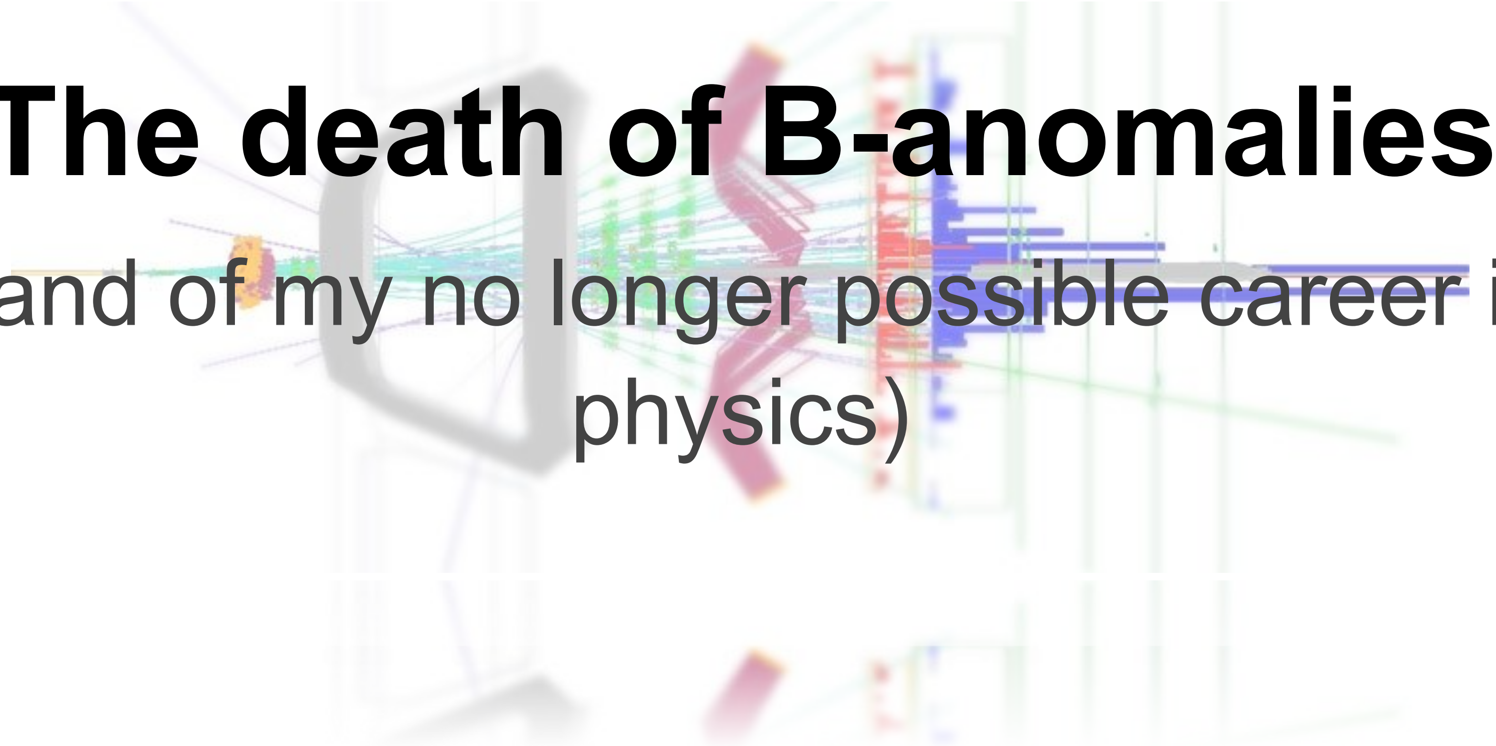


The death of B-anomalies

(and of my no longer possible career in physics)

Yann Monceaux - JRJC - 24/10/2023

The Standard Model : an incomplete theory

Still some unresolved problems :

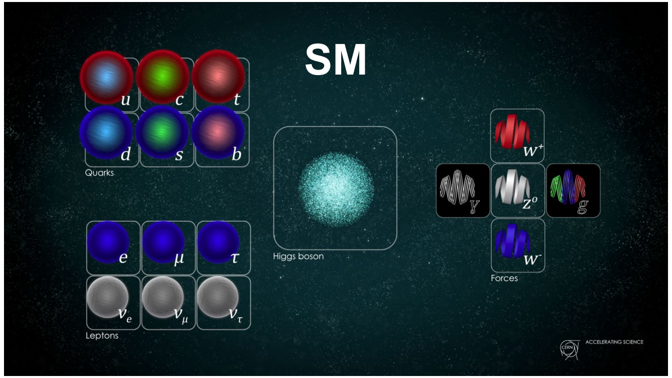
What do we do about the prefou?

- **P**roblem of neutrino masses
- **R**euniting Quantum theory and Gravity
- **E**lectroweak hierarchy problem
- **F**lavor puzzle
- **O**bservables anomalies
- **U**nknown nature of Dark Matter

