LHCb: Run I Results & Future Prospects

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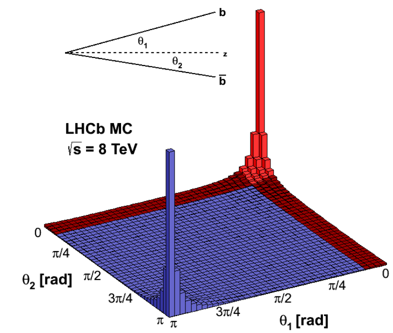
MIAPP workshop on Indirect Searches for New Physics in the LHC and Flavour Precision Era

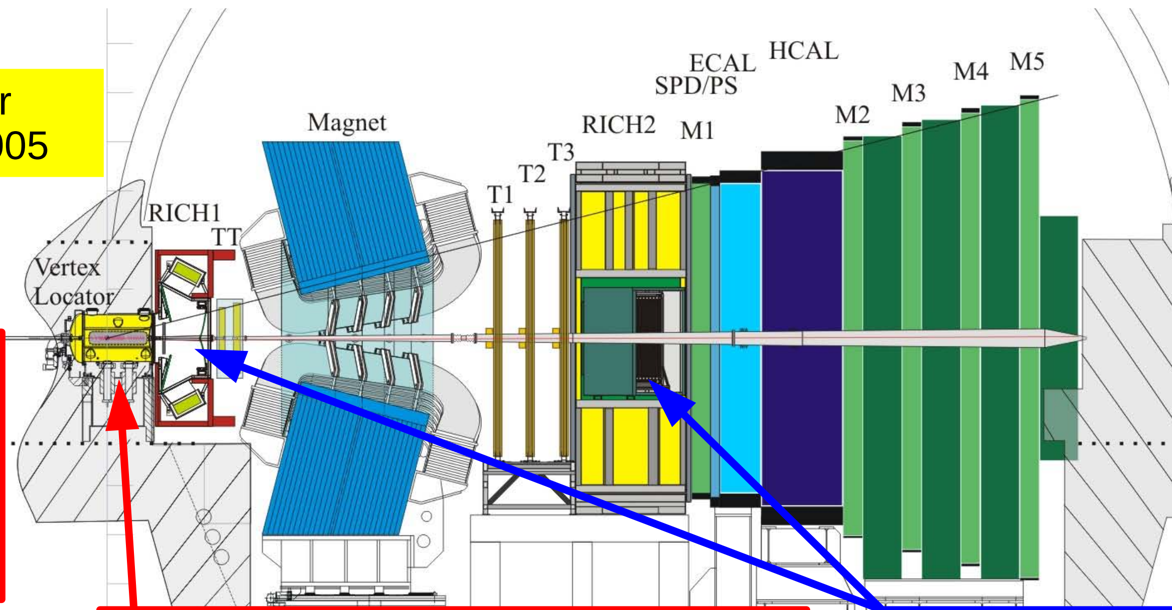
24th June 2015

The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer
  - a new concept for HEP experiments



The LHCb Detector
JINST 3 (2008) S08005



Precision primary and secondary vertex measurements

Excellent K/π separation capability

The LHCb Run 1 trigger

JINST 8 (2013) P04022

Challenge is

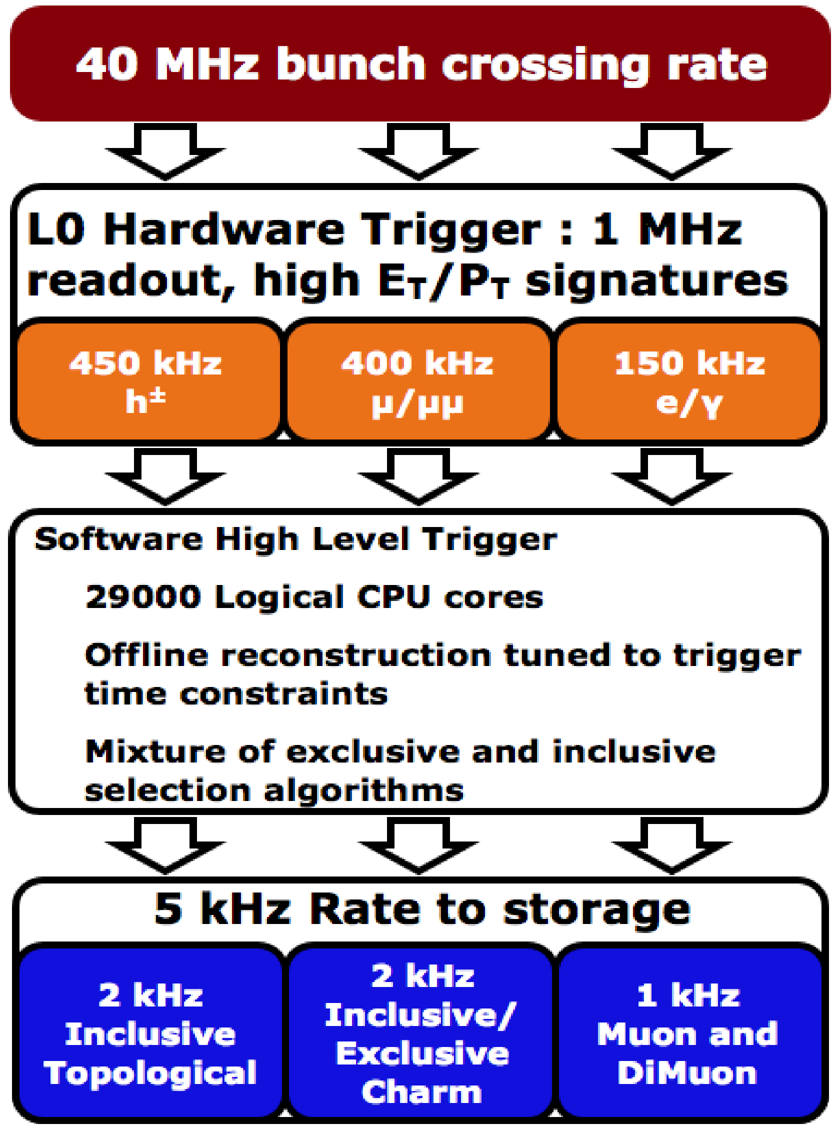
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- "minimum bias" inelastic pp scattering
- other charm and beauty decays

Handles

- high p_T signals (muons)
- displaced vertices



Content of this talk

Focus on areas with recent experimental progress

Will end with future perspectives

Towards New SM In 12 Steps

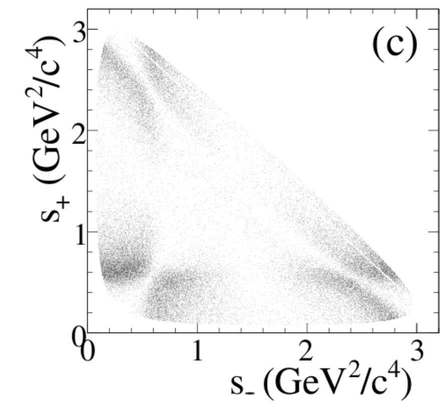
1. **CKM from Trees** — γ & V_{ub}
2. **Lattice**
3. **$\Delta F=2$ Observables** — $\sin(2\beta)$, φ_s
4. $B_{s,d} \to \mu^+\mu^-$, $B_{s,d} \to \tau^+\tau^-$ — $B_{d,s} \to \mu\mu$
5. $B^+ \to \tau^+\nu_\tau$ — $B \to D^{(*)}\tau\nu$
6. $B \to X_s\gamma$, $B \to K^*\gamma$
7. $B \to X_s l^+l^-$, $B \to K^*(K) l^+l^-$ — $B^0 \to K^*\mu\mu$ & $B_s \to \varphi\mu\mu$
8. $K \to \pi\nu\bar{\nu}$
9. $B \to X_s\nu\bar{\nu}$, $B \to K^*(K)\nu\bar{\nu}$
10. ε'/ε
11. **Charm, Top** — LHCb top observation
12. **LFV, EDMs, $(g-2)_{\mu,e}$**

Clock from Buras & Girrbach, RPP 77 (2014) 086201

$D \to \pi^+\pi^-\pi^0$ – a quasi-CP eigenstate

PRL 99 (2007) 251801

- Seminal Dalitz plot analysis from BaBar
  - Gives the parameter x_0 = 0.850 (without uncertainty)
  - Relation to fractional CP-even content: $x_0 = 2F_+ - 1$

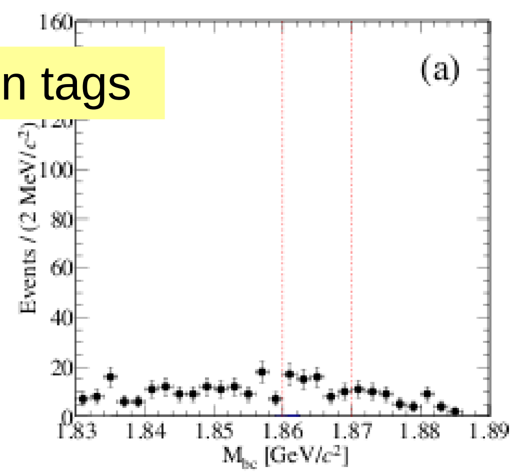


- Exploit CLEOc $\Psi(3770) \to D\bar{D}$ data for direct measurement of CP content: $F_+ = 0.973 \pm 0.017$

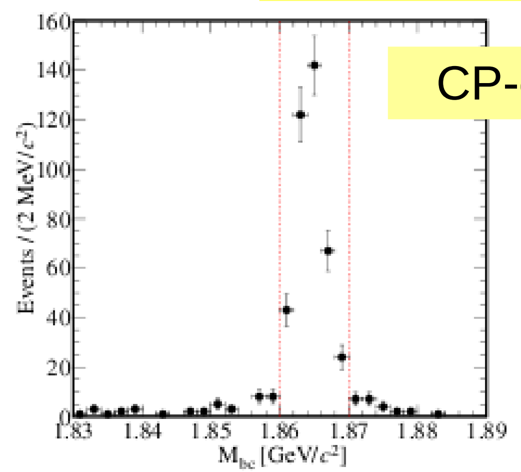
PLB 740 (2015) 1 & arXiv:1504.05878

Unexpected!

