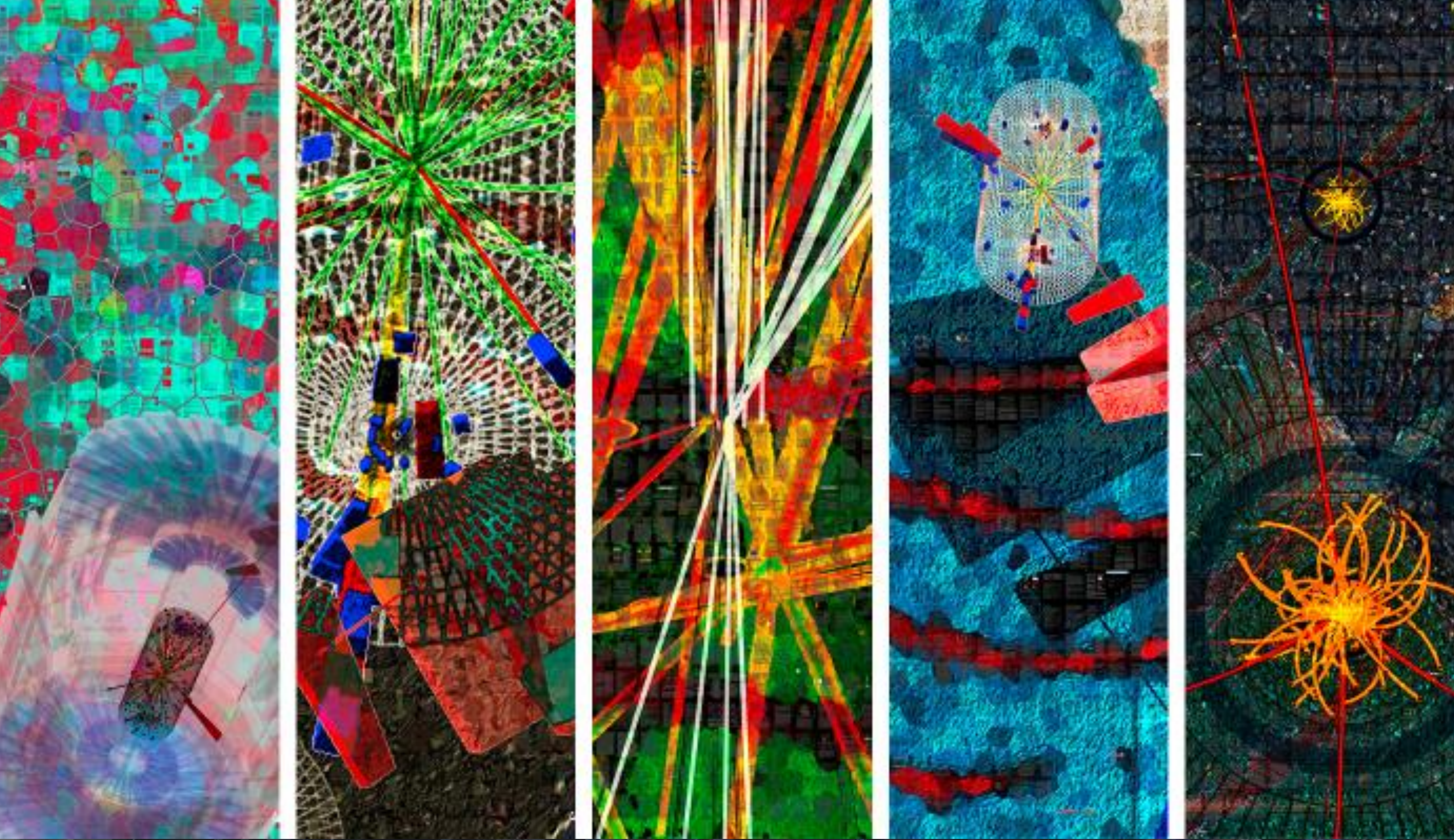

Course on Physics at the LHC

PROGRAM

02 MARCH - 26 JUNE 2020

Rare Decays

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why rare?

- Processes suppressed in the SM ➡ NP effects more readily detectable
- Virtual particles in loops (FCNC) ➡ High mass reach (up to O(100TeV))
- Model-independent New Physics searches
- LHC: high luminosity ➡ high sensitivity for discovery !

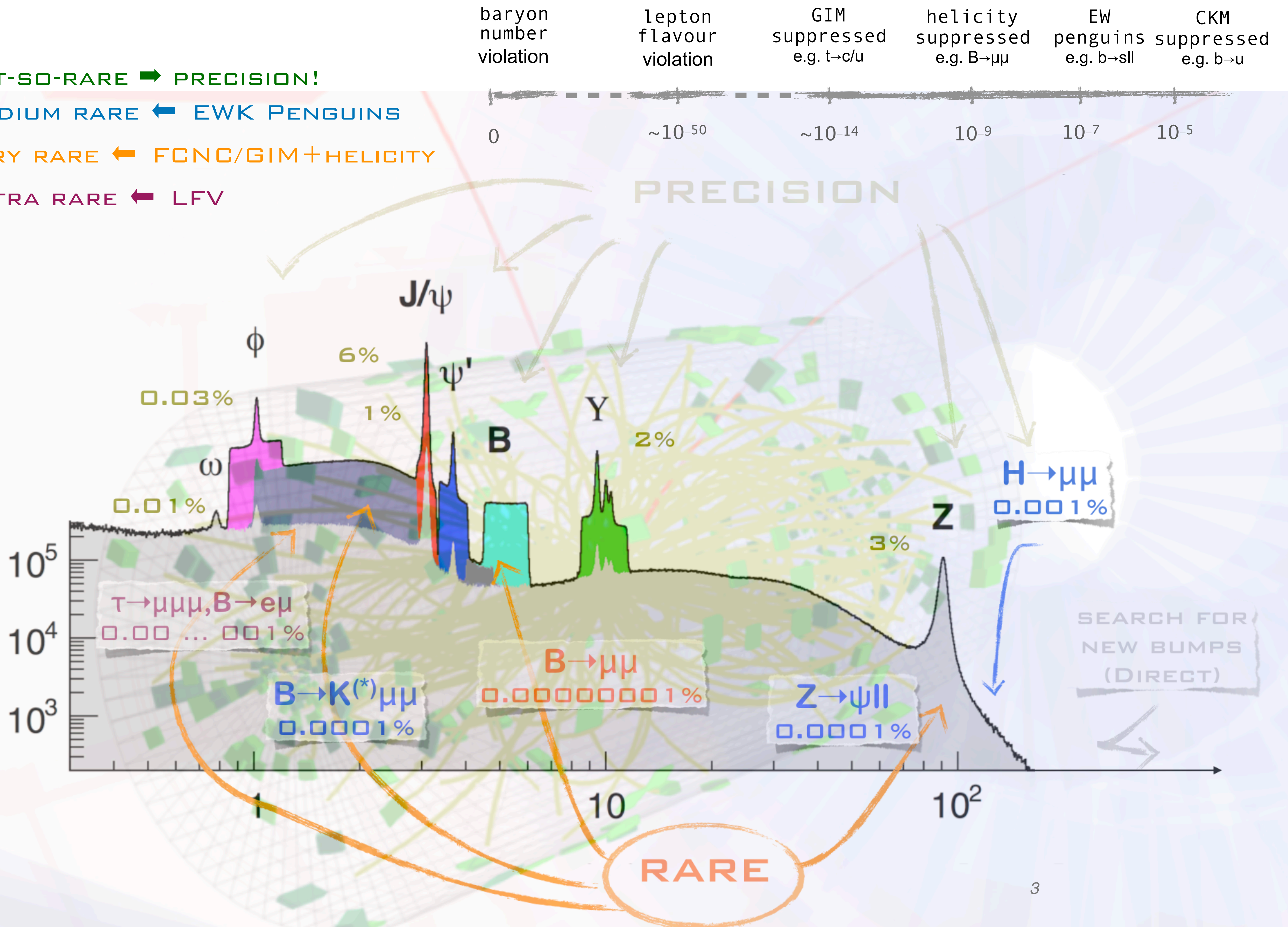
how rare?

NOT-SO-RARE ➡ PRECISION!

MEDIUM RARE ⬅ EWK PENGUINS

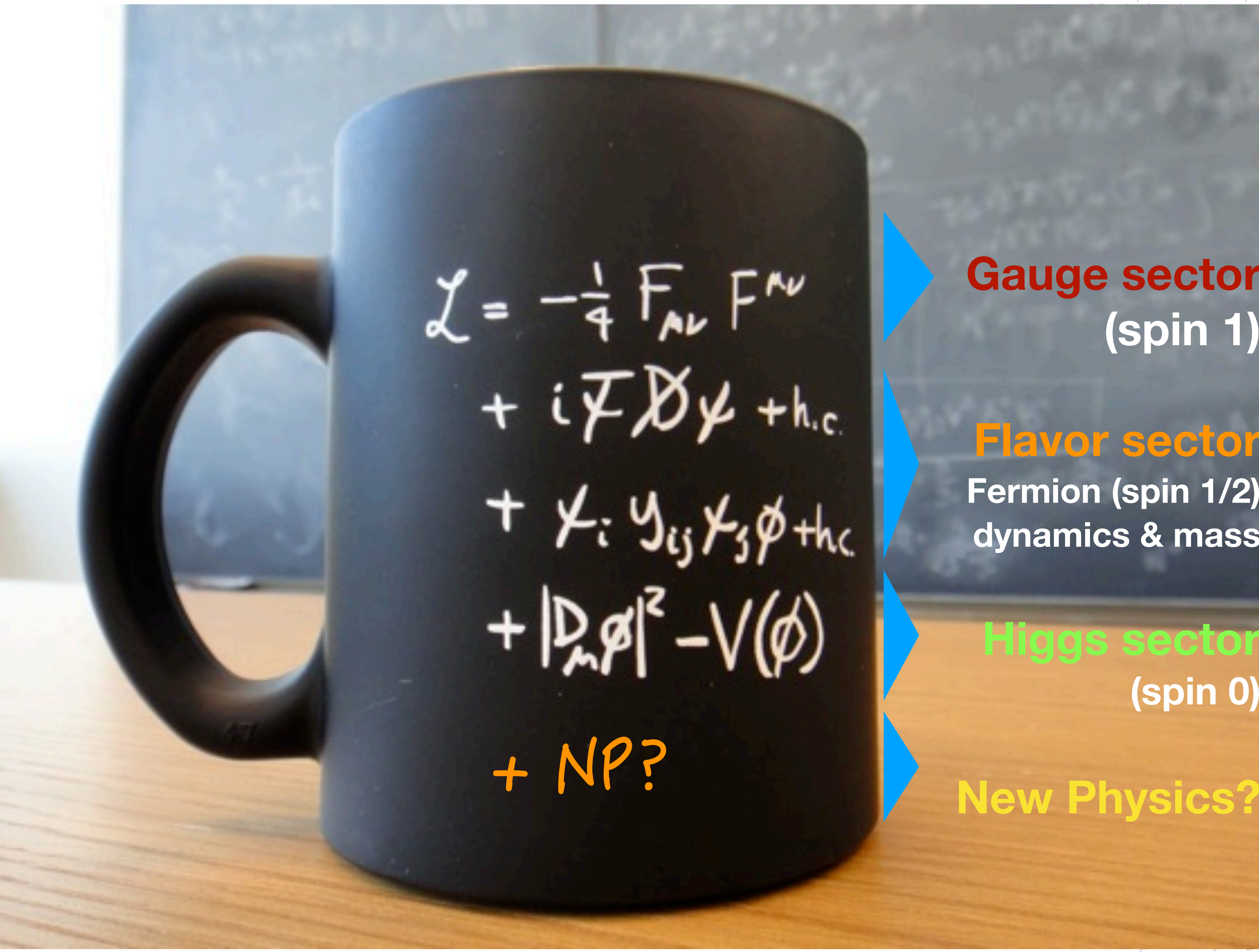
VERY RARE ⬅ FCNC/GIM+HELICITY

ULTRA RARE ⬅ LFV



the standard model *(of particle physics)*

the SM Lagrangian



Gauge sector (spin 1)

Flavor sector Fermion (spin 1/2) dynamics & mass

} **describes everything experimentally confirmed before 2012**

Higgs sector (spin 0)

} **Yukawa coupling w/ scalar (new interaction type, 2018)**

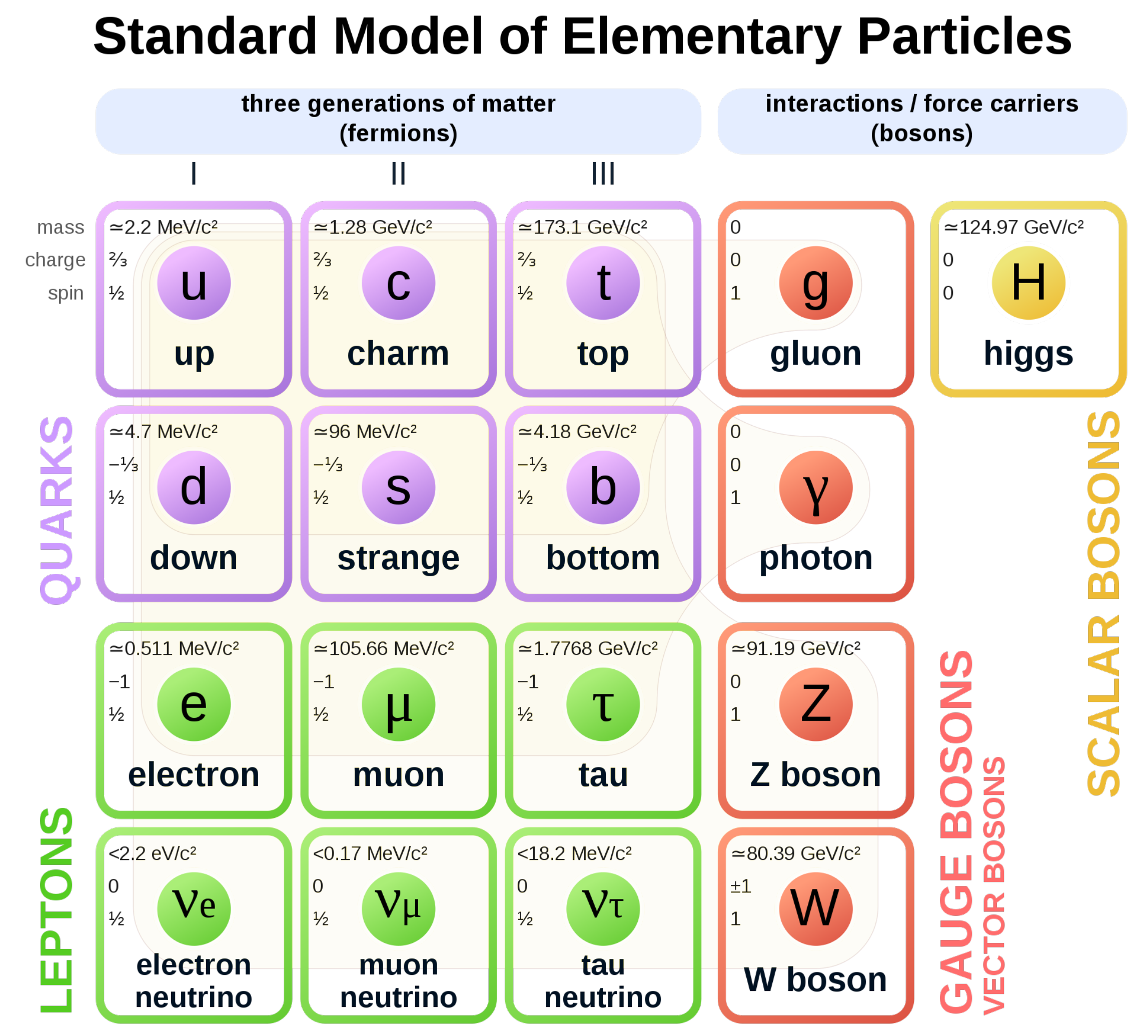
} **Scalar self-interaction and with gauge bosons**

New Physics?

} **New hidden sector, new particles or interactions (?)**

SM: a great triumph of 20th century science.

- bosons
  - Gauge: W, Z
  - γ does not decay (afawk)
  - Higgs
- quarks
  - except for the top quark
  - quarks bind into hadrons via strong force
  - hadrons decay via strong and weak forces
  - sensitive to NP via. rare decays (& mixing)
  - light hadrons: rare kaon decays (NA62, KOTO, KLEVER)
- leptons
  - neutrinos: studied in dedicated experiments (SNO, Minos, Nova, MicroBoone, DayBay, T2K, SK, etc; DUNE, HK, SHIP...)
  - charged leptons studied mostly in dedicated experiments, study rare or forbidden decays: MEG ($\mu^+ \rightarrow e^+ \gamma$), Mu2e ($\mu \rightarrow e$), Mu3e ($\mu \rightarrow eee$), $\tau \rightarrow \mu\mu\mu$ (LHC, Belle(II); SHIP, TauFV), anomalous magnetic dipole moment (g-2)



«flavor» !?

- the SM flavor sector arises from interplay of fermion-weak–gauge and fermion-Higgs couplings

Electroweak symmetry breaking:
Masses for gauge bosons and fermions [Higgs mechanism]

Three generations of quarks and leptons

Left-handed doublets: $\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L, \quad \begin{pmatrix}u \\ d\end{pmatrix}_L, \begin{pmatrix}c \\ s\end{pmatrix}_L, \begin{pmatrix}t \\ b\end{pmatrix}_L$ T = ½

Right-handed singlets: $e_R, \quad \mu_R, \quad \tau_R, \quad u_R, d_R, \; c_R, s_R, \; t_R, b_R$ T = 0

Rich flavor phenomenology ...

The parameters of the SM

- 3 gauge couplings
- 2 Higgs parameters
- strong CPV parameter, $\bar{\theta}$
- 6 quark masses
- 3 quark mixing angles + 1 phase (CKM)
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase (PMNS))

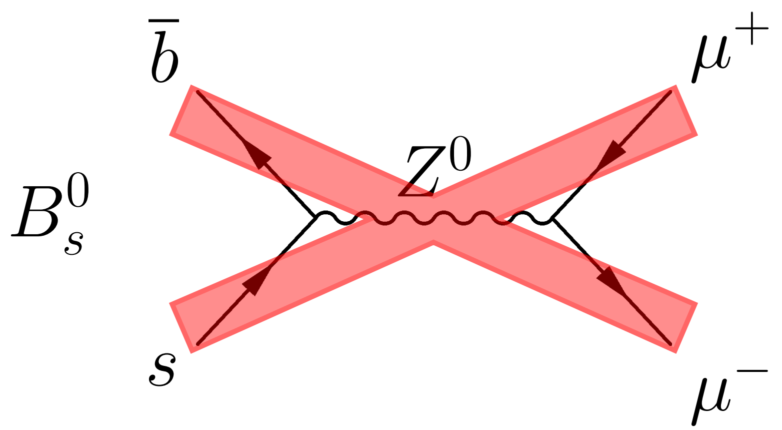
( ) = with Dirac neutrino masses

Out of the19 parameters of the SM (excluding neutrino masses/mixing), 14 arise from the flavor sector.

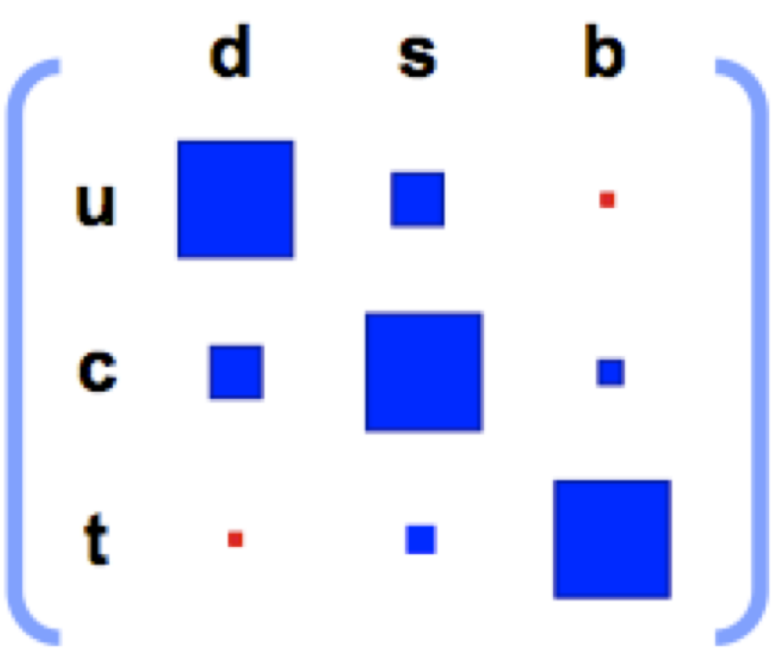
} flavor parameters

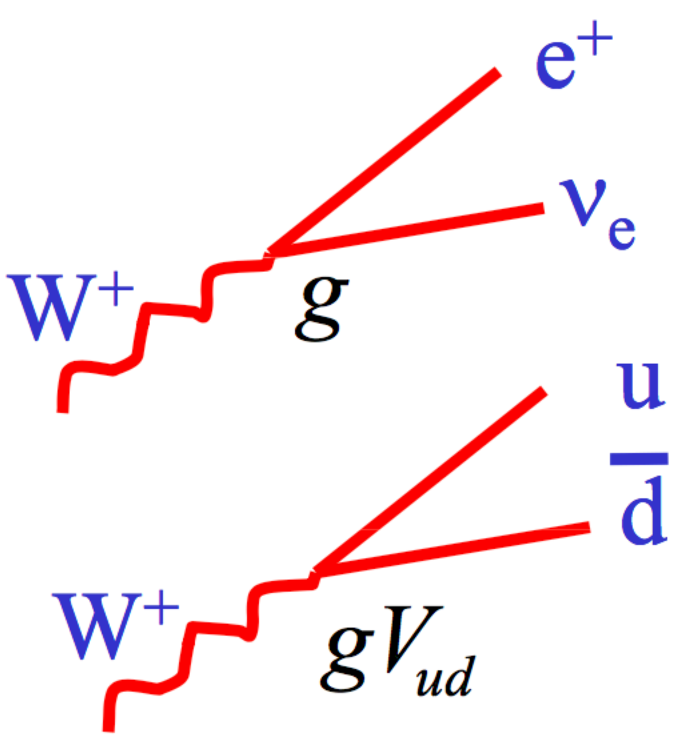
flavor changing interactions

- flavour changing neutral currents, **FCNC**: absent (at tree level) in SM

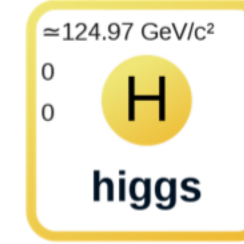


- charged currents
  - Leptons: ~universal
    - Lepton Flavor Universality Violation (LFV, **LFUV**) → NP
  - Quarks: flavor mixing

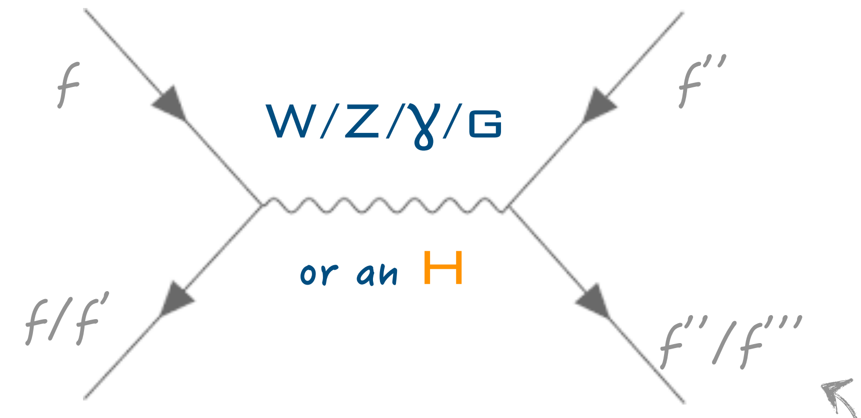




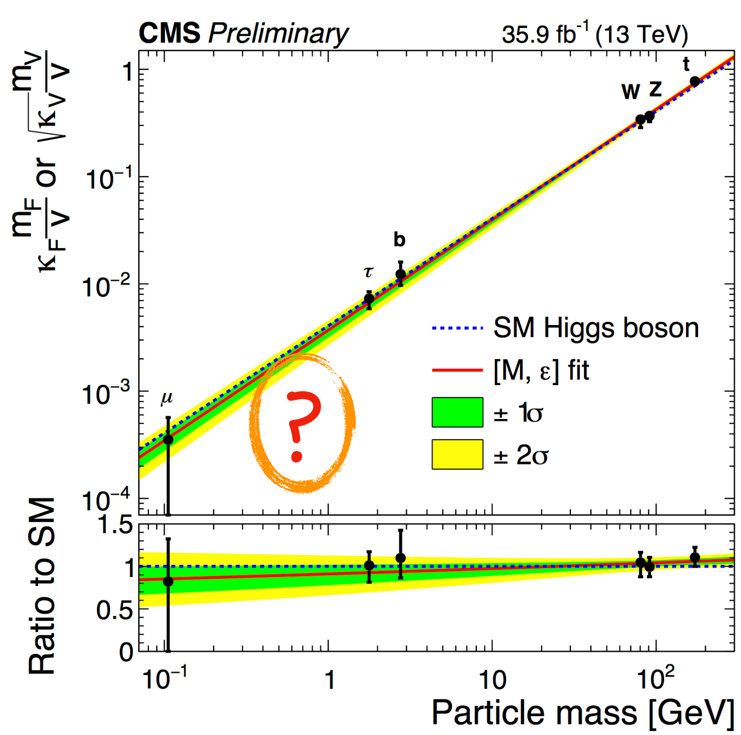
flavor & Higgs: Yukawa



- the *direct* coupling of Higgs to tau (2017), top and b (2018) have just been observed
- this establishes the Yukawa interaction
  - a ‘new kind’ of interaction: only force that does not directly arise from gauge principle
- the Yukawa coupling is at the origin of the flavour structure of the SM

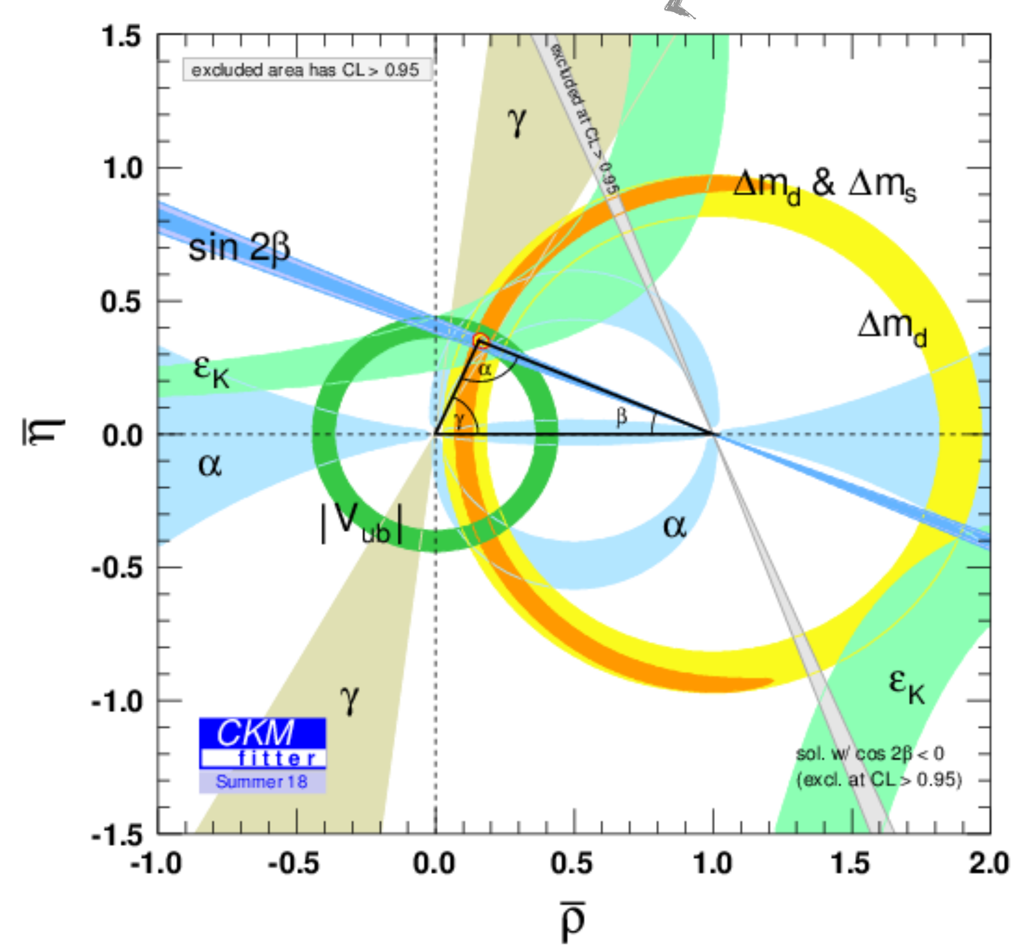


$$y_\psi \bar{\psi}\Phi\psi \rightarrow y_\psi \bar{\psi} v \psi + y_\psi \bar{\psi} H \psi$$



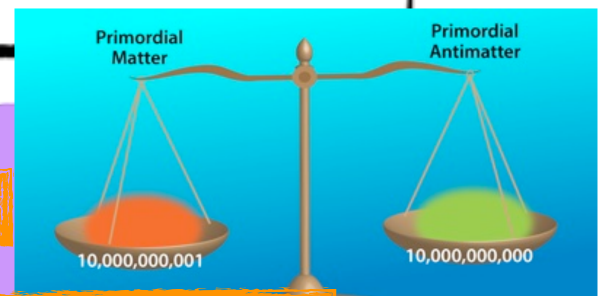
Higgs couplings just detected to the 3rd (heaviest) fermion generation

Quark flavour mixing (CKM) studied to increasing precision

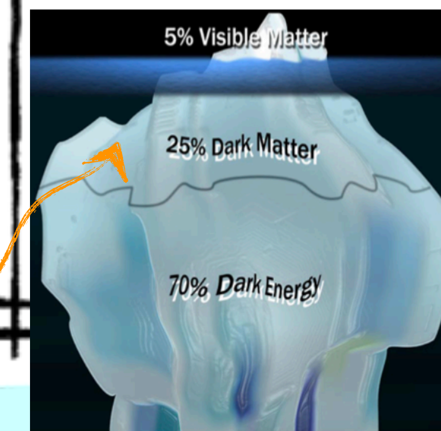


outstanding questions in particle physics circa 2020

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation



Neutrinos:
- ❑ *ν* masses and their origin
- ❑ what is the role of *H*(125) ?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile *ν* ?



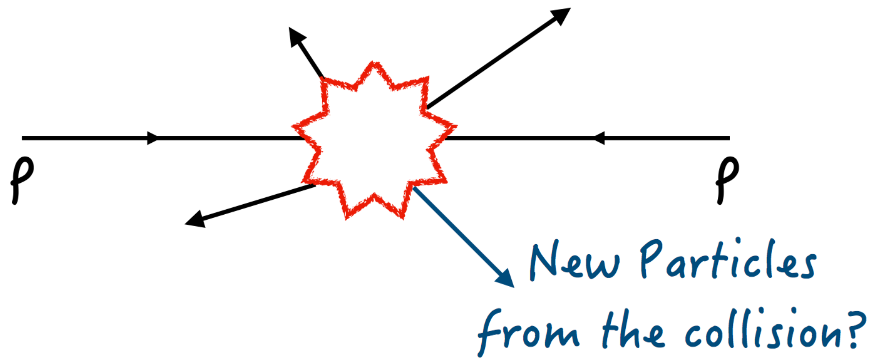
Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

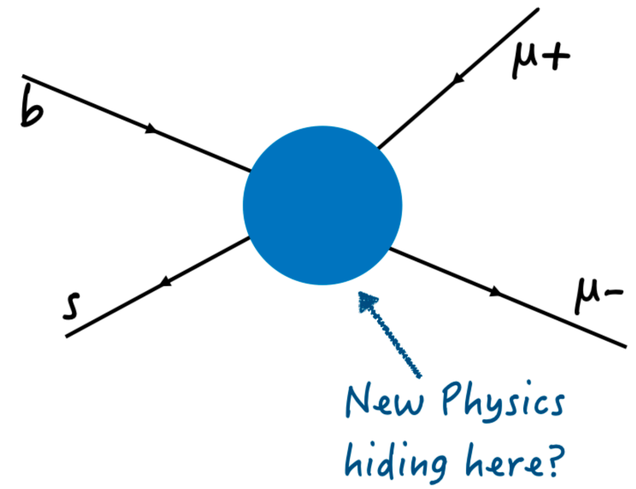
Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

(complementary!) paths to NP @LHC

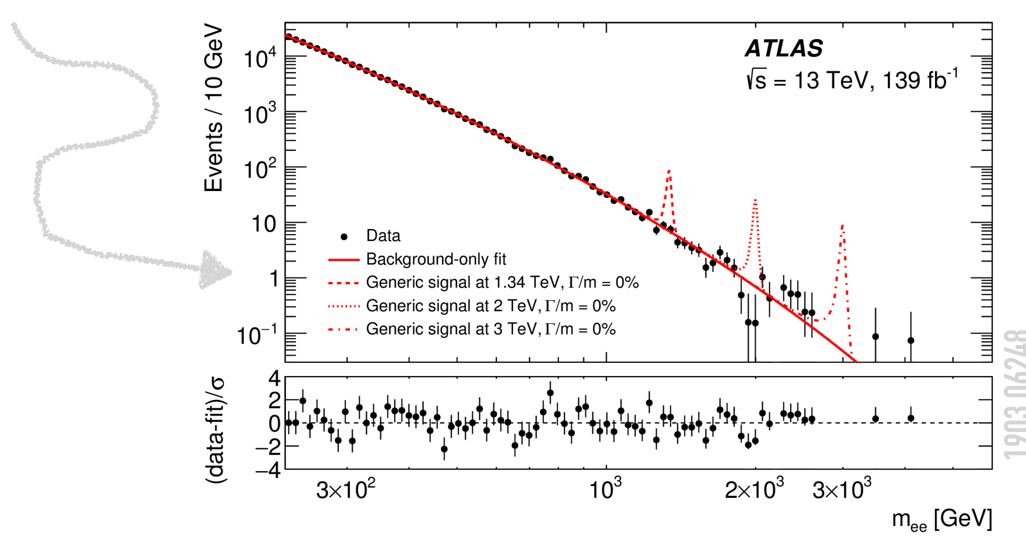




Rare decays!