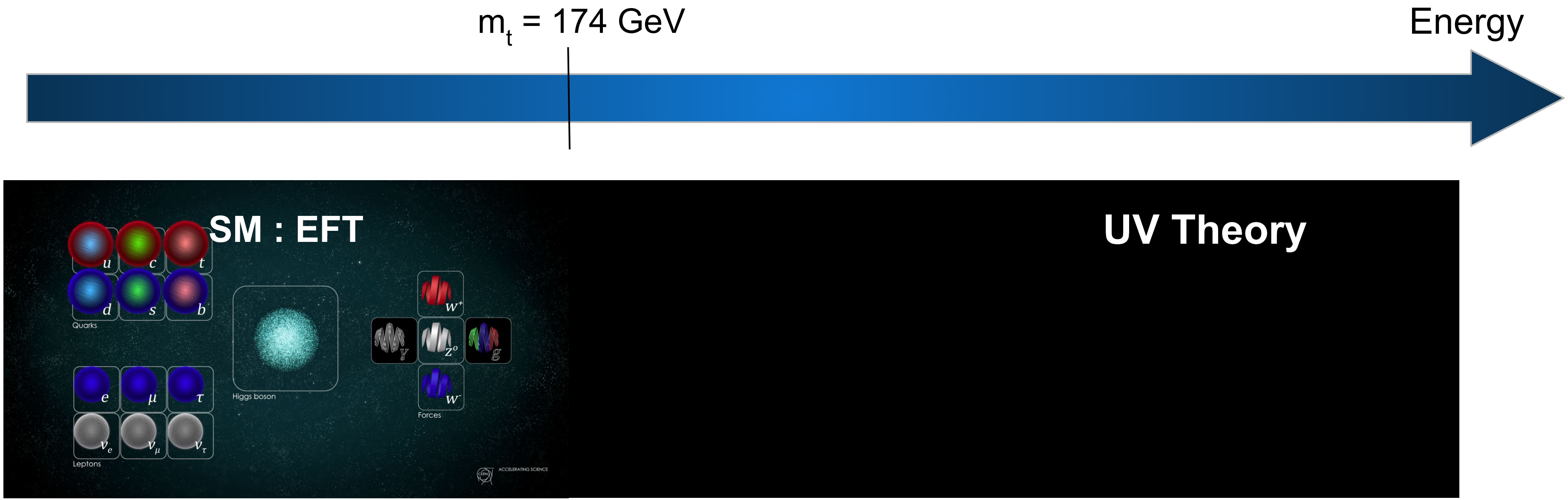
UV Theory and NP search

m_t = 174 GeV

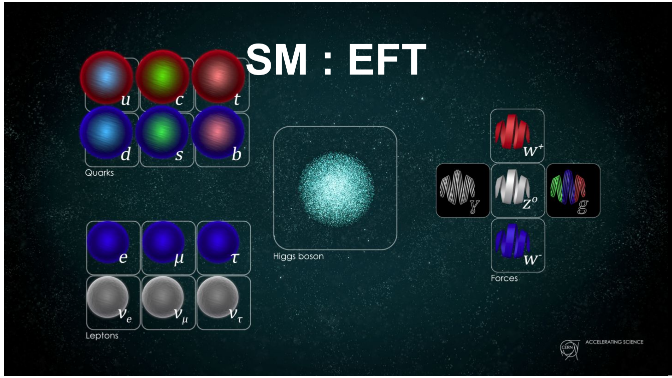
Energy



UV Theory and NP search



UV Theory and NP search



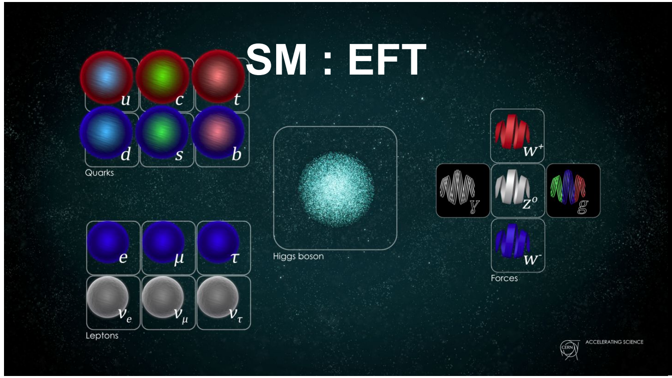
BUT !!!

UV Theory

UV Theory and NP search

m_t = 174 GeV ? Energy

SM : EFT



BUT !!!

UV Theory

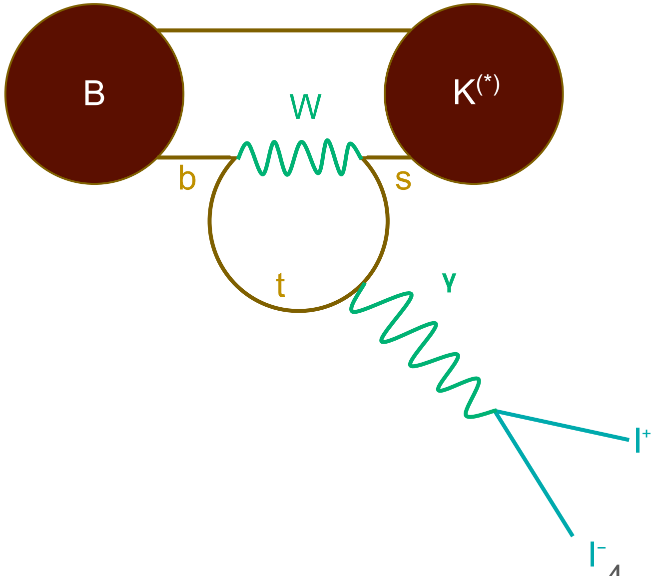
INDIRECT SEARCH

Semi-leptonic B-decays

$b \rightarrow s l^+ l^-$ transitions through Flavor Changing Neutral Current (FCNC)

→ No contribution at tree-level in SM
→ CKM suppressed

⇒ **Sensitive to new physics !**



Semi-leptonic B-decays

$b \to s l^+ l^-$ transitions through F
Current (FCNC)

→ No contribution at tree-level in SM
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⇒ **Sensitive to ne**
physics !

