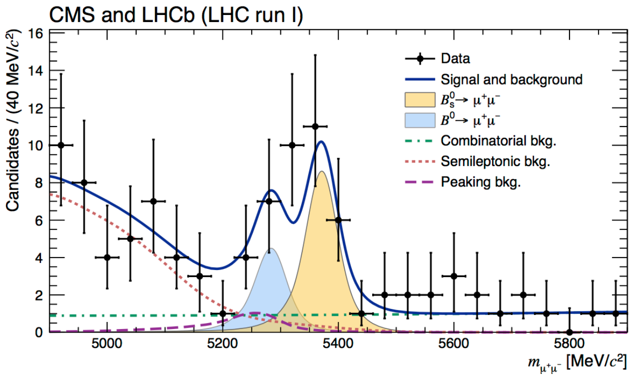
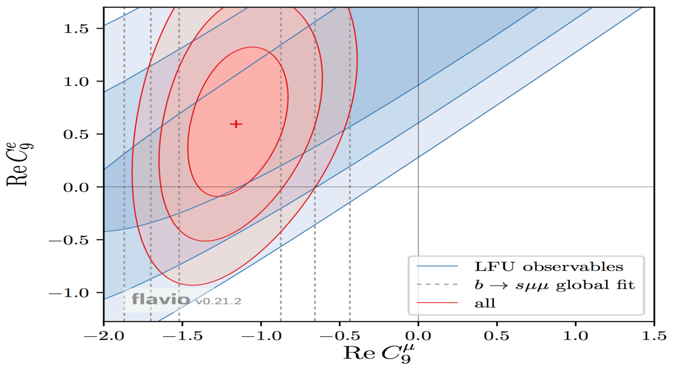
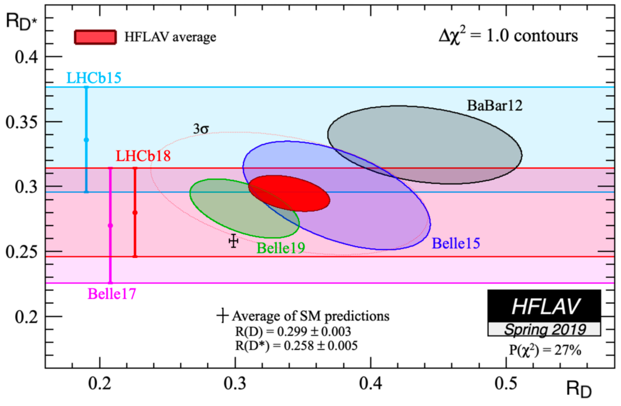






Lecture on

flavor (anomalies!) & BSM

Nuno Leonardo

LIP & IST, nuno@cern.ch

COURSE ON

PHYSICS AT THE LHC

Lisbon, PORTUGAL
01 MARCH - 10 MAY 2021

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTICULAS

Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

recap from last time:

- Intro to heavy flavor (motivation, scope, state of the art)
- Production (cross section measurement)
- Spectroscopy (hidden and open flavor, exotic hadrons)
- Heavy ions (flavor probes of the QGP primordial medium)
- Lifetime (distinctive experimental signature: displaced decay vertex)
- Meson oscillations & flavour tagging (measurement of Bs mixing)
- CKM & Unitary matrix (constraining the unitary triangle)
- CP violation (mixing phase, CPV in b and c sectors)

quantum mechanics (i)

- an unstable particle may be described by an effective hamiltonian
- through the non-relativistic Schrodinger equation
- the solution reproduces the law of radioactive decay

$$\mathcal{P}(t) \sim \frac{1}{\tau} e^{-t/\tau}$$

τ is the **lifetime**

- t is the proper decay time, experimentally it is measured from the decay length L and momentum p (or their projections on the transverse plane)

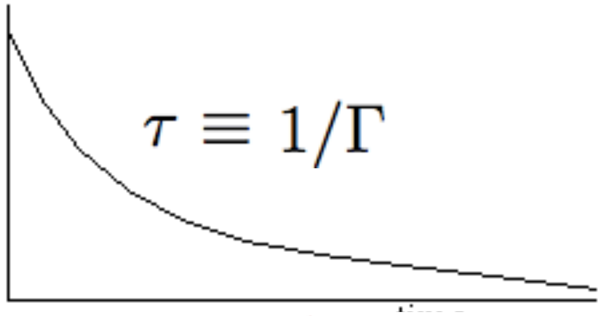
$$t = \frac{L}{\underbrace{\beta\gamma}_{\text{Lorentz boost factor}}} = L\frac{M}{p} = L_{xy}\frac{M}{p_T}$$

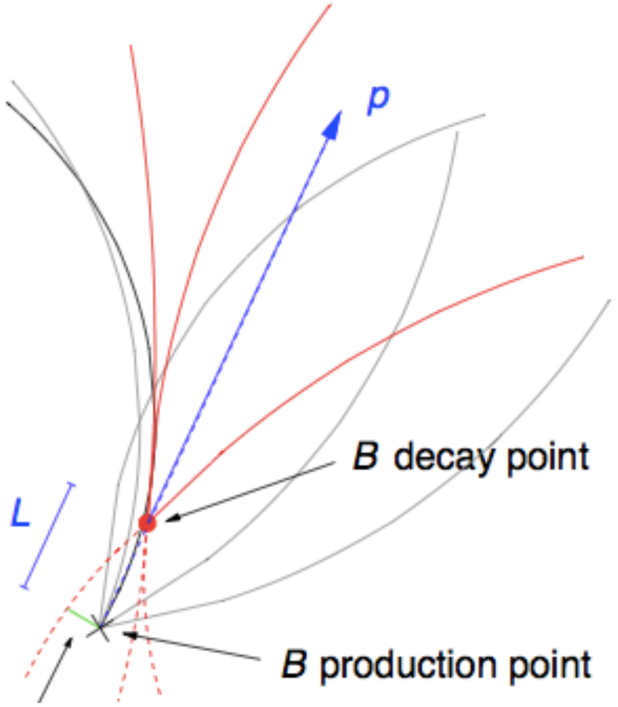
$$\mathcal{H} = m - \frac{i}{2}\Gamma$$

$$i\partial_t \psi = \mathcal{H}\psi$$

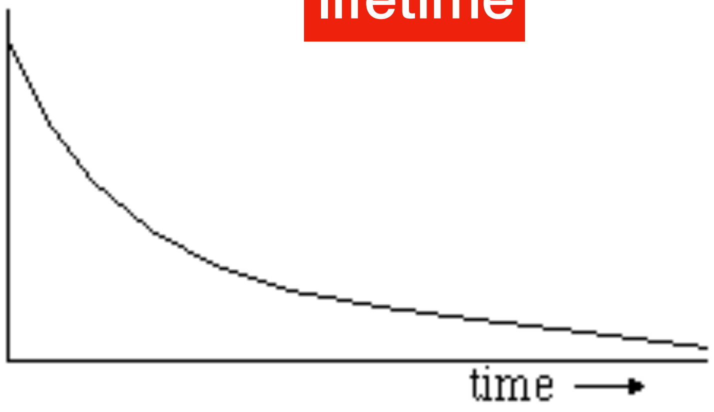
$$|\psi\rangle_t = e^{-imt} e^{-\frac{1}{2}\Gamma t} |\psi_0\rangle$$

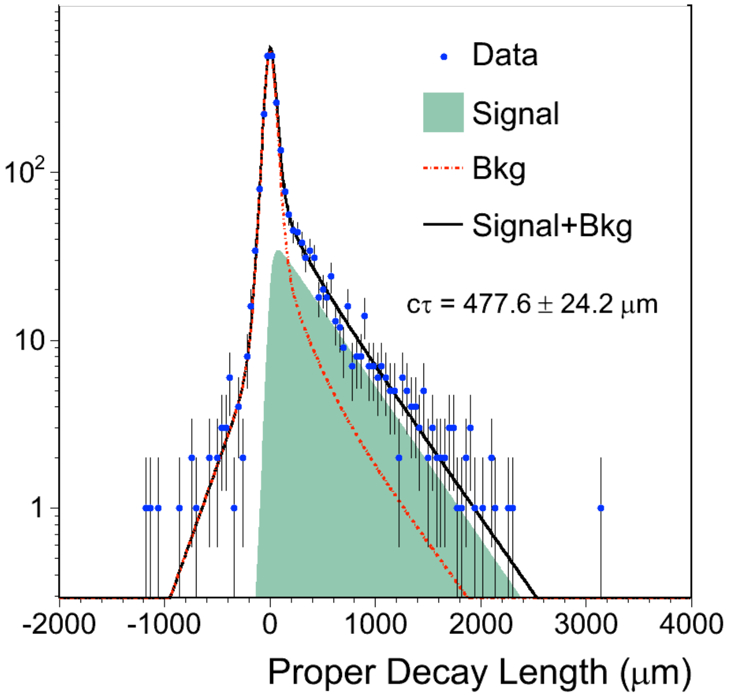
$$|\langle\psi_0|\psi\rangle_t|^2 = e^{-\Gamma t},$$





lifetime





$$\mathcal{P}(t) \sim \frac{1}{\tau} e^{-t/\tau}$$

$$L(t|\sigma_t, \tau) \;=\; \frac{1}{\mathcal{N}} \cdot [\; \frac{1}{\tau} e^{-\frac{t}{\tau}} \theta(t) \otimes G(t; \sigma_t) \;] \cdot \mathcal{E}(t)$$

quantum mechanics (ii)

- allowing for a flavor-changing perturbation (ΔF) in the hamiltonian

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{\Delta F} \qquad i\,\frac{d}{dt}\psi = \mathcal{H}\,\psi \qquad i\,\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} m - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

$$|\psi\rangle = a\,|P^0\rangle + b\,|\bar{P}^0\rangle$$

- a pure flavor eigenstate at t=0 will evolve to an admixture
    - non-diagonal elements in H ⇒ flavor eigenstates differ from mass eigenstates
- flavor eigenstates

$$\begin{aligned} |P_L\rangle &= p\,|P^0\rangle + q\,|\bar{P}^0\rangle \\ |P_H\rangle &= p\,|P^0\rangle - q\,|\bar{P}^0\rangle \end{aligned} \qquad \text{with} \quad |p|^2 + |q|^2 = 1$$

- time evolution of flavor eigenstates (after finding H eigenvalues $\lambda_{H,L}$)

$$|P_{L,H}\rangle_t \;=\; e^{-i\,\lambda_{L,H}\,t}\,|P_{L,H}\rangle \;=\; e^{-i\,m_{L,H}\,t - \frac{1}{2}\Gamma_{L,H}\,t}\,|P_{L,H}\rangle$$

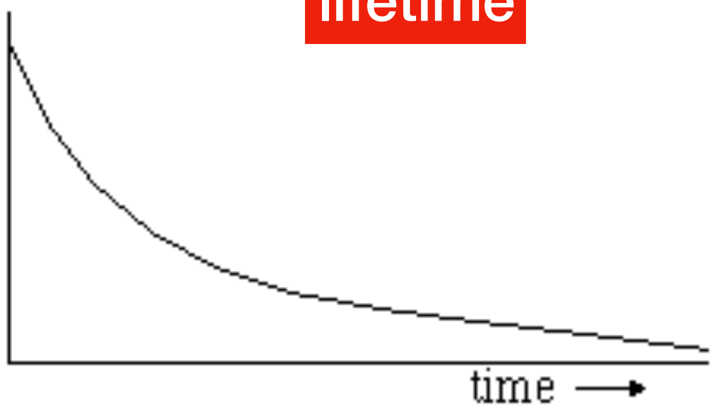
- probability for particle-antiparticle transition

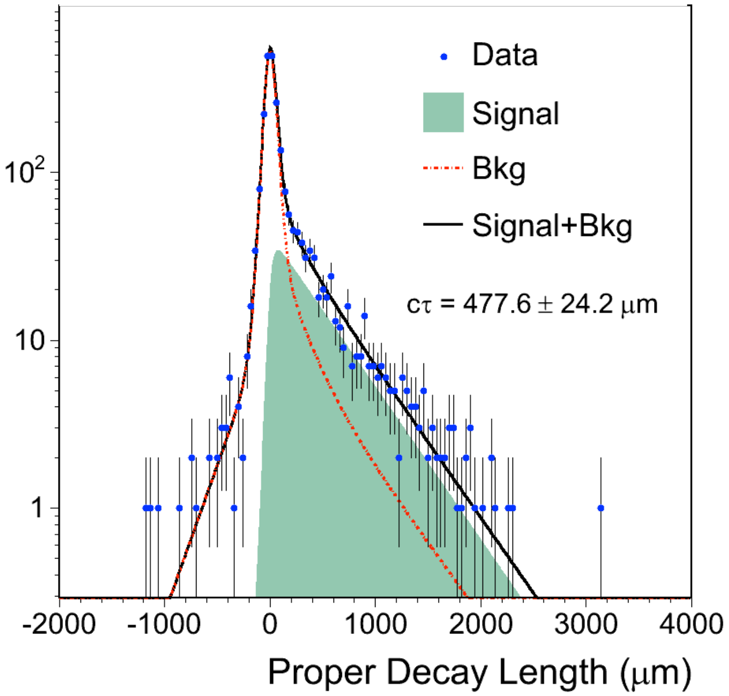
$$|\langle P^0|\mathcal{H}|\bar{P}^0\rangle|^2 \;=\; \left|\frac{p}{q}\right|^4 |\langle \bar{P}^0|\mathcal{H}|P^0\rangle|^2 \;=\; \left|\frac{p}{q}\right|^2 \frac{1}{2}e^{-\Gamma t}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m\,t\right)\right]$$

    - with $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$ and $\Delta m \equiv m_H - m_L$
- neglecting CPV in mixing (i.e. p/q=1) and ΔΓ, the mixing probability is:

$$\mathcal{P}_{B_q^0 \to \bar{B}_q^0}(t) \;=\; \mathcal{P}_{\bar{B}_q^0 \to B_q^0}(t) \;=\; \frac{\Gamma}{2}e^{-\Gamma\,t}\left[1 - \cos\left(\Delta m\,t\right)\right]$$

lifetime

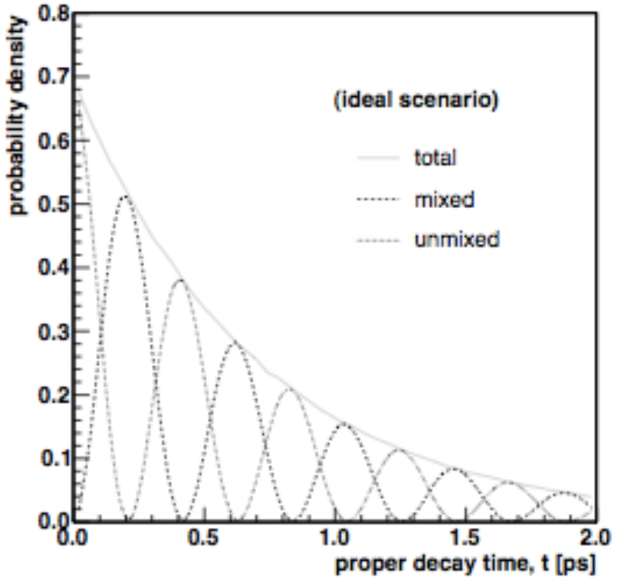


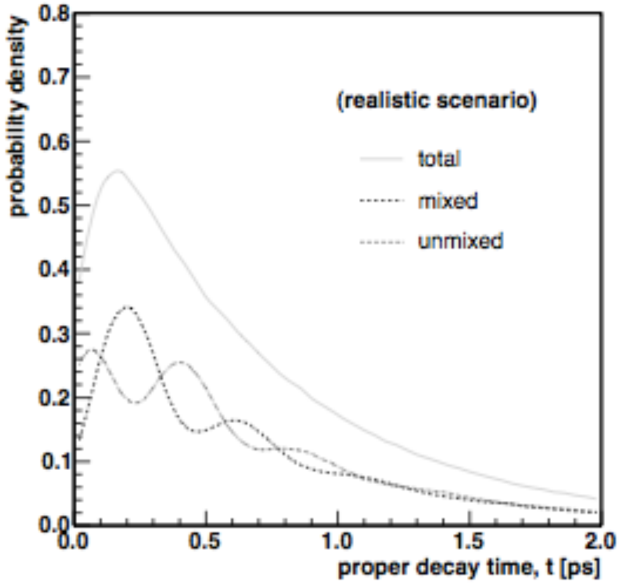


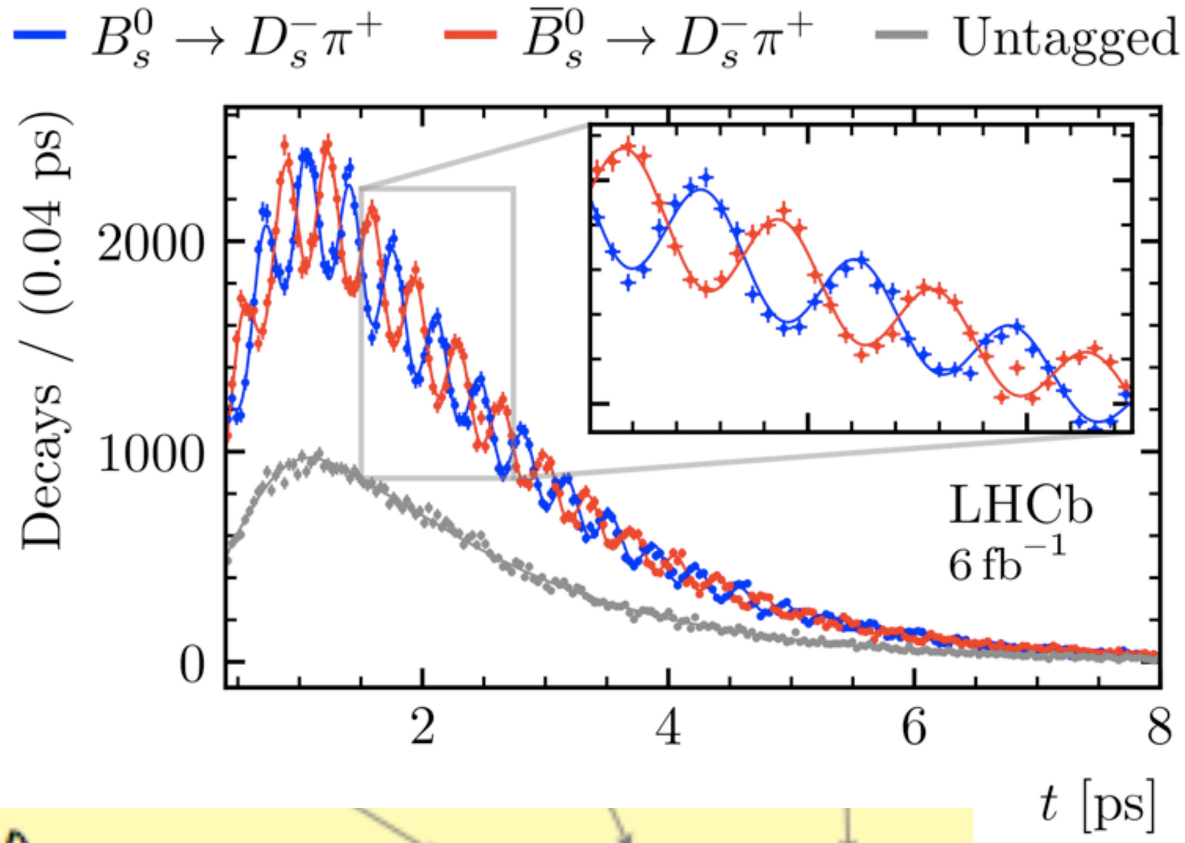
$$\mathcal{P}(t) \sim \frac{1}{\tau} e^{-t/\tau}$$

$$L(t|\sigma_t, \tau) = \frac{1}{\mathcal{N}} \cdot [\ \frac{1}{\tau} e^{-\frac{t}{\tau}} \theta(t) \otimes G(t; \sigma_t)\ ] \cdot \mathcal{E}(t)$$

oscillations

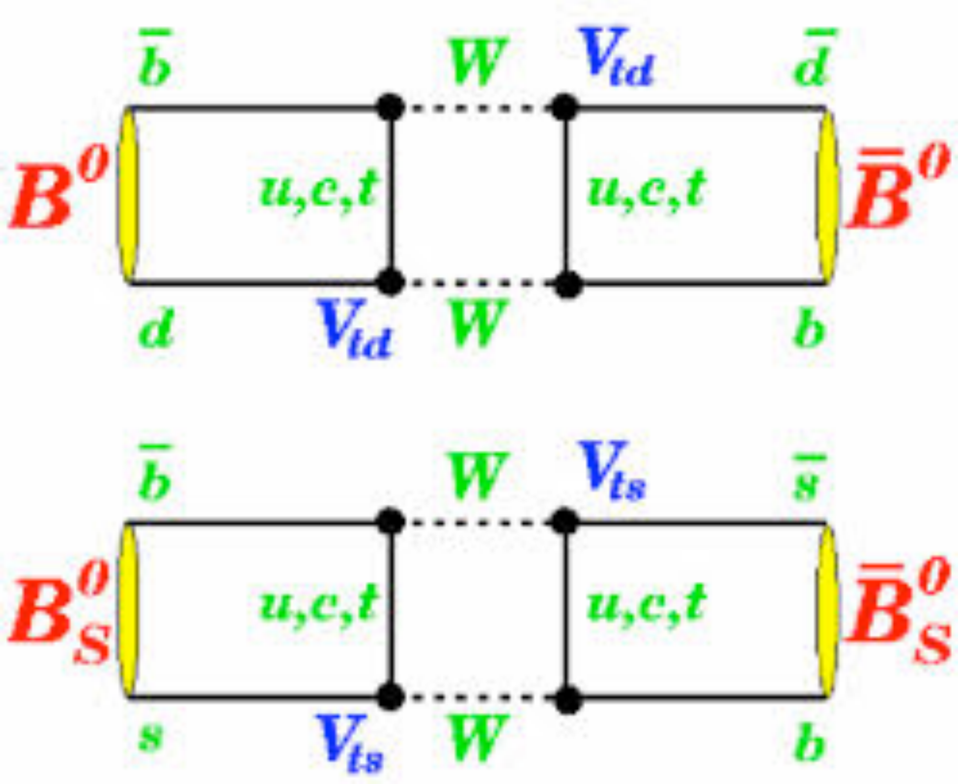


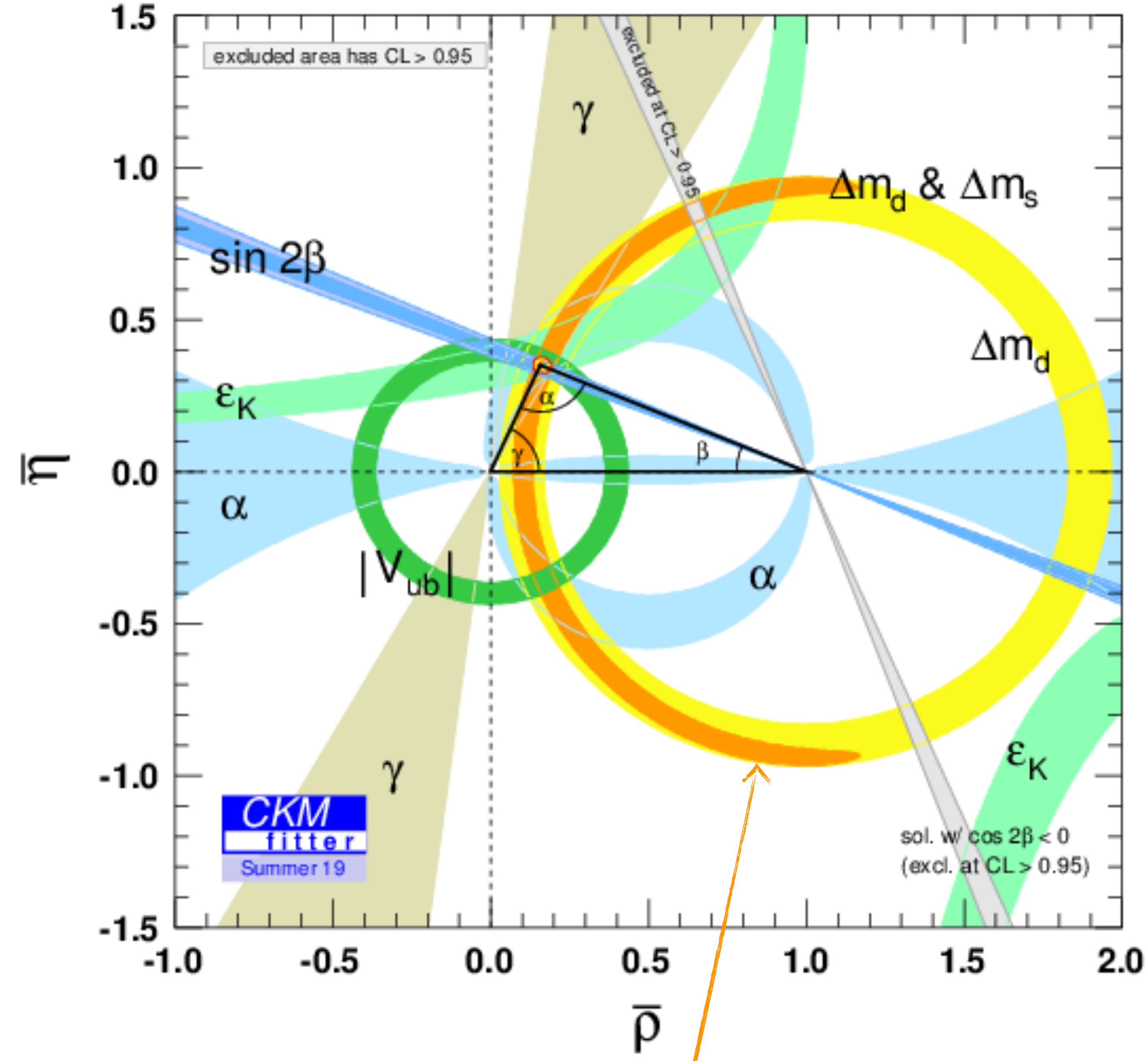




$$\mathcal{P}_{B_q^0 \to \bar{B}_q^0}(t) = \mathcal{P}_{\bar{B}_q^0 \to B_q^0}(t) = \frac{\Gamma}{2} e^{-\Gamma t} [1 - \cos(\Delta m\, t)]$$

$$\mathcal{L}_t = \frac{1}{N} \kappa \frac{e^{-\frac{\kappa t'}{\tau}}}{\tau} \frac{1 \pm A\, S_D\, D \cos(\Delta m_s\, \kappa\, t')}{2} \otimes R(t - t'; S_{\sigma_t} \sigma_t) \cdot \mathcal{E}(t) \otimes F(\kappa)$$





$$\Delta m_q = C_q \left|V_{tb}^* V_{tq}\right|^2 , \qquad (q = d, s)$$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{C_d}{C_s}\frac{|V_{td}|^2}{|V_{ts}|^2} = \frac{m_{B^0}}{m_{B_s}}\xi_\Delta^{-2}\frac{|V_{td}|^2}{|V_{ts}|^2}$$

$$\frac{\Delta m_s}{\Delta m_d} = \xi_\Delta^2 \frac{m_{B_s}}{m_{B^0}}\left(\frac{1-\frac{1}{2}\lambda^2}{\lambda}\right)^2 \frac{1}{(1-\bar\rho)^2+\bar\eta^2}$$

$$\Rightarrow \quad \boxed{(1-\bar\rho)^2+\bar\eta^2 = c}$$

quantum mechanics (iii)

- discrete symmetries
  - **C**harge conjugation: particle→ antiparticle
  - **P**arity: x→-x
  - **T**ime reversal: t →-t
- C and P are maximally violated in weak interactions
  - no right handed neutrinos, no left-handed antineutrinos)
- CPT is conserved in any Lorentz invariant gauge field theory; thus, CP⇔T

- under CP, an operator O(**x**,t) transforms as
- the effective Lagrangian (L=L†) has the structure
  - CP violation thus requires $a^* \neq a$, i.e. a complex phase

$$O\,(\vec{x},t) \rightarrow O^\dagger\,(-\vec{x},t)$$

$$\mathcal{L} = aO + a^* O^\dagger \overset{CP}{\rightarrow} aO^\dagger + a^* O = \mathcal{L}$$

- Yuakawa term
- Charged current term

$$-\mathcal{L}_{Yukawa} = Y_{ij}\overline{\psi_{Li}}\,\phi\,\psi_{Rj} + Y^*_{ij}\overline{\psi_{Rj}}\,\phi^\dagger\,\psi_{Li}$$

$$\mathcal{L}_W = \frac{g}{\sqrt{2}}\overline{u_{iL}}V_{ij}\gamma_\mu W^{-\mu}d_{iL} + \frac{g}{\sqrt{2}}\overline{d_{iL}}V^*_{ij}\gamma_\mu W^{+\mu}u_{iL}$$

Exercise: verify that CP invariance applied to Yukawa and W currents would imply $Y_{ij}=Y_{ij}^*$ and $V_{ij}=V_{ij}^*$ using CP transformations recalled in tables below

Field		P	C
Scalar field	$\phi(\vec{x},t)$	$\phi(-\vec{x},t)$	$\phi^\dagger(\vec{x},t)$
Dirac spinor	$\psi(\vec{x},t)$	$\gamma^0\psi(-\vec{x},t)$	$i\gamma^2\gamma^0\overline{\psi}^T(\vec{x},t)$
	$\overline{\psi}(\vec{x},t)$	$\overline{\psi}(-\vec{x},t)\gamma^0$	$-\psi^T(\vec{x},t)C^{-1}$
Axial vector field	$A_\mu(\vec{x},t)$	$-A^\mu(-\vec{x},t)$	$A^\dagger_\mu(\vec{x},t)$

	Bilinear	P	C	T	CP	CPT
scalar	$\overline{\psi}_1\psi_2$	$\overline{\psi}_1\psi_2$	$\overline{\psi}_2\psi_1$	$\overline{\psi}_1\psi_2$	$\overline{\psi}_2\psi_1$	$\overline{\psi}_2\psi_1$
pseudo scalar	$\overline{\psi}_1\gamma_5\psi_2$	$-\overline{\psi}_1\gamma_5\psi_2$	$\overline{\psi}_2\gamma_5\psi_1$	$-\overline{\psi}_1\gamma_5\psi_2$	$-\overline{\psi}_2\gamma_5\psi_1$	$\overline{\psi}_2\gamma_5\psi_1$
vector	$\overline{\psi}_1\gamma_\mu\psi_2$	$\overline{\psi}_1\gamma^\mu\psi_2$	$-\overline{\psi}_2\gamma_\mu\psi_1$	$\overline{\psi}_1\gamma^\mu\psi_2$	$-\overline{\psi}_2\gamma^\mu\psi_1$	$-\overline{\psi}_2\gamma_\mu\psi_1$
axial vector	$\overline{\psi}_1\gamma_\mu\gamma_5\psi_2$	$-\overline{\psi}_1\gamma^\mu\gamma_5\psi_2$	$\overline{\psi}_2\gamma_\mu\gamma_5\psi_1$	$\overline{\psi}_1\gamma^\mu\gamma_5\psi_2$	$-\overline{\psi}_2\gamma^\mu\gamma_5\psi_1$	$-\overline{\psi}_2\gamma_\mu\gamma_5\psi_1$
tensor	$\overline{\psi}_1\sigma_{\mu\nu}\psi_2$	$\overline{\psi}_1\sigma^{\mu\nu}\psi_2$	$-\overline{\psi}_2\sigma_{\mu\nu}\psi_1$	$-\overline{\psi}_1\sigma^{\mu\nu}\psi_2$	$-\overline{\psi}_2\sigma^{\mu\nu}\psi_1$	$\overline{\psi}_2\sigma_{\mu\nu}\psi_1$

quantum mechanics (iv)

- consider neutral meson P^0 decays to a final state f
- the time dependent decay rates may be expressed as

$$\begin{aligned}\bar{A}(f) = &\ \langle f|T|\bar{P}^0\rangle \\ A(f) = &\ \langle f|T|P^0\rangle\end{aligned}$$

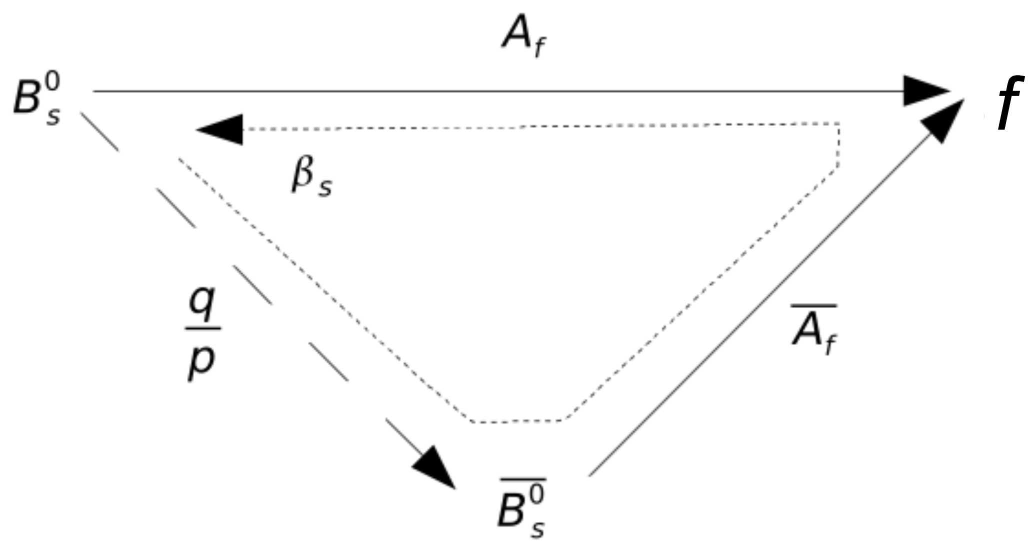
$$\begin{aligned}\Gamma_{P^0\to f}(t) &= |A_f|^2 \quad (1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f\sinh\frac{1}{2}\Delta\Gamma t + C_f\cos\Delta mt - S_f\sin\Delta mt\right) \\ \Gamma_{\bar{P}^0\to f}(t) &= |A_f|^2\left|\frac{p}{q}\right|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma t}}{2}\left(\cosh\frac{1}{2}\Delta\Gamma t + D_f\sinh\frac{1}{2}\Delta\Gamma t - C_f\cos\Delta mt + S_f\sin\Delta mt\right)\end{aligned}$$

- with $\lambda_f = \boxed{\frac{q}{p}\frac{\bar{A}_f}{A_f}}$ $\quad D_f = \frac{2\Re\lambda_f}{1+|\lambda_f|^2}$ $\quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$ $\quad S_f = \frac{2\Im\lambda_f}{1+|\lambda_f|^2}$
  - sin and sinh terms are associated to interference of decays with and without oscillation
- CP violation classification
  - CPV in decay $\quad \Gamma(P^0\to f)\neq\Gamma(\bar{P}^0\to\bar{f}) \quad \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|\neq 1$
  - CPV in mixing $\quad \text{Prob}(P^0\to\bar{P}^0)\neq\text{Prob}(\bar{P}^0\to P^0) \quad \left|\frac{q}{p}\right|\neq 1$
  - CPV in interference between decay with and without mixing $\quad \Gamma(P^0{}_{(\rightsquigarrow\bar{P}^0)}\to f)(t)\neq\Gamma(\bar{P}^0{}_{(\rightsquigarrow P^0)}\to f)(t) \quad \Im\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right)\neq 0$

$$A_{CP}(t) = \frac{\Gamma_{P^0(t)\to f} - \Gamma_{\bar{P}^0(t)\to f}}{\Gamma_{P^0(t)\to f} + \Gamma_{\bar{P}^0(t)\to f}} = \frac{2C_f\cos\Delta mt - 2S_f\sin\Delta mt}{2\cosh\frac{1}{2}\Delta\Gamma t + 2D_f\sinh\frac{1}{2}\Delta\Gamma t}$$

CPV in interference w/or w/o mixing

- defined by Im $\lambda_f \neq 0$
- available to modes in which both B and $\underline{B}$ decay to a same final state f
- example: $B_s \rightarrow J/\psi\Phi$

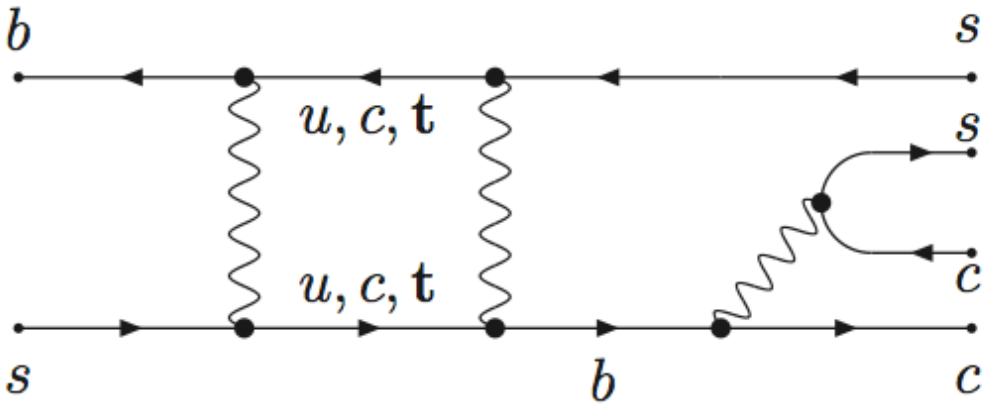


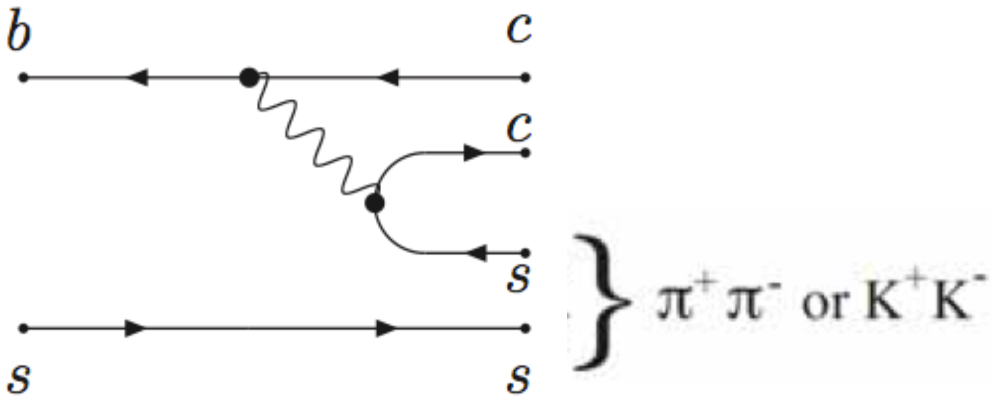
$$\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = \mathcal{O}(\lambda^2)$$

$$2\beta_s \approx -\phi$$

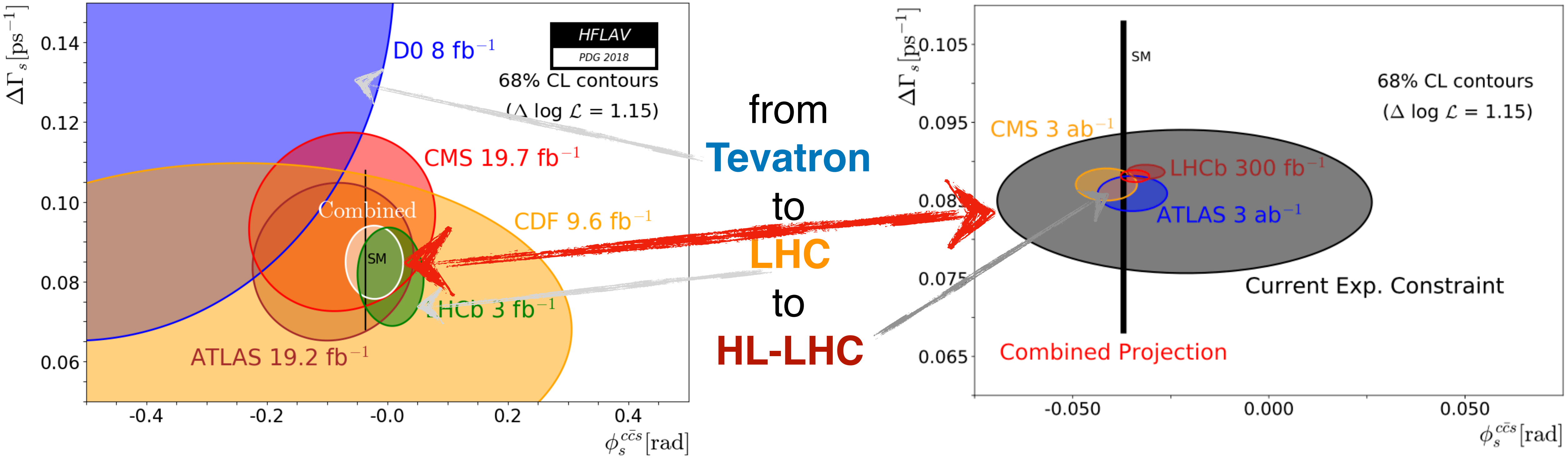
$\phi_s = \phi_s^{SM} + \phi_s^{NP}$

ϕ_{SM} ~ -0.04
NP can add large phases



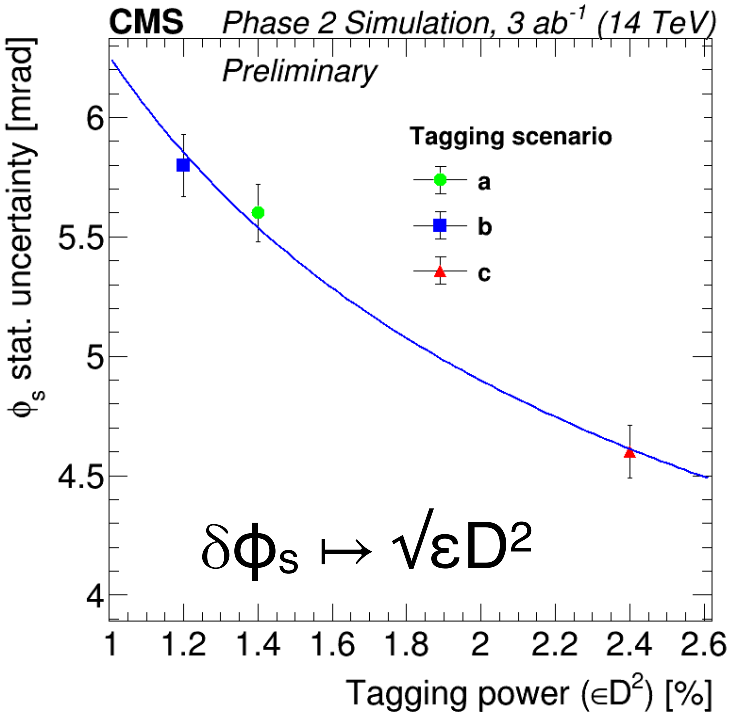


CPV: B_s mixing phase


from **Tevatron** to **LHC** to **HL-LHC**

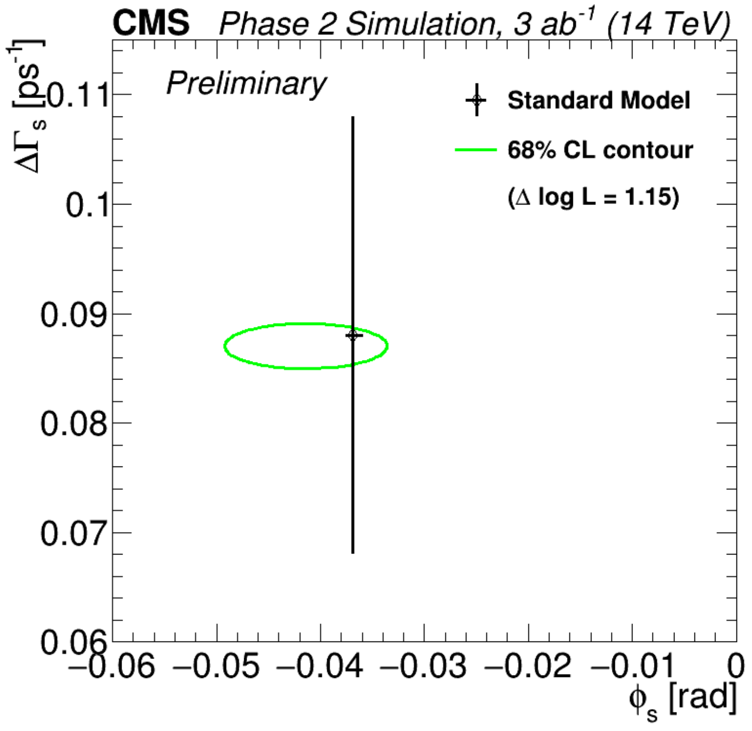
projected HL-LHC improvements in proper decay uncertainty and flavor tagging power

ϵ [%]	ω [%]	ϵD^2 [%]	σ_{ϕ_s} [mrad]
32	39.4	1.4	5.6
8	30.2	1.2	5.8
33	36.4	2.4	4.6



$\delta\phi_s \mapsto \sqrt{\epsilon D^2}$

CMS-PAS-FTR-18-041



CPV in decay: B→Kπ

$$A_{dir}^{CP} = \frac{\Gamma(B^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\bar{B}^0 \to \bar{f}) + \Gamma(B^0 \to f)}$$

- B factories: BABAR, BELLE (2004)
  - Babar Collaboration *Phys. Rev. Lett.* **97**, 171805 (2006)
    Belle Collaboration *Phys. Rev.* **D87**, 031103 (2013)
- Tevatron: CDF (2012)

$$\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = -0.083 \pm 0.013 \pm 0.003$$

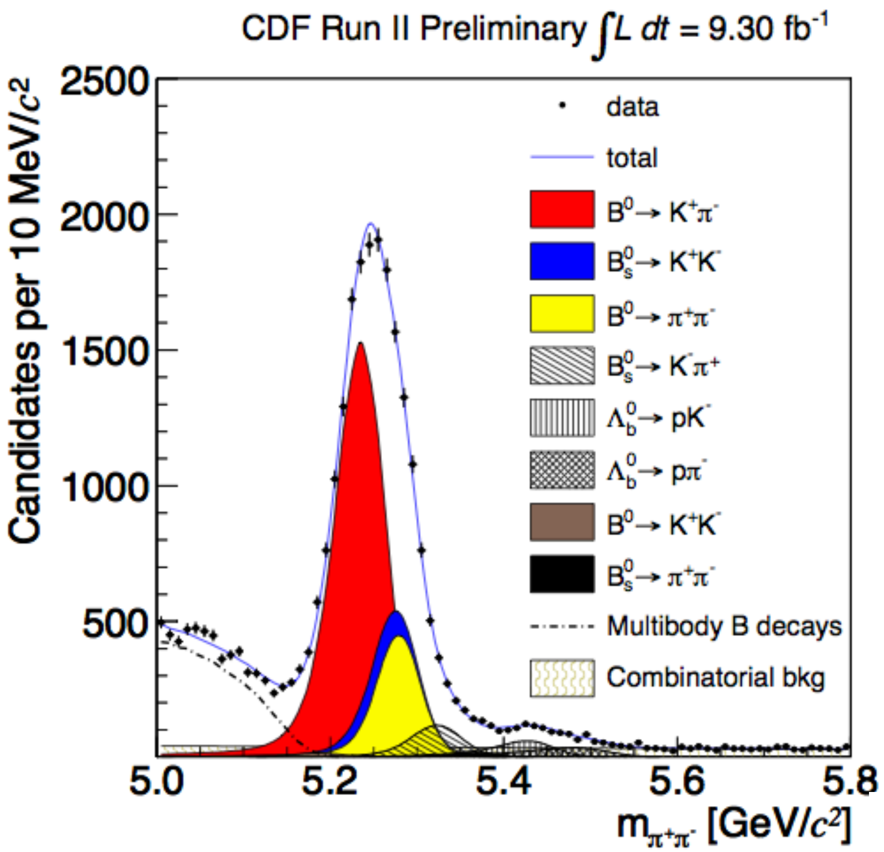
$$\mathcal{A}_{CP}(B^0_s \to K^-\pi^+) = +0.22 \pm 0.07 \pm 0.02$$

- LHC: LHCb (2013)

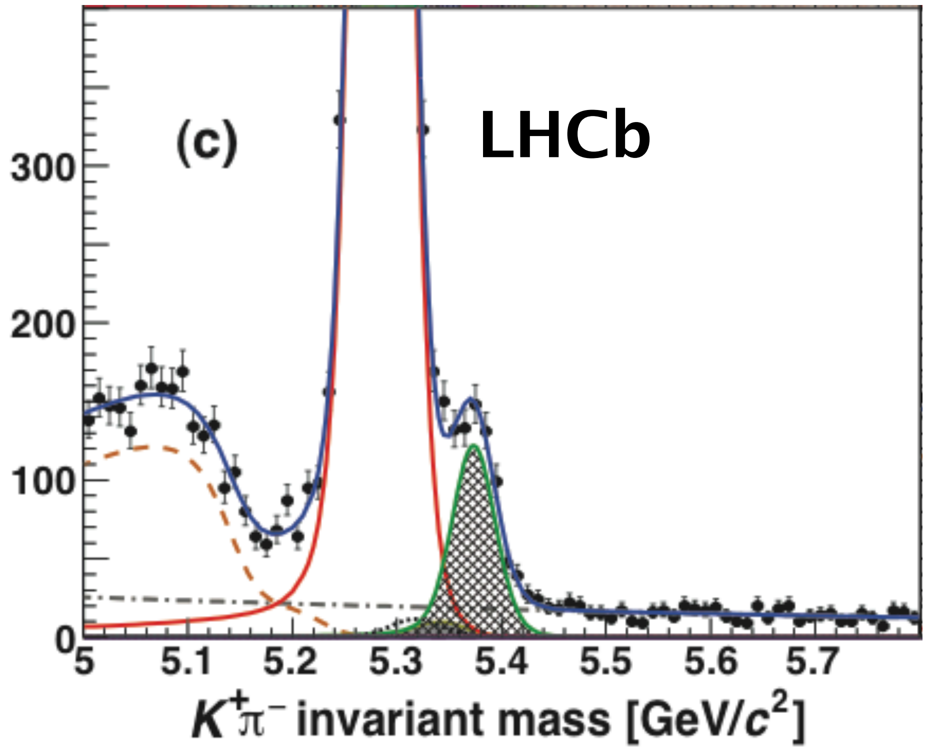
$$A_{CP}(B^0 \to K^+\pi^-) = -0.080 \pm 0.007\,(\text{stat}) \pm 0.003\,(\text{syst})$$

$$A_{CP}(B^0_s \to K^-\pi^+) = 0.27 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$$

  - first observation (>5σ) of CPV in B_s



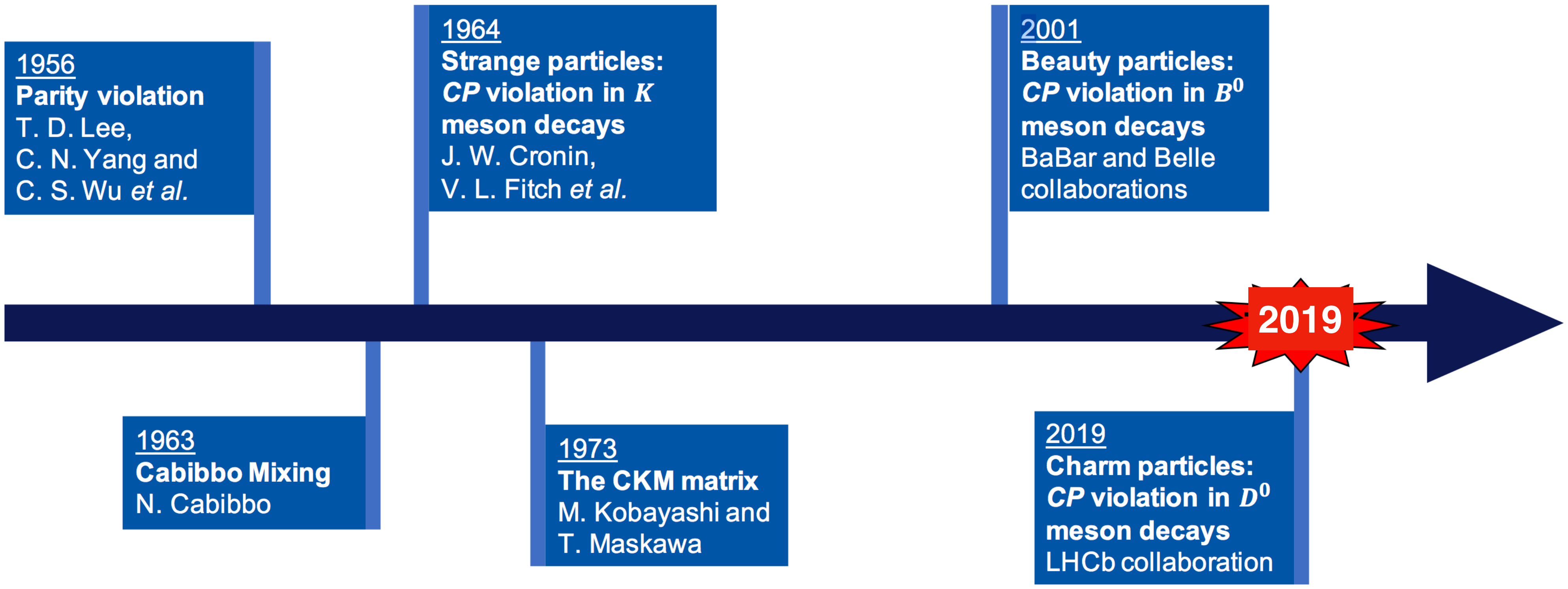
PRL 108 (2012) 211803



PRL 110 (2013) 221601

CPV: in K, B, … and D!