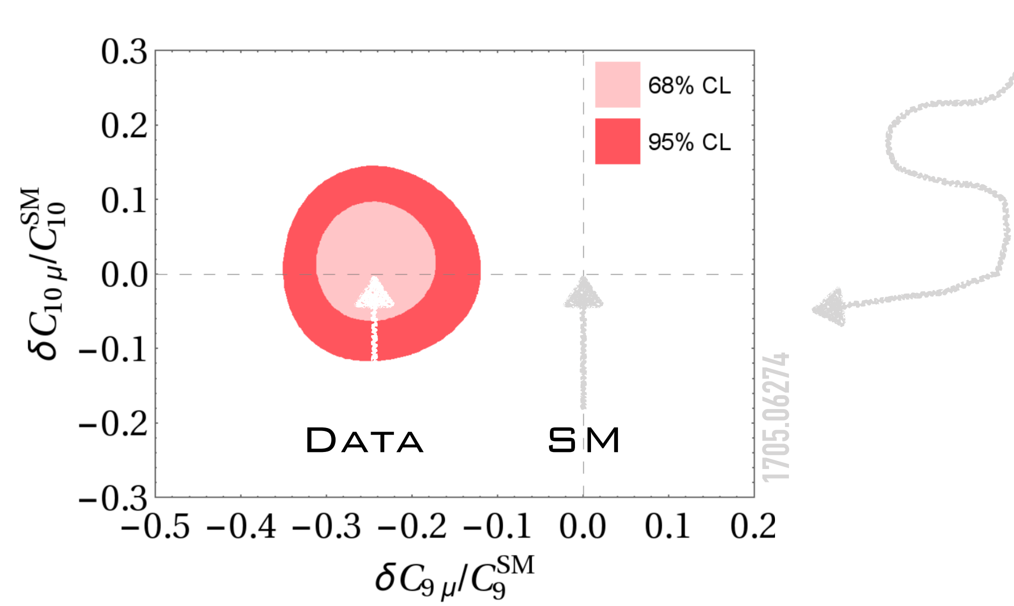
Direct

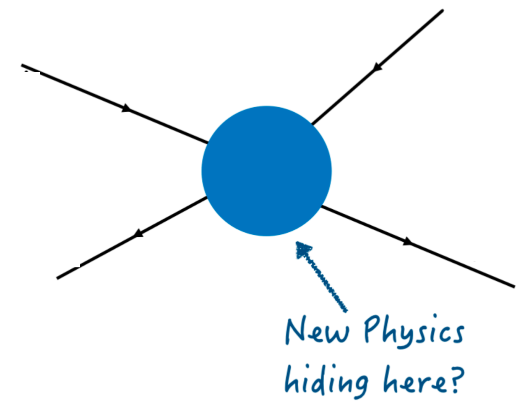
- searching for the decay products of potentially produced NP particles



Indirect

- searching for NP particles running in quantum loops (virtual)





Rare Decays

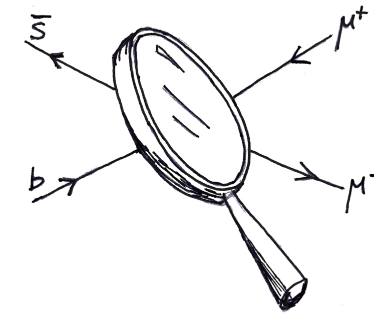
of SM particles, towards NP

beauty
charm
strangeness
top
W,Z
Higgs
leptons

SUSY
Z',W'
leptoquarks
unexpected

?

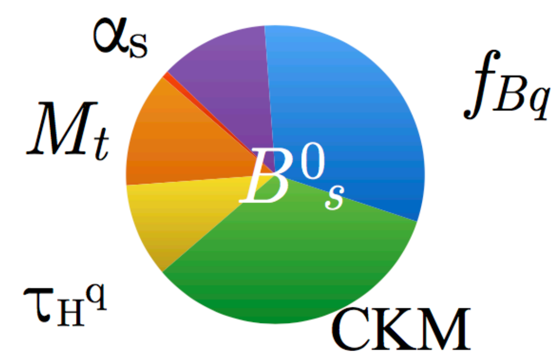
rare beauty | B→μμ



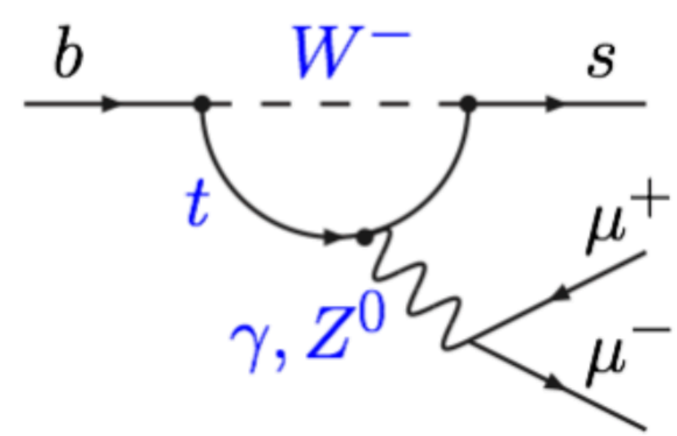
- decays highly suppressed in SM
  - FCNC- but also helicity-suppressed $(m_\mu/m_B)^2$
- theoretically clean ➡ precise SM prediction

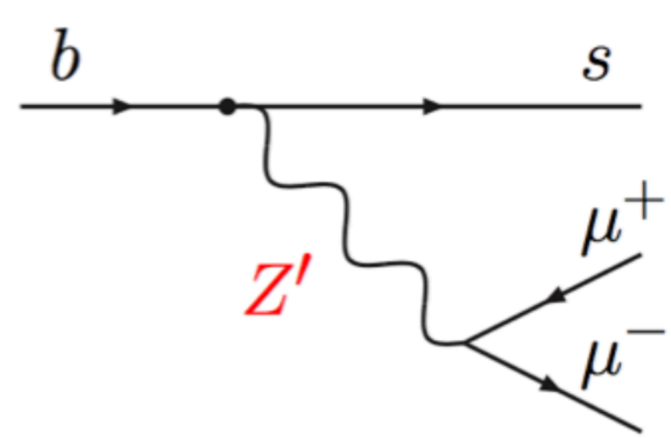
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

(~6-8%)



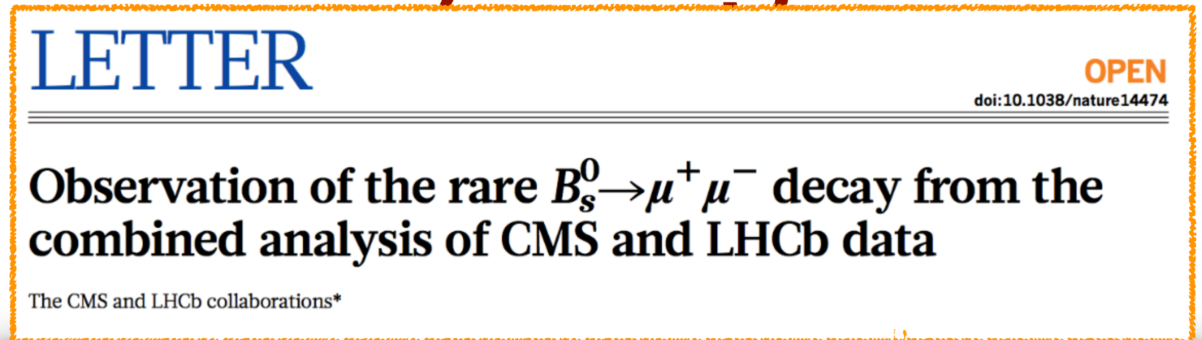
- high sensitivity to NP
  - large class of NP scenarios predicted large enhancements in decay rates
- experimentally clean
  - searched for at various colliders





$B_s \rightarrow \mu\mu$: a (3-decade) long search

a milestone discovery of the LHC physics program

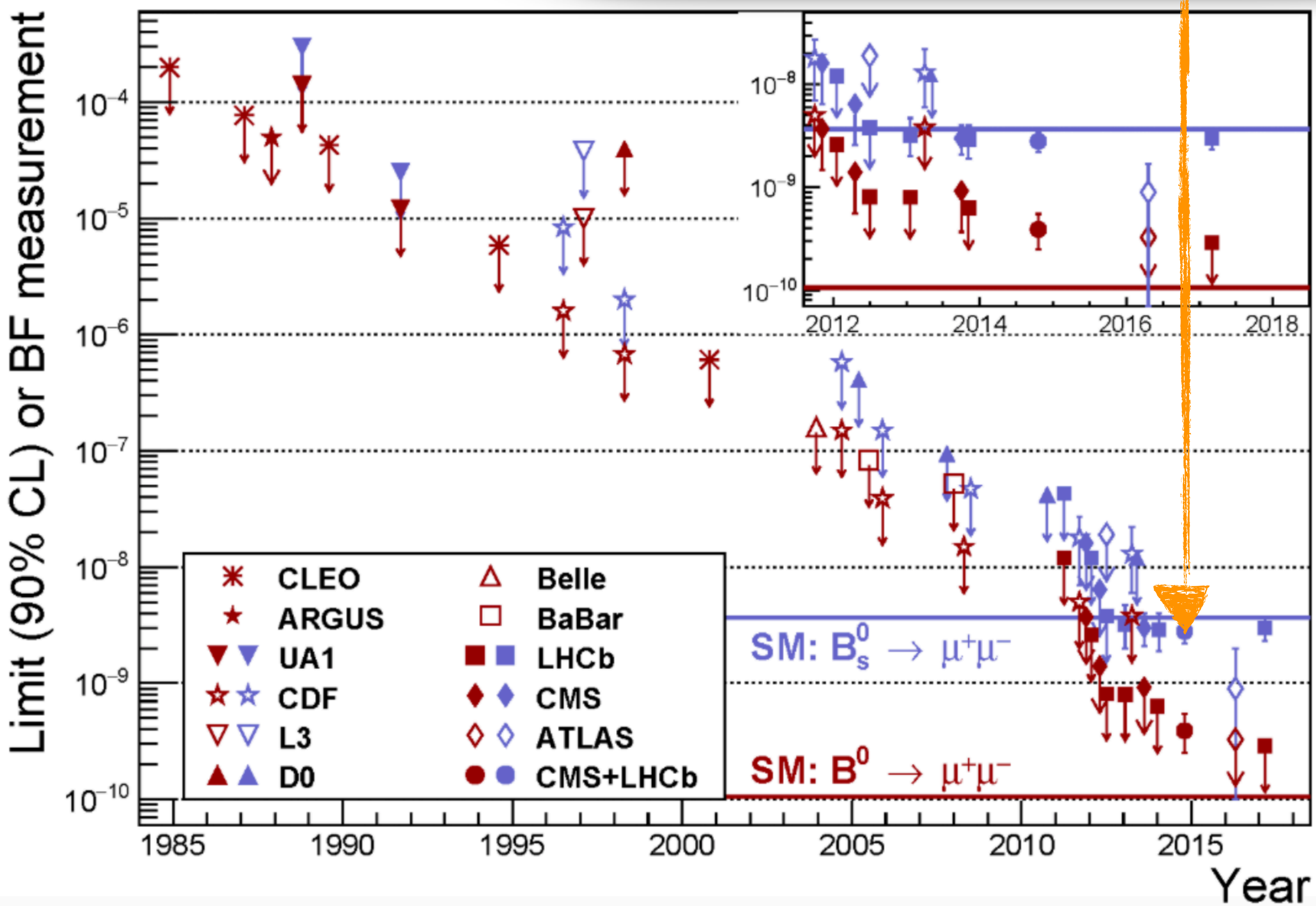

LETTER

OPEN

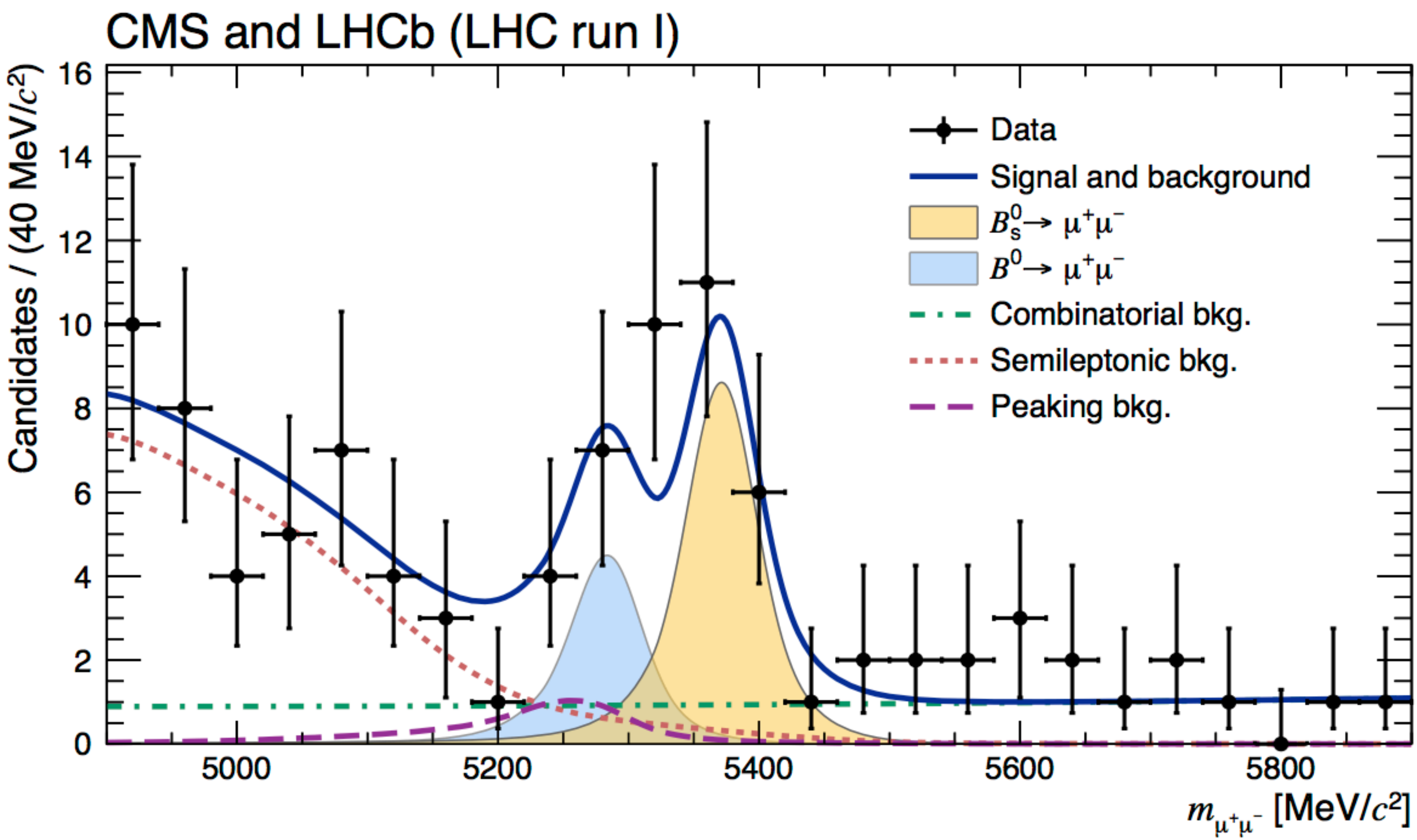
doi:10.1038/nature14474

Observation of the rare $B_s^0 \rightarrow \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data

The CMS and LHCb collaborations*

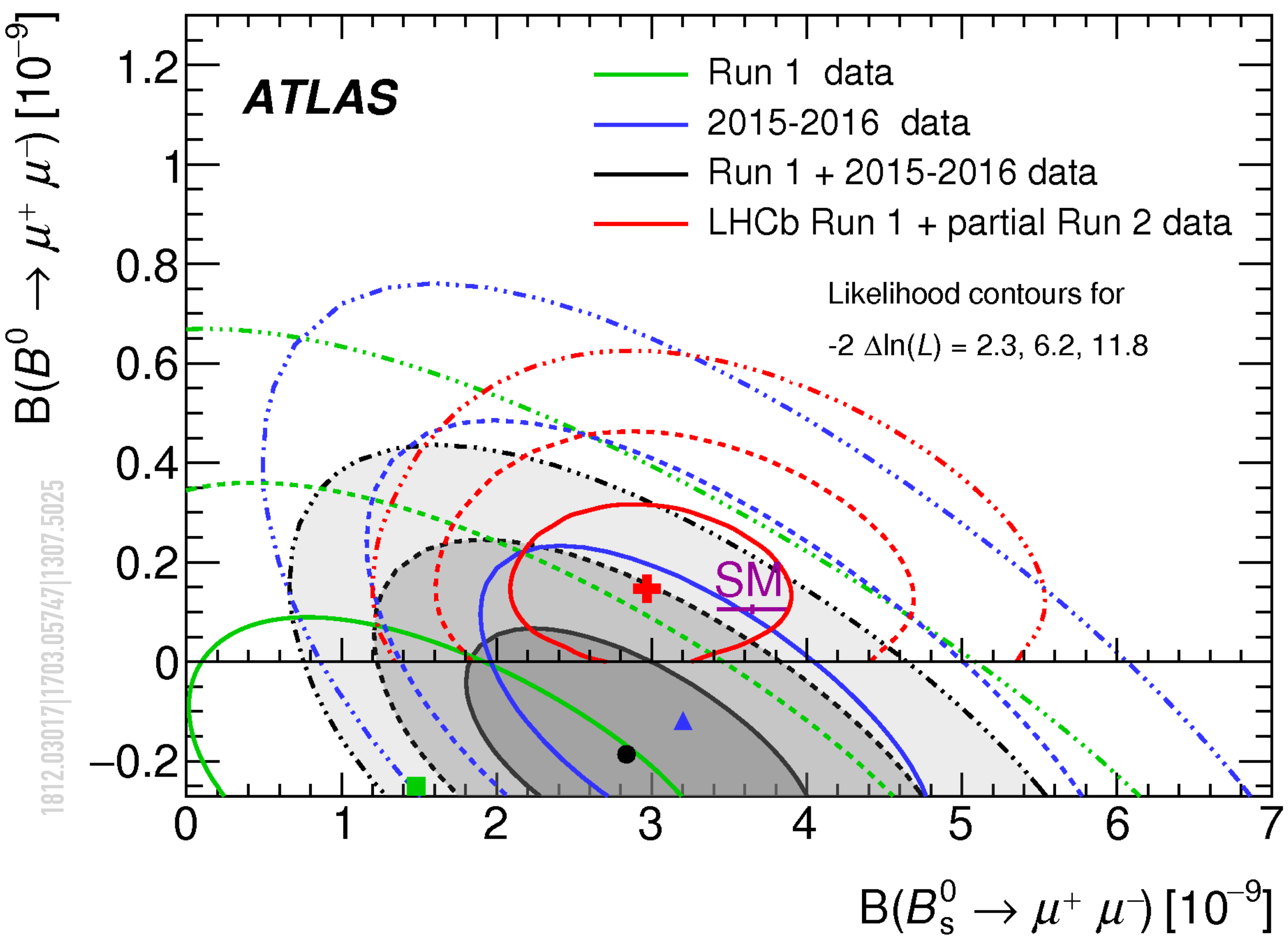


$B \to \mu\mu$ | Run1 discovery



B→μμ | Run2 updates

RunI + Run2 (partial)



- Results all of 3 experiments agree between themselves, and with the SM, within 1-2σ

- **LHCb**
  - added first 13TeV data
  - RunI+Run2 (3+1.4 fb^{-1}) yields first single-experiment $B_s \to \mu\mu$ >5σ observation

$BF(B_s \to \mu\mu) = (3.0 \pm 0.7) \times 10^{-9}$ (7.8σ)

$BF(B^0 \to \mu\mu) < 0.34 \times 10^{-9}$ (95%CL) (1.6σ)

- **ATLAS**
  - RunI+Run2 (25+26.3fb^{-1}) data

$BF(B_s \to \mu\mu) = (2.8 \pm 0.8) \times 10^{-9}$ (4.6σ)

$BF(B^0 \to \mu\mu) < 0.21 \times 10^{-9}$ (95%CL)

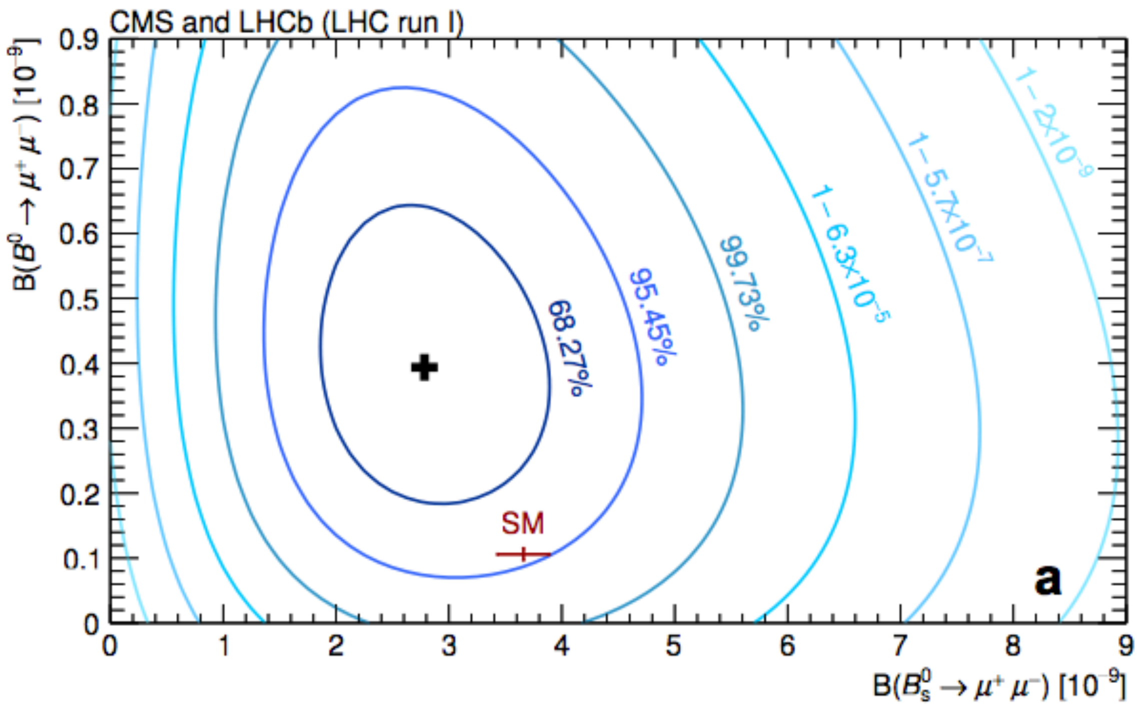
- **CMS**
  - recent results with 2011+2012+2016 data:

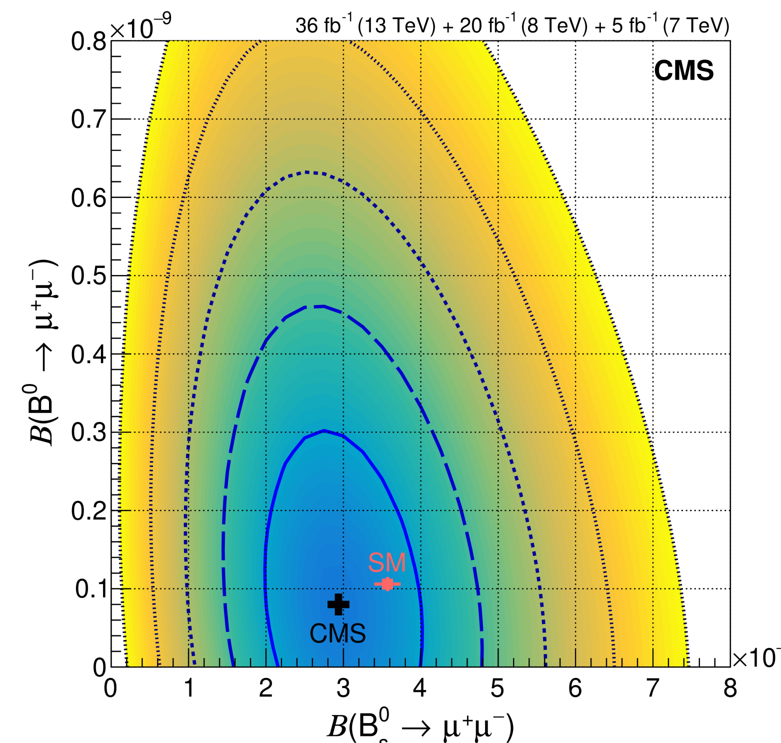
$BF(B_s \to \mu\mu) = (2.9 \pm 0.7) \times 10^{-9}$ (5.6σ)

$BF(B^0 \to \mu\mu) < 0.36 \times 10^{-10}$ @95%CL

B→μμ | comparison to theory expectation

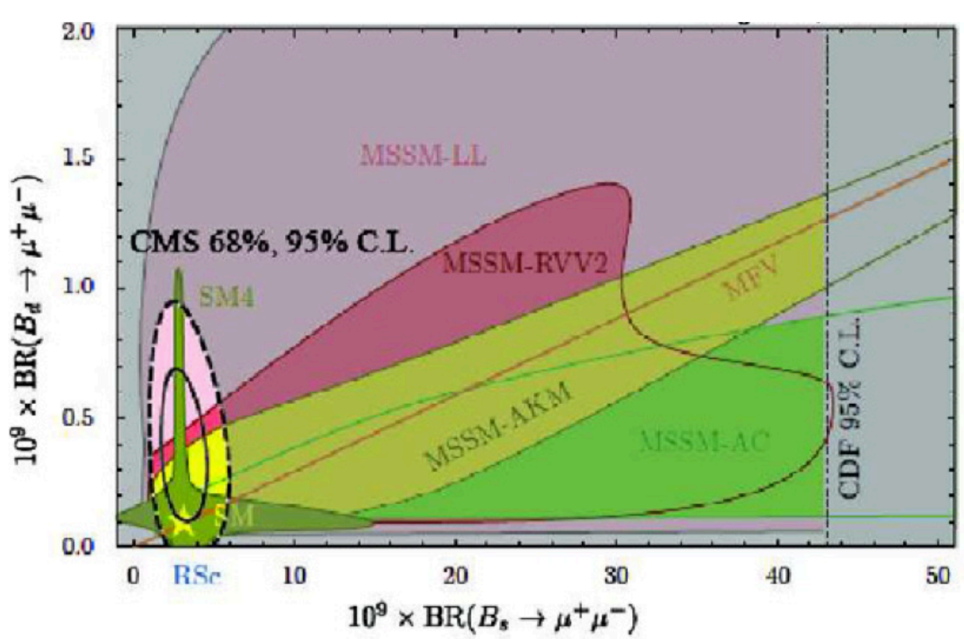
SM ➠

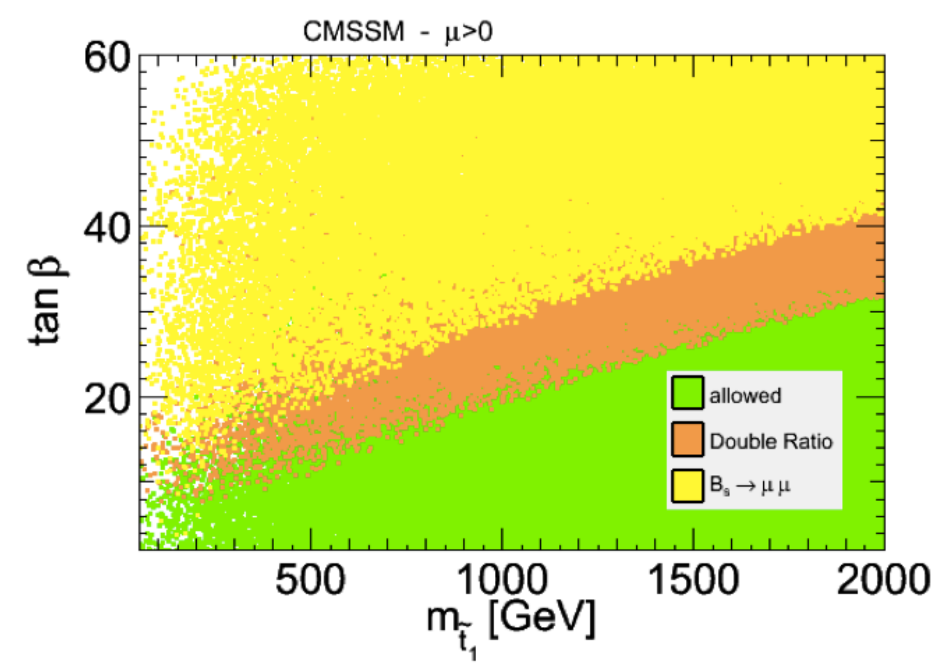




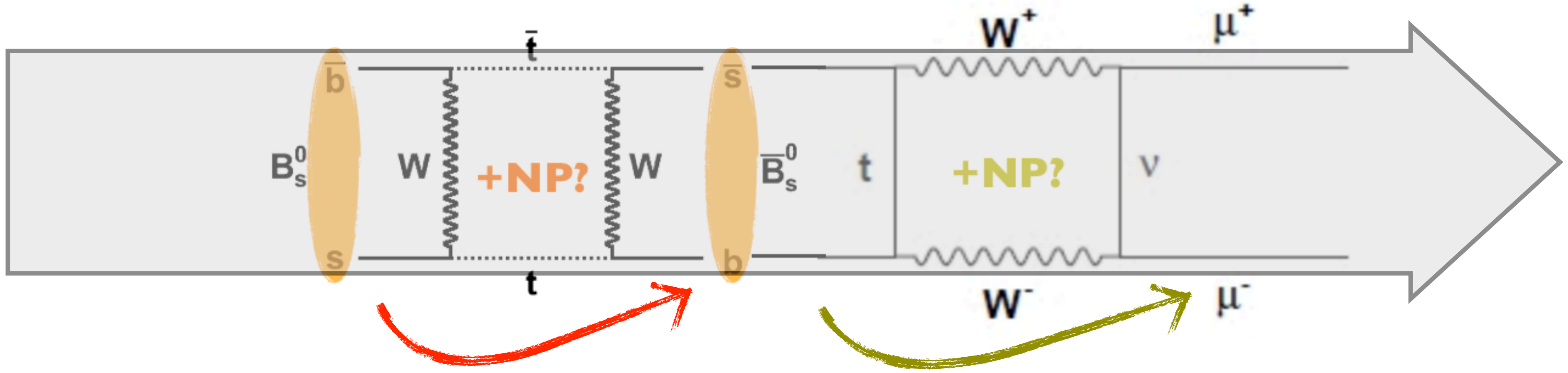
agreement with SM within current level of precision

NP ➠





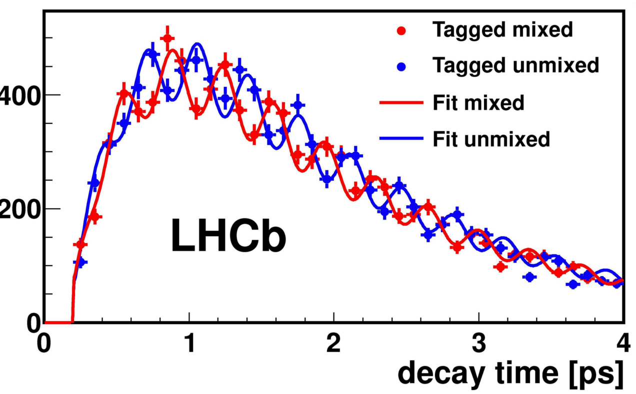
the (‘natural’) SUSY parameter space became much constrained

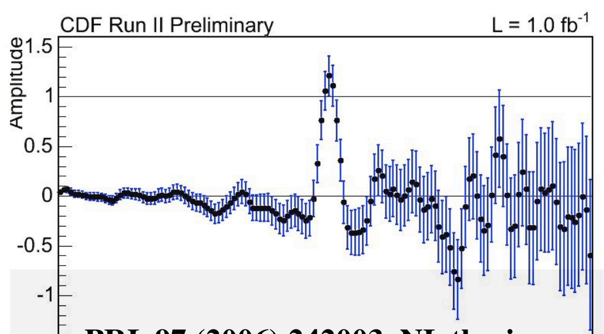
B  μμ

MIXING DECAY

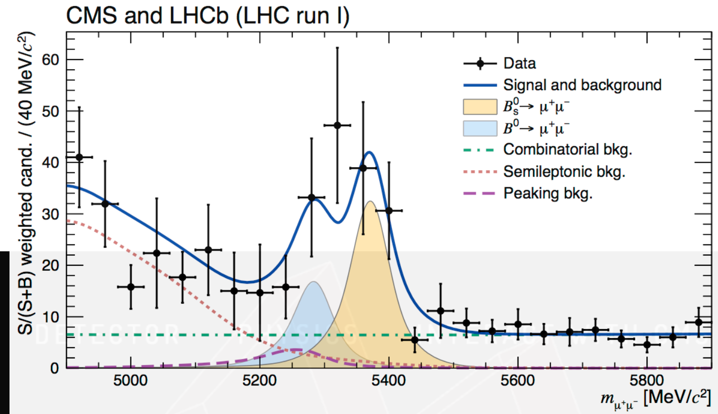
"fast and rare"

"doubly sensitive to NP"





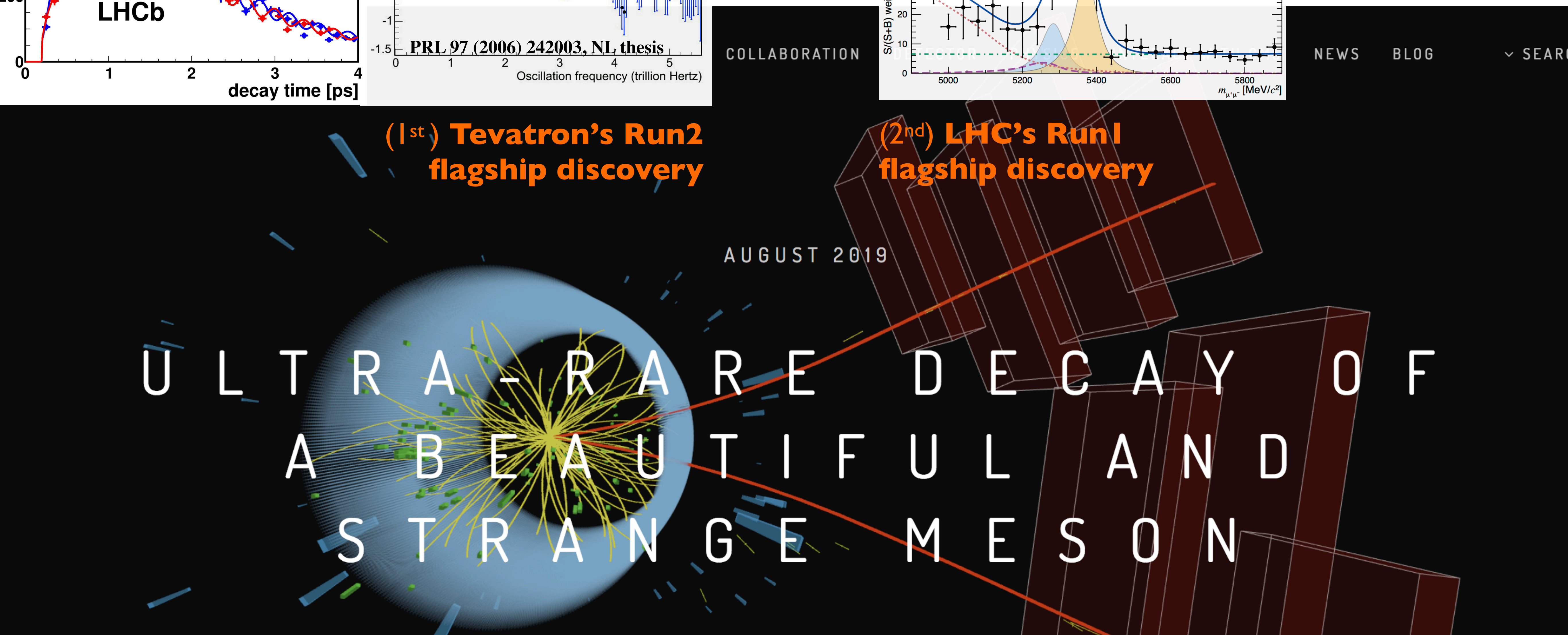
PRL 97 (2006) 242003, NL thesis



Nature 522 (2015) 68

(1st) **Tevatron's Run2 flagship discovery**

(2nd) **LHC's Run I flagship discovery**



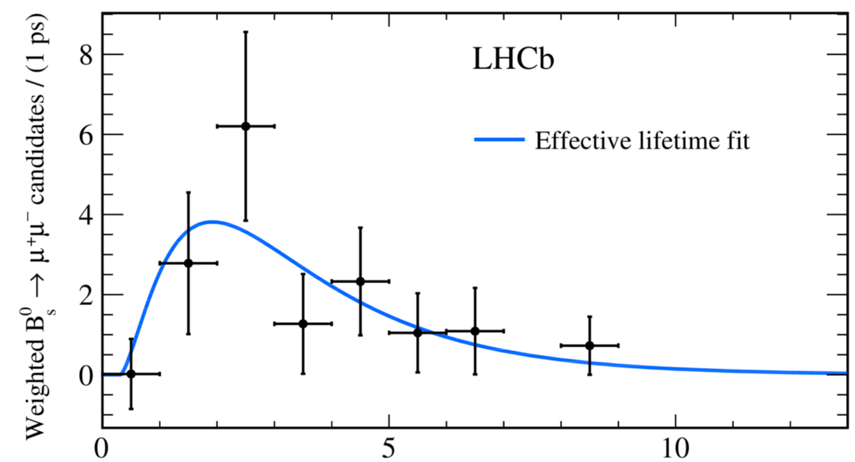
$B_s \to \mu\mu$ | efective lifetime

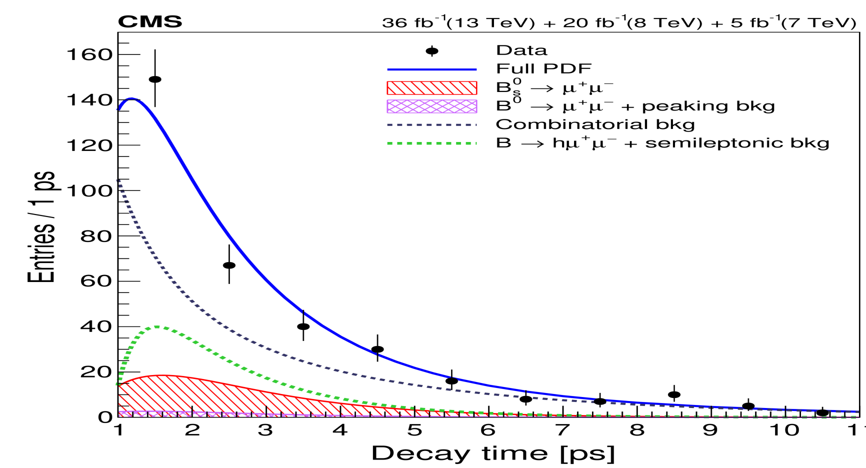
- Effective lifetime: complementary NP probe
  - in SM, only heavy eigenstate decays to μμ (not in NP!)

