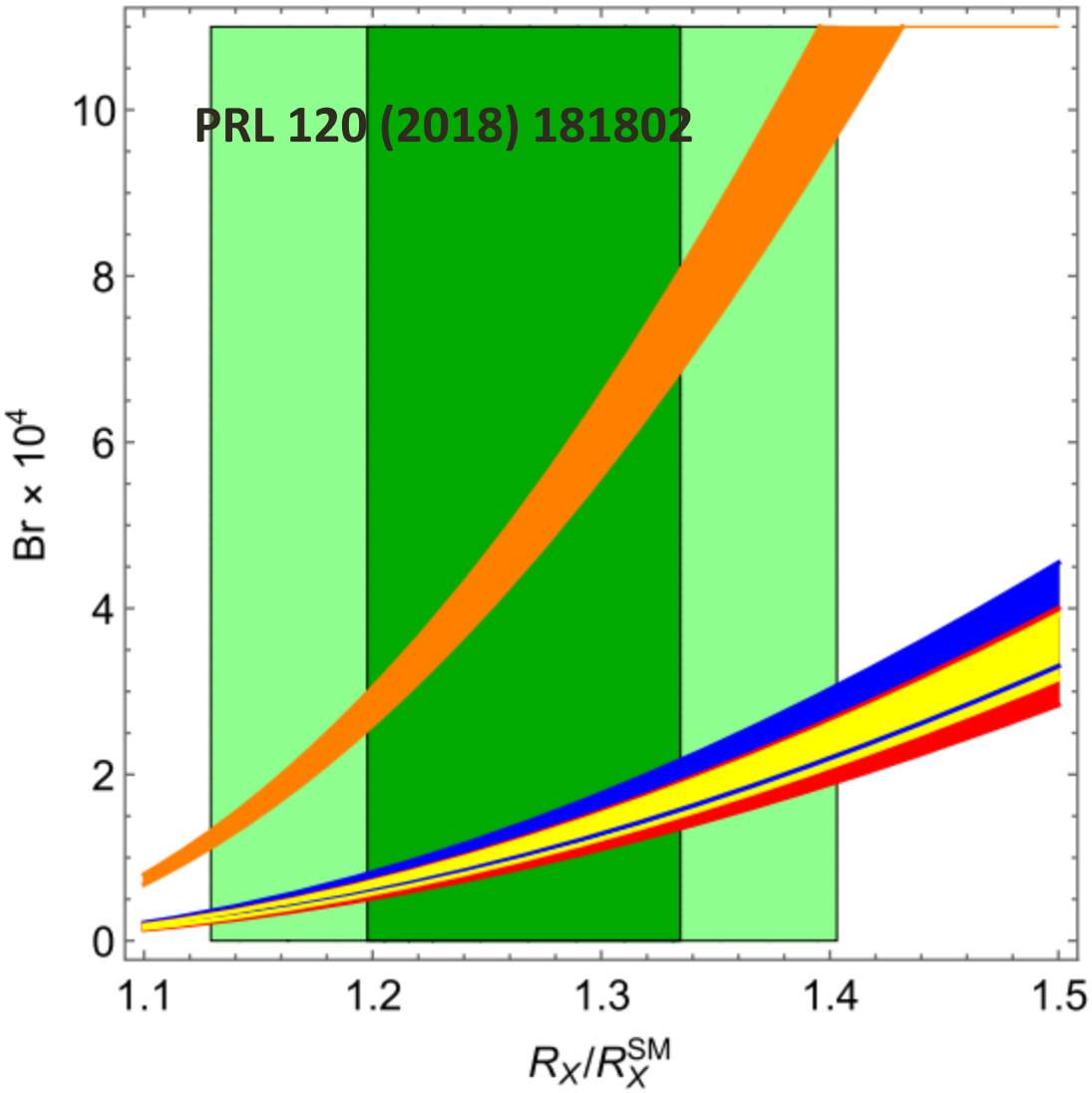
https://arxiv.org/pdf/2207.06307.pdf - Belle II Snowmass