CPV history



1956
Parity violation
T. D. Lee,
C. N. Yang and
C. S. Wu *et al.*

1963
Cabibbo Mixing
N. Cabibbo

1964
Strange particles:
***CP* violation in K**
meson decays
J. W. Cronin,
V. L. Fitch *et al.*

1973
The CKM matrix
M. Kobayashi and
T. Maskawa

2001
Beauty particles:
***CP* violation in B^0**
meson decays
BaBar and Belle
collaborations

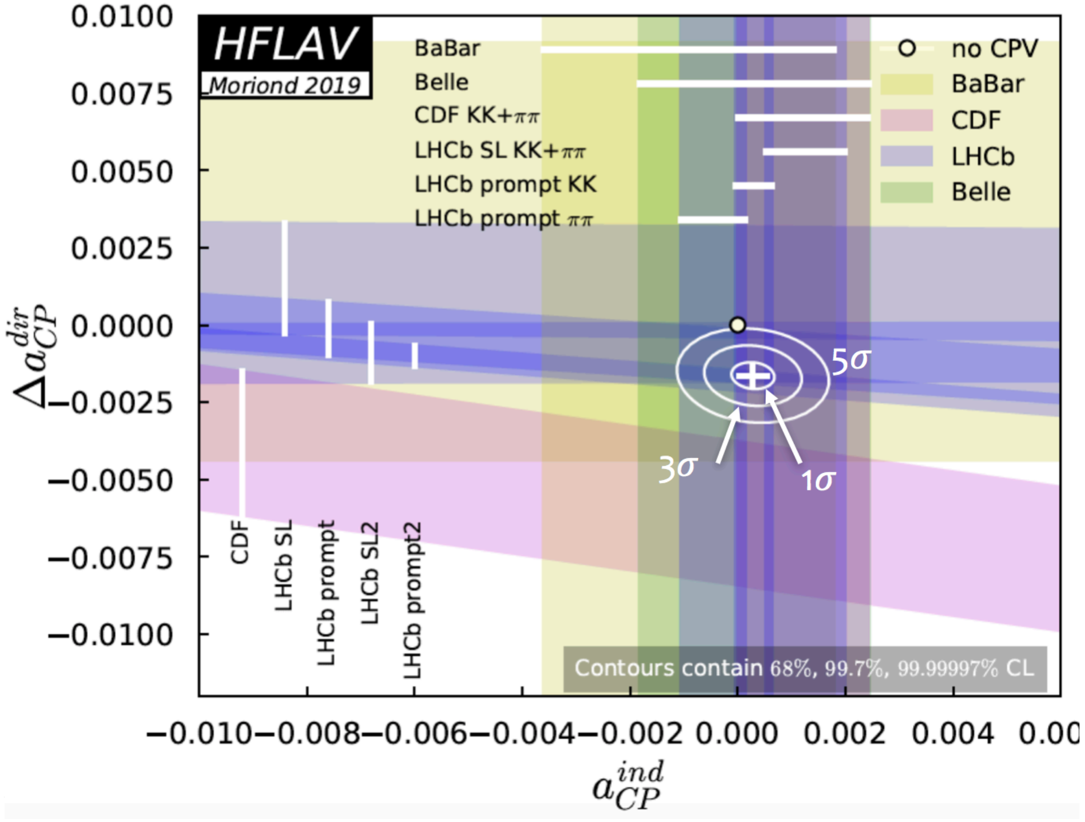
2019

2019
Charm particles:
***CP* violation in D^0**
meson decays
LHCb collaboration

$$A_{CP}(f) = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \overline{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \overline{f})}$$

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^-K^+) - A_{CP}(D^0 \to \pi^-\pi^+)$$

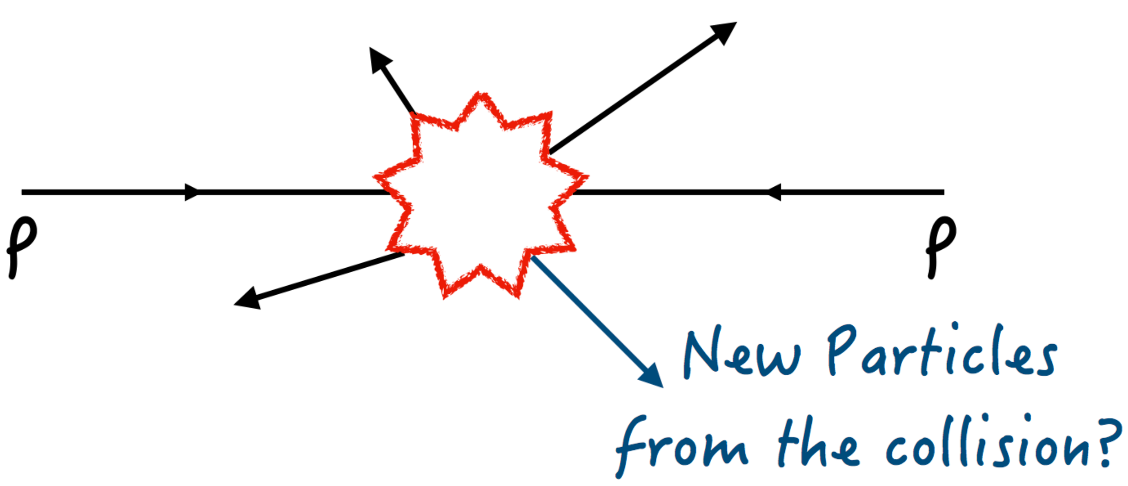
$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$$



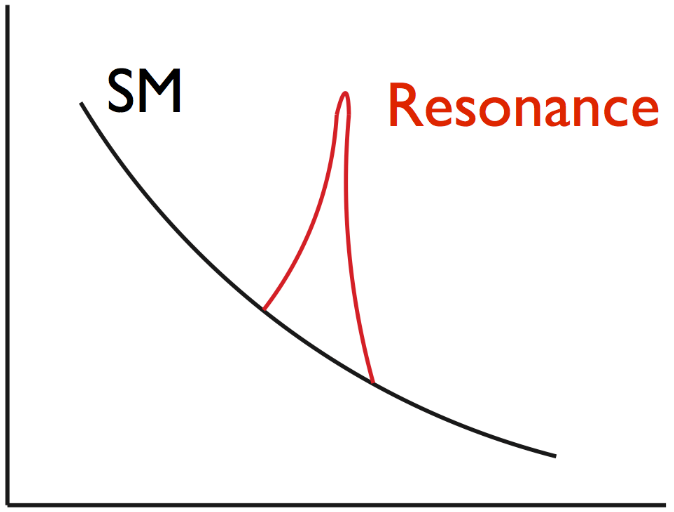
LHCb observes for first time CP violation in charm decays, with 5.3σ significance

(end of last lecture's recap)

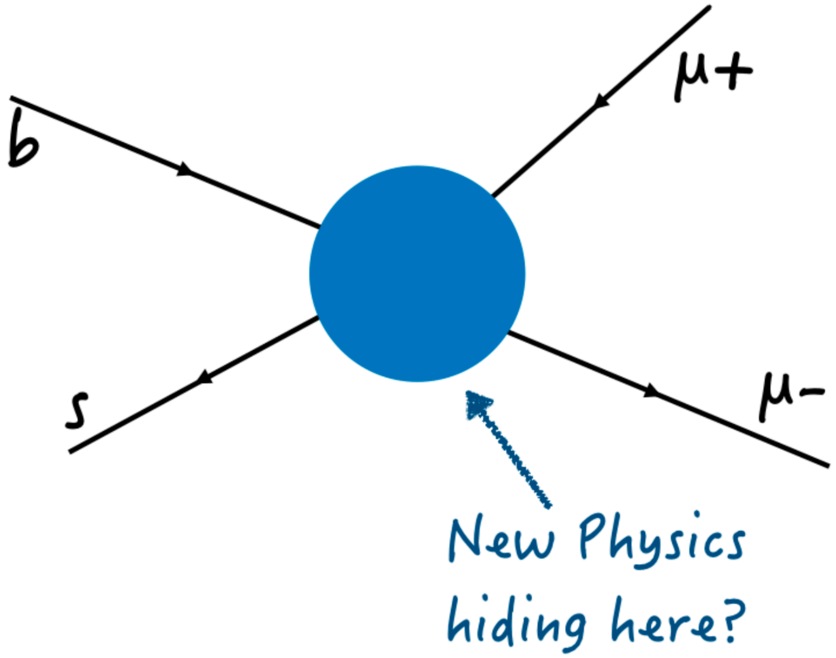
Direct search for NP



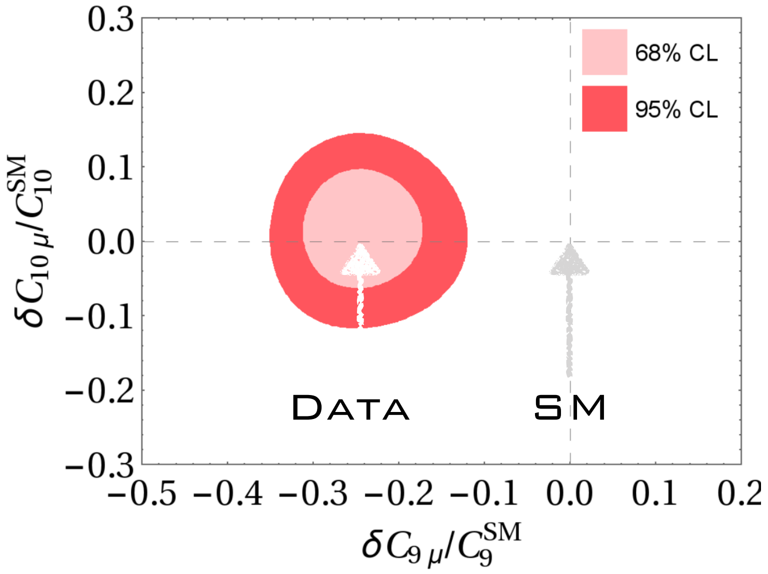
- searching for the decay products of NP particles produced in collision



Indirect search for NP



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



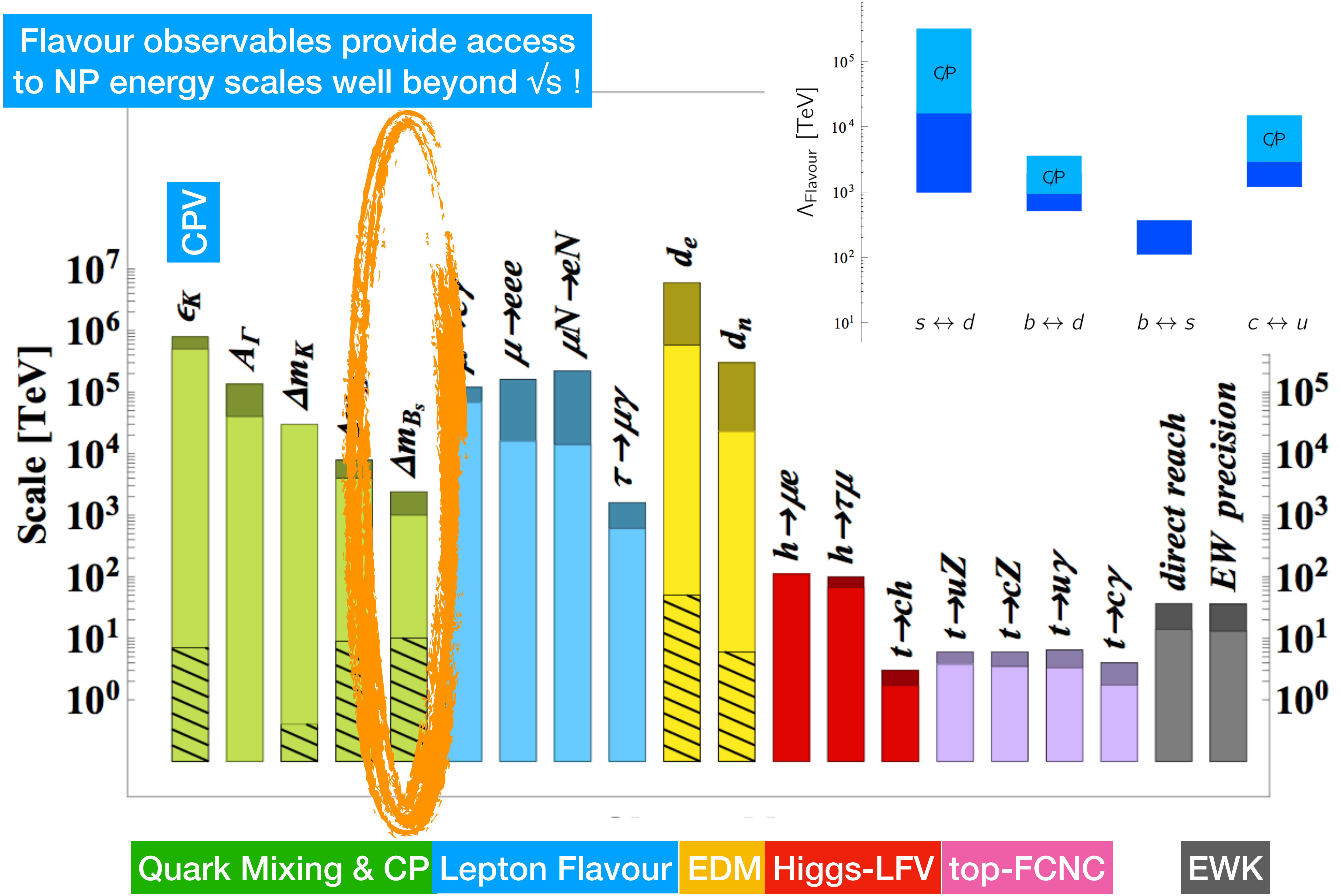
Flavour!

today’s menu:

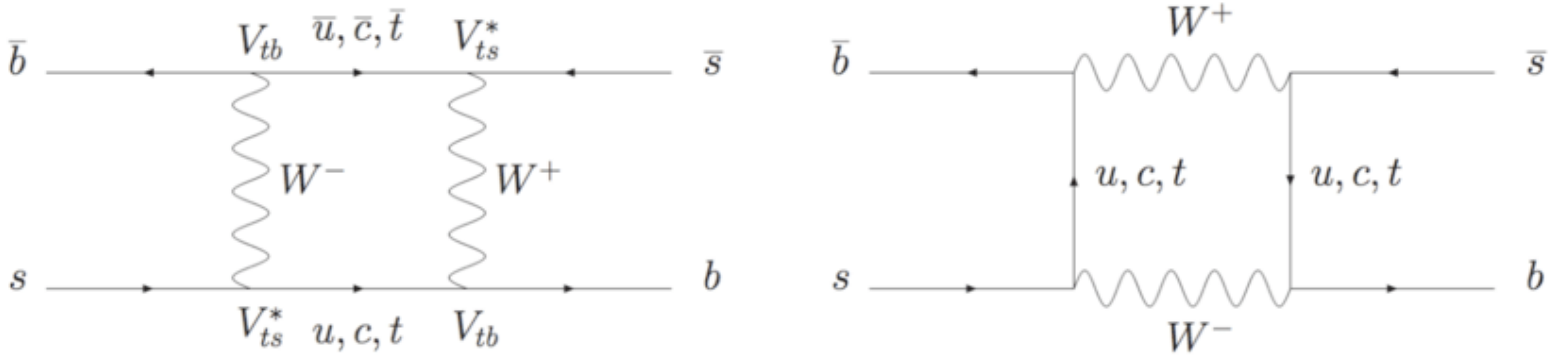
- flavour vs new physics
- precision (mixing & CPV)
- rare decays (B→μμ)
- flavour anomalies
  - b→smumu (angular analysis, P_5’)
  - LFU b→sll (l=μ,e)
  - LFU b→clν (l=μ,τ)
- global fits and favoured NP candidates
- neutrinos @ LHC

Indirect searches: fuelled by Quantum Mechanics

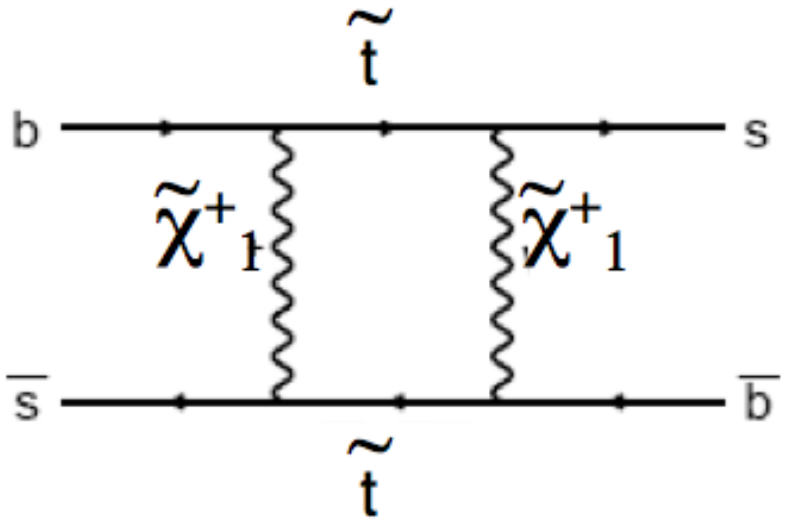
Flavour observables provide access to NP energy scales well beyond √s !



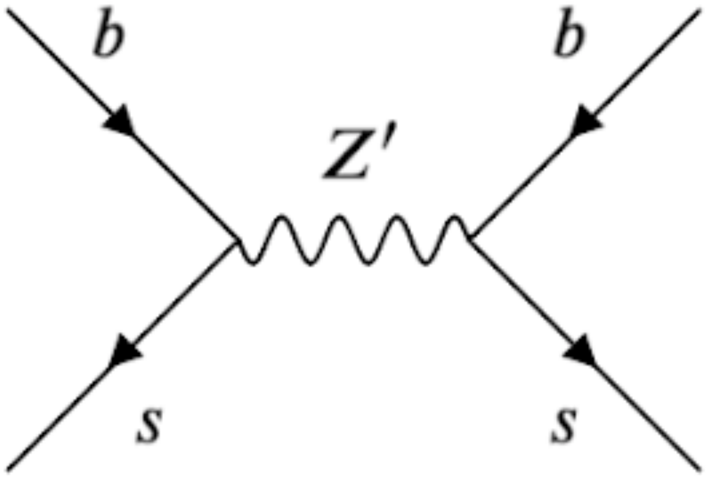
SM


$\bar{b}$
V_{tb}
$\bar{u}, \bar{c}, \bar{t}$
V_{ts}^*
$\bar{s}$
W^-
W^+
s
b
V_{ts}^*
u, c, t
V_{tb}
$\bar{b}$
W^+
$\bar{s}$
u, c, t
u, c, t
s
b
W^-

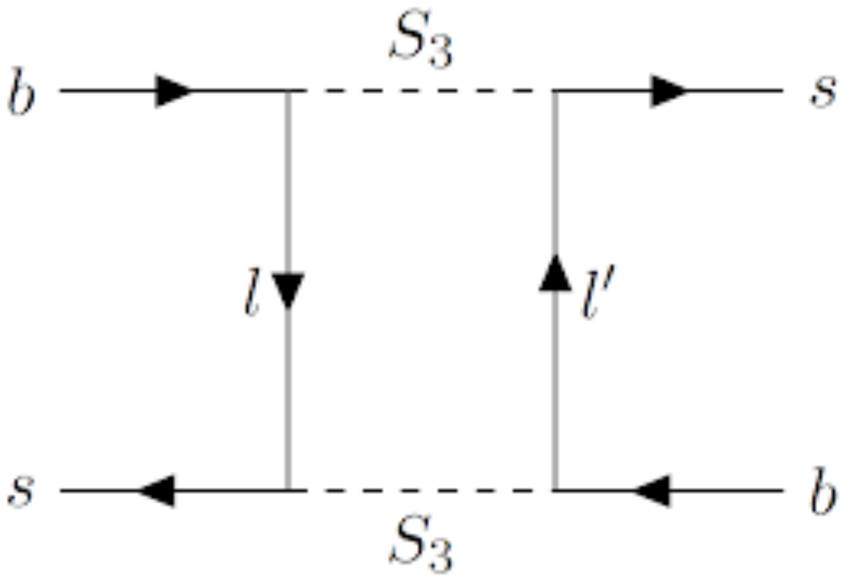
SUSY


$\tilde{t}$
b
s
$\tilde{\chi}^+_1$
$\tilde{\chi}^+_1$
$\bar{s}$
$\bar{b}$
$\tilde{t}$

Z’


b
b
Z'
s
s

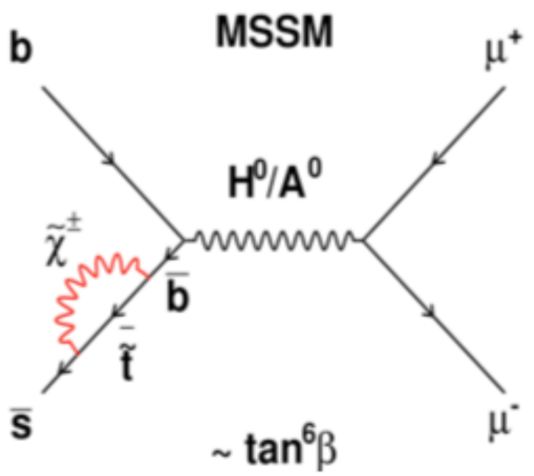
LQ

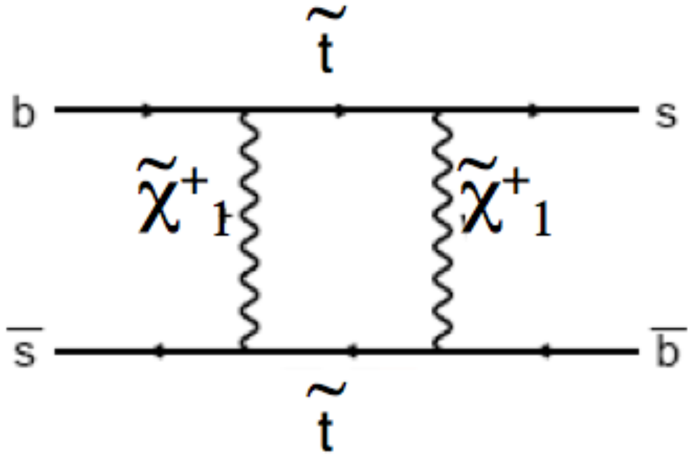

S_3
b
s
l
l'
s
b
S_3

Rare Decays

a path to new physics

- the effects of NP can be searched for and revealed indirectly through the virtual exchange of NP particles
  - general quantum effects in flavor loops
  - eg: SUSY particles can contribute in addition to SM; Z’, LQ, could affect effective couplings
- if NP hides behind SM interactions
  - either NP mass scale is very LARGE
  - or NP couplings mimic Yukawa couplings (minimal flavor violation scenario, MFV)
- in all cases study of flavor observables expected to enlighten or constrain theory





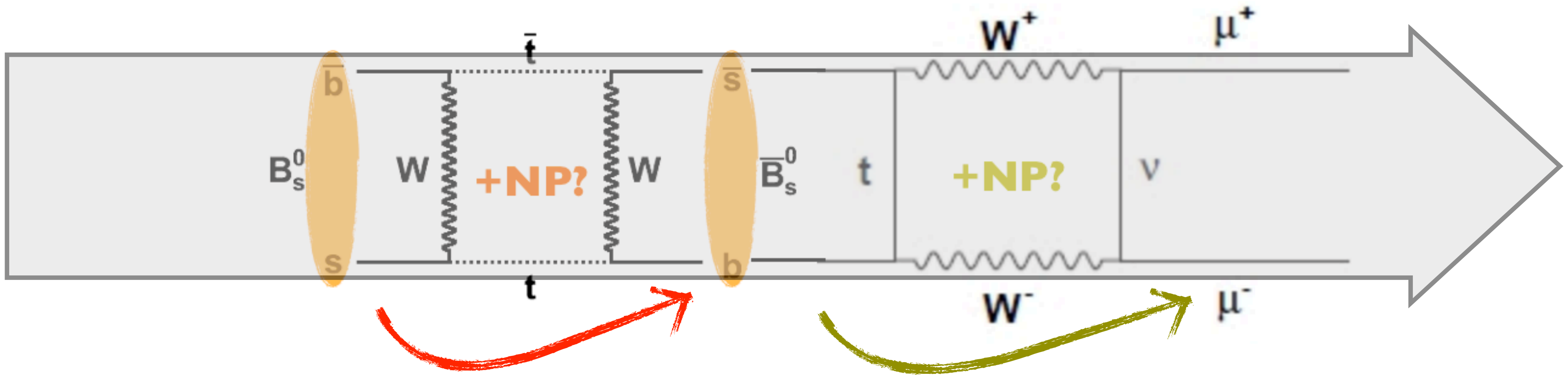
<u>note</u>: flavor-sector constraints at the LHC comparable (or stronger) than direct search limits, e.g. for large regions of the parameter space of minimal supersymmetry models

rare NP probes

- search for virtual contributions of new heavy particles in loops
- most interesting processes are those highly suppressed in SM
  - flavor-changing neutral current (FCNC), forbidden at tree level in SM
  - lepton flavor violation (LFV)
  - CKM suppressed
  - helicity suppressed
  - dominance of short distance effects, SM uncertainties under control
- experimental probes with precise theory prediction
  - uncertainty typically dominated by QCD; e.g. prefer leptonic to hadronic final states
- processes that may be modified (enhanced or suppressed) by orders of magnitude by NP
  - SUSY, 2HDM, LHT, Z', RS models ....

$$A(b \to \underset{s}{d})_{\rm FCNC} \sim c_{\rm SM}\frac{y_t^2 V_{td}^* V_{tb}}{16\pi^2 M_W^2} + c_{\rm NP}\frac{\delta_{3d}}{16\pi^2 \Lambda_{NP}^2}$$

B

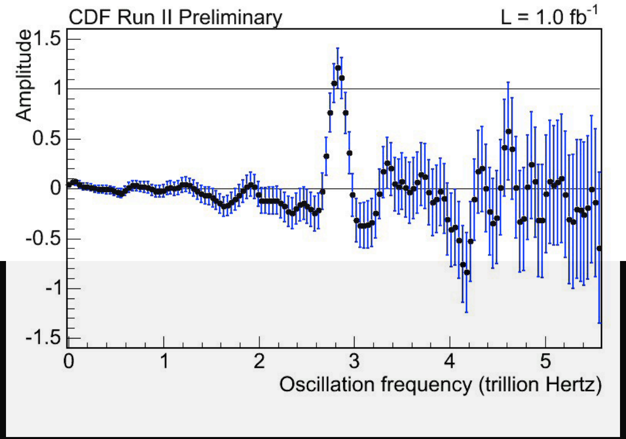


μμ

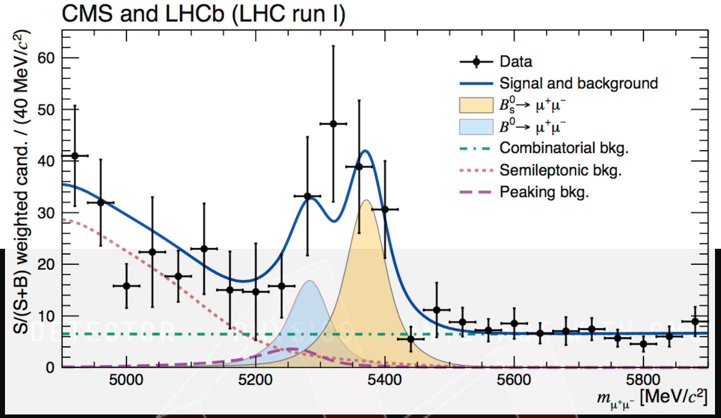
MIXING

DECAY

PRL 97 (2006) 242003, NL thesis



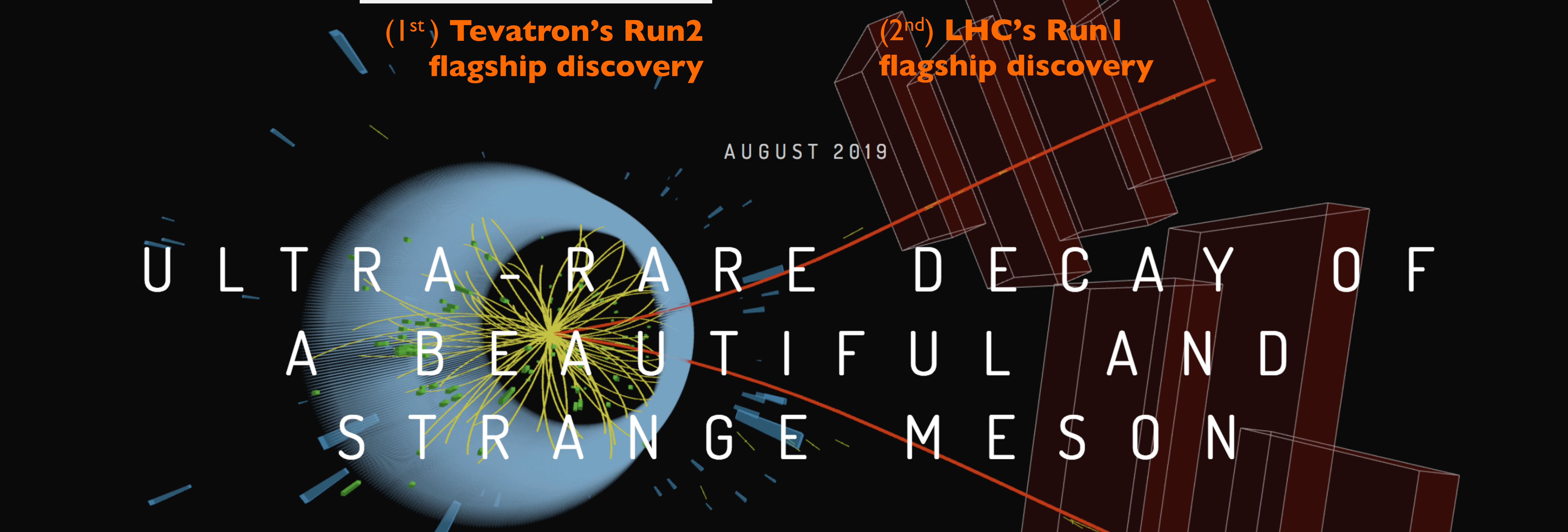
(1st) **Tevatron's Run2 flagship discovery**



Nature 522 (2015) 68

(2nd) **LHC's Run1 flagship discovery**

COLLABORATION NEWS BLOG SEARC

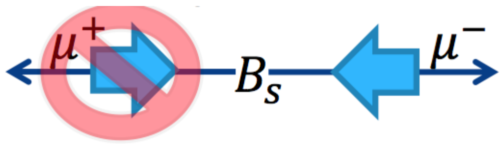


AUGUST 2019

ULTRA-RARE DECAY OF A BEAUTIFUL AND STRANGE MESON

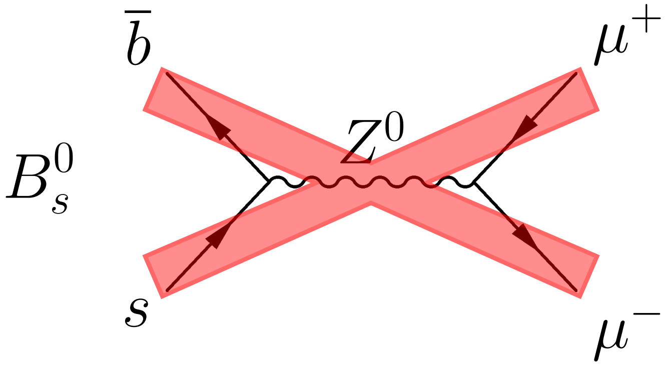
B→μμ

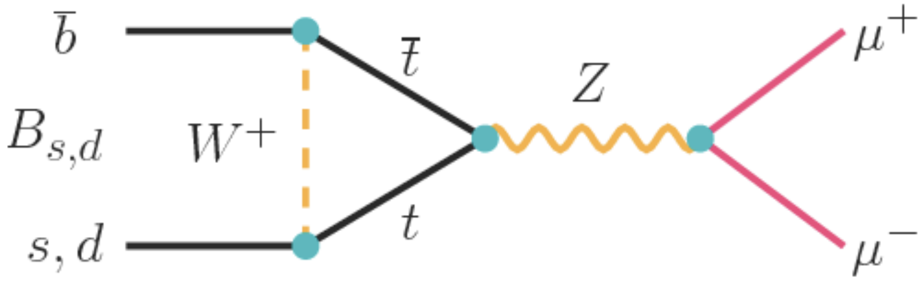
- in the Standard Model $B_{d/s}\to\mu\mu$ decays are highly suppressed
  - helicity suppressed, by factor of $(m_\mu/m_B)^2$

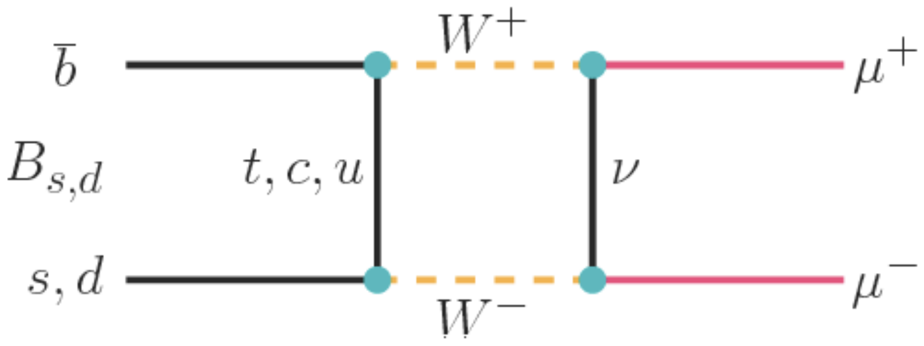


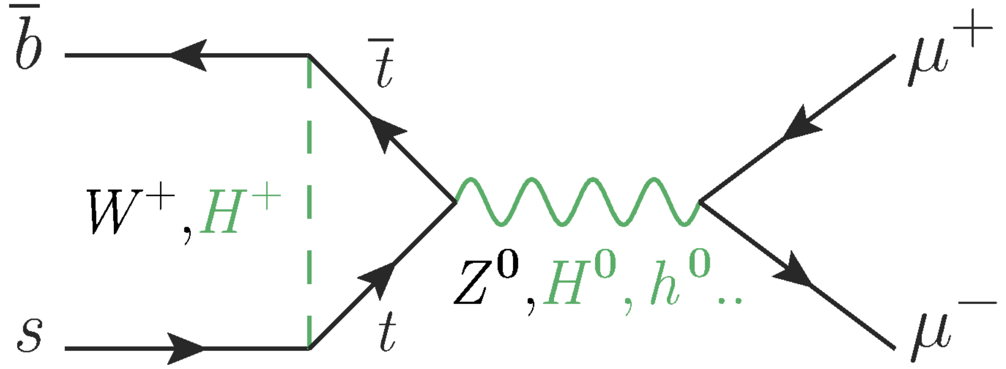
  - in the limit of massless muons, the process would be forbidden by spin conservation
  - FCNC, forbidden at tree level, in SM, can only proceed through higher-order loop diagrams
  - Cabibbo suppressed $|V_{ts(td)}|^2$
- Possible new particles in the loops!
  - may enhance *or* suppress the decay rates

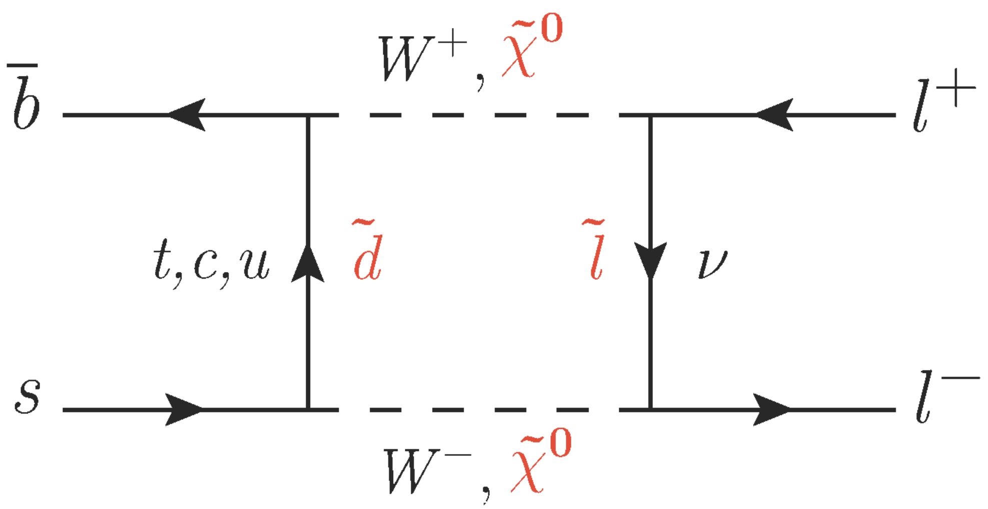
Standard Model

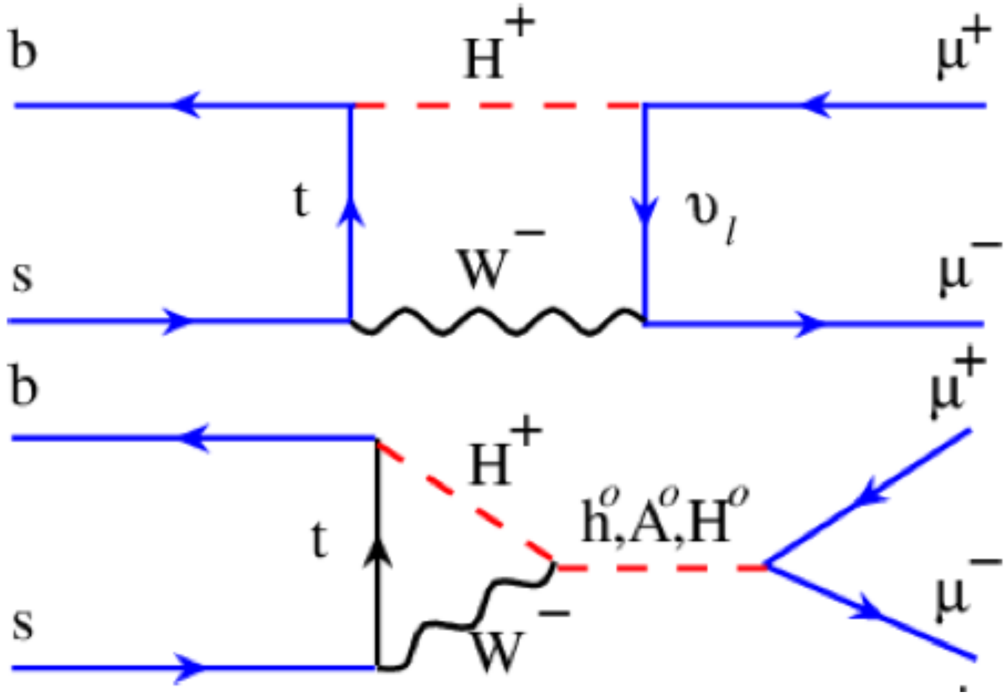


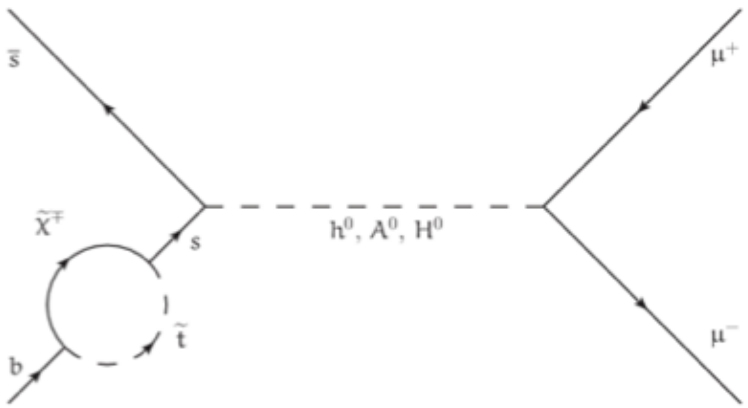




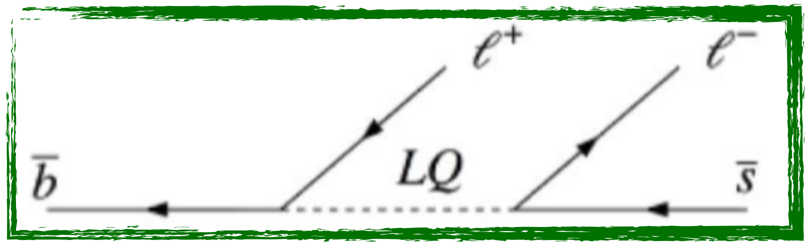

$\bar{b}$
$\bar{t}$
μ^+
W^+, H^+
$Z^0, H^0, h^0..$
s
t
μ^-

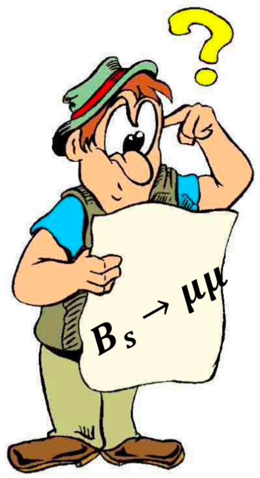

$W^+, \tilde{\chi}^0$
$\bar{b}$
l^+
t, c, u
$\tilde{d}$
$\tilde{l}$
ν
s
l^-
$W^-, \tilde{\chi}^0$

