A new physics interpretation of the W-boson mass anomaly with B anomaly

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Based on our work [2204.05962]
with
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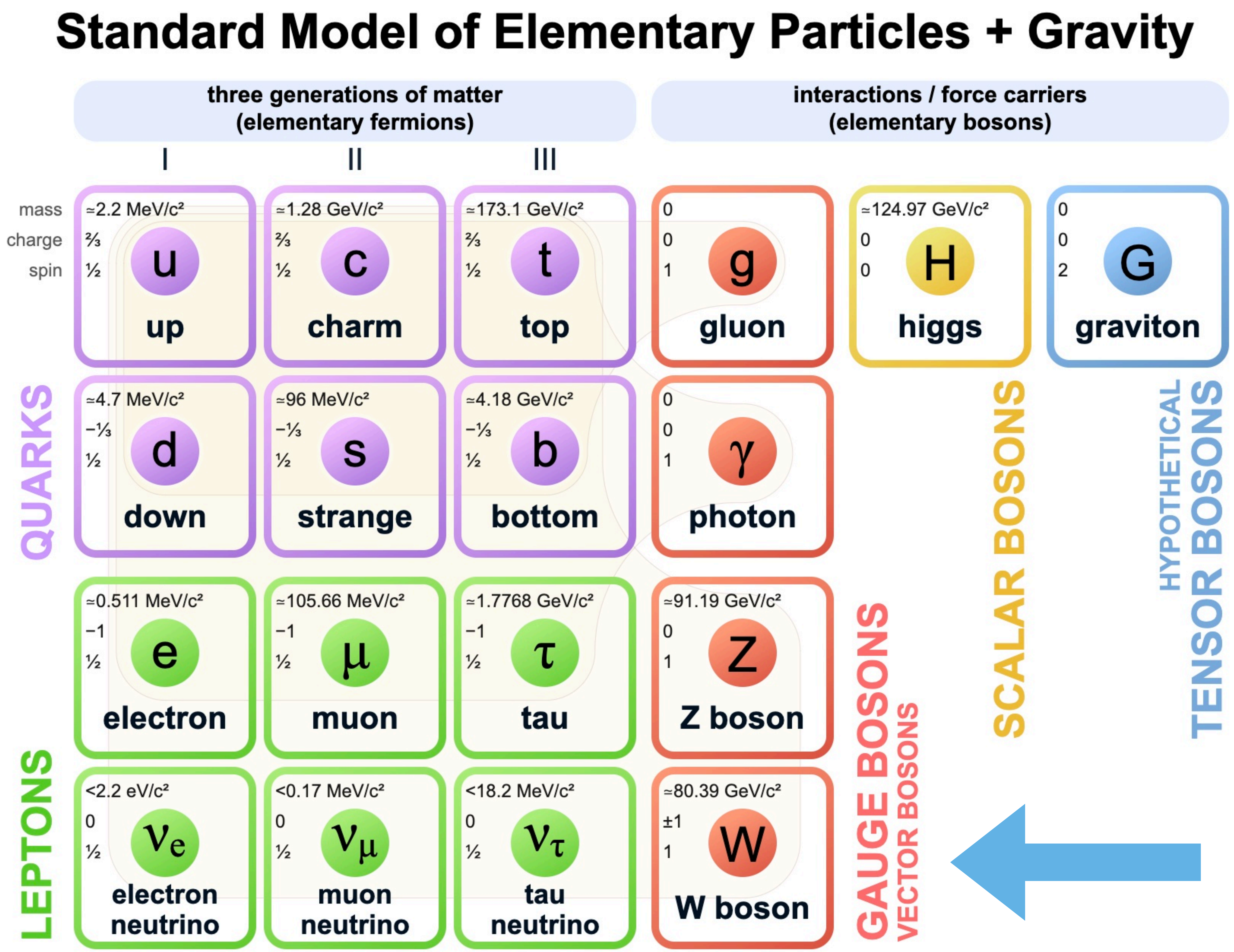


$M_W \sim 80$ GeV

$M_{p,n} \sim 1$ GeV

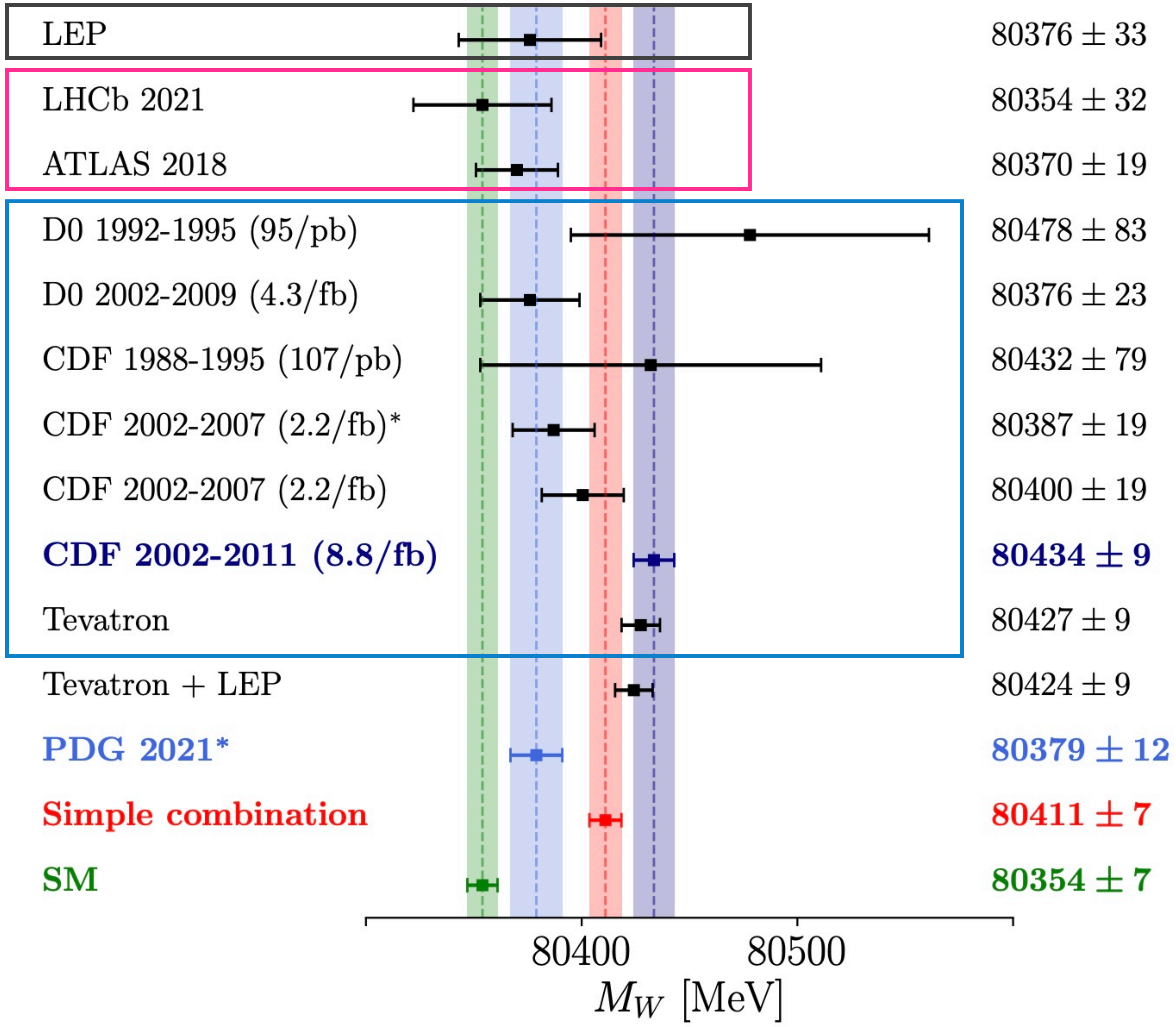
https://commons.wikimedia.org/

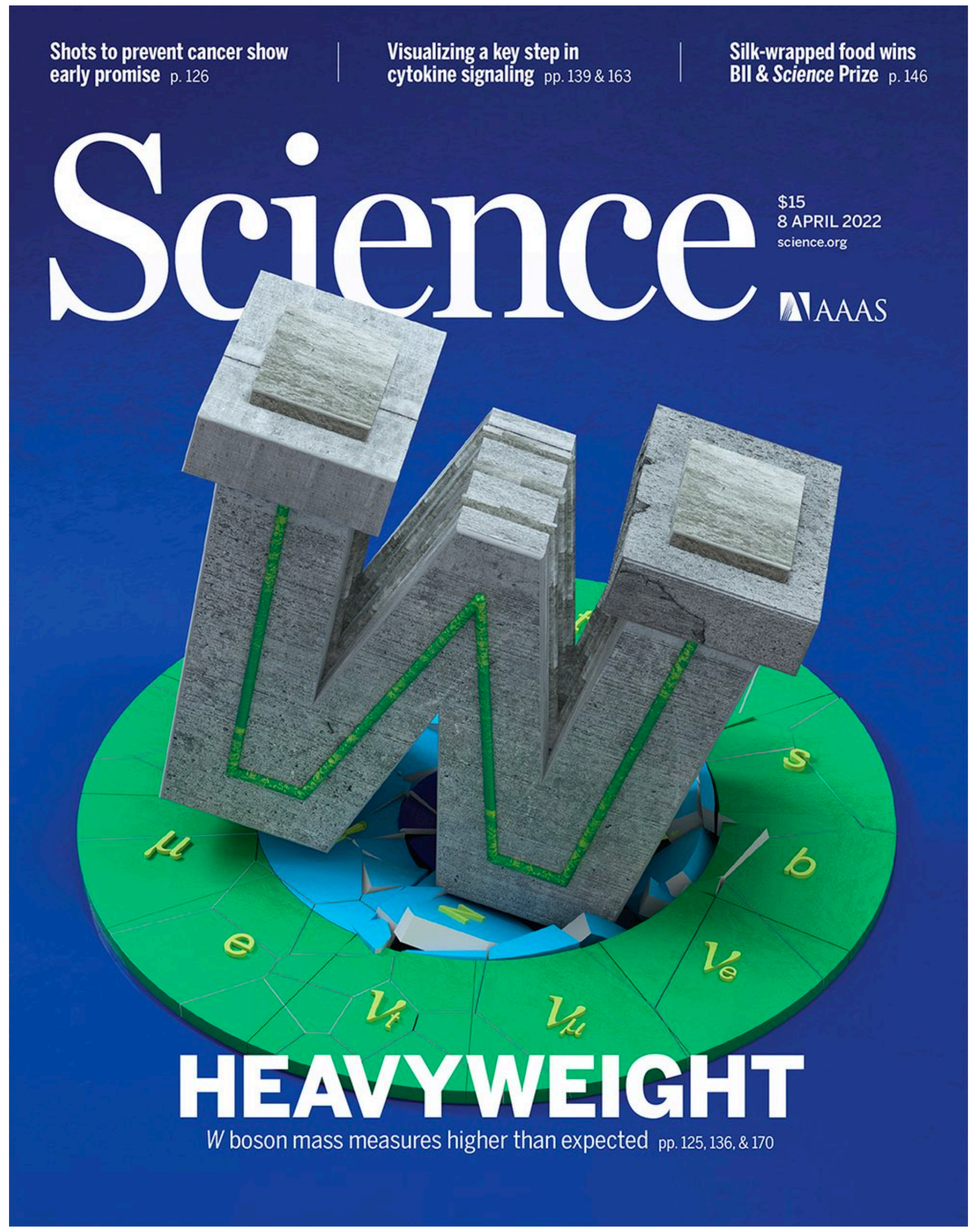
[Athron, Fowlie, Lu, Wu, Zhu, 2204.03996]

LEP (e+e-) result →

LHC (p+p+) result → (LHCb/ATLAS)

Tevatron (**p+p-**) result → (D0/**CDF**)





← **New data by CDF**

[CDF, Science, '22]

7σ deviation
between data vs SM

Data have been taken in 2002–2011 at Tevatron@Fermilab

Numbers

- All measured data provide p-value of 0.2% for compatibility = 3σ inconsistency which is independent of SM predictions
- The new world average is [de Bas, Pierini, Reina, Silvestrini, 2204.04204]

$$M_W^{\rm exp} = 80413.3 \pm 8.0\ \rm MeV$$

correlation of systematic errors is included

- The Standard Model prediction (will be explained later) is

$$M_W^{\rm SM} = 80350.5 \pm 7.7\,\rm MeV$$

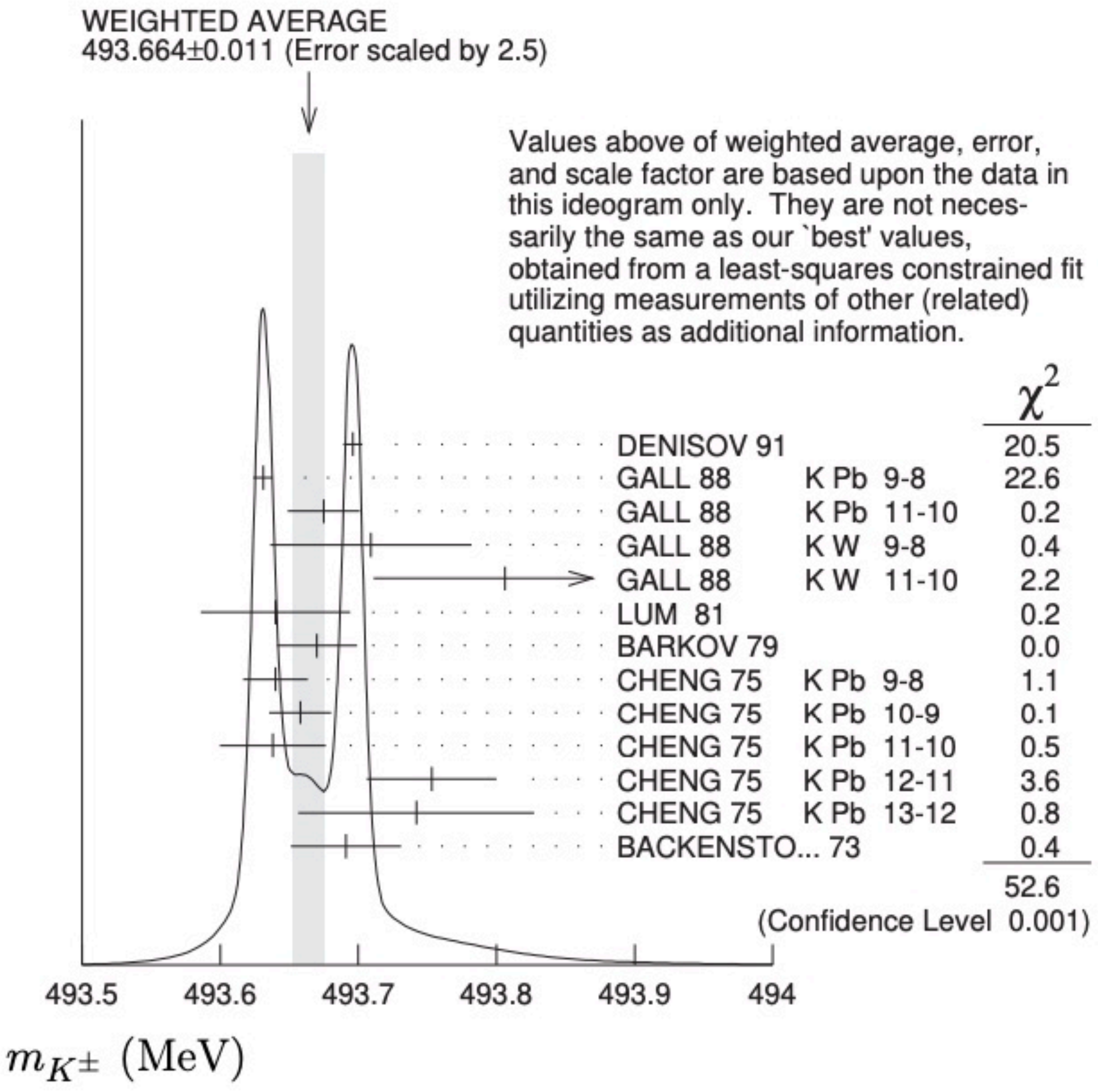
$$\Delta M_W = 62.8 \pm 11.1\,\rm MeV$$

This corresponds to 5.6σ discrepancy

Charged kaon mass

- Indeed, we know that the charged kaon mass ($K^+ = \bar{s}u$) data have given the double peak fitting result
- In that case, one has to amplify the systematic uncertainty by "scale factor *S*" in the world average of this observables

