Higgs Searches, Electroweak Measurements, and the B anomalies

W. Barter
on behalf of the LHCb experiment

Higgs Couplings 2019

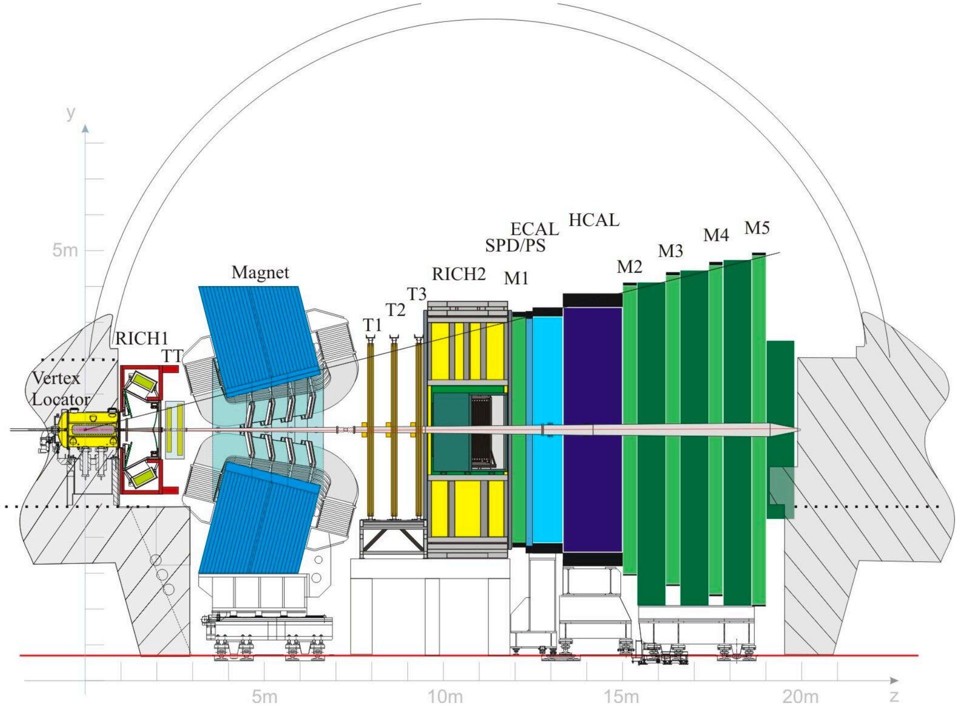
Imperial College London

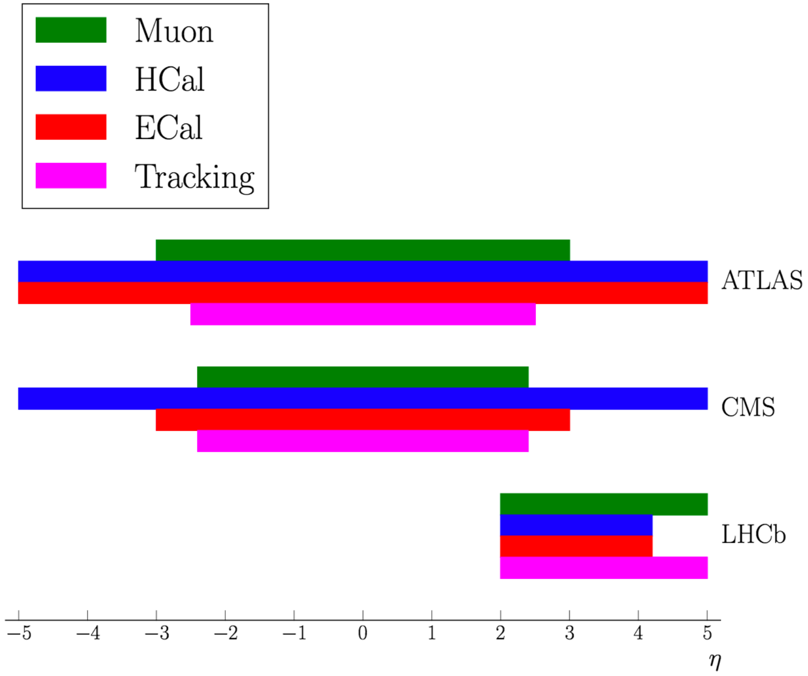
Outline

- LHCb experiment
- Higgs searches
- EW measurements
- Flavour Physics and indirect sensitivity to Higgs Physics – the B anomalies
- Conclusion

LHCb

- Single arm spectrometer, fully instrumented in the forward region.

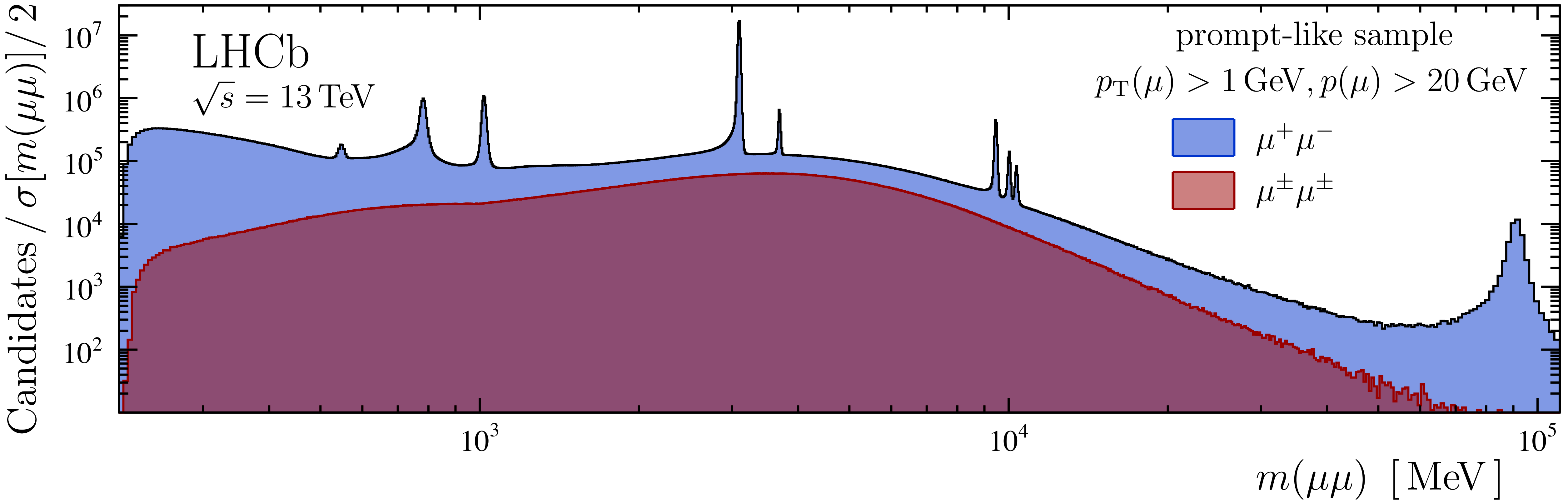




- Designed for flavour physics –but also able to act as general purpose forward detector.
- Overlap with ATLAS/CMS precision coverage in 2.0< η<2.5; unique precision coverage in 2.5<η<5.

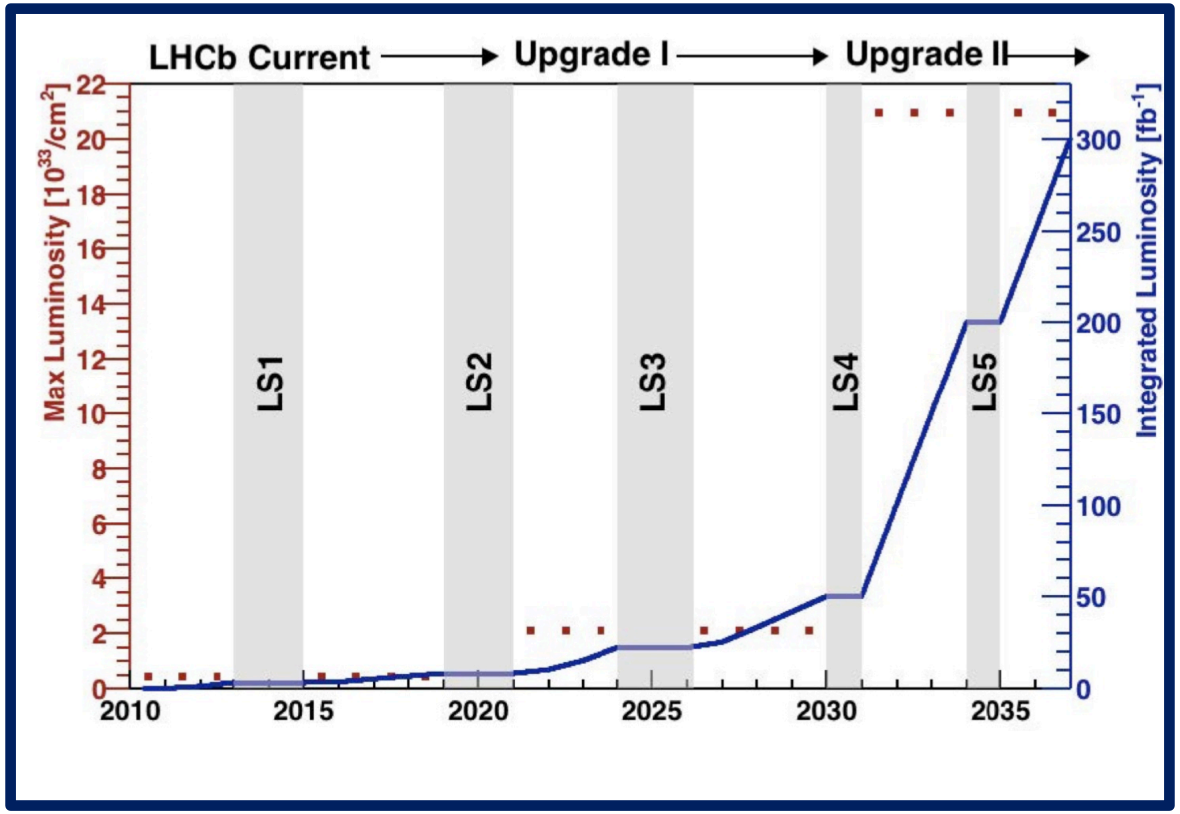
PRL 120 (2018) 061801

LHCb



LHCb - datasets

- LHCb runs at a reduced luminosity compared to ATLAS and CMS.
  - Provides very clean environment with reduced pileup.
- Integrated Luminosity recorded:
  - LHC Run 1: 3/fb @ 7, 8 TeV.
  - LHC Run 2: 6/fb @ 13 TeV.
- Proposal to record at least 300/fb of data at LHCb as part of the HL-LHC.



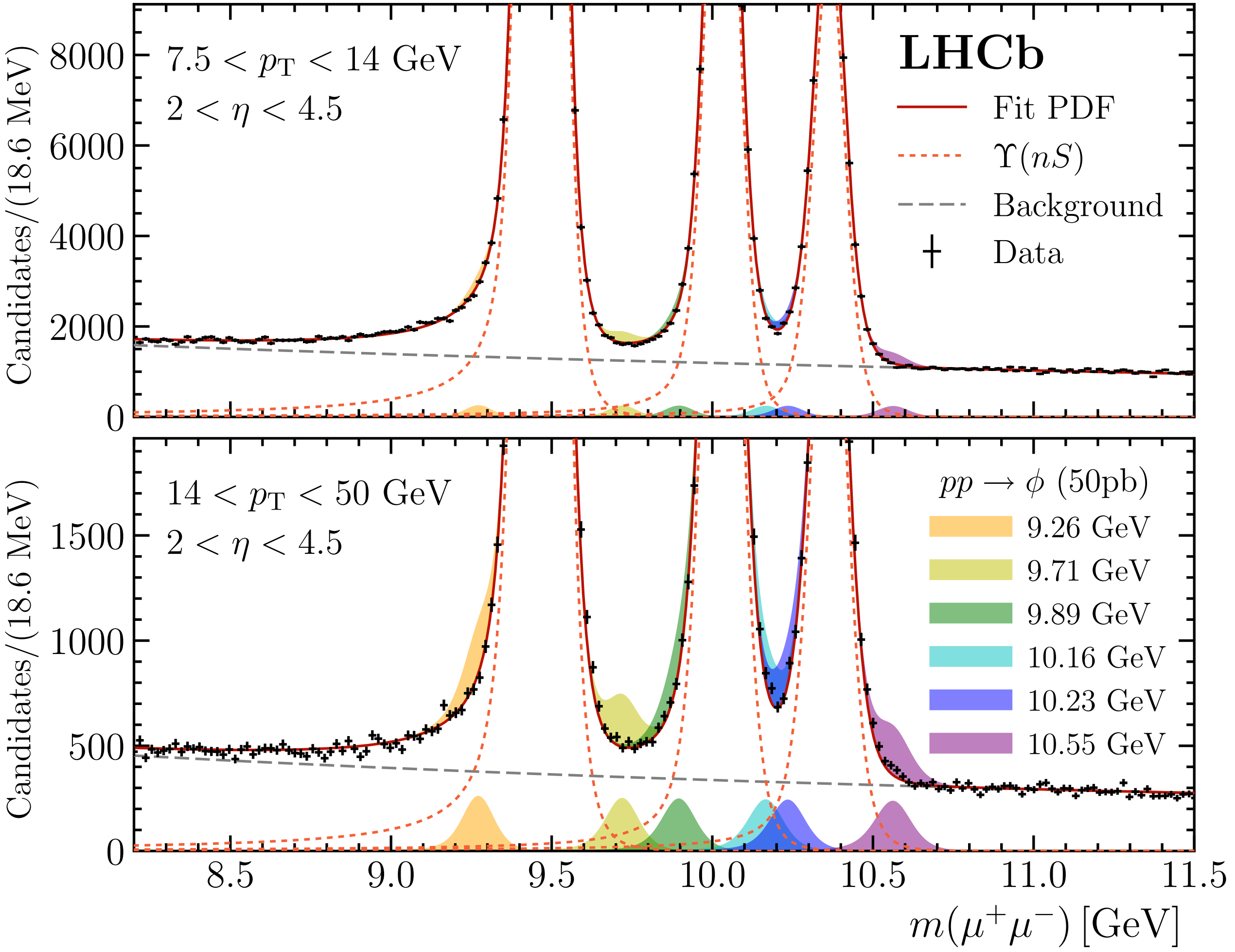
LHCb – what can we offer?

- LHCb offers direct searches:
    - Clear that with lower luminosity and small forward acceptance we are not sensitive to SM Higgs production.
    - But we do offer sensitivity to NP – particularly in relatively low mass NP scenarios where the acceptance in direct searches is larger. (eg Higgs boson decays to new Long-Lived Particle final states)
- Important measurements of the EW sector
    - Will be of increasing relevance for future iterations of the EW fit
- Flavour Physics Measurements as Indirect Searches
    - Rare Decays of B mesons place crucial constraints on the behaviour of BSM theories

Direct Searches

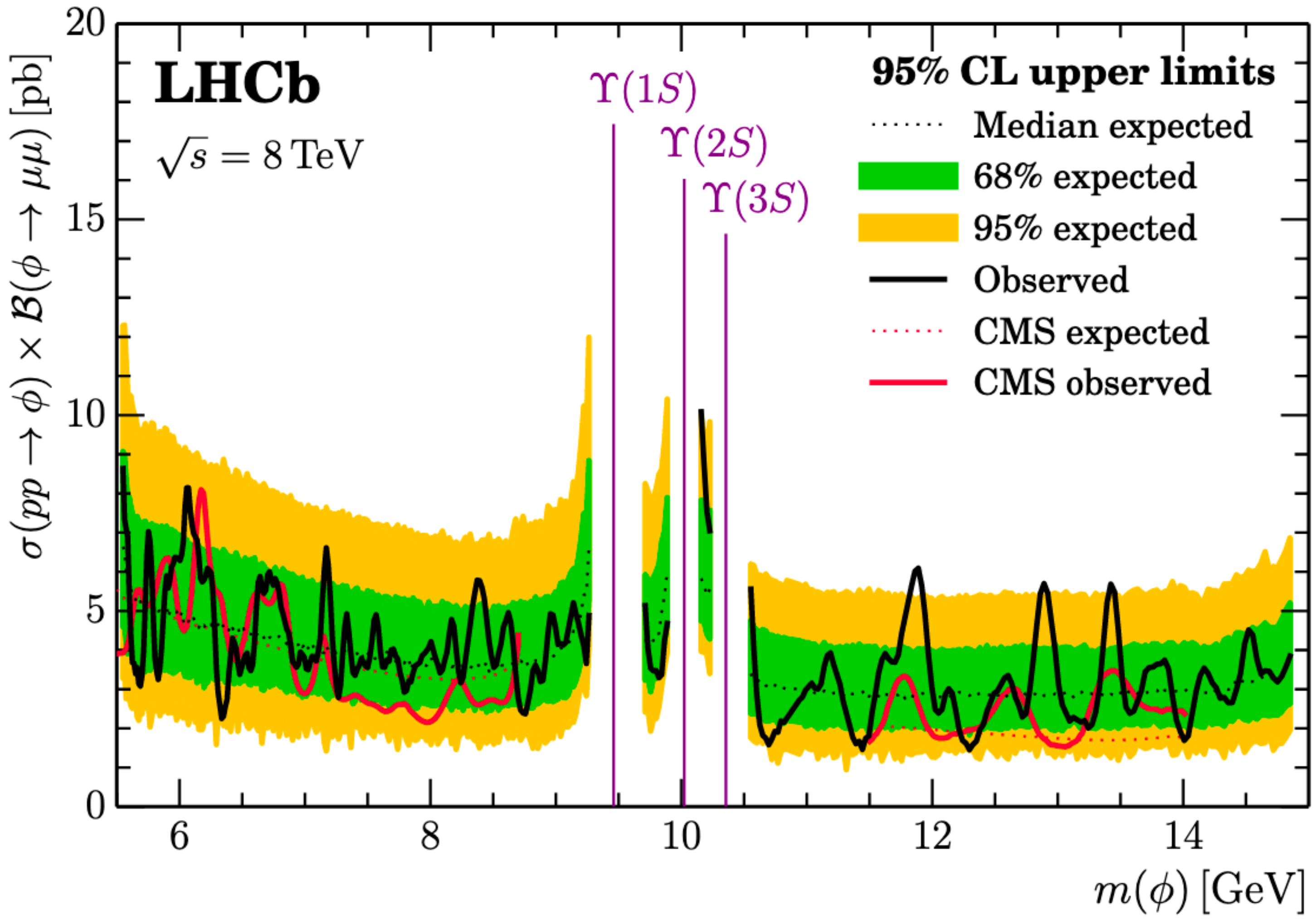
Low Mass Spin-0 boson Searches

- Search for a low mass scalar boson decaying to a dimuon final state.
- Very clean signature!
- LHCb offers precision tracking and mass resolution - can search close to the $b\bar{b}$ resonances.
- Signal model: Gaussian-smeared Hypatia function
- Background: Exponential multiplied by Legendre polynomials



