PRISMA Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

Beyond the Higgs Boson

Particle Physics at the Verge of More Discoveries?

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and PRISMA Cluster of Excellence
Johannes Gutenberg University, Mainz

25 January 2016 — 54th International Winter Meeting on Nuclear Physics, Bormio

Based on collaborations with Martin Bauer (arXiv:1511:01900, 1512:06828)

ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Mainz Institute for Theoretical Physics

Overview

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Discovery of the Higgs Boson

A new kind of particle

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Dark matter, flavor anomalies and diboson resonances

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One Leptoquark to Rule Them All

Part I: Flavor anomalies

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One Leptoquark to Rule Them All

Part II: Diphoton resonance S(750)

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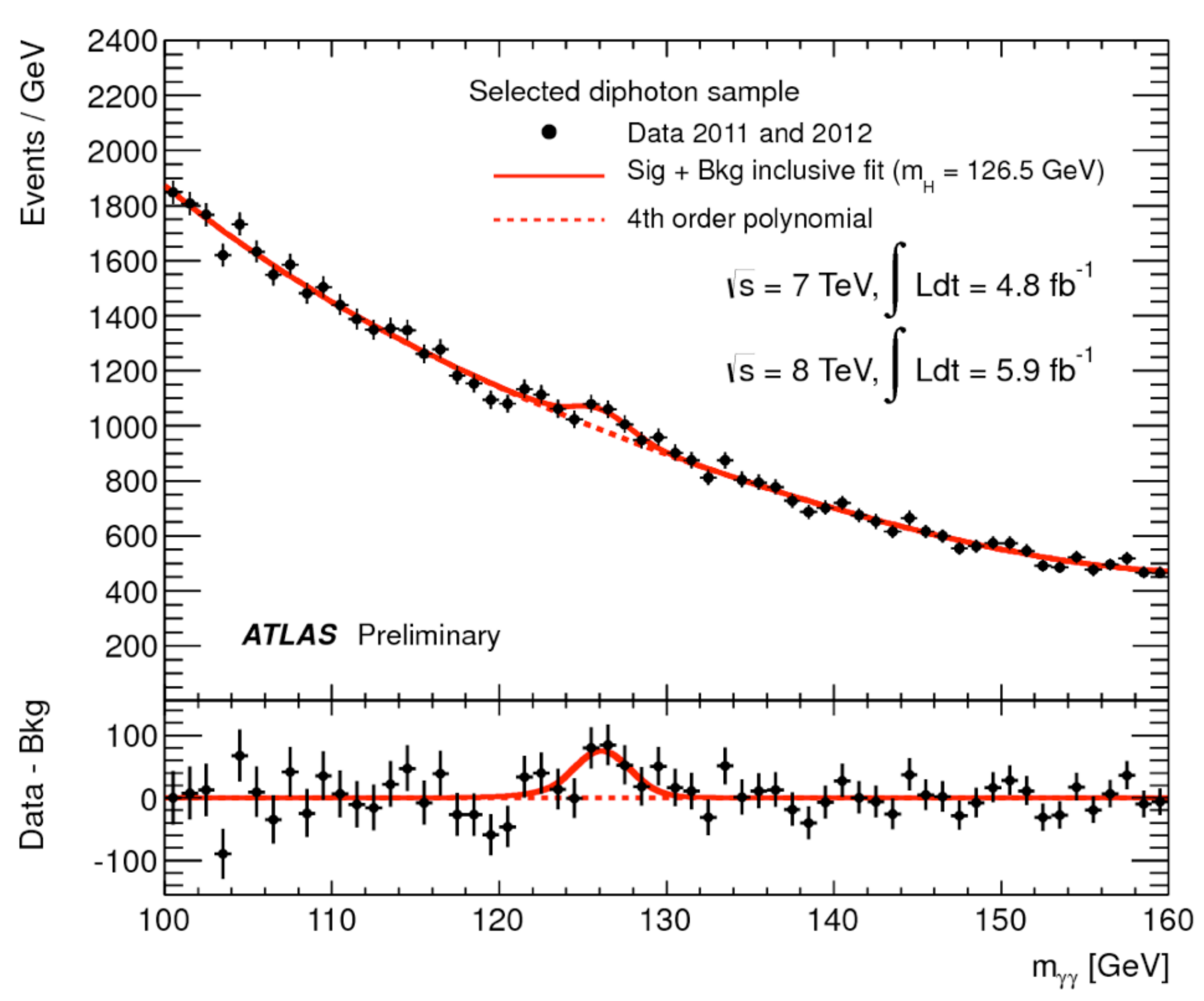
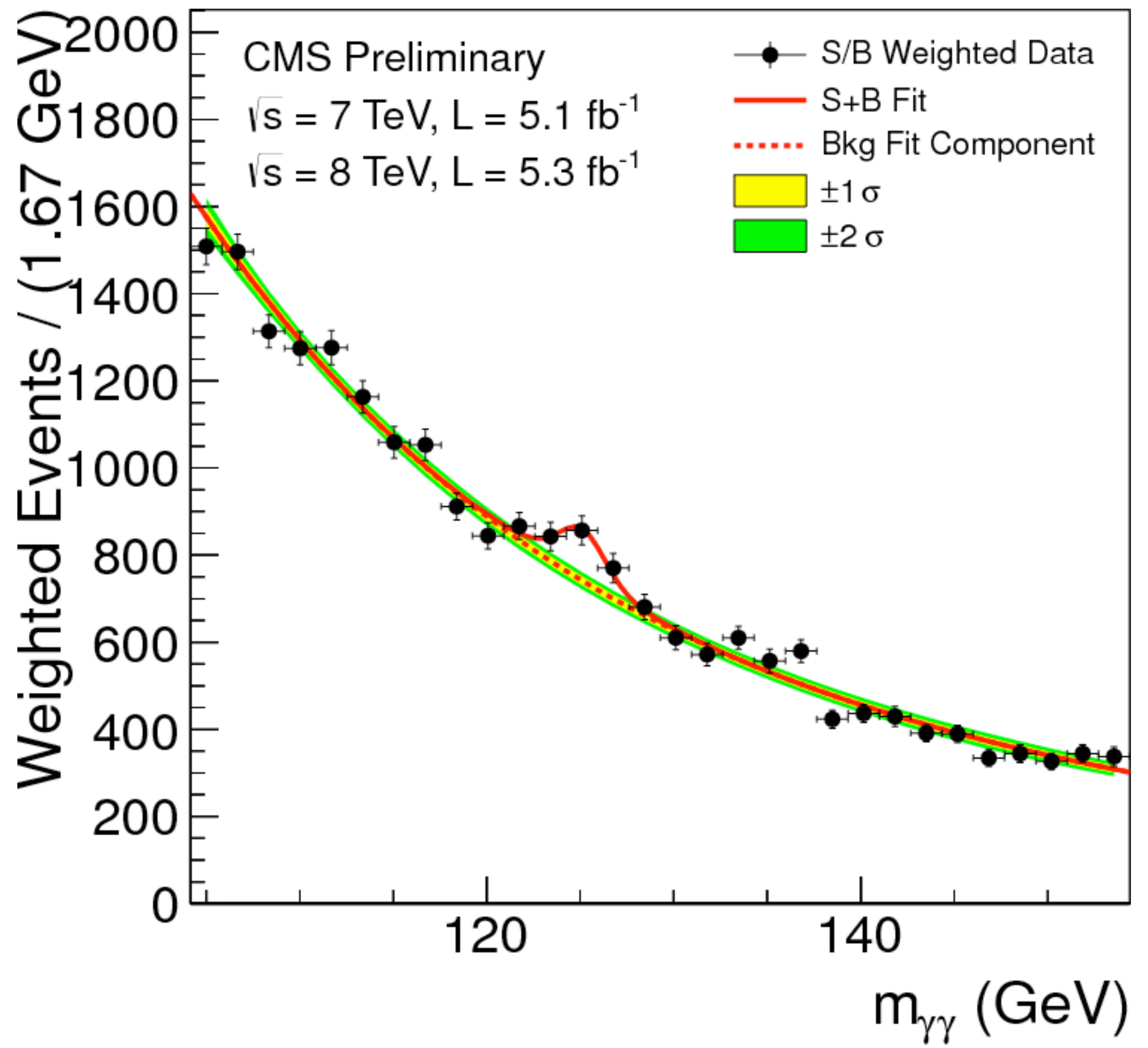
Outlook