$$e.g., S\ (M_{K^+}) = 2.8$$



More conservative numbers

- No scale factor $$M_W^{\rm exp} = 80413.3 \pm 8.0\ {\rm MeV}$$ 5.6σ discrepancy
- Multiplying the scale factor S; $S(M_W) = 2.1$ [Falkowski; Wilson]

$$M_W^{\rm exp} = 80413 \pm 15\,{\rm MeV}$$

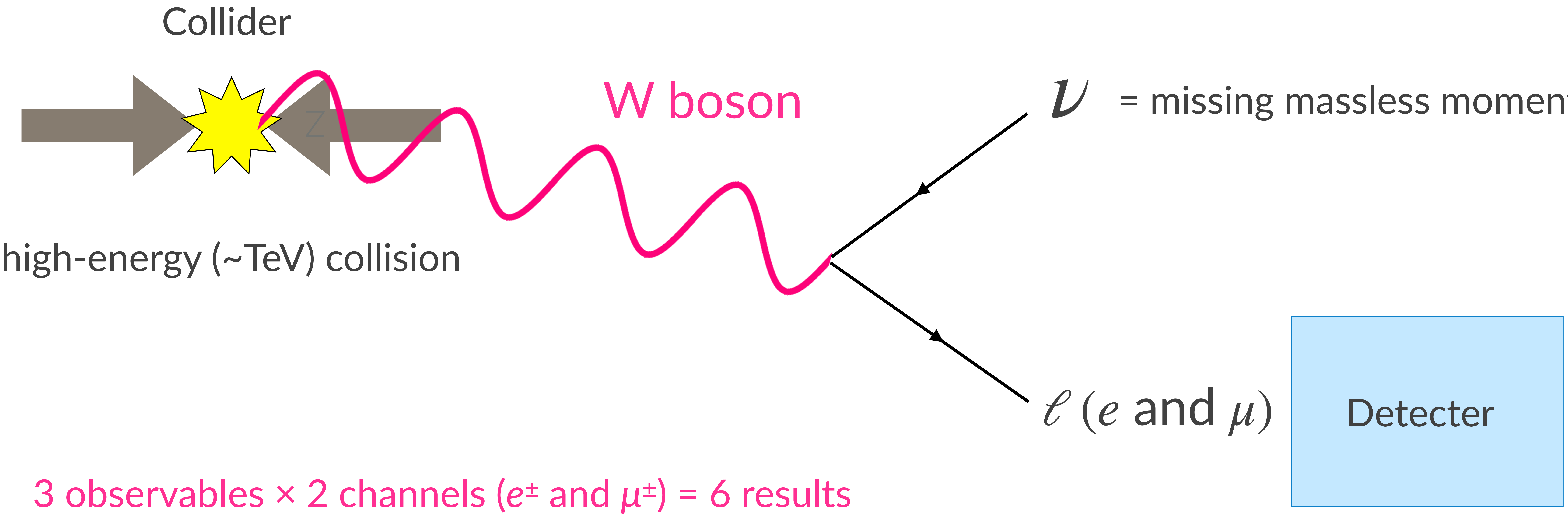
3.7σ discrepancy

- Known higher-order QCD corrections (N³LL+NNLO of α_s) via RESBOSv2 could shift the CDF result by up to -10 MeV [Isaacson, Fu, Yuan, 2205.02788]
  - But, -10 MeV shift is insufficient to explain the discrepancy
- The SM prediction is

$$M_W^{\rm SM} = 80350.5 \pm 7.7\,{\rm MeV}$$

conservative top mass uncertainty is included

How to measure M_W



3 observables × 2 channels ($e^\pm$ and $\mu^\pm$) = 6 results

1, p^ℓ_T (lepton transverse momentum)
2, p^ν_T (missing transverse momentum)
3, m_T (transverse mass) $m_T = \sqrt{2\left(p^\ell_T p^v_T - \vec{p}^{\,\ell}_T \cdot \vec{p}^{\,v}_T\right)}$

Fit each distribution by varying M_W

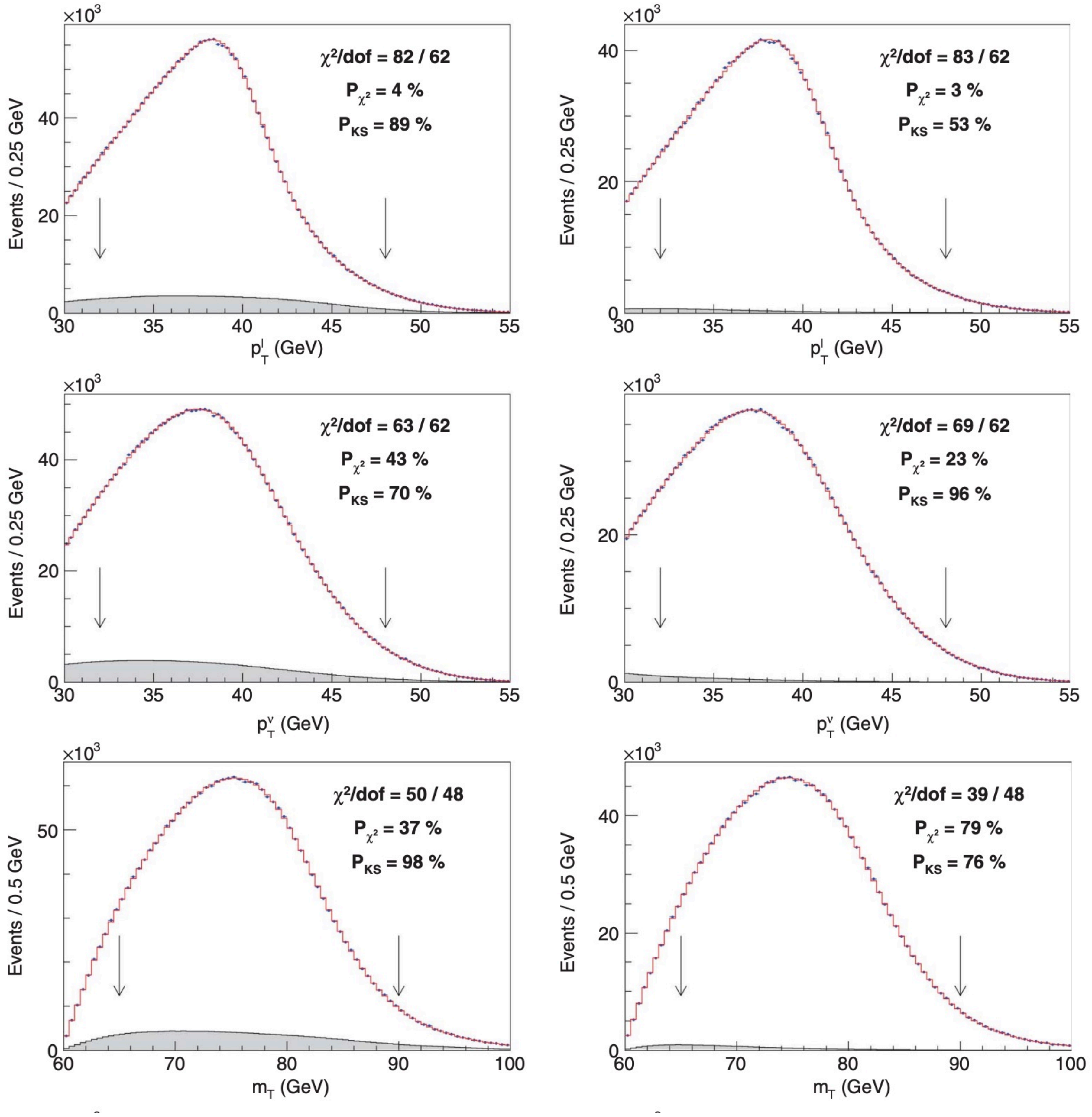
CDF result [CDF Collaboration, Science 376 (2022)]

muon electron

1, p^{ℓ}_T

2, p^{ν}_T

3, m_T



Distribution	W boson mass (MeV)
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{\text{stat}} \pm 8.5_{\text{syst}}$
$p^{\ell}_T(e)$	$80{,}411.4 \pm 10.7_{\text{stat}} \pm 11.8_{\text{syst}}$
$p^{\nu}_T(e)$	$80{,}426.3 \pm 14.5_{\text{stat}} \pm 11.7_{\text{syst}}$
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{\text{stat}} \pm 7.3_{\text{syst}}$
$p^{\ell}_T(\mu)$	$80{,}428.2 \pm 9.6_{\text{stat}} \pm 10.3_{\text{syst}}$
$p^{\nu}_T(\mu)$	$80{,}428.9 \pm 13.1_{\text{stat}} \pm 10.9_{\text{syst}}$
Combination	$80{,}433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}}$

3×2 = 6 individual fit results are consistent with each other

All 6 results deviate from the SM prediction

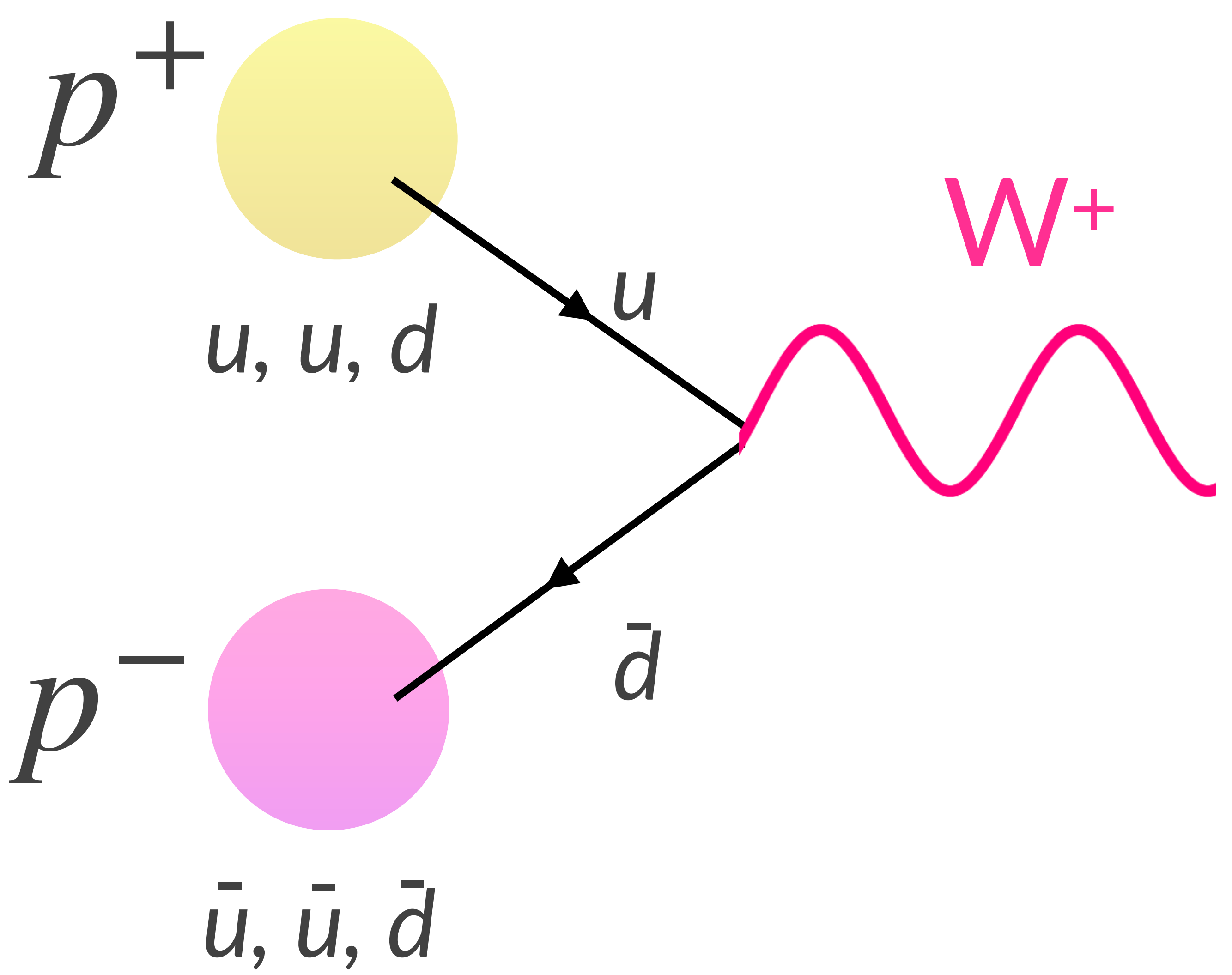
$$M_W^{\text{SM}} = 80350.5 \pm 7.7\,\text{MeV}$$