Low Mass Spin-0 boson Searches

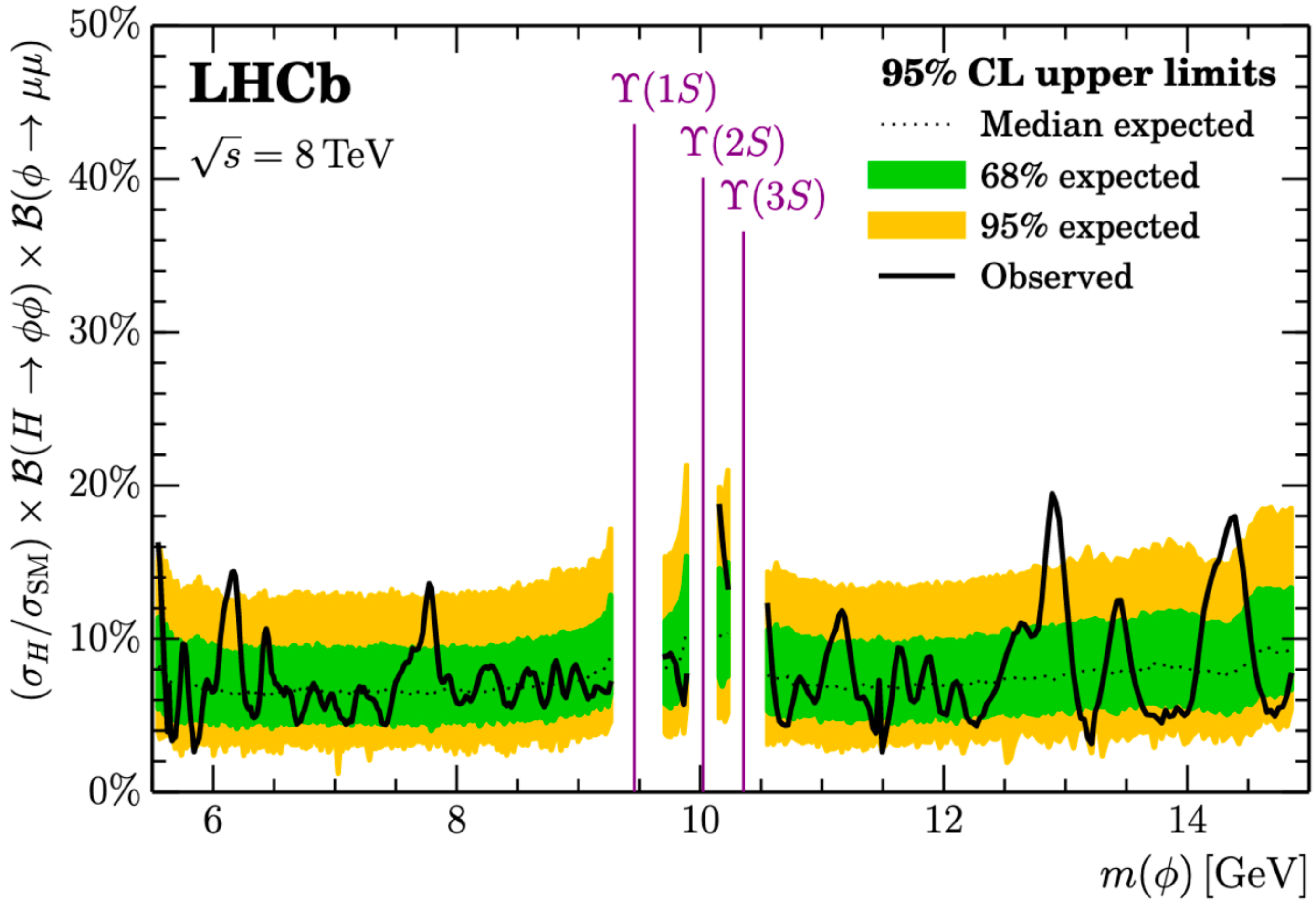
- No signal observed
- Limits set on $\sigma \times$ BF – assume direct production based on MSSM pseudoscalar production.



Low Mass Spin-0 boson Searches

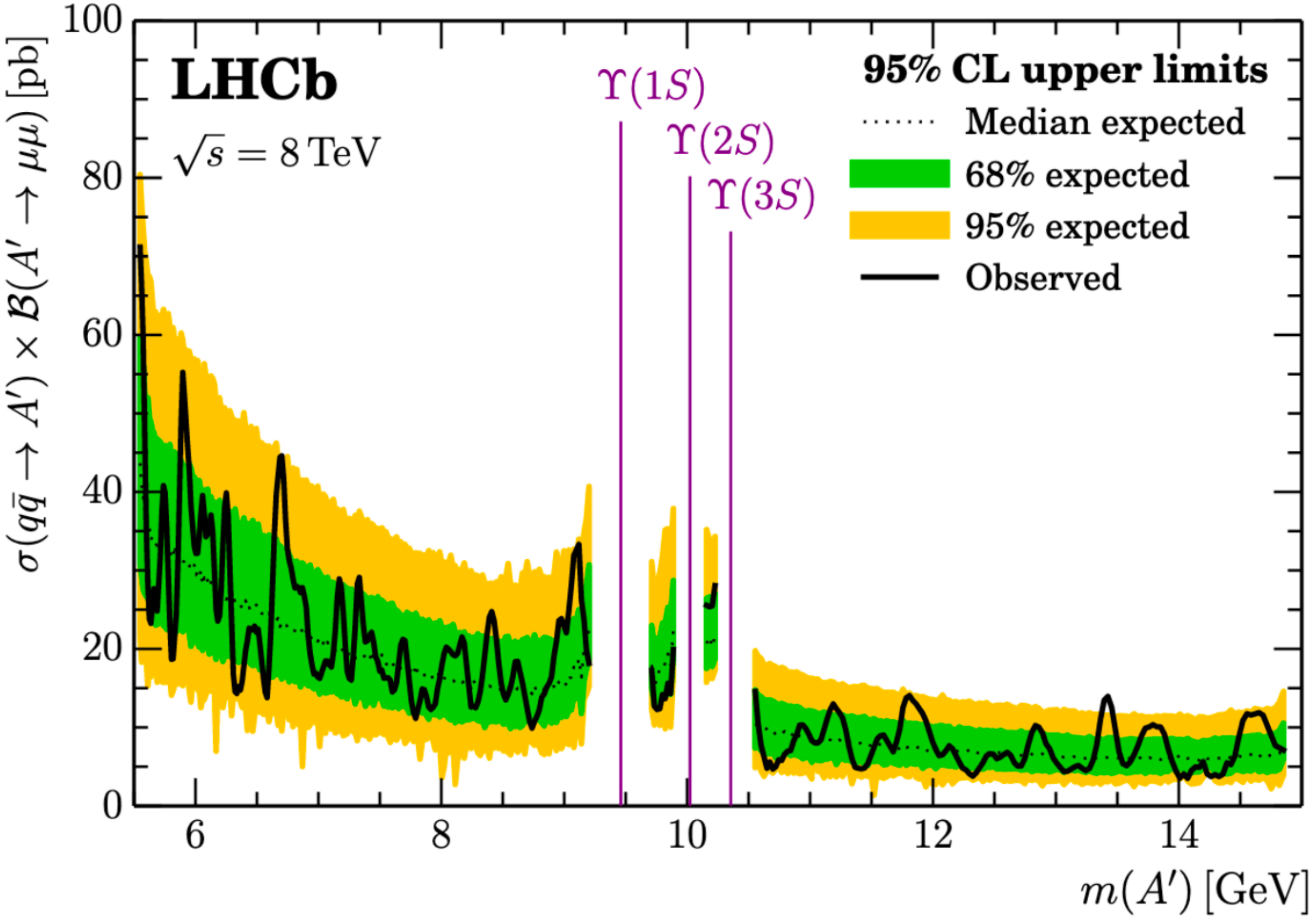
- Can recast results for different models

- Here limits based on assuming ϕ boson is produced in the decay of a Higgs boson.



Low Mass Spin-1 boson Searches

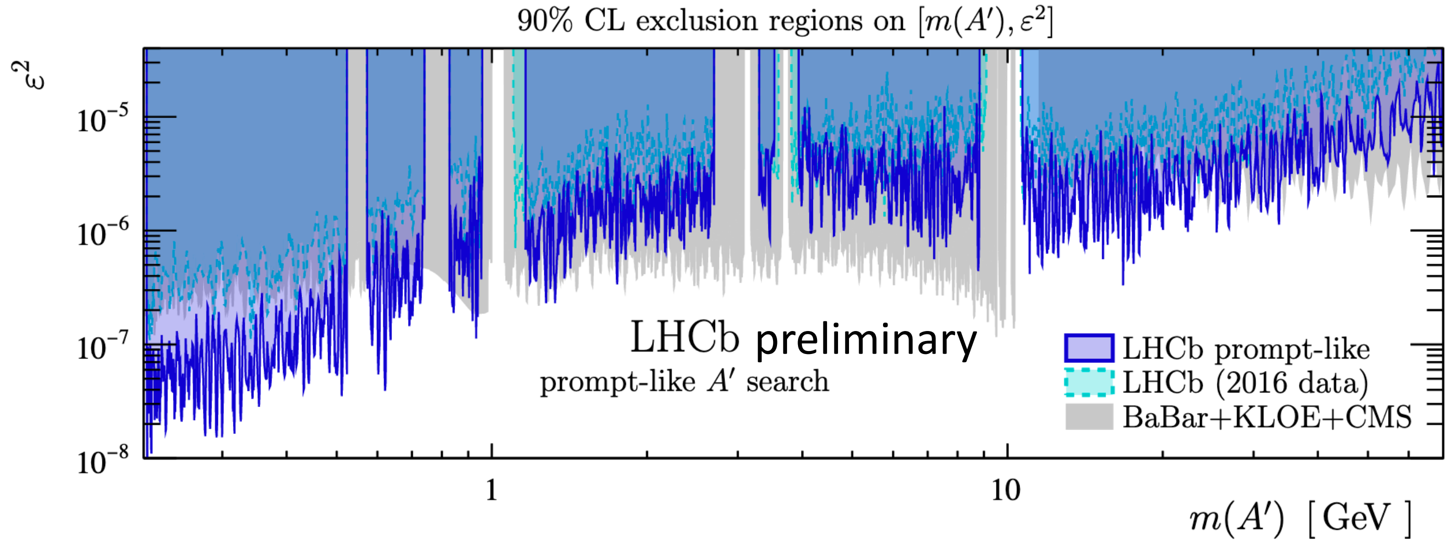
- Can recast results for different models
- Here limits based on assuming direct production of a dark photon.

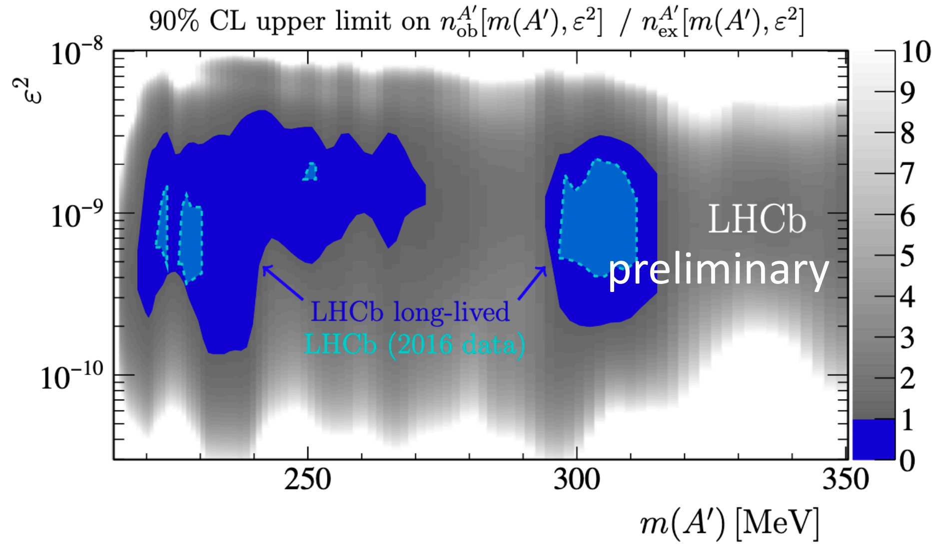


Low Mass Spin-1 boson Searches

NEW

- New results also available in search for dark photon using Full Run 2 dataset.
  - Limits set on kinetic mixing parameter between dark photon and photon.
  - Prompt and displaced decays considered.
- World Best Limits set for prompt production in range $10.6 < m < 30$ GeV.

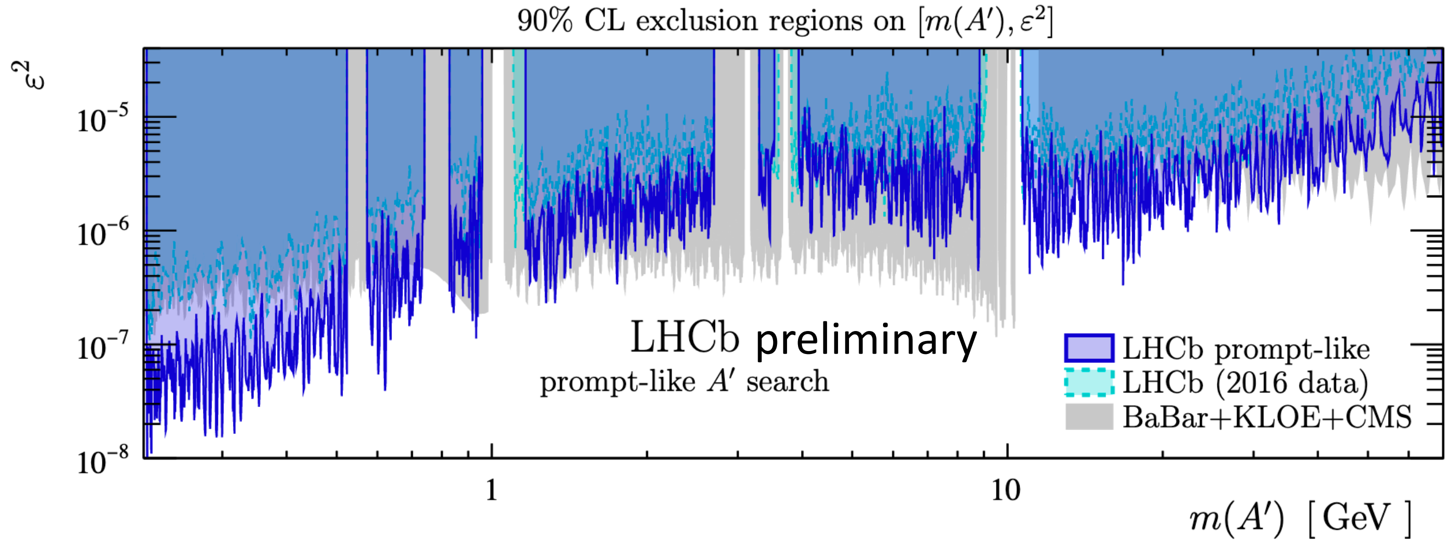


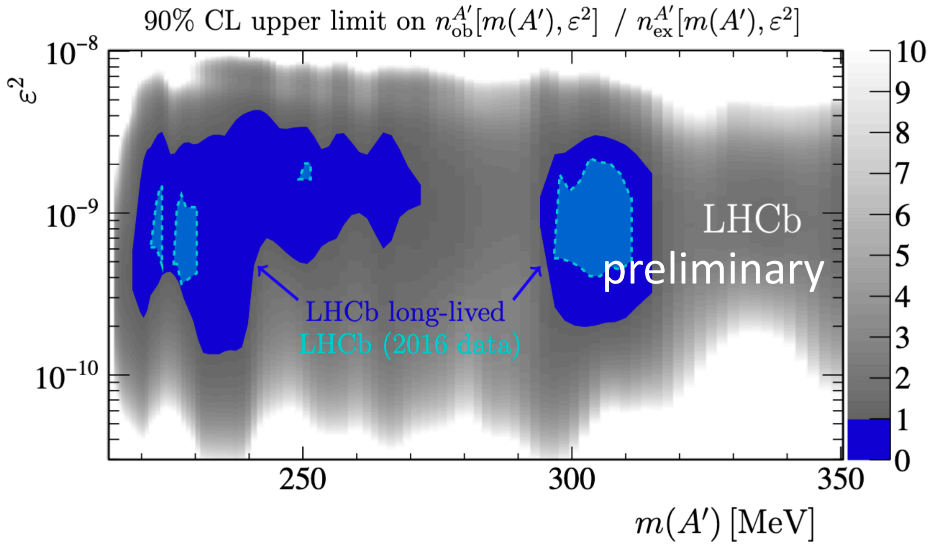


NEW

Low Mass Spin-1 boson Searches

Forthcoming paper (currently in preparation) will also recast this search into limits on direct production of a Spin-0 boson.



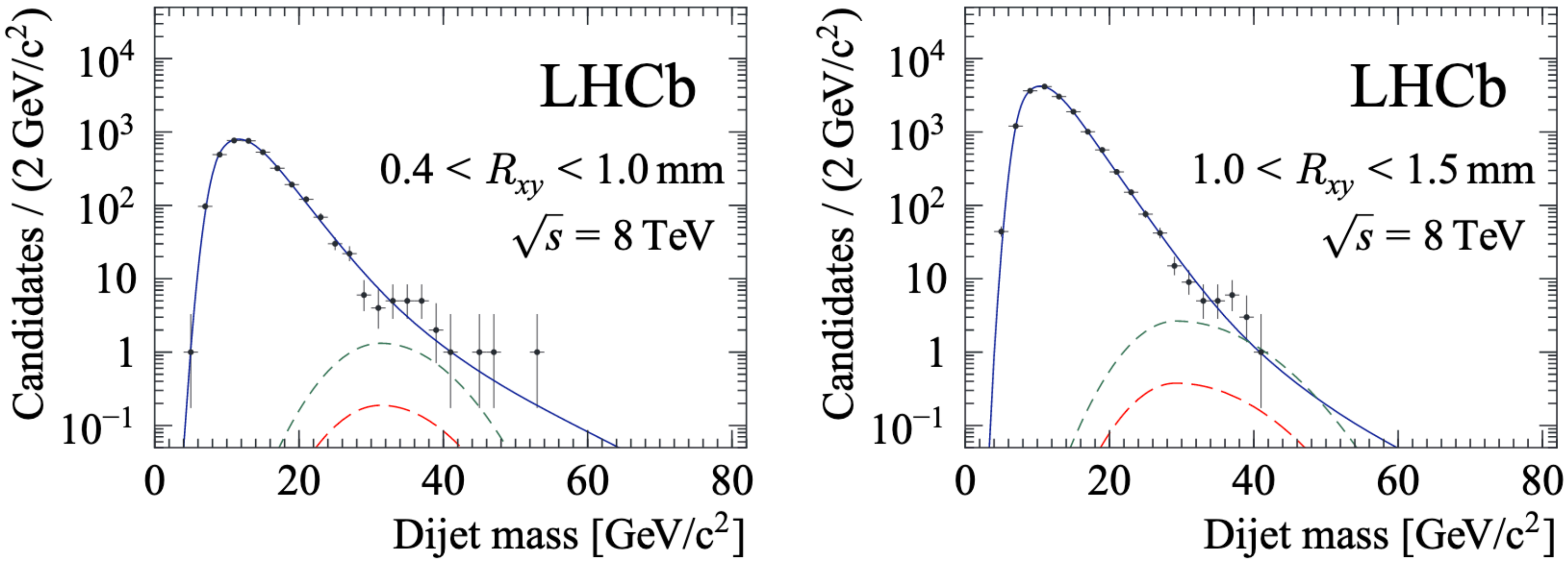


Long-Lived Particle Production

- LHCb has also searched for long lived particle production.
  - Again considered in context of a Higgs boson decay to a pair of (invisible) hidden valley pions – with each then decaying to a (displaced) $q\bar{q}$ pair.
- Signature: displaced di-jet vertex. Only search for one such vertex – increases acceptance of events within LHCb detector.
  - LHCb offers ability to access low lifetimes and small hidden valley pion masses – low pileup and vertex locator performance enables efficient separation of primary and secondary interactions.
- Selection efficiency for signal typically in range 0.1 – 1%

