B’s Behaving Badly

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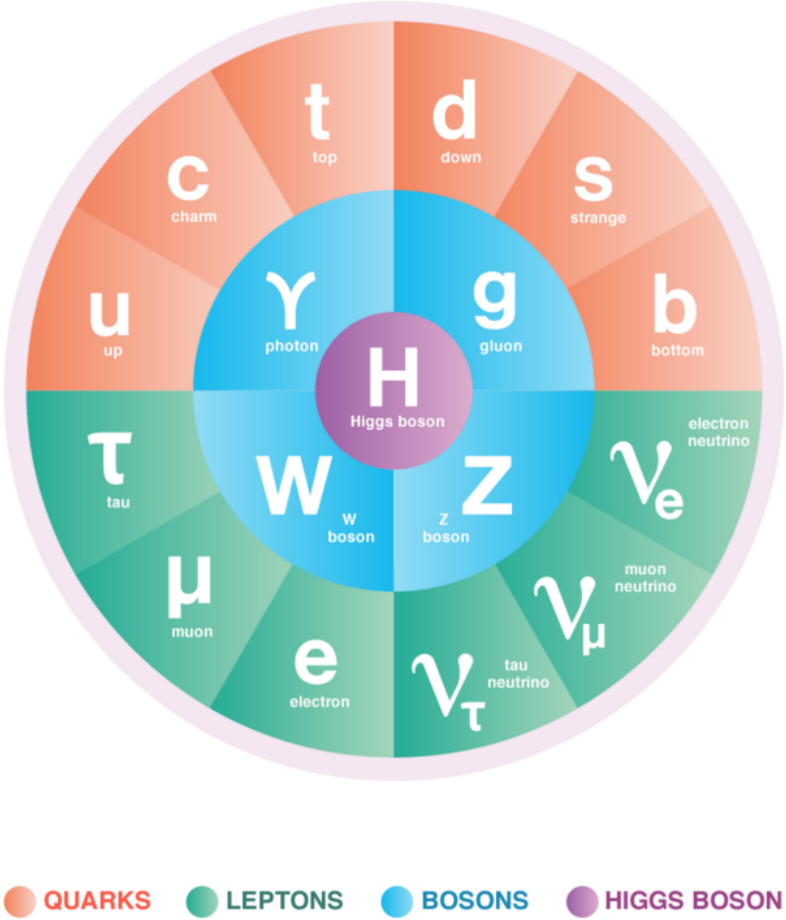
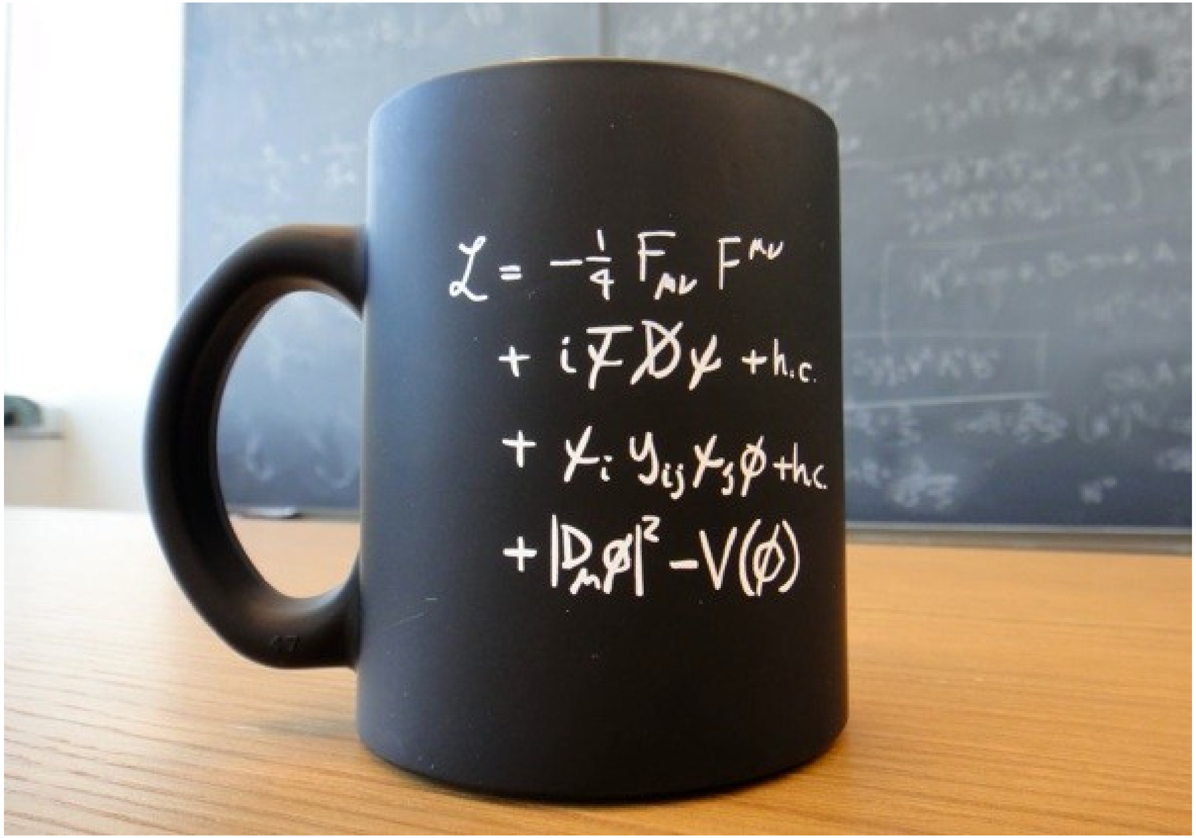
University of Washington, 7 May 2024

TEXAS
The University of Texas at Austin

ATLAS
EXPERIMENT

The Universe, per the Standard Model





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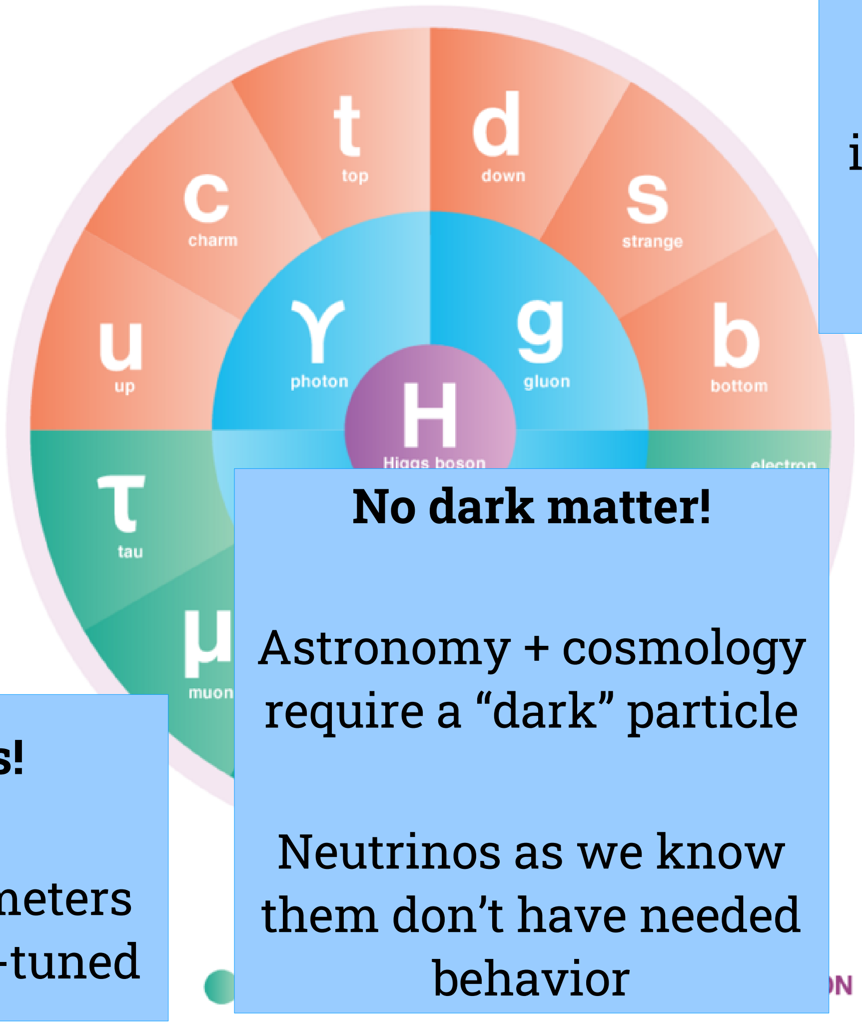


No gravity!

No verified theory of quantum gravity

No neutrino masses!

Neutrino masses require degrees of freedom beyond the SM

Naturalness!

Higgs field parameters seem highly fine-tuned

No dark matter!

Astronomy + cosmology require a “dark” particle

Neutrinos as we know them don’t have needed behavior

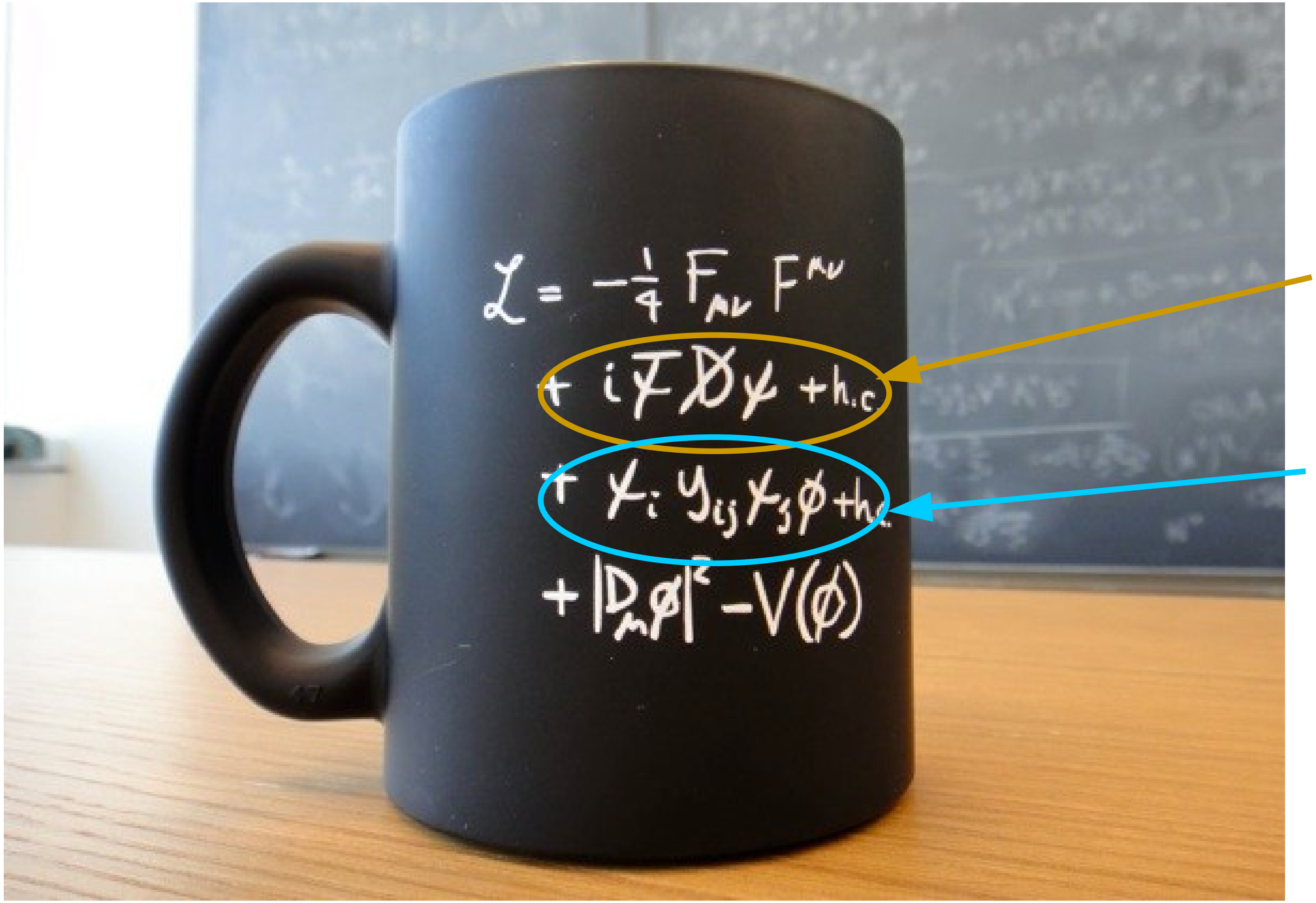
No dark energy!

