Imperial College
London

Summary of LHCb results

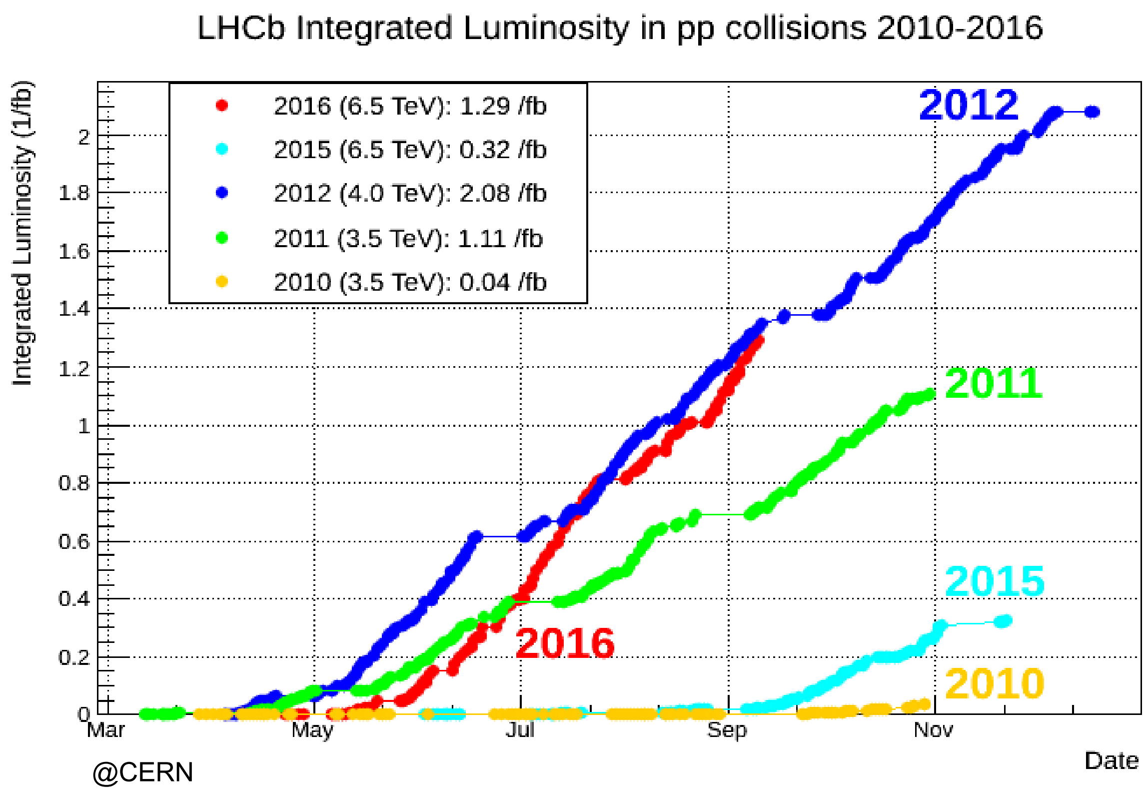
Ulrik Egede
on behalf of the LHCb collaboration

HC2NP, Tenerife 27 Sep 2016

LHC status

Fantastic progress for LHC this year is fantastic

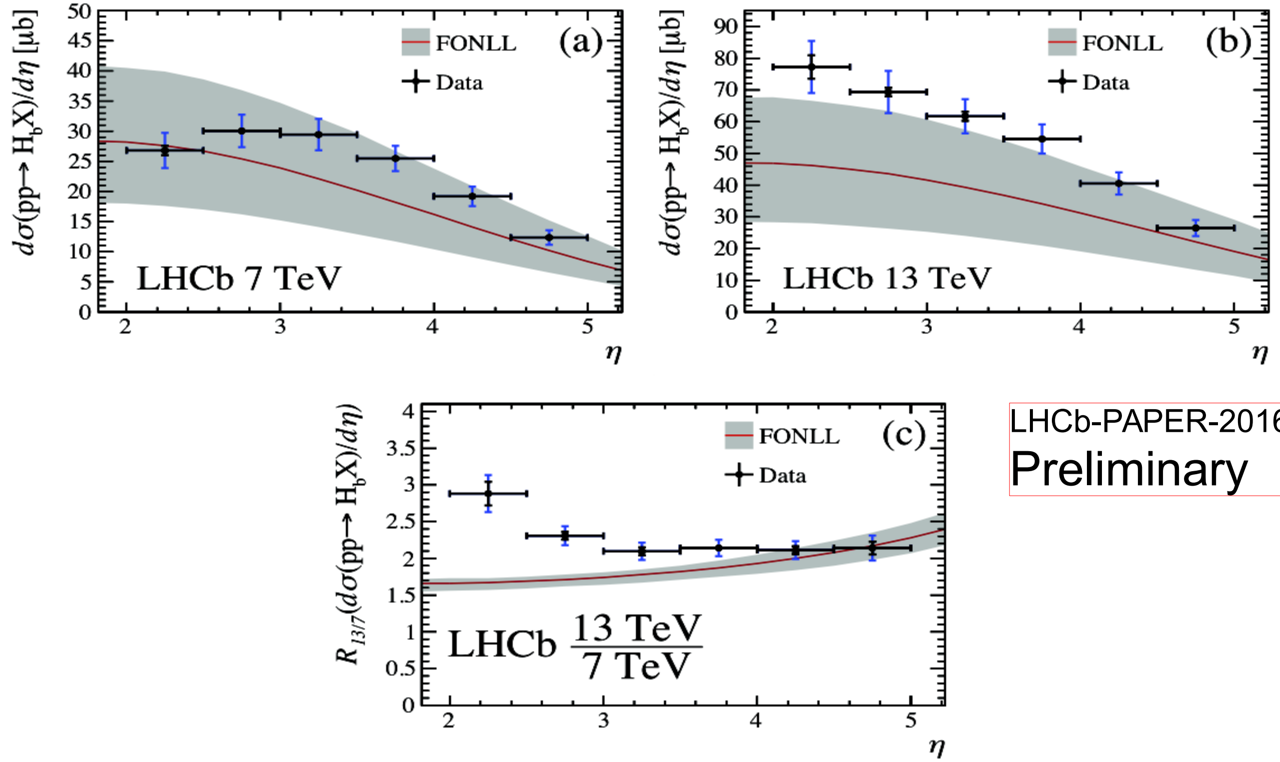
- For many LHCb analyses the effective dataset might almost double with respect to Run-I at the end of 2016



Still mainly results from Run-I but Run-I+II is getting there

Production cross section

The b production cross section $\sigma(pp \to H_b X)$ has been measured in the forward region $2<\eta<5$.



LHCb-PAPER-2016-031
Preliminary

At the increased energy the production goes more central than prediction. Overall a factor two higher.

Tree level

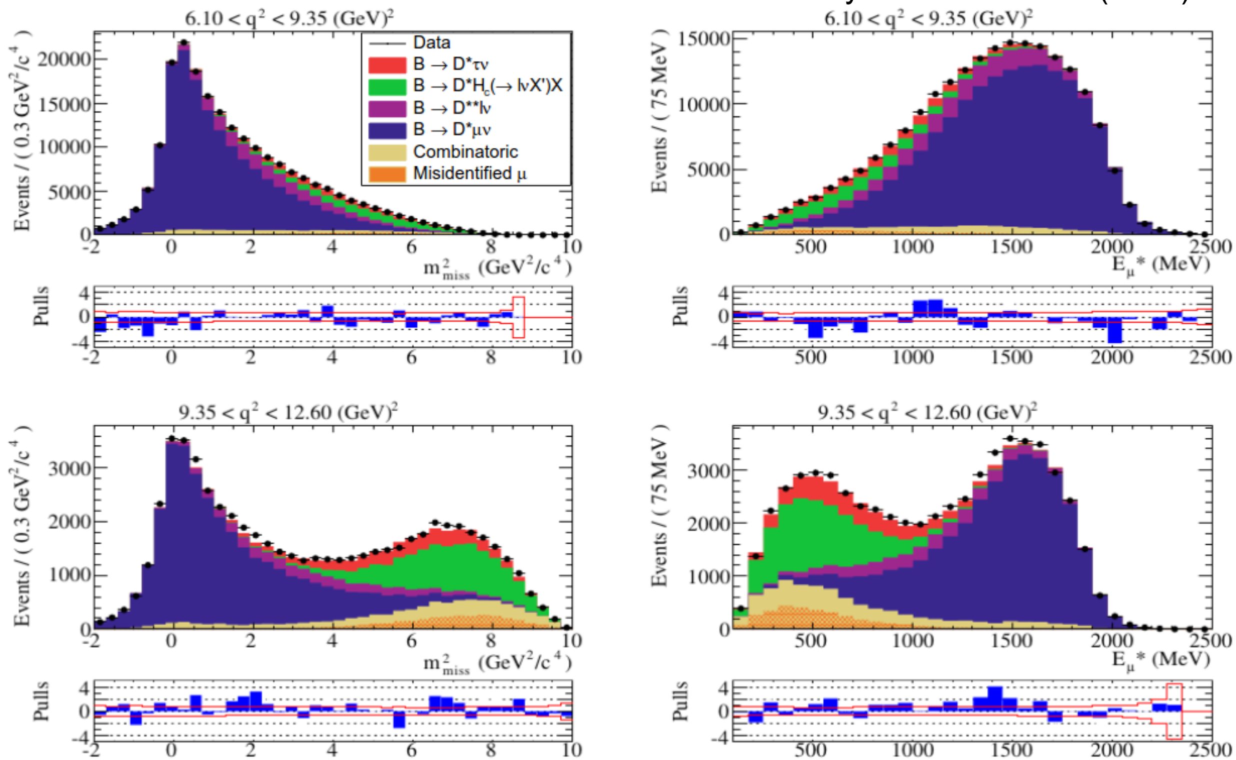
$B^0 \to D^{*+} \tau \nu$

$|V_{ub}|/|V_{cb}|$ update

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

LHCb has contributed with one measurement on lepton non-universality in B→Dlν decays

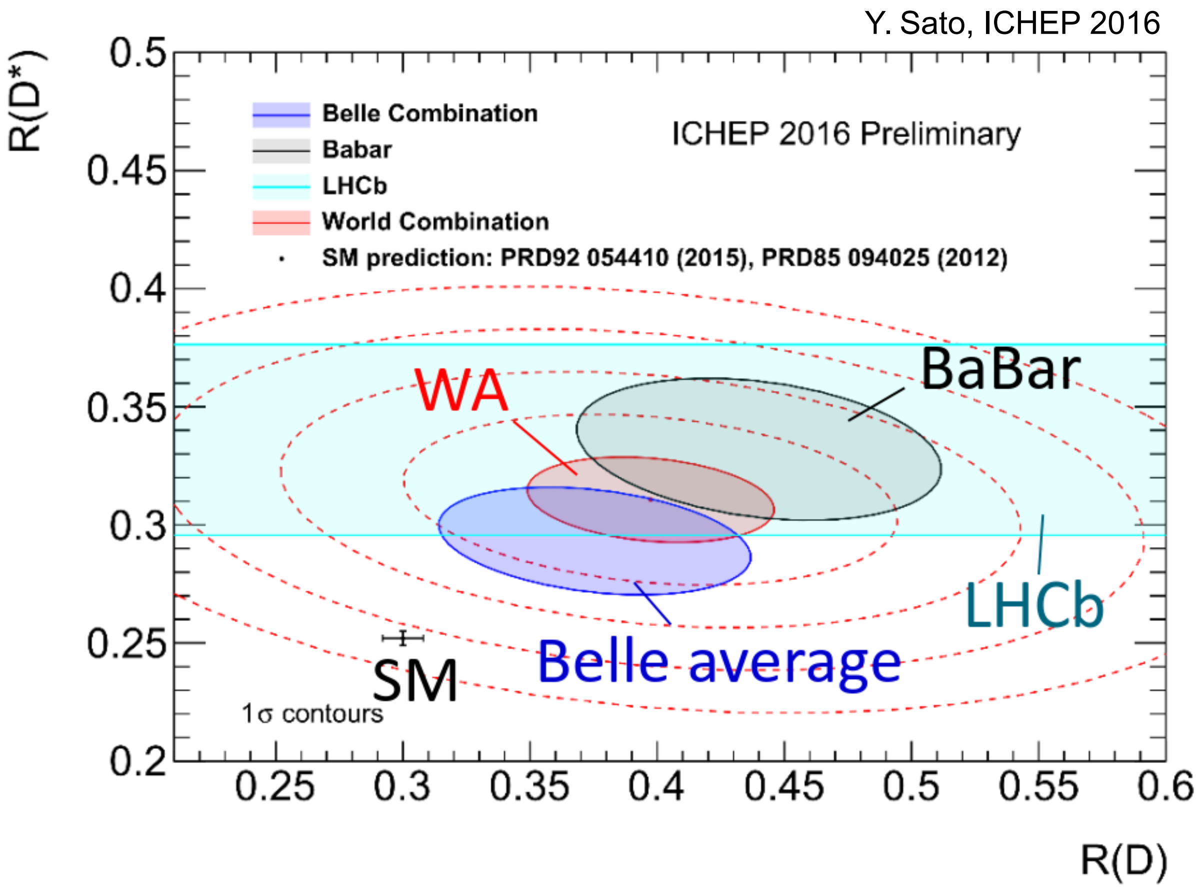
Phys. Rev. Lett. 115 (2015)



