BEAUTY AND THE LEPTONS

A tale of selected $b \to s\ell\ell^{(\prime)}$ analyses at LHCb

Habilitation à Diriger des Recherches

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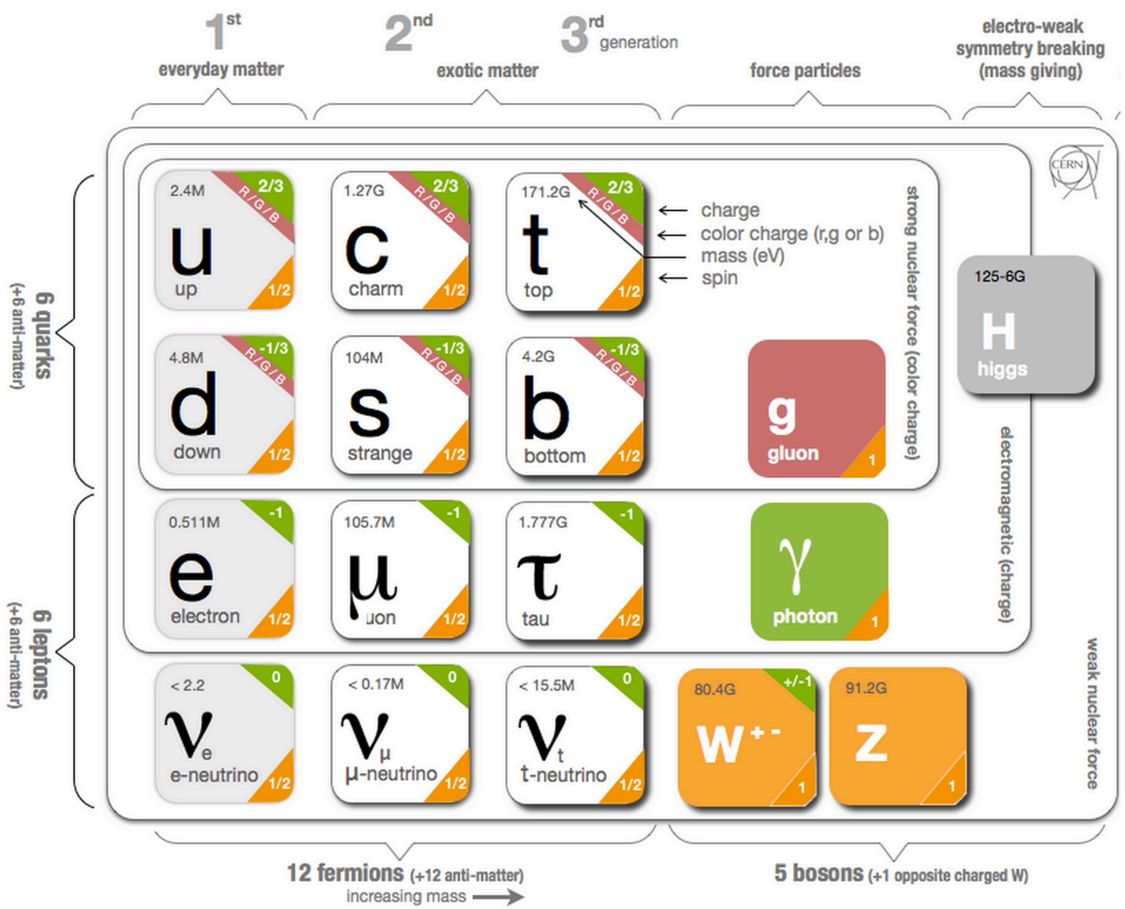
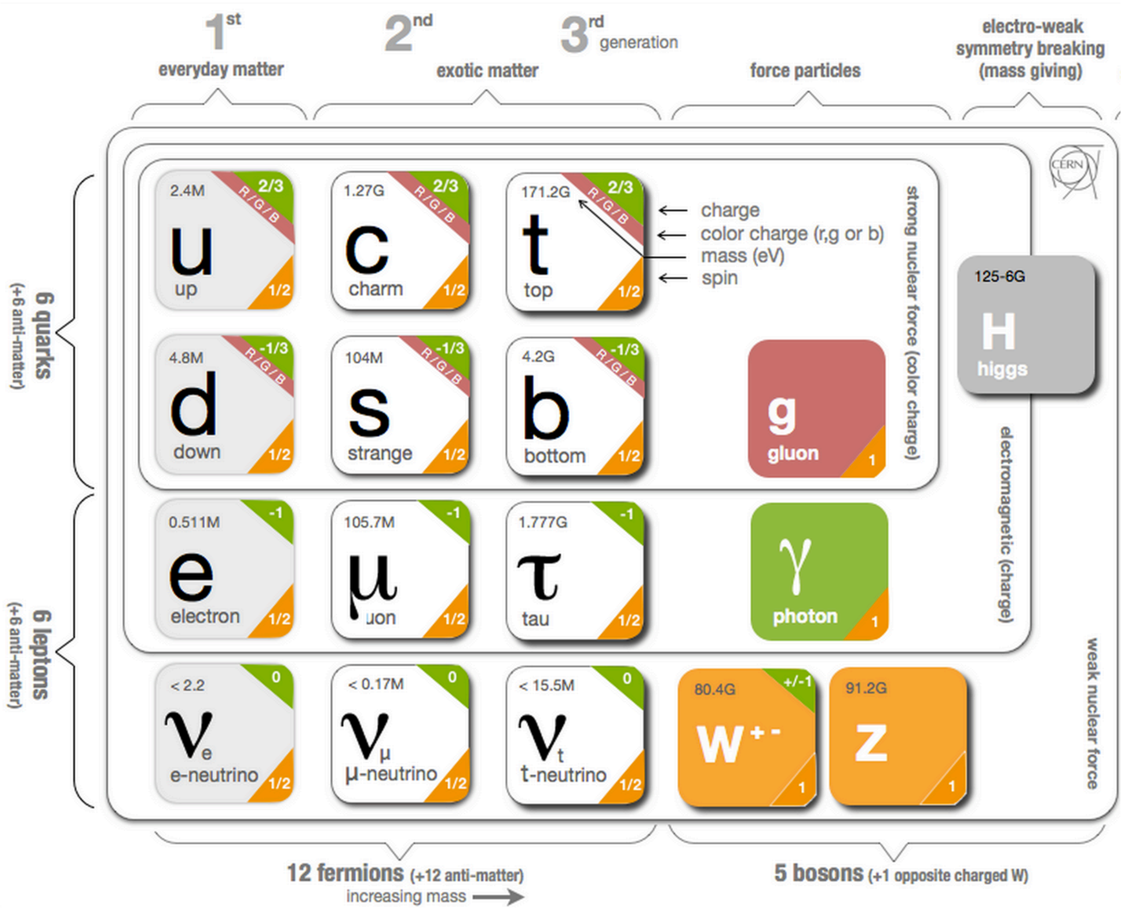
18 Decembre 2025

ONCE UPON A TIME: THE STANDARD MODEL

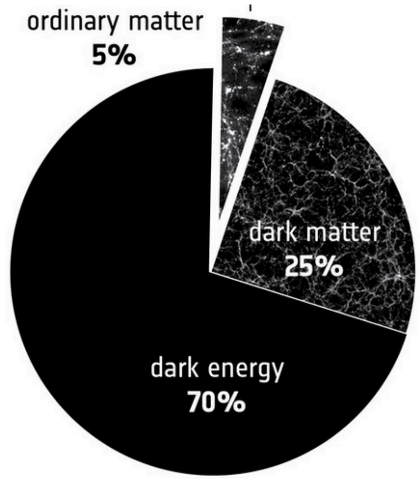


THE STANDARD MODEL



A THEORY WITH STILL MANY OPEN QUESTIONS:

- **3 generations**, same gauge interaction but **vastly different masses**?
- **Matter-antimatter asymmetry in the universe**?
- **Dark matter**?
- **Gravity**?



The Standard Model is understood as low energy approximation of a more fundamental theory

A MESSAGE FROM THE LHC

Main outcome of LHC :

1) Discovery of a SM Higgs-like boson

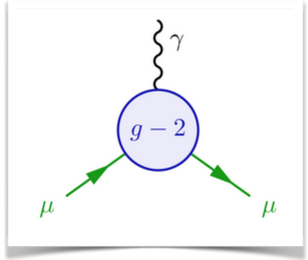
2) No direct observation of new physics particles

⇒ **New physics scale is higher than expected**

Can we explore it?

PRECISION MEASUREMENTS

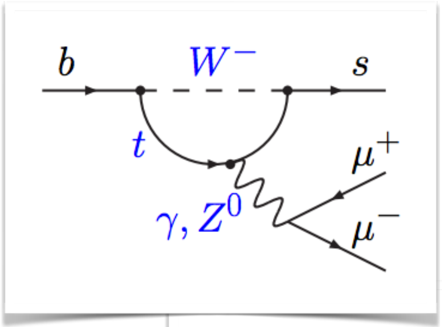
- Mesure precisely quantities predicted by the Standard Model and check consistency.
- Quantum corrections could unveil new physics effects
- Sensitivity to much higher scales and/or smaller couplings than direct searches
- Rarest decays provide highest sensitivity to NP

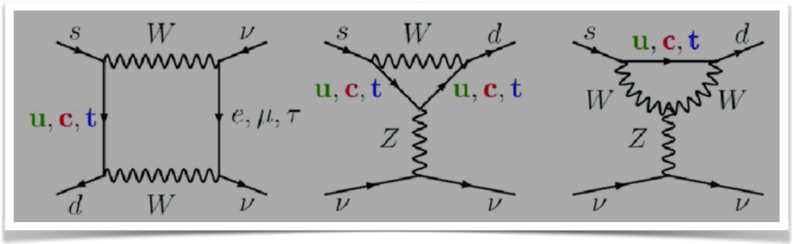


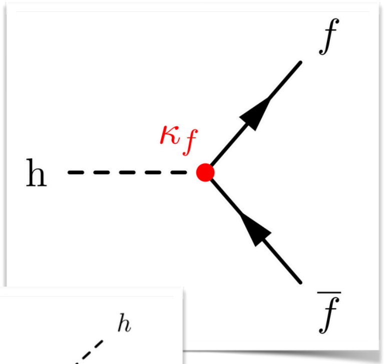
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_{NP}}{\Lambda^2}$$

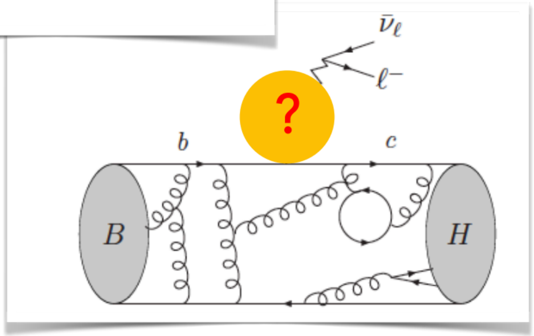
NP coupling

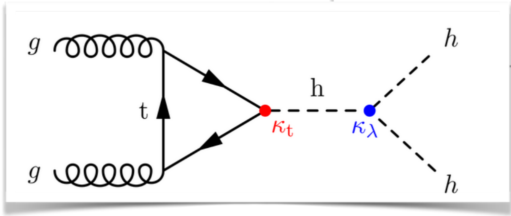
NP scale





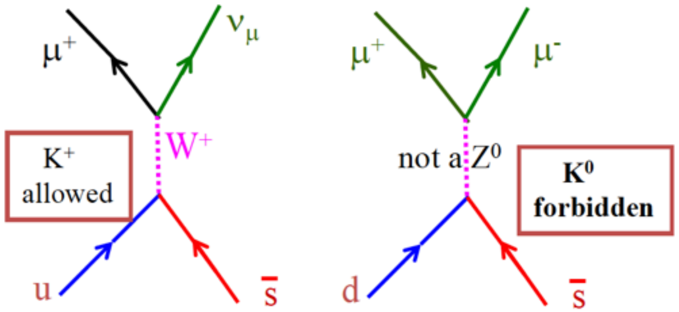






THE HISTORY OF THE b QUARK

- Early 70s : **Foundation** for a SM extension: FCNC (GIM mechanism) and CP violation in kaons (1964)

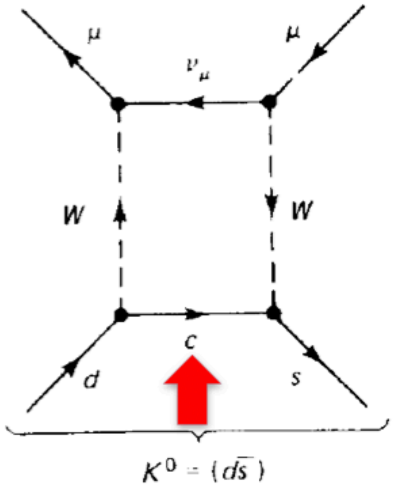


$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times 10^{-9}}{0.64} \approx 10^{-8}$$

SM with *u,d,s* only was predicting 10^{-4} ....

1970: Glashow, Iliopoulos, Maiani (GIM) propose:

- no tree level Flavor Changing Neutral Current (FCNC)
- FCNC occurs via loops, so suppressed
- A new quark to suppress *u* contribution
- ***prediction of charm quark, directly observed in 1973***



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The weak interaction acts on flavour eigenstates, different from mass eigenstates.

$$L_{cc} = -\frac{g}{\sqrt{2}} \overline{u}_i \gamma^\mu (1-\gamma_5) V_{ij} d_j W_\mu^+ + \text{h.c.}$$

The transitions between families are described by the CKM matrix

$$V_{ij} = V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM matrix is unitary. The Lagrangian does not depend on absolute phases.
These conditions implies 18-9-5= 4 independent parameters, with 1 complex phase
===> $V \neq V^*$ **==> CP violation.**

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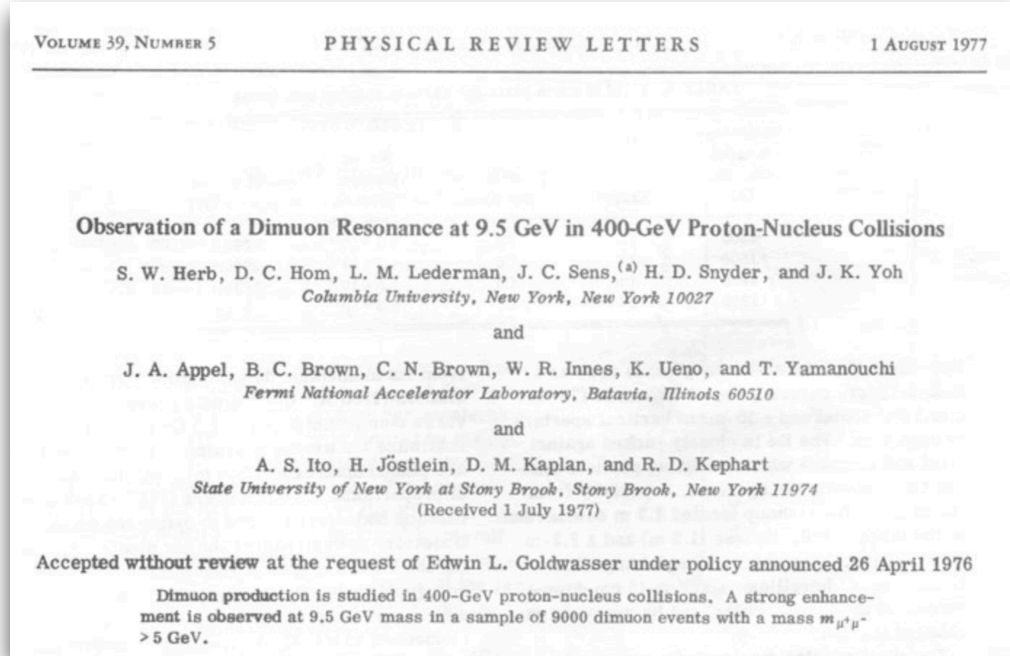
VOLUME 39, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1977

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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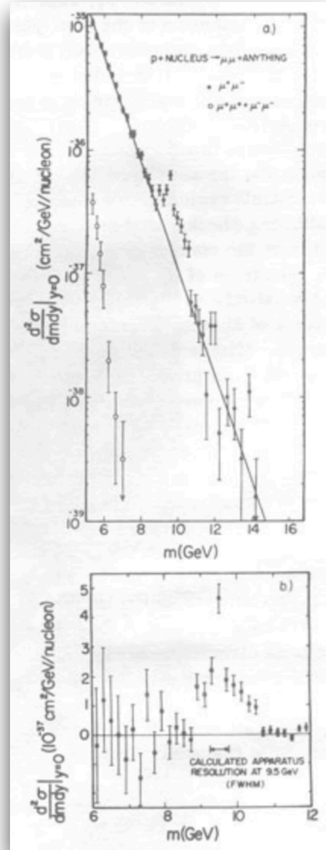
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.



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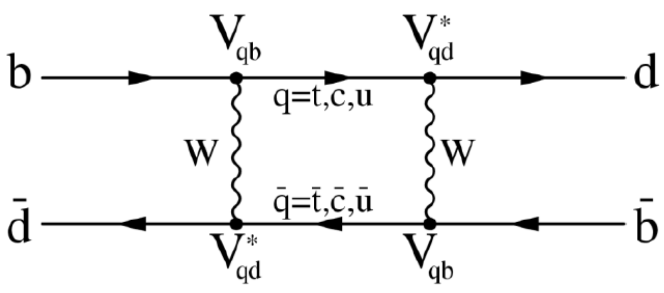
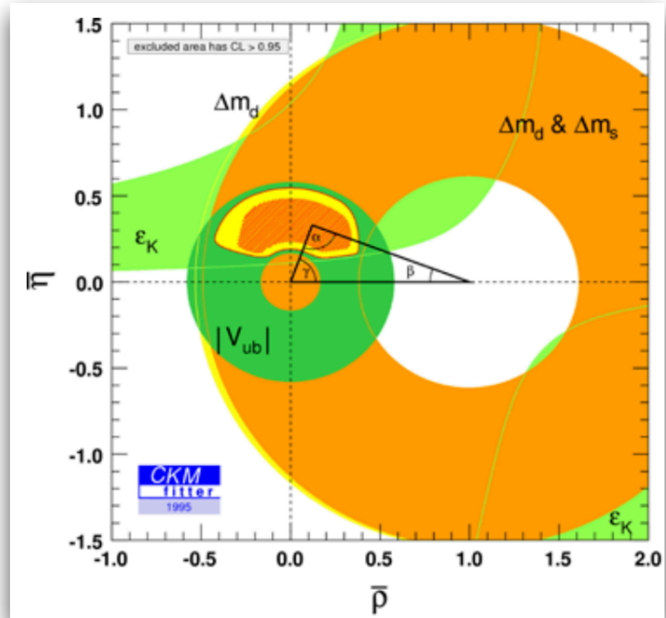
- Late 80s and 90s : **Mixing and lifetime** b-hadrons. Lifetime (1.5 ps) provides first hint of large mass of the top (discovered in 1995). **First CKM unitarity tests** (Vub, Vcb)



Argus mesure $\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$



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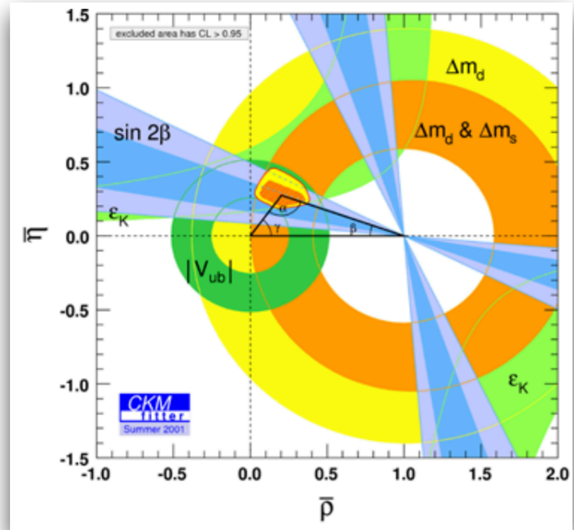
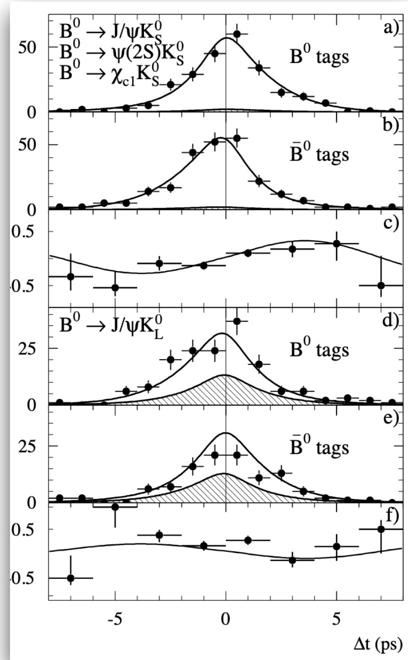
  Start of **precision tests era** for NP discovery

  (Tevatron, b-factories, LHC)





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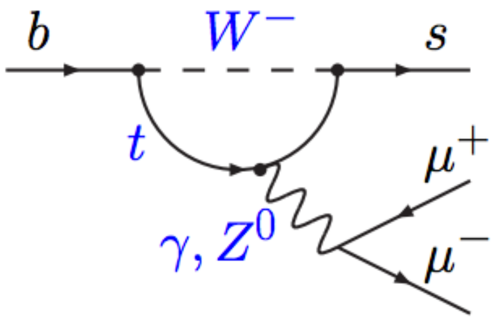
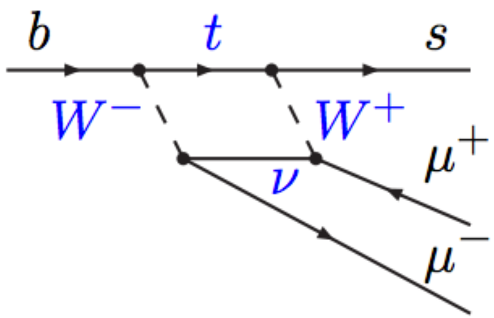
The b quark evolved from a theoretical necessity to one of the most powerful tools for testing the Standard Model and searching for new physics.

$b \to s\ell^+\ell^-$ TRANSITIONS





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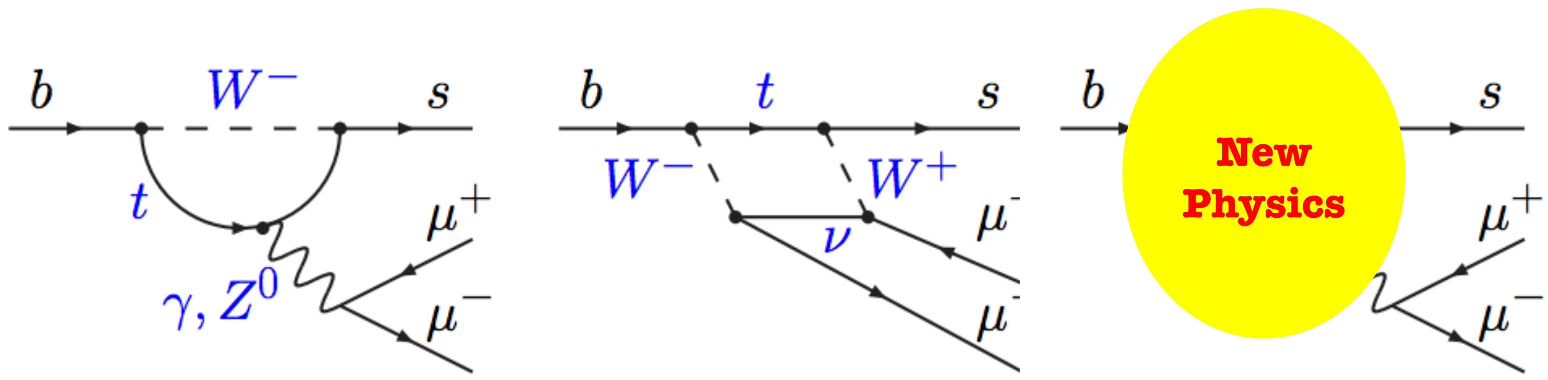
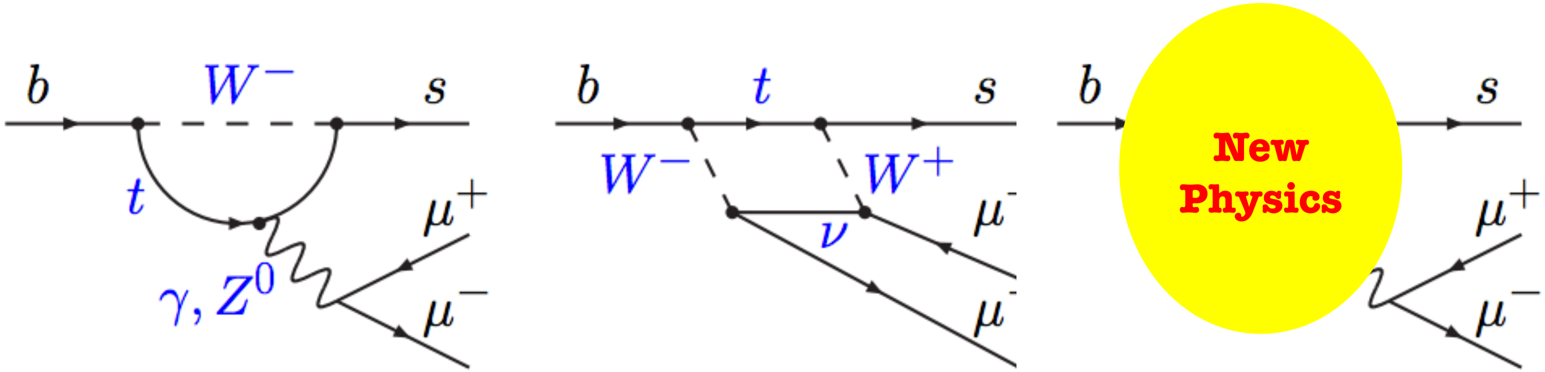


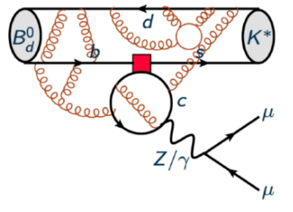
New particles in the loop could: enhance/suppress decay rates; introduce new sources of CP violation; modify angular distributions; couple differently to different lepton families.

Branching fractions **Angular analyses** **Lepton Flavour Universality tests**

$b \to s\ell^+\ell^-$ TRANSITIONS



But beware of charm loops!



New particles in the loop could: enhance/suppress decay rates; introduce new sources of CP violation; modify angular distributions; couple differently to different lepton families.

Branching fractions	Angular analyses	Lepton Flavour Universality tests
Affected by FF + $c\bar{c}$ loops	Affected by $c\bar{c}$ loops	Clean!

← increasing theoretical complexity

increasing experimental complexity →

EFFECTIVE FIELD THEORY

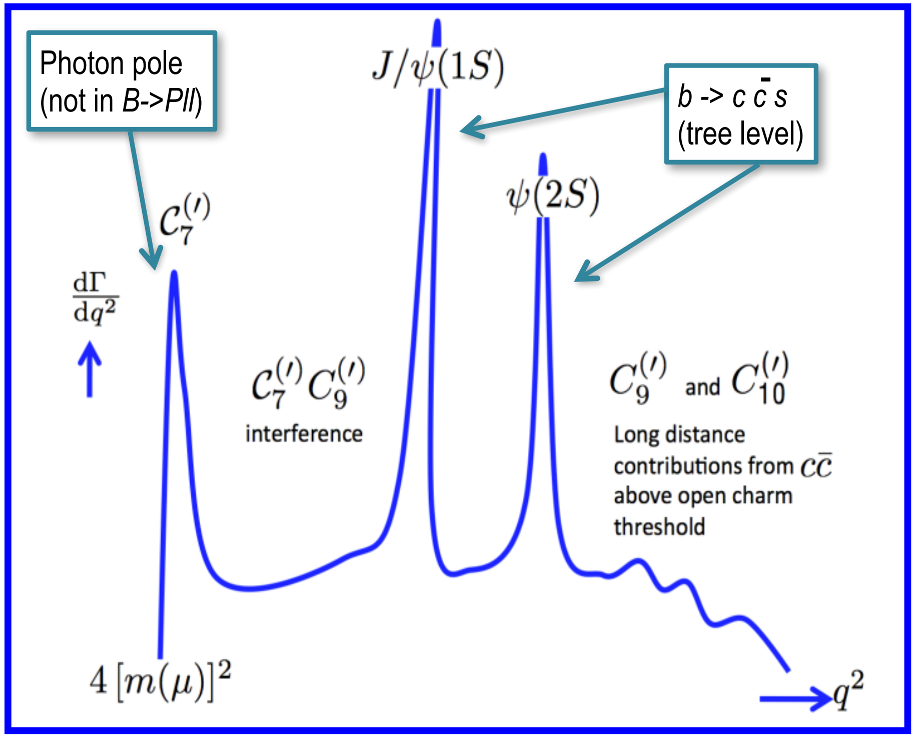
Describe low-energy phenomena without knowing the full details of high-energy theory

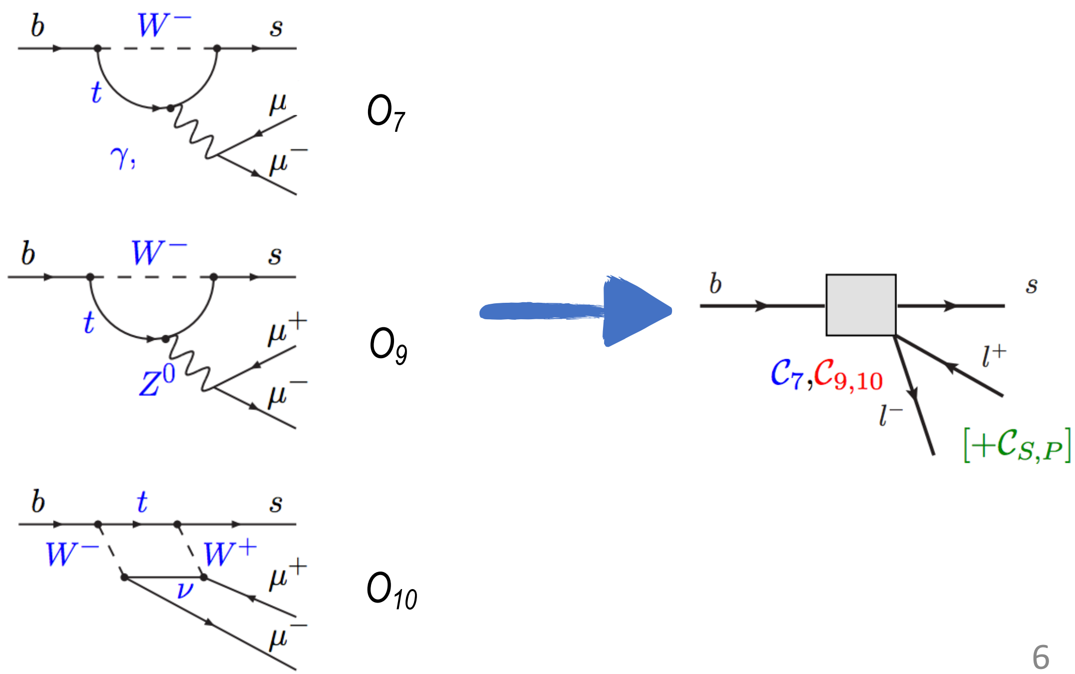
$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

i = 1, 2	Tree
i = 3 -6, 8	Gluon penguin
i = 7	Photon penguin
i = 9, 10	Electroweak penguin
i = S	Higgs (scalar) penguin
i = P	Pseudoscalar penguin

Operators O_i: non-perturbative long-distance effects

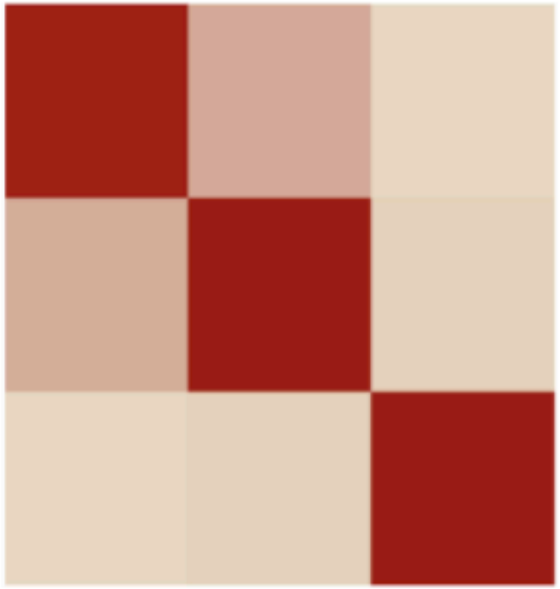
Wilson coefficients C_i: perturbative short-distance effects



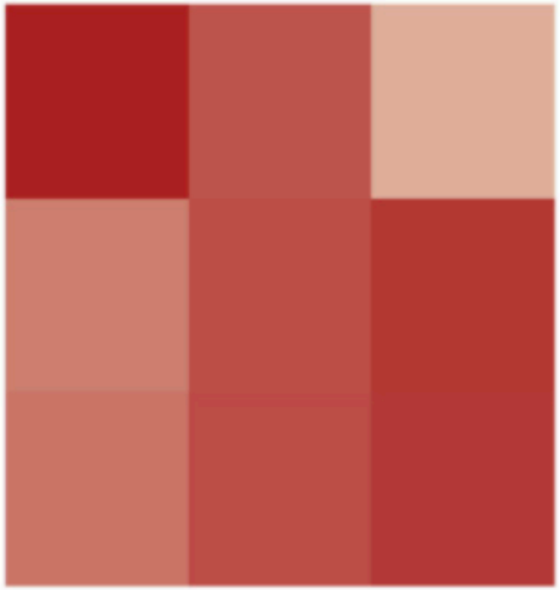


PUZZLE OF MIXING MATRICES

CKM matrix



PMNS matrix



?

Quarks

Neutrinos

Electron, muon tau

Very different mixing structure between quarks and neutrinos!