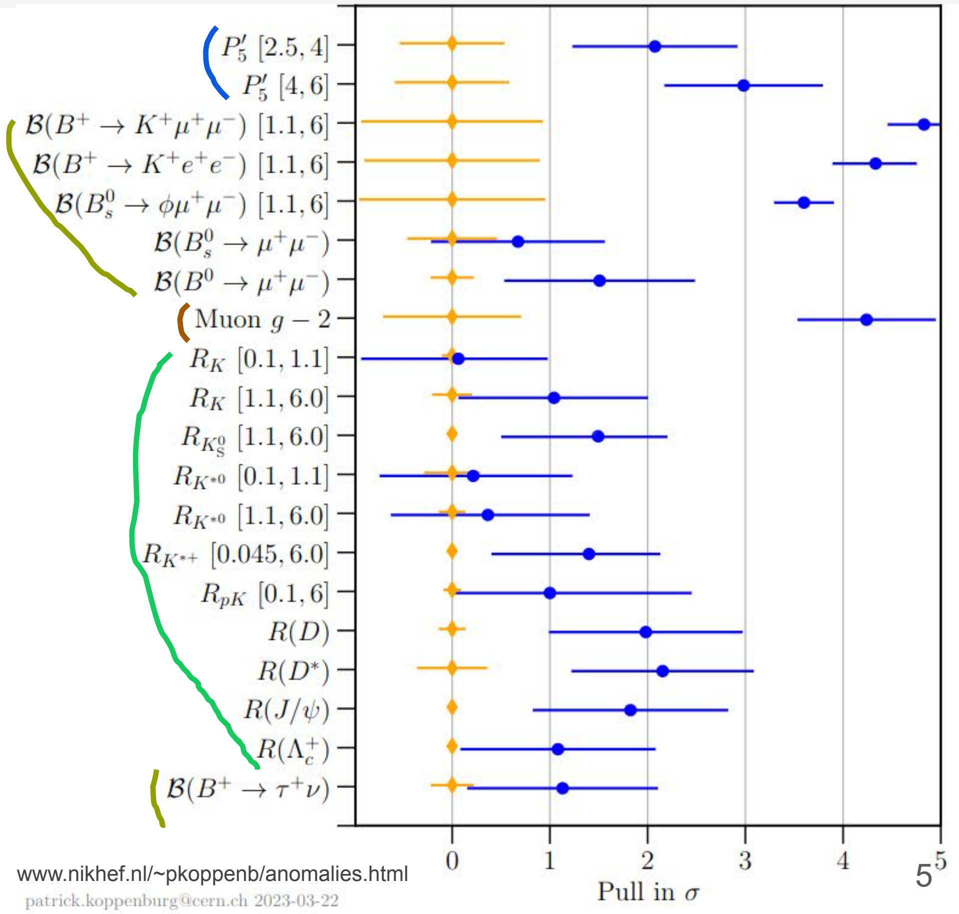
→ Hadronic uncertainties

⇒ **Theoretical**
complications

B-anomalies

orange : SM predictions
blue : experimental results

- Branching fractions
- Angular observables
- R-ratios
- Muon g-2



www.nikhef.nl/~pkoppenb/anomalies.html

B-anomalies

orange : SM predictions
blue : experimental results

- Branching fraction
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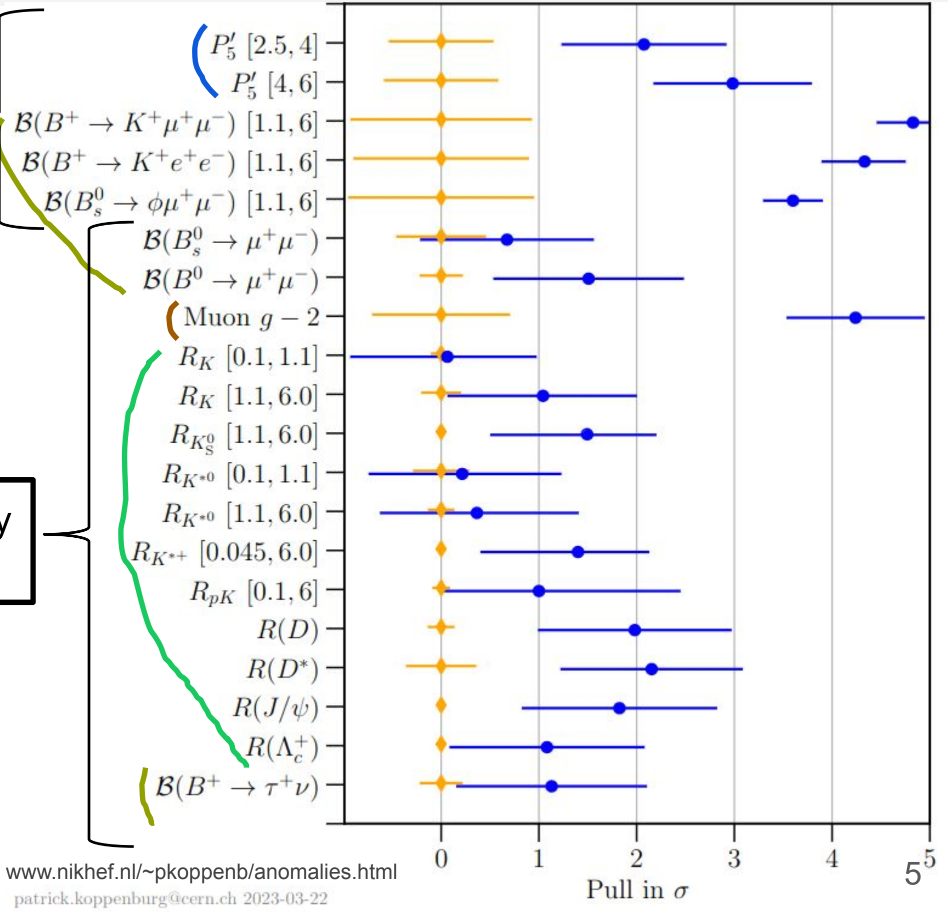
Challenging uncertainties

Theoretically 'clean'



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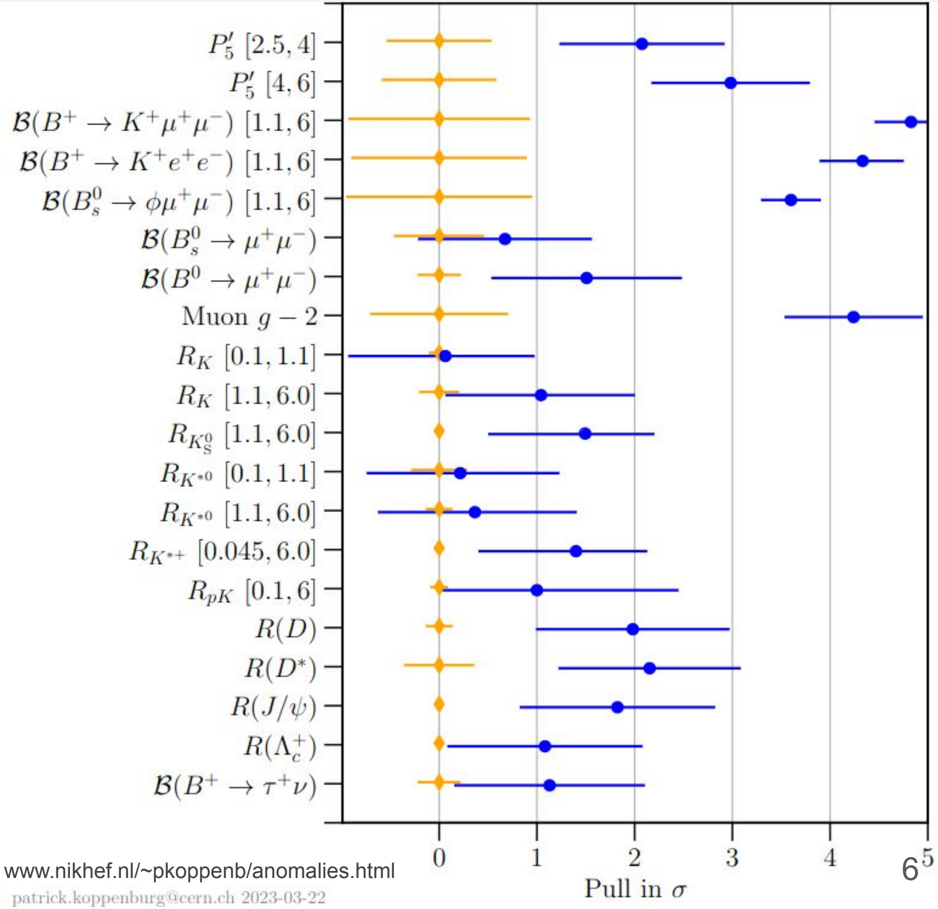
B-anomalies

Anomalies in ‘clean’ observables gone :

- ❑ R_K and R_{K^*} (LHCb 2022)
- ❑ BR($B_s \to \mu\mu$) (LHCb 2021)

Deviation in angular observables and Branching fractions at low q² still standing (q² : square of invariant mass of the two leptons in the final state)

➡ **Theoretically challenging**



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Motivation: B-anomalies status

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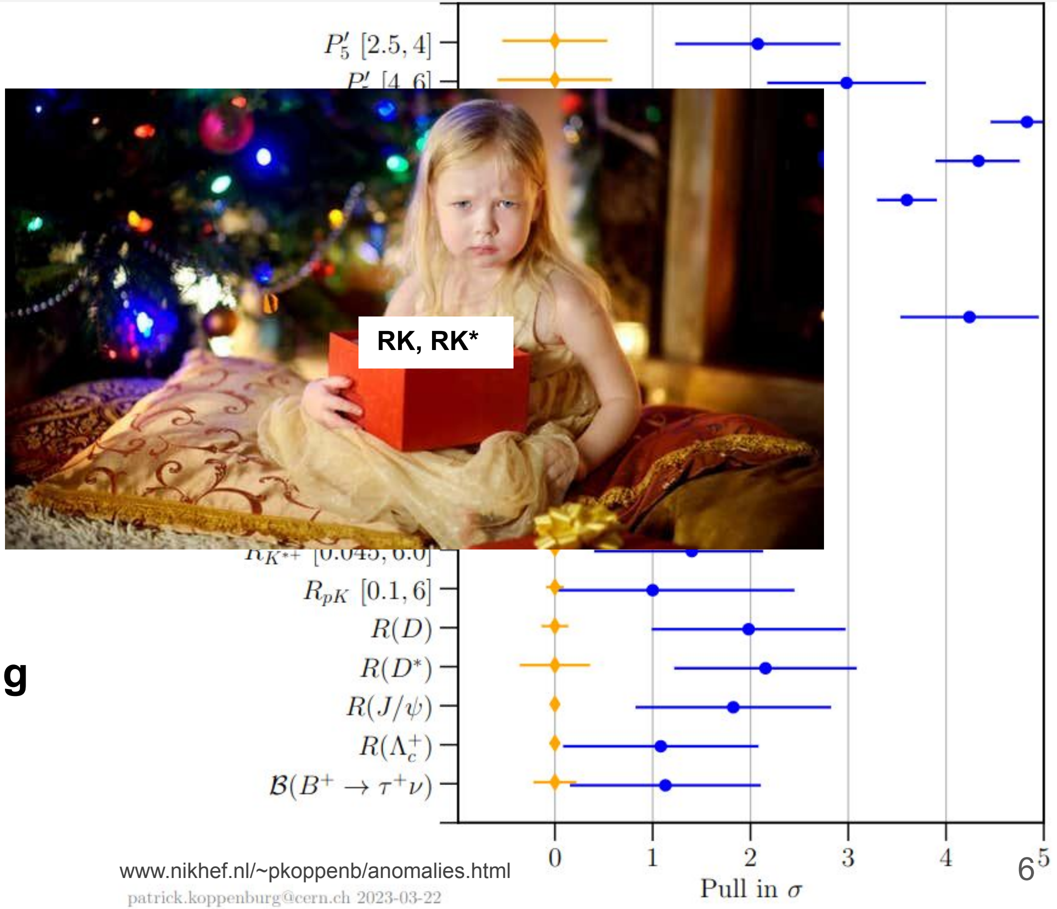


www.nikhef.nl/~pkoppenb/anomalies.html

Current status of B-anomalies

Current status of phenomenologists

Theoretical framework:

