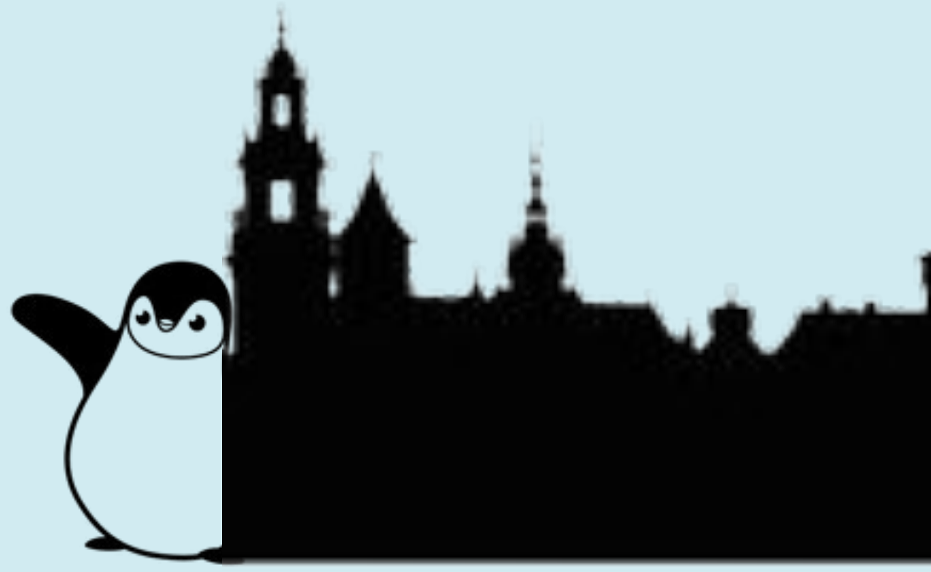
Fantastic penguins and where to find them



Seminarium Wydziału Fizyki i Informatyki Stosowanej AGH

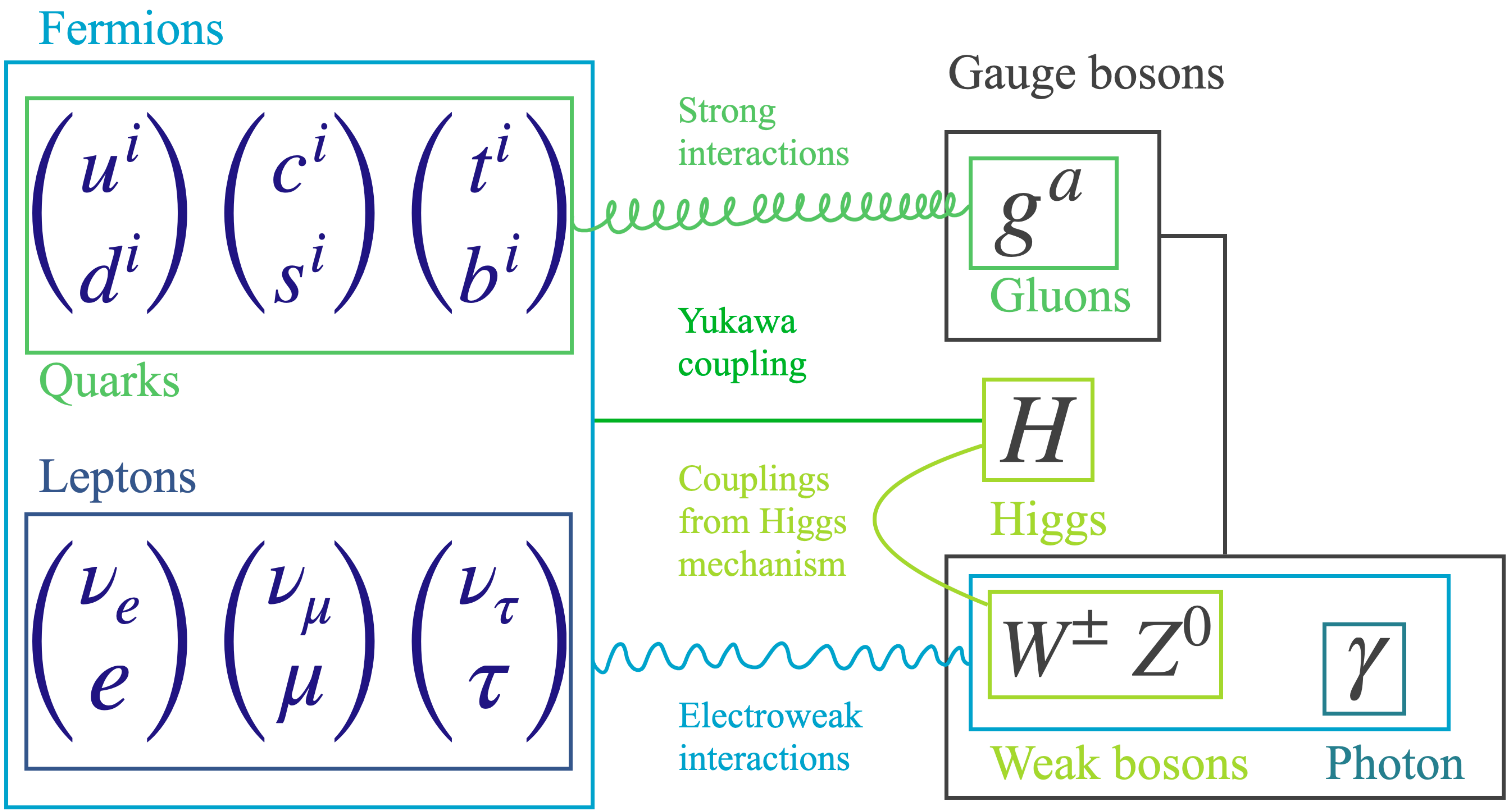
Janina Nicolini

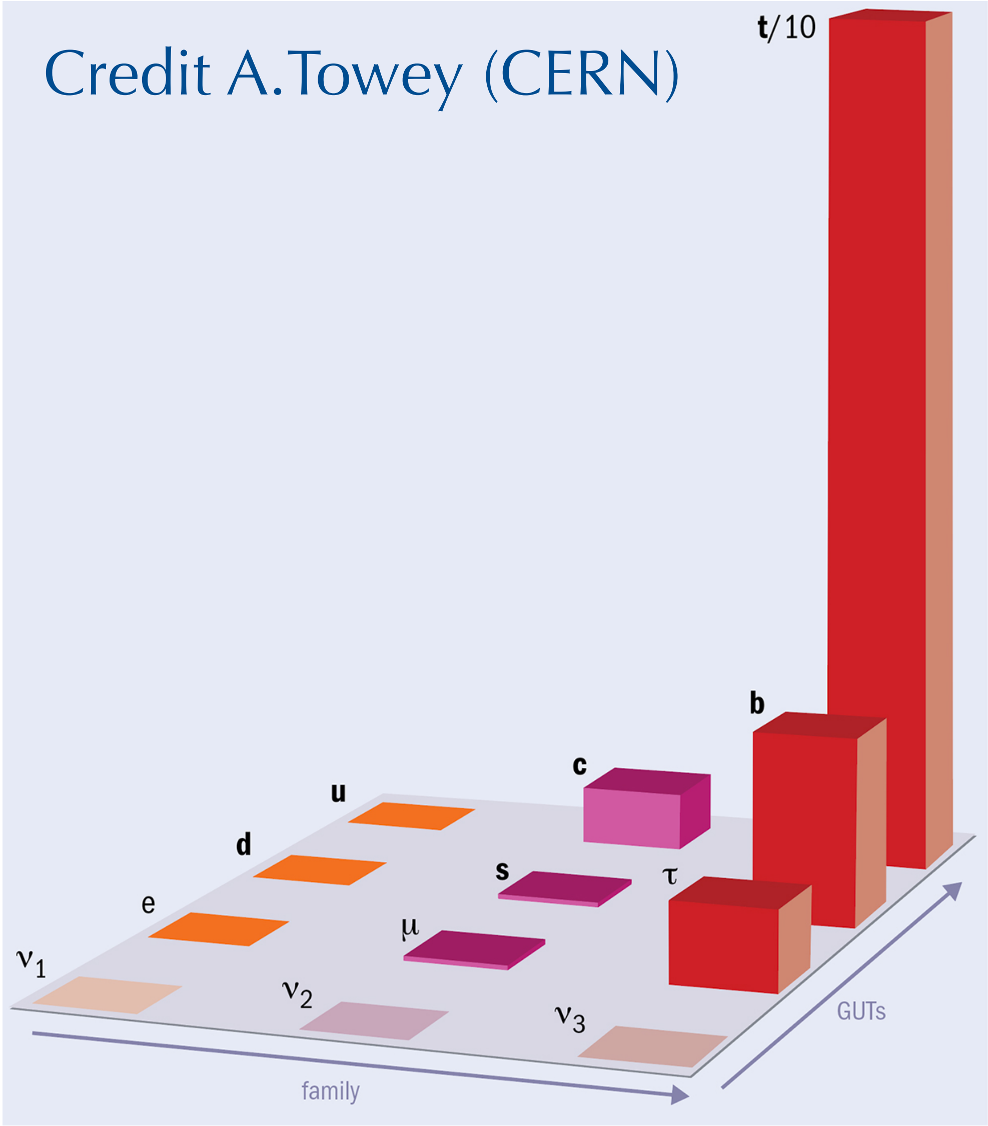
12.04.2024

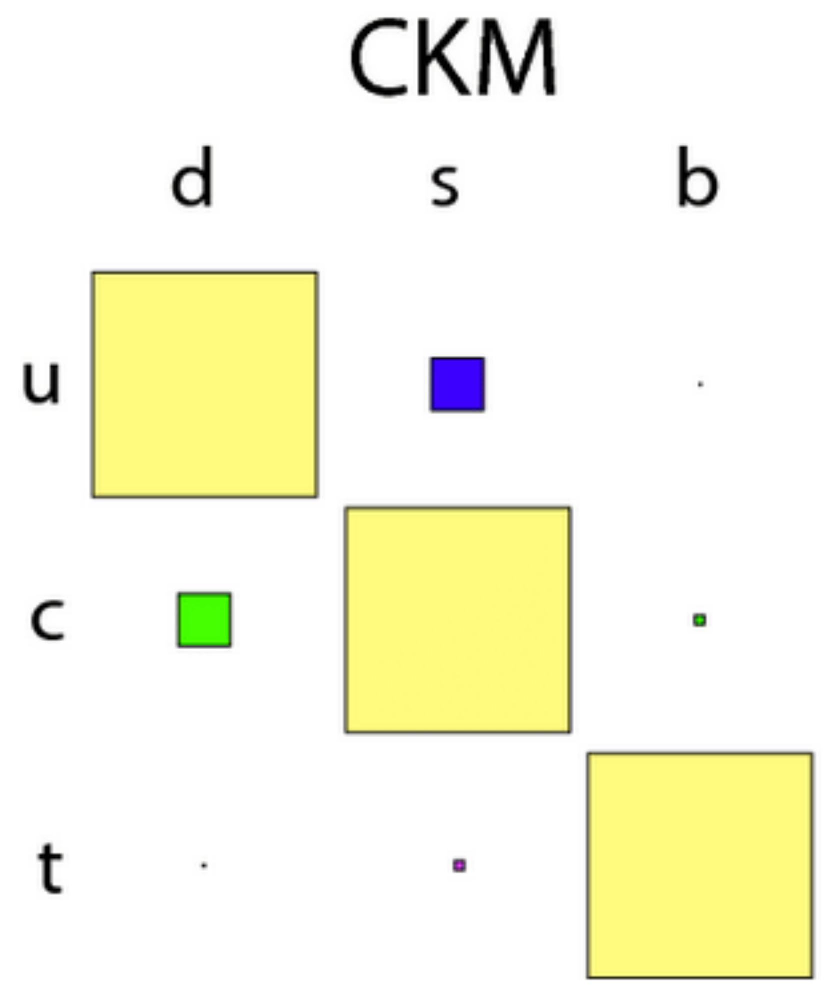
Supported by:

Studienstiftung des deutschen Volkes

The Standard Model of Particle Physics



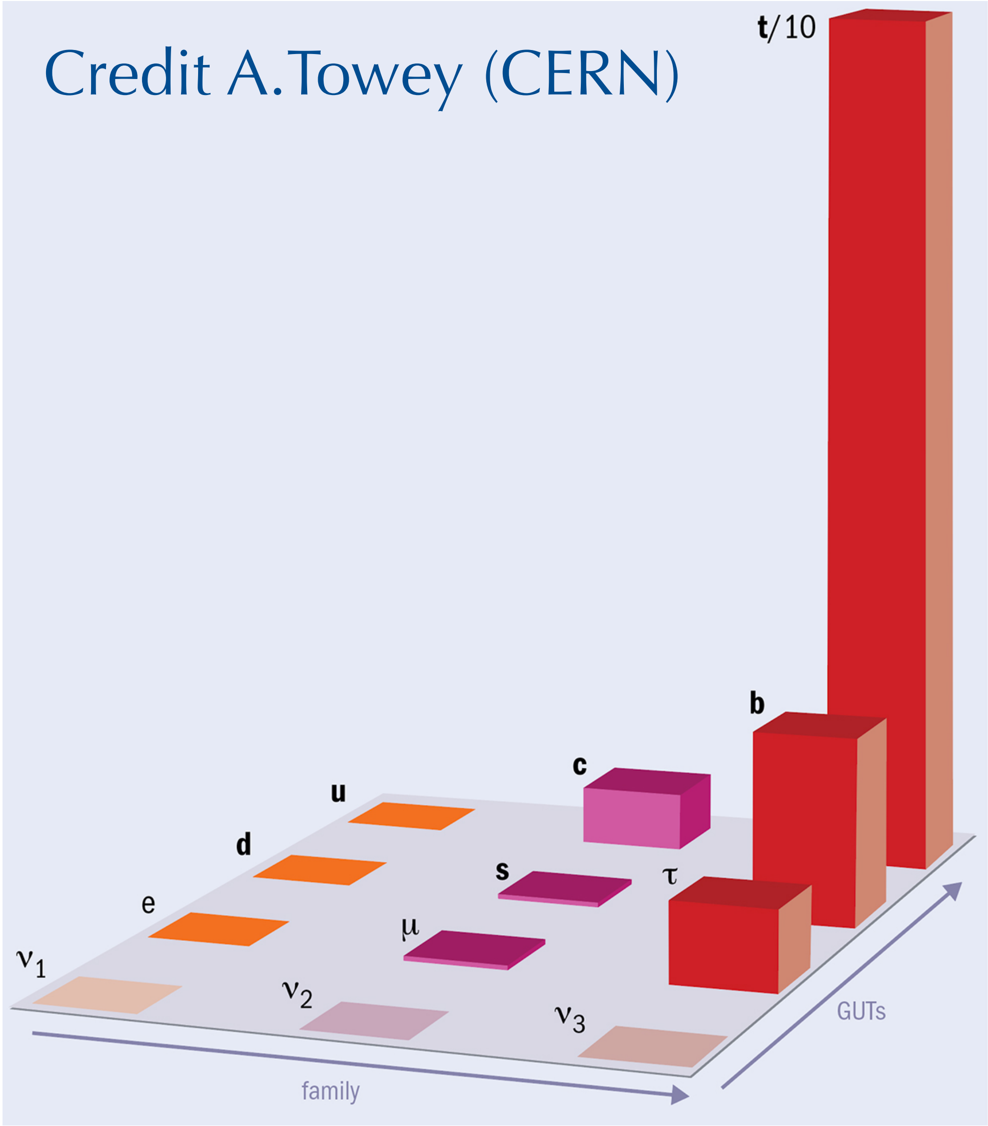




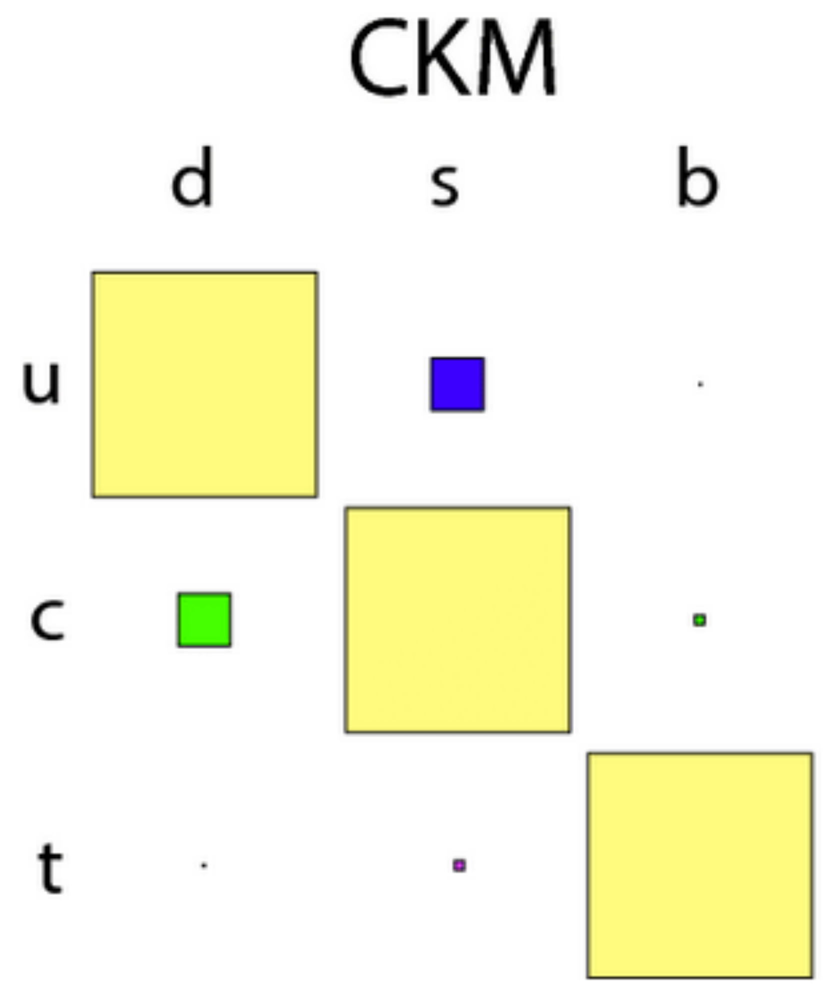
Credit J.A. Romeu

- What is the origin of the **hierarchies**? (Fermion masses, CKM)
- Why are there **three** fermion **generations**?
- How do **neutrinos** get their **masses**?
- What are **dark matter** and **dark energy**?
- …

Shortcomings of the Standard Model



Credit A.Towey (CERN)



Credit J.A. Romeu

- What is the origin of the **hierarchies**? (Fermion masses, CKM)
- Why are there **three** fermion **generations**?
- Ho
- W
- …

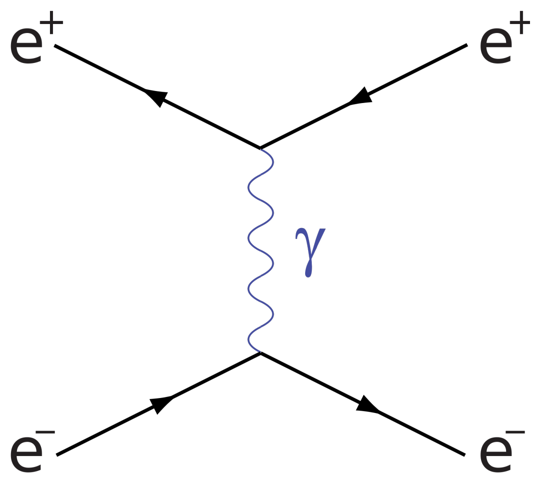
Standard model is approximation and incomplete

New particles and/or interaction?

Indirect Searches - a way forward

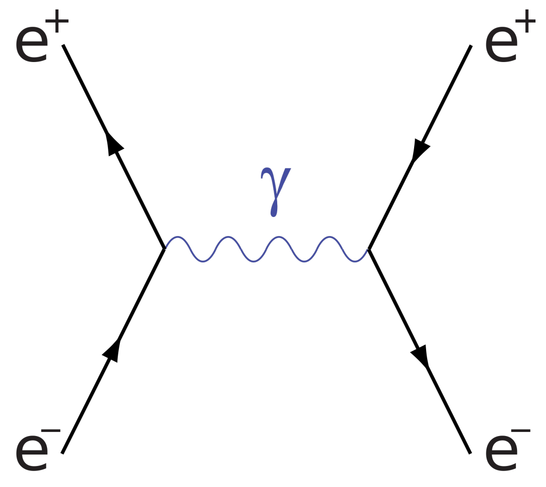
- **Heisenberg uncertainty** relation $\Delta t \Delta E \geq \frac{\hbar}{4\pi}$

- Example Bhabha scattering



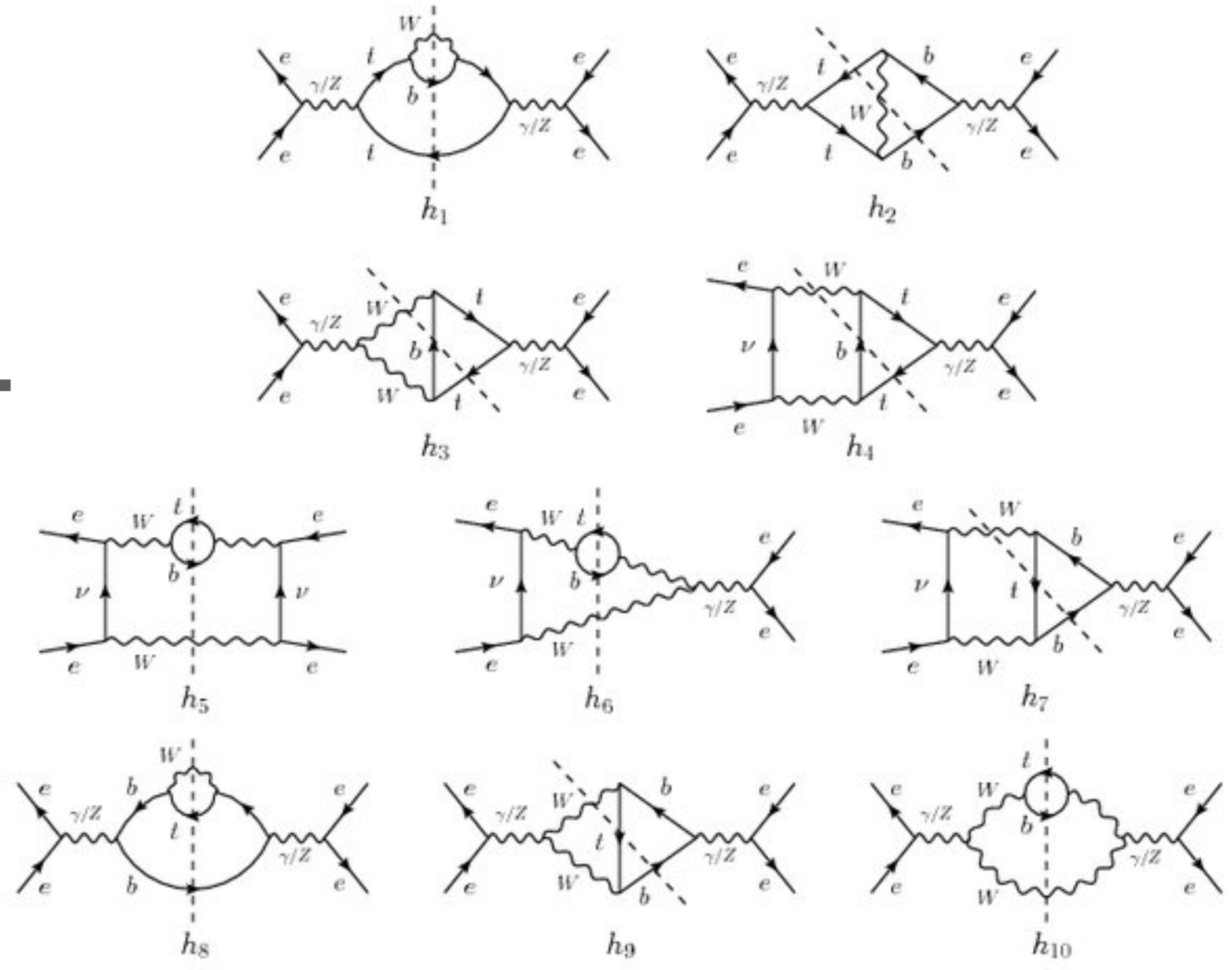
Scattering

+



Annihilation

+



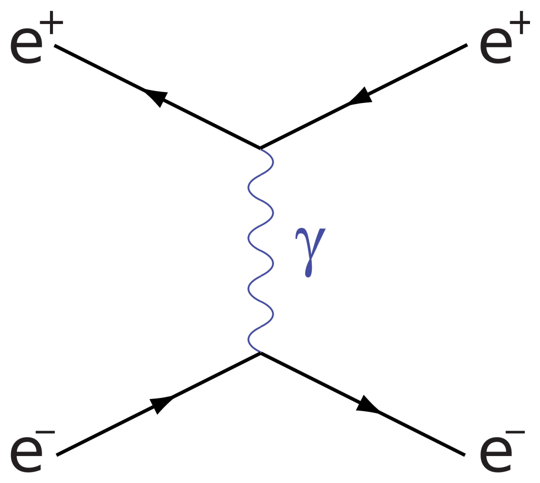
Higher order processes

Indirect Searches - a way forward

- **Heisenberg uncertainty** relation $\Delta t \Delta E \geq \frac{\hbar}{4\pi}$

- Example Bhabha scattering

- Search for **deviations**



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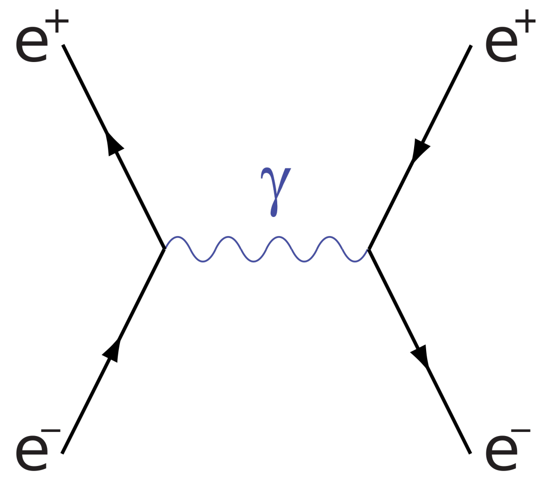

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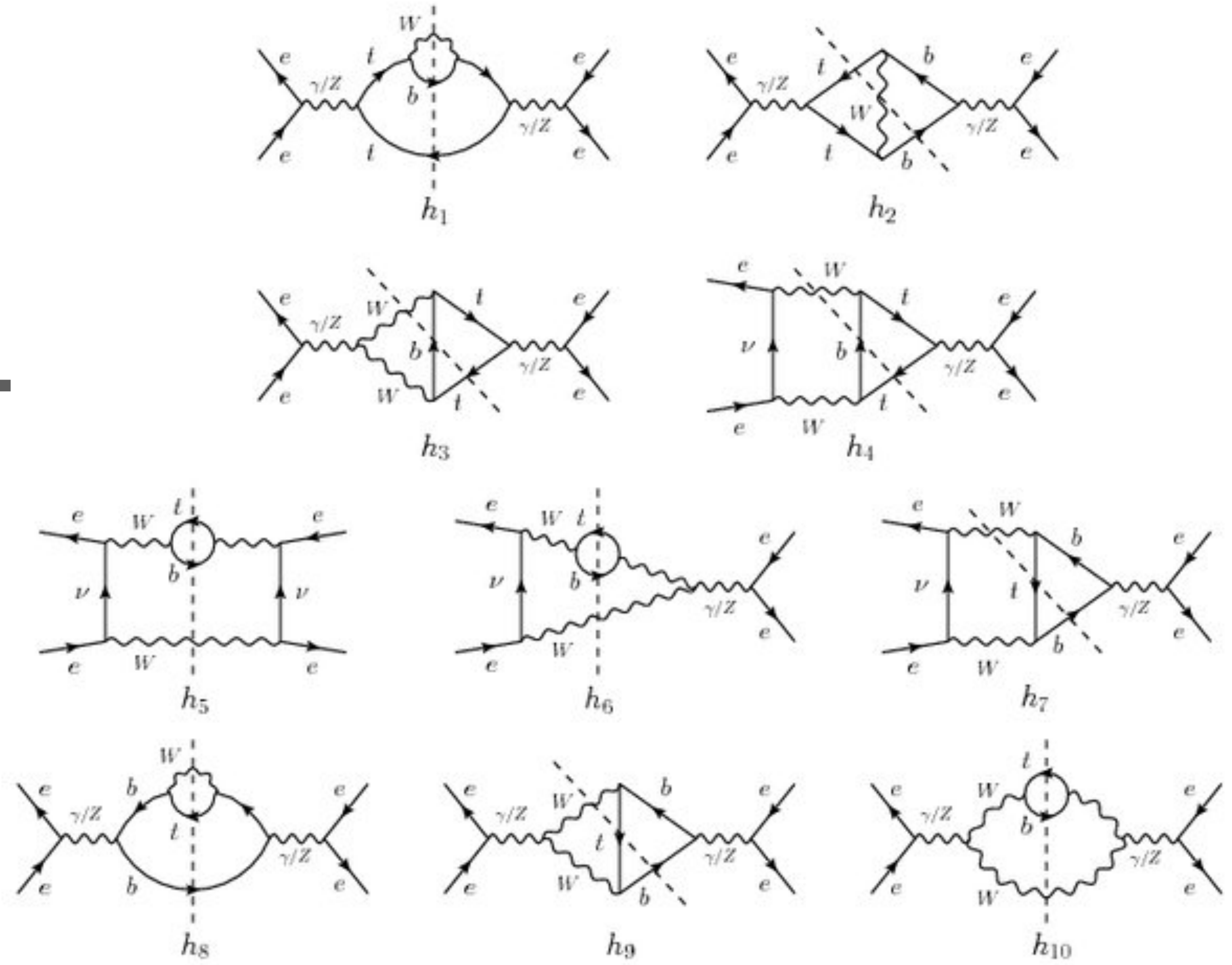

Higher order processes

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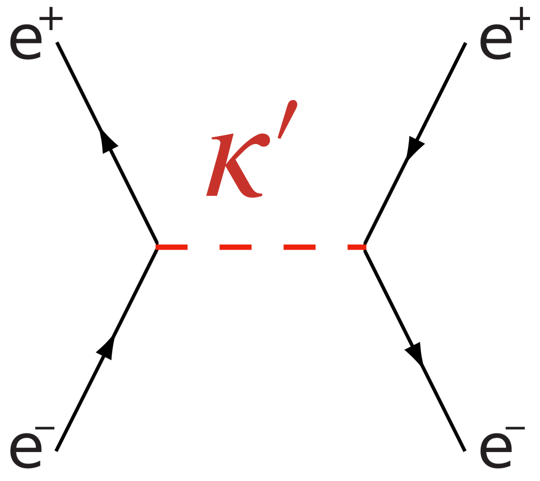
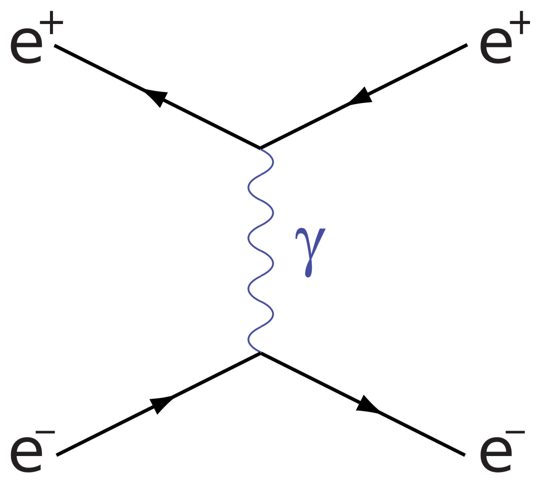


New physics

- **Heisenberg uncertainty** relation $\Delta t \Delta E \geq \frac{\hbar}{4\pi}$
- Example Bhabha scattering
- Search for **deviations**
- Large vs small dataset