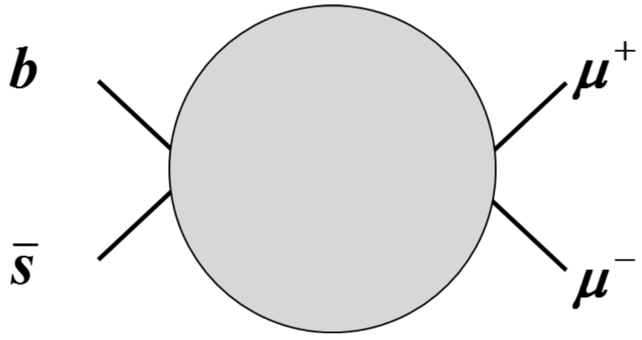

b
H+
μ+
t
υ$_l$
s
W−
μ−
b
μ+
H+
t
h°,A°,H°
μ−
s
W−


$\bar{s}$
μ+
$\tilde{\chi}^{\mp}$
s
h0, A0, H0
b
$\tilde{t}$
μ−

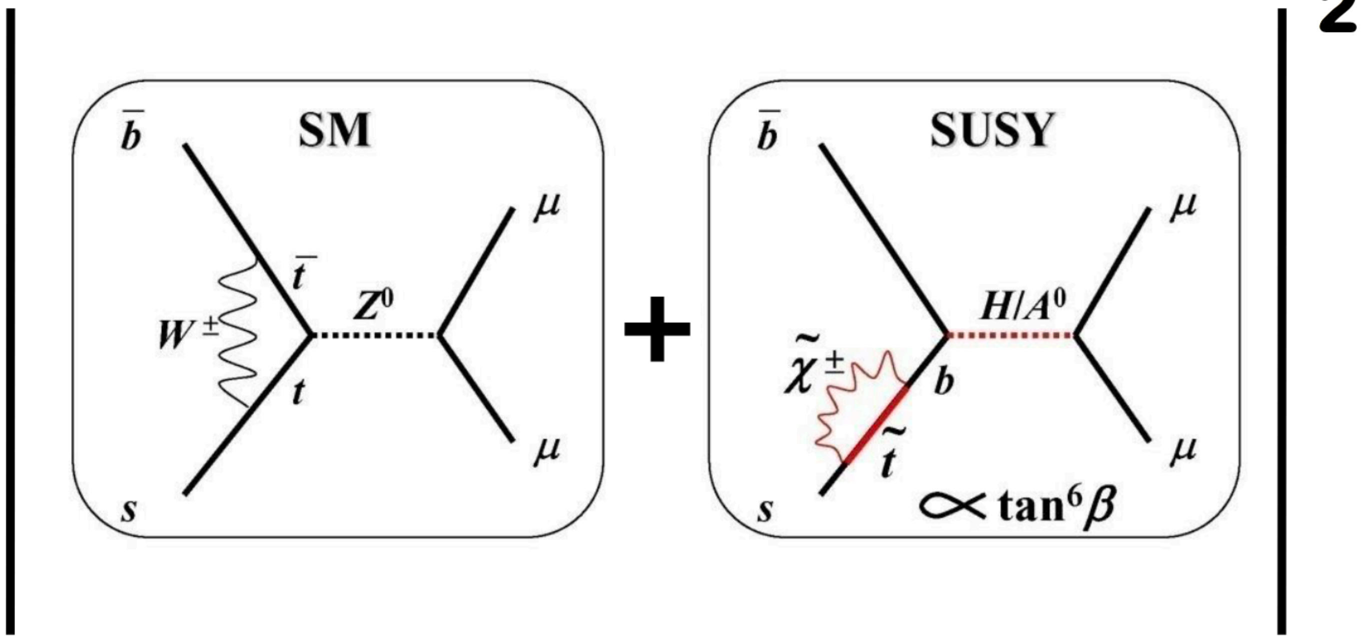

ℓ
ℓ
Z'
$\bar{b}$
$\bar{s}$


ℓ^+
ℓ^-
$\bar{b}$
LQ
$\bar{s}$



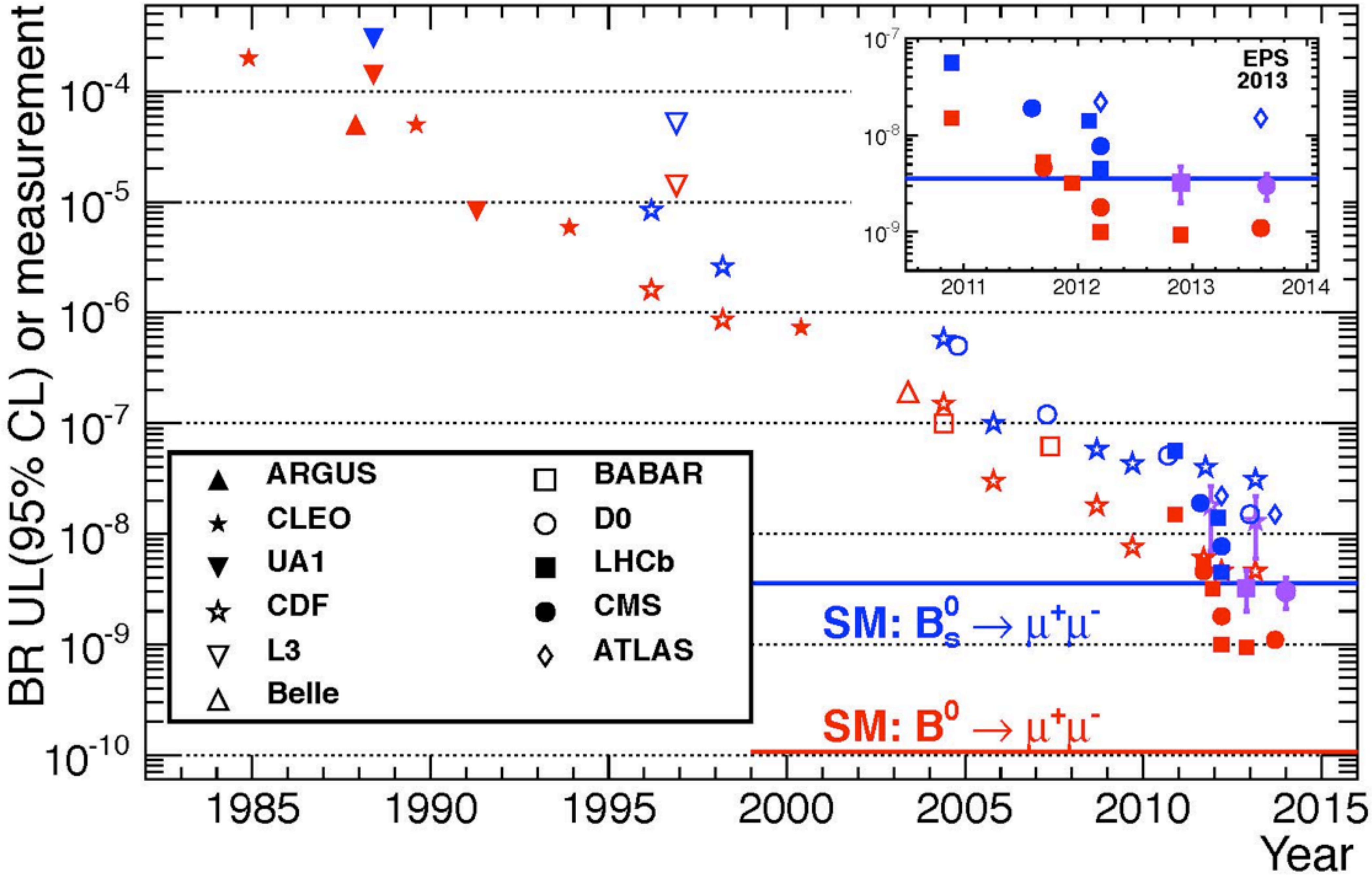


Br$(B_s \to \mu\mu)$ $\propto$



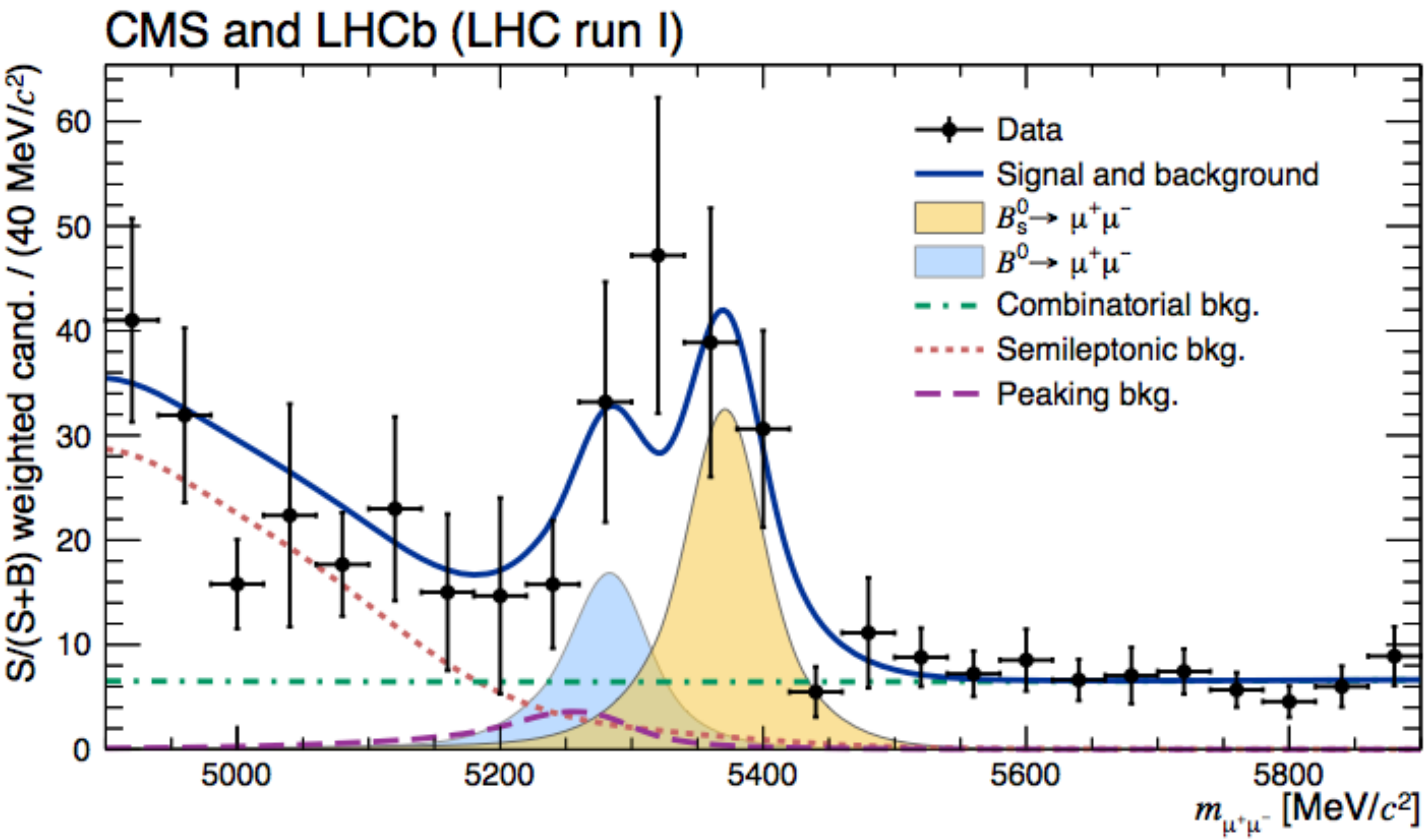
searching for an ultra-rare decay: $B \to \mu\mu$

a 3 decade long search



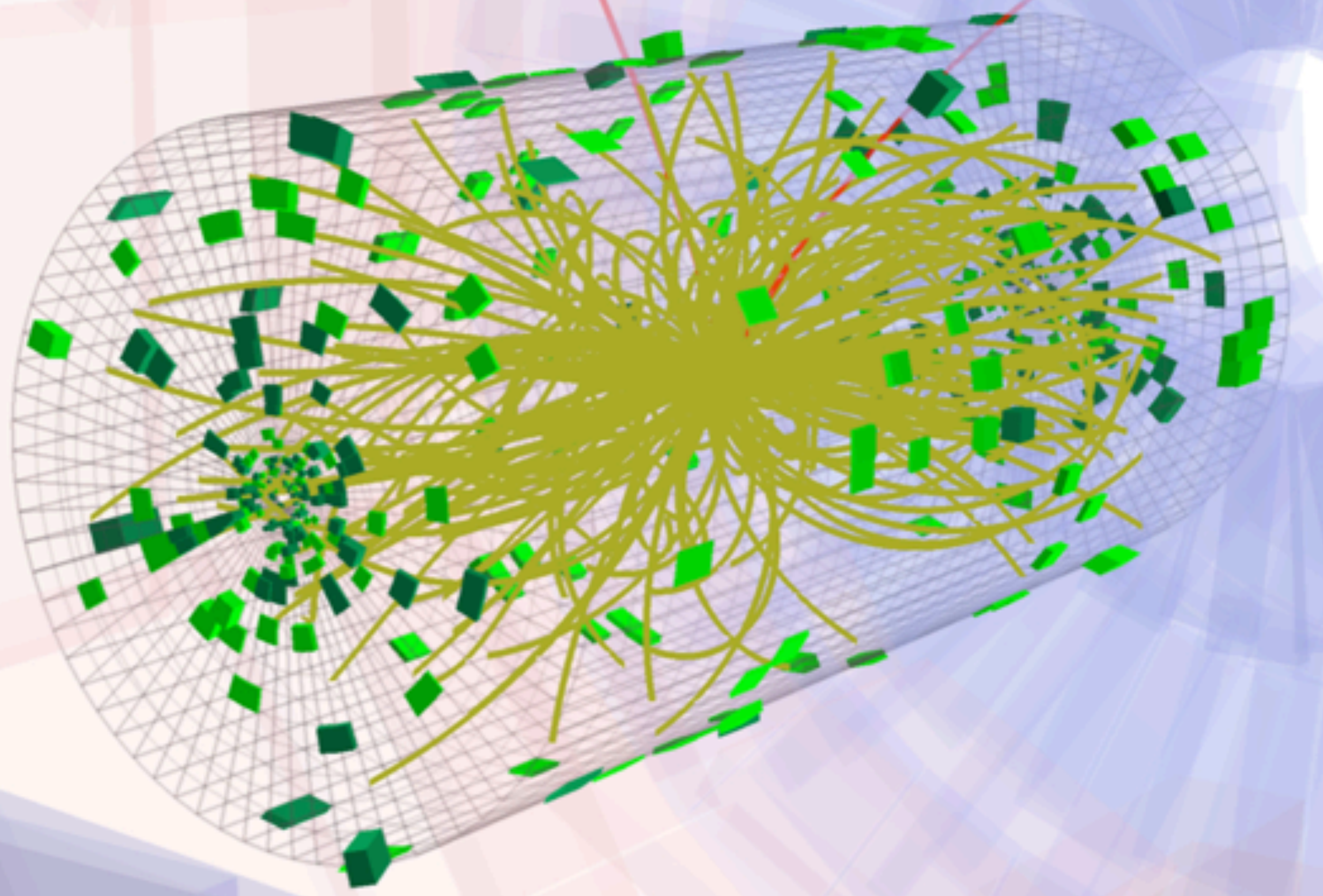
flagship LHC discovery

(CMS+LHCb)



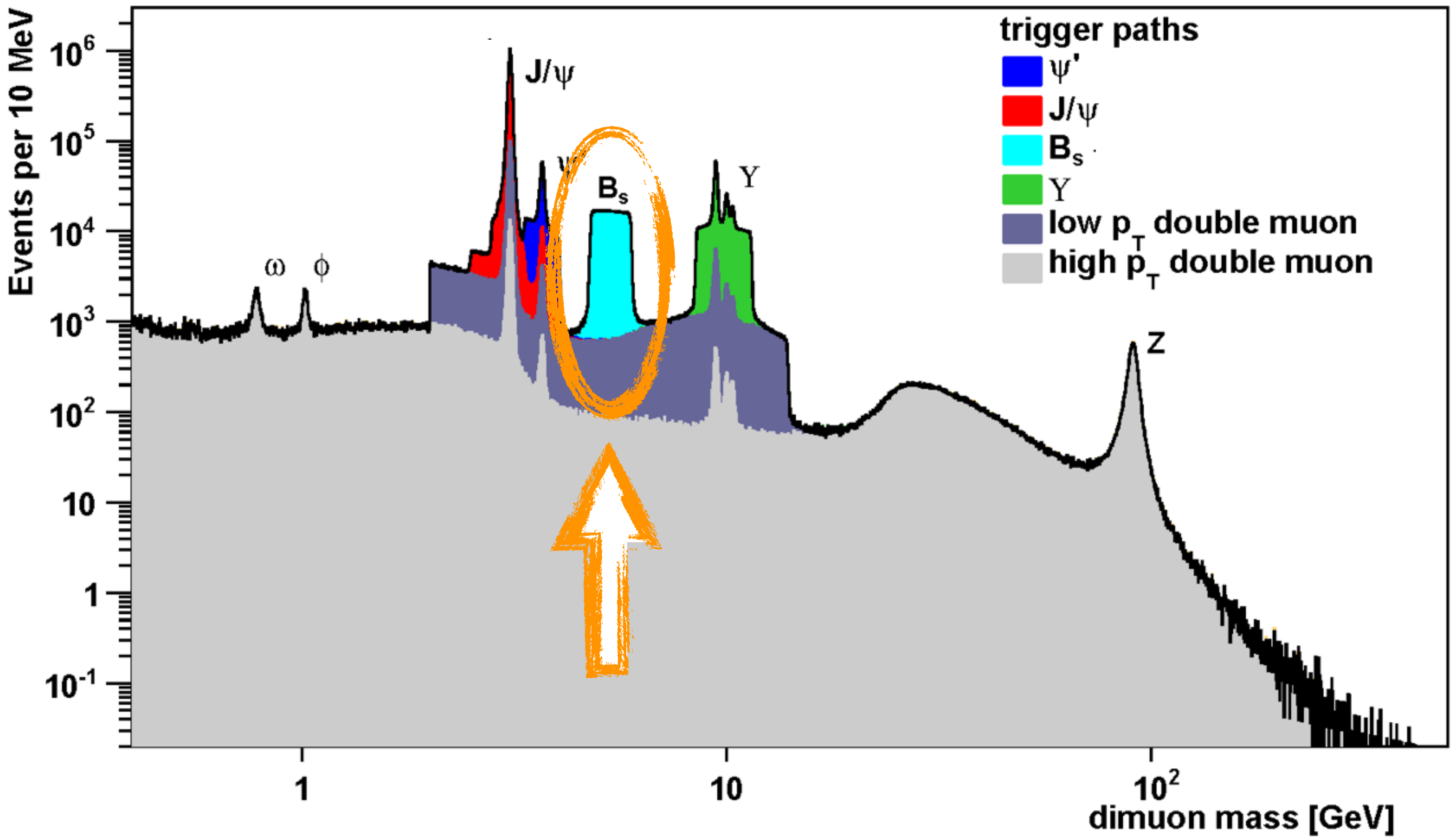
$B_s \rightarrow \mu\mu$

the ‘golden’ rare decay



*searching for an **ultra-rare** decay:* B→μμ

1. ONLINE SELECTION (TRIGGER)



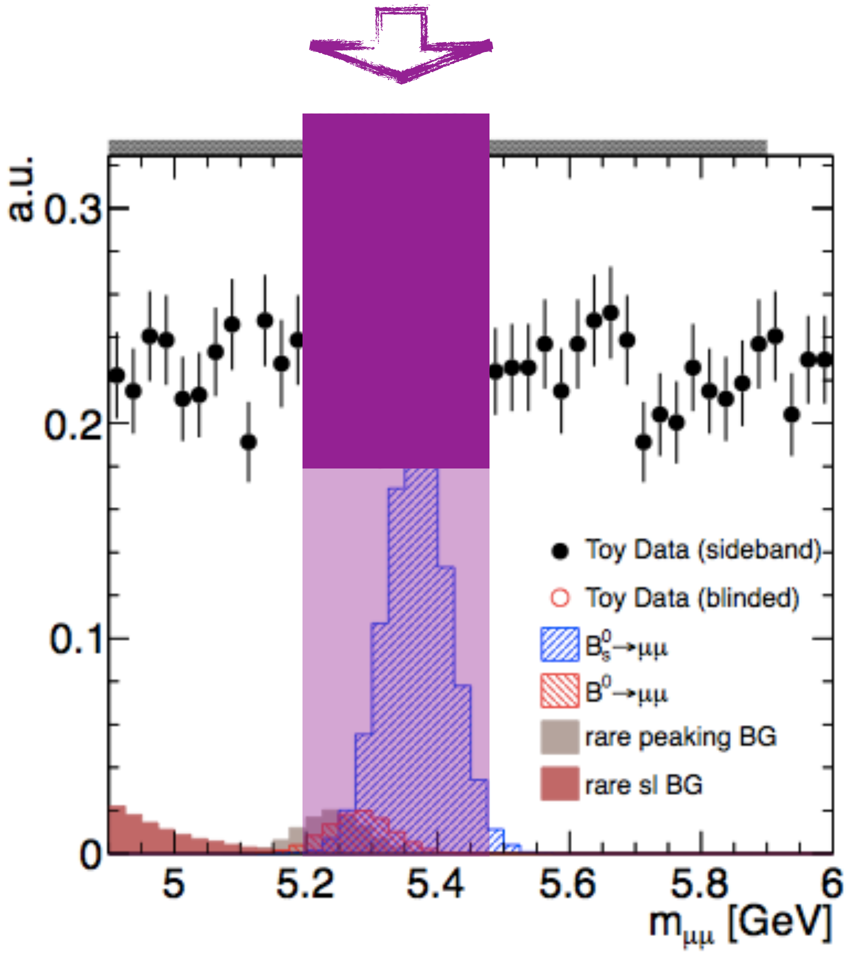
Dimuon Trigger

- L1 Hardware Trigger
  - $p_T > 3$ GeV (few kHz)
- HLT Full tracking and vertexing
- HLT $B_s \to \mu\mu$
  - Leading and sub-leading μ $p_T > 3,4$ (4,4) GeV $|\eta_{\mu\mu}| < 1.8$ ($1.8 < |\eta_{\mu\mu}| < 2.2$)
  - $p_T(\mu\mu) > 5$ (4.8-6) GeV
  - $4.8 < m(\mu\mu) < 6.0$ GeV
  - $P(\chi^2/dof) > 0.5\%$

searching for an ultra-rare decay: $B \to \mu\mu$

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)

SIGNAL
REGION
BLINDED

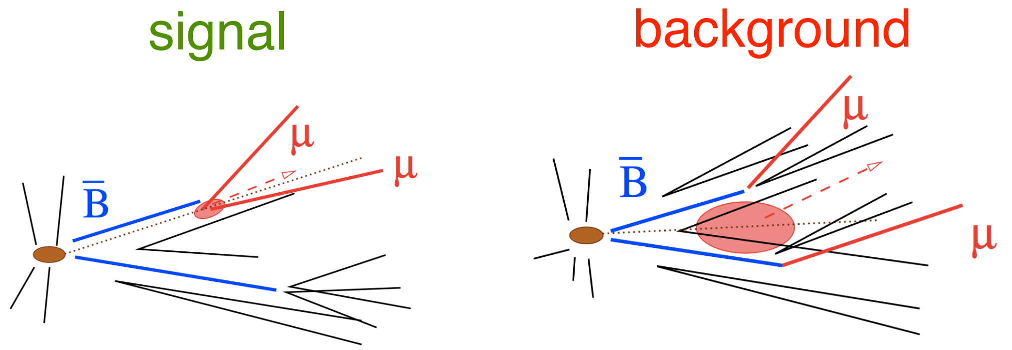


analysis procedure and event selection developed without inspecting the data in region where signal is expected

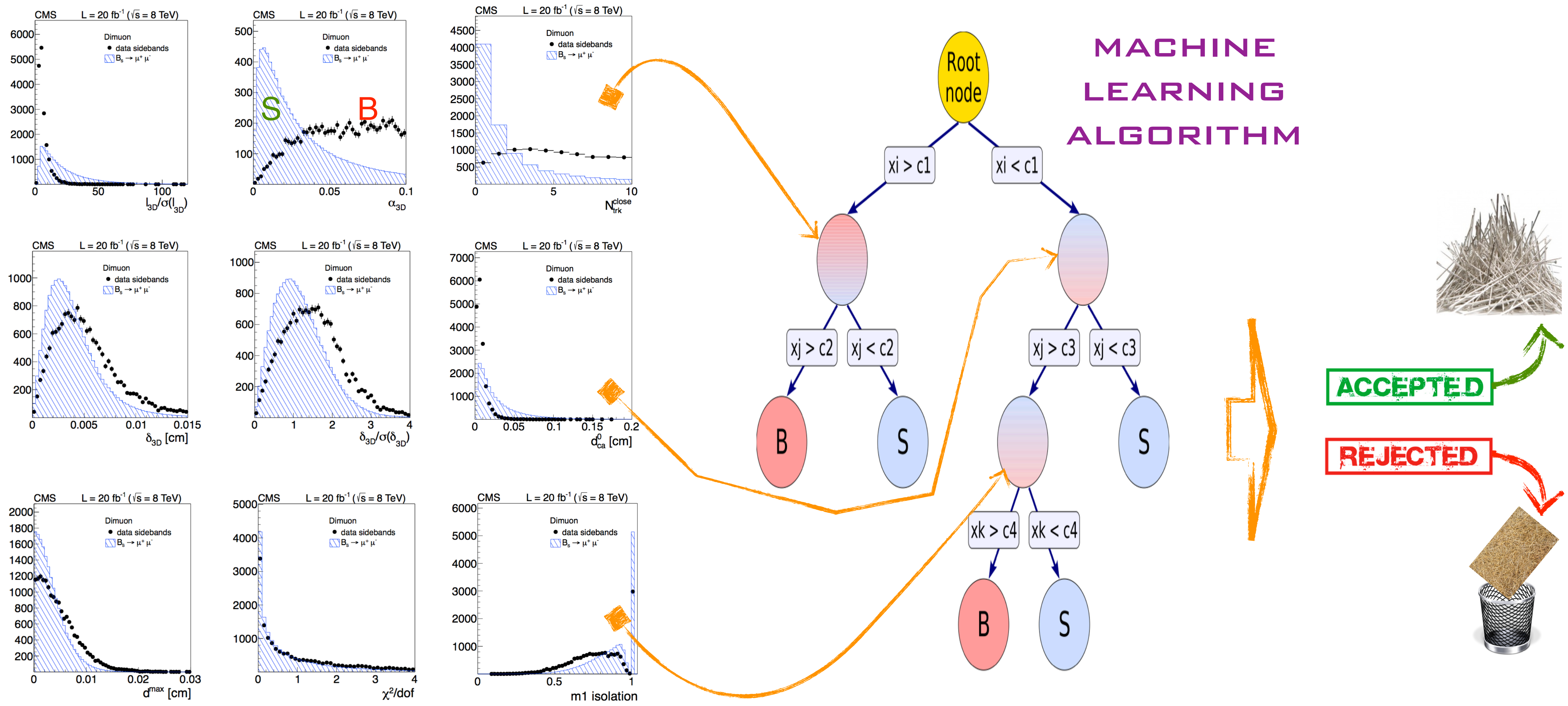
“box opening” only later, at final analysis stages

searching for an *ultra-rare* decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. **MULTIVARIATE SELECTION**



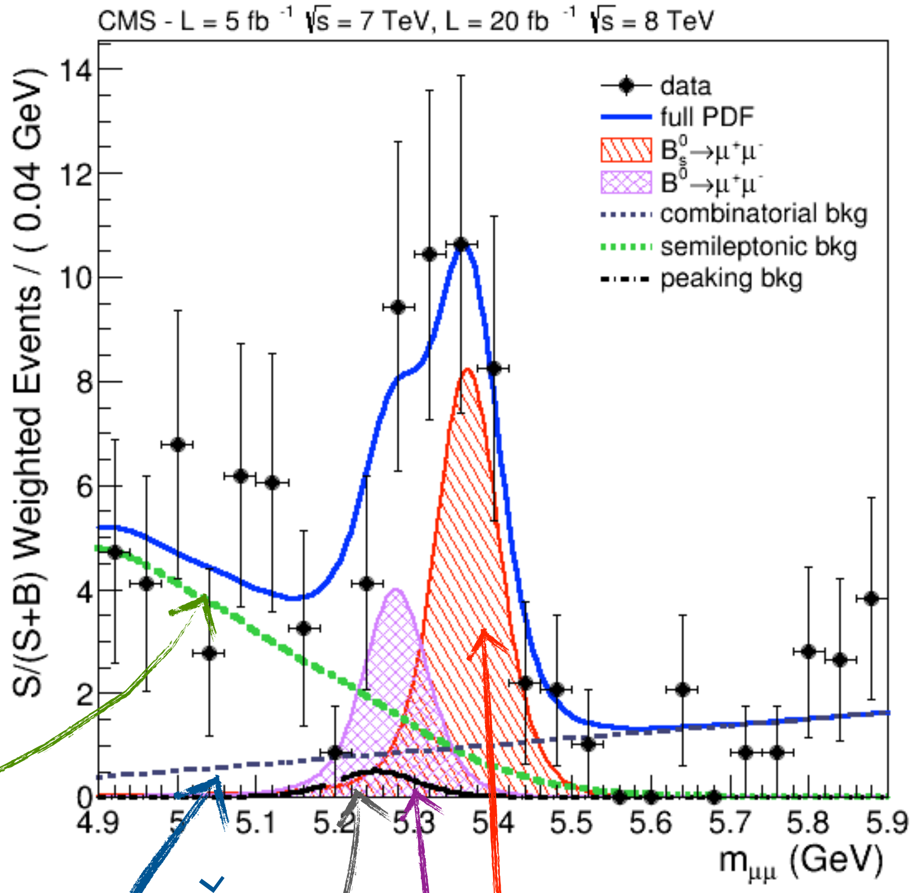
signal vs background discriminating variables



searching for an ultra-rare decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. **FIT THE DATA (LIKELIHOOD)**

Fit the data accounting for the various signal and background components



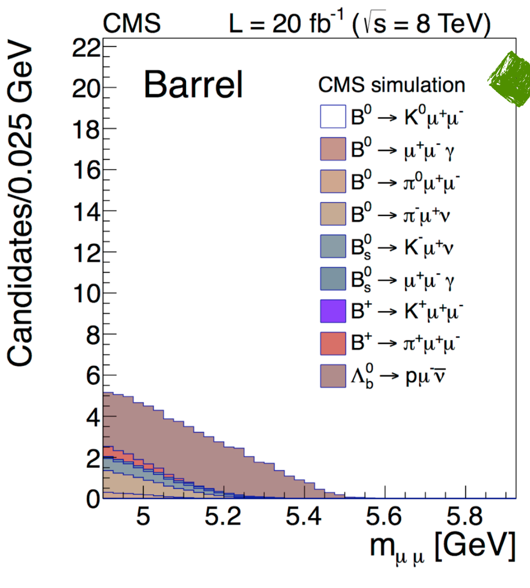
SEMILEPTONIC BKG

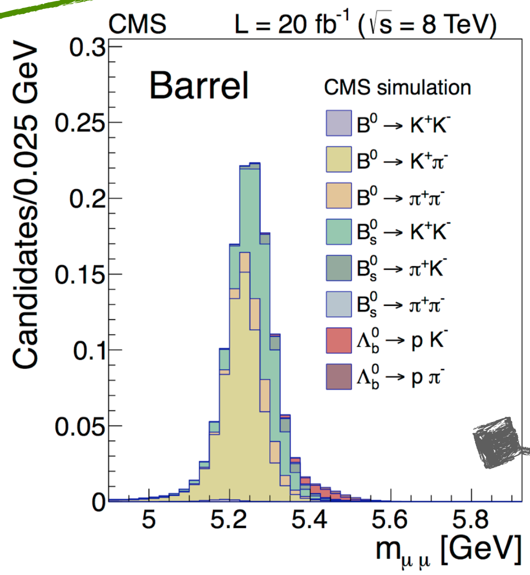
COMBINATORIAL BKG

PEAKING BKG

SIGNAL 1: $B_s \to \mu\mu$

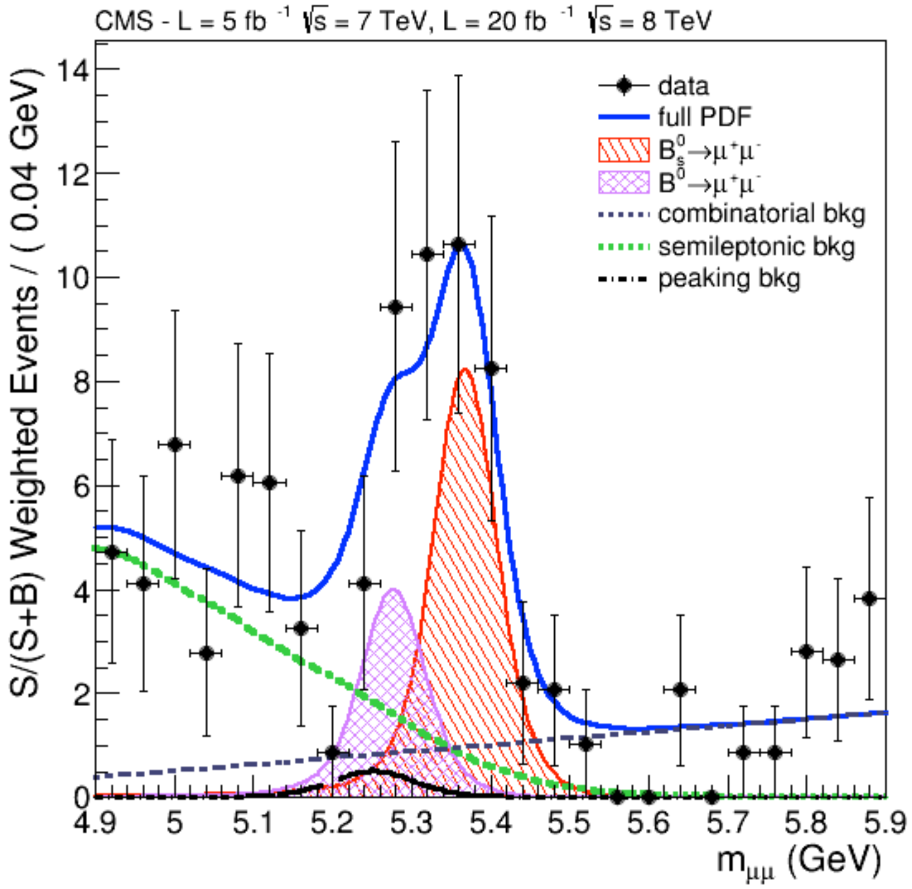
SIGNAL 2: $B^0 \to \mu\mu$



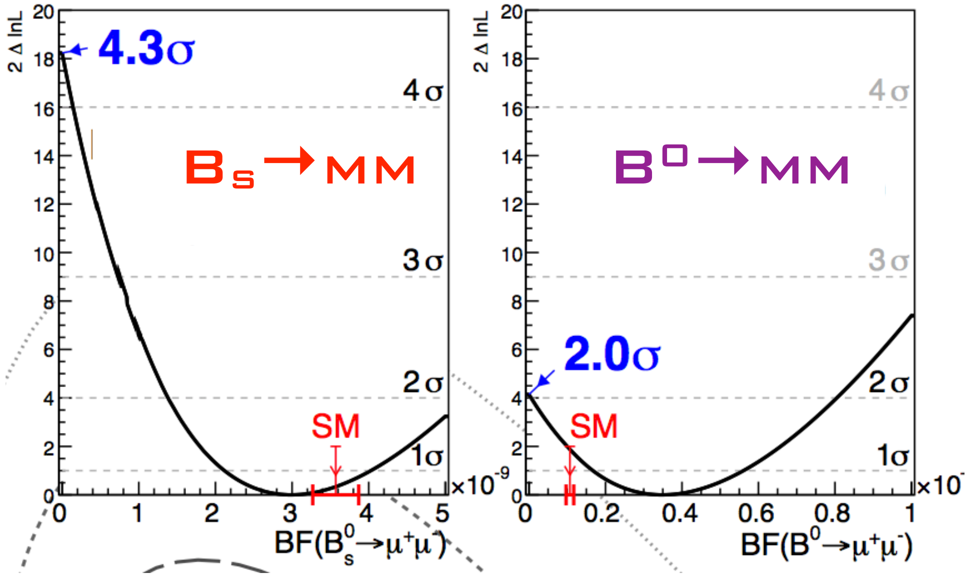


searching for an *ultra-rare* decay: B→μμ

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. **STATISTICAL SIGNIFICANCE**

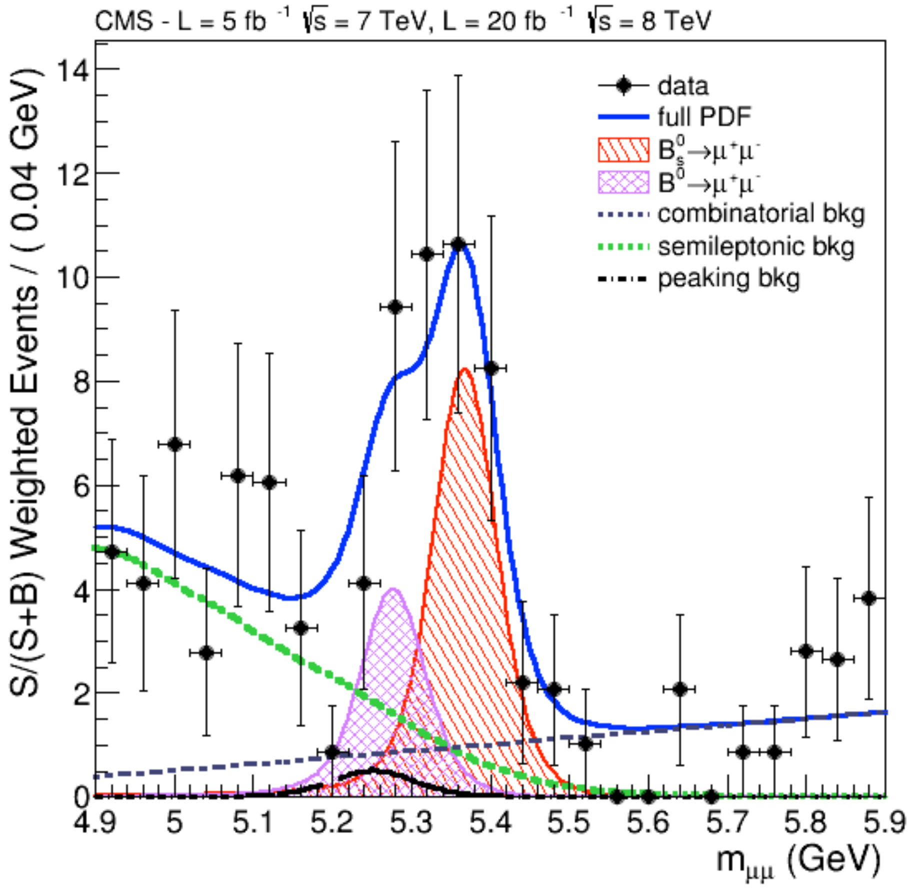


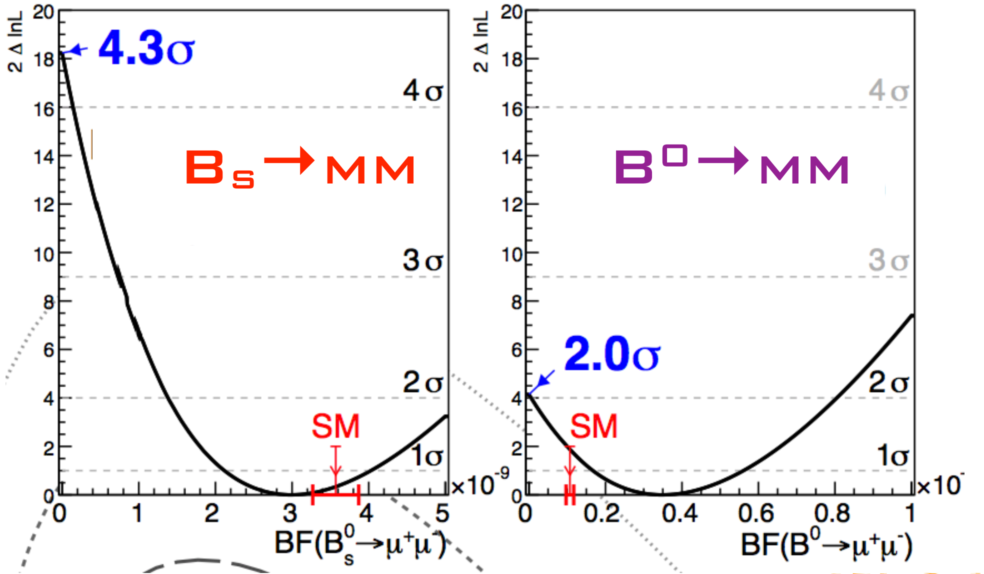
is the observed excess a genuine signal, or just a fluctuation of the background?



searching for an *ultra-rare* decay: $B\to\mu\mu$

1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. STATISTICAL SIGNIFICANCE
6. **EXTRACT MEASUREMENT**

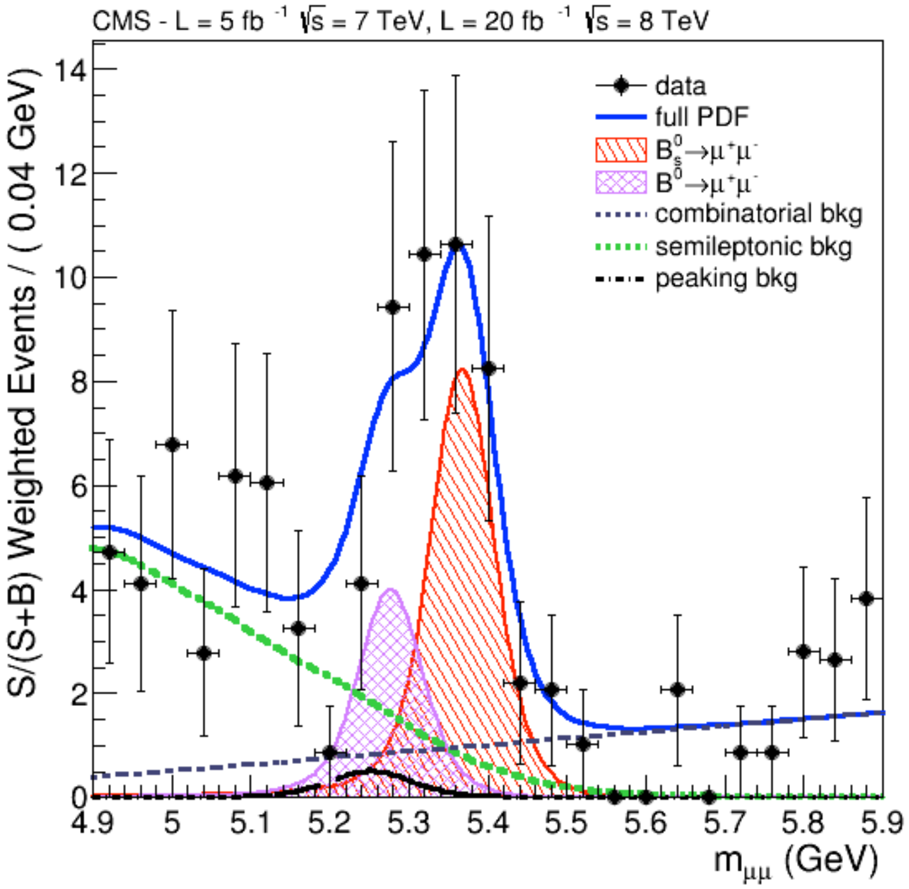




$$\mathrm{BR}(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\mathrm{stat})^{+0.6}_{-0.4}\ (\mathrm{syst})\right)\times 10^{-9}$$

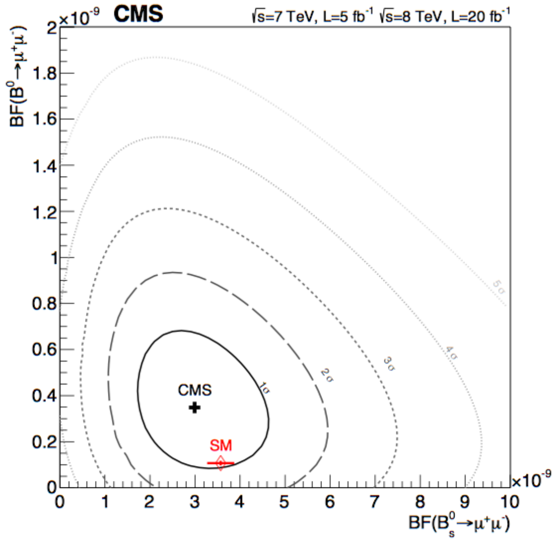
searching for an ***ultra-rare*** *decay:* **B→μμ**

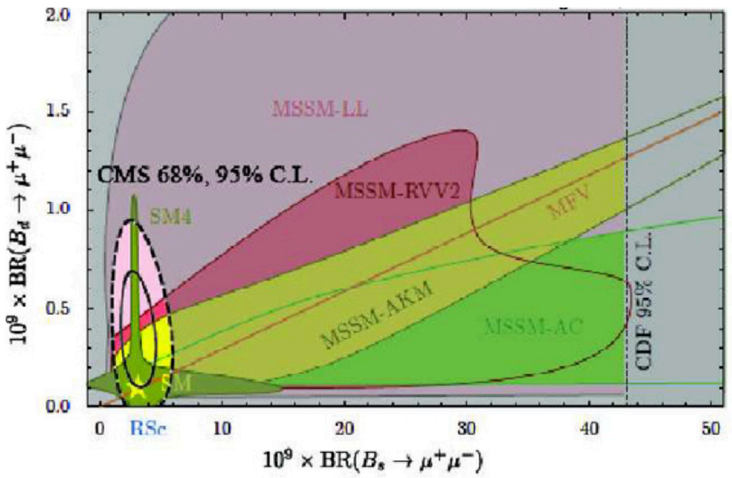
1. ONLINE SELECTION (TRIGGER)
2. BLIND THE DATA (AVOID BIAS)
3. MULTIVARIATE SELECTION
4. FIT THE DATA (LIKELIHOOD)
5. STATISTICAL SIGNIFICANCE
6. EXTRACT MEASUREMENT
7. **COMPARE TO THEORY**

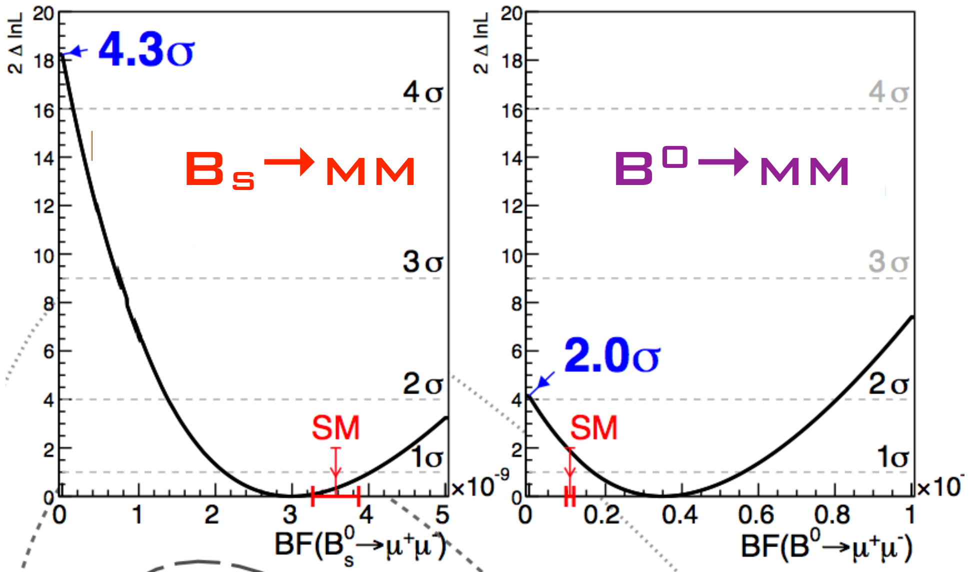


THE SM...

