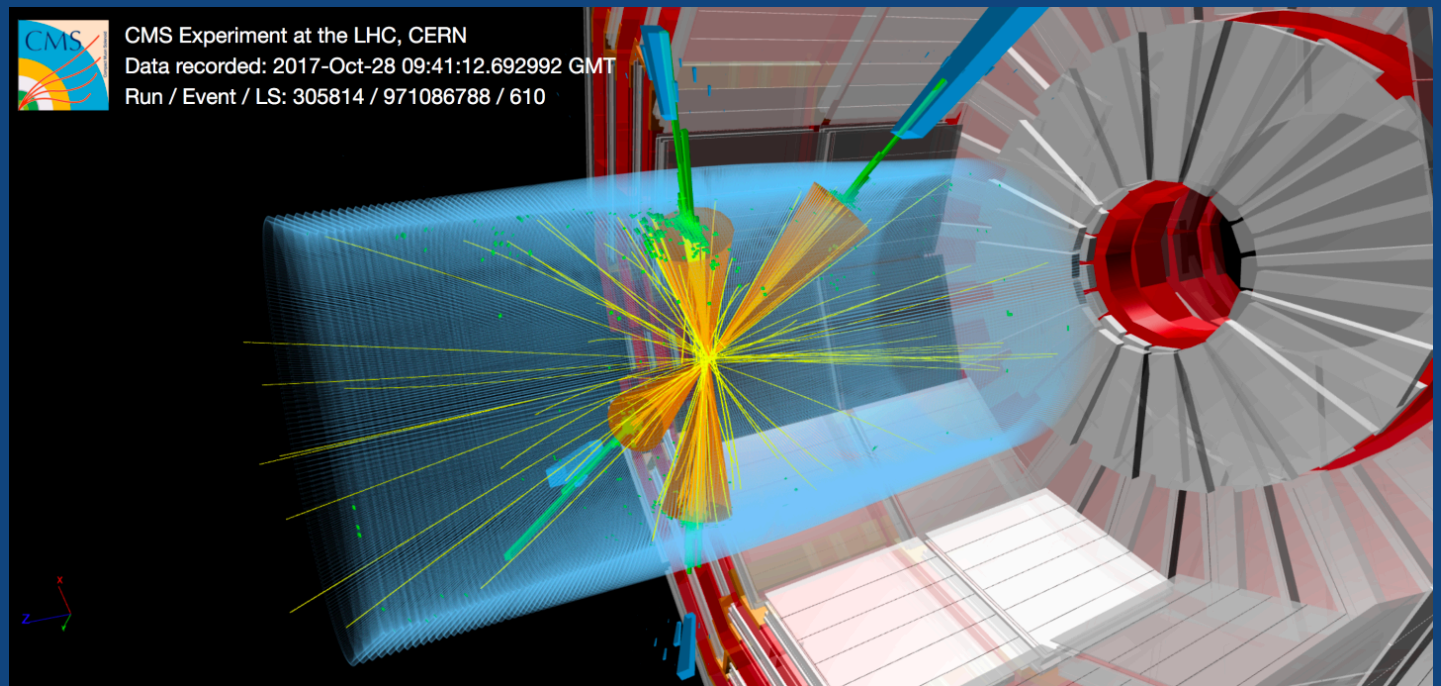
402-0703-00L

Phenomenology of Physics Beyond the Standard Model

Exp Lecture 5 : Indirect searches

Annapaola de Cosa adecosa@phys.ethz.ch



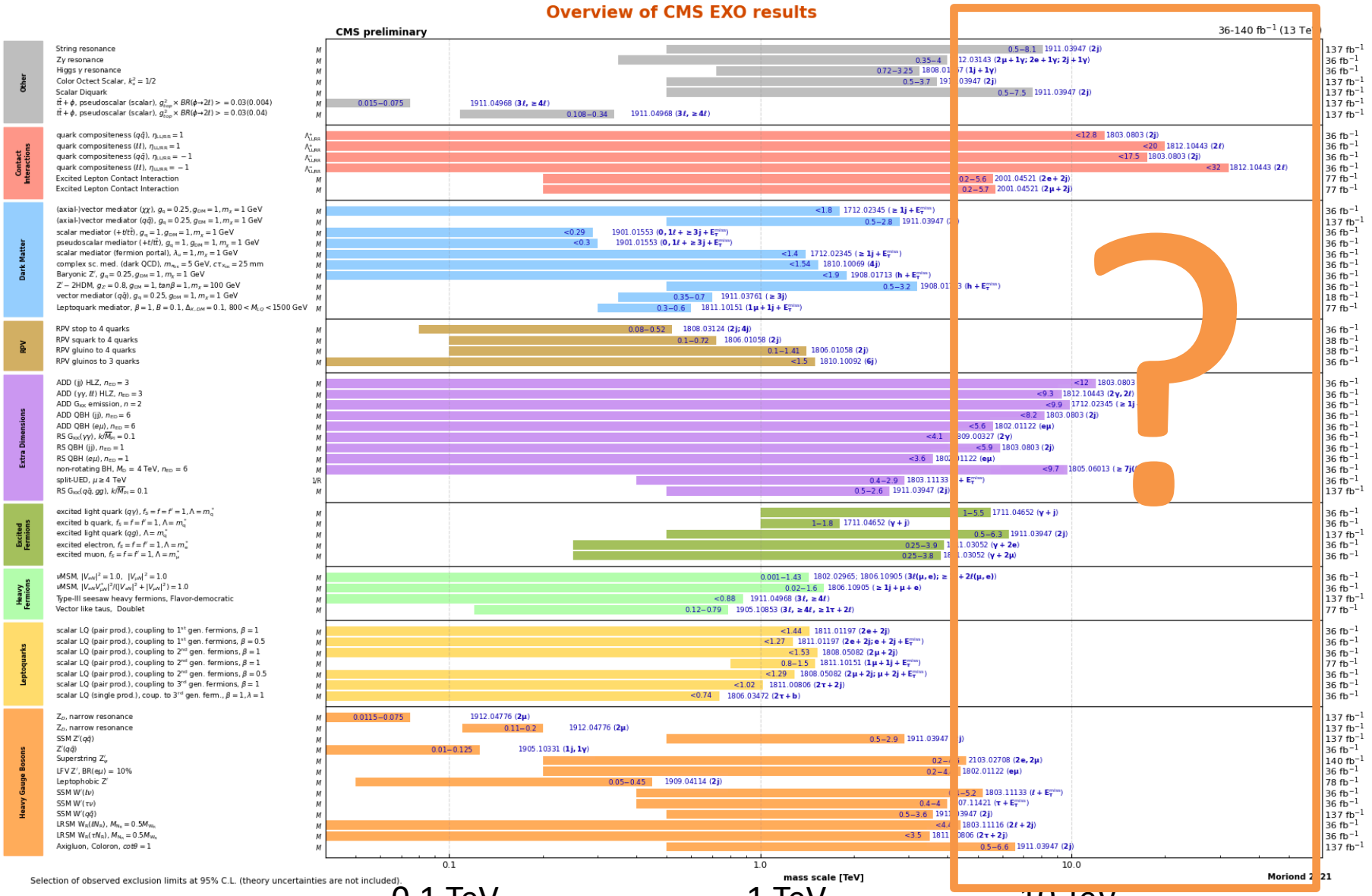
From last exp.lecture

- Dark Matter searches at colliders
  - Mainly focused on WIMP candidates
- MET-based strategies
  - MET back to back to visible objects
  - Data-driven background estimation
- Direct mediator searches
  - Can access the mediator while looking into decays to SM particles

In today's class

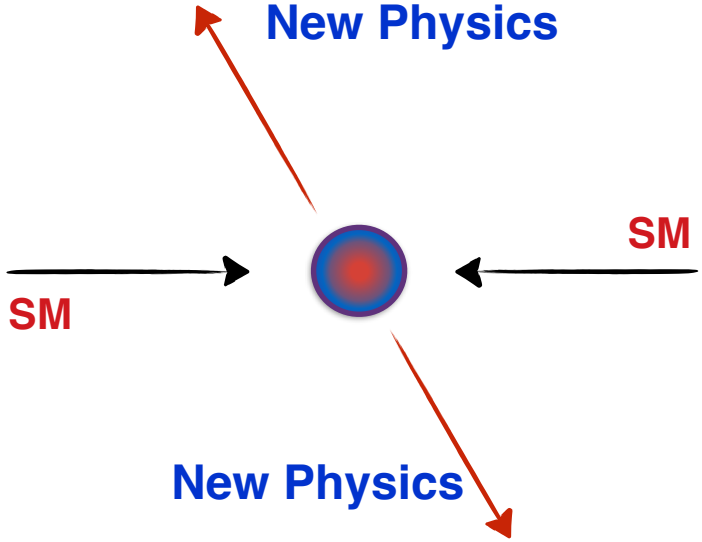
- Indirect searches for new physics
  - Looking at the known to find the unknown
  - Precisely study predicted SM process to look for any deviation from expectation
  - Searches in the B-flavour field are a nice example of such kind of searches

