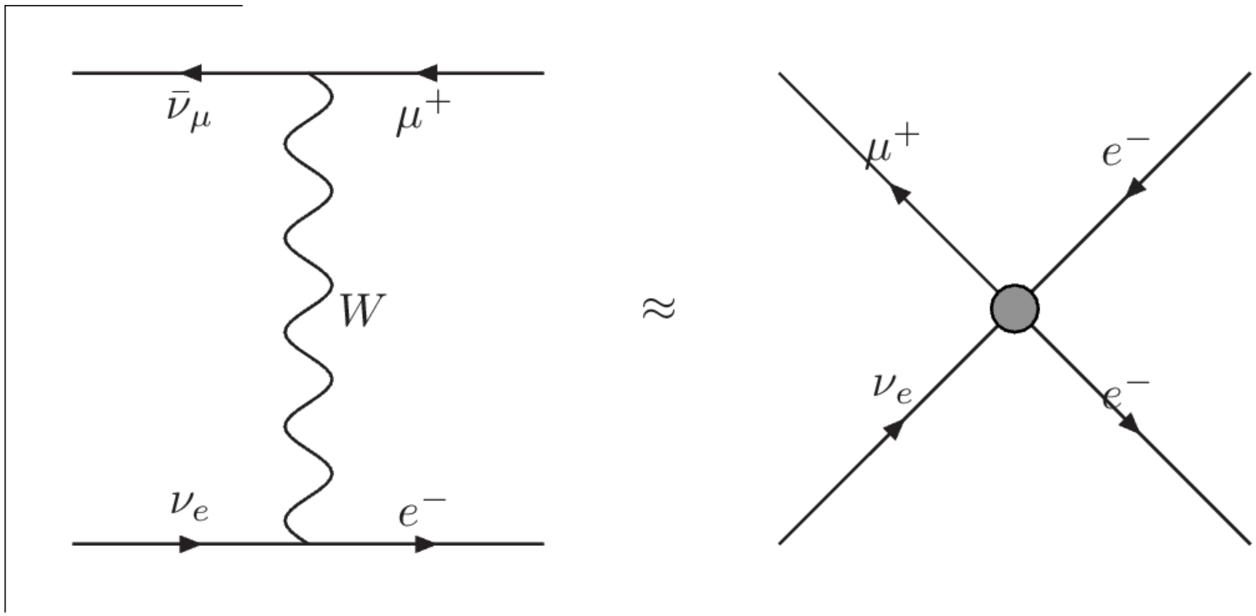
Contact Operators



At p^μ around or bigger than M_W, this approximation is bad and the rest of the propagator should be included. This method can be useful for parameterising searches for new physics at low momentum: these four-fermion operators are often called *contact operators*, e.g. for dark matter $\mathcal{L} = (\bar{q}\gamma^\mu q)(\chi\gamma_\mu\chi)$. However, for dark matter production at the LHC (e.g. in the monojet channel), the energies are often higher than the messenger mass and so a more precise (simplified?) model is needed.

Anomalous Magnetic Moment of the Muon

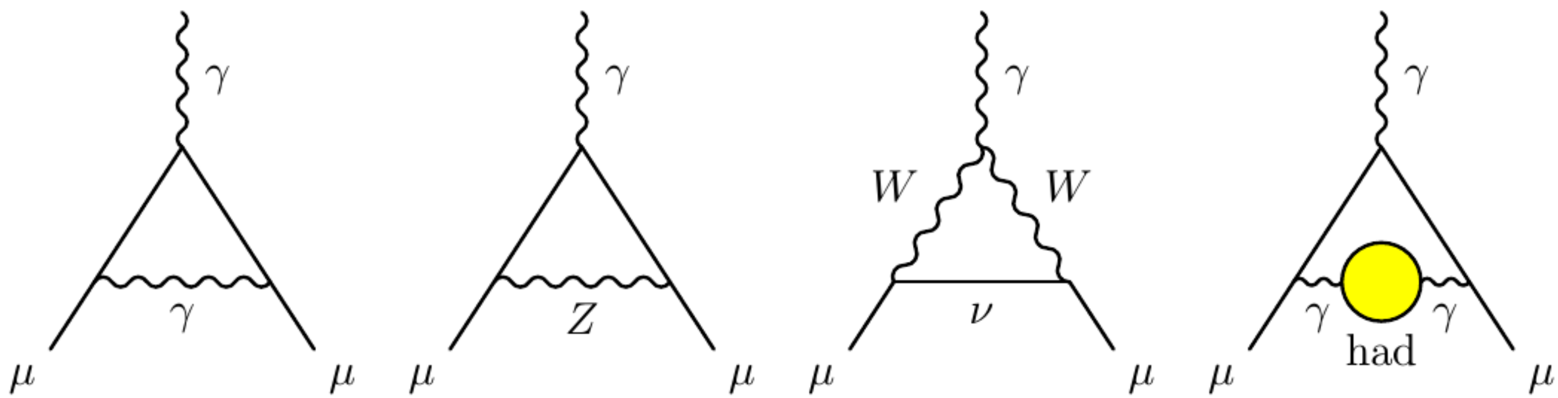
This is a particular interaction between the photon and the muon: the Dirac equation predicts a muon magnetic moment

$$\vec{M} = g_\mu \frac{e}{2m_\mu} \vec{S},$$

and at tree level, $g_\mu = 2$. However, it can be measured very precisely by storing muons in a ring with magnetic fields, then measuring the *precession frequency* of their spins. The 'anomalous' part comes from loops involving various particles:

$$a_\mu \equiv \frac{g_\mu - 2}{2}.$$

$$a_\mu^{\mathrm{exp}} = 11659209.1(5.4)(3.3) \times 10^{-10},$$
$$a_\mu^{\mathrm{SM}} = 11659180.3(4.2)(2.6) \times 10^{-10}.$$



$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 28.8(6.3)(4.9) \times 10^{-10}.$$

The measurement is thus discrepant at around the $\sim 3.6\sigma$

level, and has been for 20 years. There should be news on it from Fermilab, soon.

$R-$Parity Violation

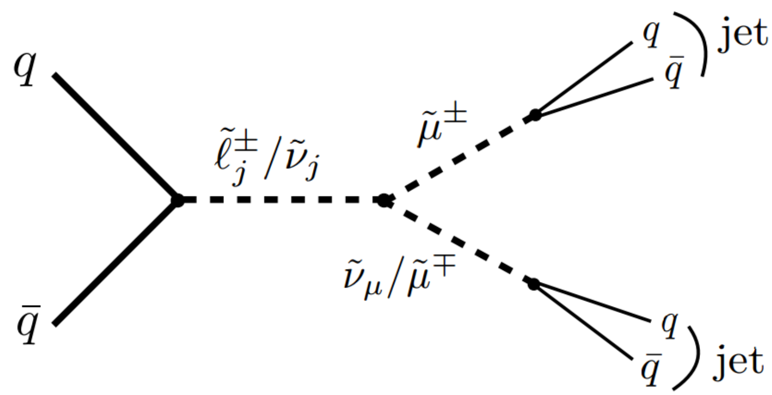
Allanach's conjecture:

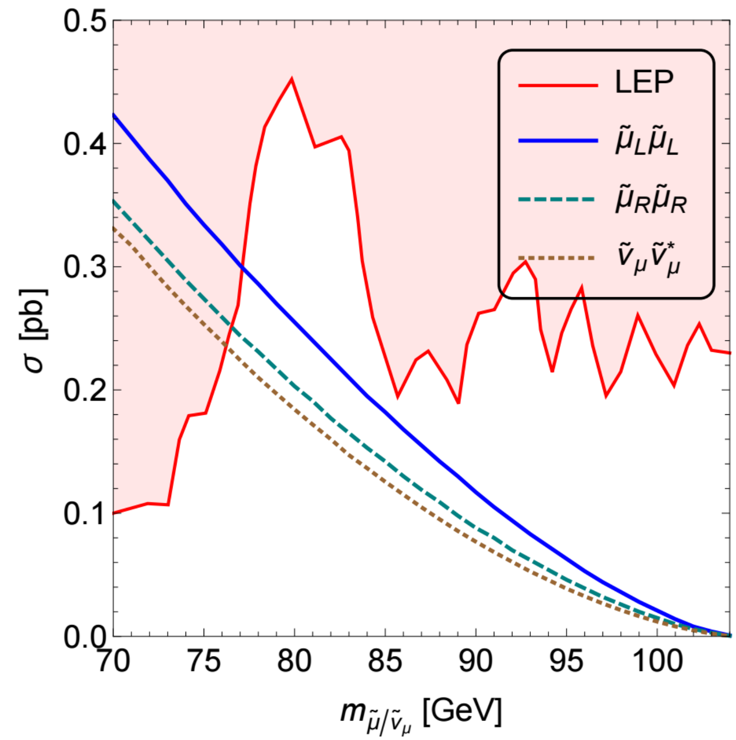
"*Any excess can be explained with $R-$parity violating supersymmetry.*"

“The Last Refuge of The Scoundrel”

$$W_{LV} = \lambda'_{j11} L_1 Q_1 \bar{D}_1 + \lambda'_{2kl} L_2 Q_k \bar{D}_l$$

$$L_{LV}^{soft} = A_{j22} \tilde{l}_j \tilde{l}_2 \tilde{\mu}_R^+ + (H.c.)$$



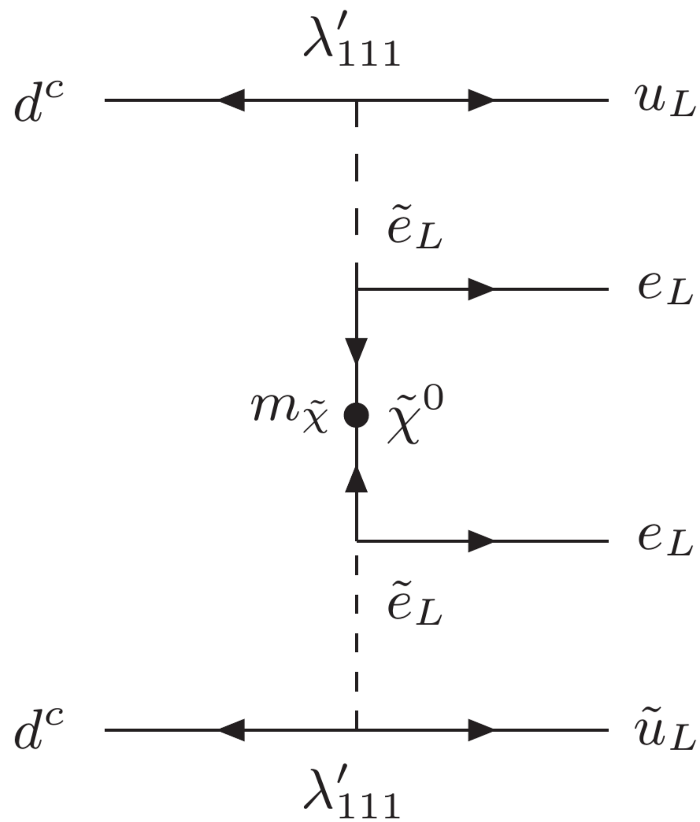


No leptons in final state

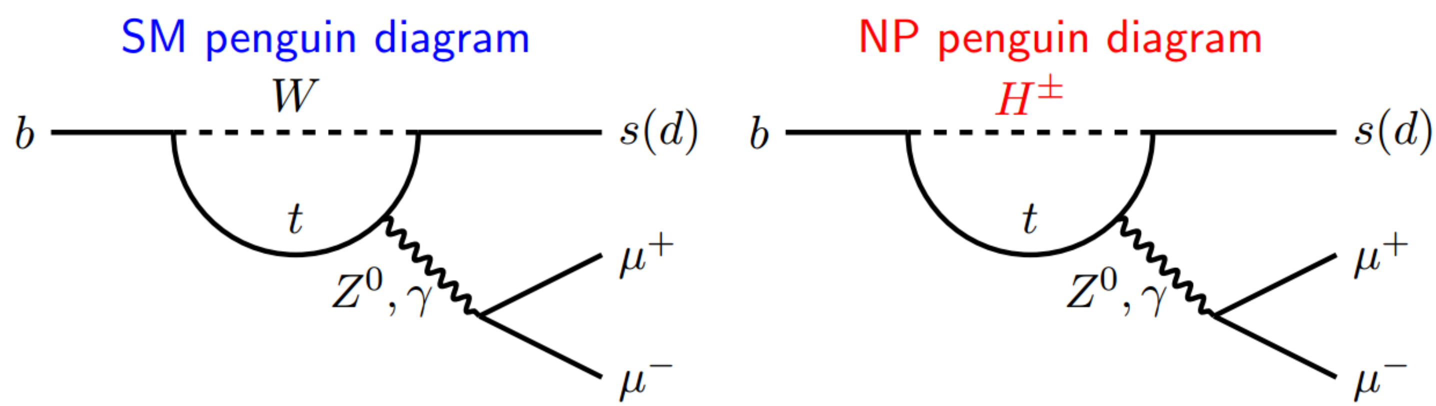
Allanach, Dev, Sakurai `arXiv:1511.01483`

Neutrinoless Double β Decay

Is *banned* in the Standard Model because it breaks lepton number: $Z \to (Z+2)e^-e^-$ Present bound from GERDA is $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yr. It should increase by a factor 10 in the next year or so.