$$\tau_{\ell^+\ell^-} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2A_{\Delta\Gamma}^{\ell^+\ell^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\ell^+\ell^-}y_s}\right]$$

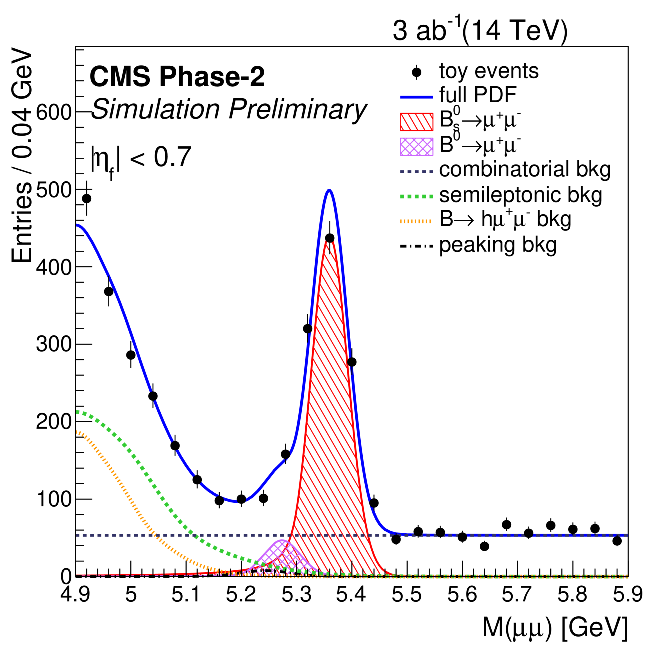
$A_{\Delta\Gamma} = +1$ in SM

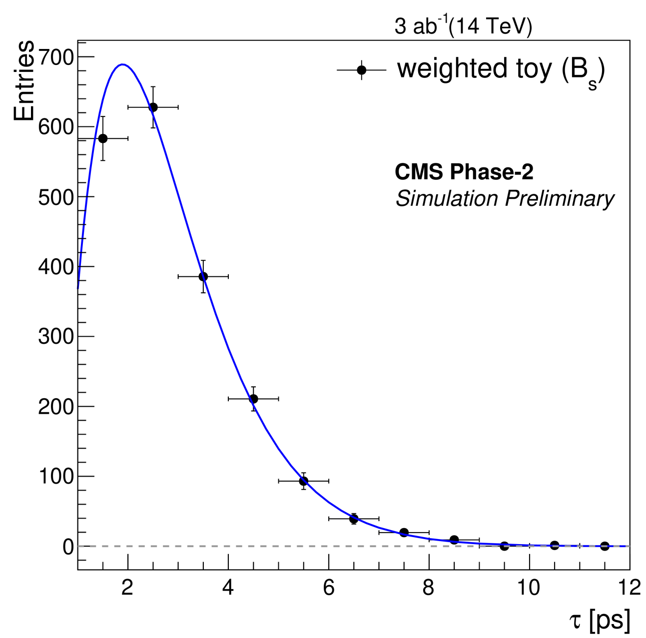
$\epsilon[-1,+1]$ in NP

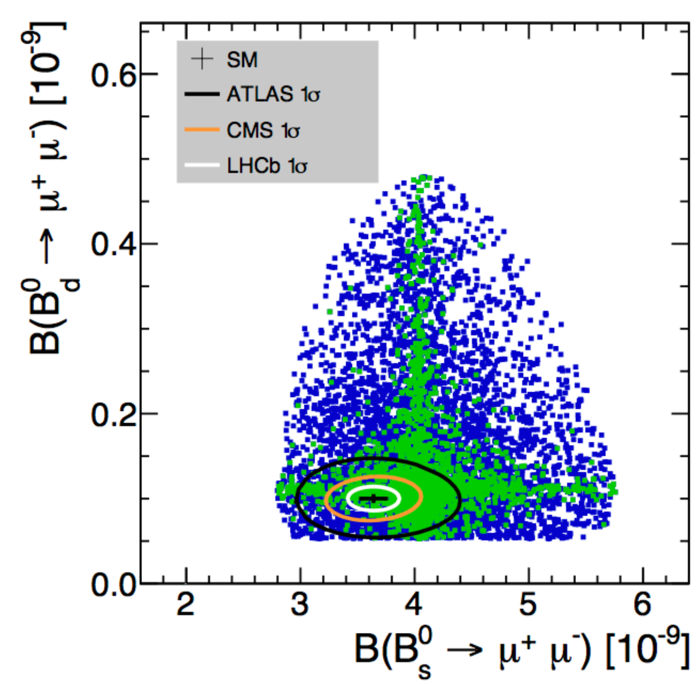




- first measurements by LHCb & CMS
  - current precision (22%) still insufficient
- HL-LHC projections (by LIP):
  - B_s: $\tau_{\mu\mu}$(2-3%), B^0: observation

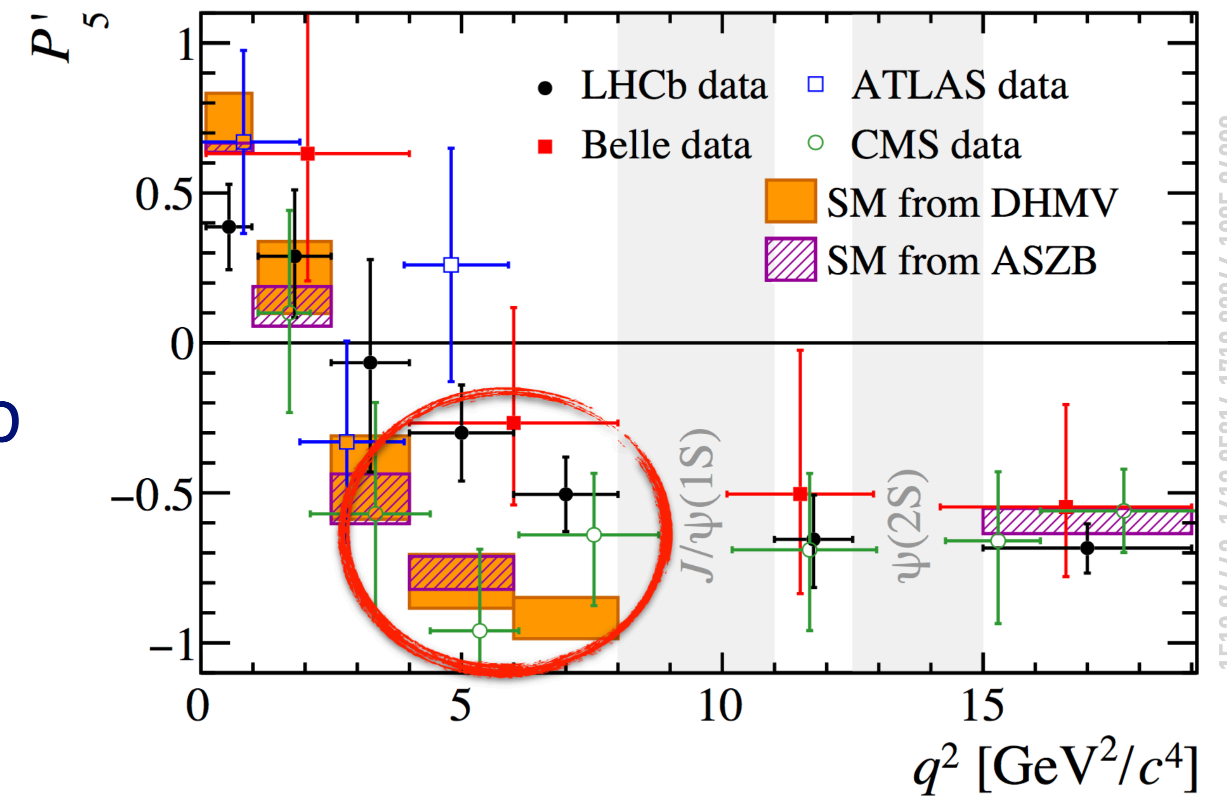






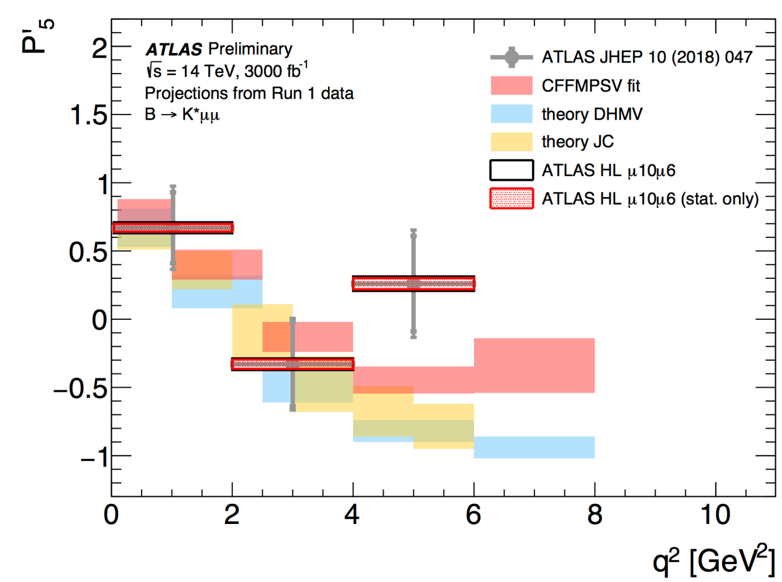
$b \to s\mu\mu$ | $B^0 \to K^{*0}\mu\mu$

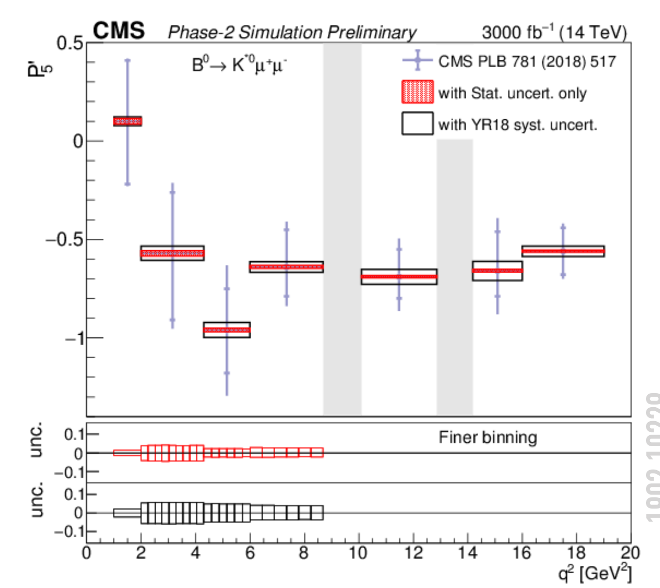
- $B \to X\mu\mu$ decays offer complementary NP-sensitive observables
  - accessible through angular analyses
  - studied at Belle, BaBar, CDF, LHC
- deviation from theory found by LHCb
  - in the angular observable P'_5 in the $B^0 \to K^*\mu\mu$ decay
  - recent measurements also by Belle, ATLAS, CMS, with reduced precision
- revise SM precision?



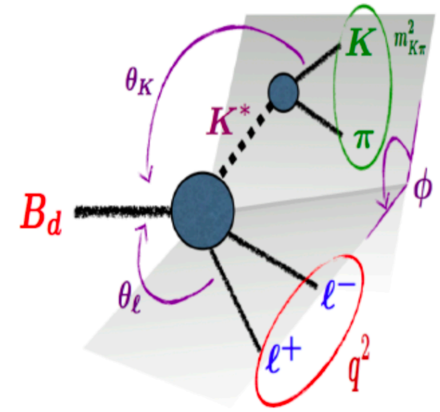
[HL-LHC PROJECTIONS]

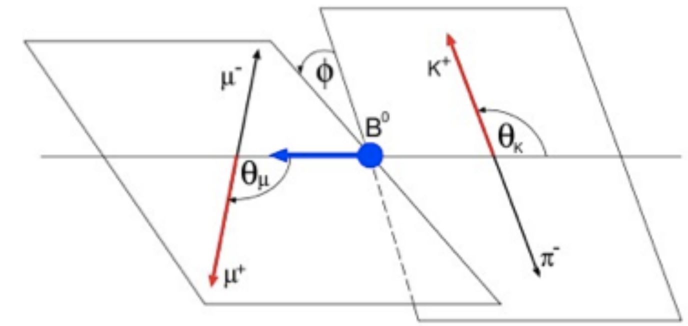
- projections
  - upcoming data will allow to independently clarify deviation





angular analysis





- fitting the data

$$\begin{aligned}\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(& S^R(m)\cdot S^a(\cos\theta_K, \cos\theta_l, \phi)\cdot \epsilon^R(\cos\theta_K, \cos\theta_l, \phi) \\ & + \frac{f^M}{1-f^M}\cdot S^M(m)\cdot S^a(-\cos\theta_K, -\cos\theta_l, -\phi)\cdot \epsilon^M(\cos\theta_l, \cos\theta_K, \phi)\Big) \\ & + Y_B \cdot B^m(m)\cdot B^{\cos\theta_K}(\cos\theta_K)\cdot B^{\cos\theta_l}(\cos\theta_l)\cdot B^{\phi}(\phi).\end{aligned}$$

⬅ Correctly tagged

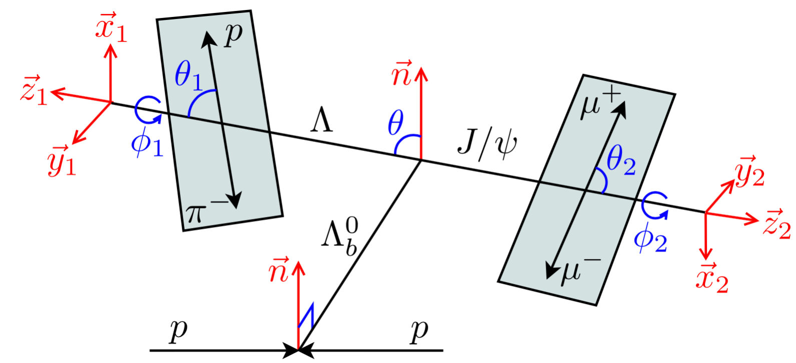
⬅ Mistagged (K↔π)

⬅ Background

- signal likelihood:

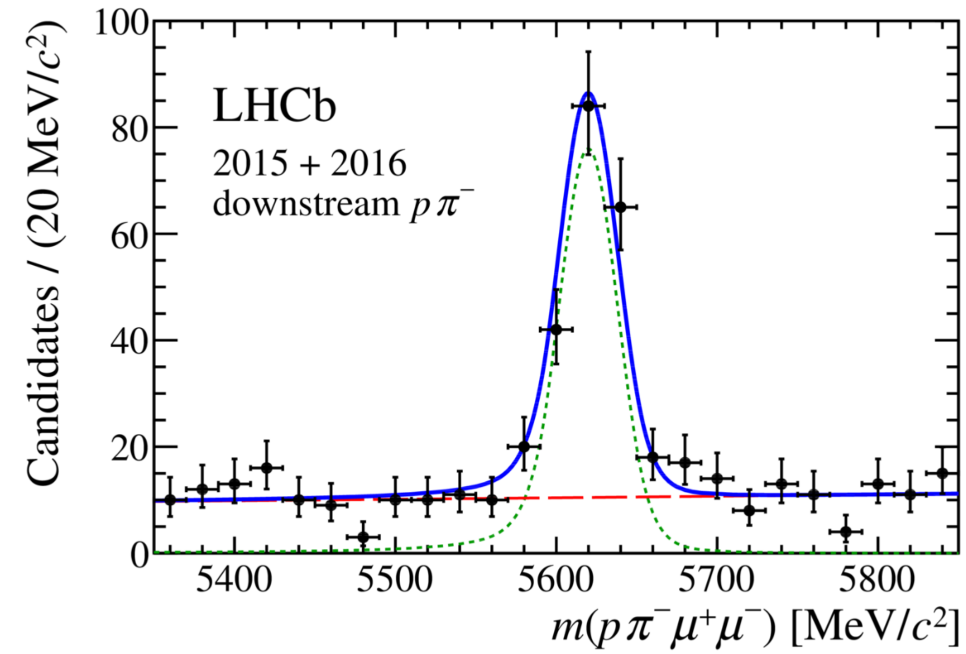
$$\begin{aligned}\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_K\mathrm{d}\phi} = \frac{9}{8\pi}\Big\{ & \frac{2}{3}\Big[(F_S + A_S\cos\theta_K)\left(1-\cos^2\theta_l\right) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big] \\ & + (1-F_S)\Big[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right) \\ & + \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi \\ & + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big]\Big\}\end{aligned}$$

b→sμμ | $\Lambda_b \to \Lambda\mu\mu$

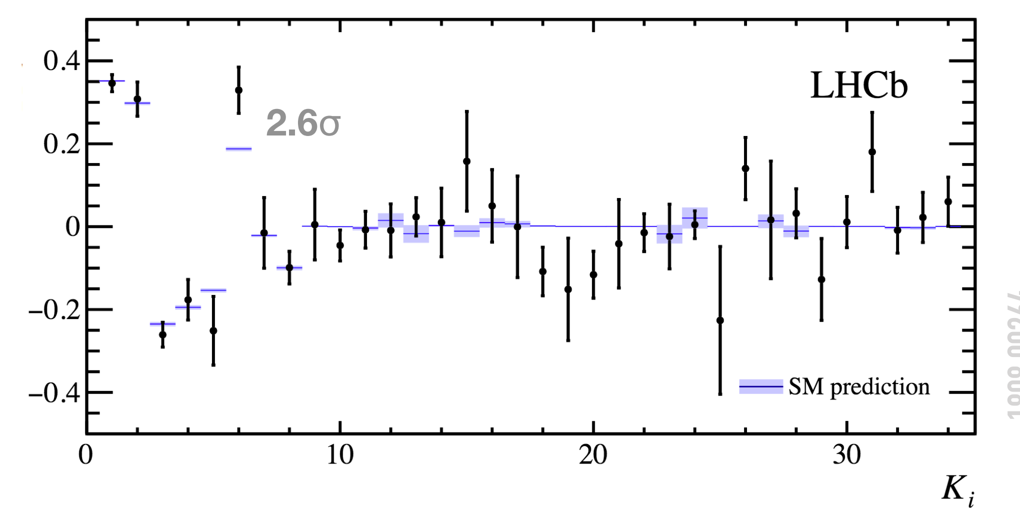


- complementary to $B^0 \to K^*\mu\mu$ in baryon sector
- $\Lambda_b \to \Lambda\mu\mu$ decay observed by CDF, and further explored by LHCb, ATLAS, CMS
- spin 1/2 ➡ 5 angles needed to describe system ➡ richer angular distribution

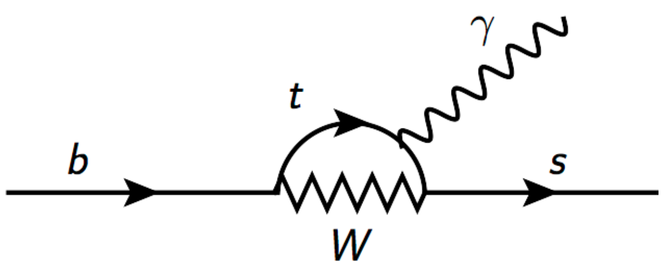
$$\frac{d^5\Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_i^{34} K_i f_i(\Omega)$$



- large number of parameters ➡ exploit method of moments (instead of likelihood fit)
- analysis update with 5fb^{-1} (2011-2016)
- results compatible with SM
  - larger discrepancy in K6 (2.6σ)
  - parameters K11-34 ~ 0 ➡ no polarization, also consistent with CMS+LHCb previous results

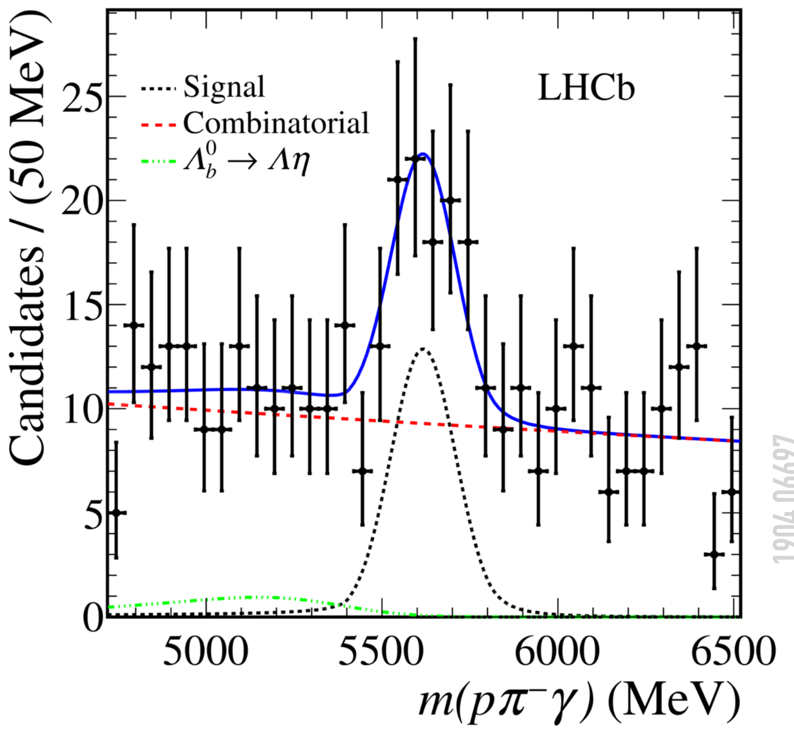


rare radiative | b→sγ



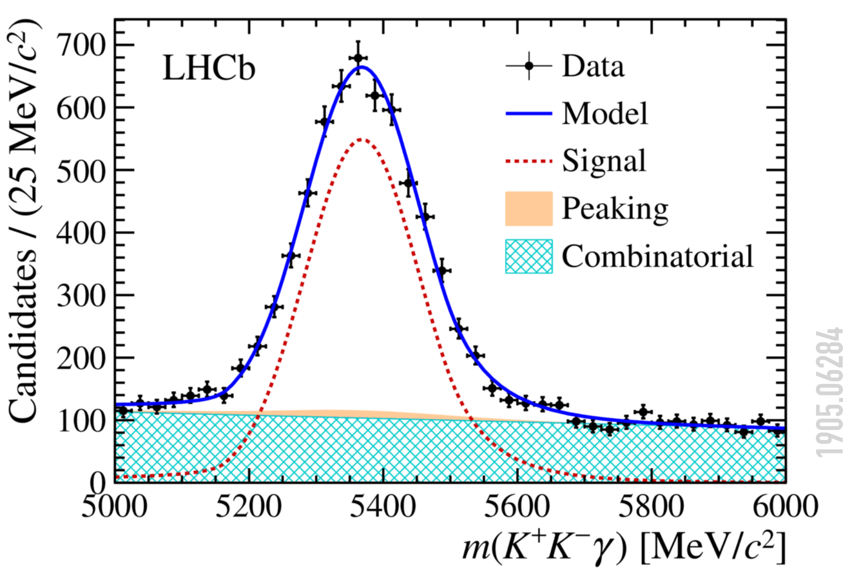
- FCNC decays
  - theo: added NP sensitivity via photon polarization
  - exp: reduced mass resolution, decay vertex
- **$\Lambda_b \to \Lambda\gamma$**
  - SM BF ~ (6-100)x10^{-7}, large form factor uncert.
  - previous best limit by CDF: BF<1.9×10^{-3} (90% CL)
  - LHCb: 1.7 fb^{-1} (2016); normalisation: $B^0 \to K^{*0}\gamma$

$$B(\Lambda_b \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$



observation: 5.6σ

- **$B_s \to \phi\gamma$**
  - LHCb updated analysis (Run1 3fb^{-1}) of time dependence rate adding flavor tagging
  - first measurements of the CP-violating and mixing-induced observables ($S_{\phi\gamma}$, $C_{\phi\gamma}$,$A^{\Delta}_{\phi\gamma}$)
  - results consistent with SM expectation



$b\to d\mu\mu$ | $B_s\to K^{*0}\mu\mu$

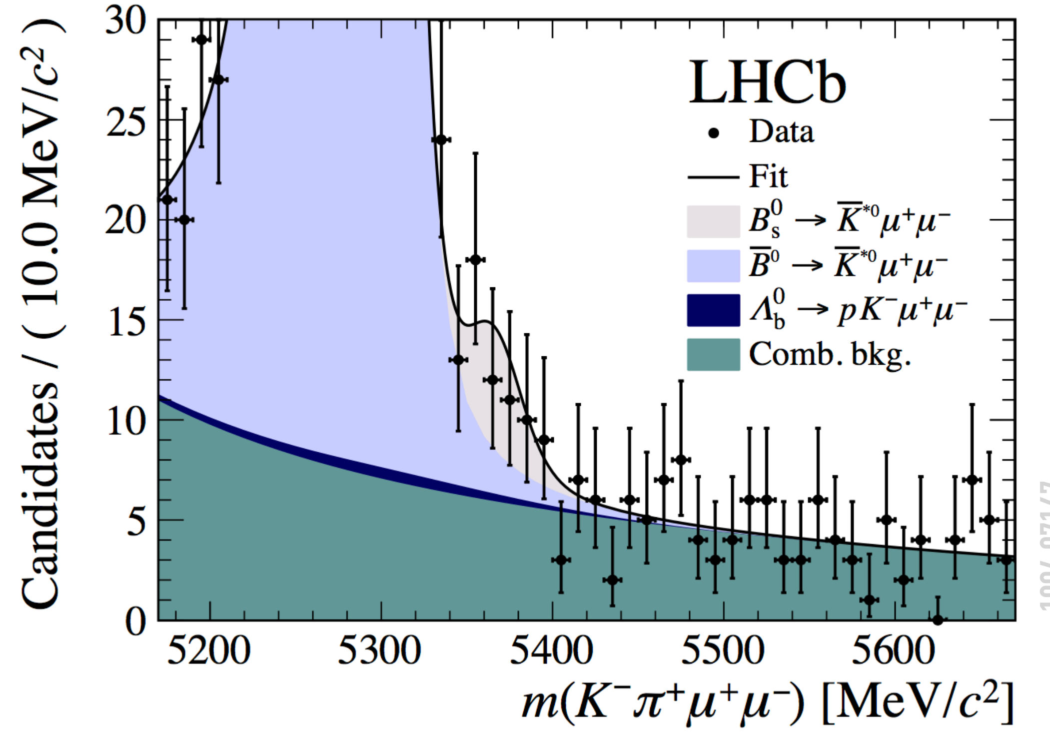
- $b\to dll$ transitions even more suppressed than $b\to sll$
  - $|V_{td}/V_{ts}| \sim 0.2$ ➡ $BF\sim10^{-8}$
- $B^0\to\mu\mu$: search ongoing
- $B^+\to\pi^+\mu\mu$: observed Run1 (LHCb)

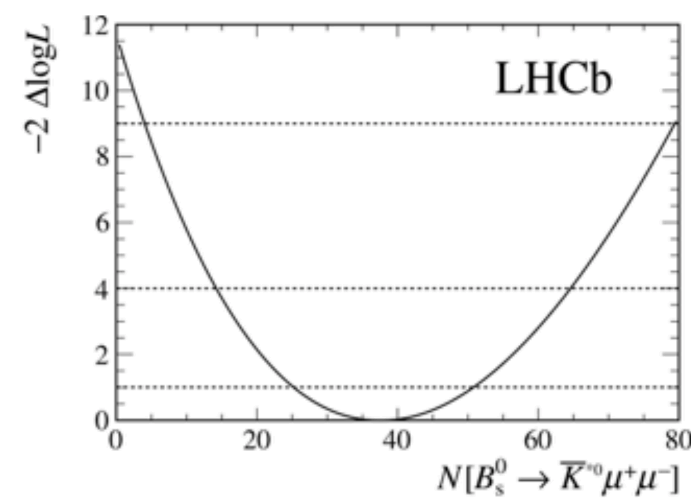
$$BF = (1.8 \pm 0.24 \pm 0.05) \times 10^{-8}$$ 1509.00414

- $\Lambda_b\to p\pi\mu\mu$: observed Run1 (LHCb)

$$BF = (6.9 \pm 1.9 \pm 1.1^{+1.3}{}_{-1.0}) \times 10^{-8}$$ 1701.08705

- **$B_s\to$ <u>K</u>$^{*0}\mu\mu$**: evidence Run2 (LHCb)
  - $4.6 fb^{-1}$; normalisation: $B^0\to J/\psi K^{*0}$
  - first evidence (3.4σ), measured BF agrees with SM prediction (1803.05876)





evidence: 3.4σ

$$B(B_s\to K^{*0}\mu\mu) = (2.9\pm1.9\pm 0.2\pm 0.3)\times10^{-8}$$

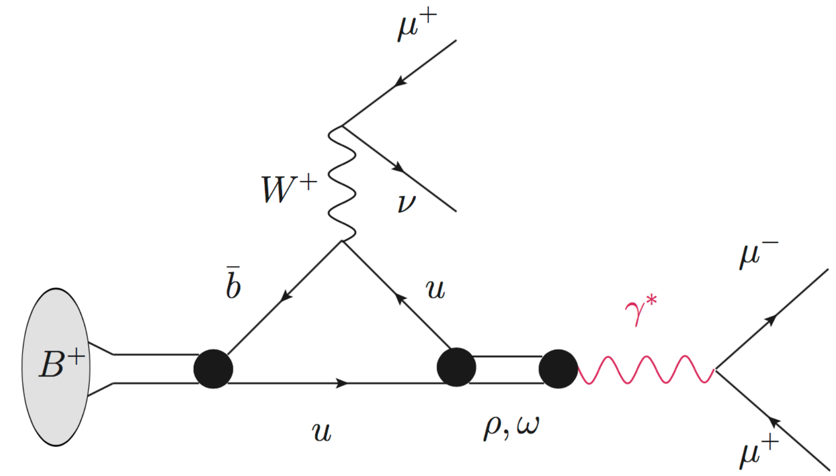
(SM: $3\text{-}4 \times 10^{-8}$)

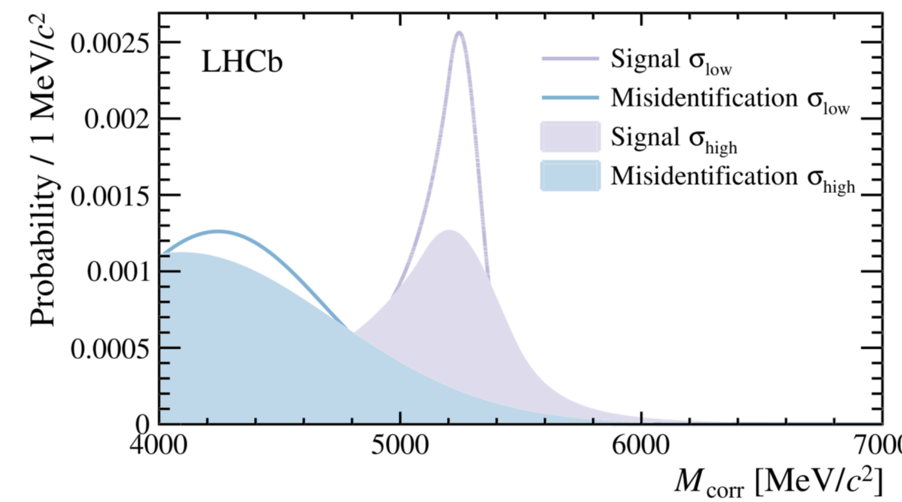
b→ull | B→μμμν

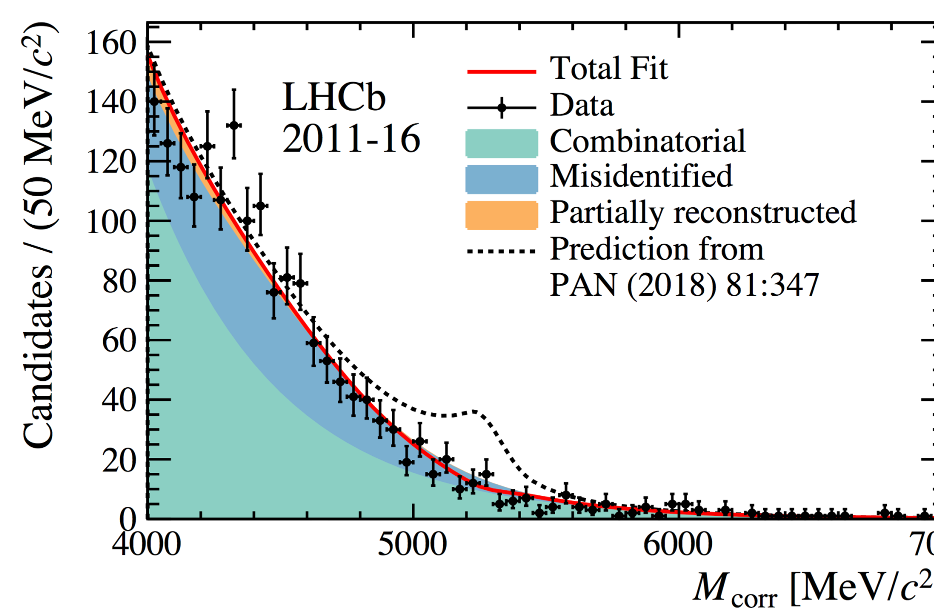
- CKM-suppressed decay
  - BF ∝ $|V_{ub}|^2$
  - NP sensitivity from helicity suppression
- current *related* best limits (by Belle)
  - $B(B^+\to\mu\nu)<1.1\times10^{-6}$, $B(B^+\to\mu\nu\gamma)<3.0\times10^{-6}$ (90%CL)
  - at LHC prefer >1 charged particles
- exploit corrected mass variable

$$M_{\text{corr}} = \sqrt{M^2_{\mu\mu\mu} + p_{\text{T}}'^2} + p_{\text{T}}'$$

- LHCb with 4.7 fb^{-1} (Run1 + 2016)
- normalisation mode: $B^+\to J/\psi K^+$
- no signal observed ➡ best world limit
  - $B(B^+\to\mu^+\mu^-\mu^+\nu_\mu) < 1.6\times10^{-8}$ (95% CL)
  - tension with a recent theory calculation (1.3×10^{-7})



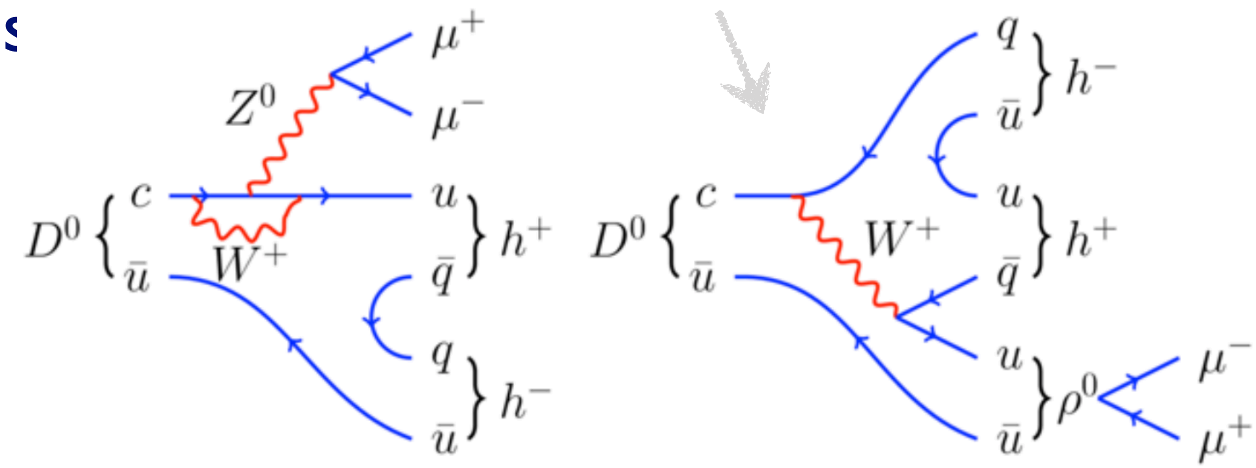




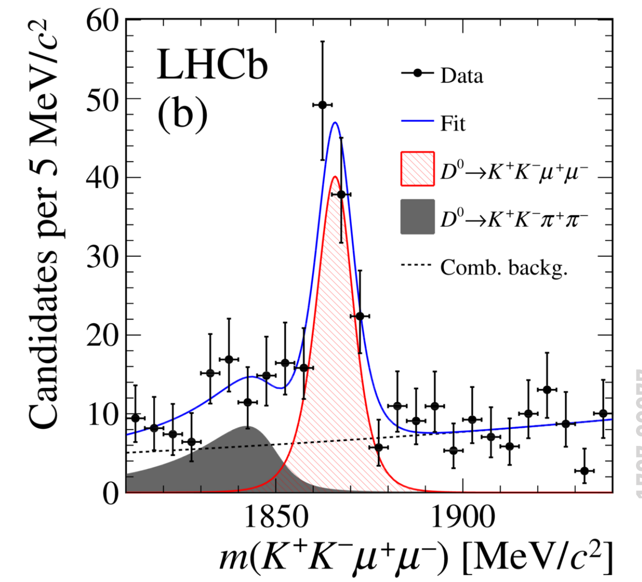
1812.06004.

