Flavour Physics part 2:

Test the Standard Model with meson decays

Content

- New physics search: The "Heisenberg way"

- Rare decays: $b \rightarrow s\, l^+ l^-$
- Lepton flavor saga
  - Lepton Flavor Violation
  - Lepton Flavour Universality e/μ
  - Lepton Flavour Universality μ/τ

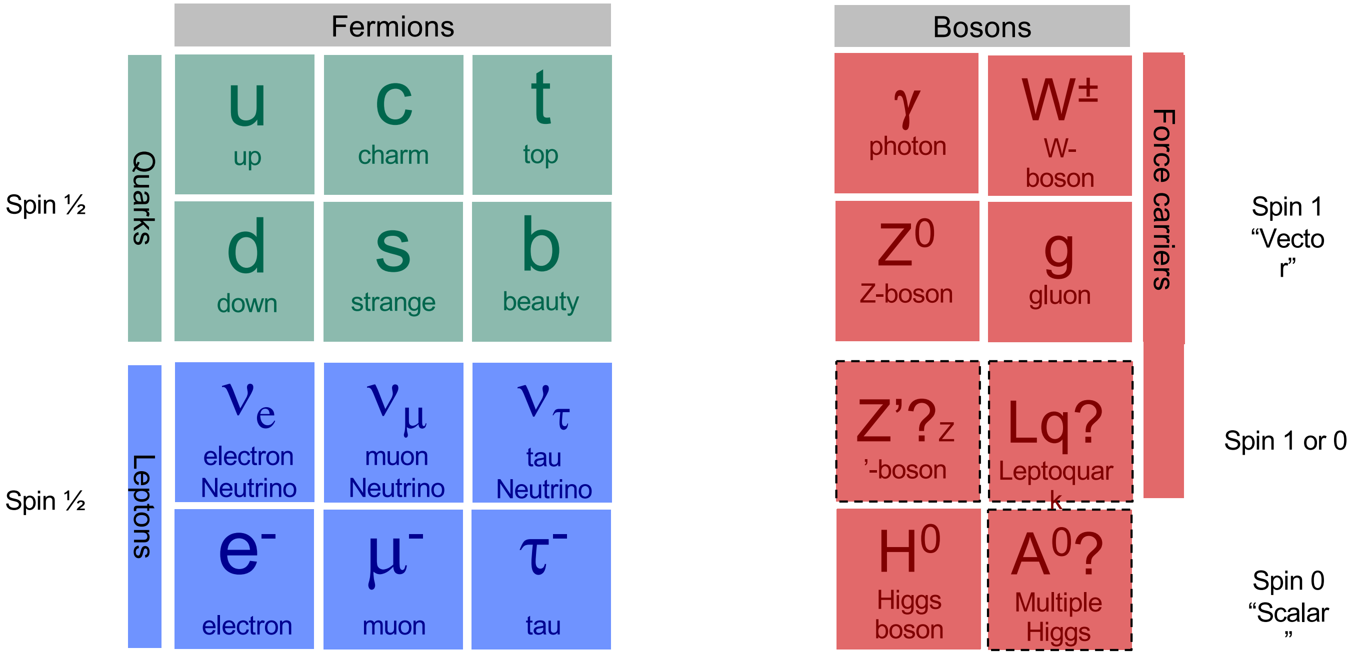
Johannes Albrecht

28. March 2023

Heisenberg-Programm

Deutsche Forschungsgemeinschaft DFG

BCD Dortmund Bologna Clermont Ferrand



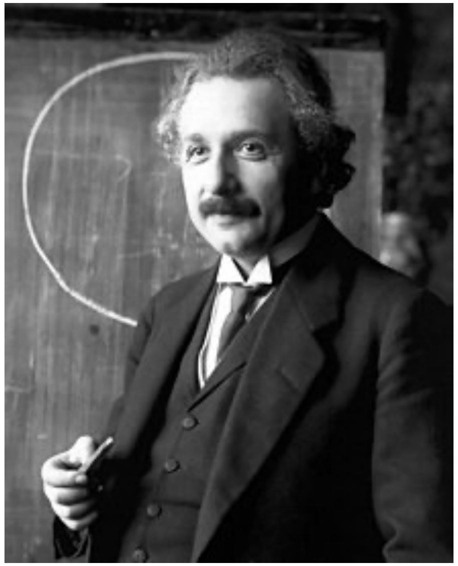
<u>Open questions of the SM</u>

– Cosmological observations: dark matter & matter-antimatter asymmetry
– Hierarchy of masses & couplings

Extended theories come with new heavy particles

How can we discover these extensions?

Einstein and Heisenberg



Einstein: $E = m\,c^2$	Heisenberg: $\Delta E \cdot \Delta t \geq \hbar/2$
Typical collider	Use quantum fluctuations
→ Limited by collider energy → LHC: O(1TeV)	→ Limited only in precision → Model dependent O(100)TeV
→ No increase in energy until ~2050	→ A lot of precision data coming (HL-LHC, Belle 2, CERN BDF, …)

Expected and unexpected discoveries

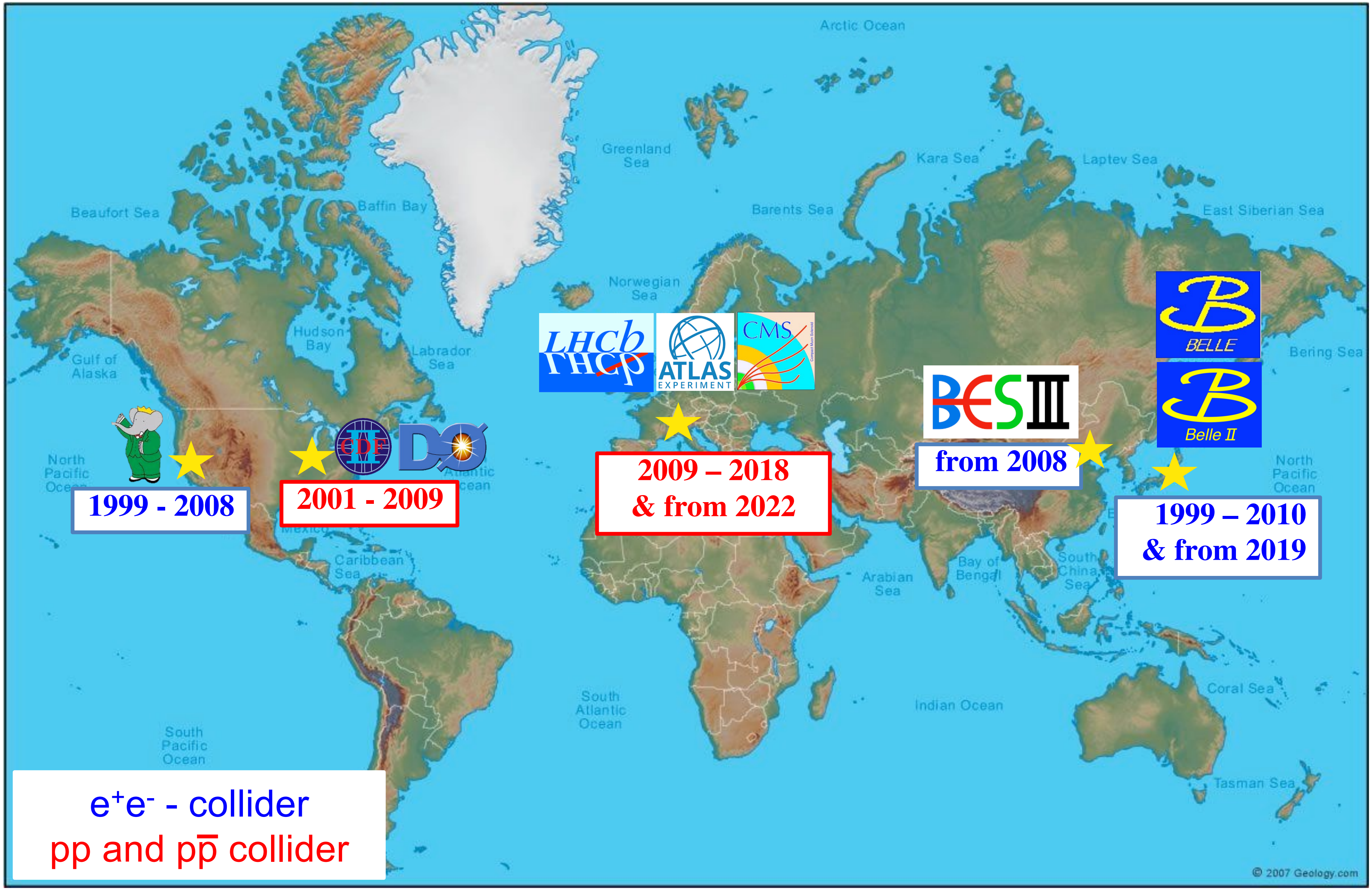
The Standard Model of particle physics

Years from concept to discovery

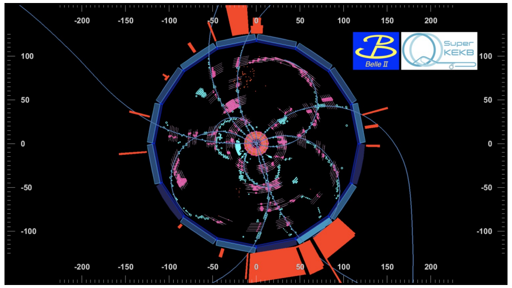
Leptons
Bosons
Quarks

Theorised/explained
Discovered

Flavour physics across the world

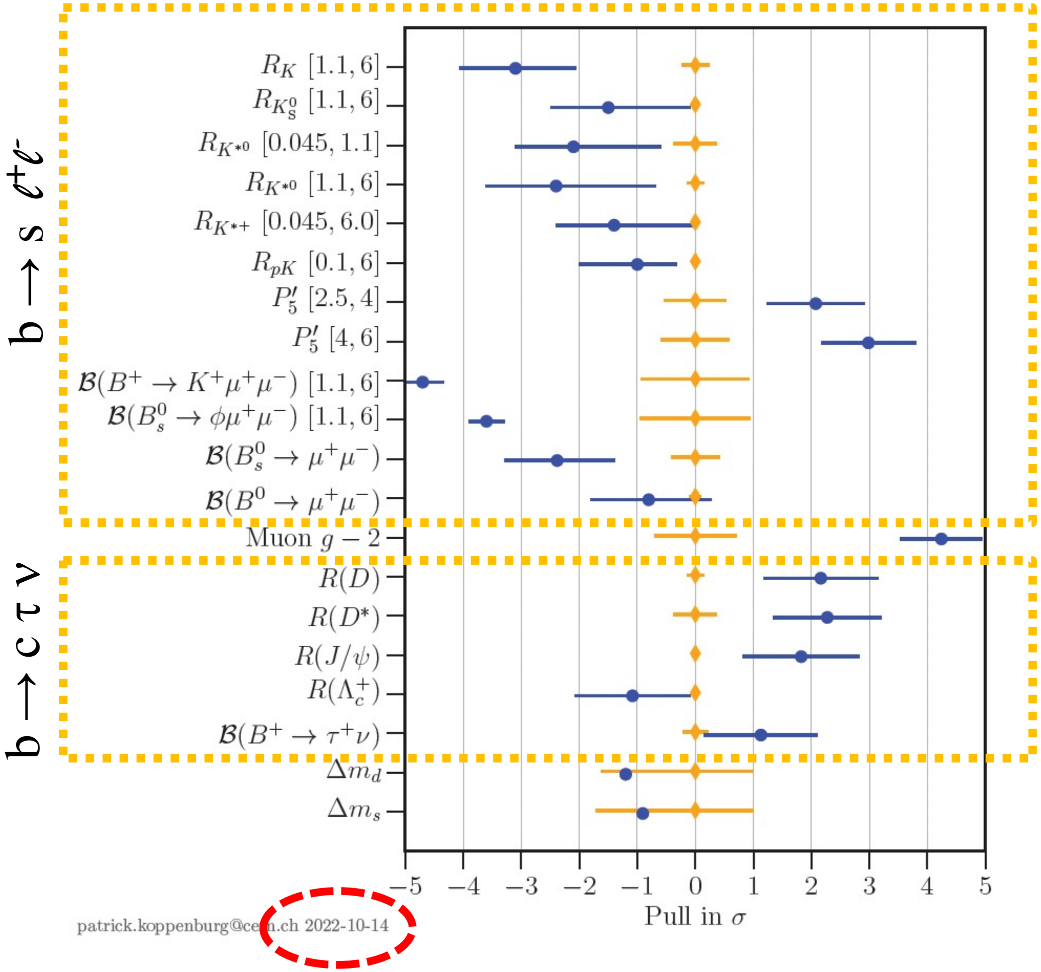


Flavor at electron and proton colliders



- Defined initial state:
  - Low trigger bias
  - Full event reconstruction, low multiplicity
  - Allows selection of inclusive and invisible decays
  - Experimentally: **$e^- \cong \mu^-$**
- Excellent for decays with difficult signatures, CP tests
  - **$B^- \to \tau^- \nu$, $B \to K^* \nu\nu$, ..**
  - **τ^- decays (LFV)**

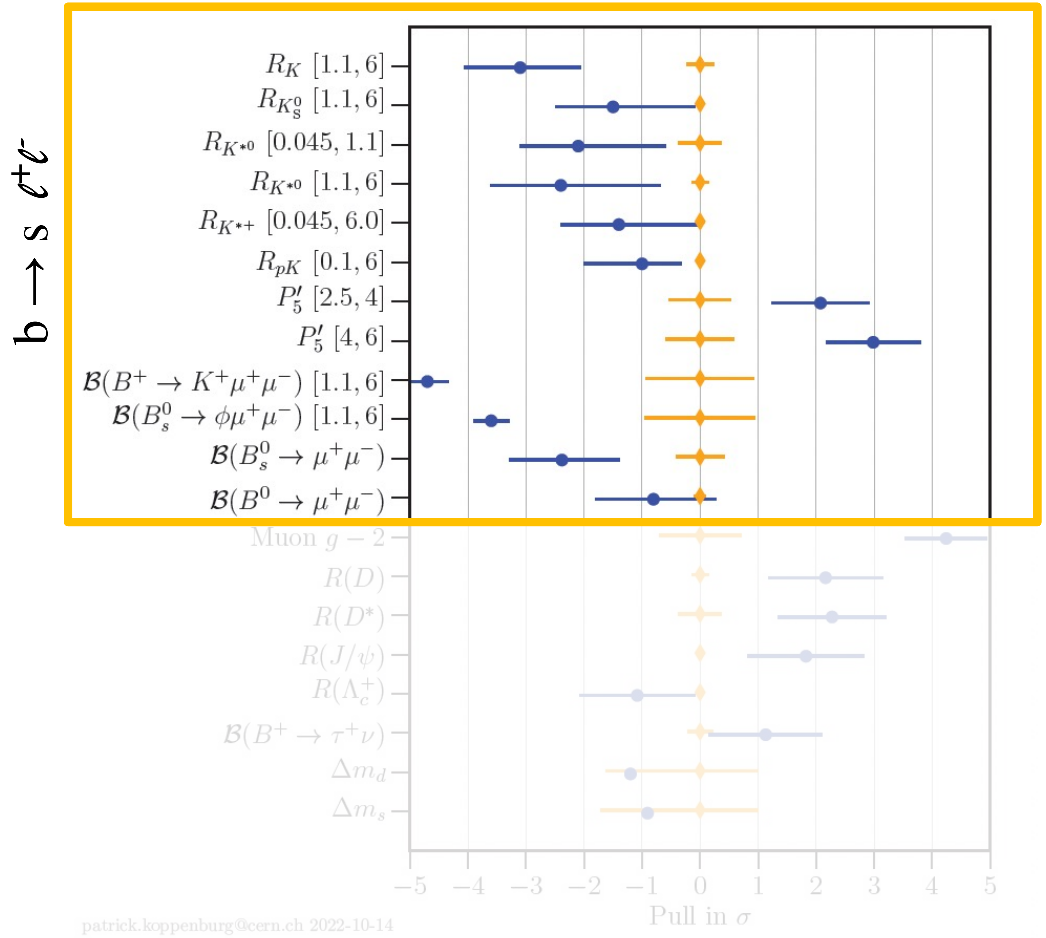
- Complex hadronic environment
- Very big $\mathbf{b\bar{b}}$ & $\mathbf{c\bar{c}}$ (and $\tau^+\tau^-$) production rate
  - Specialized on (very) rare and clean final states → then cleaner than e^+e^-
  - Leading for all charged decays **$B \to \mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, $D \to K^+\pi^-$**
- Trigger and reconstruction are significant challenges, specially for ATLAS/CMS



So far no clear 5σ sigma deviation

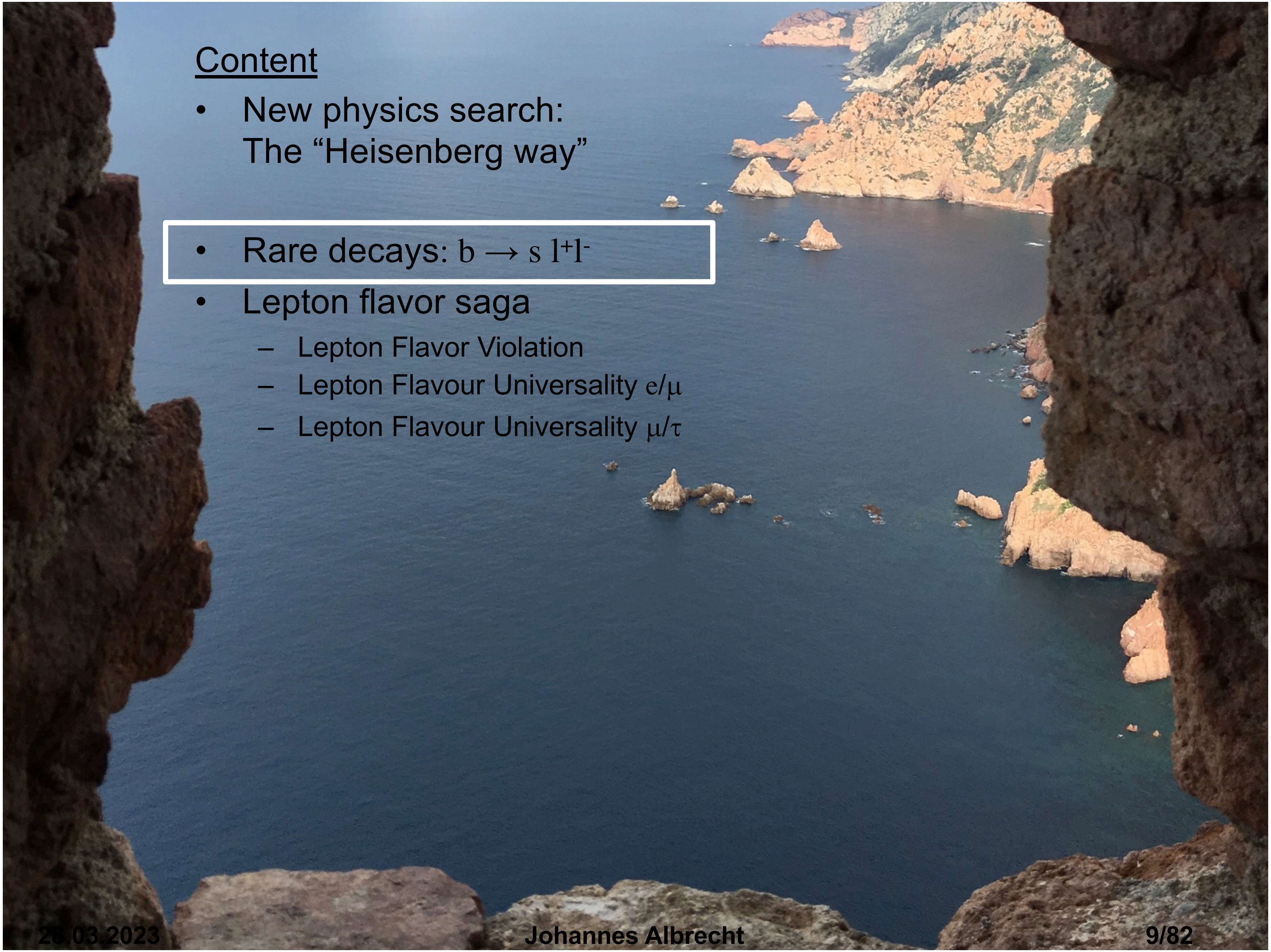
Falsifying anomalies is prime task for flavour-physicists

If any of these anomalies confirmed with 5+x sigma => huge breakthrough



Anomalies part 1:

Testing b ⟶ s $\ell^+\ell^-$ transitions



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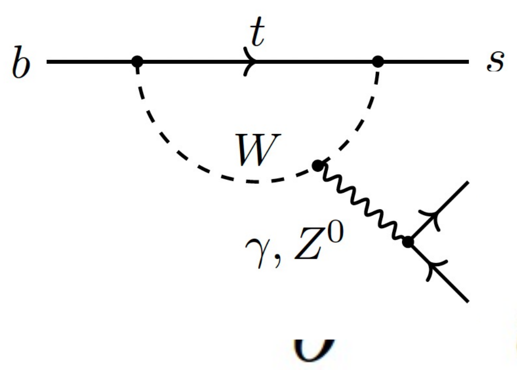
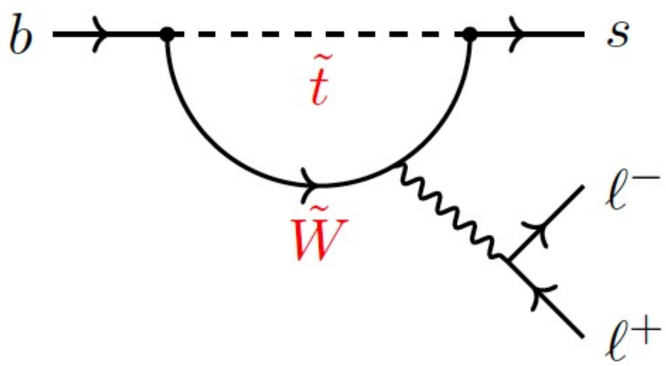
$b \to s\ell\ell$ decays in the SM



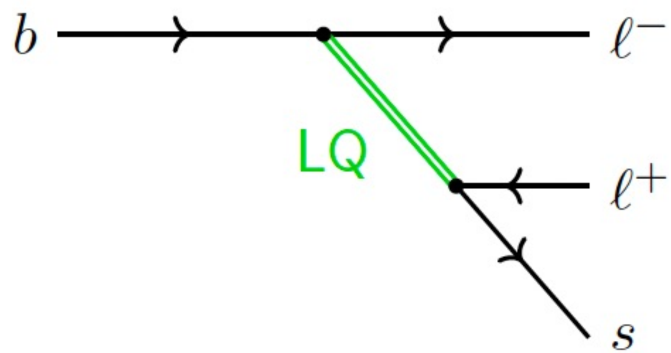
→ $s\ell\ell$ decays in the SM

Possible contributions from NP

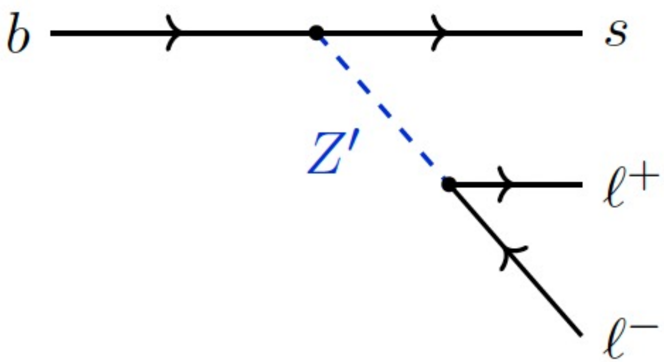
Supersymmetry



Leptoquarks

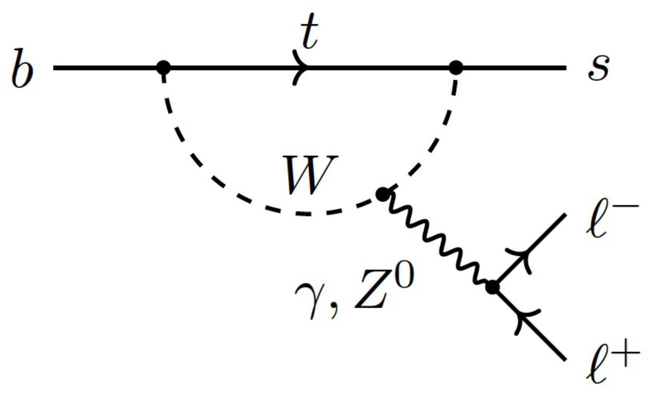


New heavy gauge bosons



Testing $b \to s \ell^+\ell^-$ transitions

$b \to s\, \mu^+\mu^-$ base diagram



- Purely leptonic
  - "add nothing"

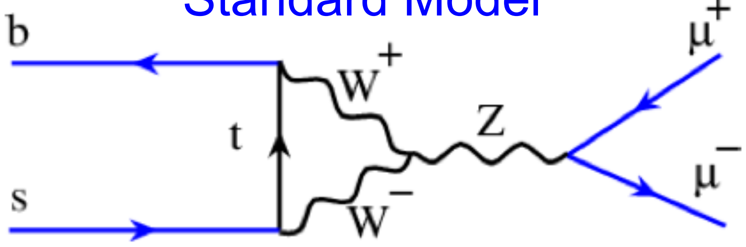
- Semileptonic
  - add d quark as spectator
    → $B^0 \to K^{*0}\, \mu^+\mu^-$
  - add s quark as spectator
    → $B_s \to \phi\, \mu^+\mu^-$
  - add u quark as spectator
    → $B^+ \to K^+\, \mu^+\mu^-$

Golden channel: $B_{s,d} \to \mu^+\mu^-$

Theory prediction: Standard Model

decay	SM
$B_s \to \mu^+\mu^-$	$3.5 \pm 0.3 \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$1.1 \pm 0.1 \times 10^{-10}$

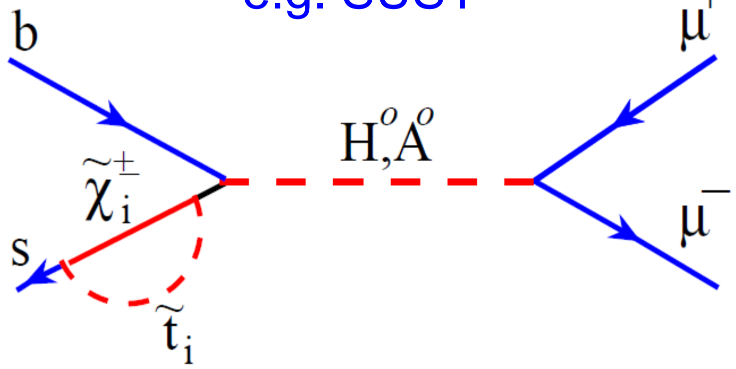
SM: Buras, Isidori et al: EPJC72(2012) 2172
Mixing effects: Fleischer et al, PRL109(2012)041801



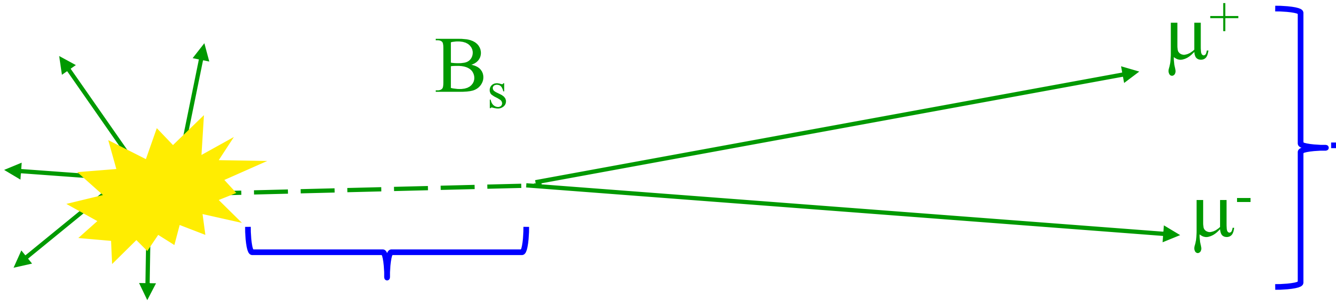
Left handed couplings
→ helicity suppressed

Discovery channel for New Phenomena

➔ Very **sensitive to an extended scalar sector**
(e.g. extended Higgs sectors, SUSY, etc.)

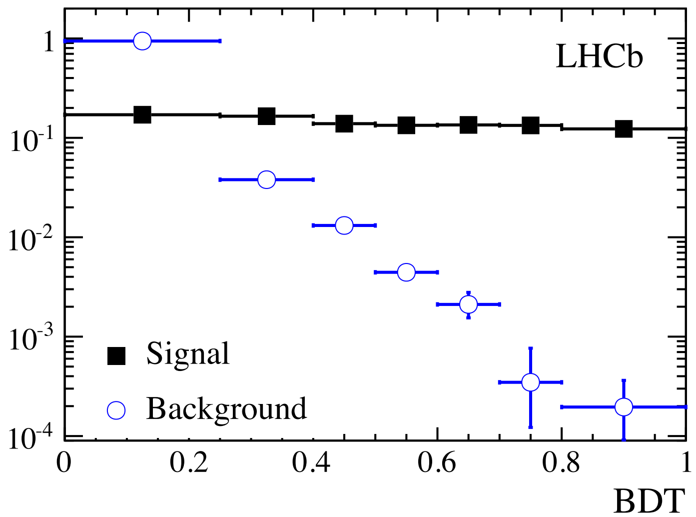


Search strategy: Example LHCb

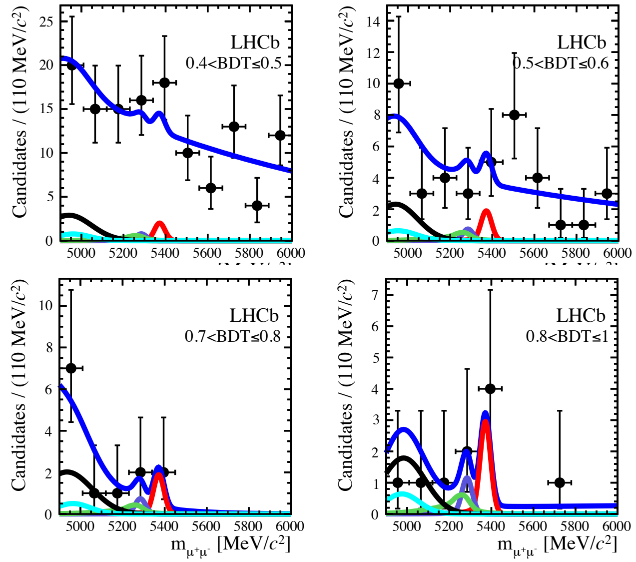


Classification of events

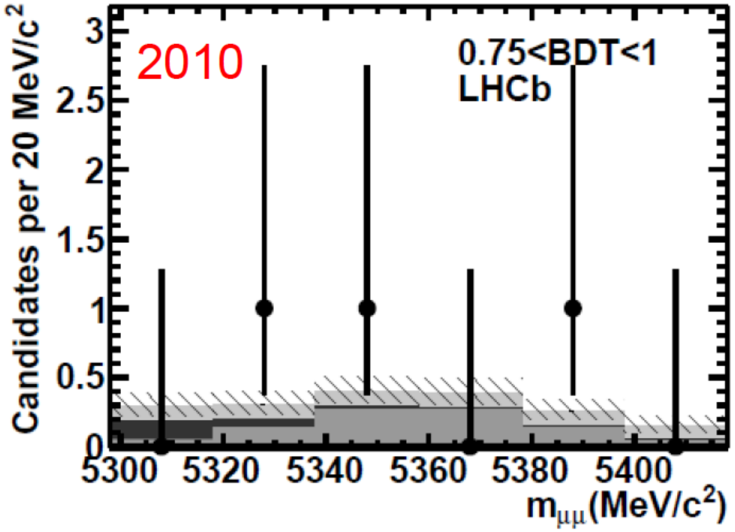
BDT (topology, kinematics)



Invariant mass



Measurement of exclusion limits or decay rates



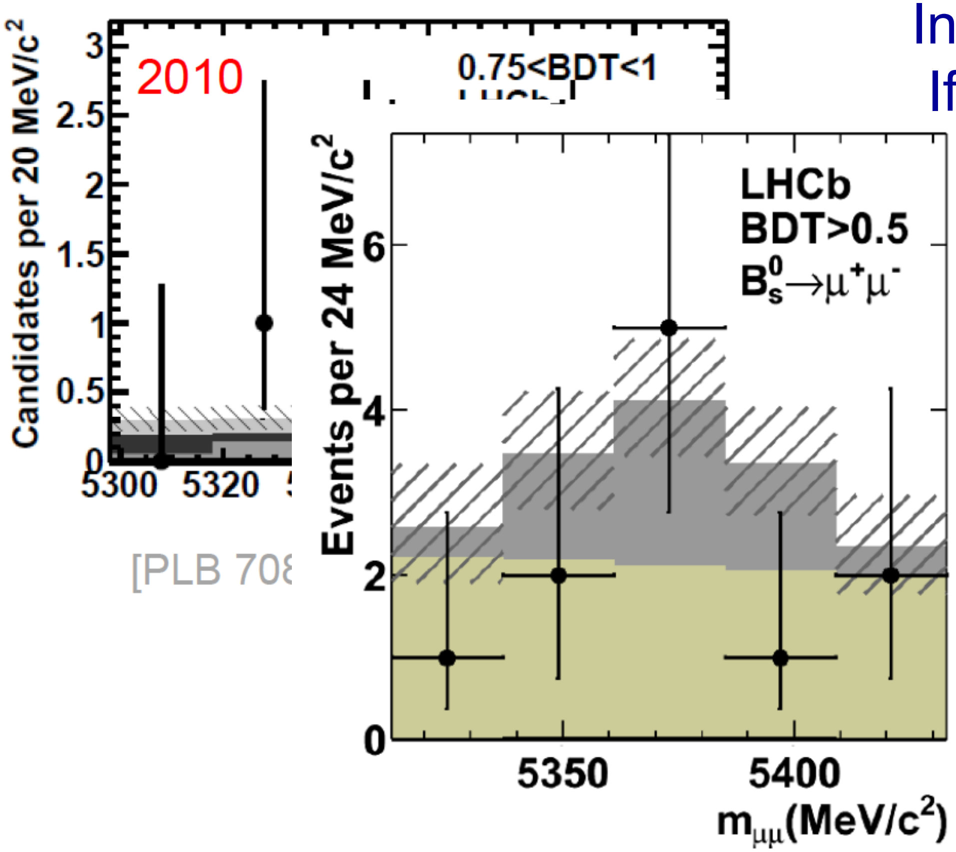
[PLB 708 (2012) 55]

Invariant mass in signal region (high BDT)
If there is a signal, we should see a peak