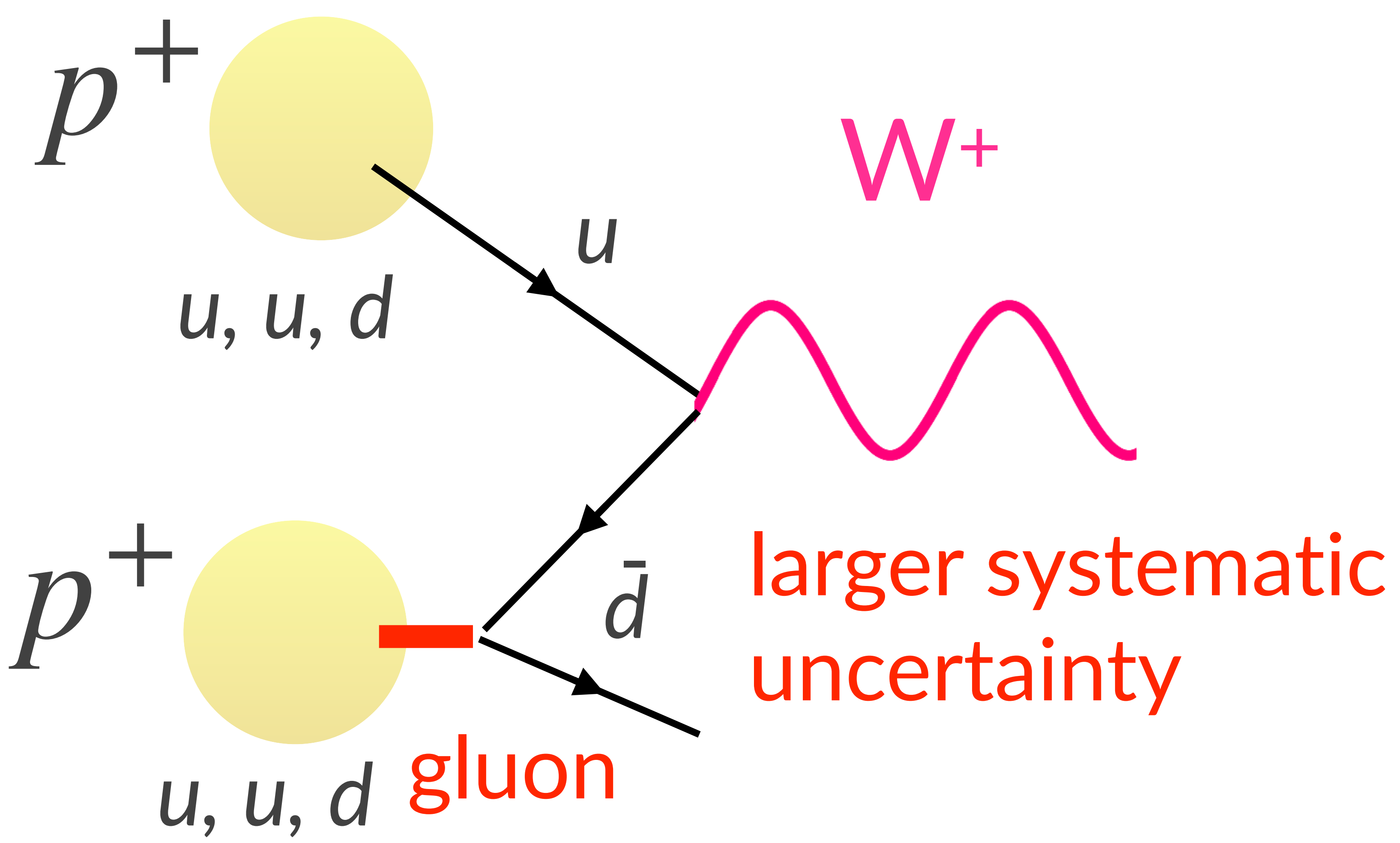
Why not LHC?

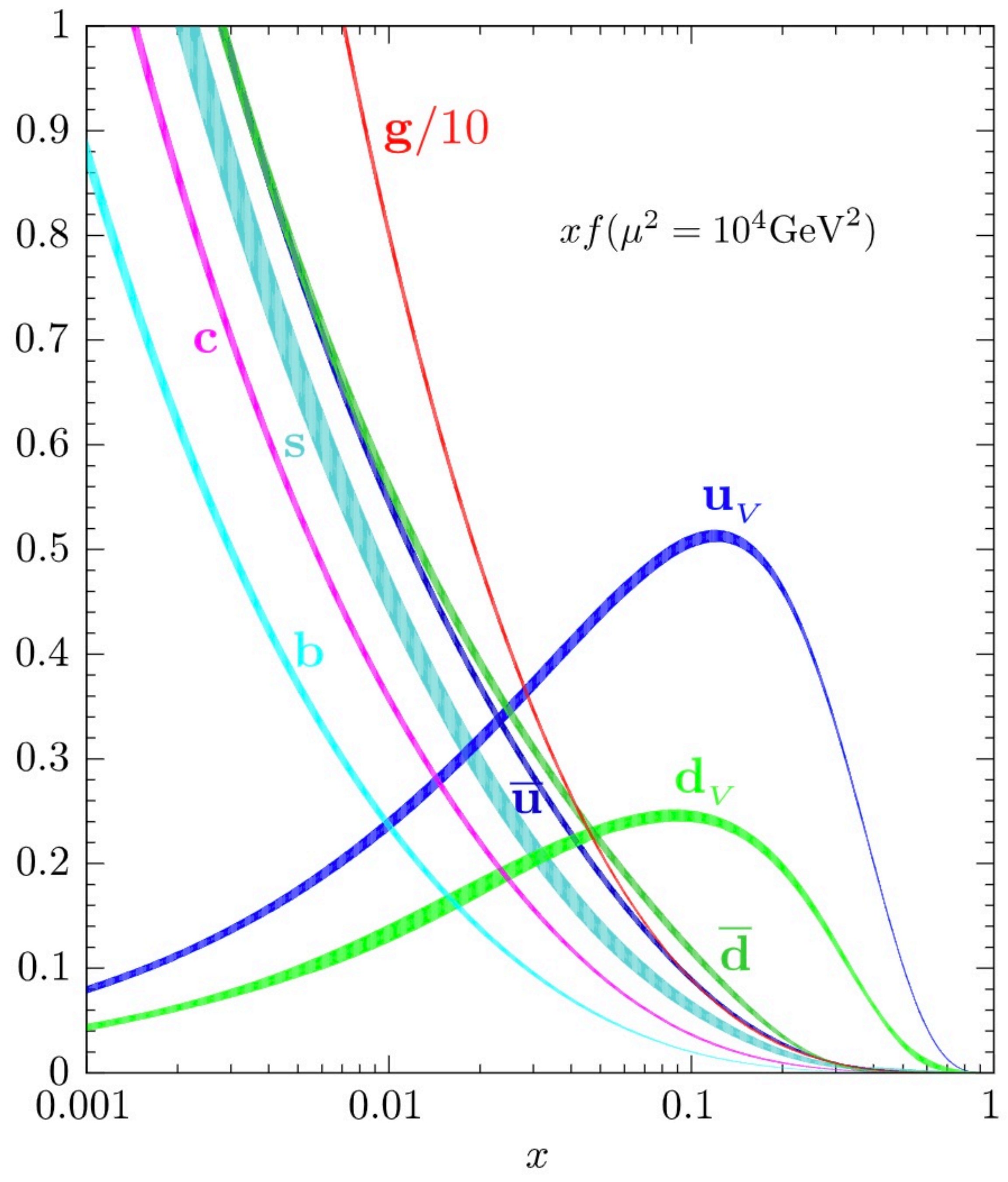
- The CDF result at Tevatron **(p+p-; Left)** is better than the LHC data **(p+p+; Right)**

LHC (7-13 TeV); x ~0.01 for W

Tevatron (1TeV); x ~0.1 for W







Also, LHC suffers from event pileup

[Gao, Harland-Lang, Rojo 2018]

Standard Model Prediction of M_W

- In the SM, the W-boson mass is not input value, but rather non-trivial prediction

tree-level relation $$M_W^2 = \frac{1}{2} g^2 v^2$$

$$M_W^{\text{tree SM}} = 80938.7\,\text{MeV}$$

0.5 GeV heavier than the CDF

1, the SM Higgs vev v is determined by G_F, which is equivalent to the muon lifetime

$$v \equiv (2\sqrt{2}G_F)^{-1/2} \qquad \tau_\mu \equiv \frac{192\pi^3}{m_\mu^5} I(m_e, m_\mu) \times G_F^{-2}$$

2, the gauge coupling g is determined by M_Z and α_{EM}

$$g^2 = \frac{M_Z^2 + M_Z\sqrt{M_Z^2 - 8\alpha_{\text{EM}}\pi v^2}}{v^2}$$

1 + 2

$$M_W^2 = \frac{M_Z^2}{2}\left\{1 + \sqrt{1 - \frac{4\pi\alpha_{\text{EM}}}{\sqrt{2}G_F M_Z^2}}\right\}$$

Standard Model Prediction of M_W

- Loop corrections have been encoded: $M_W^2 = \frac{M_Z^2}{2}\left\{1 + \sqrt{1 - \frac{4\pi\alpha_{EM}}{\sqrt{2}G_F M_Z^2}}\right\}$
  - Full one and two-loops, and the leading three and four-loops were included
    [Awramik, Czakon, Freitas, Weiglein, 0311148v3 (2021)]
  - Fitting of EW precision observables are also encoded [de Blas, et al, 2112.07274]

$$M_W^{\rm SM} = 80350.5 \pm 7.7\,{\rm MeV}$$

  - The theoretical uncertainty is dominated by the input parameter uncertainty of top quark mass $\Delta m_t = 1.0$ GeV(conservative)
  - The subdominant uncertainty comes from the missing higher-order corrections

Electroweak precision fittings

[de Blas, Pierini, Reina, Silvestrini, 2204.04204]

Global fit — Fitting without the data

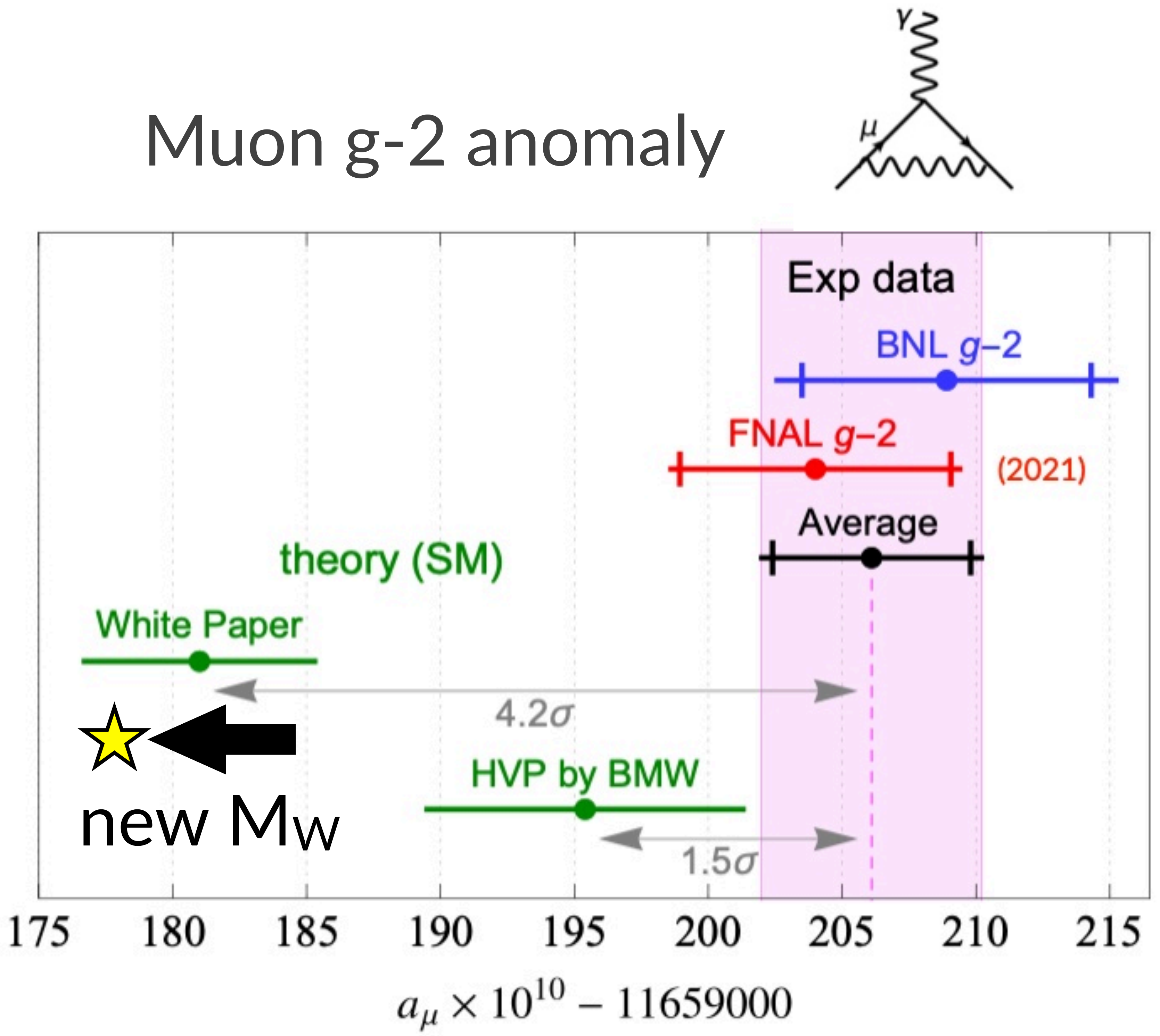
	Measurement	Posterior	Indirect/Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095 $[0.11576, 0.11946]$	0.11685 ± 0.00278 $[0.11145, 0.12233]$	0.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02766 ± 0.00010	0.027535 ± 0.000096 $[0.027349, 0.027726]$	0.026174 ± 0.000334 $[0.025522, 0.026826]$	4.3
M_Z [GeV]	91.1875 ± 0.0021	91.1911 ± 0.0020 $[91.1872, 91.1950]$	91.2314 ± 0.0069 $[91.2178, 91.2447]$	-6.1
m_t [GeV]	171.79 ± 0.38	172.36 ± 0.37 $[171.64, 173.09]$	181.45 ± 1.49 $[178.53, 184.42]$	-6.3
m_H [GeV]	125.21 ± 0.12	125.20 ± 0.12 $[124.97, 125.44]$	93.36 ± 4.99 $[82.92, 102.89]$	4.3
M_W [GeV]	80.4133 ± 0.0080	80.3706 ± 0.0045 $[80.3617, 80.3794]$	80.3499 ± 0.0056 $[80.3391, 80.3610]$	6.5
Γ_W [GeV]	2.085 ± 0.042	2.08903 ± 0.00053 $[2.08800, 2.09006]$	2.08902 ± 0.00052 $[2.08799, 2.09005]$	-0.1
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231471 ± 0.000055 $[0.231362, 0.231580]$	0.231469 ± 0.000056 $[0.231361, 0.231578]$	0.8

