Recent results from LHCb

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on behalf of the LHCb collaboration

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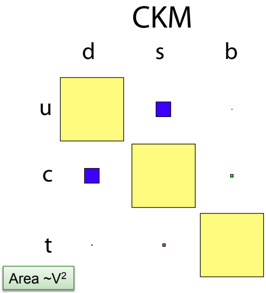
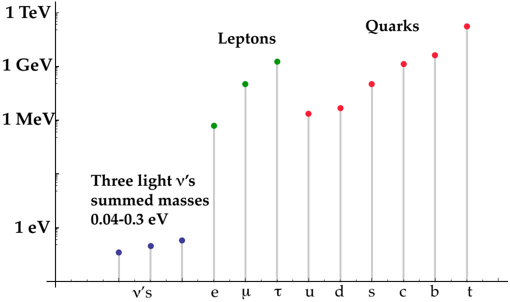
March 22, 2016

Important questions

The CKM matrix is a cornerstone of our understanding of particle physics



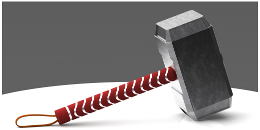


- One complex phase accounts for CPV in SM ($\mathcal{O}(10^7)$ too small)
- Do not understand relative sizes of the values ($|V_{ub}| = \mathcal{O}(10^{-3})|V_{tb}|$)
- Pattern of masses similarly puzzling ($m_u = \mathcal{O}(10^{-3})m_t$)
- How can dark matter be accommodated in SM

Experimental approaches

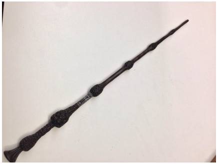
SM could be a low-energy effective theory of a more fundamental theory at higher energy scale with new particles, dynamics/symmetries.

Direct approach



- Rely on high energy collisions to produce new particle(s) on-mass-shell, observed through their decay products

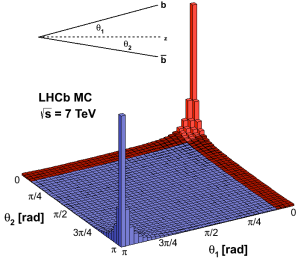
Indirect approach (typical of flavour)



- New particles appear off-mass-shell in heavy flavour processes, leading to deviations from SM expectations

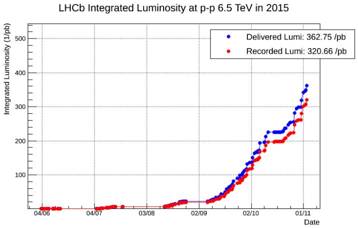
Setting the scene

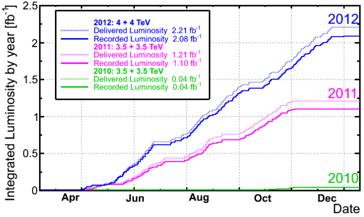
- LHC $\sigma_{b\bar{b}} = 460\,\mu$b @ $\sqrt{s} = 13$ TeV (scale $\sim$ linear with $\sqrt{s}$)
- $\sigma_{b\bar{b}}$ in LHCb acceptance $\sim 100\,\mu$b
  - c.f $\sigma_{b\bar{b}} = 0.001\,\mu$b @ B-factories



$\sim$ 60 papers since IOP HEPP 2015, $>$ 300 in total

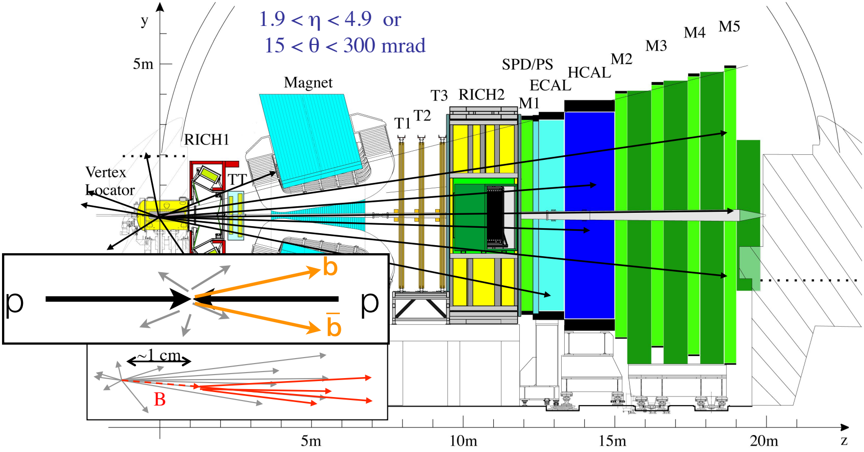
Run 2: 320pb^{-1} (current), Run 1: 3fb^{-1}





$L_{inst}^{Max} = 4 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (double the design value)

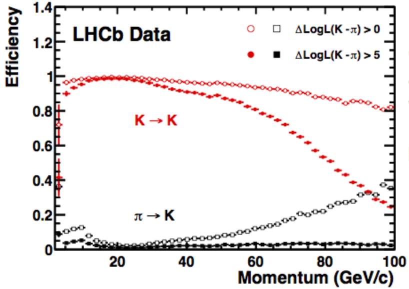
The LHCb detector

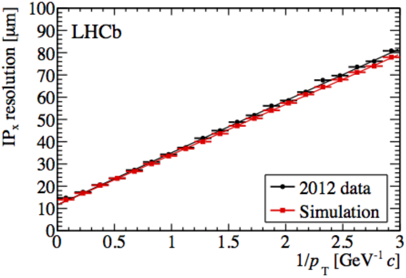


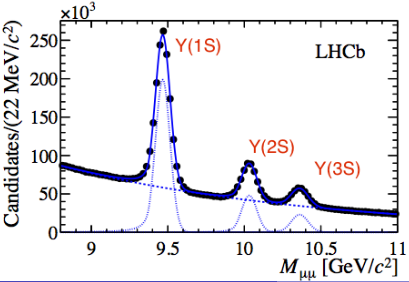
- UK responsible for VeLo and RICH systems
- *B*-lifetime means displaced secondary vertex

