The Search for LFUV in $\Lambda_b \to pK^- \ell^+ \ell^-$ at LHCb

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Eötvös Loránd University

Flavour of BSM in the LHC Era Workshop, MITP, Oct. 11, 2022

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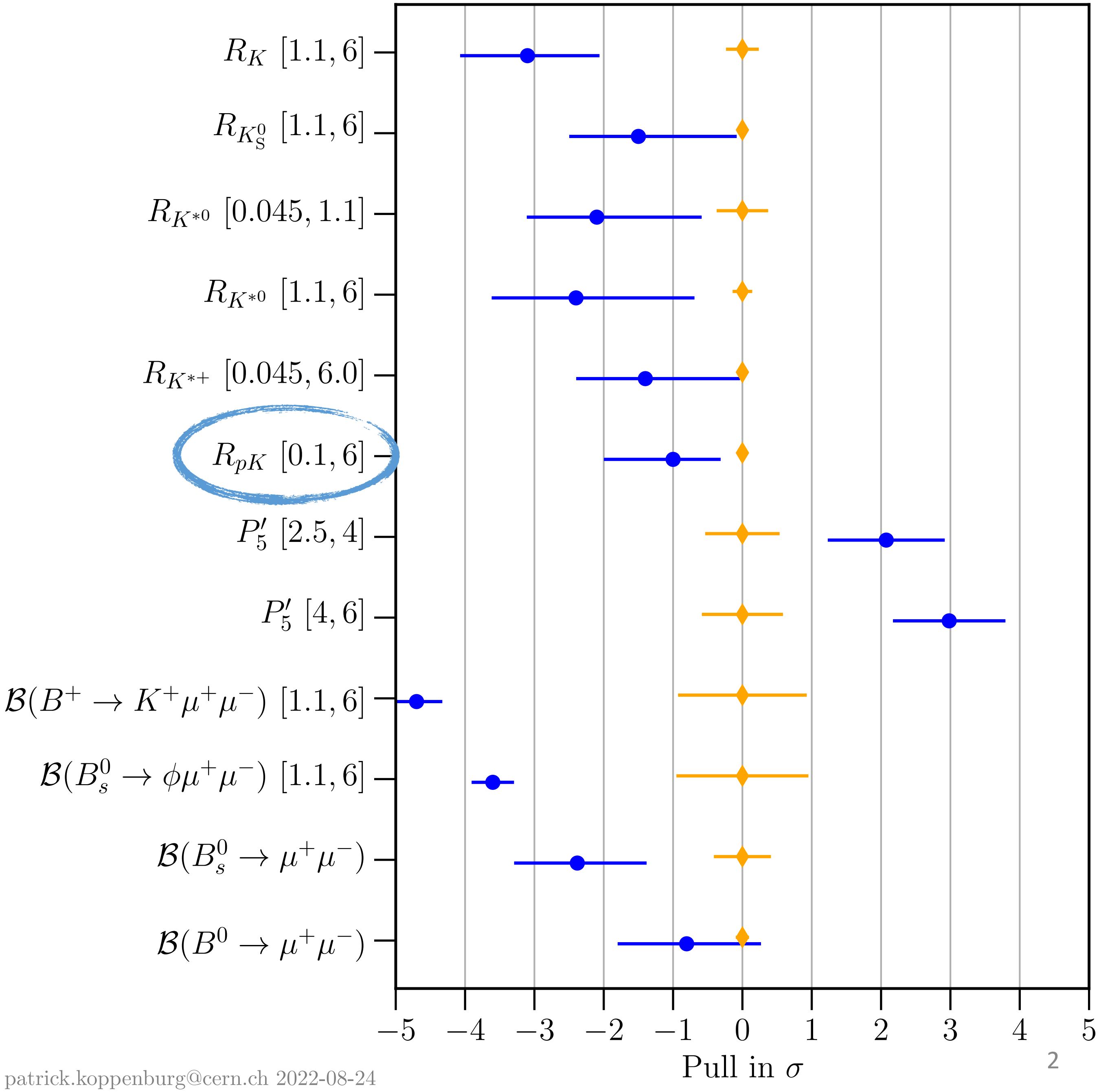
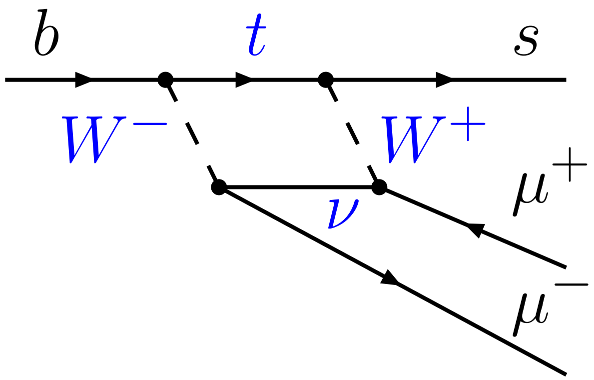
Flavour Anomalies

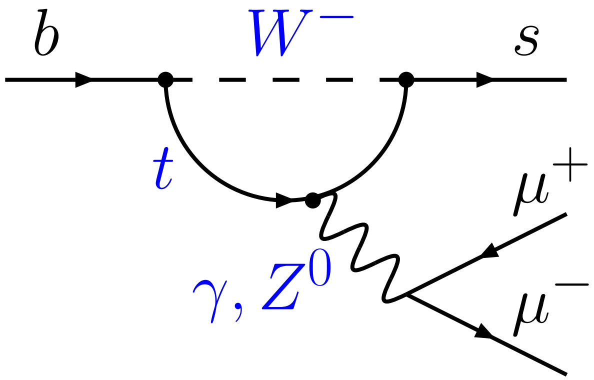
- Tensions with the standard model are evident
- Nothing discovery-level at this point
- One important measurement is R_{pK} - which involves baryons!



Quark-level reaction, $b \to s\ell^+\ell^-$

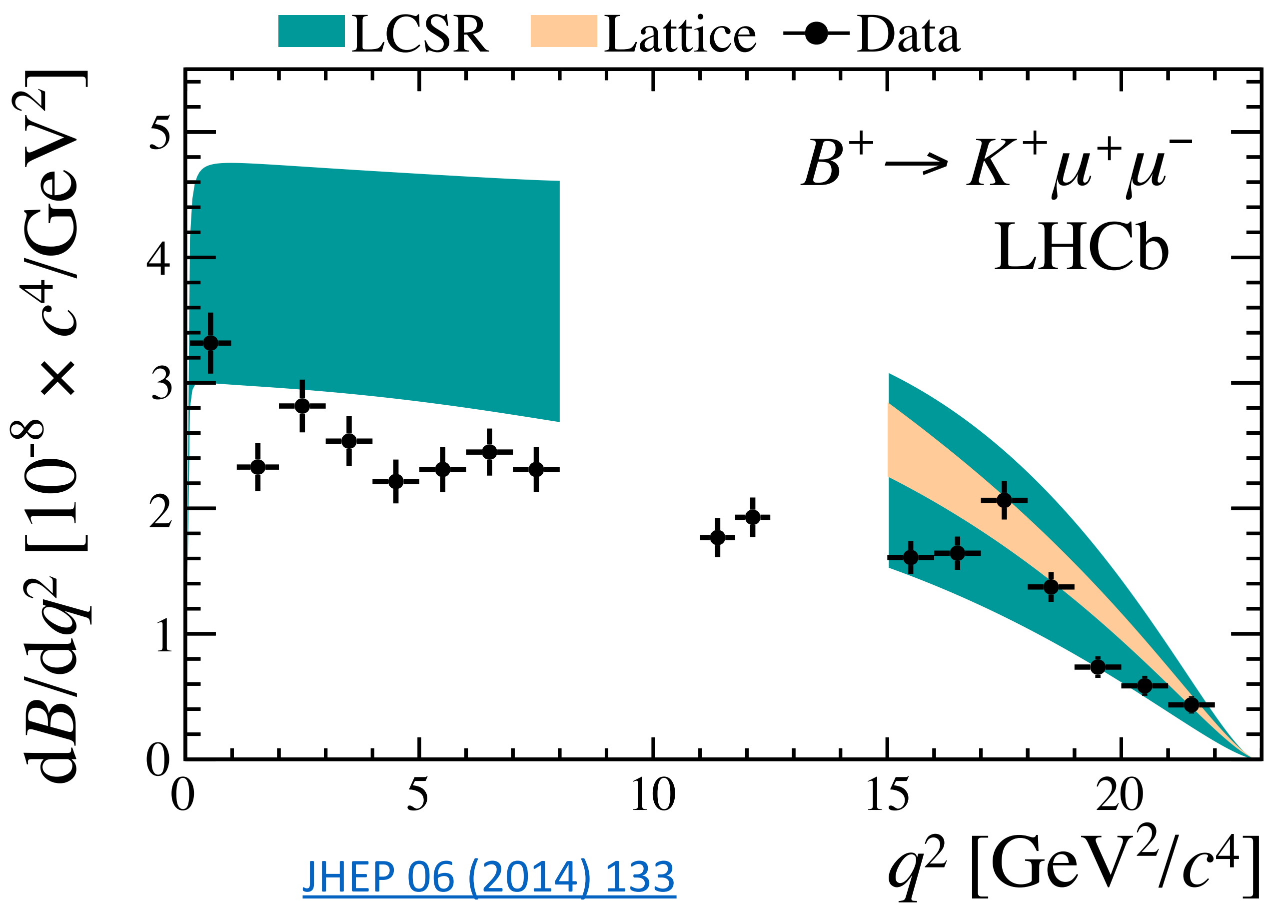
- Reaction suppressed in SM, only available at loop level
- Tree-level contributions are possible in new physics
- Sensitivity to virtual contributions from BSM particles with masses that can't be directly probed at current energies
- Can be used to test for lepton flavour universality





Branching Fractions

- (Relatively) simple to experimentally extract
- Theoretical calculations are affected by hadronic uncertainties
- Trend: $b \to s\mu^+\mu^-$ BFs systematically lower than the standard model predicts



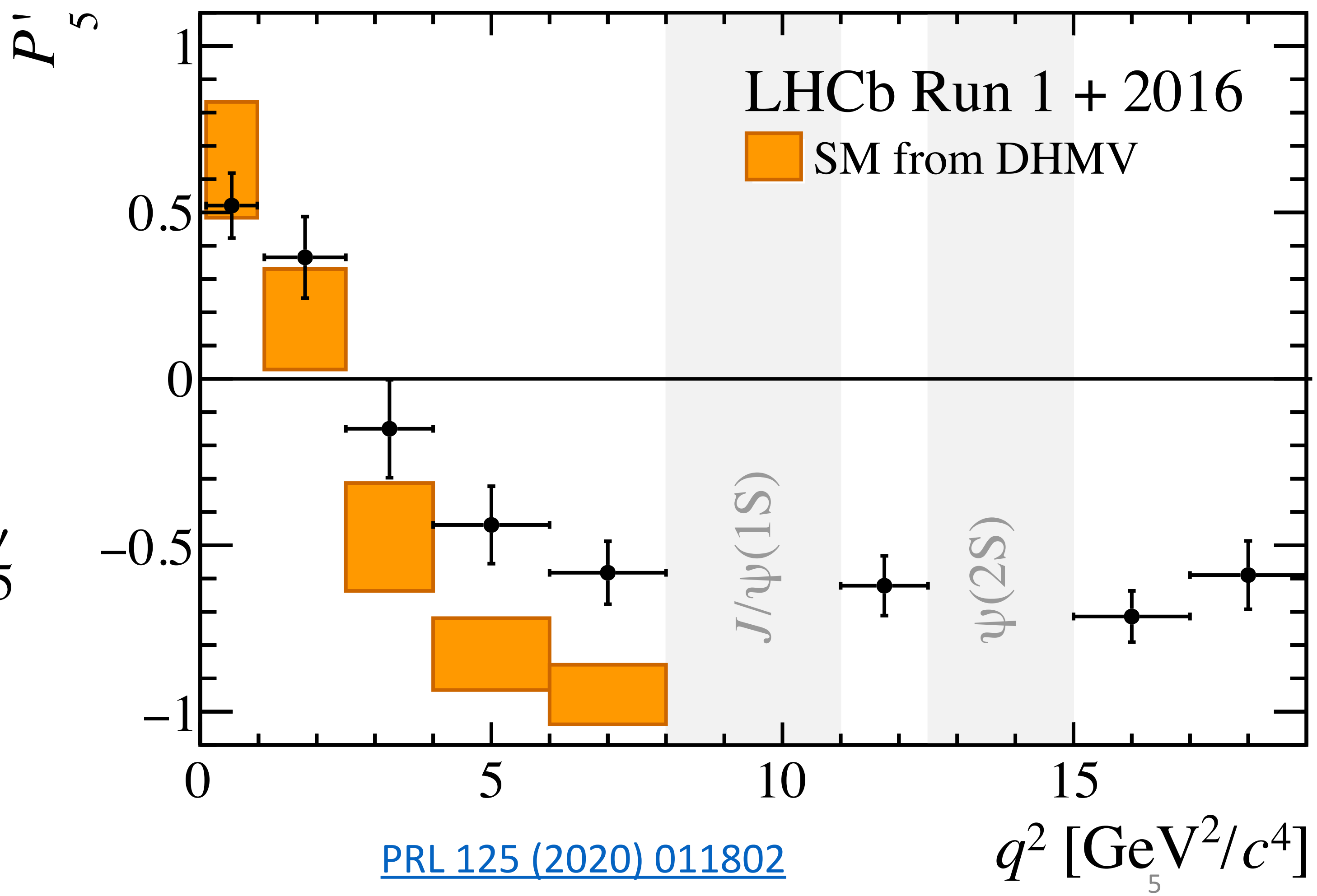
JHEP 06 (2014) 133

Theory Predictions:
JHEP 01 (2003) 074
JHEP 02 (2013) 010
PRD 88 (2013) 094004

Angular Fits

- Form factors partially cancel - clean observables!
- Need to understand detector acceptance
- Many angular parameters require large yields
- Right: Angular observable P'_5 in $B^0 \to K^{*0}\mu^+\mu^-$ decay

Theory Predictions:
JHEP 12 (2014) 125
JHEP 09 (2010) 089



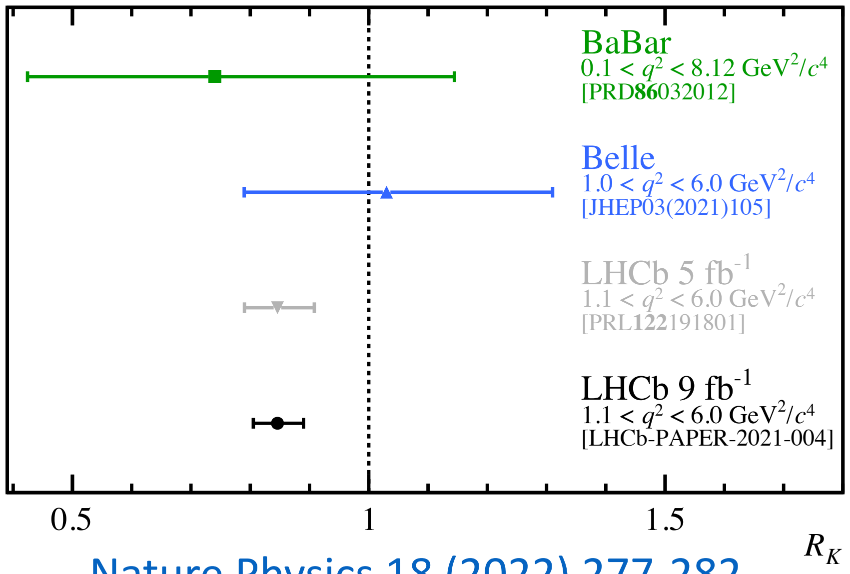
PRL 125 (2020) 011802

What is Lepton Flavour Universality?