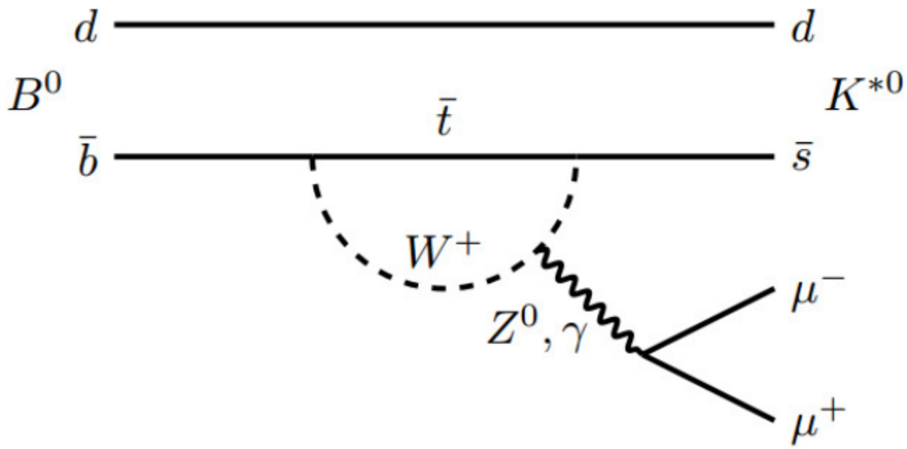
Discovering solutions to B physics anomalies

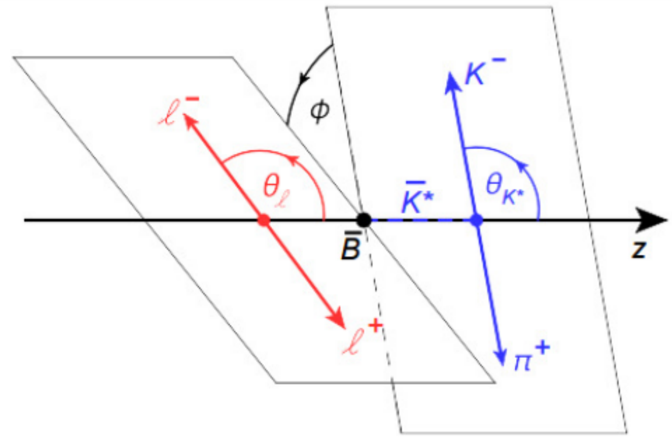


- FCNC decays loop suppressed and rare in the Standard Model
- New heavy particles in could appear in competing diagrams can affect the branching ratio and angular

distributions

$B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

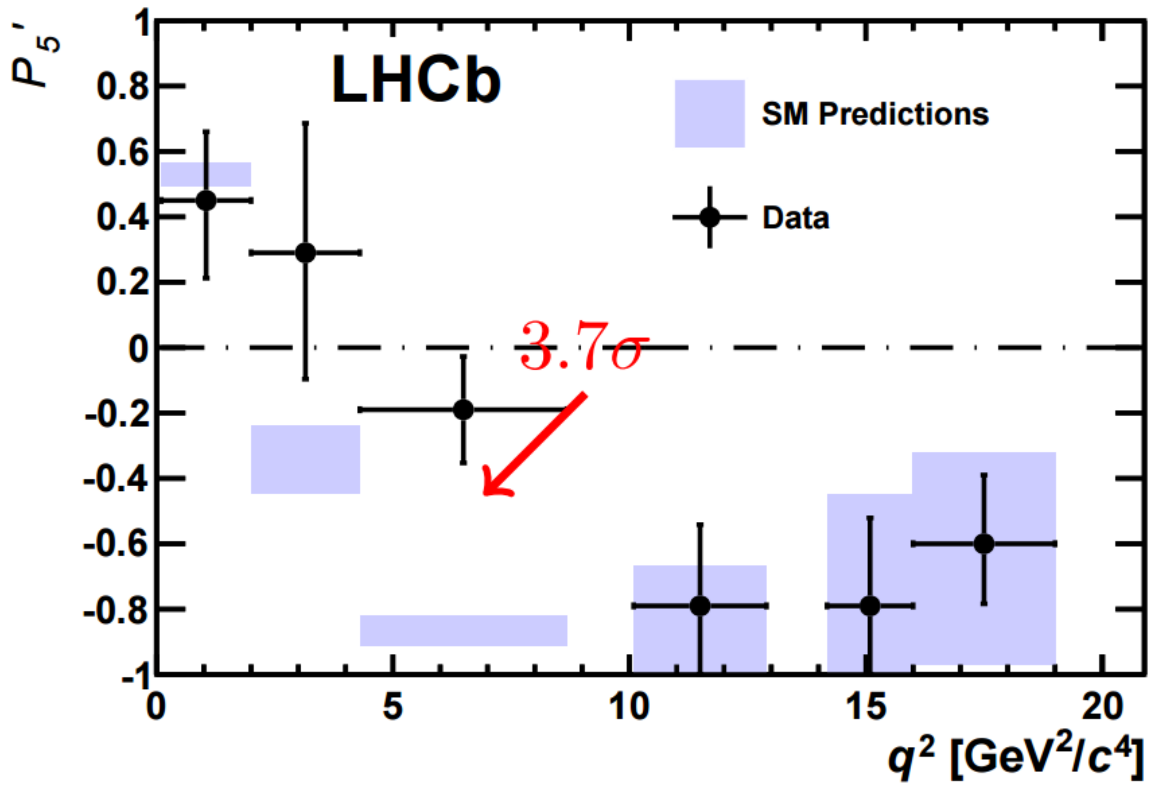




Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

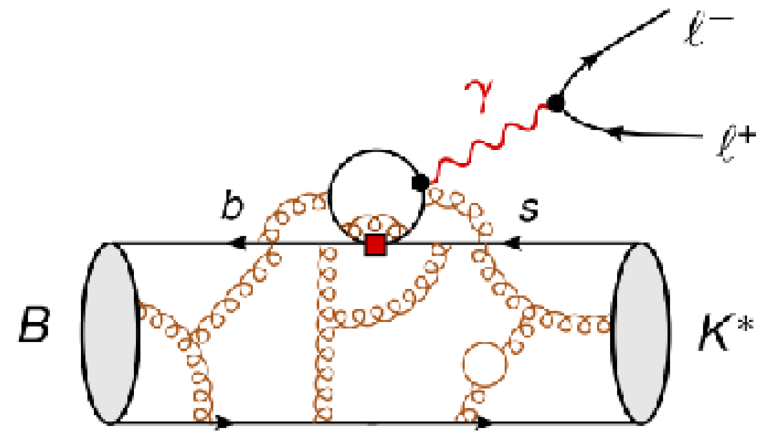
P_5'



$P_5' = S_5/\sqrt{F_L(1-F_L)}$, leading form factor uncertainties cancel. Tension already in 1 fb^{-1} and confirmed in 3 fb^{-1} LHCb-CONF-2015-002

Hadronic Uncertainties

- Hadronic effects like charm loop are photon-mediated $\Rightarrow$ vector-like coupling to leptons just like C_9

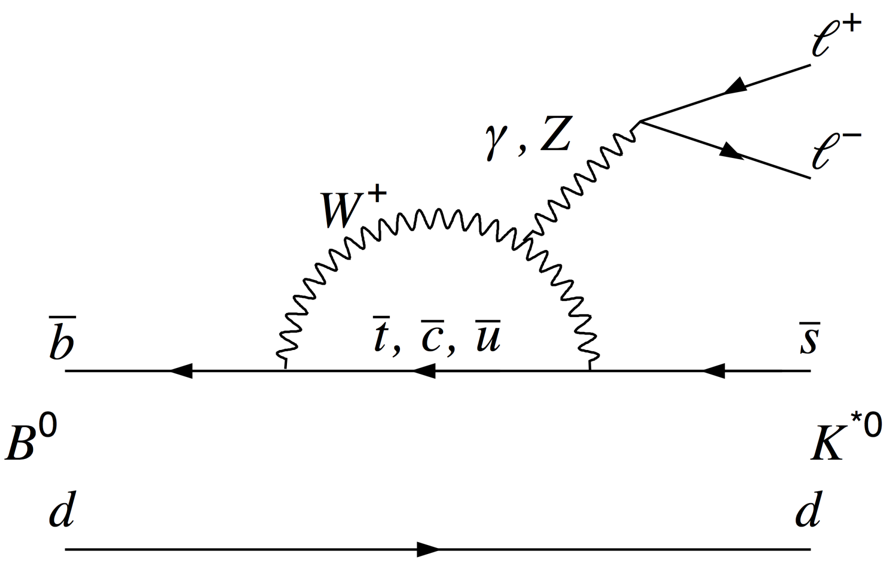


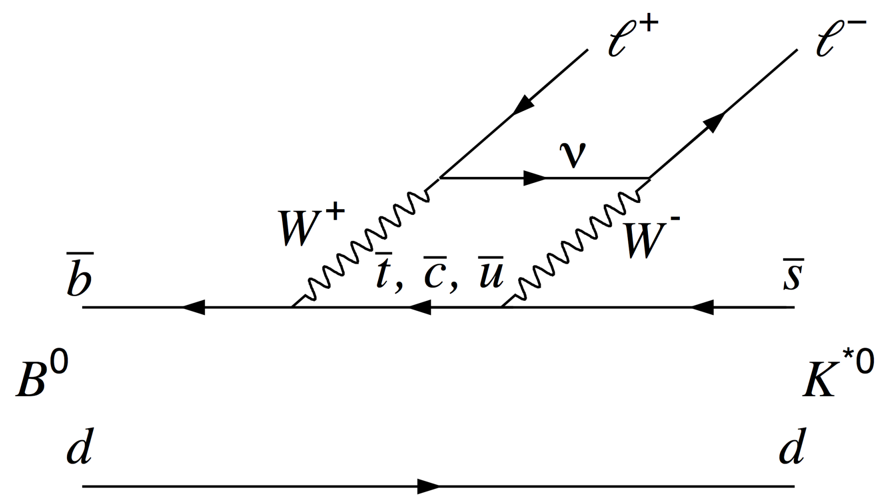
- How to disentangle NP $\leftrightarrow$ QCD?
  - Hadronic effect can have different q^2 dependence
  - Hadronic effect is lepton flavour universal ($\rightarrow R_K$!)

$R_K^{(*)}$ in Standard Model

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}, \qquad R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

These are rare decays (each BR$\sim \mathcal{O}(10^{-7})$) because they are absent at tree level in SM.

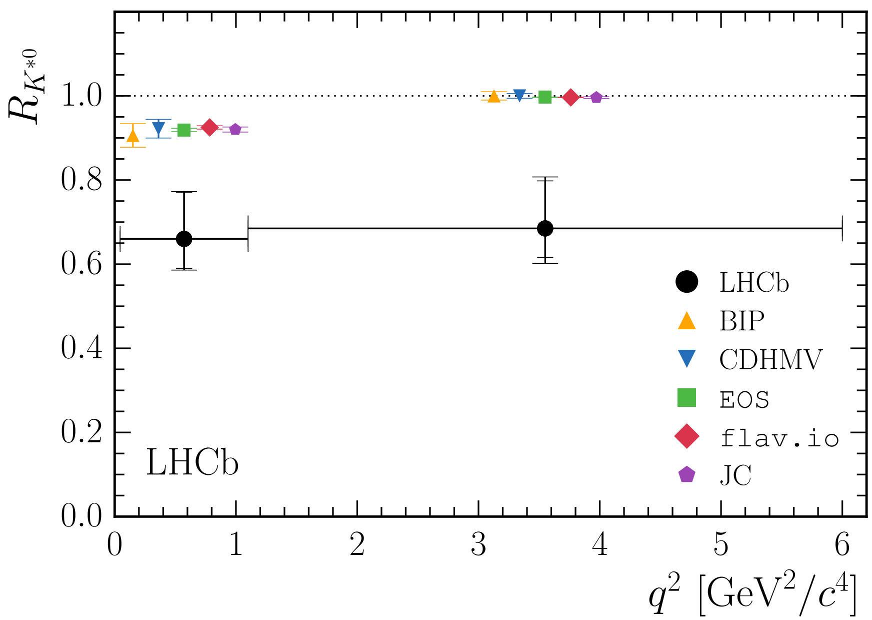


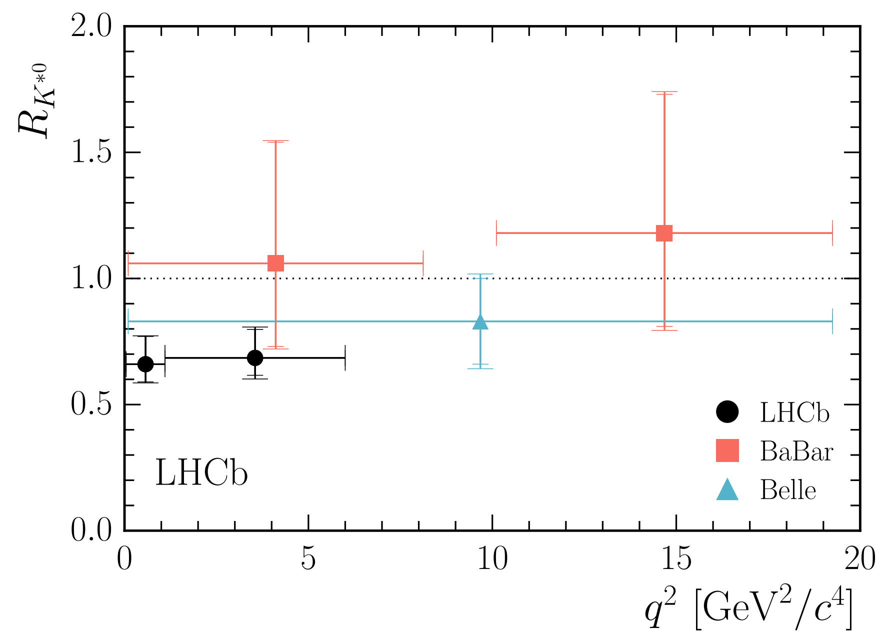


$R_{K^{(*)}}$ Measurements

LHCb results from 7 and 8 TeV: $q^2 = m_{ll}^2$.

	q^2/GeV^2	SM	LHCb 3 fb	σ
R_K	$[1, 6]$	1.00 ± 0.01	$0.745^{+0.090}_{-0.074}$	2.6
R_{K^*}	$[0.045, 1.1]$	0.91 ± 0.03	$0.66^{+0.11}_{-0.07}$	2.2
R_{K^*}	$[1.1, 6]$	1.00 ± 0.01	$0.69^{+0.11}_{-0.07}$	2.5





Wilson Coefficients $\bar{c}^l_{ij}$

In SM, can form an EFT since $m_B \ll M_W$:

$$\mathcal{O}^l_{ij} = (\bar{s}\gamma^\mu P_i b)(\bar{l}\gamma_\mu P_j l)\,.$$

$$\mathcal{L}_{\text{eff}} \supset \sum_{l=e,\mu,\tau} \sum_{i=L,R} \sum_{j=L,R} \frac{c^l_{ij}}{\Lambda^2_{l,ij}} \mathcal{O}^l_{ij}\,,$$

$$= \sum_{l=e,\mu,\tau} V_{tb}V^*_{ts} \frac{\alpha}{4\pi v^2} \left(\bar{c}^l_{LL}\mathcal{O}^l_{LL} + \bar{c}^l_{LR}\mathcal{O}^l_{LR}\right.$$

$$\left. + \bar{c}^l_{RL}\mathcal{O}^l_{RL} + \bar{c}^l_{RR}\mathcal{O}^l_{RR}\right)$$

$$\Rightarrow \bar{c}^l_{ij} = (36\ \text{TeV}/\Lambda)^2 c^l_{ij}.$$

$c^l_{ij} \sim \pm\mathcal{O}(1)$ all predicted by weak interactions in SM.

