Studying penguins in the jungle

Rare beauty baryon decays at LHCb

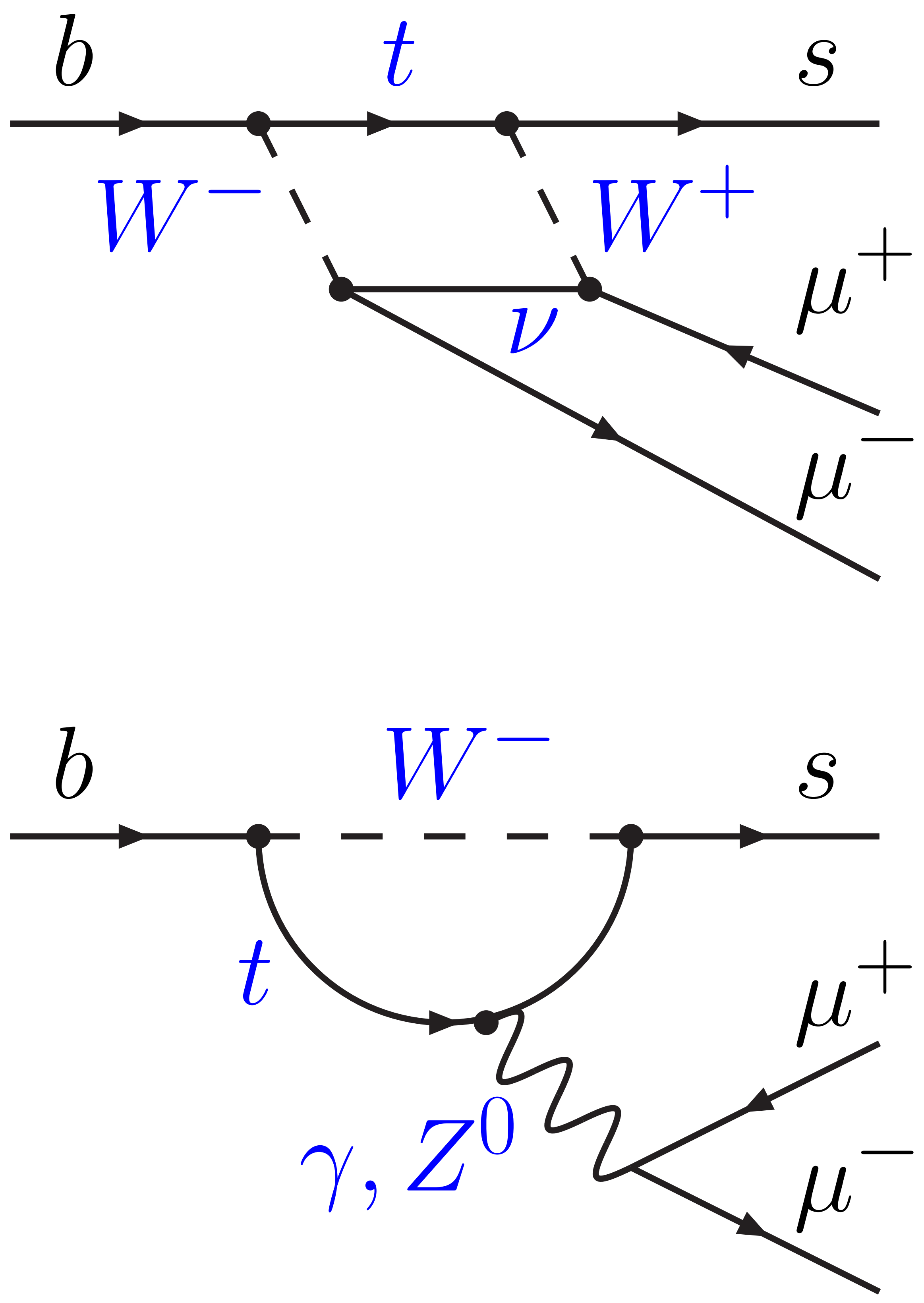
Anja Beck

Warwick EPP Seminar 26.10.23

The penguins

The penguins

- today: $b \to s\mu\mu$ transition
- SM forbids tree-level diagram
- rare in SM => BSM potentially more prominent
- access to virtual contributions



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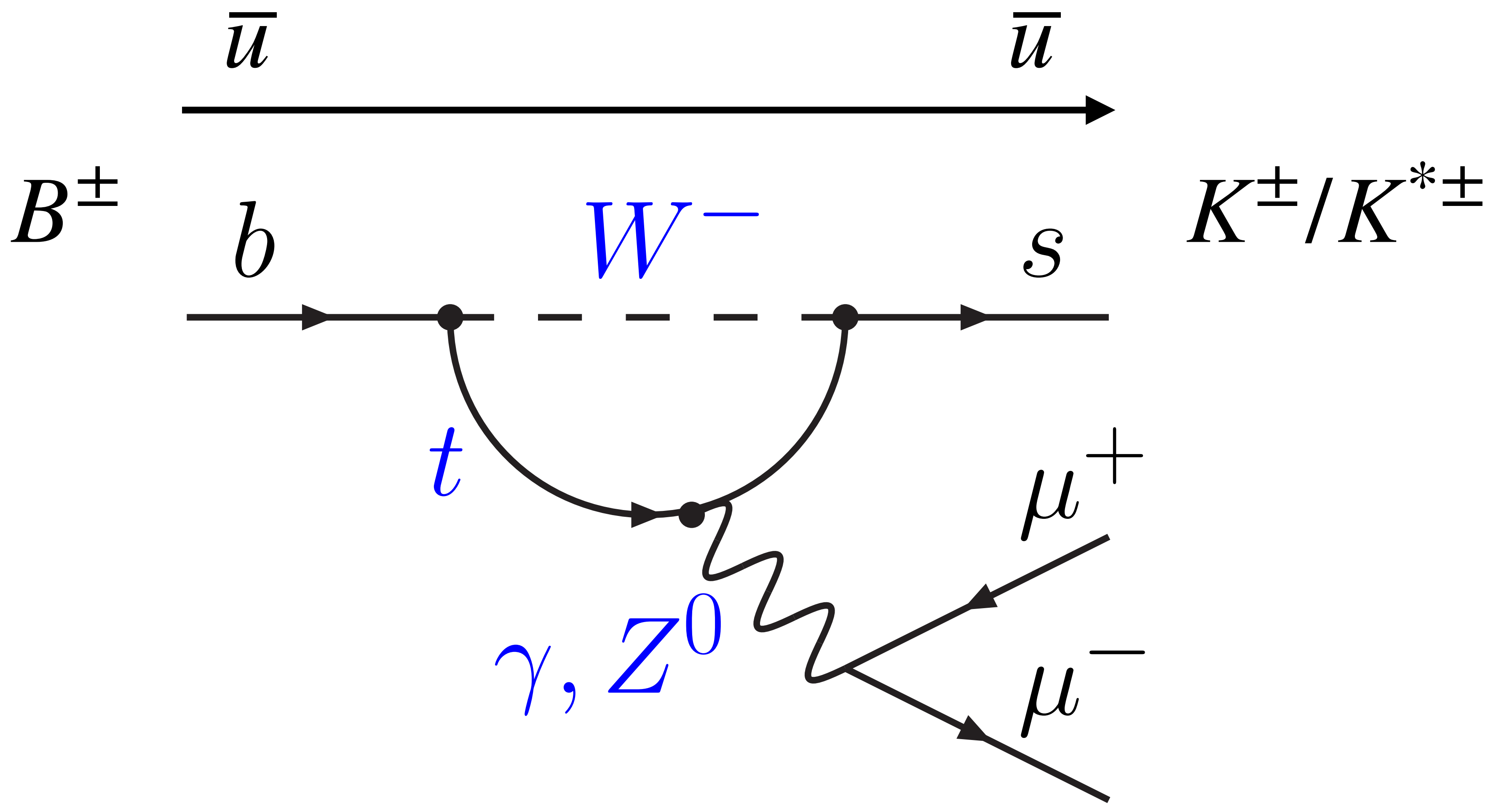

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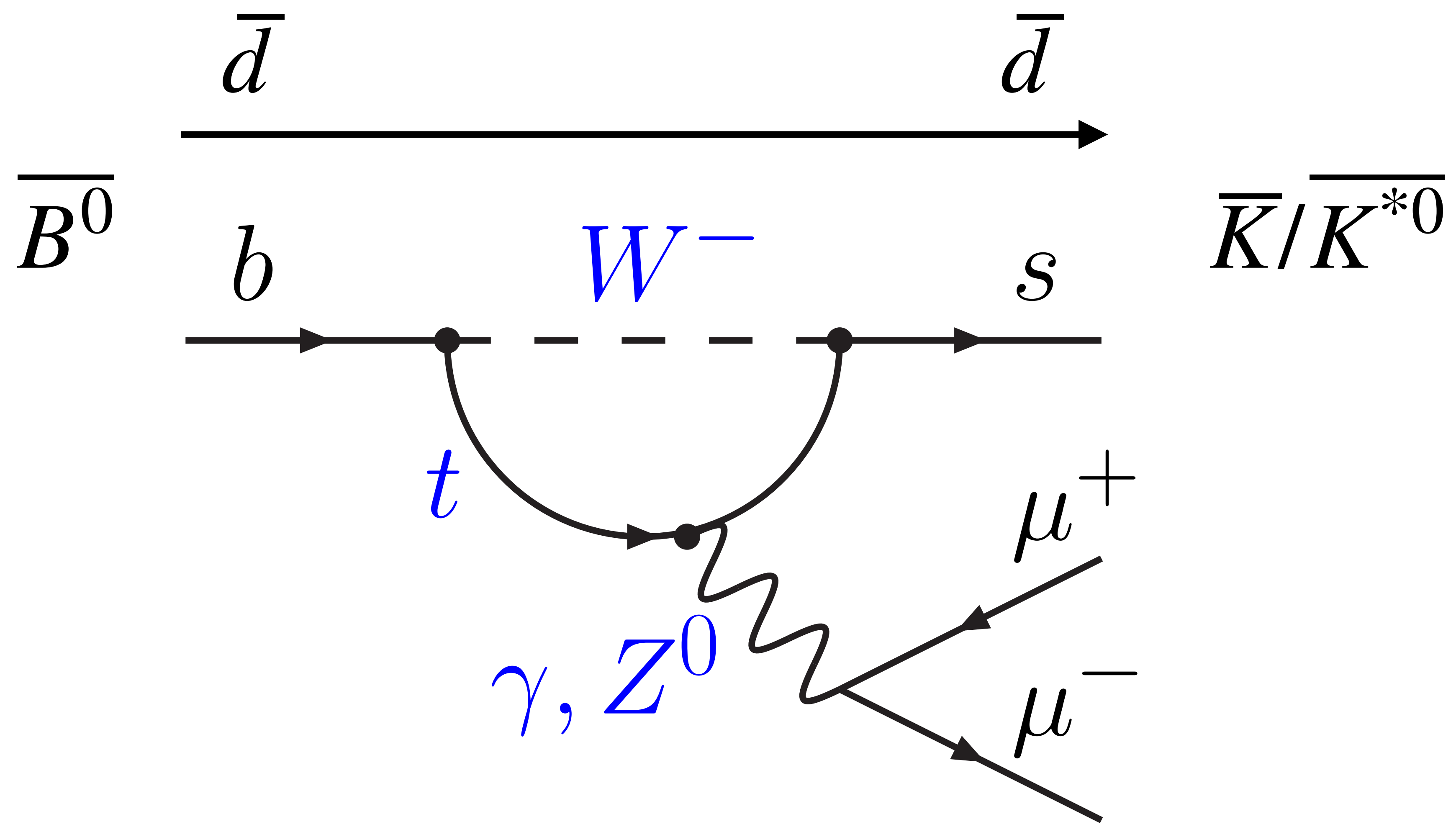

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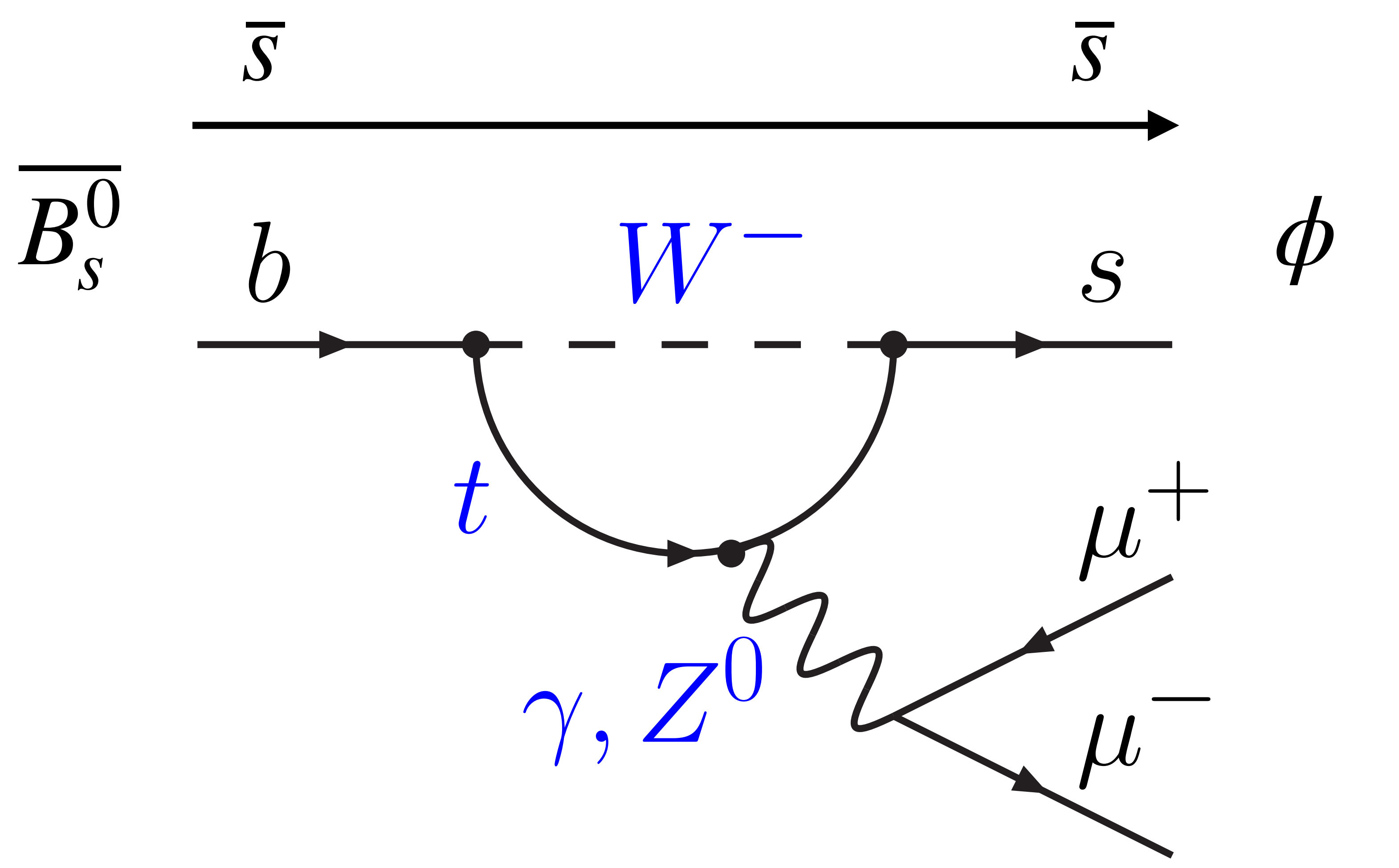

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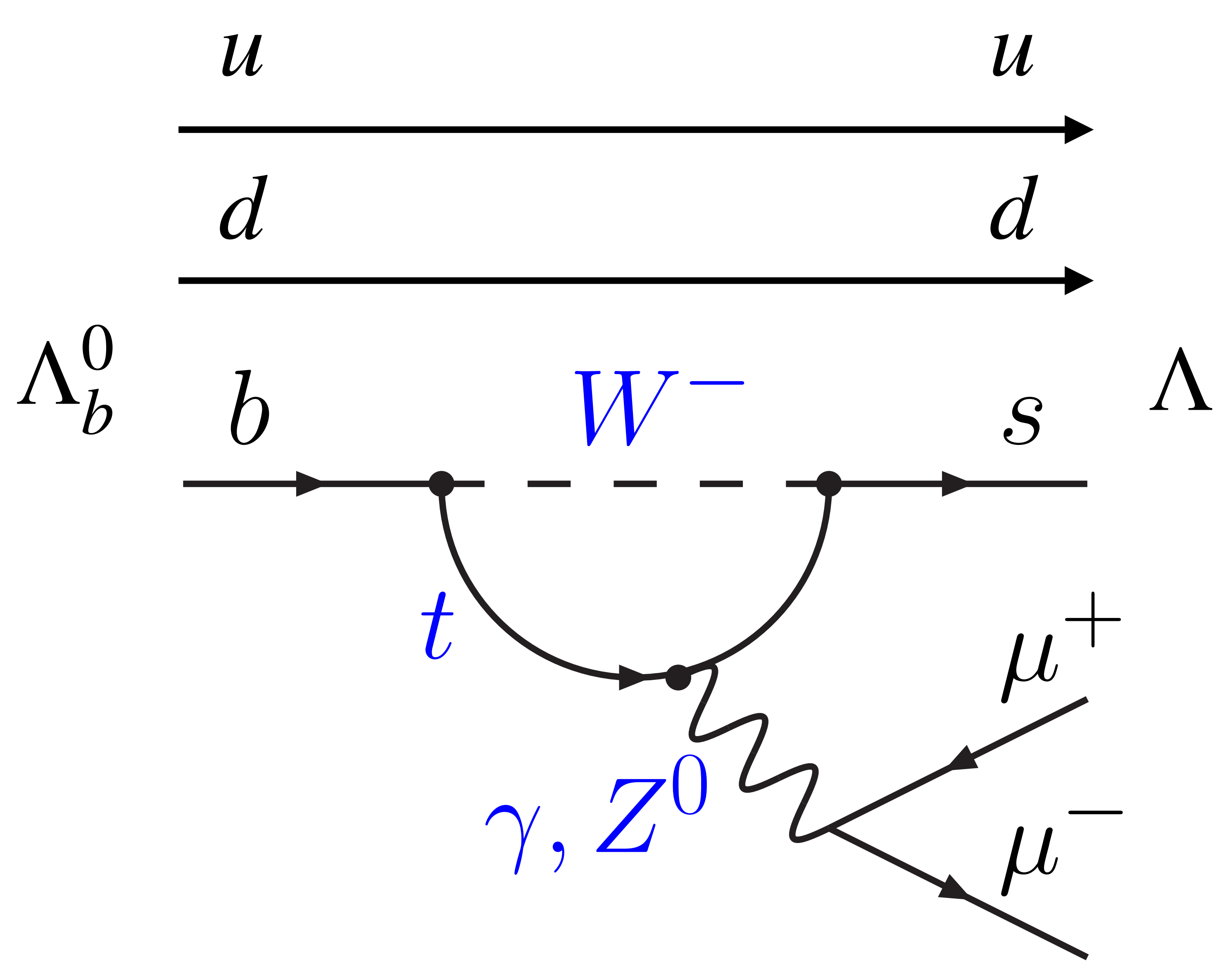
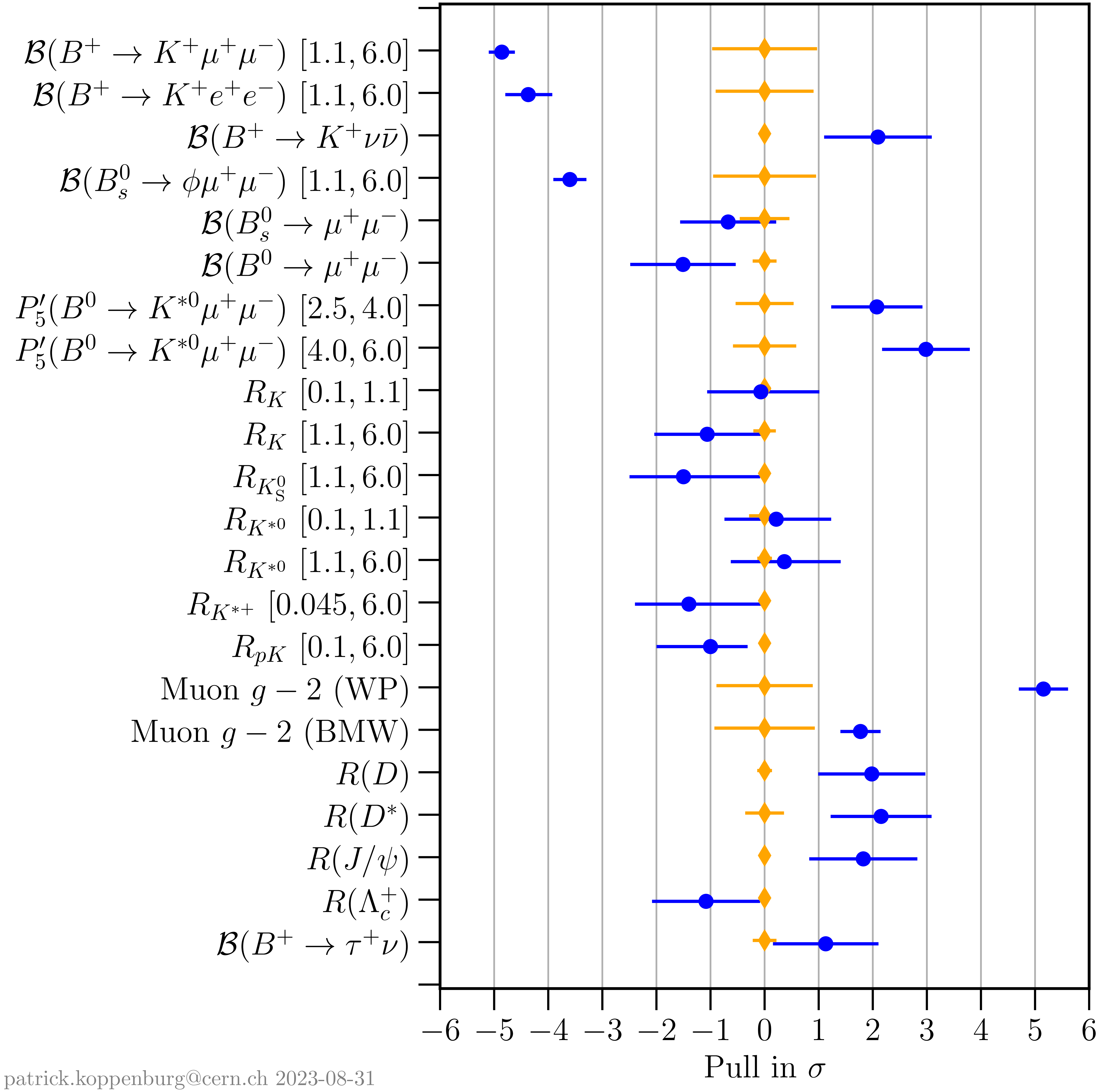


Flavour anomalies

Sometimes maybe a little tension with the SM



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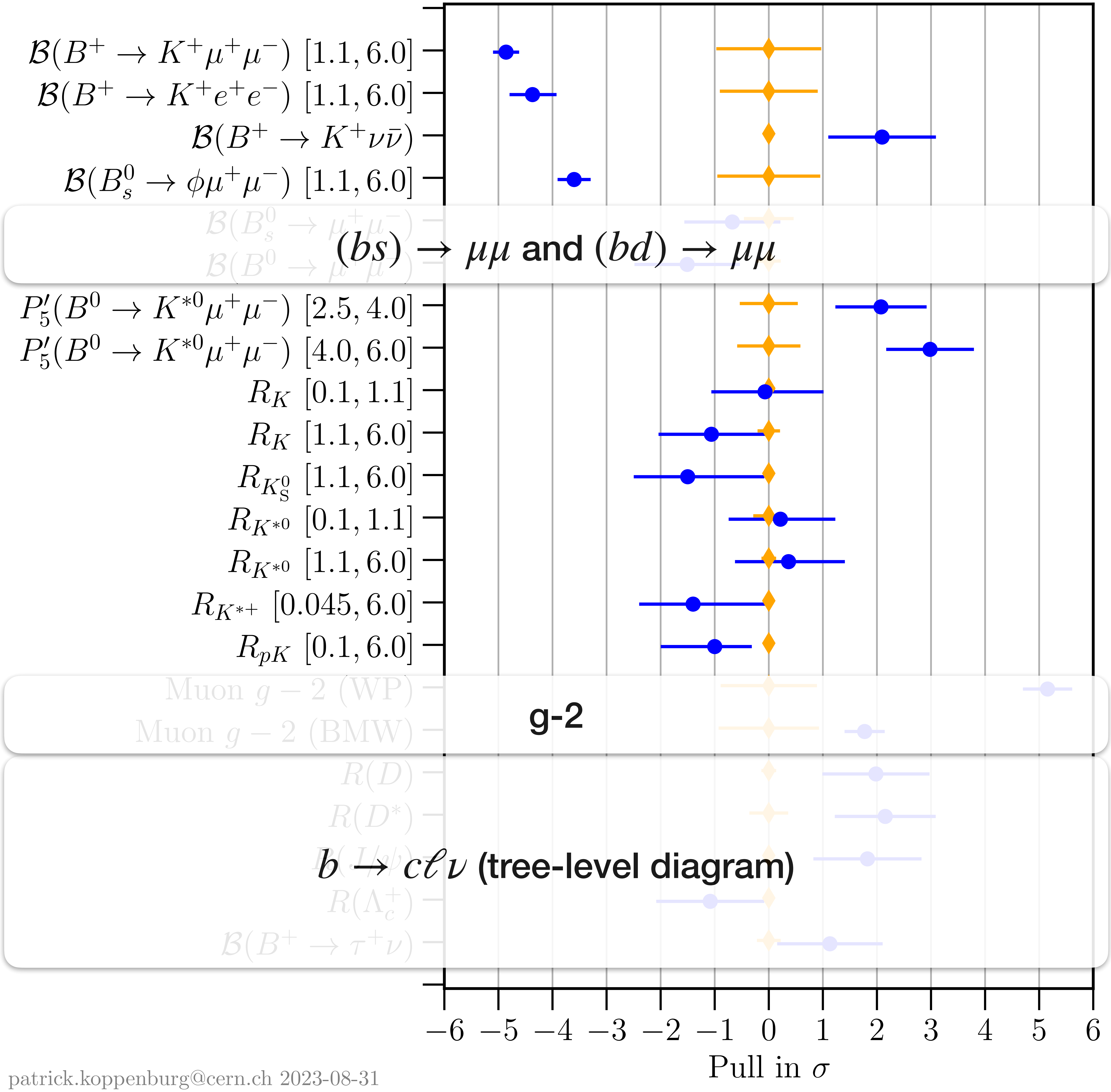

