technische universität dortmund

Experimentelle Physik V
Teilchenphysik

Studies of Lepton Flavour Universality at LHCb

particlezoo.net

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LFV/LFUV - Why and how?
08 November 2016

Outline

- Introduction
- The LHCb detector
- Tests of lepton flavour universality
  - R_K
  - R_{D^*}
  - $W \to \ell\nu$
- Outlook

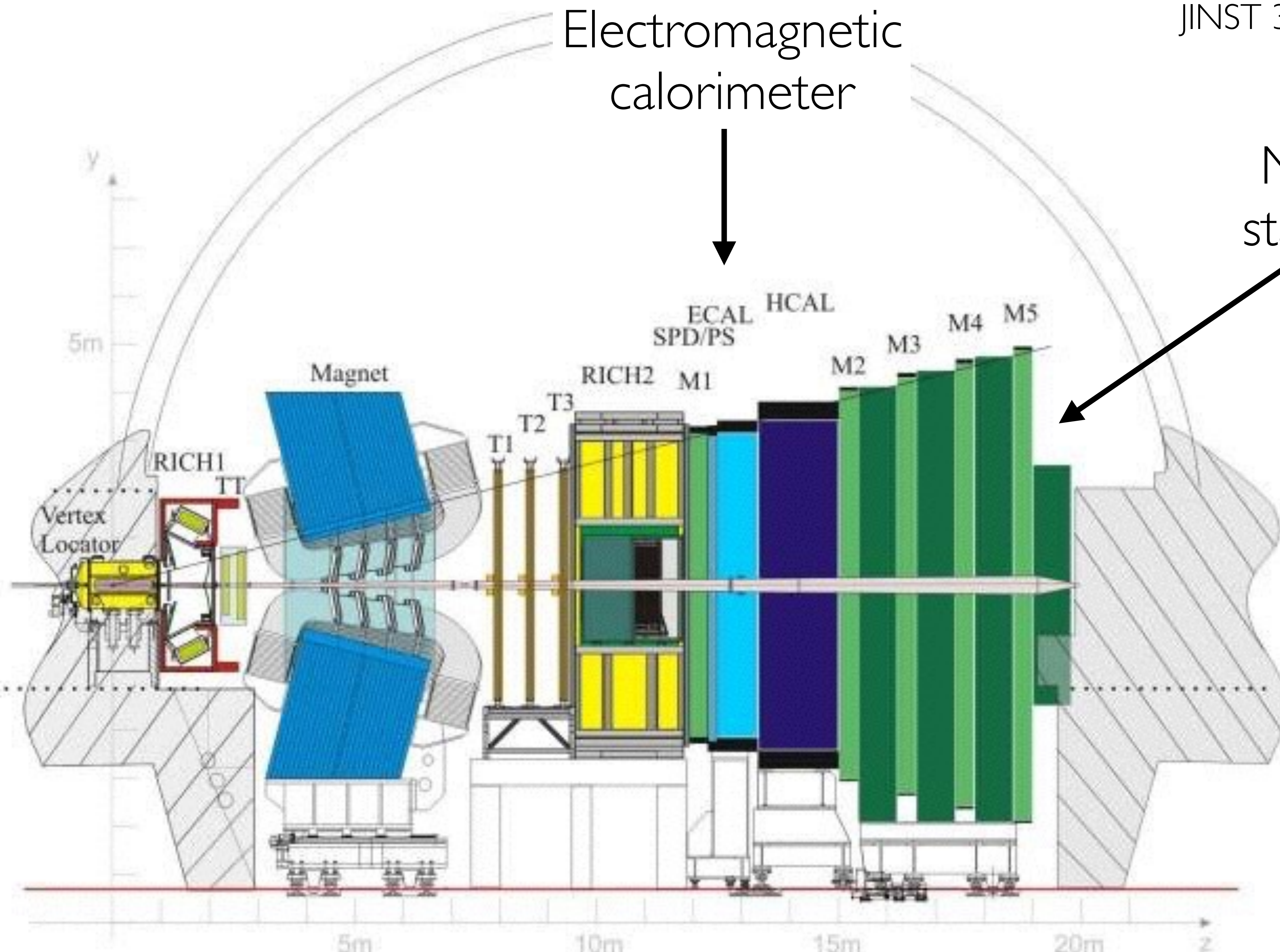
Introduction

- In the SM, the weak couplings to leptons are universal
  → evidence of lepton flavour non-universality (~~LFU~~) would hint at new physics

- ~~LFU~~ studies at LHCb in various channels, which are theoretically clean, e.g
  - b→sll process (R_K) sensitive to new (pseudo)scalar operators in models with extended Higgs sector or models with Z'
  - R(D*) sensitive to models with enhanced couplings to tau leptons

The LHCb detector

JINST 3 (2008) S08005



Forward spectrometer with acceptance $2 < \eta < 5$

Lepton identification at LHCb

- Electrons
  - match track to cluster in electromagnetic calorimeters
  - combined with information from Cherenkov detectors
  - correct for bremsstrahlung effects
- Muons
  - penetrate calorimeters and iron filters in muon stations
  - MVA classifier using information from tracking system, muon chambers, Cherenkov detectors and calorimeters
- Taus
  - difficult to reconstruct due to final states involving (several) neutrinos
  - reconstructed eg. in the channel $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

R_K

Analysis strategy

PRL 113 (2014) 151601

- Search for ~~LFU~~ in $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^+ \rightarrow K^+e^+e^-$ decays

  → measurement of R_K in given range of dilepton mass squared defined as

$$R_K = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\Gamma(B^+ \rightarrow K^+\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{d\Gamma(B^+ \rightarrow K^+e^+e^-)}{dq^2} dq^2}$$

- SM prediction: $R_K = 1.00030^{+0.00010}_{+0.00007}$ [JHEP 12 (2007) 040]
- QED corrections: $\Delta R_K = +3\%$ [Eur Phys. J. C76 (2016) 440]

Analysis strategy

PRL 113 (2014) 151601

- Measurement of R_K in $1 < q^2 < 6$ GeV^2 as double-ratio with control channel $B^+ \to J/\Psi K^+$ with $J/\Psi \to \mu^+\mu^-$ and $J/\Psi \to e^+e^-$

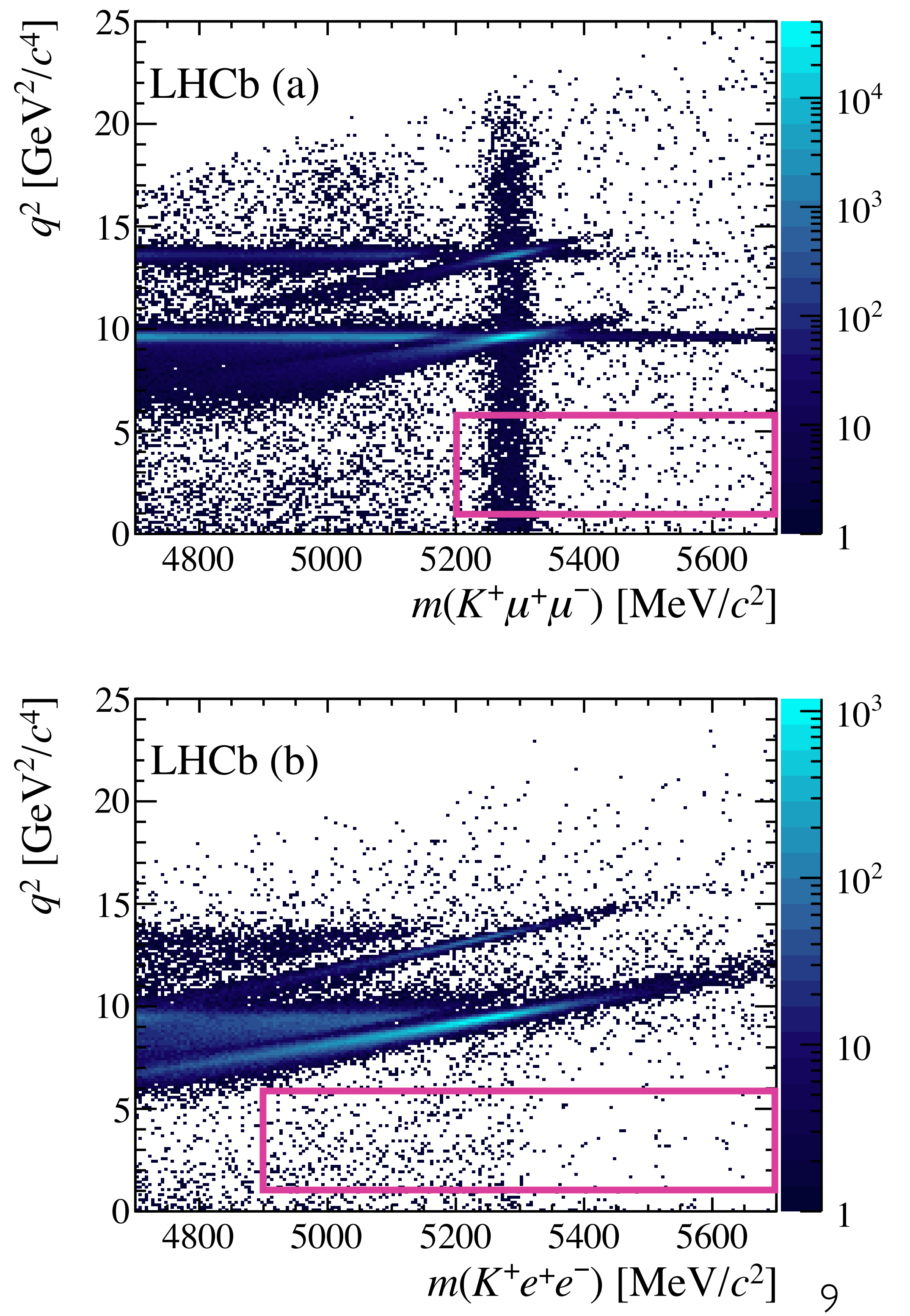
$$R_K = \frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}} \frac{\mathcal{N}_{J/\Psi(e^+e^-)K^+}}{\mathcal{N}_{J/\Psi(\mu^+\mu^-)K^+}} \frac{\varepsilon_{K^+e^+e^-}}{\varepsilon_{K^+\mu^+\mu^-}} \frac{\varepsilon_{J/\Psi(\mu^+\mu^-)K^+}}{\varepsilon_{J/\Psi(e^+e^-)K^+}}$$

- Measure yields and efficiencies of control and signal channels
- Most systematic uncertainties cancel out in double-ratio