The universe is being inflated by an invisible source of energy – what?

Not enough matter!

Unable to generate enough asymmetry between matter & antimatter in the Big Bang

Flavor physics: studying the matter sector & its interactions



Matter particle motion
+ interaction with forces

Matter particle interaction
with Higgs field

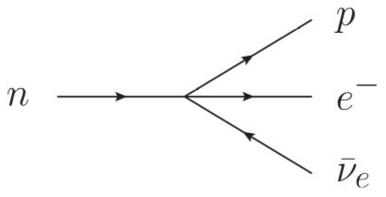
+ Matter particle interaction
with unknown things???

A Prototype

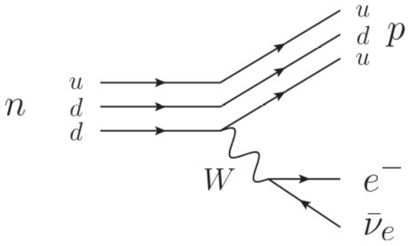
Consider neutron decay

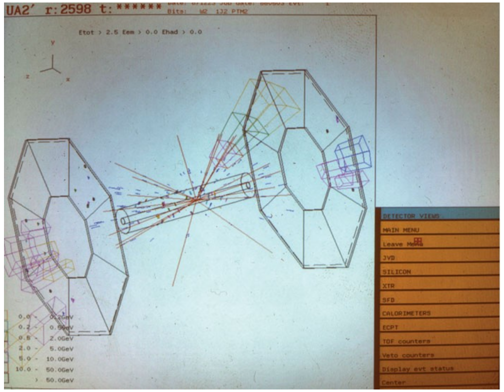
- New interaction
  - changes particle type: not electromagnetic or gravitational interaction!
  - rare: neutron half-life is quite long, ~ 10 min
- described at low energy by four fermion coupling (Fermi 1933)
  - but this predicts interaction rates that grow as $G_F^2 E^2$
  - Can guess that there should exist new physics at a scale ~ $1/G_F^{1/2}$ ~ 300 GeV
- Direct observation of force carriers W, Z in 1983 at CERN
- Fermi theory is prototype of an “effective field theory”

Nature on Fermi’s paper:
“speculations too remote from reality to be of interest to the reader”



$\propto G_F$
[GeV^{-2}]





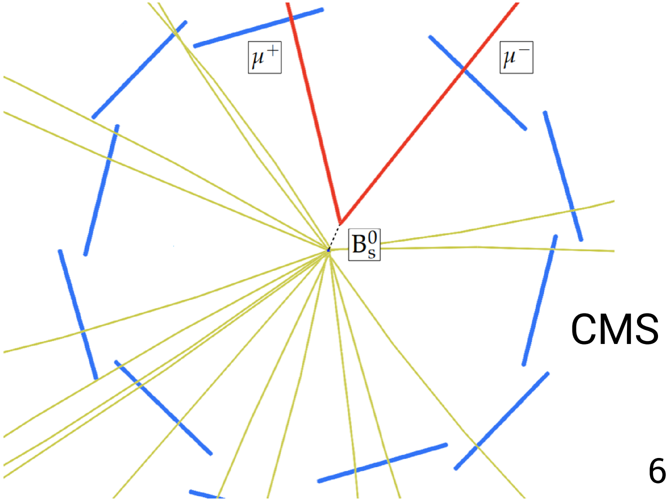
Low energy: something is going on!
High energy: let’s see what exactly it is

m_W = 80.4 GeV
m_Z = 91.2 GeV

The B Zoo

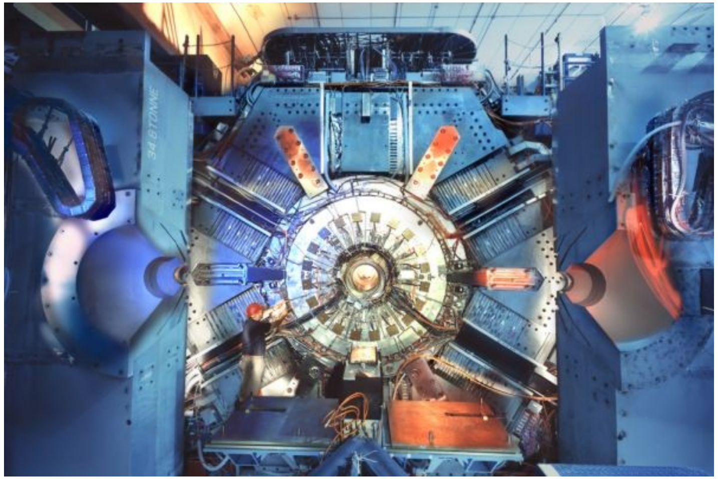
- Like other quarks, b quarks are only seen in hadrons
  - mesons ($b\bar{q}$) or baryons (bqq)
  - for flavor physics purposes generally ignore excited states or $b\bar{b}$ bound states (aka the upsilons) – the behavior of those is dominated by QCD
- b quarks are (relatively) long-lived because $|V_{cb}|$, $|V_{ub}|$ are small
  - lightest B hadron lifetimes ~ 1.5 ps
  - characteristic flight distance $c\tau$ ~ 0.5 mm: displaced decays detectable with precision tracking detectors
  - feebleness of weak decays potentially allows other forces to affect rates noticeably

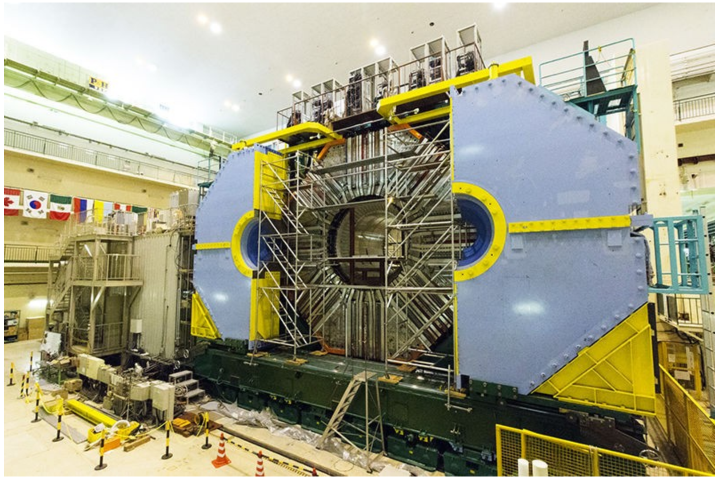
Nine times heavier than a proton, the short-lived **BOTTOM QUARK** is the 3rd generation of the down and charm quarks, all sharing a -1/3 charge. It was discovered at Fermilab in 1977.



Where do we study B hadrons? e^+e^-

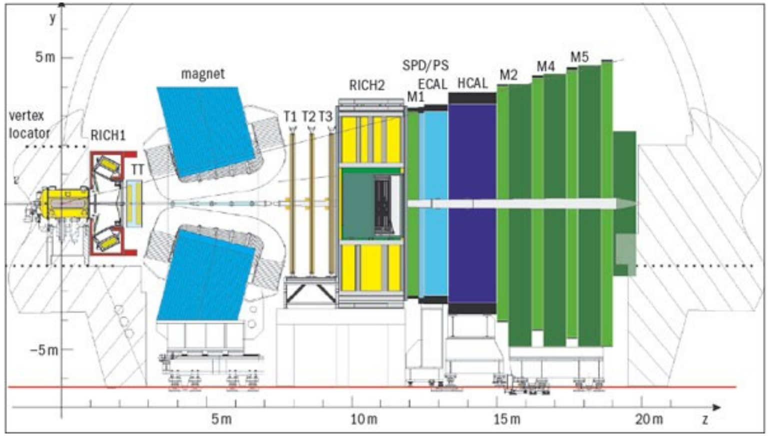
- General mode: $e^+e^- \to \Upsilon(4S) \to BB$
  - Precisely tuned to 10.58 GeV
- Previous experiments: BaBar (SLAC), Belle (KEK)
- Current experiment: Belle-II
- Advantages:
  - Clean production environment: no (few) extra particles, one collision at a time
  - Constrained kinematics (total 4-momentum is known, presence of B implies $\overline{B}$)
  - Reconstruct neutral particles (e.g. $\pi^0 \to \gamma\gamma$) relatively well
- Disadvantages:
  - Produce Υ via EM processes, cross sections are low
  - only have large samples of B^+ and B^0 since B_s etc. are too heavy

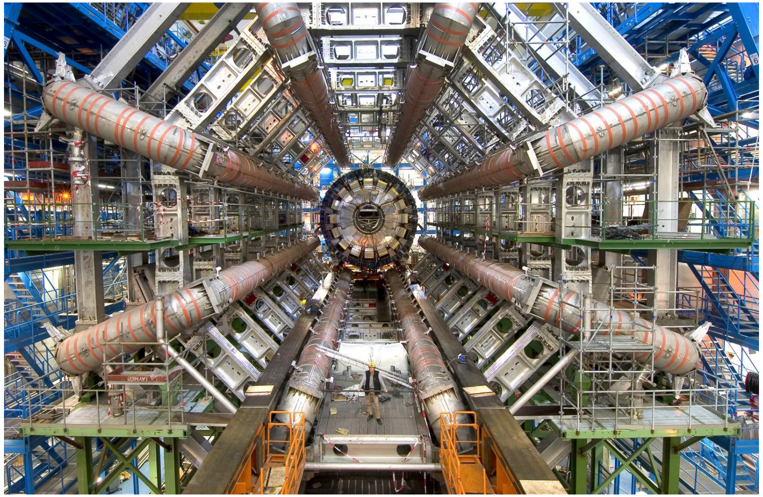




Where do we study B hadrons? pp

- General mode: $pp \to ???? \to X_b\, X_{\bar{b}}$
- Broad spectrum of B hadrons produced, at various momenta
- At the LHC:
  - dedicated experiment for B physics (LHCb)
  - two general purpose experiments that do B physics (ATLAS, CMS)
- Advantages:
  - Strong production → high cross sections
  - Produce all B hadron species
- Disadvantages:
  - Messy collision environment, few kinematic constraints
  - Generally hard to work with π^0 etc.





