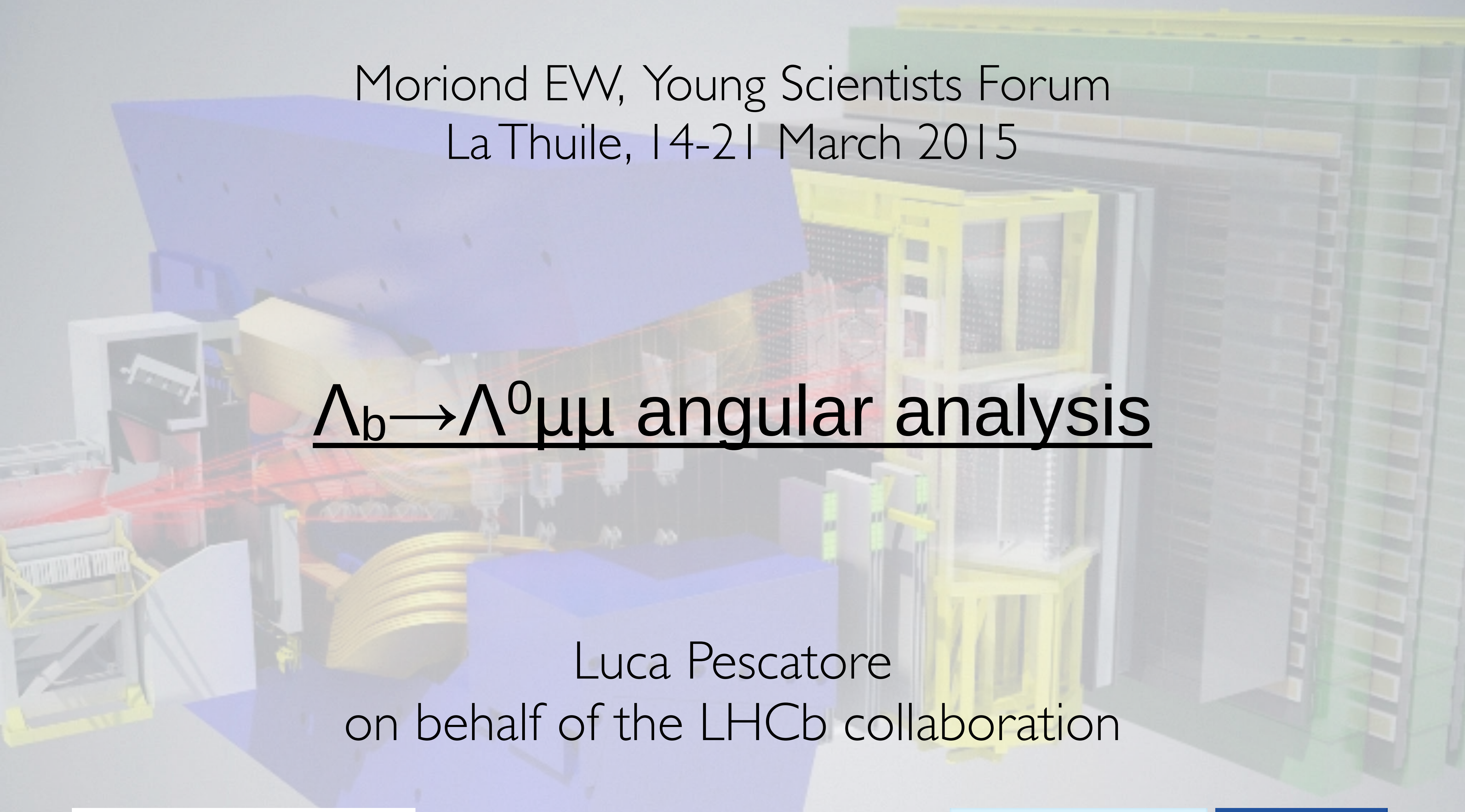
Moriond EW, Young Scientists Forum
La Thuile, 14-21 March 2015

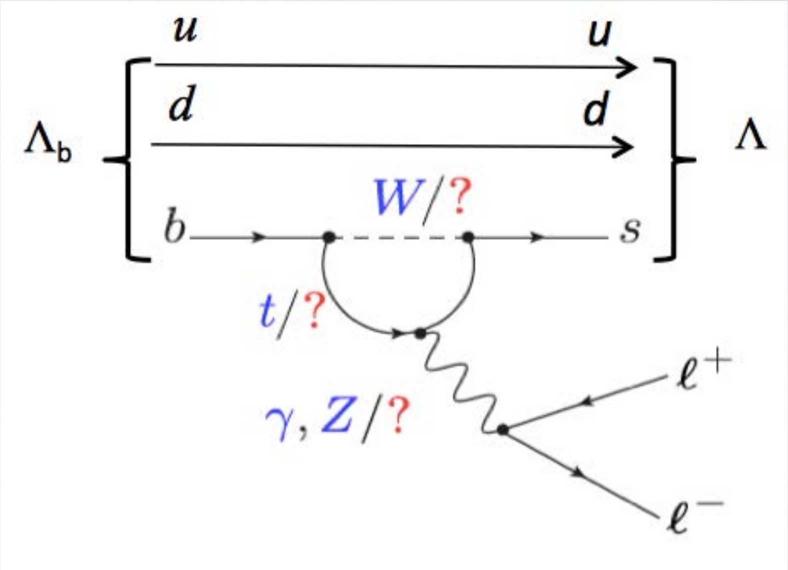


$\Lambda_b \to \Lambda^0 \mu\mu$ angular analysis

Luca Pescatore
on behalf of the LHCb collaboration

Rare decays and Λ_b

- Rare decays are suppressed in the SM and can happen at **loop level only**.
  - Flavour Changing Neutral Current processes → forbidden at tree level in the SM
- **New Physics** can enter in the loop
  - Very sensitive to new physics effects → small SM component: BR typically ~10^{-6} or less
  - No evidence in direct searches so far → loops can probe **high energy scales**

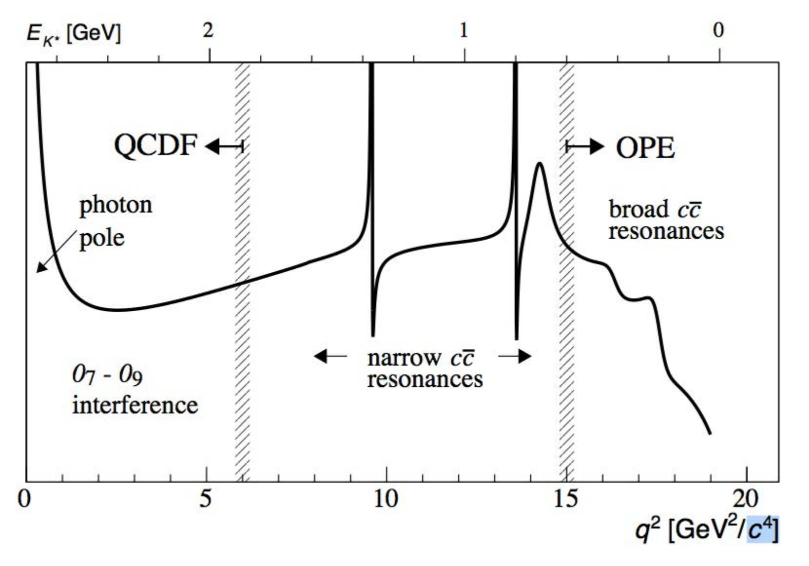


T. Gutsche et al., PRD87 (2013) 074031

Λ_b decays

- Has non-zero spin: unlike B mesons allows to improve the understanding of the helicity structure
- Particular hadronic physics (heavy quark + diquark)
- Different treatments of form factors depending on the q^2 region → can be tested comparing predictions as a function of q^2

$$q^2 = m_{\mu\mu}^2$$

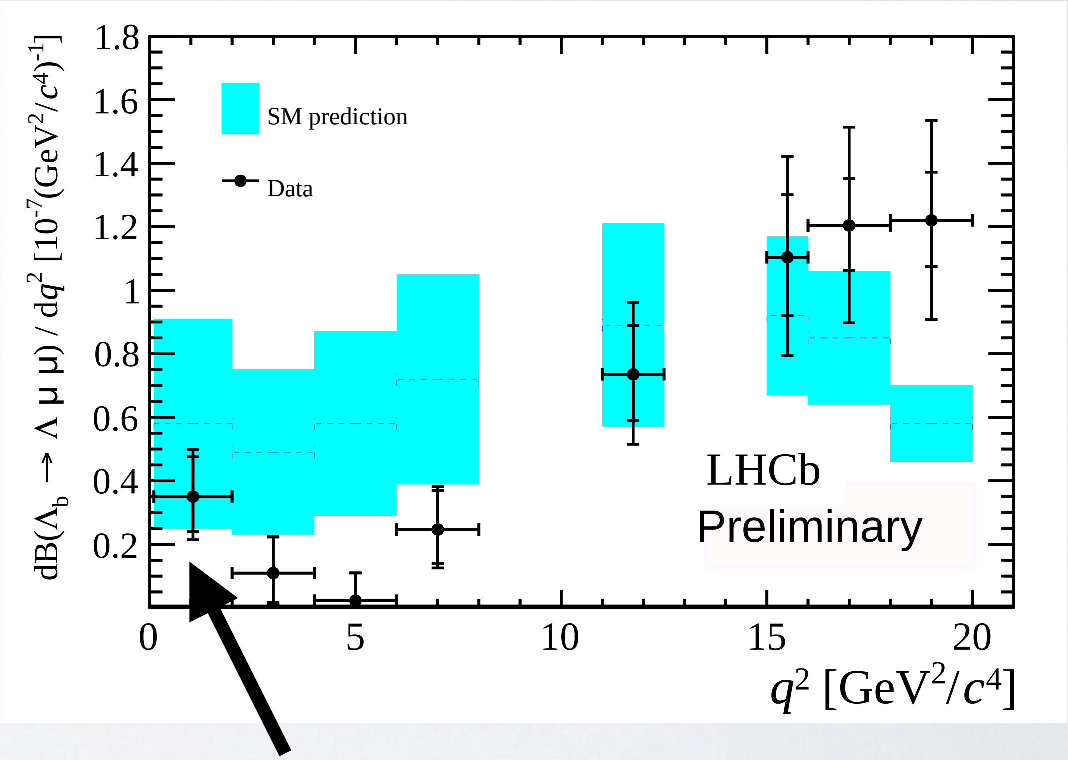


arXiv:1501.0339v1

$\Lambda_b \to \Lambda^0 \mu\mu$ branching ratio

Updated measurement

- Reconstructed using the $\Lambda^0 \to p\pi$ mode
- $J/\psi\Lambda^0$ used to normalise the BR
- Particular topology with long-lived Λ^0: only background from $B \to K_S$ decays
- Analysis on 3fb^{-1}: ~300 observed events



Prediction: PRD 87 (2013) 074502

First evidence for signal above 3σ level at low q^2

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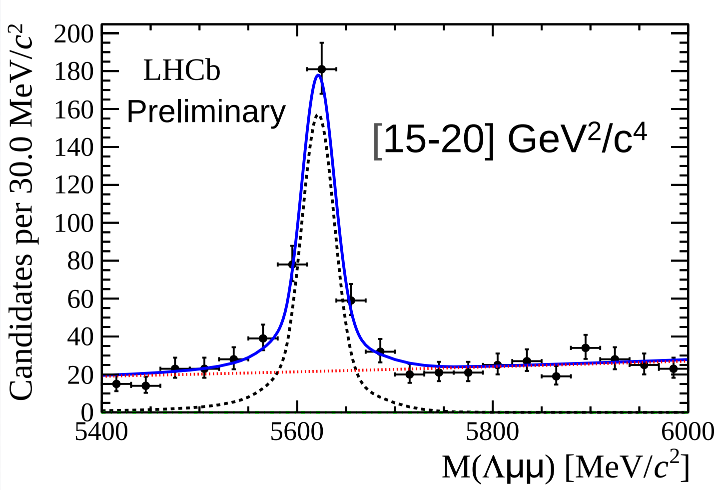
to be submitted to JHEP



Branching ratio:

$$1.1 < q^2 < 6.0 \qquad 0.09\,^{+0.06}_{-0.05}\,(\mathrm{stat})\,^{+0.01}_{-0.01}\,(\mathrm{syst})\,^{+0.02}_{-0.02}\,(\mathrm{norm})$$

$$15.0 < q^2 < 20.0 \qquad 1.18\,^{+0.09}_{-0.08}\,(\mathrm{stat})\,^{+0.03}_{-0.03}\,(\mathrm{syst})\,^{+0.27}_{-0.27}\,(\mathrm{norm})$$

Inner error: stat. + syst.

Outer error:
including normalisation (dominant)

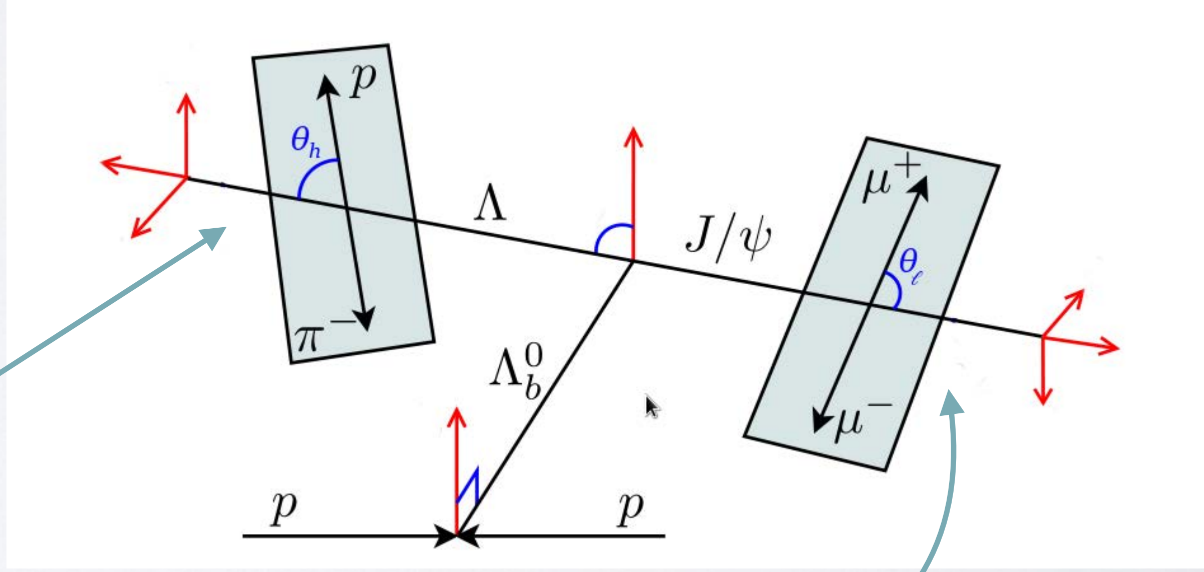
Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) only in q^2 above ψ(2S).