CP-even tags



CP-odd tags

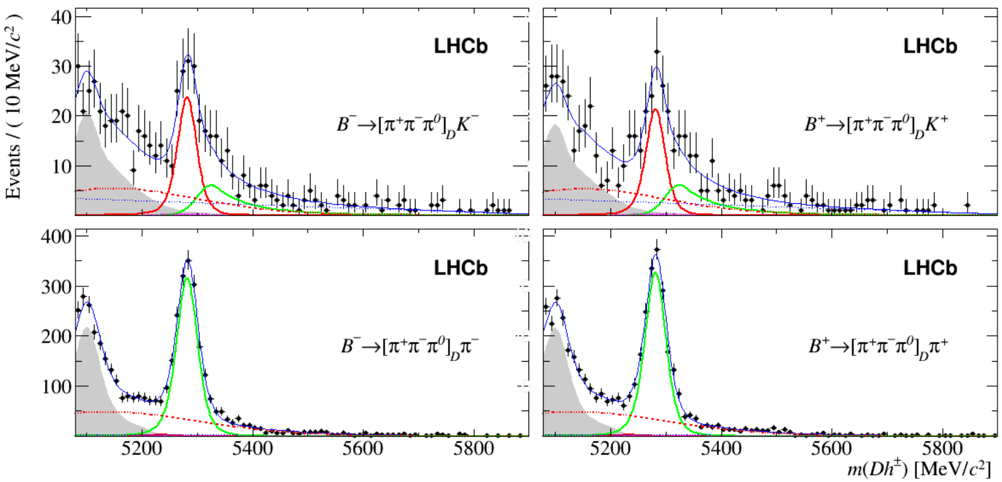


New decay modes for γ

arXiv:1504.05442

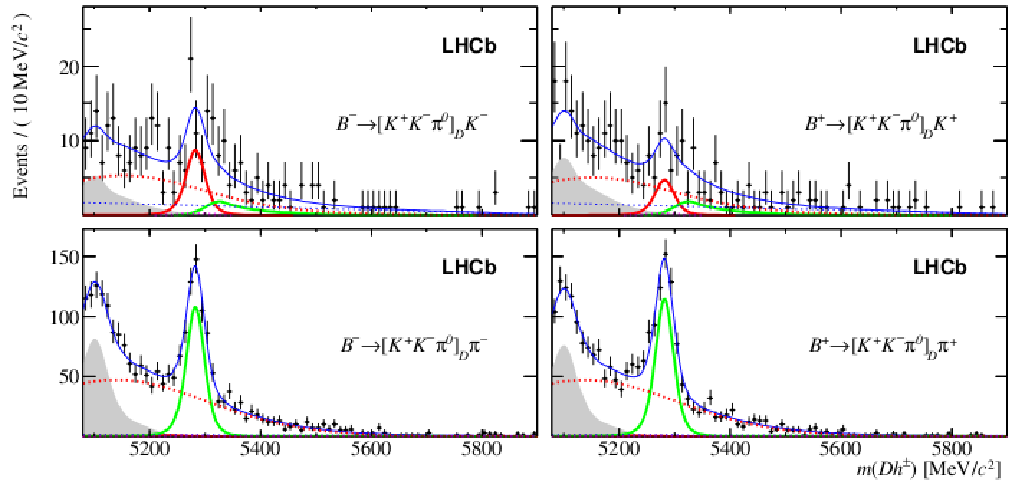
$B \to DK$, $D \to \pi^+\pi^-\pi^0$

$F_+ = 0.973 \pm 0.017$



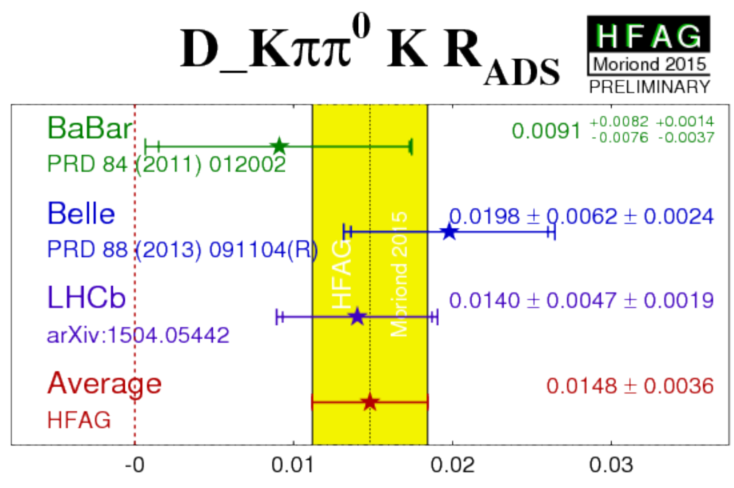
$B \to DK$, $D \to K^+K^-\pi^0$

$F_+ = 0.734 \pm 0.119$



$B \to DK$, $D \to K^+\pi^-\pi^0$

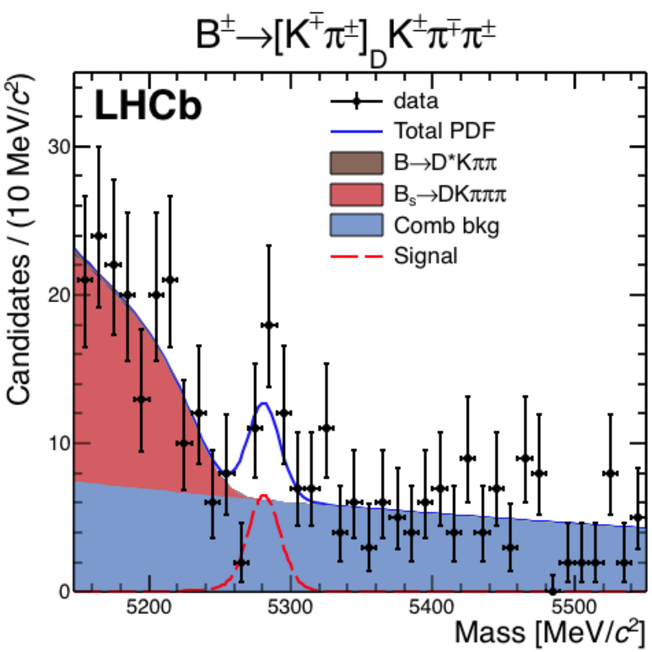
More precise than BaBar or Belle

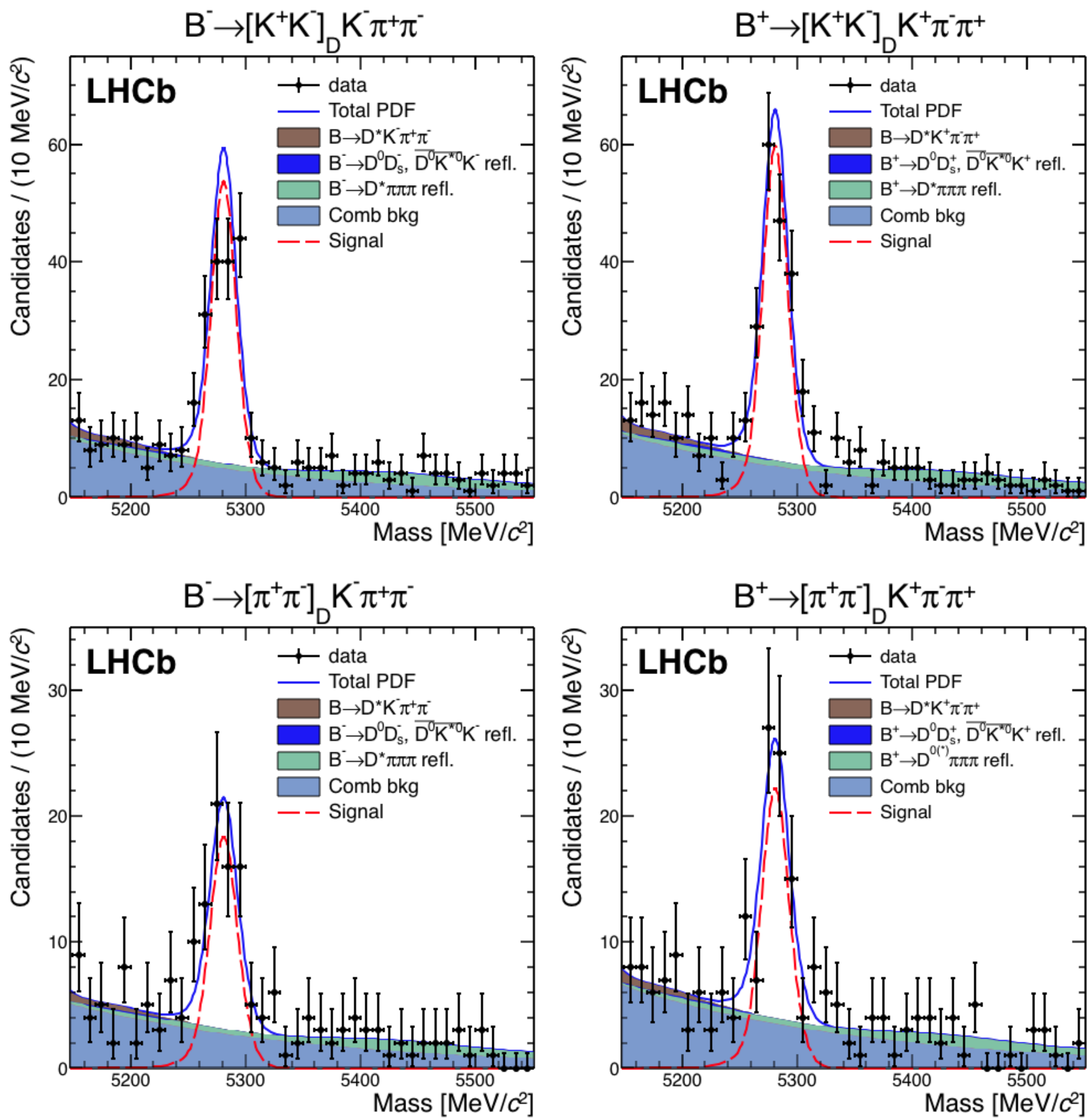


New decay modes for γ

arXiv:1505.07044

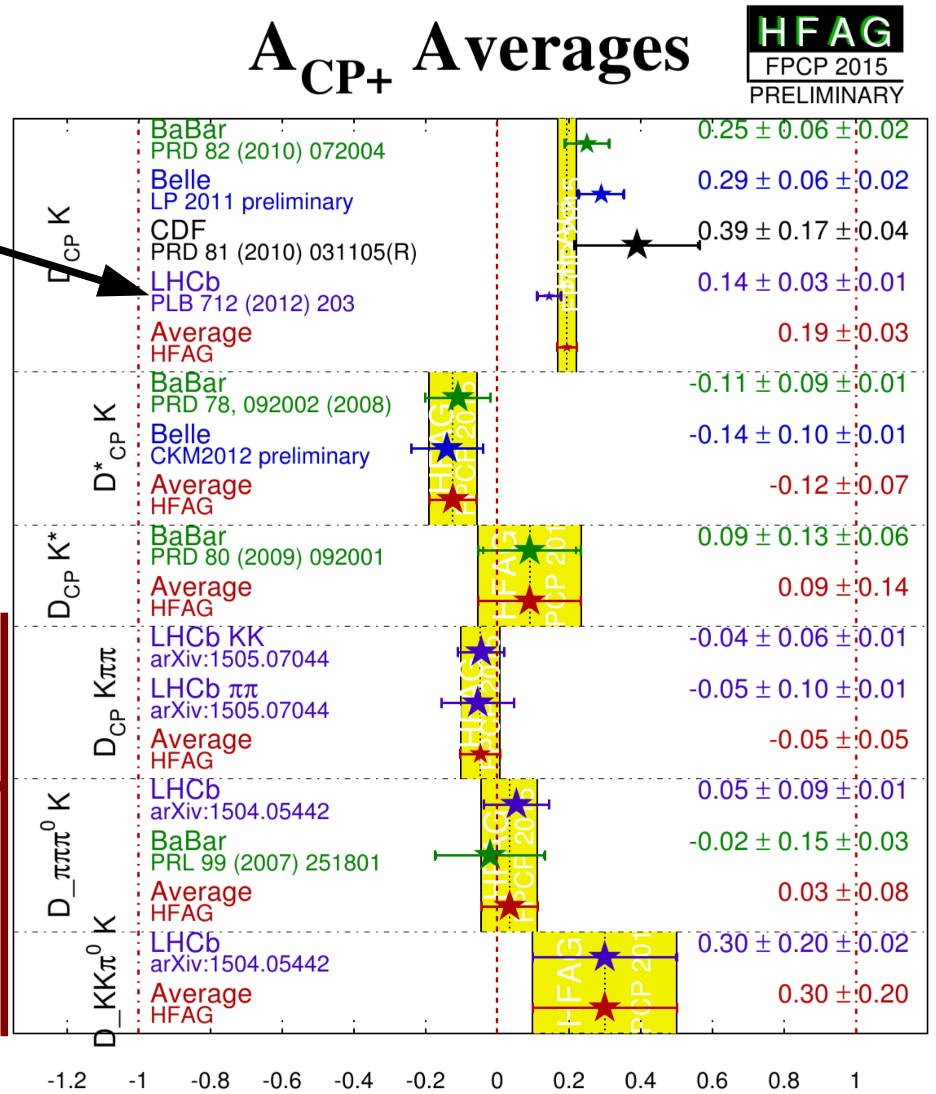
$B \to DK\pi^+\pi^-$,
$D \to K^+\pi^-, K^+K^-, \pi^+\pi^-$





γ status

- Most precise channel is $D_{CP}K$ (awaiting LHCb update with full Run I sample)
- New LHCb results with competitive sensitivity
- LHCb only combination, without latest results (but including measurements not shown in plot to right), gives $\gamma = (73^{+9}_{-10})^\circ$

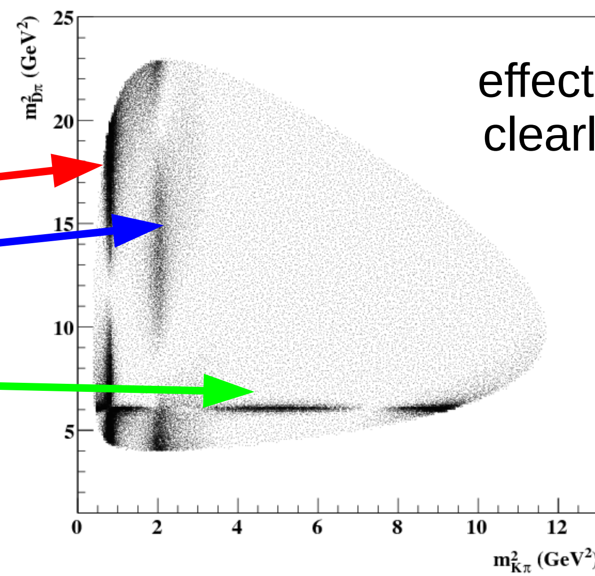


Extension to B→DπK decays

TG PRD 79 (2009) 051301(R)
TG & M. Williams PRD 80 (2009) 092002

- Extension of the method to exploit additional sources of interference that occur in multibody decays
  - $B^0 \to D(\pi^- K^+)$ decays can have CP violation
  - $B^0 \to (D\pi^-)K^+$ decays have no CP violation
    - Provides ideal reference amplitude from which to determine relative phases via interference between different resonances on the Dalitz plot

Toy example containing
$K^*(892)^0$
$K_2^*(1430)^0$
$D_2^*(2460)^-$



effects of spin clearly visible

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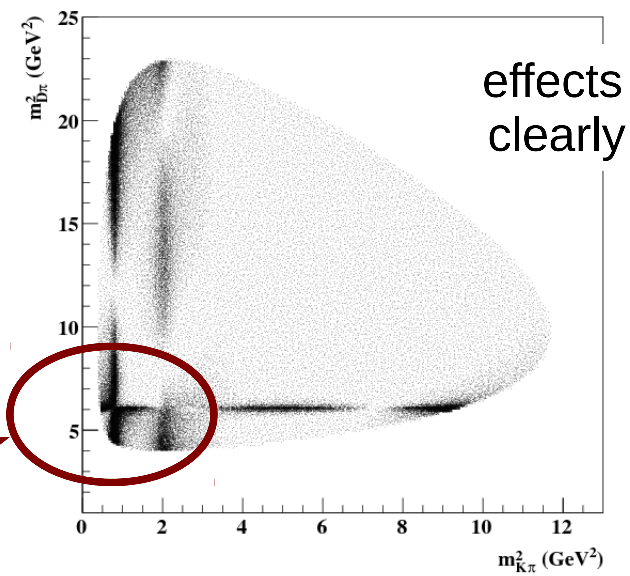
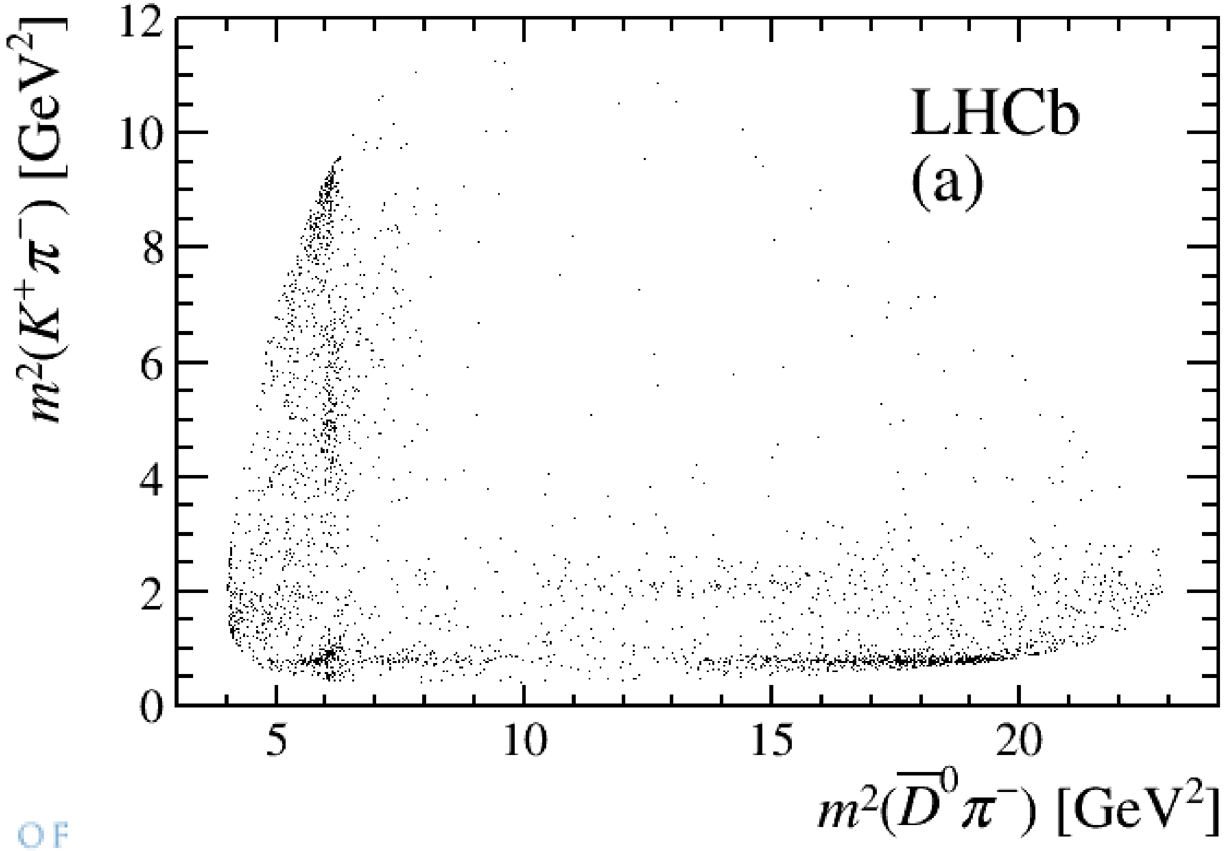


B→DπK Dalitz plot

arXiv:1505.01505

- Use D→Kπ decays to determine Dalitz plot model for favoured b→c amplitude



n.b. axes flipped c.f. previous slides

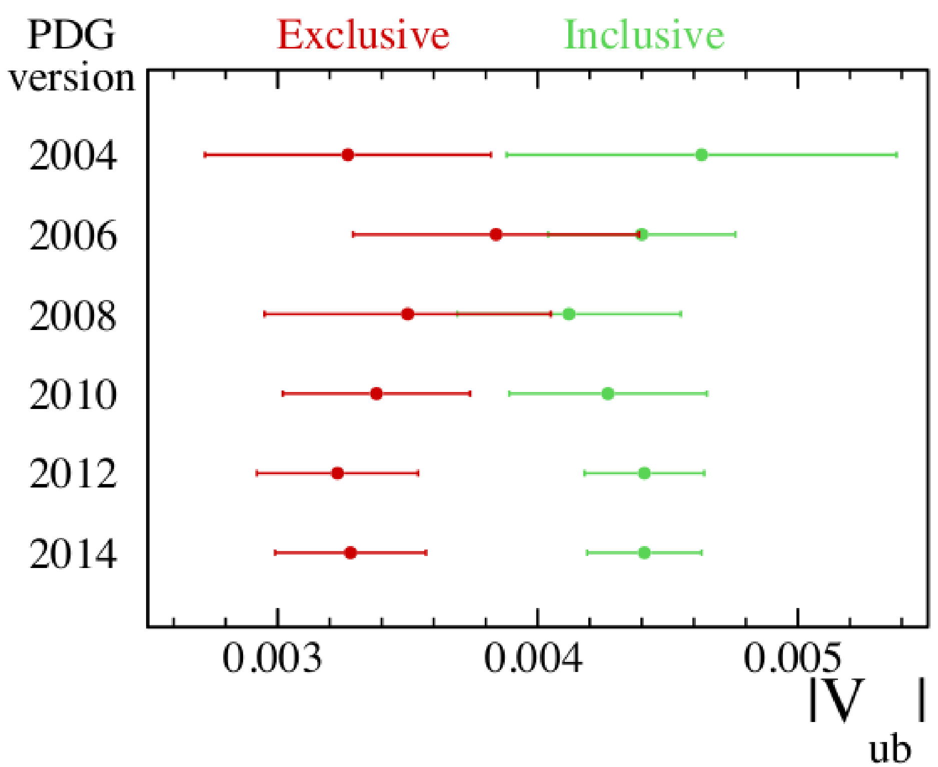
$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

arXiv:1504.01568

- Long standing discrepancy between exclusive and inclusive determinations of both V_{ub} and V_{cb}

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \qquad |V_{ub}| = (4.41 \pm 0.15 \, ^{+\,0.15}_{-\,0.17}) \times 10^{-3} \quad \text{(inclusive)},$$

$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \qquad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(exclusive)}.$$



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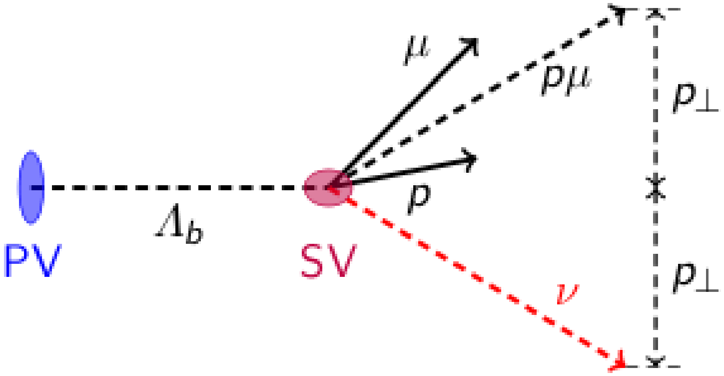
- Use of b baryon decays provides complementary alternative to B mesons
- At LHCb, exploit displaced vertex to reconstruct corrected mass

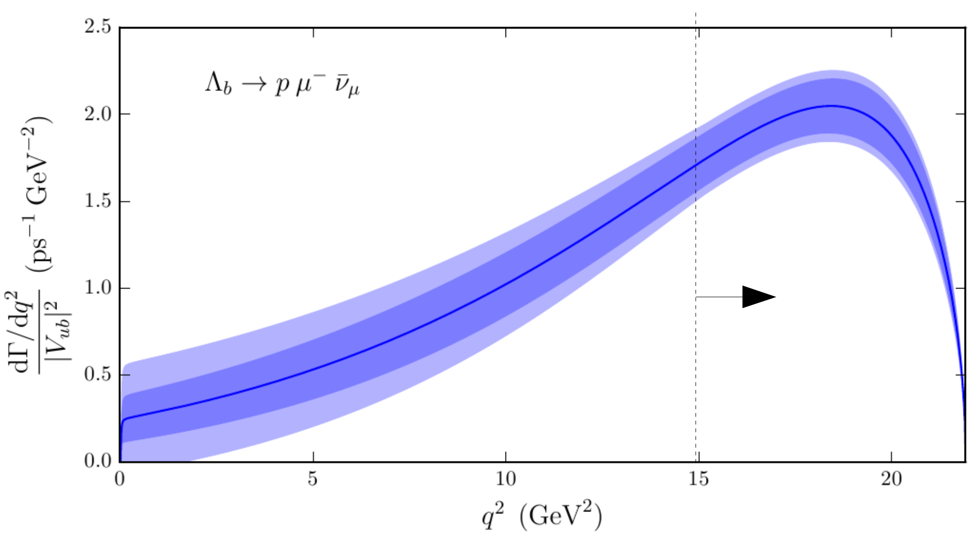
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