Past and Future

- Great project of B physics in the 2000s: demonstrating the unitarity of the CKM matrix
- Great project for the next 20 years: precision constraints on rare processes[1]

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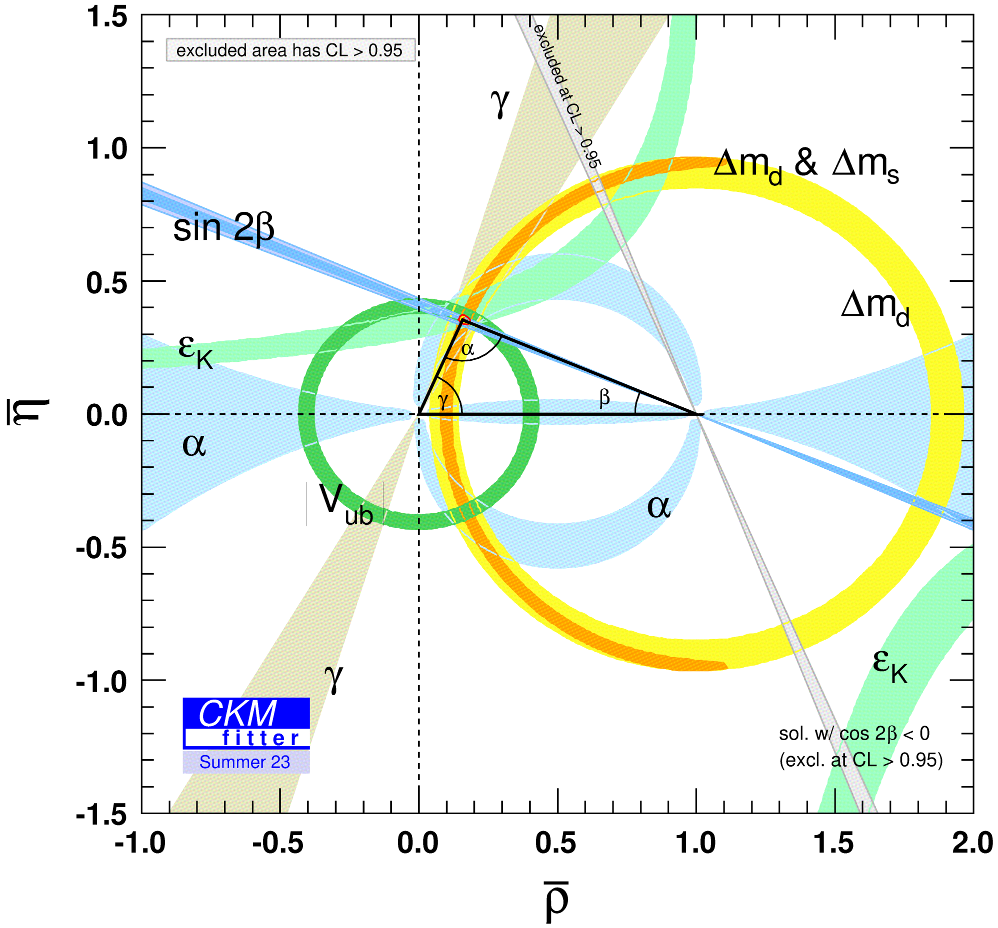
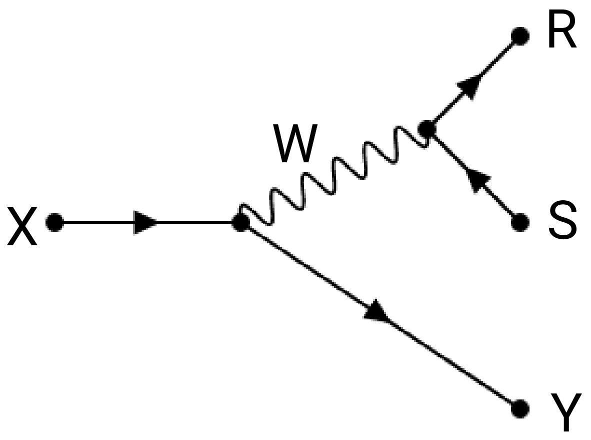
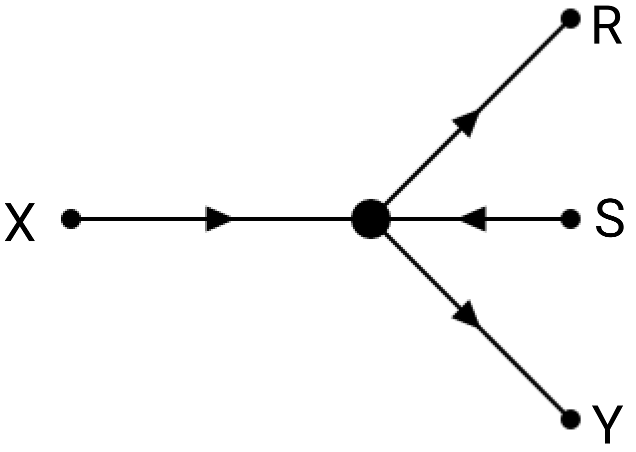
[1] Personal opinion



Four-Fermion Interactions





$$\left(\frac{g}{2\sqrt{2}}\right)^2 J^{XY}_\alpha \frac{-g^{\alpha\beta} + \frac{q^\alpha q^\beta}{M_W^2}}{q^2 - M_W^2} \overline{J}^{RS}_\beta \longrightarrow \frac{G_F}{2} J^{XY}_\alpha (\overline{J}^{RS})^\alpha$$

- Collapse an expression with two dimension 4 operators + a propagator to a dimension 6 operator, as |q| << m_W if the fermions are in hadrons
- For W exchange, currents must be left-handed

Effective Field Theory

- "Old school" QFT: only dimension 4 or lower operators can exist, because higher-dimension operators are non-renormalizable

$$\frac{2}{3} e A_\mu \bar{u} \gamma^\mu u \quad ✓ \qquad\qquad \frac{G}{\Lambda^2} (\bar{s}\gamma_\mu b)(\bar{\ell}\gamma^\mu \ell) \quad ✗$$

  - but exchange of high-mass particles will induce effective higher-dimension operators for low-energy interactions
- "New" QFT: generically work with higher-dimension operators
  - standard in B physics for a long time: compare measurements to SM predictions to search for discrepancies
  - calculate with them without worrying about the underlying ultraviolet completion

Wilson coefficients

e.g. for b → s transitions:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + \text{h.c.}$$

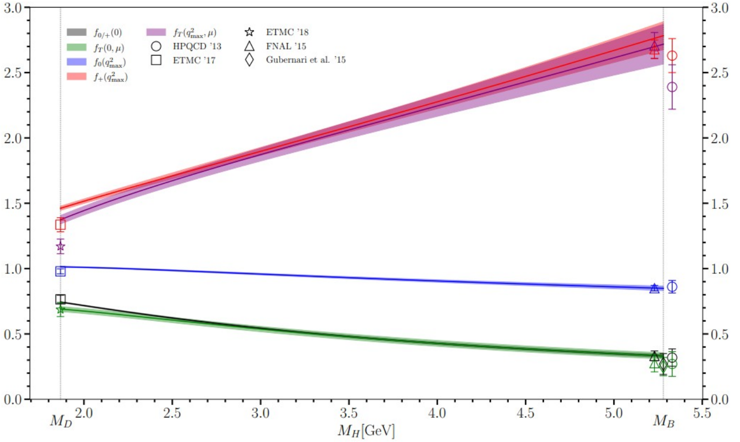
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)(\ell\gamma^\mu \ell)$$

Hadronic Physics

- Need amplitude for quarks from a short-distance interaction to coalesce into a particular final state hadron
  - a priori lattice gauge theory calculations should be accurate, but have limitations (in particular large hadronic recoil, and for strongly-decaying hadrons in the final state)
  - otherwise typically fit form factors from data using models/approximations
- Also have to care about "long-distance" physics, i.e. what hadrons do
  - for example, by far the biggest contributors to inclusive $b \to s\ell\ell$ are CKM-allowed $b \to sc\bar{c}$, followed by $c\bar{c} \to \ell\ell$



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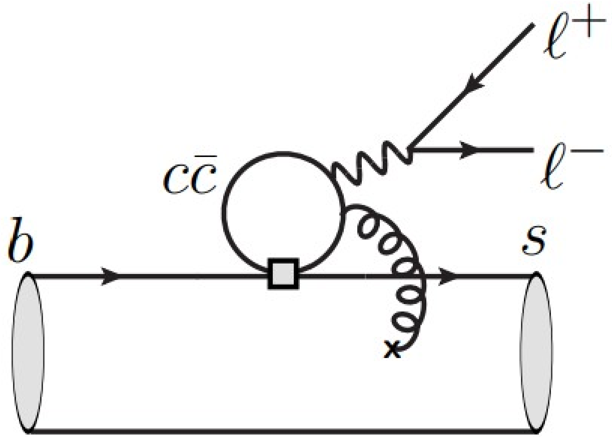
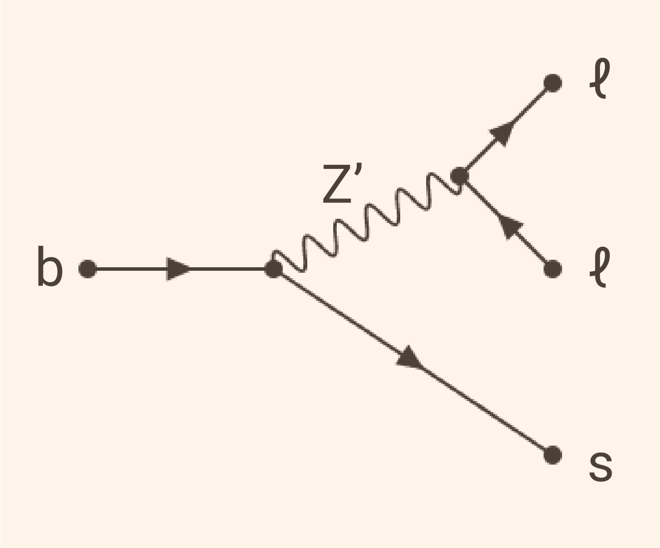
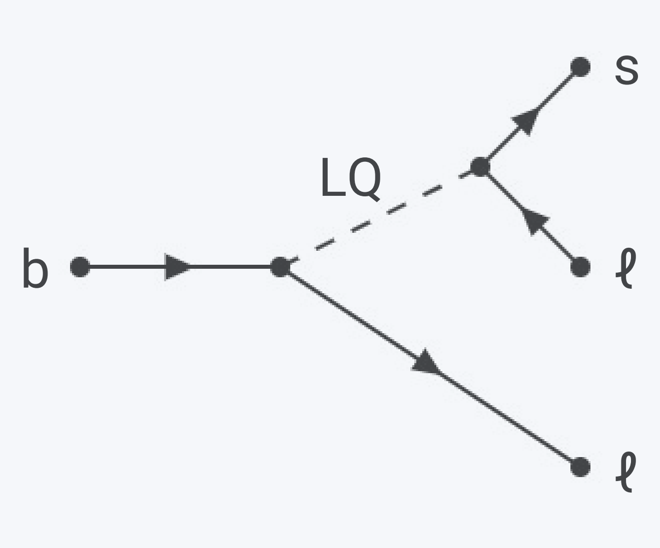
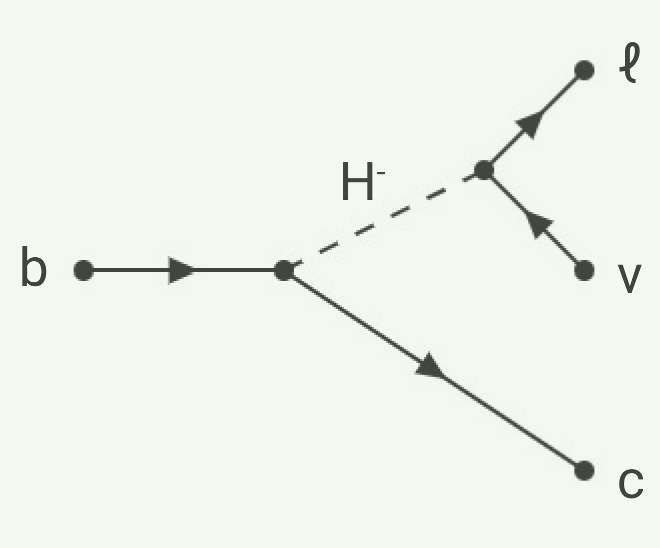


Things To Look For

Some new physics ideas...







Non-diagonal Z’, leptoquarks, charged Higgs, ...

Each would leave a different pattern in the Wilson coefficients

Anomalies

Two classes of potential anomalies under study:

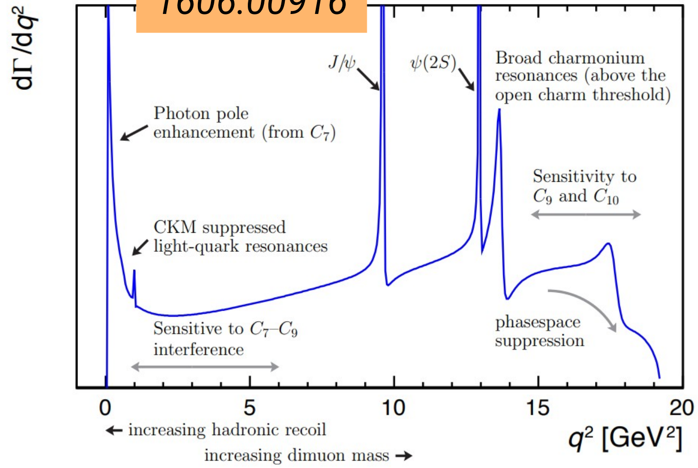
- b → sℓℓ processes:
  - non-resonant b → sμμ shows non-SM m(μμ) and angular distributions

- b → cℓν processes:
  - lepton flavor universality violation: τ/μ ratio > SM (τ mass means ratio is not 1)

Will show details from ATLAS analyses, when available...