Detector performance

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





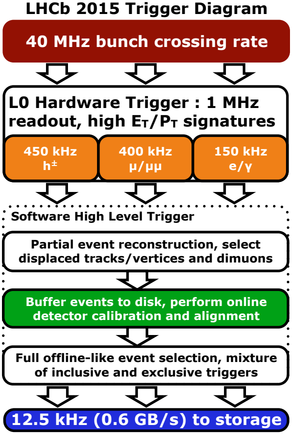


- **Tracking** $\delta p/p = 0.4 - 0.6\%$
- **Muon** $\epsilon_{\mu}^{id} = 98\%$ for 1% mis-id
- Mass resolution $J/\psi \rightarrow \mu\mu$
  - LHCb: 13 MeV
  - CMS: 28 MeV [arXiv:1011.4193]
  - ATLAS: 46 MeV [arXiv:1104.3038]

The LHCb trigger in Run 2

The challenge

- Only 1 in 200 pp inelastic events contain a *b*-quark
- Looking for *B*-hadron decays with $BF \sim 10^{-6} - 10^{-9}$



Major development for Run 2:

- Buffer all events after HLT1 to perform calibrations and alignment
  - Determine calibration and alignment constants per fill (minutes) [UK led]
  - Global offline-like reconstruction using these constants
  - Major step towards realising upgrade trigger strategy (see later)

$\rightarrow$ More selective triggers e.g offline like particle ID in the trigger!

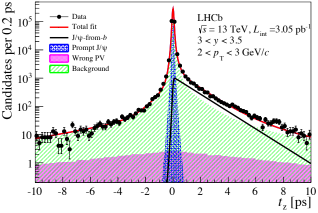
$\rightarrow$ Physics measurement with data straight out of HLT2

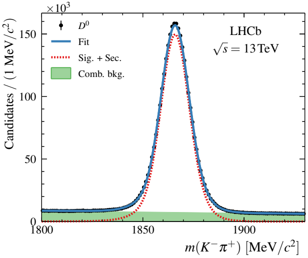
- Output rate of HLT2 ~~5kHz~~ 12.5kHz

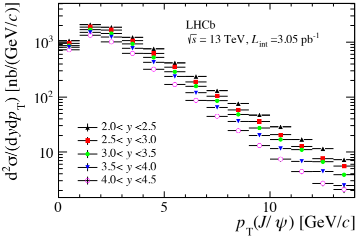
Measurements straight out of trigger

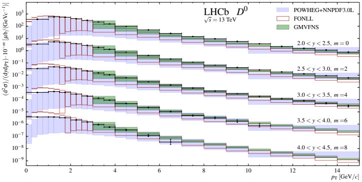
- → Measurement of prompt J/ψ production at 13TeV
- → Measurement of prompt D^0, D^+, D_s and D^{*+} production at 13TeV

[JHEP10(2015)172], [arXiv:1510.01707]









Cracks appearing in the SM?

Cracks appearing in the SM?

1. **Measurements of decay rates and angular distributions of $B \to K^{(*)}\mu^+\mu^-$ and $B_s \to \phi\mu^+\mu^-$ are all in tension with SM. Combined significance $> 4\sigma$**
   - As described in Tom's talk

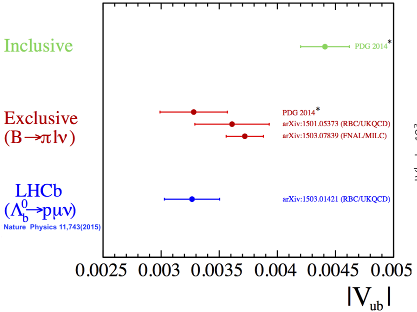
2. **Tension between inclusive and exclusive determinations of $|V_{ub}|$**
   - LHCb measurement possible due to close collaboration with Lattice QCD community

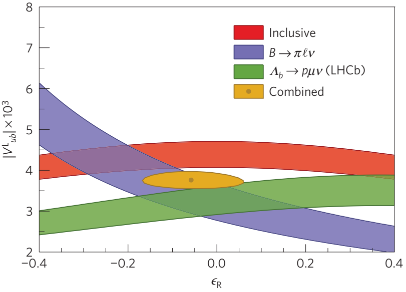
3. **Tension in measurements of** $\dfrac{\mathcal{B}(B^0 \to D^*\tau\nu)}{\mathcal{B}(B^0 \to D^*\mu\nu)}$

All three topics are UK led

$|V_{ub}|$ at LHCb: Results

[Nature Physics 11,743,(2015)]

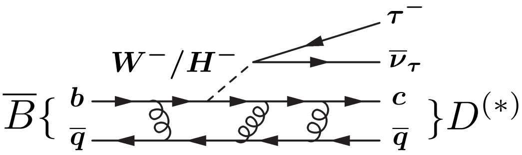




- Tension between inclusive and exclusive determination of $|V_{ub}|$
- LHCb's $\Lambda_b \to p\mu\nu$ measurement disfavours interpretations invoking the presence of right handed currents in order to explain tension between inclusive and exclusive $|V_{ub}|$

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$

- Test lepton universality by measuring $R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B}\to D^{(*)}\mu\bar{\nu})}$
- Sensitive to NP coupling differently to 1st and 3rd generations (e.g charged Higgs)
- Note this is a tree-level test of universality compared to $\frac{\mathcal{B}(B\to Kee)}{\mathcal{B}(B\to K\mu\mu)}$



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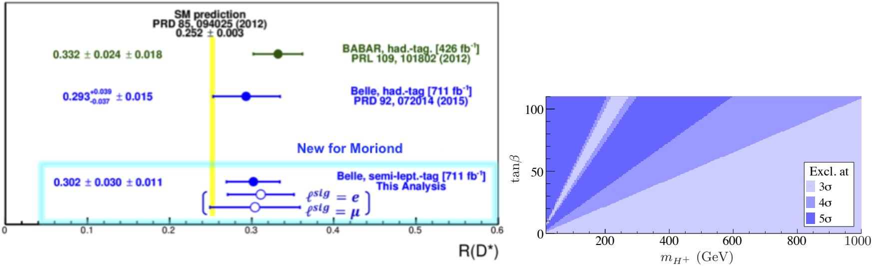


