Flavor experiments

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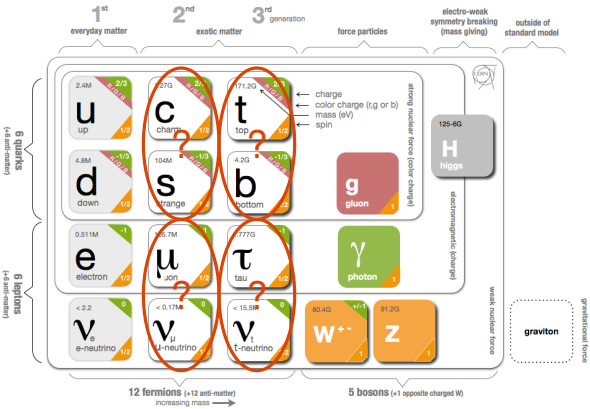
Fermilab–CERN Hadron Collider Physics Summer School
August 18, 2022

Introduction

- Why do particles have different flavors?
- Where is the new physics?
- Precision flavor measurements potentially hold the answer



What this talk

does

- Share some highlights of flavor measurements
- Connect them to experimental methods

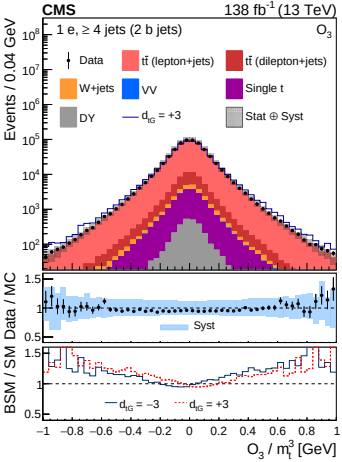
isn't

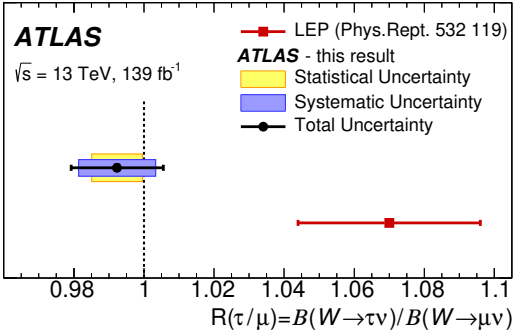
- comprehensive
- theoretically motivated (see Wolfgang's talk on Tuesday)

- Only time for a taste of the wide variety of flavor physics!

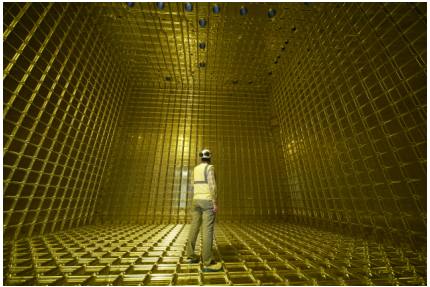
What counts as flavor?

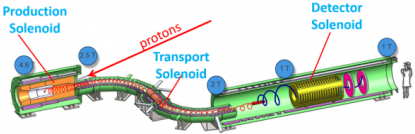
At colliders

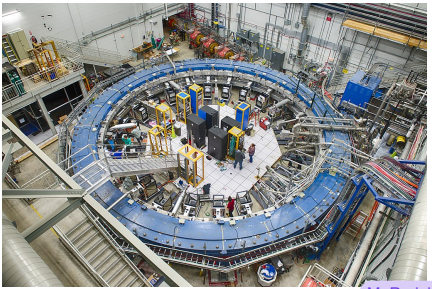




Beyond colliders



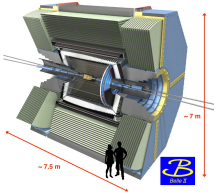


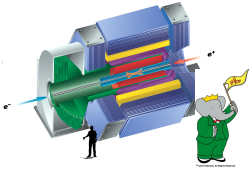


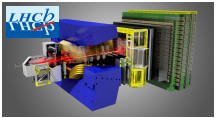
Heavy flavor

Heavy flavor experiments

- Will focus on “heavy flavor” (b and c only, sorry t)
- Many world best results from e^+e^- b-factories: BaBar and Belle
  - Belle II getting going now
- LHCb competing at a hadron collider







How many B?

