Flavor observables at HE/HL LHC in view of anomalies

HL/HE LHC Meeting
Fermilab

April 5, 2018

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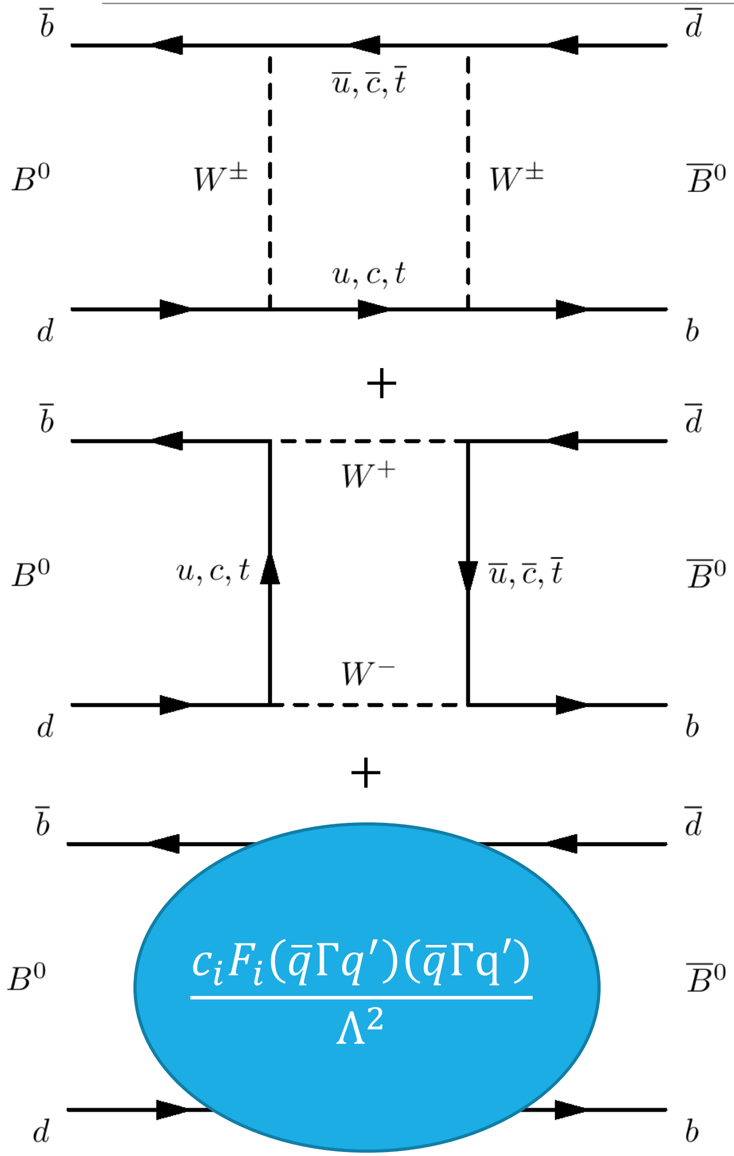
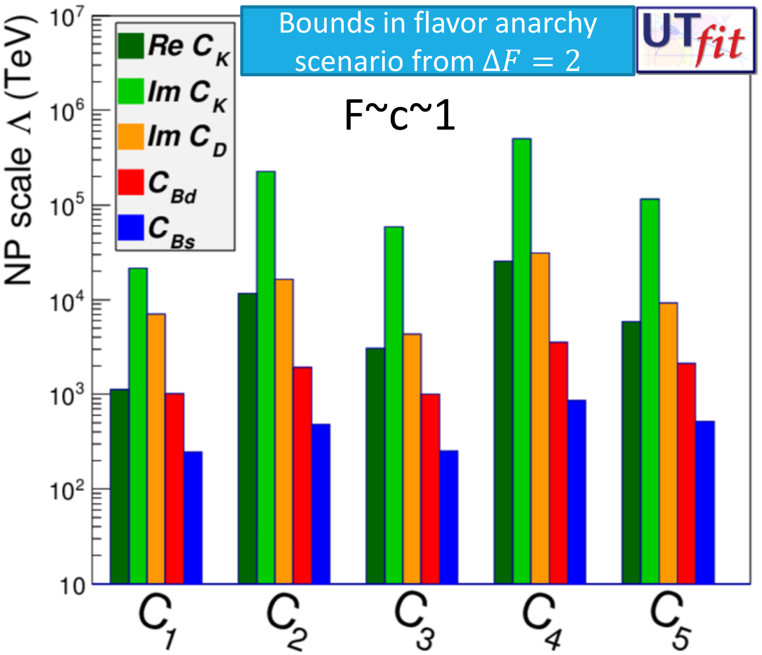
On behalf of the LHCb Collaboration

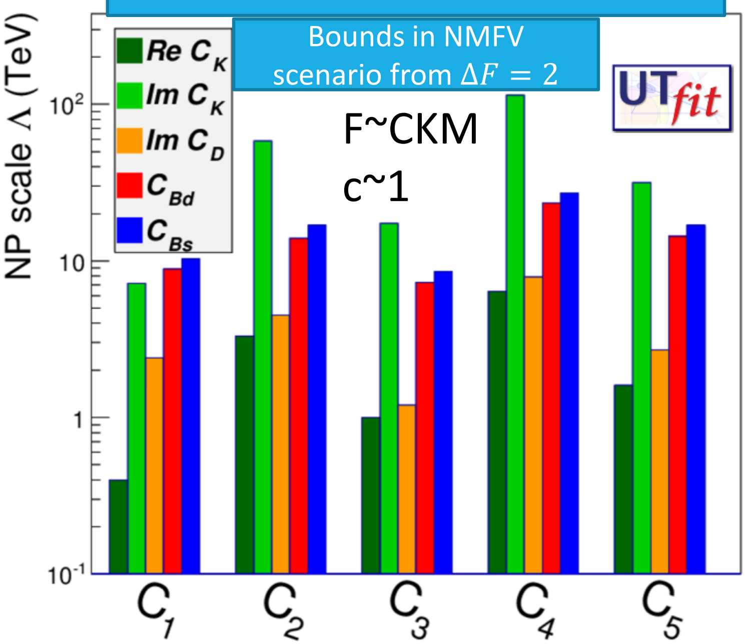
Flavor's Reach



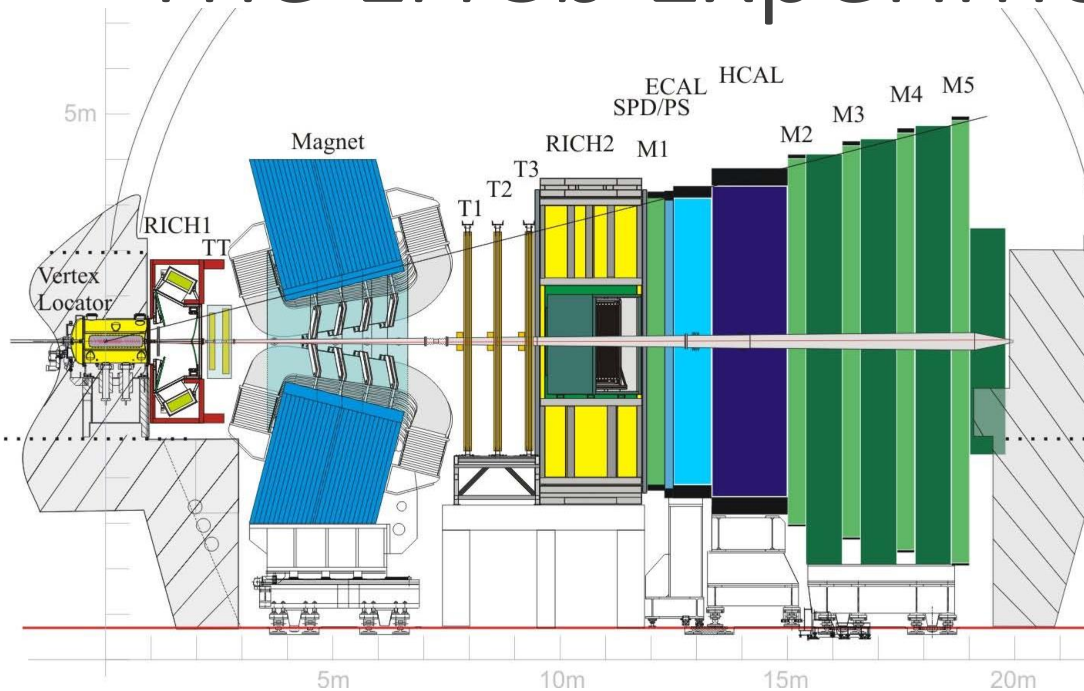
Diagrams from C. Elsasser's FDL

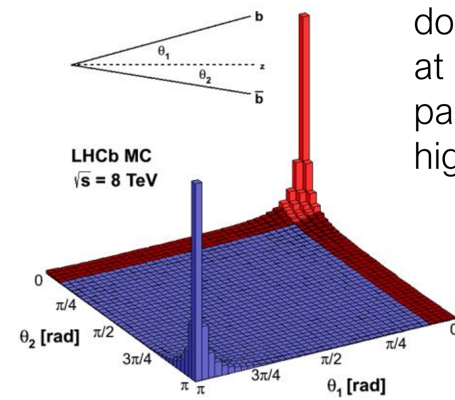


UTFit collaboration arXiv:1710.09644



The LHCb Experiment





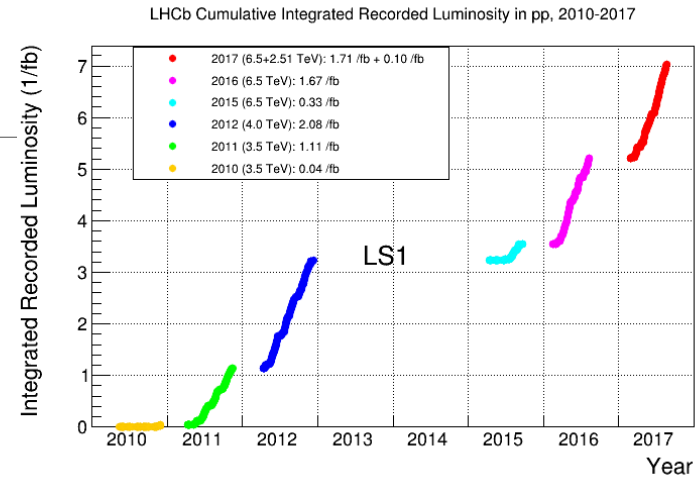
$b\bar{b}$ production dominantly at lower p_T: parton CM frame highly boosted