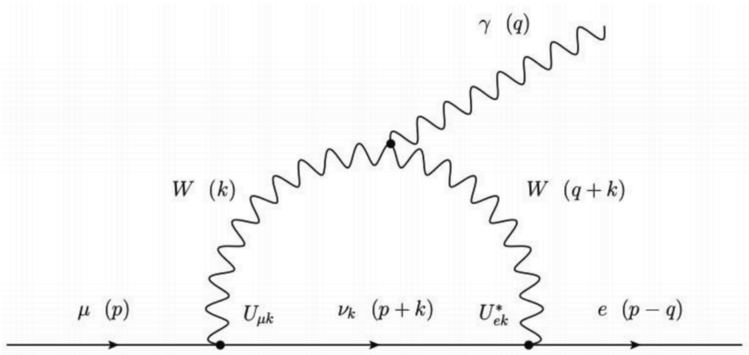
And why charged lepton are the only fermions not directly mixing?

CHARGED LEPTON FLAVOR VIOLATION

- Lepton flavour violation in the Standard Model through neutrino oscillations (Br < 10^{-40})

=> **charged LFV decays in the SM have rates of the order of 10^{-54} !**

Observation would be a striking sign of new physics!



$$\mathcal{B}(\mu \to e\gamma) \simeq \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U^{*}_{ek} m^2_{\nu_k}}{M^2_W} \right|^2$$
$$\simeq 10^{-55} - 10^{-54}$$

- **LFV in *B* decays is potentially, but not necessarily, related to LFU violation :** [Glashow, Guadagnoli, Lane] PhysRevLett.114.091801

$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \sim 3 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2$$

$$\mathcal{B}(B \to K(e^{\pm},\mu^{\pm})\tau^{\mp}) \sim 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2$$

[Hiller, Loose, Schönwald (2016)]

TIMESCALE OF THE ANALYSES

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

- 2016: $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis (3 fb-1)
- 2017: $R_{K^{*0}}$
- 2019: $B^+ \to K^+\mu^\pm e^\mp$
- 2023: R_X
- 2023: $B^0 \to K^{*0}\tau^\pm\mu^\mp$
- 2025: $B^0 \to K^{*0}\tau^\pm e^\mp$
- 2025: $B^0 \to K^{*0}\mu^+\mu^-$ angular analysis (9 fb-1)

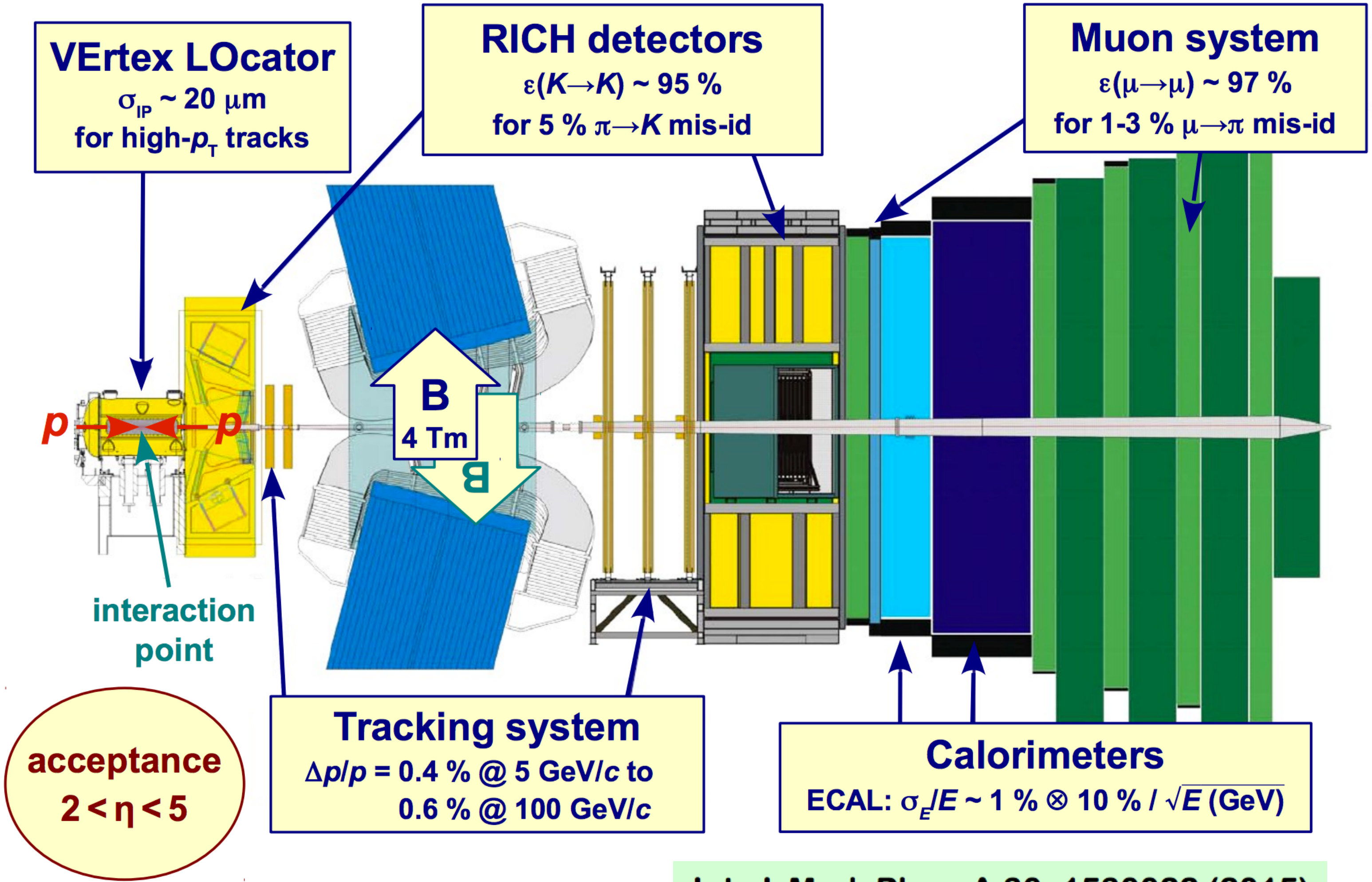
Co-direction de theses:

- Samuel Coquereau
- Andrea Mogini
- Tommaso Fulghesu

Supervision des postdocs:

- Giulio Dujany
- Steffen George Weber

LHCb: A DETECTOR FOR FLAVOR PHYSICS



Int. J. Mod. Phys. A 30, 1530022 (2015)

LEPTONS AT LHCb

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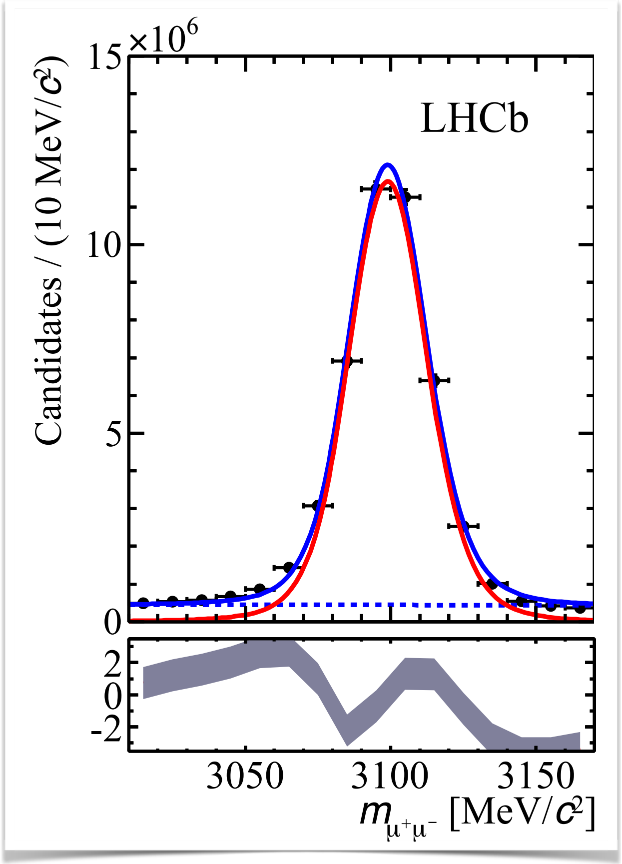
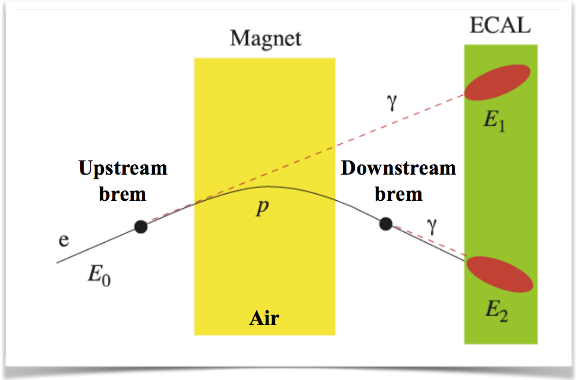
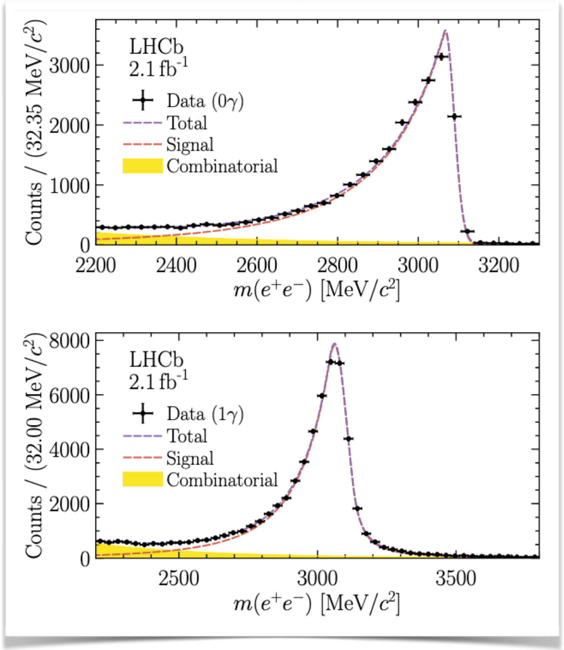


- **Clear trigger signature**
- **Very good di-muon resolution.**

LEPTONS AT LHCb





Problems:
1) ***bremsstrahlung***
2) ***trigger inefficiencies***

→

Solutions:
1) ***Recovery and brew categories***
2) ***Additional triggers***

LEPTONS AT LHCb

Leptonic:

- $BR(\tau^- \to \mu^- \nu\nu) = 17.41 \pm 0.04$ %
- $BR(\tau^- \to e^- \nu\nu) = 17.83 \pm 0.04$ %

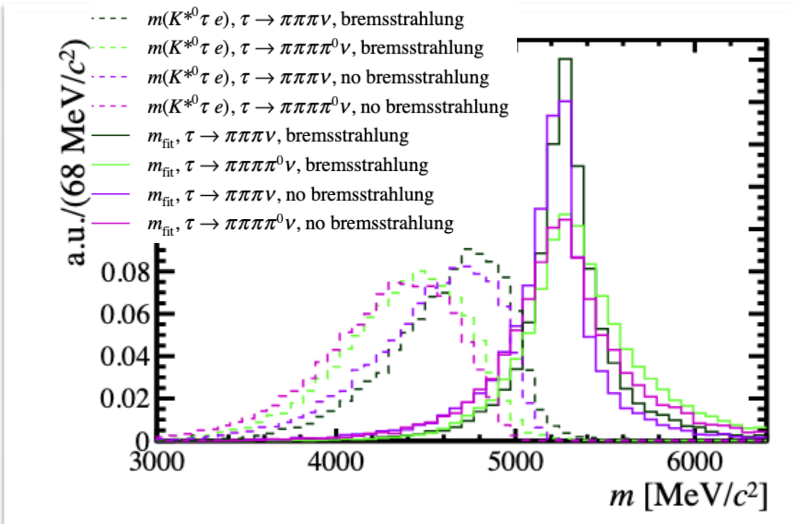
Hadronic:

- $BR(\tau^- \to \pi^- \nu) = 10.83 \pm 0.06$ %
- $BR(\tau^- \to \pi^- \pi^0 \nu) = 25.52 \pm 0.09$ %
- $BR(\tau^- \to \pi^- \pi^0 \pi^0 \nu) = 9.30 \pm 0.11$ %
- $BR(\tau^- \to \pi^- \pi^+ \pi^- \nu) = 9.31 \pm 0.06$ %
- $BR(\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu) = 4.62 \pm 0.06$ %

Problem:
- reconstructed through decays with neutrino

→

Solution:
- exploit event kinematics



BACKGROUNDS

Multiple type of **backgrounds** should be rejected:

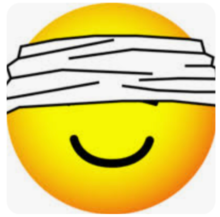
- **Combinatorial**
- **Physics backgrounds** (fully and/or partially reconstructed and/or with mis-identification) particularly annoying as could pollute physics quantities determinations.

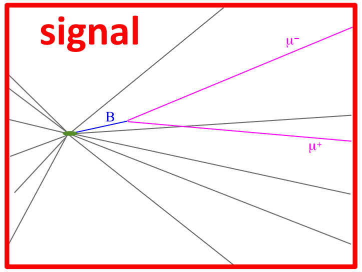
Background decay	Selection
$B^0 \to K^{*0}V(\to \ell^+\ell^-)$ $V = \rho$, ω, or ϕ	In angular: $q^2 \notin (0.98,\ 1.10)\ \text{GeV}^2/c^4$ In $R_{K^{*0}}$: contamination $< 2\%$, negligible as similar for μ and e
$B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$ $B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-)$	$q^2 \notin (8,\ 11)\ \text{GeV}^2/c^4$ $q^2 \notin (12.5,\ 15.0)\ \text{GeV}^2/c^4$
$B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$ $B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-)$ with swapped identity of one hadron (h) and one μ.	$m(h_\mu\mu)^2 \notin (8, 11)\ \text{GeV}^2/c^4$ $m(h_\mu\mu)^2 \notin (12.5,\ 15)\ \text{GeV}^2/c^4$ (h_μ is swapped hadron under muon mass hypothesis)
$B^0 \to D^-(\to K^{*0}\ell^-\overline{\nu})\ell^+\nu$ Non-peaking background with a branching fraction four orders of magnitude larger than the signal.	In angular: D veto In $R_{K^{*0}}$: $\lvert\cos\vartheta_\ell\rvert < 0.8$
$B^+ \to K^+\ell^+\ell^-$ Combined with a low-momentum π^- from the rest of the event, populates the upper mass sideband region used for training the neural-network classifiers.	In angular: $m(K^+\mu^+\mu^-) \notin (5220, 5340)$ MeV/c^2 In $R_{K^{*0}}$: $m(K^+\ell^+\ell^-) < 5100$ MeV/c^2. Candidates where the π^- from the K^* is misidentified as a kaon and paired with a π^+ are similarly rejected.
$B^0_s \to \phi(\to K^+K^-)\ell^+\ell^-$ One kaons is misidentified as a pion.	In angular: Tight PID criteria if $m(K\pi_K\mu\mu)$ and $m(K\pi_K)$ are consistent with the known B^0_s and ϕ masses. In $R_{K^{*0}}$: $m(K\pi_K) > 1040\,\text{MeV}/c^2$.
$B^{0,+} \to K^{*0,+}\ell^+\ell^-$ Pion from $K^{*0,+}$ replaced by another pion in the event.	Not peaking, included in combinatorial parameterization
$B^0 \to K^{*0}\ell^+\ell^-$ Can be background to $\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ (and vice versa) if the K^+ (K^-) is misidentified as the π^+ (π^-) and the π^- (π^+) is misidentified as the K^- (K^+).	Tight PID criteria.
$\Lambda^0_b \to pK^-\mu^+\mu^-$ Proton misidentified as pion.	Tight pion PID if $m(\pi_p K\mu\mu)$ close to $m(\Lambda^0_b)$
$\Lambda^0_b \to pK^-\mu^+\mu^-$ Double misidentification of the hadrons, i.e., where the proton is misidentified as a kaon and the kaon is misidentified as a pion.	Tight PID criteria.

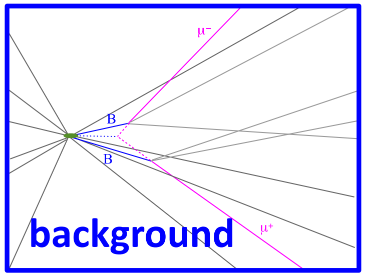
Table 2.6.1: Summary of relevant background decays and selection strategies for the angular and $R_{K^{*0}}$ analyses.

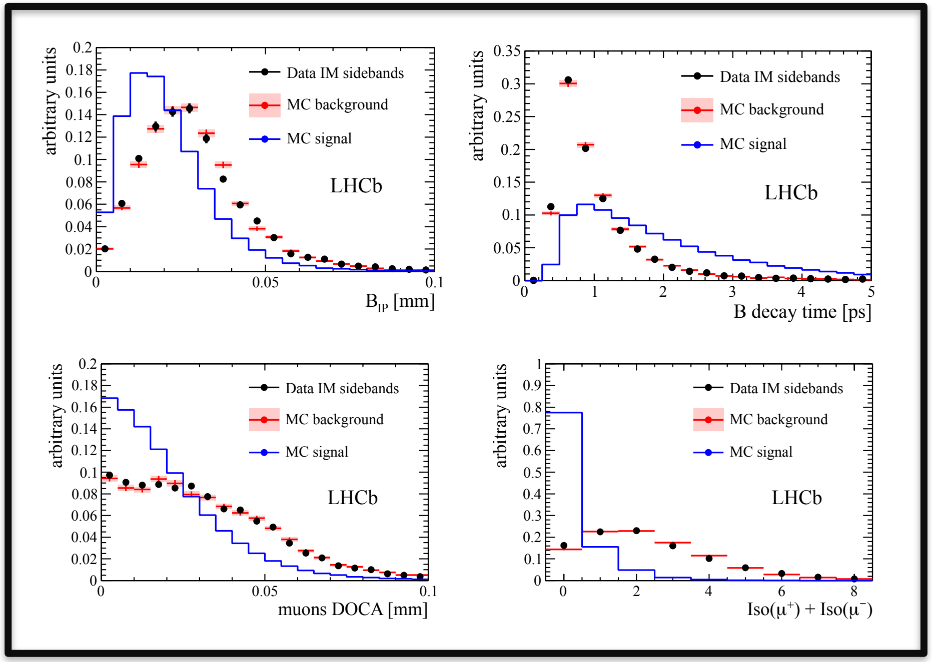
A TYPICAL ANALYSIS AT LHCb

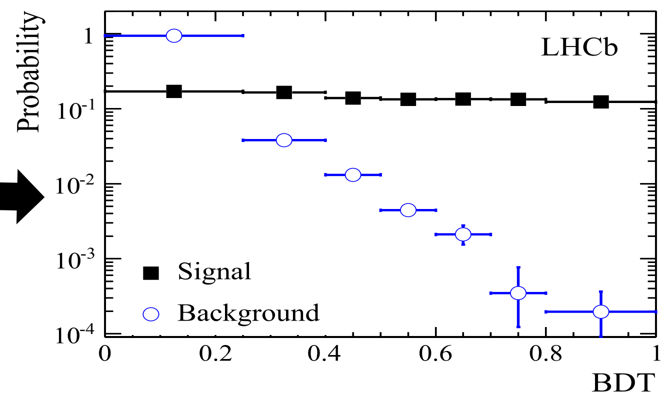
- **Trigger**
- **“stripping”**, i.e. central preselection
- **Multivariate techniques** exploiting **kinematics and topology**
- **Specific vetoes** to remove or reduce peaking backgrounds
- Particle **Id**entification requirements
- **Control channels** to correct simulations
- **Normalization channels** to reduce systematics (no absolute BR)
- **Statistical methods** on a final set of discriminating variables











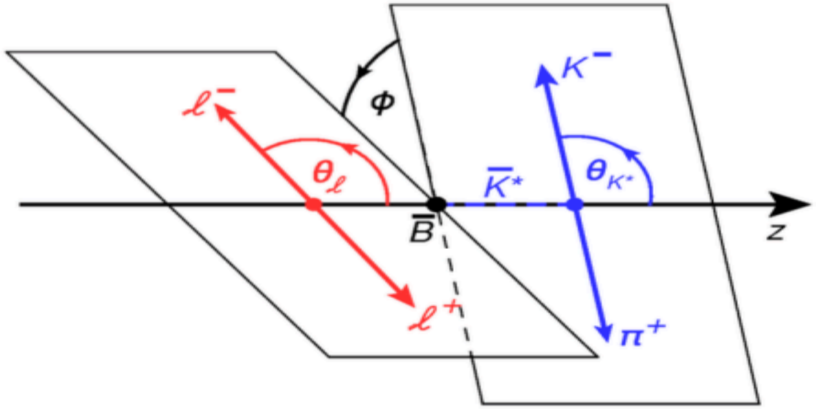
$B^0 \to K^{*0}\mu^\pm\mu^\mp$ ANGULAR ANALYSIS

$B^0 \to K^{*0}\mu^\pm\mu^\mp$ ANGULAR ANALYSIS

$$\frac{d^4\Gamma[\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega})$$

i	I_i	f_i
1s	$\frac{3}{4}\left(\lvert A_\parallel^L\rvert^2 + \lvert A_\perp^L\rvert^2 + \lvert A_\parallel^R\rvert^2 + \lvert A_\perp^R\rvert^2\right)$	$\sin^2\vartheta_K$
1c	$\left(\lvert A_0^L\rvert^2 + \lvert A_0^R\rvert^2\right)$	$\cos^2\vartheta_K$
2s	$\frac{1}{4}\left(\lvert A_\parallel^L\rvert^2 + \lvert A_\perp^L\rvert^2 + \lvert A_\parallel^R\rvert^2 + \lvert A_\perp^R\rvert^2\right)$	$\sin^2\vartheta_K \cos 2\vartheta_\ell$
2c	$-\left(\lvert A_0^L\rvert^2 - \lvert A_0^R\rvert^2\right)$	$\cos^2\vartheta_K \cos 2\vartheta_\ell$
3	$\frac{1}{2}\left(\lvert A_\perp^L\rvert^2 - \lvert A_\parallel^L\rvert^2 + \lvert A_\perp^R\rvert^2 - \lvert A_\parallel^R\rvert^2\right)$	$\sin^2\vartheta_K \sin^2\vartheta_\ell \cos 2\phi$
4	$\sqrt{2}\,\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})$	$\sin 2\vartheta_K \sin 2\vartheta_\ell \cos\phi$
5	$\sqrt{2}\,\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*})$	$\sin 2\vartheta_K \sin\vartheta_\ell \cos\phi$
6s	$2\,\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*})$	$\sin^2\vartheta_K \cos\vartheta_\ell$
7	$\sqrt{2}\,\mathrm{Im}(A_0^L A_\parallel^{L*} - A_0^R A_\parallel^{R*})$	$\sin 2\vartheta_K \sin\vartheta_\ell \sin\phi$
8	$\sqrt{2}\,\mathrm{Im}(A_0^L A_\perp^{L*} + A_0^R A_\perp^{R*})$	$\sin 2\vartheta_K \sin 2\vartheta_\ell \sin\phi$
9	$\mathrm{Im}(A_\parallel^{L*} A_\perp^L + A_\parallel^{R*} A_\perp^R)$	$\sin^2\vartheta_K \sin^2\vartheta_\ell \sin 2\phi$
10	$\frac{1}{3}\left(\lvert A_S^L\rvert^2 + \lvert A_S^R\rvert^2\right)$	1
11	$\sqrt{\frac{4}{3}}\,\mathrm{Re}(A_S^L A_0^{L*} + A_S^R A_0^{R*})$	$\cos\vartheta_K$
12	$-\frac{1}{3}\left(\lvert A_S^L\rvert^2 + \lvert A_S^R\rvert^2\right)$	$\cos 2\vartheta_\ell$
13	$-\sqrt{\frac{4}{3}}\,\mathrm{Re}(A_S^L A_0^{L*} + A_S^R A_0^{R*})$	$\cos\vartheta_K \cos 2\vartheta_\ell$
14	$\sqrt{\frac{2}{3}}\,\mathrm{Re}(A_S^L A_\parallel^{L*} + A_S^R A_\parallel^{R*})$	$\sin\vartheta_K \sin 2\vartheta_\ell \cos\phi$
15	$\sqrt{\frac{8}{3}}\,\mathrm{Re}(A_S^L A_\perp^{L*} - A_S^R A_\perp^{R*})$	$\sin\vartheta_K \sin\vartheta_\ell \cos\phi$
16	$\sqrt{\frac{8}{3}}\,\mathrm{Im}(A_S^L A_\parallel^{L*} - A_S^R A_\parallel^{R*})$	$\sin\vartheta_K \sin\vartheta_\ell \sin\phi$
17	$\sqrt{\frac{2}{3}}\,\mathrm{Im}(A_S^L A_\perp^{L*} + A_S^R A_\perp^{R*})$	$\sin\vartheta_K \sin 2\vartheta_\ell \sin\phi$



$$S_i = \frac{I_i + \bar{I}_i}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}}$$

CP-averaged observables

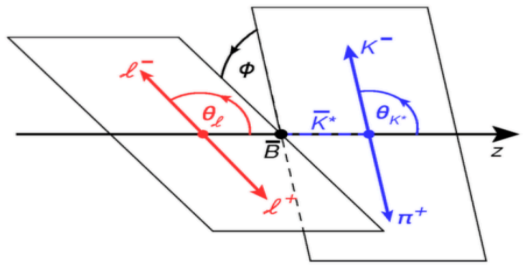
$$A_i = \frac{I_i - \bar{I}_i}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}}$$

CP-asymmetries

THE ANGULAR DISTRIBUTION

- The full angular distribution (θ_l, θ_K,ϕ) is described by **eight independent observables**:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi + \frac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi + S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$



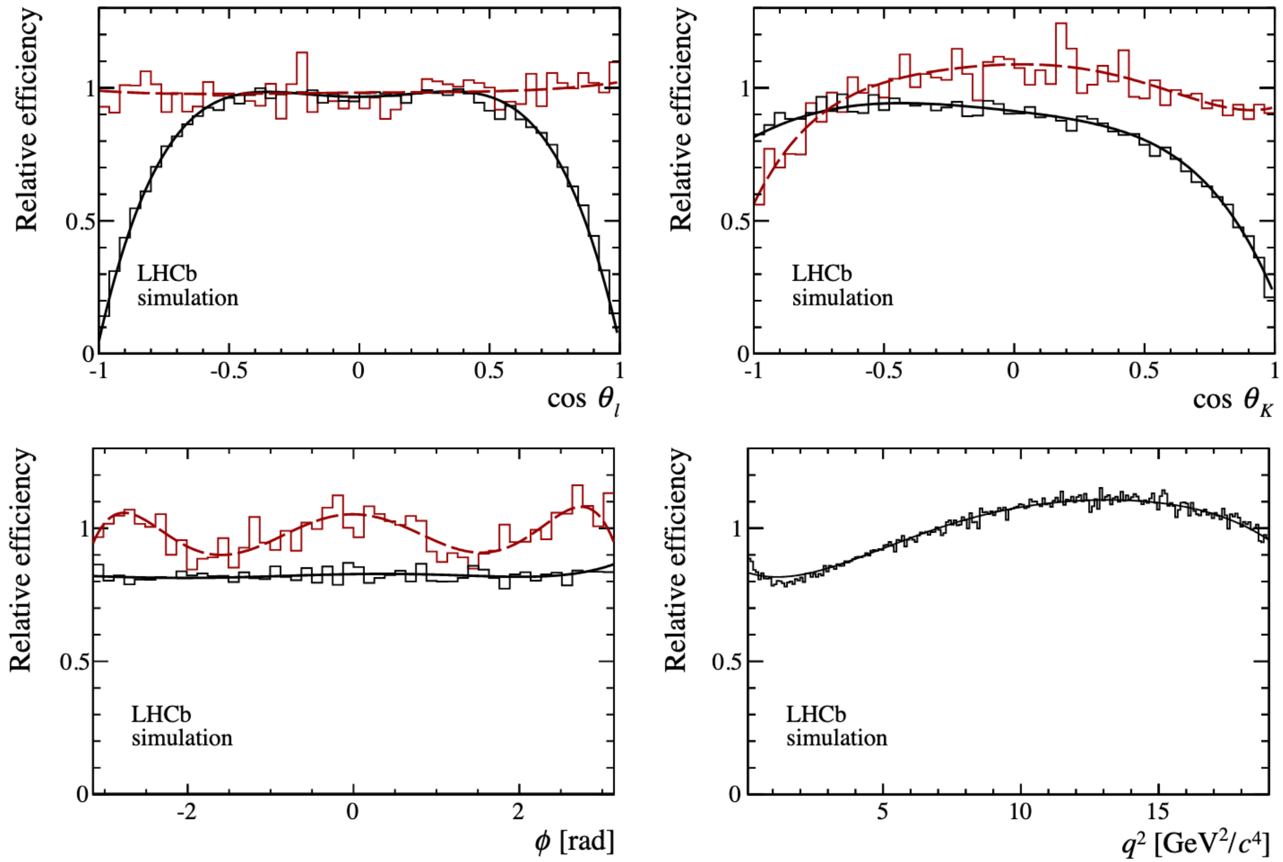
- Observables (A_{FB}, F_L and S_j) are **function of the Wilson coefficients**.

- **P' is a set of observables** where hadronic form factor uncertainties cancels at the leading order (JHEP 1305(2013)137). Example:

$$P_5' \equiv \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

EFFICIENCY SHAPE

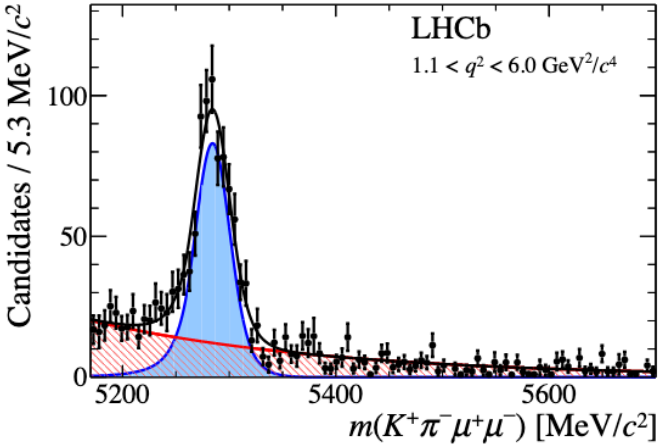
$$\varepsilon(\cos\vartheta_\ell, \cos\vartheta_K, \phi, q^2) = \sum_{i,j,m,n} c_{ijmn}\, L_i(\cos\vartheta_\ell)\, L_j(\cos\vartheta_K)\, L_m(\phi)\, L_n(q^2)$$

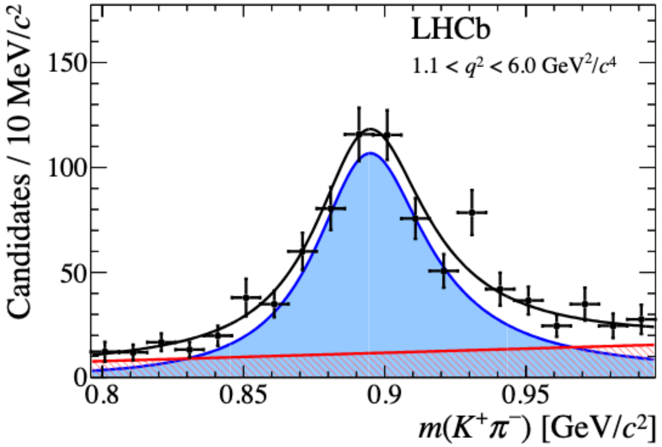


0.10 < q2 < 0.98 GeV2/c4

18 < q2 < 19 GeV2/c4

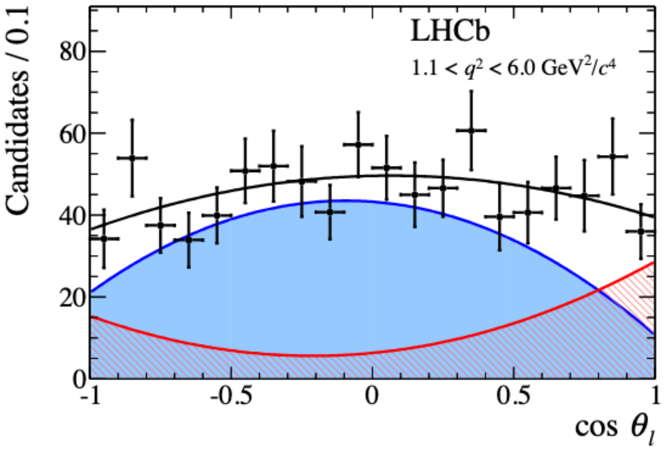
MAXIMUM LIKELIHOOD FIT

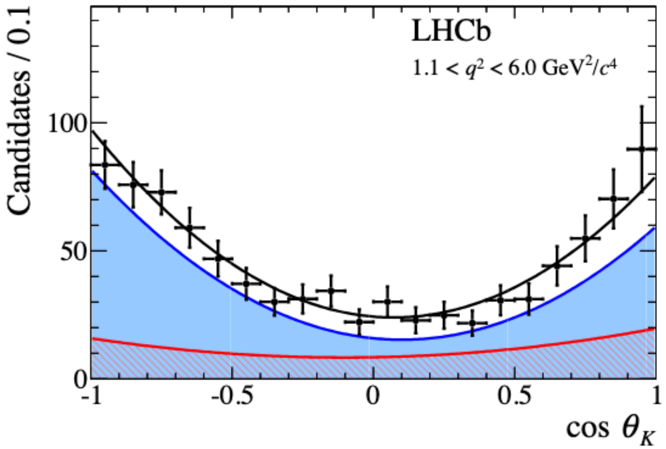


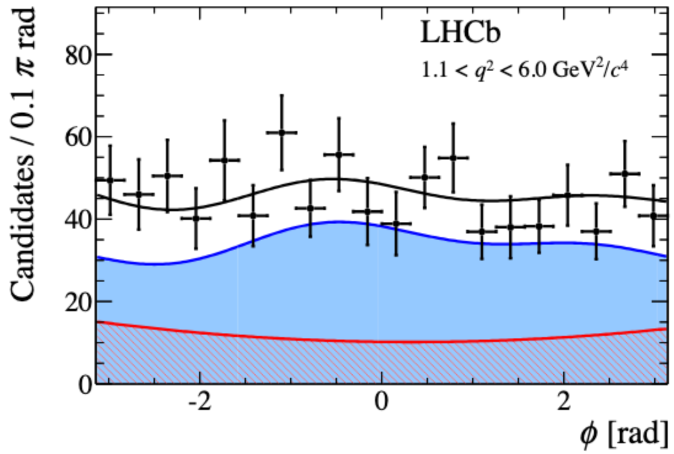


First full angular analysis of B->K* μμ, using Run1 (3 fb^{-1})