Very rough estimation

LHCb

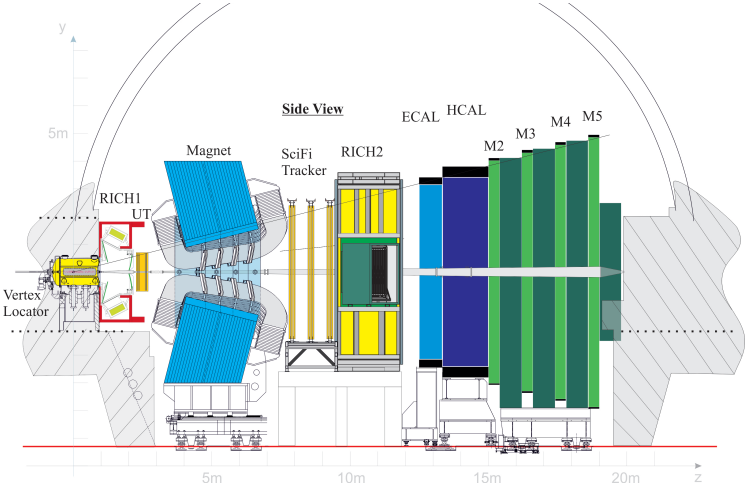
$$pp \to b\bar{b} + X$$

Belle

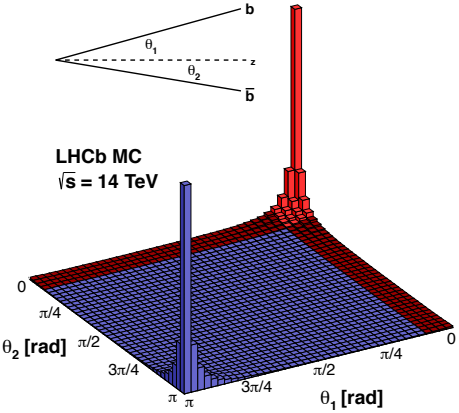
$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

	LHCb	Belle
Luminosity	$50\,\mathrm{fb}^{-1}$	$50\,\mathrm{ab}^{-1}$
$N(b\bar{b})$	$\mathcal{O}(10^{12})$	$\mathcal{O}(10^{10})$

LHCb layout

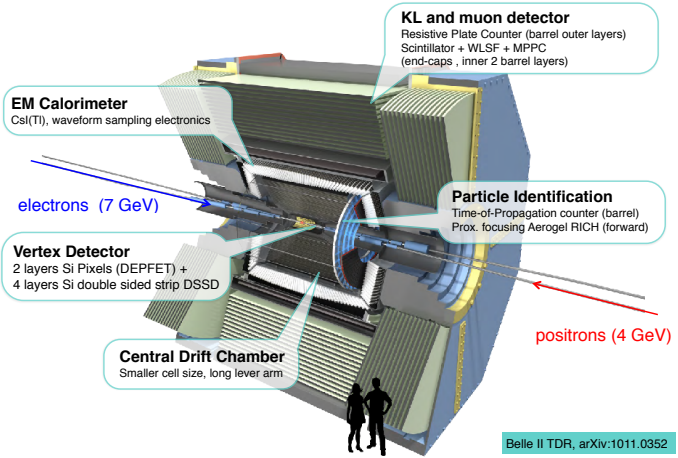

Side View
y
5m
Magnet
SciFi
Tracker
RICH2
ECAL
HCAL
M2
M3
M4
M5
RICH1
UT
Vertex
Locator
5m
10m
15m
20m
z

Why does it look like that?