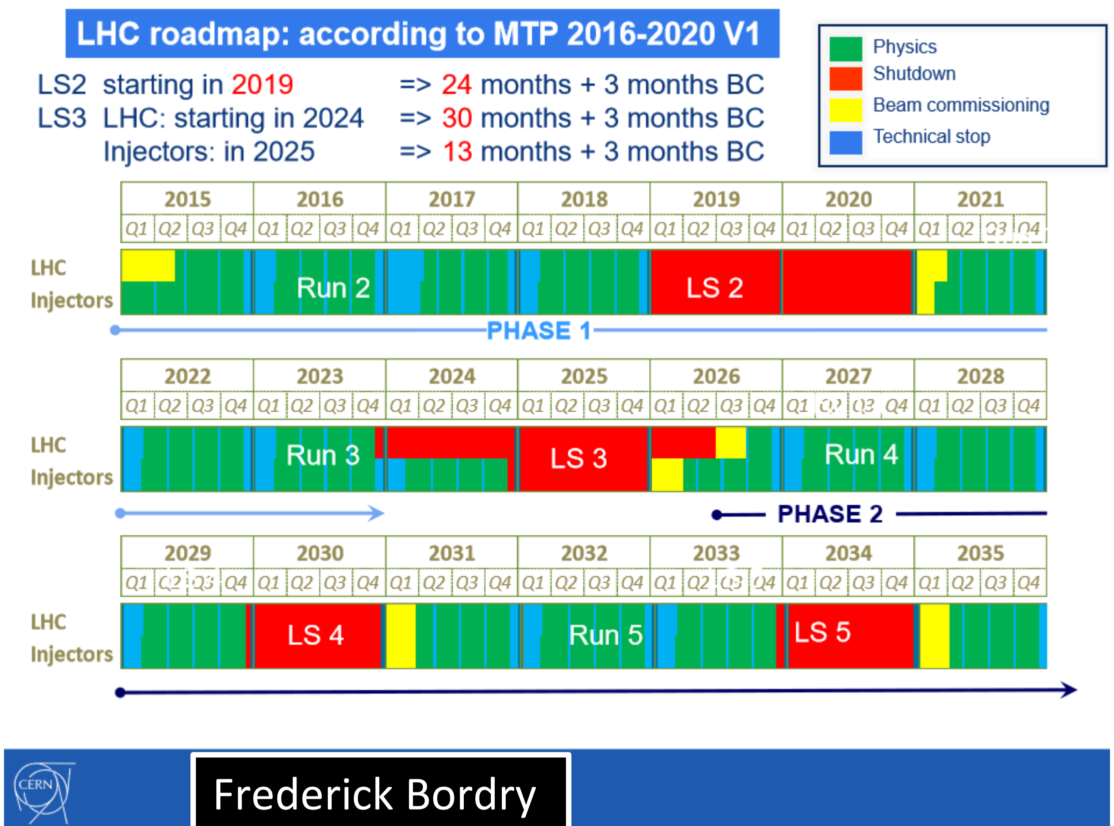
At 7 TeV:
σ_{inel} ~70 mb
$\sigma_{c\bar{c}}$ ~ 6 mb
$\sigma_{b\bar{b}}$ ~ 280 μb

- Focus on forward direction to exploit highly-boosted b quark production in multi-TeV collisions: cover 27% (25%) of (pair) production while instrumenting < 3% of the solid angle (value!)
- Single arm spectrometer optimized for beauty and charm physics at large η:
  - Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
  - Tracking: σ_p/p ~ 0.4%–0.6% (p from 5 GeV to 100 GeV), $\sigma_{IP} = (15 + 29/p_T[\text{GeV}])\mu\text{m}$
  - Vertexing: σ_τ ~ 45 fs for $B_s \to J/\psi\phi$
  - PID: 97% μ ID for 1-3% $\pi \to \mu$ misID, 95% K ID for 5% $\pi \to K$ misID

LHCb in the HL-LHC Era

- LHCb is on target to hit ~ 8/fb by LS2
  - Goal: increase dataset by an order of magnitude (50/fb) over runs 3&4
    - Run 4 concurrent with HL-LHC running of CMS & ATLAS
  - Key ingredients:
    - 40 MHz readout plus all-software trigger
      - Online detector alignment and calibration for offline-quality reco in trigger proven in Run2
    - Improved segmentation; pixel vertex detector

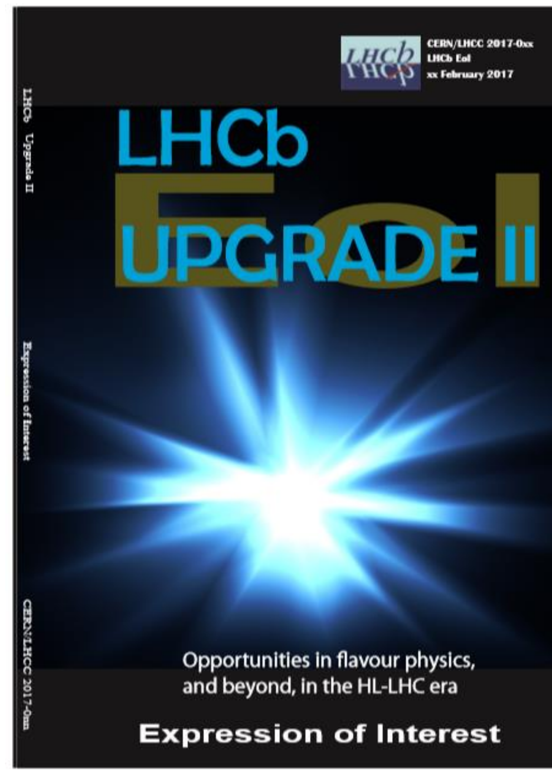




LHCb Upgrade Phase 2

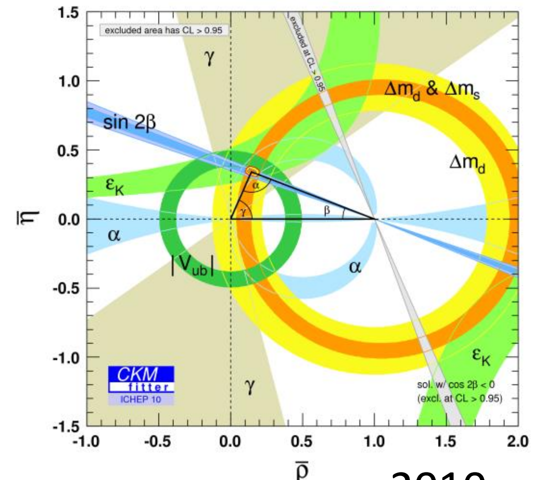
- HL-LHC upgrades can be exploited at point 8 by allowing LHCb to run at 10^{34} without disrupting high PT experiments
- Machine potential:
  - HL-LHC can run point 8 at $2 \times 10^{34}/cm^2s$ with negligible lumi impact for CMS and ATLAS
  - Total Point 8 integrated luminosity limited by radiation hardness of optics to ~ 300/fb
- LHCb must be re-upgraded and re-optimized to retain present performance at a pileup of 50
  - Requires further improvement in segmentation, improved pixel VELO with O(200ps) timing

G. Wilkinson
Theatre of Dreams: Beyond the LHCb Phase 1 Upgrade

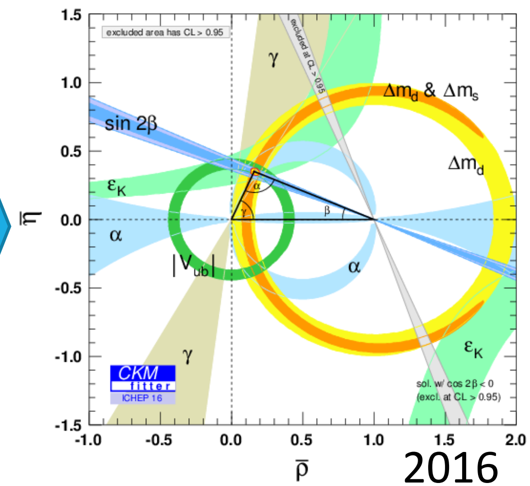


Impact of flavor at LHC

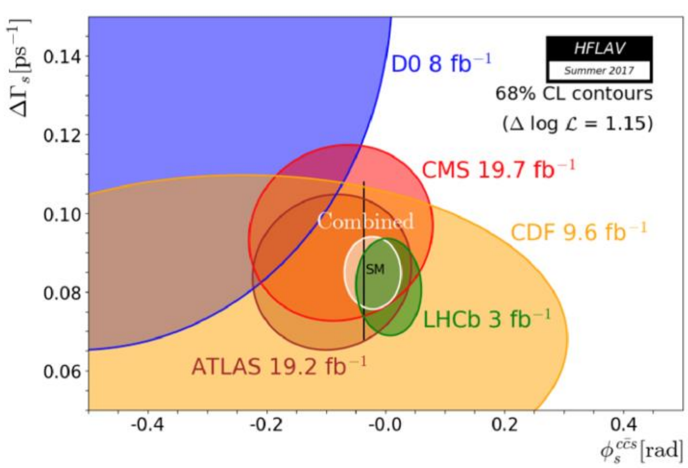
- CKM uncertainties steadily shrinking – huge impact on knowledge of γ



2010

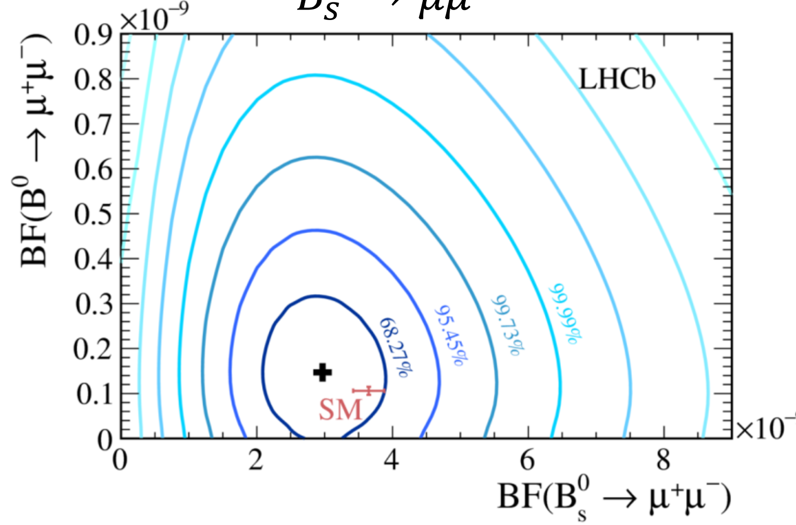


2016



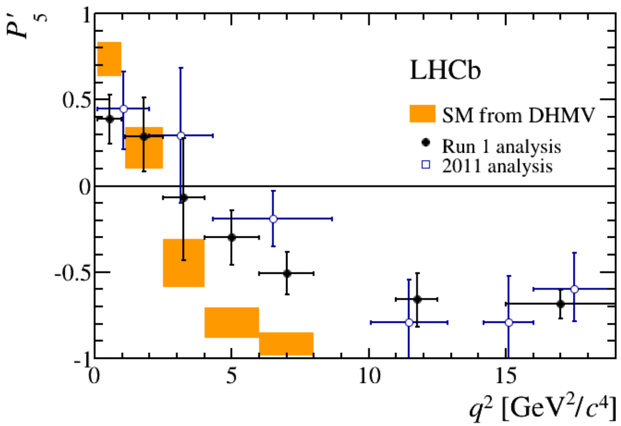
- B_s^0 mixing parameters and NP contributions to becoming steadily more constrained, plus competitive contributions to B^0 mixing parameters