- full set of CP-averaged angular terms
- full set of CP-asymmetries
- correlation matrix published
- form-factor independent ratios of observables measured (P')

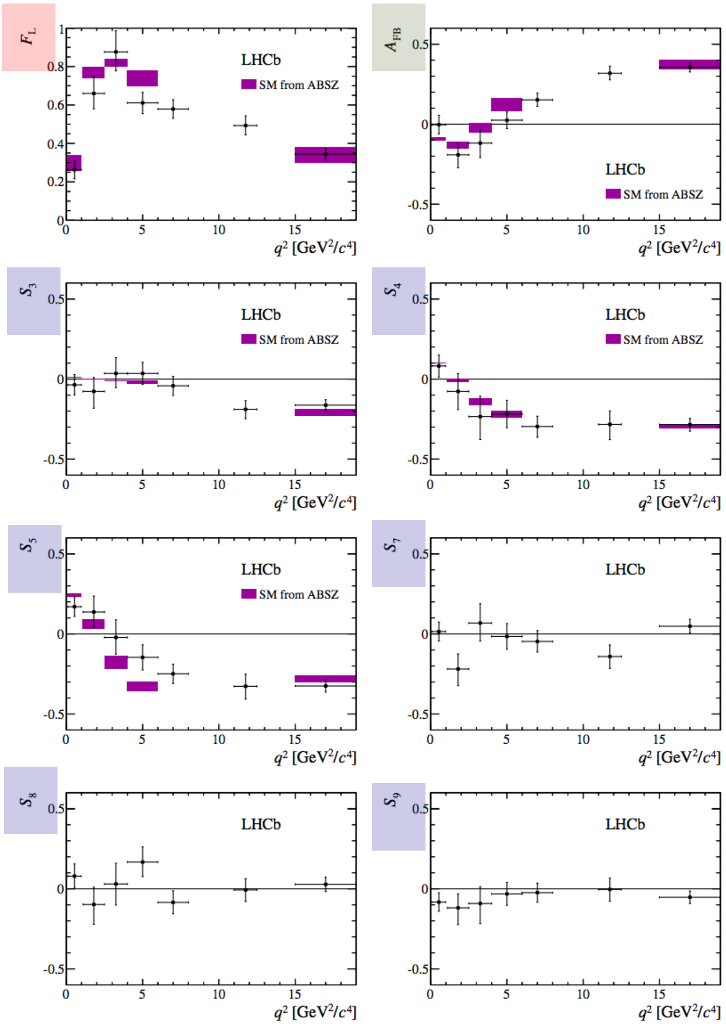




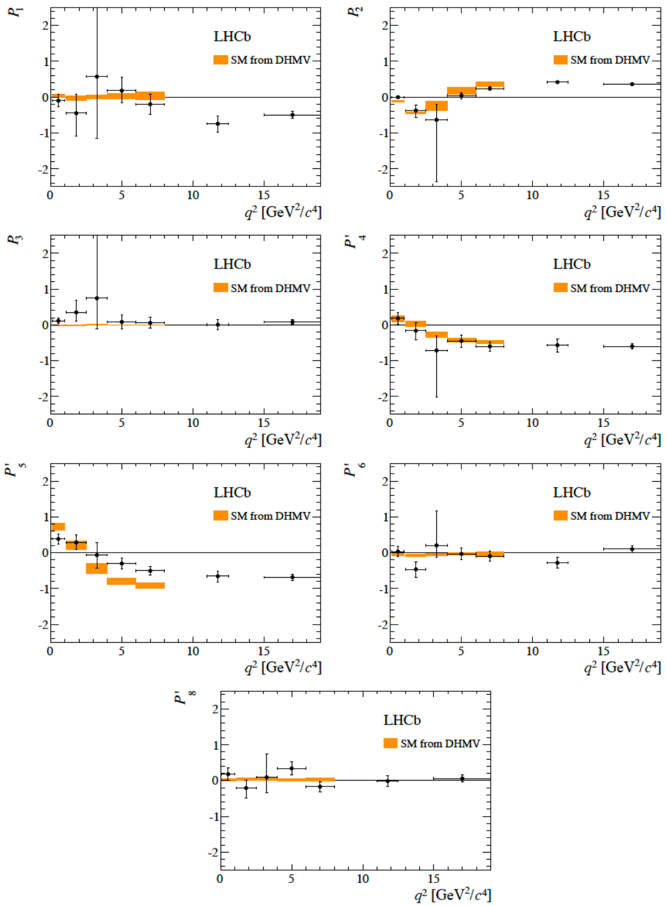


RESULTATS

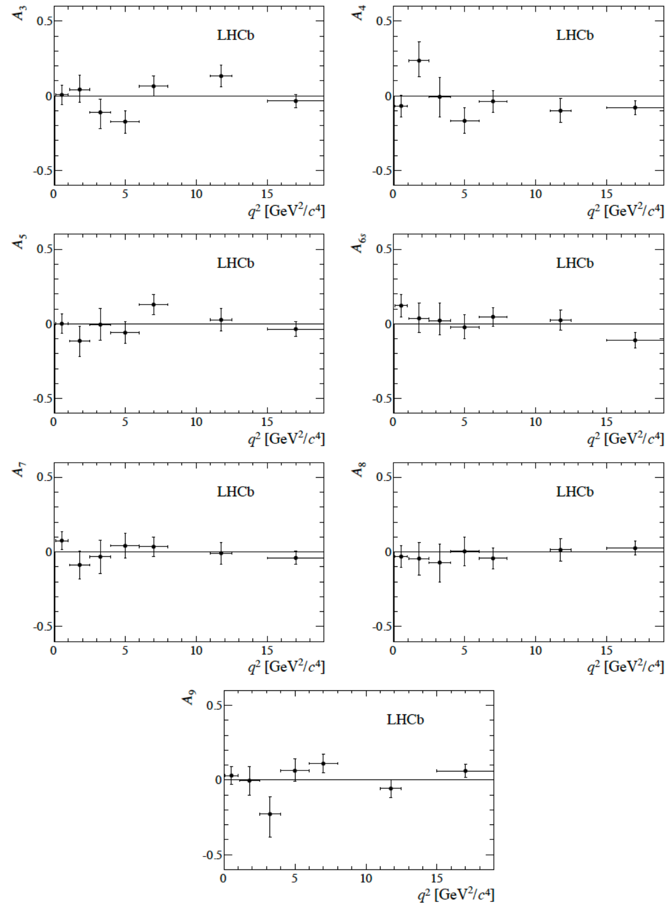
CP-averaged observables



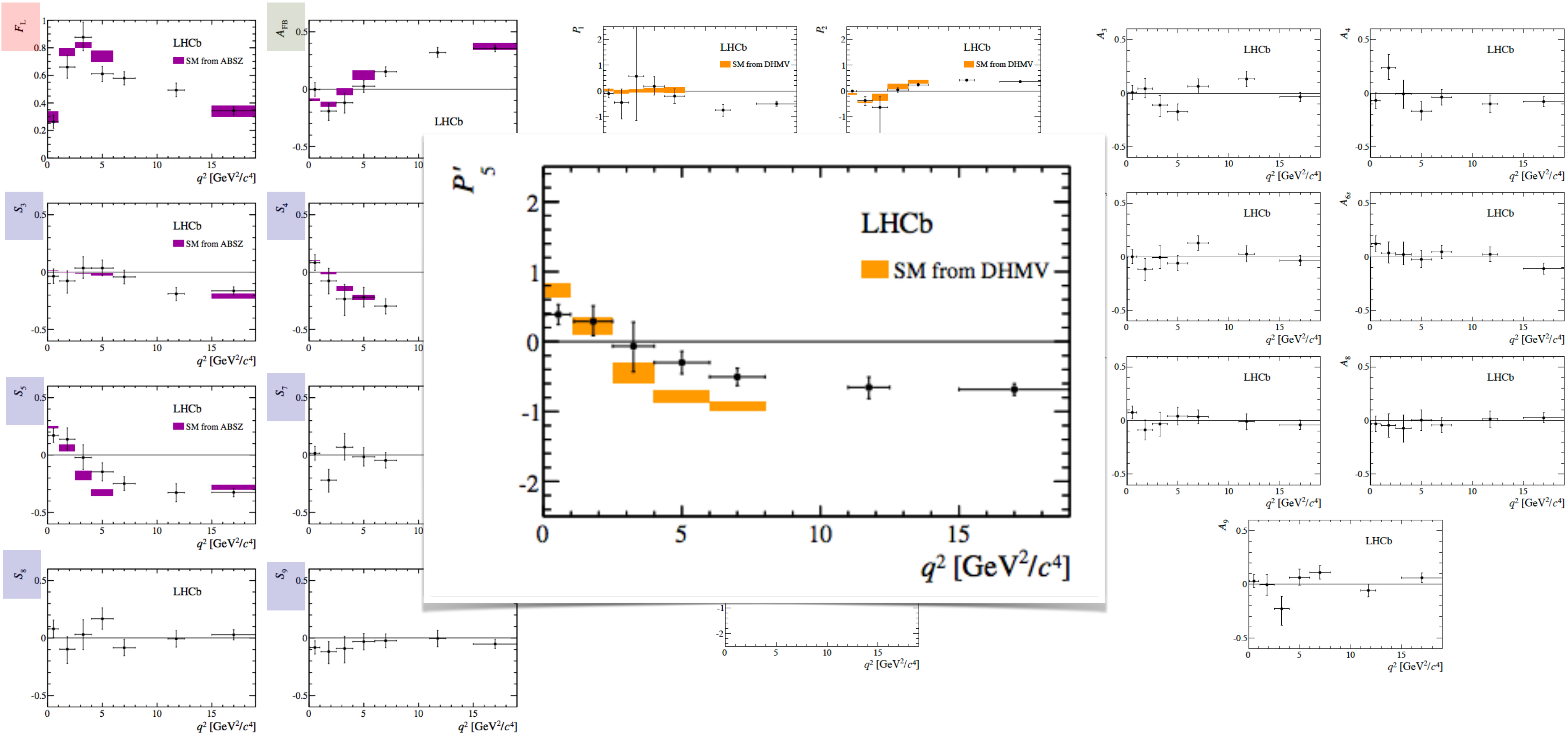
CP-averaged P’



CP-asymmetries



RESULTATS



Puzzling discrepancy of about 3.4 σ

SYSTEMATIC UNCERTAINTIES

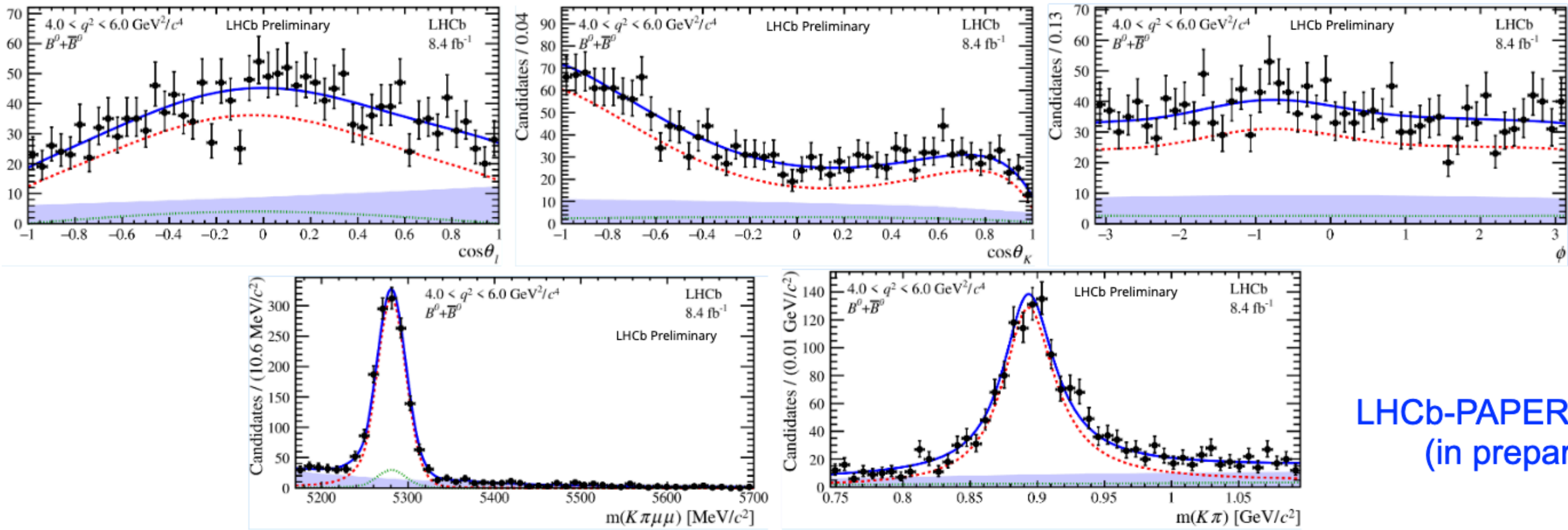
Source	F_L	S_3–S_9	A_3–A_9	P_1–P'_8
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01	< 0.01
Acceptance polynomial order	< 0.01	< 0.02	< 0.02	< 0.04
Data-simulation differences	0.01–0.02	< 0.01	< 0.01	< 0.01
Acceptance variation with q^2	< 0.01	< 0.01	< 0.01	< 0.01
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.01	< 0.03
Background model	< 0.01	< 0.01	< 0.01	< 0.02
Peaking backgrounds	< 0.01	< 0.01	< 0.01	< 0.01
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.01	< 0.02
Det. and prod. asymmetries	–	–	< 0.01	< 0.02

Errors on the measurements are statistically dominated.

THE LEGACY LHCb RUN 1-2 RESULT

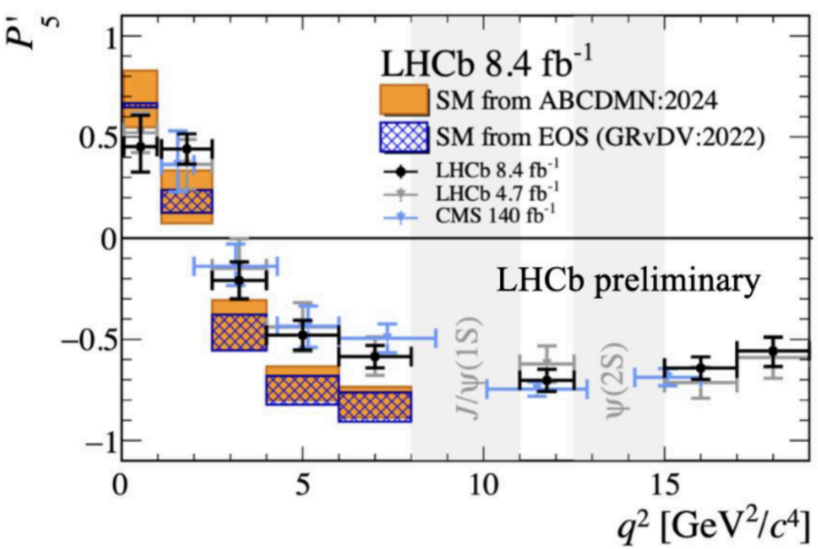
- 8.4 fb-1
- Accounts for non-negligible muon mass, extension of lowest bin to 0.06 Gev2/c4
- Measurement of interference terms of P and S wave

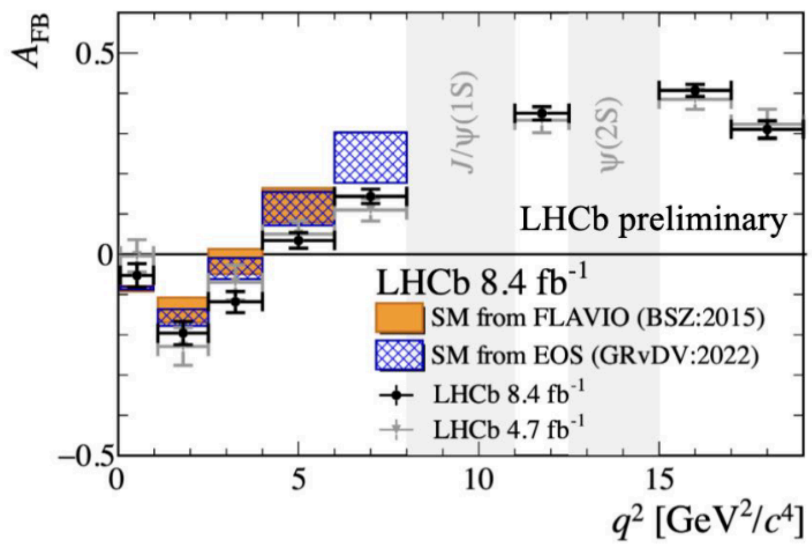
$$4.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$$



LHCb-PAPER-2025-041
(in preparation)

2025 LHCb UPDATE: LEGACY LHCb RUN 1-2

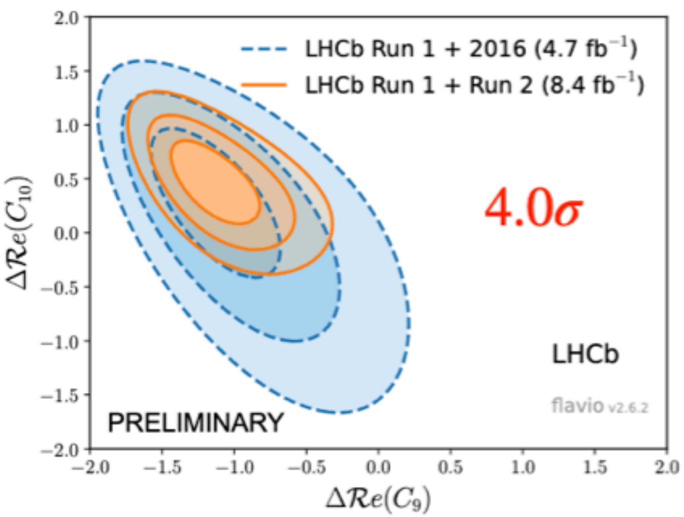




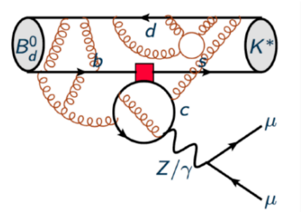
The tension strengthened!

$\Delta Re(C_9) = -0.94^{+0.22}_{-0.22}$

Significance: 4.0σ



But beware of charm loops!



TEST OF LEPTON FLAVOR UNIVERSALITY

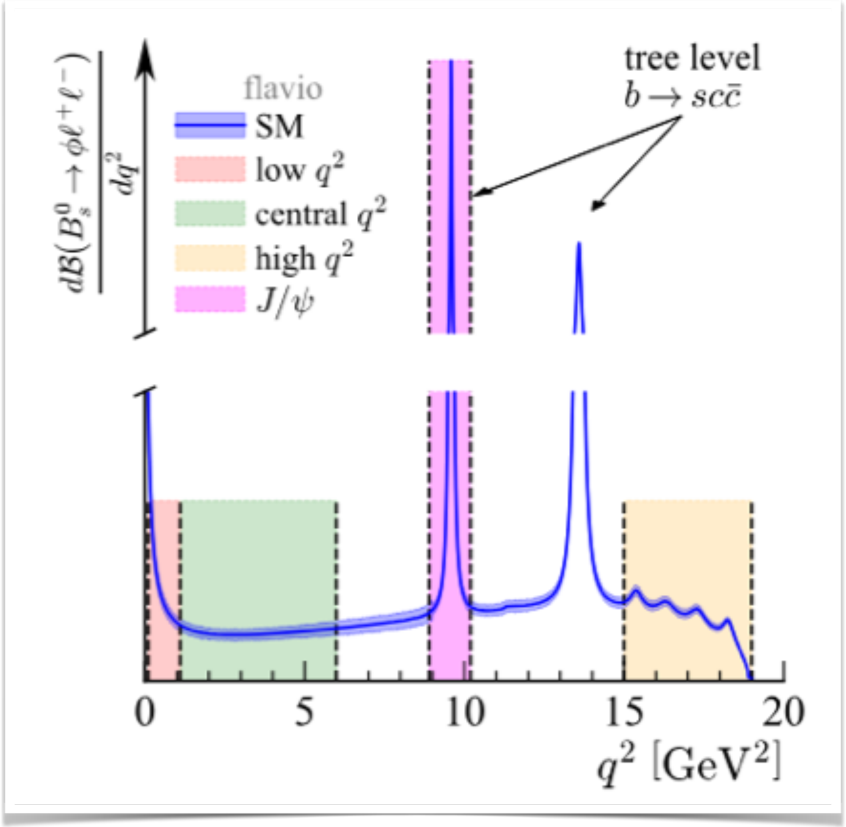
LEPTON FLAVOR UNIVERSALITY TEST RK*

$$R_{H_s} = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(H_b \to H_s \mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(H_b \to H_s e^+e^-)}{dq^2} dq^2}$$

$H_s = K, K^*, \phi$

R_{Hs} =1 (at 10^{-3}) in the SM

QED effects ~ % arXiv:1605.07633



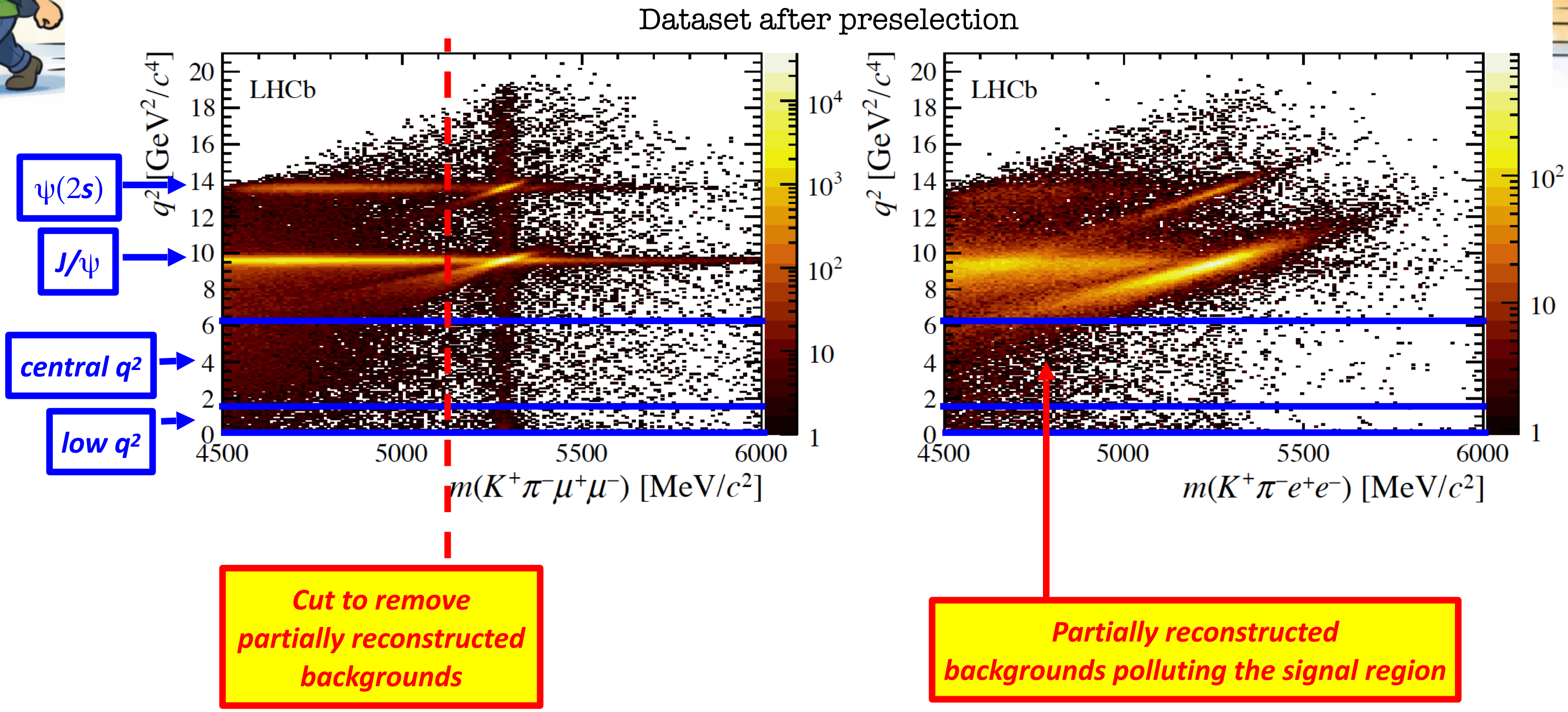
- **Theoretically: ratio cancels hadronic uncertainties**
- **Experimentally: double ratio reduces systematic uncertainties**

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

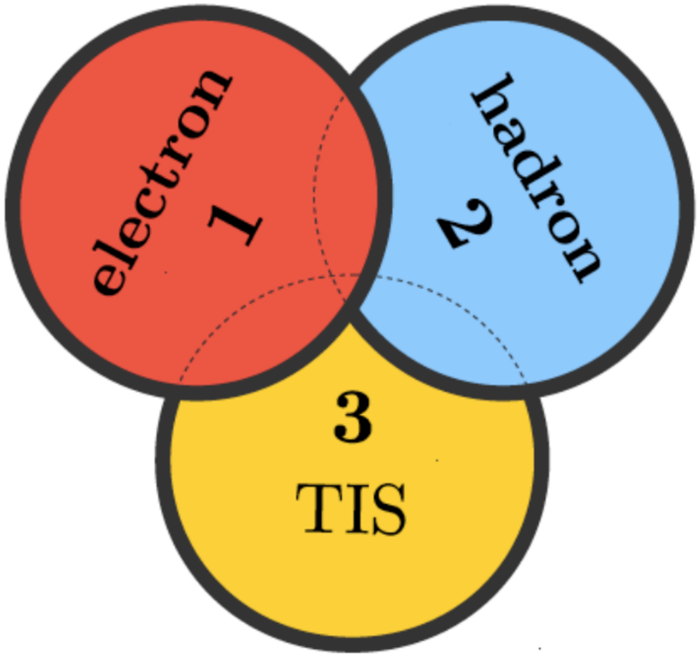
$$= \frac{N(B^0 \to K^{*0}\mu\mu)}{N(B^0 \to K^{*0}J/\psi(\mu\mu))} \times \frac{N(B^0 \to K^{*0}J/\psi(ee))}{N(B^0 \to K^{*0}ee)} \times \frac{\epsilon(B^0 \to K^{*0}J/\psi(\mu\mu))}{\epsilon(B^0 \to K^{*0}\mu\mu)} \times \frac{\epsilon(B^0 \to K^{*0}ee)}{\epsilon(B^0 \to K^{*0}J/\psi(ee))}$$

RK* : DATASET AFTER PRESELECTION

- Integrated luminosity: $3 fb^{-1}$
- Analysis in two q^2 bins:
  - low-q^2 [0.045, 1.1] GeV^2/c^4
  - central-q^2 [1.1, 6] GeV^2/c^4



EFFICIENCY PER TRIGGER CATEGORIES

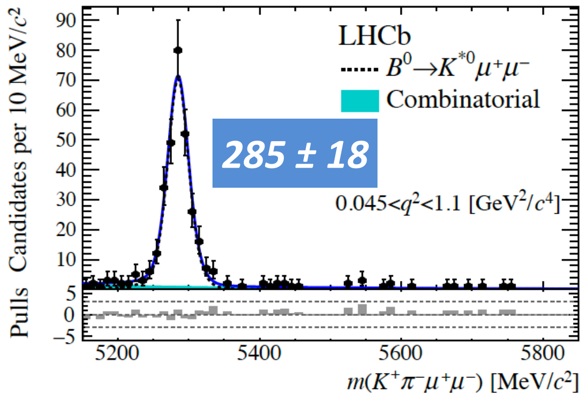


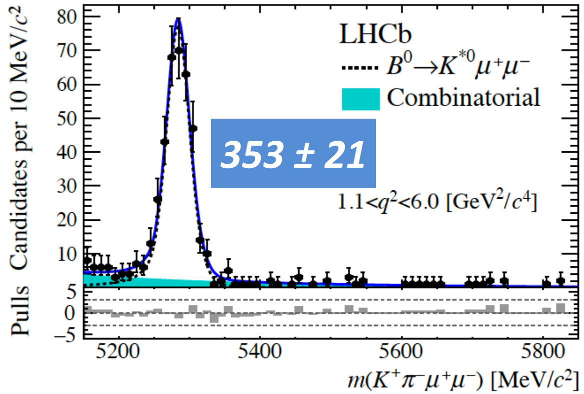
	$\varepsilon_{\ell^+\ell^-}/\varepsilon_{J/\psi(\ell^+\ell^-)}$	
	low-q^2	central-q^2
$\mu^+\mu^-$	0.679 ± 0.009	0.584 ± 0.006
e^+e^- (L0E)	0.539 ± 0.013	0.522 ± 0.010
e^+e^- (L0H)	2.252 ± 0.098	1.627 ± 0.066
e^+e^- (L0I)	0.789 ± 0.029	0.595 ± 0.020

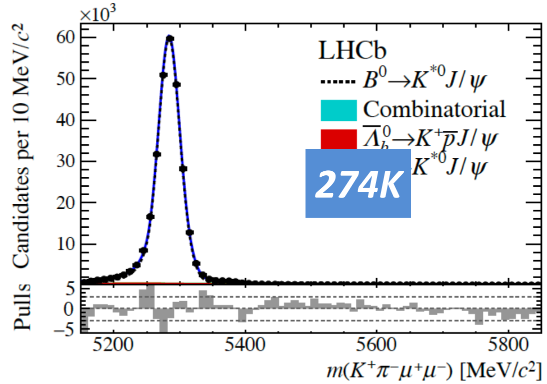
YIELDS

Low q2 | *Central q2* | *Normalization mode*

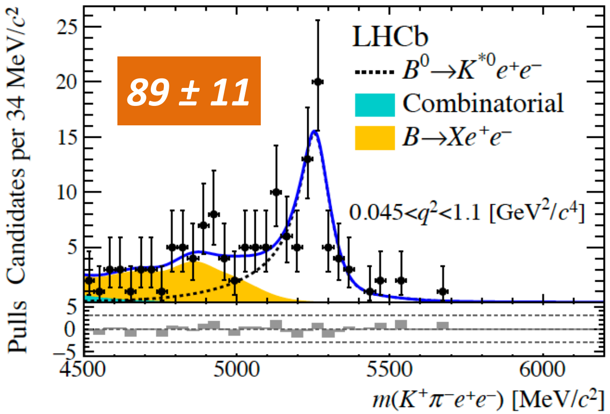
$B^0 \to K^{*0}\mu\mu$

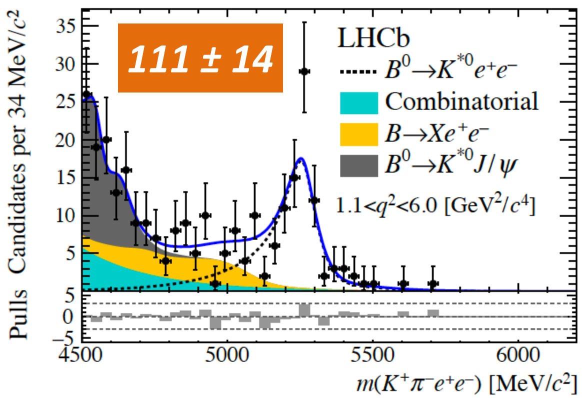


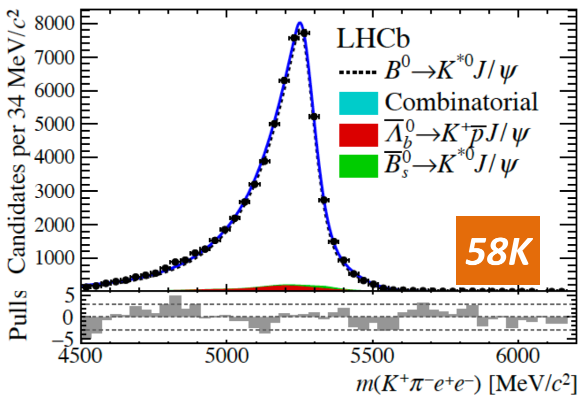




$B^0 \to K^{*0}ee$







CROSSCHECKS

- ***$r_{J/\psi}$* ratio** : ***=> very stringent test! (not a double ratio)***

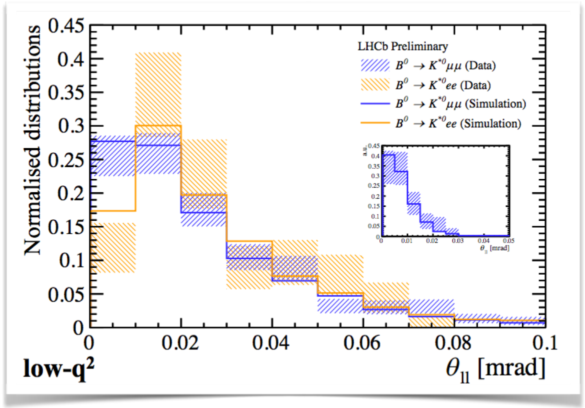
$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006\,(\text{stat}) \pm 0.045\,(\text{syst})$$

Compatible with 1 and flat as function of kinematics and event multiplicity

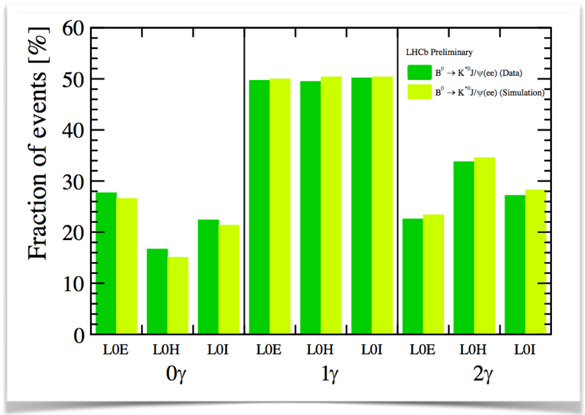
- **$R_{\psi(2s)}$ and r_γ ratios** : consistent with expectations

$$\mathcal{R}_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$

$$r_\gamma = \frac{\mathcal{B}(B^0 \to K^{*0}\gamma(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))}$$



- ***BR(B->K*μμ)*** : in agreement with published LHCb result [arXiv:1606.04731].
- **No corrections to MC** : less than 5% variation on R_{K^*}.
- **Population of bremsstrahlung categories** : consistent between data and MC.
- **Kinematic distributions** : consistent among MC/background subtracted data.