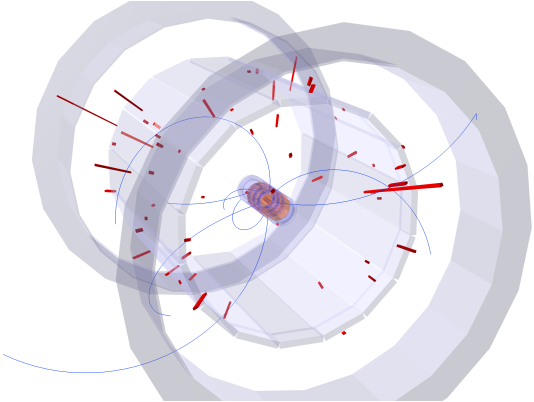
from C. Elsasser

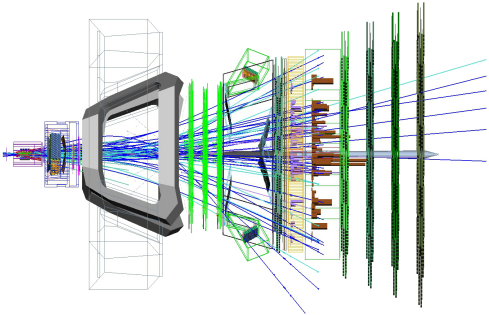
Belle II layout



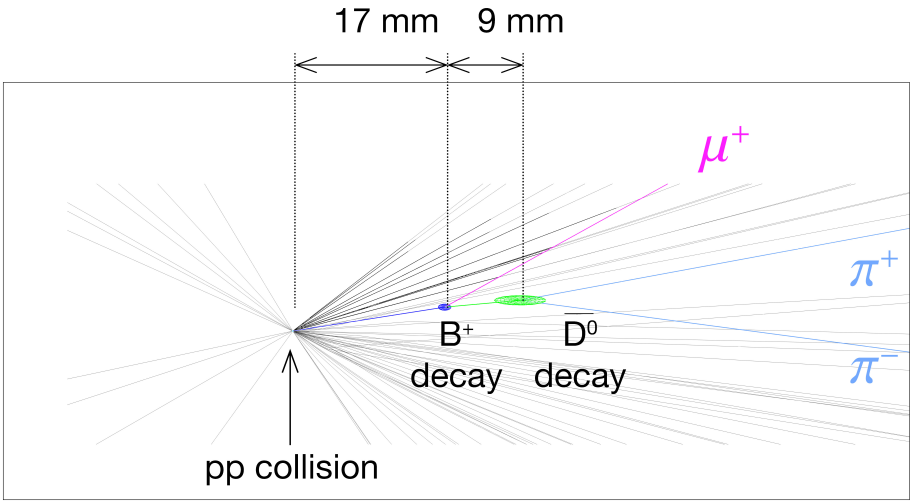
Belle II TDR, arXiv:1011.0352

Event comparison



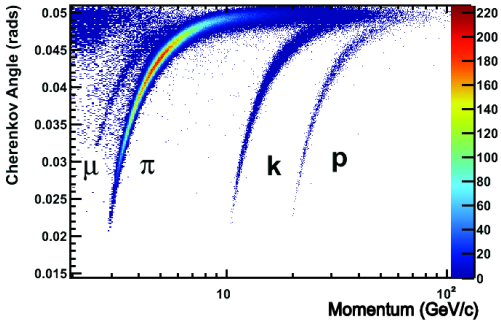


LHCb vertexing

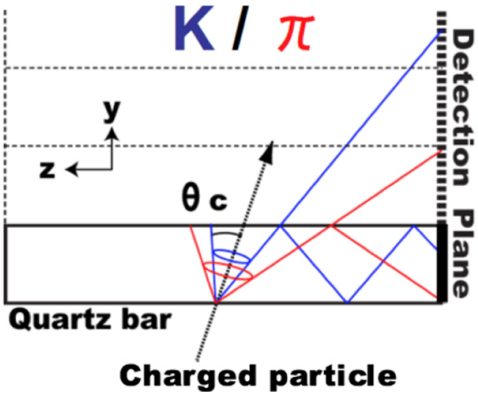


Particle ID

Cherenkov detectors



Ring-Imaging Cherenkov detector @ LHCb



Time Of Propagation @ Belle II

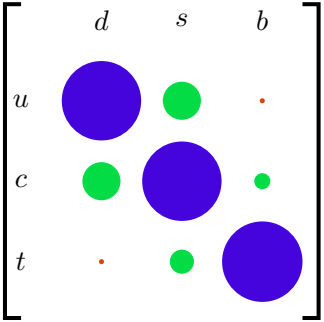
Current status and outlook

- SuperKEKB working to improve luminosity to deliver 50 ab^{-1} for Belle II by mid-2030s
  - Potential future upgrades under consideration
- LHCb Upgrade in Runs 3 and 4 to collect 50 fb^{-1}— fully software trigger!
- LHCb planning future upgrade to collect 300 fb^{-1} ($> 30 \times$ now)
  - Needs $\mathcal{O}(10\,\mathrm{ps})$ timing!

Physics results

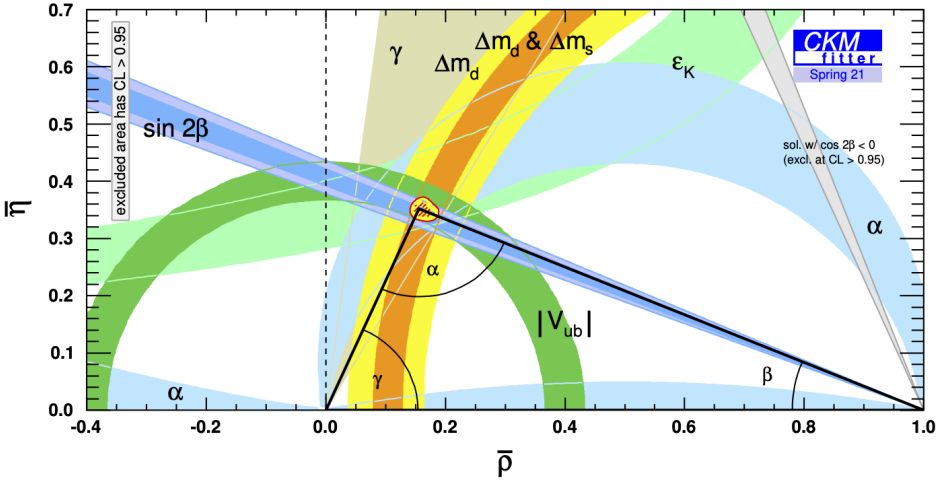
Quark flavor and CKM

- 6 quark flavors are not aligned with weak interaction
- Mixing described by CKM matrix
- Contains one complex phase that causes CP violation
- Now on the cusp of precision tests of consistency