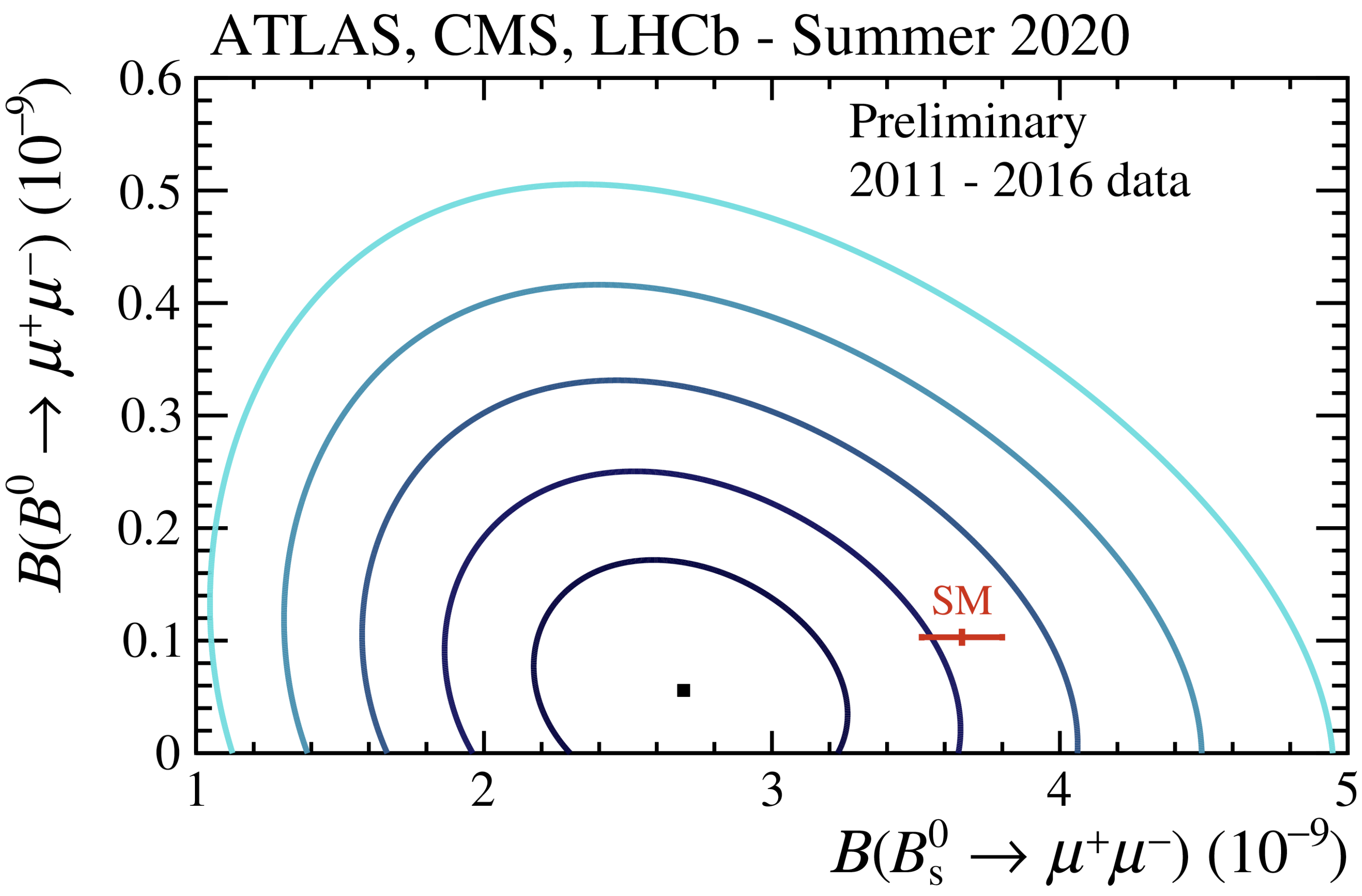
AND BEYOND



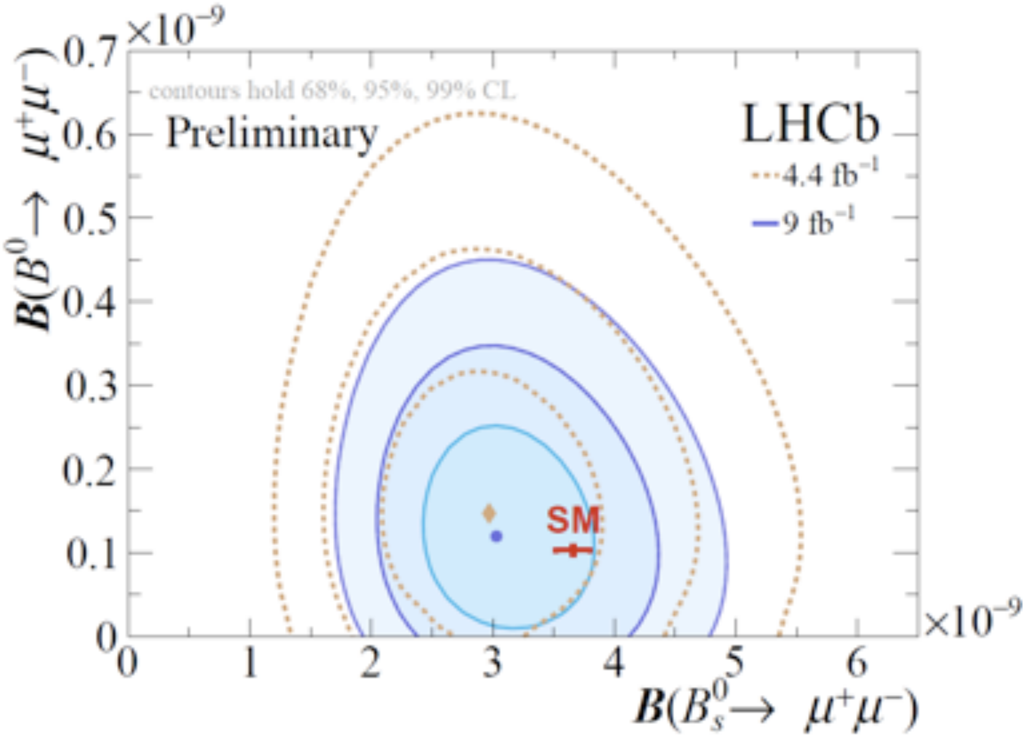


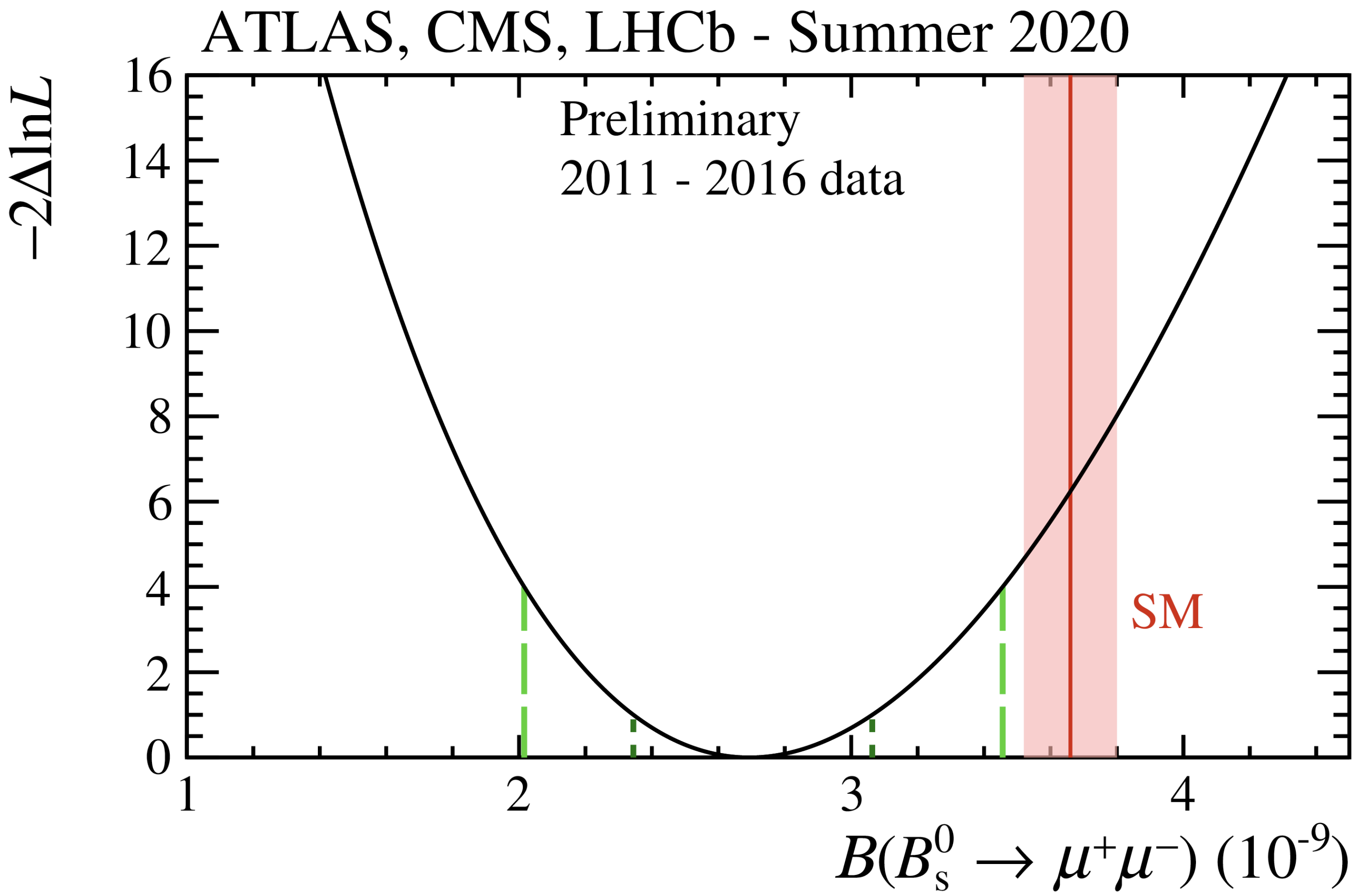


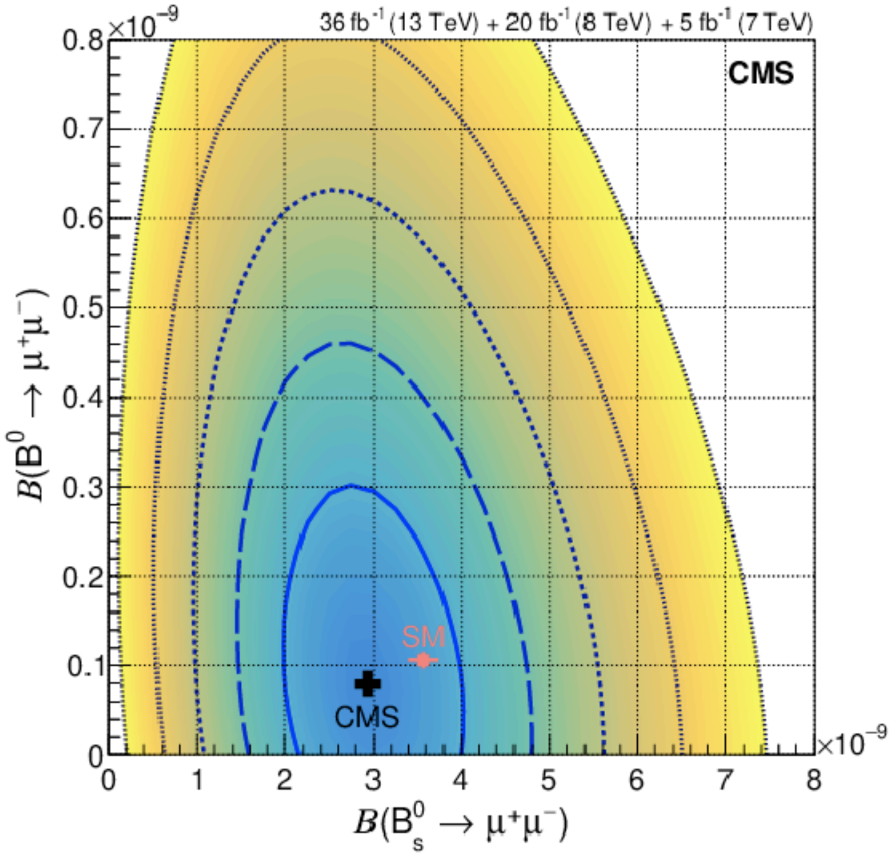
$$\mathrm{BR}(B_s\to\mu\mu)=\left(3.0^{+0.9}_{-0.8}\ (\mathrm{stat})^{+0.6}_{-0.4}\ (\mathrm{syst})\right)\times10^{-9}$$


ATLAS, CMS, LHCb - Summer 2020
Preliminary
2011 - 2016 data
SM
$B(B^0 \to \mu^+\mu^-)$ (10^{-9})
$B(B_s^0 \to \mu^+\mu^-)$ (10^{-9})
0
0.1
0.2
0.3
0.4
0.5
0.6
1
2
3
4
5

March 2021


$\times10^{-9}$
contours hold 68%, 95%, 99% CL
Preliminary
LHCb
4.4 fb^{-1}
9 fb^{-1}
SM
$B(B^0 \to \mu^+\mu^-)$
$B(B_s^0 \to \mu^+\mu^-)$
$\times10^{-9}$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
1
2
3
4
5
6


ATLAS, CMS, LHCb - Summer 2020
Preliminary
2011 - 2016 data
SM
$-2\Delta\ln L$
$B(B_s^0 \to \mu^+\mu^-)$ (10^{-9})
0
2
4
6
8
10
12
14
16
1
2
3
4


$\times10^{-9}$
36 fb^{-1} (13 TeV) + 20 fb^{-1} (8 TeV) + 5 fb^{-1} (7 TeV)
CMS
SM
CMS
$B(B^0 \to \mu^+\mu^-)$
$B(B_s^0 \to \mu^+\mu^-)$
$\times10^{-9}$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0
1
2
3
4
5
6
7
8

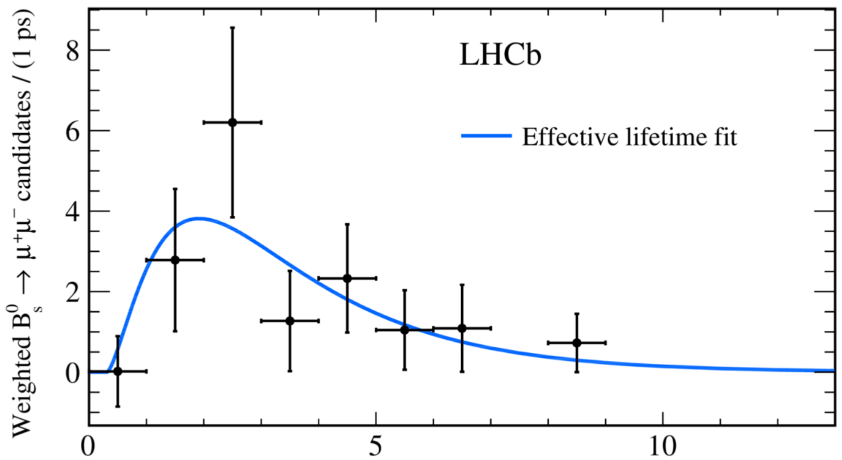
$B_s \to \mu\mu$ | efective lifetime

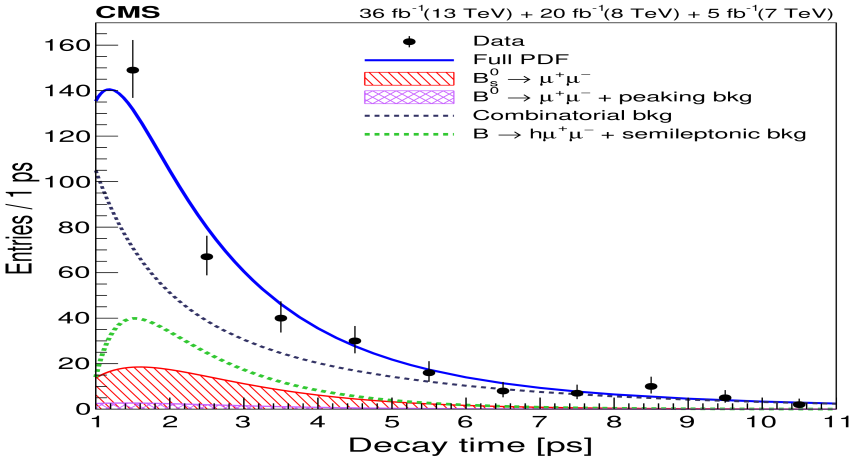
- Effective lifetime: complementary NP probe
  - in SM, only heavy eigenstate decays to μμ (not in NP!)

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

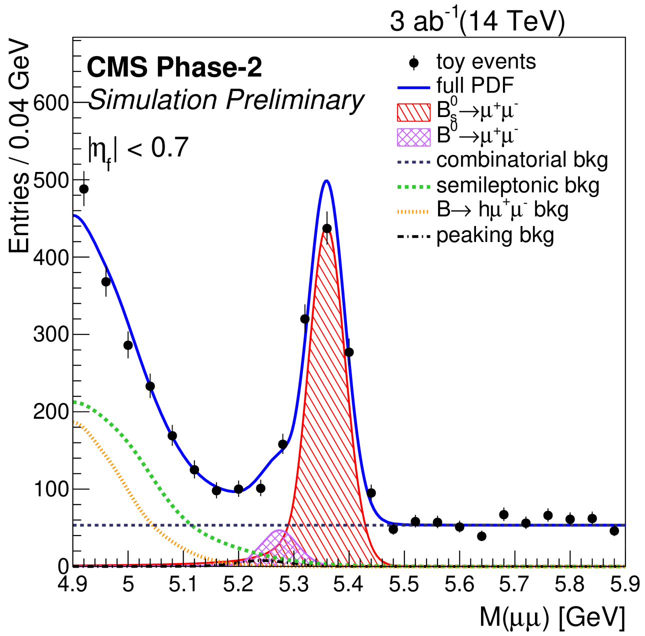
$\mathbf{A}_{\Delta\Gamma} = +1$ in SM

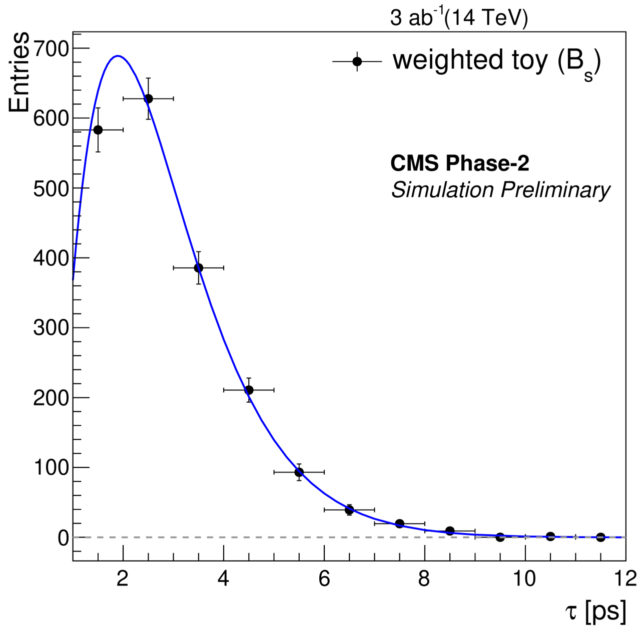
$\epsilon[-1,+1]$ in NP

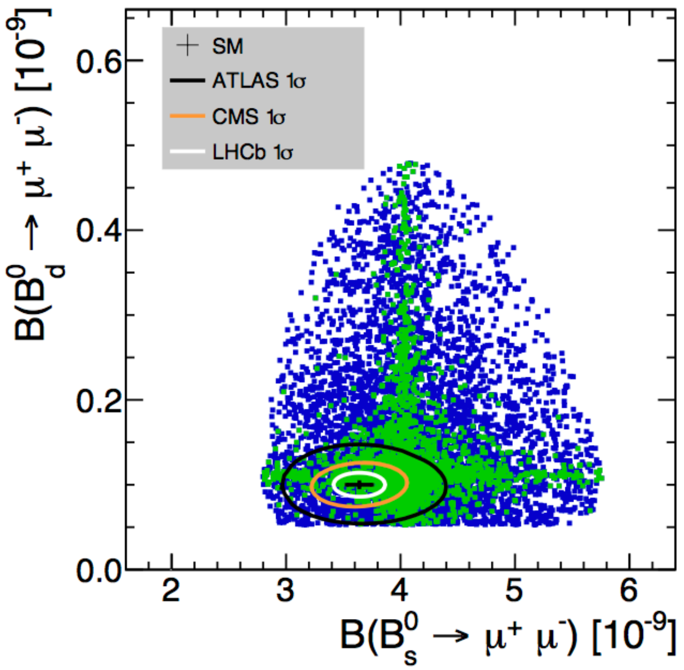




- first measurements by LHCb & CMS
  - current precision (22%) still insufficient
- HL-LHC projections (by LIP):
  - B_s: $\tau_{\mu\mu}$(2-3%), B^0: observation

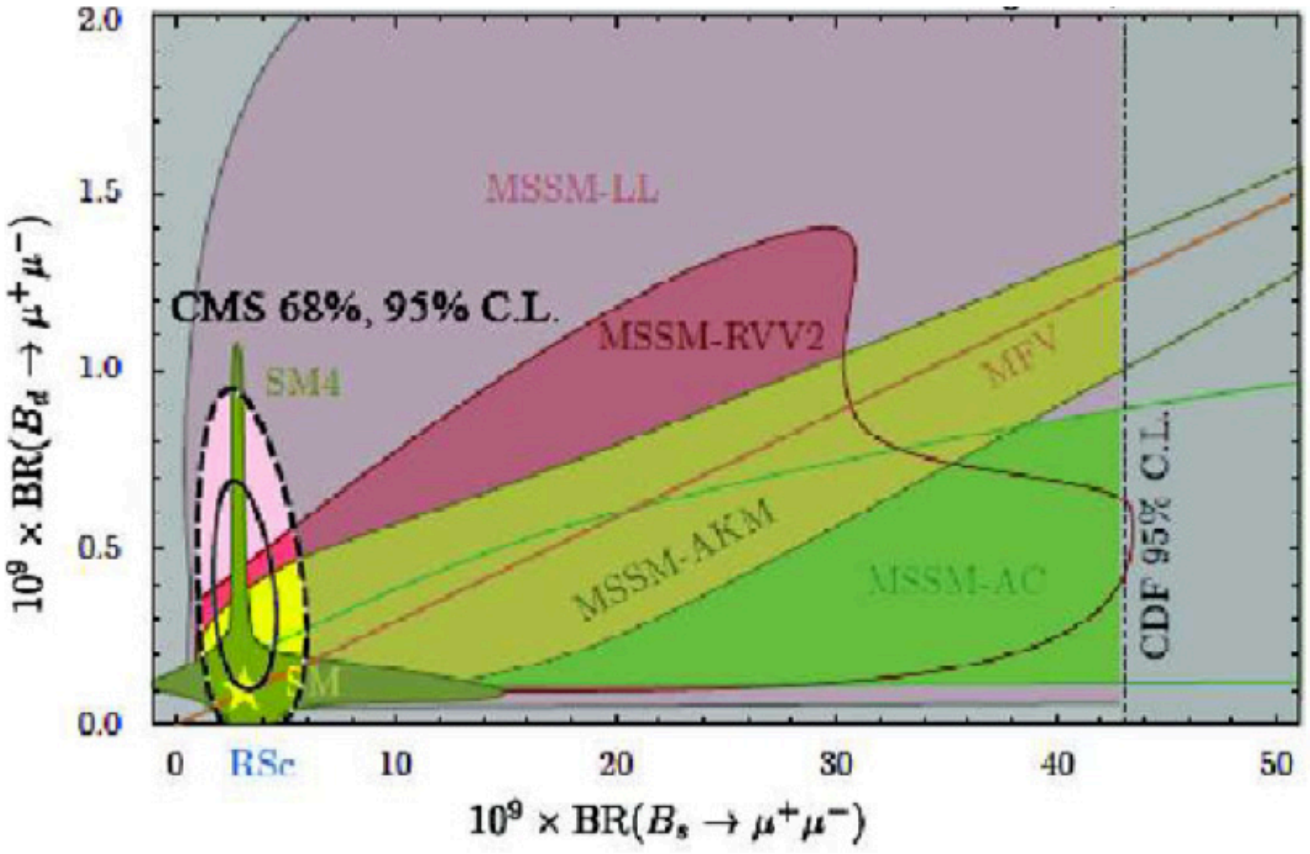






NP constraints

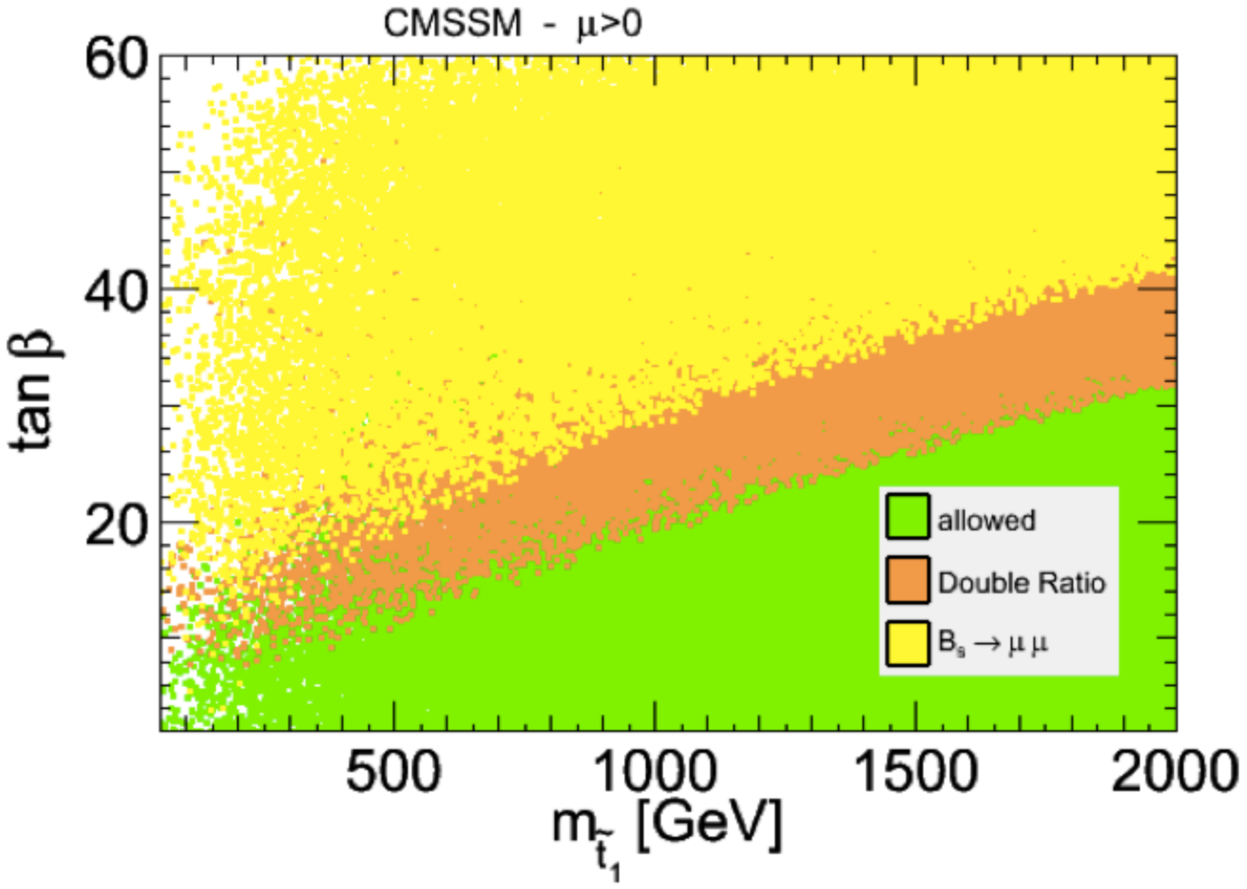
- Measurement results in strong constraints to the parameter space of certain classes of NP models; some specific examples:



D. Straub et al, arXiv:1012.3893

Constraints on MSSM (incl. models with abelian/non-abelian flavor symmetries), 4th generation, RS, and MFV models

JHEP 0903 (2009) 108, JHEP 1009 (2010) 106
JHEP 06 (2008) 068 ,Nucl.Phys.B831 (2010) 26

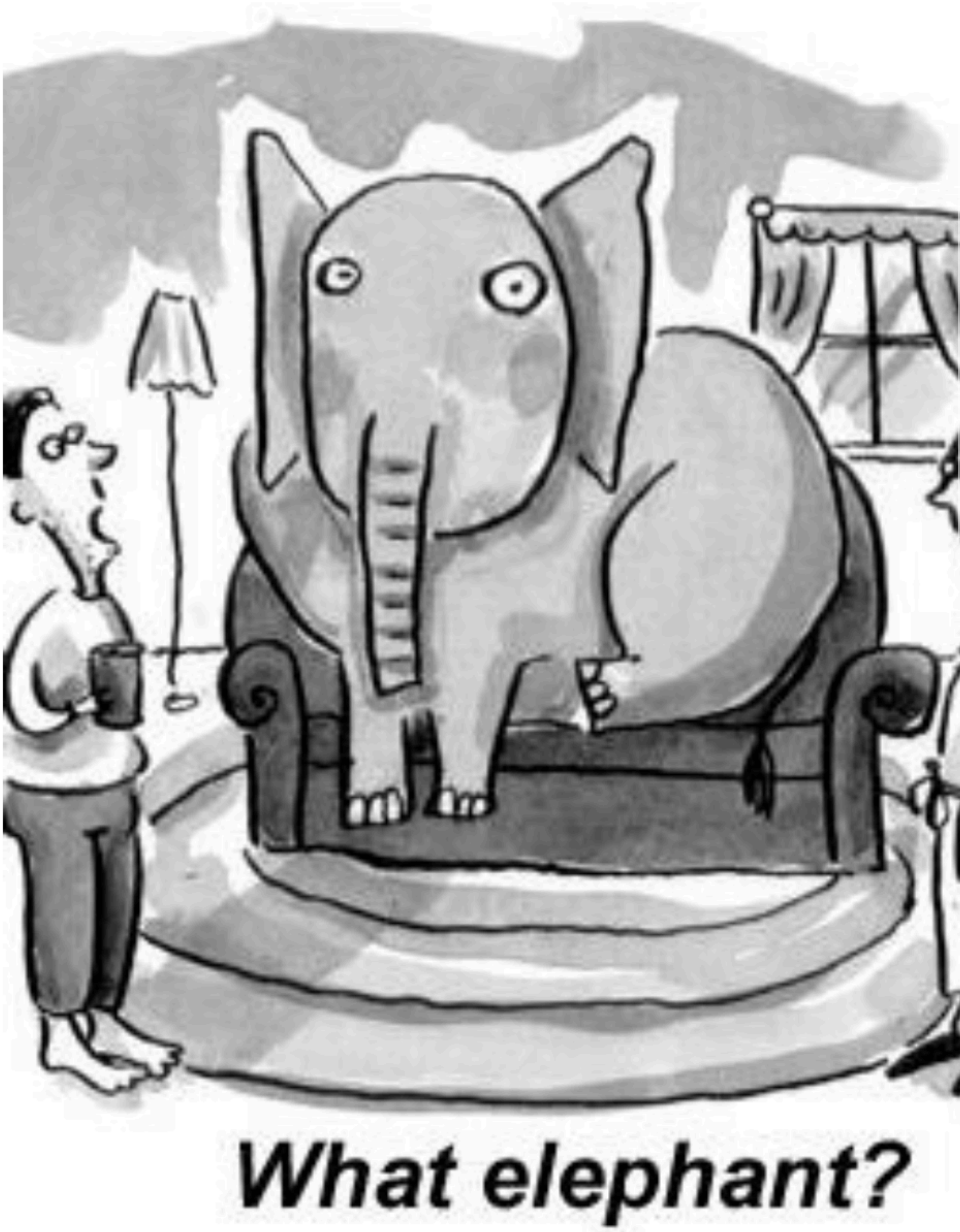


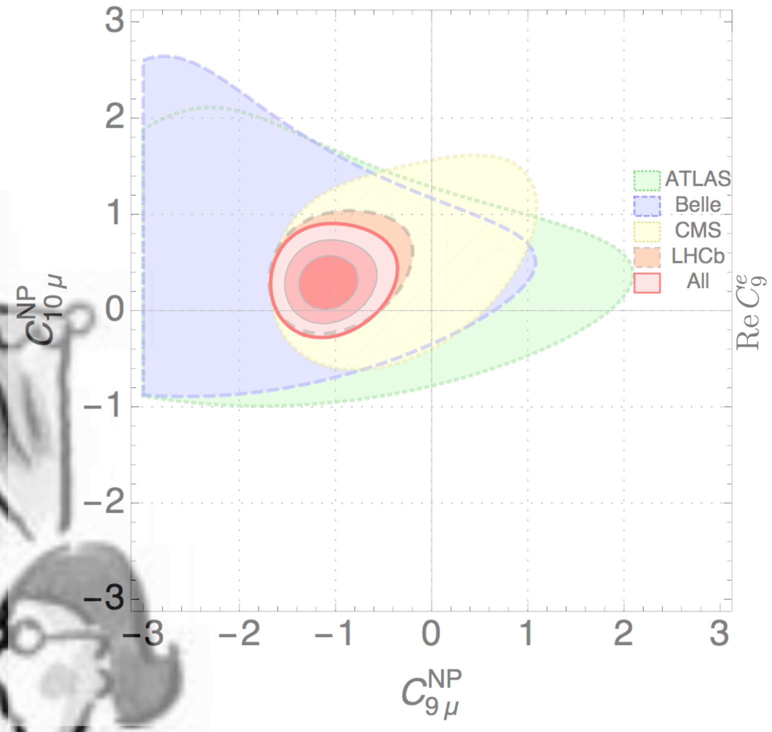
A. Akeroyd et al, JHEP 1112 (2011) 088

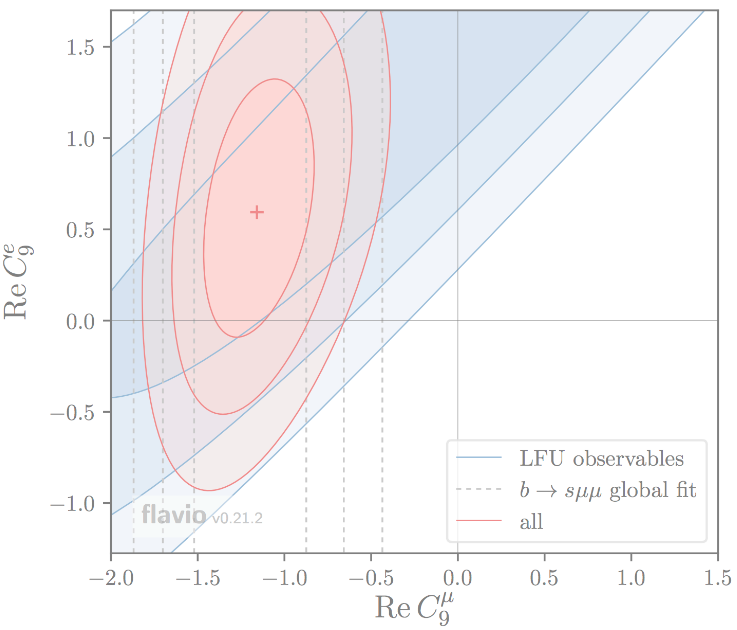
Constraints on CMSSM, in the case of a SM-like $B_s \to \mu\mu$

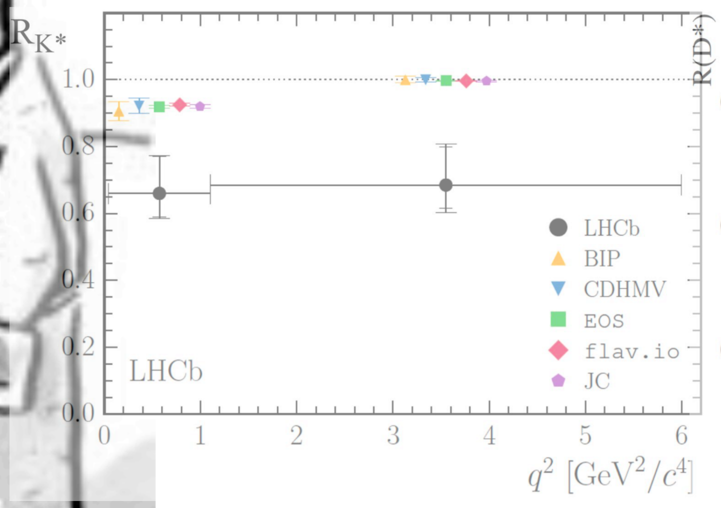
Anomalies!

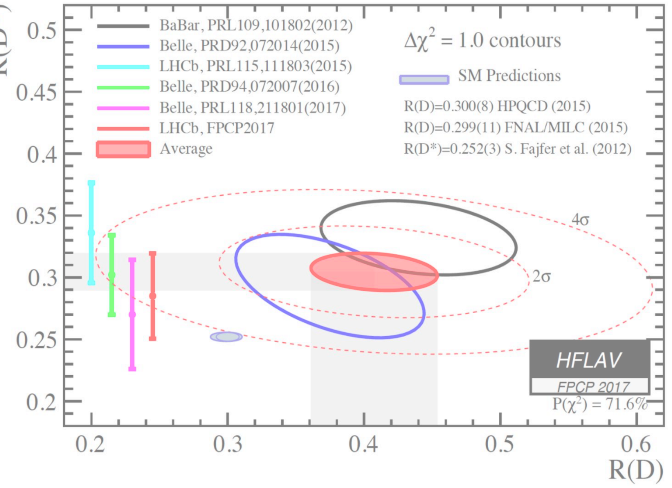
LHC data (so far) show no definite signal of NP ··· but there's an elephant in the room !



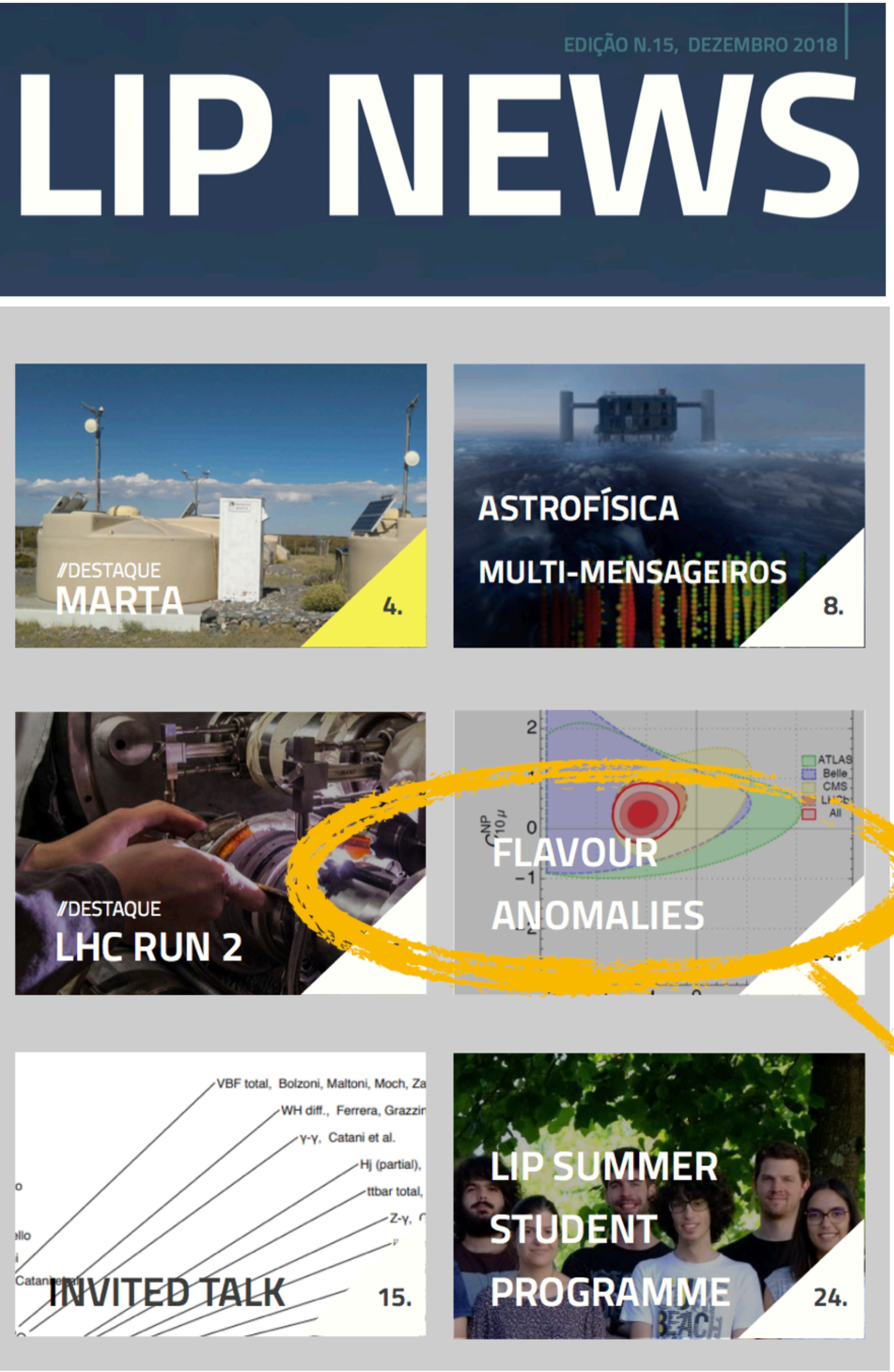








Taken together, the **flavor anomalies** are most significant deviation from SM, and the **strongest indication of NP** in current collider data **!**



EDIÇÃO N.15, DEZEMBRO 2018

LIP NEWS

/DESTAQUE
MARTA
4.

ASTROFÍSICA
MULTI-MENSAGEIROS
8.

/DESTAQUE
LHC RUN 2

FLAVOUR
ANOMALIES

INVITED TALK
15.

LIP SUMMER
STUDENT
PROGRAMME
24.

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.

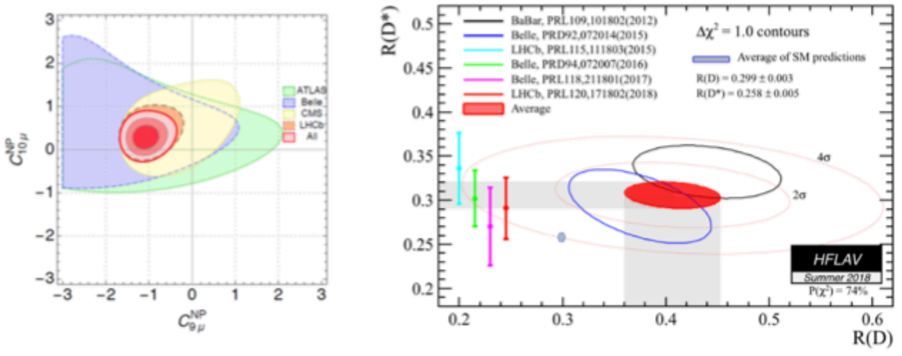
The neutral-current transitions, b→sll, are realised in various rare B decays, both leptonic, e.g. $B_s \to \mu^+\mu^-$, and semileptonic, e.g. $B \to S\mu^+\mu^-$, where S stands for a strange-[illegible]ark hadron (e.g. K, K*, Φ, Λ). [illegible]n addition to d[illegible] the latter class o[illegible]s many NP-sensitive obse[illegible] associa[illegible] to the angular distributions of the d[illegible] products. Deviations are detect[illegible] 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.

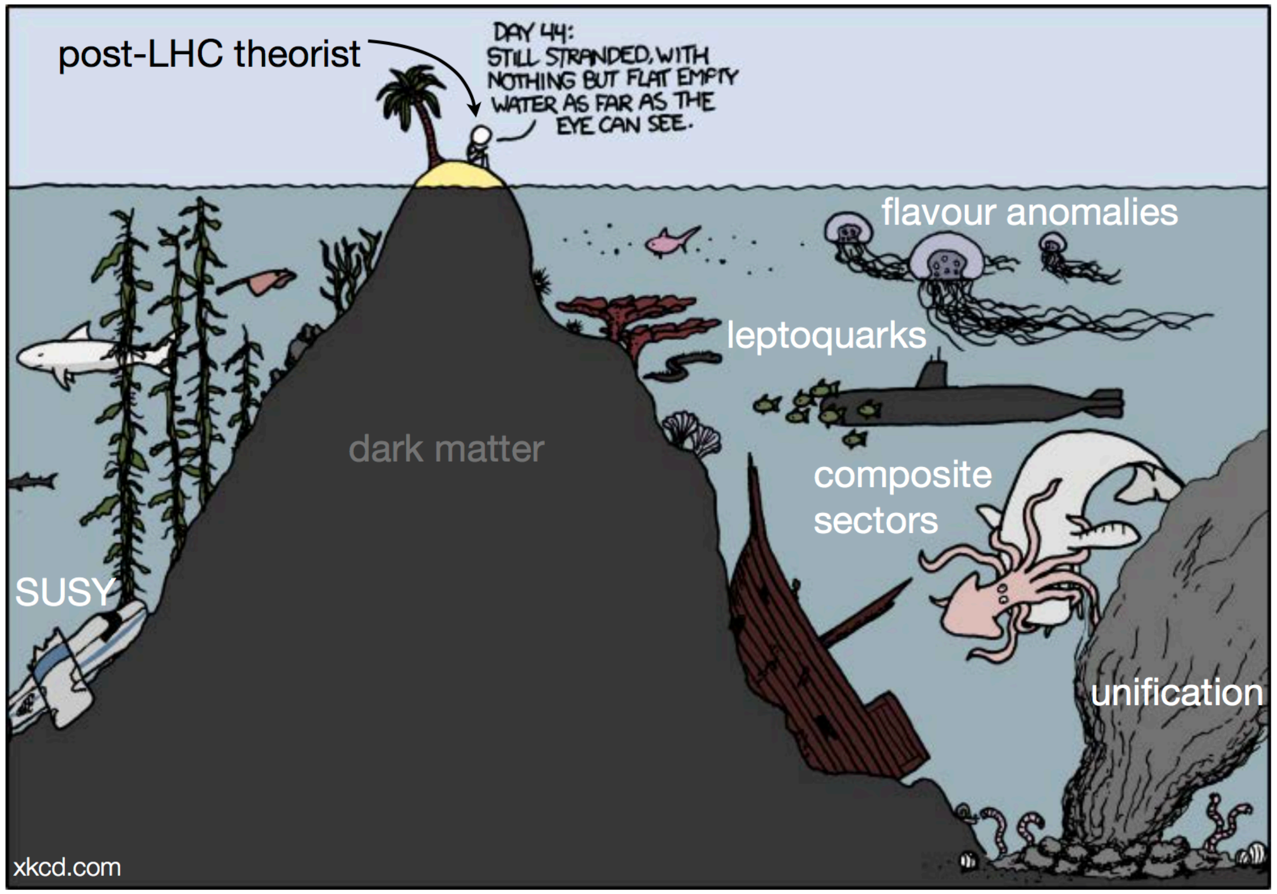
From the experimental side, a clarification will be sought by thoroughly exploiting the LHC Run 2 data. Not only will the LHCb measurements be repeated to reach increased precision, contributions from ATLAS and CMS will offer independent input with orthogonal systematics. For example, during 2018 a large, 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.

Thanks for taking part!



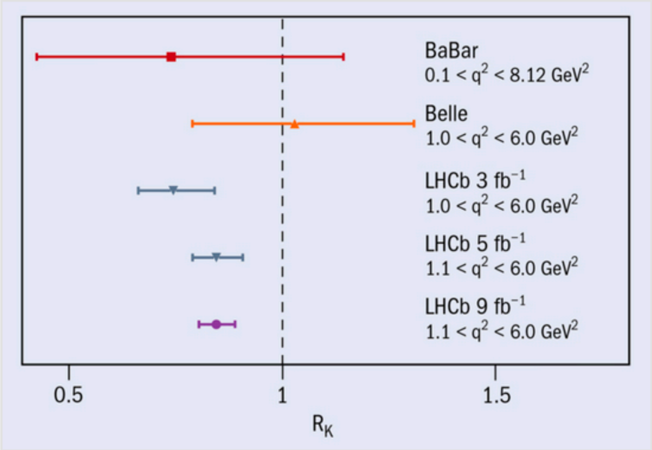
taken from: NL's conference summary talk at BEACH'18, final slide

FLAVOUR PHYSICS | **NEWS**

New data strengthens R_K flavour anomaly

23 March 2021

A report from the LHCb experiment



Comparison between R_K measurements In addition to the LHCb result, the measurements by the BaBar and Belle collaborations, which combine $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K_S{}^0\ell^+\ell^-$ decays, are also shown. Credit: LHCb

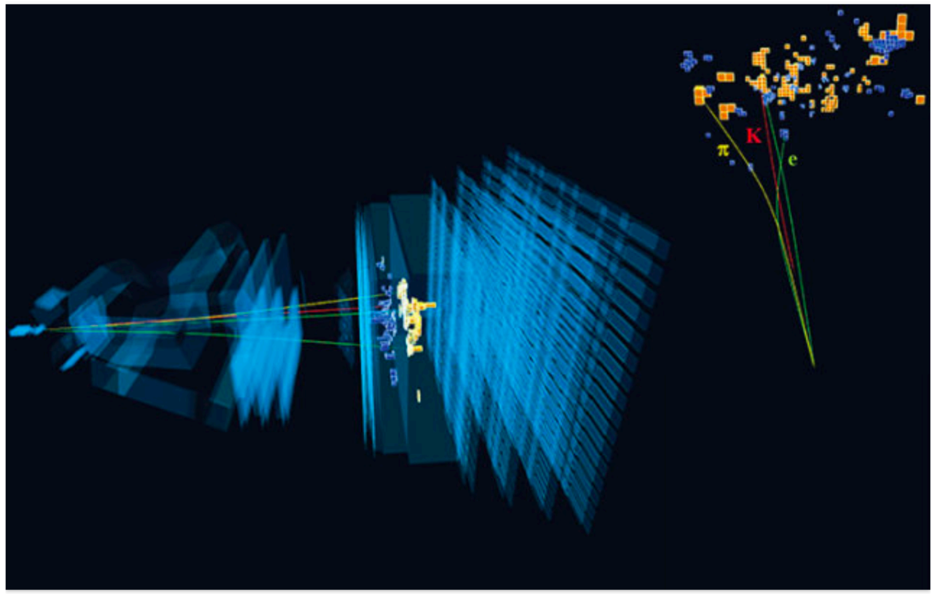
The principle that the charged leptons have identical electroweak interaction strengths is a distinctive feature of the Standard Model (SM). However, this lepton-flavour universality (LFU) is an accidental symmetry in the SM, which may not hold in theories beyond the SM (CERN Courier May/June 2019 p33). The LHCb collaboration has used a number of rare decays mediated by flavour-changing neutral currents, where the SM

March'2021
@CERN

Intriguing new result from the LHCb experiment at CERN

The LHCb results strengthen hints of a violation of lepton flavour universality

23 MARCH, 2021



Very rare decay of a beauty meson involving an electron and positron observed at LHCb (Image: CERN)

FLAVOUR PHYSICS | **FEATURE**

The flavour of new physics

8 May 2019

Recent experimental results hint that some electroweak processes are not lepton-flavour independent, contrary to Standard Model expectations. If the effect strengthens as more data are gathered, possible explanations range from new gauge forces to leptoquarks.