2010: nothing

$B\to \mu^+\mu^-$: Progress through run 1

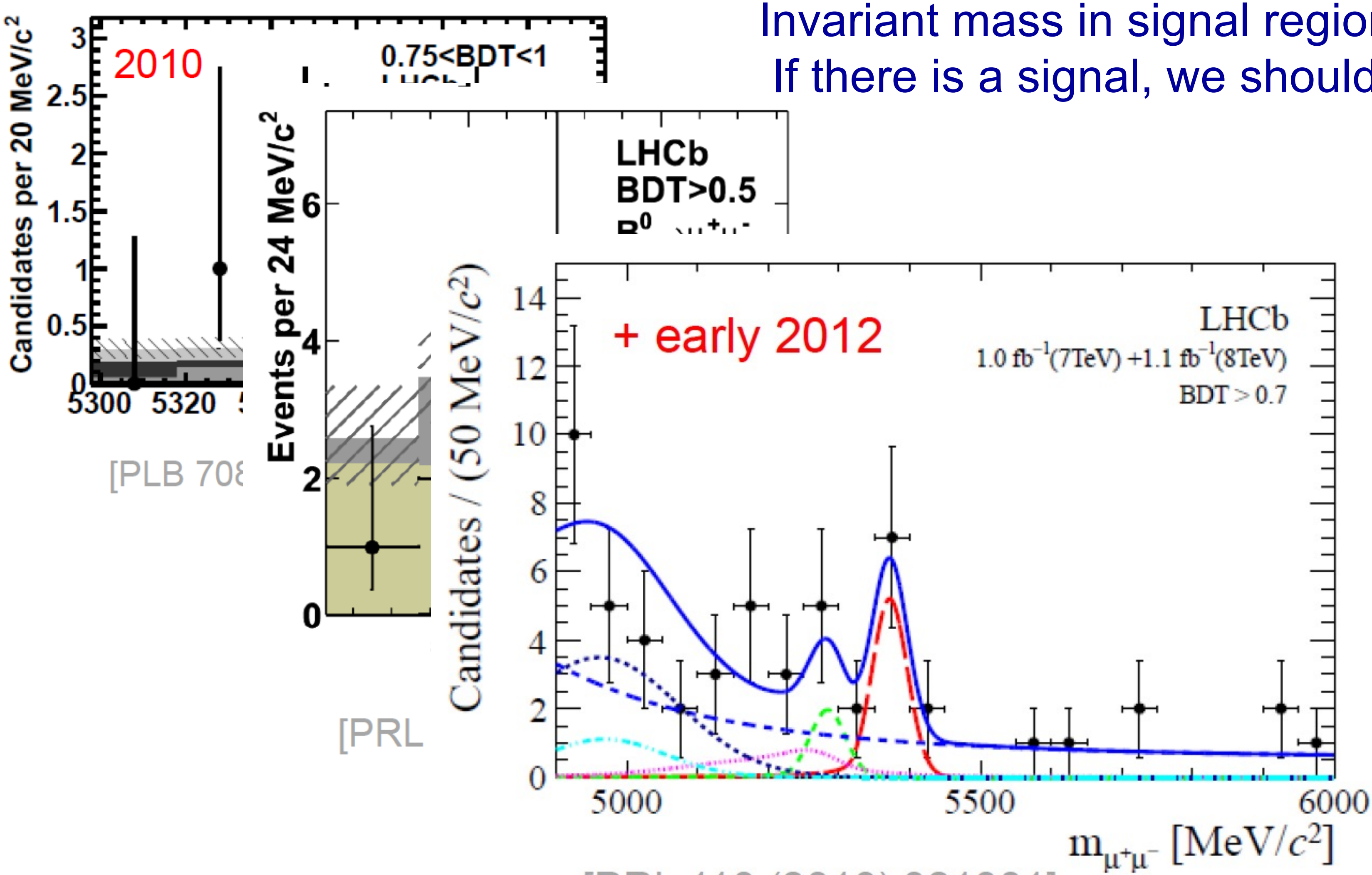
Invariant mass in signal region (high BDT)
If there is a signal, we should see a peak



[PRL 108 (2012) 231801]

+2011: maybe??
But not significant enough for any claims

Invariant mass in signal region (high BDT)
If there is a signal, we should see a peak

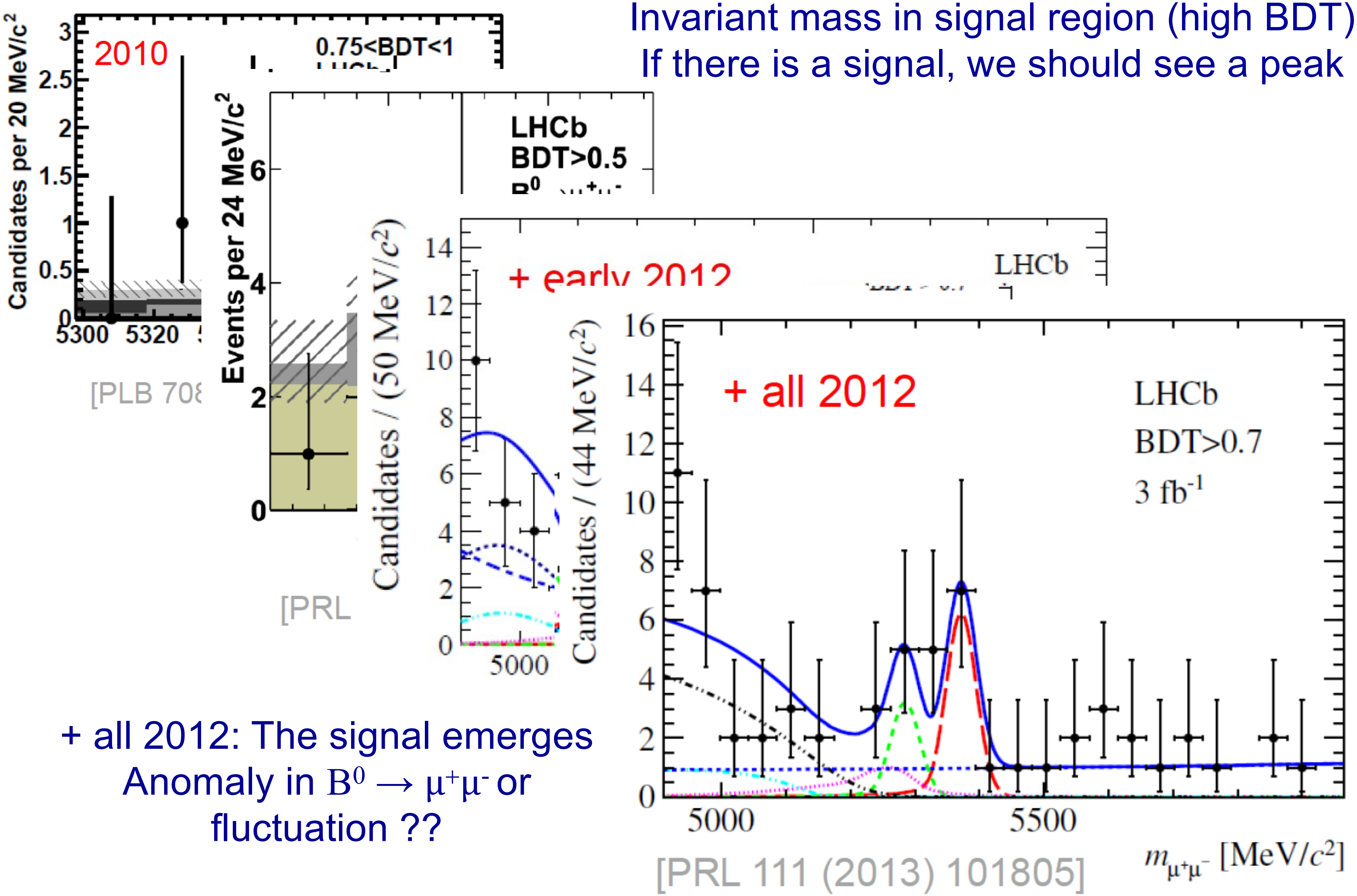


[PRL 110 (2013) 021801]

+ early 2012: First evidence of $B_s \to \mu^+\mu^-$!
Shown at HCP in Kyoto

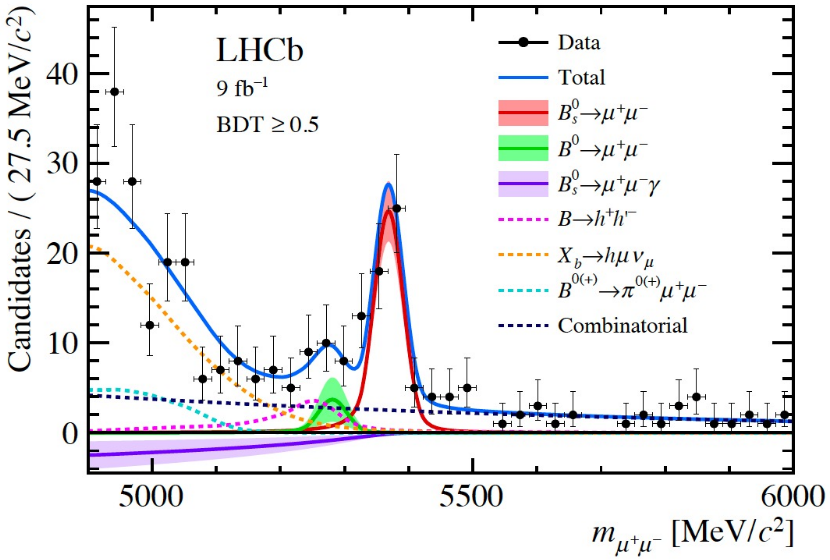
$B \to \mu^+\mu^-$: Progress through run 1

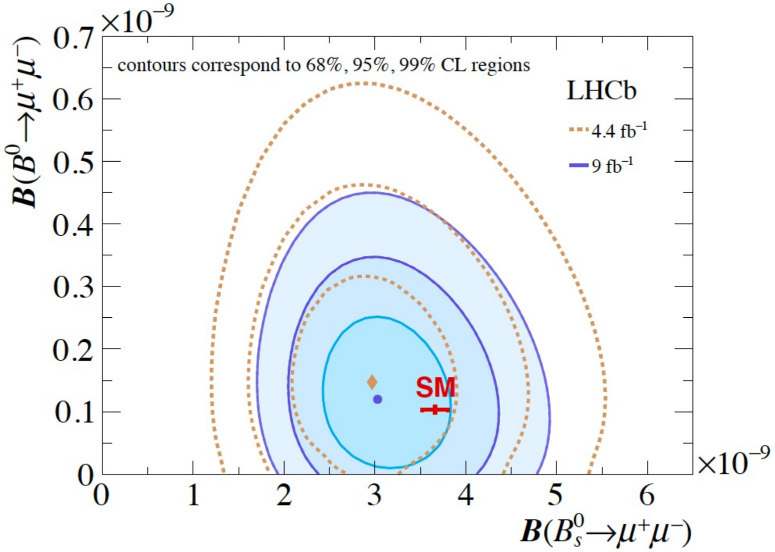
Invariant mass in signal region (high BDT)
If there is a signal, we should see a peak



+ all 2012: The signal emerges
Anomaly in $B^0 \to \mu^+\mu^-$ or fluctuation ??

[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]



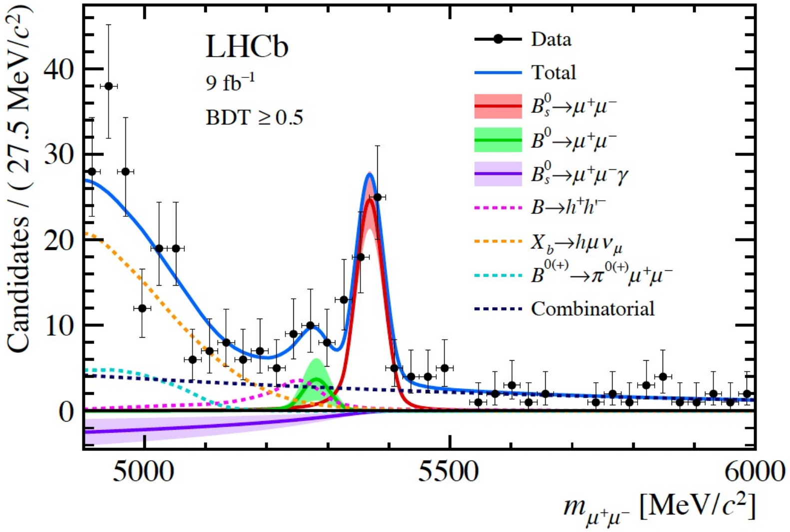


- Recent LHCb measurement [PRL 128 (2022) 041801] [PRD 105 (2022) 012010]

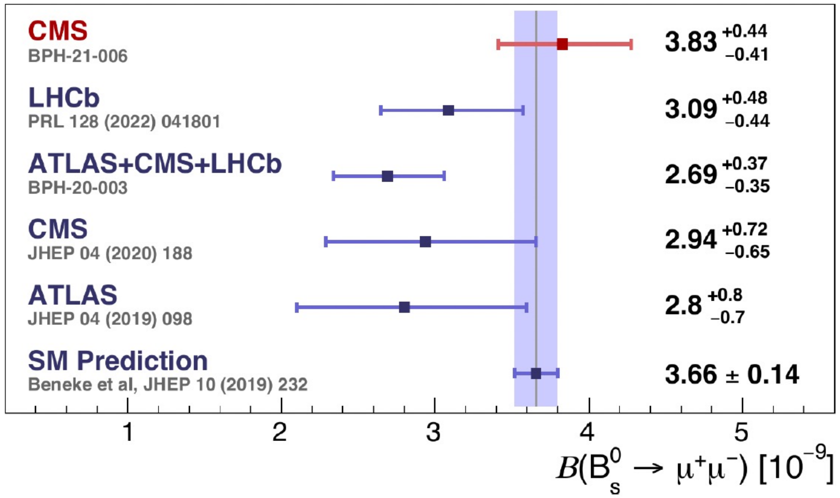
$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.09^{+0.46}_{-0.43}{}^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10} \quad (\mathcal{B} < 2.6 \times 10^{-10} \text{ @ } 95\% \text{ CL})$$

Golden channel: $B_{s,d} \to \mu^+\mu^-$ from LHCb .. and CMS

[PRL 128 (2022) 041801] [PRD 105 (2022) 012010]



[CMS-PAS-BPH-21-006]



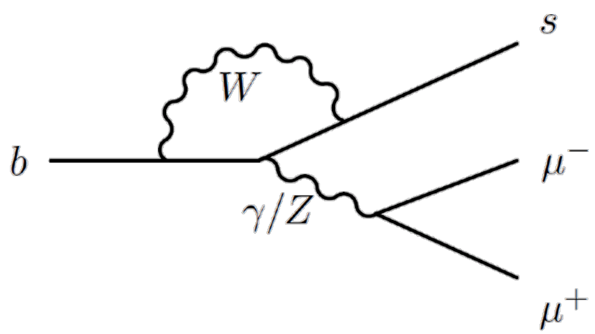
- New precise CMS measurement moves average further to SM [CMS-PAS-BPH-21-006]

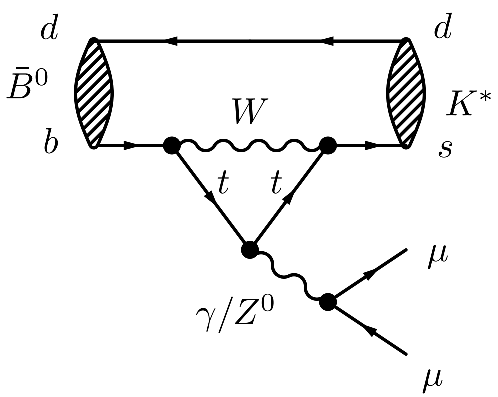
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.83^{+0.38}_{-0.36}(\text{stat})^{+0.19}_{-0.16}(\text{syst})^{+0.14}_{-0.13}(f_s/f_u)) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (0.37^{+0.75}_{-0.67}{}^{+0.08}_{-0.09}) \times 10^{-10} \quad (\mathcal{B} < 1.9 \times 10^{-10} \text{ @ } 95\% \text{ CL})$$

- Precision approaches 10%

- Upcoming milestones: B_d discovery, B_s lifetime and electron modes

$b \to s\ \mu^+\mu^-$ base diagram





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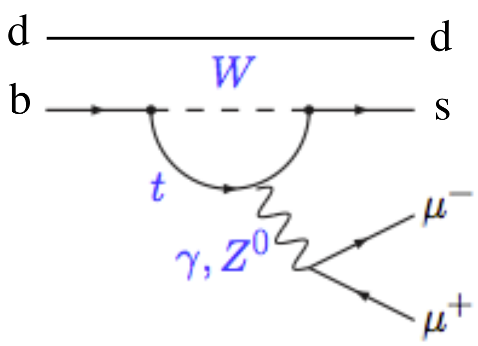
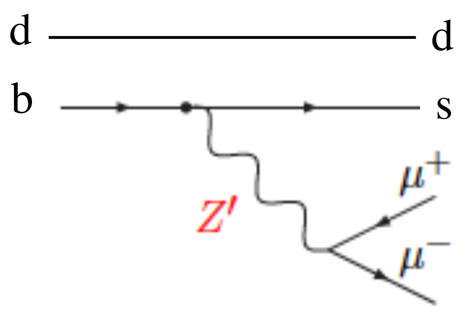
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$





$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + $$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

fraction of longitudinal polarisation of the K* (F_{L})

forward-backward asymmetry of the dilepton system (A_{FB})

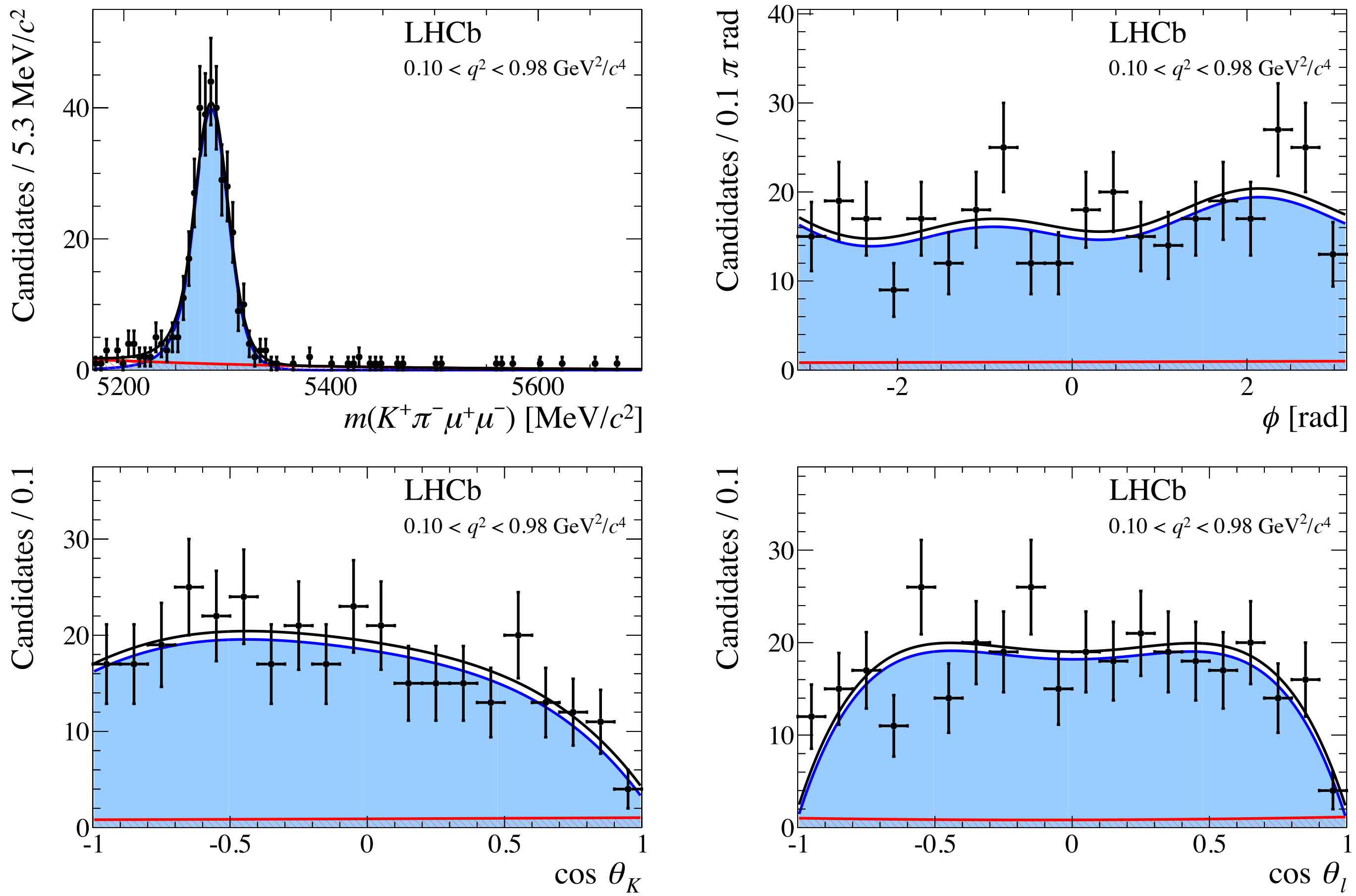
Observables depend on B→K* form factors and on short distance physics

Angular analysis of $B^0 \to K^{*0} \mu^+\mu^-$

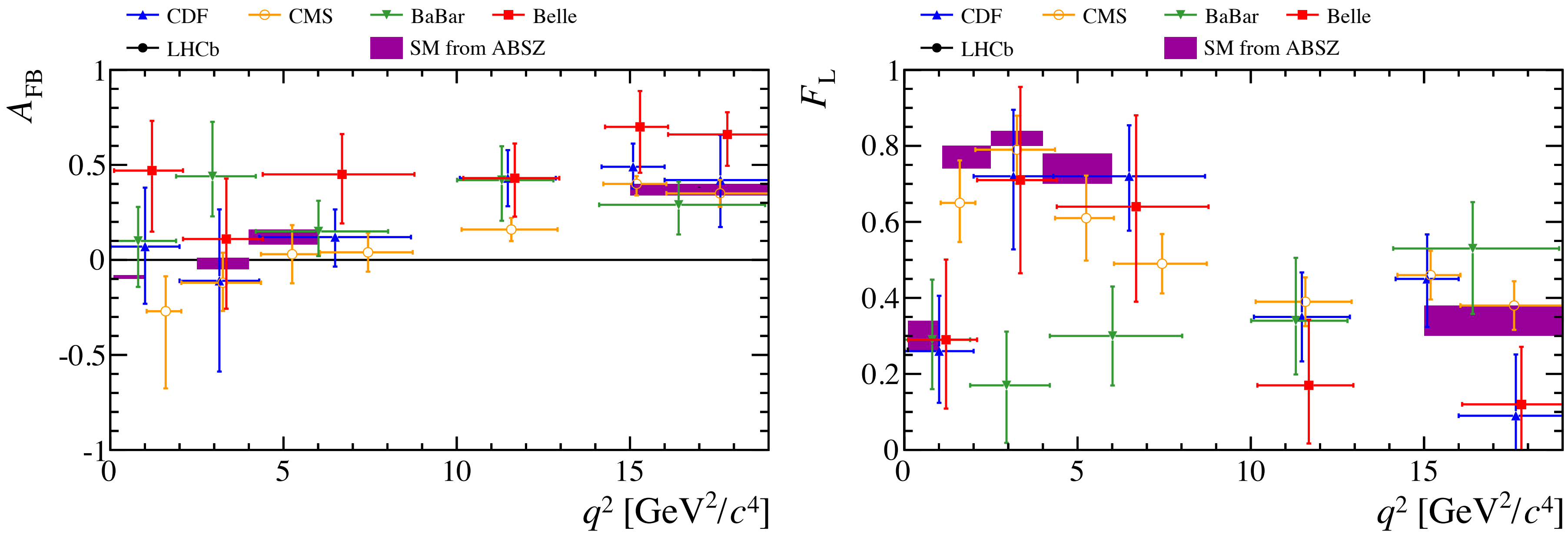
- LHCb published the first full angular analysis of the decay
  - Unbinned maximum likelihood fit to $K\pi\mu\mu$ mass and three decay angles
  - Simultaneously fit $K\pi$ mass to constrain s-wave configuration
  - Efficiency modelled in four dimensions
  - Binned in $q^2 = m_{\mu\mu}^2$

JHEP02(2016)104

Example fit projections in low q^2 bin

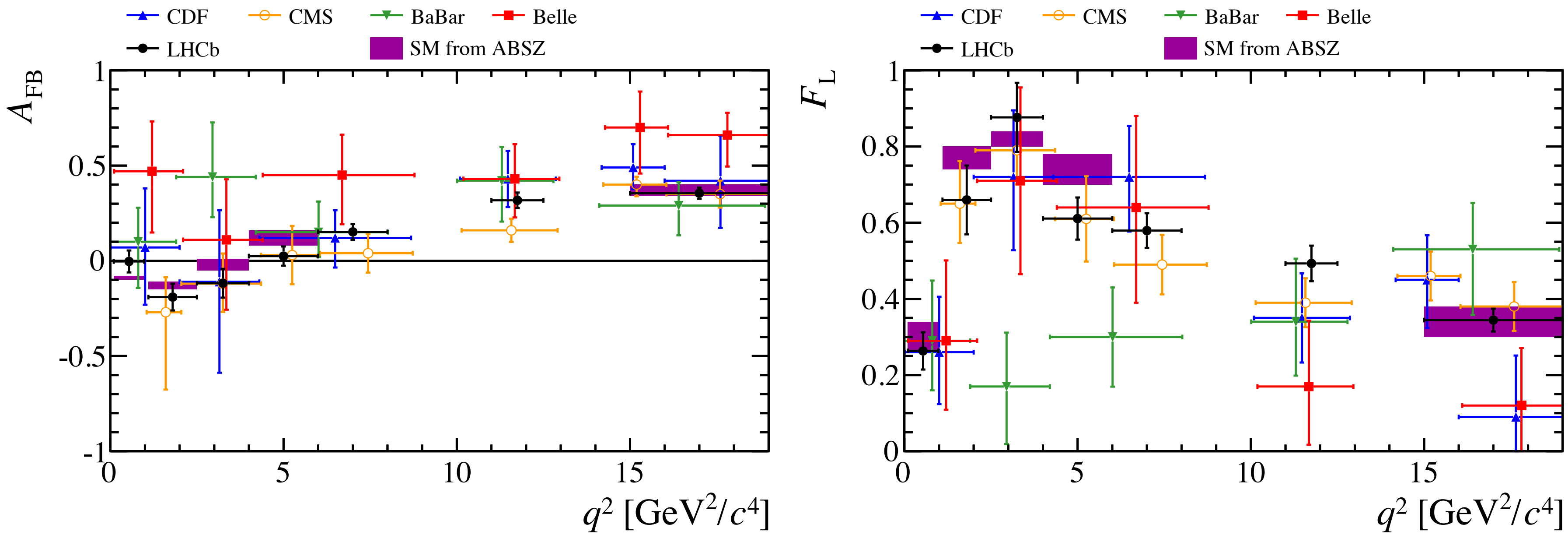


Results



References:
LHCb [JHEP 02 (2016) 104] ,
CMS [PLB 753 (2016) 424]
BaBar [arXiv:1508.07960]
CDF [PRL 108 (2012) 081807]
Belle [PRL 103 (2009) 171801].

Results



- Situation unclear. Clean up by smarter observables

$P_i^{(\prime)}$ **basis** ***Reparameterise the fit to obtain optimised observables:***

form factor uncertainties cancel at first order

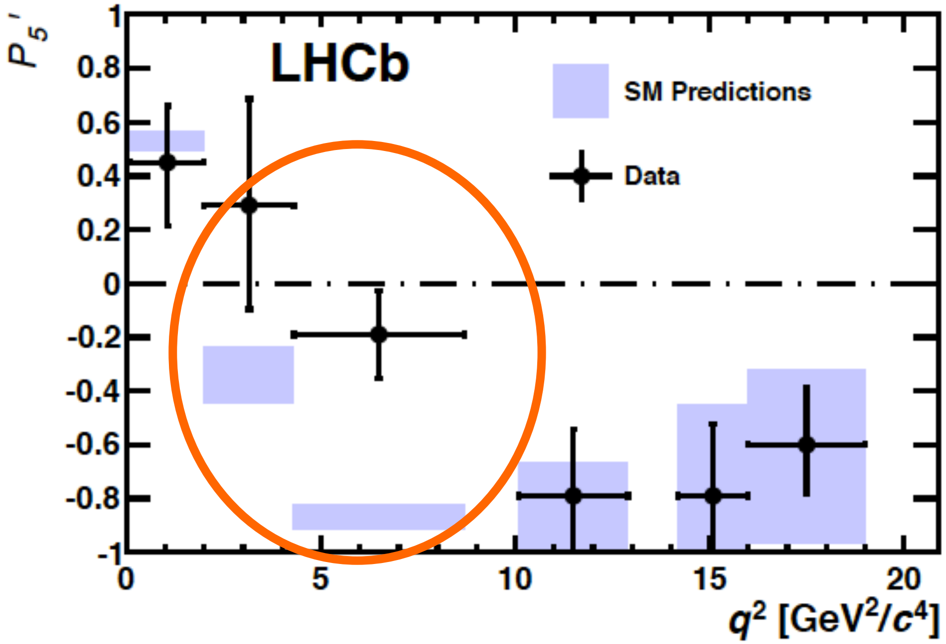
JHEP 12 (2014) 125, JHEP 09 (2010) 089

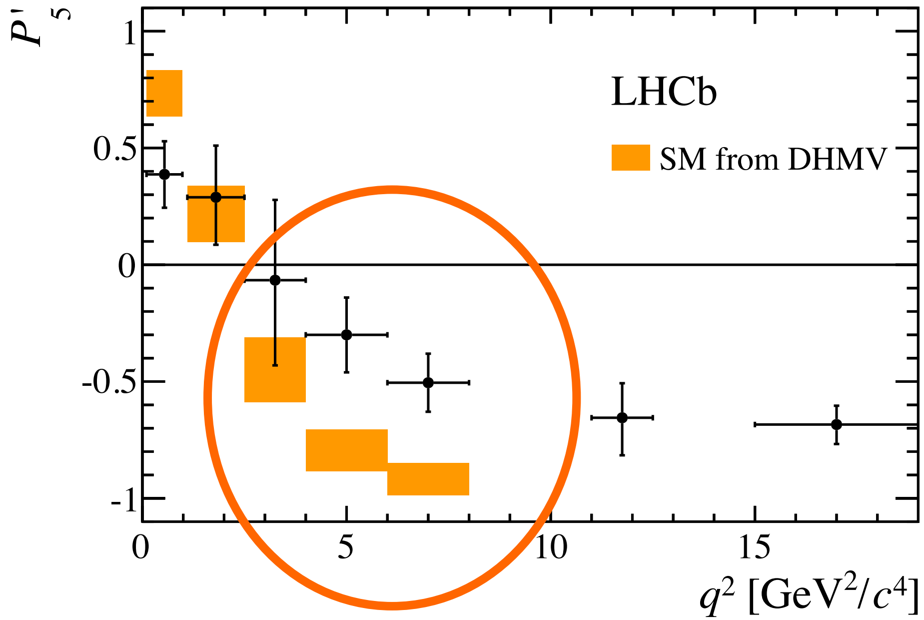
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_{\mathrm{L}}(1 - F_{\mathrm{L}})}}$$

Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys.Rev.Lett. 111 (2013) 191801





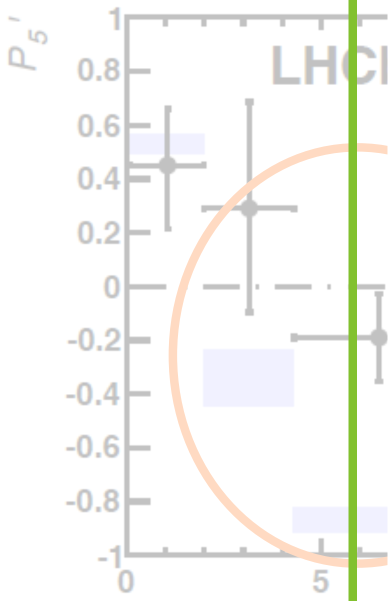
[LHCb, JHEP 02 (2016) 104]

- Full Run 1 analysis confirms effect
  Run 2 update coming

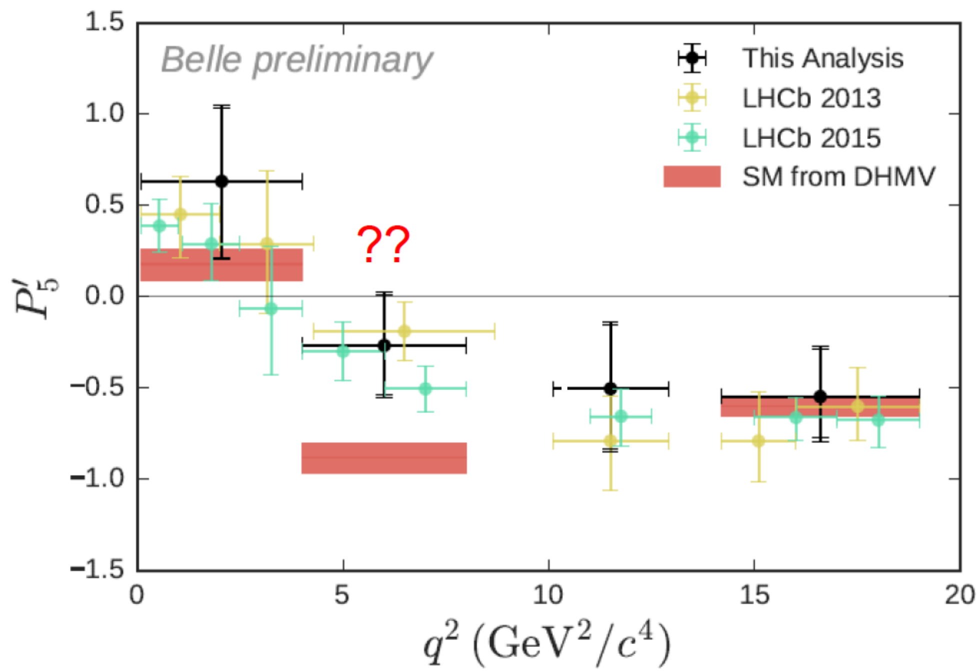
Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observables in $B^0 \to K^{*0} \mu^+\mu^-$ decays

LHCb, Phys.

