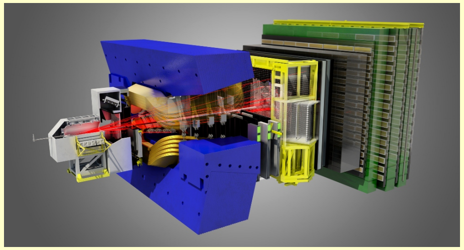
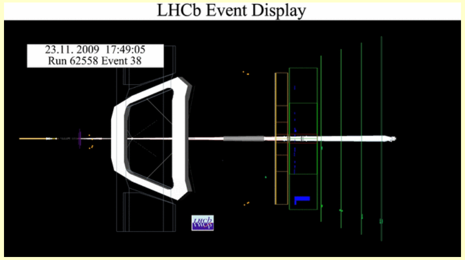
Selected Physics Highlights at LHCb



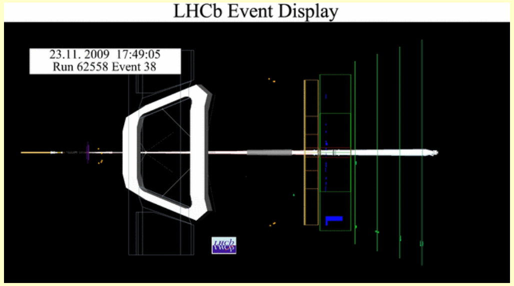


Nigel Watson / Univ. Birmingham
on behalf of the LHCb Collaboration

The 22nd Particles and Nuclei International Conference

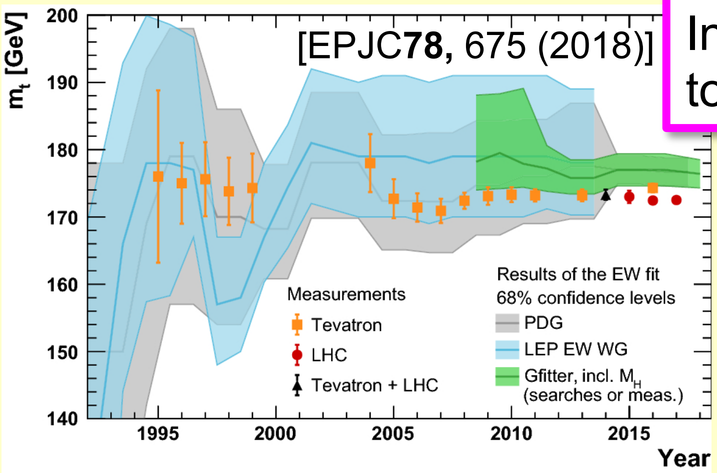
5 Sep. – 10 Sep., 2021

Lisbon / online



Outline

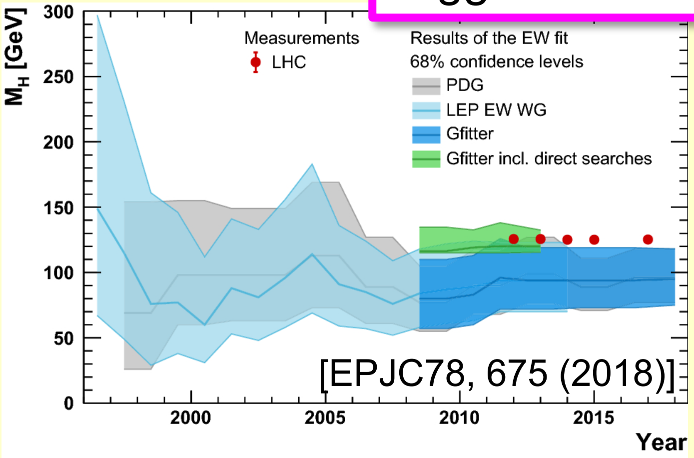
- Why flavour?
- New physics may hide as virtual particles in loops
- Indirect probe accesses higher energy scale than direct searches
  - Convenient detection mechanism
  - Identifying origin needs models



Indirect / direct top quark mass

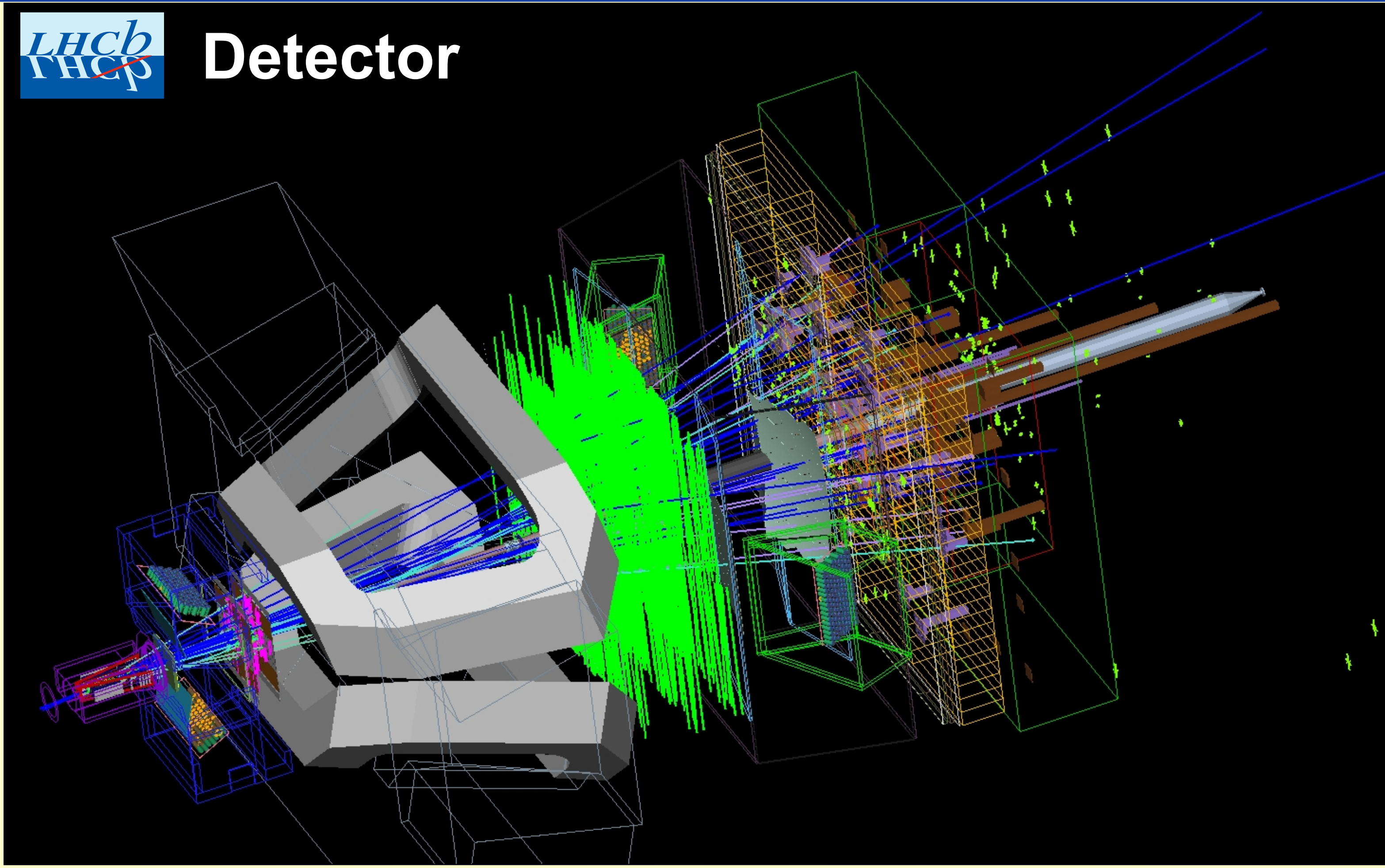
- **Very** selected LHCb highlights
  - Intrinsic charm in proton
  - W boson mass
  - Exotic hadrons
  - Lepton flavour universality

Indirect / direct Higgs mass



- See also
  - CKM/CP (Tommaso Pajero);
  - Rare decays (Zhenzi Wang)
  - QCD (Davide Zuliani);
  - ALP searches (Adrian Casais Vidal)

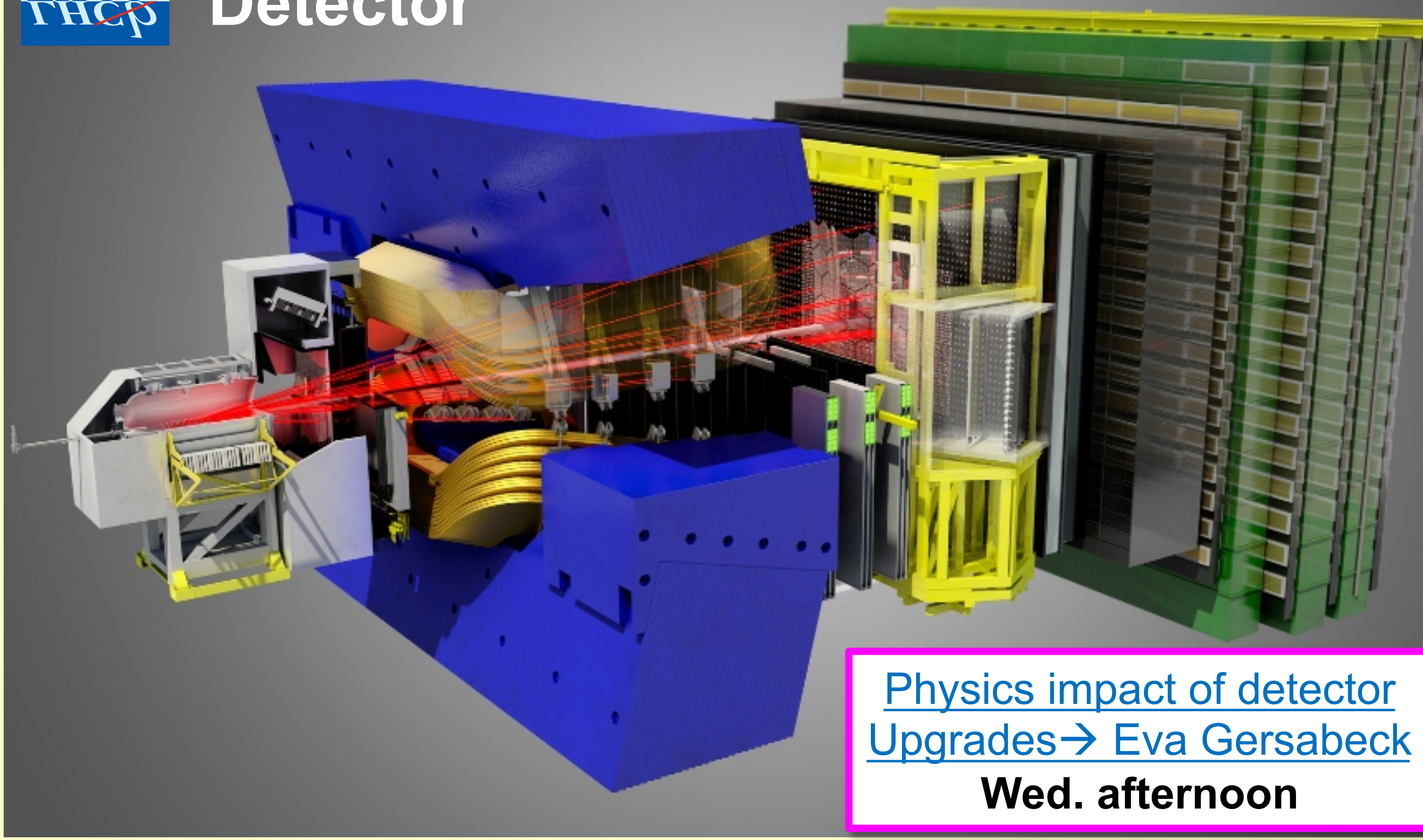
Detector



[Int. J. Mod. Phys. A **30** (2015) 1530022]
[JINST **3** (2008) S08005]

- General-purpose detector in the forward region: $\sim 0.6^{\circ} - 16^{\circ}$
- Excellent vertex resolution: Si detectors (VELO)
- Particle Identification: RICH detectors; calorimeters; muon systems
- Stress testing the Standard Model
  - Precise measurements
  - Direct/indirect searches for physics beyond SM in decays of b, c hadrons and τ decays

Detector



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Physics impact of detector Upgrades→ Eva Gersabeck

Wed. afternoon

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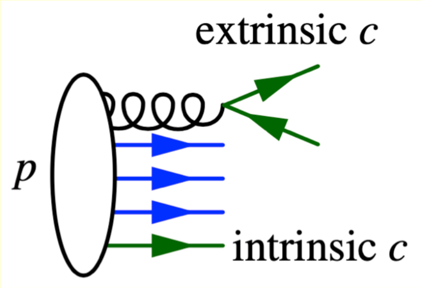
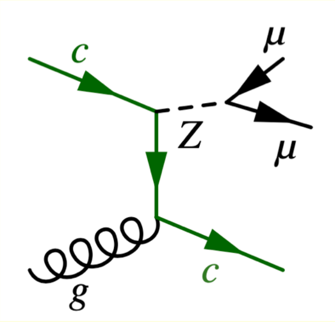
Why: Intrinsic charm of proton?

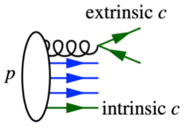
Q: Does p wavefunction contain charm quarks $|uudc\bar{c}\rangle$?

or is charm content from $g \to c\bar{c}$ splitting?



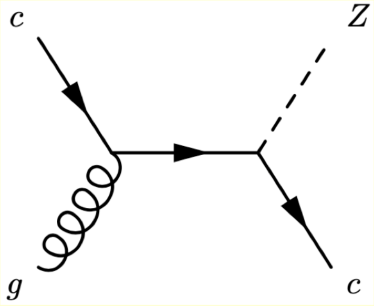


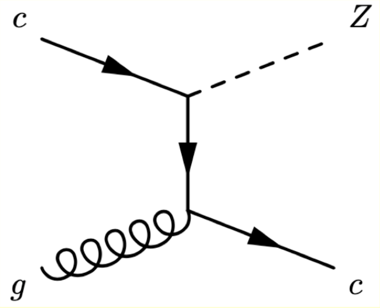
- Impacts
  - Non-perturbative dynamics inside nucleon
  - Affects c hadron rates, kinematics in cosmic-ray proton interactions
    - → semileptonic decays, important background source in astrophysical neutrinos
  - Many predicted cross-sections at accelerators, eg. Higgs production also affected
- Recent measurements of Intrinsic Charm inconclusive

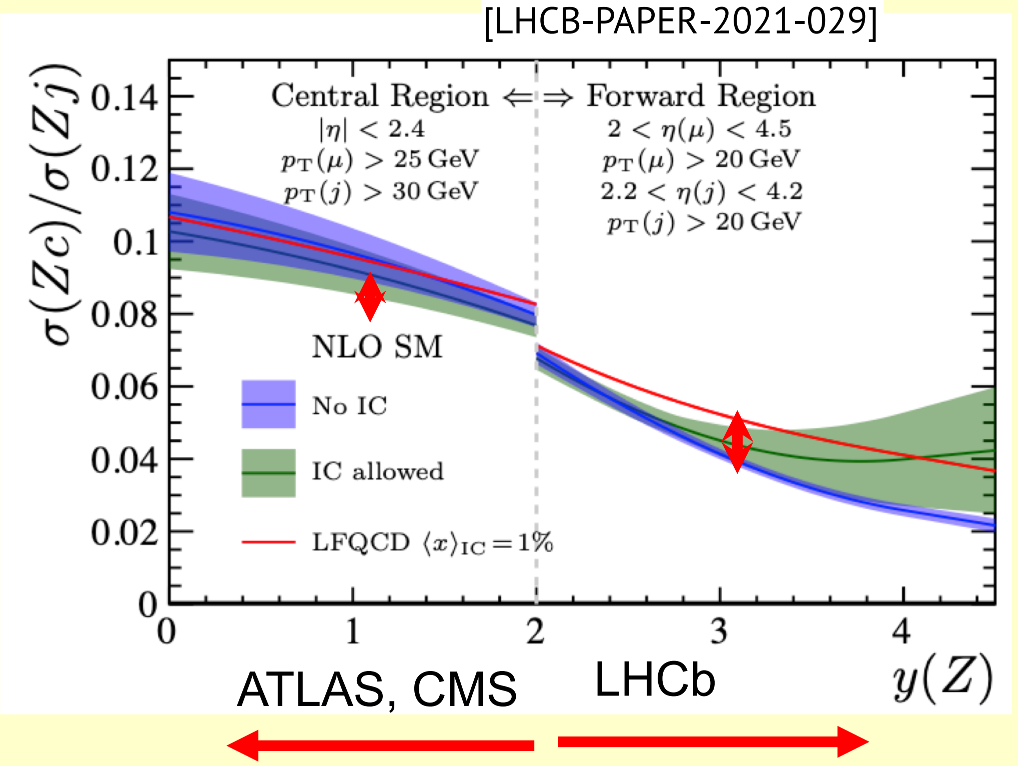


Intrinsic charm in protons

- Fraction of Z+jets that have charm, measured as ratio of cross-sections
  - Sigma(Z+c-jet)/sigma(Z+all-jet)

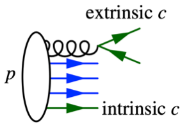






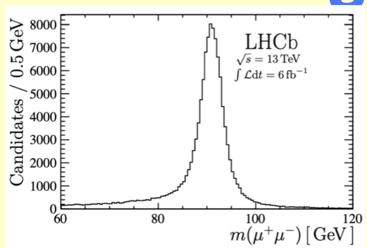
- Leading Order; in forward region one parton has large *x, so LHCb probes valence region*