$b \to s\ell\ell$

- The “spectator quark” determines the actual hadrons involved
  - down: $\mathbf{B^0} \to [K^{*0} \to K^+\pi^-]\ell\ell$, $(K_S^0 \to \pi^+\pi^-)\ell\ell$
  - up: $\mathbf{B^+} \to [K^{*+} \to K_S^0\,\pi^+]\ell\ell$, $K^+\ell\ell$
  - strange: $\mathbf{B_s^0} \to [\varphi \to K^+K^-]\ell\ell$, $\ell\ell$
  - baryon: $\mathbf{\Lambda_b^0} \to pK^-\ell\ell$
- Different final states can probe different EFT operators
- Avoid charmonium resonance regions populated by the (not rare) b → ccs process
- Can look at muon/electron ratio for processes that might not be lepton flavor-universal
- Can also look at various distributions – e.g. branching fraction vs dilepton mass, or angular distributions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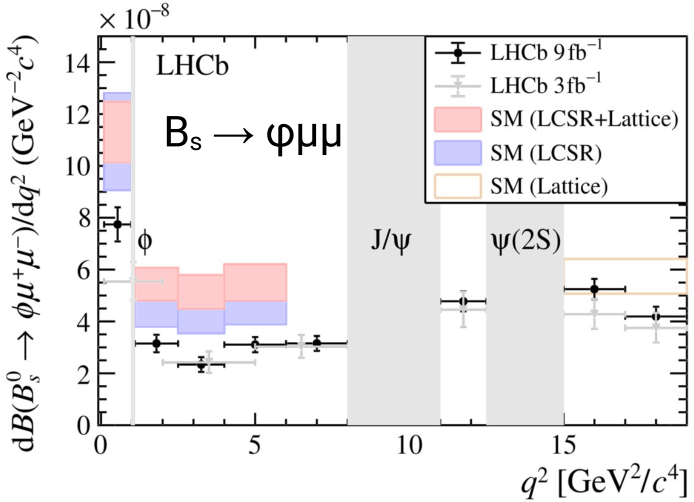
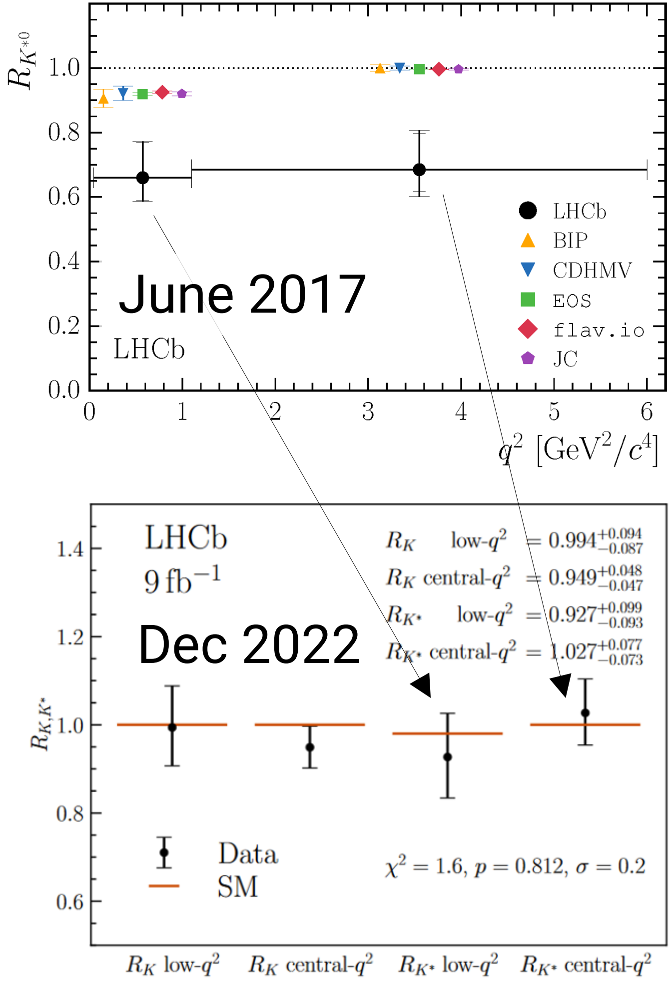


The Anomaly That Wasn’t: Universality Violation

- Differences between muon and electron rates would be a smoking gun for new physics
  - could not be faked by hadronic physics
- Significant evidence was reported in multiple channels by LHCb
- Turned out to be a consistent underestimation of electron backgrounds
- Discovery of new physics in these kinds of channels will require evidence from multiple experiments

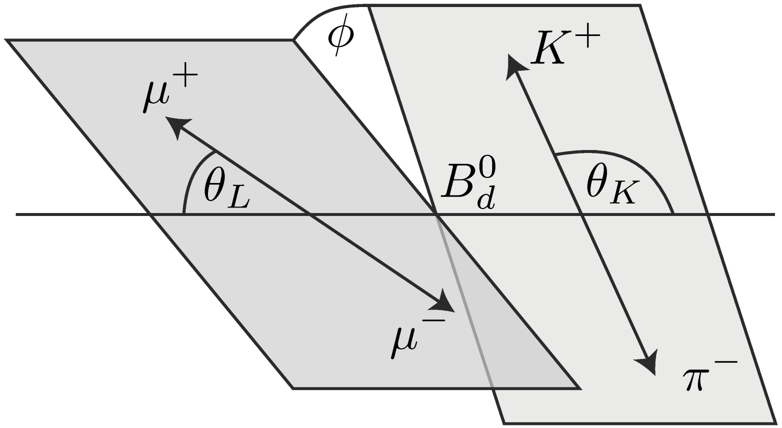


June 2017

Dec 2022

$B^0 \rightarrow K^*\mu\mu$ Angular Distributions

- New physics in $b \rightarrow s\mu\mu$ can alter the angular distributions of the decay products in $B^0 \rightarrow K^*\mu\mu \rightarrow K^+\pi^-\mu\mu$
  - relies on K* being a vector with two different quarks
- "P'_5" coefficient shows a potential deviation from SM
  - look in different bins of $q^2(\mu\mu)$, avoiding J/ψ, ψ(2S), ϕ resonances
- ATLAS result from Run 1, 20 fb^{-1}



$$\frac{9}{32\pi}\Bigg[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Bigg]$$

$$P'_{j=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

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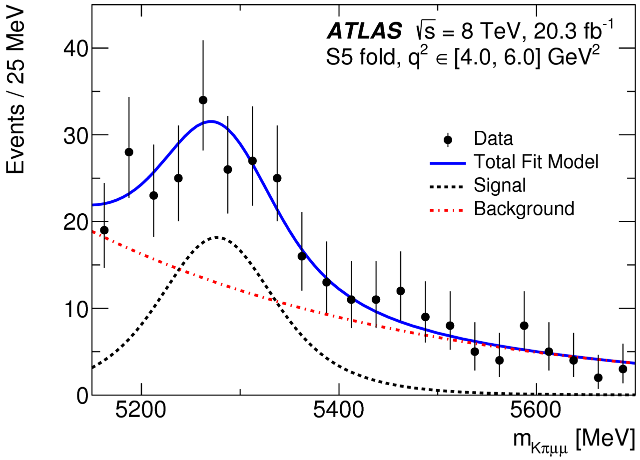
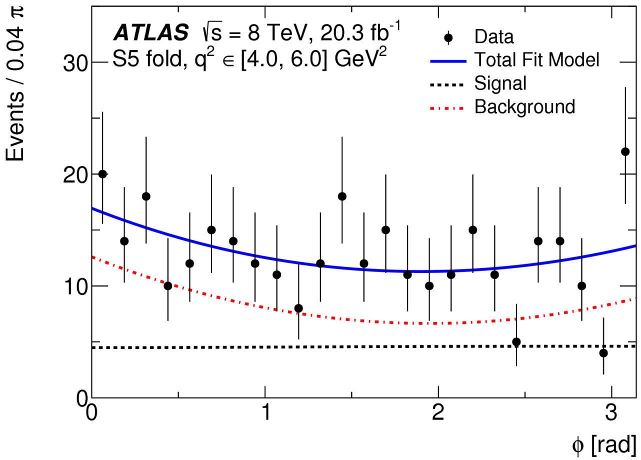
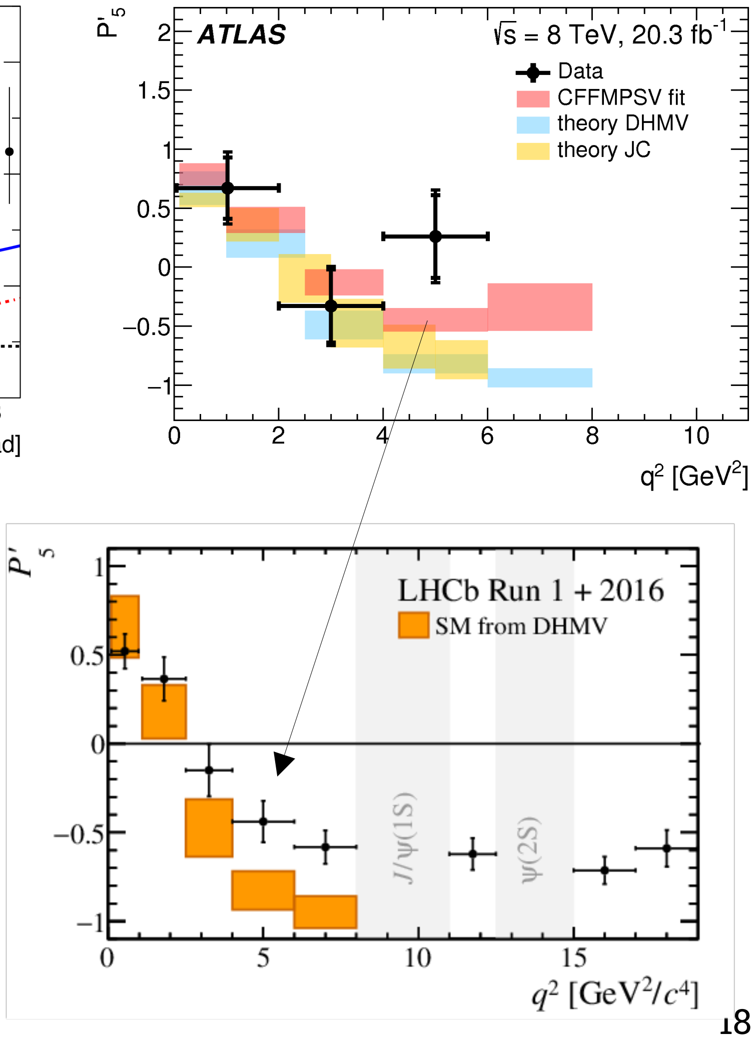
$B^0 \rightarrow K^*\mu\mu$ Angular Distributions







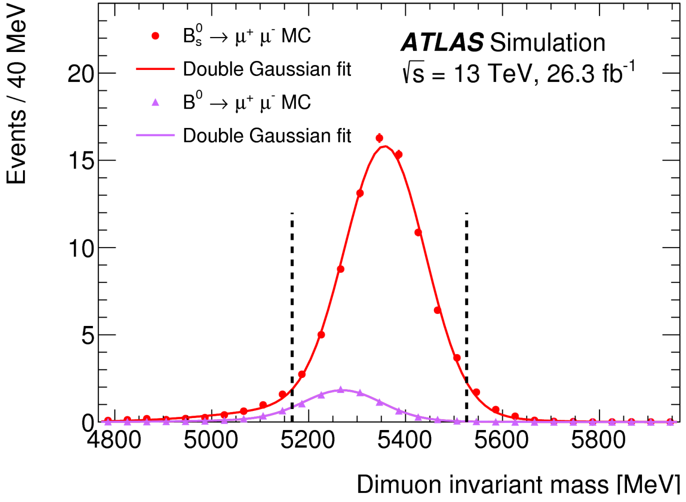
- "Most interesting bin" is P'_5, $q^2 \in [4 \text{ GeV}, 6 \text{ GeV}]$
- Can see e.g. lack of expected cos φ modulation in signal fit: $P'_5 \approx 0$ in our fit for this bin
  - of course, simultaneous fit to θ_K and θ_L as well
  - not a significant difference from predictions but deviation in the same direction as other results