Analysis strategy

PRL 113 (2014) 151601

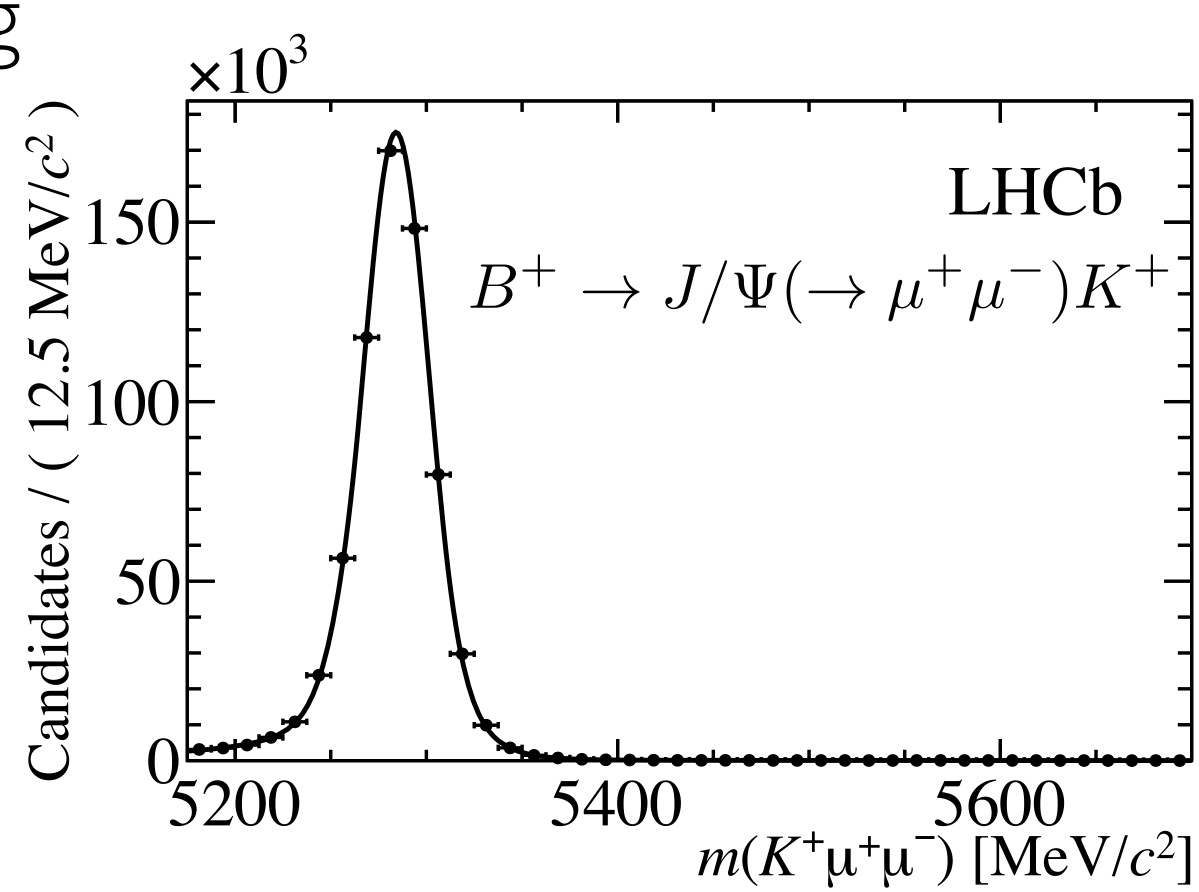
- Analysis performed on LHCb's 2011 and 2012 dataset of 3\fb recorded at centre-of-mass energies of 7 and 8TeV
- Similar selection of signal and control channel
- Remove contributions from charmonium in signal channel
  - $B^+ \to J/\Psi K^+$, and
  - $B^+ \to \Psi(2S)K^+$



Selection

PRL 113 (2014) 151601

- Trigger and cut-based preselection followed by MVA
  → suppress combinatorial bkg
  - $B^+ \to J/\Psi(\to \ell^+\ell^-)K^+$ as signal proxy
  - upper sideband in $m(K\ell\ell)$ of $B^+ \to K^+\ell^+\ell^-$ as background
  - training variables: kinematic, topological, vertex quality, …
    → retains 60-70% of the signal while removing 95% of bkg
    → remaining combinatorial background included in fit of $m(K\ell\ell)$ mass



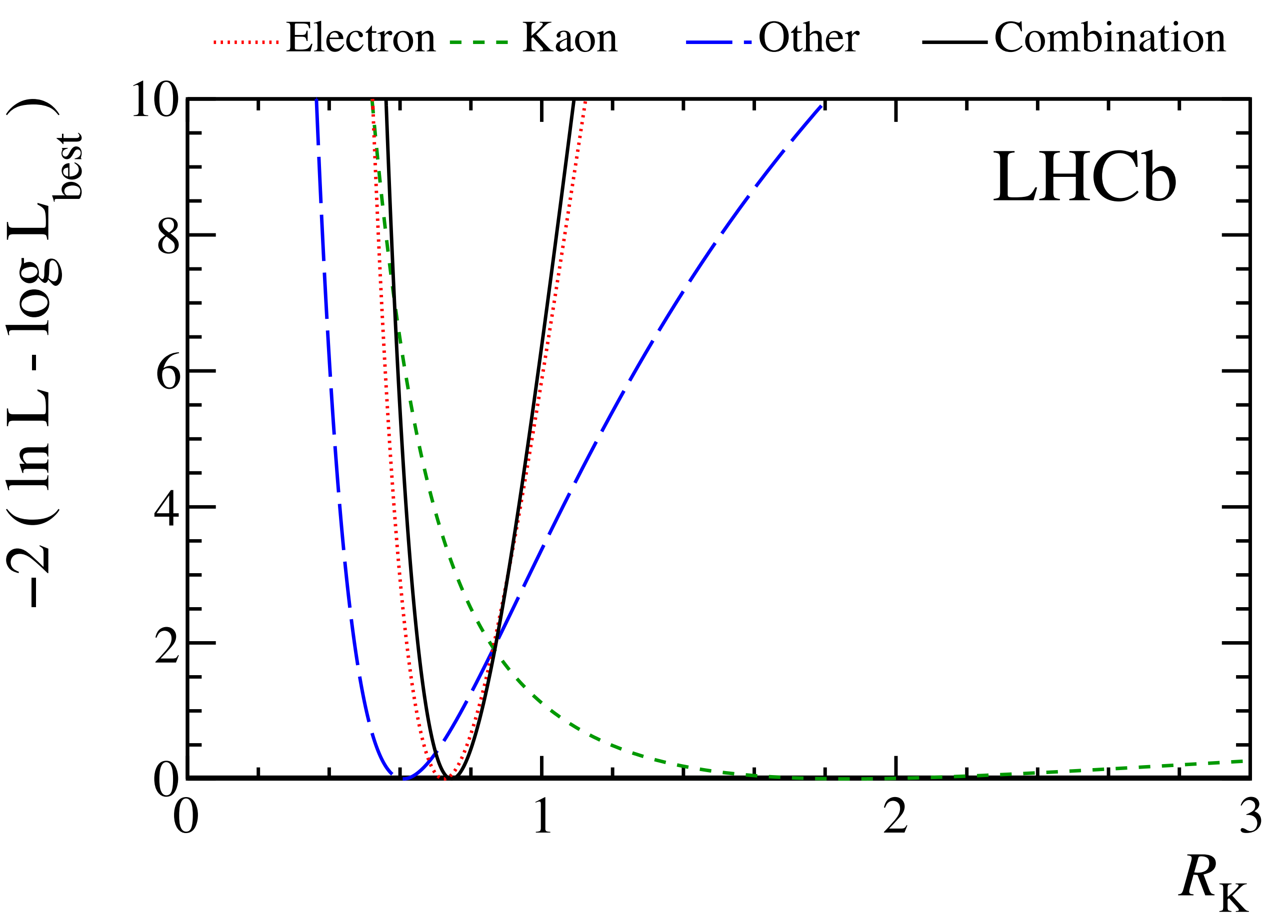
Backgrounds

PRL 113 (2014) 151601

- Misreconstructed $B^+ \to J/\Psi K^+$ and $B^+ \to \Psi(2S)K^+$ decays through kaon $\leftrightarrow$ lepton identification
  → excluded by requirements on mass, particle identification and acceptance
- Semileptonic B decays, eg. $B^+ \to \bar{D}^0(\to K^+\pi^-)\ell^+\nu_\ell$ by misidentification of one hadron as lepton
  → veto based on $K\ell$ mass under hadron mass hypothesis
- Partially reconstructed B decays with reconstructed B masses shifted to the lower sideband
  → excluded in $B^+ \to K^+\mu^+\mu^-$ due to choice of signal mass window
  → accounted for in fit to $m(K\ell\ell)$

Signal yield extraction

- Signal yields extracted from unbinned extended maximum likelihood fit to $m(K\ell\ell)$
- Signal shapes studied on control sample
- For the electron mode, signal shape depends on
  - # bremsstrahlungs photons associated with the electrons
  - electron p_T & event occupancy
- Data split in categories depending on trigger and # bremsstrahlungs photons



