Highlights and prospects from LHCb

“Gearing up for LHC13”

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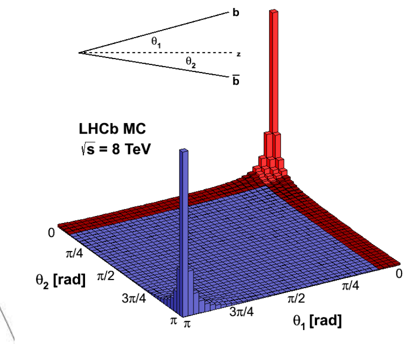
On behalf of the LHCb Collaboration

15th October 2015

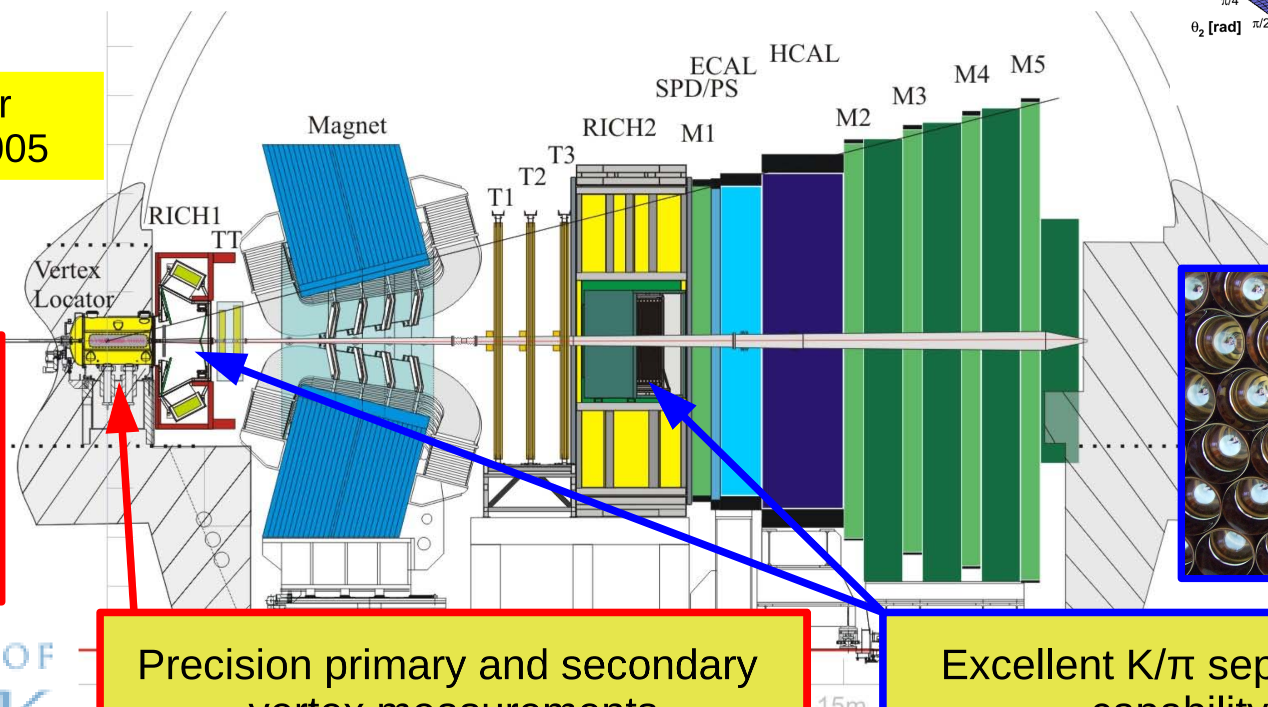
European Research Council

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

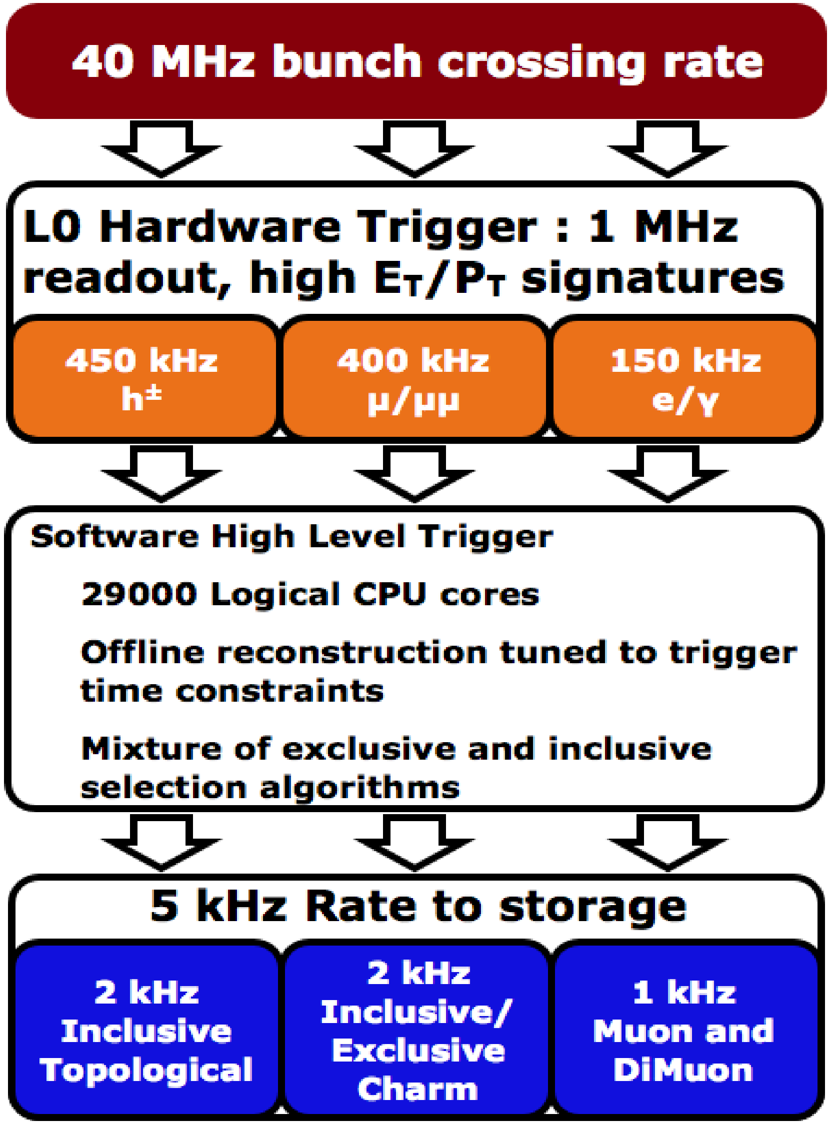
The LHCb Run 1 trigger

JINST 8 (2013) P04022

Challenge is
- to efficiently select most interesting events
- while maintaining manageable data rates

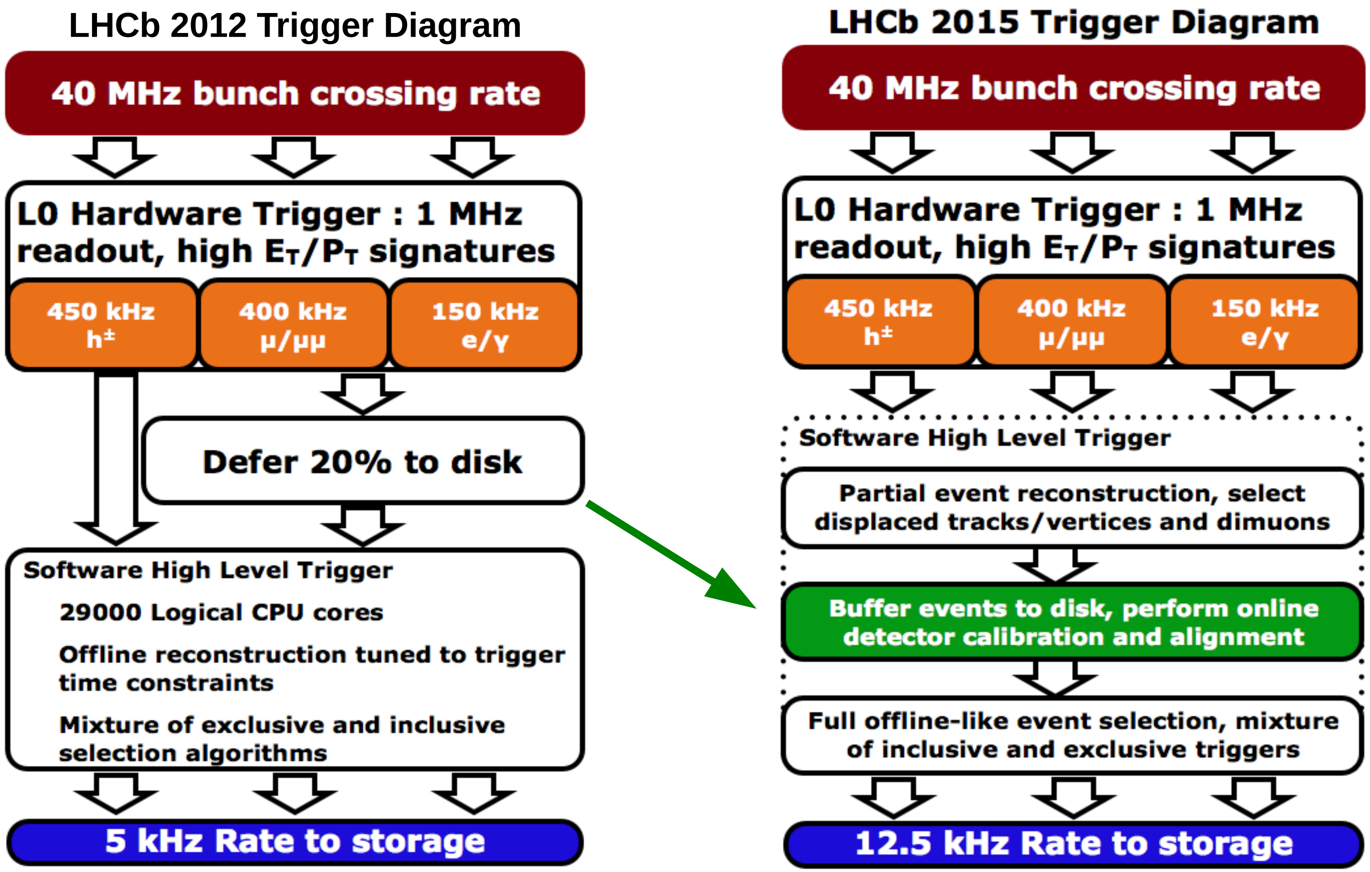
Main backgrounds
- "minimum bias" inelastic pp scattering
- other charm and beauty decays

Handles
- high p_T signals (muons)
- displaced vertices



Run II data taking

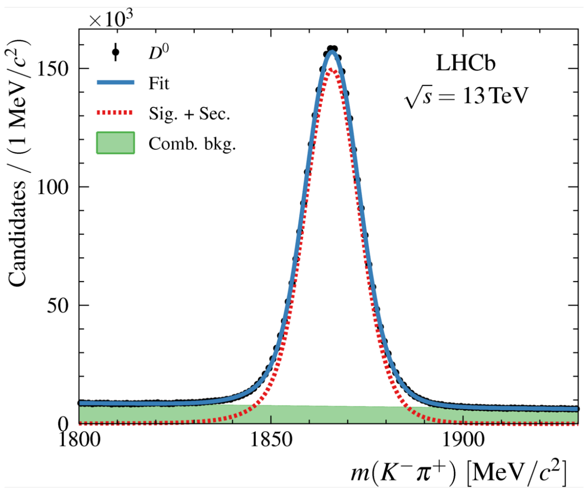
- At 13 TeV, LHCb gains from higher √s (increased production) and 25 ns bunch spacing (lower pile up)
- During LS1: some subdetector consolidation; new HERSCHEL forward shower counters; change of data flow in trigger



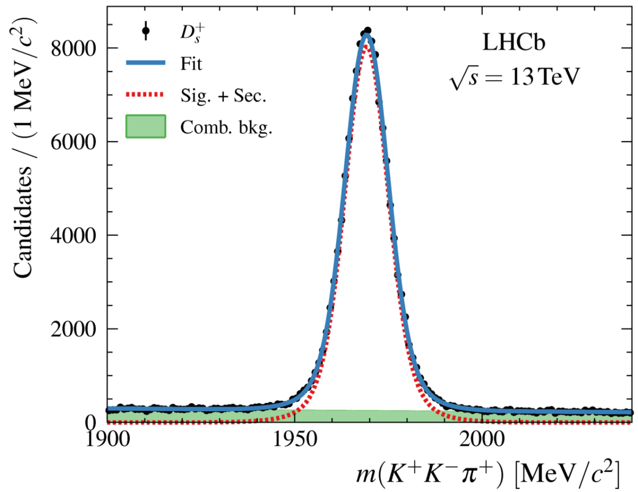
First results from Run II

arXiv:1510.01707

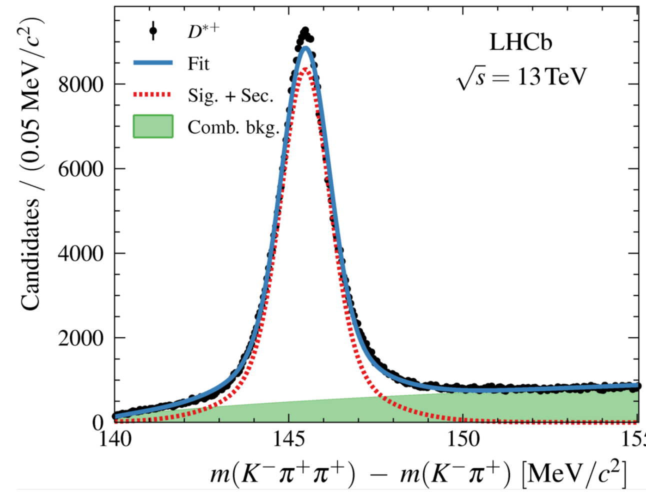
$D \rightarrow K\pi$



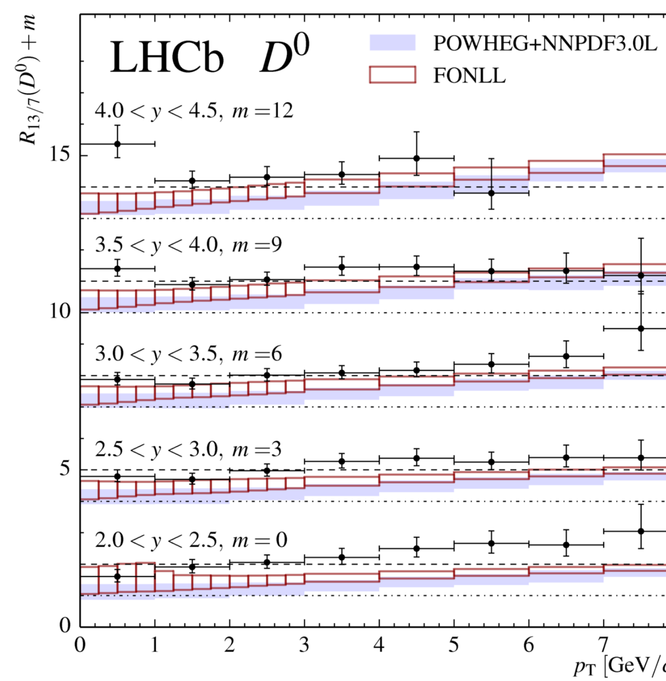
$D_s \rightarrow KK\pi$



$D^* \rightarrow D\pi$; $D \rightarrow K\pi$

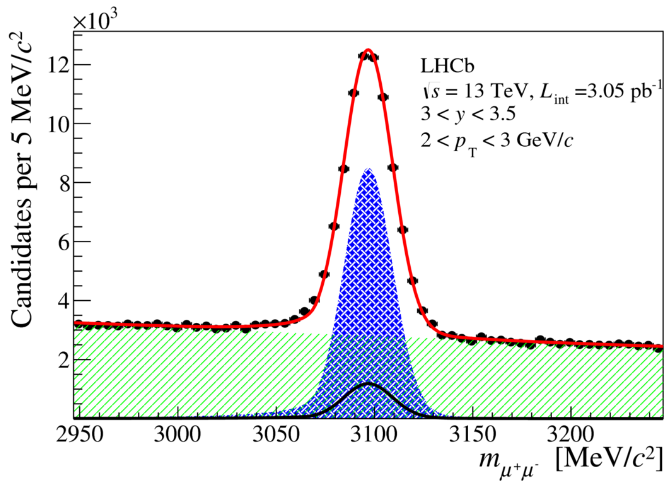


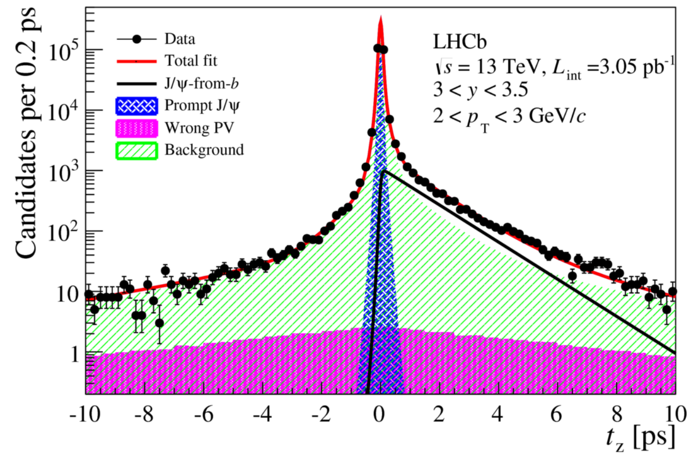
Increases of production cross-section from $\sqrt{s} = 7 \rightarrow 13$ TeV at upper end of range of expectation