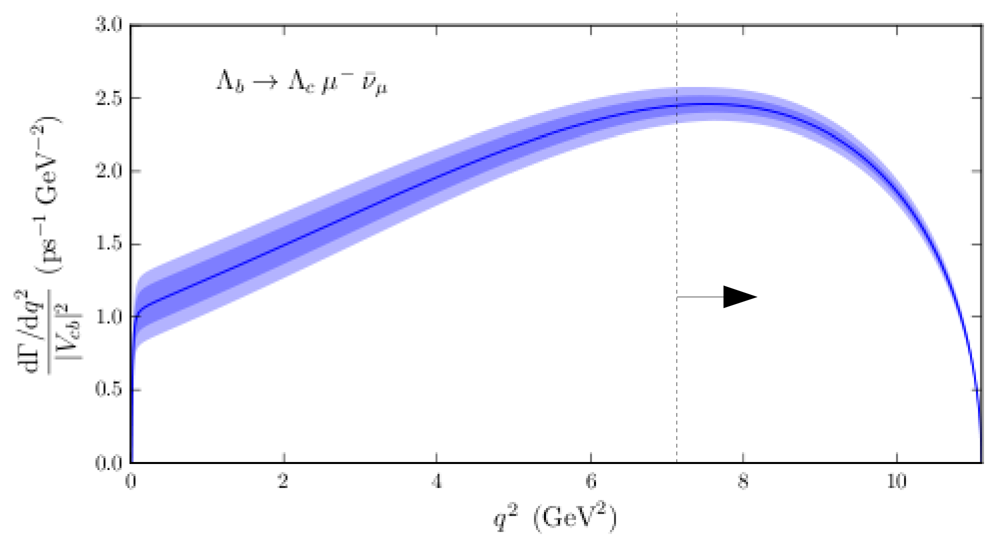


$|V_{ub}/V_{cb}|$ from $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

arXiv:1504.01568

- Can then reconstruct $q^2 = m(\mu\nu)^2$
  - Select events with $q^2 > 15$ GeV^2 ($p\mu\nu$)/ 7 GeV^2 ($\Lambda_c\mu\nu$)
  - Highest rate, best resolution & most reliable theory (lattice) predictions



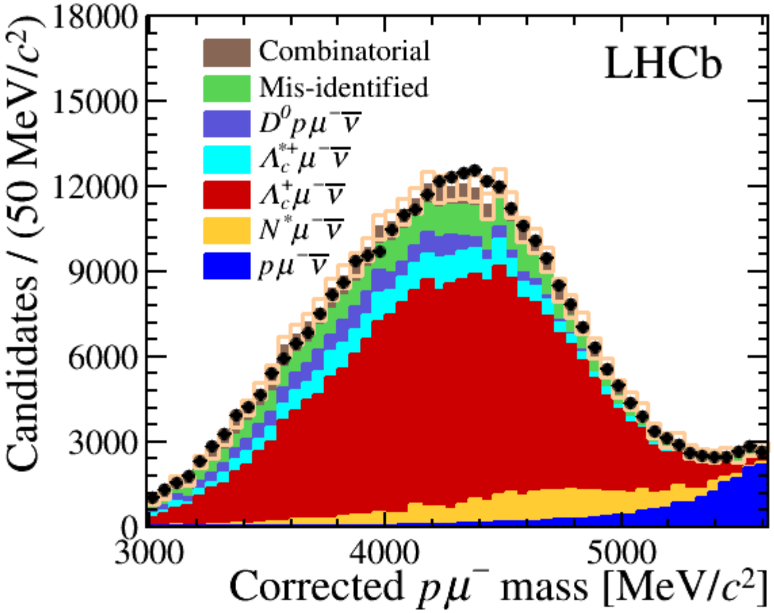


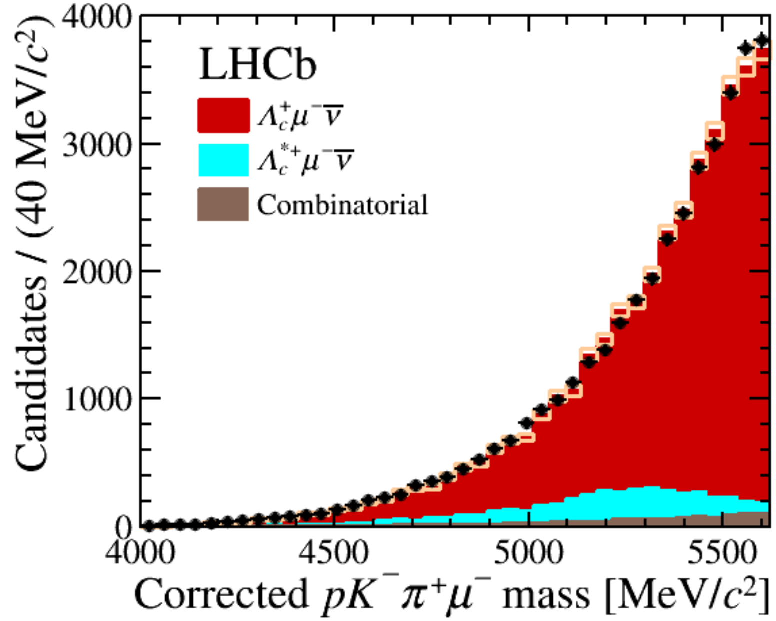
arxiv:1503.01421

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

arXiv:1504.01568

- Use isolation MVA to suppress background
- Fit M_{corr} to obtain signal yields





$N(\Lambda_b \to p\mu\nu) = 17687 \pm 733$

$N(\Lambda_b \to \Lambda_c\mu\nu) = 34255 \pm 571$

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

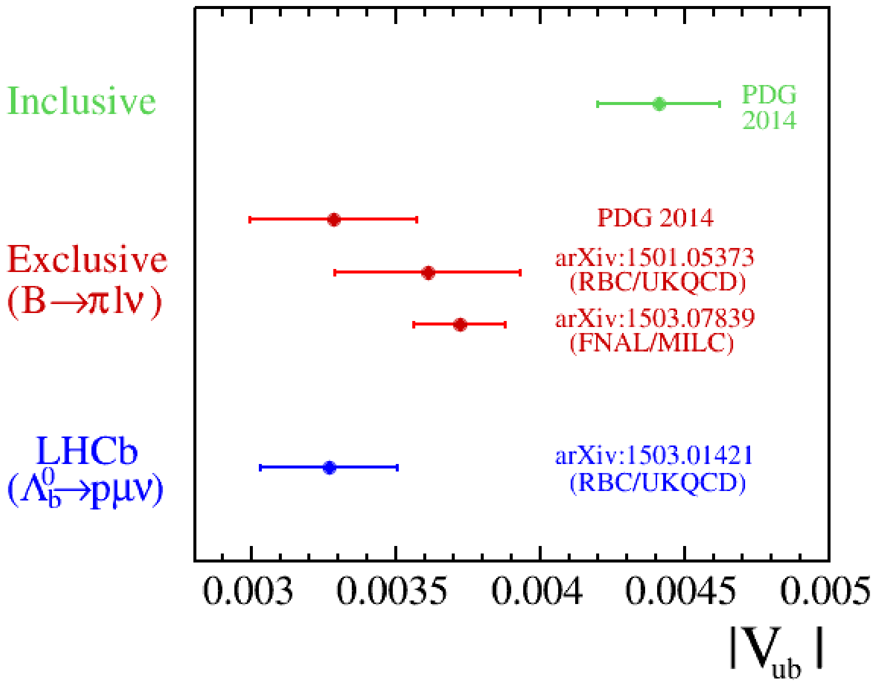
arXiv:1504.01568

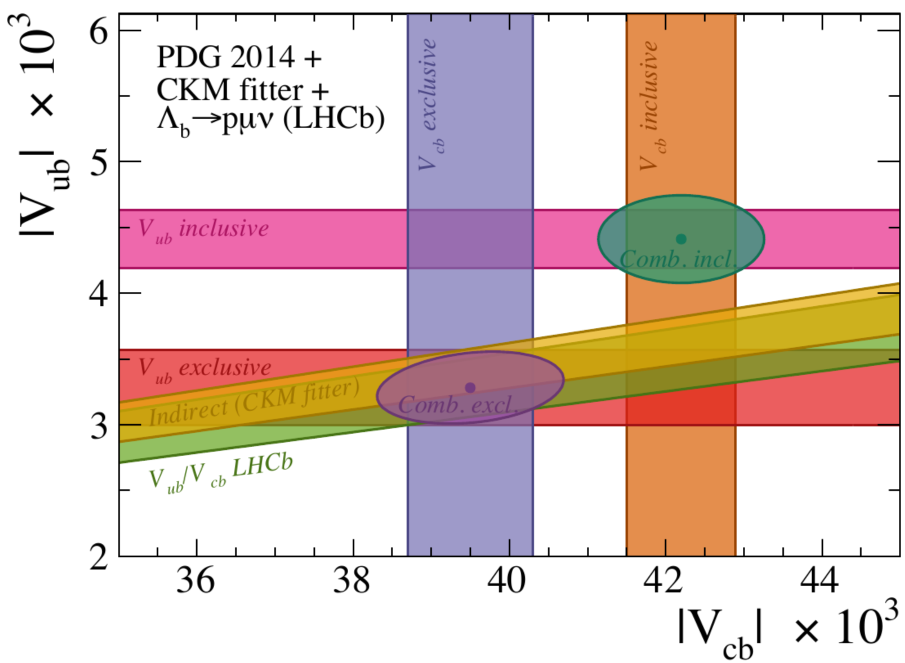
Systematic uncertainties

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
N^* 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	$^{+7.8}_{-8.2}$

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

arXiv:1504.01568





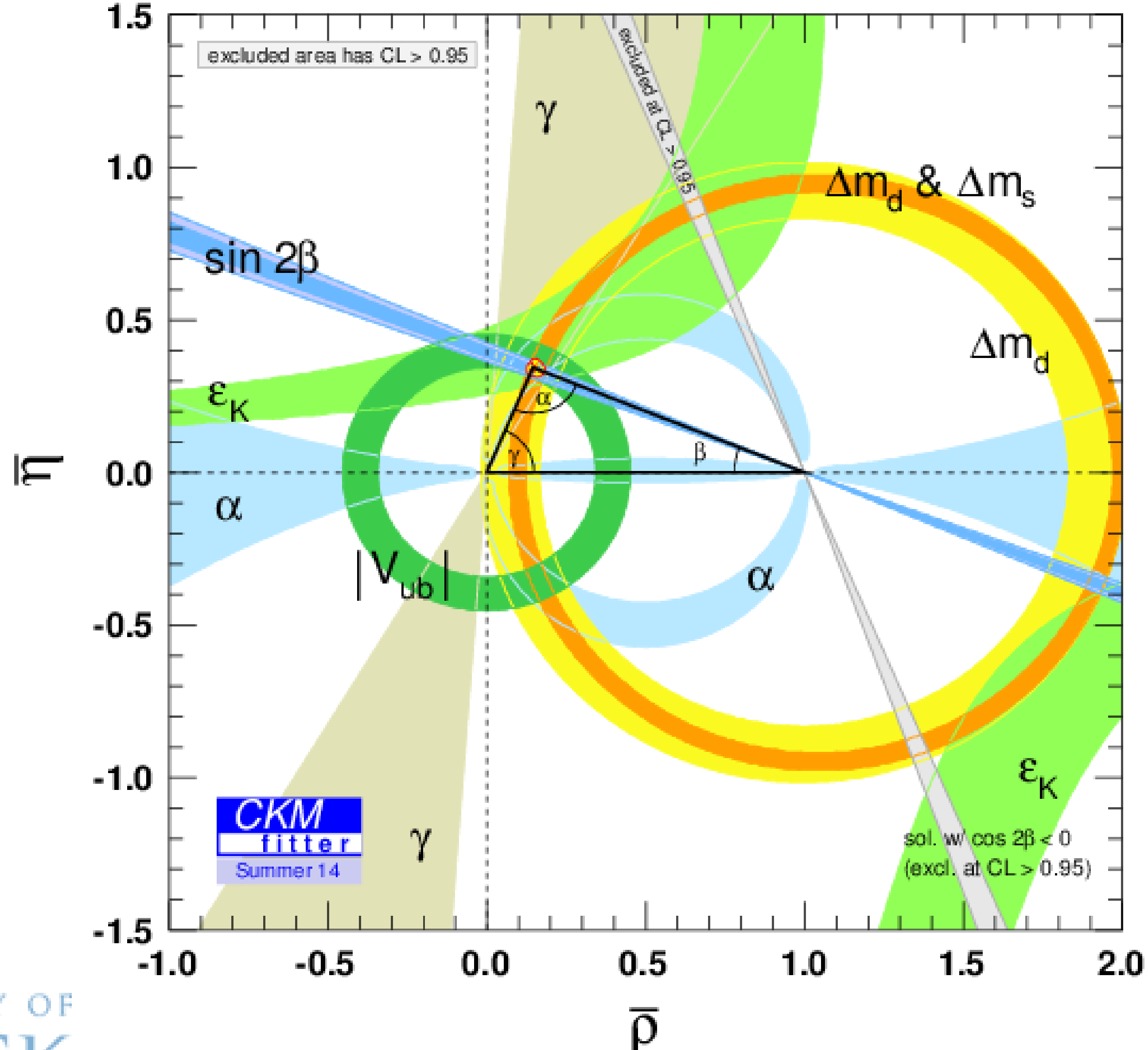
$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\mathrm{expt}) \pm 0.004(\mathrm{lattice})$$

- Rules out models with RH currents
- Compatible with UT fit (β,γ)

Unitarity Triangle

not including latest results



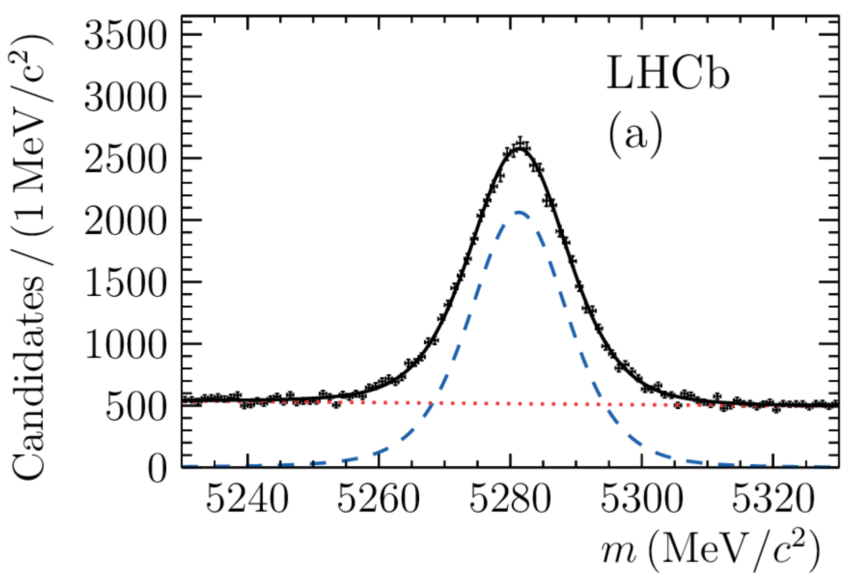
sin(2β)

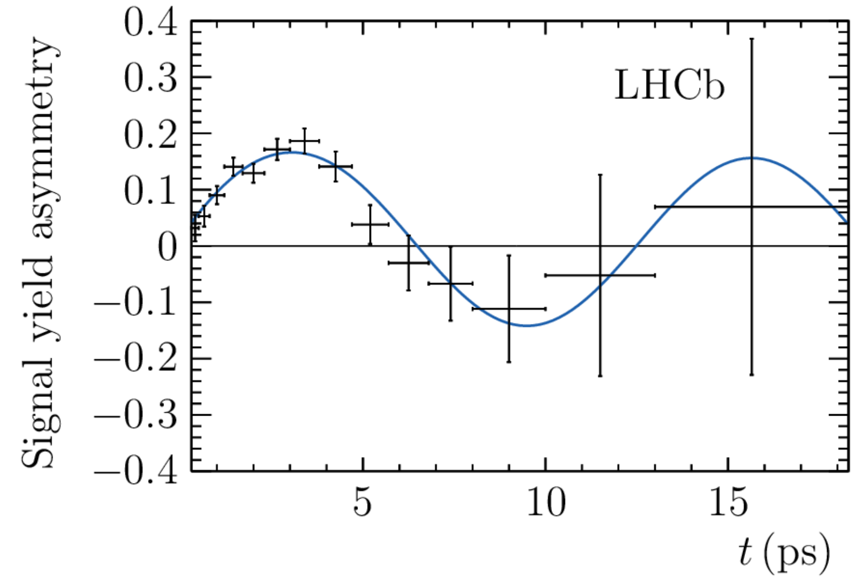
Decay-time dependent CP asymmetry in $B^0 \to J/\psi K_S$

arXiv:1503.07089

→ golden mode to measure sin(2β)

Previously measured by BaBar & Belle … now LHCb becomes competitive





41 560 ± 270
tagged $B^0 \to J/\psi K_S$ decays

S = 0.731 ± 0.035 ± 0.020
C = −0.038 ± 0.032 ± 0.005

Effective tagging
efficiency: 3.02 ± 0.05 %

sin(2β)

Decay-time dependent CP asymmetry in $B^0 \to J/\psi K_S$ → golden mode to measure sin(2β)

arXiv:1503.07089

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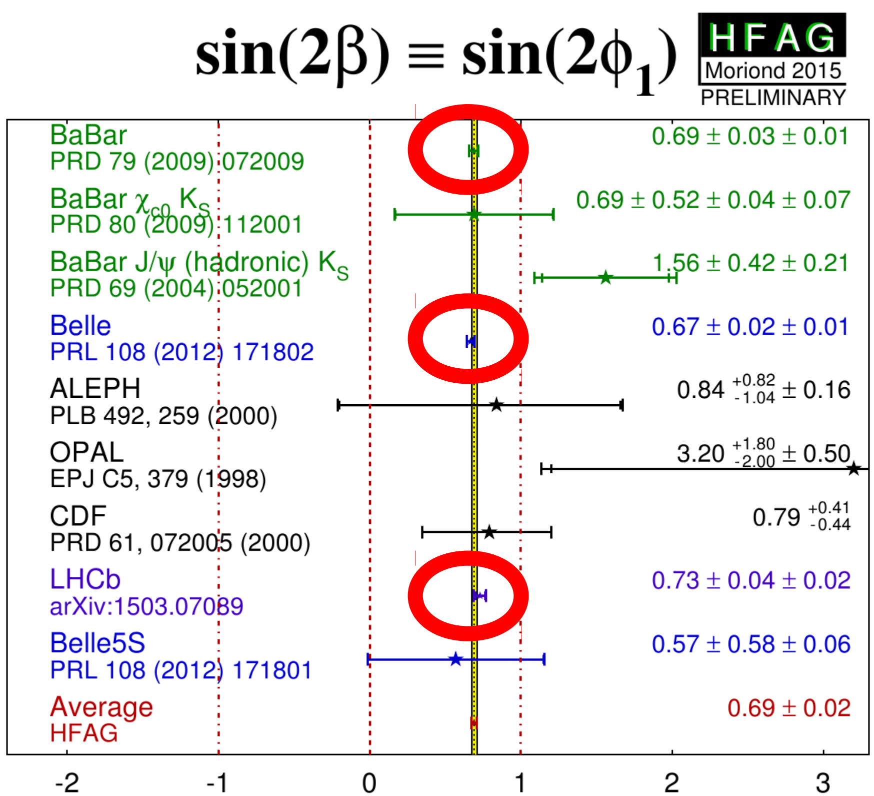