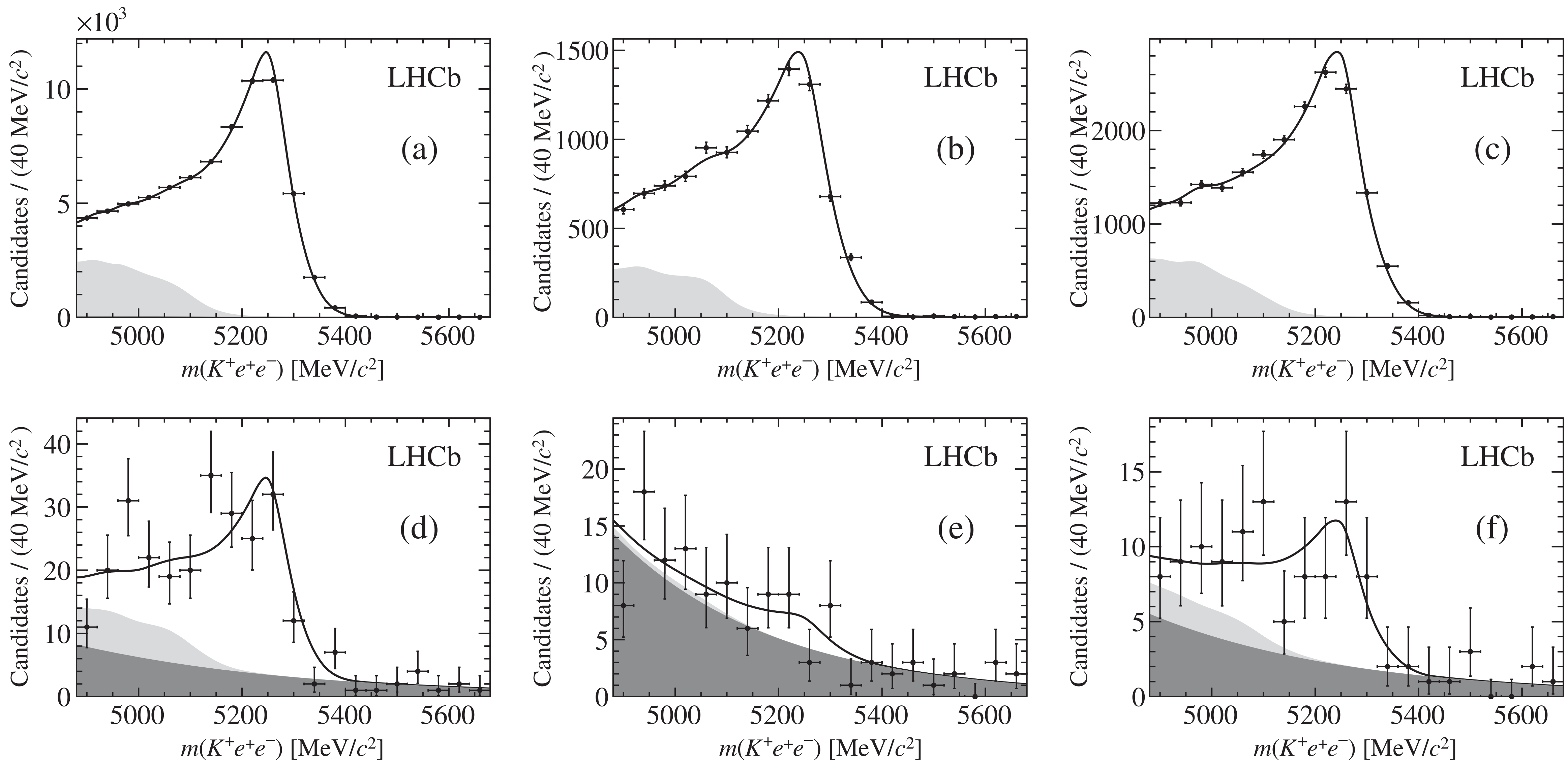
Fit results

PRL 113 (2014) 151601

Electron triggered | Hadron triggered | Other

$B^+ \to J/\psi(\to e^+e^-)K^+$

$B^+ \to K^+e^+e^-$



Results and systematic uncertainties

PRL 113 (2014) 151601

- R$_K$ extracted from $\mathcal{N}_{B^+\to K^+\mu^+\mu^-} = 1126 \pm 41$ and from $B^+ \to K^+e^+e^-$ samples for different trigger categories

Triggered by	Electron	Hadron	Other
Yield	$172\pm^{+20}_{-19}$	20^{+16}_{-14}	62 ± 13
R$_K$	$0.72^{+0.09}_{-0.08}{}^{+0.04}_{-0.04}$	$1.85^{+1.15}_{-0.82}{}^{+0.04}_{-0.04}$	$0.61^{+0.17}_{-0.07}{}^{+0.04}_{-0.04}$

- Dominant systematics
  - Mass shape of $B^+ \to K^+e^+e^-$
    - resolution
    - partially reconstructed backgrounds
  - Trigger efficiencies

Results

PRL 113 (2014) 151601

- R_K is measured to be

$$\boxed{R_K = 0.745^{+0.090}_{-0.074} \pm 0.036}$$

→ 2.6σ deviation from SM prediction

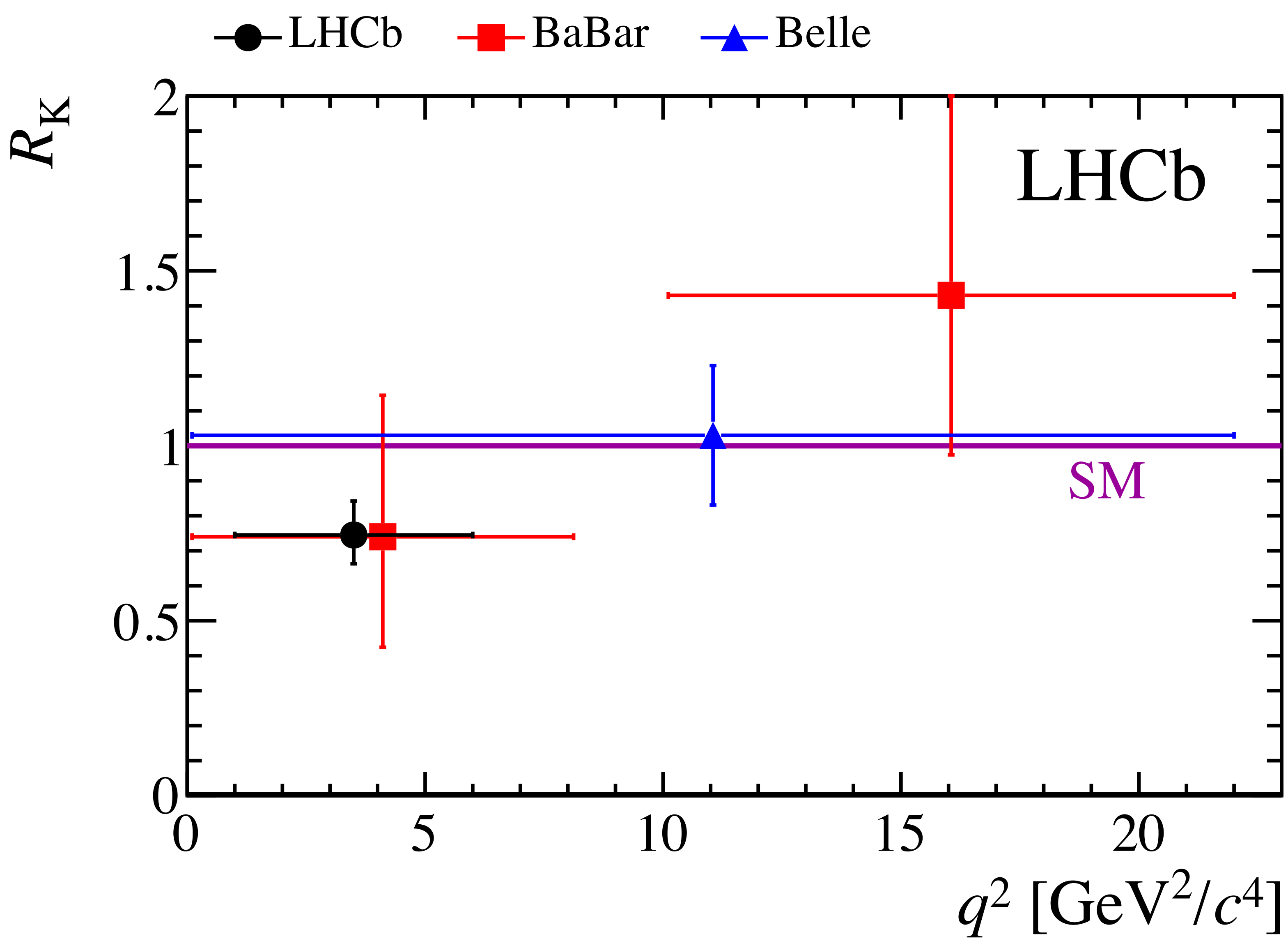
- Branching fraction of $B^+ \to K^+ e^+ e^-$ extracted from ratio

$$\frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to J/\Psi(\to e^+ e^-) K^+)}$$

$$\boxed{\mathcal{B}(B^+ \to K^+ e^+ e^-) = \left(1.56^{+0.19}_{-0.15}\,{}^{+0.06}_{-0.04}\right) \times 10^{-7}}$$

Result compared to Belle & BaBar

PRL 113 (2014) 151601



LHCb: [PRL 113 (2014) 151601]

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Belle: [PRL 103 (2009) 171801]

$$R_K = 1.03 \pm 0.19 \pm 0.06$$

BaBar: [PR D86 (2012) 032012]

$$R_K = 0.74^{+0.40}_{-0.31} \pm 0.06$$

BaBar: [PR D86 (2012) 032012]

$$R_K = 1.43^{+0.65}_{-0.44} \pm 0.12$$

R(D*)

Analysis strategy

PRL 115 (2015) 111803

- Similar to R$_K$, measure ~~LFU~~ in semileptonic B decays through

$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$$

- BaBar has observed a deviation of 2.7σ from the SM prediction of $R(D^*) = 0.252 \pm 0.003$ [PR D85 (2012) 094025]
- Analysis is performed on LHCb's 3/fb dataset
- Signal and normalisation decay chains are reconstructed with $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decays, resulting in the same visible final state
- First measurement of R(D*) at a hadron collider!