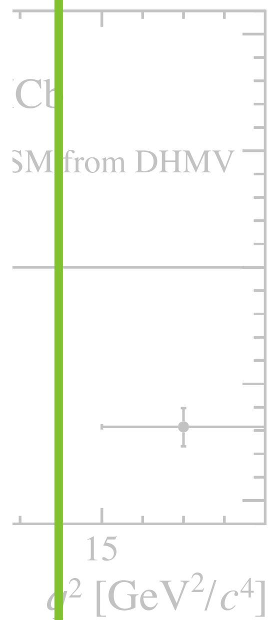


Belle still has a word to say



Belle PRL118(2017)111801

Lower statistical power, but very consistent



[LHCb, JHEP 02 (2016) 104]

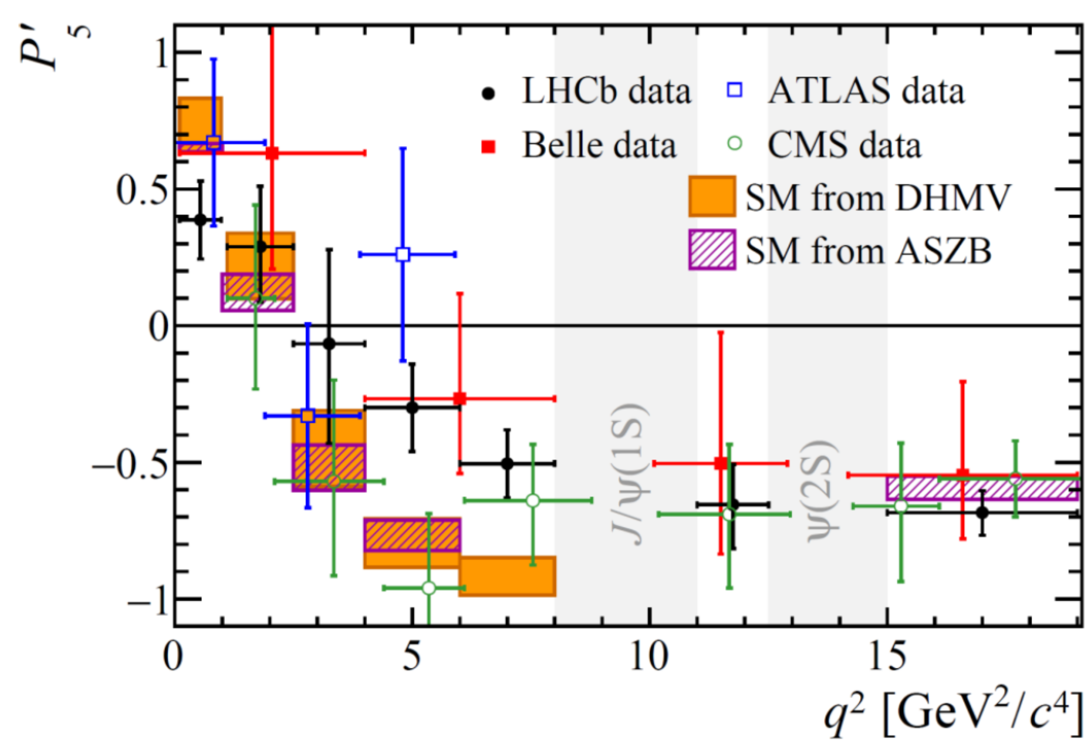
- Full Run

Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$

- 2013, LHCb has observed a deviation in angular observa... decays

LHCb, Phys.

.. and ATLAS and CMS



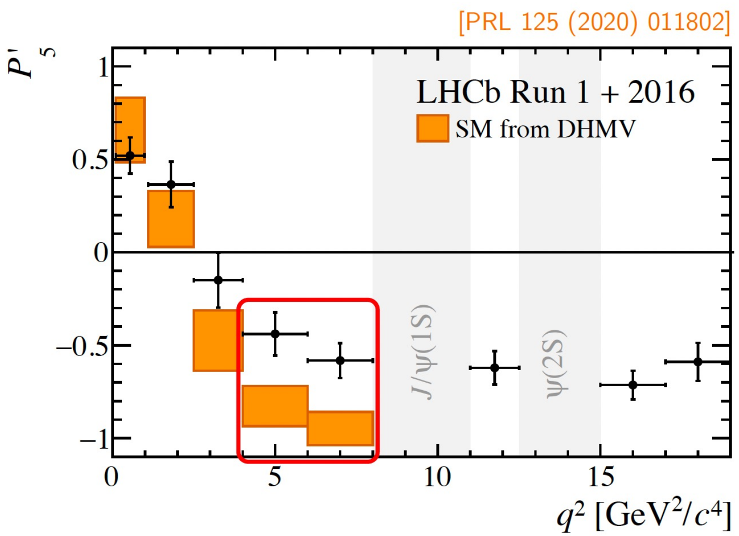
[ATLAS-CONF-2017-023, CMS-PAS-BPH-15-007]

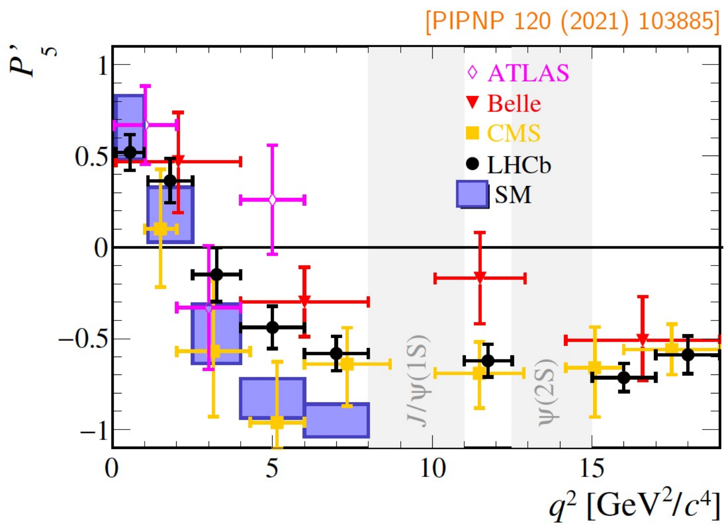
[LHCb, JHEP 02 (2016) 104]

- Full Run

Situation unclear…. If real, expect discrepancies in **other $b \to s$ decays** ..

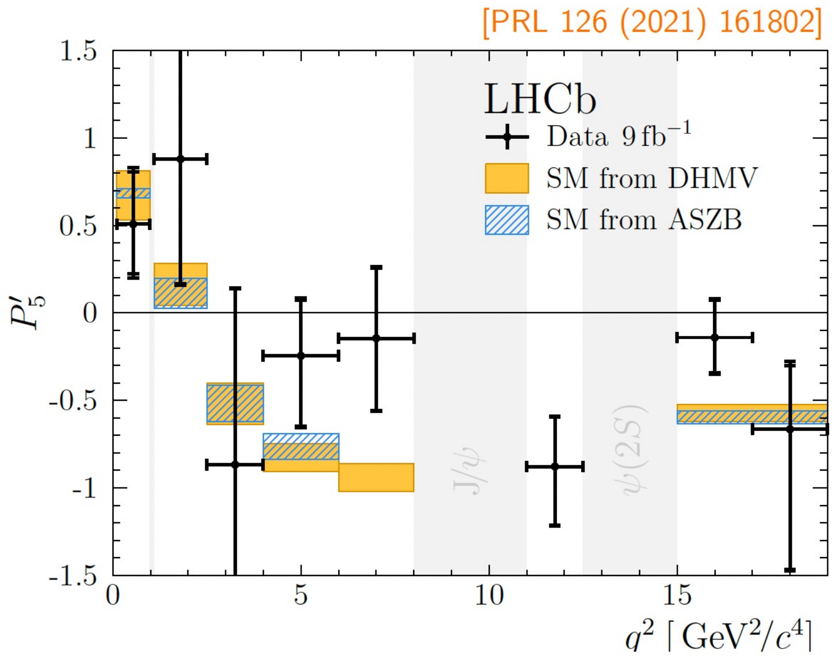
Puzzling deviations: $B^0 \to K^{*0} \mu^+\mu^-$





- LHCb analysis finds global 3.3σ tension
  - [LHCb, PRL 125 (2020) 011802] consistent with [Belle, PRL 118 (2017) 111801] [CMS, PLB 781 (2018) 517] [ATLAS, JHEP 10 (2018) 047]
- More data needed to clarify picture
  - LHCb update underway

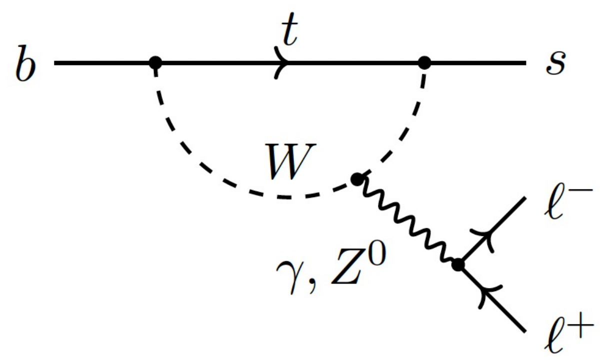
Puzzling deviations: $B^+ \rightarrow K^{*+} \mu^+\mu^-$



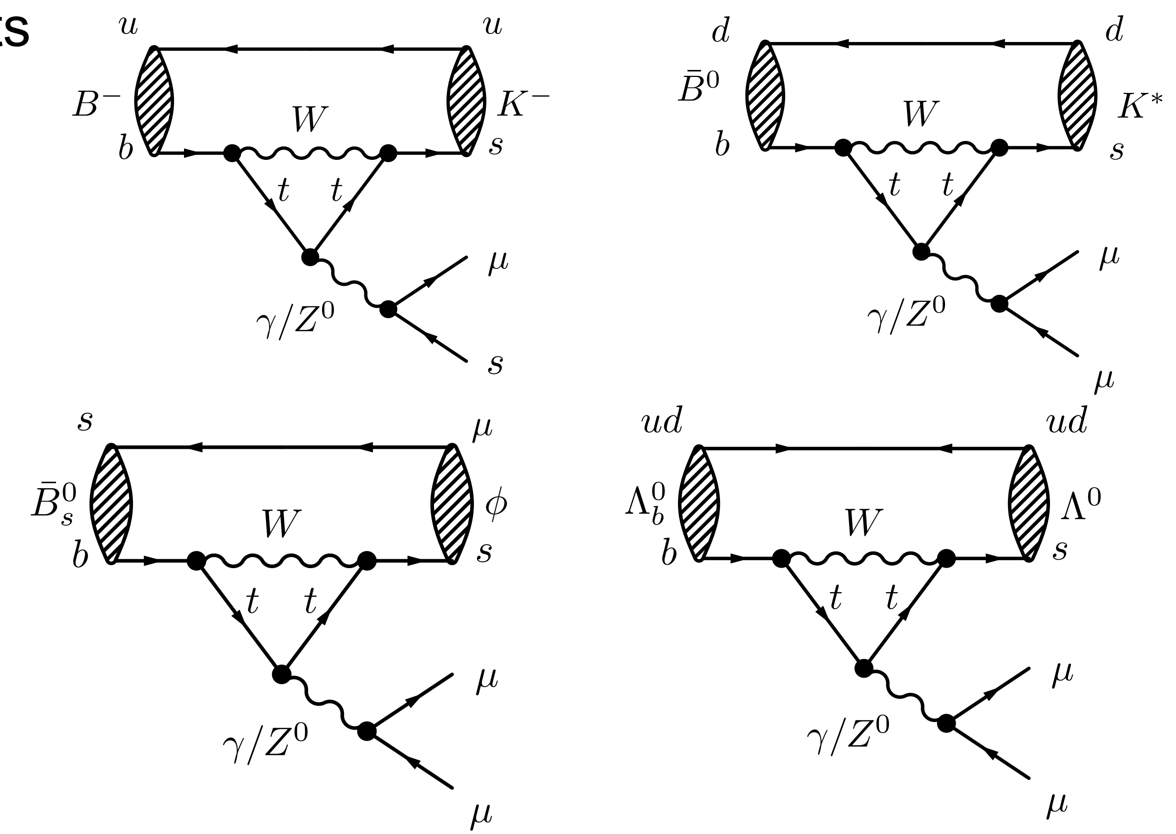
- Recent LHCb measurement using Run 1+2 data [PRL 126 (2021) 161802]
- Global tension corresponding to 3.1σ, consistent with $B^0 \rightarrow K^{*0} \mu^+\mu^-$

Other $b \rightarrow s\, \mu^+\mu^-$ decays

- Decay modes with same effective Feynman diagram accessible
  → different spectator quarks

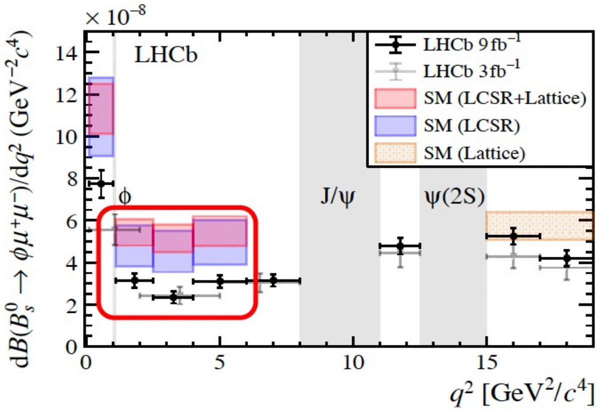


- Test for same new effects
  → expect suppressed
  branching fractions

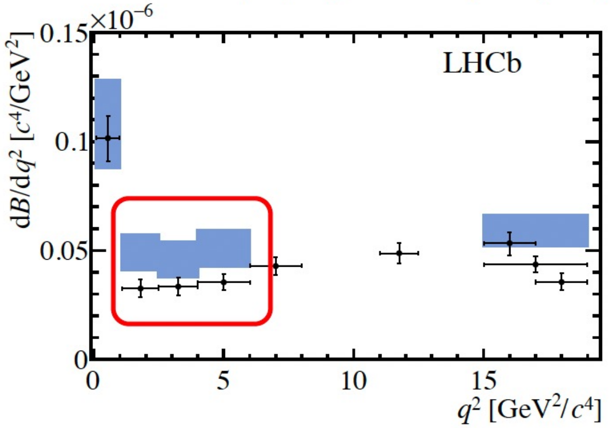


$b \rightarrow s\, \ell^+\ell^-$ branching fraction measuremetns

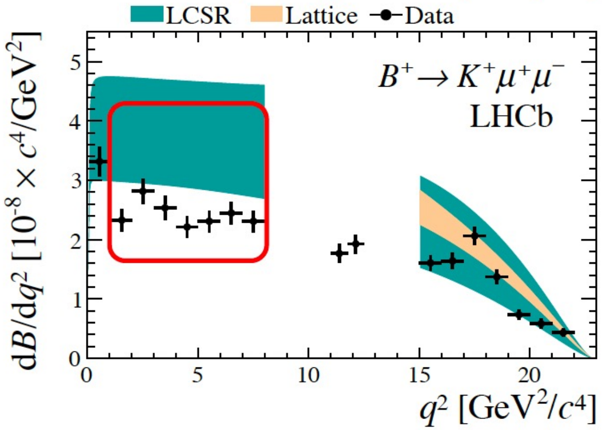
LHCb $B_s^0 \rightarrow \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



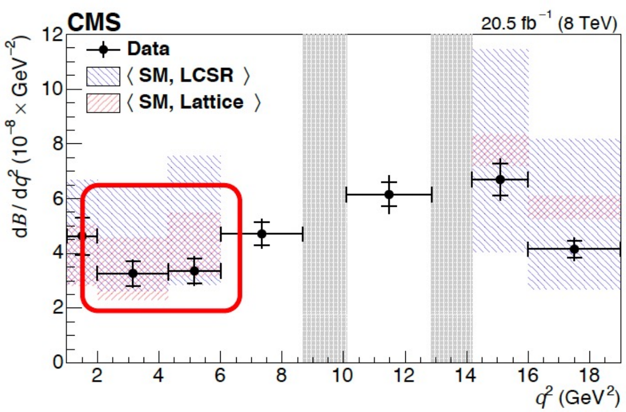
LHCb $B^0 \rightarrow K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



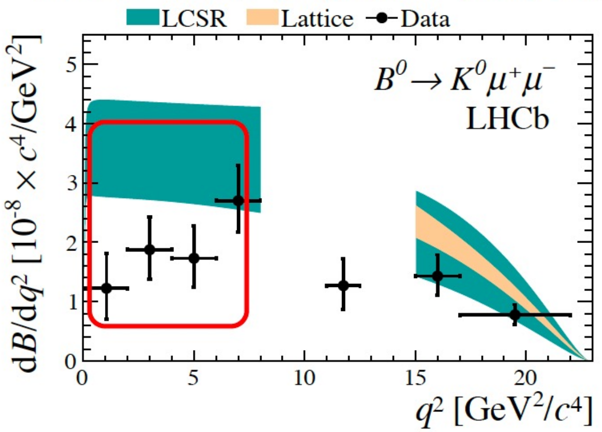
LHCb $B^+ \rightarrow K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



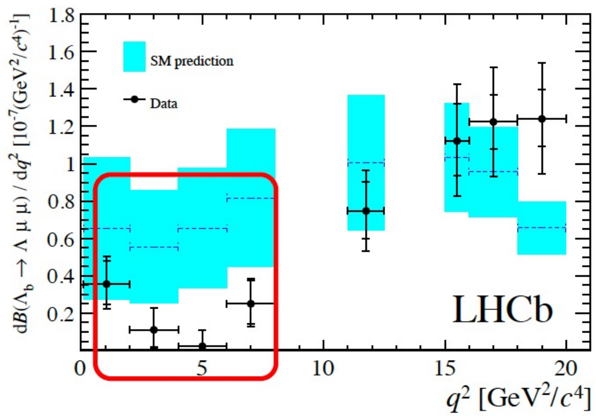
CMS $B^0 \rightarrow K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



LHCb $B^0 \rightarrow K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



LHCb $\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]

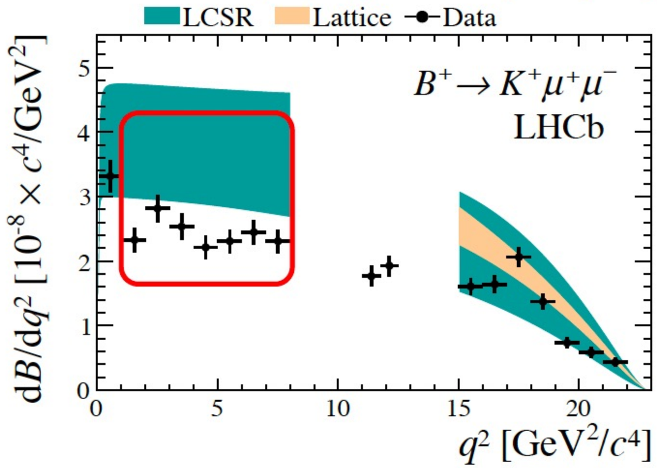


- Data consistently below SM predictions (particularly at low q^2)
- Tensions at 1–3σ level, SM predictions exhibit sizeable had. uncertainties

$b \to s\, \ell^+\ell^-$ branching fraction measurements

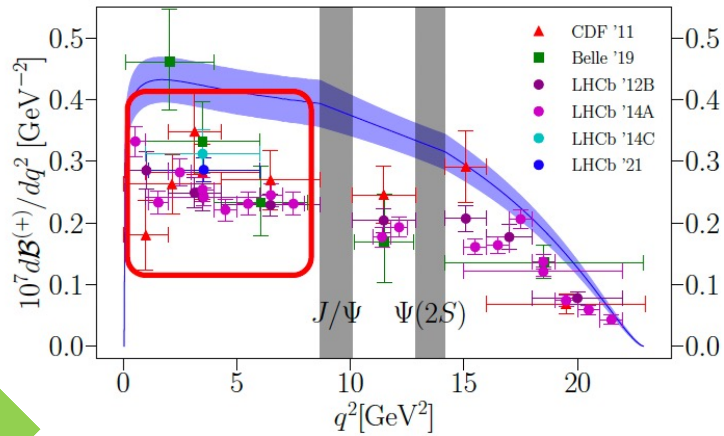
- Recent developments on non-local corrections [JHEP 09 (2022) 133] and new results from Lattice QCD [HPQCD, arXiv:2207.13371]

LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]

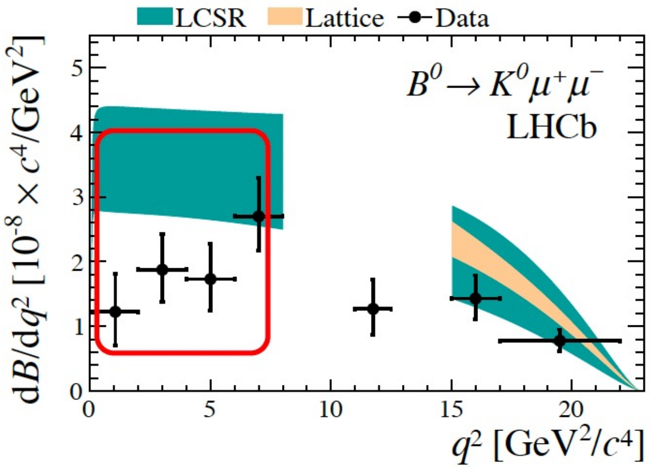


TH developments

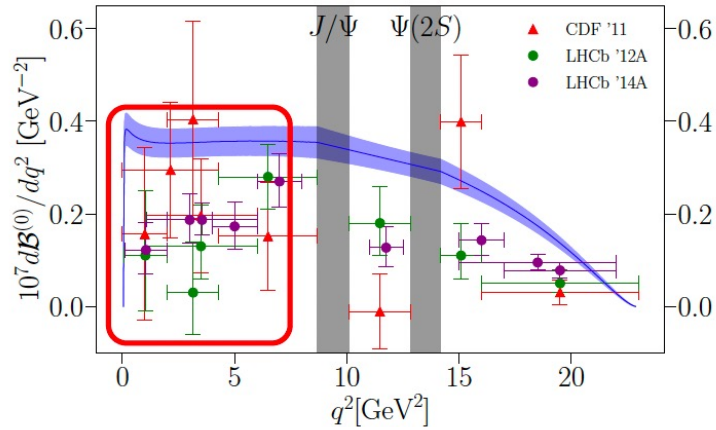
Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]



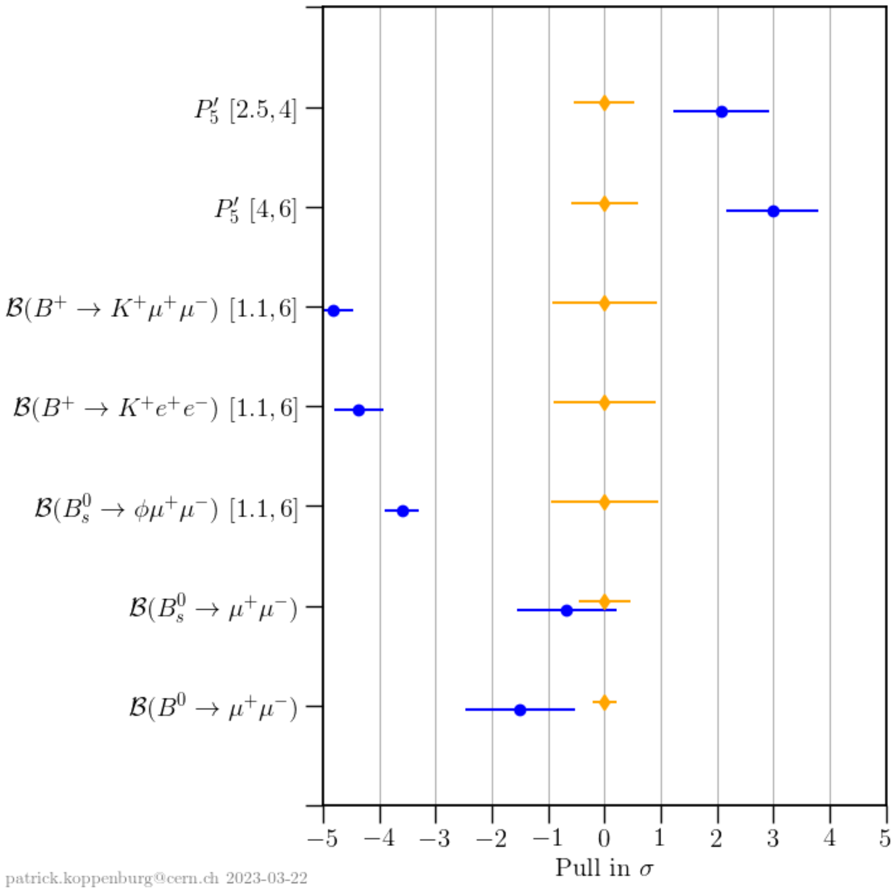
LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



Lattice $B^0 \to K^0\mu^+\mu^-$ [arXiv:2207.13371]



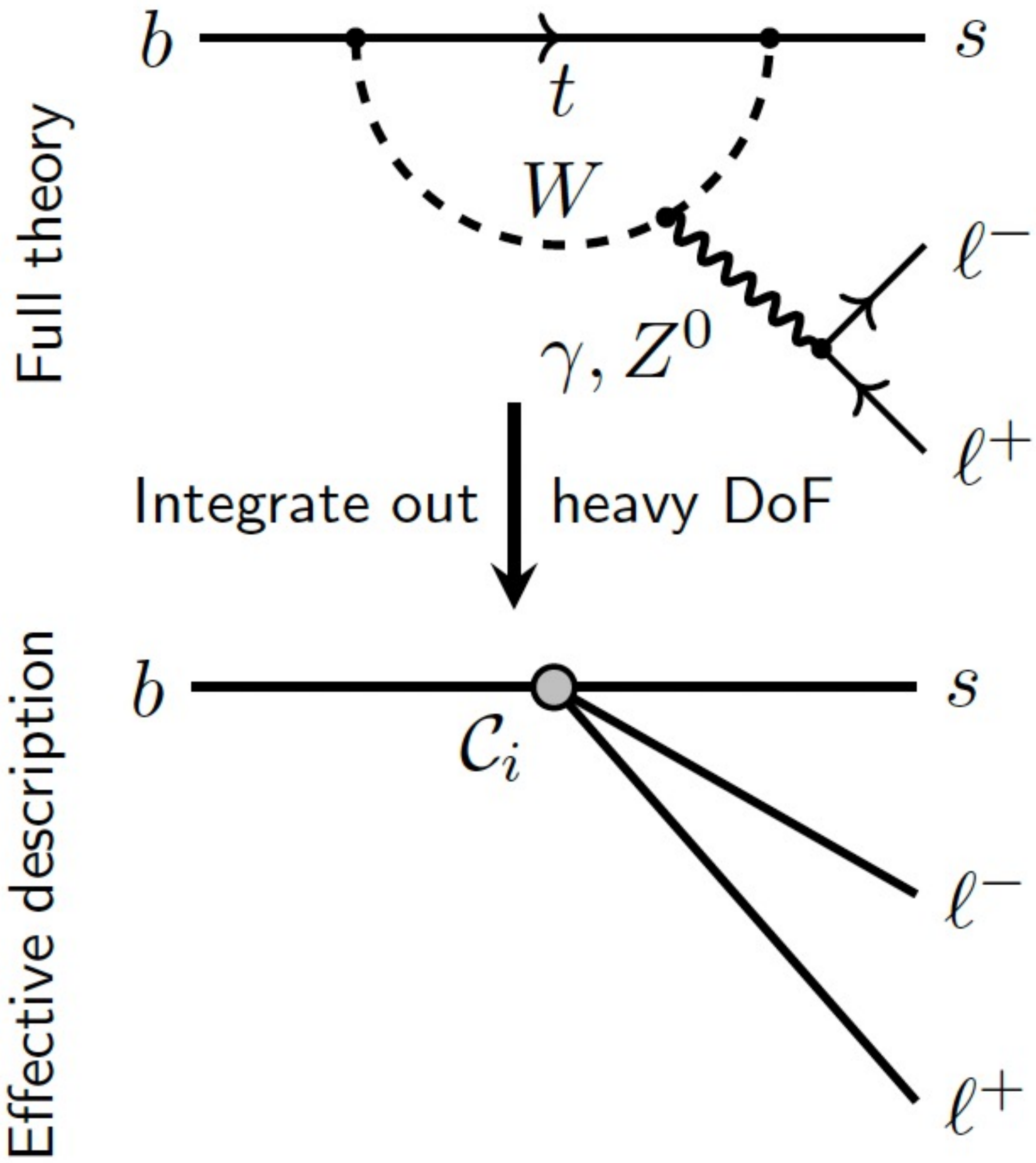
Branching fractions of $b \to s\, \mu^+\mu^-$



- Analysis of large class of $b \to s,d\, \mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - Tendency to undershoot prediction of differential x-sections
    → **intriguing hint or theoretical issue in prediction?**

→ **Can these be consistently described (by NP) ?**

Effective field theories - 1



$b \to s\ell\ell$ transitions described model-independently in effective theory

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \mathcal{C}_i \mathcal{O}_i$$

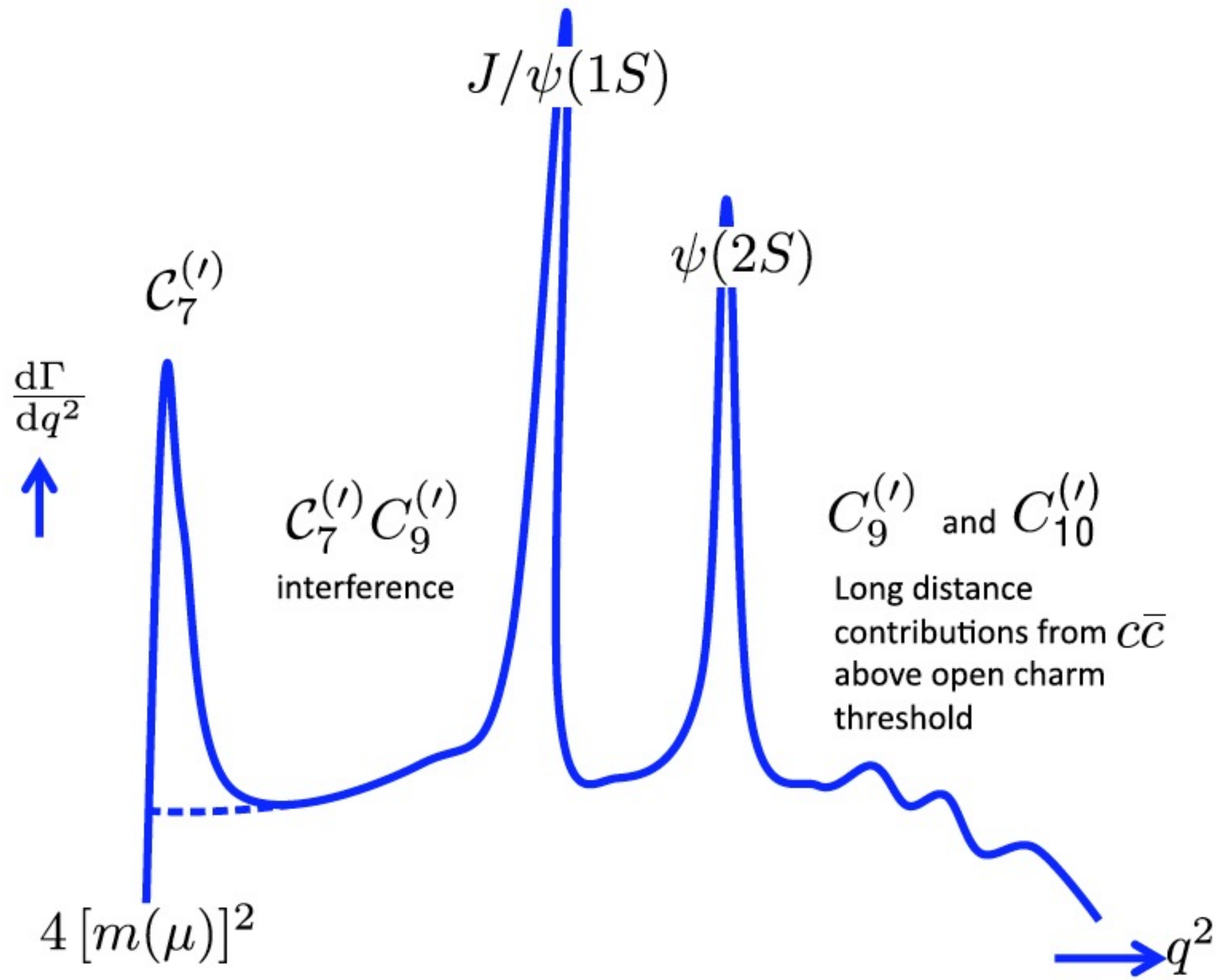
Wilson coefficient
("effective coupling")

Effective couplings in $b \to s\ell\ell$ transitions

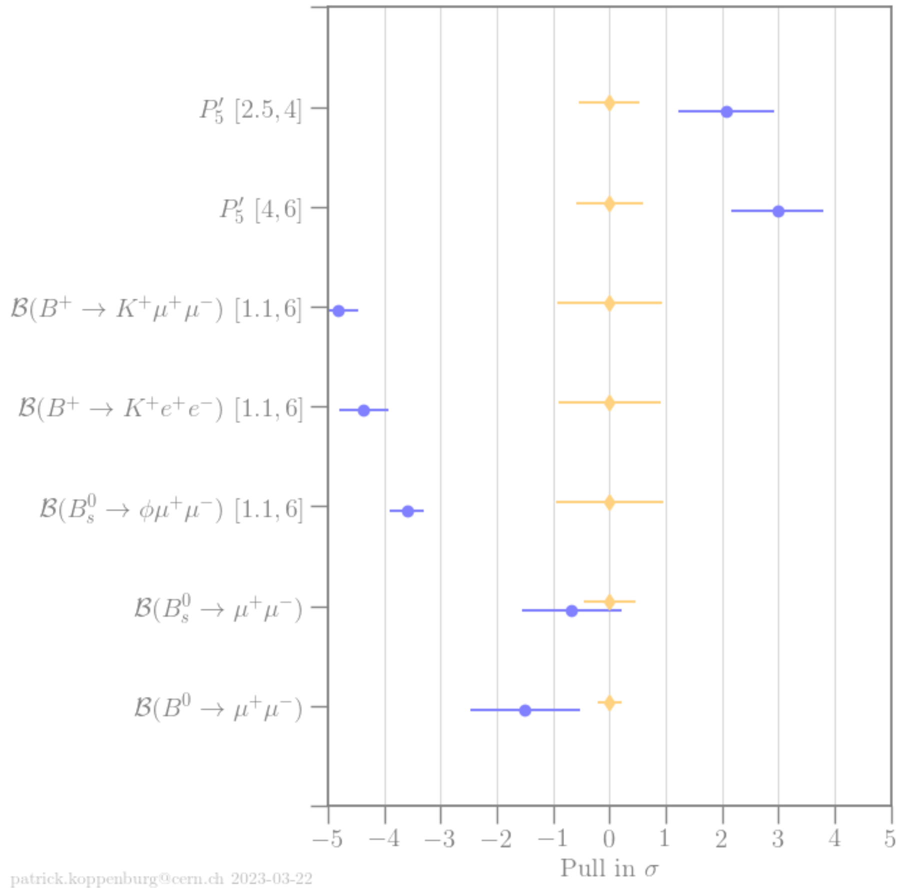
Wilson coefficient		Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b (\bar{s} P_{R(L)} b)(\bar{\mu}\gamma_5 \mu)$

Effective field theories - 3

Different $q^2 = m^2(\ell^+\ell^-)$ regions probe different operator combinations