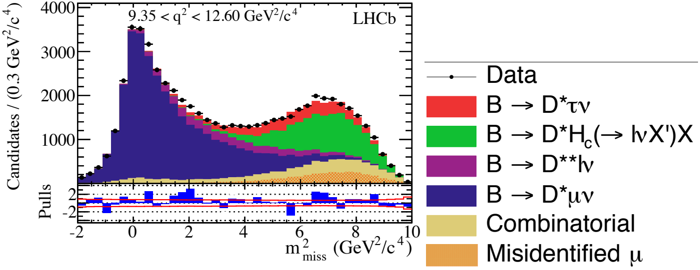
BaBar [PRD 88,072012], [Belle Moriond EWK 2016]

- Previous measurements from B factories using $\tau \to \ell\nu\nu$ decays combining D and D^* final states
- Latest BaBar result 3σ excess over SM [1303.0571]

$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ challenges at LHCb

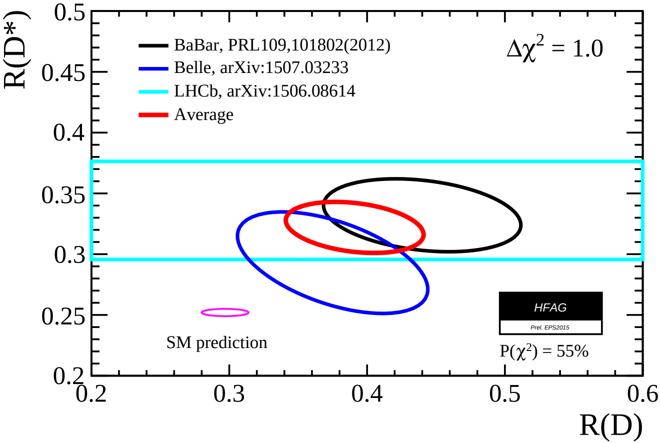
- Only D^{*+} for now with $\tau \to \mu\nu\nu$
  $\to$ No narrow peak to fit in any distribution
- Use B flight direction to measure transverse component of missing momentum
- Assume no missing momentum along flight direction of B
  $\to$ 18% resolution on B momentum
  $\to$ Template fit to rest frame quantities m^2_{missing}, E_μ, q^2

[PRL 115(2015)112001]



$\bar{B}^0 \to D^{*+}\tau\bar{\nu}$ global fit

3.9σ tension with SM excluding Belle's latest result!$\to$ Tension will increase further



- LHCb uncertainty split between statistical and systematic.
- Dominant systematic uncertainty: MC template statistics

Can we form a consistent picture?

Possible interpretations

Uncertainties underestimated?

- Experimental side to blame for lepton universality measurements?
- Theory side to blame for $b \to s\ell\ell$ observables, related to potentially significant miscalculation of charm loop effects?

- Planned measurements with Run 2 and Run 1 data will help resolve both sides

New physics? Example:
Leptoquark model **Bauer et al [1511.01900]**

- Non-universality tensions including muon (g-2) simultaneously explained through introduction of leptoquark sector

MITP/15-100
November 9, 2015

One Leptoquark to Rule Them All:
A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

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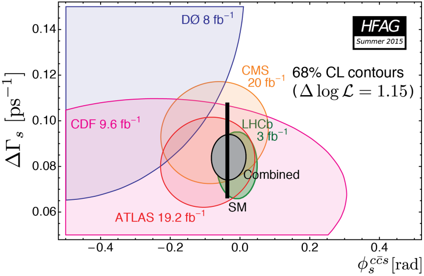
[a] *Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*
[b] *PRISMA Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany*
[c] *Department of Physics & LEPP, Cornell University, Ithaca, NY 14853, U.S.A.*

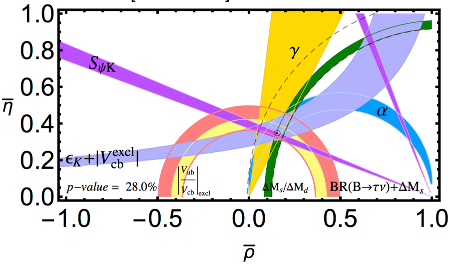
We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

Rest of heavy flavour picture

- New for Moriond: Precision measurement of $B^0 - \bar{B}^0$ oscillation frequency [LHCb-PAPER-2015-031]
  $\rightarrow \Delta m_d = (505.0 \pm 2.1(stat.) \pm 1.0(syst.))\text{ns}^{-1}$
  $\rightarrow$ World's most precise (comparable precision with global average)
  $\rightarrow 2\sigma$ agreement with SM
- Global CKM picture so far looks untouched by anomalies
  $\rightarrow$ Precision of direct determination of angle γ is key
- Precision of CPV measurements in B_s system is far below precision of predictions

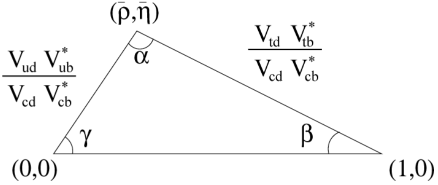


Fermi Lattice and MILC [1602.03560]

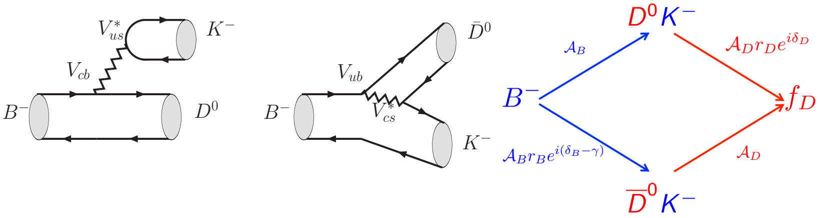


Measuring γ

- Unitarity of CKM matrix implies:
  $\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$
  $\rightarrow$ CKM unitarity triangle for B_d