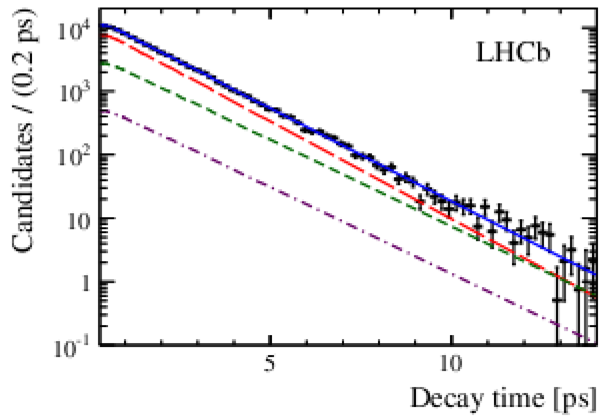
World average:

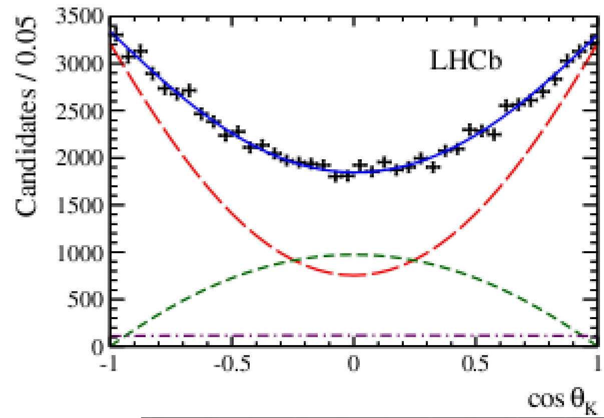
$\sin(2\beta) = 0.691 \pm 0.017$

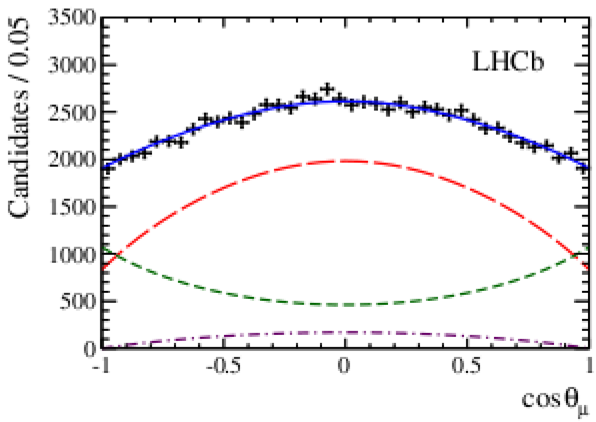
At this precision, penguin effects start to be a concern

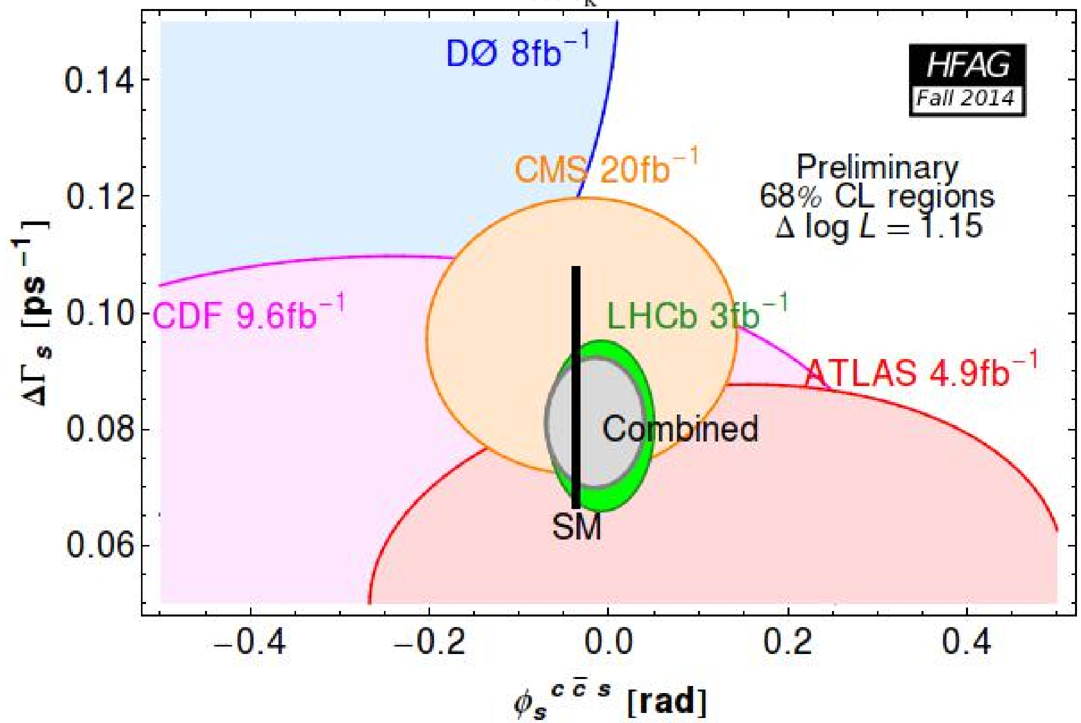
φ_s from $B_s \to J/\psi\varphi$ (etc.)

Latest LHCb results
PRL 114 (2015) 041801









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

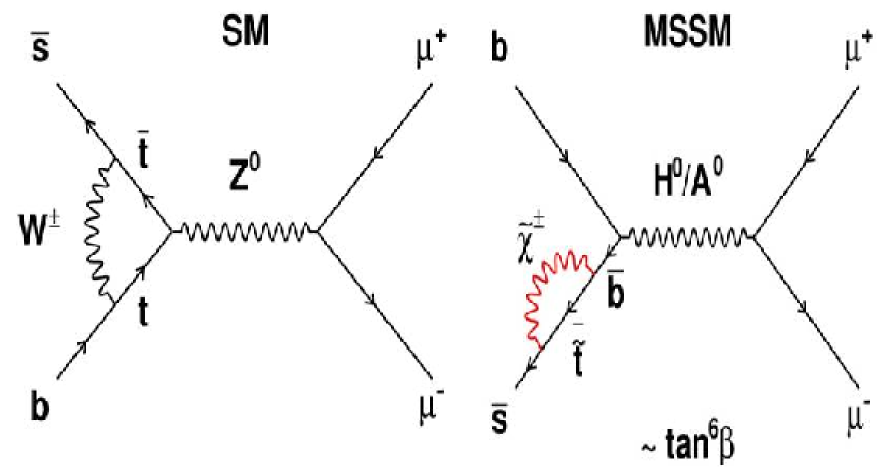
Nature 522 (2015) 68

Killer app. for new physics discovery

Very rare in Standard Model due to

- absence of tree-level FCNC
- helicity suppression
- CKM suppression

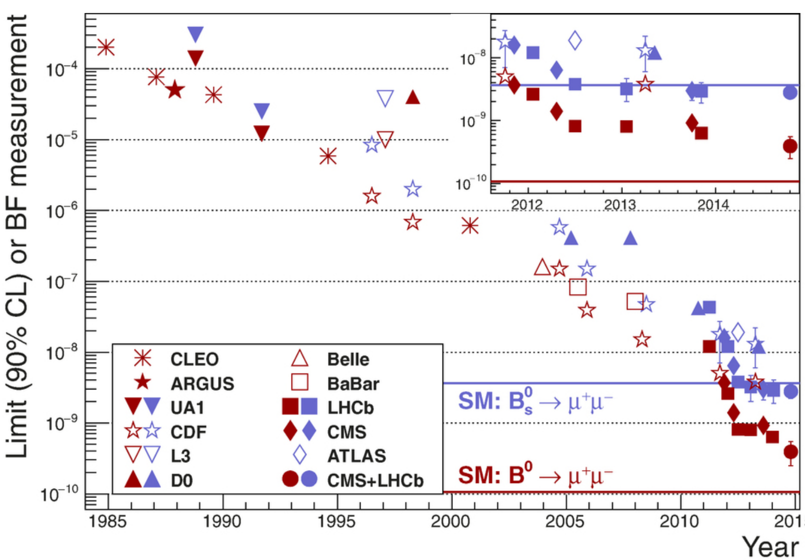
… all features which are not necessarily reproduced in extended models



$\mathcal{B}(B_s \to \mu^+\mu^-)^{SM} = (3.66 \pm 0.23) \times 10^{-9}$

$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$

Intensively searched for over 30 years!



Nature 522 (2015) 68

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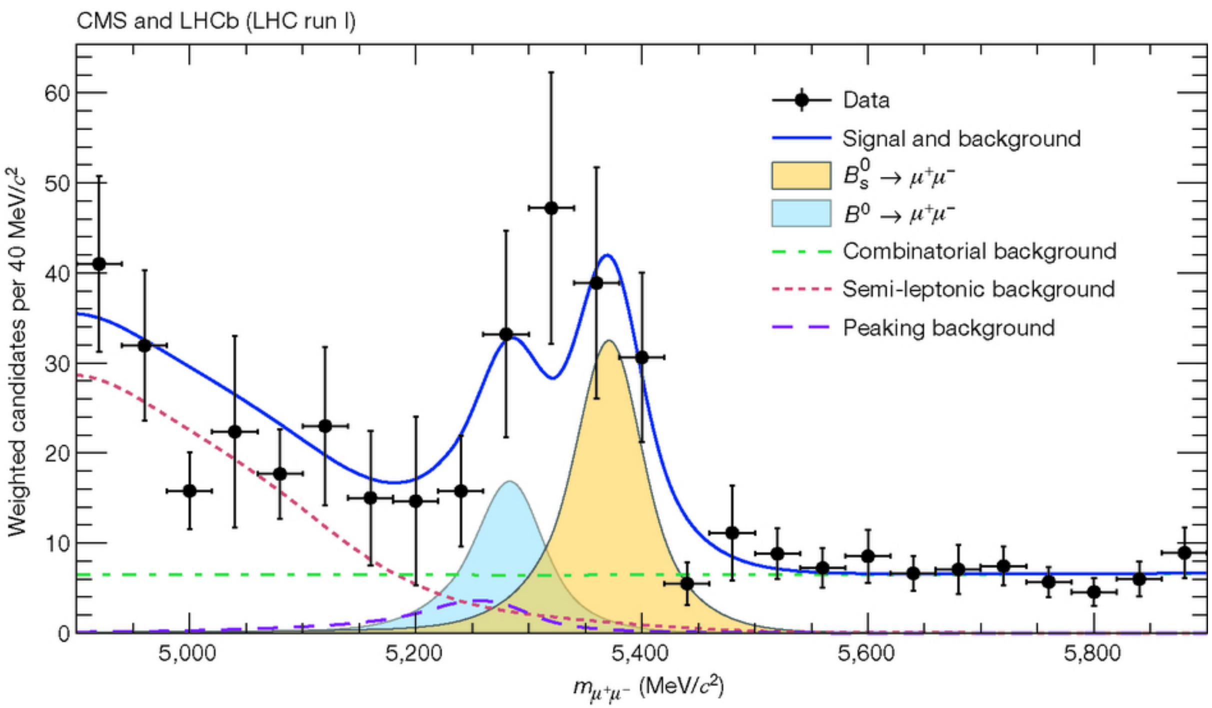
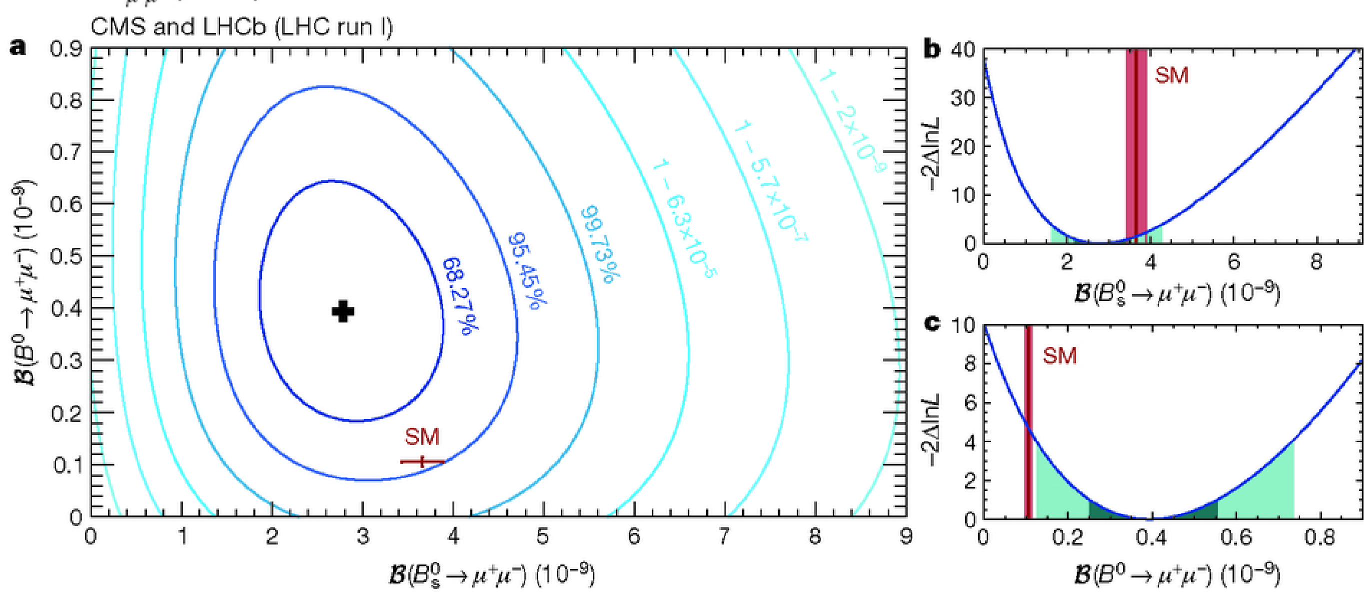


Combination of CMS and LHCb data results in first observation of $B_s \to \mu^+\mu^-$ and first evidence for $B^0 \to \mu^+\mu^-$

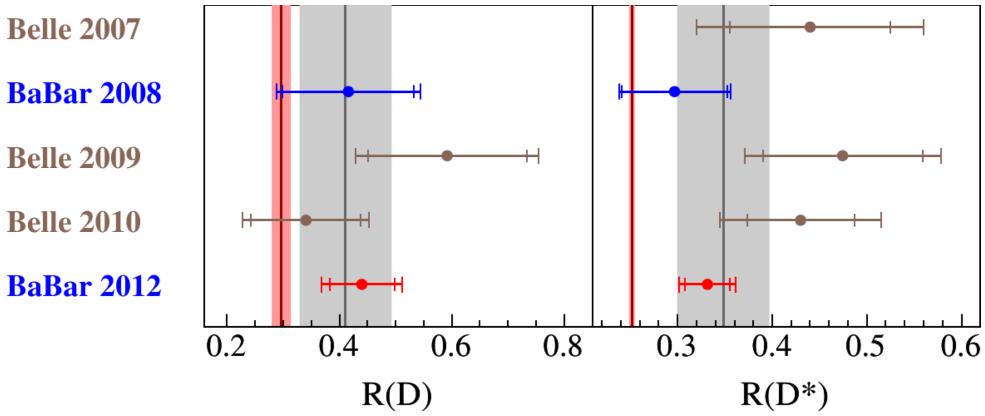
Results consistent with SM at 2σ level

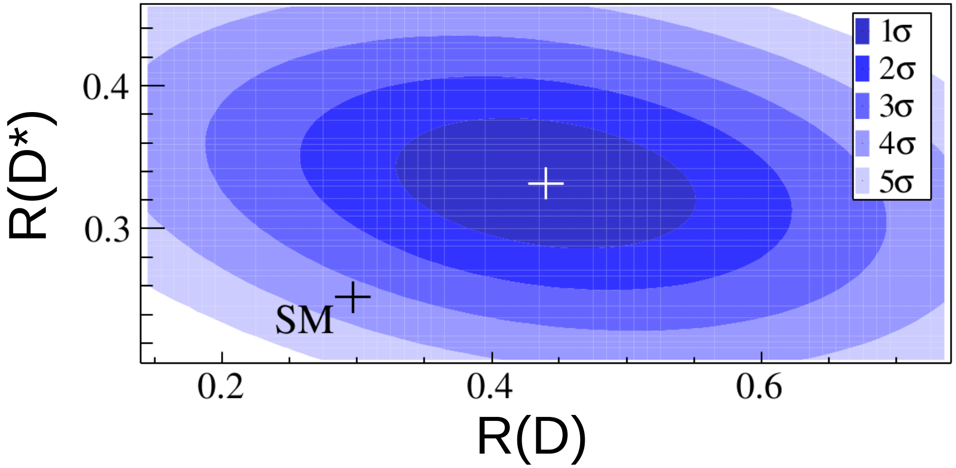


$B \to D^{(*)}\tau\nu$

- Powerful channel to test lepton universality
  - ratios $R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu)/\mathcal{B}(B \to D^{(*)}\mu\nu)$ could deviate from SM values, e.g. in models with charged Higgs
- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. R_K , $H \to \tau\mu$