$B_s^0 \rightarrow \mu\mu$

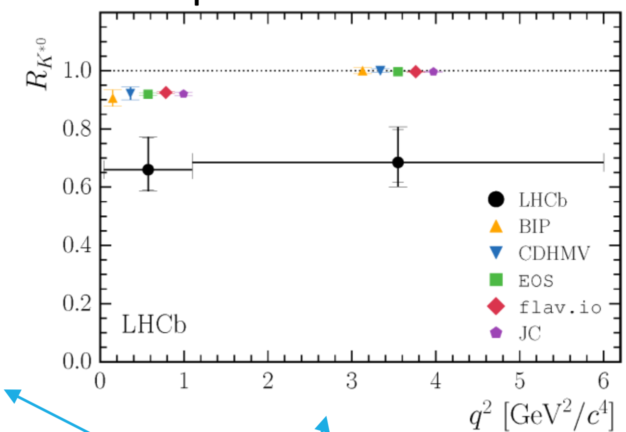


B hadron anomalies

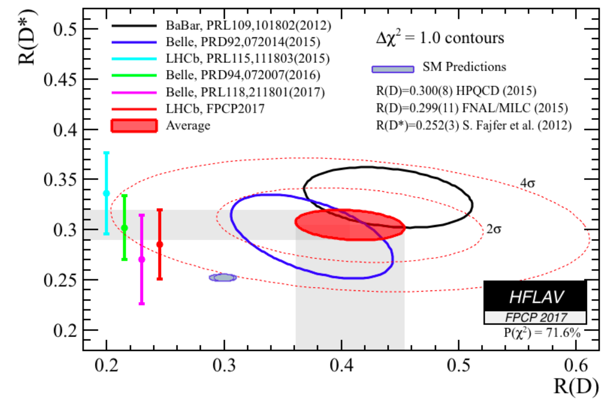
Angular distributions in $B^0 \to K^* \mu^+ \mu^-$



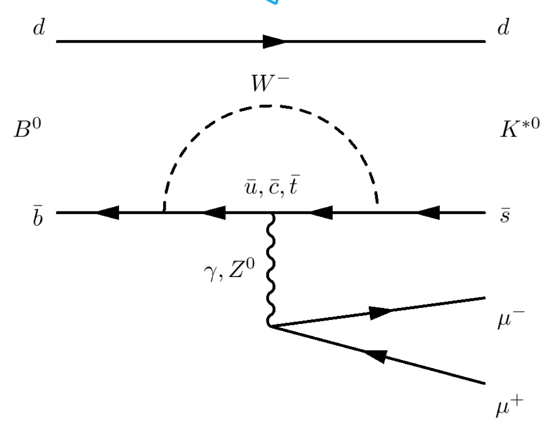
Deficit of $B \to K^{(*)}\mu\mu$ compared to $B \to K^{(*)}ee$

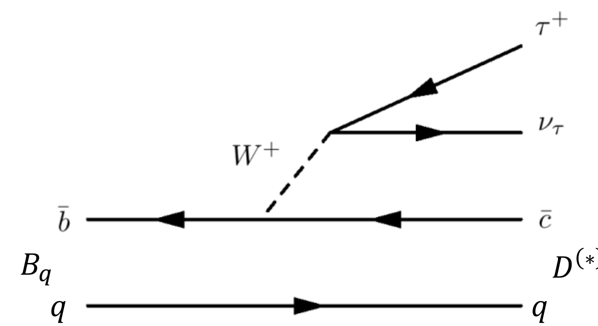


$B \to D^{(*)}\tau\nu$ excess



Quick acknowledgement: Much of this has been covered in more detail at previous workshops by Mitesh Patel, Paula Alvarez Cartelle, and Lucia Grillo, from which I'm borrowing a lot. See their linked slides for more!

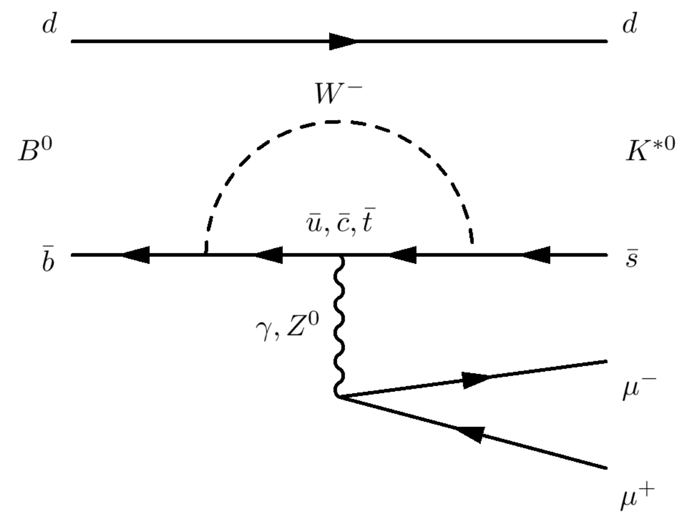


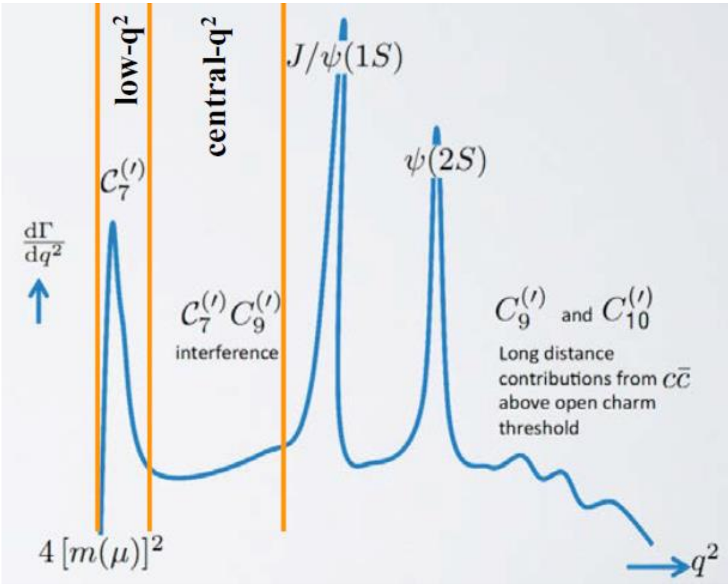


Diagrams from C. Elsasser's FDL

Electroweak Penguin Decays

- Powerful testbed of the electroweak interaction
  - All major SM EW players appearing in a FCNC loop
  - New particles connected to EWSB can introduce q^2- or angle-dependent interference
    - $q^2 \equiv (p_{\ell^+} + p_{\ell^-})^2$
- Excellent targets for both LHCb & upgrade
  - Dilepton in final state = efficient trigger in crowded events
  - Rich phenomenology of observables
  - SM calculations become unreliable near $m(\ell\ell) = m(J/\psi), m(\psi(2S))$
    - ($b \to c\bar{c}s$ amplitudes, $c\bar{c}$ vacuum polarization, long distance effects…)
    - Low q^2 preferred





FCNC Anomalies

- Run1 dataset: intriguing but inconclusive deviations, especially in angular observables
- LFU violating observables

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)} \overset{SM}{\Longrightarrow} 1 \pm \mathcal{O}\left(10^{-3}\right)$$

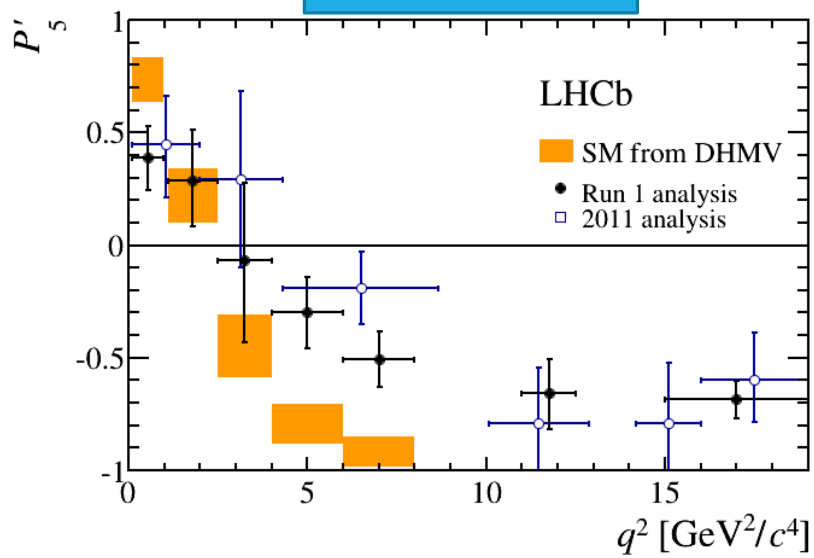
  - Clean observables, but limited by statistics of e^+e^- modes at LHCb
  - LHCb:

$$R_{K^*}\left(low\ q^2\right) = 0.66\,^{+0.11}_{-0.07} \pm 0.03$$

$$R_{K^*}\left(central\ q^2\right) = 0.69\,^{+0.11}_{-0.07} \pm 0.05$$

$$R_{K,\ q^2<6\text{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

JHEP 02 104 (2016)



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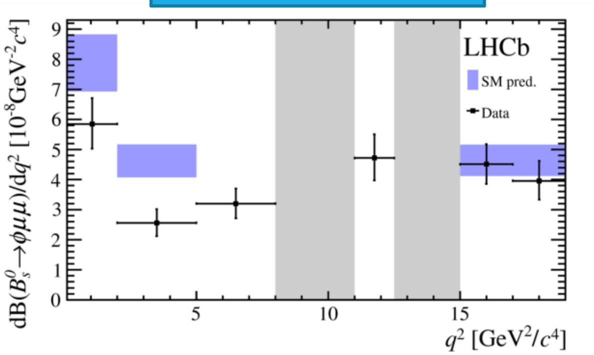

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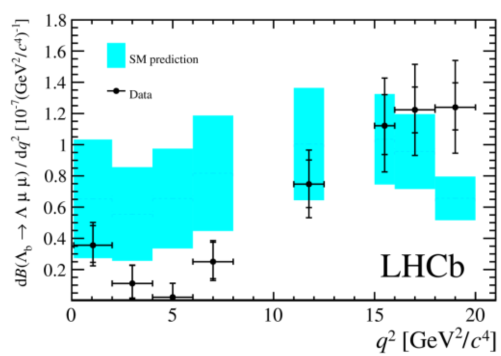