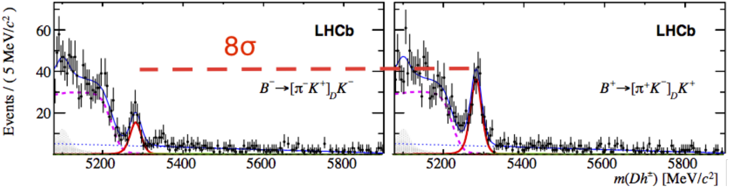
- Measuring γ is a benchmark test of the SM
- Measured through interference between two tree decay amplitudes to the same final state



Measuring γ $B^{\pm} \to DK^{\pm}$ [New for Moriond]

[LHCb-PAPER-2016-003]

- Measure asymmetries and amplitude ratios of $B^{\pm} \to DK^{\pm}$ with 2 or 4 body D decays
  $\to D^0 \to K^+K^-/\pi^+\pi^-/\pi^+\pi^-\pi^+\pi^-$ new! (GLW),
  $\to D^0 \to K^{\pm}\pi^{\mp}/K^{\pm}\pi^{\mp}\pi^+\pi^-$ (ADS)
  $\to$ 21 CP observables in total, use to determine γ, r_B and δ_B
- Use CLEO-c/LHCb/HFAG inputs to constrain parameters in charm system e.g r_D and δ_D
  $\to$LHCb [1602.07224]: Observation of $D^0 \to \overline{D}^0$ oscillations with $K3\pi$ decays sensitive to $r_D^{K3\pi}$ and $\delta_D^{K3\pi}$
- CP violation in $B^{\pm} \to DK^{\pm}$ clearly observable $\to$ Improved precision on γ

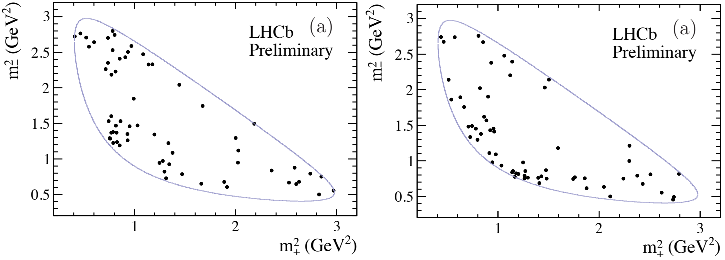


Measuring γ $B^0 \to DK^{*0}$ [New for Moriond]

Model dependent [LHCb-PAPER-2016-007], Model independent [LHCb-PAPER-2016-006]

- Fit for CP observables in the Dalitz plane of $D \to K_S^0\pi^+\pi^-$ decays for both B^0 and $\bar{B}^0$ decays (GGSZ)
  $\to$ Use an amplitude model to fit the Dalitz distribution (Model Dependent)
  $\to$ determine γ, r_B and δ_B

Left: $\bar{B}^0$ Right: B^0

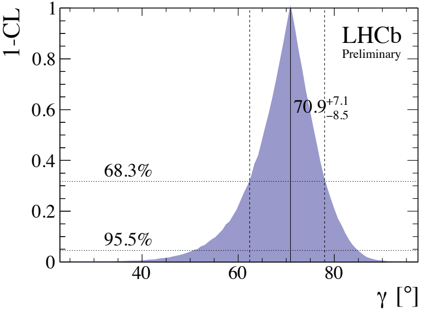


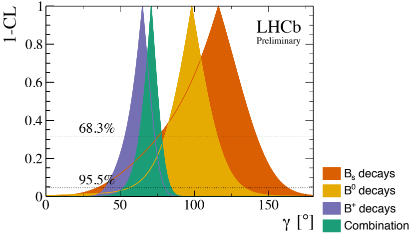
- Included in γ combination for the first time!
- Through combination with other modes maximise sensitivity to γ

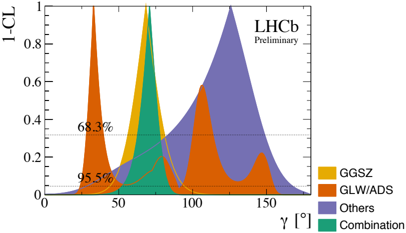
γ Combination

[LHCb-CONF-2016-001]

- Combine number of LHCb measurements (full list in backup)
- $\gamma = (70.9^{+7.1}_{-8.5})^\circ$
- Improvement of $\sim 2^\circ$
- Precision better than combined B-factories
- Still lots of space for NP to hide!
- $\rightarrow$ more precision required
- LHCb upgrade: precision 1°!





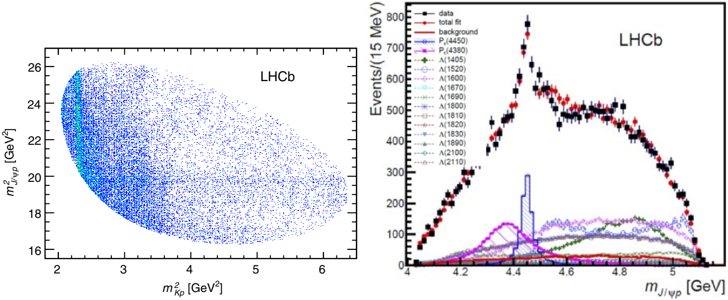


Exotic hadrons: Where dreams are created and crushed!

Pentaquark observation in $\Lambda_b \to J/\psi pK$

- 6D amplitude fit requires two additional resonant amplitudes with $J^P = (3/2^+, 5/2^-)$ in the $J/\psi p$ system ($c\bar{c}uud$) to describe the data

[PRL115,072001(2015)]



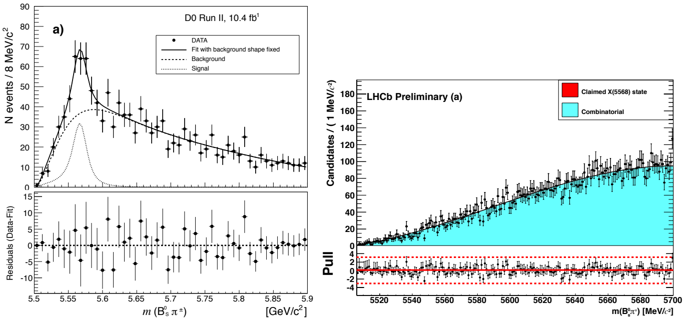
New for Moriond: Model independent approach [LHCb-PAPER-2016-009]