- Central region less sensitive to intrinsic charm

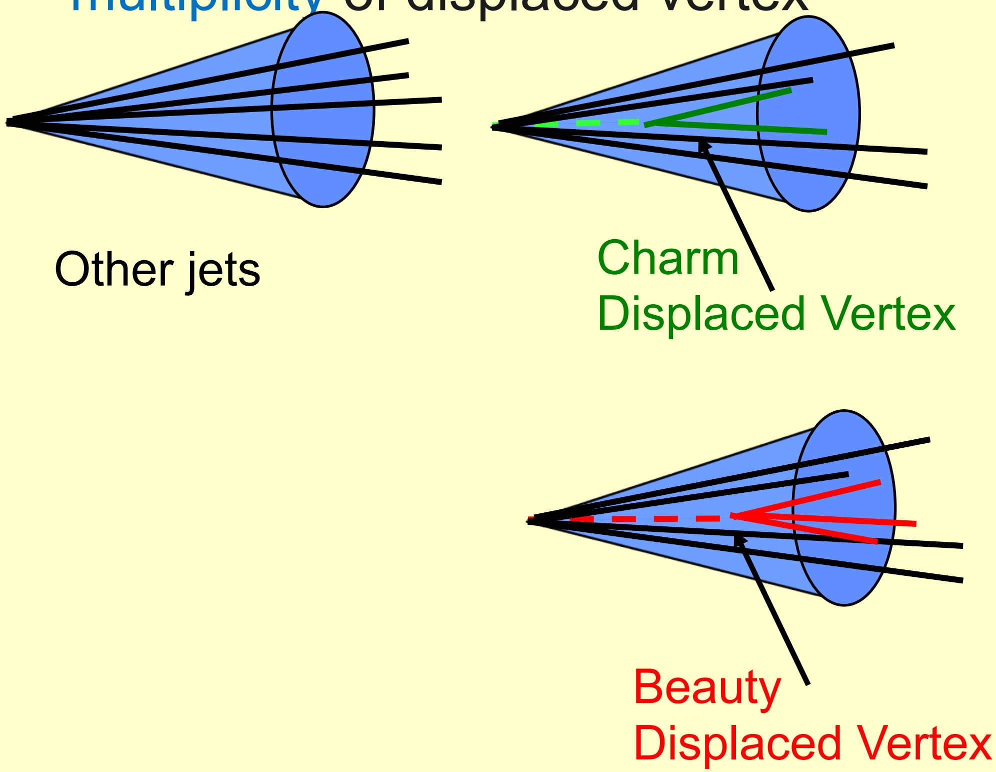


Selecting charm jets

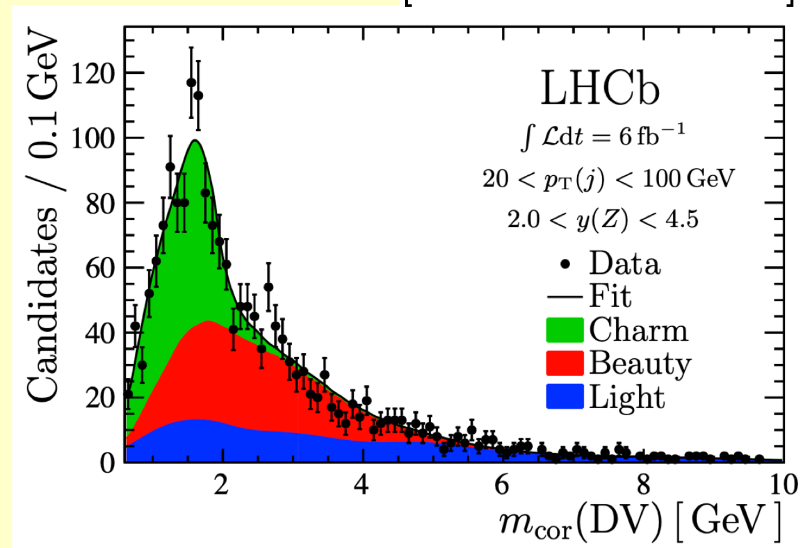
- Identify Z→ μμ

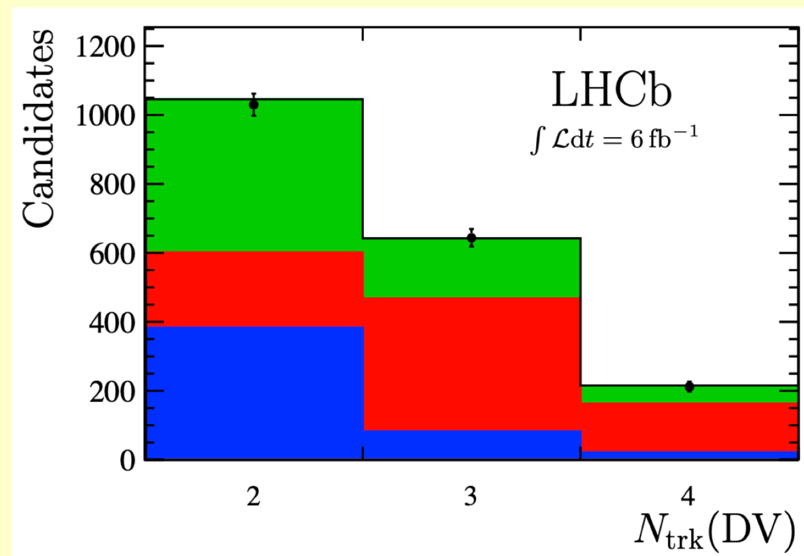


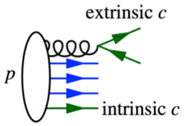
- Select c-jets using mass, particle multiplicity of displaced vertex



[LHCB-PAPER-2021-029]







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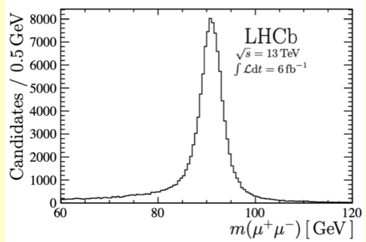

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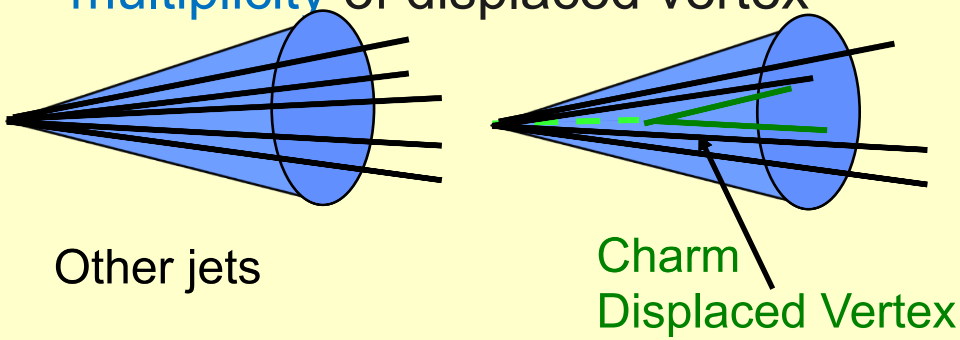

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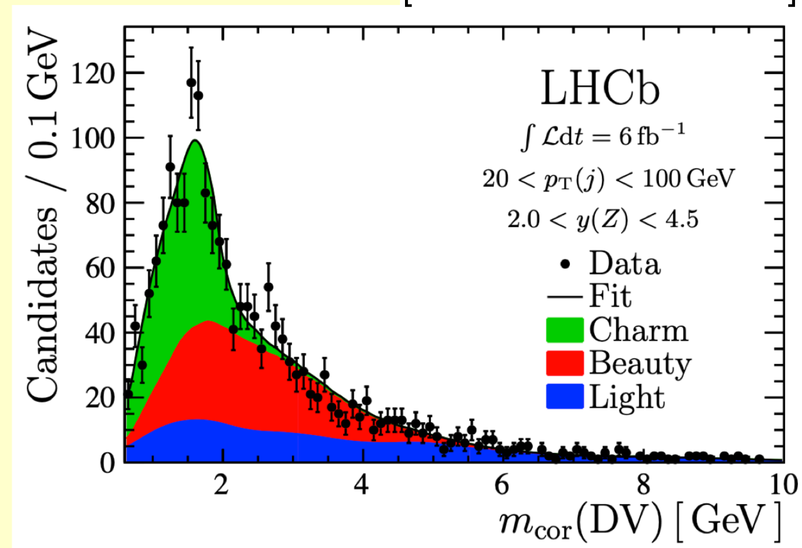
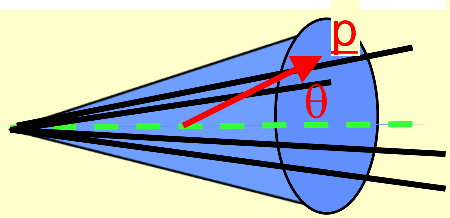
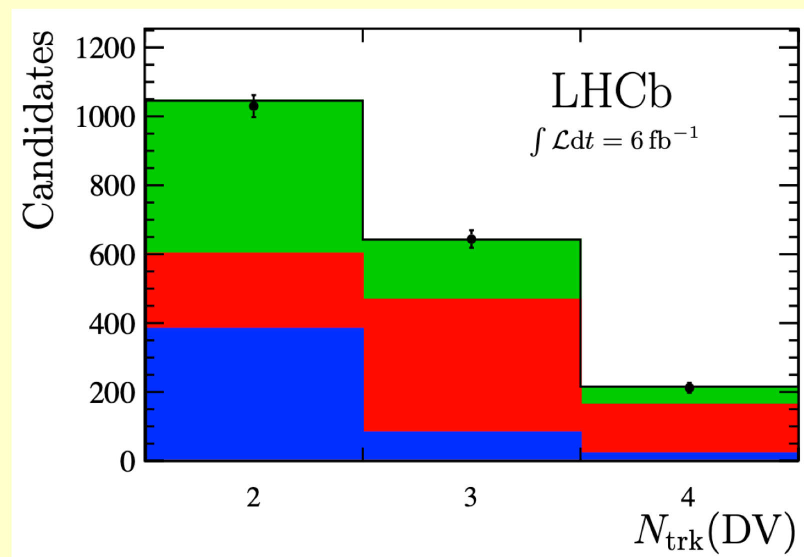
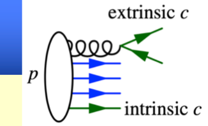


$m_{cor}(DV) \equiv$ Min. mass ~ flight distance

$$\sqrt{m(DV)^2 + [p(DV)\sin\theta]^2} + p(DV)\sin\theta$$







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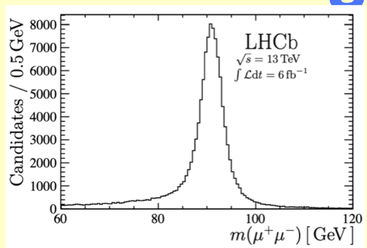

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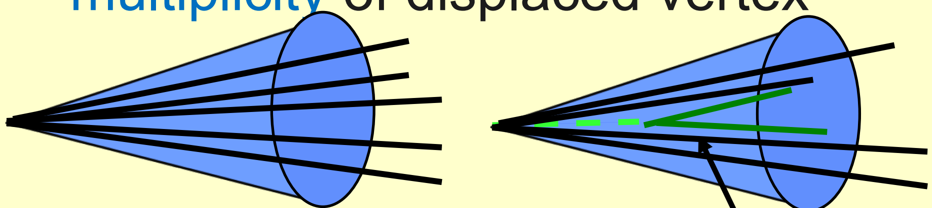
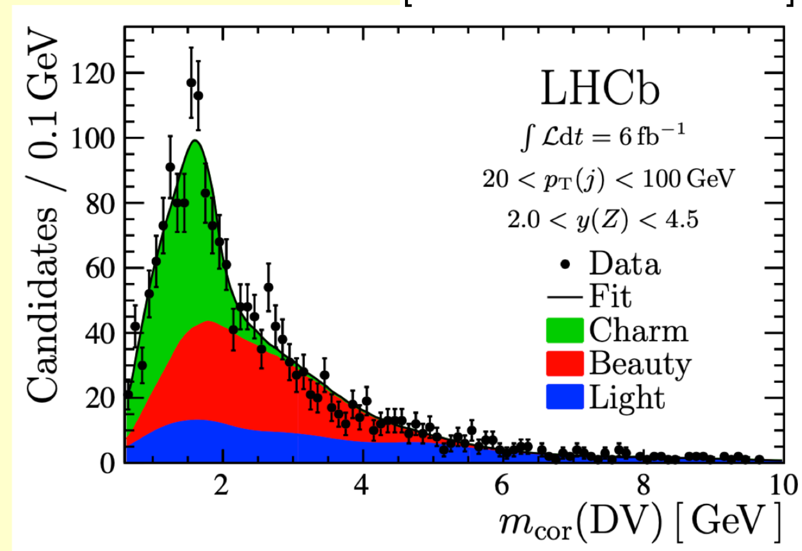


Other jets

Charm Displaced Vertex

[LHCB-PAPER-2021-029]

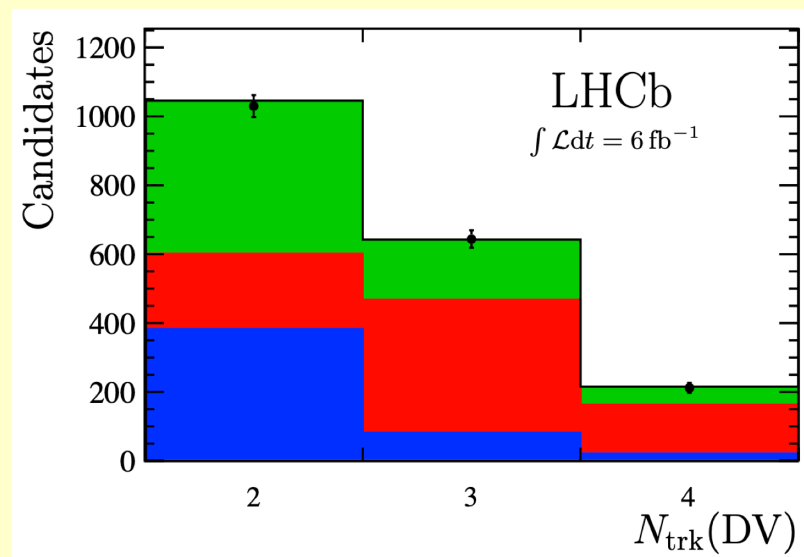


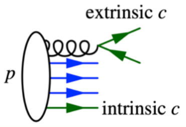
$m_{\mathrm{cor}}(\mathrm{DV}) \equiv$ Min. mass ~ flight distance

$$\sqrt{m(\mathrm{DV})^2 + [p(\mathrm{DV})\sin\theta]^2} + p(\mathrm{DV})\sin\theta$$

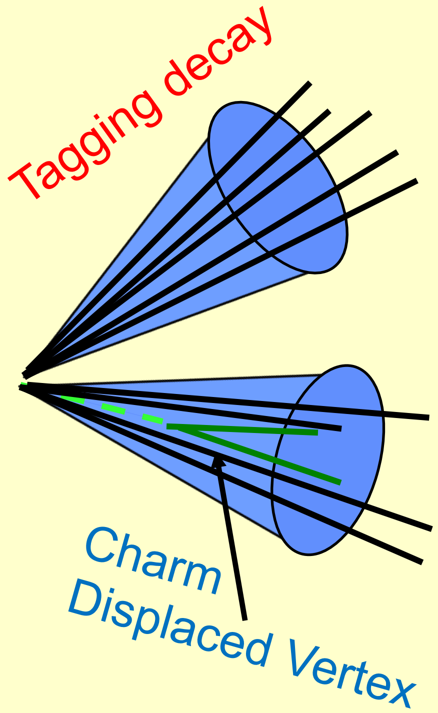
2D fit: (m_{cor} , N_{trk}), high-purity calibration sample templates

separates c-jets





Estimating charm-tagging efficiency

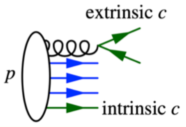


- “Tag&probe” to estimate efficiency

[LHCB-PAPER-2021-029]

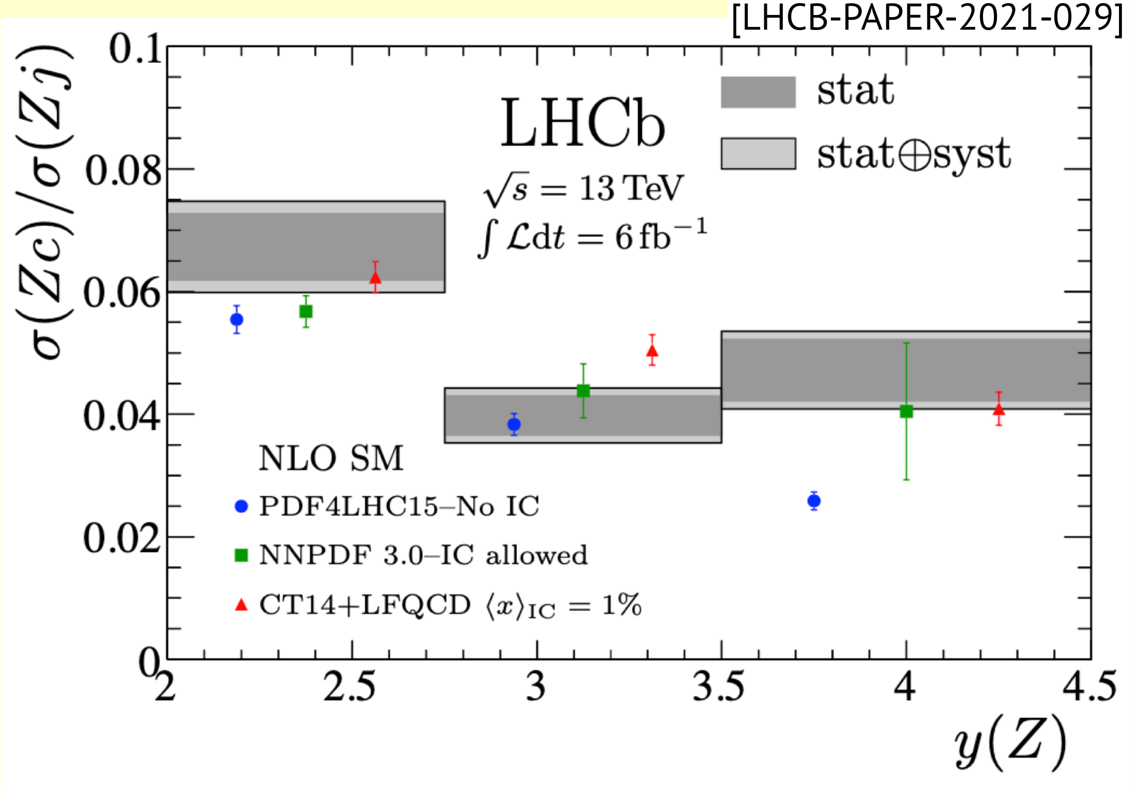
Source	Relative Uncertainty
c tagging	6–7%
DV-fit templates	3–4%
Jet reconstruction	1%
Jet p_{T} scale & resolution	1%
Total	8%

- Efficiency ~24% and independent of p_T
- Dominant systematic uncertainty



Direct probe of intrinsic charm

[LHCB-PAPER-2021-029]



"Allowing IC": large forward-region uncertainty - low sensitivity of previous expts. to large-x charm PDF

- ~20% consistency with no-IC and IC hypotheses, more central *y(Z)*
- Enchancement in forward region compared to no-IC scenario
  - Where largest IC effects expected
  - Consistent with contribution from IC
- Global PDF analysis to make firm conclusions (+Run-3 data to come)

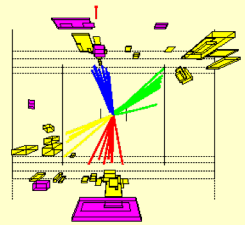
Why: W boson mass?