Scattering

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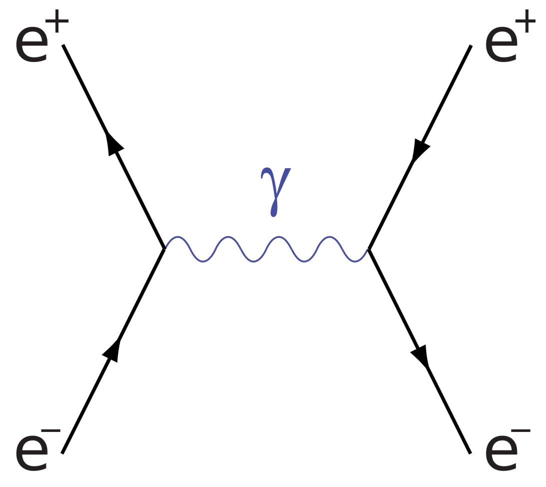

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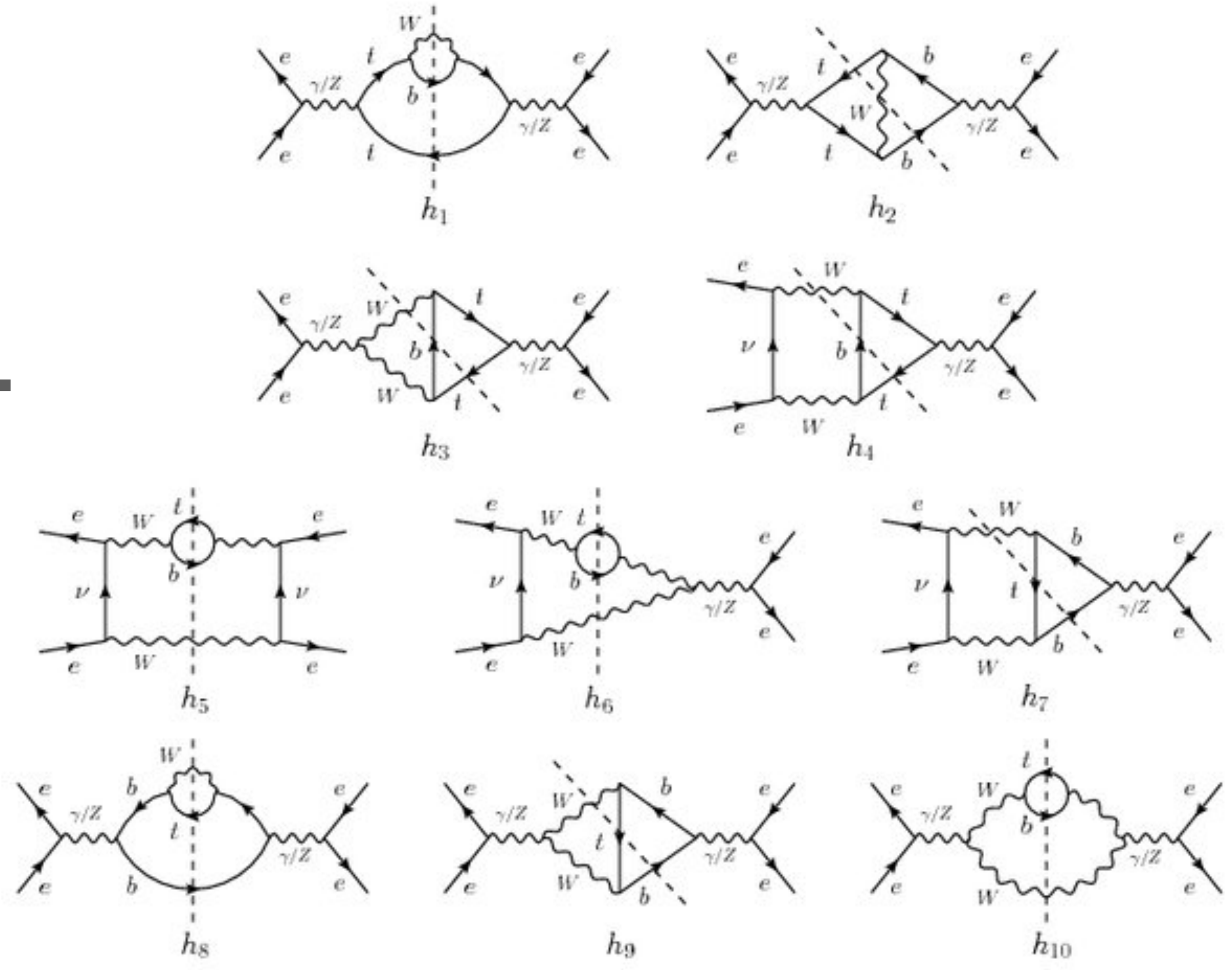
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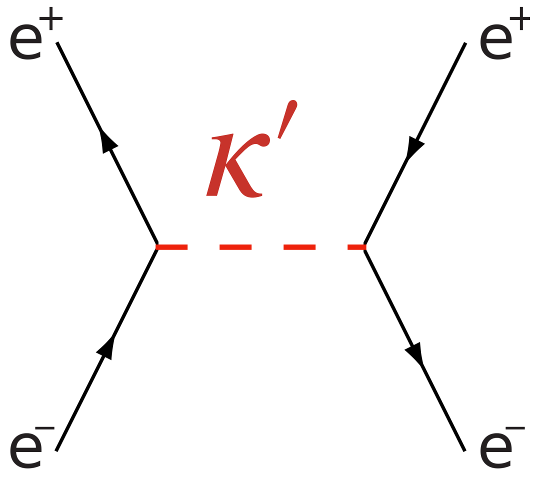
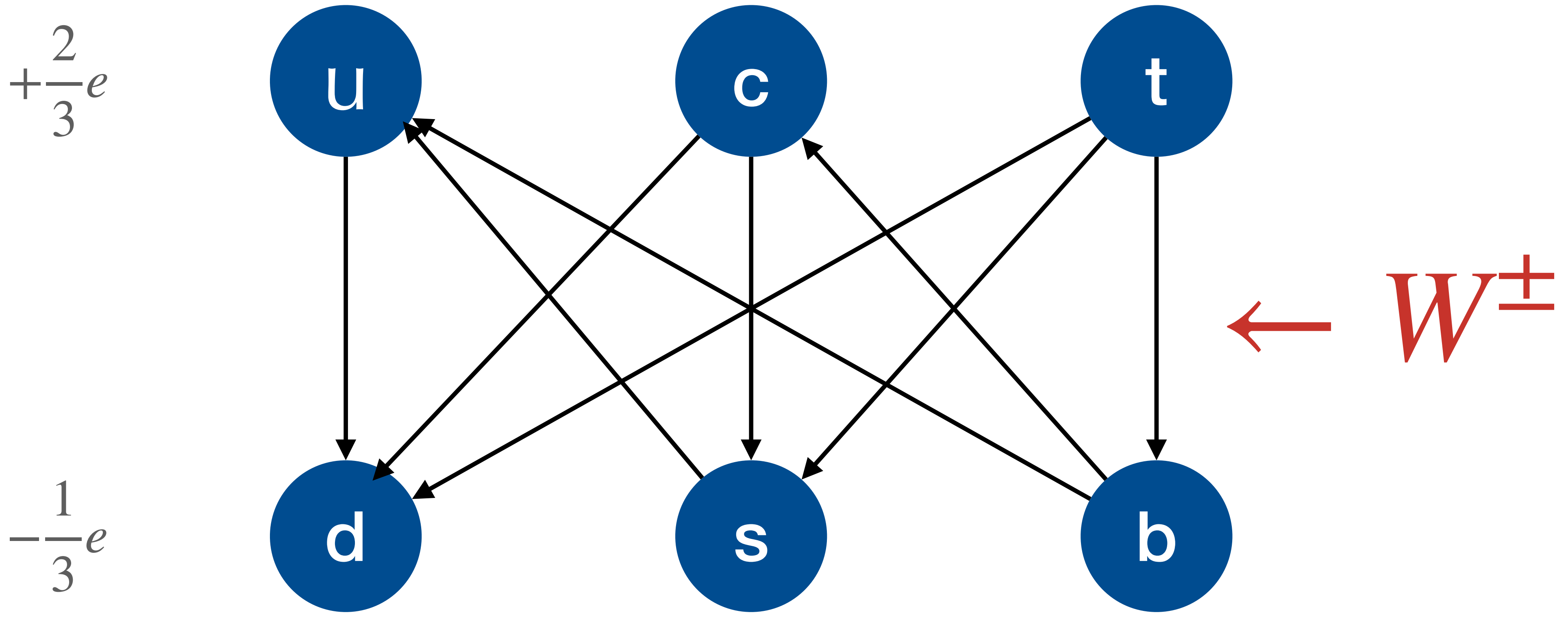


New physics

So what about penguins?

Electric charge



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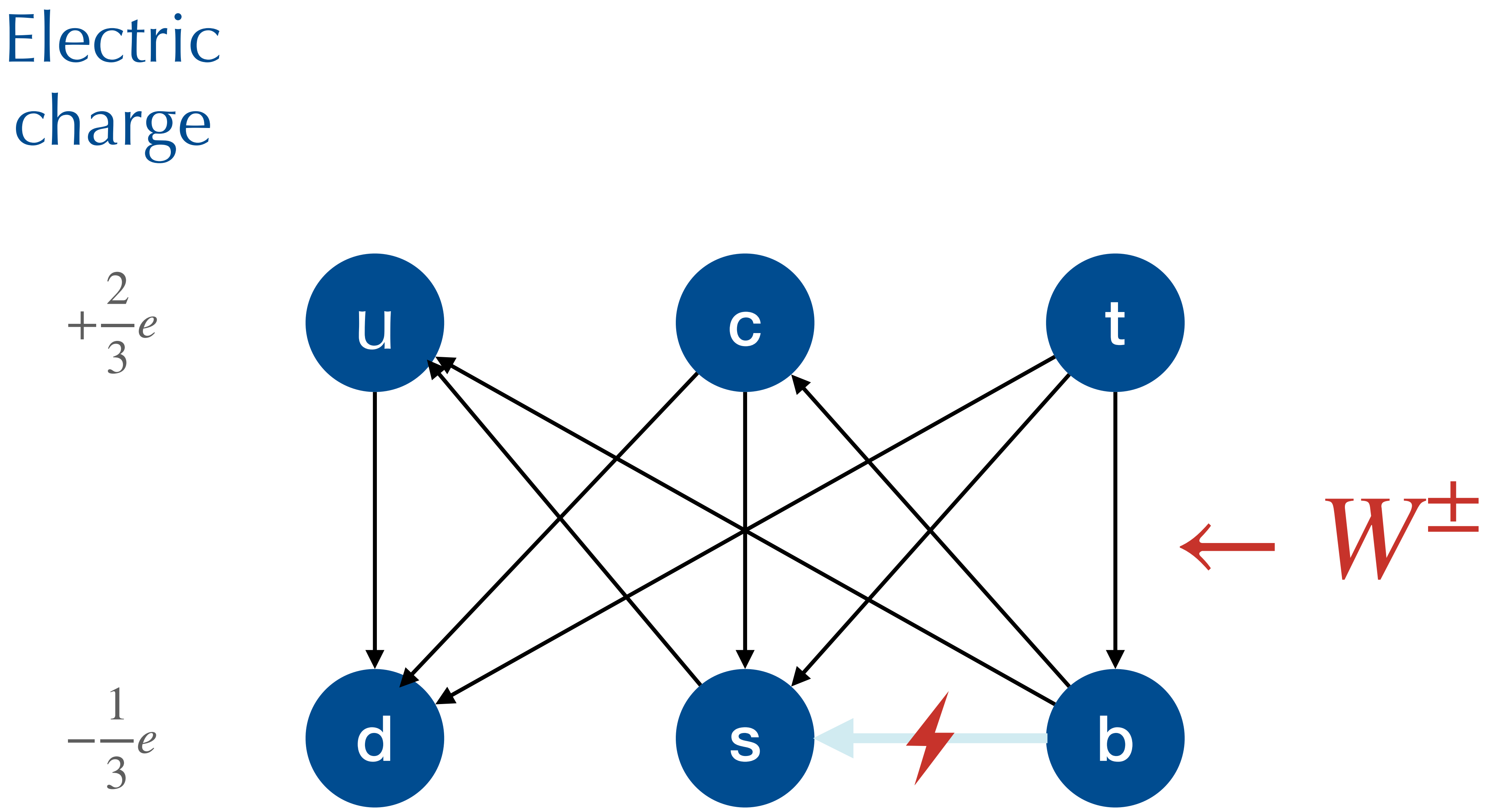
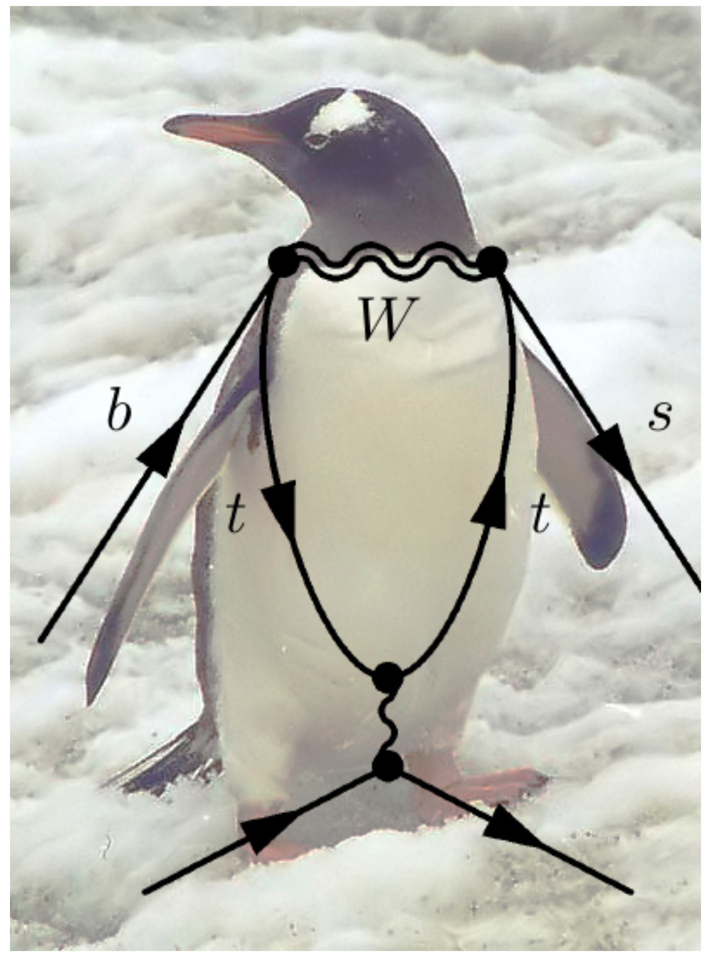
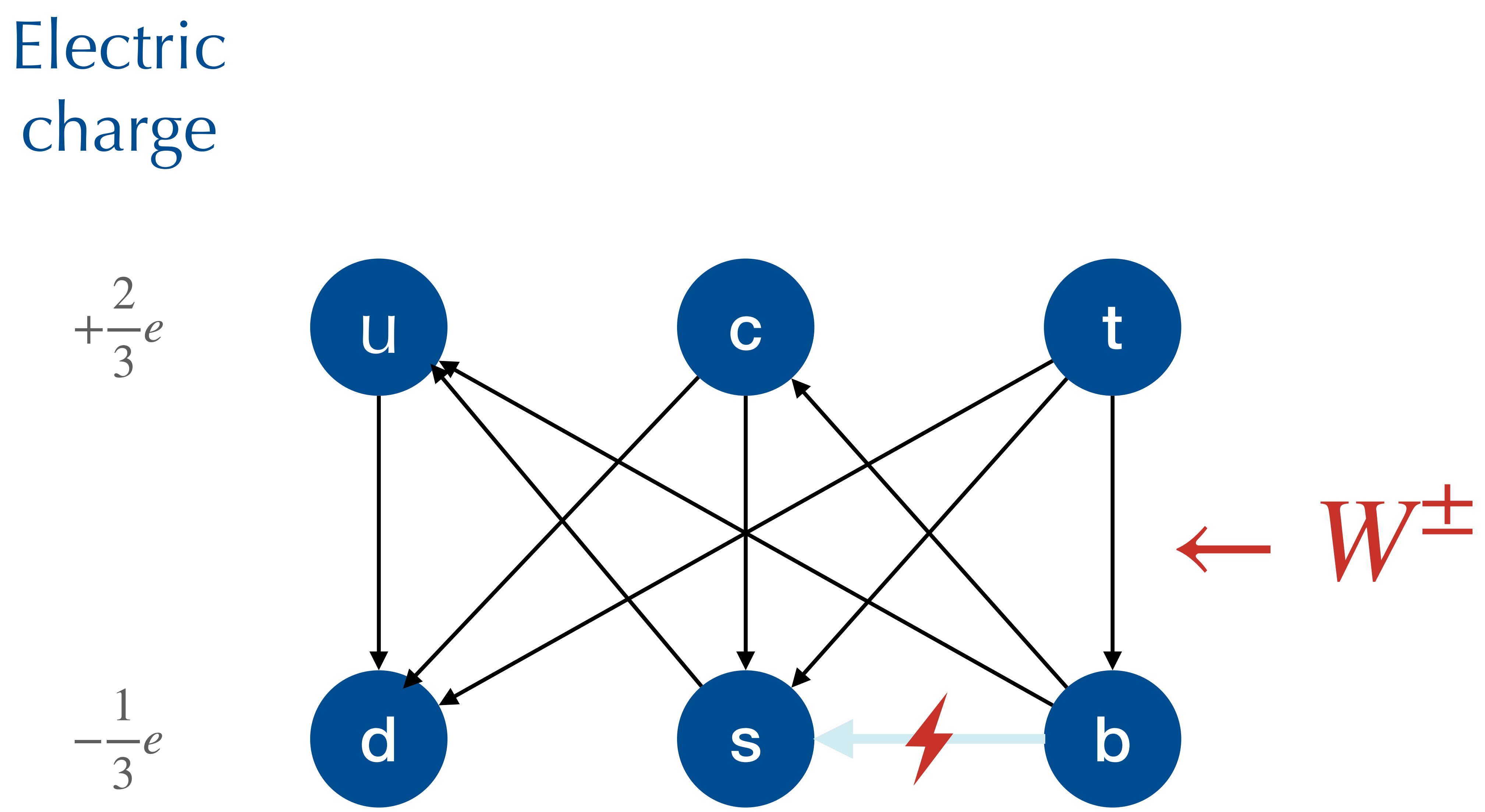




- $b \to s\ell^+\ell^-$ transition
- Direct $b \to s$ same charge
- Penguin diagrams

Flavour-changing neutral currents (FCNC)

So what about penguins?



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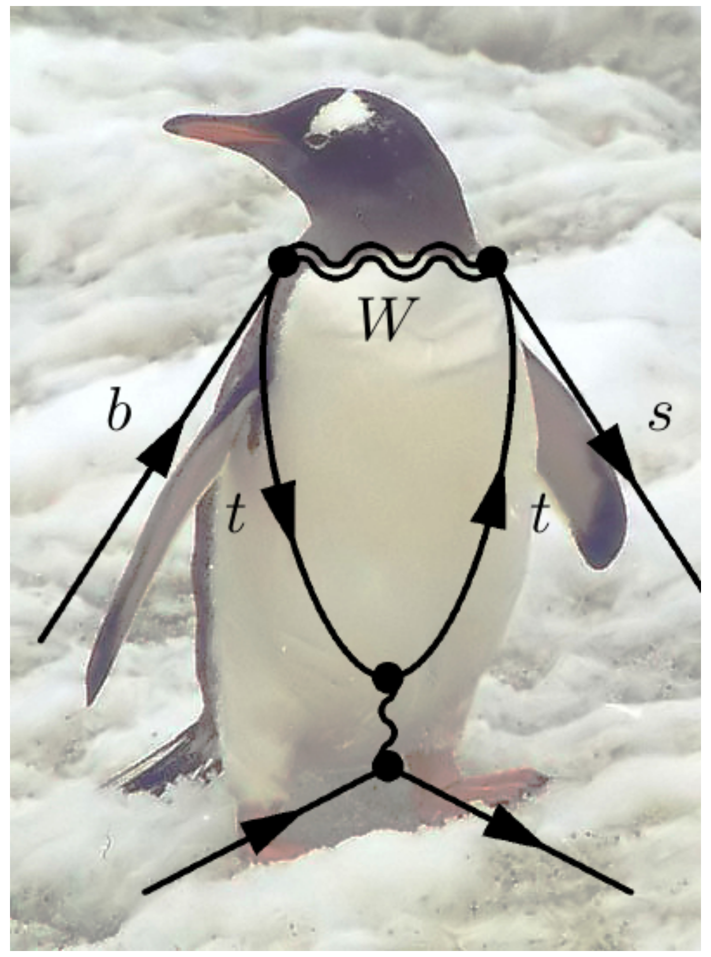
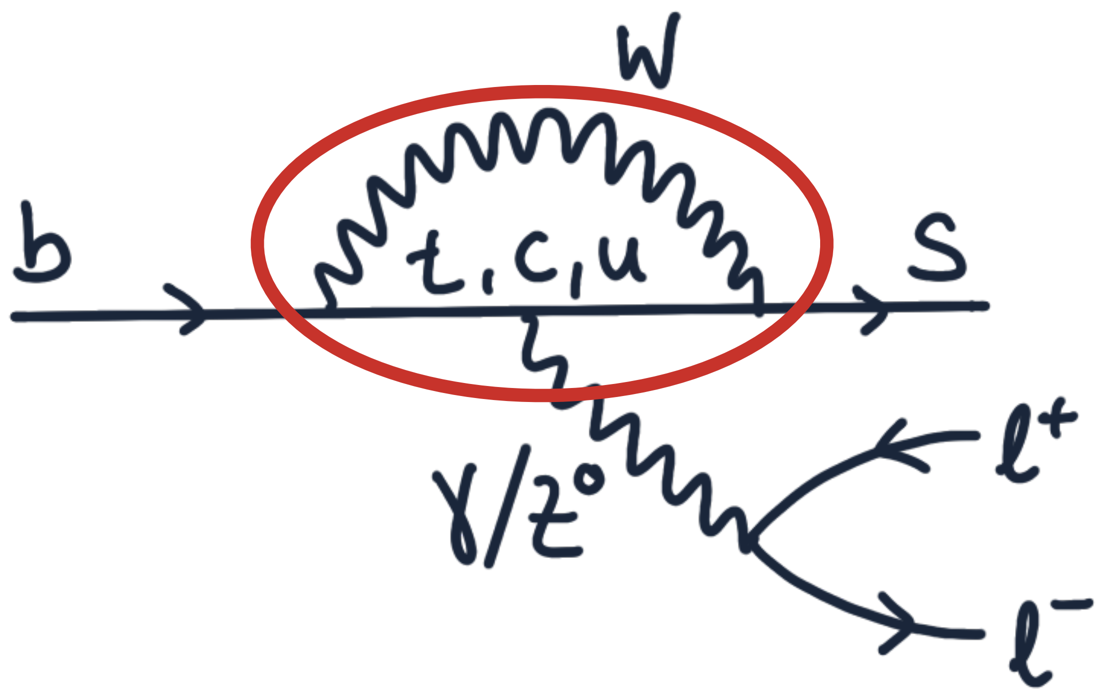
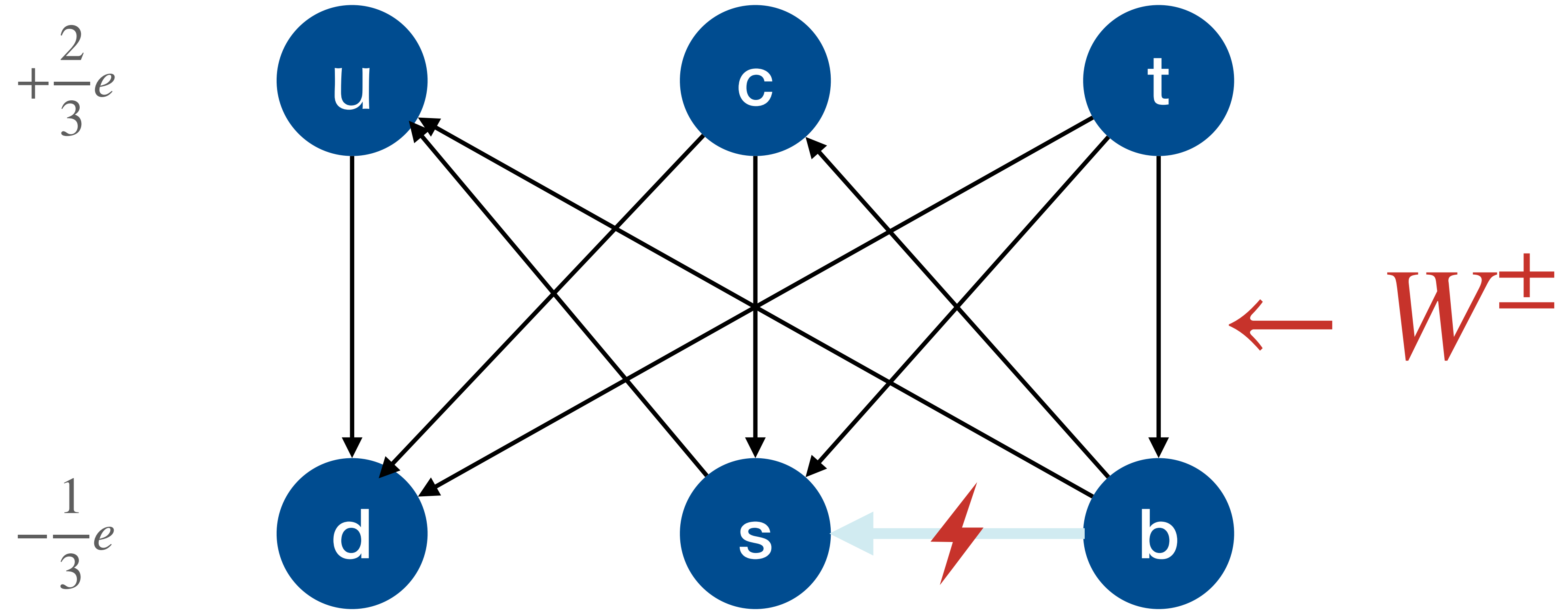




Strongly suppressed BF $\sim 10^{-6}$

So what about penguins?

Electric charge



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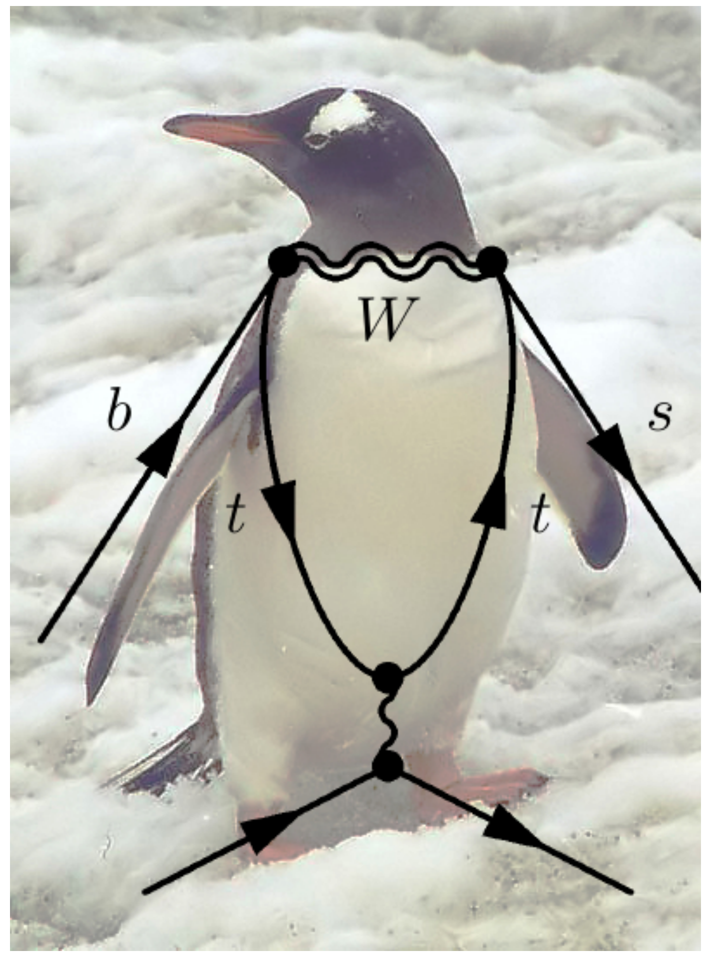
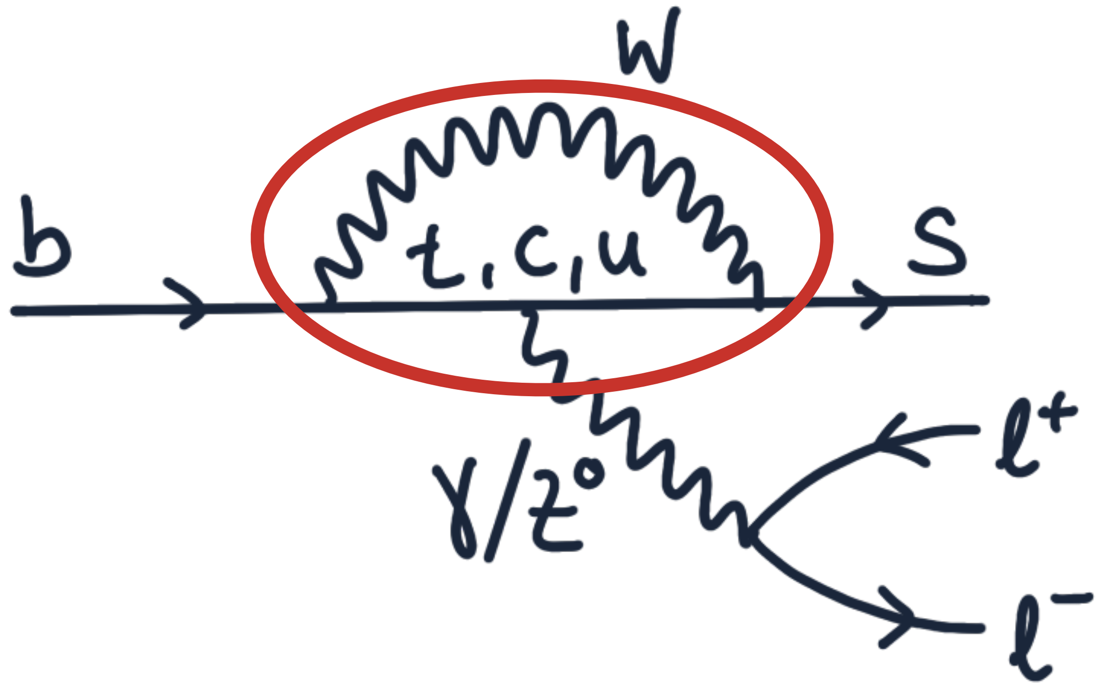
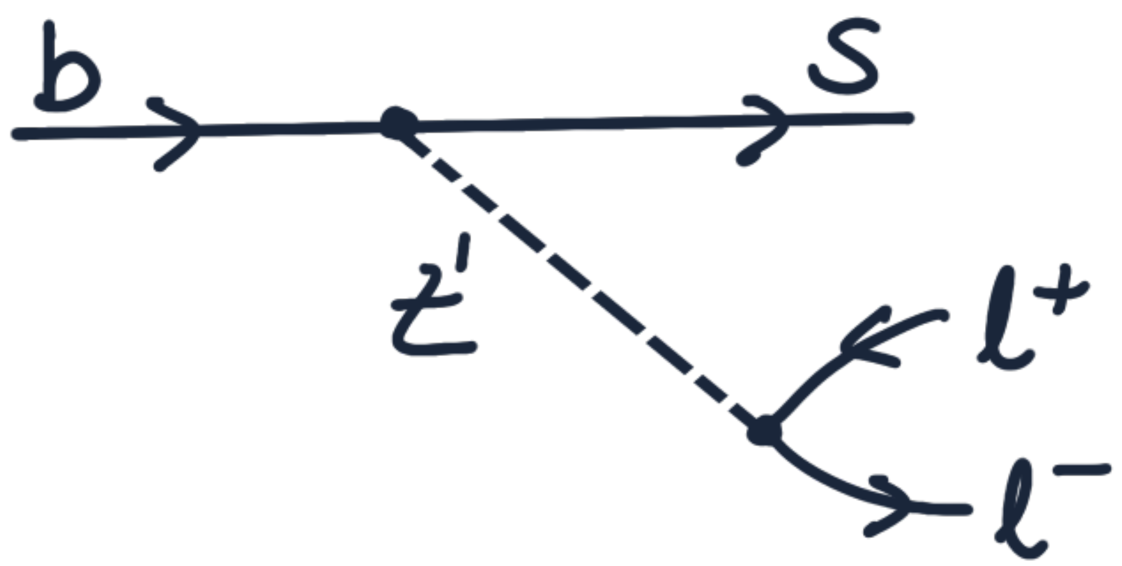