First results from Run II

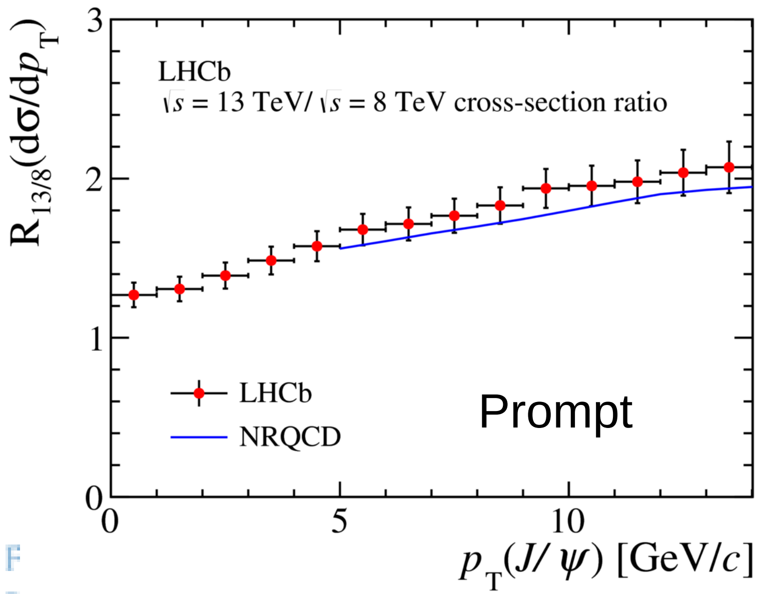
arXiv: 1509.00771

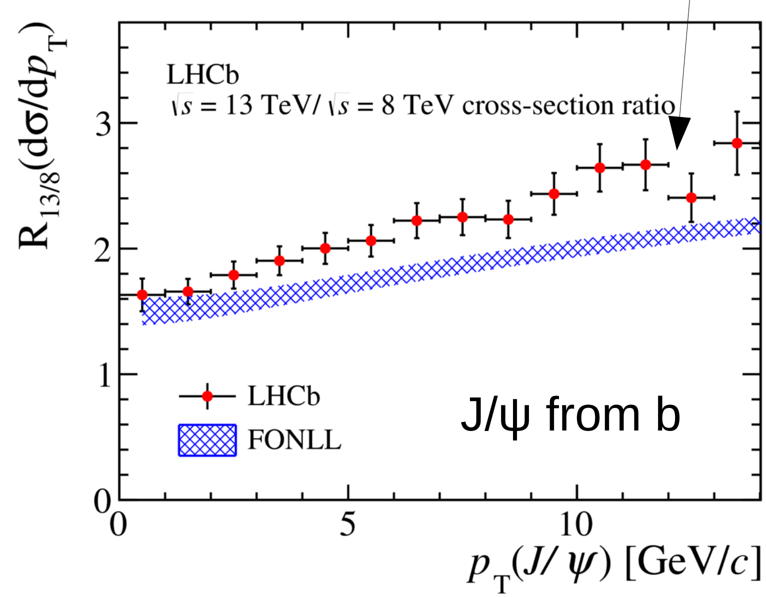




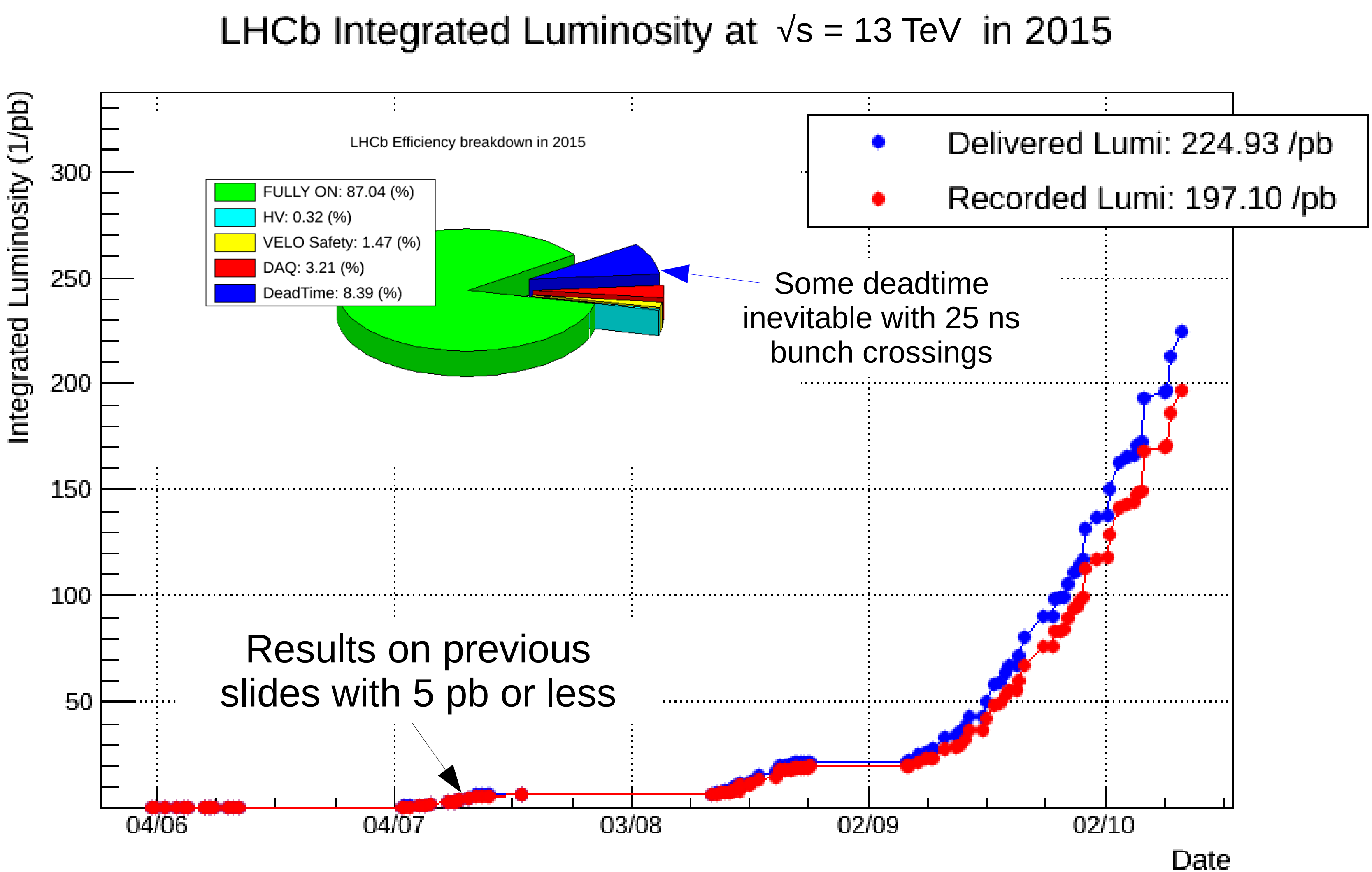
high-p_T b-hadrons tend to have lower background & better tagging

Increases from √s = 8 → 13 TeV at upper end of range of expectation





Data taken so far in Run II



c.f. 1/fb in 2011 @ 7 TeV; 2/fb in 2012 @ 8 TeV

Contents

- Miscellanea
- Rare decays
- Probes of lepton universality
- CKM Unitarity Triangle sides and angles
- Other BSM CP violation searches

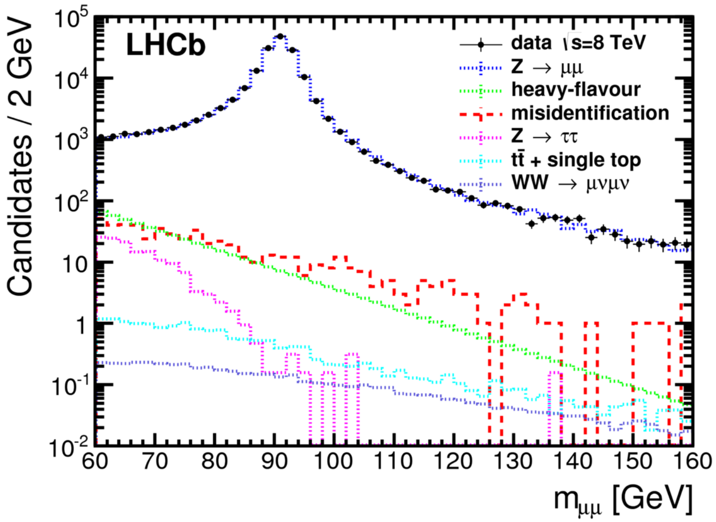
- For each discuss recent results and prospects

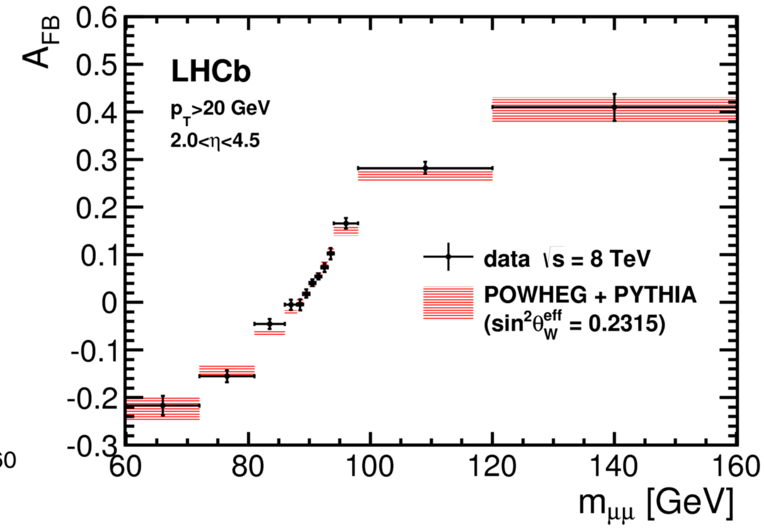
Miscellanea

Measurement of $\sin^2\theta_W$

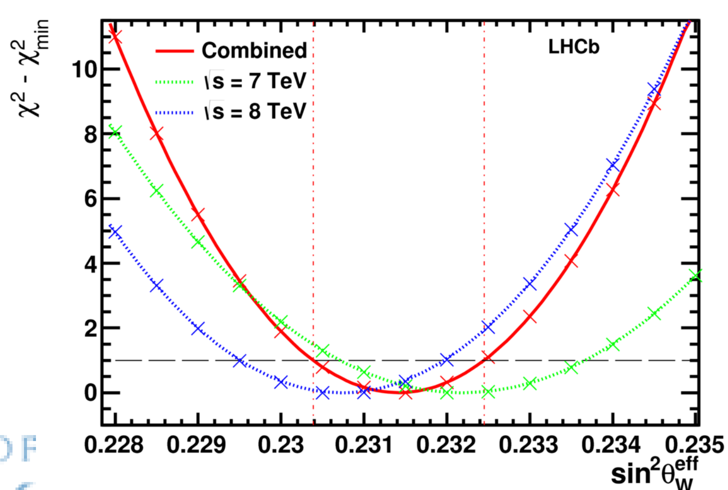
Exploit forward-backward asymmetry in $Z/\gamma^* \to \mu^+\mu^-$ in LHCb acceptance

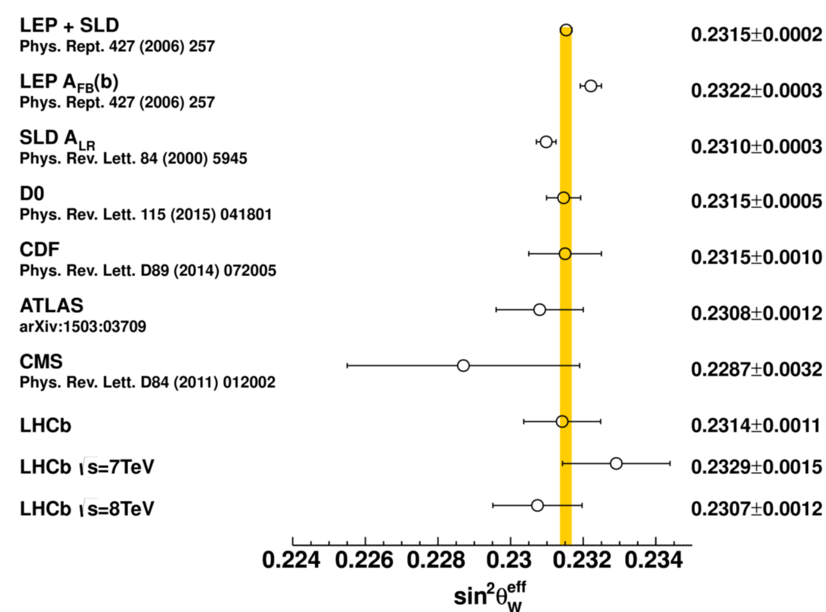
arXiv:1508.04094





Most precise from LHC and will improve with √s = 13 TeV data





Top observation at LHCb

PRL 115 (2015) 112001

- 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 JINST 10 P06013

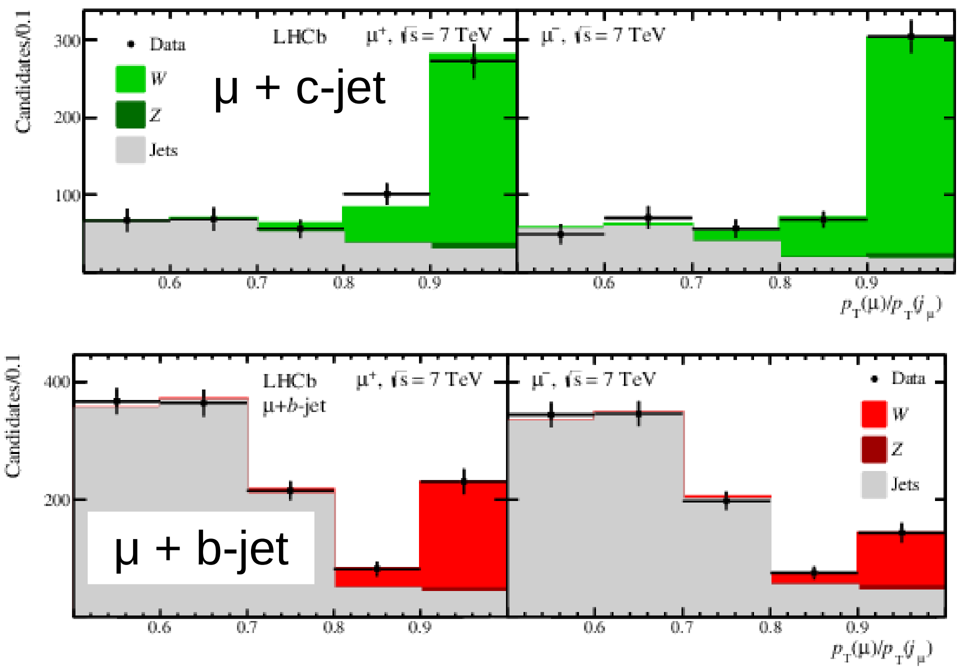
Exploits LHCb's excellent vertexing capability

W+b,c-jet observation at LHCb

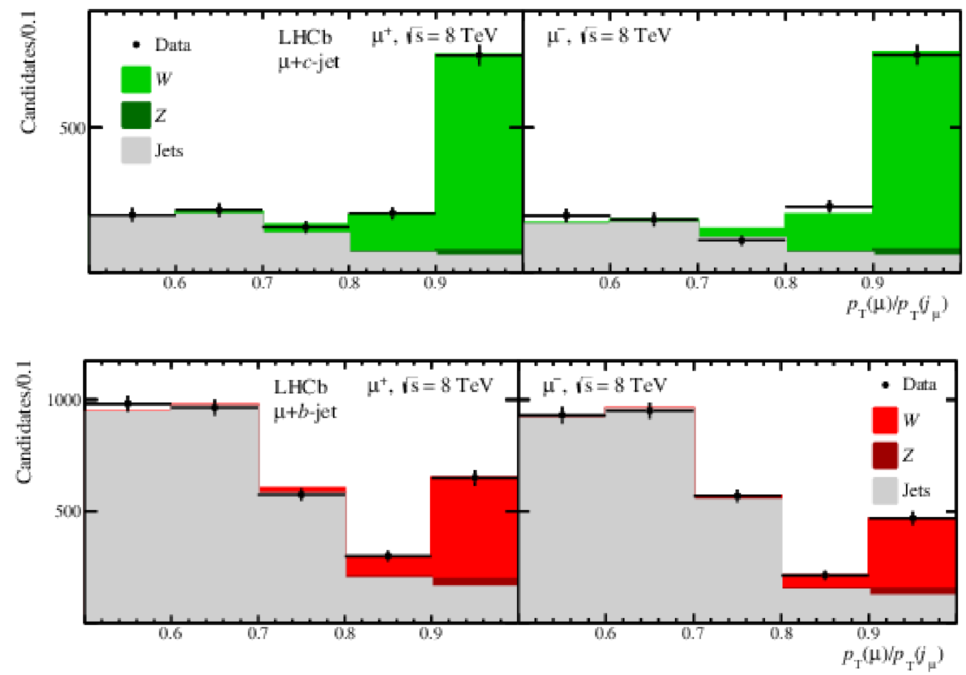
PR D92 (2015) 052001

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

7 TeV



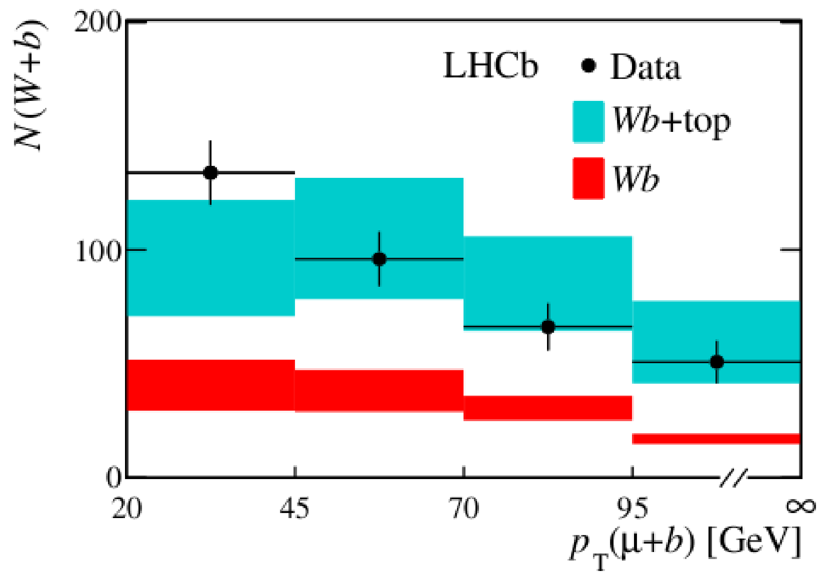
8 TeV

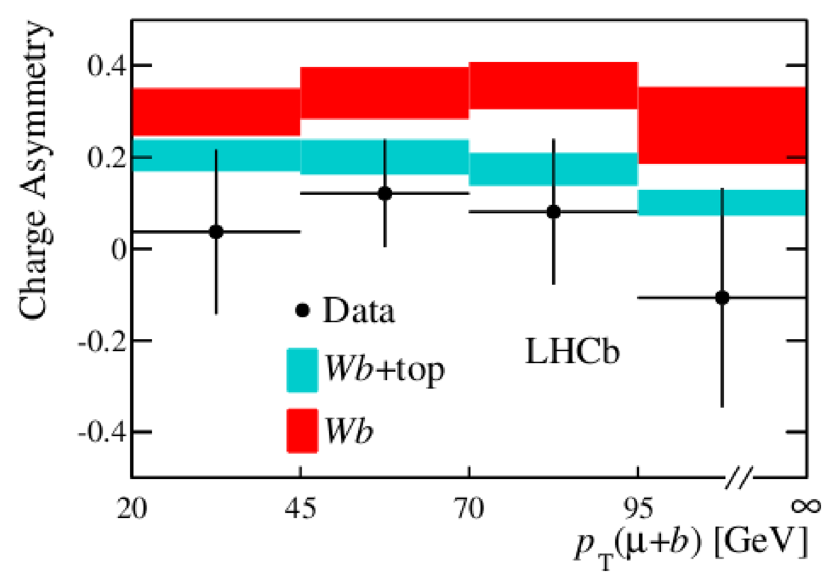


Top observation at LHCb

PRL 115 (2015) 112001

- 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)



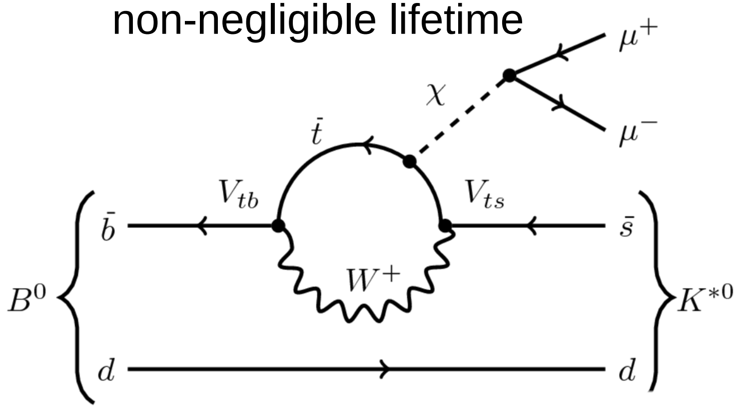


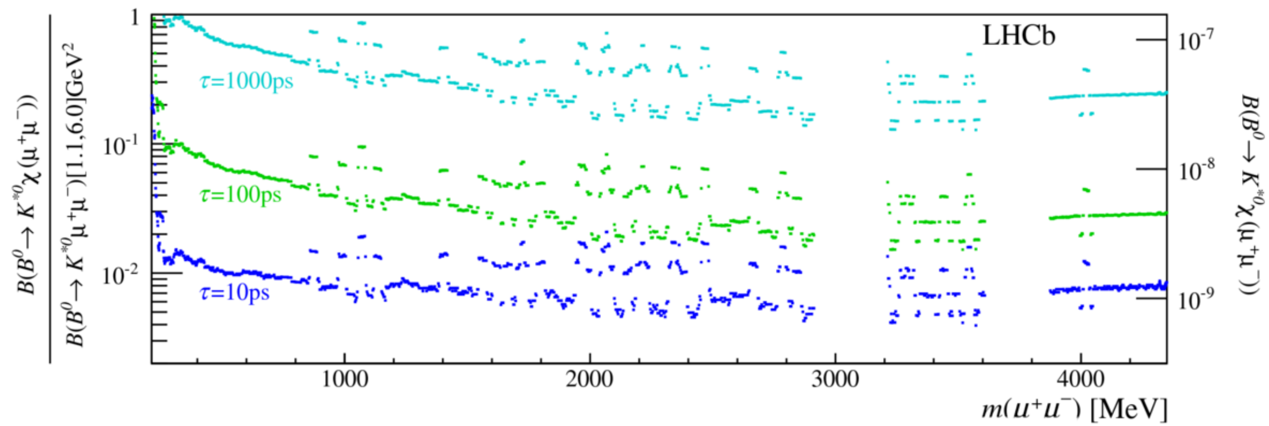
5.4σ observation of top production in the forward region

