EFT interpretation of low-PT results

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for the ATLAS & CMS Collaborations

CKM 2021

11TH INTERNATIONAL WORKSHOP ON THE CKM UNITARITY TRIANGLE

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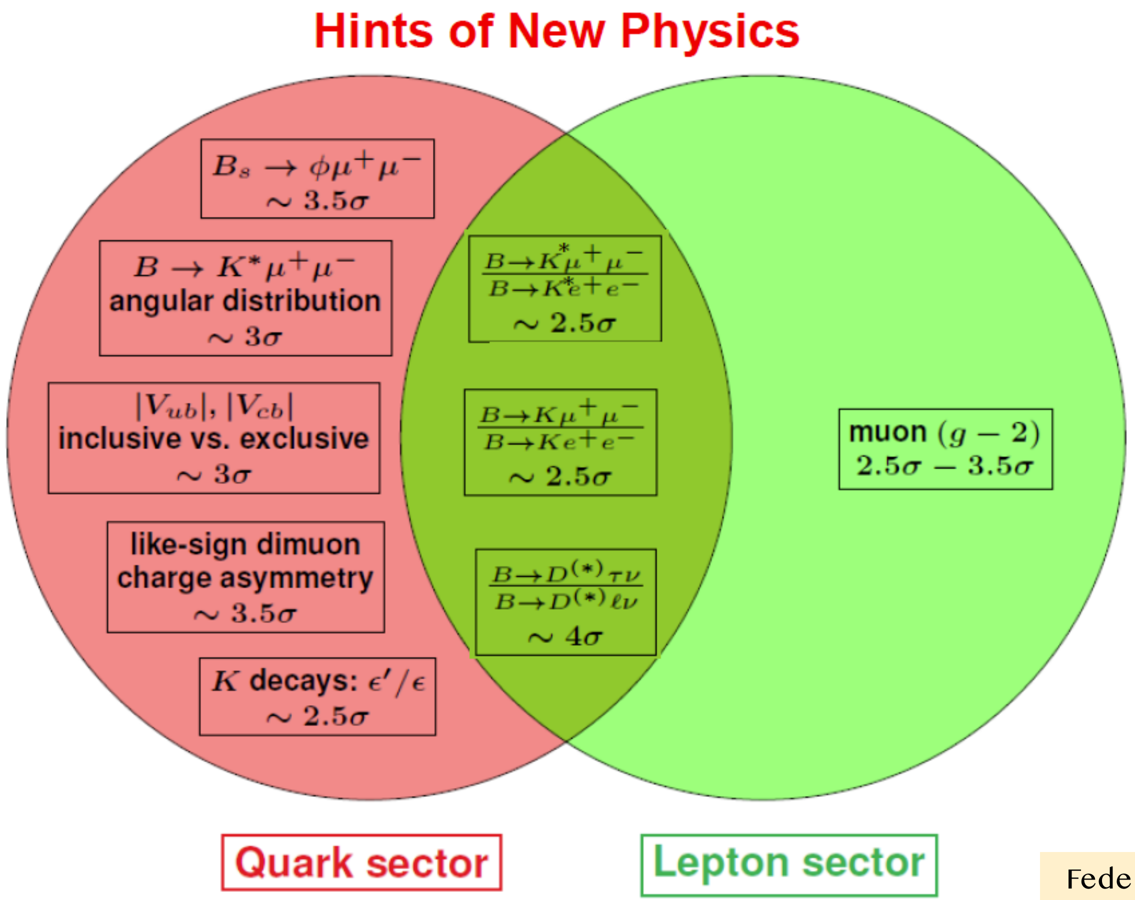
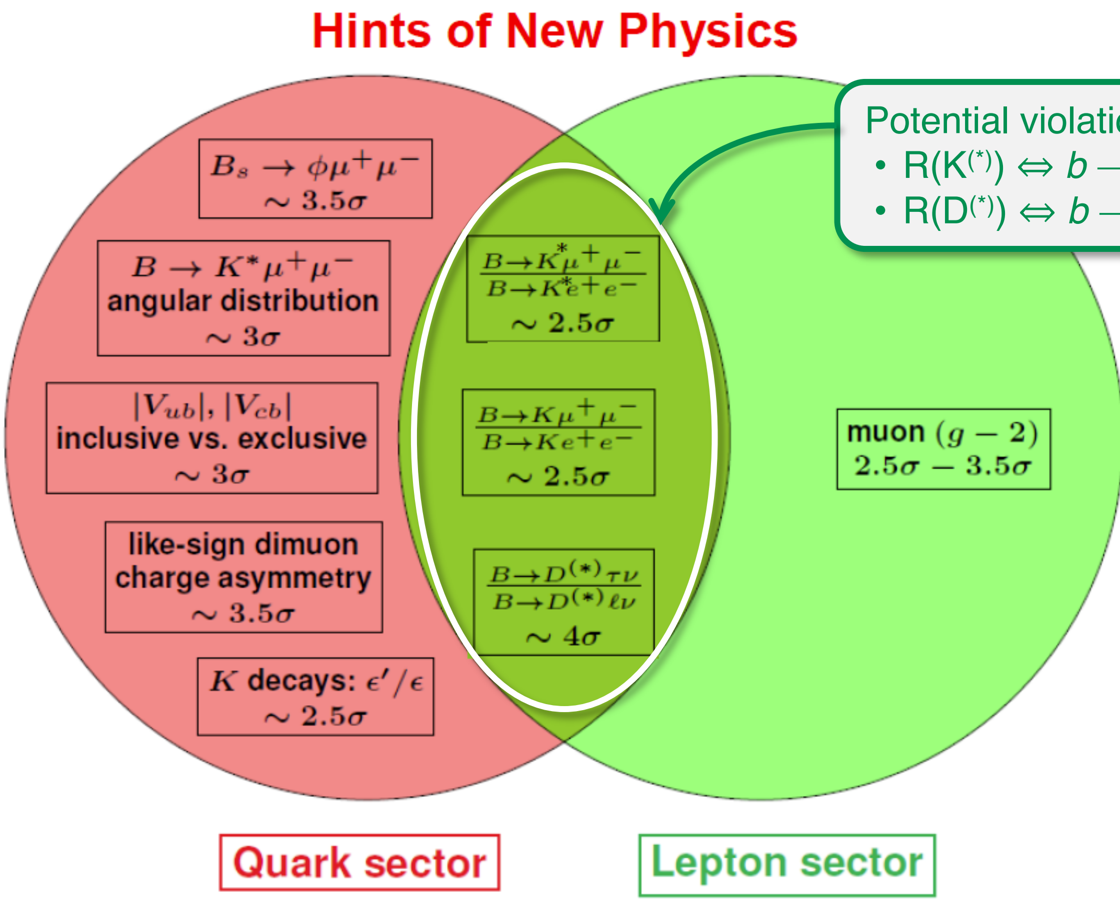
Flavour anomalies 2021



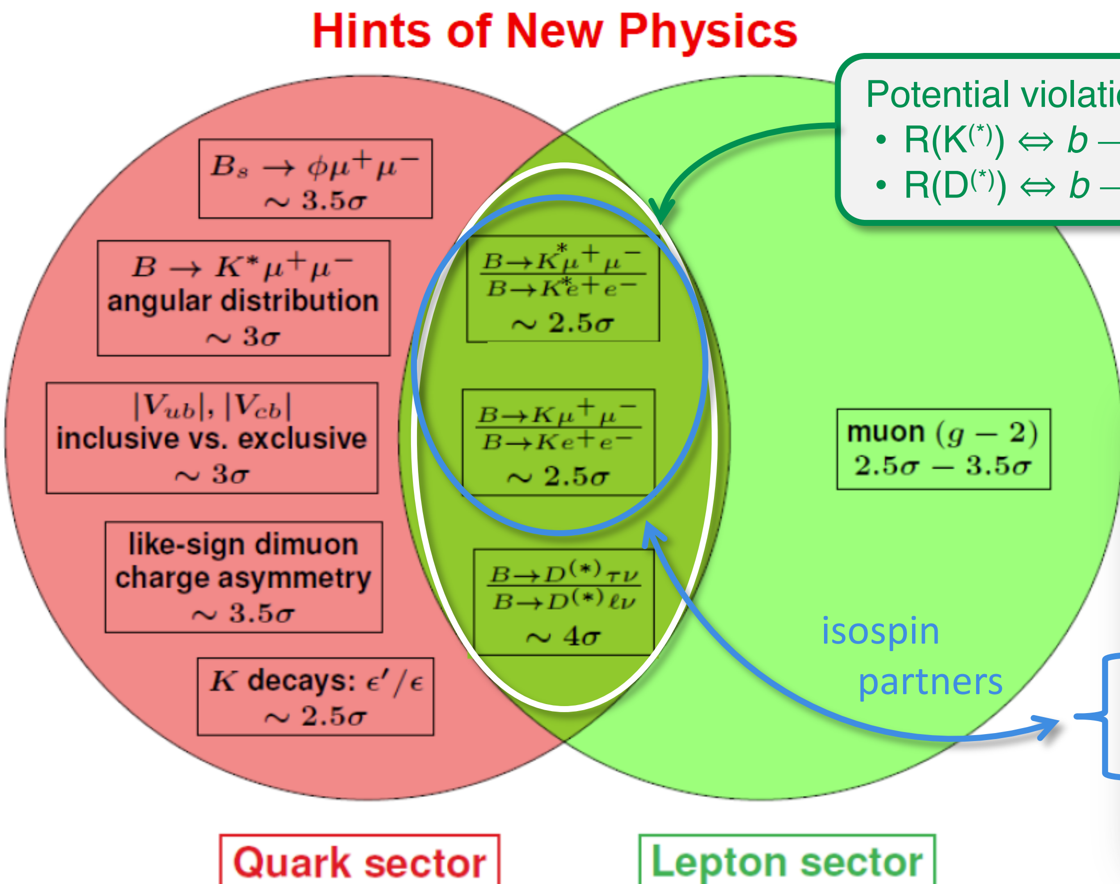
Federico Mescia, Red LHC 2021

Flavour anomalies 2021

Potential violation of lepton-flavour universality (LFUV)
- $R(K^{(*)}) \Leftrightarrow b \to s\ell^+\ell^-$ (neutral current): $\mu < e$
- $R(D^{(*)}) \Leftrightarrow b \to c\ell\nu$ (charged current): $\tau > e, \mu$