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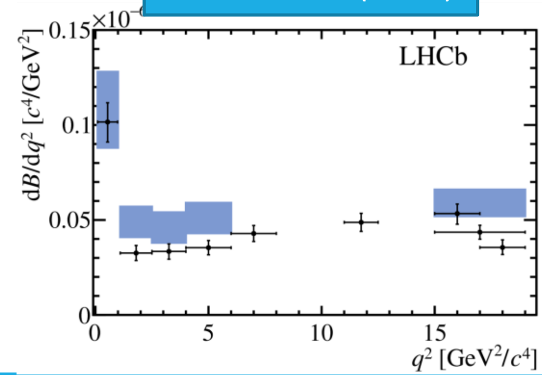
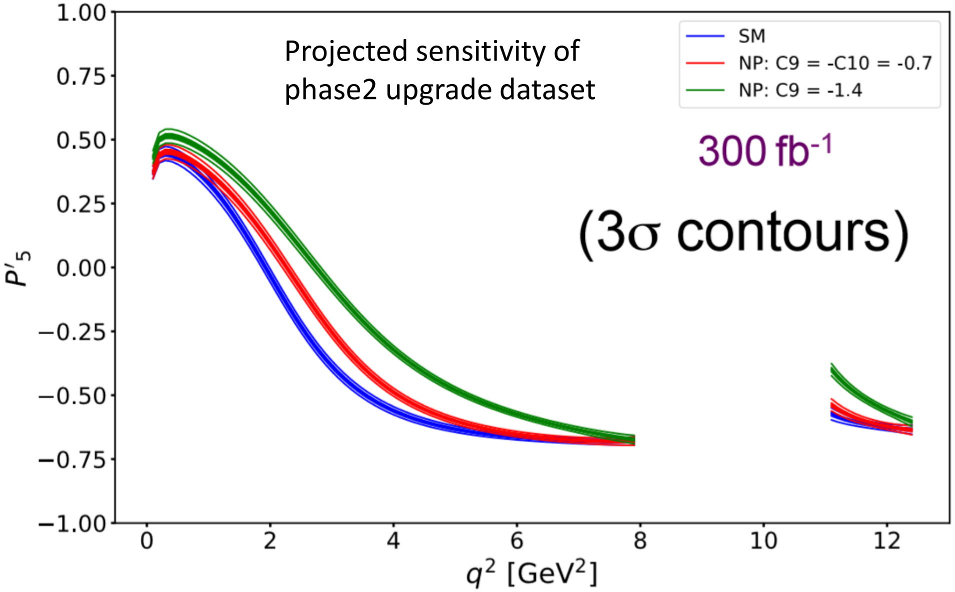
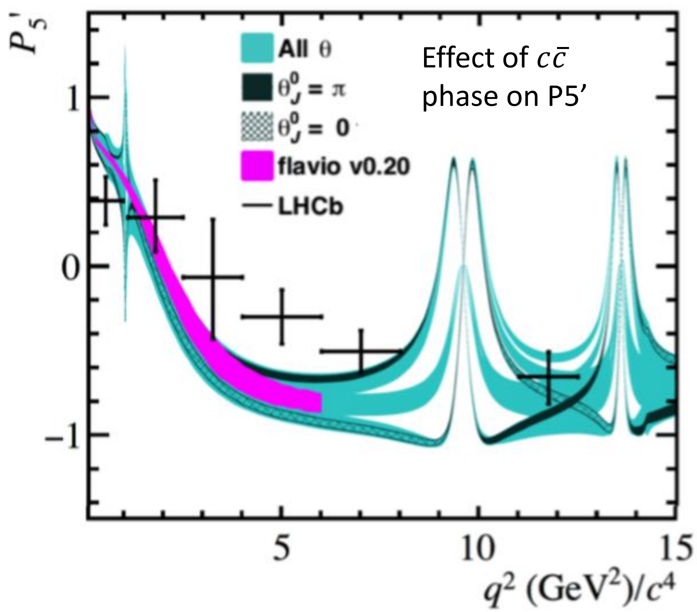


Prospects for Differential Observables

M. Patel, 3rd Workshop on LHCb Upgrade II

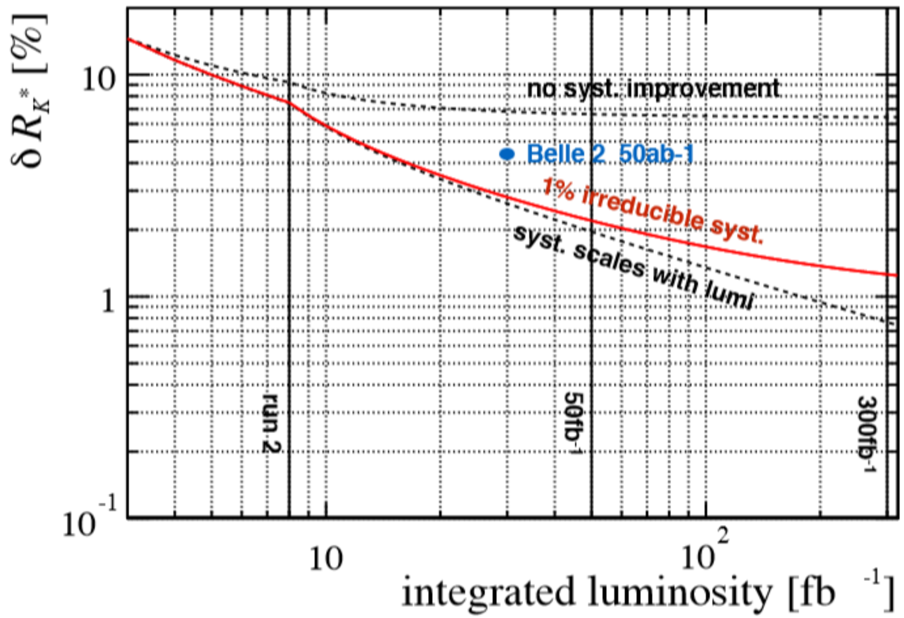


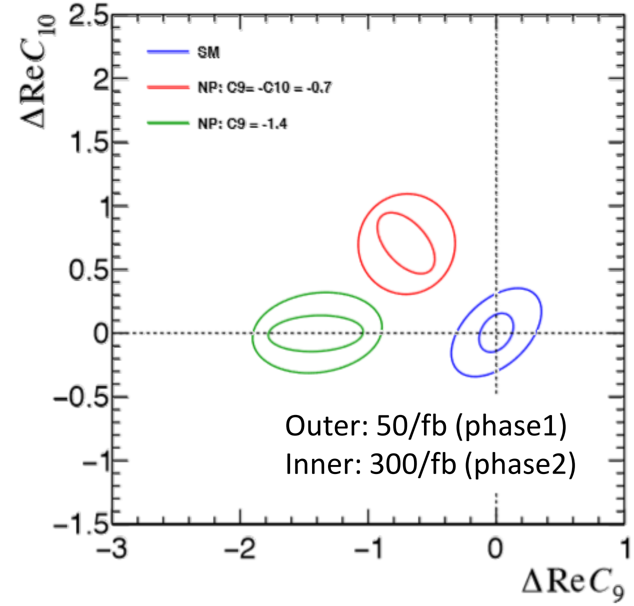
[Blake et al., arXiv:1709.03921]



- 50 (or 300)/fb will allow for extremely precise differential measurements
- With enough related data, can directly fit for parameters in models of hadronic form-factors
  - Can also potentially fit for effects of $c\bar{c}$ resonances directly from the data (with an appropriate model)
- Requires muon system performance similar to present detector to fully exploit in spite of busier events and larger radiation backgrounds

LFU plus angular observables





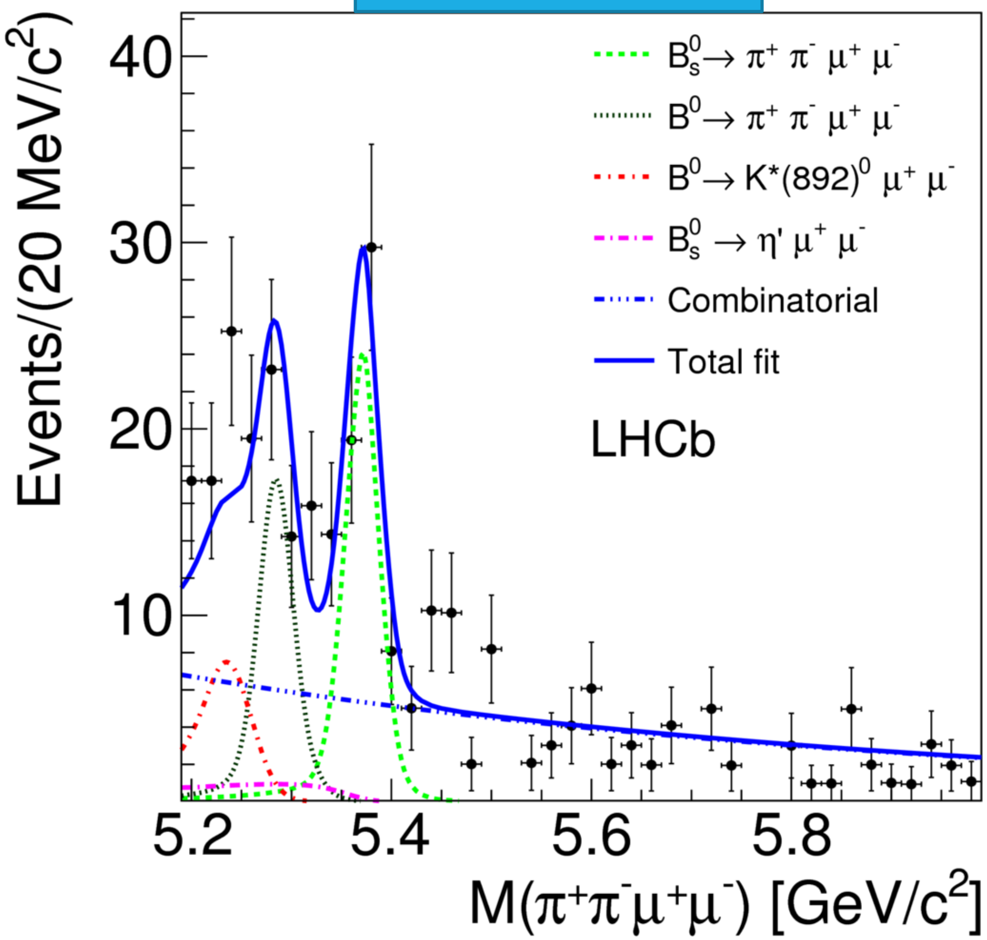
- Powerful idea going forward will be measuring LFU-violating differences in angular observables
  - Best of both worlds, potentially a very powerful probe to characterize what other observables may be presently hinting at

- Will require improvements to LHCb ECAL for Phase-II to boost $e^{\pm}$ performance and bremsstrahlung recovery

New Possibilities

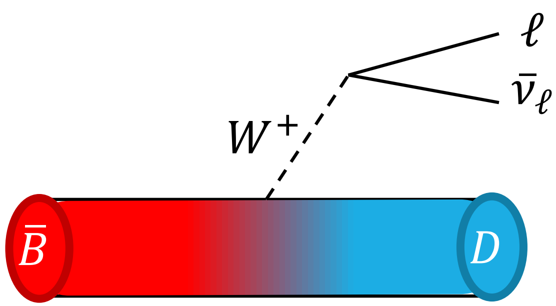
- $b \to d\ell\ell$
  - $B_s^0 \to \overline{K}^{*0}\mu\mu$ in phase 2 at similar statistics similar to current measurements in B^0 decay
  - $B^0 \to \rho^0\mu\mu$ requires flavor tag, careful treatment of $\pi\pi$ resonances
    - Flavor tagging expected to be limiting factor in statistics here, but contrarywise small improvements in FT can potentially dramatically boost sensitivity
  - LFU tests with $B \to \pi\ell\ell$

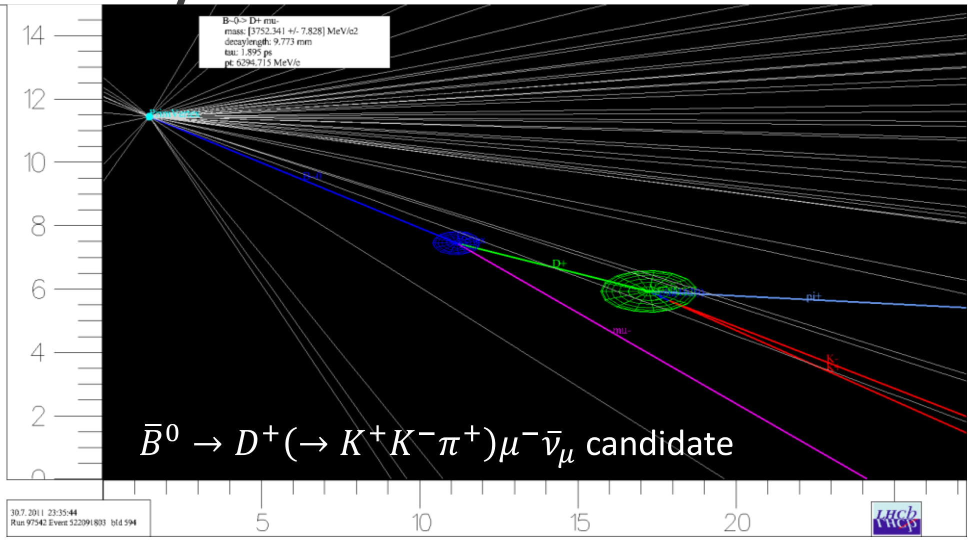
PLB 743, 46 (2015)



- Sum of exclusives $b \to X_s\ell\ell$ also interesting with enough statistics?