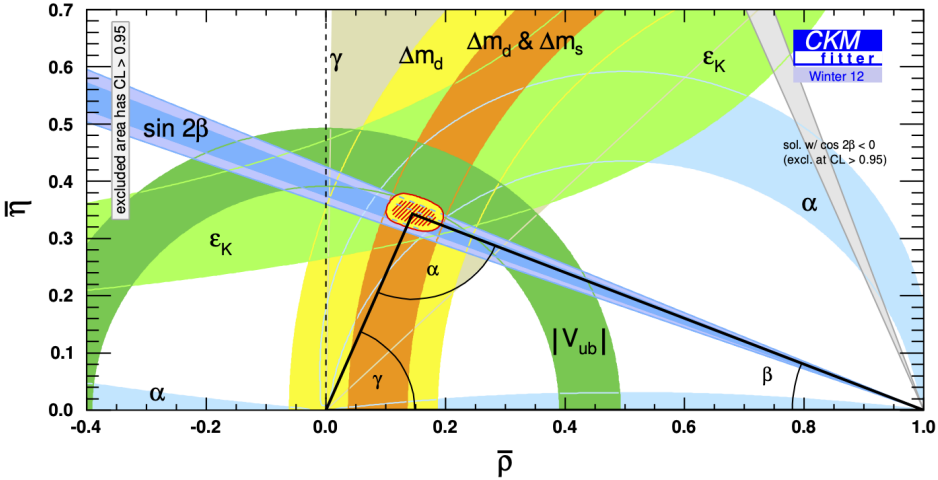
Unitarity triangle

Now



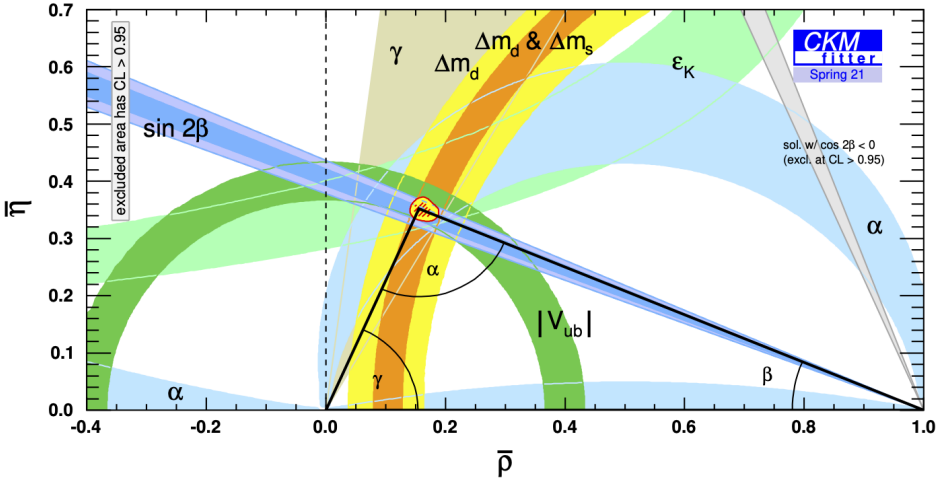
Unitarity triangle

10 years ago



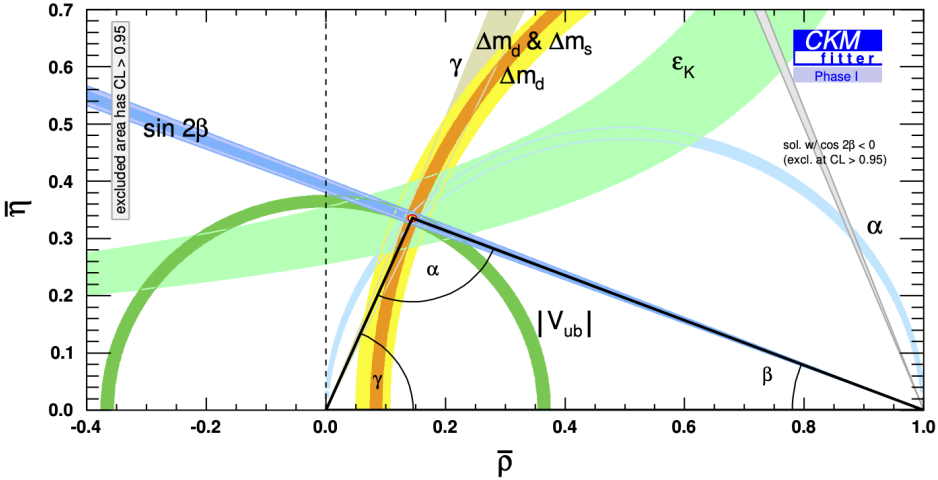
Unitarity triangle

Now



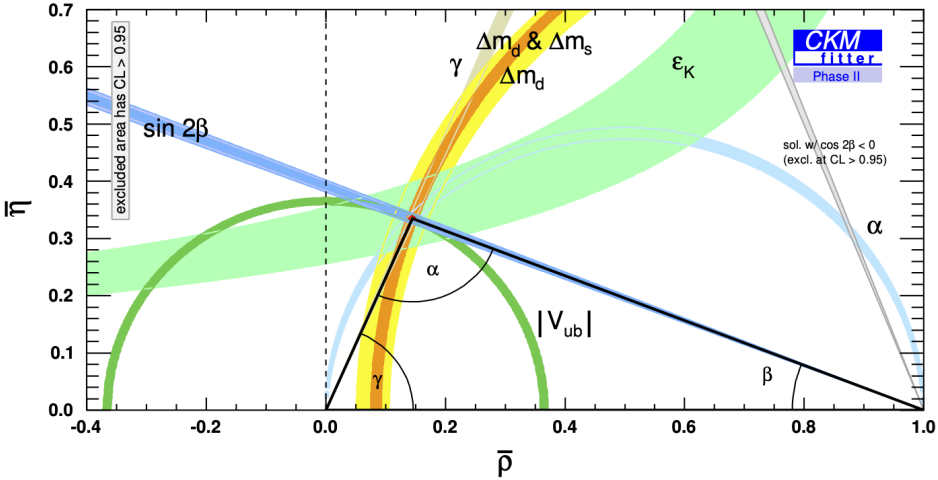
Unitarity triangle

Mid 2020s



Unitarity triangle

2030s



Measuring angle γ

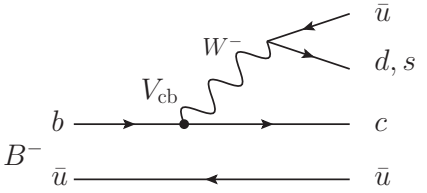
- γ can be measured using tree level B decays

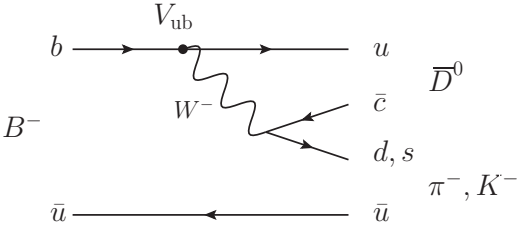
$$\gamma = \arg\left(\frac{V_{ud}\,V_{ub}^*}{V_{cd}\,V_{cb}^*}\right)$$

- Small theoretical uncertainty but difficult experimentally