Results from direct searches

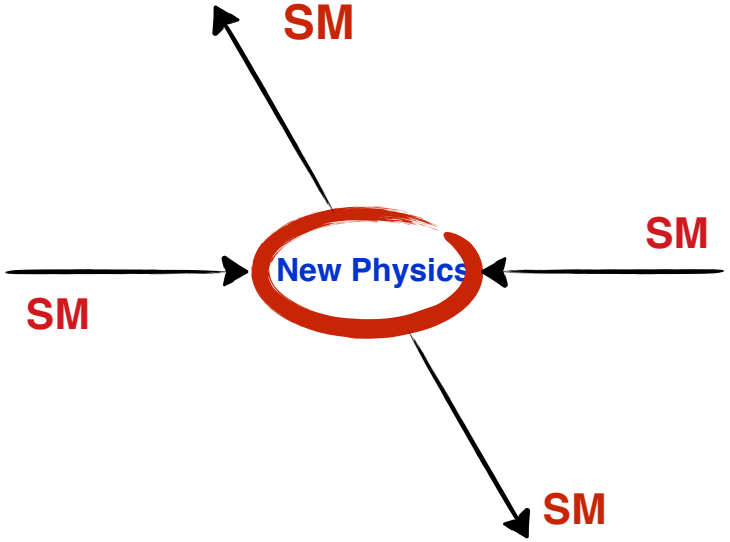


0.1 TeV 1 TeV 10 TeV

Direct vs Indirect search

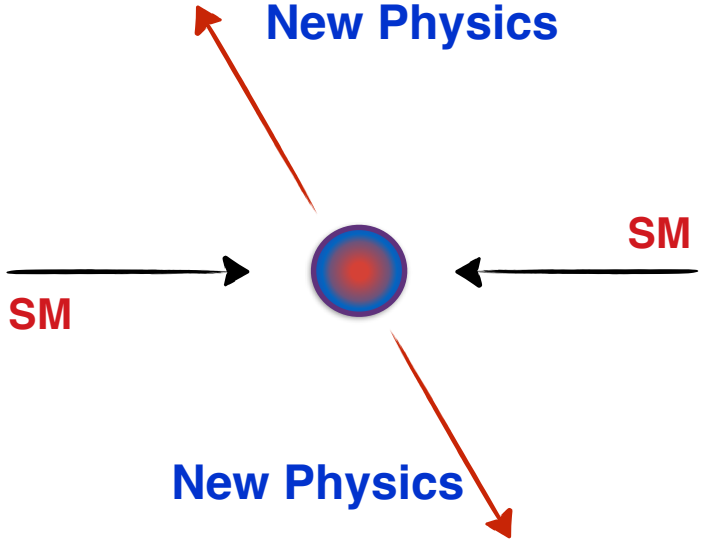


- Search for decay products of new heavy states produced directly in particle collisions

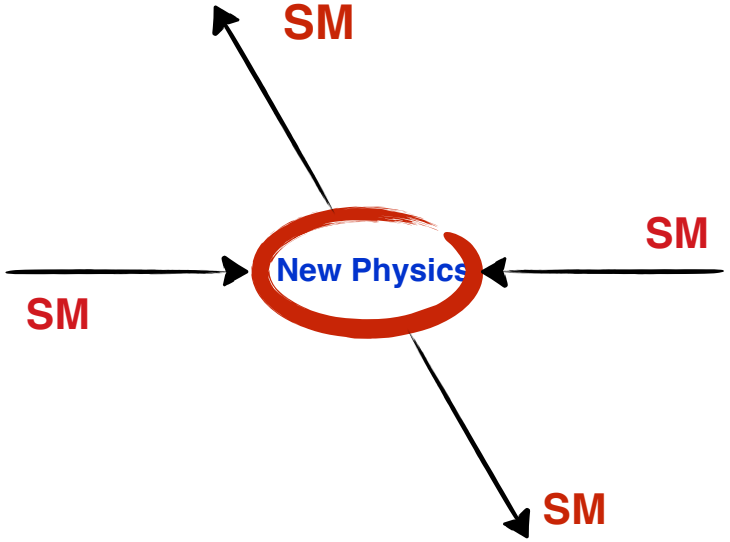


- Search for indirect effects of New Physics (NP) SM processes

Direct vs Indirect search



- Search for decay products of new heavy states produced directly in particle collisions
- Accessible scale limited by collision centre-of-mass energy (cme)



- Search for indirect effects of New Physics (NP) SM processes
- Can probe mass scales much higher that the cme due to virtual contributions

Searching for indirect effects of NP

or how to look at the known to find the unknown

Decay rates of rare processes

- SM processes suppressed at tree level have low probability. Their rate is sensitive to contributions from NP appearing in loop diagrams and can be significantly enhanced or further suppressed wrt SM prediction.

Ratios of decay rates

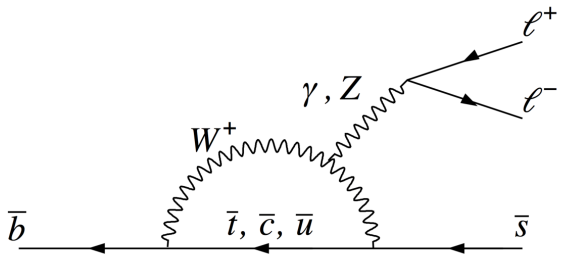
- The cleanest observables are ratios of observables. Most theoretical and systematics uncertainties cancel out leaving clean observables that can signal unexpected effects.

Particle or decay properties

- Charge or charge-parity asymmetries, angular distributions, lifetimes, etc…

Semileptonic B decays

Neutral currents

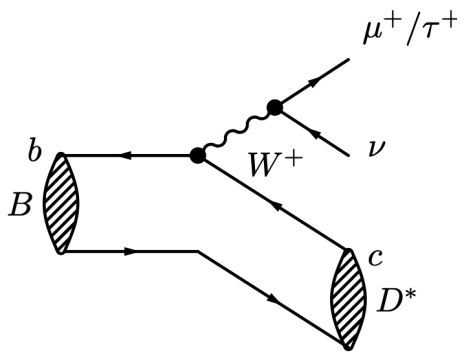


Forbidden at tree level,
rare processes

Low branching ratios, O(10^{-6})

NP sensitivity **up to about 50 TeV**

Charged currents



Can proceed via tree level

Large branching ratios, O(%)

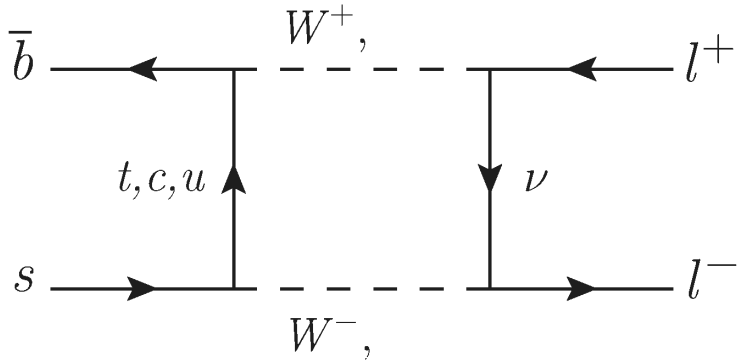
NP sensitivity **up to about 1 TeV**

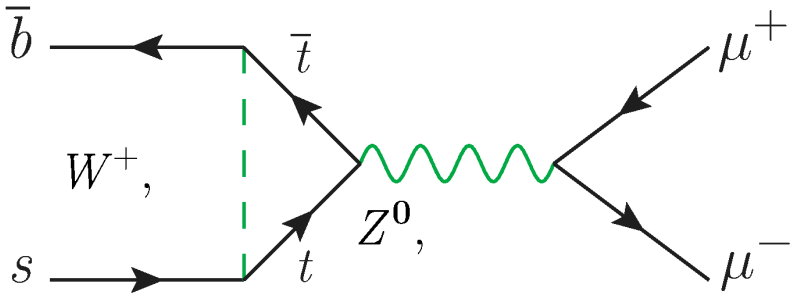
Rare decays: $B_s^0/B^0 \rightarrow \mu^+\mu^-$

B^0_s and B^0 into $\ell^+\ell^-$ are forbidden at tree level and proceed via higher order diagrams (through Flavour Changing Neutral Currents, FCNC). They are also CKM and helicity suppressed

High precision calculations, low theoretical uncertainties:

- $BR(B_s^0 \rightarrow \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
- $BR(B^0 \rightarrow \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$

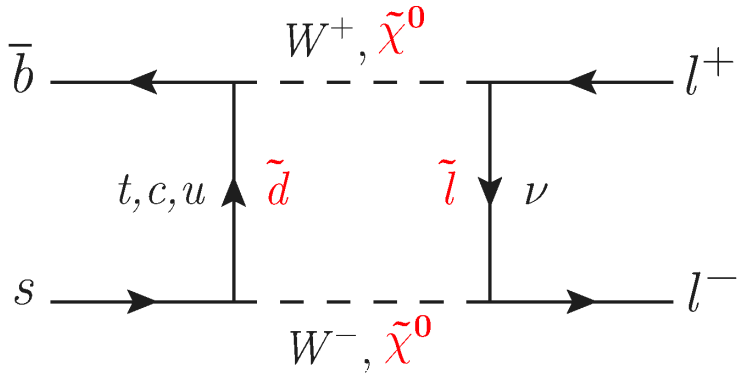


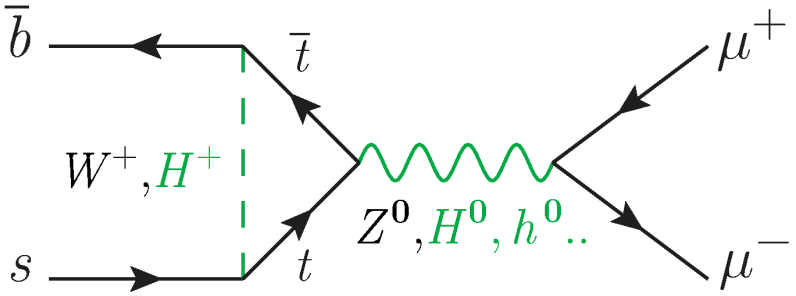


Rare decays: $B_s^0/B^0 \rightarrow \mu^+\mu^-$

B^0_s and B^0 into $\ell^+\ell^-$ proceed are forbidden at tree level and proceed via higher order diagrams (through Flavour Changing Neutral Currents, FCNC). They are also CKM and helicity suppressed