Flavour anomalies 2021



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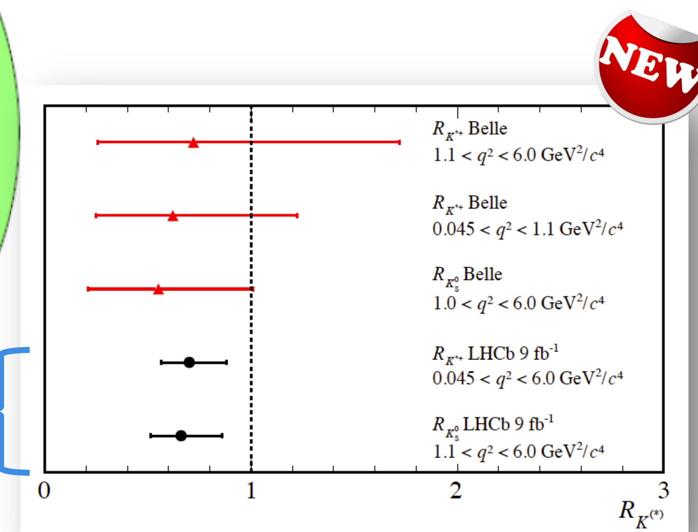
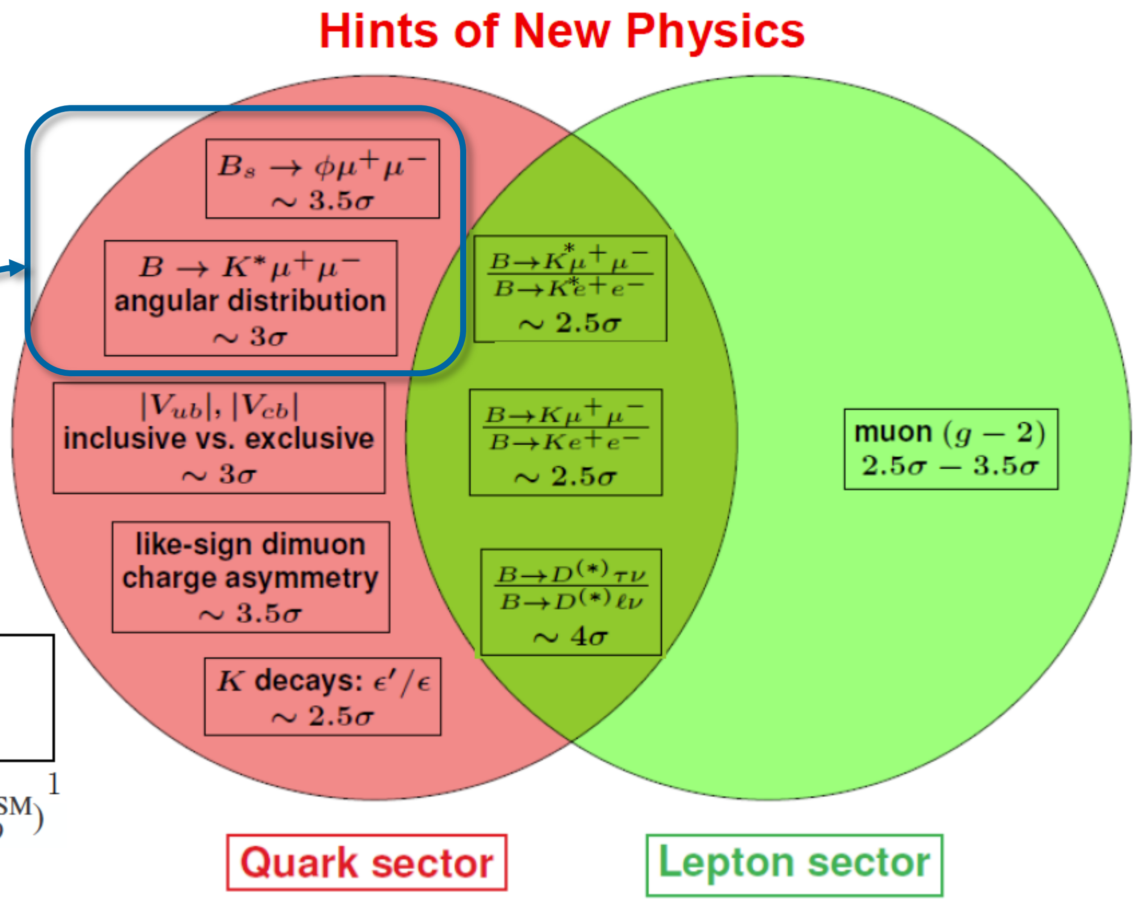


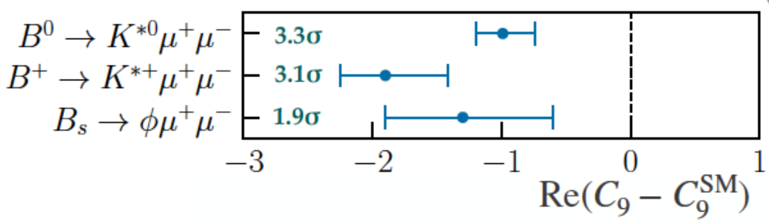
LHCb, arXiv:2110.09501 [hep-ex]

Flavour anomalies 2021



LHCb results

[M. Borsato, Flavour Anomaly w/s 2021]



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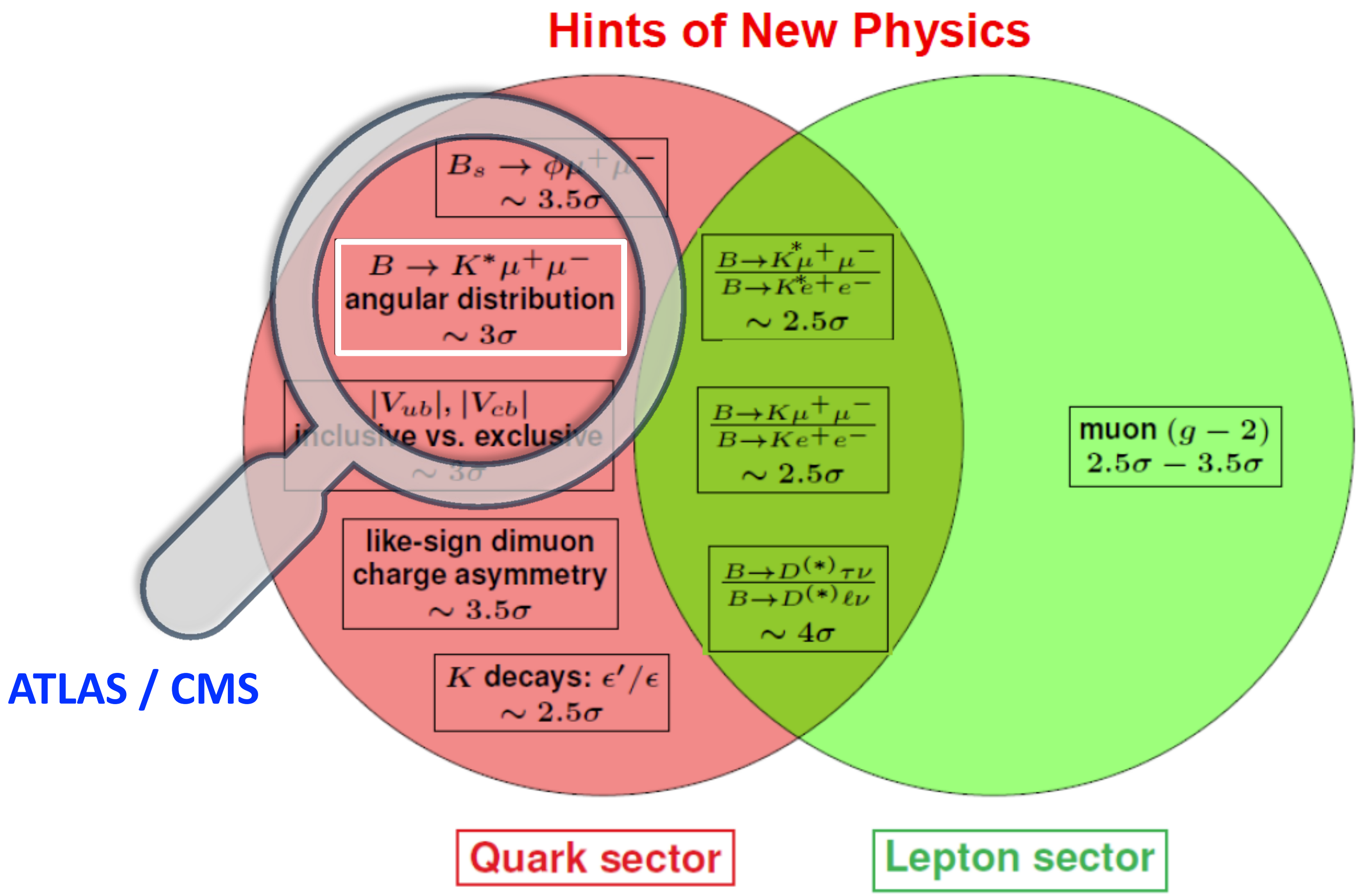
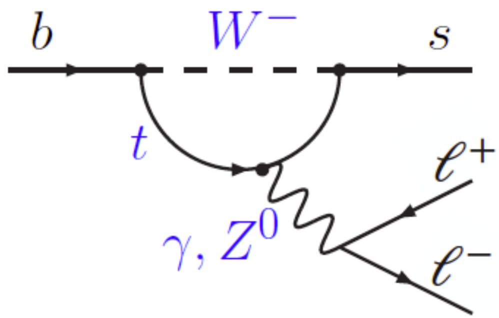