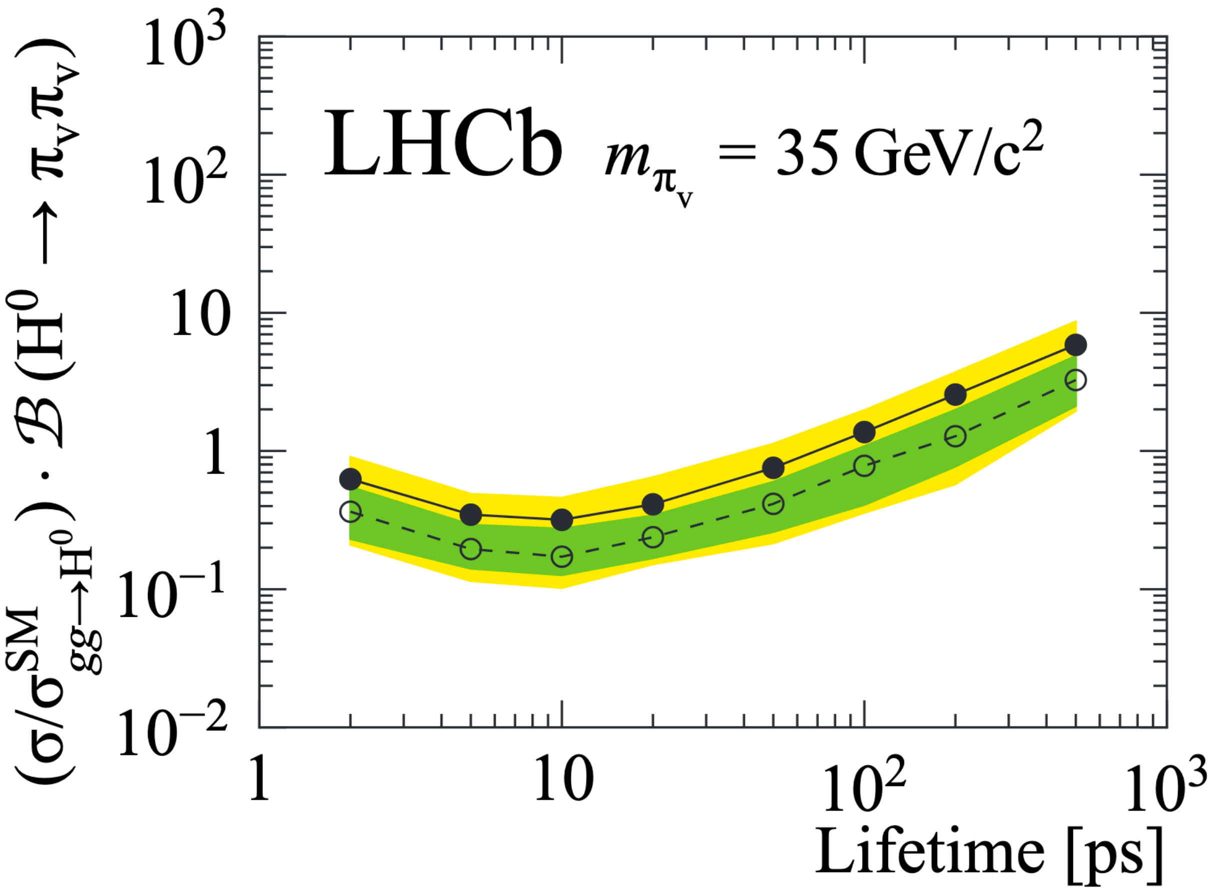
Long-Lived Particle Production

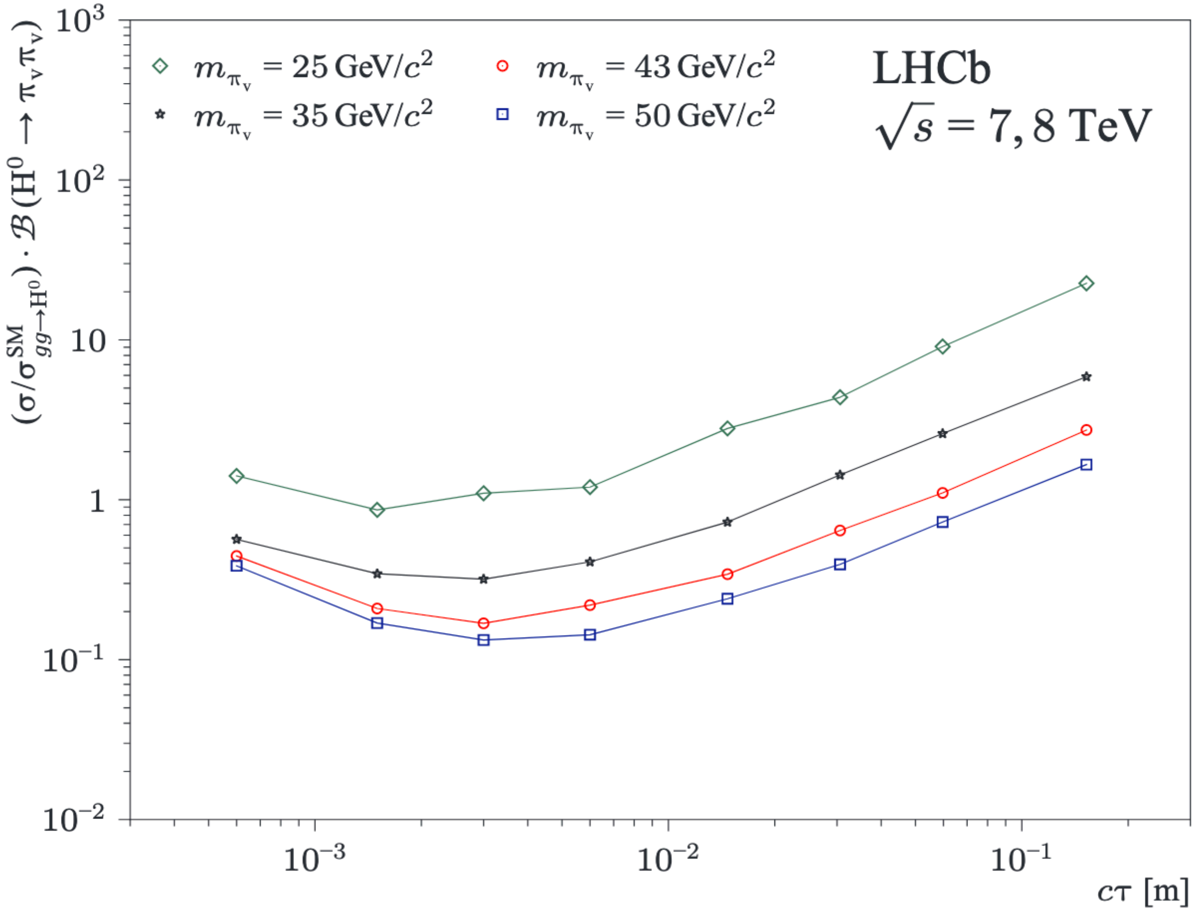
- Signal Model: Gaussian, with parameters set using simulation
- Background Model:
  - Displaced HF decays: Bifurcated Gaussian convolved with an exponential
  - Additional (smaller) component to describe prompt pollution from SM dijet.



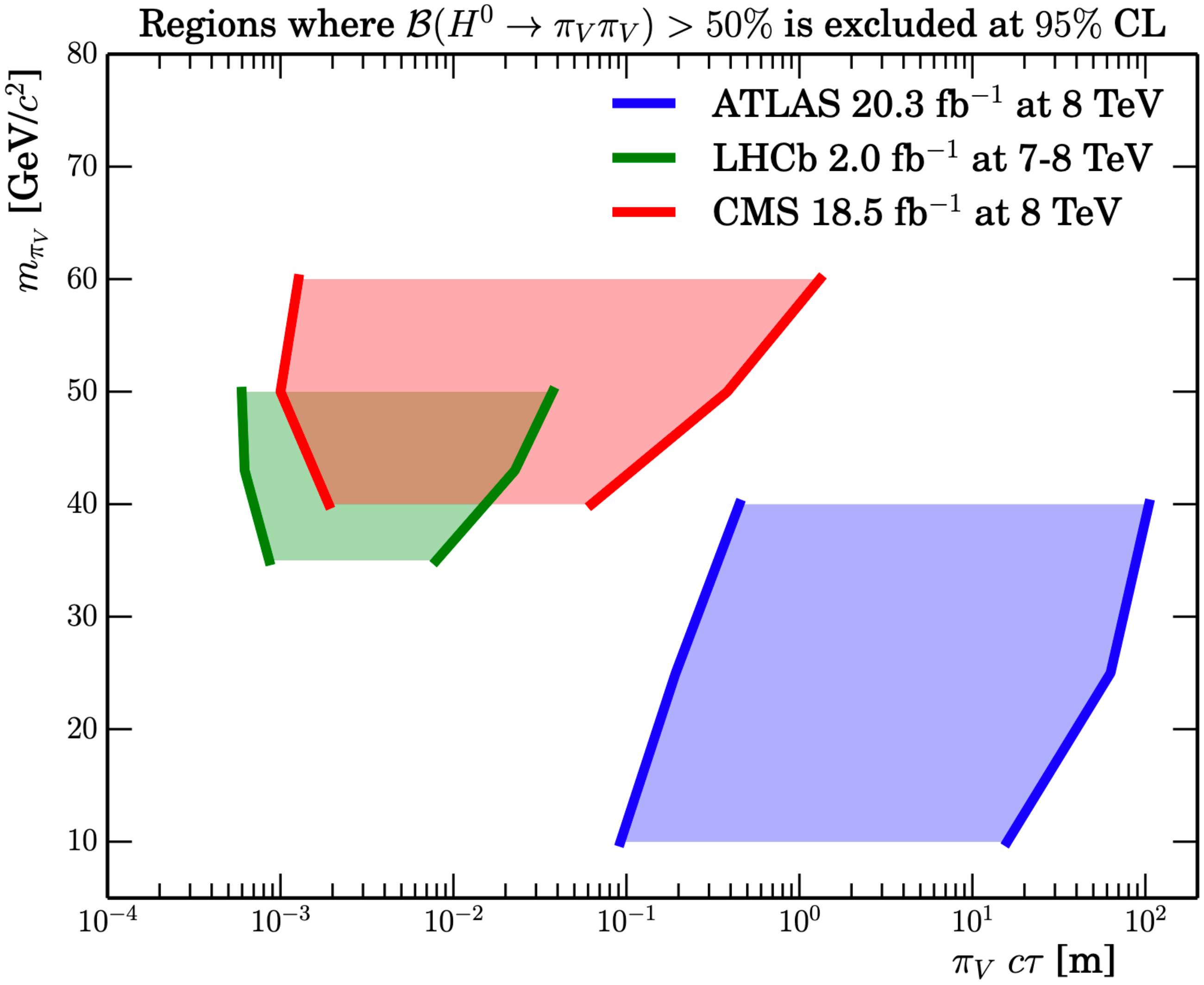
Long-Lived Particle Production

- No signal observed; limits set on $\sigma \times$ BF





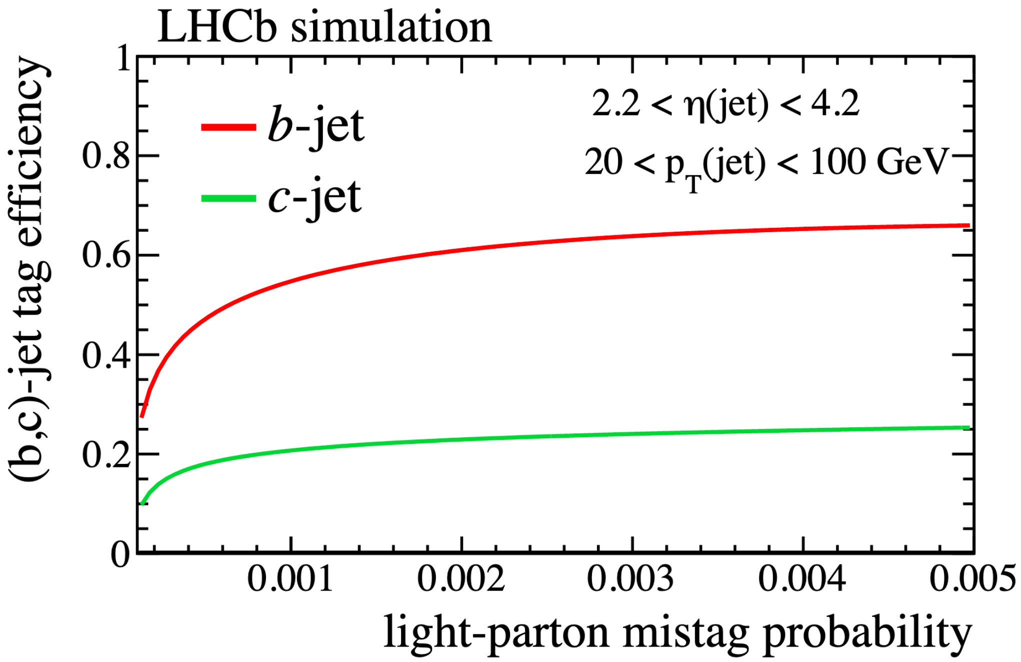
Long-Lived Particle Production

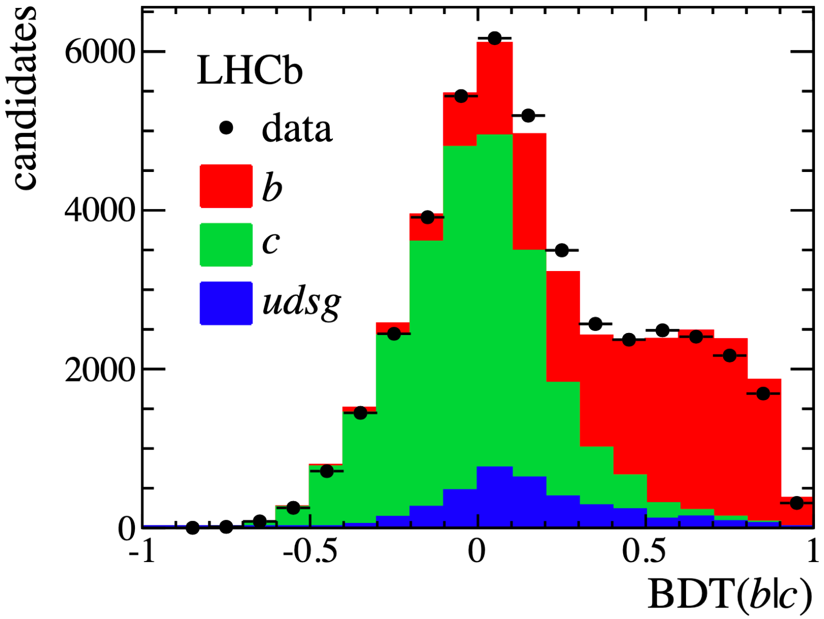


Longer Future – SM Higgs Couplings?

- LHCb also has a programme in measuring forward HF jets.

- Measurements made probing top physics, V+jj.
  - lepton + bb(cc) final state also sensitive to WH and ZH contributions.
  - Run 1 data set limits: $y^b < 7\ y^b_{SM}; y^c < 80\ y^c_{SM}$





What sensitivity could we reach with 300/fb? Any determination of y^c depends on ability to distinguish beauty and charm jets.

Longer Future – SM Higgs Couplings?

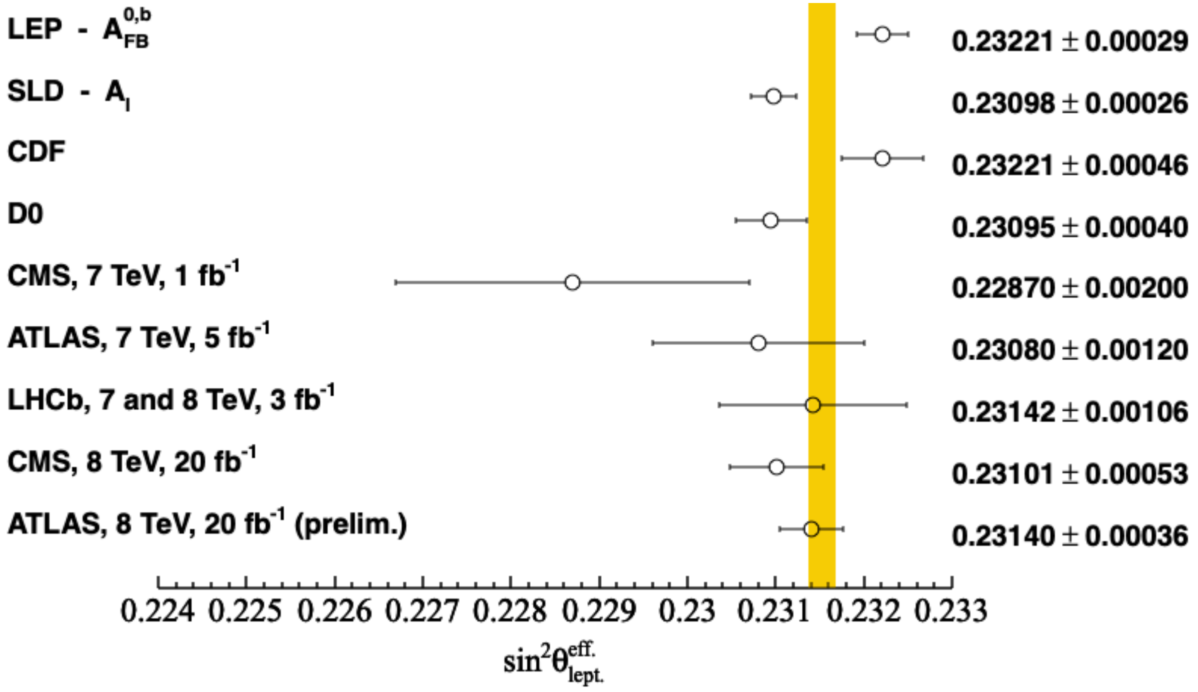
- Production cross-section increases by a factor of 7 within LHCb acceptance between 8 TeV and 14 TeV.
  - Scaling Run 1 limits reaches $y^c < 7\ y^c_{SM}$ for 300/fb.
- Loosen c-jet tagging criteria on second jet – dominant background is cc final state anyway.
  - Run 1 analysis had dijet tag efficiency of about 2% - could reach 25%.
  - Limit would reach $y^c < 4\ y^c_{SM}$ with this assumption.
- Use electrons and muons equally (Run 1 just considered muons): $y^c < 3\ y^c_{SM}$
- If separation of b- and c- jets improved so that only c-jet background important: $y^c < 2\ y^c_{SM}$

Limits on y^c should be roughly in range 2 - 7 y^c_{SM} using full LHCb Upgrade II dataset (depending on performance assumptions – clearly some more feasible than others).