$b \longrightarrow sll$ in the weak effective theory

At the scale m_b $$H_{eff} = H_{eff,sl} + H_{eff,had}$$

- $$H_{eff,sl} = \underbrace{-\frac{4G_F\alpha_{em}^2}{\sqrt{2}} V_{tb}V_{ts}^*}_{\mathcal{N}} \sum_{i=7,9,10,S,P} (C_i^l O_i^l + C_i'^l O_i'^l)$$ ⟵ $O_7^{(')} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$, $O_9^{(')} = (\bar{s}\gamma_\mu P_{R(L)}b)(\bar{l}\gamma^\mu l)$, $O_{10}^{(')} = (\bar{s}\gamma_\mu P_{R(L)}b)(\bar{l}\gamma^\mu\gamma_5 l)$

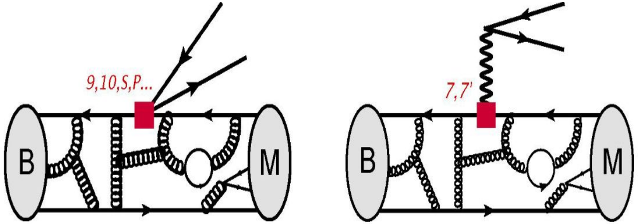
- $$H_{eff,had} = -\mathcal{N}\frac{1}{\alpha_{em}^2}\left(C_8O_8 + C_8' + O_8' + \sum_{i=1,\ldots,6} C_iO_i\right) + \text{h.c}$$ ⟵ $O_1 = (\bar{s}\gamma_\mu P_L T^a c)(\bar{c}\gamma^\mu P_L T^a b)$ ...

Amplitude of B → K$^{(*)}$ll decays

$$\mathcal{A}(B \to K^{(*)} l^+ l^-) = \mathcal{N}\left\{(C_9 L_V^\mu + C_{10} L_A^\mu)\mathcal{F}_\mu(q^2) - \frac{L_V^\mu}{q^2}\left[C_7 \mathcal{F}_\mu{}^T(q^2) + \mathcal{H}_\mu(q^2)\right]\right\}$$

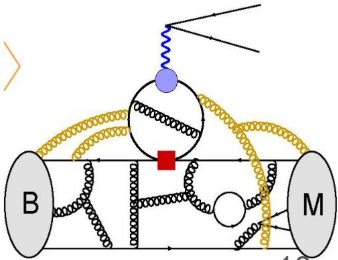
- **Local** $\mathcal{F}_\mu(q^2) = \langle \bar{K}^{(*)}(k) | O^{had}_{7,9,10} | \bar{B}(k+q) \rangle$

  Parametrized with local Form Factors



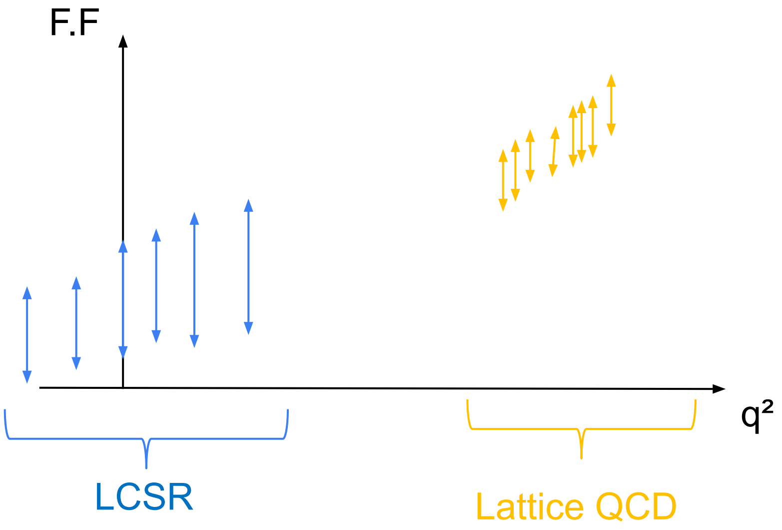
Diagrams by Javier Virto

- **Non-Local** $\mathcal{H}_\mu(q^2) = i \int d^4x e^{iq.x} \langle K^{(*)}(k) | T\{j_\mu^{em}(x), C_i O_i(0)\} | \bar{B}(k+q) \rangle$



Local Form Factors computation:

- At high-q^2 : computed on the lattice
- At low-q^2 : (mostly) Light-Cone Sum Rule (LCSR)



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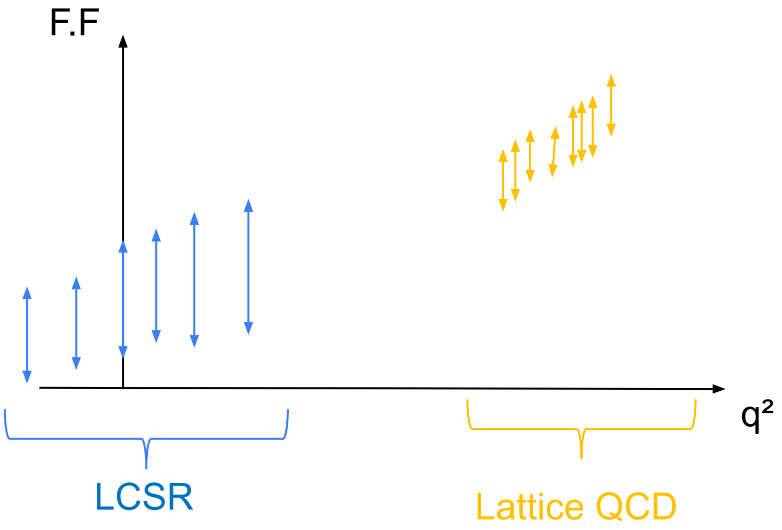
Challenging systematic uncertainties



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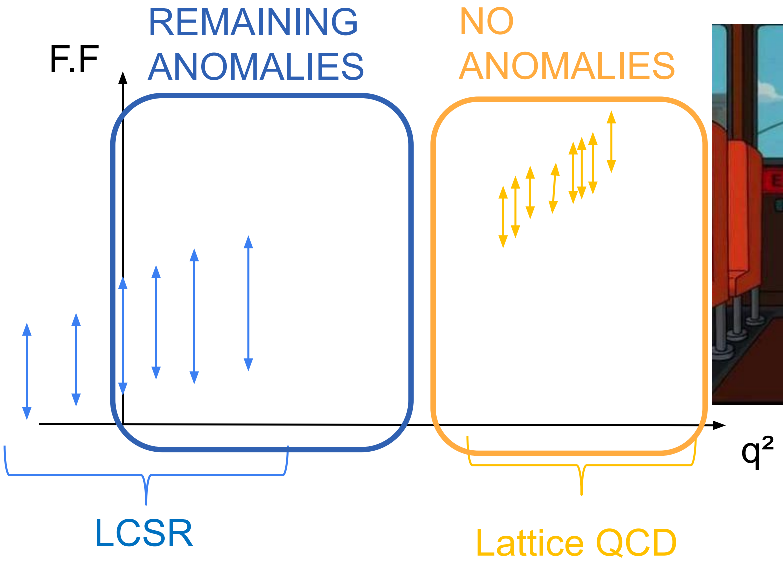
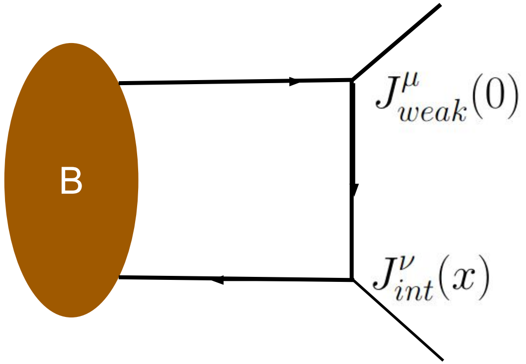