- Recent LHCb combination uses data from 15 B decays and 8 D decays

One input decay

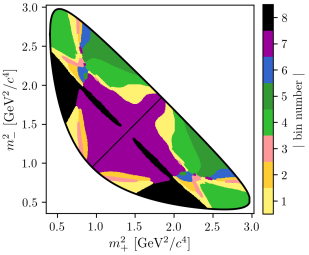
- One sensitive analysis uses $B^- \to \overset{(-)}{D}{}^0 K^-$, with $D^0 \to K_S^0 \pi^+ \pi^-$ or $D^0 \to K_S^0 K^+ K^-$
- Both $B^\pm$ can decay to $\overset{(-)}{D}$, and each the final state

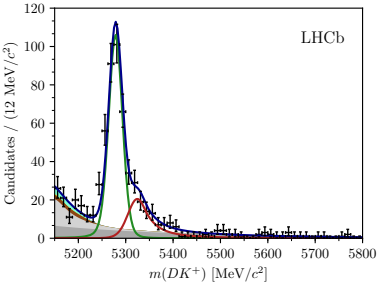


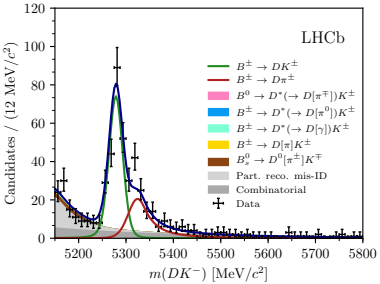


One input decay

- Study asymmetry between B^+ and B^- across D phase space, needs external input on D strong phases
- Measures γ and other decay parameters