The measurement of many more τ/μ ratios on the way

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

The measurements are internally consistent and have a 4σ tension with SM prediction



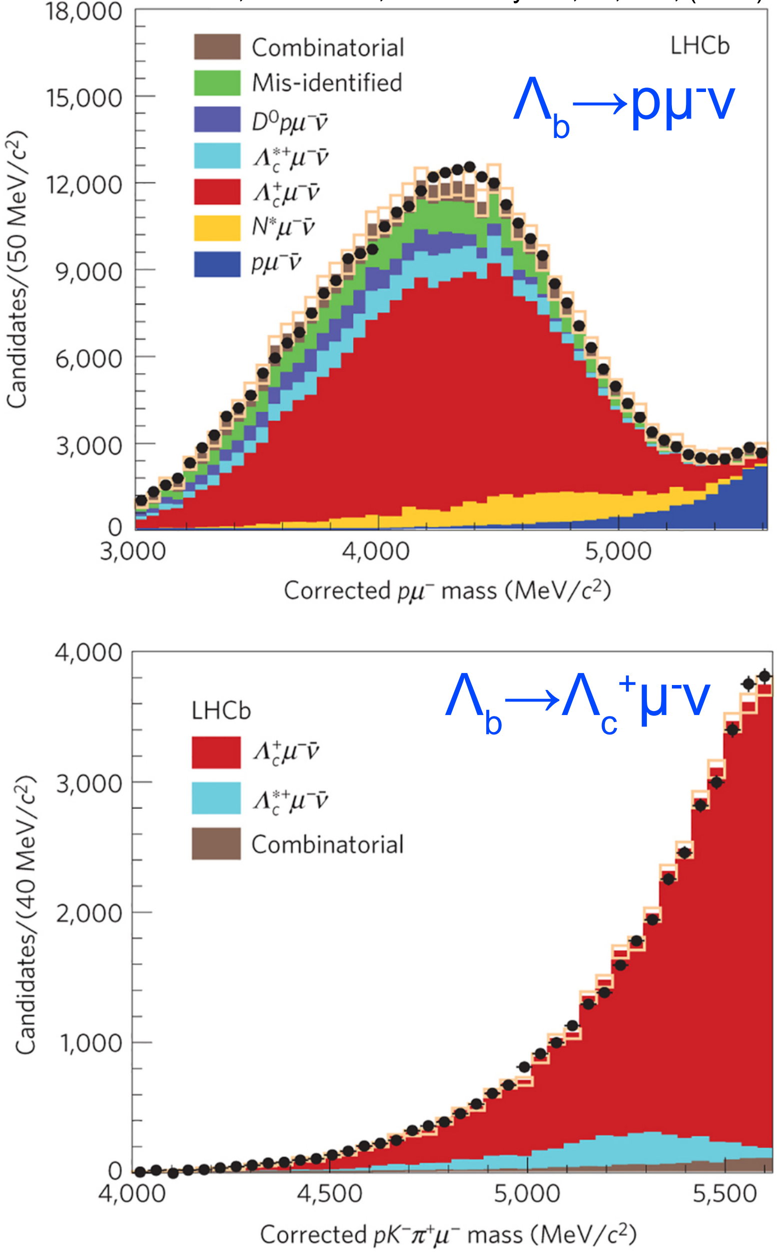
Measurement of $|V_{ub}|/|V_{cb}|$

The ratio of CKM elements can be measured from

- The BF ratio of $\Lambda_b \to p\mu^- \nu$ and $\Lambda_b \to \Lambda_c^+ \mu^- \nu$ combined with Lattice QCD prediction of form factors
- Only events in the high q^2 region is considered to lower lattice uncertainty

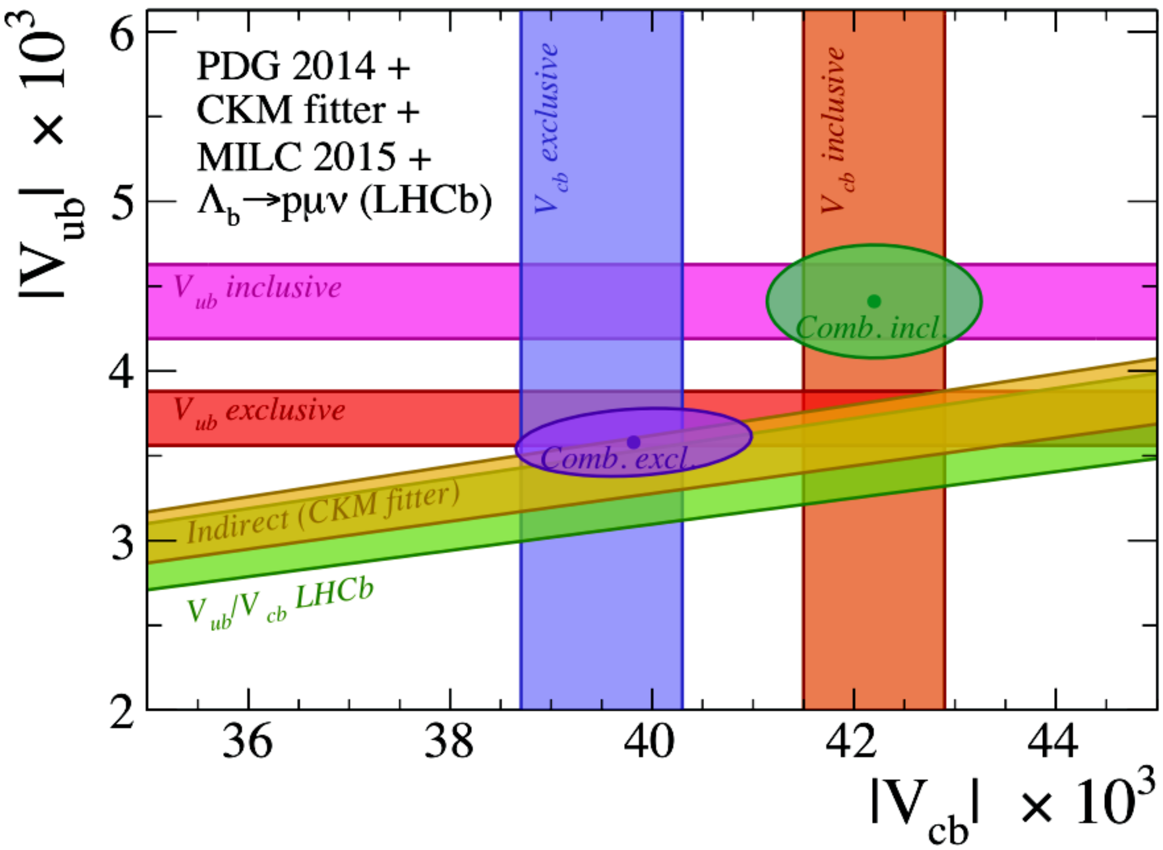
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

Uncertainty dominated by $BF(\Lambda_c^+ \to pK\pi)$ and lattice form factors



CKM matrix elements (incl. vs excl.)

Combining the new LHCb measurement with existing measurements of $|V_{cb}|$ and $|V_{ub}|$ enhance discrepancy between inclusive and exclusive measurements



CKM matrix elements (incl. vs excl.)

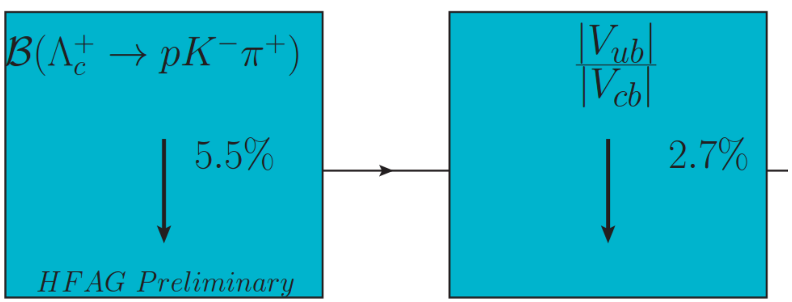
Published measurement based on normalisation with

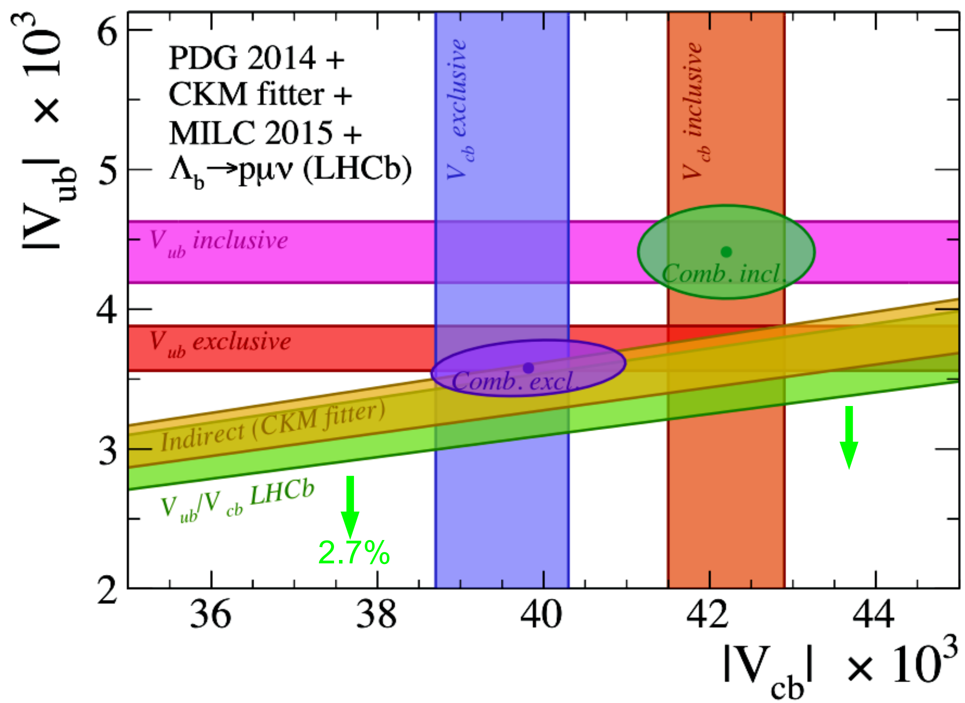
$$BF(\Lambda_c \to pK\pi) = (6.84 \pm 0.24\,^{+0.21}_{-0.27})\%$$

BES-III has since measured many Λ_c modes and their correlations

Combined fit gives

$$BF(\Lambda_c \to pK\pi) = (6.46 \pm 0.24)\%$$





Tension with inclusive is increasing slightly

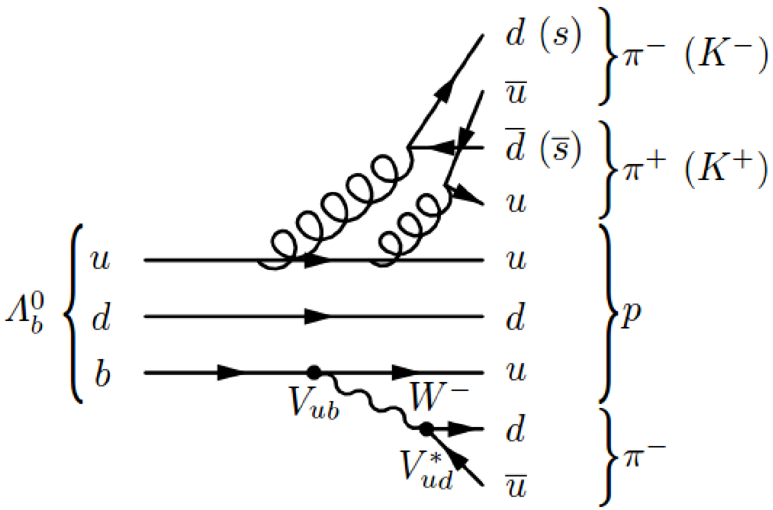
CP violation in baryon decays

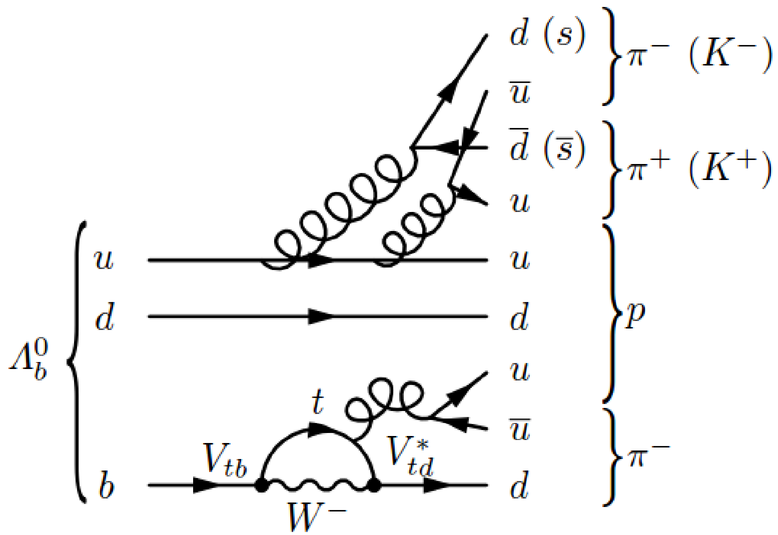
CP violation in baryon decays

So far CP violation only seen in K^0, B^0 and B^0_s decays

Never in baryons!