- In SM, electroweak couplings of all three lepton flavours are the same
- Decay properties and hadronic effects are expected to also be the same (up to leptonic mass corrections)
- For example, the branching ratio, predicted by SM to be unity with high precision away from threshold

$$R_H \equiv \frac{\mathcal{B}[B \to H\mu^+\mu^-]}{\mathcal{B}[B \to He^+e^-]}$$

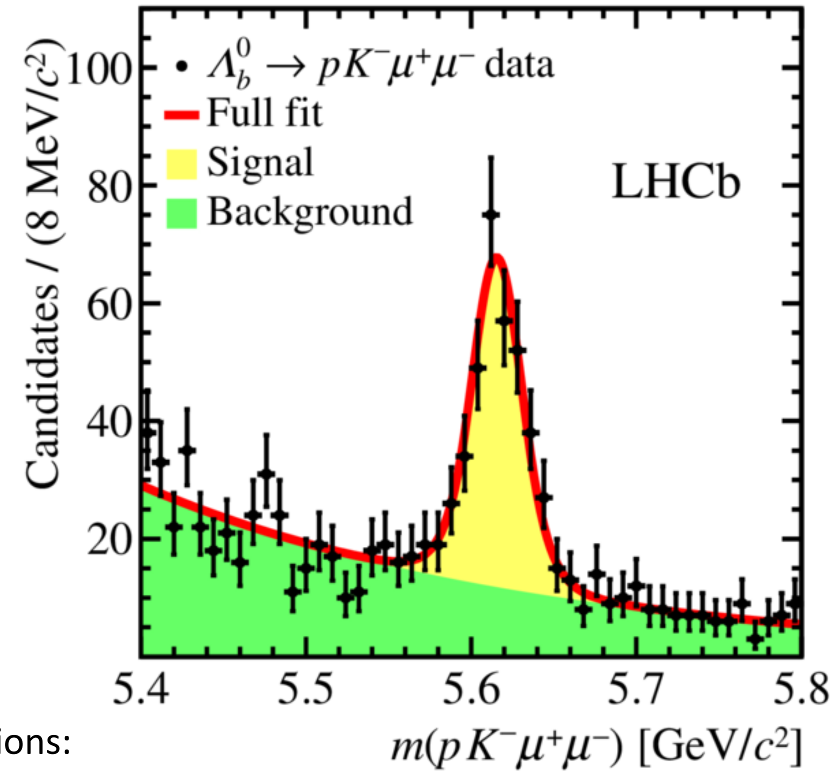
Theory Predictions:
JHEP 06 (2016) 092
JHEP 12 (2007) 040
EPJC 76 (2016) 440
JHEP 12 (2020) 104



Nature Physics 18 (2022) 277-282

History of $\Lambda_b \to \Lambda^{(*)}\ell^+\ell^-$ at LHCb

- 2017 - First observation of $\Lambda_b \to pK^-\mu^+\mu^-$
  - 3 fb^{-1}, tested for evidence of CP violation, none found
- 2018 - Angular moments of $\Lambda_b \to \Lambda\mu^+\mu^-$ measured
  - 5 fb^{-1}, consistent with SM predictions
- 2020 - Branching ratio in $\Lambda_b \to pK^-\ell^+\ell^-$ decays
  - 5 fb^{-1}, $R_{pK}^{-1} = 1.17 \left({}^{+0.18}_{-0.16}\right)_{\text{stat}} \pm (0.07)_{\text{syst}}$
  - First test of LFU with b-baryons
  - First observation of $\Lambda_b \to pK^-e^+e^-$



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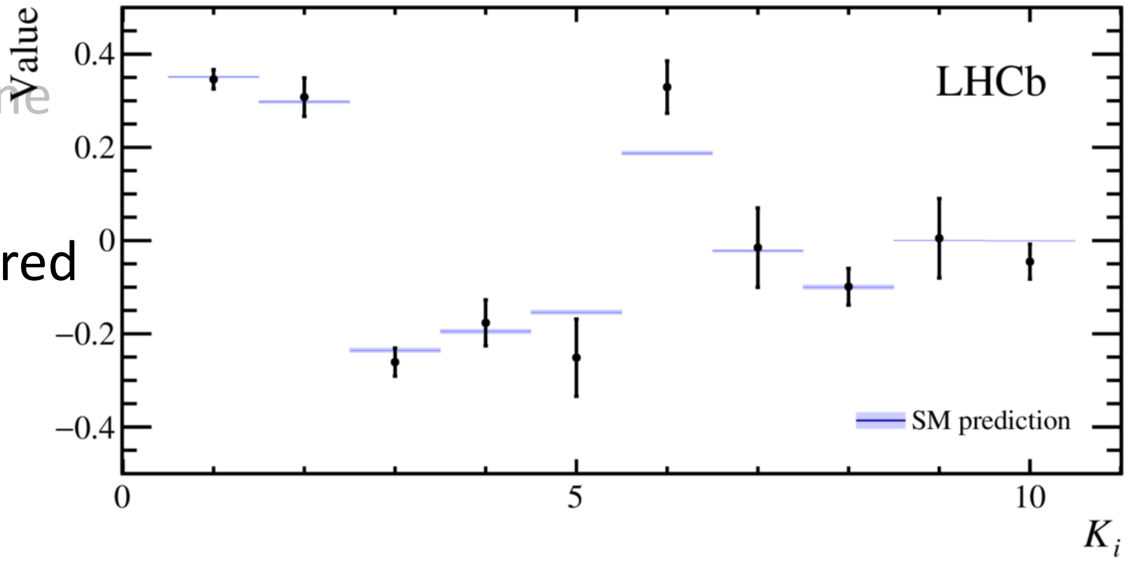

JHEP 09 (2018) 146

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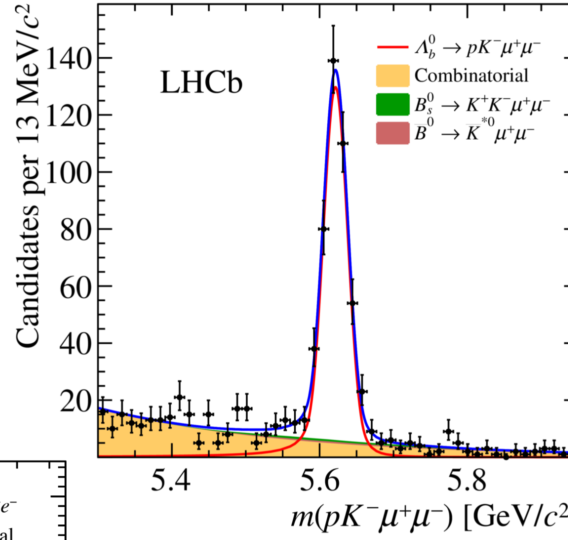
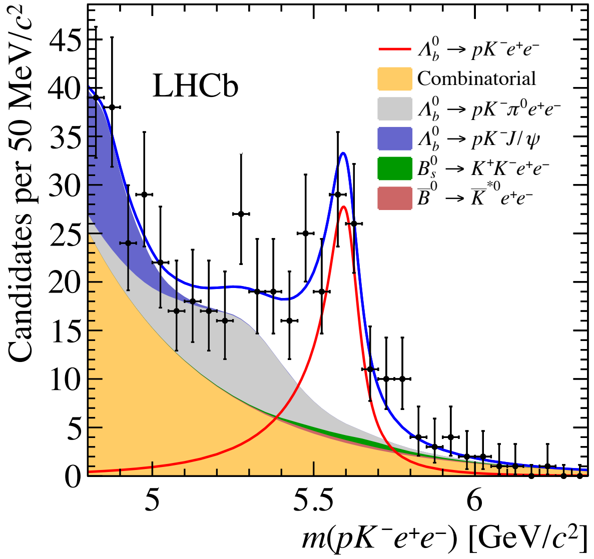


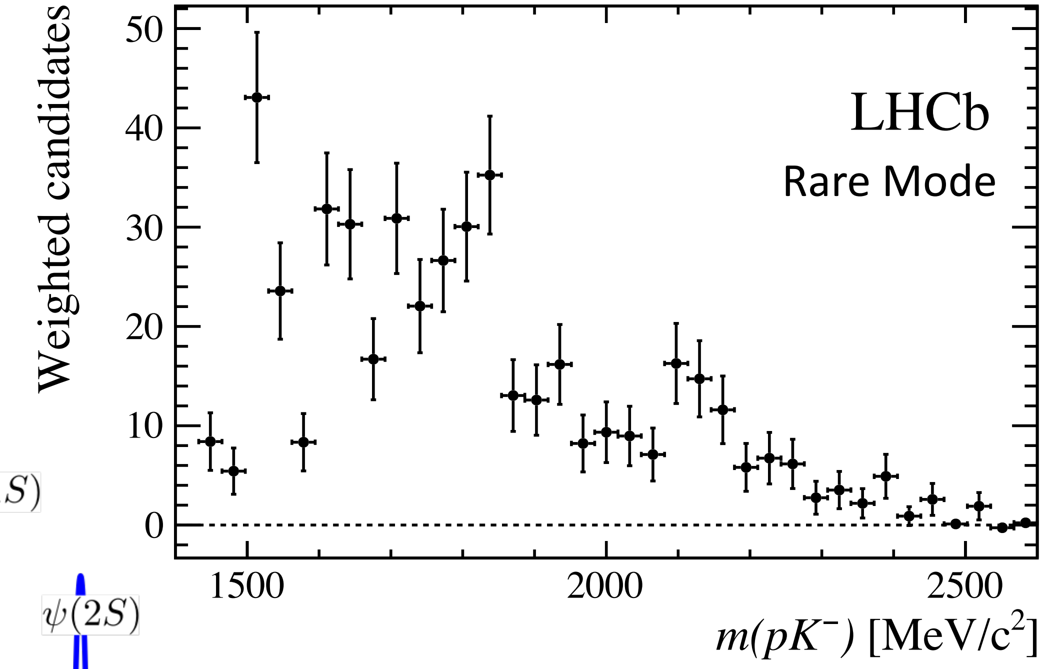


JHEP 05 (2020) 040

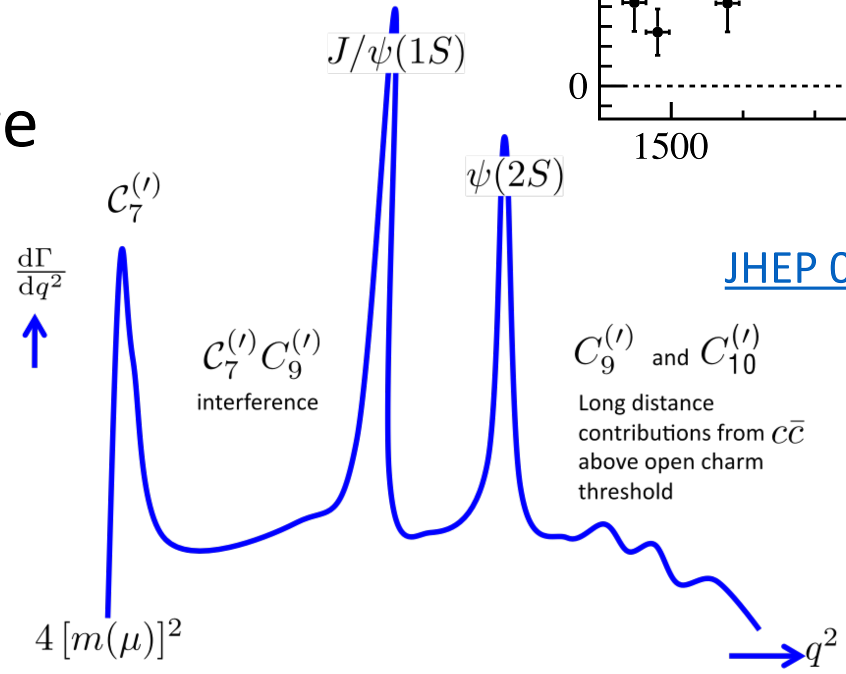
Theory Prediction:
PLB 800 (2020) 135080

Theoretical and Experimental Challenge

- LFU ratios depend on the strong phases of the intermediate states
- So many states - much more overlap than R_K or R_{K*}!
- Interpretation is a challenge

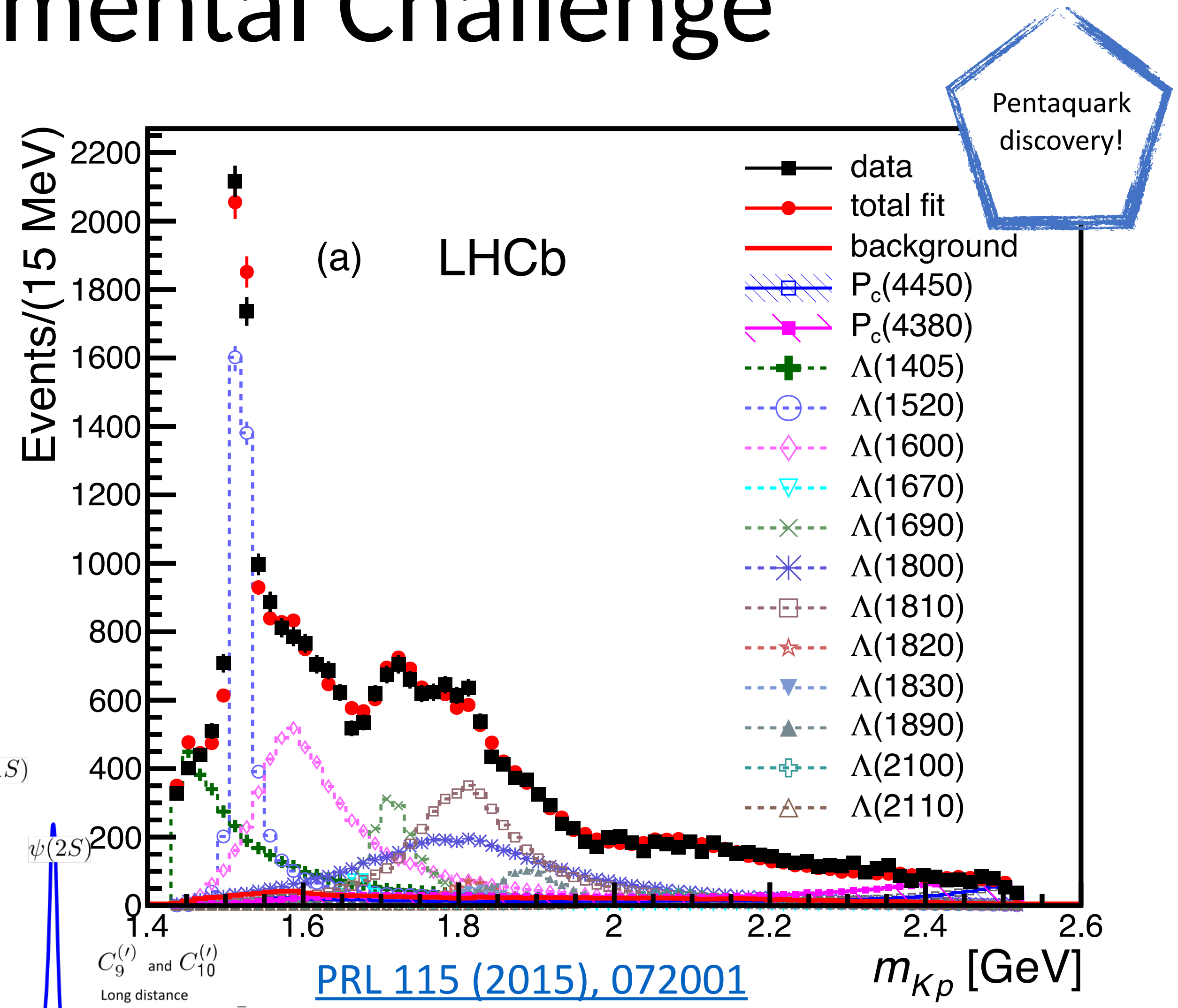


JHEP 05 (2020), 040 Supp. Mat.