Procedure for Light-Cone Sum Rules

$$\Pi^{\mu\nu}(q,k) = i \int d^4x e^{ik.x} \langle 0 | T J^{\nu}_{int}(x) J^{\mu}_{weak}(0) | \bar{B}(q+k) \rangle$$

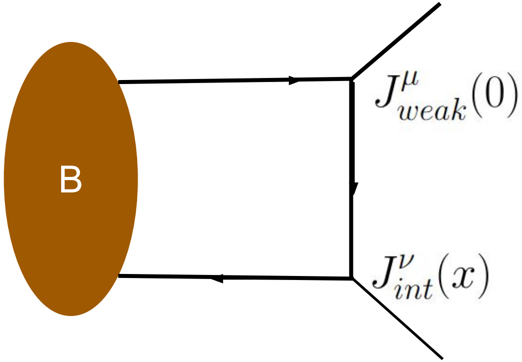
B to vacuum correlation function



Express it in function of the form factors

Compute it perturbatively on the light-cone : $x^2 \sim 0$ (expansion in growing twists)

Procedure for Light-Cone Sum Rules



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Match both expression

Procedure for Light-Cone Sum Rules

$$\Pi^{\mu\nu}(q,k) = i\int d^4x e^{ik.x} \langle 0| T J^{\nu}_{int}(x) J^{\mu}_{weak}(0) |\bar{B}(q+k)\rangle$$

Hadronic unitarity relation
+
Dispersion relation

HQET

α F.F

Density of continuum and excited states

$$\Pi^{\mu\nu}(q,k) = \frac{\langle O| J^{\nu}_{int} |M(k)\rangle \langle M(k)| J^{\mu}_{weak} |\bar{B}(q+k)\rangle}{m_M^2 - k^2} + \frac{1}{2\pi}\int_{s_0^h}^{+\infty} ds \frac{\rho^{\mu\nu}(s)}{s-k^2}$$

$$\Pi^{\mu\nu} = \int d^4x \int \frac{d^4p'}{(2\pi)^4} e^{i(k-p').x} \left[\Gamma_2^{\nu} \frac{p'+m_1}{m_1^2 - p'^2} \Gamma_1^{\mu}\right]_{\alpha\beta} \langle 0| \bar{q_2}^{\alpha}(x) h_v^{\beta}(0) |\bar{B(v)}\rangle + \dots$$

$x^2 \ll 1/\Lambda^2_{QCD}$ Light-Cone OPE

In growing twist (dimension – spin)

Non perturbative input : B-meson LC
s

What we want **What is this?** **What we have**

$$K^{(F)} \frac{F(q^2)}{m_M^2 - k^2} + \frac{1}{2\pi}\int_{s_0^h}^{+\infty} ds \frac{\rho(s)}{s-k^2} = f_B m_B \int_0^{+\infty} ds \sum_{n=1}^{+\infty} \frac{I_n(s)}{(s-k^2)^n}$$

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$$\Pi^{\mu\nu}(q,k) = i\int d^4x e^{ik.x} \langle 0| T J^{\nu}_{int}(x) J^{\mu}_{weak}(0) |\bar{B}(q+k)\rangle$$

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$$\Pi^{\mu\nu}(q,k) = \frac{\langle O| J^{\nu}_{int} |M(k)\rangle \langle M(k)| J^{\mu}_{weak} |\bar{B}(q+ \ldots}{m_M^2 - k^2} \ldots \frac{1}{\ldots}\int_{s_0^h}^{+\infty} ds \frac{\rho^{\mu\nu}(s)}{s-k^2}$$

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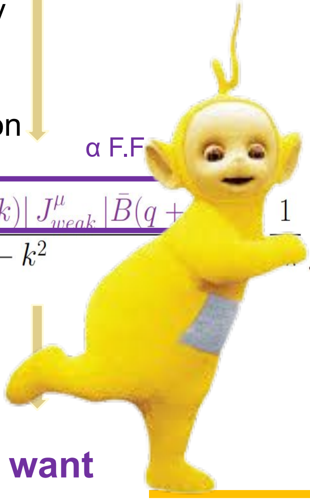

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Estimating the density

At leading twist:

$$K^{(F)}\frac{F(q^2)}{m_M^2-k^2}+\frac{1}{2\pi}\int_{s_0^h}^{+\infty}ds\frac{\rho(s)}{s-k^2}=f_Bm_B\int_0^{+\infty}ds\frac{I_1(s)}{(s-k^2)}$$

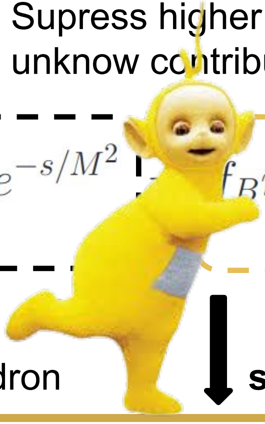
Borel transform

M^2 : Borel parameter

$$F(M^2)\equiv\mathcal{B}_{M^2}F(k^2)=\lim_{-k^2,n\to\infty \text{ and } \frac{-k^2}{n}=M^2}\frac{(-k^2)^{n+1}}{n!}\left(\frac{d}{dk^2}\right)^nF(k^2)$$

Supress higher states of unknow contribution

$$K^{(F)}F(q^2)e^{-m^2/M^2}+\frac{1}{2\pi}\int_{s_0^h}^{+\infty}ds\rho(s)e^{-s/M^2}=f_Bm_B\int_0^{+\infty}dsI_1(s)e^{-s/M^2}$$



Semi-Global Quark Hadron

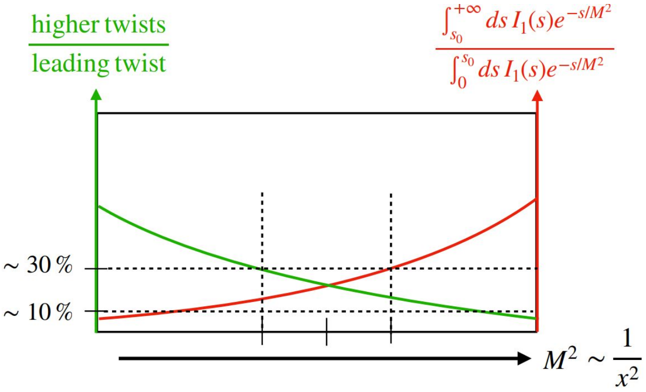
s0 : duality threshold

$$\frac{1}{2\pi}\int_{s_0^h}^{+\infty}ds\rho(s)e^{-s/M^2}\approx f_Bm_B\int_{s_0}^{+\infty}dsI_1(s)e^{-s/M^2}$$

Setting the parameters

$$F(q^2) = \frac{f_B m_B}{K^{(F)}} \int_0^{s_0} ds I_1(s) e^{-(s - m^2)/M^2}$$

- Borel parameter M² : compromise between supression of higher twists, and continuum and excited states contribution