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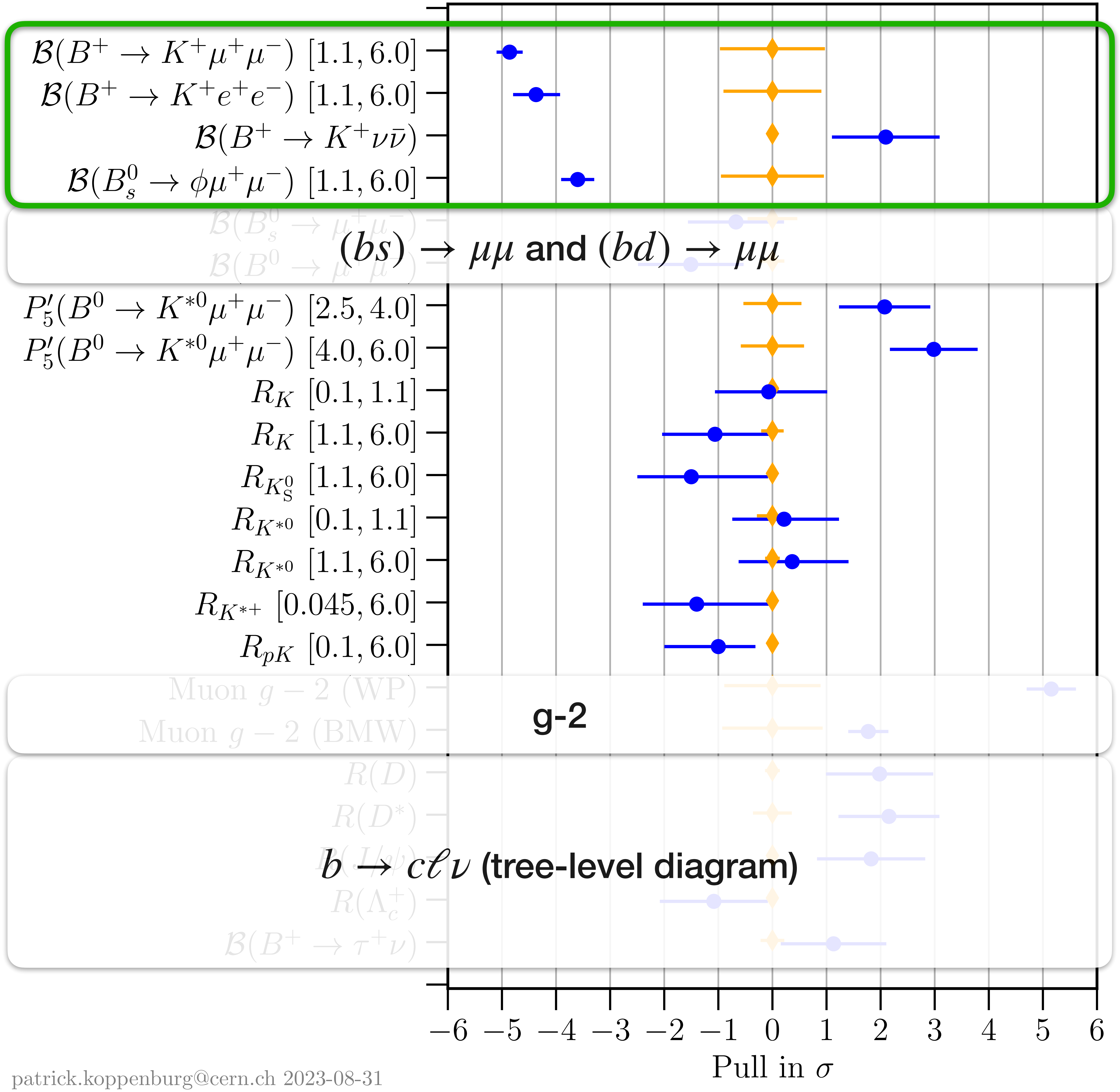
Branching fractions



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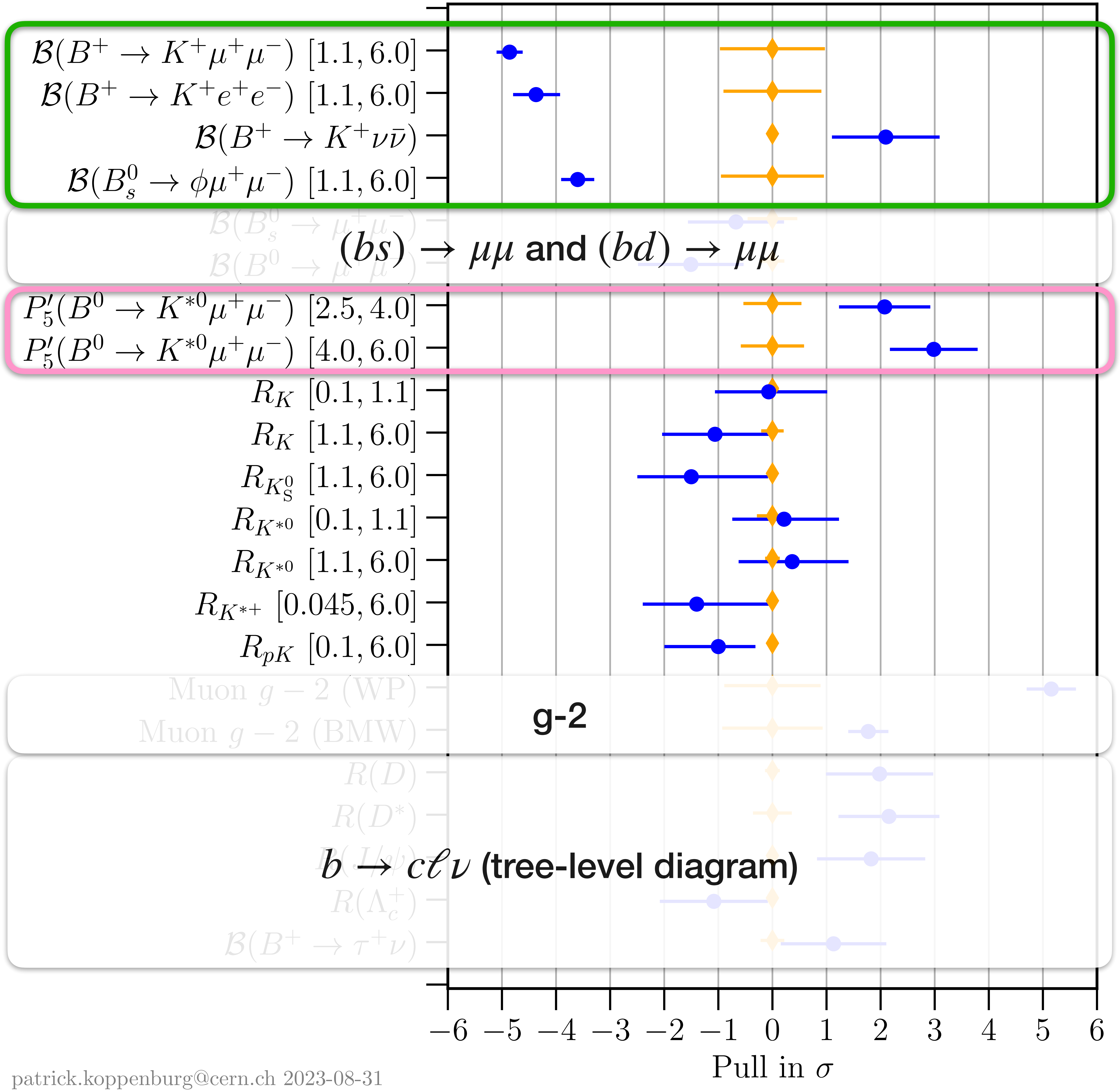
Angular observables



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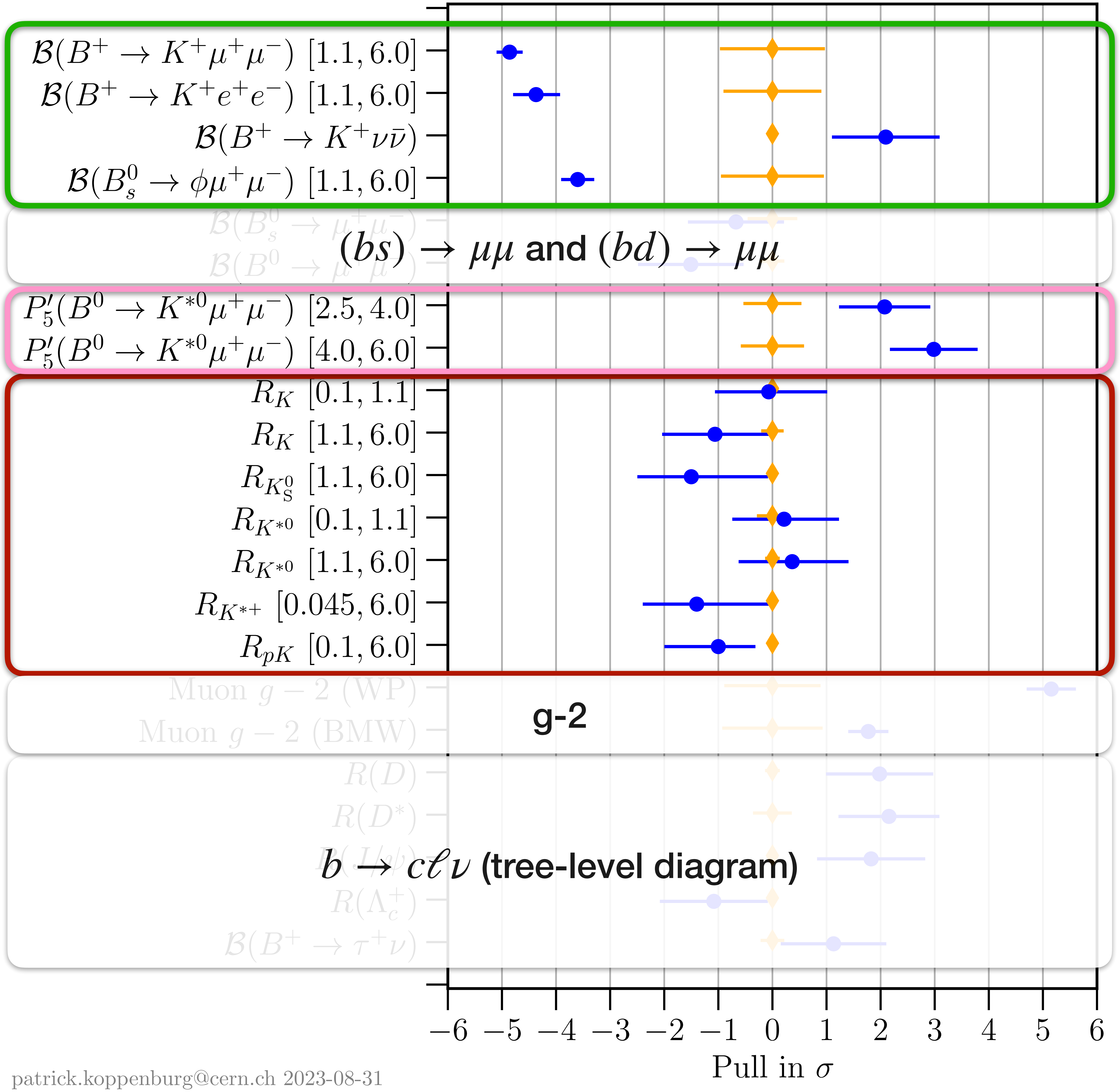
Angular observables

LFU ratios μ/e



Flavour anomalies

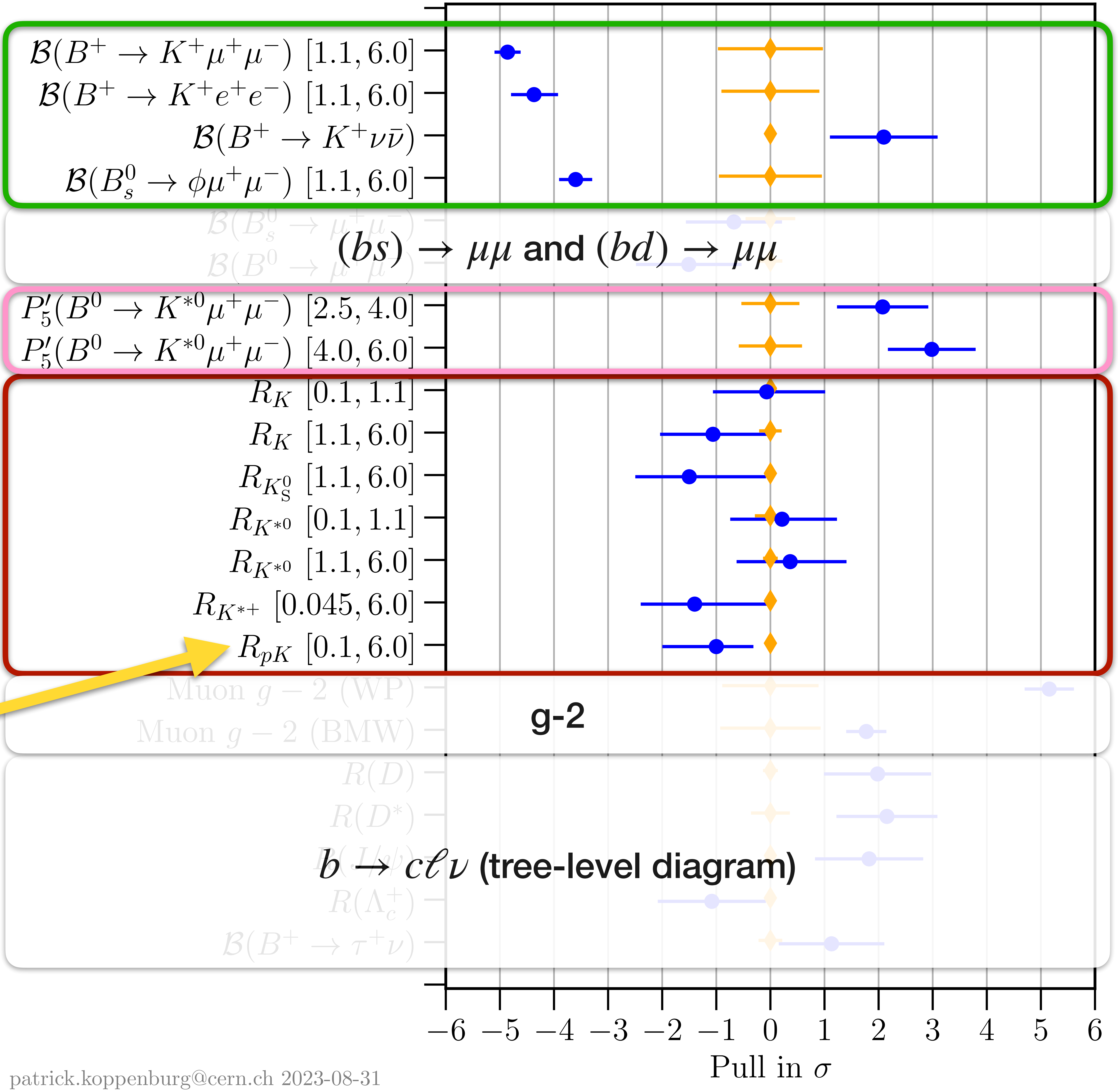
Sometimes maybe a little tension with the SM

Branching fractions

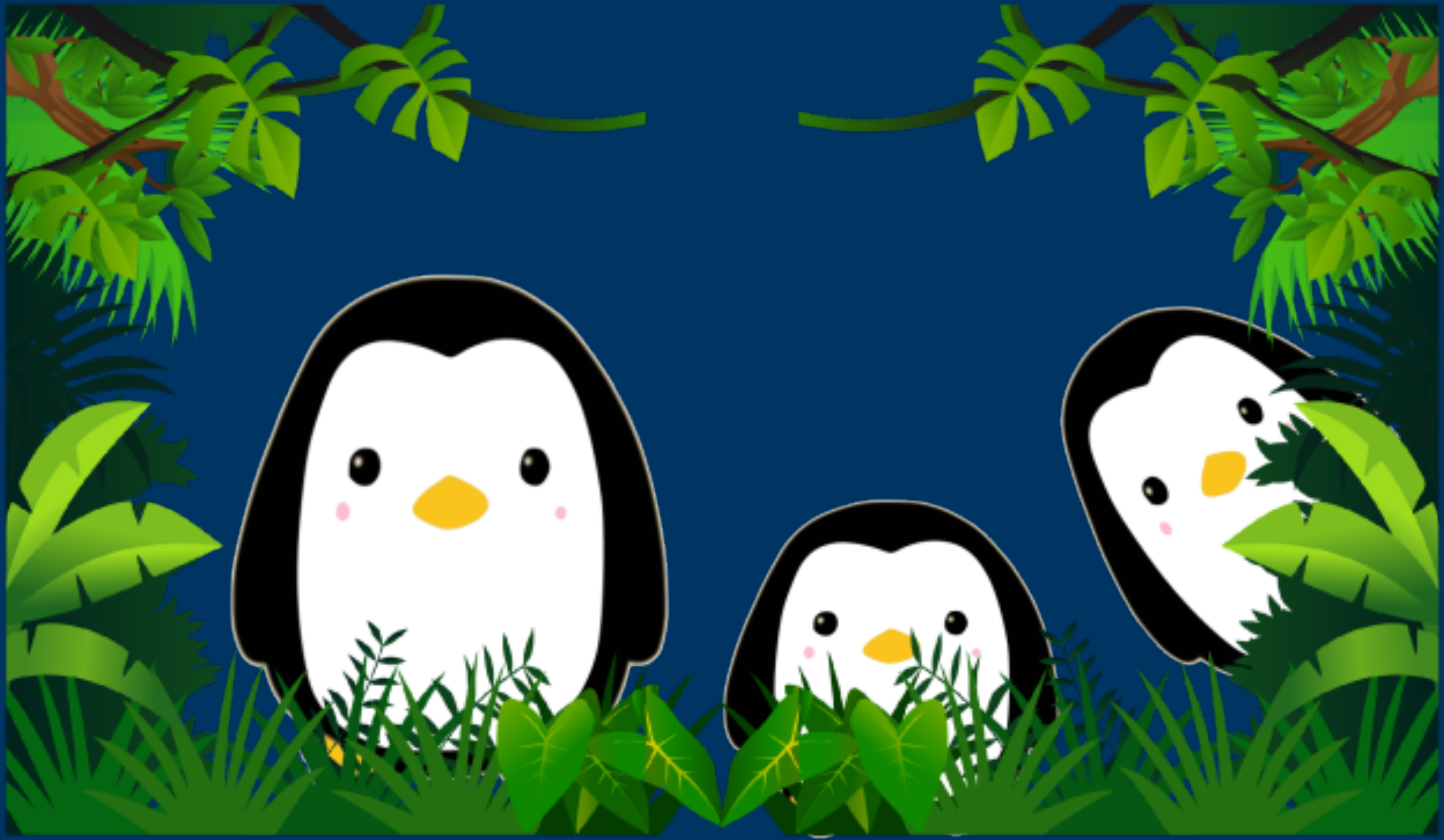
Angular observables

LFU ratios μ/e

One baryon measurement
+ prediction!