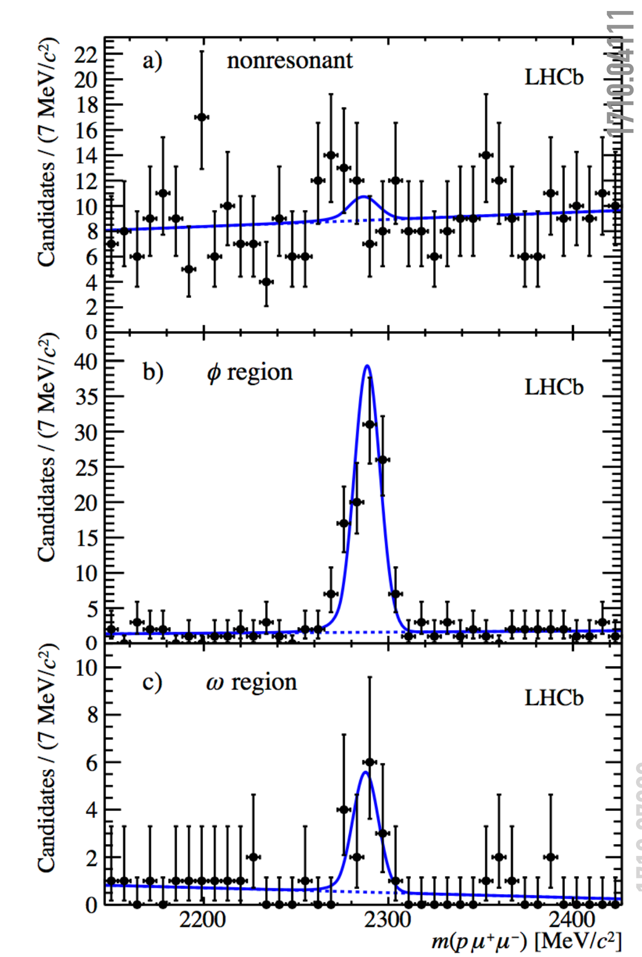
rare charm | c→uμμ

- FCNC in up-type quark sector
  - c→uμμ transition O(10^{-9}) in SM
- SM amplitude dominated by long-distance contributions ➡ q^2 regions



- **D^0→hhμμ**
  - observed with $2fb^{-1}$ Run1: rarest charm decay observed
  - B(D→KKμμ) = 1.54±0.33 x10^{-4}, B(D→ππμμ)=9.6±1.2 x10^{-4}
  - angular & CP asymmetries measured with $5fb^{-1}$ (2011-16)
- **Λ_c→pμμ**
  - no significant excess in non-resonant region:
  - BF(Λ_c→pμμ) < 9.6 x 10^{-8} @95%CL (~100 x BaBar)
  - observation in the ρ/ω region: B(Λ_c→pμμ)$_{\rho/\omega}$ = 9.4±3.9 x10^{-4}

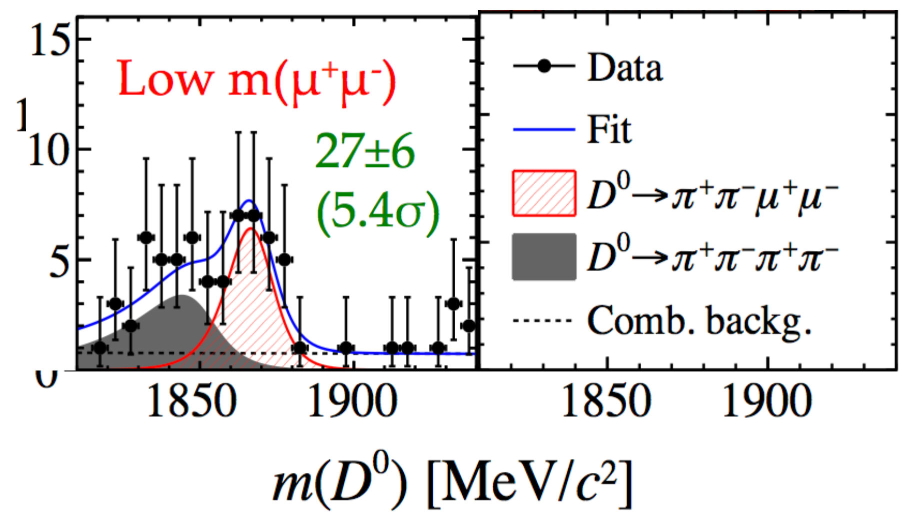




rare charm | D → llhh/ll/γγ

Decay	Note	SM	BF or best UL	Exp.
$D^0 \to \varphi\gamma$	Radiative	$\sim 10^{-5}$	$(2.8 \pm 0.2 \pm 0.1)\times 10^{-5}$	Belle
$D^0 \to \rho\gamma$	" "	$\sim 10^{-6}$	$(1.8 \pm 0.3 \pm 0.1)\times 10^{-5}$	Belle
$D^0 \to \gamma\gamma$	" "	$\sim 10^{-8}$	$< 8.5 \times 10^{-7}$	Belle
$D^+ \to \pi^+\mu^+\mu^-$	FCNC, $\mu^+\mu^-$ non-resonant	$\sim 10^{-9}$	$< 8.3 \times 10^{-8}$	LHCb
$D_s^+ \to \pi^+\mu^+\mu^-$	" "	$\sim 10^{-9}$	$< 4.8 \times 10^{-7}$	LHCb
$\Lambda_c^+ \to p\mu^+\mu^-$	" "	$\sim 10^{-9}$	$< 9.6 \times 10^{-8}$	LHCb
$D^+ \to \pi^+/K^+ e^+e^-$	FCNC, full e^+e^- spectrum	$10^{-8} \div 10^{-6}$	$< 0.3 / 1.2 \times 10^{-6}$	BESIII
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	FCNC, $\mu^+\mu^-$ non-resonant	$\sim 10^{-9}$	$(7.8 \pm 1.9 \pm 1.3)\times 10^{-8}$	LHCb
$D^0 \to \mu^+\mu^-$	FCNC	$10^{-13} \div 10^{-12}$	$< 7.6 \times 10^{-9}$	LHCb
$D^0 \to e^+e^-$	FCNC	$10^{-13} \div 10^{-12}$	$< 7.9 \times 10^{-8}$	Belle
$D^0 \to \upsilon\bar{\upsilon}$	Helicity suppressed	$\sim 10^{-30}$	$< 8.8 \times 10^{-5}$	Belle
$D^0 \to e^+\mu^-$	Lepton Flavour Violating	0	$< 1.6 \times 10^{-8}$	LHCb
$D^+ \to \pi^-\mu^+\mu^+$	Lepton Number Violating	0	$< 2.5 \times 10^{-8}$	LHCb
$D_s^+ \to \pi^-\mu^+\mu^+$	" "	0	$< 1.4 \times 10^{-7}$	LHCb
$D^+ \to \pi^-/K^- e^+e^+$	" "	0	$< 1.2 / 0.6 \times 10^{-6}$	BESIII

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ [observation]

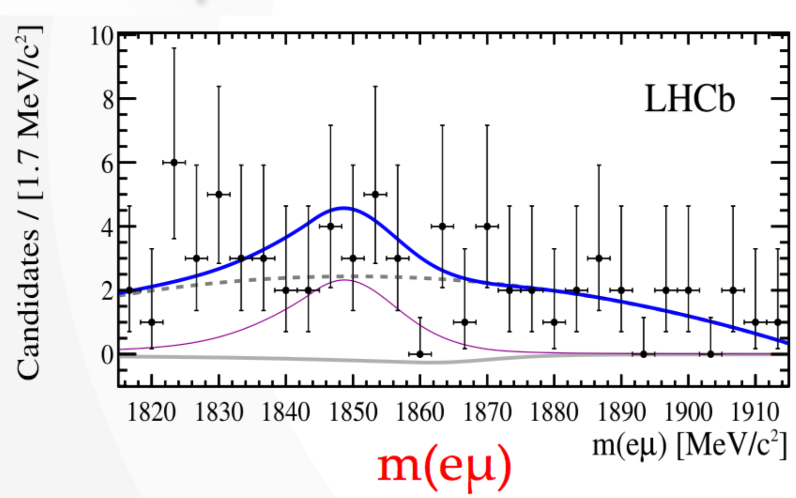


$D^0 \to \pi^+\pi^-\mu^+\mu^-$ is the rarest charm decay ever observed

$BF(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (7.8 \pm 1.9 \pm 0.5 \pm 0.8)\times 10^{-8}$

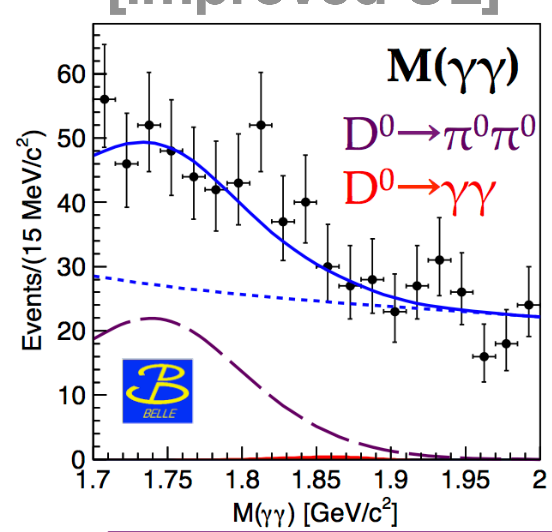
In agreement with SM

$D^0 \to e^+\mu^-$ [improved UL]



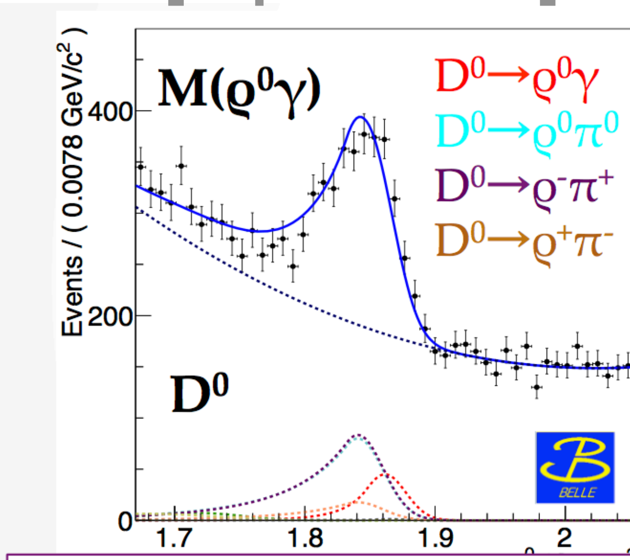
$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3\ (1.6) \times 10^{-8}$ @90 (95)% C.L.

[improved UL]



$BF(D^0 \to \gamma\gamma) < 8.5\times 10^{-7}$

[improved UL]



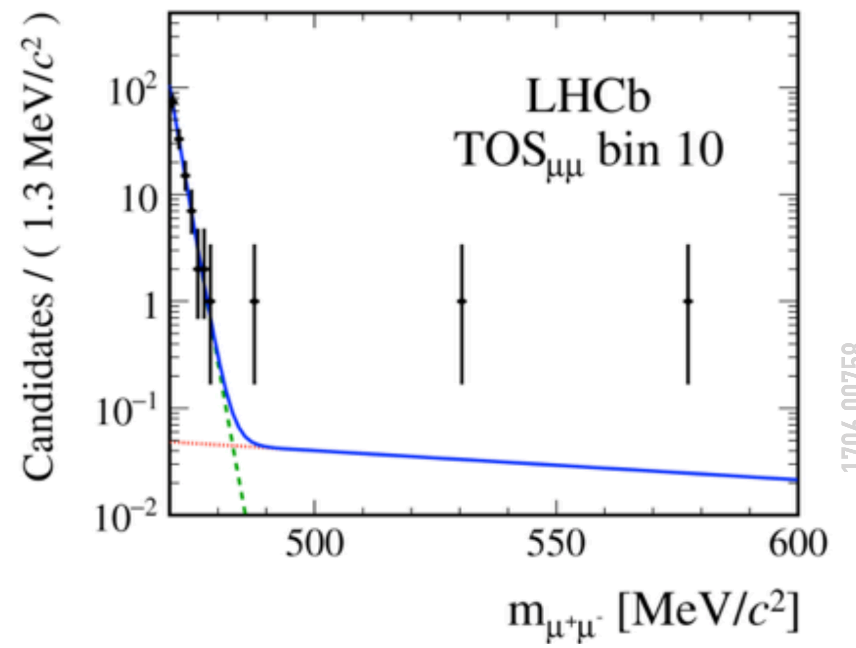
$BF(D^0 \to \rho\gamma) = (1.8 \pm 0.3 \pm 0.1)\times 10^{-5}$

rare strangeness | s→dμμ

- FCNC, O(10^{-12}) in the SM, but BF dominated by long distance contributions
- experimental challenge: low p_T of final state particles

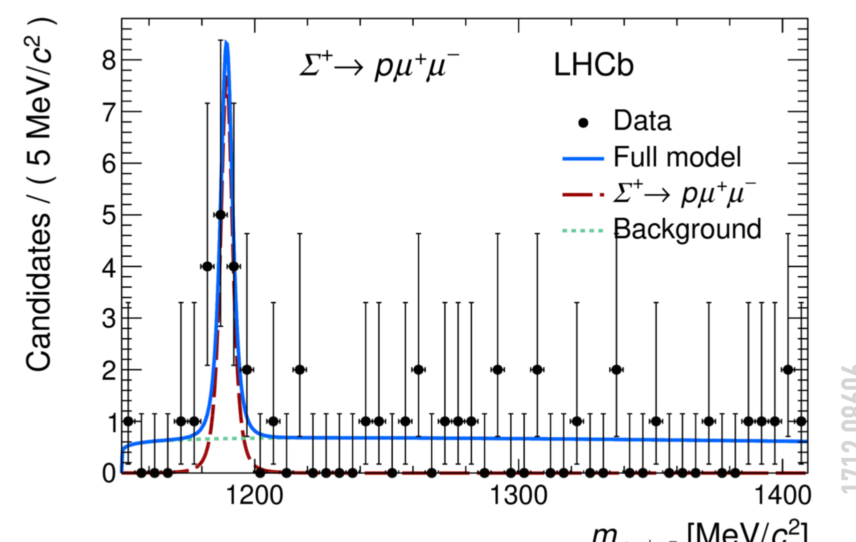
$K_S\to\mu\mu$

- updated analysis 3fb^{-1}; normalization: $K_S\to\pi\pi$
  - BF($K_S\to\mu\mu$) < 0.8 x 10^{-9} @90%CL
  - x11 improvement wrt previous LHCb result



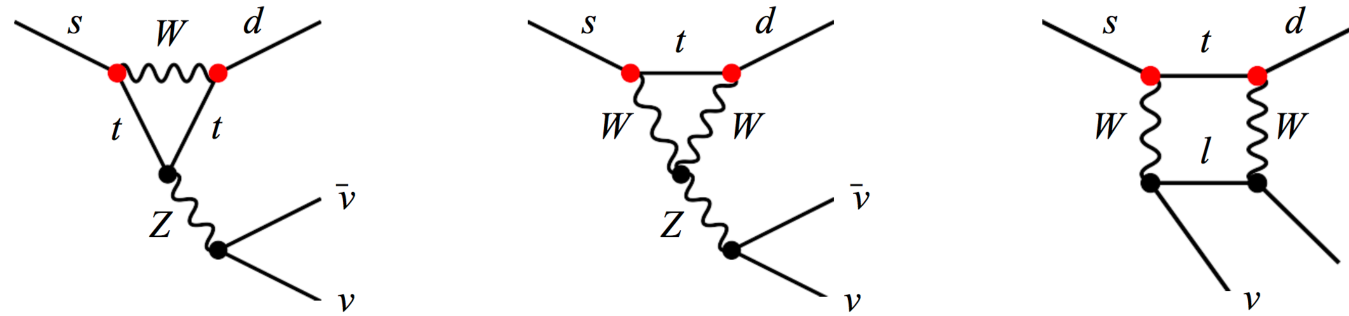
$\Sigma^+\to p\mu\mu$

- SM prediction BF ~(1.6-9)x10^{-8}
- 3fb^{-1} (Run1); normalization: $\Sigma^+\to p\pi^0$
- LHCb found 1st evidence at 4.1σ
  - BF($\Sigma^+\to p\mu\mu$) = (2.2 +1.8-1.3)x10^{-8}
  - no structure in dimuon mass
  - HyperCP excess (➡NP) at $m_{\mu\mu}$~214 MeV not confirmed



rare strangeness | s → d ν ν

Ultra rare decays (SM BF~10^{-11})



Theoretically clean

Hadronic matrix elements under control

Precise measurement of Kl3 form factor

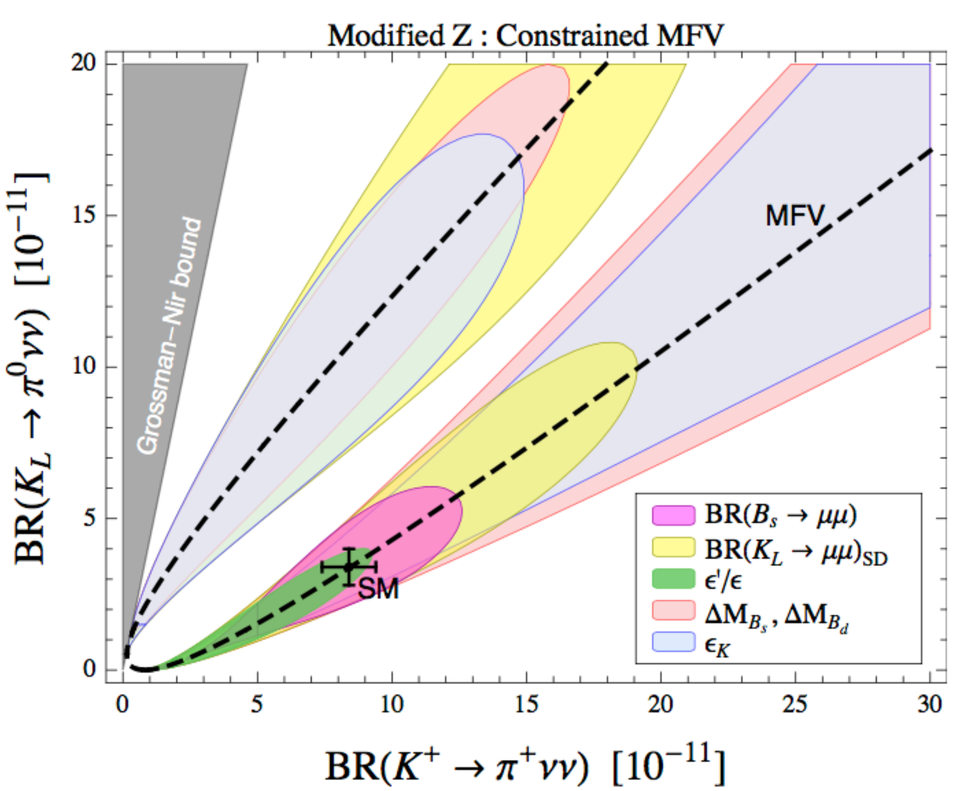
$K^+ \to \pi^0 e^+ \nu$ by NA48

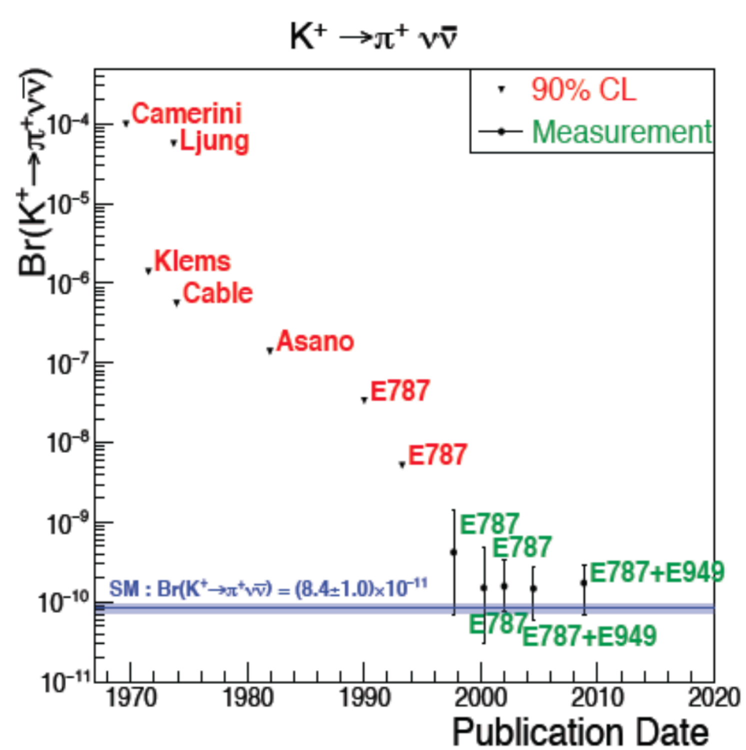
Exquisite sensitivity to NP

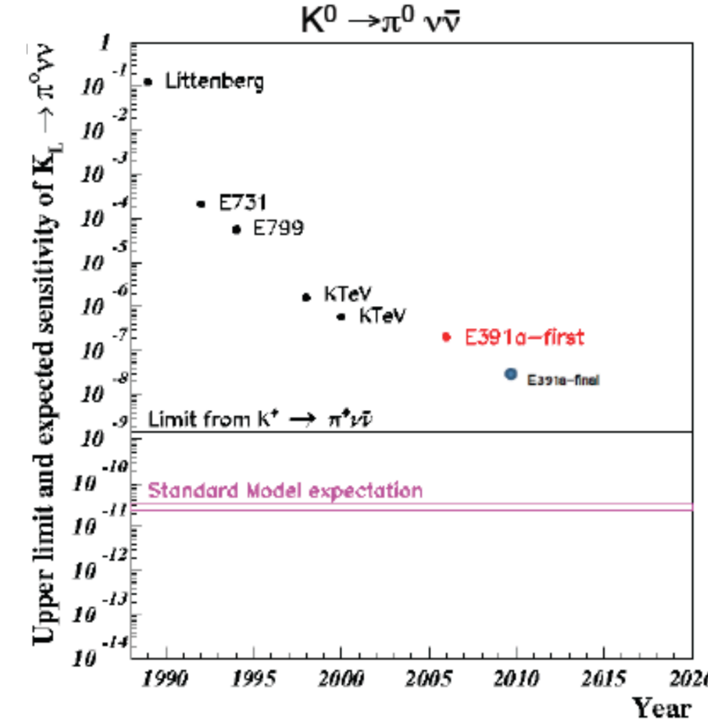
Up to very high mass scales ~2000 TeV

Discriminate among different NP scenarios

	$K^+ \to \pi^+ \nu\nu$	$K^0 \to \pi^0 \nu\nu$
SM:	$(8.4 \pm 1.0) \times 10^{-11}$	$(3.4 \pm 0.6) \times 10^{-11}$
Exp:	$(17.3^{+11.5}_{-10.5}) \times 10^{-11}$	$< 2.6\ 10^{-8}$ (90%CL)
	BNL E787 and 949 (7 events)	KEK E391a KOTO



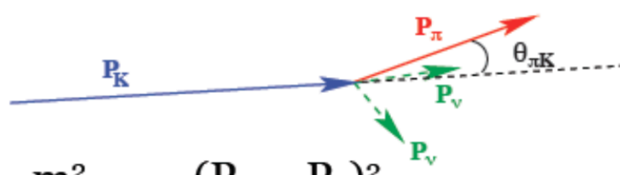




rare strangeness | K → π ν ν

K+:

- NA62 first results
  - Physics Run ongoing (2016-2018)
  - Demonstrated decay-in-flight technique

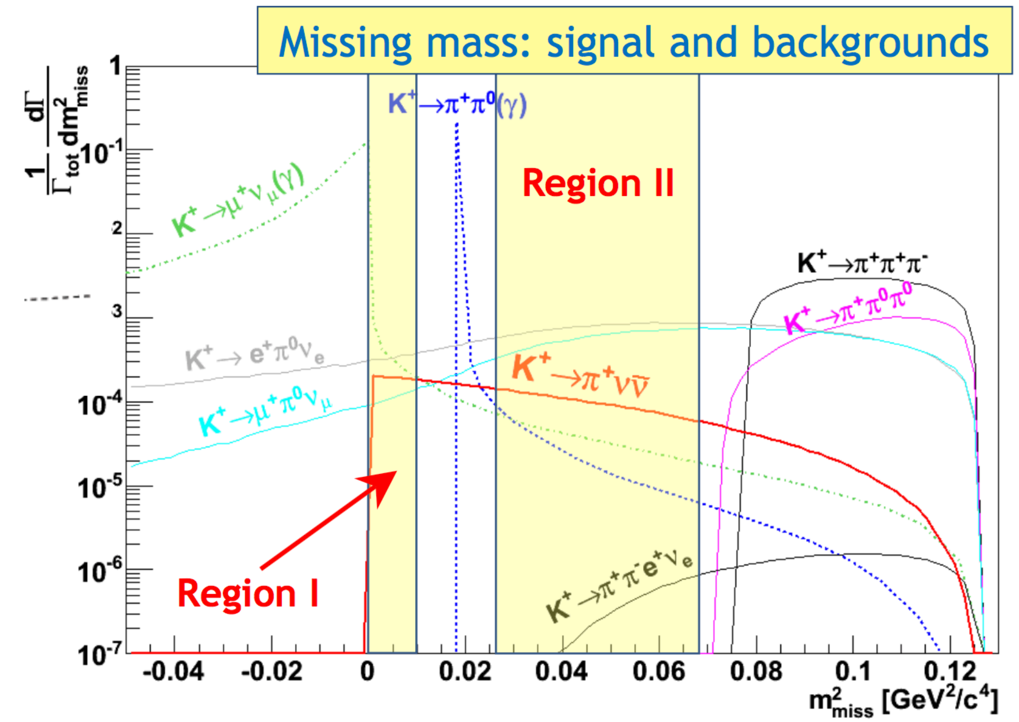


$m^2_{miss} = (P_K - P_\pi)^2$

- First results, from 2016 Run
  - One signal event observed, in 10^{11} collected

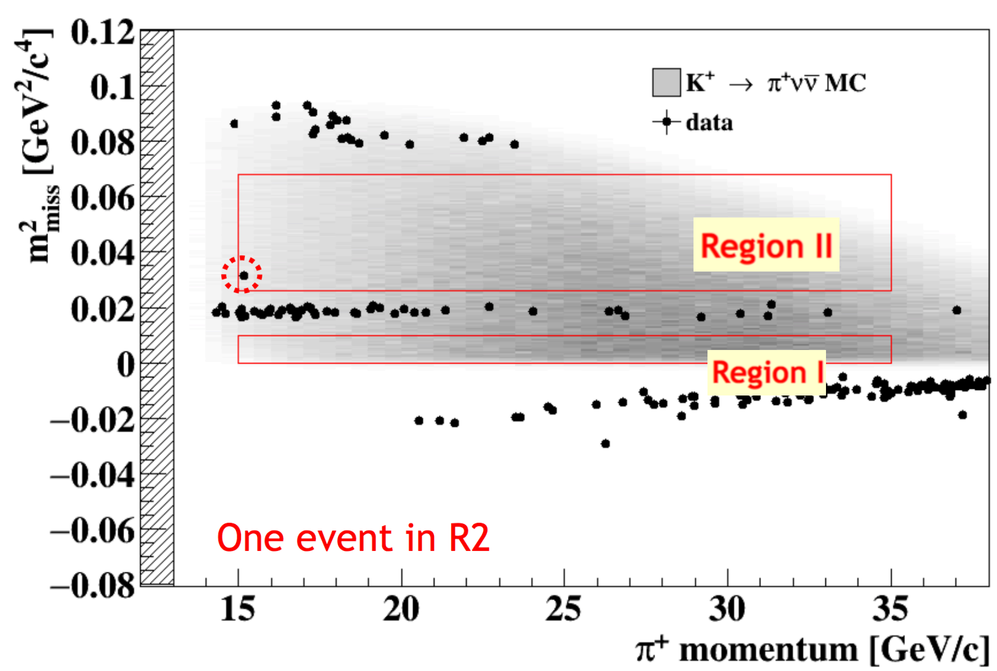
Br(K+ →π+νν) < 14 x 10^{-10} @ 95%CL

- Expect O(20) events from 2017+2018 data

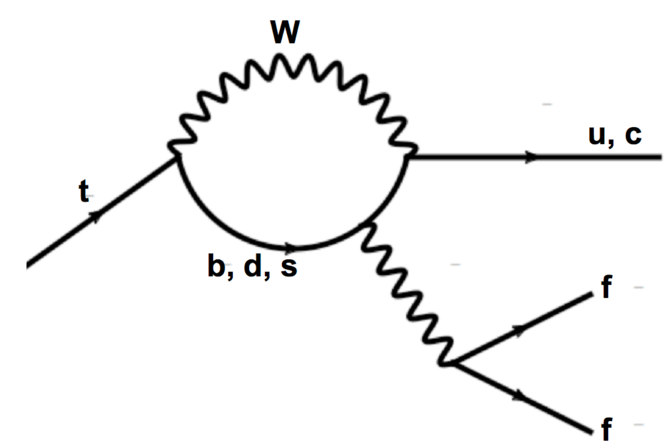


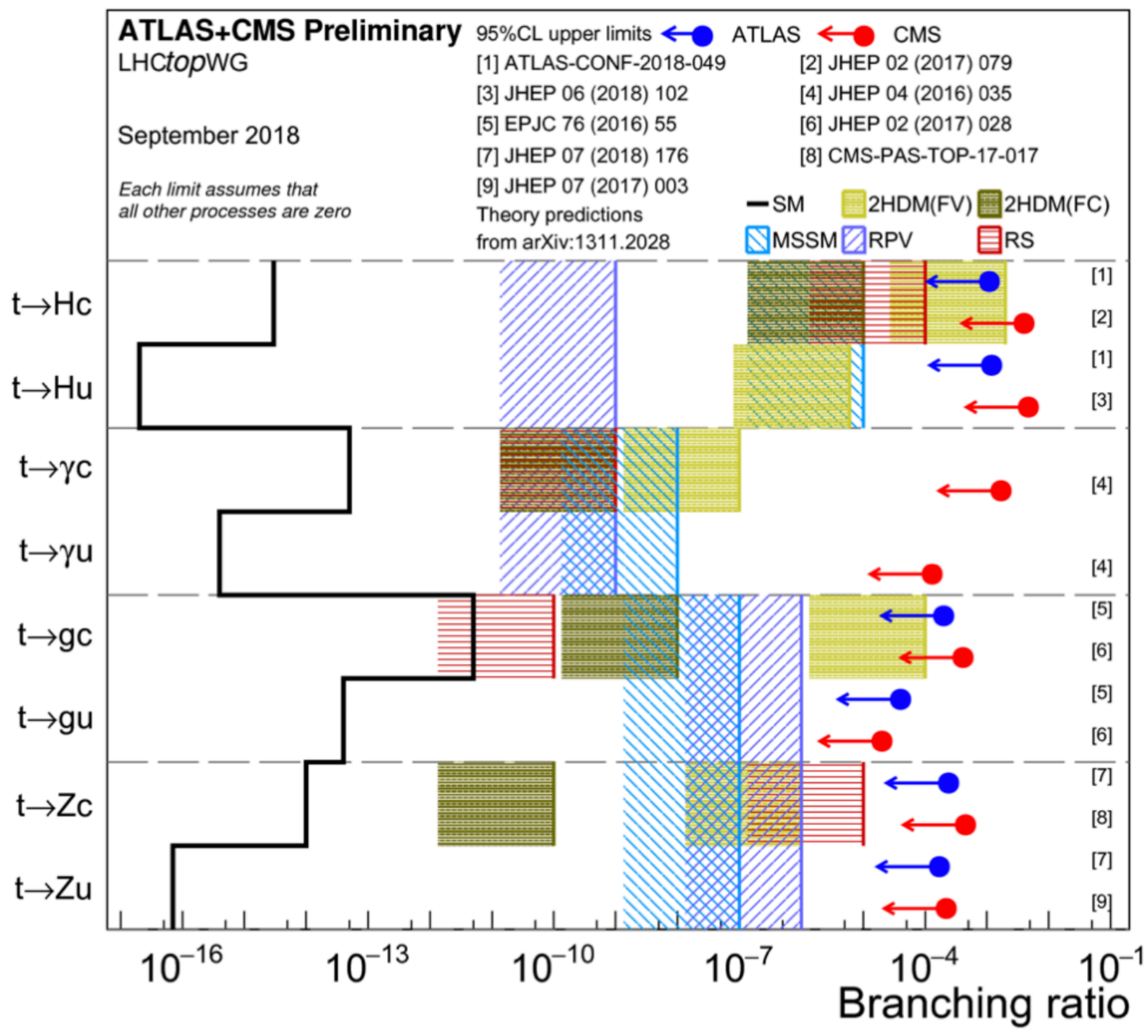
K0

- KOTO:
  - Physics Run ongoing 2018-2021
  - Future: reach O(100) SM events
- KLEVER
  - New proposal for the SPS
  - First data expected by 2026