PRL 109 (2012) 101802 & PRD 88 (2013) 072012

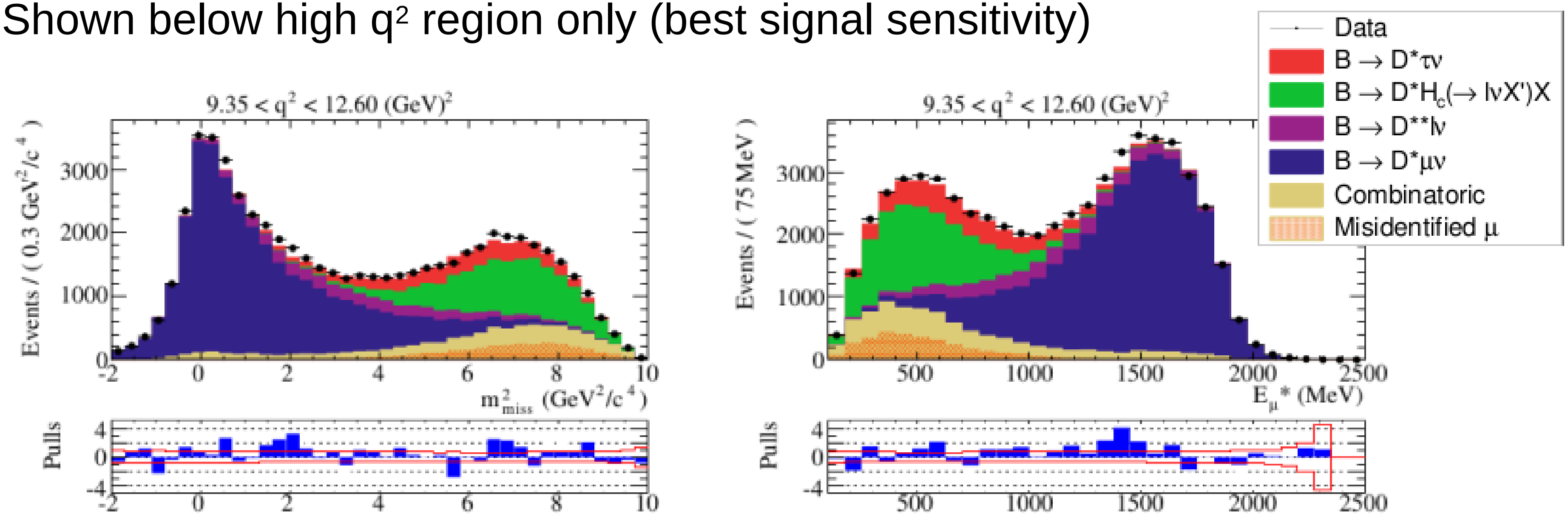




$B \to D^* \tau \nu$ at LHCb

LHCb-PAPER-2015-025

- Identify $B \to D^* \tau \nu$, $D^* \to D\pi$, $D \to K\pi$, $\tau \to \mu\nu\bar{\nu}$
  - Similar kinematic reconstruction to $\Lambda_b \to p\mu\nu$
    - Assume $p_{B,z} = (p_{D^*} + p_\mu)_z$ to calculate $M_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
  - Require significant B, D, τ flight distances & use isolation MVA
- Separate signal from background by fitting in M_{miss}^2, q^2 and E_μ
  - Shown below high q^2 region only (best signal sensitivity)

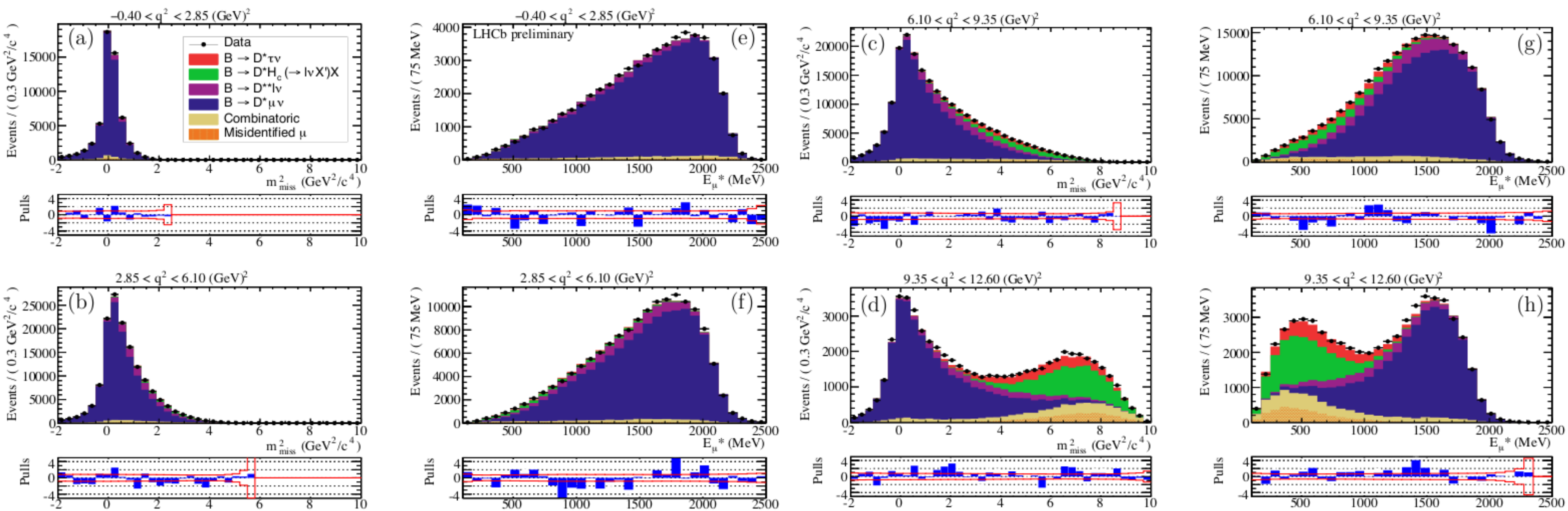


$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

B→D*τν at LHCb – all q^2 bins

LHCb-PAPER-2015-025

low q^2 high q^2



Results of simultaneous fit to M_{miss}^2, q^2 and E_μ

q^2 distribution is an input to, not an output of, the fit

B→D*τν at LHCb – systematics

R(D*) = 0.336 ± 0.027 ± 0.030

LHCb-PAPER-2015-025

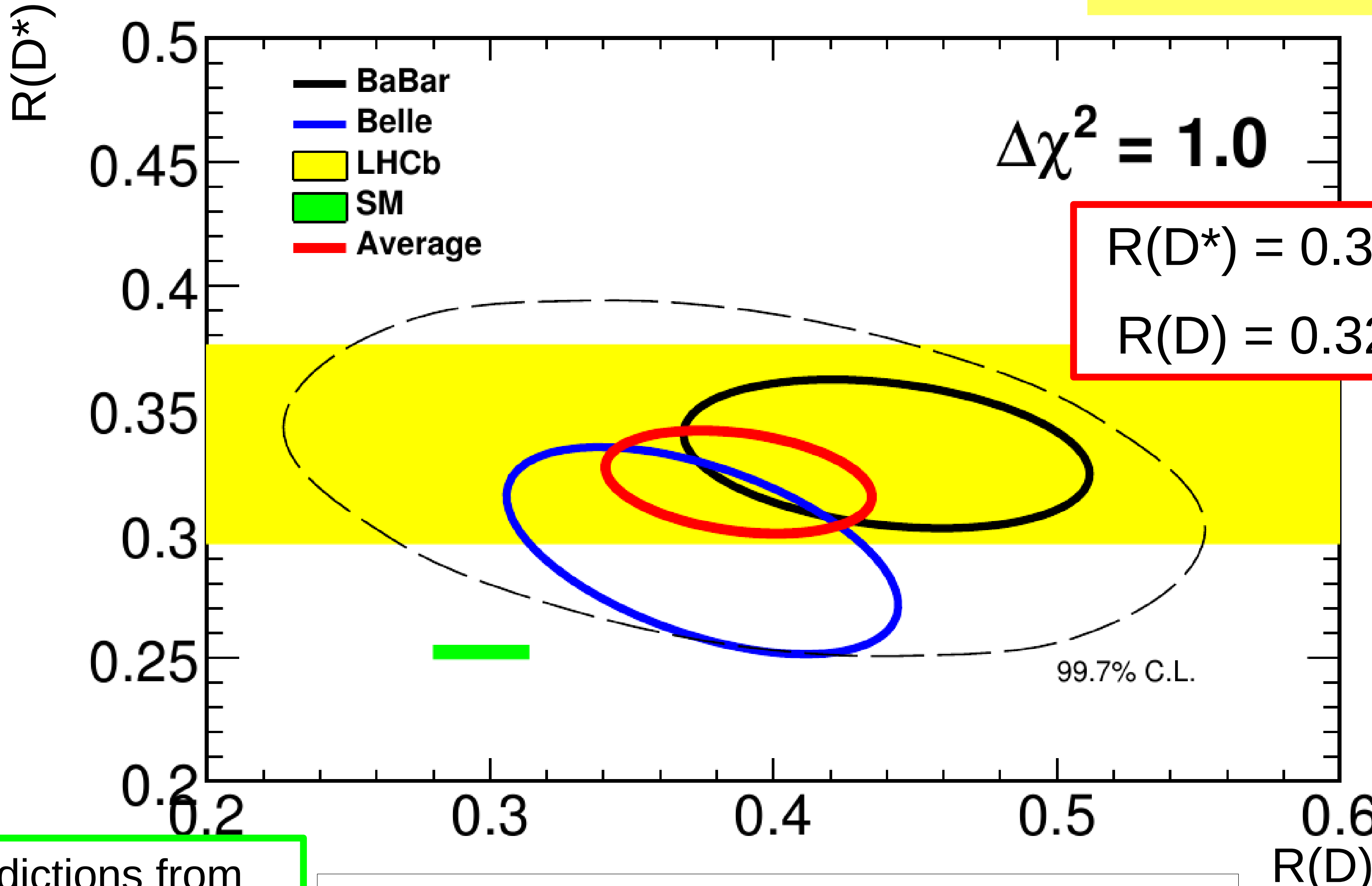
Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu}$ form factors	0.6
$\overline{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu)$	0.5
$\overline{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatoric background shape	0.3
$\overline{B} \to D^{**}(\to D^{*+}\pi)\mu^-\overline{\nu}_\mu$ form factors	0.3
$\overline{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Largest sources scale with statistics

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

Tension with SM seems to persist

Very preliminary & unofficial average including new LHCb & Belle results



R(D*) = 0.390 ± 0.047

R(D) = 0.322 ± 0.021

SM predictions from PRD 85 (2012) 094025

Careful averaging needed to account for statistical and systematic correlations

Thanks to M. Rotondo

Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

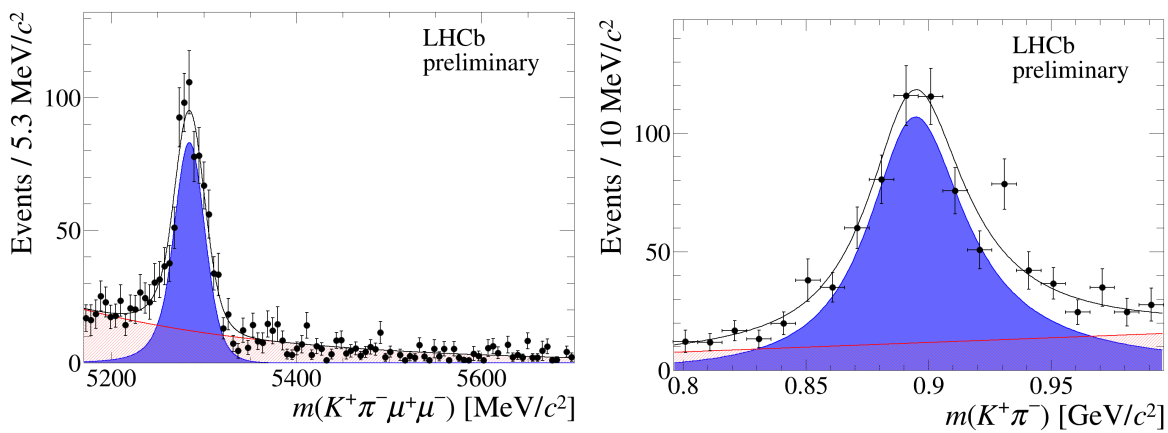
LHCb-CONF-2015-002

- $B^0 \rightarrow K^{*0}\mu^+\mu^-$ provides superb laboratory to search for new physics in $b \rightarrow sl^+l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - experimentally clean signature
  - many kinematic variables … with clean theoretical predictions
- Full set of CP conserving observables measured

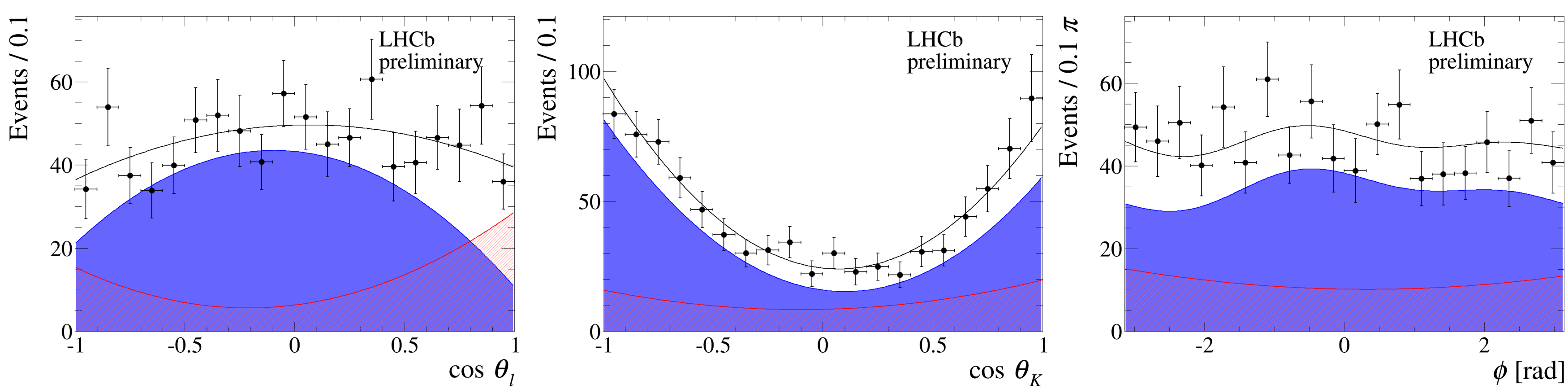
Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002