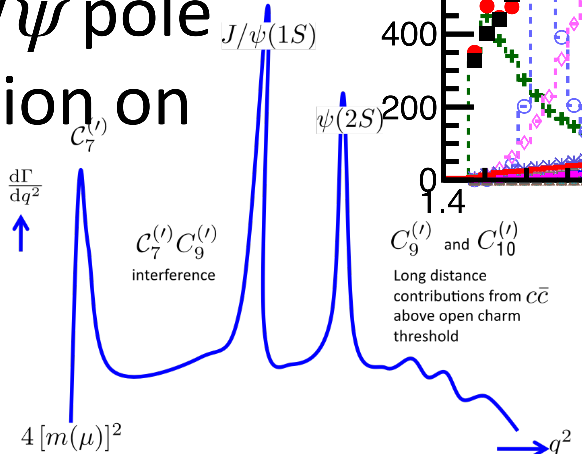


Theoretical and Experimental Challenge

- LFU ratios depend on the strong phases of the intermediate states
- So many states - much more overlap than R_K or R_{K*}!
- Interpretation is a challenge
- Better statistics at the J/ψ pole range, can give information on the spectrum



PRL 115 (2015), 072001



Decay Angles for $\Lambda_b \to pK^-\ell^+\ell^-$

- Decay rate is written in terms of three angles
  - The angle between the negative lepton and z-axis, θ_l
  - The angle between the proton and z-axis, θ_p
  - The angle between the leptonic and hadronic decay planes, $\phi = \phi_p + \phi_l$
- Assuming unpolarized Λ_b
  - True at LHCb

    JHEP 2006 (2020) 110

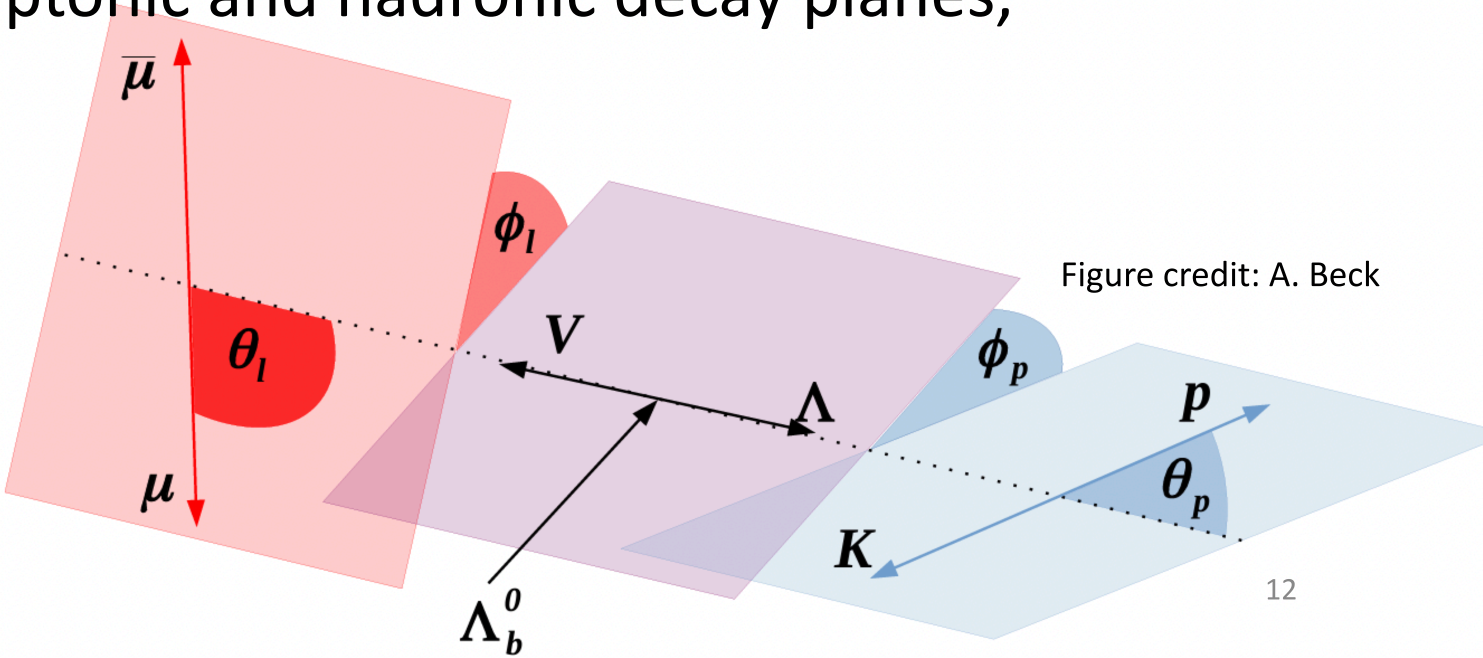


Figure credit: A. Beck

Building the Amplitude

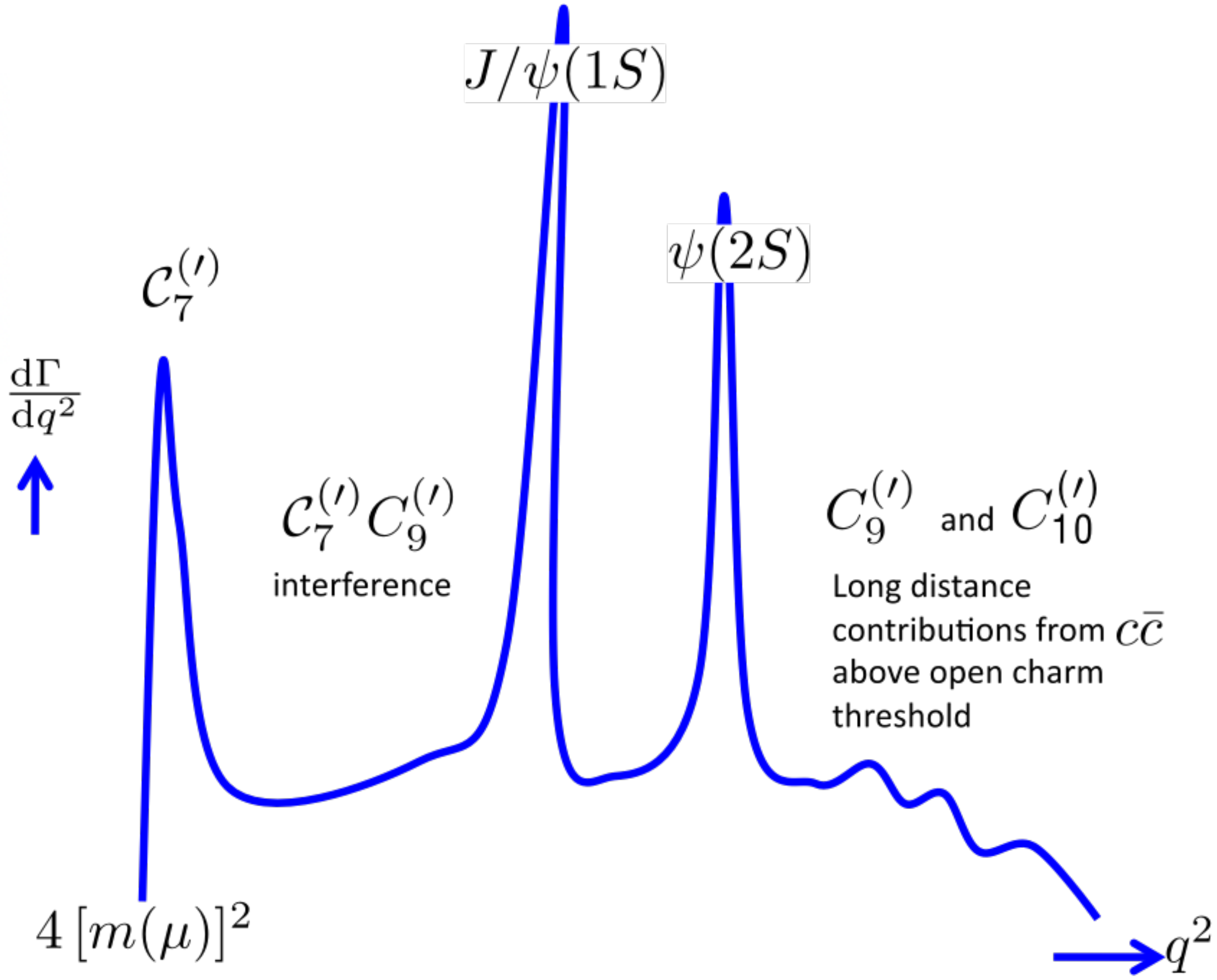
$$\mathcal{M}^{\Lambda_b\to\Lambda\ell\ell} \propto \sum_i \langle \Lambda\ell\ell|\mathcal{C}_i\mathcal{O}_i|\Lambda_b\rangle$$

$$\propto \sum_i \mathcal{C}_i \left\langle \ell\ell \middle| \mathcal{O}^{\mu}_{\mathrm{lep},i} \middle| 0 \right\rangle \langle \Lambda|\mathcal{O}^{\nu}_{\mathrm{had},i}|\Lambda_b\rangle\, g_{\mu\nu}$$

$$\mathcal{O}_{7^{(\prime)}} \propto \left(\bar{s}\sigma_{\mu\nu}P_{R(L)}b\right) F^{\mu\nu}$$

$$\mathcal{O}_{9^{(\prime)}} \propto \left(\bar{s}\gamma_{\mu}P_{L(R)}b\right) \left(\bar{l}\gamma^{\mu}l\right)$$

$$\mathcal{O}_{10^{(\prime)}} \propto \left(\bar{s}\gamma_{\mu}P_{L(R)}b\right) \left(\bar{l}\gamma^{\mu}\gamma_5 l\right)$$



A. Beck et al: Private Communication
(Publication in Preparation)

Building the Amplitude

$\Lambda_b \to \Lambda V$

$$
\begin{aligned}
\mathcal{M}(q^2, m_{pK}, \Omega) \propto e^{i\delta_\Lambda} \mathcal{H}^{\Lambda,\mathcal{O}_i}_{\lambda_\Lambda,\lambda_V}(q^2, m_{pK}) \, d^{1/2}_{\lambda_b,\lambda_\Lambda-\lambda_V}(\theta_b) \\
\times \tilde{h}^{\mathcal{O}_i,\lambda_V}_{\lambda_1,\lambda_2}(q^2) D^{J_V *}_{\lambda_V,\lambda_1-\lambda_2}(\phi_\ell, \theta_\ell, -\phi_\ell) \\
\times h^{\Lambda}_{\lambda_\Lambda,\lambda_p}(m_{pK}) D^{J_\Lambda *}_{\lambda_\Lambda,\lambda_p}(\phi_p, \theta_p, -\phi_p)
\end{aligned}
$$

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Building the Amplitude

$$\mathcal{M}(q^2, m_{pK}, \Omega) \propto e^{i\delta_\Lambda} \mathcal{H}^{\Lambda,\mathcal{O}_i}_{\lambda_\Lambda,\lambda_V}(q^2, m_{pK}) d^{1/2}_{\lambda_b,\lambda_\Lambda-\lambda_V}(\theta_b)$$
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$V \to \ell^+\ell^-$

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Building the Amplitude

$$\mathcal{M}(q^2, m_{pK}, \Omega) \propto e^{i\delta_\Lambda} \mathcal{H}^{\Lambda,\mathcal{O}_i}_{\lambda_\Lambda,\lambda_V}(q^2, m_{pK}) d^{1/2}_{\lambda_b,\lambda_\Lambda-\lambda_V}(\theta_b)$$
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$$\times h^{\Lambda}_{\lambda_\Lambda,\lambda_p}(m_{pK}) D^{J_\Lambda *}_{\lambda_\Lambda,\lambda_p}(\phi_p, \theta_p, -\phi_p)$$

$\Lambda \to pK^-$

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Initial Amplitudes for $\Lambda_b \to \Lambda V$

$$\mathcal{H}^{\Lambda,7^{(\prime)}}_{\lambda_\Lambda,\lambda_V}(q^2, m_{pK}) = -\frac{2m_b}{q^2}\frac{\mathcal{C}^{\text{eff}}_{7^{(\prime)}}}{2}\; e^{i\delta_\Lambda}\left(H^{\Lambda,T}_{\lambda_\Lambda,\lambda_V} \mp H^{\Lambda,T5}_{\lambda_\Lambda,\lambda_V}\right)$$

$$\mathcal{H}^{\Lambda,9^{(\prime)}}_{\lambda_\Lambda,\lambda_V}(q^2, m_{pK}) = \frac{\mathcal{C}^{\text{eff}}_{9^{(\prime)}}}{2}\; e^{i\delta_\Lambda}\left(H^{\Lambda,V}_{\lambda_\Lambda,\lambda_V} \mp H^{\Lambda,A}_{\lambda_\Lambda,\lambda_V}\right)$$

$$\mathcal{H}^{\Lambda,10^{(\prime)}}_{\lambda_\Lambda,\lambda_V}(q^2, m_{pK}) = \frac{\mathcal{C}_{10^{(\prime)}}}{2} e^{i\delta_\Lambda}\left(H^{\Lambda,V}_{\lambda_\Lambda,\lambda_V} \mp H^{\Lambda,A}_{\lambda_\Lambda,\lambda_V}\right)$$

$$H^{\Lambda,\Gamma^\mu}_{\lambda_\Lambda,\lambda_V} = \varepsilon^*_\mu(\lambda_V)\,\langle\Lambda|\bar{s}\Gamma^\mu b|\Lambda_b\rangle$$

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Form Factors

$$\langle\Lambda|\bar{s}\Gamma^{\mu}b|\Lambda_b\rangle_{\text{gen}} = \bar{u}_{\alpha}(\Lambda)\left[v^{\alpha}\left(X_{\Gamma^1}(q^2)\gamma^{\mu} + X_{\Gamma^2}(q^2)v^{\mu} + X_{\Gamma^3}(q^2)v'^{\mu}\right) + X_{\Gamma^4}(q^2)g^{\alpha\mu}\right]u(\Lambda_b)$$

- For $J_{\Lambda} = 1/2$:
  - 3 form factors per current: $F_1^{(T)}(q^2)$, $F_2^{(T)}(q^2)$, and $F_3^{(T)}(q^2)$
- For $J_{\Lambda} = 3/2$ or $5/2$:
  - 4 form factors per current: $F_1^{(T)}(q^2)$, $F_2^{(T)}(q^2)$, $F_3^{(T)}(q^2)$, and $F_4^{(T)}(q^2)$
- The above are for vector and tensor currents. The axial vector and axial tensor form factors are similarly named, with $F_i^{(T)} \rightarrow G_i^{(T)}$

Mott-Roberts:
IJMPA 27 05 1250016 (2012)

Form Factor History

- 2012 - Mott and Roberts calculate form factors for $\Lambda_b \to \Lambda^{(*)}$ in a non-relativistic quark model, using analytic and numeric methods (IJMPA 27 05 1250016 (2012))
  - Most general description of $\Lambda_b \to \Lambda^{(*)}$ form factors
- 2019 - Descotes-Genon and Novoa-Brunet study form factors for $\Lambda_b \to \Lambda^*(1520)$, in terms of a helicity basis (JHEP 06 (2019) 136)
- 2021 - Meinel and Rendon publish first lattice QCD calculation of form factors for $\Lambda_b \to \Lambda^*(1520)$ (PRD 103 (2021) 074505)
- 2022 - Amhis et al perform dispersive analysis of $\Lambda_b \to \Lambda^*(1520)$ and obtain predictions for some observables in $\Lambda_b \to \Lambda^*(1520)\ell^+\ell^-$ decays (arXiv:2208.08937)

Building the Amplitude

$$d\Gamma = \frac{\overline{|\mathcal{M}|}^2}{2m_{\Lambda_b}}(2\pi)^4 d\Phi_4$$

$$\frac{d^5\Gamma}{dq^2 dm_{pK} d\Omega} \propto \sum_{i=1}^{46} K_i\left(q^2, m_{pK}\right) f_i\left(\Omega\right)$$