SYSTEMATIC UNCERTAINTIES

Measurement is statistically dominated
Many systematics cancels in the double ratio

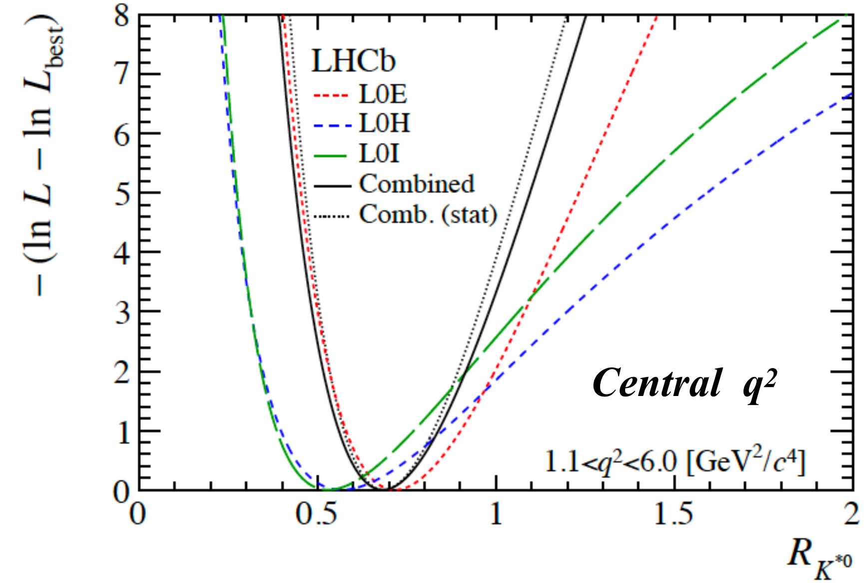
	low-q^2			central-q^2		
Trigger category	L0E	L0H	L0I	L0E	L0H	L0I
Corrections to simulation	2.5	4.8	3.9	2.2	4.2	3.4
Trigger	0.1	1.2	0.1	0.2	0.8	0.2
PID	0.2	0.4	0.3	0.2	1.0	0.5
Kinematic selection	2.1	2.1	2.1	2.1	2.1	2.1
Residual background	–	–	–	5.0	5.0	5.0
Mass fits	1.4	2.1	2.5	2.0	0.9	1.0
Bin migration	1.0	1.0	1.0	1.6	1.6	1.6
$r_{J/\psi}$ **flatness**	1.6	1.4	1.7	0.7	2.1	0.7
Total	4.0	6.1	5.5	6.4	7.5	6.7

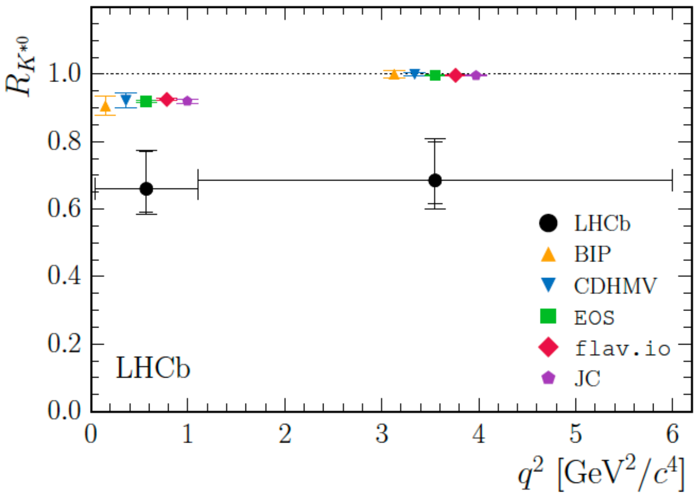
RESULTS

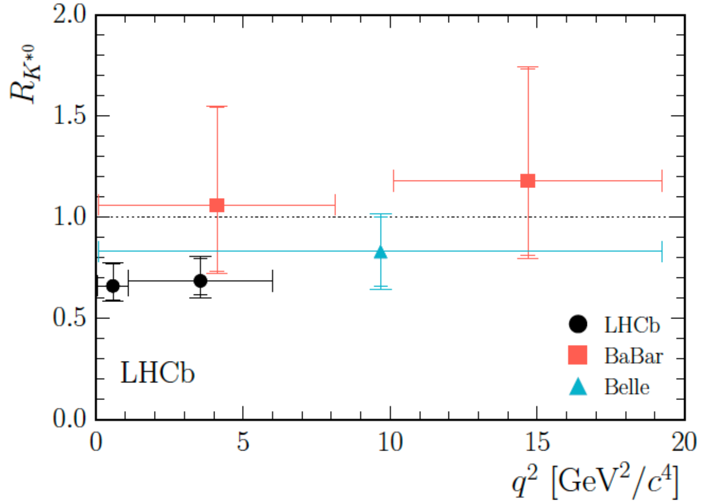
Compatibility with the SM:

- **2.1-2.3 standard deviations (low-q^2)**
- **2.4-2.5 standard deviations (central-q^2)**

	low-q^2	central-q^2
$R_{K^{*0}}$	$0.66\,^{+\,0.11}_{-\,0.07} \pm 0.03$	$0.69\,^{+\,0.11}_{-\,0.07} \pm 0.05$
95.4% CL	$[0.52, 0.89]$	$[0.53, 0.94]$
99.7% CL	$[0.45, 1.04]$	$[0.46, 1.10]$

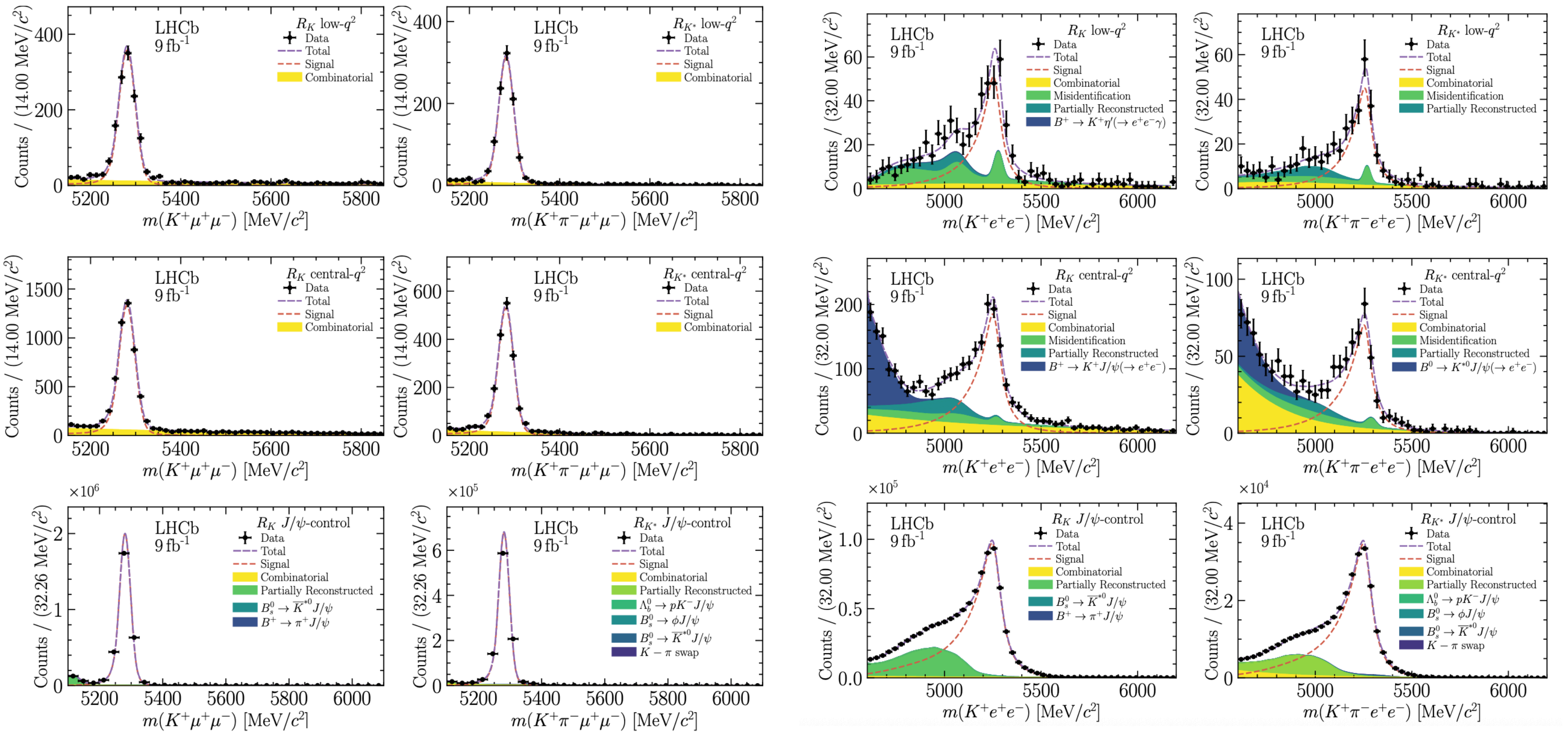






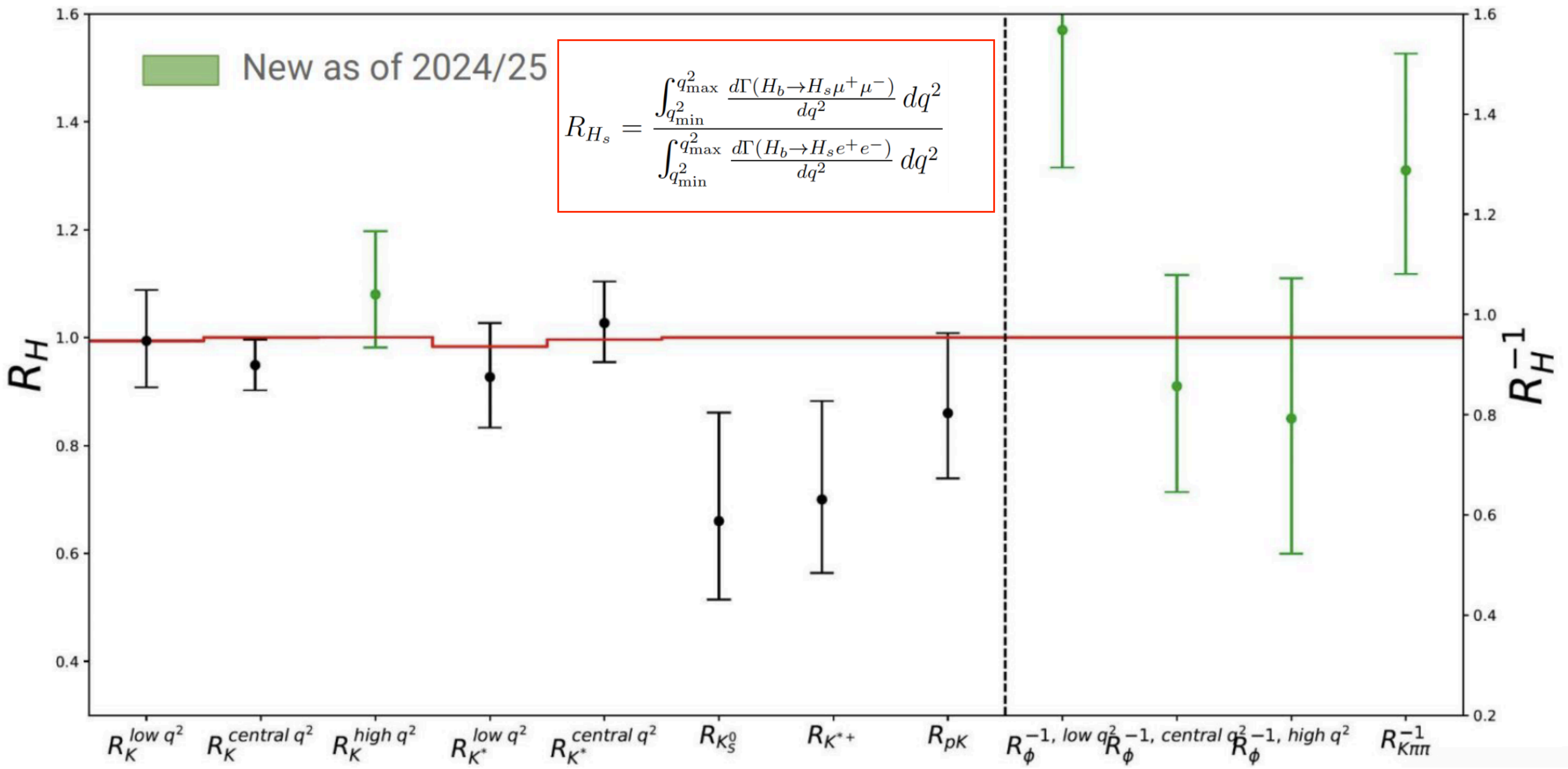
LEGACY RUN1-2 LHCb ANALYSIS RX

Simultaneous measurement of RK and RK* using all the available data



LHCb-PAPER-2022-045 LHCb-PAPER-2022-046

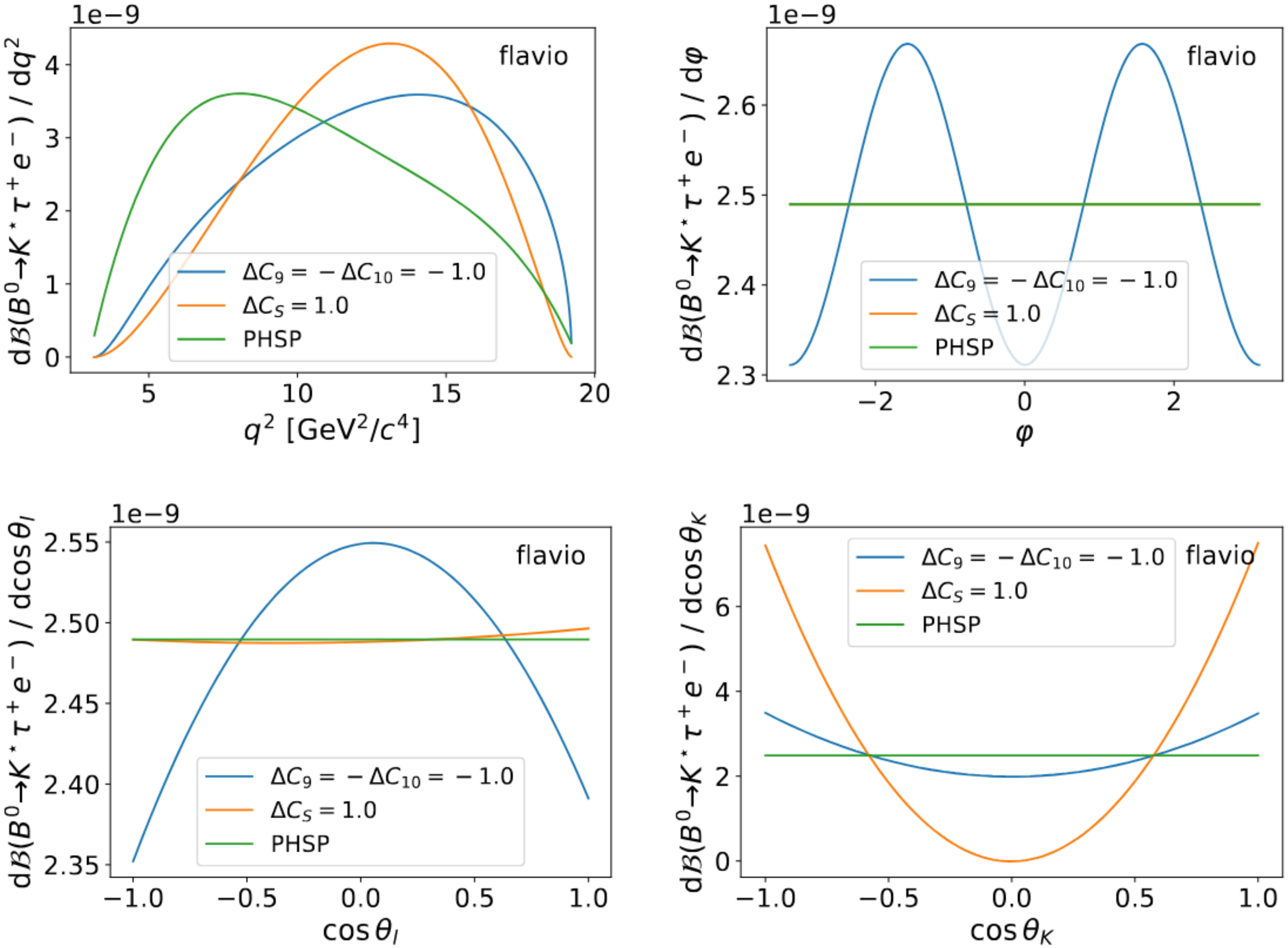
LFU IN b-HADRON DECAYS: STATUS



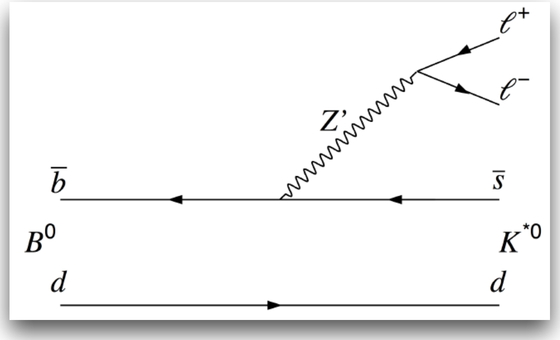
SEARCH FOR LEPTON FLAVOR VIOLATING B DECAYS

NEW PHYSICS KINEMATICS?

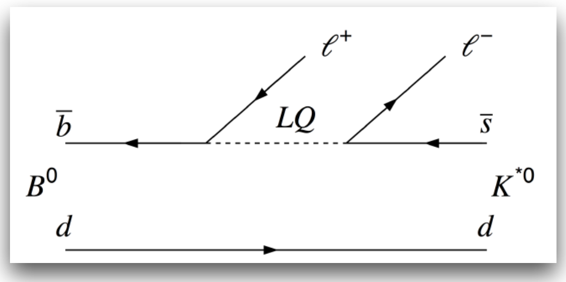
$B^0 \to K^{*0}\tau^\pm e^\mp$



Left-handed ($C_9^{\tau e} = -C_{10}^{\tau e} \neq 0$)



Scalar ($C_S^{\tau e} \neq 0$)

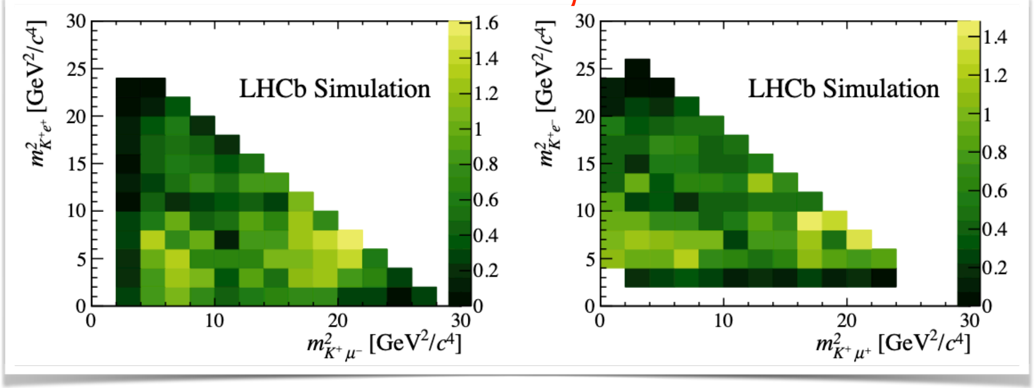


DETERMINATION OF THE EFFICIENCY SHAPE

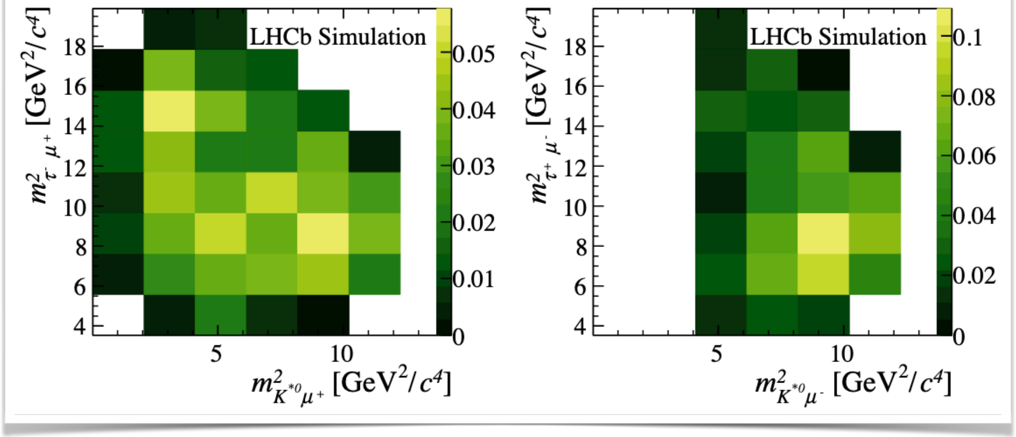
Underlining new physics kinematics is unknown.

- phase space hypothesis used as baseline;
- efficiency shapes provided for re-casting in different models.

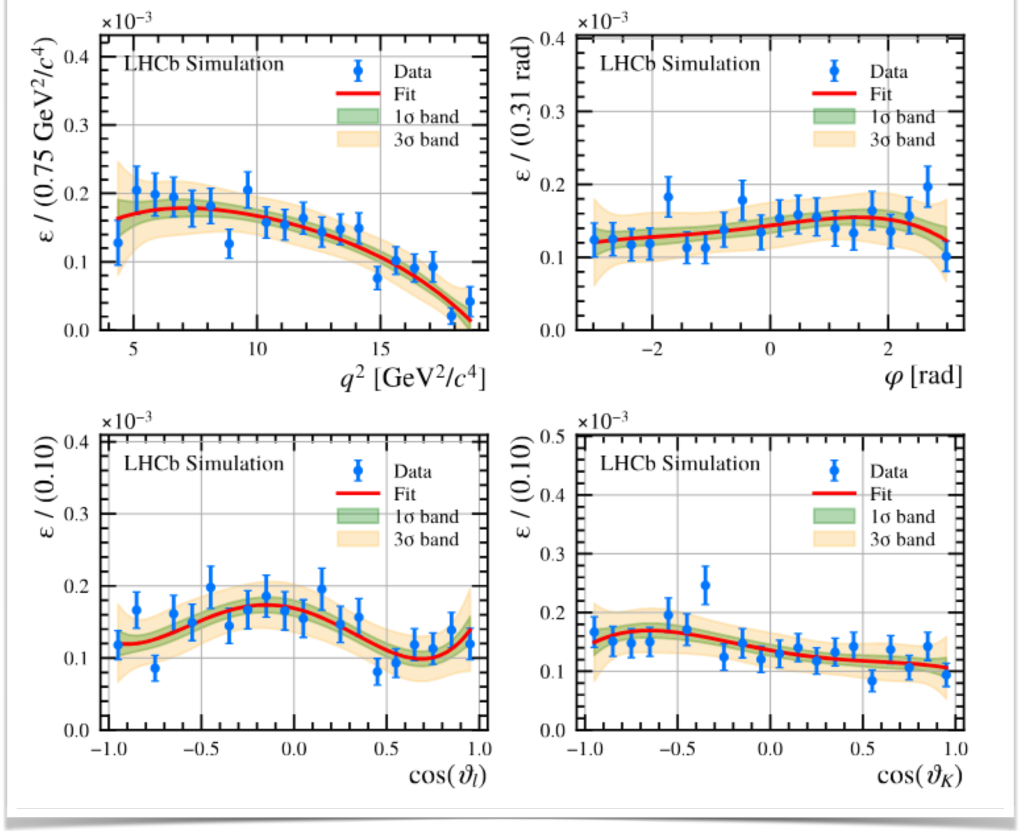
$B^+ \to K^+\mu^\pm e^\mp$



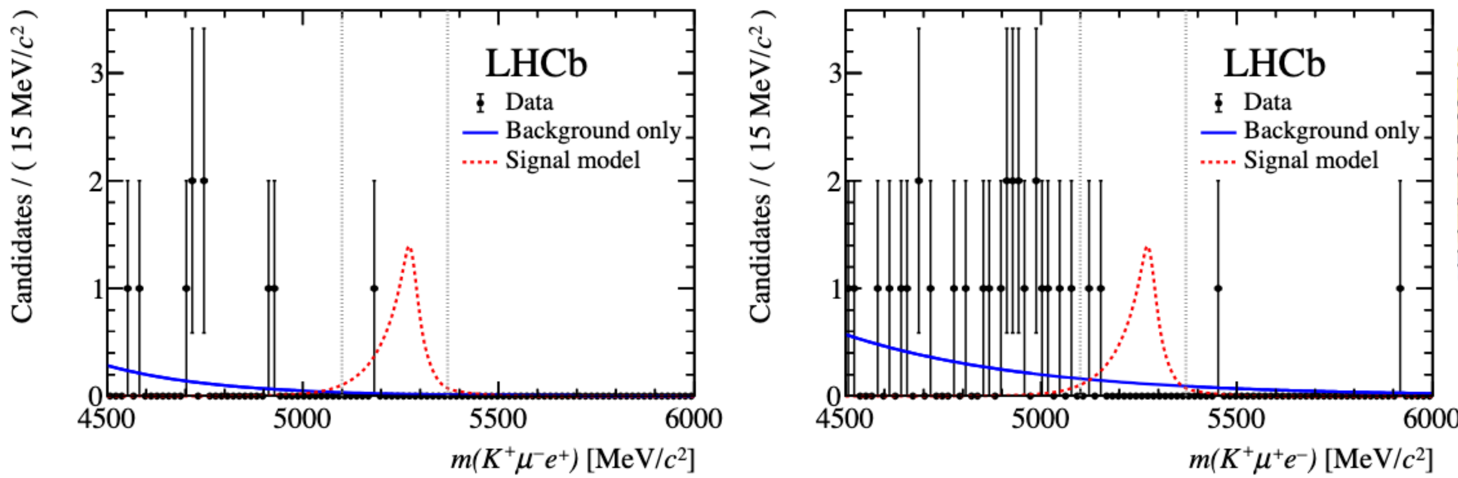
$B^0 \to K^{*0}\tau^\pm\mu^\mp$

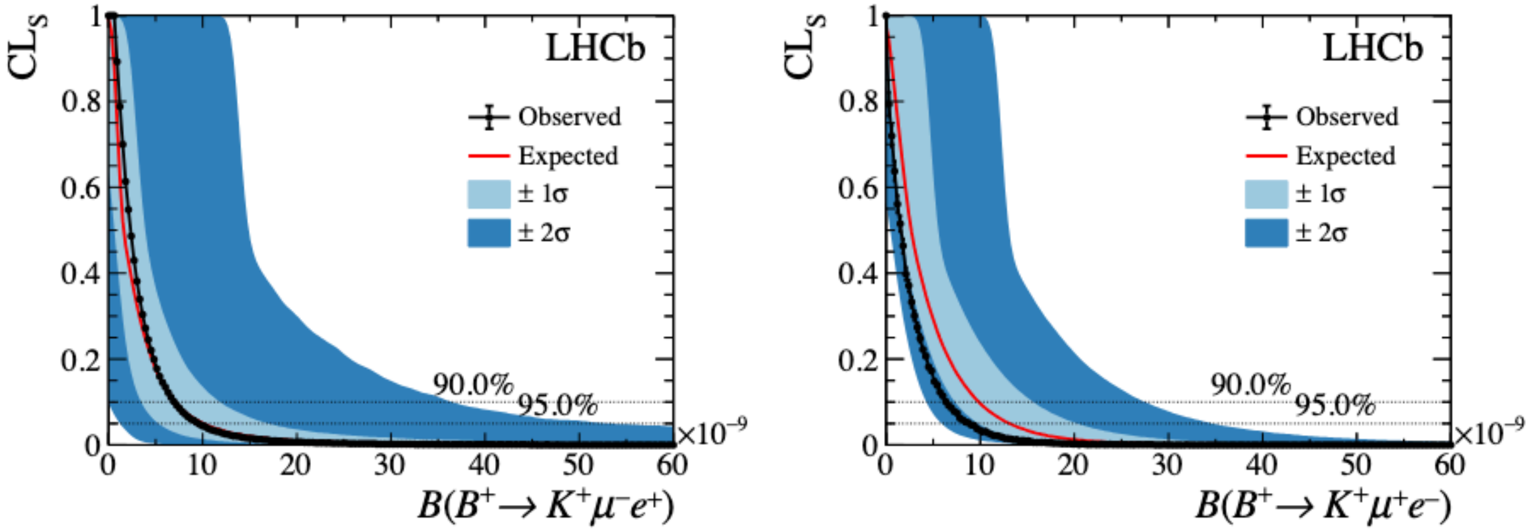


$B^0 \to K^{*0}\tau^\pm e^\mp$

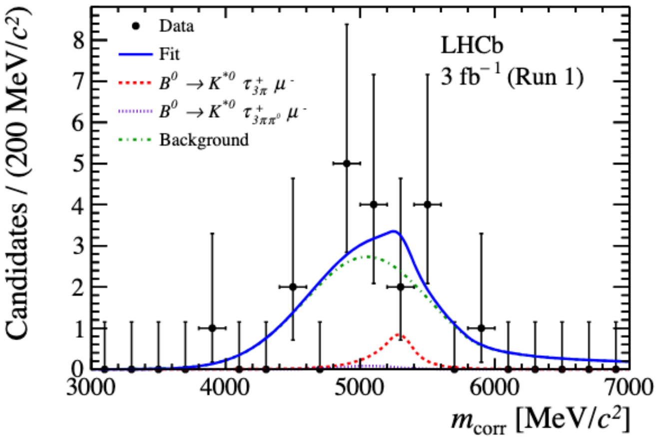


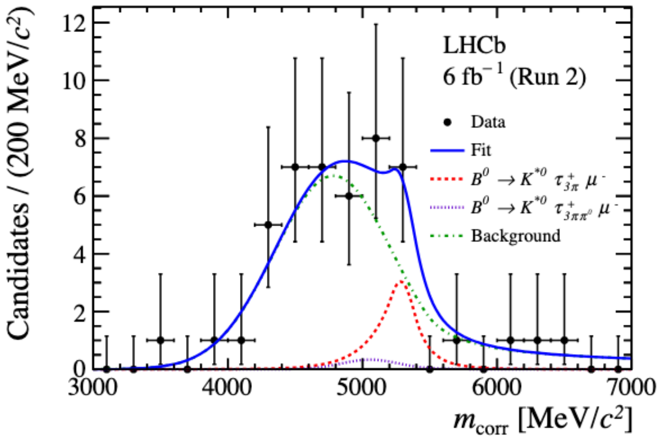
RESULTS : $B^+ \to K^+\mu^\pm e^\mp$

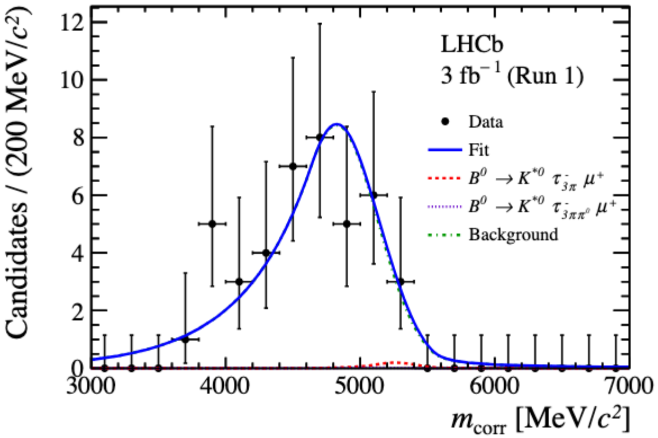


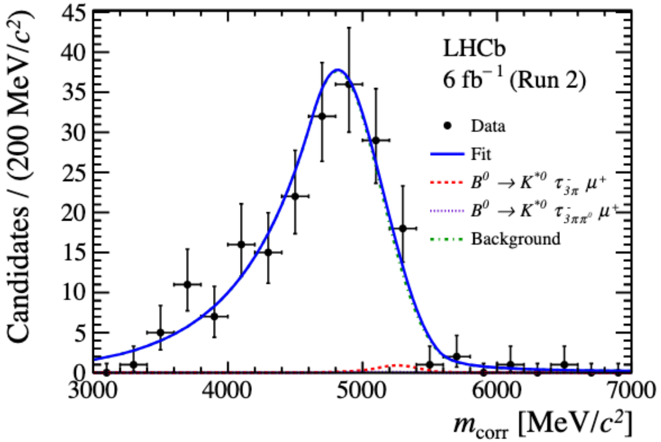


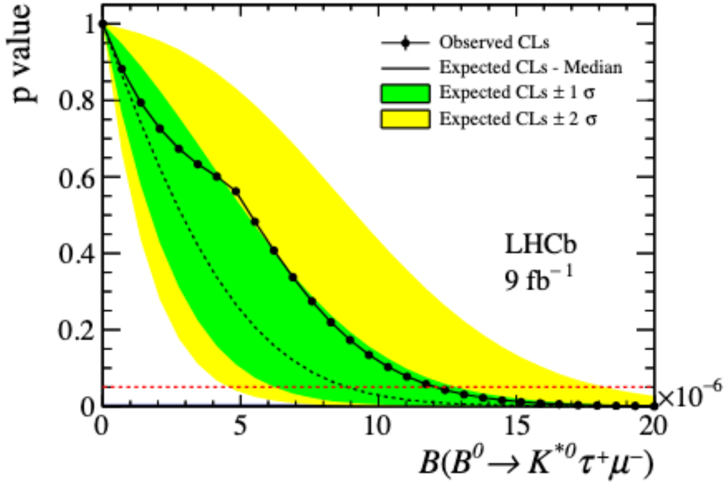
RESULTS : $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

