Rare Decays

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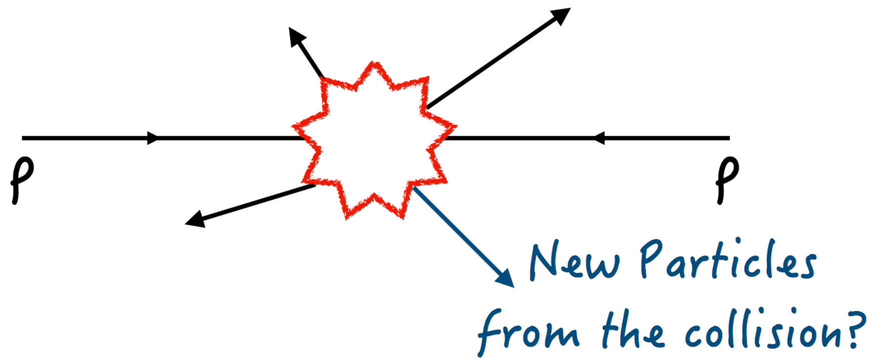
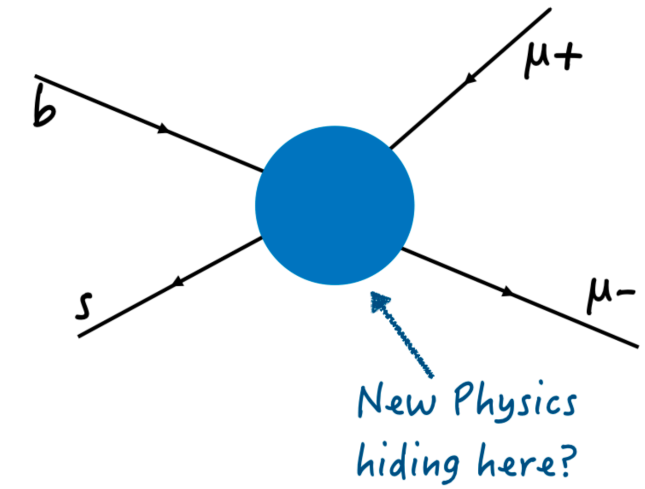
(complementary) paths to NP @LHC





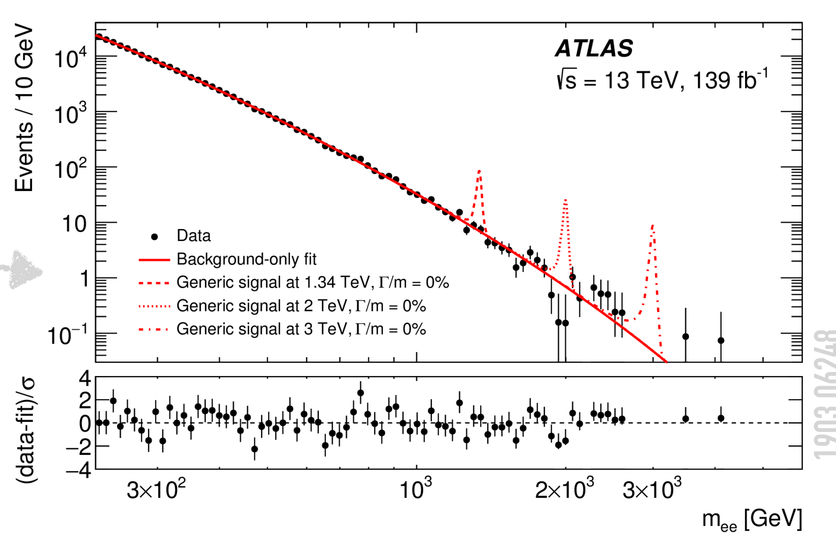
Rare decays!

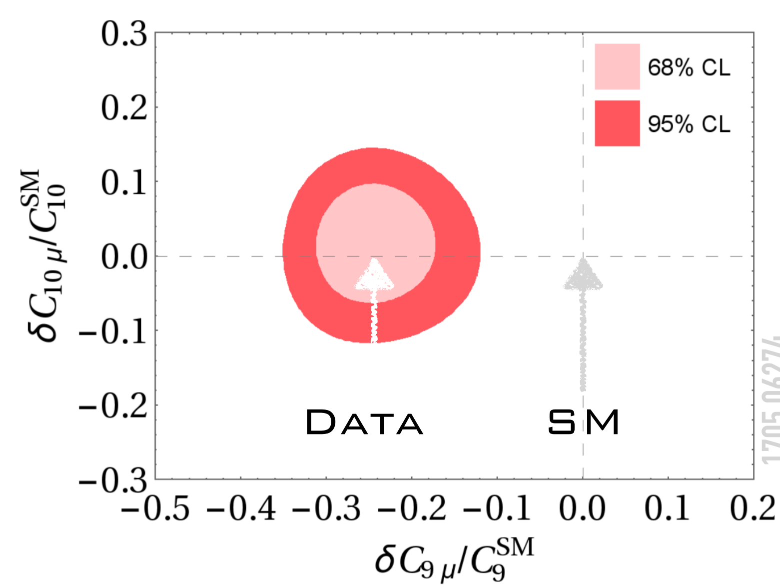
Direct

- searching for the decay products of potentially produced NP particles

Indirect

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





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 NP searches
- Historically: many particle physics discoveries
- LHC: high luminosity ➡ high sensitivity for discovery

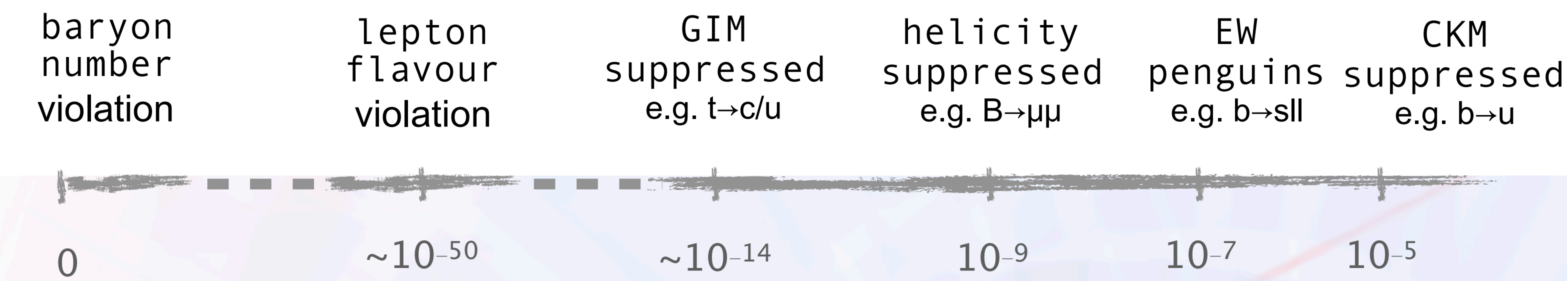
how rare?

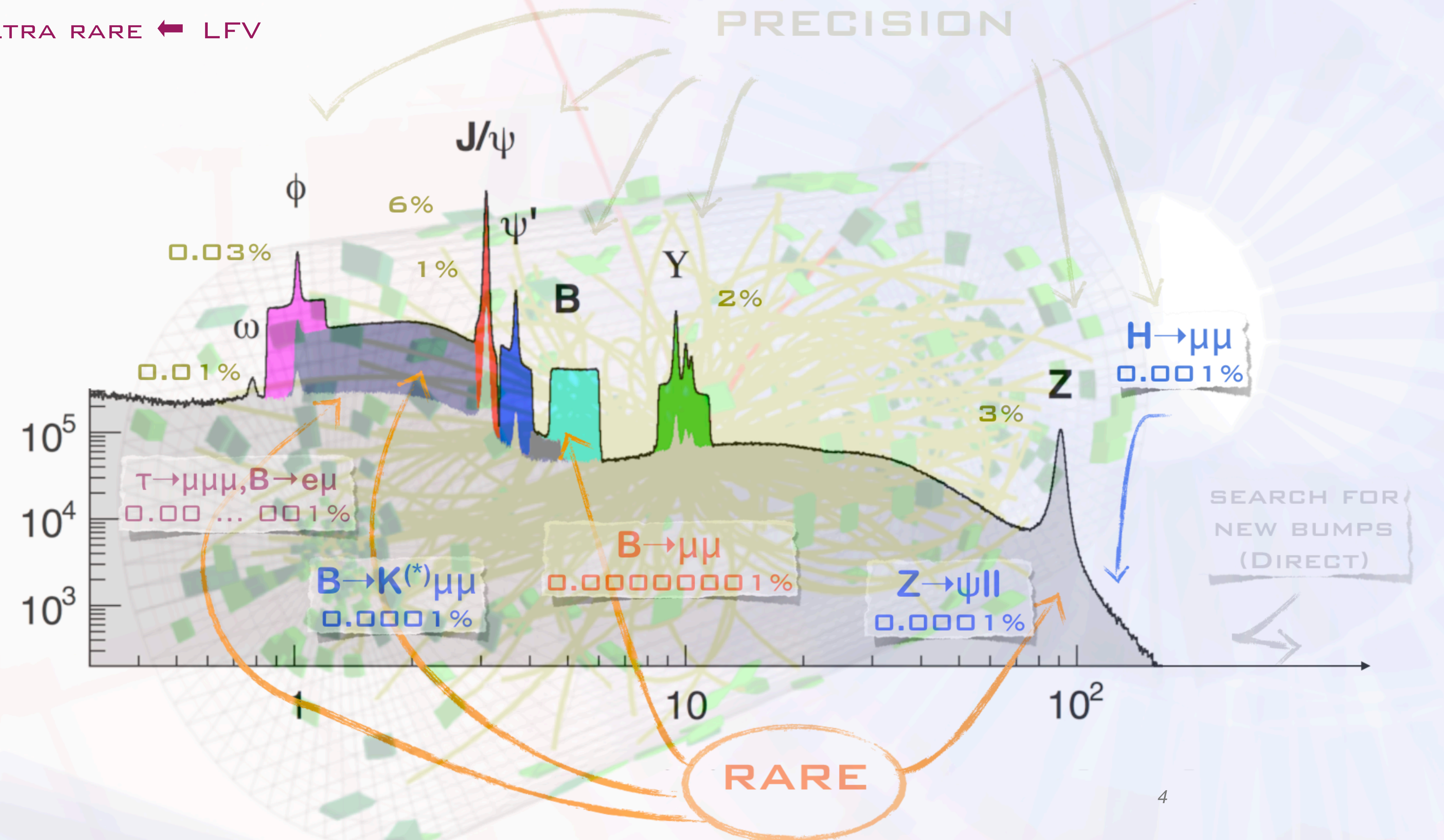
NOT-SO-RARE ➡ PRECISION!

MEDIUM RARE ⬅ EWK PENGUINS

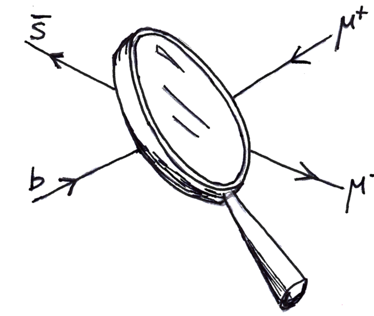
VERY RARE ⬅ FCNC/GIM+HELICITY

ULTRA RARE ⬅ LFV





rare beauty | B→μμ

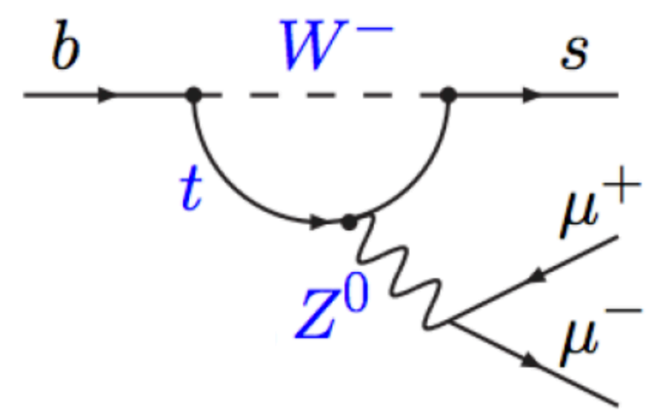


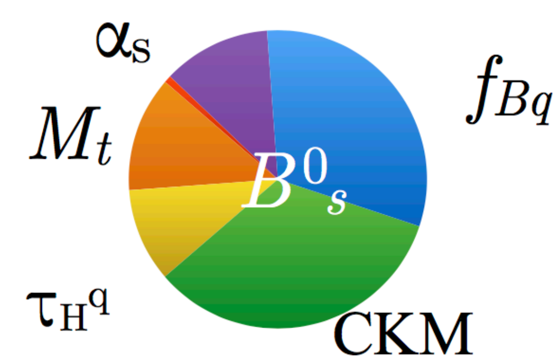
- decays highly suppressed in SM
  - FCNC- but also helicity-suppressed $(m_\mu/m_B)^2$
- theoretically clean ➡ precise SM prediction

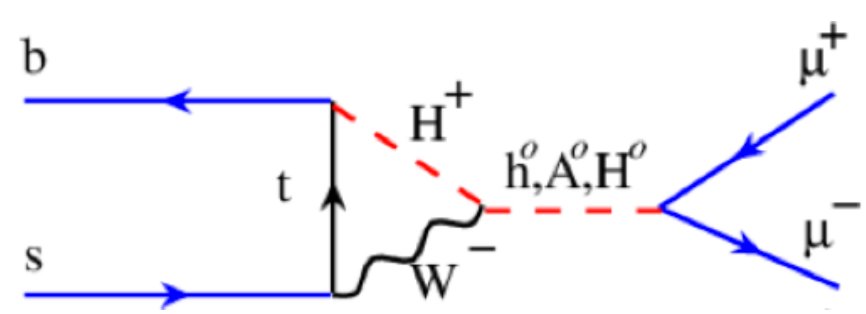
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

(~6-8%)