- Example of fits, in $1.1 < q^2 < 6.0$ GeV^2 bin

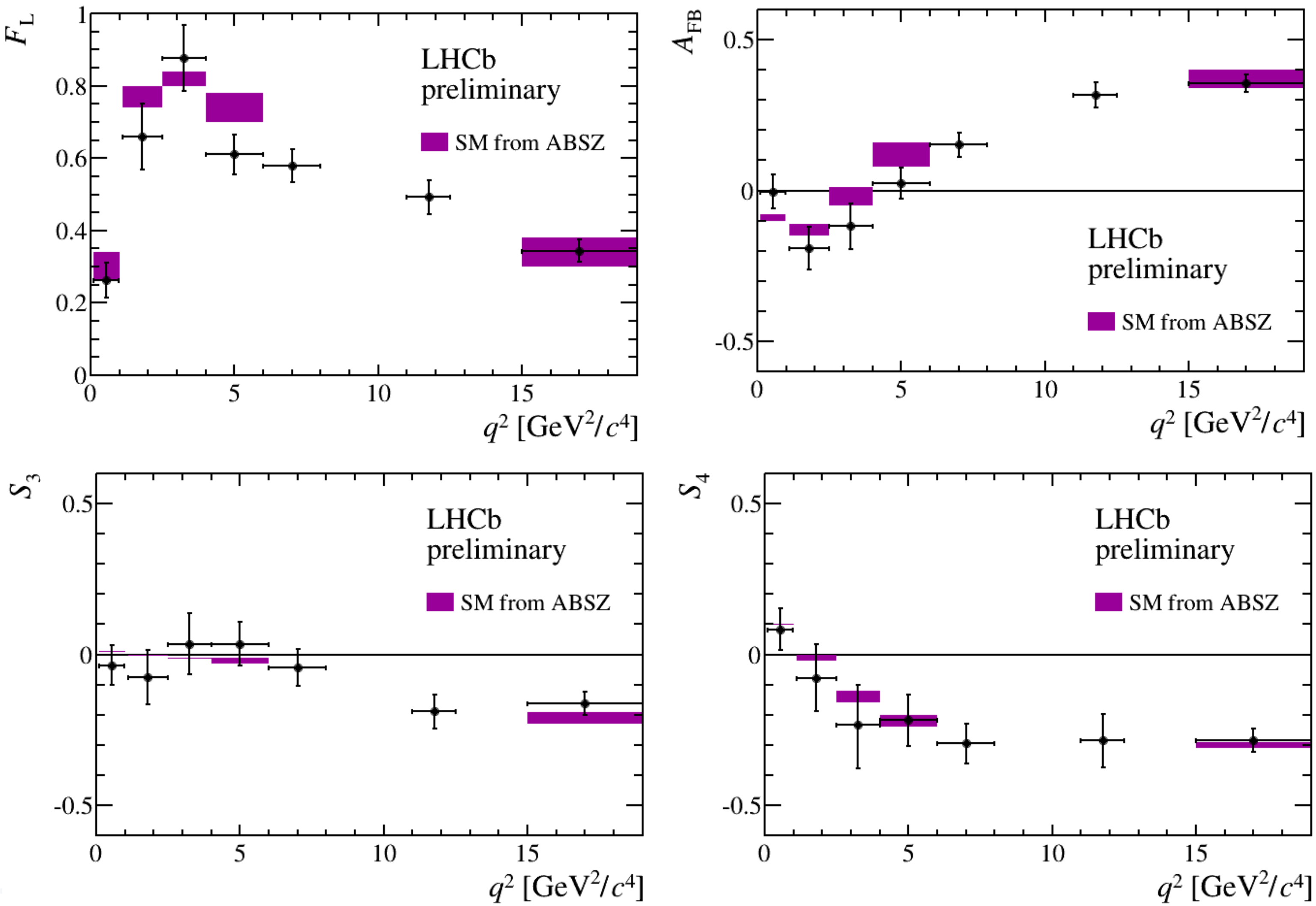


Angle and m(Kπ) projections in ± 50 MeV around B peak



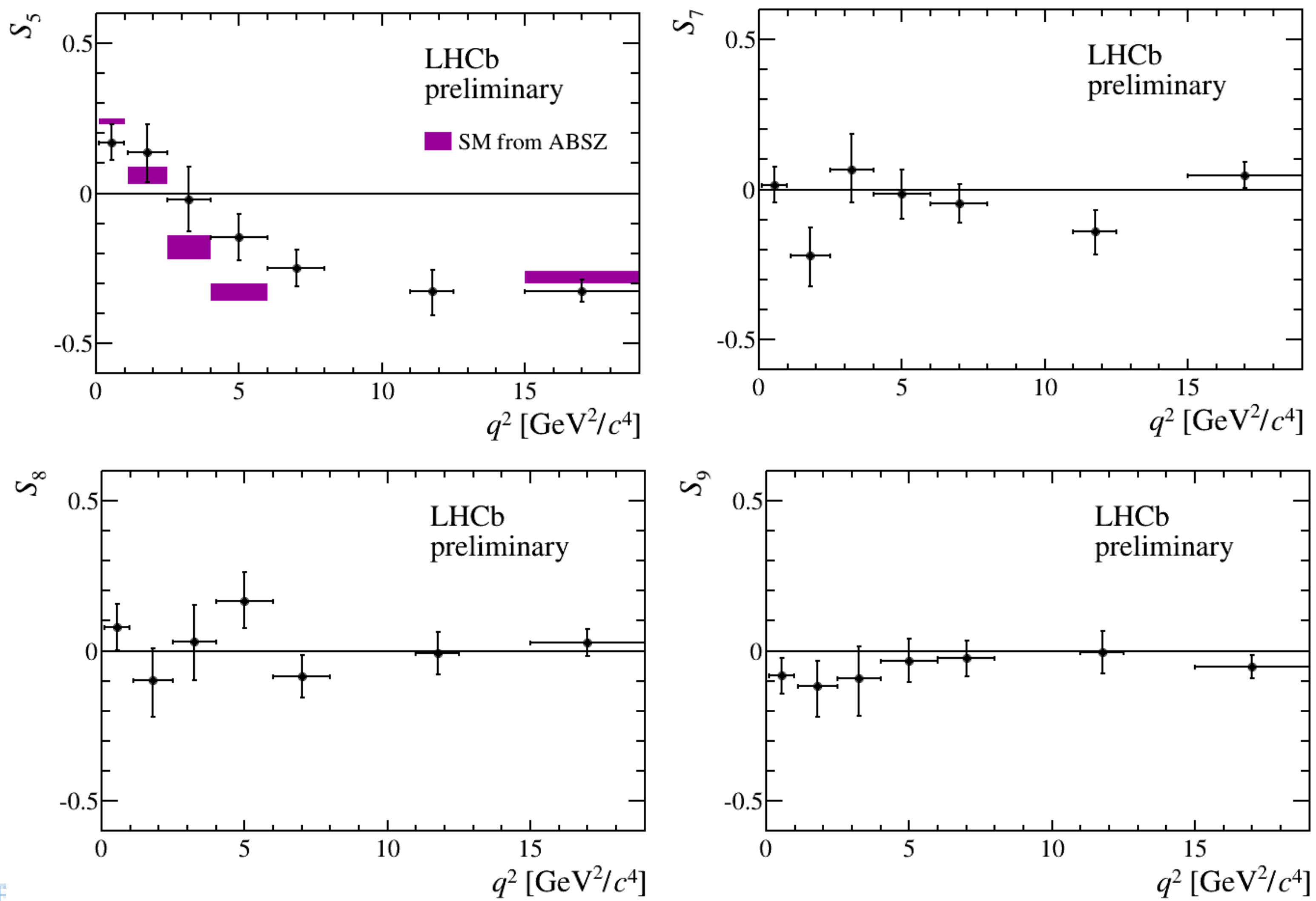
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002



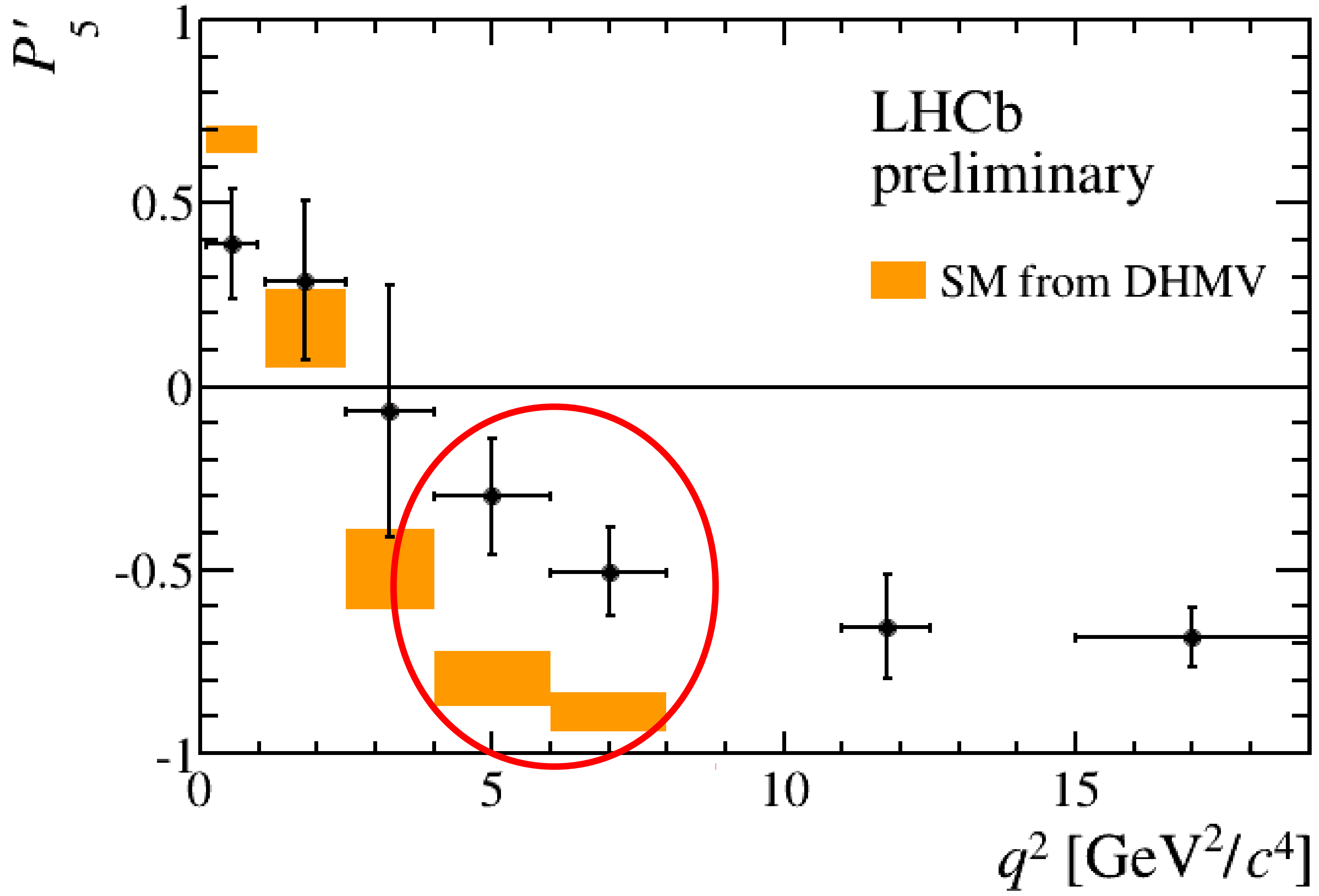
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002



Tension in P_5'

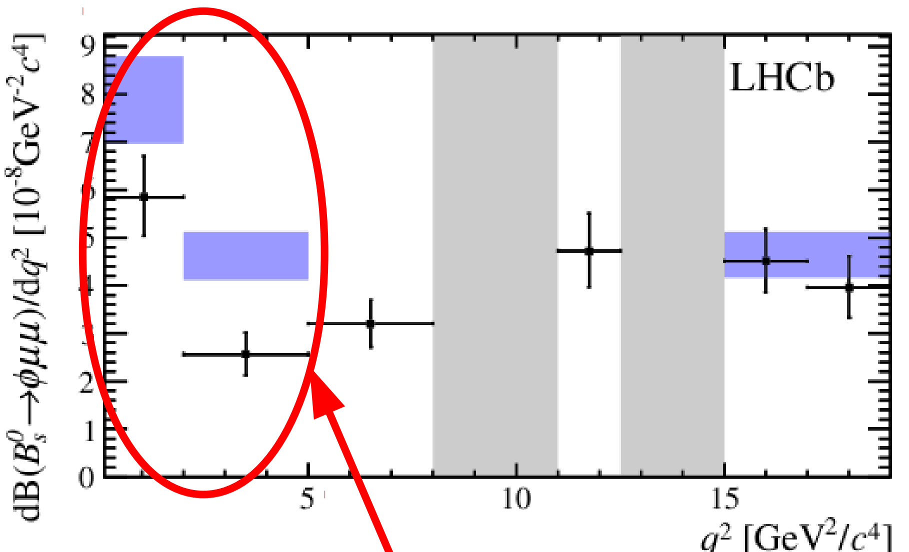
LHCb-CONF-2015-002



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

LHCb-PAPER-2015-023

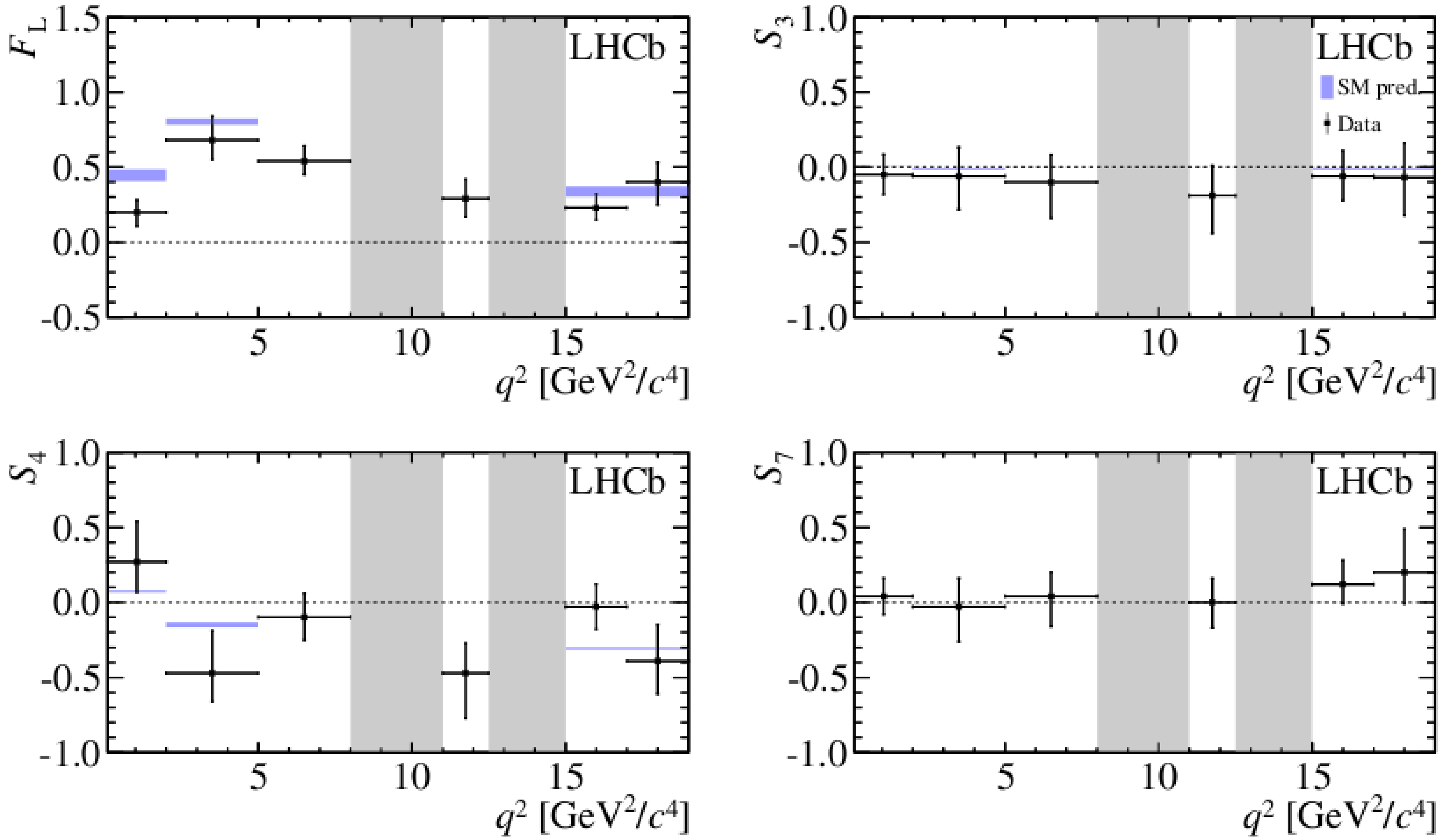
- Full angular analysis performed
- Not self-tagging → complementarity to $K^{*0}\mu^+\mu^-$
  - Measure also differential branching fraction



Tension with SM prediction – consistent picture in $b \to sl^+l^-$ branching fractions

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

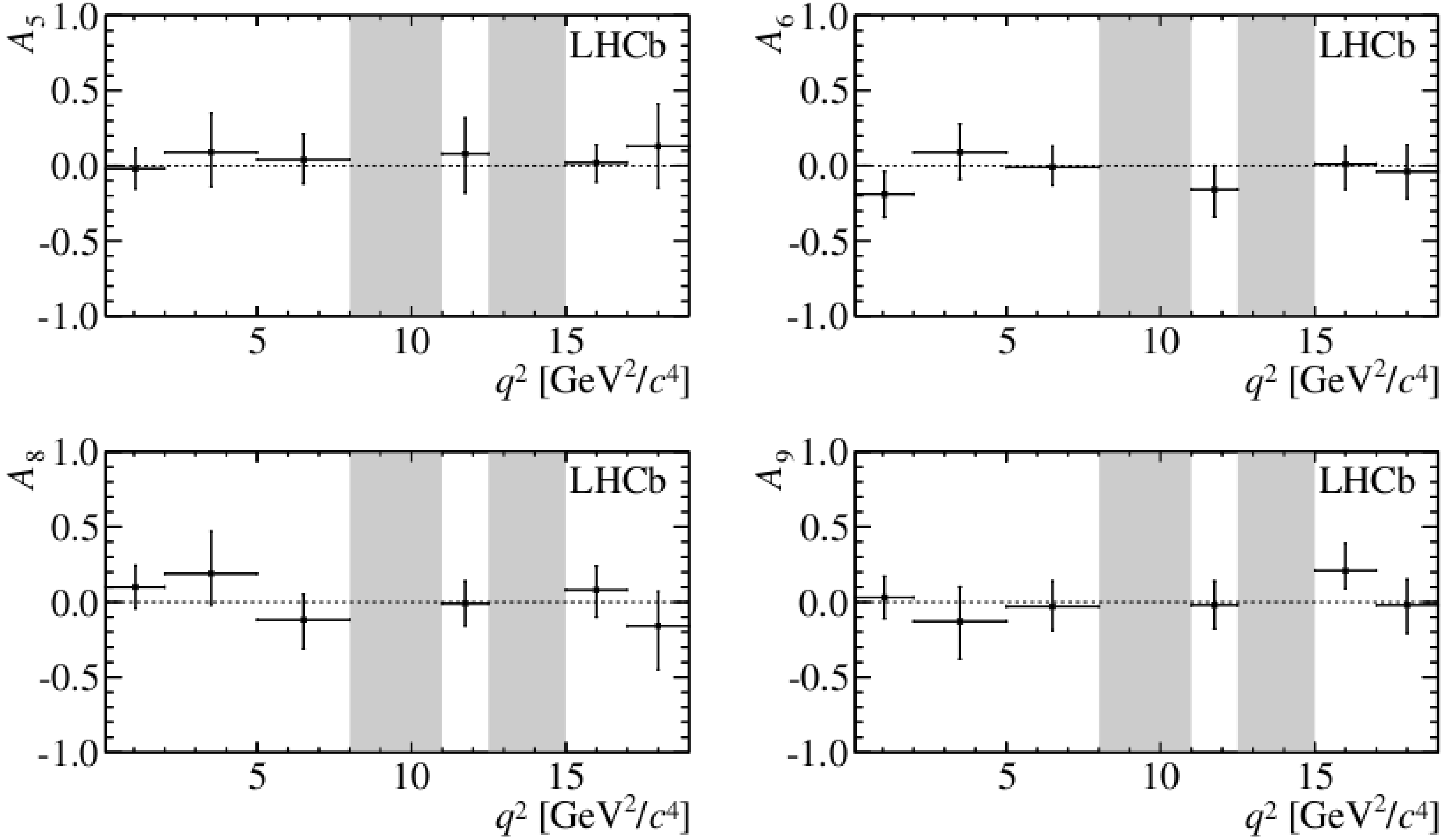
LHCb-PAPER-2015-023



All angular observables consistent with SM

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

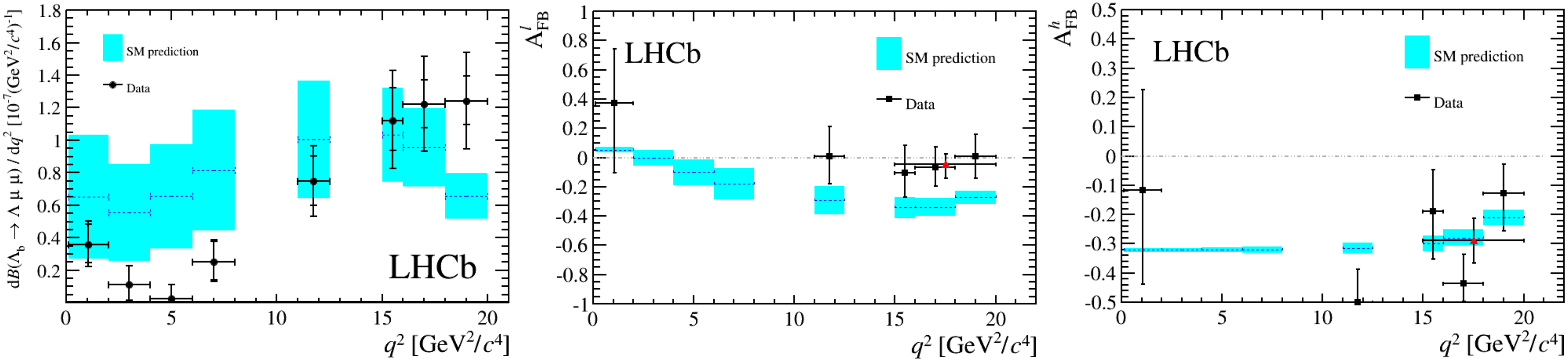
LHCb-PAPER-2015-023



All angular observables consistent with SM

$\Lambda_b \to \Lambda\mu^+\mu^-$

arXiv:1503.07138



Similar tension with SM prediction for branching fraction at low q^2

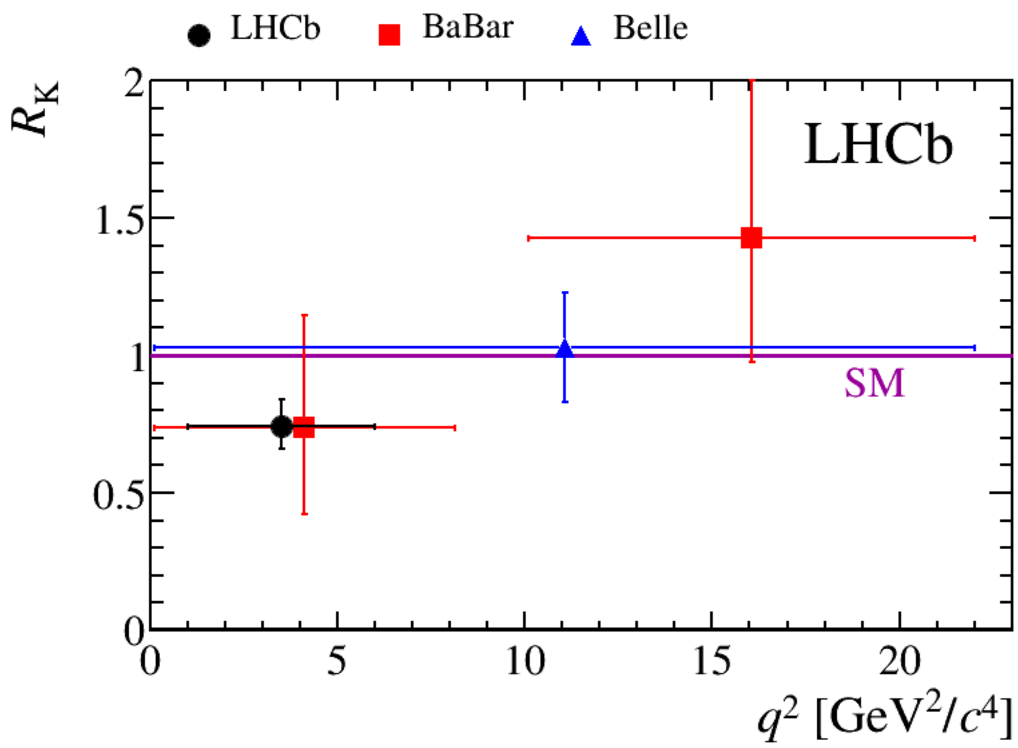
Statistics still low for angular analysis