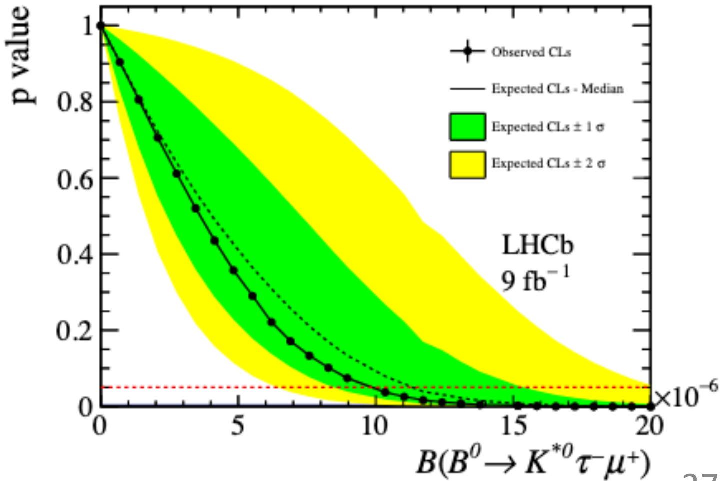






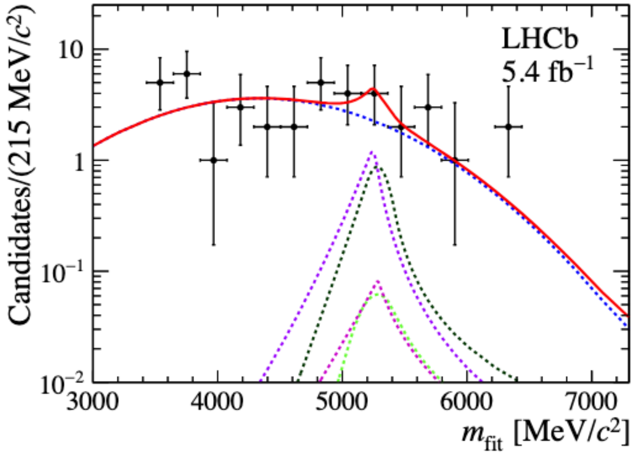




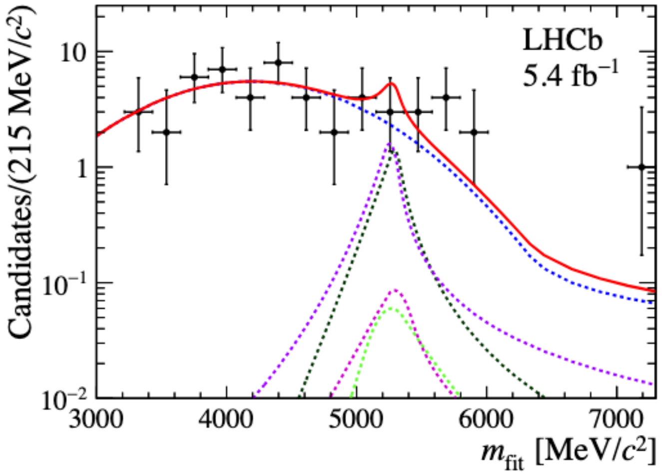


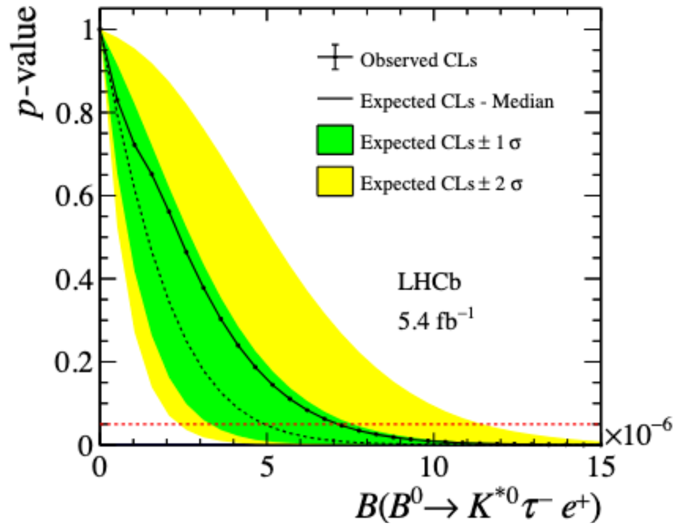
RESULTS : $B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

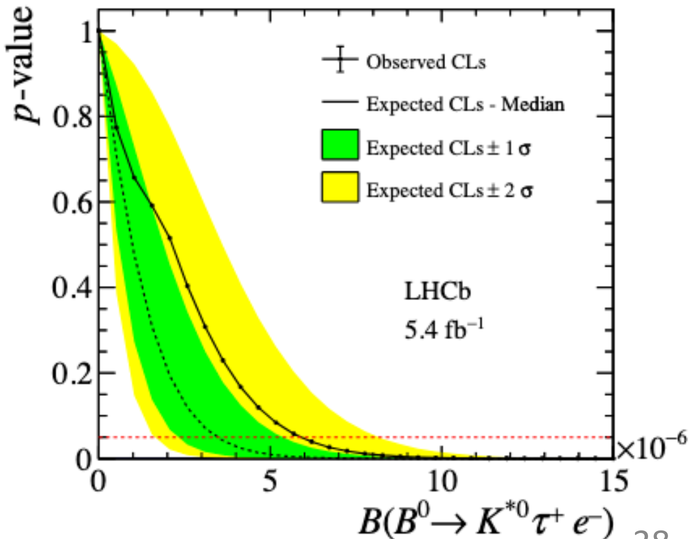
$B^0 \to K^{*0}\tau^{-}e^{+}$



$B^0 \to K^{*0}\tau^{+}e^{-}$







- Data
- $B^0 \to K^{*0}\tau^+e^-$, $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$, bremsstrahlung
- $B^0 \to K^{*0}\tau^+e^-$, $\tau^+ \to \pi^+\pi^-\pi^+\pi^0\overline{\nu}_\tau$, bremsstrahlung
- $B^0 \to K^{*0}\tau^+e^-$, $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$, no bremsstrahlung
- $B^0 \to K^{*0}\tau^+e^-$, $\tau^+ \to \pi^+\pi^-\pi^+\pi^0\overline{\nu}_\tau$, no bremsstrahlung
- Background
- Total fit

SUMMARY OF UPPER LIMITS

Branching fraction	Model	Upper limit at 90 (95)% CL
$\mathcal{B}(B^+ \to K^+\mu^-e^+)$	Phase space (PHSP)	7.0 (9.5) $\times 10^{-9}$
$\mathcal{B}(B^+ \to K^+\mu^+e^-)$	Phase space (PHSP)	6.4 (8.8) $\times 10^{-9}$
$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-)$	Phase space (PHSP)	1.0 (1.2) $\times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+)$	Phase space (PHSP)	8.2 (9.8) $\times 10^{-6}$
$\mathcal{B}(B^0 \to K^{*0}\tau^+e^-)$	Phase space (PHSP)	5.9 (7.1) $\times 10^{-6}$
	Left-handed ($C_9^{\tau e} = -C_{10}^{\tau e} \neq 0$)	6.3 (7.7) $\times 10^{-6}$
	Scalar ($C_S^{\tau e} \neq 0$)	6.6 (8.0) $\times 10^{-6}$
$\mathcal{B}(B^0 \to K^{*0}\tau^-e^+)$	Phase space (PHSP)	4.9 (5.9) $\times 10^{-6}$
	Left-handed ($C_9^{\tau e} = -C_{10}^{\tau e} \neq 0$)	5.4 (6.4) $\times 10^{-6}$
	Scalar ($C_S^{\tau e} \neq 0$)	5.7 (6.8) $\times 10^{-6}$

SYSTEMATIC UNCERTAINTIES

Effect	$B^+ \to K^+\mu^+e^-$	$B^+ \to K^+\mu^-e^+$
Data-simulation corrections	1.0%	1.0%
Electron-muon differences	1.4%	1.4%
Fitting model	2.1%	2.1%
PID resampling	4.5%	5.5%
Trigger	1.0%	1.0%
Normalisation factor	3.5%	3.5%
Total	6.4%	7.1%
Background	0.60	0.43

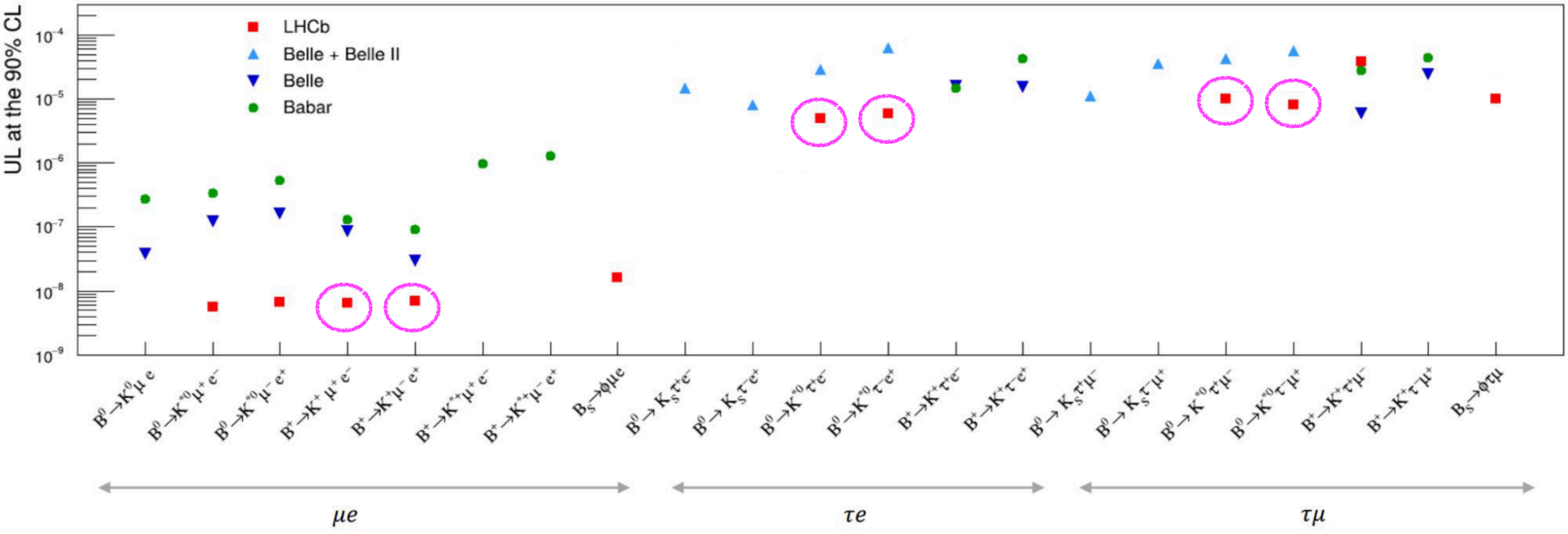
- ***The background parameterisations has the largest impact in analyses with tau leptons***
- ***Input branching fractions are also relevant***

Systematic effect	**Upper limit increase [%]**	
	$B^0 \to K^{*0}\tau^-\mu^+$	$B^0 \to K^{*0}\tau^+\mu^-$
Input branching fractions	4	3
Efficiencies	2	1
Normalisation yields	1	1
Background control region choice	18	26
Background analytical shape	1	1
Total	26	32

Systematic effect	**Upper limit increase [%]**	
	$B^0 \to K^{*0}\tau^+e^-$	$B^0 \to K^{*0}\tau^-e^+$
Input branching fractions	2.3	2.5
Normalisation yields	<0.1	<0.1
Efficiencies	1.2	1.0
Background model	4.7	5.2
Signal model	1.2	0.5
Total	9.7	9.5

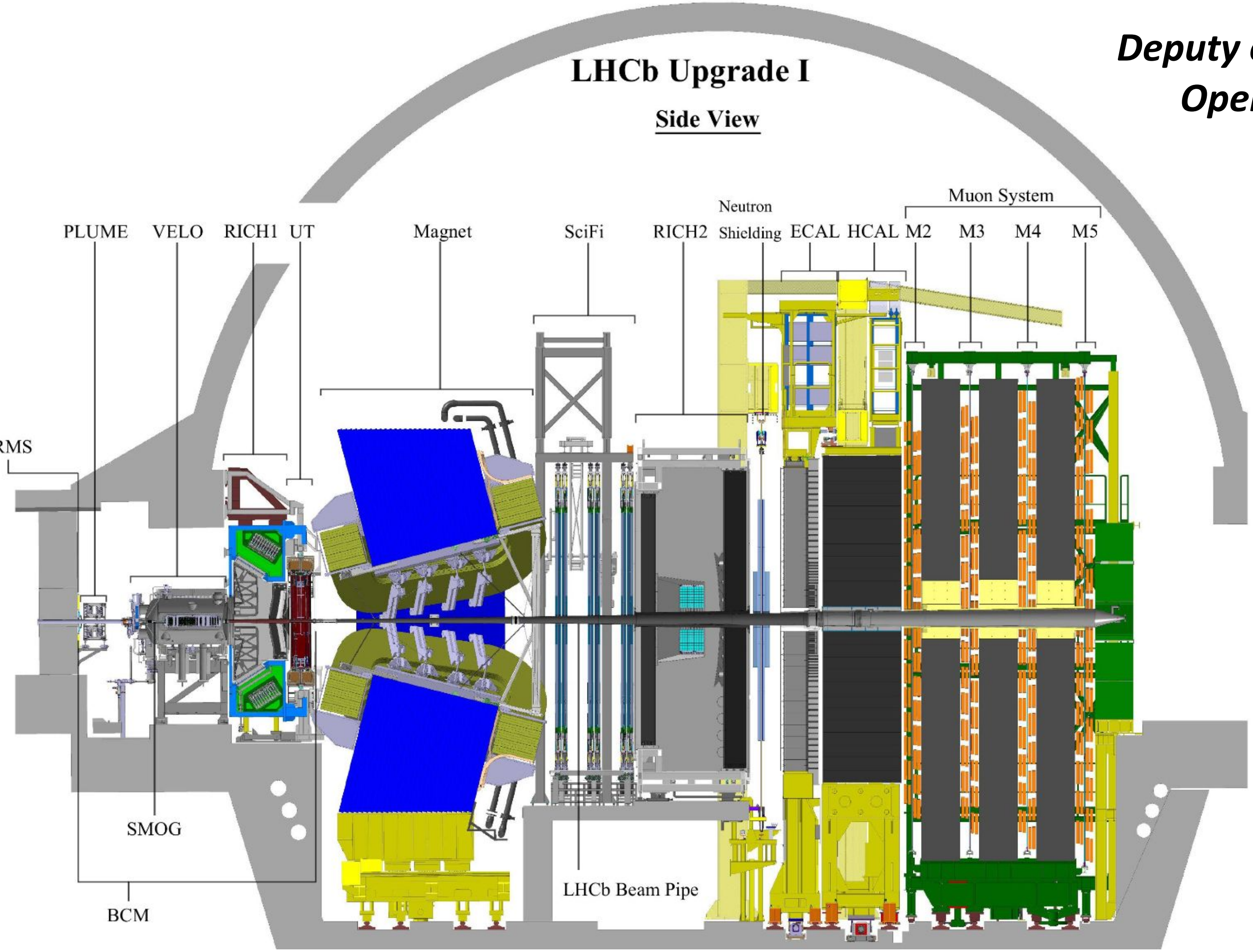
STATUS OF cLFV IN B DECAYS

Datasets:
Belle: 711 fb^{-1}; Belle II: 365 fb^{-1}; LHCb: Run 1 + Run 2 except for $B^+ \to K^+\mu e$ (Run 1) and $B^0 \to K^{*0}\tau e$ (Run 2)

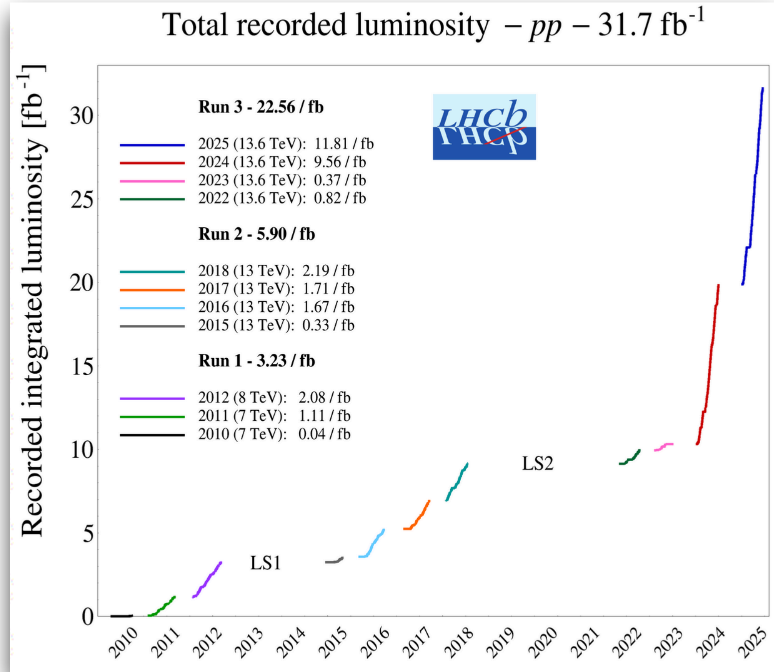


THE FUTURE

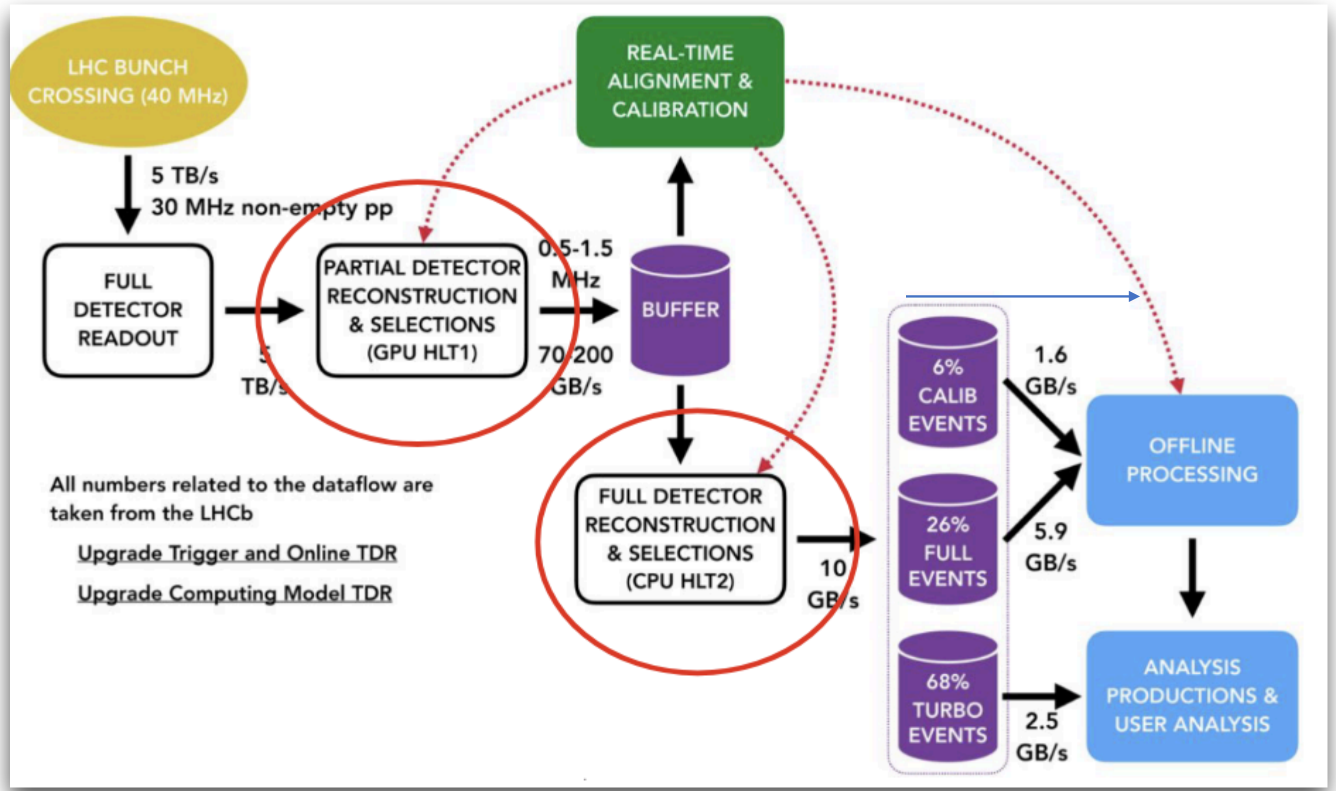
THE CURRENT LHCb

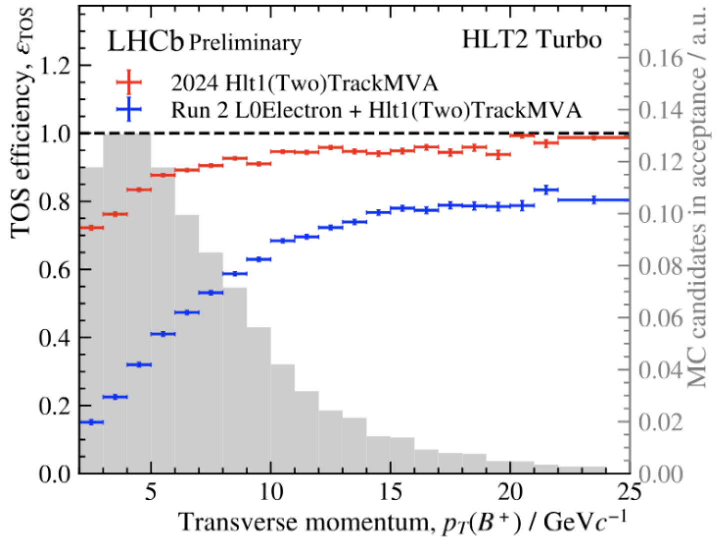


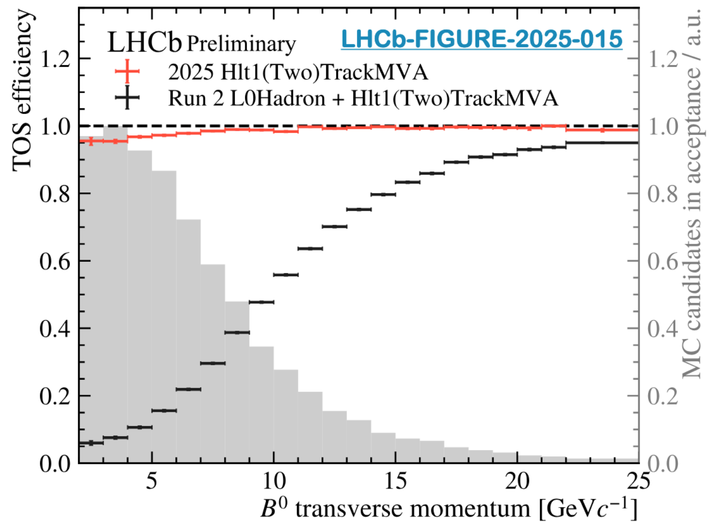
Deputy operations coordinator (9/2020 - 8/2022)
Operations coordinator (9/2022 - 8/2024)



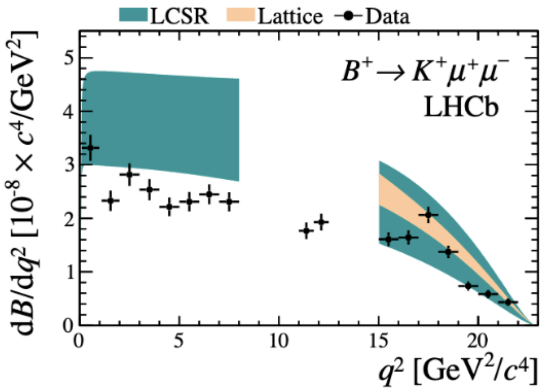
A COMPLETELY SOFTWARE TRIGGER

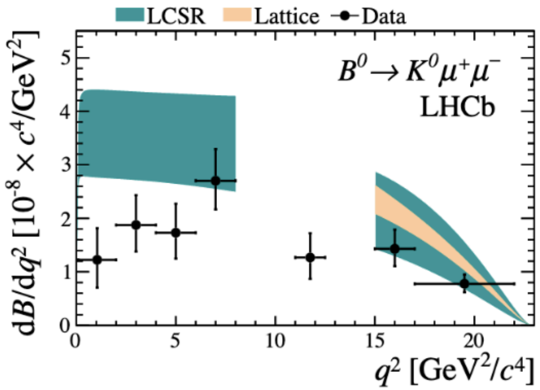


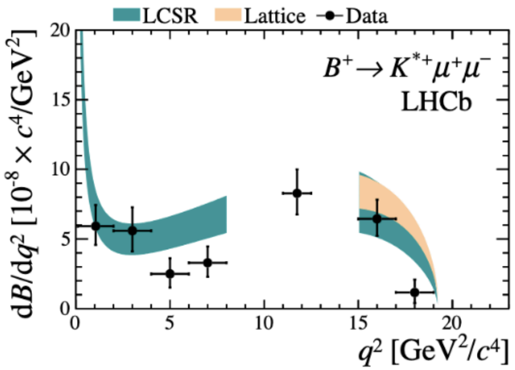




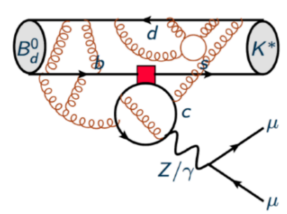
BRANCHING RATIOS AND ANGULAR OBSERVABLES STILL PUZZLING

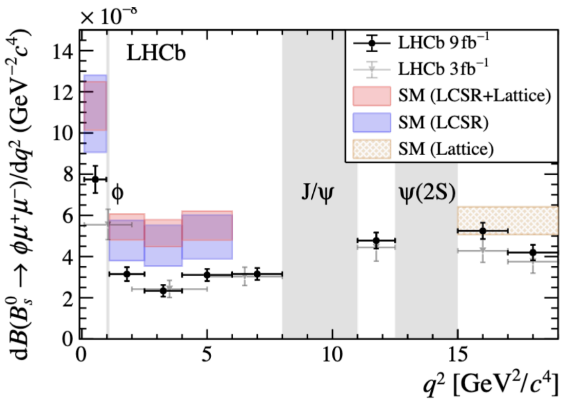


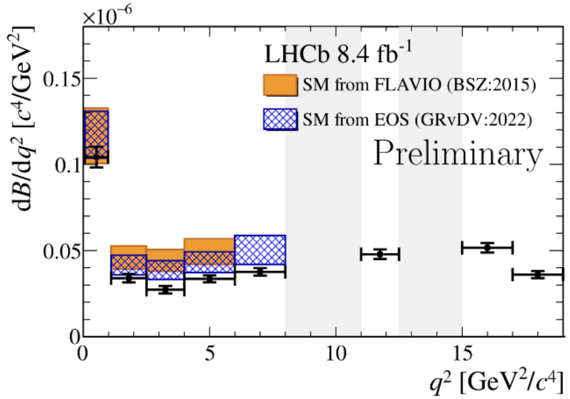


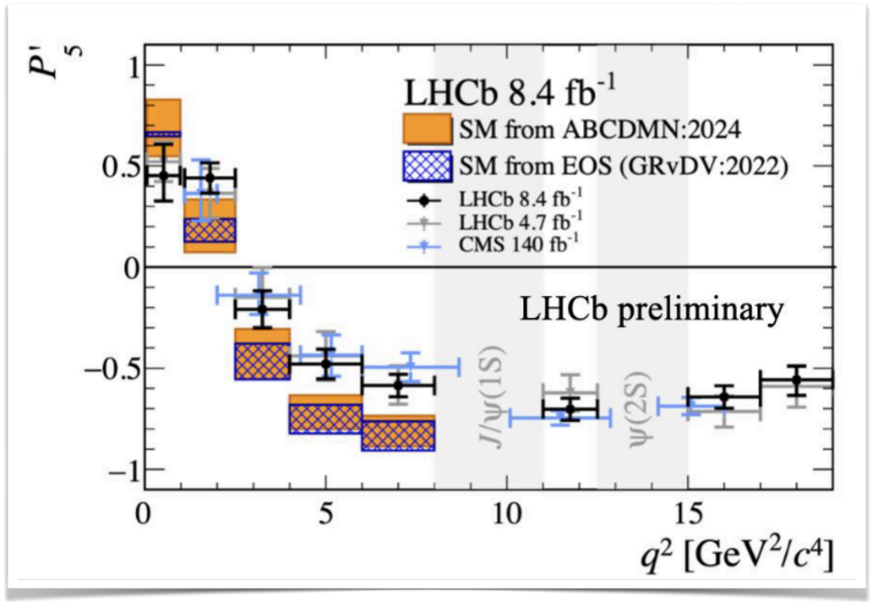


But beware of charm loops!



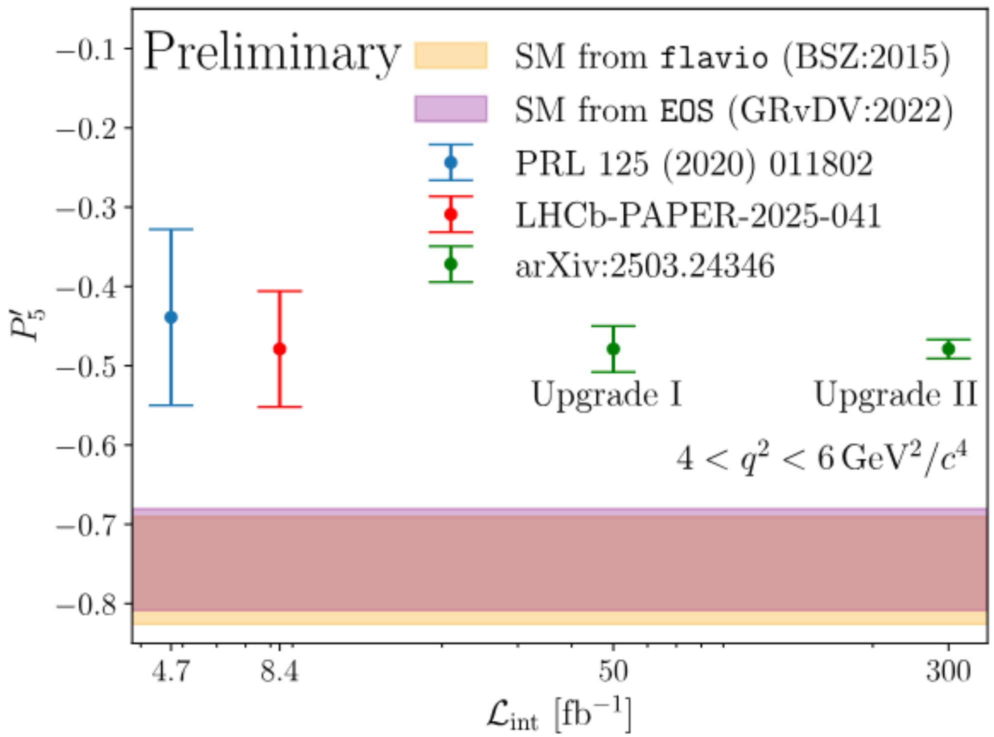


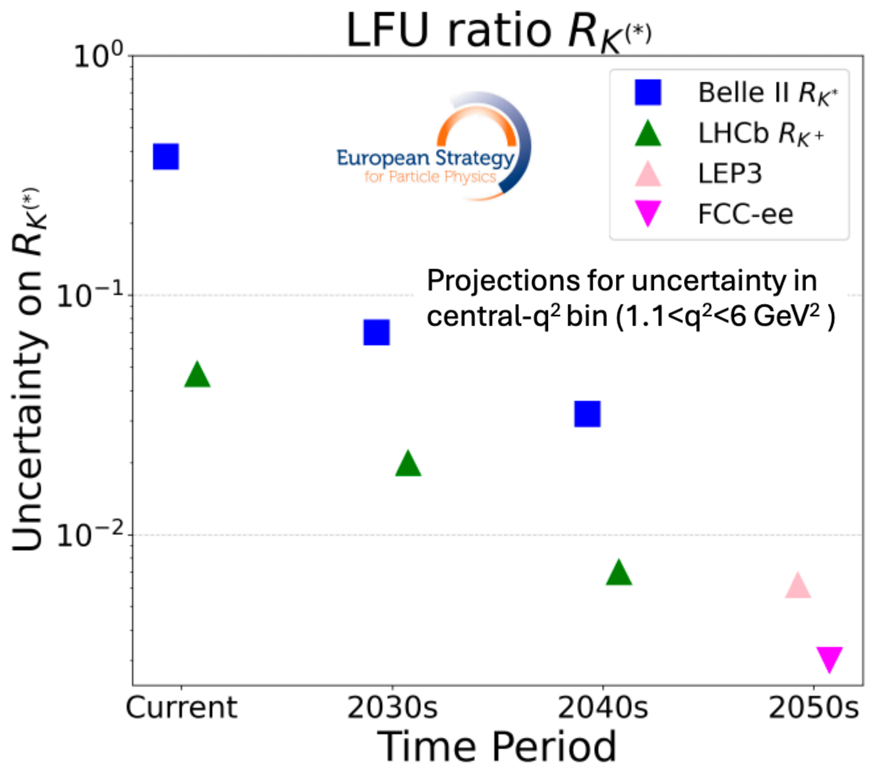




Investigation is not over.
Need to keep exploring all observables for these transitions!