EW Measurements

Weak Mixing Angle at LHCb

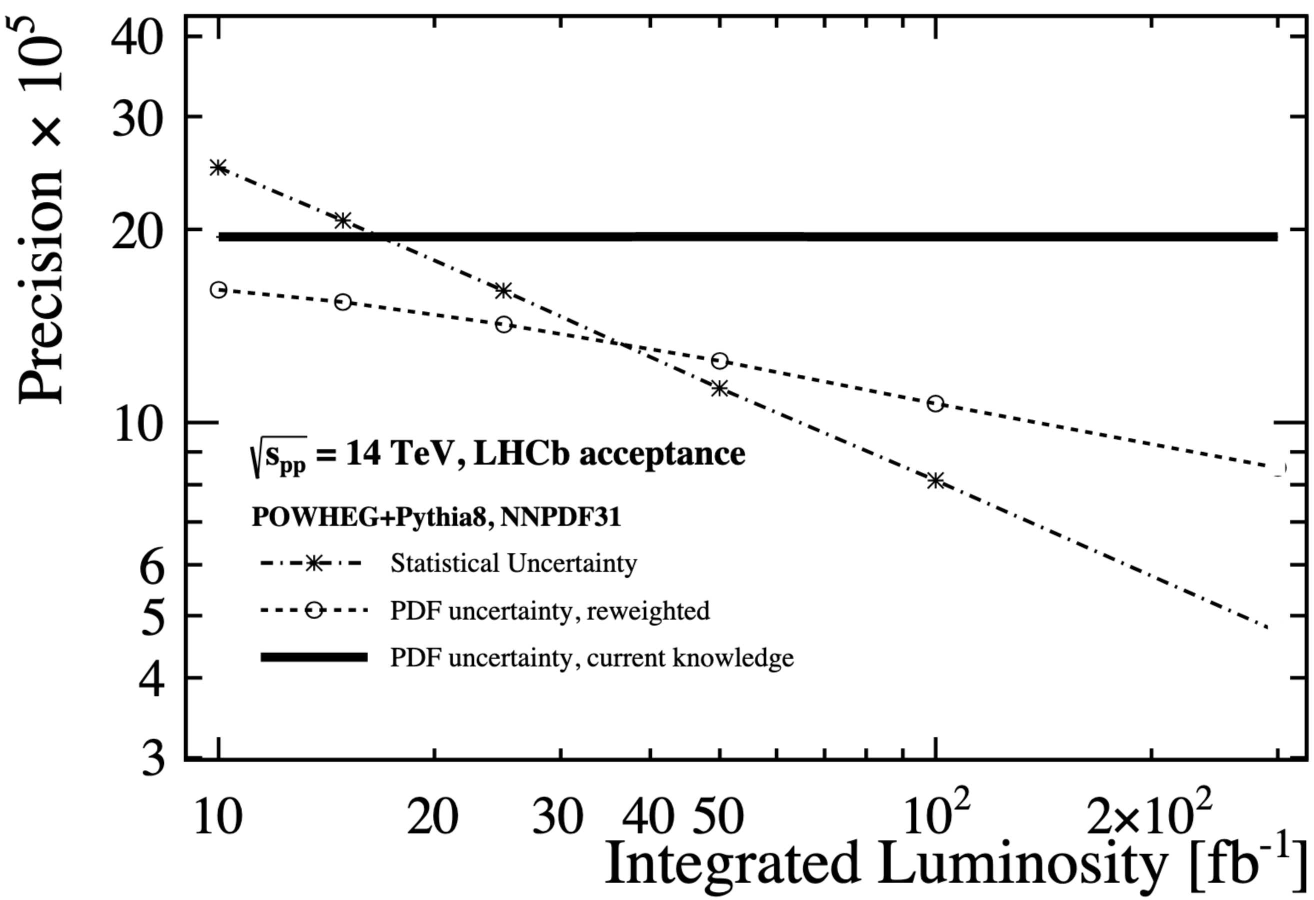
- Measure through forward-backward asymmetry in Z boson production.
- Need to know direction of colliding quark relative to anti-quark to set *z*-axis.
- This is known best in forward direction, since valence/sea collisions dominate.
- Forward direction offers smallest PDF uncertainty.



- LHCb result currently statistically limited – huge potential with 300/fb

LHCb-PUB-2018-013, and P. Azzi et al., arXiv:1902.04070
With method following A. Bodek et al, EPJC 76 (2016) 115

Weak Mixing Angle at LHCb



- Statistical uncertainty at LHCb negligible following upgrades.
- PDF uncertainty at LHCb from current knowledge is small: $\sim 20\times10^{-5}$

  [cf CMS $\sim 57\times10^{-5}$].
- With Upgrade II dataset PDF unc at LHCb can be reduced below $\sim 10\times 10^{-5}$ using PDF reweighting method

  [cf CMS@ 3000/fb,

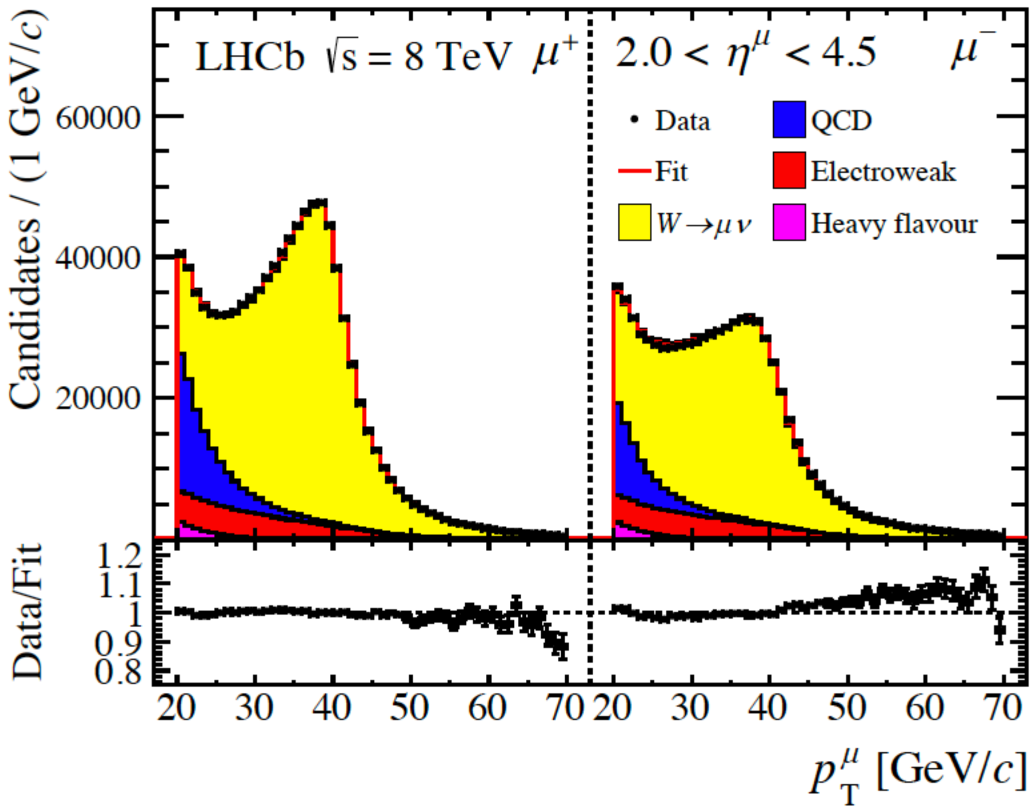
  with reweighting $\sim 10\times10^{-5}$].

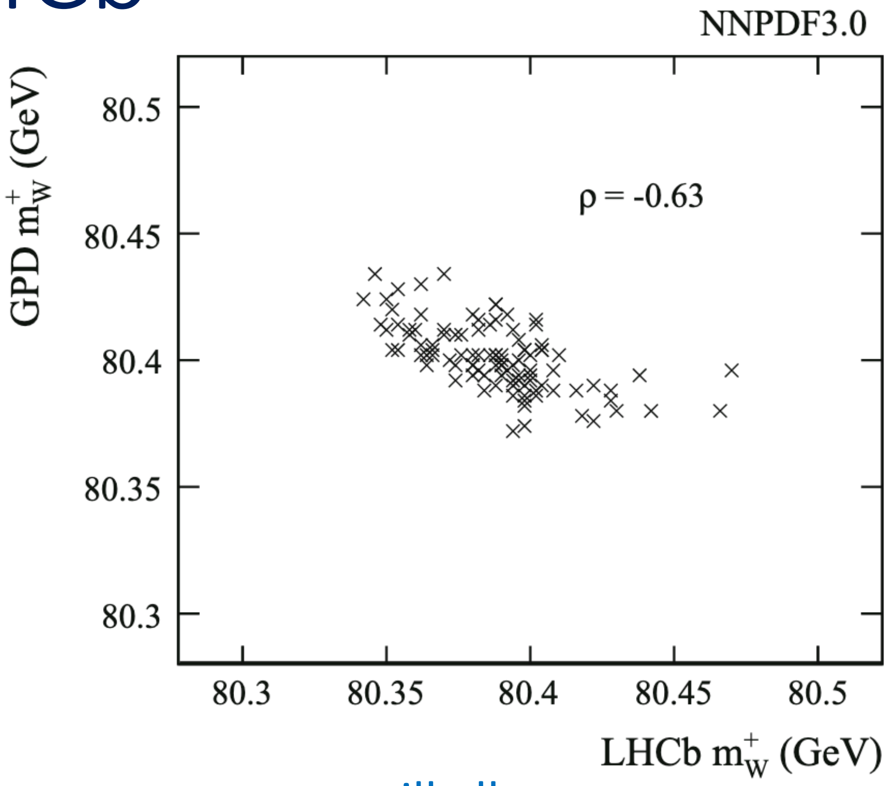
Note: ATLAS expected performance similar to CMS; CMS quoted as similar study performed to LHCb.

JHEP 01 (2016) 155, and G. Bozzi, L. Citelli, M. Vesterinen, A. Vicini, EPJC 75 (2015) 601
and S. Farry, O. Lupton, M. Pili, M. Vesterinen, EPJC 79 (2019) 497

W mass measurement at LHCb

EW boson production already (reasonably) well understood in LHCb data – cross-section papers published at 7, 8 and 13 TeV.





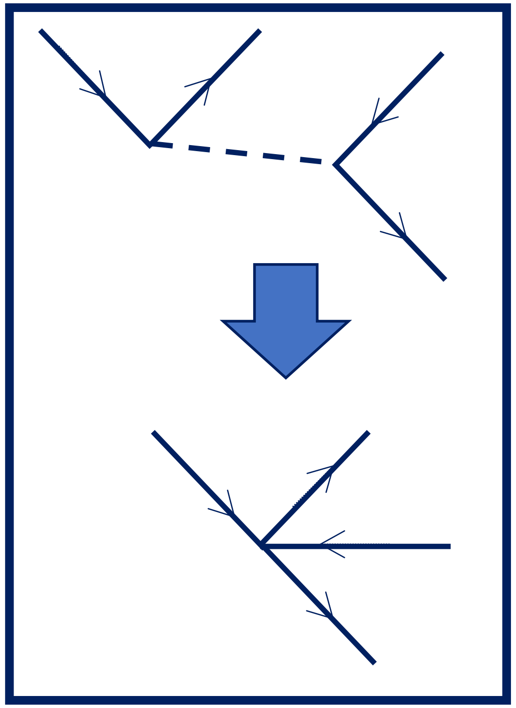
- Fit of the muon p_T spectrum will allow m_W measurement with statistical uncertainty O(10MeV), and PDF uncertainty O(10MeV) - enabling high precision.
- PDF uncertainty anti-correlated with ATLAS/CMS – LHCb will have major impact in LHC-wide combination.

B anomalies

Flavour Physics Studies as an Indirect Search

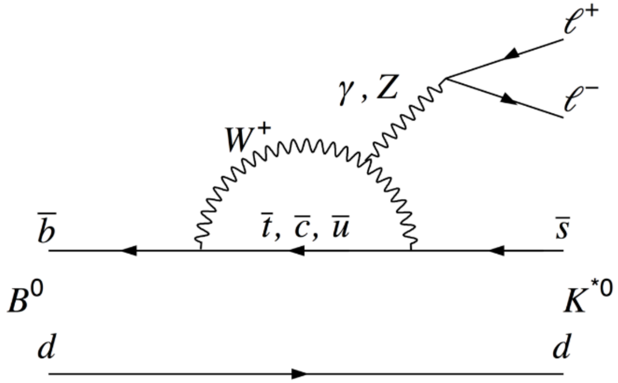
Measurements of Heavy Flavour decays can probe much higher energy theories - consider flavour changing transitions:

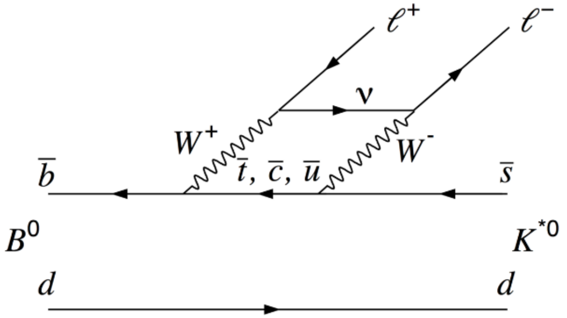
- Amplitude $\sim A_0(\frac{\kappa_{SM}}{v^2} + \frac{\kappa_{NP}}{\Lambda^2})$ - integrating out the higher energy theories, leaving energy scale for new physics, Λ.
- Large NP effects possible if $\frac{\kappa_{NP}}{\Lambda^2} \sim \frac{\kappa_{SM}}{v^2}$.
  If $\kappa_{NP} \sim 1 \implies$ large effects for $\Lambda \sim \frac{v}{\sqrt{\kappa_{SM}}}$.
- Typical limits from B-mixing depend on new physics flavour structure:
  Tree Level NP, generic couplings, $\Lambda \geq 10^4$ TeV
  Loop Level NP, generic coupling, $\Lambda \geq 10^3$ TeV
  Tree Level NP, couplings have CKM structure, $\Lambda \geq$5 TeV
  Loop Level NP, couplings have CKM structure, $\Lambda \geq$0.5 TeV



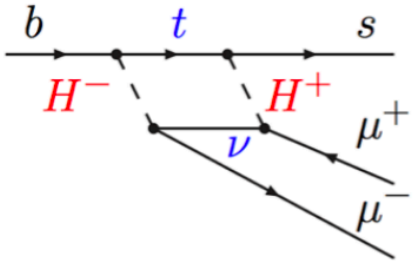
B anomalies: $b \to sll$ transitions

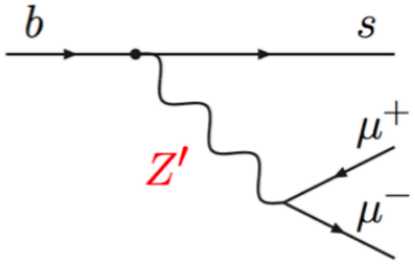
- Process significantly suppressed in SM.





- New Physics amplitudes could compete with SM amplitudes.

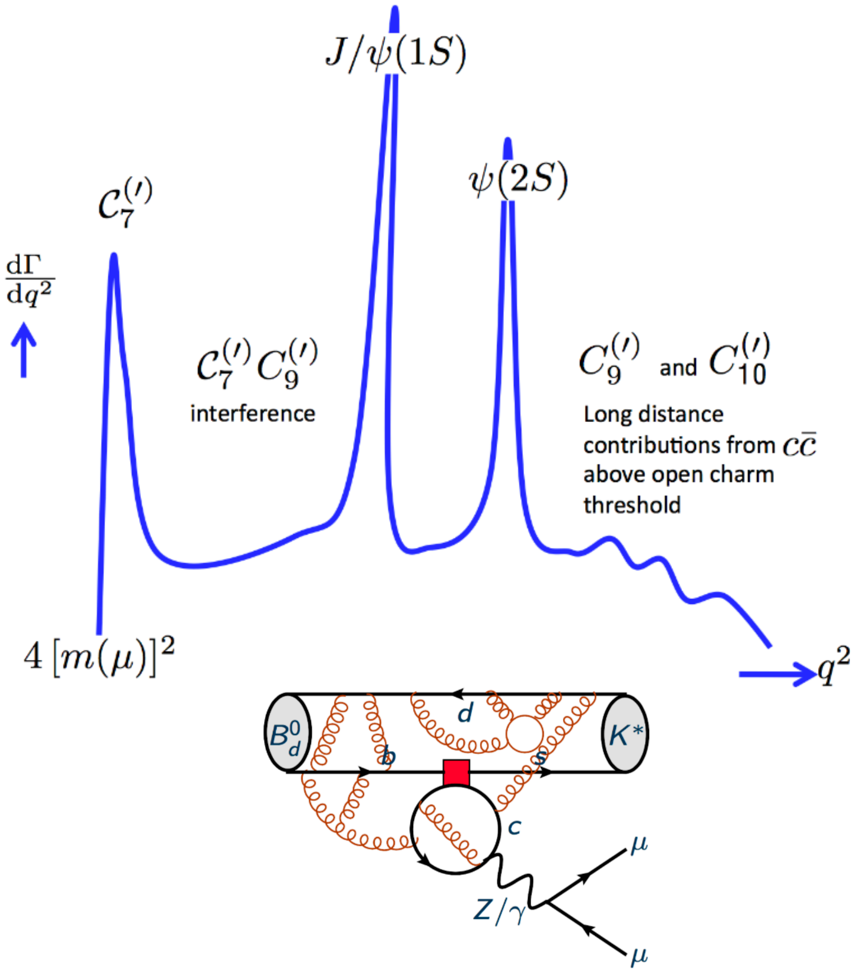




Schematic from P. Alvarez Cartelle

B anomalies: $b \rightarrow sll$ transitions

- Measurements made as a function of the invariant mass of the dilepton system, q^2.
- Different regions are sensitive to different New Physics contributions (parameterised through Wilson coefficients).
- Veto regions associated with tree-level quarkonia decays. (Use these to study and cancel systematic effects, and calibrate samples.)



B anomalies: $b \to sll$ transitions

- A series of measurements probing $b \to sll$ transitions are currently in tension with the SM.

  - Angular analysis of $B \to K^{*}\mu\mu$ shows a discrepancy in the P_5' variable (constructed by definition to have reduced dependence on form factors). 2 adjacent bins display a 2-3σ tension with SM expectation.