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

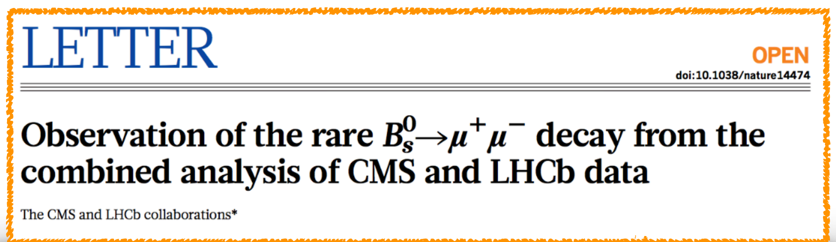


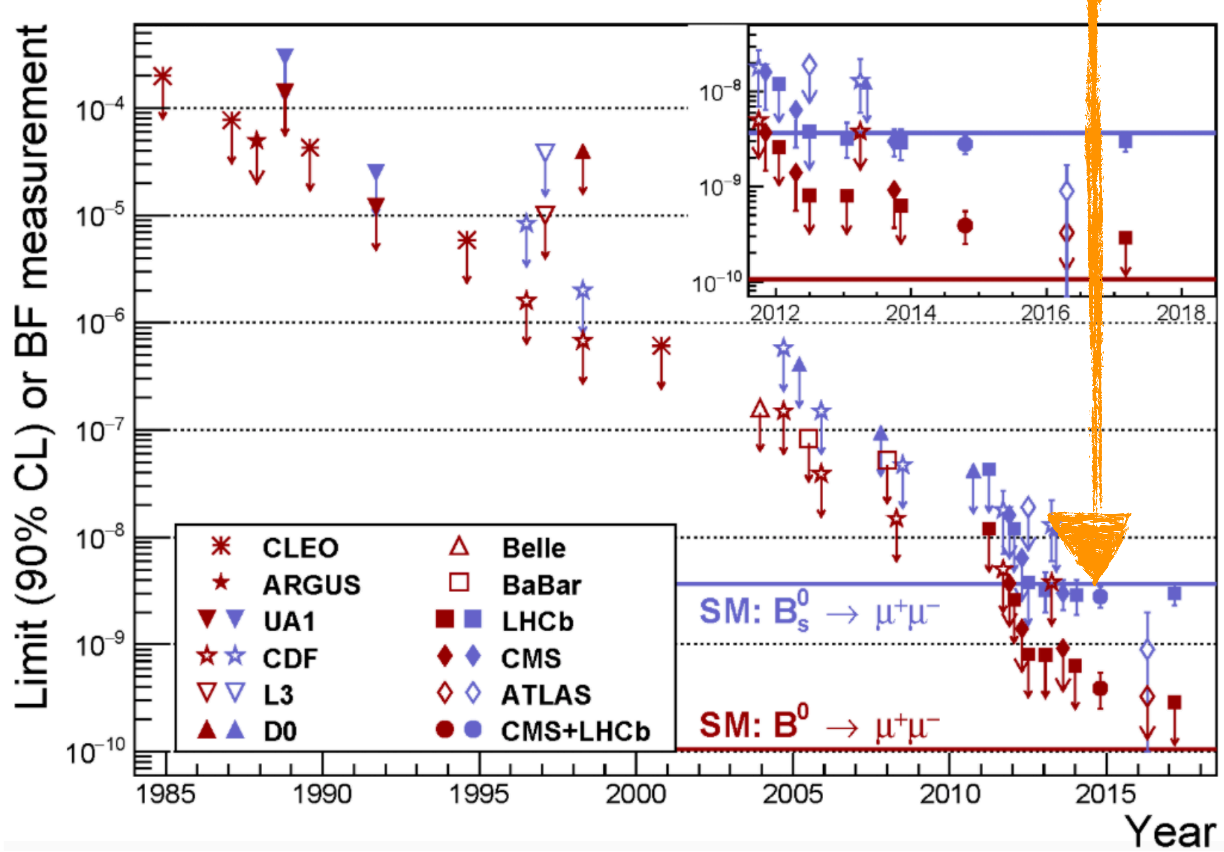


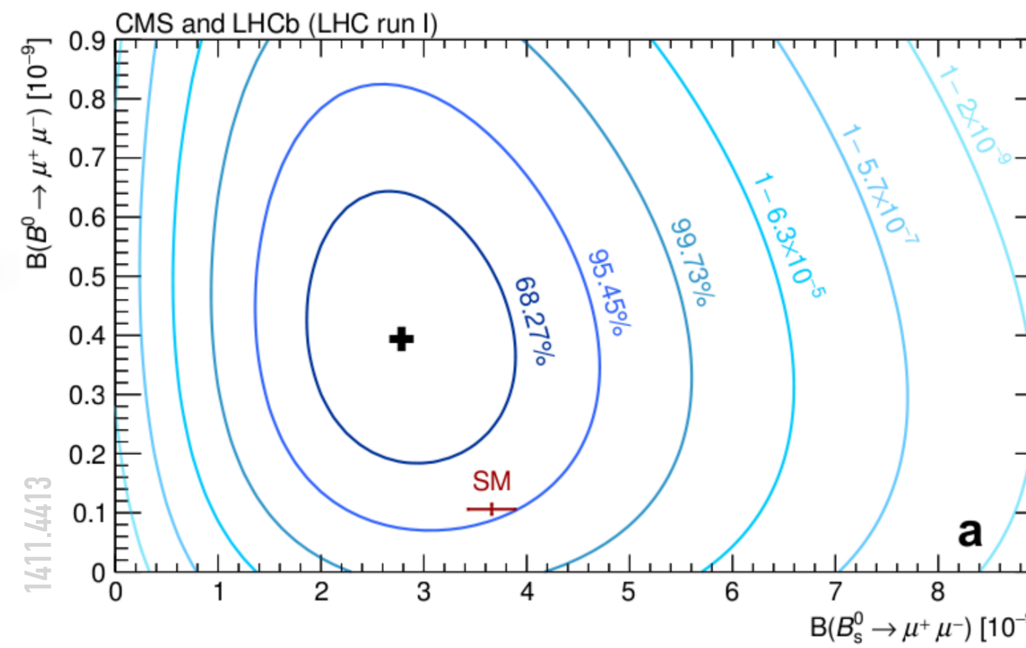


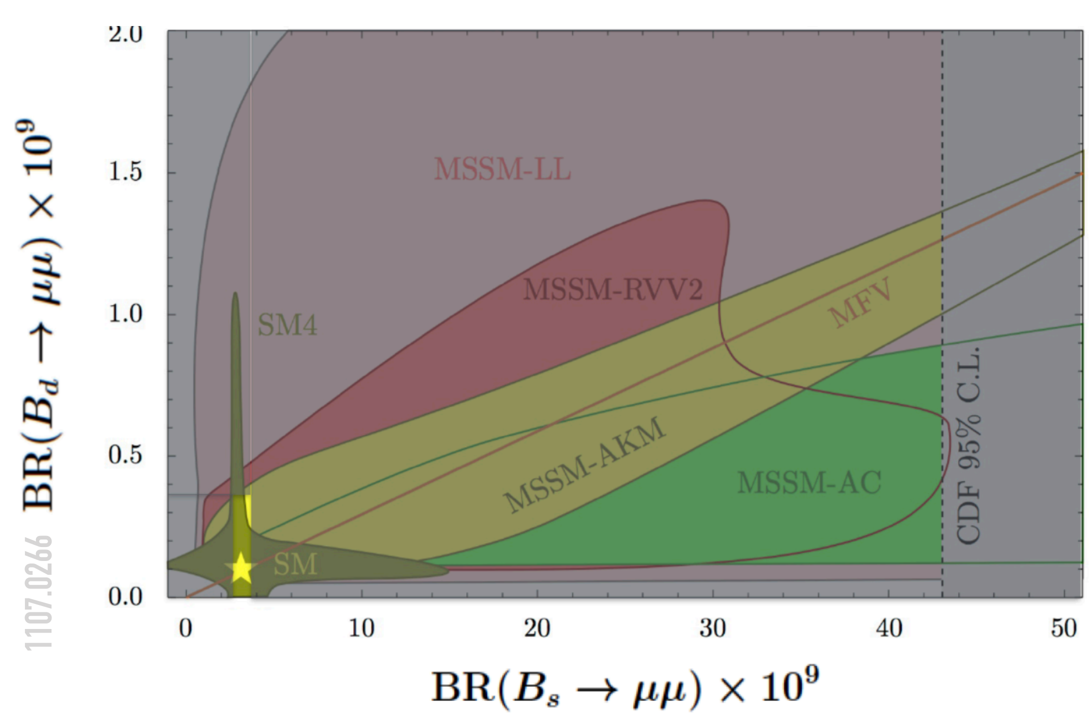
$B_s \to \mu\mu$: a (3-decade) long search

a milestone of the flavour physics program and LHC

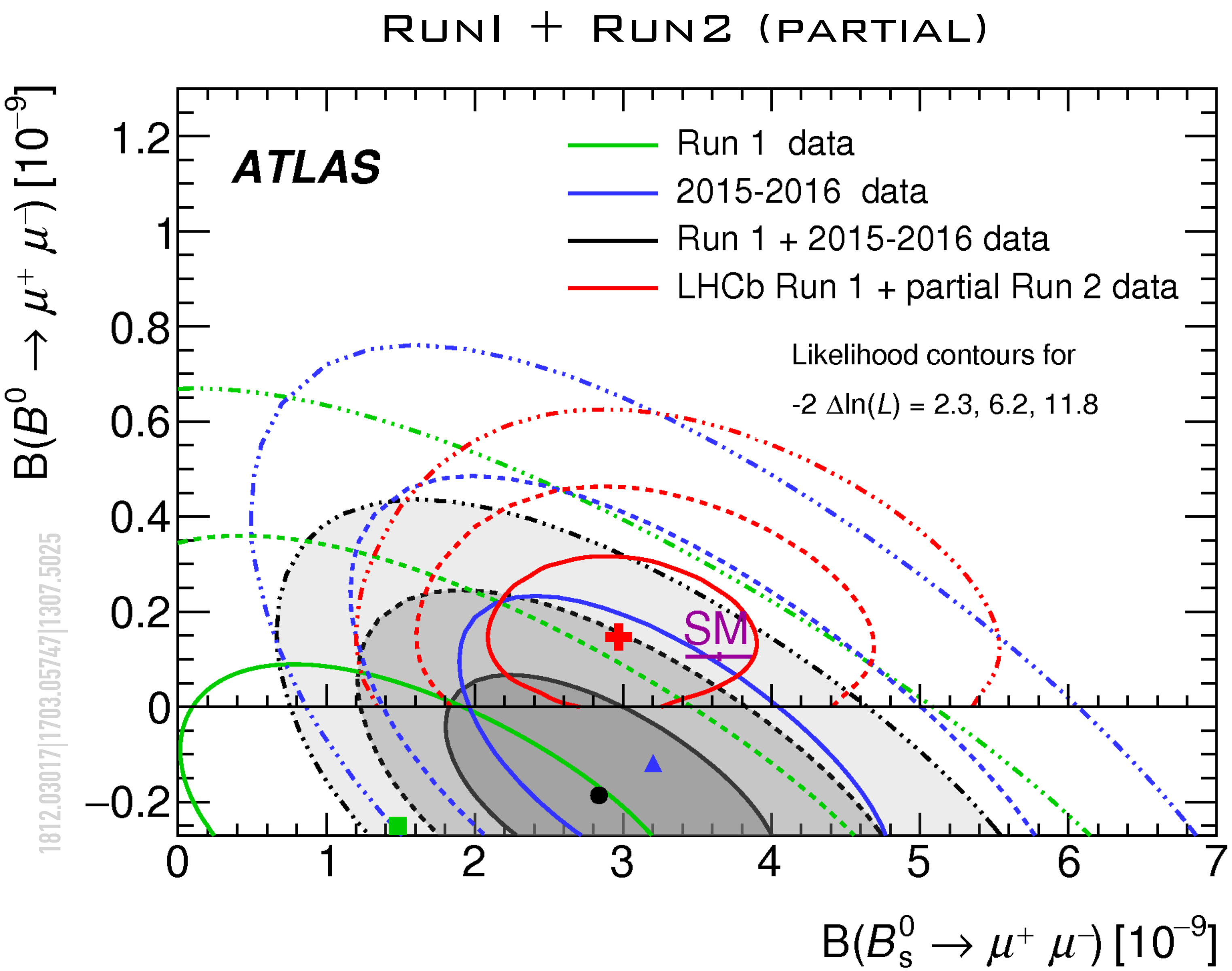

LETTER
OPEN
doi:10.1038/nature14474
Observation of the rare $B^0_s \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data
The CMS and LHCb collaborations*







B→μμ | Run2 updates



- 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±0.7)x10^{-9} (7.8σ)

BF($B^0 \to \mu\mu$) < 0.34x10^{-9} (95%CL) (1.6σ)

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

BF($B_s \to \mu\mu$) =(2.8±0.8)x10^{-9} (4.6σ)

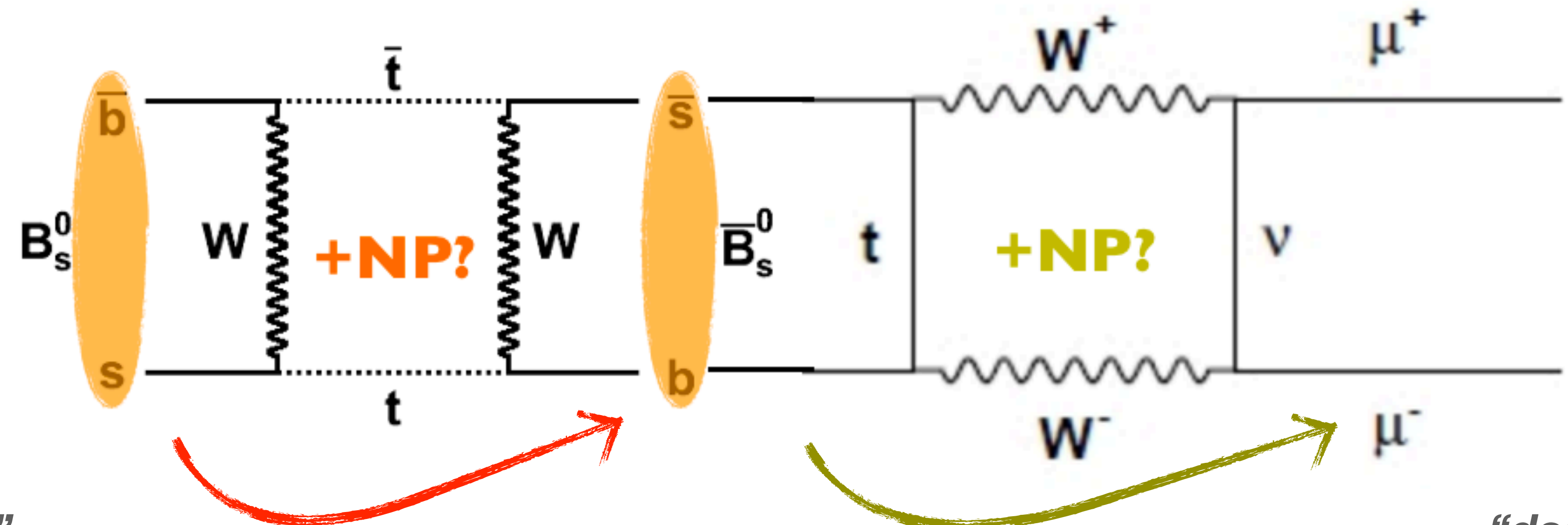
BF($B^0 \to \mu\mu$) < 0.21x10^{-9} (95%CL)

- **CMS**
  - results with Run2 data being finalised; Run1 (25fb^{-1}) only:

BF($B_s \to \mu\mu$) =(3.0±1.0)x10^{-9} (4.3σ)

BF($B^0 \to \mu\mu$) < 1.1x10^{-9} @95%CL (2.0σ)

$B_s \to \mu\mu$ | beyond decay

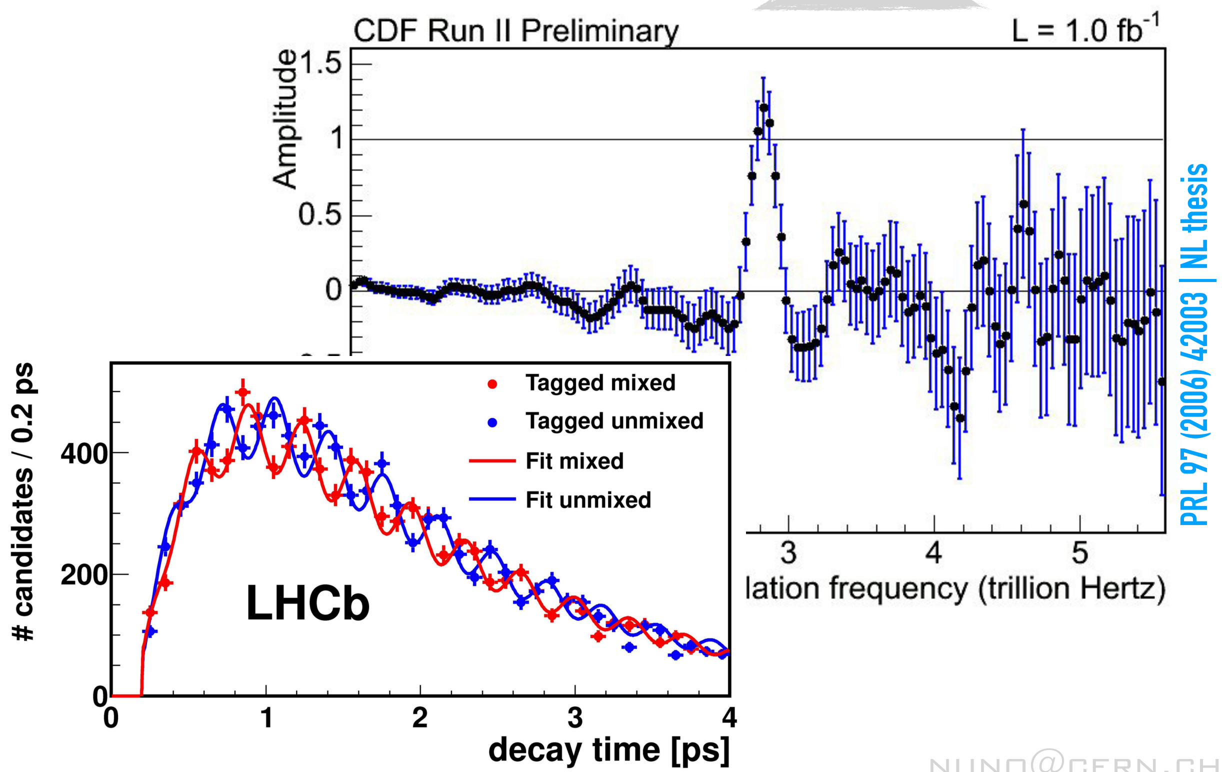


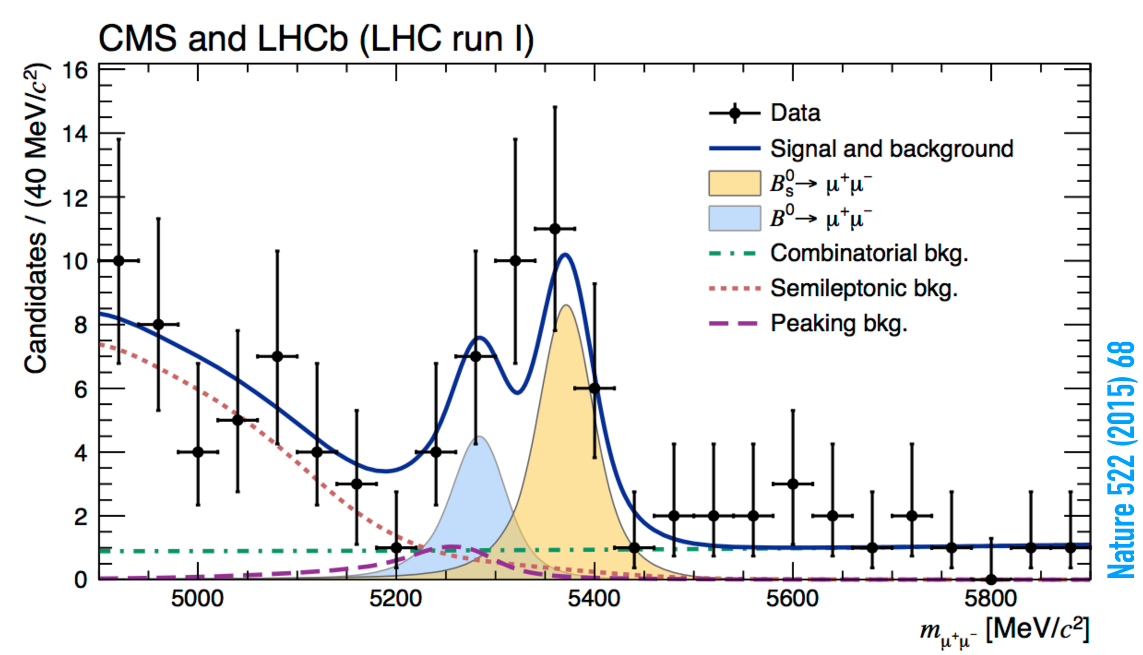
"fast and rare"

MIXING
(2-decade search)

DECAY
(3-decade search)

"doubly sensitive to NP"