$b \to s\ell^+\ell^-$ transitions



- **Rare** (decay rate < 10^{-6})
  - flavour changing neutral currents forbidden at tree-level
  - proceed through **box** or **penguin** diagrams
  - small off-diagonal CKM elements
  - new physics could enter at the same order as SM
- **Experiment-friendly**
  - ~~neutrinos~~ ⇒ fully defined final state
  - several complementary channels
  - several complementary observables
- **Beautiful** (involves a *b* quark)
  - small long-distance contributions $(m_b \gg \Lambda_{QCD})$
  - can interpret with effective theory $(m_b \ll m_W)$

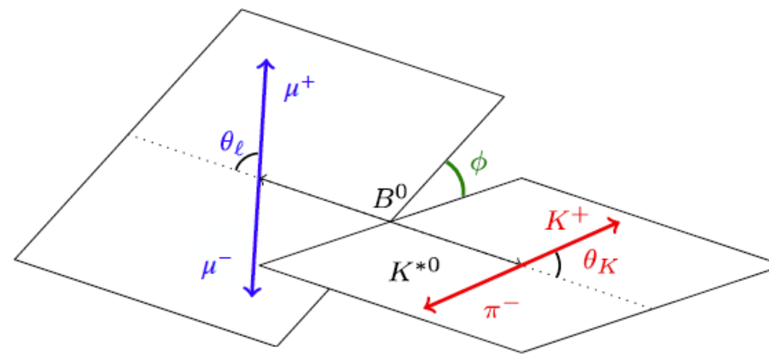
$B_s \to \ell^+\ell^-$, $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$,
$B_s \to \phi\ell^+\ell^-$, $\Lambda_b \to pK^-\ell^+\ell^-$, ...

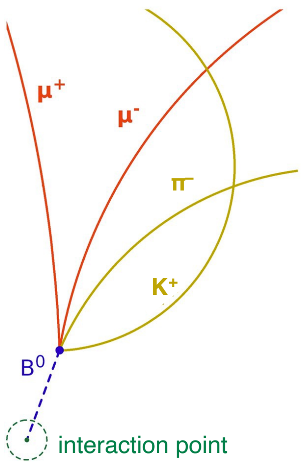
- branching ratios
- angular analyses
- symmetry tests (FB, LFU ratios, ...)

Angular analysis of $b \longrightarrow s\mu\mu$

- Angular distributions of the decay products in $B^0 \longrightarrow K^*\mu\mu \longrightarrow K^+\pi^-\mu\mu$ sensitive to new physics
- K^* is vector ⇒ 3 polarisation states
- $B \longrightarrow K^*\mu^+\mu^-$ 4-body decay described by 3 angles and q^2 $(\equiv m_{\mu\mu}{}^2)$

Fitting three angular distributions φ, θ_ℓ, θ_K
→ Wilson coefficients *(see EFT later)*





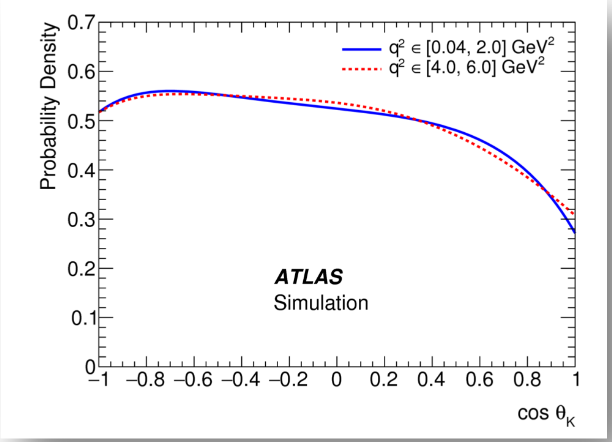
$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}F_L \sin^2\theta_K + F_L\cos^2\theta_K$$
$$+(\frac{1}{4}F_L \sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l + \frac{1}{2}P_1 F_L \sin^2\theta_K \sin^2\theta_l\cos 2\phi$$
$$+\sqrt{F_L F_L}\left(\frac{1}{2}P'_4 \sin 2\theta_K\sin 2\theta_l\cos\phi + P'_5 \sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{F_L F_L}\left(P'_6 \sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}P'_8 \sin 2\theta_K \sin 2\theta_l\sin\phi\right)$$
$$+2P_2F_L\sin^2\theta_K\cos\theta_l - P_3F_L\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

P_i **basis**: parameters optimised to reduce theoretical uncertainties
F_L: fraction of longitudinally polarised K^*

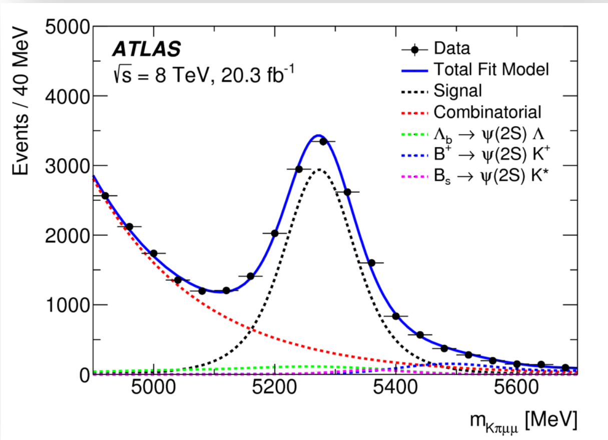
$B^0 \to K^*\mu\mu$ – calibration

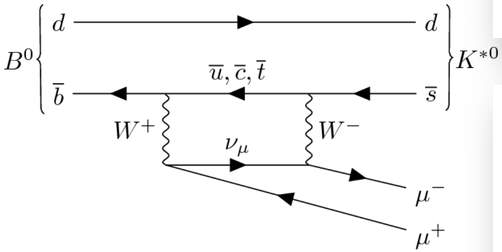
- Acceptance functions for the angular variables determined from MC simulation
- Signal mass resolution calibrated from $B \to K^*J/\psi$ and $K^*\psi(2S)$ "standard candle" samples
- Simultaneous fit to *B* candidate mass and angular distributions
  - background angular distributions described by polynomials
  - folding in angular variables permits fitting only a subset of coefficients