Several predictions deviate from the data

Global fit does not work for M_W

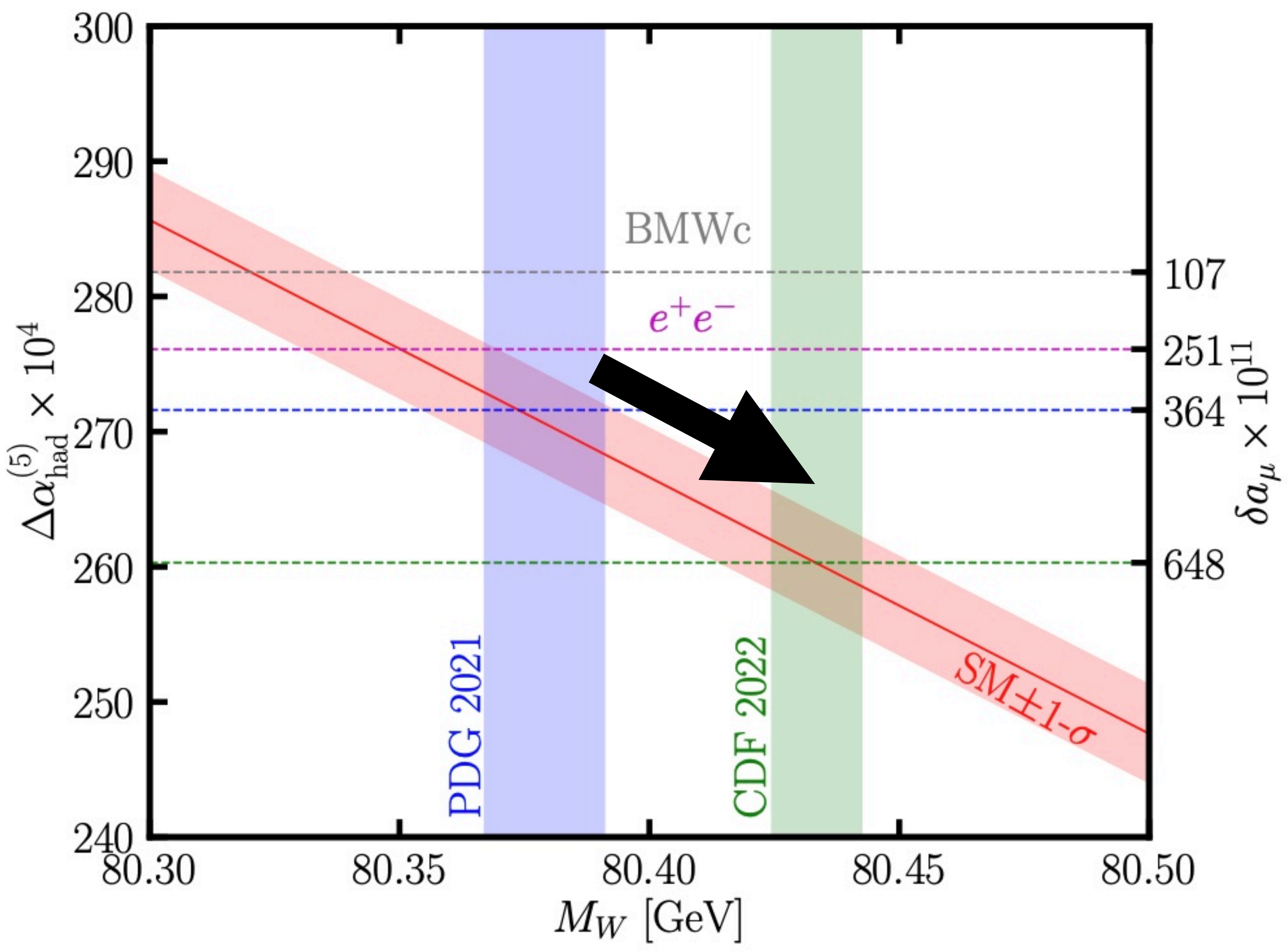
M_W anomaly vs muon g-2 anomaly [Athron, Fowlie, Lu, Wu, Zhu, 2204.03996]

Muon g-2 anomaly



The 4.2σ muon g-2 anomaly could be worsened to **5.1σ**

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = \frac{M_Z^2}{4\pi^2\alpha}\mathcal{P}\int_{m_{\pi^0}^2}^{\infty}\frac{ds}{M_Z^2 - s}\sigma_{ee\to{\rm had}}(\sqrt{s})$$

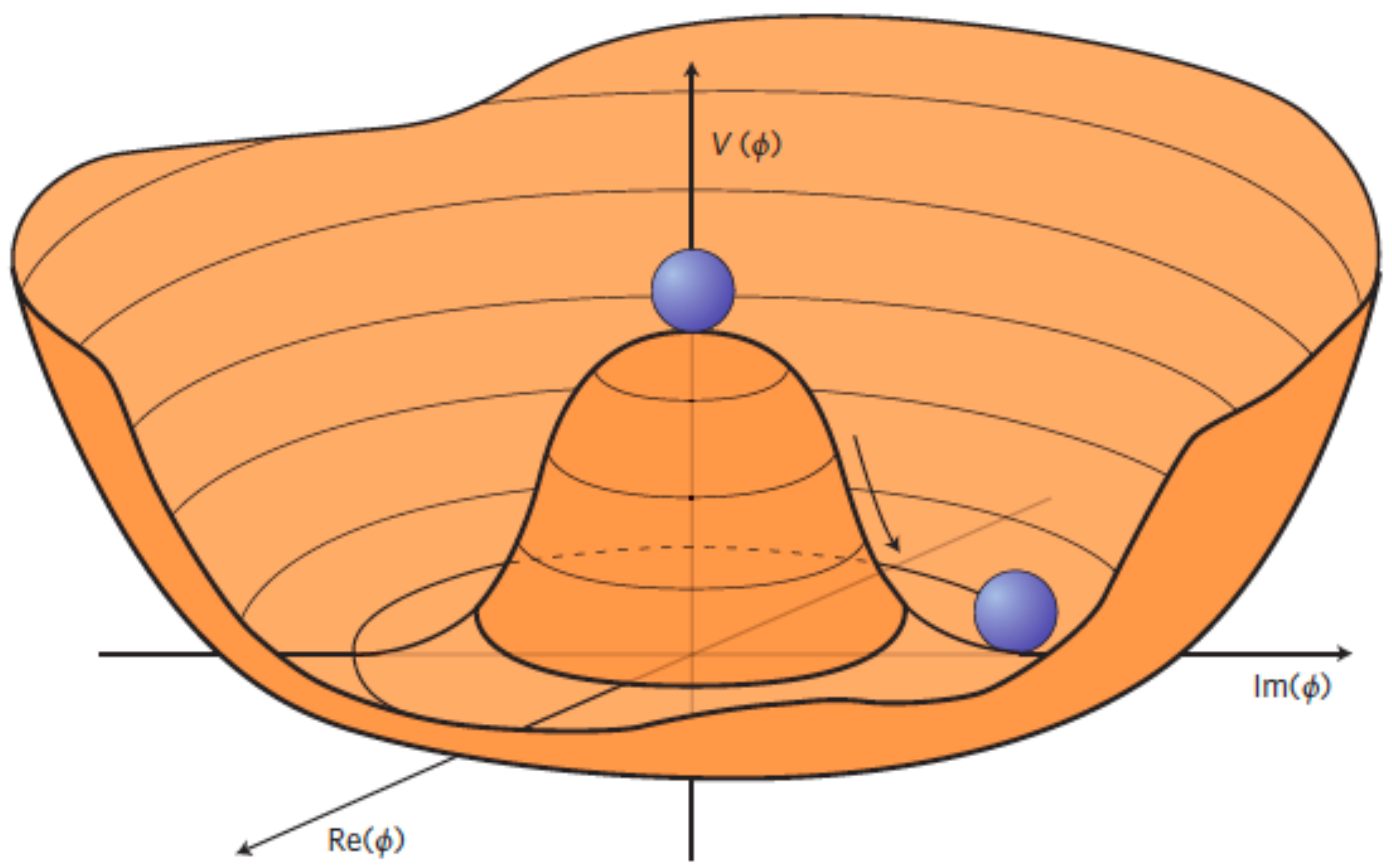


Assuming the overall rescaling of $\sigma_{ee\to{\rm had}}$, the HVP contribution to the muon g-2 reduces, and tension is amplified

New physics?

If new W-boson mass measurement is correct,
it implies the first evidence of
violation of the electroweak symmetry breaking

0.05% violation of



https://cds.cern.ch/

New physics

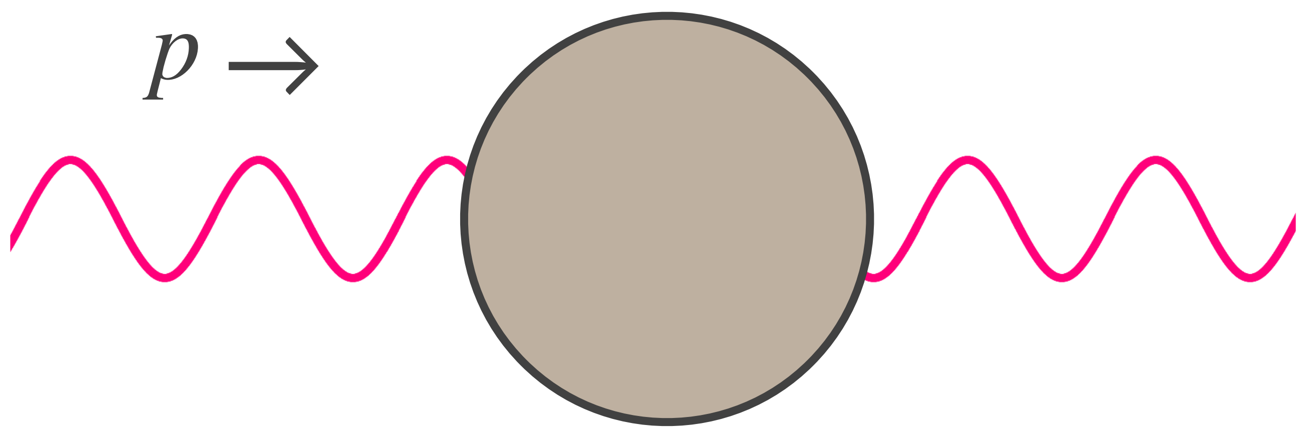
- Already, there are $O(100)$ papers on arXiv after new M_W data was announced
- Categorized into **only three types**: [Endo, Mishima, 2204.05965]
  - Dimension-six operator $Q_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$
    - The so-called "oblique *S* parameter"
  - Dimension-six operator $Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$
    - The so-called "oblique *T* parameter", the most popular scenarios and less constraint
  - Change the muon lifetime

After the electroweak symmetry breaking, these two operators produce additional W/Z boson mass

$$\tau_\mu \equiv \frac{192\pi^3}{m_\mu^5} I(m_e, m_\mu) \times G_F^{-2}$$

This relation is modified by new physics; interesting idea

Oblique corrections



- The oblique corrections are defined by the following Lagrangian

$$\mathscr{L} = -\frac{1}{2}\Pi_{W^3W^3}(p^2)W^{3\mu}W^3_\mu - \frac{1}{2}\Pi_{BB}(p^2)B^\mu B_\mu - \Pi_{W^3B}(p^2)W^{3\mu}B_\mu - \Pi_{W^+W^-}(p^2)W^{+\mu}W^-_\mu$$

- Using U(1)em symmetry and using the input values $M_Z, G_F, \alpha_{\rm EM}$, three free parameters remain; *S*, *T* and *U* parameters [Peskin, Takeuchi, '90, '92]

$$S = 16\pi \Pi'^{\rm NP}_{W^3B}(0)$$

$$T = \frac{4\pi}{s_W^2 c_{W^2}^2 M_Z^2}\left[\Pi^{\rm NP}_{W^3W^3}(0) - \Pi^{\rm NP}_{W^+W^-}(0)\right]$$

$$U = 16\pi\left[\Pi'^{\rm NP}_{W^3W^3}(0) - \Pi'^{\rm NP}_{W^+W^-}(0)\right]$$

U is dim-8 operator

dim-6 SMEFT language

$$S = \frac{8 s_W c_W}{\alpha_{\rm EM}} v^2 C_{HWB} \qquad Q_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$

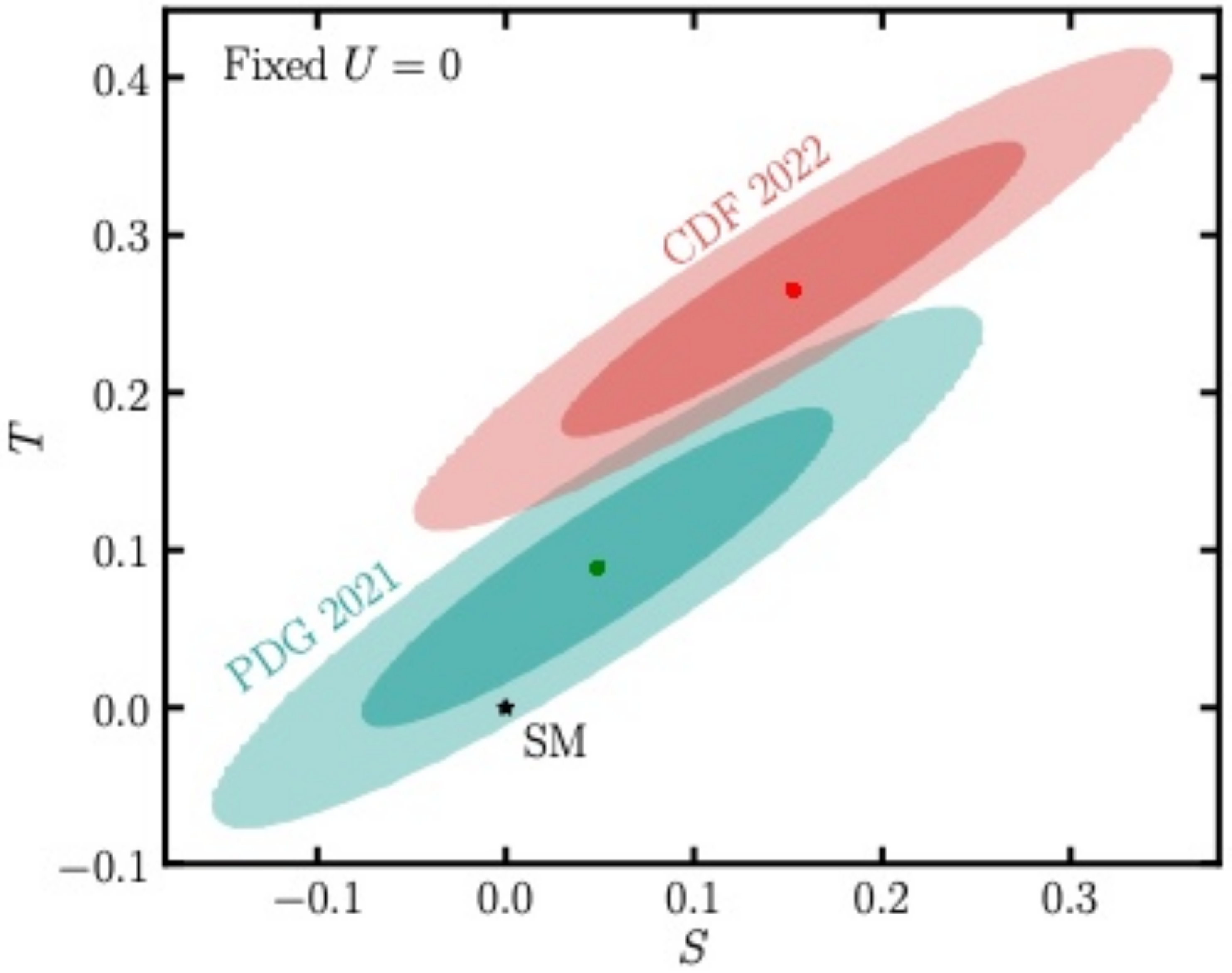
$$T = -\frac{1}{\alpha_{\rm EM}} v^2 C_{HD} \qquad Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$