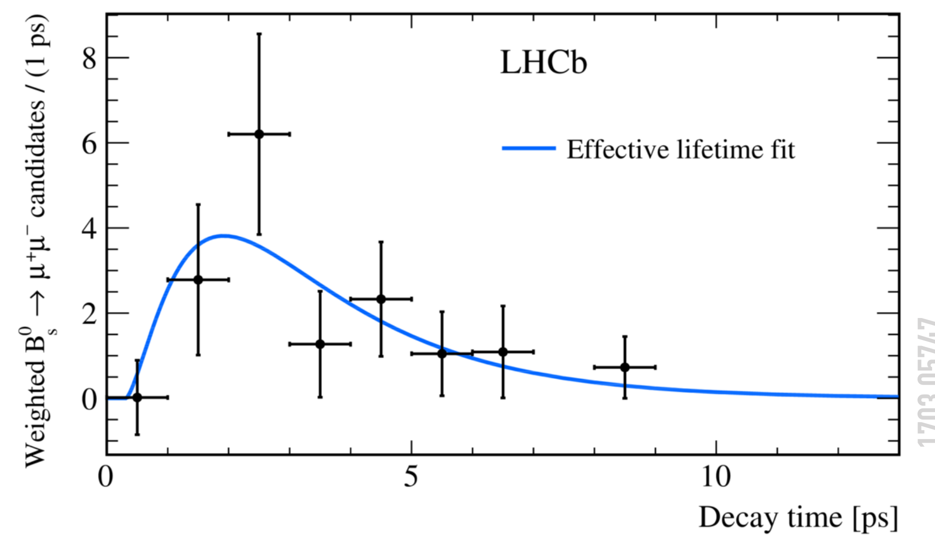


$B_s \to \mu\mu$ | lifetime

- Effective lifetime: complementary NP probe
  - in SM, only heavy eigenstate decays to μμ

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

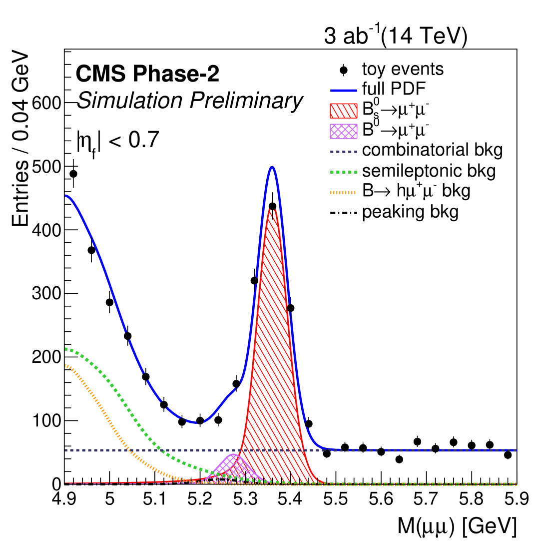
$A_{\Delta\Gamma}$ = +1 in SM
ϵ[-1,+1] in NP

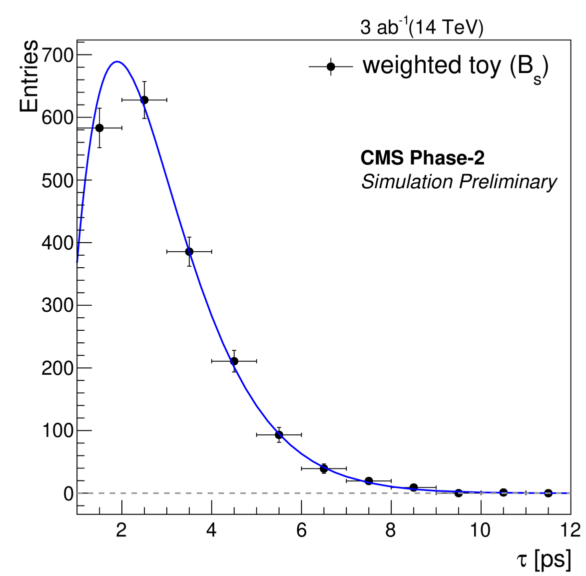


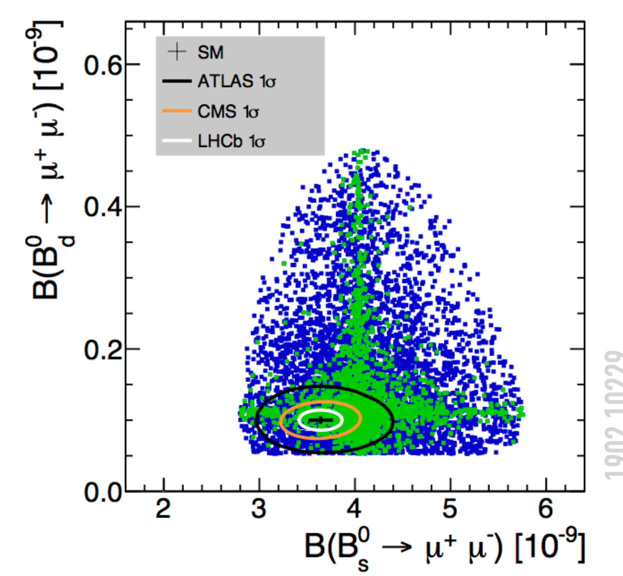
- LHCb delivered first measurement
  - current precision (22%) still insufficient

$$\tau_{\text{eff}}\left(B_s(t)\to\mu^+\mu^-\right) = (2.04 \pm 0.44 \pm 0.05)\,ps$$

- HL-LHC projections: B_s: $\tau_{\mu\mu}$(2-3%), B^0: observation

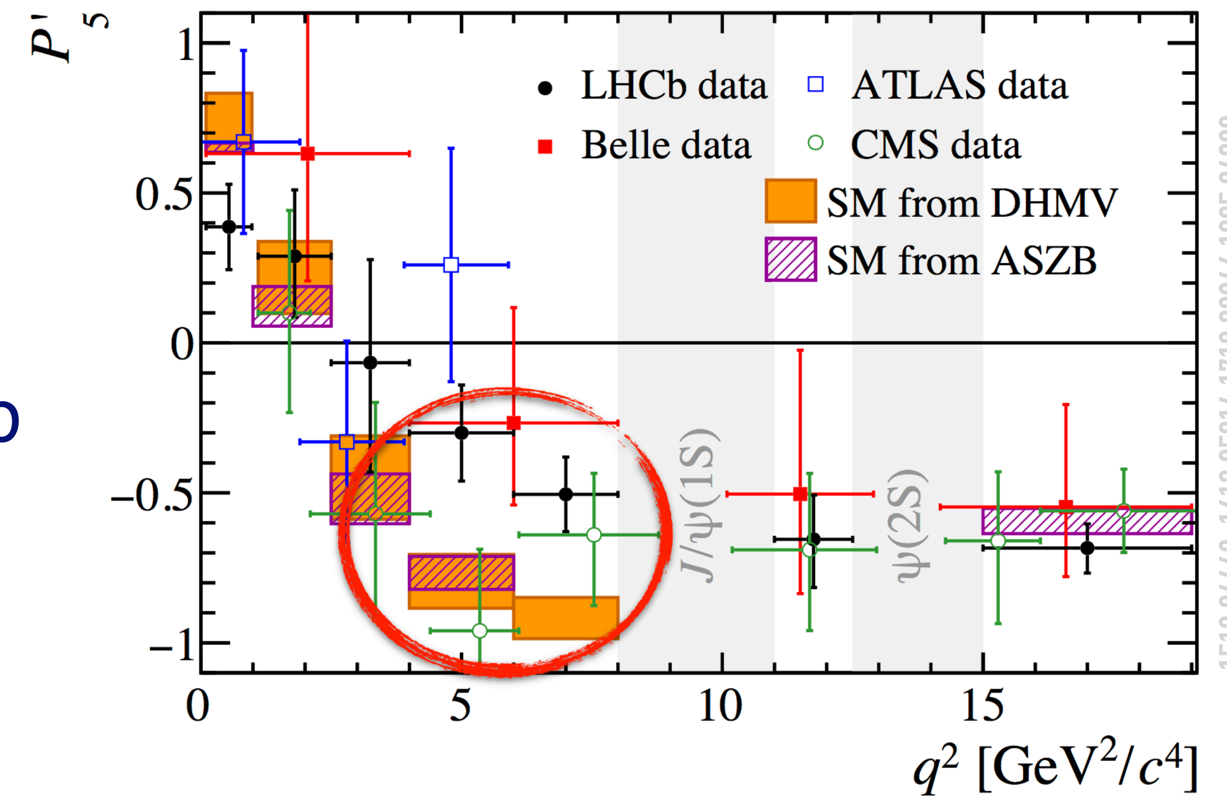




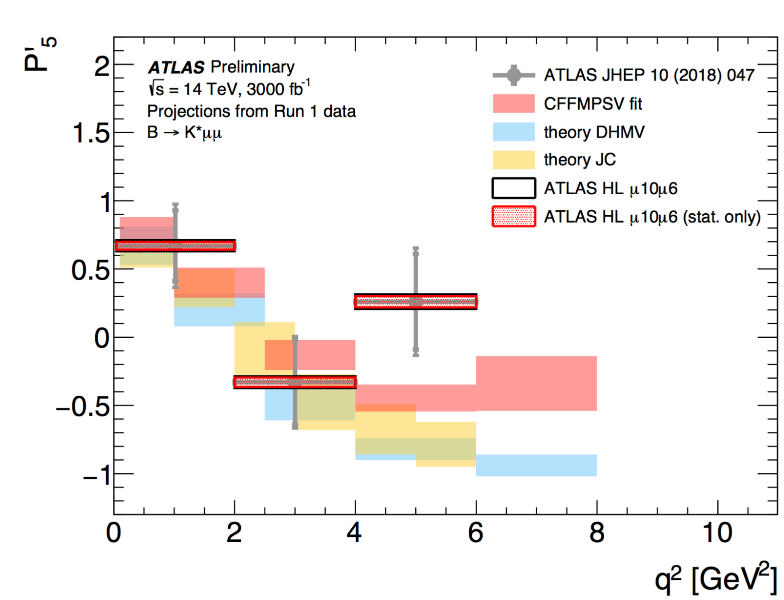


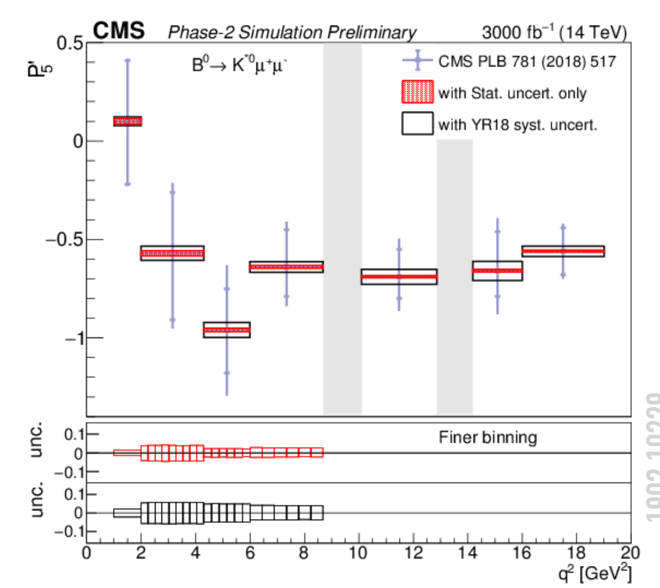
$b \to s\mu\mu$ | $B^0 \to K^{*0}\mu\mu$

- $B \to X\mu\mu$ 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?
- projections
  - upcoming data will allow to independently clarify deviation



[HL-LHC PROJECTIONS]



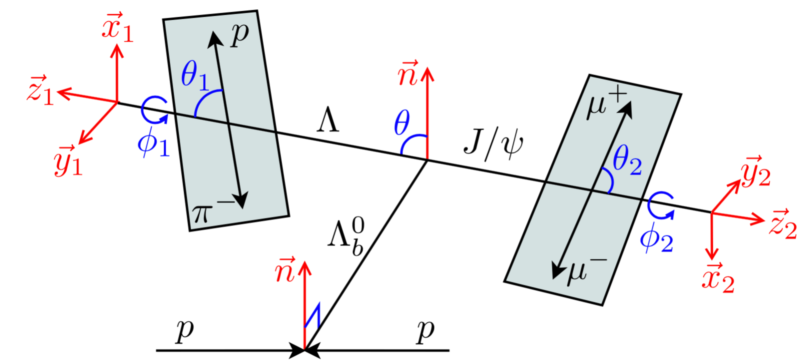


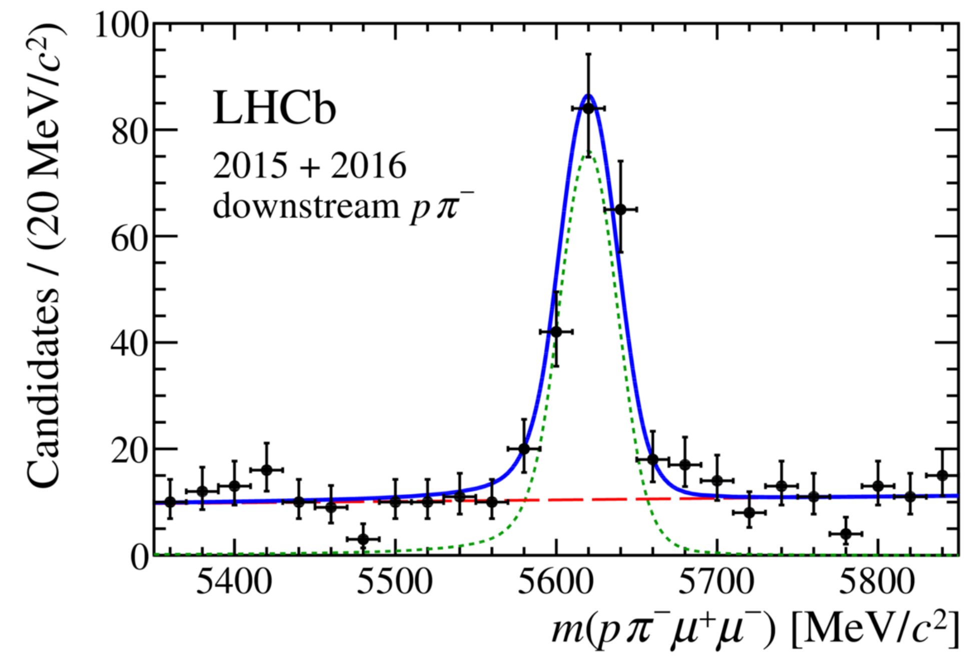
b→sμμ | $\Lambda_b \to \Lambda\mu\mu$

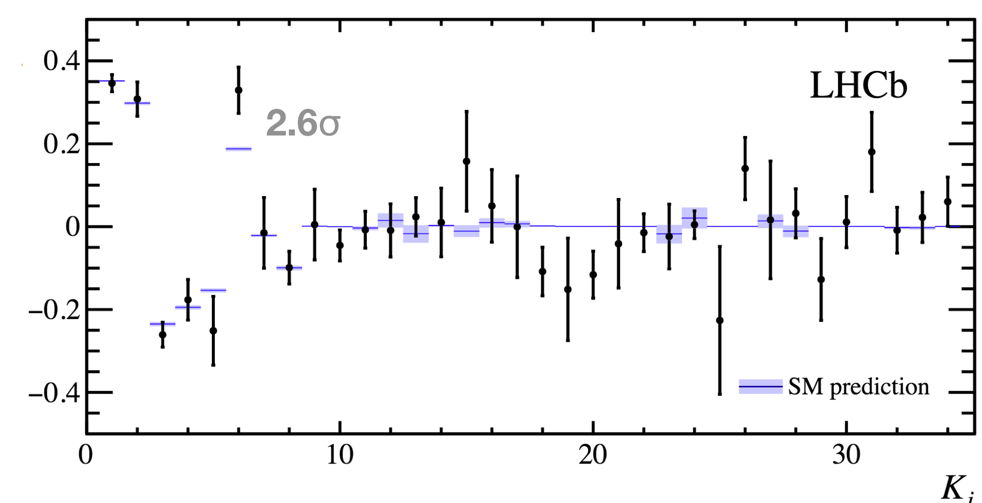
- complementary to $B^0 \to K^*\mu\mu$ in baryon sector
- $\Lambda_b \to \Lambda\mu\mu$ decay observed by CDF, and further explored by LHCb, ATLAS, CMS
- spin 1/2 ➡ 5 angles needed to describe system ➡ richer angular distribution