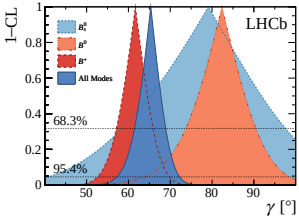


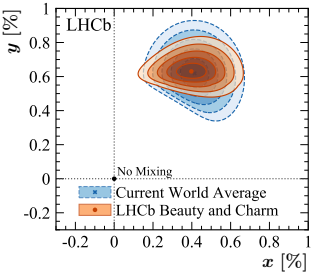
Combination

- Full combination simultaneously extracts γ and charm mixing parameters

$$\gamma = \left(65.4^{+3.8}_{-4.2}\right)^{\circ}$$

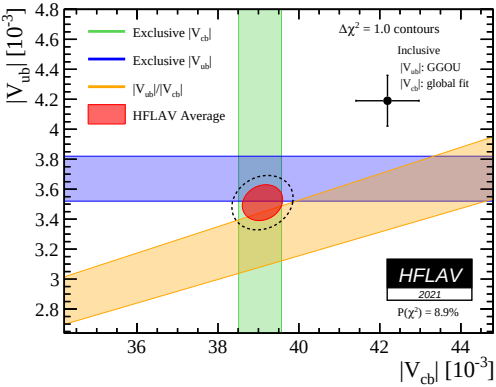
- Always working on new modes, too![†]





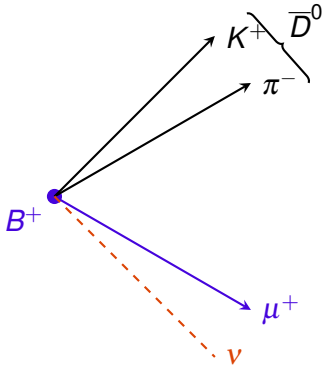
Magnitudes of V_{ub} and V_{cb}

- Analyzed in $b \to c\ell\nu$ and $b \to u\ell\nu$ decays
- Long-standing puzzle: *exclusive v. inclusive* decays
- Ongoing combined experimental–theoretical effort to unravel



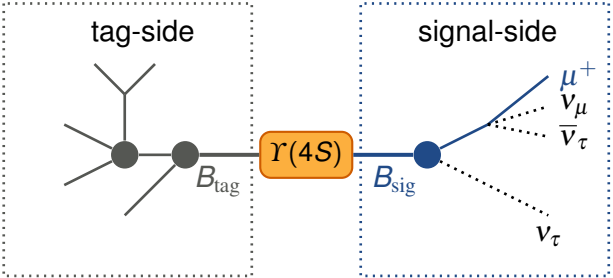
Reconstruction methods

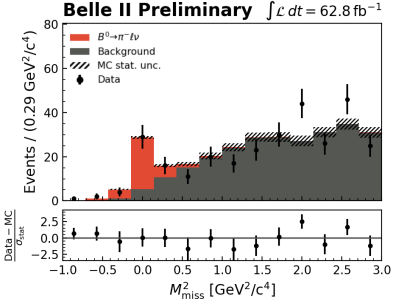
- Need to account for unmeasured neutrino to separate backgrounds and measure full kinematics of decay



FEI tagging at Belle II

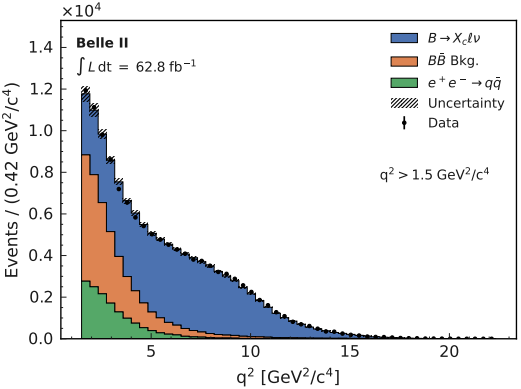
Full Event Interpretation





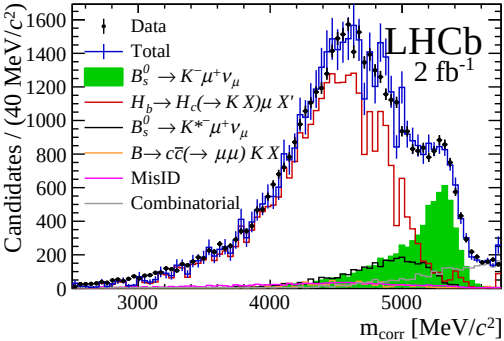
Inclusive determination

- Measure the moments of kinematic distributions
- Combine with theory to extract V_{cb}
- Most recently q^2, the mass-squared of the charge lepton and neutrino