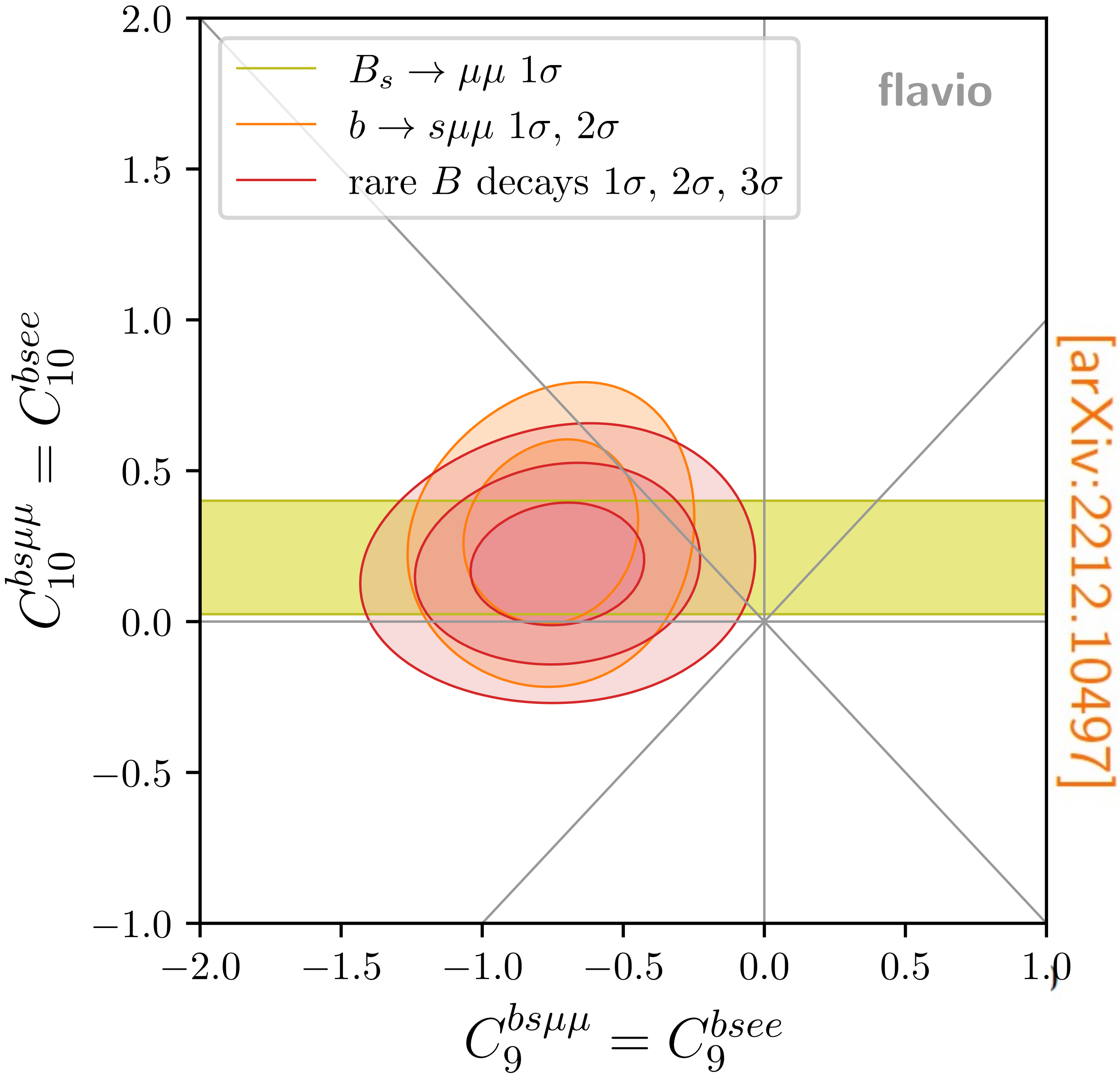
Branching fractions of $b \to s\,\mu^+\mu^-$



- Analysis of large class of $b \to s,d\,\mu^+\mu^-$ decays
  - Several tensions seen, but individual significance is moderate
  - Tendency to undershoot prediction of differential x-sections
    → **intriguing hint or theoretical issue in prediction?**

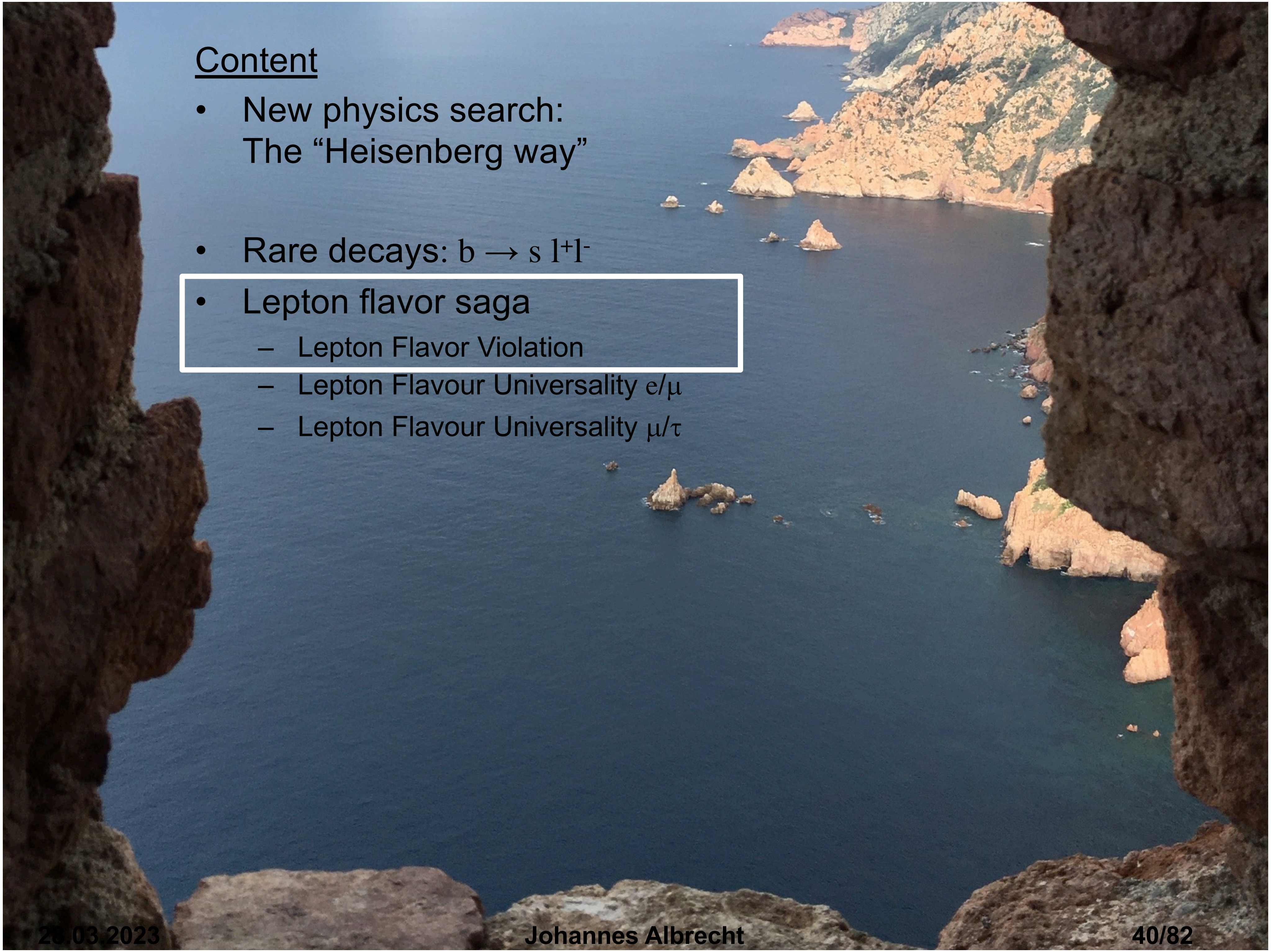
→ Can these be consistently described (by NP) ?

Analysis in effective field theory



SM tension:
Depending on details, 3-5σ significance

One symbol summary

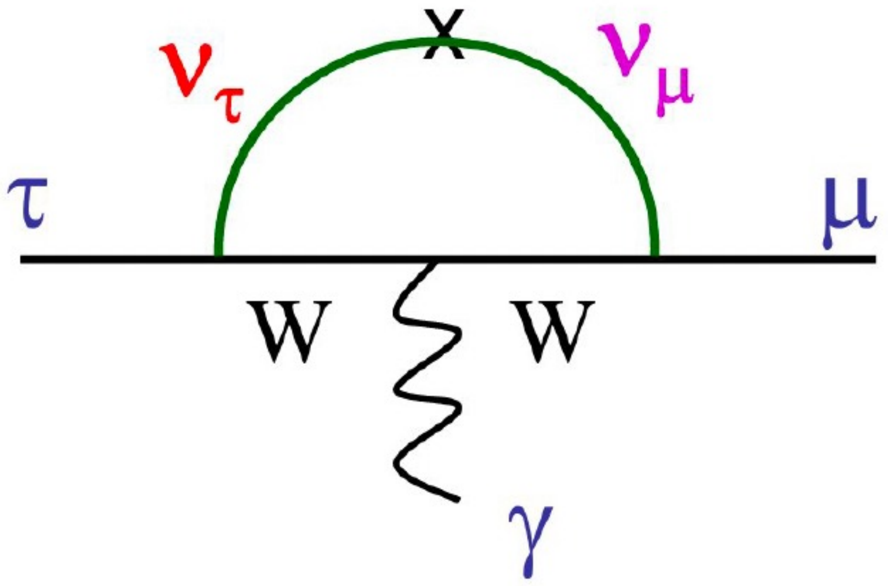


<u>Content</u>

- New physics search:
  The "Heisenberg way"

- Rare decays: $b \to s\, l^+ l^-$
- Lepton flavor saga
  - Lepton Flavor Violation
  - Lepton Flavour Universality e/μ
  - Lepton Flavour Universality μ/τ

Lepton Flavor is violated!



Models	References	$\tau \to \mu\gamma$
SM + ν mixing	Lee, Shrock, PRD 16 (1977) 1444 Cheng, Li, PRD 45 (1980) 1908	10^{-54}-10^{-40}

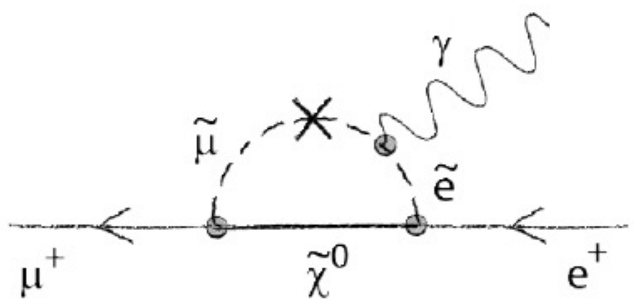
… however, which zero do you know that well ?

What level of LFV do we expect?

Models	References	$\tau \to \mu\gamma$
SM + ν mixing	Lee, Shrock, PRD 16 (1977) 1444 Cheng, Li, PRD 45 (1980) 1908	10^{-54}-10^{-40}
SUSY + Higgs	Dedes, Ellis, Raidal, PLB 549 (2002) 159 Brignole, Rossi, PLB 566 (2003) 517	10^{-10}
SM + Maj ν_R	Cvetic, Dib, Kim, Kim, PRD 66 (2002) 034008	10^{-9}
Non-universal Z'	Yue, Zhang, Liu, PLB 547 (2002) 252	10^{-9}
mSUGRA + Seesaw	Ellis et al. EPJ C14 (2002) 319 Antusch et al. JHEP 11 (2006) 090	10^{-8}- 10^{-12}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649 (2003) 189 Fukuyama et al. EPJ C56 (2008) 125	10^{-8}- 10^{-10}
MLFV	Cirigliano, Grinstein, NPB 752 (2006) 18	10^{-8}
Little Higgs	Goto et al, PRD 83 (2011) 053011 Rai Choudhury et al. PRD 75 (2007) 055011	10^{-8}- 10^{-11}

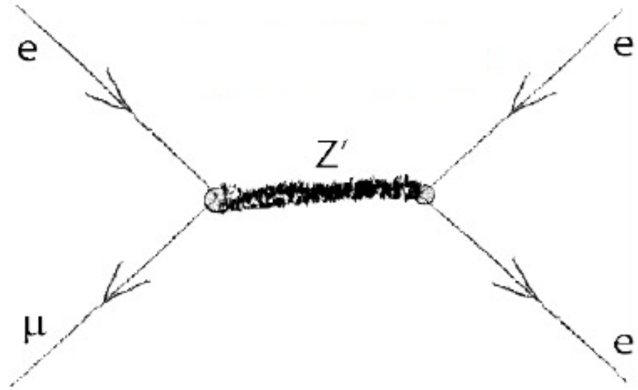
Lepton Flavour Violation in Tau Lepton decays - Jorge Portolés, CPAN 2010

Different NP, different channels



loop diagrams $\mu^- \rightarrow e^- \gamma$

- **Supersymmetry**
- **Little Higgs Models**
- **Seesaw Models**
- **GUT models (Leptoquarks)**
- **many other models**



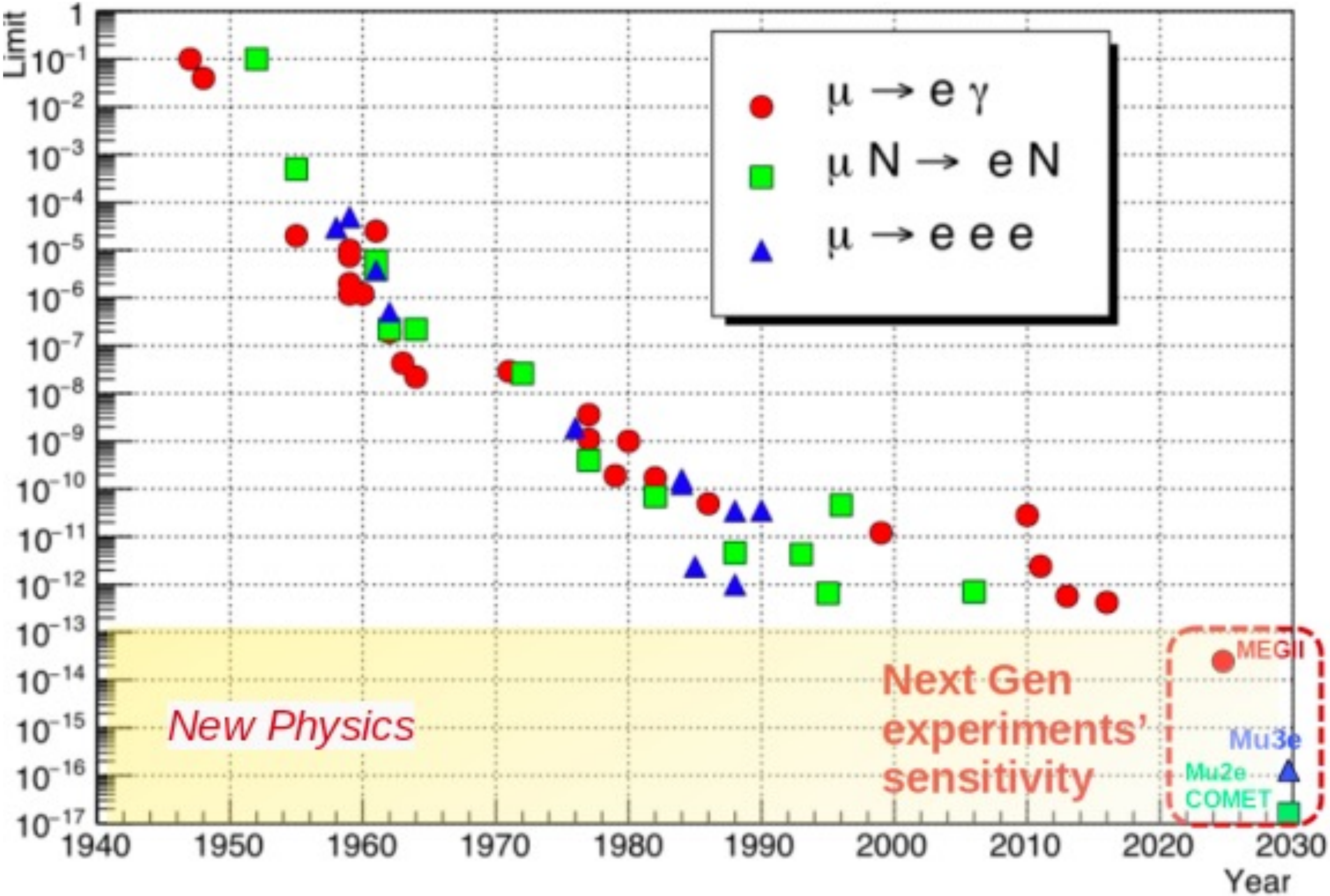
tree diagram $\mu^- \rightarrow e^- e^+ e^-$

- **Higgs Triplet Model**
- **New Heavy Vector bosons (Z')**
- **Extra Dimensions (KK towers)**

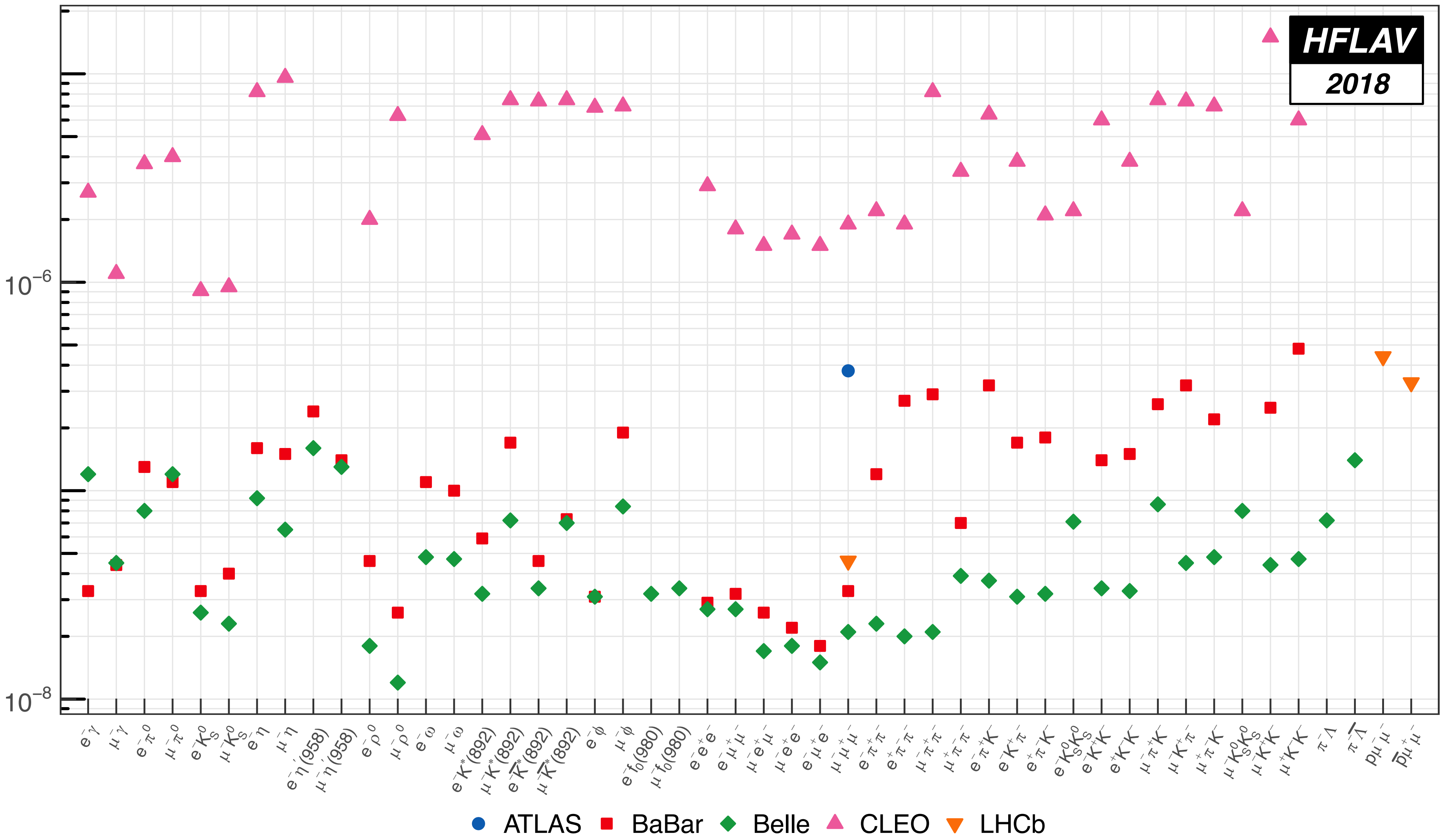
Most models “naturally” induce lepton flavor violation!

Lesson: which process is best to find LFV (first) depends on the model

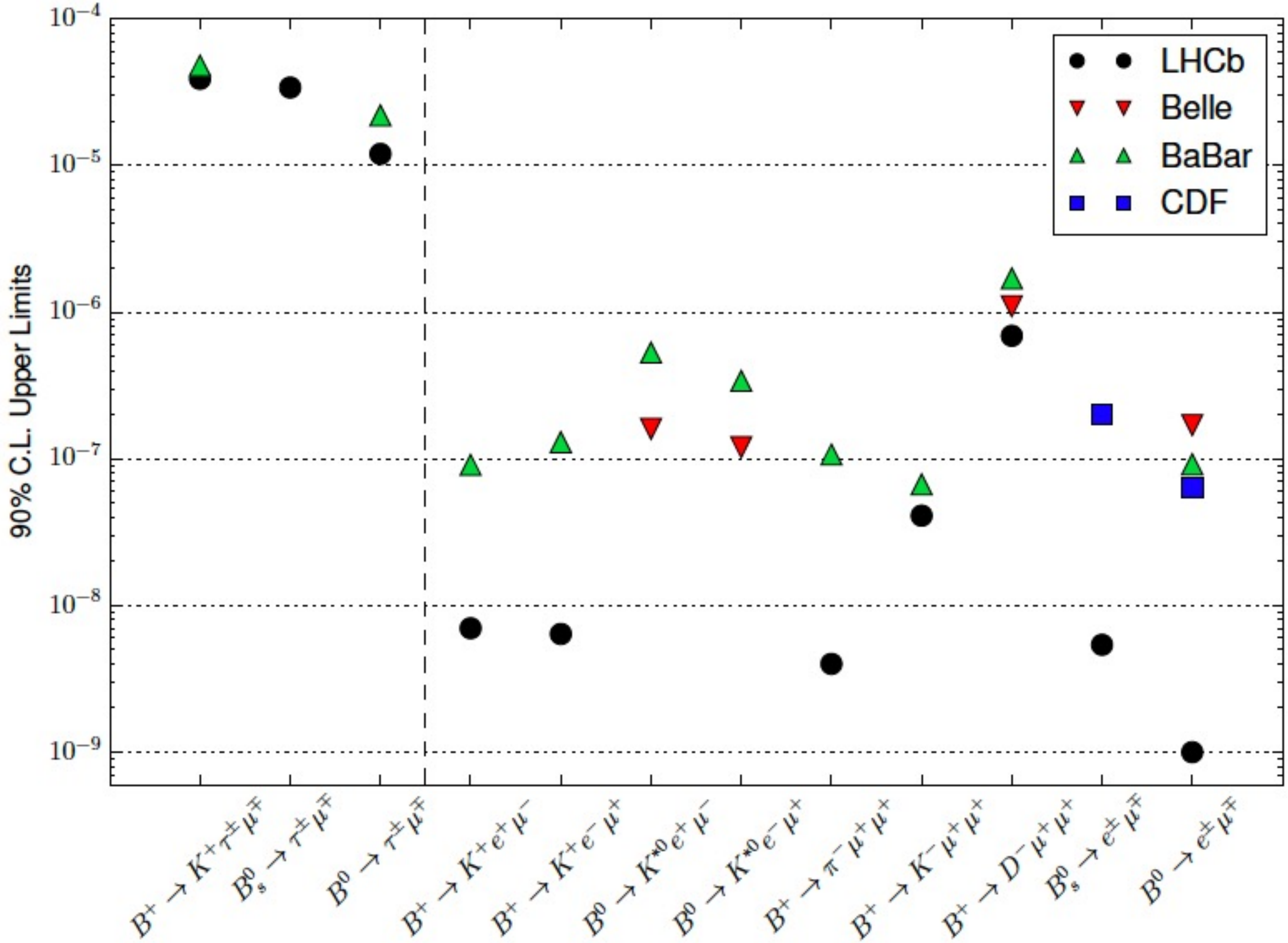
Most sensitive: Lepton decays



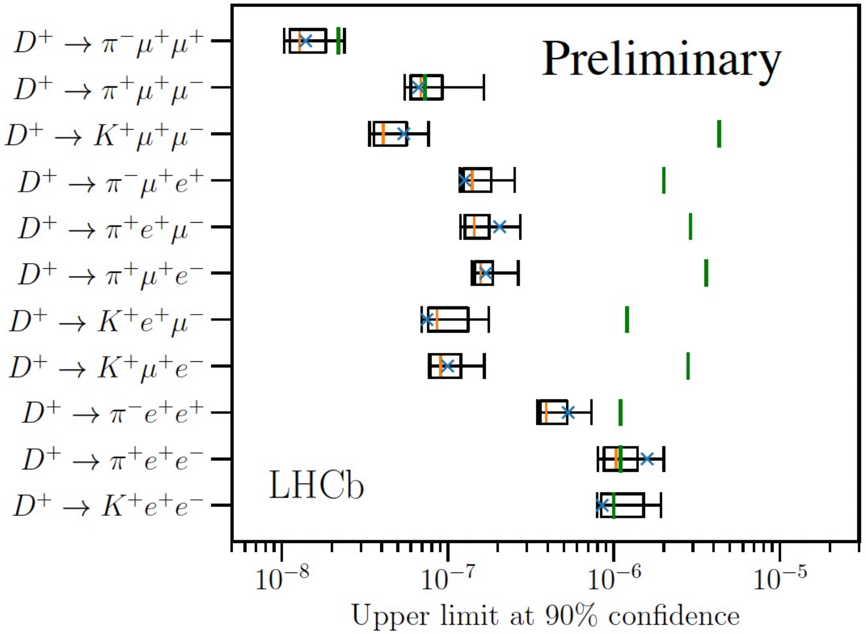
90% CL upper limits on τ LFV decays

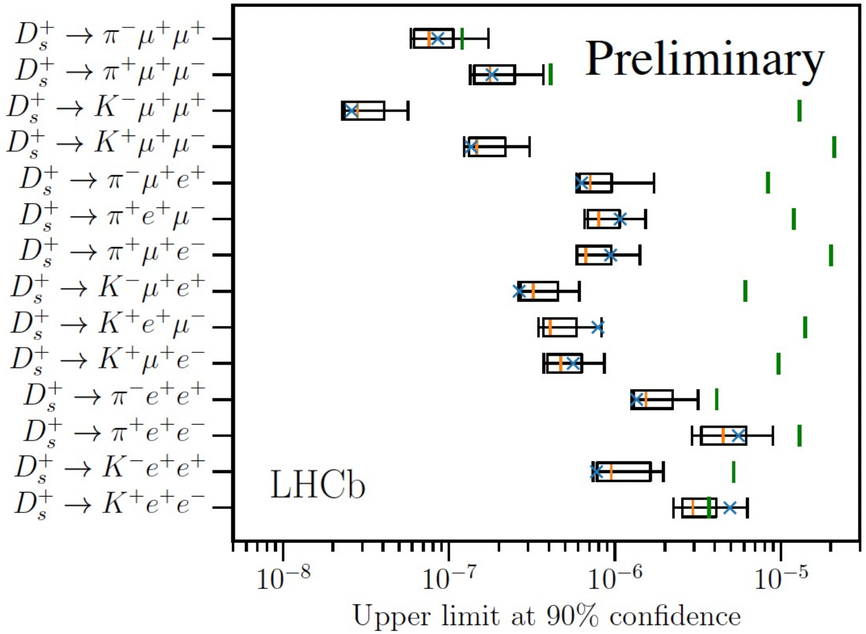


… beauty overview

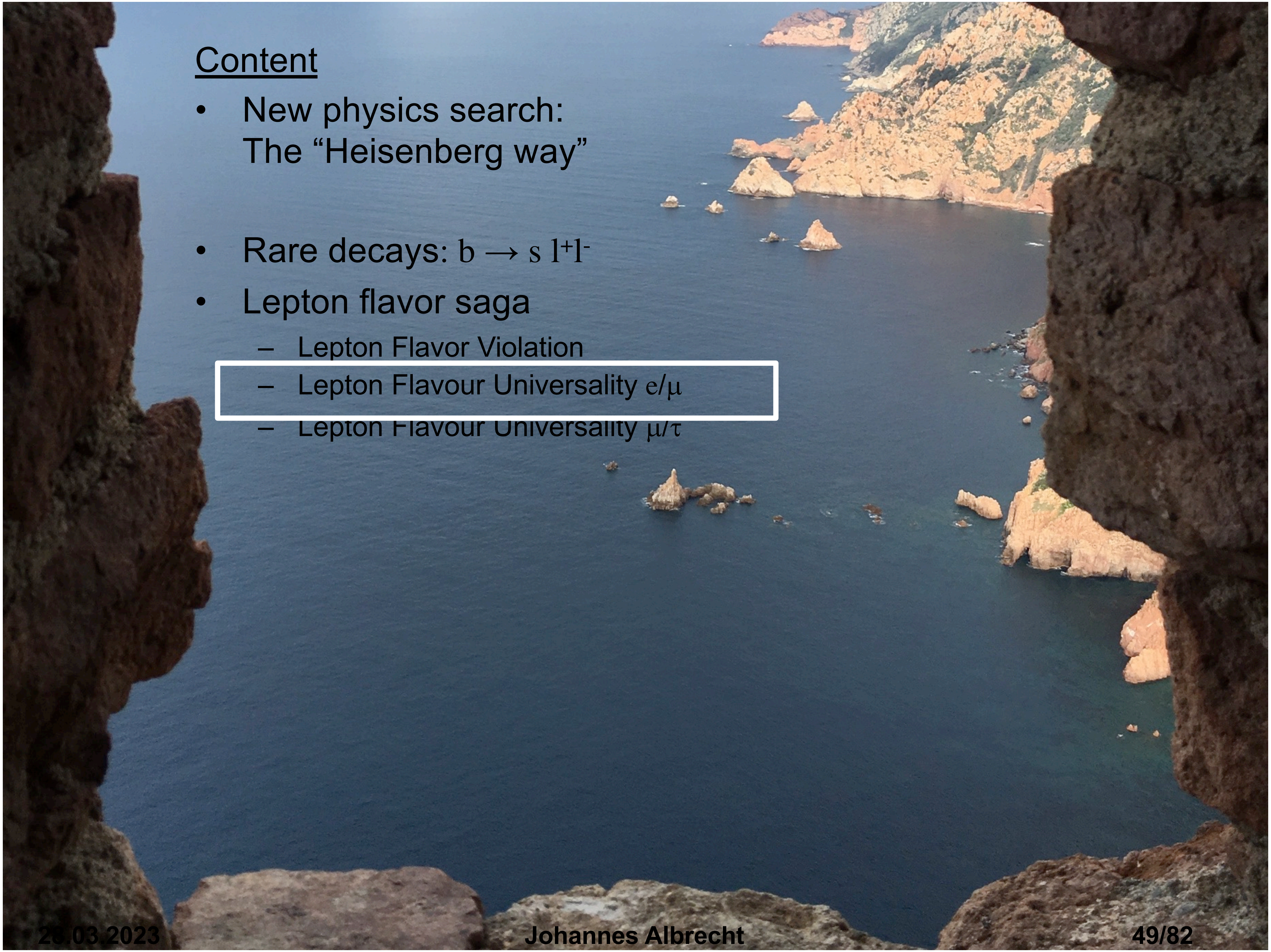


LHCb-PAPER-2020-007






STRESSED GRAVITON
LFV
I KNOW I SHOULD BE FLATTERED BY ALL THESE CLEVER PHYSICISTS DEVOTING SO MUCH EFFORT TO HUNTING FOR PROOF OF MY EXISTENCE.
BUT WHAT IF ALL THEIR OBSERVATIONS AND CALCULATIONS CONCLUSIVELY PROVE THAT I DON'T EXIST?
IT'S TOO HORRIBLE TO THINK ABOUT!
BEING A HYPOTHETICAL PARTICLE MAY NOT BE PERFECT, BUT IT'S BETTER THAN BEING A NON-EXISTENT PARTICLE.