- Fundamental parameter of Standard Model

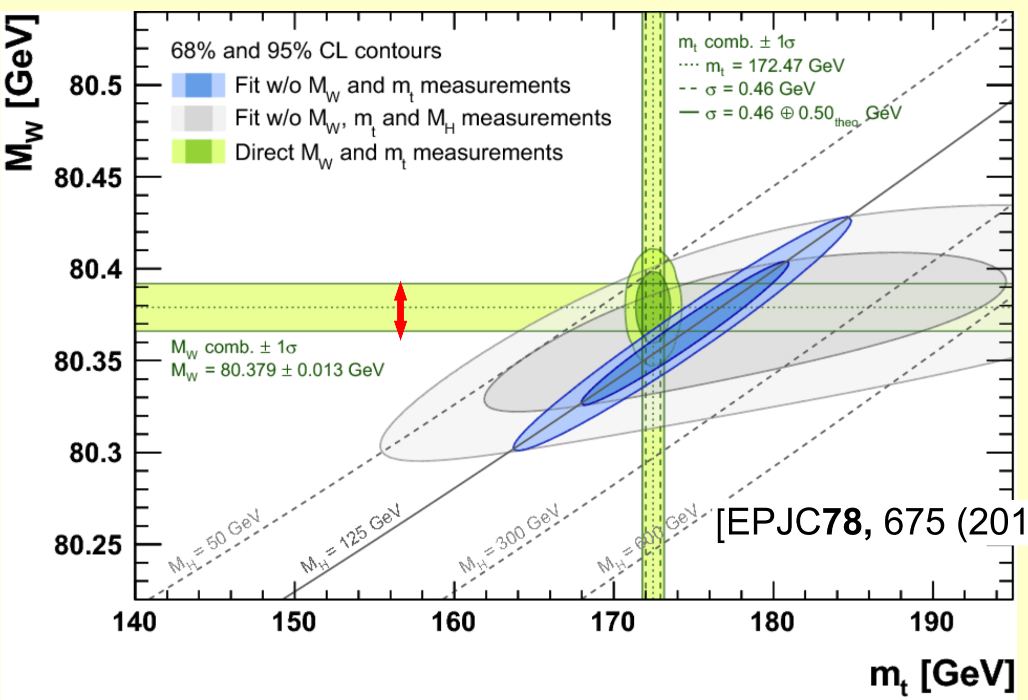
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$

Loops (NP?)

- Well-measured by many experiments
  - Hadron colliders – lepton kinematics
  - e^+e^- - all W^+W^- states
  - Indirect, EW fits



- Sensitivity to New Physics limited by direct m_W



[EPJC78, 675 (2018)]

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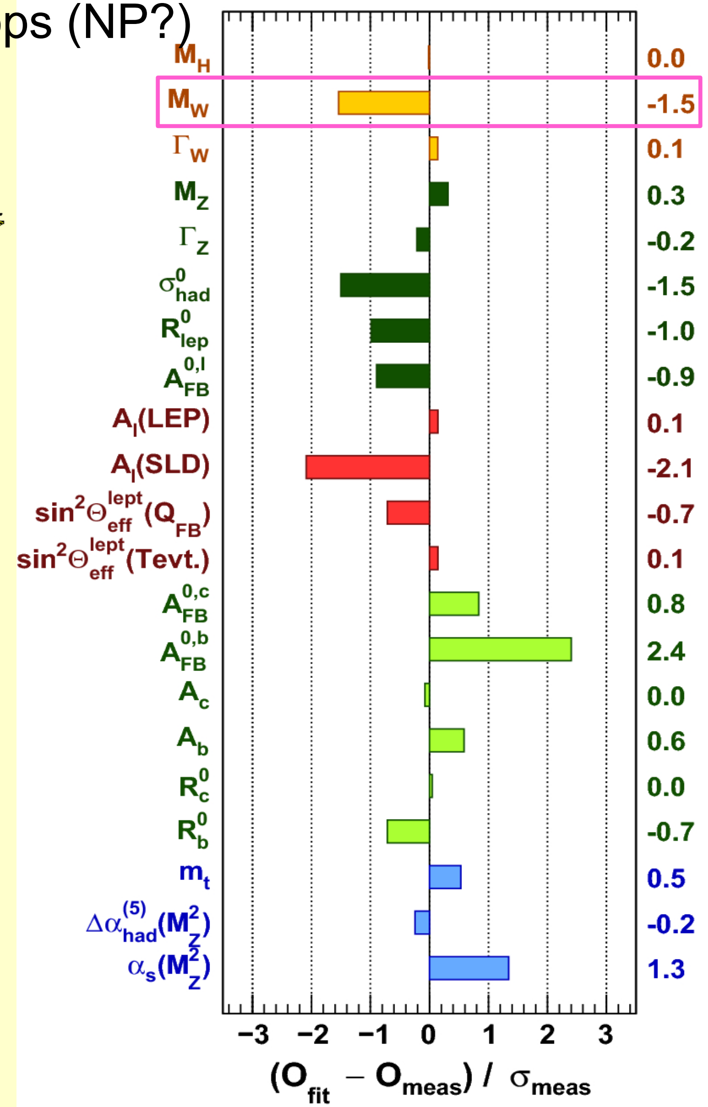
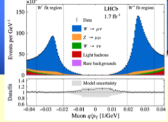




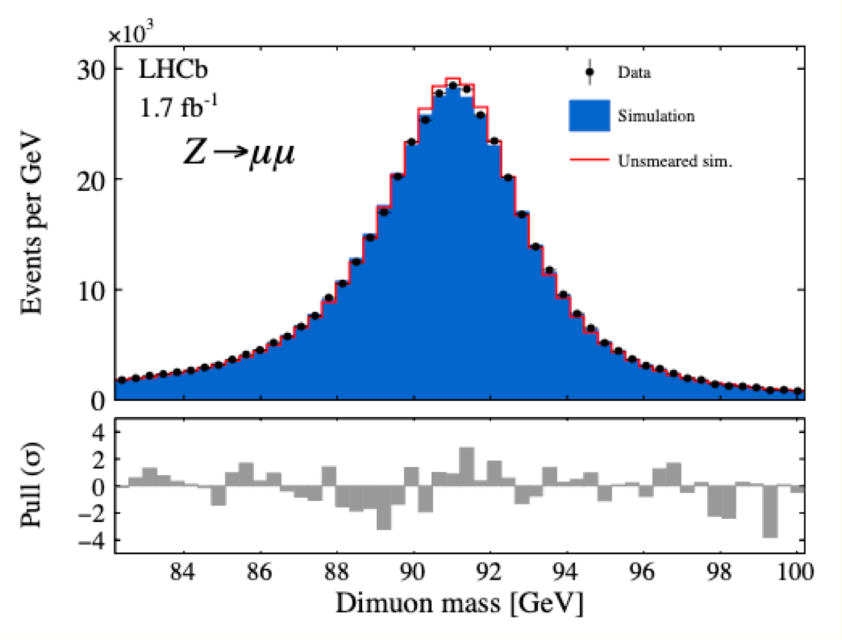
W boson mass

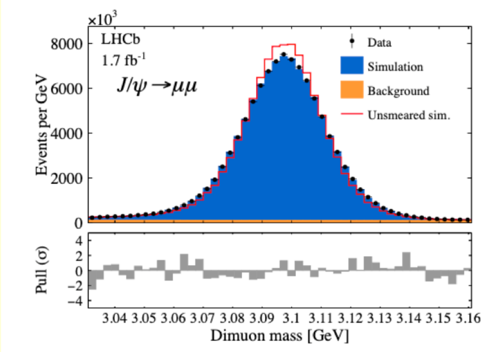
[arXiv:2109.01113]

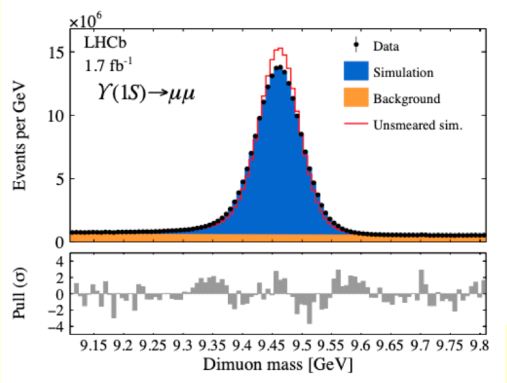
- Novel, proof-of-principle measurement, ~1/3 Run2 data, $W \to \mu\nu_\mu$
- Measured p_T of μ, peaks $\sim m_W/2$
- Spectrum depends on actual m_W
- Contamination from $Z \to \mu^+\mu^-$
  - Measure simultaneously to control

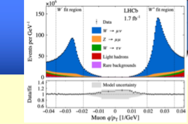
$$\phi^* = \frac{\tan((\pi - \Delta\phi)/2)}{\cosh(\Delta\eta/2)} \sim \frac{p_{\mathrm{T}}^Z}{M}$$

- Requires **complete** understanding of lepton momentum measurement and modelling









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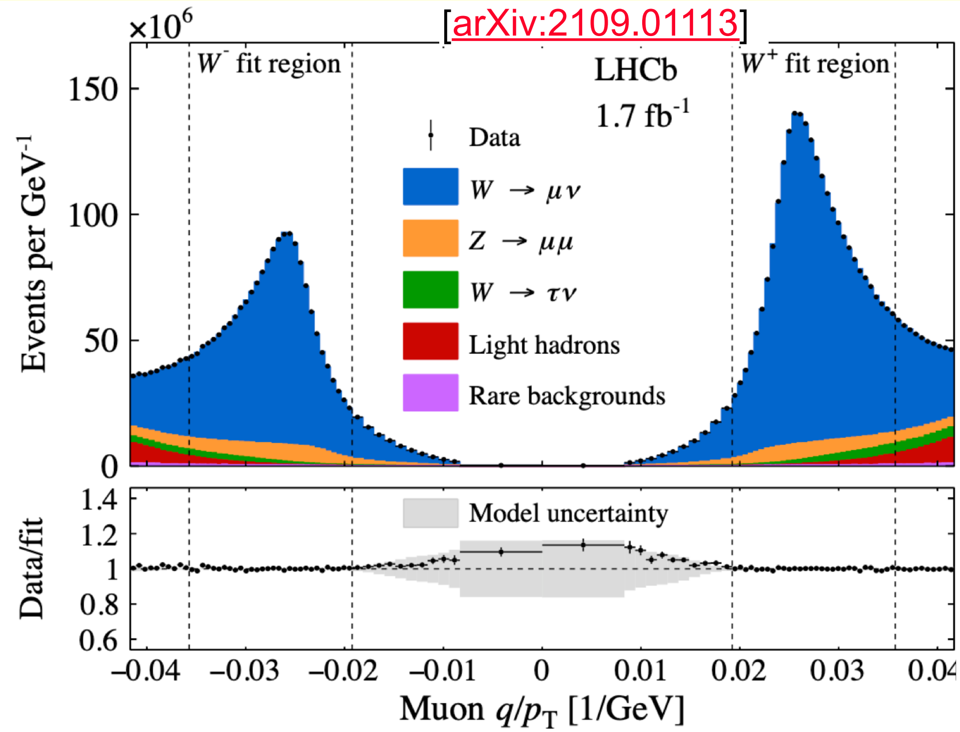
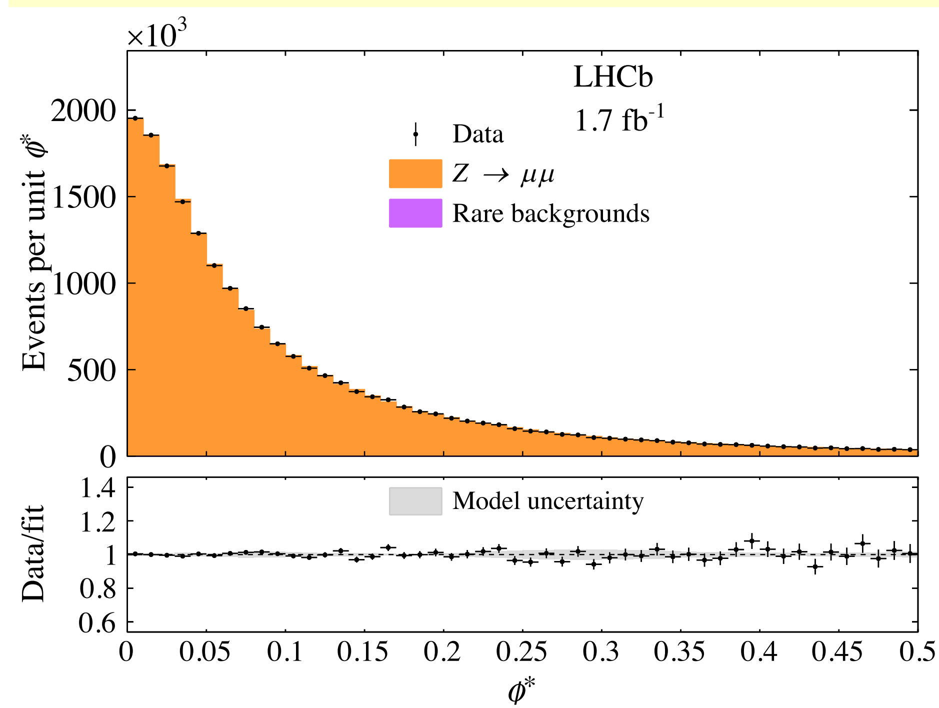
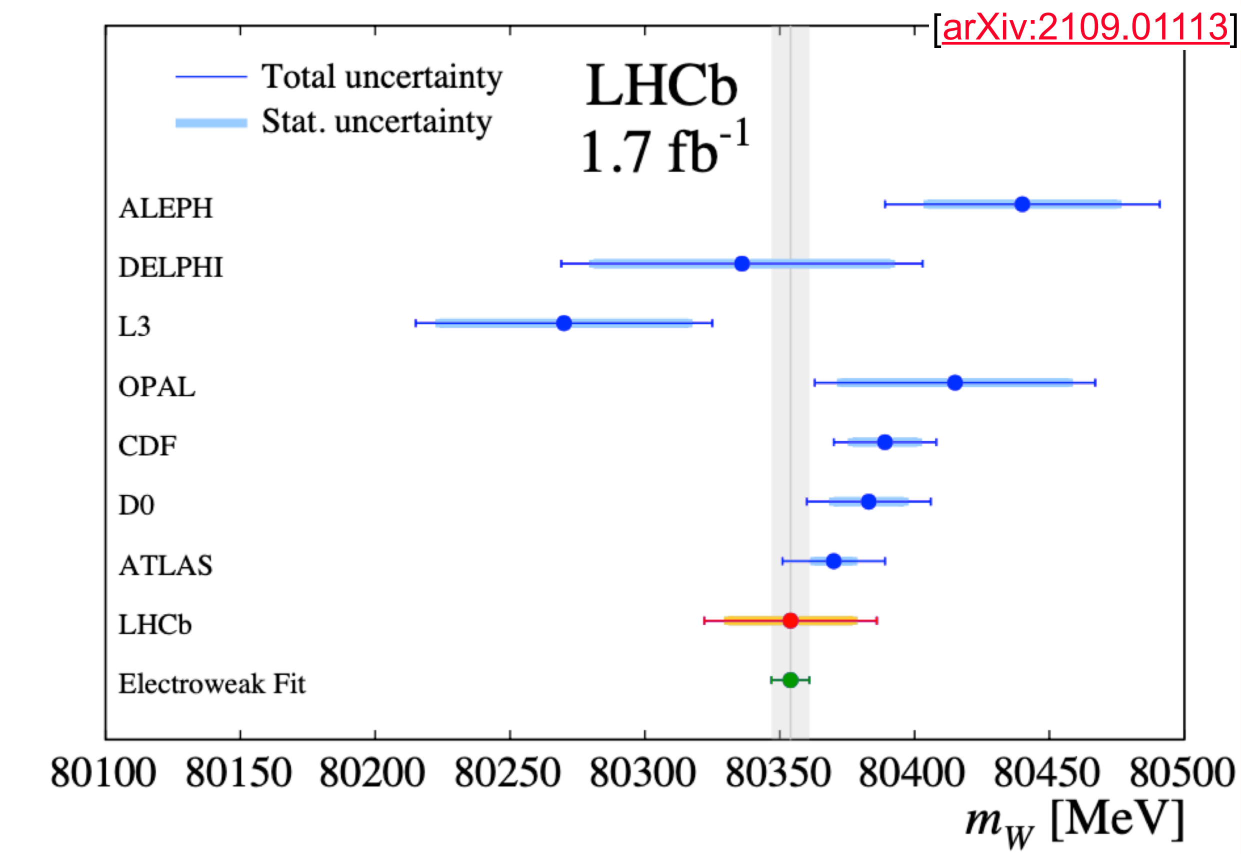


- m_W determination
  - Simultaneous fit q/p_T of W, ϕ^* of Z
- $\sim$ 2.4M W $\to \mu\nu_\mu$ candidates
- $\sim$ 0.2M Z $\to \mu\mu$ candidates



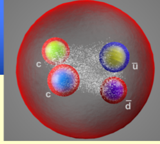
- Dominant systematic
  - Theory modelling (non-PDF)

W boson mass



[arXiv:2109.01113]

- First LHCb $m_W = 80354 \pm 23_{\mathrm{stat}} \pm 10_{\mathrm{exp}} \pm 17_{\mathrm{theory}} \pm 9_{\mathrm{PDF}}$ MeV
  - Consistent with previous measurements
- Total uncertainty ~ 20 MeV plausible with existing data
- Potential combination other LHC experiments, exploit complementary η coverage



Why: "Exotic" hadrons?