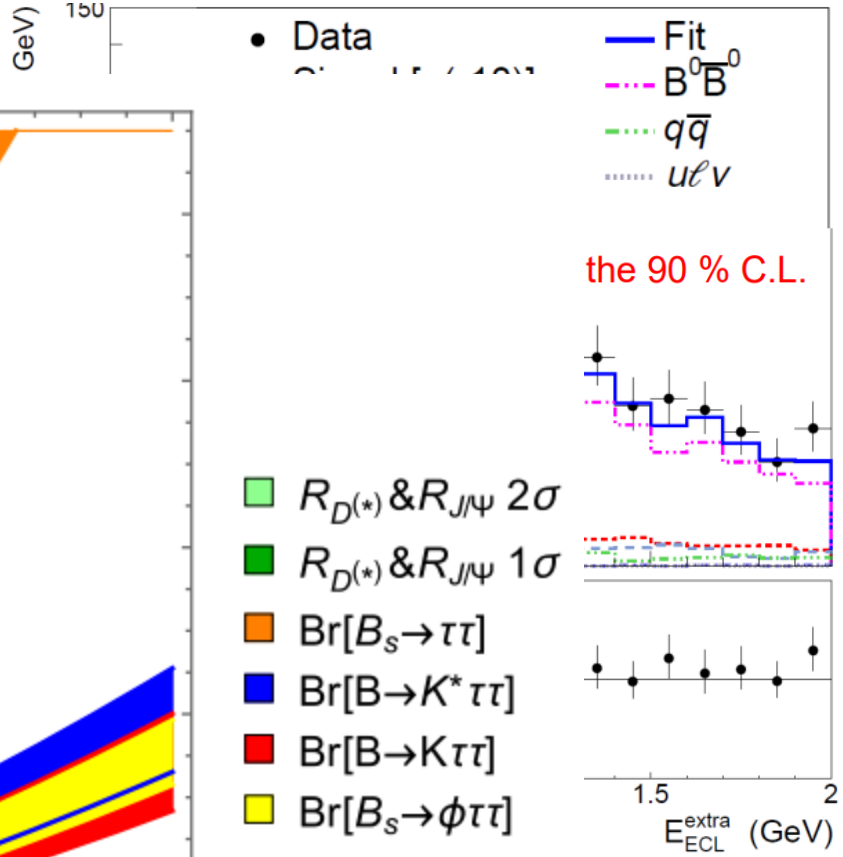
Nitty gritty and up to date predictions of what we can achieve

Some

arXiv:2110.03871





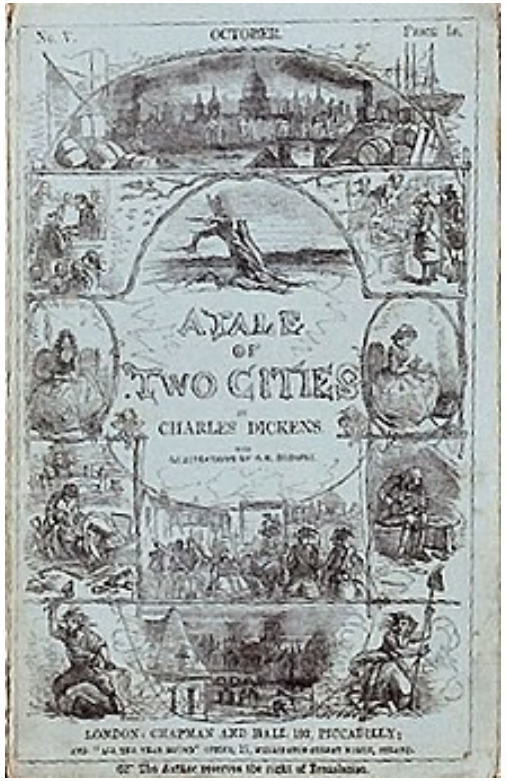


) (had tag)
mproved" scenario
$< 1.2 \times 10^{-3}$
$< 6.8 \times 10^{-4}$
$< 6.5 \times 10^{-4}$
$< 5.3 \times 10^{-4}$

https://arxiv.org/pdf/2207.06307.pdf - Belle II Snowmass
Nitty gritty and up to date predictions of what we can achieve

Conclusion

- ‘It was the best of times, …..’
  - Many measurements in B decay (and elsewhere) showing deviations from the SM – several related to lepton flavour universality violation
- ‘it was the worst of times.’
  - No single 5σ observation in a robust observable
  - No corroboration between two experiments
- However, more data coming for LHC and Belle II
- Let us see where we are by the XXVIth DAE-BRNS