New Physics may pop up in these loops and manifest through an enhancement or a further suppression of predicted SM rates





Rare decays: $B_s^0/B^0 \to \mu^+\mu^-$

BR is measured as relative to a well-known normalisation channel ($B^+ \to J/\psi K^+$) in order to reduce the systematic uncertainties

$$BR(B_s^0 \to \mu^+\mu^-) = \frac{N_{obs}^{B_s^0}}{N_{obs}^{B^+}} \frac{\epsilon^{B^+}}{\epsilon^{B^0}} \frac{f_u}{f_s} BR(B^+ \to J/\psi K^+) BR(J/\psi \to \mu^+\mu^-)$$

Number of reconstructed B^0 and B^+ decays

Reconstruction efficiencies (from simulation)

Correction for the different hadronisation probabilities for B^+ and B^0

$f_s/f_u = 0.252 \pm 0.12 \pm 0.15$

Branching ratio of the normalisation sample

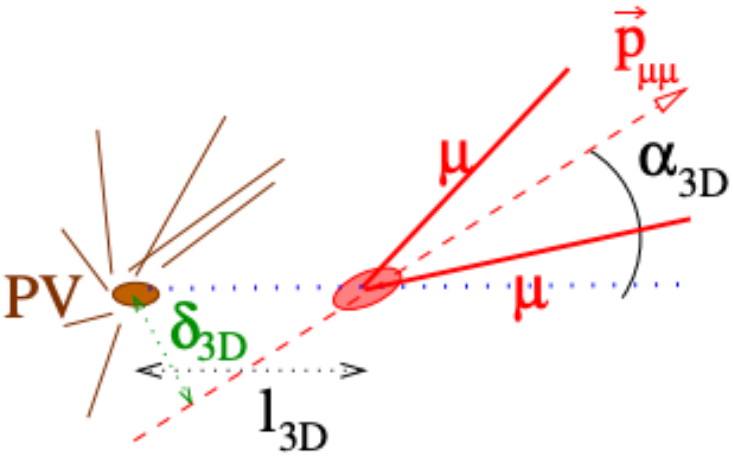
$BR(B^+ \to J/\psi K^+) = (1.01 \pm 0.03) \times 10^{-3}$

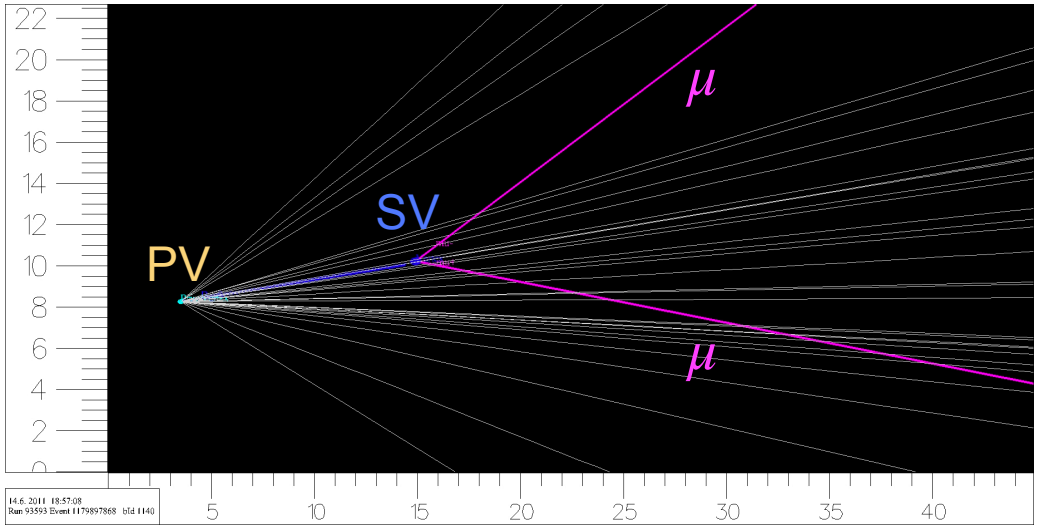
$BR(J/\psi \to \mu^+\mu^-) = (5.96 \pm 0.03) \times 10^{-2}$

$B_s^0/B^0 \to \mu^+\mu^-$: signal

Signal identikit

- Two, oppositely charged, isolated muons from one, well reconstructed decay vertex
- Momentum aligned with flight direction (PV-SV direction)
- Isolated B candidate (no other tracks reconstructed nearby)
- Mass compatible with $m_{B_s^0}$ $(5.3 < m_{\mu^+\mu^-} < 5.45\ GeV)$





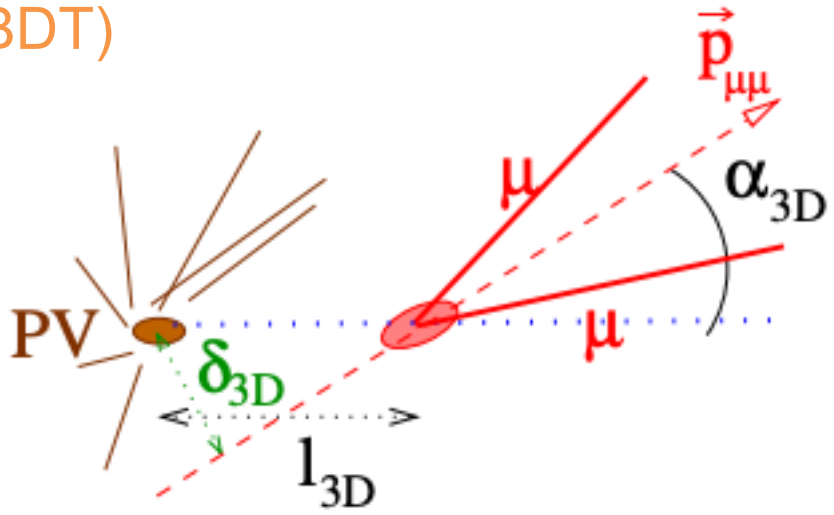
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Discriminating variables (input to a BDT)

- Flight length significance (ℓ_{3D}/σ_ℓ)
- Angle α between dimuon momentum and PV-SV direction
- Impact parameters of the B candidate (δ_{3D}) and its significance δ_{3D}/σ
- Decay time



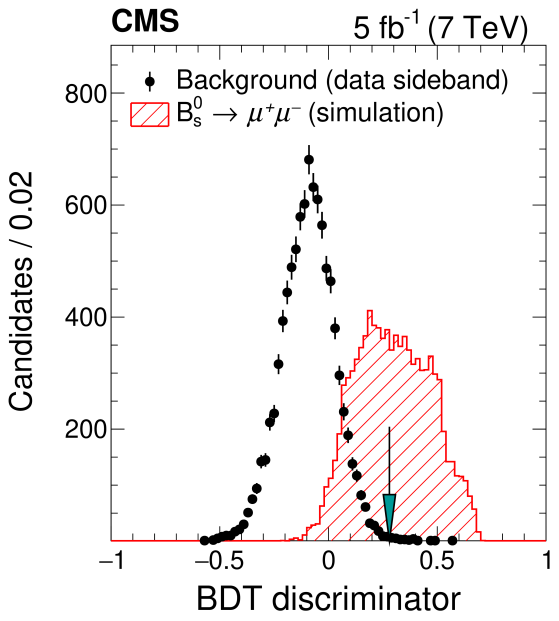
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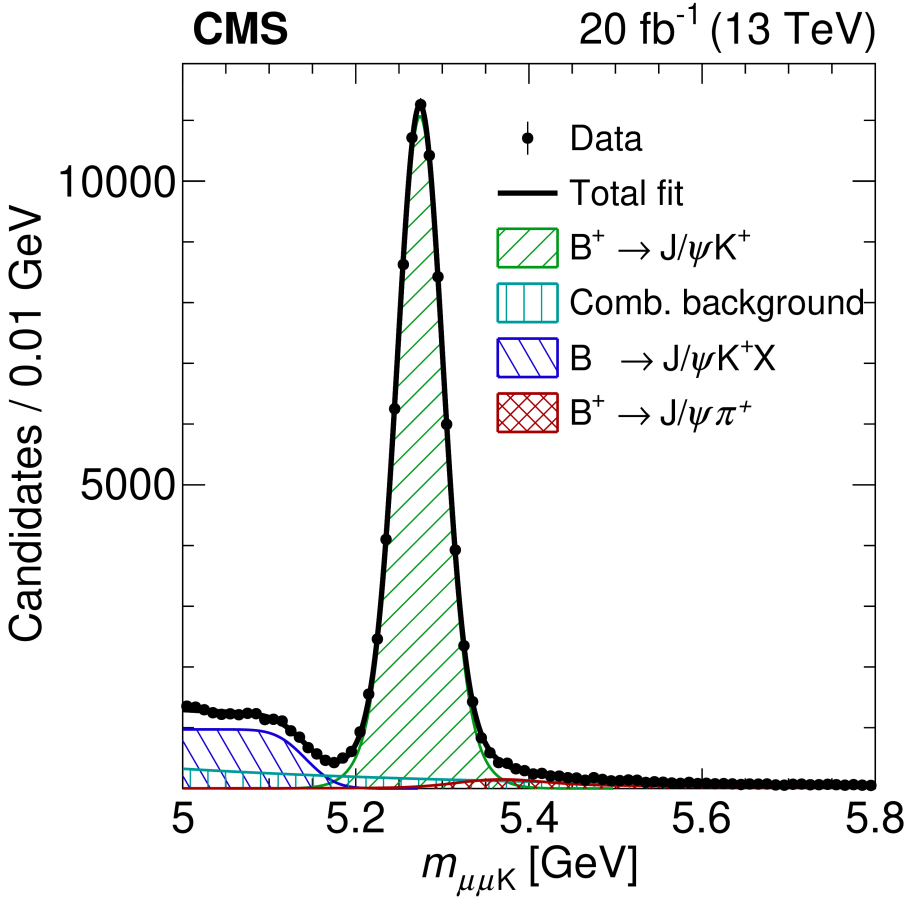
- Flight length significance (ℓ_{3D}/σ_ℓ)
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- Impact parameters of the B candidate (δ_{3D}) and its significance δ_{3D}/σ
- Decay time