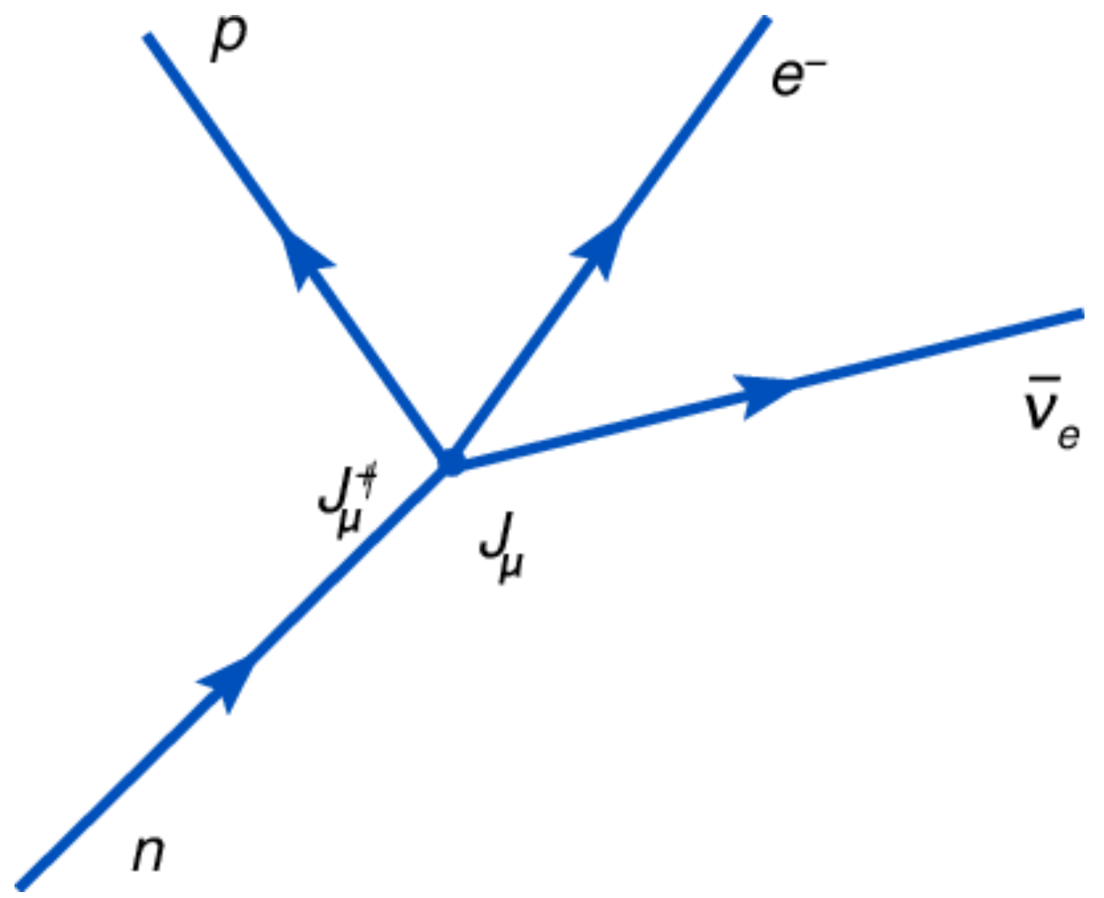


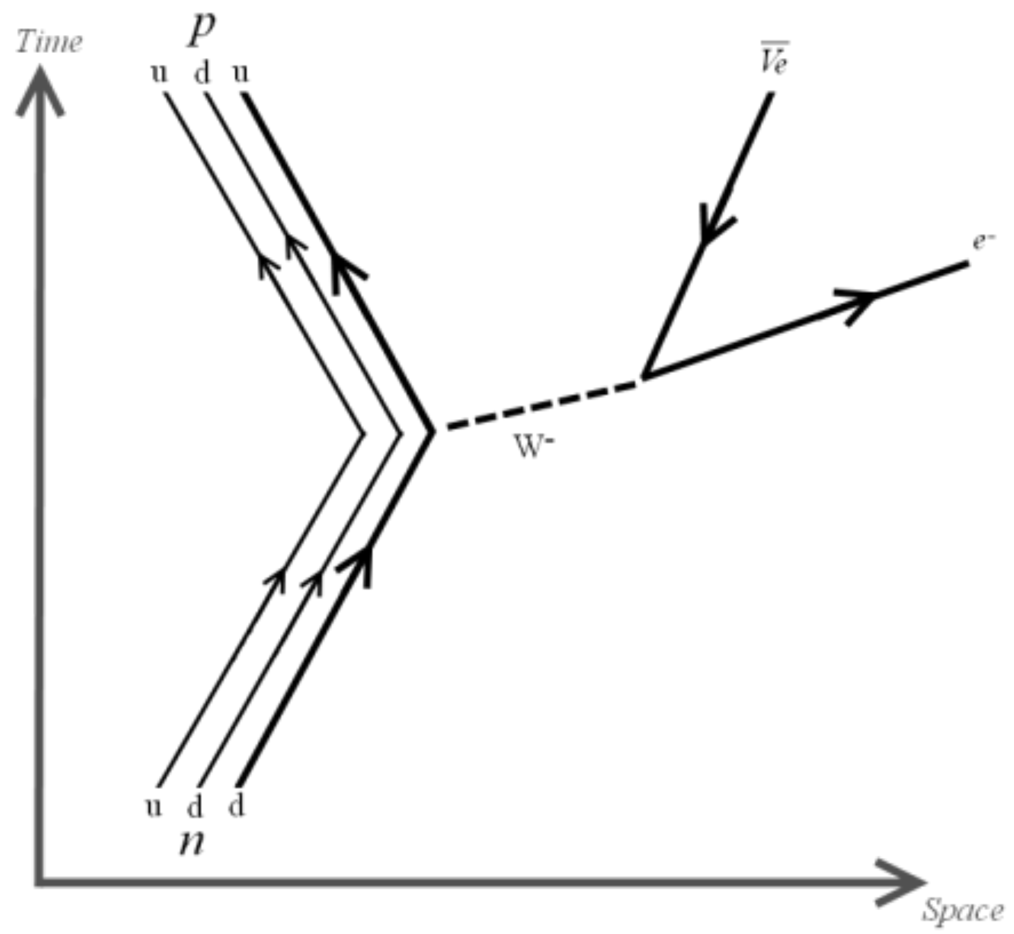
NP: no loop
→ larger BF

Effective Field Theories I

- Direct searches have not found anything

- Fermi Theory of β - decay: 1934





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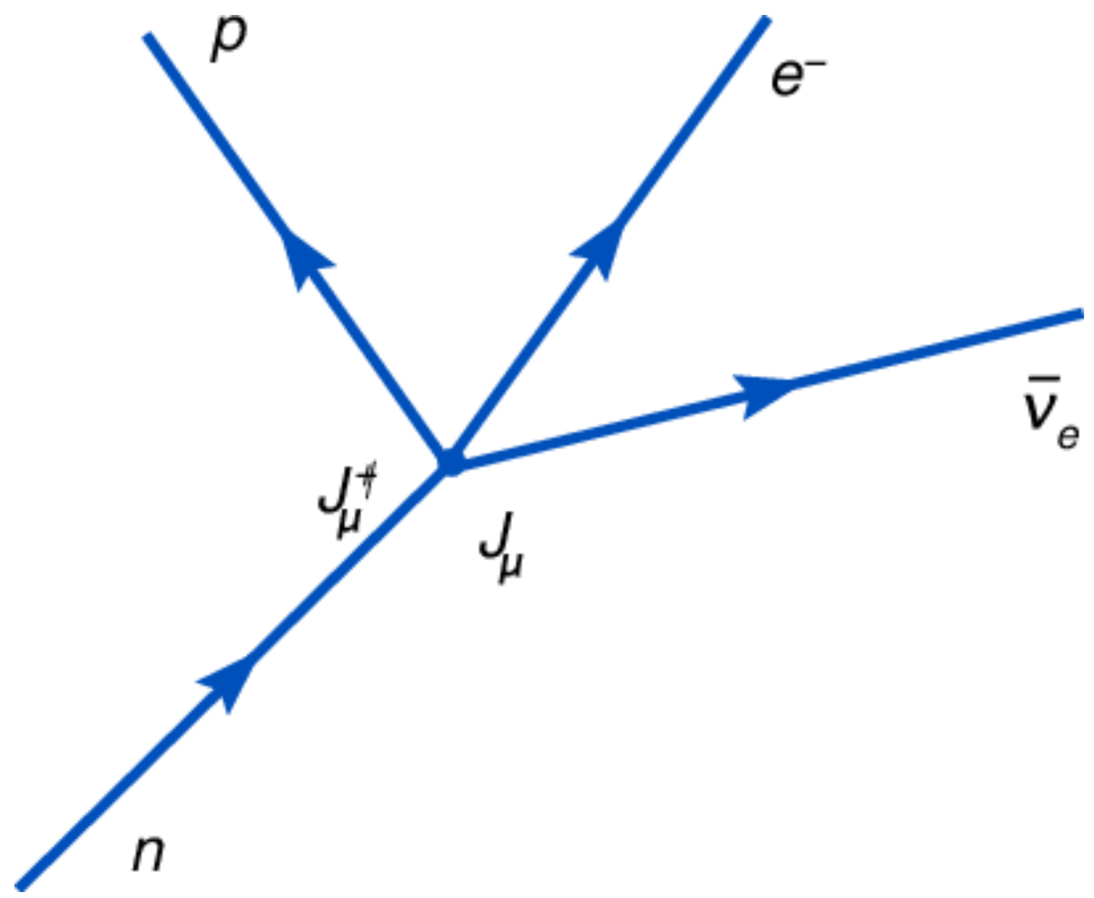
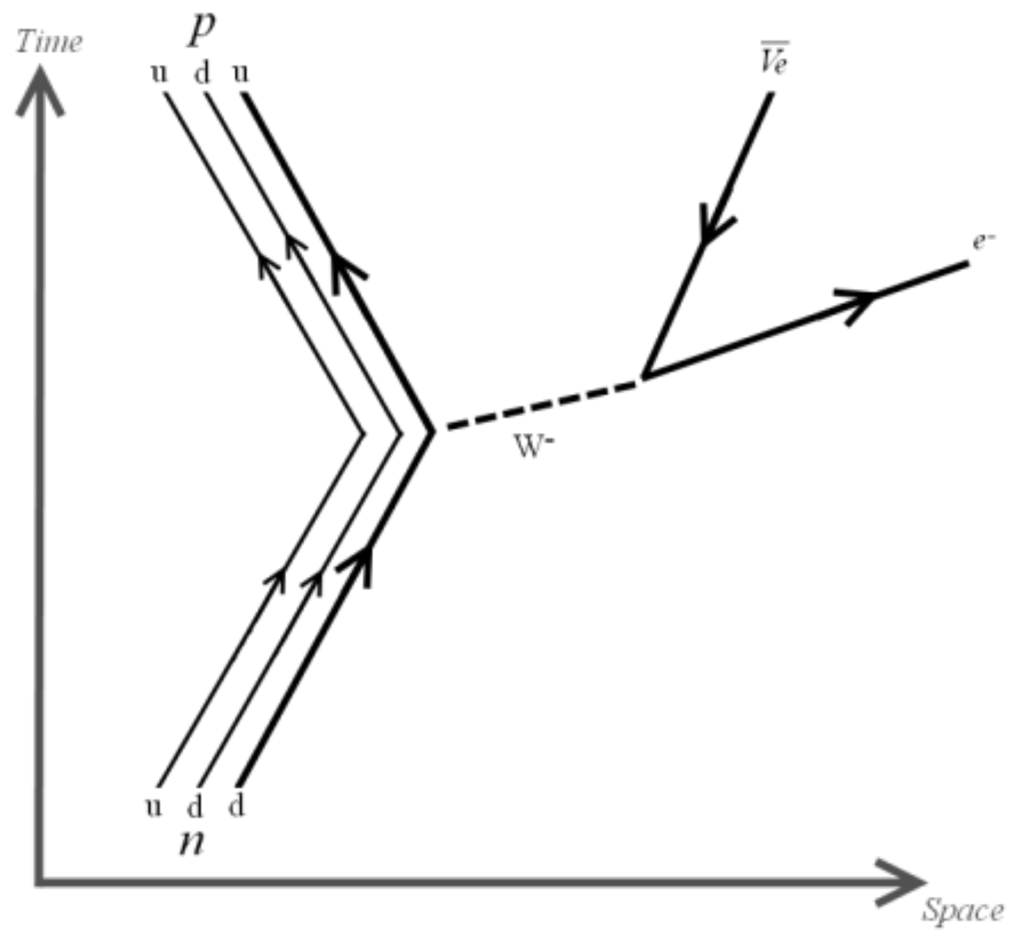
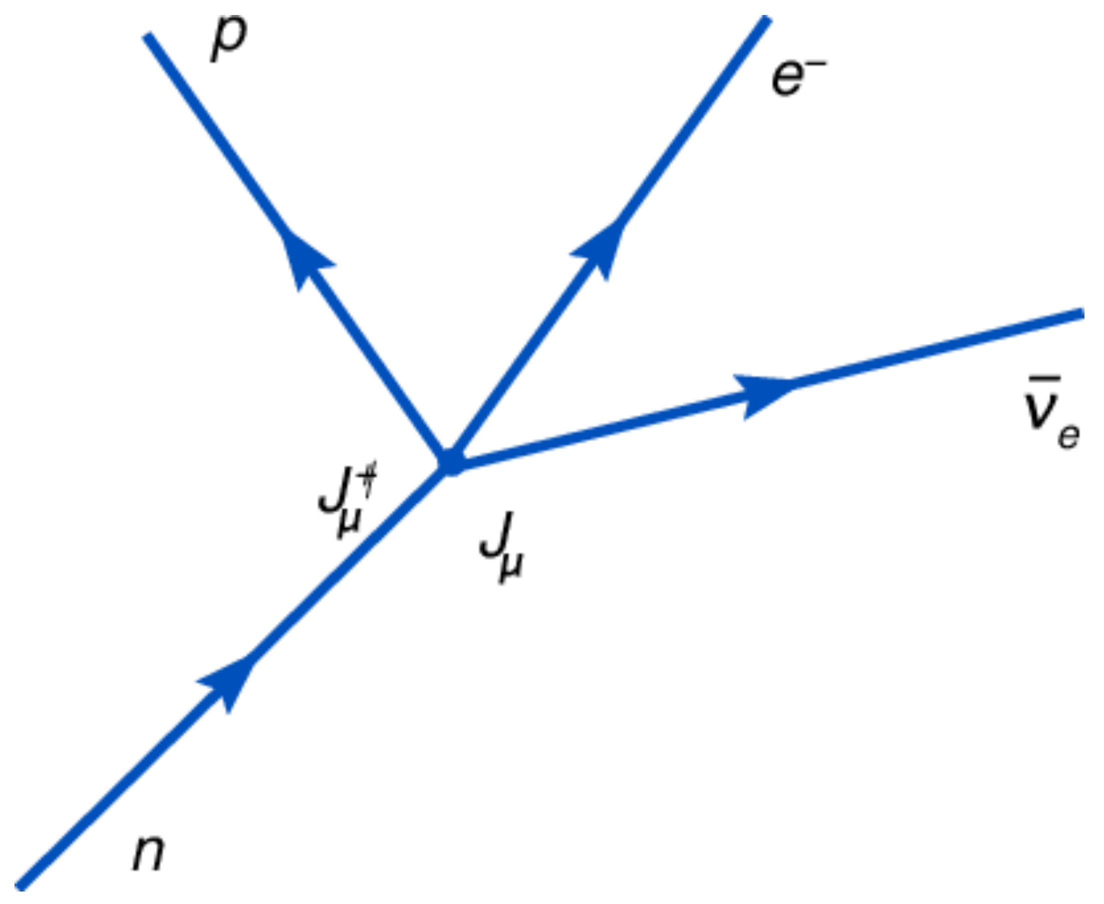
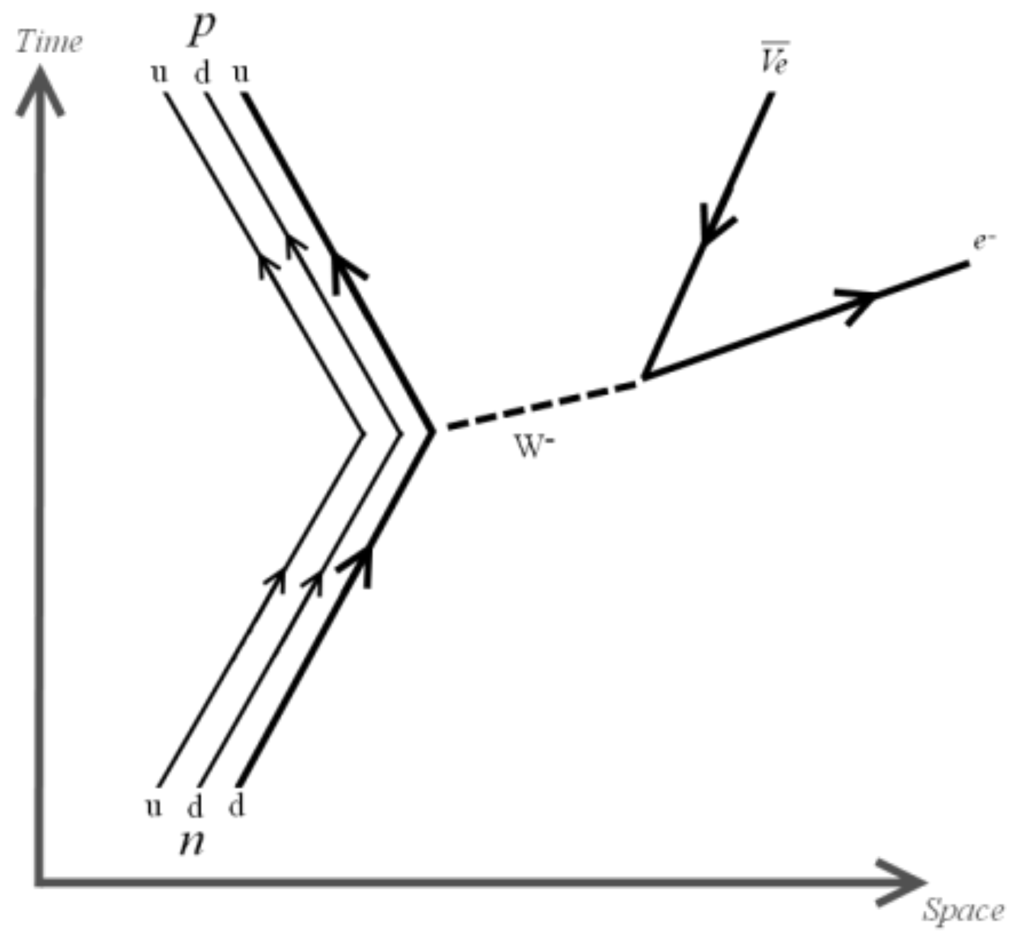




- Direct searches have not found anything
- Fermi Theory of β - decay: 1934
- W discovery : 25.01.1983
- Use **Effective Field Theory**



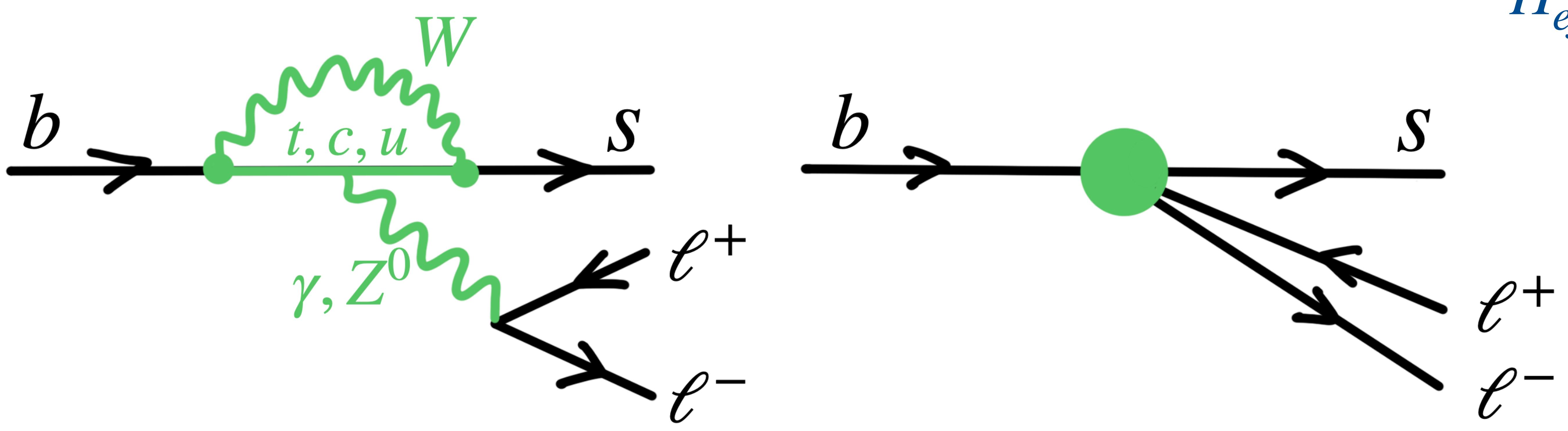


Can we learn something before getting here?

Effective Field Theories II

- EFT integrate out "heavy degree of freedom"

$$H_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_{i=1} \left(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \right)$$



- Operator O_i : low energy part

Effective Field Theories II

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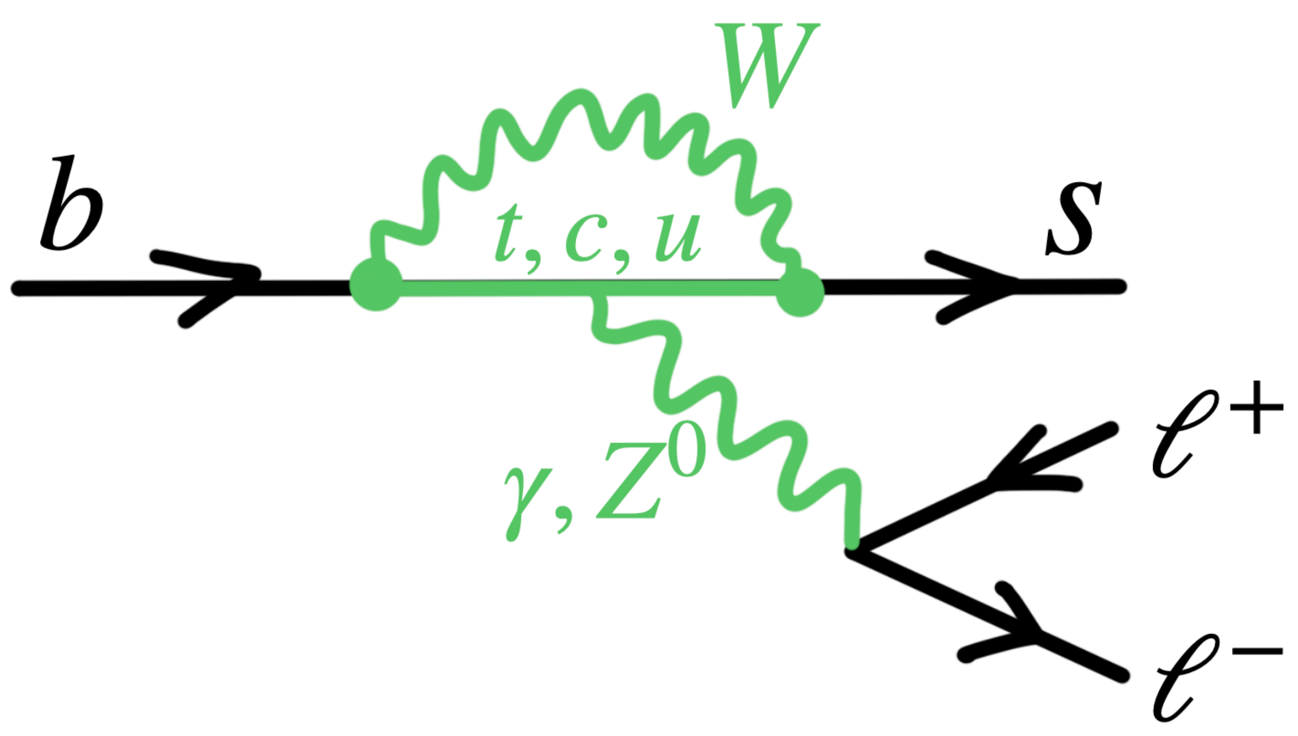
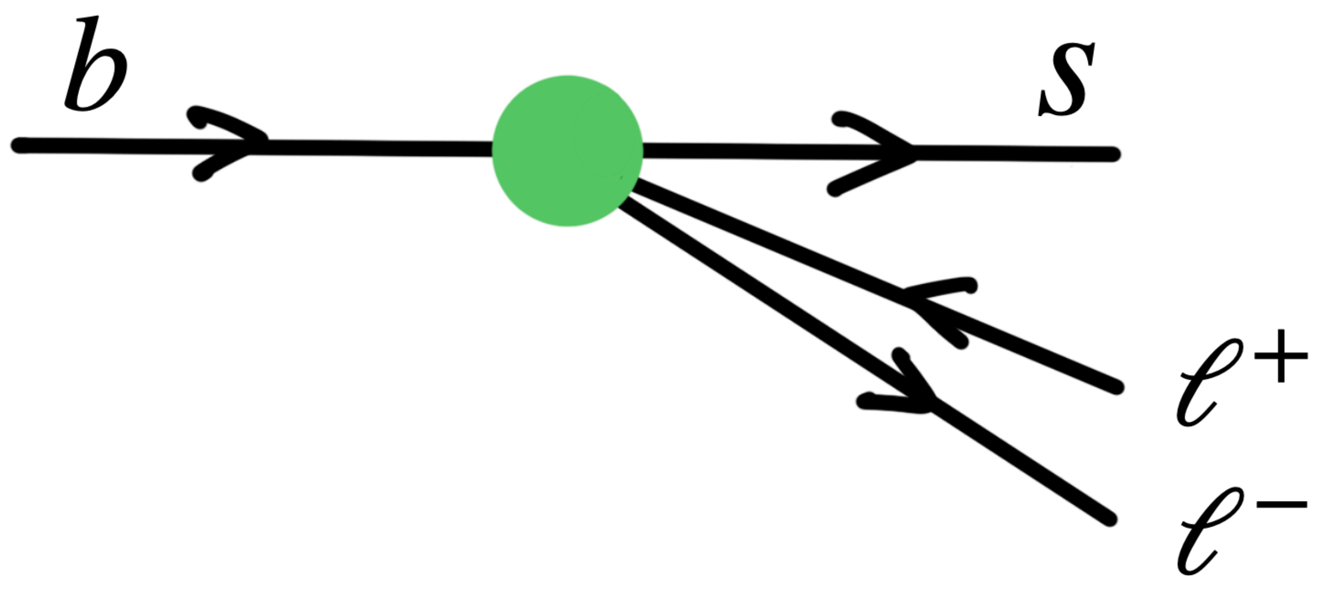
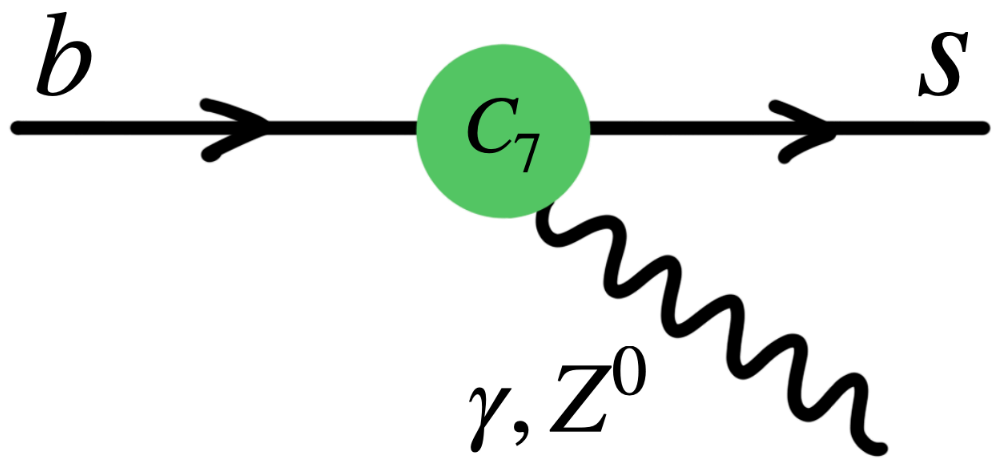
$$H_{eff} \approx -\frac{4G_F}{\sqrt{2}} V_{CKM} \sum_{i=1} \left(C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) \right)$$



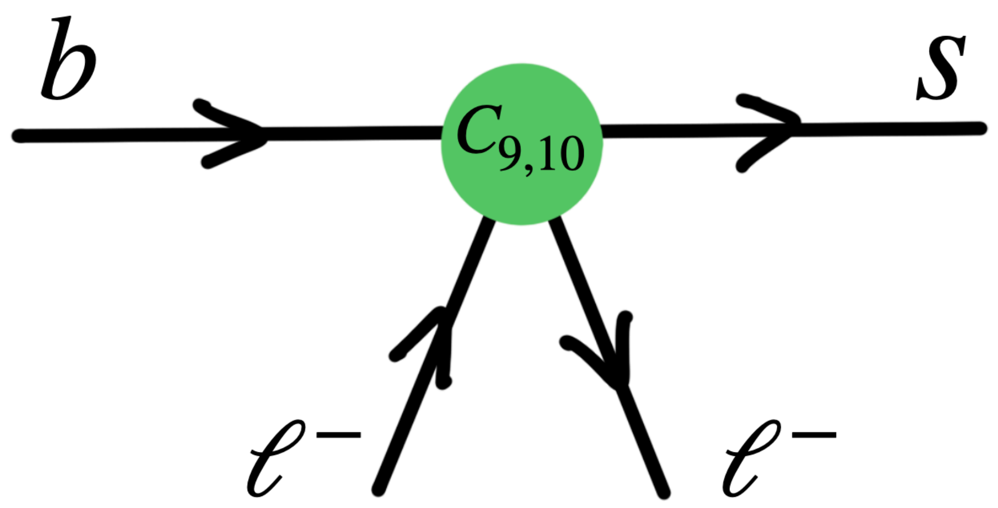




- Operator O_i : low energy part

- **Wilson coefficients** C_i : high energy part

  → something like coupling strength, can be measured!