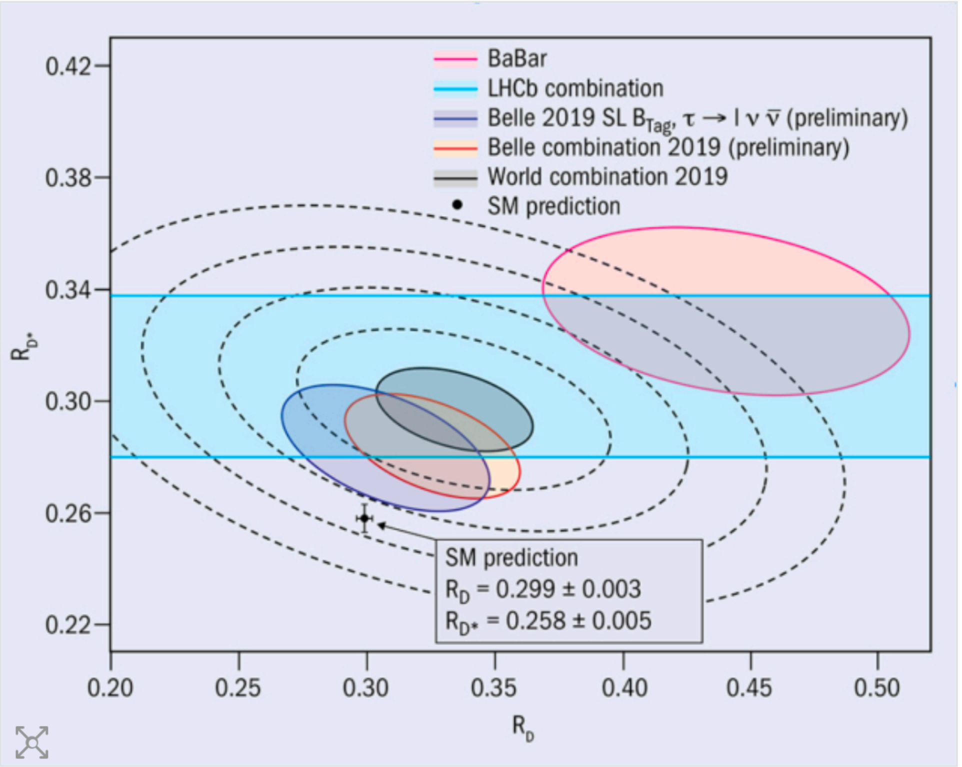
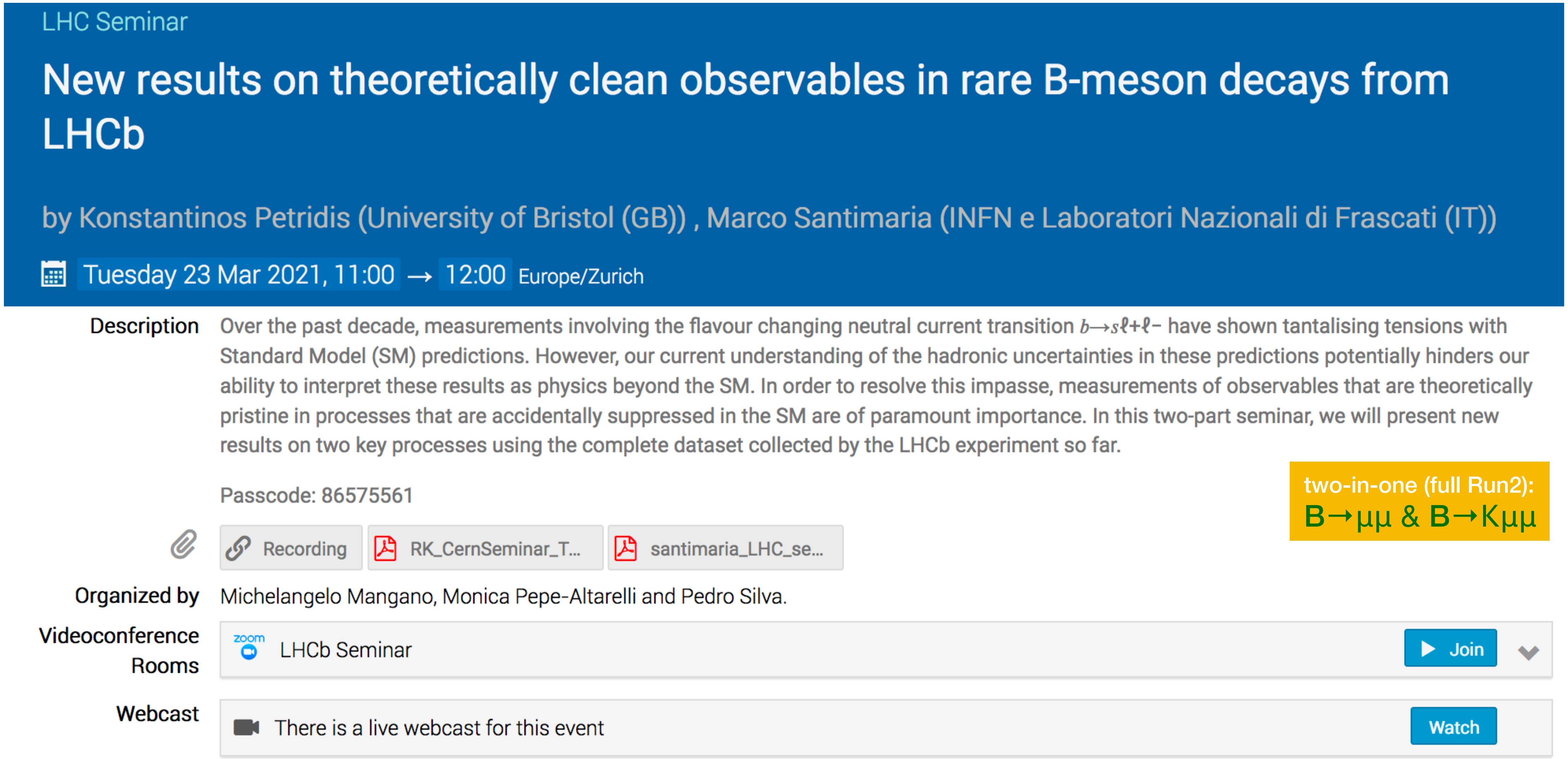


Fig. 2. Experimental results for the two observables probing lepton-flavour universality comparing $b \to c\tau^-\bar{\nu}_\tau$ and $b \to c l^-\bar{\nu}_l$ decays, $l = e, \mu$. The point with error bars shows the SM prediction, while the shaded grey region shows the world experimental results average.



LHC Seminar

New results on theoretically clean observables in rare B-meson decays from LHCb

by Konstantinos Petridis (University of Bristol (GB)) , Marco Santimaria (INFN e Laboratori Nazionali di Frascati (IT))

Tuesday 23 Mar 2021, 11:00 → 12:00 Europe/Zurich

Description Over the past decade, measurements involving the flavour changing neutral current transition $b \to s \ell^+ \ell^-$ have shown tantalising tensions with Standard Model (SM) predictions. However, our current understanding of the hadronic uncertainties in these predictions potentially hinders our ability to interpret these results as physics beyond the SM. In order to resolve this impasse, measurements of observables that are theoretically pristine in processes that are accidentally suppressed in the SM are of paramount importance. In this two-part seminar, we will present new results on two key processes using the complete dataset collected by the LHCb experiment so far.

Passcode: 86575561

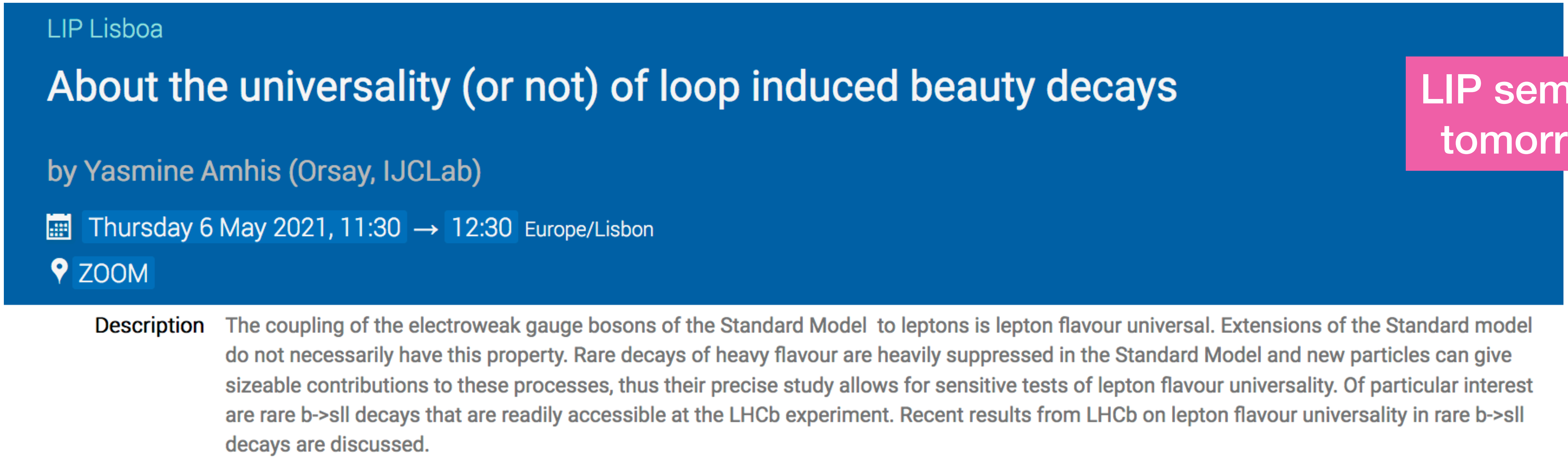
Organized by Michelangelo Mangano, Monica Pepe-Altarelli and Pedro Silva.

Videoconference Rooms LHCb Seminar

Webcast There is a live webcast for this event

two-in-one (full Run2): $B \to \mu\mu$ & $B \to K\mu\mu$

https://indico.cern.ch/event/976688/



LIP Lisboa

About the universality (or not) of loop induced beauty decays

by Yasmine Amhis (Orsay, IJCLab)

Thursday 6 May 2021, 11:30 → 12:30 Europe/Lisbon

ZOOM

Description The coupling of the electroweak gauge bosons of the Standard Model to leptons is lepton flavour universal. Extensions of the Standard model do not necessarily have this property. Rare decays of heavy flavour are heavily suppressed in the Standard Model and new particles can give sizeable contributions to these processes, thus their precise study allows for sensitive tests of lepton flavour universality. Of particular interest are rare b->sll decays that are readily accessible at the LHCb experiment. Recent results from LHCb on lepton flavour universality in rare b->sll decays are discussed.

LIP seminar tomorrow

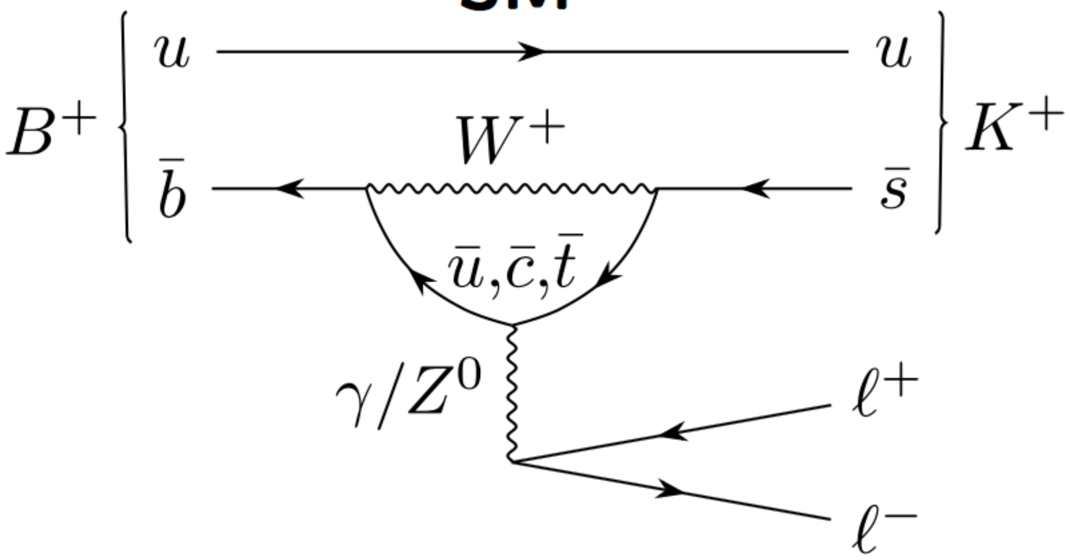
https://indico.lip.pt/event/901/

the ‘flavour anomalies’

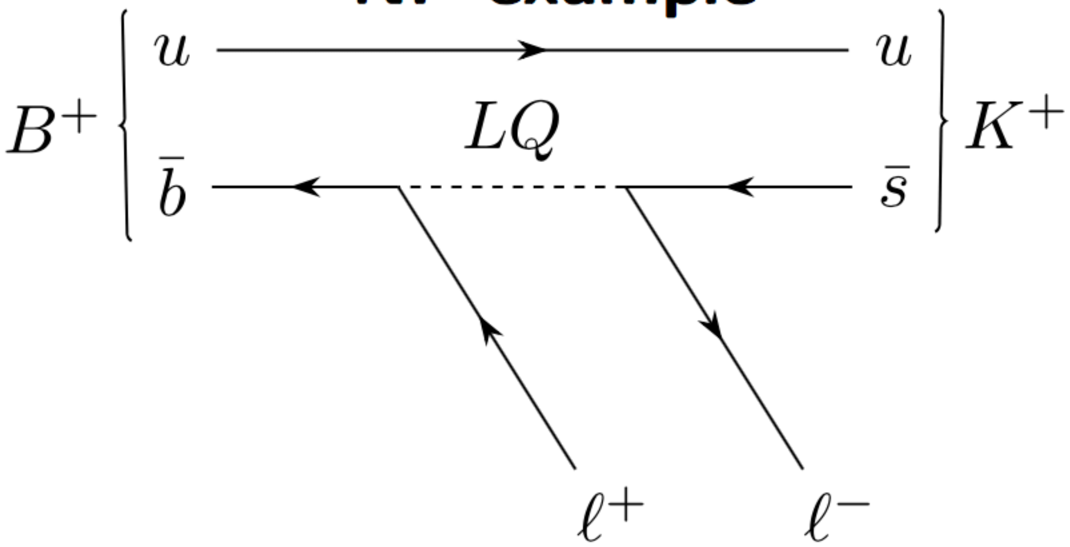
$b \to s\, ll$ anomalies	**$b \to c\, l\nu$ anomalies**
Found by LHCb (and perhaps hinted by Belle)	Found by several experiments (LHCb, BaBar and Belle)
Many observables: global pattern	Two observables: R(D) and R(D*)
Neutral current	Charged current
1-loop (and CKM-suppressed) in the SM	Tree-level in the SM
The New Physics can be heavy	The New Physics must be light

b→sll | B → K(*) ll

SM



NP example



quark level

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

complementary!

hadron level

$$B_s^0 \to \ell^+\ell^-$$

$$B^+ \to K^+\ell^+\ell^-,\ B^0 \to K^{*0}\ell^+\ell^-,\ B_s \to \phi\mu^+\mu^-,\ \Lambda_b \to \Lambda^*\ell^+\ell^- \ldots$$

b→sll anomalies

In $b \to s\ell^+\ell^-$ transitions (FCNC)

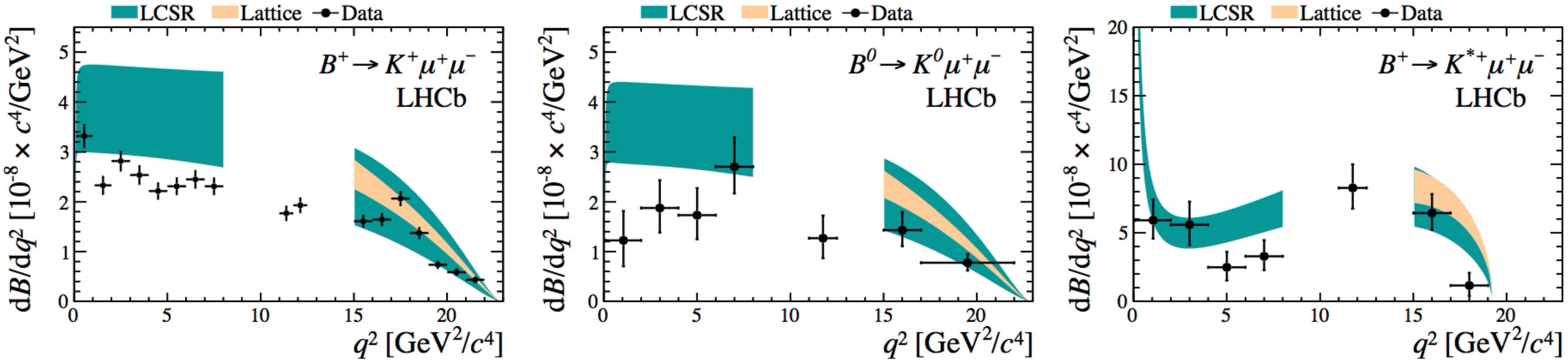
1. **Branching Fractions**
   $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$

2. **Angular analyses**
   $B \to K^{(*)}\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$

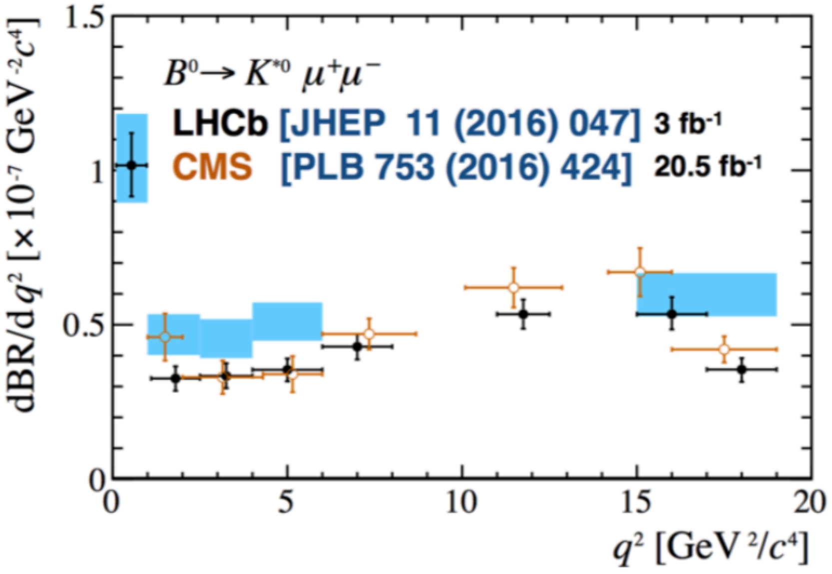
3. **Lepton Flavour Universality involving μ/e ratios**
   $B^0 \to K^{*0}\ell^+\ell^-$, $B^+ \to K^+\ell^+\ell^-$

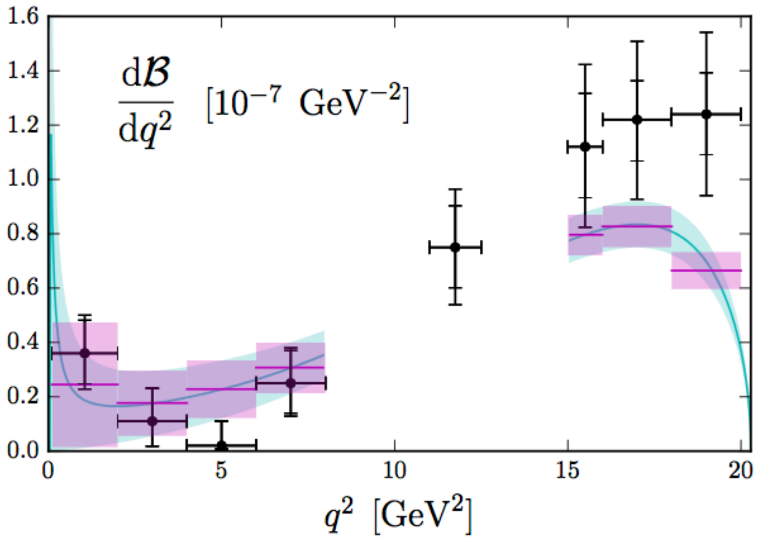
b→sμμ | decay rates (BF)

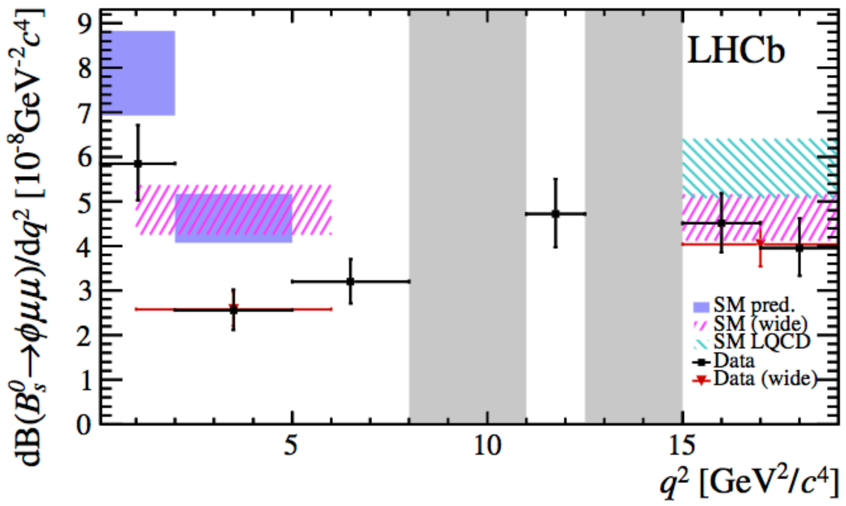
[JHEP06(2014)133]

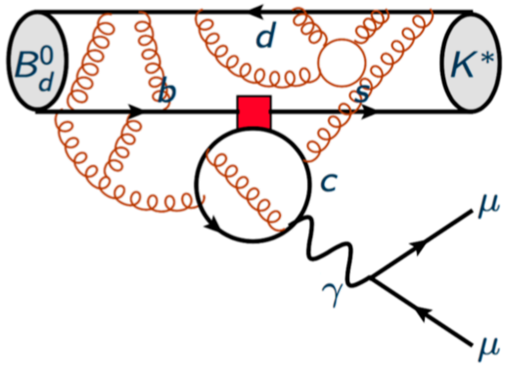


$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



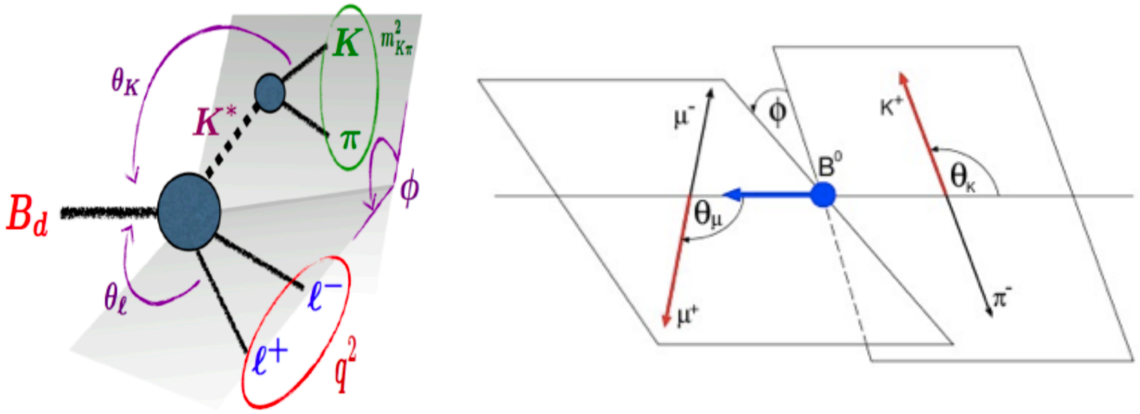






measurements tend to appear below theory, at low q2
SM predictions affected by large hadronic uncertainties

angular analysis



- fitting the data

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

⬅ Correctly tagged

⬅ Mistagged (K↔π)

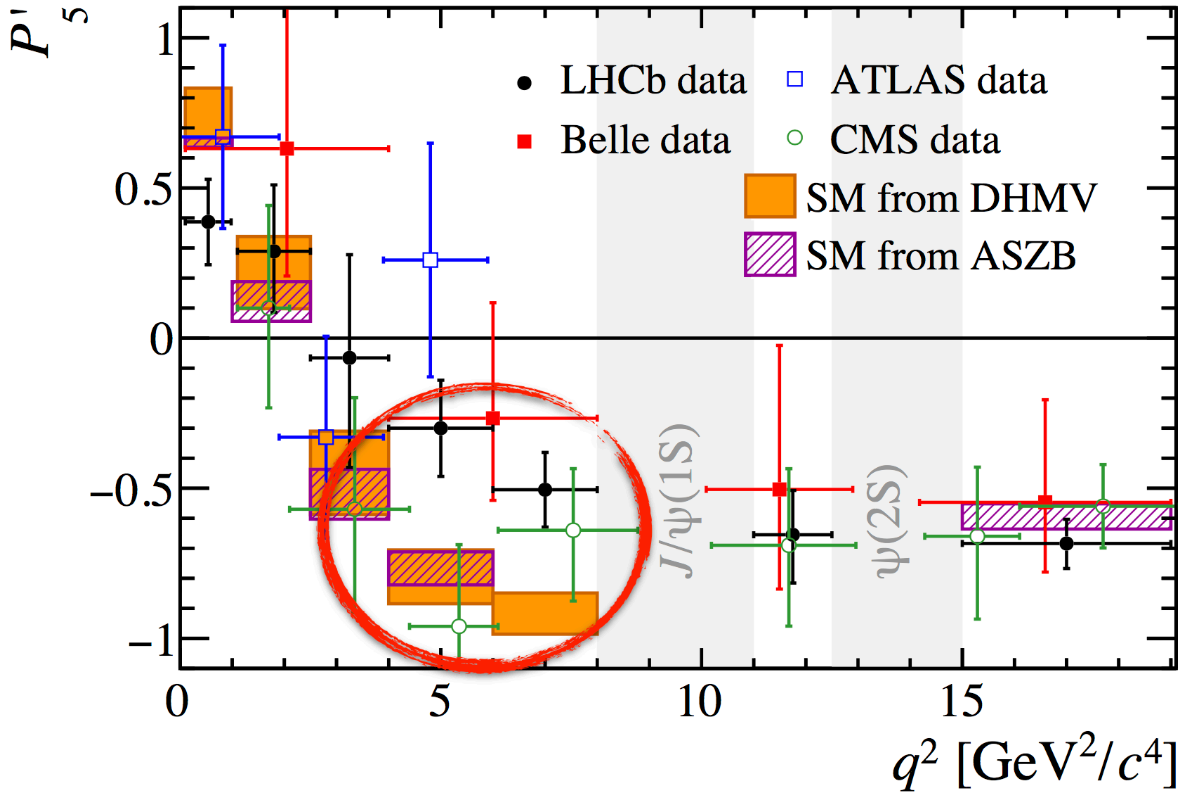
⬅ Background

- signal likelihood:

$$\begin{aligned}\frac{1}{{\rm d}\Gamma/{\rm d}q^2} \frac{{\rm d}^4\Gamma}{{\rm d}q^2 {\rm d}\cos\theta_l {\rm d}\cos\theta_{\rm K} {\rm d}\phi} = \frac{9}{8\pi} \Bigg\{ & \frac{2}{3} \Big[(F_{\rm S} + A_{\rm S} \cos\theta_{\rm K}) \left(1 - \cos^2\theta_l\right) + A_{\rm S}^5 \sqrt{1 - \cos^2\theta_{\rm K}} \sqrt{1 - \cos^2\theta_l} \cos\phi \Big] \\ & + (1 - F_{\rm S}) \Big[2F_{\rm L} \cos^2\theta_{\rm K} \left(1 - \cos^2\theta_l\right) + \frac{1}{2}(1 - F_{\rm L}) \left(1 - \cos^2\theta_{\rm K}\right) \left(1 + \cos^2\theta_l\right) \\ & + \frac{1}{2} P_1 (1 - F_{\rm L})(1 - \cos^2\theta_{\rm K})(1 - \cos^2\theta_l) \cos 2\phi \\ & + 2 P_5' \cos\theta_{\rm K} \sqrt{F_{\rm L} (1 - F_{\rm L})} \sqrt{1 - \cos^2\theta_{\rm K}} \sqrt{1 - \cos^2\theta_l} \cos\phi \Big] \Bigg\}\end{aligned}$$

$b \to s\mu\mu$ | angular analysis (P_5')

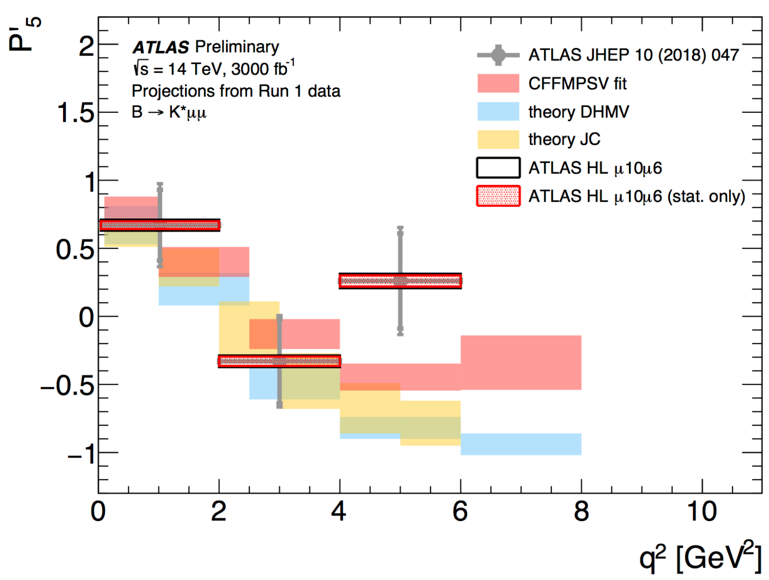
- $B \to X\mu\mu$ decays offer NP-sensitive observables, complementary to $B \to \mu\mu$
  - accessible through angular analyses
  - studied at Belle, BaBar, CDF, LHC
- deviation from theory found by LHCb
  - in the angular observable P'_5 in the $B^0 \to K^*\mu\mu$ (and $B^+ \to K^*\mu\mu$) decay
 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

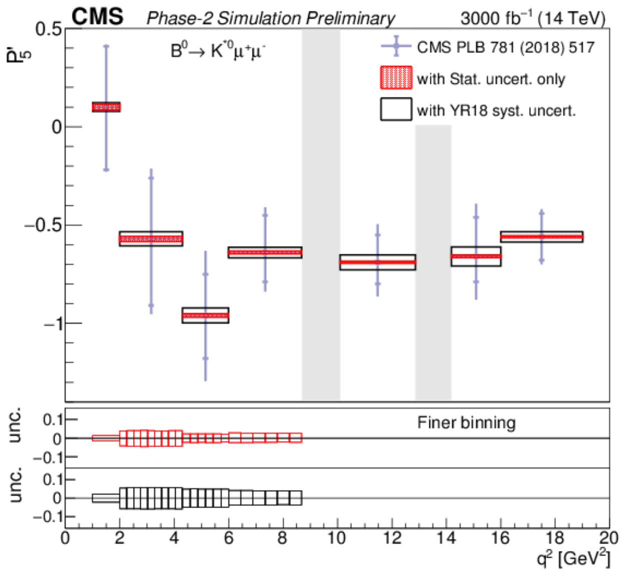


1512.04442, 1612.05014, 1710.02846, 1805.04000

- sensitive to SM precision
- projections
  - upcoming data will allow to independently clarify deviation

[HL-LHC PROJECTIONS]



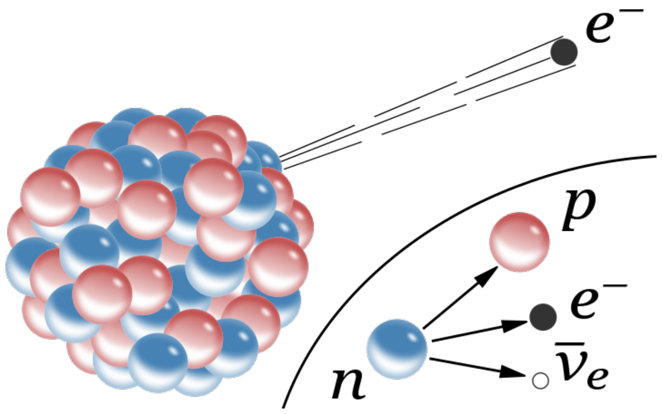


1902.10229

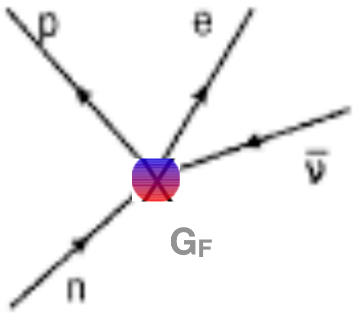
EFT

energy scale $m_{Z,W}$ m_H m_t Λ_{NP}

1930 . . . 1970 2012 2020 . . . future

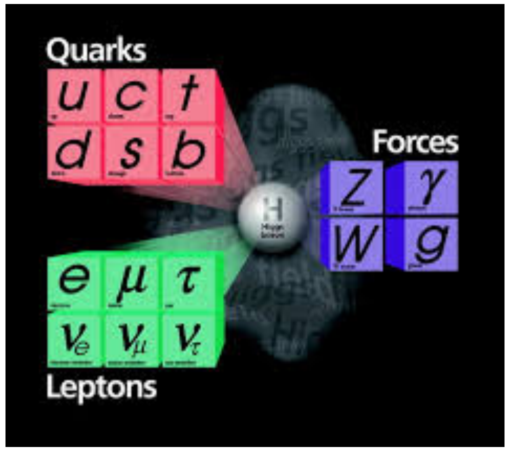


Fermi model

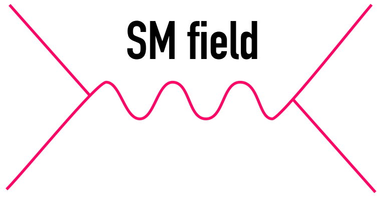


$$\mathcal{L}_{\text{Fermi}} = -\frac{G_F}{\sqrt{2}}\bar{p}\gamma_\mu n\,\bar{e}\gamma^\mu\nu + \text{h.c.}$$

a predecessor
of EWK theory

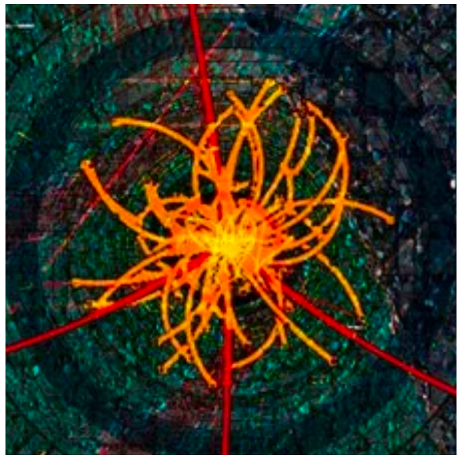


Standard Model

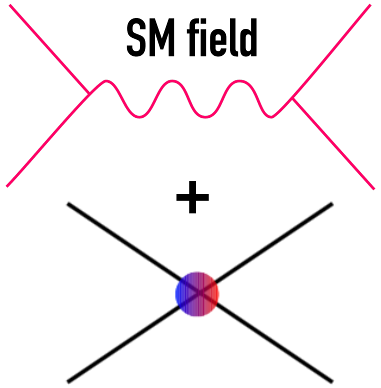


$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{higgs}}$

simple and elegant theory
describing *almost* all
microscopic phenomena

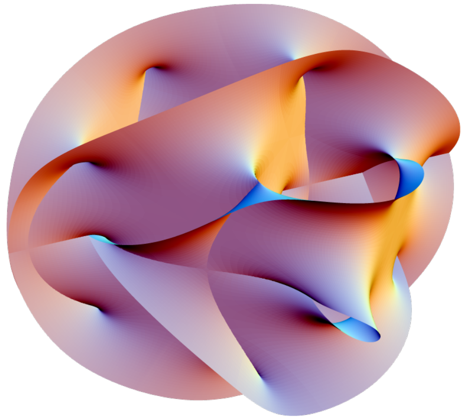


SM-EFT

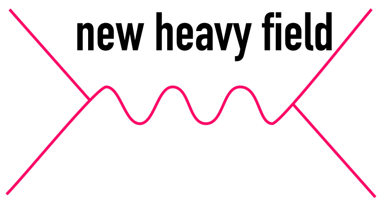


$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}}$
$+ \Sigma_i C_i O_i$

we're here!

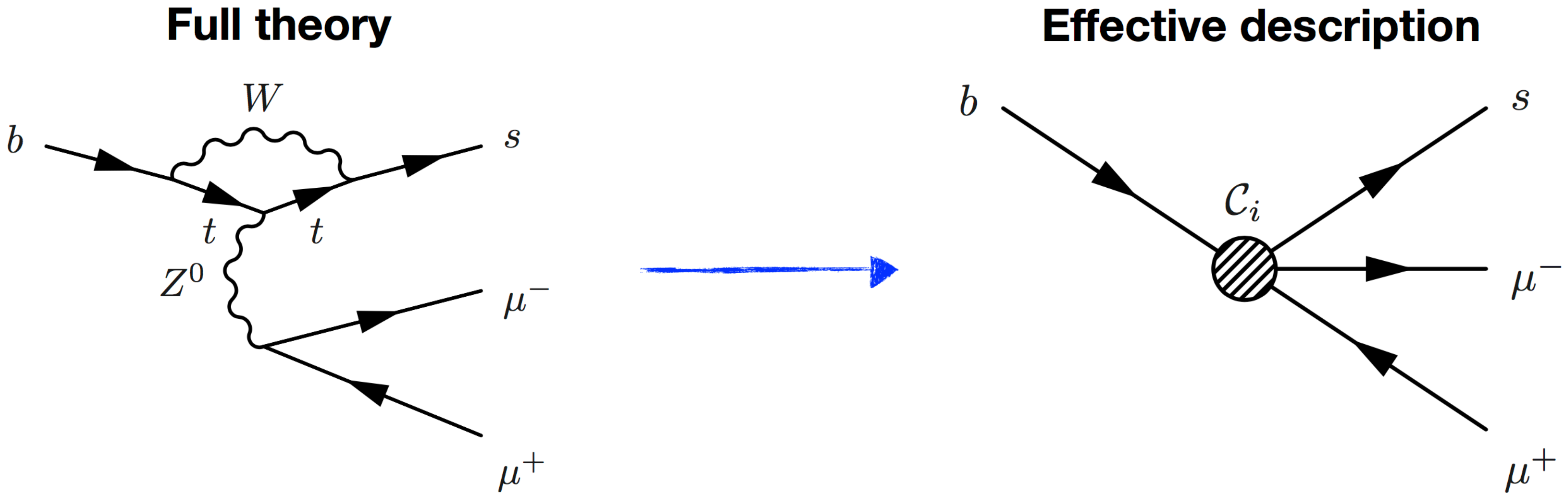


UV theory



a more fundamental
theory with new
degrees of freedom

b→sll | Effective Field Theory



Full theory

Effective description

- "point-like interaction" as in the Fermi description of the neutron decay

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{CKM} C_i(\lambda) \mathcal{O}_i(\lambda)$$

- Wilson coefficients (short-distance): evaluated in perturbation theory
- Local operators (long-distance): the corresponding form factor is computed with, e.g., lattice QCD

- NP can alter $C_i^{(\prime)}$ but also introduce new operators

$$\Delta\mathcal{H}_{\mathrm{NP}} = \frac{c_i}{\Lambda^2_{\mathrm{NP}}} \mathcal{O}_i$$

Precision measurements go well beyond collision energies!

b→sll | Effective Field Theory

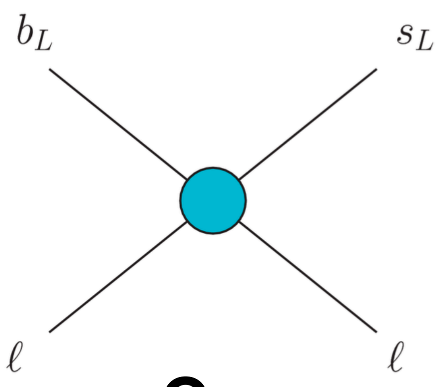
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i (C_i\mathcal{O}_i + C_i'\mathcal{O}_i') + \text{h.c.}$$

C_i : Wilson coefficients $\mathcal{O}_i$: Operators

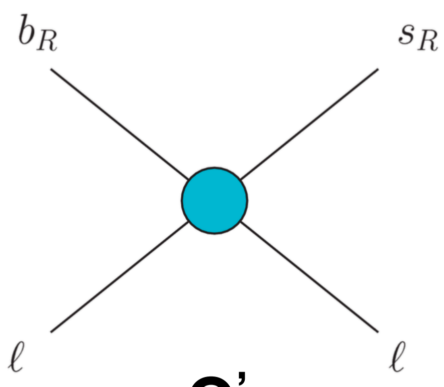
$$\mathcal{O}_7 = (\bar{s}\sigma_{\mu\nu}P_R b)\, F^{\mu\nu} \qquad \mathcal{O}_7' = (\bar{s}\sigma_{\mu\nu}P_L b)\, F^{\mu\nu}$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\, (\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)\, (\bar{\ell}\gamma^\mu \ell)$$

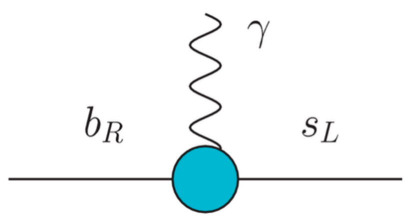
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\, (\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)\, (\bar{\ell}\gamma^\mu \gamma_5 \ell)$$



O₉



O'₉



O₇

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

calculable what we want to know

b→sll | 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) ------------------ $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

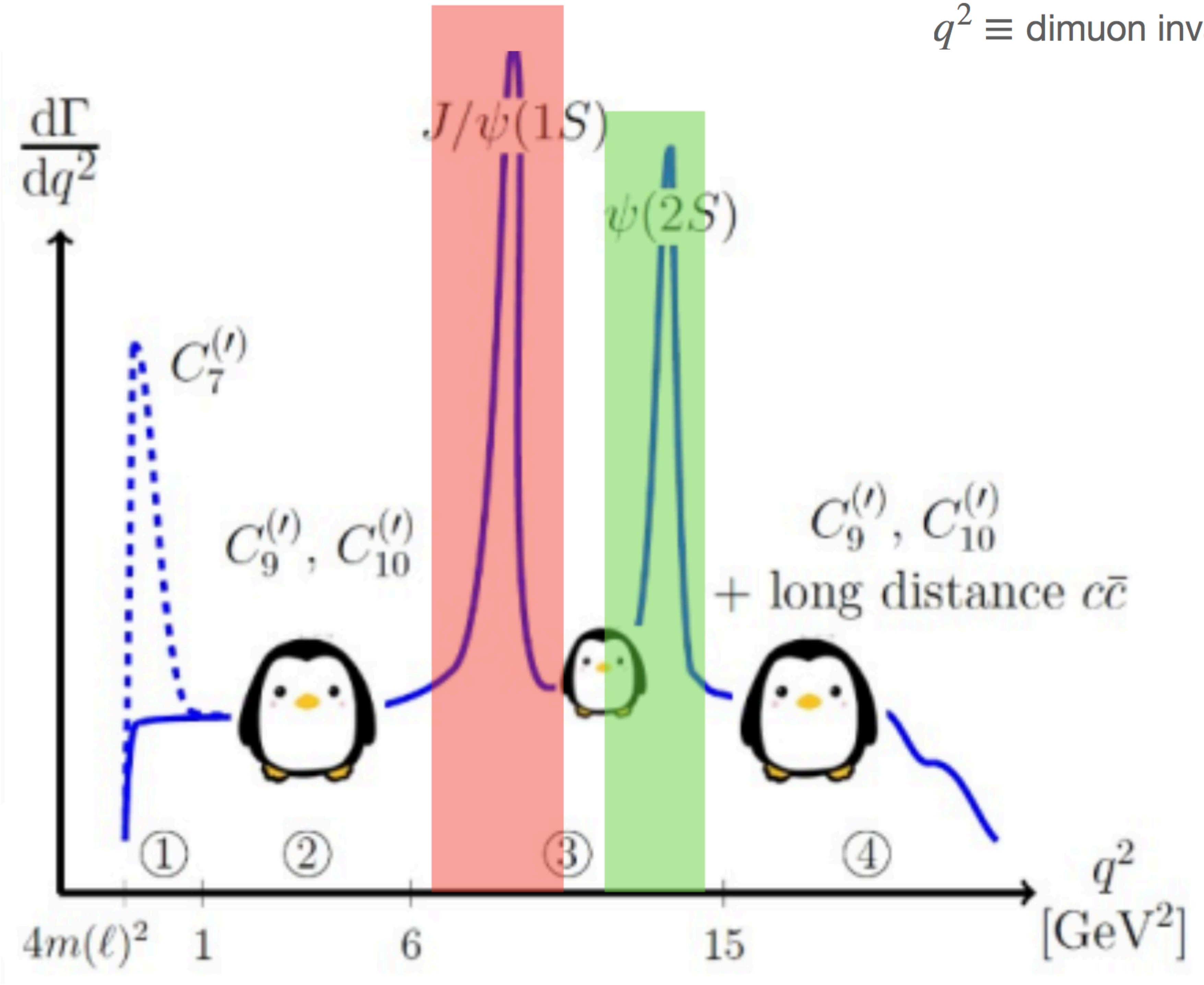
$B \to K^*\ell^+\ell^-$ (dBR/dq², angular obs.) --- $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