Normalization yield extraction

The normalisation sample is selected similarly to the signal by requiring an additional track, assumed to be a kaon

B candidate yields in normalisation sample determined with a binned maximum likelihood fit to the $m_{\mu\mu k}$ spectrum



Signal extraction

Unbinned maximum likelihood fit for B_s^0 and B^0 simultaneously
Combinatorial background extrapolated from the sidebands

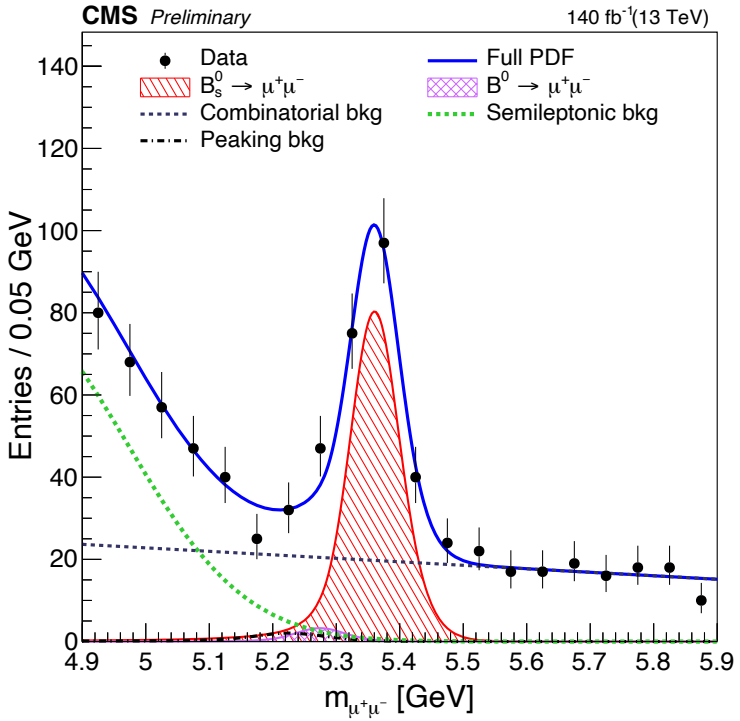
$$\mathcal{B}(\mathrm{B}_\mathrm{s}^0 \to \mu^+\mu^-) = \left[3.95^{+0.39}_{-0.37}\,(\mathrm{stat})\,^{+0.27}_{-0.22}\,(\mathrm{syst})\,^{+0.21}_{-0.19}\,(\mathrm{BF})\right] \times 10^{-9}$$

12.5 σ

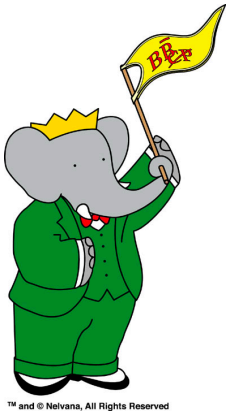
$$BR(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\,\%$$

Expectations:

- $BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$



Collider experiments as a flavour-probe



BaBar and Belle

- $e^+(3.1\ GeV)e^-(9\ GeV)$ collider experiments
  - cme 10.58 GeV
- Collected data at the Y(4S) resonance decaying to $B\bar{B}$ and $B^0\bar{B}^0$
- Clean environment: low background and well constrained kinematics
- BaBar collected 433 fb^-1 up to 2008
- Belle collected 711 fb-1 up to 2010
- Belle 2 started collecting data in 2019 and plans to keep going until at least 2032

LHCb

- p-p collider experiment
- B^+, B^0, B_s^0, B_c^+ and Λ_b^0 hadrons produced
- Large amount of b hadrons and background
- B hadrons strongly boosted, excellent separation between production and decay vertices
- Collected 3 fb-1 at $\sqrt{s} = 7 - 8$ TeV and 6 fb-1 at $\sqrt{s} = 13$ TeV
- In recent years, CMS has become competitive in some specific channels (mainly with muons)

Lepton Flavour Universality

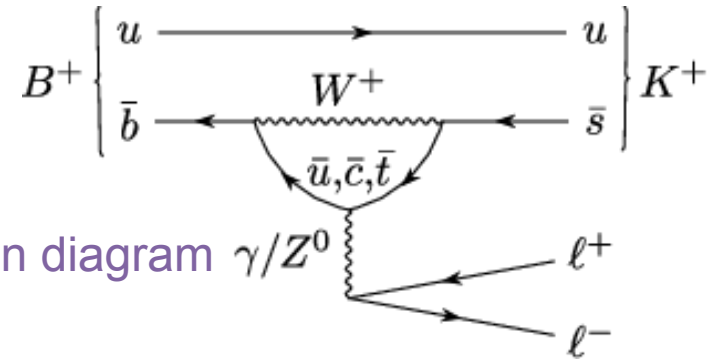
- Lepton Flavour Universality (LFU): universality of interactions for leptons of different generations
  - LFU violation implies presence of new physics: new fundamental interactions between quarks and leptons (e.g. Z' or leptoquarks, LQs)
- LPU tested at e^+e^- collider experiments (BaBar and Belle) and at the LHC (LHCb)
  - In FCNC and in semileptonic B decays
- LFU tests are a clean way to probe B decays
  - Comparing decays to different leptons we can reduce theory uncertainties
  - Allow to verify LFU

Testing LFU in $B \to K^{(*)}\ell\ell$

$B \to K^{(*)}\ell\ell$ are FCNC decays, proceeding via EWK loop diagrams and highly suppressed in the SM

- Expected BRs less than 10^{-6}

$\bar{b} \to \bar{s}$ transition



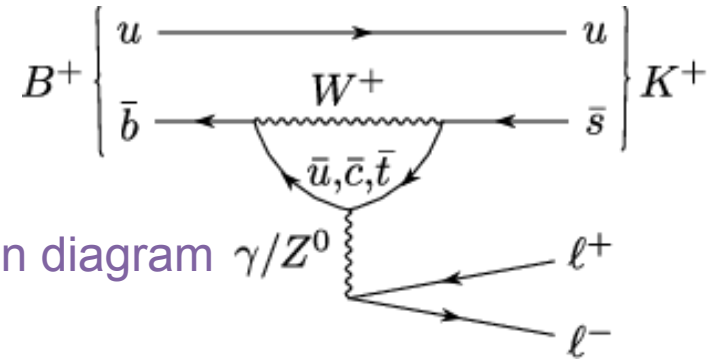
Penguin diagram

Testing LFU in $B \to K^{(*)}\ell\ell$

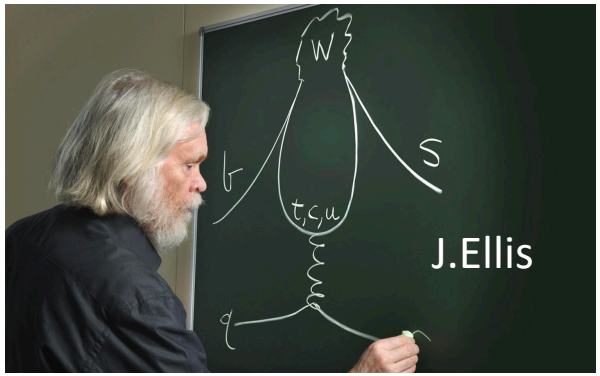
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Penguin diagram



Two physicists walk into a bar and start playing a game of darts. One turns to the other and says, “Let’s make a bet. If you lose this game, you have to use the word ‘penguin’ in your next paper.”