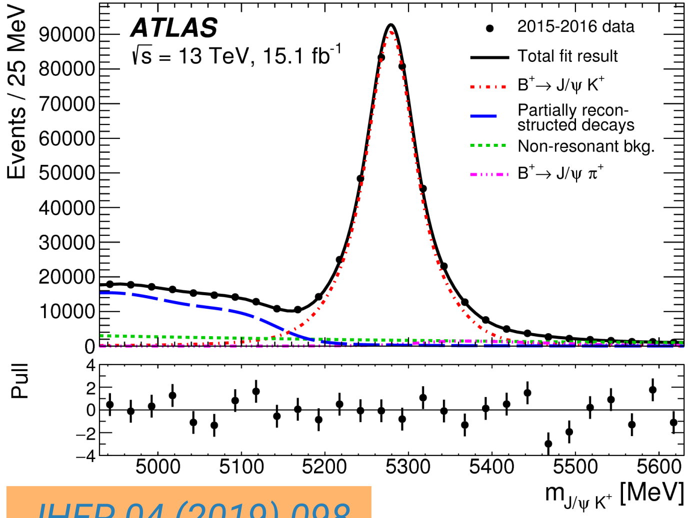
$B_{(s)} \to \mu\mu$

- $B_s \to \mu\mu$ is another process sensitive to the bsμμ vertex, but with different coupling structure
- Use 2015+2016 data, 26.3 fb^{-1} after prescales
- Rare decays sensitive to bsμμ and bdμμ couplings (incl. O_{10})
- ATLAS dimuon mass resolution not good enough to separate B_s and B peaks
  - fit simultaneously, but expect strong correlation of branching fractions
- Normalize number of observed decays to the number of $B^+ \to J/\psi K^+$:

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) =$$

$$\underbrace{\frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}}}_{\text{Efficiency-corrected } B_{(s)} \to \mu\mu \text{ yield}} \times \overbrace{[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)]}^{\text{Reference branching fraction}} \underbrace{\frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}}}_{\text{Efficiency-corrected } B \to J/\psi K \text{ yield}} \times \overbrace{\frac{f_u}{f_{d(s)}}}^{\text{Ratio of B meson species production}}$$





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$B_{(s)} \to \mu\mu$ Results

- Combine Run 1 and early 13 TeV data
  - results compatible
  - sensitive to lower BRs for $B \to \mu\mu$ vs $B_s \to \mu\mu$ because $f_d >> f_s$
  - anticorrelation of B_d and B_s BR

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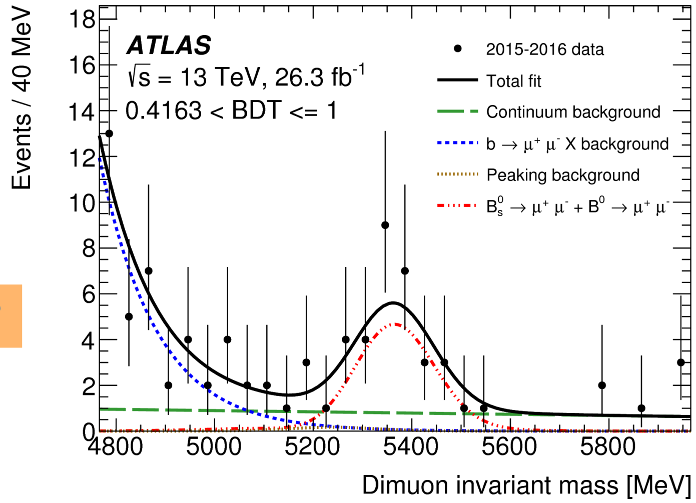
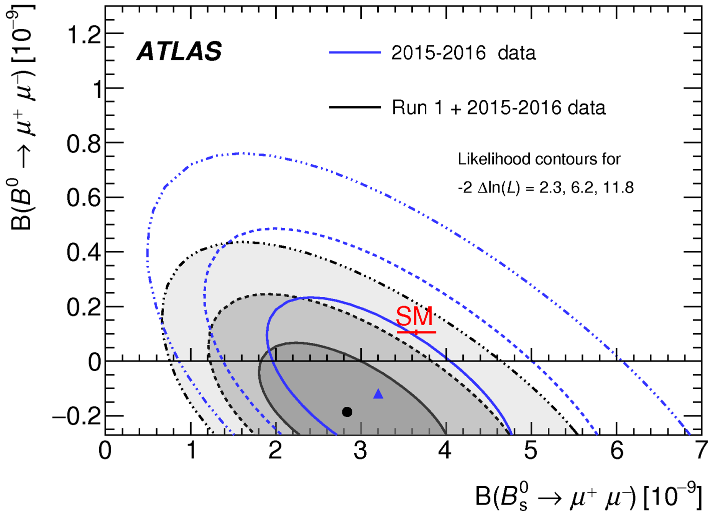


Combined
Run 1 + 2015/6

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.7) \times 10^{-9}\,,$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (-1.9 \pm 1.6) \times 10^{-10}\,.$$

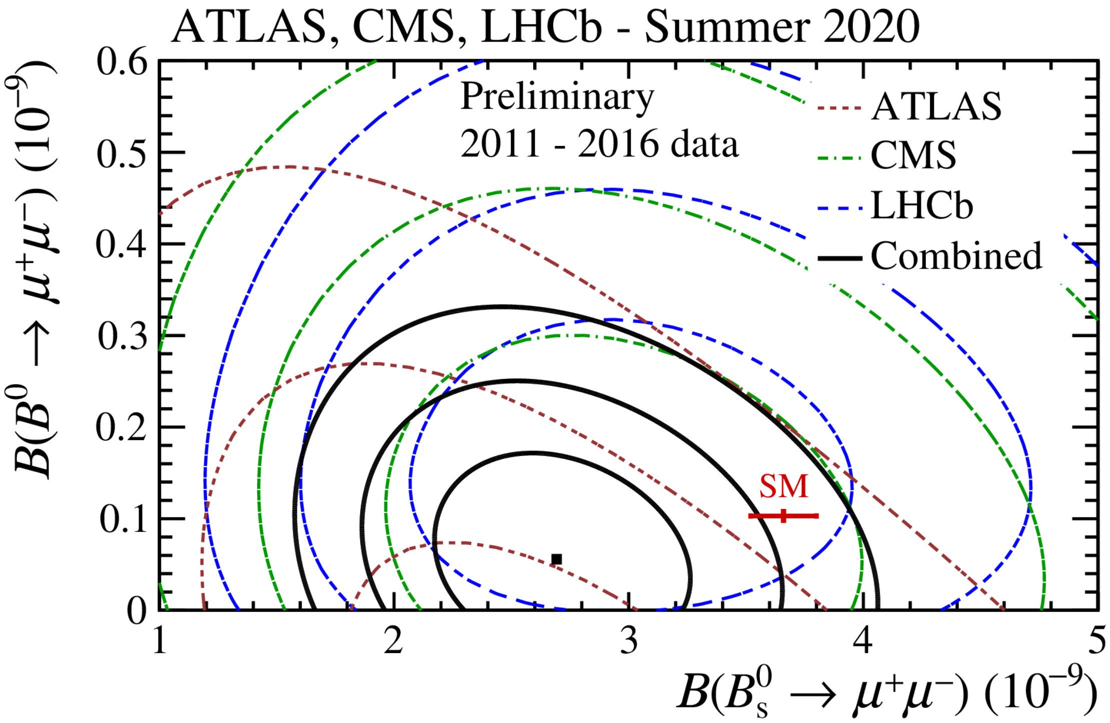
2015/6 result uncertainties

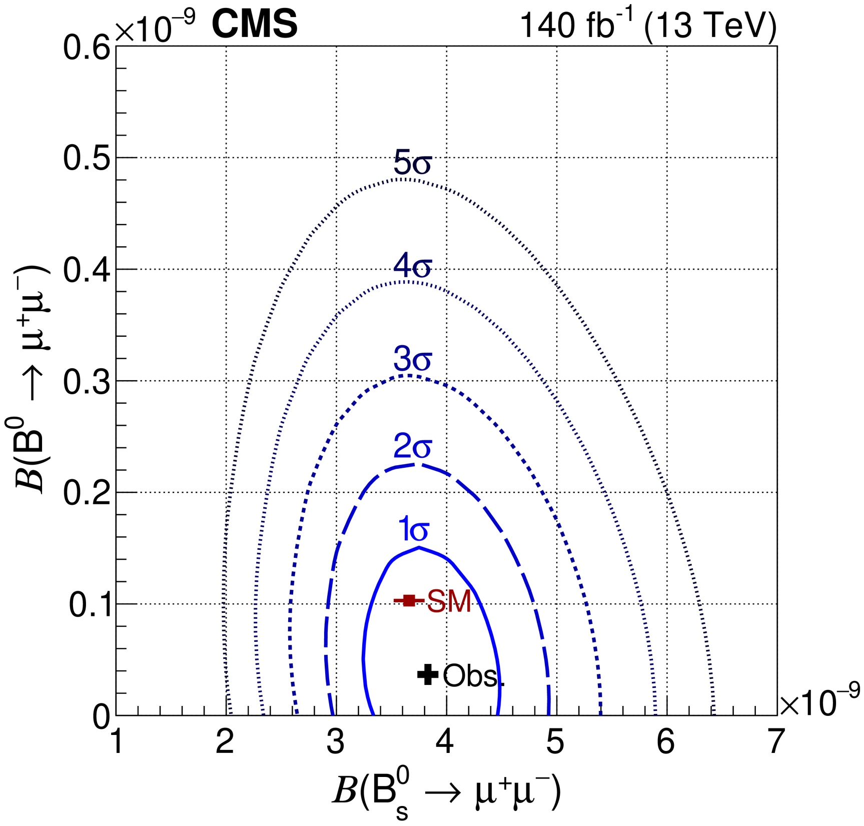
Source	B_s^0 [%]	B^0 [%]
f_s/f_d	5.1	-
B^+ yield	4.8	4.8
R_ε	4.1	4.1
$\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$	2.9	2.9
Fit systematic uncertainties	8.7	65
Stat. uncertainty (from likelihood est.)	27	150



$B_{(s)} \rightarrow \mu\mu$ Combination

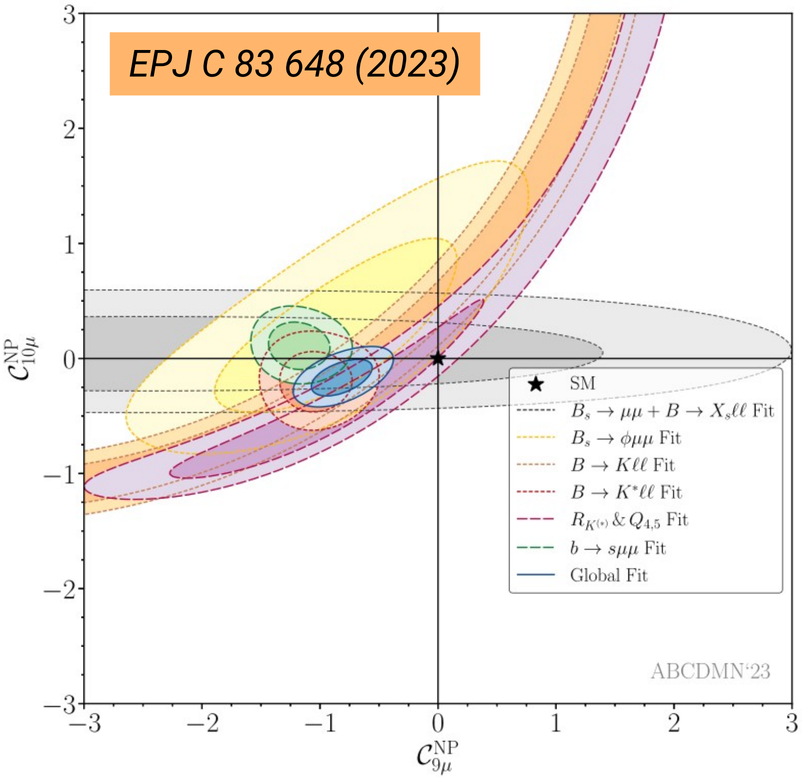
+ CMS update [PLB 842 137955 (2023)]





Fits

- Fits significantly favor non-SM C₉
  - but flavor-universal
- Remarkably consistent EFT picture
- Multi-σ discrepancies in individual measurements
- Would look to hadronic uncertainties for a SM explanation
  - some of these could be constrained with data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Wilson coefficients

$$\mathcal{H}_{\mathrm{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \mathrm{h.c.}$$