Discovery of the Higgs boson: A new kind of particle





4 July 2012: A milestone in the history of physics

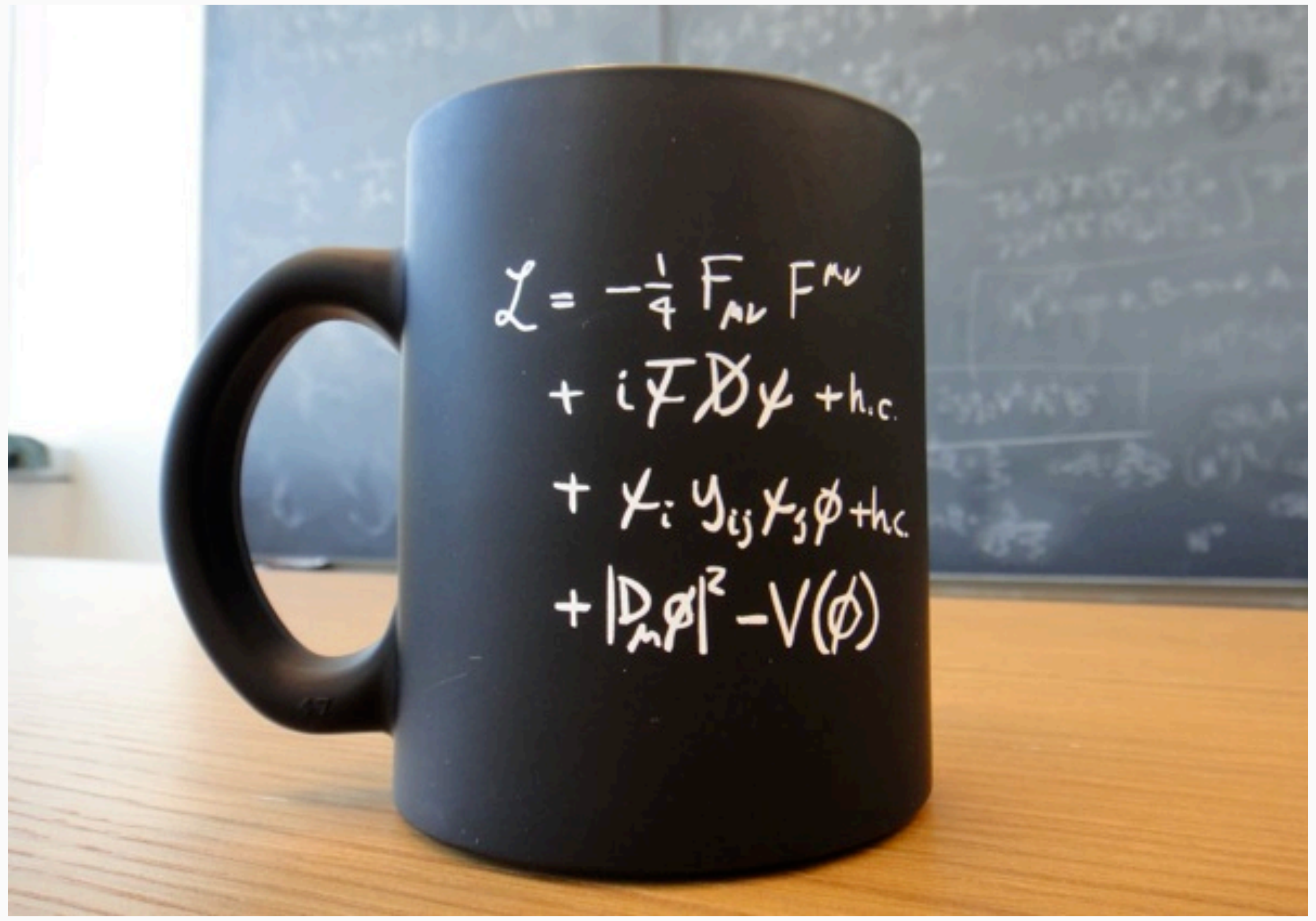
Discovery of the Higgs boson: A new kind of particle