New physics scale

- Oblique *S* parameter $Q_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$ [Fan, Li, Liu, Lyu, 2204.04805]
  - $1/\Lambda^2$ ~ $(5\text{—}10\ \text{TeV})^{-2}$ (tree) but other contributions are required
- Oblique *T* parameter $Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$ [Strumia, 2204.04191]
  - $1/\Lambda^2$ ~ $(6\ \text{TeV})^{-2}$ (tree) → ~ 1TeV (loop suppressed)
- Change the muon lifetime [Endo, Mishima, 2204.05965]
  - $1/\Lambda^2 = (5\text{—}8\ \text{TeV})^{-2}$ (tree)

Positive S & T favored

[Lu, Wu, Wu, Zhu, 2204.03796]

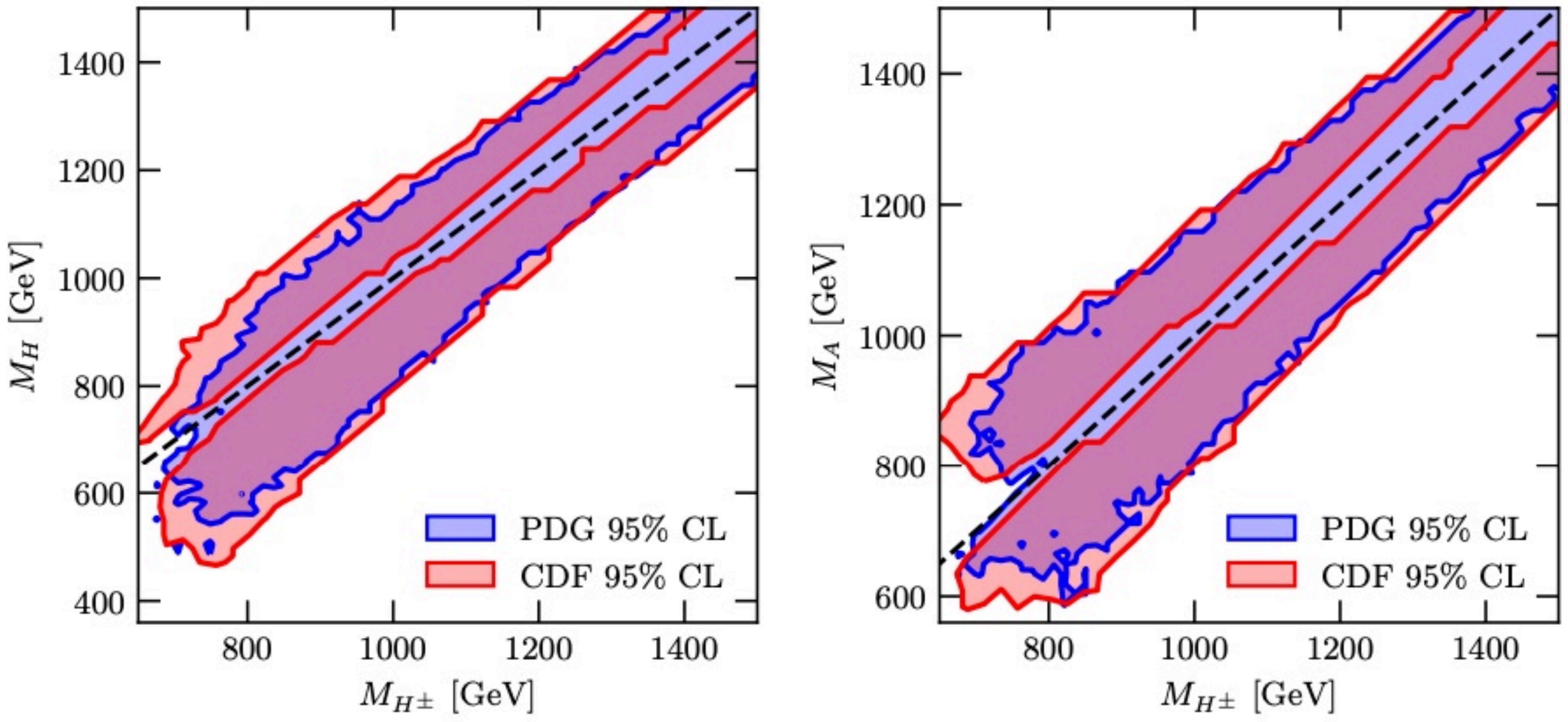


Custodial symmetry breaking (~oblique *T*)

- In the extended scalar models, a mass difference between the heavy SU(2) scalar multiplet produces a custodial symmetry breaking, leading to the higher W mass

Type-II 2HDM

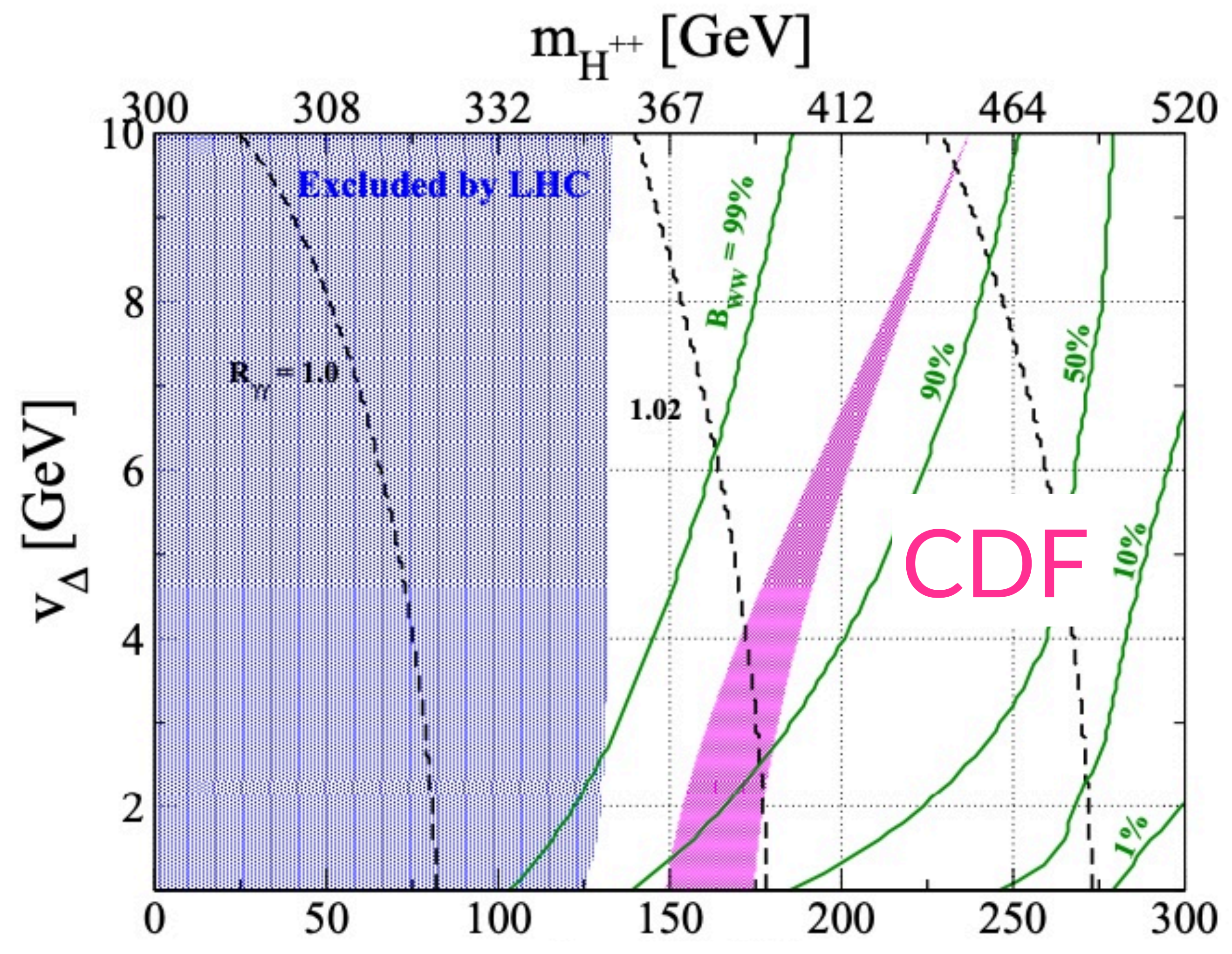
[Ahn, Kang, Ramos, 2204.06485]



Higgs triplet model

[Kanemura, Yagyu, 2204.07511]

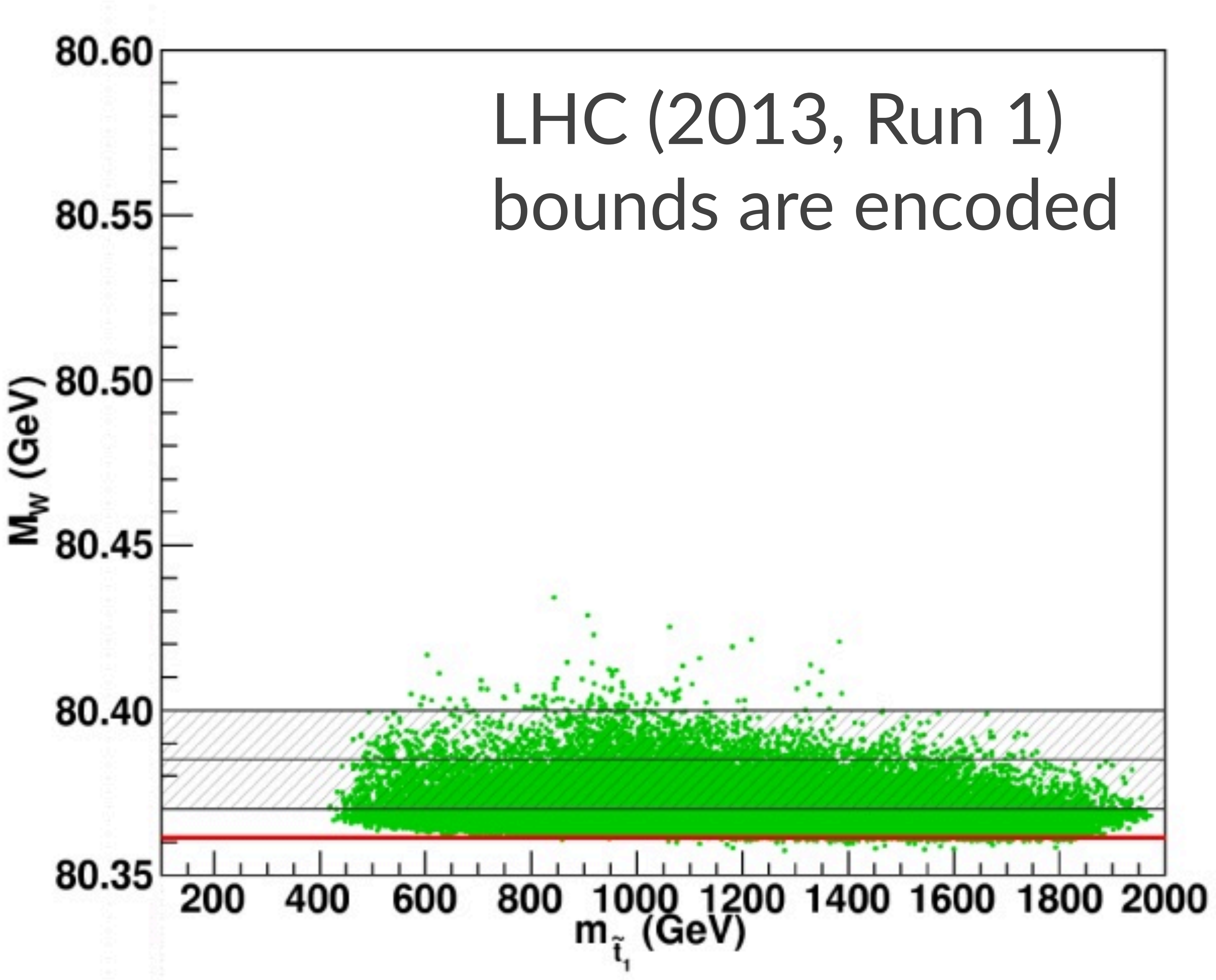
triplet vev



$$\sqrt{m_{H^{++}}^2 - m_{H^+}^2}, \sqrt{m_{H^+}^2 - m_A^2}$$

Supersymmetry

- In the supersymmetric model, several loops contribute to M_W. In particular, stop-bottom loop gives the leading contribution [Heinemeyer, Hollik, Weiglein, Zeune, 1311.1663]



stop = Scalar supersymmetric partner of top quark
sbottom = Scalar supersymmetric partner of bottom

$$M_W^{\rm exp} = 80413 \pm 15\,{\rm MeV}$$

The lightest stop mass should be **around 1TeV**

Leptoquark catalogue

[*cf.* Angelescu, Bečirević, Faroughy, Jaffredo, Sumensari, 2103.12504; Athron, Balazs , Jacob , Kotlarski, Stockinger , Stockinger-Kim, 2104.03691]

- Leptoquarks that do not lead to proton decay and can contribute precision measurements

[LQ* requires additional symmetry that forbids the proton decay, see 1603.04993]

Label	Spin	Charge	$R(D^{(*)})$	$R(K^{(*)})$	muon g-2	M_W
S_1 LQ (*)	0	$(\bar{3}, 1, 1/3)$	✓	Loop	✓	With S_3
U_1 LQ	1	(3, 1, 2/3)	✓	✓	✗	✗
R_2 LQ	0	(3, 2, 7/6 [1/6])	✓	Loop	✓	Small
V_2 LQ (*)	1	$(\bar{3}, 2, 5/6)$	Small	Electron	Small	✓
S_3 LQ (*)	0	$(\bar{3}, 3, 1/3)$	✗	✓	✗	With S_1
U_3 LQ	1	(3, 3, 2/3)	✗	✓	✗	?