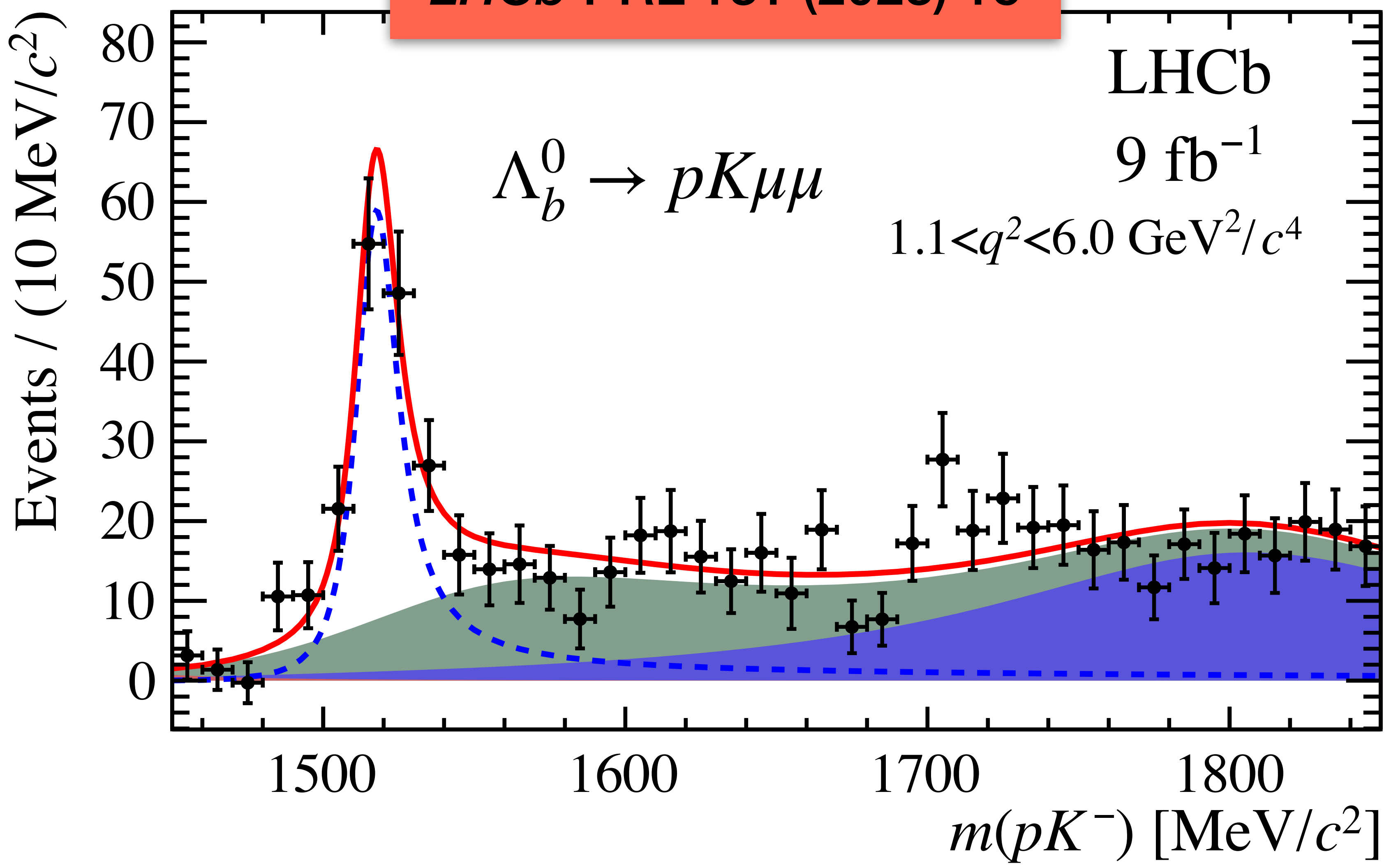


The jungle

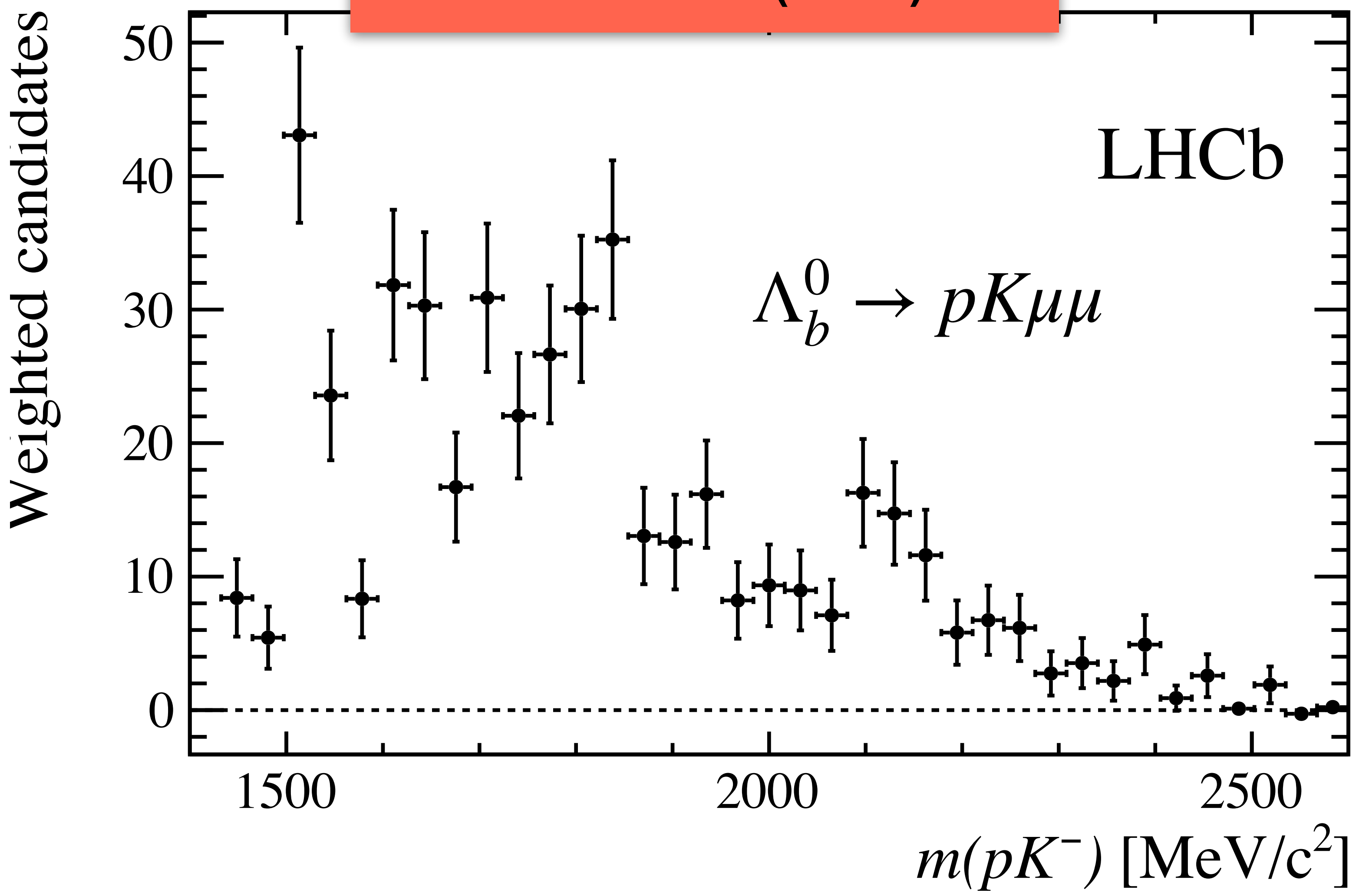


The jungle

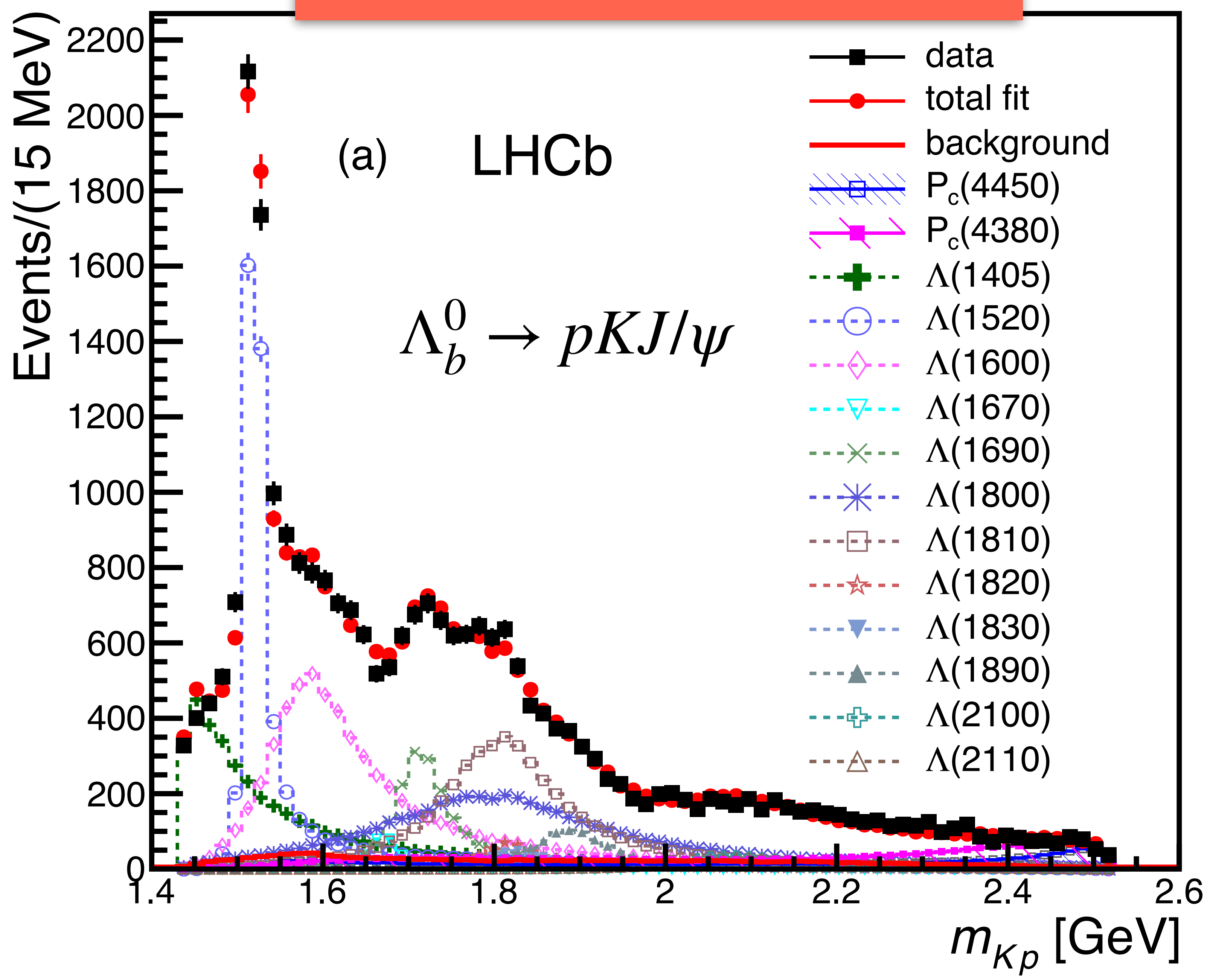
LHCb PRL 131 (2023) 15



LHCb JHEP 05 (2020) 040



LHCb PRL 115 (2015) 072001

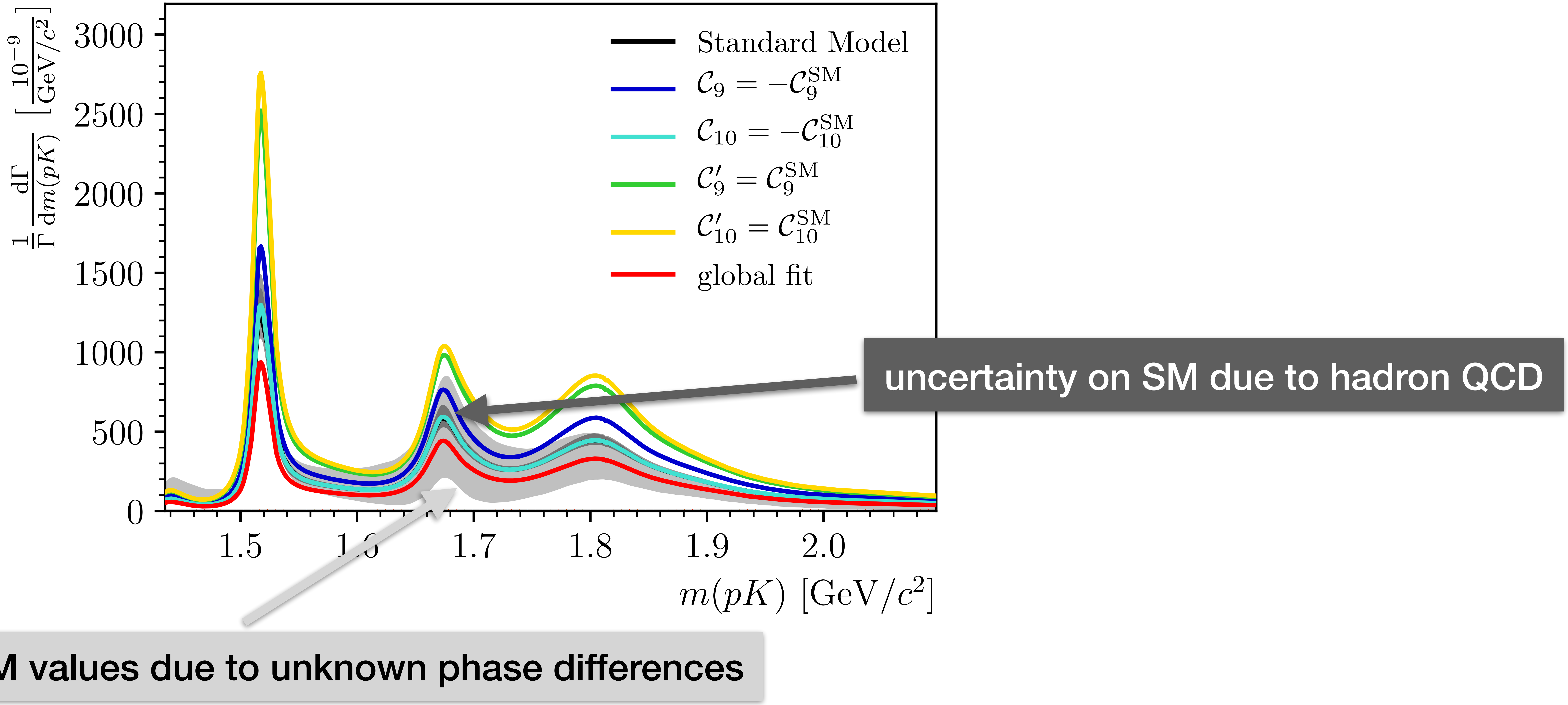


Problem A: hadron QCD is complicated + QCD resonances not fully understood

Problem B: unknown phases between the resonances => unpredictable interference

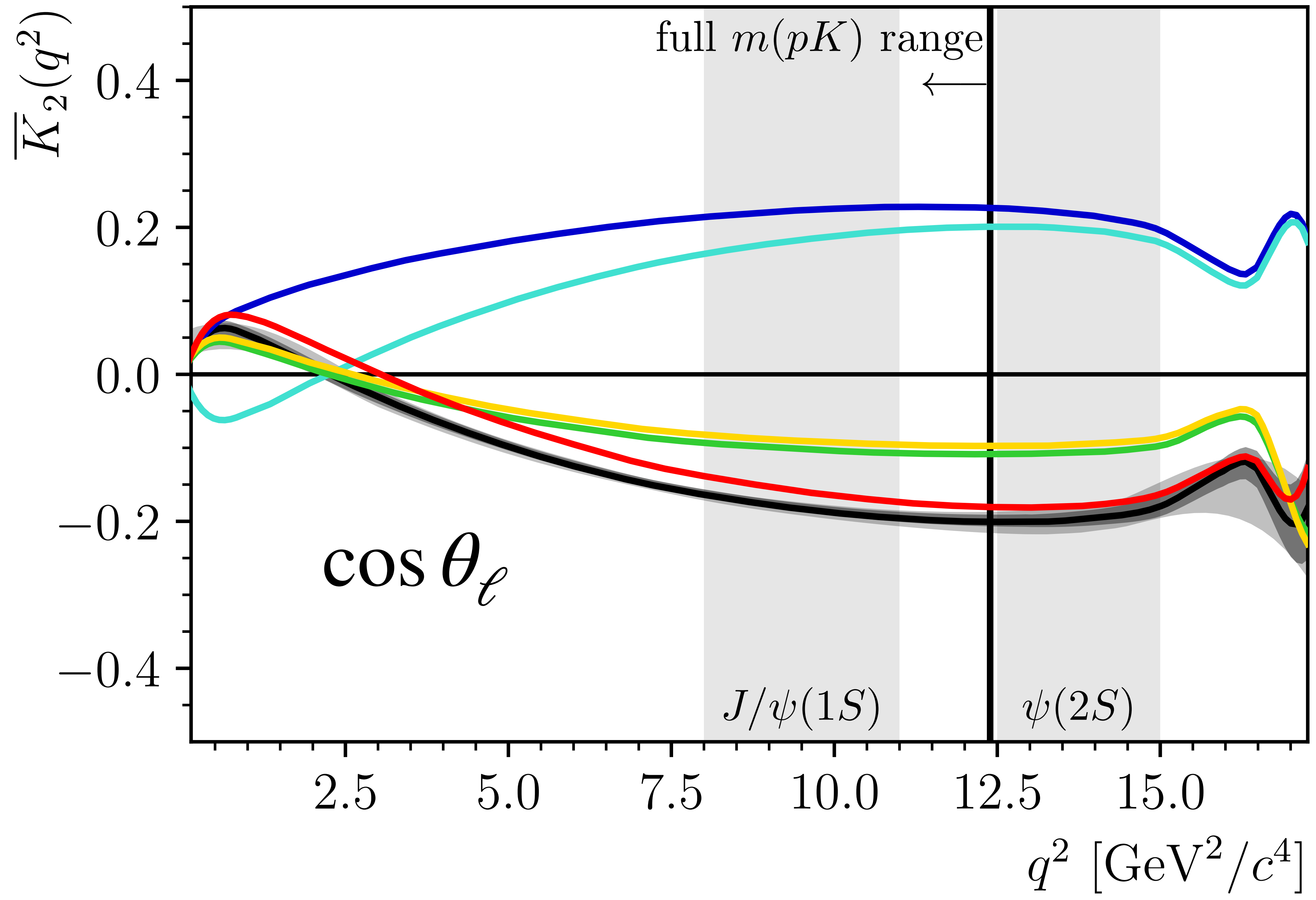
Predictions for BF($\Lambda_b^0 \to pK\mu\mu$)

AB, TB, MK JHEP 02 (2023) 189

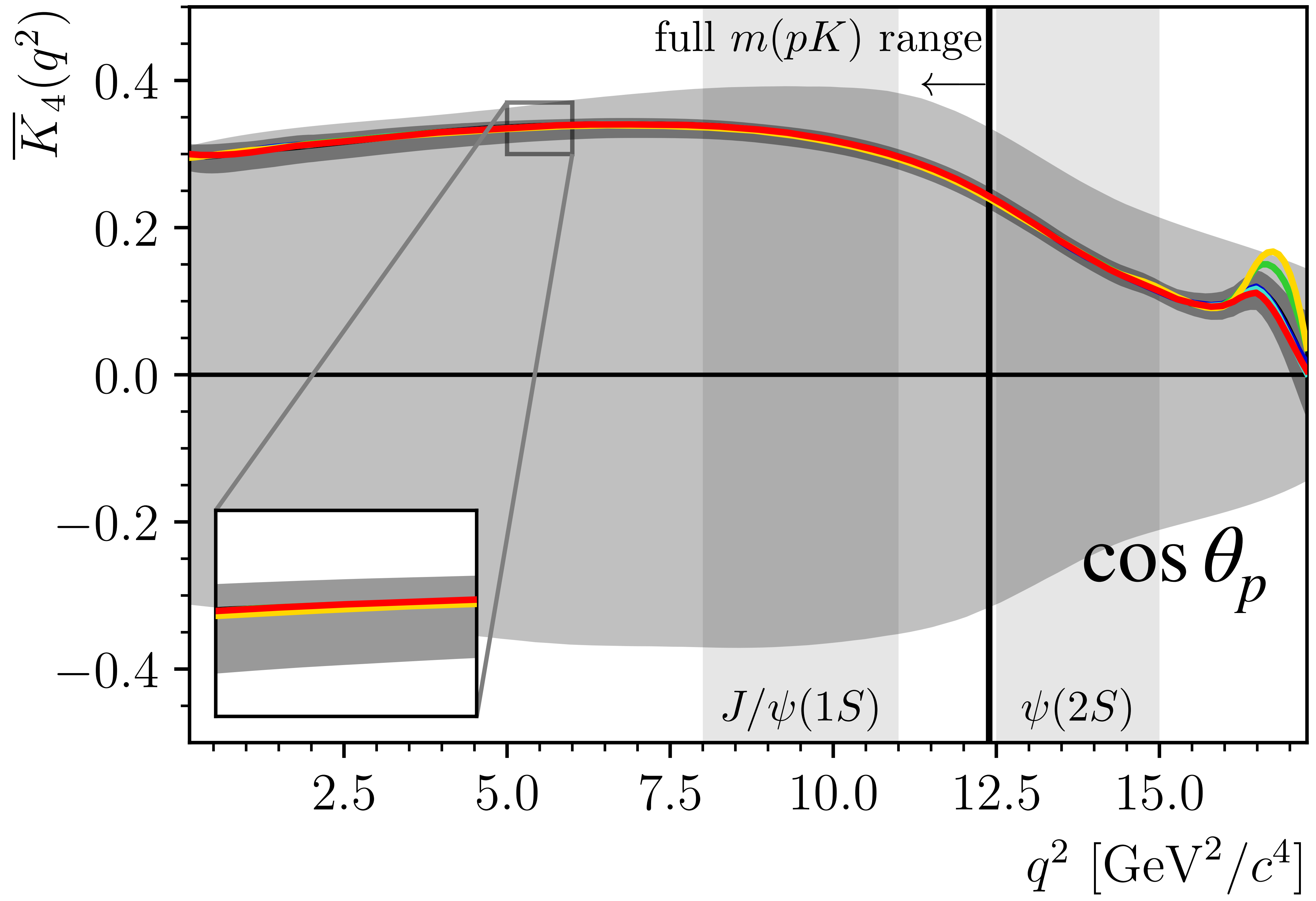


AB, TB, MK JHEP 02 (2023) 189

Predictions for angular observables in $\Lambda_b^0 \to pK\mu\mu$



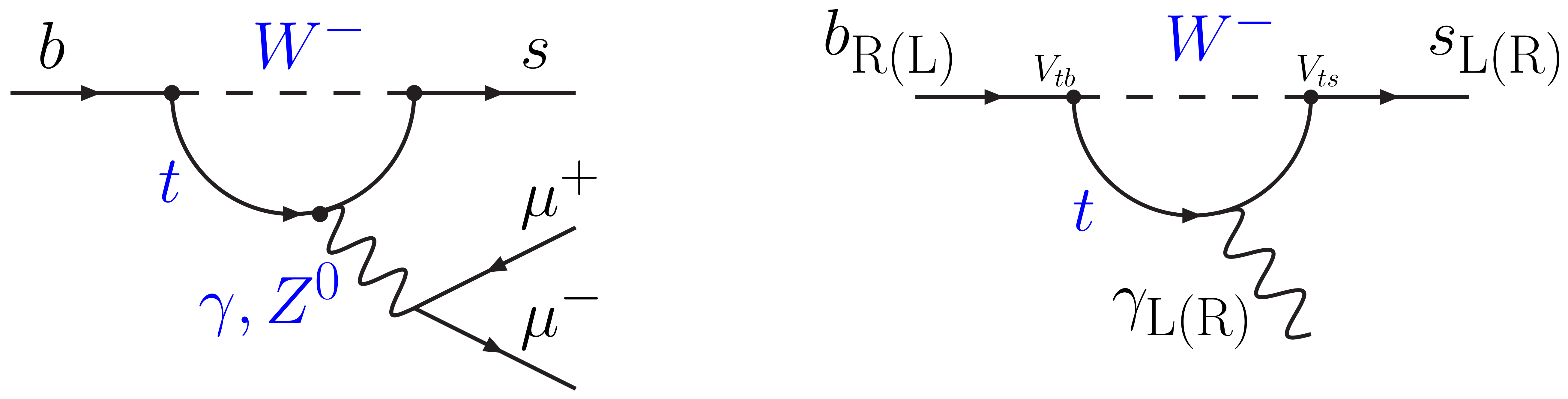
dependence on hadron QCD
and phases mostly cancels



huge dependence on phases,
some dependence on hadron QCD

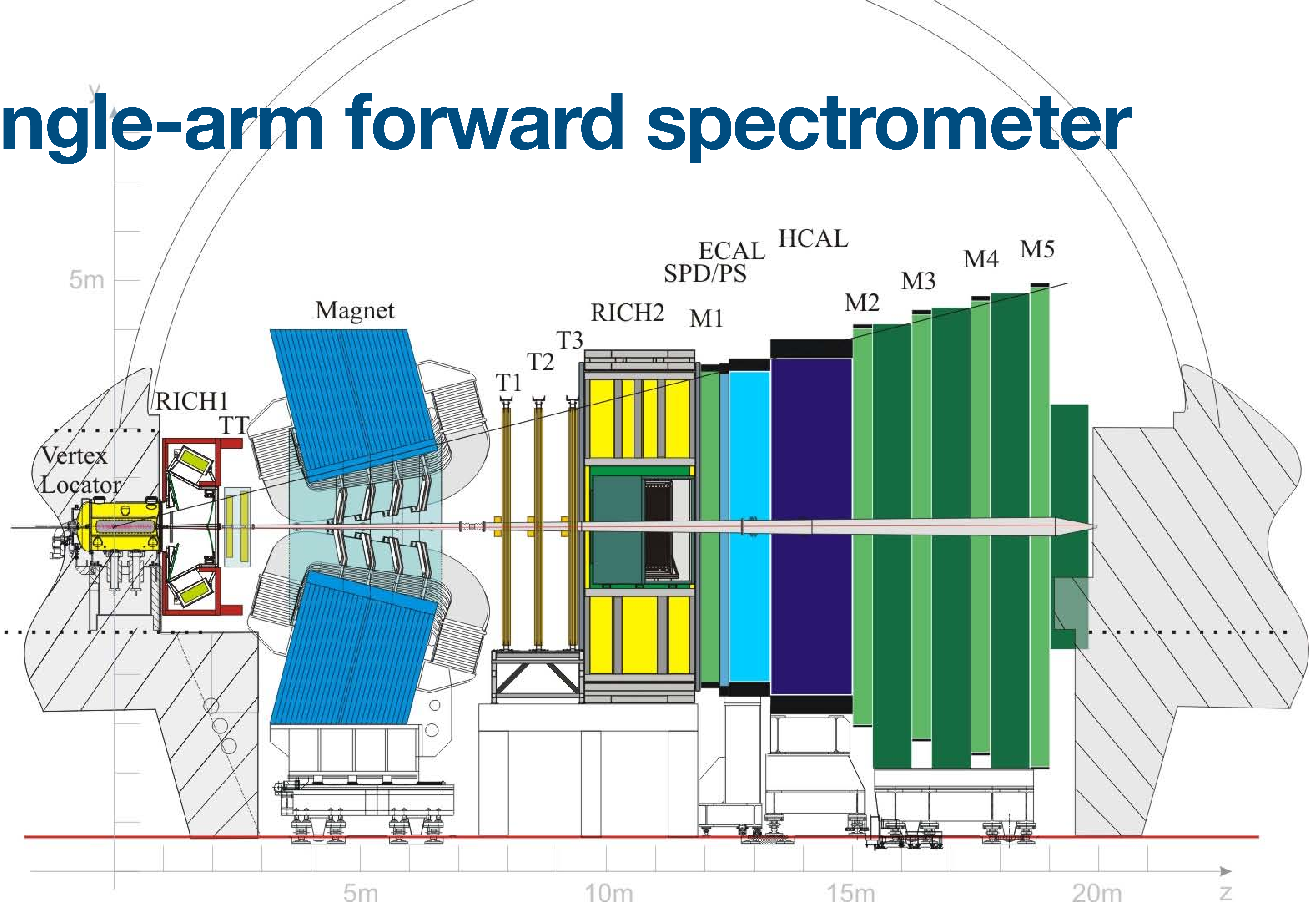
What can we do?

- Focus on single state: $\Lambda(1520)$ (some QCD calculations available) *LHCb* PRL 131 (2023) 15
- Measure the composition in a high-stats mode: $\Lambda_b^0 \to pK\gamma$ *LHCb* PAPER-2023-036 IN PREPARATION



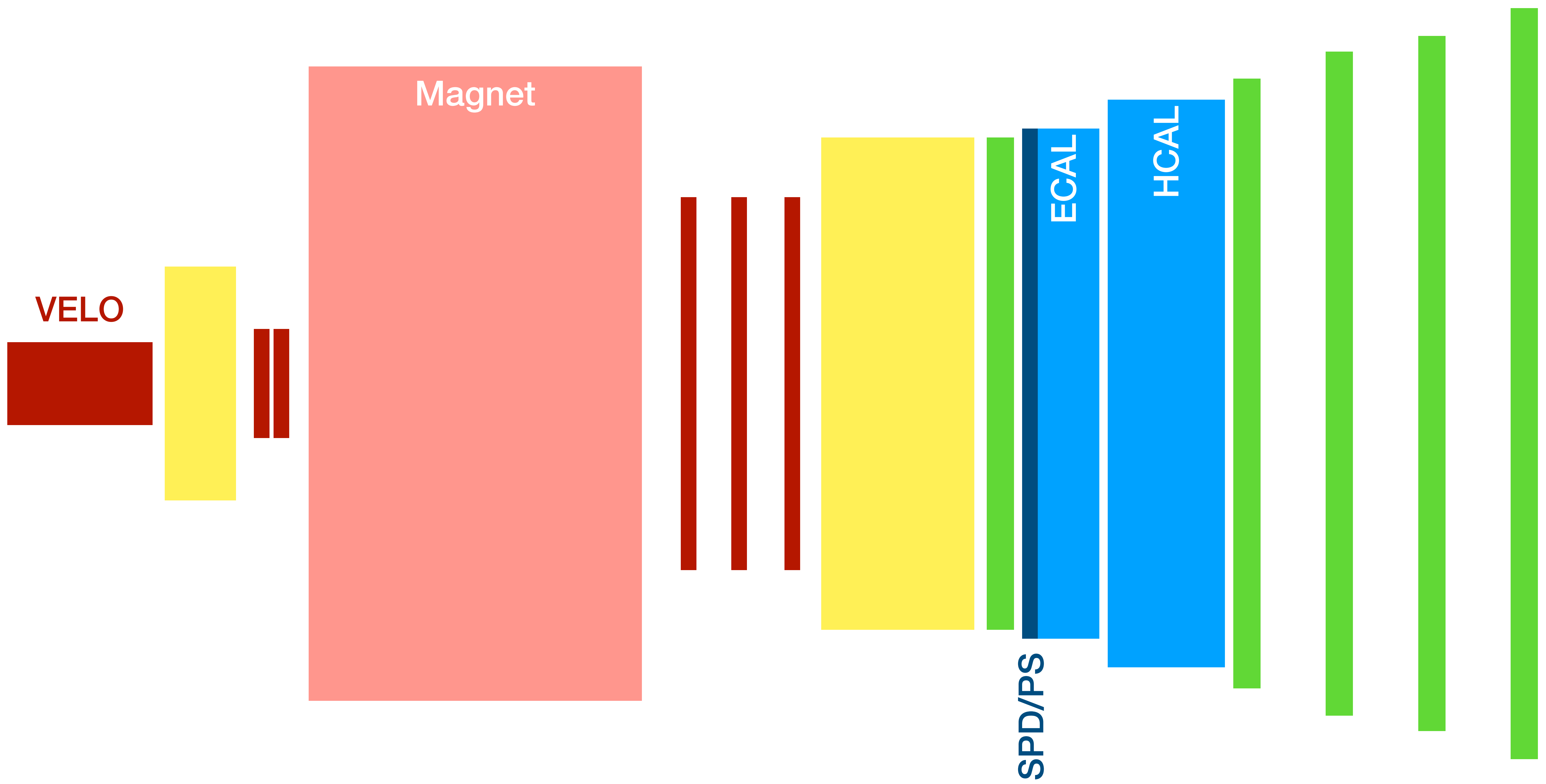
The measurements

Le single-arm forward spectrometer



Le single-arm forward spectrometer

Tracking | Hadron PID (RICH) | Electron/neutral PID | Muon Stations



Le single-arm forward spectrometer

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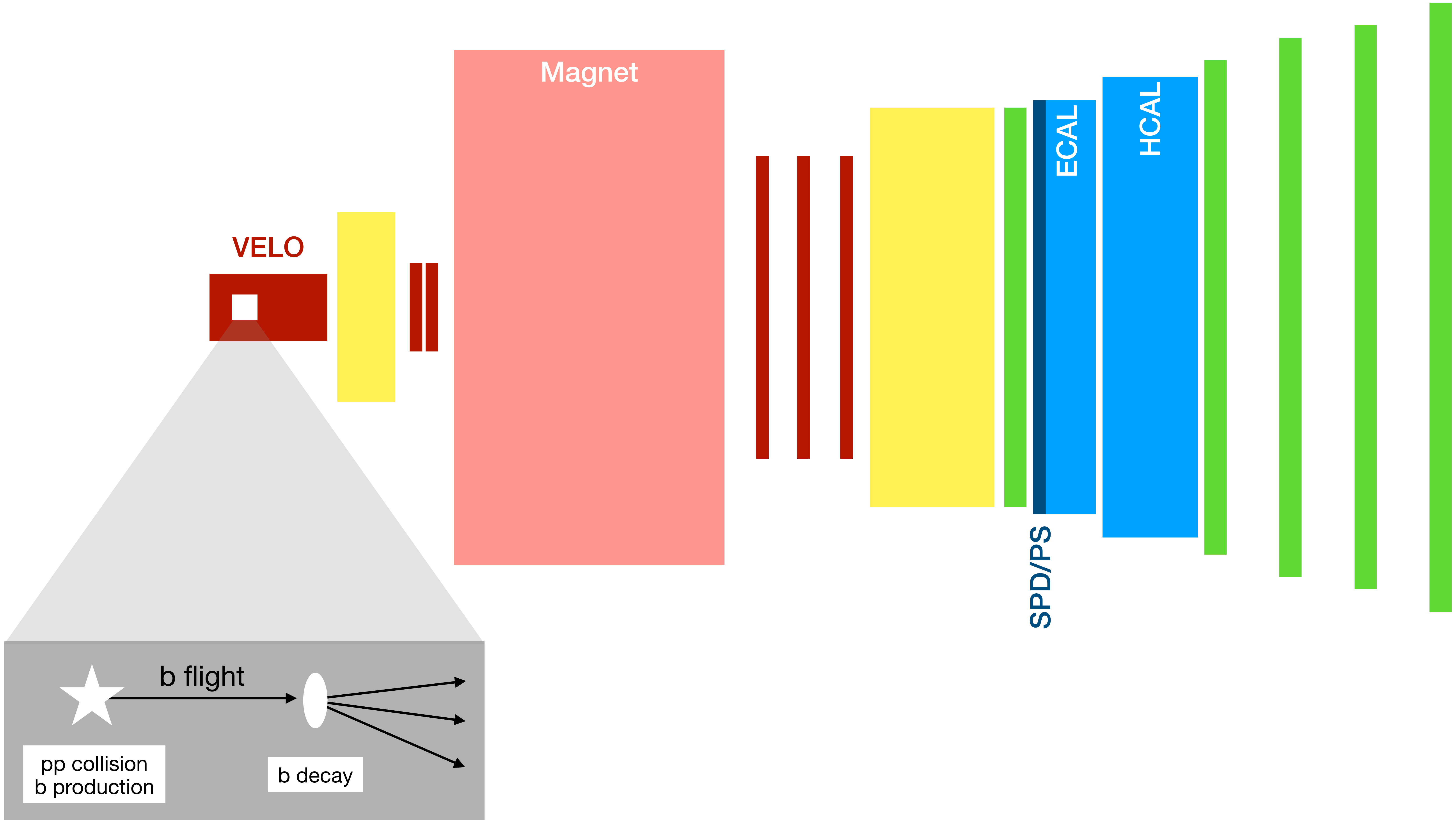