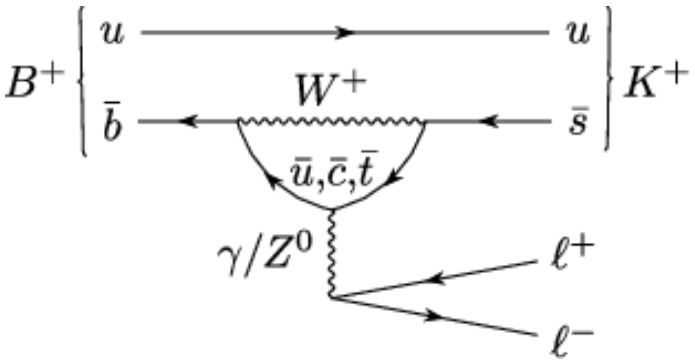
Symmetry Magazine

Testing LFU in $B \to K^{(*)}\ell\ell$

$B \to K^{(*)}\ell\ell$ are FCNC decays, proceeding via EWK loop diagrams and highly suppressed in the SM

- Expected BRs less than 10^{-6}

$\bar{b} \to \bar{s}$ transition



Less rare than $B_s^0 \to \mu^+\mu^-$

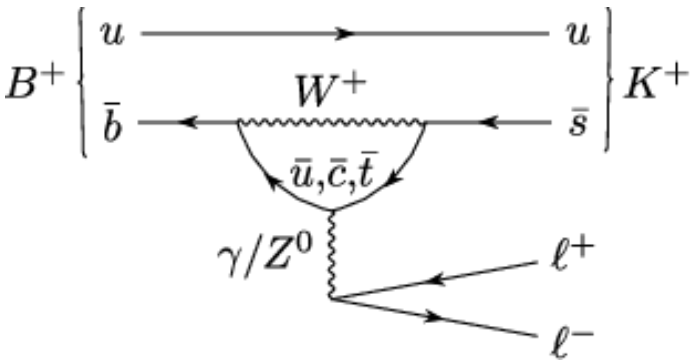
$$BR(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

Testing LFU in $B \to K^{(*)}\ell\ell$

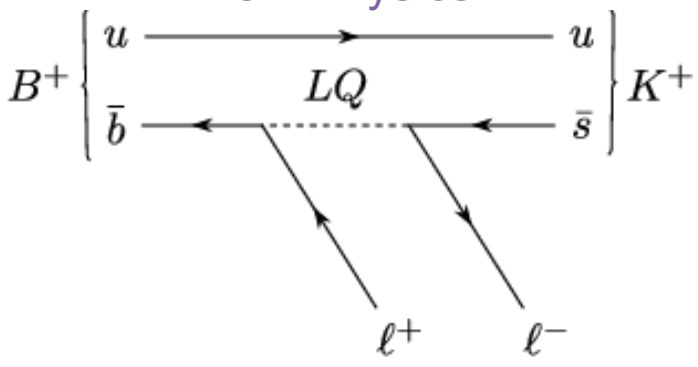
$B \to K^{(*)}\ell\ell$ are FCNC decays, proceeding via EWK loop diagrams and highly suppressed in the SM

- Expected BRs less than 10^{-6}
- New Physics can compete with the SM decay amplitude

$\bar{b} \to \bar{s}$ transition



New Physics



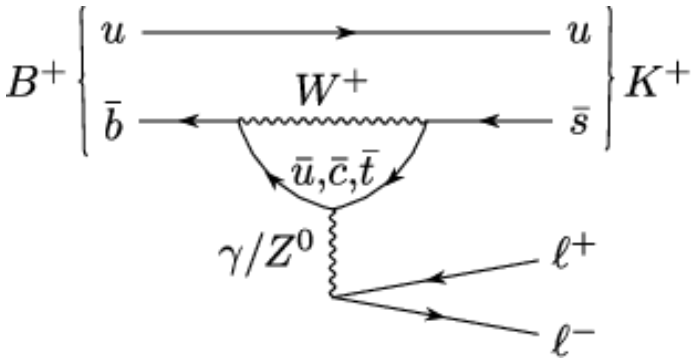
Testing LFU in $B \to K^{(*)}\ell\ell$

$B \to K^{(*)}\ell\ell$ are FCNC decays, proceeding via EWK loop diagrams and highly suppressed in the SM

- Ratio between decay muon and electron final state channels are predicted with O(1%) precision

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

$\bar{b} \to \bar{s}$ transition



Expected to be 1 in SM

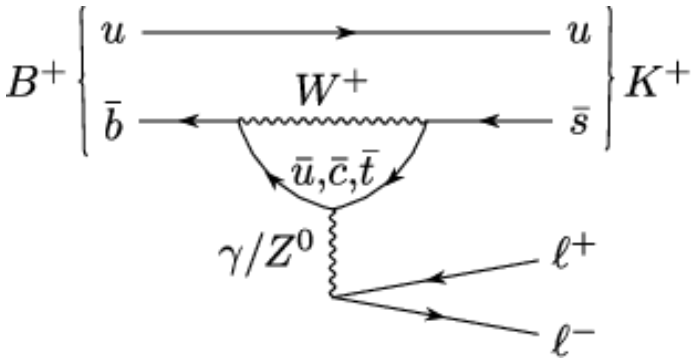
Testing LFU in $B \to K^{(*)}\ell\ell$

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

$\bar{b} \to \bar{s}$ transition



Signature: pair of tracks from opposite charged leptons originated from a common vertex displaced wrt the p-p interaction point, plus an additional track from the kaon

Testing LFU in $B \to K^{(*)}\ell\ell$

Main challenge: reduce systematic uncertainties induced by different interaction of muons and electrons with the detector

- $R_{K^{(*)}}$ is computed with respect to the resonant decays of the B mesons

Non resonant

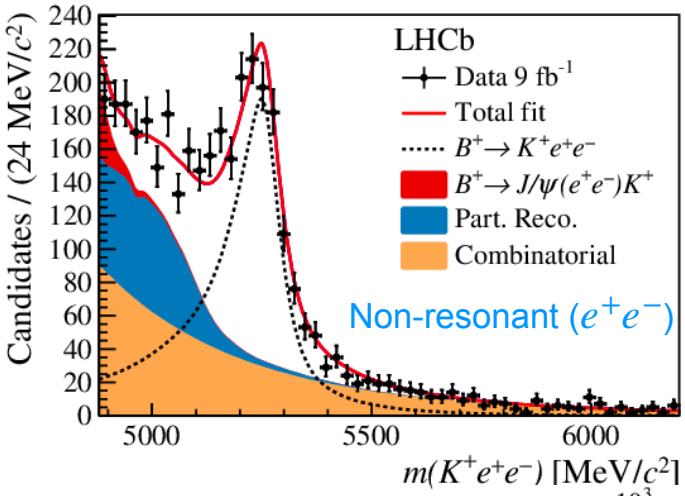
$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{BR(B \to K^{(*)}e^+e^-)}{BR(B \to K^+ J/\psi(e^+e^-))}$$

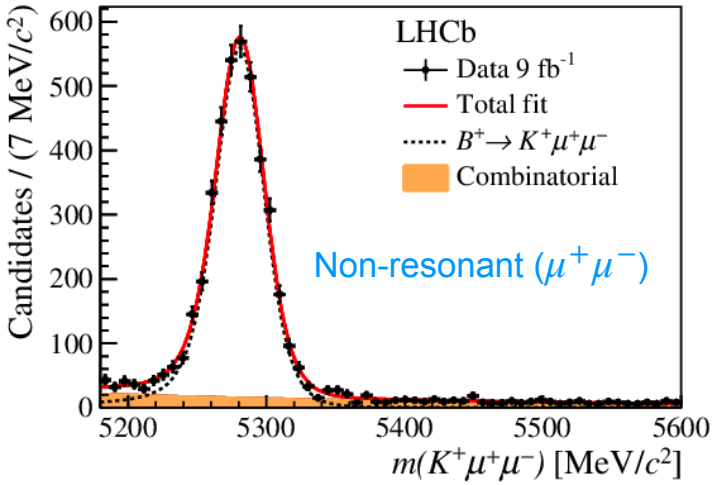
Resonant

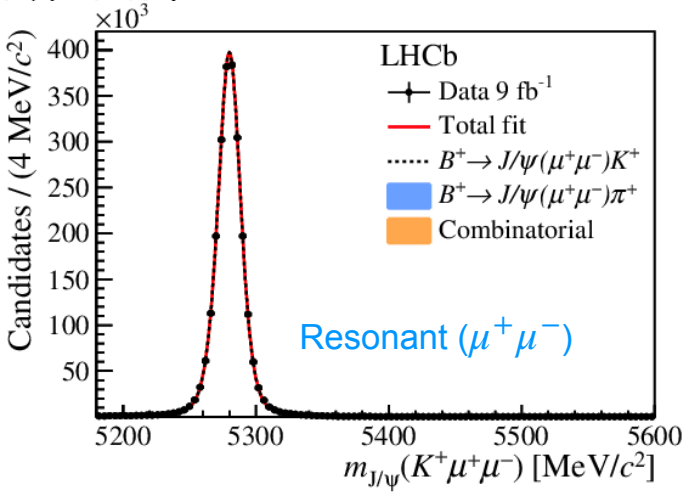
Similar reconstruction of rare channel and resonant one

Testing LFU in $B \to K^{(*)}\ell\ell$

Signal yields extracted via a unbinned extended maximum likelihood fit to the invariant mass $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$

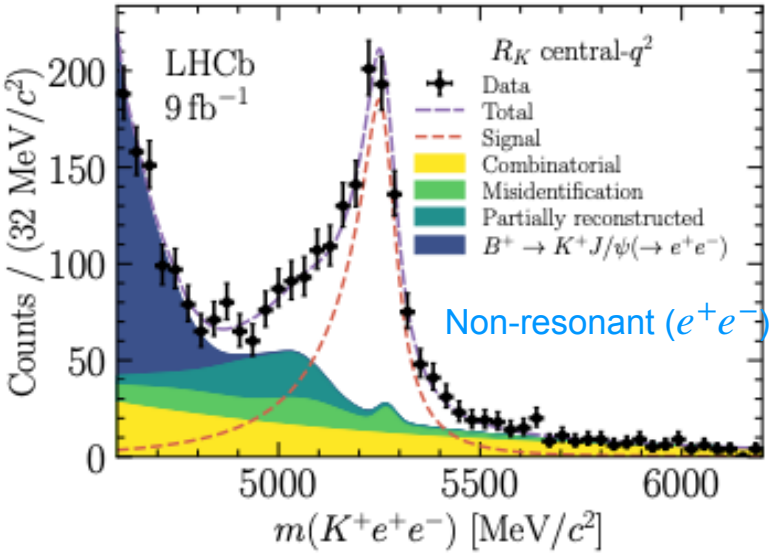






Testing LFU in $B \to K^{(*)}\ell\ell$

Signal yields extracted via an unbinned extended maximum likelihood fit to the invariant mass $m(K^+\mu^+\mu^-)$ and $m(K^+e^+e^-)$



$$R_K = 0.994^{+0.090}_{-0.082}(\text{stat})^{+0.029}_{-0.027}(\text{syst})$$

$0.1 < q^2 < 1.1$ GeV$^2c^4$

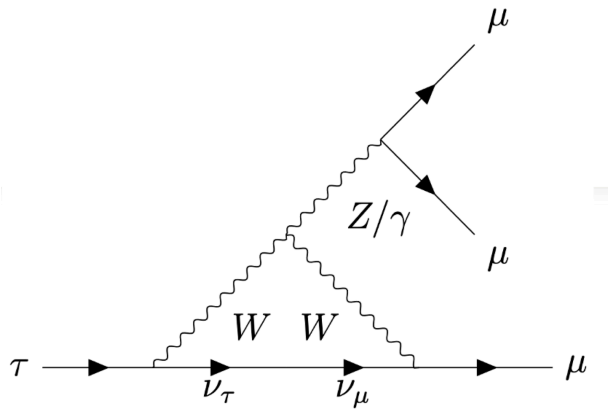
$$R_K = 0.949^{+0.042}_{-0.041}(\text{stat})^{+0.022}_{-0.022}(\text{syst})$$