Which Ones Work?

Options *for a single* *BSM* *operator*:

- $\bar{c}^{e}_{ij}$ operators fine for $R_{K^{(*)}}$ but are disfavoured by global fits including other observables.
- $\bar{c}^{\mu}_{LR}$ disfavoured: predicts *enhancement* in both R_K and R_{K^*}
- $\bar{c}^{\mu}_{RR}$, $\bar{c}^{\mu}_{RL}$ disfavoured: they pull R_K and R_{K^*} in *opposite directions*.
- $\bar{c}^{\mu}_{LL} = -1.33 \pm 0.34$ fits well globally[1].

[1] D'Amico et al, 1704.05438.

Statistics[2]

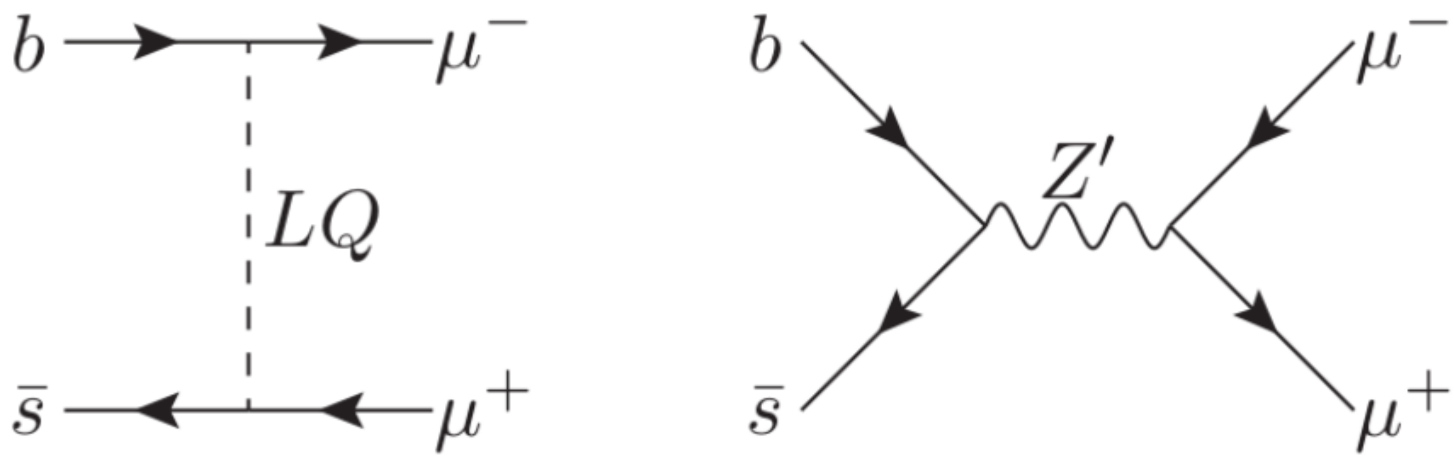
	$\bar{c}^{\mu}_{LL}$	$\sqrt{\chi^2_{SM} - \chi^2_{best}}$
clean	-1.33 ± 0.34	4.1
dirty	-1.33 ± 0.32	4.6
all	-1.33 ± 0.23	6.2
	$C_9^{\mu} = (\bar{c}^{\mu}_{LL} + \bar{c}^{\mu}_{LR})/2$	$\sqrt{\chi^2_{SM} - \chi^2_{best}}$
clean	-1.51 ± 0.46	3.9
dirty	-1.15 ± 0.17	5.5
all	-1.19 ± 0.15	6.7

Table 1: A fit to flavour anomalies for 'clean' (R_K, R_{K^*}, $B_s \to \mu\mu$) and 'dirty' (100 others) observables

[2] D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano 1704.05438

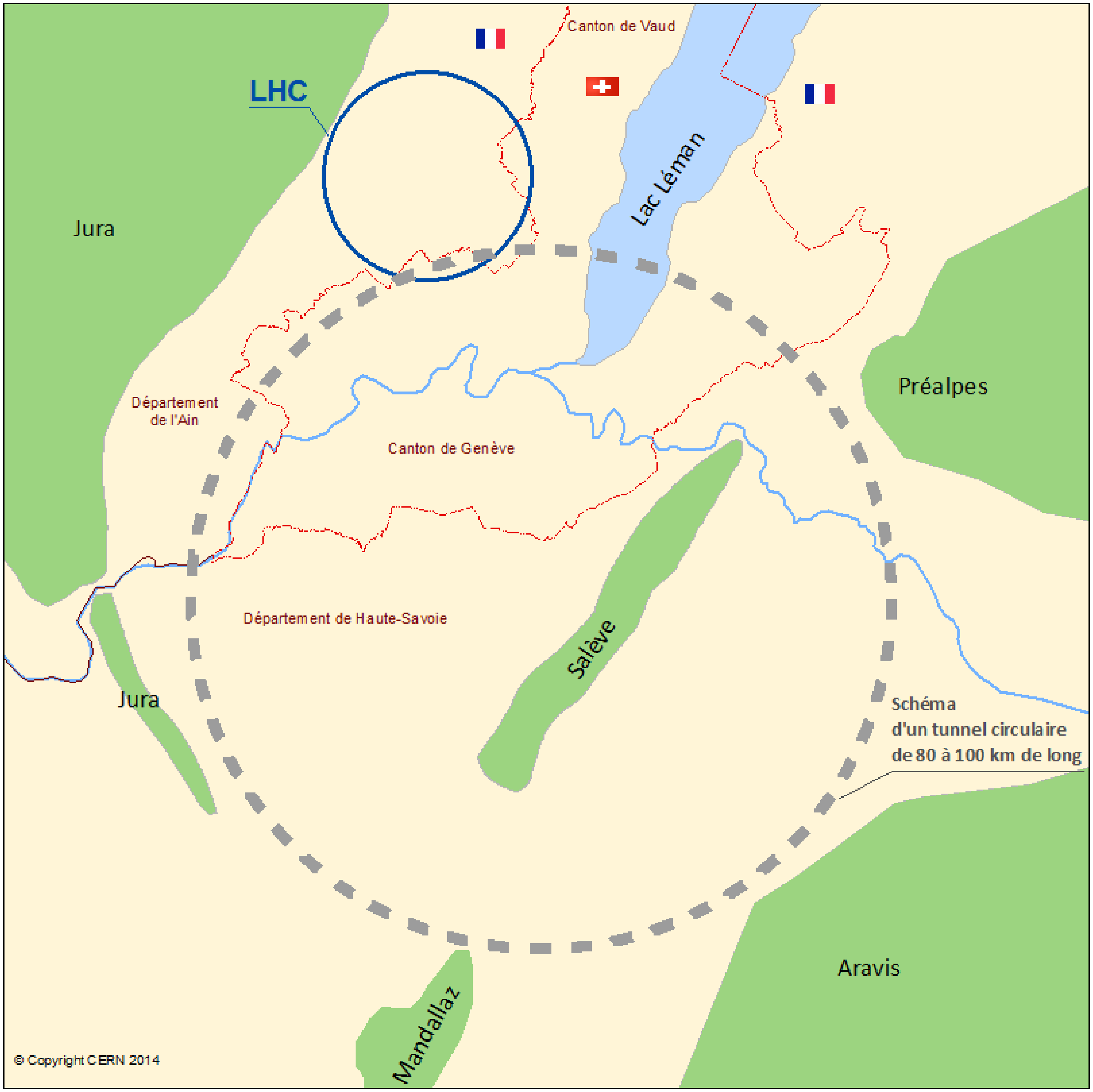
Simplified Models for c_{LL}^{μ}

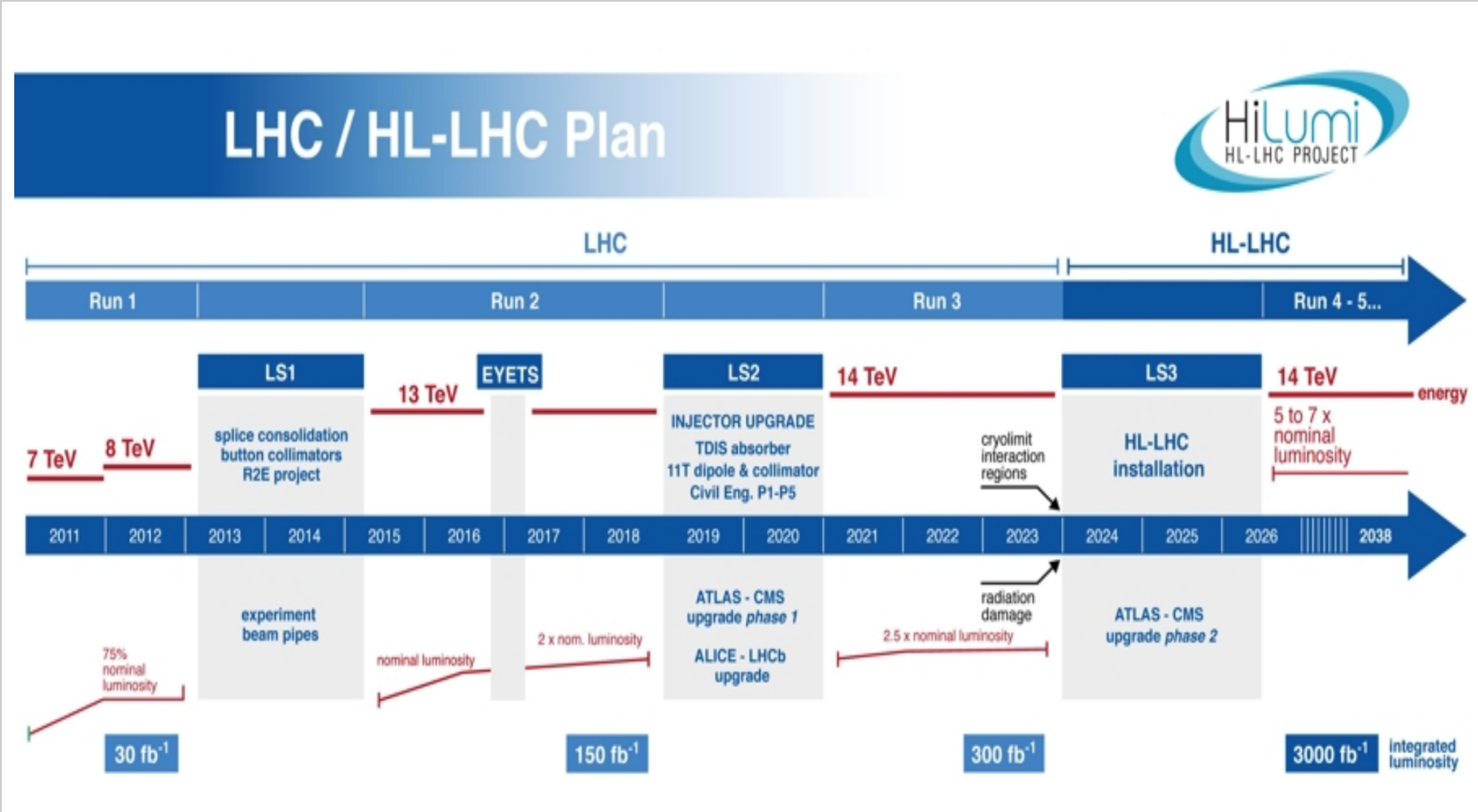
At tree-level, we have:



At loop-level, there are many more possibilities but the particles are 4π lighter: they are much easier to detect.

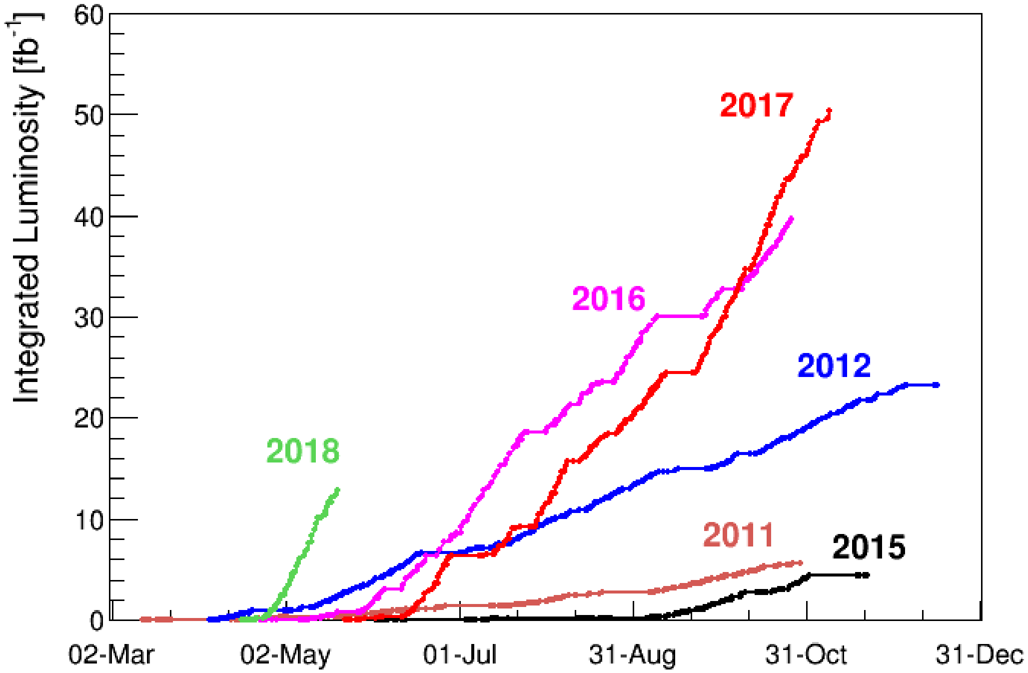
Principle of Maximal Pessimism


Canton de Vaud
LHC
Lac Léman
Jura
Département
de l'Ain
Canton de Genève
Préalpes
Département de Haute-Savoie
Salève
Jura
Schéma
d'un tunnel circulaire
de 80 à 100 km de long
Aravis
Mandallaz
© Copyright CERN 2014