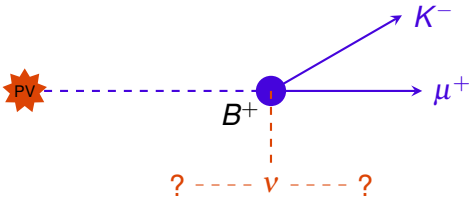
LHCb measurements

- LHCb has measured $|V_{ub}|/|V_{cb}|$ with B_s^0 and Λ_b^0 decays, *e.g.* $B_s^0 \to K^- \mu^+ \nu$ and $B_s^0 \to D_s^- \mu^+ \nu$



m_{corr}

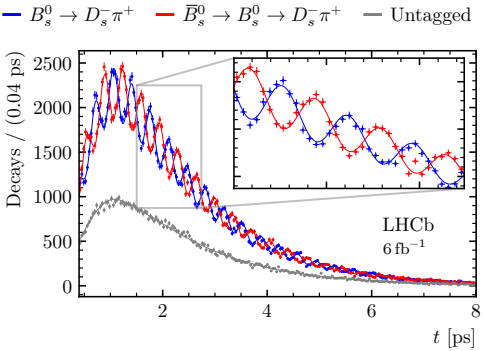
- Know B direction well, can apply momentum balance perpendicular
- m_{corr} applies minimal correction



B_s^0 oscillation

- Most precise measurement of frequency
- Effective tagging power is $\approx 6\%$

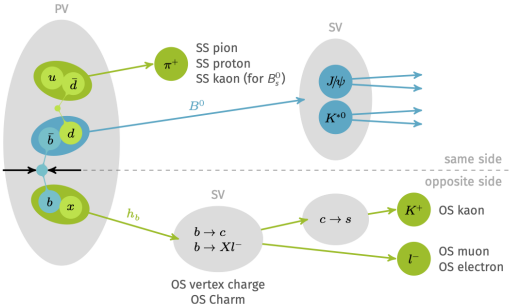
$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\,\mathrm{ps}^{-1}$$



Flavor tagging

- Need to know if B_s^0 or $\bar{B}_s^0$ at production
- Use many kinds of information to access statistically
- False positive rate (ω) harms power

$$\varepsilon_{\text{eff}} = \varepsilon(1-2\omega)^2$$



$B_s^0 \to \mu^+\mu^-$

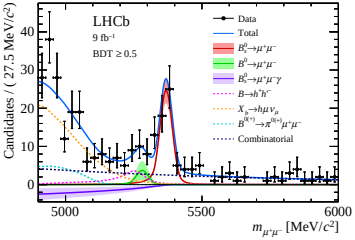
LHCb:

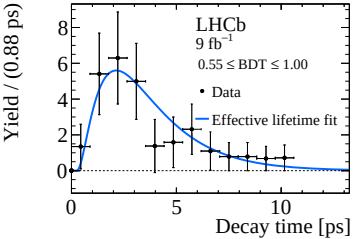
$$\mathscr{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.09^{+0.46+0.15}_{-0.43-0.11}\right) \times 10^{-9}$$

CMS:

$$\mathscr{B}\left(B_s^0 \to \mu^+\mu^-\right) = \left(3.83^{+0.38+0.24}_{-0.36-0.21}\right) \times 10^{-9}$$

- ATLAS also contributes
- Challenge is understanding small rate of muon misidentification
- At HL-LHC can measure to 10% the relative rate for $B^0 \to \mu^+\mu^-$

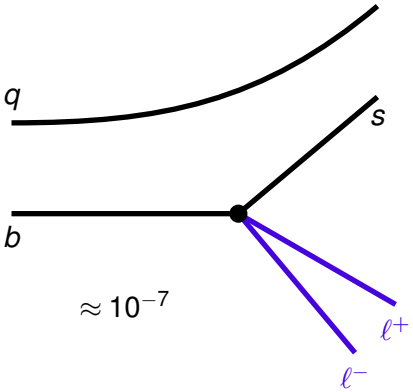




Rare decays

R_K

- Are electrons and muons equal?
- Let's count!

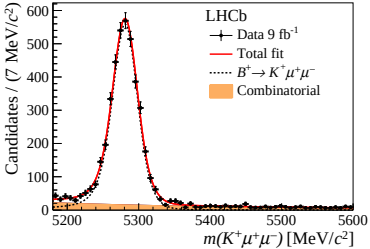


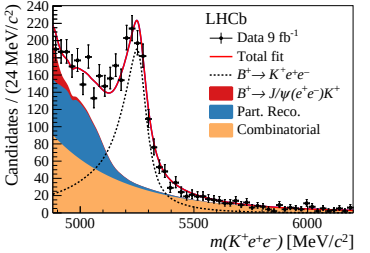
Rare decays

R_K

$$R(K) = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)}$$
$$= 0.846^{+0.044}_{-0.041}$$
$$1.1 < q^2 < 6\,\mathrm{GeV}^2$$