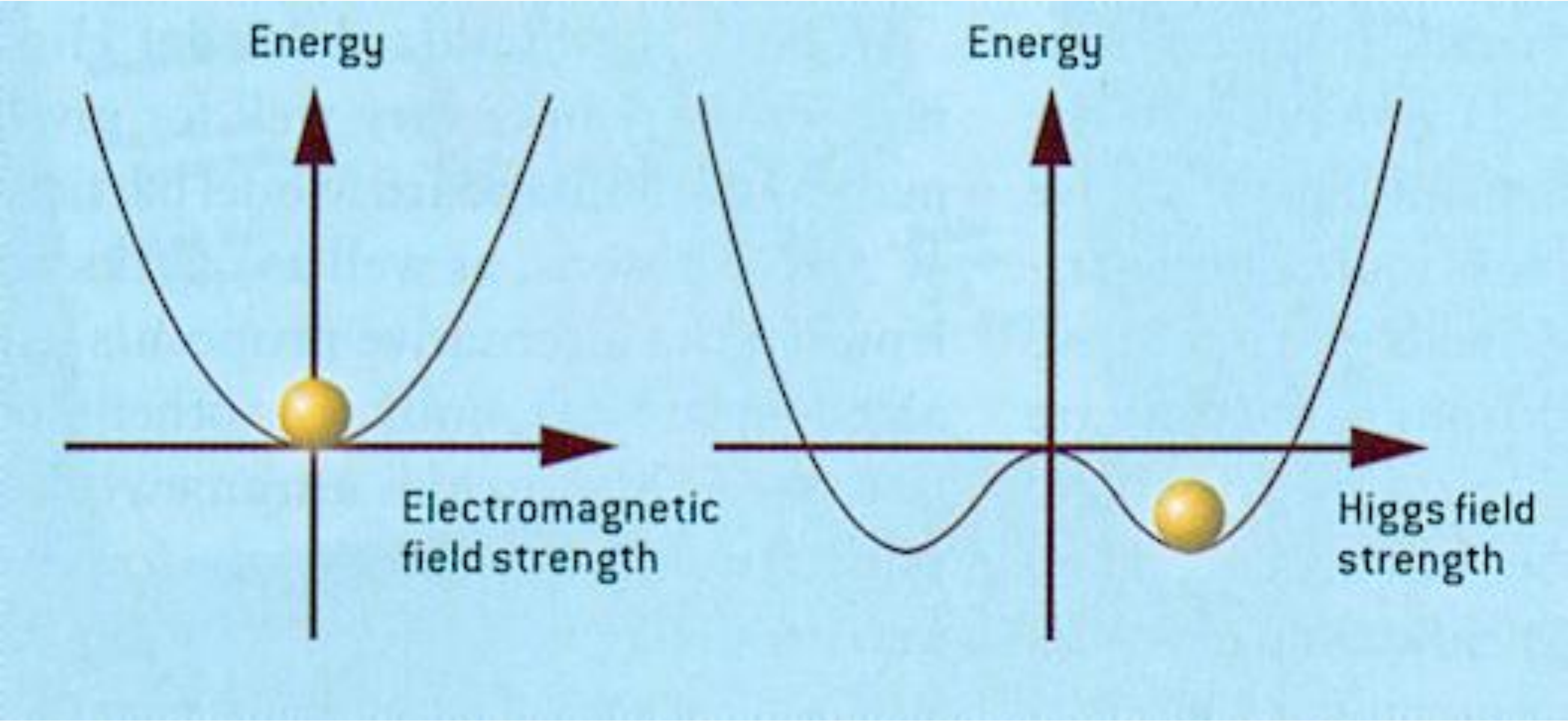
The Standard Model of particle physics is complete!