Search for direct CP violation in $\Lambda_b \to p\pi^-\pi^+\pi^-$ decays



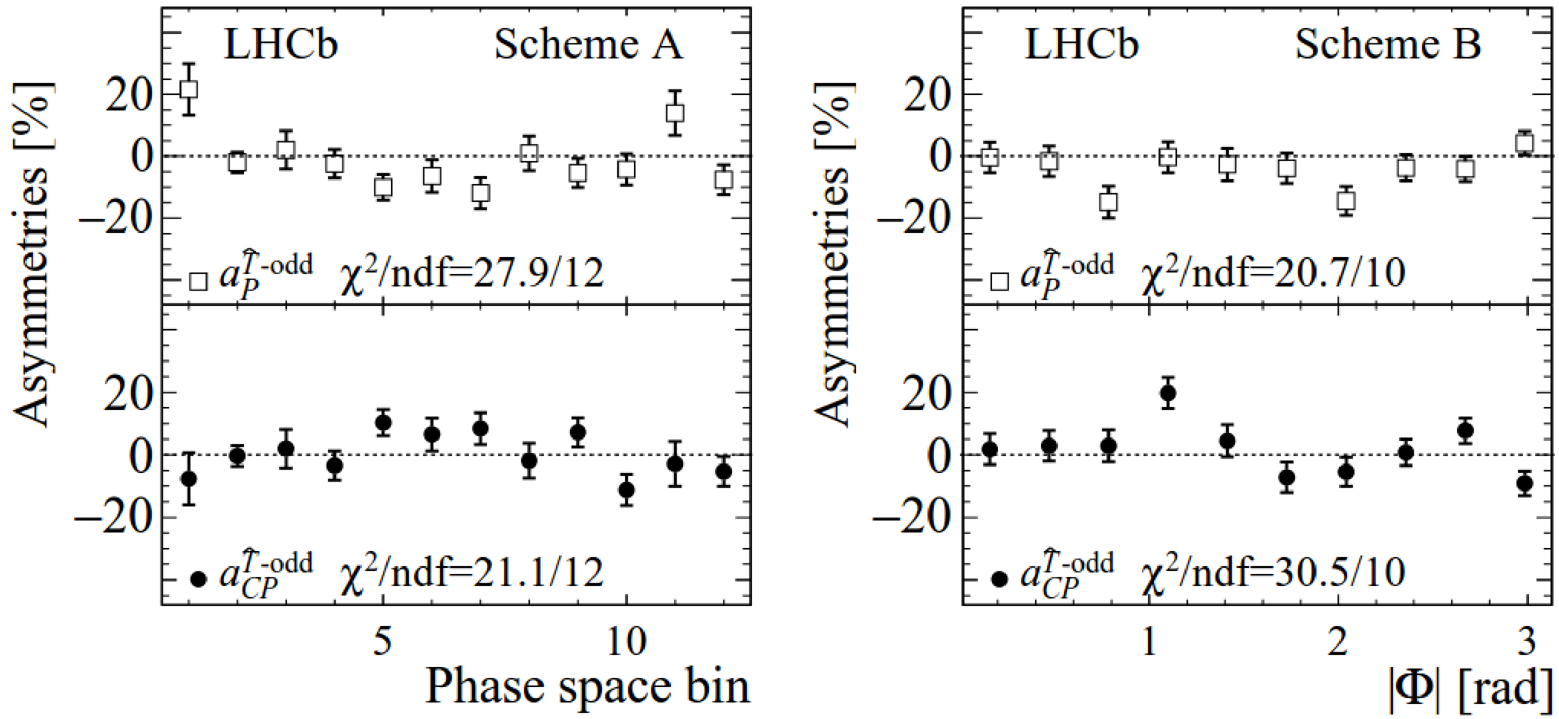


arXiv:1609.05216

CP violation in baryon decays

Looking at $\Lambda_b/\overline{\Lambda}_b$ difference in asymmetry of scalar triple products for $p\pi^+\pi^-$ system

Studied across phase space to avoid cancellations



Overall 3.3σ significance for direct CP violation in decay

Penguin decays

New results

- $\Sigma^+ \to p\mu^+\mu^-$
- $B^0_s \to \phi\gamma$
- $B^0_s \to \tau^+\tau^-$
- $B \to 4\mu$
- $K^0_s \to \mu^+\mu^-$

$B \to K^*\mu\mu$, $B \to Kll$

- HepData record
- S-wave

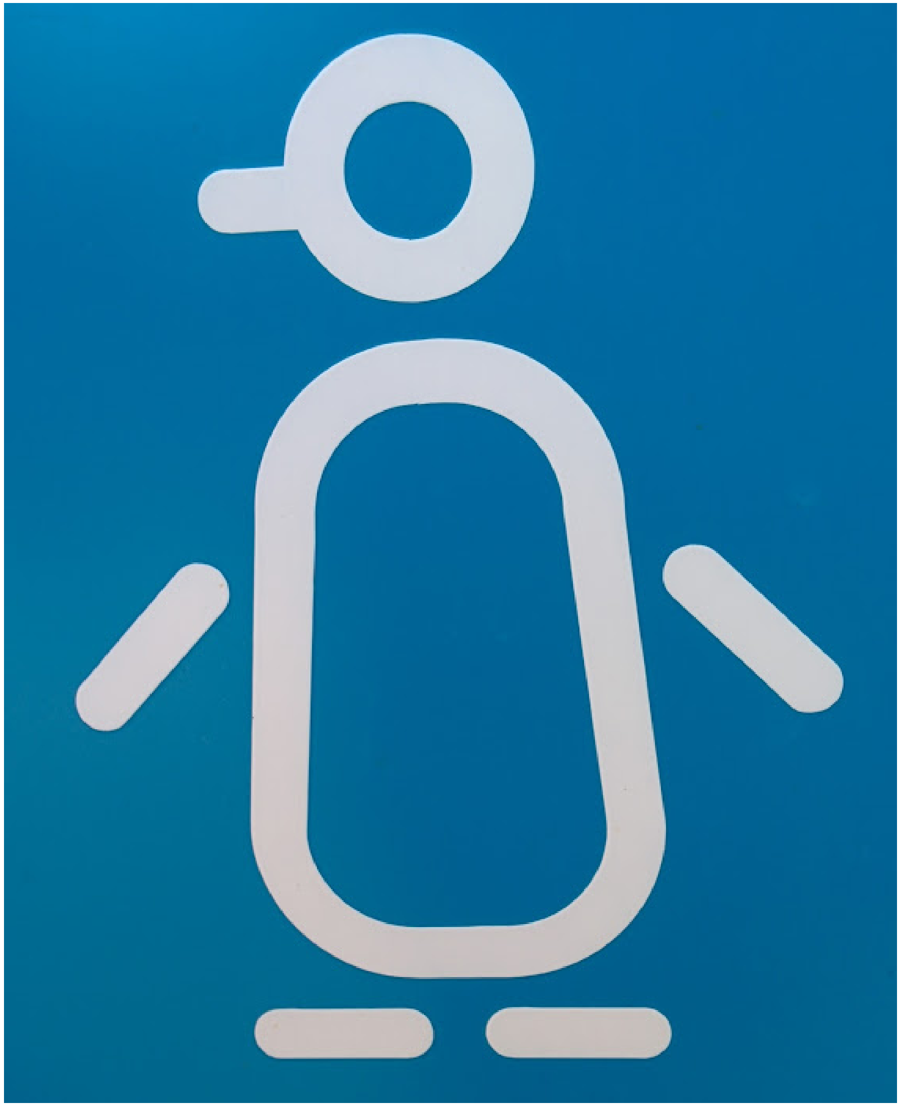
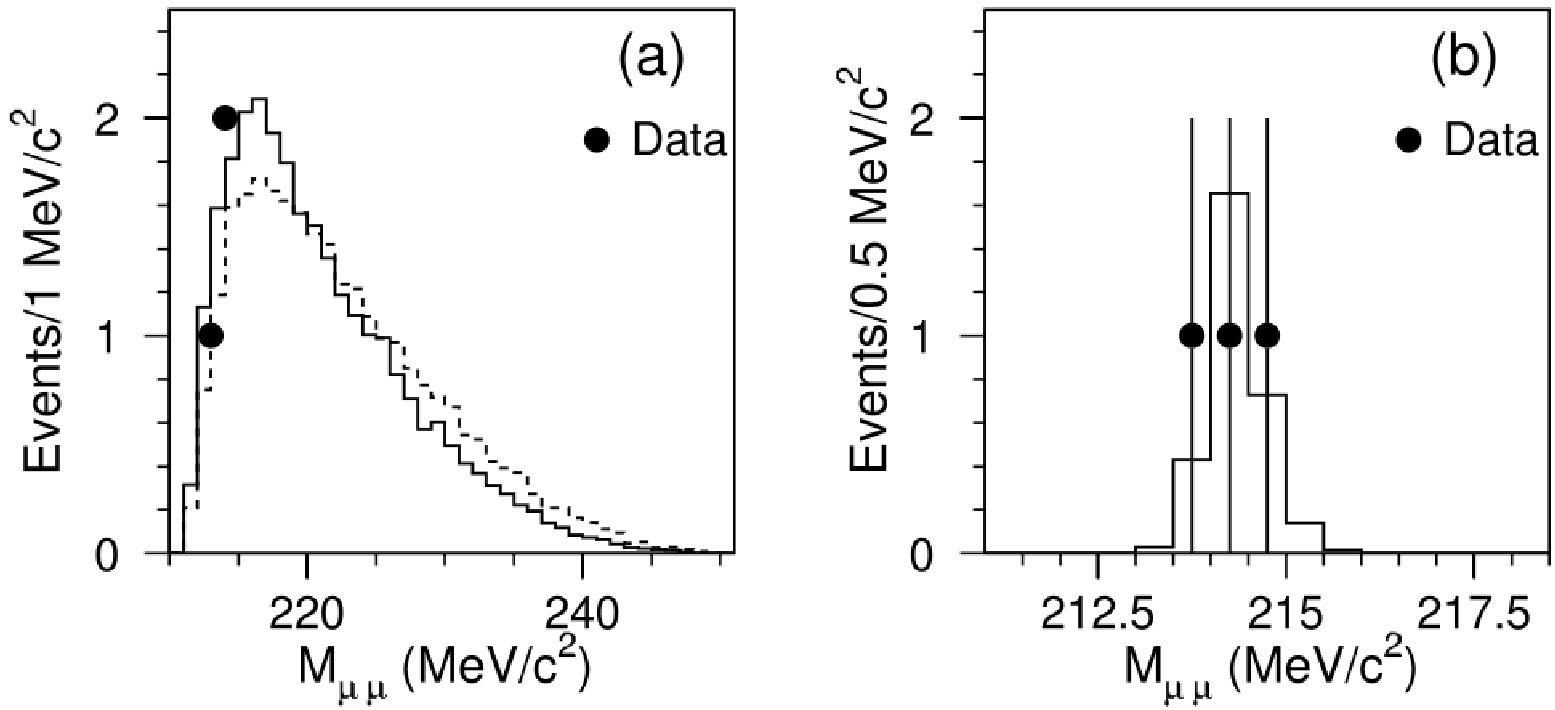