Angular analysis

New!

- In $\Lambda_b \to \Lambda^0 \mu\mu$ the Λ^0 decays weakly
  → unlike for B decays the hadronic side asymmetry is also interesting
- Measure two forward-backward asymmetries: in dimuon and Λ^0 system
- Selection based on a neural network classifier
- Fit one-dimensional angular distributions

Differential rates
as a function of the angles



$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_h} \propto (1 + 2A^h_{\mathrm{FB}}\cos\theta_h)$$

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell} \propto \frac{3}{8}(1+\cos\theta_\ell)(1-f_L) + A^\ell_{FB}\cos\theta_\ell + \frac{3}{4}f_L\sin^2\theta_\ell$$

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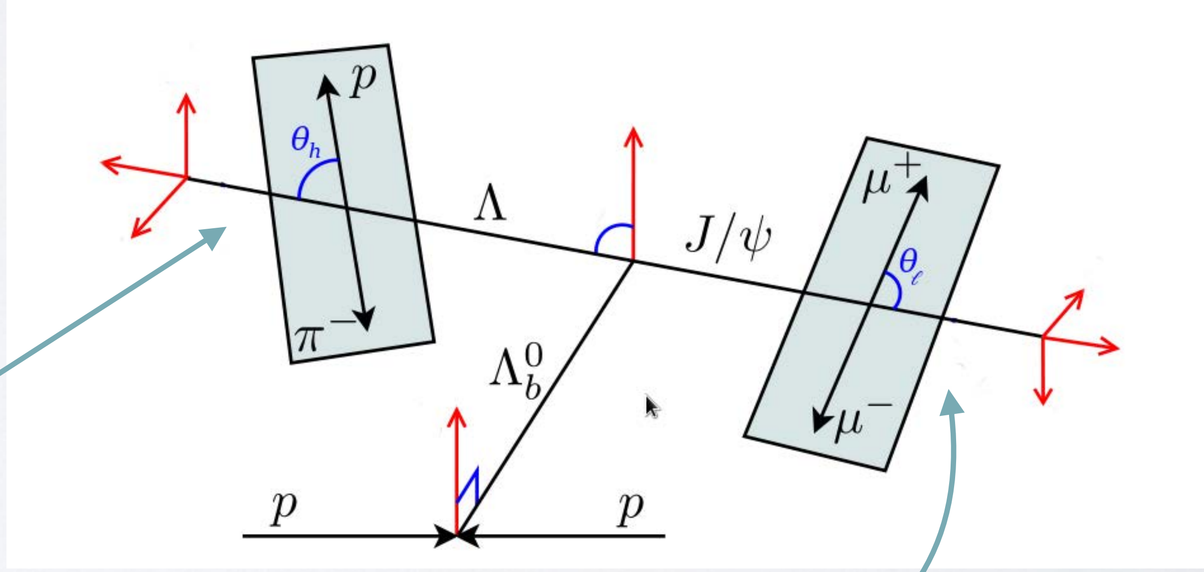

Forward-backward asymmetry in the dimuon system

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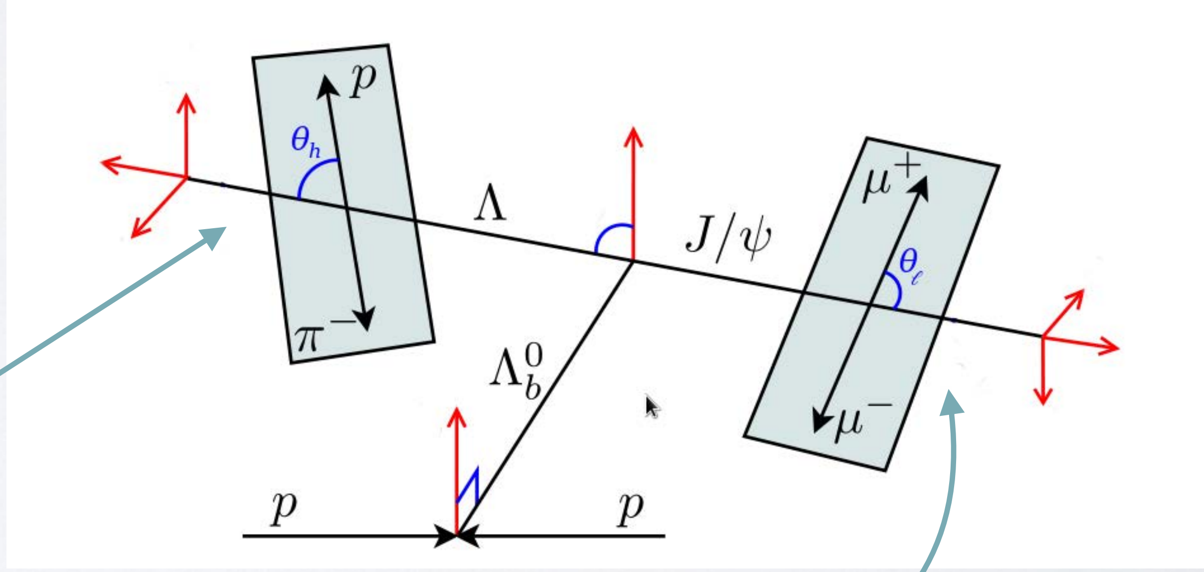

Fraction of longitudinally polarised dimuons

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_h} \propto (1 + 2A^h_{\mathrm{FB}} \cos\theta_h)$$

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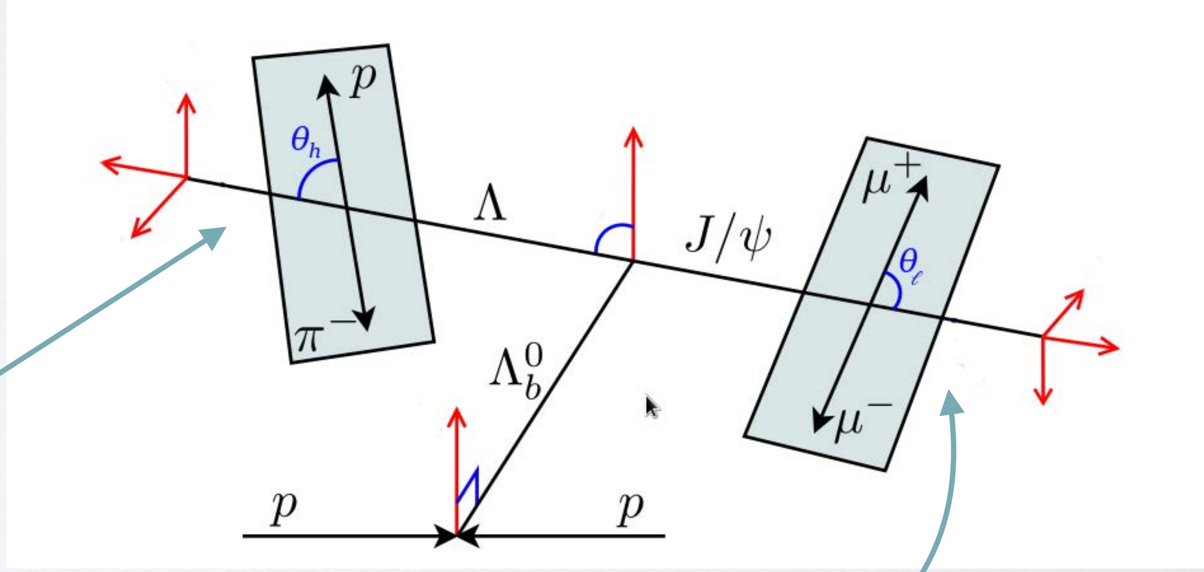
Forward-backward asymmetry in the hadronic system

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_h} \propto (1 + 2A^h_{\mathrm{FB}}\cos\theta_h)$$



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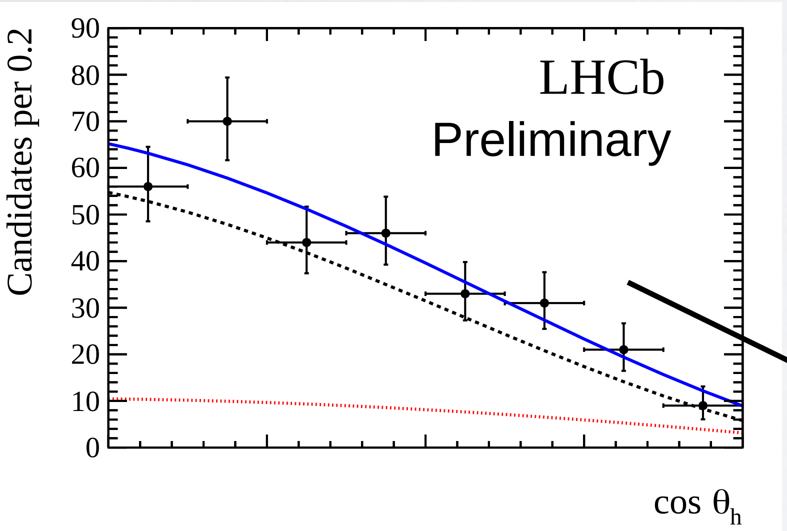
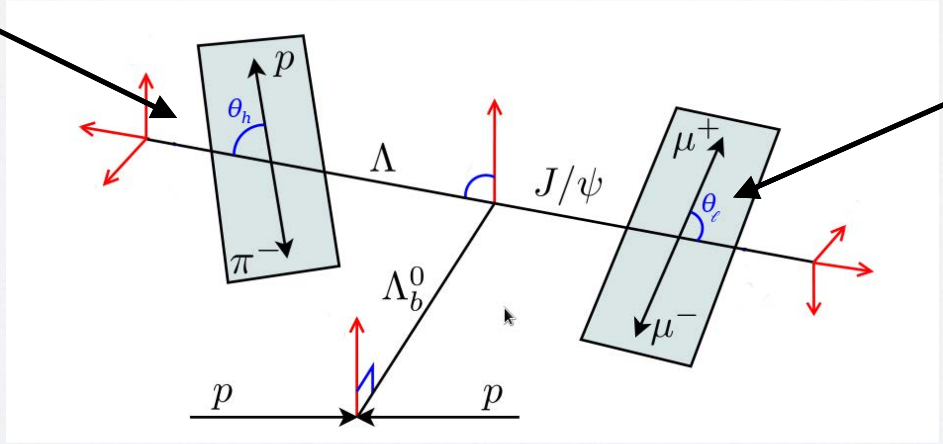
$$PDF^{tot}(\cos\theta_i) = [f^{theory}(\cos\theta_i) + f^{bkg}(\cos\theta_i)] \times \varepsilon(\cos\theta_i)$$

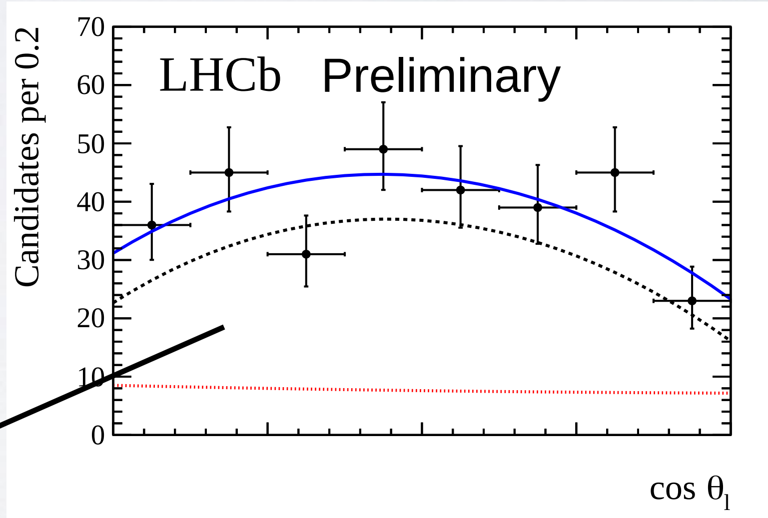


Hadronic system

Most challenging:
asymmetric acceptance.