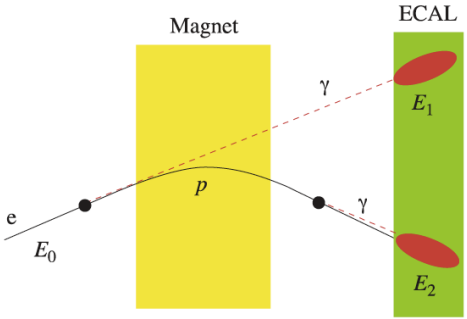
- Consistent pattern in K^{*0}, K^{*+}, K^0_S





Electrons are hard

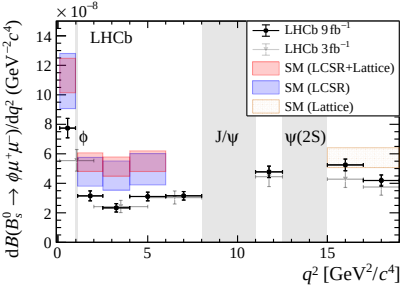
- Electron material interactions lead to brem energy loss and more difficult track reconstruction

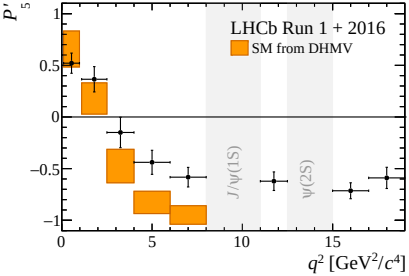


Lepton flavor universality

R_K and friends

- Many consistent measurements hint that lepton flavor universality broken
- Both rates and angular distributions
- Next frontier is difference of electron and muon angular coefficients

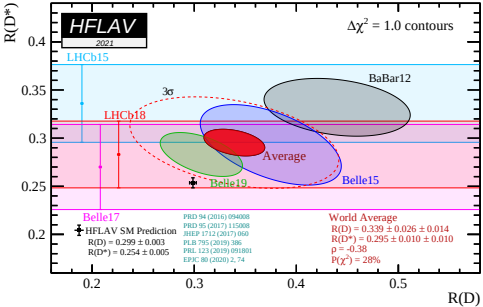




Lepton flavor universality

$R(D^{(*)})$

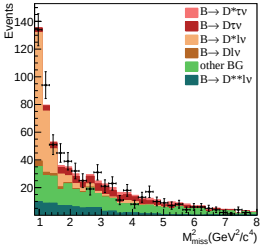
- Indication that τ decays may be more frequent than expected
- Tree-level in SM!

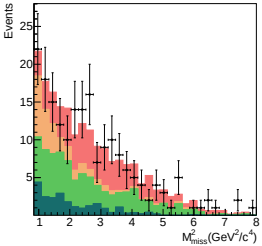


Lepton flavor universality

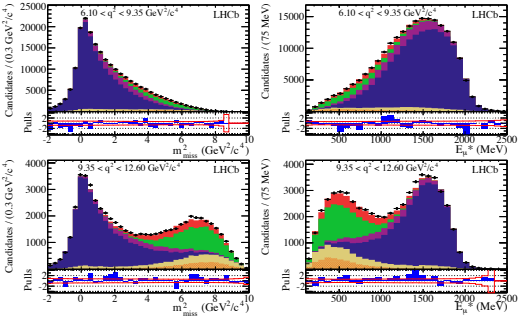
$R(D^{(*)})$

Belle



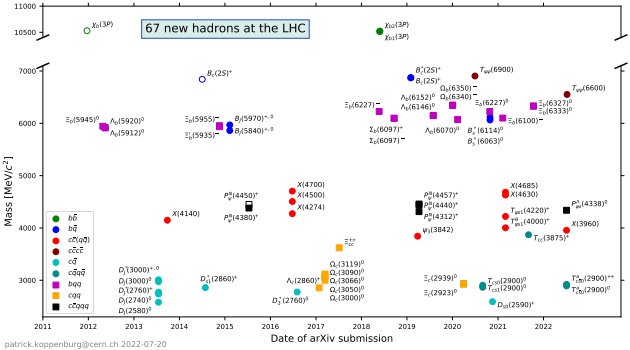


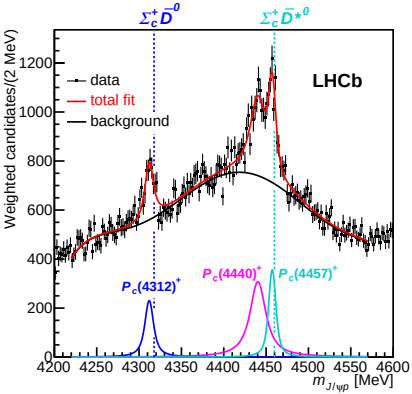
LHCb



QCD and spectroscopy

- QCD is hard – still much to unravel





Summary

- Flavor physics is a broad field addressing fundamental questions about the Standard Model with sensitivity to new physics effects up to very high energy scales
- Heavy flavor is in an exciting time with LHCb and Belle II making progress
- Stay tuned for more!