- Combinations other than $q\bar{q}$, qqq considered since 1960's
- Revitalised interest, many recent(ish) observations, Belle, CDF, D0, BESIII, LHCb – tetraquarks, pentaquarks
  - Scales a challenge for QCD
  - Measurements driving progress

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

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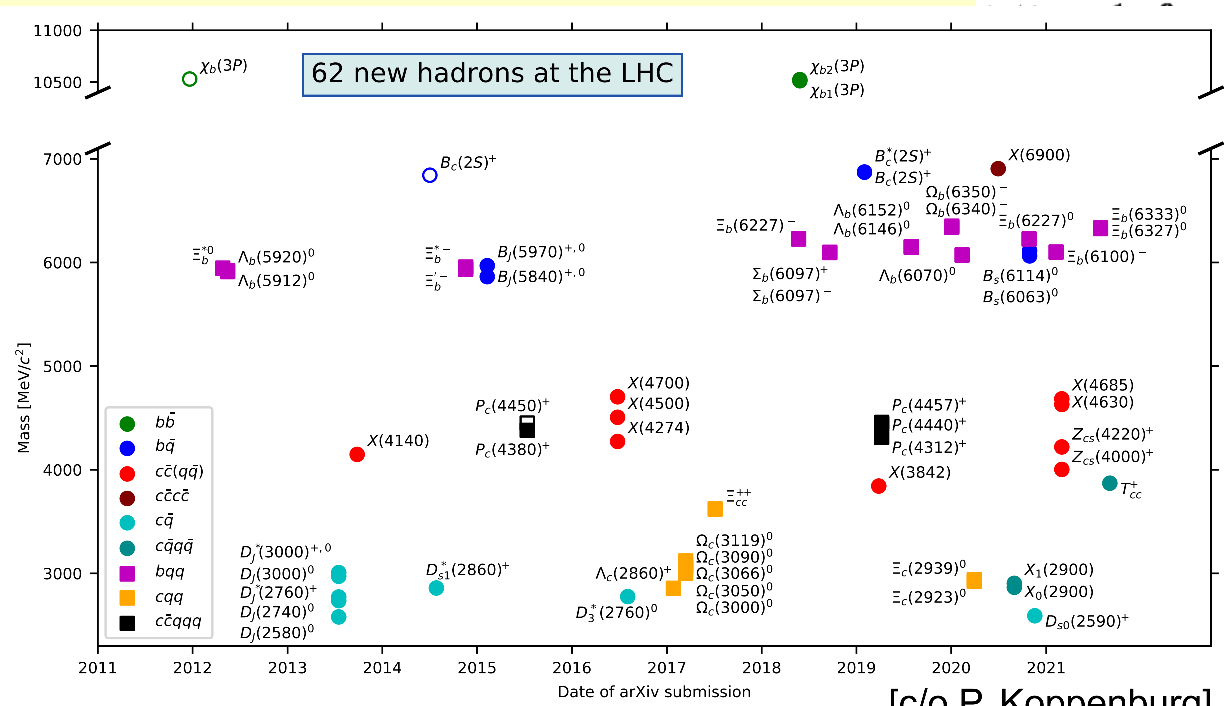
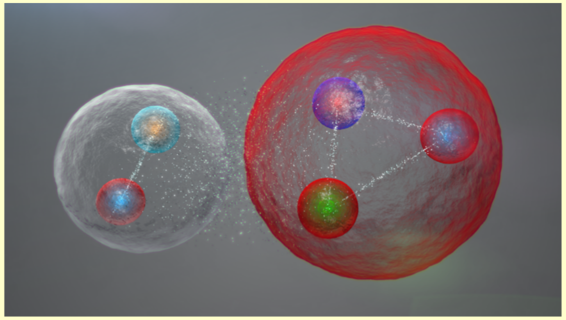
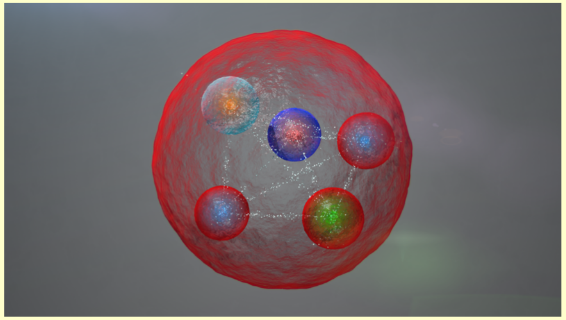
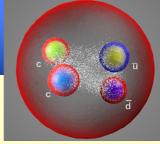


[c/o P. Koppenburg]







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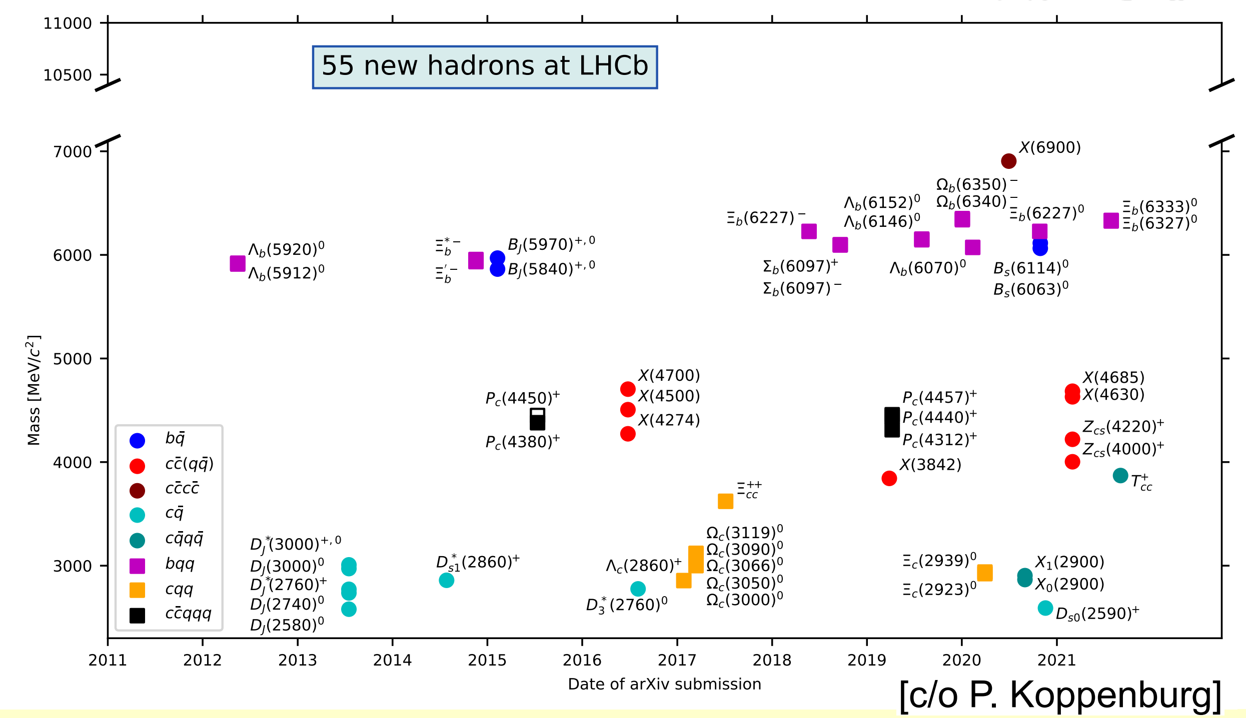

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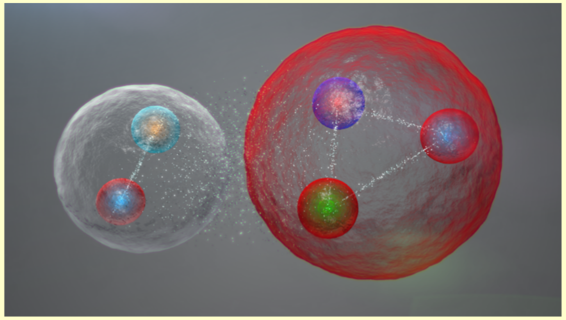

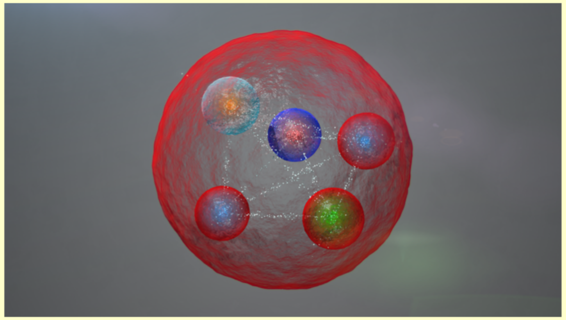

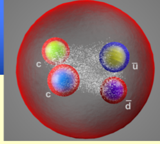

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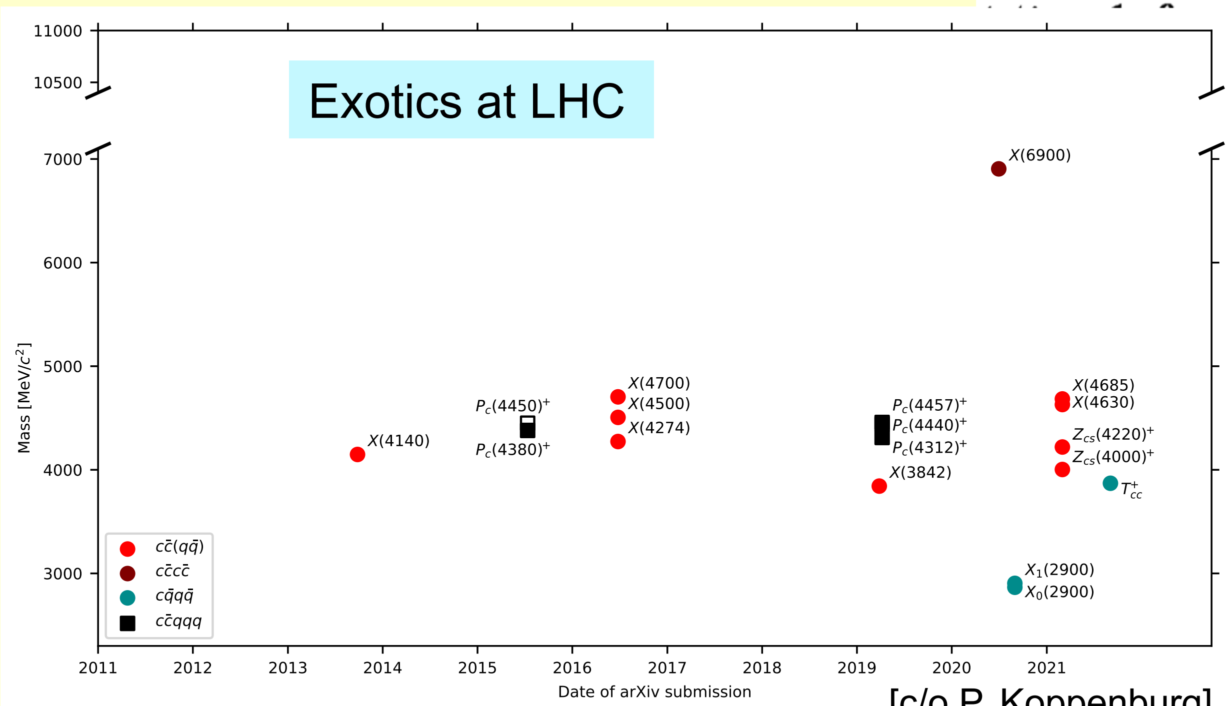
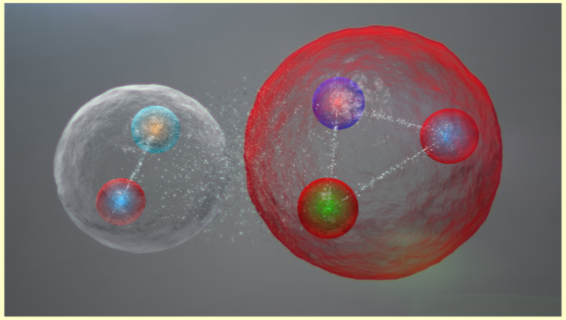
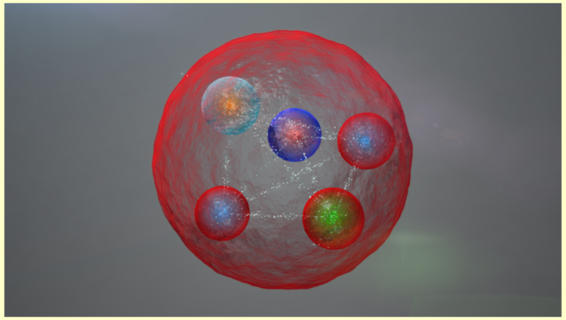
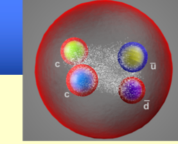


[c/o P. Koppenburg]

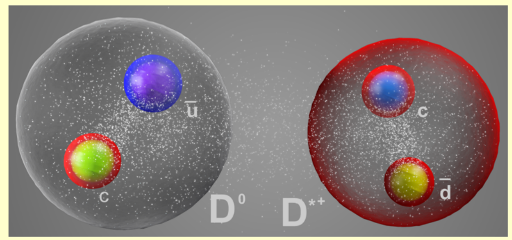


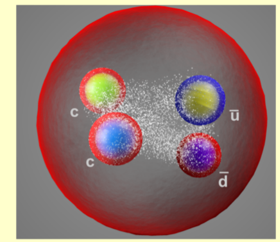




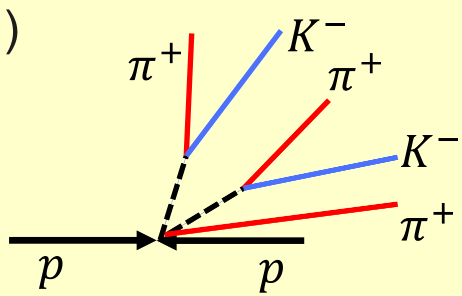
Tetraquark T_{cc}^{+} search

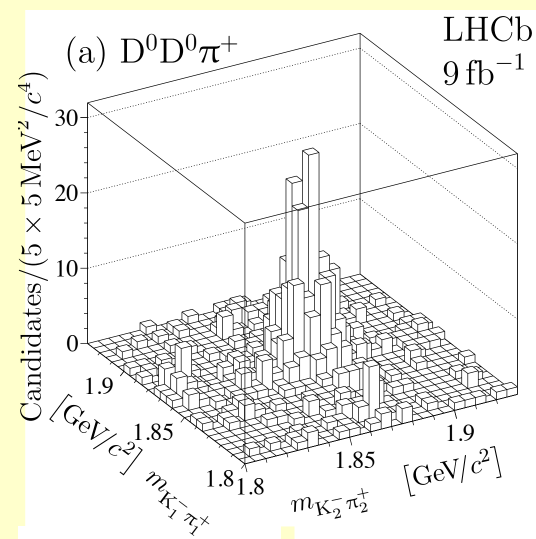
- Heavy quark symmetry
  - Predicts existence of $cc\bar{q}\bar{q}$ and $bb\bar{q}\bar{q}$ tetraquark, long-lived w.r.t. strong interaction
  - Predicted
    - existence T_{cc}^{+}, two c quarks
    - ground state $J^P = 1^+$
    - Mass ~ $\mathrm{D^*D^0}$ threshold