Content

- New physics search:
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Flavour changing currents: Leptons

- Couplings of $W^{\pm}$ and Z^0 are equal for all lepton families
- Confirmed many times, e.g. in lepton decays

g_τ : "weak coupling constant for taus"

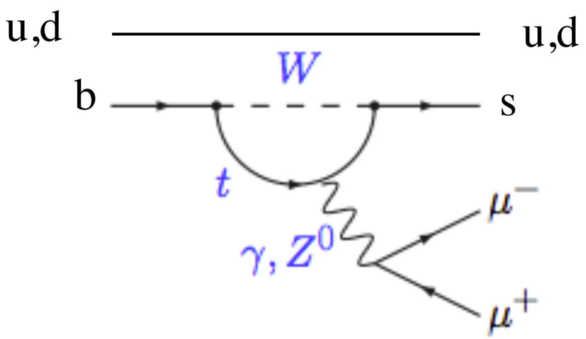
Decay rates	Measured ratio
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ und $\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$	$g_\tau / g_\mu = 0.999 \pm 0.003$
$\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ und $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$	$g_\mu / g_e = 1.001 \pm 0.004$
$\pi^+ \to e^+ \nu_e$ und $\pi^+ \to \mu^+ \nu_\mu$	$g_\mu / g_e = 1.001 \pm 0.002$

  – Similar precision confirmation with in $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$, $Z^0 \to \tau^+\tau^-$

- **Standard model: All leptons carry same weak**
  → Lepton-Flavour Universality

- In the SM, leptons couple universally to $W^{\pm}$ and Z^0
  → test this in ratios of semileptonic decays

electrons / muons [$\mathbf{b} \rightarrow \mathbf{s}$]



$$R_K = \frac{BR(B^+ \rightarrow K^+\mu^+\mu^-)}{BR(B^+ \rightarrow K^+e^+e^-)}$$

- Ratios differ from unity only by phase space


R_K = 1.0
G. Hiller and F. Krüger,
PRD69(2004) 074020
Carghese '19

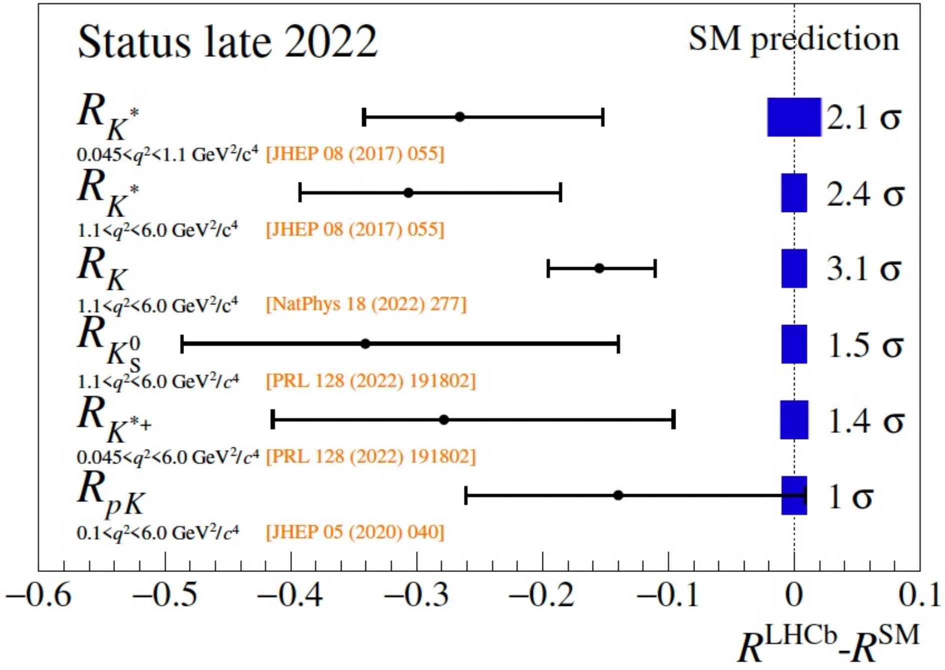
Status winter 2022

- LHCb saw low values in LFU tests of R_K and R_{K^*}

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \stackrel{\text{SM}}{=} 1.0$$

- Very low hadronic uncertainties, electroweak corrections O(1%)

EPJC76(2016)440



- Any significant deviation from 1 is a clear sign for New Physics

- Observed anomalies make a “natural pattern” with $b \to s\, \ell^+\ell^-$ anomalies
  - From P'_5 and reduced branching fractions in the muon modes, one can expect $R_{K(*)}$ reduced by ~25%
  - Electron modes compatible with SM

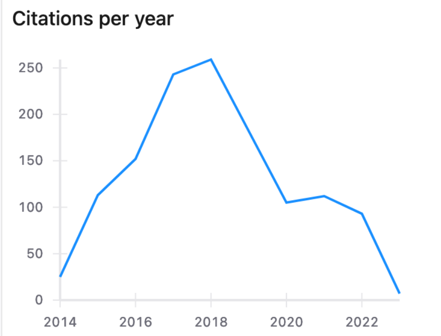
Excitement

Test of lepton universality using $B^+ \to K^+\ell^+\ell^-$ decays

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) Show All(700)

Jun 25, 2014

>1200 citations

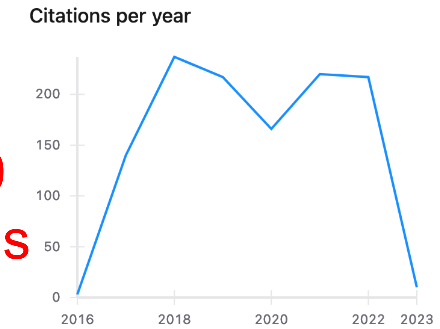


Test of lepton universality with $B^0 \to K^{*0}\ell^+\ell^-$ decays

LHCb Collaboration • R. Aaij (CERN) Show All(789)

May 16, 2017

>1200 citations

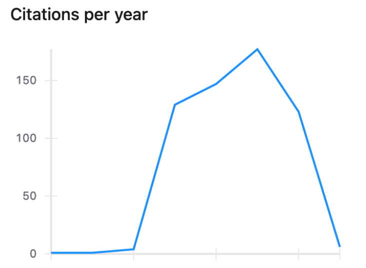


Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) Show All(850)

Mar 21, 2019

~600 citations

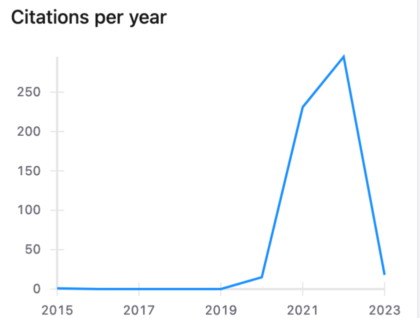


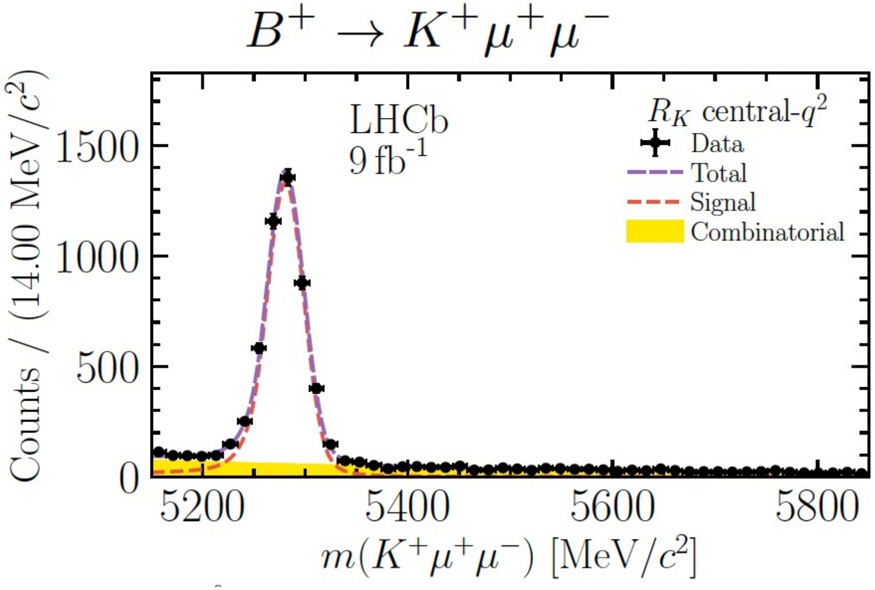
Test of lepton universality in beauty-quark decays

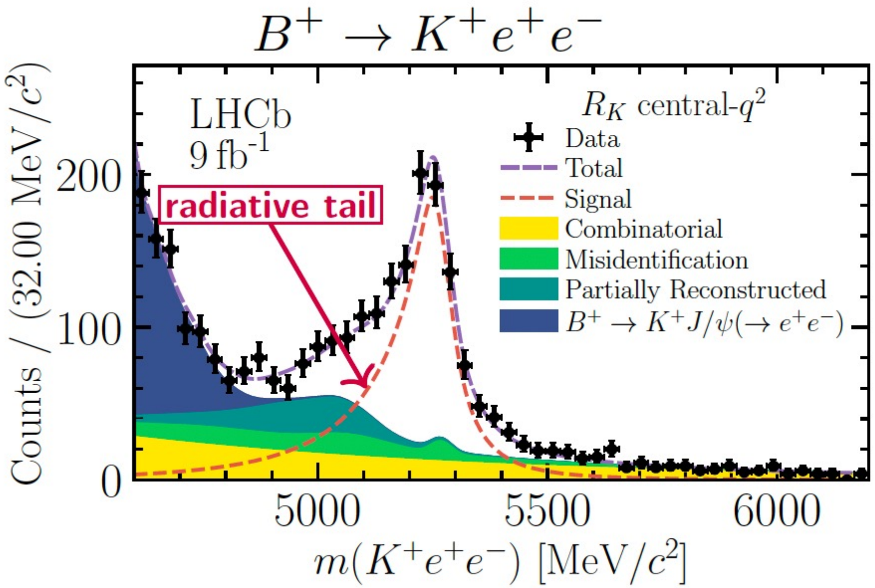
LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) Show All(961)

Mar 22, 2021

>550 citations





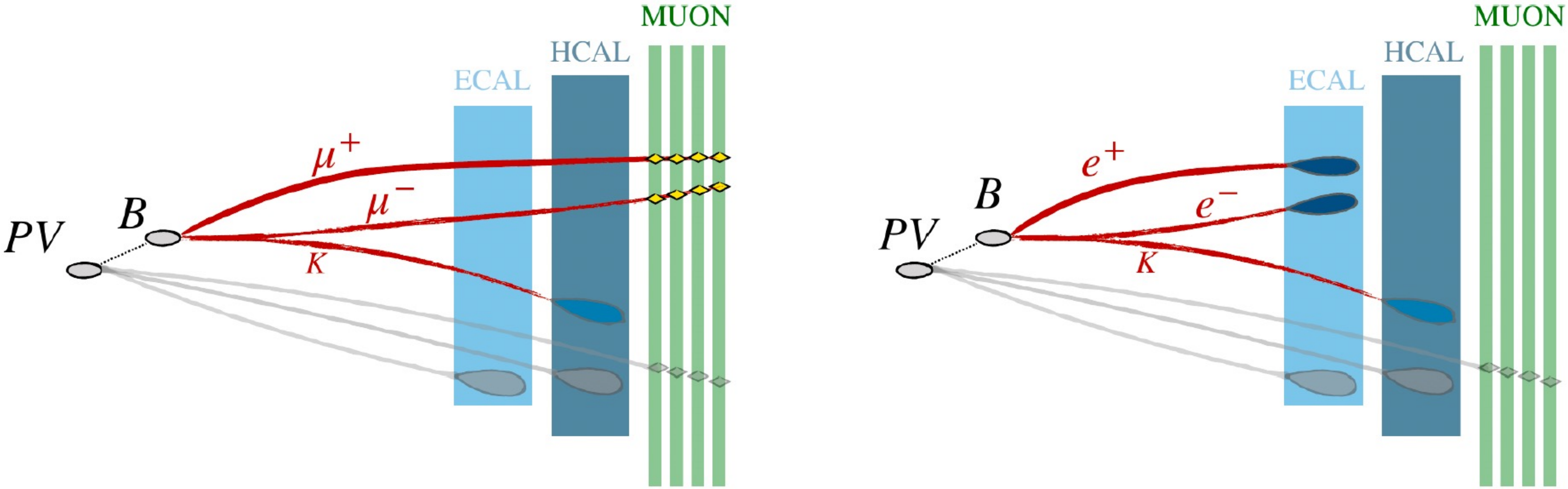


[arXiv:2212.09152] [arXiv:2212.09153]

Experimental Challenges for electron modes:

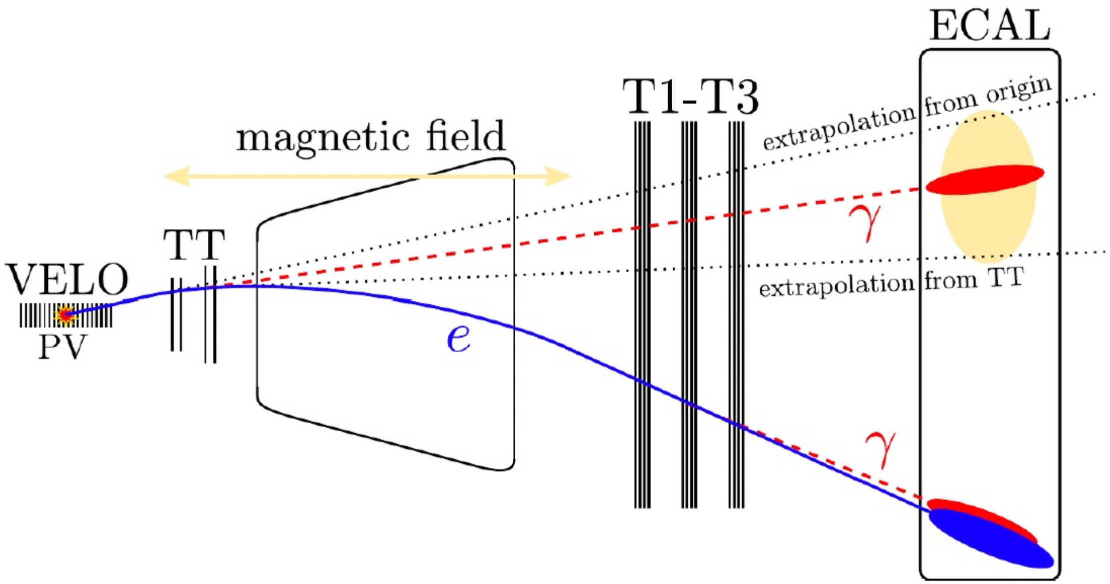
1. Low e trigger efficiencies due to higher thresholds compared to muons
2. Electrons strongly emit Bremsstrahlung traversing material
3. Contribution from several background sources, bkg. modeling critical

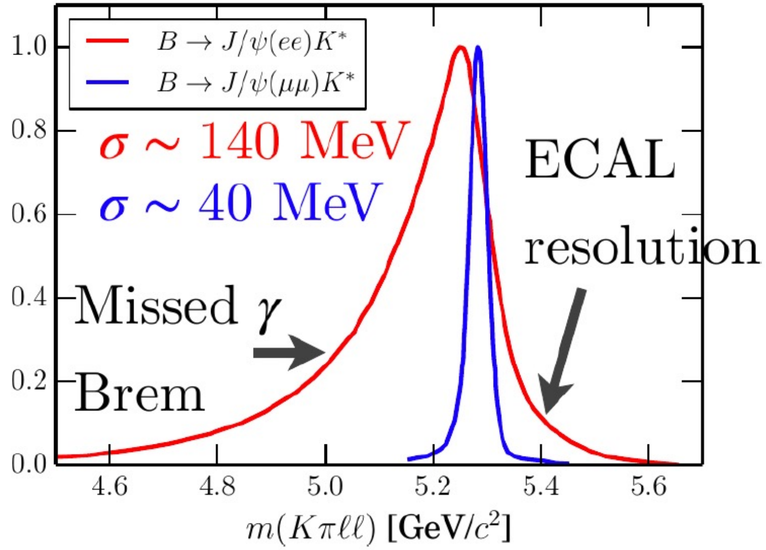
Experimental challenge: 1. Electron trigger



- Trigger signatures for muon and electron modes very different
- Lower L0 p_{T} thresholds for muons $(1.5\text{–}1.8\,\mathrm{GeV}/c)$ compared to electrons $(2.5\text{–}3.0\,\mathrm{GeV}) \rightarrow$ challenging for e^+e^- modes
- Combine exclusive trigger categories to improve ϵ for electron modes:
  1. Trigger on rest of event (independent of signal)
  2. Trigger on e/μ from signal

Experimental challenge: 2. Bremsstrahlung

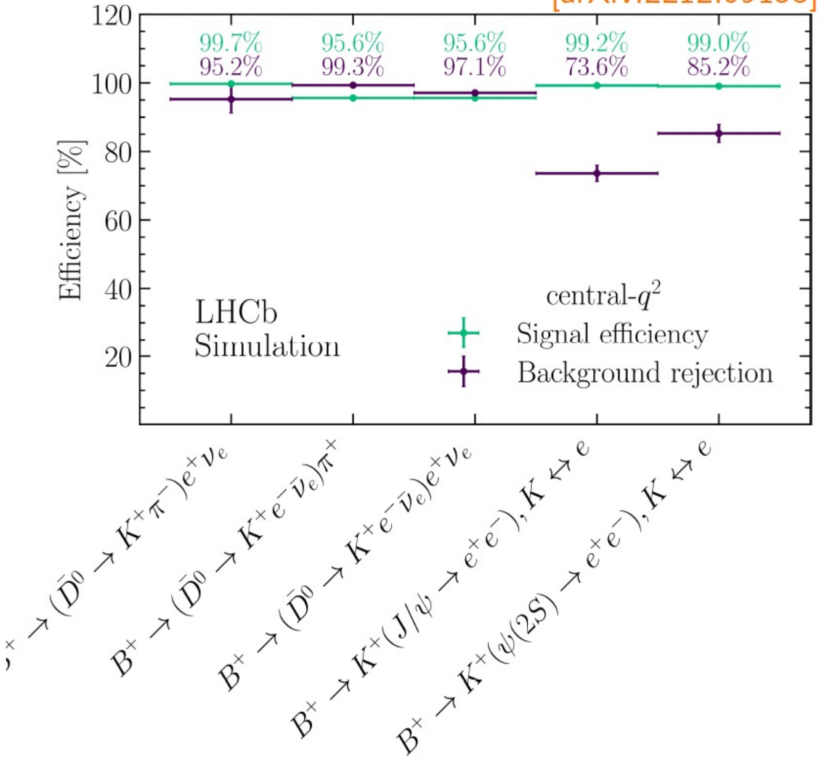




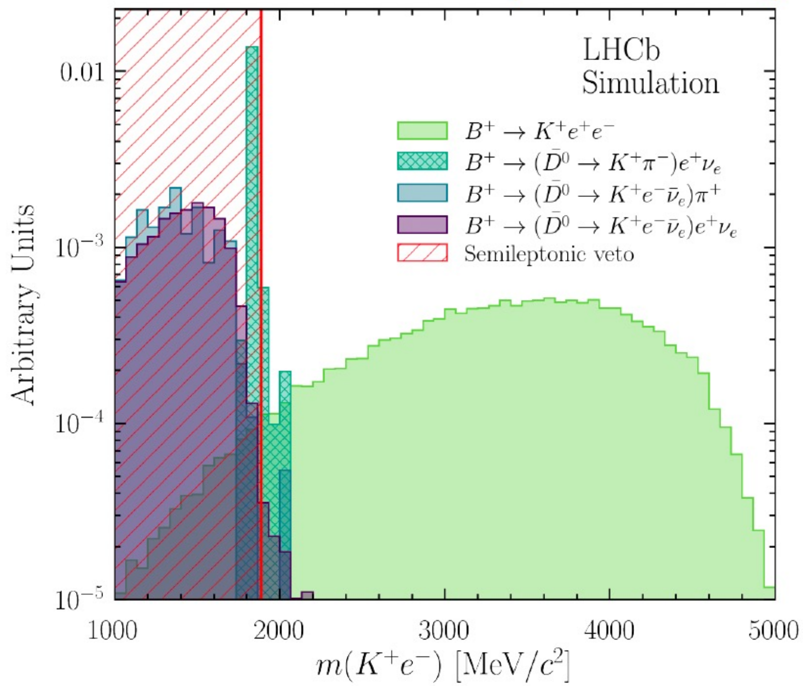
- Correct electron momentum by adding matching photons ($E_{\mathrm{T}} > 75\,\mathrm{MeV}/c^2$) reconstructed in the ECAL
- Bremsstrahlung recovery $\sim 50\%$ efficient, well simulated
- Bremsstrahlung reconstruction impacts momentum resolution
  $\rightarrow$ higher background pollution and more sensitive to bkg. modeling

Experimental challenge: 3. Background suppression

[arXiv:2212.09153]

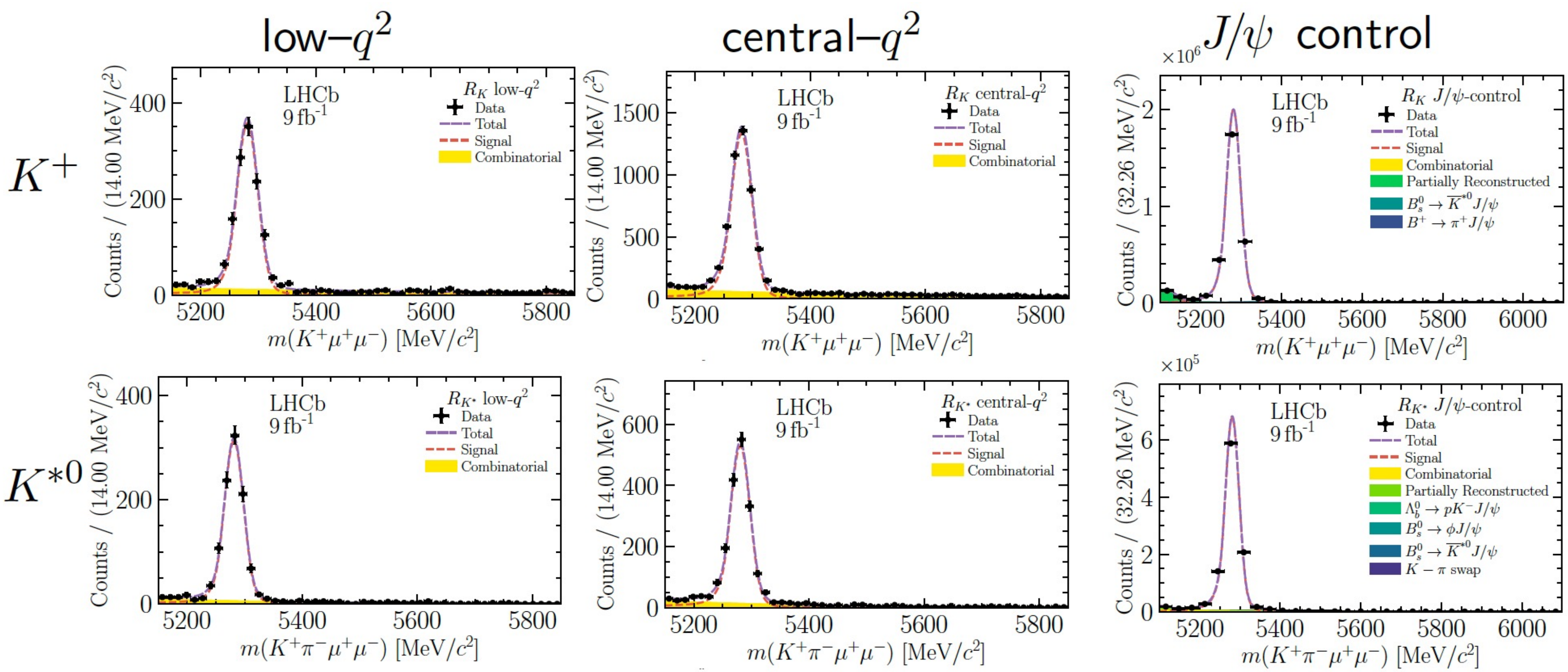


[arXiv:2212.09153]



- Combinatorial: multivariate classifier using kinematic quantities and vertex quality information
- Partially reconstructed: multivariate classifier in electron mode and corrected mass exploiting PV/SV reconstruction
- Misidentification: Lepton and hadron particle identification
  Residual backgrounds from misidentification explicitly modeled [see backup]

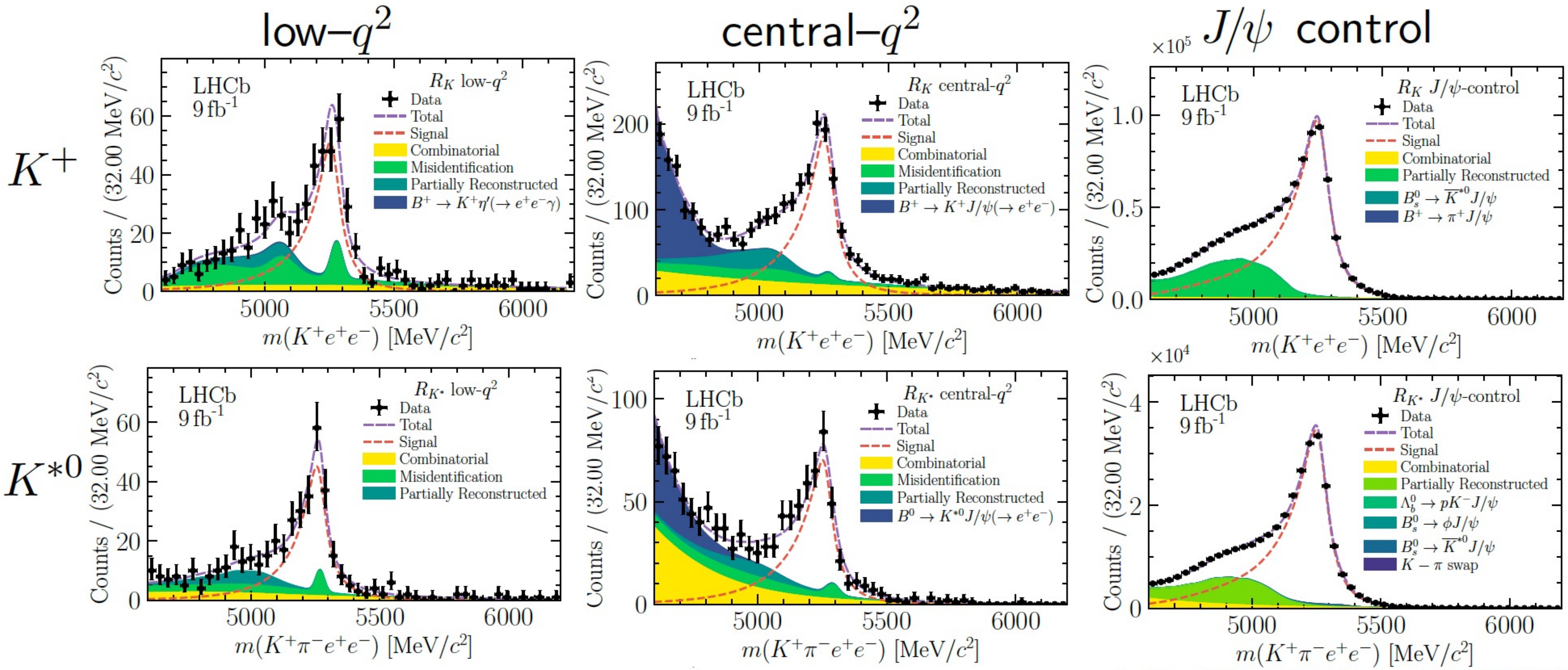
Muon mode fit



[arXiv:2212.09152] [arXiv:2212.09153]

- Muon mode is very clean!
- Muon branching fraction compatible with published results
  [JHEP 06 (2014) 133] [JHEP 11 (2016) 047]

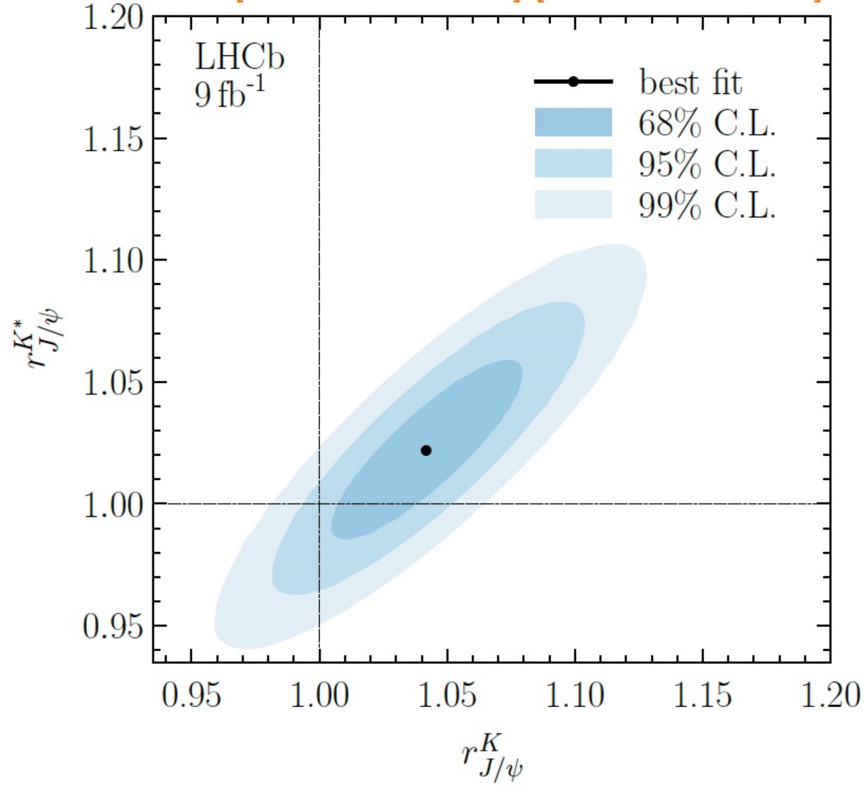
Electron mode fits



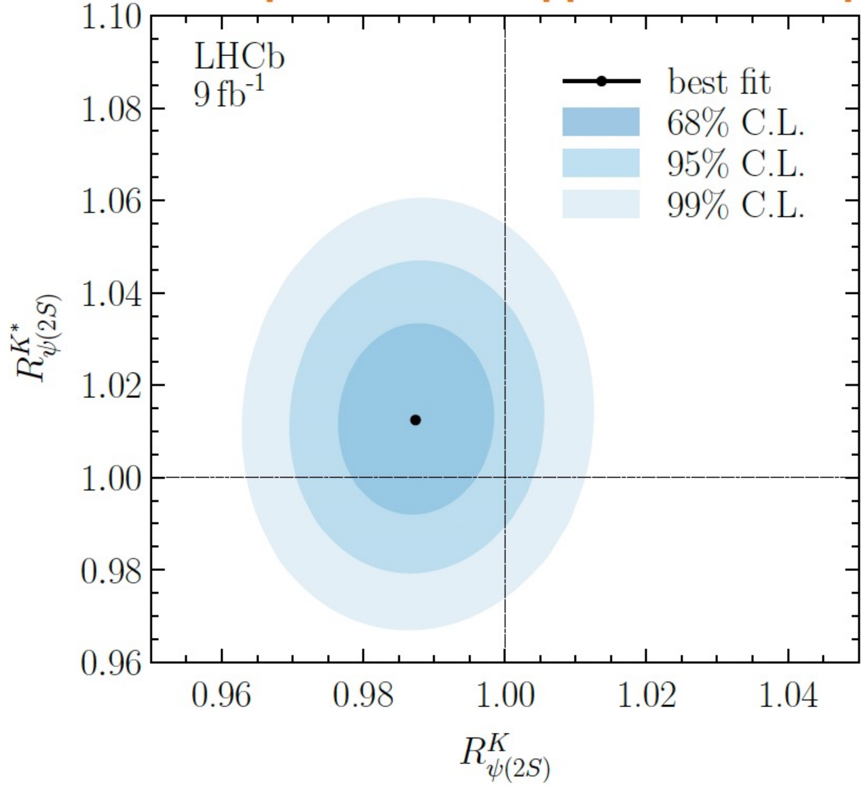
[arXiv:2212.09152] [arXiv:2212.09153]

- Brems. tails from J/ψ entering rare modes constrained in sim. fit
- Partially reconstructed bgk. from $K^{*0}e^+e^-$ constrained in $K^+e^+e^-$

[arXiv:2212.09152] [arXiv:2212.09153]



[arXiv:2212.09152] [arXiv:2212.09153]

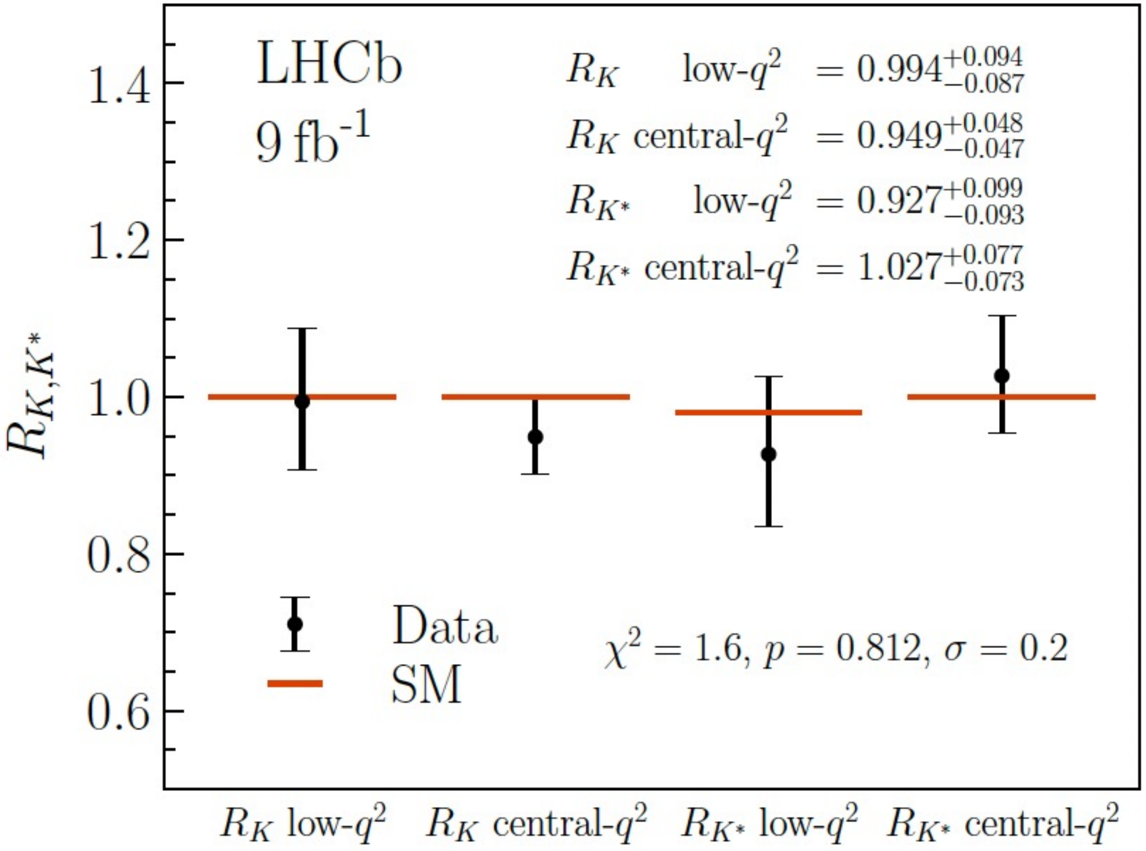


- Both $r_{J/\psi}$ and $R_{\psi(2S)}$ compatible with unity at better than $2\,\sigma$

Measurement

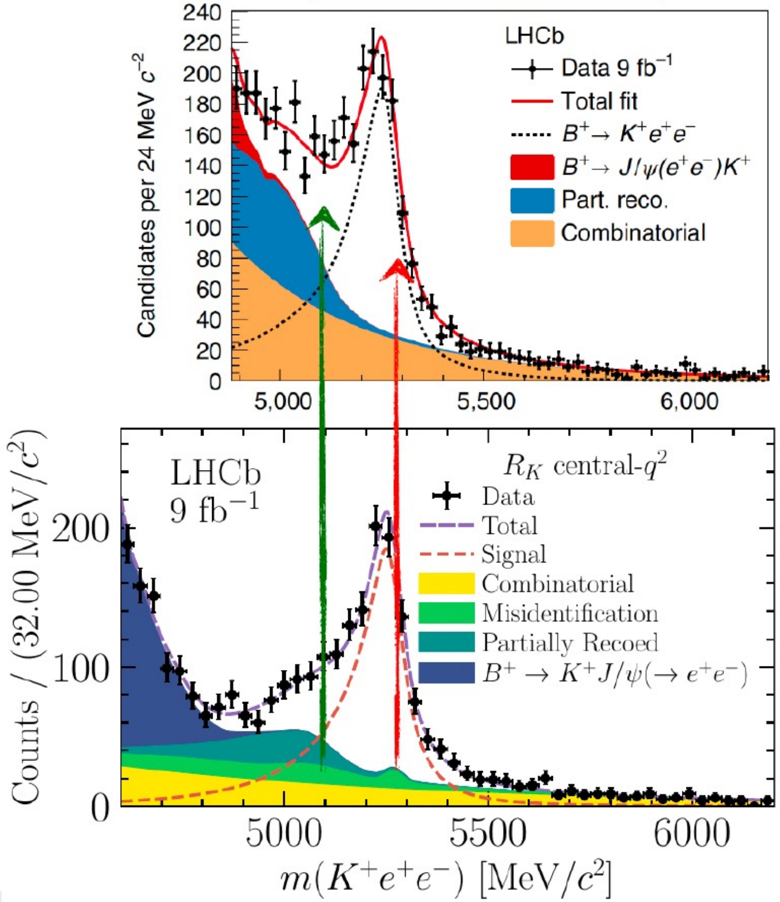
- Most precise test of Lepton Flavour Universality in $b \to s\ell^+\ell^-$ transitions
- Supersedes previous results
- Compatible with the SM at $0.2\,\sigma$ using a simple χ^2 test
- Statistical uncertainty dominates

[arXiv:2212.09152] [arXiv:2212.09153]



Shift wrt previous

[Nat. Phys. 18, 277-282 (2022)]



- Different PID cut used ➡ Allowed σ_{stat} : ± 0.033
- Mis-ID rate from $D^{*-} \to D^0(K\pi)\pi$
- With new(previous) analysis requirements