Proposed new physics scenario

[A. Crivellin, M. Kirk, **TK**, F. Mescia, 2204.05962]

PSI-PR-22-09, ZU-TH-12/22, KEK-TH-2411

Correlating $t \to cZ$ to the W Mass and B Physics with Vector-Like Quarks

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The rare flavour changing top quark decay $t \to cZ$ is experimentally very interesting due to the huge number of top quarks produced at the LHC. Furthermore, in the Standard Model the corresponding rate is suppressed, such that any observation of this process in the foreseeable future would prove the presence of new physics. However, there are few (viable) models which can generate a sizable branching ratio for $t \to cZ$ – in fact vector-like quarks seem to be the only realistic option. In this Letter, we investigate all three representations (under the Standard Model gauge group) of vector-like quarks (U, Q_1 and Q_7) that can generate a sizable branching ratio for $t \to cZ$ without violating other bounds. Nonetheless, these vector-like quarks still give rise to loop-effects in B physics and electroweak precision observables which we calculate by matching the model on the Standard Model

Vector-like quarks models 1/3

- Motivation of vector-like quark models: (vector-like means non-chiral and Left = $\overline{\text{Right}}$)
  - 1, simple renormalizable extension of the SM
  - 2, connection to the quark flavor physics (unique model predictions)
  - 3, connection to the *B* anomaly (different long-standing anomaly)
- Lagrangian $\mathcal{L} = \sum \bar{F}\left(i\not{D} - M_F\right)F\,,$ where $F = \{U,\, D,\, Q_1,\, Q_5,\, Q_7,\, T_1,\, T_2\}$

	u	d	q	H	$\boldsymbol{U}$	D	$\boldsymbol{Q_1}$	Q_5	$\boldsymbol{Q_7}$	T_1	T_2
$SU(3)_C$	3	3	3	1	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	1	1	2	2	2	3	3
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$1/2$	$2/3$	$-1/3$	$1/6$	$-5/6$	$7/6$	$-1/3$	$2/3$

Tree	U	D	Q_1	Q_5	Q_7	T_1	T_2
Z-u_L^i-u_L^j	✓	×	×	×	×	✓	✓
Z-u_R^i-u_R^j	×	×	✓	×	✓	×	×
Z-d_L^i-d_L^j	×	✓	×	×	×	✓	✓
Z-d_R^i-d_R^j	×	×	✓	✓	×	×	×

Vector-like quarks models 2/3

- Interaction term

$$\mathcal{L} = \mathcal{L}_{qq}^H + \mathcal{L}_{q\mathrm{VLQ}}^H + \mathcal{L}_{\mathrm{VLQVLQ}}^H\,,$$

$$-\mathcal{L}_{qq}^H = Y_{ij}^u \bar{q}_i \tilde{H} u_j + Y_{ij}^d \bar{q}_i H d_j + \mathrm{h.c.}\,,$$

SM Yukawa (quark-quark SM Higgs)

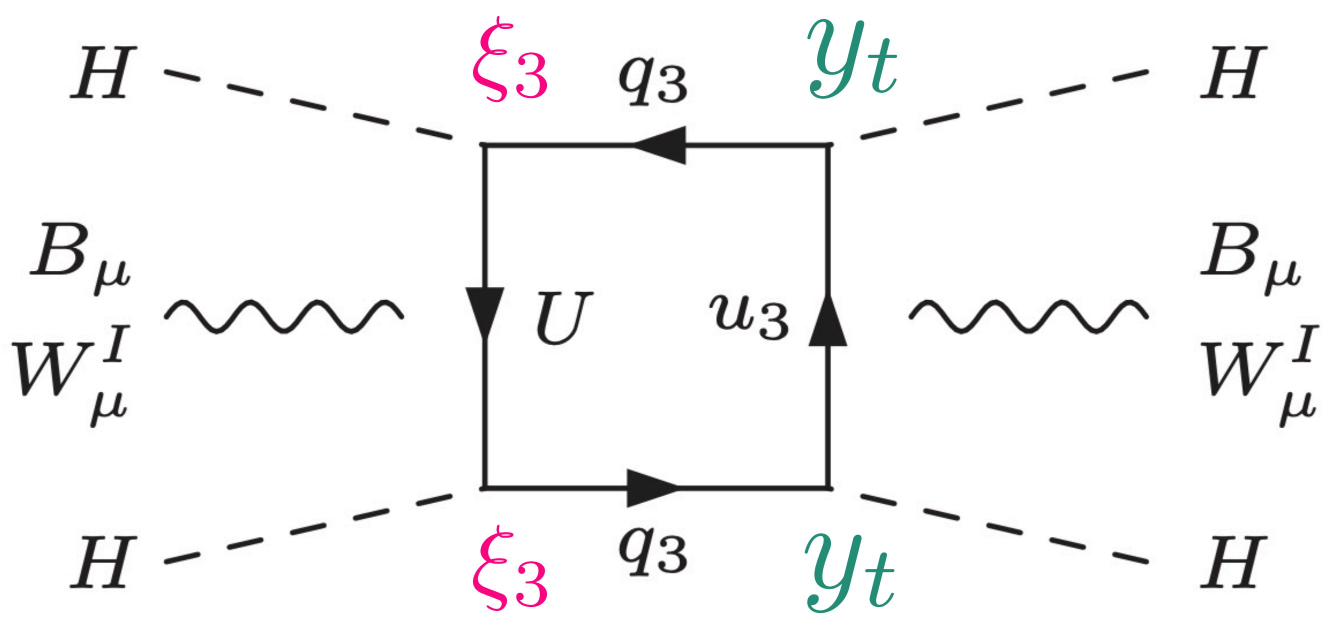
$$\begin{aligned}-\mathcal{L}_{q\mathrm{VLQ}}^H = {} & \xi_i^U \bar{U} \tilde{H}^\dagger q_i + \xi_i^D \bar{D} H^\dagger q_i + \xi_i^{u_1} \bar{Q}_1 \tilde{H} u_i \\ & + \xi_i^{d_1} \bar{Q}_1 H d_i + \xi_i^{Q_5} \bar{Q}_5 \tilde{H} d_i + \xi_i^{Q_7} \bar{Q}_7 H u_i \\ & + \frac{1}{2}\xi_i^{T_1} H^\dagger \tau \cdot \bar{T}_1 q_i + \frac{1}{2}\xi_i^{T_2} \tilde{H}^\dagger \tau \cdot \bar{T}_2 q_i + \mathrm{h.c.}\,,\end{aligned}$$

VL q-quark-SM Higgs

VL q-VL q-SM Higgs is unimportant

- W boson mass correction

→ oblique T



$$\Delta M_W^2 \propto \frac{(\xi_3)^2 (y_t)^2}{M_{\mathrm{VLq}}^2}$$

We found only U, Q_1 and Q_7 can explain the W mass anomaly

Vector-like quarks models 3/3

- We calculated three vector-like quark models (U, Q_1 and Q_7)
- One-loop matching between UV model and SMEFT (all relevant terms including top and B physics), one-loop RGE between UV to EW, and one-loop matching between SMEFT and the weak hamiltonian
- Both oblique S and T are produced

S

$$C_{HWB} = -\frac{g_1 g_2 \xi_i^U \xi_i^{U*}}{64\pi^2 M_U^2} - \frac{g_1 g_2 \xi_i^{u_1} \xi_i^{u_1*}}{96\pi^2 M_{Q_1}^2} + \frac{g_1 g_2 \xi_i^{Q_7} \xi_i^{Q_7*}}{96\pi^2 M_{Q_7}^2},$$

T

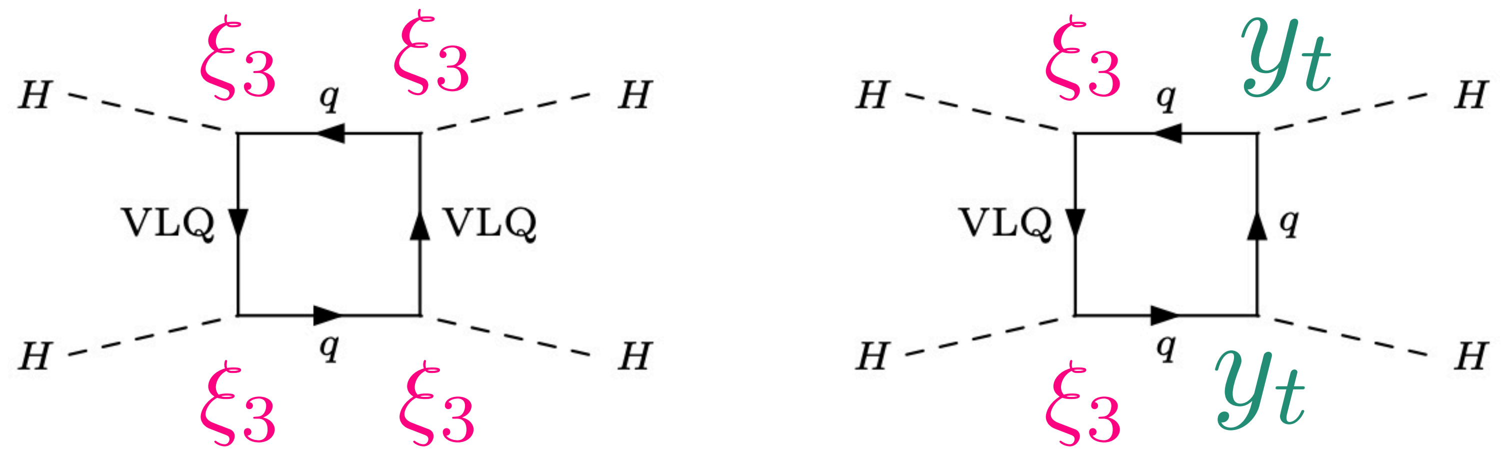
$$C_{HD} = -\frac{3\xi_i^U \xi_j^U \xi_i^{U*} \xi_j^{U*}}{32\pi^2 M_U^2} + \frac{3\xi_i^U (Y^u Y^{u\dagger})_{ij} \xi_j^{U*}}{16\pi^2} F_1(M_U)$$
$$- \frac{\xi_i^{u_1} \xi_j^{u_1} \xi_i^{u_1*} \xi_j^{u_1*}}{8\pi^2 M_{Q_1}^2} + \frac{3\xi_i^{u_1} (Y^{u\dagger} Y^u)_{ij} \xi_j^{u_1*}}{8\pi^2} F_2(M_{Q_1}) - \frac{\xi_i^{Q_7} \xi_j^{Q_7} \xi_i^{Q_7*} \xi_j^{Q_7*}}{8\pi^2 M_{Q_7}^2} - \frac{3\xi_i^{Q_7} (Y^{u\dagger} Y^u)_{ij} \xi_j^{Q_7*}}{8\pi^2} F_2(M_{Q_7}),$$

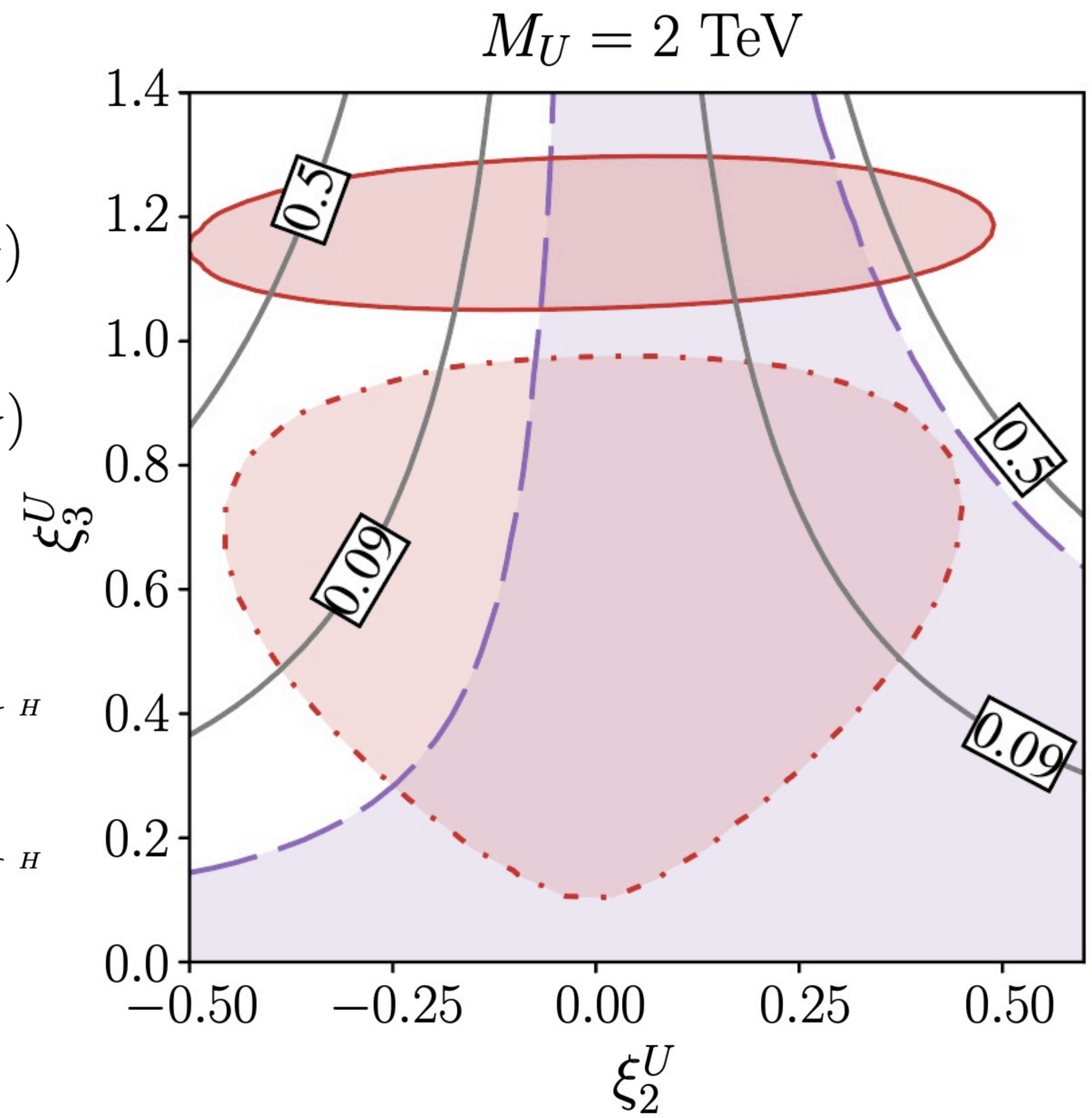
with $F_1(m) = \frac{1}{m^2}\left(\frac{1}{2} + \ln\frac{\mu^2}{m^2}\right)$, $F_2(m) = \frac{1}{m^2}\left(\frac{3}{2} + \ln\frac{\mu^2}{m^2}\right)$

A result: *U* vector-like quark model

EWPO (with CDF M_W)

EWPO (without CDF M_W)