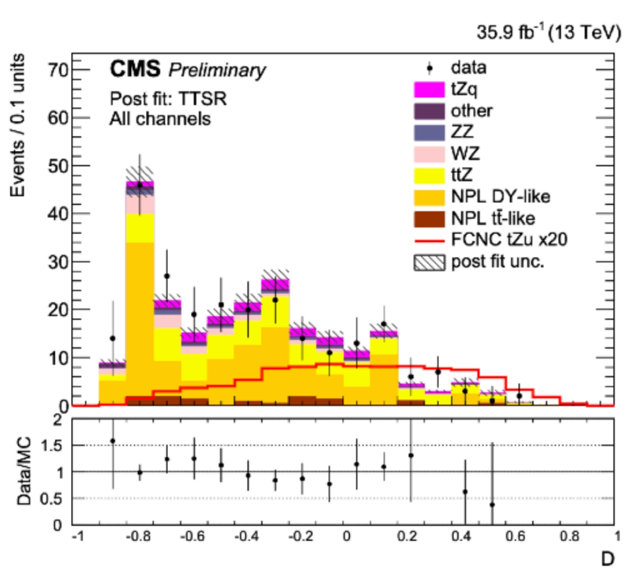


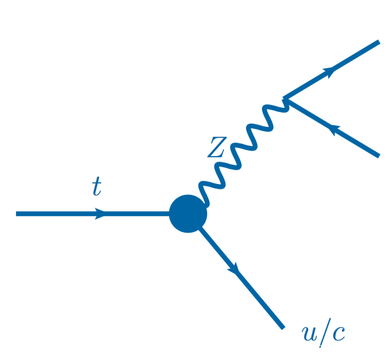
rare top | t→u/c



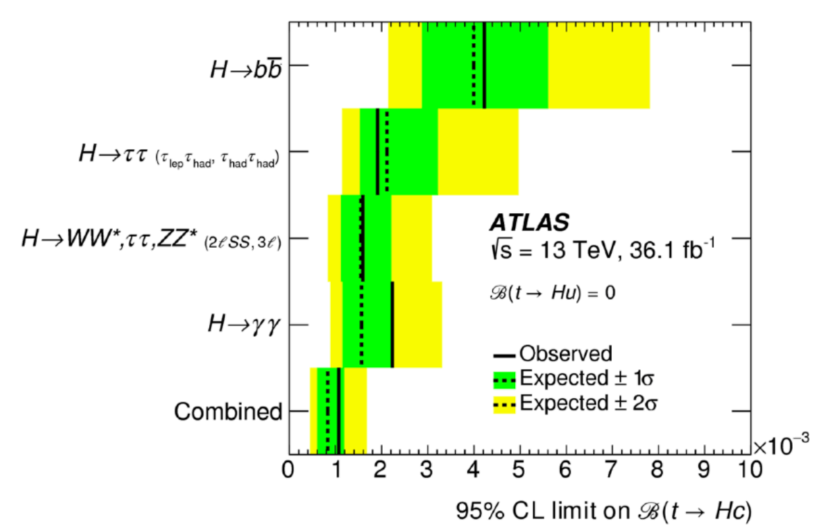


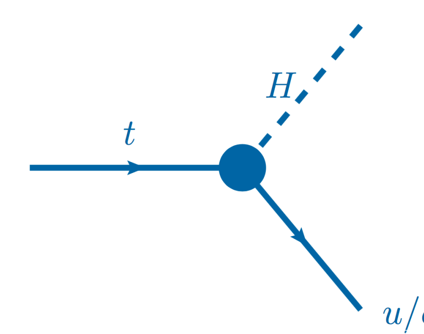
- FCNC/GIM in top sector lead to very rare processes
  - BF~10^{-14}
- rates enhanced in NP models
  - MSSM (10^{-7}), 2HDM (10^{-6}), RS(10^{-5})
- current limits ~10^{-4}





CMS-TOP-17-017





1803.09923

rare bosons | W,Z

- no exclusive hadronic decays of W and Z bosons observed yet

W→3π

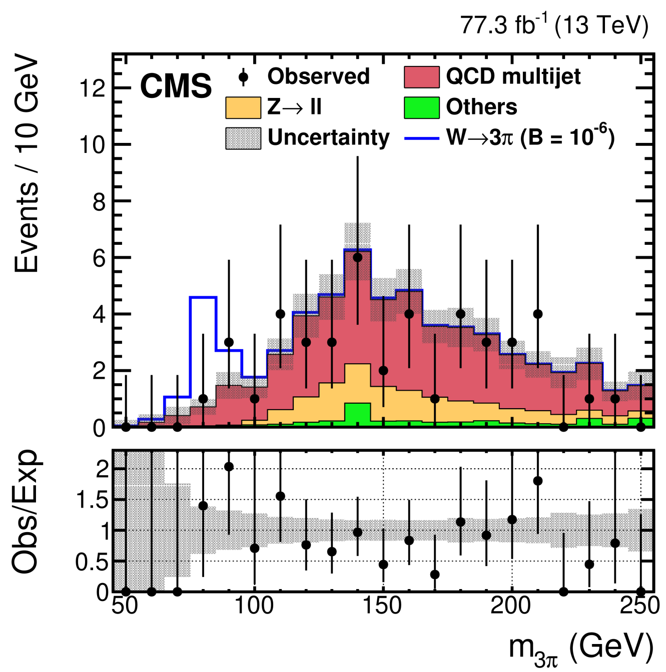
- probe exclusive W decay
  - small multiplicity decay
  - SM expectation ~10^{-8}-10^{-6}
  - inclusive production (not ttbar)
  - explore τ trigger + reco
- 95%CL limit: B(W→3π) <1.01×10^{-6}
- ➡ @HL-LHC: could allow precision M_W

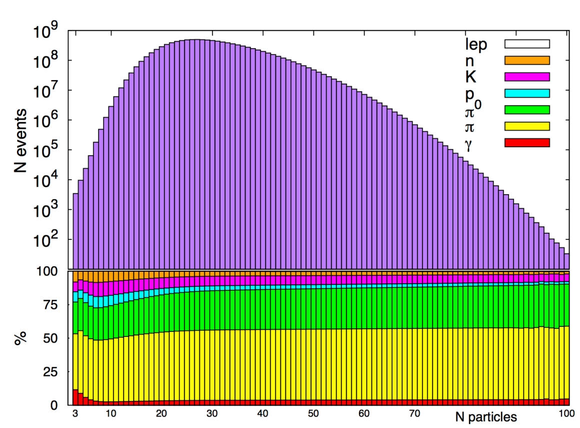
Z→ψll

- found a new Z decay
  - clean final state: ψμμ + ψee
  - SM expectation ~$(6.7\text{-}7.7)\times10^{-7}$
  - normalization: Z→μμμμ
  - obtained first observation
  - measured: B(Z→ψll) ~ 8×10^{-7}

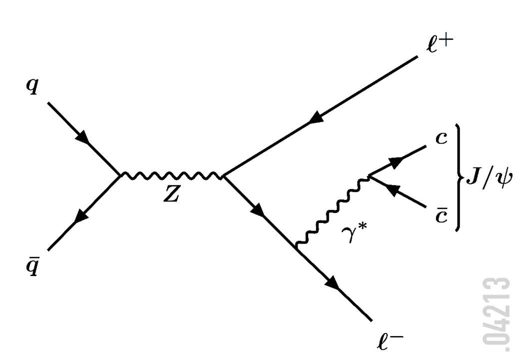
observation (5.7σ)

1901.11201

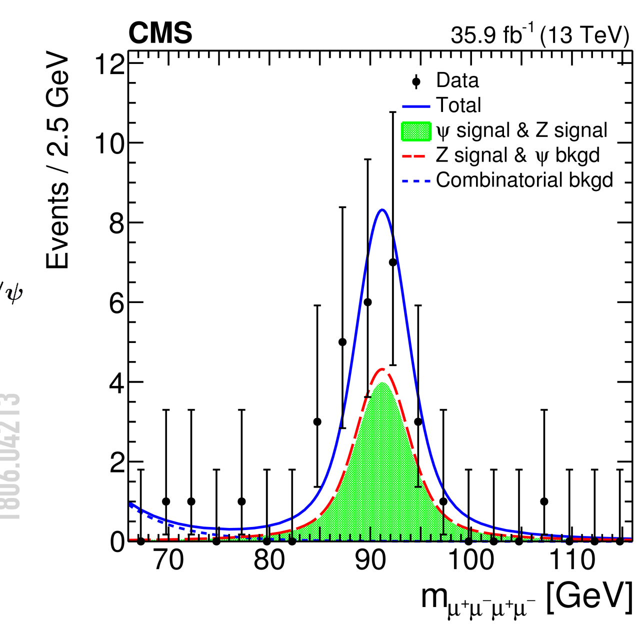




majority W,Z hadronic decays
into ~30-particle final state
1410.7475

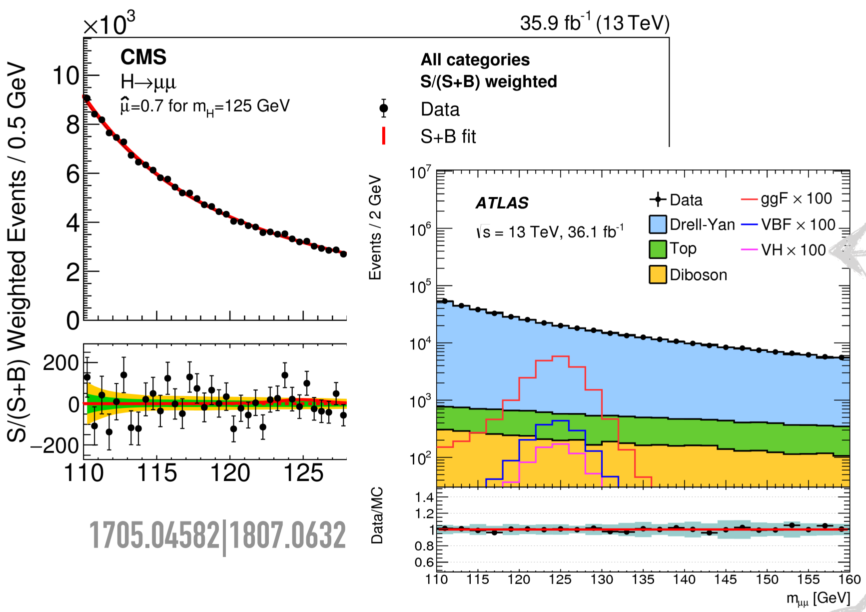


1806.04213

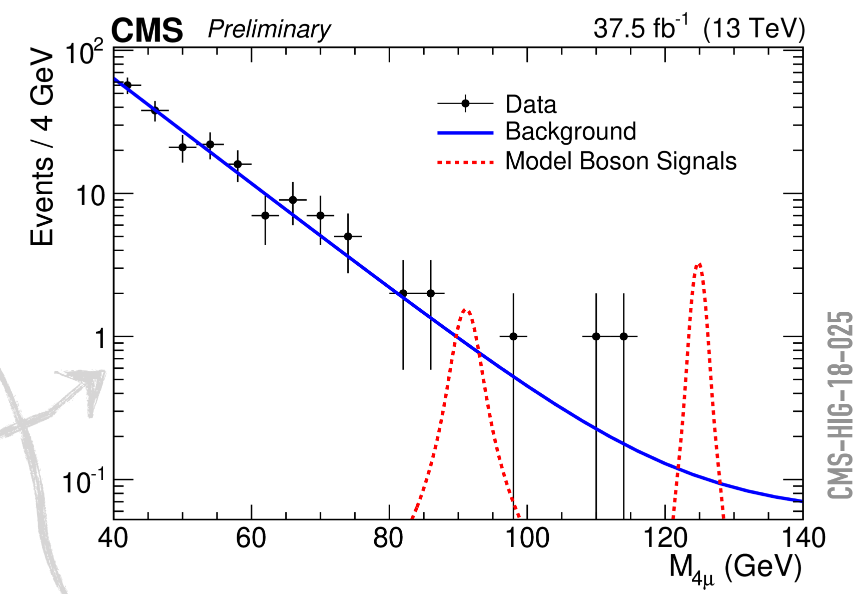


rare bosons | Higgs

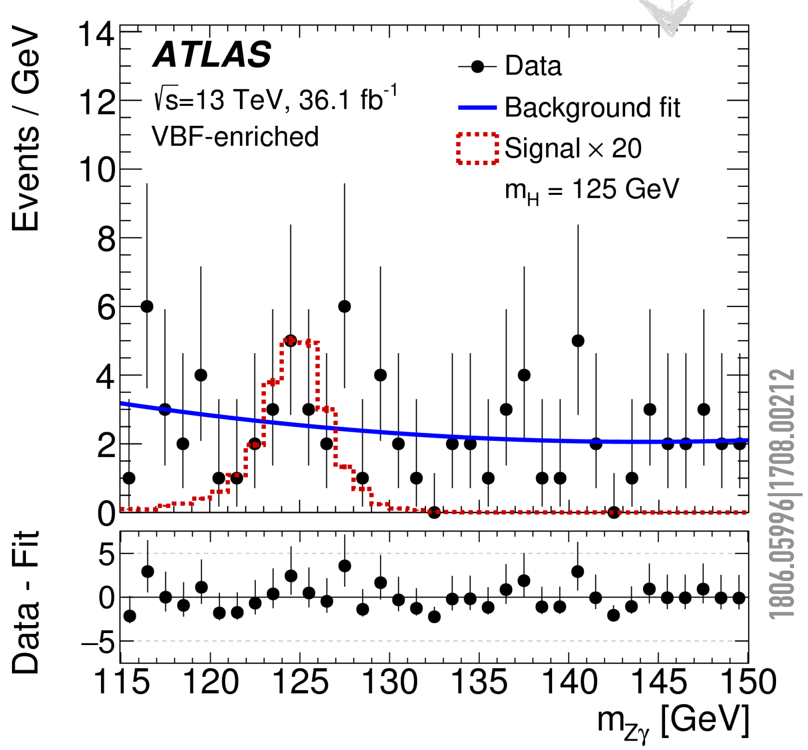
CHANNEL	BR (SM)
H → invisible	≥ 1 × 10^{-3}
H → μμ	2.17 × 10^{-4}
H → Zγ → ℓℓγ	1.01 × 10^{-4}
H → J/ψγ	3.0 × 10^{-6}
H → Υγ	~5 × 10^{-9}
H → ΥΥ	~2 × 10^{-9}
H → J/ψ J/ψ	~1.5 × 10^{-10}



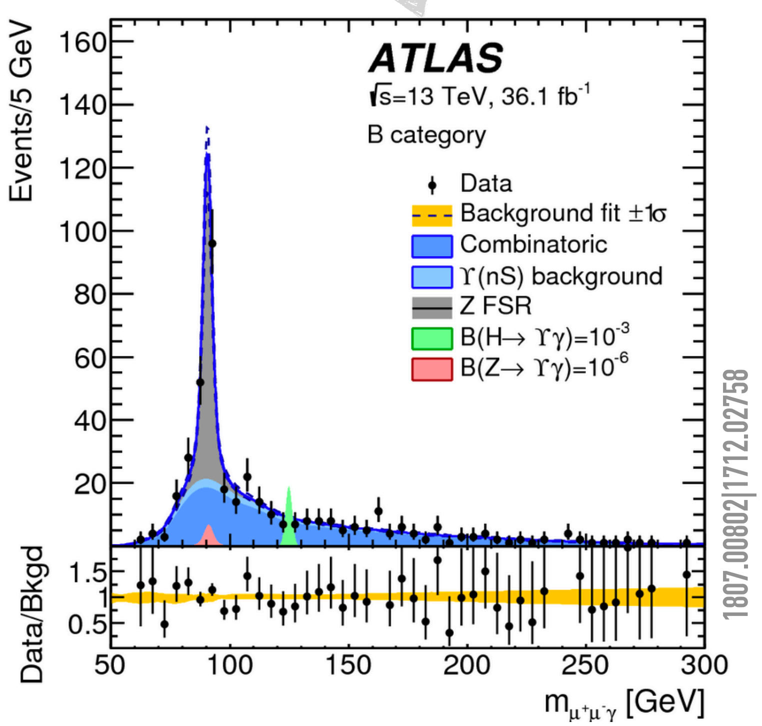
H→μμ: < 5.7x10^{-4} @95%CL



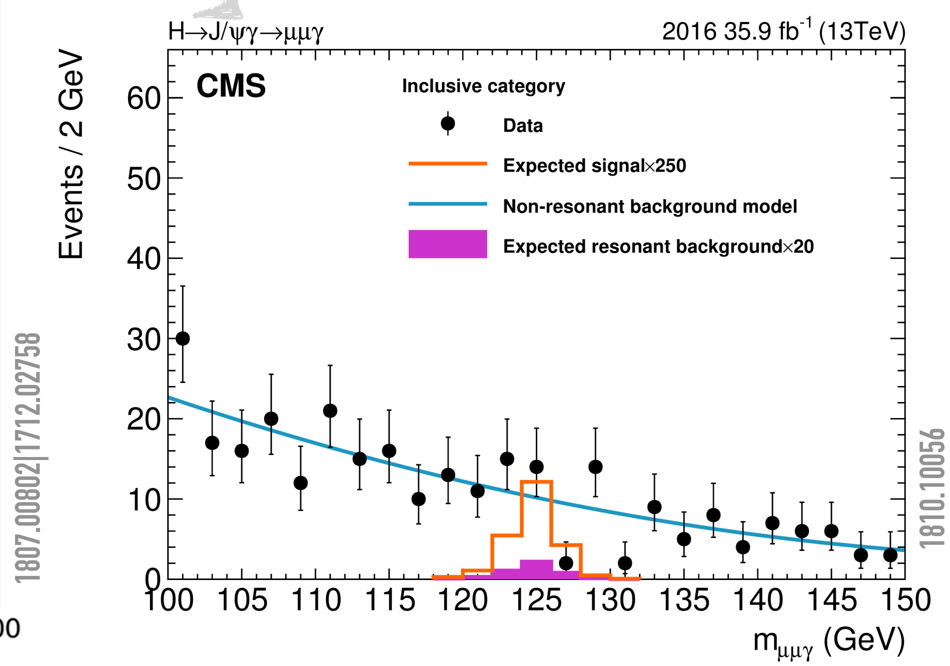
H→YY: < 1.4x10^{-3} @95%CL



H→Zγ: < 1 x 10^{-2} @95%CL

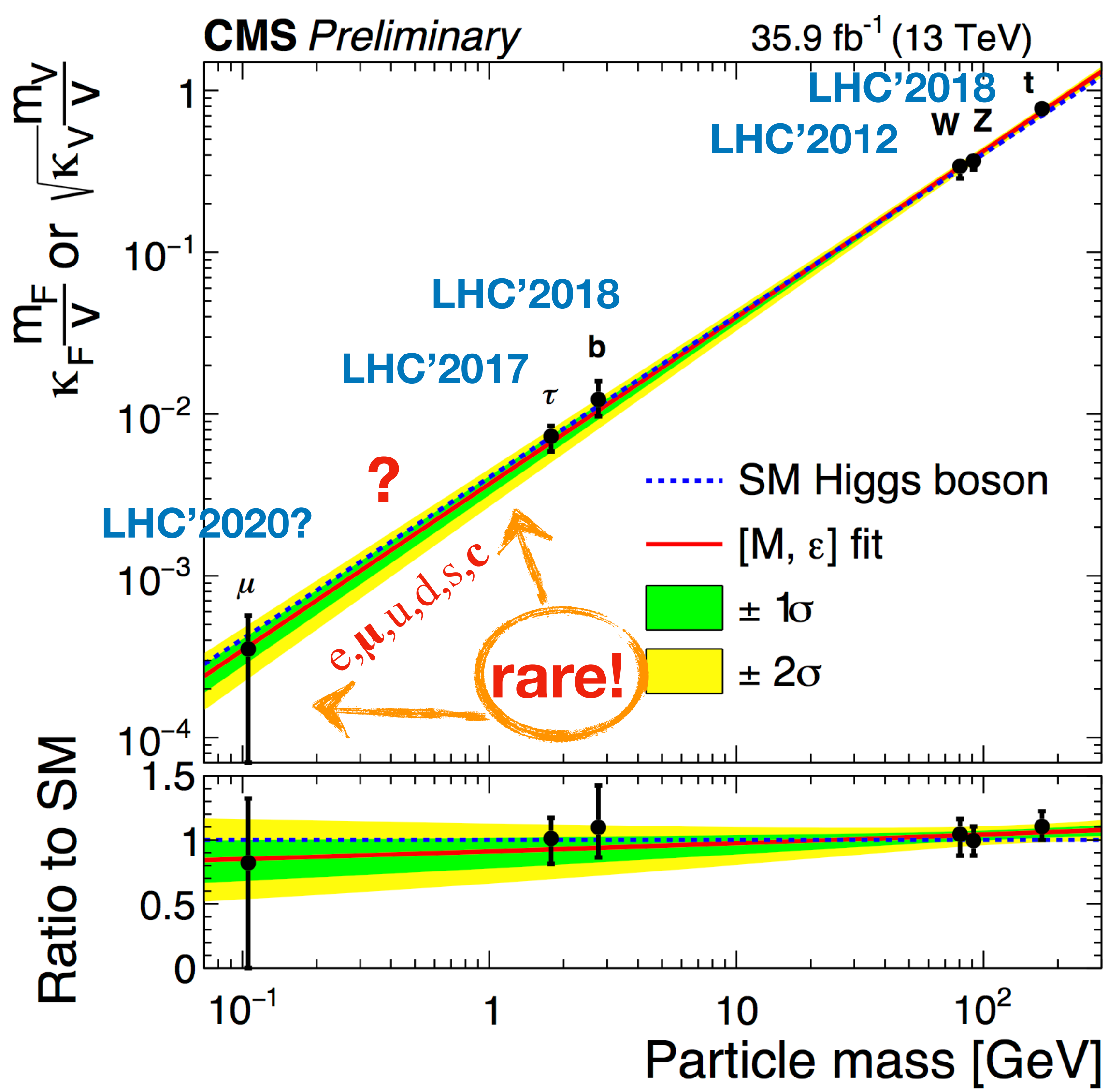


H→Yγ: < 4.9x10^{-4} @95%CL



H→Yγ: < 7.6x10^{-4} @95%CL

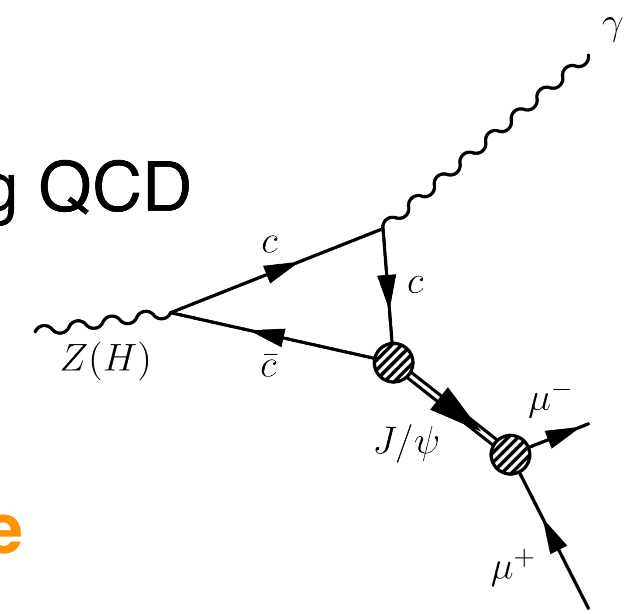
H couplings to light fermions? rare!

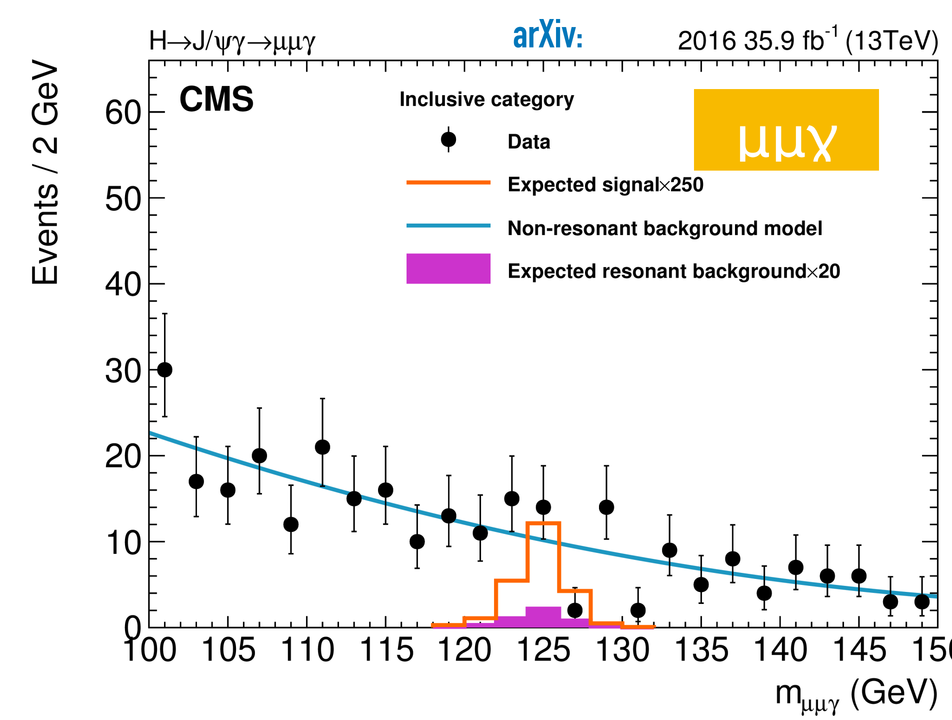


<u>Higgs couplings:</u>

- H to **W,Z,t,b,τ**: done
- H to **γ**: no mass ↠ no coupling
- H to **μ**: clean signature; expect Run2(+Run3)
- H to **c**: challenging, in reach @HL-LHC
- H to **u,d,s,e**: almost hopeless @LHC but NP!

- H→qq
  - overwhelming QCD background
- H→Qγ
  - clean but **rare**
  - H→Y/ψ/ϕ/ρ+γ





Currently @CMS

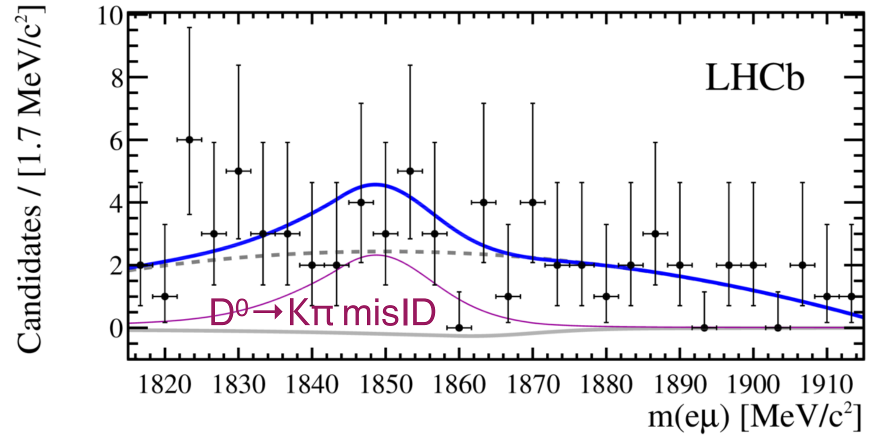
μ(H→cc) < 70 | μ(H→J/ψγ) < 220

forbidden rare | LFV, LNV, BNV

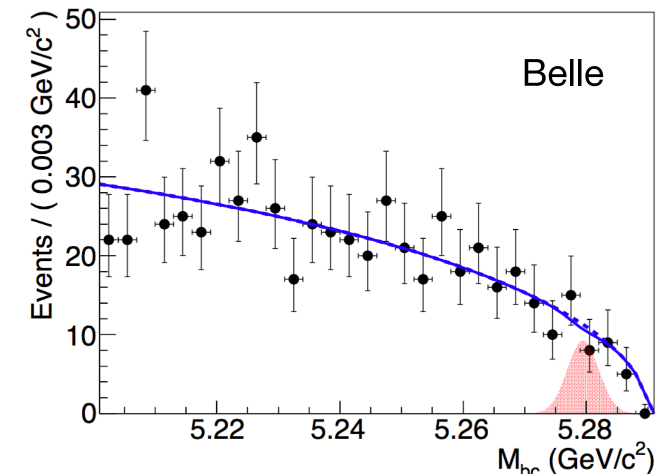
- charged Lepton Flavour Violation *practically* forbidden in SM
  - allowed by neutrino oscillations, but with BF far smaller than experimentally conceivable
  - BF in SM $<10^{-40}$, eg: 10: $B(\tau \to \mu\mu\mu) \sim B(Z \to e\mu, e\tau) \sim 10^{-54}$, $B(Z \to \mu\tau) \sim 10^{-60}$
- potentially sizeable BF enhancements from NP models
  - BF in NP up to 10^{-9}-10^{-4}, eg: Z'(10^{-8}), LQ(10^{-5}), Pati-Salam (10^{-4})
- models addressing LFU anomalies usually imply LFV/LNV/BNV
- a variety of searches is performed …