- Confirms model dependent measurement

$X(5568)$ non confirmation [New for Moriond]

- Feb 24: D0 announced mass bump $X(5568) \to B_s\pi^{\pm}$ with global significance 5.1σ [arXiv:1602.07588]
- Using $\sim$ 6K $B_s \to J/\psi\phi$ decays

Left: D0 [arXiv:1602.07588, Right: LHCb [LHCb-CONF-2016-004]



- LHCb looked in 50K $J/\psi\phi$ and 70K $D_s\pi$ decays, cannot confirm
- Upper limit on production set, more details [LHCb-CONF-2016-004]

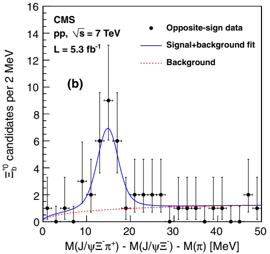
$$\rho_X^{\rm LHCb} \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi)}{\sigma(pp \to B_s^0 + \text{anything})}$$

$$\rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 5\,{\rm GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ {\rm CL}$$

$$\rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 10\,{\rm GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ {\rm CL}$$

Ξ_b^{*0} confirmation [New for Moriond]

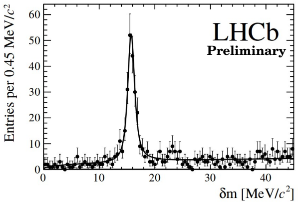
- CMS published in 2012 [PRL108,252002(2012)] observation of Ξ_b^{*0}



- LHCb already observed two excited partners of the charged Ξ_b state [PRL114,062004(2015)]
- What about Ξ_b^{*0}?

Presented tomorrow at Moriond [LHCb-PAPER-2016-010] QCD, LHCb confirms CMS

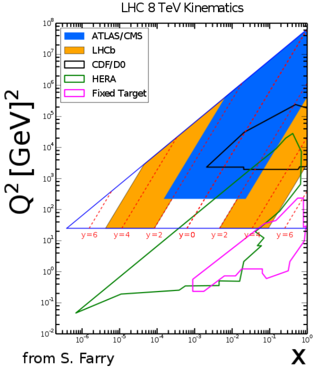
- $\Xi_b^{*0} \to \Xi_b^- \pi^+$, $\Xi_b^- \to \Xi_c^0 \pi^-$, $\Xi_c^0 \to pK^-K^-\pi^+$
- $\delta m = 15.73 \pm 0.07 \pm 0.02$MeV ($\times 10$ precision)
- $\Gamma = 0.90 \pm 0.16 \pm 0.08$MeV (first measurement)
- Expect two excited states, only one above $\Xi_b^- \pi^+$ threshold observed
  $\to$ Other state must decay via $\Xi_b \gamma$ or $\Xi_b \pi^0$



W, Z and t physics

W and Z production measurements

- Unique forward coverage of LHCb
  $\rightarrow$ Sensitivity to low and high x
- Complementary constraints on PDFs



from S. Farry

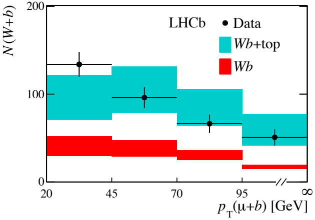
$$Q^2(x) = e^{\pm 2y} x^2 s$$

- Z's produced with large p_z
  $\rightarrow$ Increased sensitivity of $A_{\rm FB}$ to $\sin\theta_W^{eff}$
  $\rightarrow$ Among most precise determination of $\sin\theta_W^{eff}$ at hadron collider [JHEP11(2015)190]
- Jets reconstructed with energy resolution $\sim 15\%$
- Excellent b/c- vs $udsg$-jet (65%/25% vs 0.3%) and b- vs c-jet tagging [JINST 10 P06013]$\longrightarrow$ Zb[JHEP 01 (2015) 064], Wb/c[PRD92(2015)052001], W/Z+jets[LHCb-PAPER-2016-11], $A_{FC}^{b\bar{b}}$ [PRL(2014)082003], $t\bar{t}$[PRL115(2015)112001]

W/Z+jets at $\sqrt{8}$ TeV, $Z \to \mu\mu$ at $\sqrt{13}$ TeV

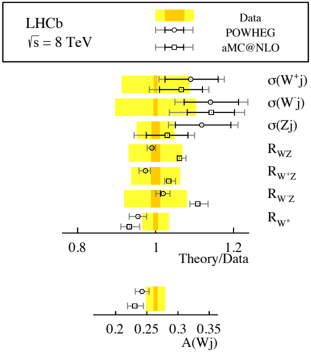
- Ldg. Jet $p_{\mathrm{T}} > 20\,GeV$, $2.2 < \eta < 4.2$
- Sensitive to large-x u/d PDFs
- Observation of t-production in fiducial region, $\sigma(8\mathrm{TeV}) = 289 \pm 43(stat) \pm 40(syst) \pm 29(theory)$

[PRL115(2015)112001]

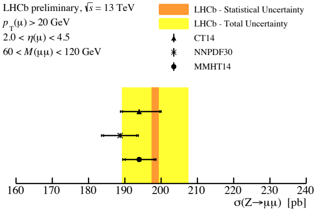


- $W + b$ (including t) yield extracted from fitting b-tagging response

New for Moriond [LHCb-PAPER-2016-011]



New for Moriond [LHCb-CONF-2016-002]



Future Directions

The LHCb upgrade

- If cracks in the SM persist in Run 2, the LHCb upgrade will allow for precision measurements of the flavour structure of New Physics
- Otherwise, LHCb upgrade will probe NP at multi-TeV energy scale
- General purpose forward experiment: Complementary non-flavour programme to ATLAS and CMS

Run 1 (2010-2012)	2012-2015	Run 2 (2015-2018)	2018-2021	Run 3 (2021-2023)	2023-2025	Run 4 (2025-2028)	2028-2030	Run 5 (2030+)
$3fb^{-1}$	Shutdown	$\sim5fb^{-1}$	Shutdown	$\sim23fb^{-1}$	Shutdown	$\sim46fb^{-1}$	Shutdown	$\sim100fb^{-1}$
LHCb			LHCb upgrade				LHCb upgrade++	
		2017-2024 Belle-II ($50ab^{-1}$)						

The problem:

- Current conditions: up to $L_{inst} = 4 \times 10^{32} cm^{-2} s^{-1}$, $\mu \sim 1.7$
- 2020 conditions: $L_{inst} = 2 \times 10^{33} cm^{-2} s^{-1}$, $\mu \sim 5$

Higher luminosities:

- More interactions per crossing, more vertices, higher track multiplicities, more ghost tracks...