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

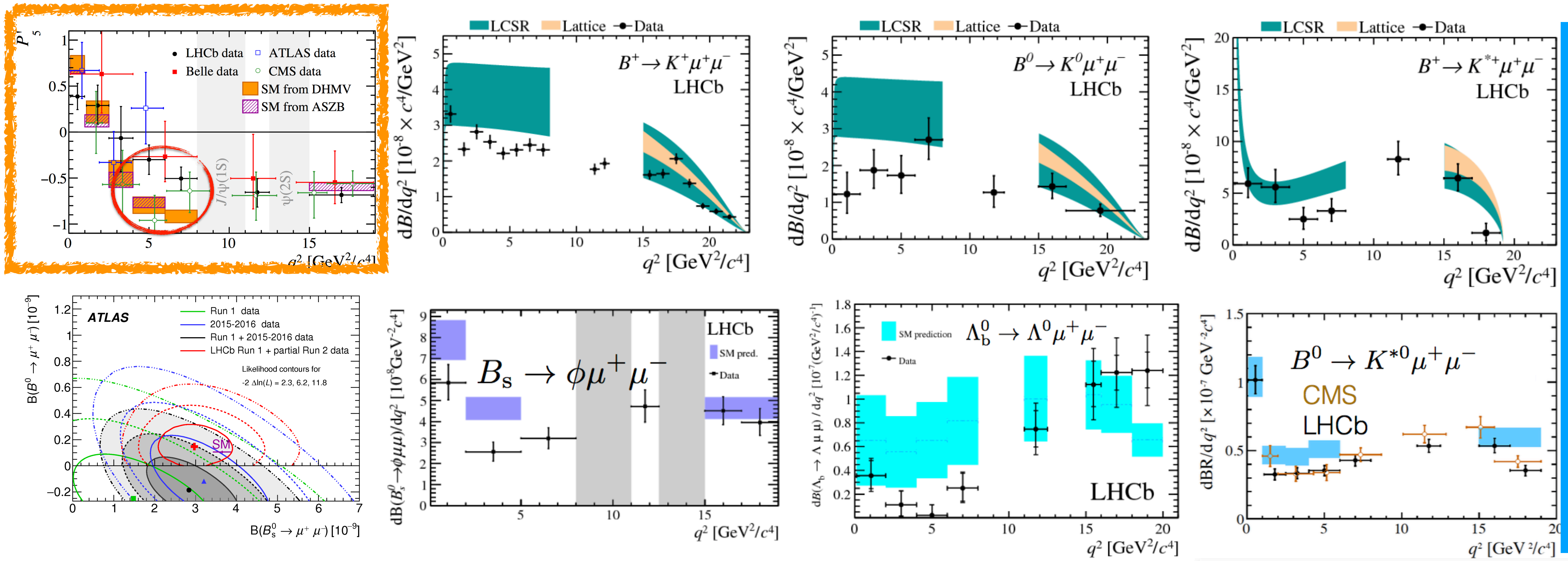
The same Wilson coefficients enter several observables $\Rightarrow$ A pattern of deviations rather than a single anomaly $\Rightarrow$ **Global fit**

q^2 dependence

$q^2 \equiv$ dimuon invariant mass squared



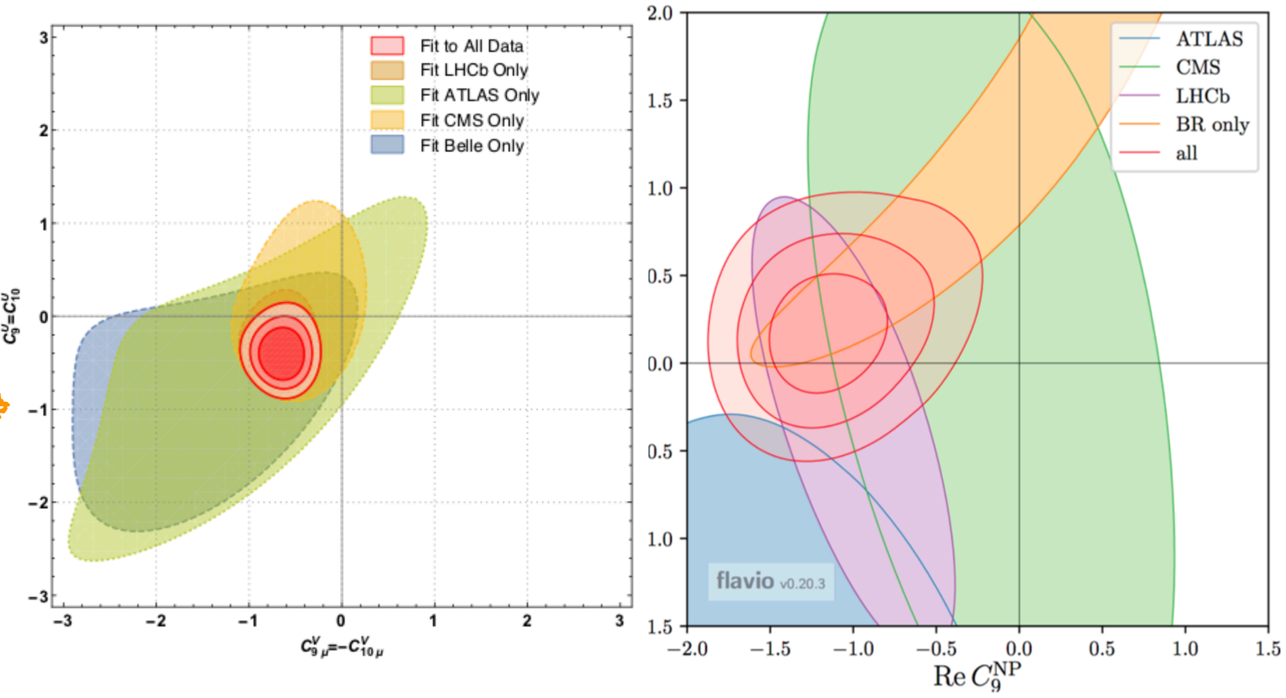
b→sμμ | global fits



Experimental measurements

SM - Effective Field Theory

$$\mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{SM}} + \Sigma_i C_i O_i$$



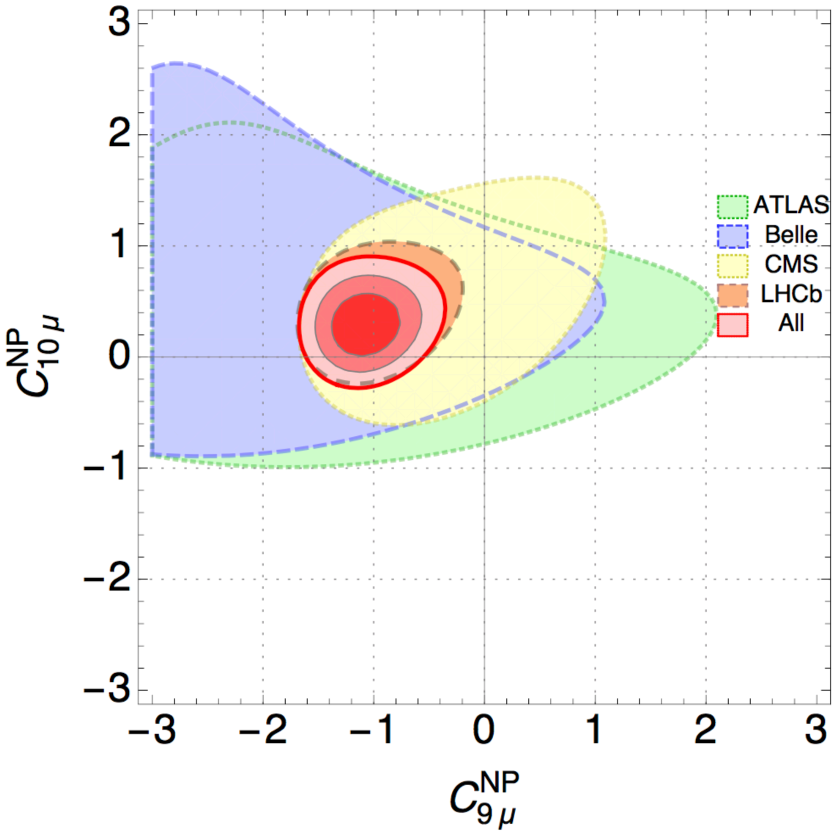
Theory space

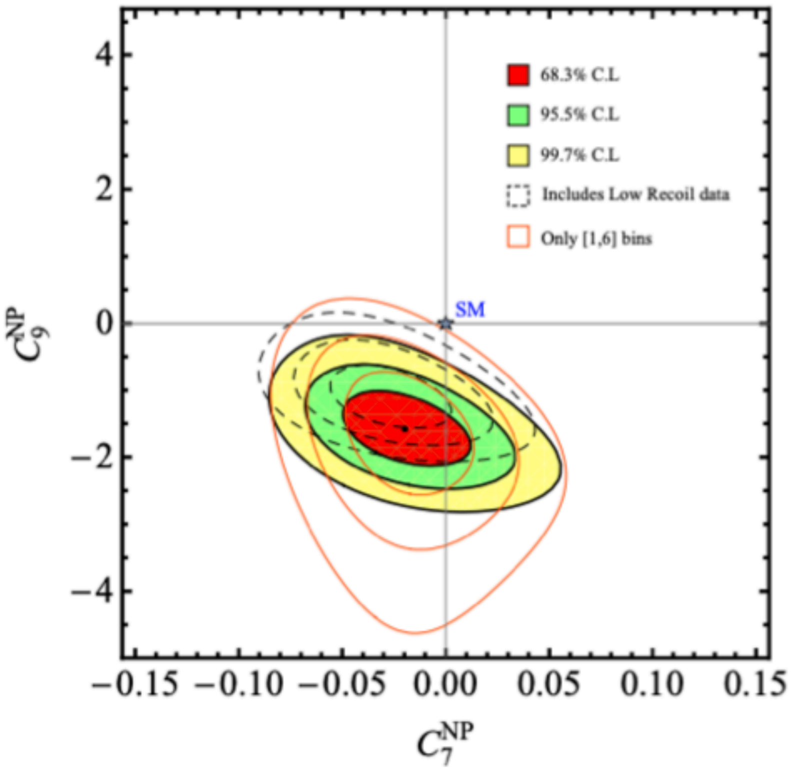
b→sμμ | global fit

1D

Coefficient	type	best fit	1σ	$\text{pull}_{\text{1D}} = \sqrt{\Delta\chi^2}$
$\boldsymbol{C_9^{bs\mu\mu}}$	$\boldsymbol{L \otimes V}$	-0.97	$[-1.11, -0.83]$	$\boldsymbol{6.4\sigma}$
$C_9^{\prime bs\mu\mu}$	$R \otimes V$	$+0.14$	$[-0.04, +0.29]$	0.7σ
$\boldsymbol{C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes A}$	$+0.72$	$[+0.59, +0.85]$	$\boldsymbol{5.8\sigma}$
$C_{10}^{\prime bs\mu\mu}$	$R \otimes A$	-0.18	$[-0.29, -0.07]$	1.7σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$L \otimes R$	$+0.16$	$[+0.03, +0.30]$	1.2σ
$\boldsymbol{C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}}$	$\boldsymbol{L \otimes L}$	-0.54	$[-0.61, -0.46]$	$\boldsymbol{6.9\sigma}$

2D





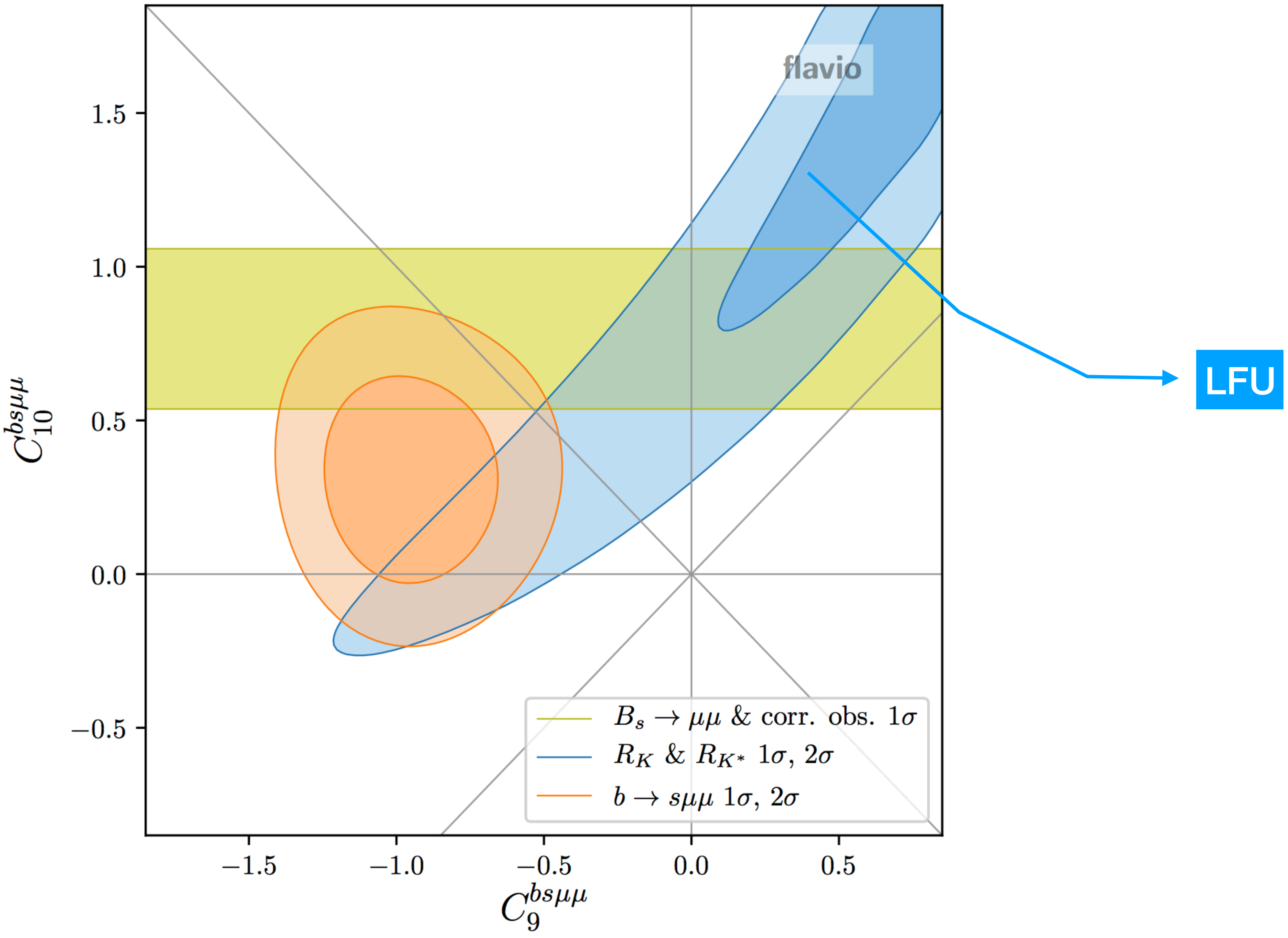
Standard Model Effective Field Theory (SMEFT)

https://flav-io.github.io/

https://github.com/wilson-eft/wilson

https://github.com/smelli/smelli

b→sμμ | global fit



LFU

Lepton Flavour Universality

Universality in neutral current interactions

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

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

Universality

Universality in charged current interactions

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

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

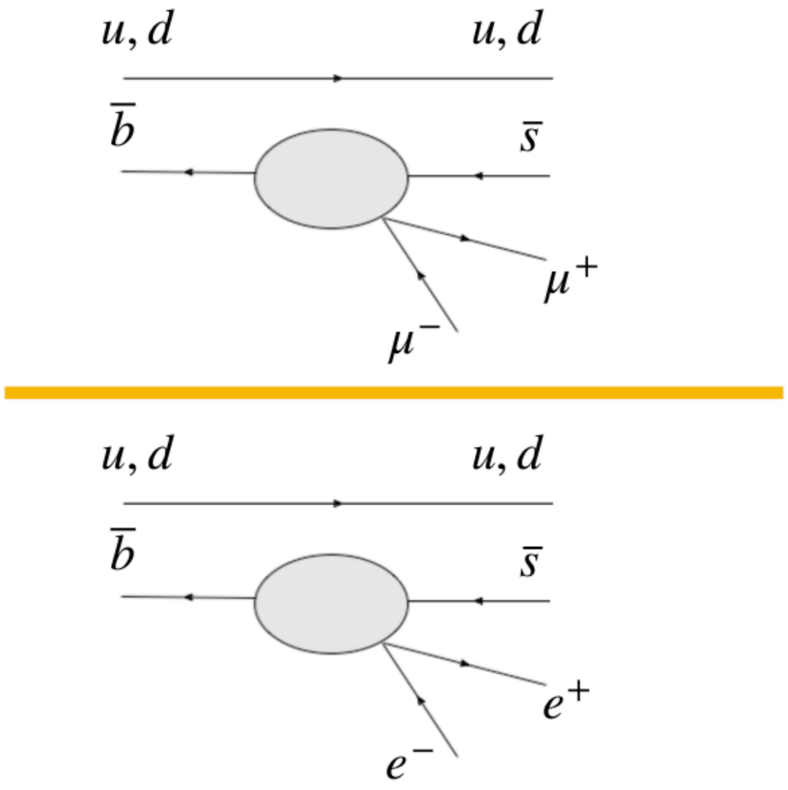
The W-boson couples
with different strengths to different lepton families

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

Universality

b→sll | LFU (e vs μ)

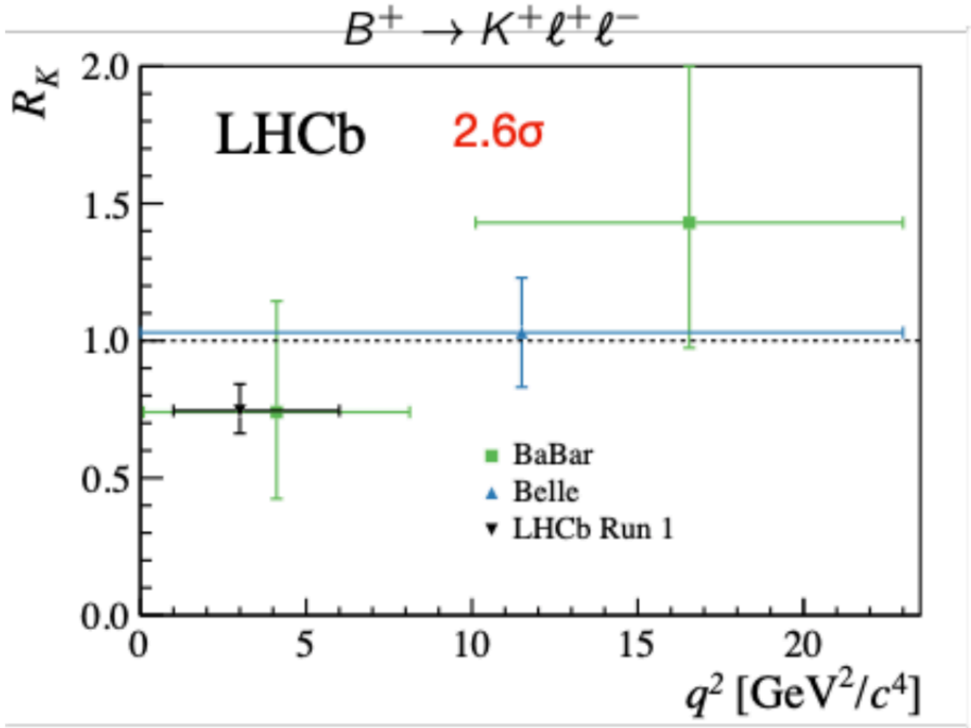
$$R_K = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} \overset{\mathrm{SM}}{\cong} 1$$

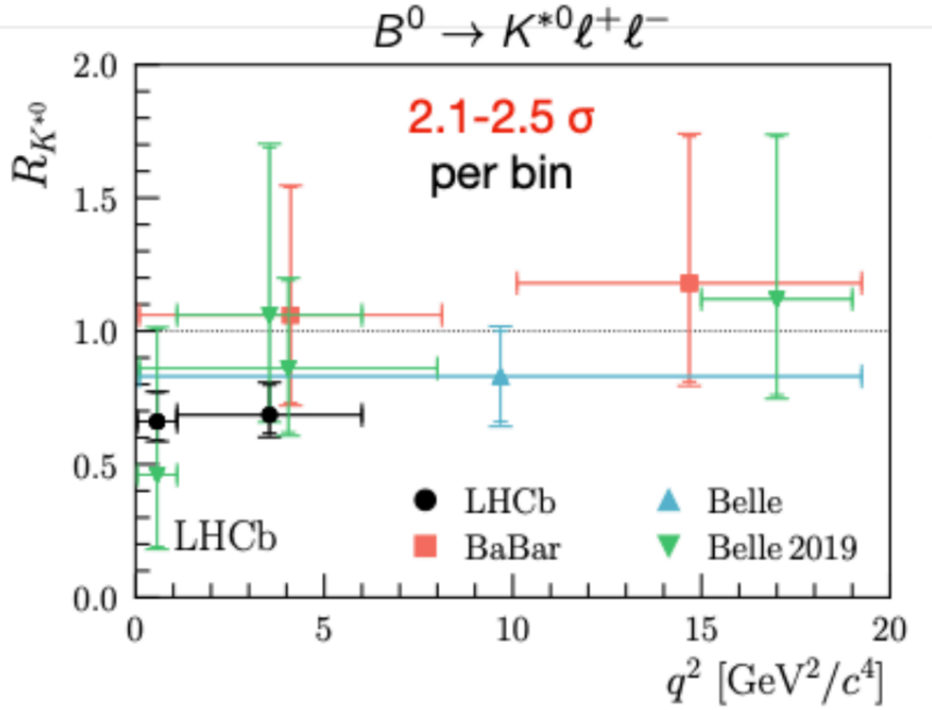


EPJC 76 (2016) 8, 440

$= 1.0 \pm 0.1$

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





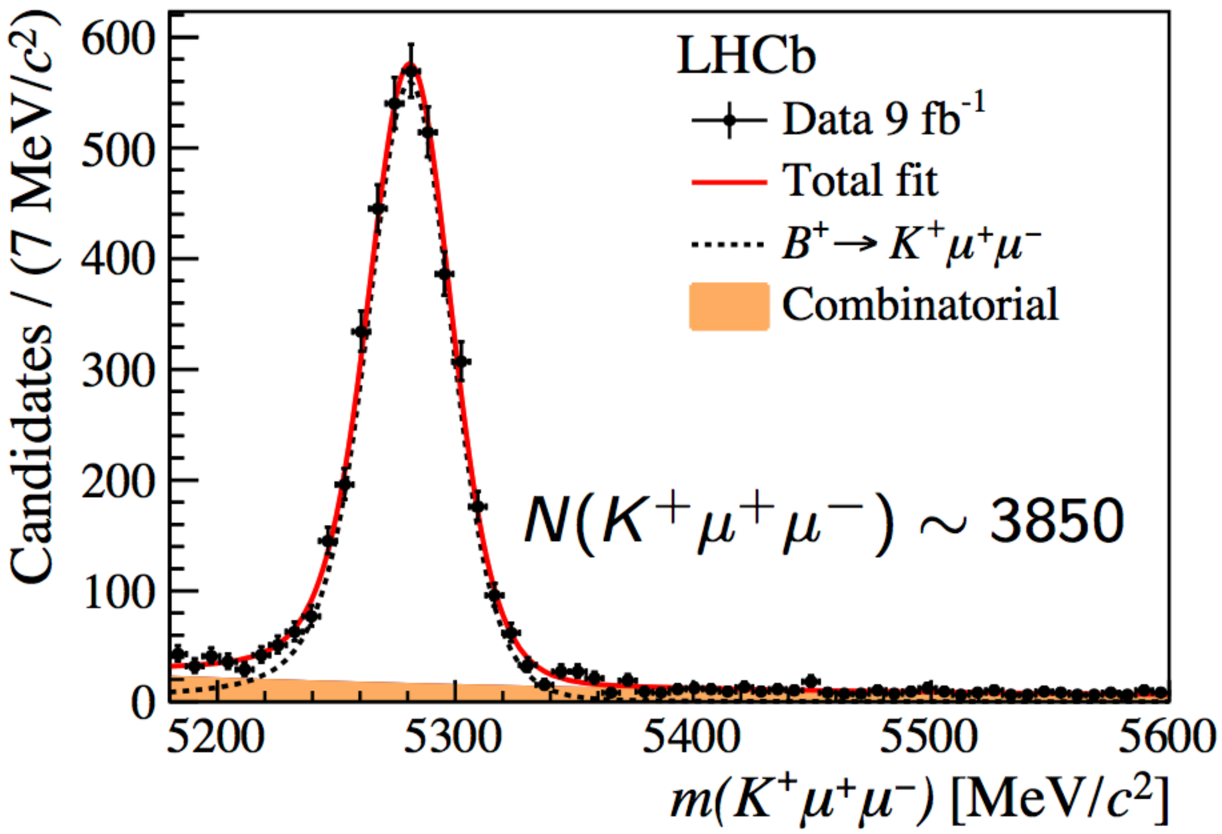
[LHCb, PRL 113 (2014) 151601]
[LHCb, JHEP 08 (2017) 055]

[BaBar, PRD 86 (2012) 032012]

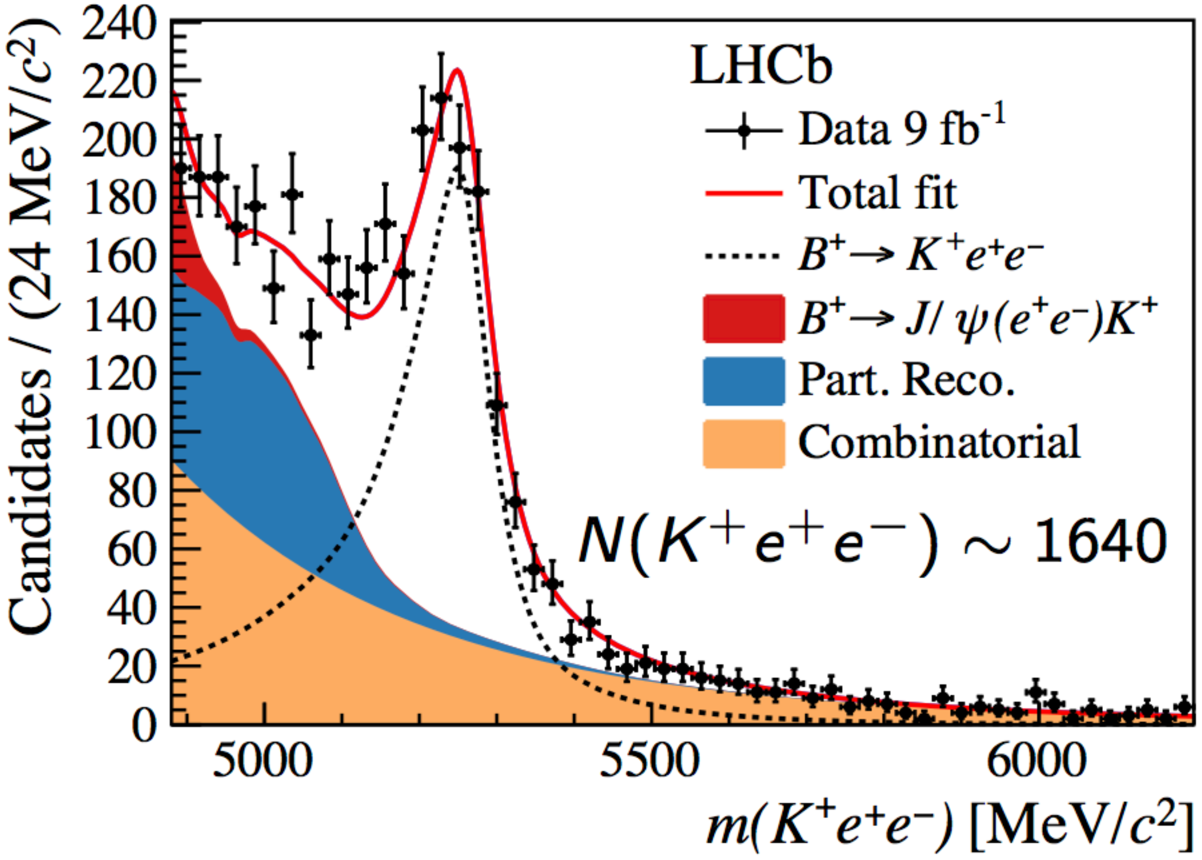
[Belle, PRL 103 (2009) 171801]
[Belle, arXiv:1904.02440]

b→sll | LFU (e vs μ)

muons



electrons

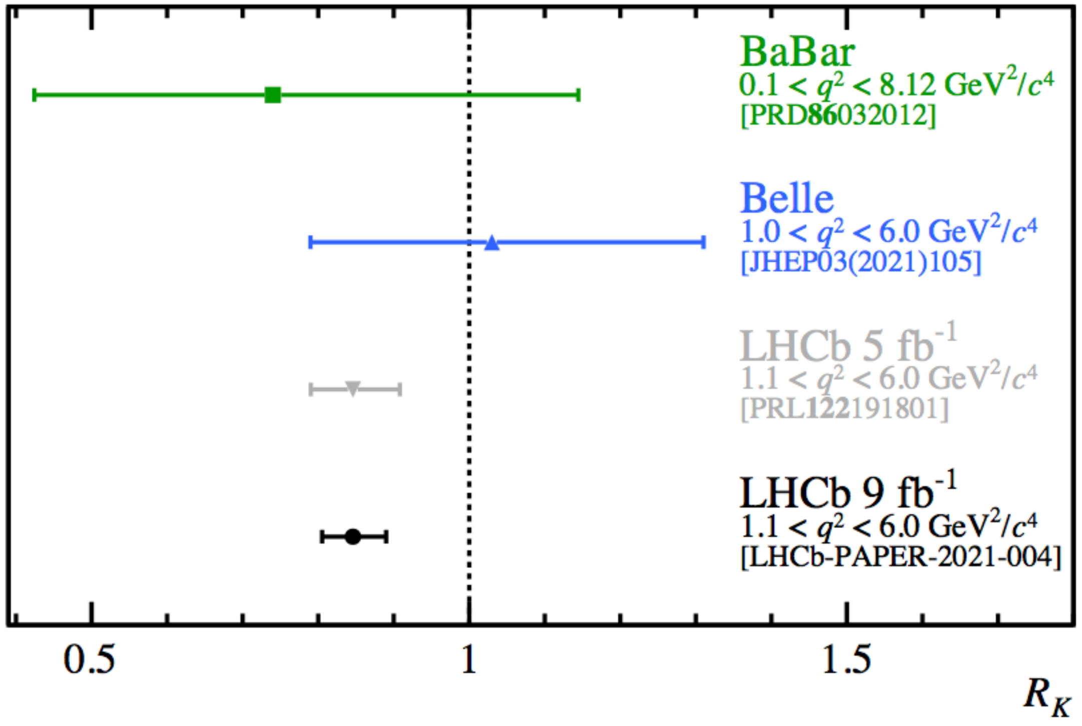


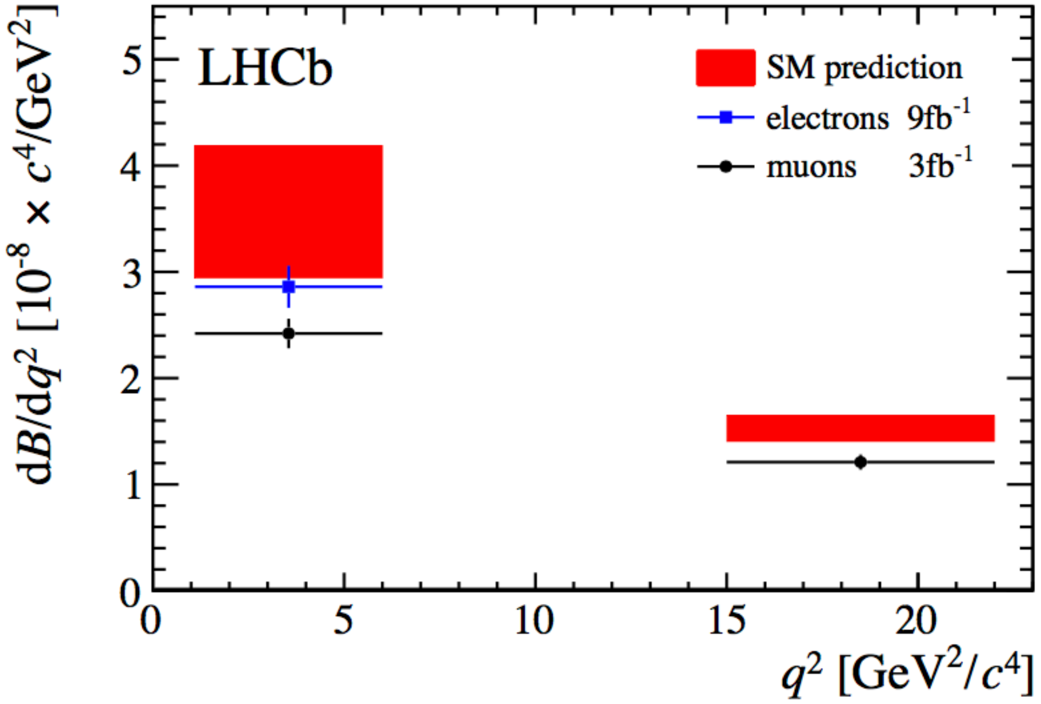
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))} = \frac{N^{\rm rare}_{\mu^+\mu^-}\ \varepsilon^{J/\psi}_{\mu^+\mu^-}}{N^{J/\psi}_{\mu^+\mu^-}\ \varepsilon^{\rm rare}_{\mu^+\mu^-}} \times \frac{N^{J/\psi}_{e^+e^-}\ \varepsilon^{\rm rare}_{e^+e^-}}{N^{\rm rare}_{e^+e^-}\ \varepsilon^{J/\psi}_{e^+e^-}}$$

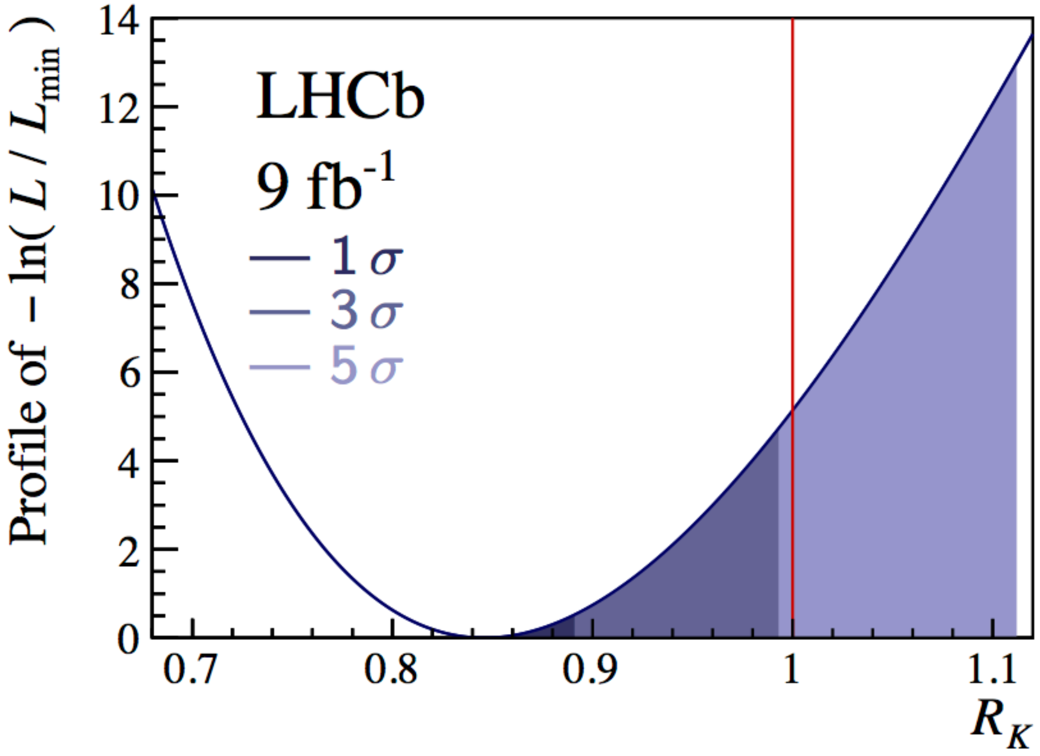
$b \to s\ell\ell$ | LFU (e vs μ)

$$R_K = 0.846\,^{+0.042}_{-0.039}\,(\text{stat})\,^{+0.013}_{-0.012}\,(\text{syst})$$

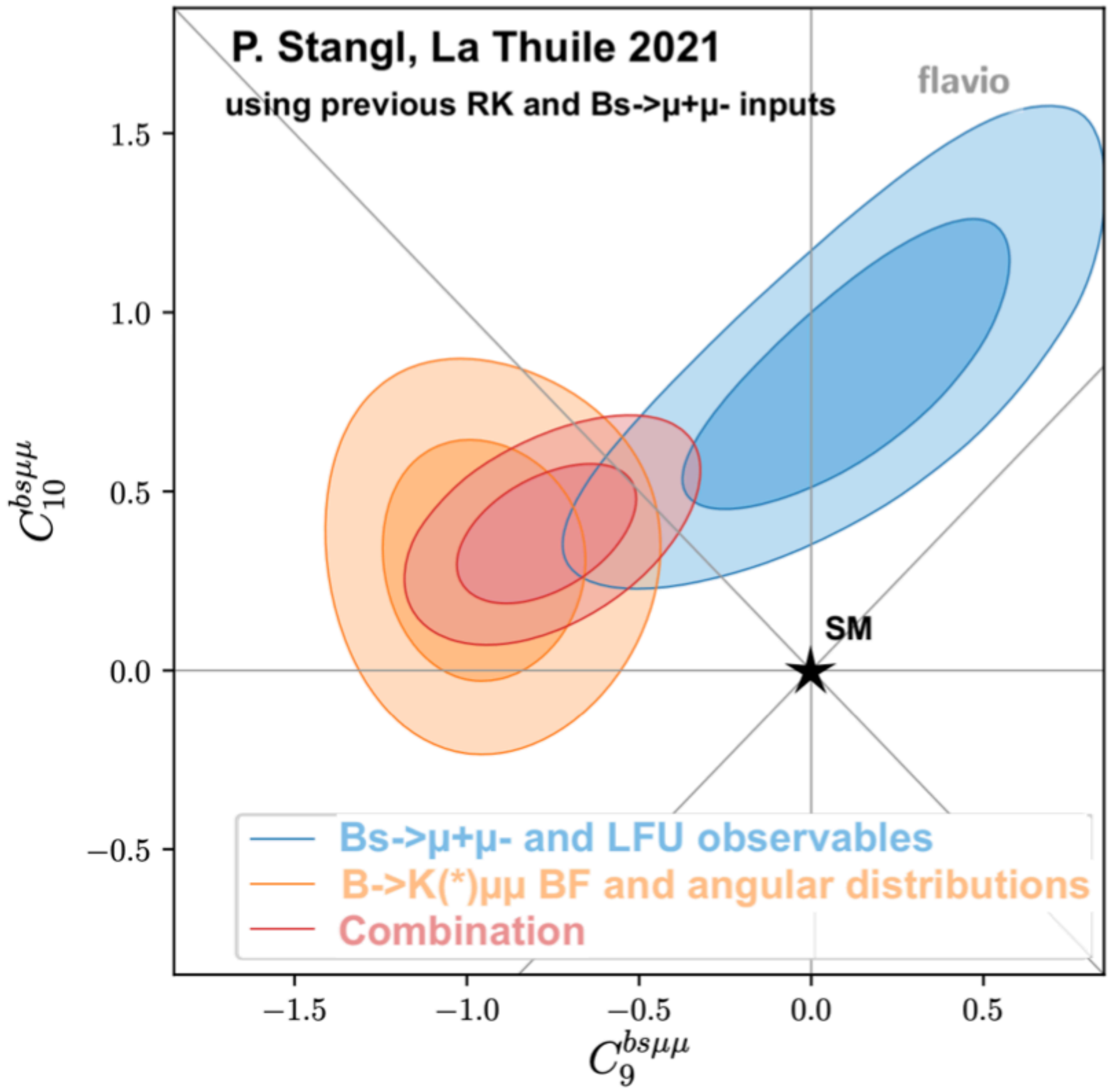
- *p*-value under SM hypothesis: 0.0010
  $\to$ Evidence of LFU violation at 3.1σ



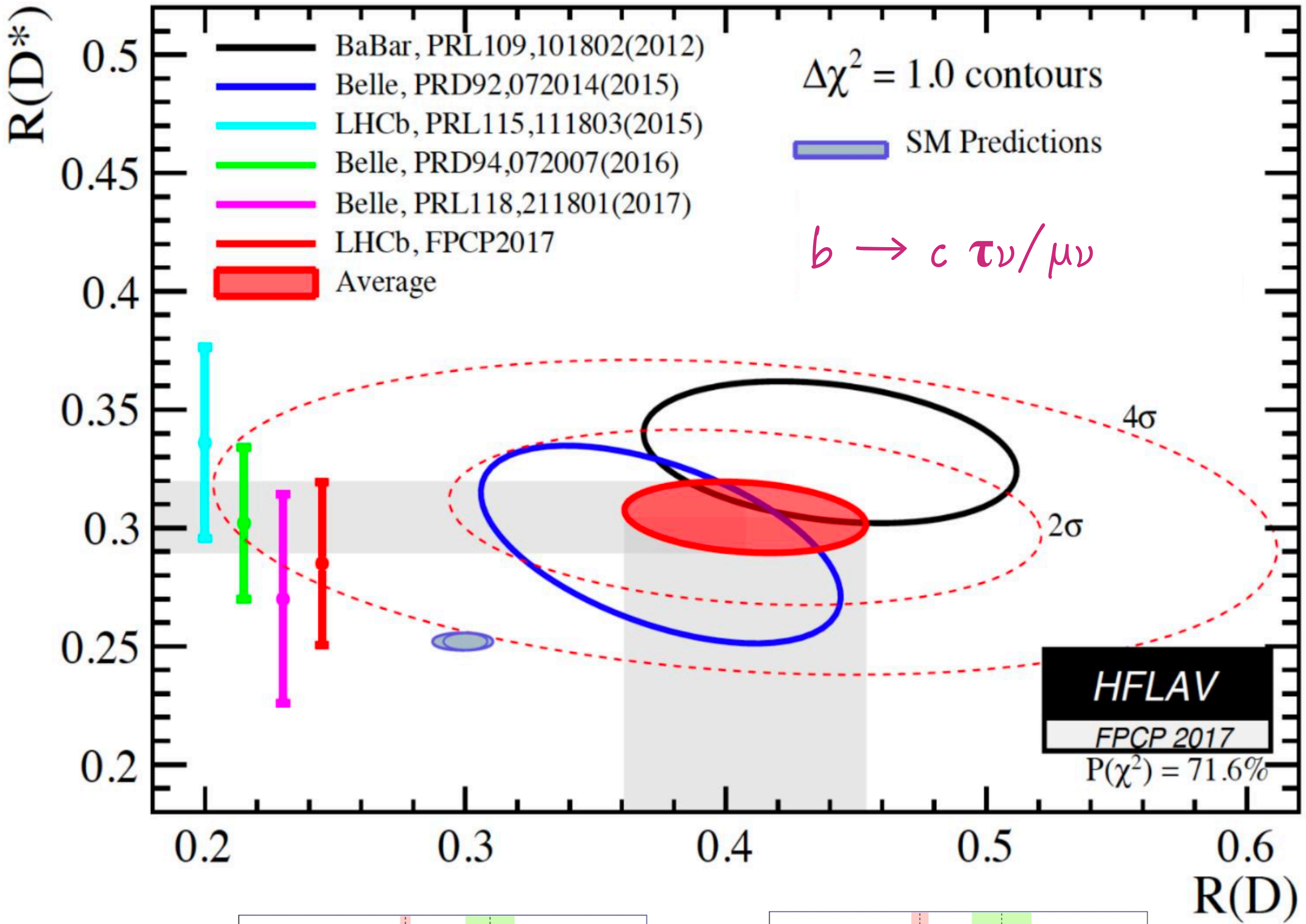




b→sll | global fit

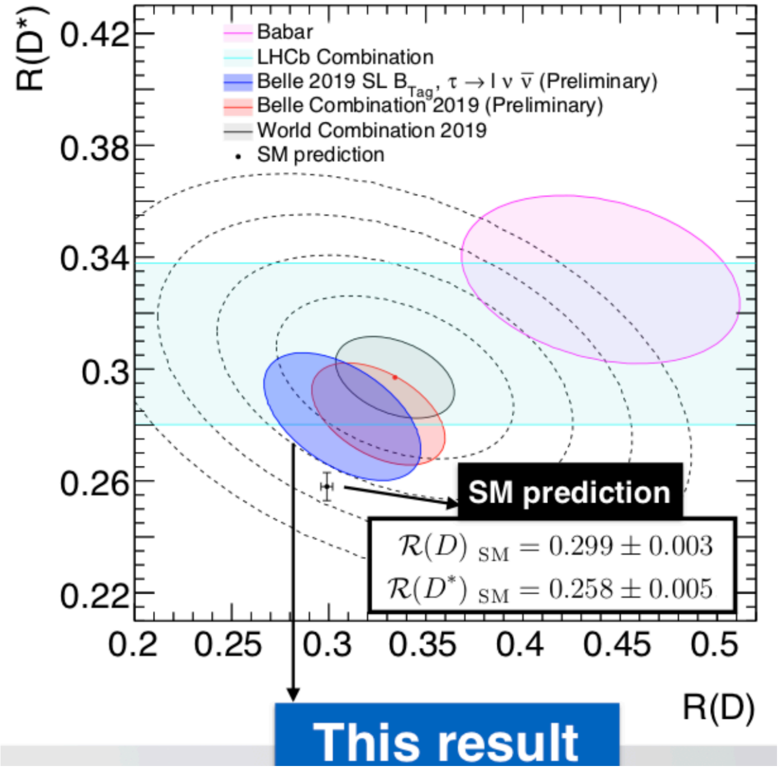


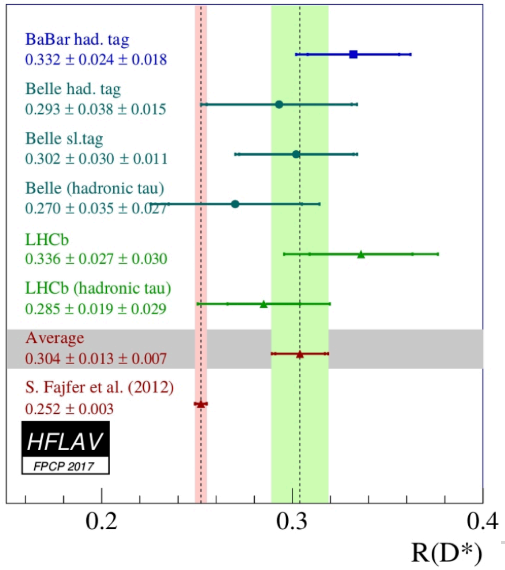
b→clν | LFU (τ vs e/μ)

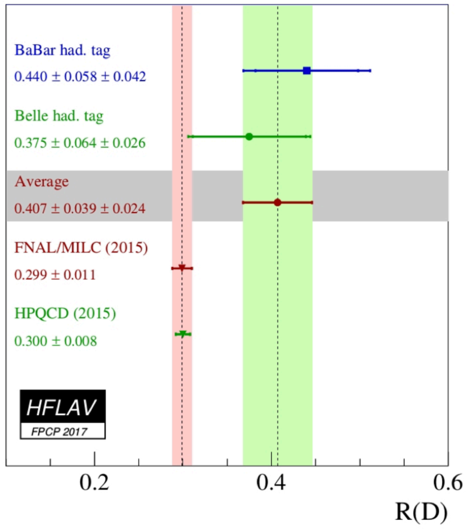


$b \to c\ \tau\nu/\mu\nu$

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



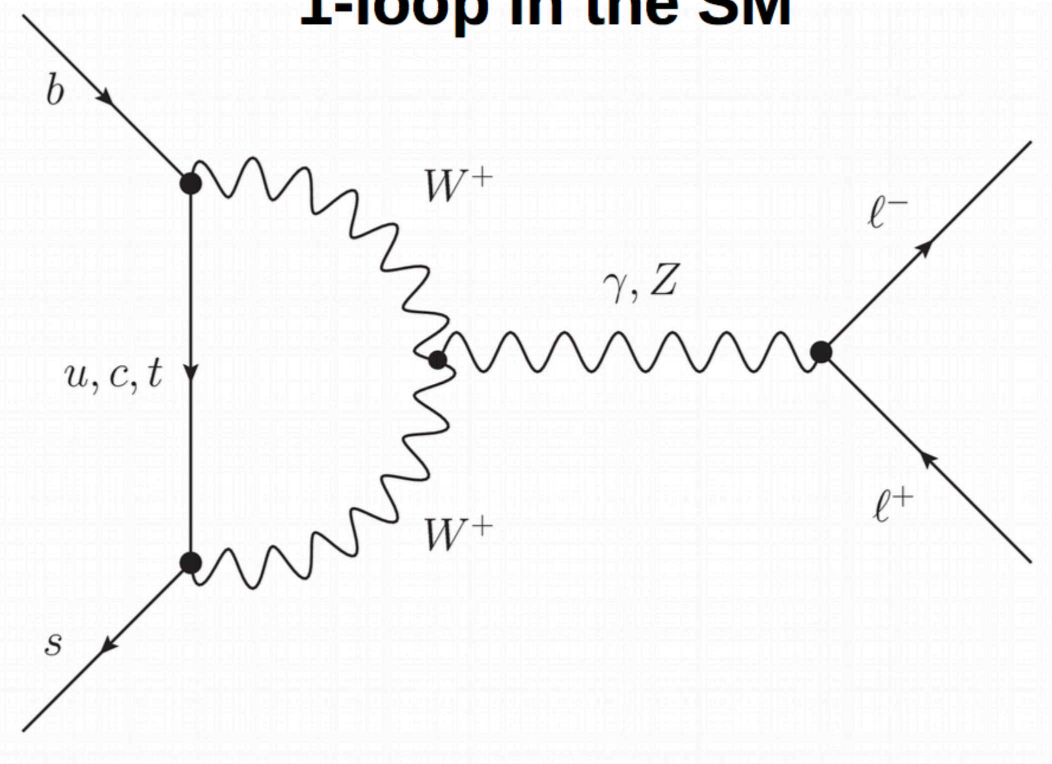




what is the scale of NP?