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i	$f_i(\vec{\Omega})$	i	$f_i(\vec{\Omega})$
1	$\frac{1}{\sqrt{3}}P_0^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	24	$\frac{1}{2}\sqrt{\frac{7}{3}}P_3^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$
2	$P_0^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	25	$\frac{1}{2}P_4^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$
3	$\sqrt{\frac{5}{3}}P_0^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	26	$\frac{3}{2\sqrt{5}}P_4^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$
4	$P_1^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	27	$\frac{1}{3}\sqrt{\frac{11}{6}}P_5^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$
5	$\sqrt{3}P_1^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	28	$\sqrt{\frac{11}{30}}P_5^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$
6	$\sqrt{5}P_1^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	29	$\sqrt{\frac{5}{6}}P_1^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
7	$\sqrt{\frac{5}{3}}P_2^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	30	$\sqrt{\frac{3}{2}}P_1^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
8	$\sqrt{5}P_2^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	31	$\frac{5}{3\sqrt{6}}P_2^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
9	$\frac{5}{\sqrt{3}}P_2^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	32	$\sqrt{\frac{5}{6}}P_2^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
10	$\sqrt{\frac{7}{3}}P_3^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	33	$\frac{1}{6}\sqrt{\frac{35}{3}}P_3^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
11	$\sqrt{7}P_3^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	34	$\frac{1}{2}\sqrt{\frac{7}{3}}P_3^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
12	$\sqrt{\frac{35}{3}}P_3^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	35	$\frac{1}{2}P_4^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
13	$\sqrt{3}P_4^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	36	$\frac{3}{2\sqrt{5}}P_4^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
14	$3P_4^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	37	$\frac{1}{3}\sqrt{\frac{11}{6}}P_5^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\sin\phi$
15	$\sqrt{15}P_4^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	38	$\sqrt{\frac{11}{30}}P_5^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\sin\phi$
16	$\sqrt{\frac{11}{3}}P_5^0(\cos\theta_p)P_0^0(\cos\theta_\ell)$	39	$\frac{5}{12\sqrt{6}}P_2^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
17	$\sqrt{11}P_5^0(\cos\theta_p)P_1^0(\cos\theta_\ell)$	40	$\frac{1}{12}\sqrt{\frac{7}{6}}P_3^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
18	$\sqrt{\frac{55}{3}}P_5^0(\cos\theta_p)P_2^0(\cos\theta_\ell)$	41	$\frac{1}{12\sqrt{2}}P_4^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
19	$\sqrt{\frac{5}{6}}P_1^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$	42	$\frac{1}{12}\sqrt{\frac{11}{42}}P_5^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\cos 2\phi$
20	$\sqrt{\frac{3}{2}}P_1^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$	43	$\frac{5}{12\sqrt{6}}P_2^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$
21	$\frac{5}{3\sqrt{6}}P_2^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$	44	$\frac{1}{12}\sqrt{\frac{7}{6}}P_3^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$
22	$\sqrt{\frac{5}{6}}P_2^1(\cos\theta_p)P_1^1(\cos\theta_\ell)\cos\phi$	45	$\frac{1}{12\sqrt{2}}P_4^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$
23	$\frac{1}{6}\sqrt{\frac{35}{3}}P_3^1(\cos\theta_p)P_2^1(\cos\theta_\ell)\cos\phi$	46	$\frac{1}{12}\sqrt{\frac{11}{42}}P_5^2(\cos\theta_p)P_2^2(\cos\theta_\ell)\sin 2\phi$

Table 2: Orthonormal basis functions for the angular terms $f_1(\vec{\Omega})$–$f_{50}(\vec{\Omega})$ that arise in the unpolarised case, where $\phi = \phi_p + \phi_\ell$.

The Method of Moments - Why?

- Extract individual angular "moments" from a data sample
- Advantages:
  - Don't need to do a fit
  - Can extract model-independent observables
  - Robustness of result doesn't depend on the size of the dataset
- Disadvantage: uncertainties are 10-30% higher than those from a good fit
- Well-established procedure from B-factory era, has been used in several LHCb analyses

PRD 91 (2015) 114012

JHEP 12 (2016) 065
PRL 117 (2016) 8, 082002
JHEP 09 (2018) 146

The Method of Moments - How?

- Derive/choose an angular basis $f_i(\Omega)$:

$$\frac{d\Gamma}{dq^2 dm_{pK} d\Omega} = \sum_i K_i\left(q^2, m_{pK}\right) f_i(\Omega)$$

- Derive weighting functions $w_j(\Omega)$ orthogonal to the basis, such that

$$\int f_i(\Omega) w_j(\Omega) d\Omega \propto \delta_{ij}$$

- And then it's just addition*

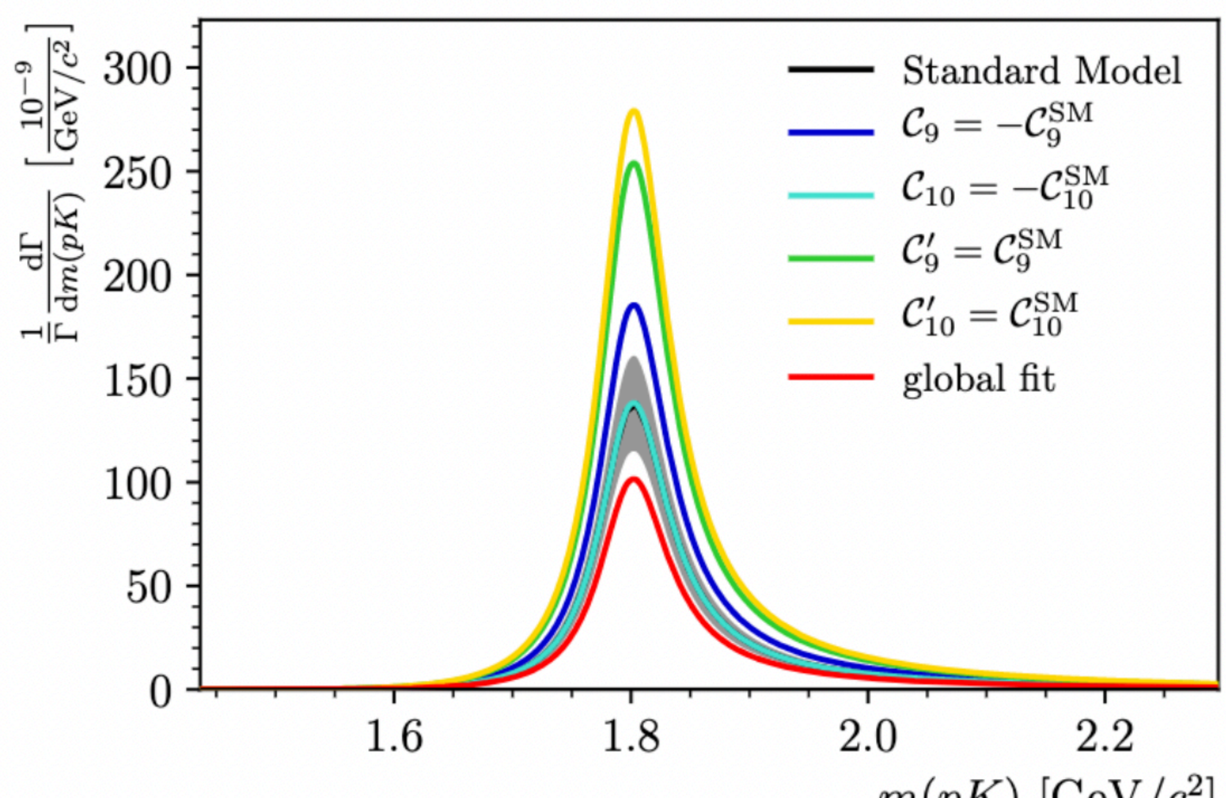
$$K_j\left(q^2, m_{pK}\right) = \int \sum_i K_i\left(q^2, m_{pK}\right) f_i(\Omega) w_j(\Omega) d\Omega = \sum_n w_j(\Omega_n)$$

PRD 91 (2015) 114012

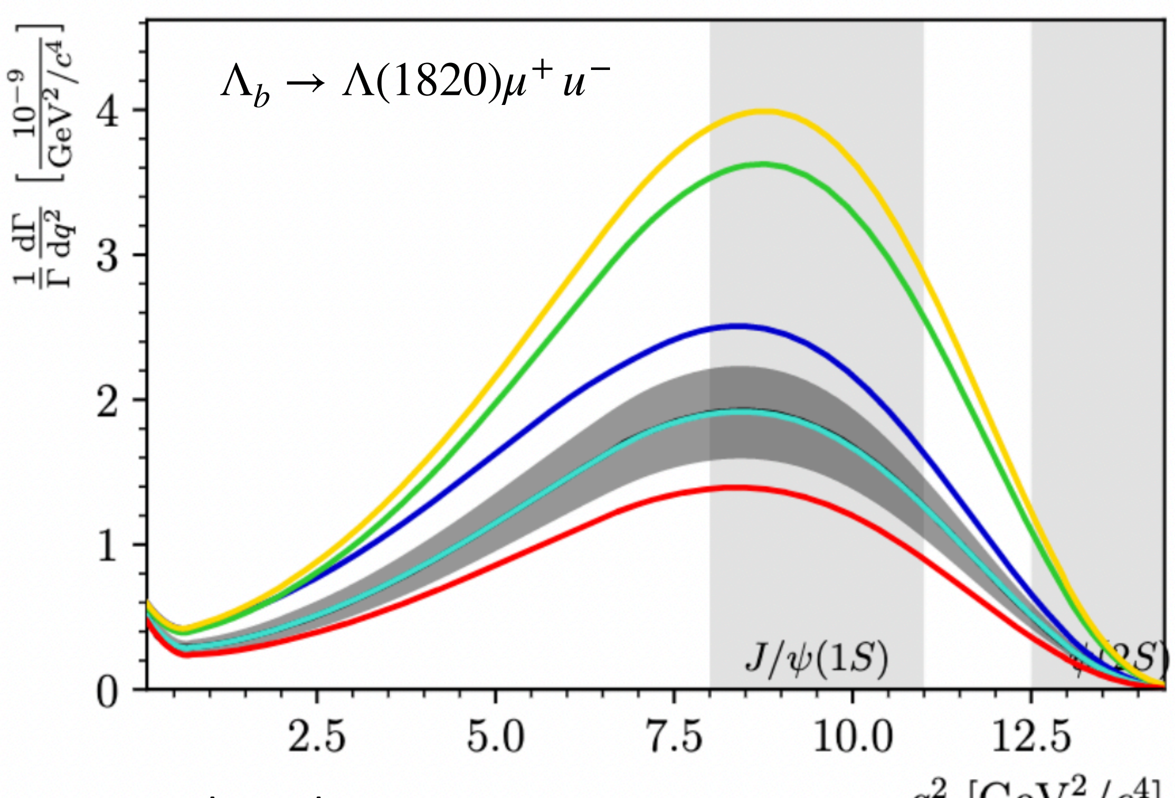
*assuming no acceptance effects

$\Lambda_b \to pK^-\mu^+\mu^-$ Studies

- Branching fraction for SM and 5 non-SM scenarios



Global Fit: EPJC 82 (2022) 326



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(Publication in Preparation)

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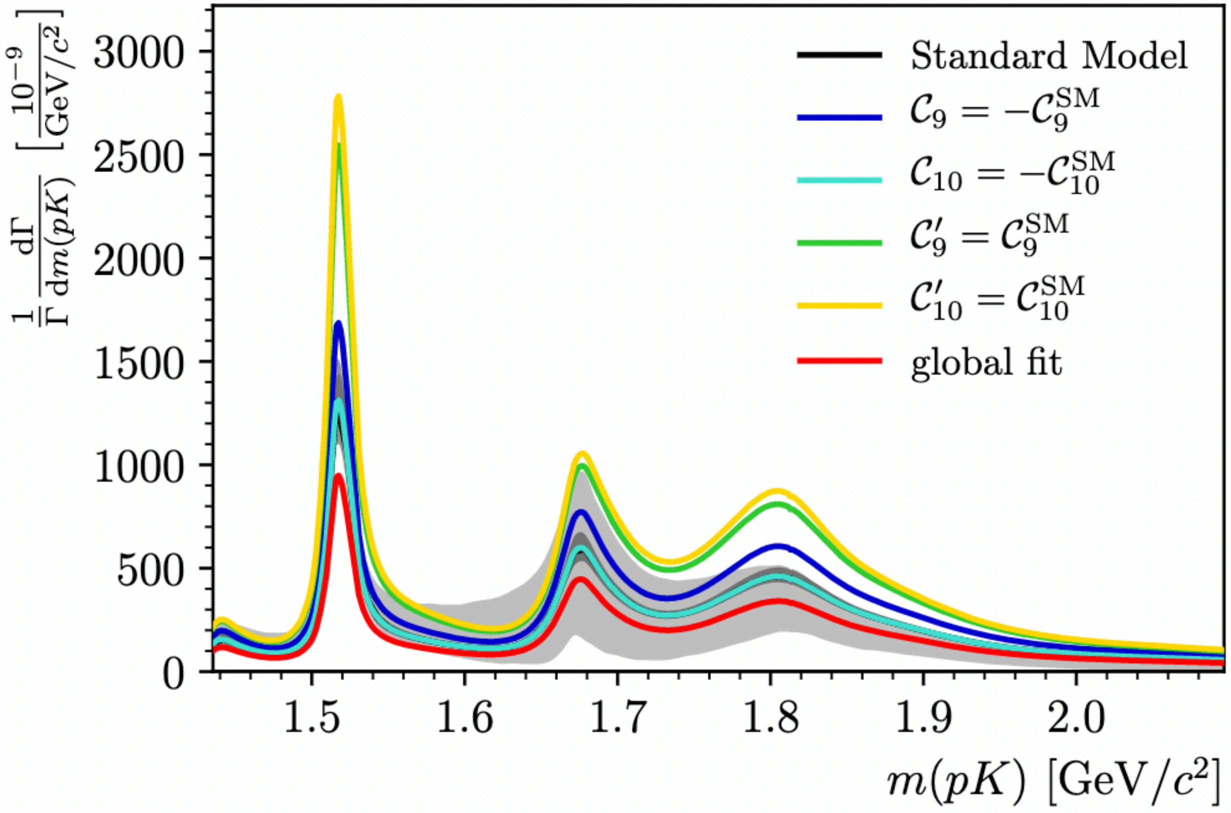