  - Branching Fractions are consistently below the SM expectation in many processes (eg $B_s \to \phi\ \mu\mu, B^{+} \to K^{+}\mu\mu, B \to K^{*}\mu\mu$)

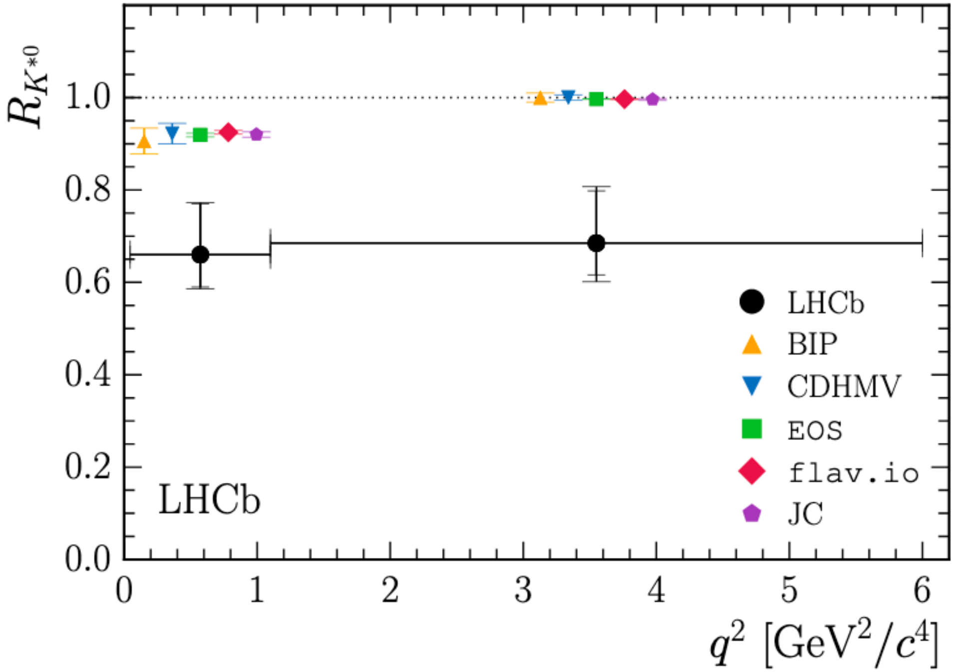
  - Lepton universality tests deviate from Standard Model expectation:

$$R_X = \frac{\mathrm{BF}(B \to X\ \mu\mu)}{\mathrm{BF}(B \to X\ J/\psi(\to\mu\mu))} \Big/ \frac{\mathrm{BF}(B \to X\ ee)}{\mathrm{BF}(B \to X\ J/\psi(\to ee))}$$

B anomalies: $b \to sll$ transitions

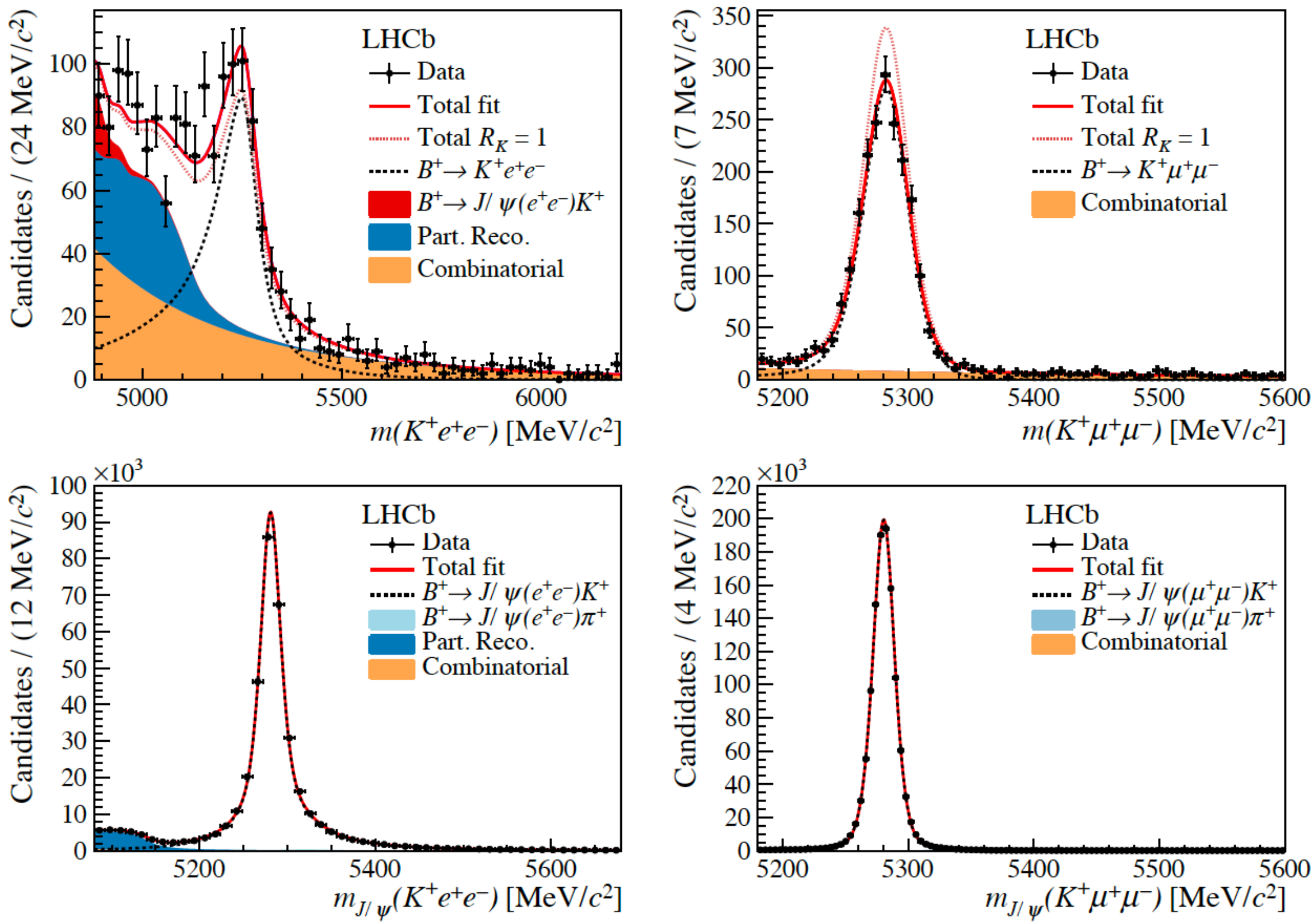
- $R_{K*}(0.045 < q^2 < 1.1\ \mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$
- $R_{K*}(1.1 < q^2 < 6.0\ \mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$

Significant tension with the SM in two bins at >2σ level.



B anomalies: $b \to sll$ transitions

- LHCb has a new measurement of R_K using the combined Run 1, 2015 and 2016 dataset.

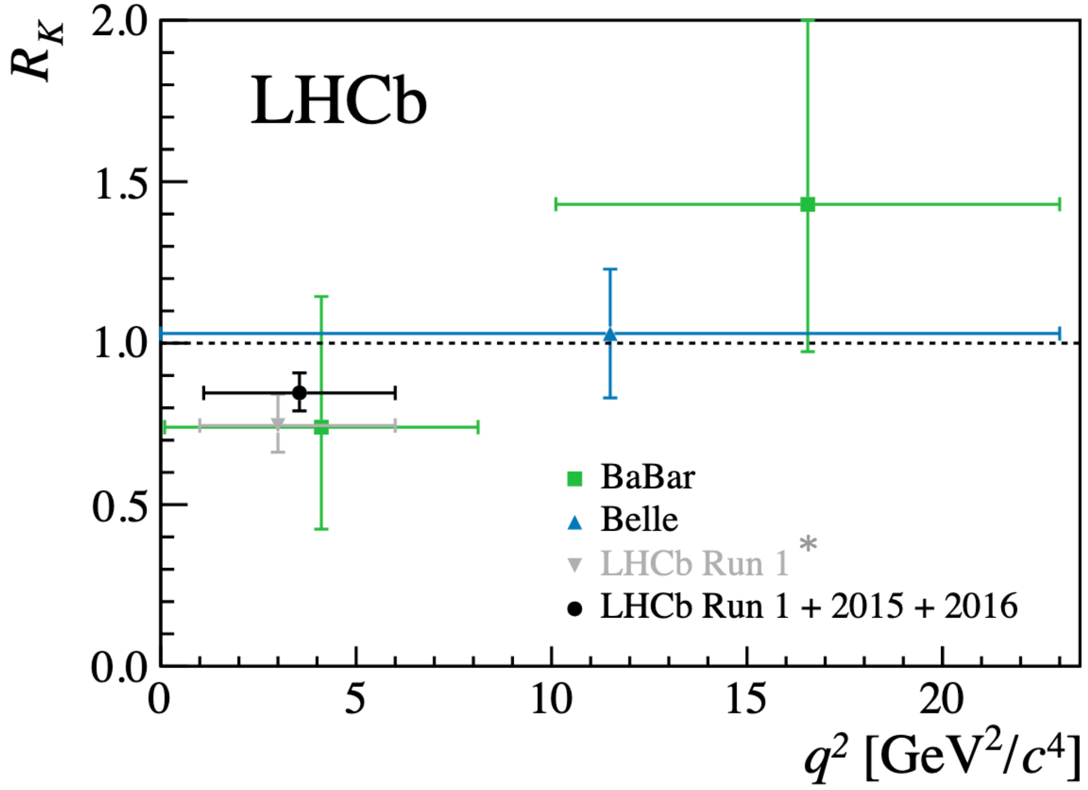


B anomalies: $b \to sll$ transitions

- Simultaneous fit to electron and muon modes to extract the value of R_K.

$$R_K = \frac{\mathrm{BF}(B^+ \to K^+ \mu\mu)}{\mathrm{BF}(B^+ \to K^+ J/\psi(\to \mu\mu))} \Big/ \frac{\mathrm{BF}(B^+ \to K^+ ee)}{\mathrm{BF}(B^+ \to K^+ J/\psi(\to ee))}$$

$$= 0.846^{+0.060}_{-0.054}(\mathrm{stat.})^{+0.016}_{-0.014}(\mathrm{syst.})$$



- Statistically limited, dominant uncertainties fit shape, trigger calibration, simulating B kinematics
- Consistent with the SM at the 2.5 σ level.
- 2017 and 2018 data already available.

J. Aebischer *et al.*, arxiv:1903.10434; M. Alguero *et al.*, arxiv:1903.09578; A. K. Alok, JHEP 06 (2019) 089; M. Ciuchini, EPJC 79 (2019) 719; G. D'Amico *et al.*, JHEP 09 (2017) 010; A. Arhrib *et al*, arxiv:1710.05898

B anomalies: $b \to sll$ transitions

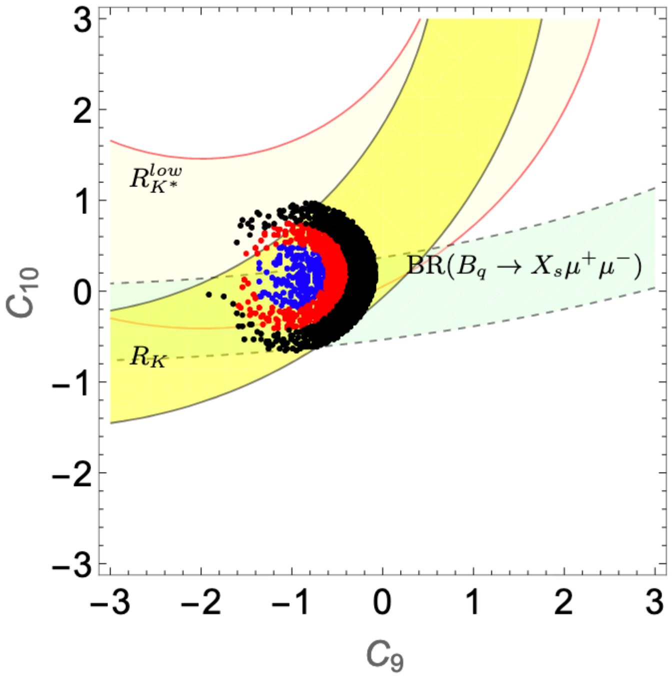
Is there a consistent explanation?

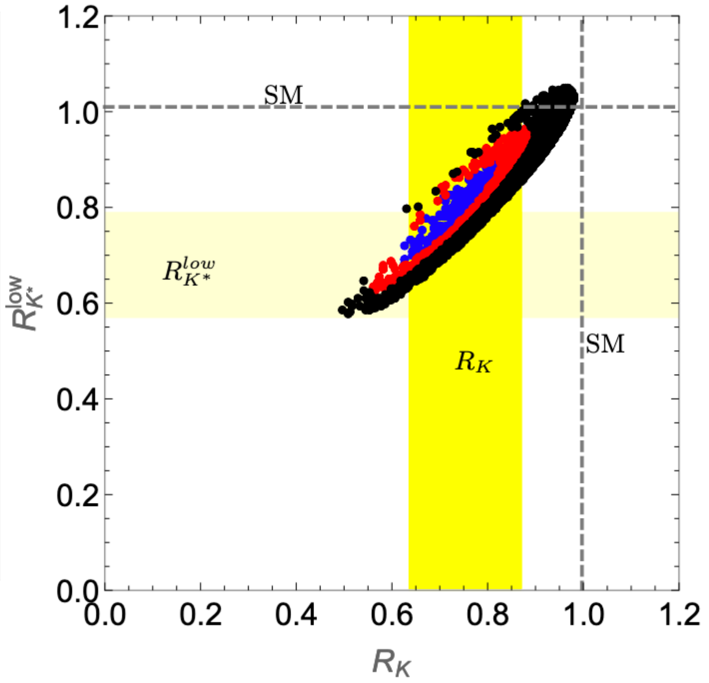
Yes – and global fits of Wilson coefficients to parameterise new physics in $b \to sll$ data show deviations from SM expectation at 5σ level with best fit for

$C_9 \approx -C_{10} \sim -0.5$ for muons.

(though some tension explaining the newest results)

Can also add model building e.g. Type III 2HDM* (though currently theory favours LQ or Z' solutions)





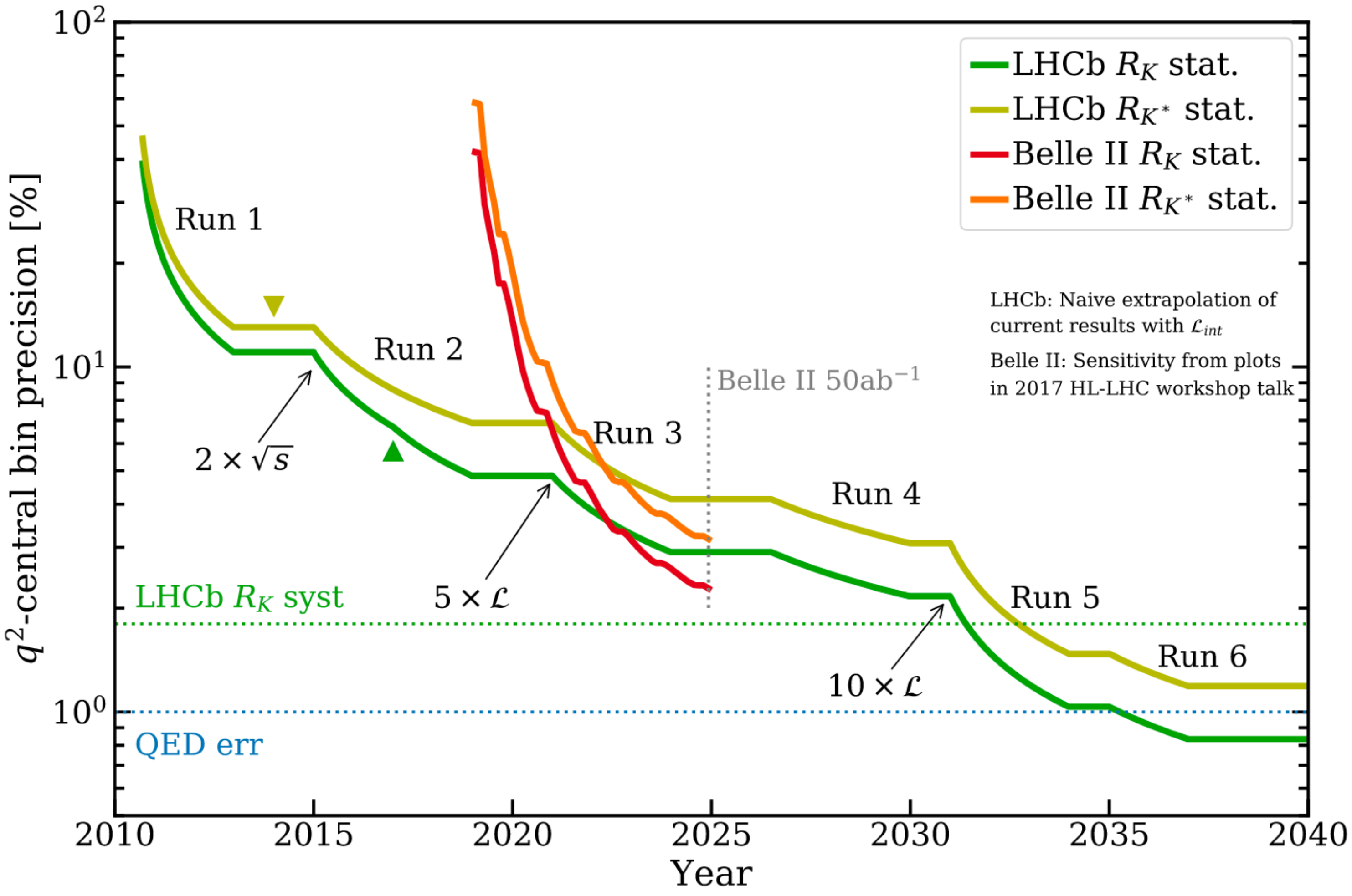
Note: Type II 2HDM already excluded in full tan β / m_{H^+} space as sole explanation for B anomalies

Plot from P. Alvarez Cartelle

B anomalies: $b \to sll$ transitions

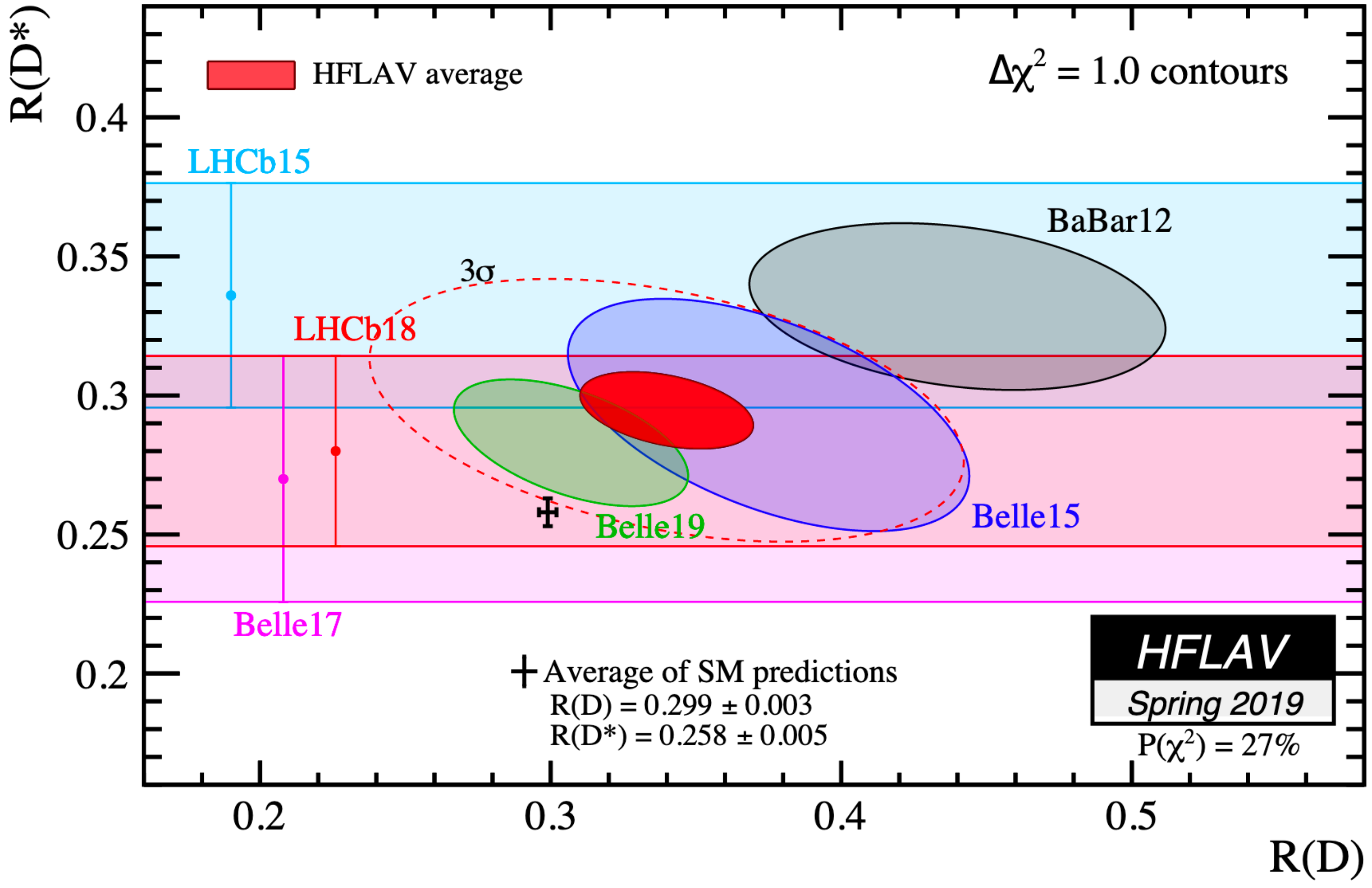
Prospects

Entering high precision era – will be able to confirm if this is NP.