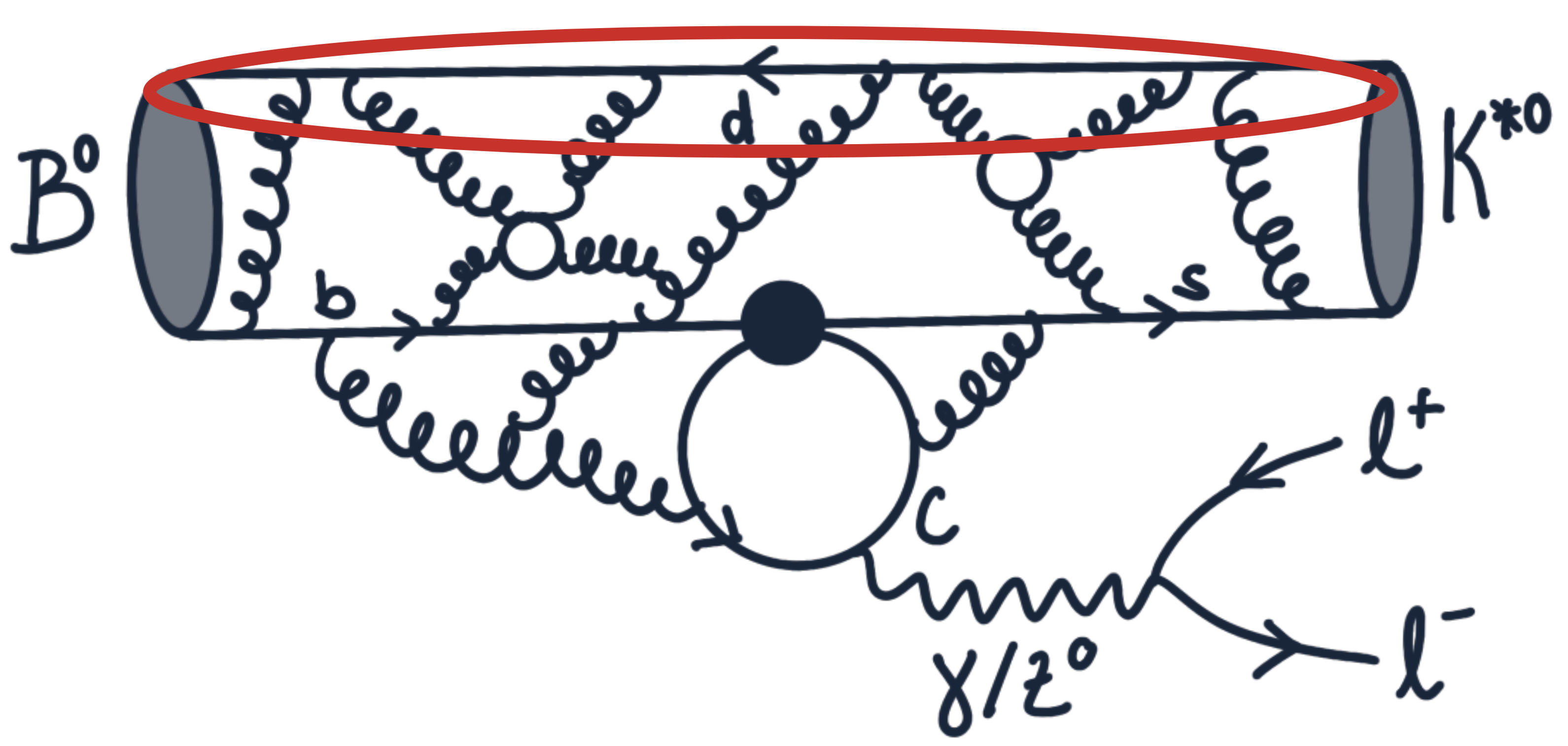
How can we measure them?

- Strong interaction → **hadron bound states**
- Need to predict hadronic state

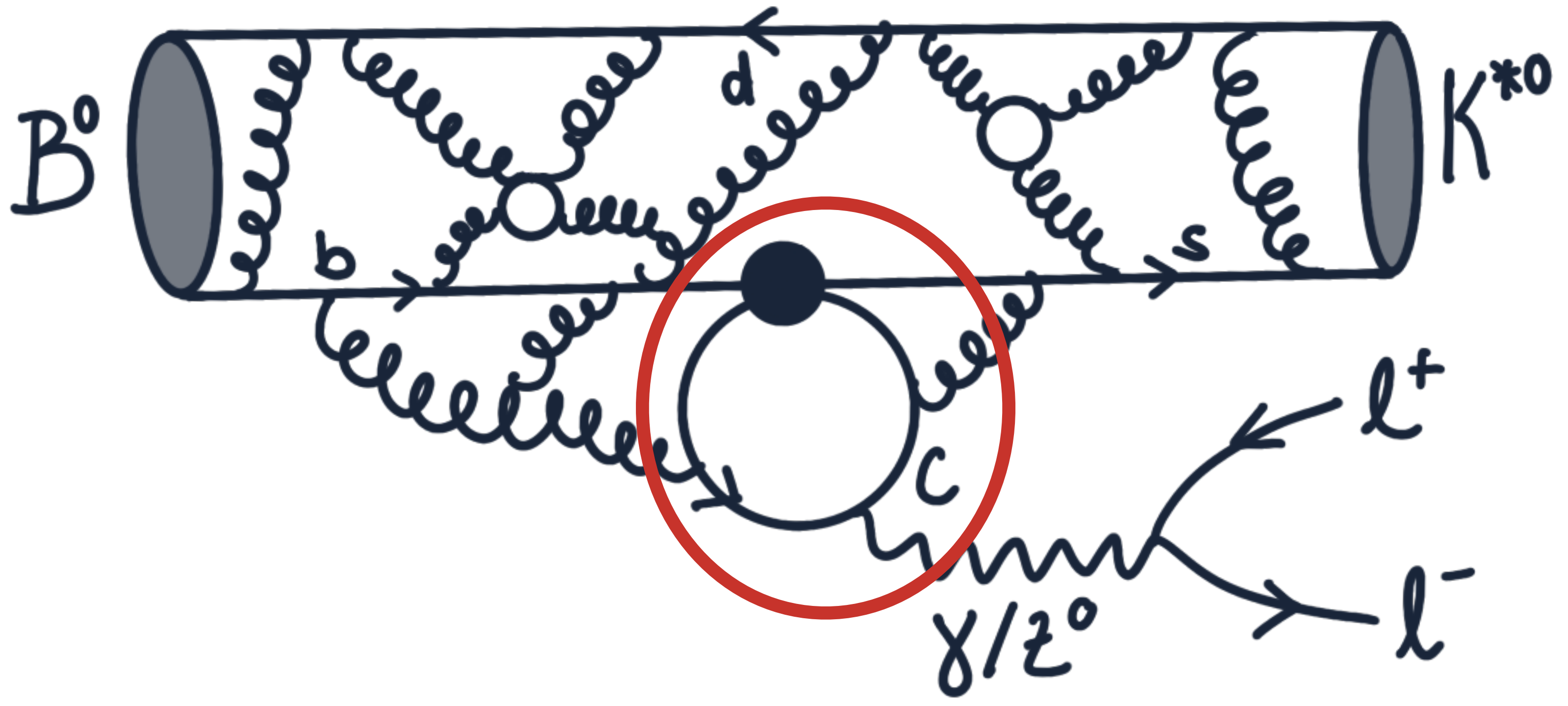
  → non-pertubative

  → form factor predictions

Spectator quark



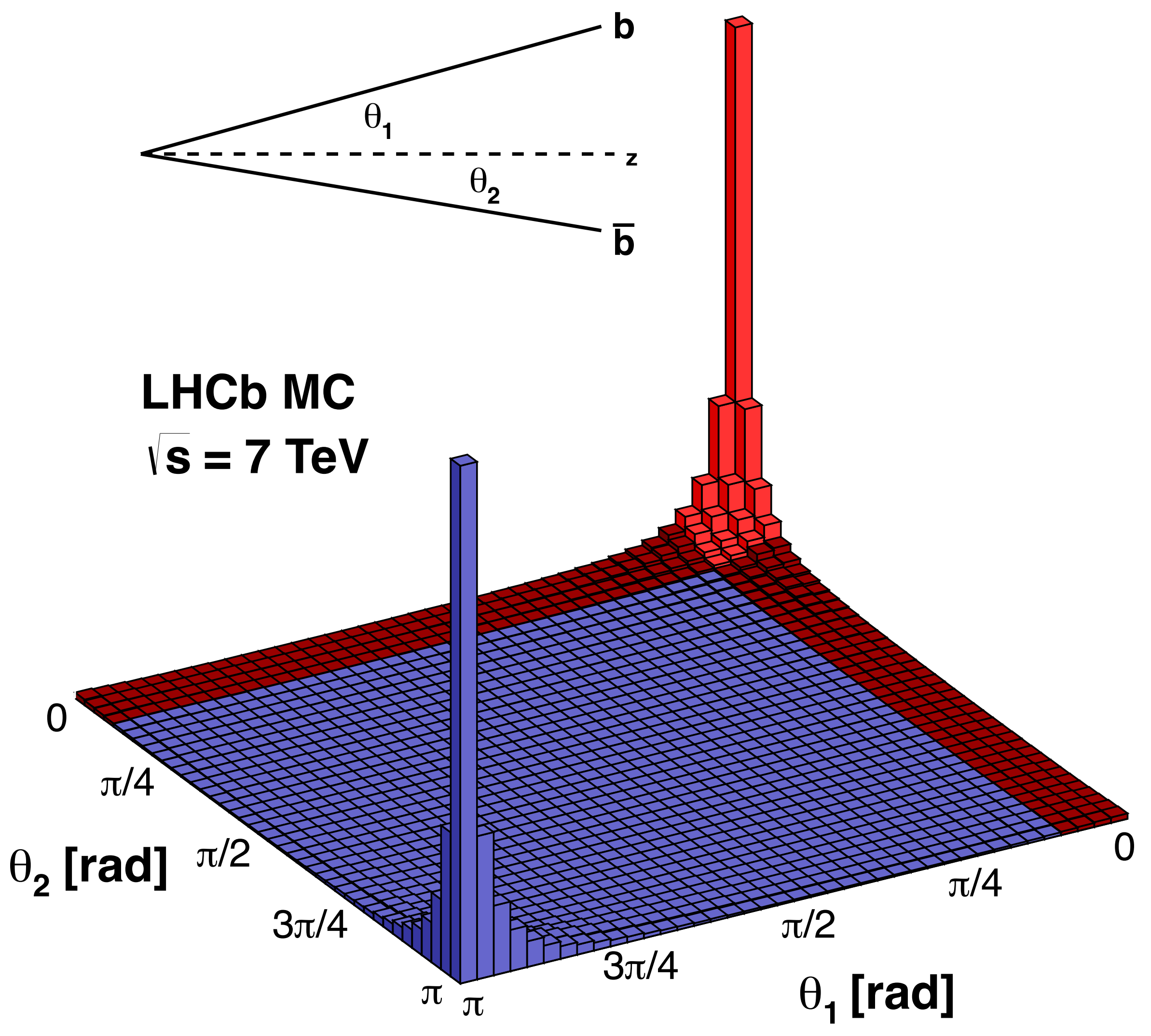
- Strong interaction → hadron bound states
- Need to predict hadronic state
  - → non-pertubative
  - → form factor predictions
- **Charm loops**
- Measure $b \to s\ell^+\ell^-$ in decay chains of hadrons

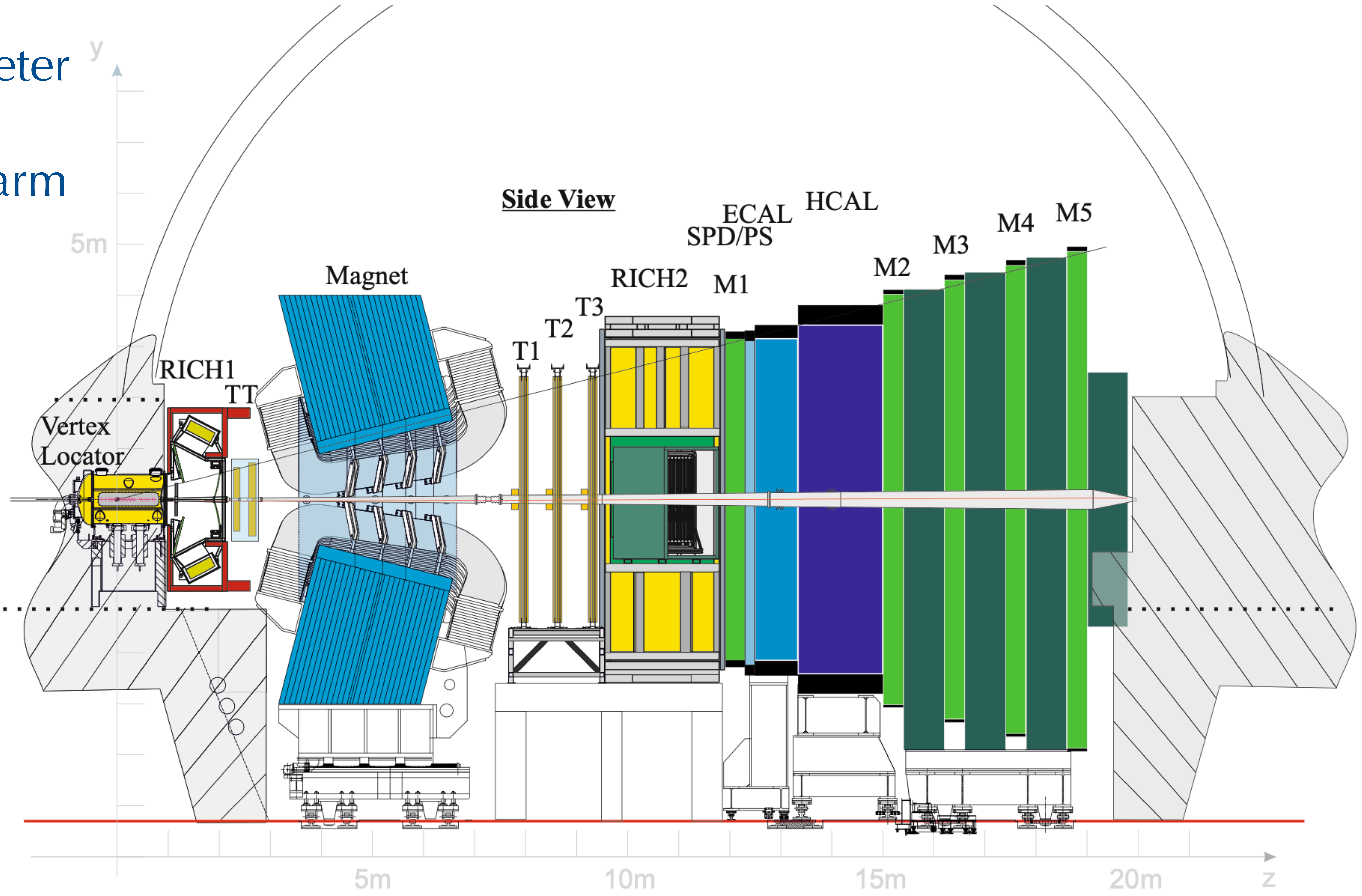


The LHCb experiment

- Single-arm forward spectrometer
- Optimised for beauty and charm

  → forward boost

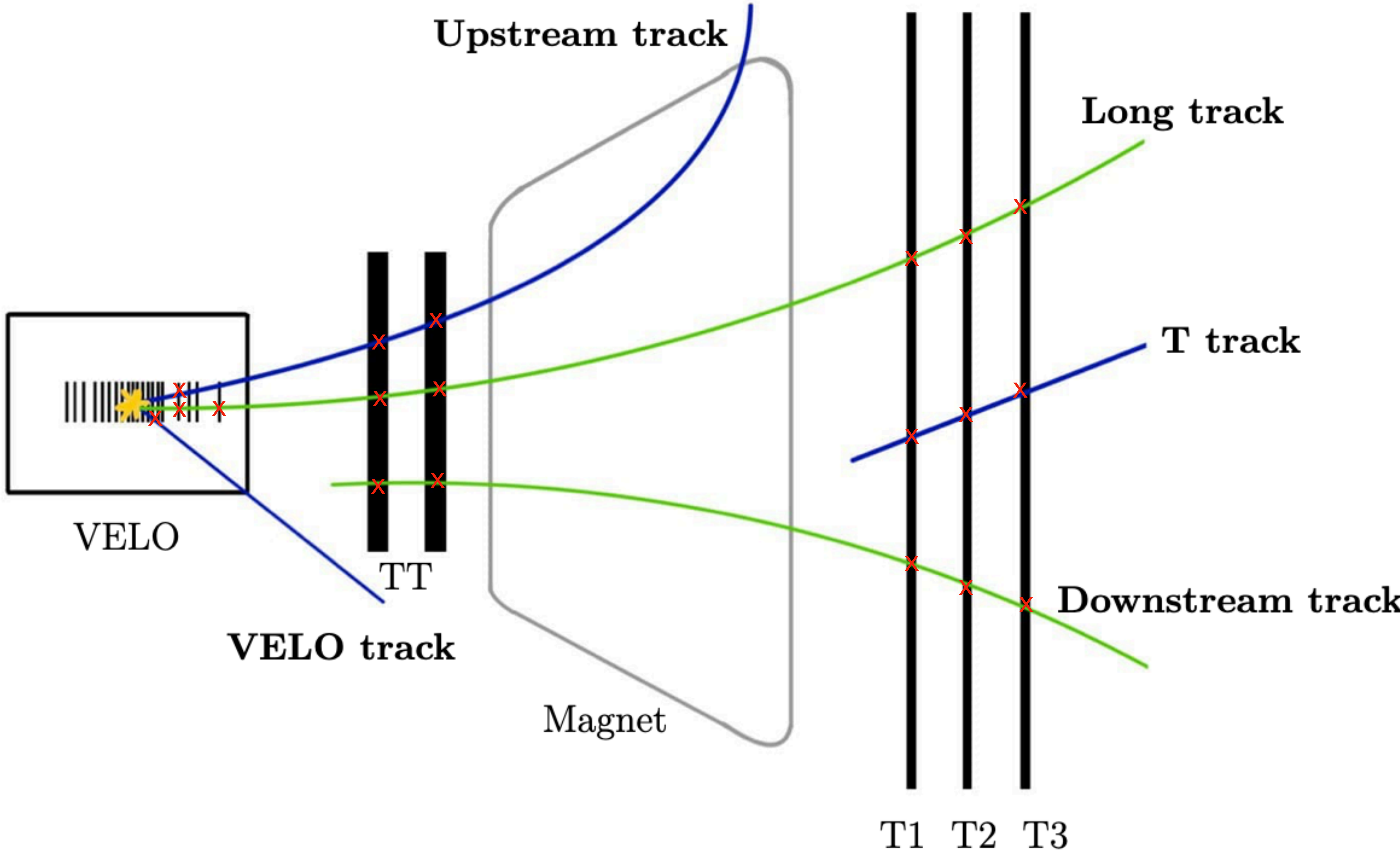




Why is it a spectrometer?

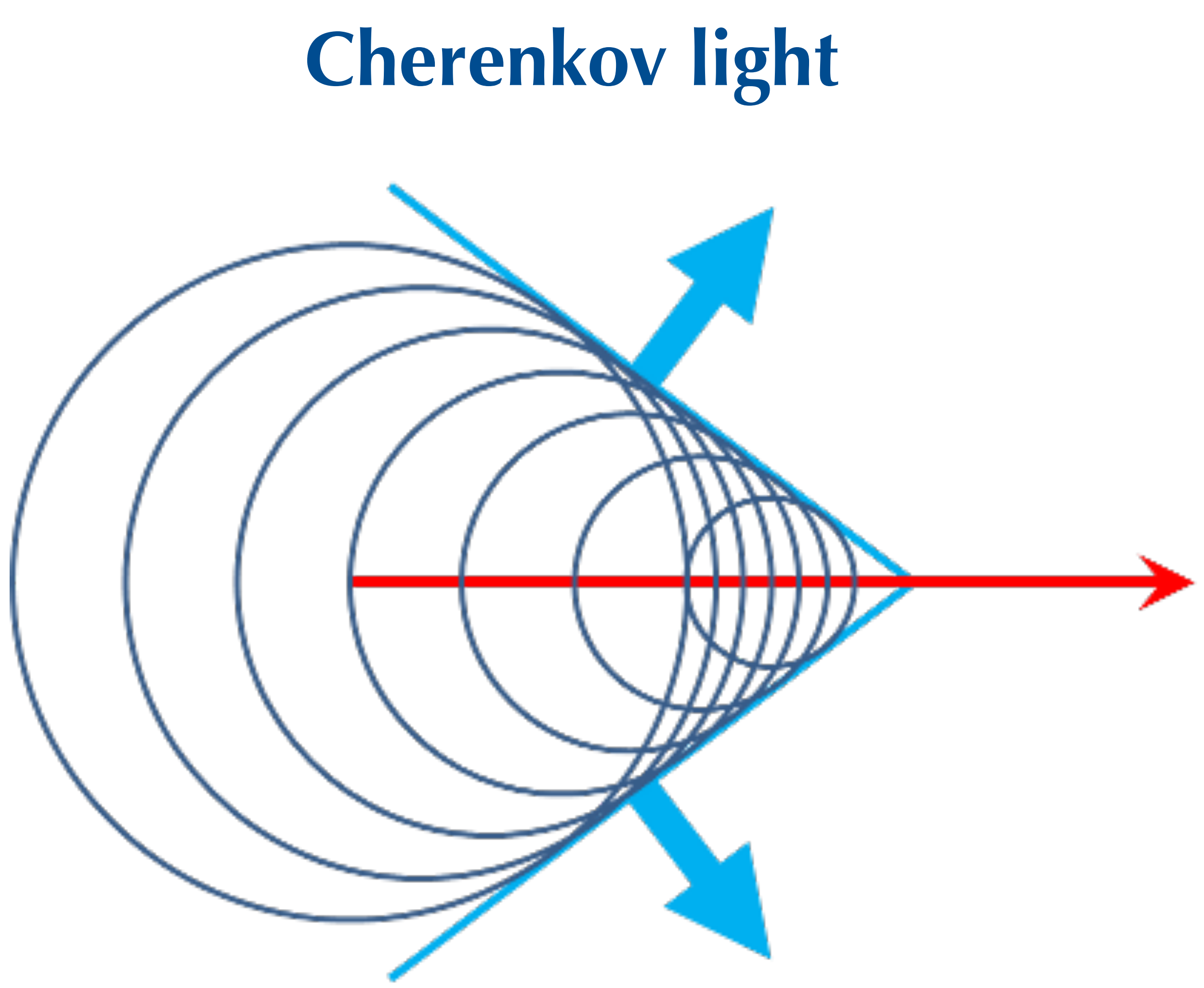
- Tracking of charged particles

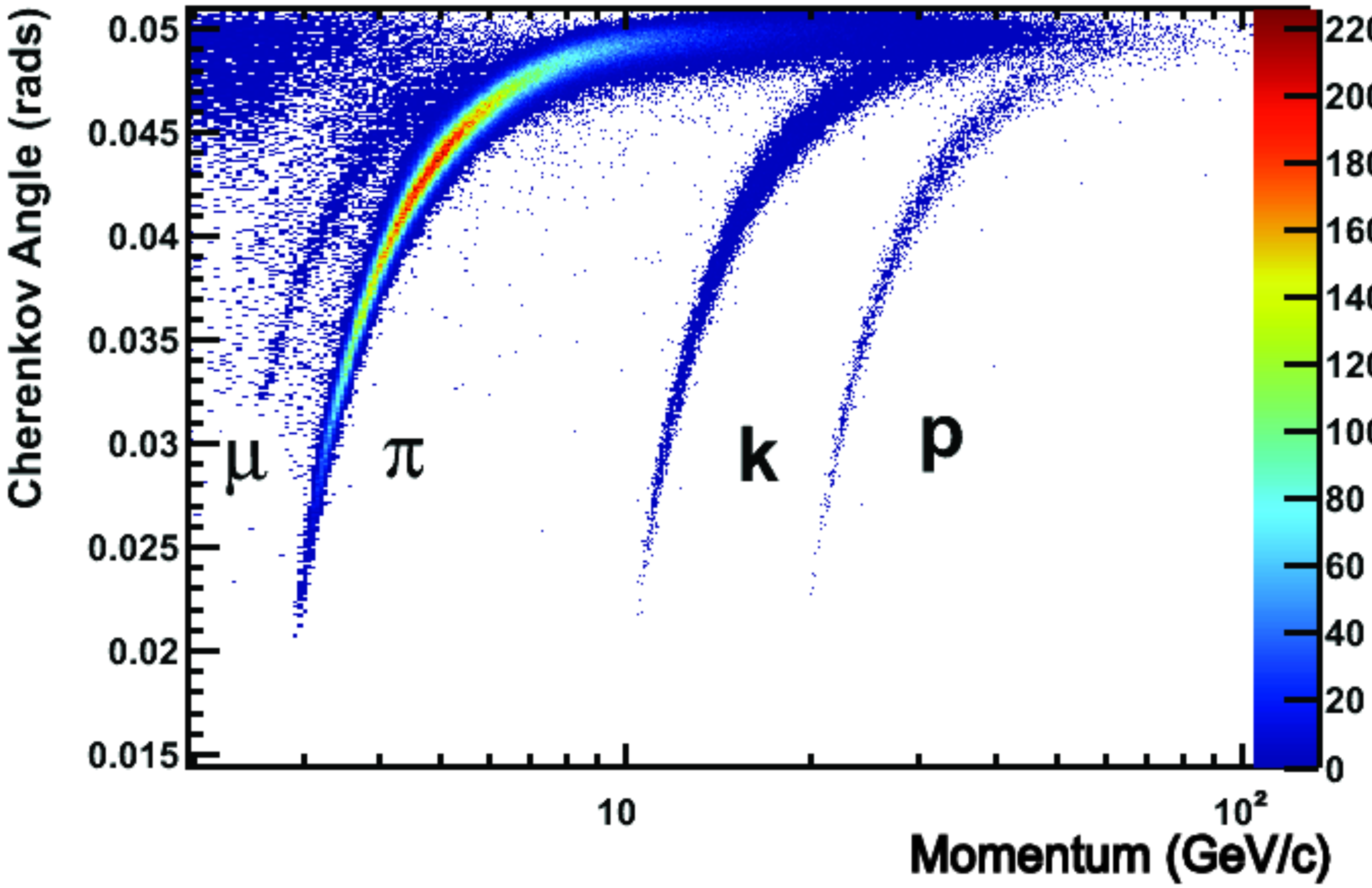
Momentum through Lorentz force



Why is it a spectrometer?

- Tracking of charged particles
- RICH system





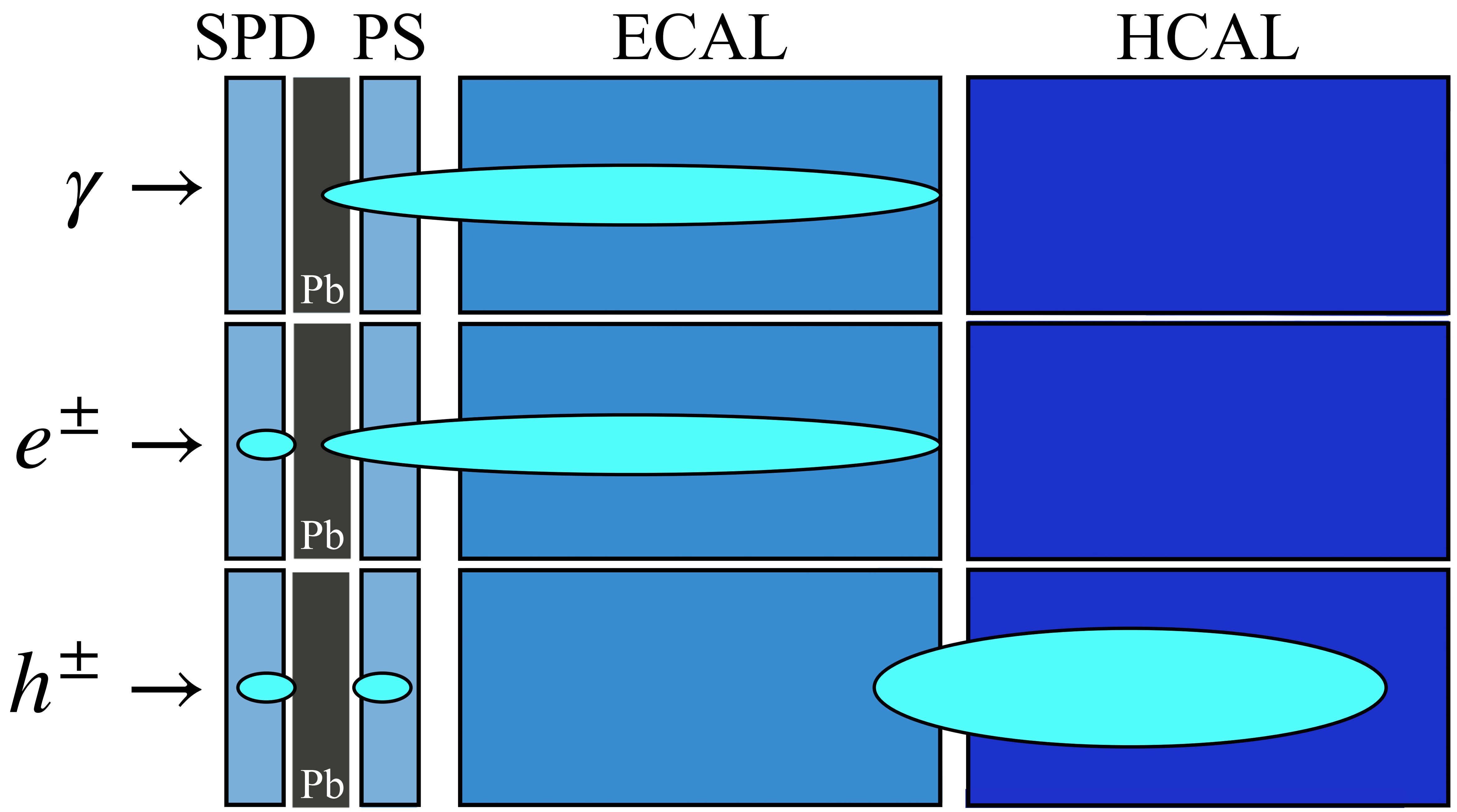
Angle is velocity dependent $v = m \cdot p$

$$E = \sqrt{m^2c^4 + p^2c^2}$$

Why is it a spectrometer?