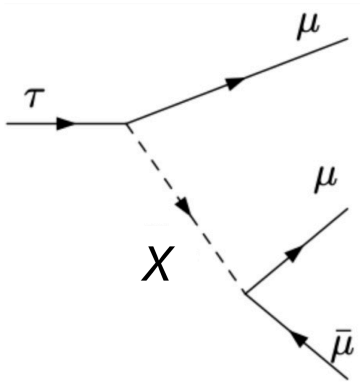
$1.1 < q^2 < 6.0$ GeV$^2c^4$

Consistent with the SM prediction

Search for LVF $\tau \rightarrow 3\mu$ decay

- Test “accidental” conservation of per-family lepton number in SM





Allowed in the SM via neutrino oscillations, but vanishingly small BR

$$BR(\tau \rightarrow 3\mu) \sim 10^{-55}$$

Enhanced in many BSM scenarios by many orders of magnitude

$$BR_{BSM}(\tau \rightarrow 3\mu) \sim 10^{-10} - 10^{-8}$$

Search for LVF $\tau \rightarrow 3\mu$ decay

- An example where CMS/ATLAS can be competitive with Belle II/ BaBar/LHCb in the flavour space

Compared to LHCb:
- cannot discern different charged hadrons from each other effectively
+ much higher luminosity, excellent muon momentum resolution

Compared to Belle/BaBar:
- cannot discern different charged hadrons from each other effectively
- more polluted collision environment
+ additional source of τ leptons from W boson decays (higher cme)

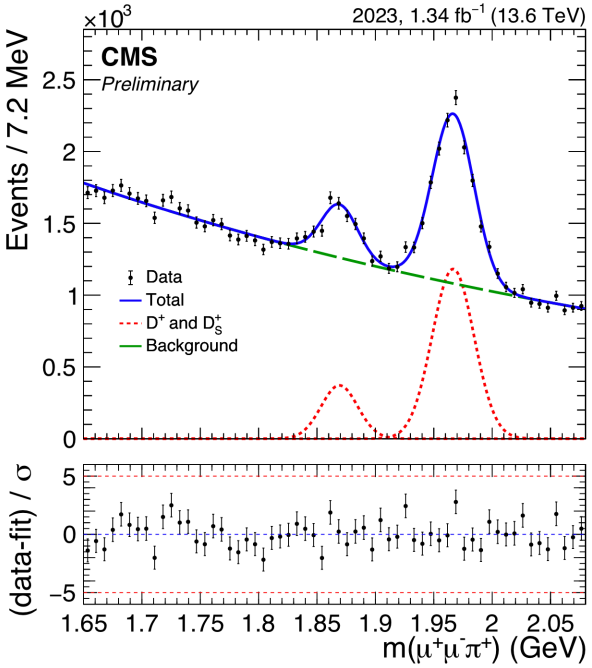
- At CMS/ATLAS, 99.99% of τ leptons come from B and D mesons, 0.01% from W decays
- W much cleaner (higher momentum, missing energy)
- The two channels end up being competitive in sensitivity

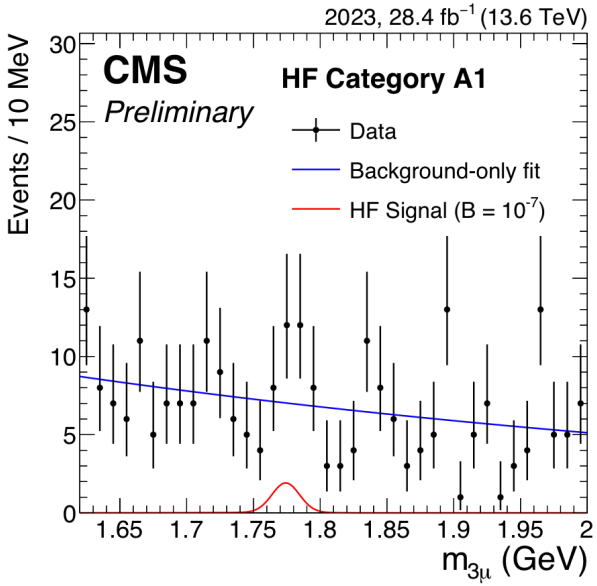
Search for LVF $\tau \to 3\mu$ decay

- B/D decays to 2 muons and a pion as normalising channel

$$N_{3\mu(\mathrm{D})} = N_{\mu\mu\pi} \frac{\mathcal{A}_{3\mu(\mathrm{D})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{D})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{D})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \times \frac{\mathcal{B}(\mathrm{D}_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(\mathrm{D}_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \mathcal{B}(\tau \to 3\mu),$$

$$N_{3\mu(\mathrm{B})} = N_{\mu\mu\pi}\, f\, \frac{\mathcal{A}_{3\mu(\mathrm{B})}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\mathrm{reco}}_{3\mu(\mathrm{B})}}{\epsilon^{\mathrm{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\mathrm{trig}}_{3\mu(\mathrm{B})}}{\epsilon^{2\mu\mathrm{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu) \times \frac{\mathcal{B}(\mathrm{B} \to \tau + \mathrm{X})}{\mathcal{B}(\mathrm{B} \to \mathrm{D}_s^+ + \mathrm{X})\mathcal{B}(\mathrm{D}_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)},$$





Search for LVF $\tau \rightarrow 3\mu$ decay

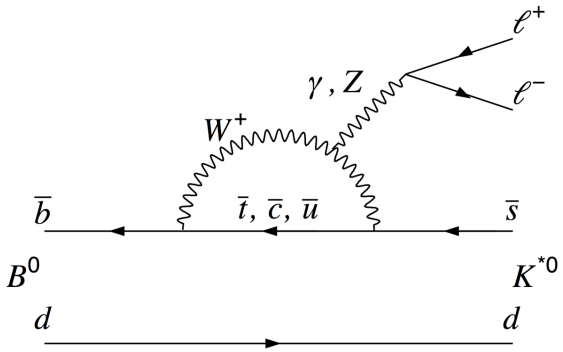
- In the end, all experiments are quite competitive:

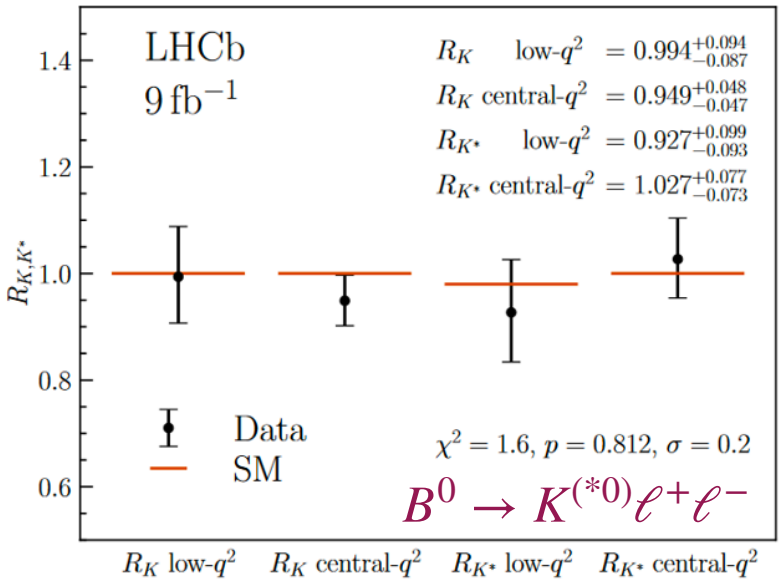
Year	Collab.	Process	Exp. UL *	Obs. UL *
2010	Belle	$ee \rightarrow \tau\tau$	-	2.1
2010	BaBar	$ee \rightarrow \tau\tau$	4.0	3.3
2024	CMS	B/D and W	2.4	2.9
2024	**Belle II**	$ee \rightarrow \tau\tau$	**1.8**	**1.9**
2026	**LHCb**	$D/B \rightarrow \tau X$	**2.0**	**1.9**
2026	ATLAS	B/D and W	7.5	8.7

* $\times 10^{-8}$ @ 90% C.L.