The LHCb upgrade cont'd

The solution:

- More flexible trigger, reading out full detector at 40 MHz and HLT output between 20 and 100 kHz

LHCb UK

→ VELO upgrade:

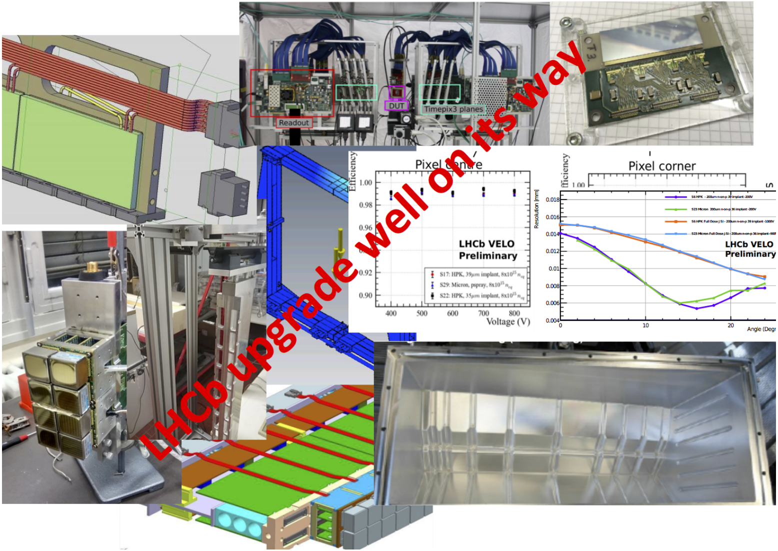
- ▷ Silicon microstrips → Pixel sensors
- ▷ 40MHz readout
- ▷ Closer to the beam (8mm→5mm)
- ▷ Microchannel cooling and RF foil

→ RICH upgrade:

- ▷ Replace HPDs with MaPMTs in RICH1,2
- ▷ 40MHz readout
- ▷ Upgrade photodetector assembly in RICH1,2
- ▷ Complete redesign of RICH1 mechanical structure to reoptimise optics and easier access

→ Major upgrades to tracking as well

[LHCb-TDR-013], [LHCb-TDR-014], [LHCb-TDR-015],[LHCb-TDR-016]



Phase 1 upgrade of LHCb firmly established

→ Momentum building for developing a detector for Run4,5...

→ Theatre of Dreams Beyond the LHCb Phase 1 upgrade: 6-7 April Manchester [link]

Other flavour prospects

NA62 status

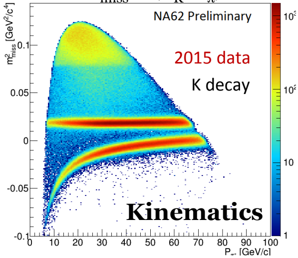
Main goal: measure **BR($K^+ \to \pi^+ \nu\nu$)** at **10%** precision

But also: rare decays, searches for **LFV**, **HNL**, …

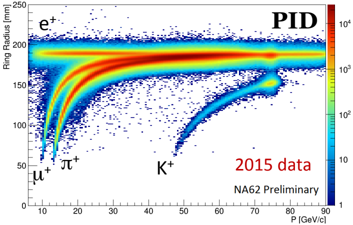
First physics run in 2015:

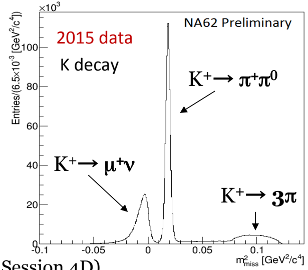
- Low intensity data used for quality studies
- Detector performance for $K^+ \to \pi^+ \nu\nu$ measurement is in line with design
- High intensity beam in **2016-2018** for physics runs (next run: ~200 days starting in April 2016)

$m^2_{miss} = (P_K - P_\pi)^2$



Ring radius in RICH vs Momentum





see talk by A. Romano (Wed 23 April, Session 4D)

Conclusions

- Presented biased set of LHCb's highlights over the past year
- Tensions with the SM persist and appear in new places
  - Can be explained through extensions to the SM
  - Can be attributed to large unexpected experimental or theory effects
  - More tests underway
- Precision of CPV and mixing parameters in charm and beauty sector is rapidly increasing

As LHC pushes energy scale of new physics $\gg$1TeV, Minimal Flavour Violation constraints get lifted $\rightarrow$ Increase chances to see NP in flavour

Backup

$|V_{ub}|/|V_{cb}|$ $\Lambda_b \to p\mu\nu$ systematics

Table 1 | Summary of systematic uncertainties.

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

The table shows the relative systematic uncertainty on the ratio of the $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ branching fractions broken into its individual contributions. The total is obtained by adding them in quadrature. Uncertainties on the background levels are not listed here as they are incorporated into the fits.