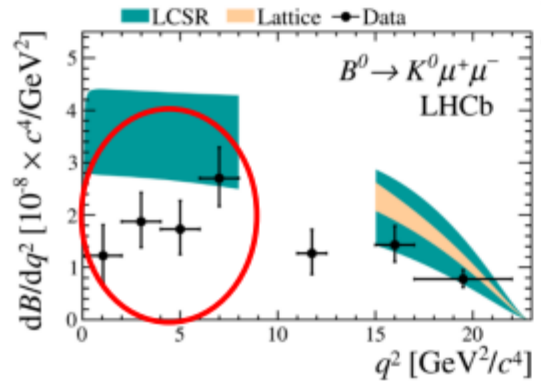


BACKUP

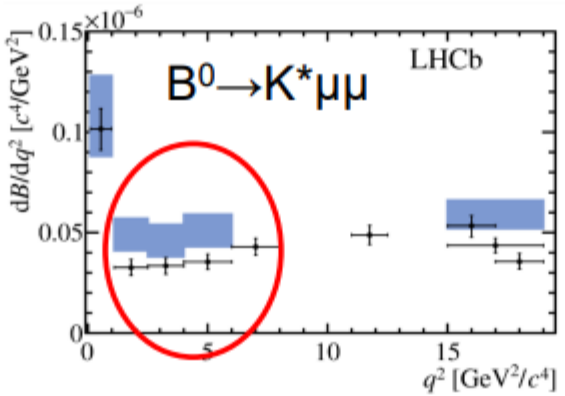
b→sll (& dll) exhibit A: differential BFs

Systematic failure of theory to describe the differential branching fractions at low q^2.

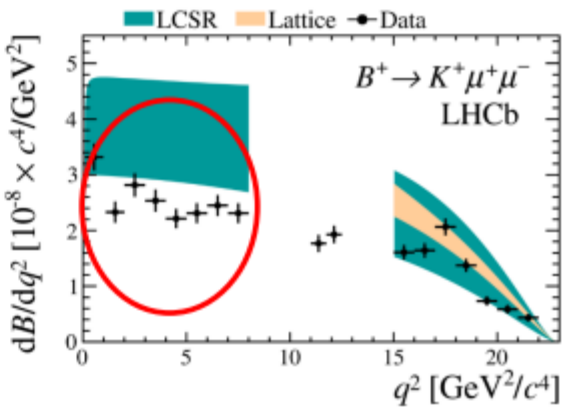
[JHEP 06 (2014) 133]



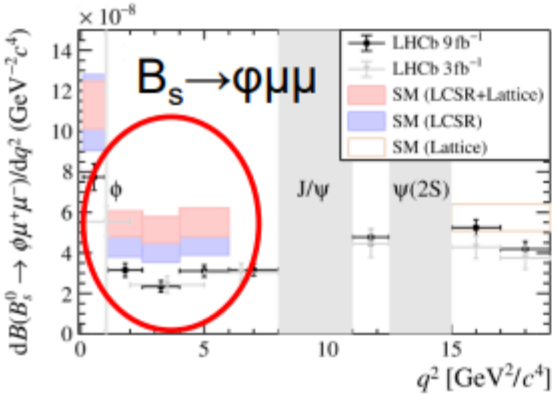
[JHEP 04 (2017) 142]



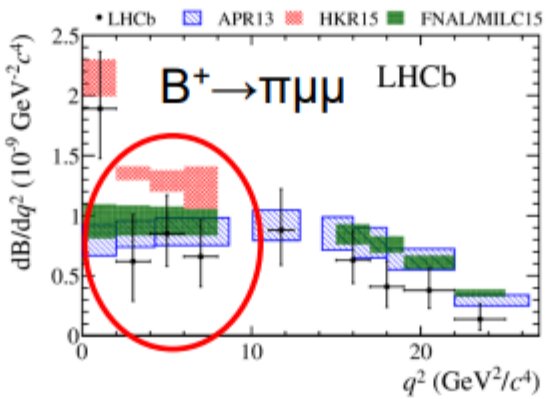
[JHEP 06 (2014) 133]



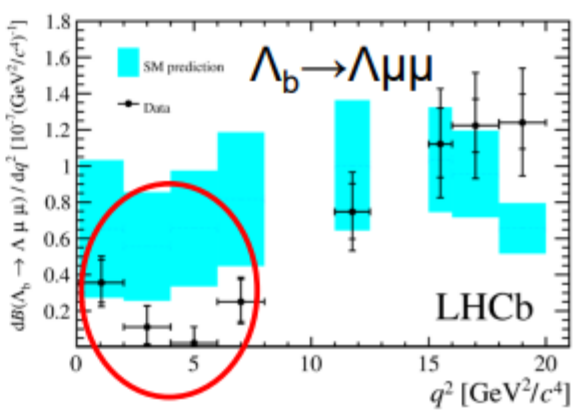
[PRL 127 (2021) 151801]



[JHEP 10 (2015) 034]



[JHEP 06 (2015) 009]



This is unquestionably a real effect. But maybe the theory uncertainties are underestimated. The differential BFs are not clean observables by any means.