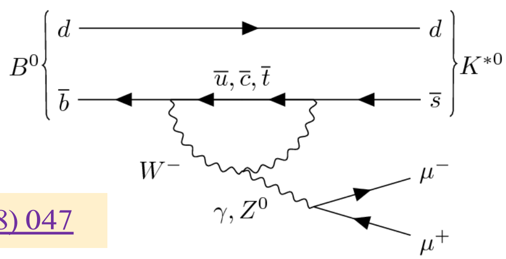
acceptance

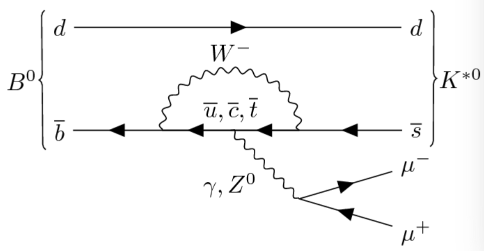


calibration





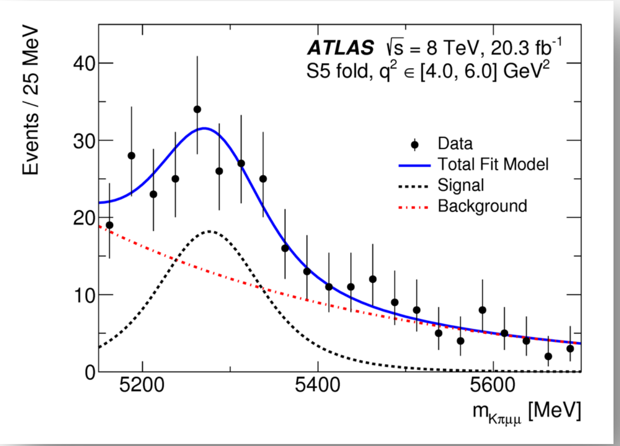


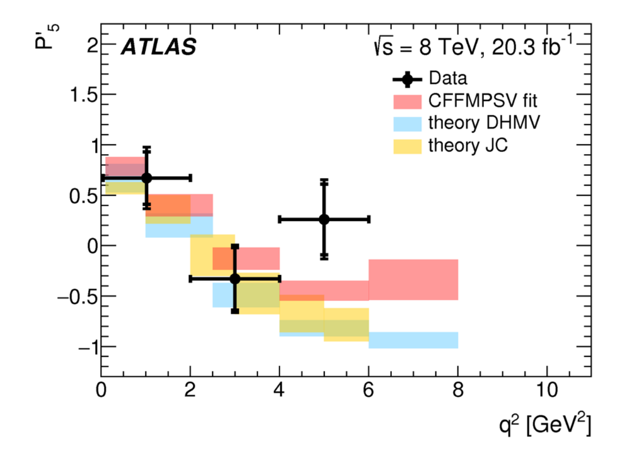


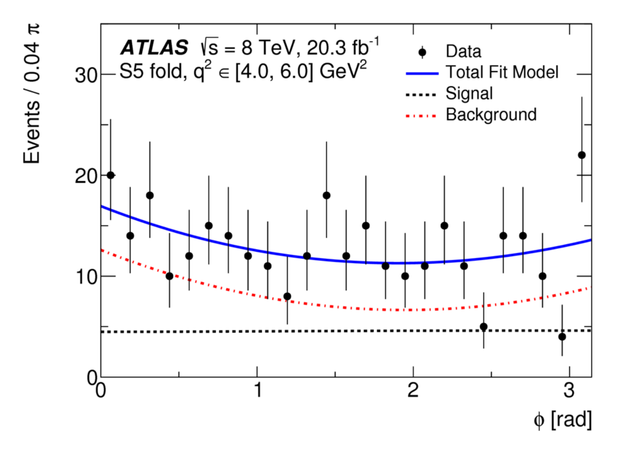
JHEP 10 (2018) 047

$B^0 \rightarrow K^*\mu\mu$ – ATLAS results

- Particular interest in P'_5, especially bin $q^2 \in [4, 6]$ GeV^2
  - LHCb observed a $>2\sigma$ deviation [PRL 125 (2020) 011802]
- Can see e.g. lack of expected $\cos\varphi$ modulation in signal fit: $P'_5 \approx 0$ in our fit for this bin
  - simultaneous fit to θ_K and θ_L as well
  - not significant difference from predictions







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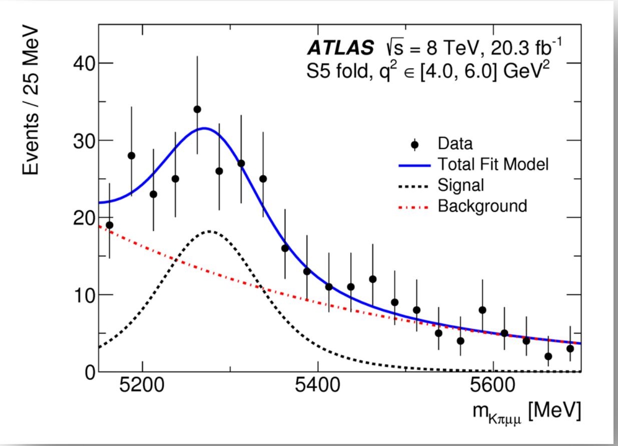
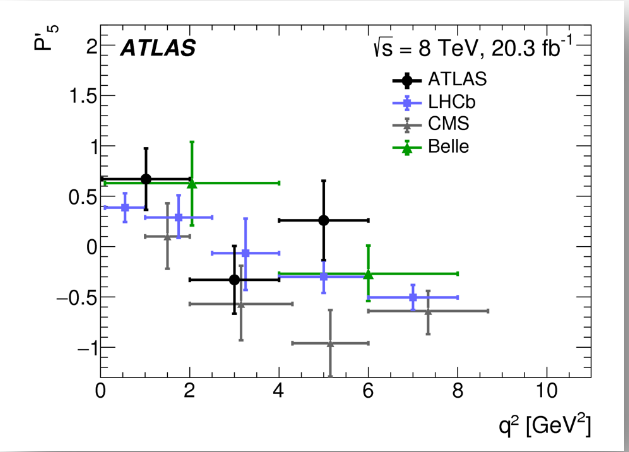
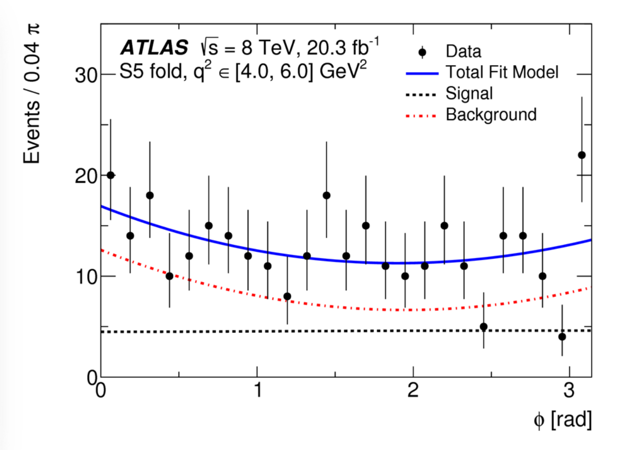
  - simultaneous fit to θ_K and θ_L as well
  - not significant difference from predictions
  - deviation in the same direction as other results
- Results for other coefficients: P_1, P'_4, P'_6, P'_8
- Compatible within 3σ with SM



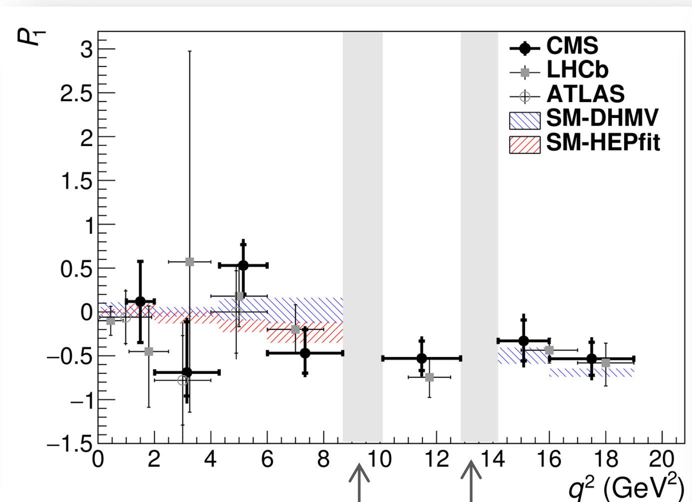


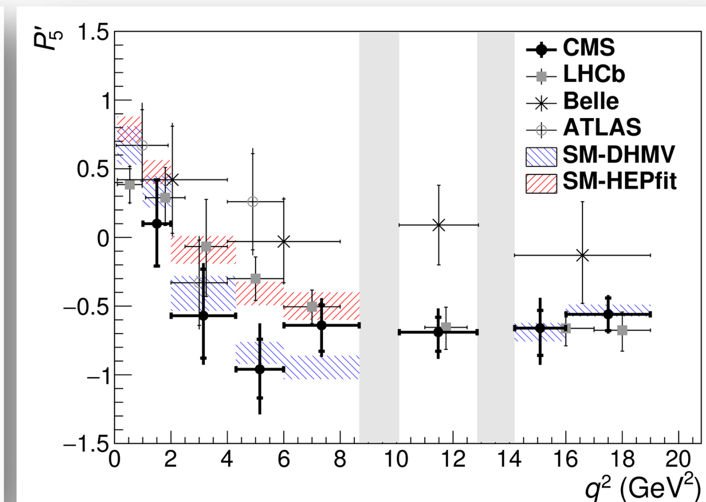


JHEP 10 (2018) 047

$B^0 \rightarrow K^*\mu\mu$ – CMS results and summary

- Similar analysis from CMS measures P_1 and P'_5
  - limited statistics ⇒ only few parameters extracted
- Measurements are in agreement with predictions based on the standard model





J/ψ ψ(2S)

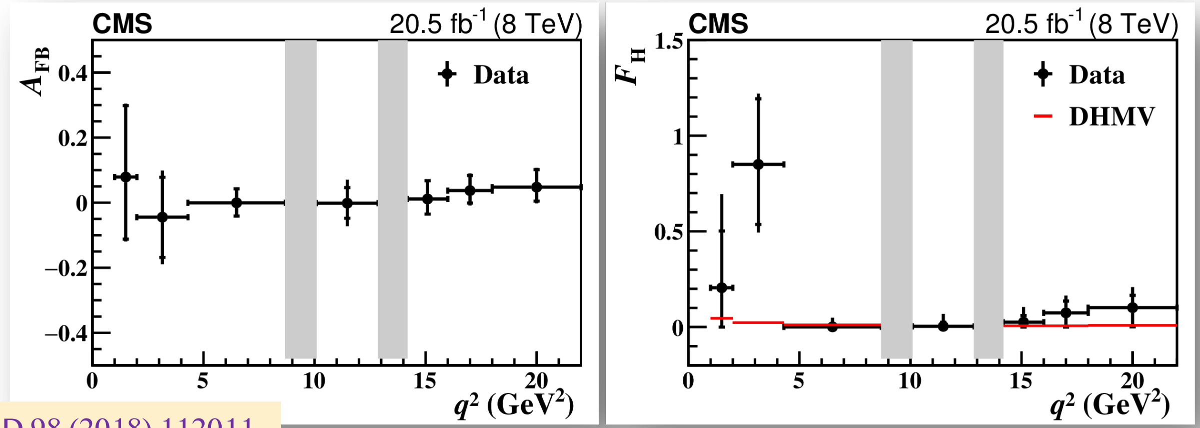
LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: JHEP 10 (2018) 047
SM-DHMV:
JHEP 06 (2016) 092
PLB 442 (1998) 381
SM-HEPfit:
PRD 61 (2000) 074024
PRD 62 (2000) 094023