Photo U.Egede, @ Phillip Island Nature Parks

$\Sigma^+ \rightarrow p\mu^+\mu^-$

Since many years the HyperCP result has been hinting at some intermediate particle, $\Sigma^+ \rightarrow pP^0$, $P^0 \rightarrow \mu^+\mu^-$ with mass 214.3 MeV/c^2

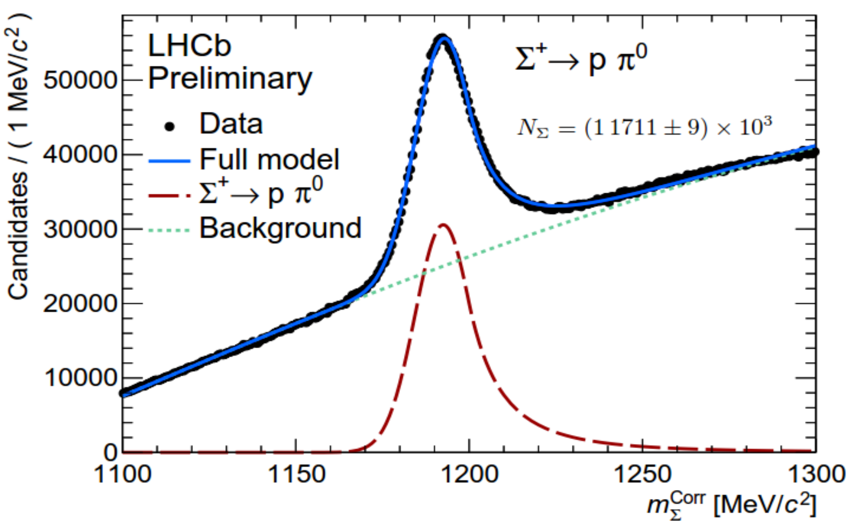
@APS, Phys. Rev. Lett. 94, 021801



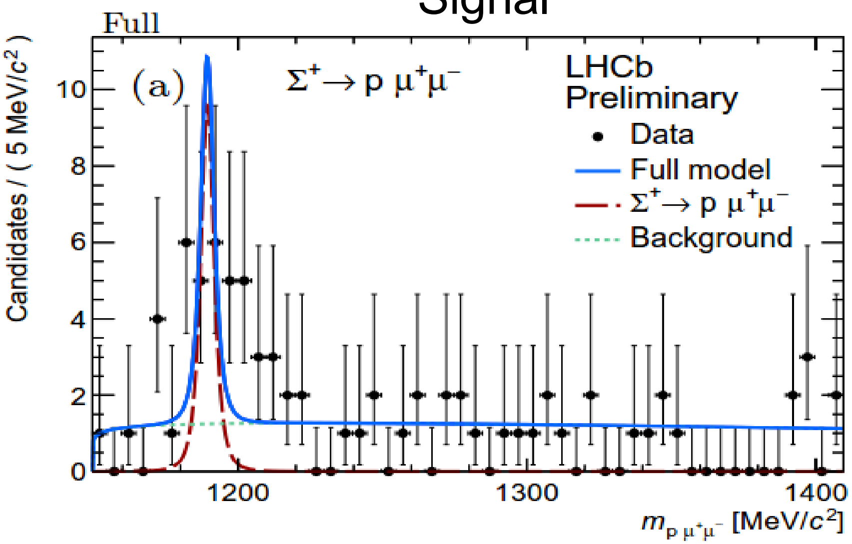
$\Sigma^+ \rightarrow p\mu^+\mu^-$

- LHCb has searched for decay from prompt Σ^+ baryons
  - A challenge due to the small Q value of decay and long lifetime of Σ^+
- A clear signal is seen with $12.9^{+5.1}_{-4.2}$ events. Significance 4σ
  - Preliminary result is missing normalisation for part of data
  - Thus only upper limit rather than BF. BF < 6.3 10^{-8} @95%CL

Normalisation mode



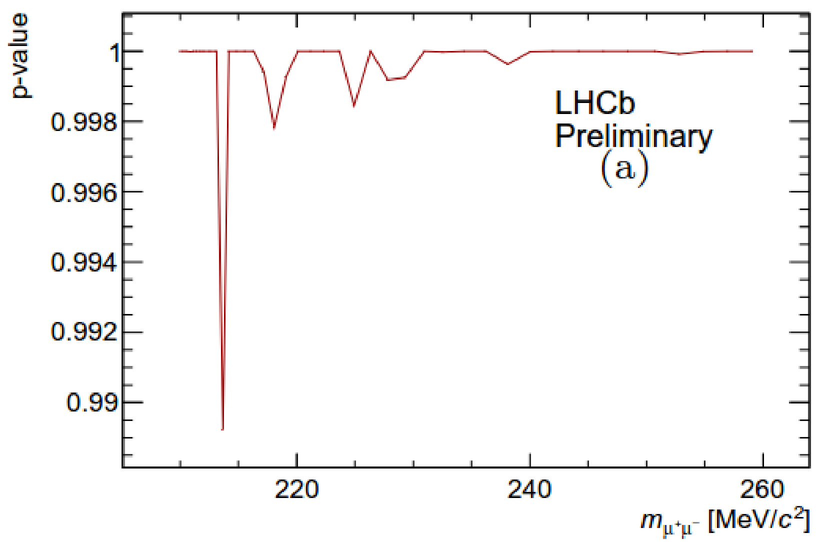
Signal

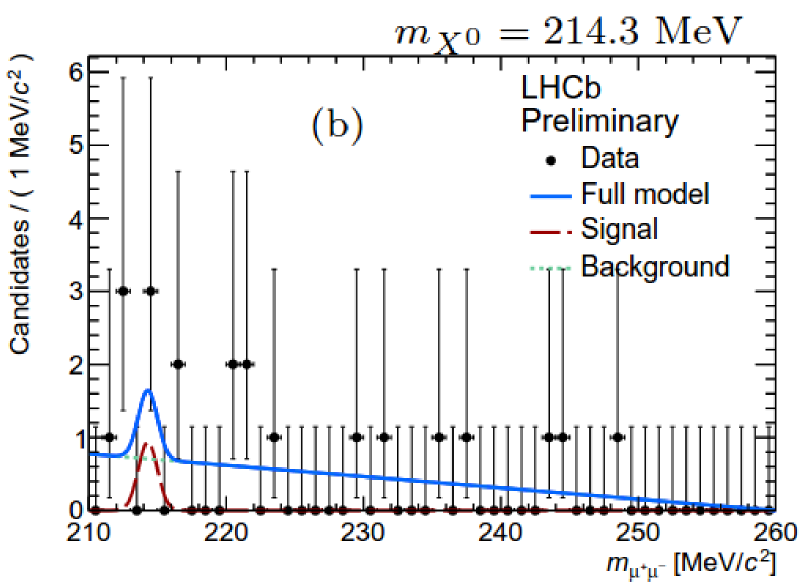


$\Sigma^+ \to p\mu^+\mu^-$

The data was background subtracted and then a fit made for a possible narrow peak in the dimuon mass

No sign for a narrow peak at all in spectra





$B^0_s \rightarrow \phi\gamma$

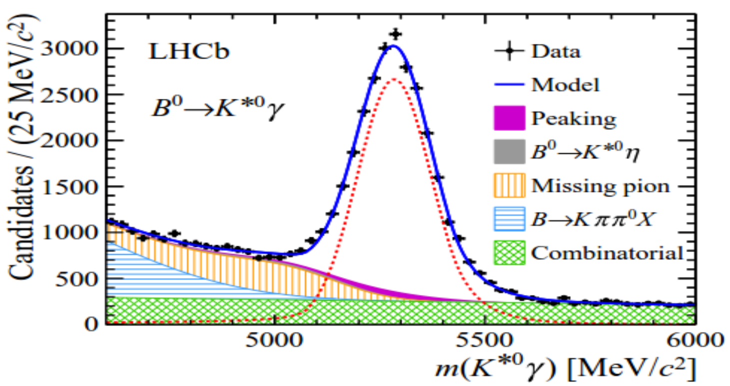
An analysis of the lifetime distribution in $B^0_s \rightarrow \phi\gamma$ can in principle reveal the presence of right handed currents in the decay

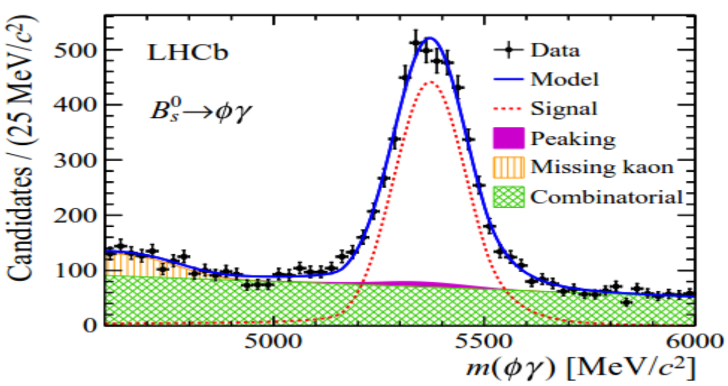
$$\mathcal{P}(t) \propto e^{-\Gamma_s t}\{\cosh(\Delta\Gamma_s t/2) - \mathcal{A}^{\Delta}\sinh(\Delta\Gamma_s t/2)\}$$

with $A^{\Delta} \propto 2\frac{\gamma_R}{\gamma_L}$. $A^{\Delta}_{SM} = 0.05 \pm 0.03$

Deviation from pure exponential is small and is correlated to efficiency as a function of decay time.

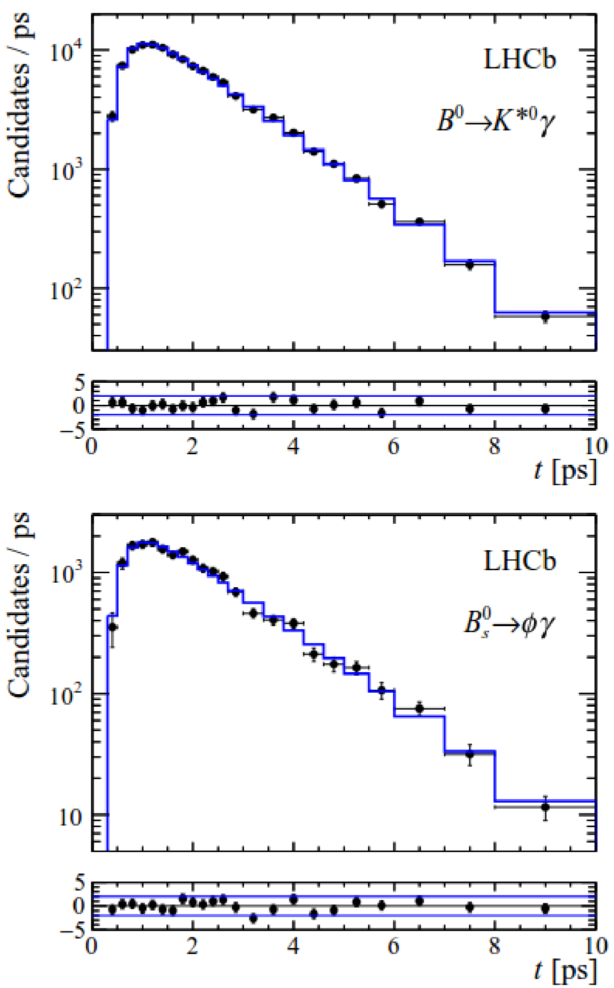
Use ratio to $B^0 \rightarrow K^{*0}\gamma$ to minimise this problem