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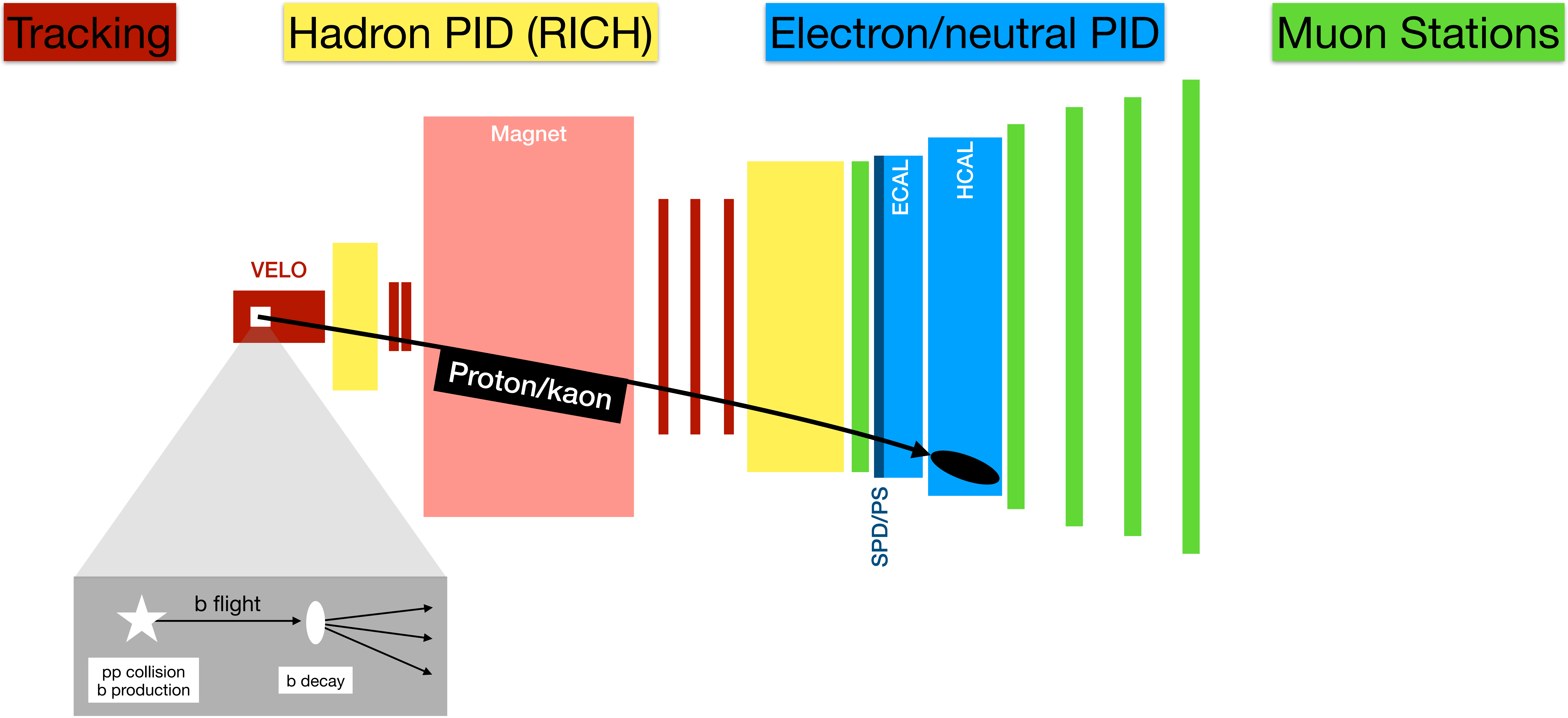

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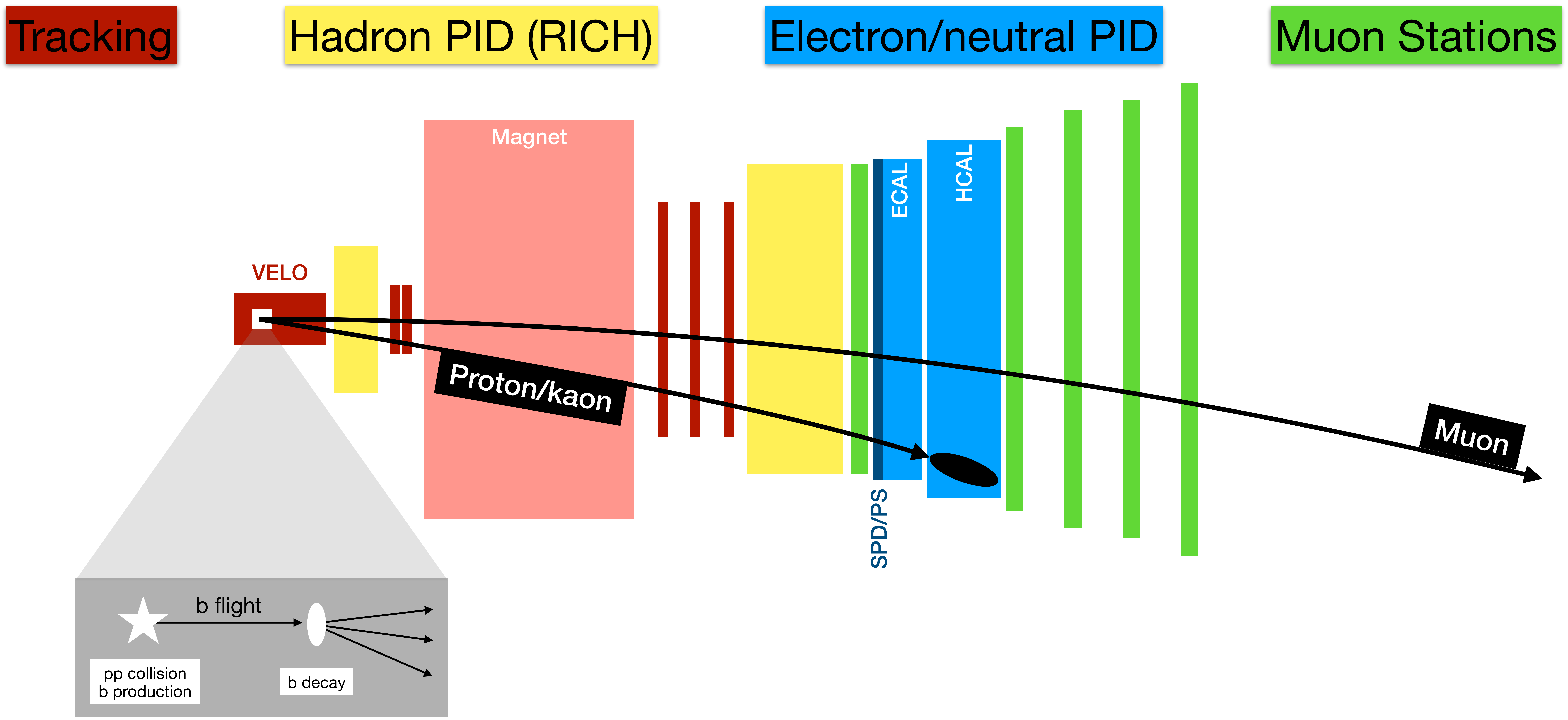

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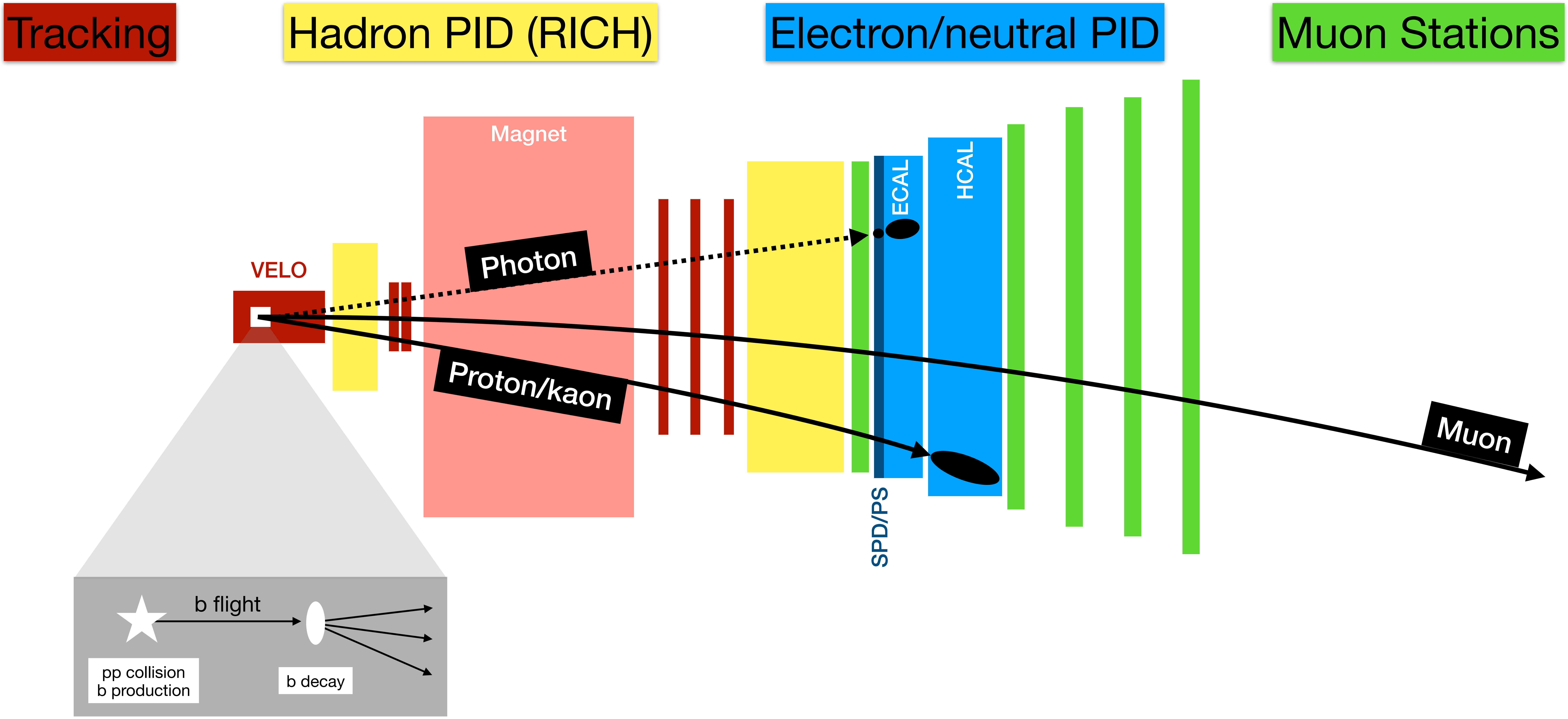


LHCb PRL 131 (2023) 15

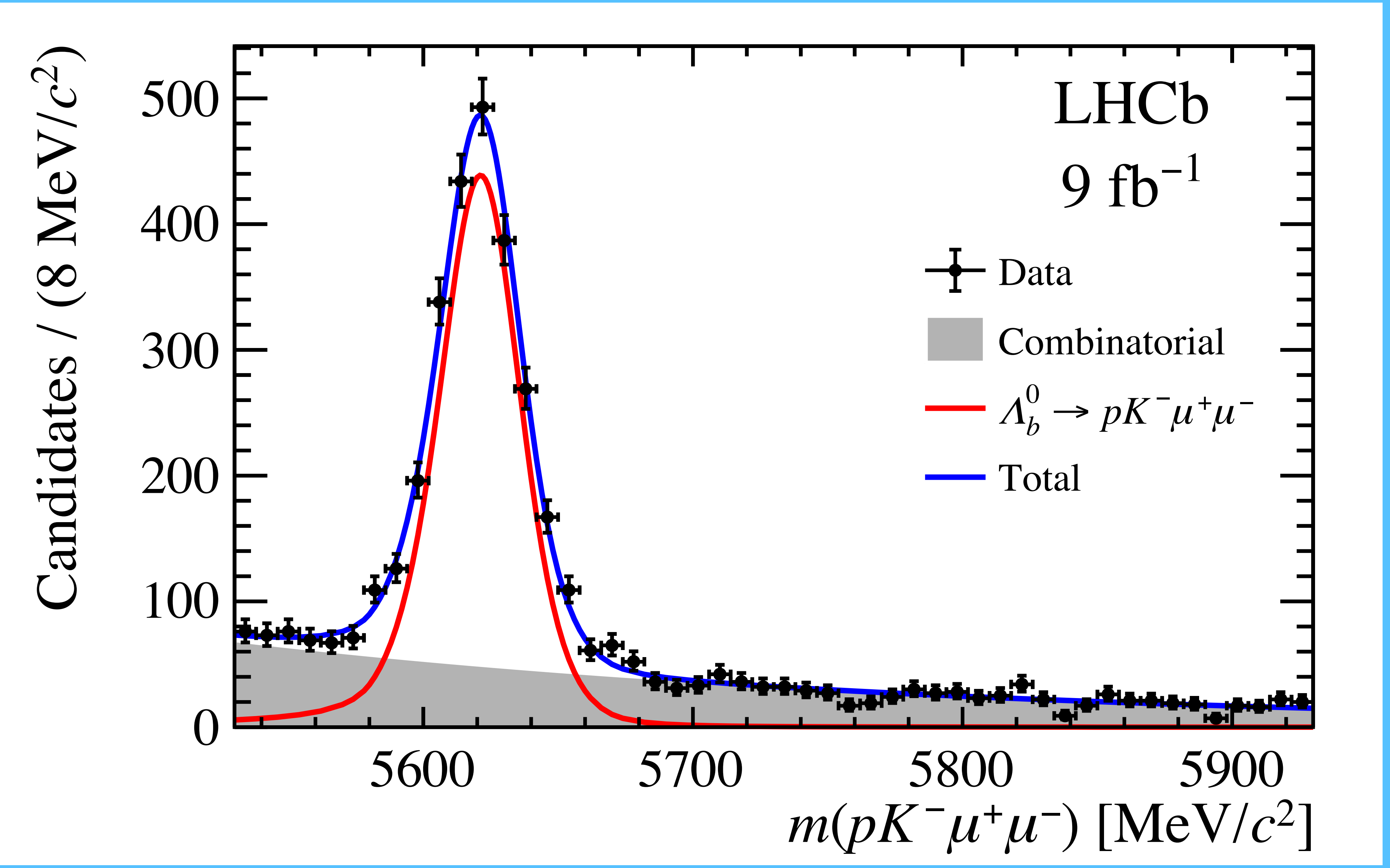
Measurement 1: $\Lambda(1520)$

Extract a single state

LHCb PRL 131 (2023) 15

BF($\Lambda_b^0 \to \Lambda(1520)\mu\mu$)

Separate $\Lambda_b^0 \to pK\mu\mu$ from background



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LHCb PRL 131 (2023) 15

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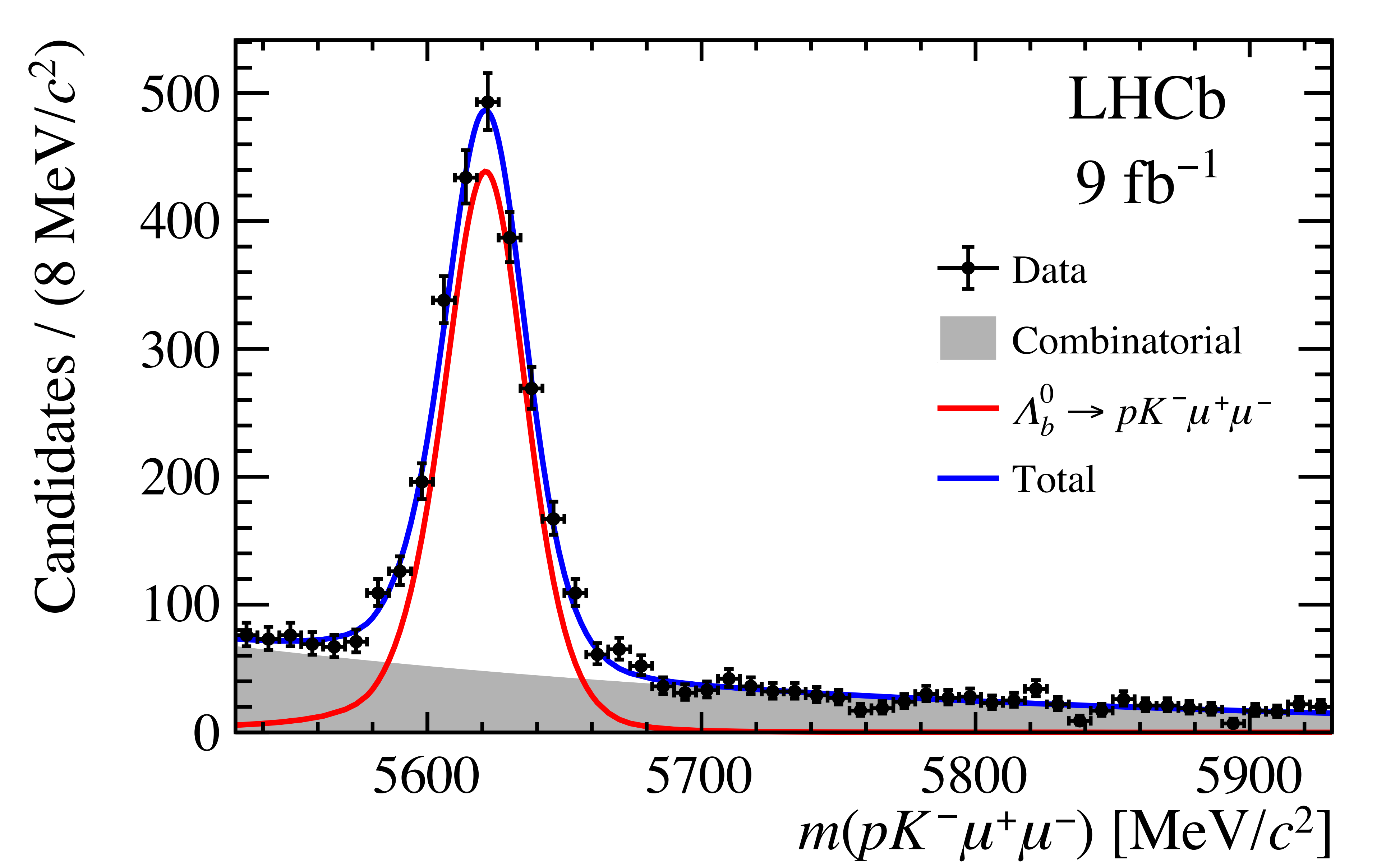
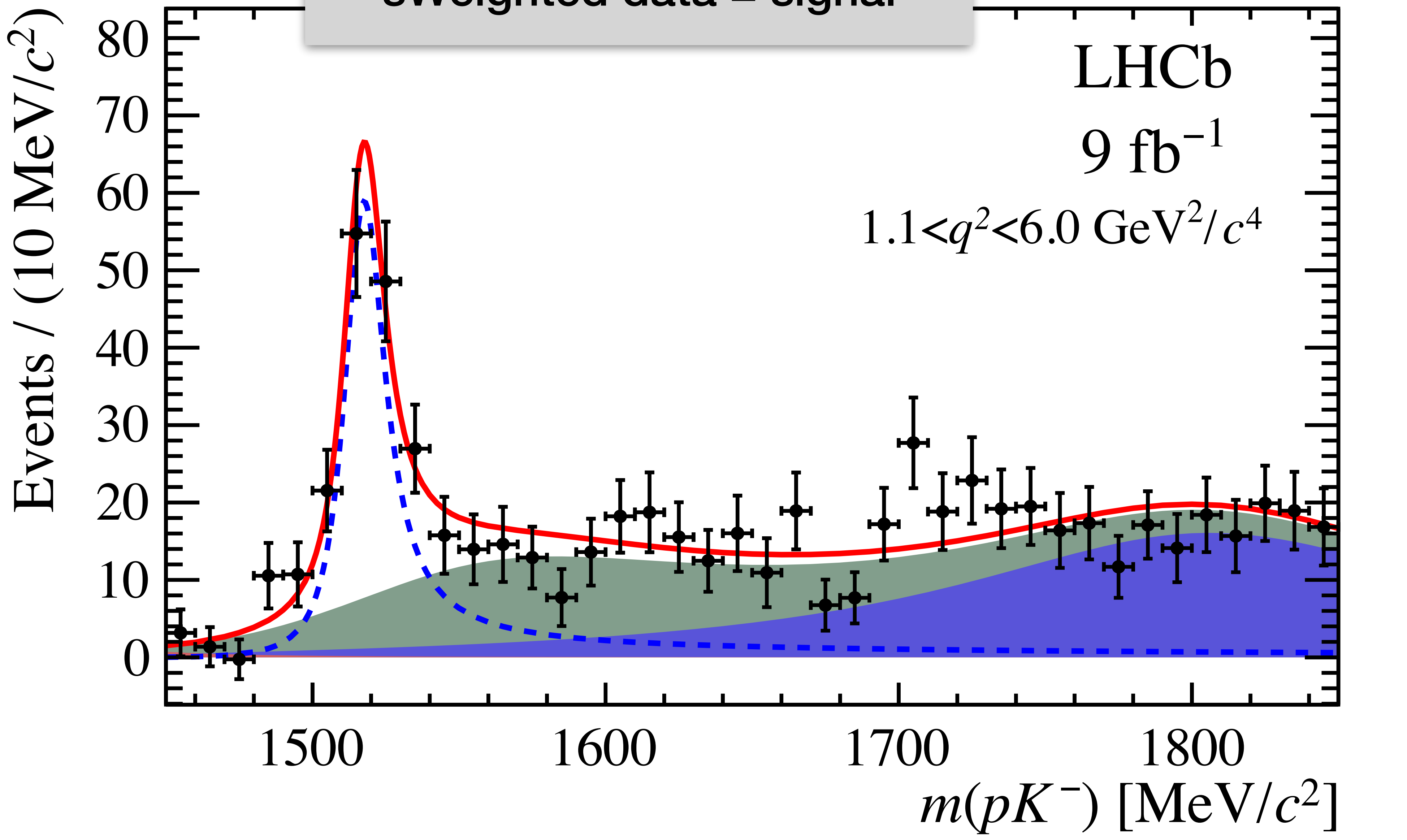


Determine contribution from $\Lambda(1520)$

sWeighted data = signal



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LHCb PRL 131 (2023) 15

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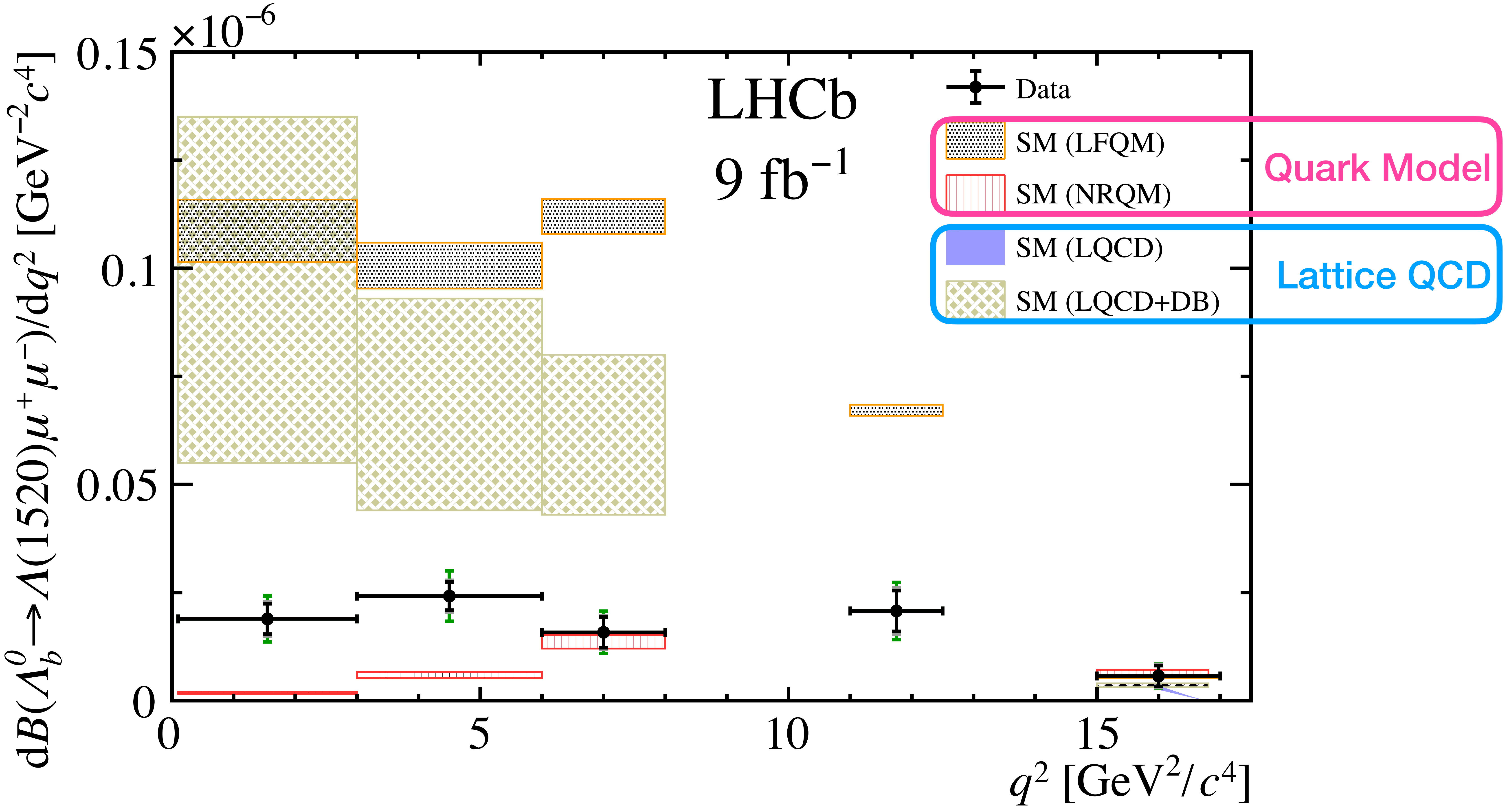