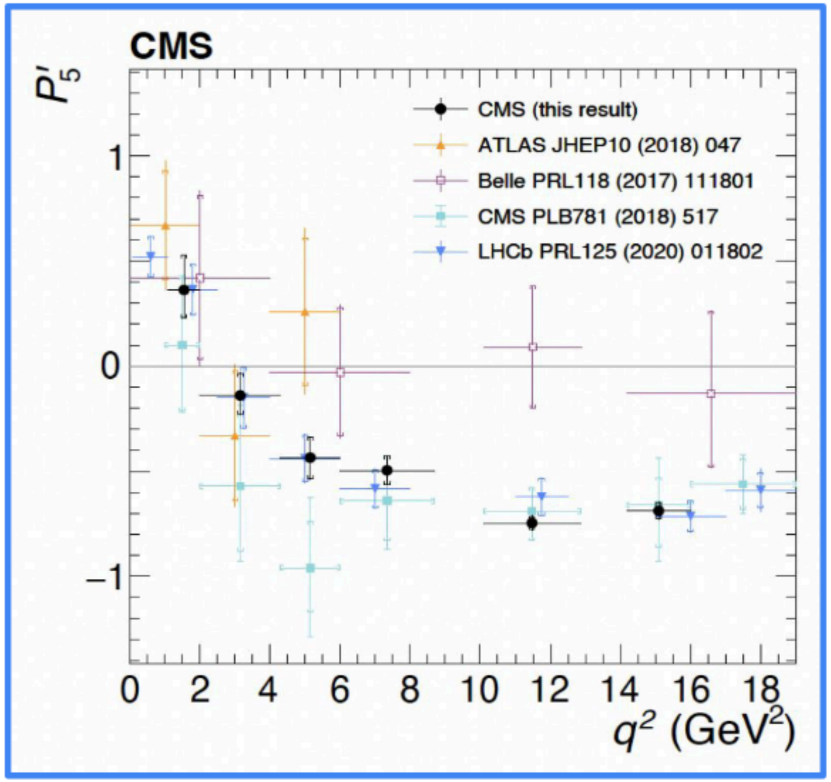
LHCb PROSPECTS





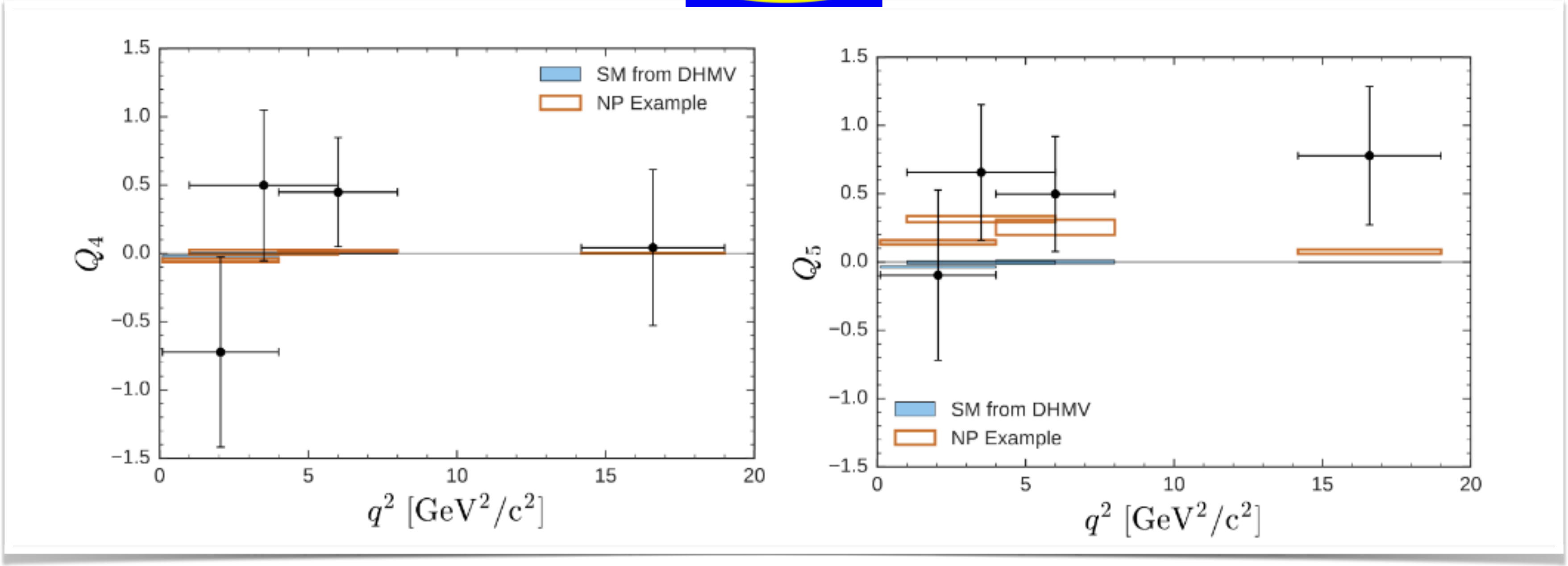
COMPLEMENTARY MEASUREMENTS ARE NEEDED

- Complementary measurements are performed in different b —> s ll transitions
- Other experiments are also now performing angular and LFU measurements



Decays	LFU test	q^2 range (GeV$^2/c^4$)	Experiment
$B^0 \to K^{*0}\ell^+\ell^-$	$R_{K^*} = 0.927^{+0.093+0.036}_{-0.087-0.035}$	$[0.1, 1.1]$	LHCb [113, 114]
	$R_{K^*} = 1.027^{+0.072+0.027}_{-0.068-0.026}$	$[1.1, 6.0]$	LHCb [113, 114]
$B^+ \to K^+\ell^+\ell^-$	$R_K = 0.994^{+0.090+0.029}_{-0.082-0.027}$	$[0.1, 1.1]$	LHCb [113, 114]
	$R_K = 0.949^{+0.042+0.022}_{-0.041-0.022}$	$[1.1, 6.0]$	LHCb [113, 114]
	$R_K = 1.08^{+0.11\ +0.04}_{-0.09\ -0.04}$	$q^2 > 14.3$	LHCb [118]
	$R_K = 0.78^{+0.47}_{-0.23}$	$[1.1, 6.0]$	CMS [119]
$B^0_s \to \phi\ell^+\ell^-$	$R^{-1}_{\phi} = 1.57^{+0.28}_{-0.25} \pm 0.05$	$[0.1, 1.1]$	LHCb [120]
	$R^{-1}_{\phi} = 0.91^{+0.20}_{-0.19} \pm 0.05$	$[1.1, 6.0]$	LHCb [120]
	$R^{-1}_{\phi} = 0.85^{+0.24}_{-0.23} \pm 0.10$	$[15.0, 19.0]$	LHCb [120]
$B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$	$R^{-1}_{K\pi\pi} = 1.31^{+0.18+0.12}_{-0.17-0.09}$	$[1.1, 7.0]$	LHCb [117]
$B^0 \to K^0_S\ell^+\ell^-$	$R_{K^0_S} = 0.66^{+0.20\ +0.02}_{-0.14\ -0.04}$	$[1.1, 6.0]$	LHCb [116]
$B^+ \to K^{*+}\ell^+\ell^-$	$R_{K^{*+}} = 0.70^{+0.18\ +0.03}_{-0.13\ -0.04}$	$[0.045, 6.0]$	LHCb [116]
$\Lambda^0_b \to pK^-\ell^+\ell^-$	$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$	$[0.1, 6.0]$	LHCb [115]

NEW FRONTIER : LFU ANGULAR ANALYSIS



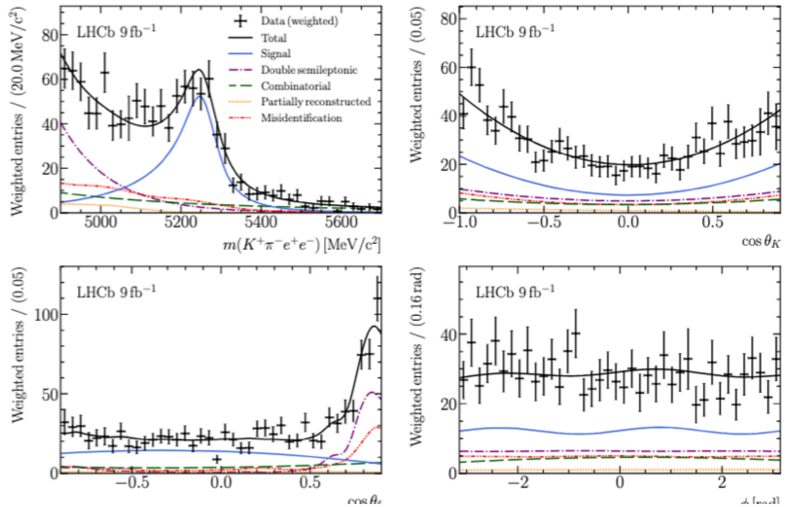
LFU observables

$$Q_i = P_i^{(\mu)} - P_i^{(e)}$$

NEW FRONTIER : LFU ANGULAR ANALYSIS

- Angular analysis of $B^0 \to K^{*0} e^+ e^-$ decays
- Results based on $9\,\mathrm{fb}^{-1}$ of Run 1+2 data
  Analysis performed in central q^2 region
  $(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/\mathrm{c}^4)$

- No significant disagreement with SM predictions
- No evidence for LFU violations when analysing electron and muon modes together



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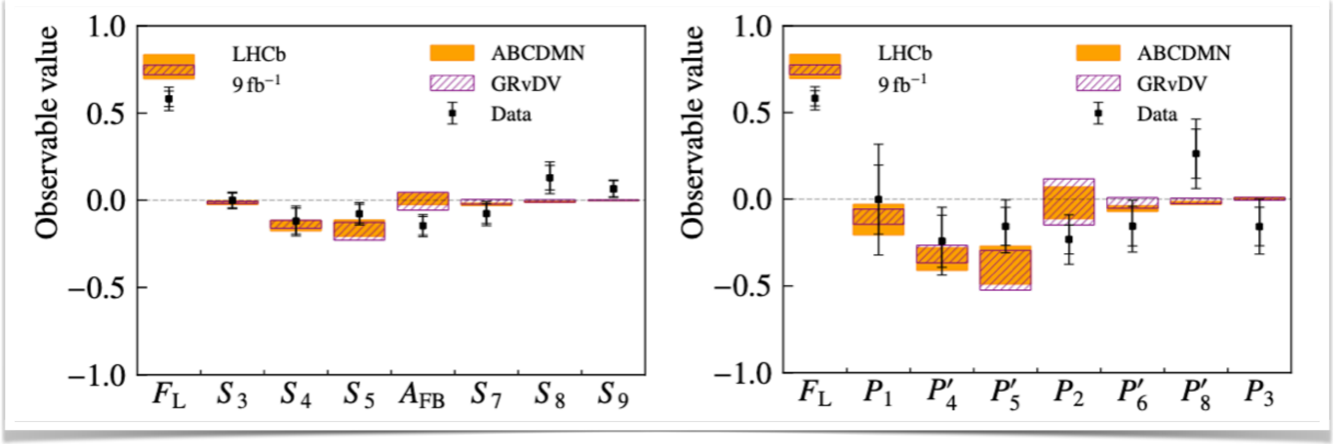
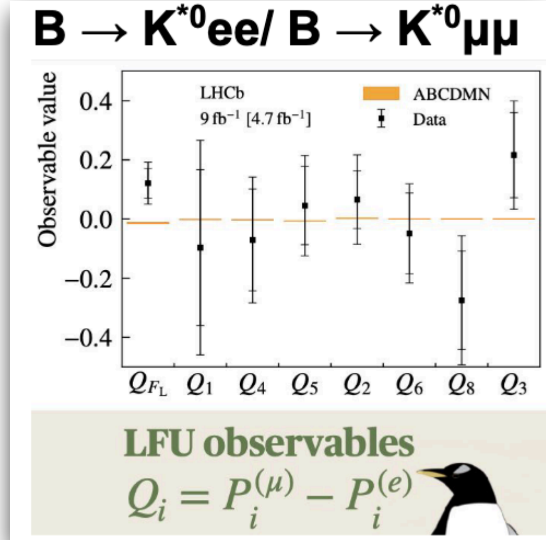
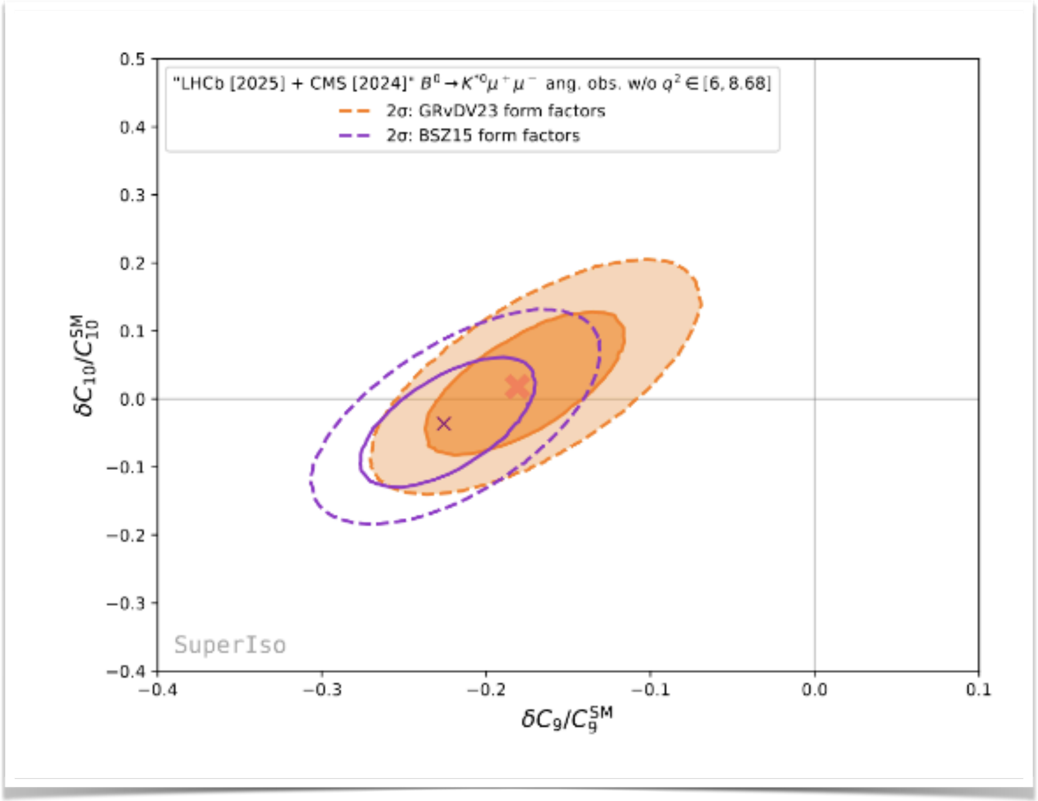
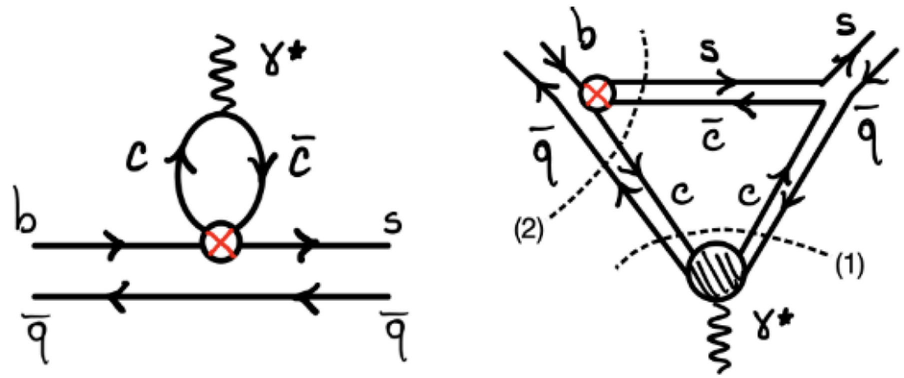




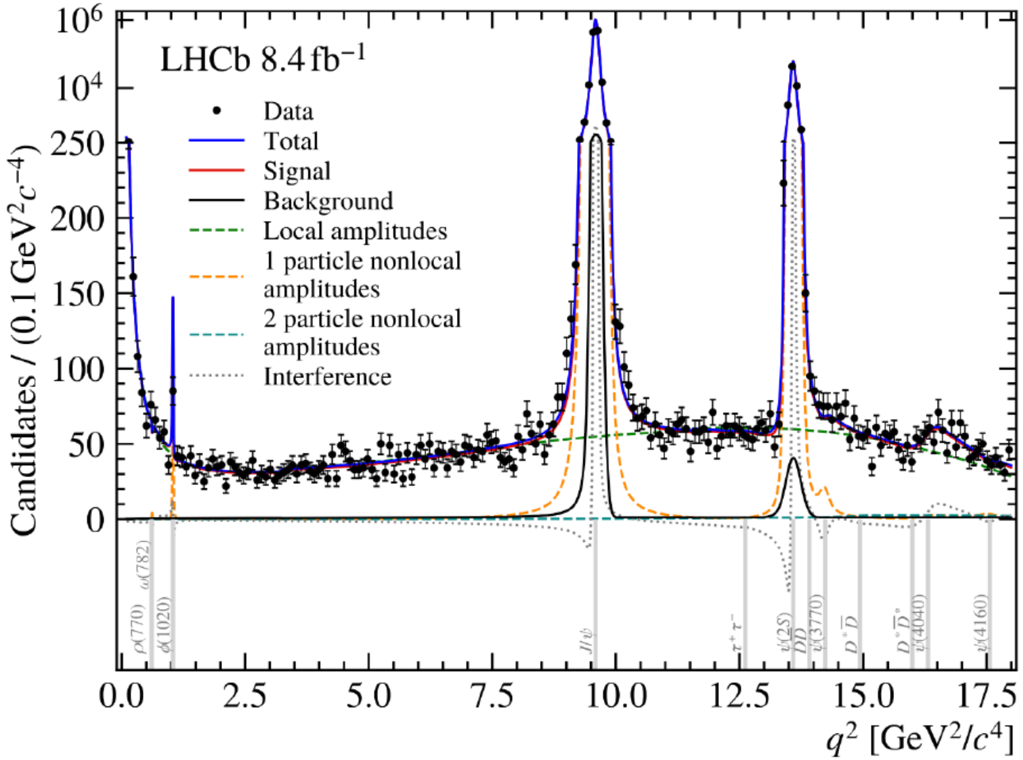
NEED THEORY PROGRESS

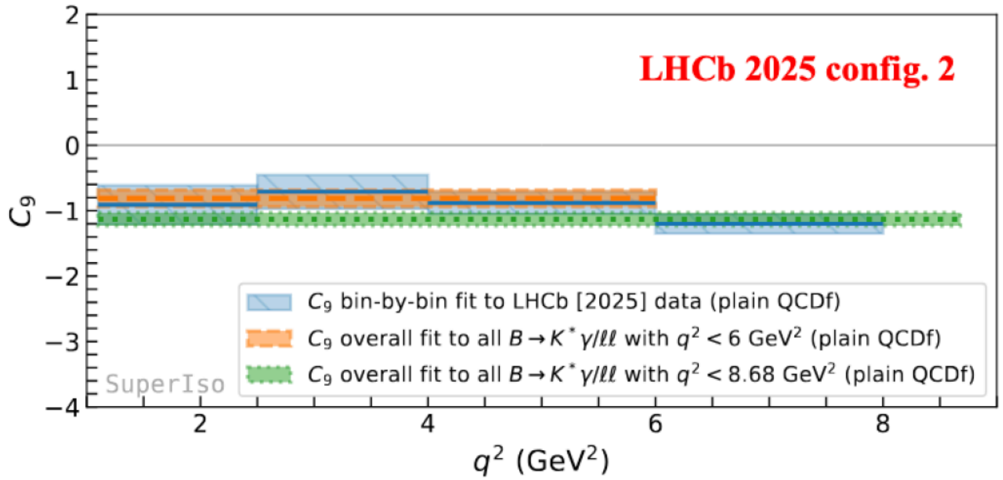




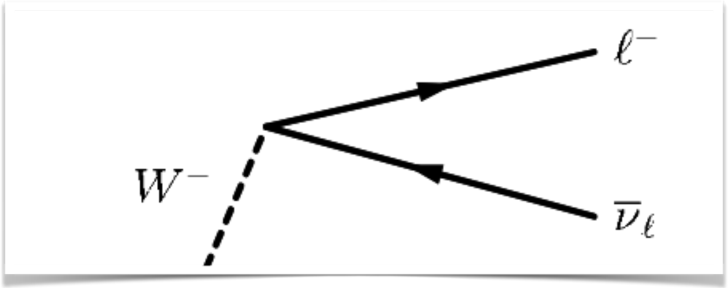
- New hope from calculation of non-local contribution from LQCD (but will take time)

MEANWHILE AMPLITUDE ANALYSIS AND q2 DEPENDENCE



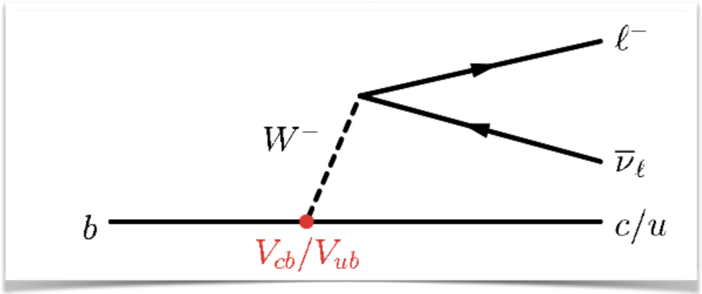


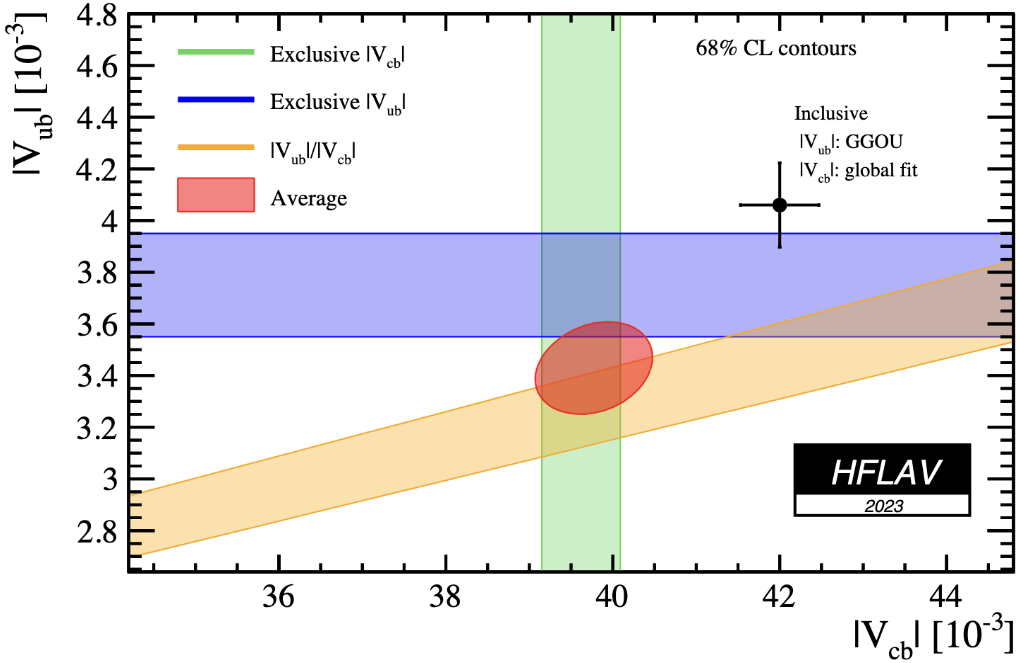
- Unbinned amplitude analysis introduce degrees of freedom to fit non-local contributions
- Non-local contributions are q2 dependent

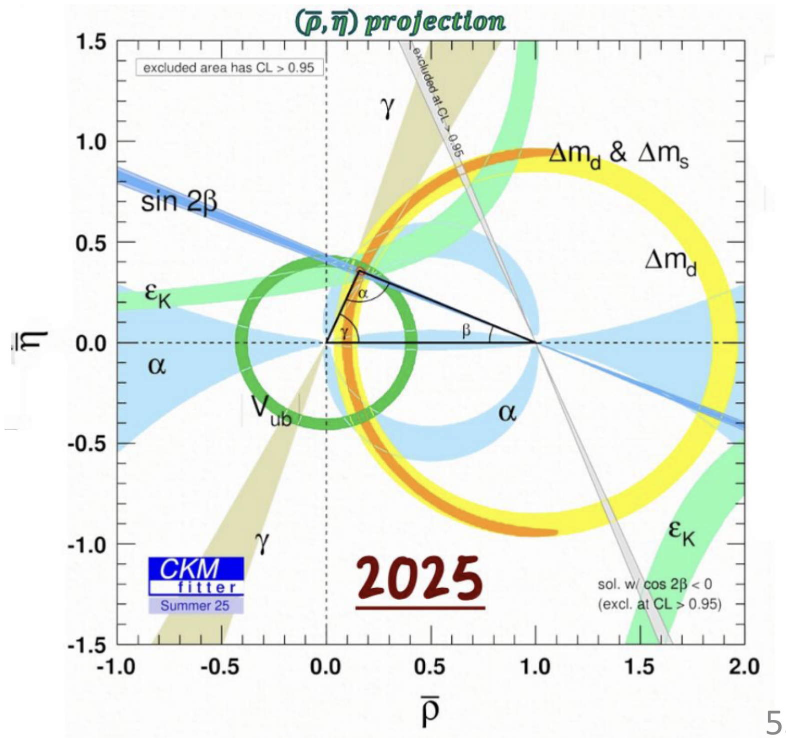


MY RESEARCH PROJECT FOR THE FUTURE

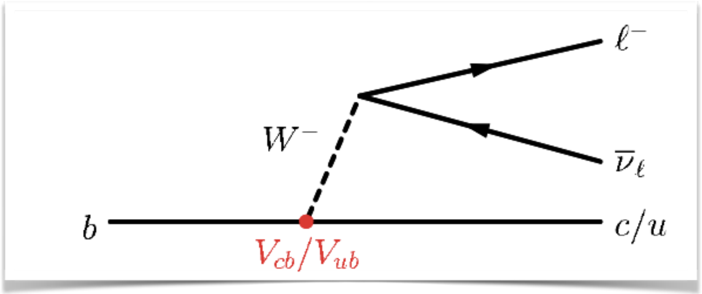
IMPROVE Vub MEASUREMENT

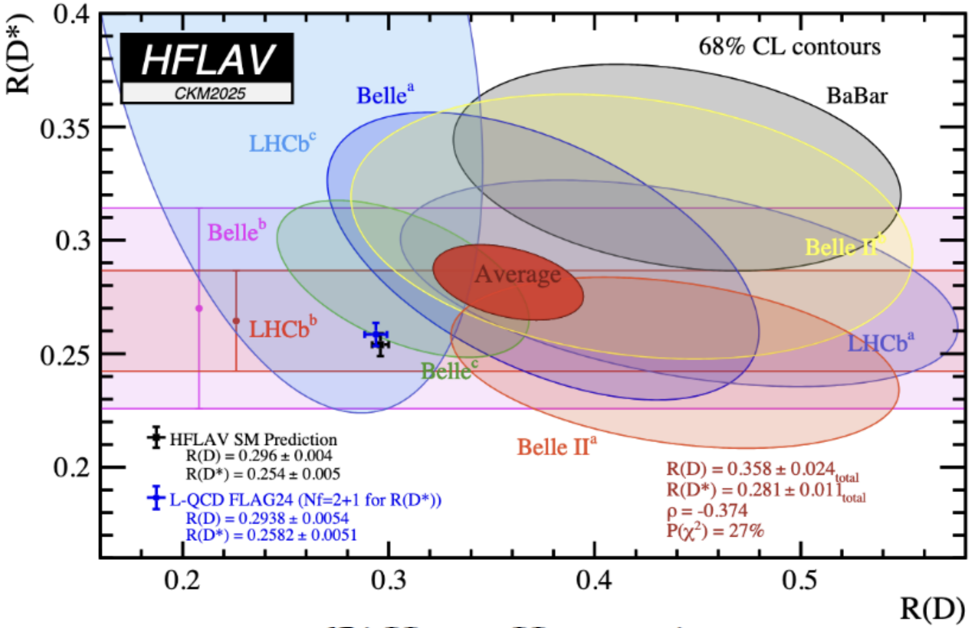






NEW LFU TESTS





$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c\,\tau^-\overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\,\ell'^-\overline{\nu}_{\ell'})}$$

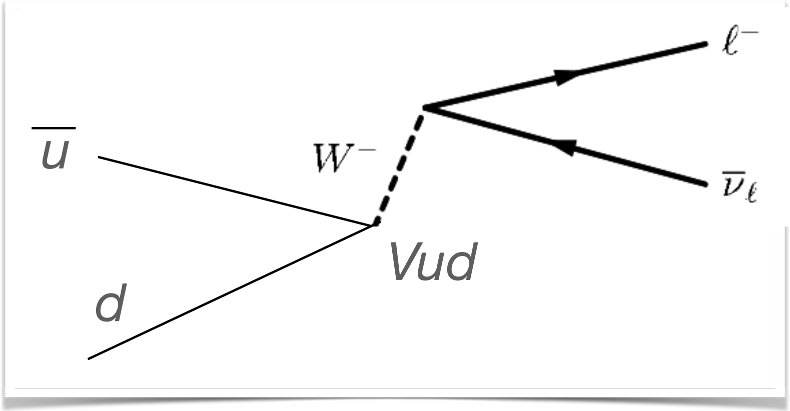
$$R_{K\tau\mu} = \frac{\mathcal{B}(B_s \to K^-\tau^+\nu_\tau)}{\mathcal{B}(B_s \to K^-\mu^+\nu_\mu)}$$

$$R_{Ke\mu} = \frac{\mathcal{B}(B_s \to K^-e^+\nu_e)}{\mathcal{B}(B_s \to K^-\mu^+\nu_\mu)}$$

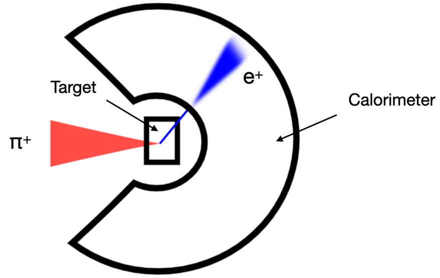
New, complementary measurements!

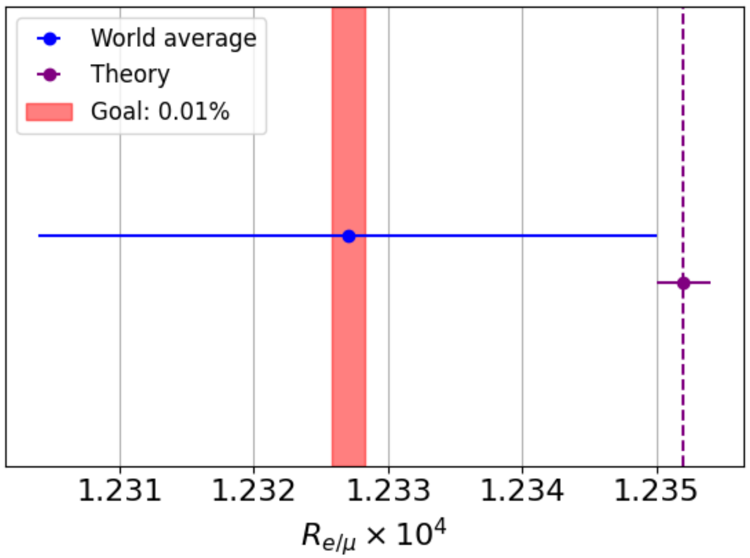
LFU TEST IN RARE PION DECAYS

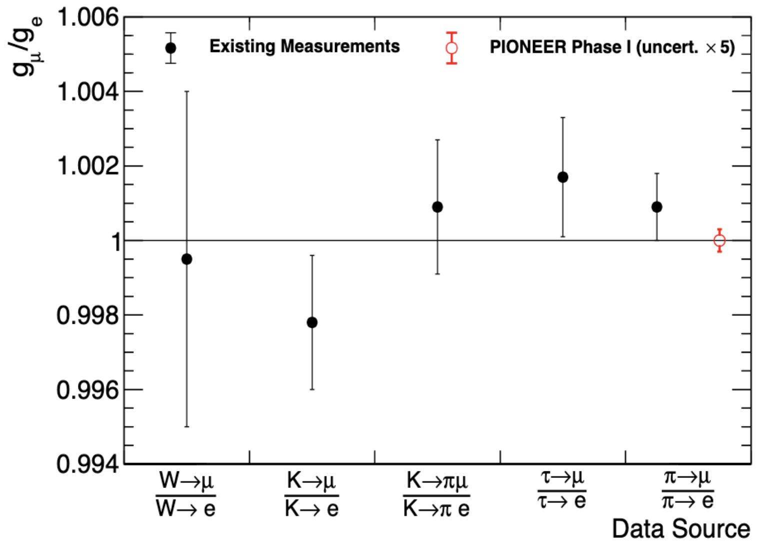
$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu_\mu(\gamma))}$$



PIONEER

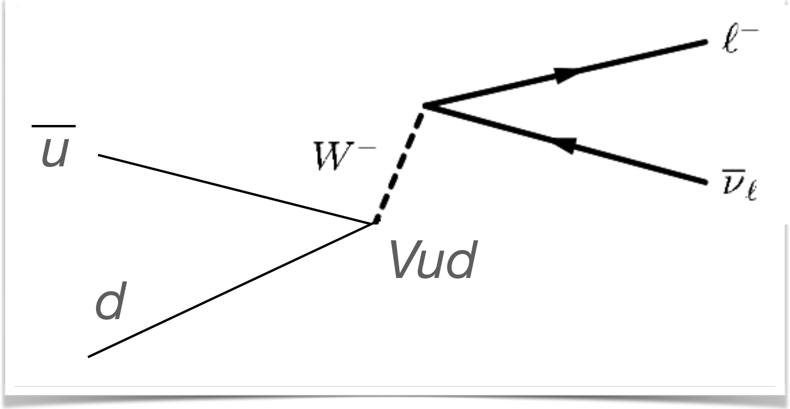


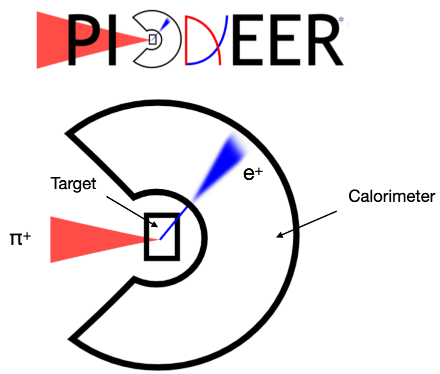




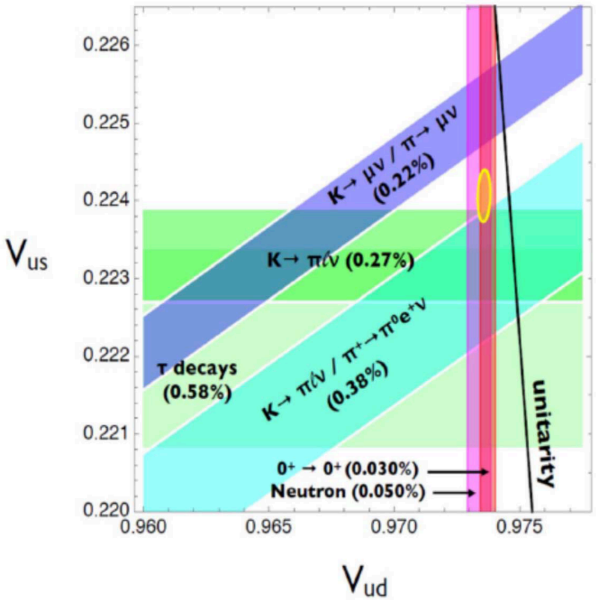
Vud MEASUREMENT IN RARE PION DECAYS

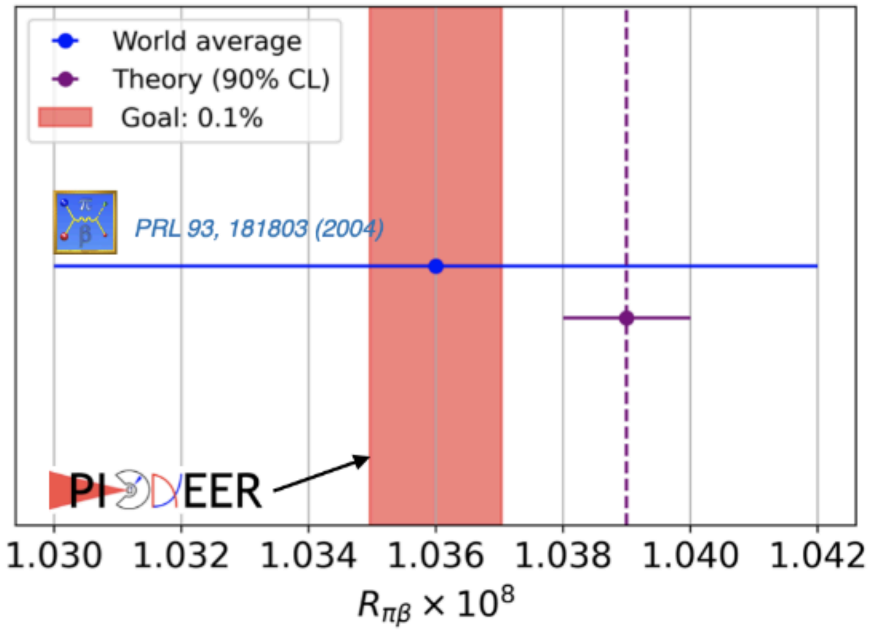
$$R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu_e)}{\Gamma(\pi^+ \to \text{all})}$$





$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$





CONCLUSIONS

Nature is telling us that the Standard Model is not the ultimate theory. Yet, it is working hard to hide new physics from our sight. In my opinion, a diversified approach is the key to unveiling the mysteries of nature, and I am proud and excited to keep contributing to this fascinating work of investigation.