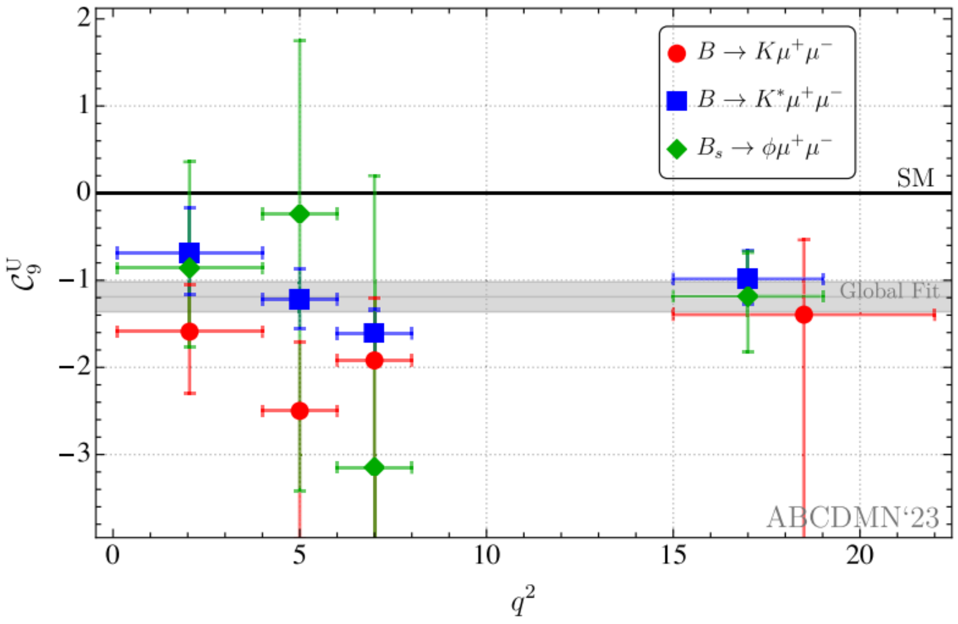
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

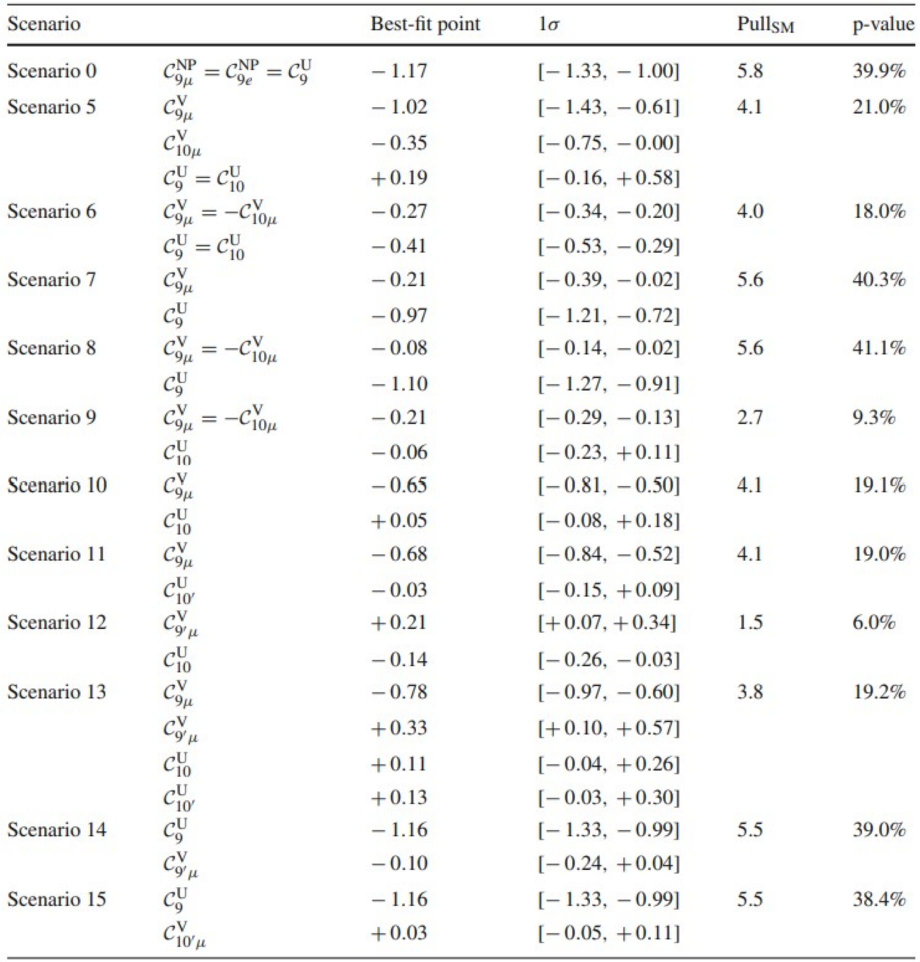
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)(\ell\gamma^\mu \ell)$$

Fits

- Consistency of fit across bins
- Different NP scenarios leave different fingerprints in Wilson coefficients

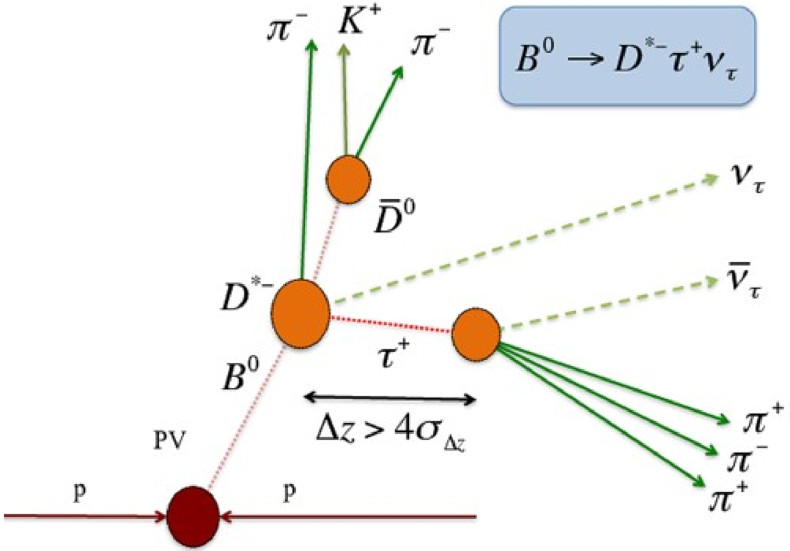




Scenario		Best-fit point	1σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
Scenario 0	$\mathcal{C}_{9\mu}^{\mathrm{NP}} = \mathcal{C}_{9e}^{\mathrm{NP}} = \mathcal{C}_9^{\mathrm{U}}$	-1.17	$[-1.33, -1.00]$	5.8	39.9%
Scenario 5	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-1.02	$[-1.43, -0.61]$	4.1	21.0%
	$\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.35	$[-0.75, -0.00]$		
	$\mathcal{C}_9^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	$+0.19$	$[-0.16, +0.58]$		
Scenario 6	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.27	$[-0.34, -0.20]$	4.0	18.0%
	$\mathcal{C}_9^{\mathrm{U}} = \mathcal{C}_{10}^{\mathrm{U}}$	-0.41	$[-0.53, -0.29]$		
Scenario 7	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.21	$[-0.39, -0.02]$	5.6	40.3%
	$\mathcal{C}_9^{\mathrm{U}}$	-0.97	$[-1.21, -0.72]$		
Scenario 8	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.08	$[-0.14, -0.02]$	5.6	41.1%
	$\mathcal{C}_9^{\mathrm{U}}$	-1.10	$[-1.27, -0.91]$		
Scenario 9	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.21	$[-0.29, -0.13]$	2.7	9.3%
	$\mathcal{C}_{10}^{\mathrm{U}}$	-0.06	$[-0.23, +0.11]$		
Scenario 10	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.65	$[-0.81, -0.50]$	4.1	19.1%
	$\mathcal{C}_{10}^{\mathrm{U}}$	$+0.05$	$[-0.08, +0.18]$		
Scenario 11	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.68	$[-0.84, -0.52]$	4.1	19.0%
	$\mathcal{C}_{10'}^{\mathrm{U}}$	-0.03	$[-0.15, +0.09]$		
Scenario 12	$\mathcal{C}_{9'\mu}^{\mathrm{V}}$	$+0.21$	$[+0.07, +0.34]$	1.5	6.0%
	$\mathcal{C}_{10}^{\mathrm{U}}$	-0.14	$[-0.26, -0.03]$		
Scenario 13	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.78	$[-0.97, -0.60]$	3.8	19.2%
	$\mathcal{C}_{9'\mu}^{\mathrm{V}}$	$+0.33$	$[+0.10, +0.57]$		
	$\mathcal{C}_{10}^{\mathrm{U}}$	$+0.11$	$[-0.04, +0.26]$		
	$\mathcal{C}_{10'}^{\mathrm{U}}$	$+0.13$	$[-0.03, +0.30]$		
Scenario 14	$\mathcal{C}_9^{\mathrm{U}}$	-1.16	$[-1.33, -0.99]$	5.5	39.0%
	$\mathcal{C}_{9'\mu}^{\mathrm{V}}$	-0.10	$[-0.24, +0.04]$		
Scenario 15	$\mathcal{C}_9^{\mathrm{U}}$	-1.16	$[-1.33, -0.99]$	5.5	38.4%
	$\mathcal{C}_{10'\mu}^{\mathrm{V}}$	$+0.03$	$[-0.05, +0.11]$		

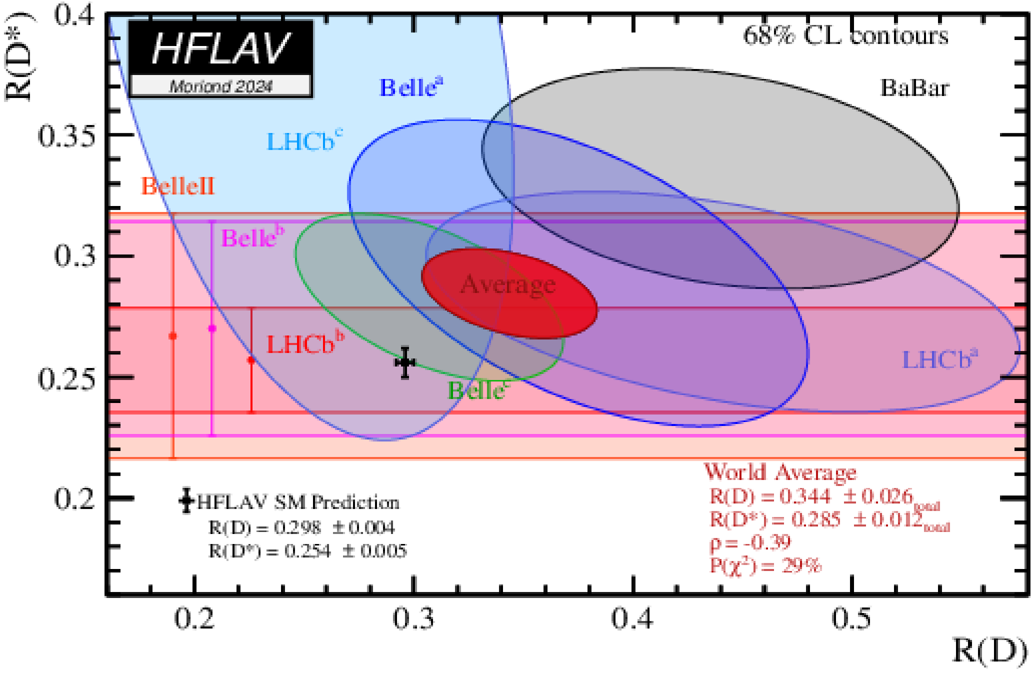
$b \to c\ell\nu$

- With spectator quarks:
  - $\mathbf{B^0} \to [D^- \to K^+\pi^-\pi^-]\, \ell^+\nu$,
    $[D^{*-} \to (\overline{D}^0 \to K^+\pi^-)\pi^-]\, \ell^+\nu$
  - $\mathbf{B_s^0} \to [D_s \to (\varphi \to K^+K^-)\pi]\, \ell^+\nu$
  - $\mathbf{B_c^+} \to J/\psi\, \ell^+\nu$
  - $\mathbf{\Lambda_b} \to \Lambda_c\, \ell^+\nu$
- Harder to do at hadron colliders due to neutrinos
  - needs detailed modeling of higher multiplicity decays (e.g. $B \to D^{*-}\pi^0\ell\nu$, where the π^0 is missed)
- Can potentially be done with both leptonic and hadronic τ decays