Additional measurements

Measurements testing LFU in FCNC decays are carried out at collider experiments, still all statistically limited





$$R_{K^{*0}} = 0.927^{+0.093}_{-0.087}(\text{stat})^{+0.034}_{-0.033}(\text{syst})$$

$0.1 < q^2 < 1.1$ GeV$^2c^4$

$$R_{K^{*0}} = 1.027^{+0.072}_{-0.068}(\text{stat})^{+0.027}_{-0.027}(\text{syst})$$

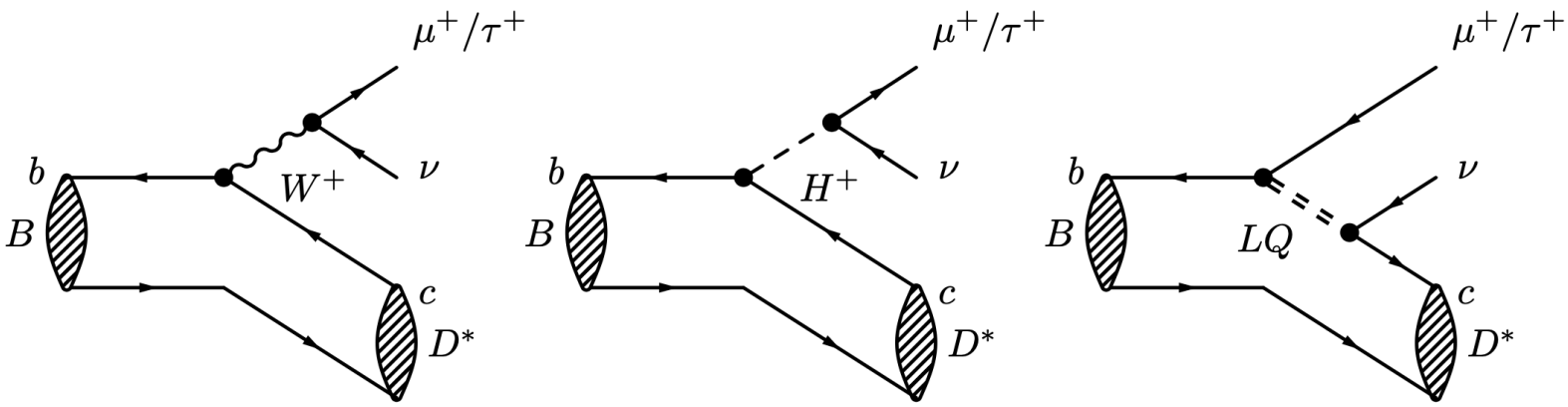
$1.1 < q^2 < 6.0$ GeV$^2c^4$

Testing LFU in $b \to c\tau\nu_\tau$

Phys. Rev. Lett. 115 (2015) 111803

Testing LFU in charged current B decays

- Larger rates enable probing decays to tauonic final states
- Possible to probe coupling to 3rd generation leptons



Testing LFU in $b \to c\tau\nu_\tau$

Phys. Rev. Lett. 115 (2015) 111803

Testing LFU in charged current B decays

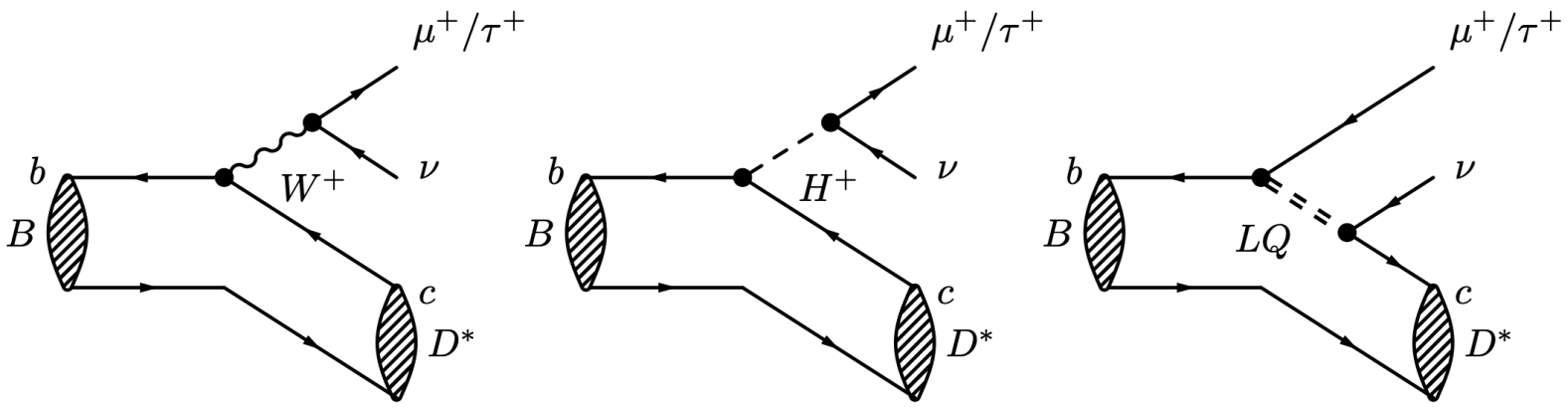
- Larger rates enable probing decays to tauonic final states
- Possible to probe coupling to 3rd generation leptons

$$R_{H_c} = \frac{BR(H_b \to H_c \tau \nu_\tau)}{BR(H_b \to H_c \ell \nu_\ell)}$$

Signal channel

Normalization channel

Cancellation of some systematic uncertainties in the ratio



Testing LFU in $b \to c\tau\nu_\tau$

Phys. Rev. Lett. 115 (2015) 111803

Testing LFU in charged current B decays

- Larger rates enable probing decays to tauonic final states
- Possible to probe coupling to 3rd generation leptons

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

$\tau \to \mu\nu_\mu\nu_\tau$

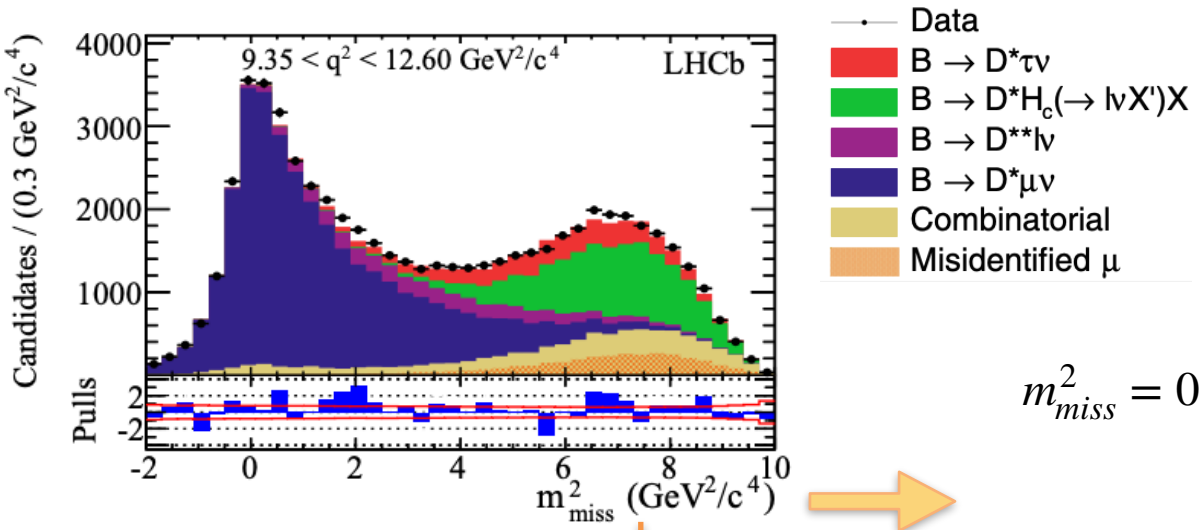
$D^* \to D^0(\to K\pi)\pi$

Final states:
3 charged tracks plus a muon

2 additional neutrinos in the signal

Testing LFU in $b \to c\tau\nu_\tau$

- 3D fit to kinematic variables to separate muonic and tauonic modes
  - missing mass squared, m^2_{miss}, muon energy, E^*_μ, and the square of the four momentum transferred to the lepton system, q^2



$$m^2_{miss} = 0$$ Normalization channel

$$m^2_{miss} \neq 0$$ Signal channel

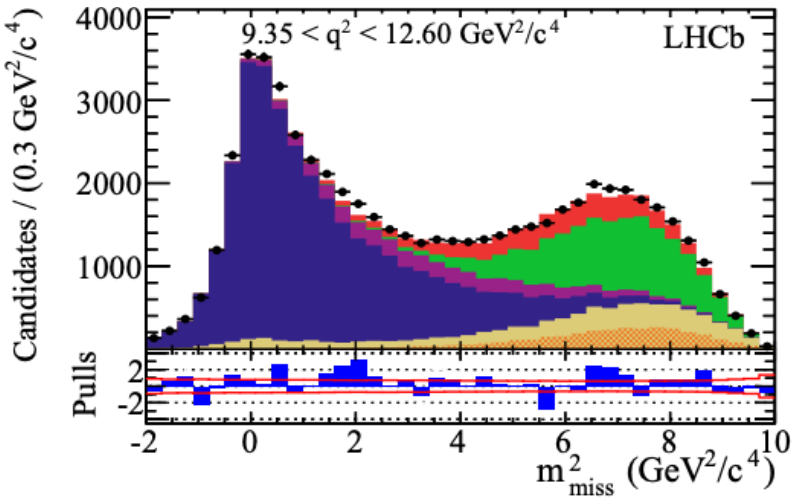
$$m^2_{miss} = (p^2_B - p^2_D - p^2_\mu)$$

Testing LFU in $b \to c\tau\nu_\tau$

- 3D fit to kinematic variables to separate muonic and tauonic modes
  - missing mass squared, m^2_{miss}, muon energy, E^*_μ, and the square of the four momentum transferred to the lepton system, q^2

- $R_{D^*} = 0.281 \pm 0.018(\text{stat}) \pm 0.024(\text{syst})$ — 2.26 σ above SM expectation