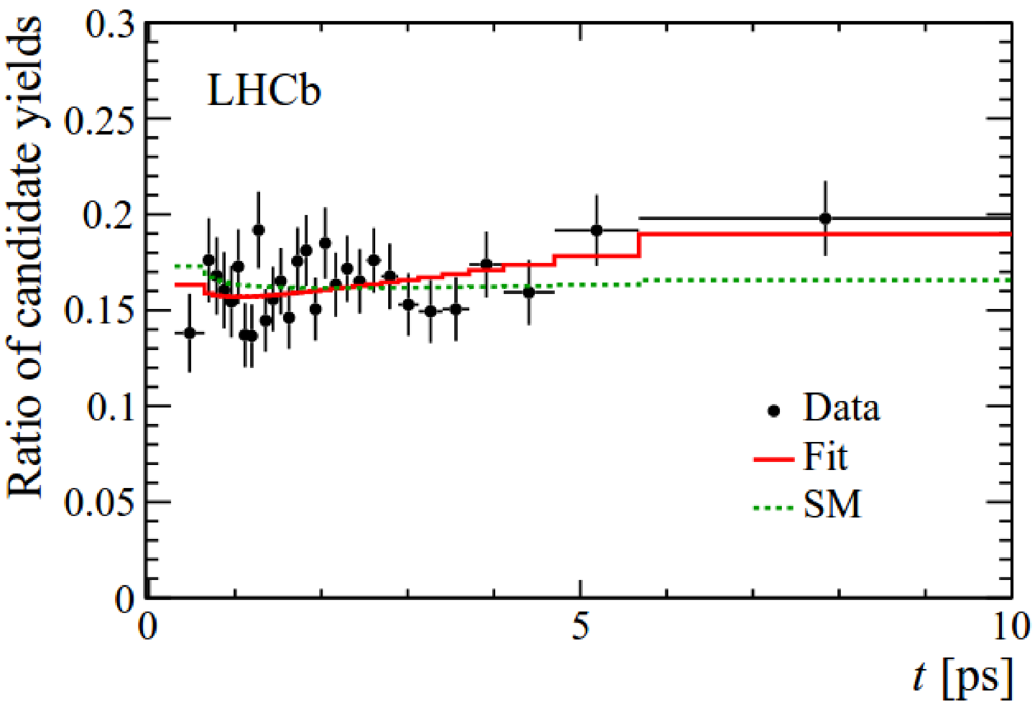


$B^0_s \rightarrow \varphi\gamma$

An analysis of the lifetime distribution in $B^0_s \rightarrow \varphi\gamma$ can in

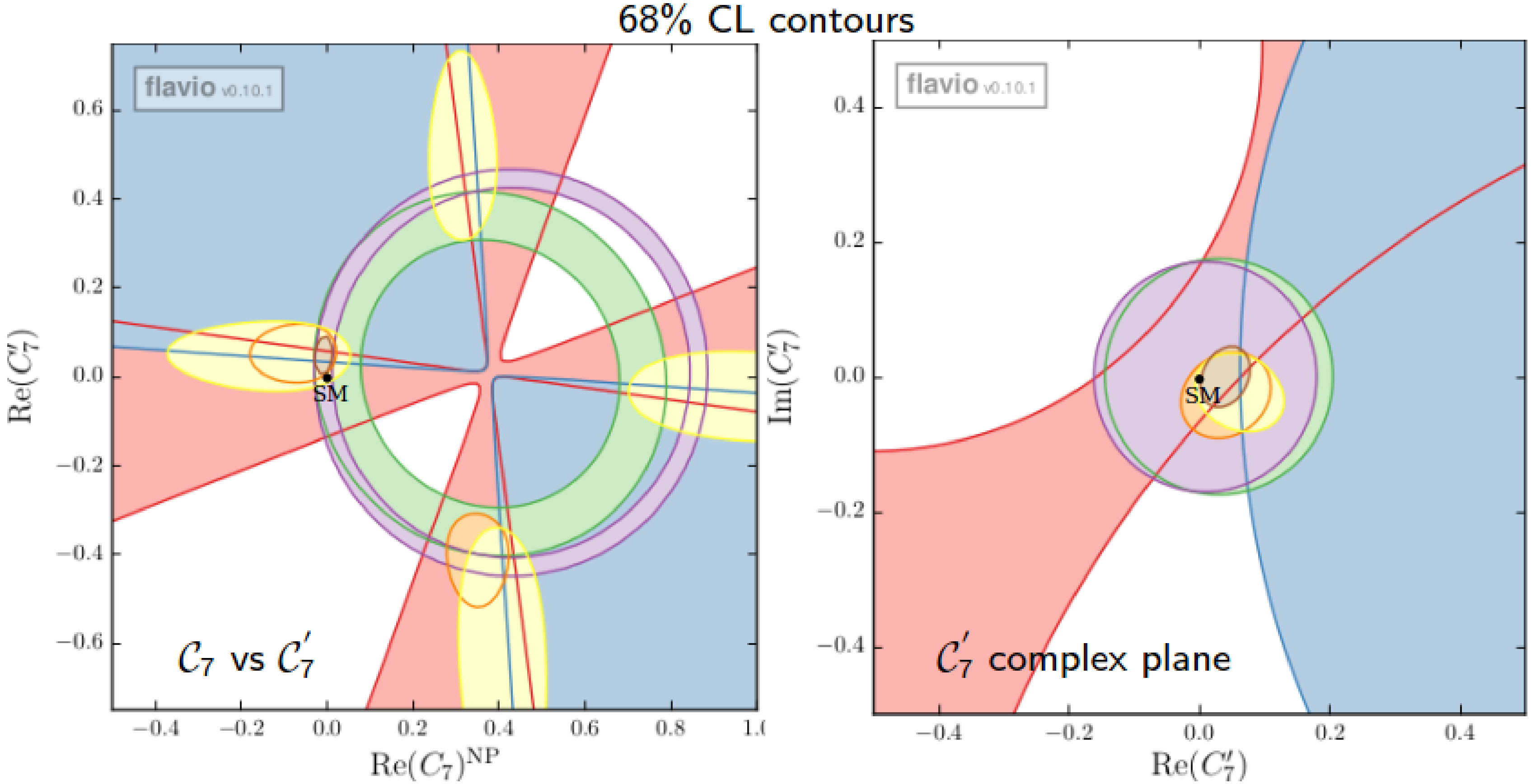


$$A^{\Delta} = -0.98 \,{}^{+0.46}_{-0.52}\, {}^{+0.23}_{-0.20}$$



$B^0_s \to \phi\gamma$

Constraints on right-handed currents

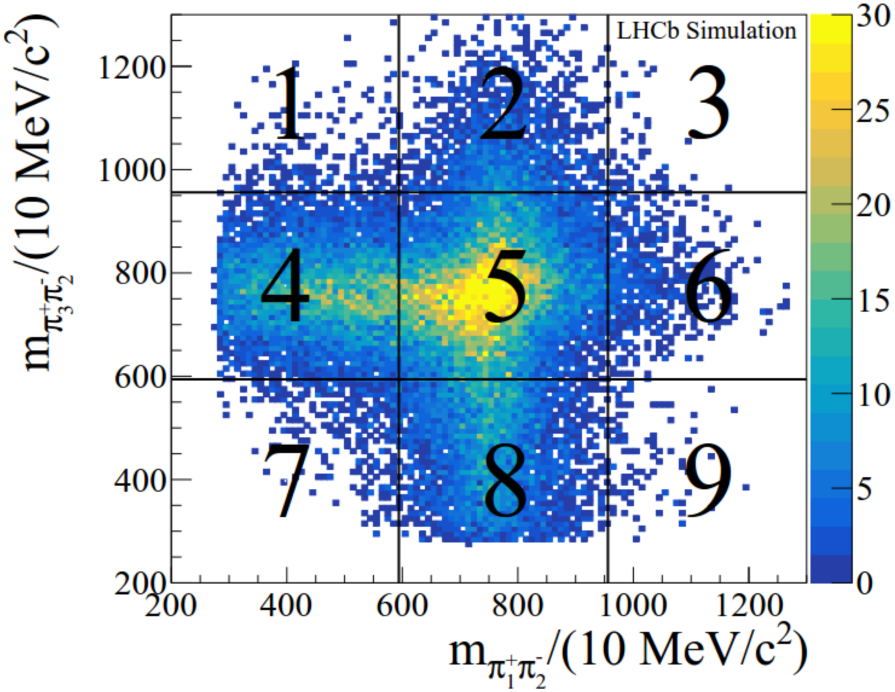


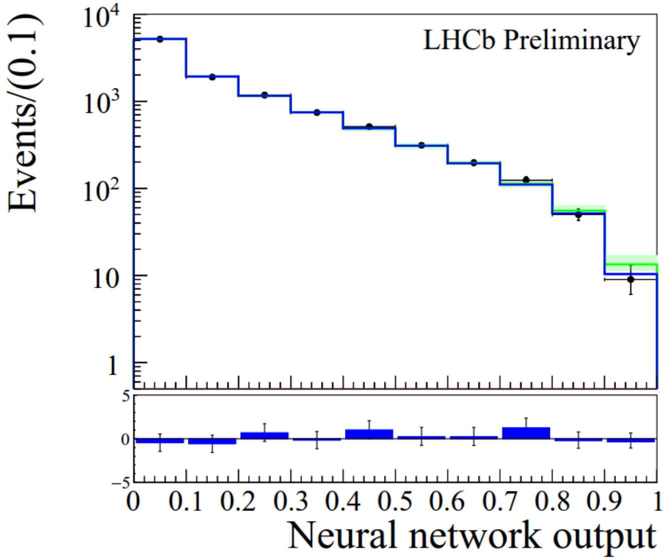
All combined
$\mathcal{A}^{\Delta}(B^0_s \to \phi\gamma)$ [LHCb: arXiv:1609.02032]
$\mathrm{ang}(B^0 \to K^{*0}e^+e^-)$ [LHCb: JHEP 04(2015)064]
$\mathrm{ang}(B^0 \to K^{*0}\mu^+\mu^-)$ [LHCb: JHEP 1602(2016)104]
$S_{K*\gamma}$ [HFAG: arXiv:1207.1158]
$\mathrm{BR}(B \to X_s\gamma)$ [HFAG: arXiv:1207.1158]
$\mathrm{BR}(B^0_s \to \phi\gamma)$ [LHCb: Nucl.Phys. B867(2013)1-18]
[Belle: PRD91 1(2015)011101]

$B^0_{(s)} \to \tau^+\tau^-$

The decays $B^0_{(s)} \to \tau^+\tau^-$ very interesting to search for

- The hadronic 3-prong decay of τ's used
  - Fewer neutrinos in signal but more background from D^+ and D^+_s decays





$n_{\mathrm{signal}} = -46 \pm 51$

$\mathrm{BF}\left(B_s^0 \to \tau^+\tau^-\right) < 3.0 \times 10^{-3}$ @ 95% CL

$K^0_s \to \mu^+\mu^-$, $B \to 4\mu$

Further limits are set on very rare decays

Limit on $K^0_s \to \mu^+\mu^-$ of

$$\mathrm{BF}\left(K_s^0 \to \mu^+\mu^-\right) < 6.9\times10^{-9} \text{ @ 95\% CL}$$

Set very strict limits for $B \to 4\mu$ decays

- Excludes the SM resonance regions (e.g. $B0s \to J/\psi\varphi$)
- Assumes that any NP intermediate resonances are short lived

$$\mathrm{BF}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 2.5\times10^{-9} \text{ @ 95\% CL}$$

$$\mathrm{BF}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 6.9\times10^{-10} \text{ @ 95\% CL}$$

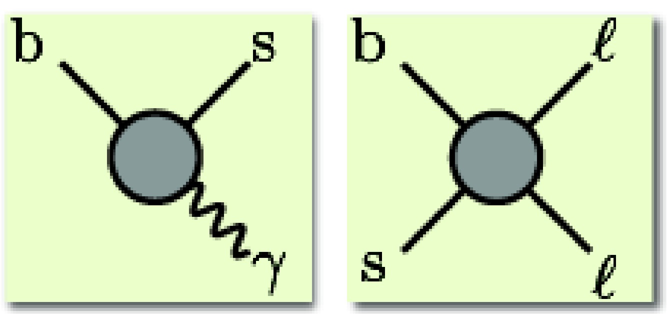
The penguin laboratory

The decay $B^0 \to K^{*0}\mu^+\mu^-$, $K^{*0} \to K^-\pi^+$ is in the SM only possible at loop level

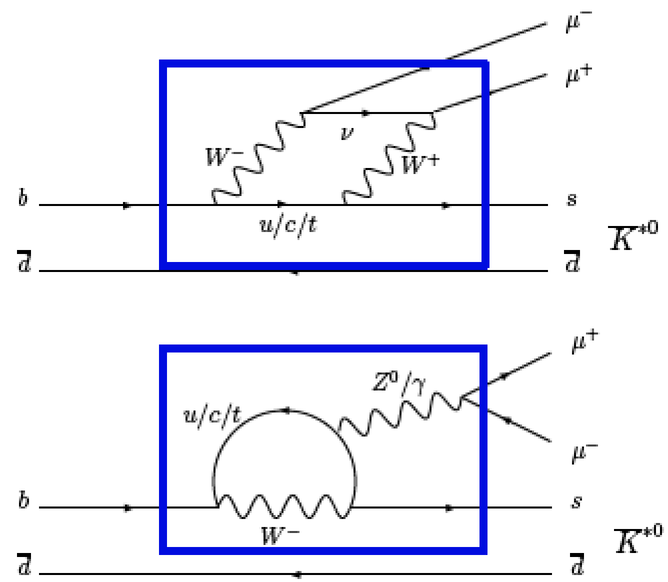
On the other hand NP can show up at either tree or loop level