$15 < q^2 < 20$ GeV^2/c^4





Dimuon system

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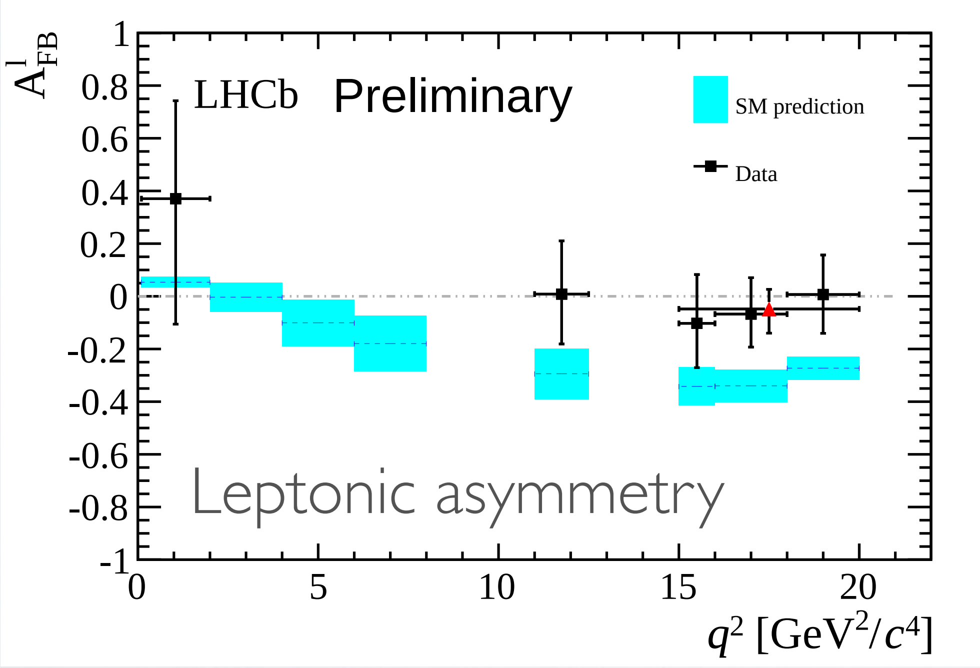
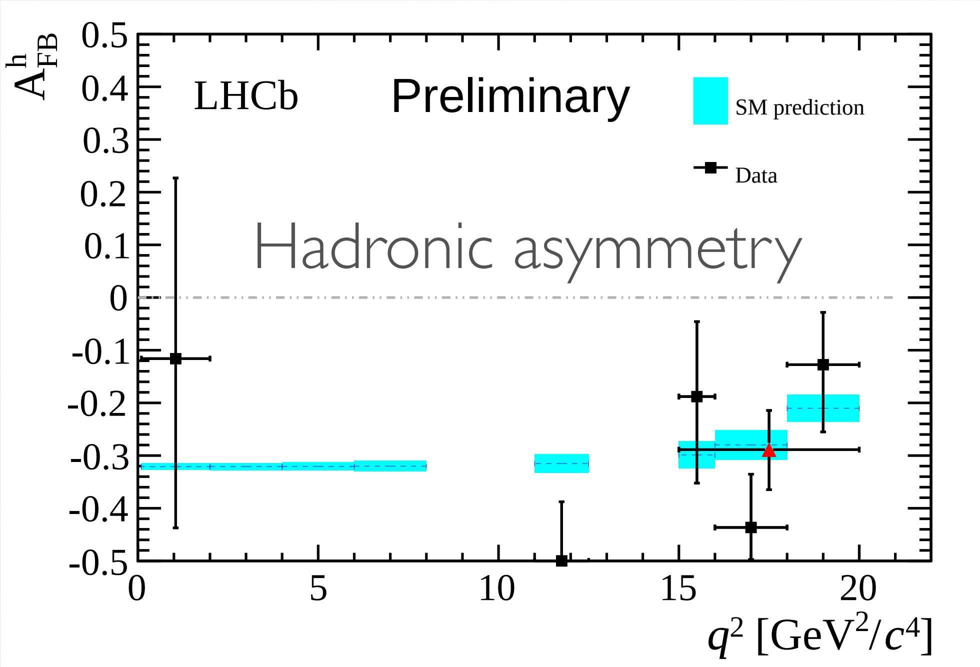
Angular analysis: results

New!





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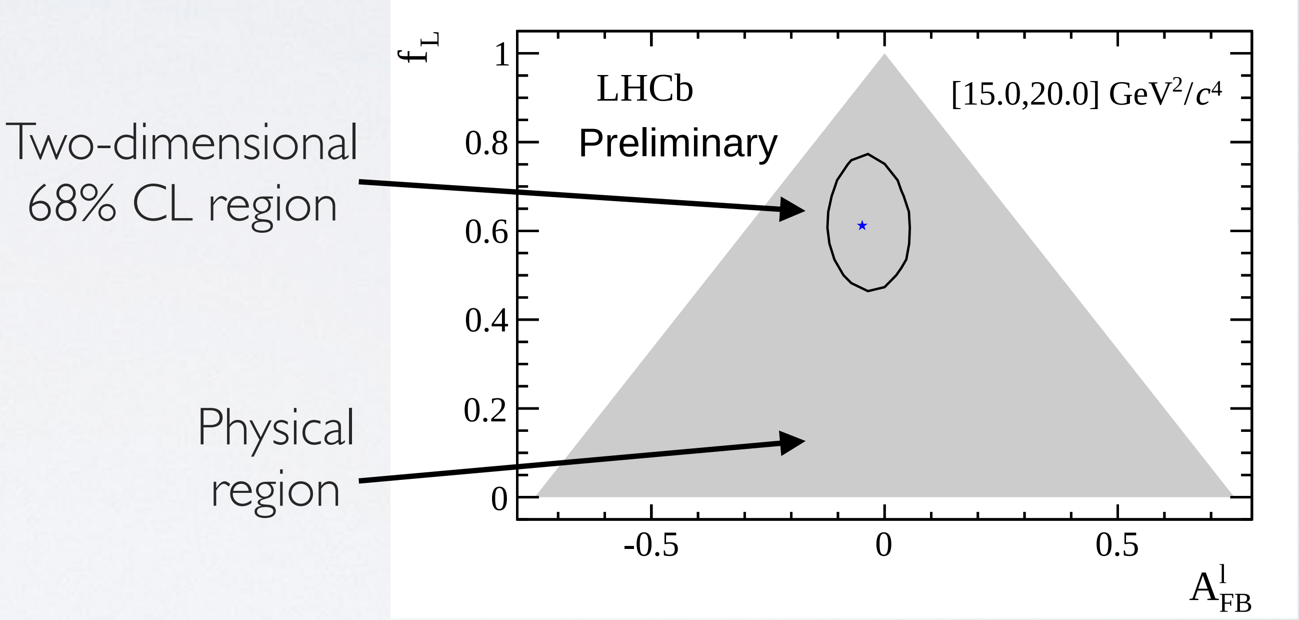
Theory: arXiv:1401.2685

- Asymmetries as a function of q^2
- Only where the signal significance is above 3σ
- Physical boundaries in the parameter-space:
  → using Feldman-Cousins inspired “plug-in” method



Two-dimensional 68% CL region

Physical region

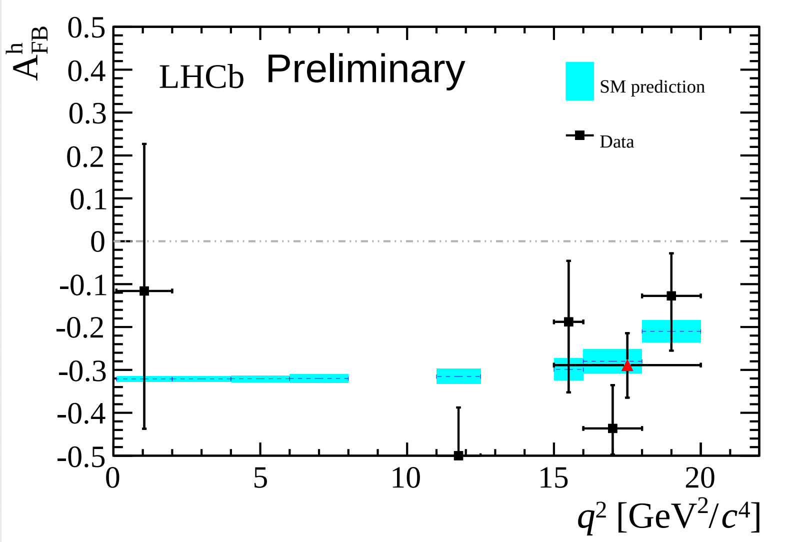
- A^{h}_{FB} is in good agreement with SM prediction
- A^{l}_{FB} is compatible within 2 sigma but consistently above the prediction

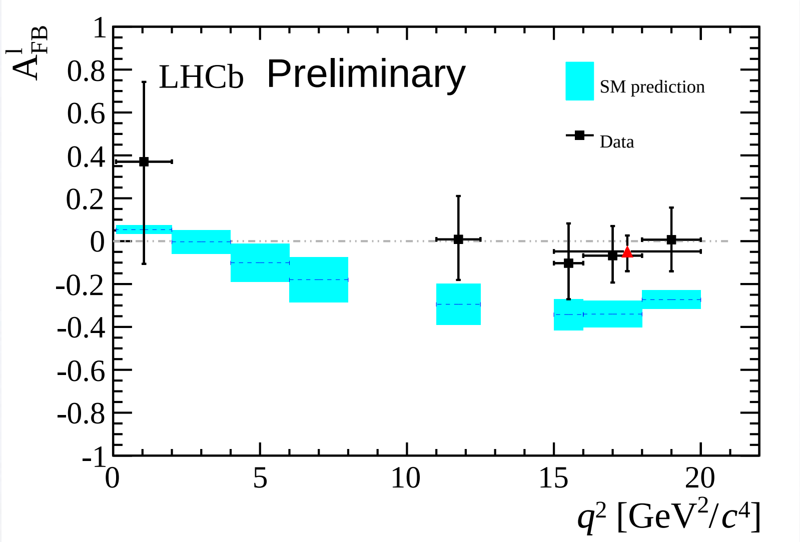
→ Could be due large $c\bar{c}$ contributions.

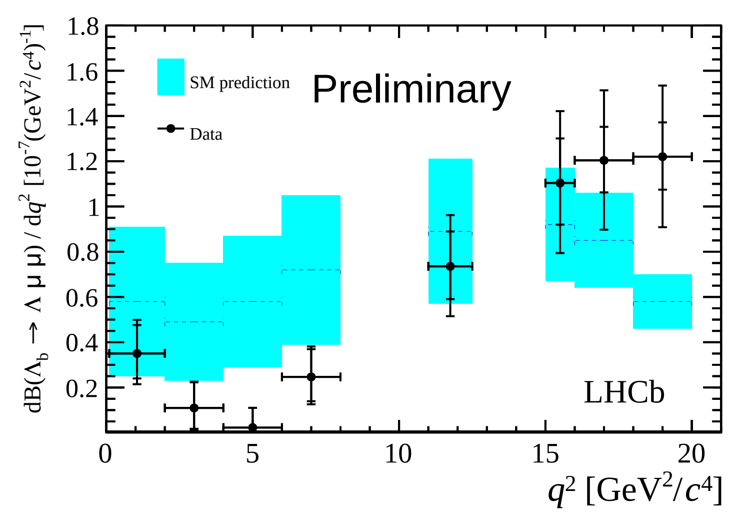
Summary

- Updated measurement of $\Lambda_b \rightarrow \Lambda^0 \mu\mu$ with errors improved by a factor of ~3
- First evidence of signal al low q^2
- First measurement of angular observables
- The study of Λ_b and its decays is still young but staidly growing:
  → recent measurements of mass, lifetime, polarisations and more.

Thank you for listening!





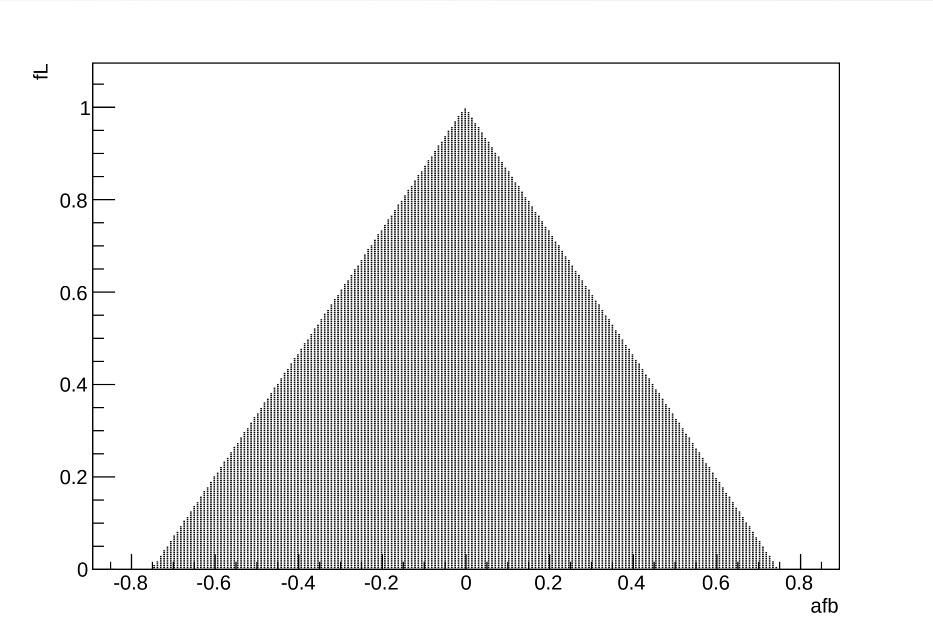


Backup

Angular analysis: uncertainties

- **Statistical uncertainties:**
  - Lepton side PDF has physical boundaries → can bias the uncertainties
  - Likelihood-ordering method treating nuisance parameters with the plug-in method used for uncertainties (arXiv:1109.0714)
    - ✓ Based on toy experiments
    - ✓ Well defined frequentist coverage

Dark area: region of the parameter space where the PDF is positive.