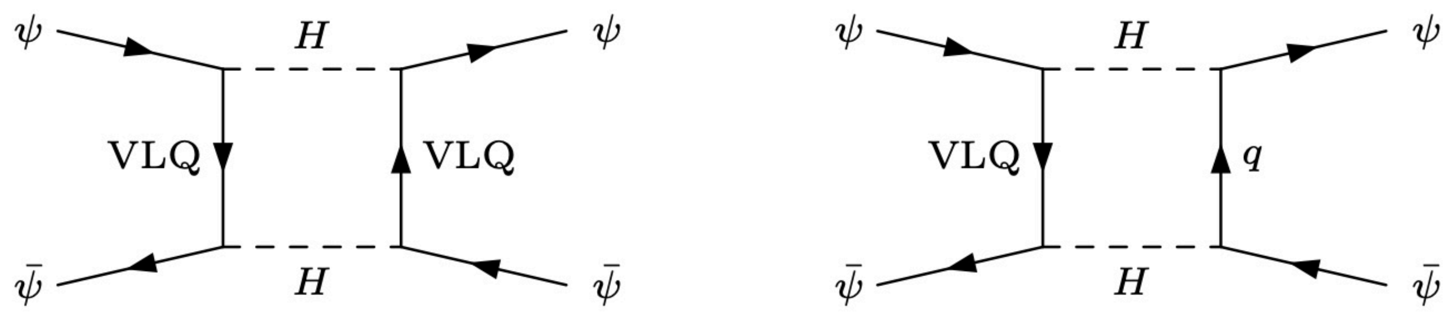




tree-level top FCNC:
unique prediction in VL q model

$\mathrm{Br}(t \to cZ) \times 10^5$

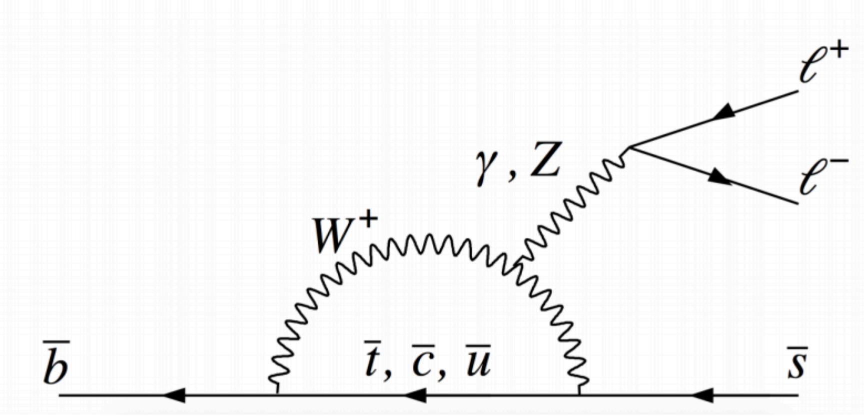
ΔM_s B_s–$\overline{B}_s$ mixing

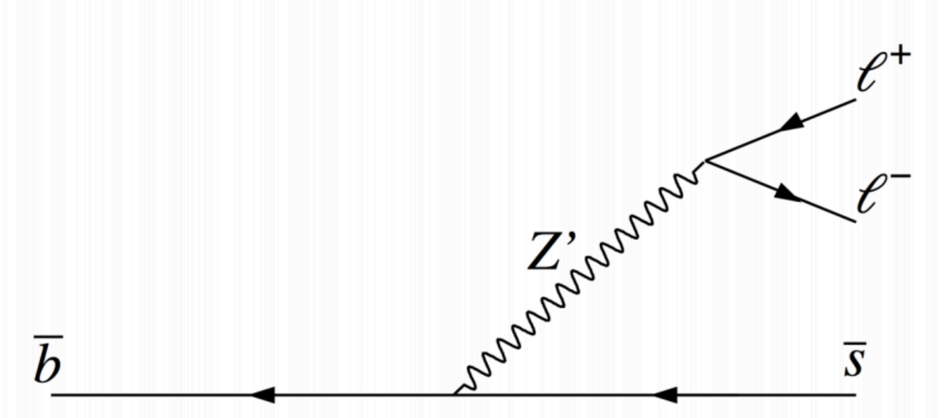


$b \to s\gamma$ has been checked,
but it is irrelevant

Lepton flavor universality observables $R(K)$ and $R(K^*)$

$$R(K^{(*)}) = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)}$$



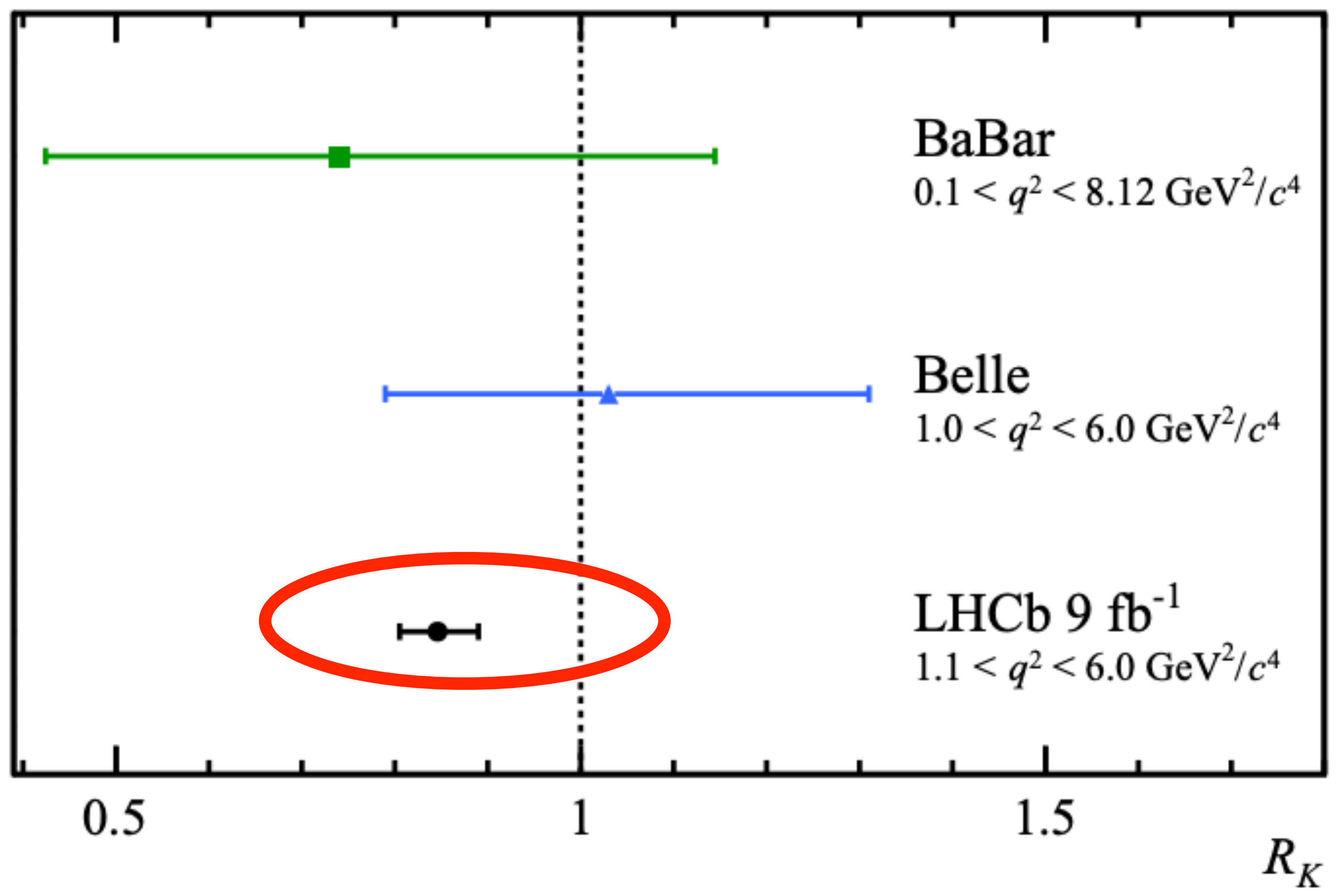


SM vs. NP, *e.g.*, Z' boson

SM predictions:

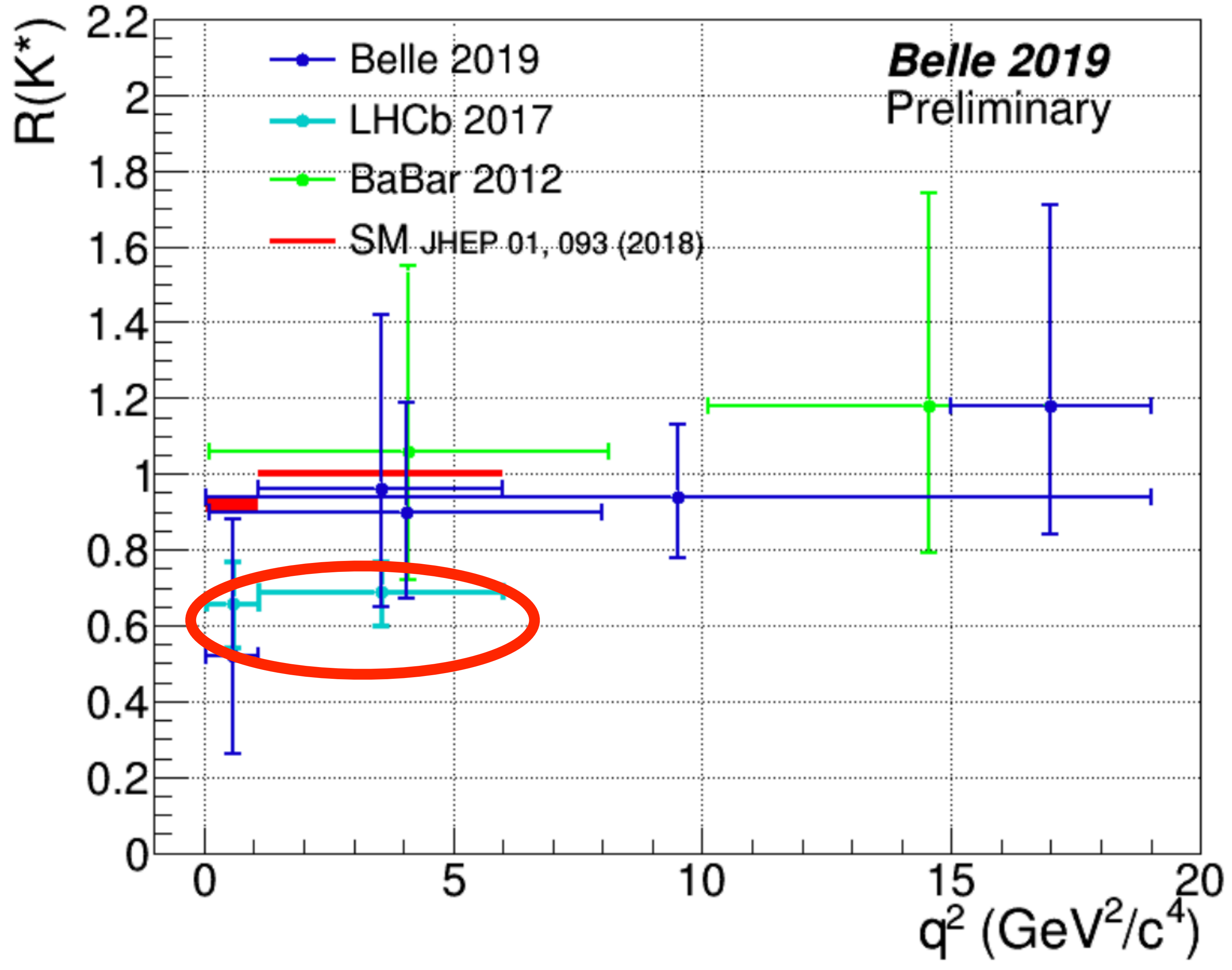
$$R(K) \simeq R(K^*) \simeq 1$$

$R(K)$



~ 3.1σ below the SM

$R(K^*)$

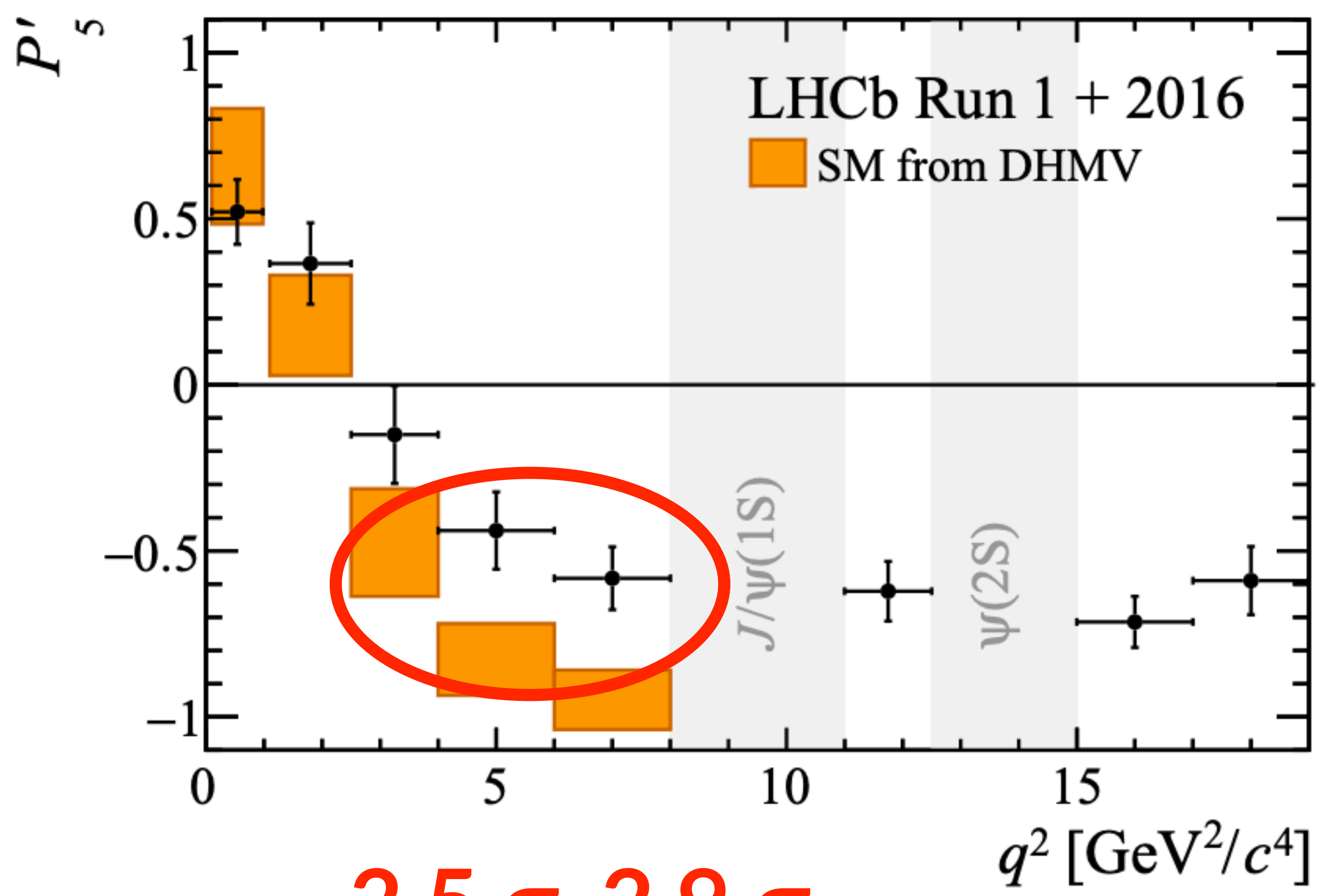


~ 2.5σ below the SM

$b \to s\mu^+\mu^-$ (not ratio) anomalies

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

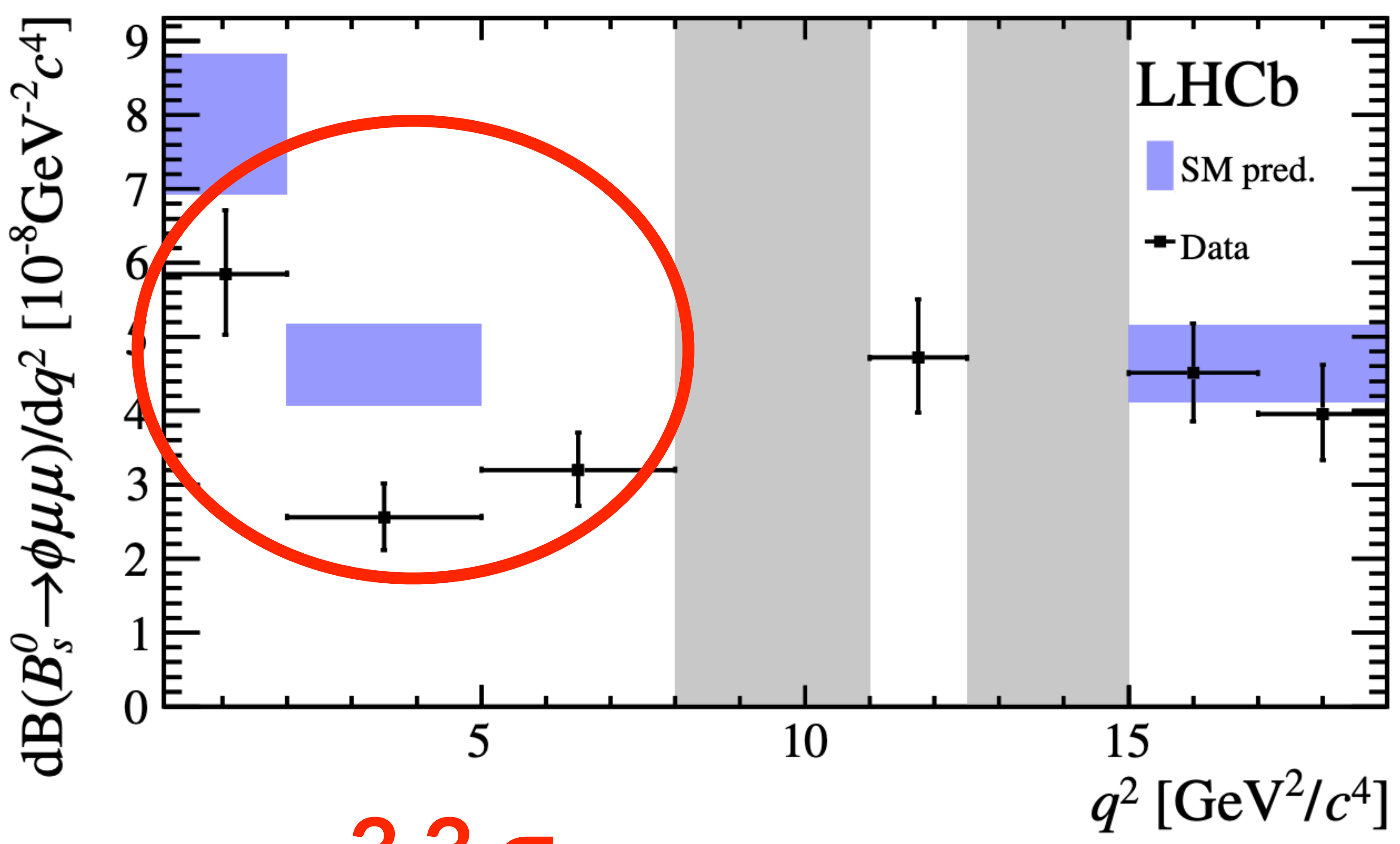
[LHCb, 2003.04831]



2.5 σ, 2.9 σ

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

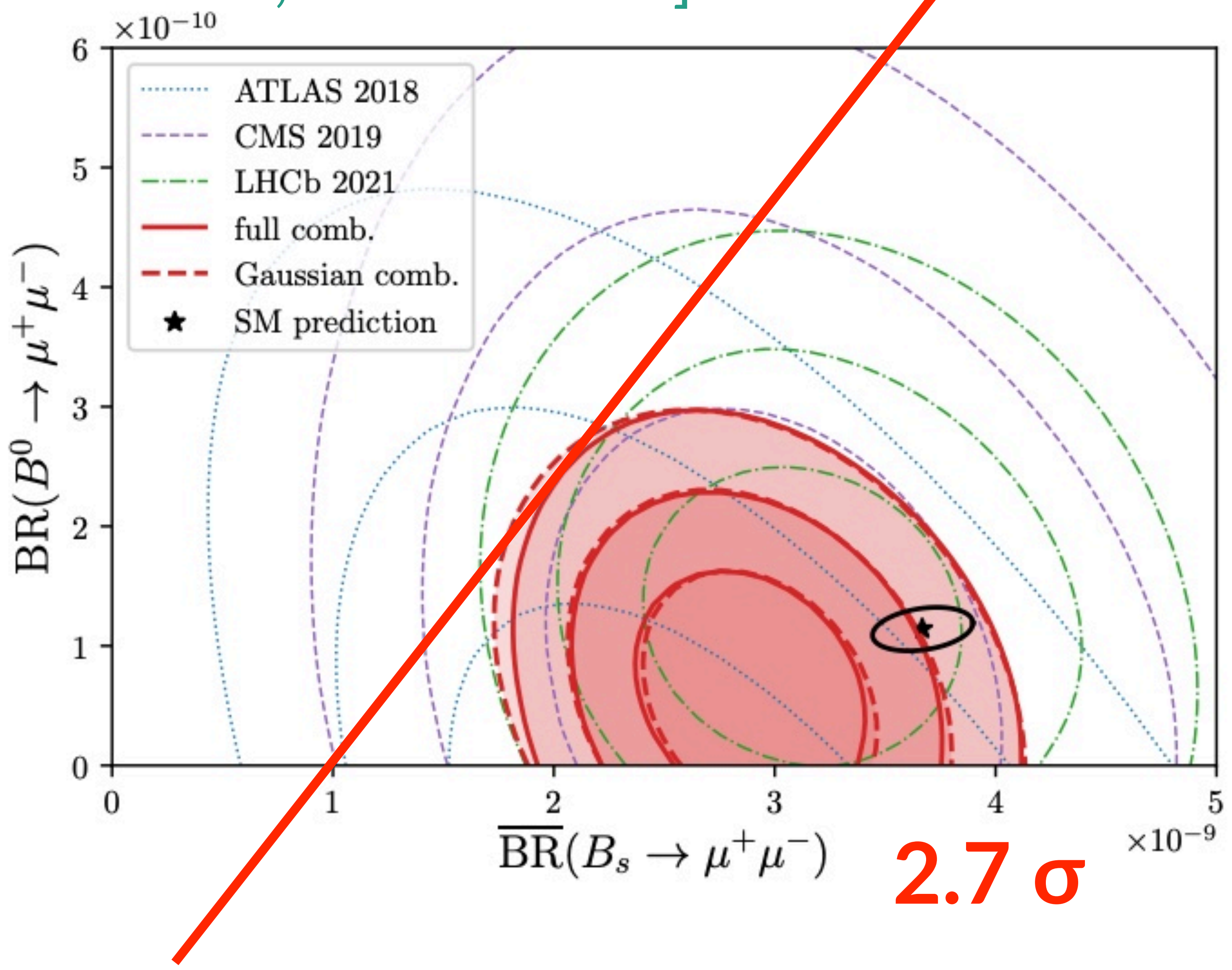
[LHCb, 1506.08777]



3.3 σ

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

[Altmannshofer, Stangl, 2103.13370; Buras, 2205.01118]



2.7 σ

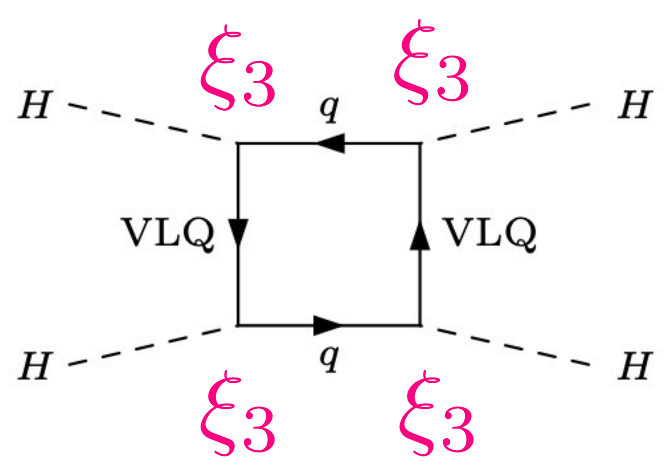
Now, no anomaly [CMS, ICHEP2022]

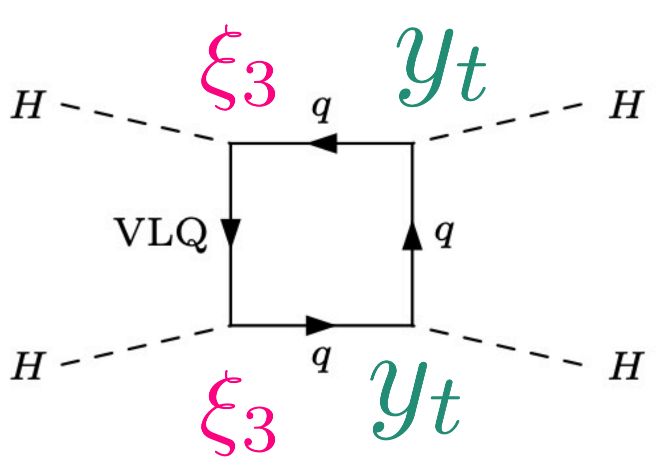
- Angular distribution of $\Lambda_b \to \Lambda\mu^+\mu^-$ [K_6] is also deviated **at 2.6 σ** [LHCb, 1808.00264]

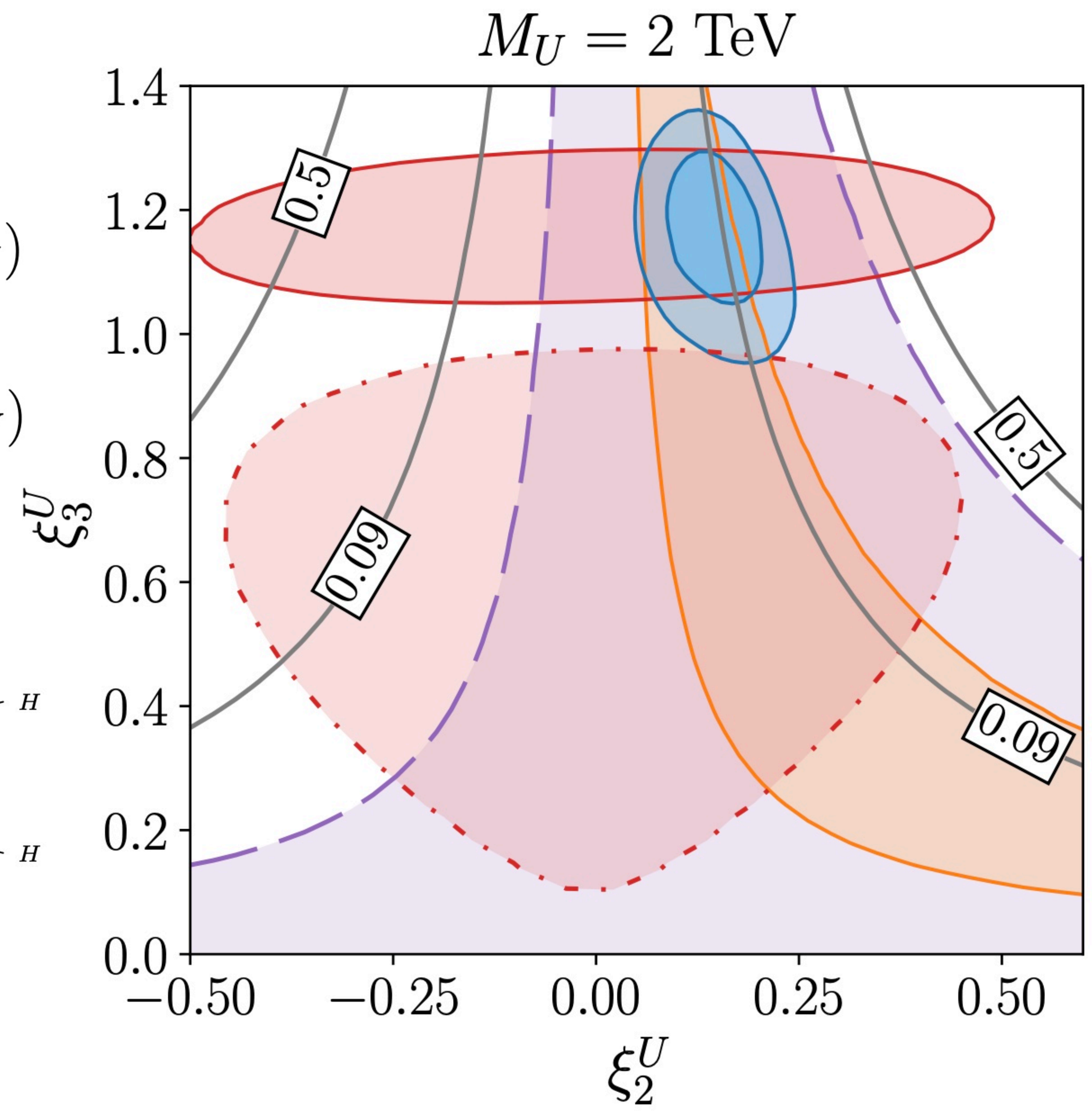
Final result: *U* vector-like quark model

EWPO (with CDF M_W)

EWPO (without CDF M_W)







global

tree-level top FCNC:
unique prediction in VL q model

$\mathrm{Br}(t \to cZ) \times 10^5$

ΔM_s B_s–$\overline{B}_s$ mixing

$b \to s\ell\ell$

B anomaly
favored region

Predicted top FCNC can be probed by future 100TeV collider

Conclusion

- New W mass measurement from CDF is **inconsistent at 3σ level** with the other colliders
- Conservatively, the tension could become **3σ level between average of data vs. SM**
- Future electron colliders (ILC/CEPC/FCC-ee) are required to crosscheck [$\mathcal{O}(1)$ MeV precision]
- Many new physics models have been proposed; can be categorized into only three types
- 2HDM, HTM, Supersymmetry work well
- TeV scale vector-like quark can explain the M_W as well as B anomaly (our work), predicting unique signal in top FCNC decays