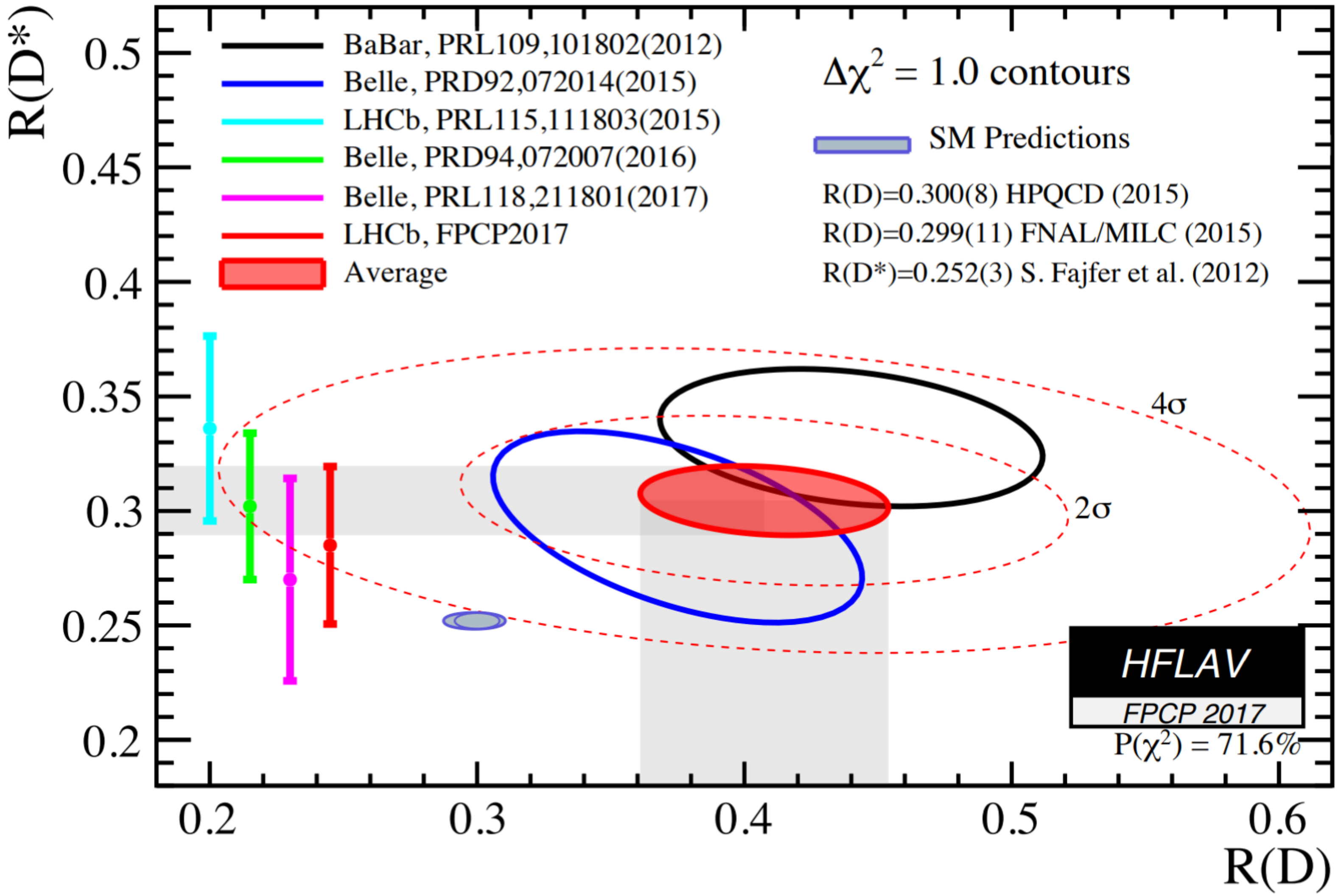
LHC / HL-LHC Plan
HiLumi
HL-LHC PROJECT
LHC
HL-LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS2
LS3
7 TeV
8 TeV
13 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5
cryolimit
interaction
regions
HL-LHC
installation
5 to 7 x
nominal
luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2038
radiation
damage
experiment
beam pipes
ATLAS - CMS
upgrade phase 1
ALICE - LHCb
upgrade
ATLAS - CMS
upgrade phase 2
75%
nominal
luminosity
nominal luminosity
2 x nom. luminosity
2.5 x nominal luminosity
30 fb-1
150 fb-1
300 fb-1
3000 fb-1
integrated
luminosity

LHC Upgrades



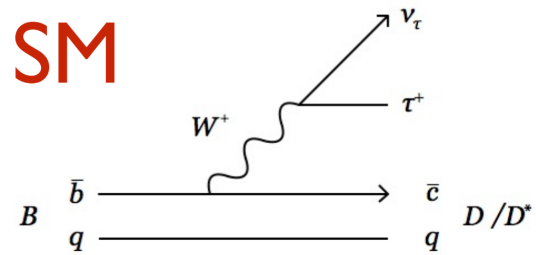
High Luminosity (HL) LHC: go to 3000 fb^{-1} (3 ab^{-1}).
High Energy (HE) LHC: Put FCC magnets (16 Tesla rather than 8.33 Tesla) into LHC ring: roughly *twice* collision energy: 27 TeV.

$$R_{D^{(*)}} = BR(B^- \to D^{(*)}\tau\nu)/BR(B^- \to D^{(*)}\mu\nu)$$



BSM Explanation

. . . has to compete with



$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\tau}_L\gamma_\mu\nu_{\tau L}\right) + H.c.$$

$$\Lambda = 3.4 \text{ TeV}$$

A factor 10 lower than required for $R_{K^{(*)}} \Rightarrow$ *different explanation?*

PMP$\Rightarrow$we ignore $R_{D^{(*)}}$.

Z' $\mu\mu$ ATLAS 13 TeV 36 fb^{-1}

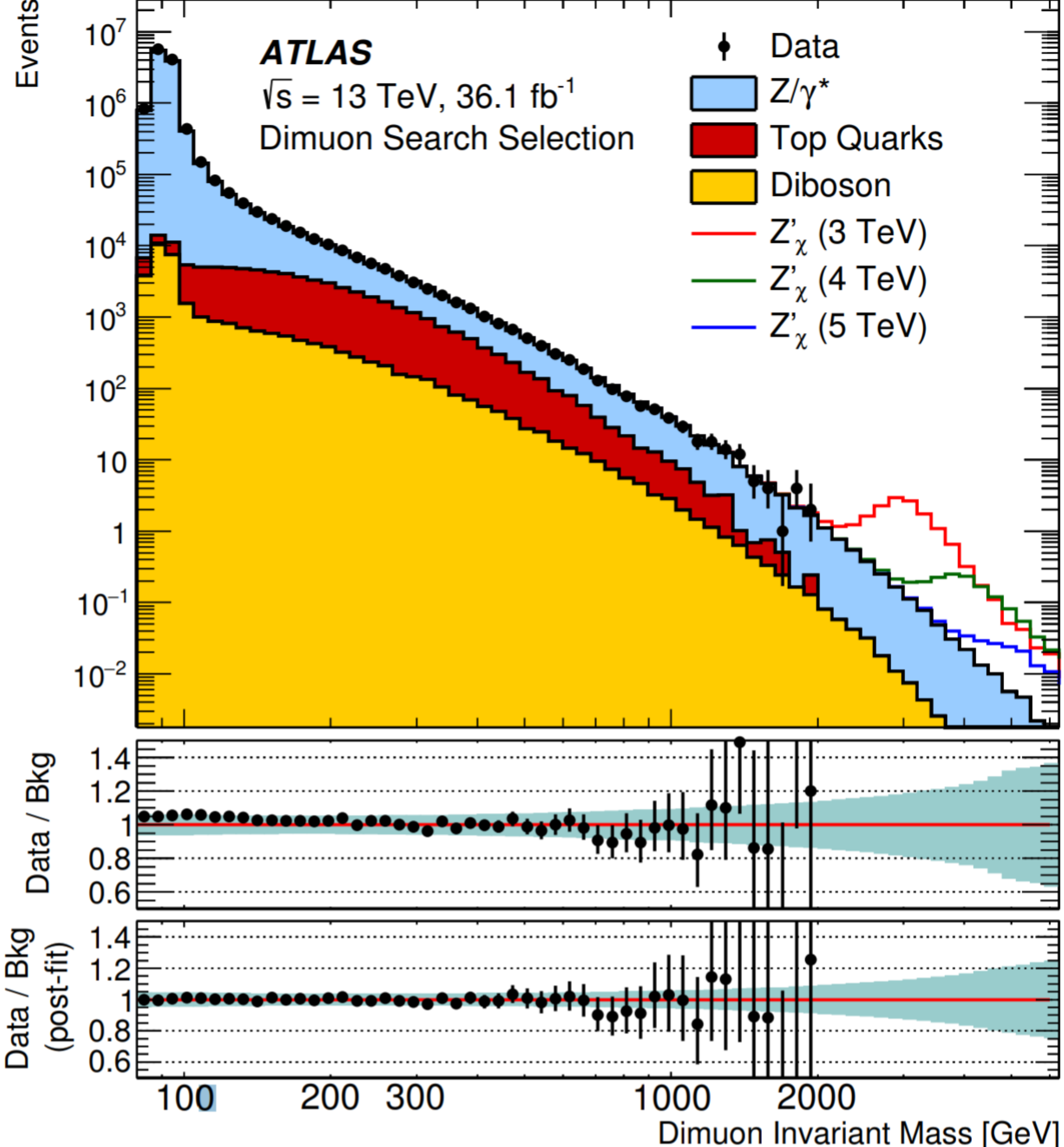
ATLAS analysis: look for two track-based isolated μ, $p_T > 30$ GeV. One reconstructed primary vertex. Keep only highest scalar sum p_T pair[3].

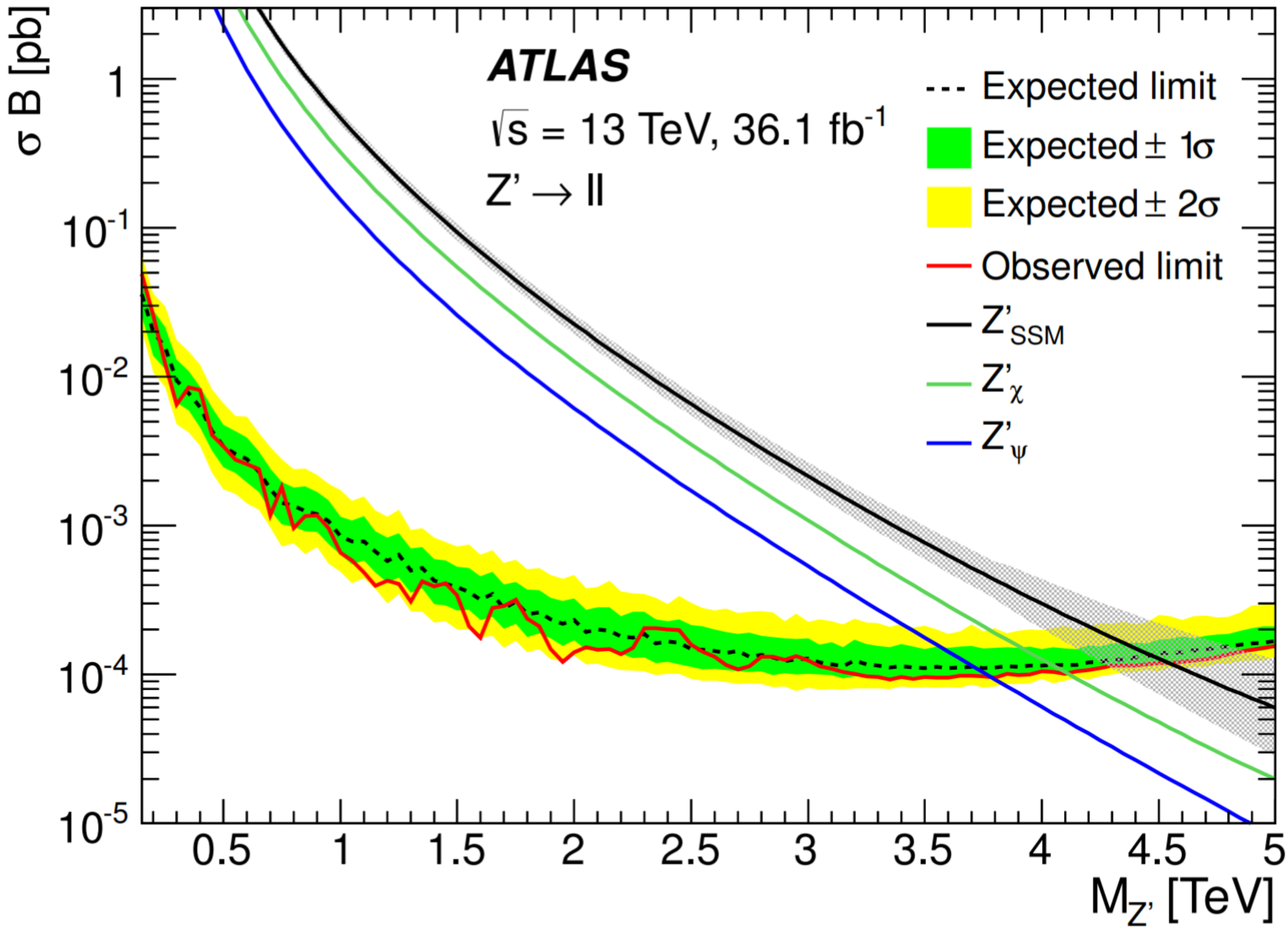
$$m^2_{\mu_1\mu_2} = (p_1^\mu + p_2^\mu)\left(p_{1\mu} + p_{2\mu}\right)$$

CMS also have released[4] a similar 36 fb^{-1} analysis.