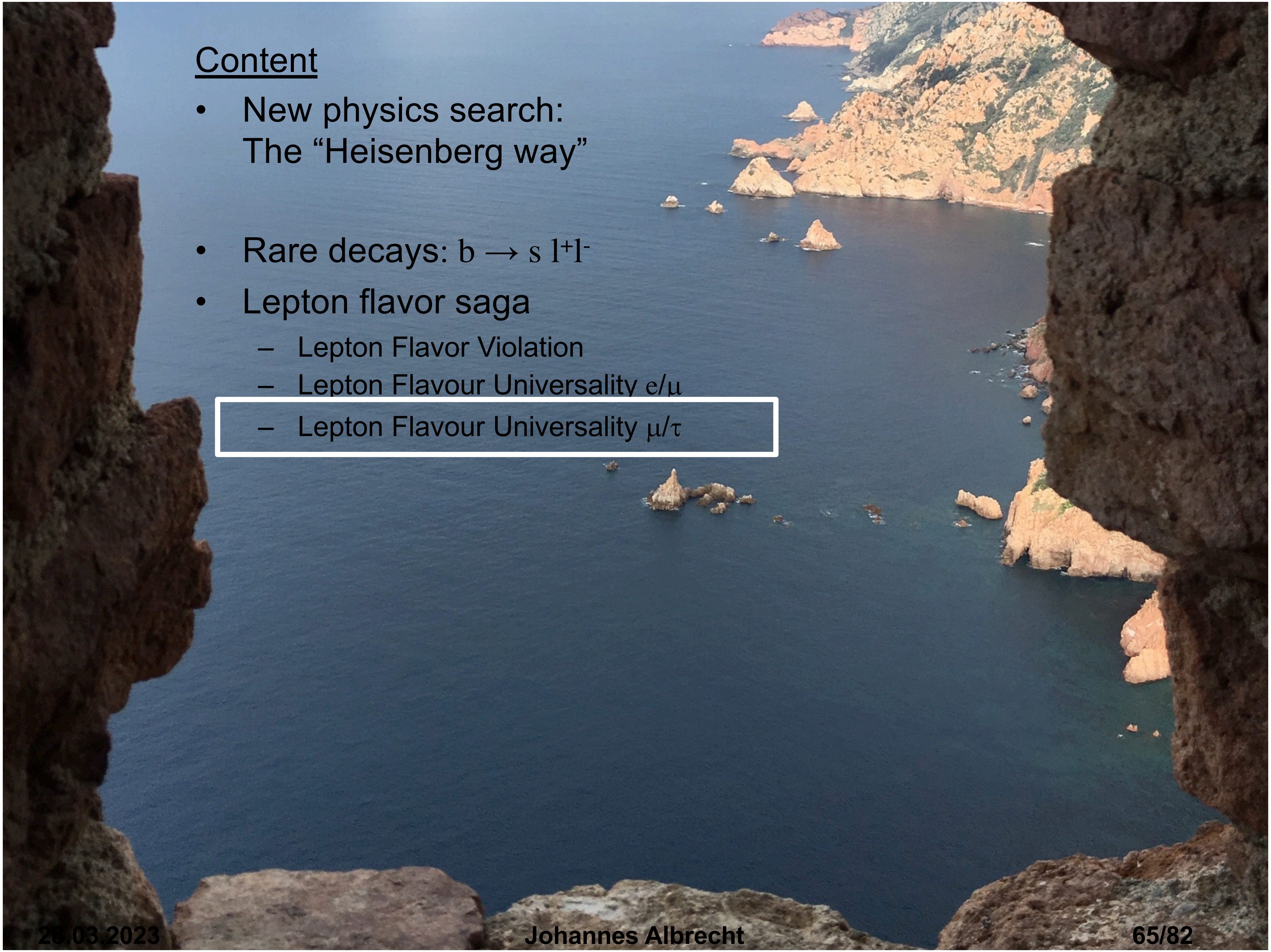
	Sample	$\pi \to e$	$K \to e$
(11+12)	Run 1	1.78 (1.70) %	0.69 (1.24) %
(15+16)	Run 2p1	0.83 (1.51) %	0.18 (1.25) %
(17+18)	Run 2p2	0.80 (1.50) %	0.16 (1.23) %

single-misID	× 1 (Run1) × 2 (Run2)	× 2 (Run1) × 7 (Run2)
double-misID	× 1^2 (Run1) × 2^2 (Run2)	× 2^2 (Run1) × 7^2 (Run2)

- Shift due to contamination at looser working point : **+0.064**
- Shift due to not inclusion of background in mass fit: **+0.038**

Adds linearly

Summary LFU Electrons Vs Muons



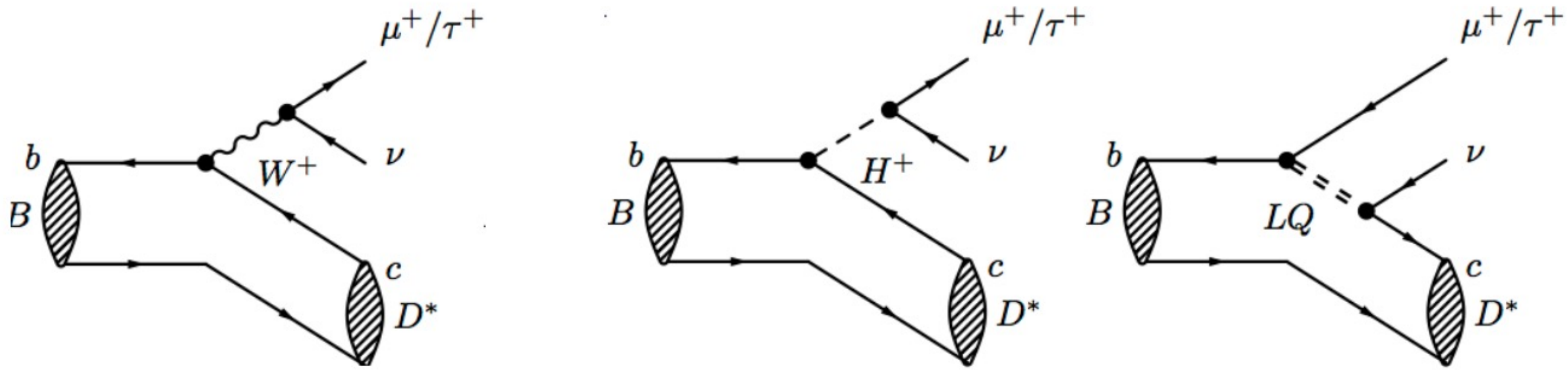
Content

- New physics search:
  The "Heisenberg way"

- Rare decays: $b \rightarrow s\, l^+ l^-$
- Lepton flavor saga
  - Lepton Flavor Violation
  - Lepton Flavour Universality e/μ
  - Lepton Flavour Universality μ/τ

Lepton flavour universality in $\mathbf{b \rightarrow c}$

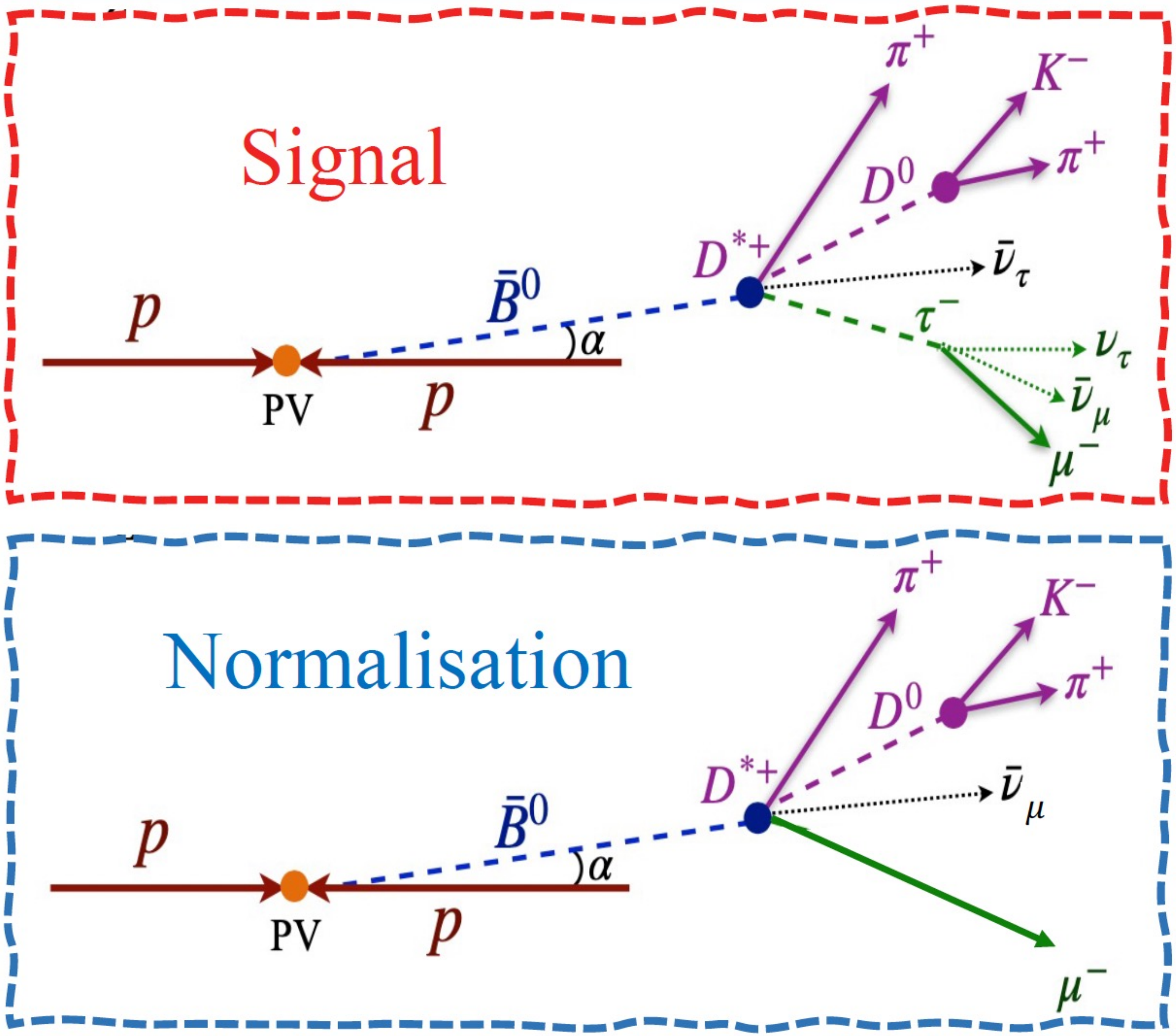
- Surprises possible in tree-level analyses



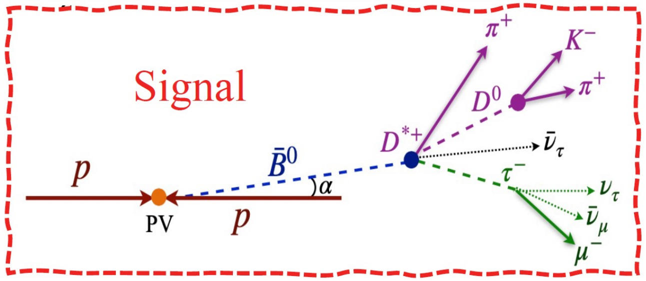
- $B^0 \rightarrow D^{(*)} \ell \nu$ Measures ratio τ^- / μ^-
  - Multiple experiments: Belle, Babar, LHCb
  - Multiple D-modes: D, D*
  - Multiple tau final states: $\mu^-\nu$, 1-prong, 3 prong
- Challenging Analyses
  - Missing neutrino, complex backgrounds (e.g. $B \rightarrow D^{**} \mu$)

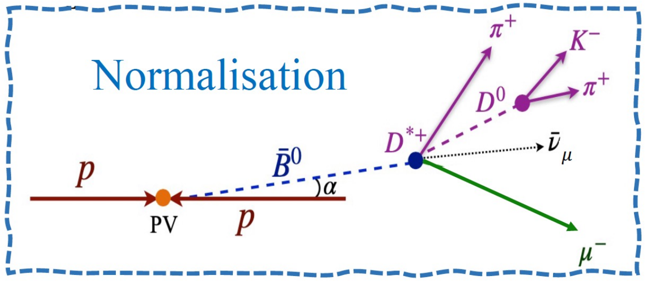
$$R_{D^*} = \frac{BR(B^0 \rightarrow D^{*+} \tau^- \bar{\nu})}{BR(B^0 \rightarrow D^{*+} \mu^- \bar{\nu})}$$

Signal and normalization



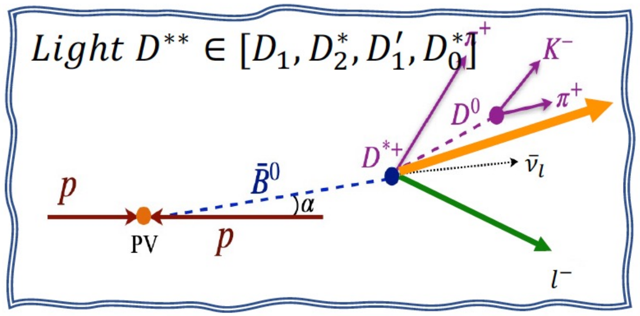
Signal and normalization … and backgrounds



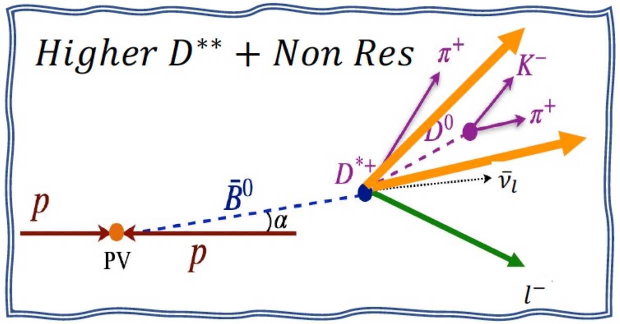


Backgrounds

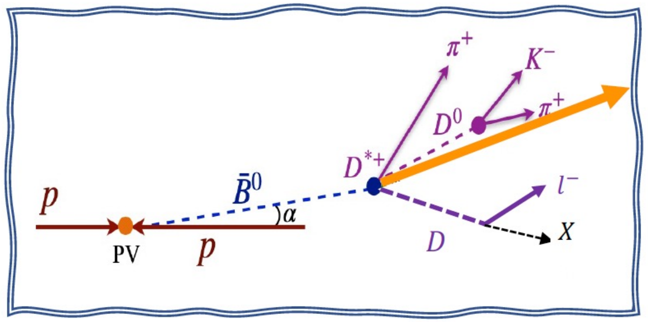
$\bar{B} \to D^{**}(\to D^{(*)}\pi^-)\, l^- \nu$



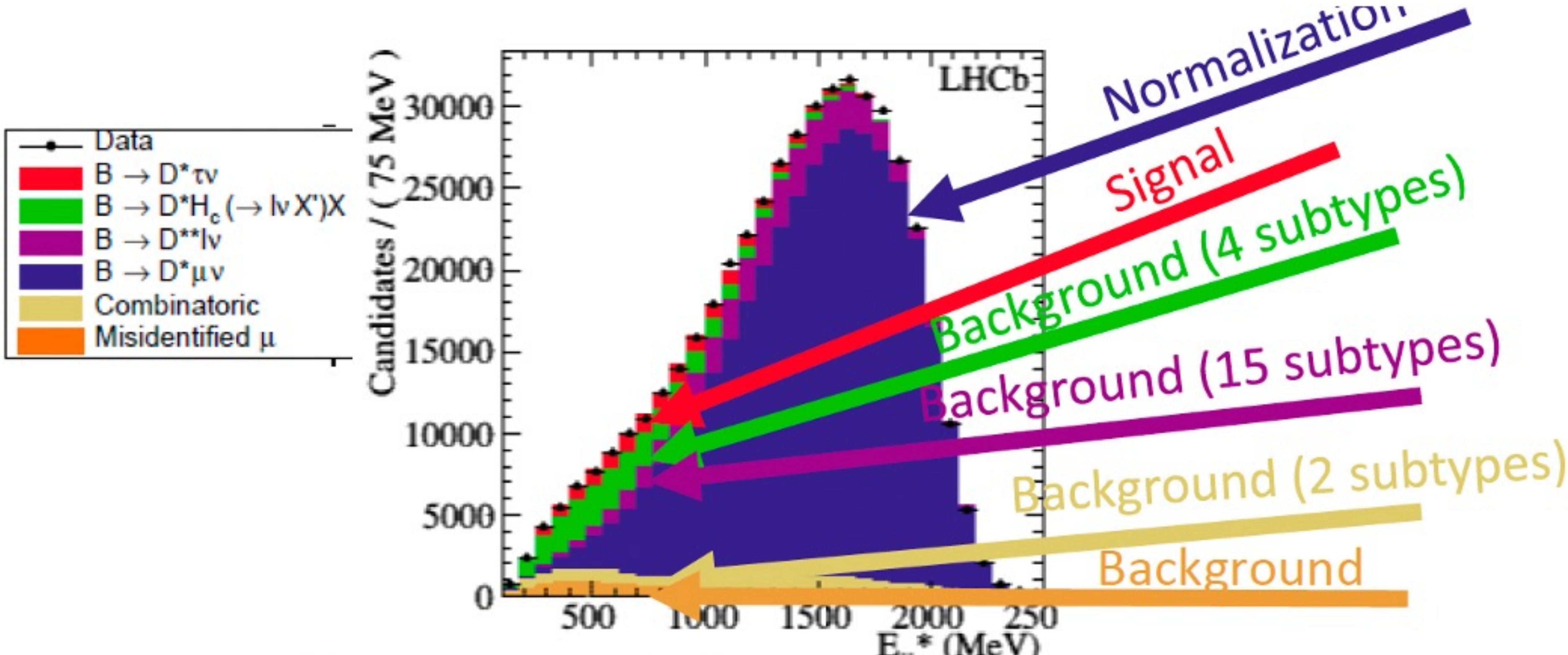
$\bar{B} \to D^{**}(\to D^{(*)}\pi^-\pi^+)\, l^- \nu$



$\bar{B} \to D^{(*)} D(\to l^- X) K$

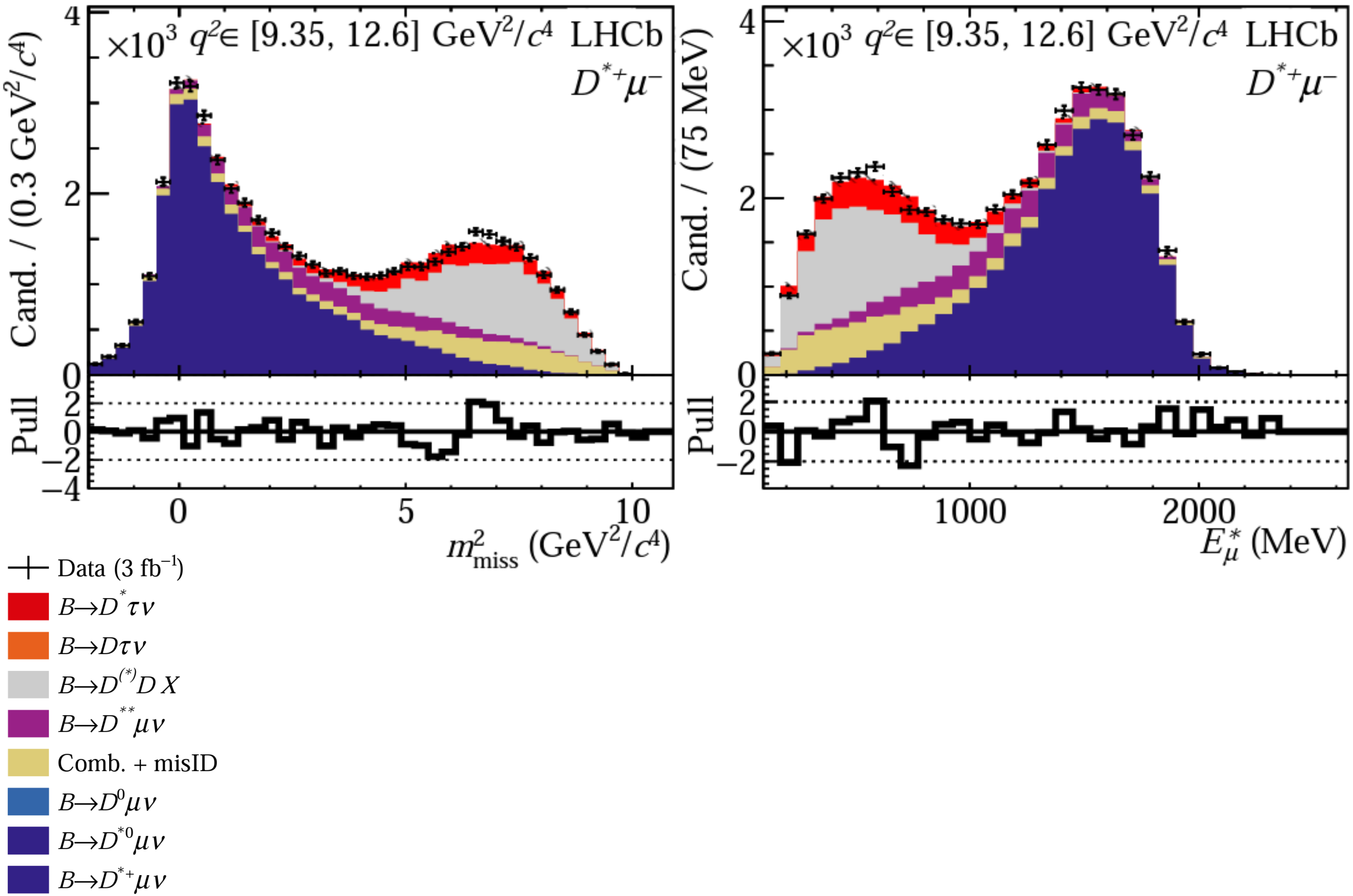


Hadron colliders: challenges

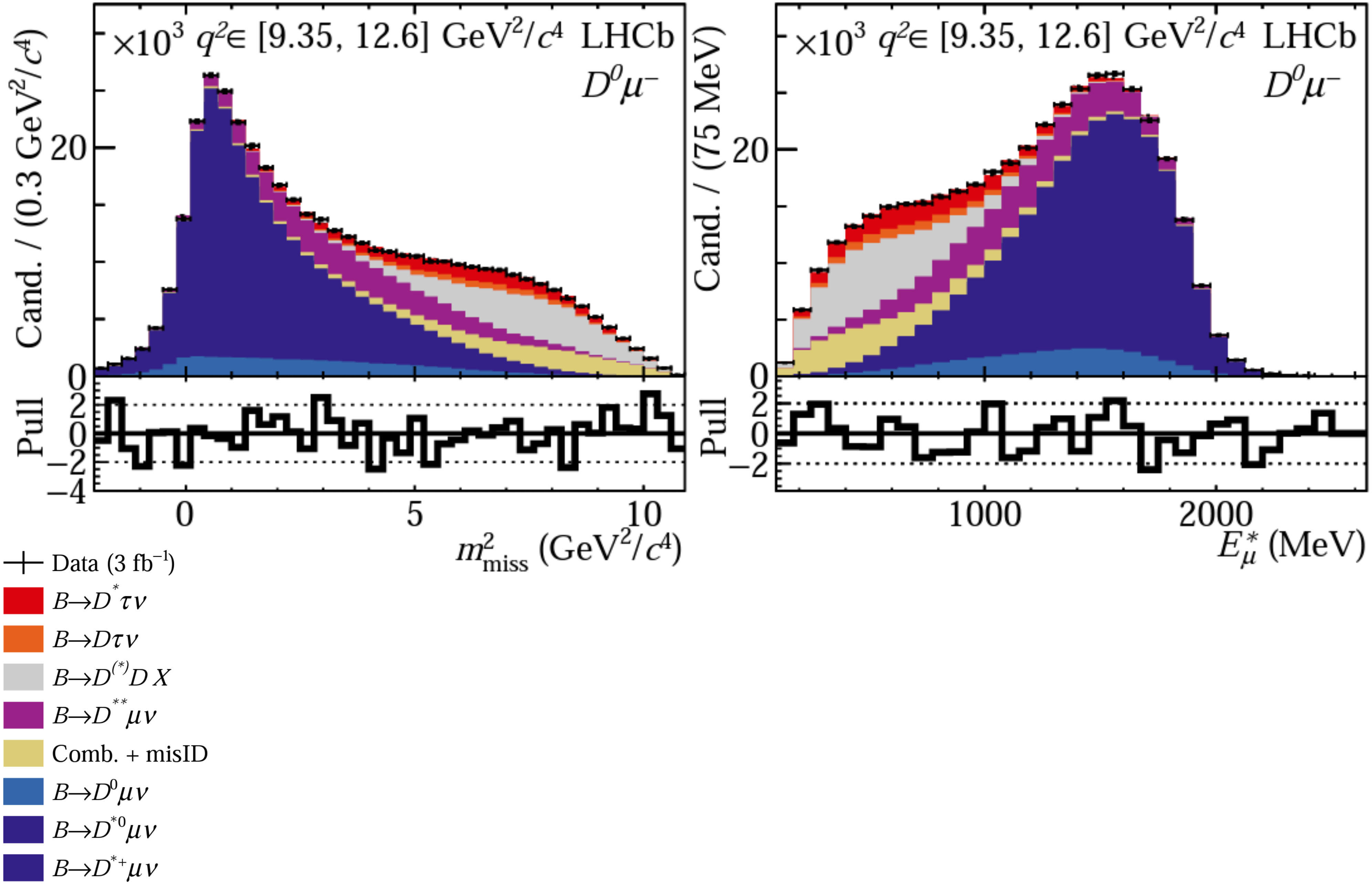


PRL 115 (2015) 111803

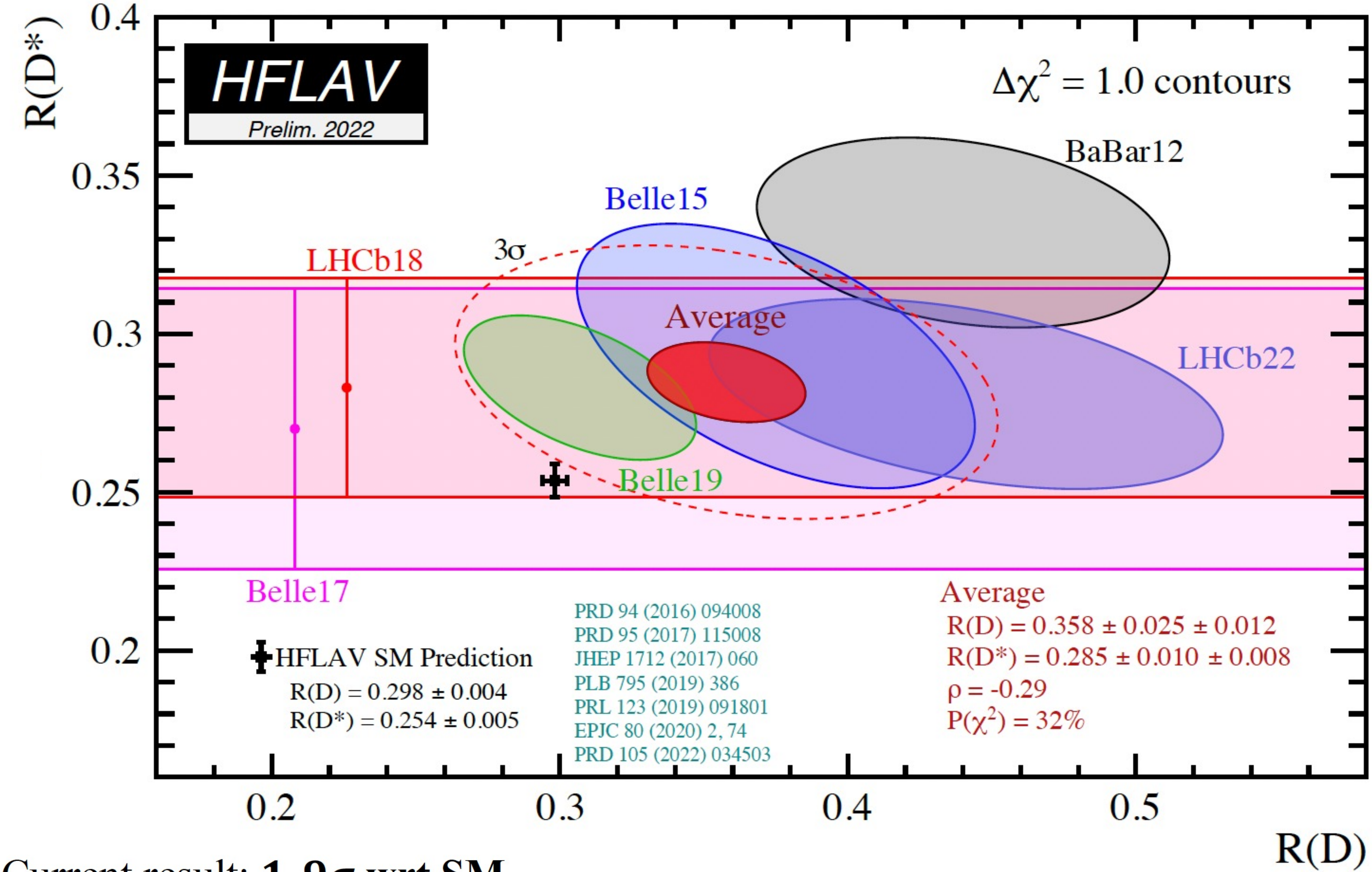
Fit for signal: $D^{*+}\,\mu^-$



Fit for signal: $D^0\ \mu^-$



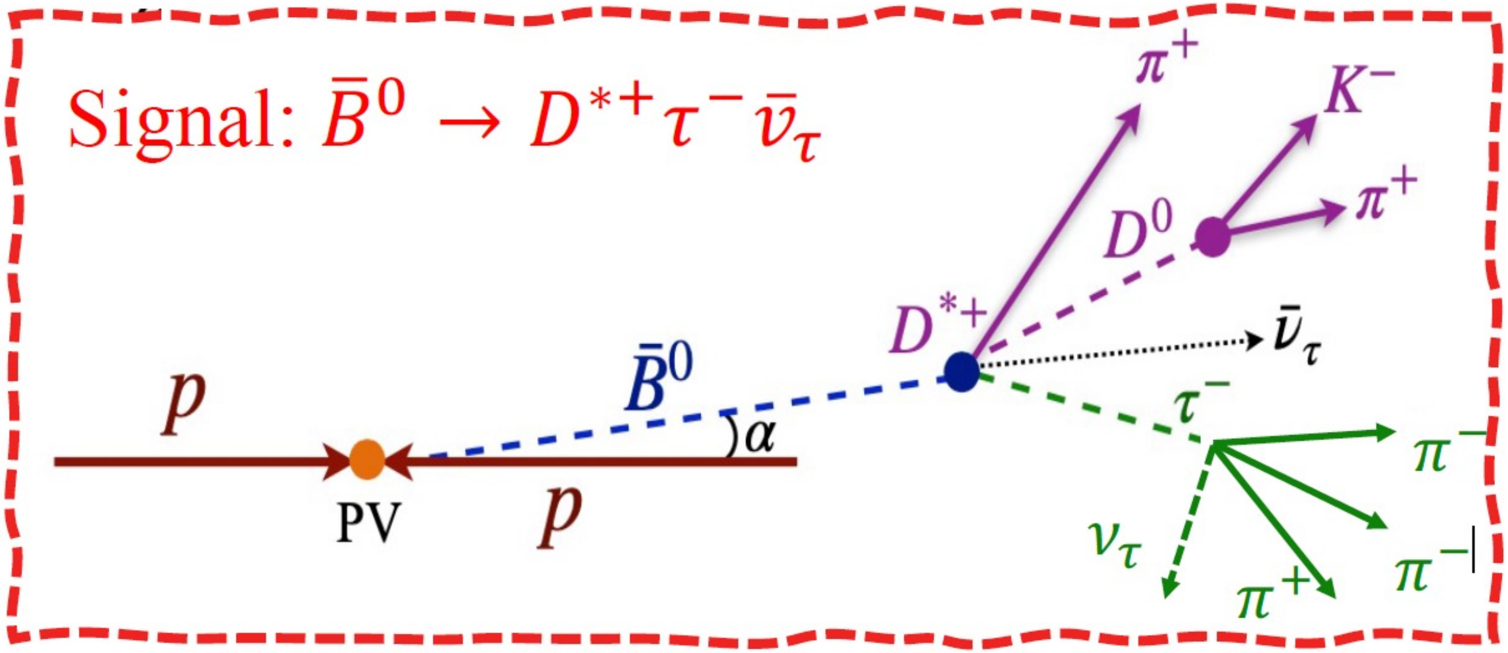
Fit result

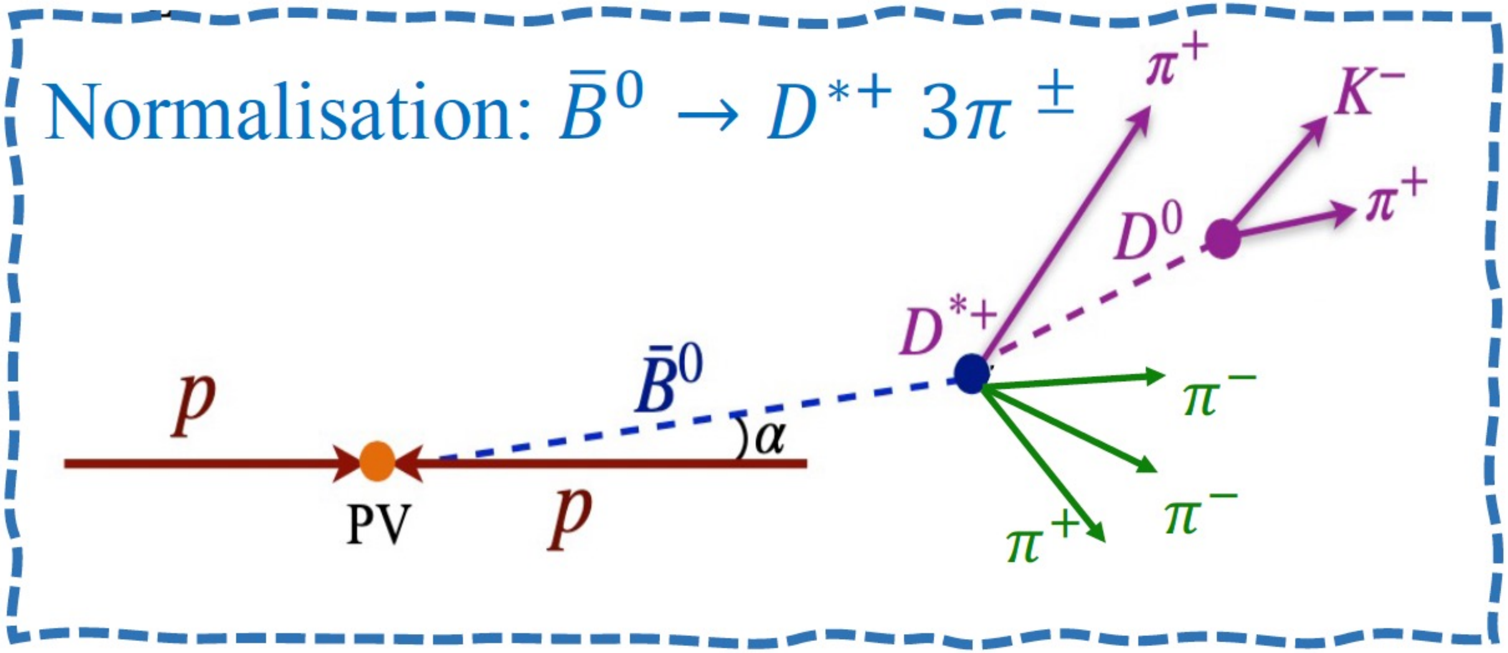


Current result: $\mathbf{1.9\sigma}$ **wrt SM**

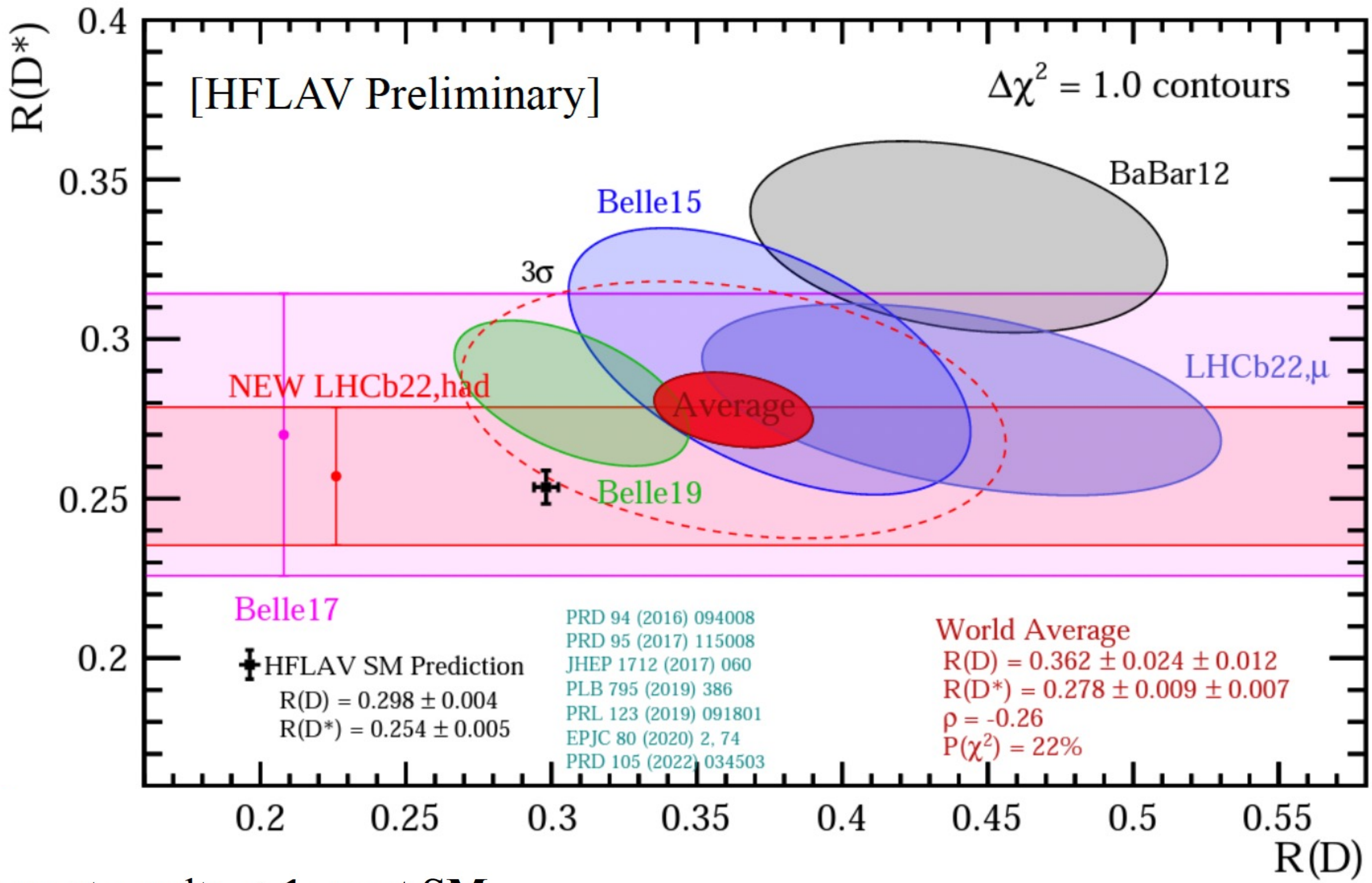
WA: 3.3σ $\rightarrow$ $\mathbf{3.2\sigma}$ **wrt SM**