searches for
LFV, LNV, BNV
in decays of
τ,D,B,Z,H,t

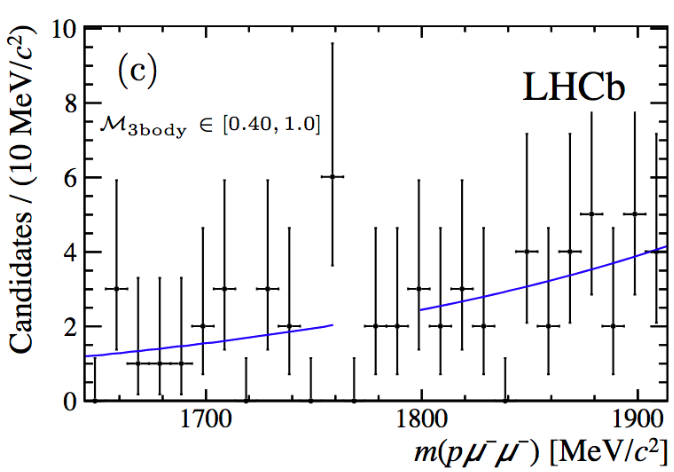
D → μe   1512.00322

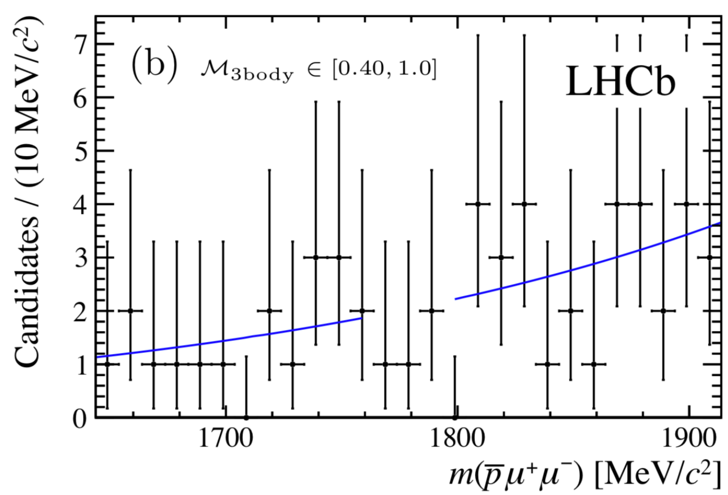


B → K*μe   1807.03267

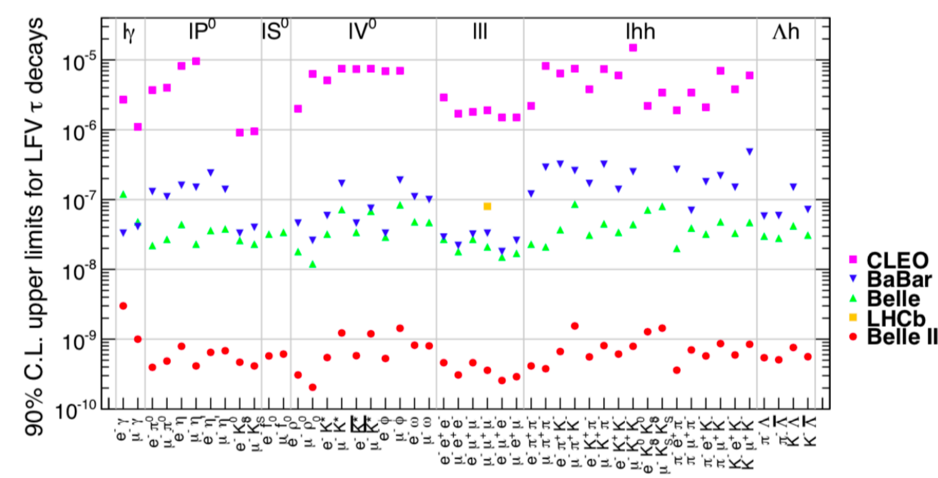


LNV/BNV τ decays   1304.4518

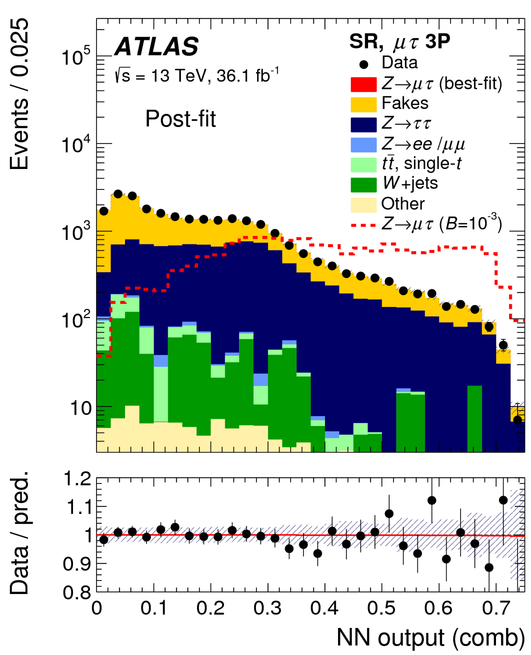




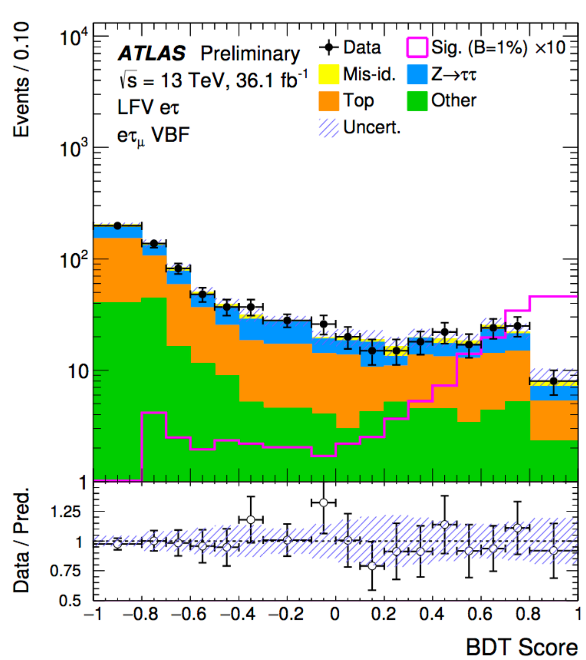
LFV τ decays   1812.04225



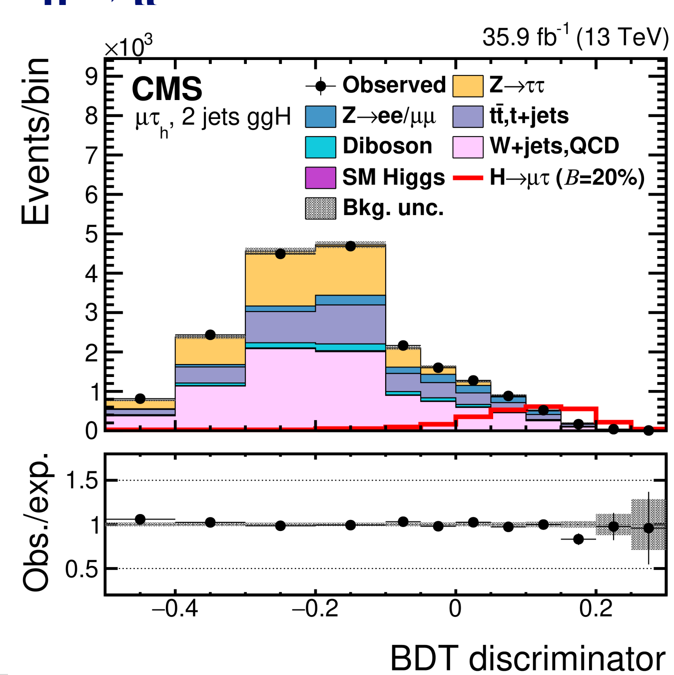
Z → ll'   1804.09568



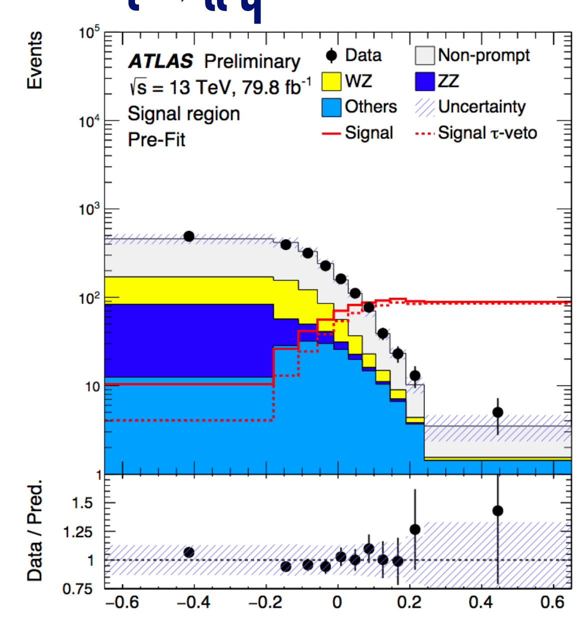
ATLAS-CONF-2019-013



H → ll'   1712.07173

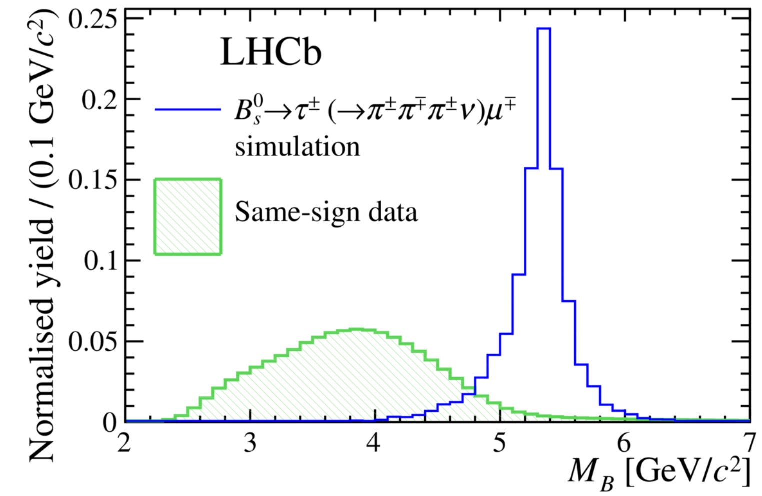


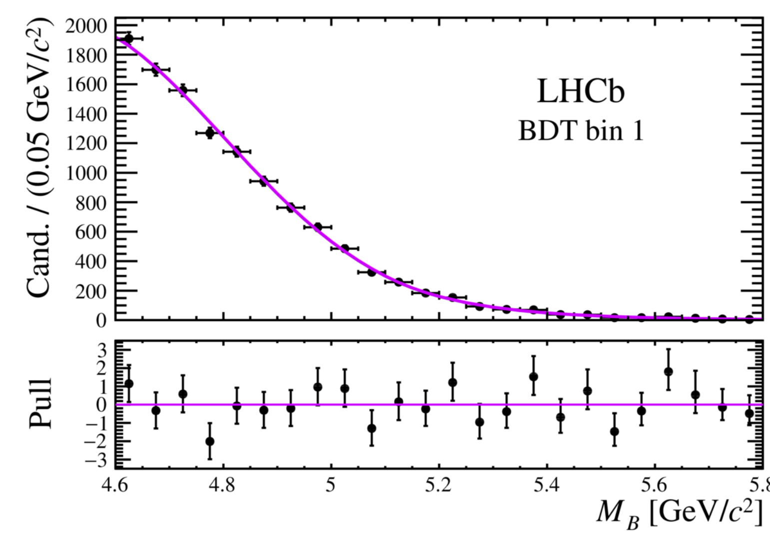
t → ll'q   ATLAS-CONF-2018-044



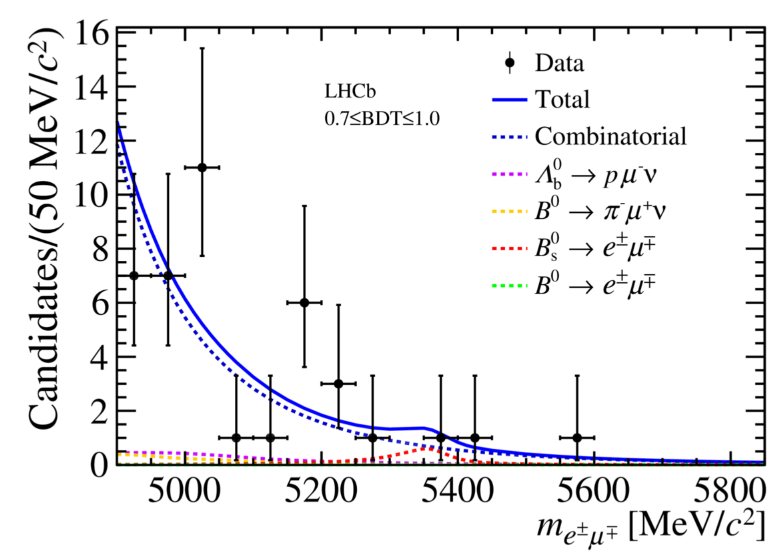
forbidden rare | B→ll'

- **$B_{(s)}\to\tau\mu$**
  - tau reconstructed as $\tau\to\pi\pi\pi\nu$
  - dataset: $3fb^{-1}$
  - normalisation: $B\to D^-(\to K\pi\pi)\pi$
  - limited separation of B^0 and B_s ➡ limits derived assuming contributions from each at a time
  - $BF(B^0\to\tau\mu) < 1.4 \times 10^{-5}$ (@95%CL)
  - $BF(B_s\to\tau\mu) < 4.2 \times 10^{-5}$ (@95%CL)
- **$B_{(s)}\to e\mu$**
  - dataset: $3fb^{-1}$
  - normalisation: $B\to K\pi$, $J/\psi K$
  - $BF(B^0\to e\mu) < 1.3 \times 10^{-8}$ (@95%CL)
  - $BF(B_s\to e\mu) < 6.3 \times 10^{-8}$ (@95%CL)





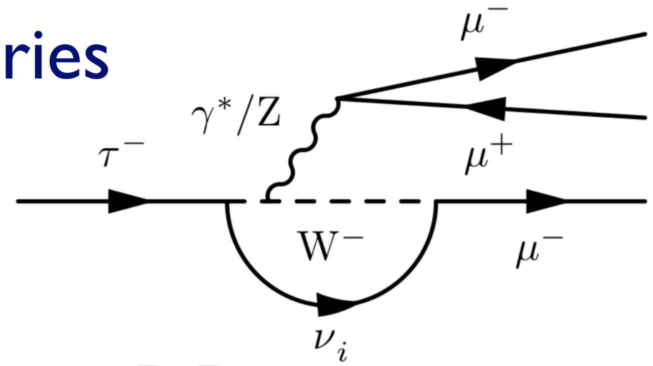
1905.06614



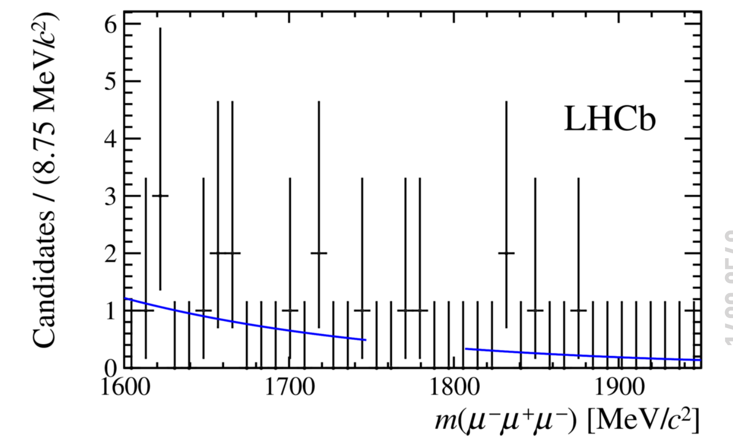
1710.04111

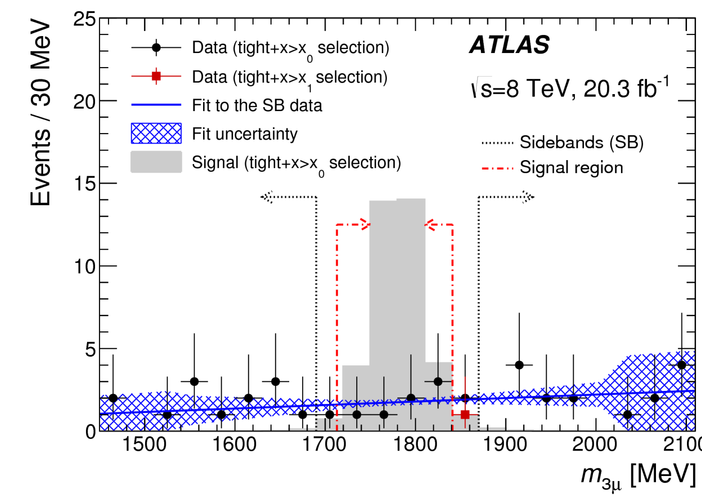
rare lepton | τ→μμμ

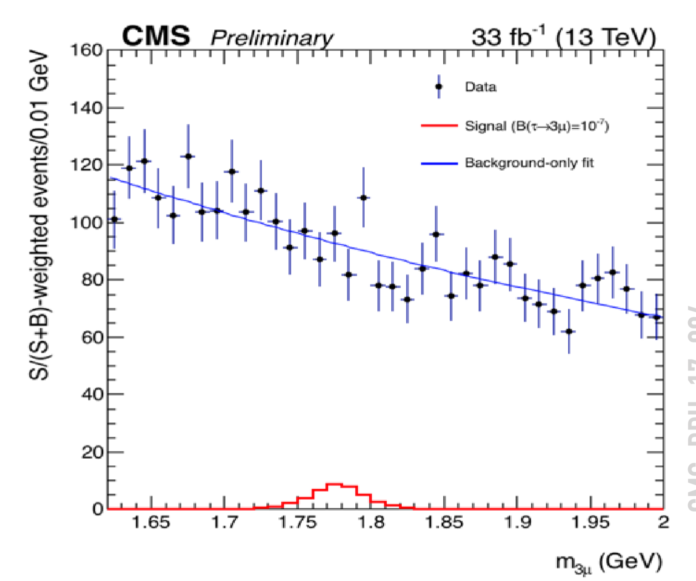
- clean final state, searched for at various colliders
- most stringent limit by B factories
  - BF < 2.1 x 10^{-8} @90% CL

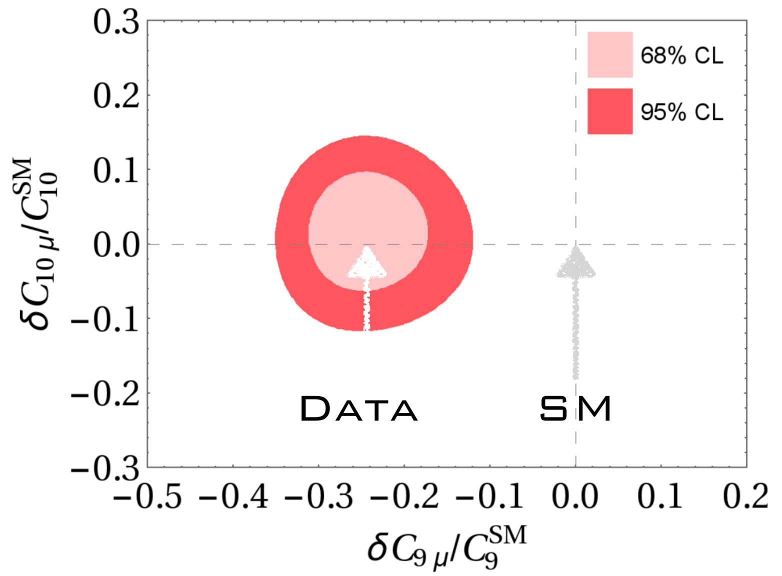


- LHCb
  - 3fb⁻¹; normalisation D_s→ϕπ; source; B,D→τ
  - BF < 4.6 x 10^{-8} @90% CL
- ATLAS
  - 20fb⁻¹ (Run1); normalisation W→τν; source: W→τ
  - BF < 3.8 x 10^{-7} @90% CL
- CMS
  - 33fb⁻¹ (Run2); normalisation D_s→ϕπ; source: B,D→τ
  - BF < 8.8 x 10^{-8} @90% CL
- prospects
  - HL-LHC: O(10^{-9}) | Belle II: O(10^{-10})







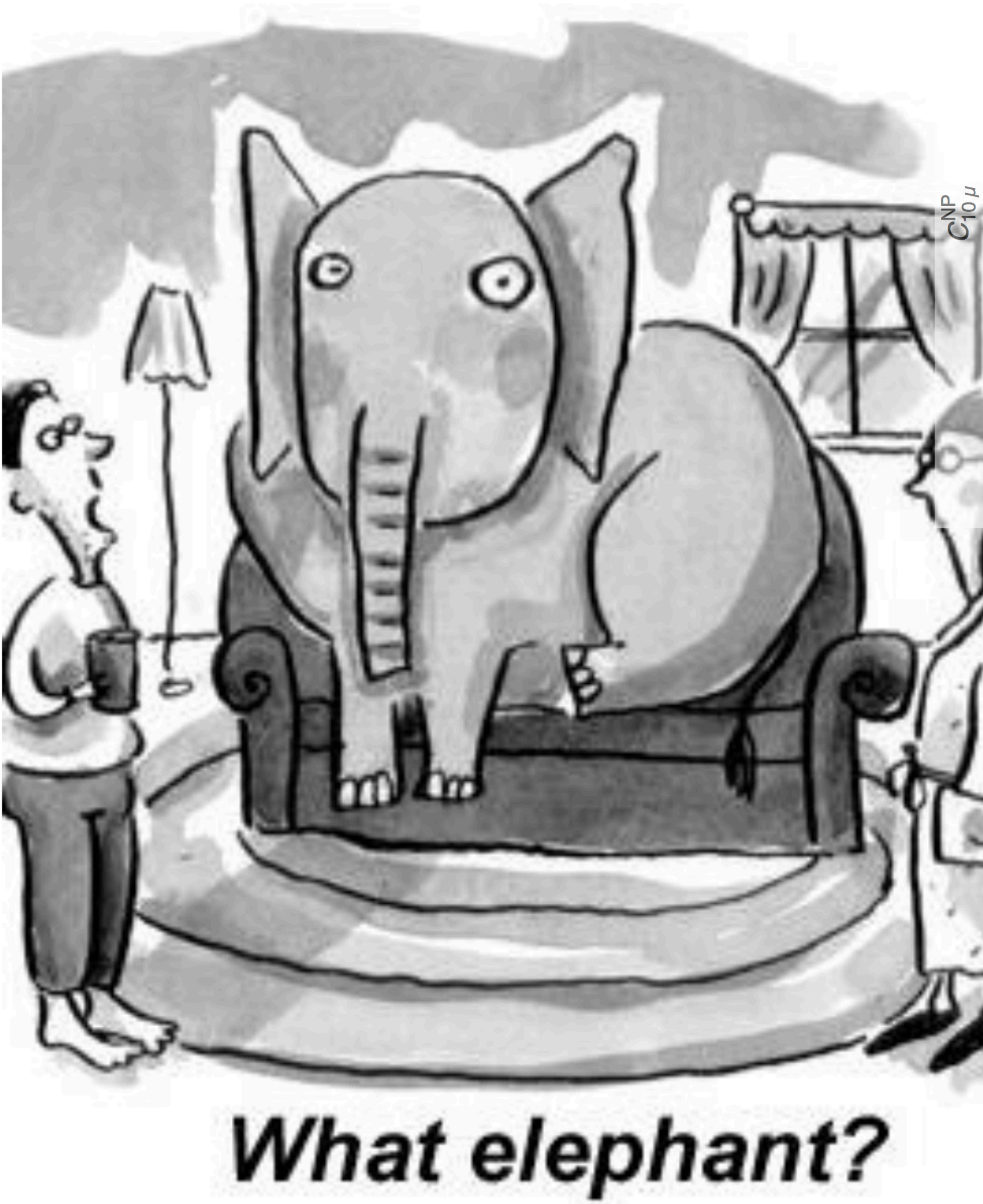


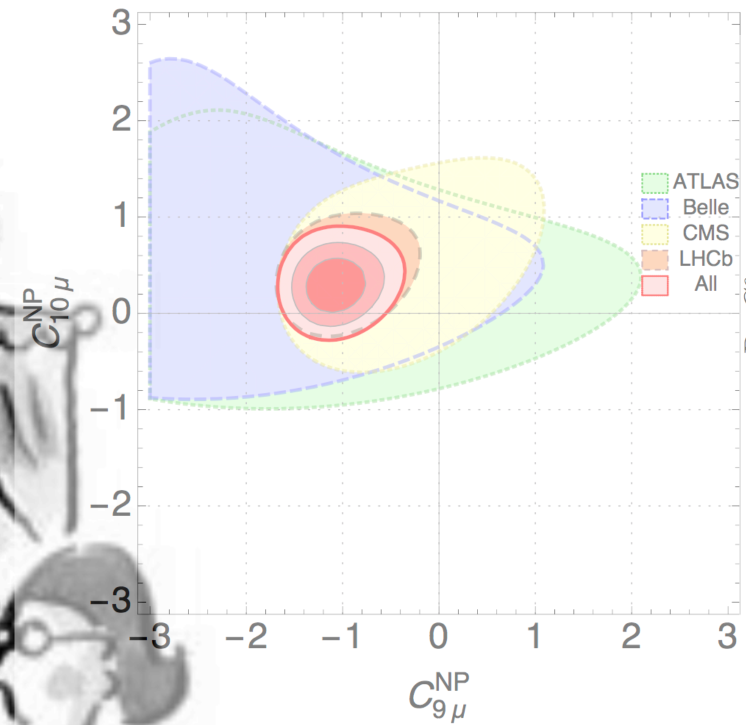
Lepton Flavor Universality & Flavour Anomalies

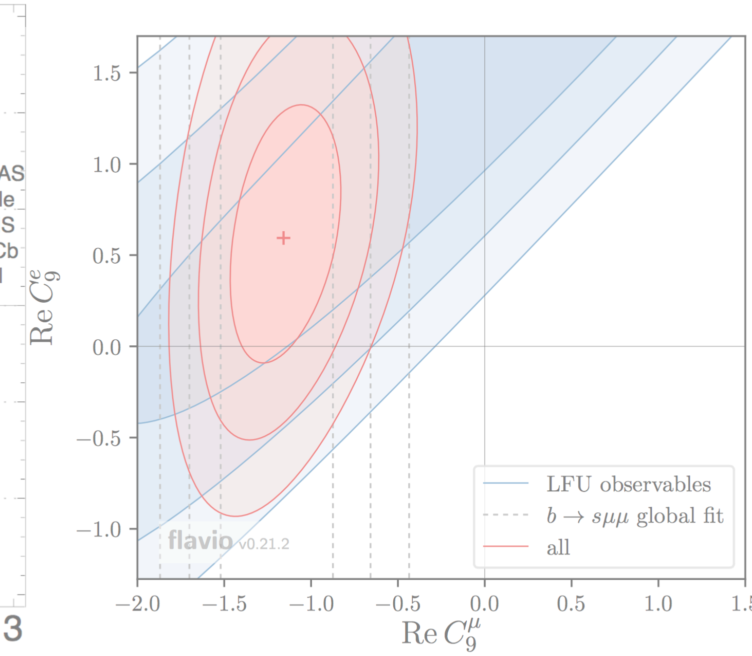
b→sll
c→slν

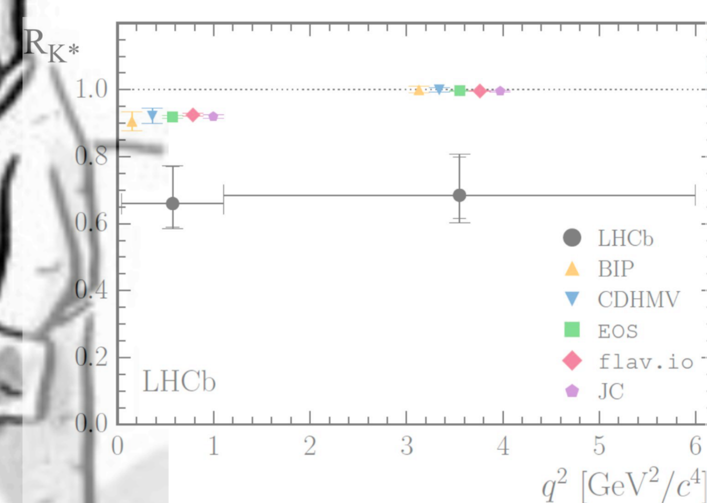
Z’,W’
leptoquarks
?

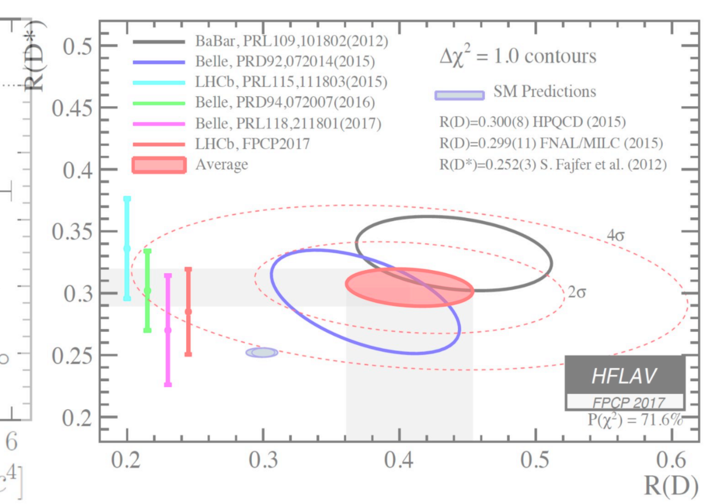
LHC data (so far) show no definite signal of NP … but there's an elephant in the room !





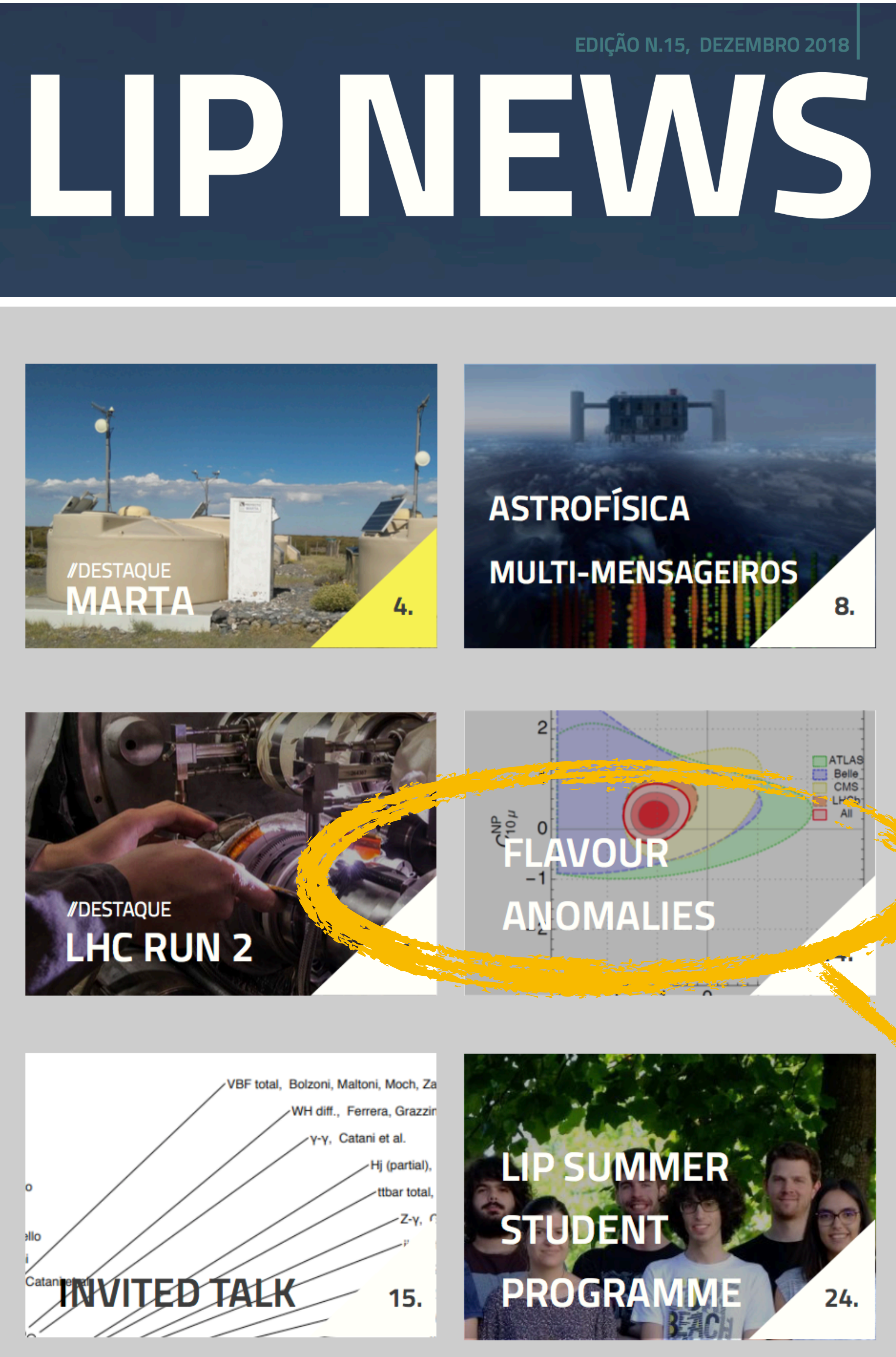






Taken together, the **flavor anomalies** are most significant deviation from SM, and the **strongest indication of NP** in current collider data **!**

http://www.lip.pt/outreach/lipnews/pdfs/issue15_pt.pdf



Flavour Anomalies

First hints of New Physics at the LHC?

Nuno Leonardo

Over the last few years, a persistent set of deviations from the Standard Model (SM) predictions has emerged from the data. These have been detected in decays of b-quark hadrons. While the deviations are not sufficiently significant if considered individually, when taken together they are. These so-called "flavour anomalies" stand currently as a most exciting indication of New Physics (NP) and a hottest topic in the field of HEP at the moment.

New phenomena beyond the standard theory of particle physics are pursued in a multitude of paths. At the LHC, a main path, which explores the energy frontier, aims at directly detecting new heavy particles, beyond those of the SM. These NP particles may be produced in the collisions, and their presence detected through the products of their decay. Another path, which explores the luminosity frontier, aims at detecting the presence of NP indirectly, through precision measurements. Here, NP particles may virtually contribute to the amplitude of SM-allowed processes, and be revealed through measured deviations relative to the SM expectation, in observable particle properties. The two approaches are complementary and each is actively pursued by exploring a large variety of processes.

Hints of the presence of NP may accordingly be revealed through excesses in distributions (e.g. a bump in the mass spectrum) or measured deviations (e.g. on a particle's decay rate). And as it happens, several such hints, of both kinds, have turned up in the LHC data. However, so far, none of sufficiently high statistical significance, so as to unequivocally exclude possible background fluctuations as their source. Nonetheless, in the case of certain b-hadron decays, several such deviations from theory expectation seem to conspire together — while each individual deviation is still not significant *per se*, the coherent pattern displayed by their ensemble is.

Each deviations is associated to one of two underlying b-quark transitions: (i) b→sll, i.e. bottom to strange quark plus pair of opposite-charge leptons, and (ii) b→clν, i.e. bottom to charm quark plus charged lepton and neutrino. The former can occur only at loop level in the SM (flavor changing neutral current, that is forbidden in SM, at tree level), with high sensitivity to NP (where NP particles can run in the loops). The latter (charged current) occurs at tree level.

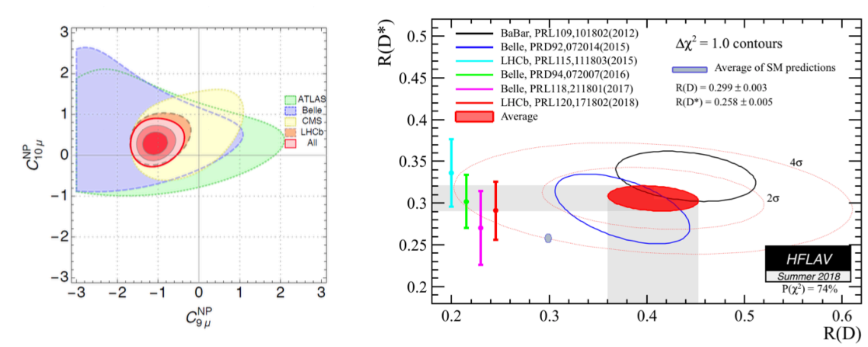
The neutral-current transitions, b→sll, are realised in various rare B decays, both leptonic, e.g. $B_s \to \mu^+\mu^-$, and semileptonic, e.g. $B \to S\mu^+\mu^-$, where S stands for a strange-[illegible]ark hadron (e.g. K, K*, Φ, Λ). [illegible]n addition to d[illegible] the latter class o[illegible]s many NP-sensitive obse[illegible] associa[illegible] to the angular distributions of the d[illegible] products. Deviations are detect[illegible]th varying degree in many of th[illegible]e. The departure from theory was initially detected by LHCb in one such angular observable, denoted P'_5, in the decay $B^0 \to K^{*0}\mu^+\mu^-$. It should be remarked here that for this decay a challenge arises in calculating the theory predictions — specifically, going from the underlying quark-level transition b→sll to the experimentally observed B-meson decay, there are QCD contributions involved whose estimation is non-trivial. And while the P'_5 observable is constructed in such a way as to be more robust in terms of such QCD (B→S) form-factor determinations, some debate persists on the theory front.

There is another major chapter in the saga of flavor anomalies. And this time perhaps even more dramatic: it involves violation of lepton flavor universality (LFU). Apart from the differences in their masses, the SM interactions do not distinguish between the different leptons. This means, for example, that the rates of the decays $B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}e^+e^-$ involving muons and electrons should be comparable.The LHCb data has however revealed that their ratio, R_{K^*}, seems to display a noticeable departure from unit. Important to remark here is that the above-mentioned form-factor uncertainties cancel in the ratios, rendering these observables rather robust theoretically. Indications of LFU violation had actually been also detected earlier at the B factories (BaBar and Belle experiments), between taus and muons, in the decays $B \to D^{(*)}\tau\nu$ and $B \to D^{(*)}\mu\nu$, where the corresponding ratios, R_D and R_{D^*}, exhibit departures from their SM expectations (see figure). These were quite unexpected, with the underlying transitions b→clν occurring at tree level.

Naturally, the anomalies have raised a large excitement amongst both experimentalists and theorists. After all, the ensemble of anomalies when interpreted collectively appear to indicate a departure from the SM, with a significance above the 5σ mark (see figure). Theorists have been actively putting forward classes of models that attempt to explain the anomalies, along with other tensions in the flavor sector, e.g. $(g-2)_\mu$, while simultaneously accommodating other experimental constraints, e.g. from B_s mixing and dilepton mass spectra. Among these, models with extra gauge bosons (Z') or leptoquarks (LQ) appear to be favoured.

From the experimental side, a clarification will be sought by thoroughly exploiting the LHC Run 2 data. Not only will the LHCb measurements be repeated to reach increased precision, contributions from ATLAS and CMS will offer independent input with orthogonal systematics. For example, during 2018 a large, dedicated dataset has been collected by CMS specifically for this purpose. Belle2 is coming online, and within a few years its data will provide decisive input. Dedicated searches for scenarios addressing the anomalies, including Z' and LQ, will be pursued at the LHC.

Whether the source of the anomalies turns out to be more mundane statistical fluctuations, underestimations in theory calculations, or genuine NP, it is exciting that a clarification is within reach over the next few years. A confirmation of these flavour anomalies would point to new particles or interactions and have profound implications for our understanding of particle physics.