Phys.Lett.B 781 (2018) 517

Other $B \to K\mu\mu$ analyses

- A_{FB}: muon forward-backward asymmetry
- F_H: contribution from pseudoscalar, scalar and tensor amplitudes to the decay width

$$B^+ \to K^+\mu^+\mu^-$$

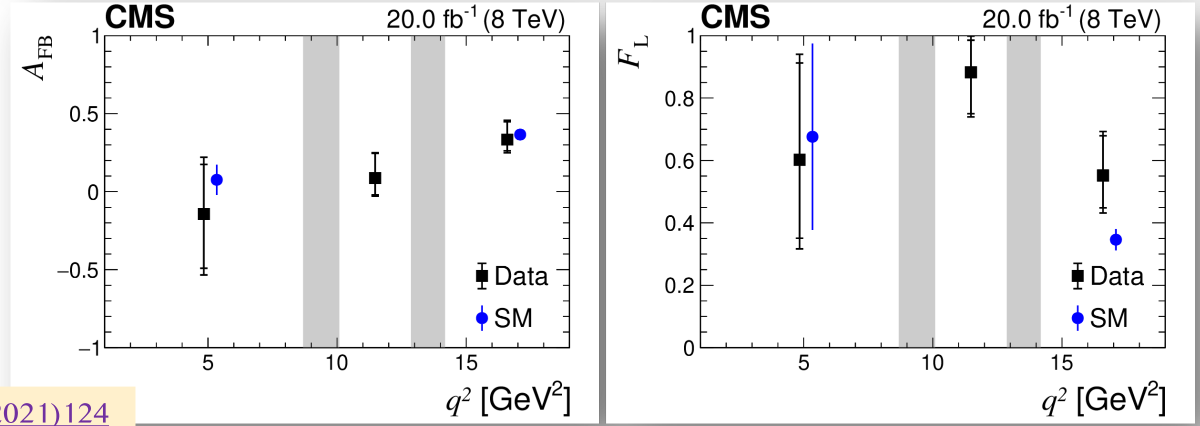


Phys Rev D 98 (2018) 112011

- F_L: K^{*+} longitudinal polarization fraction

$$B^+ \to K^*(892)\mu^+\mu^-$$

Results consistent with previous measurements, and compatible with SM predictions

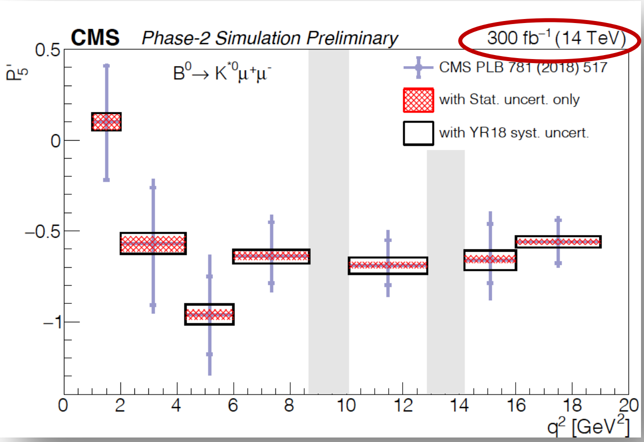


JHEP04(2021)124

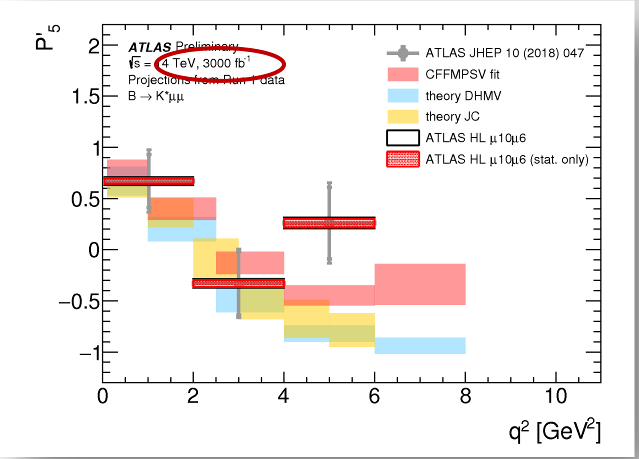
Future developments & prospects

- Lepton flavour universality variables require trigger on electrons and single muons
  → CMS *B-parking* [CMS-DP-2019/043]
  - dynamically adjust trigger p_T thresholds during fill to keep high rate despite falling luminosity within fill

- **HL-LHC**: Precision in measuring the P'_5 parameter is expected to improve by a factor of $O(10)$
  - depends on muon trigger options
  - precision improvement in other observables: F_L, $P_i^{(')}$
  - with 3000 fb^{-1}, finer binning in q^2 is possible



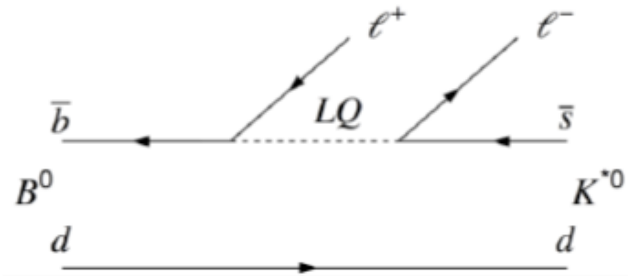
CMS-PAS-FTR-18-033

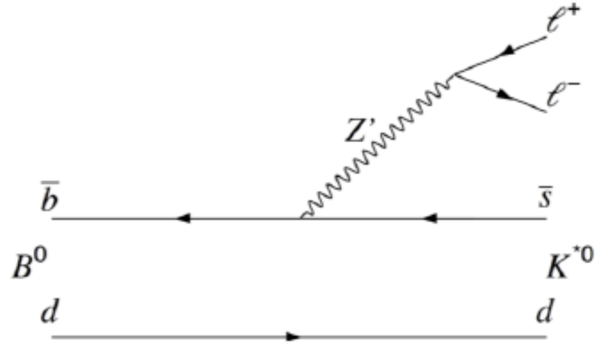


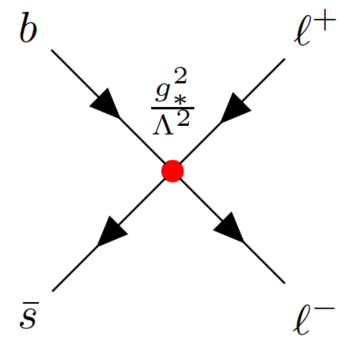
ATL-PHYS-PUB-2019-003

previously presented results obtained with **~20 fb^{-1} @ 8 TeV**

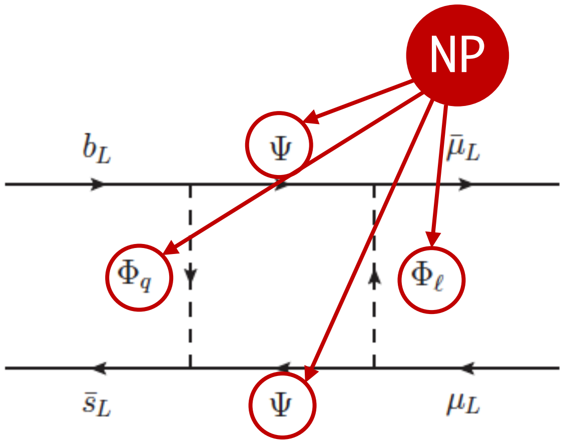
Deviation from SM ⇒ New Physics?



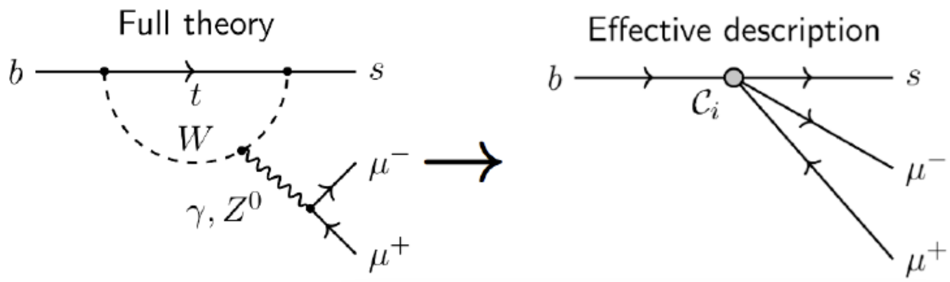




- High-p_T searches → heavy new particles at tree-level
  - respect full SM gauge symmetry
  - leptoquarks and heavy resonances *(W′, Z′)*
  - ☛ *previous talk by Gianantonio Pezzullo*
- Contact interactions → fit to data at scale g^2/Λ^2 ~ (30 GeV)$^{-2}$
  - ☛ *Tuesday talk by Yoav Afik*
- Focus on **low-p_T → NP in loop effects**
  - **EFT fit to $b \to s\ell\ell$ data**