$b \to s$ anomalies

1-loop in the SM

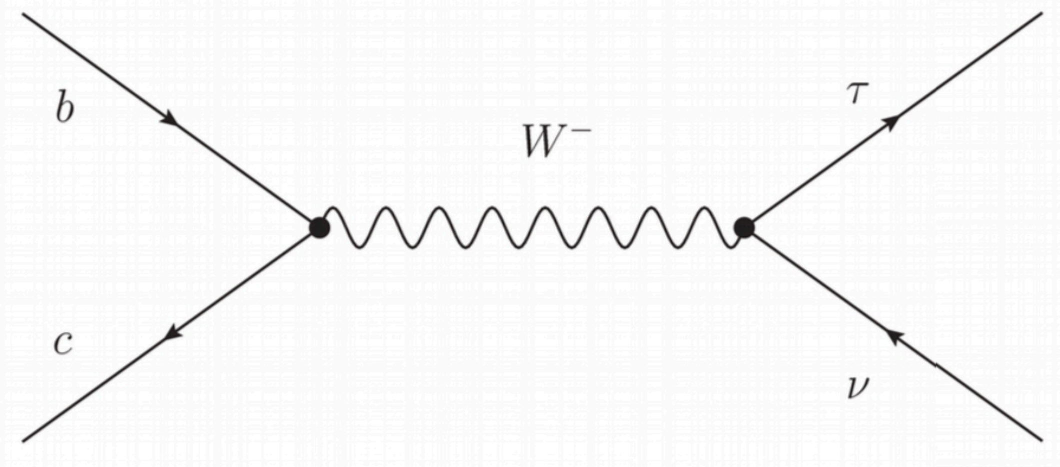


The scale of NP can be “*high*”

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

$b \to c$ anomalies

Tree-level in the SM

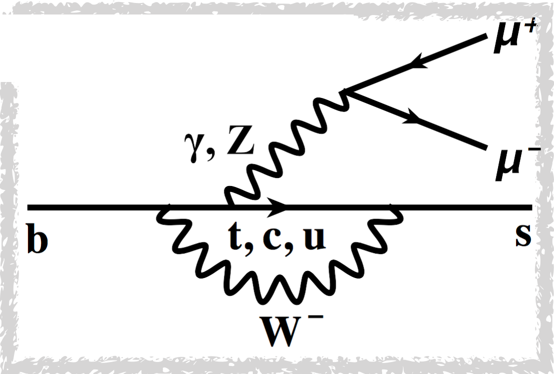


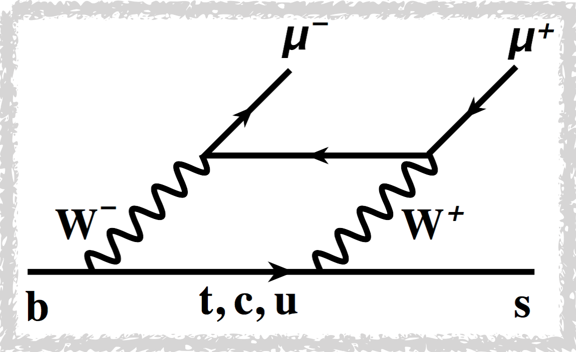
The scale of NP must be “low”

$$\Lambda \sim \mathrm{TeV}$$

anomalies: NP explanations?

b→sll
quark transitions
in the **SM**

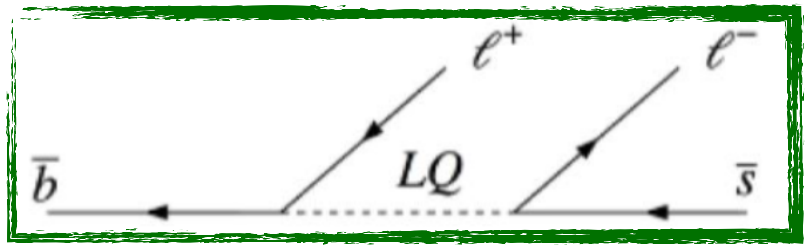




- could existing NP scenarios account for the anomalies?
  - while still respecting strict constraints imposed by other measurements!
- current best candidates:

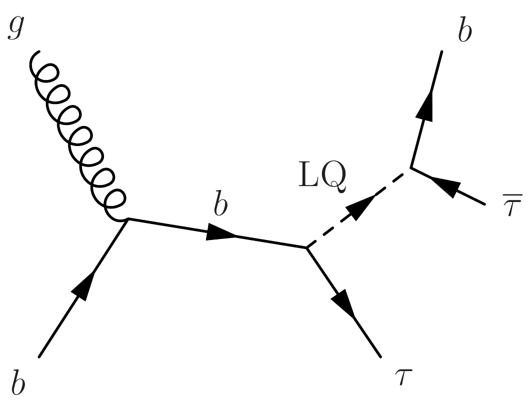
1) **New gauge bosons**
   - Z', associated to a new symmetry

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

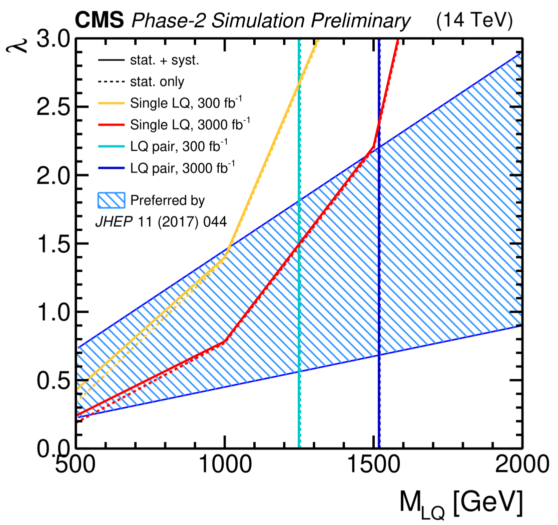


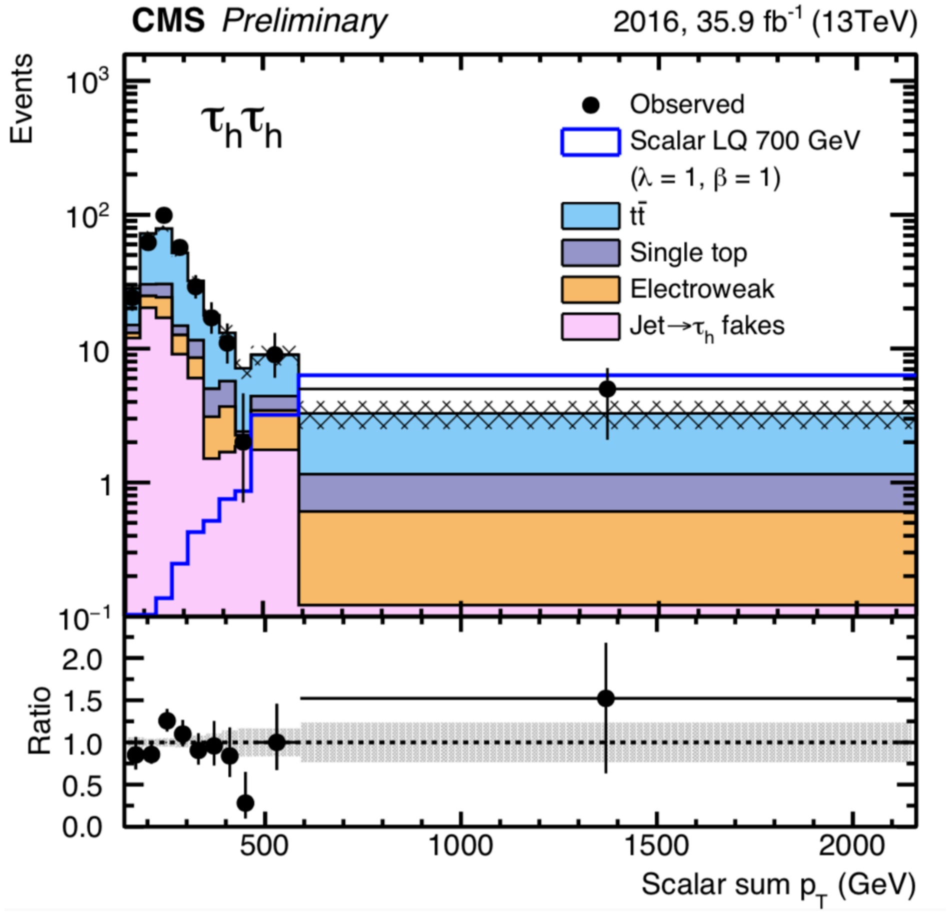
search for LQ→τb

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



CMS-PAS-FTR-18-028





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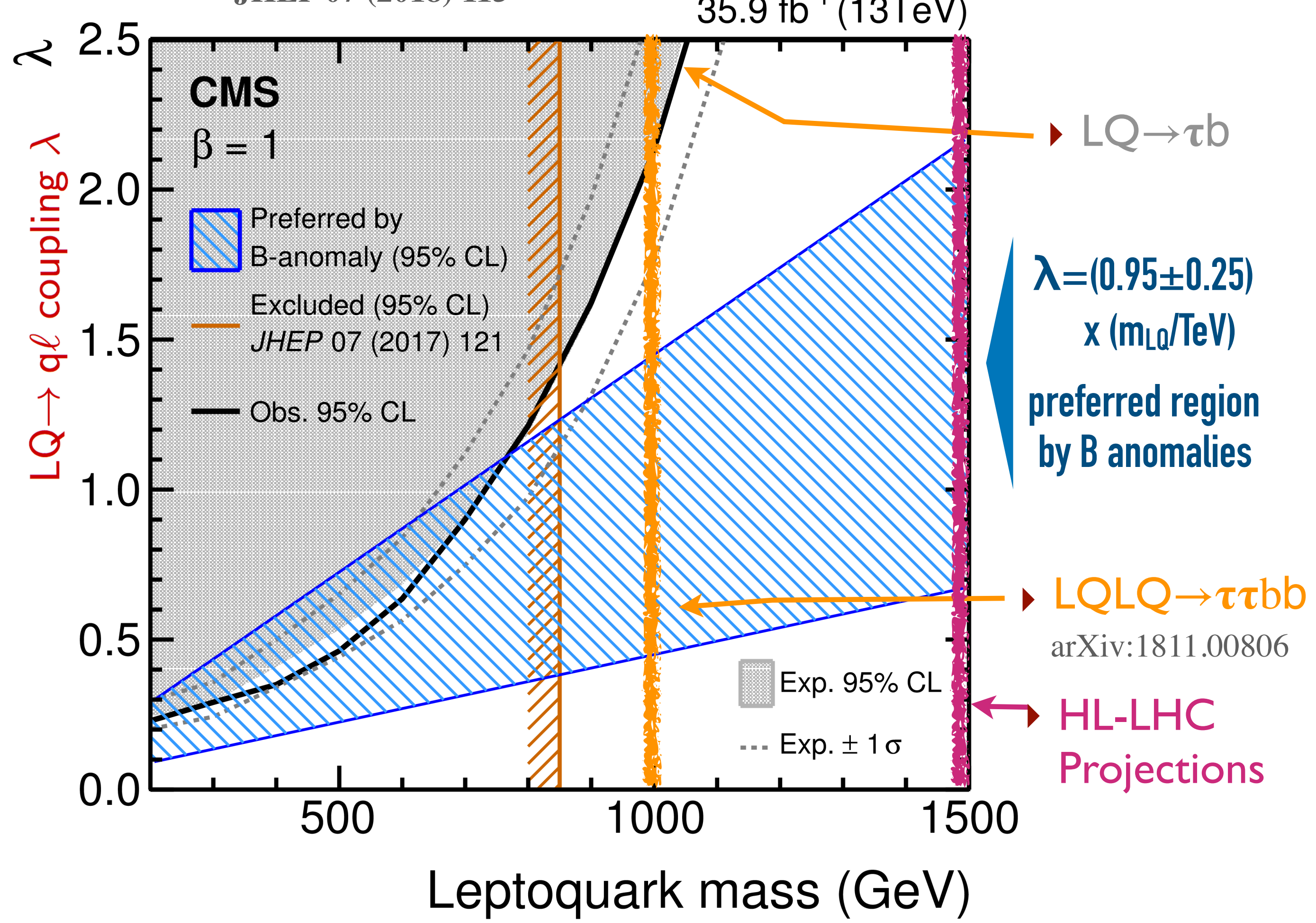


LQ→τb

λ=(0.95±0.25) x (m_{LQ}/TeV)

preferred region by B anomalies

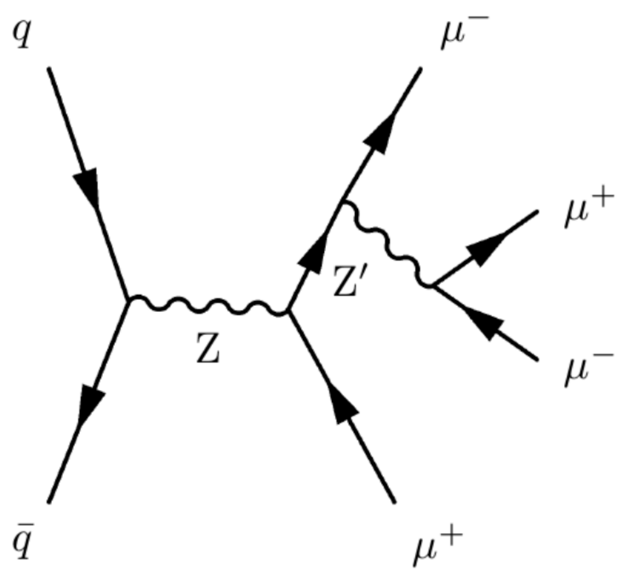
LQLQ→ττbb

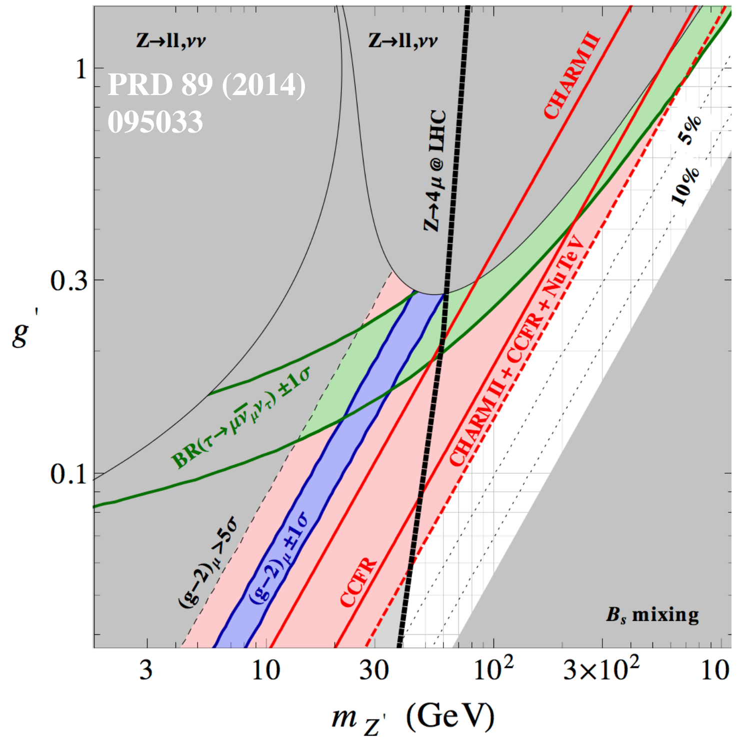
arXiv:1811.00806

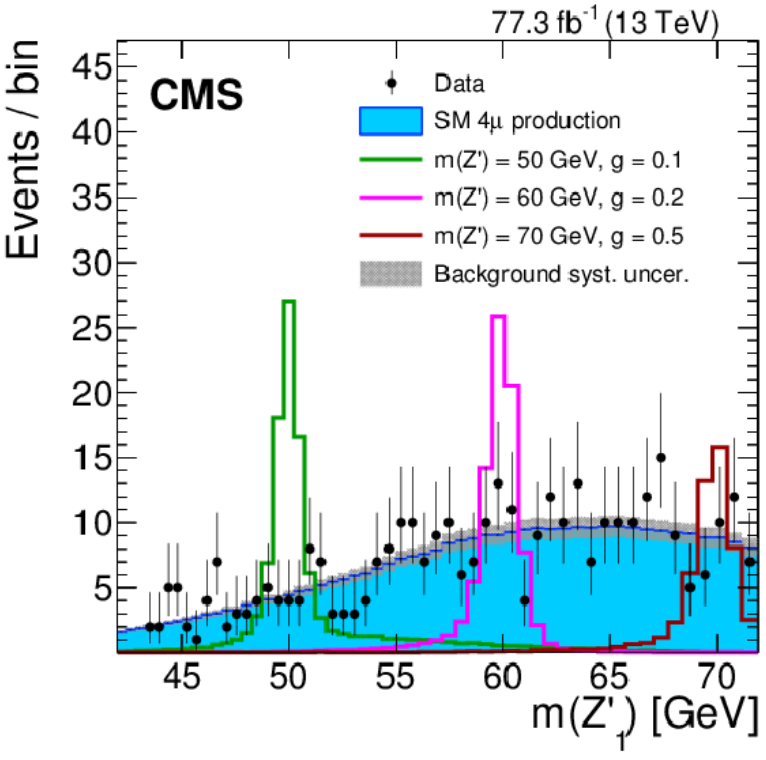
HL-LHC Projections

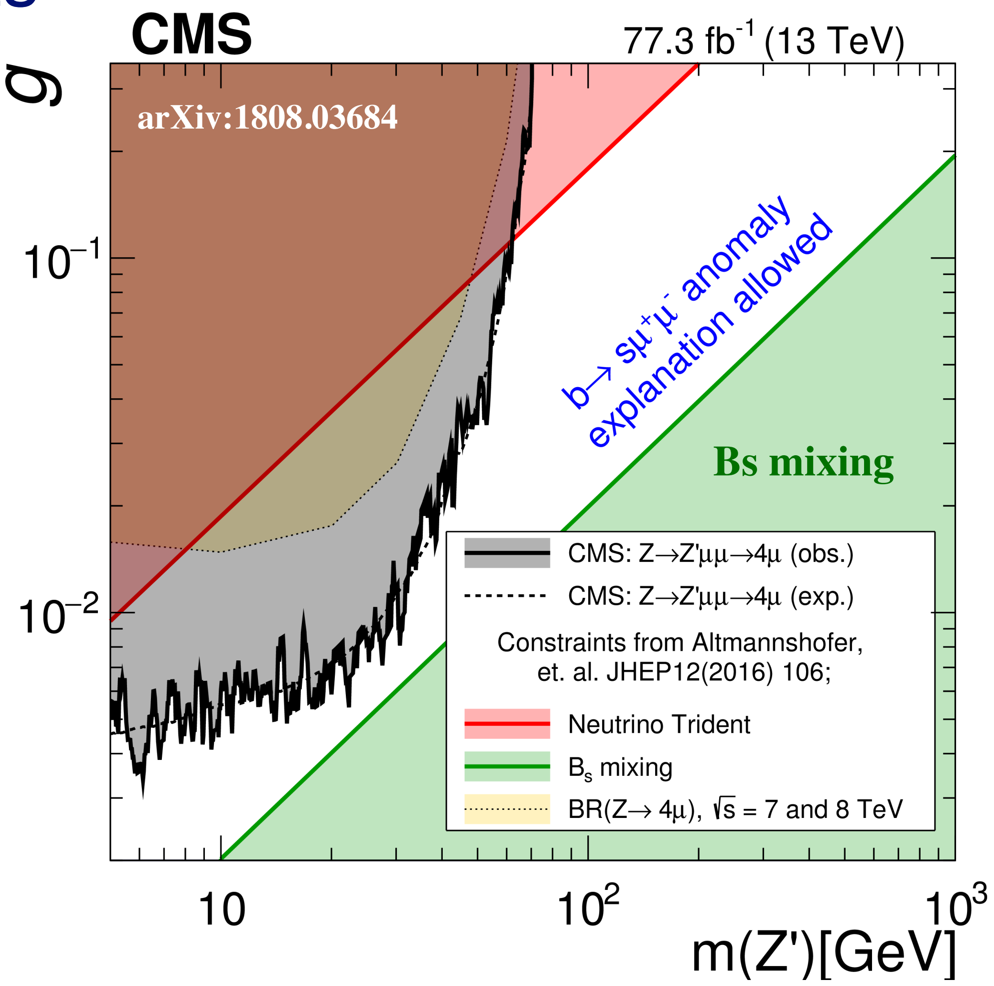
search for Z' in $Z \to 4\mu$ (L_μ-L_τ)

- 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



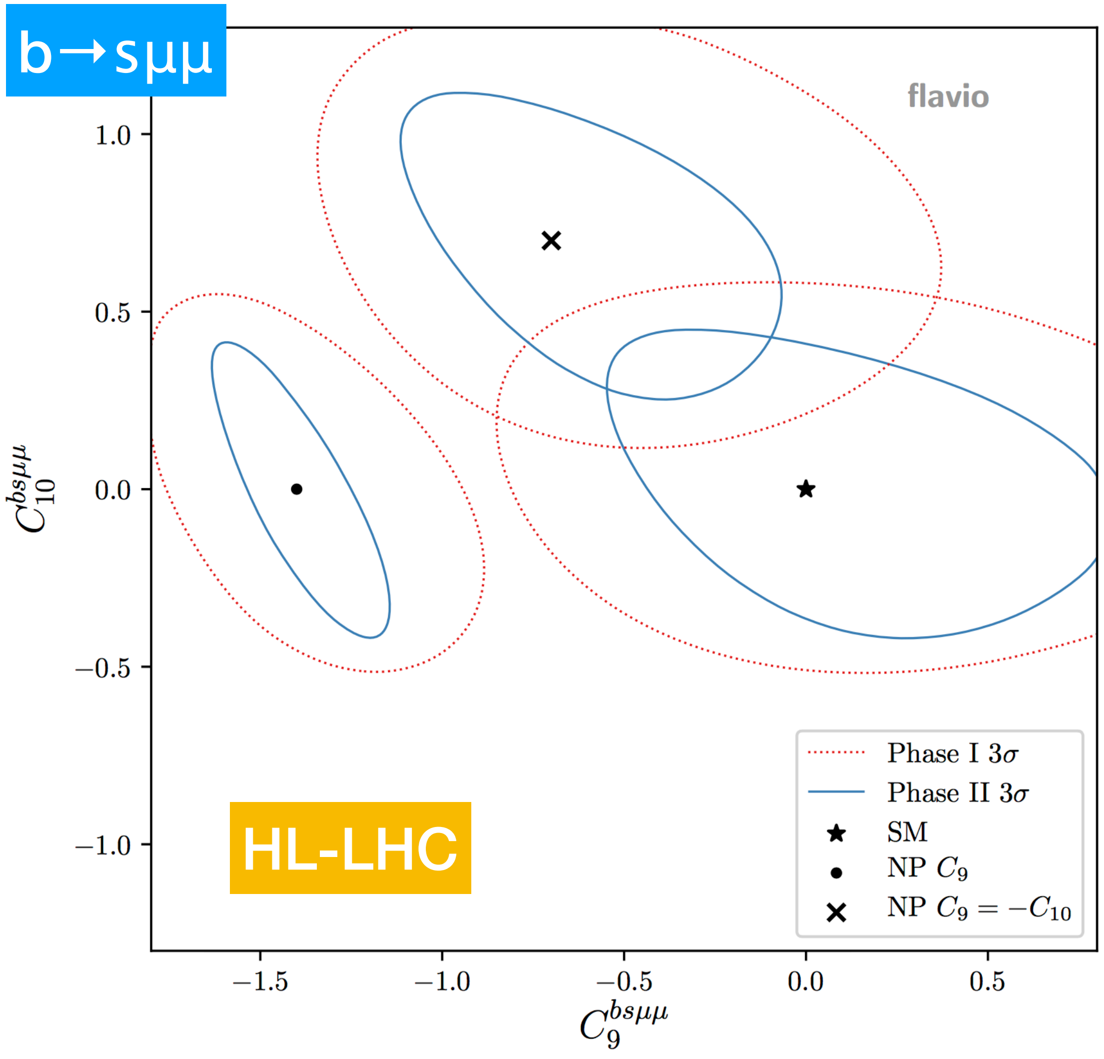






Flavour Anomalies

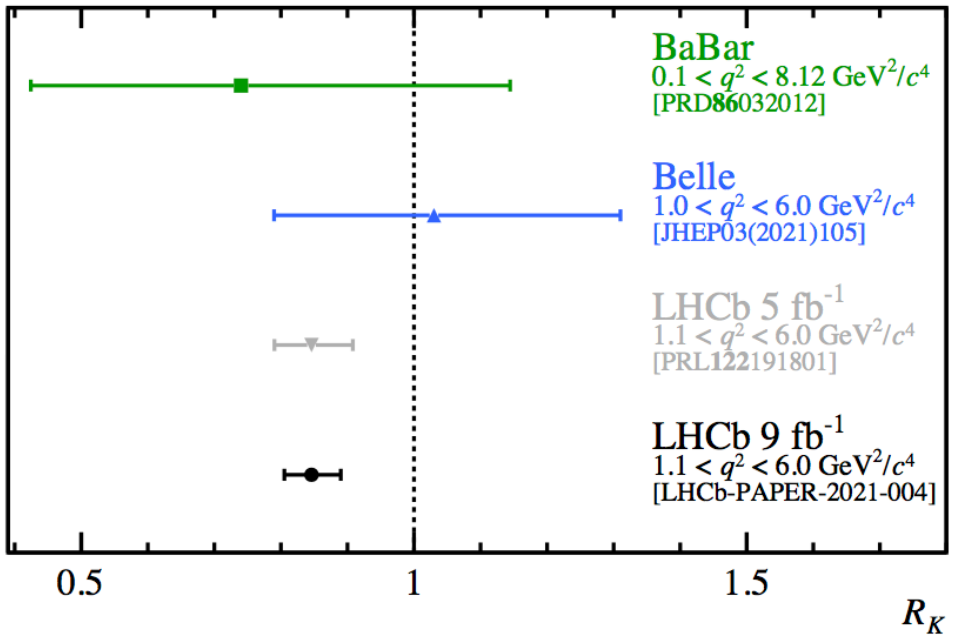
b→sμμ



Clarification being actively pursued experimentally by LHCb,CMS,ATLAS and BelleII + theory calculations and model building

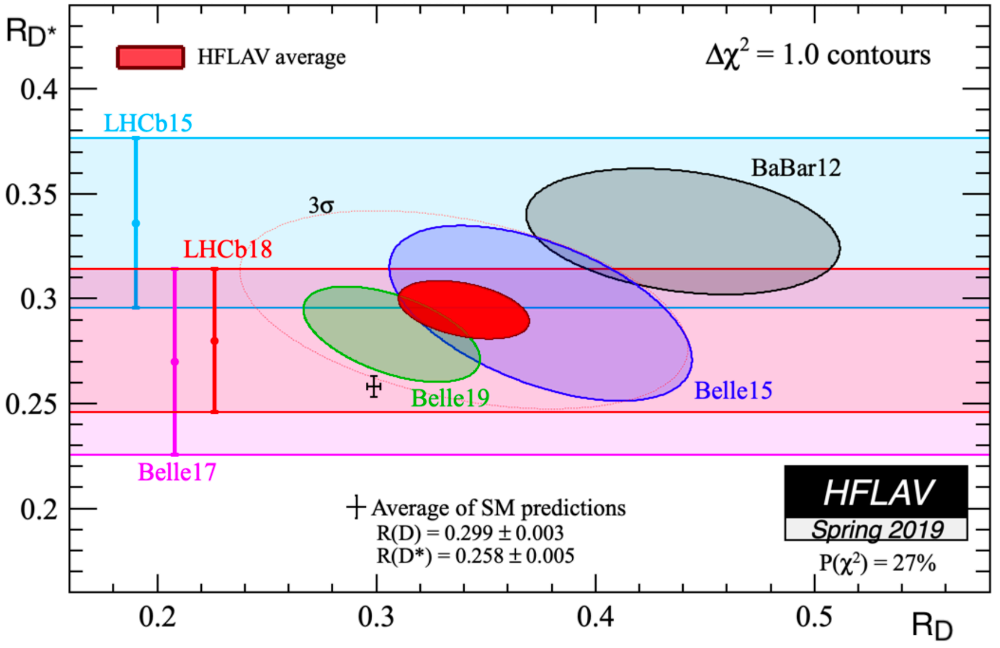
LFUV b→sll

e vs μ



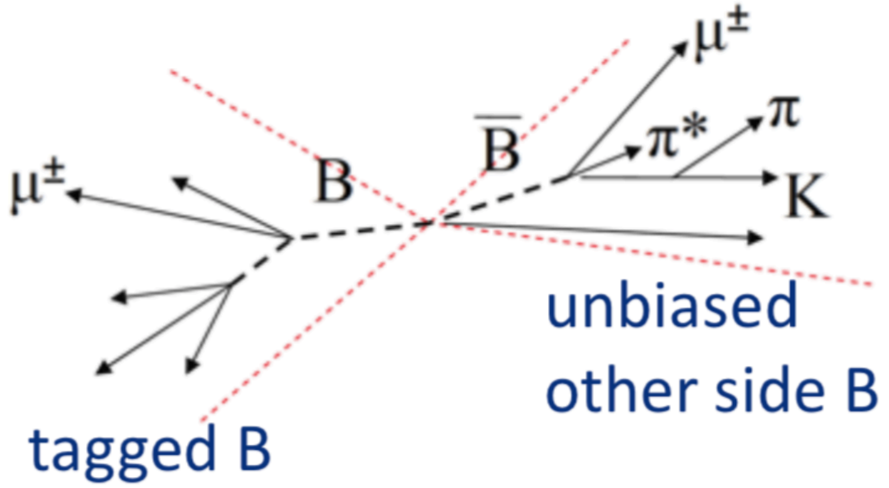
LFUV b→clν

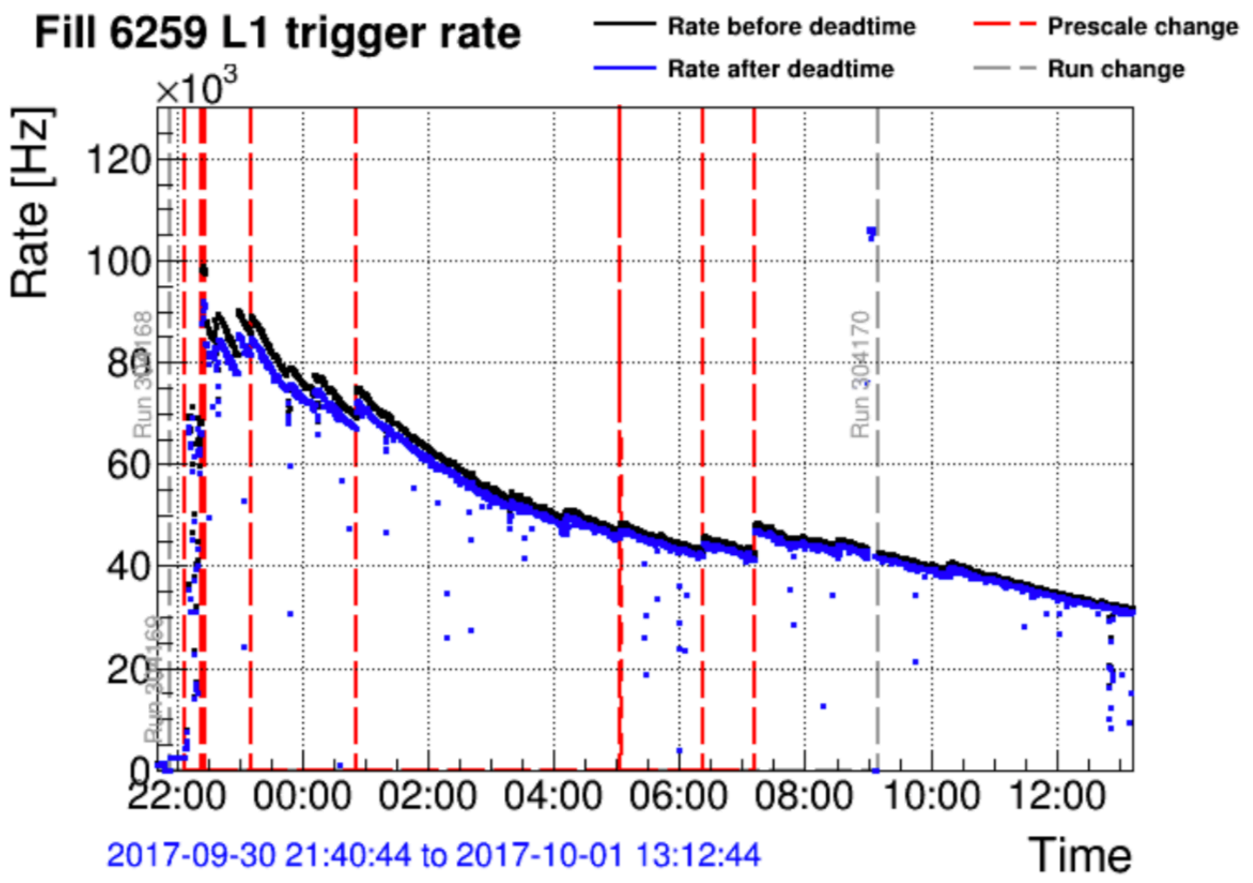
τ vs μ

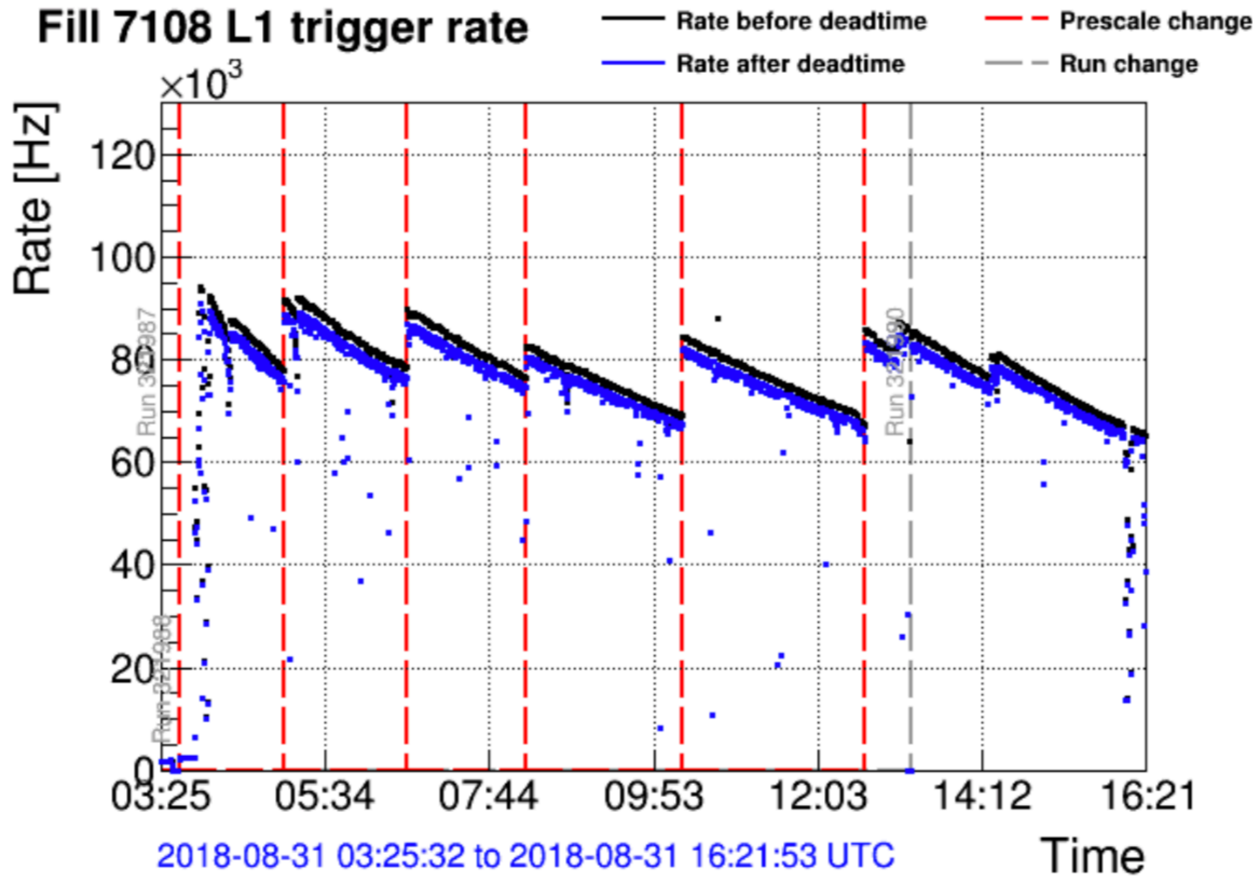


bonus: parked Run2 data (CMS)

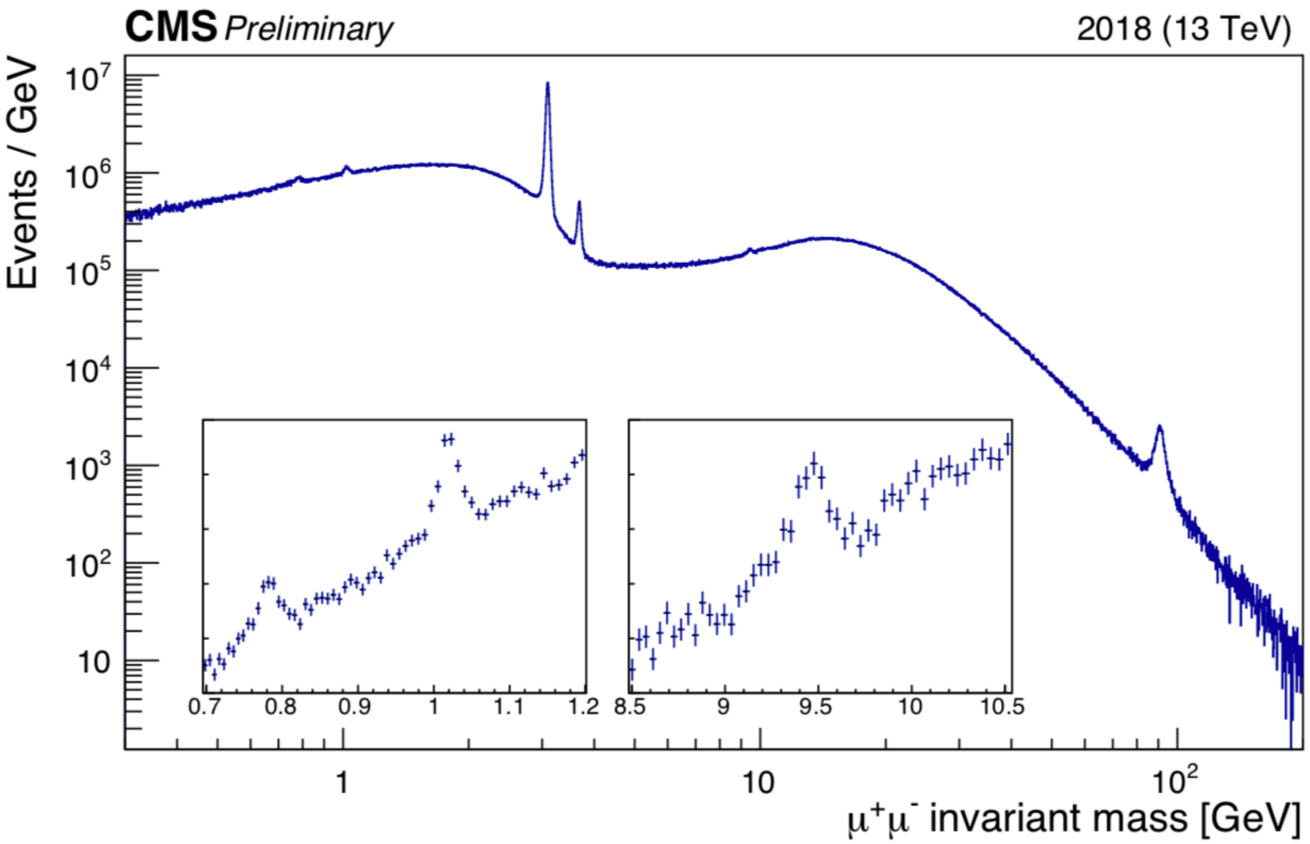
- bulk of B physics at CMS/ATLAS based on (di)muons in final state
- main challenge: the trigger!
- CMS has collected special data in 2018
  - trigger on opposite-side b
  - triggered 12B unbiased B's on tape



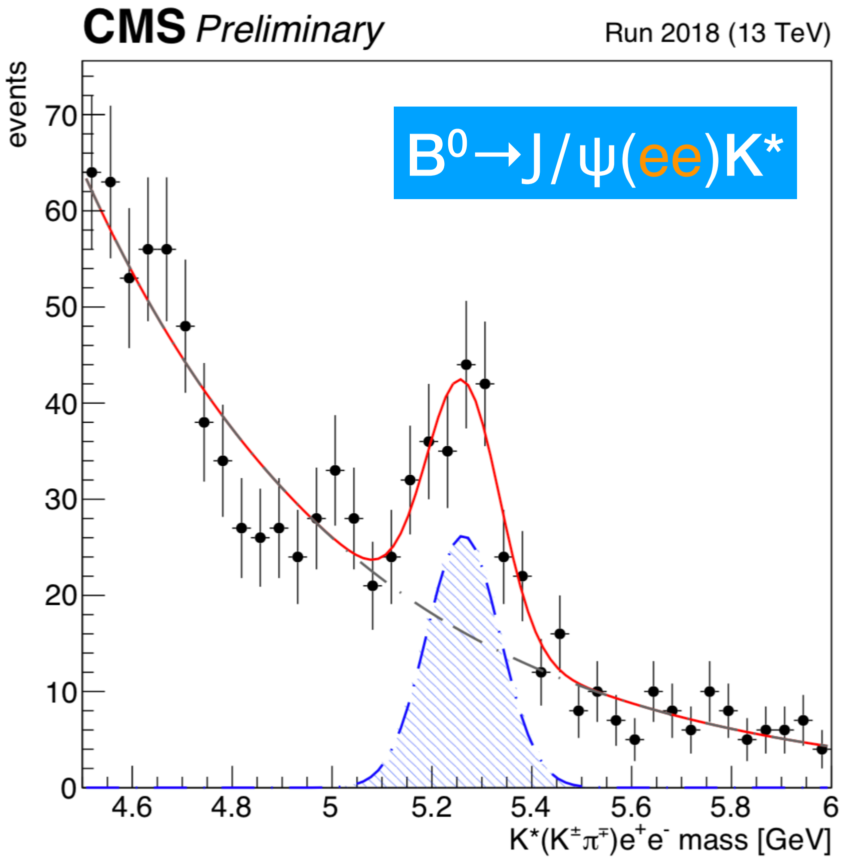


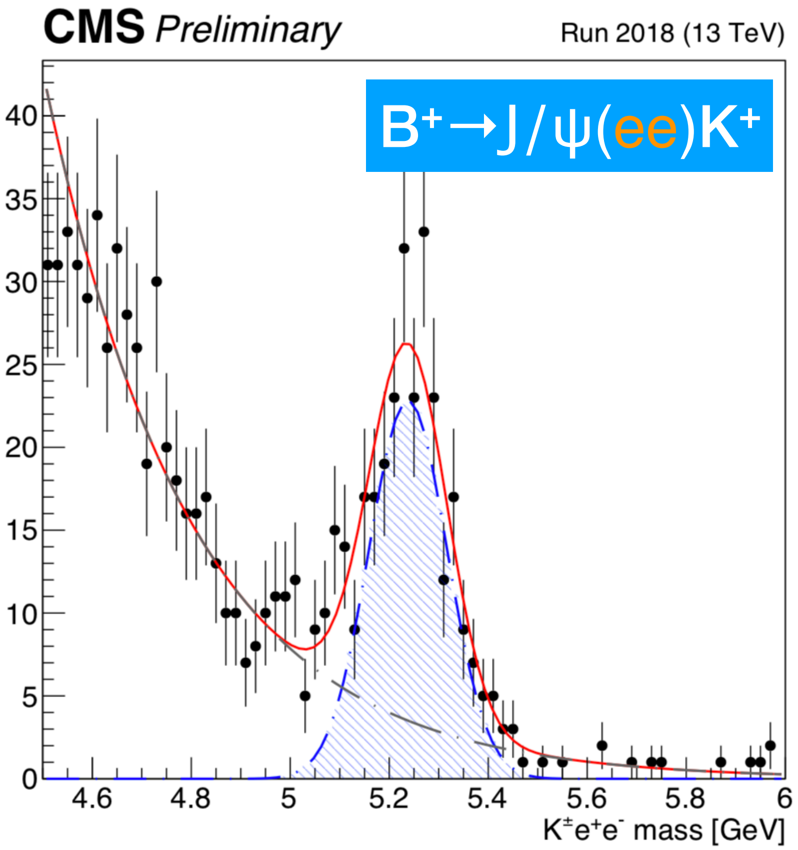


B’s from parked data (CMS)



Mode	N_{2018}	f_B [17]	$\mathcal{B}$
Generic B hadrons			
B_d^0	4.99×10^9	0.4	1.0
$B^\pm$	4.99×10^9	0.4	1.0
B_s	1.56×10^9	0.1	1.0
b baryons	1.56×10^9	0.1	1.0
B_c	1.25×10^7	0.001	1.0
B hadrons total	1.25×10^{10}	1.0	1.0
Interesting B decays			
$B^0 \to K^*\ell^+\ell^-$	3290	0.4	$\frac{2}{3} \times 9.9 \times 10^{-7}$ [14]
$B^\pm \to K^\pm\ell^+\ell^-$	2250	0.4	4.51×10^{-7} [15]



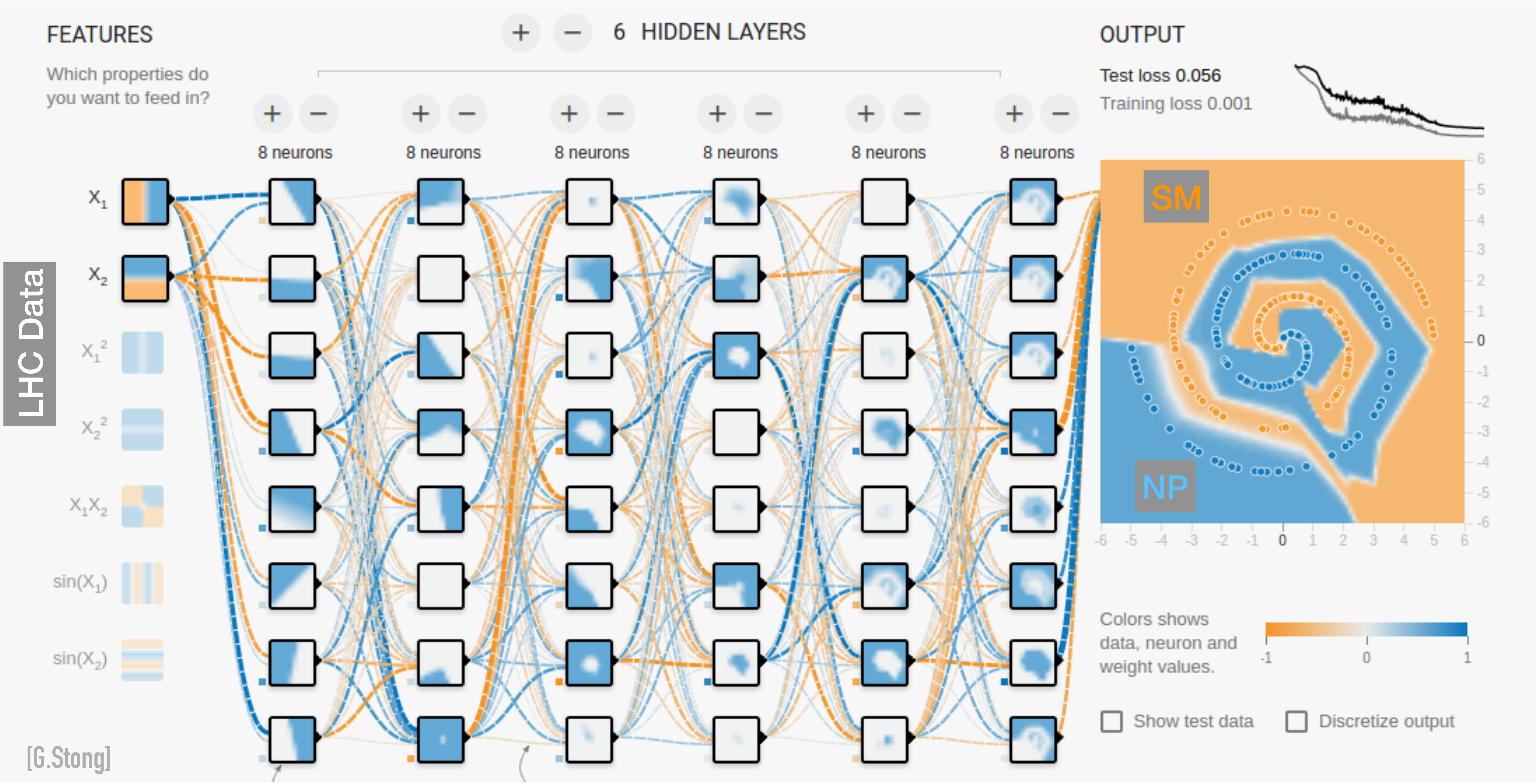


flavor anomalies I a summary

- flavour physics provides one of the best avenues for detecting NP
  - rare decays will benefit enormously from high luminosity at LHC
- a coherent pattern of deviations has emerged from the data
  - individually, each deviation is not statistically significant yet
  - taken together, the set of deviations is significant
- anomalies to be clarified
  - more data (2017, 2018), more experiments (now LHC, soon also Belle2)
  - new dedicated analyses from the low and high p_T fronts
- possibly, NP will be revealed at the LHC
  - through a combined detailed analysis of multiple observables, in a multi-messenger fashion (flavour anomalies provide such an illustration!)

multi-variate analysis

a.k.a. multi-messenger … a.k.a. machine learning



FEATURES

Which properties do you want to feed in?