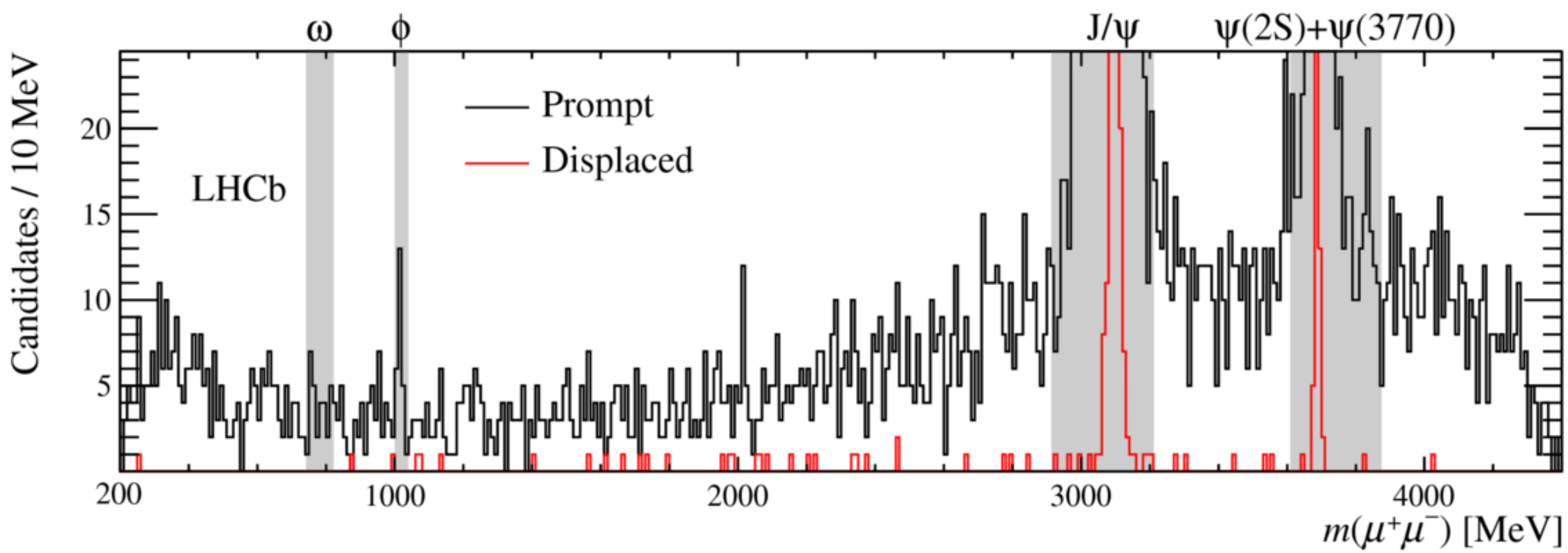
Search for hidden sector bosons

arXiv:1508.04094

Search for narrow μμ peak in $B \to K^{*0}\mu\mu$ decays corresponding to χ with either negligible or non-negligible lifetime







No significant peak away from known resonances

Miscellanea summary

- Many interesting measurements that exploit that forward acceptance of LHCb become much more sensitive at $\sqrt{s}$ = 13 TeV
  - top production is an excellent example
  - need to accumulate statistics to surpass Run I sensitivity is less great in this area
  - potential for new results in 2016

Rare decays

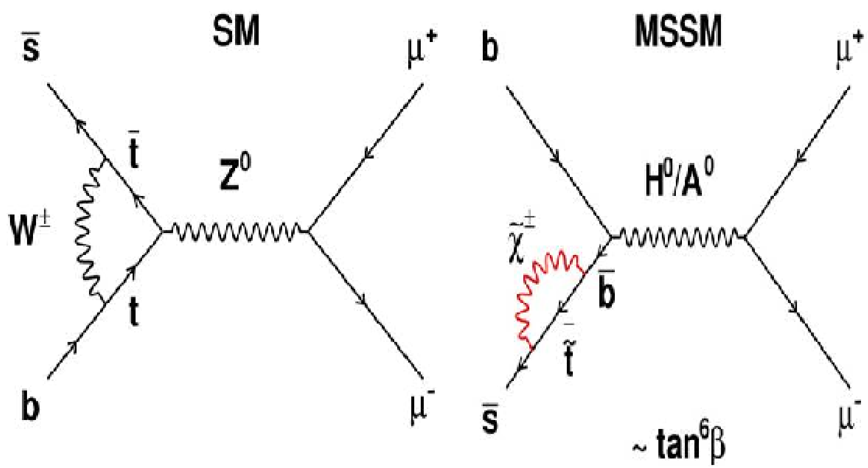
$B_s \to \mu^+\mu^-$

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

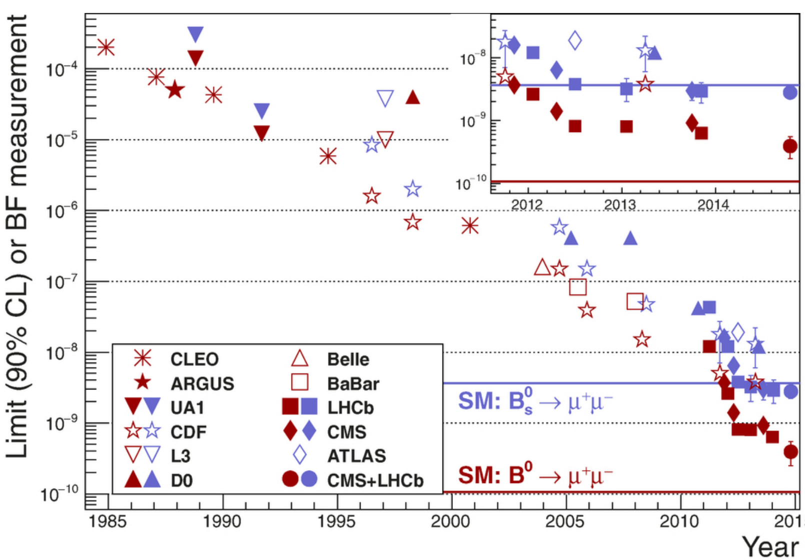
… all features which are not necessarily reproduced in extended models



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

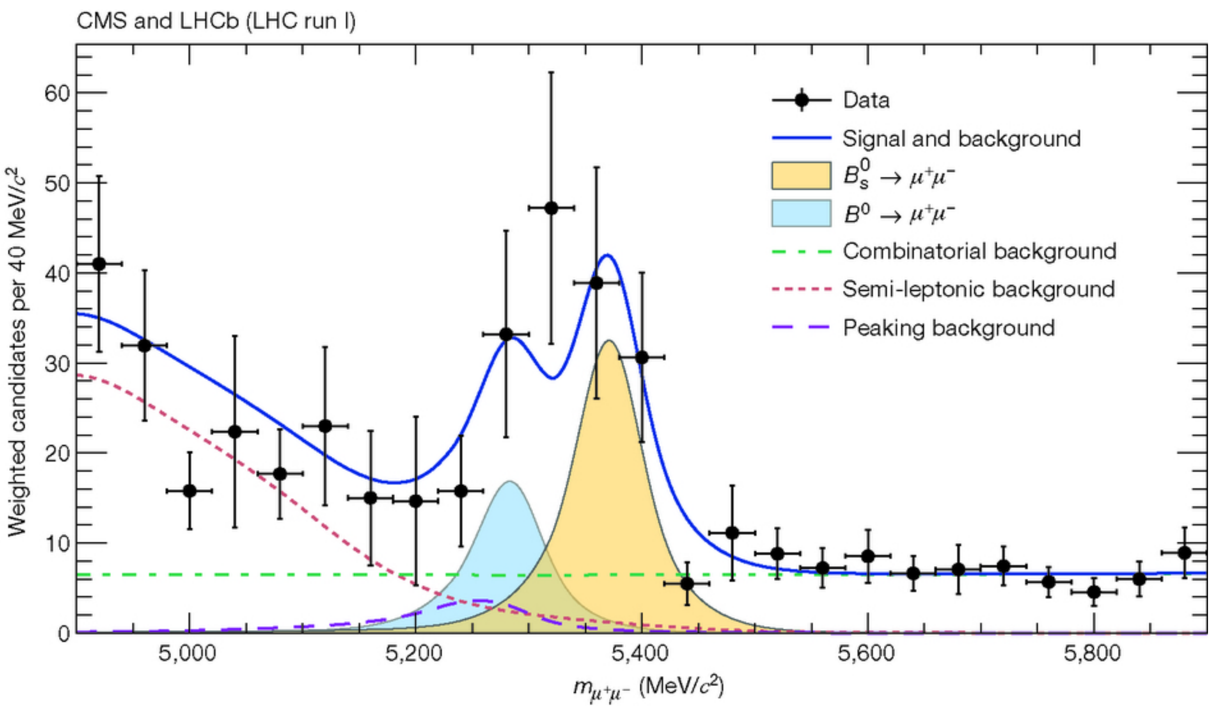
$\mathcal{B}(B_s \to \mu^+\mu^-)^{MSSM} \sim \tan^6\beta / M^4_{A0}$

Intensively searched for over 30 years!



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

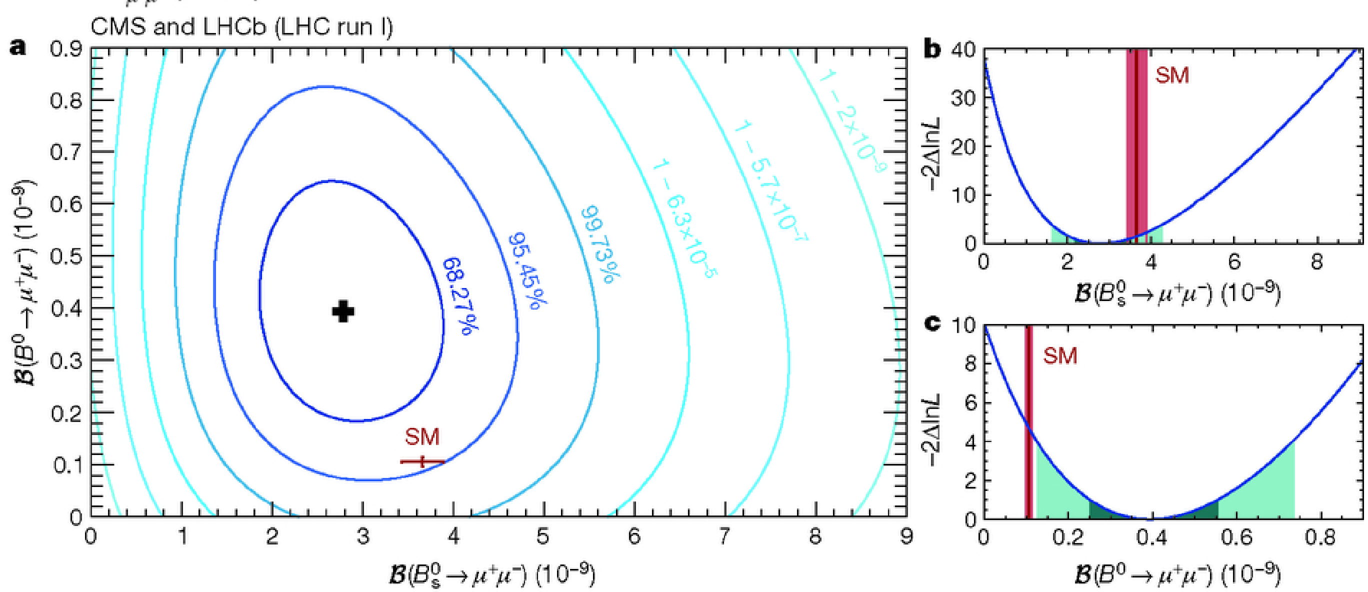
Nature 522 (2015) 68



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

Strong constraints on new (pseudo)scalar couplings



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

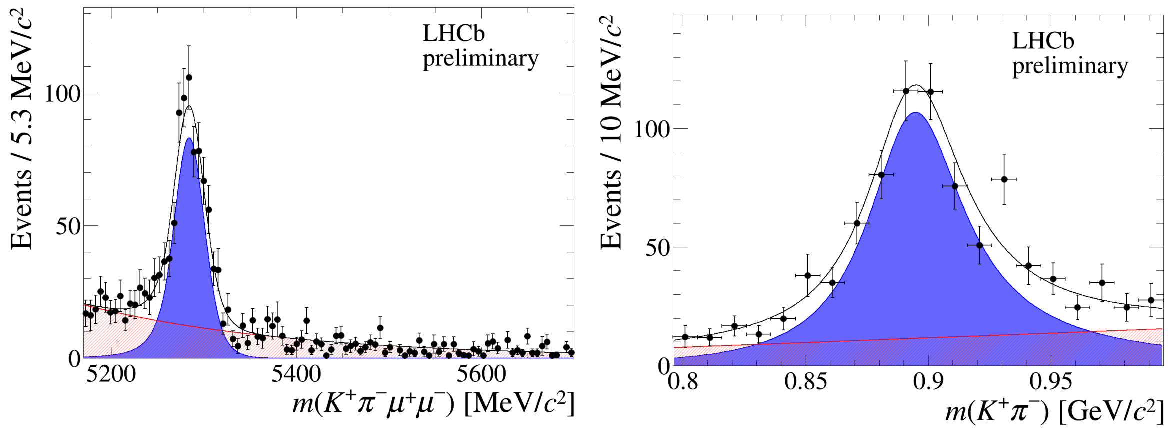
LHCb-CONF-2015-002

- $B^0 \to K^{*0}\mu^+\mu^-$ provides superb laboratory to search for new physics in $b \to sl^+l^-$ 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
  - CP asymmetries will be added in forthcoming publication

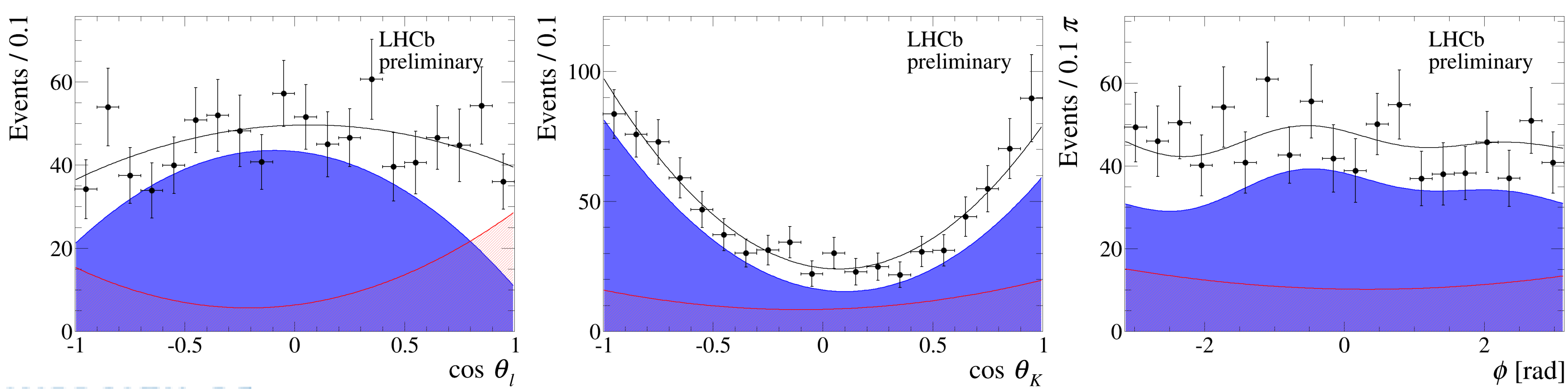
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002

- Example of fits, in $1.1 < q^2 < 6.0$ GeV^2 bin
  - proper treatment of Kπ S-wave for first time