LHCb PAPER-2023-036
IN PREPARATION

Measurement 2: $\Lambda_b^0 \to pK\gamma$

Signal selection and extraction

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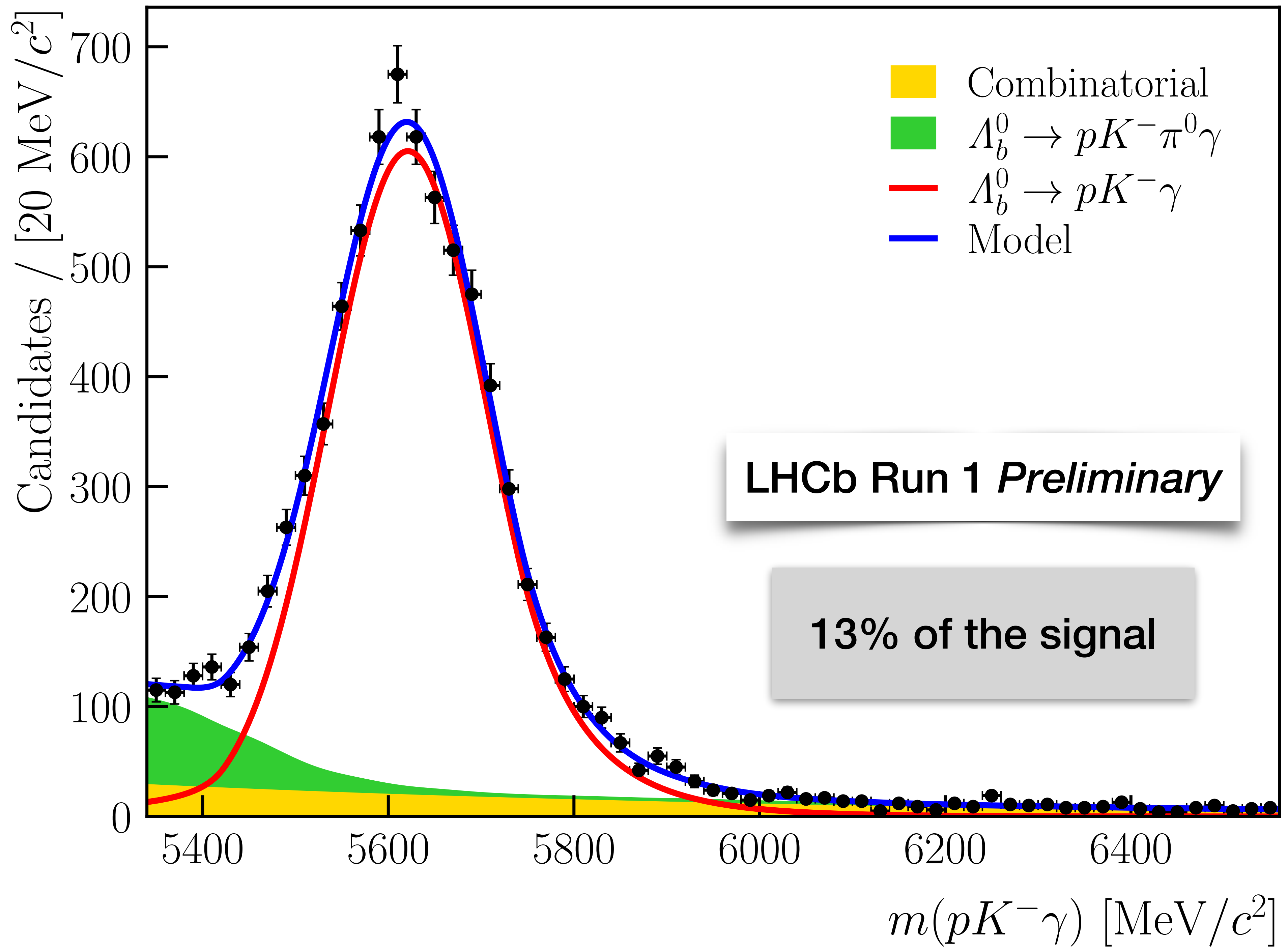
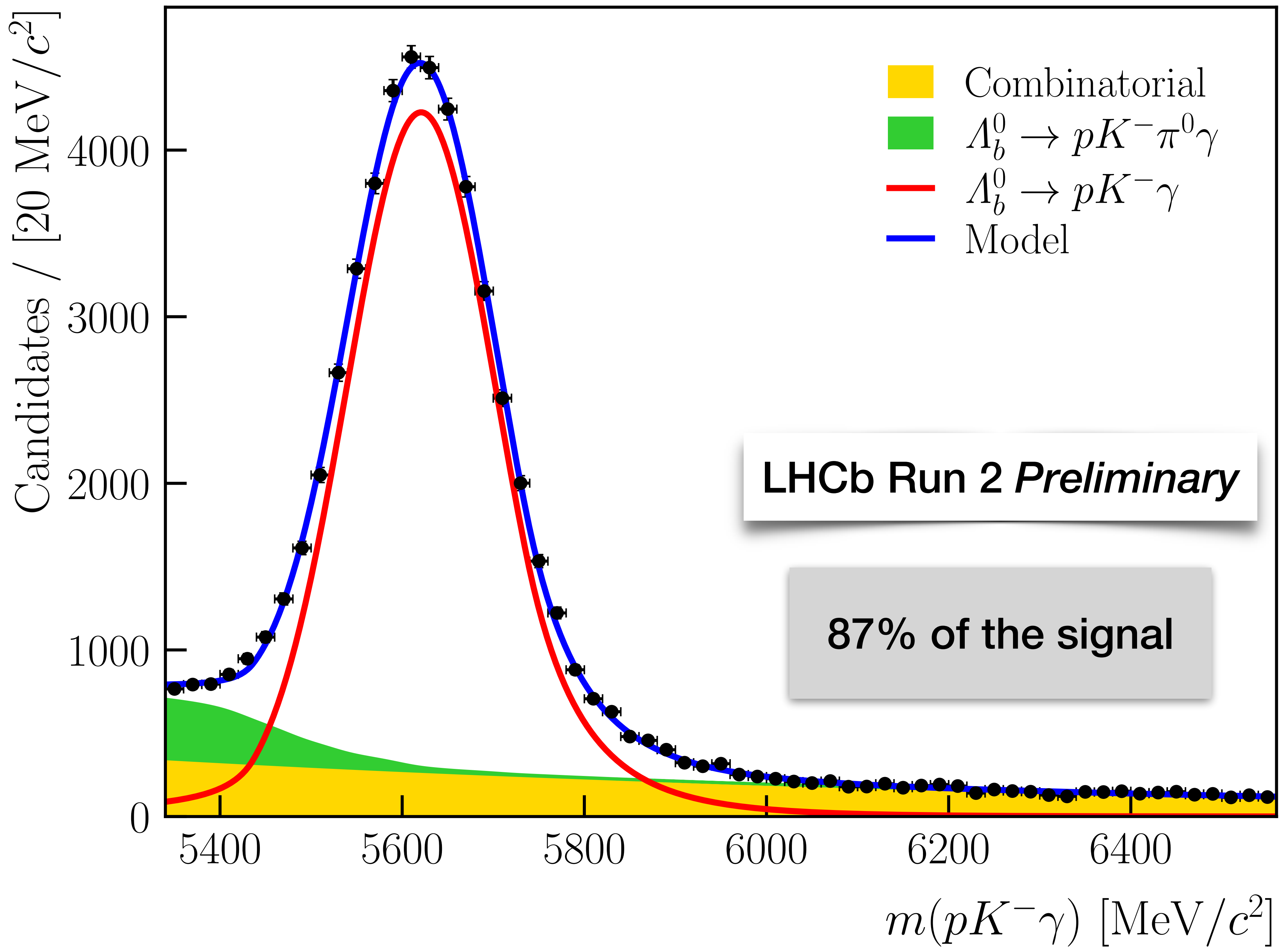
IN PREPARATION

~50k signal candidates

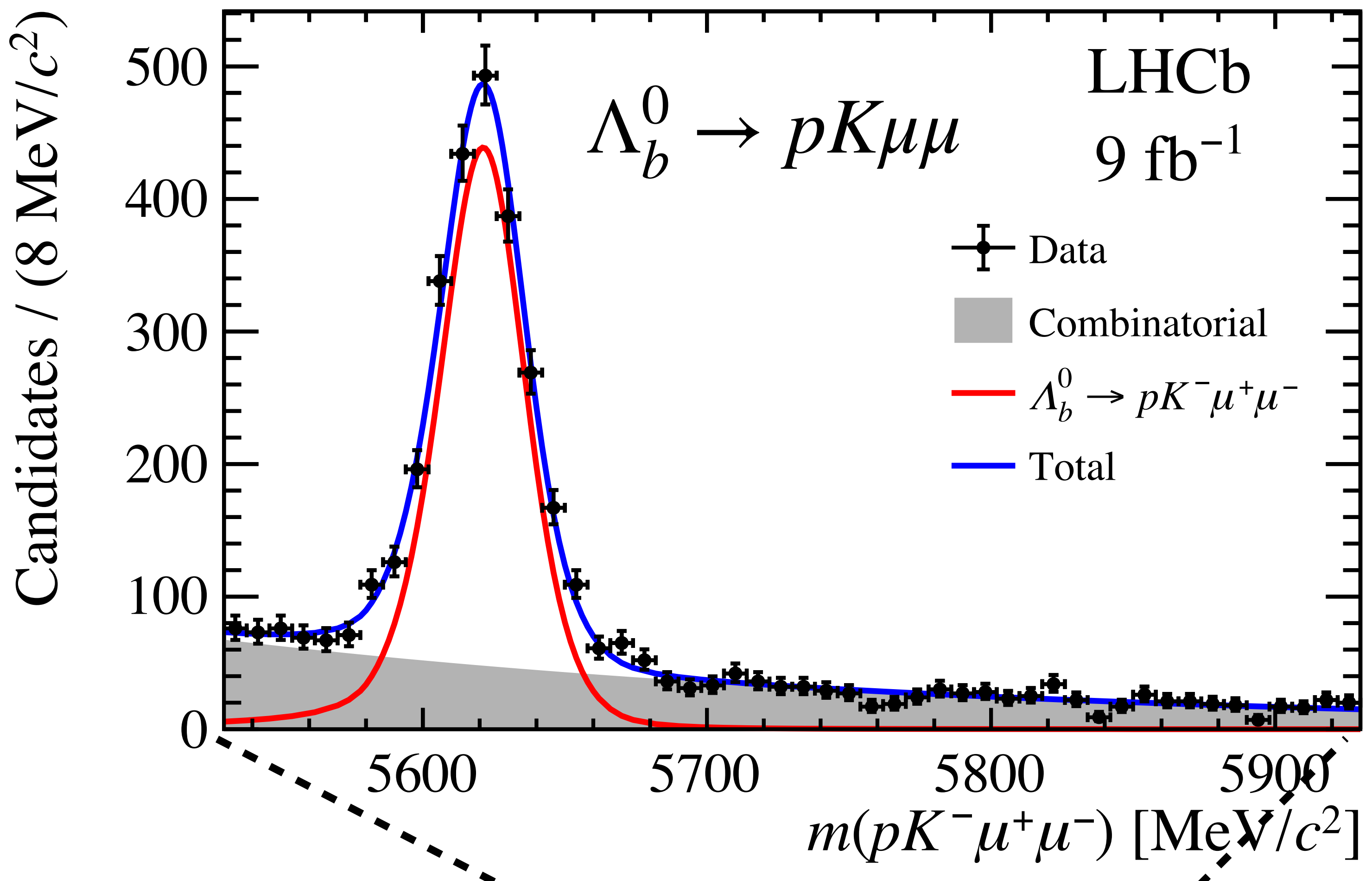




Very different photon HLT2 triggers in Run 1/2

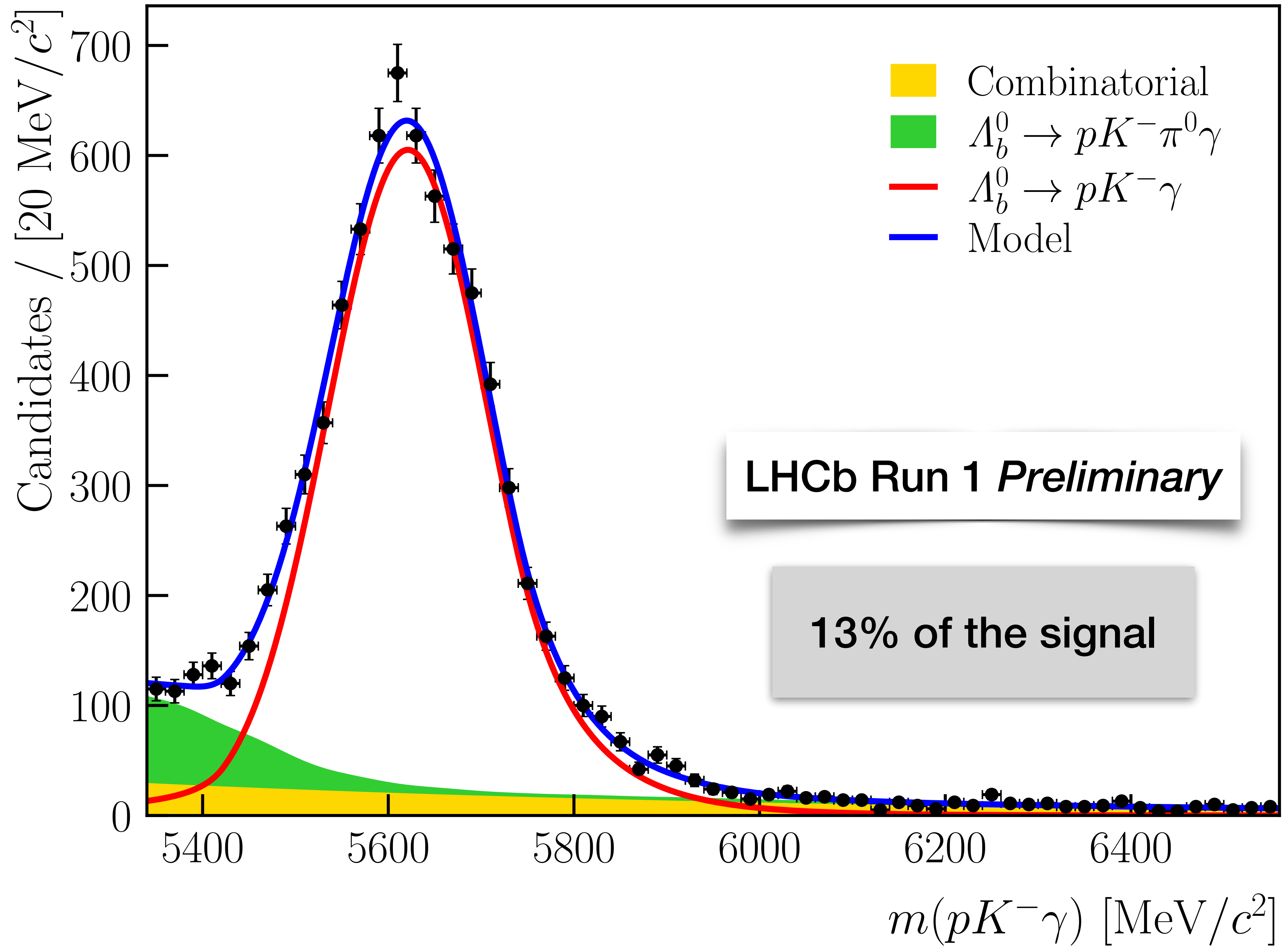
Signal selection and e

~50k signal candidates



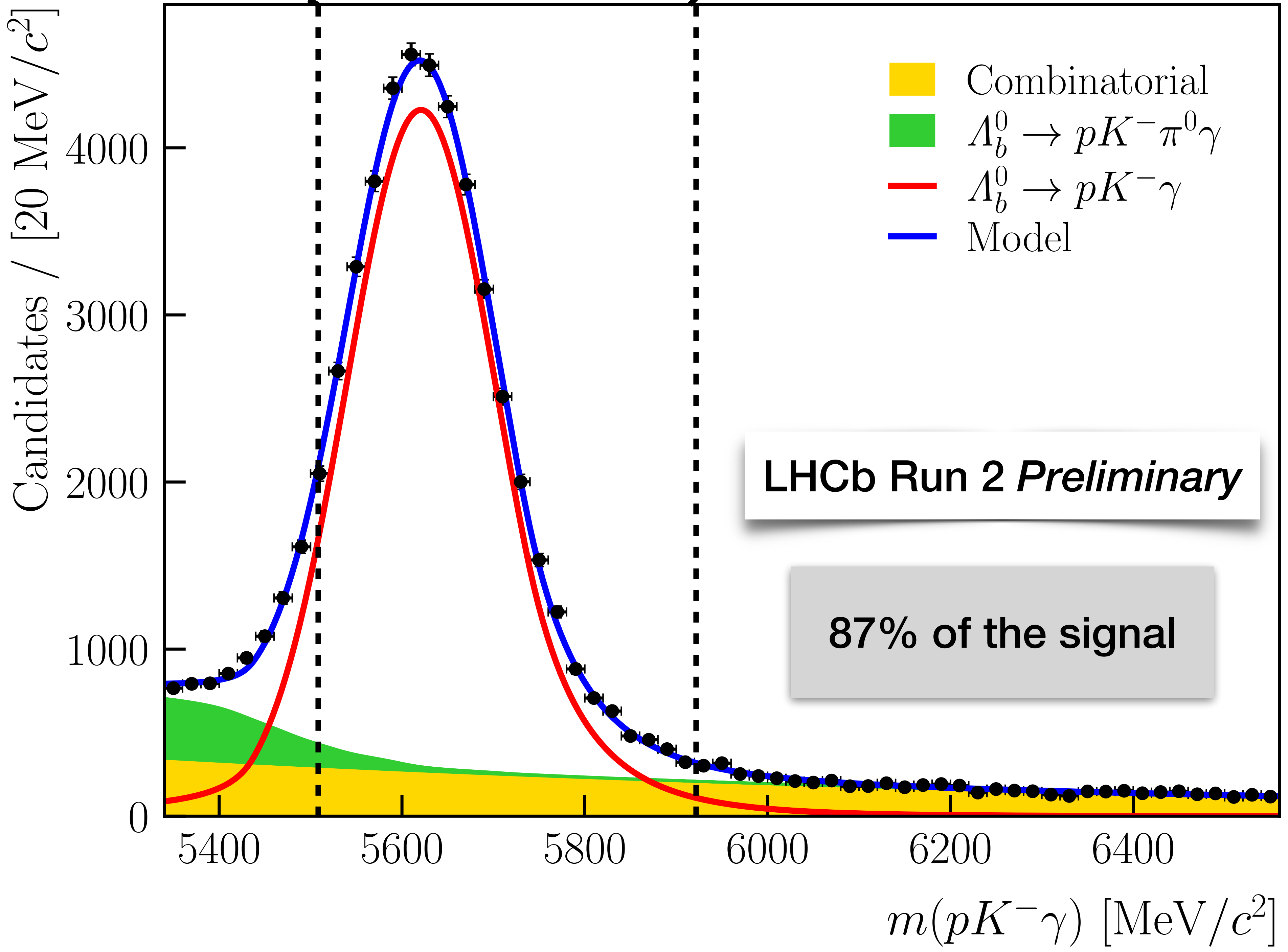
LHCb PAPER-2023-036 IN PREPARATION

FWHM muons
FWHM photon



LHCb Run 1 *Preliminary*

13% of the signal



LHCb Run 2 *Preliminary*

87% of the signal

Very different photon HLT2 triggers in Run 1/2

The signal distribution

LHCb PAPER-2023-036
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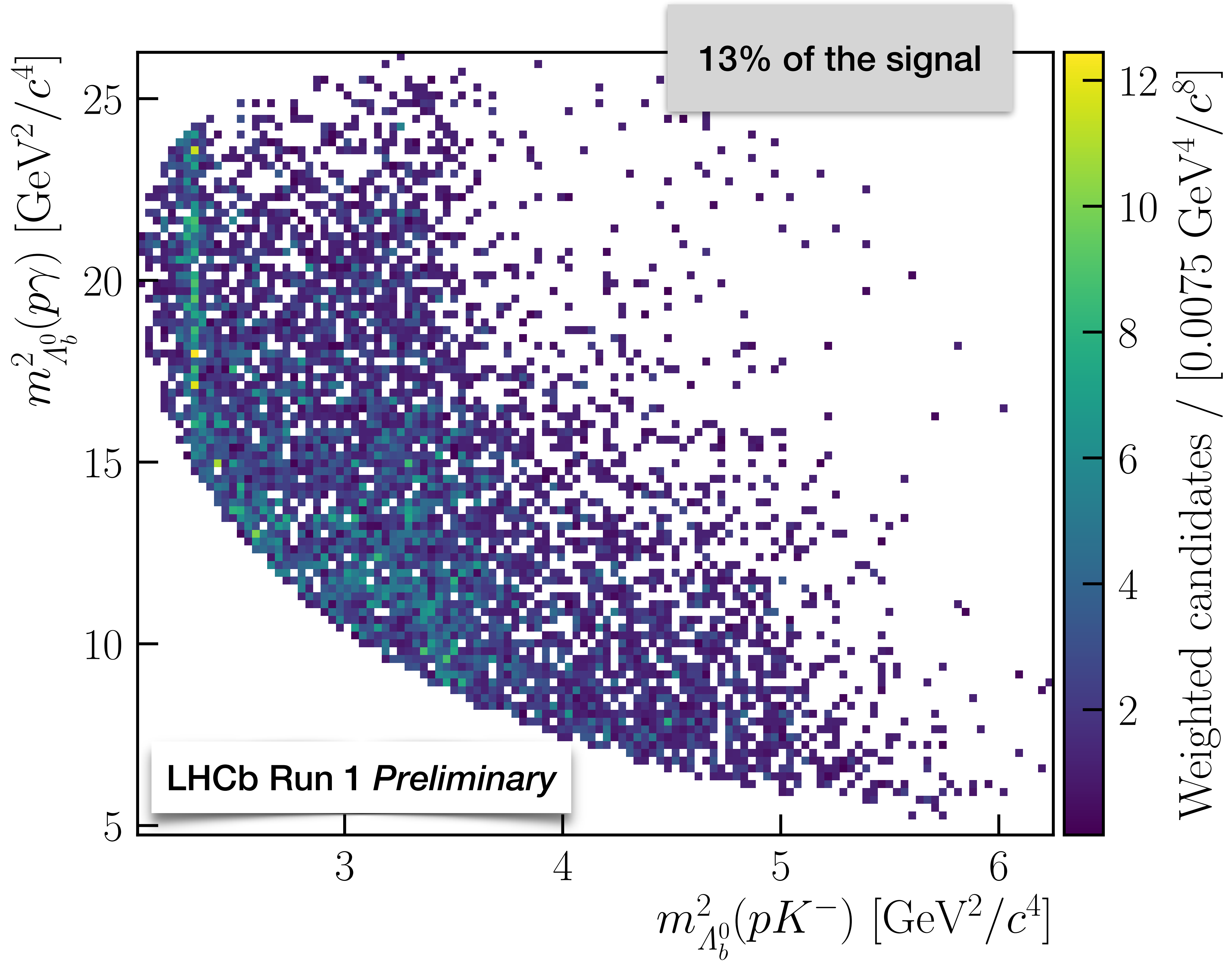
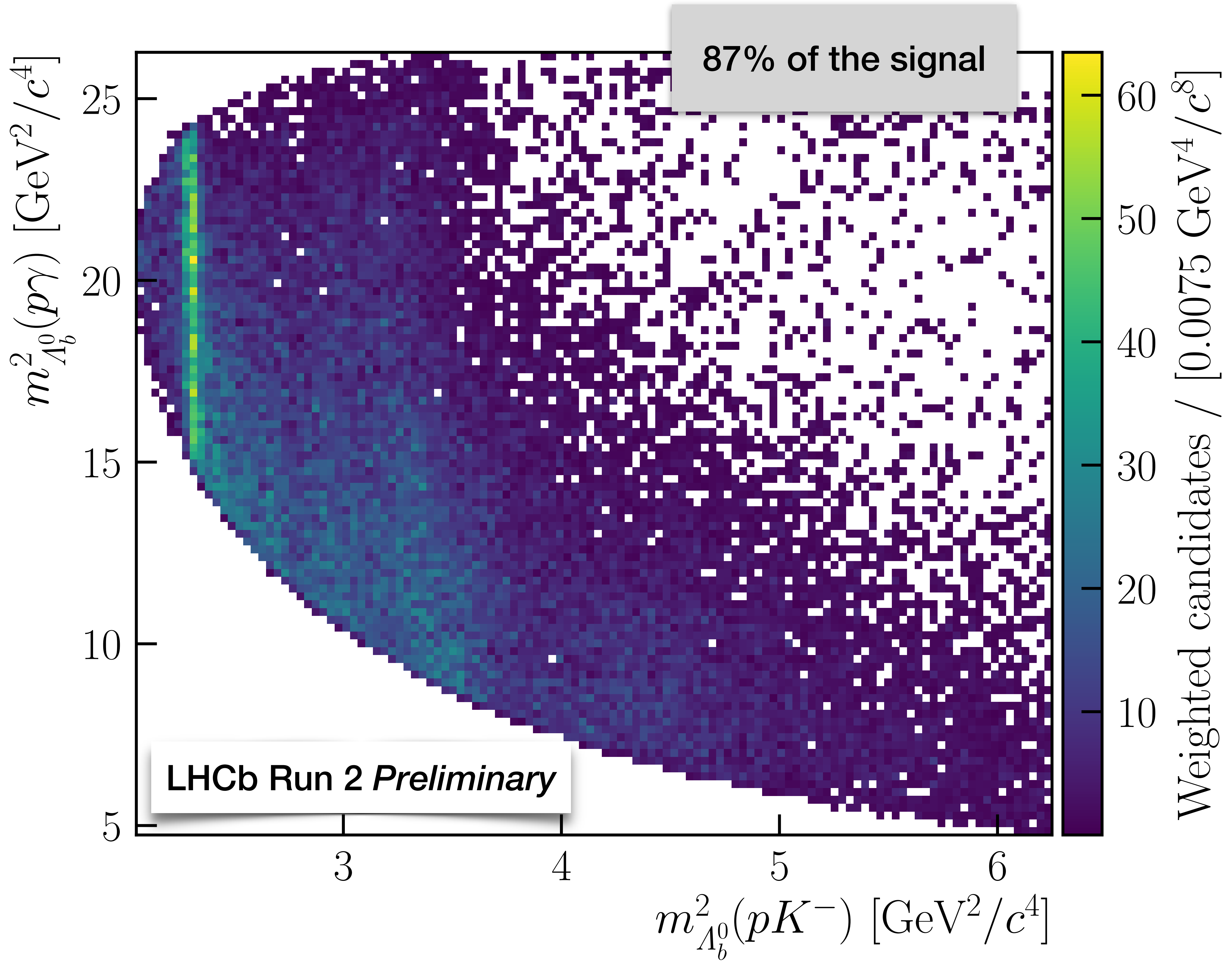