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

- 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

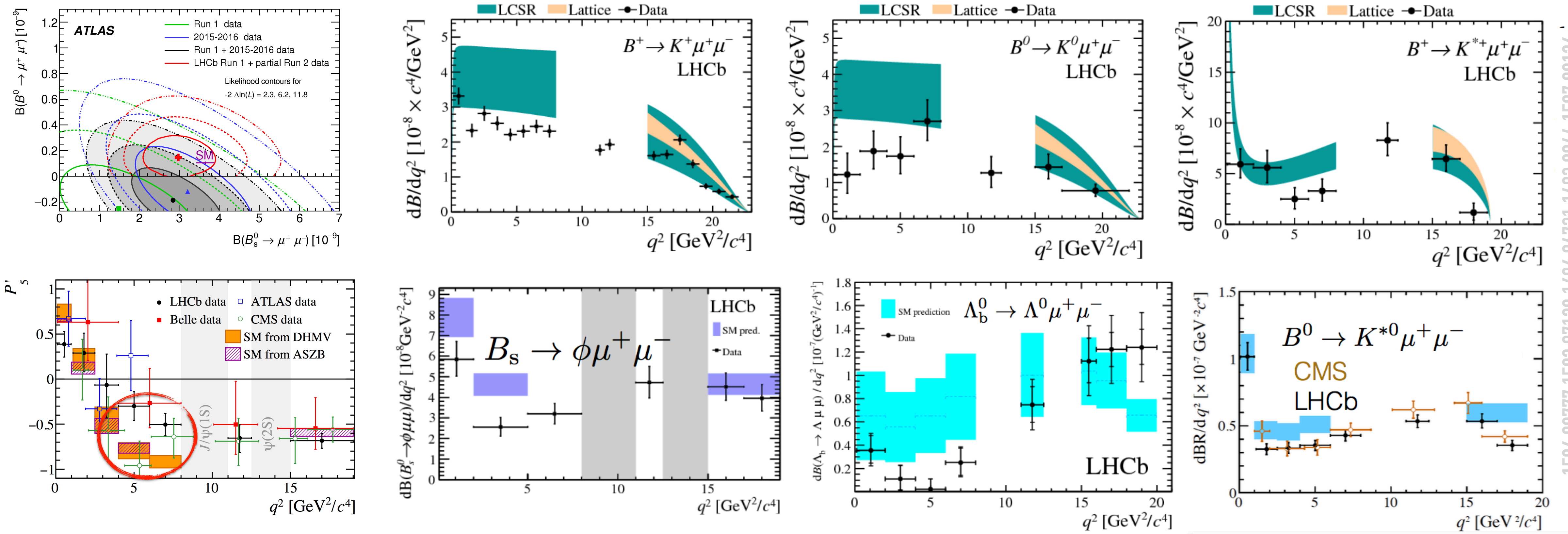


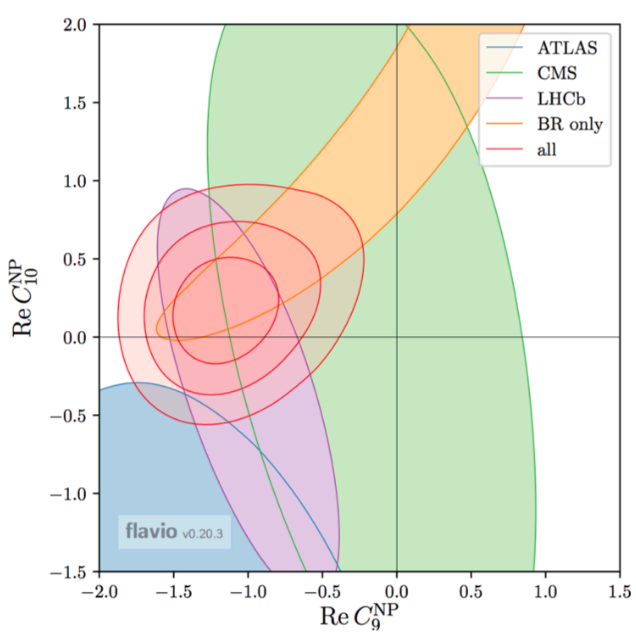




1808.00264

b→sμμ | global fits



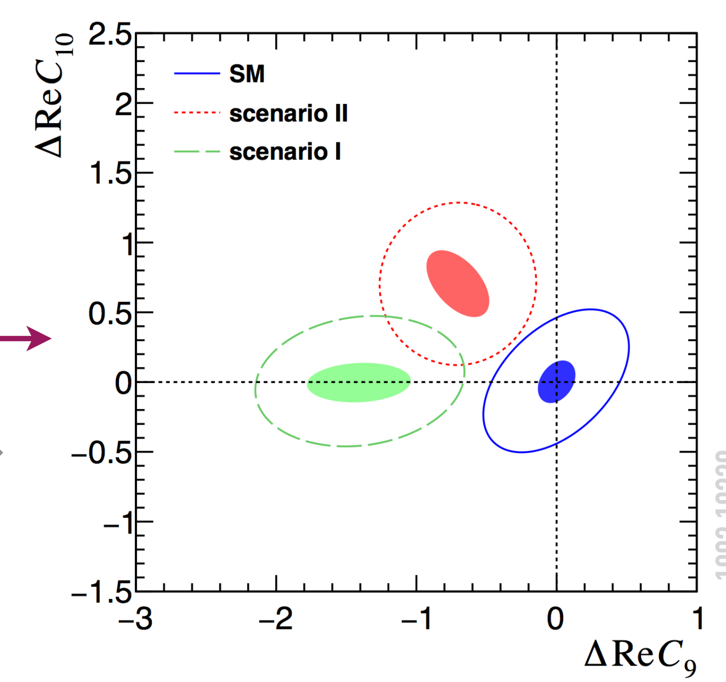


Effective Field Theory

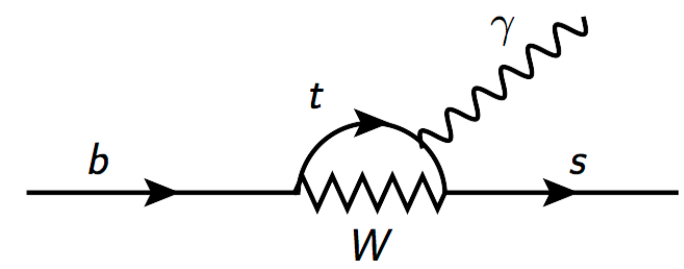
$$H_{eff} \propto \sum_i \left(C_i^{SM} + C_i^{NP} \right) \cdot O_i$$

⬅ Now HL-LHC ➡

complemented by lepton *flavour universality* tests !

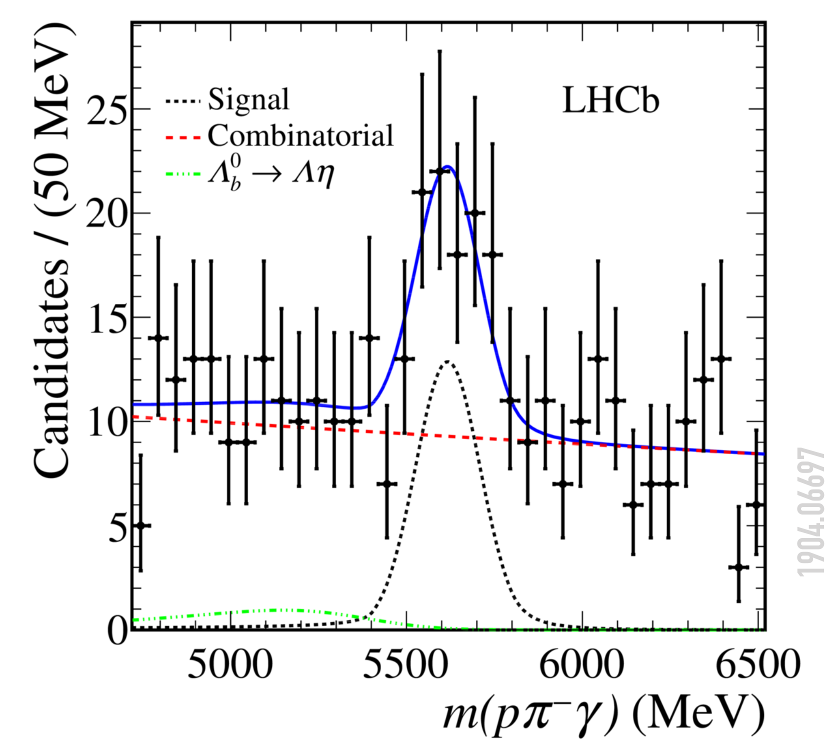


rare radiative | b→sγ

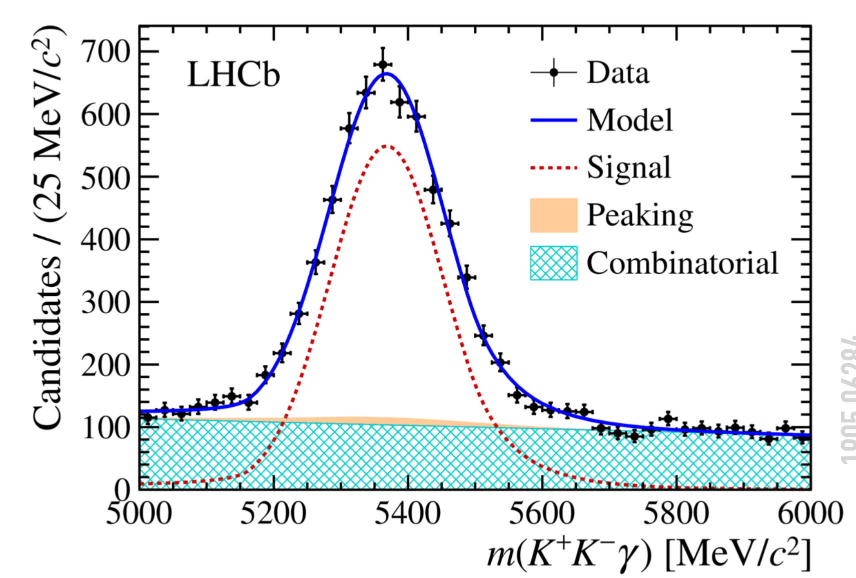


- FCNC decays
  - theo: added NP sensitivity via photon polarization
  - exp: reduced mass resolution, decay vertex
- $\Lambda_b \to \Lambda\gamma$
  - SM BF ~ (6-100)x10^{-7}, large form factor uncert.
  - previous best limit by CDF: BF<1.9×10^{-3} (90% CL)
  - LHCb: 1.7 fb^{-1} (2016); normalisation: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

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



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

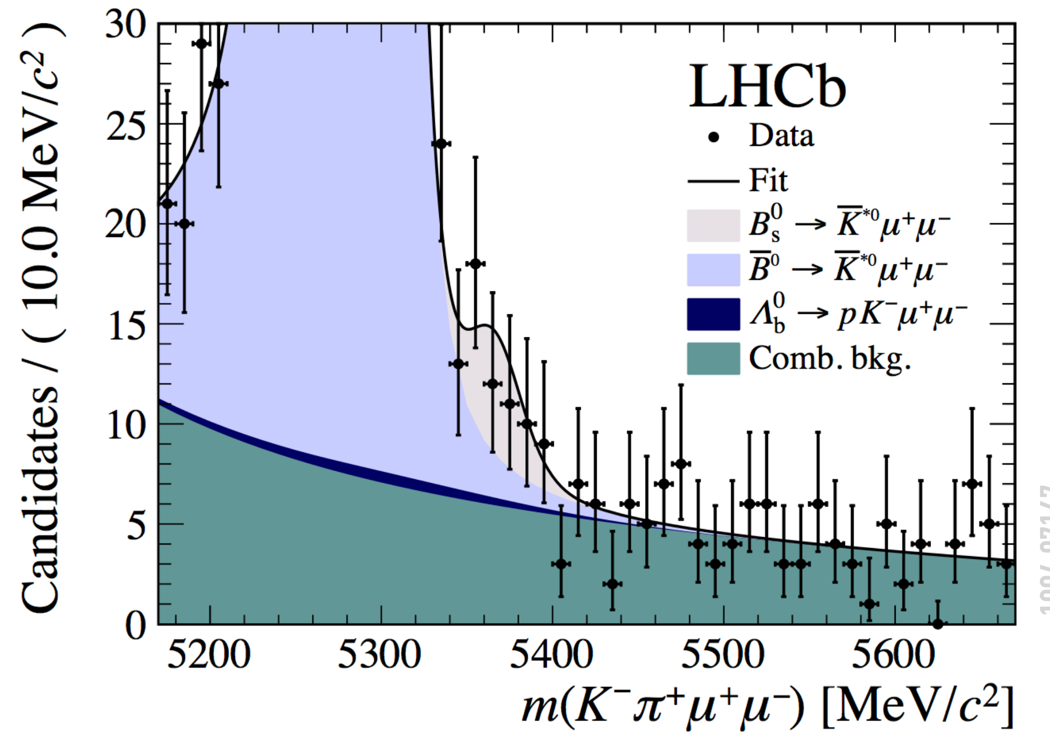
- $b \to dll$ transitions even more suppressed than $b \to sll$
  - $|V_{td}/V_{ts}| \sim 0.2$ ➡ $BF \sim 10^{-8}$
- $B^0 \to \mu\mu$: search ongoing
- $B^+ \to \pi^+\mu\mu$: observed Run1 (LHCb)

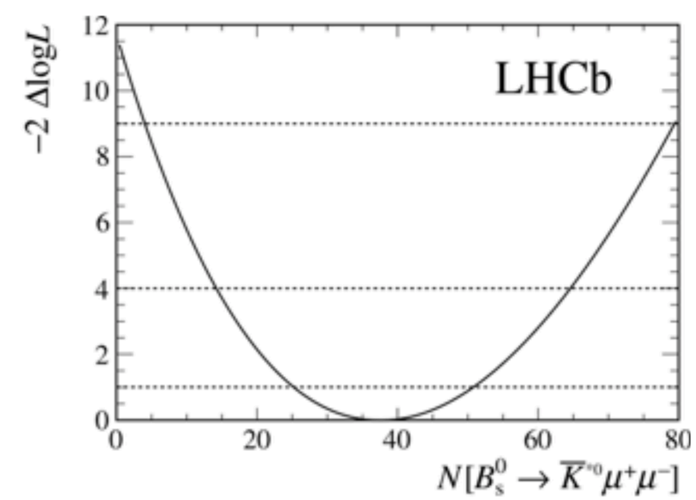
$BF = (1.8 \pm 0.24 \pm 0.05) \times 10^{-8}$ 1509.00414

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

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

- **$B_s \to K^{*0}\mu\mu$**: 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

$B(B_s \to K^{*0}\mu\mu) = (2.9 \pm 1.9 \pm 0.2 \pm 0.3) \times 10^{-8}$

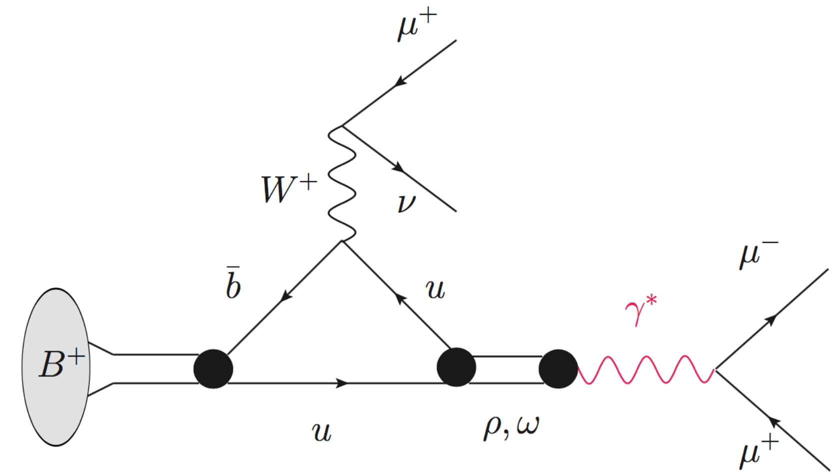
(SM: $3\text{-}4 \times 10^{-8}$)

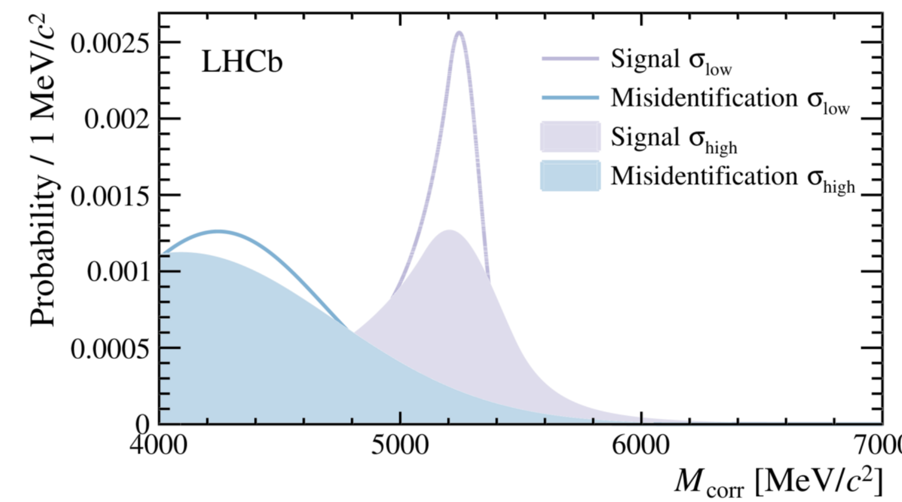
b→ull | B→μμμν

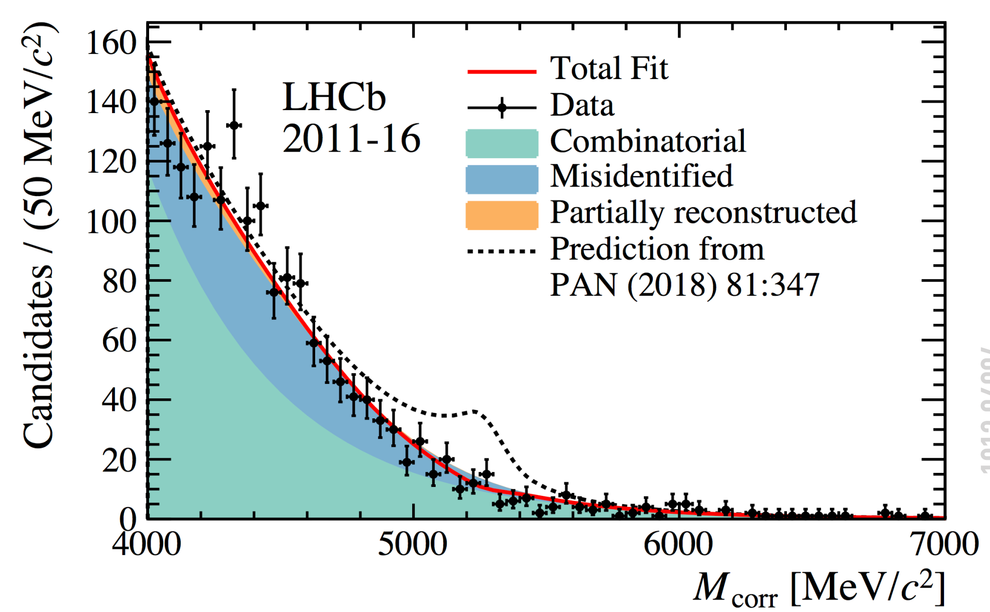
- CKM-suppressed decay
  - BF ∝ $|V_{ub}|^2$
  - NP sensitivity from helicity suppression
- current *related* best limits (by Belle)
  - $\mathcal{B}(B^+\to\mu\nu)<1.1\times10^{-6}$, $\mathcal{B}(B^+\to\mu\nu\gamma)<3.0\times10^{-6}$ (90%CL)
  - at LHC prefer >1 charged particles
- exploit corrected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