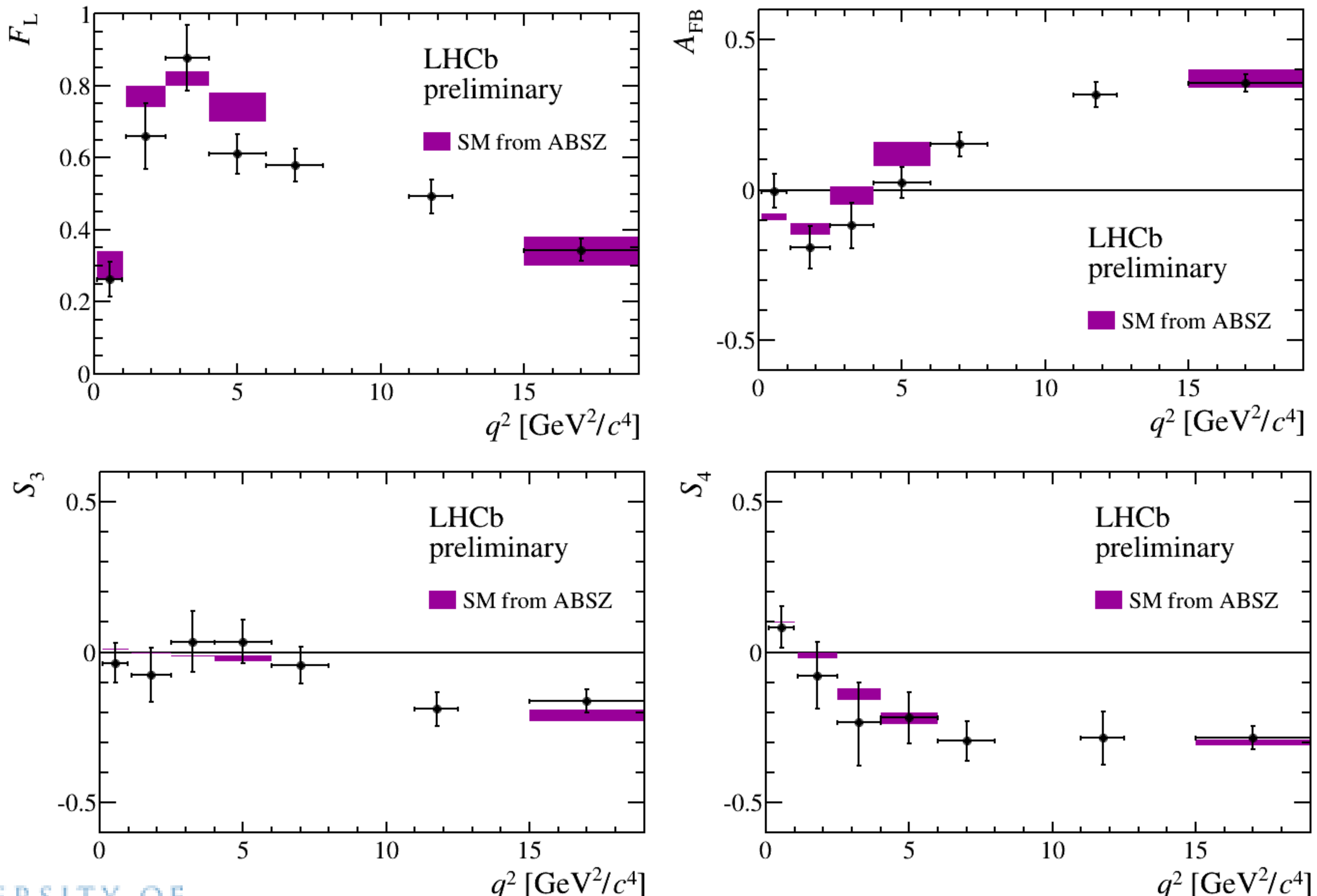


Angle and m(Kπ) projections in ± 50 MeV around B peak



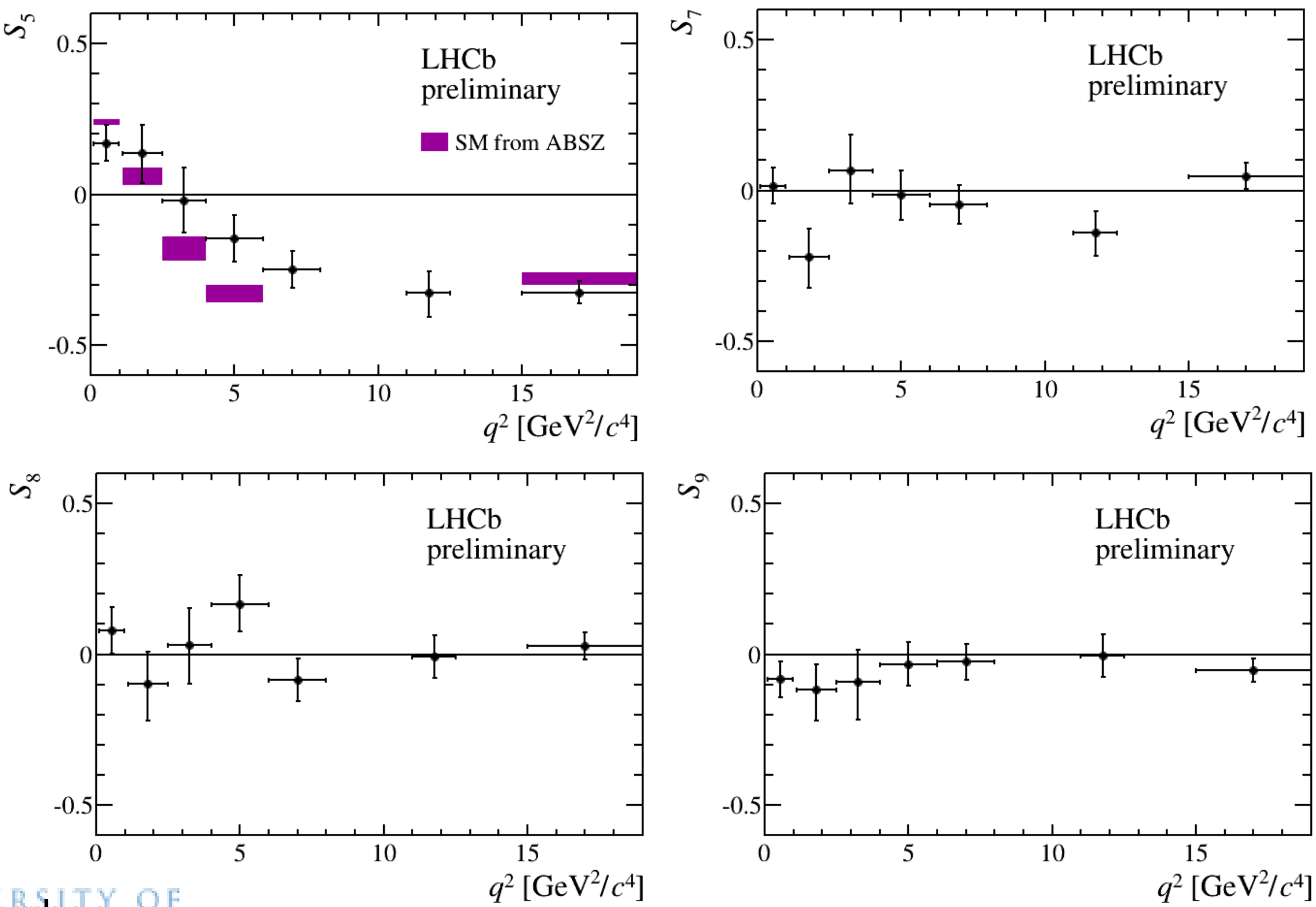
Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002



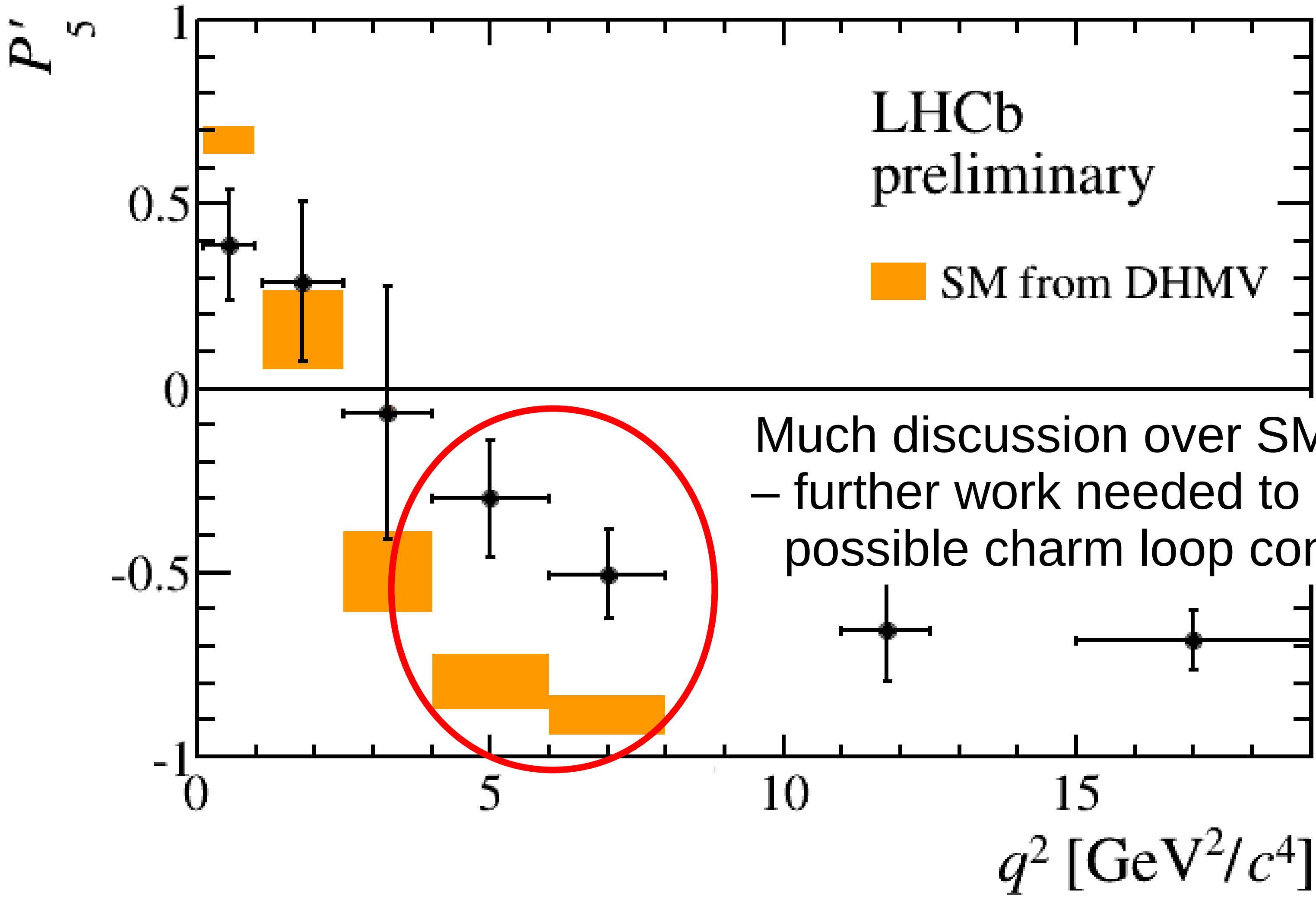
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

LHCb-CONF-2015-002



Tension in P_5'

LHCb-CONF-2015-002

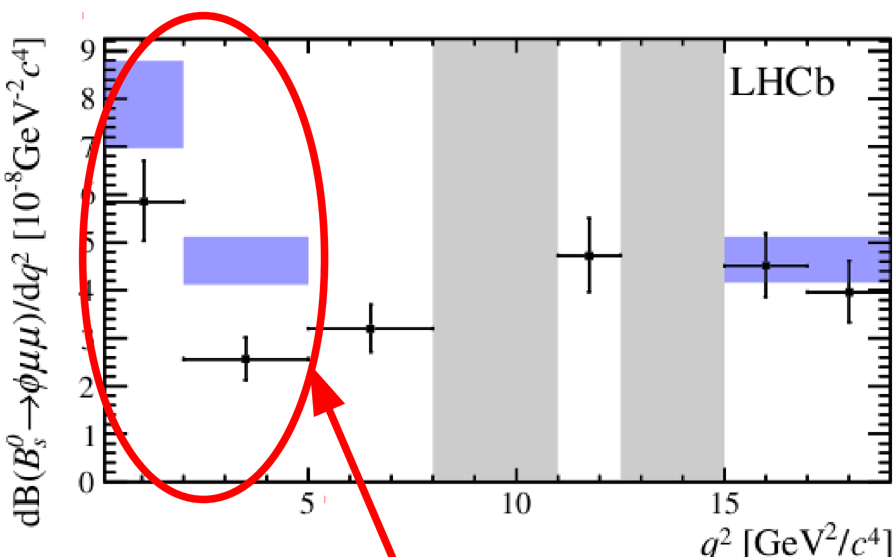


Much discussion over SM prediction – further work needed to understand possible charm loop contributions

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

JHEP 09 (2015) 179

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



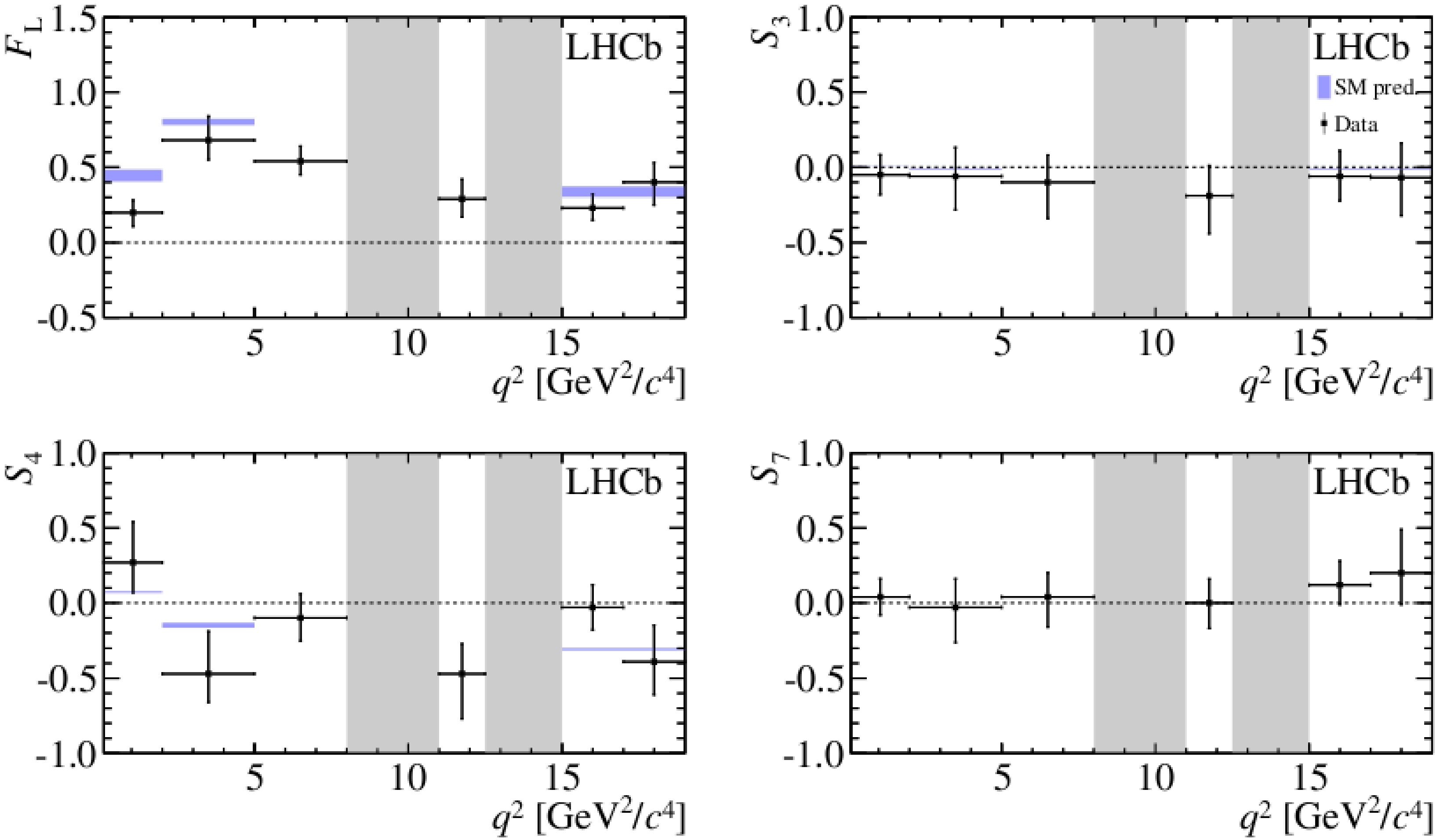
SM predictions from arXiv:1411.3161, arXiv:1503.05534

3.3σ tension with SM prediction – consistent picture in b → sl^+l^- branching fractions