Range of the Borel parameter
E.g. for $B \to K$: $M^2 \in [0.5,1.5]\,\mathrm{GeV}^2$

- Duality threshold s0 : Independence of F(q²) w.r.t M² :

Daughter Sum Rule : $\frac{d}{dM^2} F(q^2) = 0$

Preliminary results:

s_0 from SVZ sum rules Khodjamirian-Mannel hep-ph/0308297 (arrow pointing to the Gubernari et al. 2018 column)

Form Factor $q^2 = 0$	Our Result	Gubernari et al. 2018	Other results
$f_+^{B\to\pi}$	0.249 ± 0.064 PRELIMINARY	0.21 ± 0.07	0.258 ± 0.031 [1] 0.25 ± 0.05 [2] 0.301 ± 0.023 [3] 0.280 ± 0.037 [4]
$f_T^{B\to\pi}$	0.259 ± 0.065 PRELIMINARY	0.19 ± 0.06	0.253 ± 0.028 [1] 0.21 ± 0.04 [2] 0.273 ± 0.021 [3] 0.26 ± 0.06 [4]
$f_+^{B\to K}$	0.376 ± 0.068 PRELIMINARY	0.27 ± 0.08	0.331 ± 0.041 [1] 0.31 ± 0.04 [2] 0.395 ± 0.033 [3] 0.364 ± 0.05 [4]
$f_T^{B\to K}$	0.367 ± 0.053 PRELIMINARY	0.25 ± 0.07	0.358 ± 0.037 [1] 0.27 ± 0.04 [2] 0.381 ± 0.027 [3] 0.363 ± 0.08 [4]

- Results in agreement with previous calculations

[1] Ball and Zwicky 2005, light meson DA's

[2] Khodjamirian, Mannel, Offen 2007, B meson DA's

[3] Khodjamirian, Rusov, LCSR + CKM

[4] Lu, Shen, Wang, Wei, LCSR + QCD SR up to twist 6

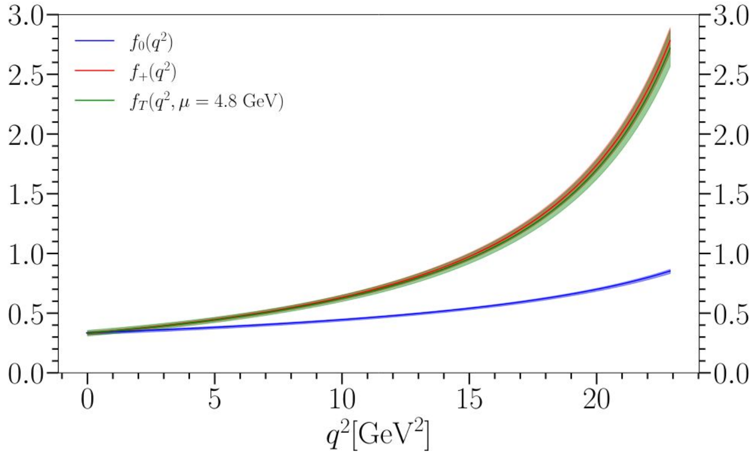
After working on LCSR for a few weeks

After working on LCSR for a few months

Local Form Factors computation

- At high-q^2 : computed on the lattice
- At low-q^2 : (mostly) Light-Cone Sum Rule (LCSR)

HPQCD (Lattice QCD)



LCSR soon obsolete ?

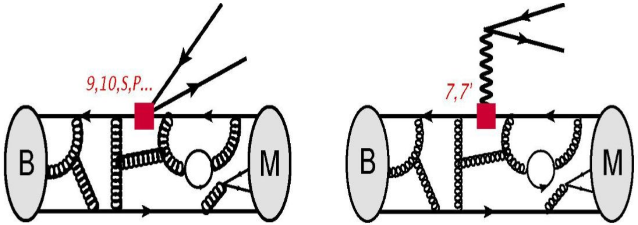
Amplitude of B → K(*)ll decays

$$\mathcal{A}(B \to K^{(*)} l^+ l^-) = \mathcal{N}\left\{ (C_9 L_V^\mu + C_{10} L_A^\mu)\mathcal{F}_\mu(q^2) - \frac{L_V^\mu}{q^2}\left[C_7 \mathcal{F}_\mu{}^T(q^2) + \mathcal{H}_\mu(q^2) \right] \right\}$$

- **Local**

$$\mathcal{F}_\mu(q^2) = \underbrace{\langle \bar{K}^{(*)}(k) | O_{7,9,10}^{had} | \bar{B}(k+q) \rangle}_{\text{Parametrized with local Form Factors}}$$

Parametrized with local Form Factors



Diagrams by Javier Virto

- **Non-Local**

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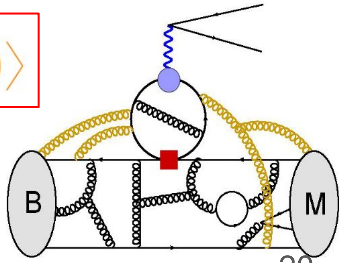
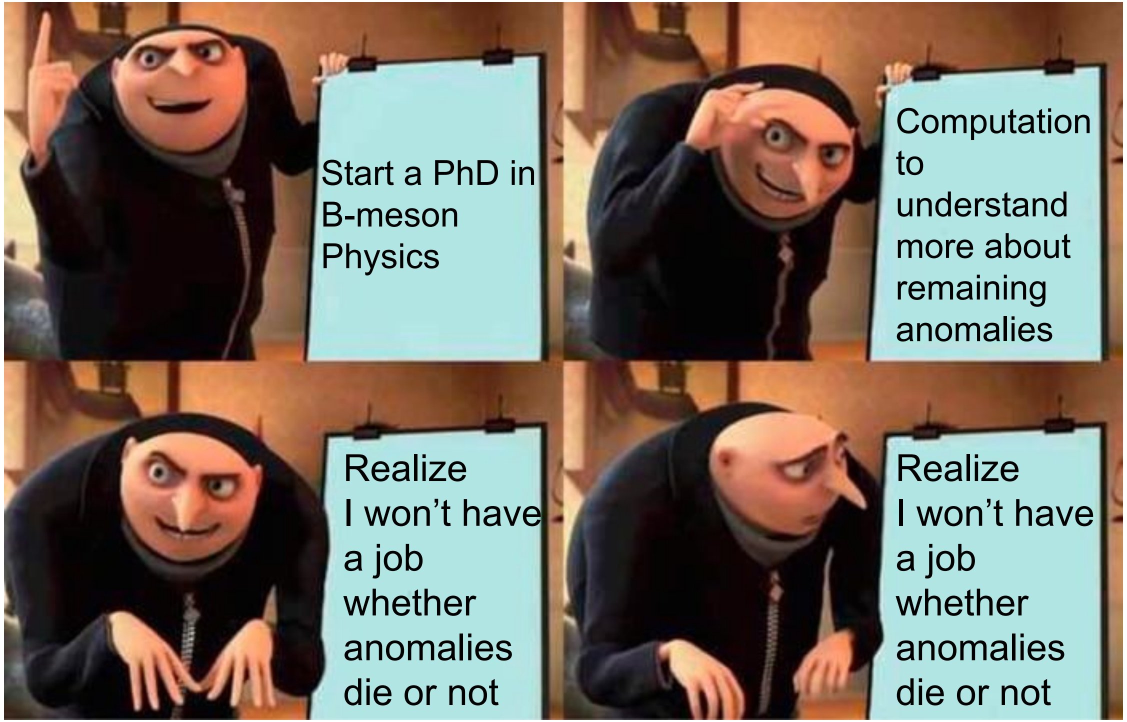
Only with LCSR



Conclusion


Start a PhD in B-meson Physics
Computation to understand more about remaining anomalies
Realize I won’t have a job whether anomalies die or not
Realize I won’t have a job whether anomalies die or not

THANK YOU FOR YOU ATTENTION !!!