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

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

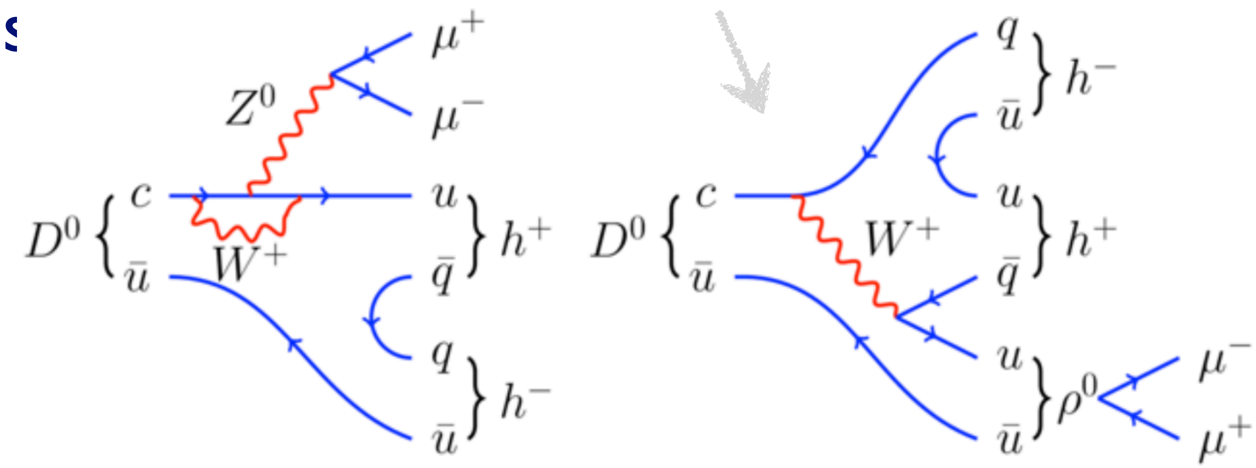




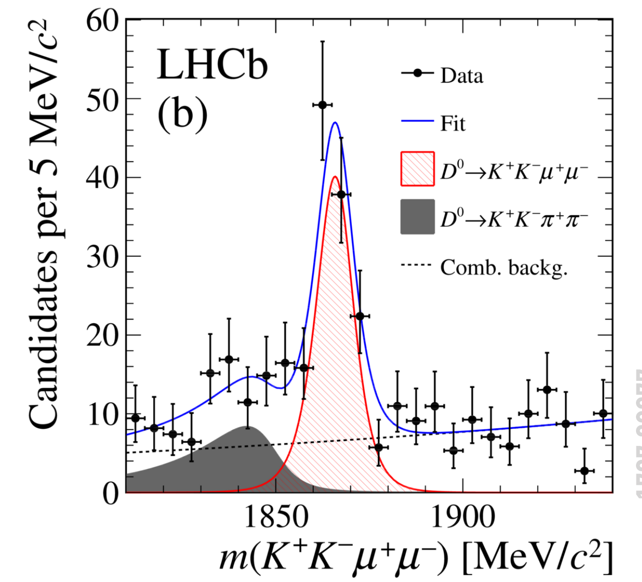


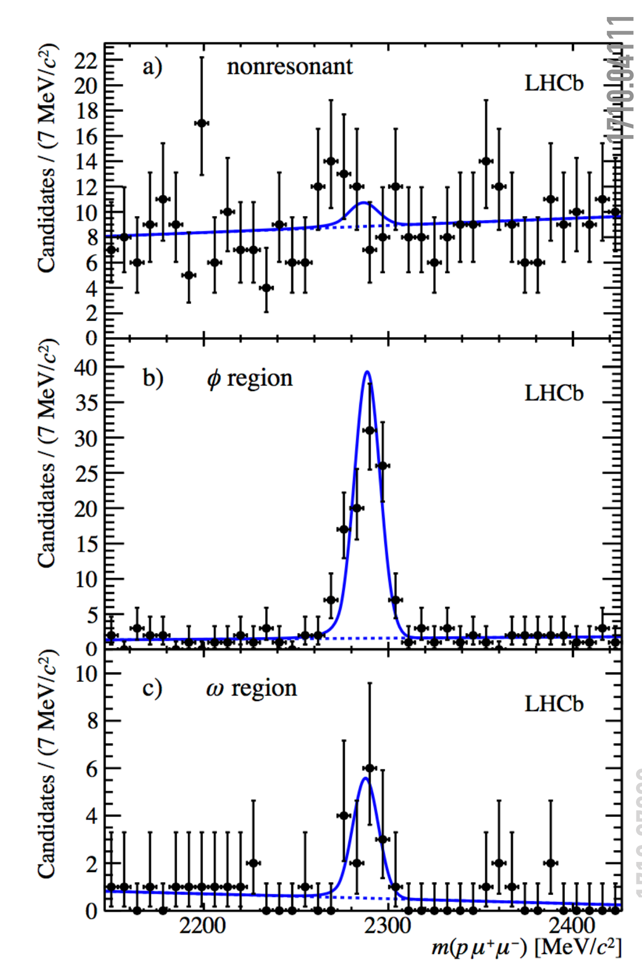
rare charm | c→uμμ

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



- **D⁰→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



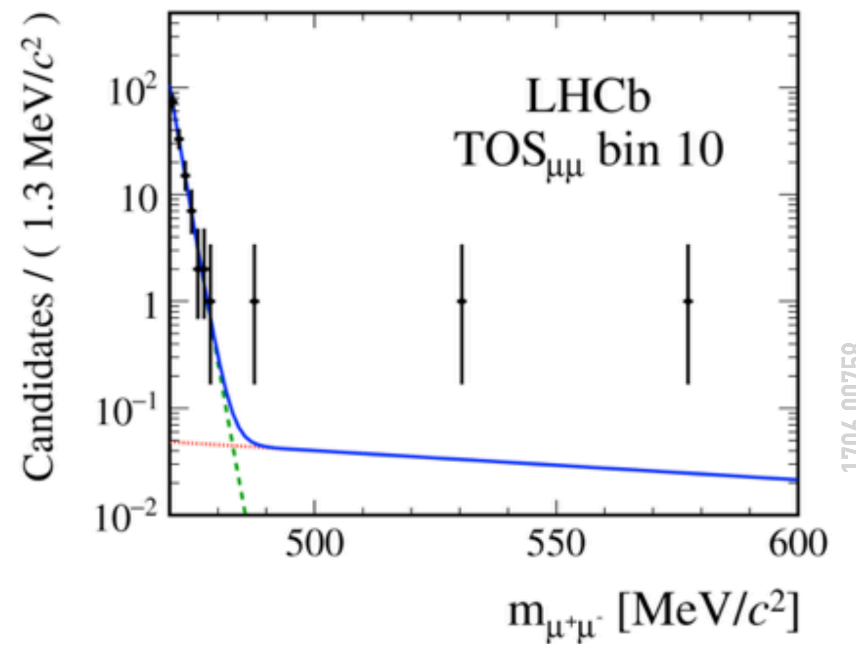


rare strangeness | $s \to d\mu\mu$

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

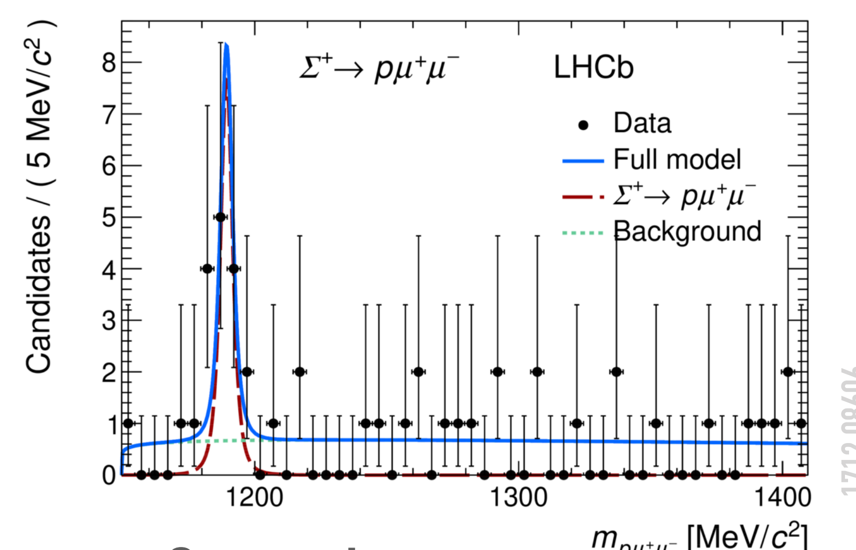
$K_S \to \mu\mu$

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

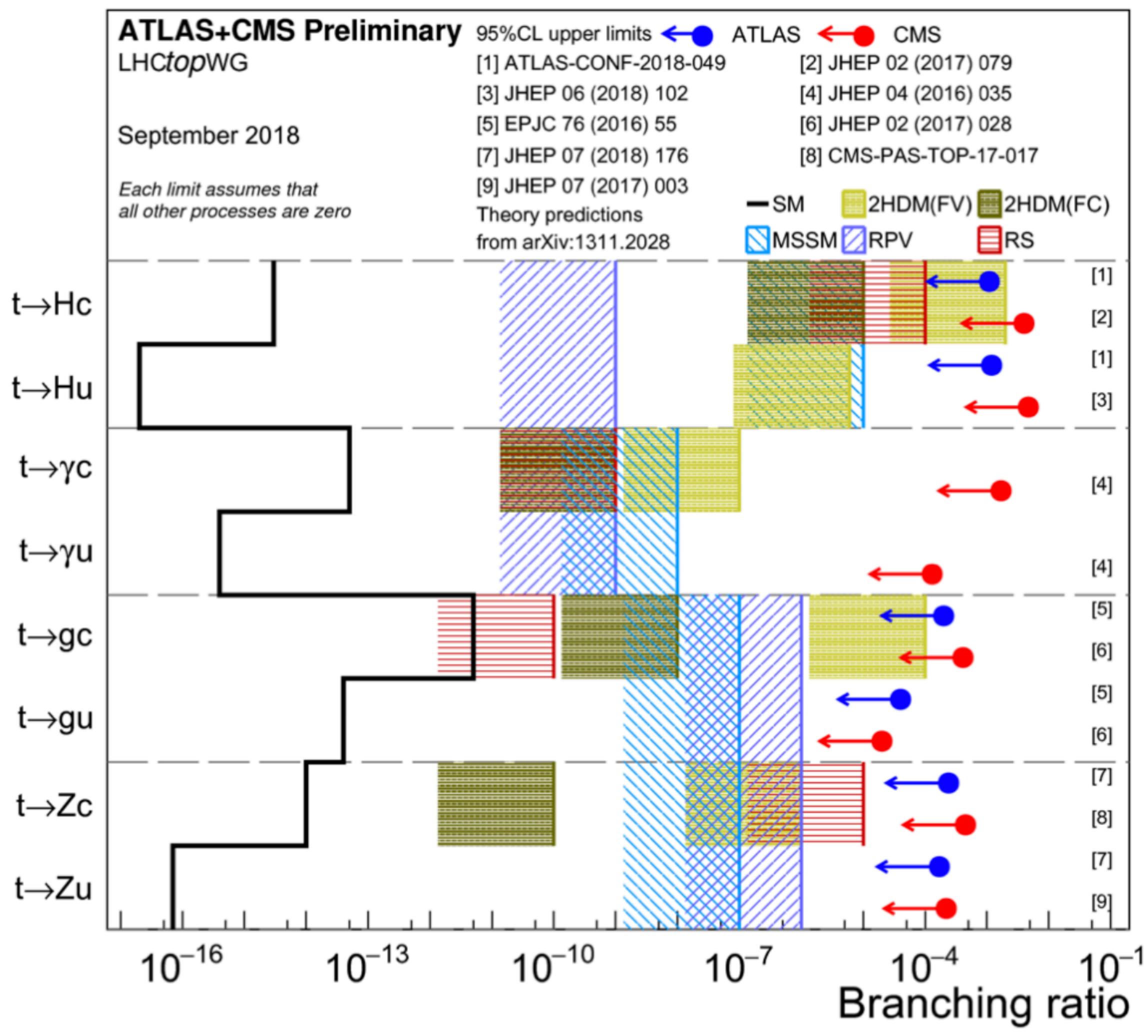


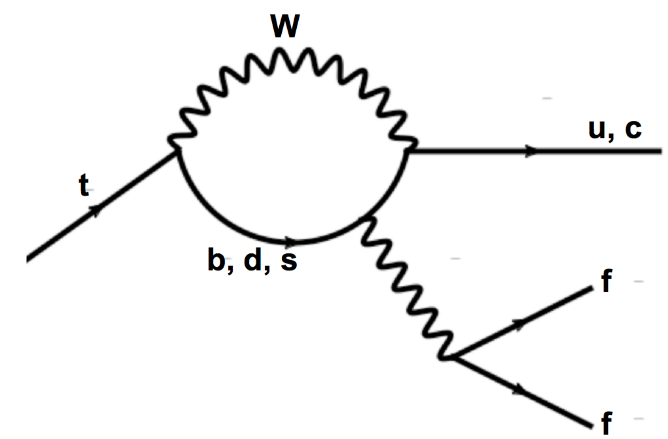
$\Sigma^+ \to p\mu\mu$

- SM prediction BF ~$(1.6\text{-}9)\times10^{-8}$
- $3fb^{-1}$ (Run1); normalization: $\Sigma^+ \to p\pi^0$
- LHCb found 1st evidence at 4.1σ
  - $BF(\Sigma^+ \to p\mu\mu) = (2.2\ {+1.8}{-1.3})\times10^{-8}$
  - no structure in dimuon mass
  - HyperCP excess (➡NP) at $m_{\mu\mu}$~214 MeV not confirmed

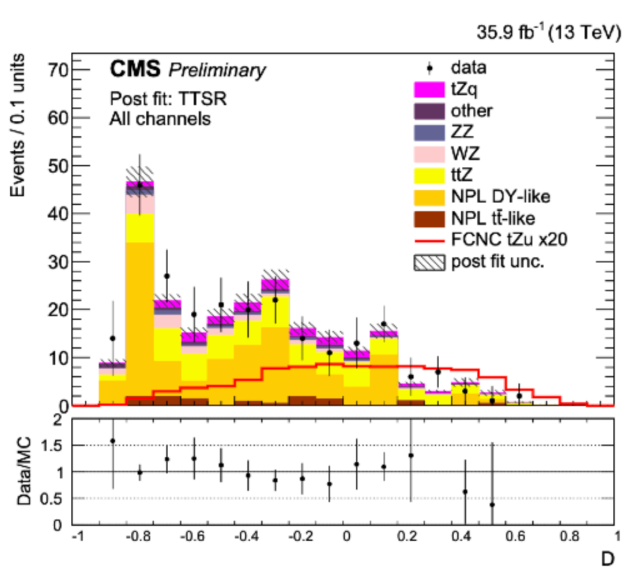


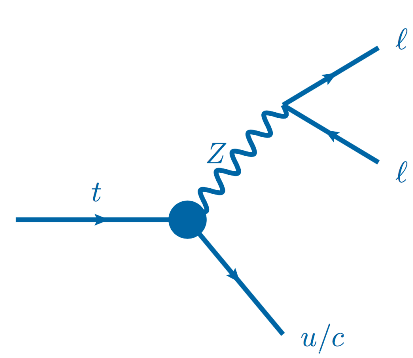
rare top | t→u/c



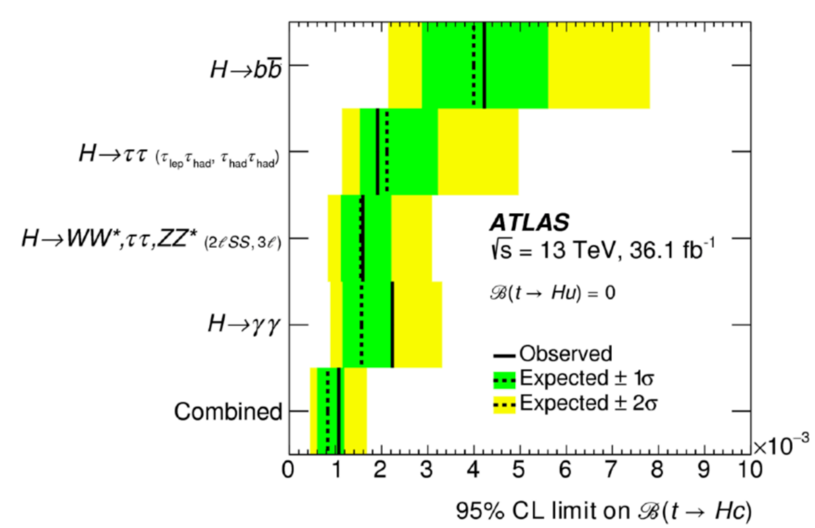


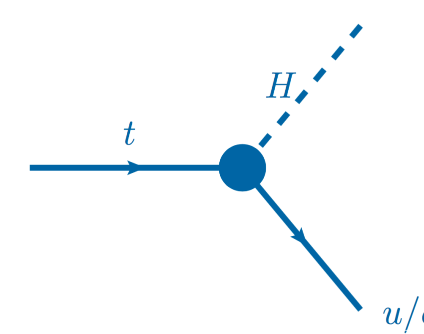
- FCNC/GIM in top sector lead to very rare processes
  - BF~10^{-14}
- rates enhanced in NP models
  - MSSM (10^{-7}), 2HDM (10^{-6}), RS(10^{-5})
- current limits ~10^{-4}