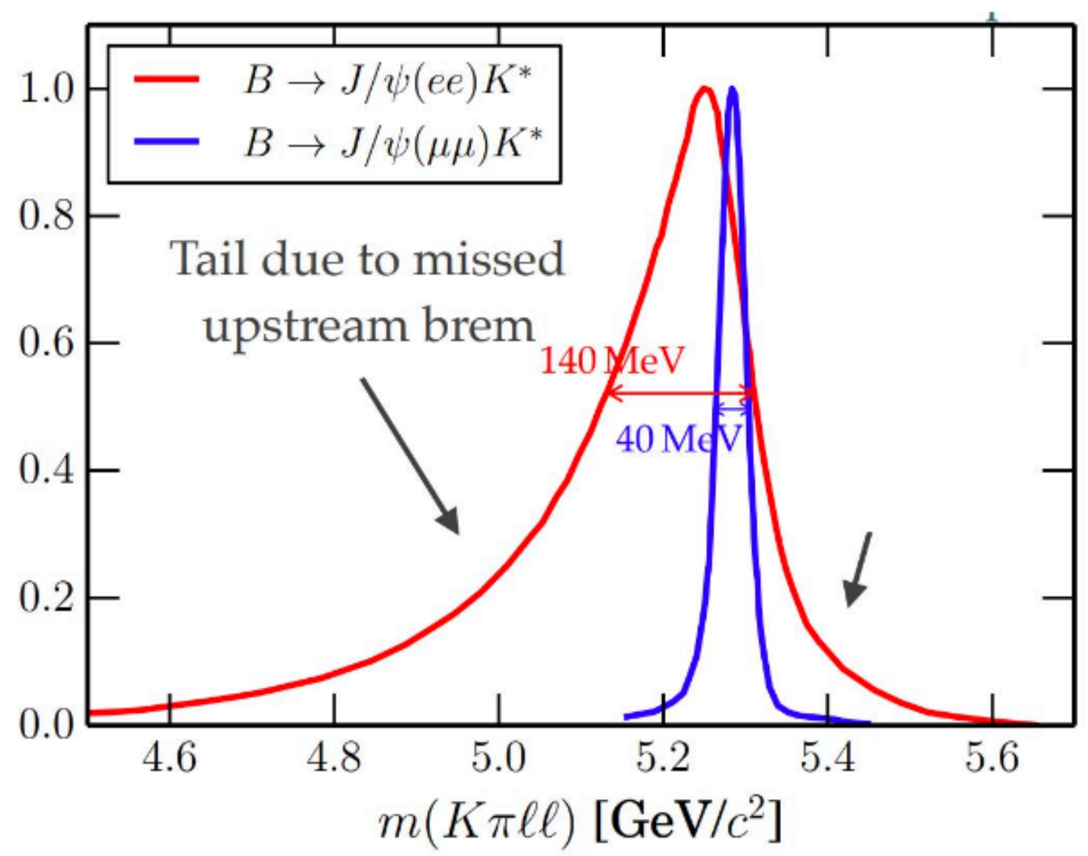
- Tracking of charged particles
- RICH system
- CALO for PID for all

  → energy for neutrals only

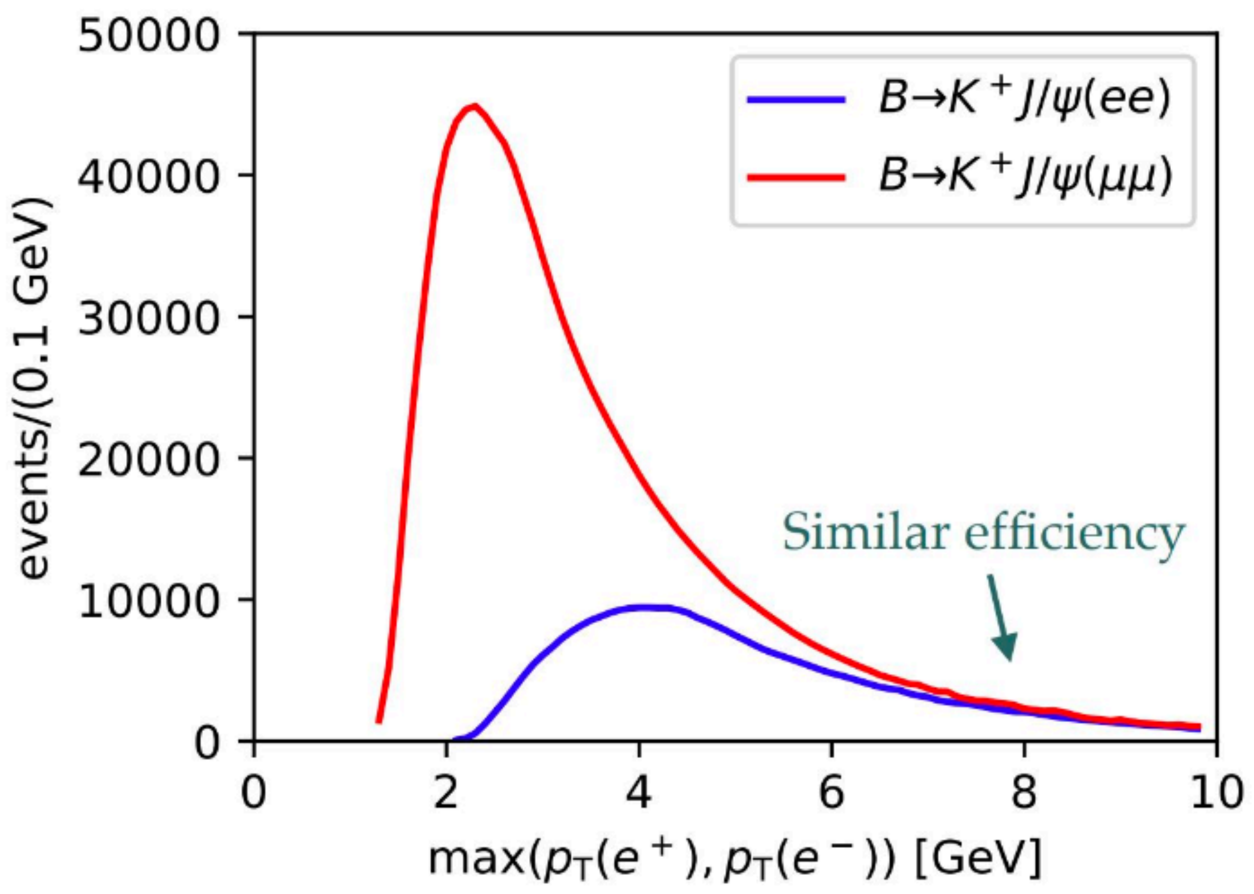


Exkurs: Electron vs Muon

Worse momentum resolution



Reduced signal efficiency



- Muons easy to identify
- Electrons suffer significantly from bremsstrahlung loss

Exkurs: Electron vs Muon

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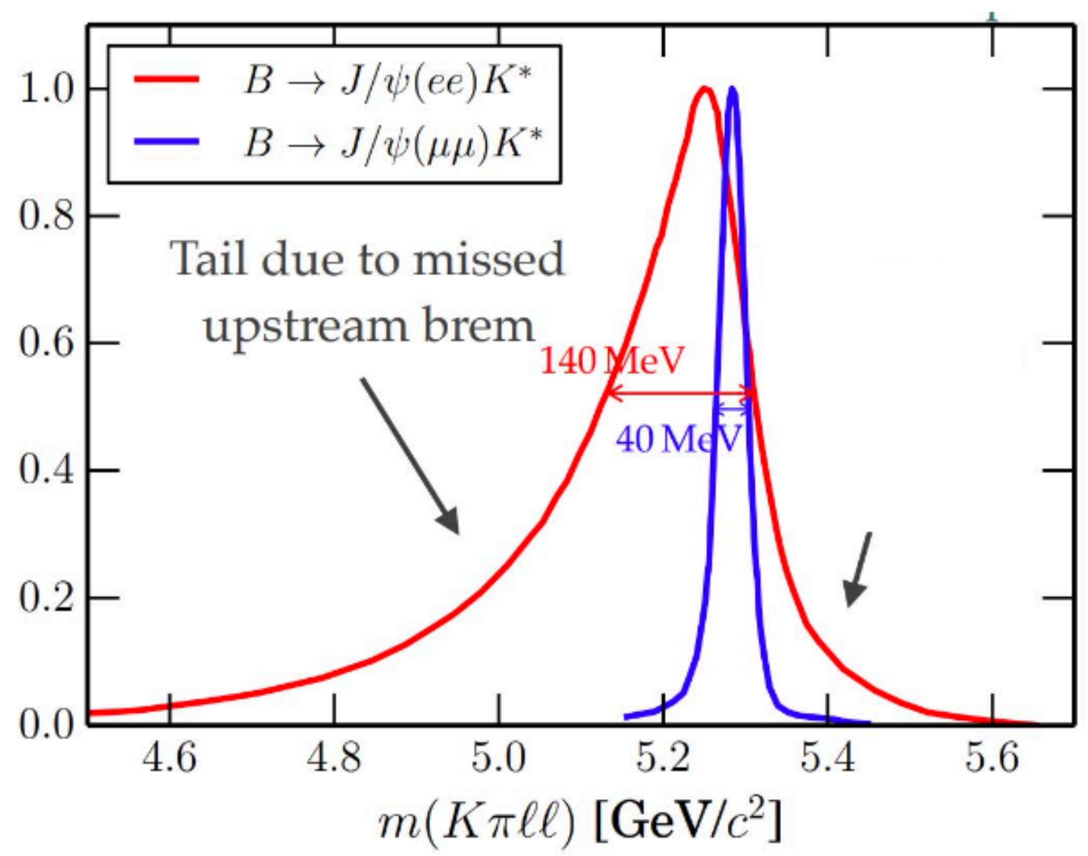

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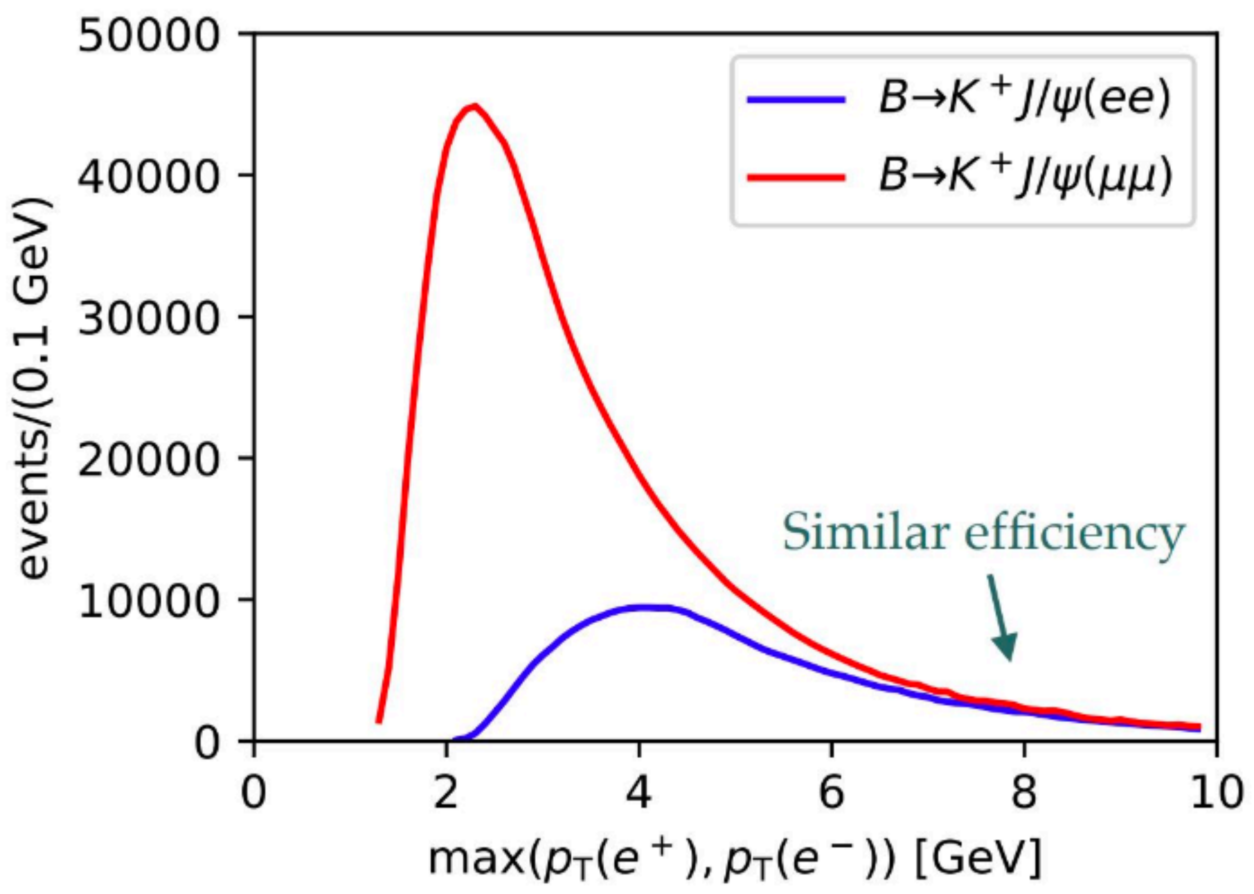

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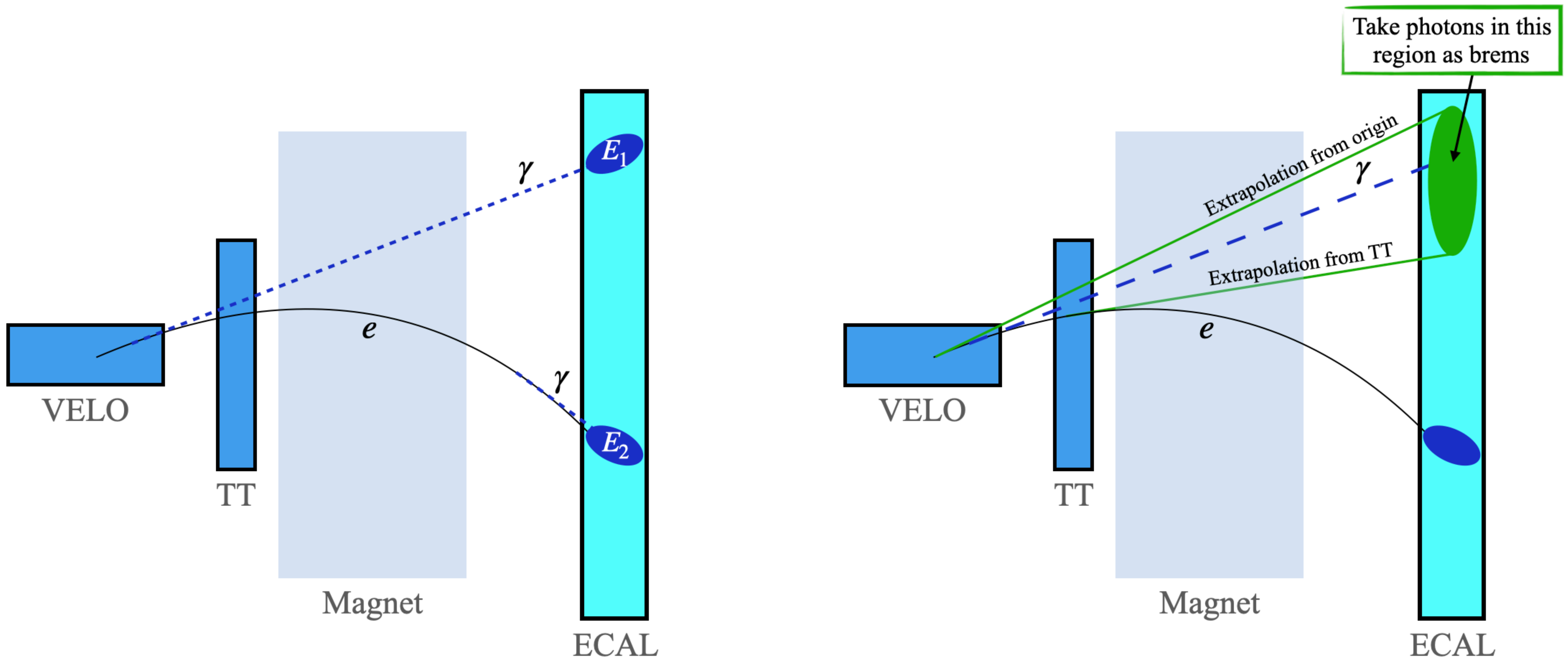
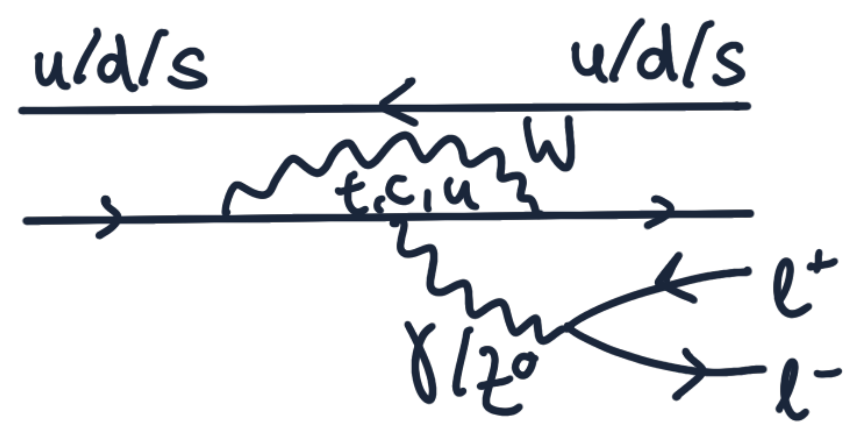


What channel do we choose?

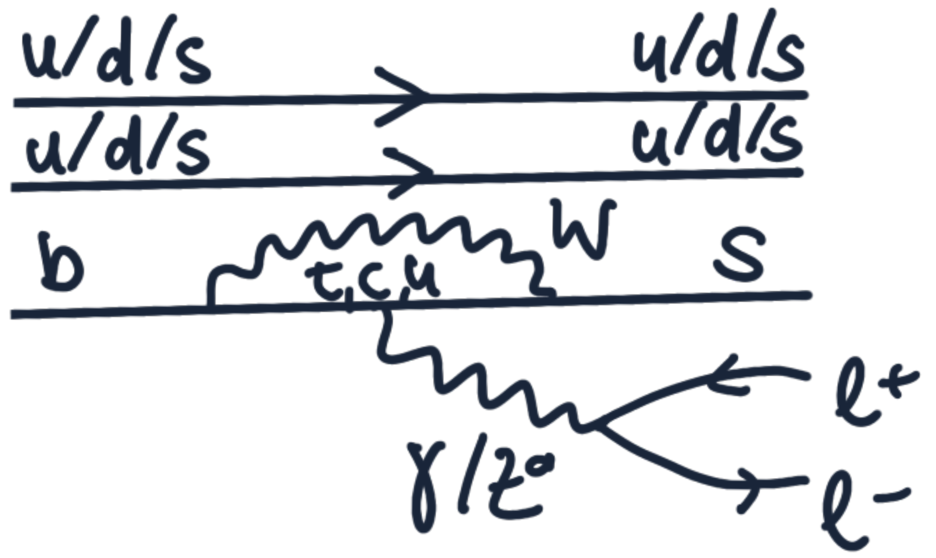
Mesons

$0 \to 0$	$0 \to 1$	$0 \to 2$
$B \to K\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$	$B \to K_2^*(1430)\ell^+\ell^-$
$B_s \to f_0(980)\ell^+\ell^-$	$B_s \to \phi\ell^+\ell^-$	$B_s \to f_2(1525)\ell^+\ell^-$



Baryons

$1/2 \to 1/2$	$1/2 \to 3/2$	$1/2 \to 5/2$
$\Lambda_b^0 \to \Lambda\ell^+\ell^-$	$\Lambda_b^0 \to \Lambda^*(1520)\ell^+\ell^-$	$\Lambda_b^0 \to \Lambda^*(1820)\ell^+\ell^-$
$\Xi_b \to \Xi\ell^+\ell^-$	$\Xi_b \to \Xi^*(1820)\ell^+\ell^-$	
	$\Omega_b^- \to \Omega^-\ell^+\ell^-$	



spin = intrinsic angular momentum

What channel do we choose?

Mesons

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	$\boxed{\Omega_b^- \to \Omega^-\ell^+\ell^-}$	

'narrow' final state hadron

→ easy to select

'broad' final state hadron

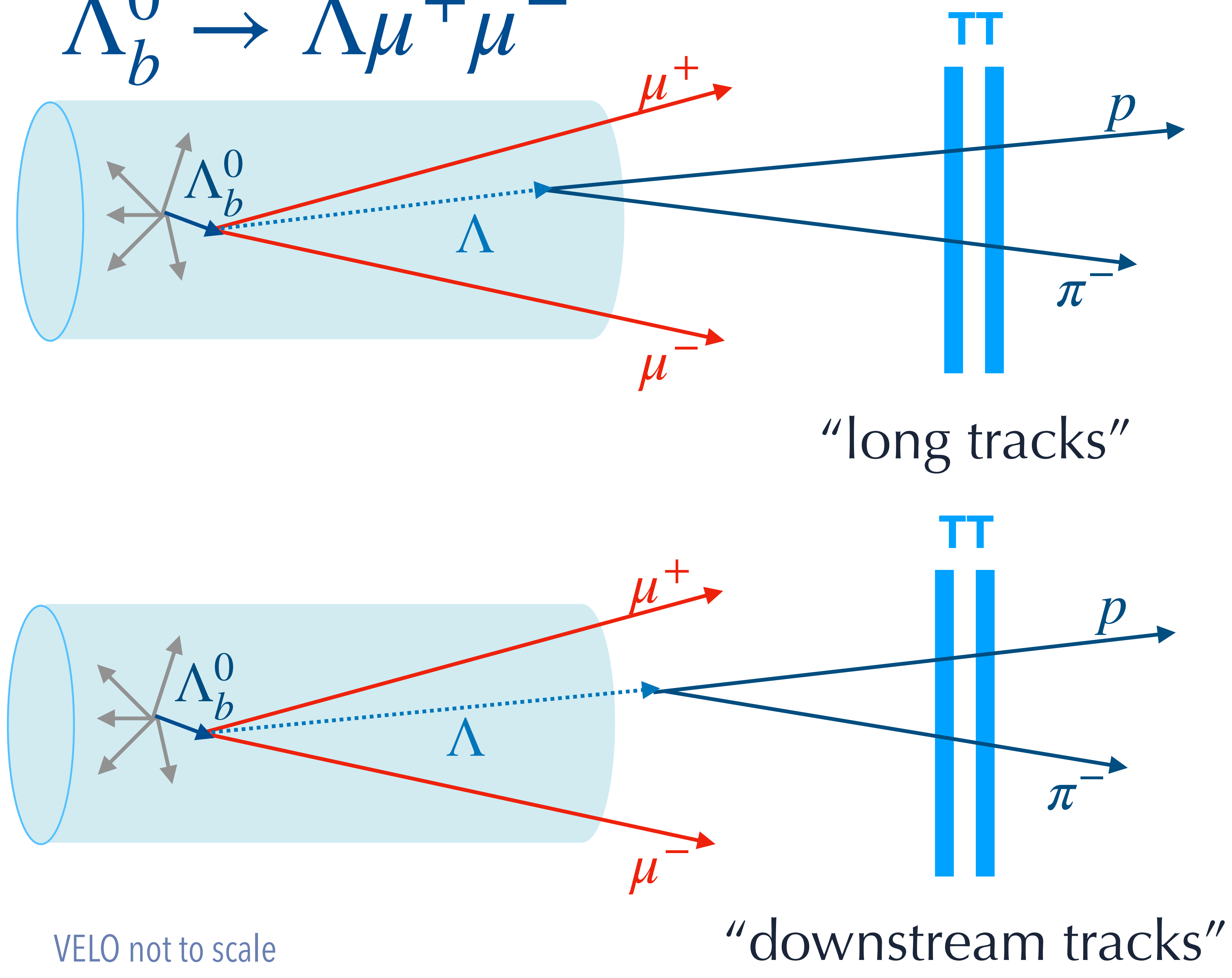
→ interferences of overlapping states

weakly-decaying final state

→ easier theoretical interpretation

Weak vs narrow vs broad final state

$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

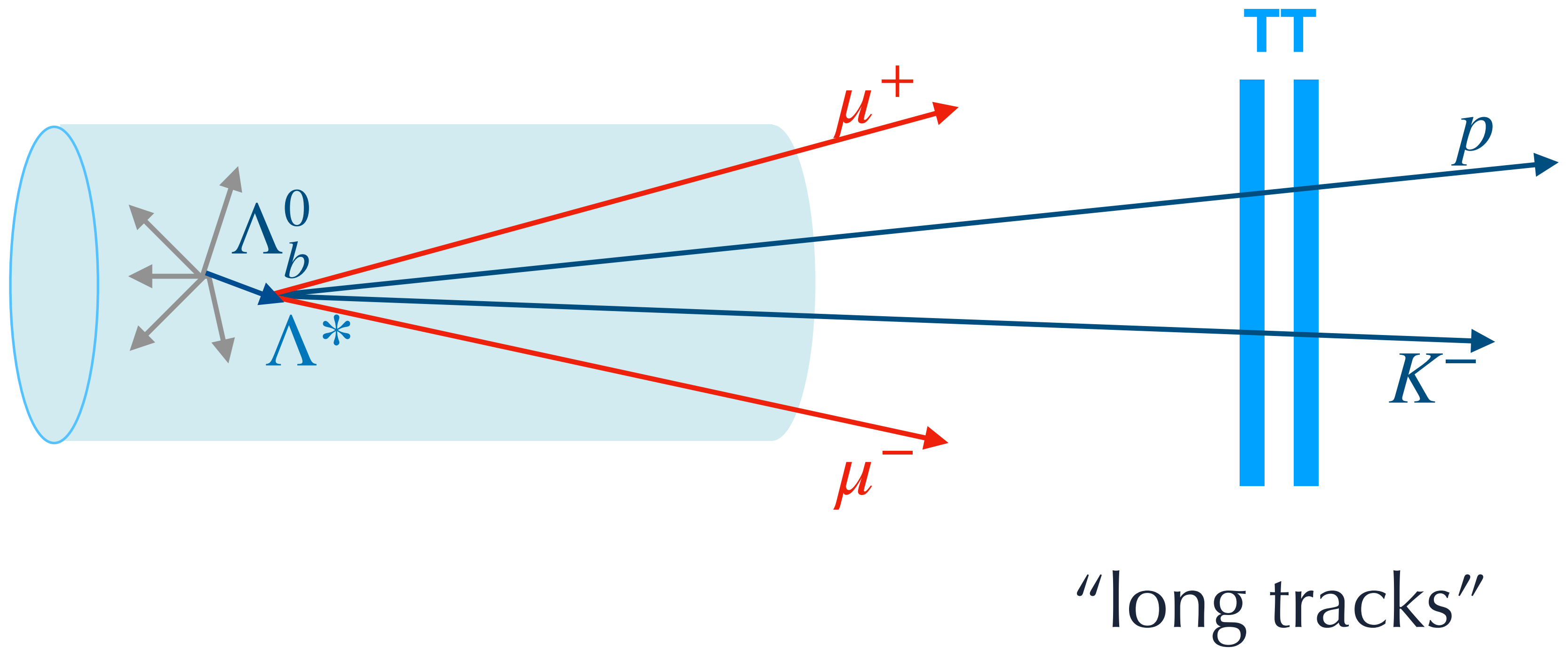


- Λ weakly-decaying hyperon
- lower efficiency to detect in acceptance
- lower efficiency to reconstruct vertex

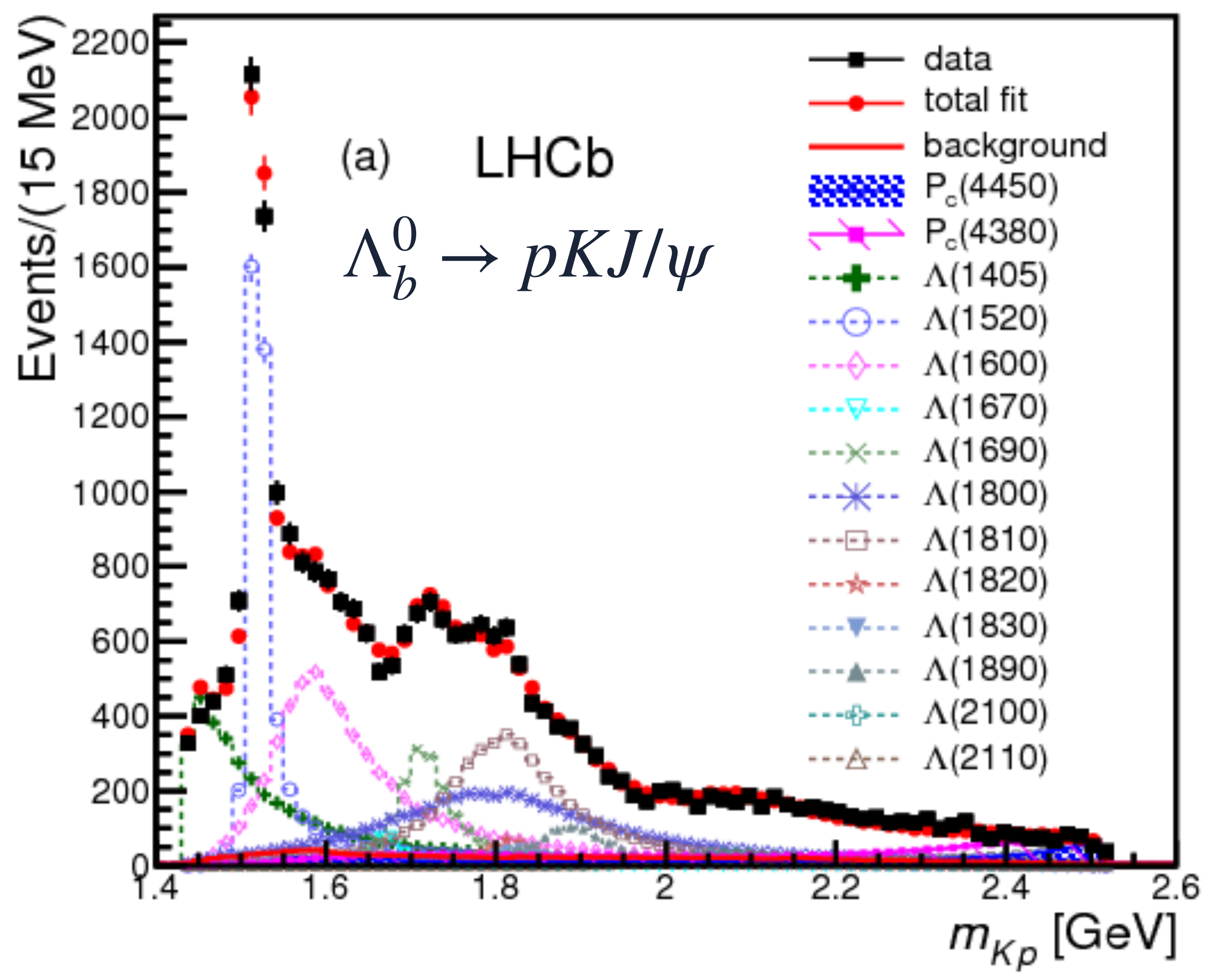
Weak vs narrow vs broad final state

$\Lambda_b^0 \to \Lambda \mu^+ \mu^-$

$\Lambda_b^0 \to \Lambda^* \mu^+ \mu^-$
$\equiv \Lambda_b^0 \to p K^- \mu^+ \mu^-$



Phys. Rev. Lett. 115, 072001



Λ^*: excited states, **decay strongly**

- ✓ Λ weakly-decaying hyperon
- ✗ lower efficiency to detect in acceptance
- ✗ lower efficiency to reconstruct vertex

- ✗ interferences with other resonances
- ✓ Λ^* always decays in acceptance
- ✓ easy to reconstruct vertex

Mesons

$0 \to 0$	$0 \to 1$	$0 \to 2$
$B \to K\ell^+\ell^-$	$B \to K^*\ell^+\ell^-$	$B \to K_2^*(1430)\ell^+\ell^-$
$B_s \to f_0(980)\ell^+\ell^-$	$B_s \to \phi\ell^+\ell^-$	$B_s \to f_2(1525)\ell^+\ell^-$

Testing different spin configurations
Weakly-decaying hadrons rich angular structure

Baryons

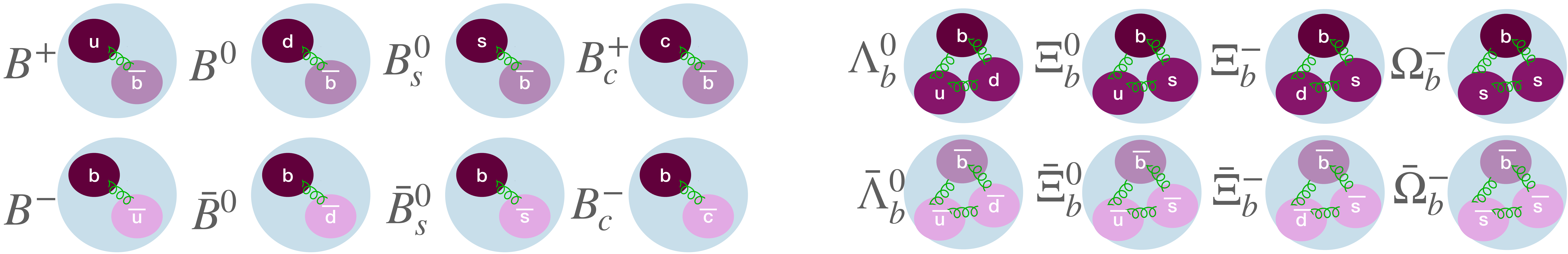
$1/2 \to 1/2$	$1/2 \to 3/2$	$1/2 \to 5/2$
$\Lambda_b^0 \to \Lambda\ell^+\ell^-$	$\Lambda_b^0 \to \Lambda^*(1520)\ell^+\ell^-$	$\Lambda_b^0 \to \Lambda^*(1820)\ell^+\ell^-$
$\Xi_b \to \Xi\ell^+\ell^-$	$\Xi_b \to \Xi^*(1820)\ell^+\ell^-$	
	$\Omega_b^- \to \Omega^-\ell^+\ell^-$	

spin = intrinsic angular momentum

Exkurs: Production fractions

About 1 000 000 000 000 $b\bar{b}$ pairs/year

How often to they hadronise into each type?



f_i	35%	35%	8.5%	0.3%	18%	1.5%*	1.5%	0.5%

*educated guess

About 1 000 000 000 000 $b\bar{b}$ pairs/year

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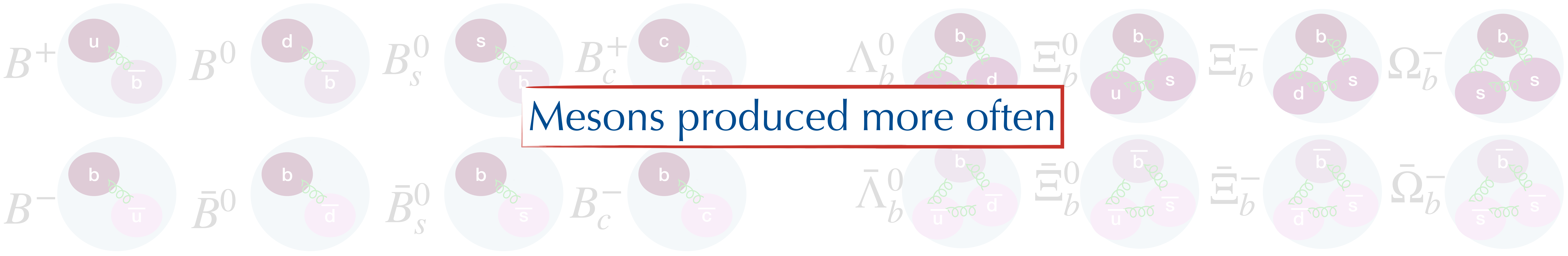


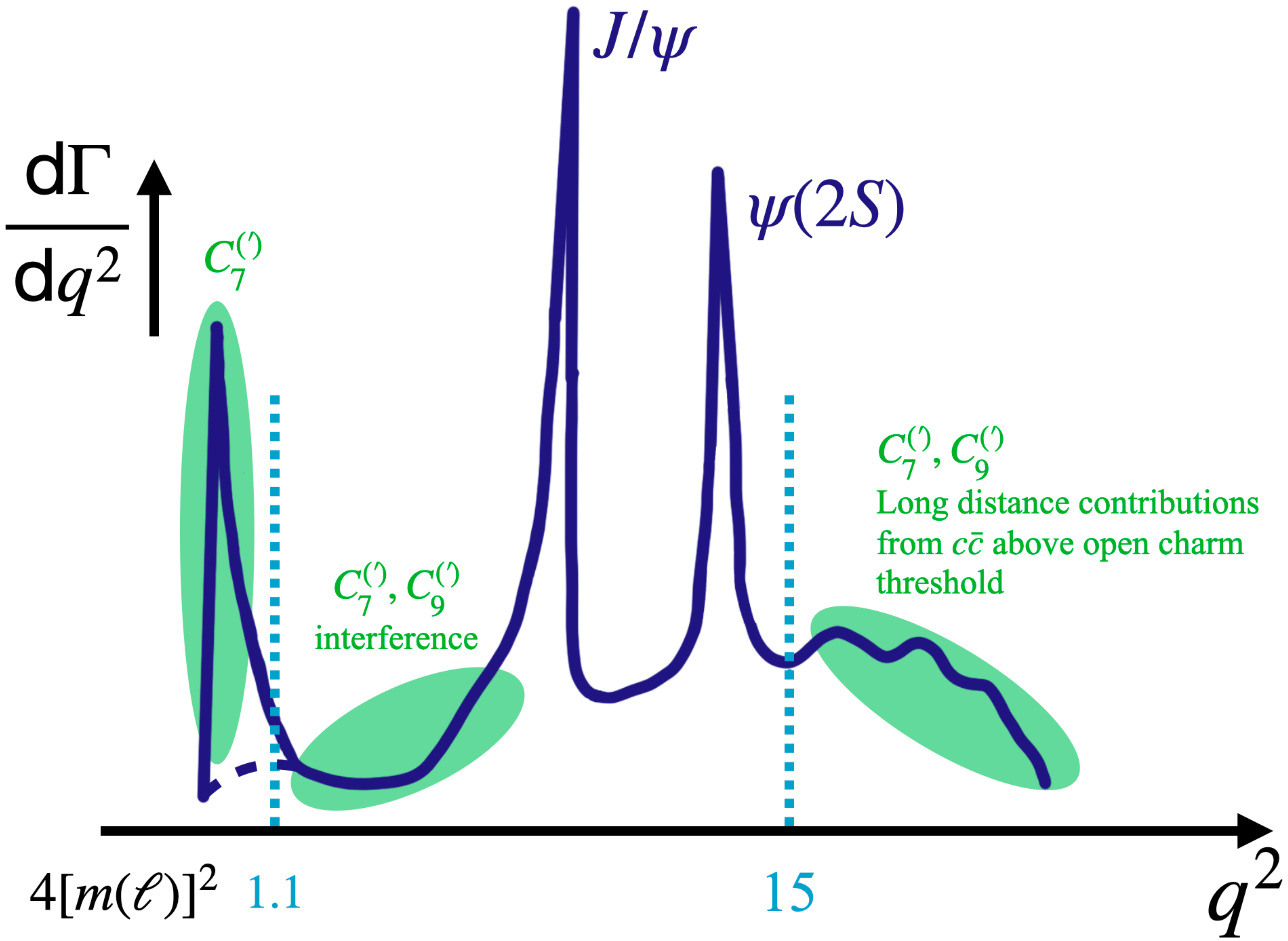
Mesons produced more often

f_i	35%	35%	8.5%	0.3%	18%	1.5%*	1.5%	0.5%

*educated guess

Branching fractions

- Fraction of initial hadron decaying into defined final state
- Usually energy dependent
- Choose q^2 : transferred momentum in the $b \to s$ transition



Different regions sensitive to different C_i

What observable do we choose?