[3] 1707.02424

[4] 1803.06292


ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Dimuon Search Selection
Data
Z/γ*
Top Quarks
Diboson
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
Data / Bkg
Data / Bkg (post-fit)
Dimuon Invariant Mass [GeV]



ATLAS
√s = 13 TeV, 36.1 fb-1
Z' → ll
Expected limit
Expected ± 1σ
Expected ± 2σ
Observed limit
Z'SSM
Z'χ
Z'ψ
σ B [pb]
MZ' [TeV]

1607.03669

Limit Extrapolotion

Have 95% CL limits on $[\sigma \times BR](s_0,\ L_0;\ M_{Z'})$ at eg $\sqrt{s_0} = 13$ TeV and $L_0 = 3.2$ fb^{-1}. Want to extrapolate to $s = 100$ TeV, $L = 1$ ab^{-1}, producing new $[\sigma \times BR](s,\ L;\ m_{Z'})$ curves.

Limits[5] for n_S in a narrow resonance are driven by *number of background events* $B(s_0,\ L_0,\ M^0_{Z'})$ under it. For each $M_{Z'}$, we find "equivalent mass" $M^0_{Z'}$ that gave the same number of background events at s_0: solve

$$B(s,\ L,\ M_{Z'}) = B(s_0,\ L_0,\ M^0_{Z'}).$$

NB Assumes efficiency/acceptance doesn't change

[5] Thamm, Torre, Wulzer, 1502.01701; Salam, Weiler "Collider Reach"

Now $B = \sigma_B L$ and

$$\sigma_B(M, s) \propto \sum_{i,j} \int_{M^2(1-\Delta)}^{M^2(1+\Delta)} d\hat{s} \frac{dL_{ij}}{d\hat{s}} \sigma_{ij}(\hat{s}).$$

$$\frac{dL_{ij}}{d\hat{s}} = \frac{1}{s} \int_{\hat{s}/s}^{1} \frac{dx}{x} f_i \left(x, \mu^2\right) f_j \left(\frac{\hat{s}}{sx}, \mu^2\right)$$

is approximately constant and $\sigma_{ij}(\hat{s}) \approx C_{ij}/\hat{s}$, where C_{ij} is a constant

$$\Rightarrow \sigma_B(M, s) \approx \ln[(1+\Delta)/(1-\Delta)] \sum_{i,j} C_{ij} \frac{dL_{ij}}{d\hat{s}}(M, s).$$

Our equal backgrounds equation becomes

$$L_0 \sum_{i,j} C_{ij} \frac{dL_{ij}}{d\hat{s}}(M_0, s_0) \approx L' \cdot \sum_{i,j} C_{ij} \frac{dL_{ij}}{d\hat{s}}(M', s').$$

We solve this for M', and we know what the limit on n_S is there: it's the same as the reference search. This is easily turned into a limit on $\sigma_S \times BR$ by dividing by L'.

Caveats

There is agreement to factor 2 in $\sigma \times BR$ limit from di-lepton bump search[6]. Δm much smaller.

Extrapolated exclusion depends on L_0/L'.

- If $L' = L_0$, $M'_{min} = M_{0min}$.
- If $L' > L_0$, M'_{min} much higher.
- If $L' < L_0$, M'_{min} much lower.

Thus, starting point is arbitrary. We vary lumi up to L' and take strongest limit for each mass: only affects masses $< M'_{min}$: weaker than a realistic limit.

[6] Thamm et al, arXiv:1502.01701

Z' **Models**

Naïve model: only include couplings to $\bar{b}s/b\bar{s}$ and $\mu^+\mu^-$ (*less model dependent*).

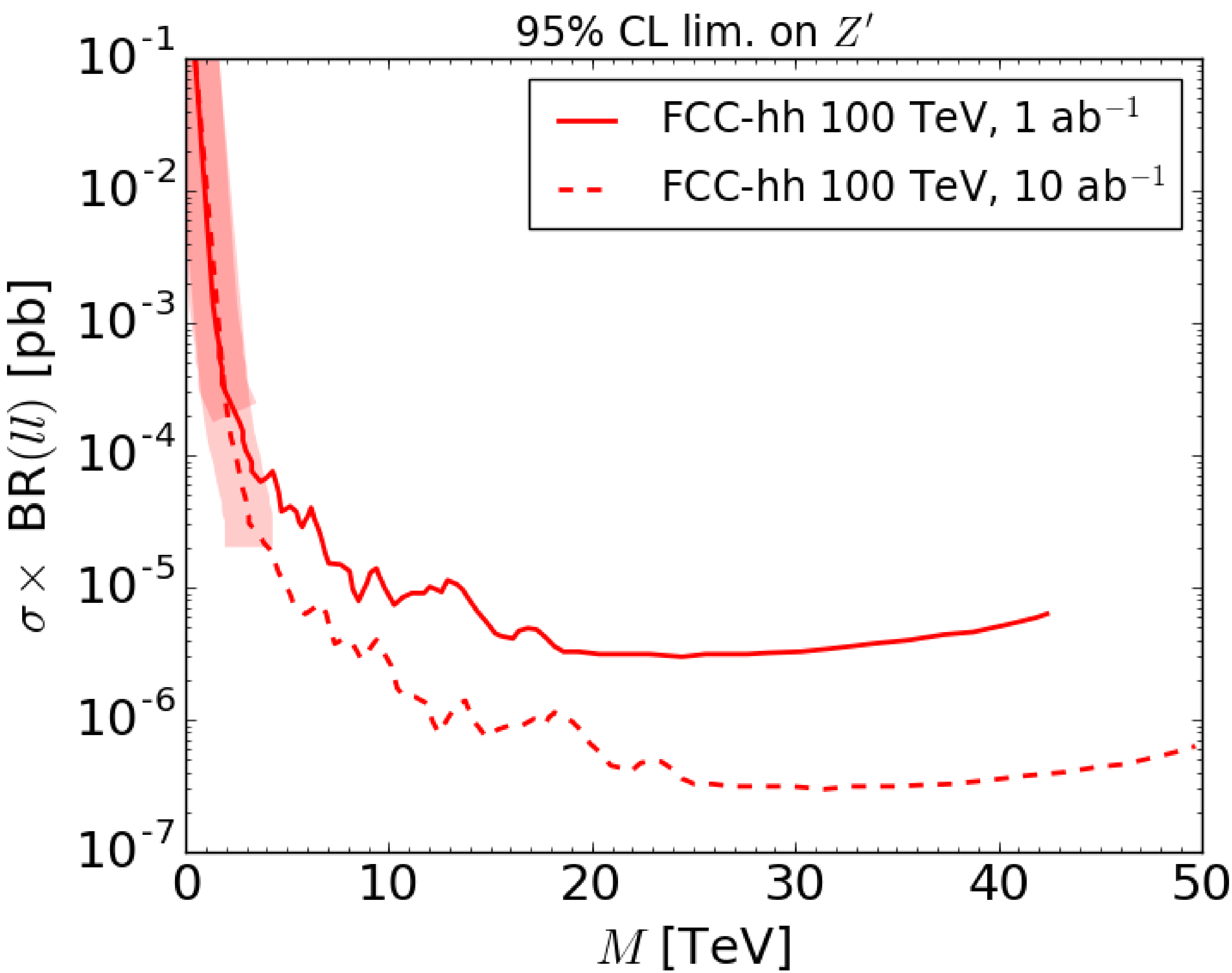
$$\mathcal{L}_{Z'}^{\text{min.}} \supset \left(g_L^{sb} Z'_\rho \bar{s}\gamma^\rho P_L b + \text{h.c.}\right) + g_L^{\mu\mu} Z'_\rho \bar{\mu}\gamma^\rho P_L \mu \,,$$

which contributes to the $\mathcal{O}_{LL}^{\mu}$ coefficient with

$$\bar{c}_{LL}^{\mu} = -\frac{4\pi v^2}{\alpha_{\text{EM}} V_{tb} V_{ts}^*} \frac{g_L^{sb} g_L^{\mu\mu}}{M_{Z'}^2},$$

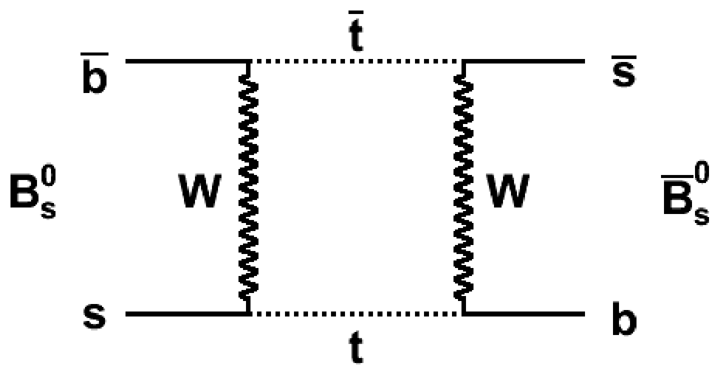
$$\Rightarrow g_L^{sb} g_L^{\mu\mu} \left(\frac{36\ \text{TeV}}{M_{Z'}}\right)^2 = -1.33 \pm 0.34\ (\text{clean}).$$

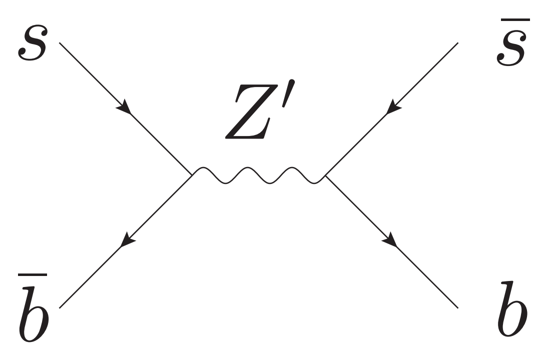
13 TeV ATLAS 3.2 fb^{-1} $\mu\mu$



Other Constraints

$B_s - \bar{B}_s$ Mixing: $\bar{g}_L^{sb} \lesssim \sqrt{2} M_{Z'}/210$ TeV.

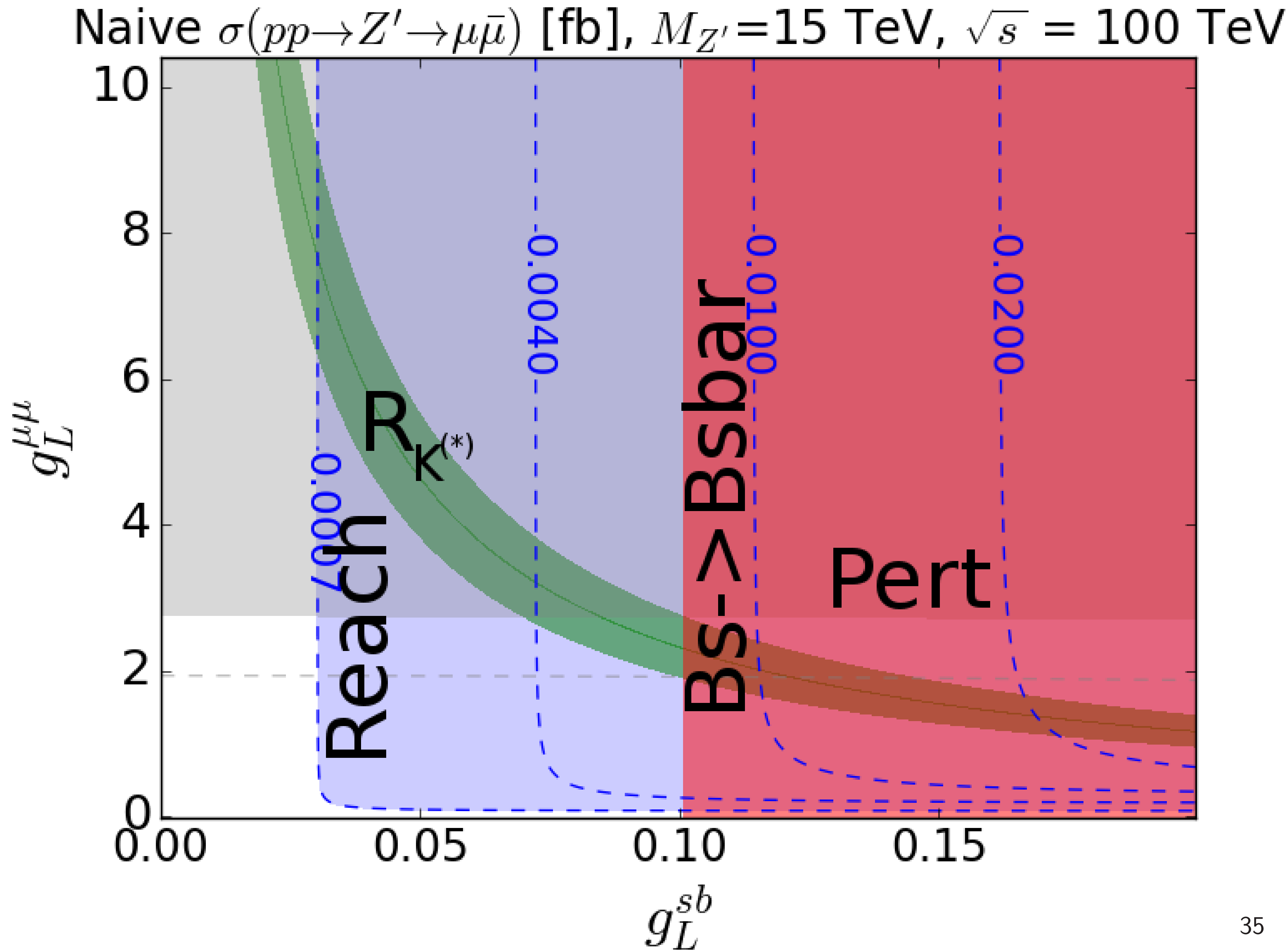




Perturbativity: No Landau pole below M_{Pl}

$$\frac{\Gamma_{Z'}}{M_{Z'}} < \frac{\pi}{2 \log(M_{Pl}/M_{Z'})}.$$

Strengthened by scalars/fermions (weakened by vectors)



Naive $\sigma(pp \to Z' \to \mu\bar{\mu})$ [fb], $M_{Z'}$=15 TeV, $\sqrt{s}$ = 100 TeV
$g_L^{\mu\mu}$
g_L^{sb}
0.00
0.05
0.10
0.15
0
2
4
6
8
10
0.0007
0.0040
0.0100
0.0200
$R_{K^{(*)}}$
Reach
Bs->Bsbar
Pert

$33\mu\mu$ model

We start with a $\not{Z}'$ coupling to the third generation of LH quarks and the second generation of LH leptons in the weak eigenbasis:

$$\mathcal{L}_{Z'}^{33\mu\mu} \supset i\frac{1}{2}\left[g_L^q \overline{Q_{L3}} \not{Z}' Q_{L3} + g_L^{\mu\mu} \overline{L_2} \not{Z}' L_2\right] + H.c.$$