Baryonic system provides sensitivity to additional observables

Lepton universality – R_K (reminder)

PRL 113 (2014) 151601

Deficit of $B \to K\mu^+\mu^-$ compared to expectation also seen in $K\mu^+\mu^-/Ke^+e^-$ ratio (R_K)



$$R_K(1 < q^2 < 6\ \text{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

<3σ from SM but suggestive

Top observation at LHCb

arXiv:1506.00903

- Top production in the forward region is sensitive to the low-x part of the gluon PDF; also potentially more sensitive to asymmetries than in central region
- Challenge is to be able to see signal with low $t\bar{t}$ production cross-section (at $\sqrt{s}$=7,8 TeV) and low luminosity (1,2/fb)
  - Cannot get full final state in LHCb acceptance
  - Use highest yield mode: ($W \rightarrow \mu$) + b-jet
  - Need high p_T b-jet, excellent b-tagging and good control of (non-t) Wb background
    - Jets reconstructed (anti-kT with R = 0.5) as in JHEP01 (2014) 033 (Z+jet)
    - b- & c-tagging described in arXiv:1504.07670

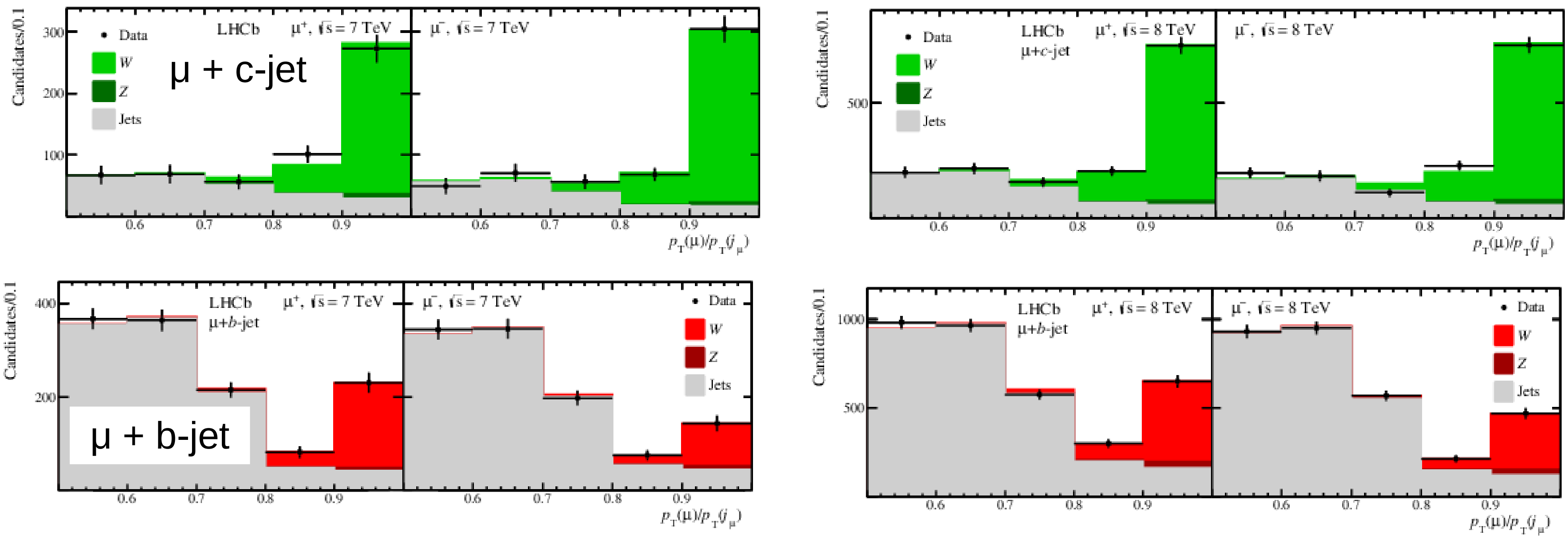
Exploits LHCb's excellent vertexing capability

W+b,c-jet observation at LHCb

arXiv:1505.04051

Separate signal from background using $p_T(\mu)/p_T(j_\mu)$

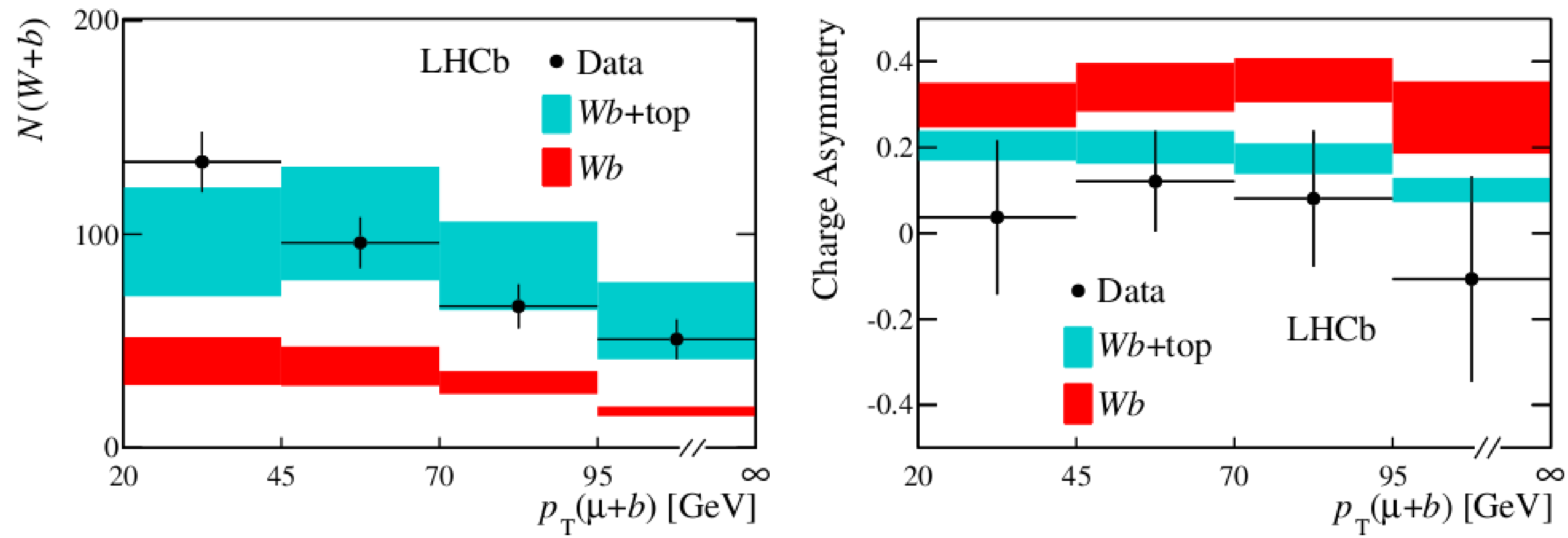
7 TeV 8 TeV



Top observation at LHCb

arXiv:1506.00903

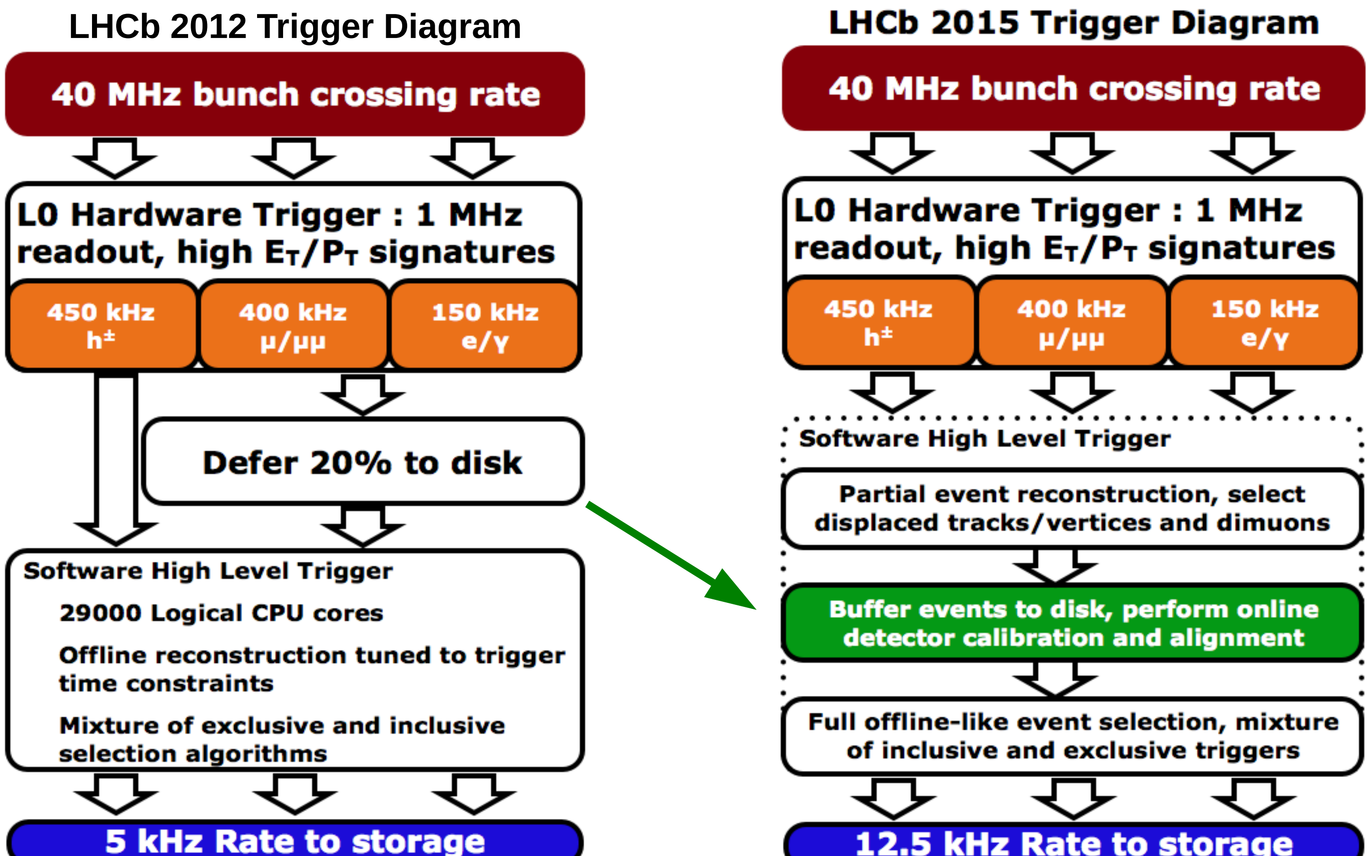
- W+b-jet sample contains top. To determine relative amount:
  - tighten fiducial requirements ($p_T(\mu)$>25 GeV; 50 < p_T(b-jet) < 100 GeV)
  - control rate of non-t W+b-jet from precise prediction for σ(W+b-jet)/σ(W+jet) & measured σ(W+jet)
    - validate method using W+c-jet (no top contribution)



5.4σ observation of top production in the forward region

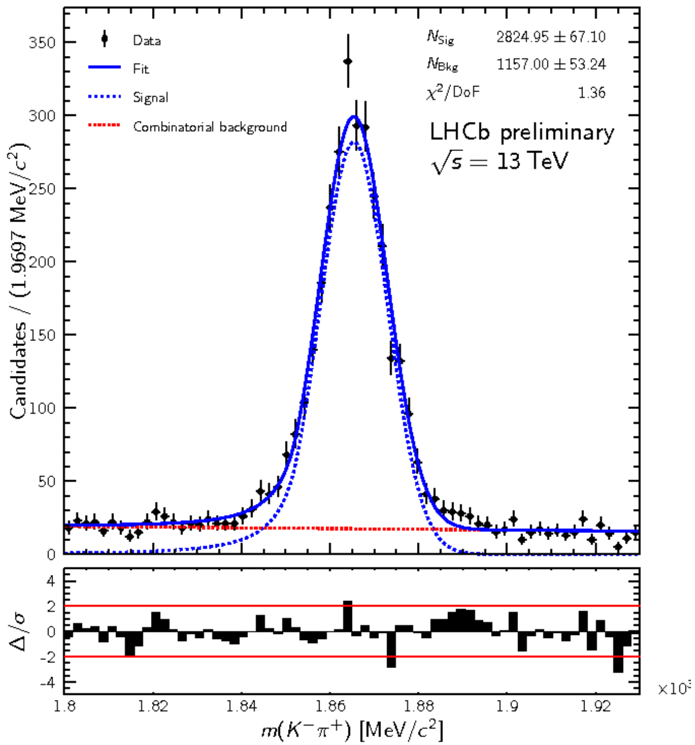
Run II data taking

- LHCb is ready! Will gain from higher √s (increased production) and 25 ns bunch spacing (lower pile up)
- During LS1: some subdetector consolidation; new HERSCHEL forward shower counters; change of data flow in trigger