Current status of the flavor anomalies. Left: Global fit to b→sll observables, with results projected on the plane of two EFT coefficients. Right: Fit to b→clν observables. The red elipses represent the regions favoured by the data. The SM lies at the origin (0,0) of the left plot and on the small region at about (0.3,0.25) on the right plot. The tension between data and SM is clearly visible.

the ‘flavour anomalies’

$b \to s\, ll$ anomalies

Found by LHCb (and perhaps hinted by Belle)

Many observables: global pattern

Neutral current

1-loop (and CKM-suppressed) in the SM

The New Physics can be heavy

$b \to c\, l\nu$ anomalies

Found by several experiments (LHCb, BaBar and Belle)

Two observables: R(D) and R(D*)

Charged current

Tree-level in the SM

The New Physics must be light

b→sll | Effective Field Theory

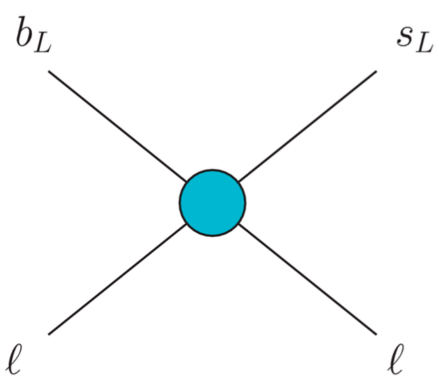
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right) + \text{h.c.}$$

C_i : Wilson coefficients

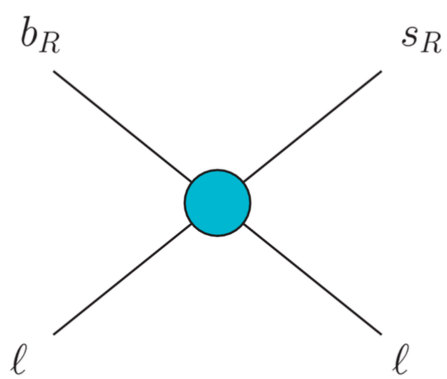
$\mathcal{O}_i$: Operators

$$\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu} P_R b)\, F^{\mu\nu}$$
$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

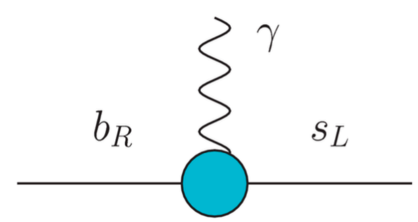
$$\mathcal{O}_7' = (\bar{s}\sigma_{\mu\nu} P_L b)\, F^{\mu\nu}$$
$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)\ (\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)\ (\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



O₉



O'₉



O₇

$$C_i = C_i^{\text{SM}} + C_i^{\text{NP}}$$

calculable (C_i^{SM}) — what we want to know (C_i^{NP})

$b \to s\ell\ell$ | processes & observables

Inclusive

$B \to X_s \gamma$ (BR) ------------------------ $C_7^{(\prime)}$

$B \to X_s \ell^+ \ell^-$ (dBR/dq²) ---------------- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

Exclusive leptonic

$B_s \to \ell^+ \ell^-$ (BR) ------------------------ $C_{10}^{(\prime)}$

Exclusive radiative/semileptonic

$B \to K^* \gamma$ (BR, S, A_I) ------------------ $C_7^{(\prime)}$

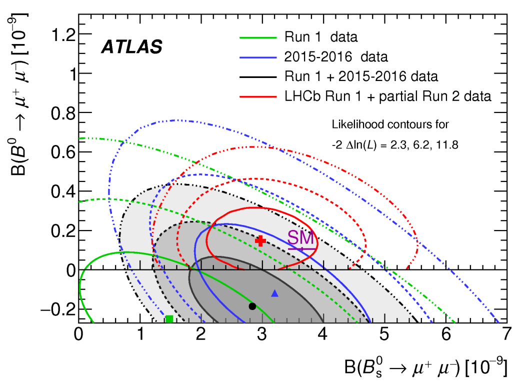
$B \to K \ell^+ \ell^-$ (dBR/dq²) ----------------- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

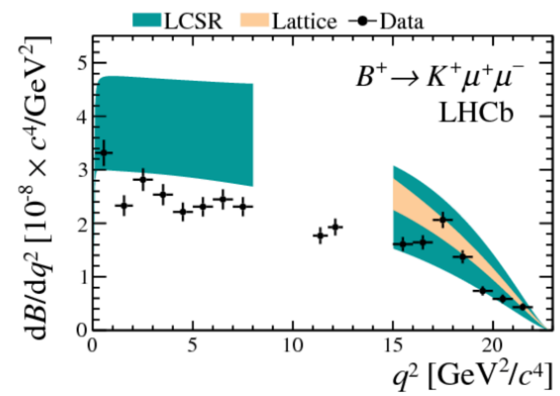
$B \to K^* \ell^+ \ell^-$ (dBR/dq², angular obs.) --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

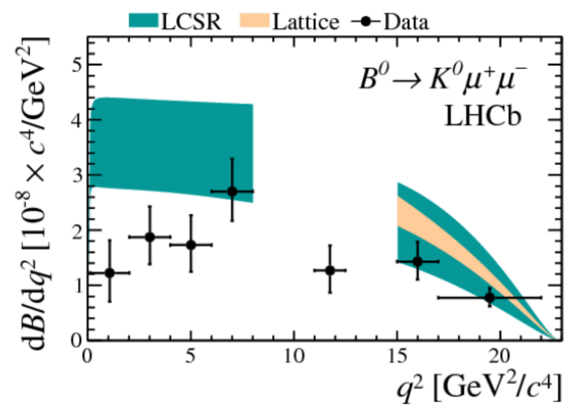
$B_s \to \phi \ell^+ \ell^-$ (dBR/dq², angular obs.) --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

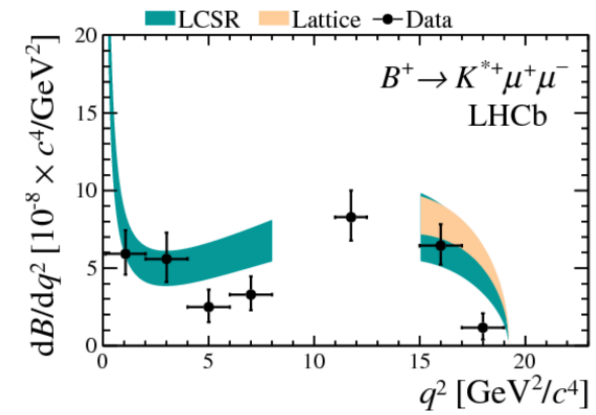
The same Wilson coefficients enter several observables $\Rightarrow$ A pattern of deviations rather than a single anomaly $\Rightarrow$ **Global fit**

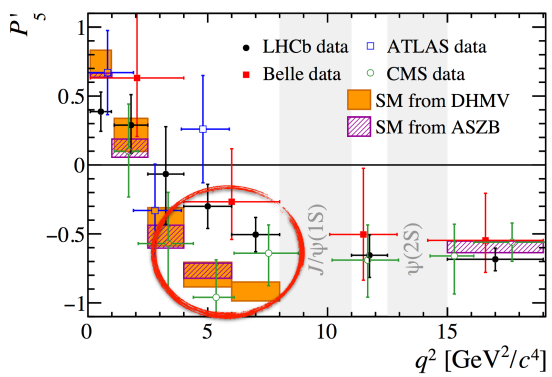
b→sμμ | global fits

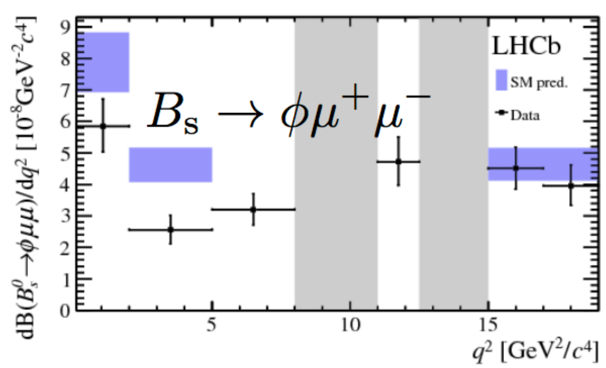


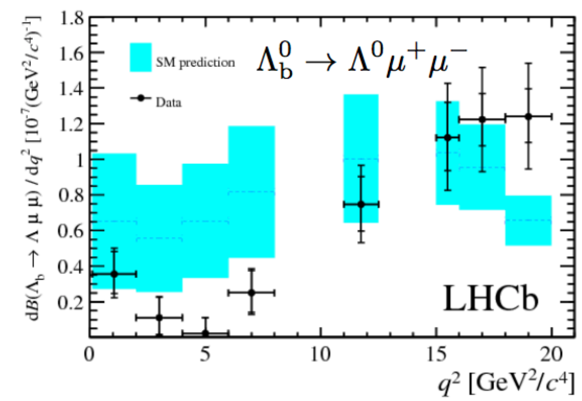


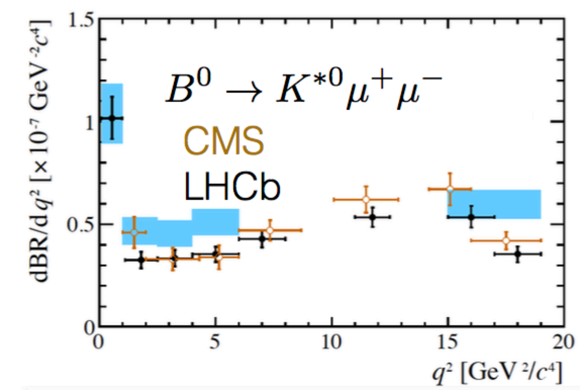




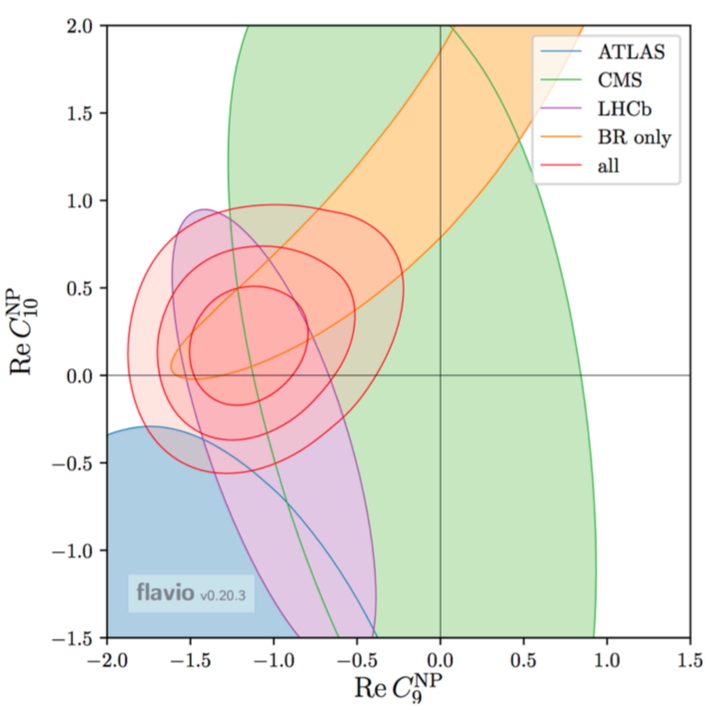








1506.08777,1503.07138,1606.04731,1403.8044,1507.08126

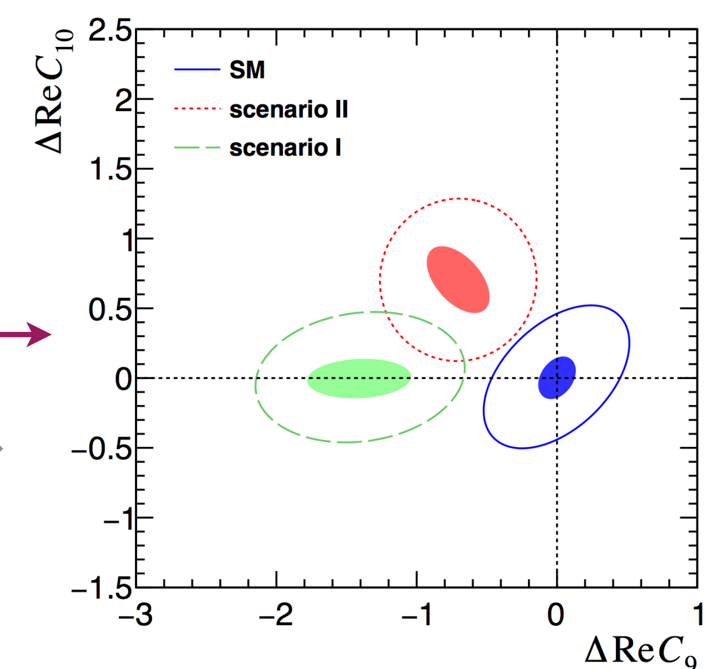


Effective **F**ield **T**heory

$$H_{eff} \propto \sum_i \left(C_i^{SM} + C_i^{NP} \right) \cdot O_i$$

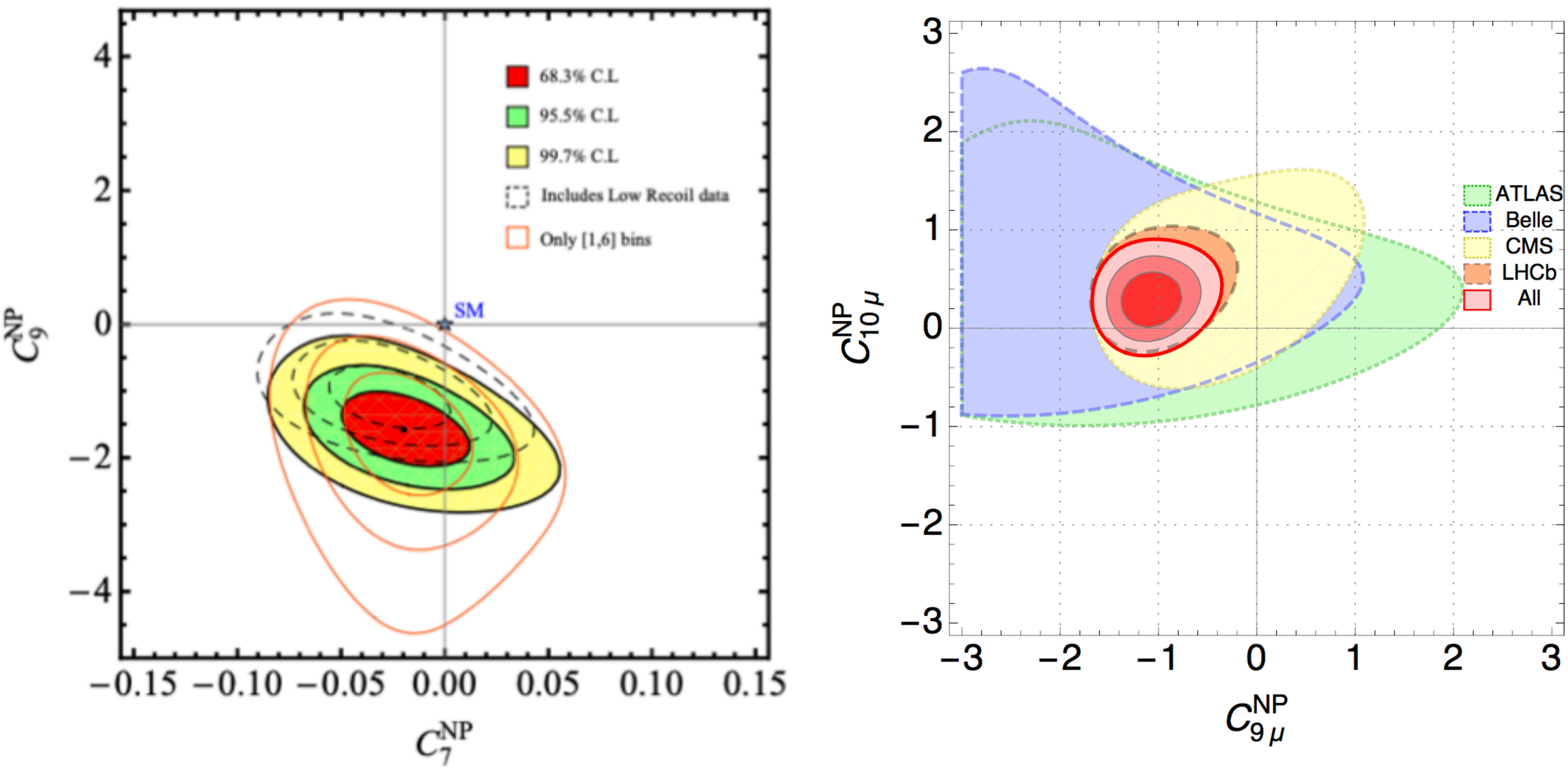
⬅ Now HL-LHC ➡

complemented by lepton *flavour universality* tests !



1902.10229

b→sμμ | global fit



Lepton Flavour Universality

Universality in neutral current interactions

$$U^\dagger U = V^\dagger V = \mathbb{I}_{3\times 3} \;\Rightarrow\; \mathcal{L}^{\ell}_{\rm nc} \equiv \left(\overline{\widehat{e}}\gamma_\mu \widehat{e} + \overline{\widehat{\mu}}\gamma_\mu \widehat{\mu} + \overline{\widehat{\tau}}\gamma_\mu \widehat{\tau}\right)\left(g_\gamma A^\mu + g_Z Z^\mu\right)$$

The photon and Z-boson couple
with the same strength to the three lepton families

Universality

Universality in charged current interactions

$$\mathcal{L}^{\ell}_{\rm cc} \equiv g_W \overline{\widehat{\nu}}_L \gamma_\mu V_{\rm PMNS} \widehat{e}_L W^{+\mu} + \text{h.c.}$$

$$= g_W \sum_{i=1,2,3} \overline{\widehat{\nu}}^i_L \gamma_\mu \left(V^{ie}_{\rm PMNS}\widehat{e}_L + V^{i\mu}_{\rm PMNS}\widehat{\mu}_L + V^{i\tau}_{\rm PMNS}\widehat{\tau}_L\right) W^{+\mu} + \text{h.c.}$$

The W-boson couples
with different strengths to different lepton families

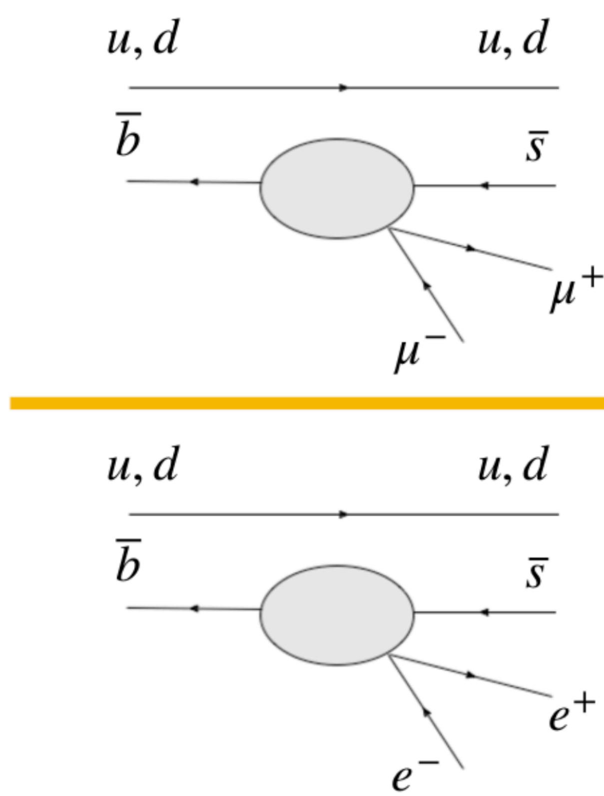
However: if the neutrino flavor is not observed $\quad |\mathcal{M}_j|^2 \propto \sum_{i=1,2,3} |V^{ij}_{\rm PMNS}|^2 = 1 \;\; \forall j$

Universality

b→sll | LFU (e vs μ)

$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{\cong} 1$$

$$R_K = \frac{\int_{1.1\,\text{GeV}^2}^{6.0\,\text{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{1.1\,\text{GeV}^2}^{6.0\,\text{GeV}^2} \frac{\mathrm{d}\mathcal{B}(B^+\to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$



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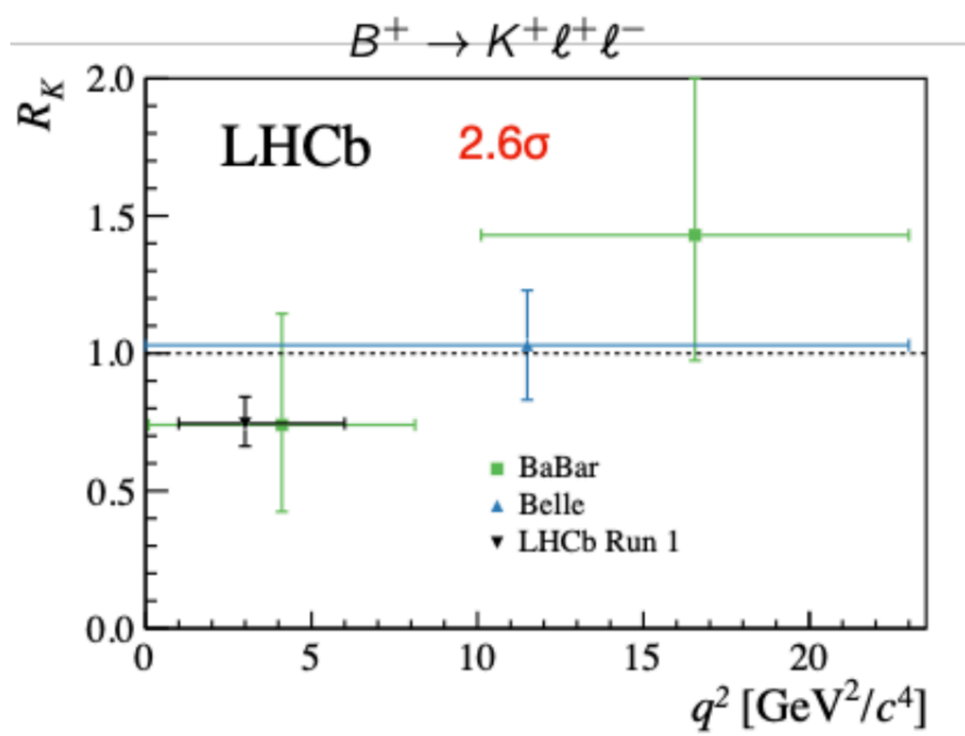
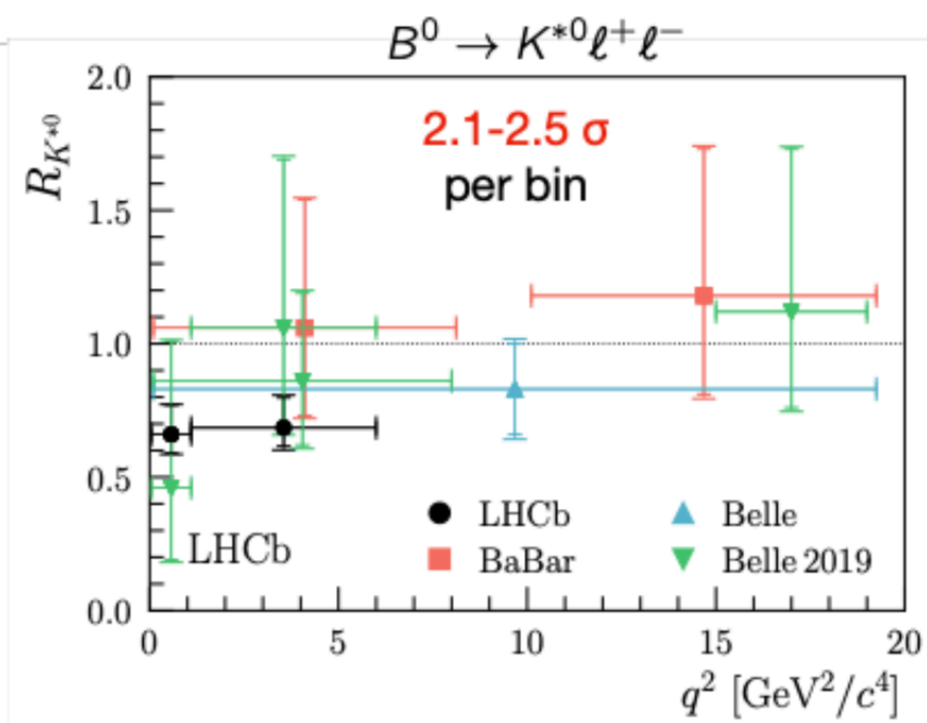
$= 1.0 \pm 0.1$



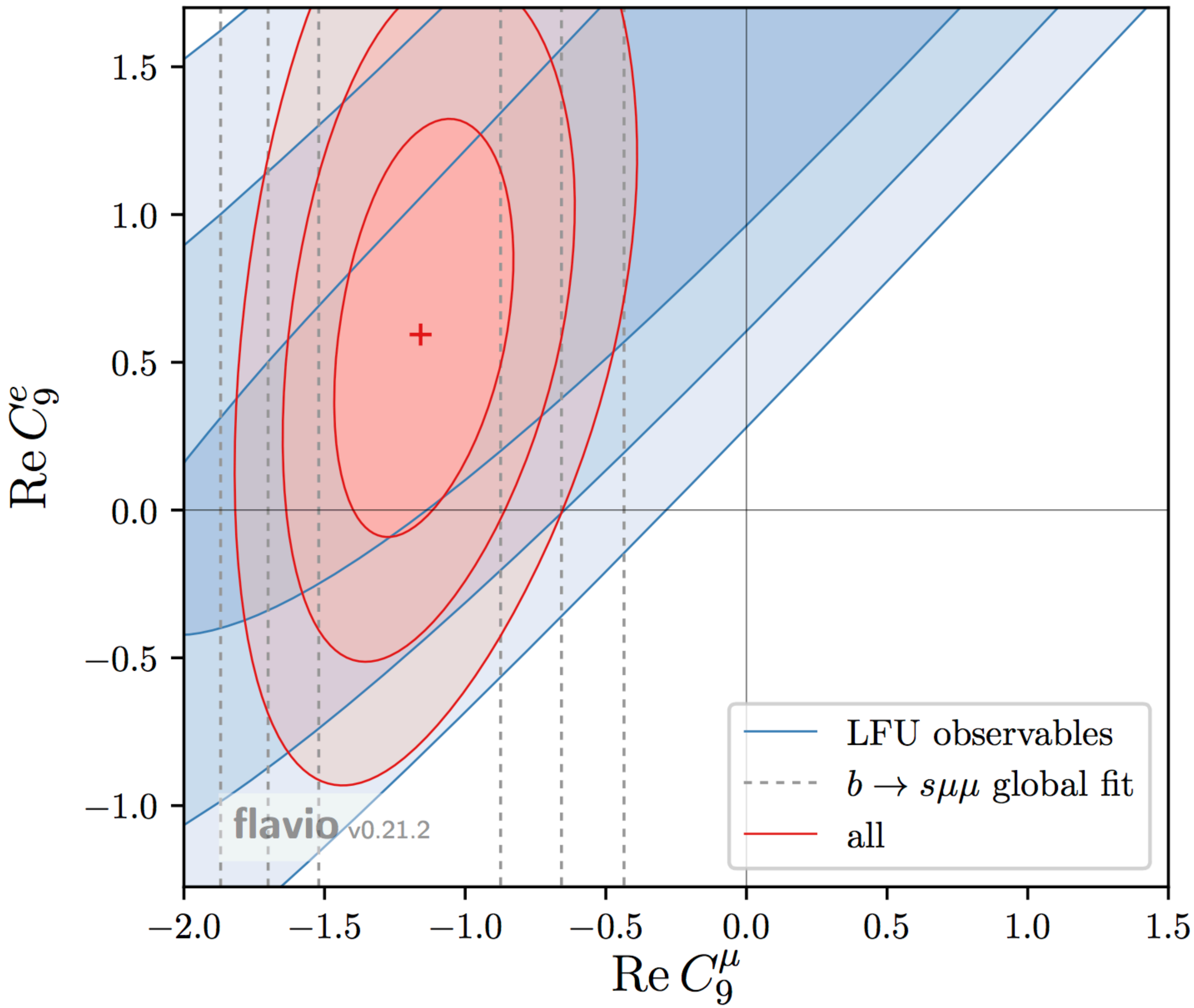


[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]

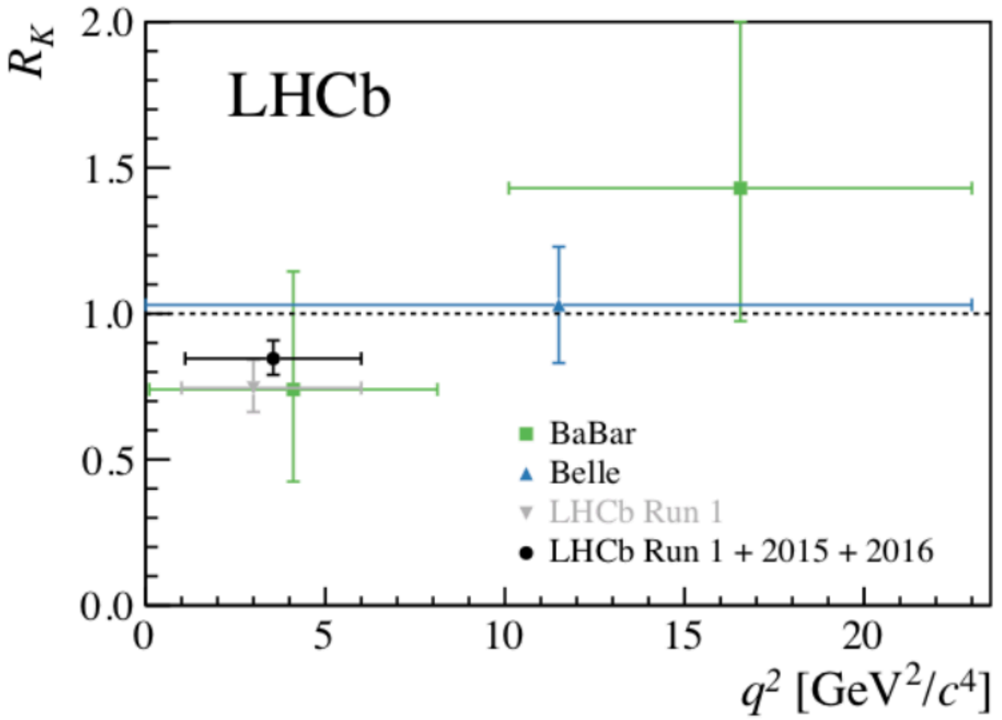
[BaBar, PRD 86 (2012) 032012]

[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

b→sll | global fit



b→sll | updates



Using 2011 and 2012 LHCb data, R_K was:

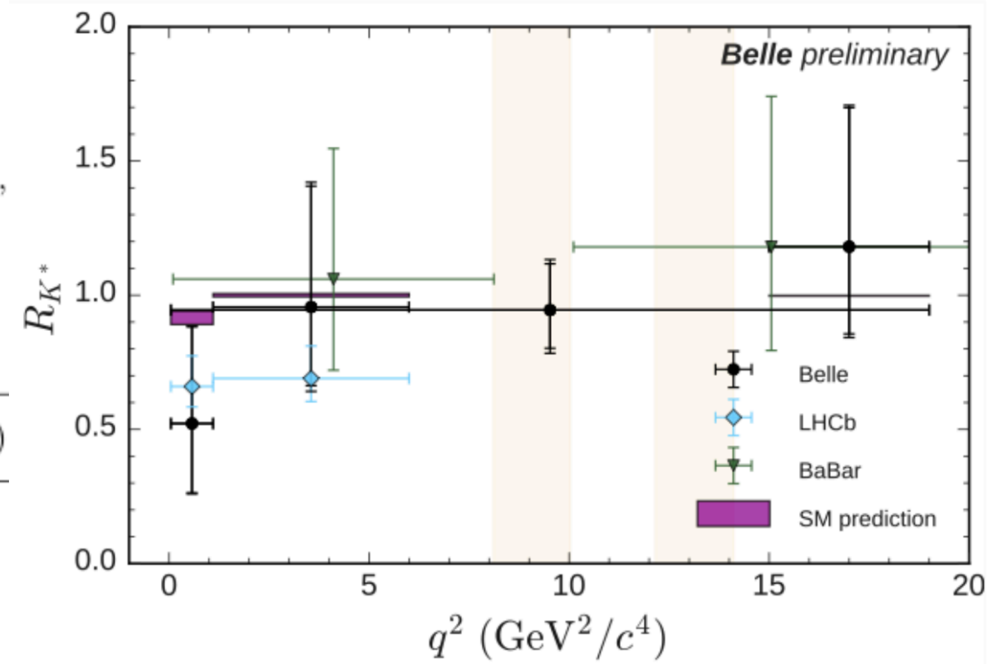
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat.}) \pm 0.036(\text{syst.}),$$

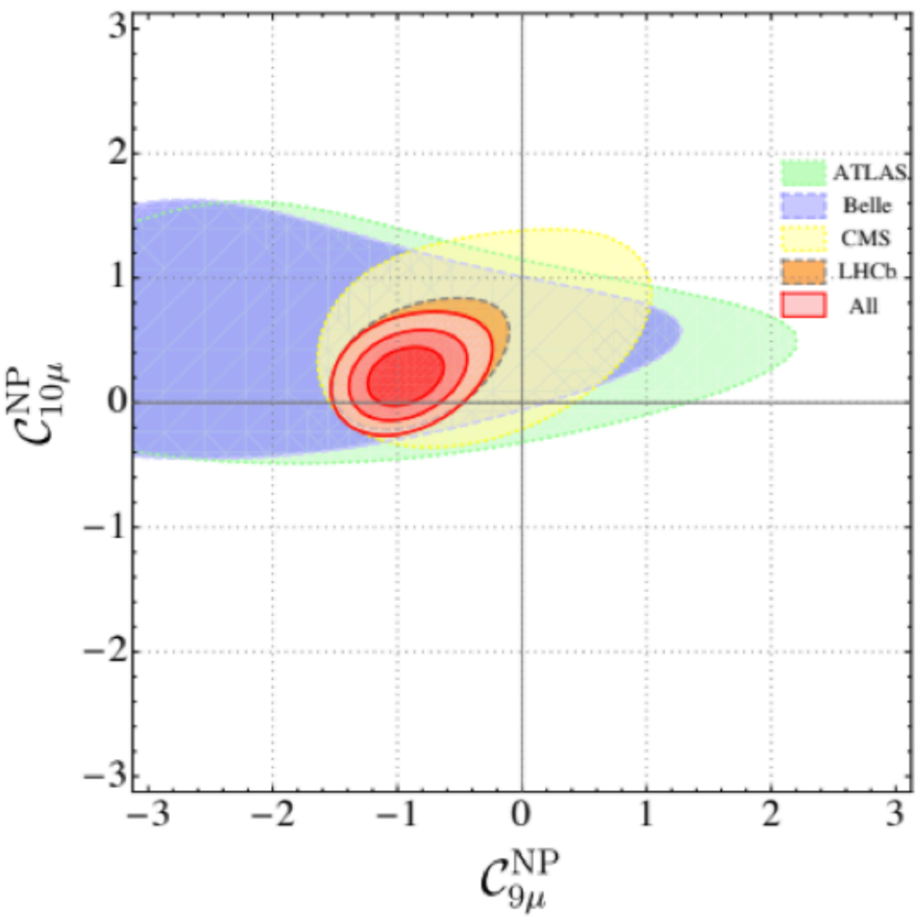
$\sim 2.6\sigma$ from SM (PRL113(2014)151601).

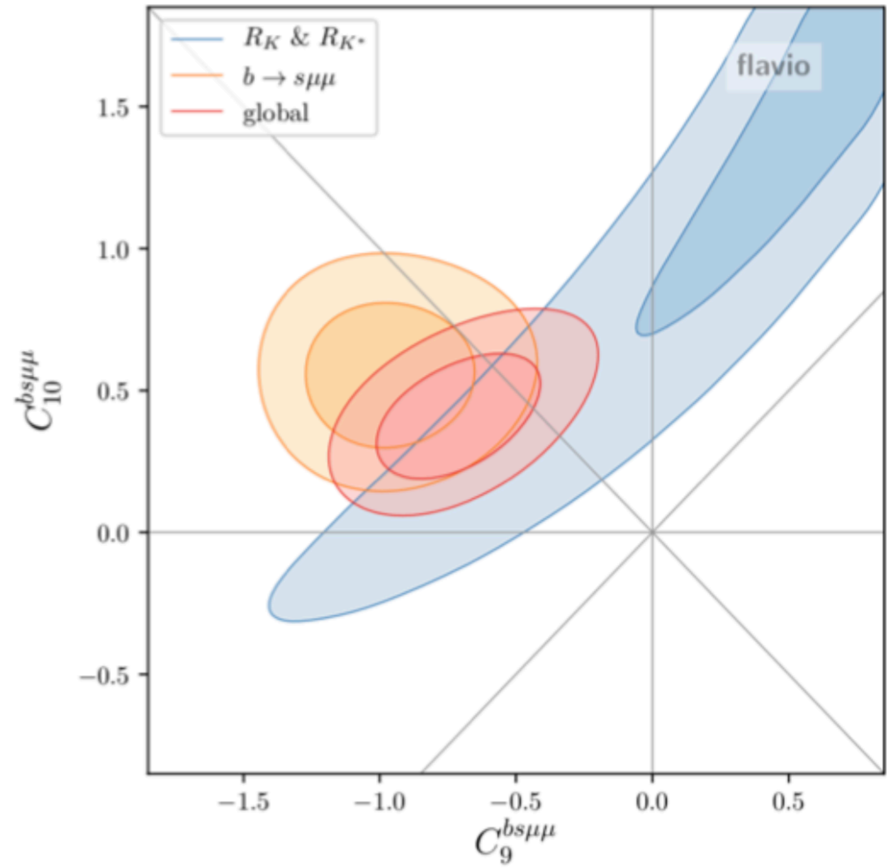
Adding 2015 and 2016 data, R_K becomes:

$$\boldsymbol{R_K = 0.846\ ^{+0.060}_{-0.054}(\text{stat.})\ ^{+0.016}_{-0.014}(\text{syst.})}$$

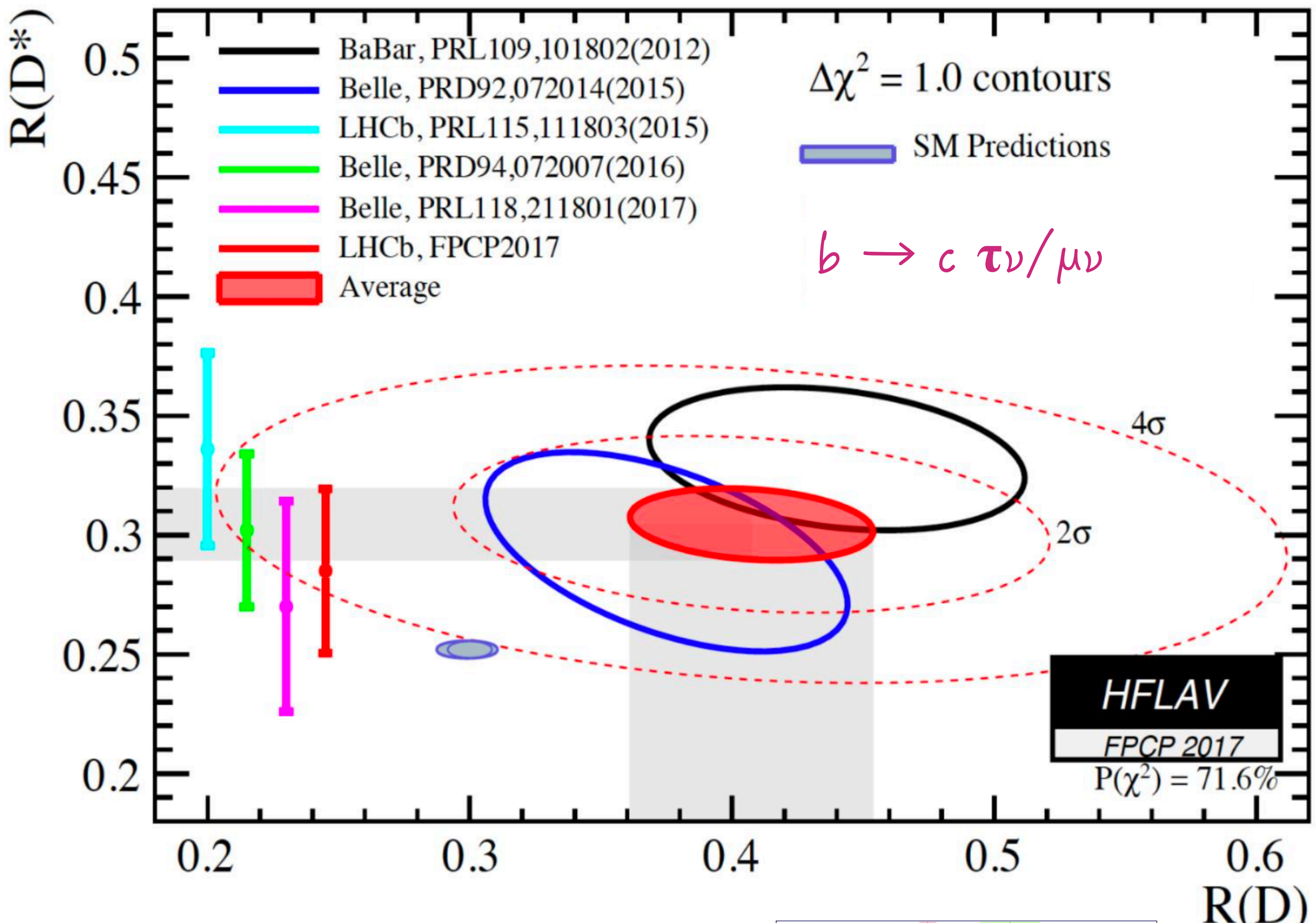
$\sim$ **2.5 σ** from SM.