Selection

PRL 115 (2015) 111803

- Trigger selection chosen to preserve distinct kinematic distributions of signal and normalisation channel
- Followed by cut-based preselection to reduce combinatorics
- Samples for background studies
  - $D^{*+}\mu^{+}$ - combinations of D* and random muons
  - $D^{0}\pi^{-}\mu^{-}$ - misreconstructed D* decays
  - $D^{*+}h^{\pm}$ - misidentification of hadrons as muons
- Isolation requirement on $D^{*+}\mu^{-}$ suppresses partially reconstructed B decays
- MVA classifier to retain events with signal B decays

Selection

PRL 115 (2015) 111803

- Signal, normalisation and background channels separated by exploiting distinct kinematic distributions caused by the $\tau - \mu$ mass difference and presence of neutrinos
- Most discriminating variables; computed in B rest frame
  - missing mass squared m^2_{miss}
  - squared four-momentum transfer q^2
  - muon energy E^*_μ
- Estimation of B momentum
  - vector from PV to B decay vertex → B momentum direction
  - $(p_B)_z = (m_B/m_{\mathrm{reco}})(p_{\mathrm{reco}})_z$
- Resolution of rest frame variables ~15-20%

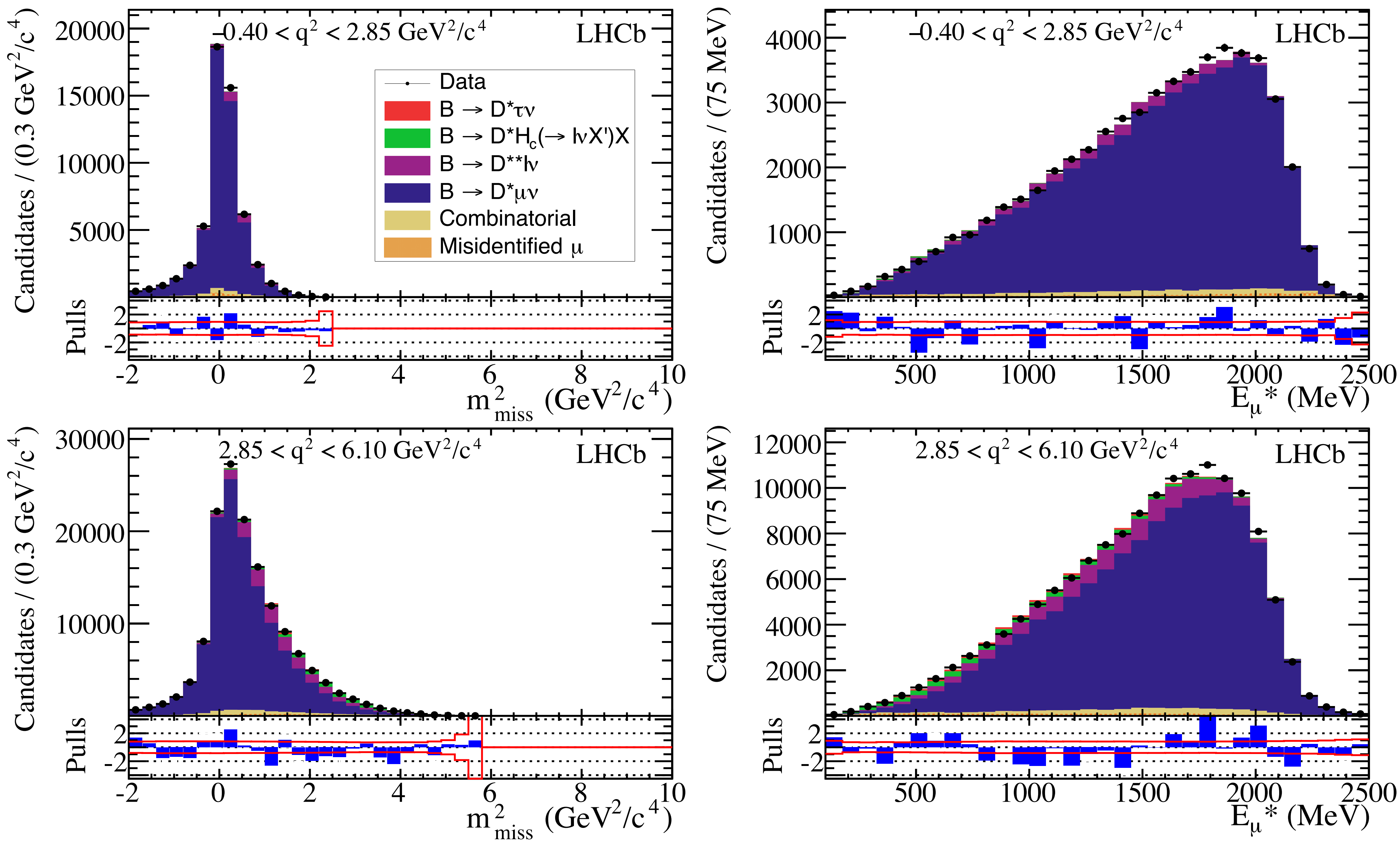
Multidimensional fit

PRL 115 (2015) 111803

- Maximum likelihood fit of binned three-dimensional E_μ^*, m^2_{miss}, q^2 templates for signal, normalisation and background contributions
- Kinematic distributions for signal, normalisation and background channels derived from simulation
- Fit constraints from form factors of $B \to D^{*/**}\ell\nu_\ell$, $\ell = \mu, \tau$
- Fit parameters
  - relative contributions of signal and normalisation channels
  - form factor parameters
  - background yields and relative yields

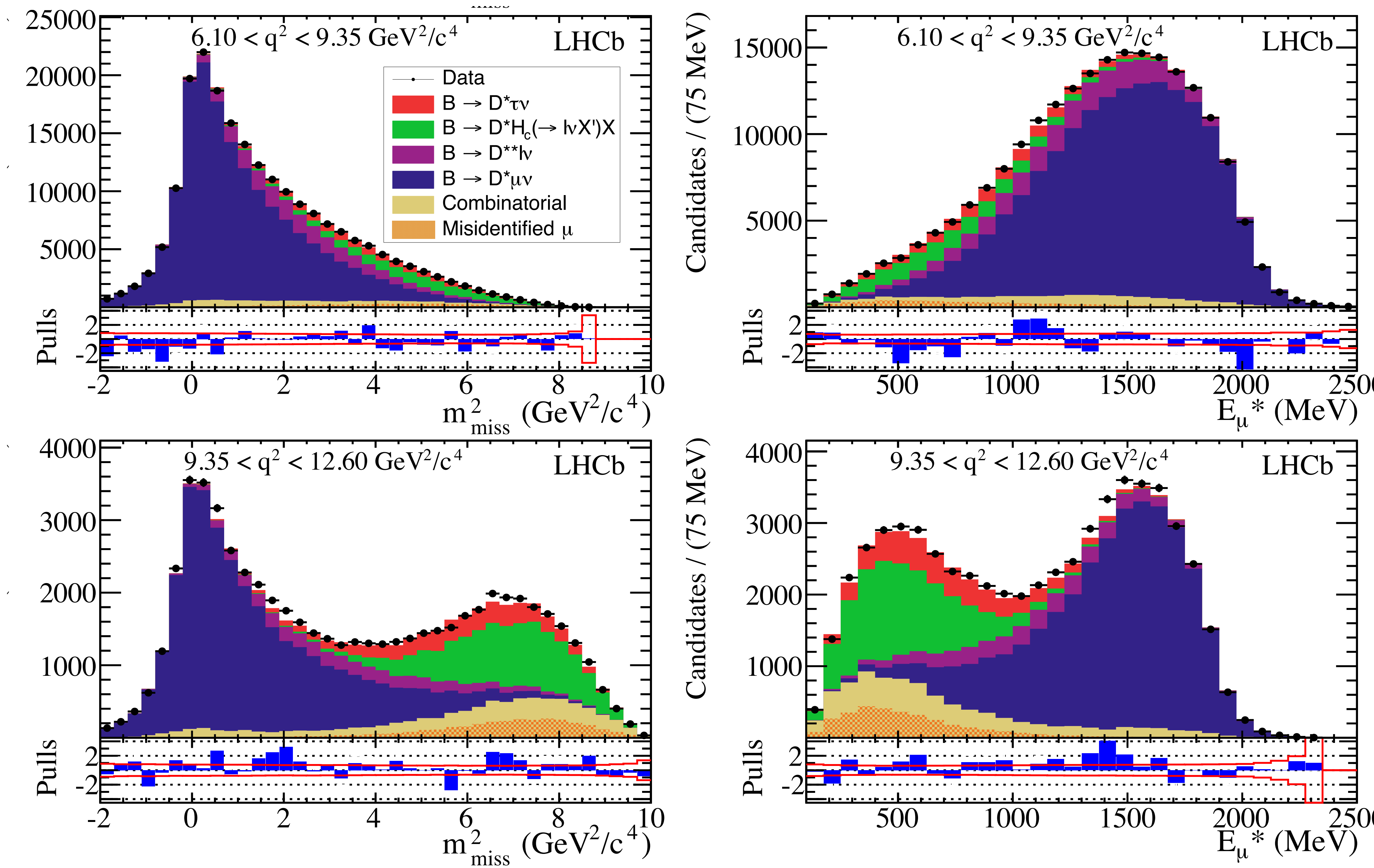
Fit projections

PRL 115 (2015) 111803



Fit projections

PRL 115 (2015) 111803



Result and systematic uncertainties

PRL 115 (2015) 111803

- $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ signal yield 363.000 ± 1.600
- Uncorrected ratio

$$\frac{N(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = (4.54 \pm 0.46)\%$$

- Accounting for efficiencies and $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$