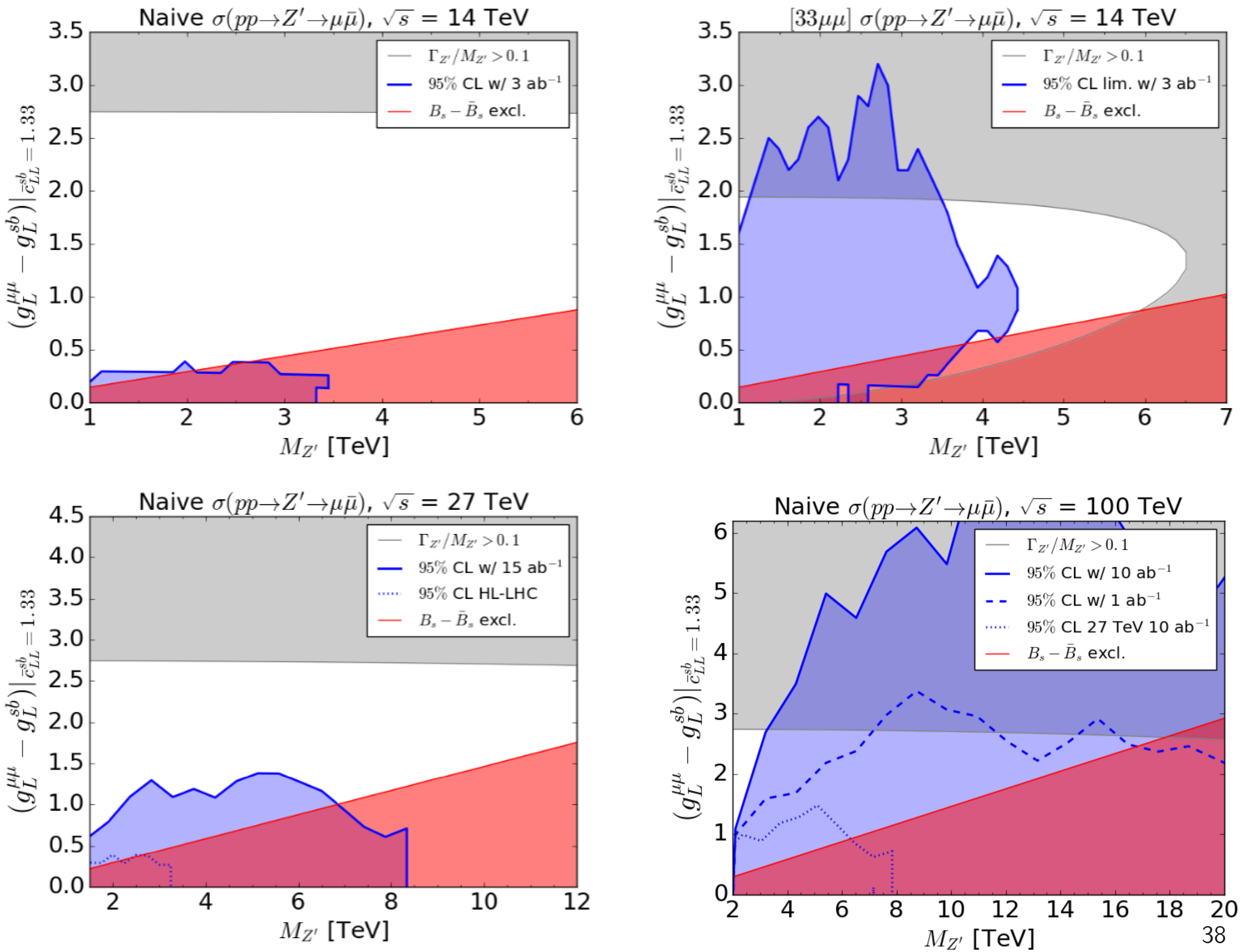
Assuming that CKM mixing is due purely to mixing of down quarks and PMNS is due purely to neutrino mixing.

$33\mu\mu$ model

$$\mathcal{L}_{Z'}^{33\mu\mu} \supset i\frac{1}{2}\Big[g_L^q\Big(\bar{t}\not{Z}'P_Lt+|V_{tb}|^2\bar{b}\not{Z}'P_Lb+|V_{td}|^2\bar{d}\not{Z}'P_Ld$$
$$+|V_{ts}|^2\bar{s}\not{Z}'P_Ls+V_{tb}V_{ts}^*\bar{b}\not{Z}'P_Ls+V_{ts}^*V_{td}\bar{d}\not{Z}'P_Ls$$
$$+V_{tb}V_{td}^*\bar{b}\not{Z}'P_Ld\Big)$$
$$+g_L^{\mu\mu}\left(\bar{\mu}\not{Z}'P_L\mu+\sum_{i,j}\bar{\nu}_iU_{i\mu}\not{Z}'P_LU_{\mu j}^*\nu_j\right)\Big]+H.c.$$

We introduce this model to provide contrast to the naïve model:

$\mathcal{Q}$: How different are the results to naïve model?



Naive $\sigma(pp \to Z' \to \mu\bar{\mu})$, $\sqrt{s}$ = 14 TeV
$\Gamma_{Z'}/M_{Z'} > 0.1$
95% CL w/ 3 ab^{-1}
$B_s - \bar{B}_s$ excl.
$(g_L^{\mu\mu} - g_L^{sb})|_{\bar{c}_{LL}^{sb}=1.33}$
$M_{Z'}$ [TeV]
[33$\mu\mu$] $\sigma(pp \to Z' \to \mu\bar{\mu})$, $\sqrt{s}$ = 14 TeV
$\Gamma_{Z'}/M_{Z'} > 0.1$
95% CL lim. w/ 3 ab^{-1}
$B_s - \bar{B}_s$ excl.
$(g_L^{\mu\mu} - g_L^{sb})|_{\bar{c}_{LL}^{sb}=1.33}$
$M_{Z'}$ [TeV]
Naive $\sigma(pp \to Z' \to \mu\bar{\mu})$, $\sqrt{s}$ = 27 TeV
$\Gamma_{Z'}/M_{Z'} > 0.1$
95% CL w/ 15 ab^{-1}
95% CL HL-LHC
$B_s - \bar{B}_s$ excl.
$(g_L^{\mu\mu} - g_L^{sb})|_{\bar{c}_{LL}^{sb}=1.33}$
$M_{Z'}$ [TeV]
Naive $\sigma(pp \to Z' \to \mu\bar{\mu})$, $\sqrt{s}$ = 100 TeV
$\Gamma_{Z'}/M_{Z'} > 0.1$
95% CL w/ 10 ab^{-1}
95% CL w/ 1 ab^{-1}
95% CL 27 TeV 10 ab^{-1}
$B_s - \bar{B}_s$ excl.
$(g_L^{\mu\mu} - g_L^{sb})|_{\bar{c}_{LL}^{sb}=1.33}$
$M_{Z'}$ [TeV]

LQ Models

Scalar[7] $S_3 = (\bar{3},\ 3,\ 1/3)$ of $SU(2) \times SU(2)_L \times U(1)_Y$:

$$\mathcal{L} = \ldots + y_3 QLS_3 + y_q QQS_3^\dagger + \text{h.c.}$$

Vector $V_1 = (\bar{3}, 1, 2/3)$ or $V_3 = (3, 3, 2/3)$

$$\mathcal{L} = \ldots + y_3' V_3^\mu \bar{Q} \gamma_\mu L + y_1 V_1^\mu \bar{Q} \gamma_\mu L + y_1' V_1^\mu \bar{d} \gamma_\mu l + \text{h.c.}$$

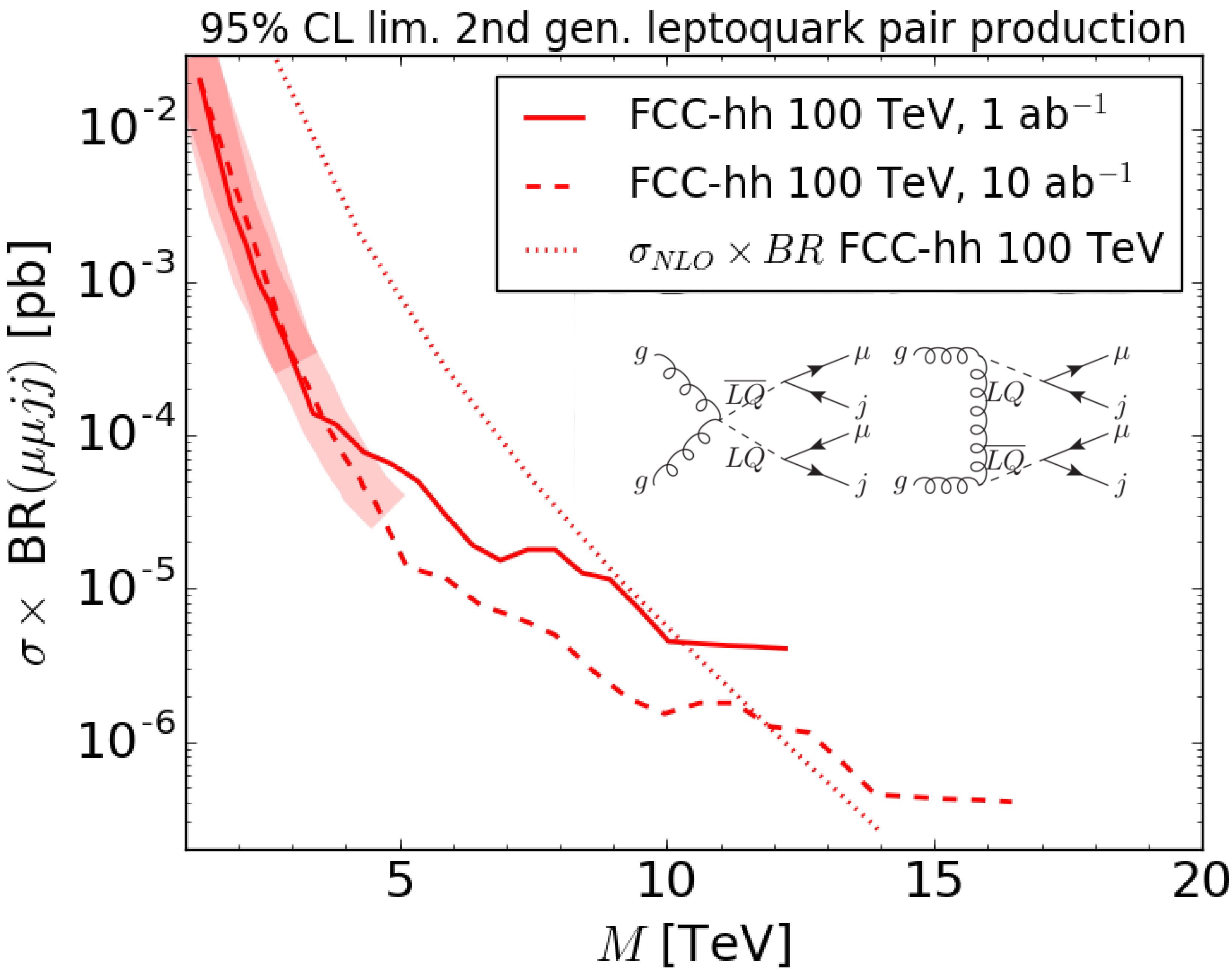
$$\Rightarrow \bar{c}_{LL}^\mu = \kappa \frac{4\pi v^2}{\alpha_{\text{EM}} V_{tb} V_{ts}^*} \frac{|y_i|^2}{M^2}.$$

$\kappa = 1, -1, -1$ and $y = y_3, y_1, y_3'$ for S_3, V_1, V_3.

[7] Capdevila *et al* 1704.05340, Hiller and Hisandzic 1704.05444, D'Amico *et al* 1704.05438.

CMS 8 TeV 20fb^{-1} 2nd gen

CMS-PAS-EXO-12-042: $M > 1.07$ TeV.



Other Constraints

Note that the extrapolation is very rough for pair production. Fix $M = 2M_{LQ}$, assuming they are produced close to threshold: $\Delta = 0.1$.

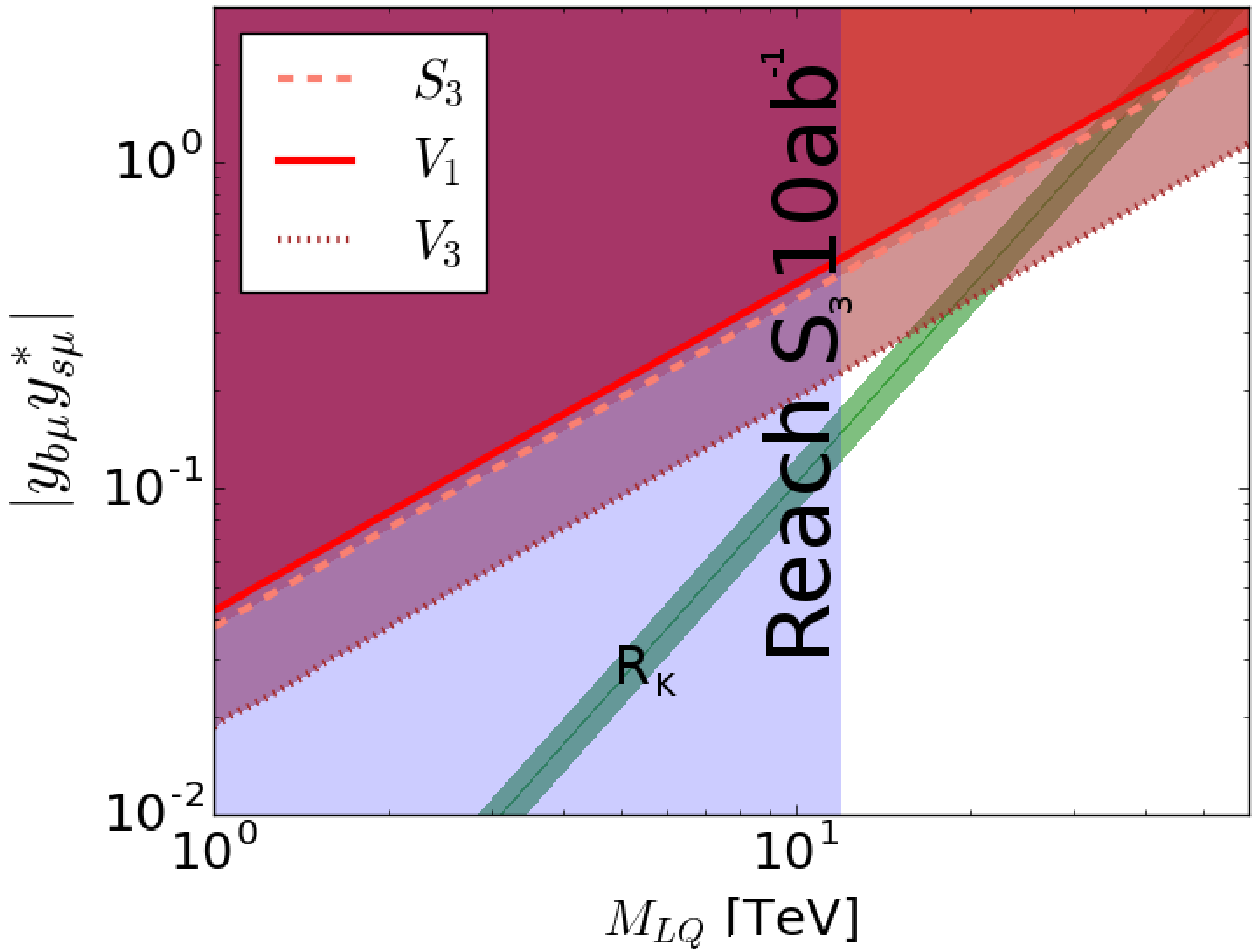
$B_s - \bar{B}_s$ mixing is at one-loop:

$$\mathcal{L}_{\bar{b}s\bar{b}s} = k\frac{\left|y_{b\mu}y_{s\mu}^*\right|^2}{32\pi^2 M_{LQ}^2}\left(\bar{b}\gamma_\mu P_L s\right)\left(\bar{s}\gamma^\mu P_L b\right) + \text{h.c.}$$