- **Systematics:**
  - Effect of a non-flat efficiency on the integration of the full 5D angular PDF
  - Data-MC discrepancies (MC used for most of the efficiencies)
  - Particular choice of background parameterisation
  - Effect of finite angular resolution → asymmetric bin migration

Feldman-Cousins method

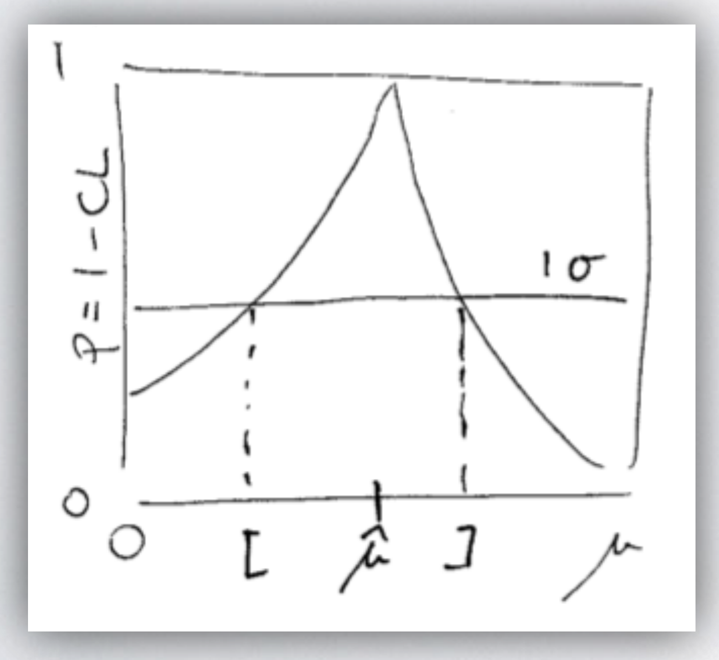
arXiv:physics/9711021

- Feldman-Cousins method plug-in method to extract confidence bands
  - Choose Parameters of Interest (PoI) and fit data with PoI free and fixed
  - Generate toys with PoI fixed to tested values and nuisance parameters (all other parameters) from fixed fit on data.
  - Fit toys with free and fixed PoI
  - Look how may times log likelihood ratio in data is smaller than MC
  - Scan values to look for 68%, 95% etc.

$$\left(\frac{logL_{free}}{logL_{fixed}}\right)_{data} < \left(\frac{logL_{free}}{logL_{fixed}}\right)_{MC}$$

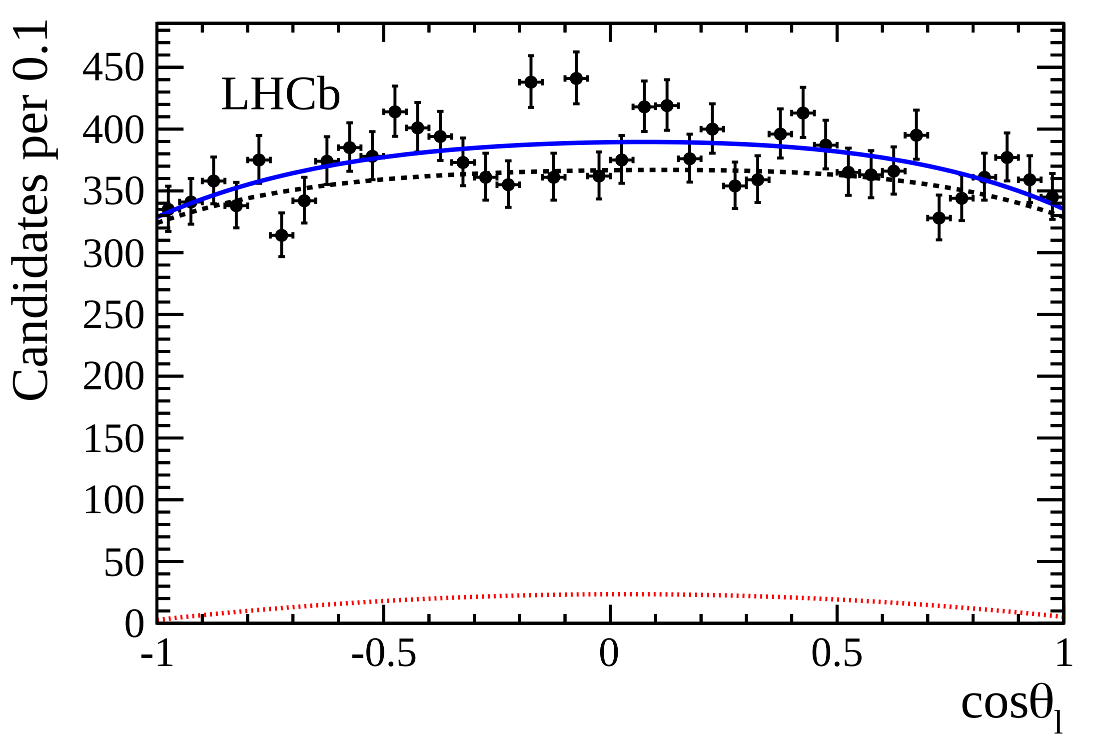
Statistica Sinica 19 (2009) 301

arXiv:1109.0714v1



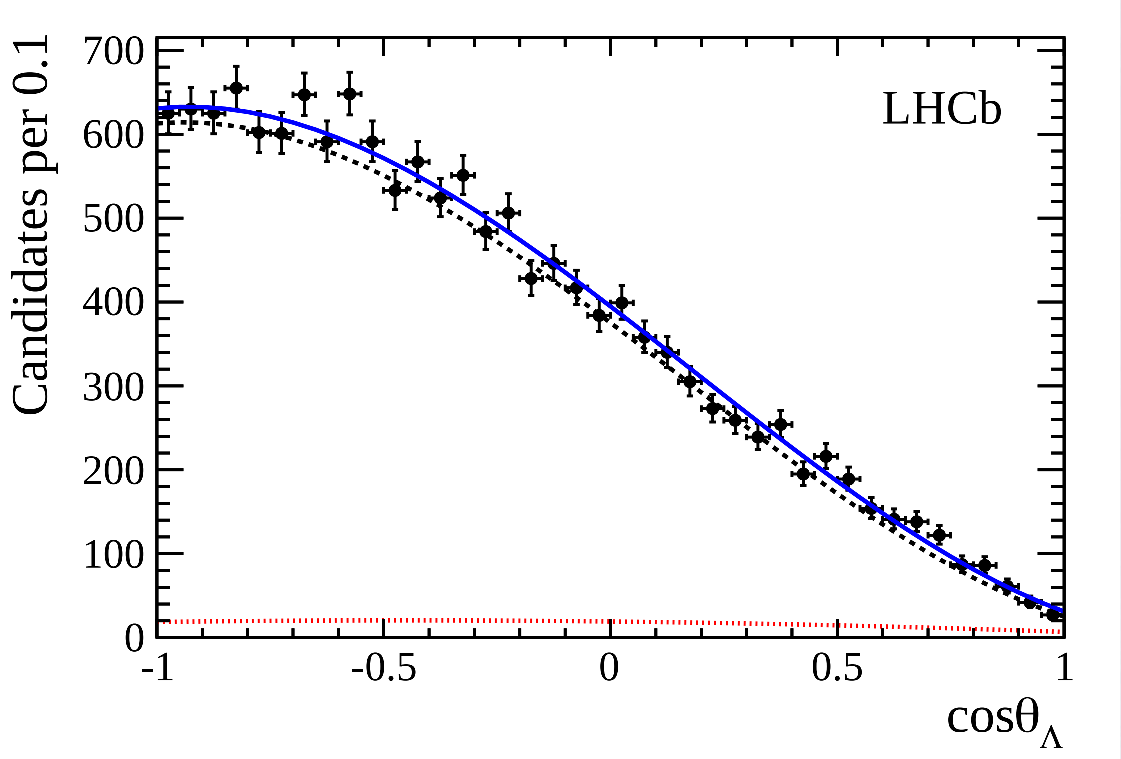
- Starts to be widely used in LHCb
- Allows to consider nuisance parameters: no confidence belt
- Guarantees full coverage
- Returns 2-side intervals and upper limits in a unified approach

Using J/ψΛ for cross-check



Leptonic angle

Hadronic angle



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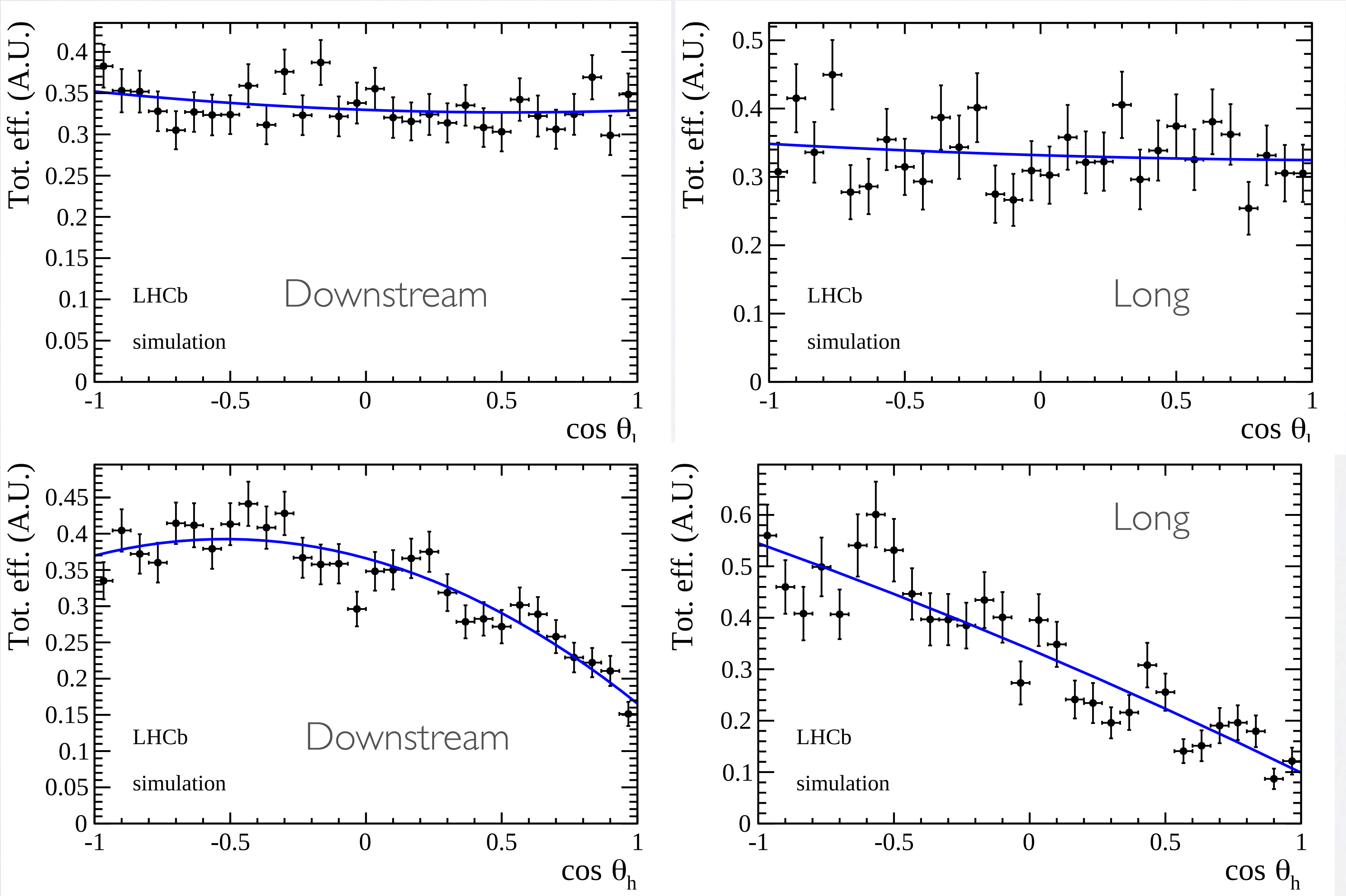
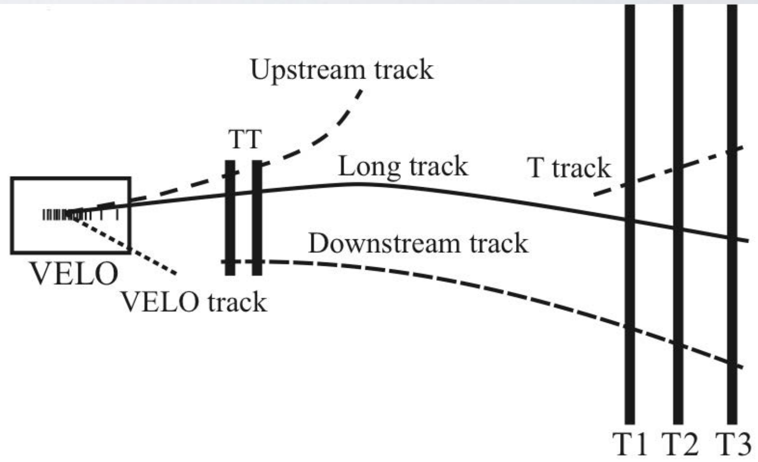
Angular acceptances

In LHCb long-lived particles, like Λ^0, can be reconstructed with hits in the VELO (log) or without hits in the VELO (downatream).