Remember to go watch **Stitch, the live action** in 2024!

Backup

Procedure for Light-Cone Sum Rules :

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$x^2 \ll 1/\Lambda_{QCD}^2$ Light-Cone OPE

In growing twist (dimension – spin)

Non perturbative input : B-meson LC

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What we want **What is this?** **What we have**

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Supress higher states of unknow contribution

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Setting the parameters:

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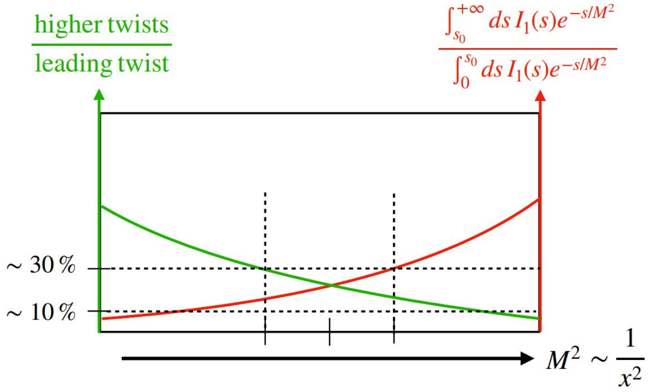
- Borel parameter M² : compromise between supression of higher twists, and continuum and excited states contribution



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- Duality threshold s0 : Independence of F(q²) w.r.t M² :

Daughter Sum Rule : $\frac{d}{dM^2} F(q^2) = 0$

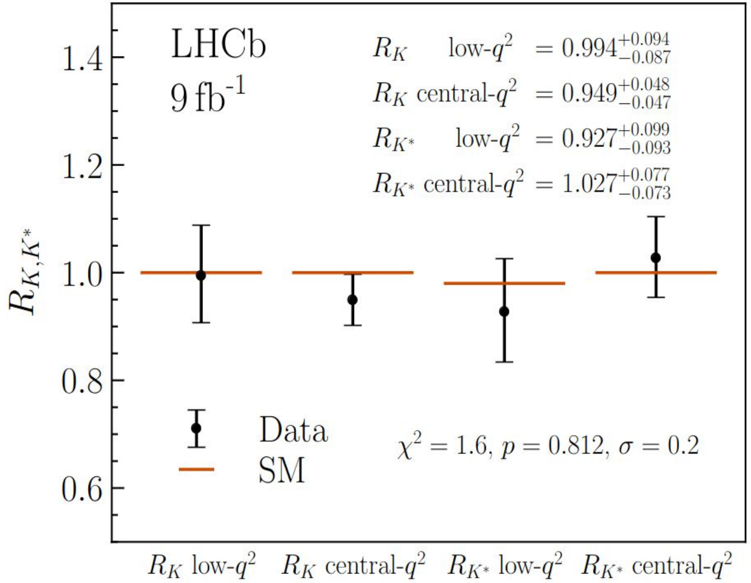
R-ratios

R-ratios :

- Mostly free of hadronic uncertainties
- Search for lepton flavor universality violation

Recent update of R_K and R_{K^*} by LHCb

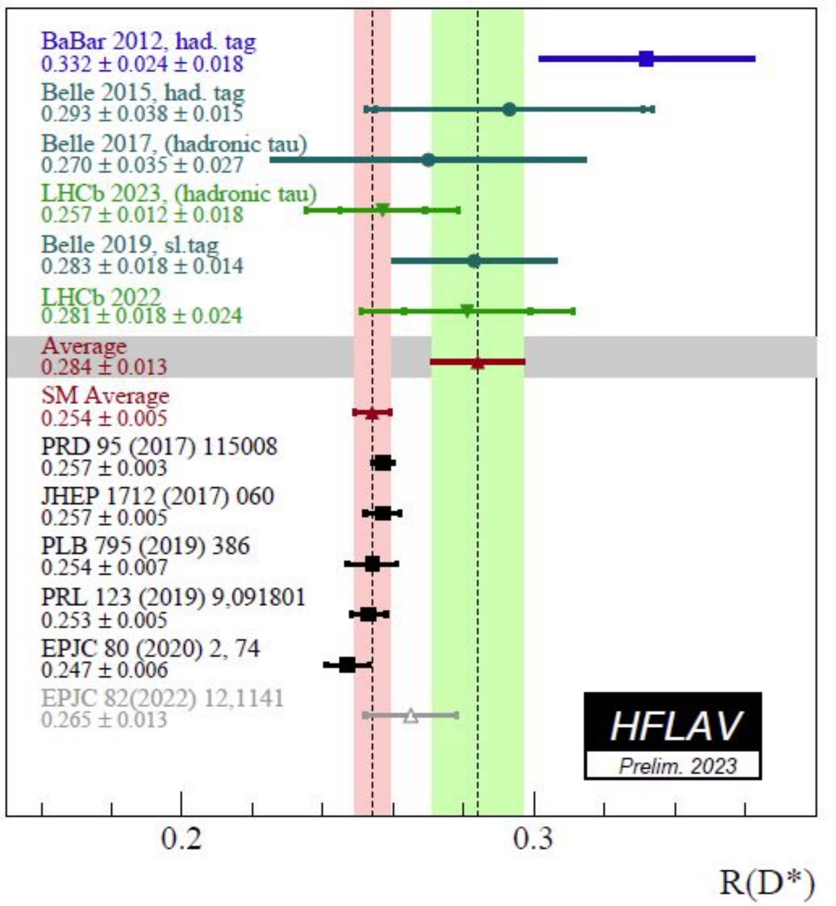
(2212.09152)



R-ratios

March 2023 LHCb (**including part of run 2**):

$R(D^*)=0.257\pm0.012\pm0.014\pm0.012$

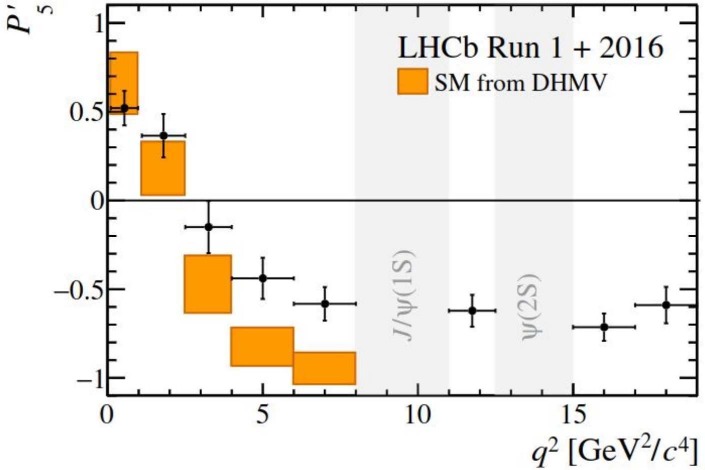


Angular observables : P’5

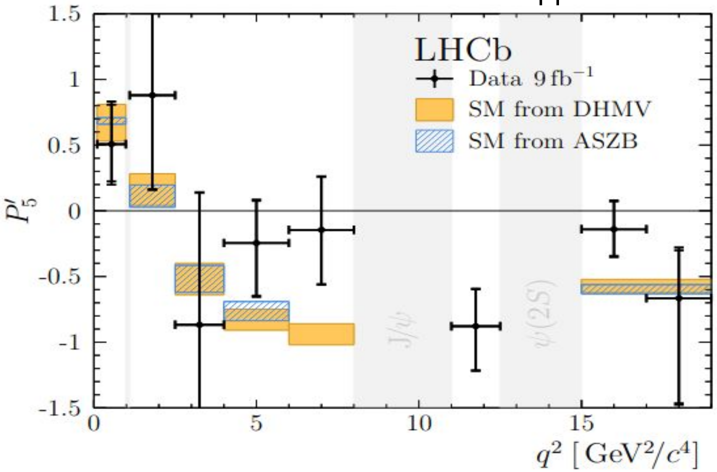
Appropriate ratios of angular coefficients