CMS-TOP-17-017





1803.09923

rare bosons | W,Z

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

$W \to 3\pi$

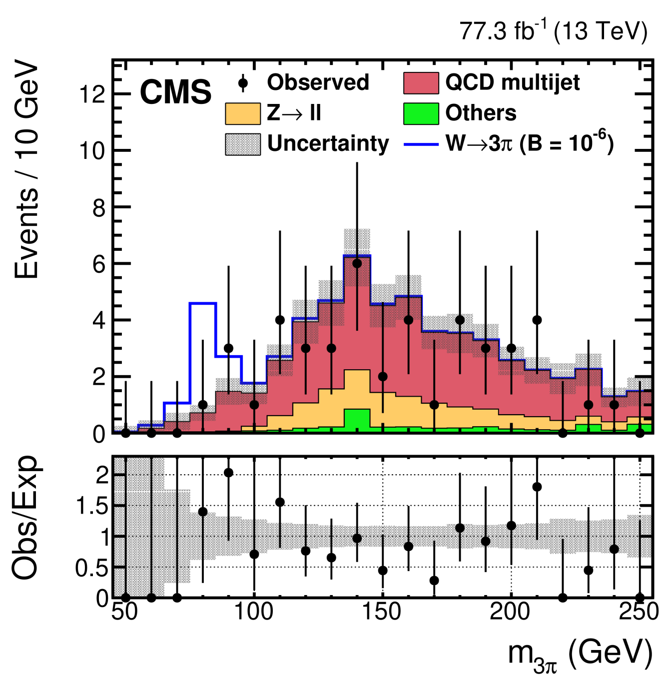
- probe exclusive W decay
  - small multiplicity decay
  - SM expectation ~10^{-8}-10^{-6}
  - inclusive production (not ttbar)
  - explore τ trigger + reco
  - 95%CL limit: $B(W \to 3\pi) < 1.01 \times 10^{-6}$
  - ➡ @HL-LHC: could allow precision M_W

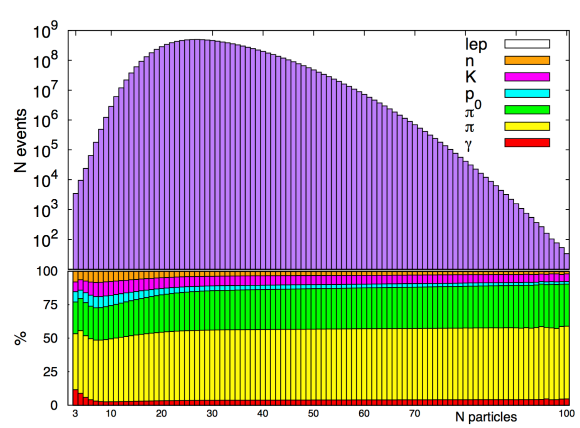
$Z \to \psi ll$

- found a new Z decay
  - clean final state: $\psi\mu\mu$ + ψee
  - SM expectation ~$(6.7\text{-}7.7) \times 10^{-7}$
  - normalization: $Z \to \mu\mu\mu\mu$
  - obtained first observation
  - measured: $B(Z \to \psi ll) \sim 8 \times 10^{-7}$

observation (5.7σ)

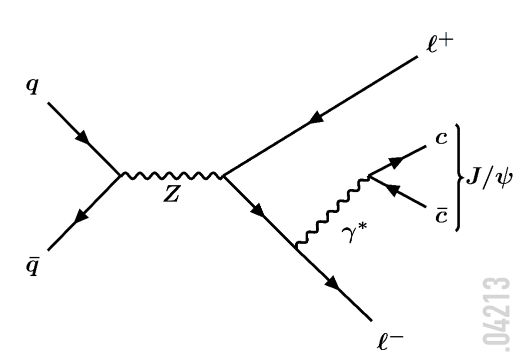
1901.11201



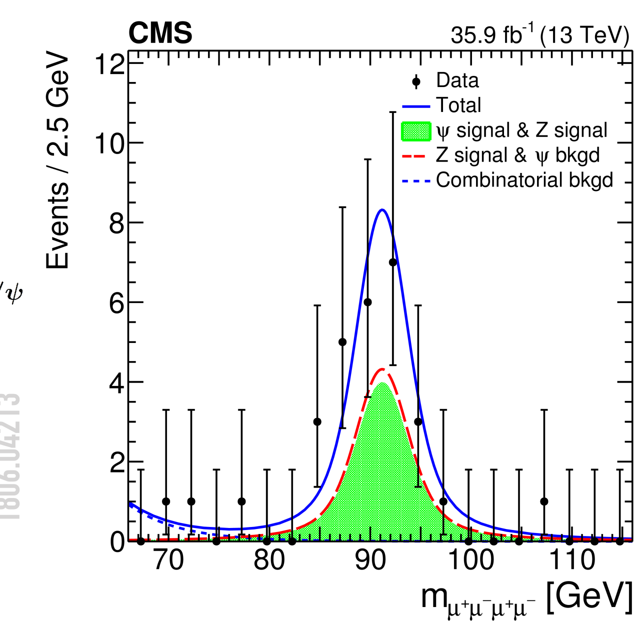


majority W,Z hadronic decays
into ~30-particle final state

1410.7475

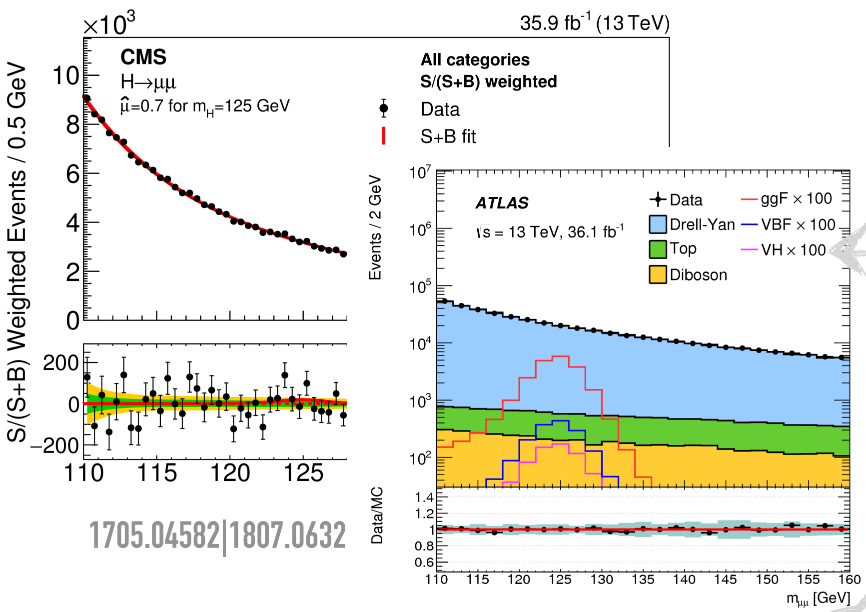


1806.04213

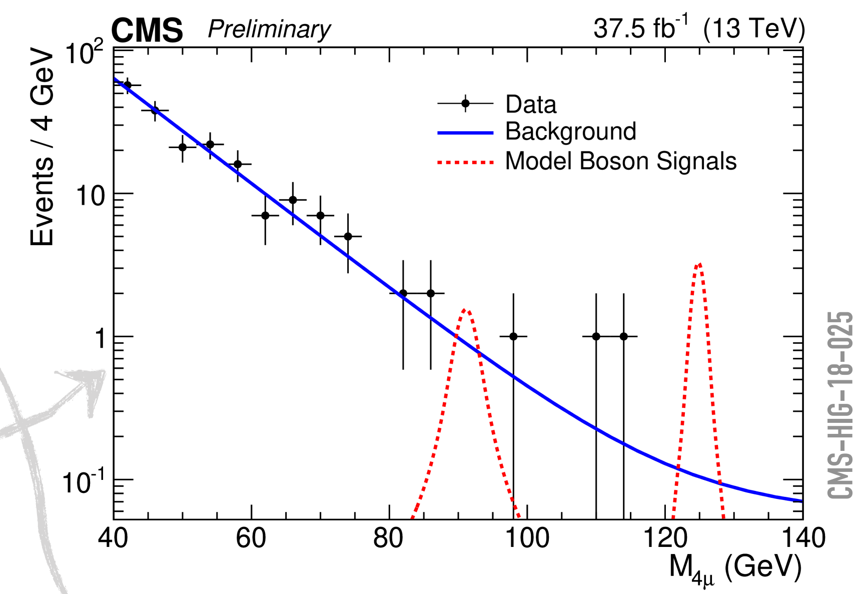


rare bosons | H

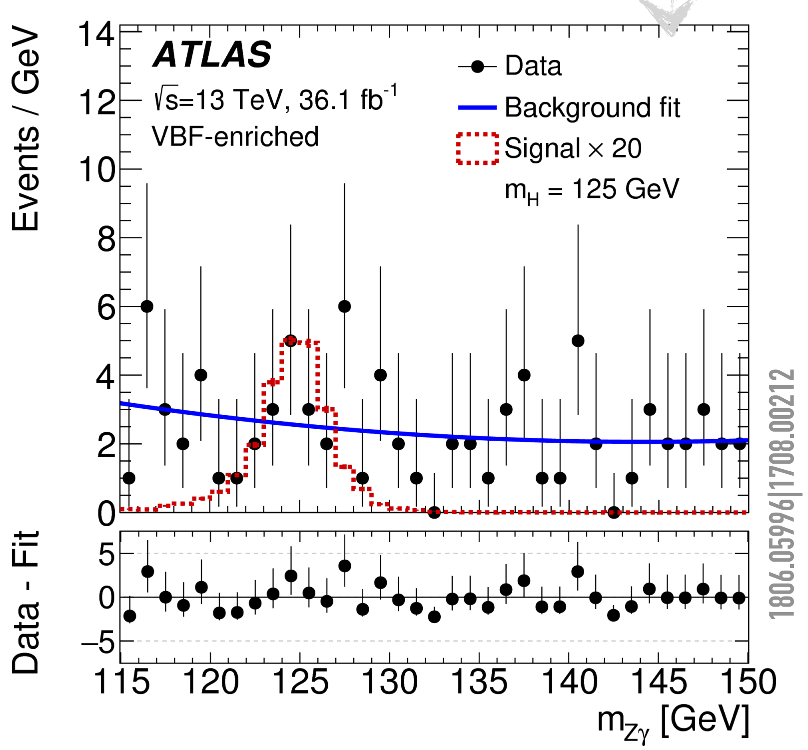
CHANNEL	BR (SM)
H → invisible	≥ 1 × 10^{-3}
H → μμ	2.17 × 10^{-4}
H → Zγ → ℓℓγ	1.01 × 10^{-4}
H → J/ψγ	3.0 × 10^{-6}
H → Υγ	~5 × 10^{-9}
H → ΥΥ	~2 × 10^{-9}
H → J/ψ J/ψ	~1.5 × 10^{-10}



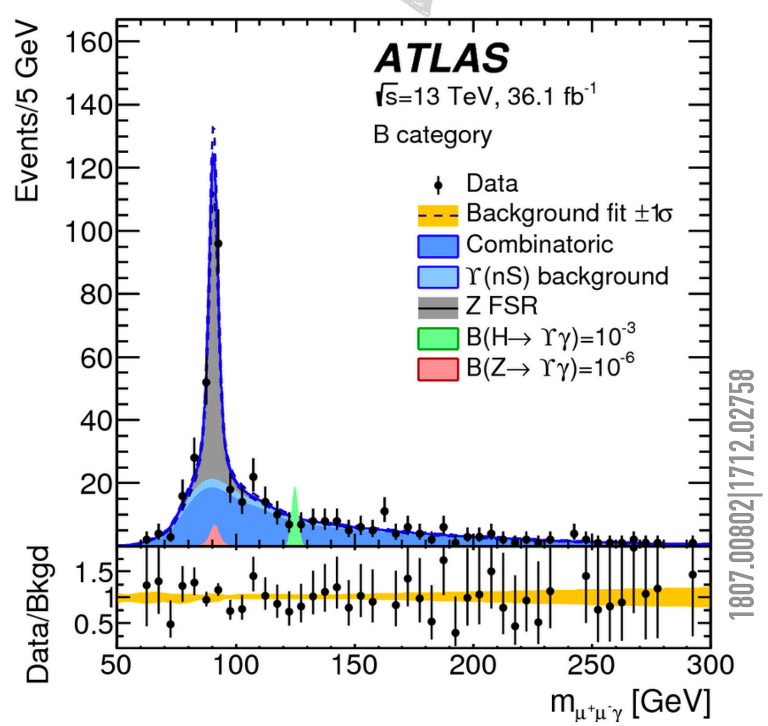
H→μμ: < 5.7x10^{-4} @95%CL



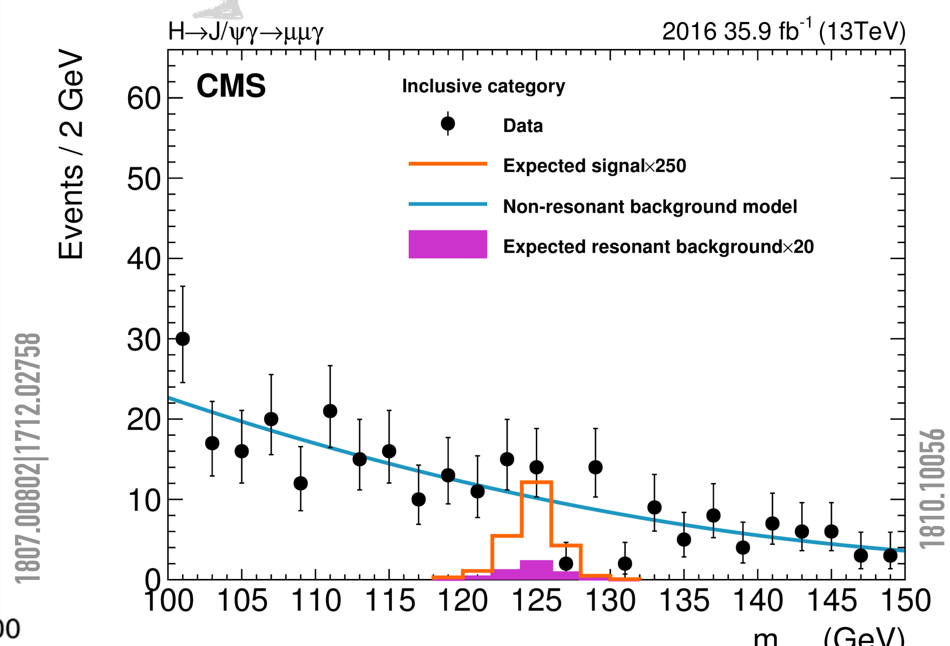
H→YY: < 1.4x10^{-3} @95%CL



H→Zγ: < 1 x 10^{-2} @95%CL



H→Yγ: < 4.9x10^{-4} @95%CL



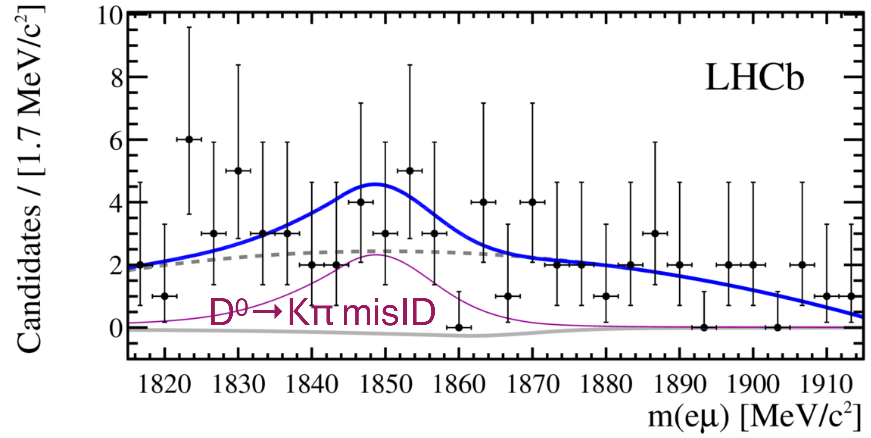
H→Yγ: < 7.6x10^{-4} @95%CL

forbidden rare | LFV, LNV, BNV

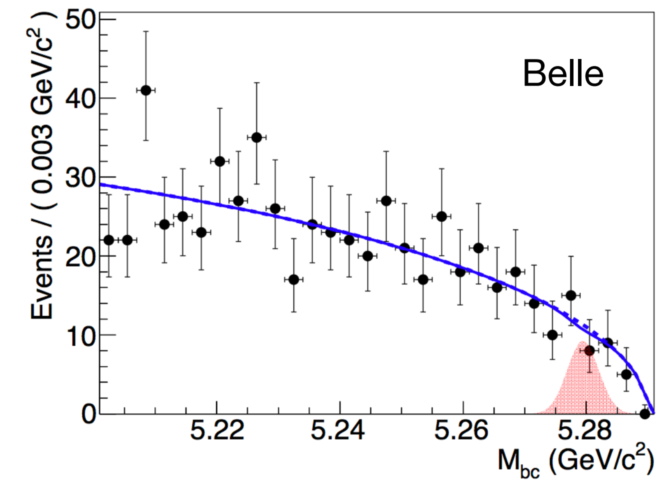
- charged Lepton Flavour Violation *practically* forbidden in SM
  - allowed by neutrino oscillations, but with BF far smaller than experimentally conceivable
  - BF in SM $<10^{-40}$, eg: 10: $B(\tau\to\mu\mu\mu)\sim B(Z\to e\mu, e\tau)\sim 10^{-54}$, $B(Z\to\mu\tau)\sim 10^{-60}$
- potentially sizeable 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