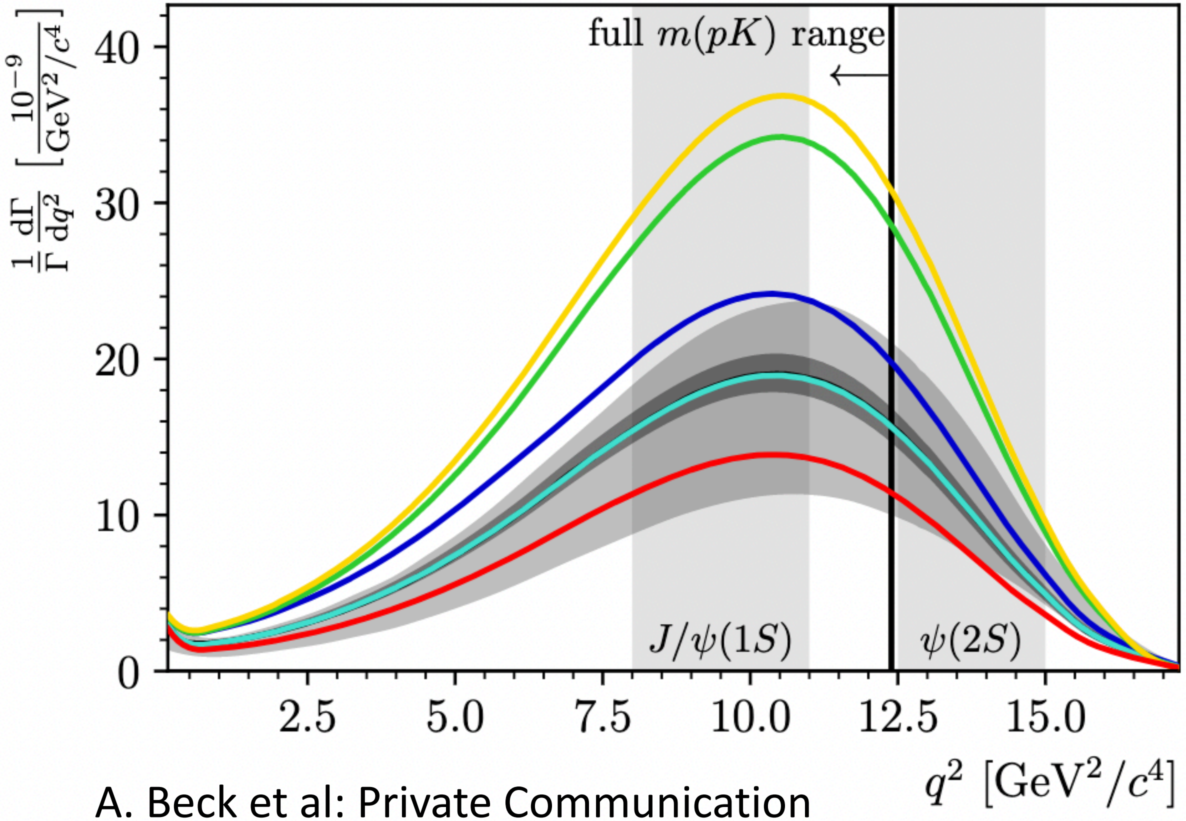

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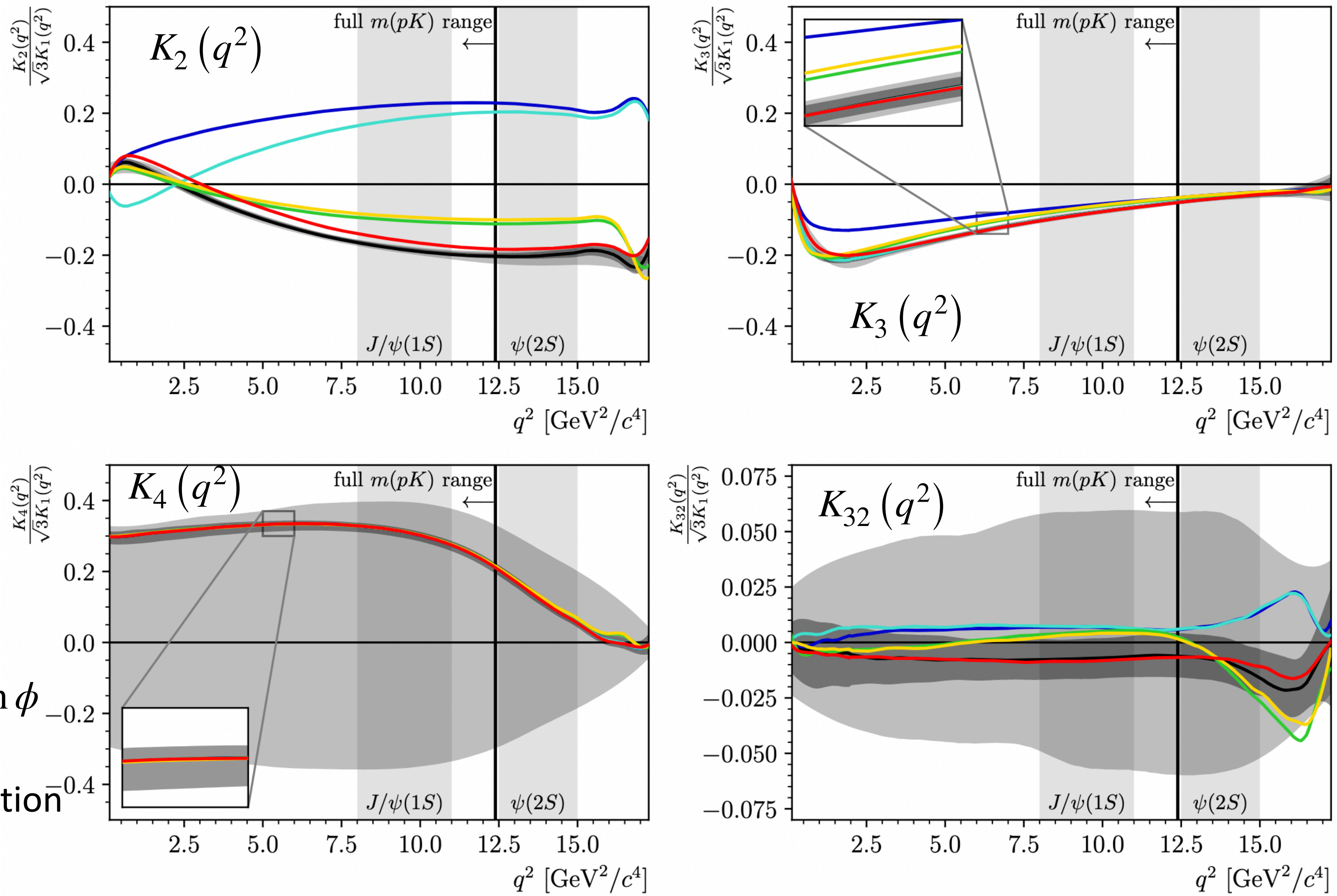
$\Lambda_b \to pK^- \mu^+ \mu^-$ Observables

- Standard Model
- $\mathcal{C}_9 = -\mathcal{C}_9^{\mathrm{SM}}$
- $\mathcal{C}_{10} = -\mathcal{C}_{10}^{\mathrm{SM}}$
- $\mathcal{C}'_9 = \mathcal{C}_9^{\mathrm{SM}}$
- $\mathcal{C}'_{10} = \mathcal{C}_{10}^{\mathrm{SM}}$
- global fit



$w_2(\Omega) \propto \cos\theta_\ell$

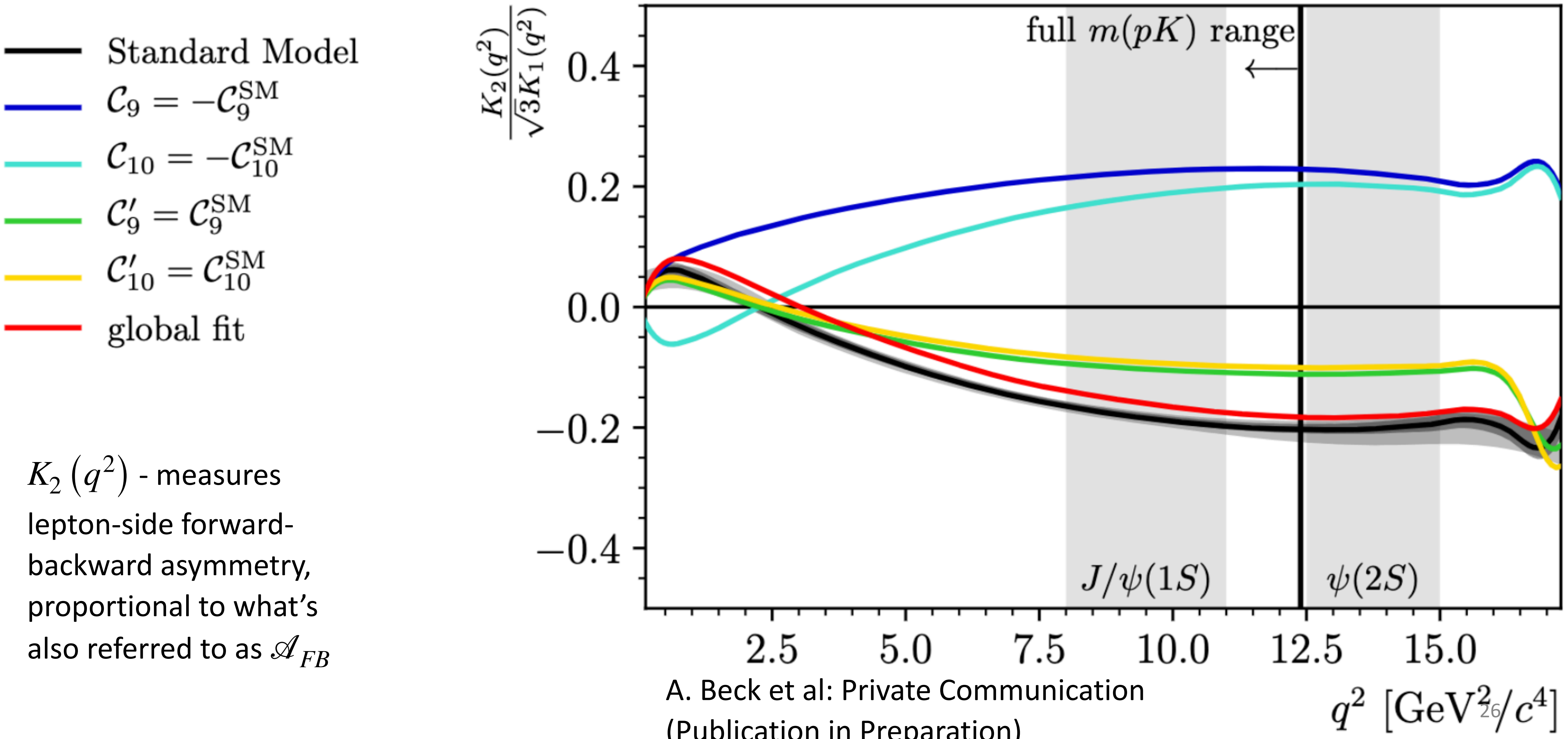
$w_3(\Omega) \propto 3\cos^2\theta_\ell - 1$

$w_4(\Omega) \propto \cos\theta_p$

$w_{32}(\Omega) \propto \sin\theta_\ell \sin\theta_p \cos\theta_p \sin\phi$

A. Beck et al: Private Communication
(Publication in Preparation)

$\Lambda_b \to pK^-\mu^+\mu^-$ Observables



$K_2\left(q^2\right)$ - measures lepton-side forward-backward asymmetry, proportional to what's also referred to as $\mathscr{A}_{FB}$

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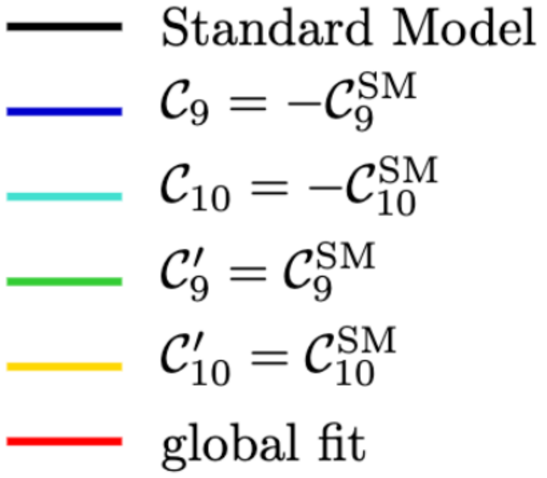
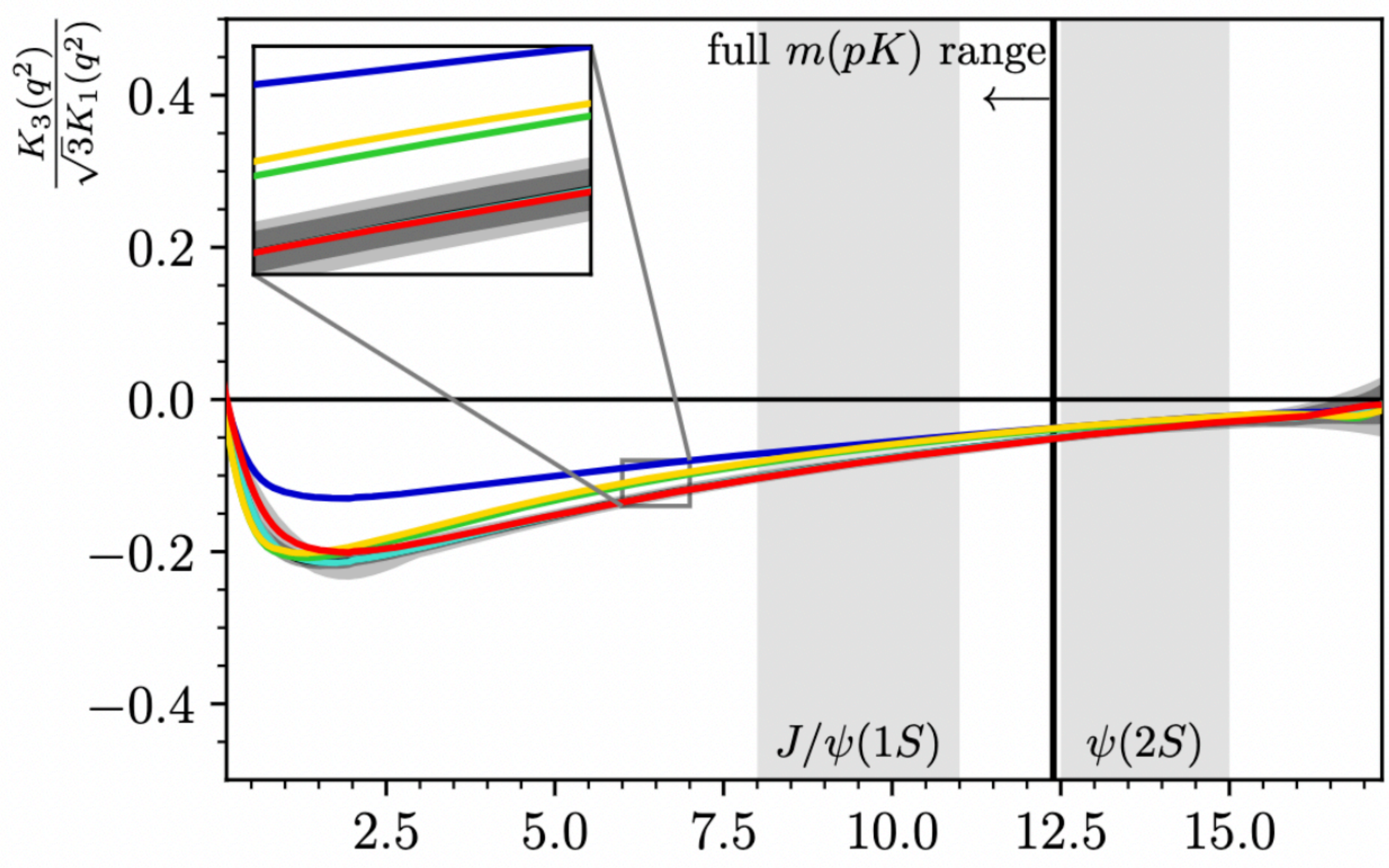
$\Lambda_b \to pK^-\mu^+\mu^-$ Observables





$K_3\left(q^2\right)$ - asymmetry in the squares of the amplitudes between amplitudes with $|\lambda_V| = 1$ and $\lambda_V = 0$