Angular analysis of 4-body $K^-\pi^+\mu^+\mu^-$ final state brings large number of observables

Interference between these



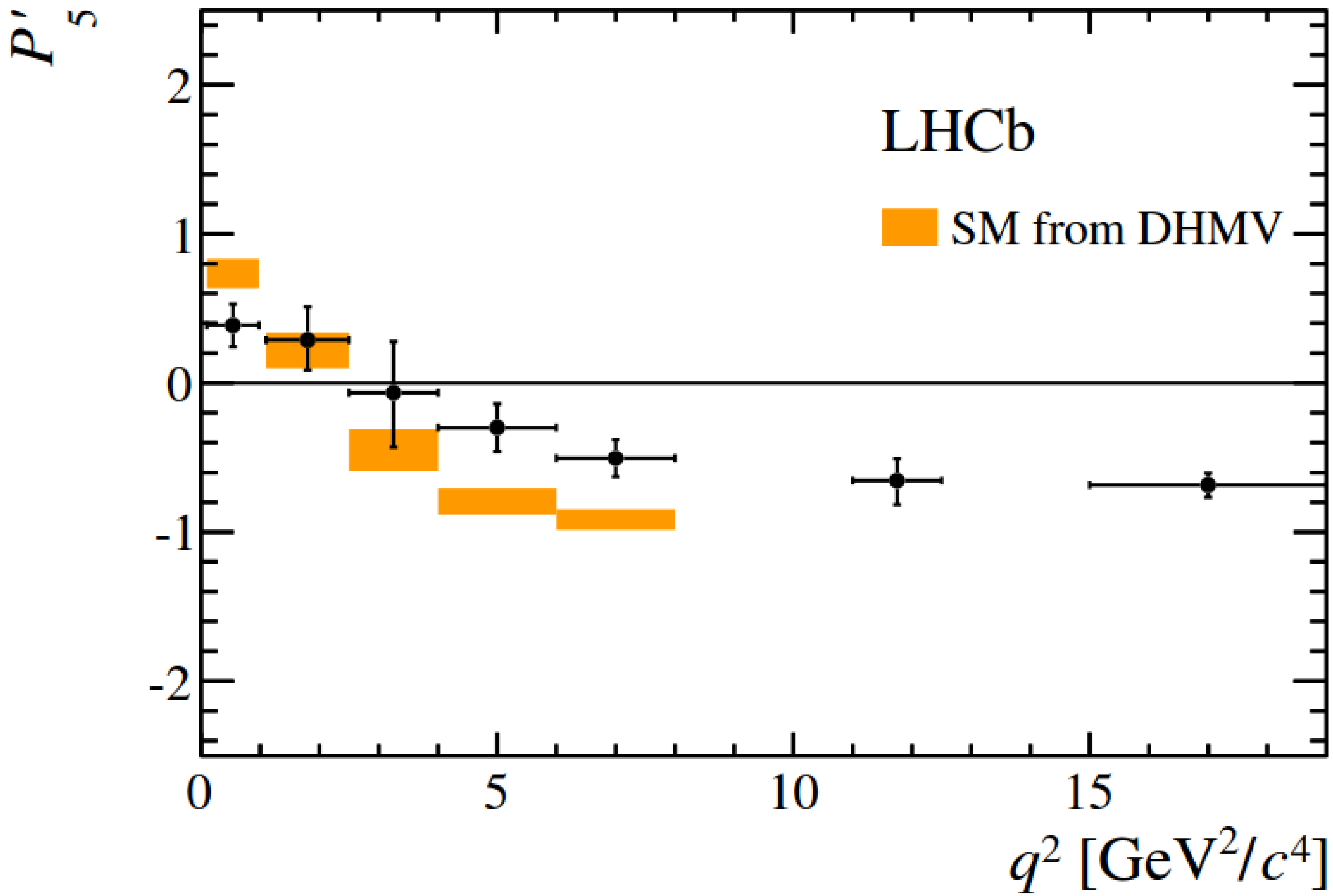
$O_{7\gamma}$ $O_{9,10}$



... and their right-handed counterparts

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

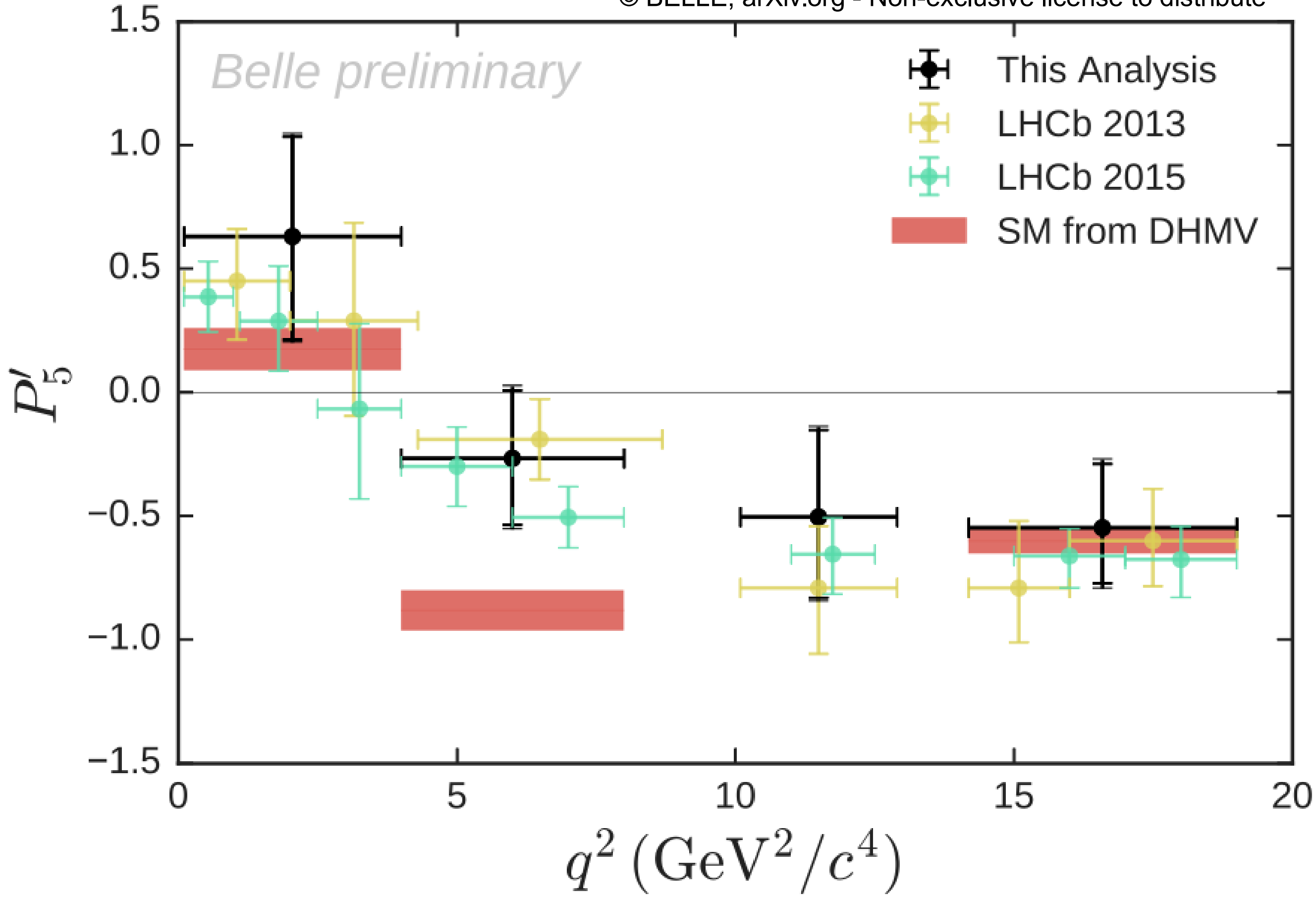
Results based on 3 fb^{-1} from LHCb



arXiv:1604.04042

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

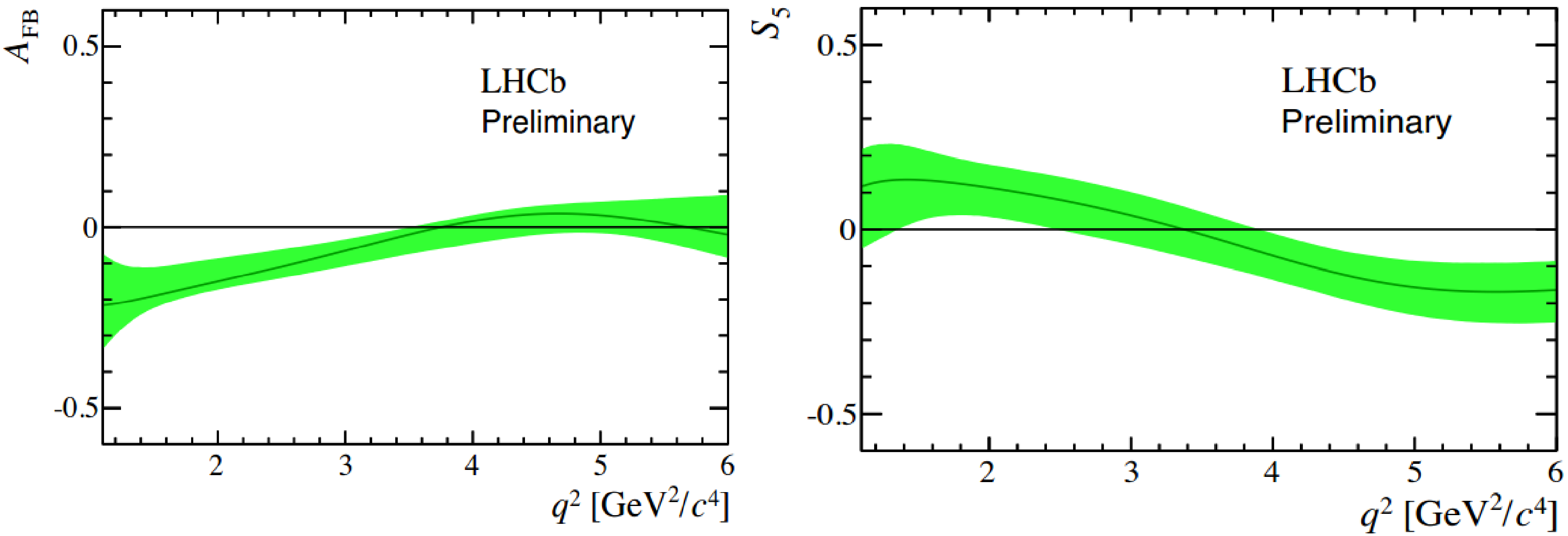
Preliminary result from BELLE supports the deviation from SM expectation



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

Unbinned fit result in region $1<q^2< 6$ GeV^2

See JHEP 06 (2015) 084 for method



$$q_0^2(S_5) \in [2.49, 3.95]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

$$q_0^2(A_{\mathrm{FB}}) \in [3.40, 4.87]\,\mathrm{GeV}^2/c^4 \quad @\ 68\%\ \mathrm{CL}$$

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

HEPdata record

- For global fits, it has long been a request to provide results in machine readable format

The Durham HepData Project

REACTION DATABASE • DATA REVIEWS • PDF PLOTTER

Reaction Database Full Record Display

View short record or as: input, plain text, AIDA, PyROOT, YODA, ROOT, mpl, DMelt, MarcXML or YAML

AAIJ 2016 — Angular analysis of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay using 3 fb^{-1} of integrated luminosity

Experiment: **CERN-LHC-LHCb (LHCb)**
Published in **JHEP 1602,104** (DOI:10.1007/JHEP02(2016)104)
Preprinted as **CERN-PH-EP-2015-314**
Preprinted as **LHCB-PAPER-2015-051**
Archived as: **ARXIV:1512.04442**
Record in: **INSPIRE**
Record in: **CERN Document Server**
Record in: **HEPData** (new site in development)

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

HEPdata record

For global fits, it has long been a request to provide results in machine readable format

The Durham HepData Project

All the tables from paper

REACTION D

Reaction

View short record

AAIJ 20
integrat

Experiment:
Published in
Preprinted as
Preprinted as
Archived as:
Record in: IN
Record in: CE
Record in: HI

Table 2 (Appendix B, Table 3, Figure 6.) HIDE DATA or as: input, plain text, AIDA, PyROOT, YODA, ROOT, mpl,
CP-averaged angular observables evaluated by the unbinned maximum likelihood fit.