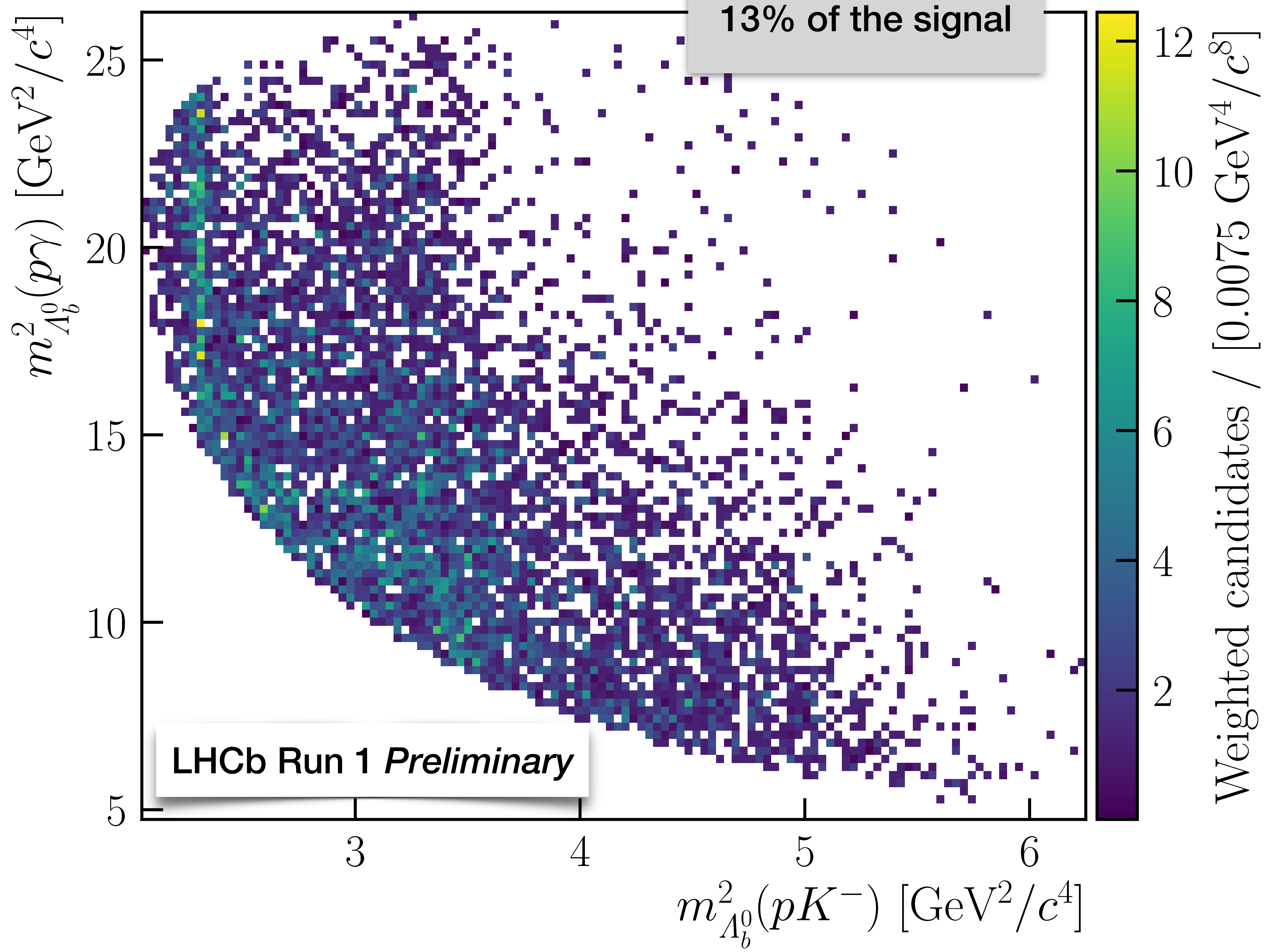


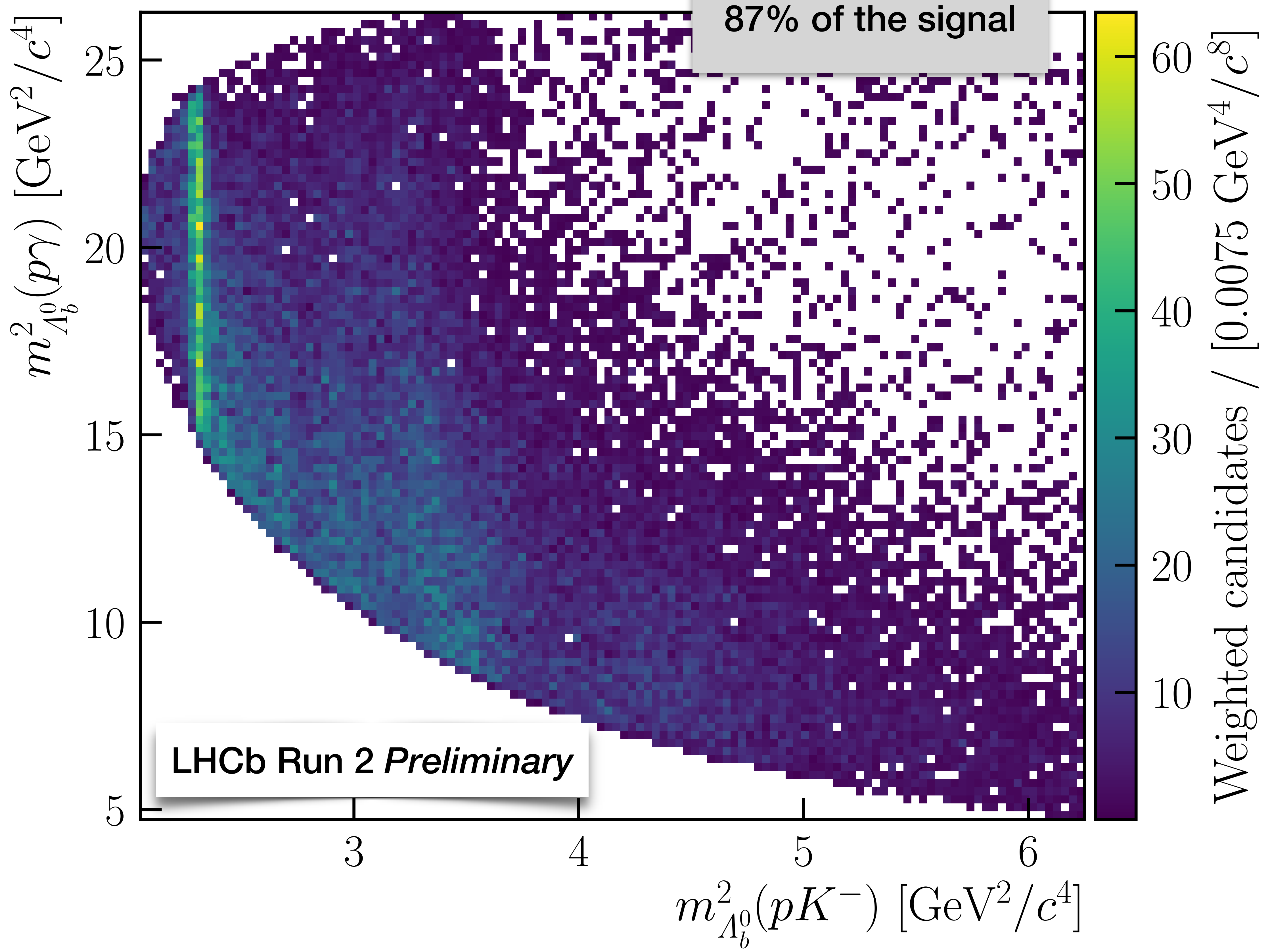
Very different photon HLT2 triggers in Run 1/2

The signal distribution

Improved resolution by fixing $m(pK\gamma)$ to the true Λ_b^0 mass in the vertex fit

LHCb PAPER-2023-036 IN PREPARATION





Very different photon HLT2 triggers in Run 1/2

Amplitude model from the helicity formalism

JA, YA, AB, CM JHEP 06 (2020) 116

Amplitude for a given Λ state and fixed helicities $\lambda_\Lambda, \lambda_p, \lambda_\gamma$

$$\mathcal{A}(\Lambda, \lambda_\Lambda, \lambda_p, \lambda_\gamma) \propto \underbrace{d^{J_\Lambda}_{\lambda_p \lambda_\Lambda}(\theta_p)}_{\text{Wigner d matrix}} \times \sum_{L,S} \left[\underbrace{C_1^{\Lambda\gamma} C_2^{\Lambda\gamma} C_1^{pK^-} C_2^{pK^-}}_{\text{Clebsch-Gordans}} \underbrace{A_{LS}}_{\text{coupling}} \underbrace{\left(\frac{p}{M_{\Lambda_b^0}}\right)^L \left(\frac{q}{M_\Lambda}\right)^\ell}_{\text{orb. ang. mom. barriers}} \underbrace{B_L(p) B_\ell(q)}_{\text{Blatt-Weisskopf form factors}} \underbrace{\mathrm{BW}(m_{pK})}_{\text{lineshape}} \right]$$

Full decay rate depending on the Dalitz variables $\mathcal{D} = (\cos\theta_p, m_{pK}) \equiv (m^2_{pK}, m^2_{p\gamma})$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\mathcal{D}} \propto \sum_{\lambda_p, \lambda_\gamma} \left| \sum_{\Lambda} \sum_{\lambda_\Lambda} \mathcal{A}(\Lambda, \lambda_\Lambda, \lambda_p, \lambda_\gamma) \right|^2$$

10+ resonances x 2 or 4 complex couplings per resonance
= *ouch* amount of unconstrained fit parameters

=> remove parameters by remove couplings with large L

The well-known part of the jungle

Resonance	J^P	m_0	Γ_0	Δm_0	$\Delta\Gamma_0$	σ_{m_0}	σ_{Γ_0}	l	L
$\Lambda(1405)$	$1/2^-$	1405	50.5	±1.3	±2	1.3	2	0	0, 1
$\Lambda(1520)$	$3/2^-$	1519	16	1518 – 1520	15 – 17	1	1	2	0, 1, 2
$\Lambda(1600)$	$1/2^+$	1600	200	1570 – 1630	150 – 250	30	50	1	0, 1
$\Lambda(1670)$	$1/2^-$	1674	30	1670 – 1678	25 – 35	4	5	0	0, 1
$\Lambda(1690)$	$3/2^-$	1690	70	1685 – 1695	50 – 70	5	10	2	0, 1, 2
$\Lambda(1800)$	$1/2^-$	1800	200	1750 – 1850	150 – 250	50	50	0	0, 1
$\Lambda(1810)$	$1/2^+$	1790	110	1740 – 1840	50 – 170	50	60	1	0, 1
$\Lambda(1820)$	$5/2^+$	1820	80	1815 – 1825	70 – 90	5	10	3	1, 2, 3
$\Lambda(1830)$	$5/2^-$	1825	90	1820 – 1830	60 – 120	5	30	2	1, 2, 3
$\Lambda(1890)$	$3/2^+$	1890	120	1870 – 1910	80 – 160	20	40	1	0, 1, 2
$\Lambda(2100)$	$7/2^-$	2100	200	2090 – 2110	100 – 250	10	100	4	2, 3, 4
$\Lambda(2110)$	$5/2^+$	2090	250	2050 – 2130	200 – 300	40	50	3	1, 2, 3
$\Lambda(2350)$	$9/2^+$	2350	150	2340 – 2370	100 – 250	20	100	5	3, 4, 5

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Rich spin (= angular) structures

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$\Lambda(1820)$	$5/2^+$	1820	80	1815 – 1825	70 – 90	5	10	3	1, 2, 3
$\Lambda(1830)$	$5/2^-$	1825	90	1820 – 1830	60 – 120	5	30	2	1, 2, 3
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The ~~well~~-known part of the jungle

Rich spin (= angular) structures

Poorly known resonance parameters

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The amplitude fit

Setup

Simultaneous maximum likelihood fit to Run 1/2

Floating couplings, fixed masses/widths

Complicated likelihood with ambiguities and many local minima

Different starting values lead to

- similar NLL
- very different fitted parameters
- similar fit fractions (= relative amount of each resonance)

=> Fit several times with randomized starting values

=> keep the one with the lowest NLL

=> Use the fit fractions as observables NOT the fit parameters (= couplings)

How to find your favourite model

Step 1) find a minimal good model

a. start from all well-established resonances in the PDG
b. remove large orb. ang. momenta L until the fit gets worse

Step 2) modify the model

a. add new states
b. modify the resonance models

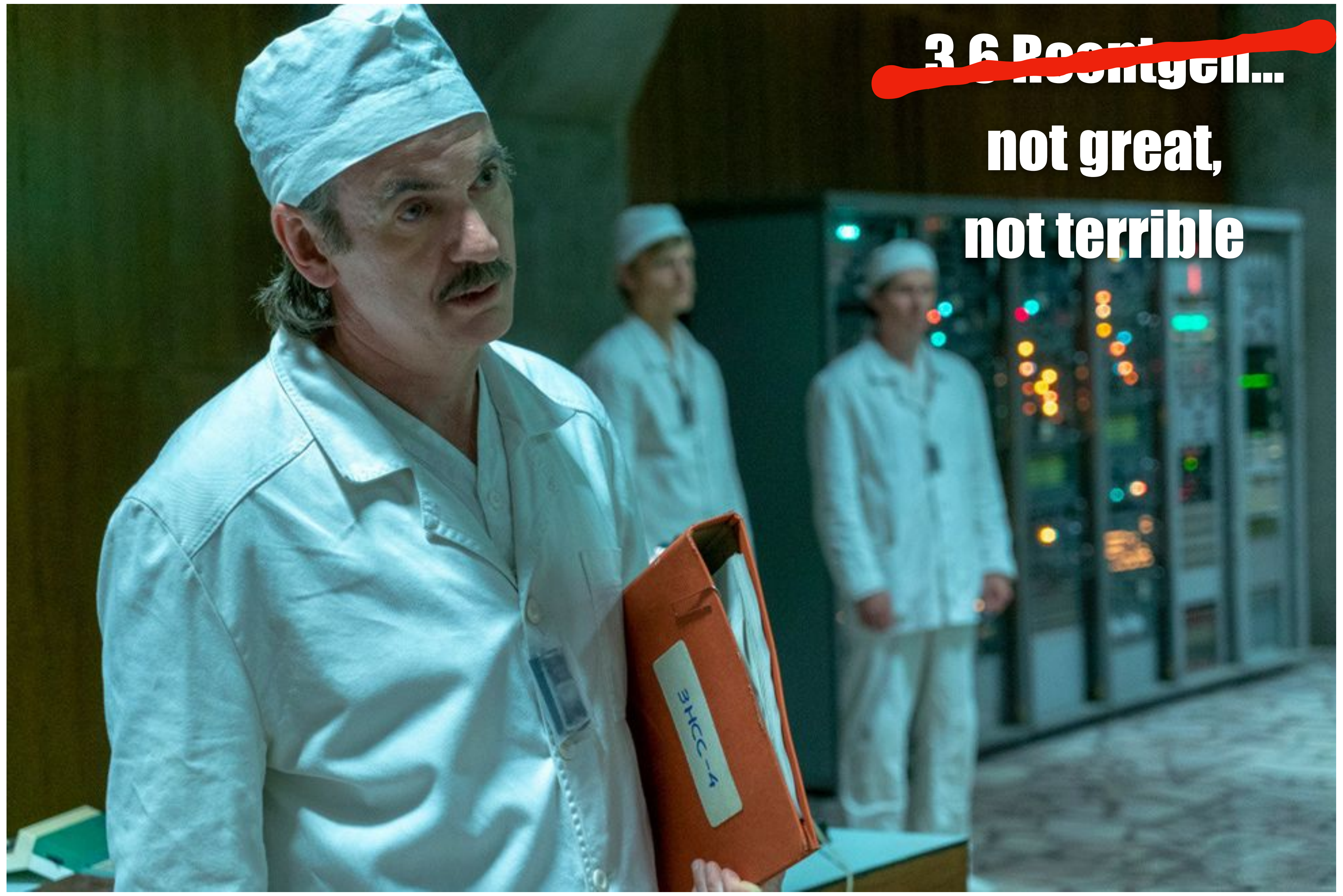
The fit quality

χ^2 distance between the 2D Dalitz histogram of data and fit result

The smallest model

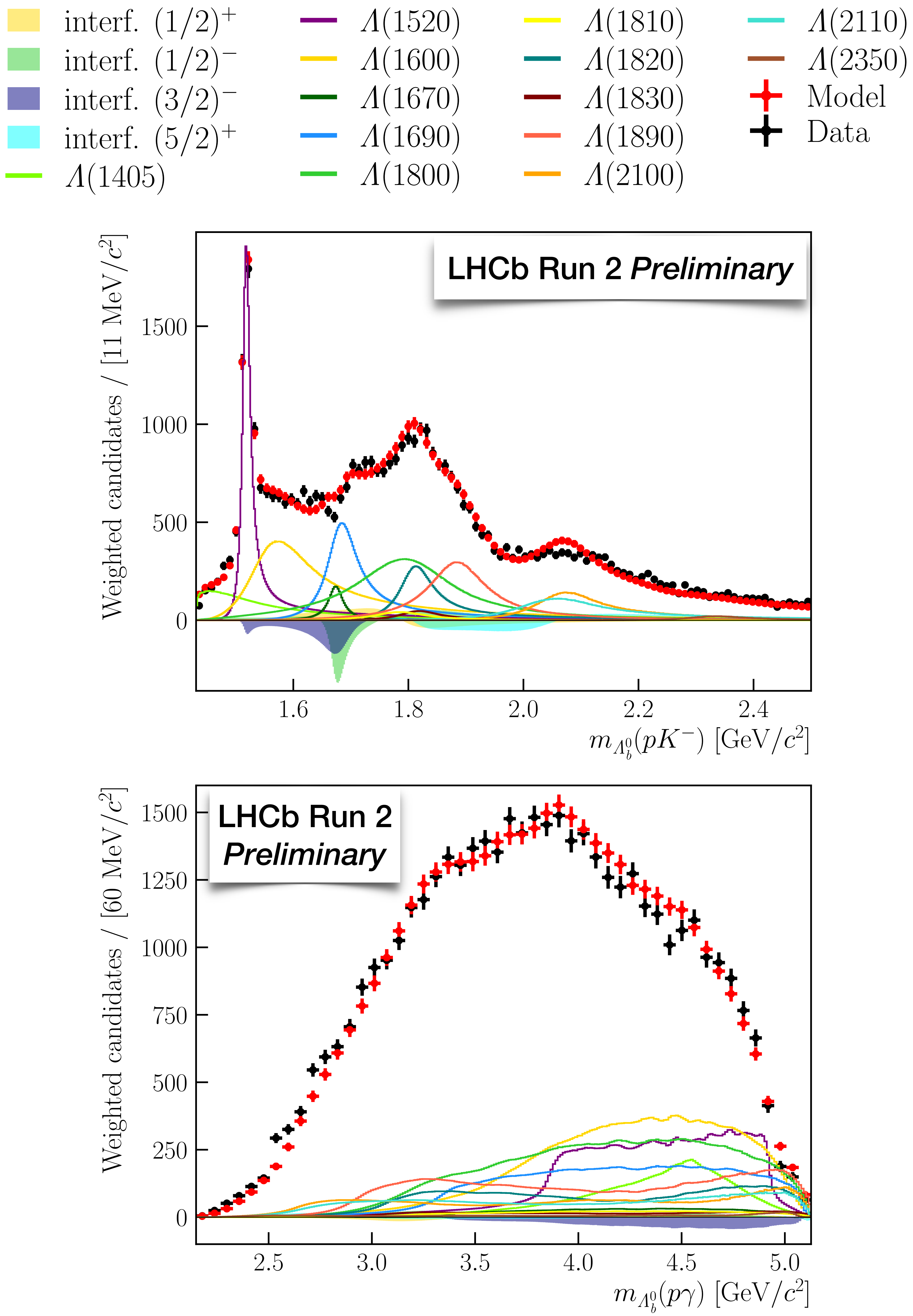
$L \leq 3$

this small model



Allowing larger L does not change the fit quality.

$L \leq 2$ has much worse fit quality.



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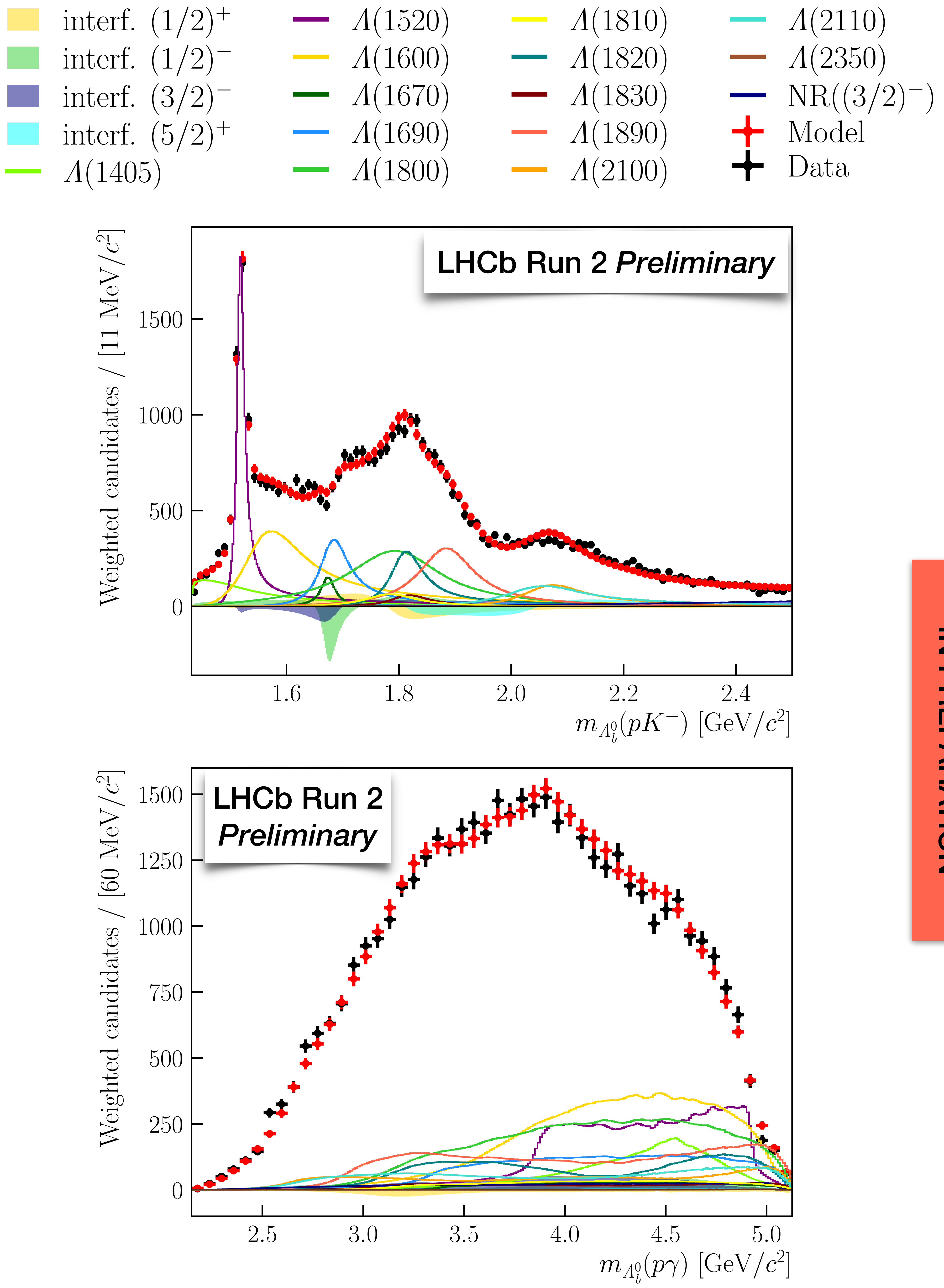
The best model