- Up- and down-stream events are characterised by different efficiency and resolution
- A simultaneous fit is performed on the two categories





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Results tables

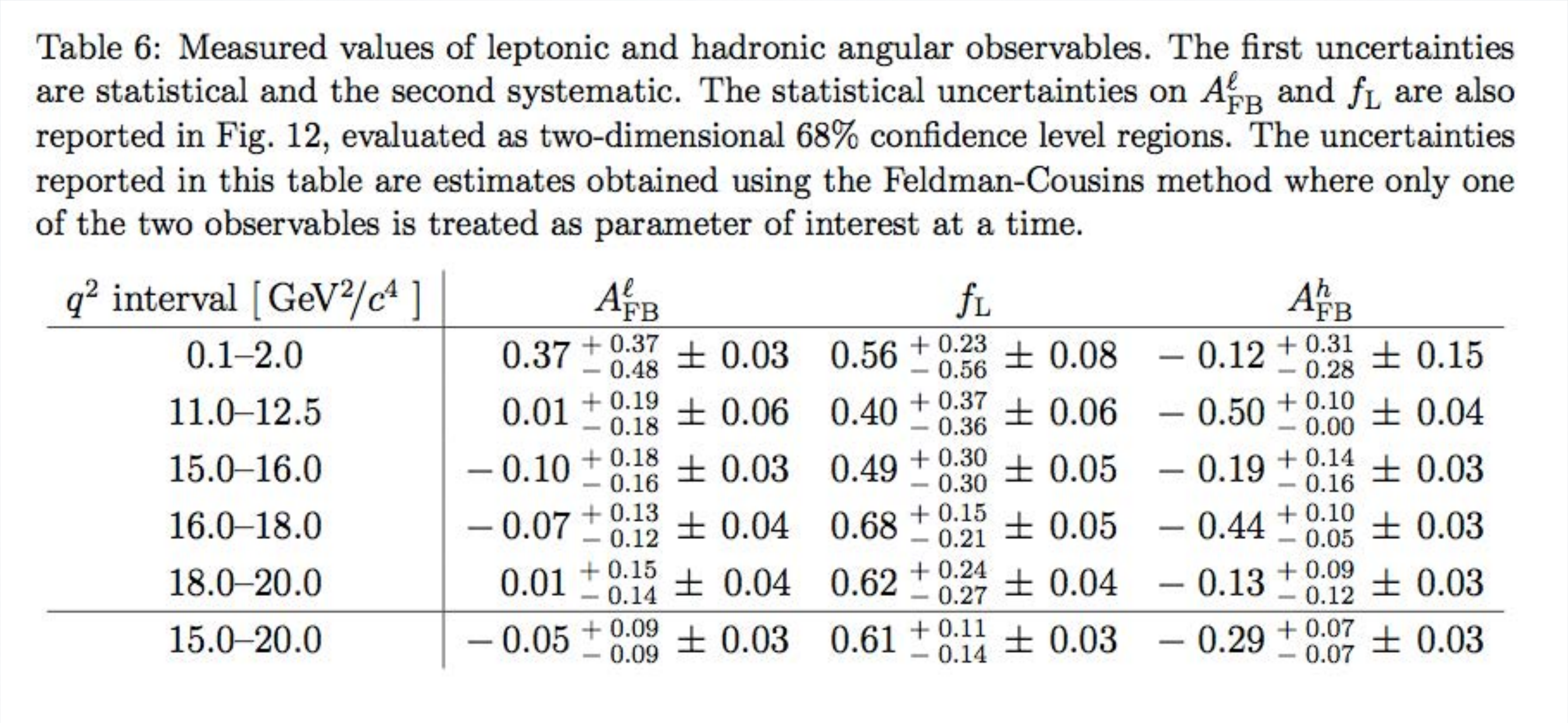

Table 6: Measured values of leptonic and hadronic angular observables. The first uncertainties are statistical and the second systematic. The statistical uncertainties on $A_{\rm FB}^{\ell}$ and $f_{\rm L}$ are also reported in Fig. 12, evaluated as two-dimensional 68% confidence level regions. The uncertainties reported in this table are estimates obtained using the Feldman-Cousins method where only one of the two observables is treated as parameter of interest at a time.

q^2 interval $[\,{\rm GeV}^2/c^4\,]$	$A_{\rm FB}^{\ell}$	$f_{\rm L}$	$A_{\rm FB}^{h}$
0.1–2.0	$0.37\,^{+\,0.37}_{-\,0.48} \pm 0.03$	$0.56\,^{+\,0.23}_{-\,0.56} \pm 0.08$	$-\,0.12\,^{+\,0.31}_{-\,0.28} \pm 0.15$
11.0–12.5	$0.01\,^{+\,0.19}_{-\,0.18} \pm 0.06$	$0.40\,^{+\,0.37}_{-\,0.36} \pm 0.06$	$-\,0.50\,^{+\,0.10}_{-\,0.00} \pm 0.04$
15.0–16.0	$-\,0.10\,^{+\,0.18}_{-\,0.16} \pm 0.03$	$0.49\,^{+\,0.30}_{-\,0.30} \pm 0.05$	$-\,0.19\,^{+\,0.14}_{-\,0.16} \pm 0.03$
16.0–18.0	$-\,0.07\,^{+\,0.13}_{-\,0.12} \pm 0.04$	$0.68\,^{+\,0.15}_{-\,0.21} \pm 0.05$	$-\,0.44\,^{+\,0.10}_{-\,0.05} \pm 0.03$
18.0–20.0	$0.01\,^{+\,0.15}_{-\,0.14} \pm 0.04$	$0.62\,^{+\,0.24}_{-\,0.27} \pm 0.04$	$-\,0.13\,^{+\,0.09}_{-\,0.12} \pm 0.03$
15.0–20.0	$-\,0.05\,^{+\,0.09}_{-\,0.09} \pm 0.03$	$0.61\,^{+\,0.11}_{-\,0.14} \pm 0.03$	$-\,0.29\,^{+\,0.07}_{-\,0.07} \pm 0.03$

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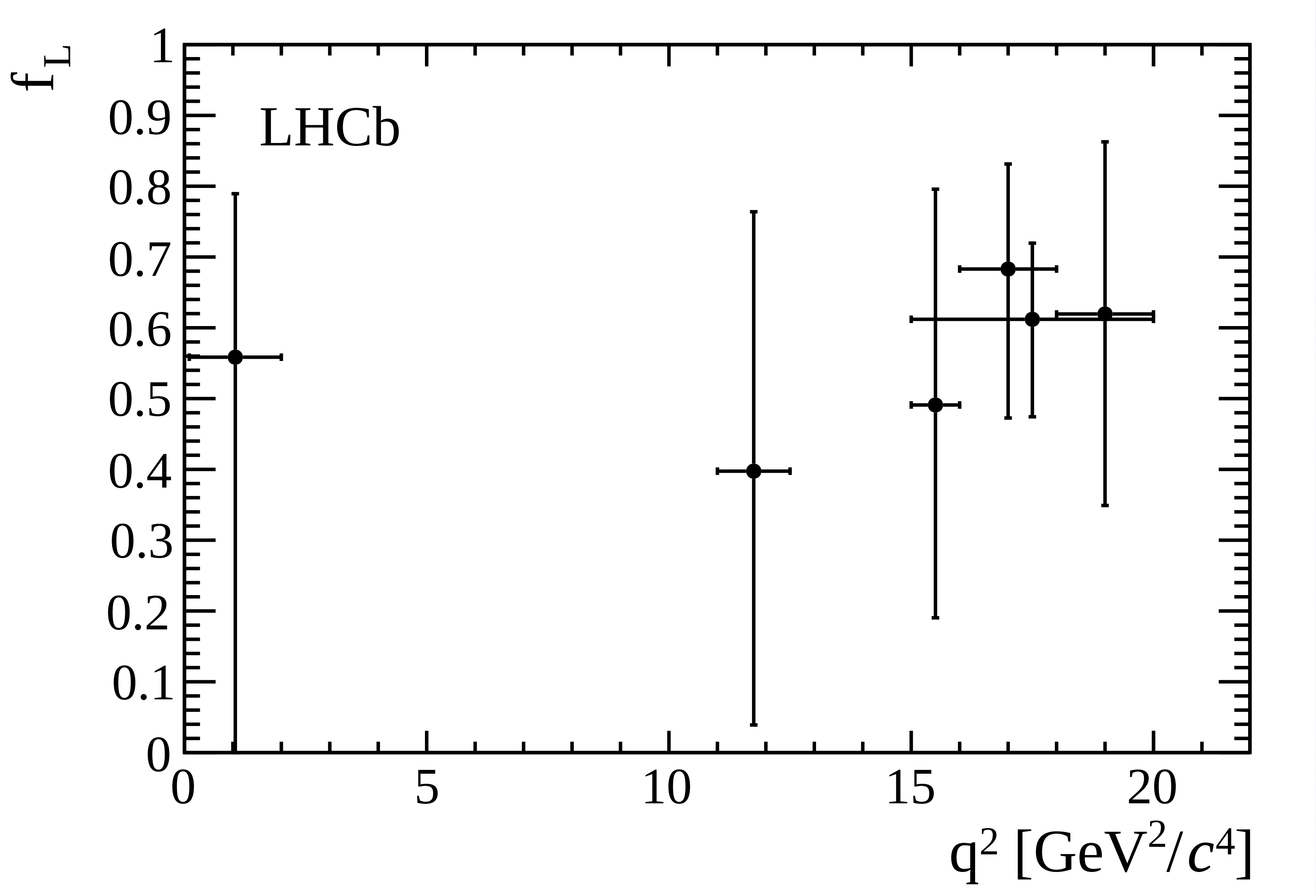
fL values



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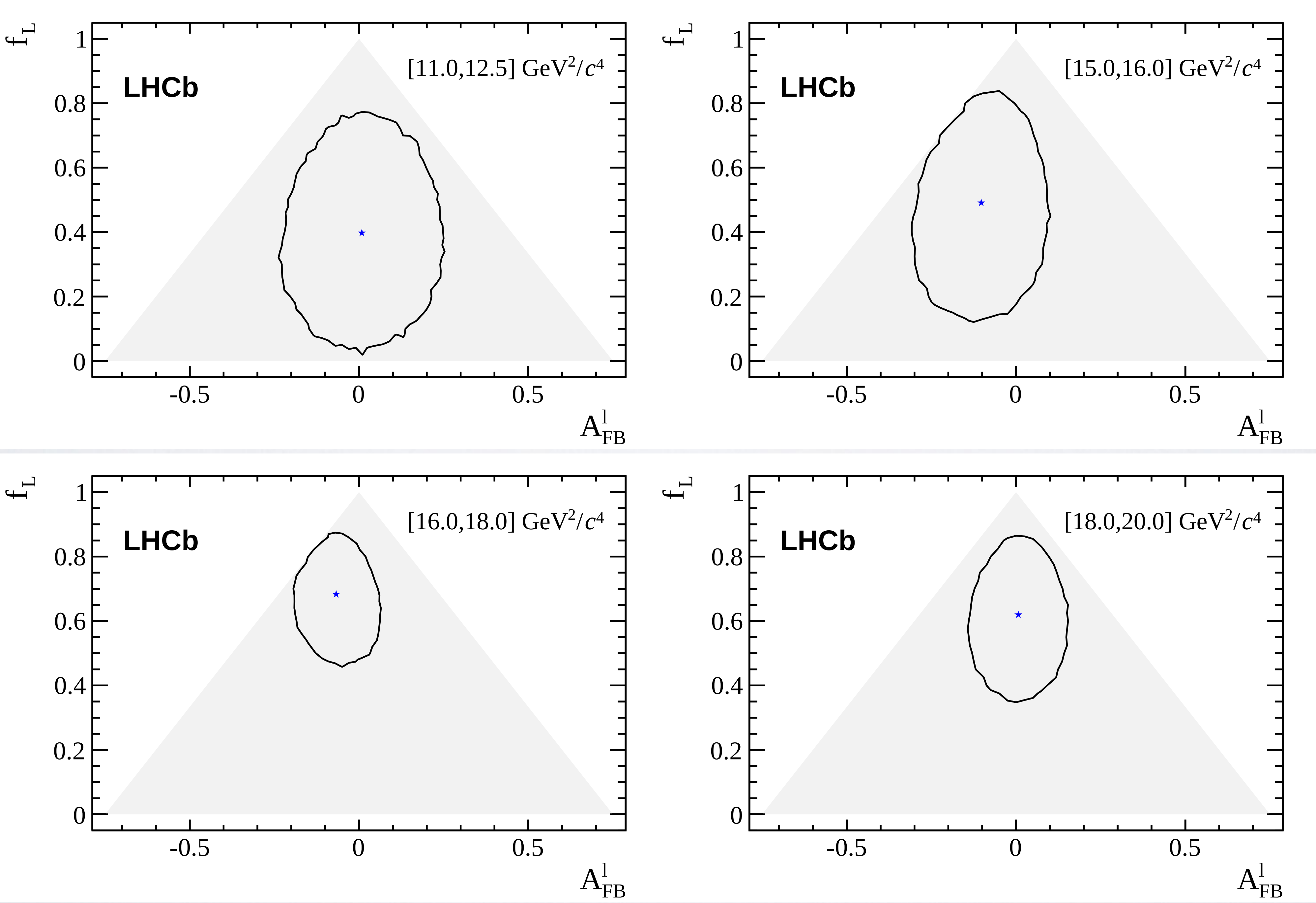
Confidence regions