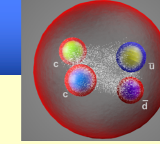
- Search strategy
  - *Narrow* exotic state, same-sign double-charmed mass spectrum
- Mass is ~ $D^{*+}D^0$ and $D^{*0}D^+$ thresholds
- Select $D^0D^0\pi^+$ ($D^0 \to K^-\pi^+$)



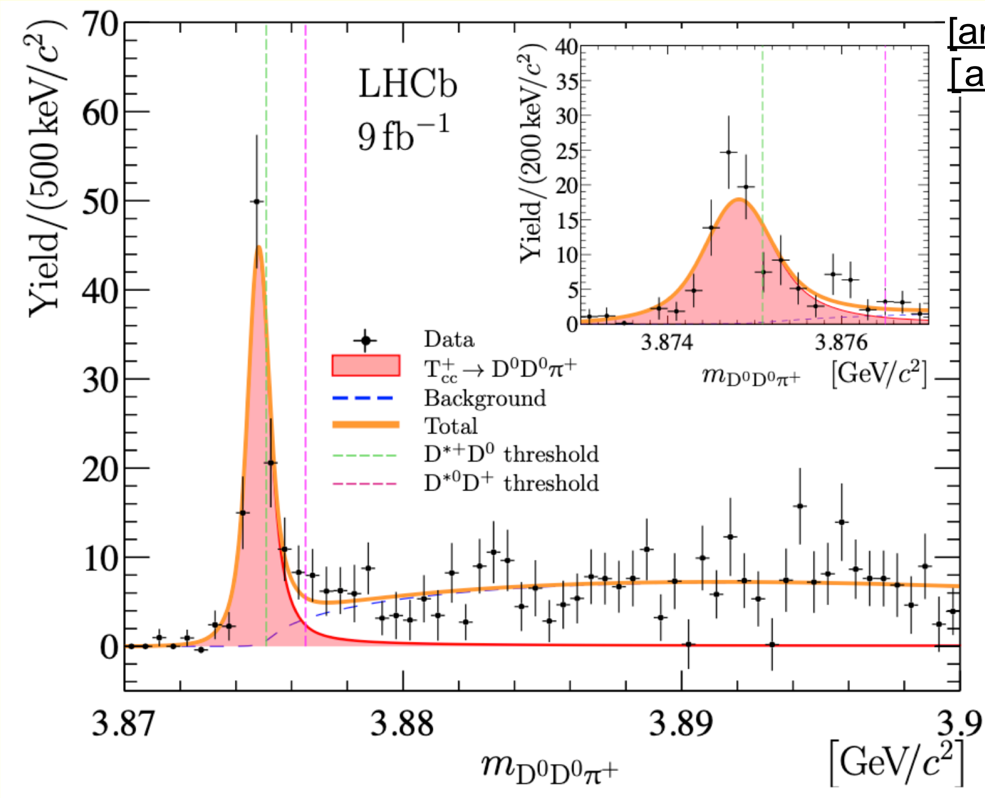


- Unbinned fit to 2-D D^0 mass combinations of $D^0D^0\pi^+$candidates
- Subtract combinatorial $K^-\pi^+$contribution

[arXiv:2109.01038]
[arXiv:2109.01056]



Tetraquark T_{cc}^{+} search

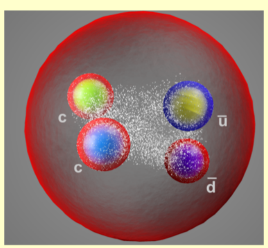


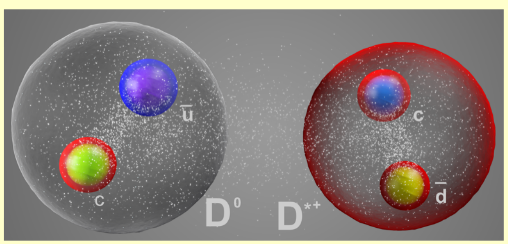
[arXiv:2109.01038]
[arXiv:2109.01056]

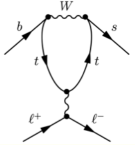
- *Very* narrow state in $D^0D^0\pi^+$
  - Consistent with $cc\bar{u}\bar{d}$ tetraquark
- Nature of T_{cc}^{+} candidate
  - P-wave RBW fit (δm relative to $D^{*+}D^0$ threshold)

$$\begin{aligned} \delta m_{\mathrm{BW}} &= -273 \pm 61 \pm 5\,^{+11}_{-14}\ \mathrm{keV}/c^2\,, \\ \Gamma_{\mathrm{BW}} &= 410 \pm 165 \pm 43\,^{+18}_{-38}\ \mathrm{keV}\,, \end{aligned}$$

  - Signal significance >10σ
  - *Just* below $D^{*+}D^0$ threshold
  - Most precisely measured 'exotic' mass w.r.t. corresponding threshold
  - Adds support for a $bb\bar{u}\bar{d}$ tetraquark, stable to strong and EM decays







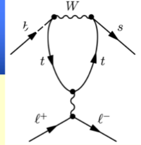
Why: Lepton Flavour Universality?

- One aspect of wide range of rare decay studies, $\mathcal{B} \sim 10^{-6} - 10^{-10}$
  - More details in Rare decays (Zhenzi Wang)

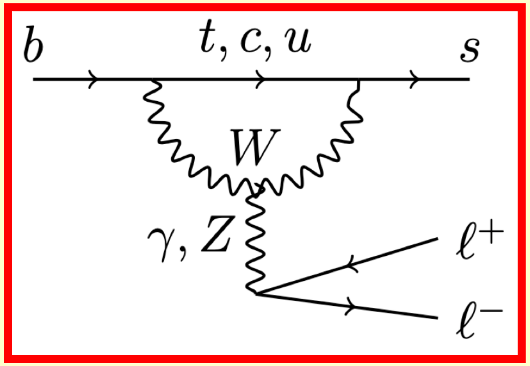
- LHCb ideal – high rate, excellent particle ID, low pile-up exclusive candidates

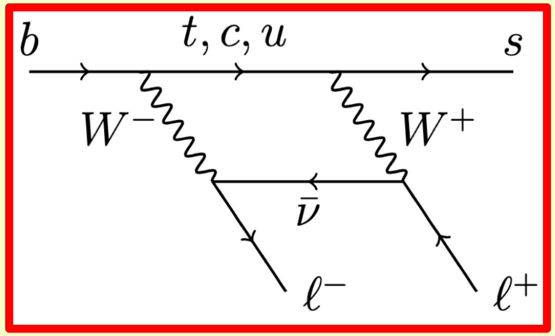
- Standard Model behavior of e, μ, τ leptons is universal
- Differences due to mass alone
- Fundamental principle, conceptually simple tests
  - Branching fractions
  - Angular distributions
- Set of related measurements, possible hints of …?

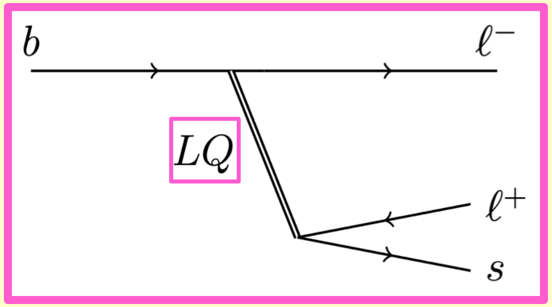
- Rare decays → results (still) limited by sample size

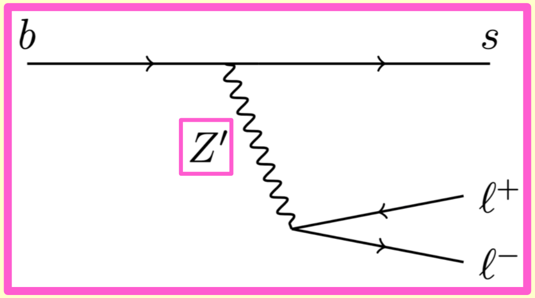


Rare $b \to s\ell^+\ell^-$ decay processes

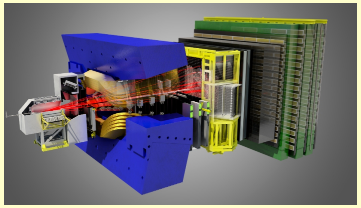


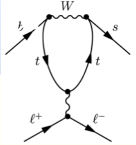






- SM needs loop / box diagrams, electroweak ‘penguins’
  - No Flavour-Changing Neutral Current at tree level
- New physics particles, *also possible* in loops, affect
  - Branching fractions
  - Angular observables (× many, 4-particle final states)
  - Asymmetries
- Candidate signatures
  - Clean
  - Low backgrounds (resolution, particle ID)
- Predictions well-established
  - Varying degrees of theoretical uncertainty
  - Hadronic form factors (non-pert. QCD)





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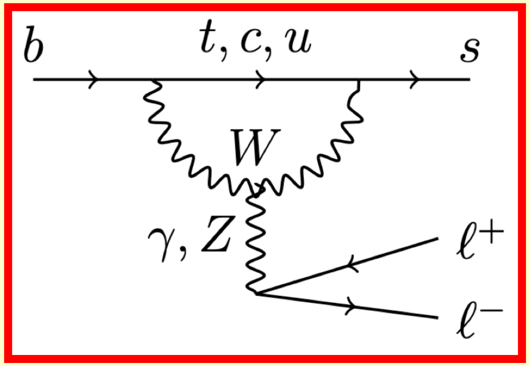
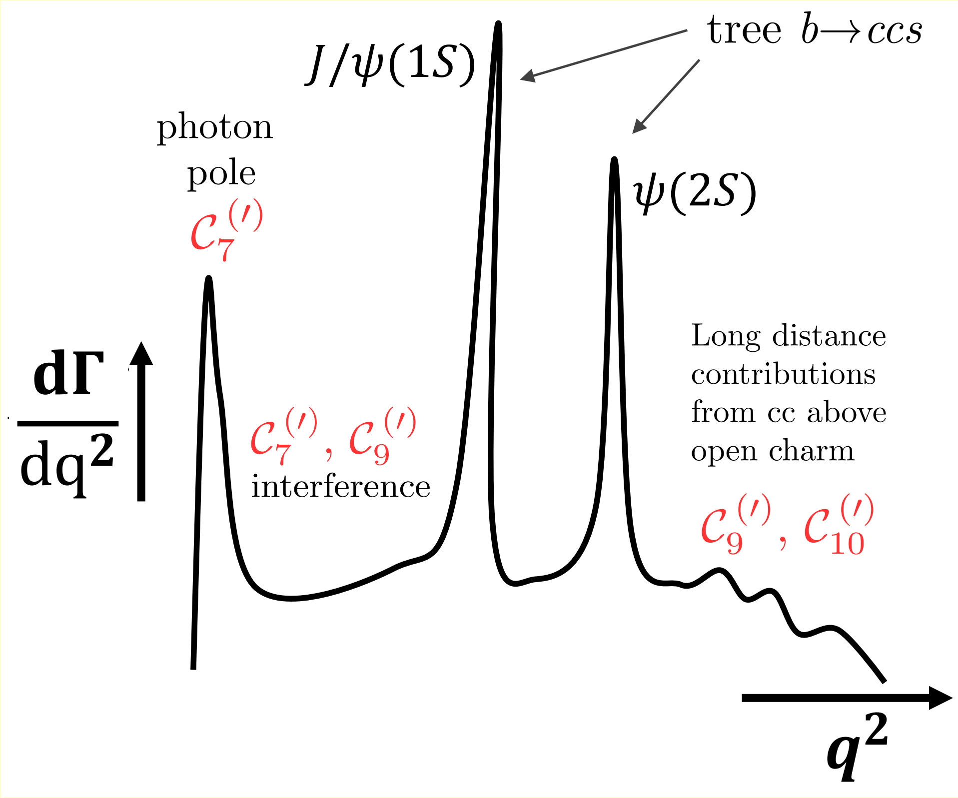
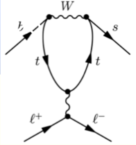




- Multiple, very different scales
  - Λ_{QCD}
  - b quark mass
  - W, t masses
  - $\Lambda_{New\ Physics}$??
- Interplay of operators, couplings in EFT vary with $q^2 = m^2(\ell^+\ell^-)$
- Analyses made as f(q^2)
  - Exclude large resonances, use a control/normalisation



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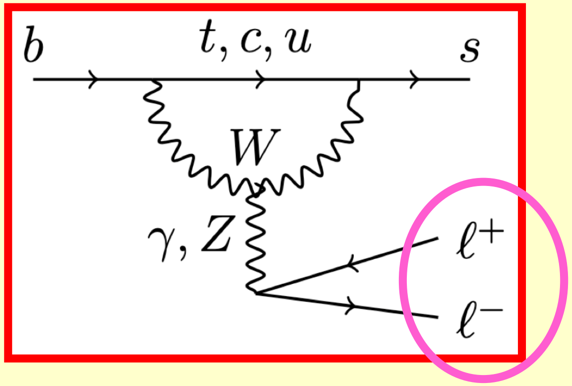

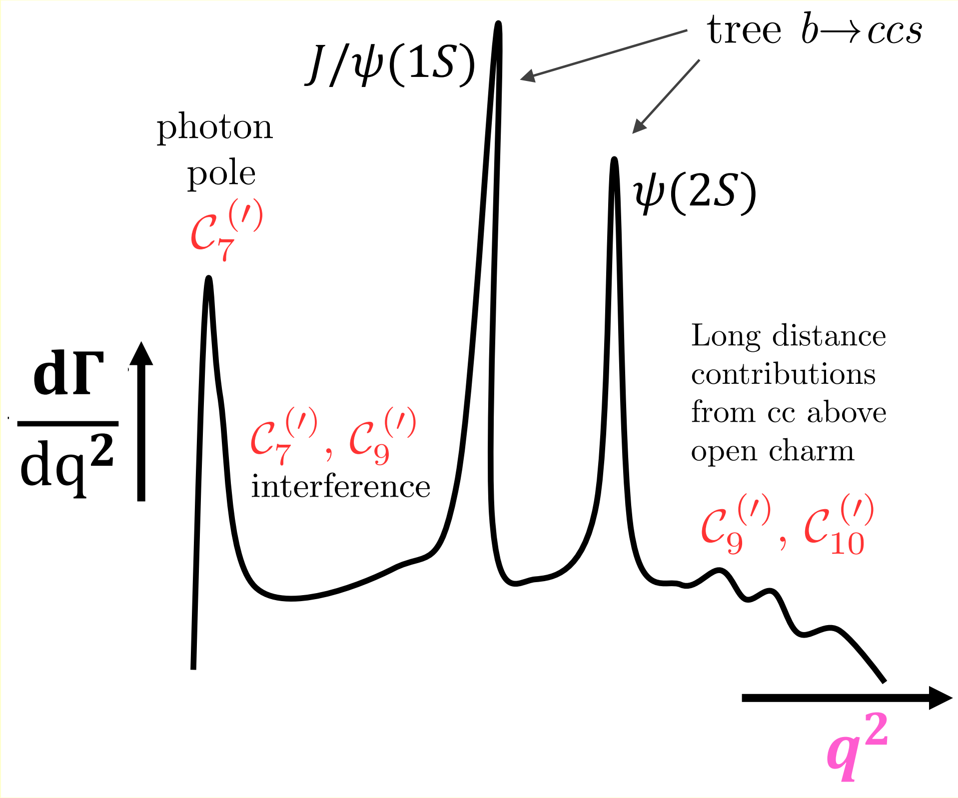

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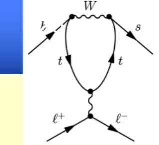

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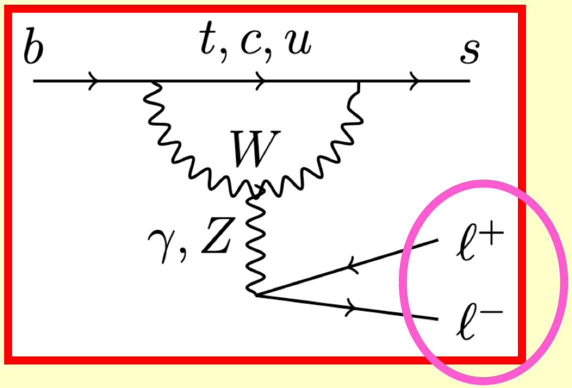