Semileptonic B decays



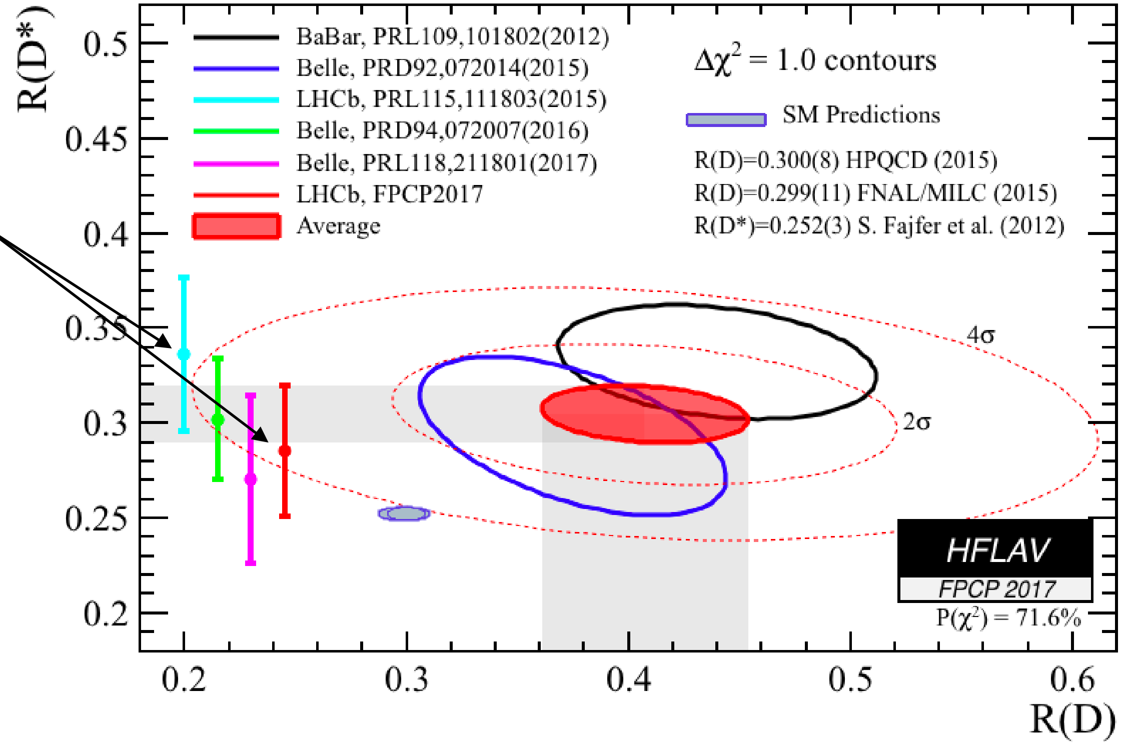


- "Beta decay" of B hadrons – signature is lepton (μ or e (or τ!)) , recoiling hadronic system, and missing momentum
- Theoretically well-understood in the SM
  - No QCD interaction between the lepton-neutrino system and the recoiling hadron(s)
  - Nonperturbative hadronic matrix element can be parameterized and fit in data/lattice
- Main LFU observable:

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{(*)}\mu^-\bar{\nu}_\ell)} = \begin{cases} D^* \to 0.252(3) \text{ [PRD } \mathbf{85} \text{ 094025 (2012)] (CLN)} \\ D \to 0.300(8) \text{ [EPJ } \mathbf{C77} \text{ 112 (2017)](Lattice/FLAG)} \end{cases}$$

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

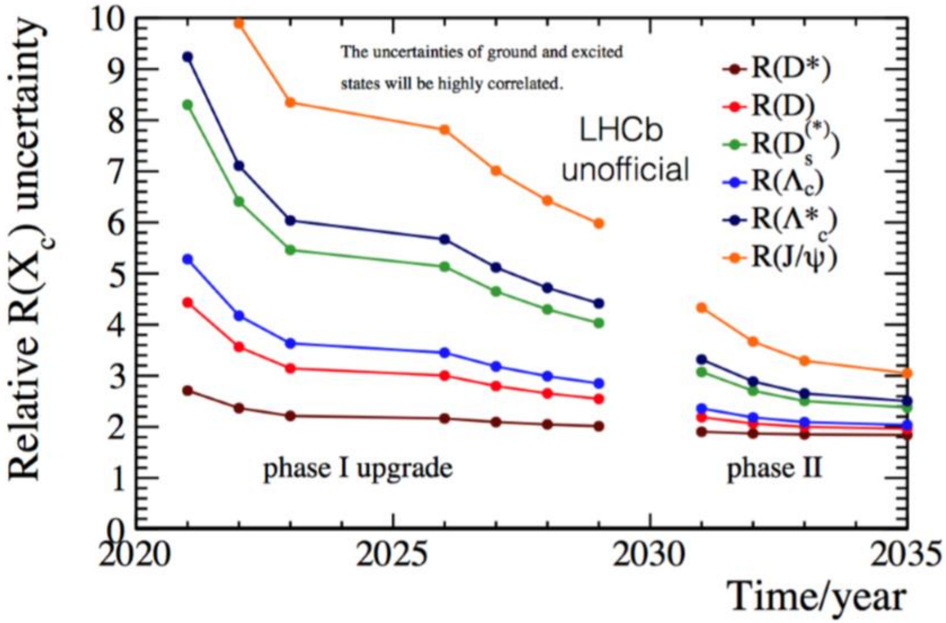
LHCb Results
(so far)



- With new LHCb result, deviation of world average from SM remains at about 4σ
- Preferred NP models look like W' or Leptoquarks, and suggest complimentary searches in $B \to K^{(*)}\nu\bar{\nu}$ and $B \to K^*\mu\tau$
- Highest experimental priority is improved measurements – only one single result over 3σ (BaBar), must be cautious with judicious averaging

LFU Ratio prospects

- General prospects for increasing precision of core observables ($R(X_c)$) are relatively well-established
  - Ultimate sensitivity depends on what systematics become limiting
  - Large datasets -> large control samples -> most systematics can be reduced

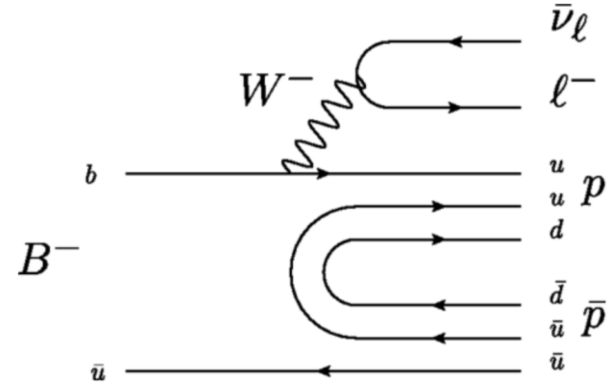


- Right: projections if limiting systematics become combinatorial background shapes, PID efficiencies, data/MC corrections

- Absolutely crucial that computing keep up with data (need simulation ~4x data to keep up)
  - Raw power/architecture improvements?
  - Improved FastMC? (systematics?)

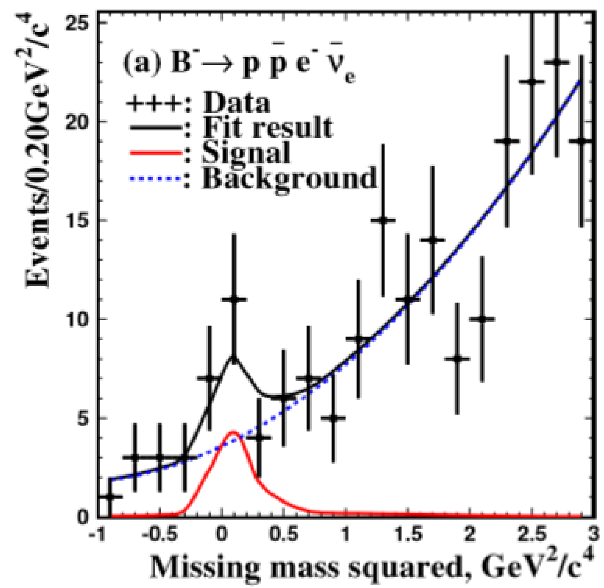
$b \to u\tau\nu$

- $b \to u$ semileptonics are challenging due to very large combinatoric backgrounds
  - Low daughter multiplicity, no tertiary vertex
  - One handle: rarer X_u systems (p, K instead of π)
  - Example: Existing LHCb result on $|V_{ub}|$ in $\Lambda_b^0 \to p\mu\nu$ is already systematics limited with just Run1
    - External inputs dominate – form factors, $\Lambda_c^+ \to pK\pi$



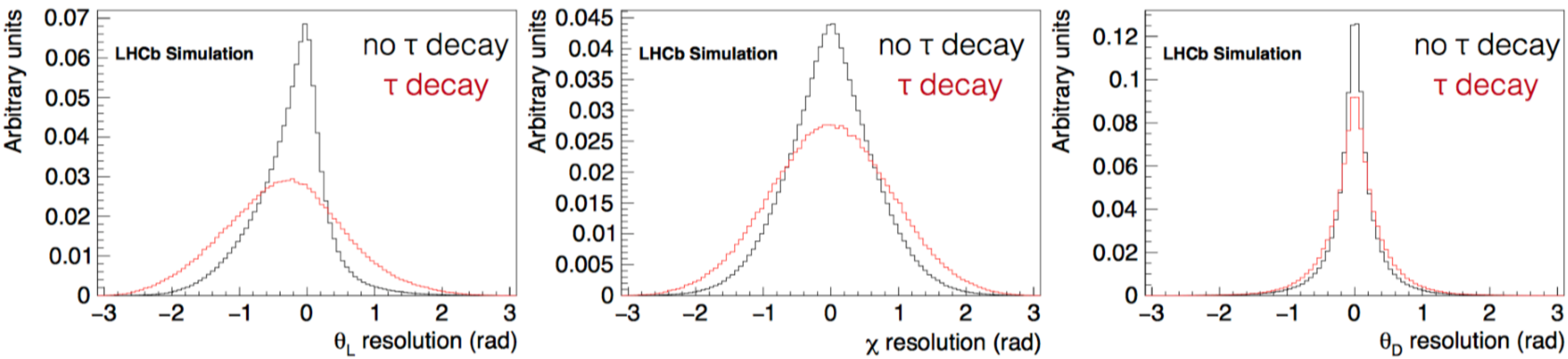
Belle - PRD 89, 011101 (2014)

$$\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6}$$

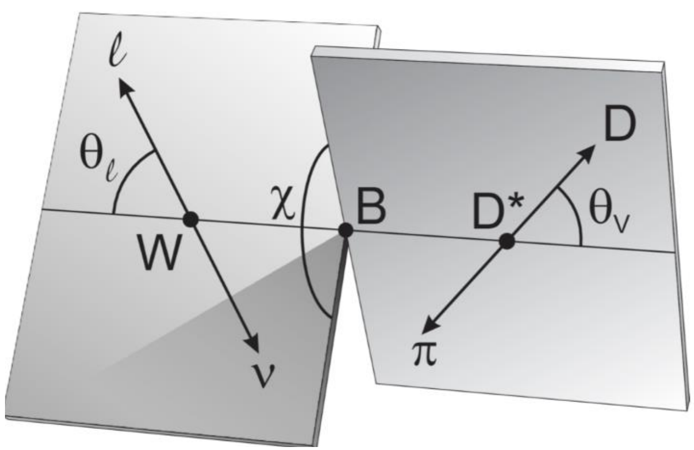


- Probably the most promising target: $B^- \to p\bar{p}\tau\nu$
  - Expect O(1000) normalization in first search for this mode at LHCb, by Run5 could have similar stats to 2015 LHCb R(D*) measurement
  - Many challenging partially reconstructed bkgds

Angular observables



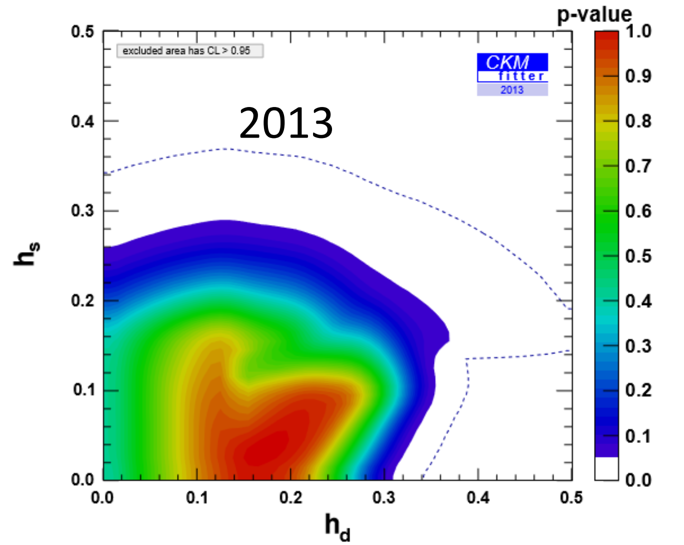
- With very high statistics more handles become available for differential measurements in angles or other variables
  - Can nail down spin structure of NP contributions
  - Also useful for model-independent SM characterization



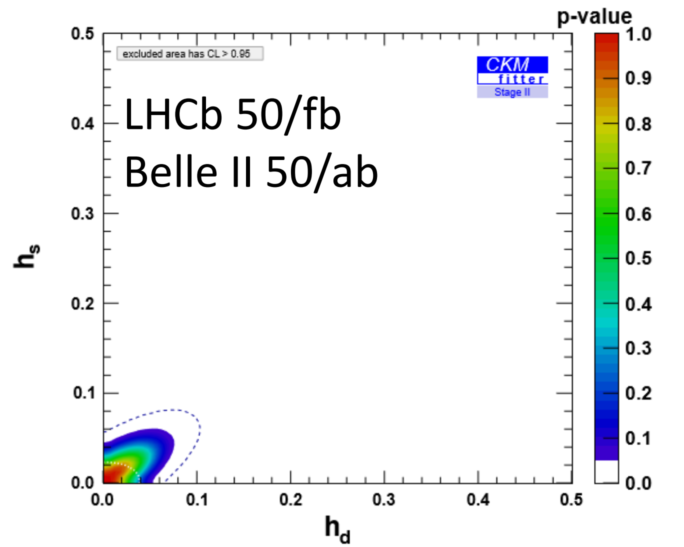
- Resolutions are wide – unfolding (or forward-folding BSM models) and very high statistics is a must
  - Tools (HAMMER) and workflows underway to reweight detector and reconstruction-folded MC to arbitrary model (plugins provided by theorist) – potentially powerful paradigm

Conclusion

- Broad picture: Next decade will see a huge step forward for flavor datasets and associated HEP instrumentation, with a possible second large step immediately afterwards
  - NP contributions to, e.g., B mixing can be pushed to 1% level, probing O(20 TeV) scales for tree-level NP



- Current B physics anomalies present an intriguing path for further exploration
  - LHCb upgrade datasets will be able to push the core observables to new levels of sensitivity as well as cover a host of complimentary ones
    - Many of these complementary observables are good discovery tools in their own right!
  - Statistics in both signal and associated control samples are key to this program
  - Vital to keep current detector performance at higher pileup to fully exploit this data



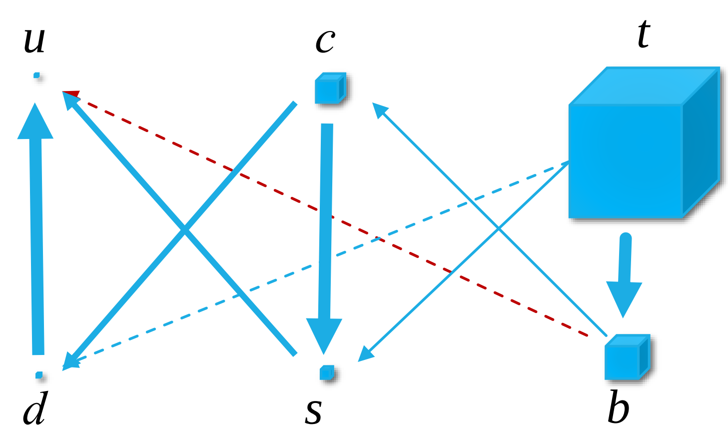
Backups

Quark flavor, CKM, and b-physics

- V_{CKM} hierarchical & nearly diagonal
  - Transitions mixing different generations suppressed
  - 3rd generation especially "isolated"
- -> Suppression of all tree-level b quark decay amplitudes
  - $|Vcb| \sim 0.04$
  - Makes B physics quite sensitive to NP generically misaligned with CKM
  - Also leads to long b quark lifetime: $c\tau_B \sim 400\mu m$! (= about 2x charm lifetime)

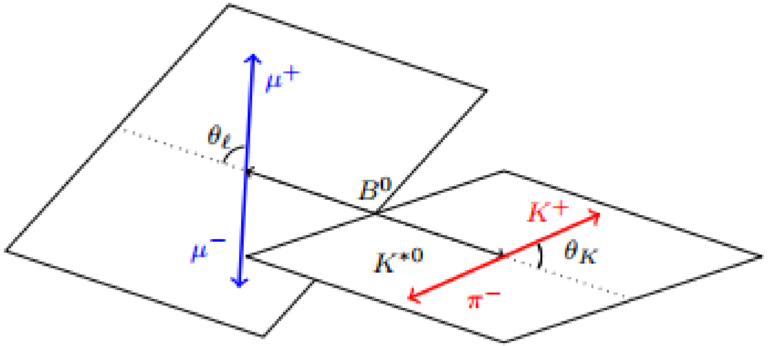
Quarks spin =1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \longrightarrow$$



K*μμ Angular Distribution

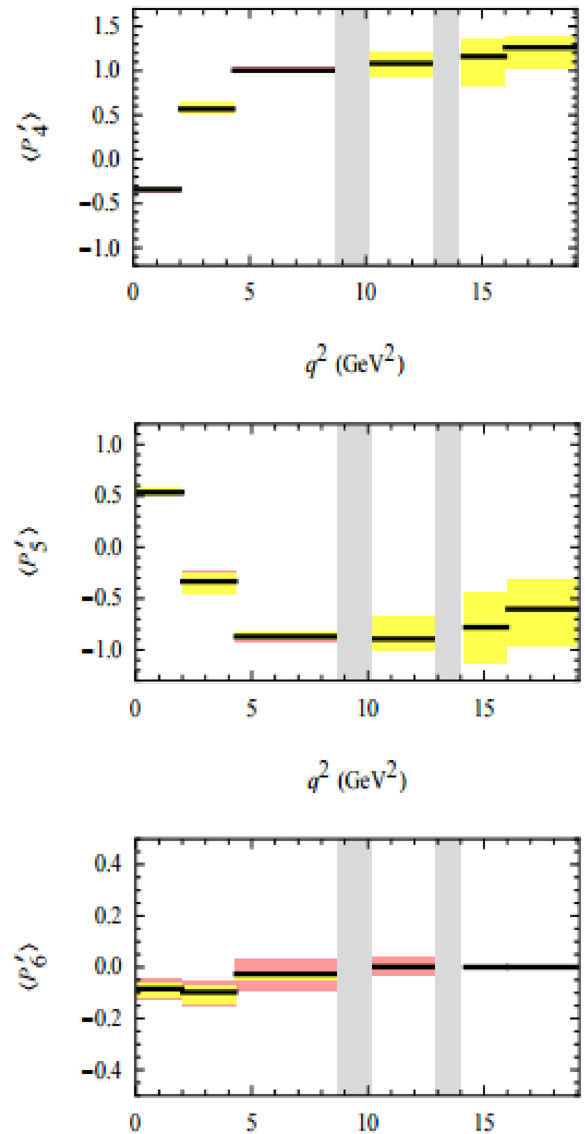
j	I_j	f_j
1s	$\frac{3}{4}\left[|\mathcal{A}_\parallel^{\rm L}|^2 + |\mathcal{A}_\perp^{\rm L}|^2 + |\mathcal{A}_\parallel^{\rm R}|^2 + |\mathcal{A}_\perp^{\rm R}|^2\right]$	$\sin^2\theta_K$
1c	$|\mathcal{A}_0^{\rm L}|^2 + |\mathcal{A}_0^{\rm R}|^2$	$\cos^2\theta_K$
2s	$\frac{1}{4}\left[|\mathcal{A}_\parallel^{\rm L}|^2 + |\mathcal{A}_\perp^{\rm L}|^2 + |\mathcal{A}_\parallel^{\rm R}|^2 + |\mathcal{A}_\perp^{\rm R}|^2\right]$	$\sin^2\theta_K \cos 2\theta_\ell$
2c	$-|\mathcal{A}_0^{\rm L}|^2 - |\mathcal{A}_0^{\rm R}|^2$	$\cos^2\theta_K \cos 2\theta_\ell$
3	$\frac{1}{2}\left[|\mathcal{A}_\perp^{\rm L}|^2 - |\mathcal{A}_\parallel^{\rm L}|^2 + |\mathcal{A}_\perp^{\rm R}|^2 - |\mathcal{A}_\parallel^{\rm R}|^2\right]$	$\sin^2\theta_K \sin^2\theta_\ell \cos 2\phi$
4	$\sqrt{\frac{1}{2}}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_\ell \cos\phi$
5	$\sqrt{2}{\rm Re}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin\theta_\ell \cos\phi$
6s	$2{\rm Re}(\mathcal{A}_\parallel^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_\parallel^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin^2\theta_K \cos\theta_\ell$
7	$\sqrt{2}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_0^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin 2\theta_K \sin\theta_\ell \sin\phi$
8	$\sqrt{\frac{1}{2}}{\rm Im}(\mathcal{A}_0^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_0^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin 2\theta_K \sin 2\theta_\ell \sin\phi$
9	${\rm Im}(\mathcal{A}_\parallel^{\rm L*}\mathcal{A}_\perp^{\rm L} + \mathcal{A}_\parallel^{\rm R*}\mathcal{A}_\perp^{\rm R})$	$\sin^2\theta_K \sin^2\theta_\ell \sin 2\phi$
10	$\frac{1}{3}\left[|\mathcal{A}_{\rm S}^{\rm L}|^2 + |\mathcal{A}_{\rm S}^{\rm R}|^2\right]$	1
11	$\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K$
12	$-\frac{1}{3}\left[|\mathcal{A}_{\rm S}^{\rm L}|^2 + |\mathcal{A}_{\rm S}^{\rm R}|^2\right]$	$\cos 2\theta_\ell$
13	$-\sqrt{\frac{4}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_0^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_0^{\rm R*})$	$\cos\theta_K \cos 2\theta_\ell$
14	$\sqrt{\frac{2}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\parallel^{\rm R*})$	$\sin\theta_K \sin 2\theta_\ell \cos\phi$
15	$\sqrt{\frac{8}{3}}{\rm Re}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin\theta_\ell \cos\phi$
16	$\sqrt{\frac{8}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\parallel^{\rm L*} - \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin\theta_\ell \sin\phi$
17	$\sqrt{\frac{2}{3}}{\rm Im}(\mathcal{A}_{\rm S}^{\rm L}\mathcal{A}_\perp^{\rm L*} + \mathcal{A}_{\rm S}^{\rm R}\mathcal{A}_\perp^{\rm R*})$	$\sin\theta_K \sin 2\theta_\ell \sin\phi$



- Full angular distribution described by 6 amplitudes $A_{0,\parallel,\perp}^{L,R}$ (+2 $A_S^{L,R}$ for S-wave component)
  - In turn these are dependent on $C_{7\text{-}9}$ and $C'_{7\text{-}9}$
  - Full angular distribution left

- Of particular interest are integrated decay rate vs q^2, forward-backward asymmetry, and particular combinations for which form factors cancel to leading order

Optimized Angular Observables



- Descotes-Genon, Hurth, Matais and Virto introduced a more optimized basis
  - Cancels leading FF uncertainties in theoretical predictions
  - (JHEP, 1305:137, (2013))
- Angular observables given by:
  (with corresponding CP asymmetry variables given by taking differences in numerators)

$$\langle P_1 \rangle_{\text{bin}} = \frac{1}{2} \frac{\int_{\text{bin}} dq^2 [J_3 + \bar{J}_3]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} ,$$

$$\langle P_2 \rangle_{\text{bin}} = \frac{1}{8} \frac{\int_{\text{bin}} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} ,$$

$$\langle P_3 \rangle_{\text{bin}} = -\frac{1}{4} \frac{\int_{\text{bin}} dq^2 [J_9 + \bar{J}_9]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} ,$$

$$\langle P'_4 \rangle_{\text{bin}} = \frac{1}{\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_4 + \bar{J}_4] ,$$

$$\langle P'_5 \rangle_{\text{bin}} = \frac{1}{2\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_5 + \bar{J}_5] ,$$

$$\langle P'_6 \rangle_{\text{bin}} = \frac{-1}{2\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_7 + \bar{J}_7] ,$$

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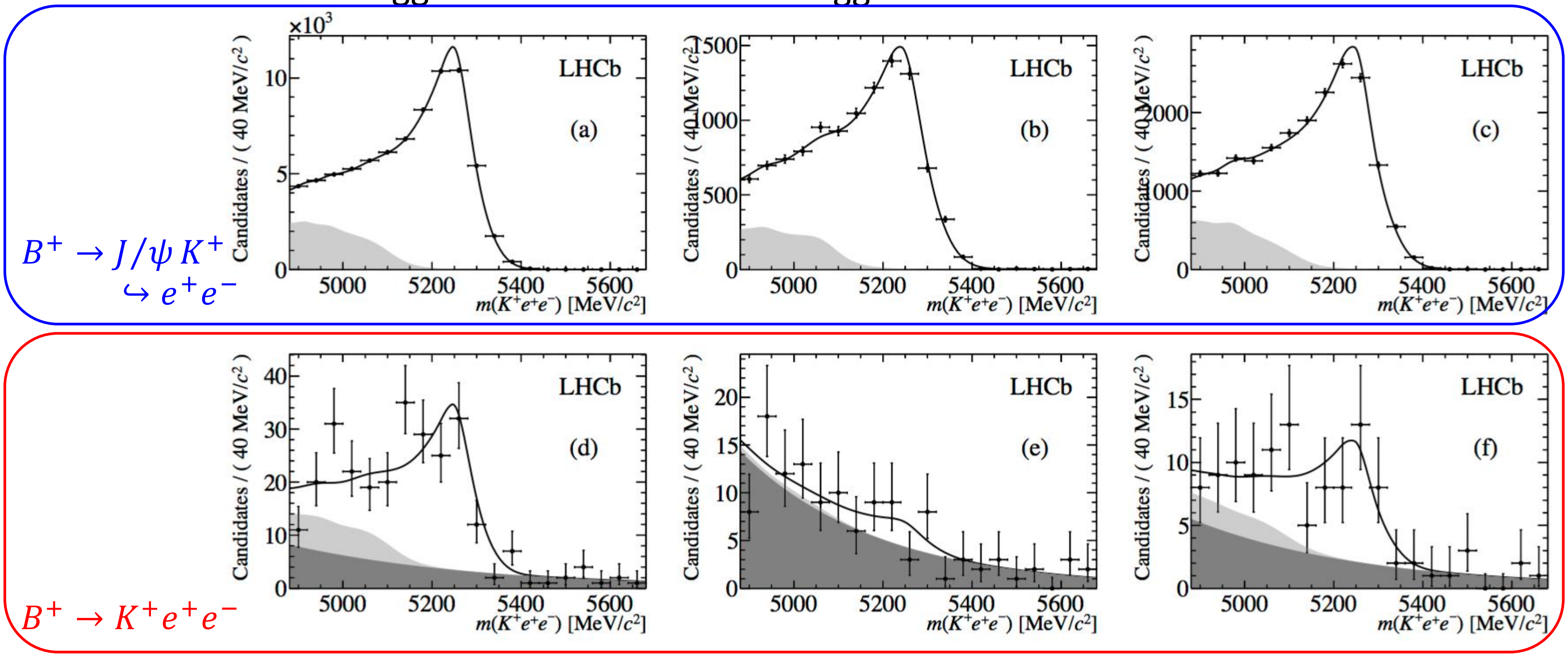
Fitting the electron mode

Trigger on $e^{\pm}$ | Trigger on K^{+} | Trigger on rest of event



- Mass shape in electron mode is sum of shapes corresponding to one, two, or three recovered photons
  - Fit separately in each of [electron triggered, kaon triggered, other] categories
  - Parameters fixed in signal decays to those obtained in fit to $B^{+} \to J/\psi\, K^{+}$

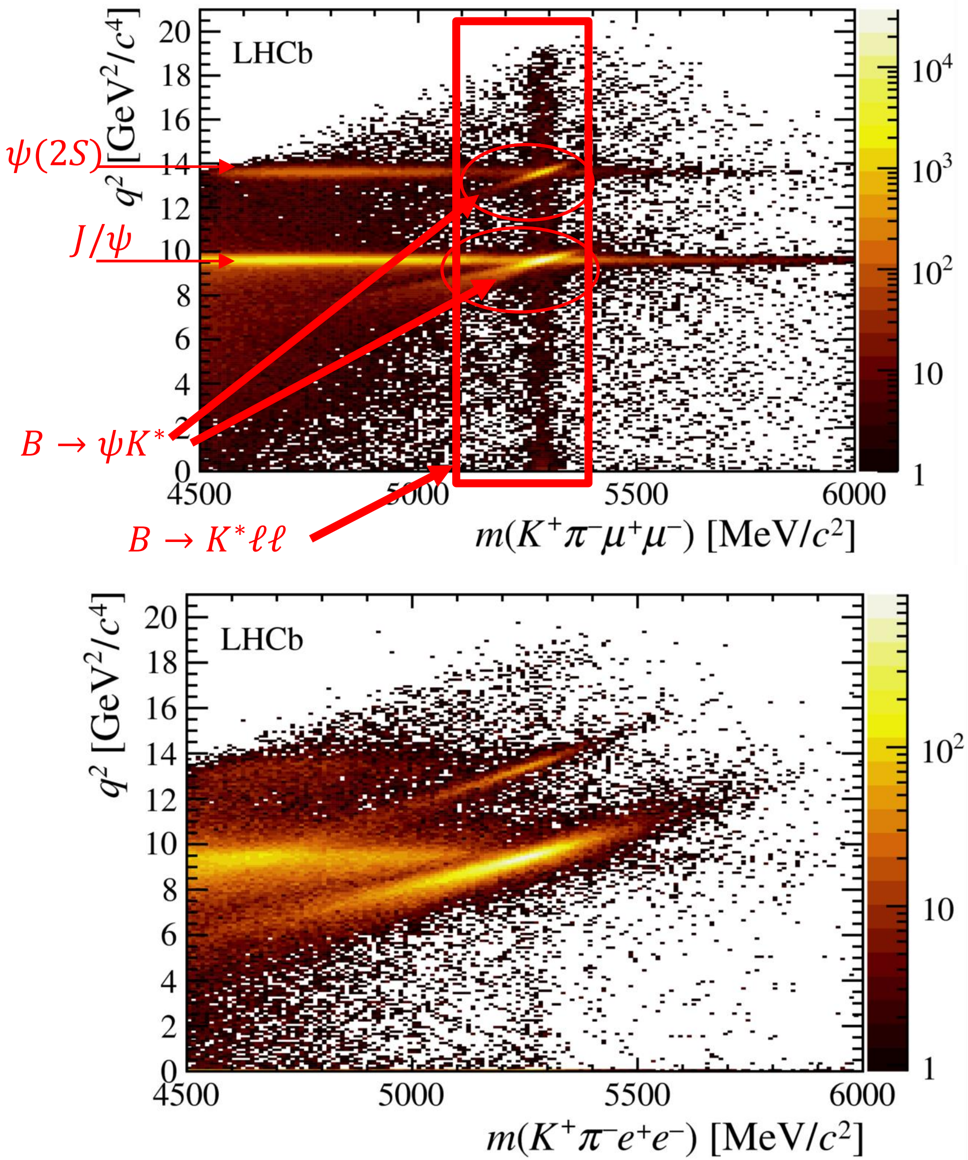
RK* event selection and raw yields

- Main challenge experimentally at LHCb: **electron reconstruction**
  - Electron momentum resolution is considerably worsened by bremsstrahlung
    - Charged particles at LHCb see $X/X_0 \approx 60\%$ before RICH2, $\approx 30\%$ before magnet
    - Recovery algorithms find the hardest pre-magnet emissions ($E_T > 75$ MeV)
    - Limitations of E_T threshold, unassociated clusters misidentified as brem. and inefficiency of isolation limit resolution
  - Dielectron mass resolution also strongly dependent on trigger path

- Measure double ratio

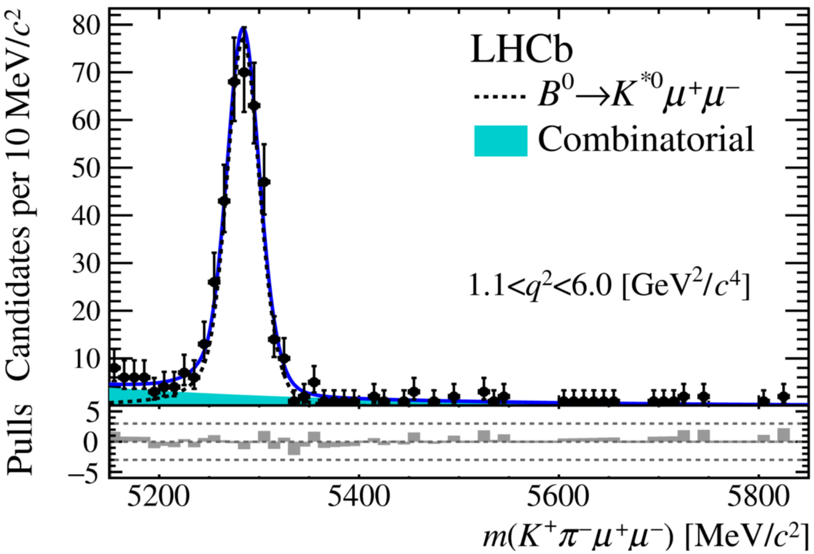
$$\frac{\mathcal{B}(B\to K^*\mu\mu)}{\mathcal{B}(B\to J/\psi[\to\mu\mu]K^*)} \Big/ \frac{\mathcal{B}(B\to K^*ee)}{\mathcal{B}(B\to J/\psi[\to ee]K^*)} = \frac{\mathcal{B}(B\to K^*ee)}{\mathcal{B}(B\to K^*\mu\mu)} \Big/ r_{J/\psi}$$

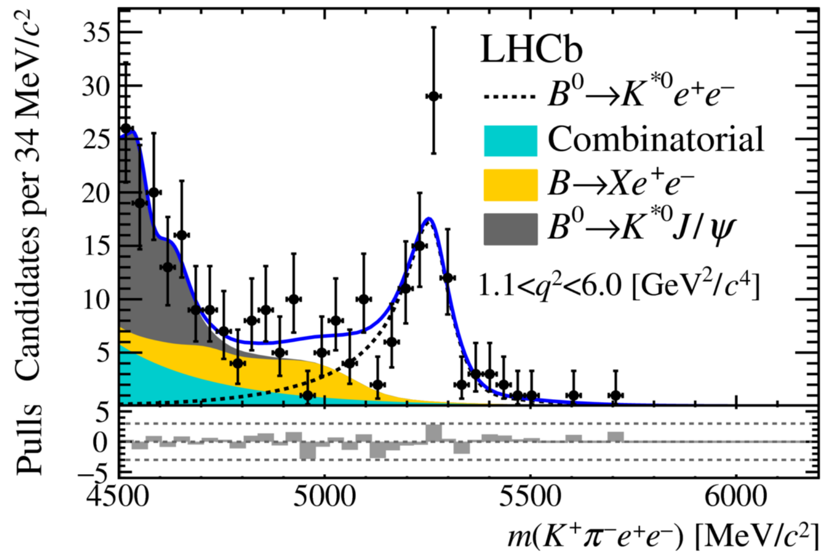
to minimize impact of reconstruction systematics on LFU observables



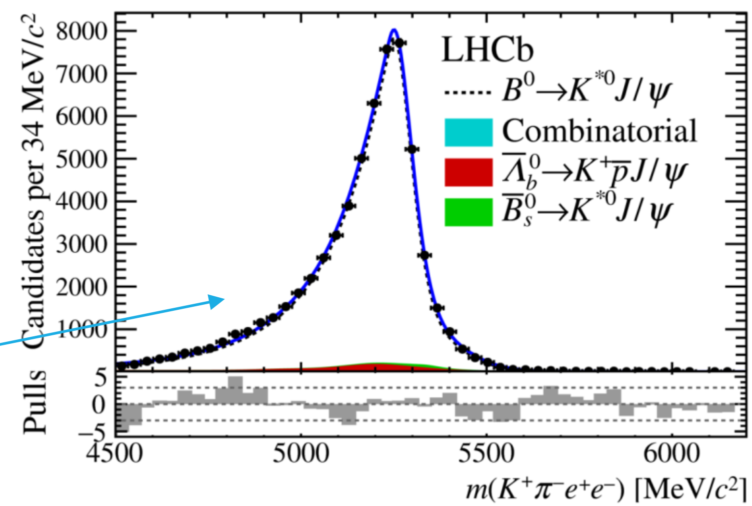
arXiv:1705.05802

R_{K^*} fit





- Mass shape in electron mode is sum of shapes corresponding to zero, one, or two or more recovered photons
  - Fit separately in each of [electron triggered, kaon triggered, other] categories
  - Parameters fixed in signal decays to those obtained in fit to $B \to J/\psi\, K^*$



RK* results

arXiv:1705.05802

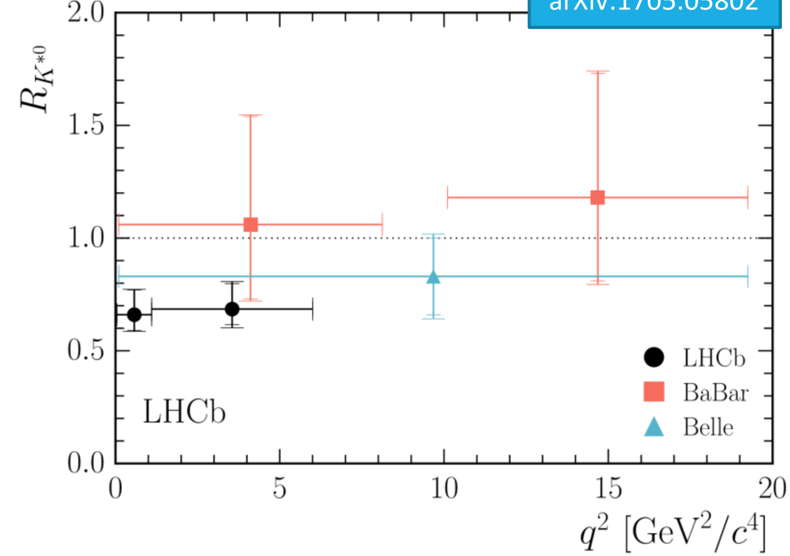
- This result:
  - $R_{K^*}(low\ q^2) = 0.66\ ^{+0.11}_{-0.07} \pm 0.03$
    - $2.1 - 2.3\sigma$ below predictions (~0.92)
  - $R_{K^*}(central\ q^2) = 0.69\ ^{+0.11}_{-0.07} \pm 0.05$
    - $2.4 - 2.5\sigma$ below predictions (~1.0)

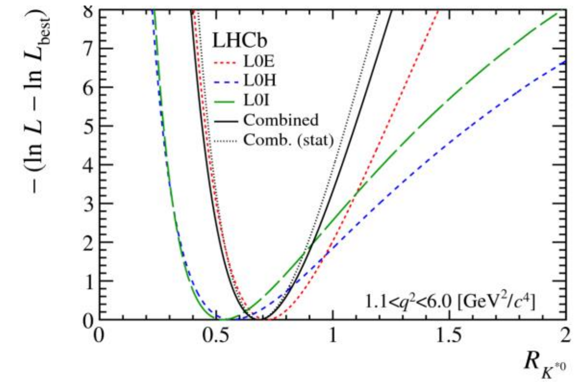
- Previous LHCb result:
  - $R_{K,\ q^2<6\mathrm{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$

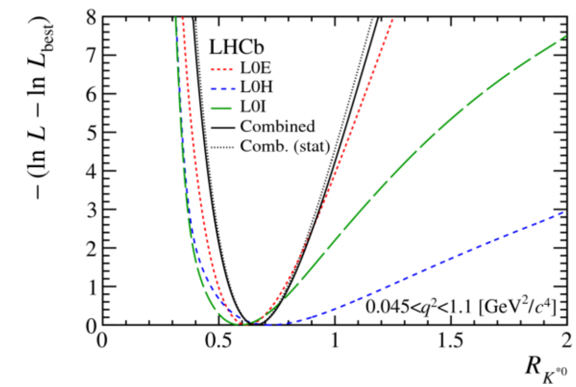
- Result cross-checked by studying the *single ratio* $r_{J/\psi} = \frac{\mathcal{B}(B\to J/\psi[\to\mu\mu]K^*)}{\mathcal{B}(B\to J/\psi[\to ee]K^*)} = 1.043 \pm 0.006 \pm 0.045$
  - Fewer cancellations than double ratio means it is more sensitive to systematic issues with efficiencies and yield extraction
  - Further cross-checks measure double ratio for $\psi(2S)$ → result is 1 within 2%(=stat error)

- Consistent with $C_9/C_9 - C_{10}$-type new physics picture preferred by global fits to $b \to s\ell\ell$ data – eg

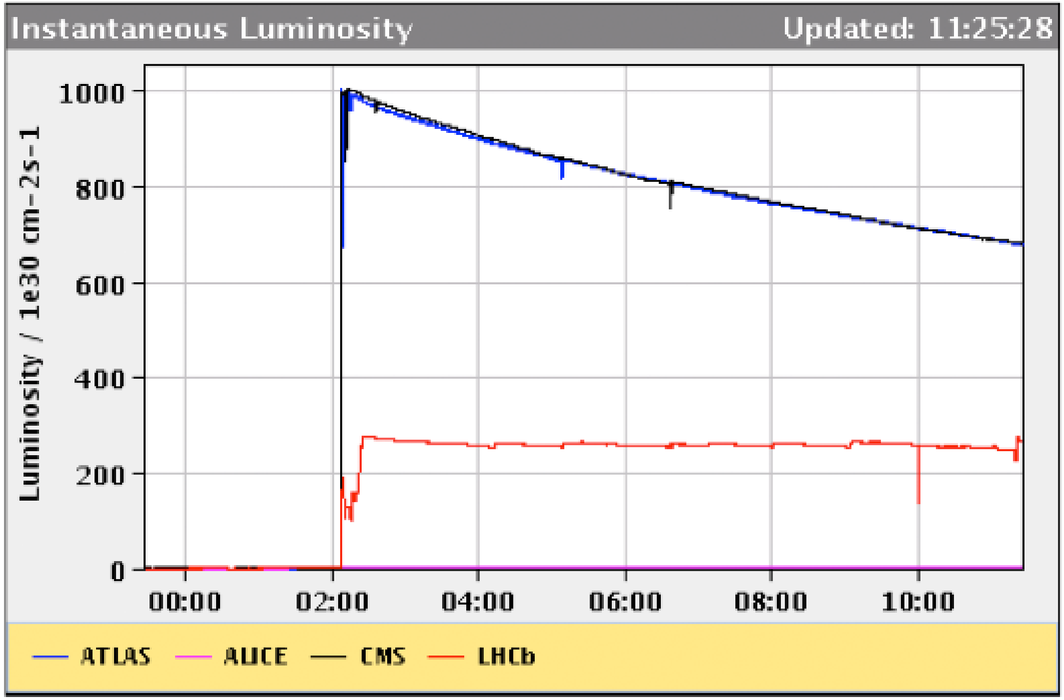
- Currently this is the “poster child” of statistics-limited measurements. Expect fast improvement with Run2!







LHCb Datataking



- LHCb requirements:
  - Lower peak Lumi ($2 - 4 \times 10^{32}$)
  - Stable intra-fill pileup
- LHC machine solution: Lumi levelling scheme at point 8
  - Possible use in high-pt experiments in HL-LHC