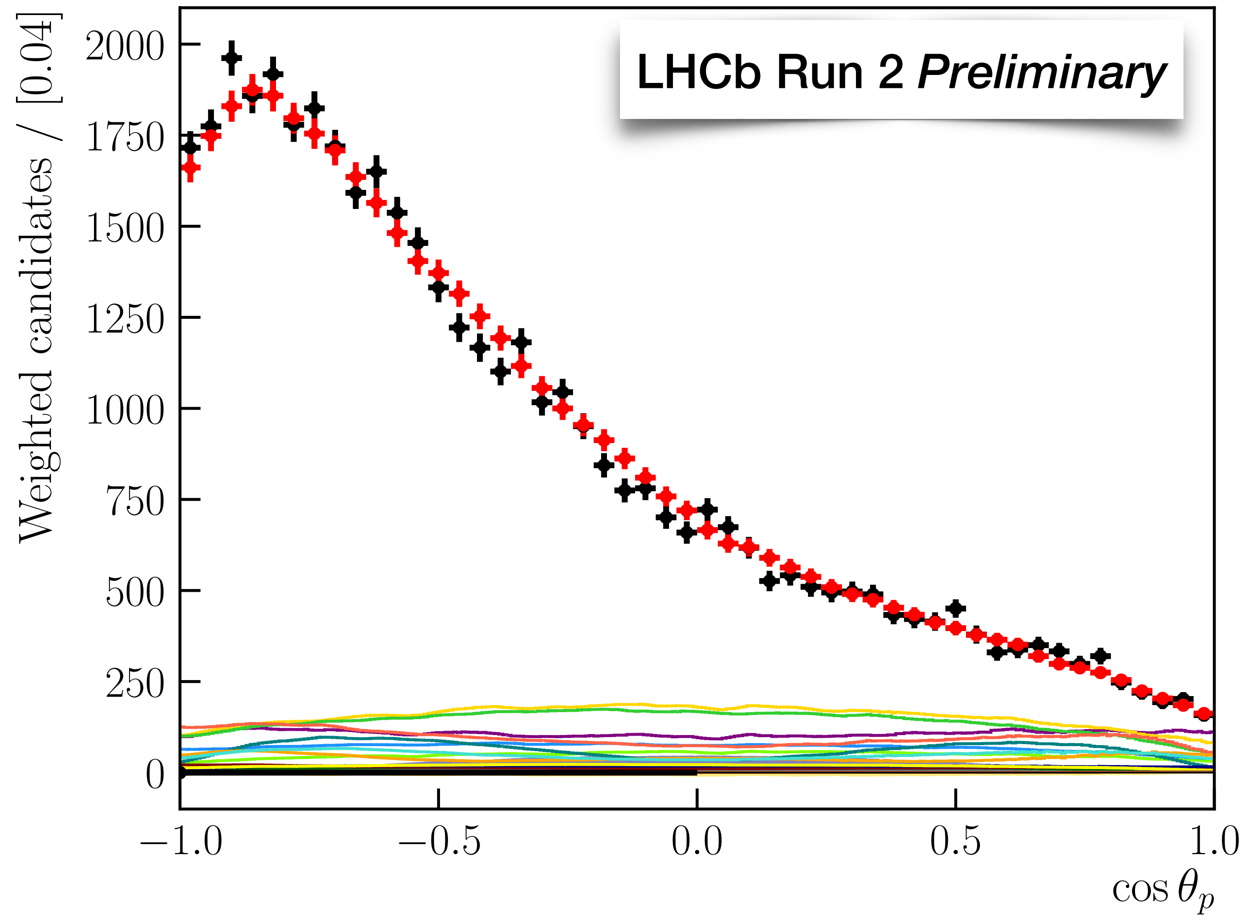
Small model + non-resonant component

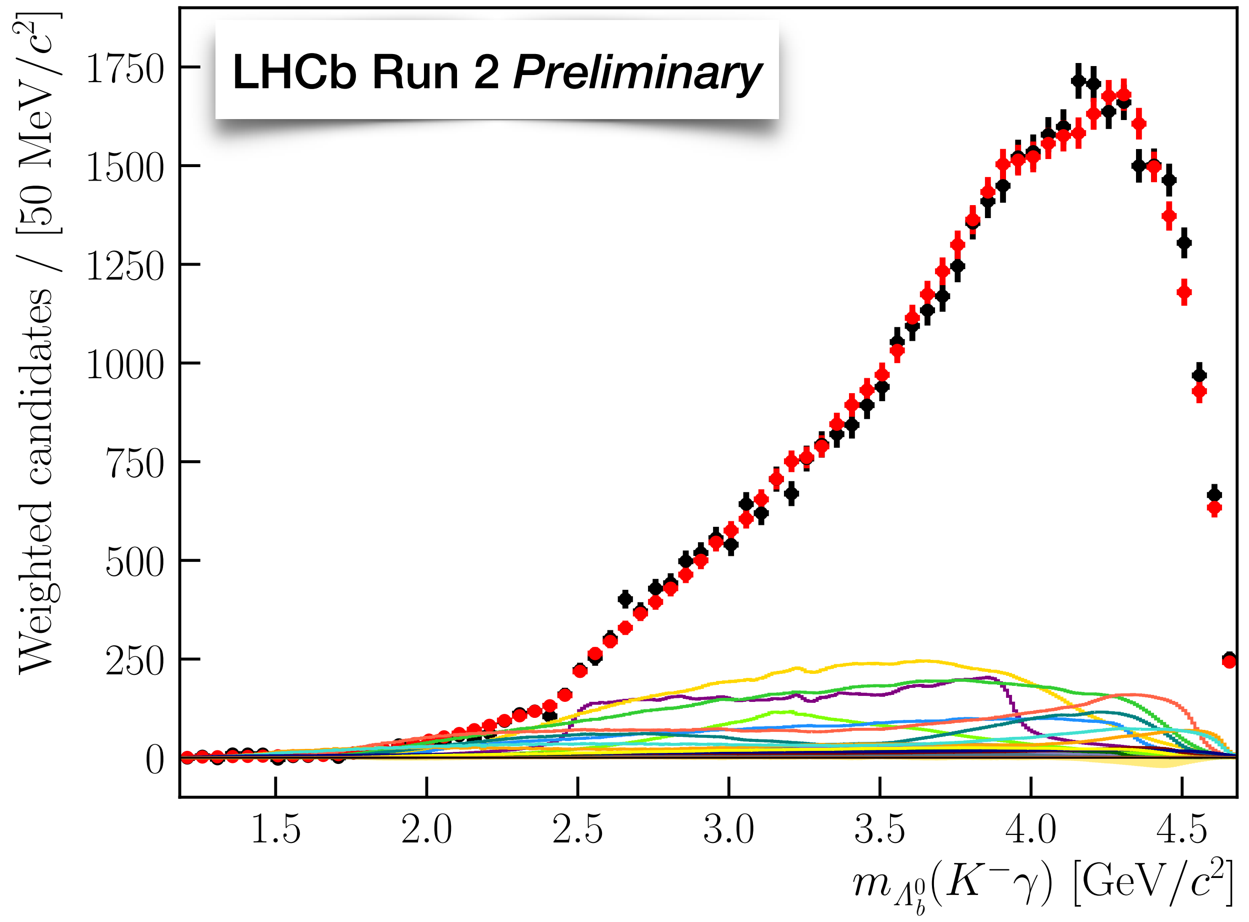


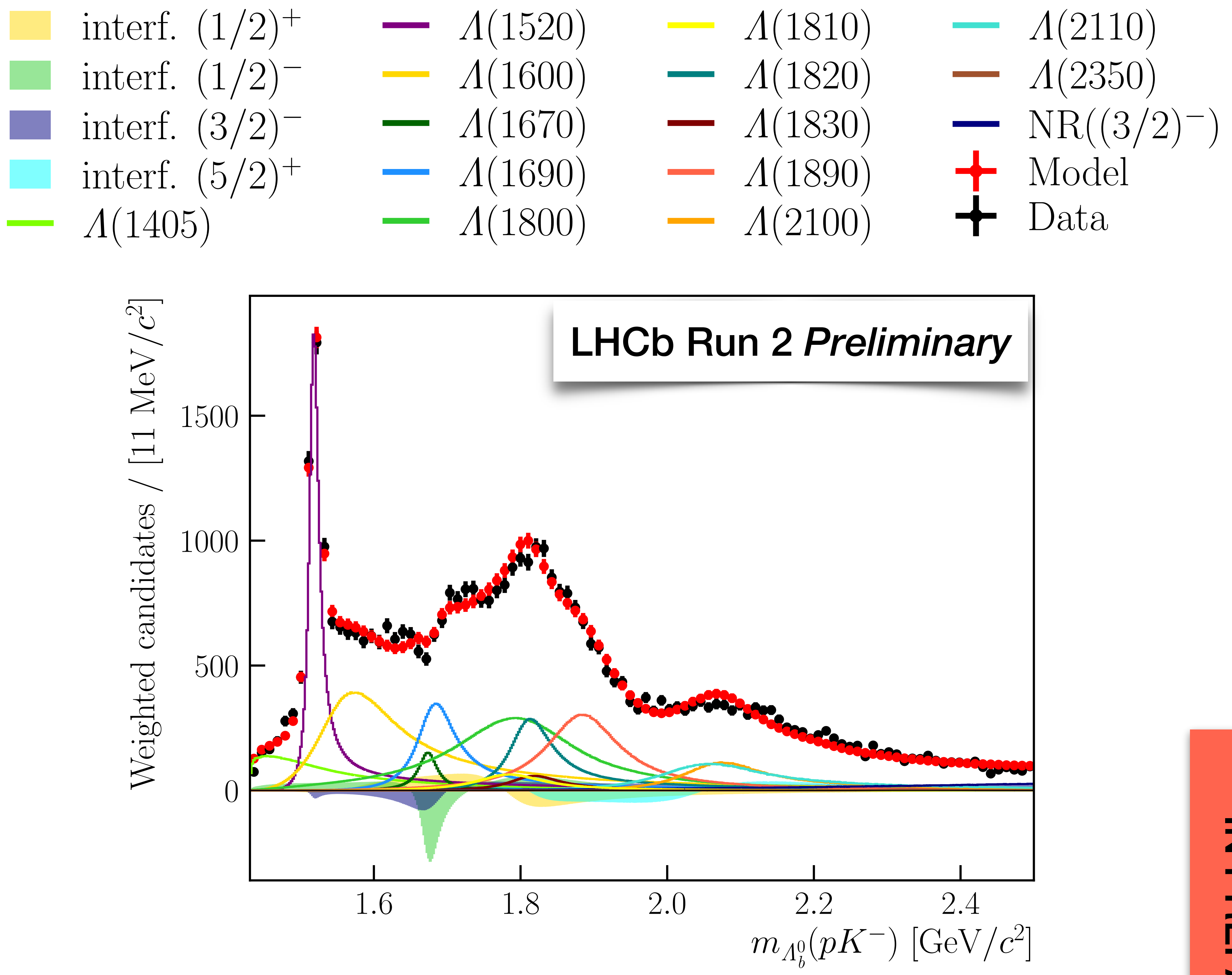
LHCb PAPER-2023-036
IN PREPARATION

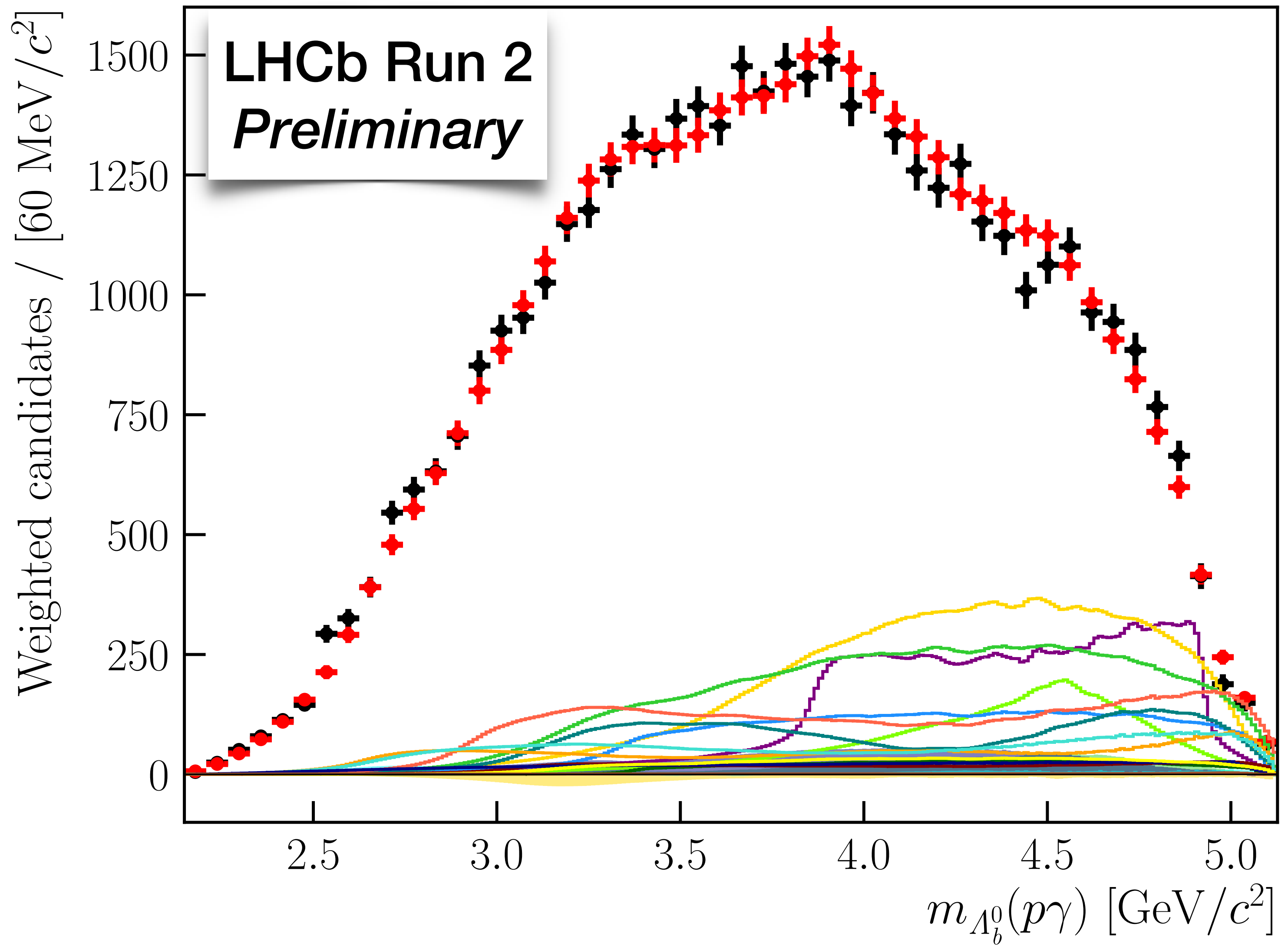
The best model

Small model + non-resonant component









Asymmetric angle due to interference

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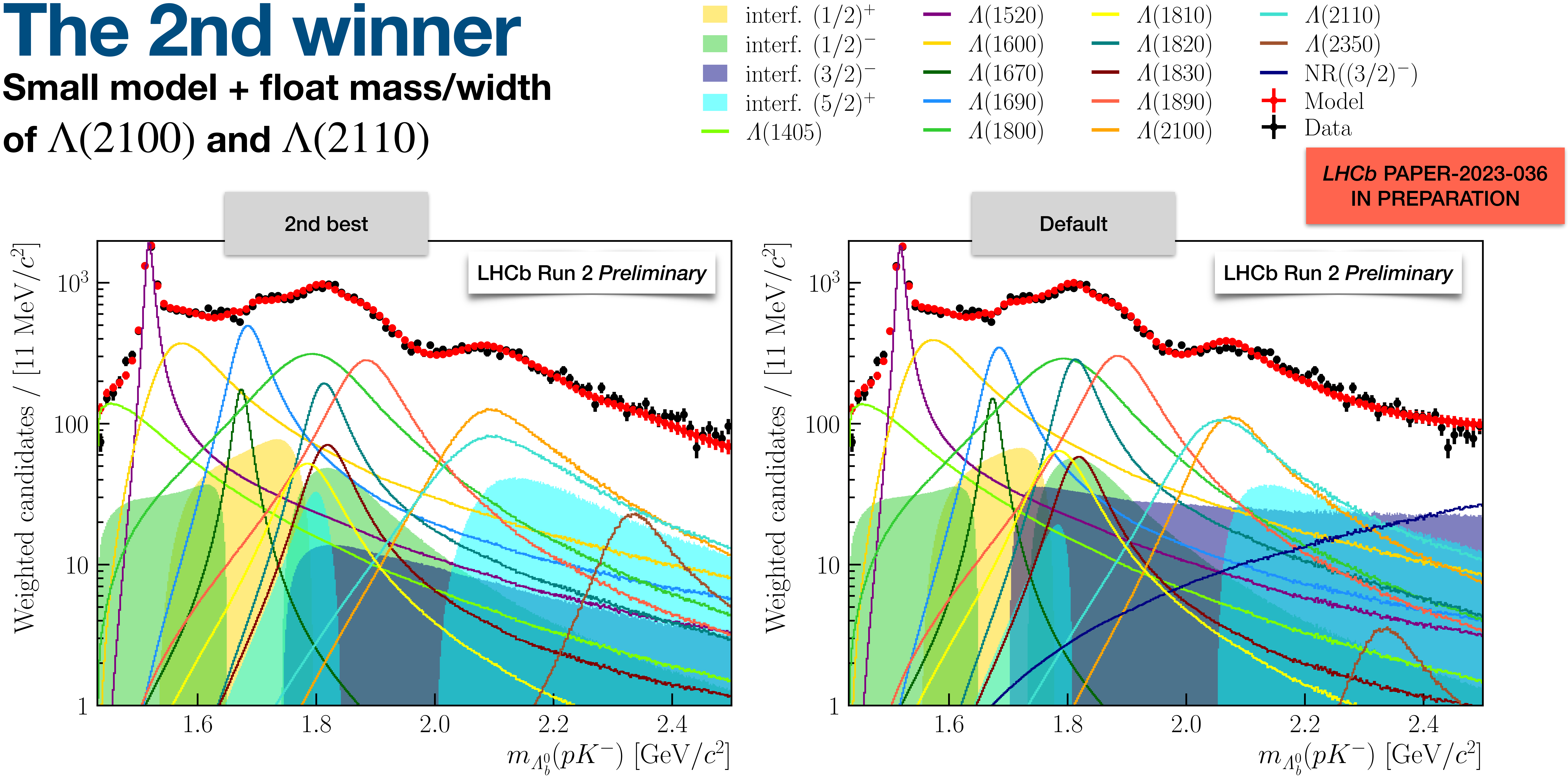
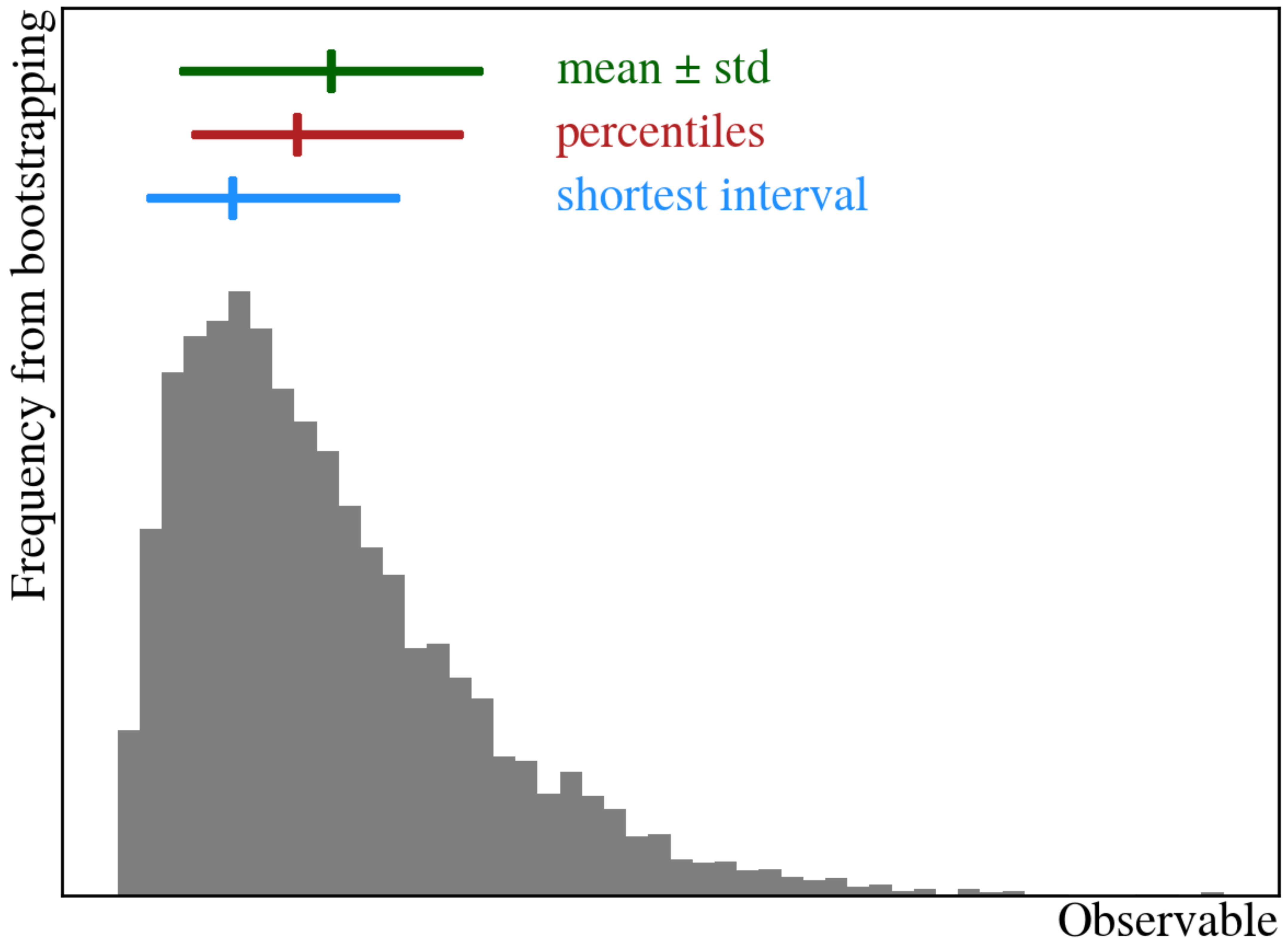
The 2nd winner

Small model + float mass/width of $\Lambda(2100)$ and $\Lambda(2110)$



Uncertainties due to limited data

From bootstrapping



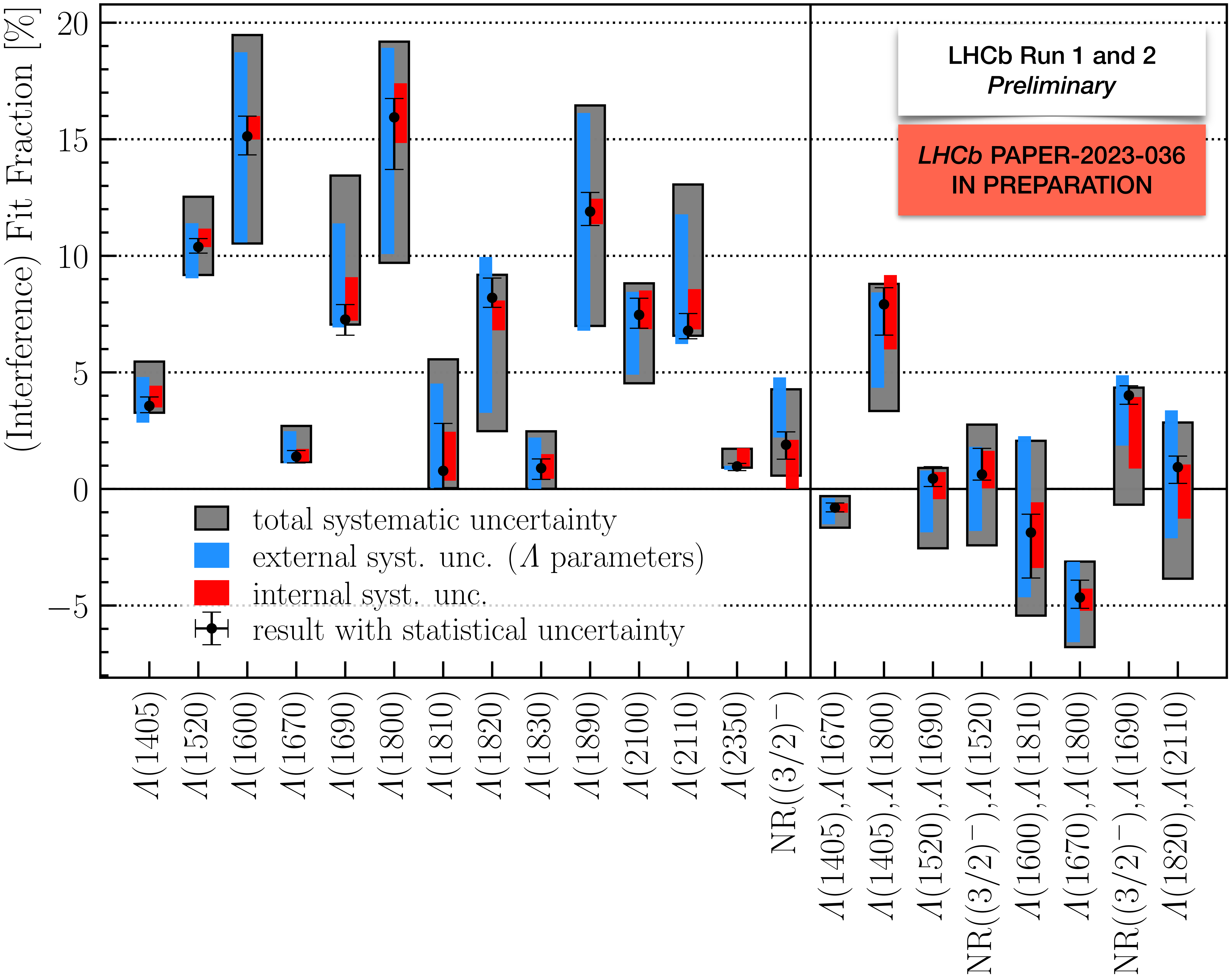
Systematic uncertainties

In decreasing order

- Resonance parameters (mass, width, radius) [external]
- Amplitude model and resolution
- Acceptance model and simulation
- Massfit model

Combine asymmetric uncertainties
by convolving the distributions

Result

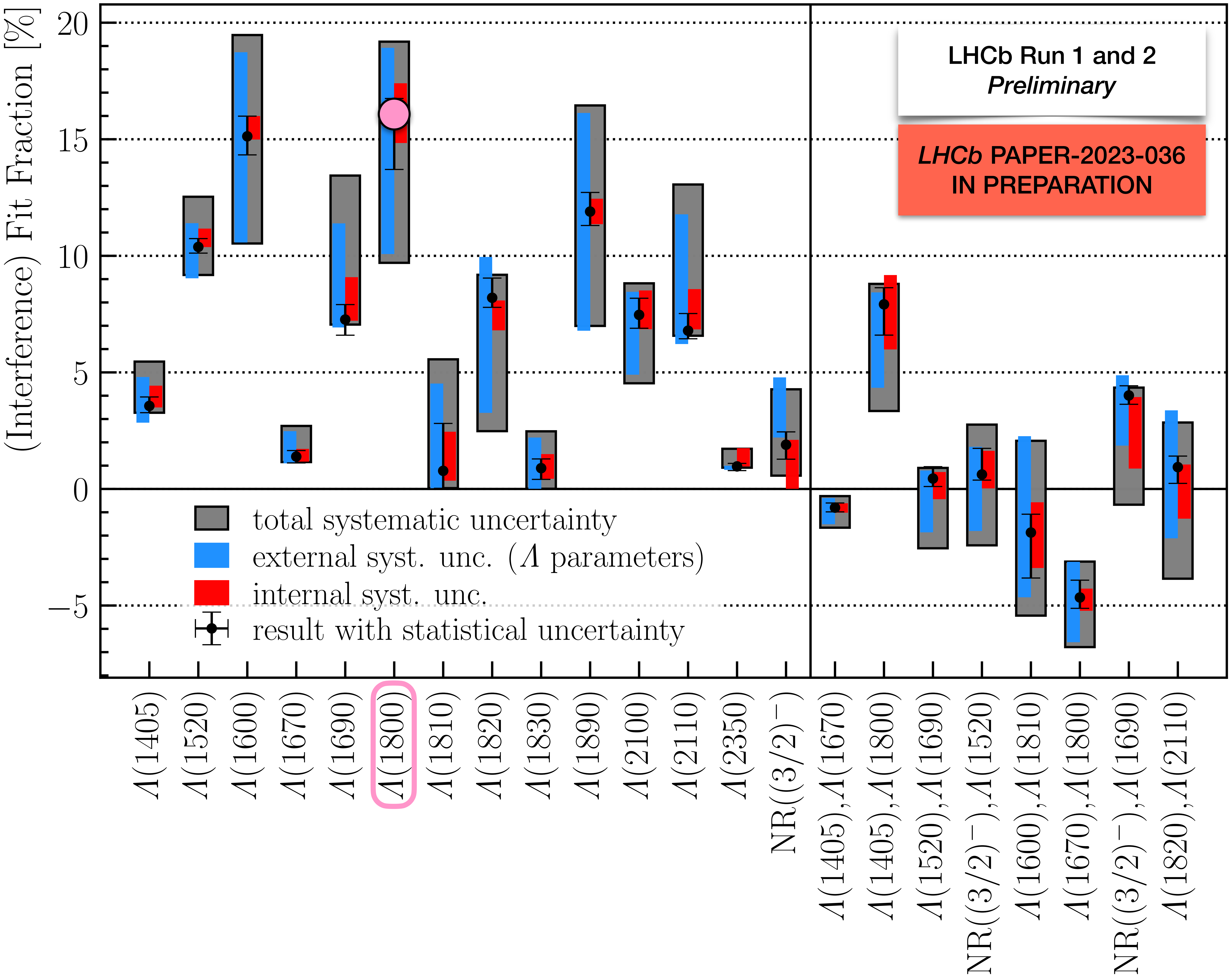


(Interference) Fit Fraction [%]
20
15
10
5
0
−5
LHCb Run 1 and 2
Preliminary
LHCb PAPER-2023-036
IN PREPARATION
total systematic uncertainty
external syst. unc. (Λ parameters)
internal syst. unc.
result with statistical uncertainty
Λ(1405)
Λ(1520)
Λ(1600)
Λ(1670)
Λ(1690)
Λ(1800)
Λ(1810)
Λ(1820)
Λ(1830)
Λ(1890)
Λ(2100)
Λ(2110)
Λ(2350)
NR((3/2)⁻)
Λ(1405),Λ(1670)
Λ(1405),Λ(1800)
Λ(1520),Λ(1690)
NR((3/2)⁻),Λ(1520)
Λ(1600),Λ(1810)
Λ(1670),Λ(1800)
NR((3/2)⁻),Λ(1690)
Λ(1820),Λ(2110)