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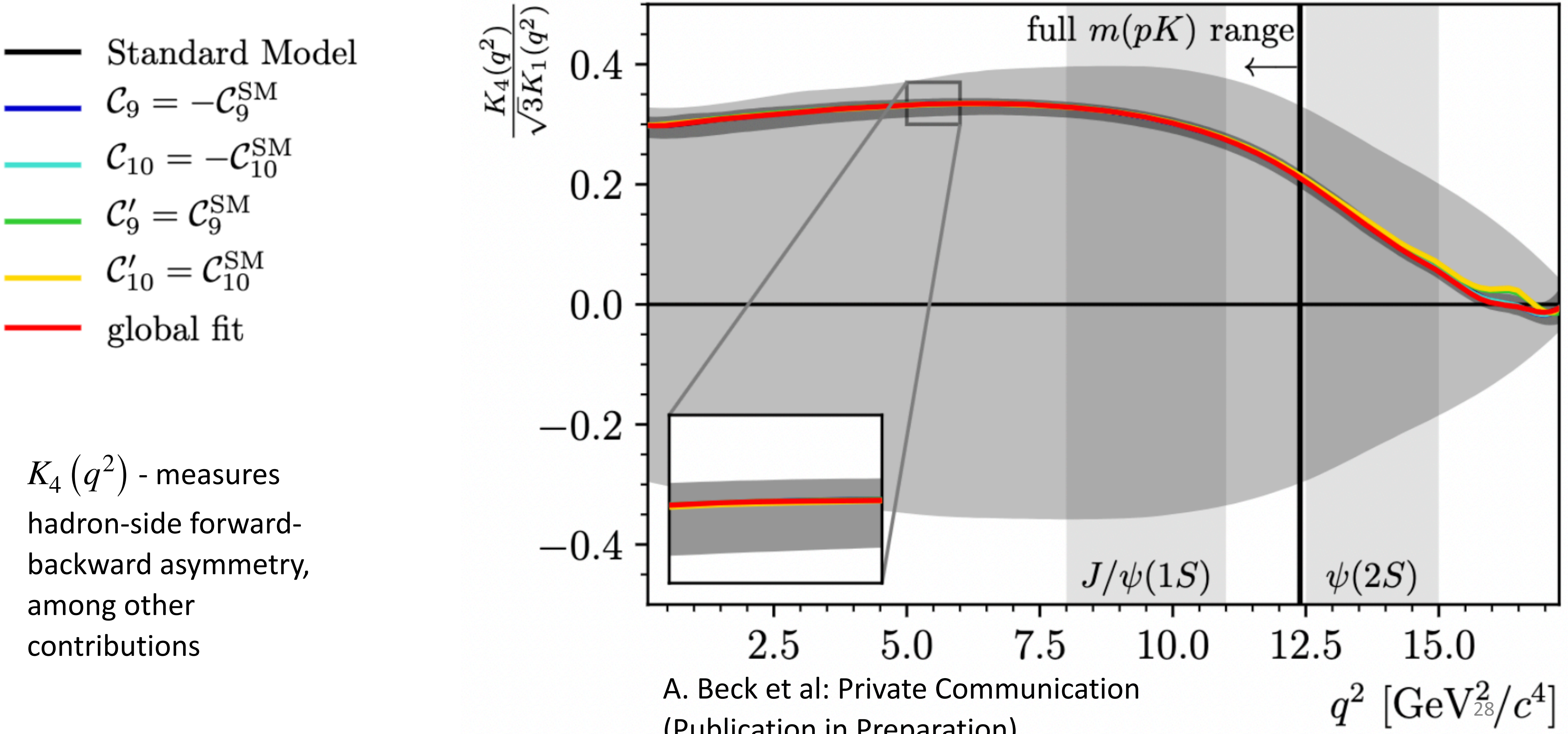
$\Lambda_b \to pK^-\mu^+\mu^-$ Observables



$K_4\left(q^2\right)$ - measures hadron-side forward-backward asymmetry, among other contributions

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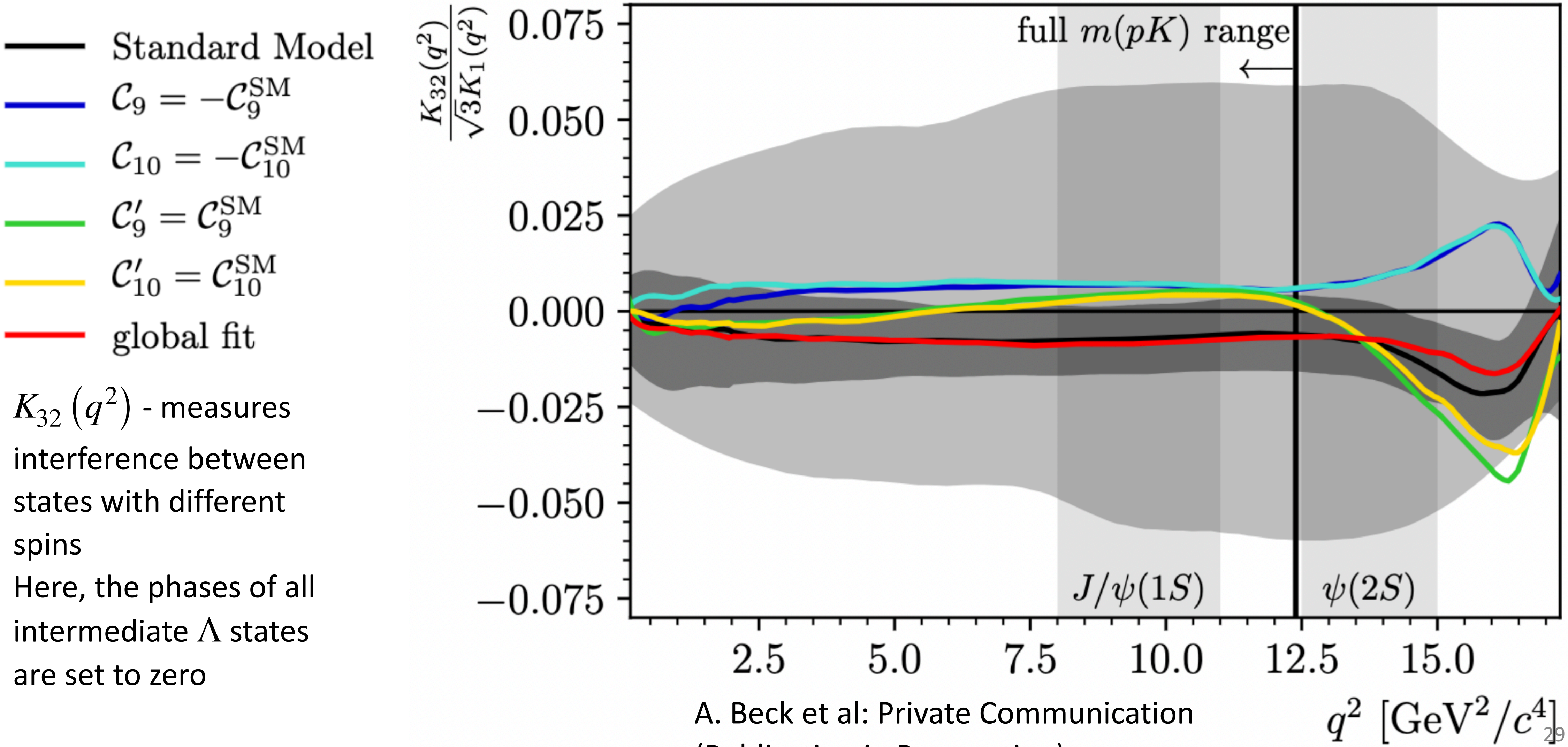
$\Lambda_b \to pK^-\mu^+\mu^-$ Observables

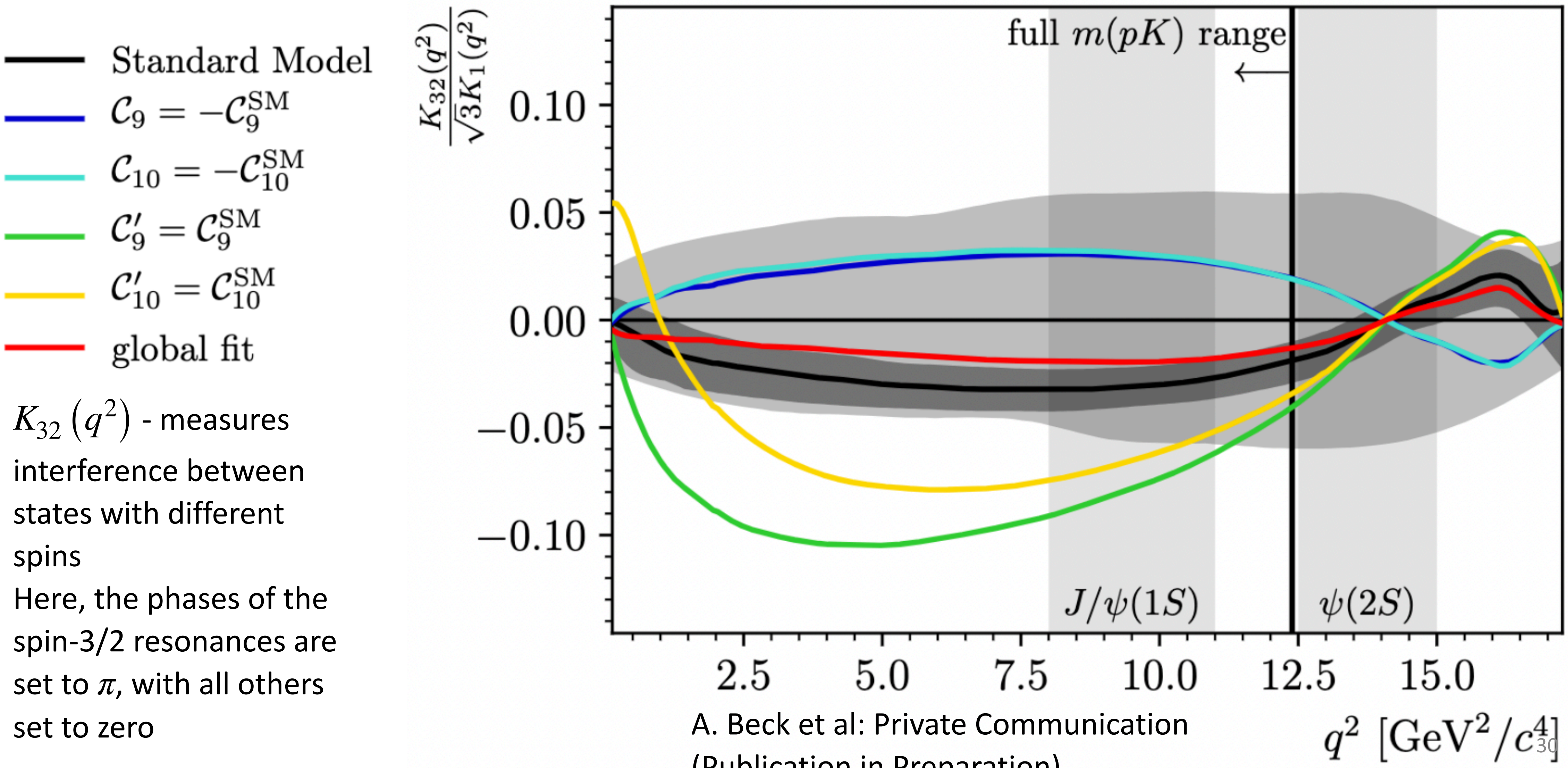


$K_{32}(q^2)$ - measures interference between states with different spins

Here, the phases of all intermediate Λ states are set to zero

A. Beck et al: Private Communication (Publication in Preparation)

$\Lambda_b \to pK^-\mu^+\mu^-$ Observables



$K_{32}\left(q^2\right)$ - measures interference between states with different spins

Here, the phases of the spin-3/2 resonances are set to π, with all others set to zero

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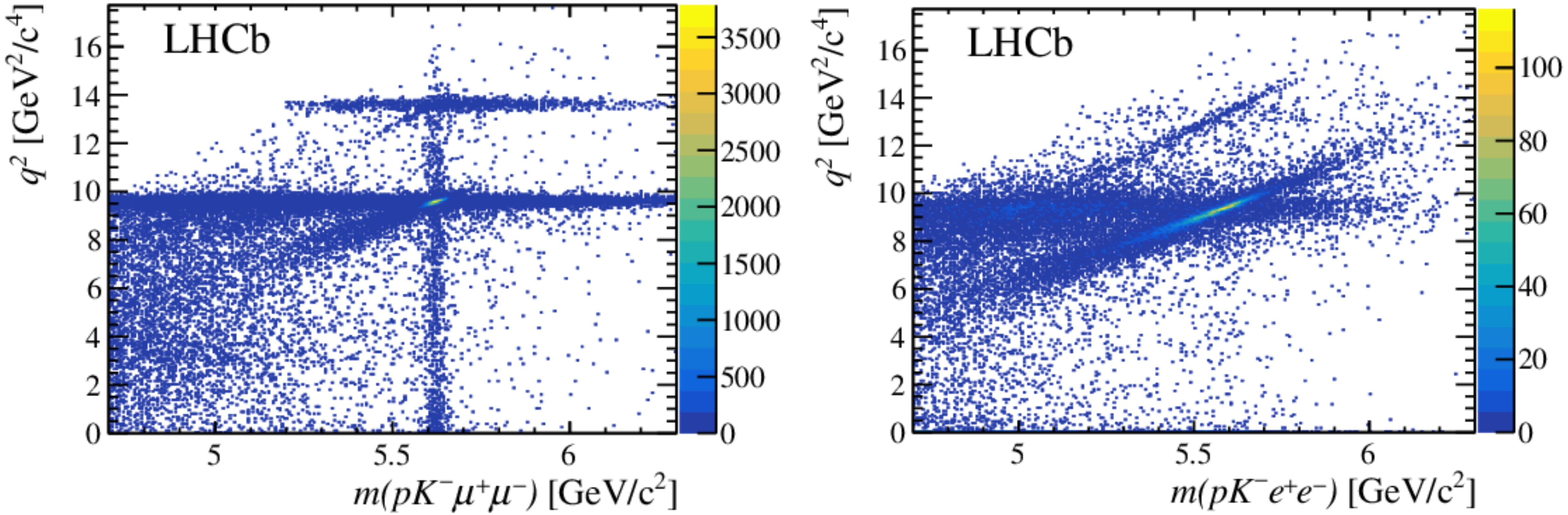
Experimental Challenges with Electrons