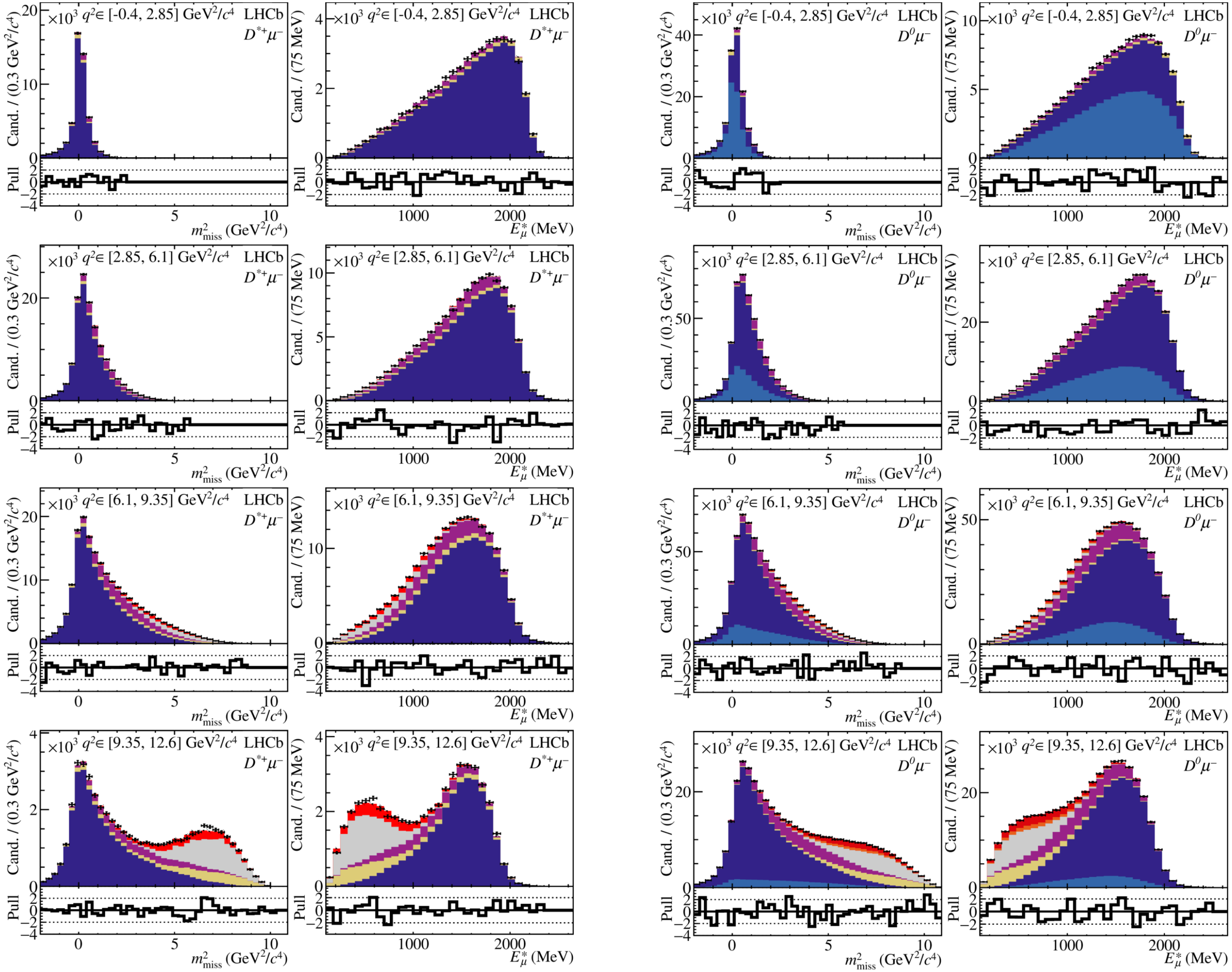
More on $b \to c\ell\nu$

- Experimental situation more challenging than for $b \to s\ell\ell$
- $R(D^*)$ and $R(J/\psi)$ are more accessible to hadron colliders than $R(D)$ because D^* are more pure
  - tag with $D^* \to D^0\pi$
- Need theory for semileptonic decay form factor prediction; updated lattice computations in progress



LHCb Data

PRL 131 111802 (2023)



+ Data (3 fb^{-1})