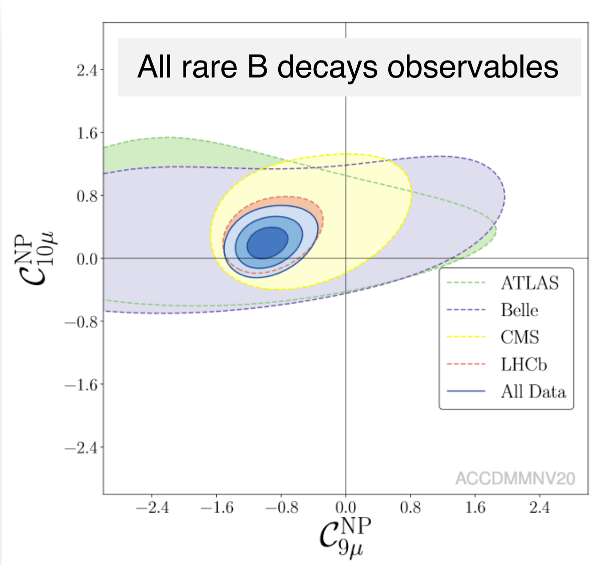
Effective field theory



- An EFT probes different couplings

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

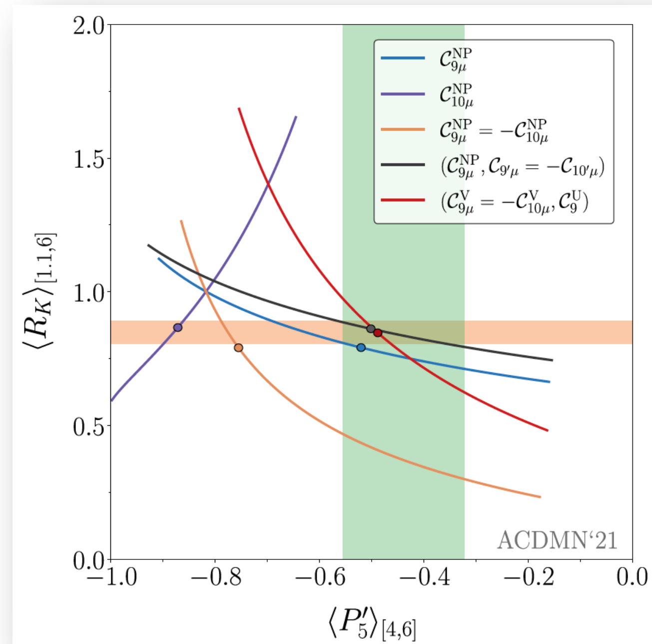
  - fermion operators O_i, Wilson coefficients C_i
- Important Wilson coefficients (for SM and NP)
  - $C_9{}^{\mu}$ – vector current, dominant contributions to angular observables, LFU observables
  - $C_{10}{}^{\mu}$ – axial current, dominant contributions to $B_s \to \mu\mu$, LFU observables
- **Global fits indicate consistent deviation: reduction of C_9 for muons**



Alguero et al, Eur.Phys.J.C 80, 511 (2020)

EFT fit to $b \to s\ell\ell$ data – R_K and P'_5

- R_K and P'_5 important in indicating favoured scenarios
- Most favoured 1D scenario ➜ vector coupling to μ encoded in $C_{9\mu}^{NP}$
  - preferred over SM with Pull$_{SM}$ 7σ fitting all $\boldsymbol{b \to s\mu\mu}$ observables
- $\boldsymbol{C_{9\mu}}^{V} = -\boldsymbol{C}_{10\mu}^{V}$, $\boldsymbol{C_9}^{U}$
  - $\boldsymbol{C_9}^{U}$ encodes the presence of a lepton-flavour *universal* NP component to $\boldsymbol{C_9}$, i.e., $b \to see$, $b \to s\mu\mu$ and $b \to s\tau\tau$
  - $b \to s\mu\mu$ LFUV NP contribution to $(\boldsymbol{C_9}, \boldsymbol{C_{10}})$
- $\boldsymbol{C_{9\mu}}^{NP}$, $\boldsymbol{C}_{9'\mu} = -\boldsymbol{C}_{10'\mu}$
  - pattern with right-handed couplings to muons
  - large negative NP contribution to $\boldsymbol{C_{9\mu}}$



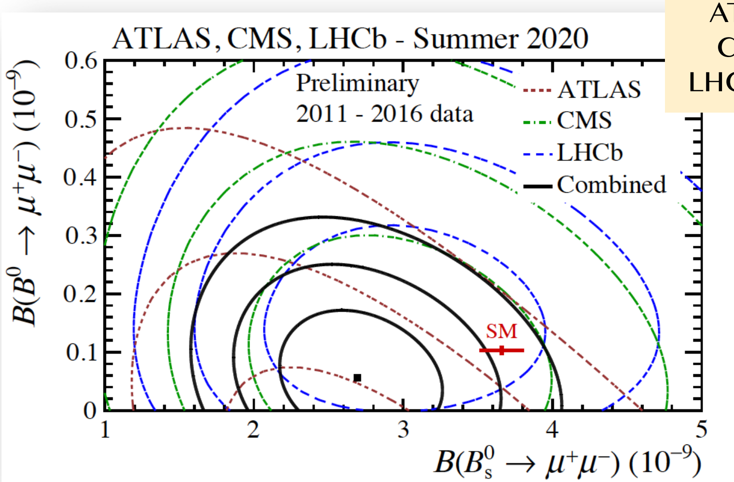
Alguero, Capdevila, Descotes-Genon, Matias, Novoa-Brunet, 2104.08921 [hep-ph]

More fits by other groups:

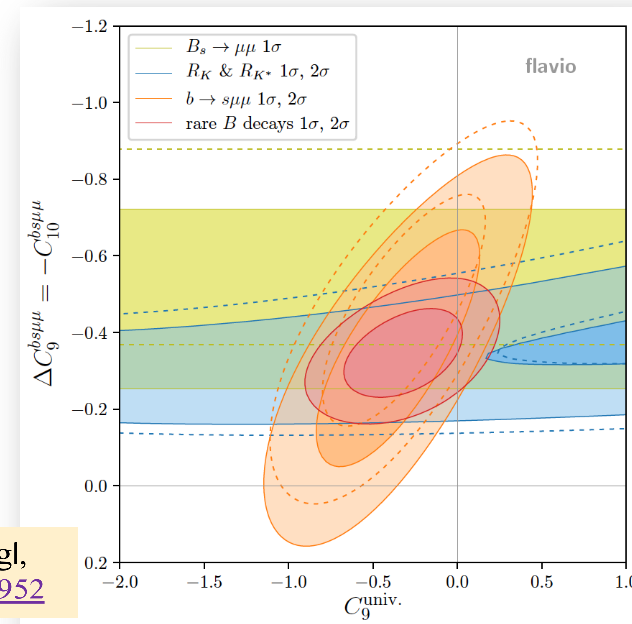
- Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli, PRD 103 (2021) 015030
- Hurth, Mahmoudi, Martínez-Santos, Neshatpour, arXiv:2104.10058
- Geng et al., PRD 104 (2021) 035029
- Alok et al., JHEP 06 (2019) 089
- Datta et al., PLB 797 (2019) 134858
- Kowalska et al., EPJC 79 (2019) 840
- D'Amico et al., JHEP 09 (2017) 010
- Hiller et al., PRD 96 (2017) 035003

EFT fit to $b \to s\ell\ell$ data – $B_{s,d} \to \mu^+\mu^-$

- Absolute branching ratio of the purely leptonic decay $B_s \to \mu\mu$ is considered as theoretically clean
- All measurements statistically limited
- $\mathrm{BR}(B_s \to \mu\mu)$ plays an important role in constraining the Wilson coefficient C_{10}
- If all rare B decays are considered, best fit of $(C_9^{\mathrm{U}}, C_{9\mu}^{\mathrm{V}}) \simeq (-0.32, -0.34)$ with a pull 5.4σ
- Overall, good agreement between fits of different groups despite different approaches ➜ robust $b \to s\ell\ell$ global analyses



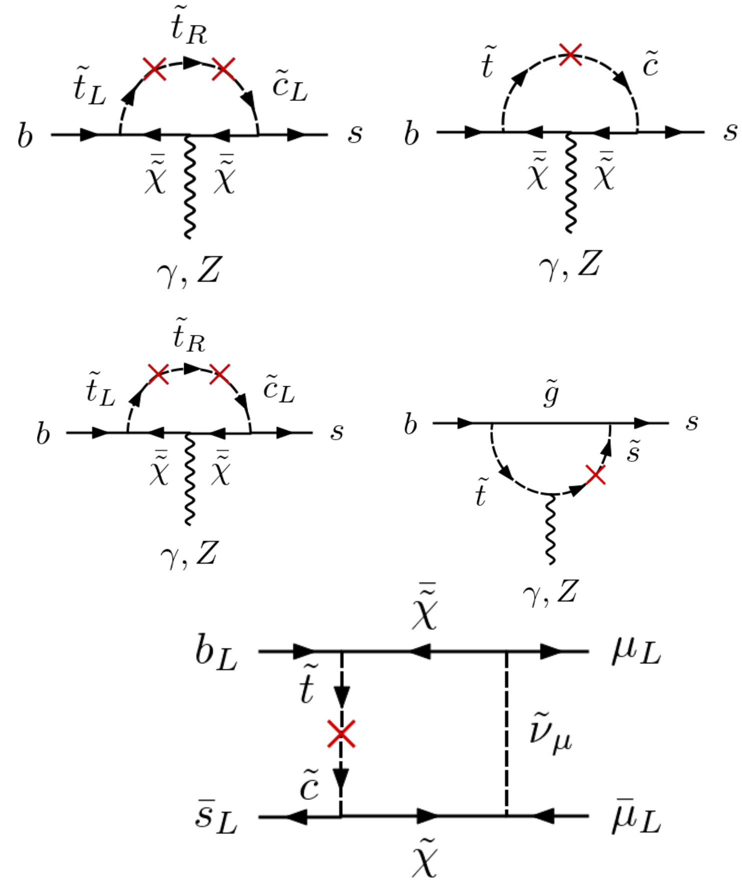
ATLAS, JHEP 04 (2019) 098
CMS, JHEP 04 (2020) 188
LHCb, PRL 118 (2017) 191801