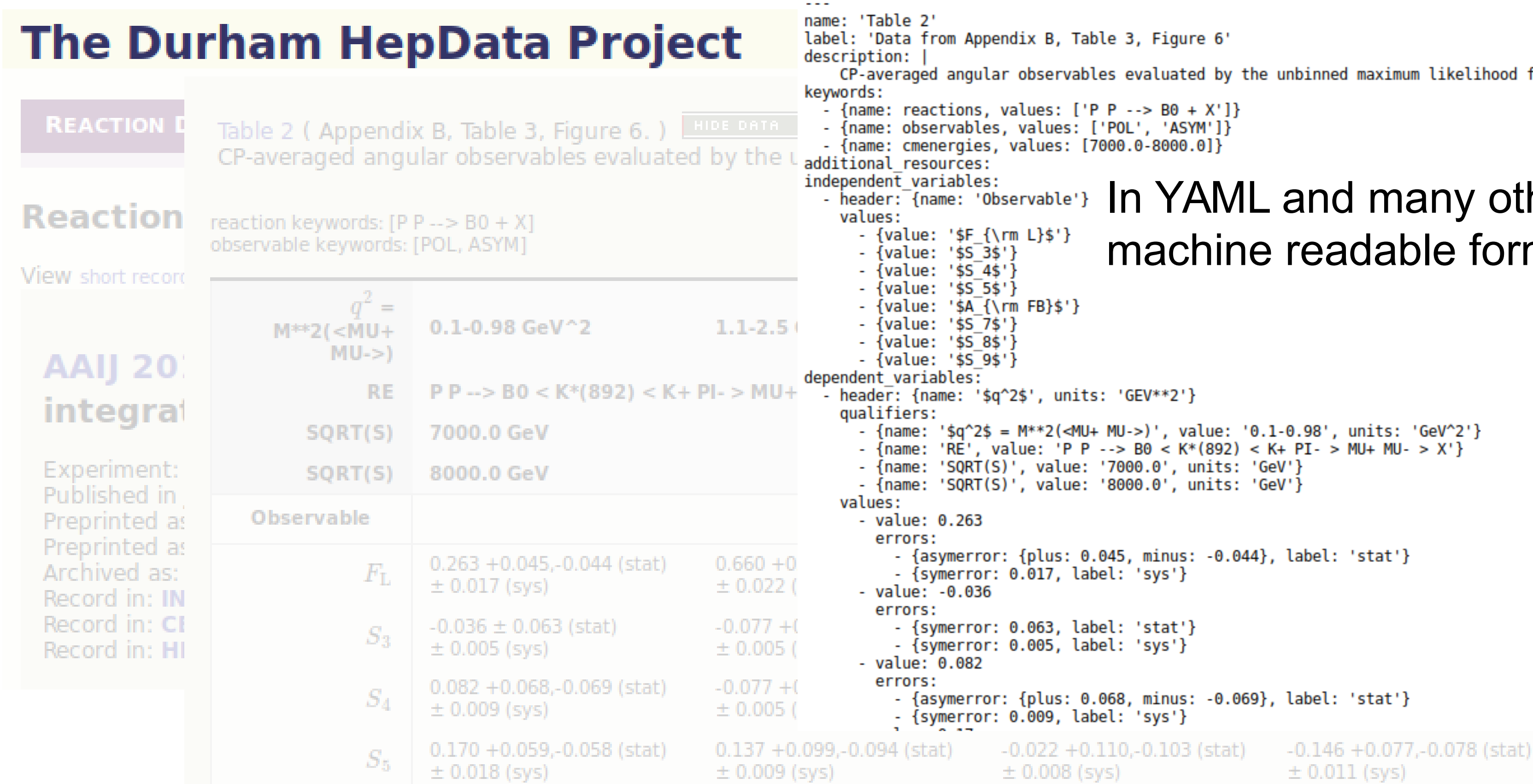
reaction keywords: [P P --> B0 + X]
observable keywords: [POL, ASYM]

q^2 = M**2(<MU+ MU->)	0.1-0.98 GeV^2	1.1-2.5 GeV^2	2.5-4.0 GeV^2	4.0-6.0 GeV^2
RE	P P --> B0 < K*(892) < K+ PI- > MU+ MU- > X			
SQRT(S)	7000.0 GeV			
SQRT(S)	8000.0 GeV			
Observable				q^2 IN
F_L	0.263 +0.045,-0.044 (stat) ± 0.017 (sys)	0.660 +0.083,-0.077 (stat) ± 0.022 (sys)	0.876 +0.109,-0.097 (stat) ± 0.017 (sys)	0.611 +0.052,-0.053 (stat) ± 0.017 (sys)
S_3	-0.036 ± 0.063 (stat) ± 0.005 (sys)	-0.077 +0.087,-0.105 (stat) ± 0.005 (sys)	0.035 +0.098,-0.089 (stat) ± 0.007 (sys)	0.035 +0.069,-0.068 (stat) ± 0.007 (sys)
S_4	0.082 +0.068,-0.069 (stat) ± 0.009 (sys)	-0.077 +0.111,-0.113 (stat) ± 0.005 (sys)	-0.234 +0.127,-0.144 (stat) ± 0.006 (sys)	-0.219 +0.086,-0.084 (stat) ± 0.008 (sys)
S_5	0.170 +0.059,-0.058 (stat) ± 0.018 (sys)	0.137 +0.099,-0.094 (stat) ± 0.009 (sys)	-0.022 +0.110,-0.103 (stat) ± 0.008 (sys)	-0.146 +0.077,-0.078 (stat) ± 0.011 (sys)

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

HEPdata record

- For global fits, it has long been a request to provide results in machine readable format




```
---
name: 'Table 2'
label: 'Data from Appendix B, Table 3, Figure 6'
description: |
    CP-averaged angular observables evaluated by the unbinned maximum likelihood fit.
keywords:
  - {name: reactions, values: ['P P --> B0 + X']}
  - {name: observables, values: ['POL', 'ASYM']}
  - {name: cmenergies, values: [7000.0-8000.0]}
additional_resources:
independent_variables:
  - header: {name: 'Observable'}
    values:
      - {value: '$F_{\rm L}$'}
      - {value: '$S_3$'}
      - {value: '$S_4$'}
      - {value: '$S_5$'}
      - {value: '$A_{\rm FB}$'}
      - {value: '$S_7$'}
      - {value: '$S_8$'}
      - {value: '$S_9$'}
dependent_variables:
  - header: {name: '$q^2$', units: 'GEV**2'}
    qualifiers:
      - {name: '$q^2$ = M**2(<MU+ MU->)', value: '0.1-0.98', units: 'GeV^2'}
      - {name: 'RE', value: 'P P --> B0 < K*(892) < K+ PI- > MU+ MU- > X'}
      - {name: 'SQRT(S)', value: '7000.0', units: 'GeV'}
      - {name: 'SQRT(S)', value: '8000.0', units: 'GeV'}
    values:
      - value: 0.263
        errors:
          - {asymerror: {plus: 0.045, minus: -0.044}, label: 'stat'}
          - {symerror: 0.017, label: 'sys'}
      - value: -0.036
        errors:
          - {symerror: 0.063, label: 'stat'}
          - {symerror: 0.005, label: 'sys'}
      - value: 0.082
        errors:
          - {asymerror: {plus: 0.068, minus: -0.069}, label: 'stat'}
          - {symerror: 0.009, label: 'sys'}
```


In YAML and many other machine readable formats

Lepton non-universality

Lepton universality is one of the corner stones of the Standard Model

Only theoretical uncertainty in ratios of semileptonic decays is from different masses of quarks

Z decays tested lepton universality at the per-mille level

Heavy flavour decays test e-μ universality in $B \to Kl\nu$ at the 5% level

For μ-τ universality to constraints are poorer

- In charm, a single constraint by $BF(D_s^+ \to \tau^+\nu)/BF(D_s^+ \to \mu^+\nu)$ at 10% level

LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

Due to lepton universality, the B→Kμμ and B→Kee decays should have same BF to within a factor 10^{-3}

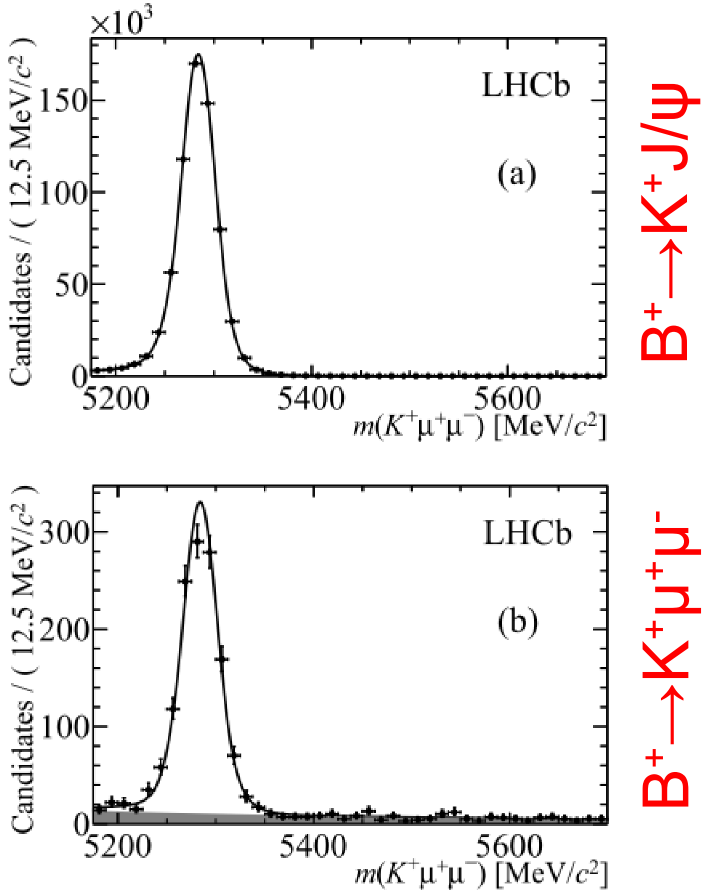
The ratio

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

Sensitive to lepton flavour violating NP

Look in $q^2 < 6\ \mathrm{GeV}^2$ region

Muon mode and its control mode $B^+ \to K^+ J/\psi$, $J/\psi \to \mu\mu$ are easy

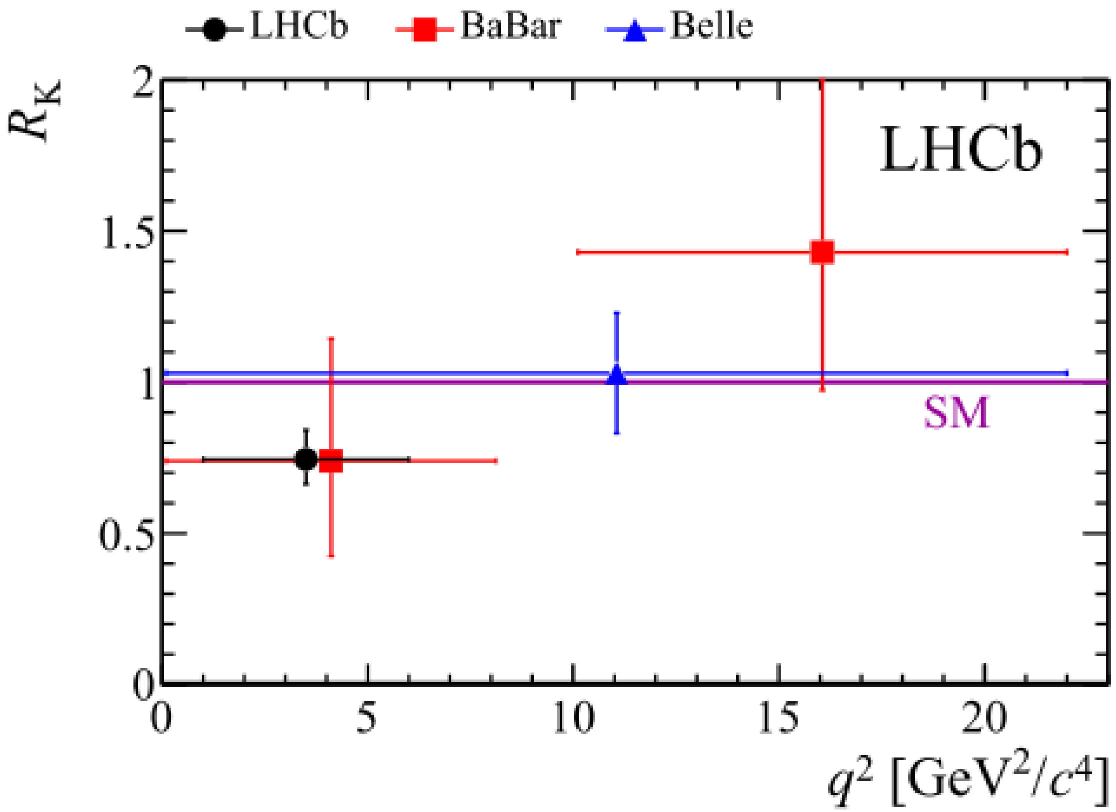


LHCb : PRL113, 151601 (2014)