Lepton Flavour Universality (LFU) ratios

- $E >> m(\mu, e)$ relativistic limit $m(\mu, e) \rightarrow 0$
- Branching fractions should be identical

  $\rightarrow$ form factor uncertainty cancels

$$r = \frac{\mathrm{BF}(H_b \rightarrow H_s \mu^+ \mu^-)}{\mathrm{BF}(H_b \rightarrow H_s e^+ e^-)}$$

What observable do we choose?

Lepton Flavour Universality (LFU) ratios

- $E >> m(\mu, e)$ relativistic limit $m(\mu, e) \rightarrow 0$
- Branching fractions should be identical

  $\rightarrow$ form factor uncertainty cancel
- Experimentally challenge: difference in reconstruction

  $\rightarrow$ double ratio with each having a normalisation mode
- Theoretically and experimentally clean

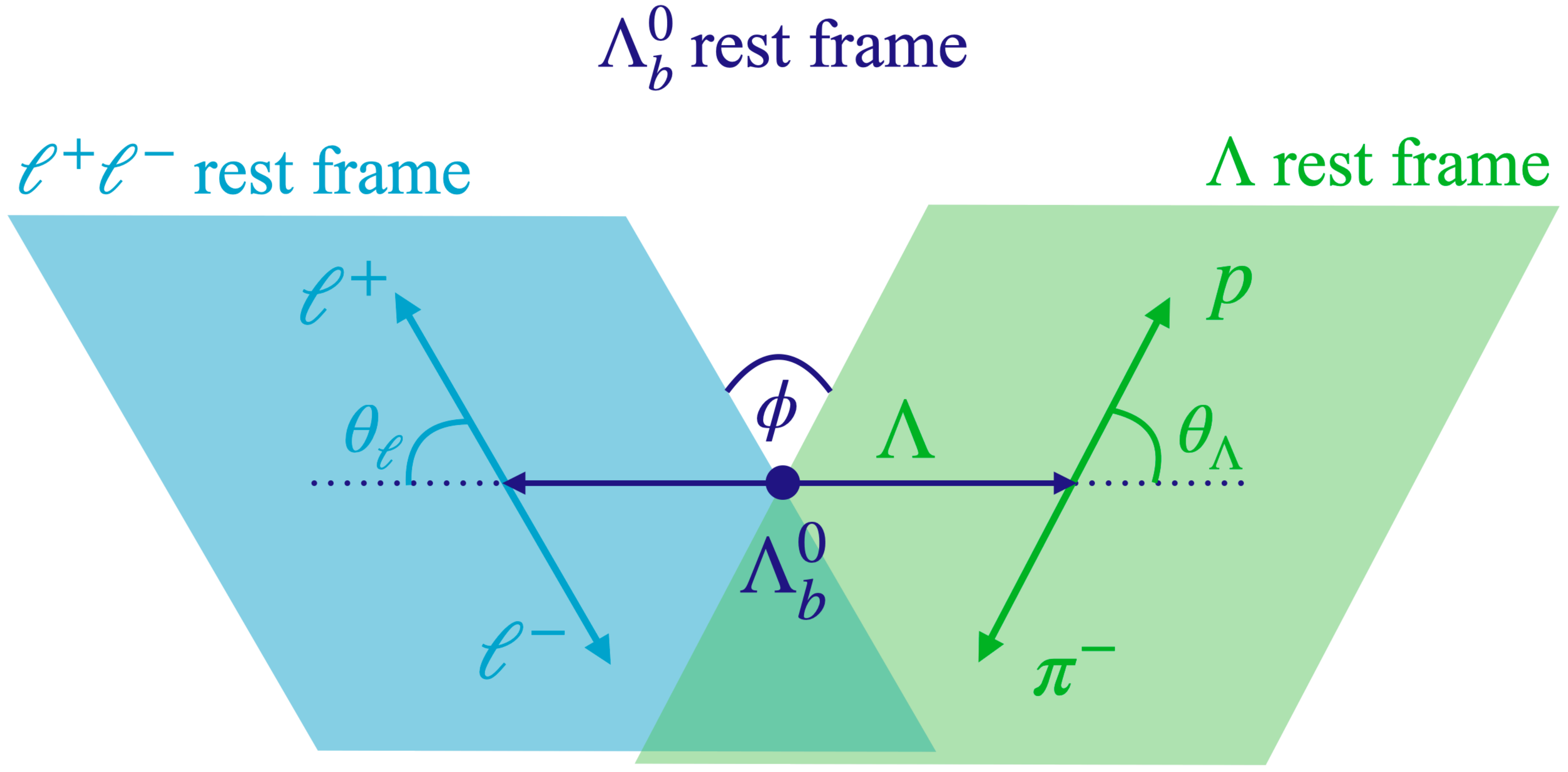
$$\boxed{R = \frac{\mathrm{BF}(H_b \rightarrow H_s \mu^+ \mu^-)}{\mathrm{BF}(H_b \rightarrow H_s J/\psi(\mu^+ \mu^-))} \times \frac{\mathrm{BF}(H_b \rightarrow H_s J/\psi(e^+ e^-))}{\mathrm{BF}(H_b \rightarrow H_s e^+ e^-)}}$$

What observable do we choose?

Angular analysis

- Study angles between momenta of particles
- Many observables (angular coefficients)

  → Easier to disentangle Wilson coefficients



Angular analysis

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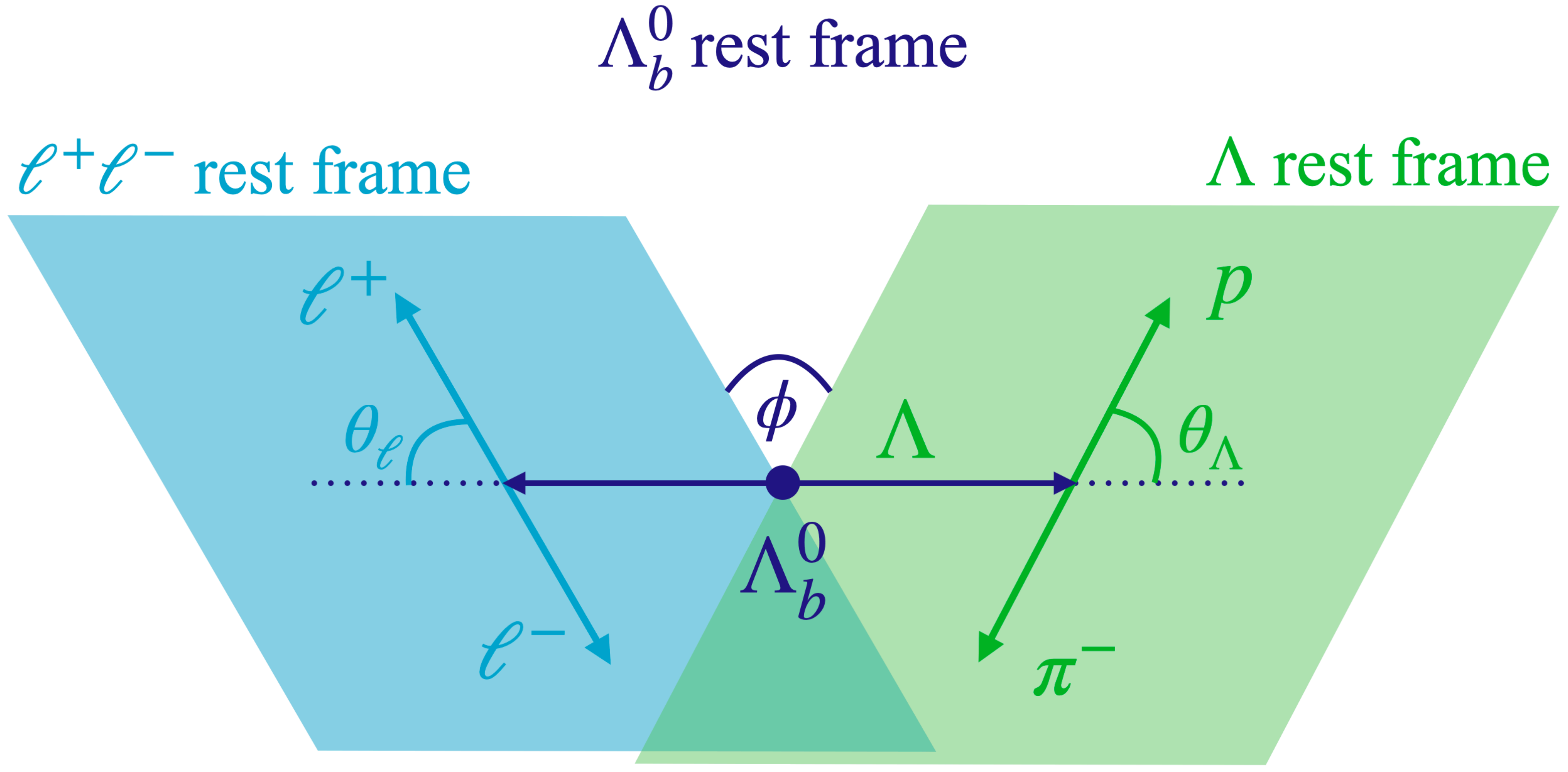


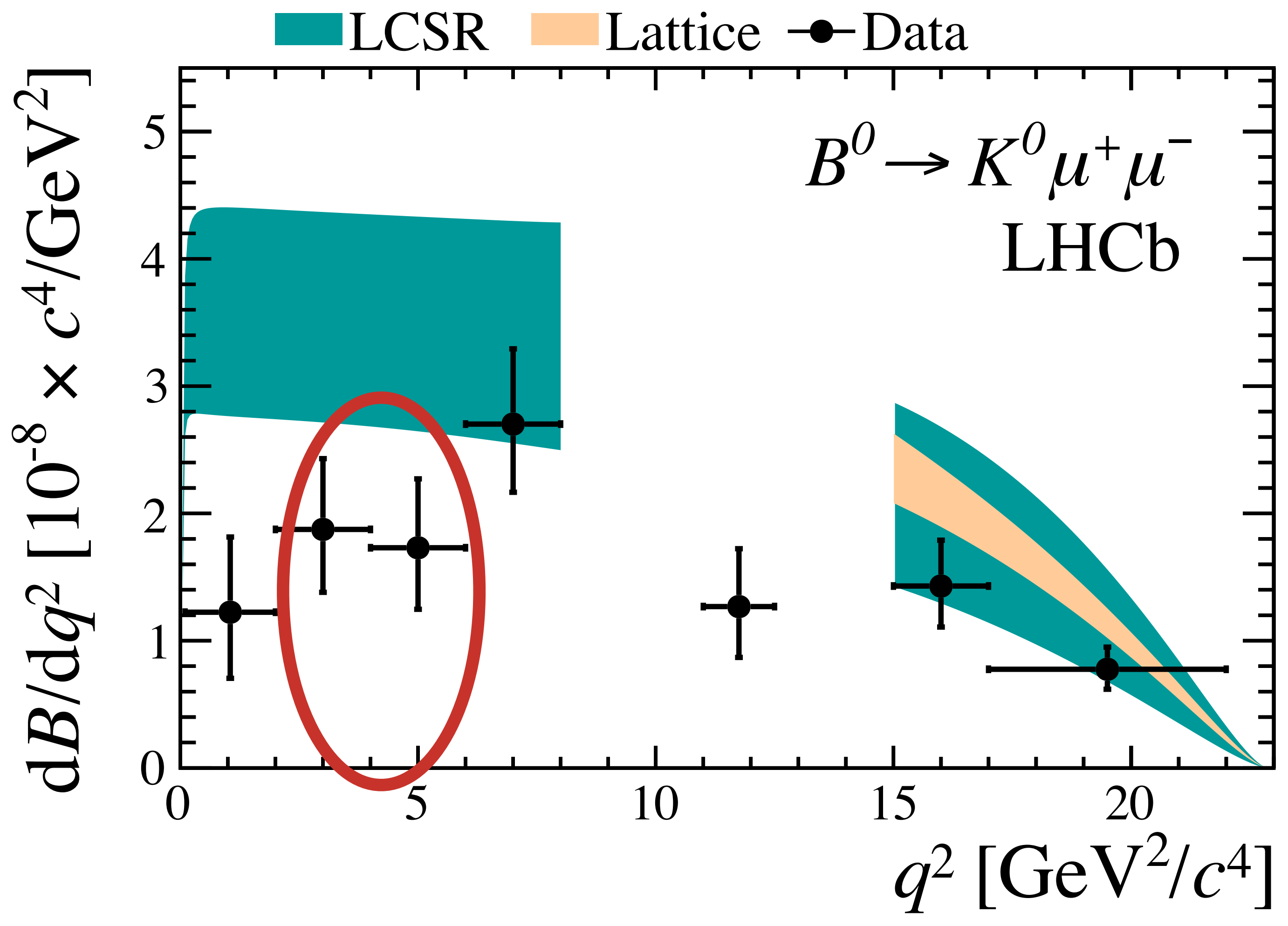
- $\frac{d\Gamma}{dq^2} = \sum_\lambda |A_\lambda|^2$ with A_λ being transversity amplitudes
- $A_\lambda(H_i(FF), C_j)$ depend on helicity amplitudes H_i

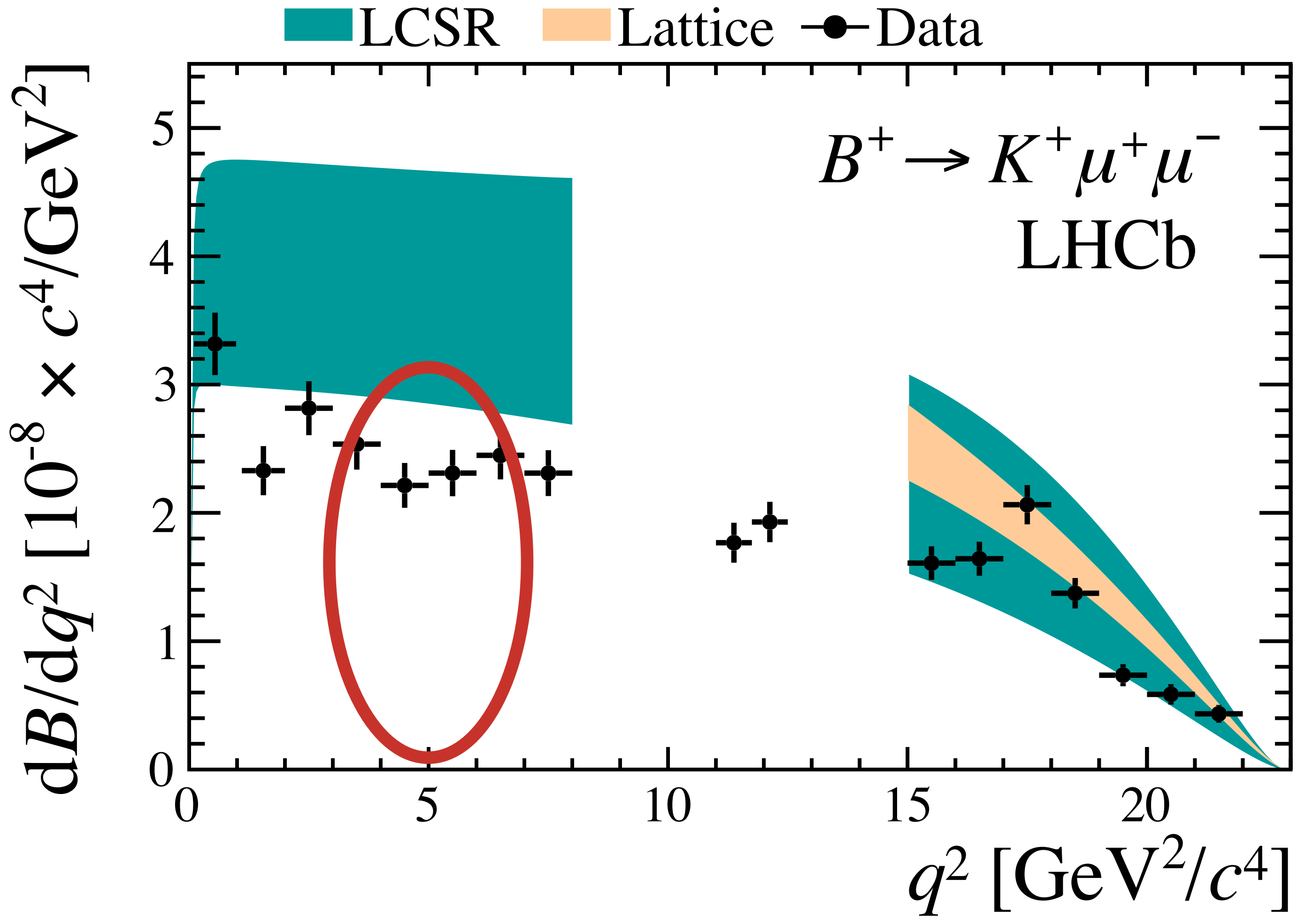
  → non-local FF contributions introduce q^2 dependence

$\boxed{\text{Ratio of different angular coefficients to cancel FF uncertainties } P^{(\prime)}}$

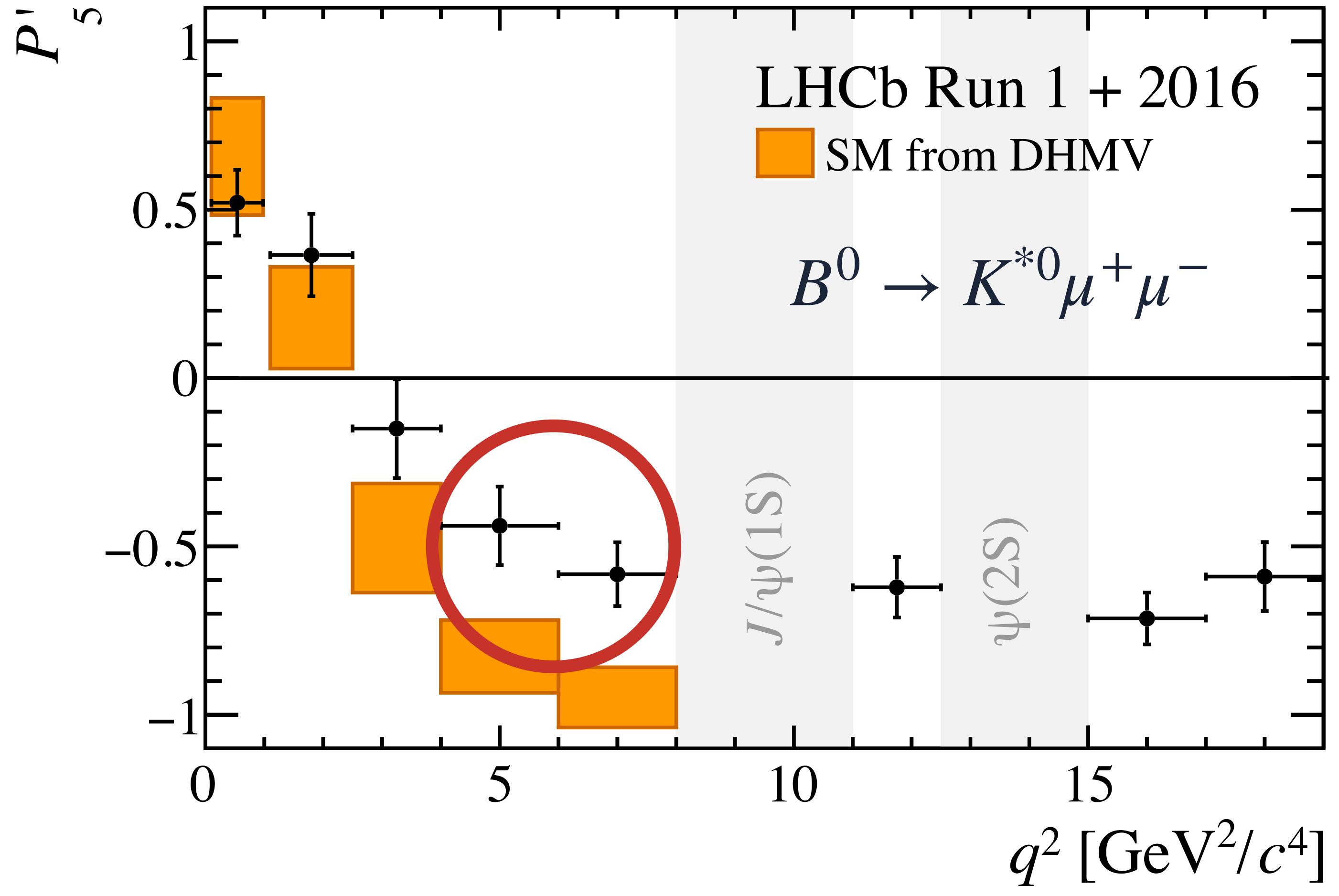
What happened in the last decade?

Branching fractions

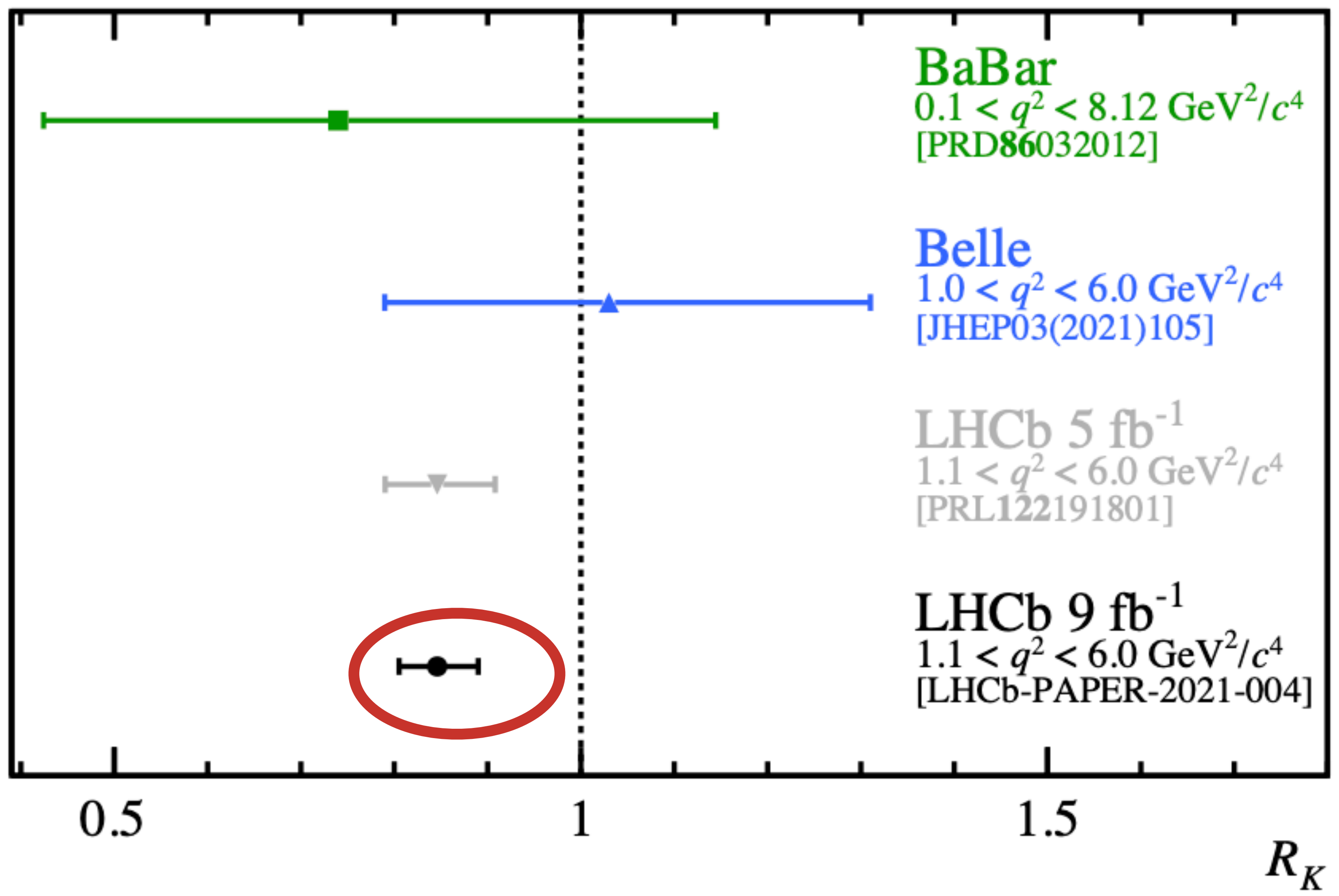




Angular observables



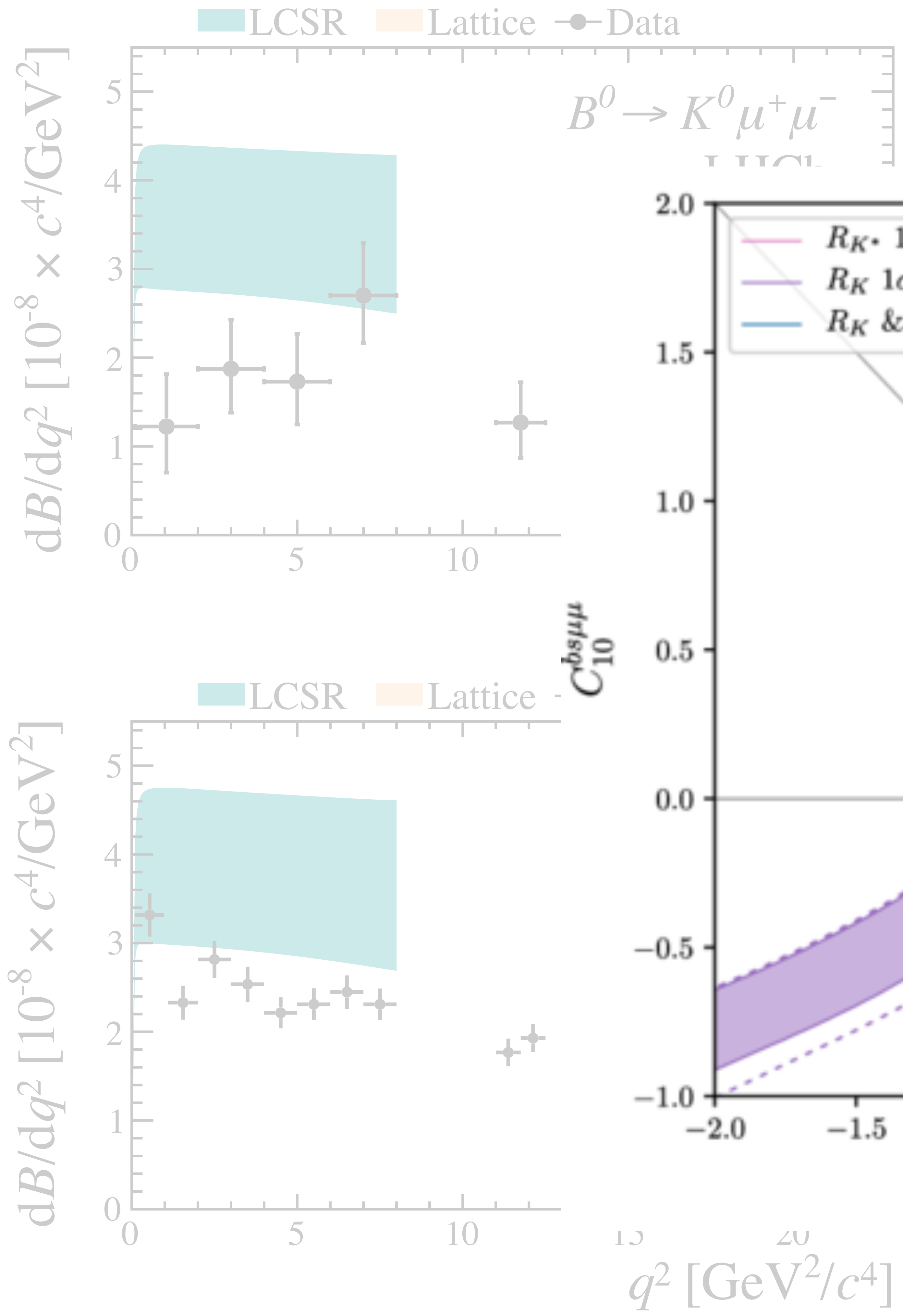
LFU ratios



Only some examples

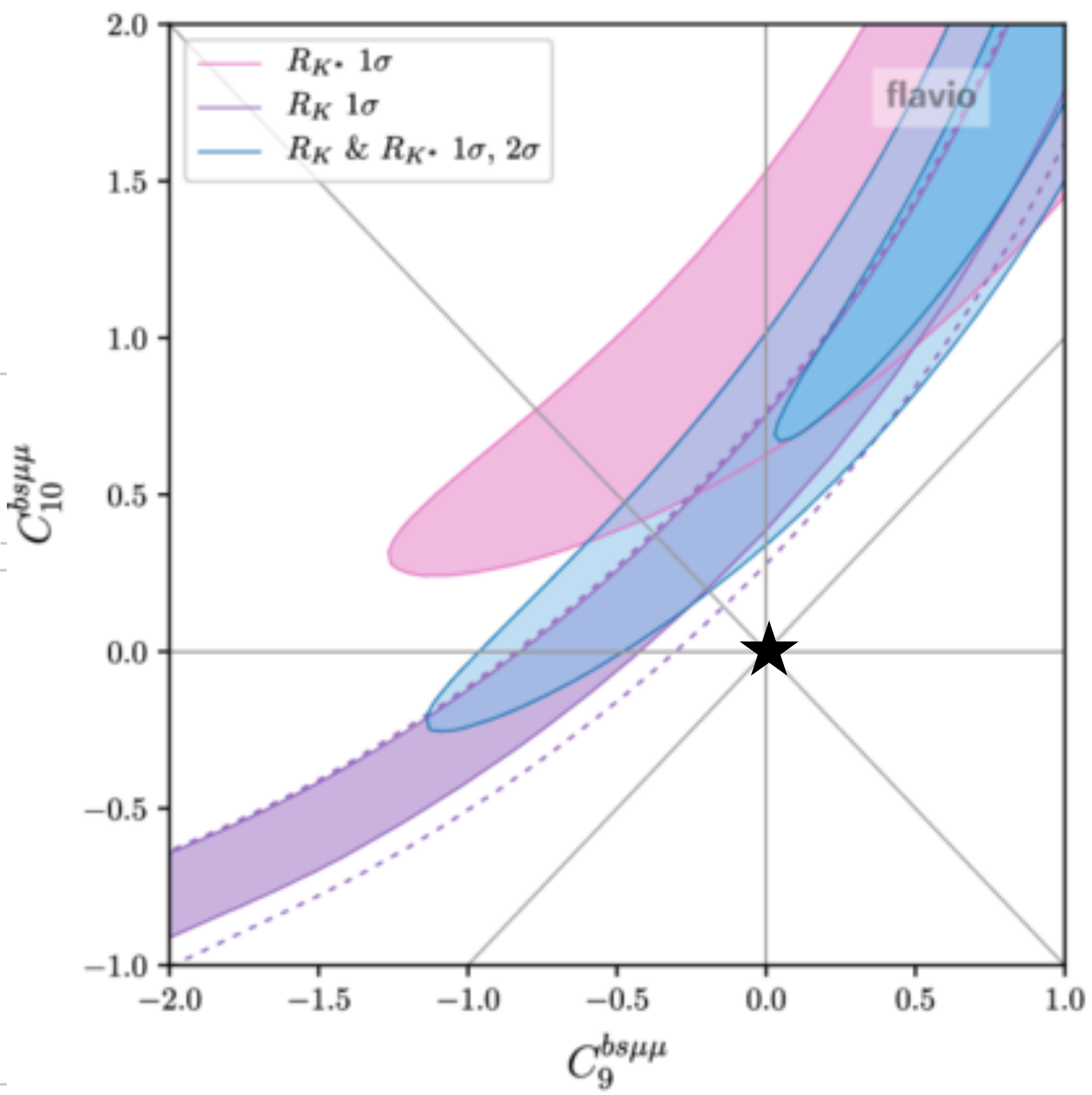
What happened in the last decade?