🟥 $B\to D^*\tau\nu$

🟧 $B\to D\tau\nu$

⬜ $B\to D^{(*)}D\,X$

🟪 $B\to D^{**}\mu\nu$

🟨 Comb. + misID

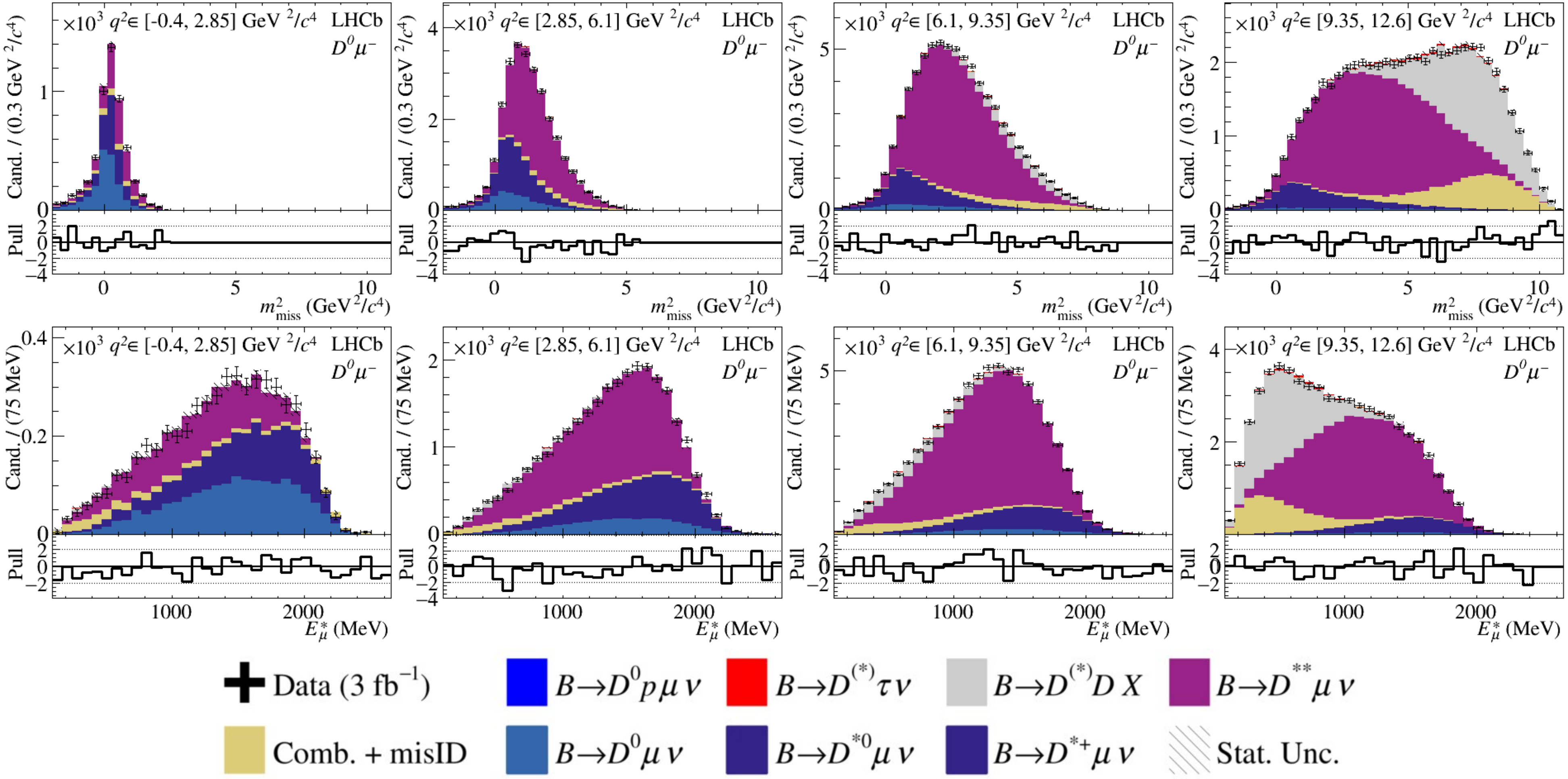
🟦 $B\to D^0\mu\nu$

🟦 $B\to D^{*0}\mu\nu$

🟦 $B\to D^{*+}\mu\nu$

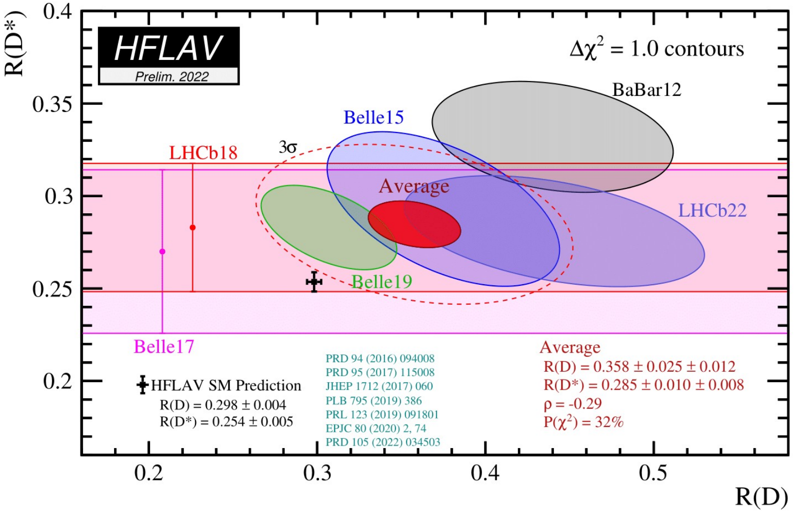
LHCb: Example Control Region

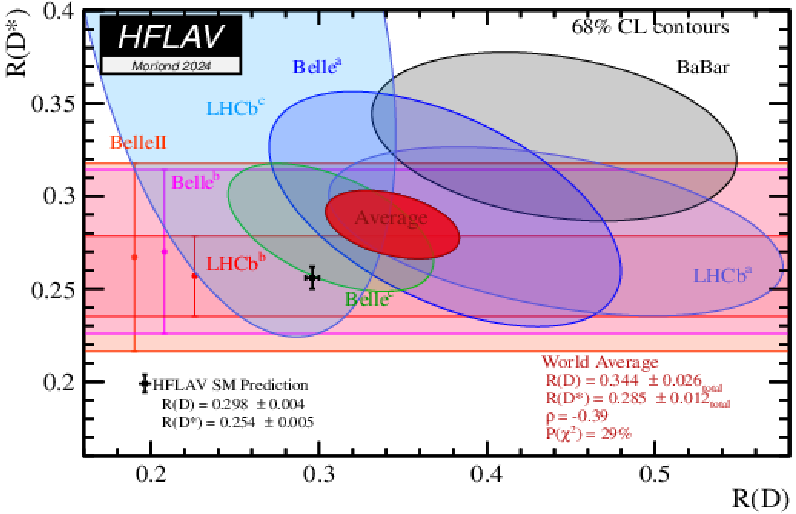
$D^0\mu$ + exactly one additional π



Interpretation of $b \to c\ell\nu$

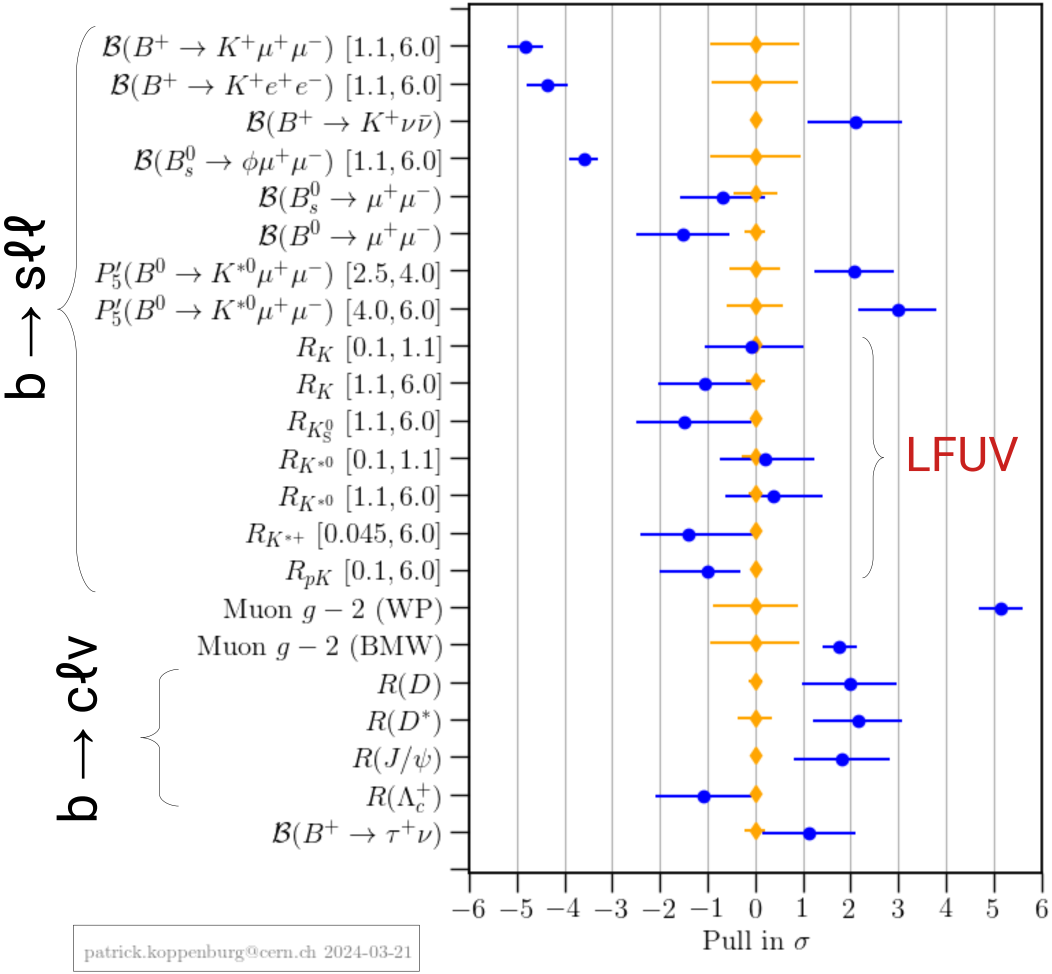
- The process is tree-level in the SM: visible modifications require large BSM contribution
  - presumably tree-level
- Measurements pulling away from SM are combined R(D)/R(D*) determinations
- No conclusive single experiment measurements, frustrating situation





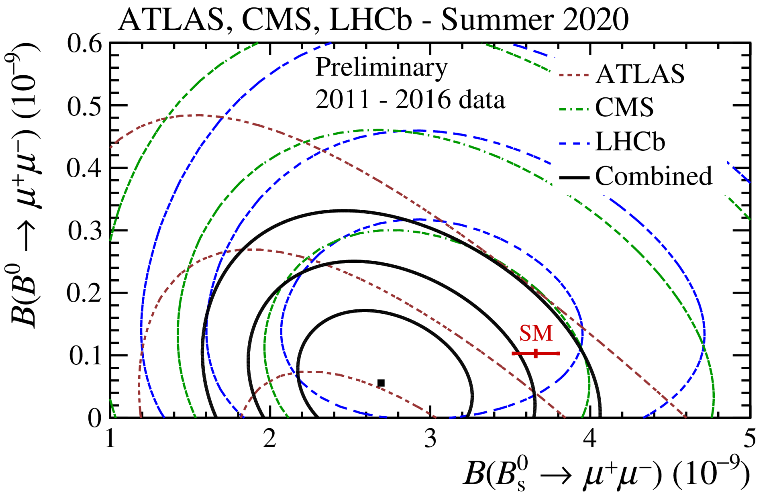
Anomaly summary

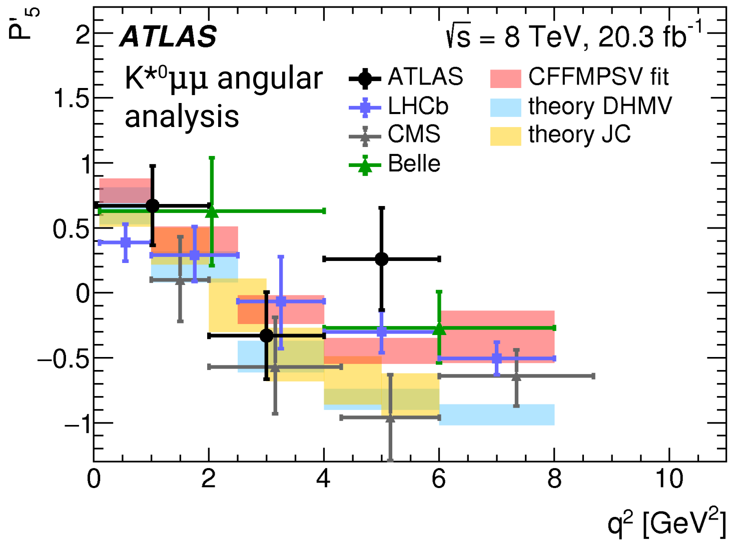
- Lots of channels show few-σ departures from prediction
- $b \to s\ell\ell$ completely driven by LHCb except for P_5' and $B_{(s)} \to \mu\mu$
- $b \to c\ell\nu$ has important contribution from B factories (especially R(D))



ATLAS × B anomalies

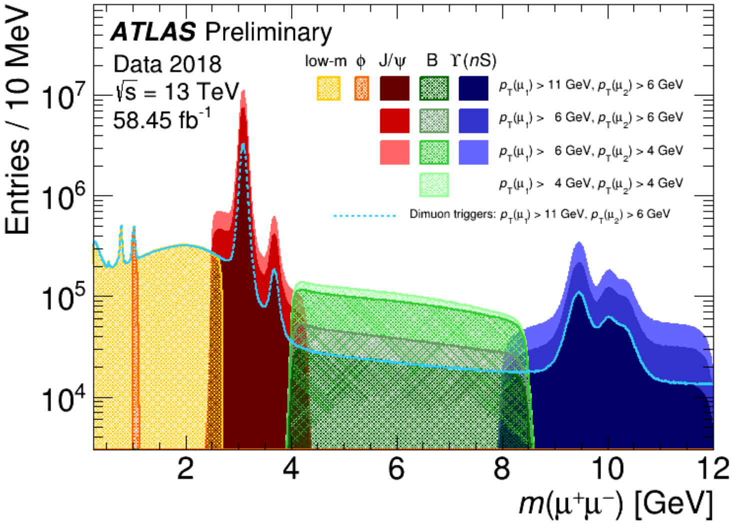
- Overall, ATLAS has a lot of data
  - in many cases we can be competitive with LHCb, e.g. $B_s \to \mu\mu$ for the same years of running has similar sensitivity for all experiments
- We also are an independent experiment with different systematics
  - observation of new physics needs confirmation
- Our capabilities depend strongly on triggers
  - OK with inclusive dimuon, great if we can do dimuon + X
- Lack of particle ID not so important if intermediate resonances are used to reduce background

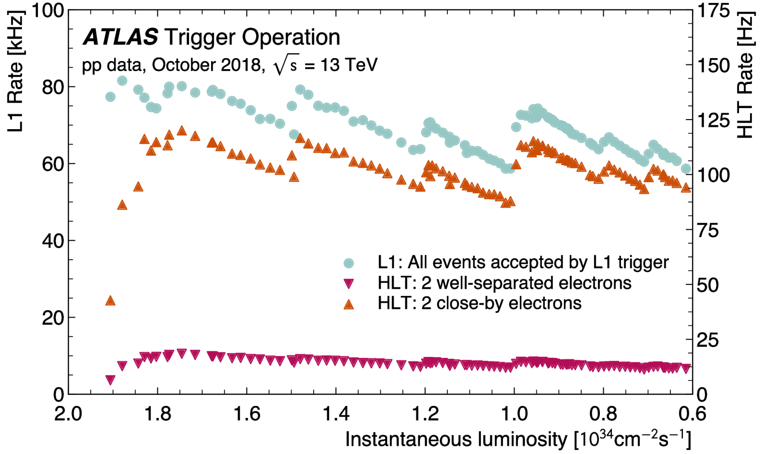




ATLAS Triggers

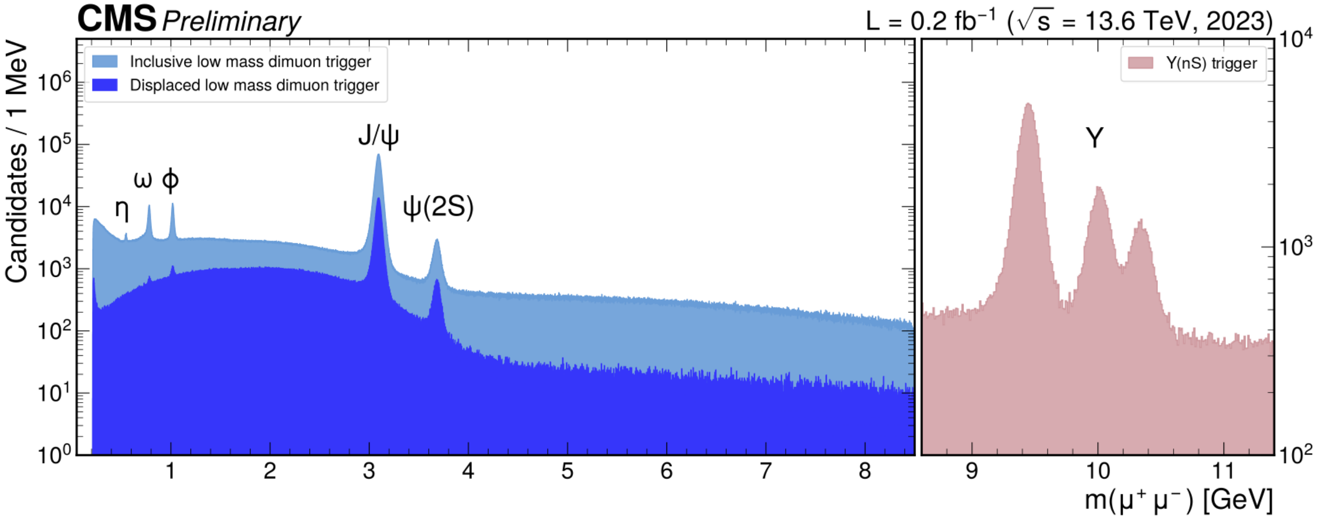
- L1 dimuon triggers are the base for muon channels
  - Dedicated chains at HLT which find additional tracks and reconstruct μμ+X to boost rate
- Dielectron triggers use all L1 accepts and searches for soft electrons at HLT
  - looking to reduce the set of L1 items to those that produce reasonable rate
  - separate chains that use L1 EM+EM (or jet+EM) items





ATLAS vs CMS Triggering Strategies

- CMS has cleaner low-p_T hardware triggers for muons than does ATLAS, can tolerate a higher rate into the software trigger
- CMS has a few strategies for increasing data rate:
  - "parking": record events to be reconstructed later, when offline resources become available. Trigger on muon from a "tag" B decay.
  - "scouting": reconstruct muons in the software trigger, write out only very high-level information.
- ATLAS can do these, as well as writing "partial events" (writing out only parts of the raw data for an event)
  - our studies do not find these to be optimal strategies for us



Summary & Outlook

- Precision measurement in B physics complements direct searches for new physics
- Lepton flavor universality is gone, but regardless, still very significant departures from SM expectation in $b \to s\ell\ell$
- $b \to c\ell\nu$ anomalies still there but (to my taste) less compelling
- However experiments other than LHCb need to step up and confirm measurements
  - ATLAS and CMS have capabilities in this regard