SM predictions from arXiv:1411.3161, arXiv:1503.05534

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

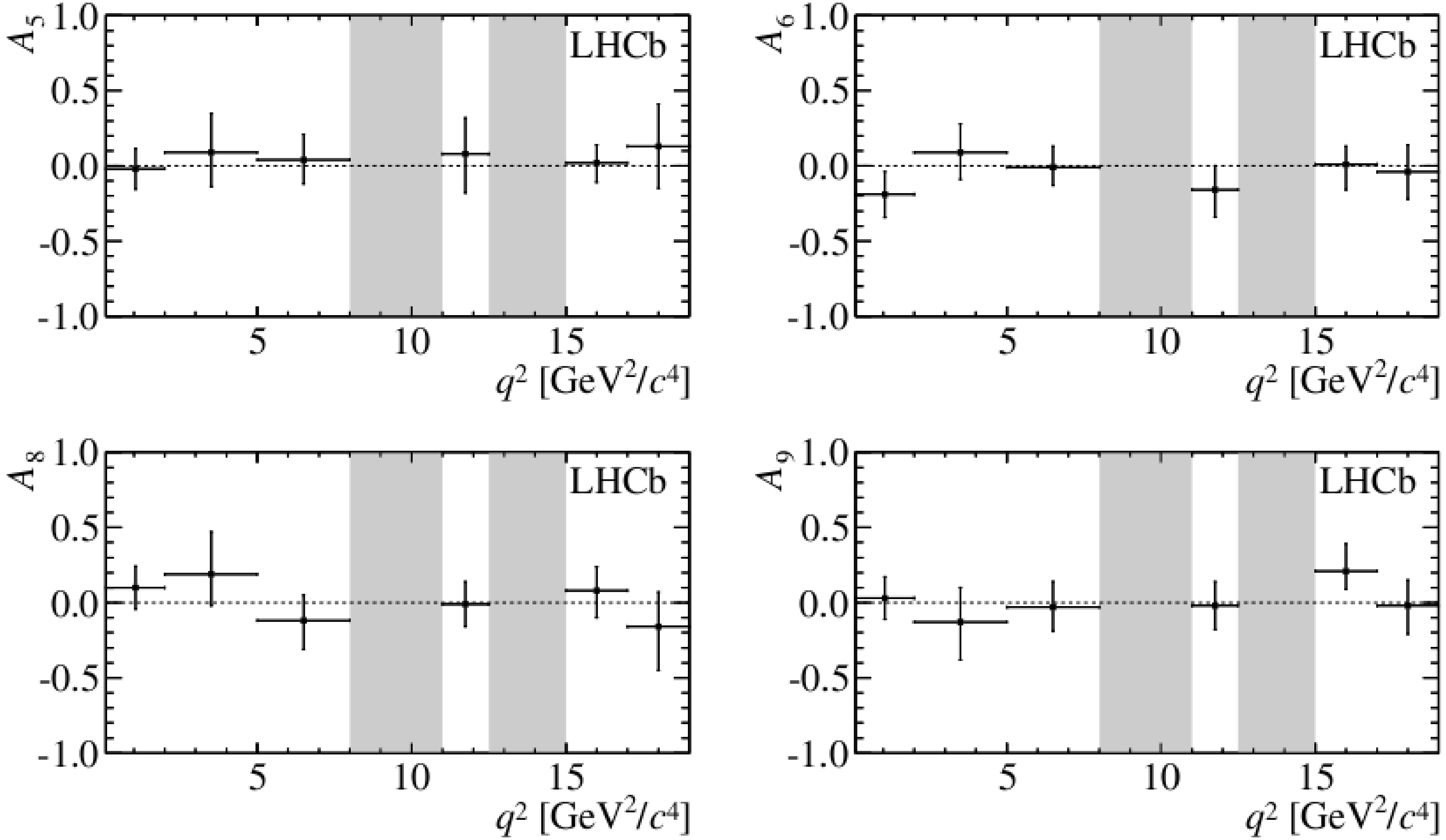
JHEP 09 (2015) 179



All angular observables consistent with SM

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

JHEP 09 (2015) 179

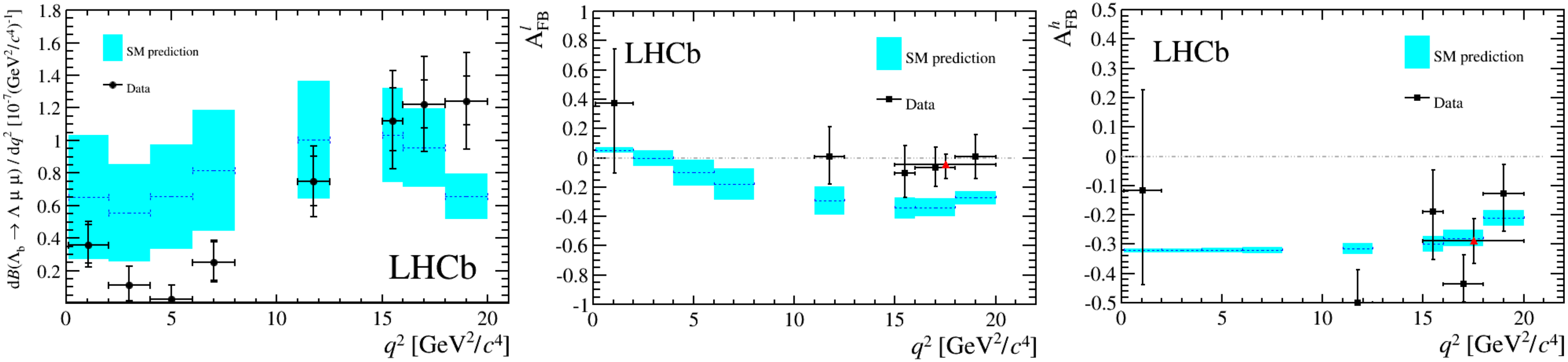


All angular asymmetries consistent with SM

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

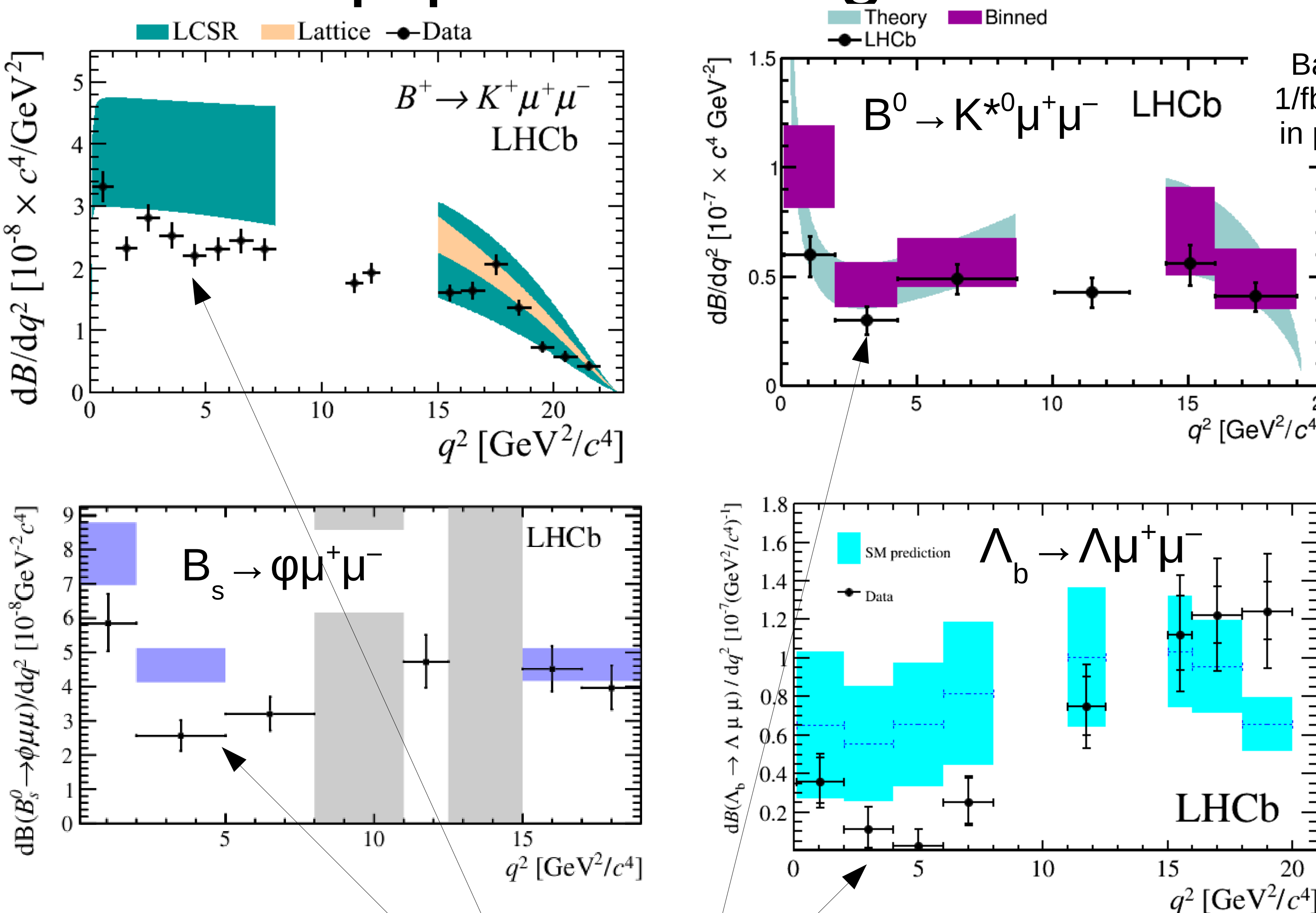
SM predictions from
arXiv:1212.4827

JHEP 06 (2015) 115



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

$b \rightarrow s\mu^+\mu^-$ branching fractions



Based on 1/fb; update in progress

Trend to be below SM prediction at low q^2?

Rare decays summary

- Move towards precision era for $B_{(s)} \rightarrow \mu^+\mu^-$ decays
  - Search for B^0 decay particularly interesting
- Full angular analyses of $b \rightarrow s\mu^+\mu^-$ decays now possible
  - Ongoing discussion to understand how best to control potential hadronic uncertainties
  - Sensitivity to $b \rightarrow d\mu^+\mu^-$ decays also becoming interesting
- Several ~3σ hints of BSM effects
  - Not enough for strong claims, but possible to explain consistently
- Few new results on radiative decays, but still great potential to be explored
- Expect to move towards global fits for Wilson coefficients to optimally combine all available information

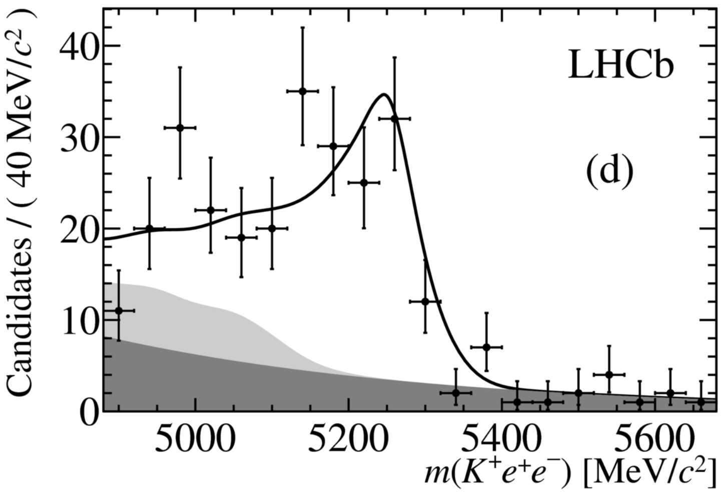
Probes of lepton universality

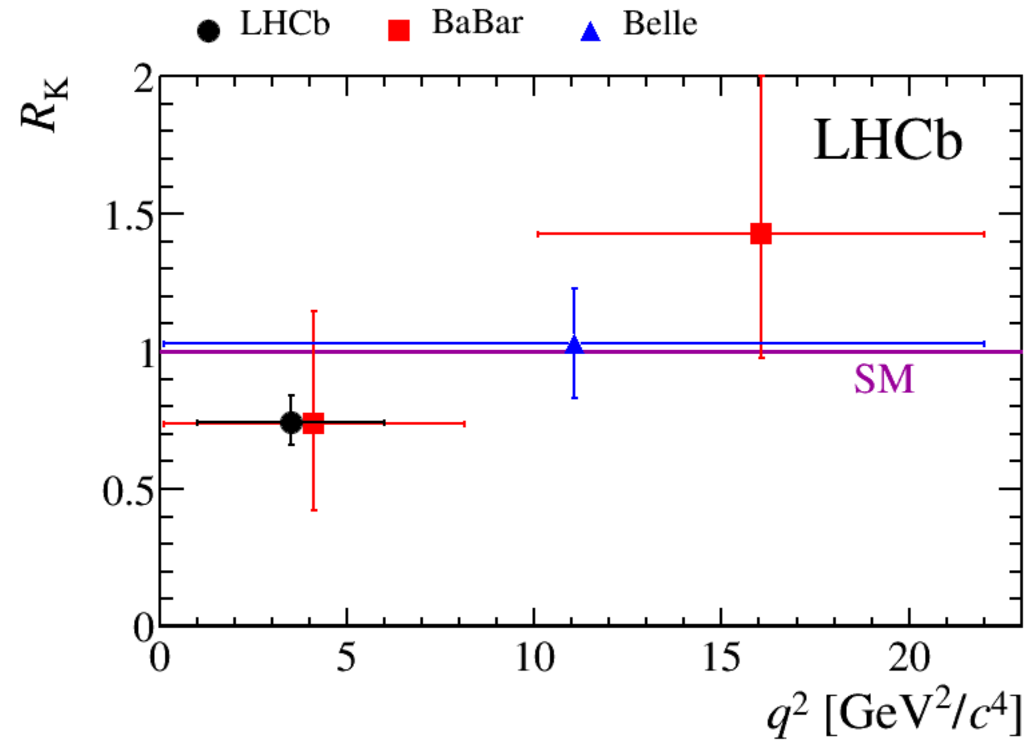
Lepton universality – R_K

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)

Example mass fit for Ke^+e^-
Note huge tail due to energy loss





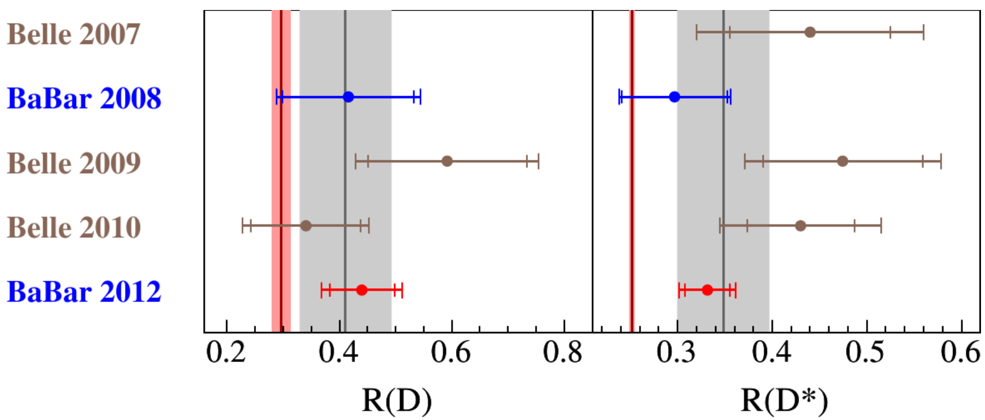
$$R_K(1 < q^2 < 6\ \mathrm{GeV}^2) = 0.745\ ^{+0.090}_{-0.074} \pm 0.036$$

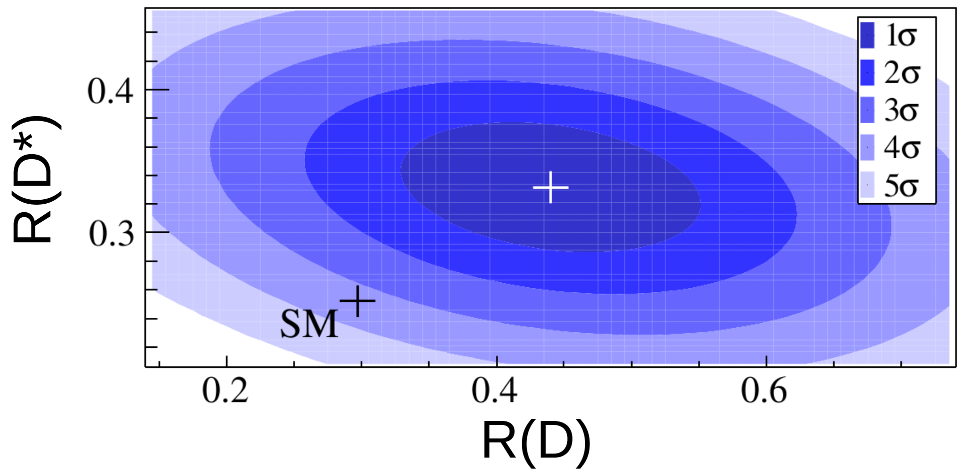
Only 2.6σ from SM but suggestive

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

- 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 bosons
- 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

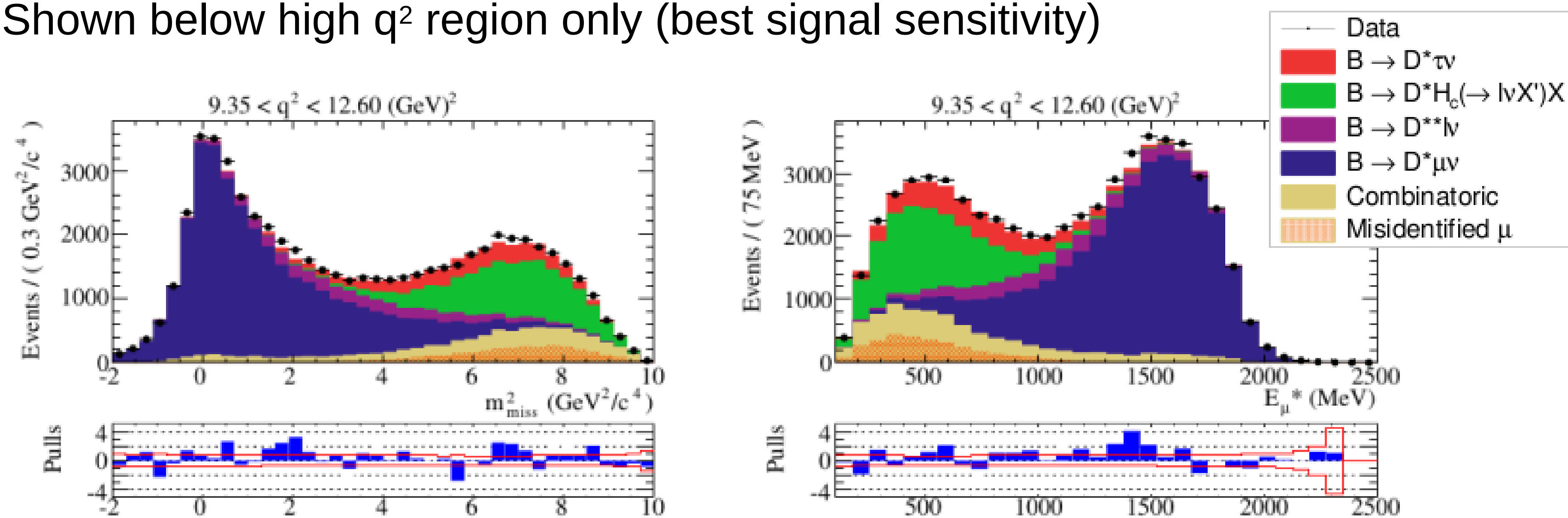




$B \to D^* \tau \nu$ at LHCb

PRL 115 (2015) 112001

- 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 – systematics

PRL 115 (2015) 112001

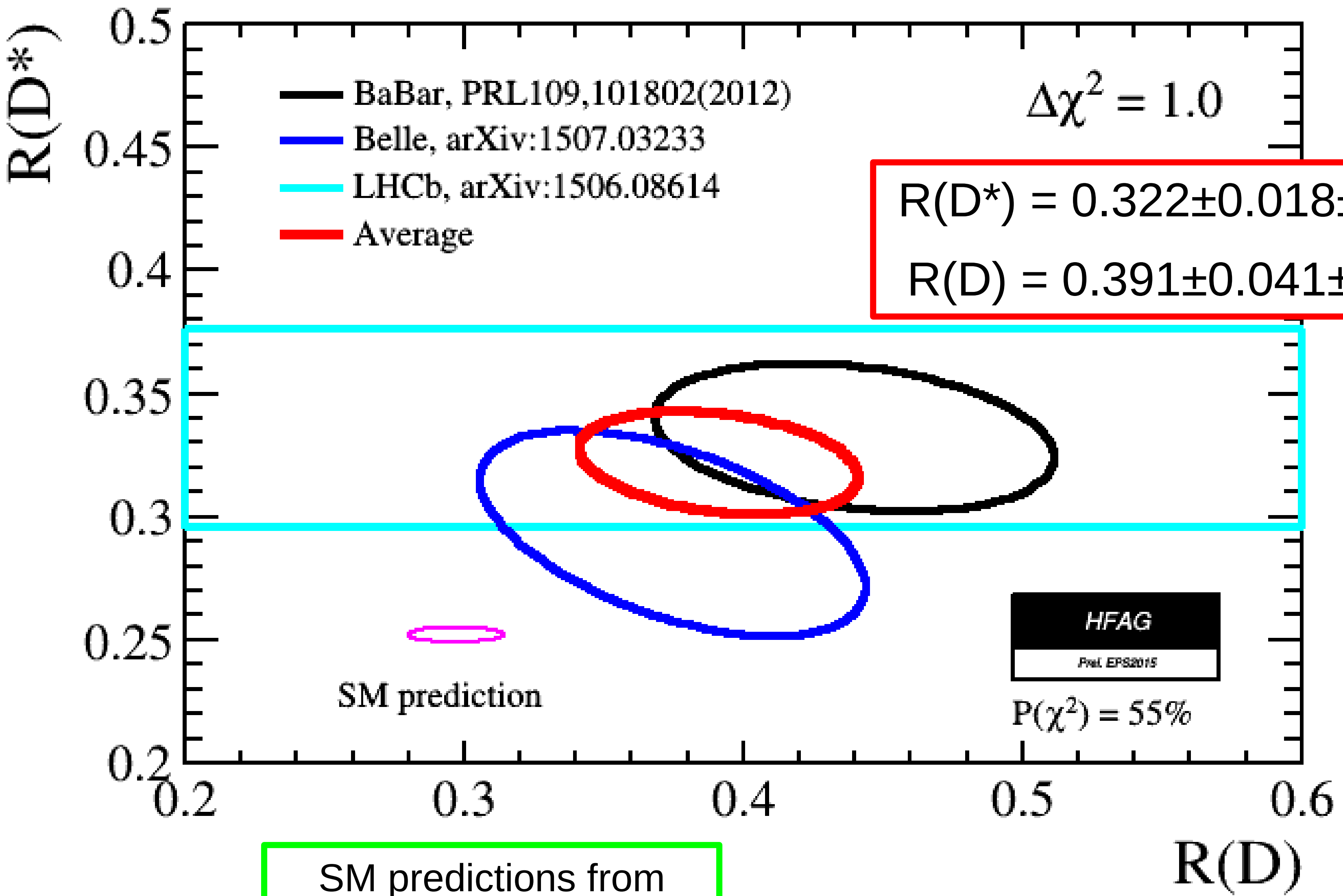
R(D*) = 0.336 ± 0.027 ± 0.030

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 at 3.9σ



$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

$R(D) = 0.391 \pm 0.041 \pm 0.028$

SM predictions from
PRD 85 (2012) 094025

Lepton universality summary

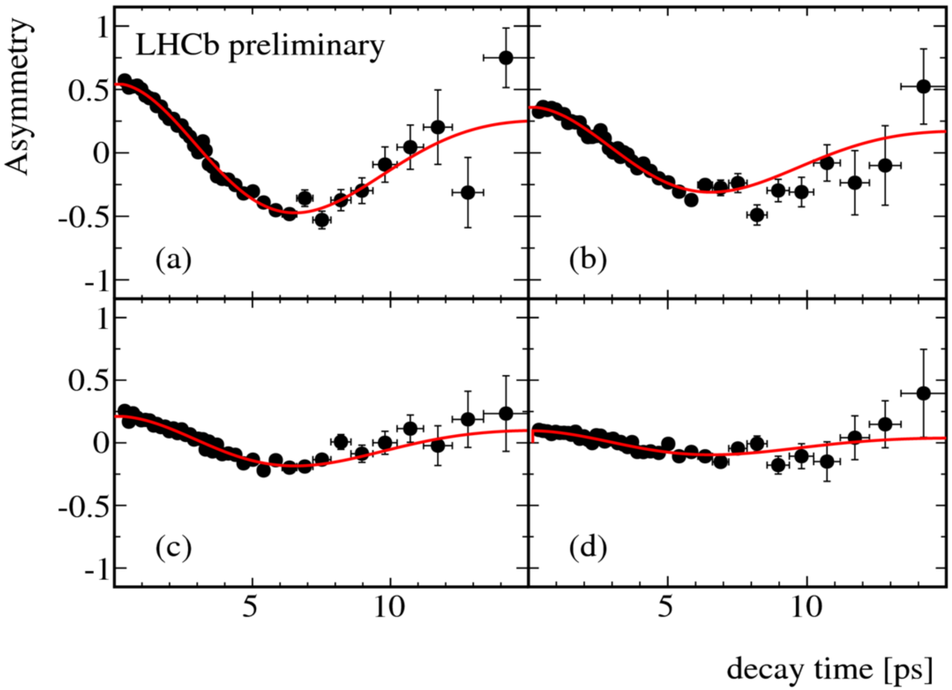
- Expand physics programme to more modes with electrons and taus
  - not only R_K ($B \to Ke^+e^-/B \to K\mu^+\mu^-$) but similar ratios with different hadronic systems (K^*, φ, Λ, etc.)
  - not only $D^*\tau\nu$, but also $D\tau\nu$, $D_s\tau\nu$, $\Lambda_c\tau\nu$, etc.
    - also trying hadronic tau decays
- Search for lepton number violation in parallel
  - many possible channels, e.g. $B \to \tau\mu$, $K\tau\mu$, $Ke\mu$ etc.