$R(D^*)$ systematics

Model uncertainties	Size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
D^* form factors	0.6
$B \to D^* DX$ shape	0.5
$\mathcal{B}(B \to D^{**}\tau\nu)/\mathcal{B}(B \to D^{**}\mu\nu)$	0.5
$B \to [D^*\pi\pi]\mu\nu$ shape	0.4
Corrections to simulation	0.4
Combinatoric background shape	0.3
D^{**} form factors	0.3
$B \to D^*(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**

Multiplicative uncertainties	Size ($\times 10^{-2}$)
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau \to \mu\nu\nu)$	< 0.1
Total multiplicative uncertainty	**0.9**
Total systematic uncertainty	**3.0**

γ Combination

table courtesy of M. Kenzie

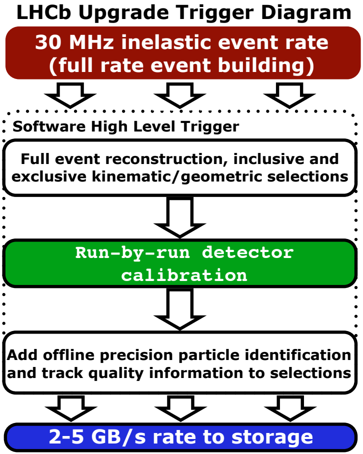
	B decay	D decay	Type	$\int \mathcal{L}$	Ref.
LHCb Inputs	$B^+ \to DK^+$	$D \to hh$	GLW/ADS	3 fb^{-1}	[LHCb-PAPER-2016-003]
	$B^+ \to DK^+$	$D \to h\pi\pi\pi$	GLW/ADS	3 fb^{-1}	[LHCb-PAPER-2016-003]
	$B^+ \to DK^+$	$D \to hh\pi^0$	GLW/ADS	3 fb^{-1}	[arXiv:1504.05442]
	$B^+ \to DK^+$	$D \to K^0_S hh$	GGSZ	3 fb^{-1}	[arXiv:1405.2797]
	$B^+ \to DK^+$	$D \to K^0_S K\pi$	GLS	3 fb^{-1}	[arXiv:1402.2982]
	$B^0 \to D^0 K^{*0}$	$D \to K\pi$	ADS	3 fb^{-1}	[arXiv:1407.3186]
	$B^+ \to DK^+\pi\pi$	$D \to hh$	GLW/ADS	3 fb^{-1}	[arXiv:1505.07044]
	$B^0_s \to D_s^{\mp} K^{\pm}$	$D_s^+ \to hhh$	TD	1 fb^{-1}	[arXiv:1407.6127]
	$B^0 \to D^0 K^+\pi^-$	$D \to hh$	Dalitz	3 fb^{-1}	[arXiv:1602.03455]
	$B^0 \to D^0 K^{*0}$	$D \to K^0_S \pi\pi$	GGSZ	3 fb^{-1}	[LHCb-PAPER-2016-007]

	Decay	Parameters	Source		Ref.
Auxiliary Inputs	Charm mixing		HFAG	-	[arXiv:1412.7515]
	$D \to K\pi\pi\pi$	$(\delta_D, \kappa_D, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430]
	$D \to \pi\pi\pi\pi$	(F^+)	CLEO	-	[arXiv:1504.05878]
	$D \to K\pi\pi^0$	$(\delta_D, \kappa_D, r_D)$	CLEO+LHCb	-	[arXiv:1602.07430]
	$D \to hh\pi^0$	(F^+)	CLEO	-	[arXiv:1504.05878]
	$D \to K^0_S K\pi$	(δ_D, κ_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	CLEO	-	[arXiv:1203.3804]
	$D \to K^0_S K\pi$	(r_D)	LHCb	-	[arXiv:1509.06628]
	$B^0 \to D^0 K^{*0}$	$(\kappa_B, \bar{R}_B, \bar{\Delta}_B)$	LHCb	-	[arXiv:1602.03455]
	$B^0_s \to D_s^+ K^-$	(ϕ_s)	LHCb	-	[arXiv:1411.3104]
Combination:					[LHCb-CONF-2016-001]

New or updated since last combination

Upgrade Trigger

The problem: saturation of L0 Hadronic trigger rate on hadronic decays at $> 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$

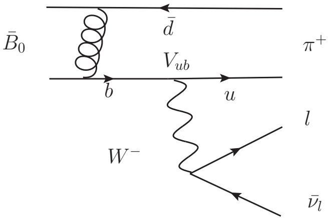


LHCb upgrade

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}	–

Measuring $|V_{ub}|$ through exclusive decays

- B-factories: $\bar{B}^0 \rightarrow \pi^+ \mu \bar{\nu}$ most precise
- LHCb: $\Lambda_b \rightarrow p \mu \nu$ better choice
  - $\rightarrow$ Lower backgrounds (proton vs π)
  - $\rightarrow$ 20% of b-hadrons are Λ_bs

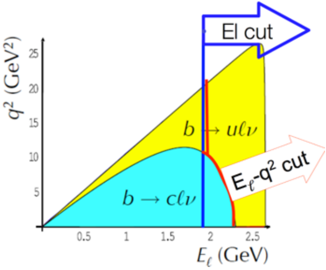


$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2 p_\pi^3}{24\pi^3} |f^+(q^2)|^2$$

- Decay rate factorises electroweak and strong part
- Form factor calculated using Lattice QCD (greatest precision at high q^2)
- Normalise $\Lambda_b \rightarrow p \mu \nu$ rate to $\Lambda_b \rightarrow \Lambda_c \mu \nu$
  - $\rightarrow$ Use lattice prediction for ratio of Form Factors Detmold et al [1503.01421]
  - $\rightarrow$ Extract $|V_{ub}|/|V_{cb}|$

Measuring $|V_{ub}|$ through inclusive decays

- By not focusing at particular final state, simply measure $b \to u\ell\nu$ without worrying about form factors
- Experimentally very challenging as suffer from large $b \to c$ related backgrounds
- Require tight fiducial cut introducing strong dependence on non perturbative effects $\to$ large systematic



- $|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.19}) \times 10^{-3}$ [PDG 2014]
- Tension between inclusive and exclusive $\sim 2.5\sigma$

  Prior to FNAL/MILC 2015 tension $> 3\sigma$

$|V_{ub}|$ at LHCb: Background suppression

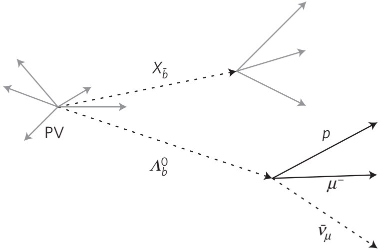
Main backgrounds from V_{cb} decays (1000 larger rate)