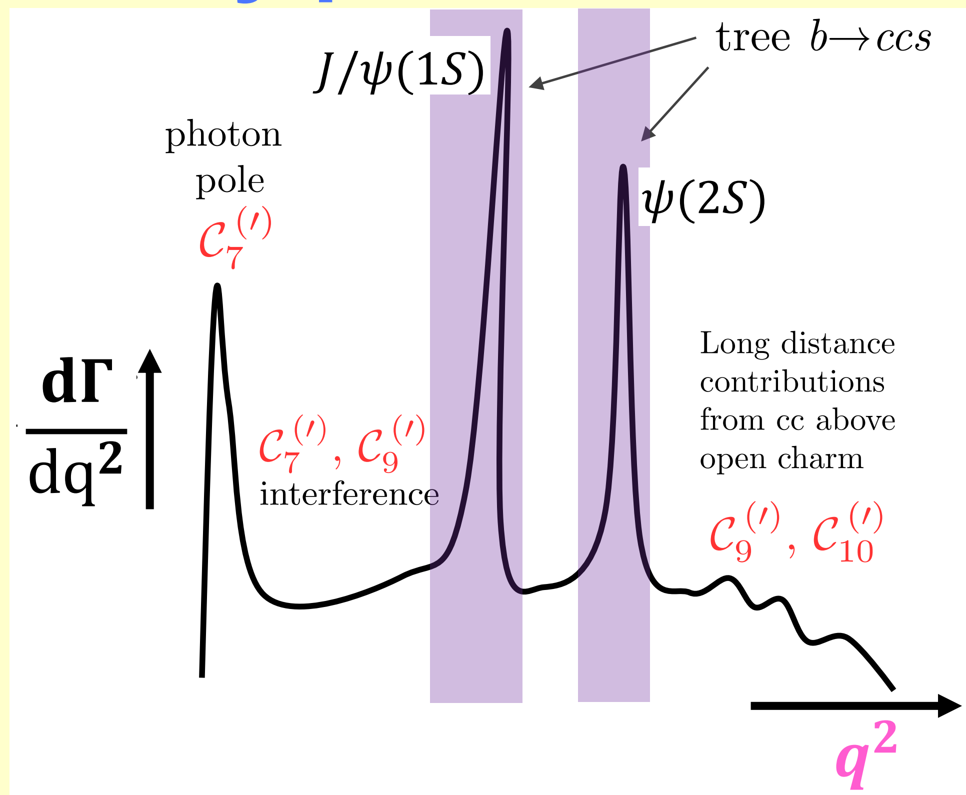

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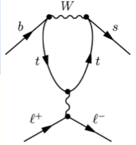
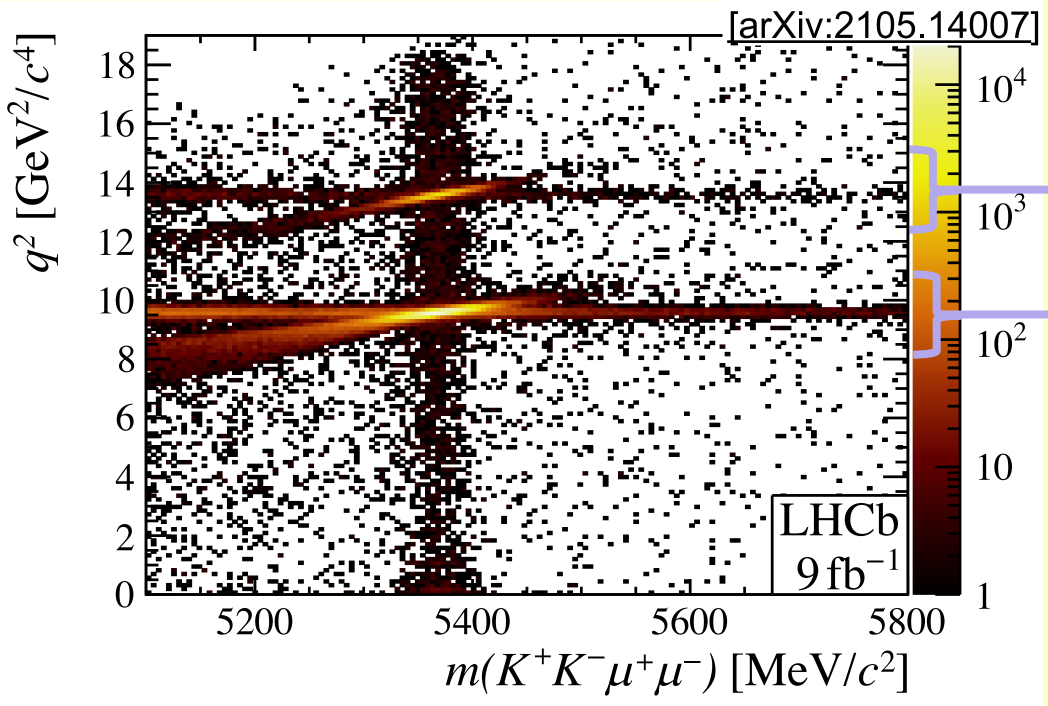
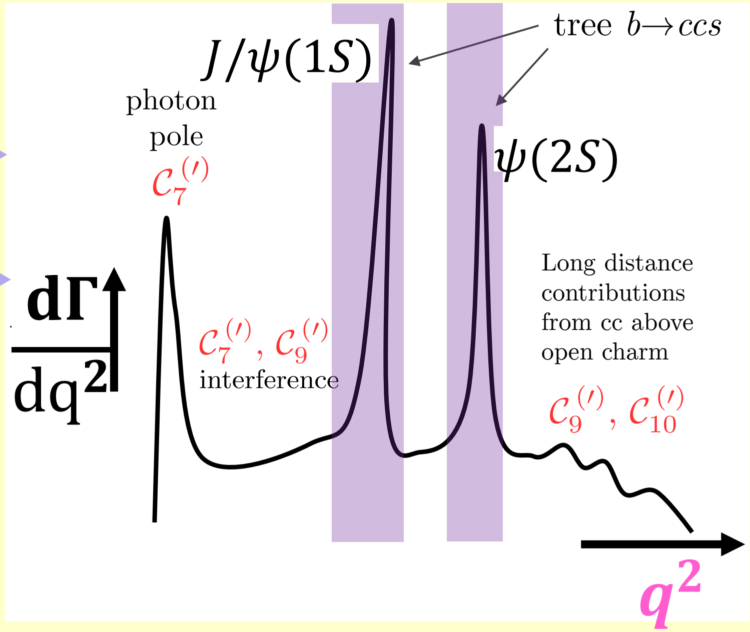
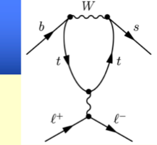


$B_s^0 \to \phi(\to K^+K^-)\mu^+\mu^-$ branching fraction





- $\phi \to K^+K^-$, $\pm$12 MeV window
- Multivariate selection: kinematic, topological and particle ID variables
  - Signal proxy: $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$; background proxy: signal upper mass sideband
  - Extended maximum liklihood fit
    - Signal: double Gaussian function +power-law tails, parameters from proxy decays
    - Background: exponential
- Specific kinematic/PID criteria to suppress exclusive backgrounds



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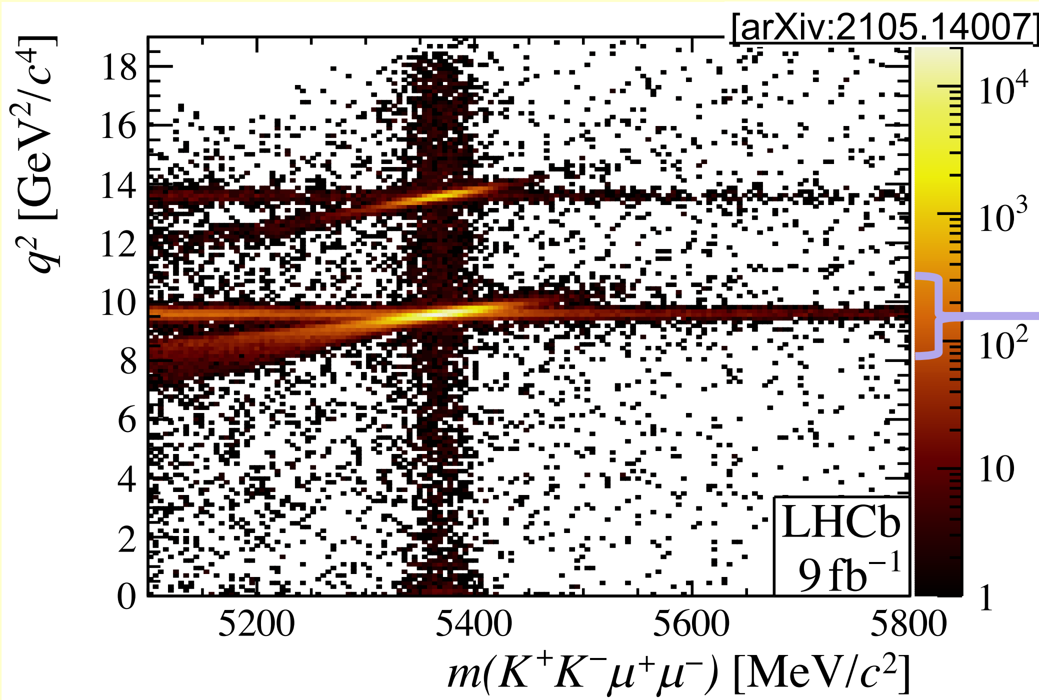
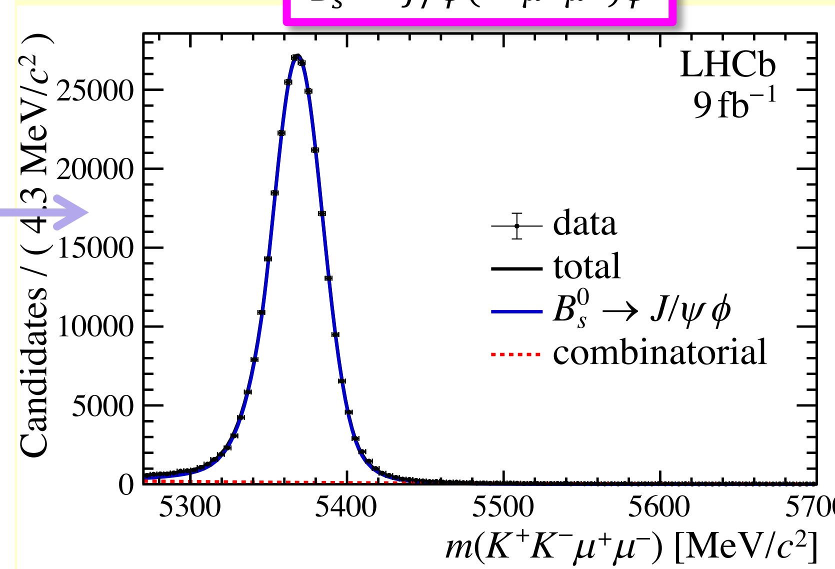


Normalisation
$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$



[arXiv:2105.14007]

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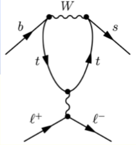

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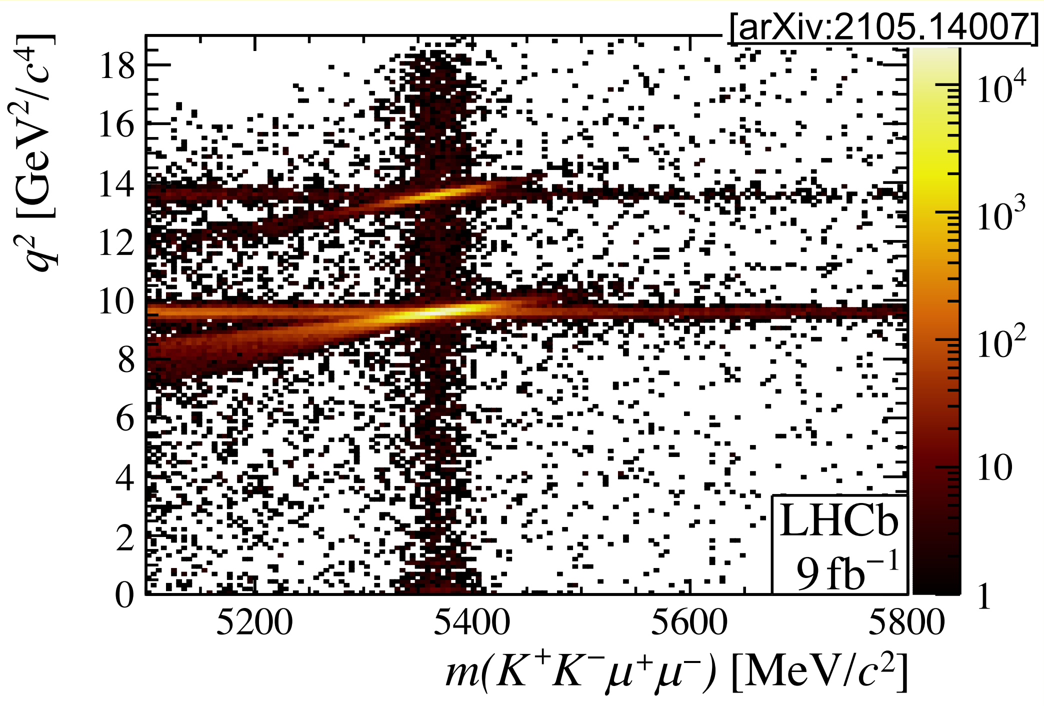

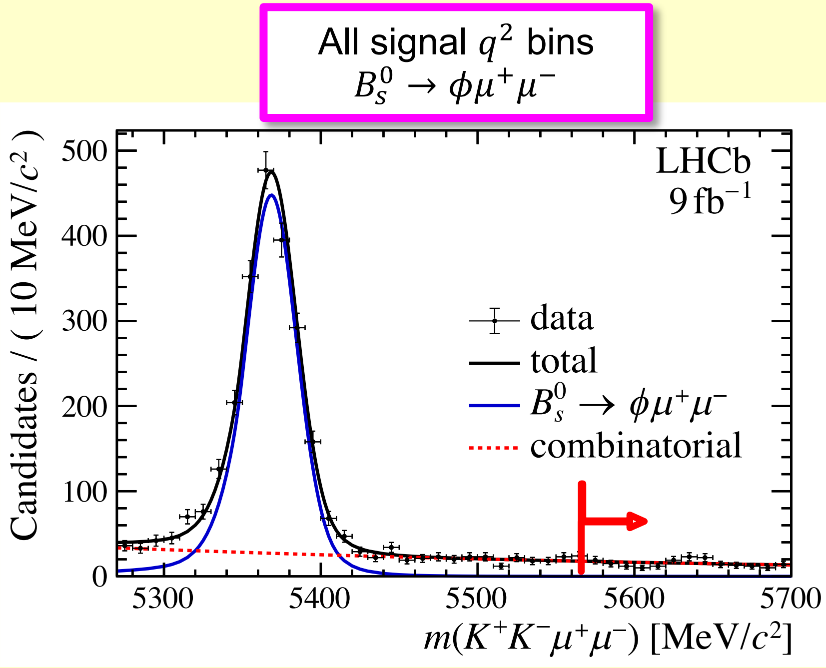

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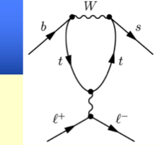

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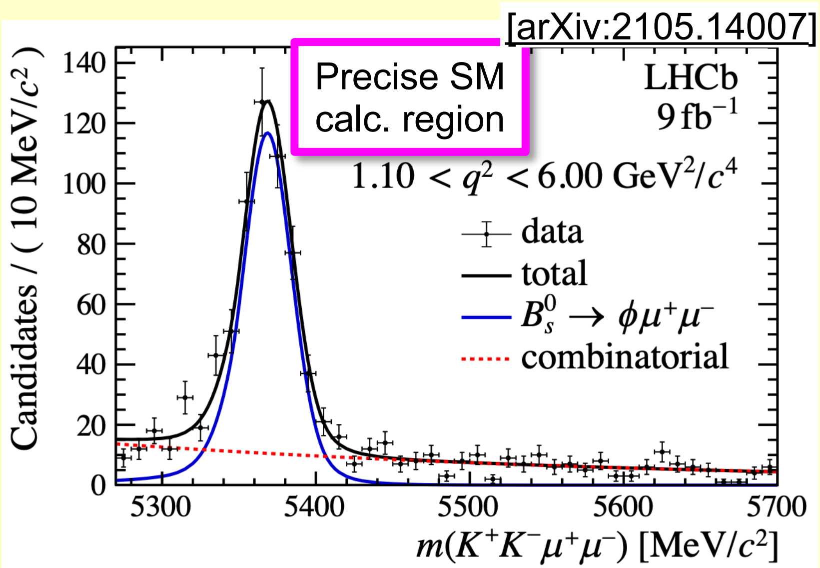
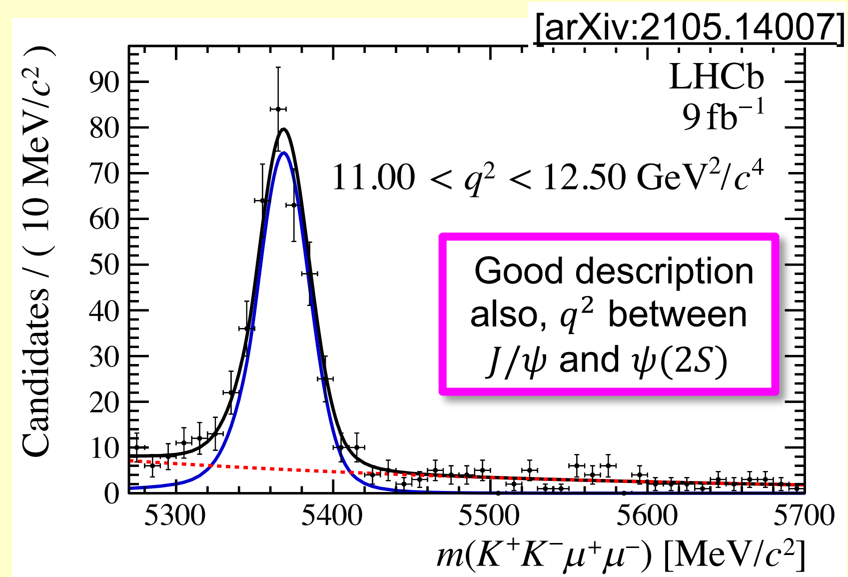


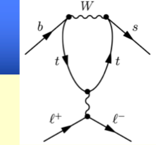


- Measure $\mathcal{B}$ in narrow q^2 bins, relative to normalisation mode
  - Relative efficiencies from simulation (per q^2 , run-period)

$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = \frac{\mathcal{B}(B_s^0 \to J/\psi\phi) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{q^2_{\rm max} - q^2_{\rm min}} \times \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \times \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\phi\mu^+\mu^-}}$$