CKM Unitarity Triangle sides and angles

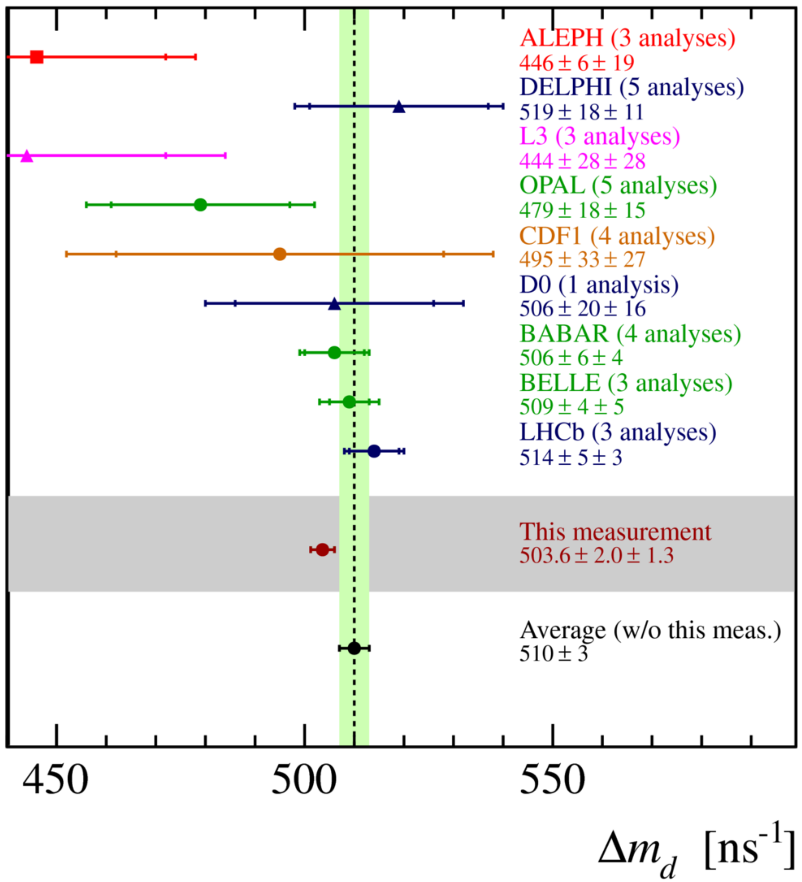
$|V_{td}/V_{ts}|$ from $\Delta m_d/\Delta m_s$

LHCb-CONF-2015-003

Use semileptonic $B^0 \to D^{(*)}\mu\nu X$ decays to make world leading Δm_d determination
(world's best Δm_s in NJP 15 (2013) 053021 from 1/fb of $B_s \to D_s\pi$ decays)



(a)-(d) are different flavour tagging categories



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

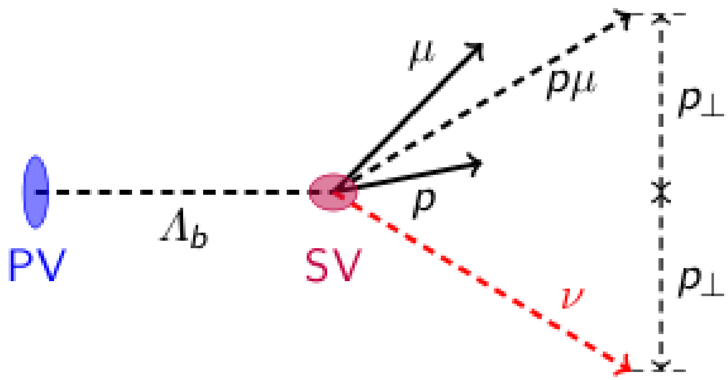
Nature Phys. 11 (2015) 743

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

$$|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \qquad |V_{ub}| = (4.41 \pm 0.15 \,^{+\,0.15}_{-\,0.17}) \times 10^{-3} \quad \text{(inclusive)},$$
$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \qquad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \quad \text{(exclusive)}.$$

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

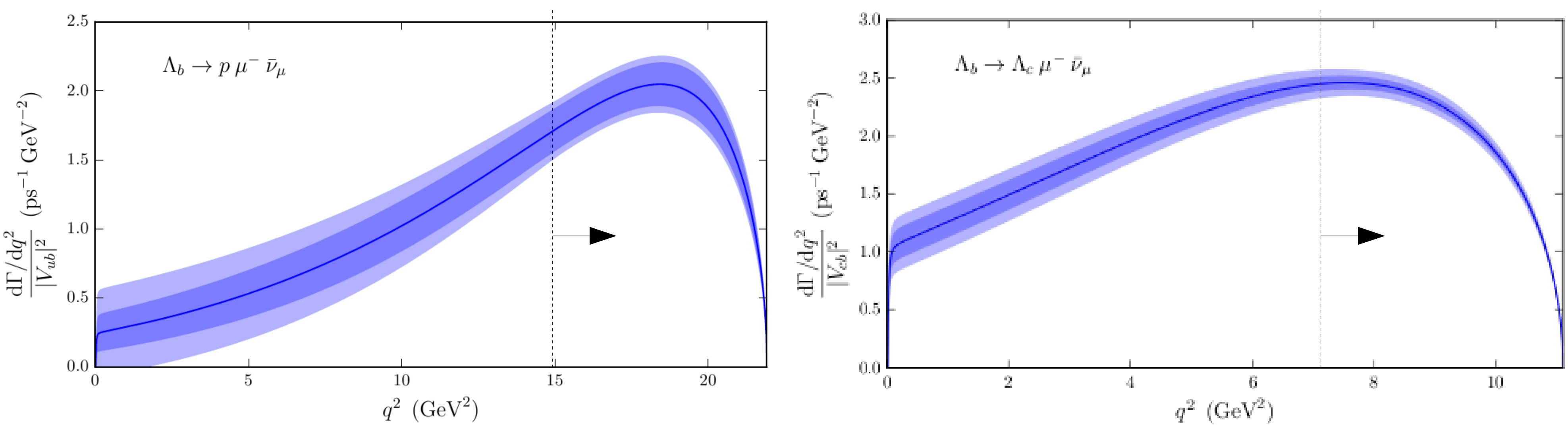
$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$



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

Nature Phys. 11 (2015) 743

- 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

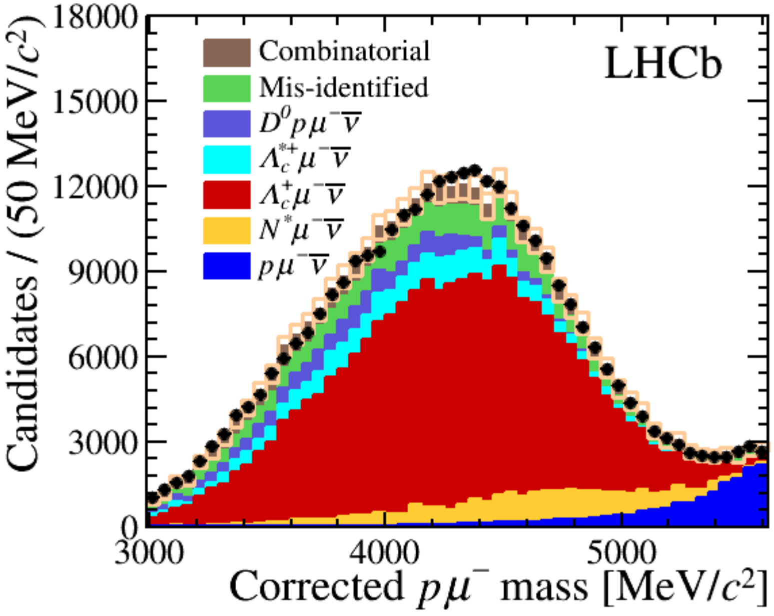


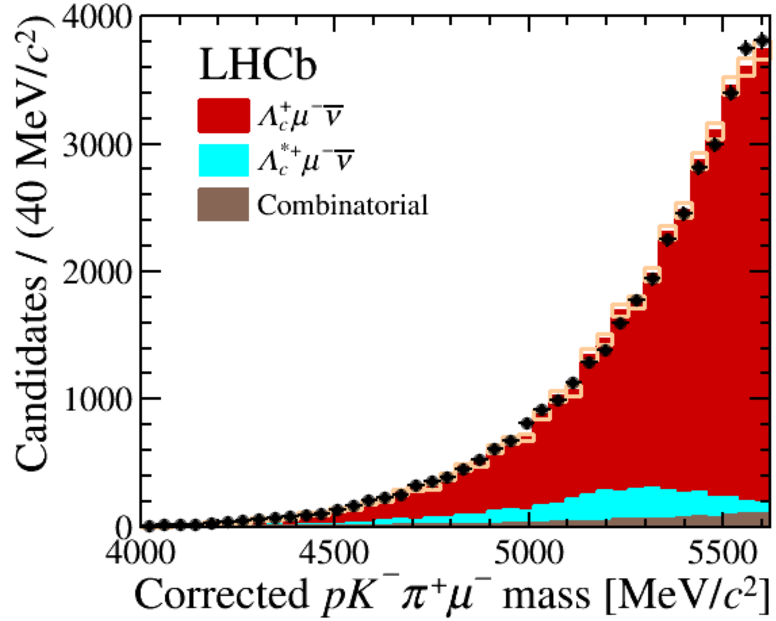
arxiv:1503.01421

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

Nature Phys. 11 (2015) 743

- 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 $\Lambda_b \to p\mu\nu / \Lambda_b \to \Lambda_c\mu\nu$

Nature Phys. 11 (2015) 743

Systematic uncertainties

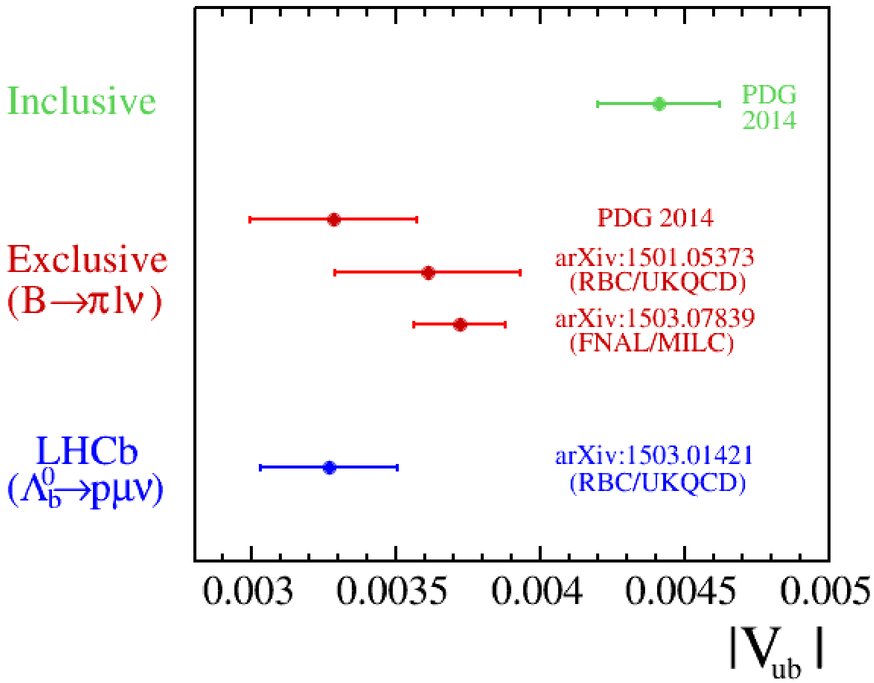
Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	${}^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
N^* shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	${}^{+7.8}_{-8.2}$

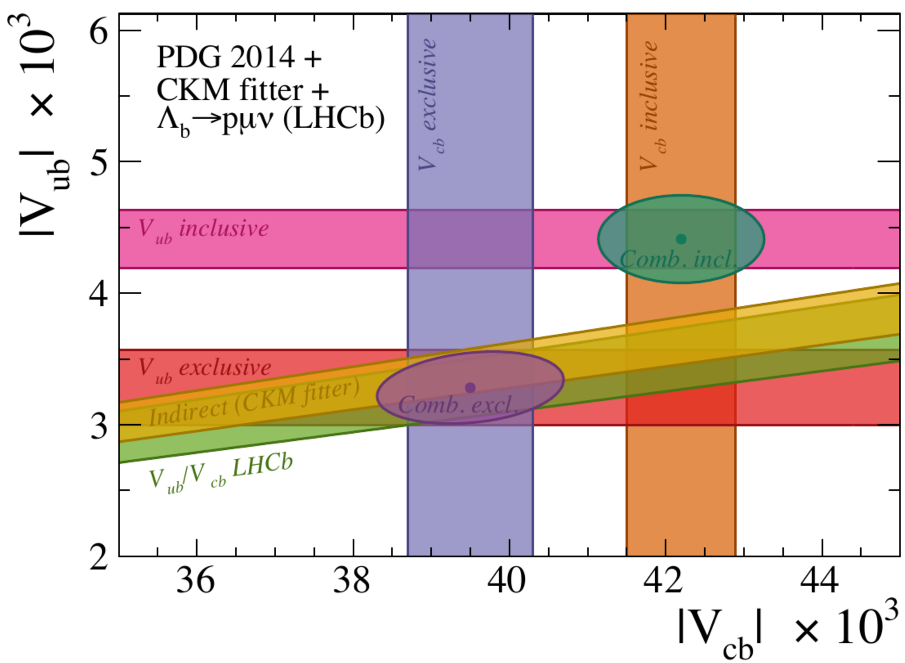
Hope for improvement from BESIII & Belle II

Other sources of uncertainty should be reducable

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

Nature Phys. 11 (2015) 743





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

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

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

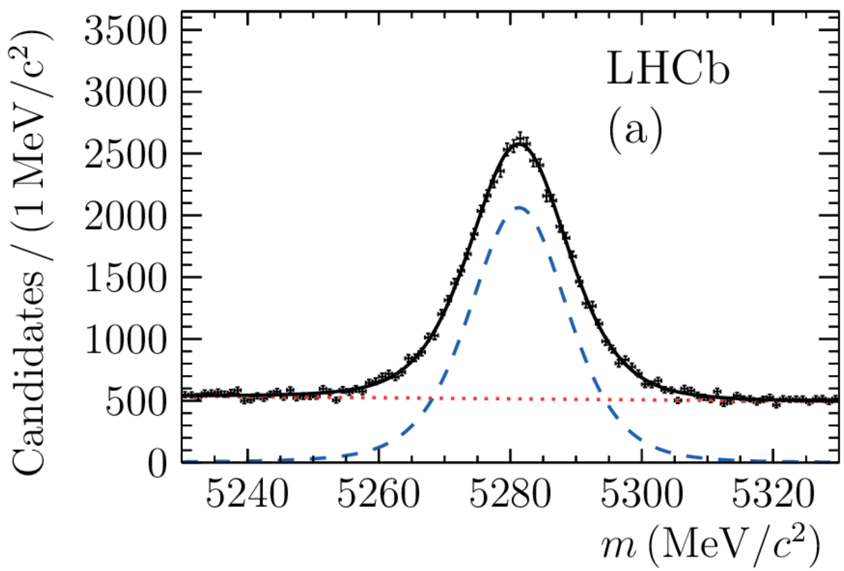
sin(2β)

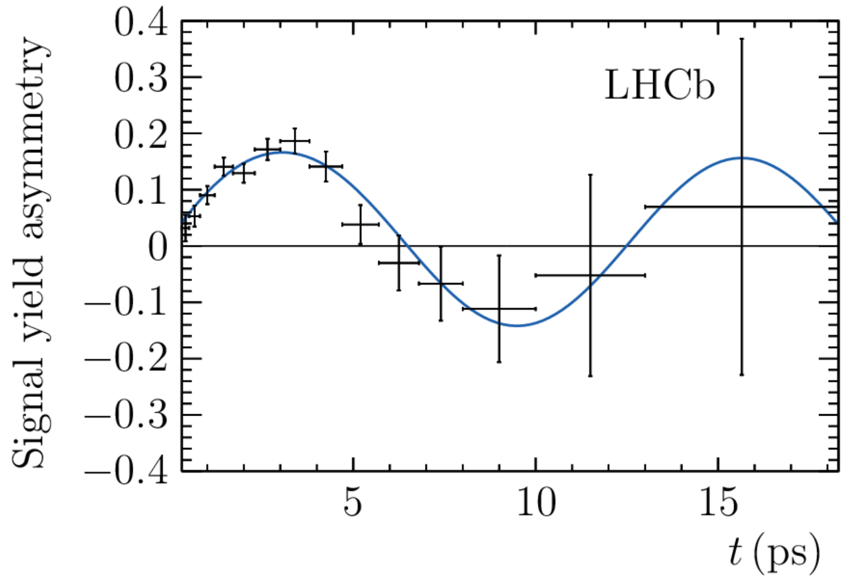
Decay-time dependent CP asymmetry in $B^0 \to J/\psi K_S$

PRL 115 (2015) 031601

→ 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

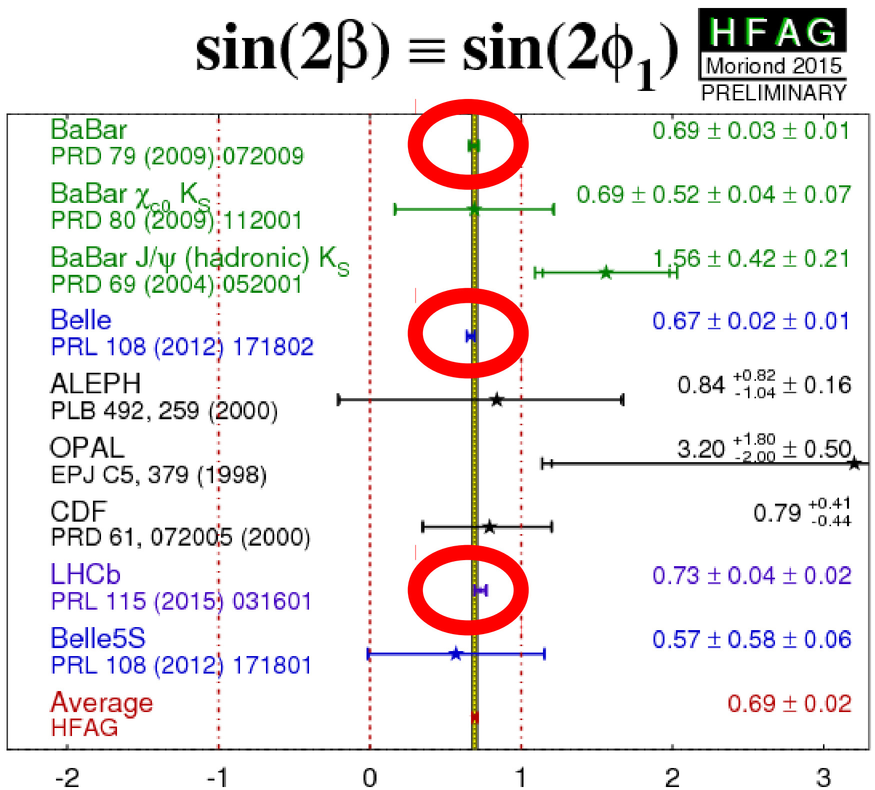
Effective tagging efficiency:
3.02 ± 0.05 %

sin(2β)