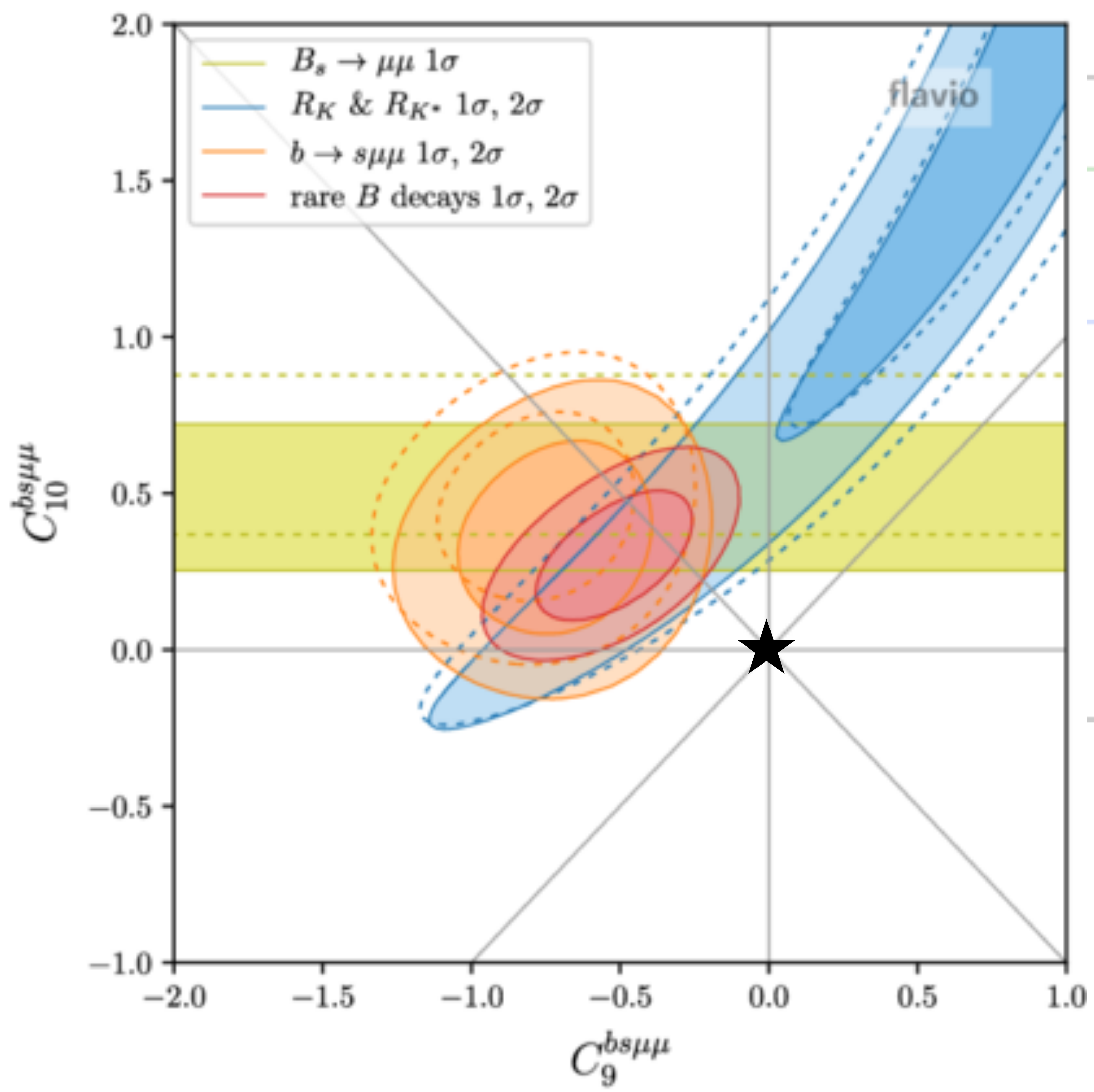
Branching fractions



These are called B anomalies

LFU ratios

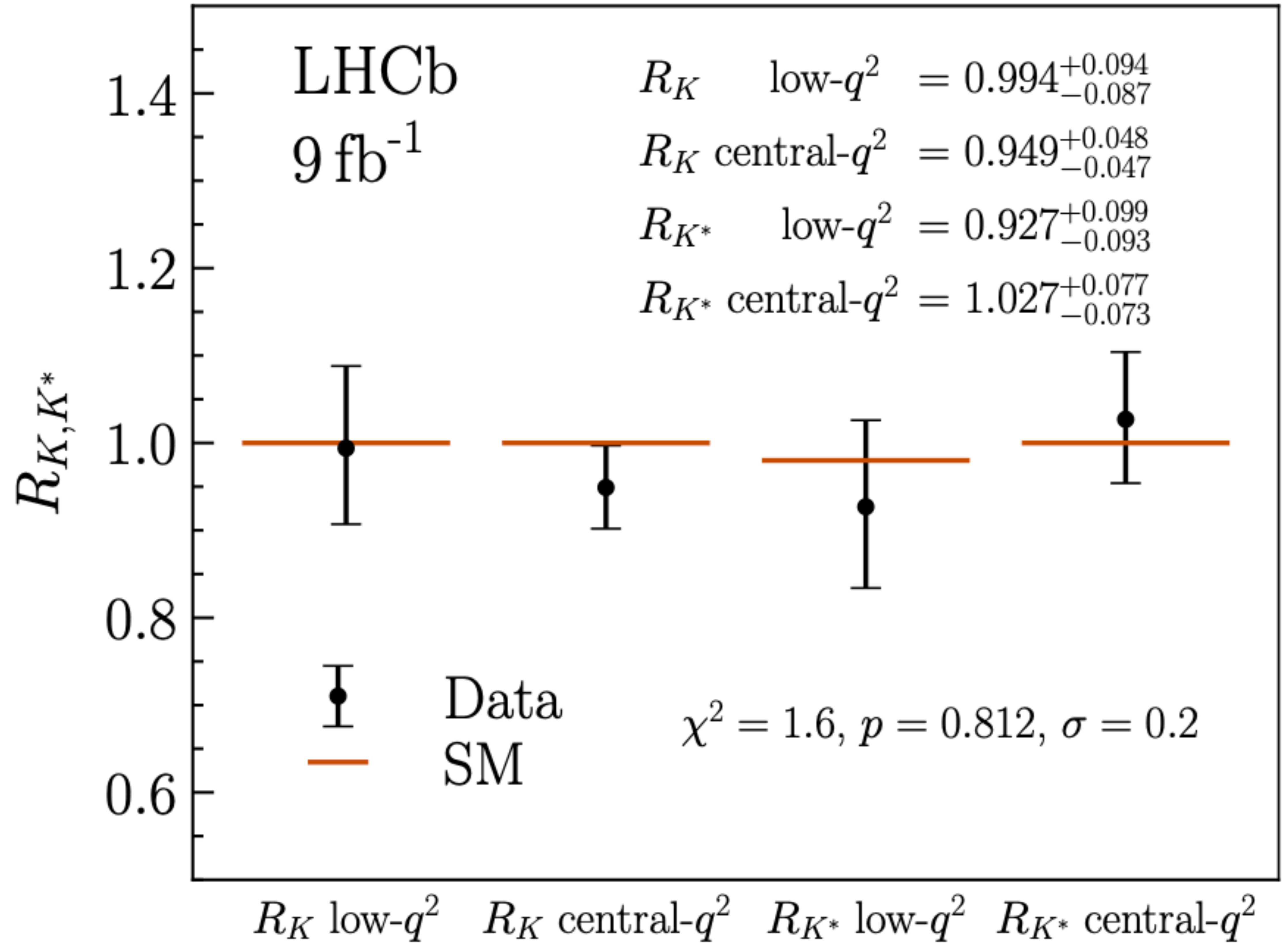




★ SM

Latest LFU ratio

Simultaneous extraction of ratio for $B^+ \to K^+\ell^+\ell^-$ $(R(K))$ and $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ $(R(K^*))$



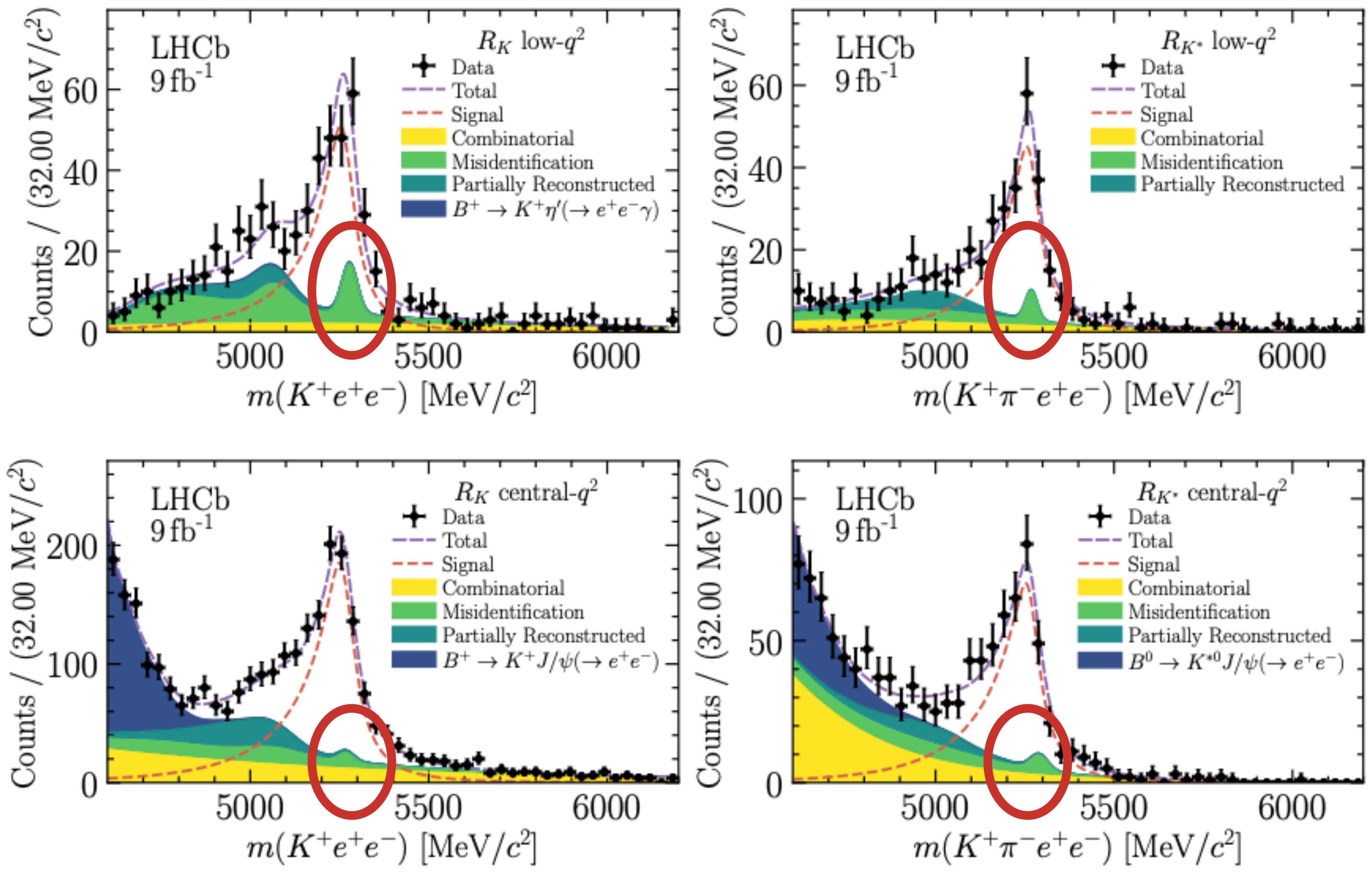
Compatible with the SM.
What went wrong?

Latest LFU ratio

PRD 108 (2023) 032002

Simultaneous extraction of ratio for $B^+ \to K^+\ell^+\ell^-$ ($R(K)$) and $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ ($R(K^*)$)

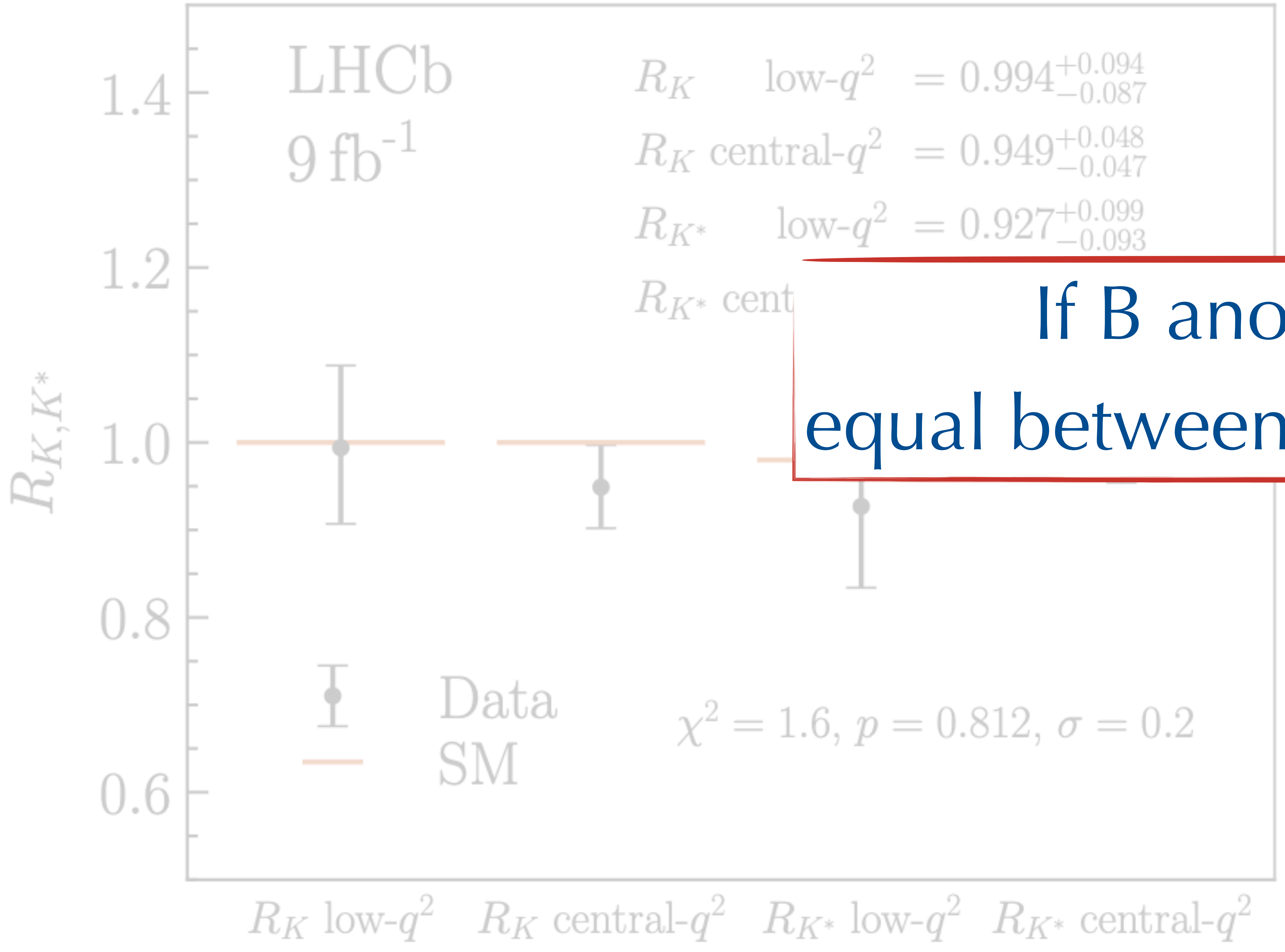
$R(K)$ $R(K^*)$



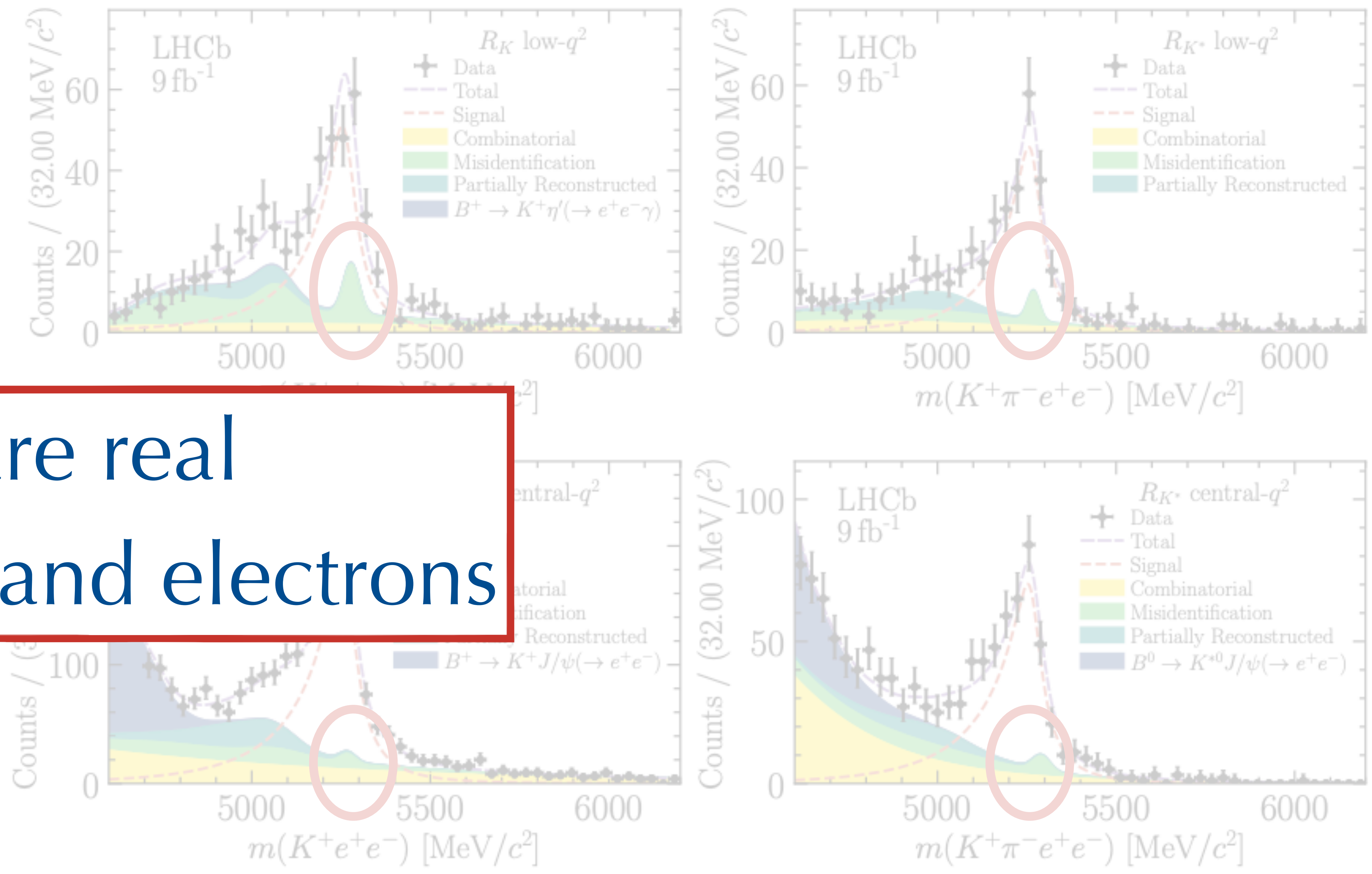
- Saw too many electrons
- BKG non negligible → peaks under signal

PRD 108 (2023) 032002

Simultaneous extraction of ratio for $B^+ \to K^+\ell^+\ell^-$ $(R(K))$ and $B^0 \to K^{*0}(\to K^+\pi^-)\ell^+\ell^-$ $(R(K^*))$



$R(K)$ $R(K^*)$

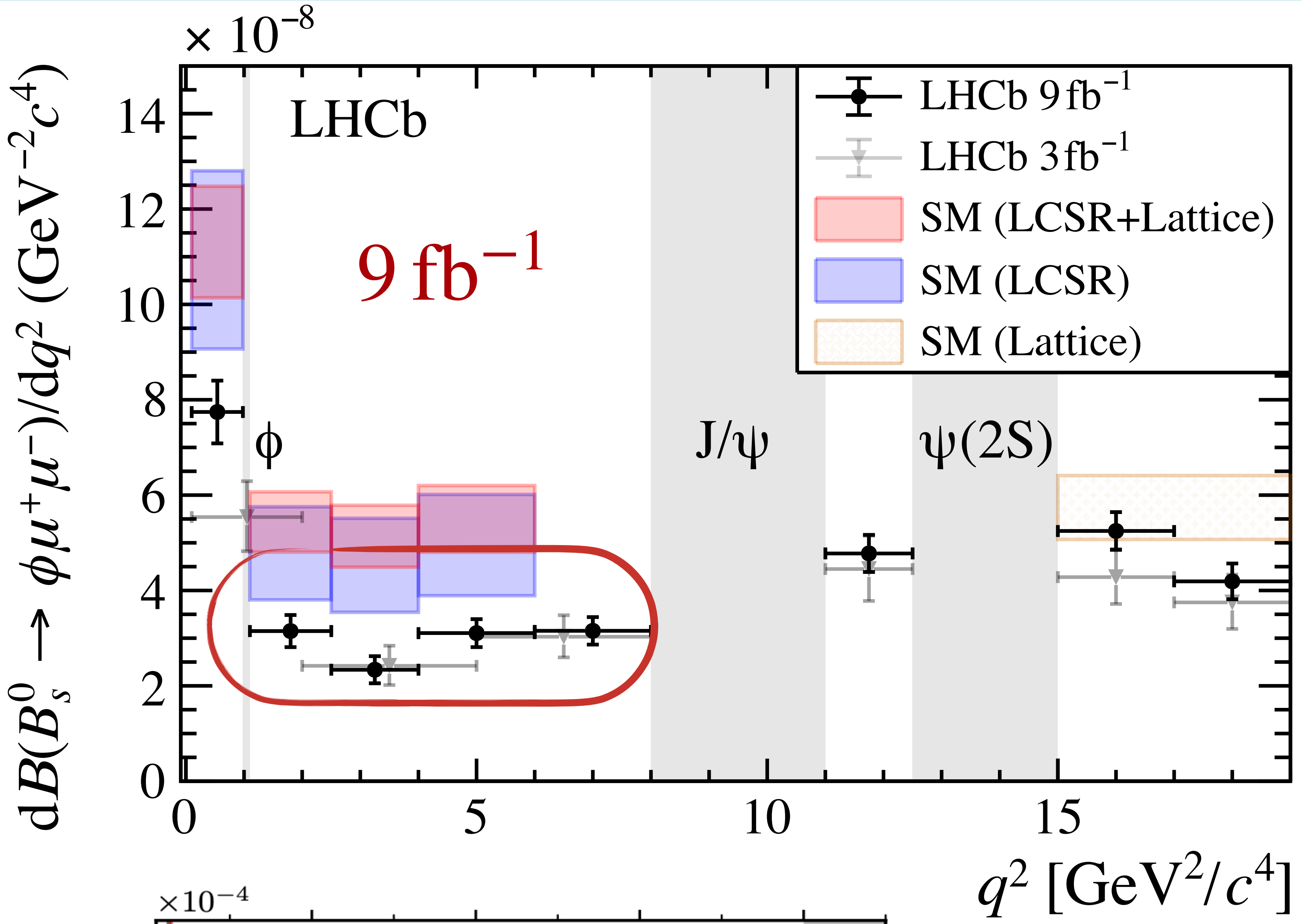


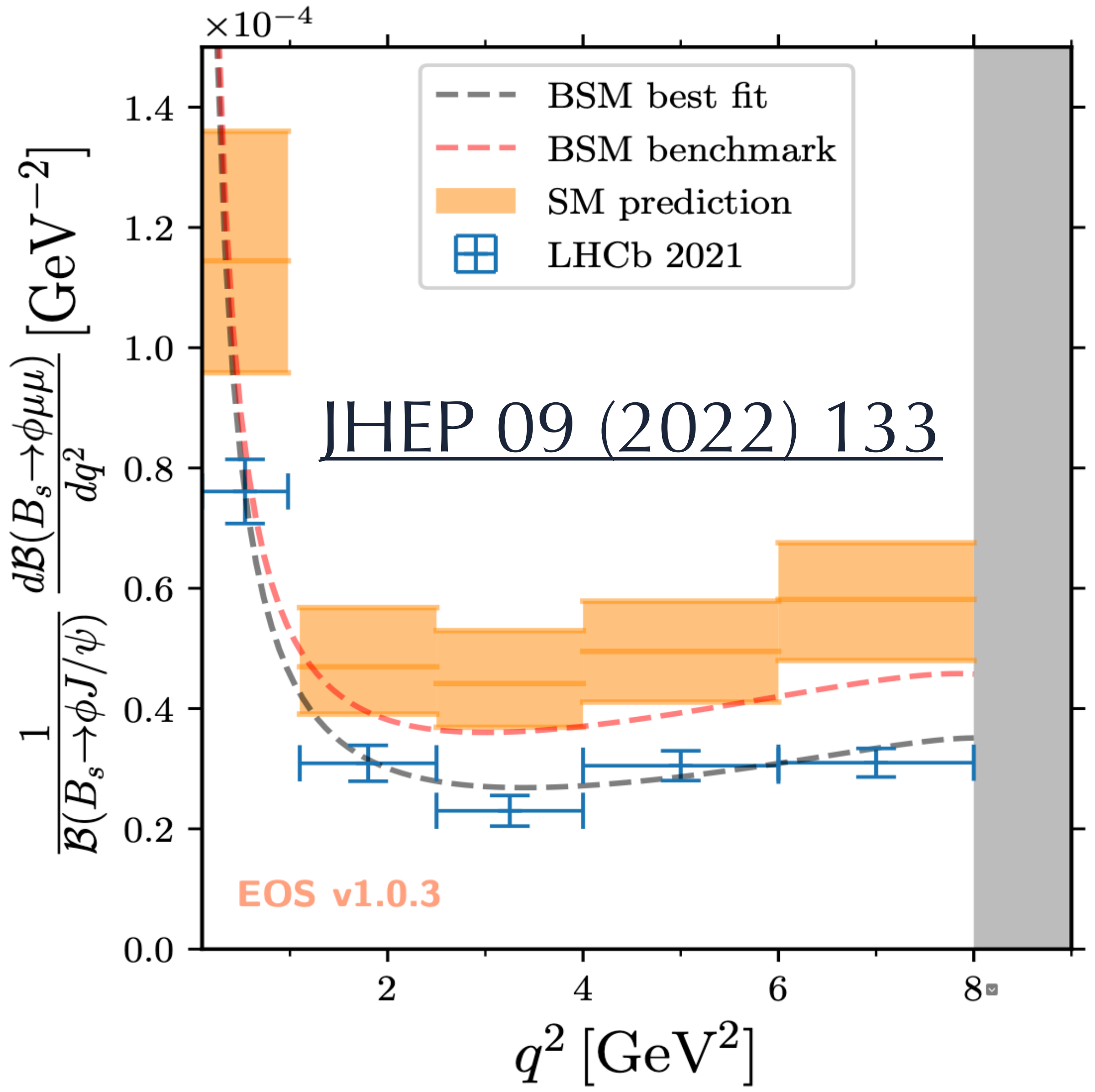
If B anomalies are real
equal between muons and electrons