BACKUP

https://videos.cern.ch/record/2302130

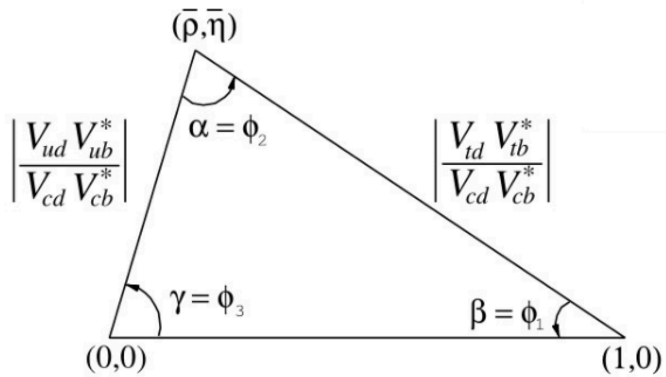
UNITARITY TRIANGLE

$$V_{CKM} V_{CKM}^{+} = 1$$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

$$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right] \equiv \pi - \alpha - \beta.$$

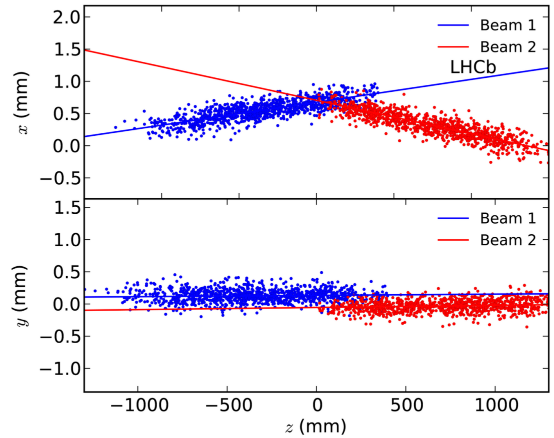
$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

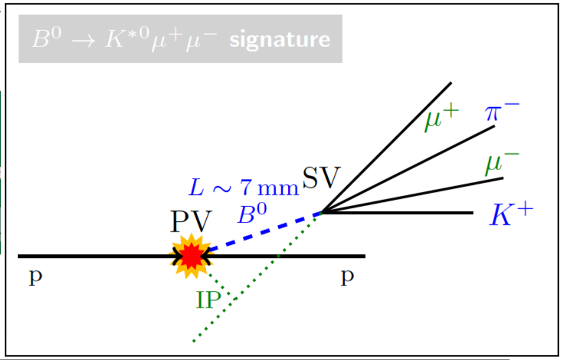


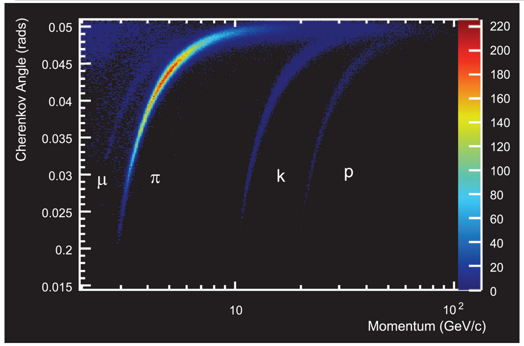
REQUIREMENTS FOR FLAVOR PHYSICS AT LHC

Key ingredients:

- ***High luminosity*** *to collect large data samples*
- ***Performing triggers*** *(for LHC: ex low pT triggers in GPD, real time analysis in LHCb)*
- *Be able to* ***cope with high pileup*** *(up to hundreds p-p interactions in GPD, few but now increasing in LHCb)*
- ***Vertex reconstruction capabilities*** *to identify the B decay, especially important for time-dependent measurements*
- ***Good mass resolution*** *to identify signal over backgrounds*
- ***Flavor tagging of initial states*** *for CPV measurements*
- ***Particle identification***







S-wave

$$
\begin{aligned}
\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\vec{\Omega}}\bigg|_{S+P} &= (1-F_S)\,\frac{1}{d(\Gamma+\bar{\Gamma})/dq^2}\frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\,d\vec{\Omega}}\bigg|_{P} \\
&+ \frac{3}{16\pi}F_S\sin^2\vartheta_\ell \\
&+ \frac{9}{32\pi}(S_{11}+S_{13}\cos 2\vartheta_\ell)\cos\vartheta_K \\
&+ \frac{9}{32\pi}(S_{14}\sin 2\vartheta_\ell + S_{15}\sin\vartheta_\ell)\sin\vartheta_K\cos\phi \\
&+ \frac{9}{32\pi}(S_{16}\sin\vartheta_\ell + S_{17}\sin 2\vartheta_\ell)\sin\vartheta_K\sin\phi
\end{aligned}
$$

F_S denotes the S-wave fraction,

$$
F_S = \frac{|A_S^L|^2+|A_S^R|^2}{|A_S^L|^2+|A_S^R|^2+|A_0^L|^2+|A_0^R|^2+|A_\parallel^L|^2+|A_\parallel^R|^2+|A_\perp^L|^2+|A_\perp^R|^2}
$$

REDUCING FORM FACTOR UNCERTAINTIES: P' OBSERVABLES

$$P_1 = \frac{2S_3}{(1-F_L)} = A_T^{(2)},$$

$$P_2 = \frac{2}{3}\frac{A_{\mathrm{FB}}}{(1-F_L)},$$

$$P_3 = -\frac{S_9}{(1-F_L)},$$

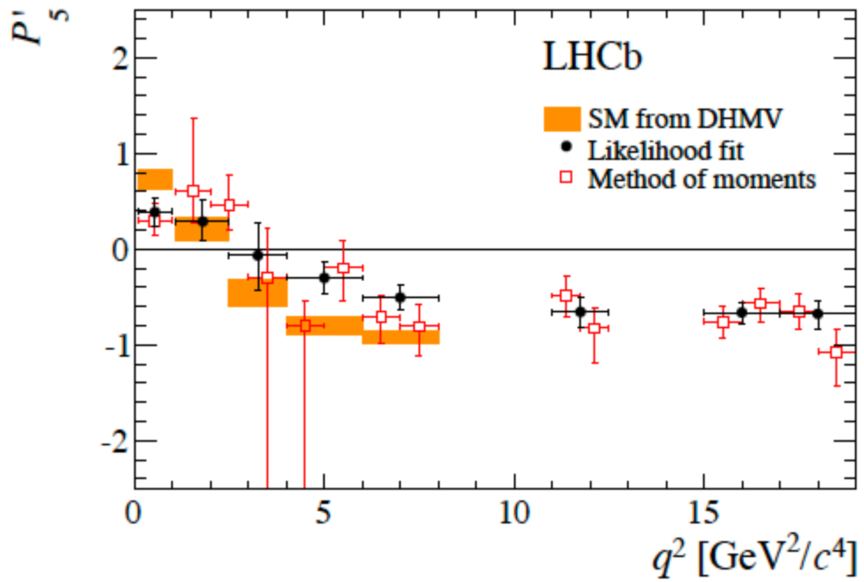
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}},$$

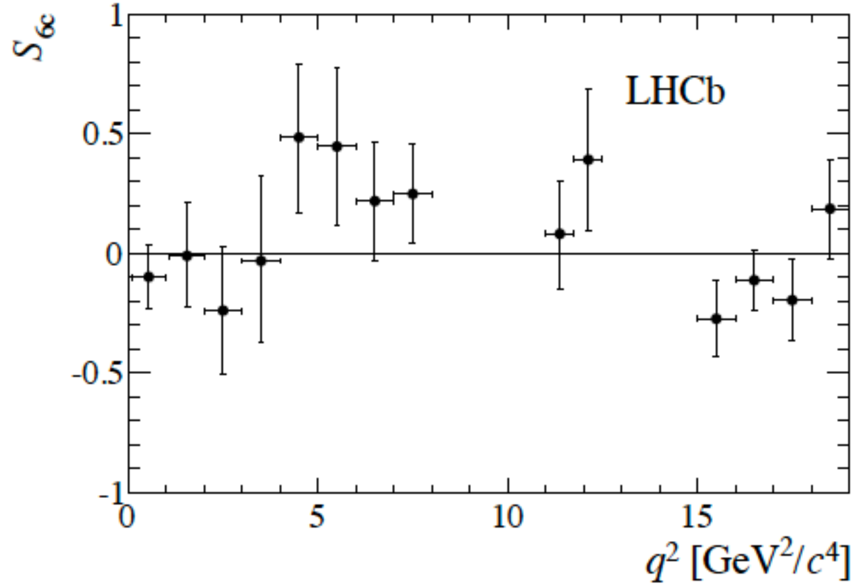
$$P'_6 = \frac{S_7}{\sqrt{F_L(1-F_L)}}.$$

COMPLEMENTARY APPROACHES: METHOD OF MOMENTS

$$M_i(q^2) = \frac{1}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}} \int \frac{d^4(\Gamma+\bar{\Gamma})}{dq^2\, d\vec{\Omega}} f_i(\vec{\Omega})\, d\vec{\Omega}$$

$$M_i = \begin{cases} \frac{8}{25}(1-F_S)S_i & \text{if } i = 3,4,8,9, \\ \frac{2}{5}(1-F_S)S_i & \text{if } i = 5,6s,7, \\ \frac{2}{5}(1-F_S)(2-F_L) + \frac{2}{3}F_S & \text{if } i = 1s. \end{cases}$$

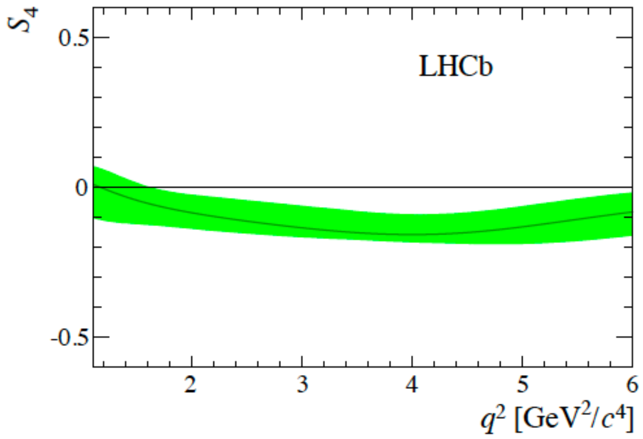


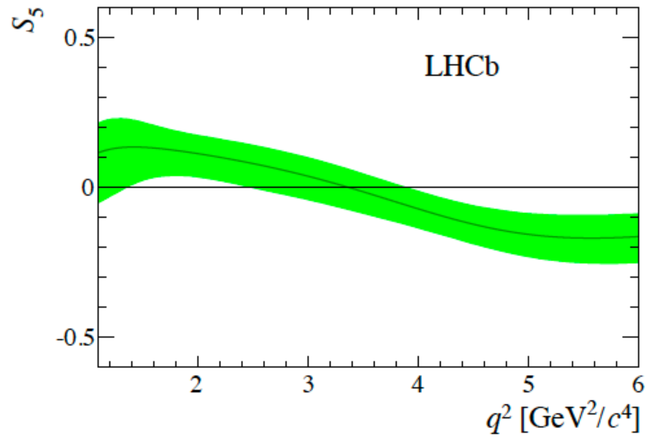


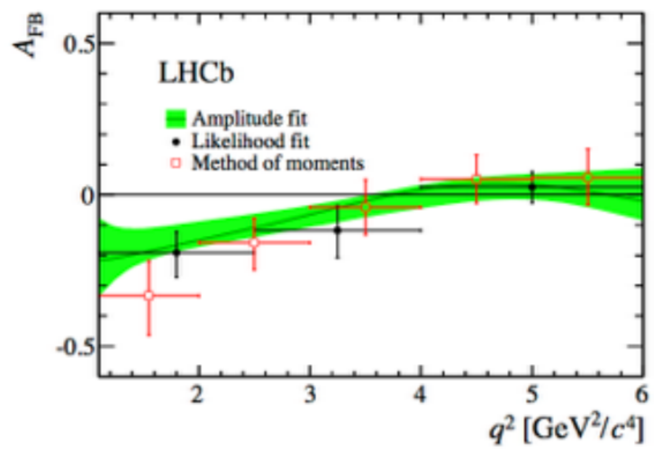
COMPLEMENTARY APPROACHES: AMPLITUDE ANALYSIS

Additional measurement of zero-crossing points, parameterizing the angular distribution with q^2 dependent decay amplitudes

$$A^{L,R}_{i=0,\|,\perp}(q^2) = \alpha_i^{L,R} + \beta_i^{L,R} q^2 + \frac{\gamma_i^{L,R}}{q^2}$$







$$q_0^2(S_5) \in [2.49,\ 3.95]\ \mathrm{GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}$$

$$q_0^2(A_{\mathrm{FB}}) \in [3.40,\ 4.87]\ \mathrm{GeV}^2/c^4 \text{ at } 68\% \text{ C.L.}$$

$$q_0^2(S_4) < 2.65\ \mathrm{GeV}^2/c^4 \quad \text{at } 95\% \text{ C.L.}$$

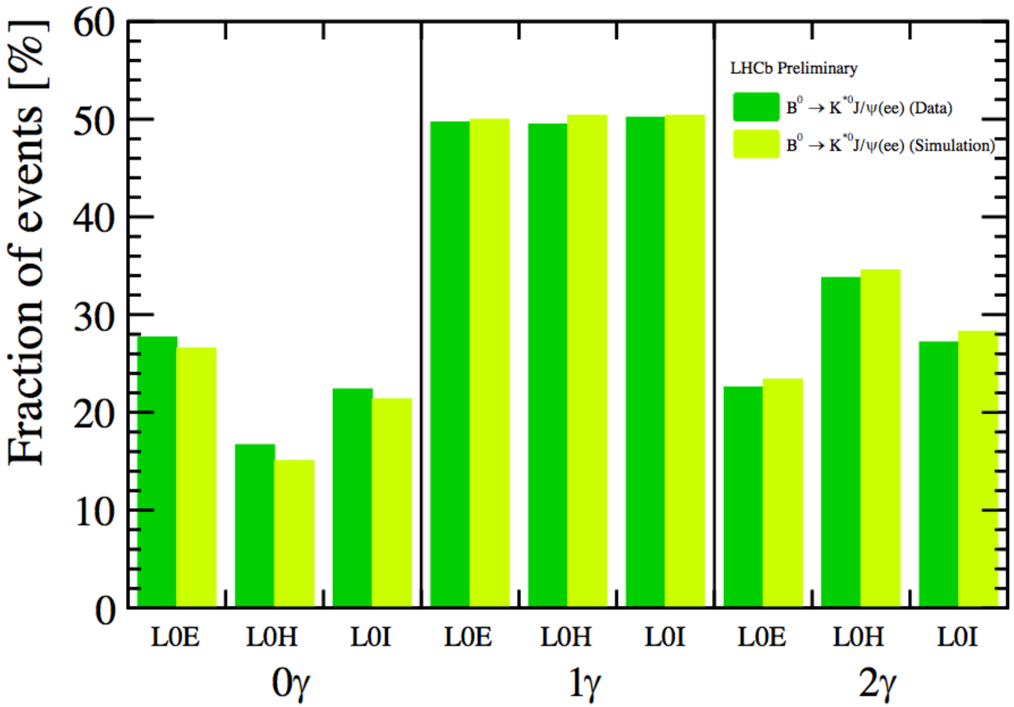
SM: $q_0^2(A_{\mathrm{FB}}) \sim [3.9, 4.4]\ \mathrm{GeV}^2/c^4$

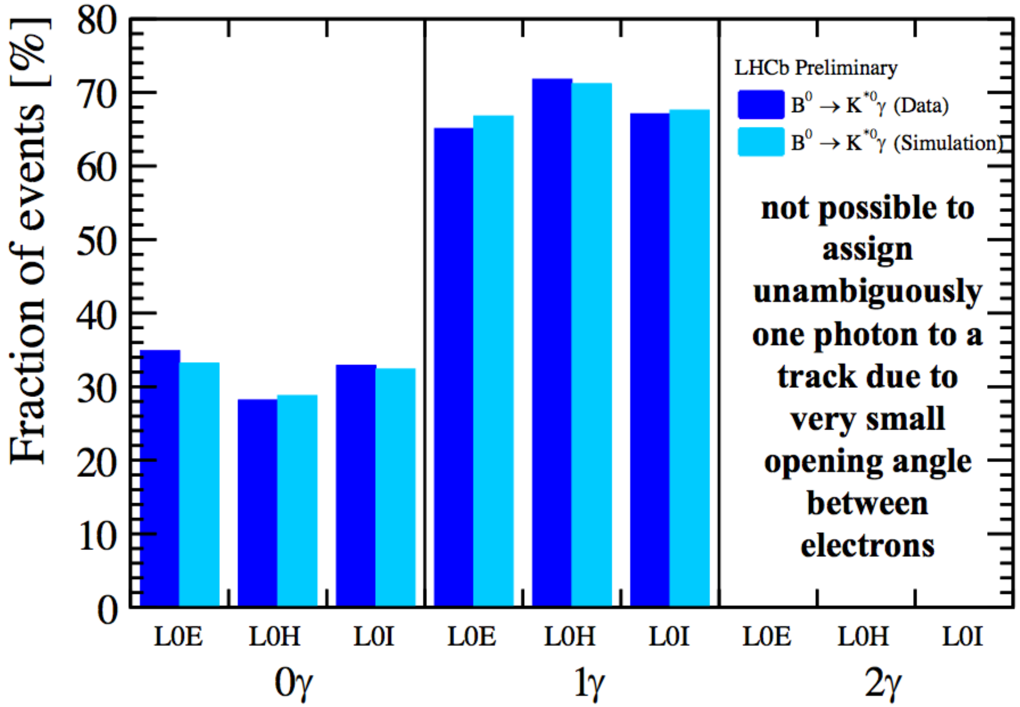
[JHEP 01 (2012) 107, EPJ C41 (2005) 173, EPJ C47 (2006) 625]

SYSTEMATICS

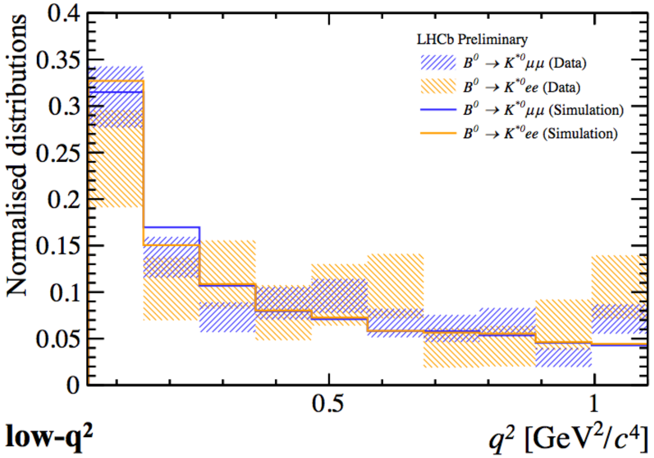
Source	F_L	S_3–S_9	A_3–A_9	P_1–P'_8	q_0^2 GeV^2/c^4
Acceptance stat. uncertainty	< 0.01	< 0.01	< 0.01	< 0.01	0.01
Acceptance polynomial order	< 0.01	< 0.02	< 0.02	< 0.04	0.01–0.03
Data-simulation differences	0.01–0.02	< 0.01	< 0.01	< 0.01	< 0.02
Acceptance variation with q^2	< 0.01	< 0.01	< 0.01	< 0.01	–
$m(K^+\pi^-)$ model	< 0.01	< 0.01	< 0.01	< 0.03	< 0.01
Background model	< 0.01	< 0.01	< 0.01	< 0.02	0.01–0.05
Peaking backgrounds	< 0.01	< 0.01	< 0.01	< 0.01	0.01–0.04
$m(K^+\pi^-\mu^+\mu^-)$ model	< 0.01	< 0.01	< 0.01	< 0.02	< 0.01
Det. and prod. asymmetries	–	–	< 0.01	< 0.02	–

CROSSCHECKS: BREMSSTRAHLUNG

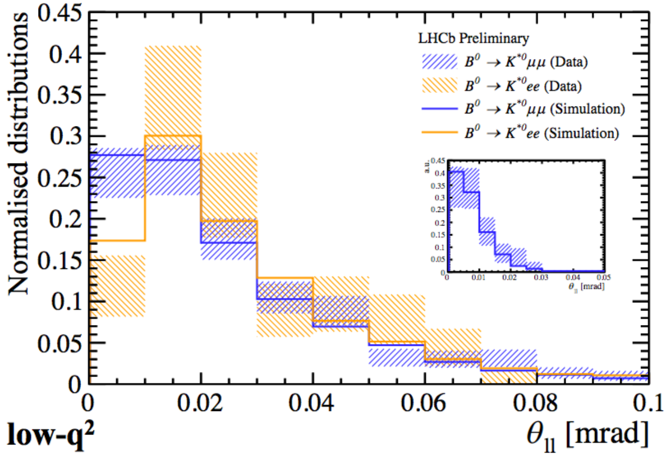




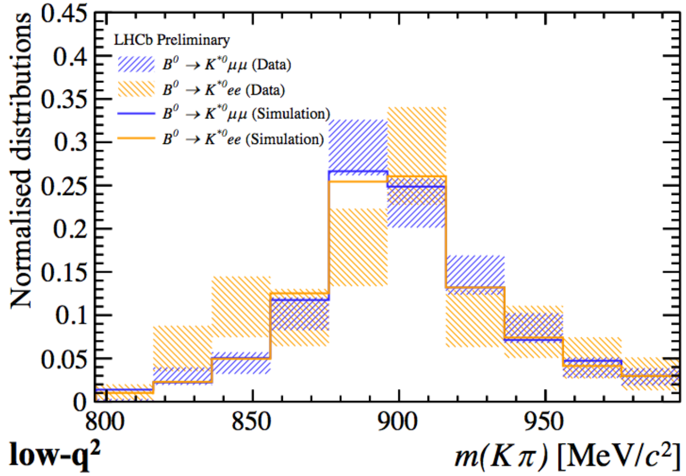
CROSSCHECKS: KINEMATICS



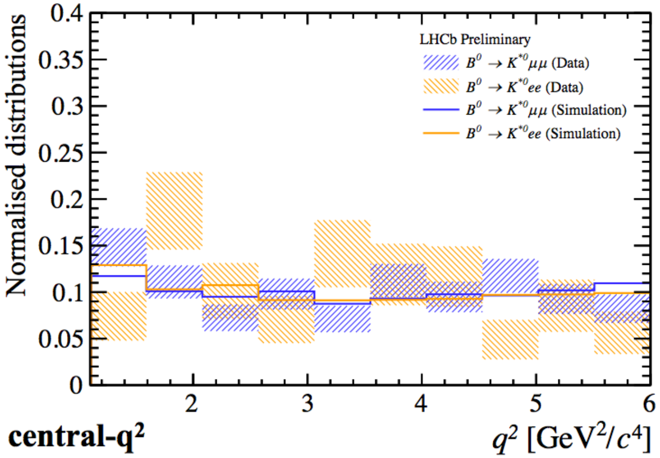
low-q^2



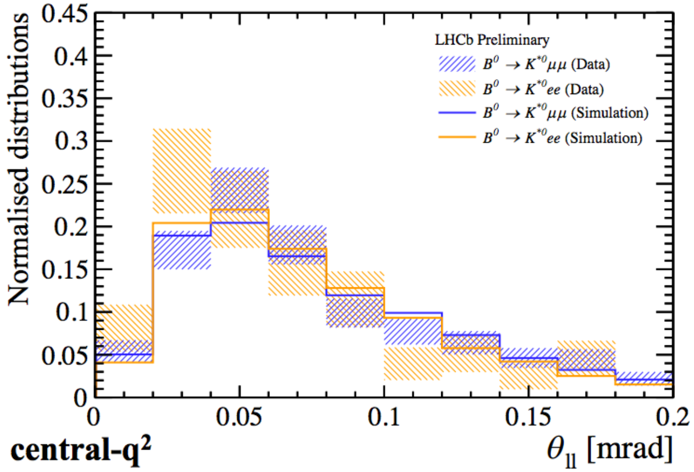
low-q^2



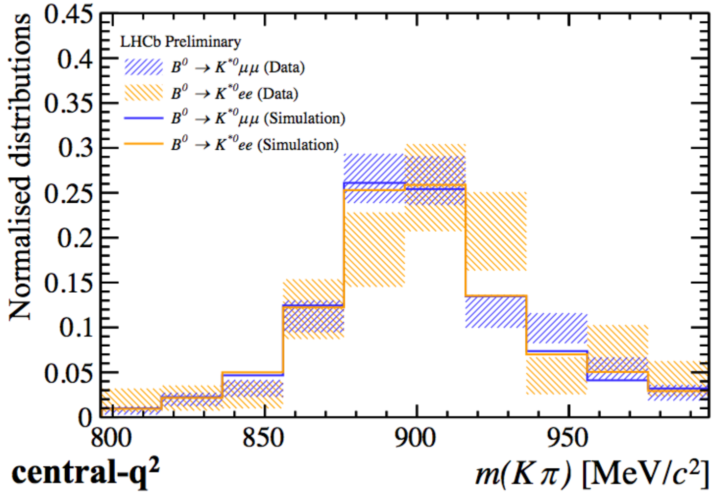
low-q^2



central-q^2



central-q^2

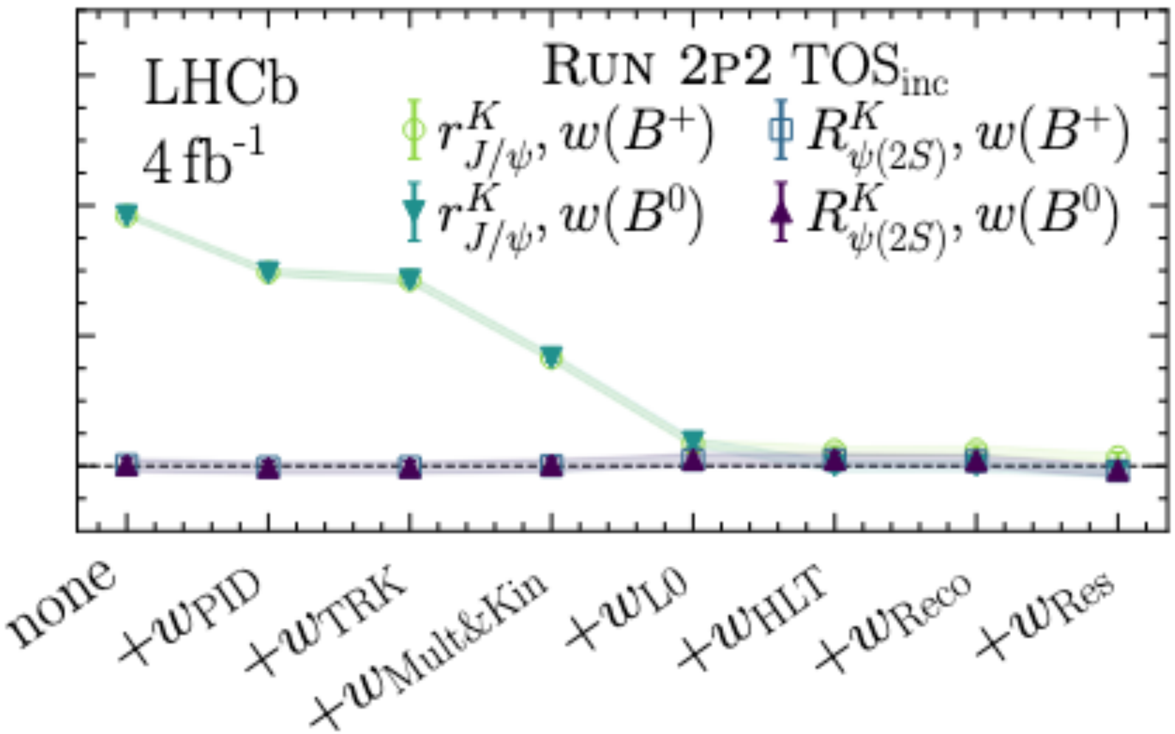


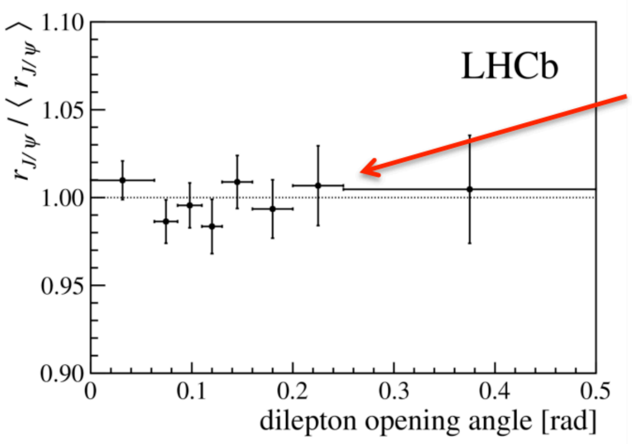
central-q^2

RX ANALYSIS: EFFICIENCIES

LHCb-PAPER-2022-045

LHCb-PAPER-2022-046





r(J/Ψ) =1 demonstrates that the efficiencies are under very good control

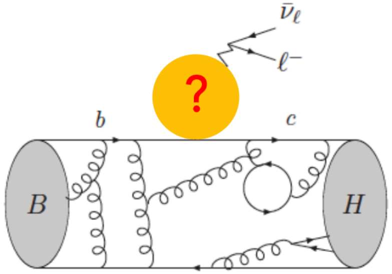
LFU IN b—>c l nu TRANSITIONS

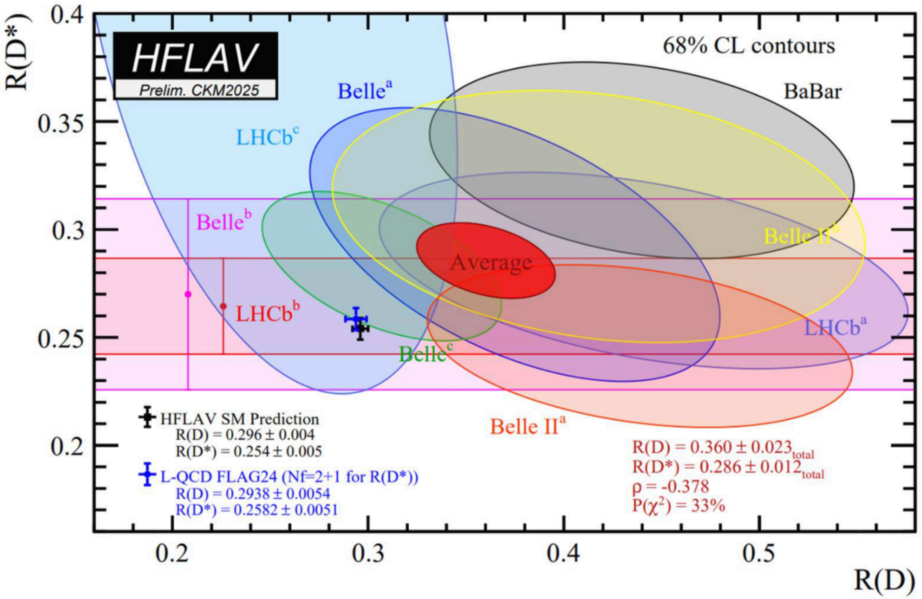
$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau^- \overline{\nu}_\tau)}{\mathcal{B}(H_b \to H_c \ell'^- \overline{\nu}_{\ell'})}$$