6 HIDDEN LAYERS

OUTPUT

Test loss 0.056

Training loss 0.001

Colors shows data, neuron and weight values.

☐ Show test data ☐ Discretize output

neutrinos @ LHC !

+ FIPs, LLP, LDM

https://home.cern/fr/news/news/experiments/cern-approves-new-lhc-experiment

CERN approves new LHC experiment

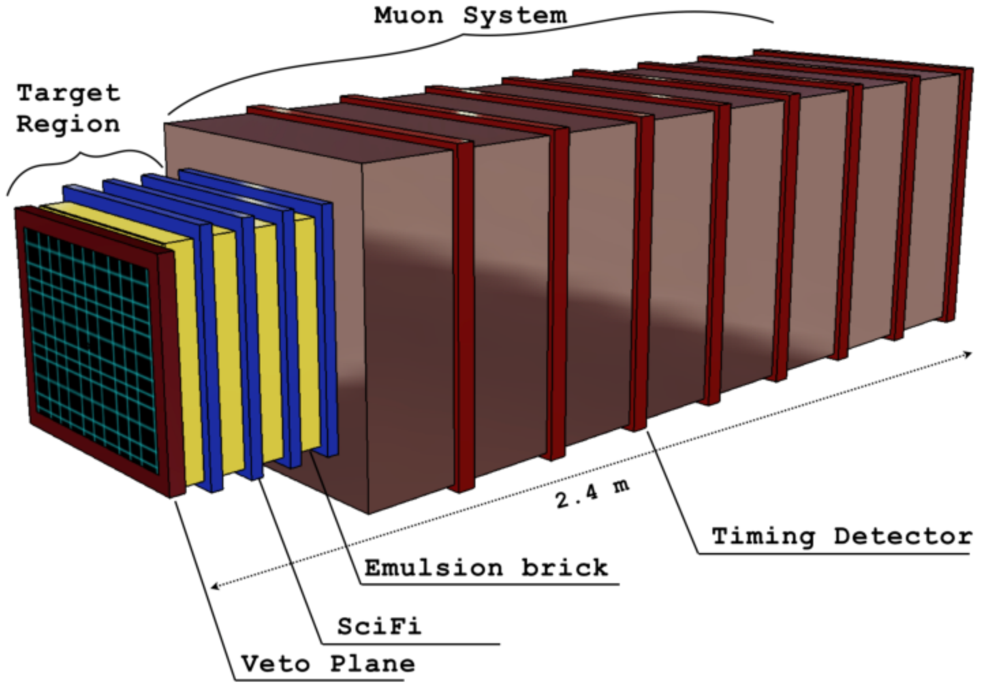
SND@LHC, or Scattering and Neutrino Detector at the LHC, will be the facility's ninth experiment

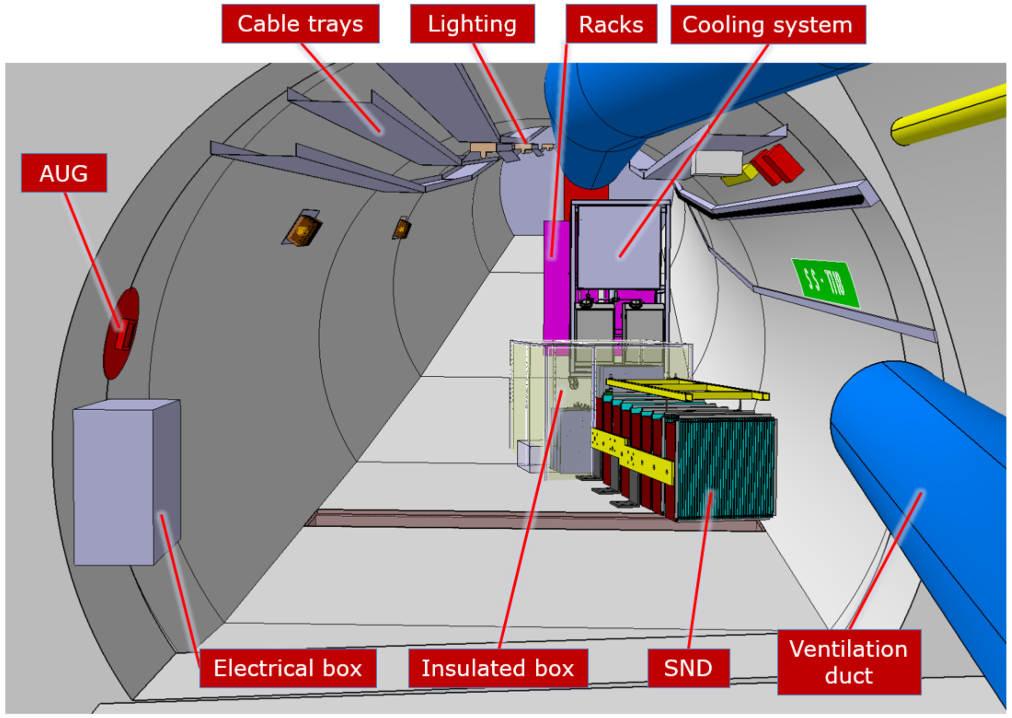
27 AVRIL, 2021 | Par Ana Lopes

The SND@LHC experiment consists of an emulsion/tungsten target for neutrinos (yellow) interleaved with electronic tracking devices (grey), followed downstream by a detector (brown) to identify muons and measure the energy of the neutrinos. (Image: Antonio Crupano/SND@LHC)

Neutrinos @ LHC !

SND@LHC





The 9th LHC experiment just approved!
Getting ready to take data at start of Run3!

SND@LHC Physics goals

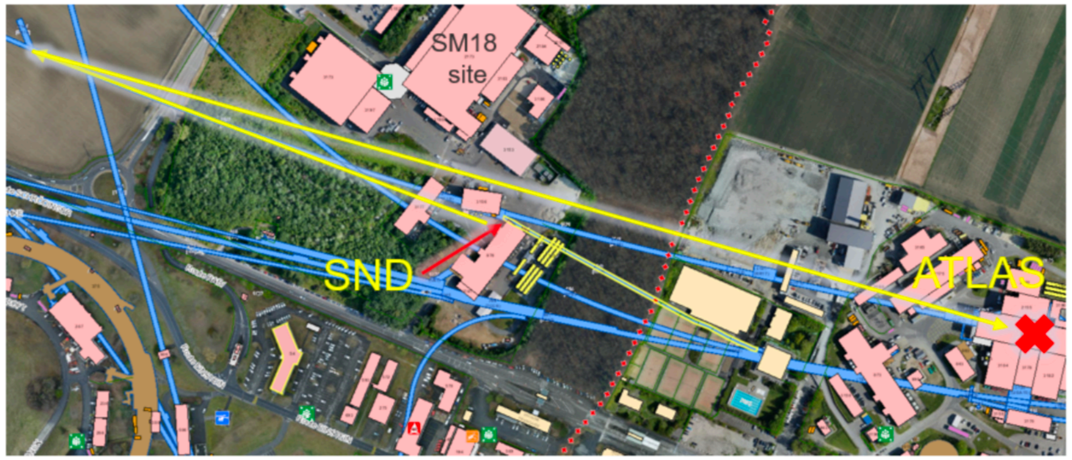
Detect collider neutrinos for first time

Energy range so far unexplored (350GeV-10TeV)

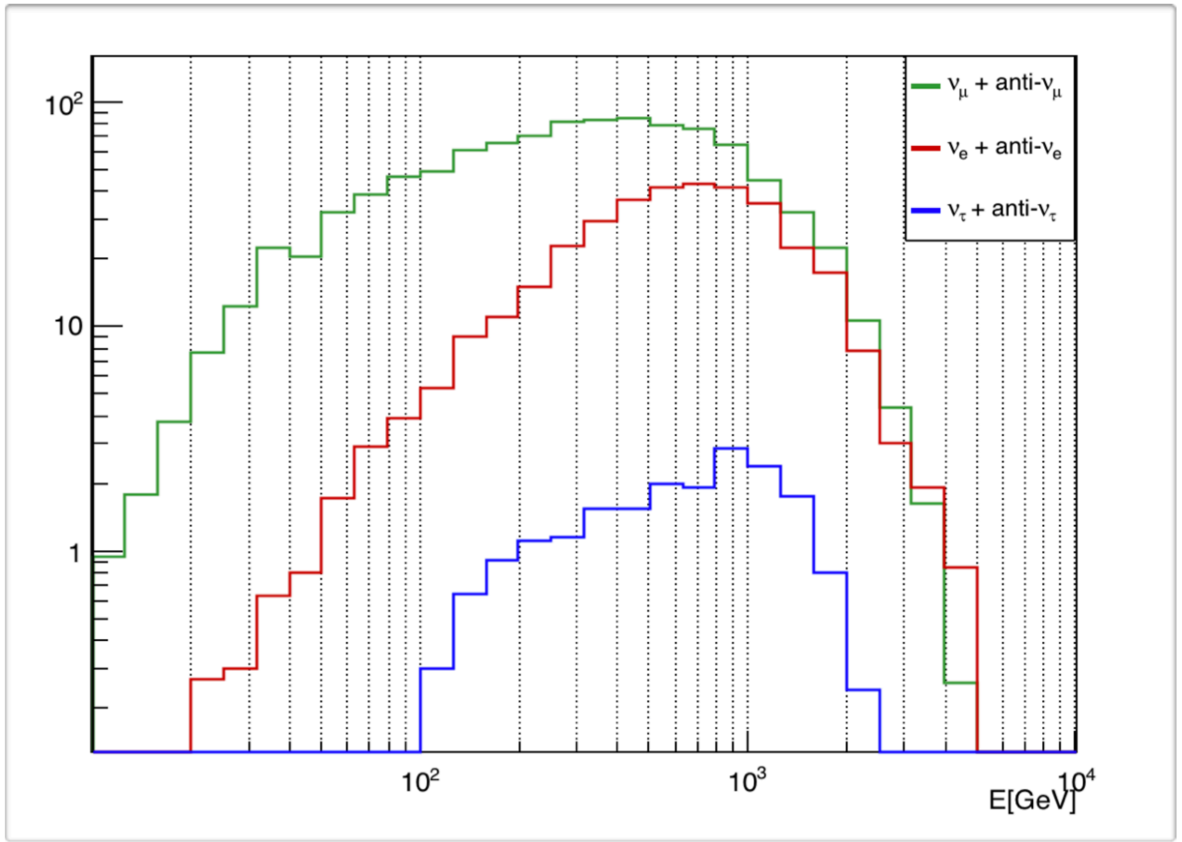
Measure HF production in so-far unexplored region
(not covered by any other LHC experiment)

LFU tests

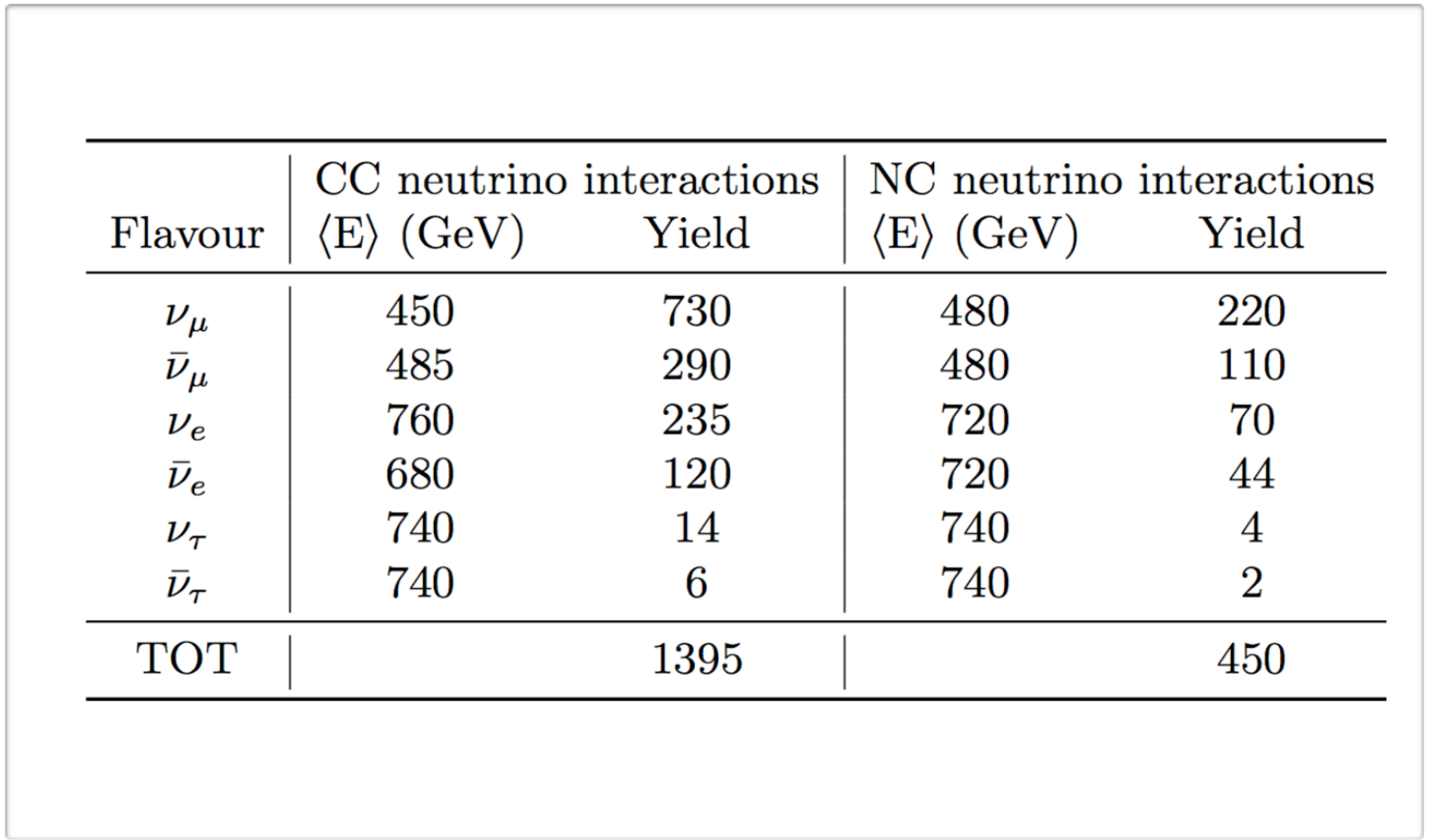
Search for FIPs and Light Dark Matter



- Spectra of neutrinos interacting in SND@LHC



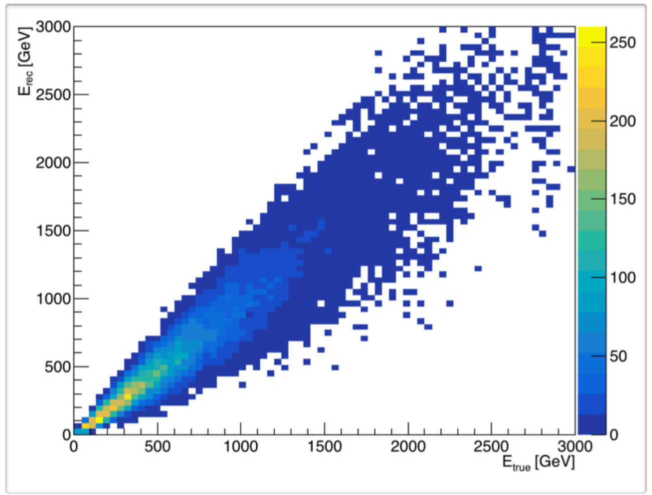
- Expectations in 150 fb^{-1}



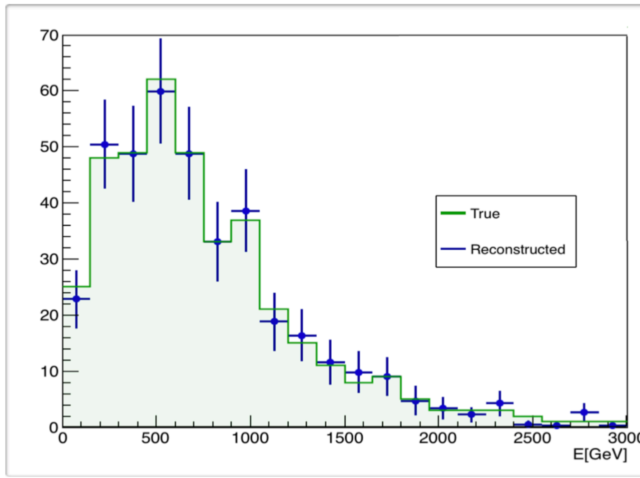
	CC neutrino interactions		NC neutrino interactions	
Flavour	⟨E⟩ (GeV)	Yield	⟨E⟩ (GeV)	Yield
ν_μ	450	730	480	220
$\bar{\nu}_\mu$	485	290	480	110
ν_e	760	235	720	70
$\bar{\nu}_e$	680	120	720	44
ν_τ	740	14	740	4
$\bar{\nu}_\tau$	740	6	740	2
TOT		1395		450

1. MEASUREMENT OF pp⟶ν_eX CROSS-SECTION

- 90% ν_e & anti-ν_e from the decay of charmed hadrons
- ν_e as a probe of charm production in this η range after unfolding instrumental effects
- Unfolding applied to the *measured* energy spectrum to retrieve the reconstructed energy
- Deconvolution of neutrino (SM) cross-section to get the flux in SND@LHC acceptance

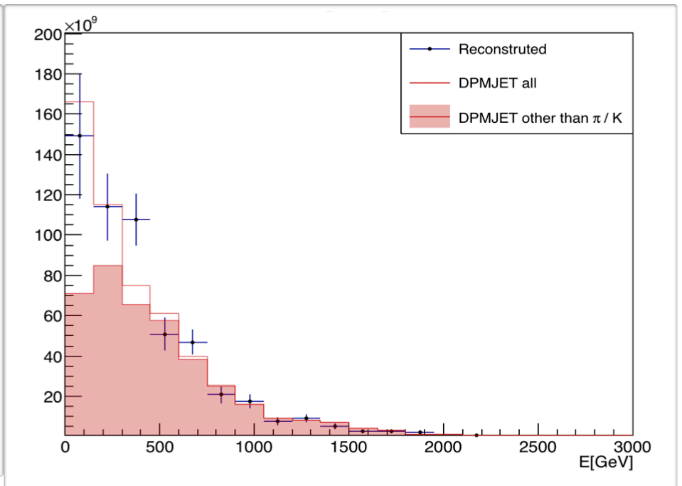


Response matrix (E_{rec} vs E_{true}) estimated with full simulation



Errors: statistical (entries in each bin) + systematic (unfolding procedure)

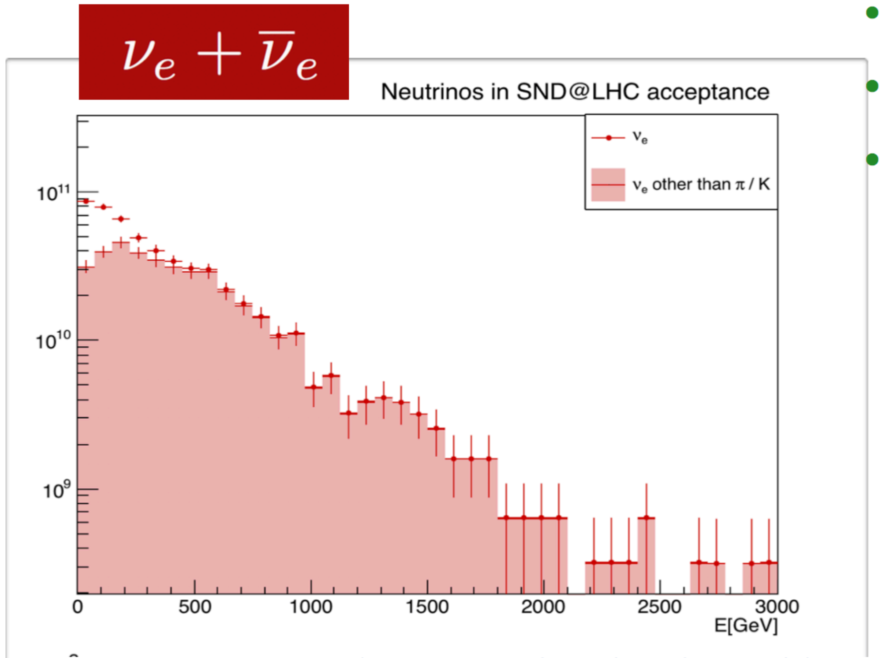
Uncertainty: 15%



Reconstructed ν_e flux at SND@LHC

3. Lepton flavour universality test in ν interactions

- The identification of 3 ν flavours offers a unique possibility to test LFU in ν interactions
  - ν_τs produced essentially only in D_s decays
  - ν_es produced in the decay of all charmed hadrons (D^0, D, D_s, Λ_c)
  - The ratio depends only on charm hadronisation fractions
  - Sensitive to ν-nucleon cross-section ratio



$$R_{13} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\tau+\overline{\nu}_\tau}} = \frac{\sum_i \tilde{f}_{c_i}\tilde{Br}(c_i \to \nu_e)}{\tilde{f}_{D_s}\tilde{Br}(D_s \to \nu_\tau)},$$

$$R_{13} = \frac{\nu_e}{\nu_\tau}$$

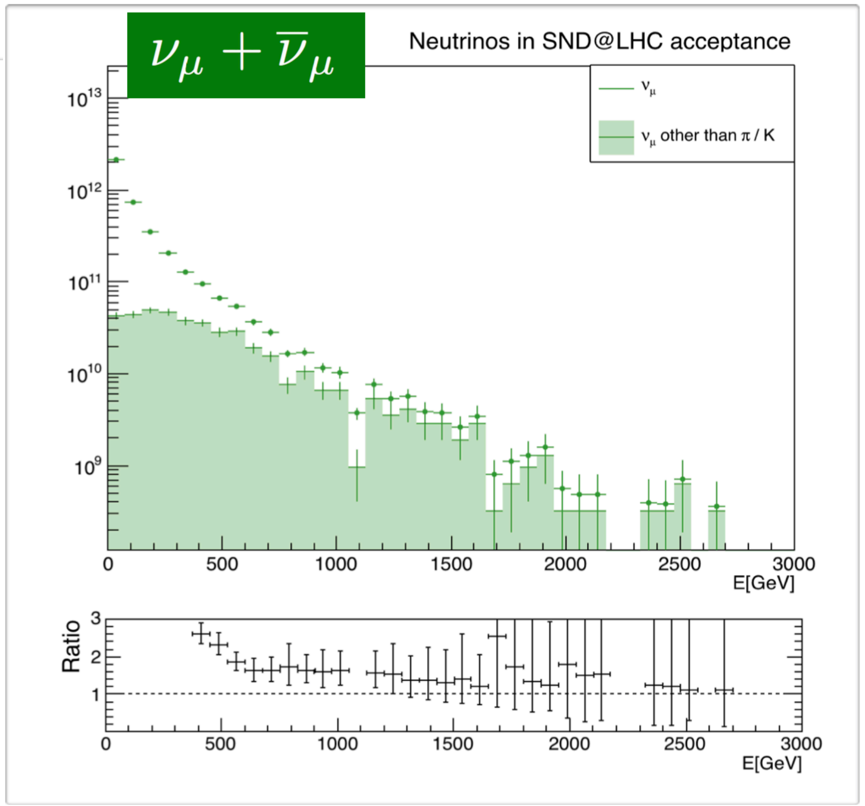
- Error on f_c evaluated as the discrepancy between Pythia8 and Herwig7 generators: **22%**

- ν_μ spectrum at low energies dominated by neutrinos produced in π/k decays
- For E>600 GeV the contamination of neutrinos from π/k keeps constant (~35%) with the energy

$N(\nu_\mu + \overline{\nu}_\mu)[E > 600\,GeV] = 294$ in 150 fb^{-1}

$N(\nu_e + \overline{\nu}_e)[E > 600\,GeV] = 191$ in 150 fb^{-1}

$$R_{12} = \frac{\nu_e}{\nu_\mu}$$

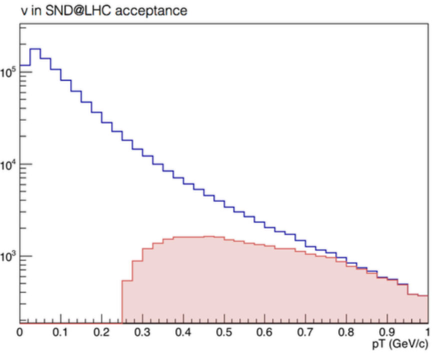


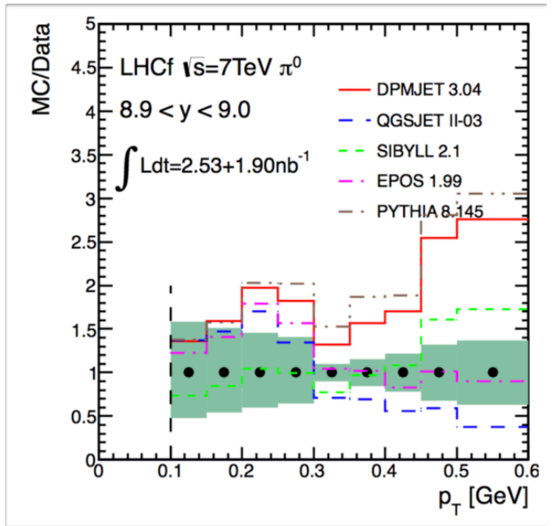
- ν_e/ν_μ as a LFU test in ν int for E>600 GeV
- No effect of uncertainties on f_c (and Br) since charmed hadrons decay almost equally in ν_μ and ν_e

$$R_{12} = \frac{N_{\nu_e+\overline{\nu}_e}}{N_{\nu_\mu+\overline{\nu}_\mu}} = \frac{1}{1+\omega_{\pi/k}}.$$

contamination from π/k

- Statistcal error: **10%**
- Systematic uncertainty from the knowledge of π/k contamination: **10%**





Phys. Rev. D 86, 092001 (2012)

FIPs!

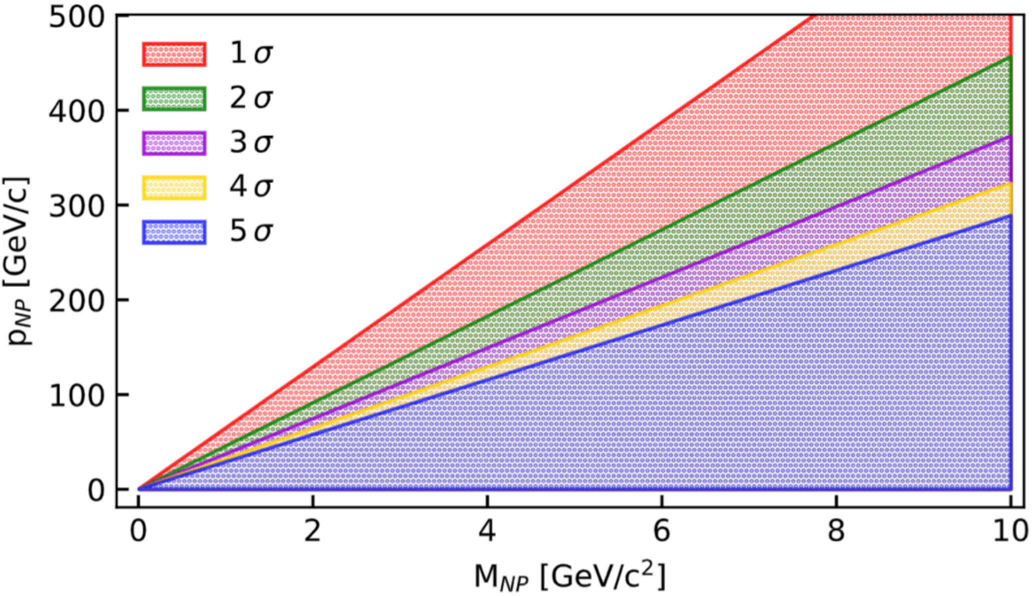
FEEBLY INTERACTING PARTICLES

- Search for Light Dark Matter scattering off atomic electrons

$$\chi e^- \rightarrow \chi e^-$$

	$\chi e \rightarrow \chi e$	
	Selection eff	Background
EL	3.6×10^{-2}	0.16
CC RES	4.0×10^{-3}	0.002
CC QE	2.2×10^{-2}	0.11

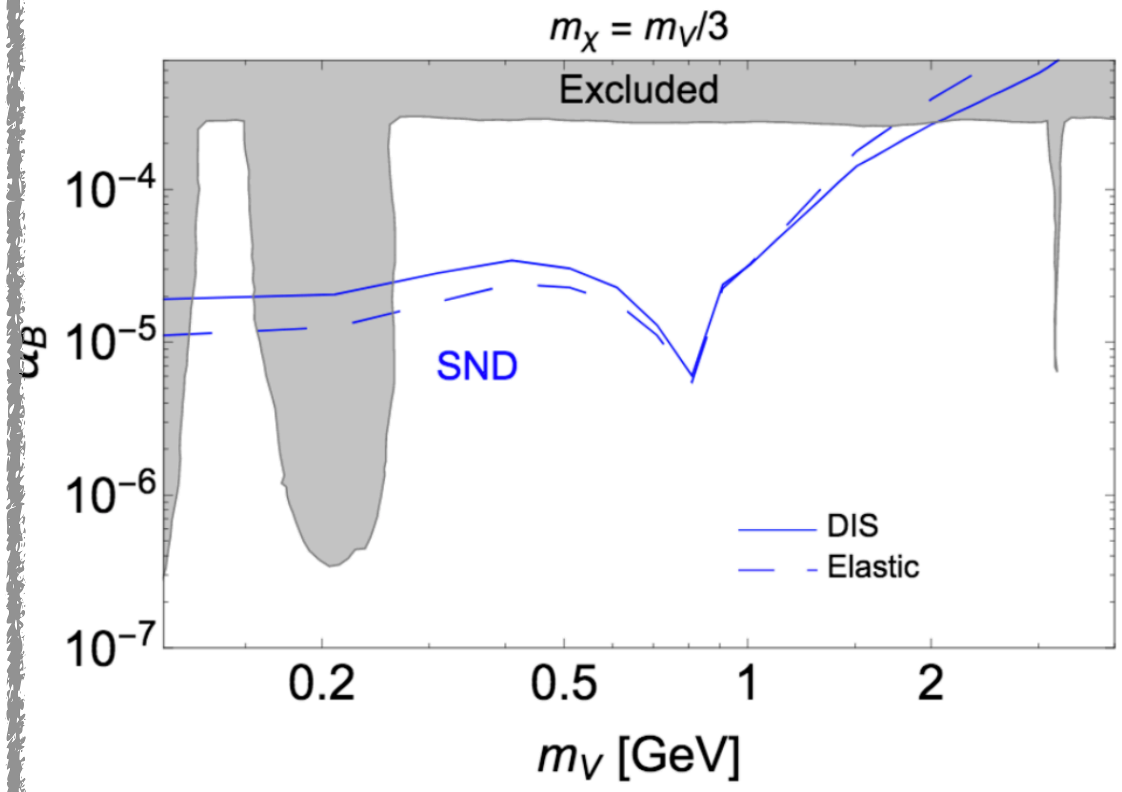
Further kinematical analysis to make the background negligible



Assume a time resolution of~200 ps, dominated by the bunch size

$$\mathcal{L}_{\text{leptophob}} = -g_B V^\mu J^B_\mu + g_B V^\mu(\partial_\mu\chi^\dagger\chi + \chi^\dagger\partial_\mu\chi),$$

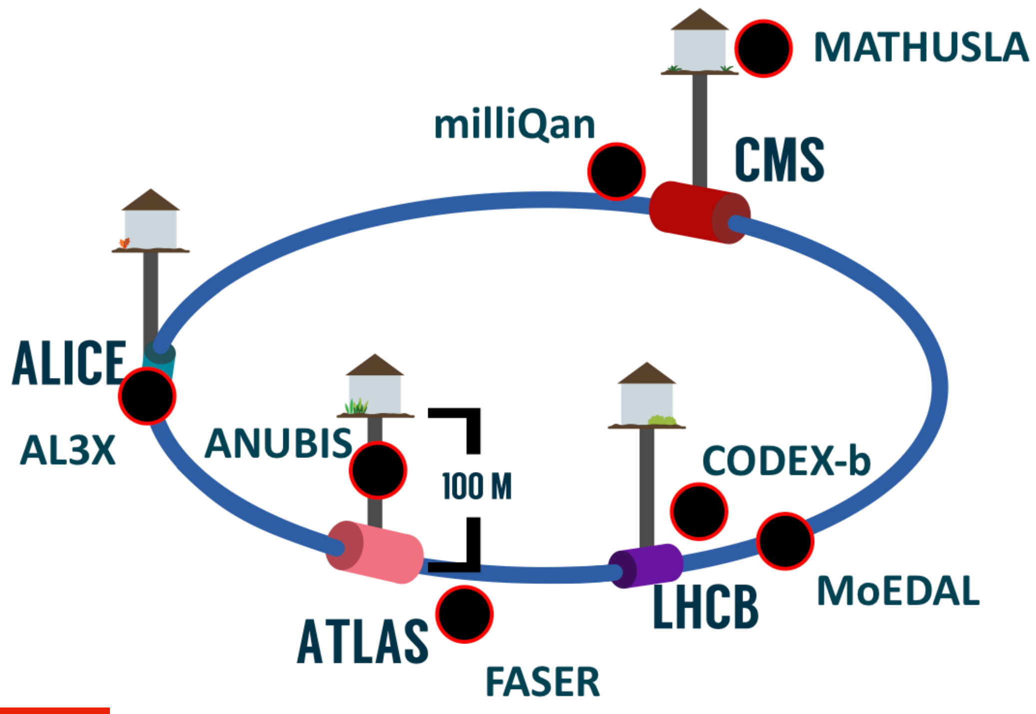
Current limits: CDF monojets, J/Ψ BES, E949
K rare decays, π^0 decays Brookhaven

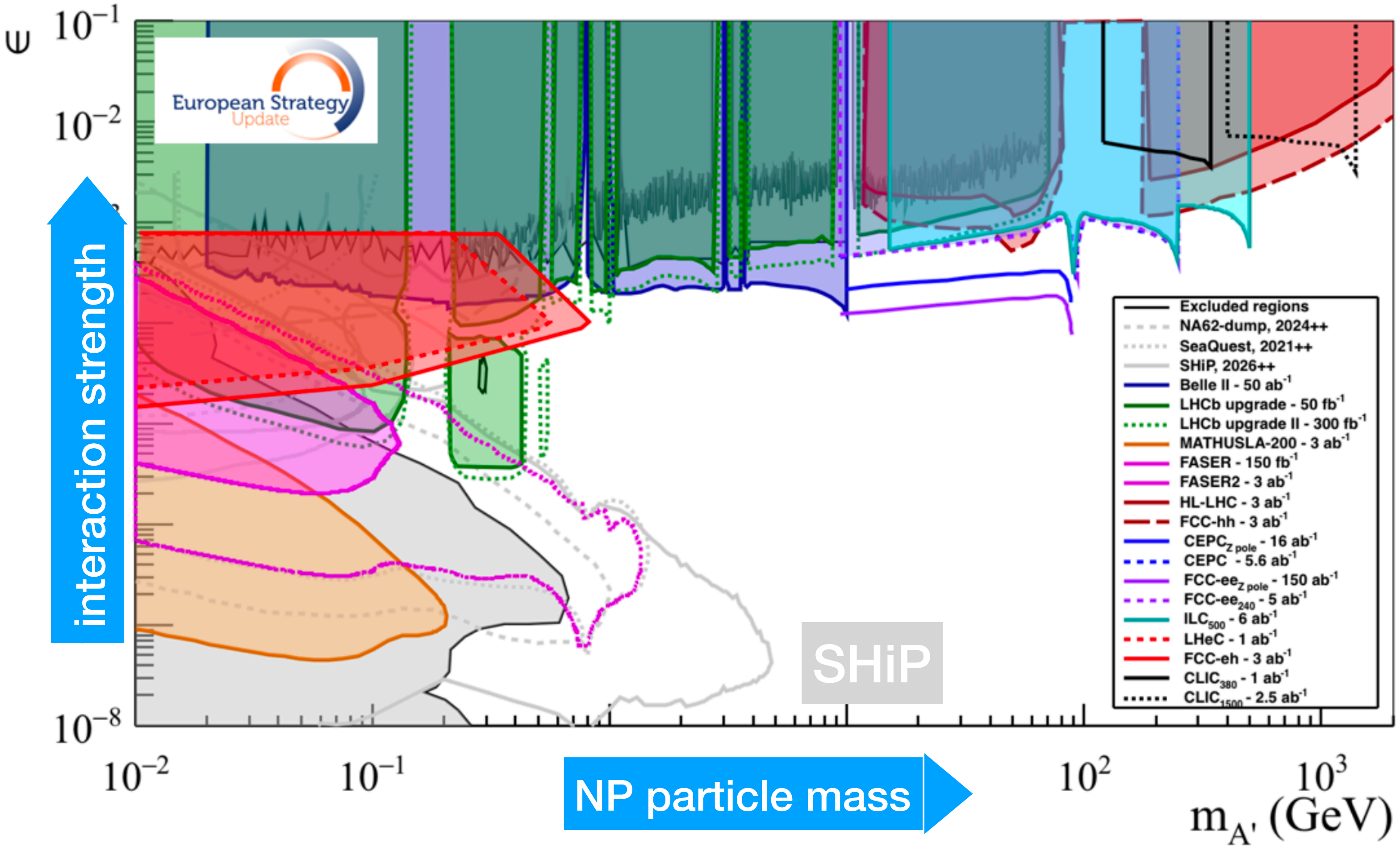


Feebly Interacting Particles

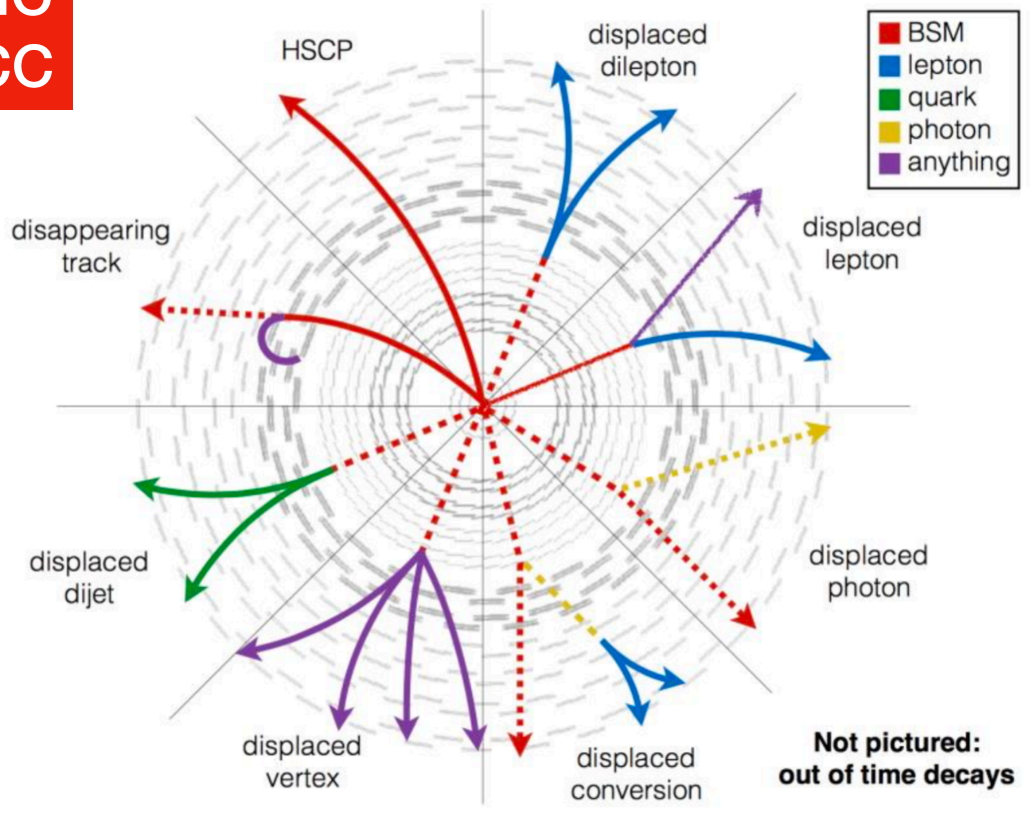
Explore the exotic & unconventional

New trigger strategies
New experimental signatures
New dedicated detectors
At LHC and beyond



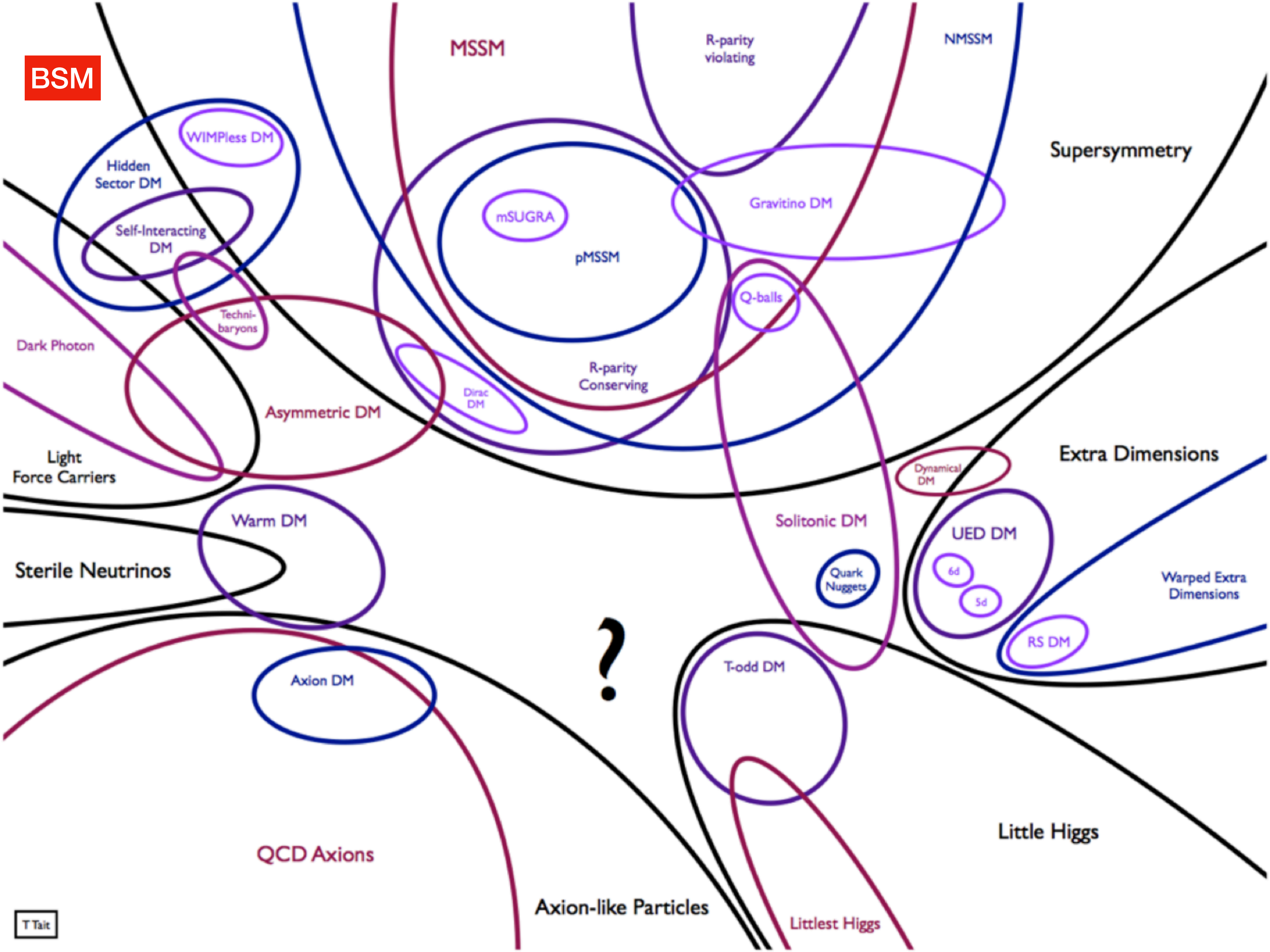


LHC
FCC



Not pictured: out of time decays

BSM


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
Dark Photon
Asymmetric DM
Light Force Carriers
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dynamical DM
Extra Dimensions
Warm DM
Sterile Neutrinos
Solitonic DM
Quark Nuggets
UED DM
6d
5d
Warped Extra Dimensions
RS DM
?
Axion DM
T-odd DM
QCD Axions
Little Higgs
Axion-like Particles
Littlest Higgs

T Tait

a *flavour*ful summary

- **flavour** is at the core of the SM, facilitates precision tests
- **flavour** provides portal to BSM, sensitivity well beyond √s
- **flavour** anomalies (LHC and elsewhere) currently hottest topic
- **flavour** observable and global fits hinting to possible NP ↔ μ
- **flavour** measurements actively evolving (last weeks: LFU, MU g-2)
- **flavour** at the LHC is now reaching also the neutrino sector
- **flavour** has bright future, at **LHC**, HL-LHC, Belle||, FNAL, etc

any question, interest, contact me: ***nuno@cern.ch***