Altmannshofer, Stangl, Eur.Phys.J.C 81 (2021) 952

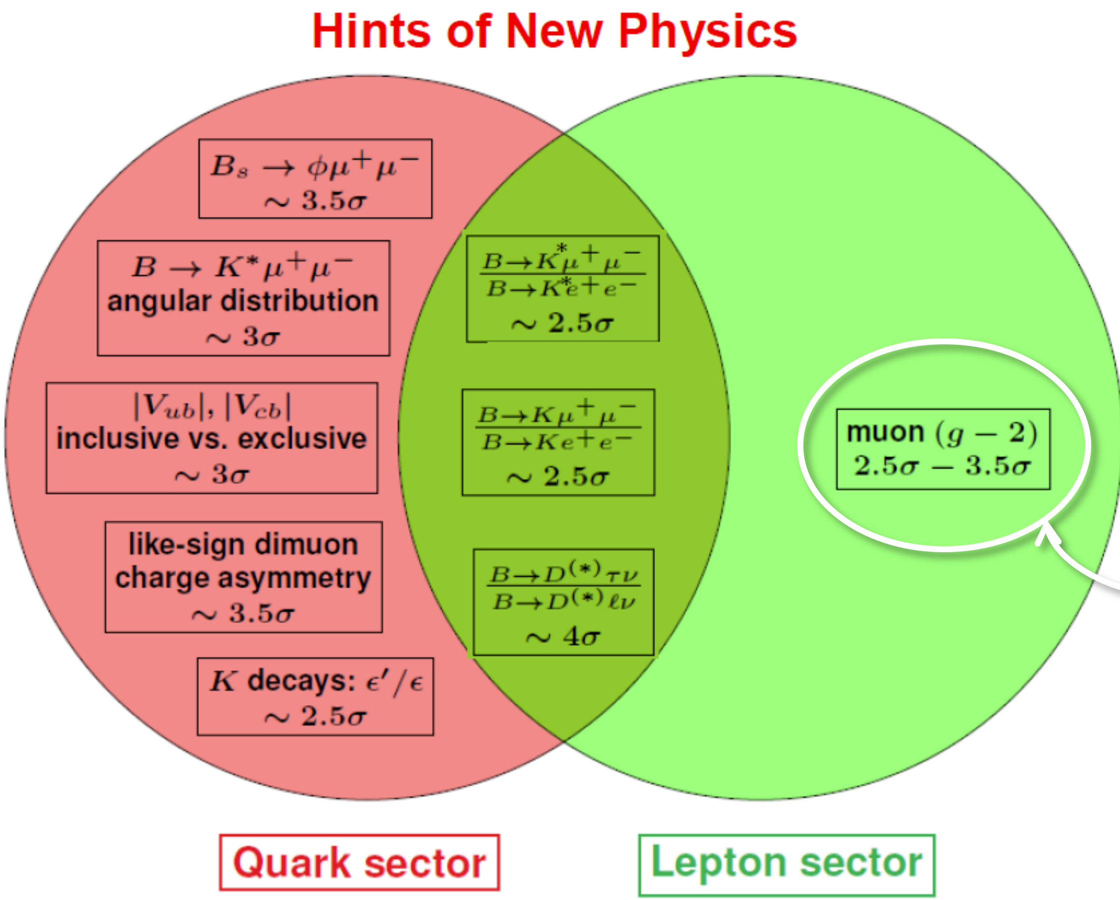
Loop-level solutions to *B*-anomalies

- Addition of **supersymmetric** fields brings new penguin and box diagrams in the $b \to s\ell\ell$ picture
  - mass insertion approximation may be required for consistency with B-anomalies
  - if $m(\Psi) < m(\Phi_{q,\ell})$, then Ψ can be a EW gaugino: chargino $\tilde{\chi}^{\pm}$, neutralino $\tilde{\chi}^{0}$
  - if Ψ is the lightest neutralino, $\tilde{\chi}_1^{0}$, then it can be can be a dark-matter candidate
  - Φ_ℓ can be the smuon, $\tilde{\mu}$ or the sneutrino, $\tilde{\nu}_\mu$
- Collider searches have set bounds in various of the involved sparticles
- Have these SUSY scenarios been ruled out by LHC?
- Can $(g-2)_\mu$ be accommodated, too?



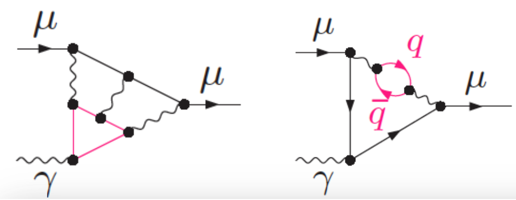
Boussejra, Mahmoudi, arXiv:2111.07938 [hep-ph]

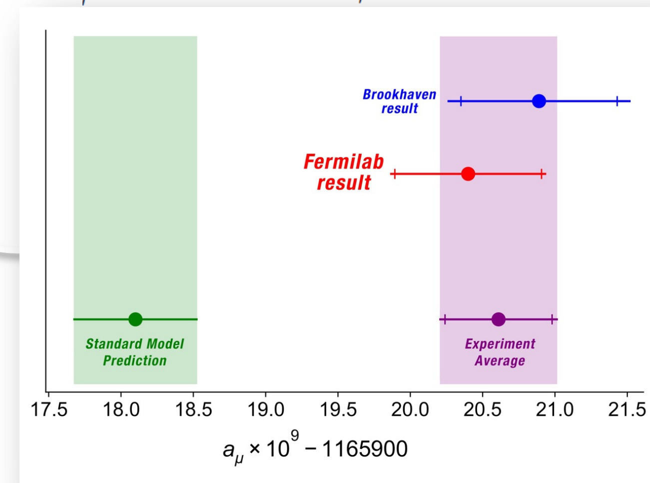
Flavour anomalies 2021



(g-2)$_\mu$ tension with SM first observed in BNL, confirmed by *Muon g-2* @ Fermilab

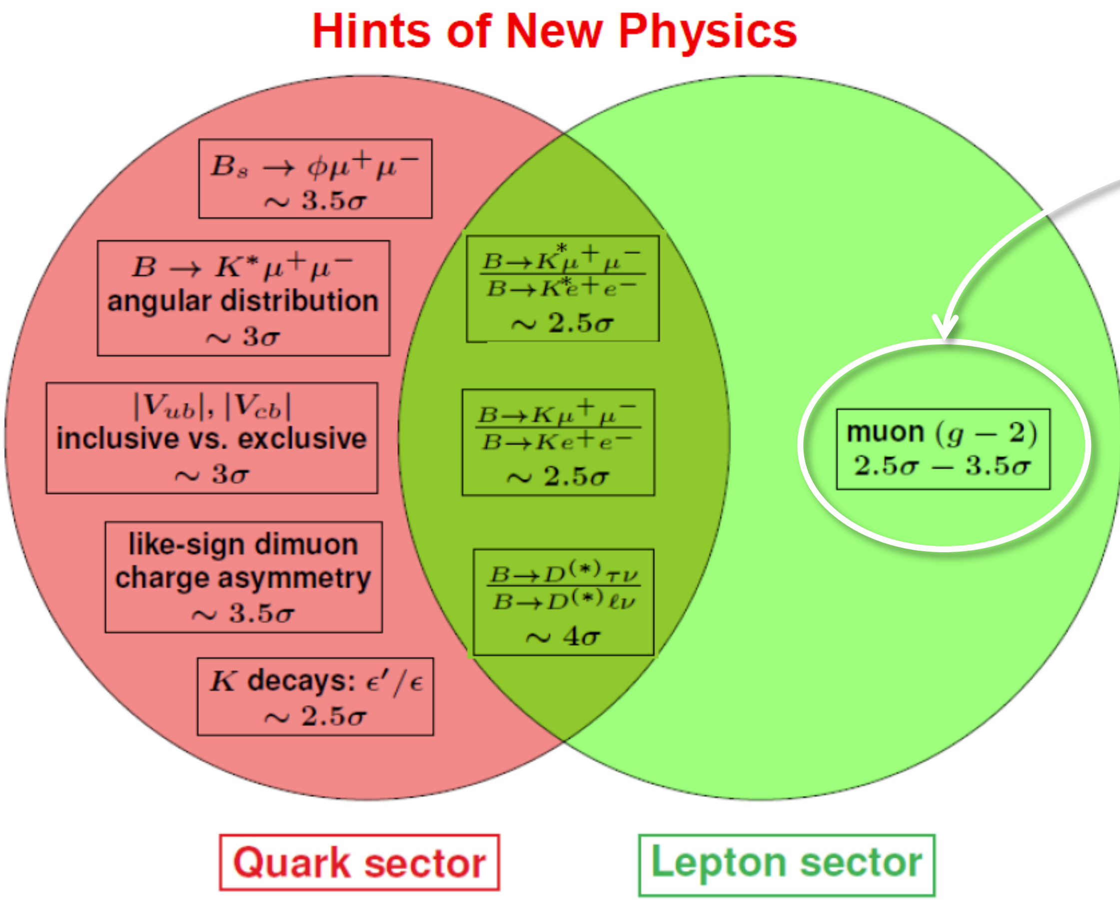
(that is if theory end is confirmed)



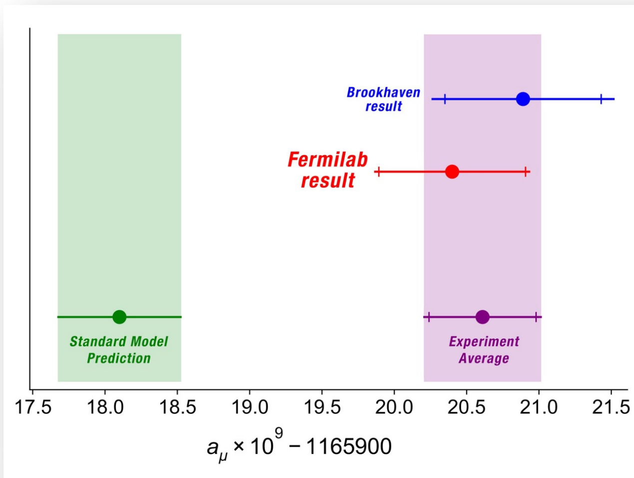


Muon g-2, [Phys. Rev. Lett. 126 (2021) 141801]

Flavour anomalies 2021

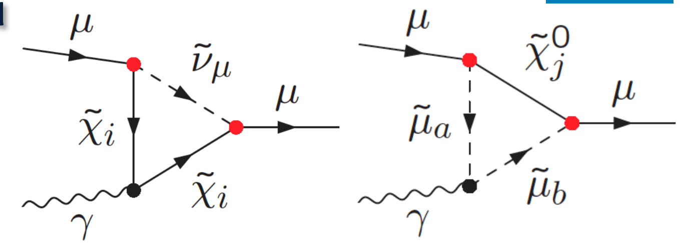


Is it possible to find a common solution for B-anomalies and $(g-2)_\mu$ measurement?