B anomalies: $b \to cl\nu$ transitions

- In addition, anomalies also remain in $b \to cl\nu$ transitions, measuring ratio of BF($b \to c\tau\nu$) to BF($b \to c\mu\nu$).
- Potentially more puzzling – tree level process in SM.
- HFLAV combination and analysis: "difference [of measurements] with the SM predictions … corresponds to about 3.08 σ".
- Deviation from SM predictions driven by BaBar measurement.



Conclusion

Conclusion

- Covered a wide variety of physics:
    - Searches for (low mass) New Physics (Spin-0 bosons, LLP produced in Higgs boson decays).
    - Measurements (and prospects) in the broader EW sector, and the prospect for measuring/constraining y^c at LHCb.
    - B anomalies – what they are, and (a little) on how they can be interpreted.
- LHCb is not a Higgs experiment – and we're not pretending it is!
    - But hopefully the measurements I have presented are interesting and clearly connected to Higgs physics!
    - Let us know if you think there is something else we should measure or target!
- Huge potential ahead of us – prospect of collecting at least 300/fb with future upgrade.

Backup Slides

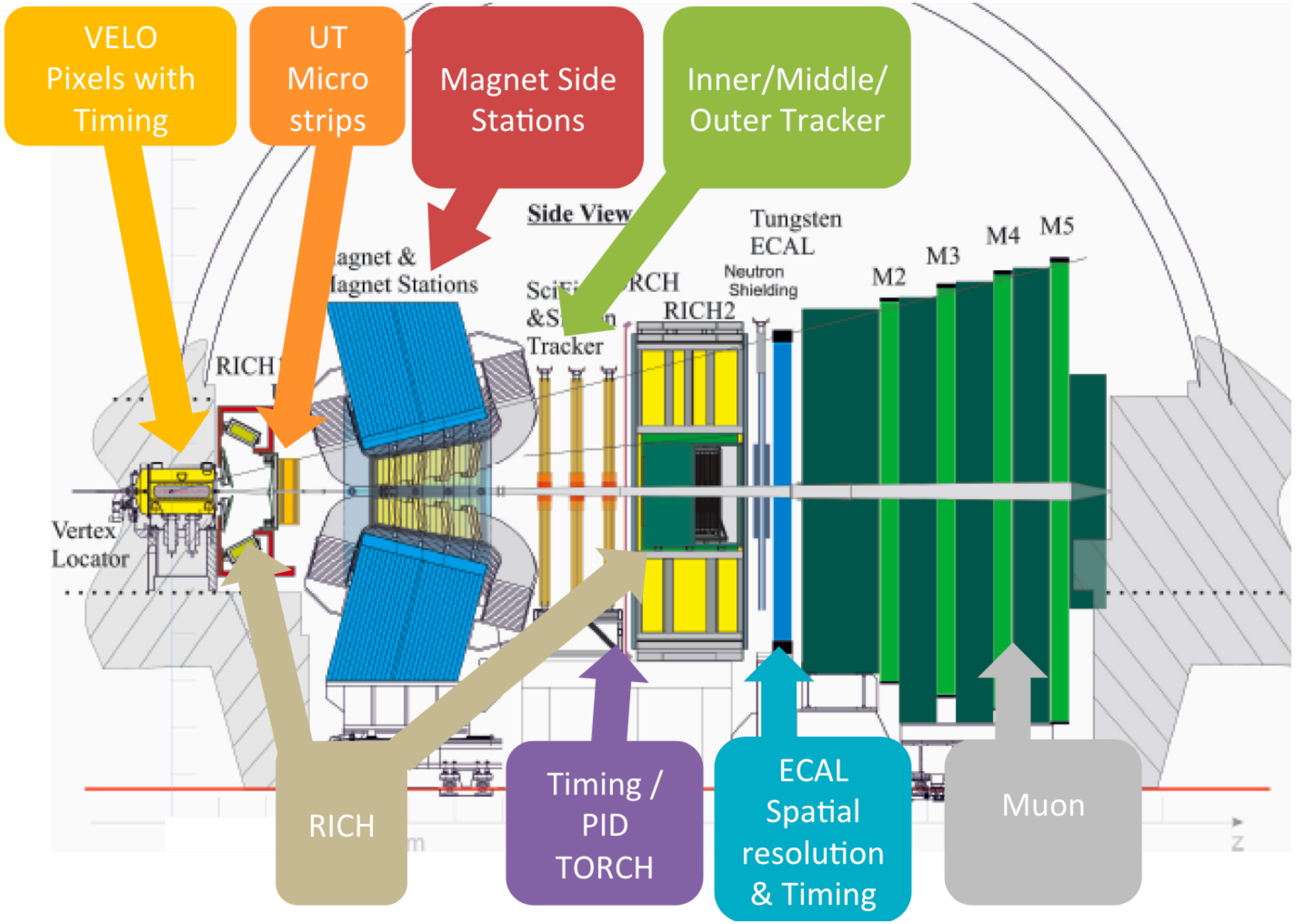
Taking stock – key dates for LHCb

2008-2010	2010-2012	2013-2015	2015-2018	2019-2020
LHC startup and initial collisions	**LHC Run 1:** pp collisions at $\sqrt{s} = 7$ and 8 TeV. Beams have 50ns bunch spacing.	**Long Shutdown 1:** Upgrade to higher energies and luminosities; LHCb Trigger Upgrade	**LHC Run 2:** pp collisions at $\sqrt{s} = 13$ TeV. Beams have 25ns bunch spacing.	**Long Shutdown 2:** Includes LHCb Upgrade I

2021-2023	2024-2026	2026-2029	Early 2030s	2030s+
LHC Run 3: Collisions in LHCb achieve 5 times higher luminosity	**Long Shutdown 3:** Upgrade Ib for LHCb (Main Upgrade for ATLAS and CMS)	**LHC Run 4:** HL/LHC era begins. LHCb dataset at least 50/fb.	**Long Shutdown 4:** LHCb Upgrade II To allow collisions in LHCb with 10 times higher lumi	**LHC Run 5+:** To infinity and beyond! LHCb dataset at least 300/fb

We are 10 years into a decades-long programme!

Upgrade II Detector

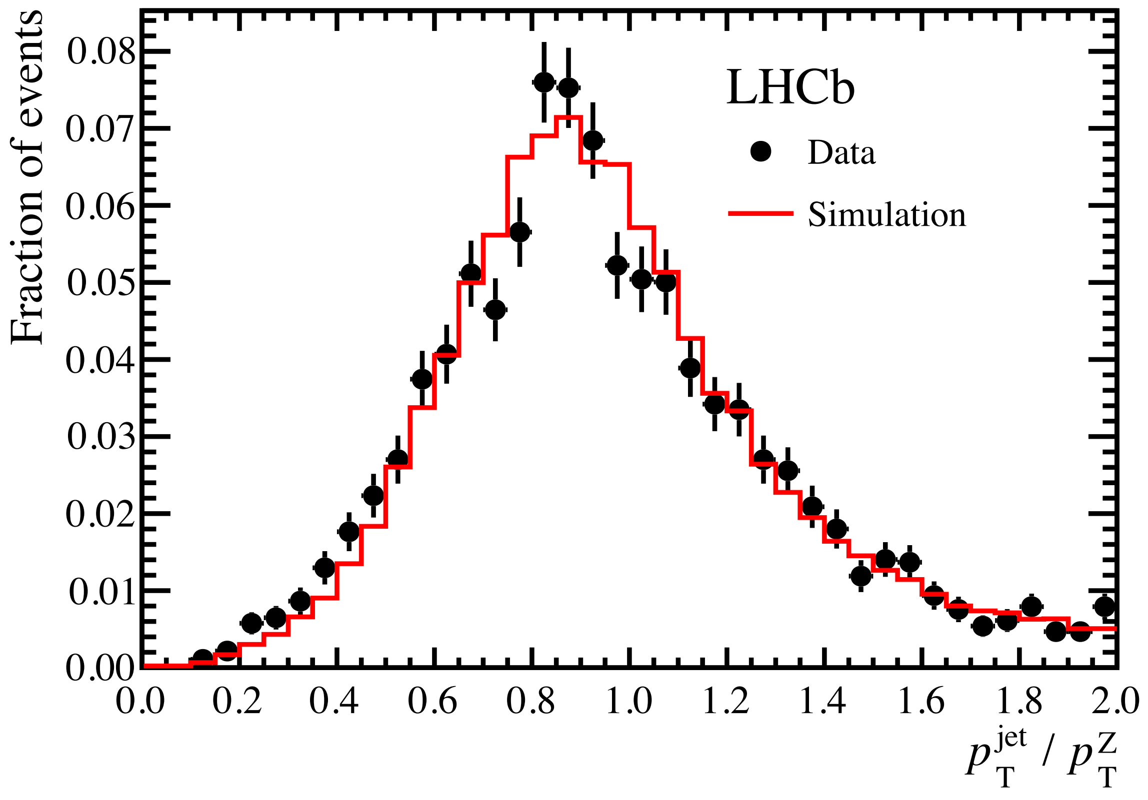


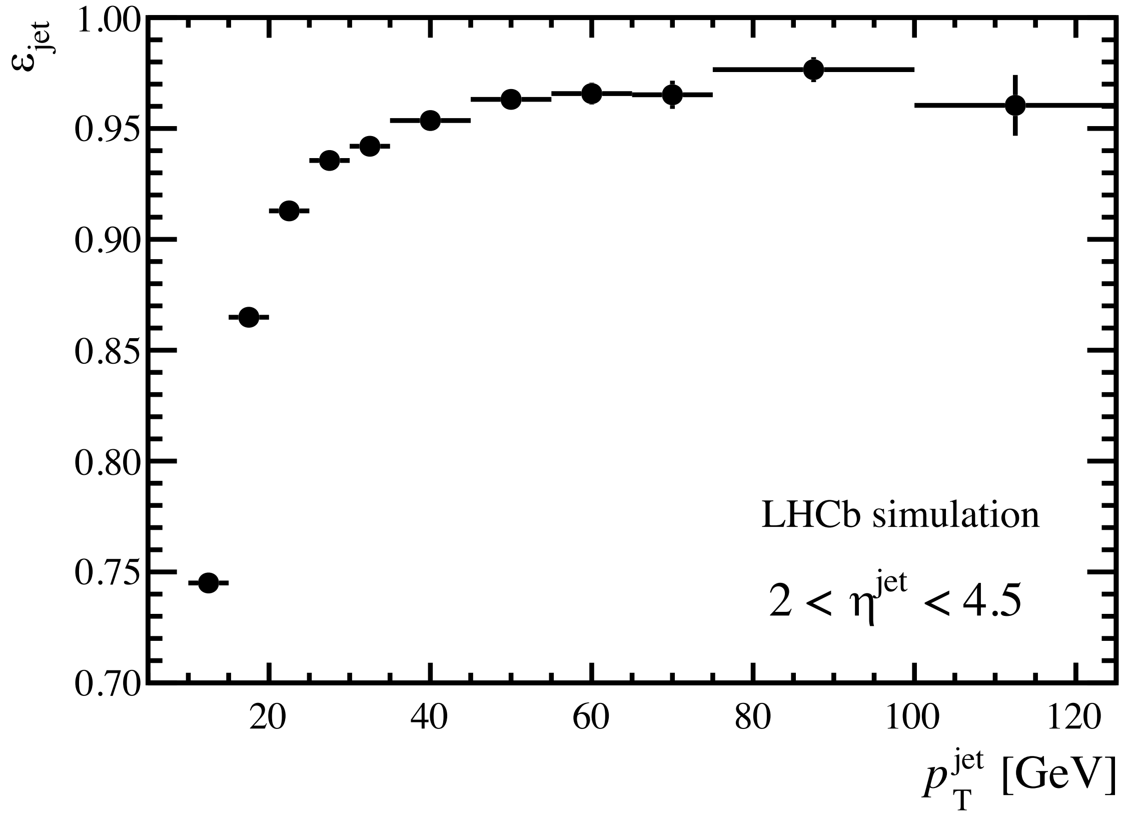
LLP Searches

Table 3: Overview of the contributions to the relative systematic uncertainty on the signal efficiency and luminosity (in percent) for different signal samples in 2012 conditions. The uncertainty on the total efficiency is obtained by summing the individual contributions in quadrature.

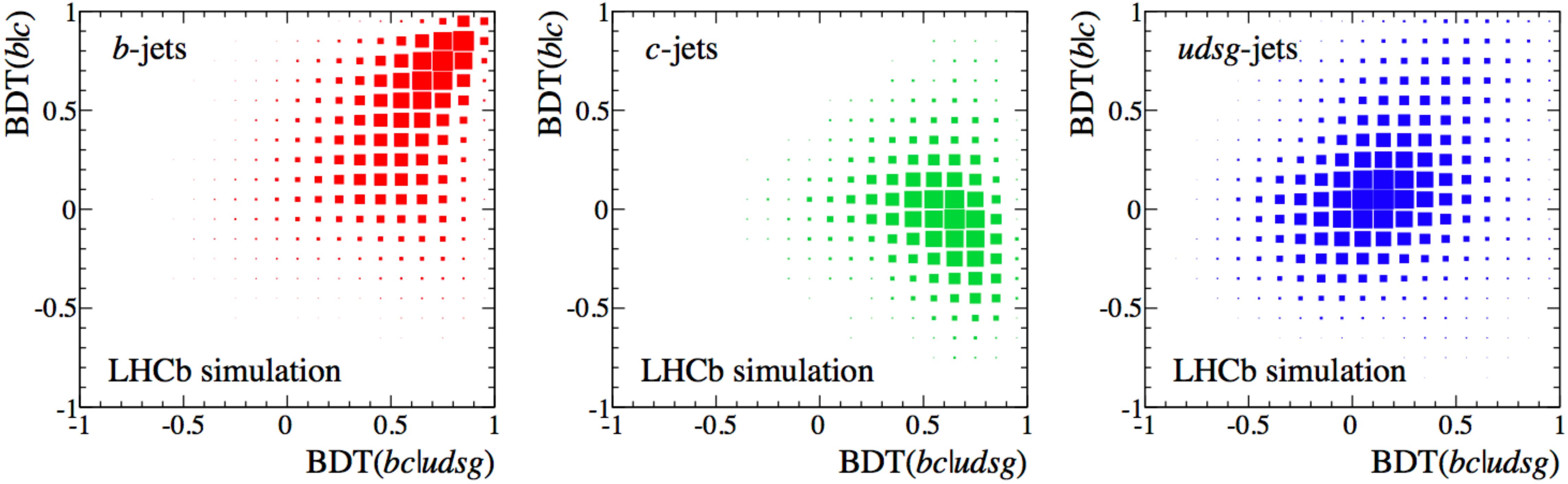
π_v mass (GeV/c^2)	25		35		43		50		35, $c\bar{c}$	35, $s\bar{s}$
π_v lifetime (ps)	10	100	10	100	10	100	10	100	10	10
Tracking efficiency	3.1	2.8	2.4	2.4	2.2	2.1	2.0	1.7	1.2	1.1
Vertex finding	4.2	4.5	3.8	4.4	3.4	4.1	3.1	3.9	3.4	3.5
Jet reconstruction	2.7	2.7	1.1	1.1	0.7	0.7	0.3	0.3	0.9	1.0
Jet identification	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Jet direction	5.8	5.8	5.3	5.3	6.1	6.1	7.9	7.9	5.3	5.8
L0	4.0	4.0	2.5	2.5	2.0	2.0	2.0	2.0	2.0	2.0
N_{SPD}	2.2	2.2	2.5	2.5	2.5	2.5	2.5	2.5	2.4	2.1
HLT1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
HLT2	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Total efficiency	10.5	10.6	9.2	9.4	9.1	9.5	10.4	10.6	8.6	8.9
Luminosity	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Jets at LHCb


LHCb
Data
Simulation
Fraction of events
p_T^{jet} / p_T^Z

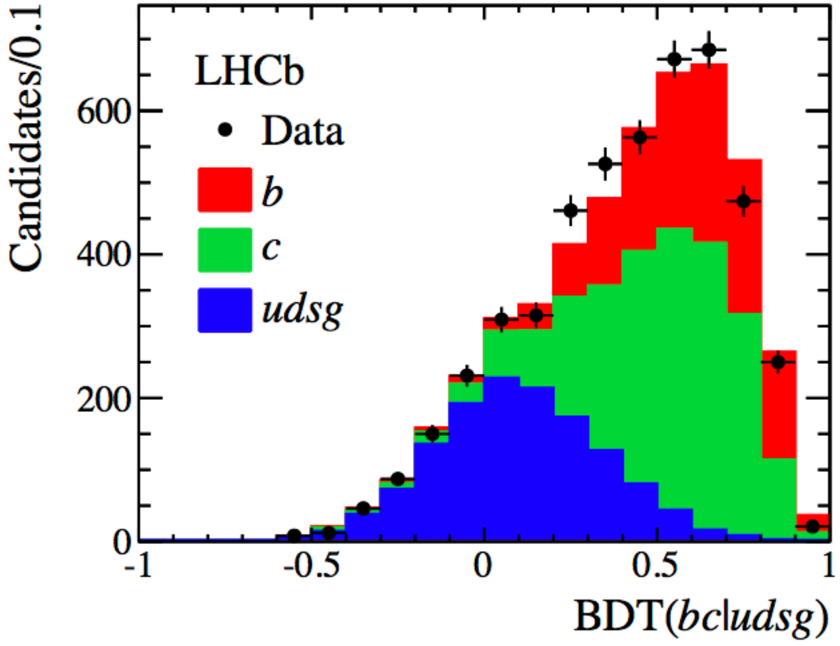

ε_{jet}
LHCb simulation
$2 < \eta^{jet} < 4.5$
p_T^{jet} [GeV]