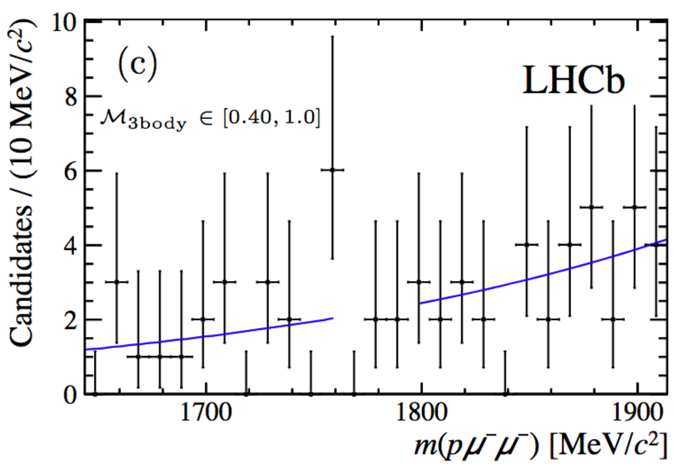
D→μe 1512.00322

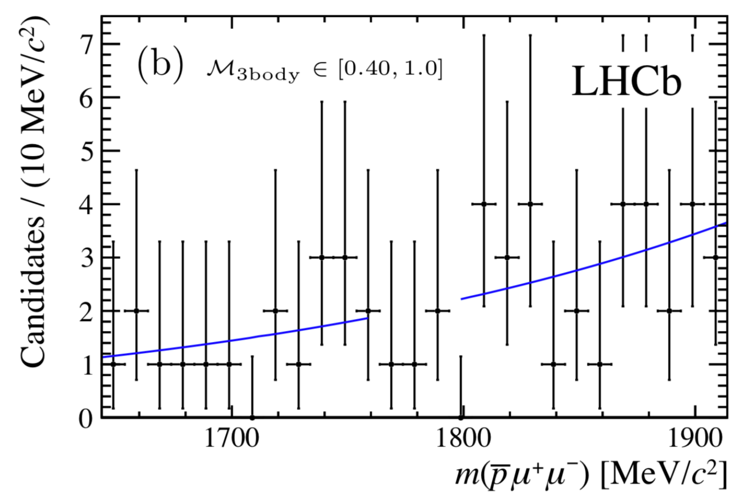


B→K*μe 1807.03267

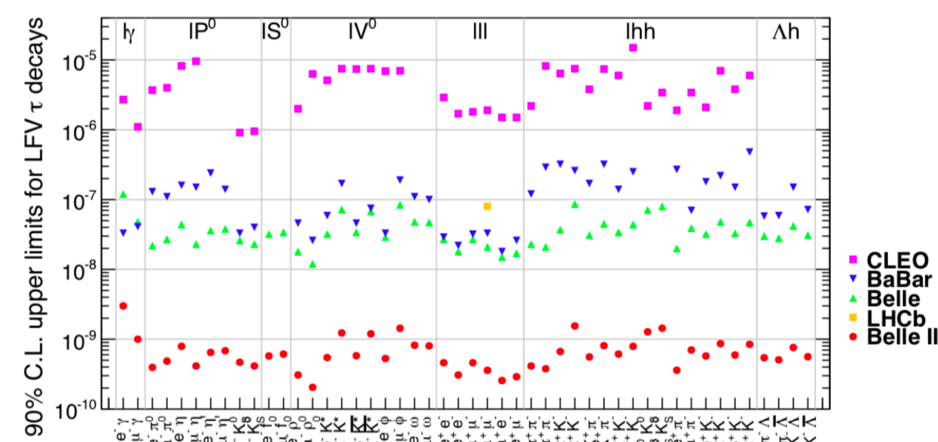


LNV/BNV τ decays 1304.4518

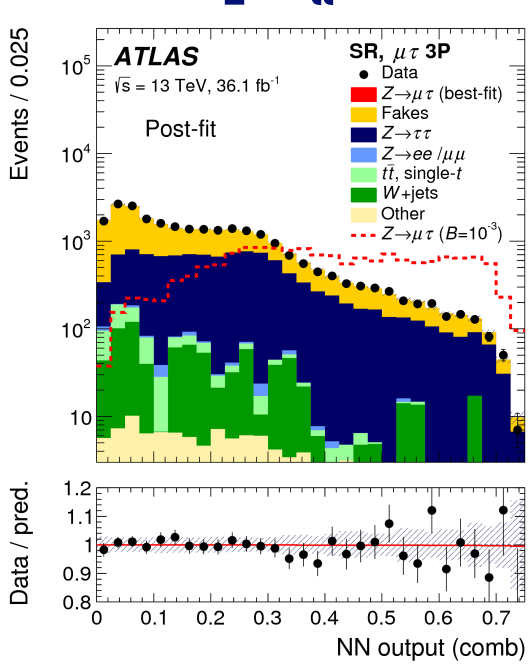




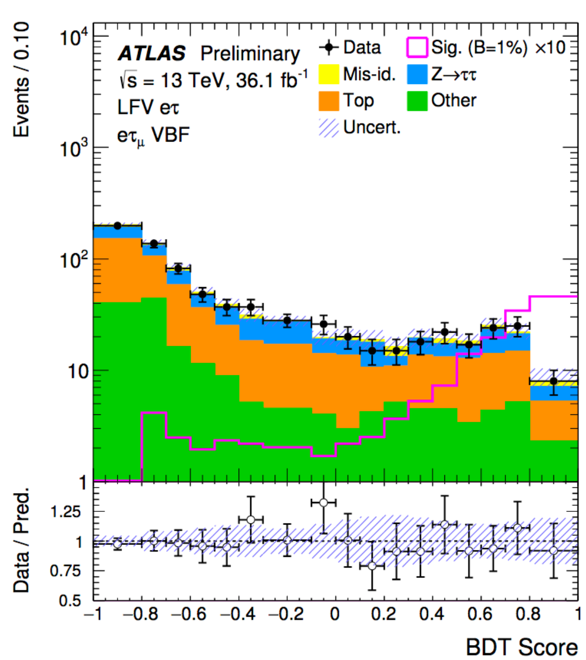
LFV τ decays 1812.04225



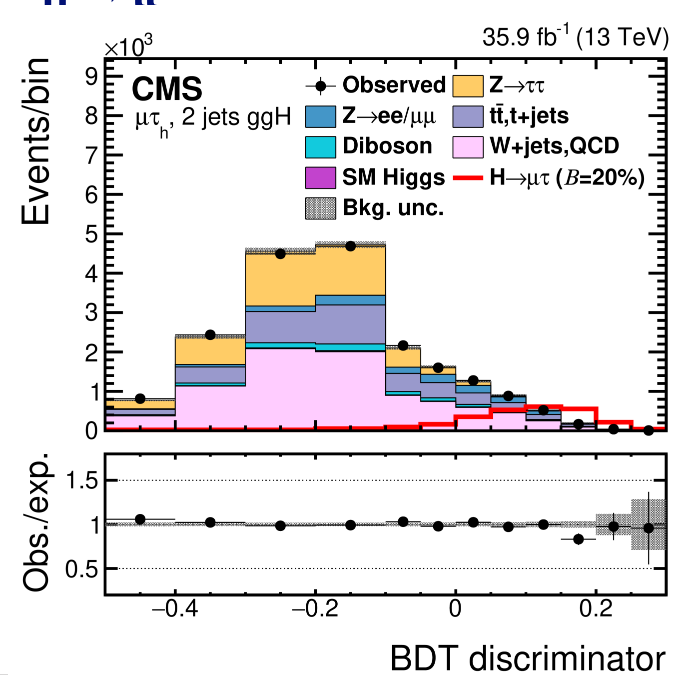
Z→ll′ 1804.09568



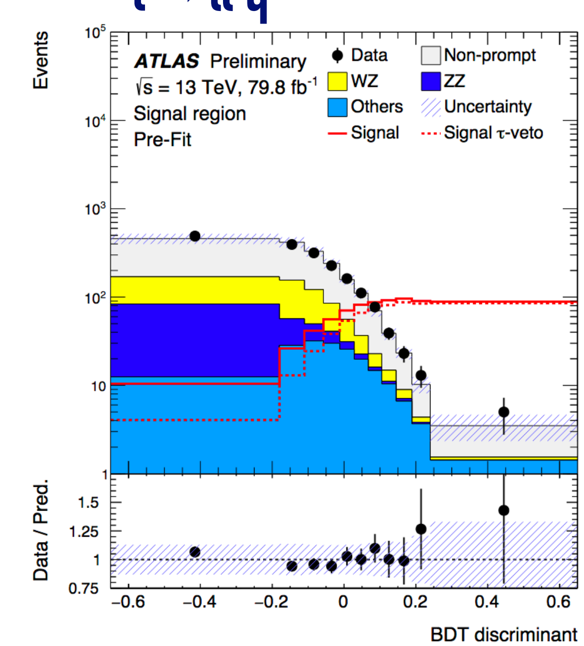
ATLAS-CONF-2019-013



H→ll′ 1712.07173

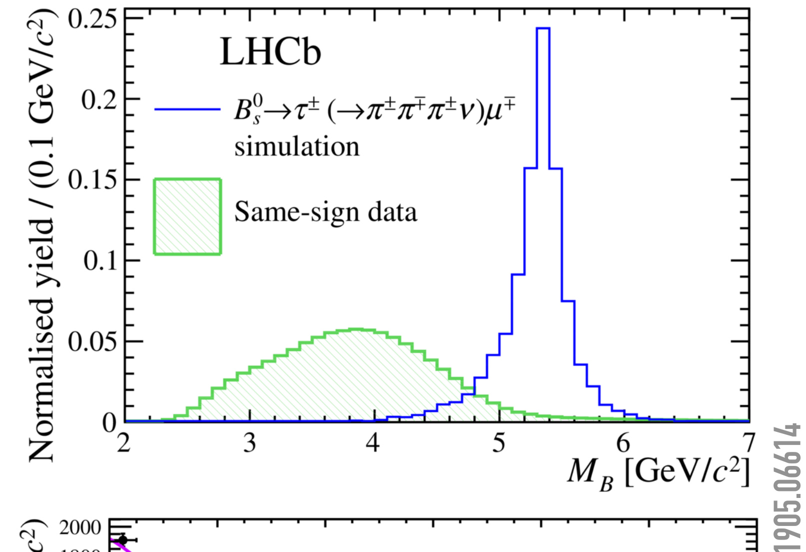


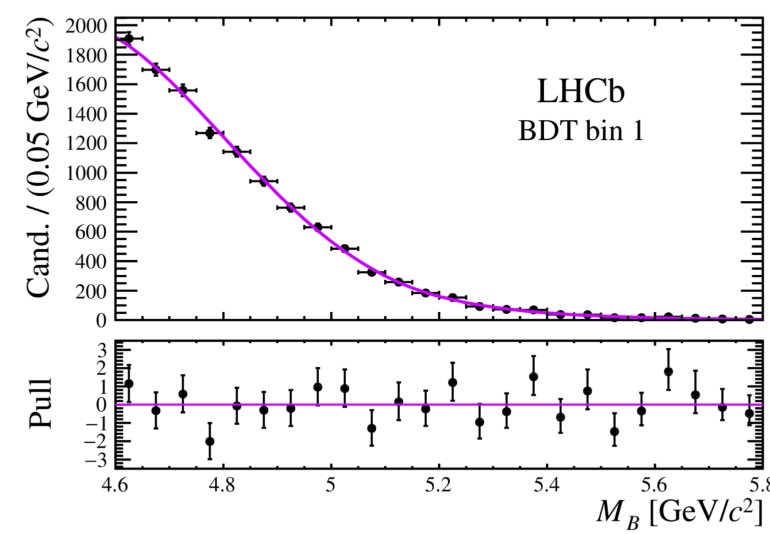
t→ll′q ATLAS-CONF-2018-044



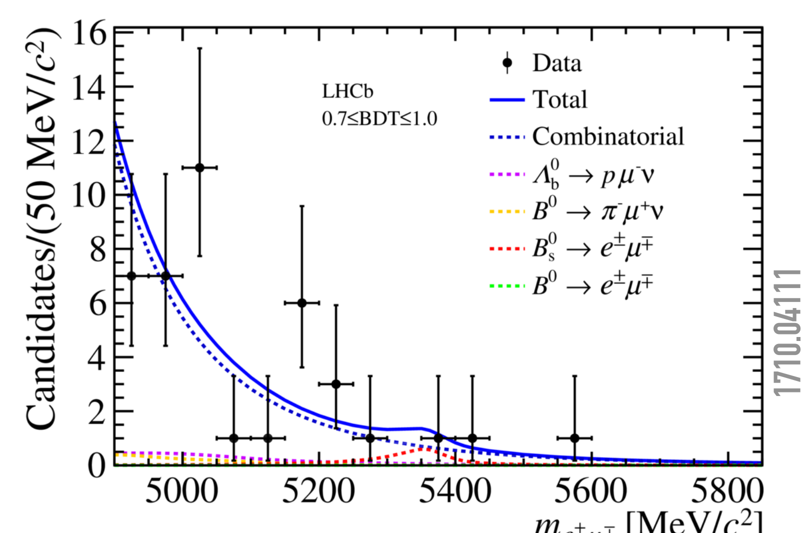
forbidden rare | B→ll’

- **$B_{(s)}$→τμ**
  - tau reconstructed as τ→πππν
  - dataset: $3fb^{-1}$
  - normalisation: B→D-(→Kππ)π
  - limited separation of B^0 and B_s ➡ limits derived assuming contributions from each at a time
  - BF(B^0→τμ) < 1.4 x 10^{-5} (@95%CL)
  - BF(B_s→τμ) < 4.2 x 10^{-5} (@95%CL)



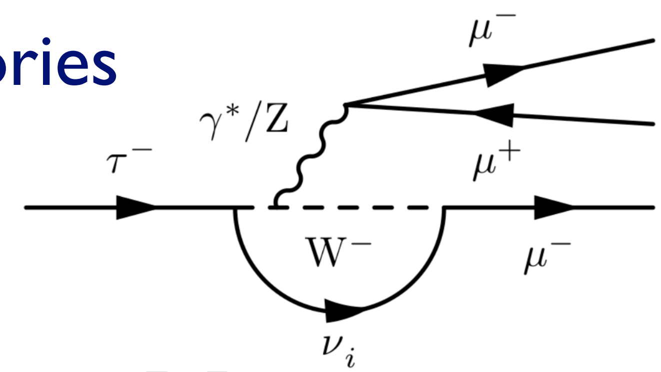


- **$B_{(s)}$→eμ**
  - dataset: $3fb^{-1}$
  - normalisation: B→Kπ, J/ψK
  - BF(B^0→eμ) < 1.3 x 10^{-8} (@95%CL)
  - BF(B_s→eμ) < 6.3 x 10^{-8} (@95%CL)

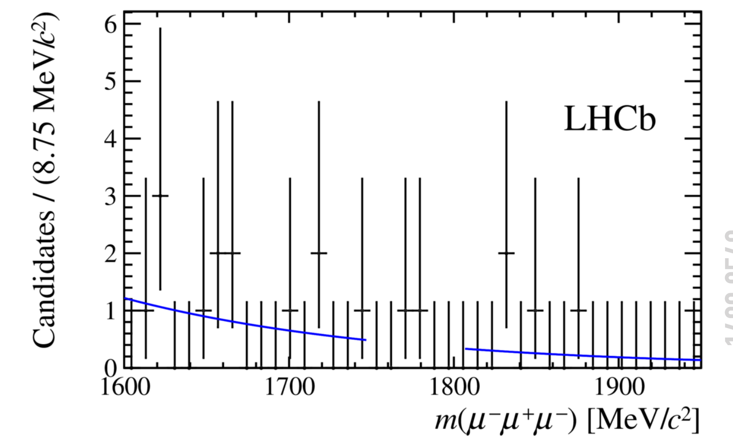


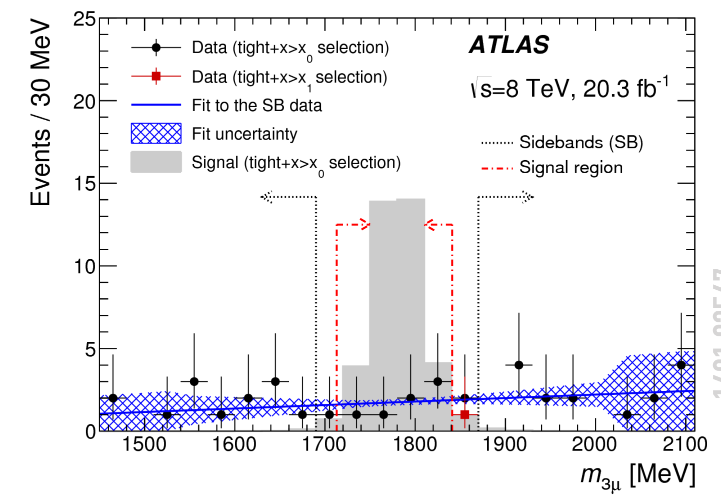
rare lepton | $\tau \to \mu\mu\mu$

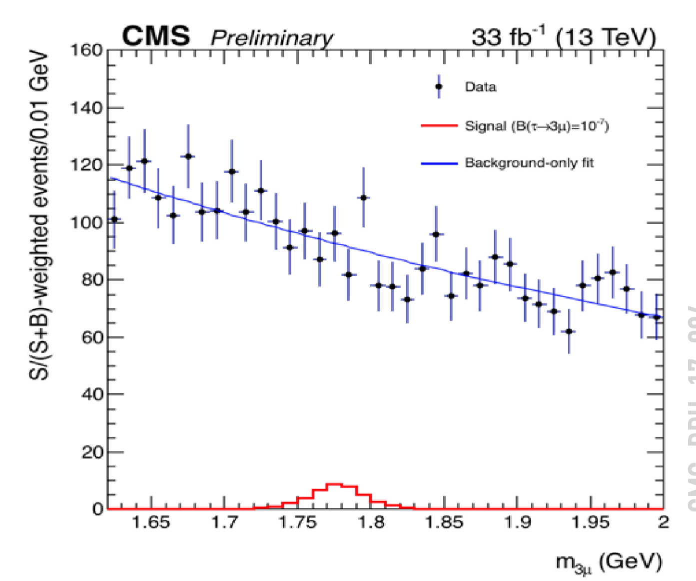
- clean final state, searched for at various colliders
- most stringent limit by B factories
  - BF < 2.1 x 10^{-8} @90% CL



- LHCb
  - 3fb^{-1}; normalisation $D_s \to \phi\pi$; source; $B,D \to \tau$
  - BF < 4.6 x 10^{-8} @90% CL
- ATLAS
  - 20fb^{-1} (Run1); normalisation $W \to \tau\nu$; source: $W \to \tau$
  - BF < 3.8 x 10^{-7} @90% CL
- CMS
  - 33fb^{-1} (Run2); normalisation $D_s \to \phi\pi$; source: $B,D \to \tau$
  - BF < 8.8 x 10^{-8} @90% CL
- prospects
  - HL-LHC: O(10^{-9}) | Belle II: O(10^{-10})