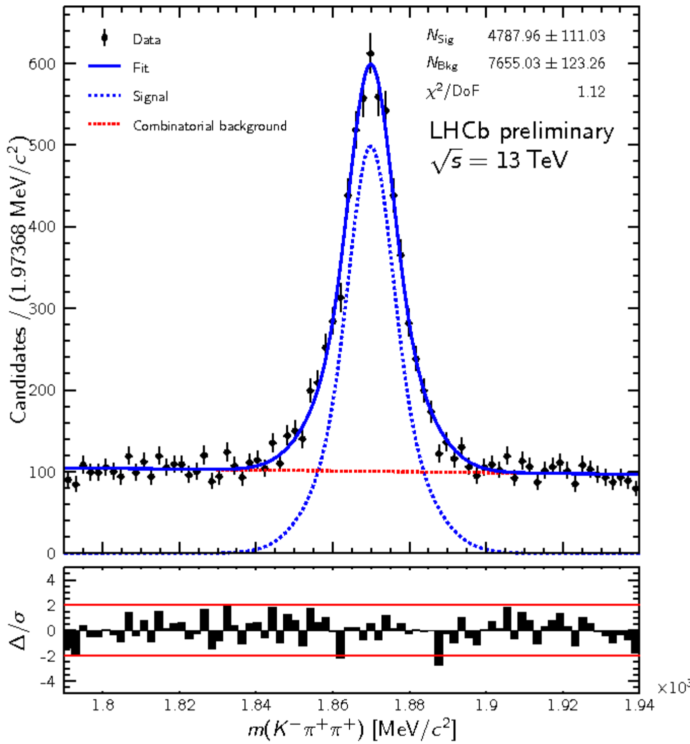


First signals from Run II

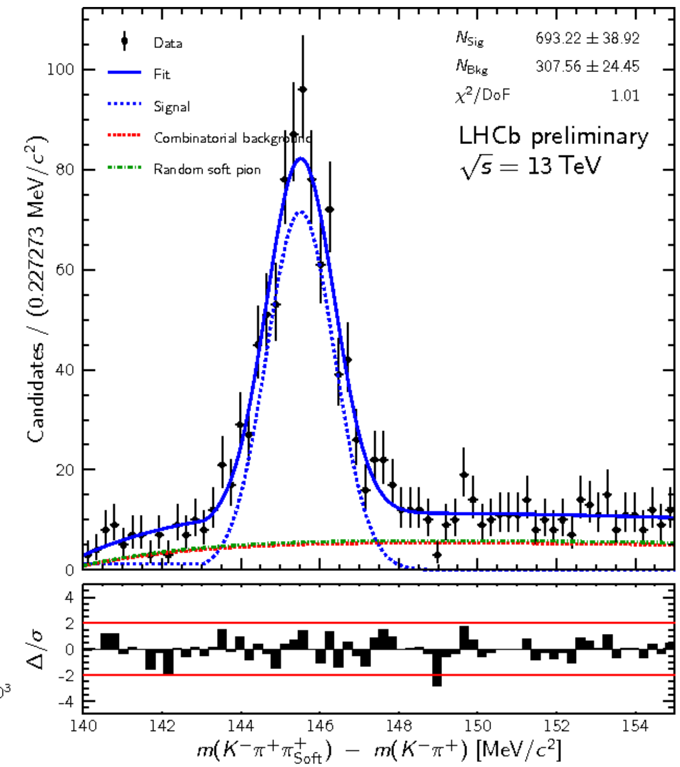
D → Kπ



D → Kππ



D* → Dπ; D → Kπ

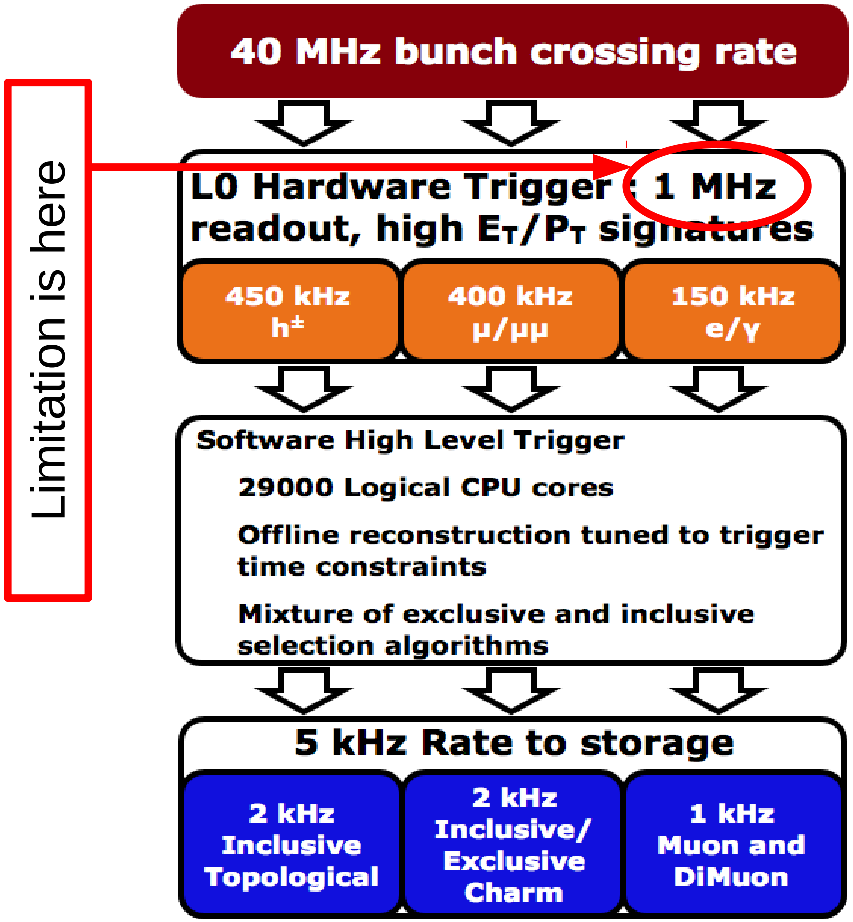


It works!

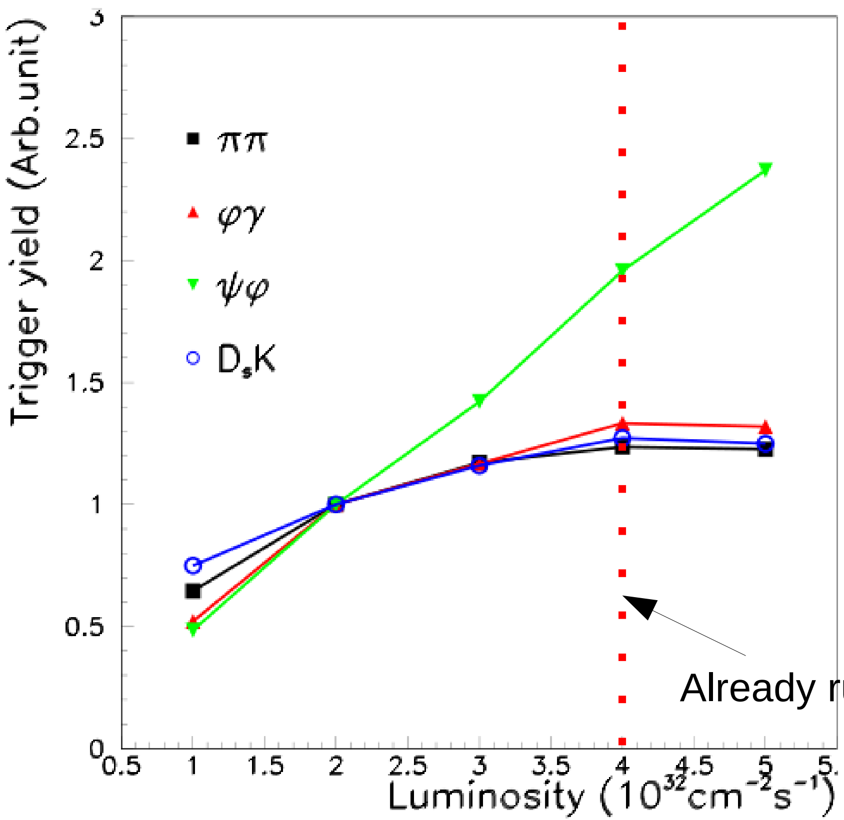
Beyond Run II – the LHCb Upgrade

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Will upgrade the LHCb detector in the LHC LS2 (2018-20)
  - Upgrade subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Operation at much higher luminosity with improved efficiency
    - order of magnitude improvement in precision (compared to today)
- Upgrade will be performed during LSII (now expected to be 2019-20)
  - Restart data taking in 2021 at instantaneous luminosity up to 2 $10^{33}/cm^2/s$
  - Upgrade detector qualified to accumulate 50/fb

LHC upgrade and the all important trigger

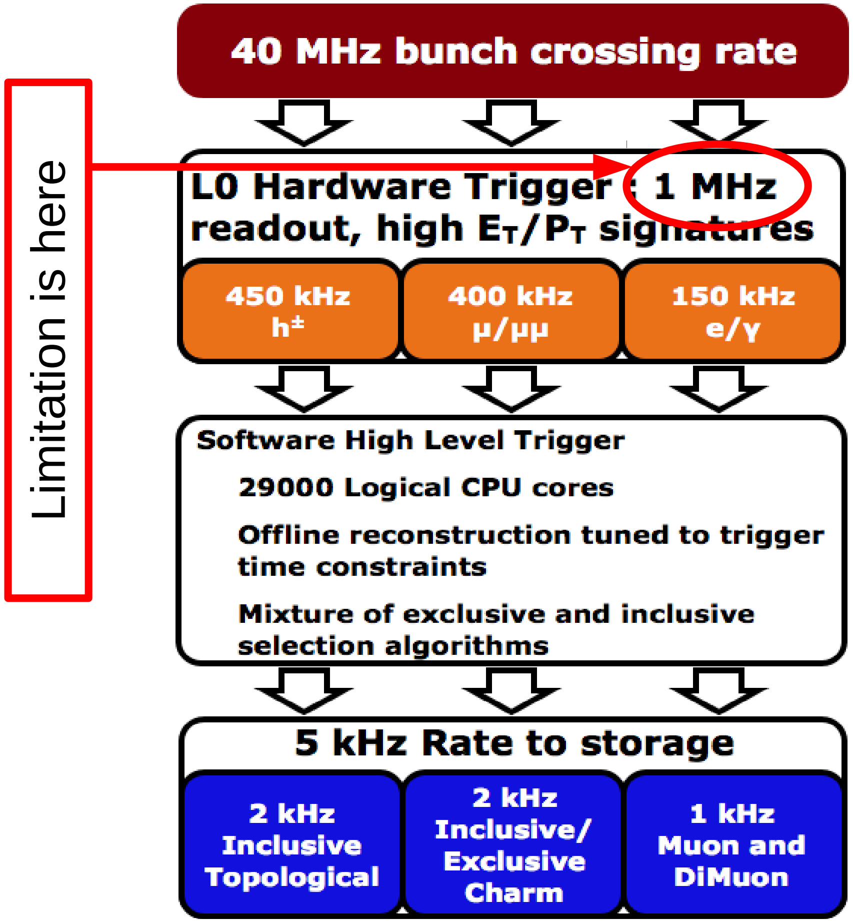


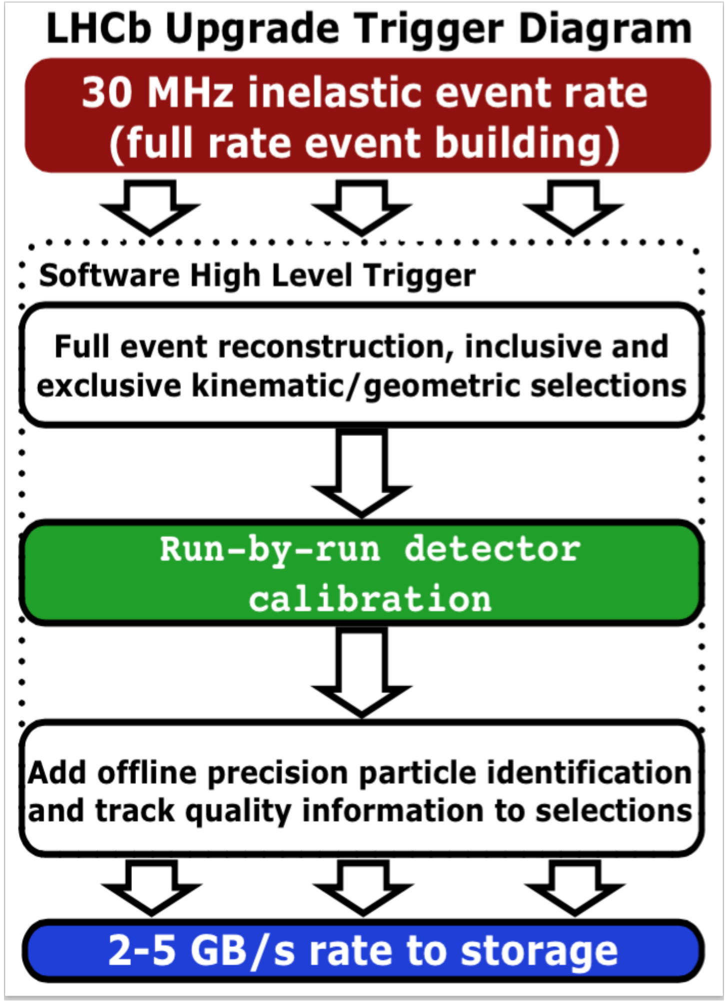
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 $10^{33}/cm^2/s$

LHC upgrade and the all important trigger

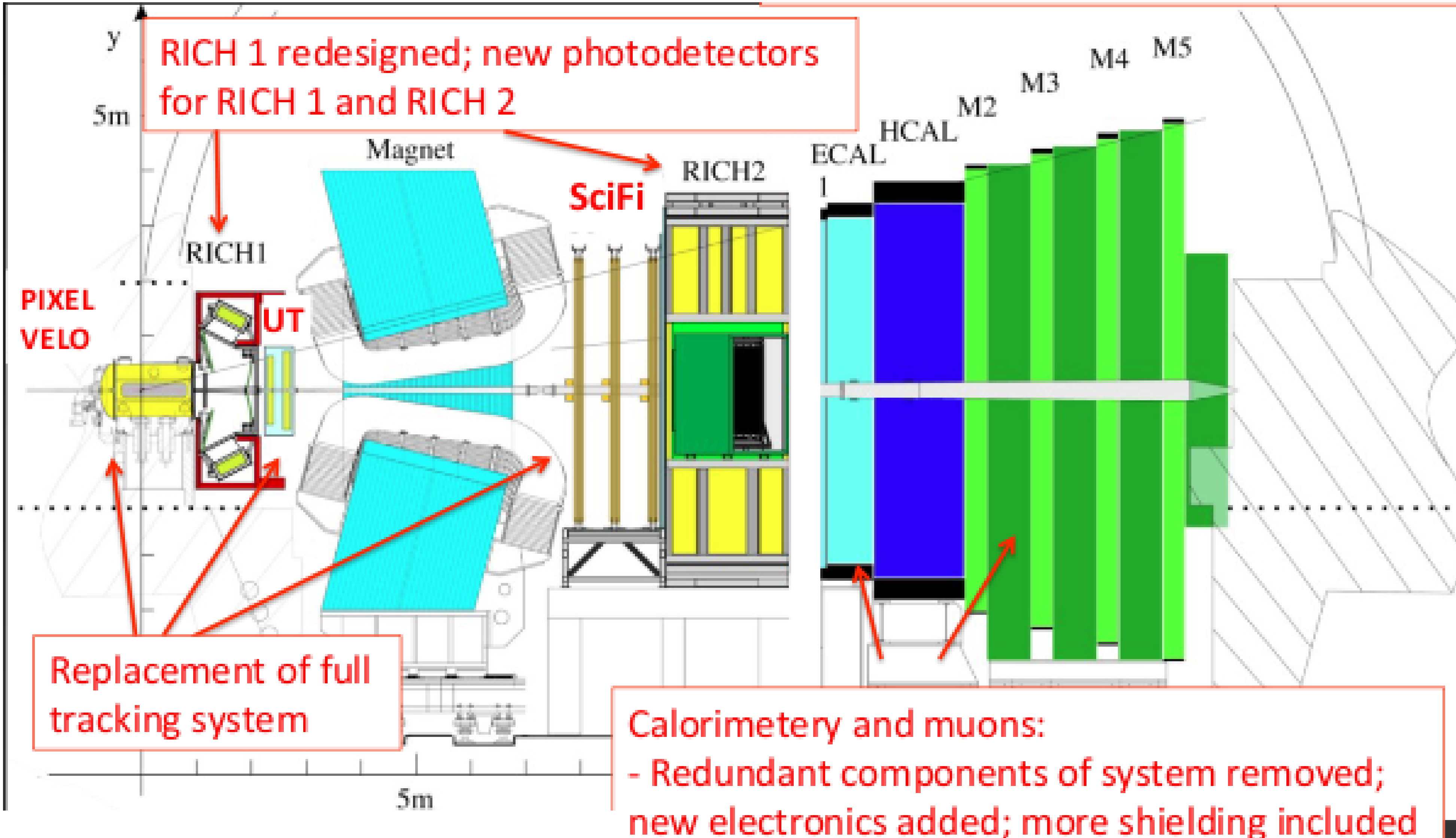




- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

LHCb-TDR-{13,14,15,16}

LHCb detector upgrade



+ novel trigger and offline data management strategies

LHCb & upgrade sensitivities

Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming $5\,\mathrm{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\mathrm{fb}^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.050	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.023**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	~ 7%
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	~ 10%
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	~ 5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

Studies for ECFA HL-LHC workshop

Table 2: Expected sensitivities that can be achieved on key heavy flavour physics observables, using the total integrated luminosity recorded until the end of each LHC run period. Discussion of systematic uncertainties is given in the text. Uncertainties on ϕ_s are given in radians. The values for flavour-changing neutral-current top decays are expected 95% confidence level upper limits in the absence of signal.

		LHC era			HL-LHC era	
		Run 1	Run 2	Run 3	Run 4	Run 5+
$\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$	CMS	$>100\%$	71%	47%	...	21%
	LHCb	220%	110%	60%	40%	28%
$q_0^2\ A_{\mathrm{FB}}(K^{*0}\mu^+\mu^-)$	LHCb	10%	5%	2.8%	1.9%	1.3%
	Belle II	—	50%	7%	5%	—
$\phi_s(B^0_s\to J/\psi\phi)$	ATLAS	0.11	0.05–0.07	0.04–0.05	...	0.020
	LHCb	0.05	0.025	0.013	0.009	0.006
$\phi_s(B^0_s\to\phi\phi)$	LHCb	0.18	0.12	0.04	0.026	0.017
γ	LHCb	7°	4°	1.7°	1.1°	0.7°
	Belle II	—	11°	2°	1.5°	—
$A_\Gamma(D^0\to K^+K^-)$	LHCb	3.4×10^{-4}	2.2×10^{-4}	0.9×10^{-4}	0.5×10^{-4}	0.3×10^{-4}
	Belle II	—	18×10^{-4}	$4–6\times10^{-4}$	$3–5\times10^{-4}$	—
$t\to qZ$	ATLAS	...	...	23×10^{-5}	...	$4.1–7.2\times10^{-5}$
	CMS	100×10^{-5}	...	27×10^{-5}	...	10×10^{-5}
$t\to q\gamma$	ATLAS	...	...	7.8×10^{-5}	...	$1.3–2.5\times10^{-5}$

	Run 1	Run 2	Run 3	Run 4	Run 5+
LHCb ∫ *L* dt	3/fb	8/fb	23/fb	46/fb	70/fb (?)
ATLAS/CMS ∫ *L* dt	25/fb	100/fb	300/fb	...	3000/fb

Beyond the LHCb Upgrade

- LHCb upgrade is qualified for 50/fb
  - Anticipate to accumulate this data set approximately by LS4
  - Essential to prove that 40 MHz readout works
- The HL-LHC will run well beyond LS4
  - It will be the most copious source of heavy flavoured particles (inter alia) for many years
- Is there a physics case to operate a forward spectrometer at $O(10^{34}/cm^2/s)$, and accumulate O(500/fb)?
  - ECFA HL-LHC studies give a mandate to think about this
  - Many conventional flavour observables become systematics or theory limited
  - Need to think "out of the box". Possible ideas:
    - $B_s \to \mu\mu$ effective lifetime, $H \to c\bar{c}$, … your thoughts welcome!

Summary

- A great harvest of physics from LHC Run I
- LHCb expanding from its core physics programme
  - results on modes with electrons, photons, neutral pions and neutrinos
  - also top, heavy ion physics, central exclusive production, lots of baryons, charm ... (not enough time to cover everything today, or any day)
  - in some cases doing things previously thought impossible
- Several hints of BSM effects
  - R(D*), R_K, $\mathcal{B}(B_s \to \phi\mu\mu)$, $\mathcal{B}(\Lambda_b \to \Lambda\mu\mu)$, P_5' … does a consistent picture emerge?
- Run II is starting, and prospects look good
- Excellent progress on the LHCb upgrade
  - We are just getting started ...