Alternative way to measure the same





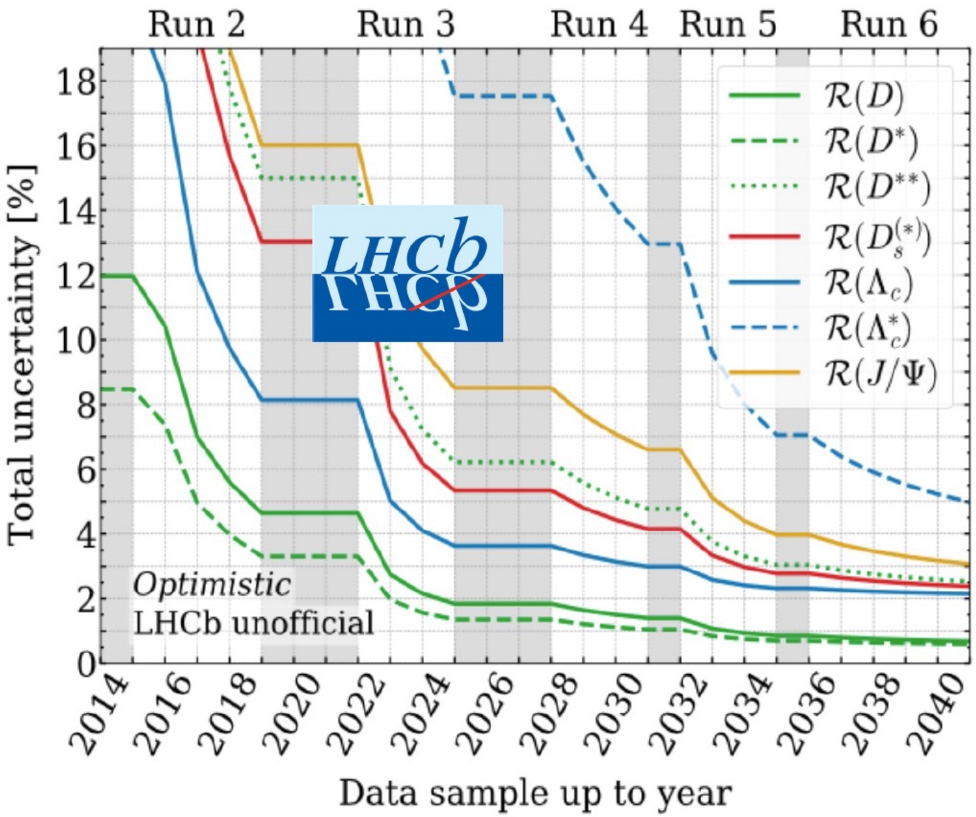
Summary b → c l nu



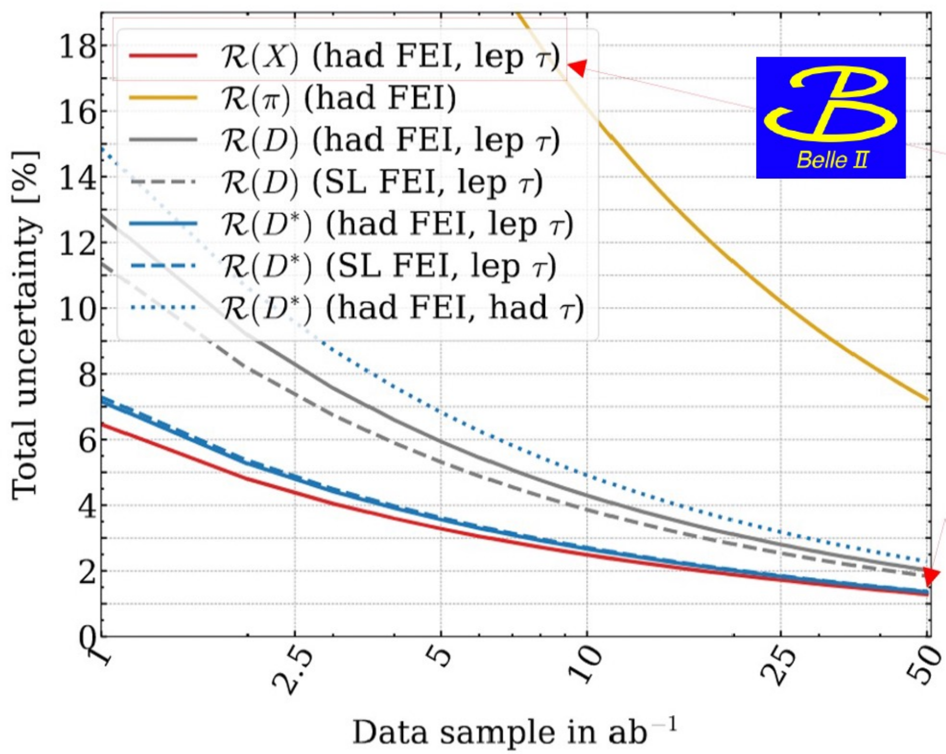
Current result: < **1σ wrt SM**

WA: 3.2σ → **3 σ wrt SM**

When will we know more?



[[Rev. Mod. Phys. 94, 015003 (2022)]]

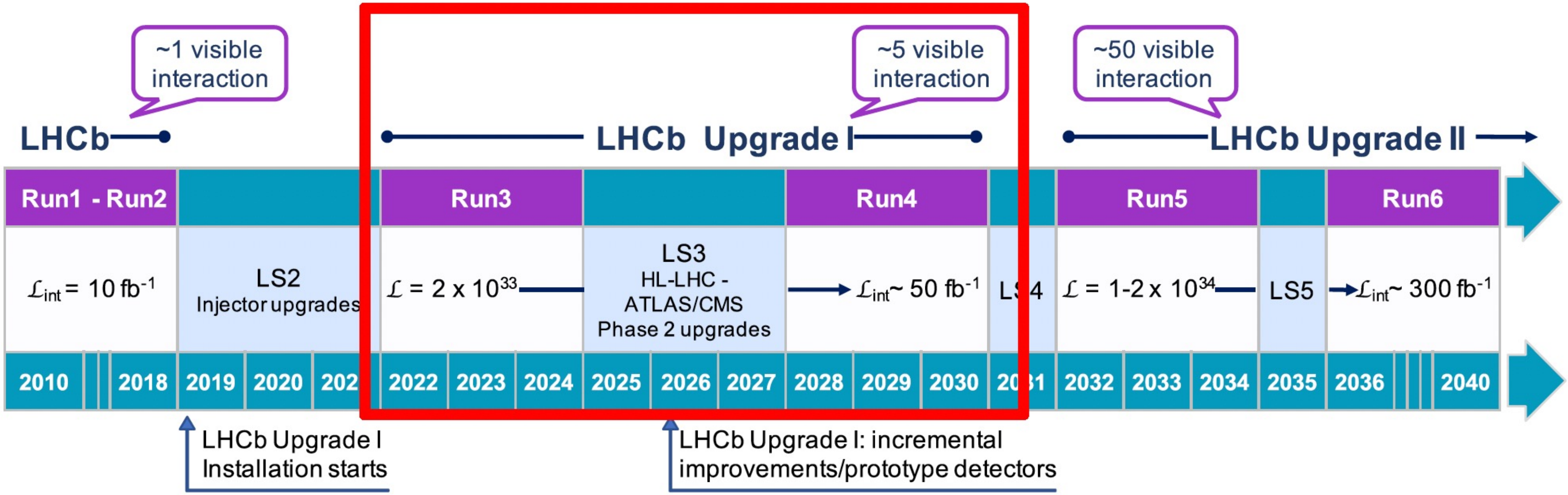


[[Belle II talk @ Beyond Flavour Anamolies III]]

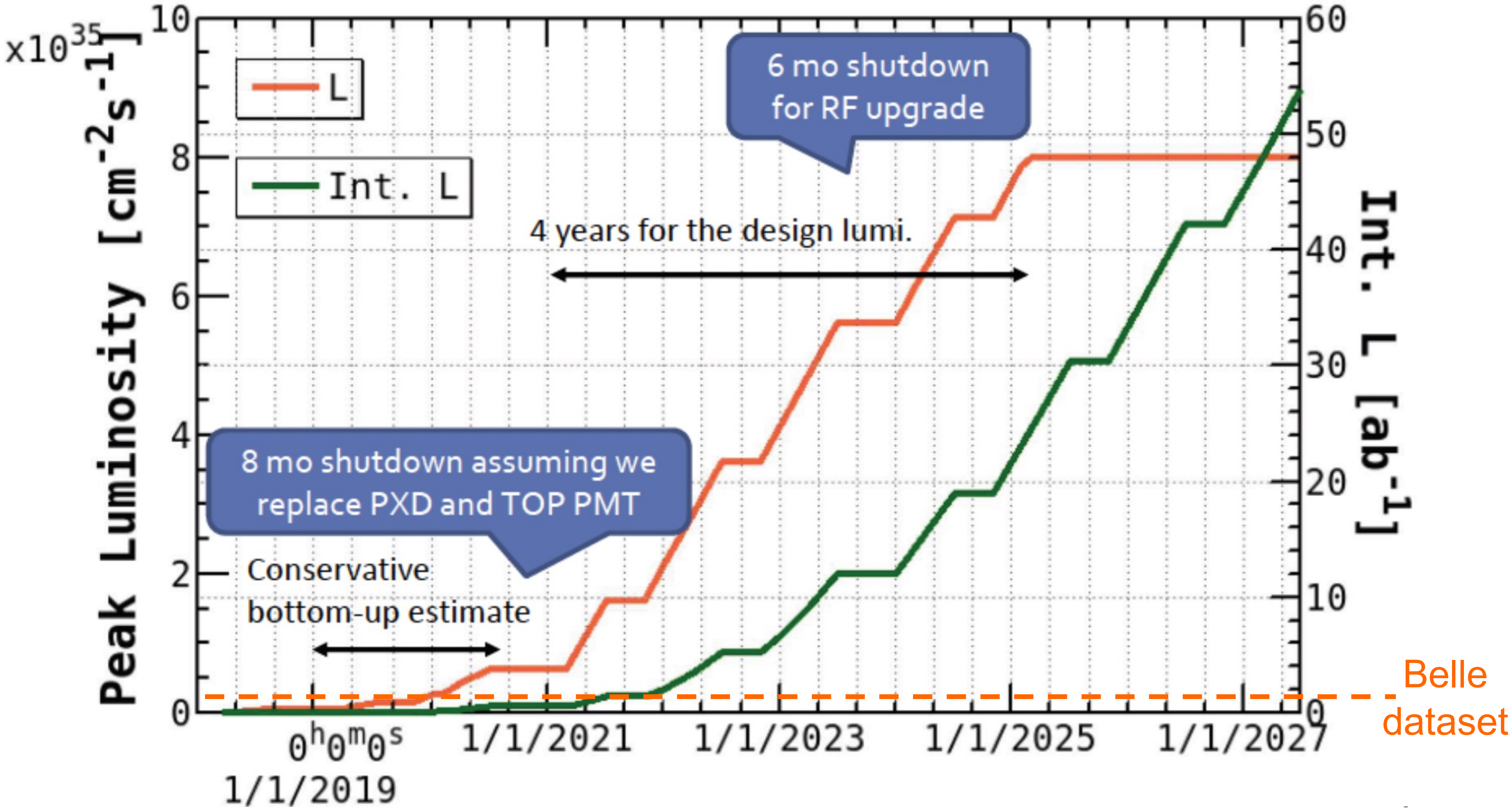
State of the art

A look to the future

LHC long term plan



	Integrated luminosity	
	LHCb	GPD
Run 1	3	25
Run 2	9	100
Run 3	23	300
Run 4	50	+300+/a
Run 5,6	300+	+300+/a



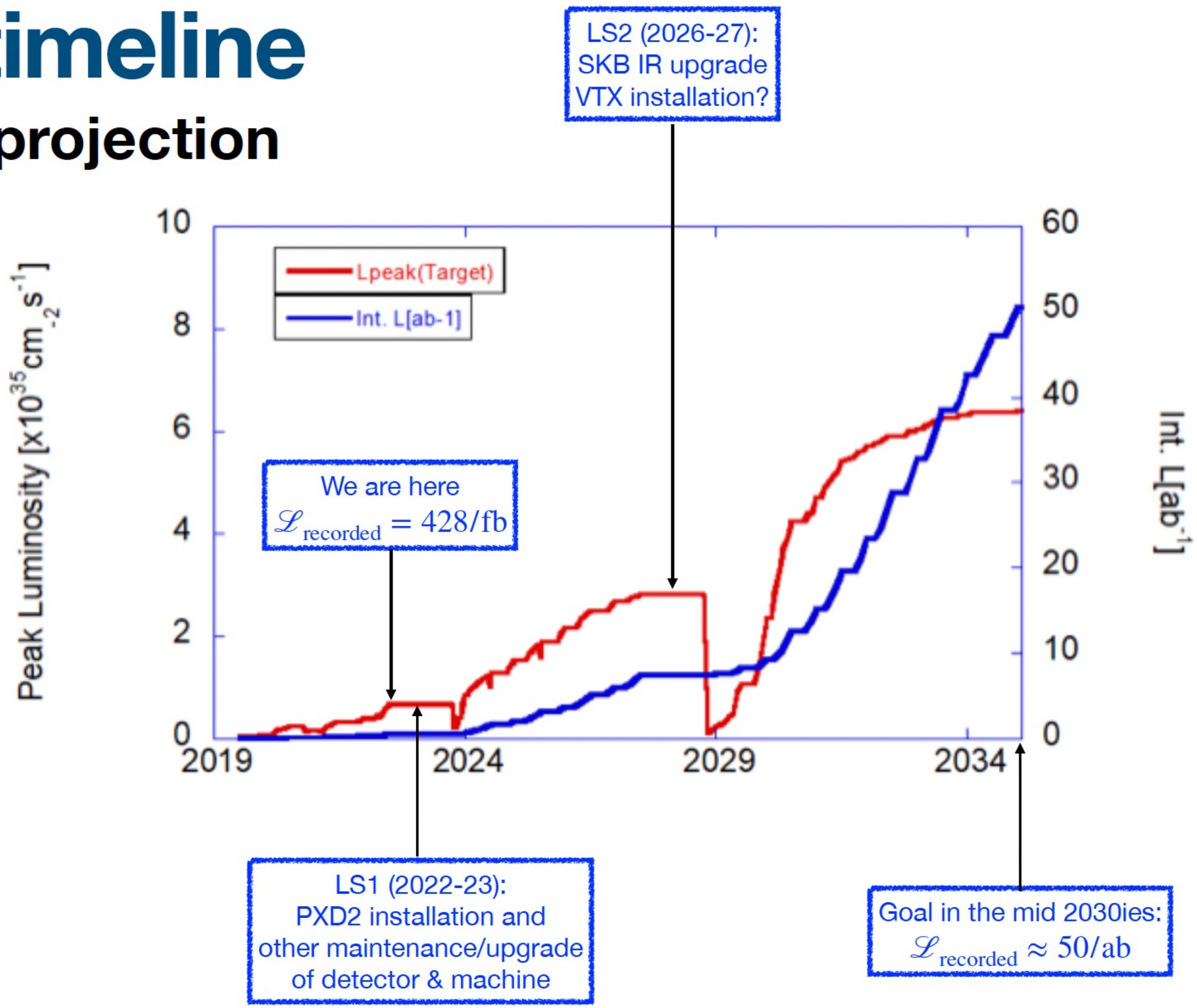
- Physics run of Belle 2 started
  - First results envisaged for LP2019
  - Significant luminosity ~2022

G. Mohanty, Moriond EW 2019

.. More realistically (?)

Belle II timeline

Luminosity projection

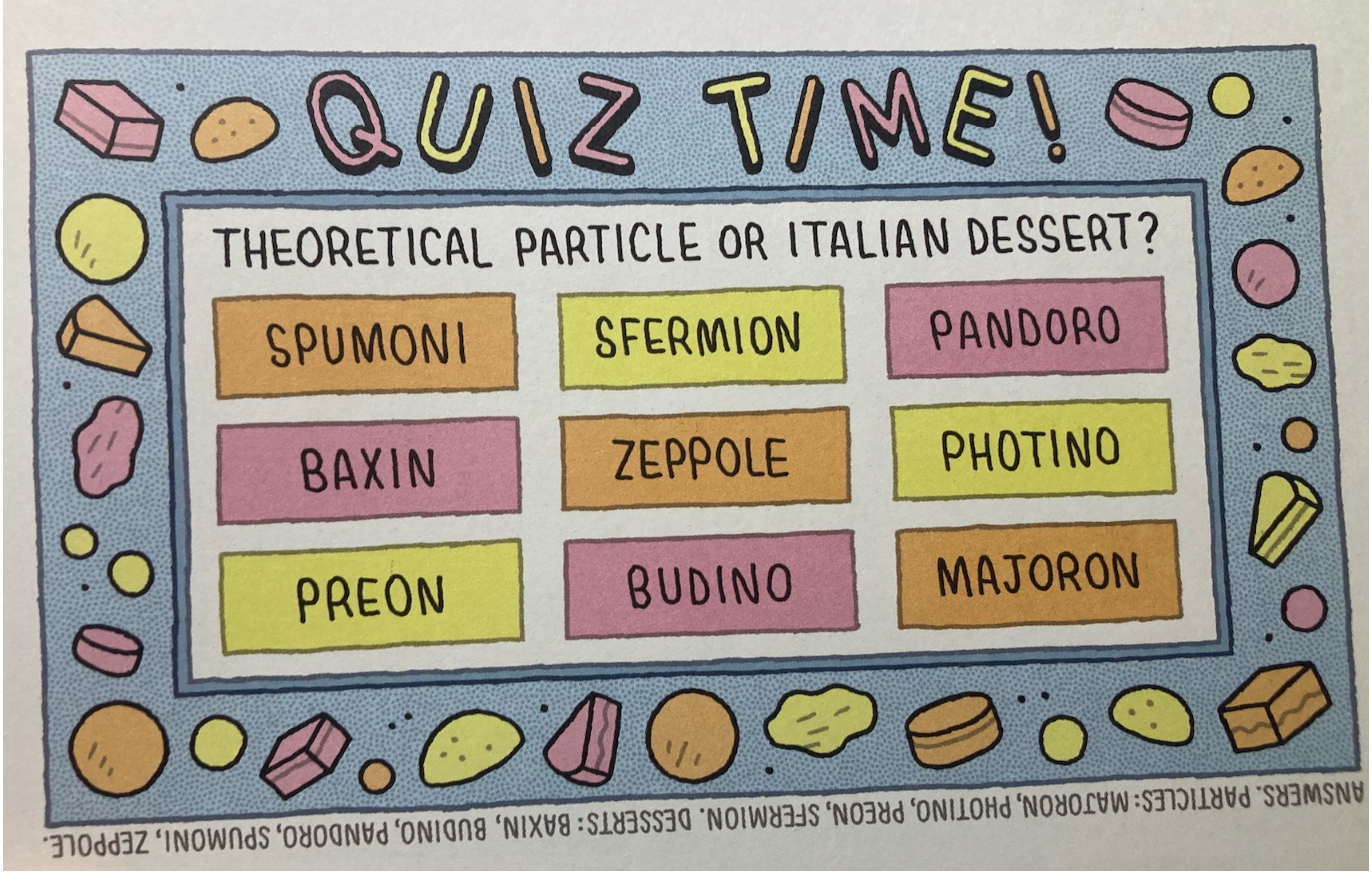


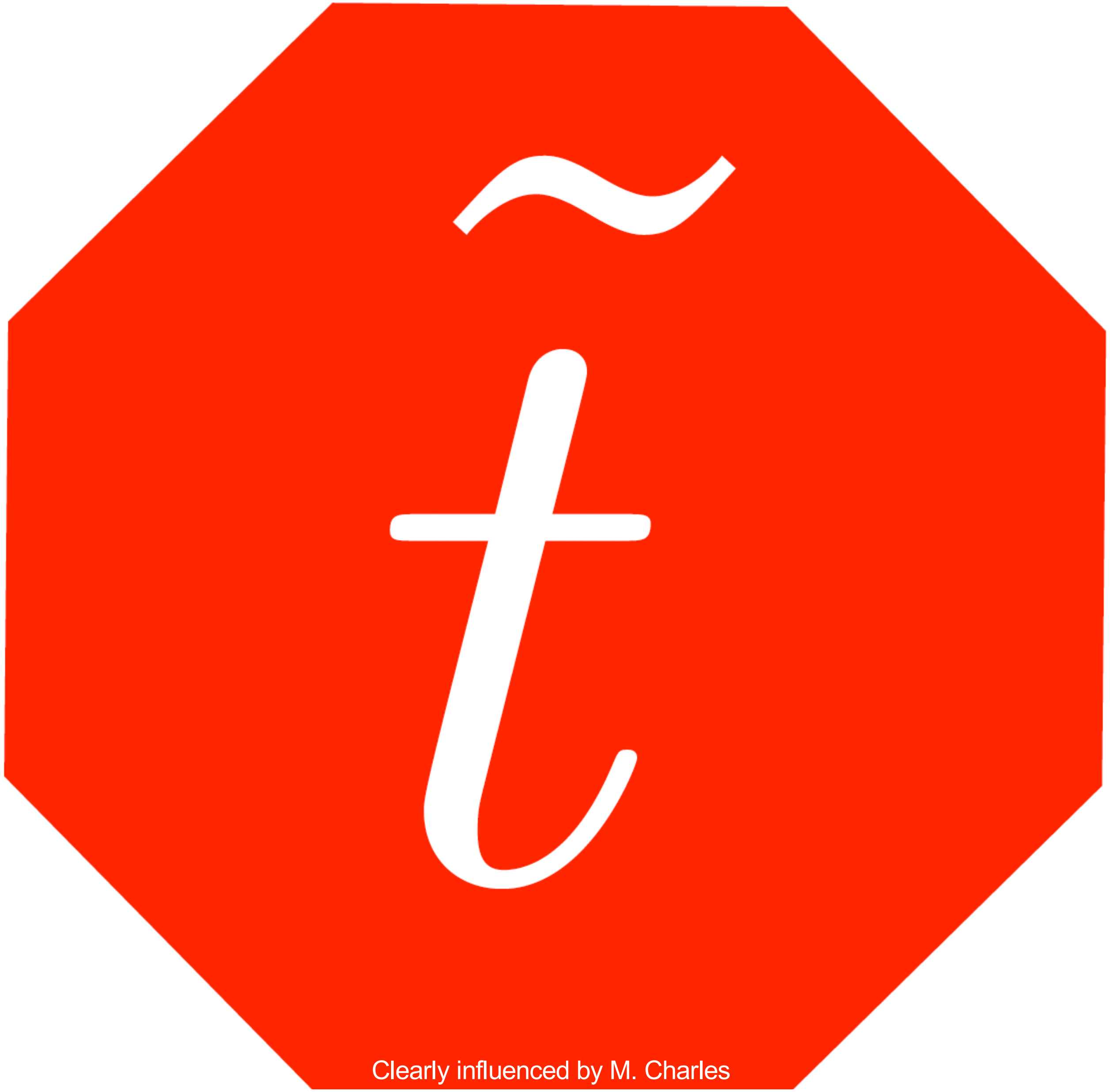
C. Schwanda, MEW '23

Summary

- We don’t know if the flavour anomalies are a fluctuation or a revolution
- Intense experimental program ongoing verify anomalies
- Coming decades will be dominated by Heisenberg

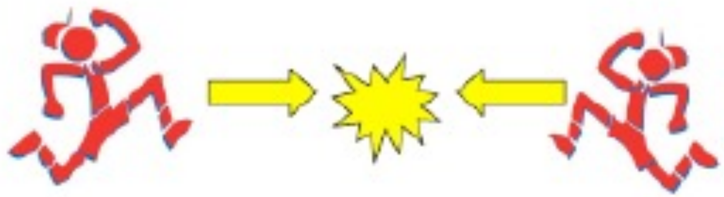
New Physics Quizz




$\tilde{t}$
Clearly influenced by M. Charles

Experimental environment: e^+e^-

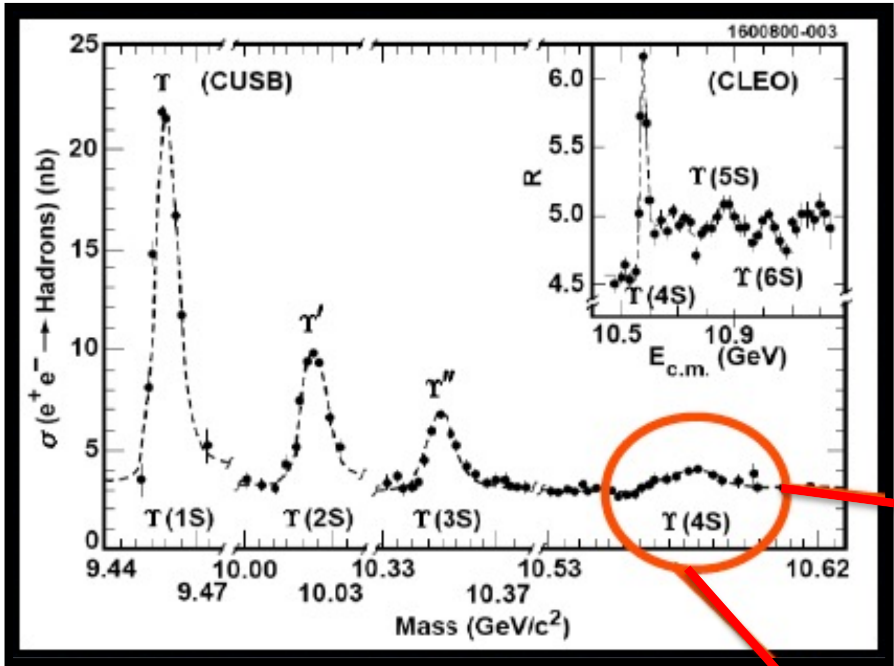
Lepton collider
(collision of pointlike objects)



Hadron collider
(collision of extended objects)

[Karl Jakobs]

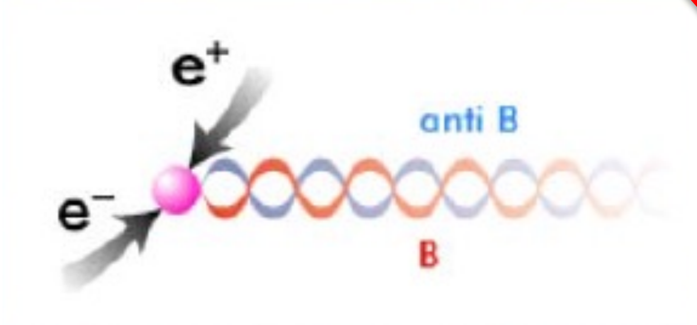
Υ (4S) resonance

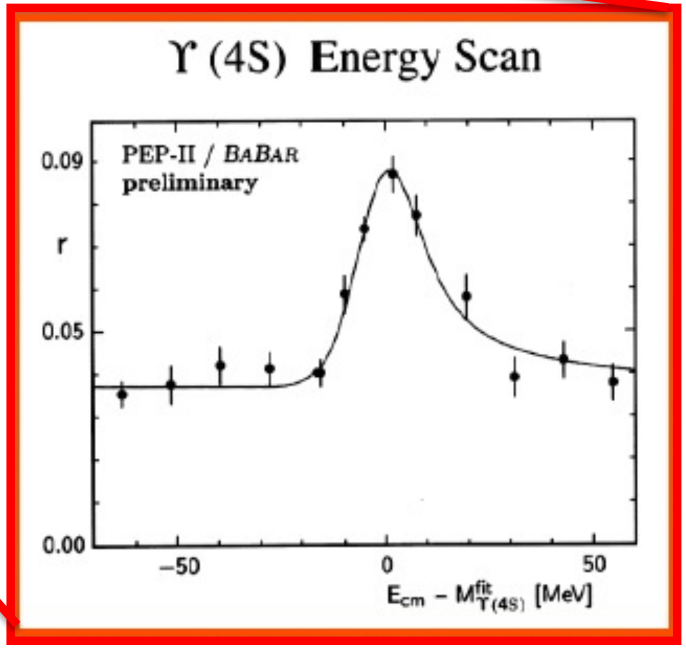


Cleanest way to produce B mesons:
e^+e^- collisions at

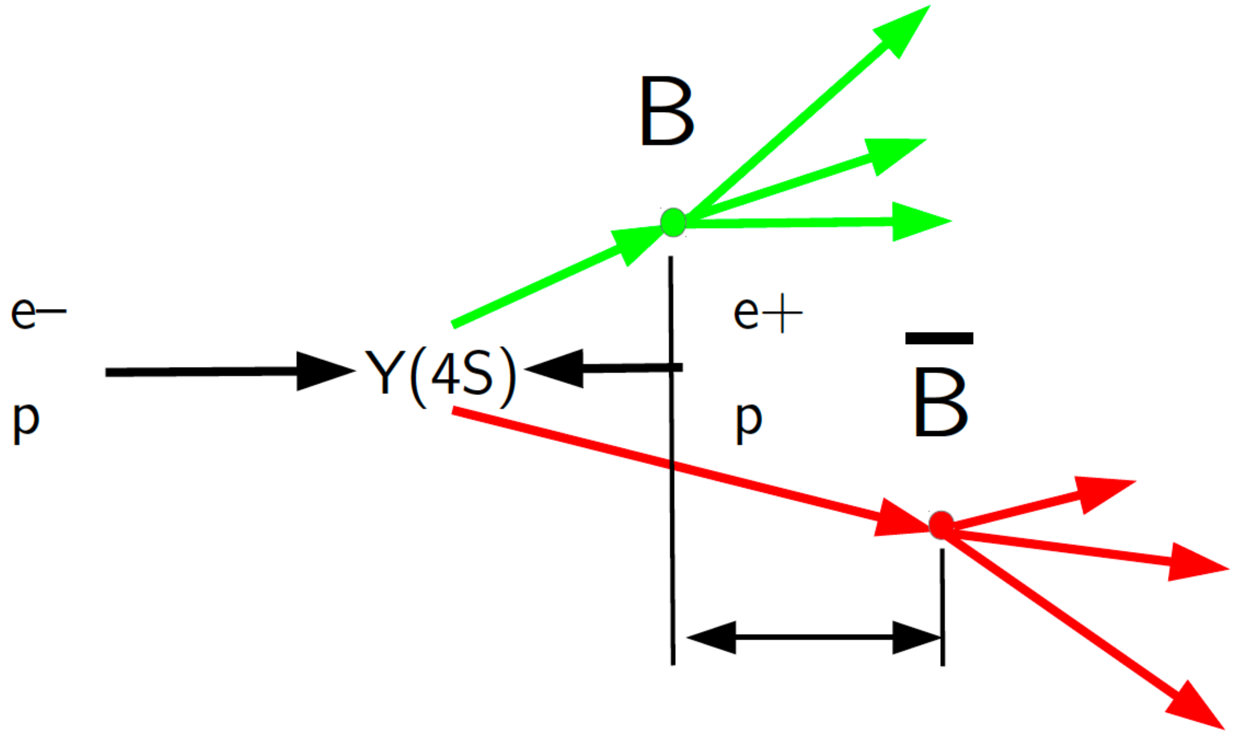
$\sqrt{s}$ = 10.58GeV

~1.1M $B\bar{B}$ pairs per fb^{-1}
$\sigma_{bb} / \sigma_{continuum}$ ~ 1/3





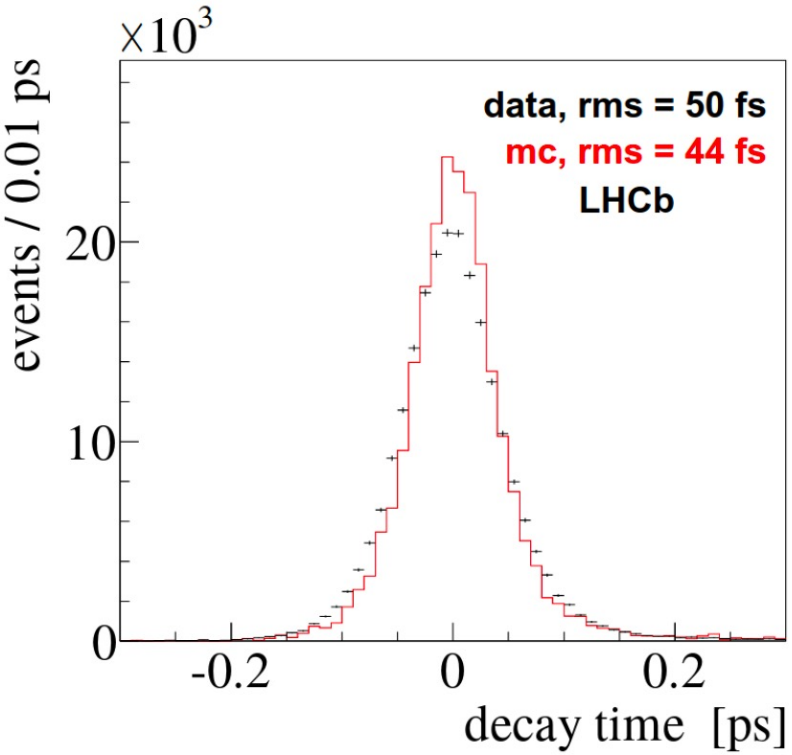
$B\bar{B}$ pair is produced in a coherent state
→ two B mesons evolve until one decays