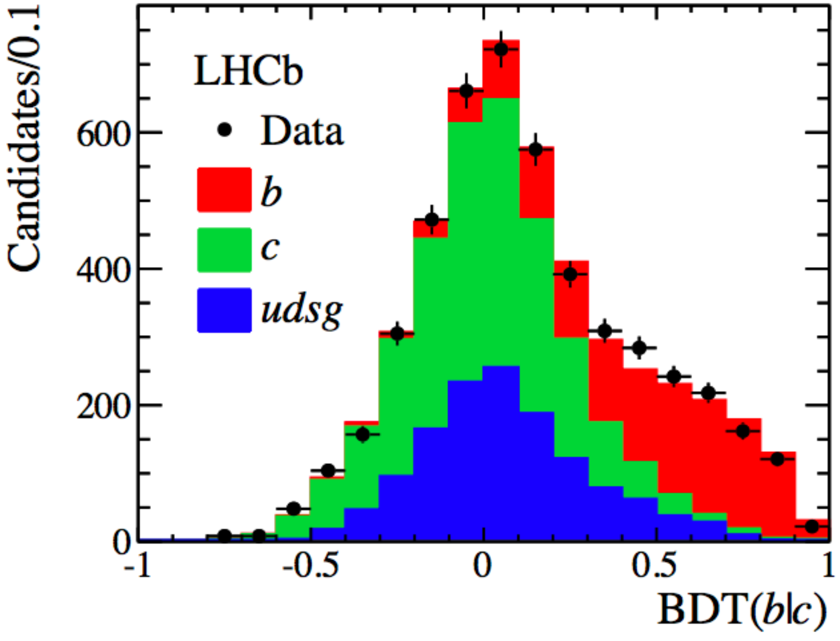
Jets at LHCb



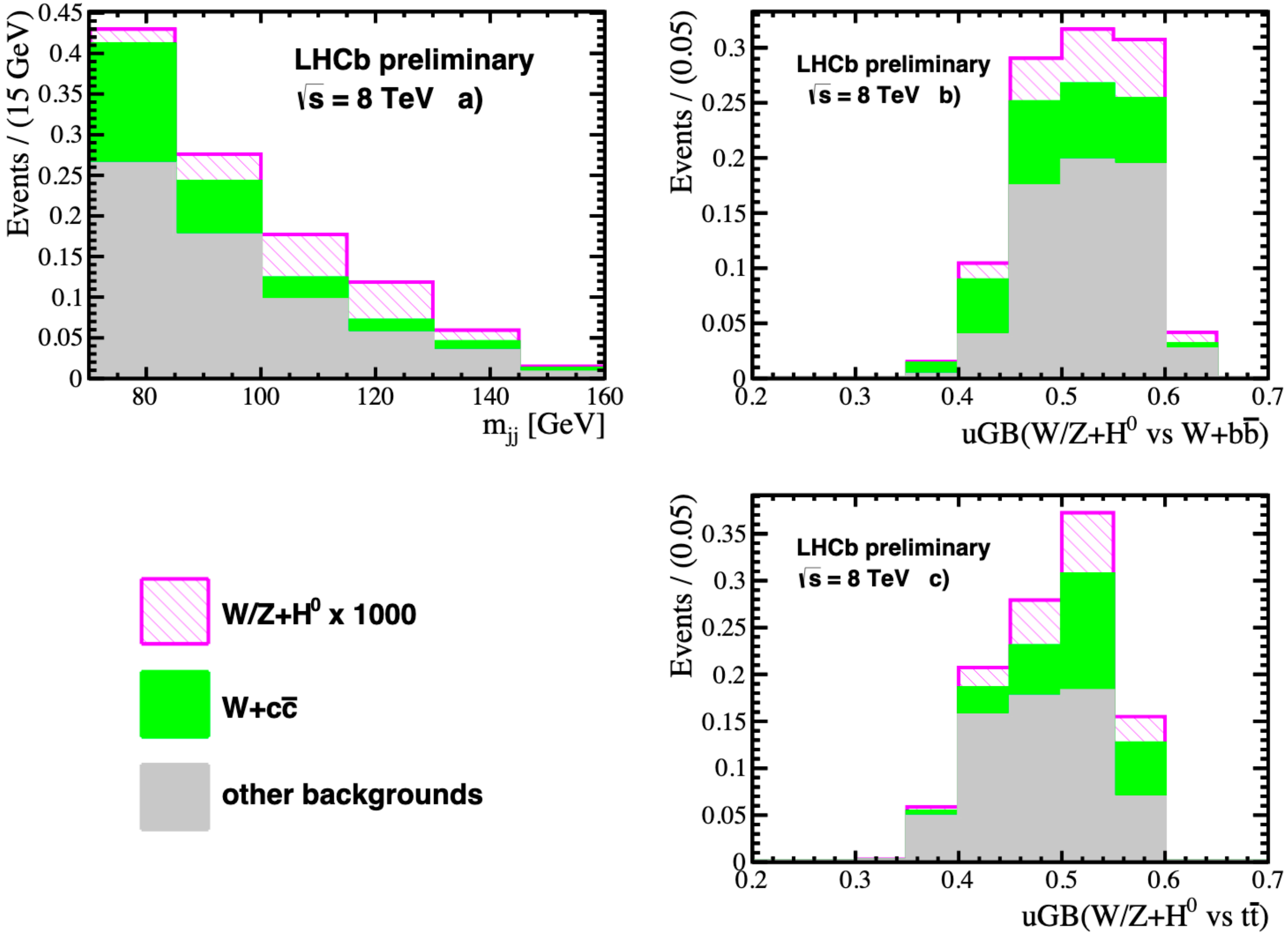
b-jets
c-jets
udsg-jets
LHCb simulation
LHCb simulation
LHCb simulation
BDT(b|c)
BDT(bc|udsg)

Jets at LHCb

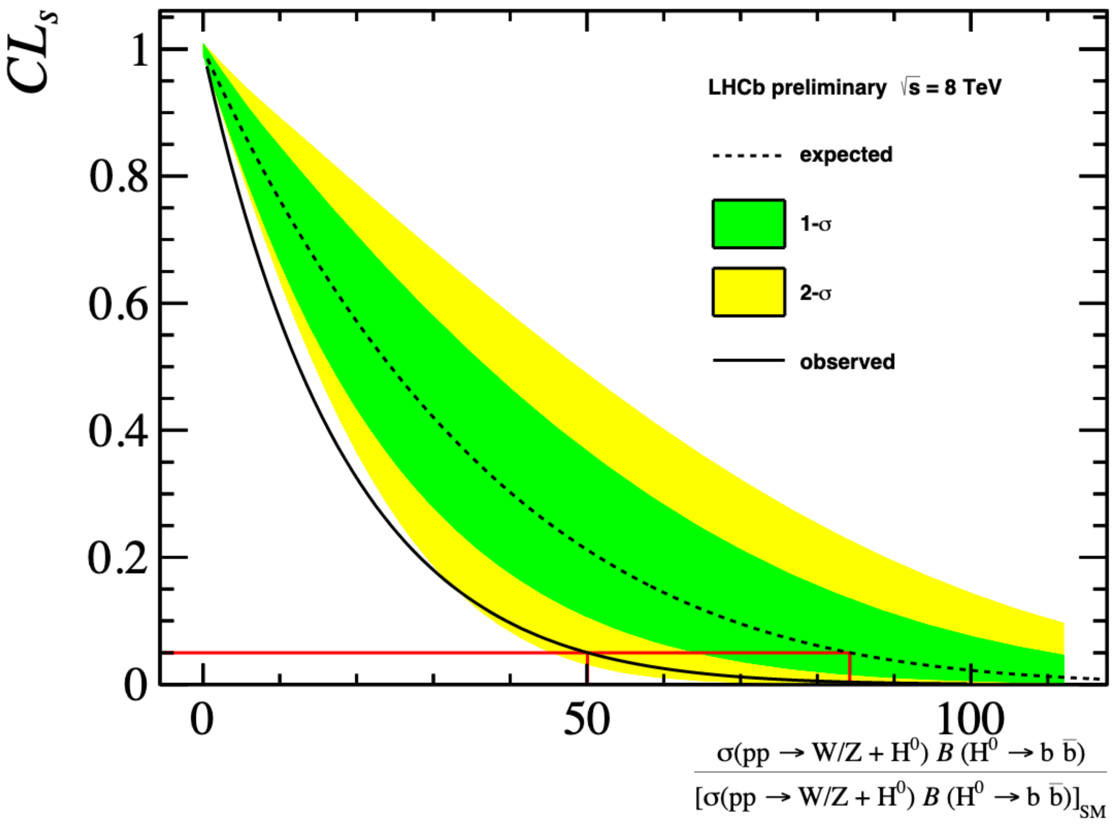

LHCb
Data
b
c
udsg
Candidates/0.1
BDT(bc|udsg)

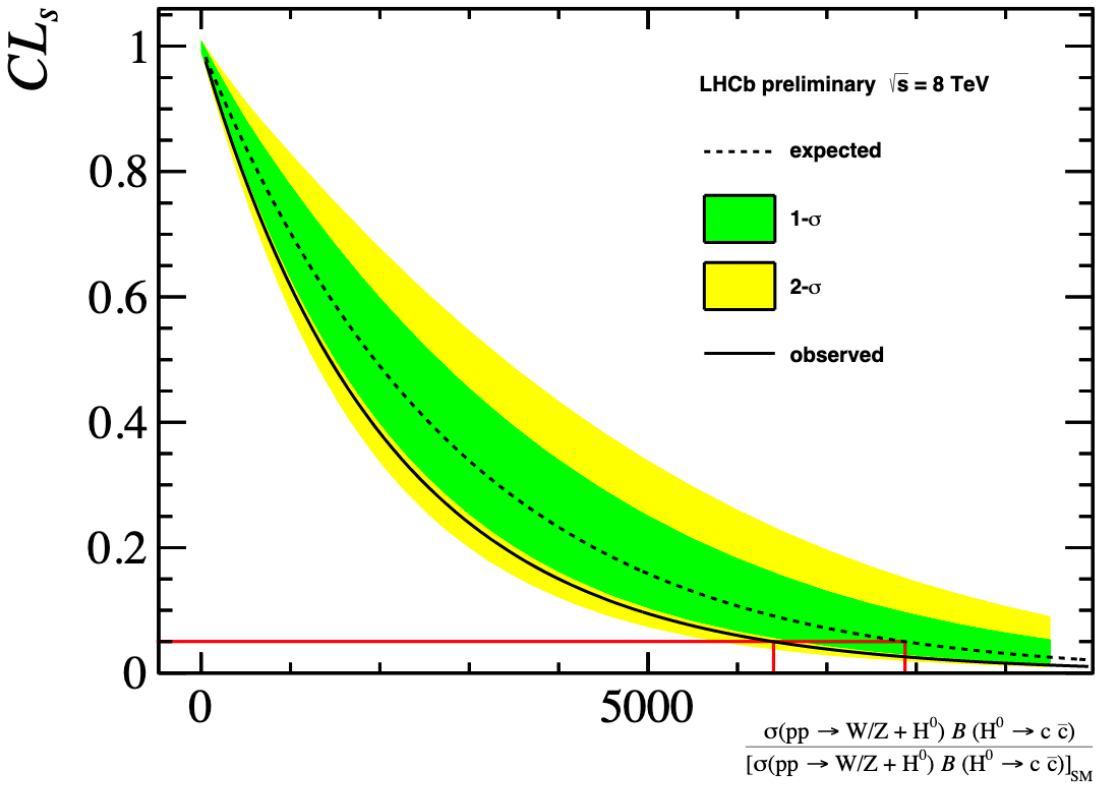

LHCb
Data
b
c
udsg
Candidates/0.1
BDT(b|c)

Higgs at LHCb



Higgs at LHCb



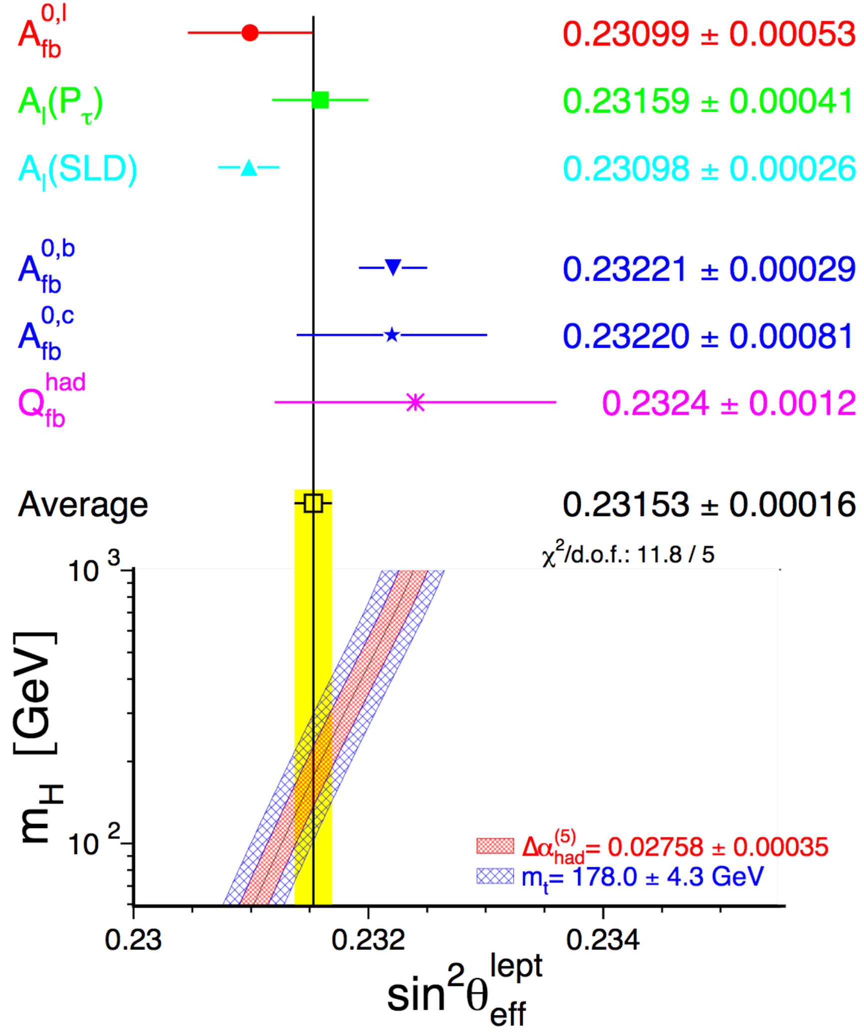


Angular Structure of Z boson decays

$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+A_2 \frac{1}{2}\sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + \boldsymbol{A_4 \cos\theta}$$
$$+A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta\sin\phi$$

Phys. Rept. 427:257-454,2006

Weak mixing at LHCb

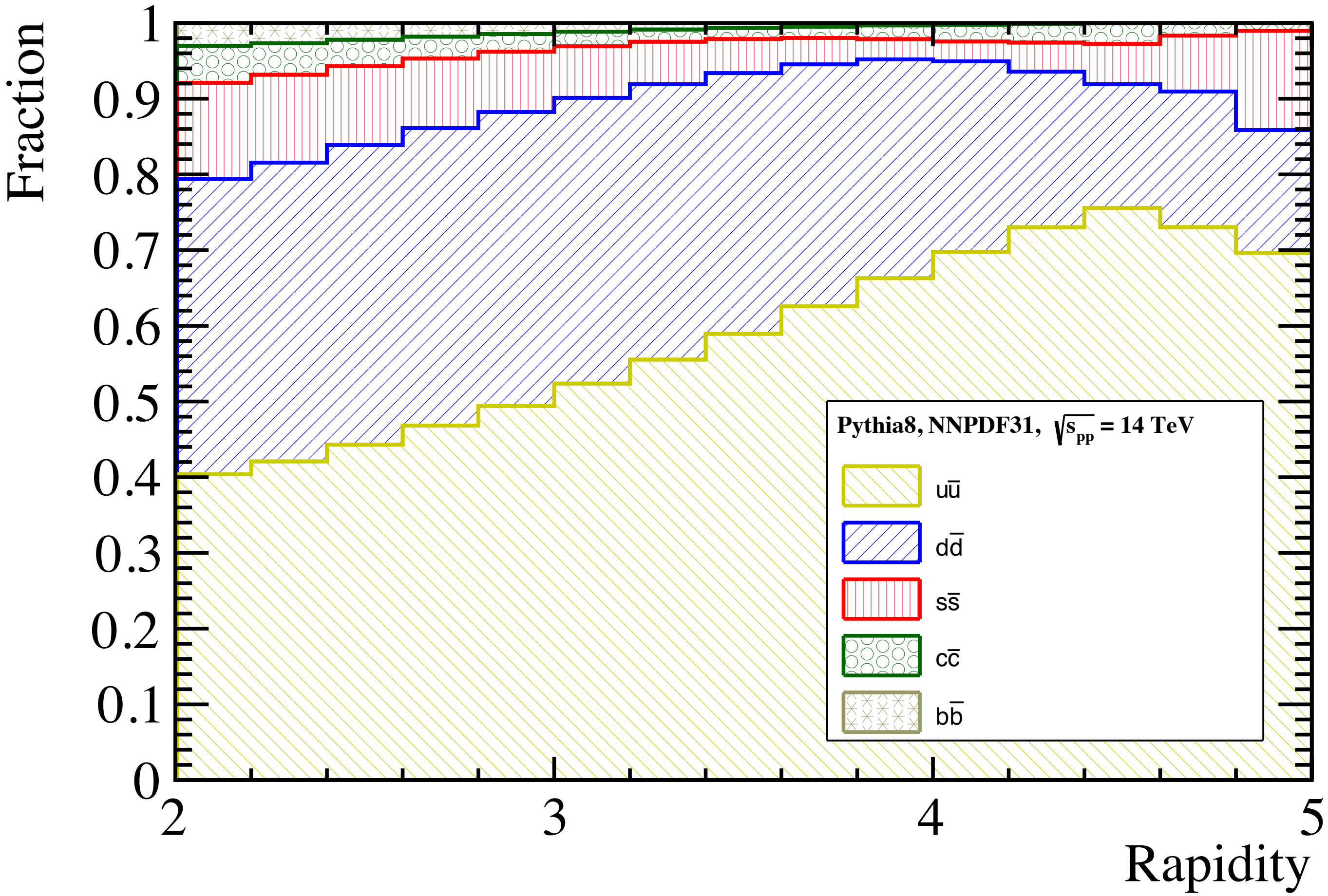


$$\mathcal{G}_{Vf} = \sqrt{\mathcal{R}_f}\,(T_3^f - 2Q_f\mathcal{K}_f \sin^2\theta_W)$$
$$\mathcal{G}_{Af} = \sqrt{\mathcal{R}_f}\,T_3^f\,.$$

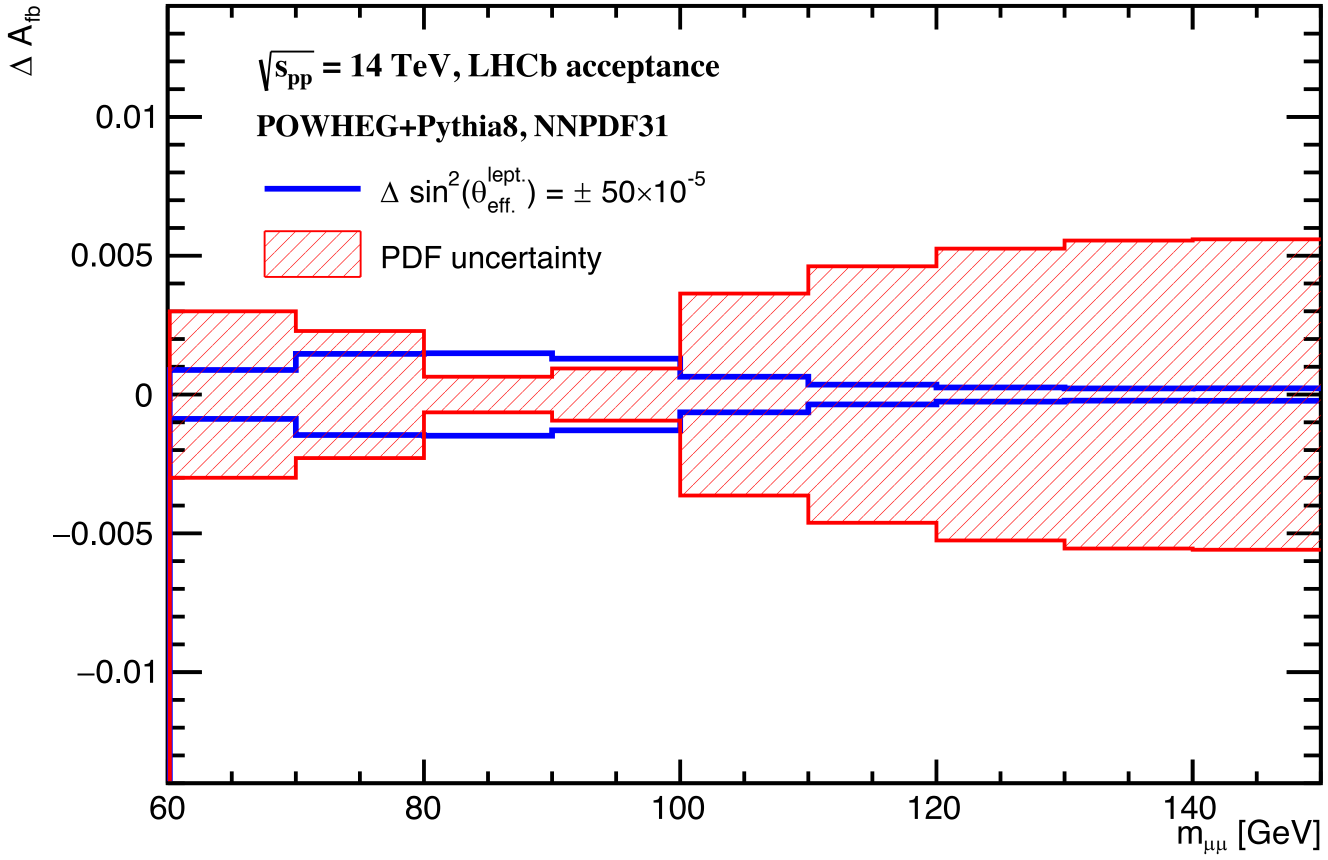
$$\frac{g_{Vf}}{g_{Af}} = \Re\left(\frac{\mathcal{G}_{Vf}}{\mathcal{G}_{Af}}\right) = 1 - 4|Q_f|\sin^2\theta_{eff}^f$$

Figure 7.6: Comparison of the effective electroweak mixing angle $\sin^2\theta_{eff}^{lept}$ derived from measurements depending on lepton couplings only (top) and also quark couplings (bottom). Also shown is the SM prediction for $\sin^2\theta_{eff}^{lept}$ as a function of m_H. The additional uncertainty of the SM prediction is parametric and dominated by the uncertainties in $\Delta\alpha^{(5)}_{had}(m_Z^2)$ and m_t, shown as the bands. The total width of the band is the linear sum of these effects.