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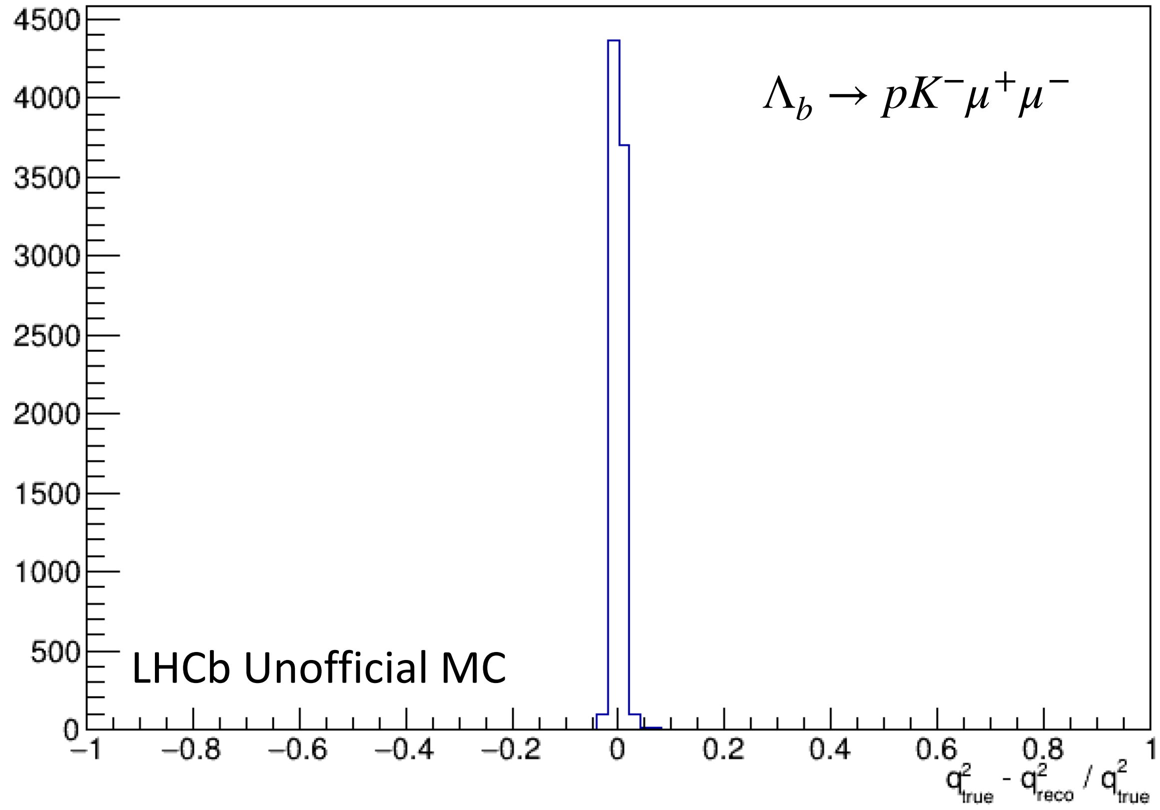
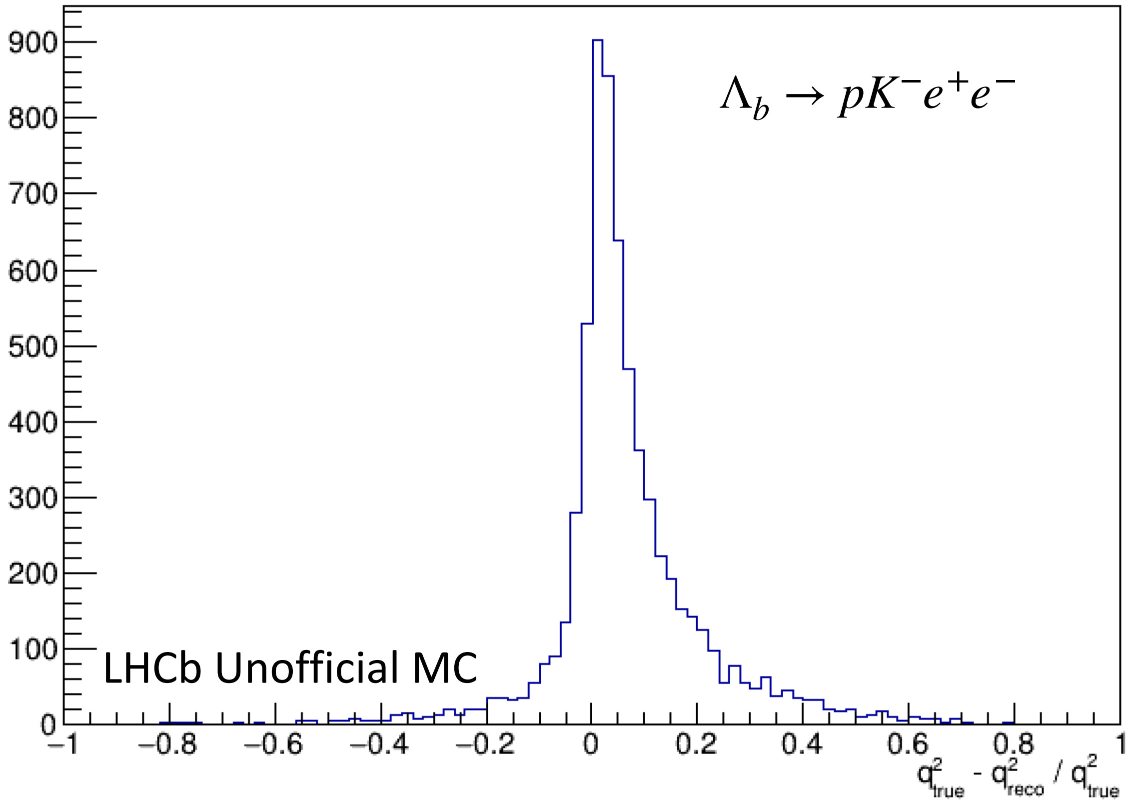
Experimental Challenges with Electrons





What Do We Do About Acceptance?

- Given a detector efficiency function $\epsilon(\Omega)$, the efficiency matrix is defined as

$$E_{(i,j,\ldots,n)} = \int \epsilon(\Omega)\Big[f_i(\Omega)f_j(\Omega)\ldots f_n(\Omega)\Big]\, d\Omega = \frac{\Phi}{N_{MC,gen}}\left[\sum_{k=1}^{N_{MC,acc}} f_i(\Omega_k)f_j(\Omega_k)\ldots f_n(\Omega_k)\right]$$

- Where the measured moments are defined in terms of the efficiency matrix and the true moments

$$K_{i,\text{meas}}\left(q^2, m_{pK}\right) = \sum_{k=1}^{N_{data}} f_i(\Omega_k) = E_{ij}K_{j,\text{true}}\left(q^2, m_{pK}\right)$$

- And we can recover the efficiency-corrected true moments by inverting the efficiency matrix

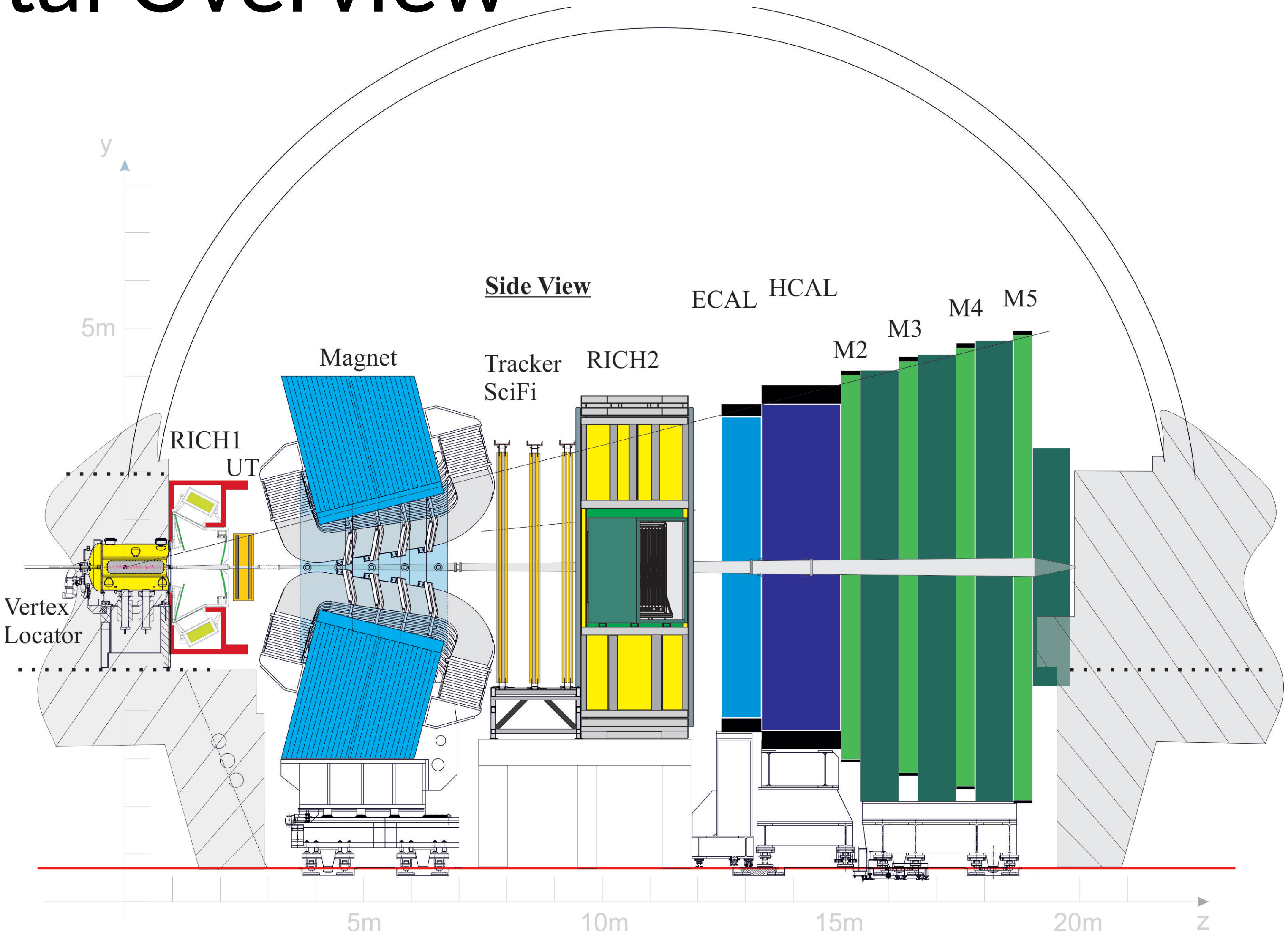
$$K_{i,\text{true}}\left(q^2, m_{pK}\right) = \left(E^{-1}\right)_{ij} K_{j,\text{meas}}\left(q^2, m_{pK}\right)$$

A Non-Trivial Calculation

- To describe the unpolarized $\Lambda_b \to pK^-\mu^+\mu^-$ decay, a basis of 46 angular moments is used - 186 are required if the Λ_b is polarized
- Detector acceptance and resolution generate higher unphysical moments that must be unfolded
- To properly extract the true observables, a much larger basis is needed than is necessary to simply describe the system
- This statement becomes more true as acceptance effects become stronger, and as detector resolution decreases
- How large of a basis do we need? We don’t know (yet)

LHCb Experimental Overview

- pp Collisions
- Forward Spectrometer
- Collected 9 fb^{-1} in Runs 1 and 2
- Run 3 ongoing
- Plan to collect over 300 fb^{-1} by end of Run 5



Brem Recovery Challenge

- $e^{\pm}$ loses energy before it reaches the ECal
- Energy reconstruction difficult
- Worse energy resolution
- At LHCb, most electrons emit one energetic brem before the magnet
- Over half of brem photons are not detected

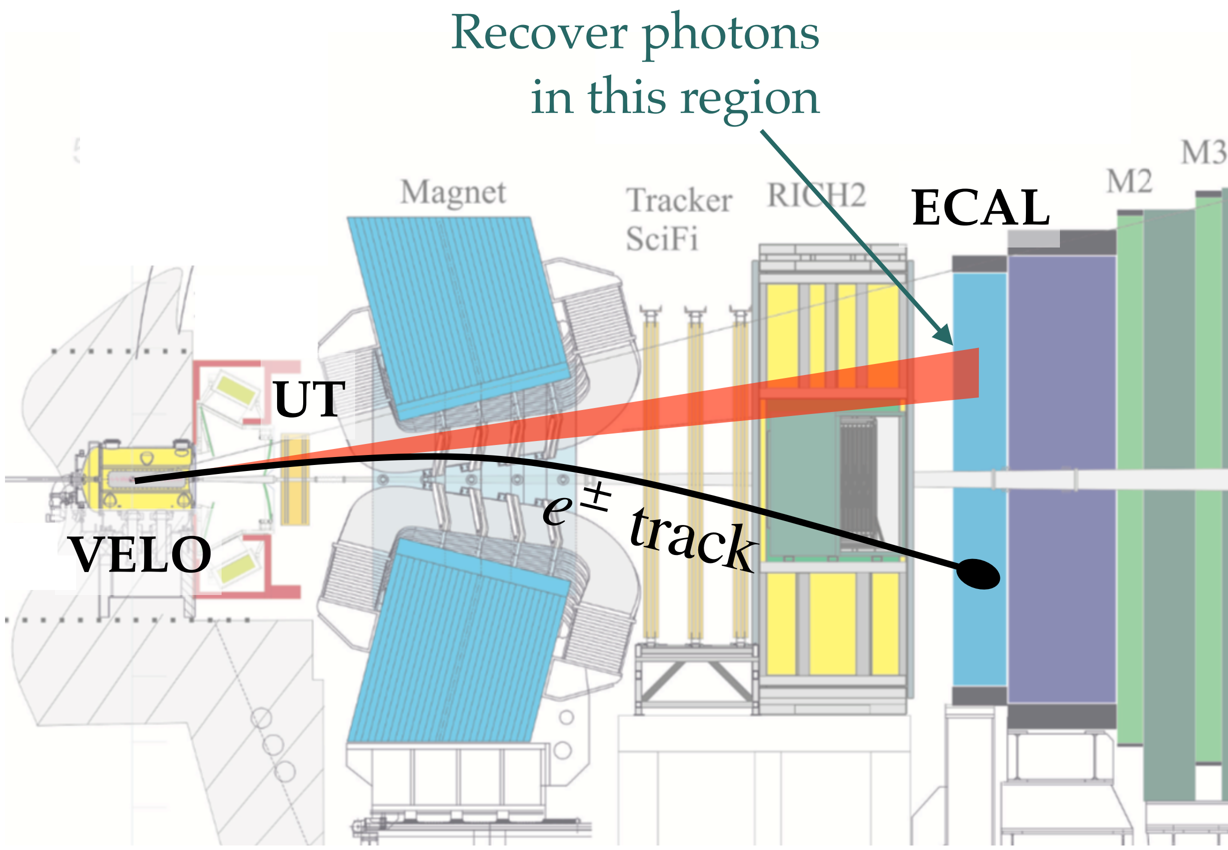


Figure credit: M. Borsato

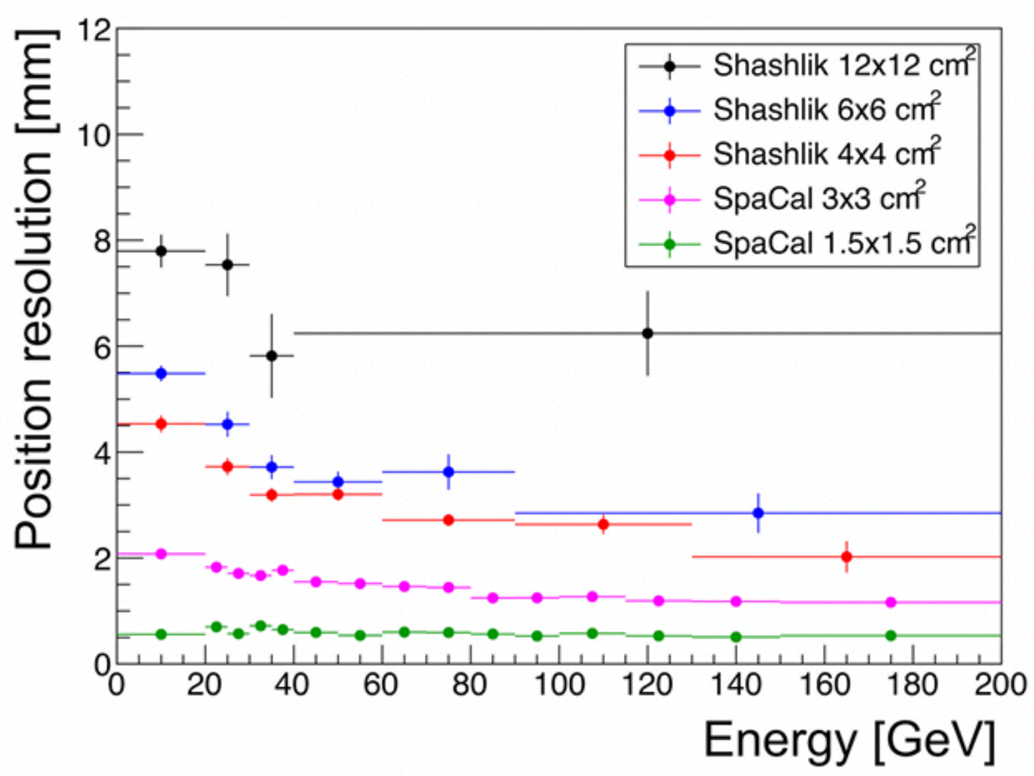
Future plans

- Future upgrades will see an overhaul of the LHCb ECal
- Goals:
  - Increase radiation tolerance
  - Maintain energy resolution
  - Include timing resolution

LHCB-TDR-023

Smaller Cell Sizes→Better Spatial Resolution

- The geometry of the proposed ECal upgrade is projected to provide better spatial resolution of our ECal showers
- Right: Position resolution of each type of ECal module for single photon cluster
- Current technology consists of large-celled modules - the addition of smaller-celled modules should improve position resolution



LHCB-TDR-023

Plans for $\Lambda_b \to pK^- e^+ e^-$

- Go beyond R_{pK} - we could also take the μ/e ratios of angular observables
- LHCb is studying this in $B^0 \to K^{*0}\ell^+\ell^-$ decays
- We could do the same for $\Lambda_b \to pK^-\ell^+\ell^-$
    - Richer spin structure $\to$ more observables
    - Better understanding of the form factors is necessary for interpretation

Summary

- Current tests of LFU show tensions with the Standard Model
- LHCb's production of *b*-baryons provides the opportunity to test LFU in the baryonic sector
- Electron reconstruction capabilities at LHCb add a level of difficulty
- Understanding the angular structure is critical
- Goal: measure μ/e ratios of angular observables
- Suggestions?