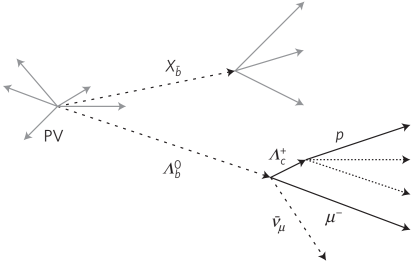
- Charm has significant lifetime

  $\rightarrow$ cut on vertex quality
- PID reduces backgrounds with real protons and muons
- Presence of additional charged hadrons

  $\rightarrow$ train MVA to decide if each track from same B-hadron or primary vertex

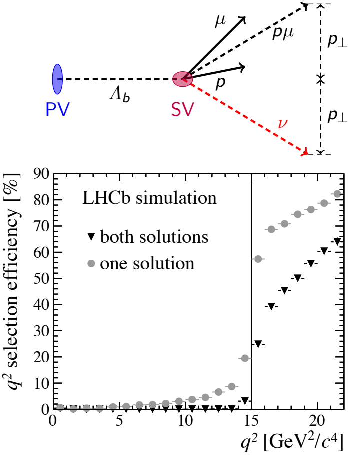
  $\rightarrow$ remove candidates with additional tracks (90% rejection 80% efficiency)
- Difficult to isolate against neutral particles





$|V_{ub}|$ at LHCb: Reconstruction techniques

- Presence of neutrino makes q^2 reconstruction difficult



[Nature Physics 11,743,(2015)]

- Use line of flight and mass of B-hadron to calculate q^2 (two fold ambiguity)
- Select solutions with $q^2 > 15$ GeV^2 to reduce migration effects
- Fit for $m_{corr} = \sqrt{m_{vis}^2 + |p_\perp|^2} + |p_\perp|$ $\rightarrow$ technique from SLD, minimum mass assuming massless single missing particle

$|V_{ub}|$ at LHCb: Results

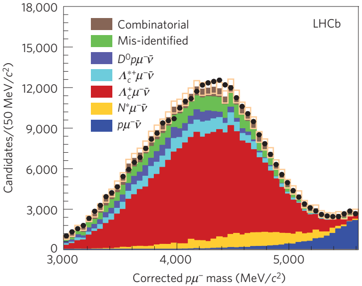
[Nature Physics 11,743,(2015)]

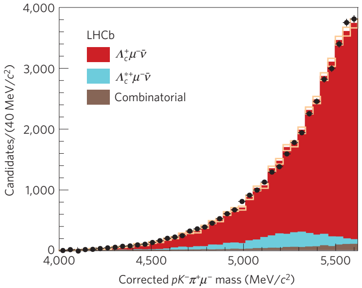
- Template shapes determined from simulation
- Background yields constrained in fit using using control modes in data
- $\Lambda_b \to N^* \mu\nu$ least known shape and yield

  $\to$ 100% uncertainty added for yield and shape due to FF knowledge

- Lattice QCD input for ratio of $\Lambda_b \to p\mu\nu$ and $\Lambda_b \to \Lambda_c\mu\nu$ Form Factors Meinel [arXiv:1503.01421]

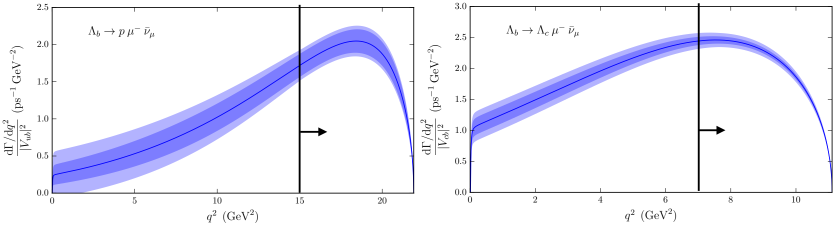
  $\frac{|V_{ub}|}{|V_{cb}|} =$
  $0.083 \pm 0.004(\text{expt.}) \pm 0.004(\text{LQCD})$
- Dominant experimental uncertainty knowledge of $\mathcal{B}(\Lambda_c \to pK^-\pi^+)$ [Belle 2014]





$|V_{ub}|$ at LHCb: Strategy

- Use line of flight and mass of Λ_b to calculate q^2 (two fold ambiguity)
  $\rightarrow$ Selection guarantees migrations negligible
- Normalise signal yield to $\Lambda_b \rightarrow \Lambda_c(pK^-\pi^+)\mu\nu$ (V_{cb})
  $\rightarrow$Cancel many systematic uncertainties including Λ_b production rate
- Measure ratio of branching fractions at high q^2
  $\rightarrow$ Use lattice prediction for Form Factors
  $\rightarrow$ Extract $|V_{ub}|/|V_{cb}|$



Detmold et al [1503.01421]

W/Z+jets systematics

Table 1: Summary of the different contributions to the total systematic uncertainty on σ_{W^+j}, σ_{W^-j}, σ_{Zj} and their ratios given as a percentage of the measured observable.

Source	σ_{W^+j}	σ_{W^-j}	σ_{Zj}	R_{WZ}	$R_{W^\pm}$
Statistical	0.4	0.5	1.1	1.2	0.7
Muon reconstruction	1.3	1.3	0.6	0.9	0.0
Jet reconstruction	1.9	1.9	1.9	0.0	0.0
Selection	1.0	1.0	0.0	1.0	0.0
GEC	0.5	0.5	0.4	0.2	0.1
Purity	5.5	7.0	0.4	6.0	2.5
Acceptance	0.6	0.6	0.0	0.6	0.0
Unfolding	0.8	0.8	0.8	0.0	0.2
Jet energy	6.5	7.7	4.3	3.4	1.2
Systematic	8.9	10.7	4.8	7.0	3.3
Luminosity	1.2	1.2	1.2	–	–

Luminosity determined through combination of Van-der-Meer scans and beam-gas imaging methods combined

W/Z+jets systematics

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Systematic	8.9	10.7	4.8	7.0	3.3
Luminosity	1.2	1.2	1.2	–	–

$X(5568)$ cone cut