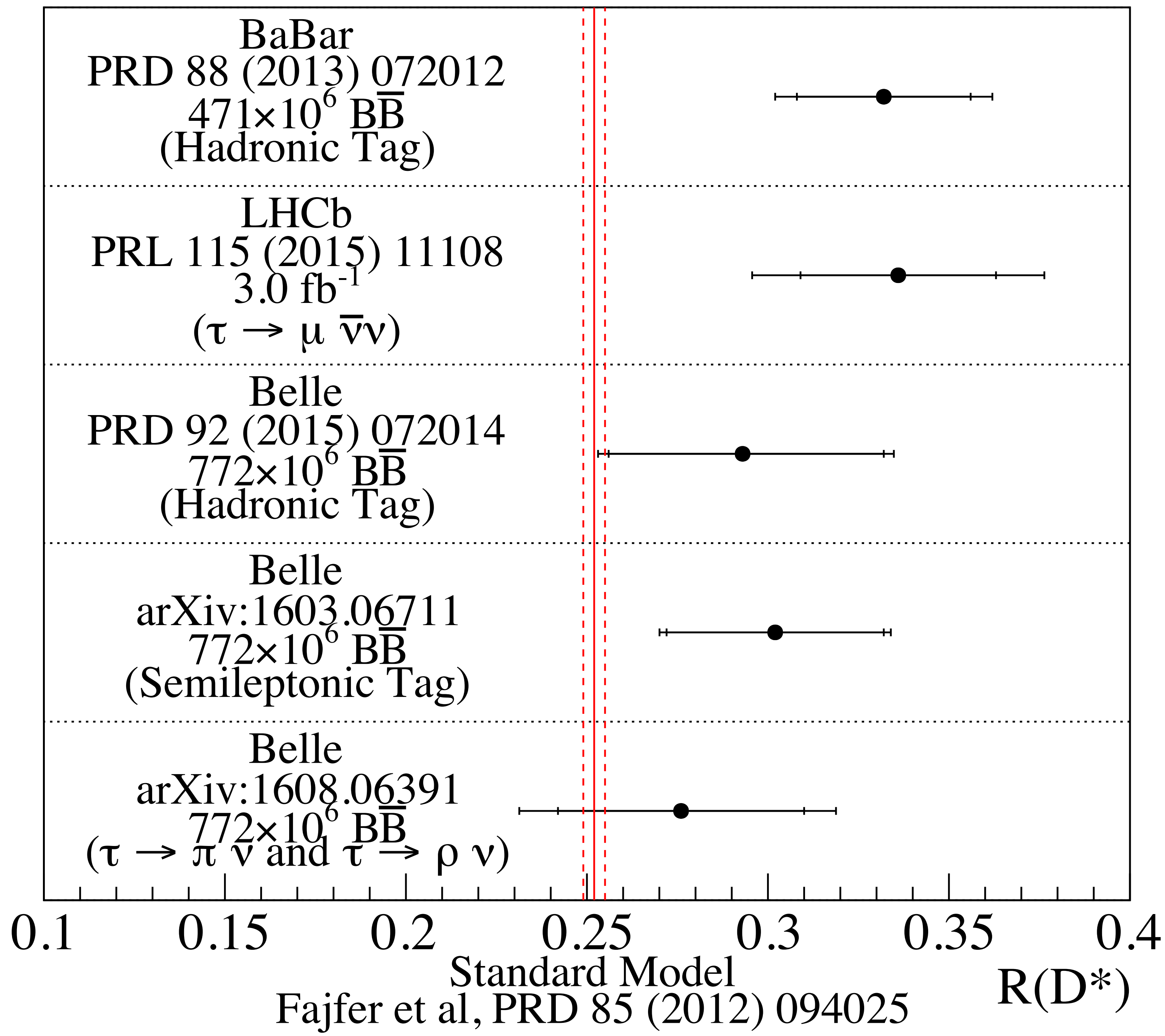
$$\boxed{R(D^*) = 0.336 \pm 0.034}$$

- 2.1σ deviation from SM prediction

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ 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
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

Comparison with previous experiments

Courtesy of K. De Bruyn



$$W \rightarrow \ell\nu$$

LFU from cross section measurement

JHEP 10 (2016) 030

- Measurement of forward $W \to e\nu$ production cross-section on LHCb data recorded in 2012 at a centre-of-mass energy of 8 TeV corresponding to 2/fb
- Cross-sections determined from binned maximum likelihood template fits to lepton p_T
- Input of $W \to \mu\nu$ production cross-section measurement performed on same dataset allows to extract $\mathcal{B}(W \to e\nu)/\mathcal{B}(W \to \mu\nu)$ for both lepton charges and compute an average
  → search for NP in trees
  → complementary to searches for NP in loops as in R_K

Analysis strategy

JHEP 10 (2016) 030

$$W \to e\nu$$

JHEP 01 (2016) 155

$$W \to \mu\nu$$

- Measured in eight bins of pseudo-rapidity per lepton charge
- Results corrected for final state radiation effects
- Selection
  - trigger including global event cut (GEC)
  - isolated electron with $p_T > 20$ GeV and within $2.00 < \eta < 4.25$
- Selection
  - trigger with GEC
  - isolated muon with $p_T > 20$ GeV and within $2.00 < \eta < 4.50$
- Efficiencies from e.g. GEC, (track) reconstruction, selection, particle identification requirements …

Analysis strategy

JHEP 10 (2016) 030

$$W \to e\nu$$

- Main backgrounds
  - $Z \to ee$ and $Z \to \tau\tau$
  - $W \to \tau(\to eX)\nu$
  - prompt $\gamma(\to ee)$ production
  - hadronic backgrounds
    - misidentified hadrons ('fake' electrons)
    - semileptonic heavy flavour decays
    - decay in flight
    - $t\bar{t}$ production

JHEP 01 (2016) 155

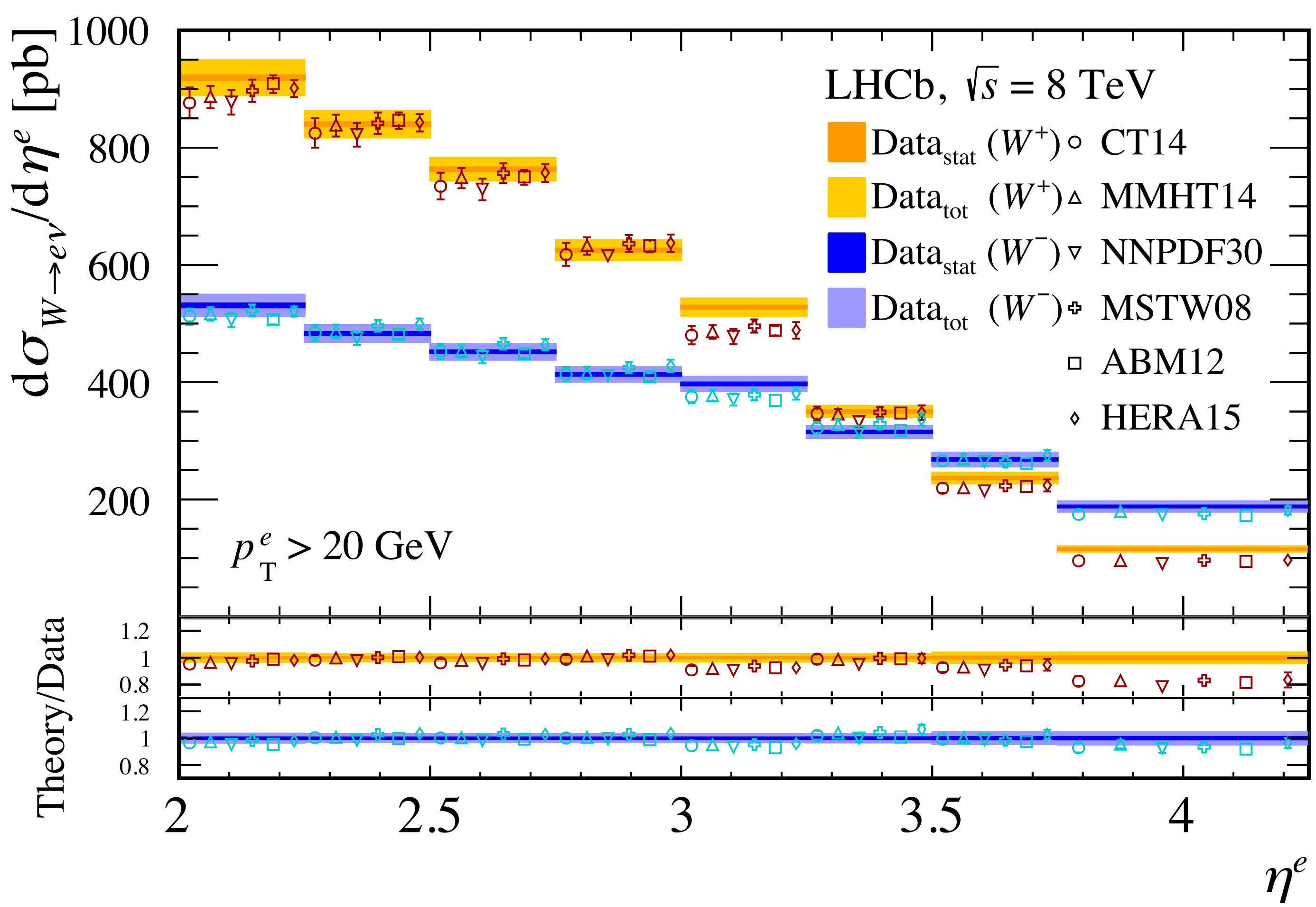
$$W \to \mu\nu$$

- Main backgrounds
  - $Z \to \tau\tau$ with $\tau \to \mu X$
  - $Z \to \mu\mu$
  - $W \to \tau(\to \mu X)\nu$
  - hadronic backgrounds
    - misidentified hadrons ('fake' electrons)
    - semileptonic heavy flavour decays

Cross-section results for $W \to e\nu$

JHEP 10 (2016) 030

- Fit templates mostly taken from simulation
  → data-driven method for 'fake' electrons and heavy flavour decays



- Ratio of $W \to \tau\nu$ to $W \to e\nu$ constrained

- Results

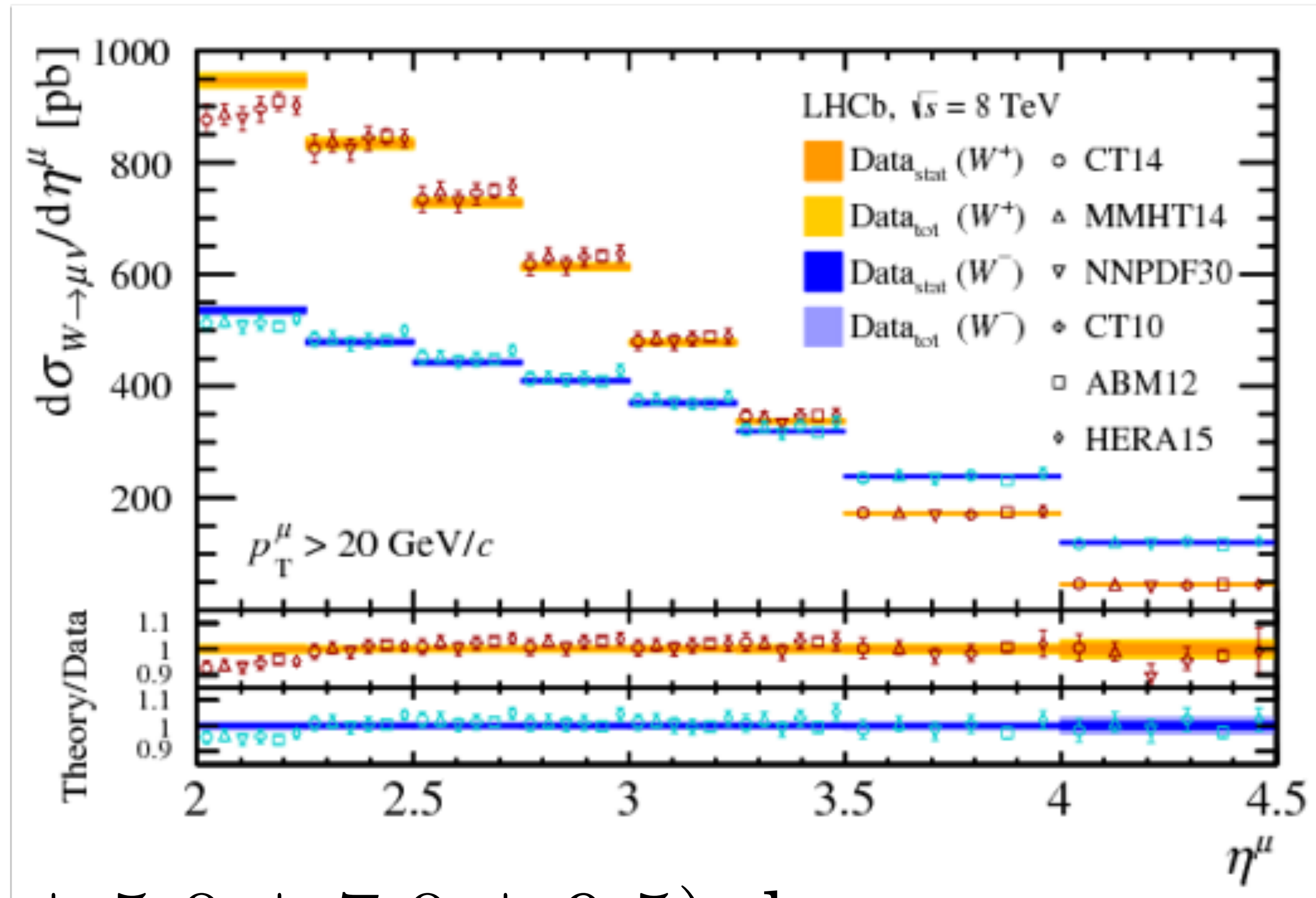
$$\sigma_{W^+\to e^-\bar{\nu}} = (809.0 \pm 1.9 \pm 18.1 \pm 7.0 \pm 9.4)\text{pb}$$
$$\sigma_{W^+\to e^+\nu} = (1124.4 \pm 2.1 \pm 21.5 \pm 11.2 \pm 13.0)\text{pb}$$

LHC beam energy luminosity

Cross-section results for $W \to \mu\nu$

JHEP 01 (2016) 155

- Fit templates mostly taken from simulation
  → data-driven method for 'fake' electrons and heavy flavour decays



- Results

$$\sigma_{W^- \to \mu^- \bar{\nu}} = (818.4 \pm 1.9 \pm 5.0 \pm 7.0 \pm 9.5)\text{pb}$$

$$\sigma_{W^+ \to \mu^+ \nu} = (1093.6 \pm 2.1 \pm 7.2 \pm 10.9 \pm 12.7)\text{pb}$$

LHC beam energy

luminosity

→ compare results from both analyses

Comparison of $W \rightarrow \ell\nu$ results

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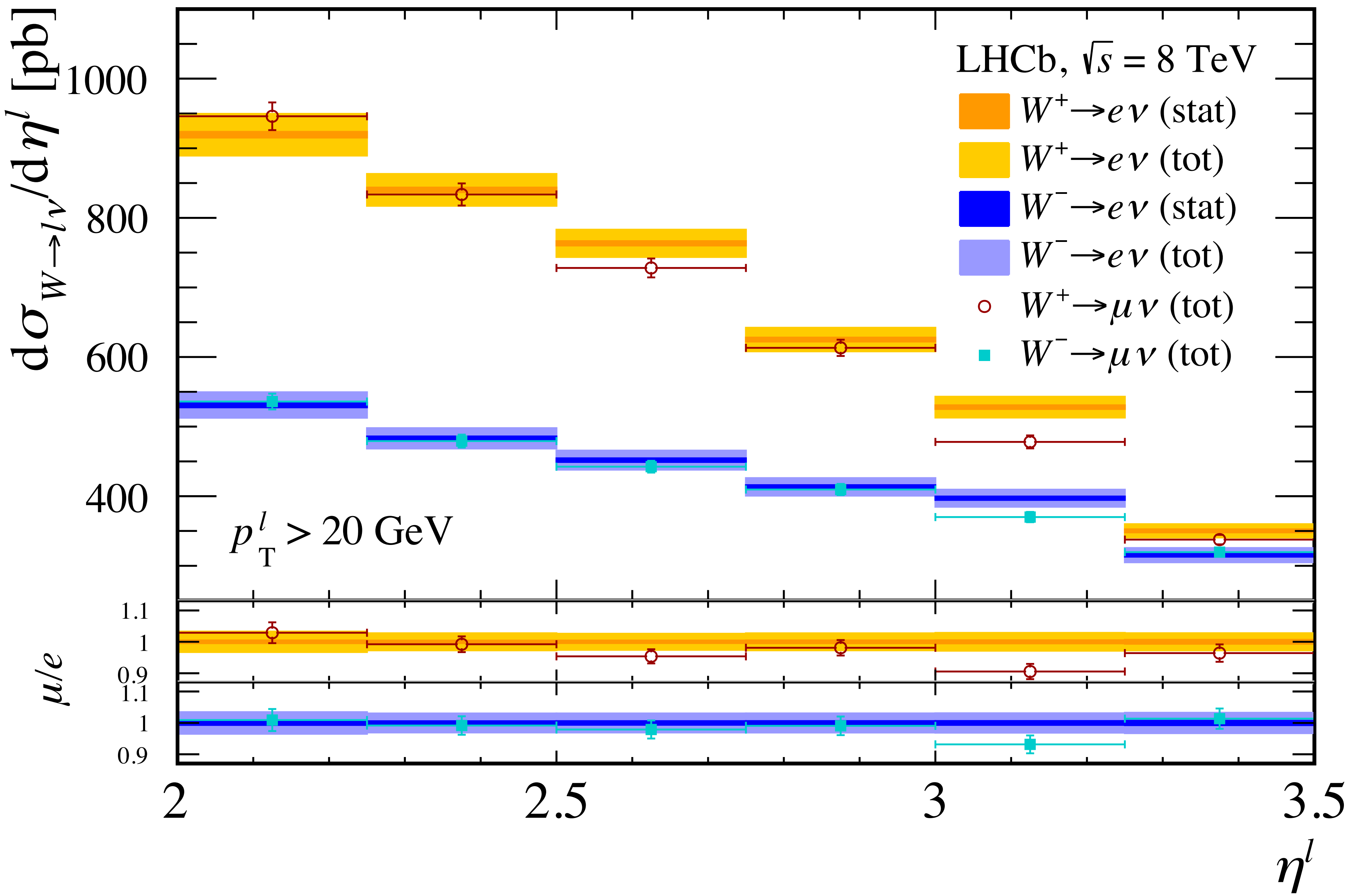

Comparison of $W \to \ell\nu$ results

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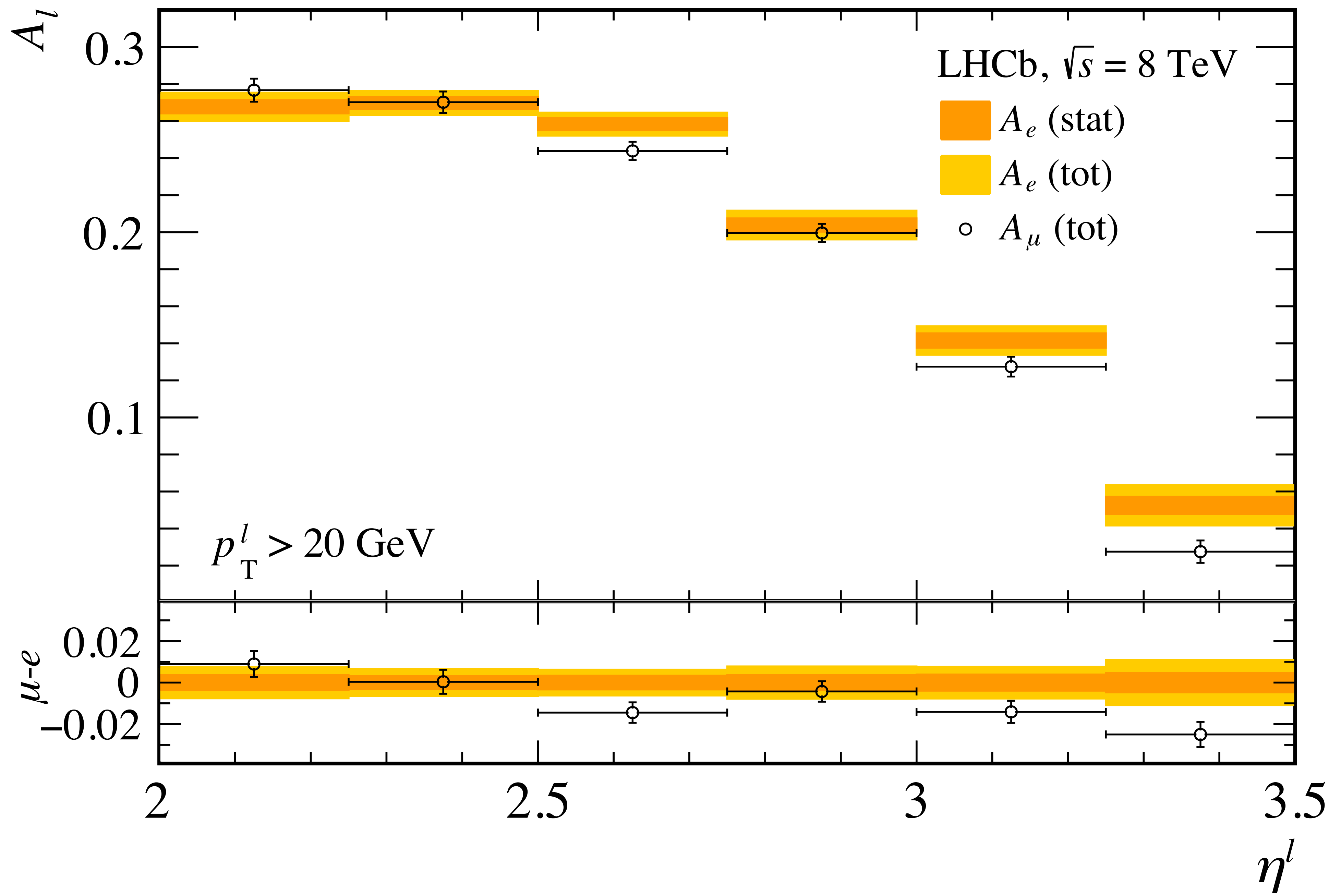

Propagation of (systematic) uncertainties

JHEP 10 (2016) 030

- Correlations between measurements in bins of η^l and lepton charge accounted for
- Statistical uncertainties assumed to be uncorrelated
- Correlations of systematic uncertainties determined by varying sources of systematic uncertainties by one standard deviation
- For the branching fraction ratio, the $W \to e\nu$ and $W \to \mu\nu$ measurements are taken to be uncorrelated
- Uncertainties due to GEC efficiency and acceptance correction assumed to be fully correlated

Results on $\mathcal{B}(W \to e\nu)/\mathcal{B}(W \to \mu\nu)$

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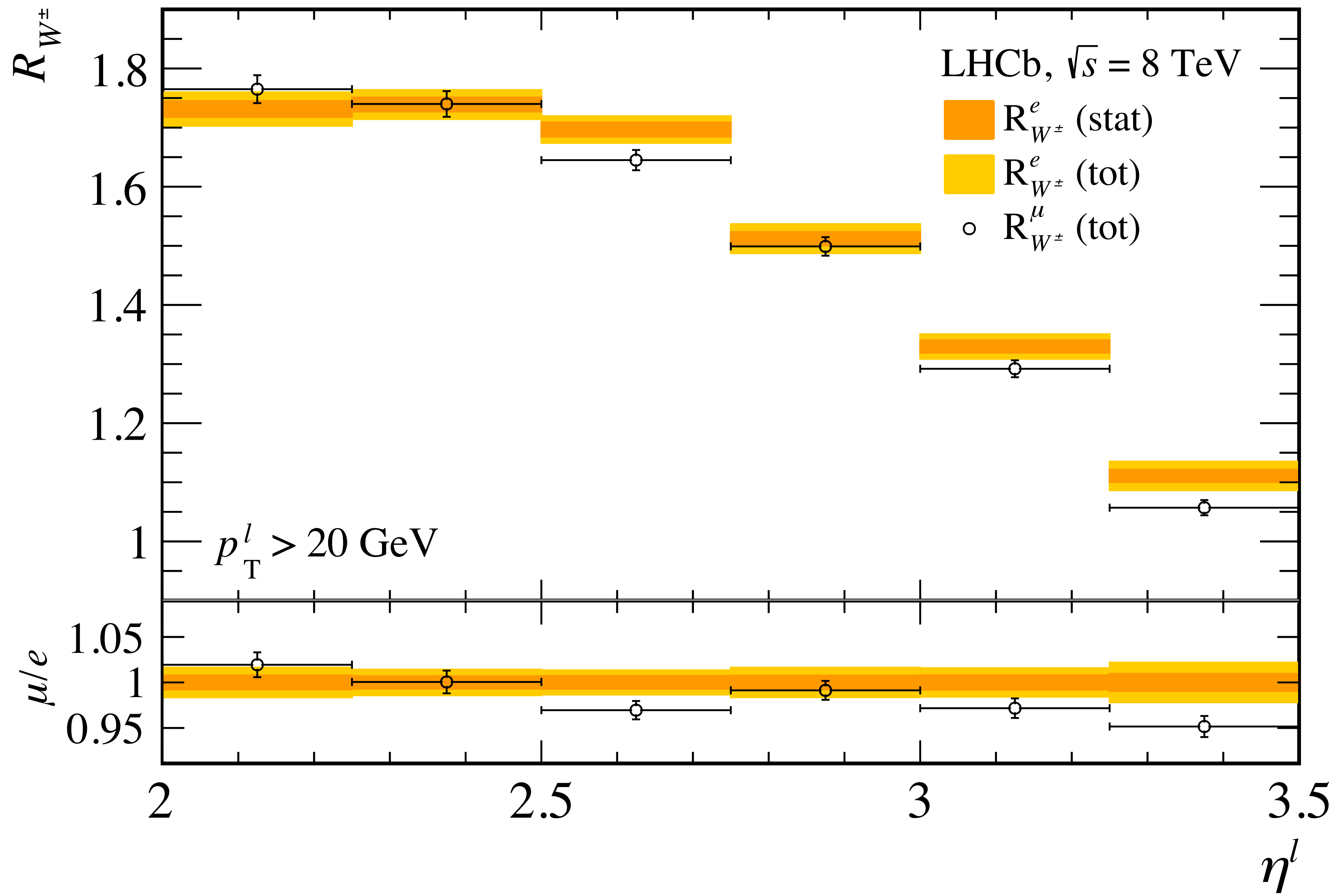
- Within $2.00 < \eta^l < 3.50$, the branching fraction ratios are



Results on $\mathcal{B}(W \to e\nu)/\mathcal{B}(W \to \mu\nu)$

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- Within $2.00 < \eta^l < 3.50$, the branching fraction ratios are

$$\frac{\mathcal{B}(W+ \to e^+\nu_e)}{\mathcal{B}(W+ \to \mu^+\nu_\mu)} = 1.024 \pm 0.003 \pm 0.019$$

$$\frac{\mathcal{B}(W- \to e^-\bar{\nu}_e)}{\mathcal{B}(W- \to \mu^-\bar{\nu}_\mu)} = 1.014 \pm 0.004 \pm 0.022$$

$$\frac{\mathcal{B}(W \to e\nu)}{\mathcal{B}(W \to \mu\nu)} = 1.020 \pm 0.002 \pm 0.019$$

Comparison with previous experiments

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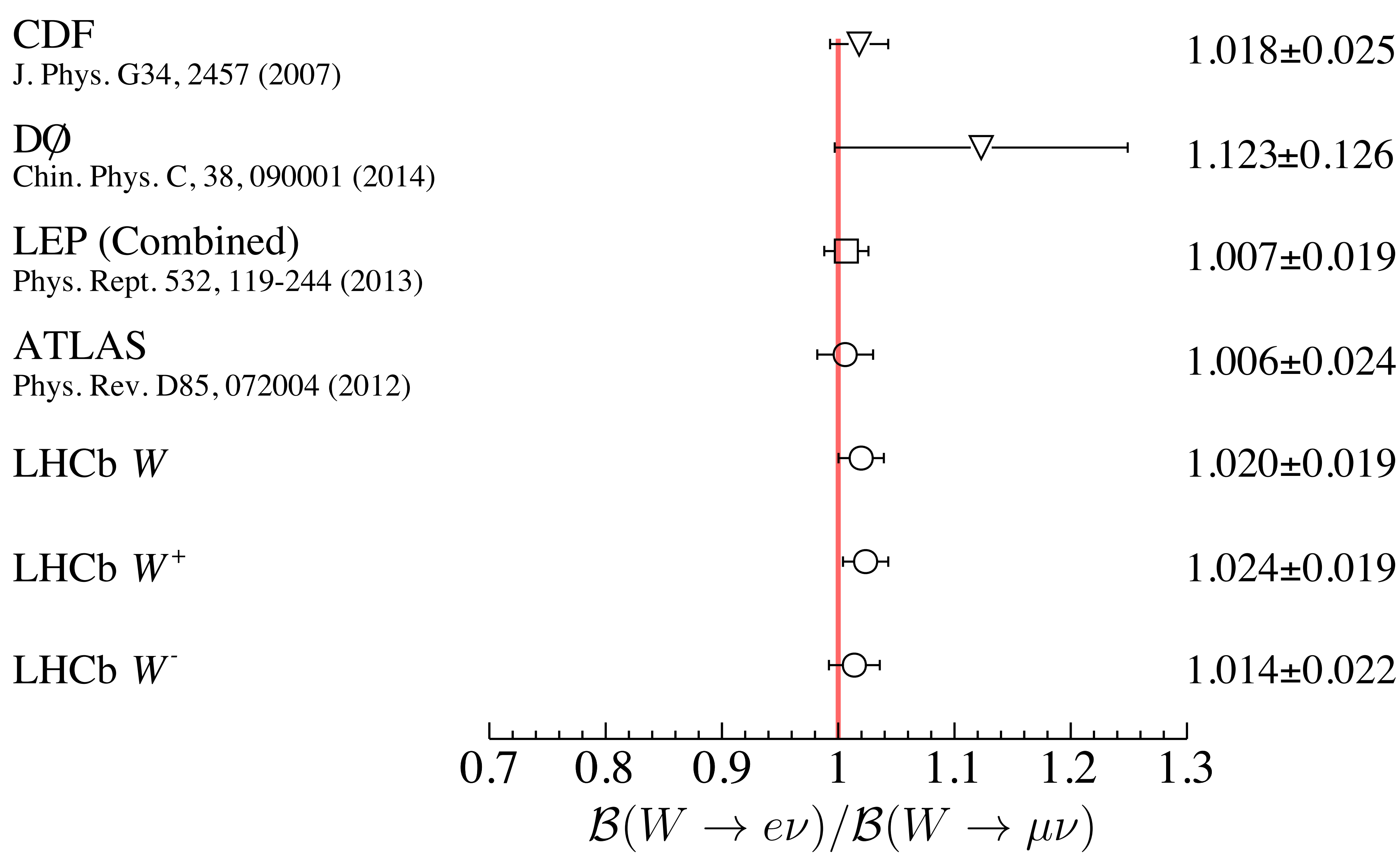
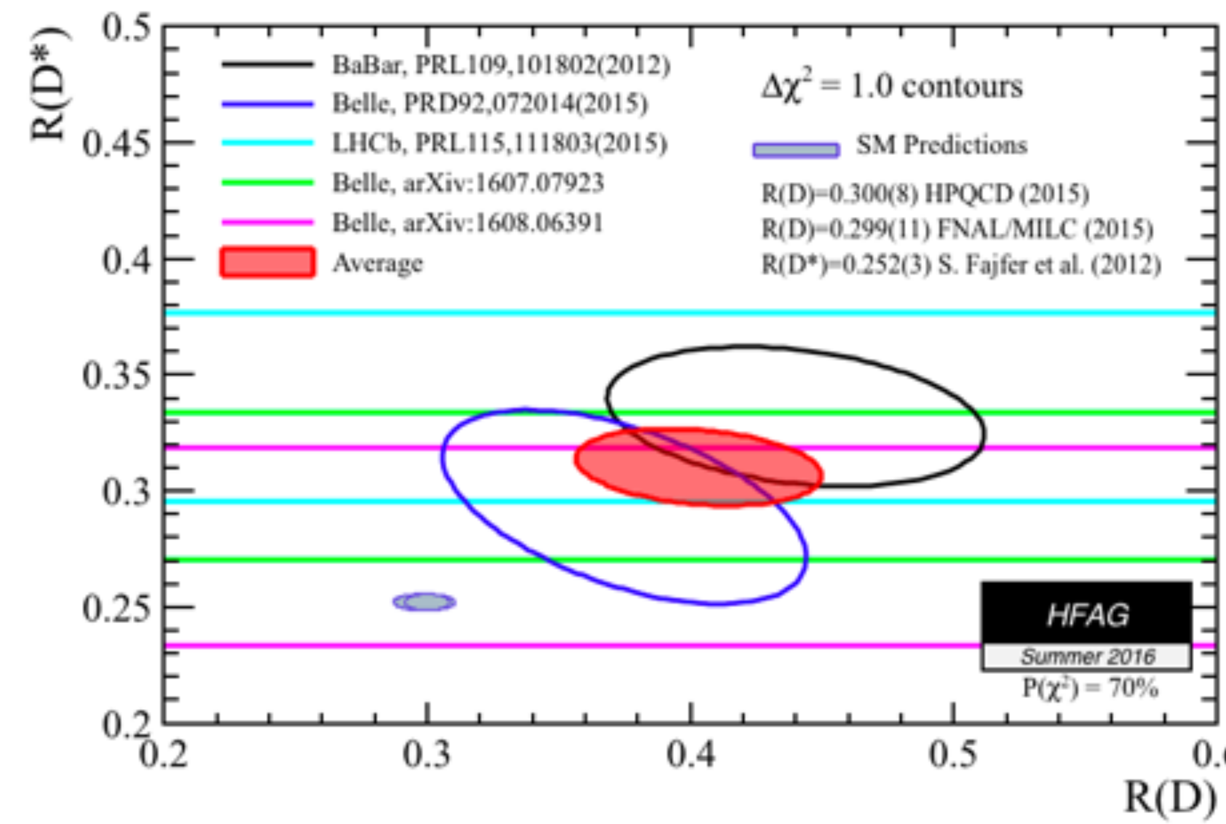