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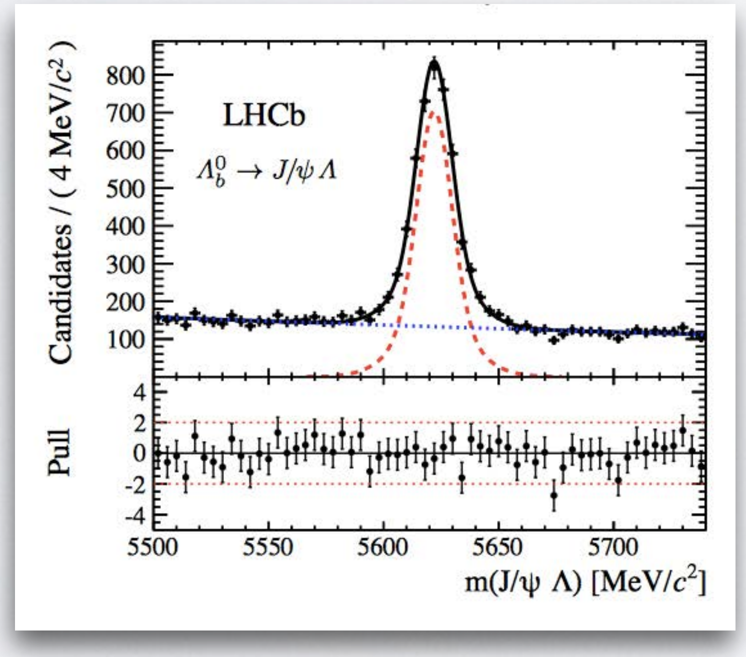
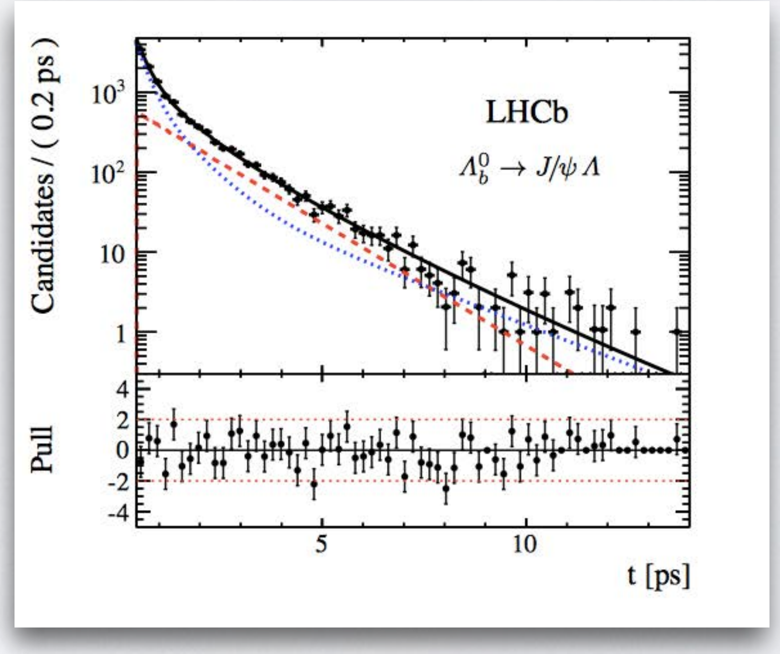
Λ_b decays

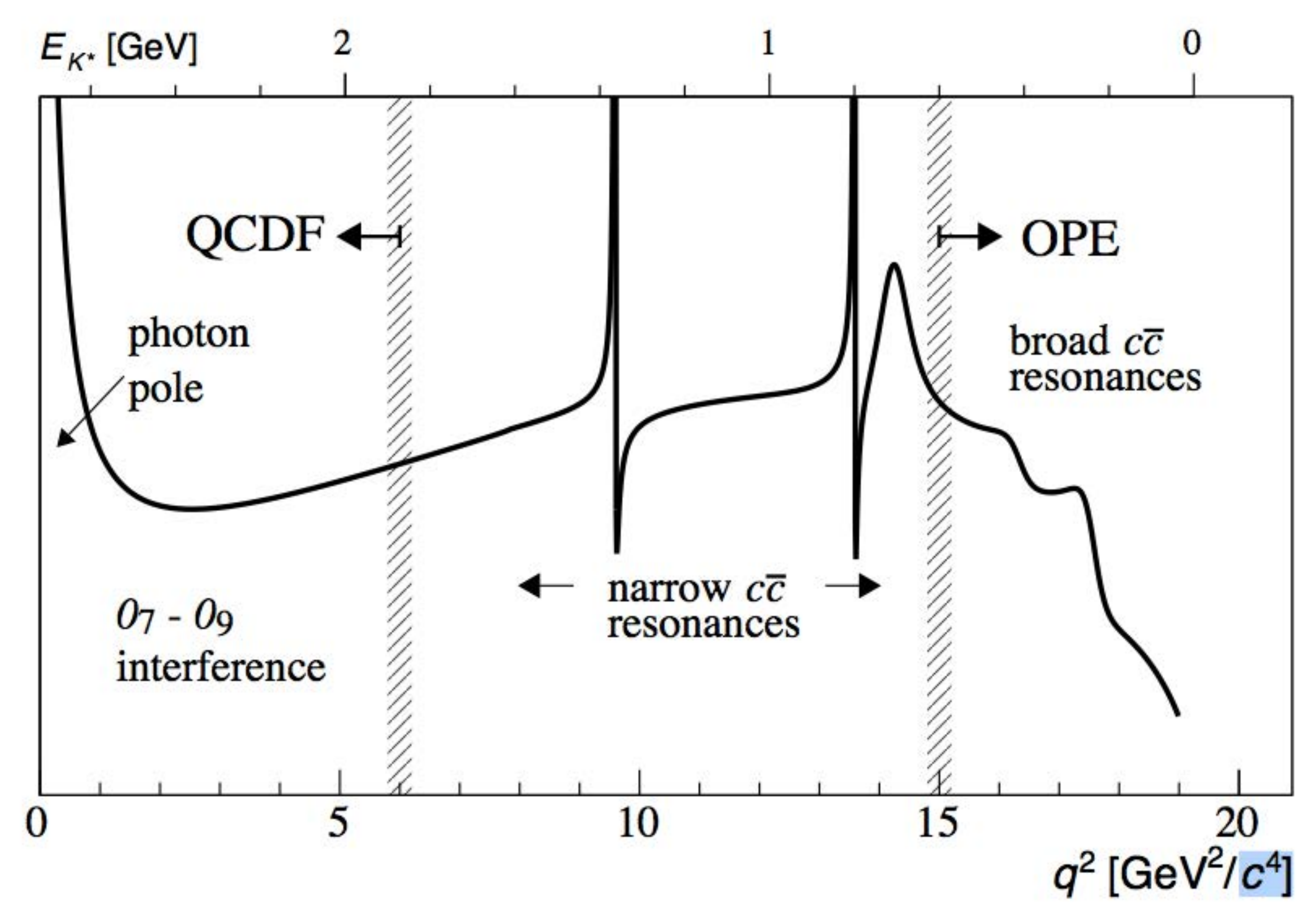
- Recent Λ_b measurements at LHCb:
  - Lifetime: 1.482 ± 0.021 ps (PRL 111 (2013) 102003)
  - Polarisation: 0.06 ± 0.09 (PLB 724 (2013) 27)
  - Mass: 5619.44 ± 0.51 (PRL 110 (2013) 182001)
  - Hadronization fraction: (PRD 85 (2012) 032008)

    $f_\Lambda/f_d = (0.387 \pm 0.043) + (0.067 \pm 0.017)(\eta - 3,198)$



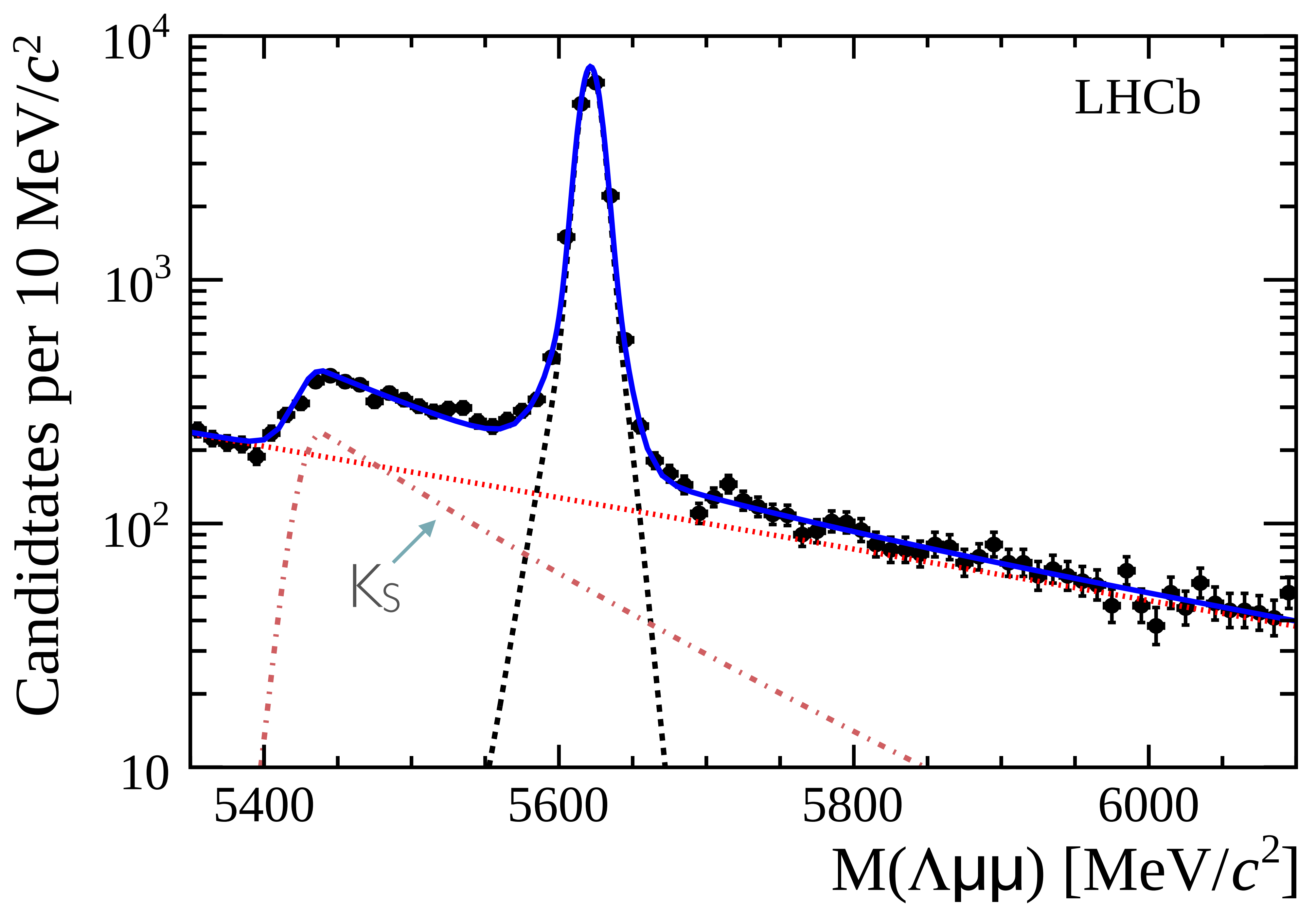


q^2 spectrum DNA

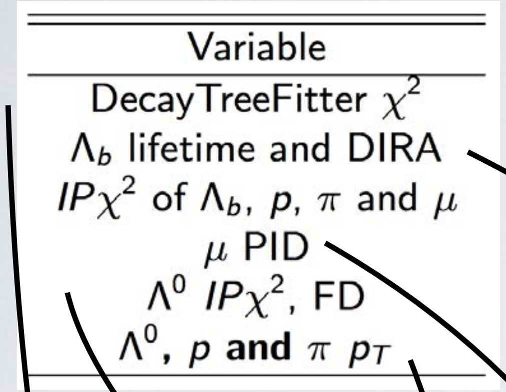


Blake, Gershon & Hiller: arXiv:1501.03309v1

Fit on J/ψΛ mass

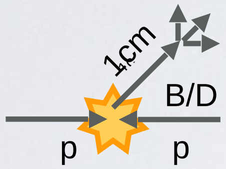


Selection



Variable
DecayTreeFitter χ^2
Λ_b lifetime and DIRA
$IP\chi^2$ of Λ_b, p, π and μ
μ PID
Λ^0 $IP\chi^2$, FD
Λ^0, p and π p_T

Flight distance

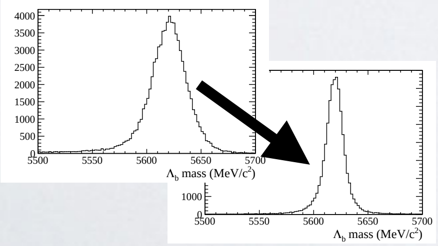


Momenta

help distinguishing combinatorial

DecayTreeFitter:

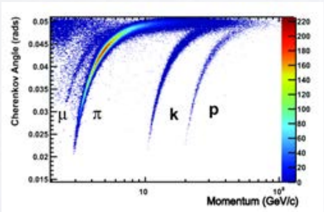
χ^2 of a kinematically constrained refit



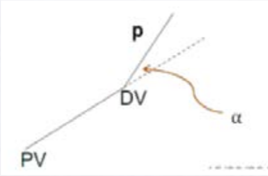
PID

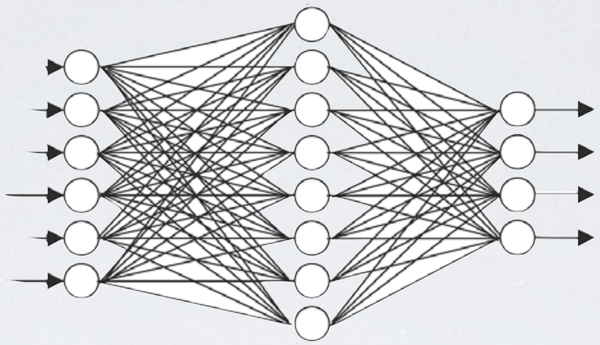
using information from RICH and muon detector

arXiv:1211.6759

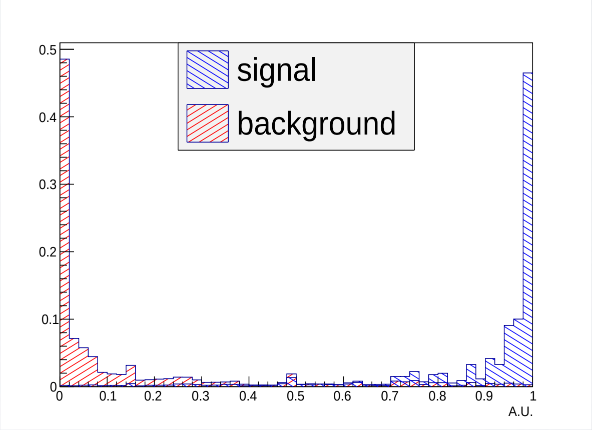


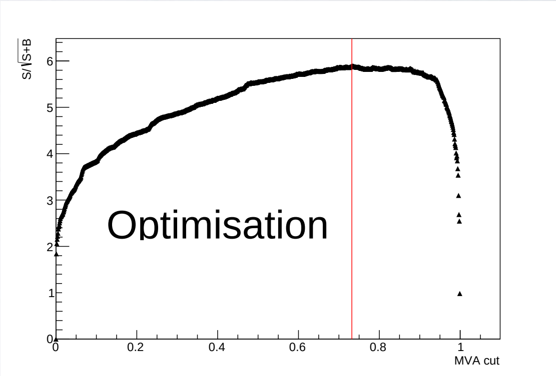
DIRA





Training: signal MC and sideband background

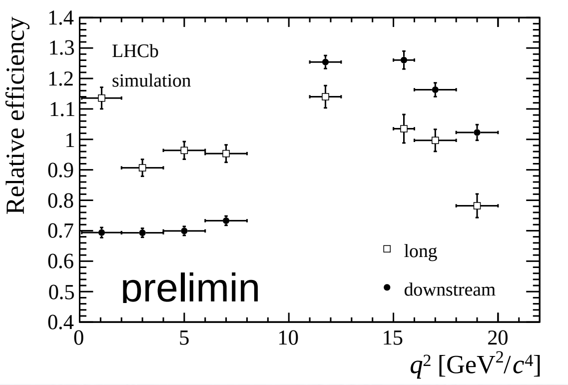




Maximised :