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

PRL 115 (2015) 031601

Previously measured by BaBar & Belle … now LHCb becomes competitive

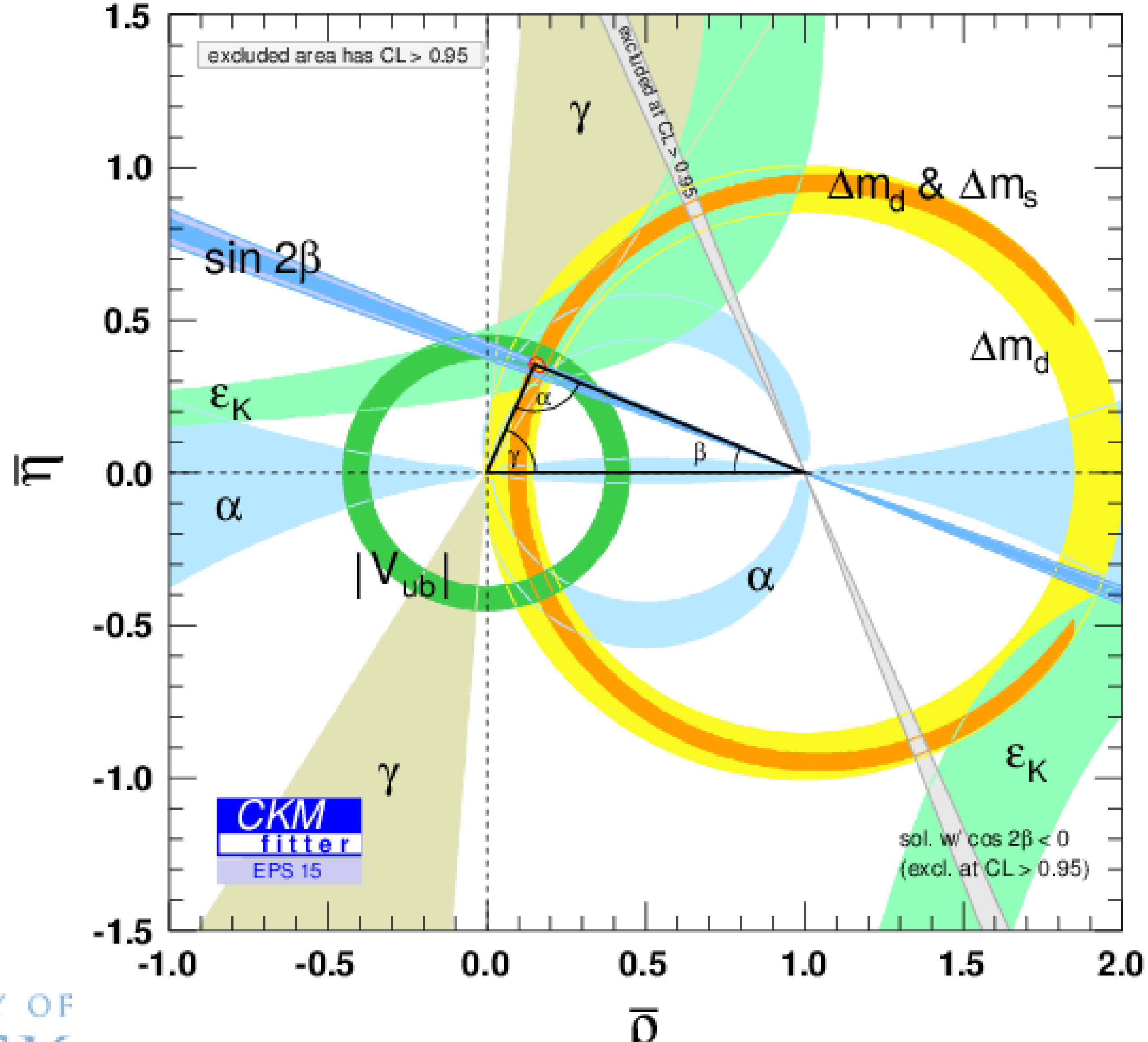


World average:

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

At this precision, penguin effects start to be a concern

Unitarity Triangle

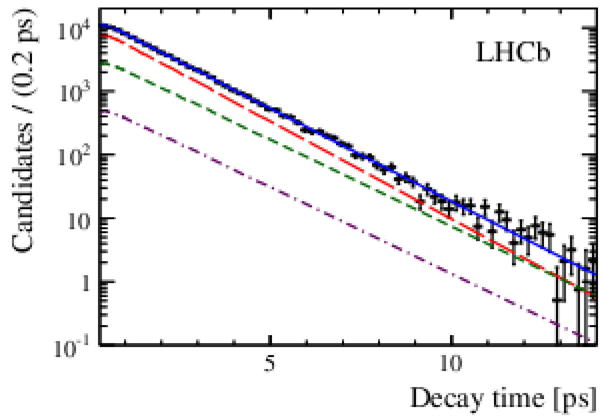


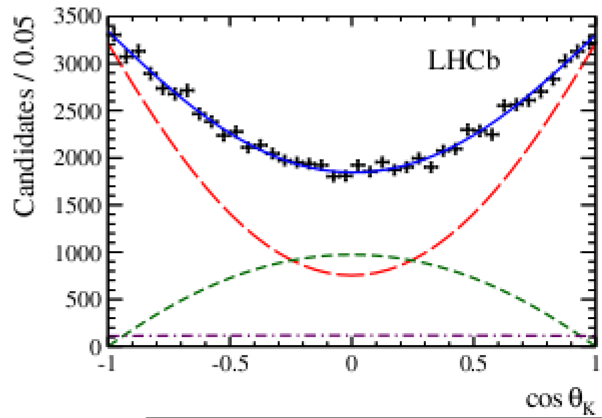
Sides and angles summary

- Precision on Δm_d and Δm_s can be improved
  - limitation on $|V_{td}/V_{ts}|$ from lattice QCD
  - $|V_{td}/V_{ts}|$ from $B^+ \to \pi^+\mu^+\mu^-/B^+ \to K^+\mu^+\mu^-$ also getting interesting (JHEP 10 (2015) 034)
- Precision on $|V_{ub}/V_{cb}|$ can also be improved
  - limitations from lattice QCD and external inputs on $B(\Lambda_c \to pK\pi)$
  - exploring new decays, in addition to $\Lambda_b \to p\mu\nu$
- Sensitivity to both β and γ is statistically limited
  - possible to do better than √N~2 for β (also for Δm_d and Δm_s) if flavour tagging can be improved
  - no new results on γ today – expect precision of ~7° when Run I analyses are completed

Other BSM CP violation searches

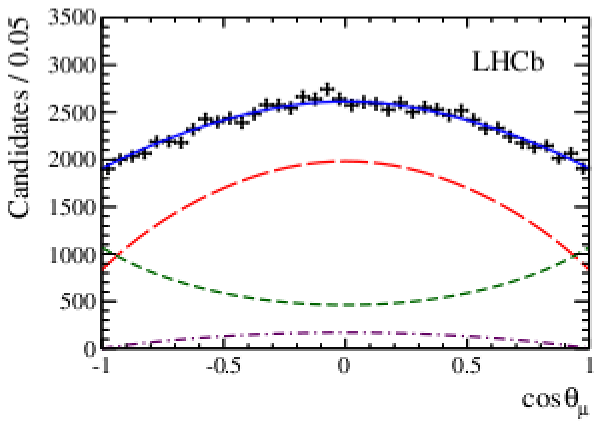
φ_s from $B_s \to J/\psi\varphi$ (etc.)

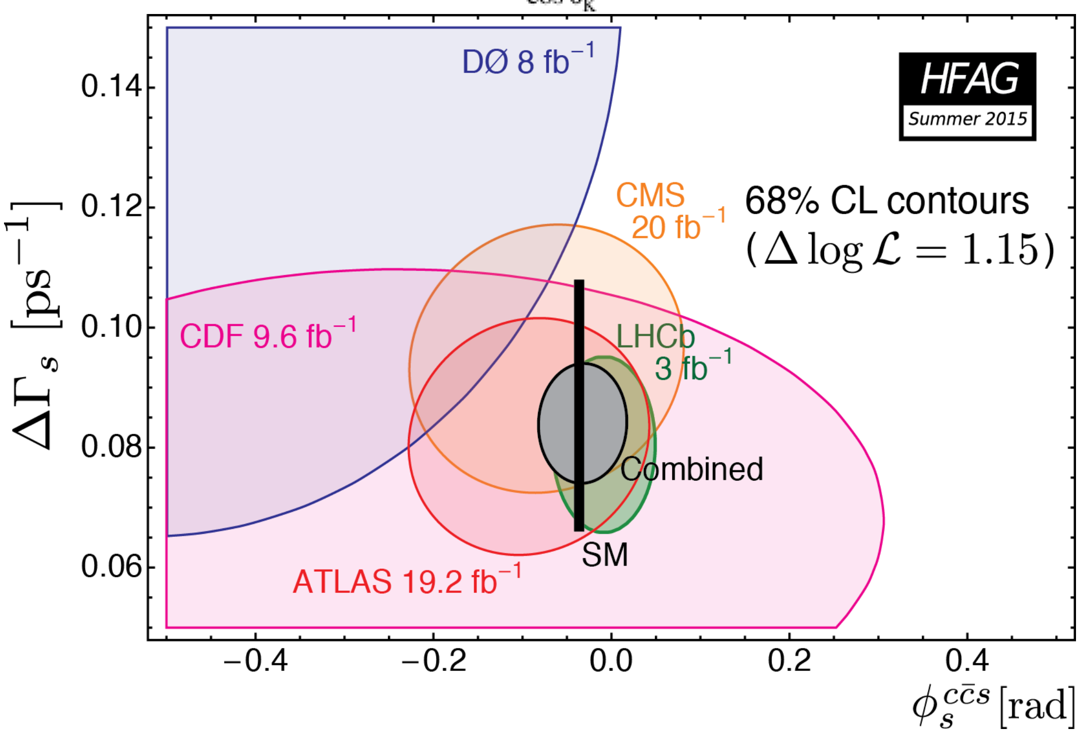




Latest LHCb results
PRL 114 (2015) 041801

$\varphi_s = -0.010 \pm 0.039$ rad





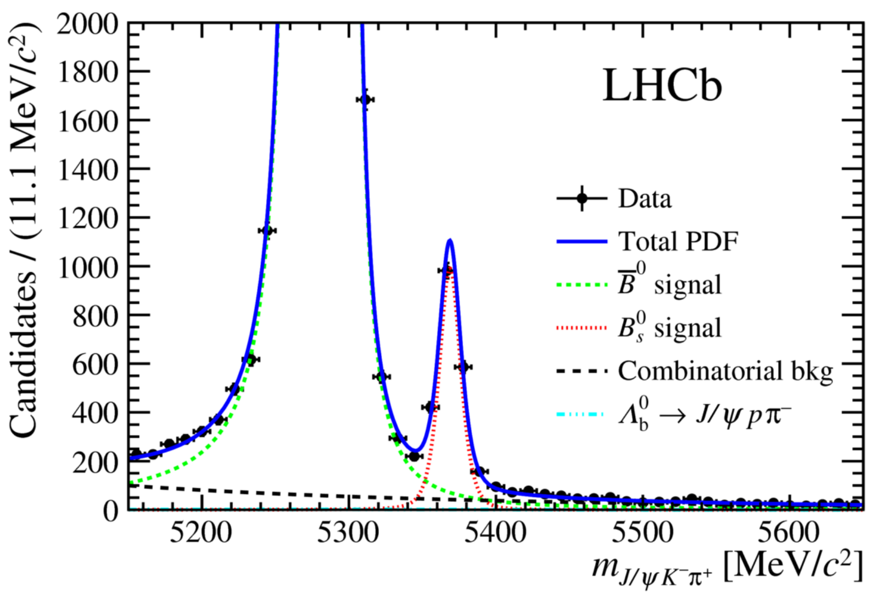
At this precision, penguin effects start to be a concern

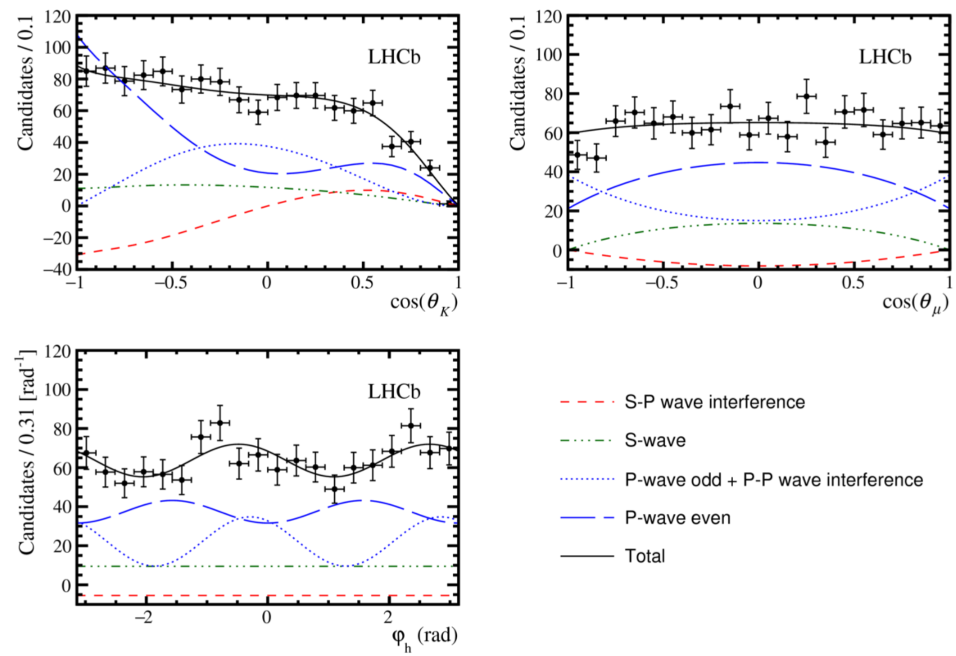
Control of possible penguin pollution

arXiv:1509.00400

Two main approaches: $B^0 \to J/\psi\rho^0$ (PL B742 (2015) 38) & $B_s \to J/\psi K^{*0}$ (new)

both relying on flavour symmetries





(Most sensitivity from $B^0 \to J/\psi\rho^0$)

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\mathrm{stat})\ {}^{+0.004}_{-0.009}\,(\mathrm{syst})\,\mathrm{rad}\,,$$

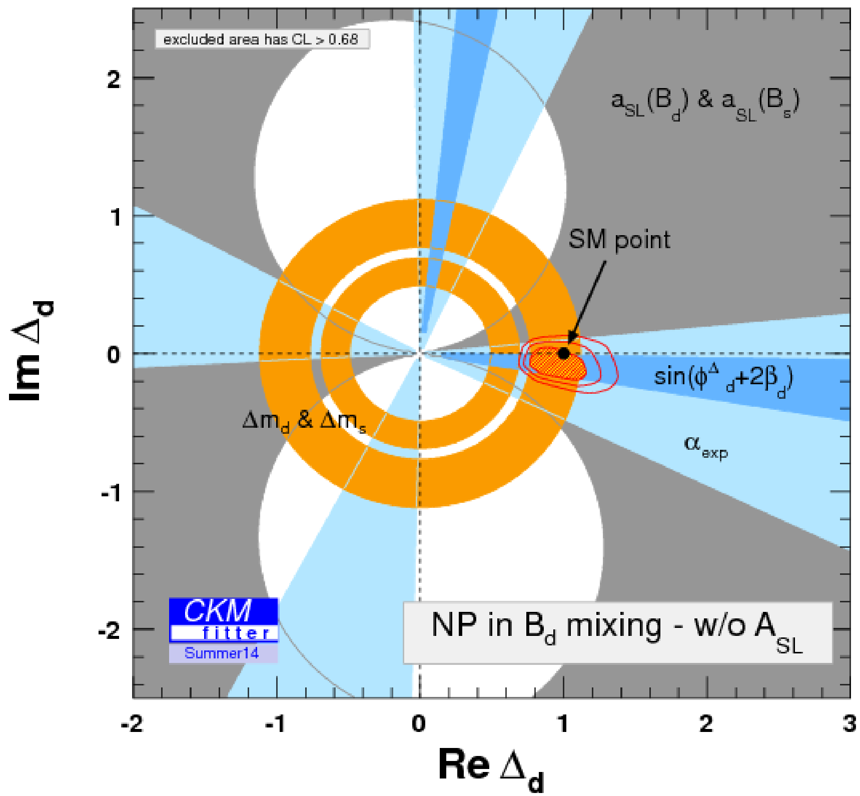
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}\,,$$

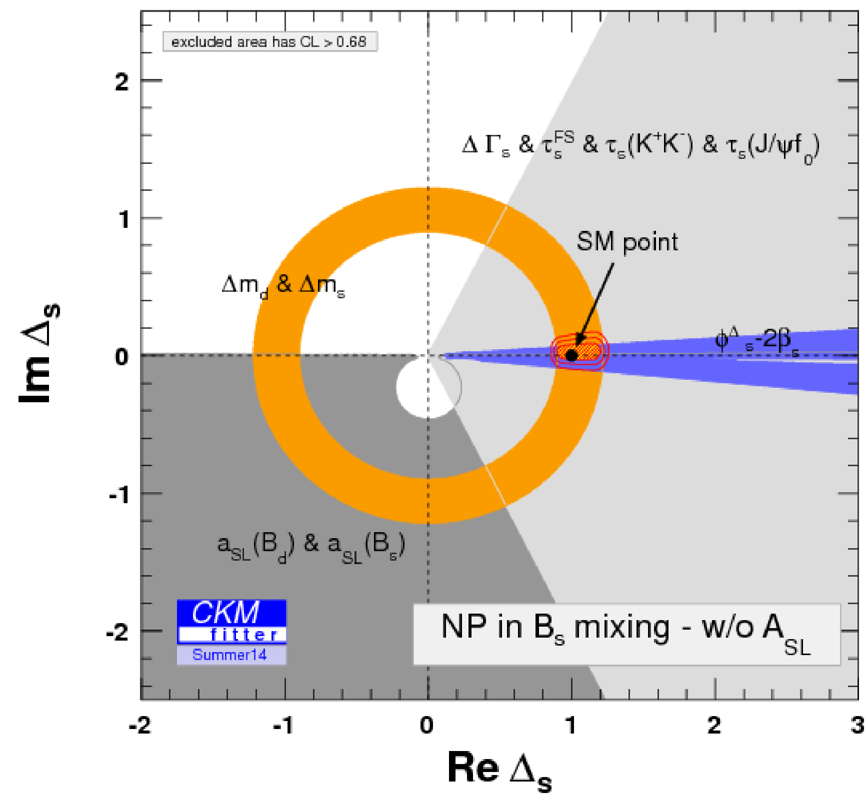
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\mathrm{stat}) \pm 0.008\,(\mathrm{syst})\,\mathrm{rad}\,.$$

Limits on BSM contributions to ΔB=2

Define $M_{12}^{q} = M_{12}^{SM,q}\,\Delta_q$ and obtain constraints on (Re Δ_q, Im Δ_q)

(here not including anomalous D0 dimuon asymmetry result – no new LHCb results on a_{SL} but work in progress)