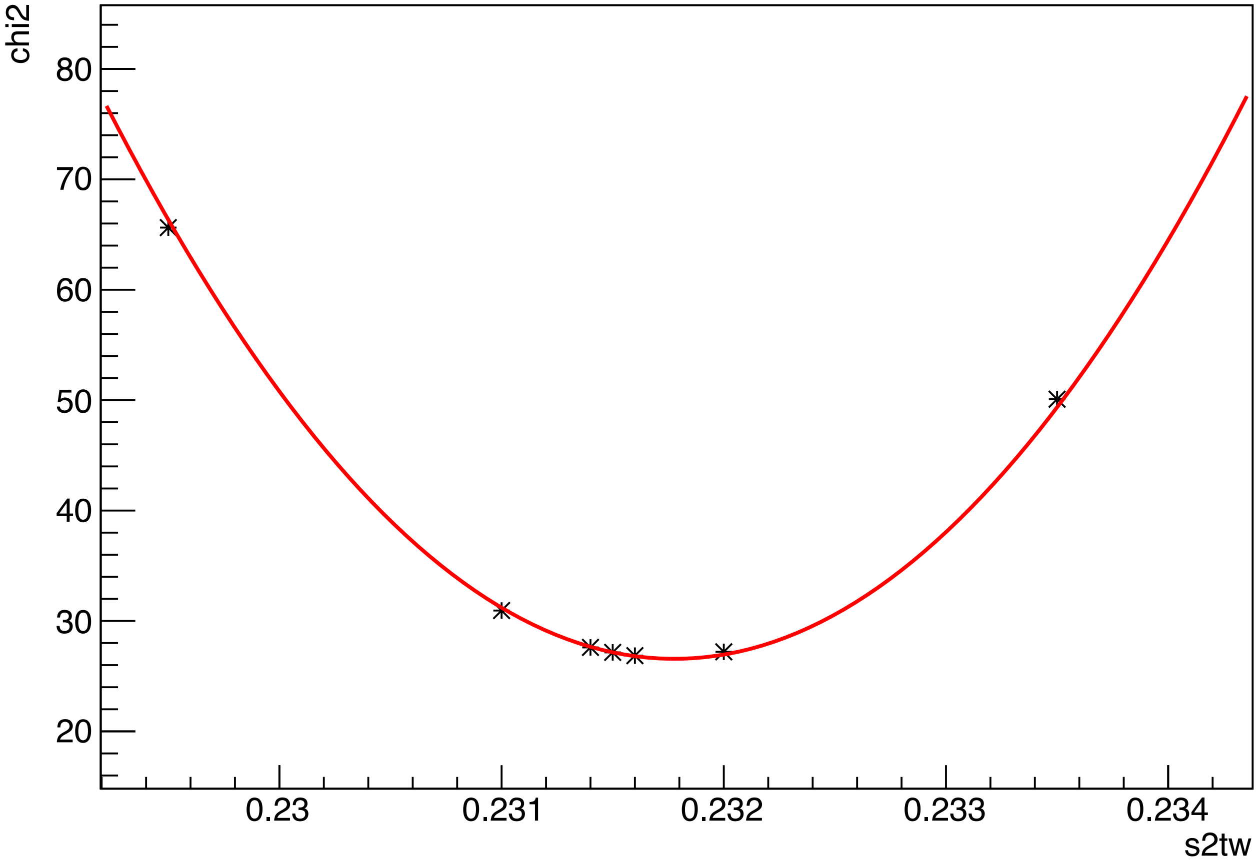
Weak mixing at LHCb



Weak mixing at LHCb



Weak mixing at LHCb



B anomalies: $b \rightarrow sll$ transitions

- Measure using several trigger categories – all consistent.

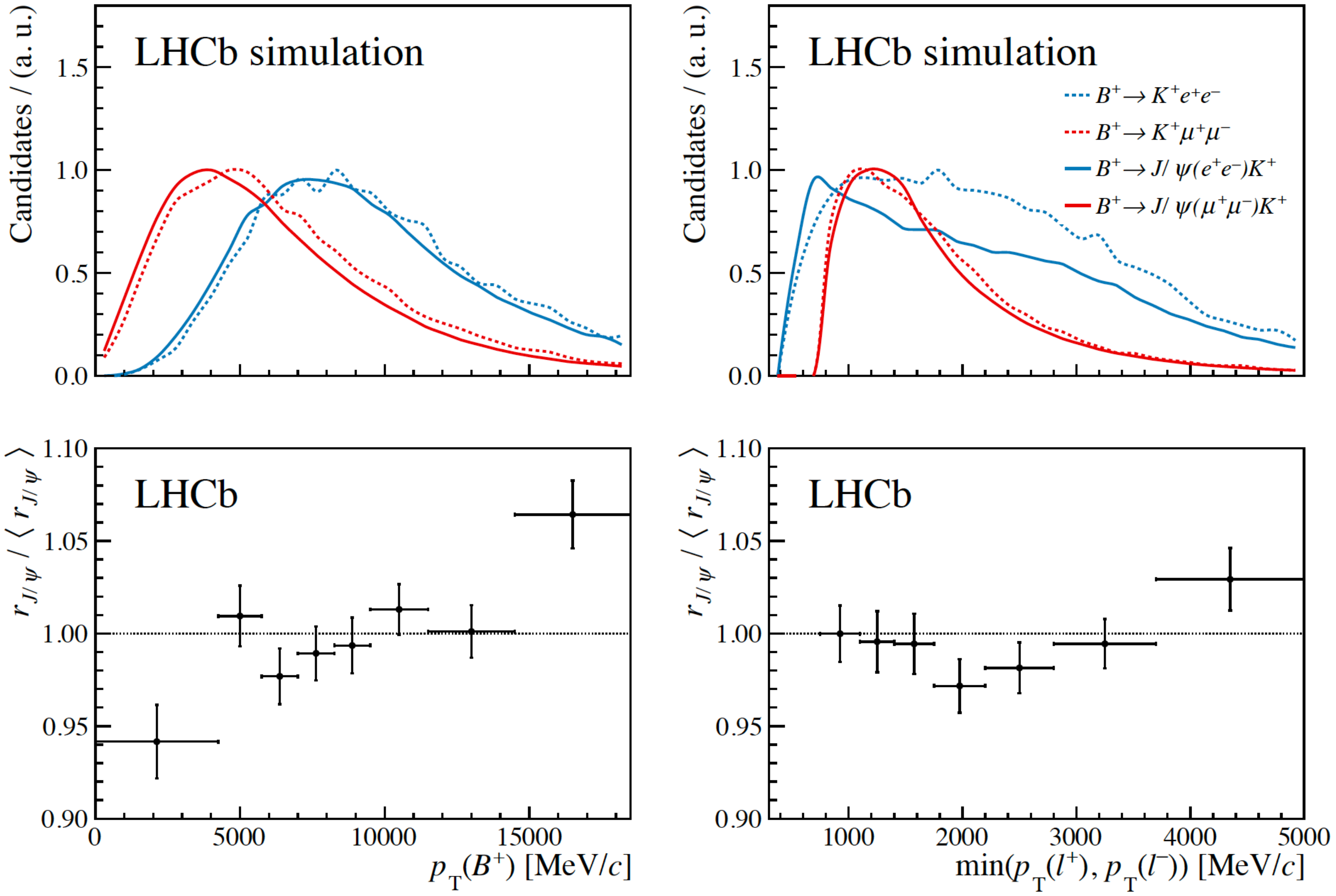
- Cross-check by finding

$$r_{J/\psi} = \frac{\mathrm{BF}(B^+ \rightarrow K^+ J/\psi(\rightarrow \mu\mu))}{\mathrm{BF}(B^+ \rightarrow K^+ J/\psi(\rightarrow ee))} = 1.014 \pm 0.035$$

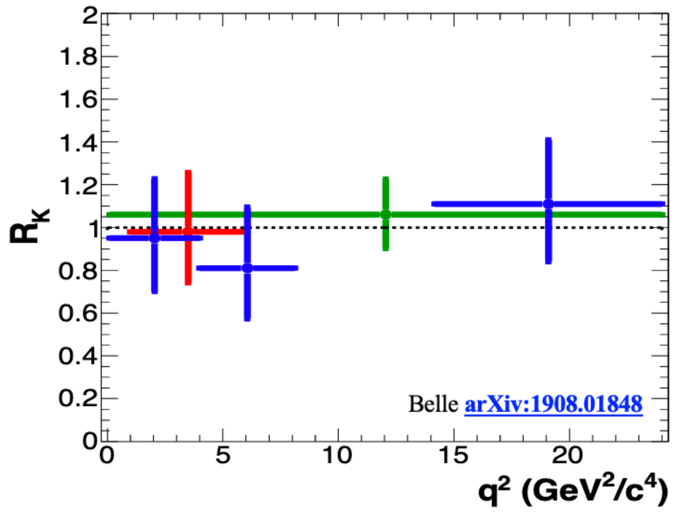
[also studied across the phase space]

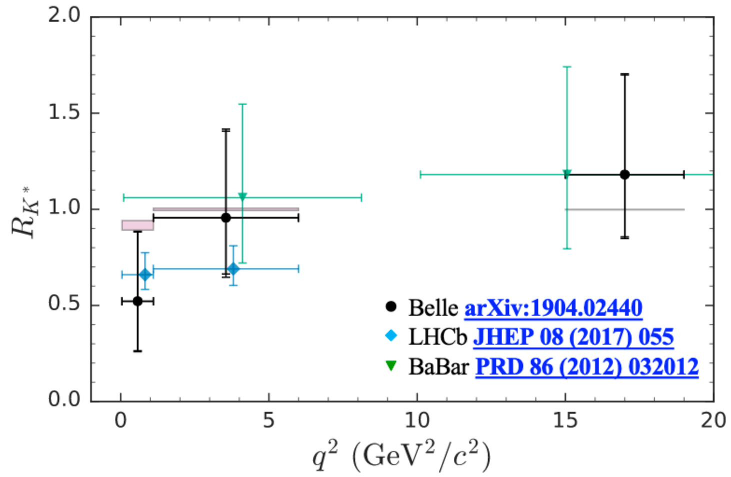
$$R_X = \frac{\mathrm{BF}(B^+ \rightarrow K^+ \psi(2S)(\mu\mu))}{\mathrm{BF}(B^+ \rightarrow K^+ J/\psi(\rightarrow \mu\mu))} \Big/ \frac{\mathrm{BF}(B^+ \rightarrow K^+ \psi(2S)(ee))}{\mathrm{BF}(B^+ \rightarrow K^+ J/\psi(\rightarrow ee))} = 0.986 \pm 0.013$$

B anomalies: $b \rightarrow sll$ transitions



B anomalies: $b \rightarrow sll$ transitions

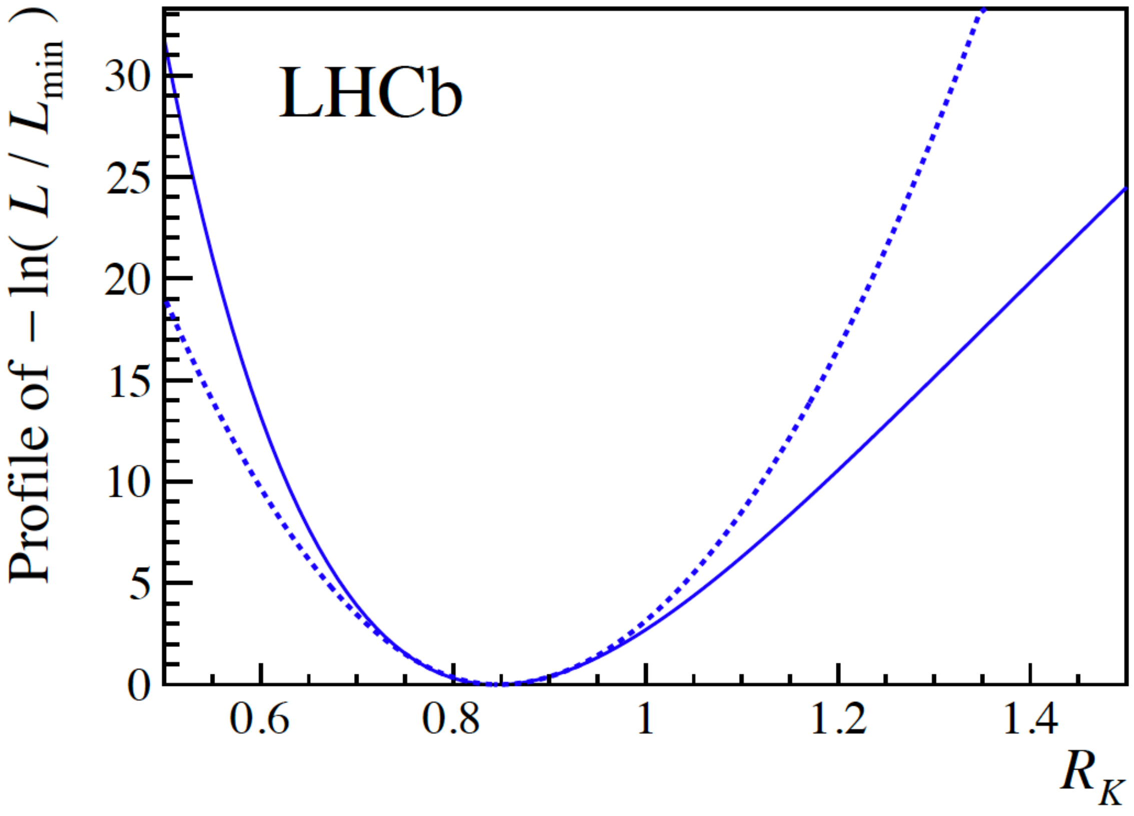




B anomalies: $b \rightarrow sll$ transitions

$$R_K^{7\,\mathrm{and}\,8\,\mathrm{TeV}} = 0.717\,^{+0.083}_{-0.071}\,^{+0.017}_{-0.016}$$

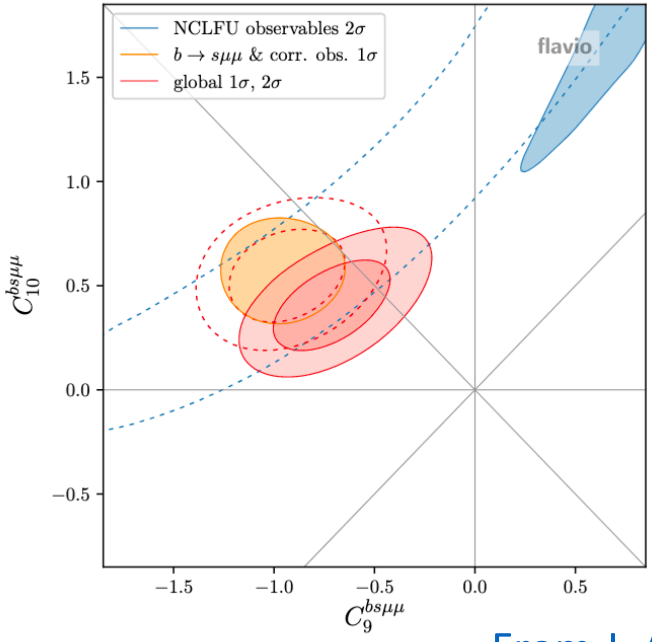
$$R_K^{13\,\mathrm{TeV}} = 0.928\,^{+0.089}_{-0.076}\,^{+0.020}_{-0.017}$$

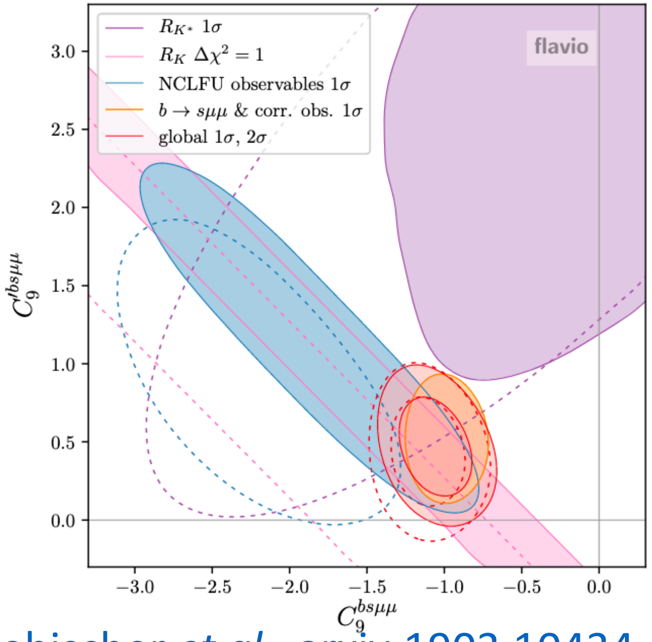


J. Aebischer *et al.*, arxiv:1903.10434

B anomalies

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$
$$O_S^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, \qquad O_S'^{bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\ell)\,,$$
$$O_P^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P'^{bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$





From J. Aebischer *et al.*, arxiv:1903.10434

Figure 1: Likelihood contours of the global fit and several fits to subsets of observables (see text for details) in the plane of the WET Wilson coefficients $C_9^{bs\mu\mu}$ and $C_{10}^{bs\mu\mu}$ (left), and $C_9^{bs\mu\mu}$ and $C_9'^{bs\mu\mu}$ (right). Solid (dashed) contours include (exclude) the Moriond-2019 results for R_K and R_{K^*}. As R_K only constrains a single combination of Wilson coefficients in the right plot, its 1σ contour corresponds to $\Delta\chi^2 = 1$. For the other fits, 1 and 2σ contours correspond to $\Delta\chi^2 \approx 2.3$ and 6.2, respectively.