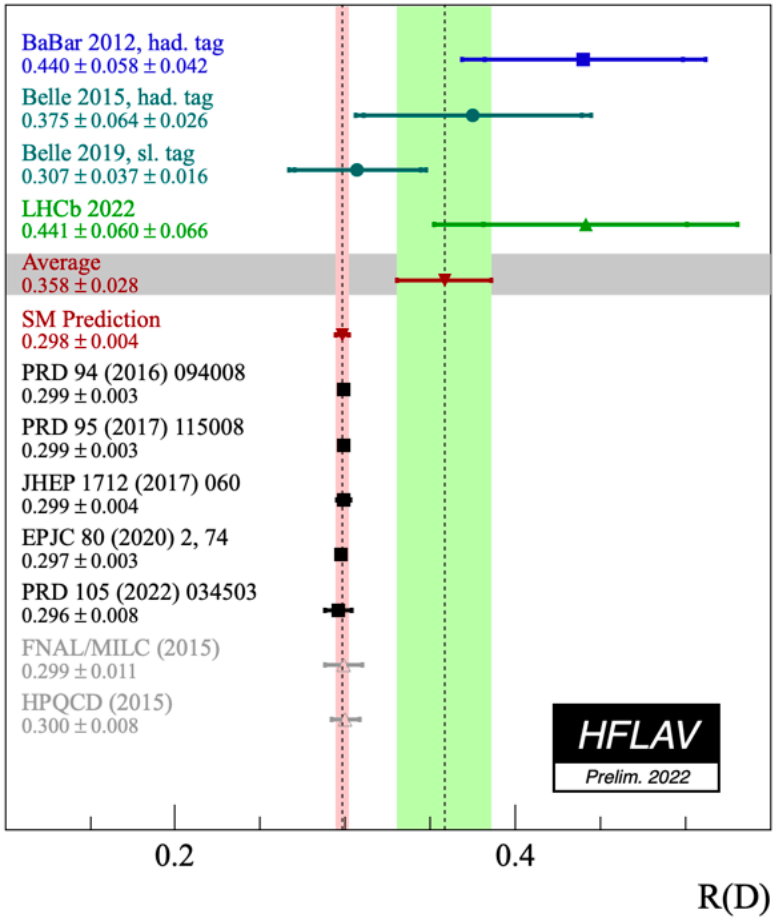
- $R_D = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$ — 2.16 σ above SM expectation

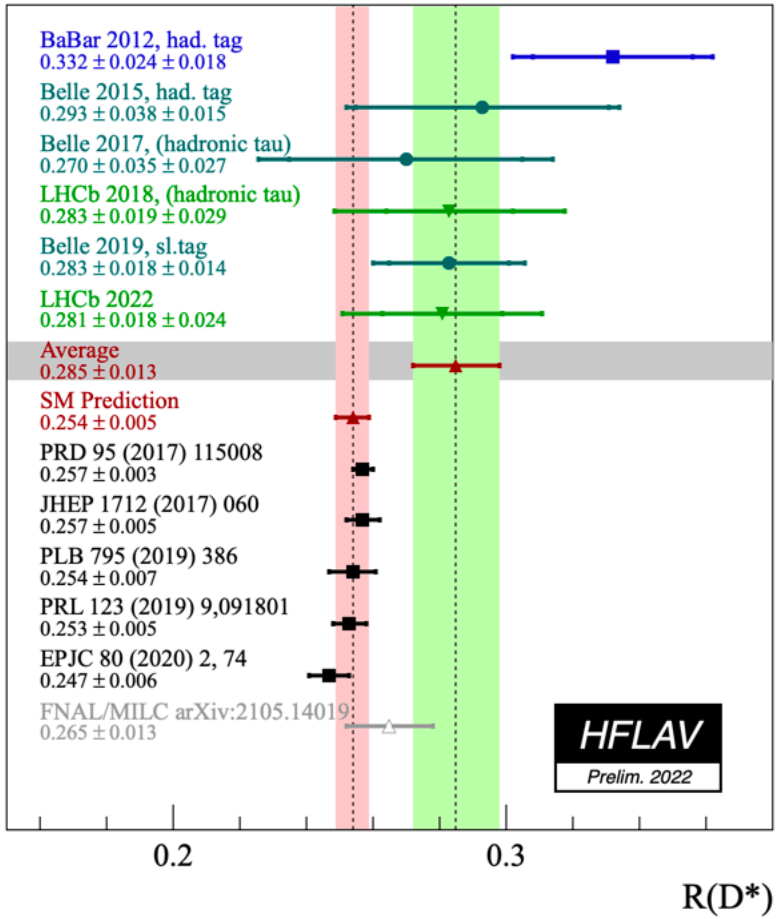


Largest contribution to the systematic uncertainty from limited size of the simulated samples

Results from other experiments

BaBar, Belle and LHCb experiments see an excess in the number of $B \to D^{(*)}\tau\nu_\tau$ candidates, though not statistically significant





$R_{J/\psi}$

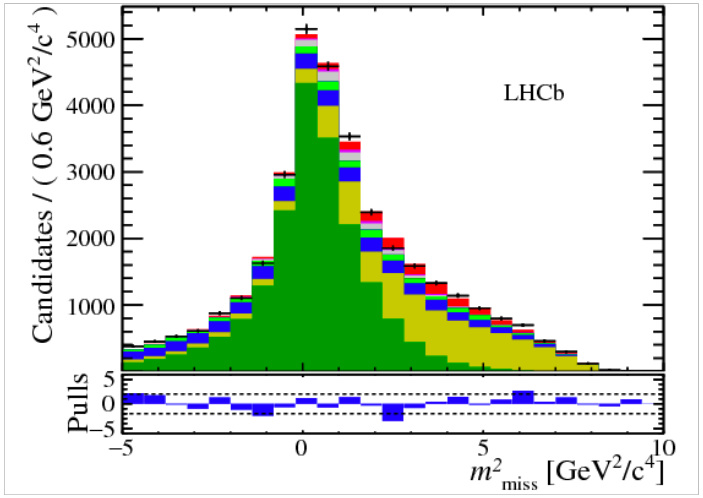
Phys. Rev. Lett. 120 (2018) 121801

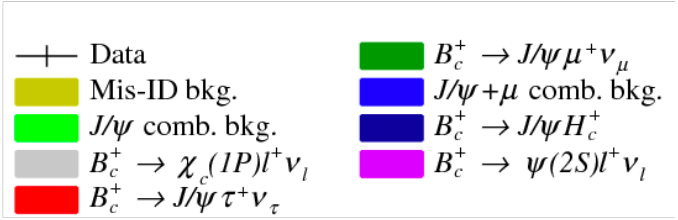
- Additional b-hadrons decay channels with semitauonic decays are studied
  - helps understanding sources of theoretical and experimental uncertainties

$$R_{J/\psi} = \frac{BR(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

$\tau \to \mu \nu_\mu \nu_\tau$

$J/\psi \to \mu^+ \mu^-$





$R_{J/\psi}$

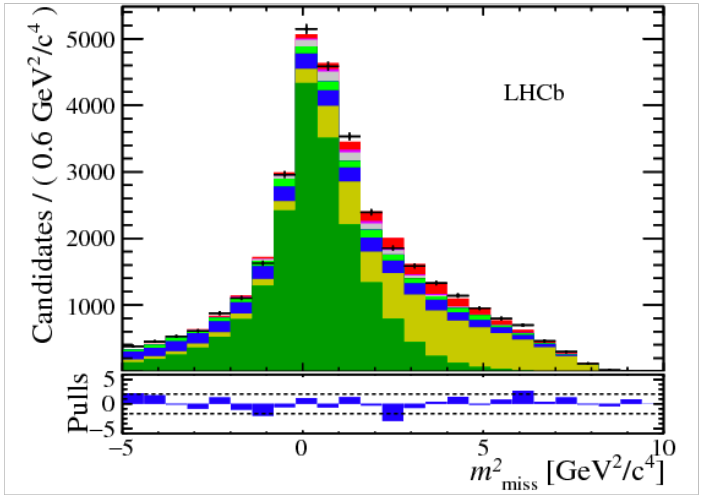
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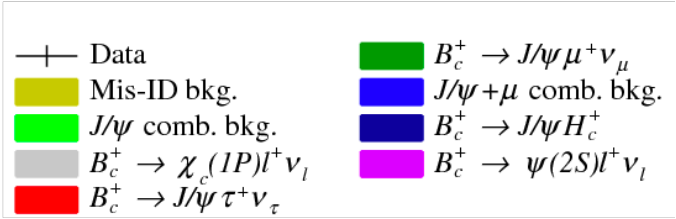
- Additional b-hadrons decay channels with semitauonic decays are studied
  - helps understanding sources of theoretical and experimental uncertainties

$$R_{J/\psi} = \frac{BR(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{BR(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

$\tau \to \mu \nu_\mu \nu_\tau$

$J/\psi \to \mu^+ \mu^-$





$$R_{J/\psi} = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

2 σ above SM expectation

Largest contribution to the systematic uncertainty from limited knowledge of the form factors

Summary

- Indirect searches enable NP probing at even higher scales that those reachable directly
- Analysis strategies differ from direct searches
  - Precise measurement of predicted SM processes
  - Focus on reducing systematic uncertainties
- A good example are measurements of charged and neutral current semi-leptonic B decays
  - Deviations from SM expectations might hint to Lepton Flavour Universality Violation

References

- LHCb Public Results
  - https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_all.html
- BaBar Public Results
  - https://www-public.slac.stanford.edu/babar/Publications.aspx
- Belle Public Results
  - https://belle.kek.jp/
- ATLAS Public Results
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- CMS Public Results
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO