Highlights of Recent Results from LHCb

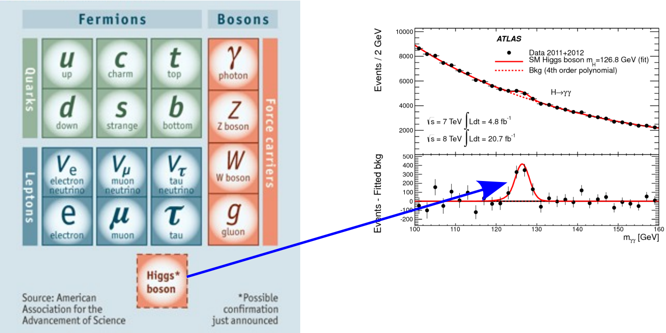
Biplab Dey

(for the LHCb Collaboration)

SLAC Summer Institute 2015

The Standard Model

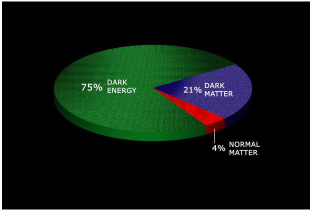
- A remarkably successful theory!
- Fine structure constant $\alpha = 0.0072973525698(24)$



- Has withstood experimental tests for over 40 years...

Yet, major difficulties...

- How does gravity fit in?
- Matter-antimatter asymmetry, neutrino oscillations, origin of mass.
- Ordinary matter (SM) accounts for only 4% of universe. What is dark matter/dark energy?

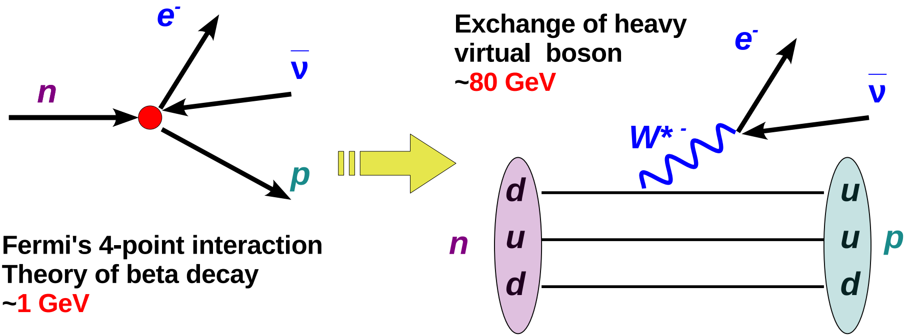


- *Compelling evidence for beyond the SM physics.* But how do we search?

Indirect searches

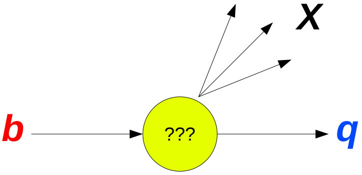
- Historically, indirect observations of "new physics" has often been the portal to infer properties of heavy particles before experiments with sufficient energy to produce them.

- β decay: particles of mass $\sim$ 1 GeV reveals physics at $\sim$ 100 GeV.



BSM searches in (quark) flavor factories

- Core principle: precision tests of SM in processes that do not preserve quark flavor.
- Heavy $\{b, c\}$ quarks decaying to lighter $q \in \{u, d, s\}$ quarks.



$$\mathcal{A} = \mathcal{A}_{\rm SM} + \mathcal{A}_{\rm BSM}$$

- $\mathcal{A}_{\rm BSM} \propto \frac{C_{BSM}}{M^2_{\rm BSM}}$ involves virtual heavy particles running inside loops.
- Carefully choose scenarios where the SM part is well-understood and suppressed (helicity, Cabibbo, FCNC, ...)
- Difference in rates or angular distributions wrt SM $\Rightarrow$ optimally chosen "clean" observables that reduce theory uncertainties.

"Anomalies" in B-physics

- Set of very interesting 3-4 σ tensions with the SM:
  - Taonic decays $B \to D^{(*)}\ell\overline{\nu}_\ell$, $\ell \in \{\tau, e, \mu\}$.
  - R_K: $B^+ \to K^+\ell^-\ell^+$, $\ell \in \{e, \mu\}$.
  - $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive measurements.
  - Several anomalies in the $b \to s\mu^-\mu^+$ sector.

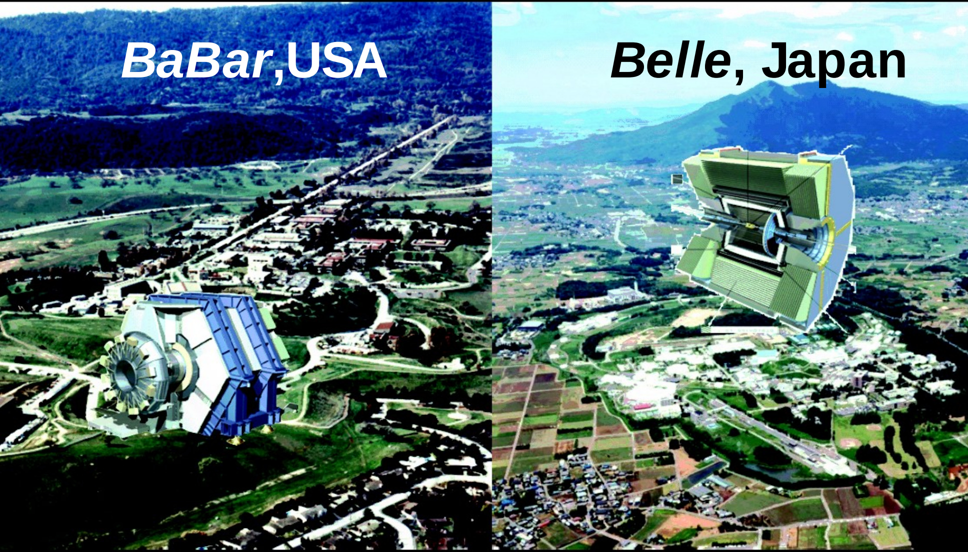
Statistical fluctuations? QCD effects?...

"Anomalies" in B-physics: NP portal?

- Set of very interesting 3-4 σ tensions with the SM:
  - Taonic decays $B \to D^{(*)}\ell\overline{\nu}_\ell$, $\ell \in \{\tau, e, \mu\}$ (LFU violation).
  - R_K: $B^+ \to K^+\ell^-\ell^+$, $\ell \in \{e, \mu\}$ (LFU violation).
  - $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive measurements. (RH currents?)
  - Several anomalies in the $b \to s\mu^-\mu^+$ sector. (heavy Z'?)

Statistical fluctuations? QCD effects?...New Physics?

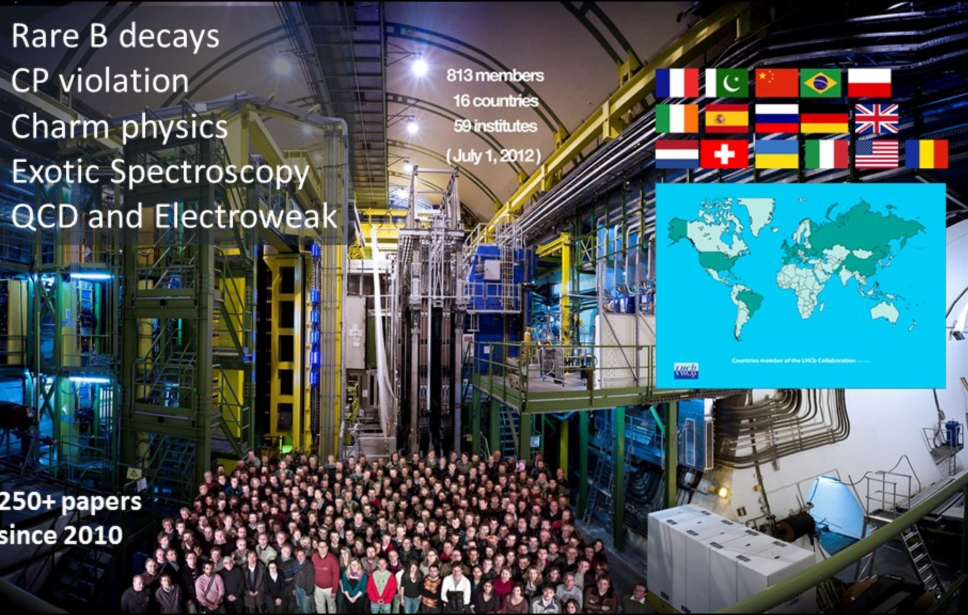
Flavor Factories



e+ ⟶ ⟵ e-

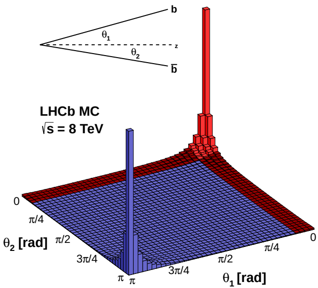
The Large Hadron Collider
p
p

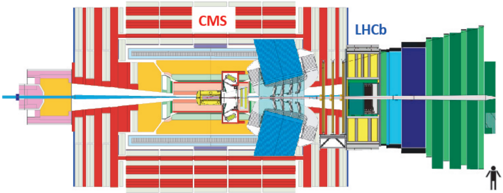
The LHCb Collaboration



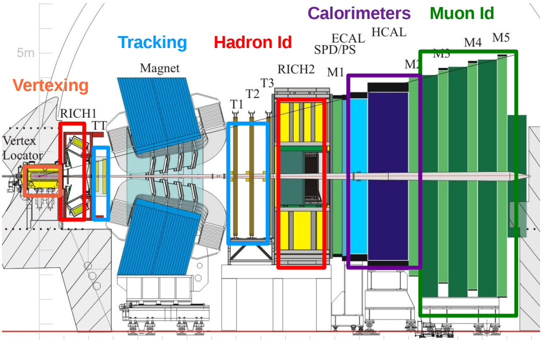
The LHCb detector

- Dedicated single-arm forward spectrometer with unique pseudo-rapidity range $1.8 < \eta < 4.9$.
- pp collisions in Run 1:
  - 2011: 1/fb at 7 TeV
  - 2012: 2/fb at 8 TeV
- High $b\bar{b}$ and $c\bar{c}$ cross-sections:
  - $\sigma(pp \to b\bar{b}) = 286\ \mu$b at 7 TeV
  - $\sigma(pp \to c\bar{c}) = \times 20$ larger
- Complementary η coverage wrt CMS/ATLAS.

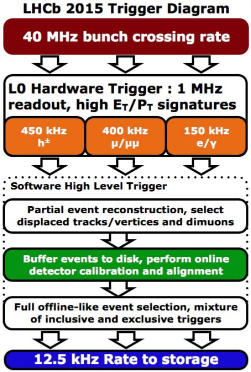




THE LHCB SUBSYSTEMS AND TRIGGER



Int.J.Mod.Phys. A30 (2015) 1530022

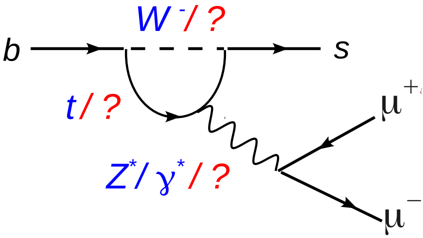


- Tracking: Magnet, VeLo, T-stations: 20 μm (IP), 0.5% (p), 45 fs (τ).
- Hadron Id: RICH system, good K/π seperation in $2 < p < 100$ GeV.
- Calorimetry: HCAL and ECAL for γ, e, π^0
- Muon detectors: 97% efficiency, $< 2.5\%$ $\pi \leftrightarrow \mu$ mis-ID

THE $b \to s\ell^+\ell^-$ "INDUSTRY" AT THE LHC

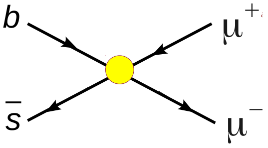
- Everybody's favorite rare "penguin" decay!
- Flavor-changing-neutral-current (FCNC).
- No tree-level diagram in the SM. Many ways where NP can enter.

- Several ways to explore this:
  - $B_s \to \mu^+\mu^-$ BF @ LHCb/CMS
  - $B \to K^{*J}\,\gamma_{\rm pol}$ @ LHCb
  - $B_d \to K^{(*)}\ell^-\ell^+$ @ LHCb/CMS
  - $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda^{(*)}\mu^+\mu^-$ ...



The Operator Product Expansion (OPE)

- Exactly as in the the case of Fermi's 4-point interaction theory of β-decay.
- Expand $\mathcal{H}_{\text{eff}}$ in a basis of local operators (OPE):



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big(\underbrace{C_i \mathcal{O}_i}_{\text{had. LH}} + \underbrace{C_i' \mathcal{O}_i'}_{\text{had. RH}} \Big)$$

i	Operator
1,2	Tree
3-6,8	Gluon Penguin
7_γ	Photon Penguin
9,10	EW Penguin
S	Scalar
P	Pseudoscalar

- The Wilson coefficients $C_i^{(\prime)}(\alpha_s, \mu)$ encode short-distance physics, sensitive to $E \geq M_{EW} \sim M_W, M_Z$. Computed at $\mu \sim m_b$.

The Wilson coefficients

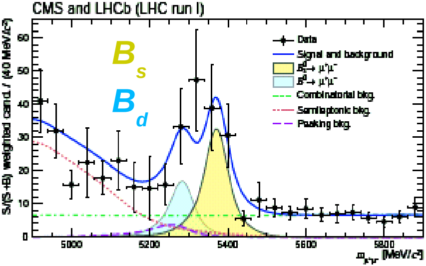
- Clues to NP signature hidden in the C_i's.

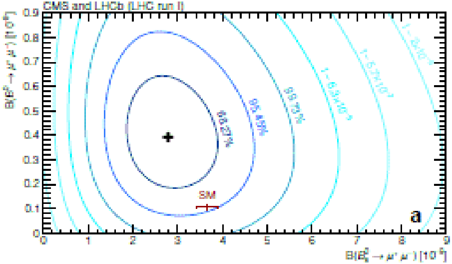
- SM hierarchy: $C_{7\gamma} \sim -0.331$, $C_{9V} \sim 4.27$, $C_{10A} \sim -4.173$. Everything else small or negligible.

- Lots of complementarity in $C_{\rm NP}$ searches:
  - $\mathcal{B}(B_s \to \ell^+\ell^-) : (C_{S,P} - C'_{S,P}), m_\ell^2(C_{10A} - C'_{10A})$.
  - $B_d \to X_s\gamma_{\rm pol}$: $C_{7\gamma}$. Photon polarization: C'_7.
  - $B_d \to K^{(*)}\mu^+\mu^-$ angular analysis: $C_{7\gamma}$, C_{9V}, $C_{10A} + \ldots$

$B_{d,s} \to \mu^+\mu^-$

- After 30 years of search, $> 4\ \sigma$ in LHCb and CMS for B_s.
- LHCb and CMS combined results (Nature, 522 (2015) 68):
  - $\mathcal{B}(B_d) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$, $3.2\ \sigma$
  - $\mathcal{B}(B_s) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$, $6.2\ \sigma$ first observation

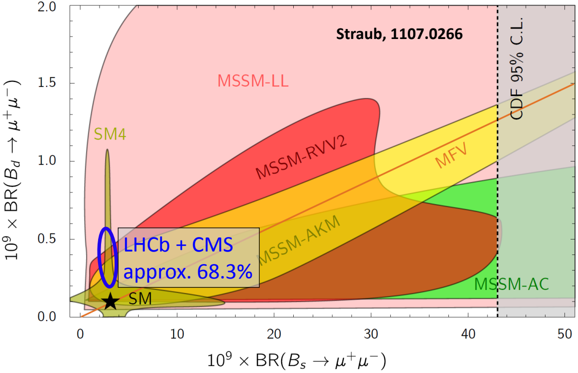




- Some slight tensions, but mostly compatible with SM.

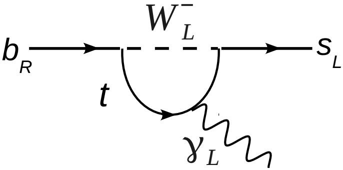
$B_{d,s} \to \mu^+\mu^-$: effect on NP models

- $\mathcal{B}(B_s \to \mu^+\mu^-)$ expected to be particularly enhanced ($\sim (\tan\beta)^6$, large $\tan\beta$) in the two-Higgs doublet models.
- LHCb+CMS result has a huge impact on SUSY parameter space.



Photon polarization in $b \to s\gamma$

- Long history of radiative penguin $B \to X_s\gamma$ (inclusive) at CLEO, *BABAR*, Belle, LHCb.
- Rate: $\mathcal{B}(b \to s\gamma) \propto |C_{7\gamma}|^2 + |C'_{7\gamma}|^2$, with $C'_{7\gamma}$ strongly suppressed in the SM.
- Novel feature: outgoing photon is almost fully left-chiral for b quark.



- $\mathcal{A}_{\rm SM} \propto m_b \bar{s}_L \sigma_{\mu\nu} q^\nu b_R + m_s \bar{s}_R \sigma_{\mu\nu} q^\nu b_L$
- $C'_{7\gamma}/C_{7\gamma} \sim m_s/m_b \approx 0.02 \ll 1$
- $\lambda_\gamma = \dfrac{|C'_{7\gamma}|^2 - |C_{7\gamma}|}{|C'_{7\gamma}|^2 + |C_{7\gamma}|} = \underbrace{-1}_{b} \, (\underbrace{+1}_{\bar{b}})$

- NP can enhance $C'_{7\gamma}$: left-right symmetric models (w/ a heavy W_R).

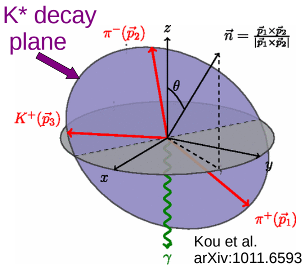
Measurement of λ_γ at LHCb

- Parity-odd triple product $\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_\pi)$ in $B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma$ decays is sensitive to λ_γ.

- Complicated Dalitz structures in $K\pi\pi$ system pushed into $C_{K\pi\pi} \sim 0.1$ (for $B^\pm$)

- Up-down asymmetry (Gronau 0205065):

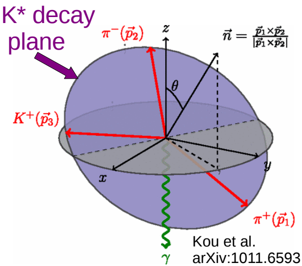
$$A_{UD} \equiv \frac{N_{\cos\theta>0} - N_{\cos\theta<0}}{N_{\cos\theta>0} + N_{\cos\theta<0}} = C_{K\pi\pi}\lambda_\gamma$$



Measurement of λ_γ at LHCb

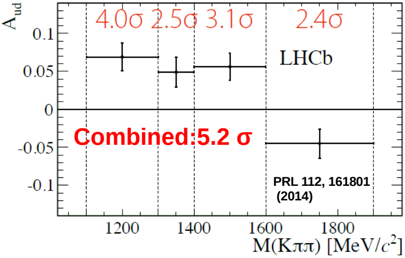
- Parity-odd triple product $\vec{p}_\gamma \cdot (\vec{p}_\pi \times \vec{p}_\pi)$ in $B^\pm \to K^\pm\pi^\mp\pi^\pm\gamma$ decays is sensitive to λ_γ.
- Complicated Dalitz structures in $K\pi\pi$ system pushed into $C_{K\pi\pi} \sim 0.1$ (for $B^\pm$)
- Up-down asymmetry (Gronau 0205065):

$$A_{UD} \equiv \frac{N_{\cos\theta>0} - N_{\cos\theta<0}}{N_{\cos\theta>0} + N_{\cos\theta<0}} = C_{K\pi\pi}\lambda_\gamma$$



Kou et al. arXiv:1011.6593

First observation of photon polarization in $b \to s\gamma$

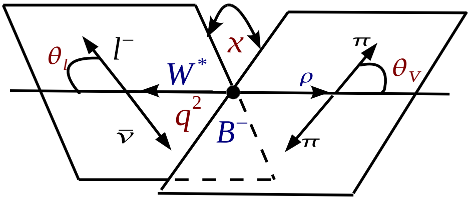


PRL 112, 161801 (2014)

- Further theory input needed on $C_{K\pi\pi}$ to extract λ_γ.

Angular analyses of $\bar{B} \to X\ell_1\ell_2$

- So far so good. No spectacular deviations from SM.
- As we will see, the "interesting" anomalies involve $\bar{B} \to X\ell_1\ell_2$.
  - Electroweak Penguins (EWP): $\ell^-\ell^+$, $\ell \in \{e, \mu\}$
  - Semileptonic (SL): $\ell^-\overline{\nu}_\ell$, $\ell \in \{e, \mu, \tau\}$
  - X is a mesonic system $\in \{\pi, K, \ \pi\pi, \ K\pi, \ KK, \ D, \ D\pi\}$
- Four kinematic variables: $\phi \in \{q^2, \theta_l, \theta_V, \chi\}$



(see for example 1505.02873, 1506.03970)

The helicity amplitudes

- Three helicity amplitudes for the spin-1 dilepton $\{W^*, Z^*, \gamma^{(*)}\}$:

$$H^{L,R}\Big|_{J=0} = \frac{2m_B \mathbf{k}}{\sqrt{q^2}} \left\{ \overline{C}^{L,R} F_1(q^2) + \overline{C}_7 \frac{2m_B}{m_B + m_X} F_T(q^2) \right\}$$

$$H^{L,R}_{\pm}\Big|_{J\geq 1} = \beta_J \left(\frac{\mathbf{k}}{m_X}\right)^{J-1} \left\{ \overline{C}^{L,R}(m_B + m_X) A_1(q^2) + \frac{2m_B}{q^2}(m_B^2 - m_X^2)\overline{C}_7 T_2(q^2) \right.$$
$$\left. \mp 2m_B \mathbf{k} \left[\overline{C}'^{L,R} \frac{V(q^2)}{m_B + m_X} + \overline{C}'_7 \frac{2m_B}{q^2} T_1(q^2) \right] \right\}$$

$$H^{L,R}_0\Big|_{J\geq 1} = \frac{\alpha_J}{2m_X\sqrt{q^2}} \left(\frac{\mathbf{k}}{m_X}\right)^{J-1} \left\{ \overline{C}^{L,R} \left[(m_B^2 - m_X^2 - q^2)(m_B + m_X) A_1(q^2) - \frac{4m_B^2 \mathbf{k}^2}{m_B + m_X} A_2(q^2) \right] \right.$$
$$\left. + 2m_B \overline{C}_7 \left[(m_B^2 + 3m_X^2 - q^2) T_2(q^2) - \frac{4m_B^2 \mathbf{k}}{m_B^2 - m_X^2} T_3(q^2) \right] \right\}$$

- QCD form-factors are the largest source of systematic uncertainties.
- Also, *non-factorizable* hadronic effects $h_\lambda(q^2)$ (more later).

THE "CLEAN" OBSERVABLES

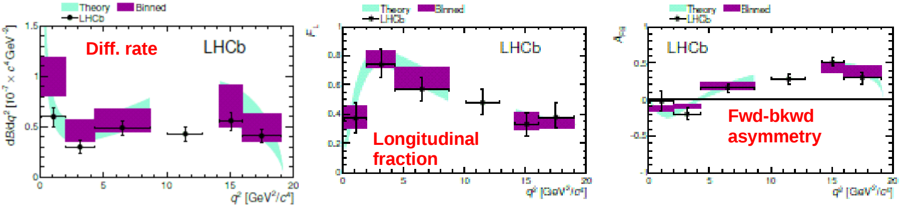
- If the X system is in spin-J, the amplitude squared reads:

$$|\overline{\mathcal{M}}|^2 = \sum_{L,R} \left| \sum_{\lambda\in\{0,\pm1\}} \sum_J \sqrt{2J+1}\mathcal{H}_\lambda^{\{L,R\},J} d^J_{\lambda,0}(\theta_V) d^1_{\lambda,\eta}(\theta_l) e^{i\lambda\chi} \right|^2$$
$$= \sum_i \Gamma_i(q^2)\, f_i(\theta_l, \theta_V, \chi)$$

- Matias *et al.* (1303,5794): ratios of the Γ_i observables.
- Leading order FF uncertainties cancel in the $q^2 \leq 6\ \mathrm{GeV}^2$ regime.
- Forward-backward zero crossing point long known to be theoretically clean.
- New observable P_5' turns out to be particularly sensitive.

$B^0 \to K^{*0}\mu^+\mu^-$ status with 1/fb data

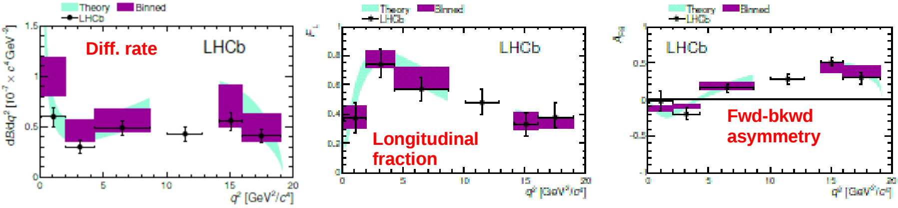
- Good agreement with the SM (JHEP 07 (2011) 067)



JHEP 08 (2013) 131

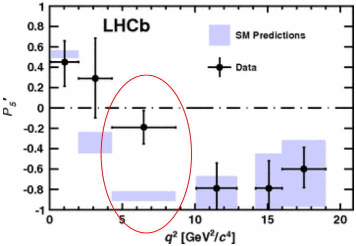
$B^0 \to K^{*0}\mu^+\mu^-$ status with $1/\text{fb}$ data

- Good agreement with the SM (JHEP 07 (2011) 067)



JHEP 08 (2013) 131

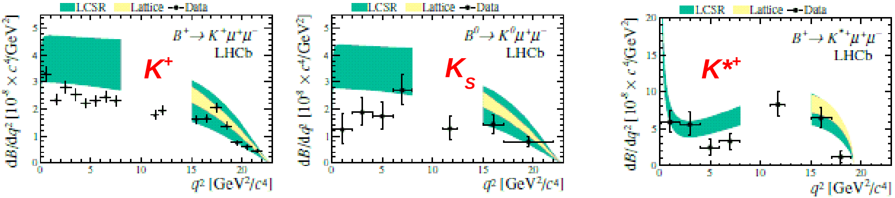
- Except 3.7σ local deviation in P_5' from SM (JHEP 05 (2013) 137):



Phys. Rev. Lett. 111, 191801

3/FB: ANOMALOUS TRENDS NOW SEEN IN $\mathcal{B}$

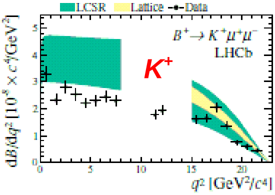
- Isospin channels: $\mathcal{B}$ tend to lie below SM (PRL 112 212003, arXiv:1411.3161)

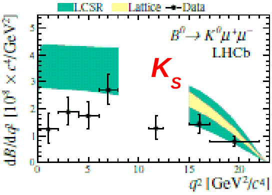


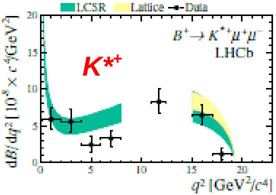
JHEP 06 (2014) 133

3/fb: Anomalous trends now seen in $\mathcal{B}$

- Isospin channels: $\mathcal{B}$ tend to lie below SM (PRL 112 212003, arXiv:1411.3161)

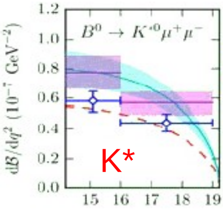




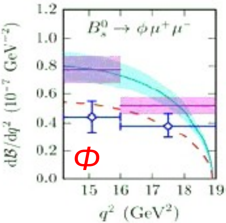


JHEP 06 (2014) 133

- Updated lattice calculations at high q^2 reflect this as well



Average of LHCb, CDF, CMS, ATLAS

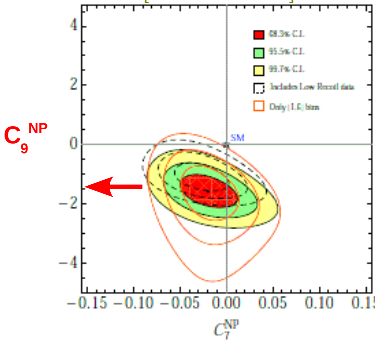


Average of LHCb, CDF

PRL 112, 212003

Effect on Wilson coefficients

Descotes-Genon et al.
[arXiv:1307.5683]



- With 2013 data, C_9 and C_7 seen as main players.
- All theory groups find $C_9^{\mathrm{NP}} < 0$

  Altmannshofer, Straub 1308.1501, Beaujean, Bobeth, van Dyk 1310.2478, Horgan et al. 1310.3887 Hambrock, Hiller, Schacht, Zwicky 1308.4379.
- Different bins, observables, statistical approaches...
- Contentions whether $C_9' \sim -C_9^{\mathrm{NP}}$ or $C_9' \to 0$ (Matias et al.)

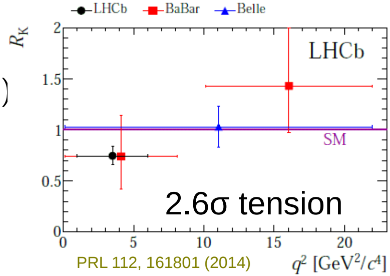
(More info. on global fits in backup)

Another unexpected development: R_K

- Other than a tiny effect from mass difference, e/μ behaves the same in SM

- $R_K \equiv \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)} = 1.0 \pm \mathcal{O}(10^{-4})$

- $R_K^{\text{LHCb}} = 0.745^{+0.090}_{-0.074} \pm 0.036$



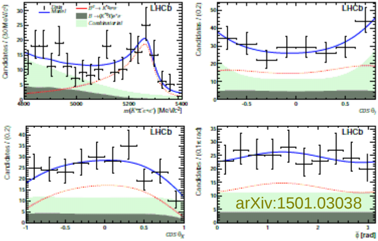
PRL 112, 161801 (2014)

Hints towards lepton universality violation in 1st and 2nd generations for the first time

ANGULAR ANALYSIS OF $B^0 \to K^* e^+ e^-$ AT LOW q^2

- Since $q^2_{\rm min} \geq 4m_\ell^2$, ee mode allows to explore the very low q^2 region.

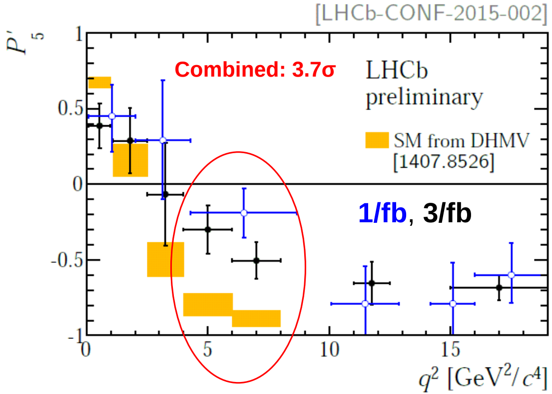
- Sensitivity to $C_{7\gamma}^{(\prime)}$ competitive with rad. penguins.
- New LHCb results: angular analysis in $q^2 \in [0.002, 1.120]$ GeV^2?
- Results consistent with SM.



- R_{K^*} could be very interesting

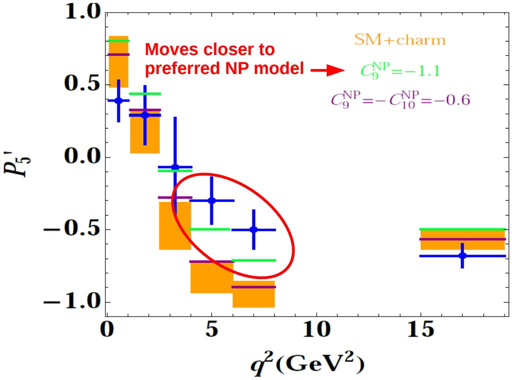
- Experimentally much more challenging than $\mu\mu$: trigger and modeling of bremsstrahlung inside detector material.

THE ANOMALY PERSISTS! (MORIOND 2015)



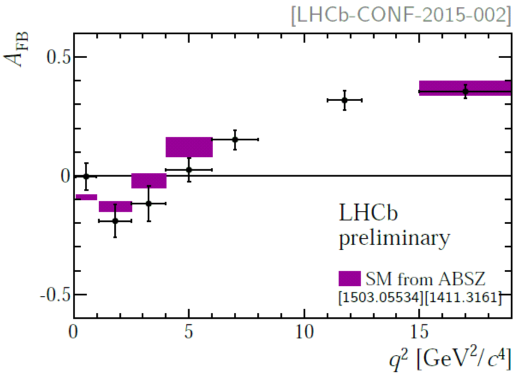
- Excellent consistency between 2011 and 2012 results.

And if we are aggressive...



- Moves closer to $C_9^{\rm NP} < 0$ as well (Quim Matias, Moriond).

Zero-crossing point in A_{FB}



- Slightly lower than SM. ZCP: $q_0^2 \sim 3.7$ GeV^2.
- Publication of full set of angular observables in preparation.
- CMS has also recently entered the game (1507.08126).

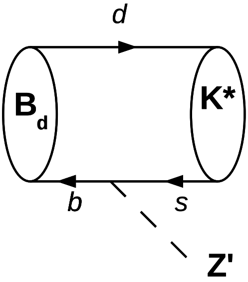
HEAVY Z' WITH NON-UNIVERSAL FLAVOR COUPLINGS?

- Numerous theory papers combining all $b \to s\ell\ell$ measurements

  Descotes-Genon et al [1307.5683], Beaujean et al [1310.2478], Gauld et al [1308.1959], Hurth et al [1312.5267], Straub et al [1308.1501], Horgan et al [1310.3887],Altmannshofer et al [1403.1269], Biancofore et al [1403.2944]...

- Simplest explanantion of $C_9^{\mathrm{NP}} \sim -1.5$ is a Z' boson with specific flavor couplings.

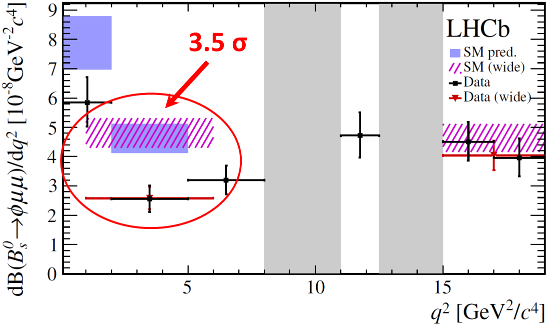
- Heavy (TeV range) Z' boson with FCNC at tree-leve
- Couples only to LH quarks.
- Couples equally with $\ell_{R,H}$, but differently to e/μ
- CPV in B_s-$\overline{B}_s$ places strong limits on the couplings.
- Difficult to accomodate within MSSM.



3/fb $B_s \to \phi\mu^-\mu^+$ angular analysis (NEW!)

- 3.5 σ tension with SM (Altmannshofer/Straub arXiv:1411.3161) in the $q^2 \in [1, 6]$ GeV^2 bin. Overall BF lower than SM.

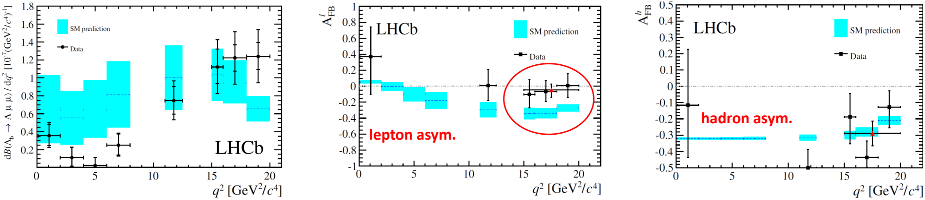
arXiv:1506.08777



- Angular observables mostly consistent with SM, though.

3/fb $\Lambda_b \to \Lambda\mu^-\mu^+$ angular analysis (NEW!)

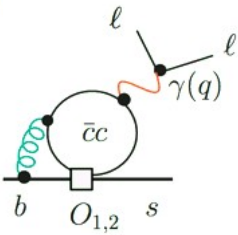
- LHCb is uniquely capable to do $b \to s\ell\ell$ in the baryonic sector (unlike Belle II).
- Branching fractions and A_{FB} in the leptonic and hadronic helicity angles (JHEP 06 (2015) 115).
- SM predictions from lattice (1401.2685, 1212.4827).



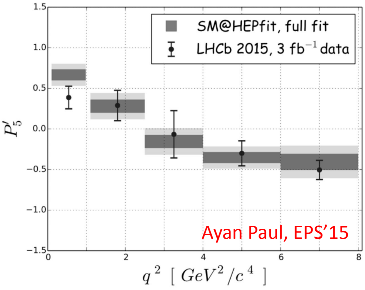
- Some tension in A^ℓ_{FB} at high q^2.

Charm-loop effects: potential show-stopper?

- Lyon-Zwicky (1406.0566): non-factorizable $c\bar{c}$ loops are large and can accomodate the P_5' anomaly.
  see also D. Straub @ Moriond'15



- OPE breaks down. Very hard to calculate.
- Can we disentangle $b \to s\ell\ell$ from $b \to sc\bar{c}$?



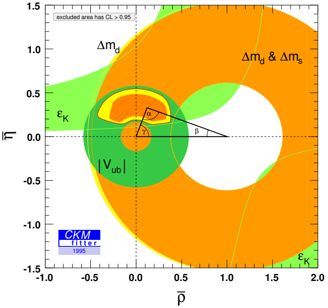
- $h_\lambda(q^2)$: non-factorizable hadronic part, quadratic ansatz
- Fits can incorporate data.

Importance of $|V_{ub}|/|V_{cb}|$

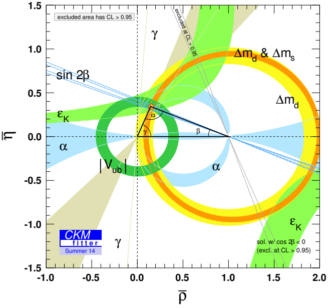
$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- In SM, unitary CKM matrix $\Rightarrow$ flavor-mixing
- Fantastic success of the CKM paradigm thru' the years...

1995:



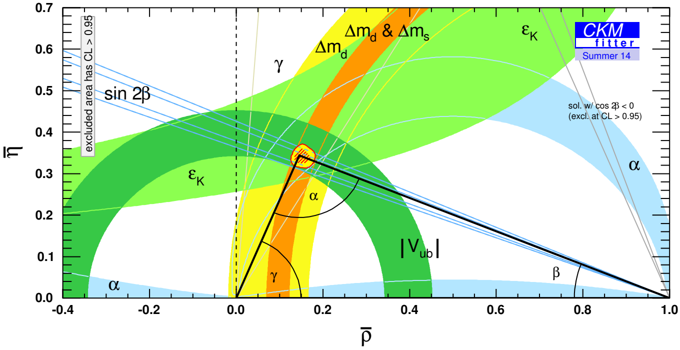
2014:



IMPORTANCE OF $|V_{ub}|/|V_{cb}|$

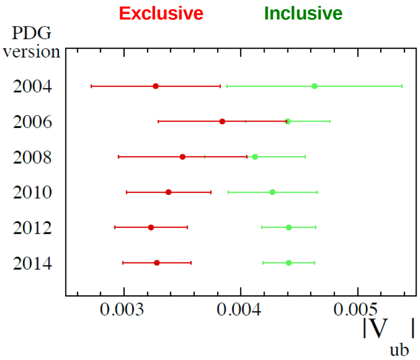
- Side opposite to β proportional to $|V_{ub}|/|V_{cb}|$. Both β and $|V_{cb}|$ known better than 3%.

- Closure test of UT mainly limited by $|V_{ub}|$.



Inclusive and exclusive $|V_{ub}|$

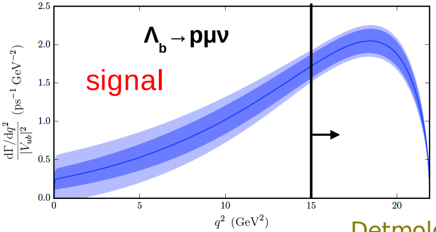
- Exclusive $\bar{B} \to \pi\ell^-\overline{\nu}_\ell$. Need QCD form-factors.
- Inclusive $\bar{B} \to X_u\ell^-\overline{\nu}_\ell$. No form-factors (sum of states), but kinematics cuts to reduce $\times 50$ large charm background.
- Different experiment/theory techniques. Persistent $\sim 3\sigma$ tension!

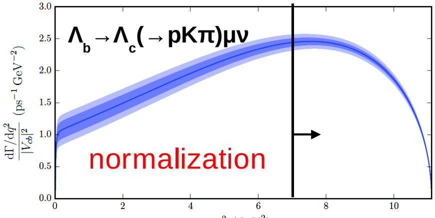


$|V_{ub}|$ at LHCb via $\Lambda_b \to p\mu\nu$

$|V_{ub}|/|V_{cb}|$ long thought to be impossible at a hadron collider

- LHCb probes $b \to u$ in exclusive baryonic $\Lambda_b \to p\mu\nu$ decay.
- High statistics ($\mathcal{O}(10^4)$) even for a rare decay!
- Critial role played by latest lattice calculations at high q^2.

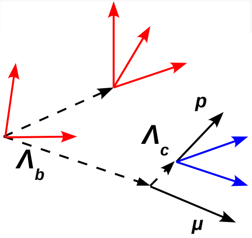




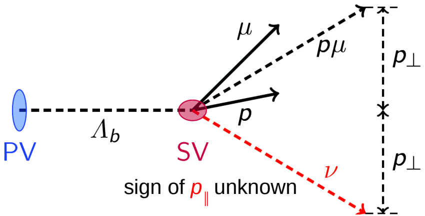
Detmold et al. (1503.01421)

Two experimental challenges

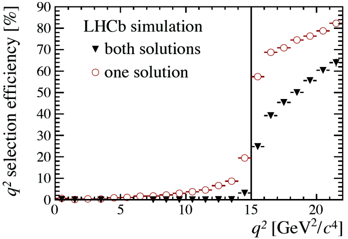
- Dominant charm backgrounds have additional tracks close to the $p\mu$ vertex.
- Multivariate classifier trained to discriminate between red and blue tracks.
- 90% rejection with 10% efficiency.



- Two-fold ambiguity in q^2:



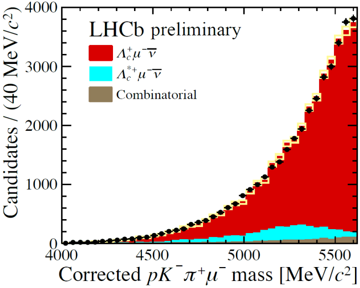
- Require both q^2 solns. ≥ 15 GeV^2:



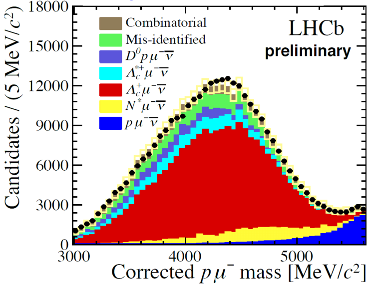
$M_{\rm corr}$ FITS

- Fit the corrected mass: $M_{\rm corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$.
  (min. b-mass compatible with flight dirn.)

$N_{\rm norm} = 34255 \pm 571$

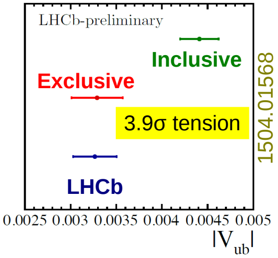


$N_{\rm sig} = 17687 \pm 733$



What can LHCb say about $|V_{ub}|$?

- $|V_{ub}|_{\text{LHCb}} = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06(|V_{cb}|)) \times 10^{-3}$ (Nature Physics 10 (2015) 1038)
- Total uncertainty is 7.2%. World's best exclusive measurement.
- Consistent with WA of $\sin(2\beta)$ and new LHCb measurement (PRL 115 031601).

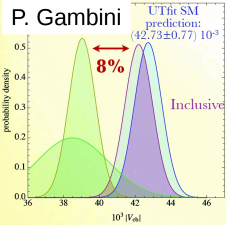


Large tension between inclusive and exclusive $|V_{ub}|$ persists

Right-handed currents in the SL sector

- SM: weak interaction is purely LH. Add a small RH admixture ϵ_R.
- If ϵ_R real and negative, can help resolve the $|V_{ub}|$ tension:
  - $|V_{ub}|_{incl.} \sim 1+\epsilon_R^2$, $|V_{ub}|_{excl.} \sim 1+\epsilon_R$
- Several papers (1408.2516, 1411.1177, 1407.1320) w/o clear picture.

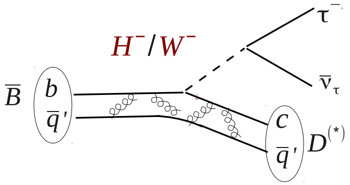
- ϵ_R difficult to decouple from the FF norm.
- Similar 3σ tensions in the $|V_{cb}|$ sector as well.
- Solution: $\bar{B} \to \{\rho, D^*\}\ell\bar{\nu}_\ell$ angular analysis?



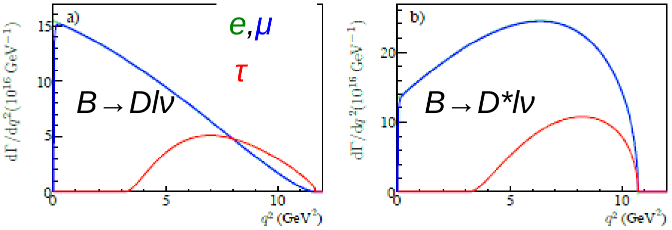
Latest lattice results for exclusives (FNAL/MILC)

The τ case is special

- For massive τ, chirality $\neq$ helicity. The W^* can have spin-0.
- Charged-Higgs enters at tree-level.
- Type 2 two-Higgs doublet model: amplitude scales as $m_\tau \left(\frac{\tan\beta}{m_{H\pm}}\right)^2$.



- Additional form-factor: $A_0(q^2)$. Different phase-space constraints:

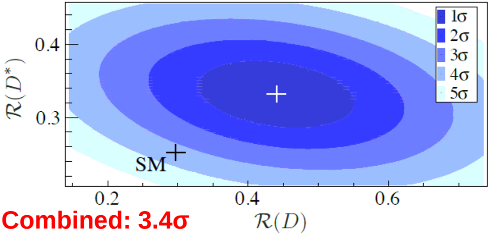


The BaBar $R(D^{(*)})$ anomaly (1205.5442)

- Measured the ratios:
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}, \; \tau \to \ell\overline{\nu}_\ell\nu_\tau.$$

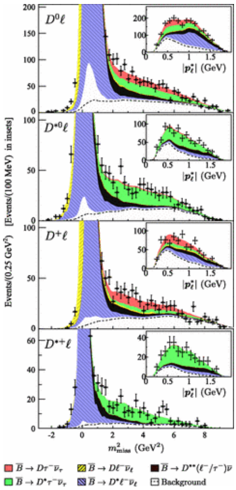
- Same final state in numerator and denominator. Many uncertainties cancel.

- $R(D^{(*)}) > 3\;\sigma$ tension with SM:



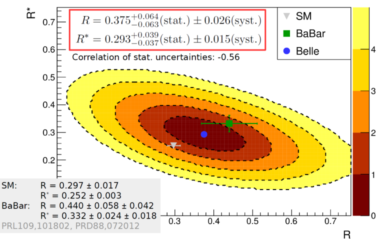
Combined: 3.4σ

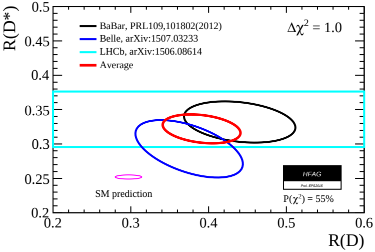
2-d fit in $p^2_{\rm miss}$ and p^*_ℓ:



$R(D^{(*)})$ from Belle and LHCb (FPCP'15)

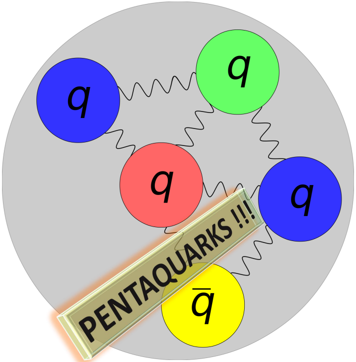
- Full Belle I dataset + updated tagging algorithm (1507.03233).
- Consistent with both BABAR and SM.





SM: PRD 85, 094025 (2012)

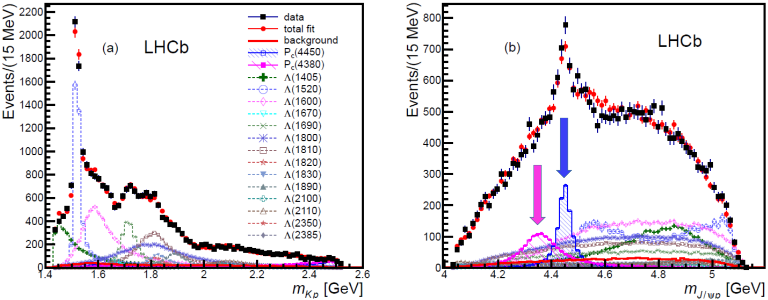
- Very challenging at LHCb due to multiple missing neutrinos. Only muons!
- Isolation from excellent tracking + background-enriched control samples.
- LHCb $\mathcal{R}(D^*)$ (1506.08614) is consistent with BABAR.
- HFAG EPS'15: SM tension is 3.9 σ



See today's PRL viewpoint

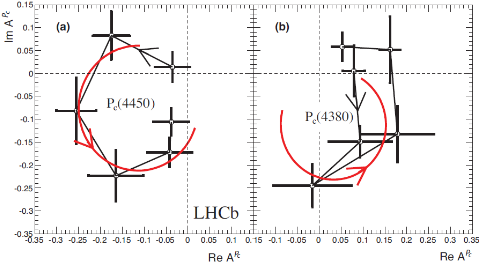
LHCb's latest exotics: pentaquarks (NEW!)

- Pentaquarks allowed by QCD, but not seen for 50 years.
- LHCb (1507.03414): two P_c^+ states in $\Lambda_b \to \{J/\psi p\}K$
  - $3/2^-$, mass (width) = 4359 (151) MeV, 9 σ
  - $5/2^+$, mass (width) = 4450 (49) MeV, 12 σ



LHCb's latest exotics: pentaquarks (cntd.)

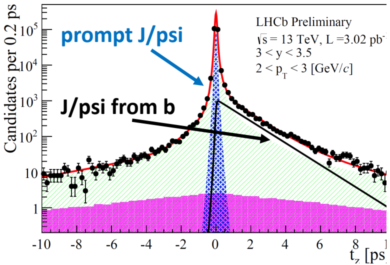
- Large number of poorly known Λ^* states is the weakest link.
- Final fit including P_c's is not perfect.
- Phase-motion looks consistent with resonance interpretations:

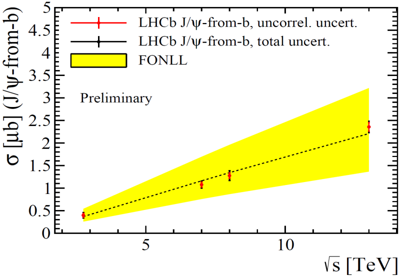


- We need to see these in other modes (photoproduction @ JLab?). Also, where are the ground states?

Run 2 @ LHCb

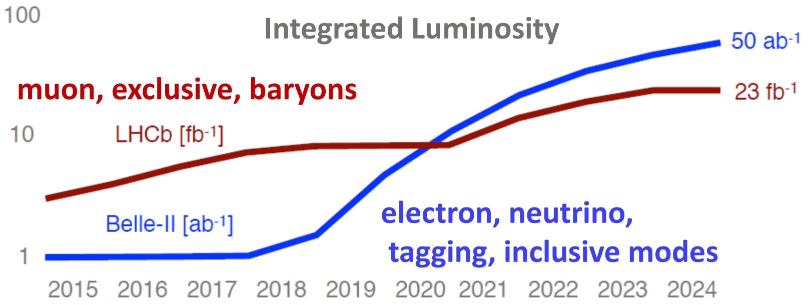
- No major hardware changes. Improved trigger (low p_T), real-time tracking, calibration, alignment and PID goes into HLT.
- Write to disk: 5 kHz (Run 1) $\Rightarrow$ 12.5 kHz (Run 2).
- Already analyzing online reconstructed data (`EPS talk`, `LHCb-PAPER-2015-037` in preparation):





LHCb and Belle II

- Complementarity with Belle II. CMS/Atlas also coming into the fold.

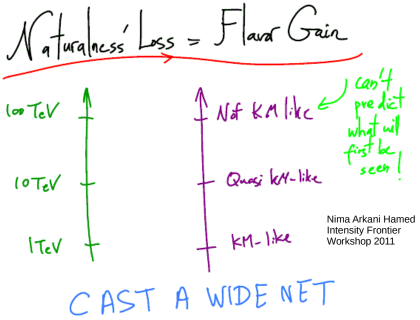


Summary and outlook

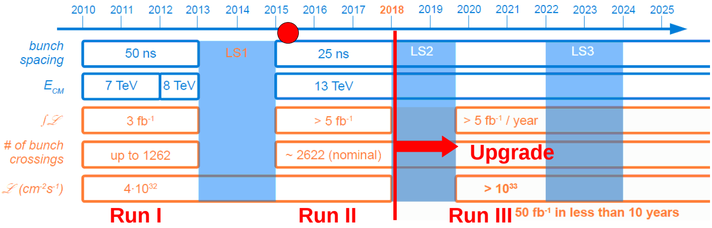
- We are in a unique situation where several very interesting tensions exist with the SM in the heavy quark flavor sector.
- Happening times – both Run II at LHC and Belle II. *Much* more data expected soon.

Summary and outlook

- We are in a unique situation where several very interesting tensions exist with the SM in the heavy quark flavor sector.
- Happening times – both Run II at LHC and Belle II. *Much* more data expected soon.
- The higher $\Lambda_{\rm NP}$ is, the more unexpected non-CKM type flavor violations. Measure everything!



LHCb upgrade



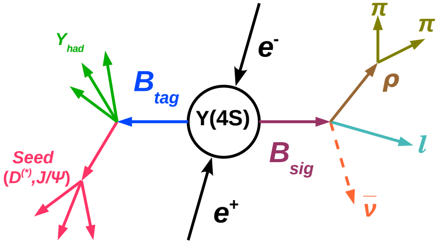
- Higher track multiplicities, ghost rates, interactions/crossing, vertices...
- Replace current hardware L0 trigger (1MHz) to more flexible software tigger
- Read out everything (40 MHz) and HLT output 20 kHz
- VeLo and tracking (new Upstream Tracker, Fiber Tracker)
- RICH system: new photo-detectors, upgraded optics

LHCb upgrade

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [19, 20]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

The BReco technique at B-factories

- In $e^+e^- \to \Upsilon(4S) \to B_{\rm sig}B_{\rm tag}$, full hadronic reconstruction of $B_{\rm tag}$
- A single missing ν: reconstructed as $p_{\rm miss}$ via kinematic fit.



- $\overline{B} \to X\mu^-\mu^+$ (LHCb) and $\overline{B} \to X\ell^-\overline{\nu}_\ell$ (BABAR) on a completely equal footing now (resolutions).
- Low efficiency, but de facto method in Belle II era for neutrinos.

RELEVANT OPERATORS IN $b \to s\ell^+\ell^-$

- $\mathcal{O}^{(\prime)}(\mu)$ are composite operators depending on hadronic matrix element $\langle K^{(*)}\ell^+\ell^-, \ell^+\ell^-|\mathcal{H}_{\rm eff}|B\rangle$
- Tree-level like with charm fields: $\mathcal{O}_1 \sim (\bar{s}_L\gamma_\mu c_L)(\bar{c}_L\gamma^\mu b_L)$
- Radiative penguin: $\mathcal{O}_{7\gamma} \sim (\bar{s}_L\sigma_{\mu\nu}b)F^{\mu\nu}$
- Electroweak: $\mathcal{O}_{9V} \sim (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$, $\mathcal{O}_{10A} \sim (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$
- (pseudo)scalar: $\mathcal{O}_S \sim (\bar{s}_L b_L)(\bar{\ell}\ell)$, $\mathcal{O}_P \sim (\bar{s}_L b_L)(\bar{\ell}\gamma_5\ell)$.
- Many more operators if one includes tensors (leptoquarks), etc...

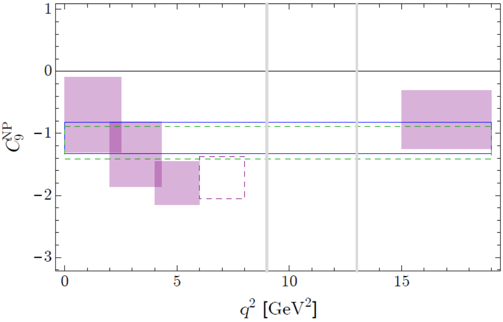
Global fits to $b \to s\mu\mu$

- 88 measurements of 76 different observables from 6 experiments. $B^0 \to K^*\mu^-\mu^+$, $B^0 \to K_s\mu^-\mu^+$, $B^+ \to K^{(*)+}\mu^-\mu^+$, $B_s \to \phi\mu^-\mu^+$, $B^0 \to K^*\gamma$, $B^0 \to X_s\gamma$, $B_s \to \mu^-\mu^+$. Altmannshofer/Straub, 1503.06199.

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.42	2.4
C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.24	1.8
C_9^{NP}	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	3.70	11.3
C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.84	2.0
C_{10}^{NP}	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	1.97	3.2
C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.87	2.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.89	2.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	3.13	7.1
$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.36	1.8
$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.93	2.0

q^2 DEPENDENCE?

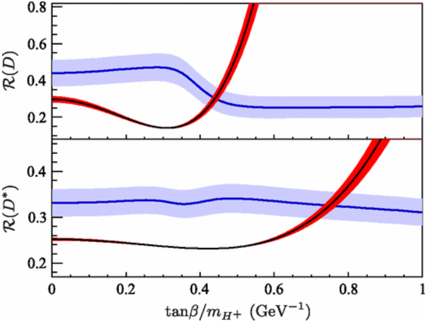
- C_9^{NP} should "mostly" be q^2 independent. Charm-loop effects instead?



Ongoing work in the $b \to s\ell^+\ell^-$ sector

- Go closer to $q^2 = m^2_{\psi^{(\prime)}}$ by improving resonant $c\bar{c}$ $(\psi^{(\prime)})$ vetoes.
- CP asymmetries. Imaginary C_i's. CPV?
- Angular analysis of $\Lambda_b \to pK\mu^-\mu^+$. LHCb is a Λ_b factory.
- In $B_d \to K\pi\mu^-\mu^+$ look at higher K^{*J} states, especially around the $K_2^*(1430)$.
- $R_{K,K^*,\phi}$: hadronic effects can't violate LFU.
- $|V_{ub}|$ from $B_s \to K^*\ell\overline{\nu}_\ell$. "Tagging" using $B_{s2}^* \to B^+K^-$ might allow $B^+ \to \rho^0\mu^+\nu_\nu$ angular analysis.

2HDM models confronting *BABAR* data

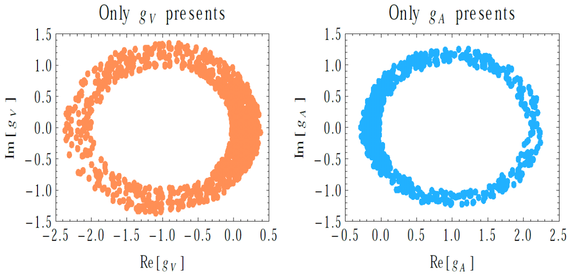


- type II 2HDM: the two Higgs doublets couple to up- and down-type quarks separately.
- Favored scenario in MSSM.
- However, can't explain $R(D)$ and $R(D^*)$ simultaneously.

- Can be accomodated in type III 2HDM (both doublets couple to up and down-type quarks). Crivellin et al. (1206.2634v2).

Connection of $R(D^{(*)})$ models to ϵ_R

- Effective Lagrangian approach with genaric 4-quark operators (Datta et al., 1206.3760) includes g_V, g_A, g_S, g_P...
- But $\frac{g_V}{g_A} \sim \frac{1+\epsilon_R}{1-\epsilon_R}$, so this should affect $\ell \in \{e, \mu\}$ cases as well.



- Angular analysis of $\overline{B} \to D^* \ell^- \overline{\nu}_\ell$ should place constraints on these models.

$|V_{ub}|$, $\sin(2\beta)$ and the UT