Lepton universality test in $B^+ \to K^+ l^+ l^-$

Measure $R_K = 0.745^{+0.090}_{-0.074}\,(\mathrm{stat}) \pm 0.036\,(\mathrm{syst})$

Compatible with earlier, but less precise measurements



Large ongoing effort to measure many other μ/e ratios

Interpretations

To understand the different anomalies, different approaches have gained some traction

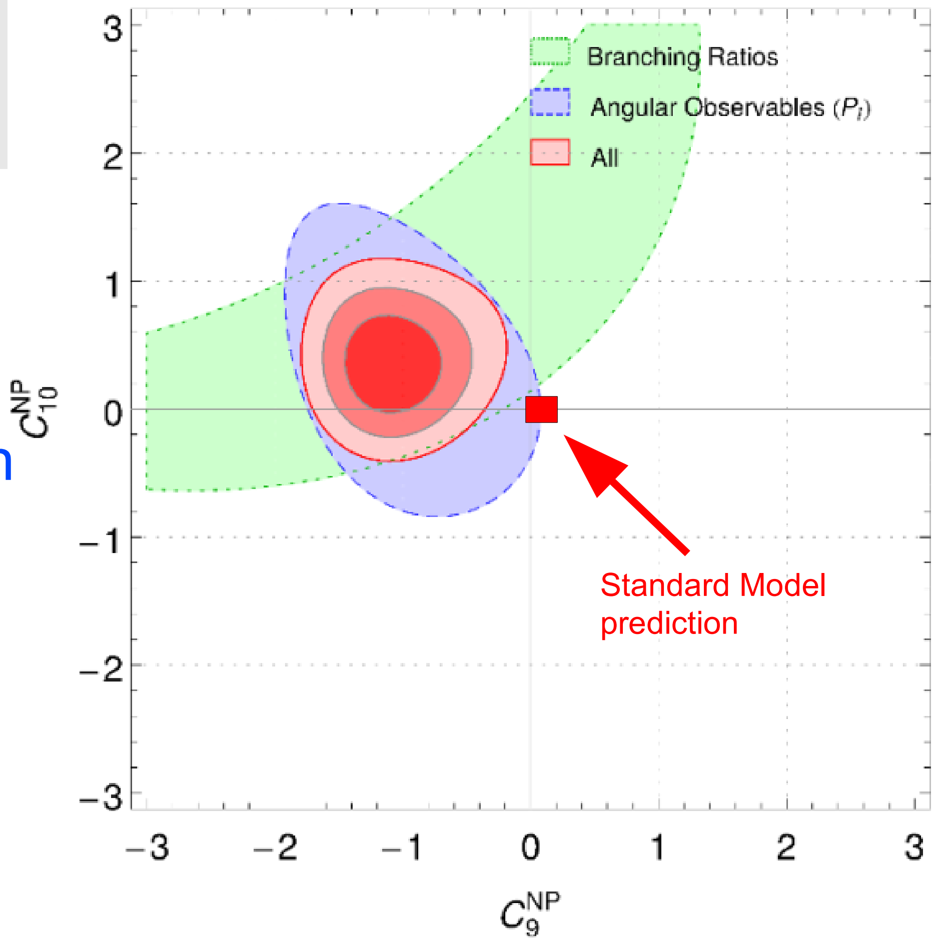
- There is a problem with the uncertainties
  - Experimental side most like for lepton non-universality measurements
  - Theory side more likely for electroweak penguin angular analysis
- Introduce a leptoquark sector
  - Provides straight forward explanation of lepton non-universality
- Introduce a Z' that allows for flavour changing neutral currents at tree level
  - Aims mainly at $B \to K^* \mu^+ \mu^-$ but can also explain R_K

Interpretation of results

Use an Operator Product expansion

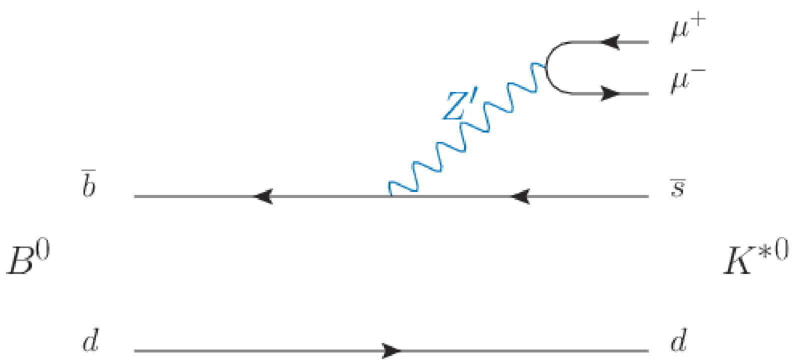
$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{j=7,9,10} \frac{e^{i\phi_j}}{\Lambda_j^2} \mathscr{O}_j$$

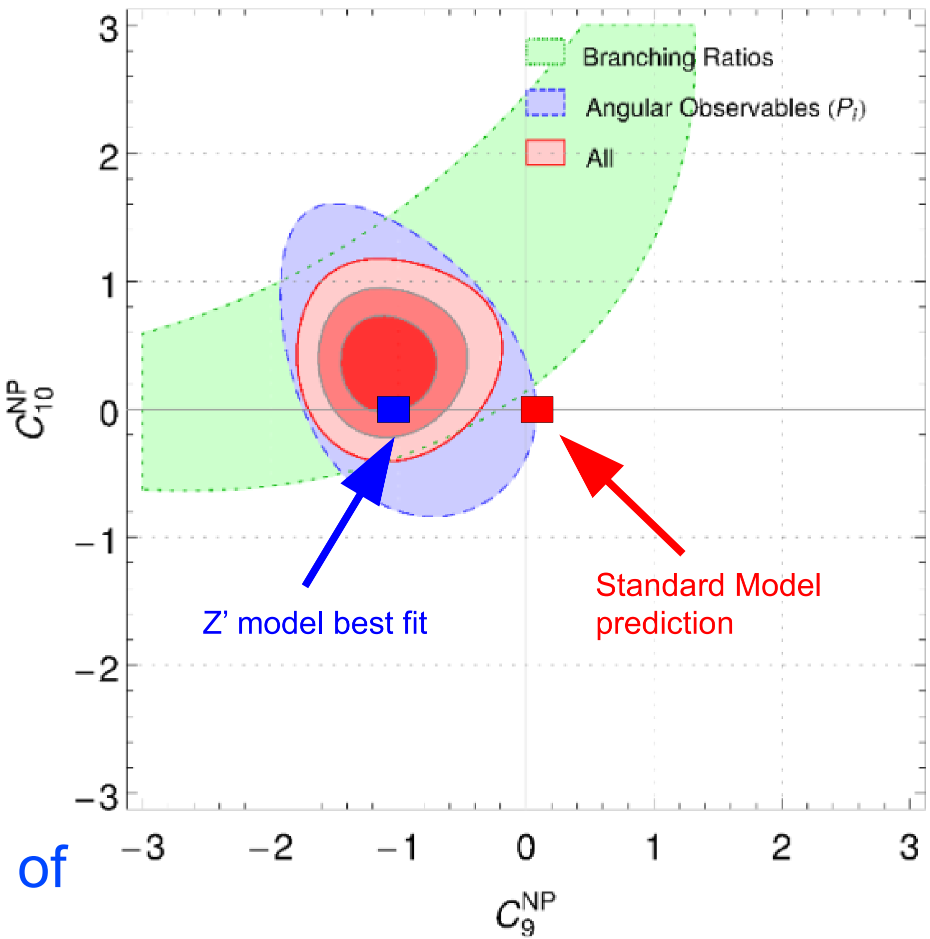
Standard Model prediction of coefficients are very precise



Interpretation of results

A new vector boson, Z', would only contribute to the O_9 operator



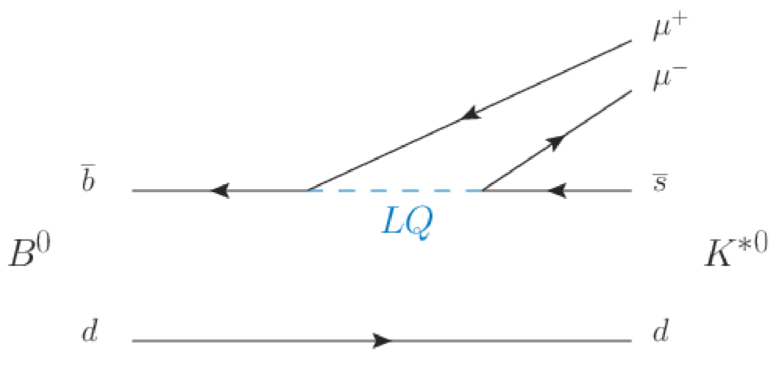


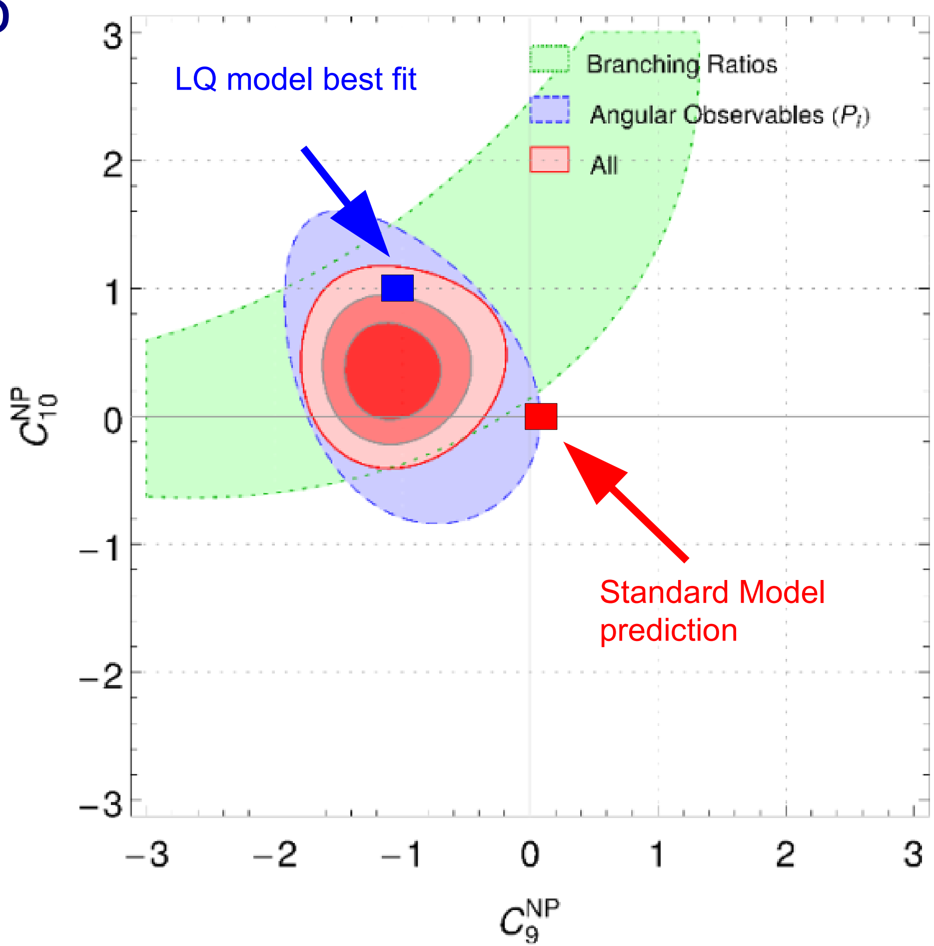
Direct observation of new boson would be fantastic

… but maybe out of reach of LHC

Interpretation of results

Alternatively a leptoquark would contribute equally to 0_9 (vector) and O_{10} (pseudo-vector)





Would naturally expect Lepton Flavour Violation

e.g. $B^+ \rightarrow K^+ e^+ \mu^-$

Conclusion

- LHCb continues as the dominating experiment for new results in quark flavour physics
  - Still many results coming out for LHC run-I with very significant updates for run-II coming soon.
- Several measurements are coming out which are in significant tension with the SM
  - $B\to K^*\mu^+\mu^-$, $B\to Kl^+l^-$, $B\to Dl\nu$
- Phenomenologists and experimentalists need to talk even more in order further understanding
  - How to cross check experimental and theoretical uncertainties
  - Develop new measurements