- Most precise measurement this $\mathcal{B}$ to date (full q^2)

$$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \pm 0.21 \pm 0.16 \pm 0.03 \pm 0.39) \times 10^{-7}$$



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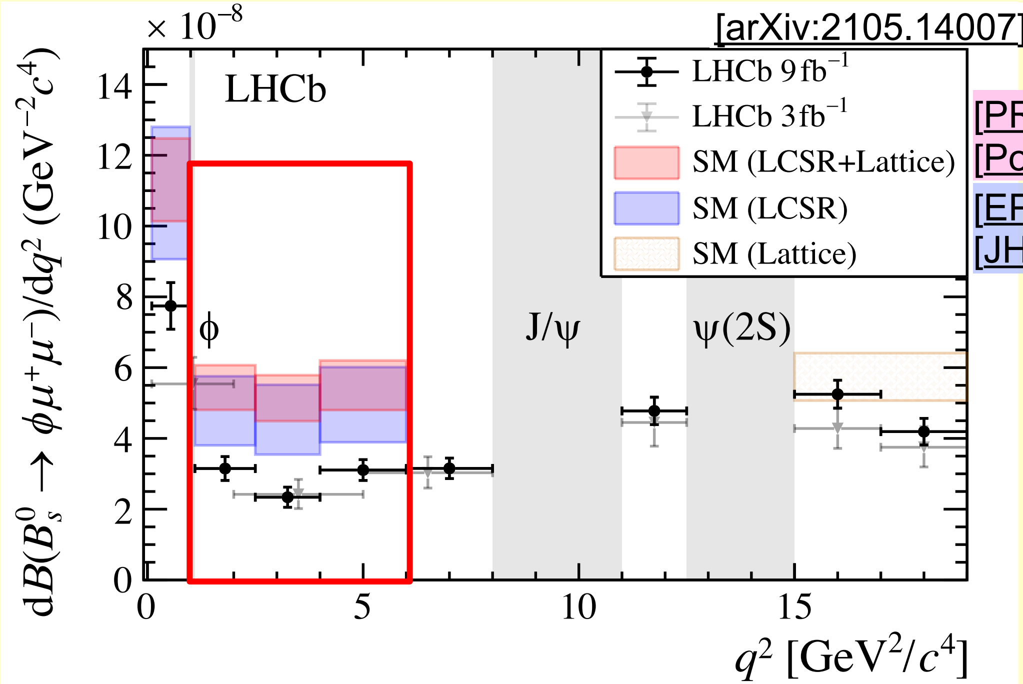
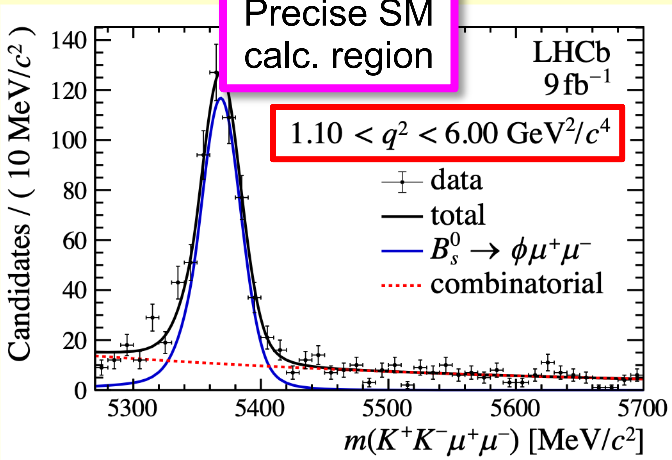
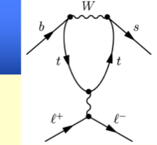


[PRL 112 (2014) 212003]
[PoS, Lattice 2014 (2015) 372]
[EPJC 75 (2015) 382]
[JHEP 08 (2016) 098]

Precise SM calc. region



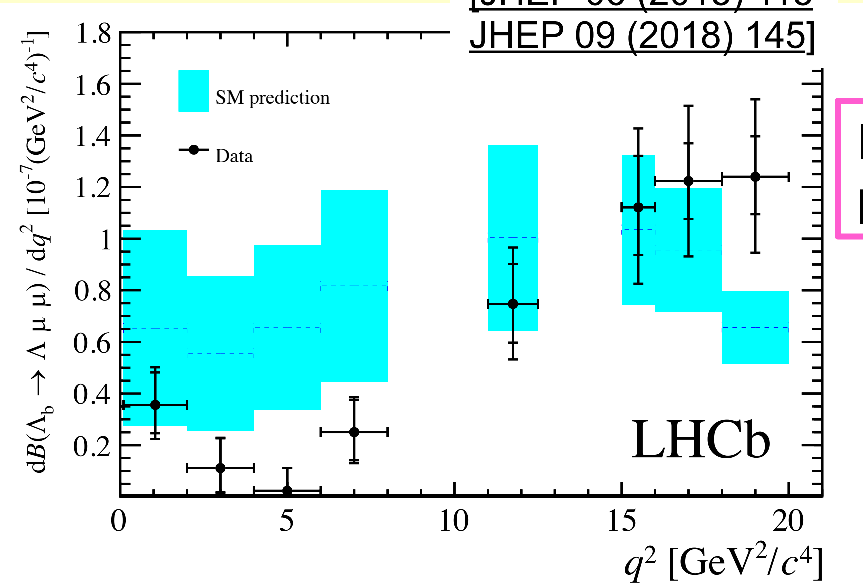
- In q^2 [$\boxed{1.1, 6.0}$] GeV$^2/c^4$
  - Measured $d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/dq^2 = (2.88 \pm 0.22) \times 10^{-8}$ GeV$^{-2}c^4$
  - SM prediction (LQCD+LCSR) $(5.37 \pm 0.66) \times 10^{-8}$ GeV$^{-2}c^4$
- Consistency $\sim 3.6\sigma$ level



Lepton universality

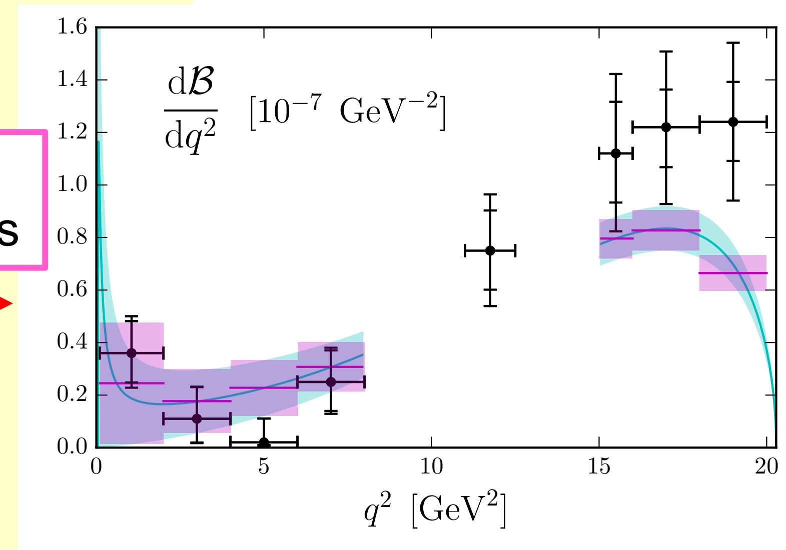
- Consistency with SM in $\mathcal{B}$ and angular measurements subject to change, e.g. $\Lambda_b \to \Lambda\mu^+\mu^-$

[JHEP 06 (2015) 115
JHEP 09 (2018) 145]



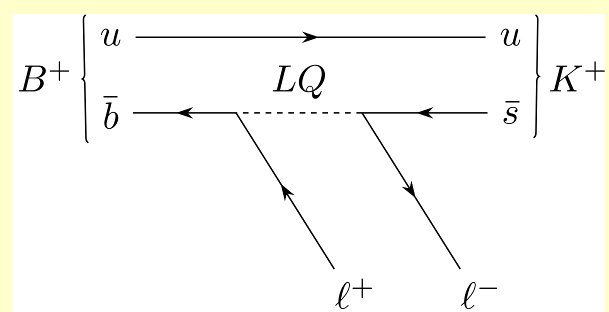
Improved predictions

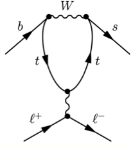
[Phys. Rev. D 93, 074501 (2016)]



  - Always cautious not to over-interpret

- Potential for new physics, e.g. $B^+ \to K^+\ell^+\ell^-$





Lepton flavour universality

- Ratios of $\mathcal{B}$ very robust, both measurement and predictions
  - $H = K, K^*, \phi, \ldots$
  - (not Higgs)

$$R_H \equiv \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\mathcal{B}(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathrm{d}\mathcal{B}(B\to He^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

≈ 1 (SM)

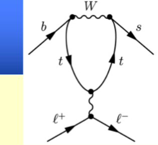
$\neq 1$ (New Physics?)

  - "Direct" LFU tests: R_K, R_{K^*}, R_ϕ, etc., various H
  - Many cancellations
- One of various golden measurments, LHCb uses double ratio

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

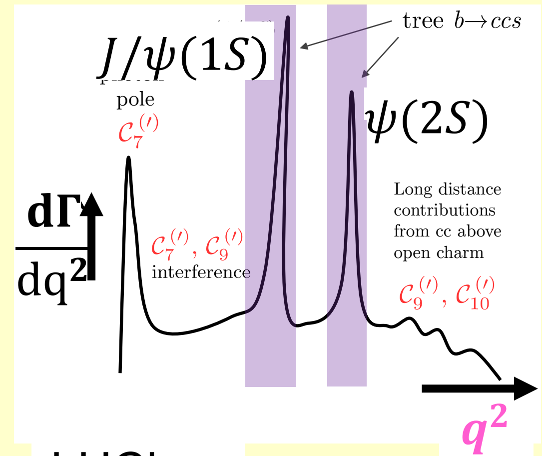
  - relative to resonant mode, even more cancellation, e.g. efficiencies

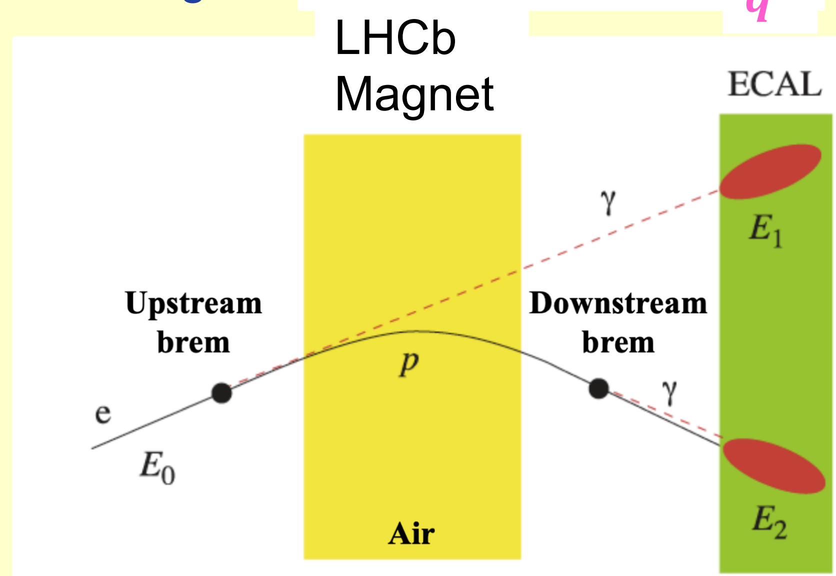
$$r_{J/\psi} = \mathcal{B}(B^+\to J/\psi(\to\mu^+\mu^-)K^+)/\mathcal{B}(B^+\to J/\psi(\to e^+e^-)K^+)$$

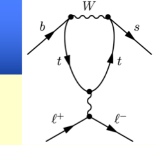


Lepton flavour universality

- Detector efficiencies from simulation, calibrated to data
- Usual, q^2 regions
  - $1.1 - 6.0\ \mathrm{GeV}^2/c^4$ rare signal
  - $\sim J/\psi(1S)$ control
  - $\psi(2S)$ cross-checks
- e^-, μ^- mass effects important in detector
  - e^- large bremsstrahlung up-/down-stream of magnet
- Very different
  - Mass, momentum resolutions
  - Trigger efficiencies
- γ emitted downstream
  - γ same calorimeter cell as e^-, $\vec{p}$ OK
- γ emitted upstream
  - γ different cell to e^-
  - $\vec{p}$ measured after recovering γ's



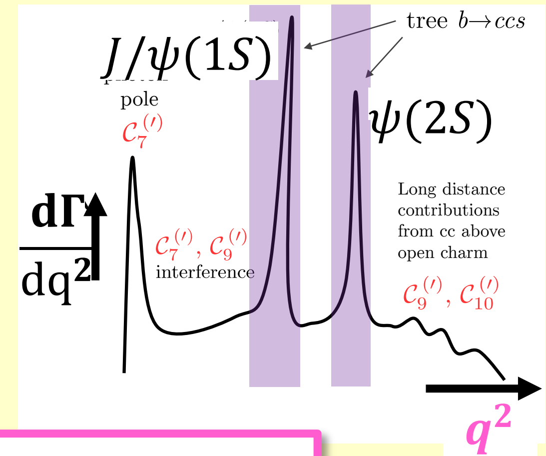


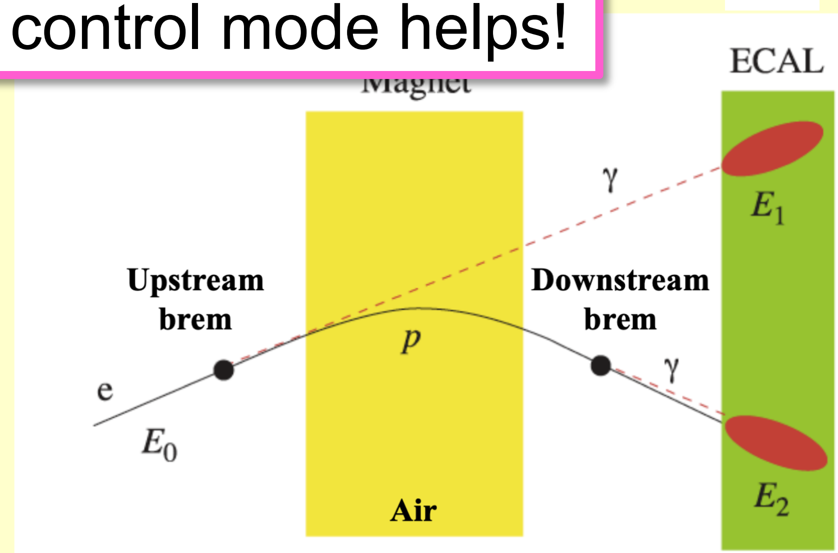


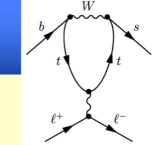
Lepton flavour universality

- Detector efficiencies from simulation, calibrated to data
- Usual, q^2 regions
  - $1.1 - 6.0\ \mathrm{GeV}^2/\mathrm{c}^4$ rare signal
  - $\sim J/\psi(1S)$ control
  - $\psi(2S)$ cross-checks
- e^-, μ^- mass effects important in detector
  - e^- large bremsstrahlung up-/down-stream of magnet
- Very different
  - Mass, momentum resolutions
  - Trigger efficiencies
- γ emitted downstream
  - γ same calorimeter cell as e^-, $\vec{p}$ OK
- γ emitted upstream
  - γ different cell to e^-
  - $\vec{p}$ measured after recovering γ's

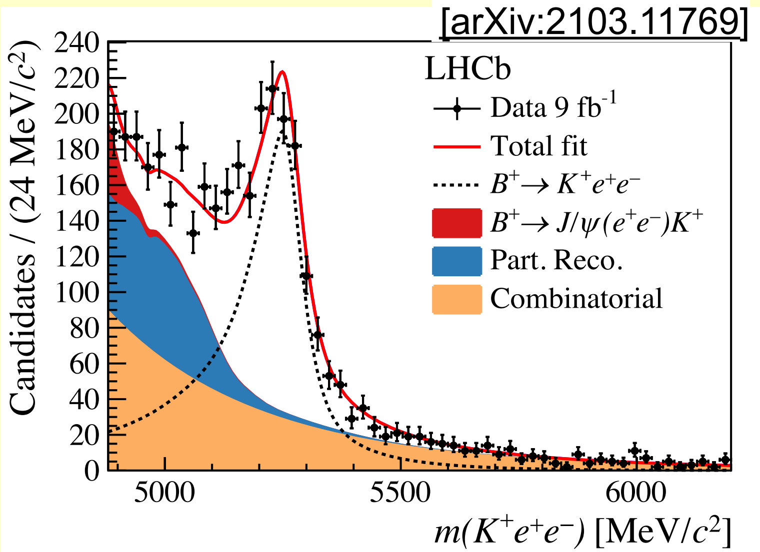
Double ratio using control mode helps!