- Significance at high q^2
- Punzi FoM at low q^2 (best for unobserved signals)

$$P = \frac{S}{n_\sigma/2+\sqrt{B}}$$



Efficiency evaluated

(LHCB-PAPER-2015-009)

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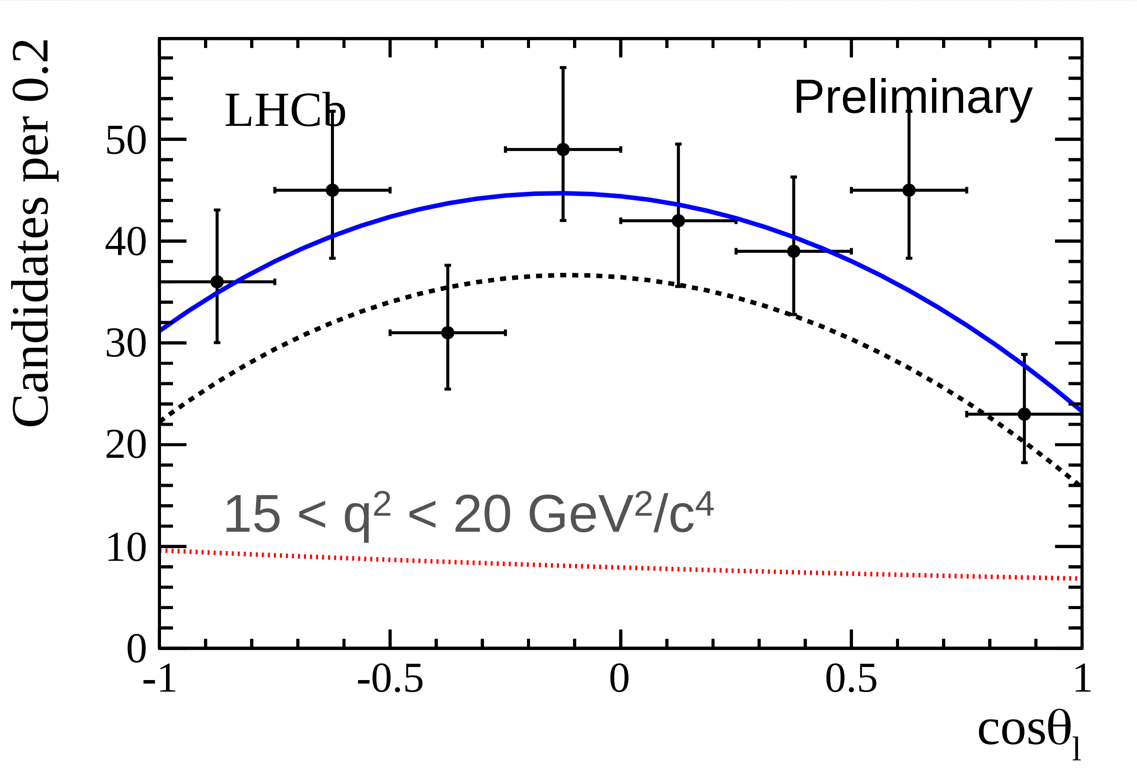
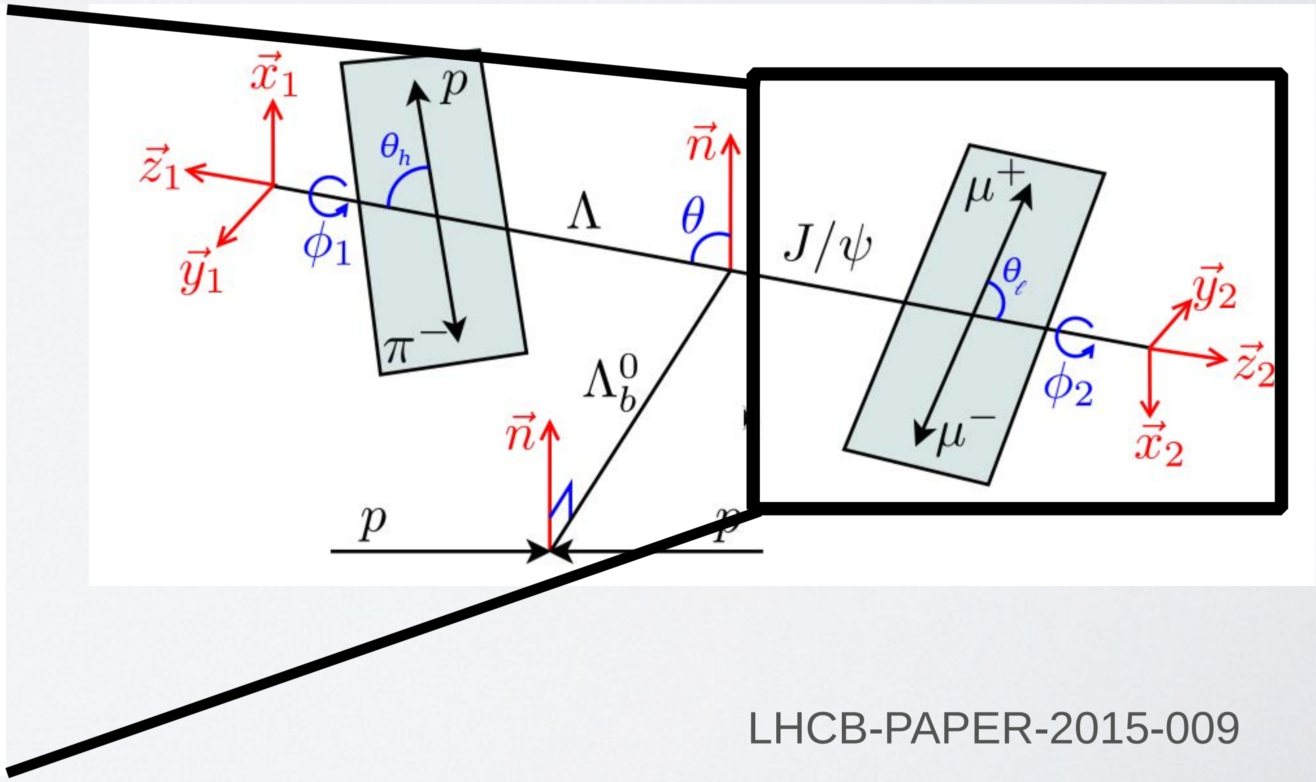
$$PDF^{tot}(\cos\theta_i) = [f^{theory}(\cos\theta_i) + f^{bkg}(\cos\theta_i)] \times \varepsilon(\cos\theta_i)$$





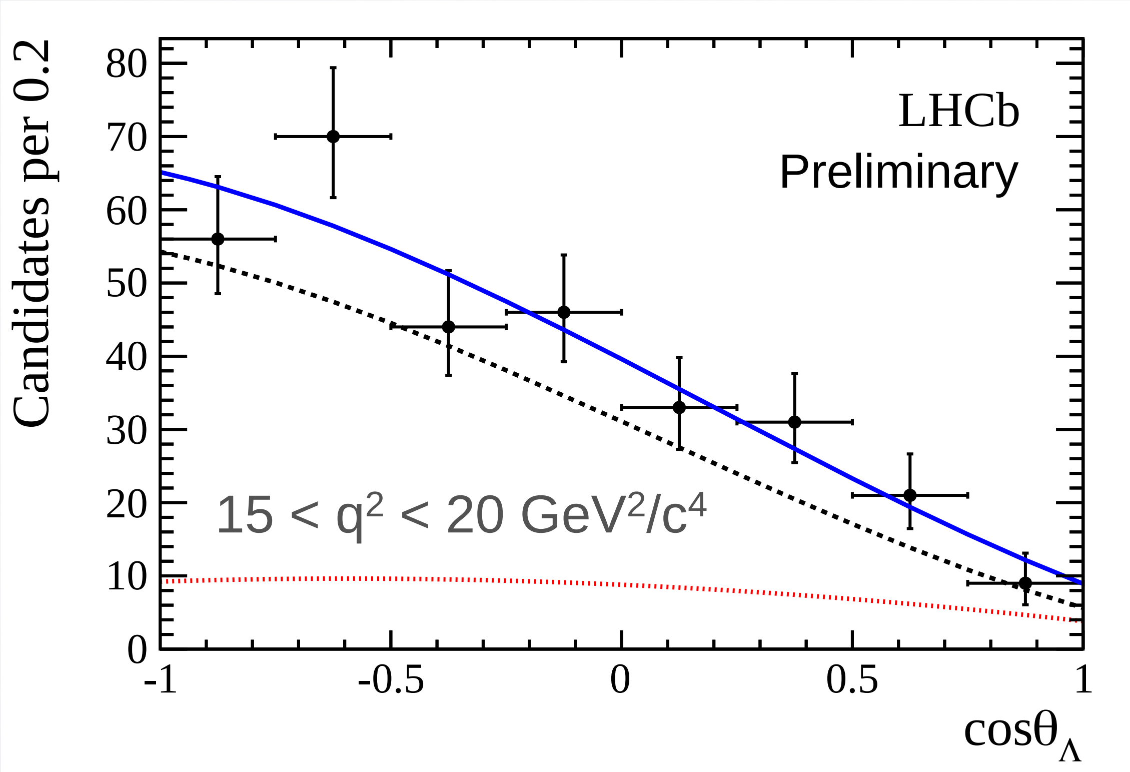
LHCB-PAPER-2015-009

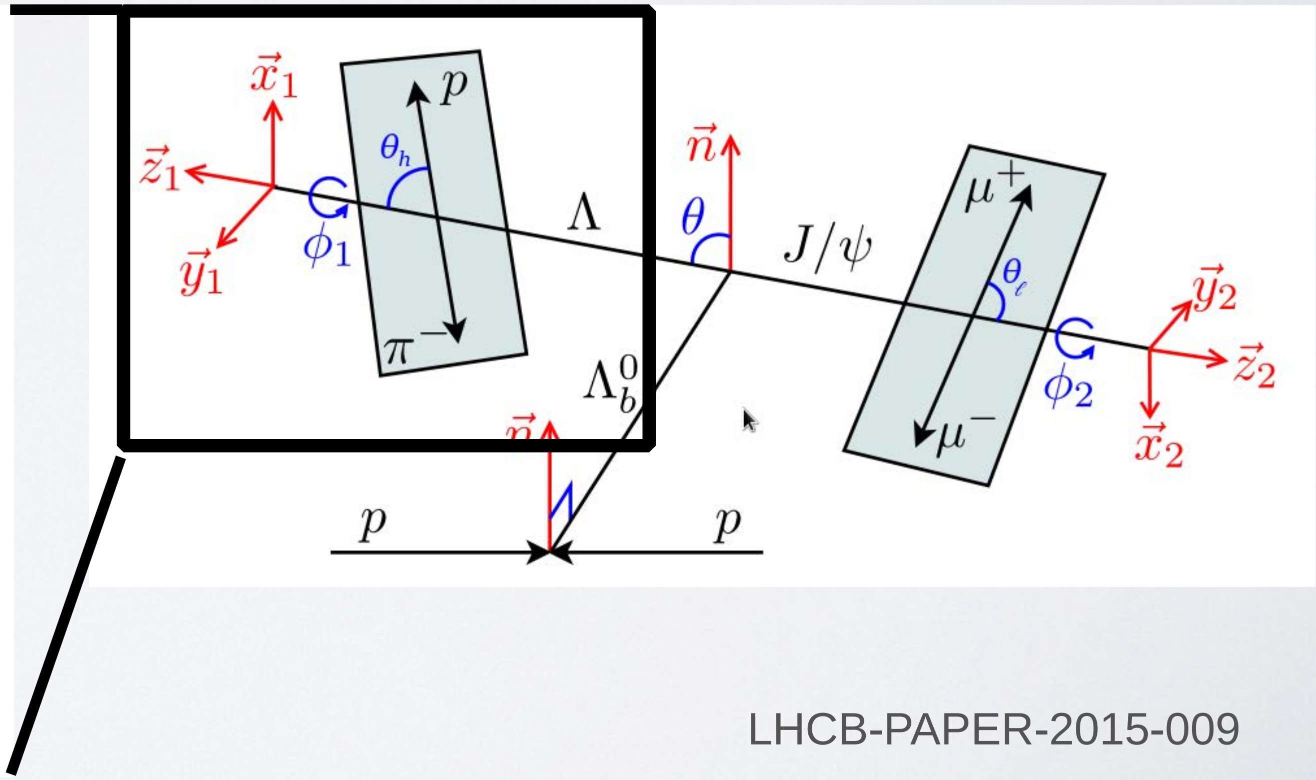
Angular analysis

New!