$y = y_3, y_1, y_3'$ and $k = 5, 4, 20$ for S_3, V_1, V_3.
Data $\Rightarrow$ $c_{LL}^{bb} < 1/(210\text{TeV})^2$. Recently, some[8] used a Fermilab MILC lattice determination of f_B which makes the SM differ from experiment at the 2σ level.

[8] Lenz *et al*, 1712.06572

8 TeV CMS 20fb^{-1} 2nd gen



Up to 14 TeV LQs with 100 TeV 10 ab^{-1} FCC-hh. $M_{LQ} < 41$ TeV.

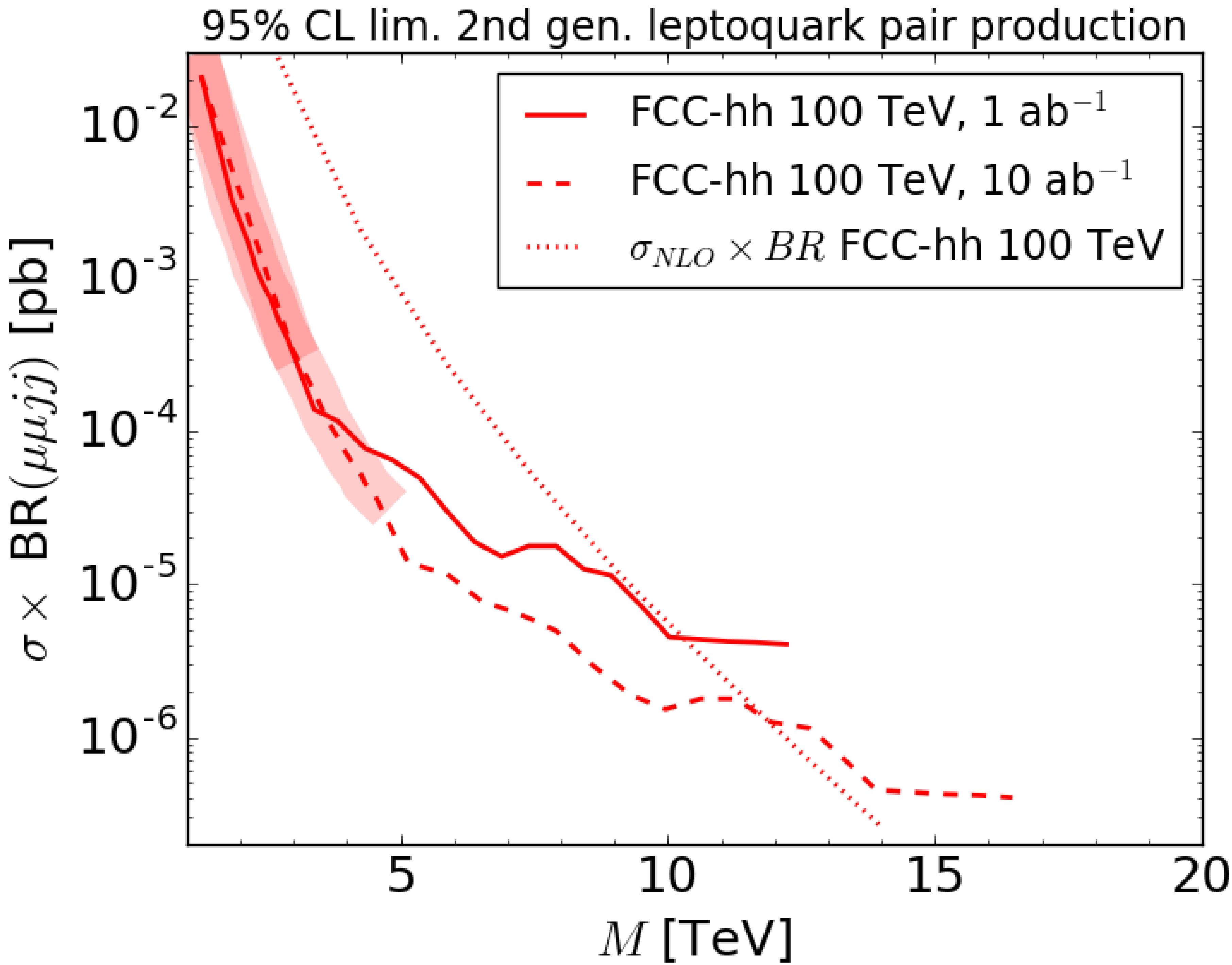
LQ Mass Limits

S_3	41 TeV
V_1	41 TeV
V_3	18 TeV

From $B_s - \bar{B}_s$ mixing and fitting $b-$anomalies.

Pair production has a reach up to 12 TeV.

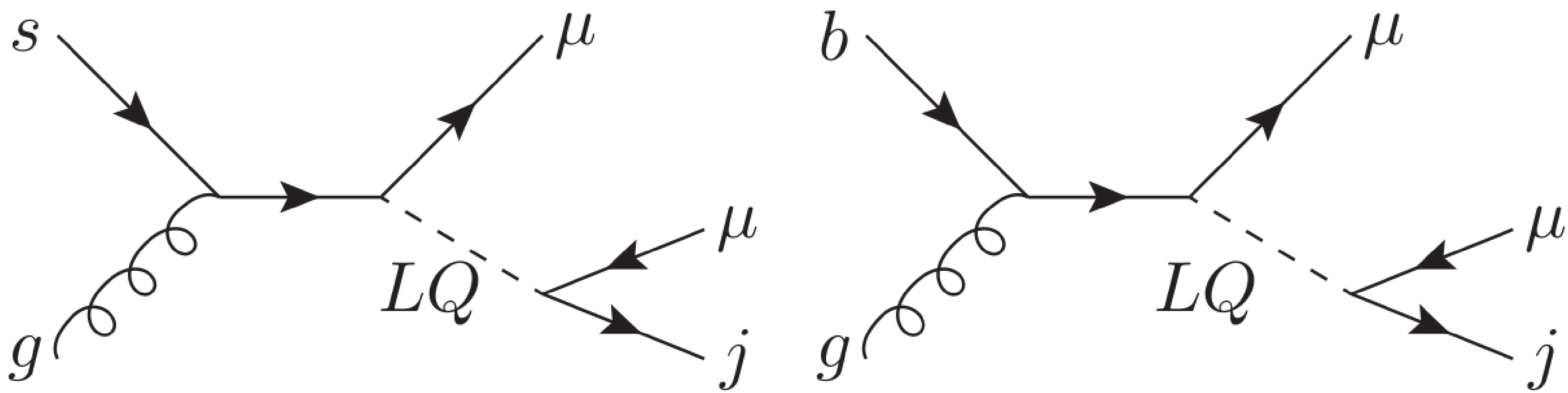
The pair production cross-section is insensitive to the representation of $SU(2)$ in this case.



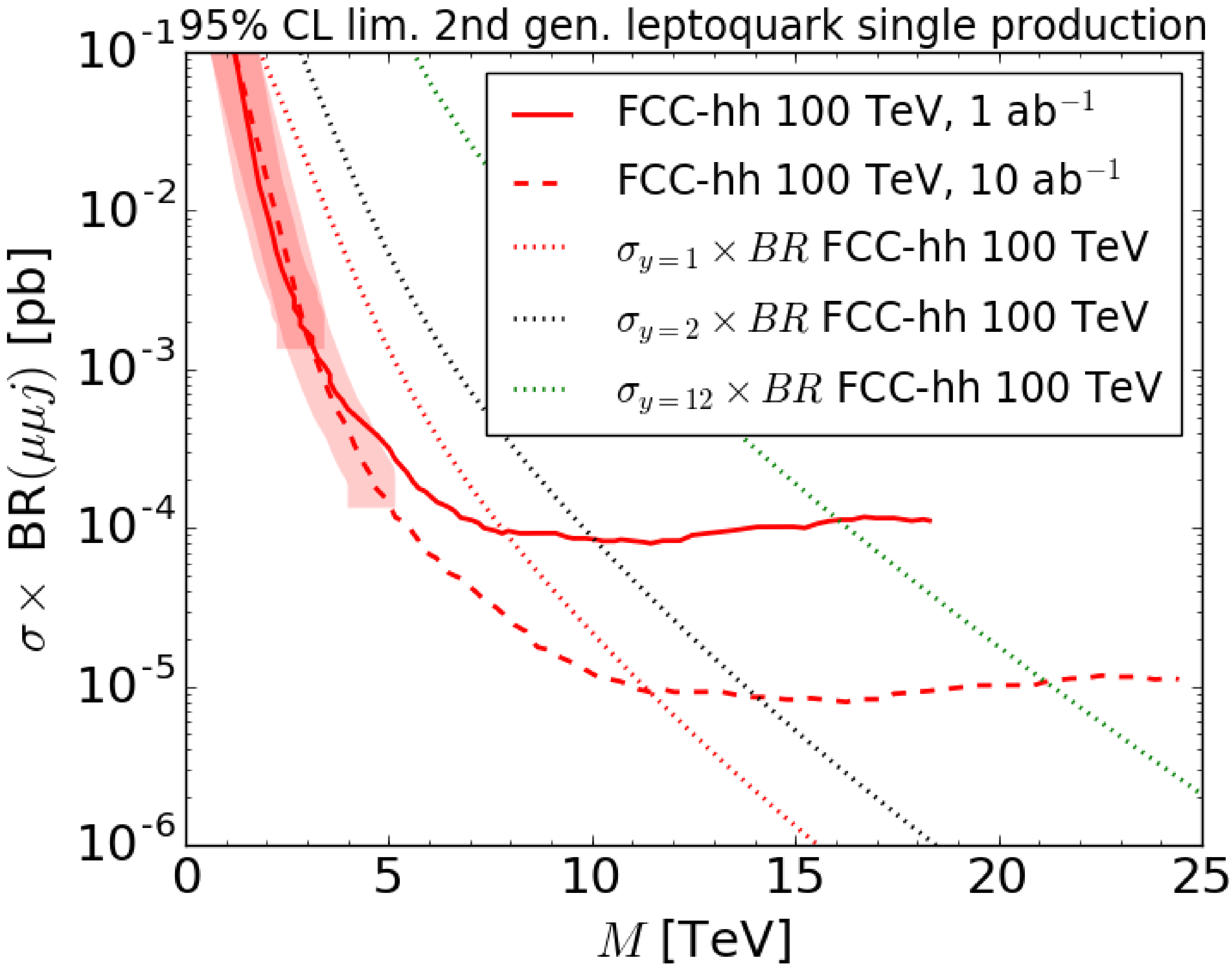
95% CL lim. 2nd gen. leptoquark pair production
FCC-hh 100 TeV, 1 ab^{-1}
FCC-hh 100 TeV, 10 ab^{-1}
$\sigma_{NLO} \times BR$ FCC-hh 100 TeV
$\sigma \times$ BR$(\mu\mu jj)$ [pb]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
5
10
15
20
M [TeV]