$H_b = B^0, B^0_s, B^+_{(c)}, \Lambda^0_b$

$H_c = D^*, D^0, D^+, D^+_s, J/\psi, \Lambda$

e or μ

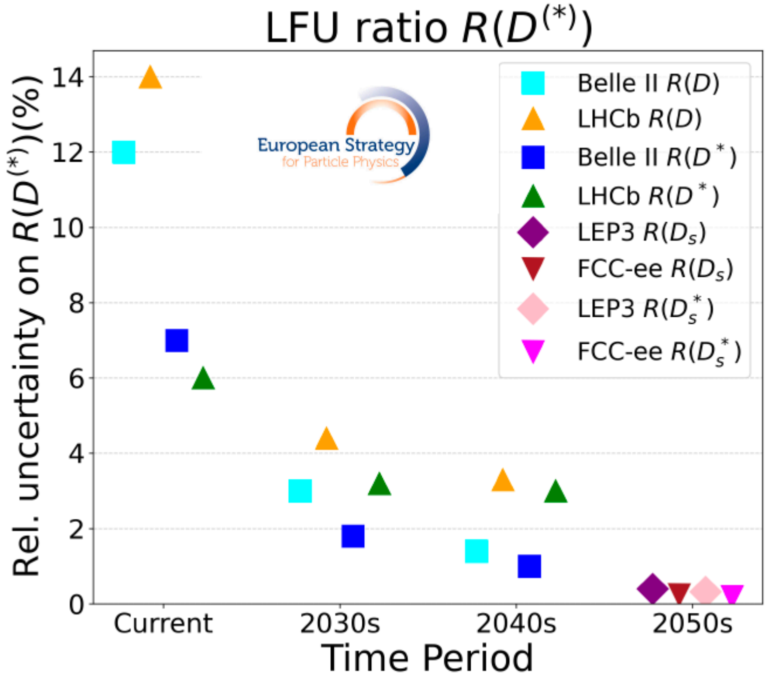




R(D) tension with SM: 2.7σ

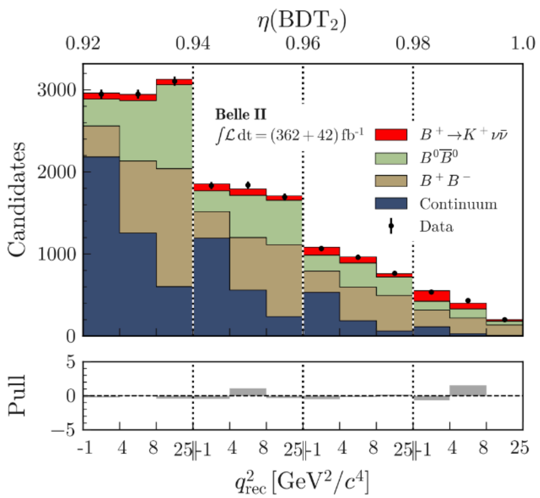
R(D*) tension with SM: 2.7σ

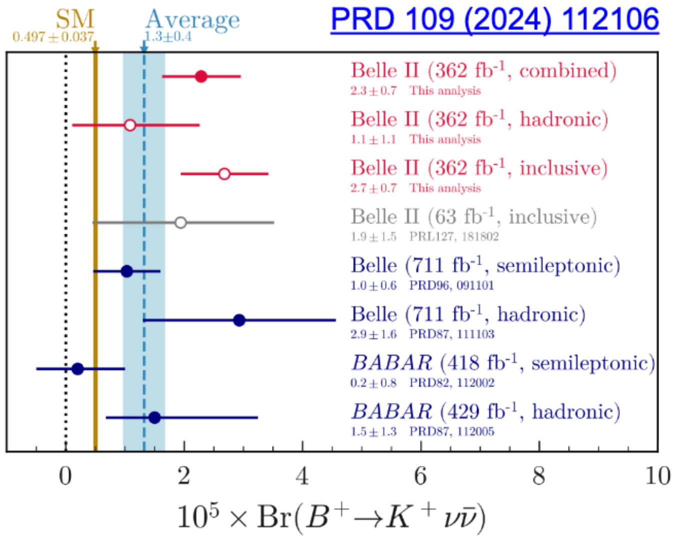
R(D)-R(D*) tension : 4.2σ



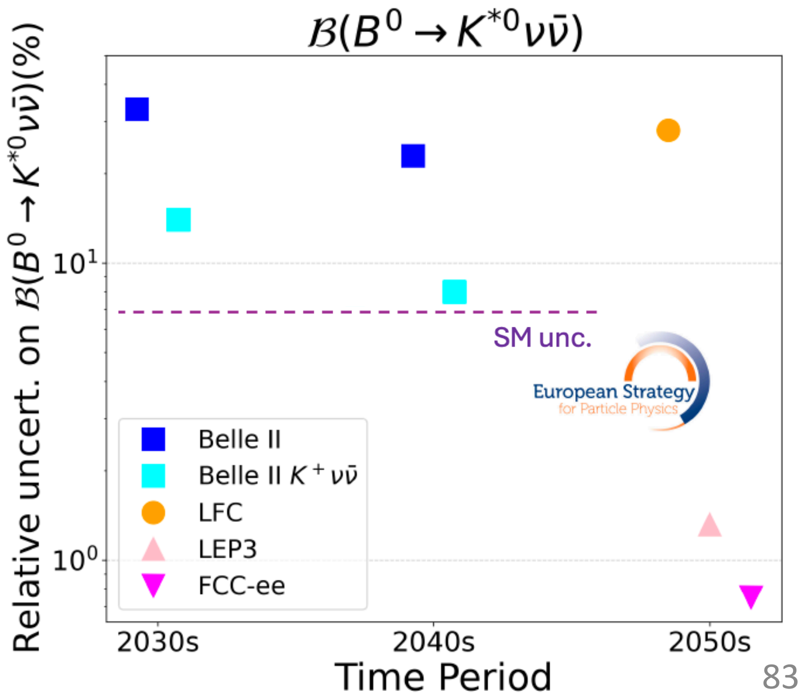
b -> s ν ν

b→sνν̄ is a clean observable, not affected by long-distance charm-loops effects





Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+ \nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0} \nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+} \nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0} \nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+} \nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–



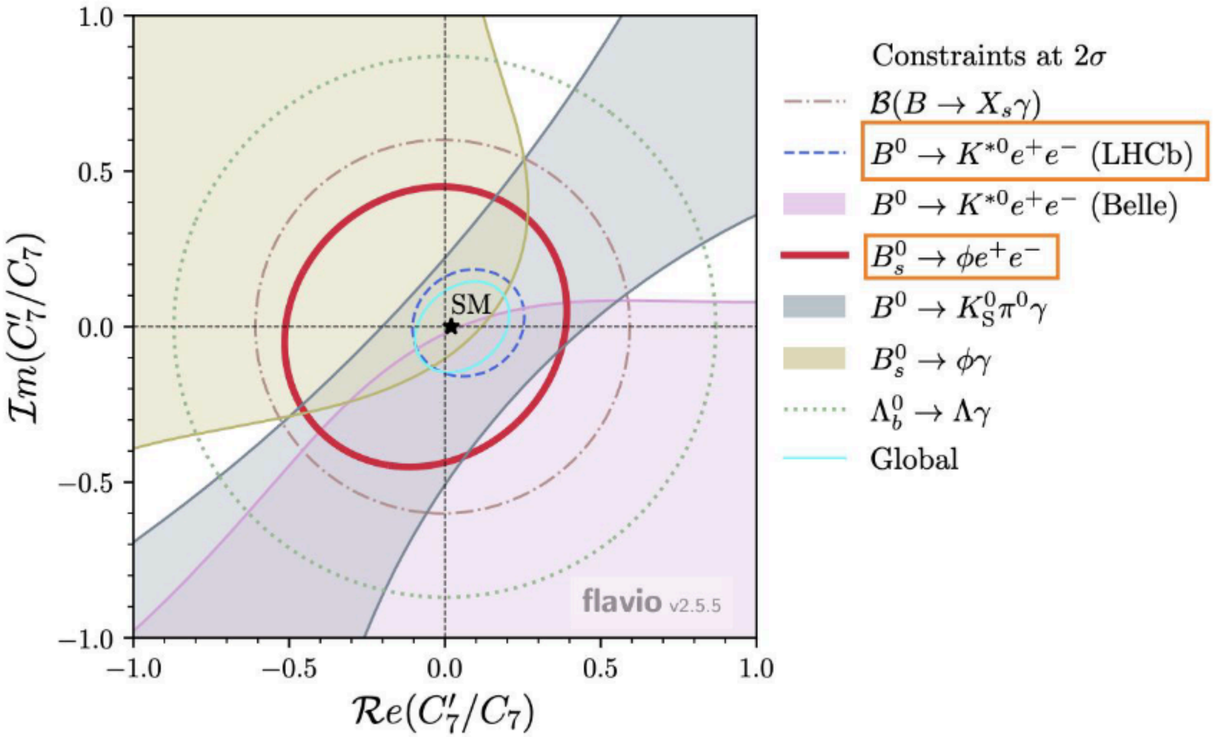
- *Belle II evidence for $B^+ \to K^+\nu\bar{\nu}$*
  - *3.1σ significant, and 2.7 σ above the SM prediction*

$$BF(B^+ \to K^+\nu\bar{\nu}) = \left(2.3 \pm 0.5^{+0.5}_{-0.4}\right)\times 10^{-5}$$

CONSTRAINTS ON PHOTON POLARIZATION

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb}\, C_7\, O_7 + \text{h.c.}$$

$$O_7 = \frac{e}{16\pi^2} m_b\, \bar{s}\, \sigma^{\mu\nu}(1+\gamma_5)\, b\, F_{\mu\nu}.$$



In b decays the photon is predominantly left-handed due to V-A structure

(In b-bar is right handed)

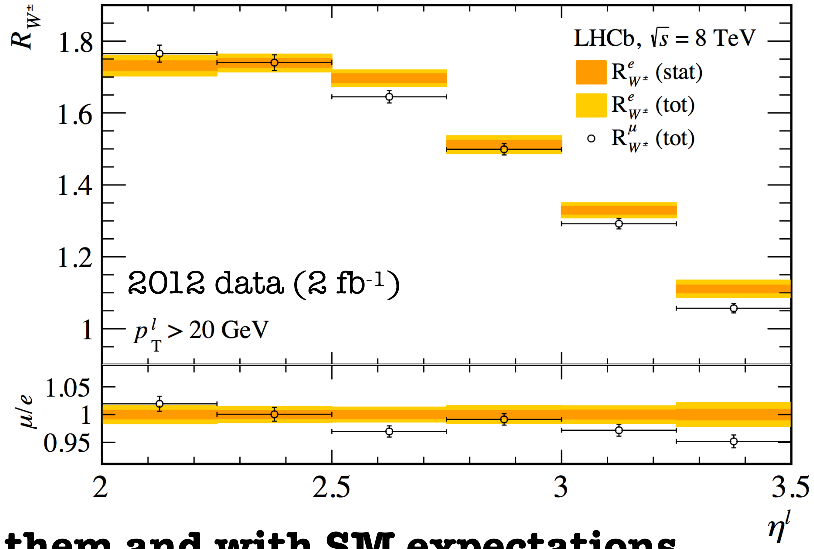
Rw

R_W : ratio of forward production cross section W->eν (JHEP 10 (2016) 030) and W->μν (JHEP 01 (2016) 155)

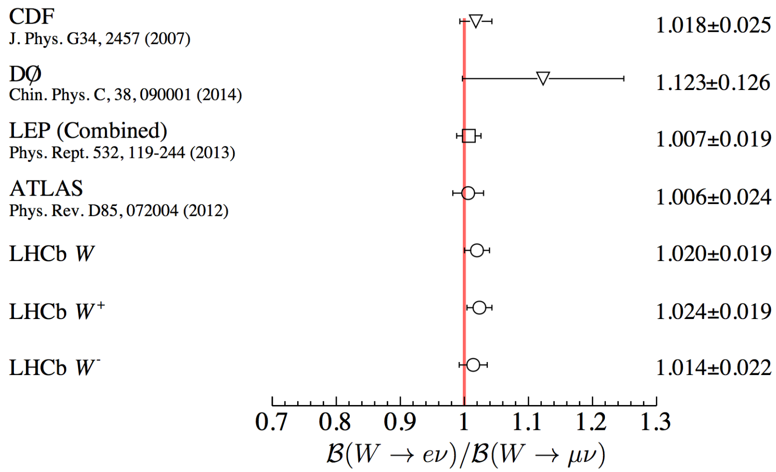
$$\frac{\mathcal{B}(W+\to e^+\nu_e)}{\mathcal{B}(W+\to \mu^+\nu_\mu)} = 1.024 \pm 0.003 \pm 0.019$$

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

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



All experiments in agreement among them and with SM expectations



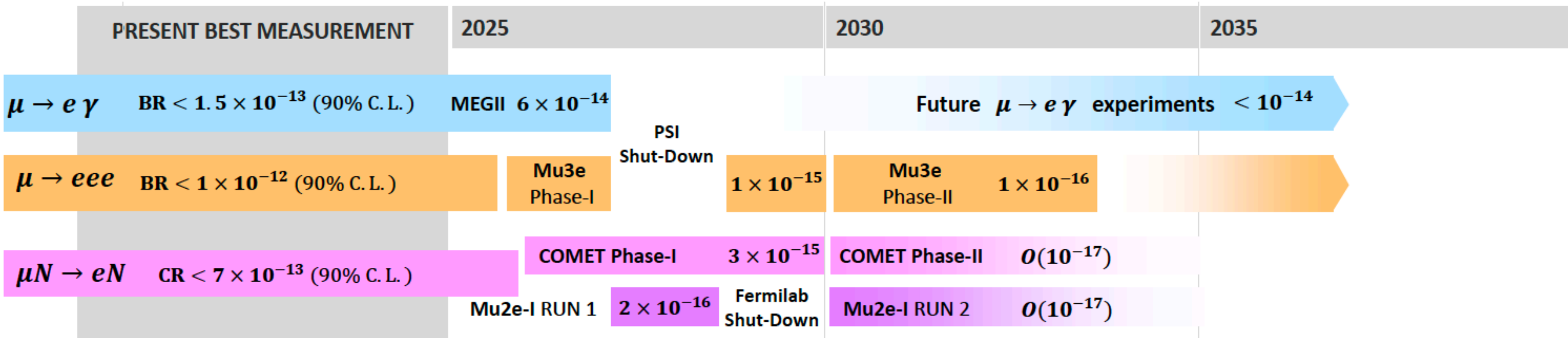
New ATLAS result: Eur. Phys. J. C 77 (2017) 367

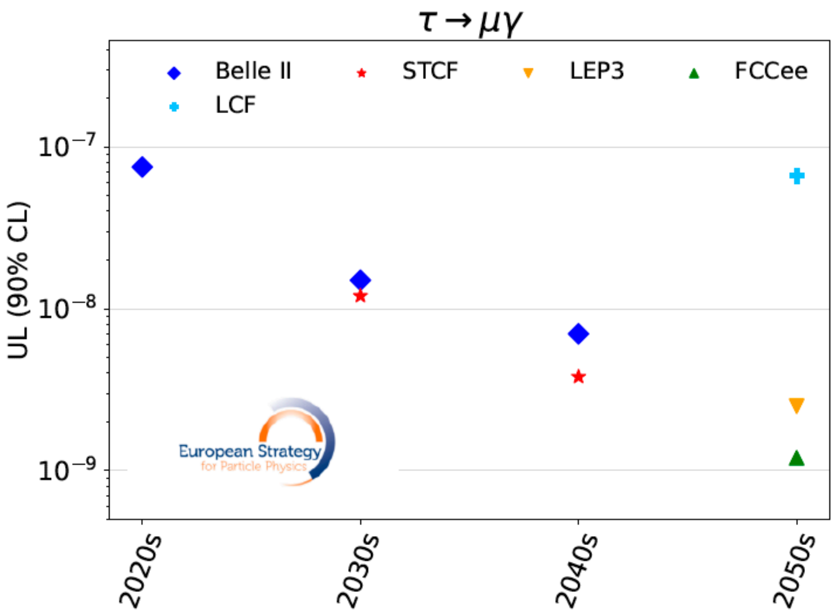
$$R_W = \frac{\sigma^{\text{fid},e}_{W\to e\nu}/E^e_W}{\sigma^{\text{fid},\mu}_{W\to\mu\nu}/E^\mu_W} = \frac{\sigma^{\text{fid}}_{W\to e\nu}}{\sigma^{\text{fid}}_{W\to\mu\nu}} = \frac{BR(W\to e\nu)}{BR(W\to\mu\nu)}$$

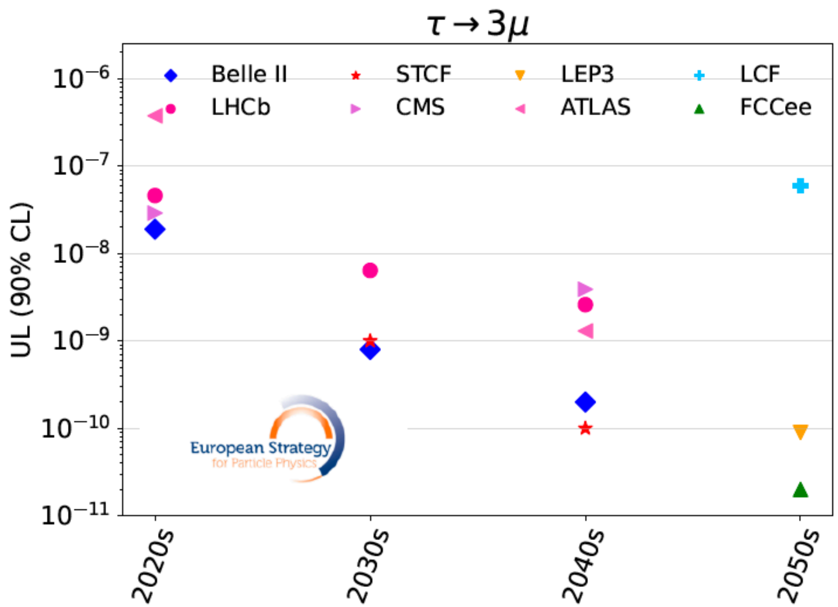
$$= 0.9967 \pm 0.0004\,(\text{stat}) \pm 0.0101\,(\text{syst})$$

$$= 0.997 \pm 0.010\,.$$

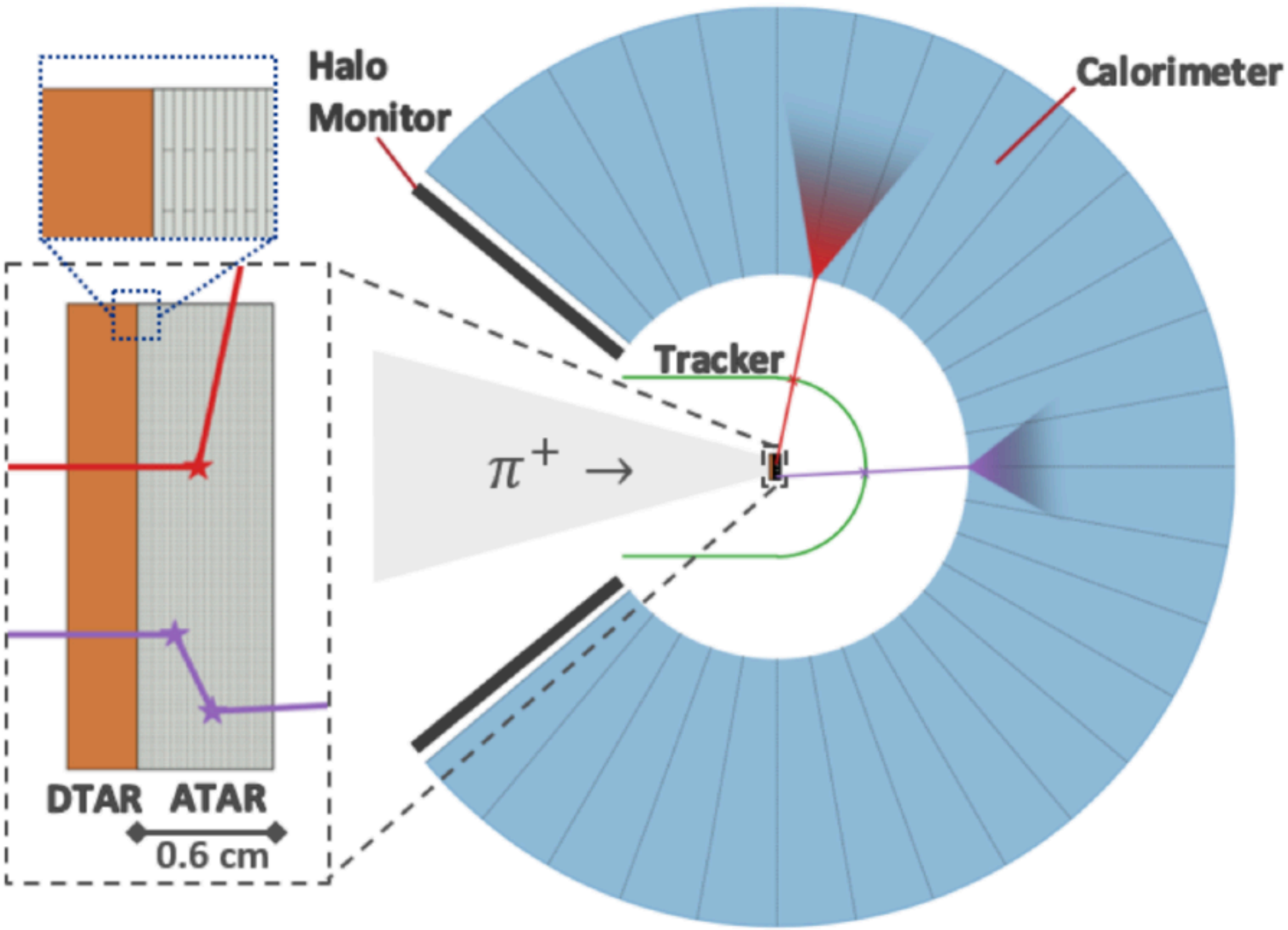
PROSPECTS FOR OTHER cLFV DECAYS



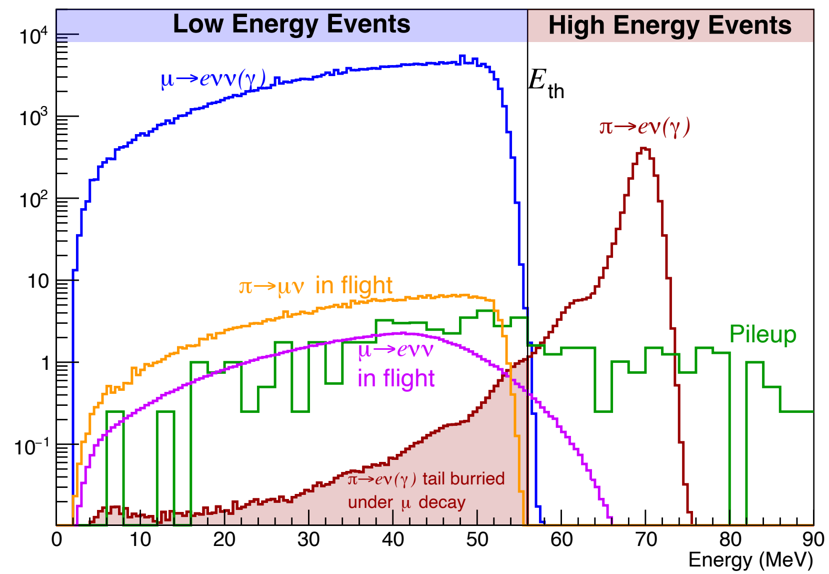




PIONEER



Halo
Monitor
Calorimeter
Tracker
$\pi^+ \rightarrow$
DTAR ATAR
0.6 cm

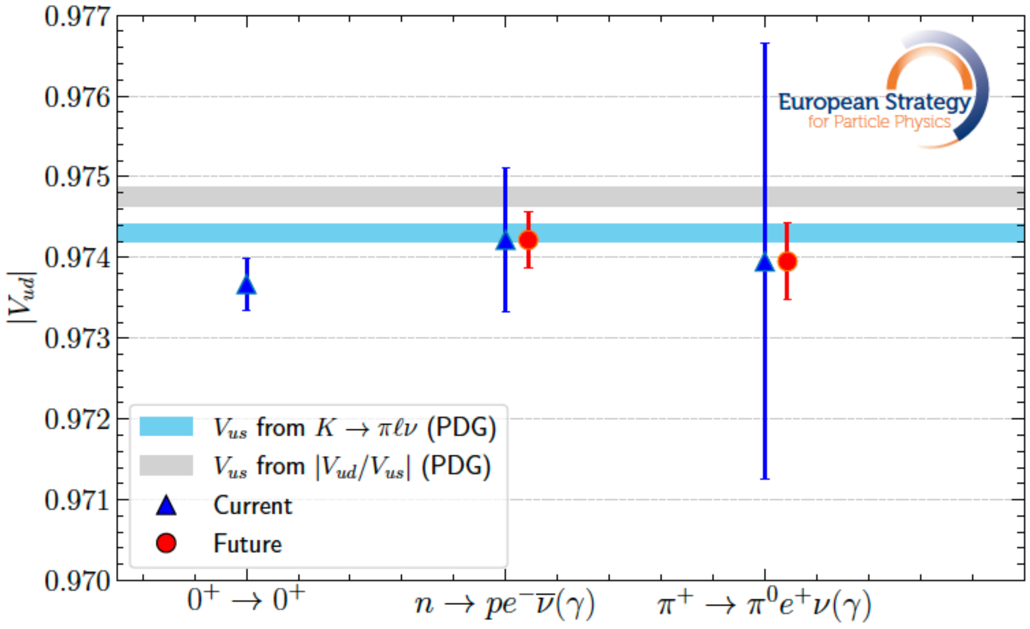


Low Energy Events
High Energy Events
$\mu \rightarrow e\nu\nu(\gamma)$
E_{th}
$\pi \rightarrow e\nu(\gamma)$
$\pi \rightarrow \mu\nu$ in flight
Pileup
$\mu \rightarrow e\nu\nu$
in flight
$\pi \rightarrow e\nu(\gamma)$ tail burried
under μ decay
Energy (MeV)

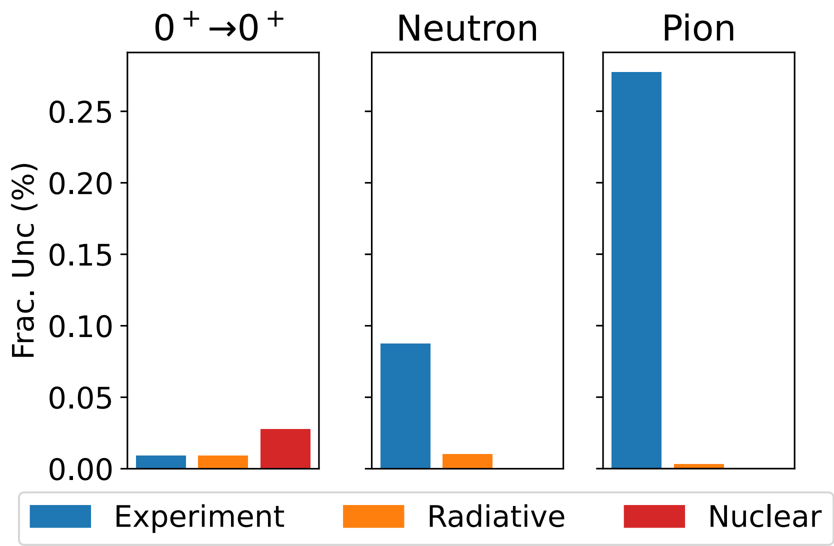
LANDSCAPE OF Vud MEASUREMENTS

PIONEER vs neutron/nuclei:

a competitive probe with a completely different error budget



Brodeur et al,
arXiv:2301.03975



$$V_{ud}^{0^+\to 0^+} = 0.97367\,(11)_{\text{exp}}\,(13)_{\Delta_V^R}\,(27)_{NS}\,[32]_{\text{total}}$$

$$V_{ud}^{n,\text{PDG}} = 0.97430\,(2)_{\Delta_f}\,(13)_{\Delta_R}\,(82)_{\lambda}\,(28)_{\tau_n}\,[88]_{\text{total}}$$

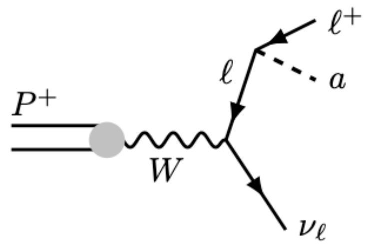
$$V_{ud}^{\pi} = 0.97386\,(281)_{\text{BR}}\,(9)_{\tau_\pi}\,(14)_{\Delta_R^\pi}\,(28)_{\Delta_f}\,[283]_{\text{total}}$$

PIONEER can verify the observed discrepancy

PIONEER : EXOTICS

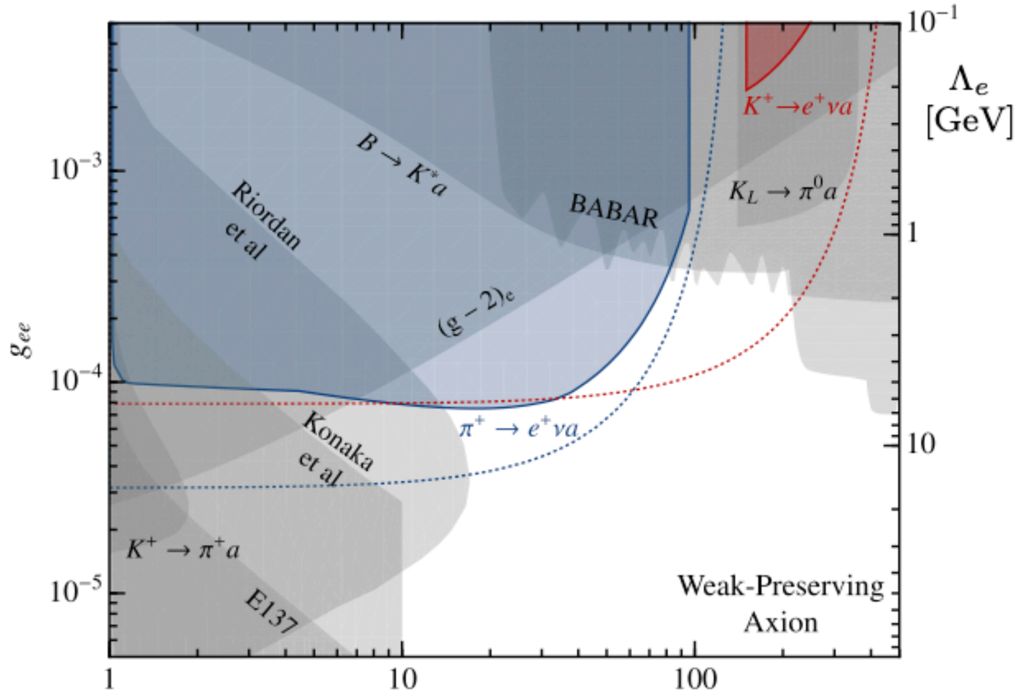
PIONEER will collect an unprecedented set of pion decays:

- surpassing existing sample by at least a factor 10
- opportunity to search for feeble interactions producing new particles in the pion decay
- look for deviation of SM quantities or modification of the energy spectrum lineshape



Recent development with Lepto-philic axion-like particles

W. Altmannshofer, J. Dror, and S. Gori
Phys. Rev. Lett. **130**, 241801



PI E NU

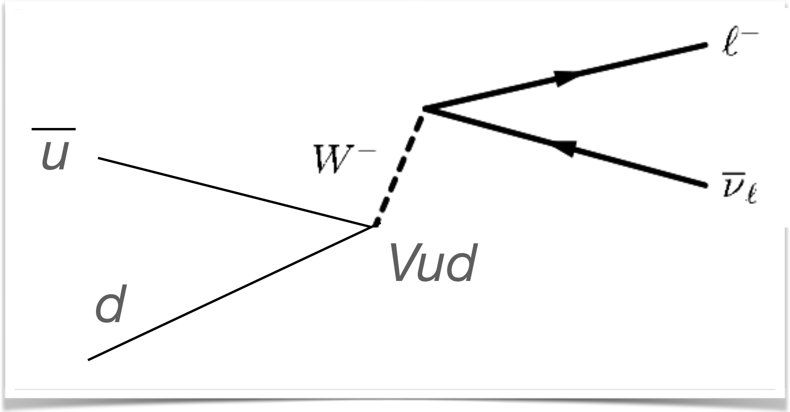
Many signatures explored by TRIUMF PIENU

$\pi \to e\nu_H$	Physical Review D 97(7) 072012 (2018)
$\pi \to \mu\nu_H$	Physics Letters B 798 134980 (2019)
$\pi \to \ell\nu_\ell\nu\overline{\nu}$	Phys. Rev. D 102, 012001 (2020)
$\mu \to eX$	Phys. Rev. D 101, 052014 (2020)
$\pi \to e\nu X$	Phys. Rev. D 103, 052006 (2021)

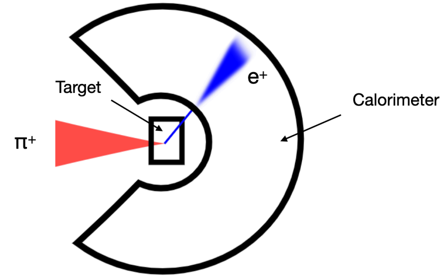
PIONEER can improve feeble interacting new particle searches (ALPs, heavy neutrinos) by an order of magnitude in the 10-100 MeV range

LFU TEST IN RARE PION DECAYS

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu_\mu(\gamma))}$$



PIONEER



$$R_{e/\mu} = \frac{m_e^2}{m_\mu^2} \times \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \times \left[1 + \text{EW corrections}\right] = 1.23524(015) \times 10^{-4}$$

'Helicity suppression' term: ~2.3 x10^{-5}

Phase space term: ~ 5.5

Fully computed at NLO
O(10^{-4}) uncertainties at NNLO