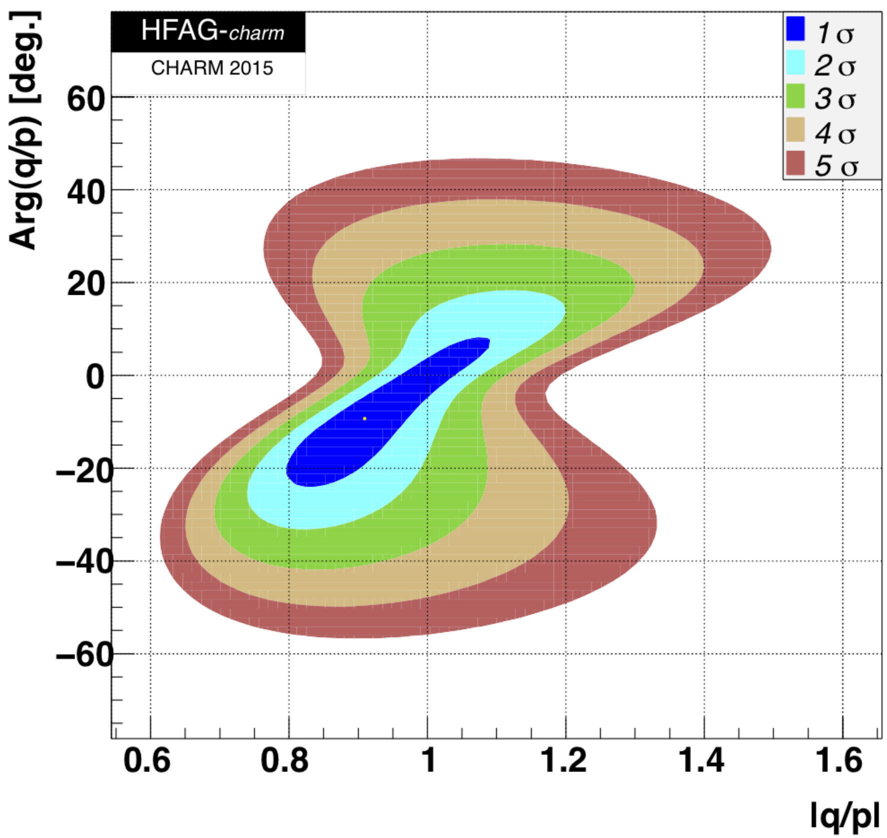


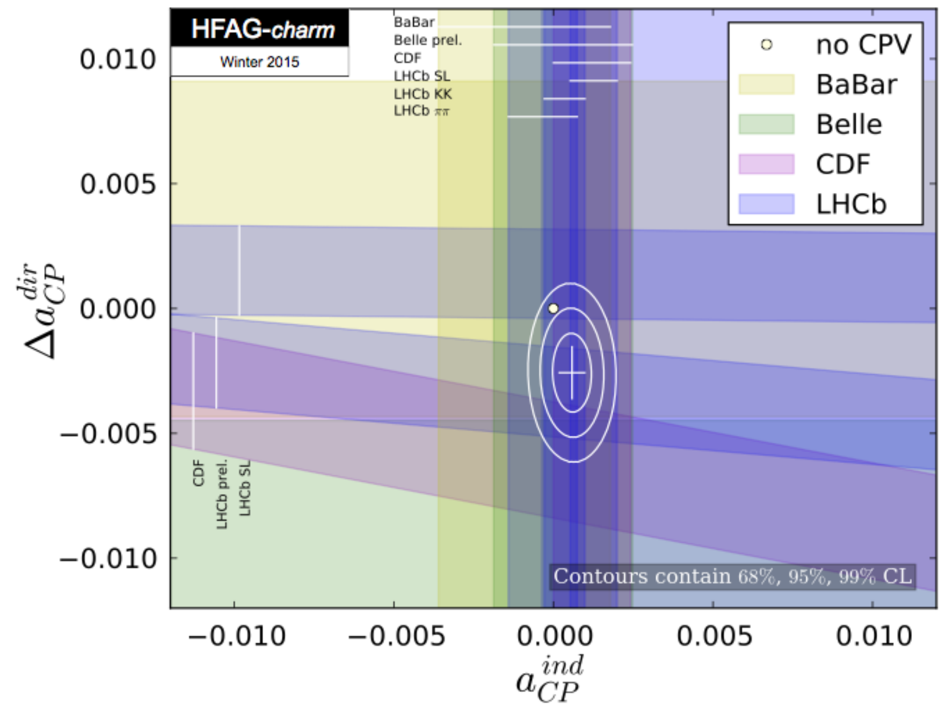


Bottom line: will significantly shrink these contours with Run II data & probe BSM contributions @ few % of SM

Charm CP violation

Main focus on searches of CP violation associated with mixing





Few new results, but important proof-of-principle for measurements with $D^0 \rightarrow K_S \pi^+ \pi^-$ decays (arXiv:1510.01664)

Other BSM CP violation summary

- No immediate limitation to reducing uncertainty on φ_s
  - Penguin pollution has been shown to be <0.01 rad
- Charm analyses will benefit from huge increases in statistics (trigger improvements)
  - Challenge is to control systematics and complete analyses in reasonable time
  - Good reasons to be optimistic, however
- Also many other possibilities not discussed today
  - CP violation effects in charmless B decays
  - CP violation in rare decays

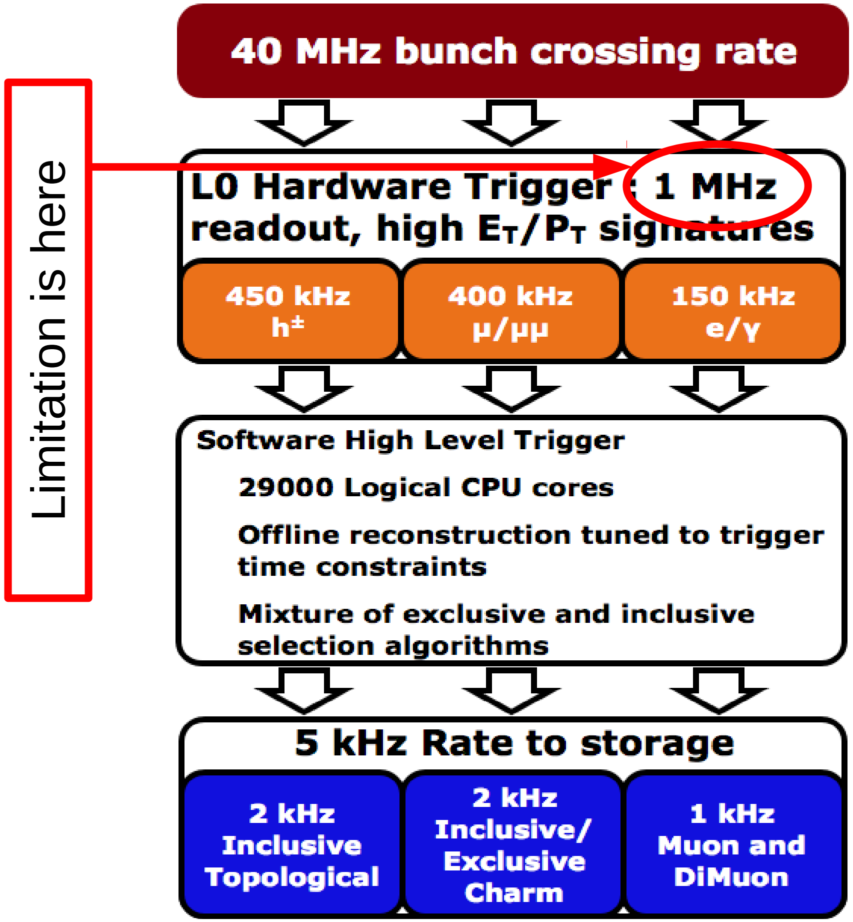
- LHCb surpassed Run I performance expectations
  - huge physics output, in “core” flavour observables but also much more
  - modes with neutrinos, previously thought to be impossible
  - … and don't forget pentaquarks (and other topics not covered today)
  - several potential hints of BSM effects to be explored further
- Important improvements in the trigger for Run II
- Data taking going well so far
  - first physics papers on Run II data already submitted
  - much to look forward to!
- Beyond Run II will move to LHCb upgrade (back up)


BACK UP!

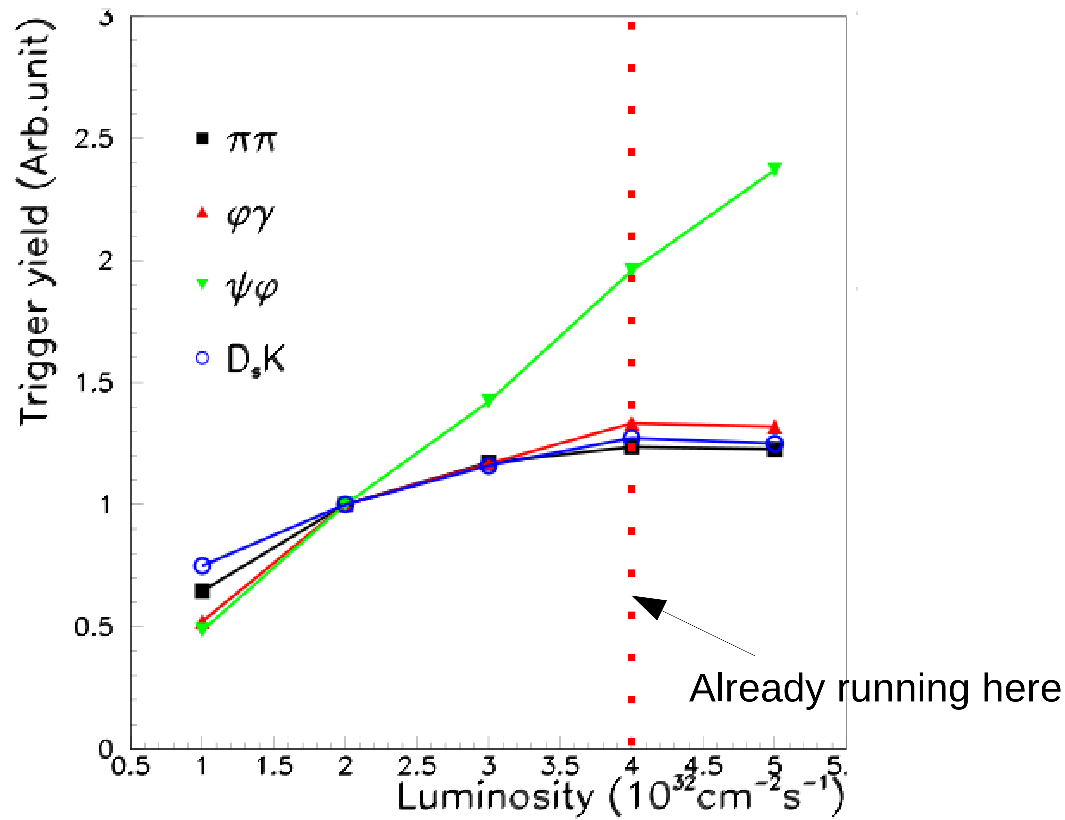
Beyond Run II – the LHCb Upgrade

- 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

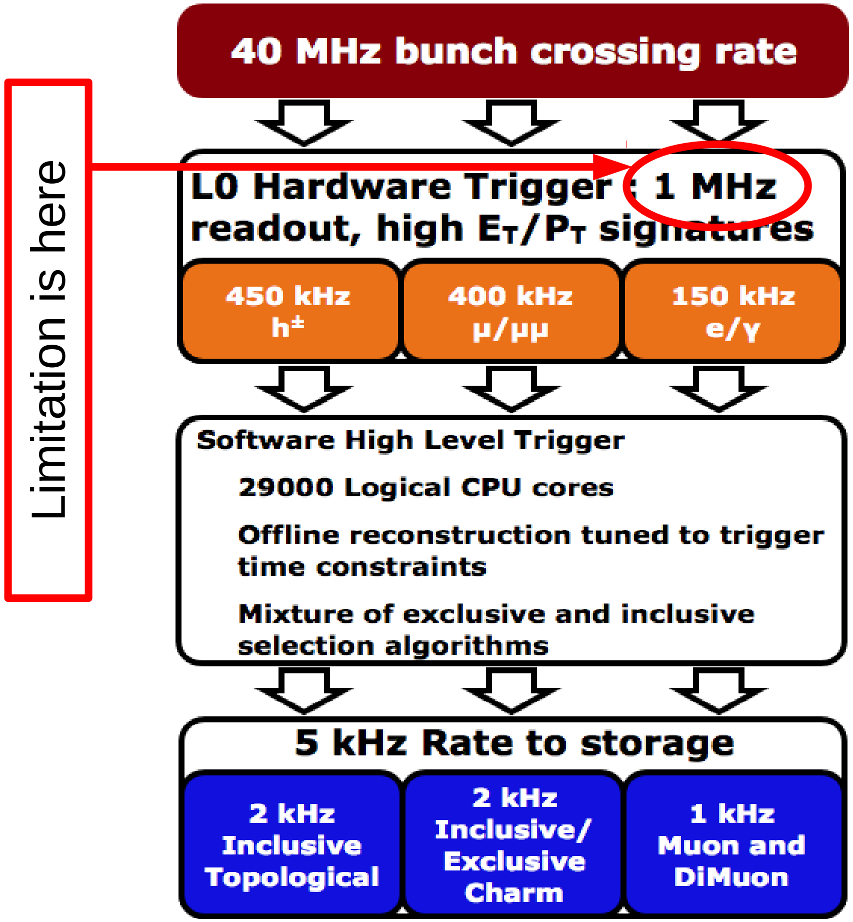


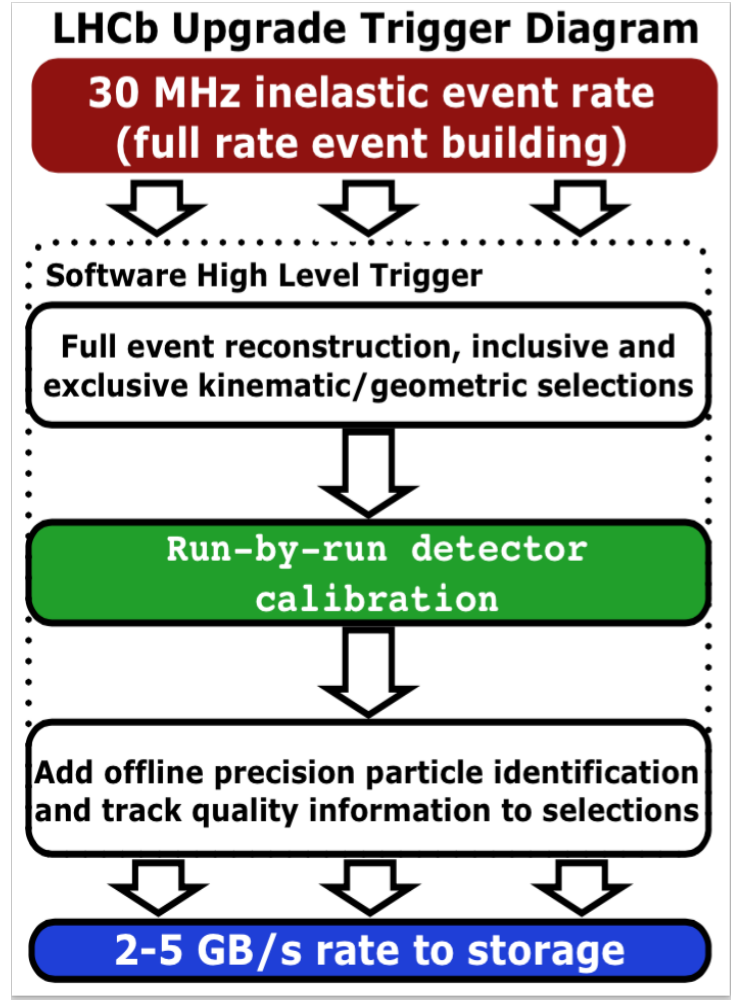
higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency



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

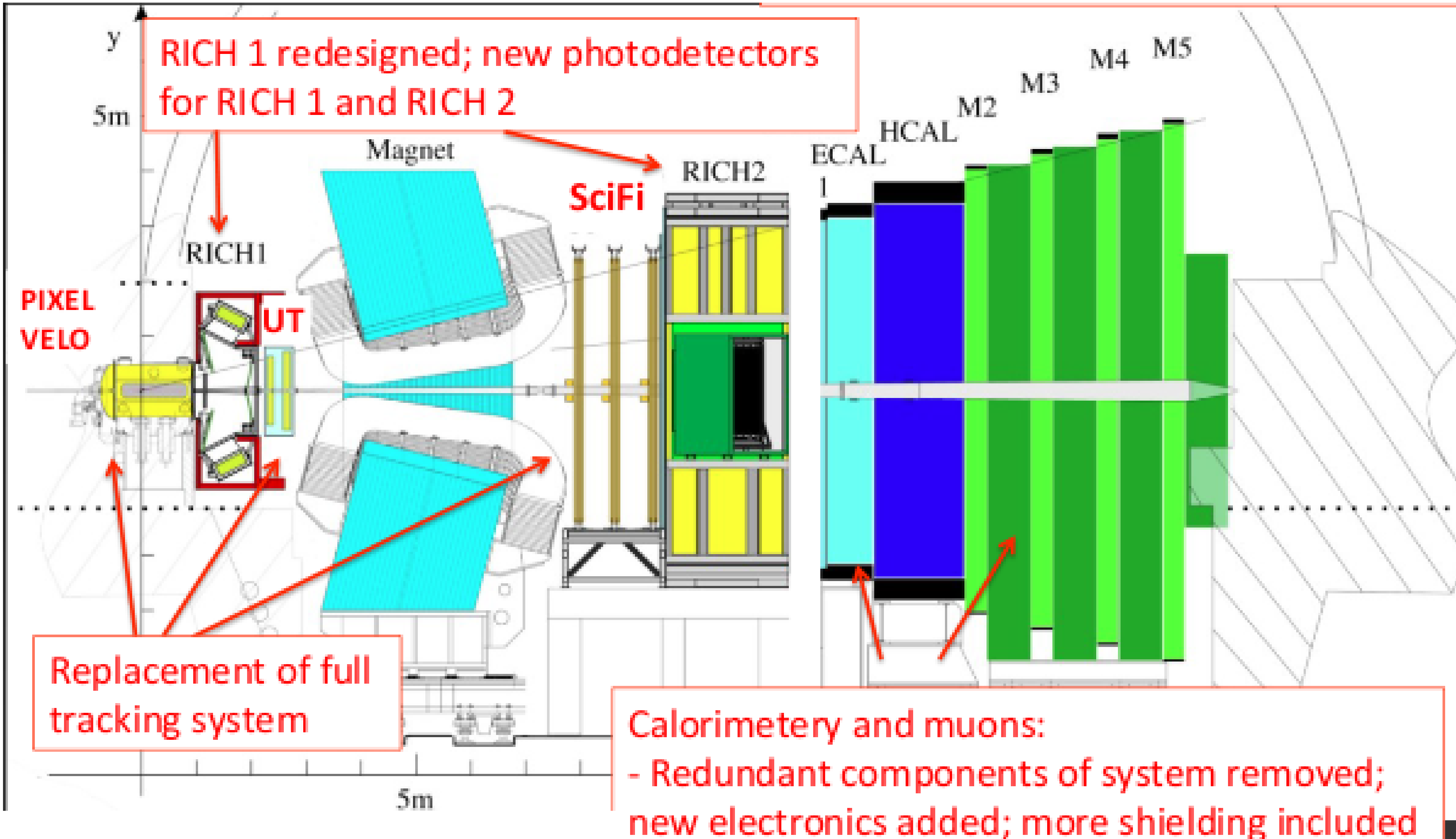
LHC upgrade and the all important trigger





- 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 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 $5\,\text{fb}^{-1}$ recorded during Run 2) and for the LHCb Upgrade ($50\,\text{fb}^{-1}$). 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	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	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%**	$\sim 10\%$
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%**	$\sim 5\,\%$
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%
$q_0^2\ A_{\rm FB}(K^{*0}\mu^+\mu^-)$	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}	...	$1.3–2.5\times10^{-5}$
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!