Single Production

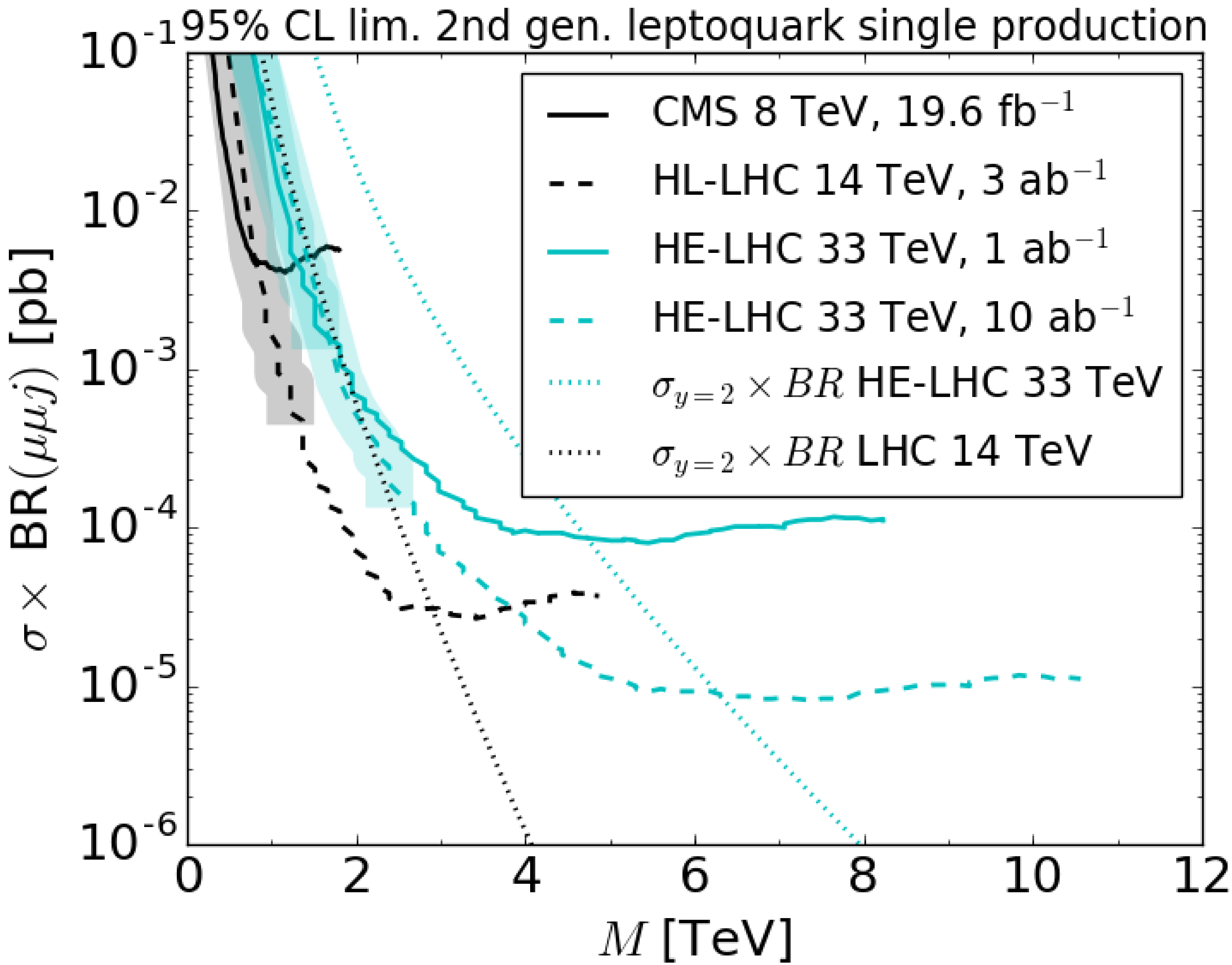
Depends upon LQ coupling as well as LQ mass



Current bound by CMS from 8 TeV 20 fb^{-1}: $M_{LQ} > 660$ GeV for $s\mu$ coupling of 1. We include b as well from `NNPDF2.3LO` ($\alpha_s(M_Z) = 0.119$), re-summing large logs from initial state b. Integrate $\hat{\sigma}$ with `LHAPDF`.



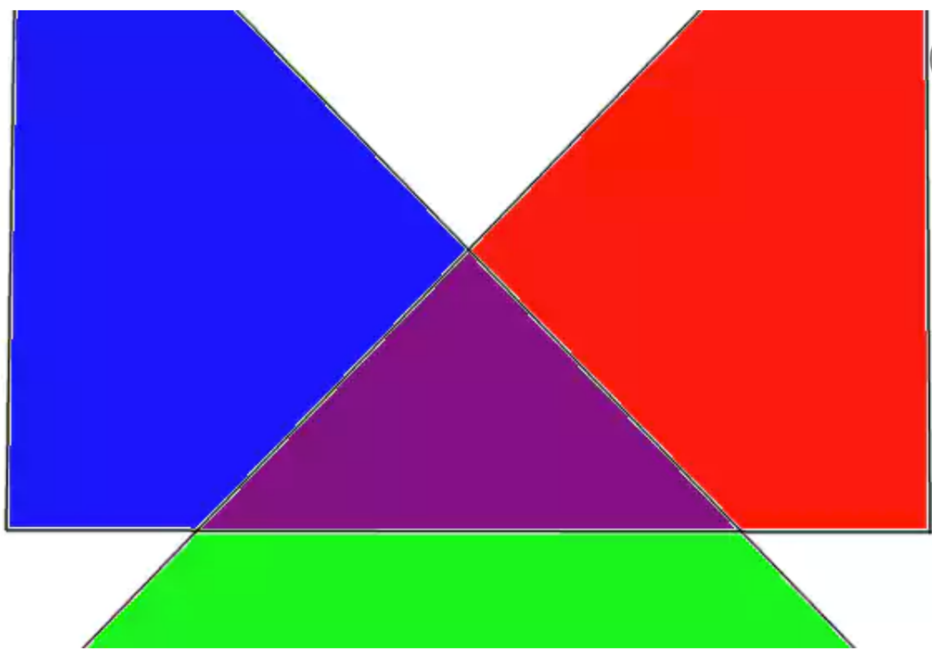
σs for S_3 with $y_{s\mu} = y_{b\mu} = y$.


95% CL lim. 2nd gen. leptoquark single production
CMS 8 TeV, 19.6 fb^{-1}
HL-LHC 14 TeV, 3 ab^{-1}
HE-LHC 33 TeV, 1 ab^{-1}
HE-LHC 33 TeV, 10 ab^{-1}
$\sigma_{y=2} \times BR$ HE-LHC 33 TeV
$\sigma_{y=2} \times BR$ LHC 14 TeV
$\sigma \times$ BR$(\mu\mu j)$ [pb]
M [TeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2
4
6
8
10
12

Science Life and Physics

Modelling the fourth colour: dispatch from de Moriond

At the particle physics conference, it's clear inconclusive LHCb data are stimulating strange new ideas

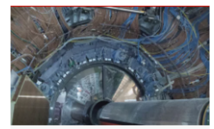


▲ Four colours (or colors?) Photograph: Ben Allanach

Ben Allanach
Sat 17 Mar 2018 10.15 GMT

In the middle of the Rencontres de Moriond particle physics conference in Italy, the scientific talks stopped to allow a standing ovation dedicated to the memory and achievements of my inspirational colleague Stephen Hawking, who we heard had died earlier that day.

The talks quickly resumed, which I think Stephen would have approved of. The most striking thing about the scientific content of the conference this year was that a whole day was dedicated to the weirdness in bottom particles that Tevong You and I wrote about last November. As Marco Nardecchia reviewed in his talk (PDF), bottom particles produced in the LHCb detector in proton collisions are decaying too often in certain particular ways, compared to predictions from the Standard Model of particle physics. Their decay products are coming out with the wrong angles too often compared with predictions, too.



Anomalous bottoms at Cern and the case for a new collider

Read more

We were hoping for an update on the data at the conference: the amount of data has roughly doubled since they were last released, and we need to see the new data to be convinced that something really new is happening in the collisions. I strongly suspect that if the effect is seen in the new data, the theoretical physics community will "go nuts" and we will quickly see the resulting avalanche of papers. If the new data look ordinary, the effect will be forgotten and everyone will move on. Taking such measurements correctly takes care and time, however, and the LHCb experiment didn't release them. We shall have to wait until other conferences later this year for the LHCb to present its analyses of the new data.

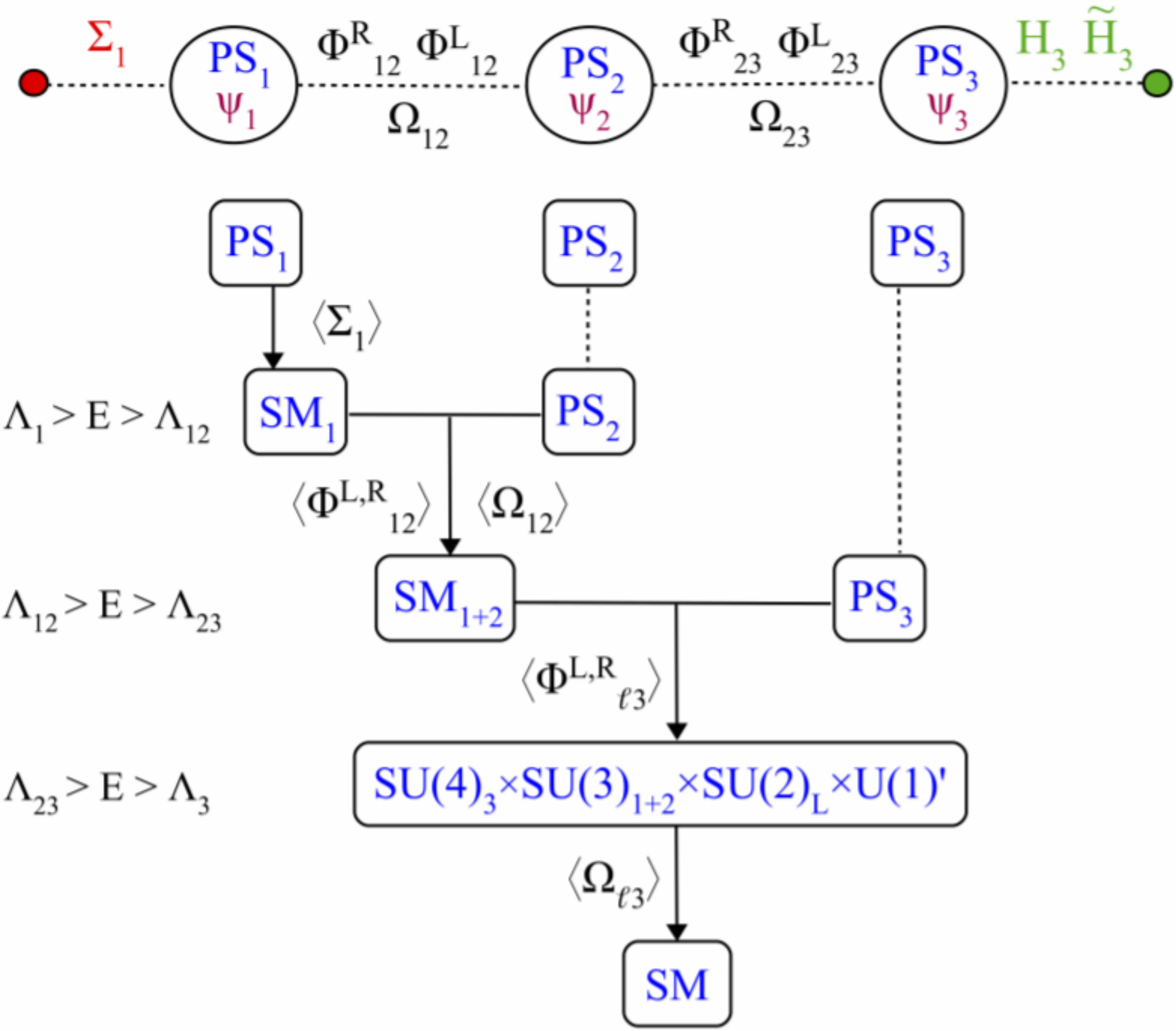
There were interesting theory talks on how new forces could explain the strange properties of the bottom particle decays. The full mathematical models look quite baroque: they need a lot of "bells and whistles" in order to pass other experimental tests. But these models prove that it can be done, and they are quite different to what has been proposed before.

One of them even unifies different classes of particle (leptons and quarks), describing the lepton as the "fourth colour" of a quark. We are used to the idea that quarks come in three (otherwise identical) copies: physicists label them red, green and blue to distinguish them. As Javier Fuentes-Martin describe (PDF), once you design the mathematics to make leptons the fourth colour, the existence of a new force-carrying particle with just the correct properties to break up the

Other Flavour Models

Realising[9] the vector LQ solution based on $PS = [SU(4) \times SU(2)_L \times SU(2)_R]^3$. SM-like Higgs lies in third generation PS group, explaining large Yukawas (others come from VEV hierarchies). Get $U(2)_Q \times U(2)_L$ approximate global flavour symmetry.

[9] Di Luzio Greljo, Nardecchia arXiv:1708.08450, Bordone, Cornella, Fuentes-Martin, Isidori, arXiv:1712.01368



Σ_1
PS_1 ψ_1
Φ^R_{12} Φ^L_{12}
Ω_{12}
PS_2 ψ_2
Φ^R_{23} Φ^L_{23}
Ω_{23}
PS_3 ψ_3
H_3 $\widetilde{H}_3$
PS_1
PS_2
PS_3
$\langle\Sigma_1\rangle$
$\Lambda_1 > E > \Lambda_{12}$
SM_1
PS_2
$\langle\Phi^{L,R}_{12}\rangle$ $\langle\Omega_{12}\rangle$
$\Lambda_{12} > E > \Lambda_{23}$
SM_{1+2}
PS_3
$\langle\Phi^{L,R}_{\ell 3}\rangle$
$\Lambda_{23} > E > \Lambda_3$
$SU(4)_3 \times SU(3)_{1+2} \times SU(2)_L \times U(1)'$
$\langle\Omega_{\ell 3}\rangle$
SM

$B_s \to \mu^+\mu^-$

Lattice QCD provides important input to

$$BR(B_s \to \mu\mu)_{SM} = (3.65 \pm 0.23) \times 10^{-9},$$

$$BR(B_s \to \mu\mu)_{exp}) = (3.0 \pm 0.6) \times 10^{-9}.$$

$$\frac{BR(B_s \to \mu\mu)}{BR(B_s \to \mu\mu)_{SM}} = \left| \frac{(\bar{c}^{\mu}_{LL} + \bar{c}^{\mu}_{RR} - \bar{c}^{\mu}_{LR} - \bar{c}^{\mu}_{RL})^{tot}}{(\bar{c}^{\mu}_{LL} + \bar{c}^{\mu}_{RR} - \bar{c}^{\mu}_{LR} - \bar{c}^{\mu}_{RL})^{SM}} \right|^2 .$$

"The road of excess leads to the palace of wisdom."

William Blake, The Marriage of Heaven and Hell

Conclusions

- Focused on *tree-level* explanations of $R_{K^{(*)}}$ as they are usually harder to discover: Z' and leptoquarks.
- More realistic models tend to be easier to discover than these pessimistic scenarios: then HE-LHC and HL-LHC rule.
- Loop holes: wide resonances, multiple messengers.
- News on $R_K^{(*)}$ expected *in 2019*. At the current central value, R_K would reach 5σ discrepancy with the SM *alone* by 2020. R_{K^*} would be close to[10] 5σ.
- $R_{K^{(*)}} \Rightarrow$ *HL-LHC, HE-LHC and FCC-hh*

[10] Albrecht *et al*, 1709.10308

Backup

HL-LHC/HE-LHC LQs