Muon g-2, Phys. Rev. Lett. 126 (2021) 141801

Supersymmetry: smuons & $(g\text{-}2)_\mu$

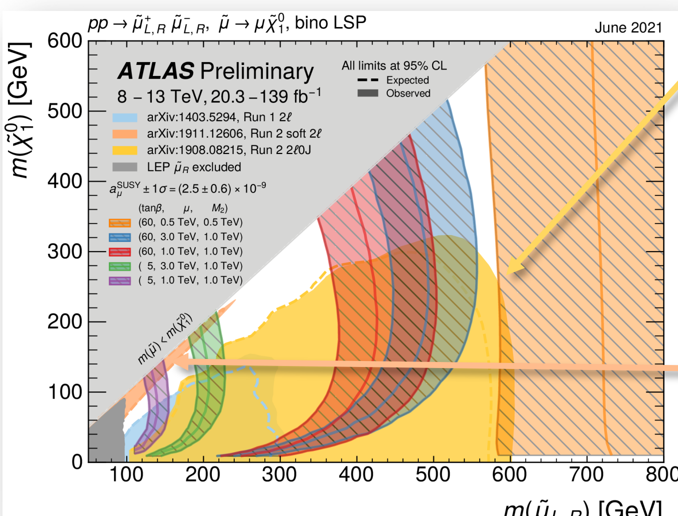


- ATLAS & CMS have looked for and constrained the existence of sleptons in various channels
- Yet there is parameter space left still compatible with the observed value of $(g\text{-}2)_\mu$
- These scenarios may also respect the $b \to s\ell\ell$ anomalies

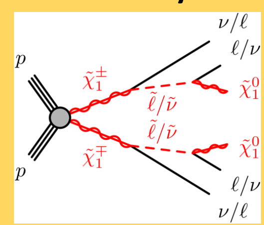
$(g\text{-}2)_\mu$-relevant SUSY parameters

- M_2: wino mass parameter
- μ: higgsino mass parameter
- $\tan\beta$: ratio of vev's of two Higgs doublets

ATL-PHYS-PUB-2021-019



2ℓ0J analysis



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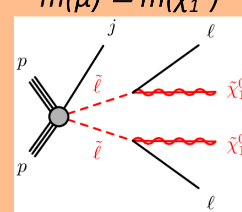
soft 2ℓ
compressed spectra
$m(\tilde{\mu}) \simeq m(\tilde{\chi}_1^0)$



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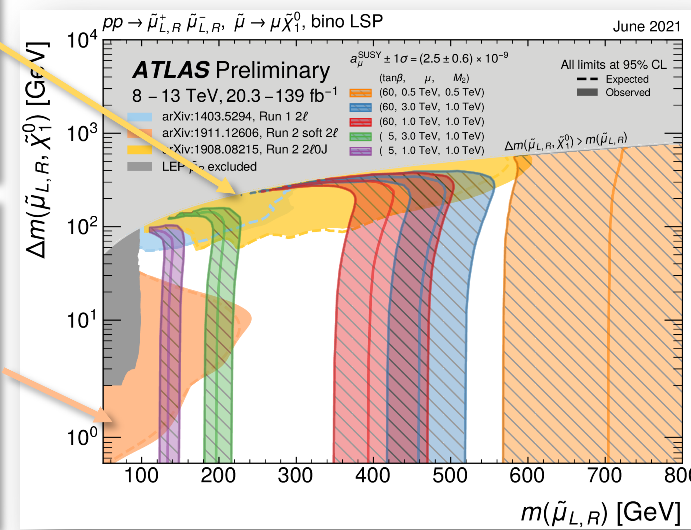
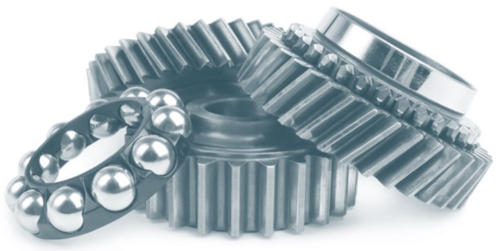


Summary & prospects

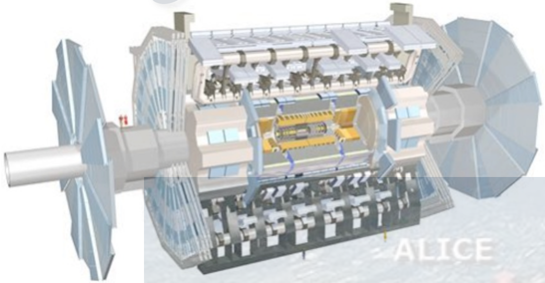
- Rare $b \to s\mu\mu$ decays are sensitive probe of new physics
  - global fits show a consistent set of anomalies across observables and experiments
  - ATLAS & CMS are performing angular-distribution analyses
- Interesting NP scenarios enter in loop diagrams
  - also in connection with $(g-2)_\mu$ tension ☞ supersymmetry
- ATLAS & CMS are adding capabilities to measure LFU observables
  - $R(K^*)$, $R(K)$ ⇦ electron channel
  - $R(D)$, $R(D^*)$ ⇦ single-muon channel, taus?
- HL-LHC will bring a ~×10 better precision in F_L, $P_i^{(\prime)}$ parameters
- **CMS & ATLAS are exploring more and more *B*-physics observables**

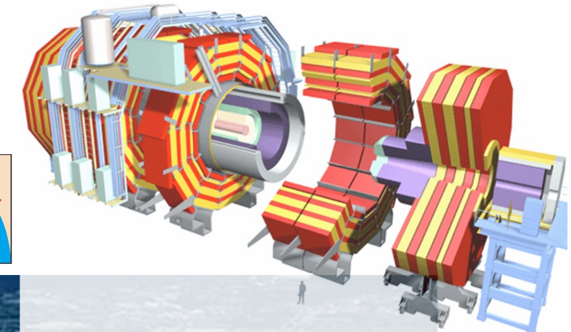
Thank you for your attention!

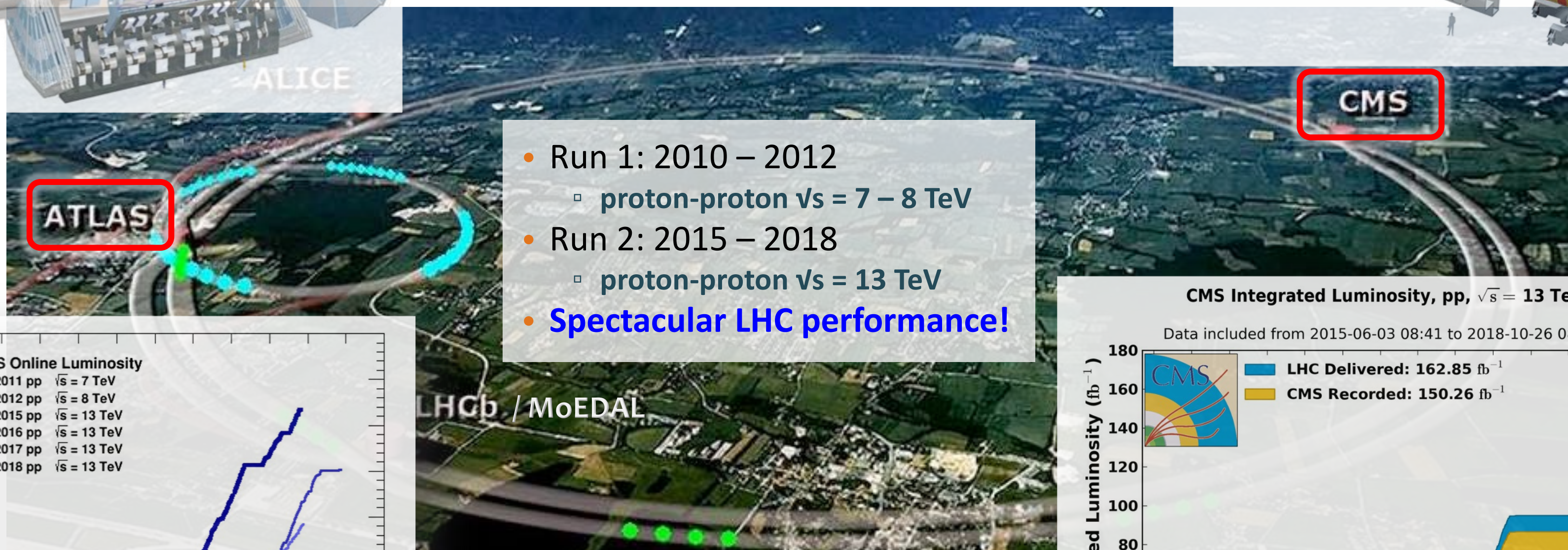
Spares



Large Hadron Collider at CERN







- Run 1: 2010 – 2012
  - proton-proton √s = 7 – 8 TeV
- Run 2: 2015 – 2018
  - proton-proton √s = 13 TeV
- **Spectacular LHC performance!**