Result

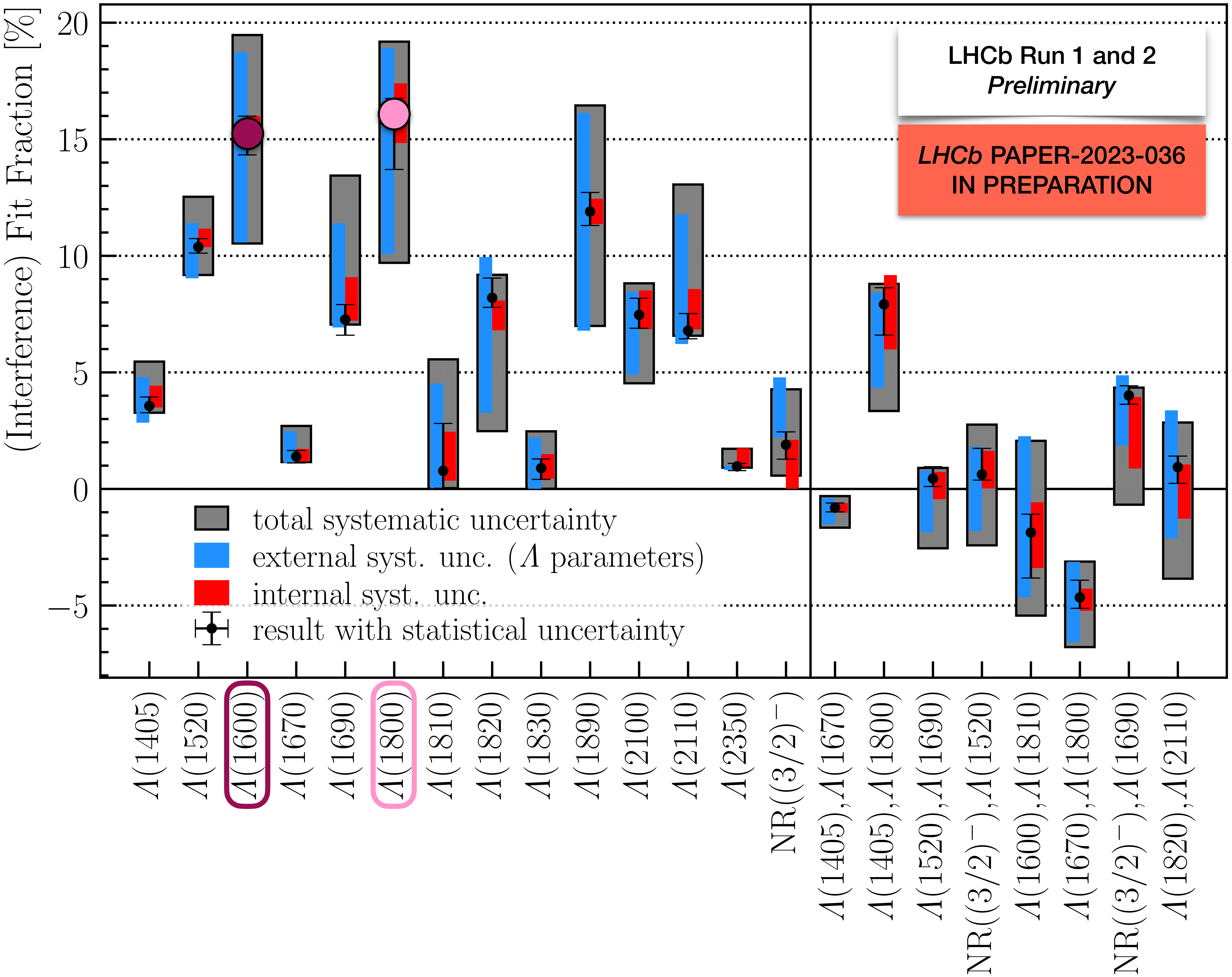
$\frac{1}{2}$

$-$

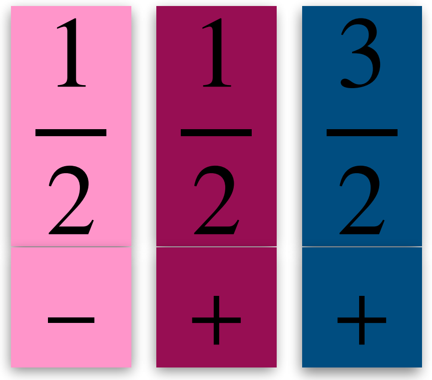


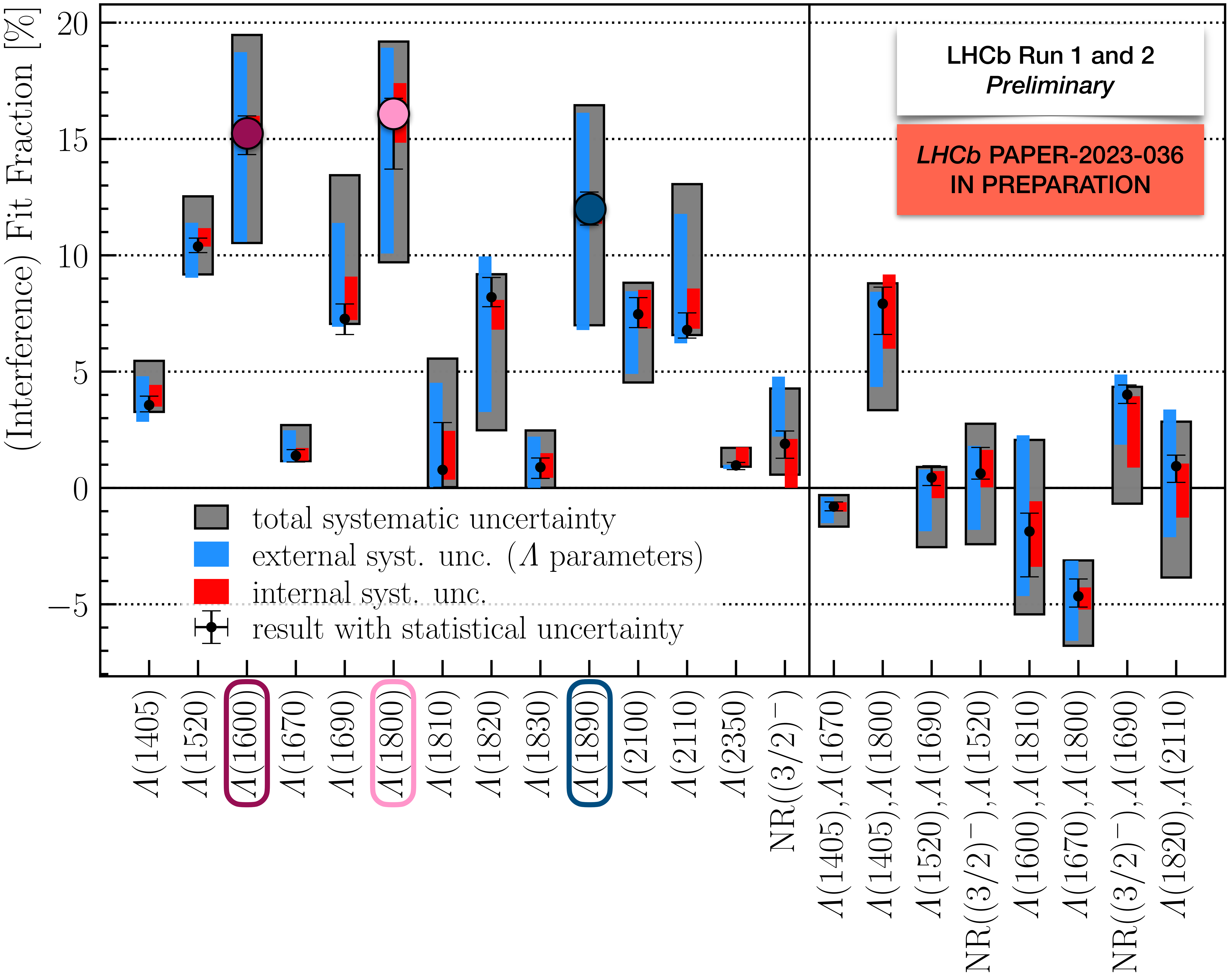
Result

$\frac{1}{2}^-$ $\frac{1}{2}^+$



Result


1/2 −
1/2 +
3/2 +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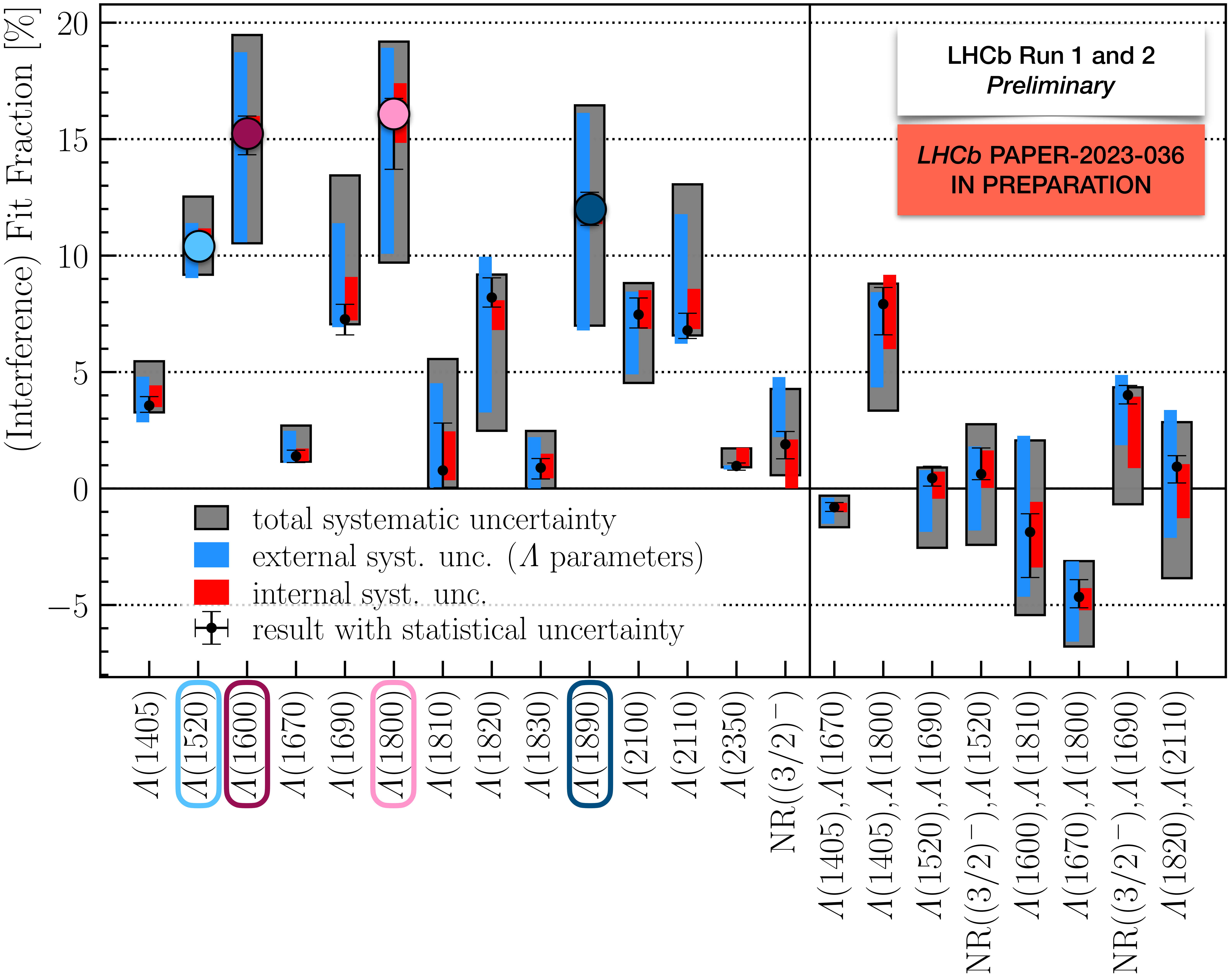
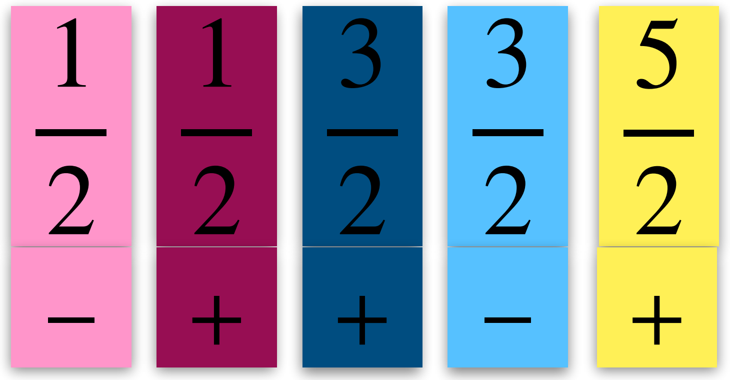
NR((3/2)⁻),Λ(1690)
Λ(1820),Λ(2110)

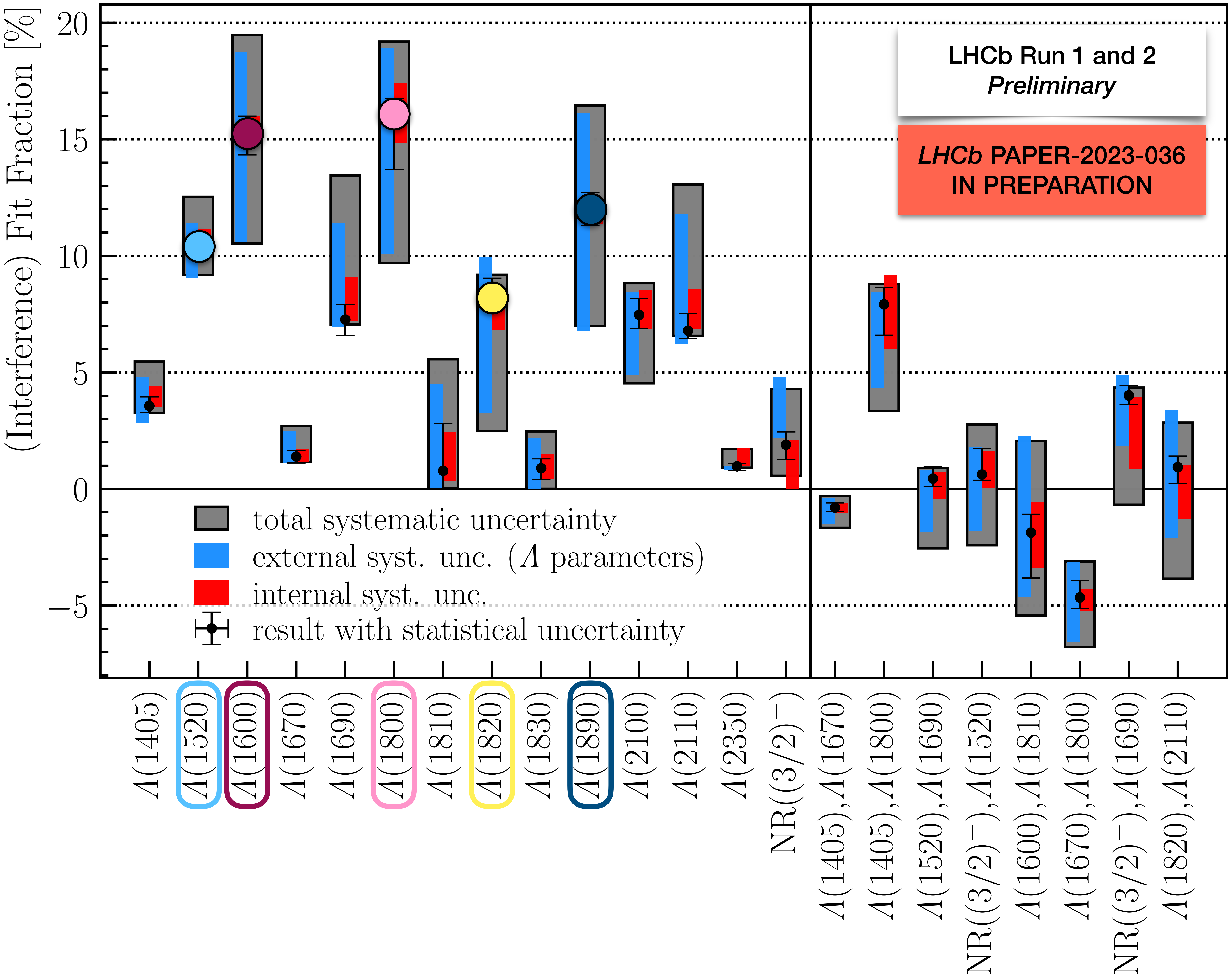
Result

$\frac{1}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{3}{2}$
−	+	+	−



Result


1/2 −
1/2 +
3/2 +
3/2 −
5/2 +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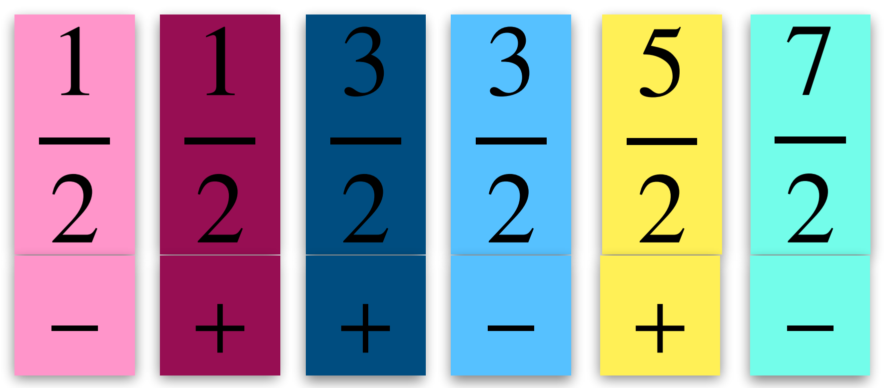
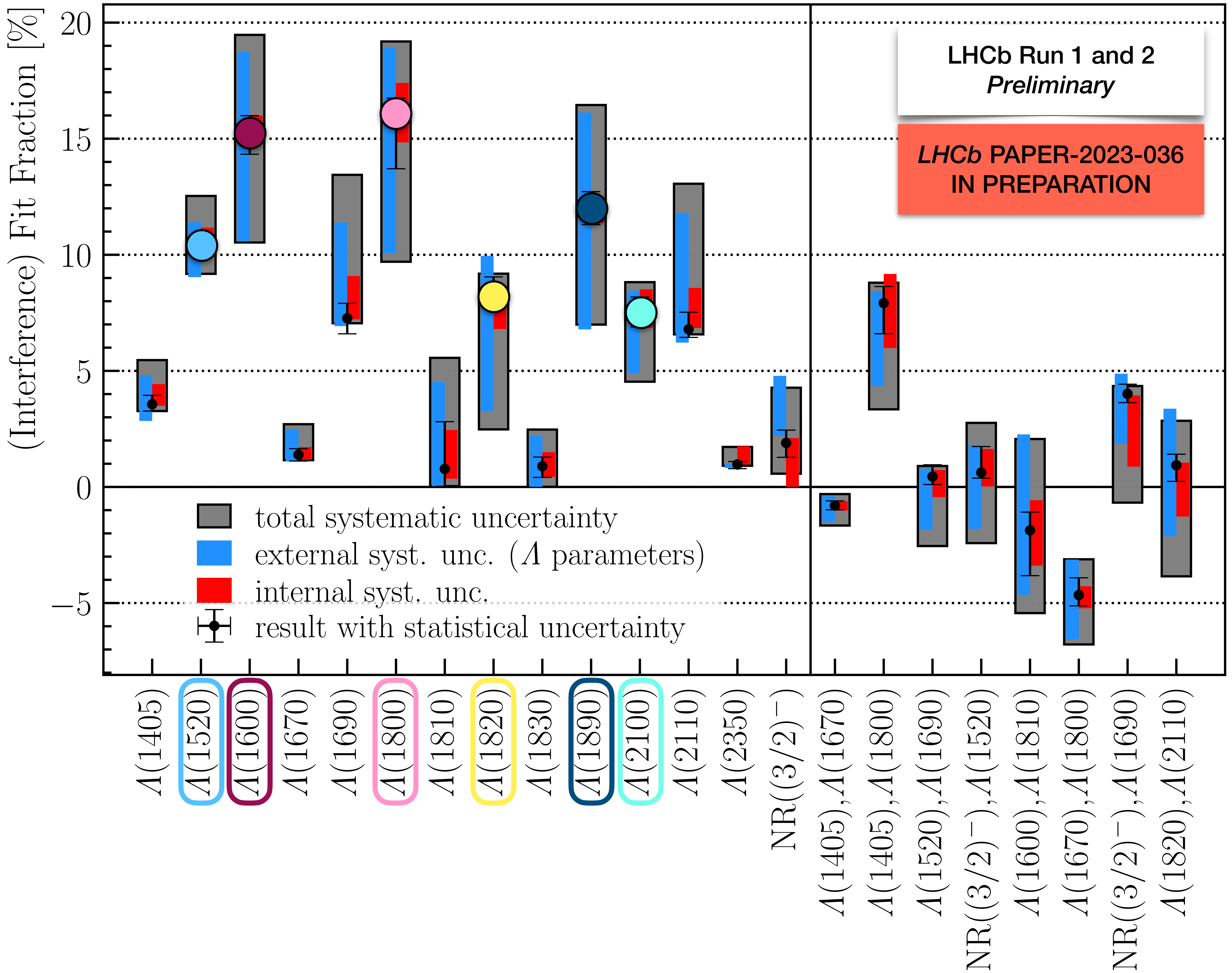


1/2 −
1/2 +
3/2 +
3/2 −
5/2 +
7/2 −



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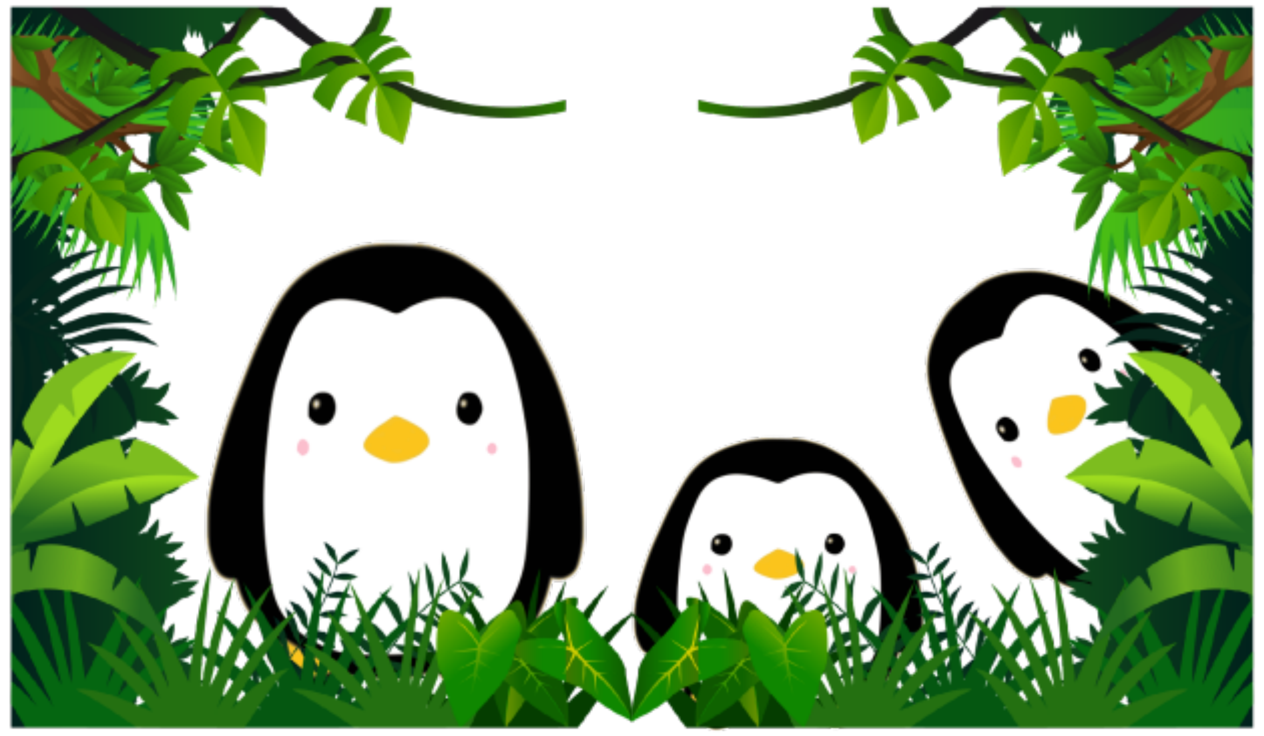
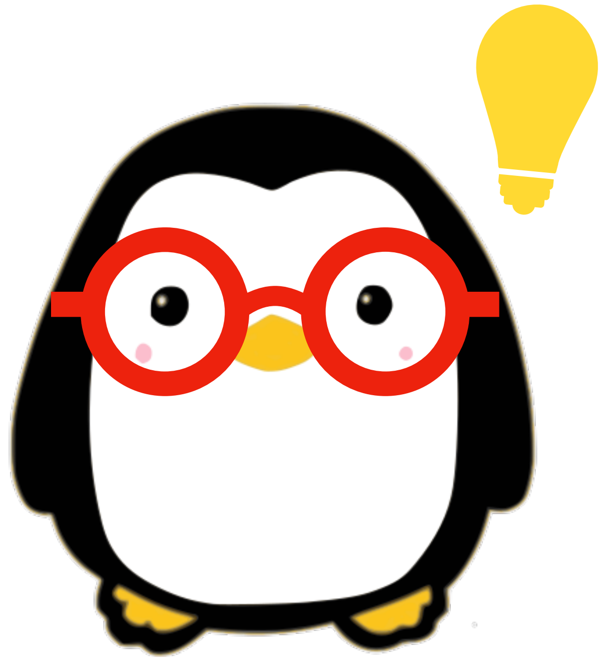
Λ(1670),Λ(1800)
NR((3/2)⁻),Λ(1690)
Λ(1820),Λ(2110)

Summary

Studying penguins in the jungle





- Penguins are useful
- With complicated final states in baryons
- Hadron QCD is complicated
  esp. for resonance spectra
- LHCb measurement of BF($\Lambda_b^0 \to \Lambda(1520)\mu\mu$)
  [predictions are easier for individual states]
- Measurement of the spectrum
  at the photon pole by LHCb