⇒ designed to cancel most of the dependence on the form factors

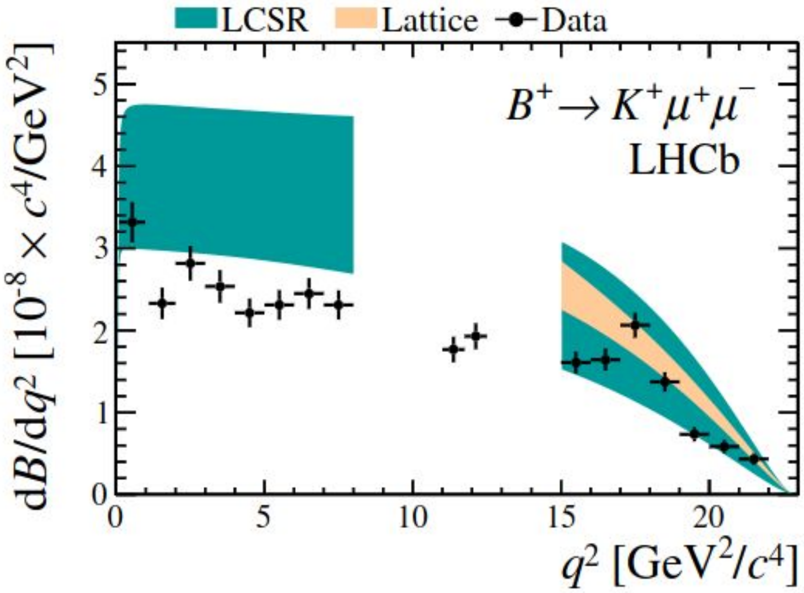
2003.04831v2 : $B^0 \to K^{*0}\mu\mu$

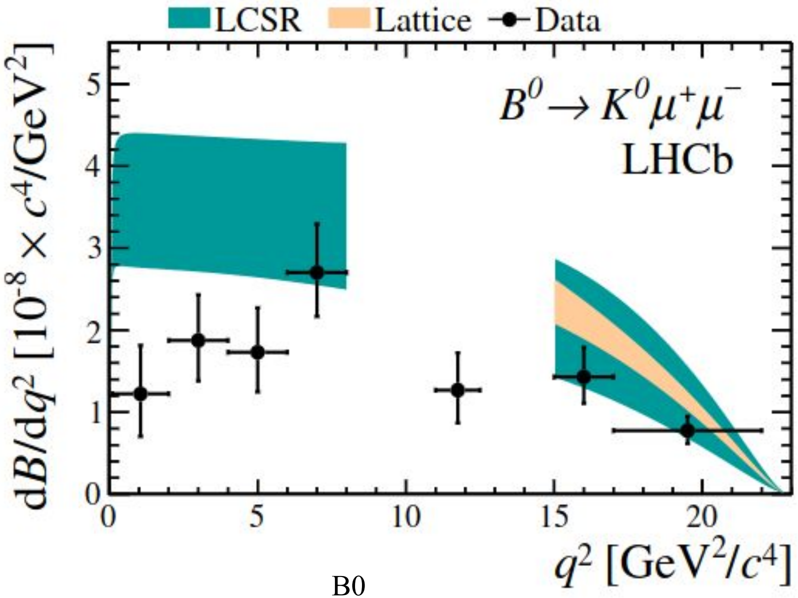


2012.13241v2 : $B^+ \to K^{*+}\mu\mu$



Branching fractions:



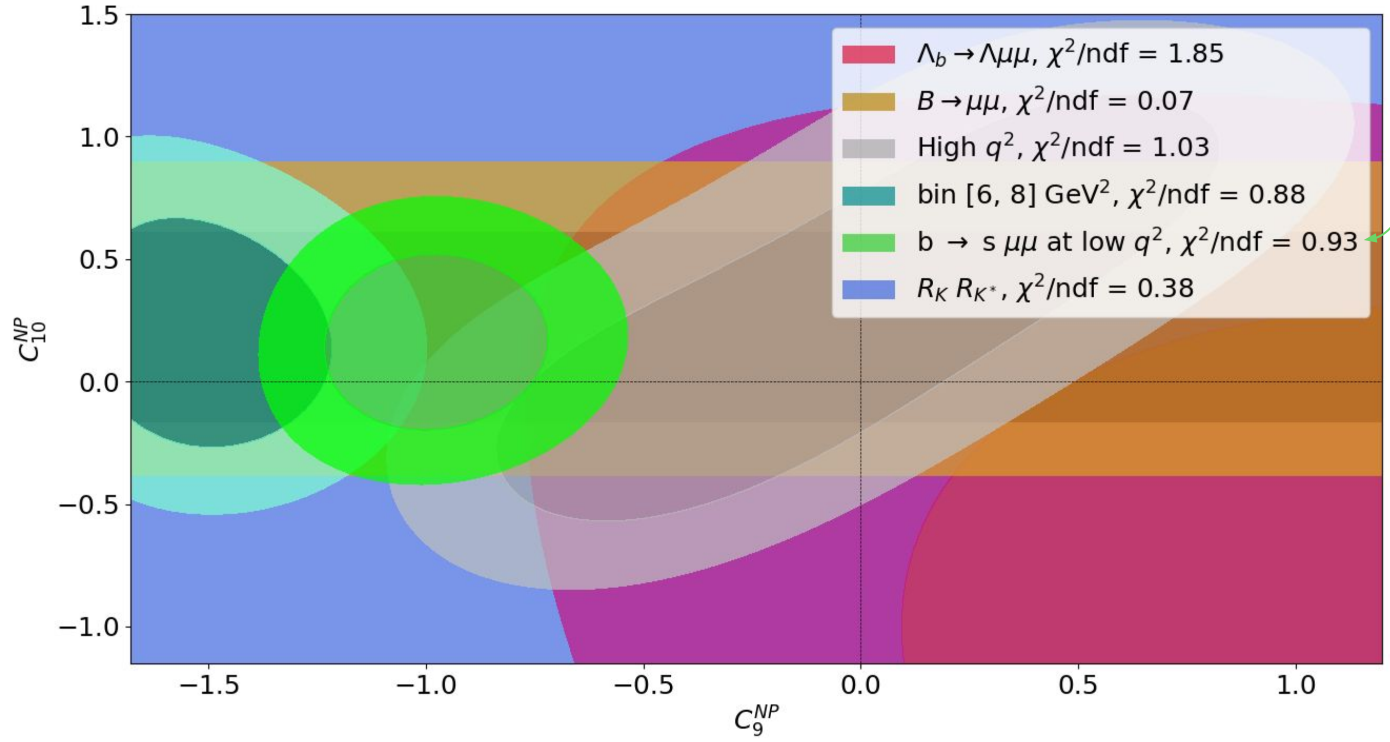


B0

LHCb : 1403.8044v3

C_9-C_{10} Global fit :

SuperIso



Angular and
Branching fractions

B□K μμ
B□K*μμ
B_s □ Φμμ