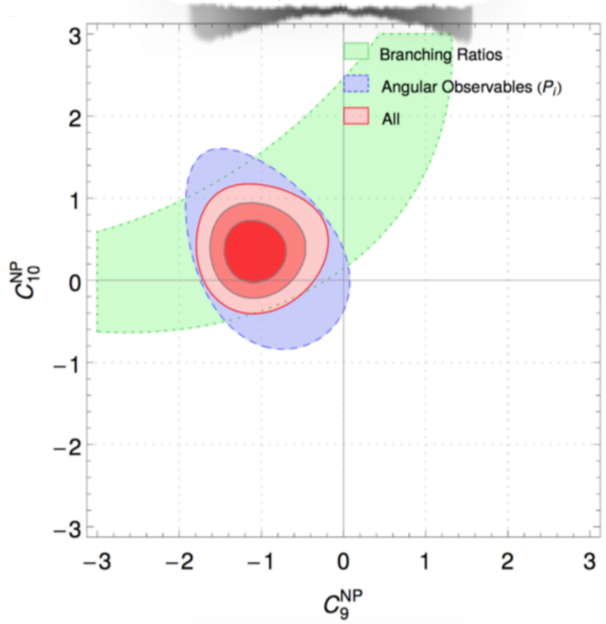
summary

- rare decays provide a sensitive place to look for NP
  - clean experimental and theoretical probes, precise predictions
  - allow to reach sensitivity to higher mass scales than direct searches
- results so far
  - place stringent constraints on NP models
  - tantalising anomalies observed (➡ complemented by LFU tests)
- 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
  - with higher luminosities at the LHC (+ Belle II + dedicated experiments)

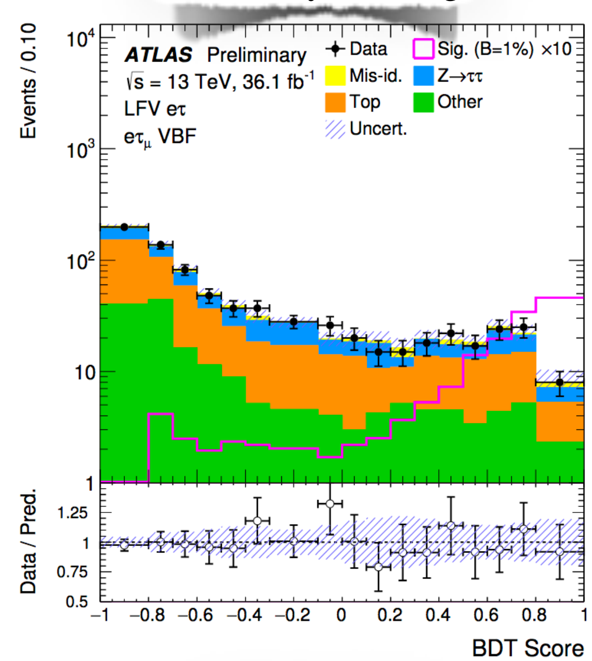
(LHC: 6% DATA RECORDED)

related reports this week:

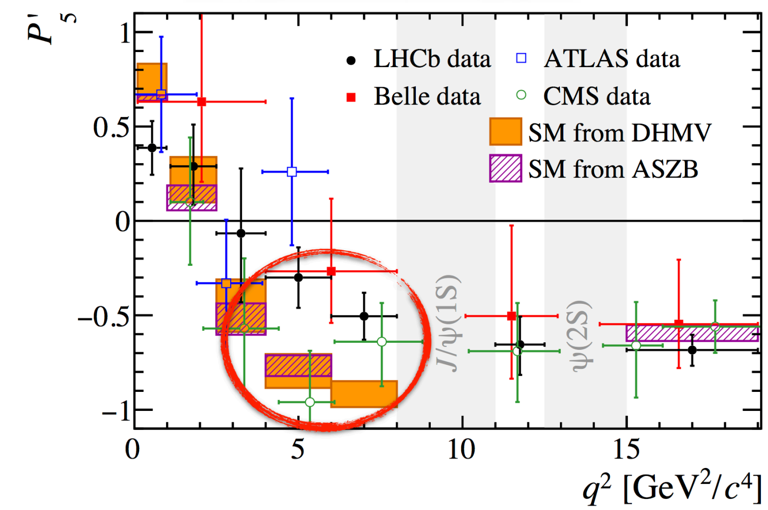
P. Cartelle
Lepton Universality
Monday afternoon



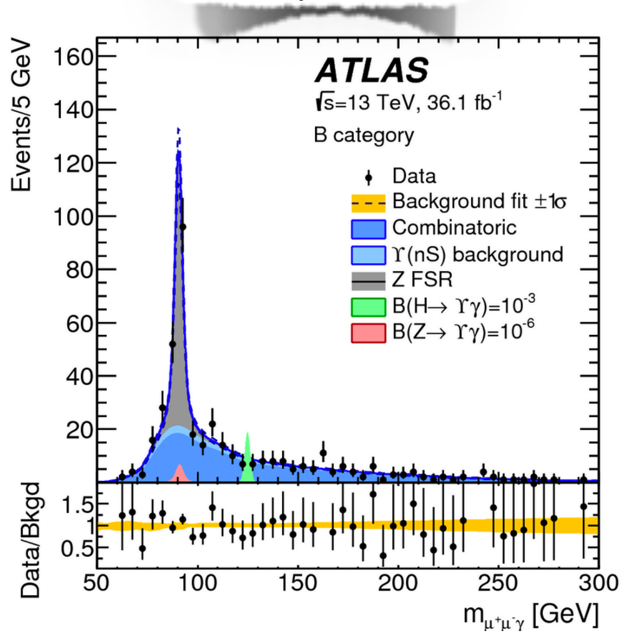
A. Sotomayor
LFV Higgs
Wednesday morning



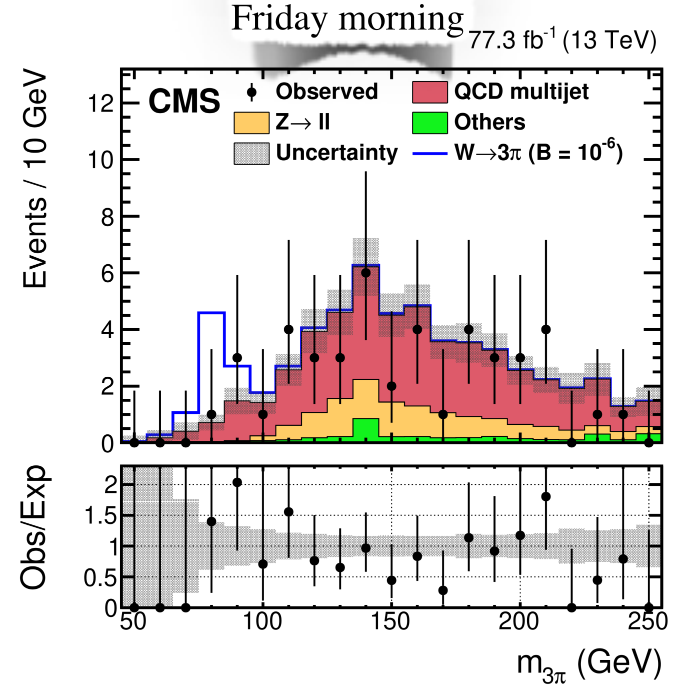
I. Heredia, V. Bellee
Rare Heavy Flavour
Thursday afternoon



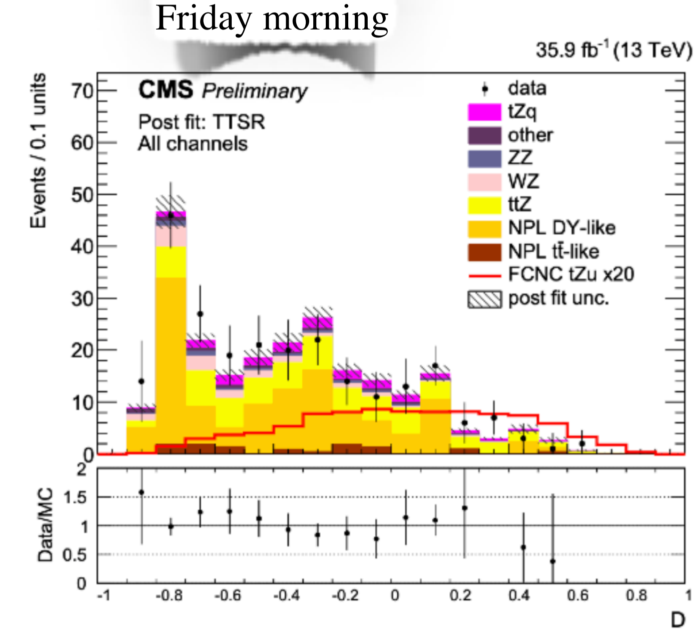
L. Finco
Rare Higgs
Thursday afternoon



P. Chang
Rare EWK
Friday morning

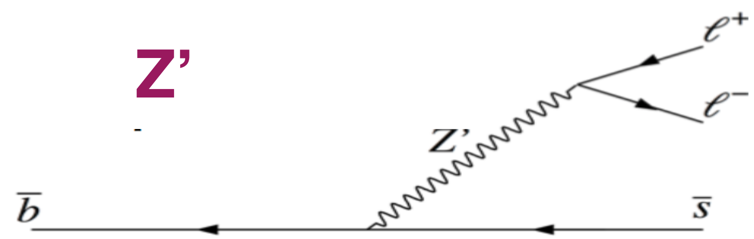


M. Llacer
Rare top
Friday morning

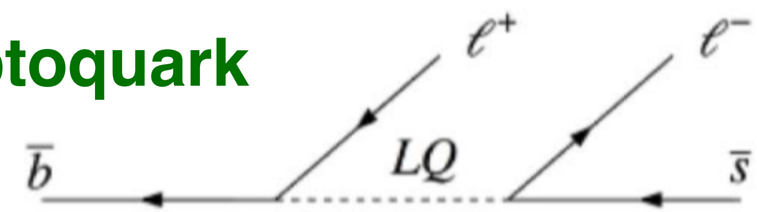


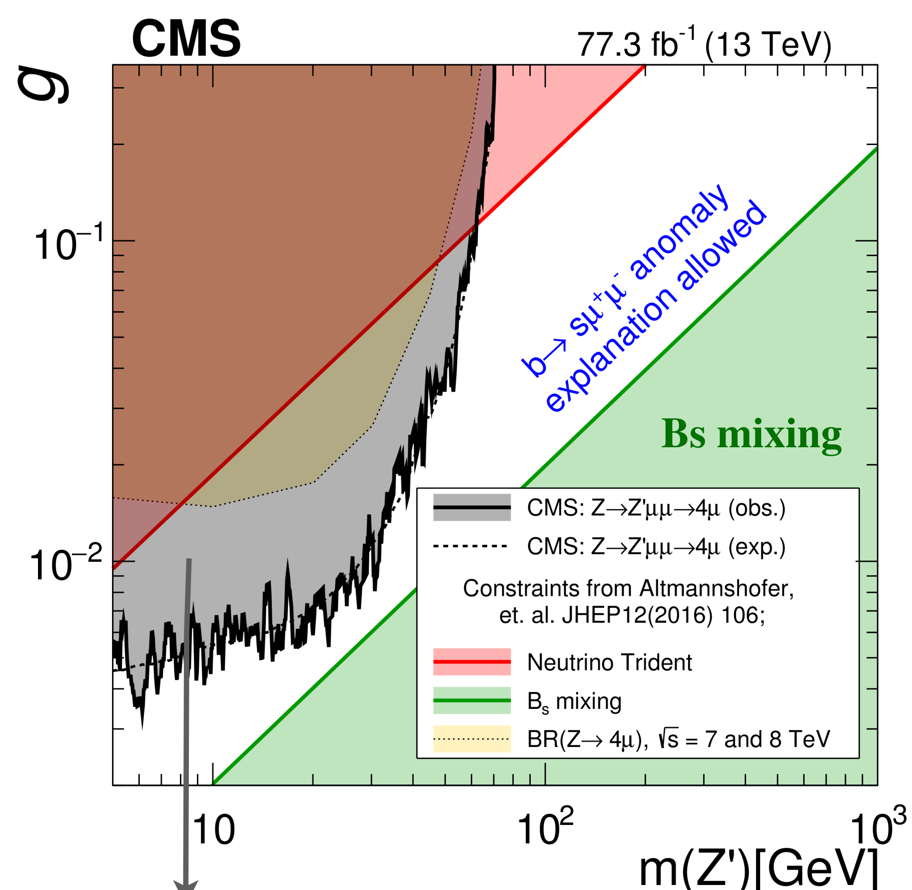
b→sll | NP candidates?

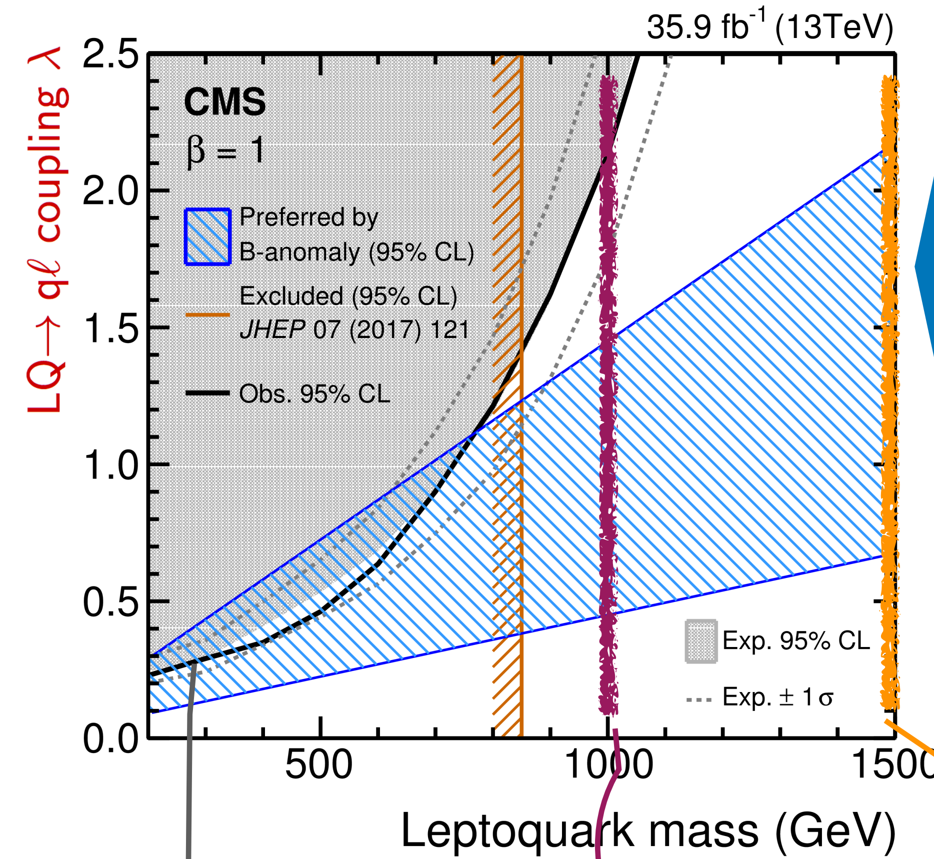
Z'



Leptoquark

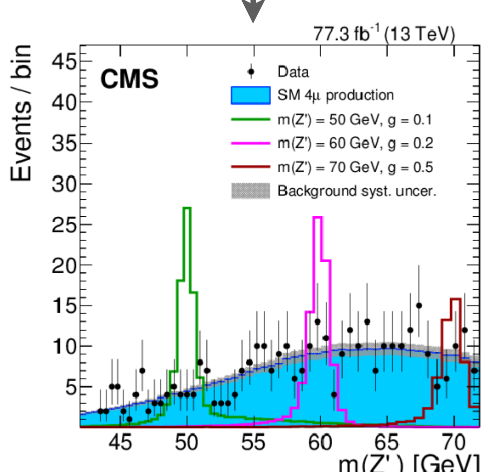


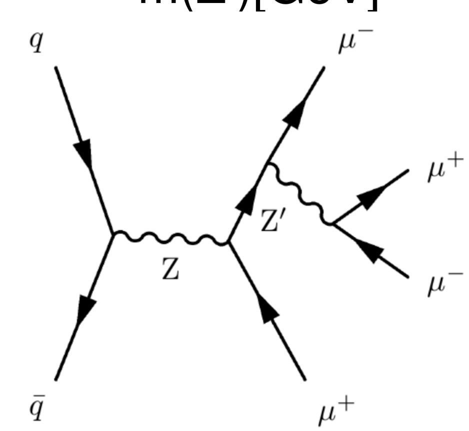




preferred region by flavor anomalies

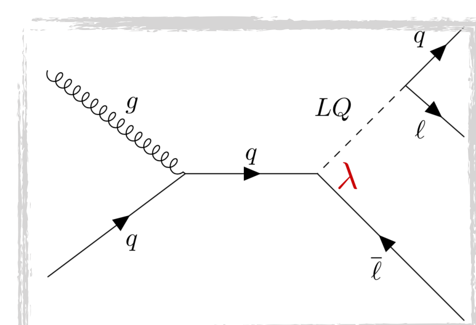
$\lambda=(0.95\pm0.25) \times (m_{LQ}/\text{TeV})$





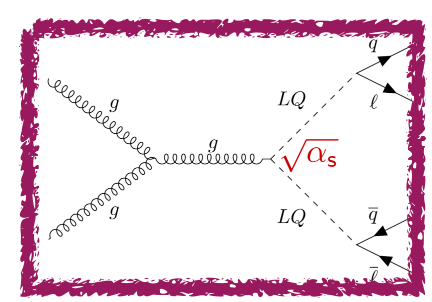
1808.03684

LQ→τb



1806.03472

LQLQ→ττbb



1811.00806

HL-LHC Projection

CMS-PAS-FTR-18-028

1812.07831

a dedicated dataset: B-Parked Run2 data

- CMS has collected during 2018 a special B sample
  - 12B triggered events on tape
- trigger on low-p_T τ's is difficult
  - instead trigger on opposite-side B
  - towards end of LHC fill
- the data is "parked"
  - delayed processing
- allow to investigate anomalies
  - improving physics object (τ,e) reconstruction for low p_T
- good opportunity to independently investigate the LHCb flavor anomalies