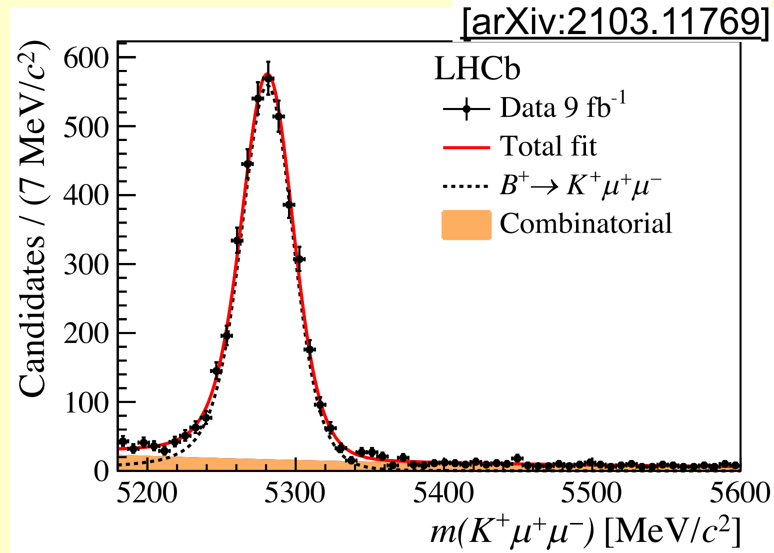


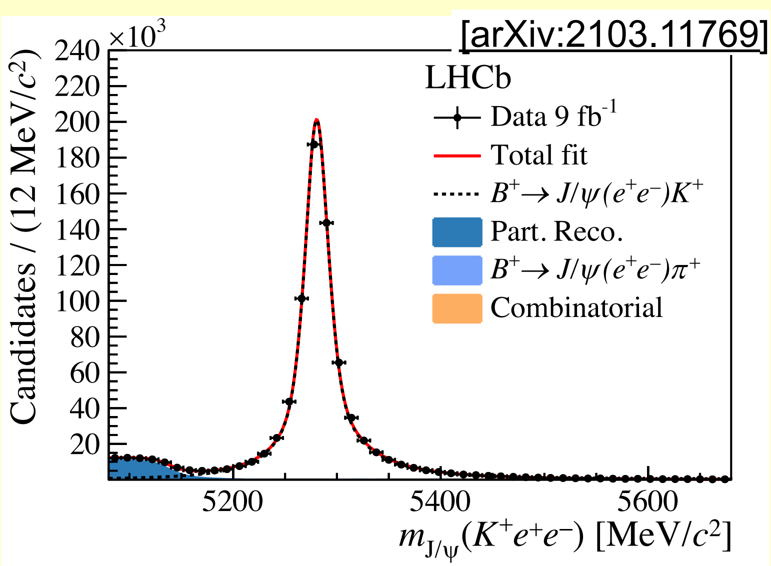


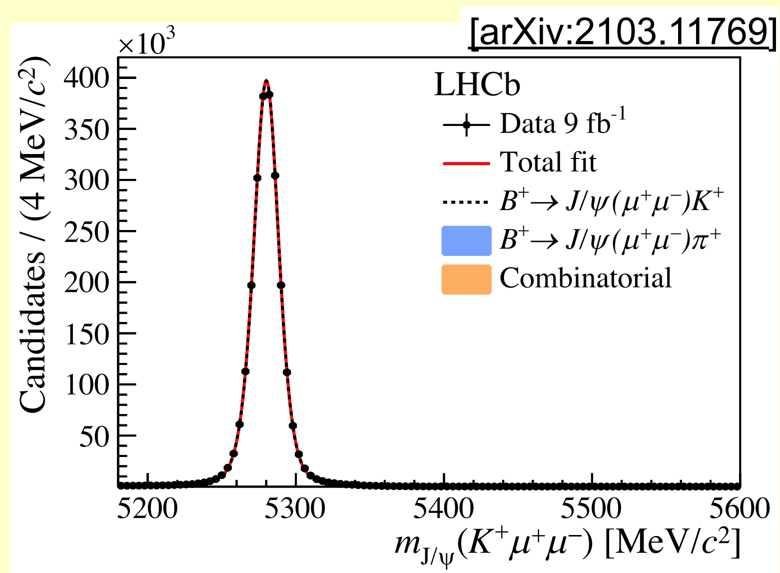


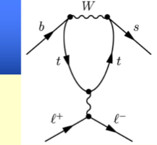
Lepton flavour universality: rare, control, e, μ



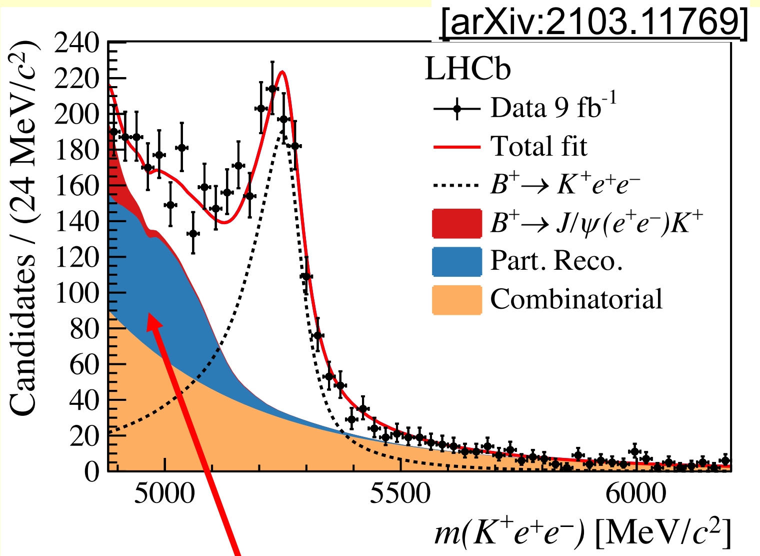


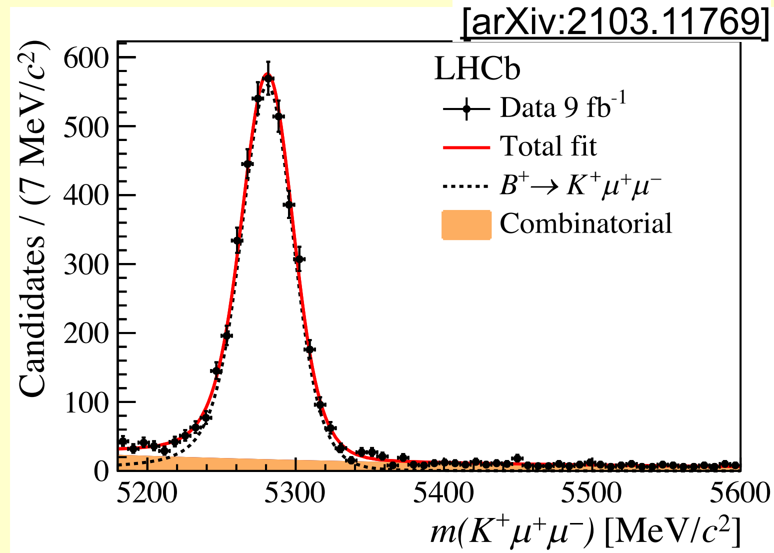




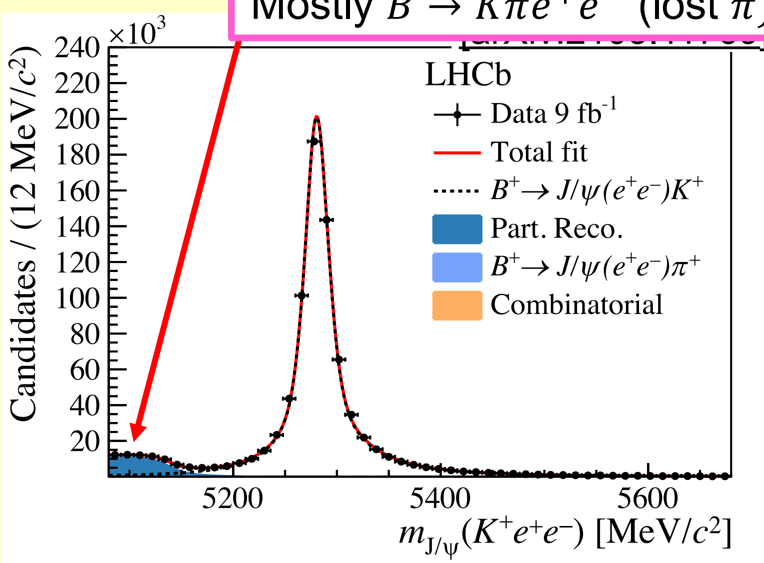


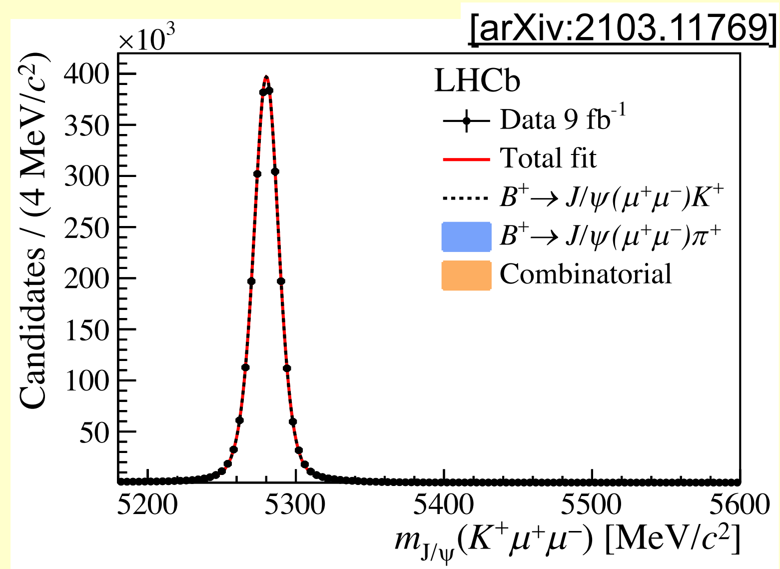
Lepton flavour universality: rare, control, e, μ

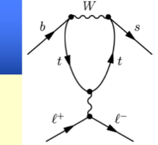




Mostly $B \to K\pi e^+e^-$ (lost π)

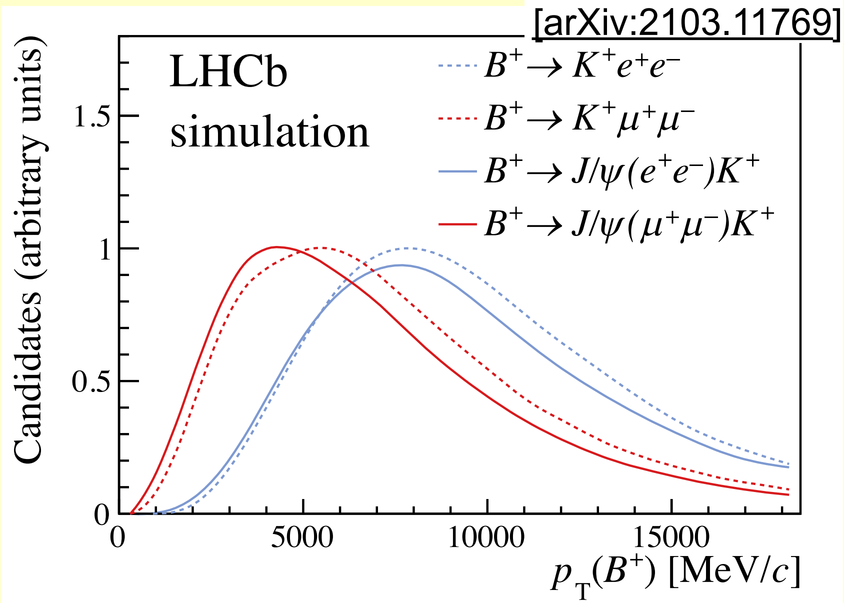




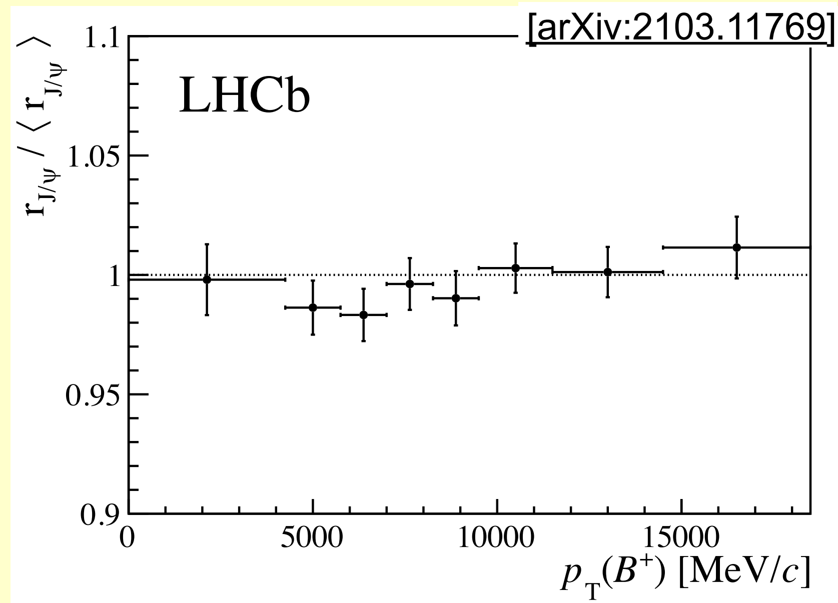


Lepton flavour universality: many cross-checks

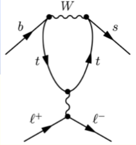
Compatible p_T spectra, signal and control



Control mode ratio stable with parent p_T



- Studied vs. many other variables, also no significant trend



Lepton flavour universality: many cross-checks

[arXiv:2103.11769]

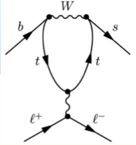
- All LHCb Run1 + Run2 data
- Factor ~ 2 increase in reconstructed candidates since previous paper

$$r_{J/\psi} = \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)/\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+) = 0.981 \pm 0.020$$

  - Strict (essential) cross-check, validates relative efficiencies and all corrections for high yield control modes

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to \psi(2S)(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to \psi(2S)(\to e^+e^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = 0.997 \pm 0.011$$

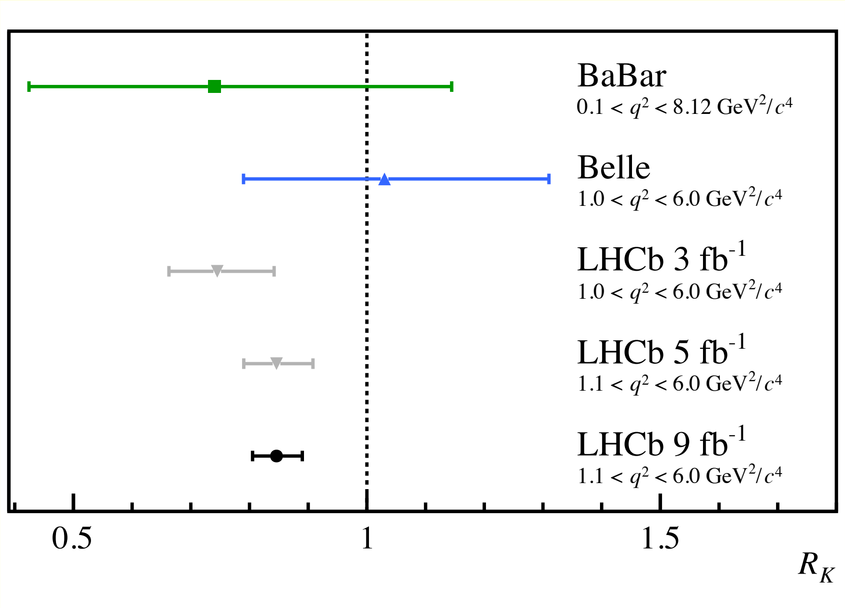
  - Validation of whole double ratio procedure
  - Also a world-leading test in itself of lepton flavour universality

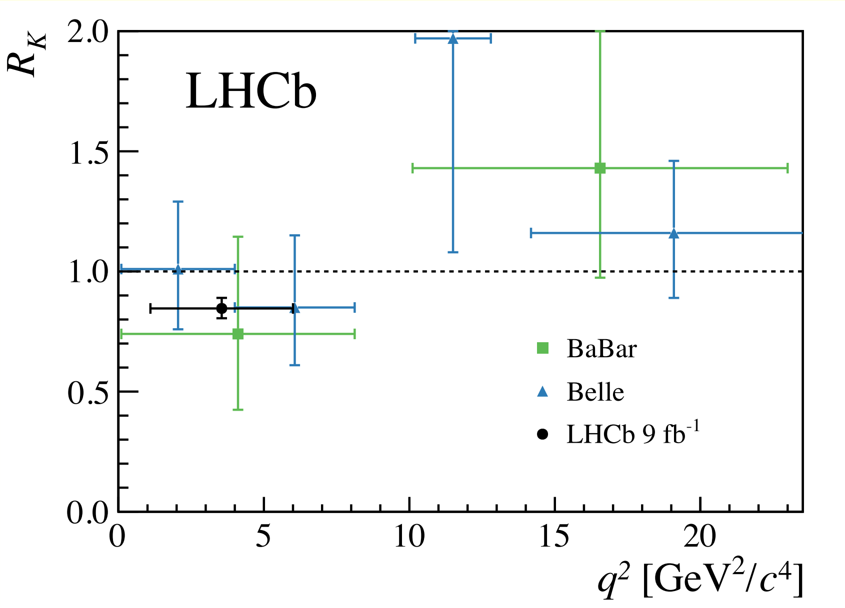


Lepton flavour universality

[arXiv:2103.11769]

$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$





- Latest LHCb measurement
  - Most precise to date
  - Consistency with SM is 3.1σ: “hints” → “evidence” → ??
  - Other LFU measurements in progress (R_{K^*},…)
  - Remember statistics limited (for some time to come)

Conclusions

- LHC provides the enabling b production rates
- LHCb are exploiting these to stress-test the SM and relatives
- First observation of very narrow, double charm tetraquark
- More support for intrinsic charm in proton
- First m_W measurement in forward region
- Lepton Universality Violation more hints, evidence, …