Backup

Ensemble of Lambdas

resonance	m_Λ [GeV/c^2]	Γ_Λ [GeV/c^2]	$2J_\Lambda$	P_Λ	$\mathcal{B}(\Lambda \to \overline{N}K)$	used $\mathcal{B}_\Lambda$
$\Lambda(1405)$	1.405	0.051	1	$-$	n/a	1.0000
$\Lambda(1520)$	1.519	0.016	3	$-$	0.45	0.2250
$\Lambda(1600)$	1.600	0.200	1	$+$	0.15 – 0.30	0.1125
$\Lambda(1670)$	1.674	0.030	1	$-$	0.20 – 0.30	0.1250
$\Lambda(1690)$	1.690	0.070	3	$-$	0.20 – 0.30	0.1250
$\Lambda(1800)$	1.800	0.200	1	$-$	0.25 – 0.40	0.1625
$\Lambda(1810)$	1.790	0.110	1	$+$	0.05 – 0.35	0.1000
$\Lambda(1820)$	1.820	0.080	5	$+$	0.55 – 0.65	0.3000
$\Lambda(1890)$	1.890	0.120	3	$+$	0.24 – 0.36	0.1500
$\Lambda(2110)$	2.090	0.250	5	$+$	0.05 – 0.25	0.0750

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(Publication in Preparation)

Hadronic Amplitudes for $\Lambda \to pK^-$

- Natural parity Λ

$$h^{\Lambda}_{\lambda_\Lambda,\lambda_p}\left(m_{pK}\right) = \frac{g}{\left(m_{pK}^2 - m_\Lambda^2\right) - i m_{pK}\Gamma\left(m_{pK}\right)} \bar{u}\left(p\right)\gamma_5 U\left(\Lambda\right)$$

$$U(k,\lambda_\Lambda) = \begin{cases} u(k,\lambda_\Lambda) & , J_\Lambda = \frac{1}{2} \\ k_1^\mu u_\mu(k,\lambda_\Lambda) & , J_\Lambda = \frac{3}{2} \\ k_1^\mu k_1^\nu u_{\mu\nu}(k,\lambda_\Lambda) & , J_\Lambda = \frac{5}{2} \end{cases}$$

- Unnatural parity Λ

$$h^{\Lambda}_{\lambda_\Lambda,\lambda_p}\left(m_{pK}\right) = -\frac{g}{\left(m_{pK}^2 - m_\Lambda^2\right) - i m_{pK}\Gamma\left(m_{pK}\right)} \bar{u}\left(p\right) U\left(\Lambda\right)$$

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Leptonic Amplitudes for $V \to \ell^+\ell^-$

$$\tilde{h}^{J_{\ell\ell}}_{\lambda_1,\lambda_2}\left(q^2\right) = \varepsilon_\mu\left(\lambda_1 - \lambda_2\right)\bar{u}\left(\ell_2\right)\Gamma^\mu v\left(\ell_1\right)$$

$$\begin{aligned}
\tilde{h}^{V,0}_{++}\left(q^2\right) &= 0\\
\tilde{h}^{V,1}_{++}\left(q^2\right) &= 2m_\ell\\
\tilde{h}^{V,1}_{+-}\left(q^2\right) &= -\sqrt{2q^2}\\
\tilde{h}^{V,J_{\ell\ell}}_{-\lambda_1,-\lambda_2}\left(q^2\right) &= -\tilde{h}^{V,J_{\ell\ell}}_{+\lambda_1,+\lambda_2}\left(q^2\right)
\end{aligned}$$

$$\begin{aligned}
\tilde{h}^{A,0}_{++}\left(q^2\right) &= 2m_\ell\\
\tilde{h}^{A,1}_{++}\left(q^2\right) &= 0\\
\tilde{h}^{A,1}_{+-}\left(q^2\right) &= \sqrt{2q^2}\beta_\ell\\
\tilde{h}^{A,J_{\ell\ell}}_{-\lambda_1,-\lambda_2}\left(q^2\right) &= \tilde{h}^{A,J_{\ell\ell}}_{+\lambda_1,+\lambda_2}\left(q^2\right)
\end{aligned}$$

$$\beta_\ell = \sqrt{1 - \frac{4m_\ell^2}{q^2}}$$

A. Beck et al: Private Communication
(Publication in Preparation)

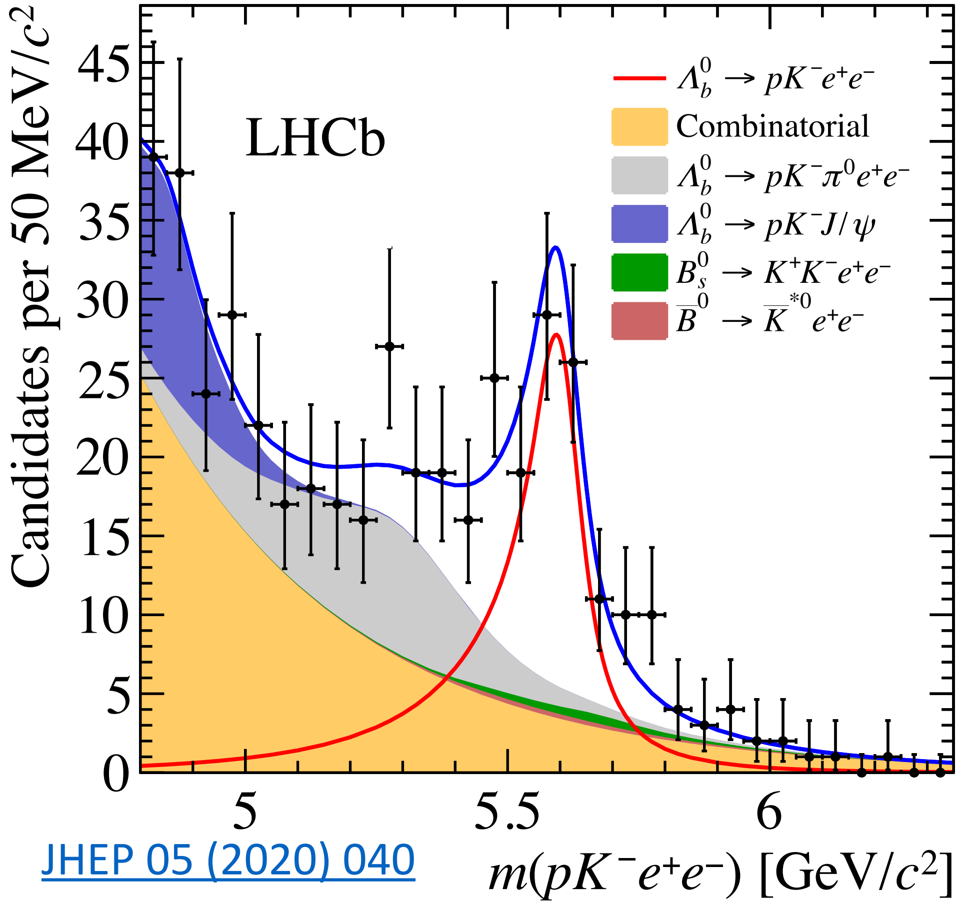
Digging Deeper Into R_{pK}

$$R_{pK}^{-1} = \frac{\mathscr{B}\left(\Lambda_b \to pK^- e^+ e^-\right)}{\mathscr{B}\left(\Lambda_b \to pK^- J/\psi(\to e^+ e^-)\right)} * \frac{\mathscr{B}\left(\Lambda_b \to pK^- J/\psi(\to \mu^+ \mu^-)\right)}{\mathscr{B}\left(\Lambda_b \to pK^- \mu^+ \mu^-\right)}$$

- Here we use the inverse definition because we expect small yields in the electron mode
- LHCb (right) found

$$R_{pK} = 0.86 \left(\begin{matrix}+0.14\\-0.11\end{matrix}\right)_{stat} \pm (0.05)_{syst}$$

- Uncertainty is dominated by statistics



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Form Factors for $\Lambda_b \to \Lambda V$

$$H^{\Lambda,\Gamma^\mu}_{\lambda_\Lambda,\lambda_V} = \varepsilon^*_\mu(\lambda_V)\langle\Lambda|\bar{s}\Gamma^\mu b|\Lambda_b\rangle$$

$$\langle\Lambda|\bar{s}\Gamma^\mu b|\Lambda_b\rangle_{\text{gen}} = \bar{u}_\alpha(\Lambda)\left[v^\alpha\left(X_{\Gamma^1}(q^2)\gamma^\mu + X_{\Gamma^2}(q^2)v^\mu + X_{\Gamma^3}(q^2)v'^\mu\right) + X_{\Gamma^4}(q^2)g^{\alpha\mu}\right]u(\Lambda_b)$$

Vector Current:

$$\langle\Lambda|\bar{s}\gamma^\mu b|\Lambda_b\rangle_{\text{gen}} = \bar{u}_\alpha(\Lambda)\left[v^\alpha\left(F_1(q^2)\gamma^\mu + F_2(q^2)v^\mu + F_3(q^2)v'^\mu\right) + F_4(q^2)g^{\alpha\mu}\right]u(\Lambda_b)$$

$$\begin{aligned}\langle\Lambda|\bar{s}\gamma^\mu b|\Lambda_b\rangle_{\text{hel}} = \bar{u}_\alpha(\Lambda)\Bigg\{p^\alpha\Bigg[&f_t^V(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{q^2}q^\mu + f_0^V(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{s_+}e^\mu \\ &+ f_\perp^V(q^2)\left(\gamma^\mu - 2\frac{m_\Lambda p^\mu + m_{\Lambda_b}p'^\mu}{s_+}\right)\Bigg] \\ &+ f_g^V(q^2)\left[g^{\alpha\mu} + m_\Lambda\frac{p^\alpha}{s_-}\left(\gamma^\mu - 2\frac{p'^\mu}{m_\Lambda} + 2\frac{m_\Lambda p^\mu + m_{\Lambda_b}p'^\mu}{s_+}\right)\right]\Bigg\}u(\Lambda_b)\end{aligned}$$

Form Factors (Helicity Basis)

- For $J_\Lambda = 1/2$:
  - (Axial) vector: 3 form factors: $f_t^{V(A)}\left(q^2\right)$, $f_0^{V(A)}\left(q^2\right)$, and $f_\perp^{V(A)}\left(q^2\right)$
  - (Axial) tensor: 2 form factors: $f_0^{T(T5)}\left(q^2\right)$ and $f_\perp^{T(T5)}\left(q^2\right)$
- For $J_\Lambda = 3/2$:

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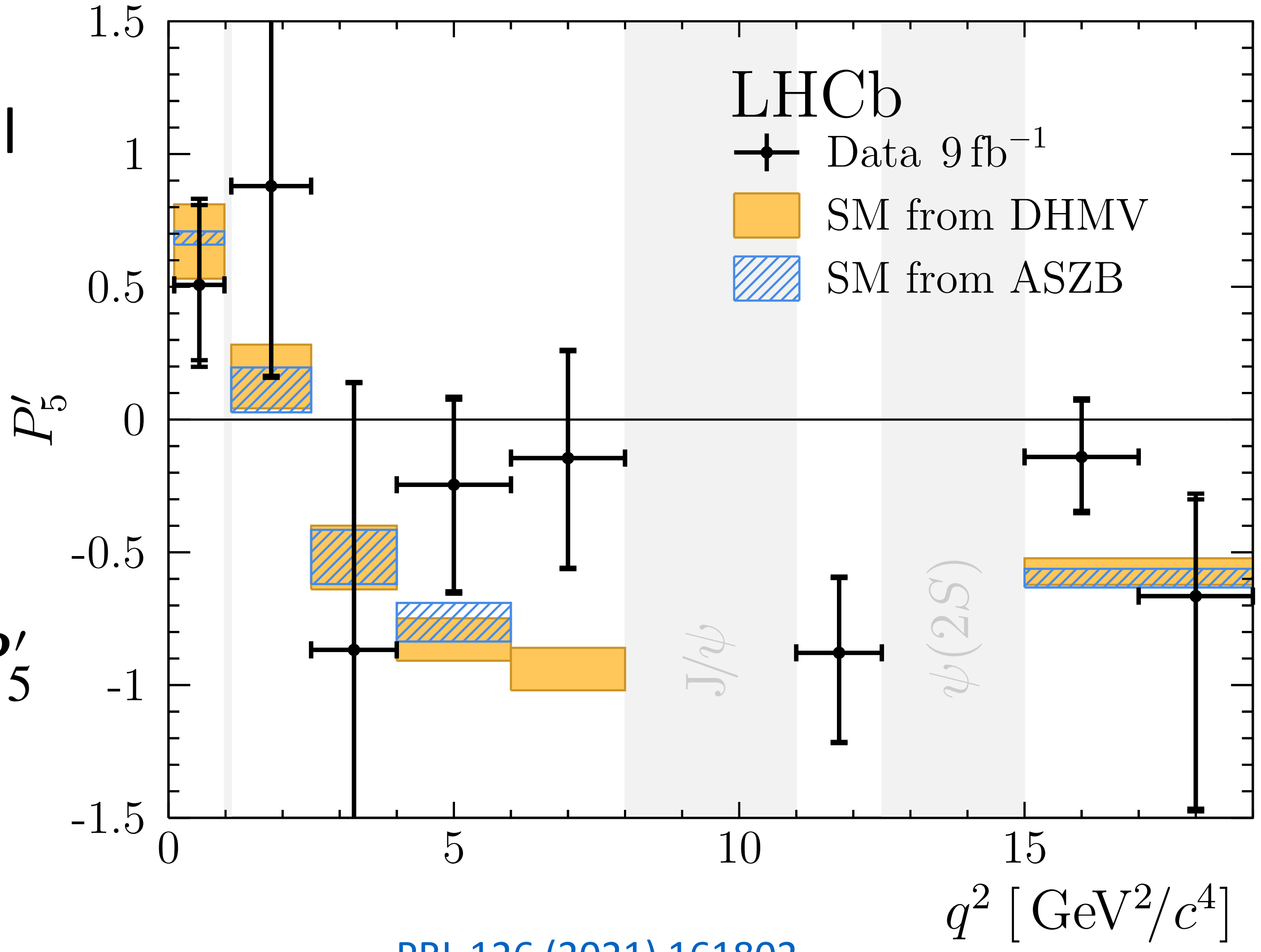
  - (Axial) vector: 4 form factors: $f_t^{V(A)}\left(q^2\right)$, $f_0^{V(A)}\left(q^2\right)$, $f_\perp^{V(A)}\left(q^2\right)$, and $f_g^{V(A)}\left(q^2\right)$
  - (Axial) tensor: 3 form factors: $f_0^{T(T5)}\left(q^2\right)$, $f_\perp^{T(T5)}\left(q^2\right)$, and $f_g^{T(T5)}\left(q^2\right)$
- Tensor and axial tensor amplitudes require fewer form factors in helicity basis than in general basis.

The Method of Moments - Who?

- 2004 - Studies of semileptonic B decays at BaBar
  - PRD 69 (2004) 111103, PRD 69 (2004) 111104, PRL 93 (2004) 011803
- 2006 - Branching Fraction and Photon Energy Moments of $B \to X_s\gamma$ at BaBar
  - PRL 97 (2006) 171803
- 2016 - Branching Fraction and Angular Moments of $B^0 \to K^+\pi^-\mu^+\mu^-$ at LHCb
  - JHEP 12 (2016) 065
- 2018 - Angular Moments of $\Lambda_b \to \Lambda\mu^+\mu^-$ at LHCb
  - JHEP 09 (2018) 146

Angular Fits

- Form factors partially cancel - clean observables!
- Need to understand detector acceptance
- Many angular parameters require large yields
- Right: Angular observable P_5' in $B^+ \to K^{*+}\mu^+\mu^-$ decay



Theory Predictions:
EPJC 75 (2015) 382
JHEP 06 (2016) 92
JHEP 01 (2018) 93

PRL 126 (2021) 161802