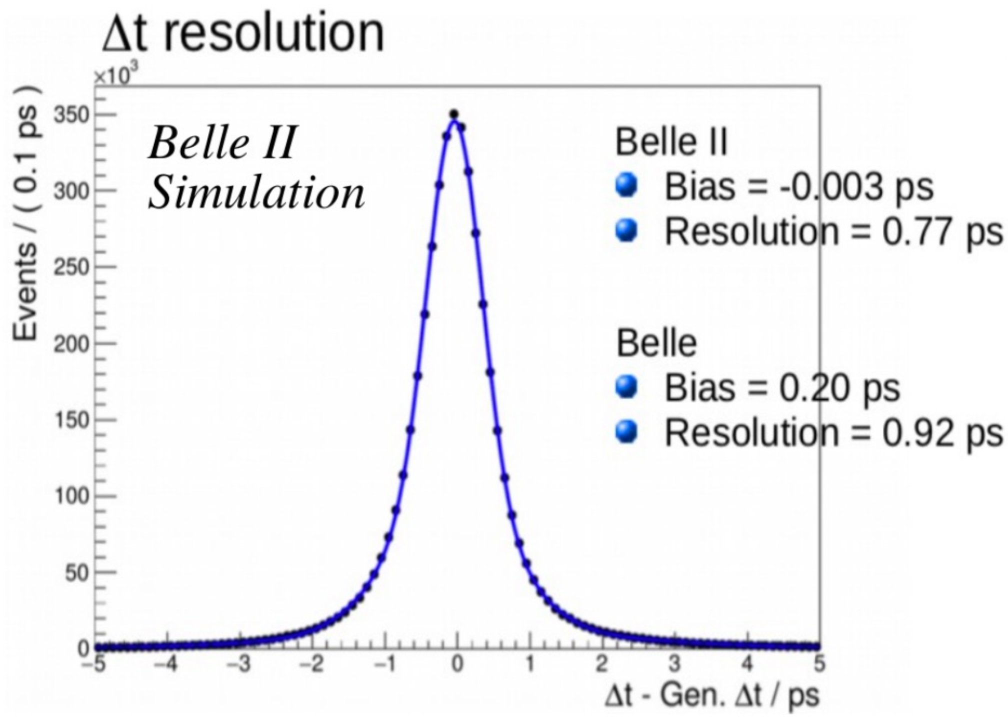


$$\Delta t = \Delta z/\beta\gamma c$$

Belle	~200 μm
Belle II	~130 μm
LHCb	~1cm

Decay time resolution

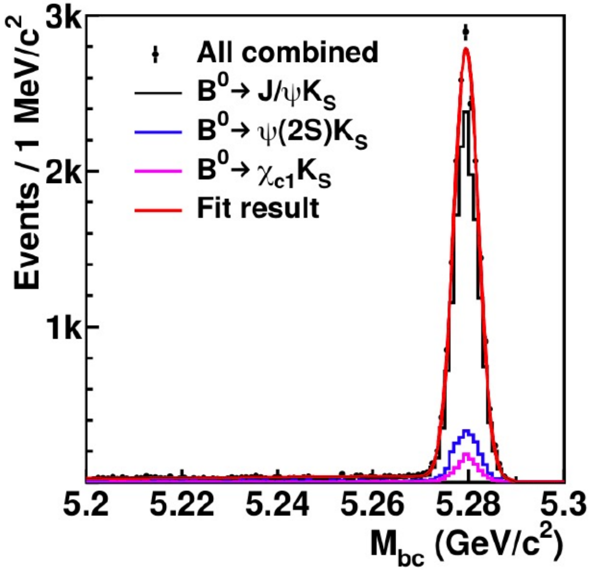


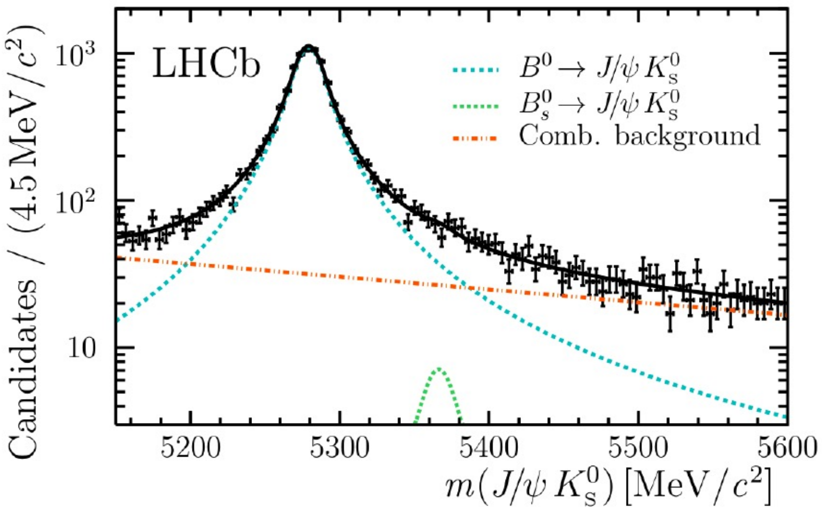


LHCb, arXiv:1405.7808[hep-ex]
Performance of vertex locator
$B_s \to J/\psi\phi$

Belle II, B. Oberhof, CKM 2018
$B \to J/\psi K_s$

B-meson mass resolution





Belle, 711/fb
PRL 108 (2012) 171802
arXiv:1201.4643 [hep-ex]

FWHM ~2–3 MeV

LHCb, 3/fb
JHEP 11 (2017) 170
arXiv:1709.03944 [hep-ex]

FWHM ~10 MeV

Note: resolutions not mentioned in the papers (not part of systematics)

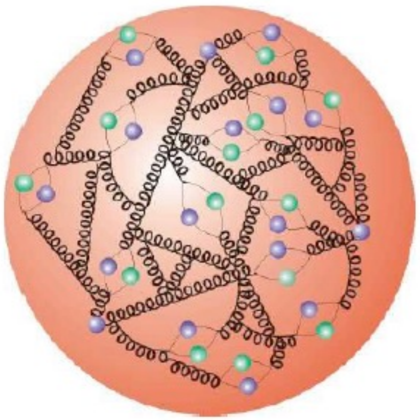
Experimental environment: pp (or p$\bar{p}$)

Lepton collider
(collision of pointlike objects)

Hadron collider
(collision of extended objects)

[Karl Jakobs]

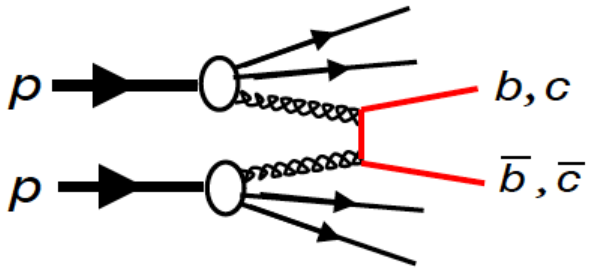
Proton Collisions



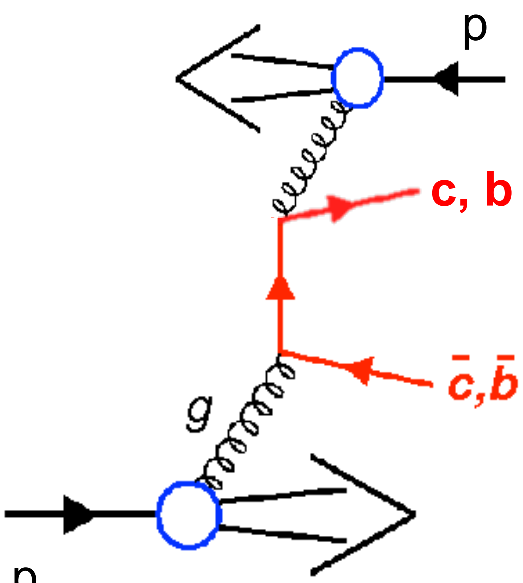
- Protons are complicated objects
  - Valence & sea quarks, gluons
- Available energy of "proton" collision depends on partons

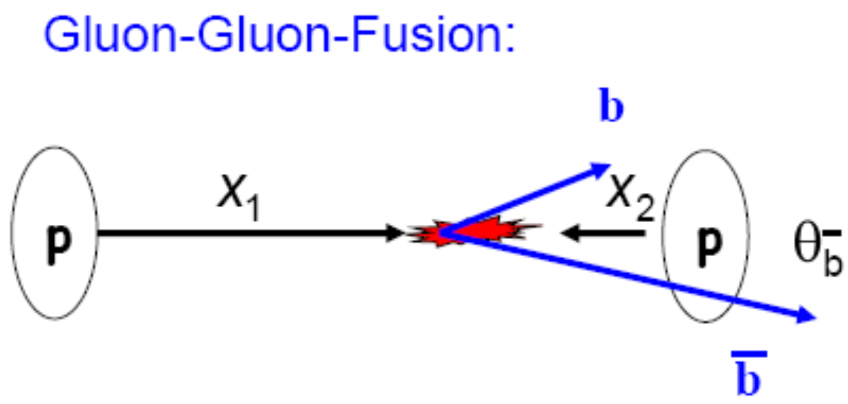
$$s' = x_1 \cdot x_2 \cdot s$$

x_i = Bjorken x (fractional momentum) of parton

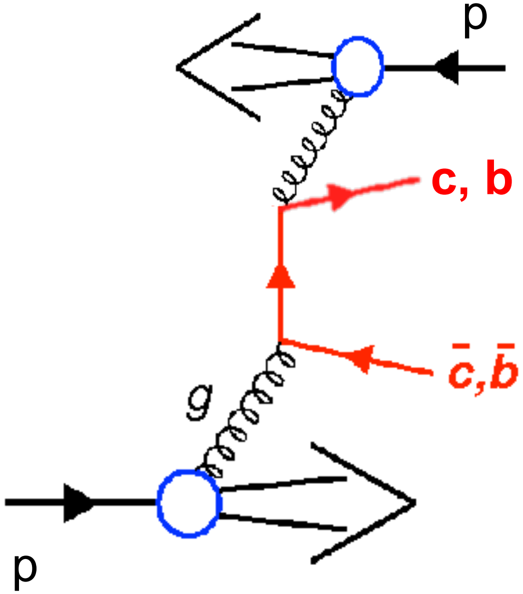


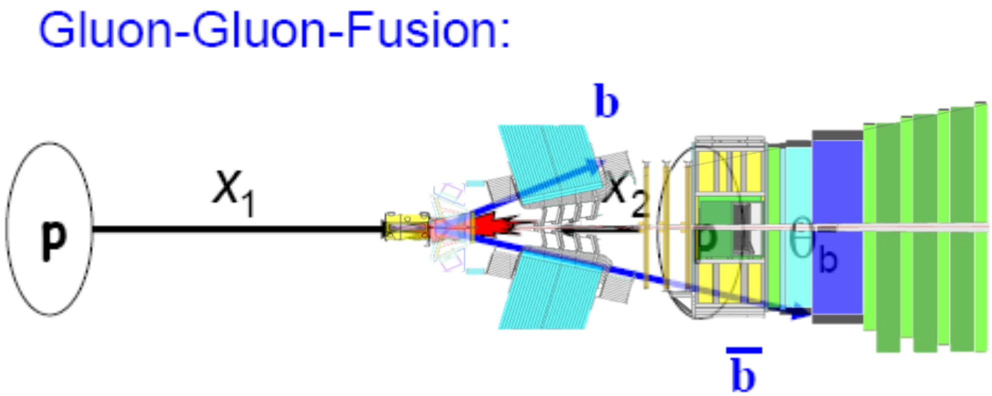
- Energy of particular collision unknown, but distributions known
  - hadron colliders "scan" a wide energy range
  - Average s' ~ 0.1 s
  - Dominant process @ LHC: gluon fusion





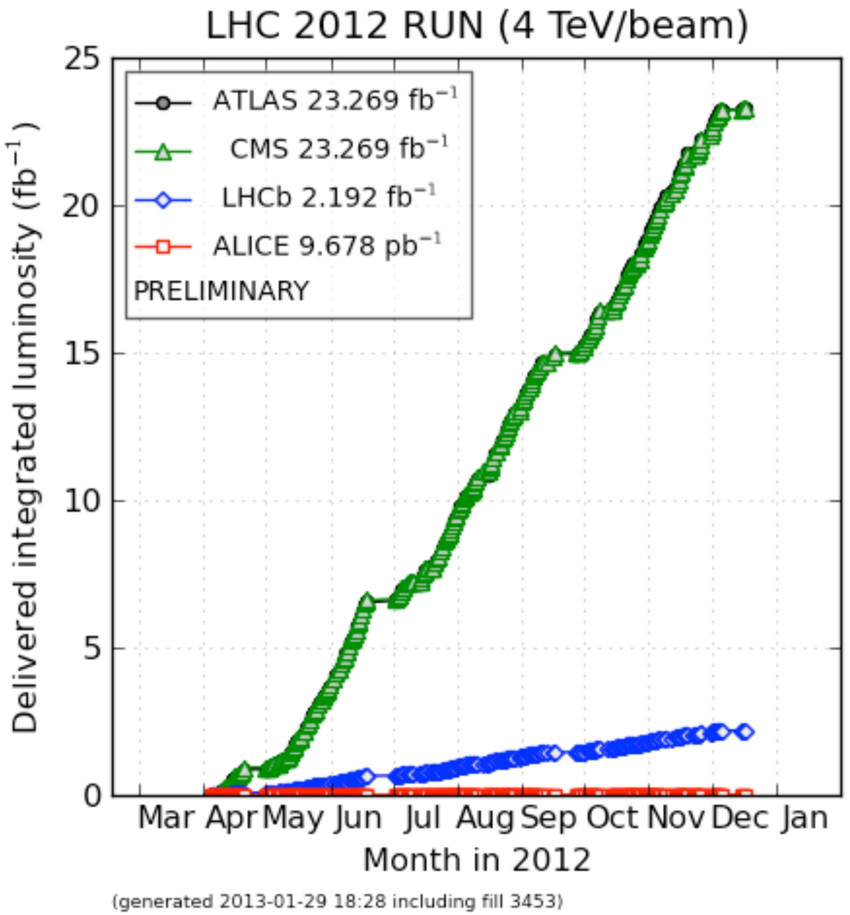
- Proton collisions at 7-13TeV:
  huge heavy flavour production cross sections
  - In LHCb acceptance: 75kHz $b\bar{b}$ and 1.5MHz $c\bar{c}$
  - ~1/10 events contains b or c signal

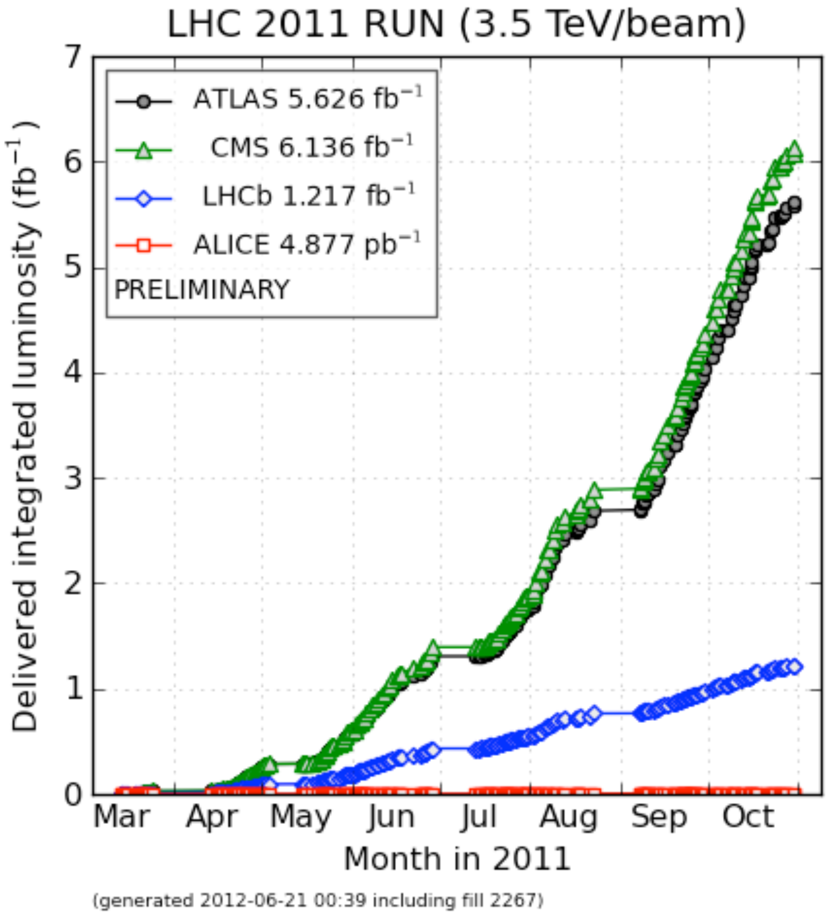




- Proton collisions at 7-13TeV: huge heavy flavour production cross sections
  - In LHCb acceptance: 75kHz $b\bar{b}$ and 1.5MHz $c\bar{c}$
  - ~1/10 events contains b or c signal
- ATLAS & CMS get more b produced, but less specific detector…

Keys for flavour-physics I: Data

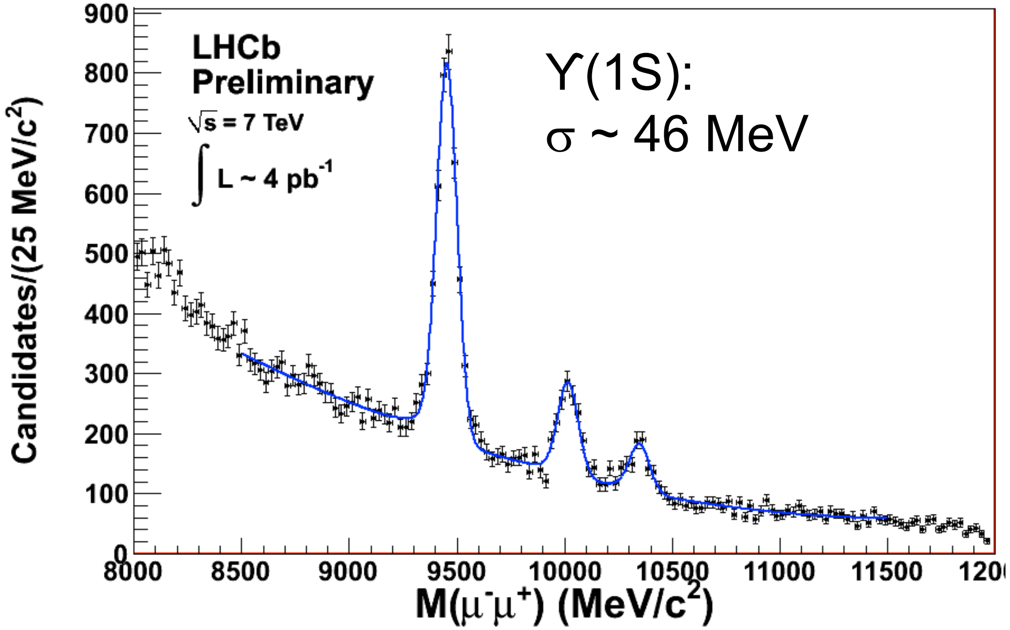


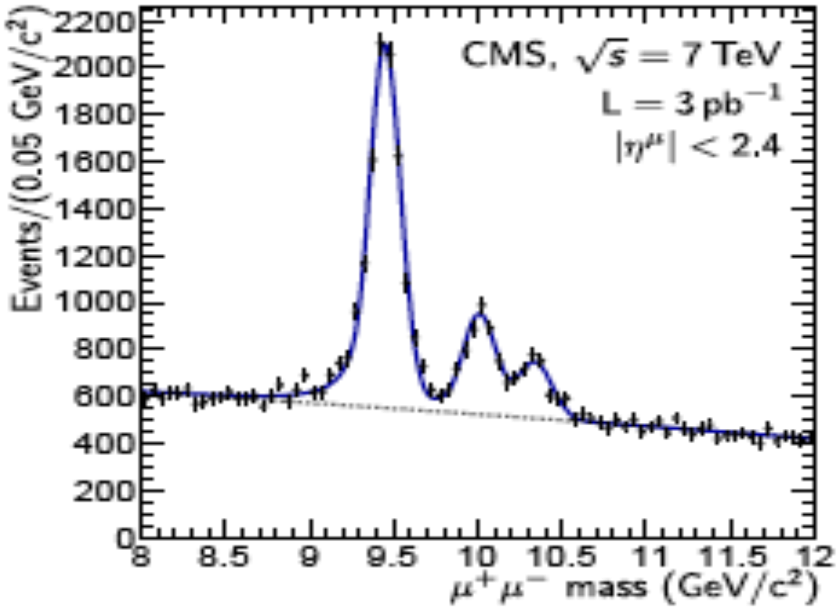


Full dataset: ATLAS = CMS = 10 * LHCb

Keys for flavour-physics II: mass resolution

ϒ(1S), ϒ(2S), ϒ(3S)



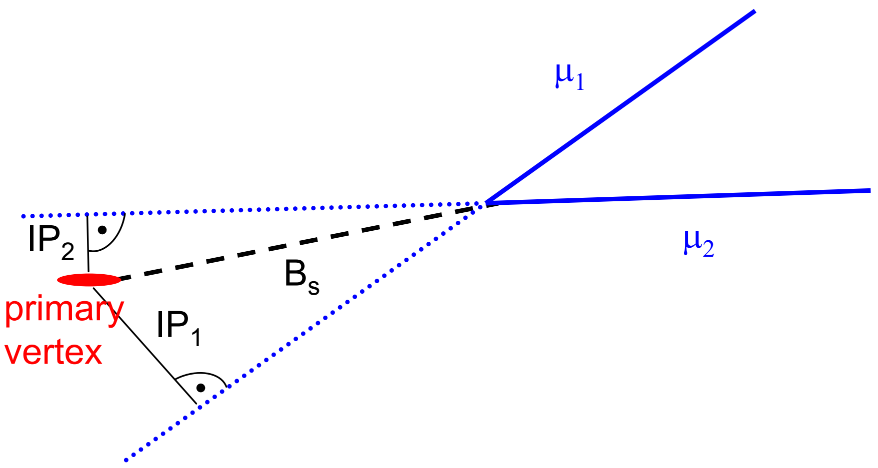


	momentum resolution	mass resolution $J/\psi \rightarrow \mu\mu$
LHCb	$\delta p/p$ = 0.4-0.6 %	13 MeV
CMS	$\delta pt/pt$ = 1-3 %	40 MeV
ATLAS	$\delta pt/pt$ = 5-6 %	71 MeV

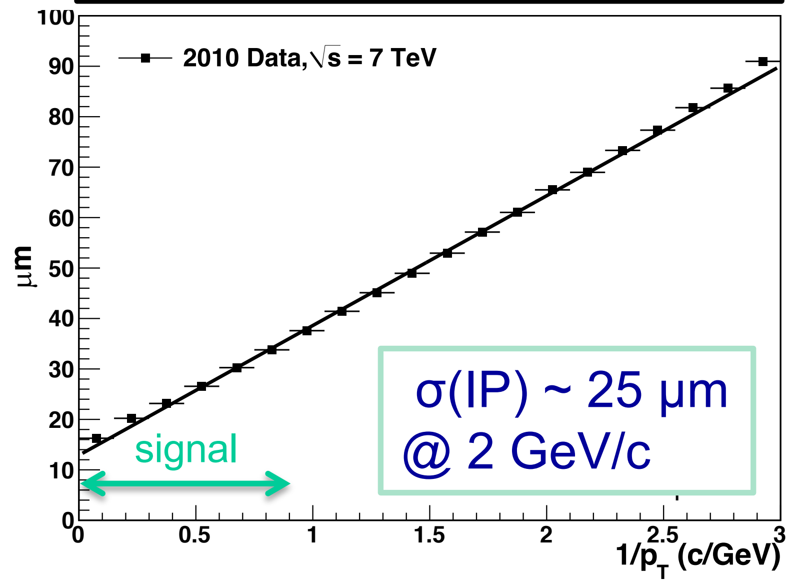
Primary vertex resolutions (25 tracks):

	LHCb [μm]	ATLAS [μm]	CMS [μm]
σ(x)	15.8	60	20-40
σ(y)	15.2	60	20-40
σ(z)	76	100	40-60

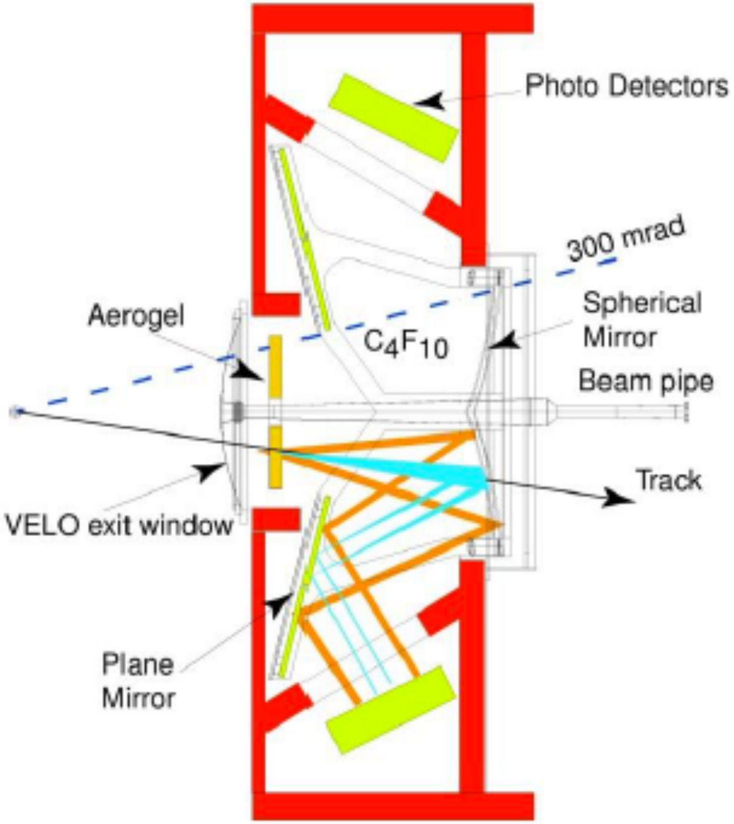
Impact parameter (IP):

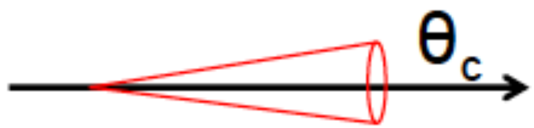


IP resolution vs 1/pT

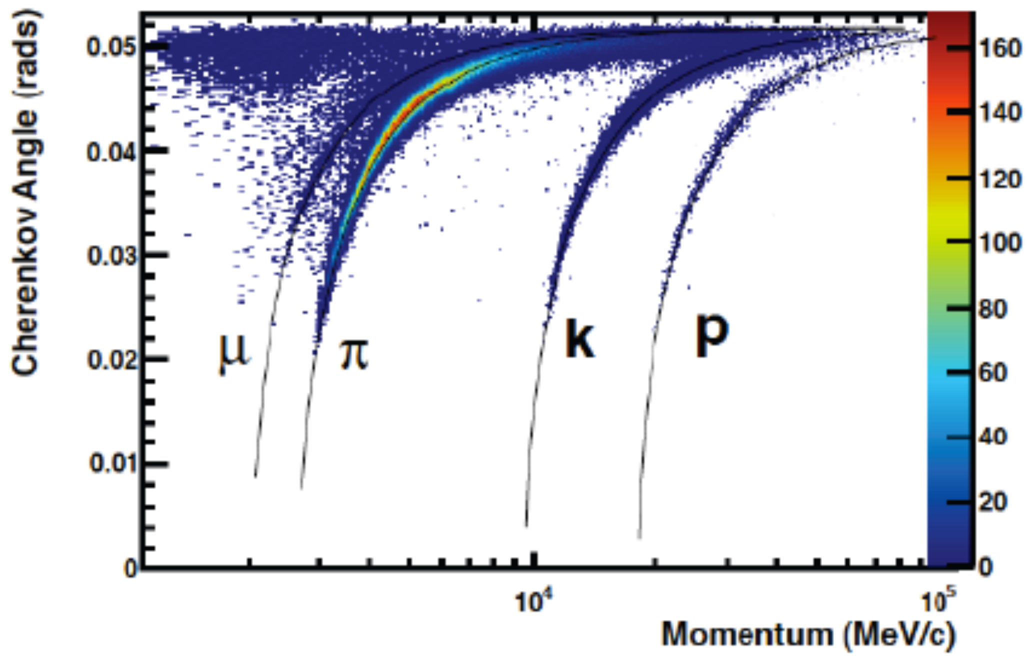


Keys for flavour-physics IV: Particle Identification





$$\cos\theta_c = \frac{1}{\beta n}$$



Keys for flavour-physics IV: Particle Identification

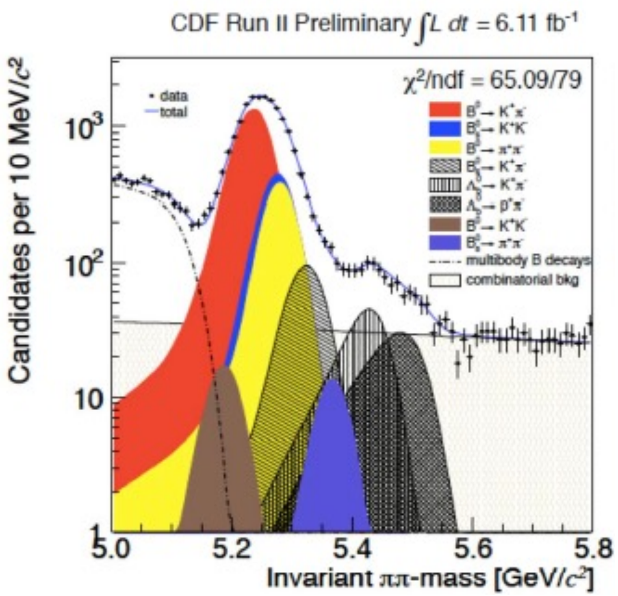
- The LHCb experiment is equipped with two Cherenkov detectors

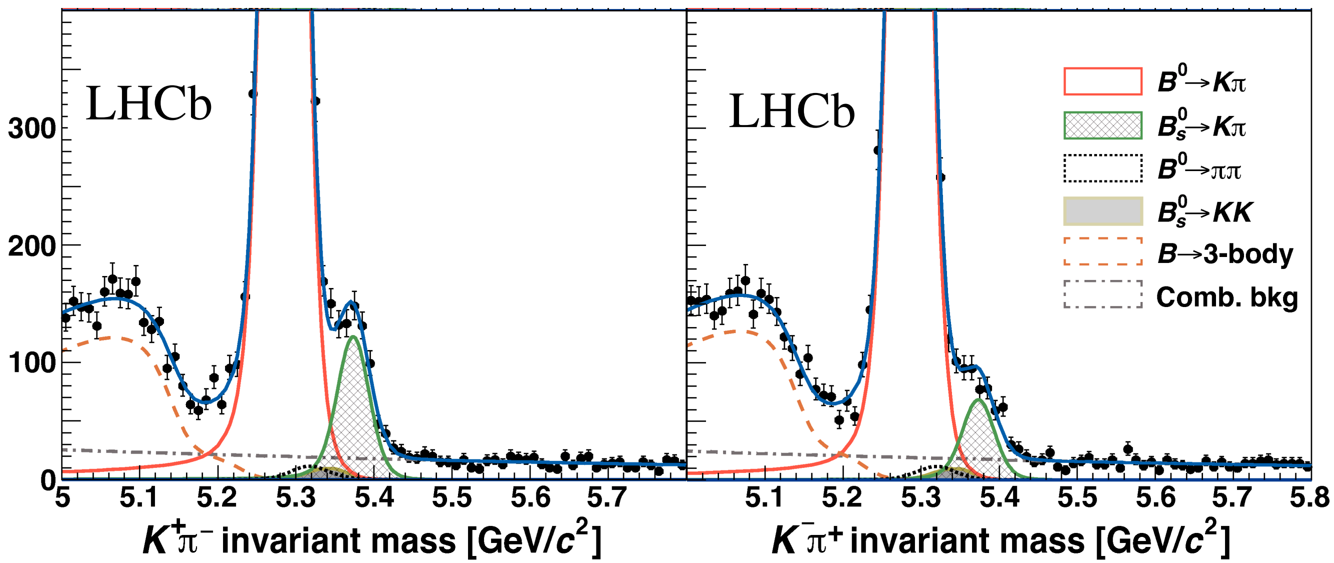
Kaon identification: K→K: 95.5% π→K: 7.1%

⇒

B → h h
$B^0 \to K\pi$
$B^0 \to \pi\pi$
$B_s \to KK$

B→h⁺h⁻ without and with RICH Particle ID





Production Rates

	BaBar / Belle (ee)	CDF / D0 (pp)	ATLAS / CMS (pp)	LHCb (pp)
√s [GeV]	10.58 (Υ(4S))	1980	7000 / 8000	7000 / 8000
BB production	coherent BB state	Incoherent BB state		
σ_{bb} [μb] in acceptance	0.0011	6.3	75	94
L [fb^{-1}]	550 / ~1000	~10	150	9
bb pairs in acceptance [10^{11}]	0.01	0.6	~200	~15
Cc pairs in acceptance [10^{11}]	~0.01		4000	300

What does 1/ab mean? N(bb) = Lumi * x-section