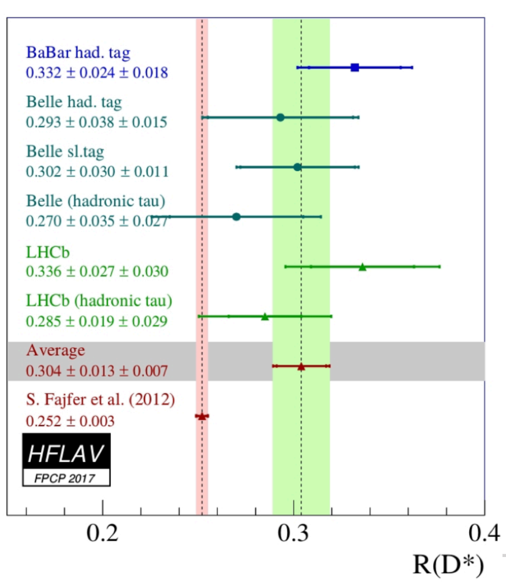


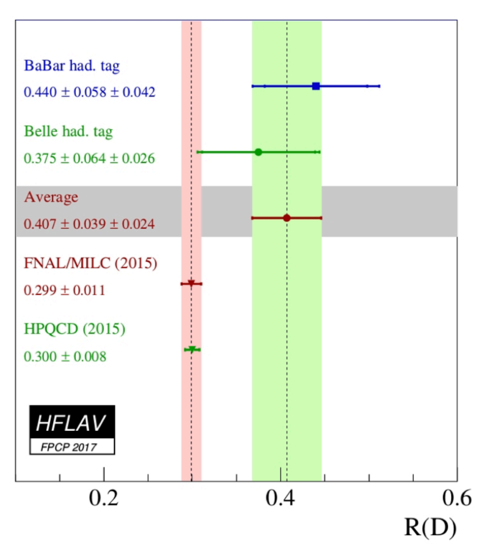


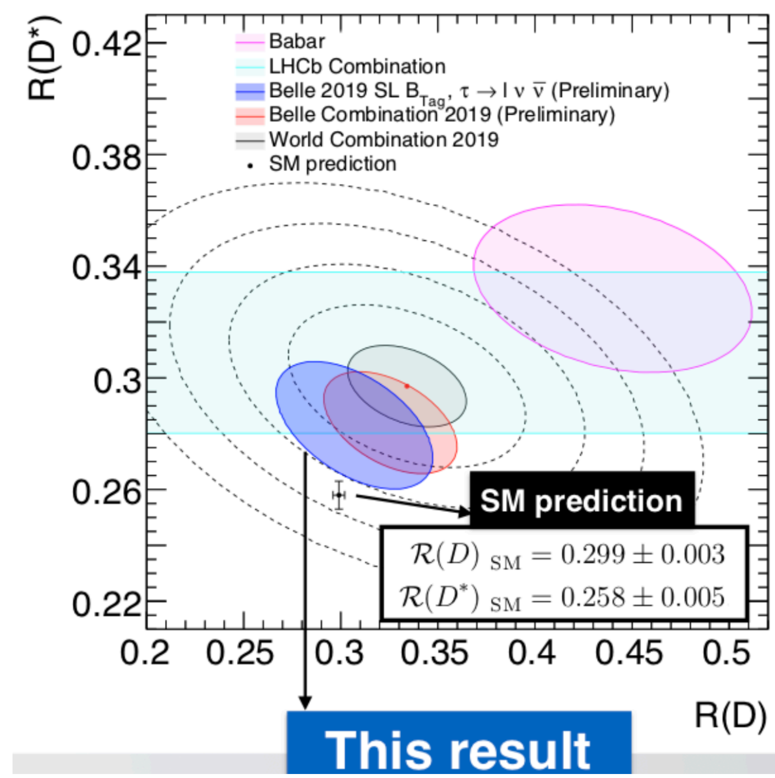
b→clν | LFU (τ vs e/μ)



$$\mathcal{R}(D^{(*)}) \equiv \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)}$$



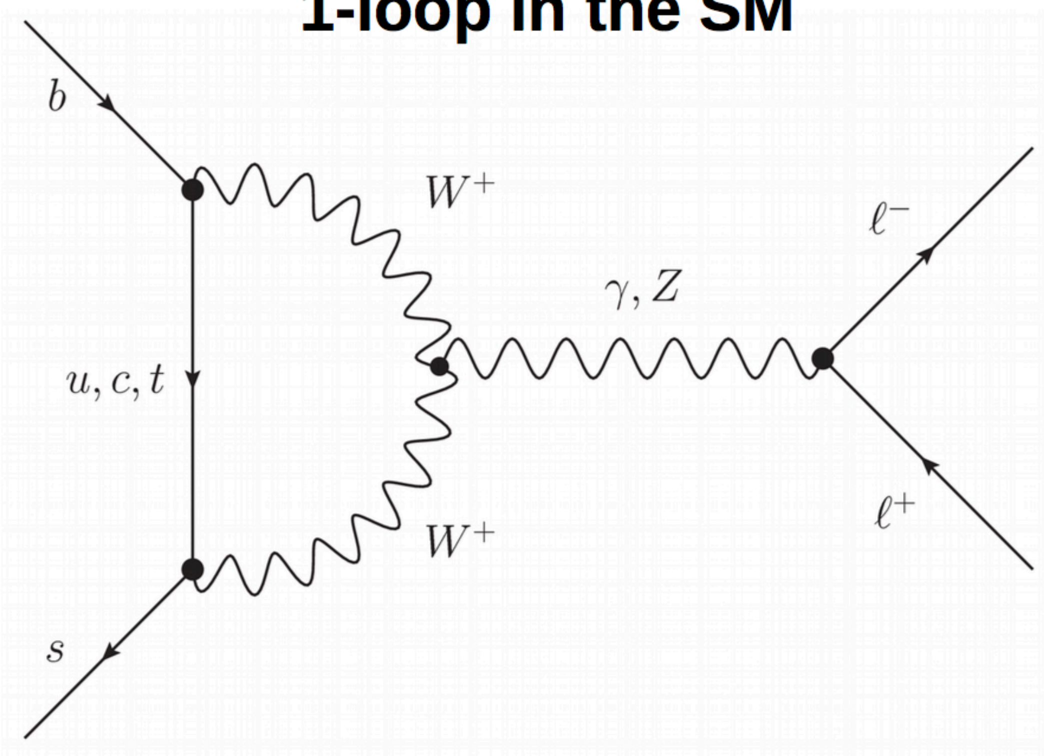




what is the scale of NP?

b → s anomalies

1-loop in the SM

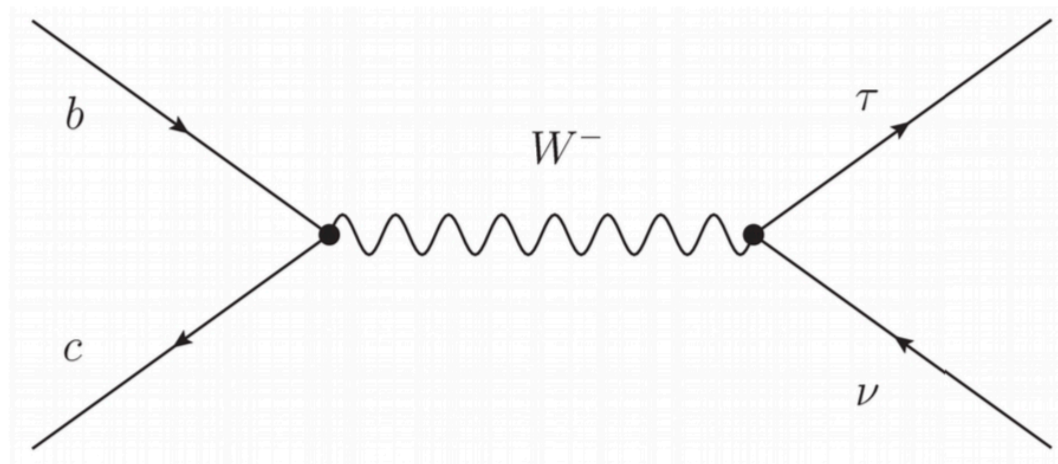


The scale of NP can be "*high*"

$$\Lambda \sim 30 - 50\,\text{TeV}$$

b → c anomalies

Tree-level in the SM

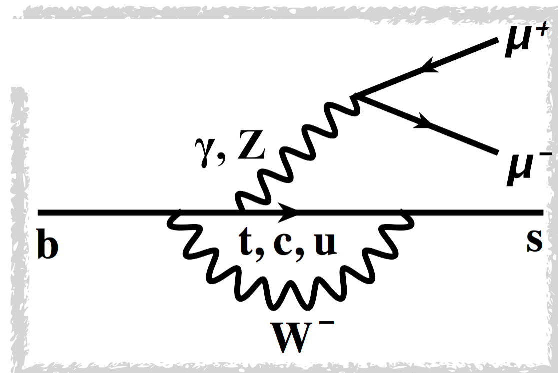


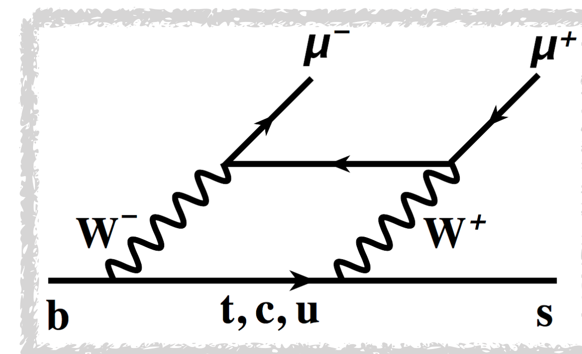
The scale of NP must be "low"

$$\Lambda \sim \text{TeV}$$

anomalies: NP explanations?

b→sll quark transitions in the **SM**

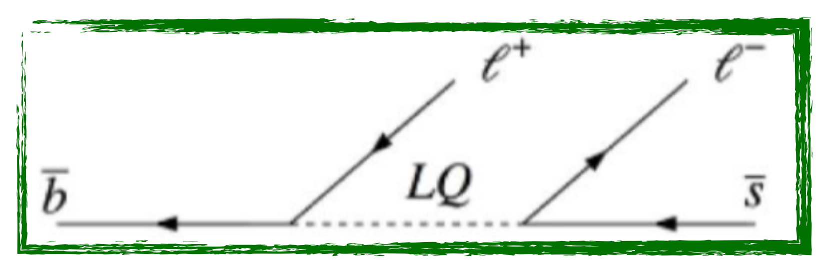




- could existing NP scenarios account for the anomalies?
  - while still respecting strict constraints imposed by other measurements!
- current best candidates:

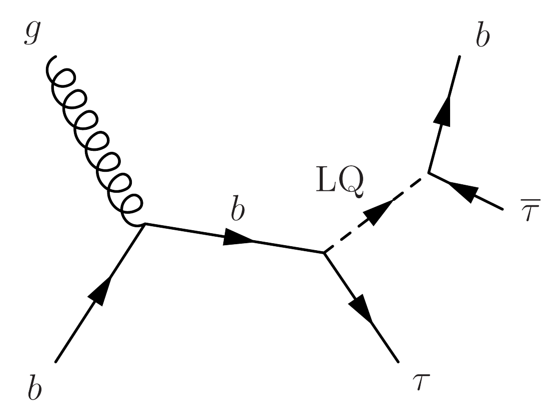
1) **New gauge bosons**
   - Z', associated to a new symmetry

2) **Leptoquark**
   - exotic particle with both lepton and baryon numbers, fractional charge

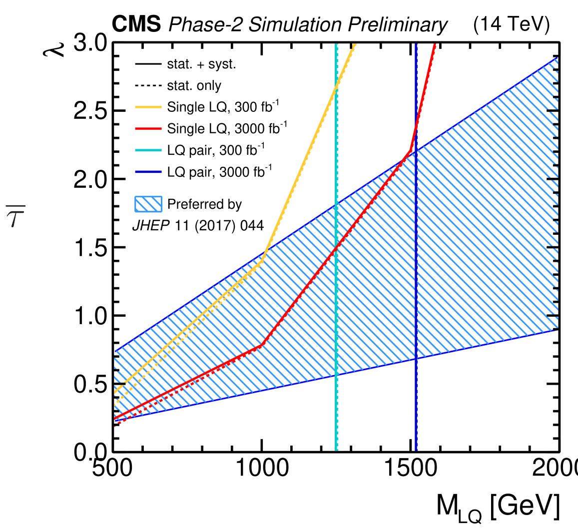


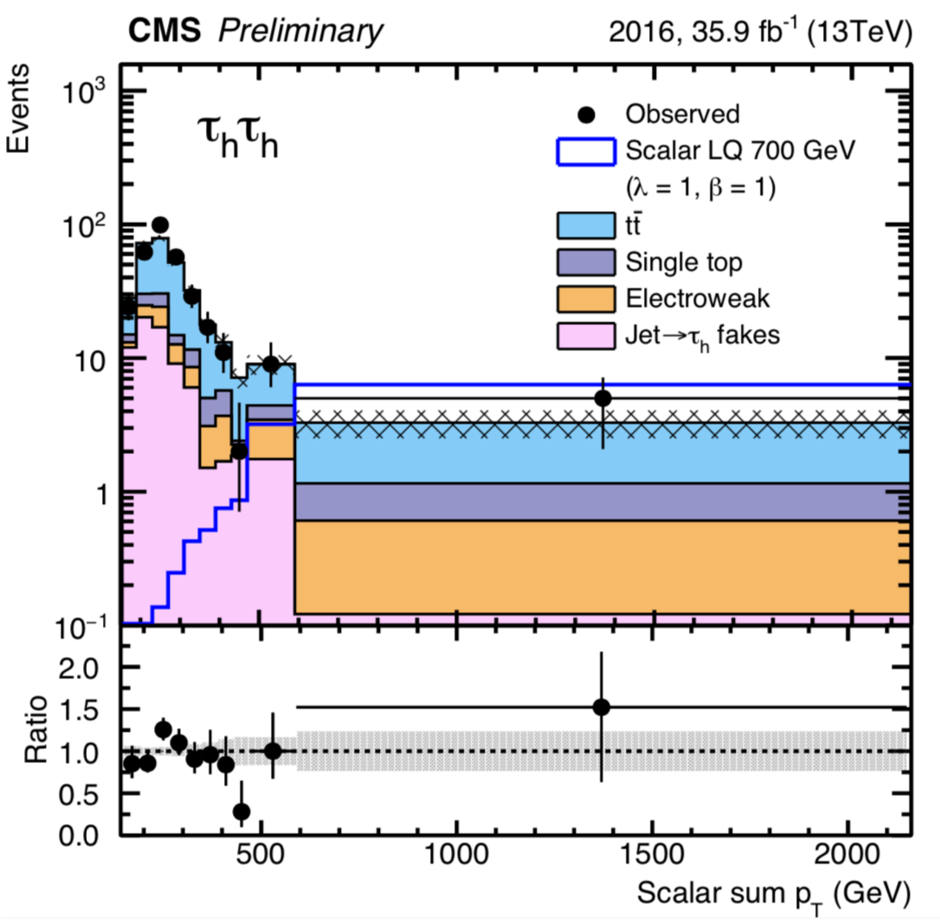
search for leptoquarks | LQ→τb

- dedicated search motivated by B anomalies
- single LQ production in ττb final state
- 3 different categories: $\tau_h + \tau_h/\tau_e/\tau_\mu$
- simultaneous fit to S_T distributions



CMS-PAS-FTR-18-028





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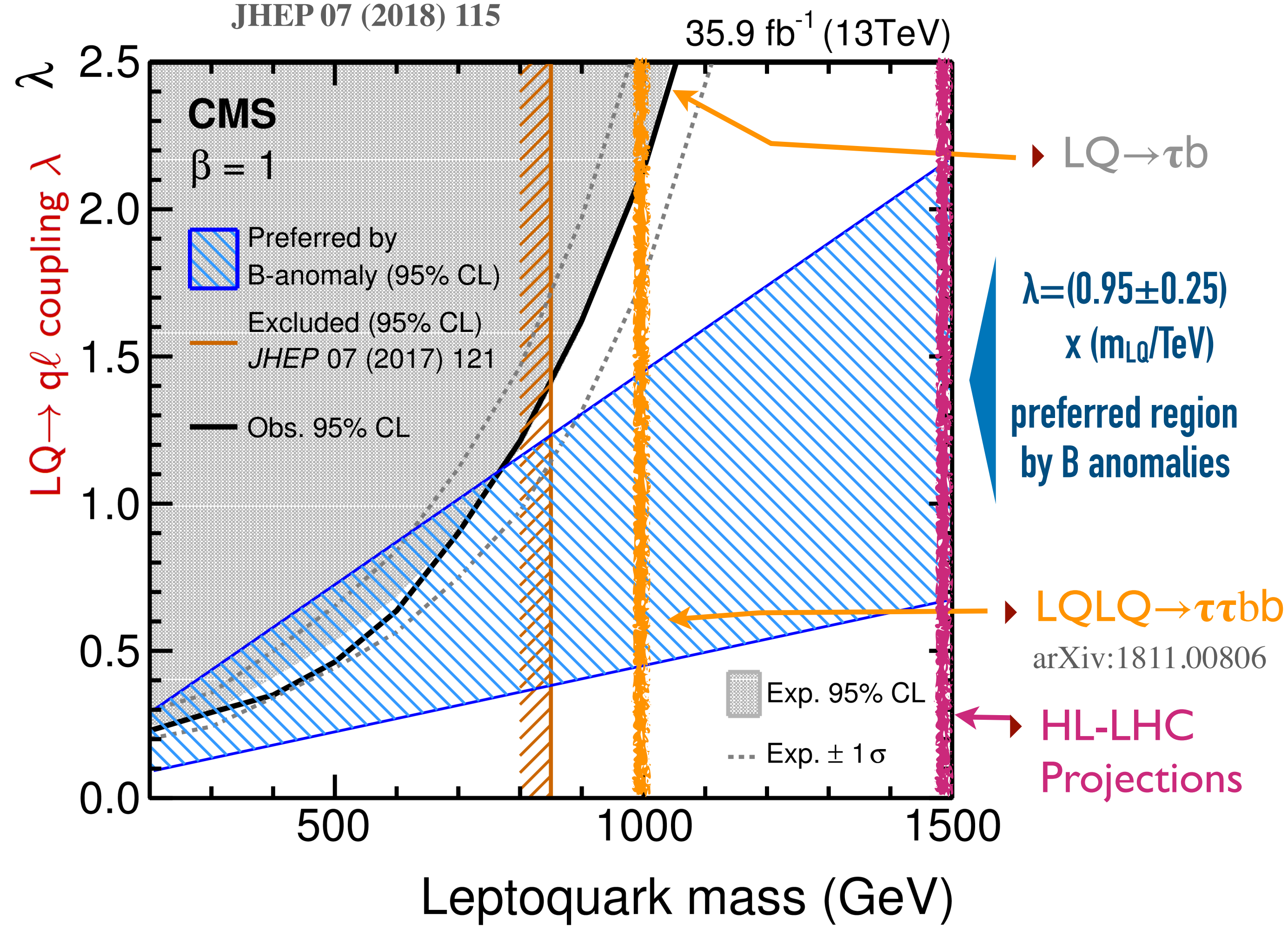
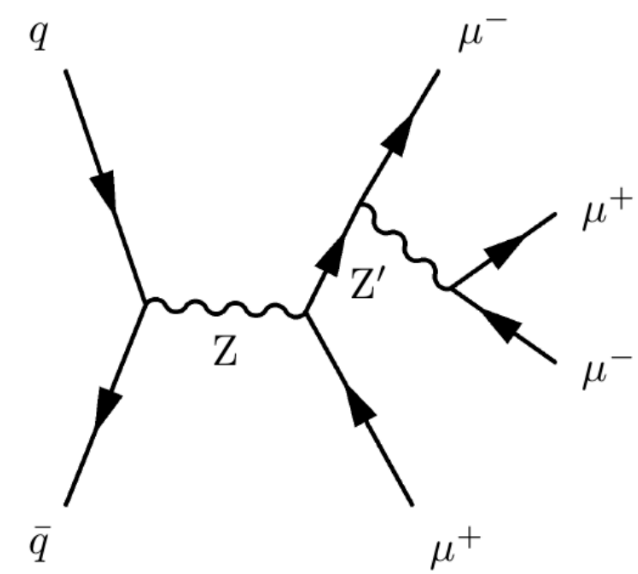
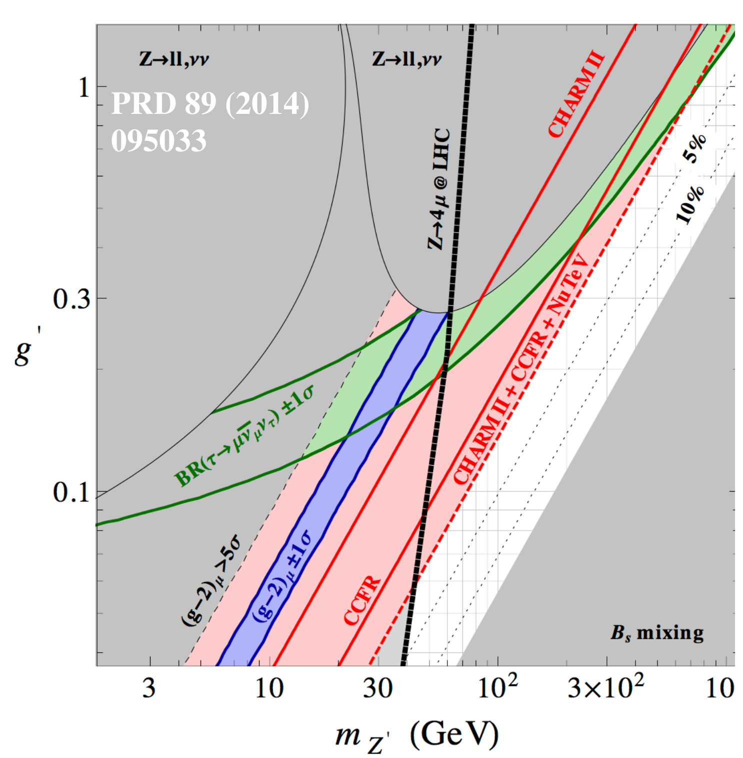
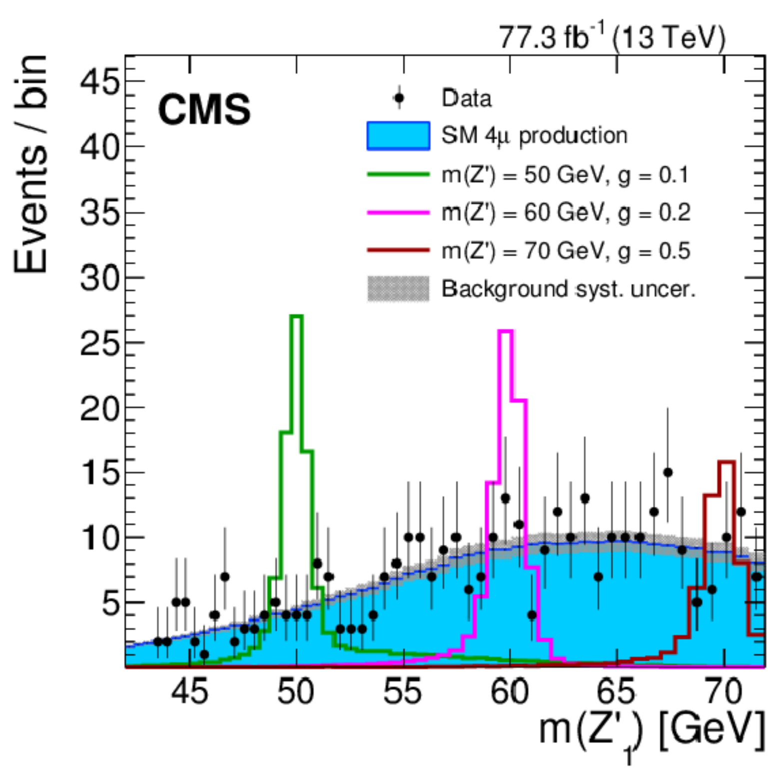


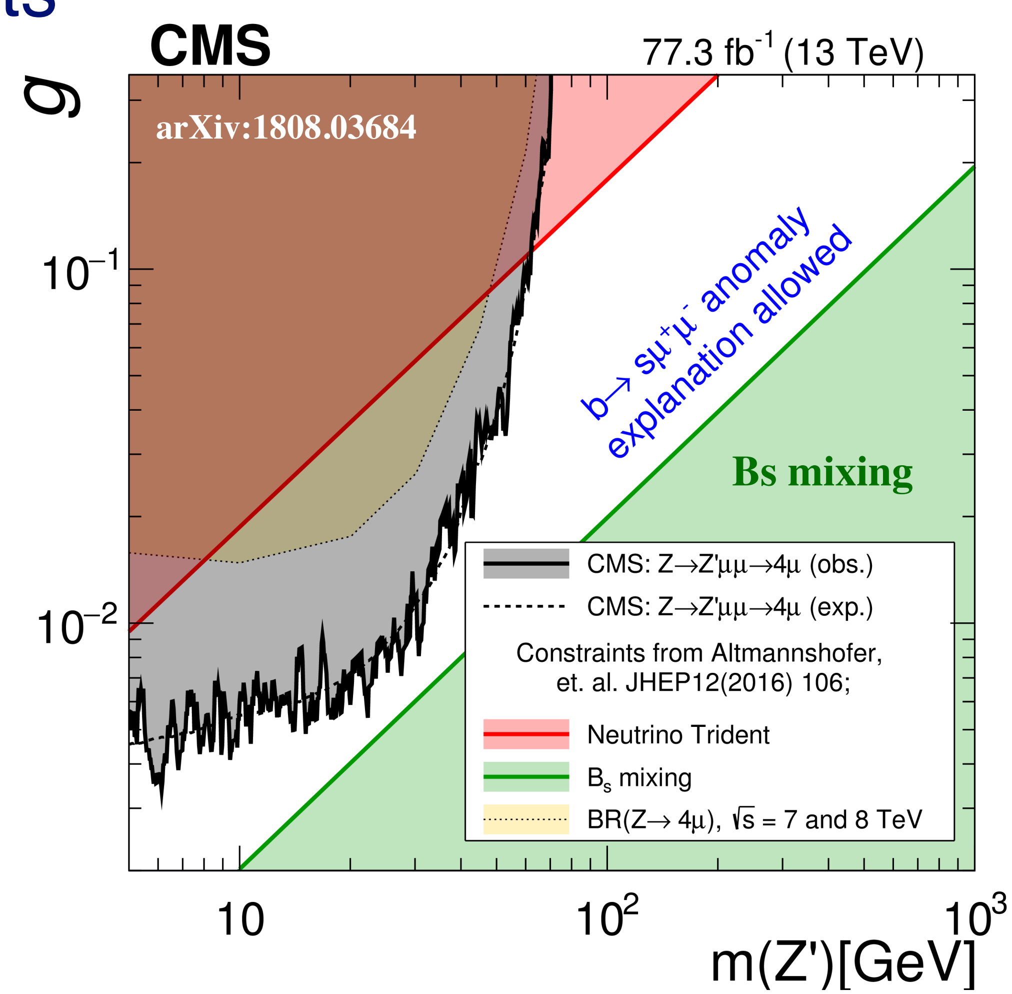
search for Z’ | Z→4μ

- first dedicated gauged L_μ-L_τ U(1)’ search at LHC
- Z’ radiated off lepton (produced ow, e.g. from Z)
- extremely clean signature: 4 muon final state
  - excellent mass resolution, high reco+trigger efficiency, almost background free
- no excess detected ➡ strict exclusion limits
  - exclude Z’ coupling strength to μ: 0.004–0.3



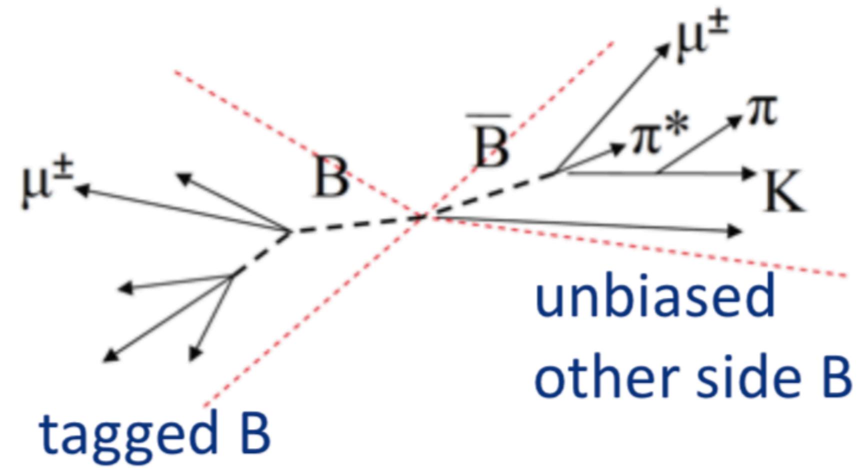


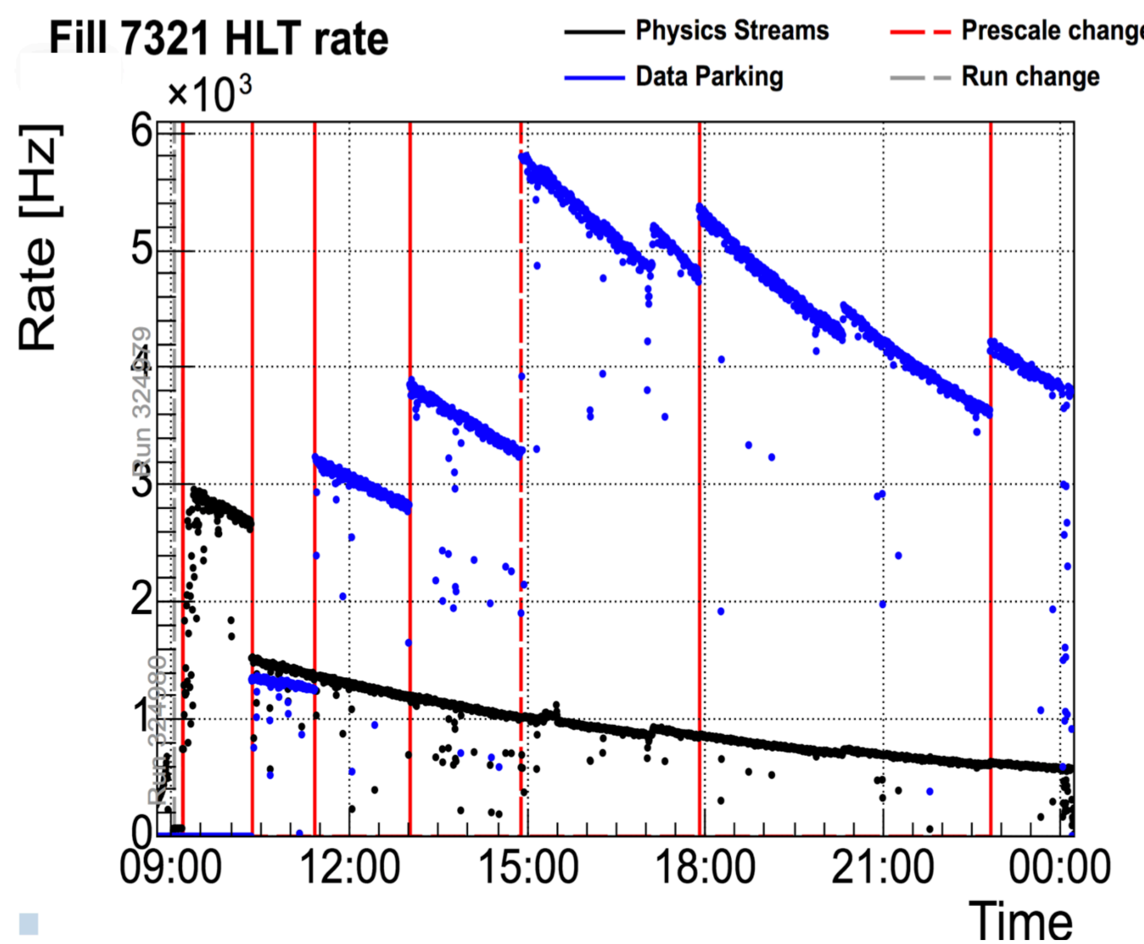




bonus: parked Run2 data

- bulk of B physics at CMS/ATLAS based on (di)muons in final state
- main challenge: the trigger!
- CMS has now collected during 2018 a special B sample
  - trigger on opposite-side B
  - 12B triggered events on tape
- the data is "parked"
  - with delayed processing
  - 1/10 already processed to development
- may allow to investigate LFUV
  - object (τ,e) reconstruction challenging at low p_T in a GPD
  - flavor anomalies from low-p_T front





7.6 PB on tape
Avg event size is 0.64 MB
(1MB for standard events)

Up to 5.5 kHz in the second part of the fill where events are smaller

summary

- rare decays provide a very sensitive place to look for NP
  - clean experimental and theoretical probes, precise predictions
  - allow to reach sensitivity to higher mass scales than direct searches
- flavour anomalies
  - our best hint for NP in current collider data overall
- results so far
  - place stringent constraints on NP models
  - tantalising, statistically significant anomalies observed
- NP may be established at LHC in a *multi-messenger*-like fashion
  - as the current flavour anomalies nicely illustrate
- **most interesting times ahead for rare decay searches**
  - rare decays will benefit enormously from high luminosity phase HL-LHC

(LHC: 6% DATA RECORDED)

  - plus dedicated experiments: BelleII + KOTO + KLEVER + SHiP + …