- In $\Lambda_b \to \Lambda^0 \mu\mu$ the Λ^0 decays weakly
  → unlike for B decays the hadronic side asymmetry is also interesting
- Measure two forward-backward asymmetries: in dimuon and Λ^0 system
- Selection based on a Neural Network using the NeuroBayes package
- Fit one-dimensional angular distributions

$$PDF^{tot}(\cos\theta_i) = [f^{theory}(\cos\theta_i) + f^{bkg}(\cos\theta_i)] \times \varepsilon(\cos\theta_i)$$



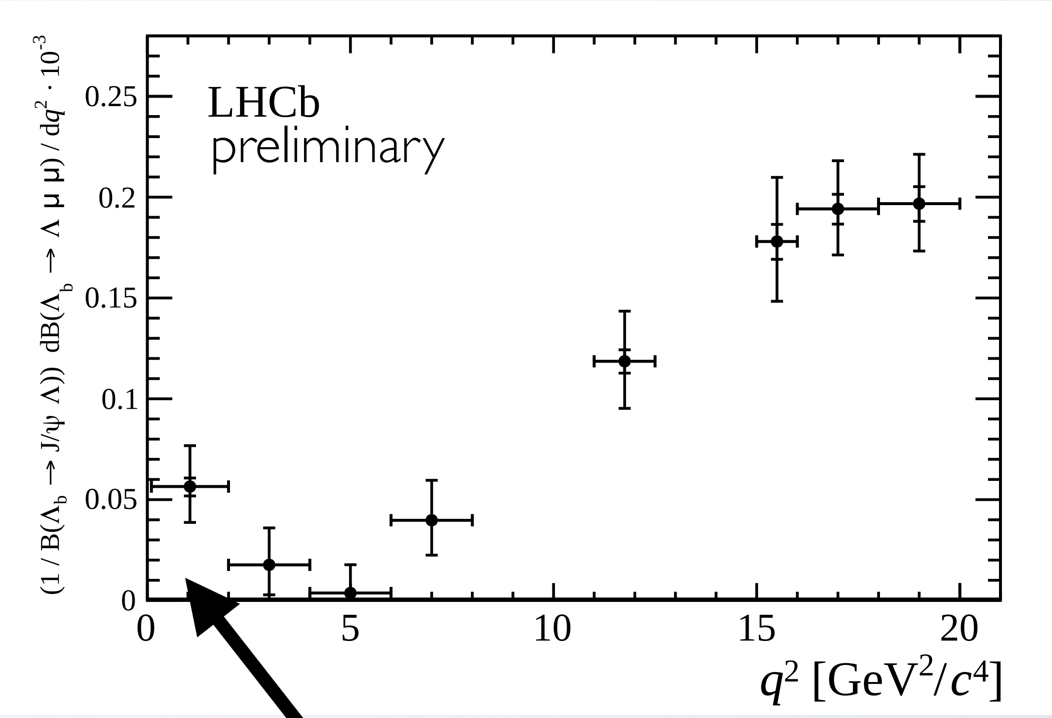


LHCB-PAPER-2015-009

$\Lambda_b \rightarrow \Lambda^0 \mu\mu$ branching ratio

- Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) but only in the low q^2 region
- Reconstructed using the $\Lambda \rightarrow p\pi$ mode
- $J/\psi\Lambda$ as normalisation to limit systematics
- Analysis on 3fb^{-1}: ~300 observed events
- Peaking background from $B \rightarrow K_S$ decays modelled in fit.

Relative branching fraction



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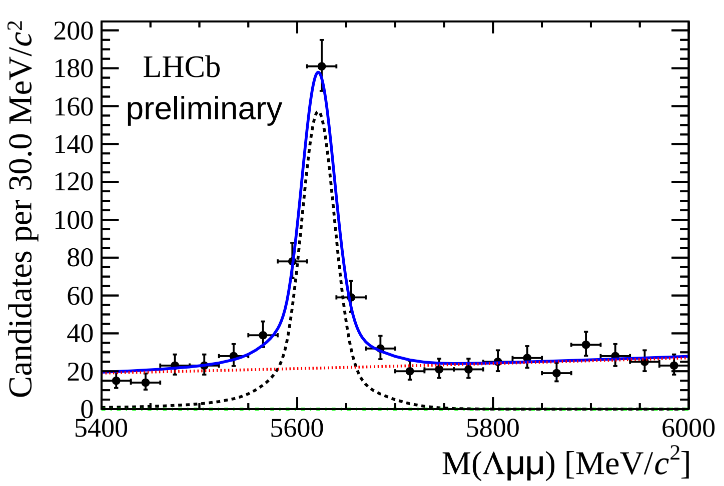
to be submitted to JHEP



First observation

at 3σ level at low q^2

Branching ratio:

$1.1 < q^2 < 6.0$	$0.09\ ^{+0.06}_{-0.05}\ \text{(stat)}\ ^{+0.01}_{-0.01}\ \text{(syst)}\ ^{+0.02}_{-0.02}\ \text{(norm)}$
$15.0 < q^2 < 20.0$	$1.18\ ^{+0.09}_{-0.08}\ \text{(stat)}\ ^{+0.03}_{-0.03}\ \text{(syst)}\ ^{+0.27}_{-0.27}\ \text{(norm)}$

Inner error: total systematic

Outer error: statistical (dominant)

$\Lambda_b \to \Lambda^0 \mu\mu$ branching ratio

- Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) but only in the low q^2 region
- Reconstructed using the $\Lambda \to p\pi$ mode
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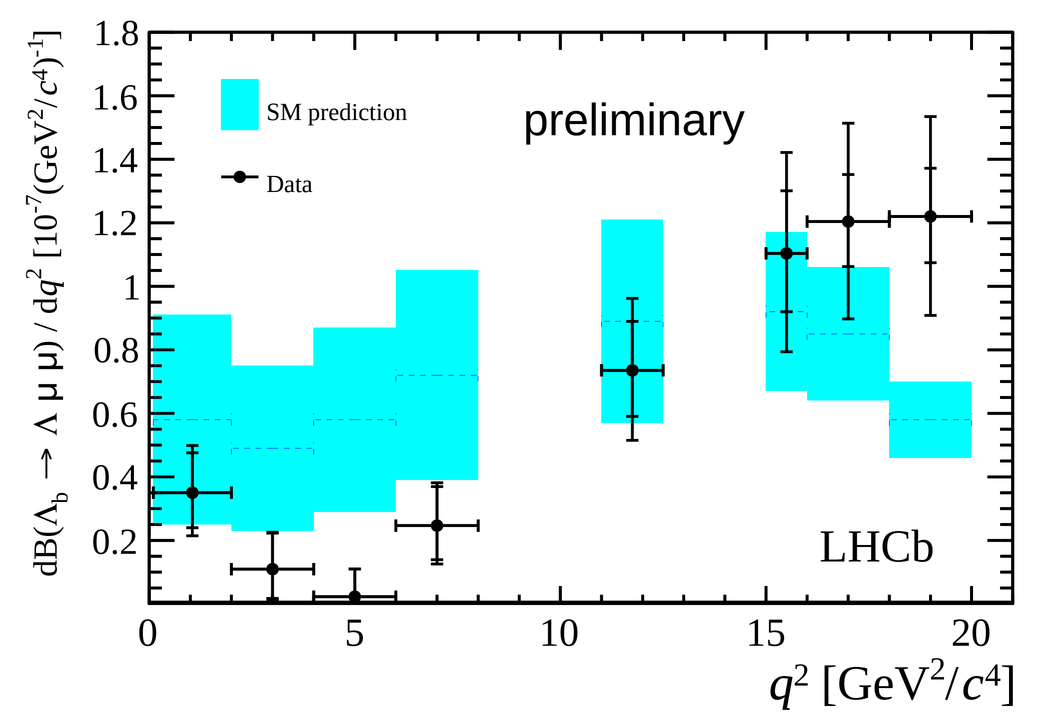
Absolute branching fraction



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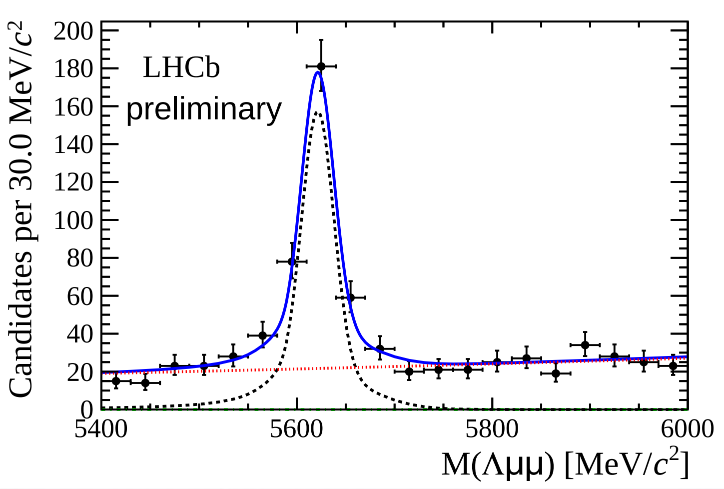

Compatible with the SM within 1.5σ.
Prediction: PRD 87 (2013) 074502

Branching ratio:

$$\begin{array}{ll}
1.1 < q^2 < 6.0 & 0.09 \,^{+0.06}_{-0.05}\,(\text{stat}) \,^{+0.01}_{-0.01}\,(\text{syst}) \,^{+0.02}_{-0.02}\,(\text{norm}) \\
15.0 < q^2 < 20.0 & 1.18 \,^{+0.09}_{-0.08}\,(\text{stat}) \,^{+0.03}_{-0.03}\,(\text{syst}) \,^{+0.27}_{-0.27}\,(\text{norm})
\end{array}$$

Inner error: stati + syst

Outer error:
including normalisation (dominant)

$\Lambda_b \rightarrow \Lambda^0 \mu\mu$ branching ratio

- Already observed at CDF (PRL 107 2011 201802) and LHCb (PLB725 2013 25) but only in the high q^2 region, above ψ(2S)
- Reconstructed using the $\Lambda \rightarrow p\pi$ mode
- $J/\psi\Lambda$ as normalisation to limit systematics
- Analysis on 3fb^{-1}: ~300 observed events
- Peaking background from $B \rightarrow K_S$ decays modelled in fit.

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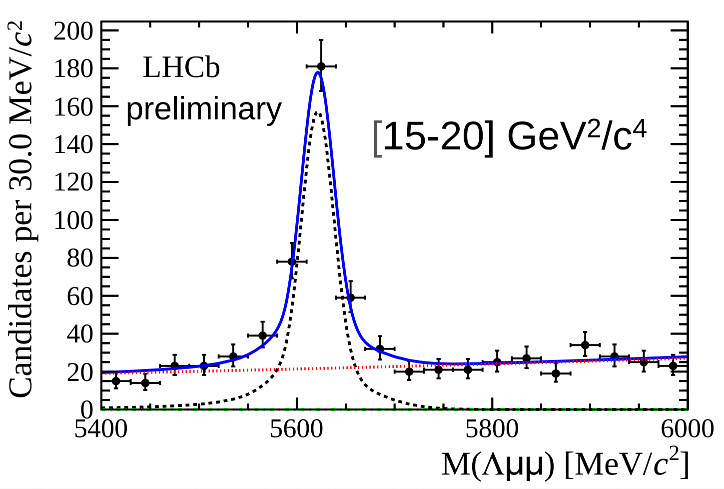

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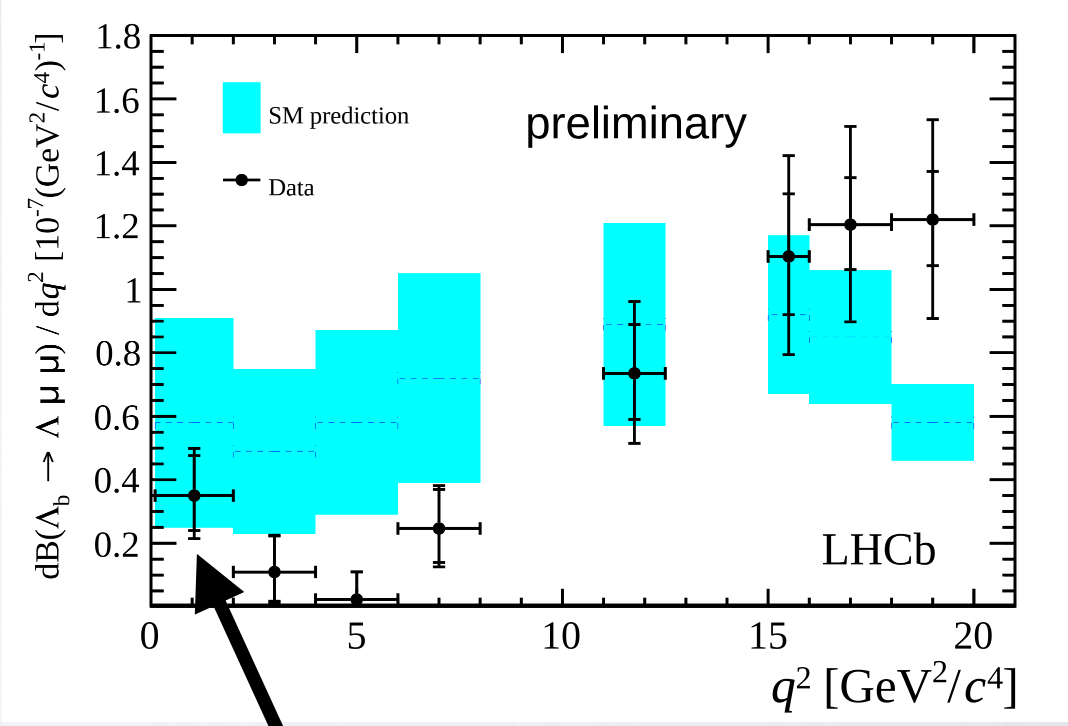

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