- Saw too many electrons
- BKG non negligible → peaks under signal

Latest branching fraction measurements

PRL 127 (2021) 151801





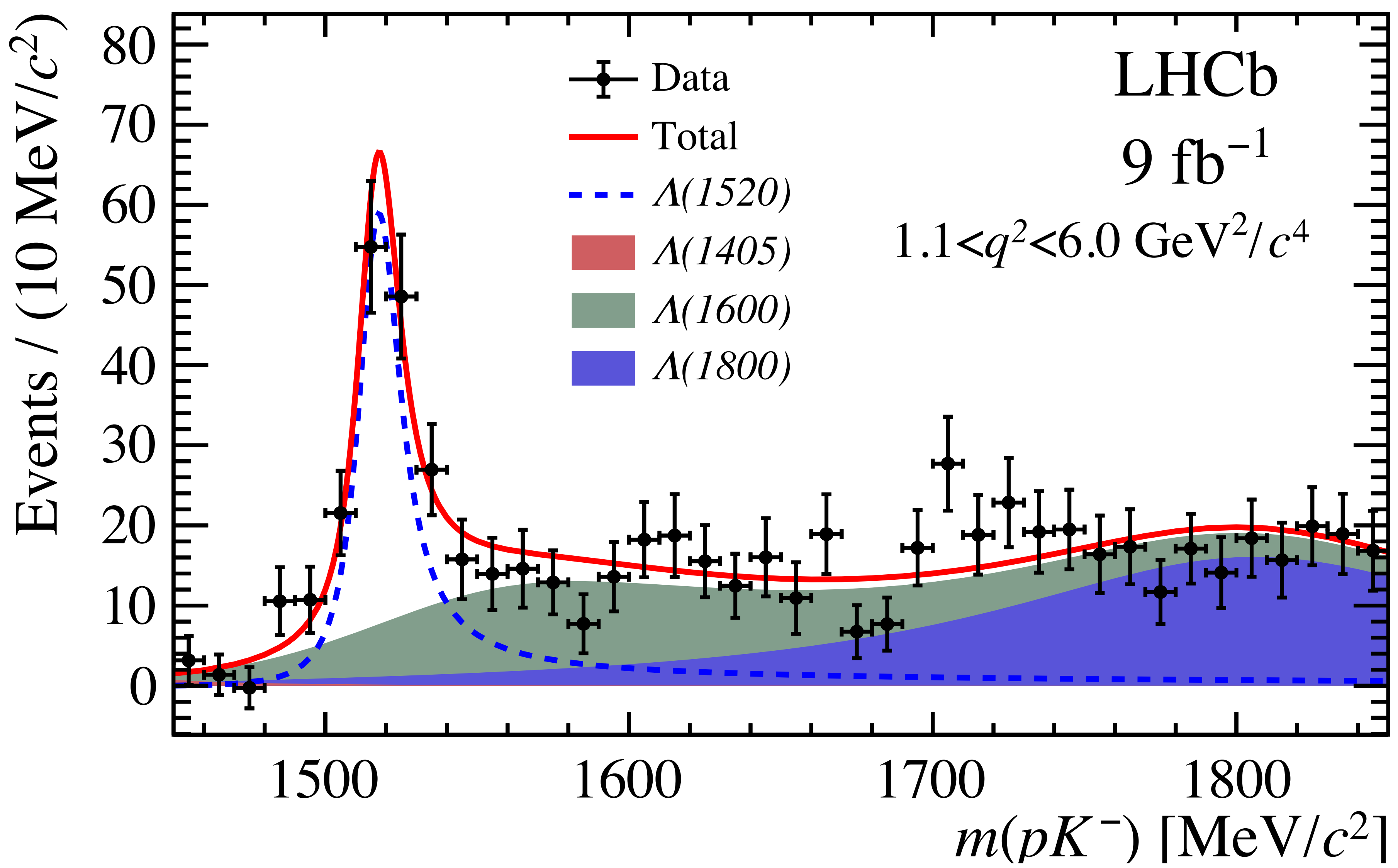
- Reconstructed via displaced $K^+K^-\mu^+\mu^-$ vertex
- Veto q^2 for $B_s^0 \to \phi(\to \mu^+\mu^-)\phi$, $B_s^0 \to \phi J/\psi$ and $B_s^0 \to \phi\psi(2S)$
- Normalised to $B_s^0 \to \phi J/\psi$
- Simultaneous fit to different q^2 bins

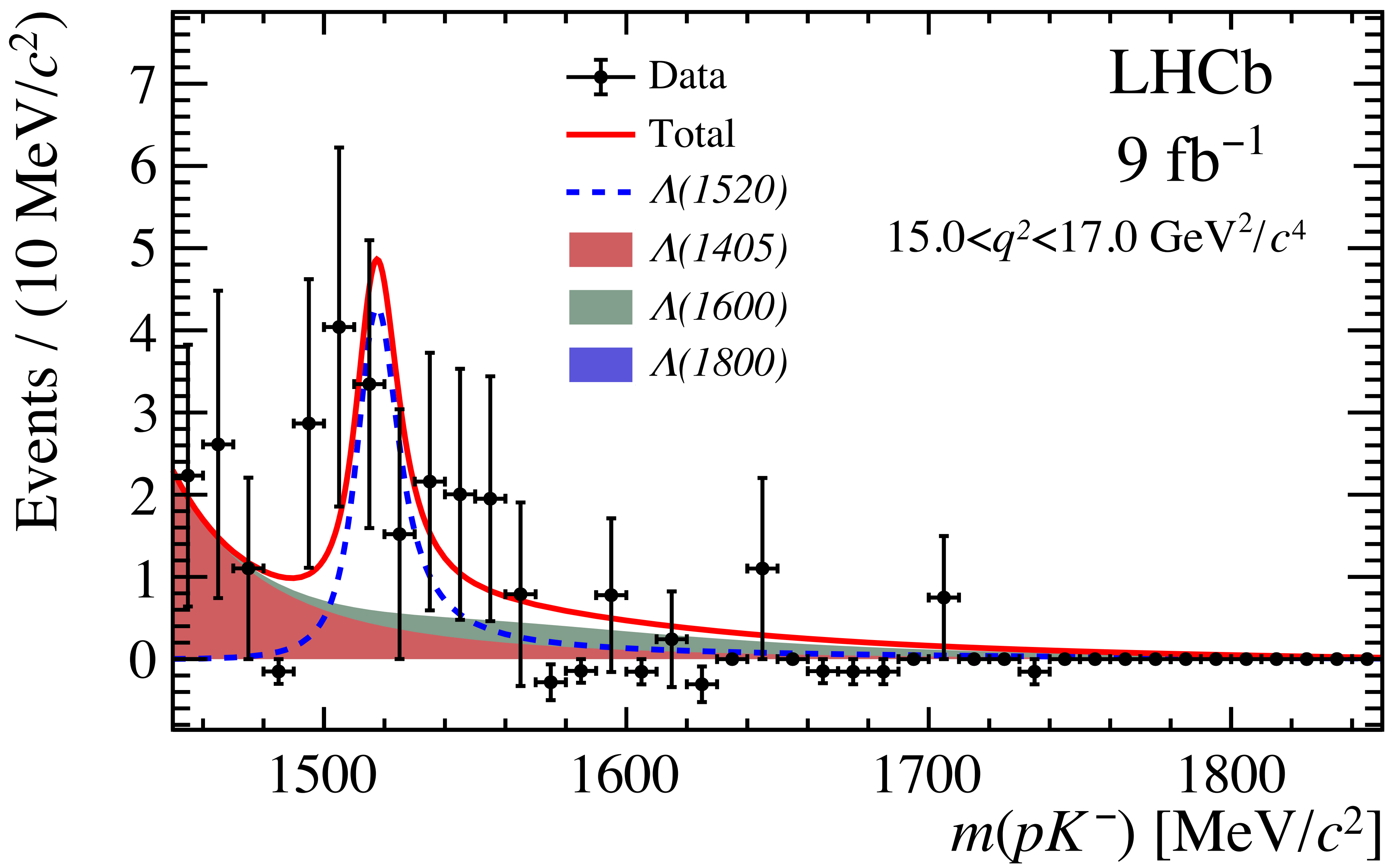
$$\mathrm{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \pm 0.22 \pm 0.16 \pm 0.39 \pm 0.03) \times 10^{-7}$$

stat. syst. abs. BF q2 extrapol.

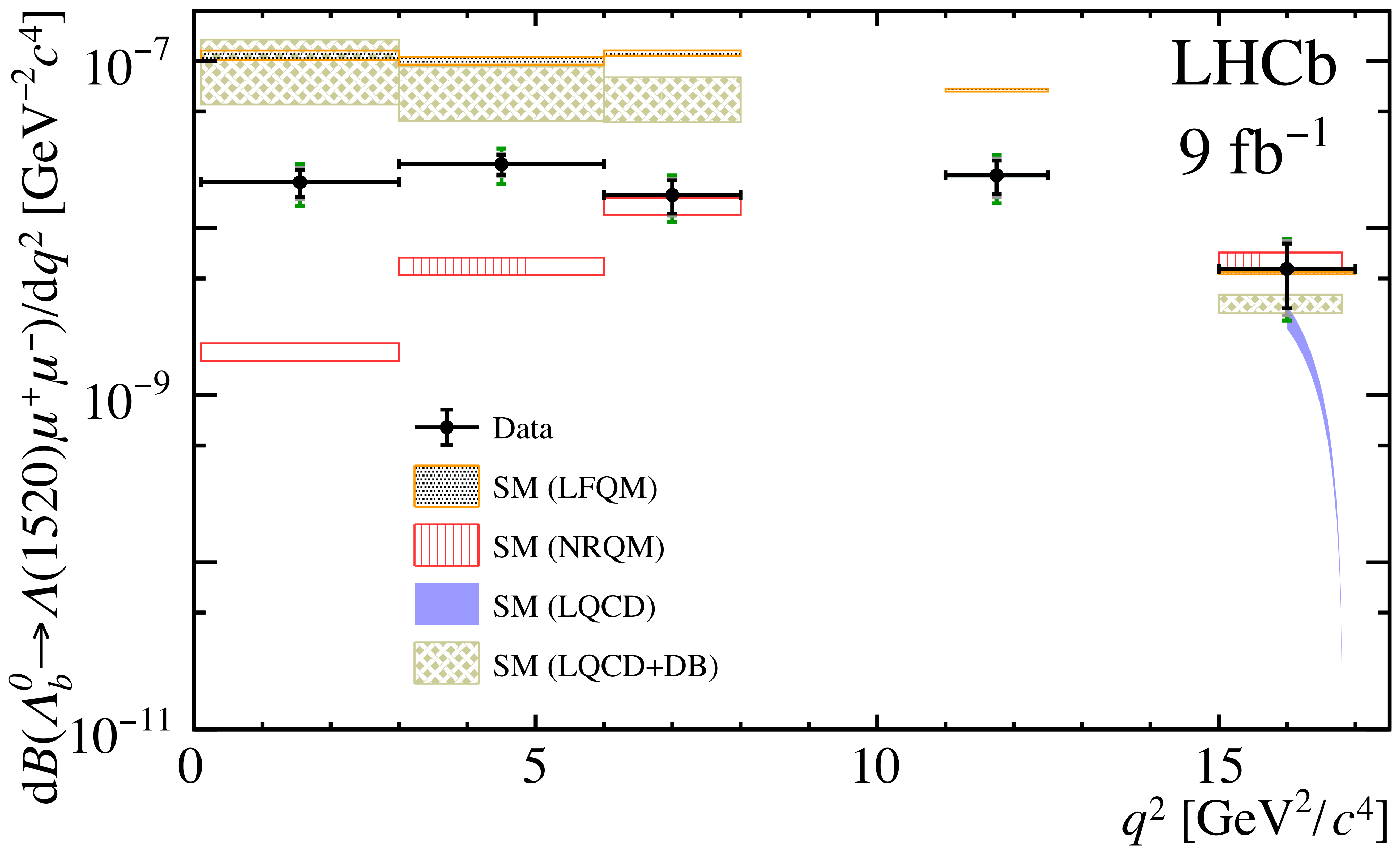
In q^2[1.1,6.0] GeV$^2/c^4$: 3.6σ (LCSR+Lattice) and 1.8σ (LCSR)

PRL 131 (2023) 151801



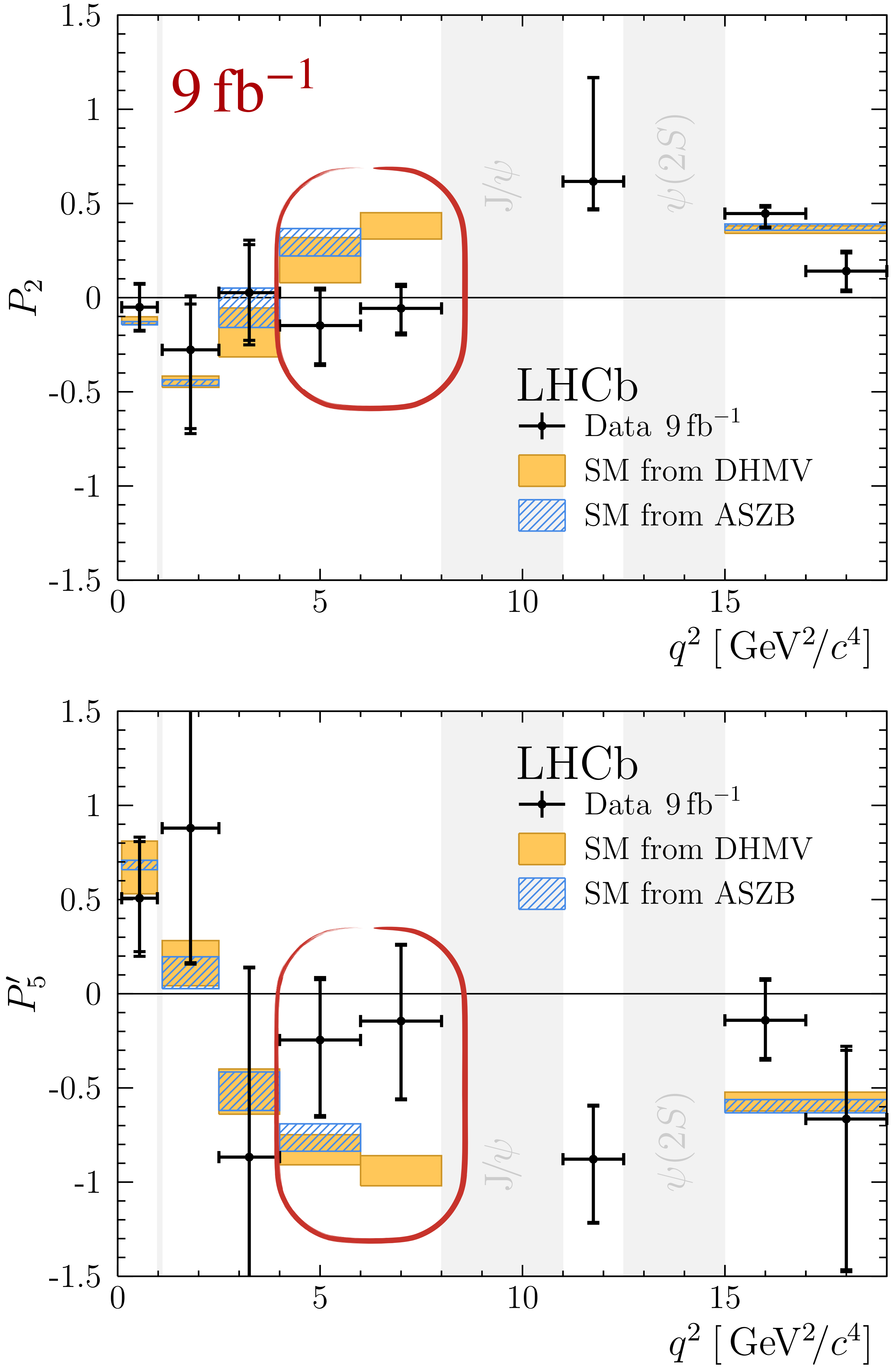


- First measurement of rare decay with $\Lambda(1520) \to pK^-$ resonance (Narrow $\Lambda(1520)$ width ~16 MeV)
- Normalised to $\Lambda_b^0 \to pK^- J/\psi$
- High-q^2 consistent with SM, low-q^2 inconclusive



Angular observables

PRL 126, 161802 (2021)



- First measurement of full set of observables
- Reconstructed via $B^+ \to K^{*+}(\to K^0_s\pi^+)\mu^+\mu^-$

  with $K^0_s \to \pi^+\pi^-$

  $\to$ lower statistics due to reconstruction of K^0_s
- General good agreement with SM predictions
- P_2 and P'_5 show same deviations as in $B^0 \to K^{*0}\mu^+\mu^-$

Unbinned angular analysis

PRD 109 (2024) 052009

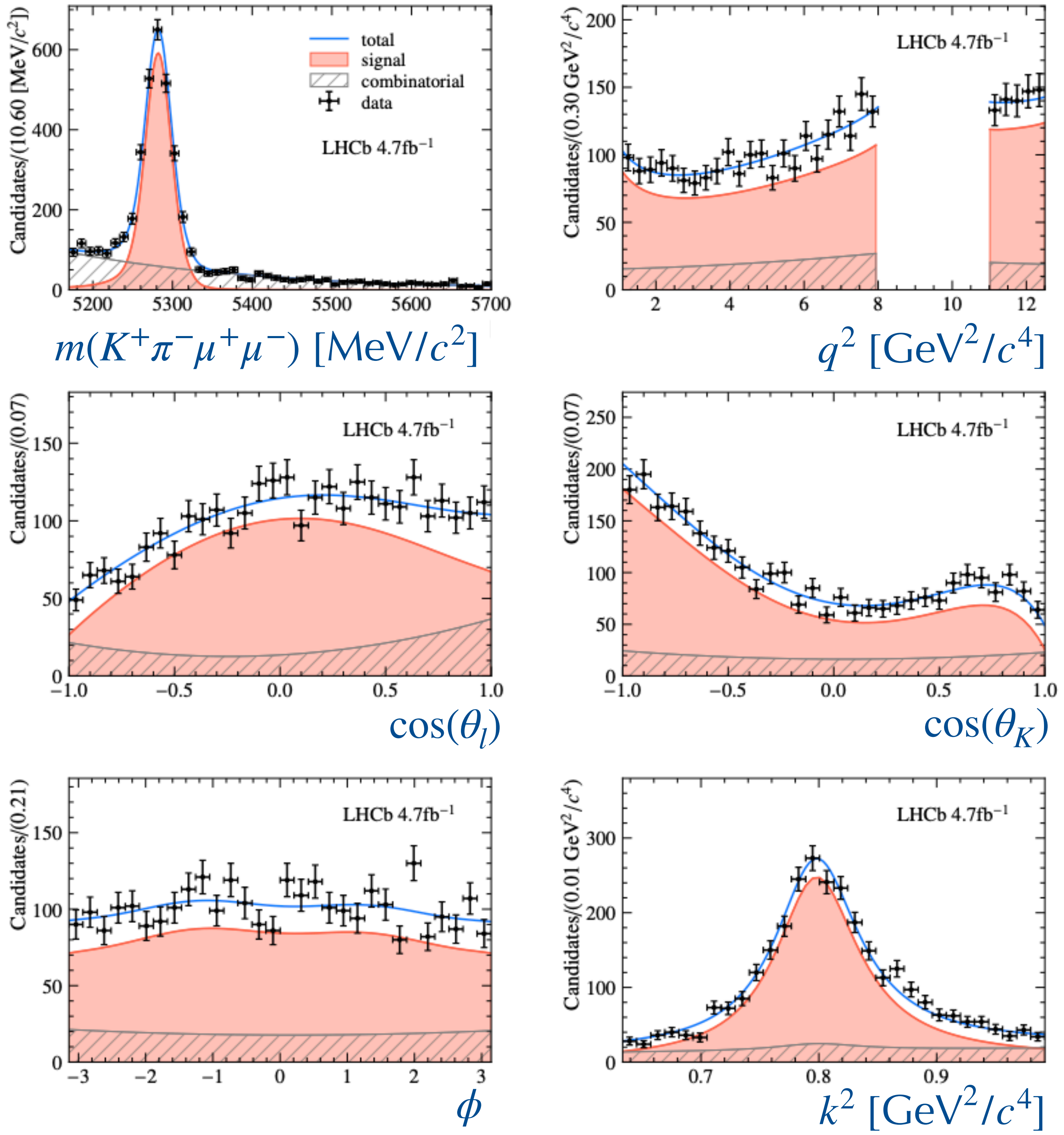
- Use $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$
- Select $K^{*0} \to K^+\pi^-$ via k^2
- Data parametrised as function of q^2

  via polynomial expansion

  $\to$ direct extraction of Wilson coefficients
- **Unbinned maximum-likelihood fit**

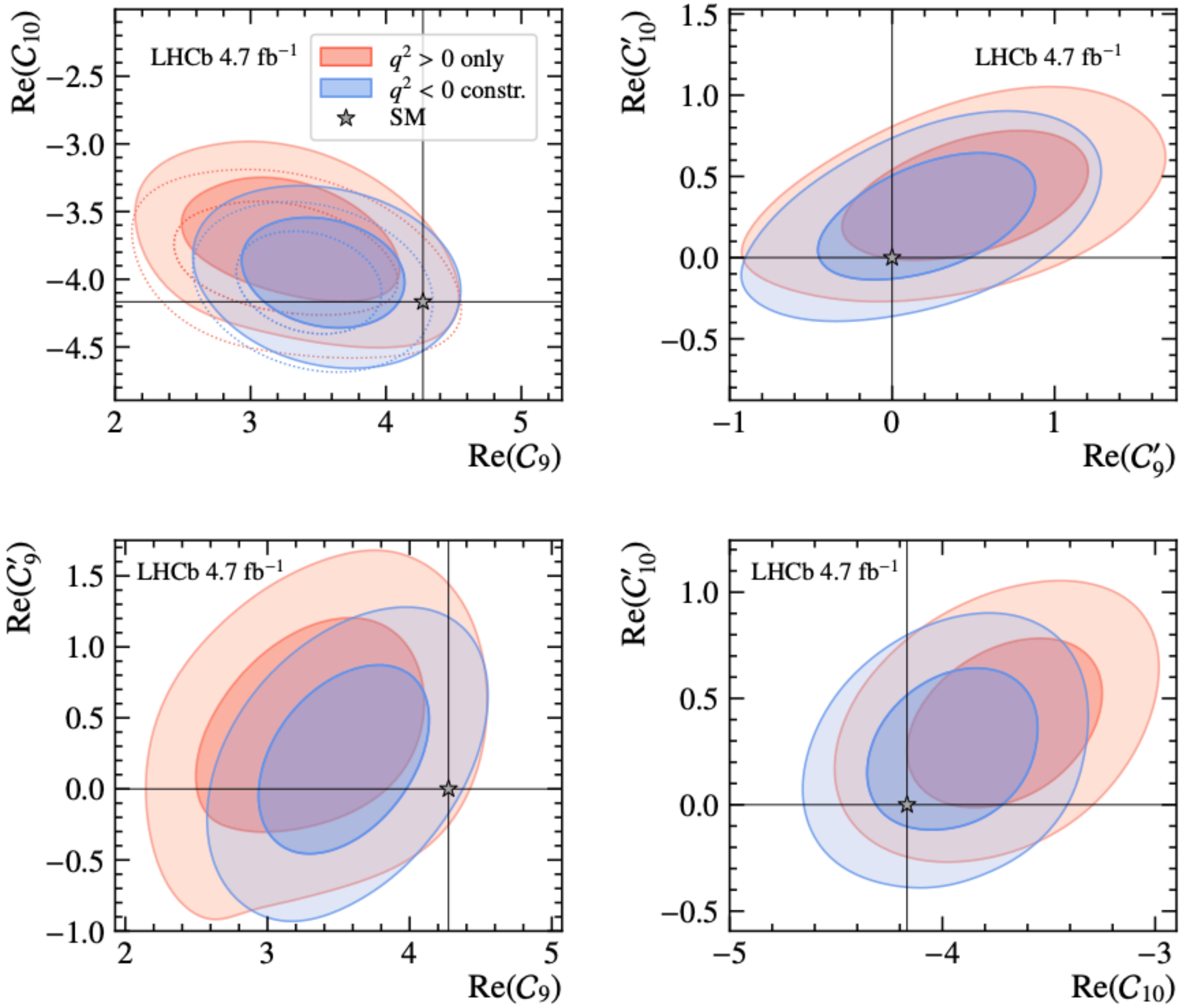
  $\to$ share all physics parameters in two q^2 regions
- Use 2011+2012+2016 data

$$
\begin{aligned}
\frac{32\pi}{9}\frac{\mathrm{d}^5\Gamma}{\mathrm{d}q^2\,\mathrm{d}k^2\,\mathrm{d}\vec{\Omega}} = {} & \frac{32\pi}{9}\frac{\mathrm{d}^5\Gamma^{\mathrm{P}}}{\mathrm{d}q^2\,\mathrm{d}k^2\,\mathrm{d}\vec{\Omega}} \\
& + \left(I_{1c}^S + I_{2c}^S\cos 2\theta_\ell\right) \\
& + \left(\tilde{I}_{1c} + \tilde{I}_{2c}\cos 2\theta_\ell\right)\cos\theta_K \\
& + \left(\tilde{I}_4\sin 2\theta_\ell + \tilde{I}_5\sin\theta_\ell\right)\sin\theta_K\cos\phi \\
& + \left(\tilde{I}_7\sin\theta_\ell + \tilde{I}_8\sin 2\theta_\ell\right)\sin\theta_K\sin\phi\,,
\end{aligned}
$$



Unbinned angular analysis

PRD 109 (2024) 052009



- First time **unbinned maximum-likelihood fit**

  → to obtain Wilson Coefficients

$$\begin{aligned}
\Delta\mathcal{C}_9 &= -0.93^{+0.53}_{-0.57} \quad (-0.68^{+0.33}_{-0.46})\,,\\
\Delta\mathcal{C}_{10} &= 0.48^{+0.29}_{-0.31} \quad (0.24^{+0.27}_{-0.28})\,,\\
\Delta\mathcal{C}_9' &= 0.48^{+0.49}_{-0.55} \quad (0.26^{+0.40}_{-0.48})\,,\\
\Delta\mathcal{C}_{10}' &= 0.38^{+0.28}_{-0.25} \quad (0.27^{+0.25}_{-0.27})\,,
\end{aligned}$$

- C_9 is in agreement within **1.8-1.9σ** with SM
- Global compatibility between all $C_{9,10}^{(\prime)}$ **1.3-1.4σ**

What are the next steps?

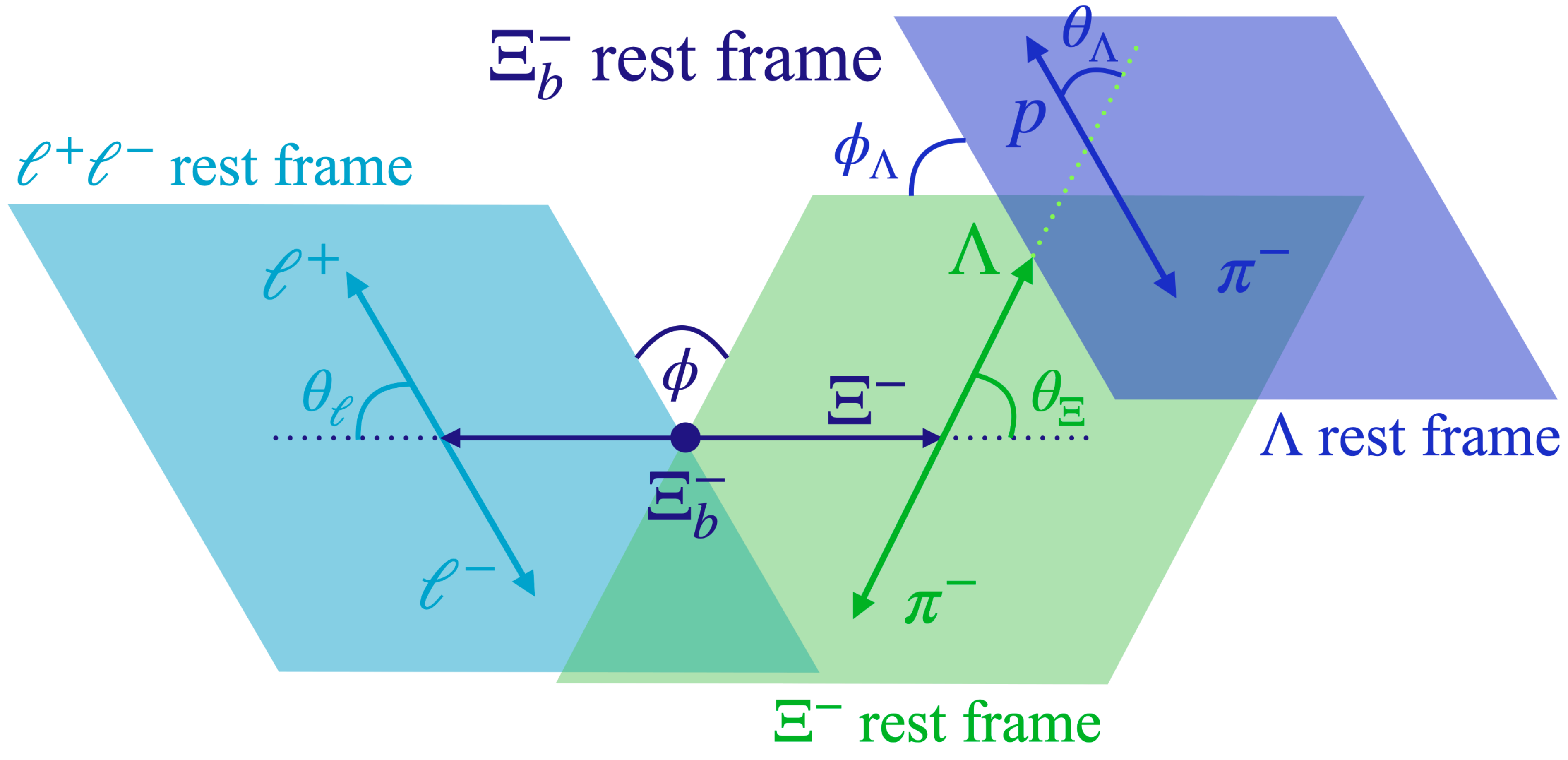
- Run 3 of LHC started

  → more data to analyse

  → more precise binning, new observables

- Look for unobserved modes e.g.

  $\Xi_b \to \Xi\mu^+\mu^-$ or $\Lambda_b^0 \to \Lambda e^+e^-$



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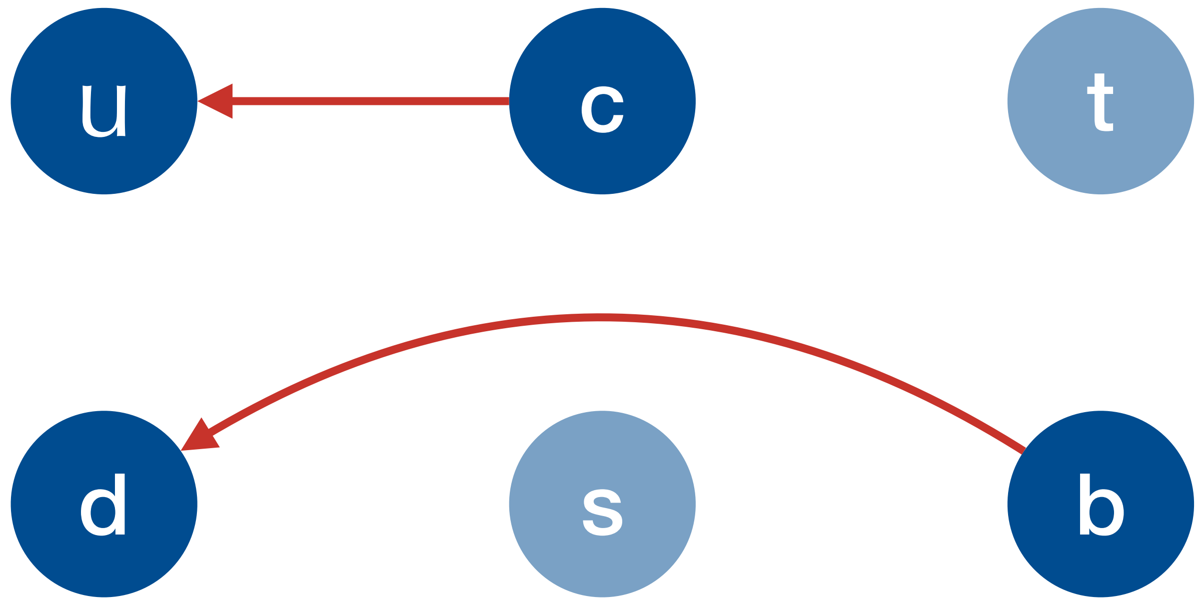
  $\Xi_b \to \Xi\mu^+\mu^-$ or $\Lambda_b^0 \to \Lambda e^+e^-$

- Study other FCNC at LHCb

  → $b \to d\ell^+\ell^-$

  → $c \to u\ell^+\ell^-$



Back-Up Amplitudes

- Amplitudes defined in different bases
- Helicity: spin projection along direction of motion
- Transversity: spin projection along direction transverse to interaction plane