Summary

- LHCb has seen deviations from SM predictions in ~~LFU~~ studies
  - in R_K of 2.6$\boldsymbol{\sigma}$ and
  - in R(D*) of 2.7$\boldsymbol{\sigma}$
  - not in $\mathcal{B}(W \to e\nu)/\mathcal{B}(W \to \mu\nu)$
- Combination of R(D*) and R(D) for various experiments exceeds the SM prediction at a 4.0$\boldsymbol{\sigma}$ level

  → hints at NP?



Courtesy of M. Rotondo

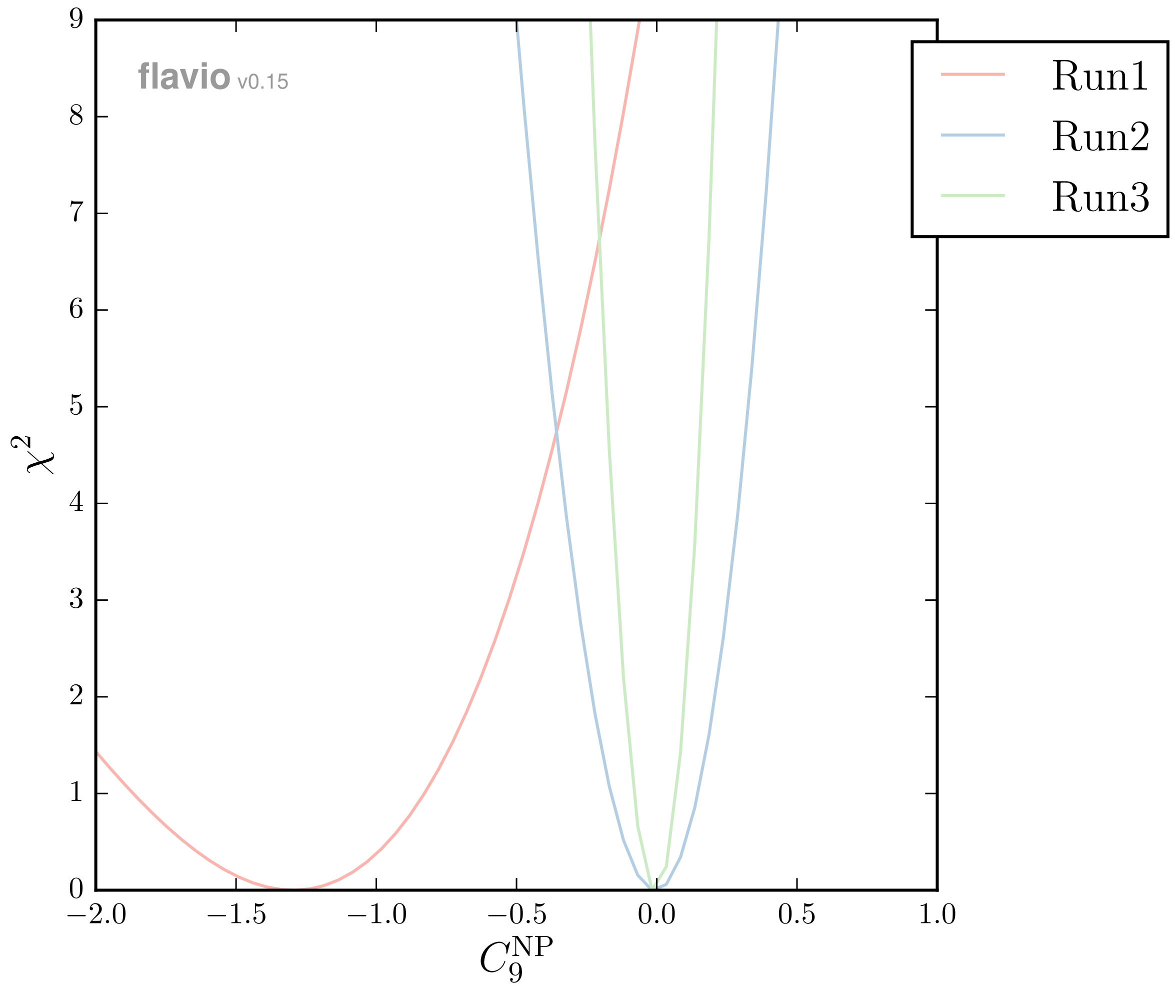
Outlook

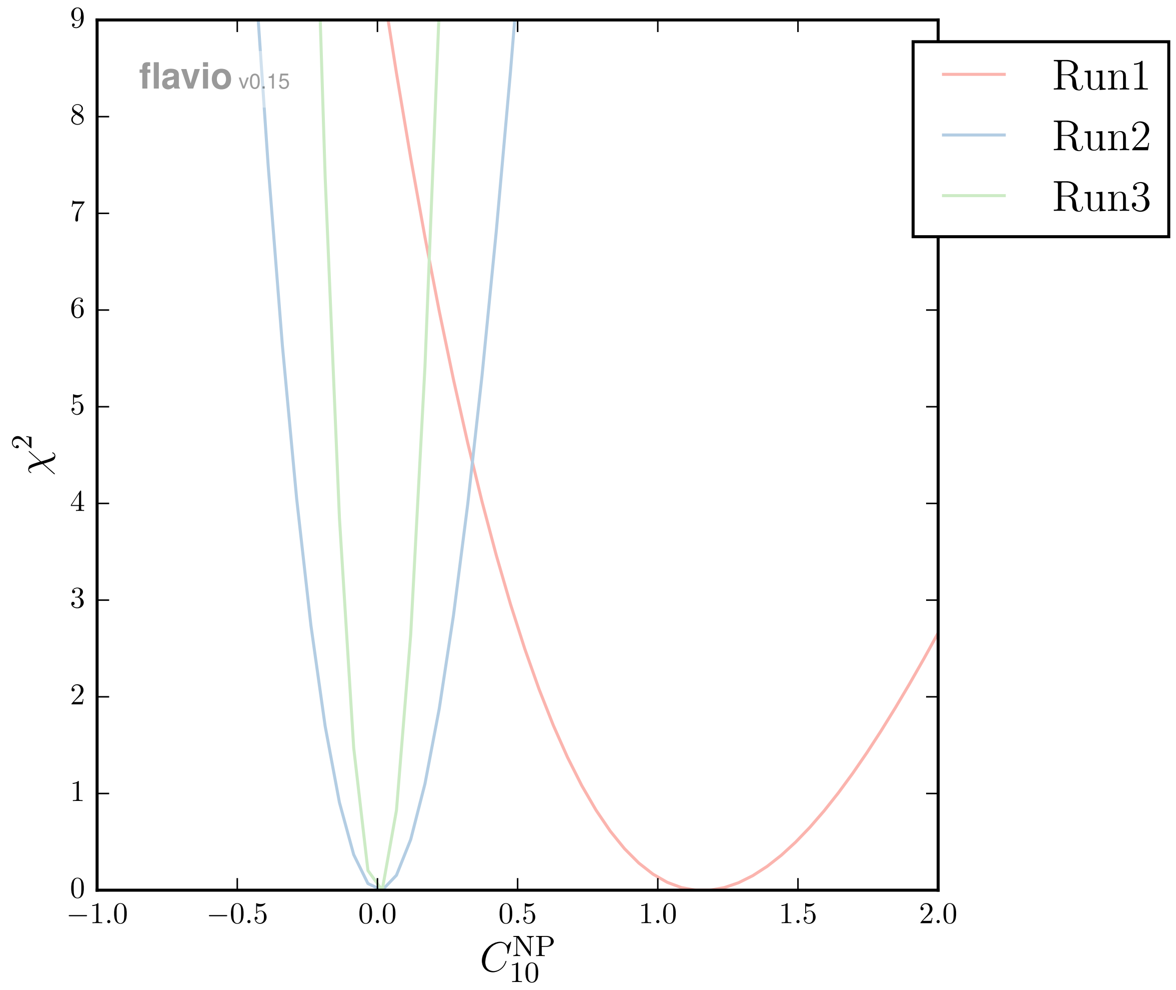
- Extend existing measurements to Run 2 data and improve analysis techniques
- Measurements of R_{K^*}, R_{Φ}, R_{Λ}, and others in preparation
- Prospects after Run 2 (8/fb) and after Run 3 (22.5\fb)
  → improved trigger [LHCB-TDR-016]
  - extrapolated statistical uncertainty from yields of angular or branching fraction measurements (with exception of R_K)
  - accounted for production cross sections and for Run 3 for trigger

	R_K (low q^2)	R_K (high q^2)	R_{K^*} (low q^2)	R_{K^*} (high q^2)	R_{Φ} (low q^2)	R_{Φ} (high q^2)	R_{Λ} (high q^2)	$R_{K\pi\pi}$ (low q^2)
Run 1	0.082	0.076	0.118	0.109	0.286	0.224	0.173	0.238
Run 2	0.042	0.039	0.060	0.056	0.146	0.126	0.088	0.122
Run 3	0.023	0.021	0.033	0.030	0.079	0.068	0.048	0.066

Outlook: Effect of R_K

Assume SM prediction for Run 2 and Run 3 as central value of R_K





Thank you.