The Higgs mechanism predicts the existence of a medium penetrating all of spacetime (like an ether)

In any relativistic quantum theory a field can be excited to vibrate — the vibrations of the Higgs medium consist of Higgs bosons

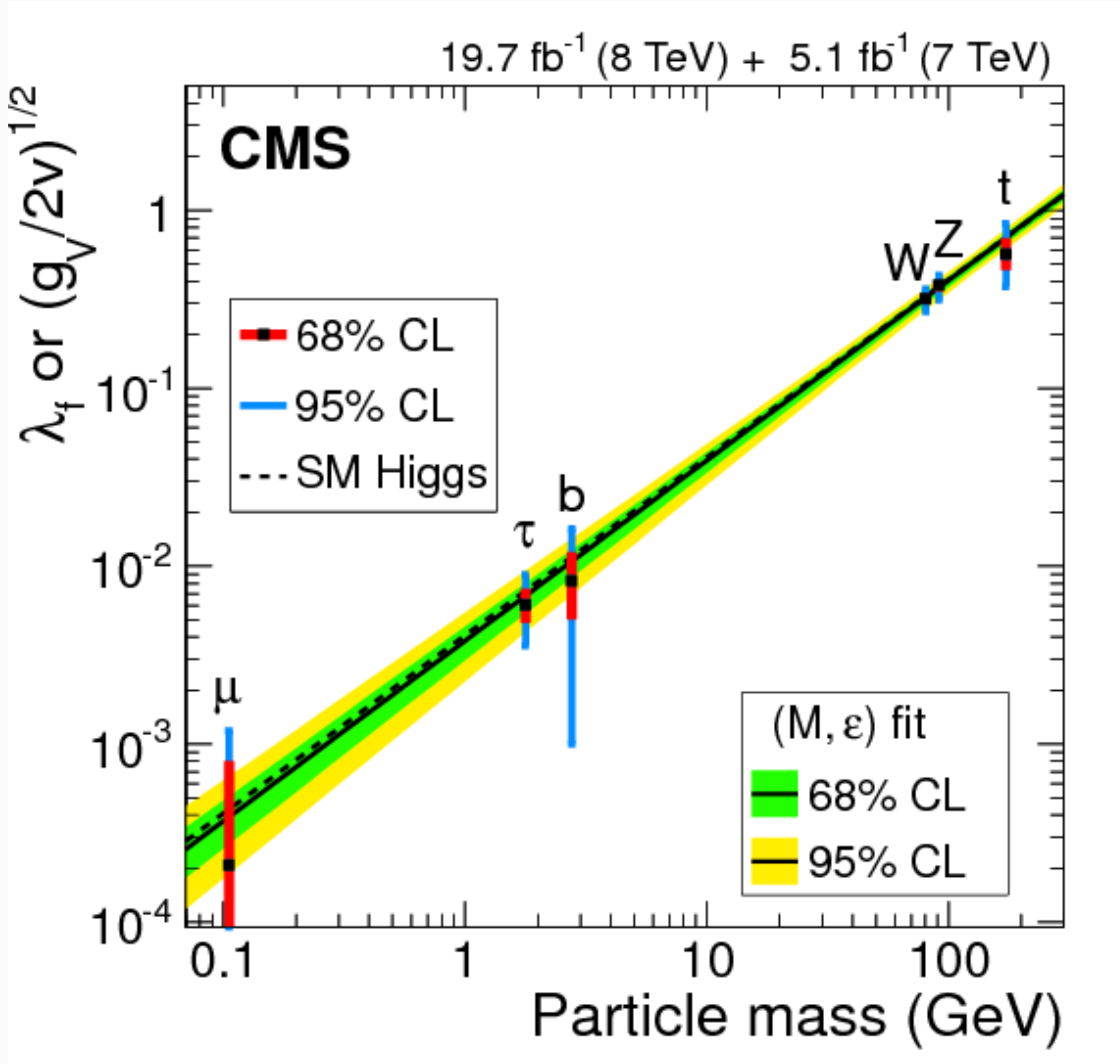
The Higgs discovery provides an experimental proof for the existence of the Higgs medium



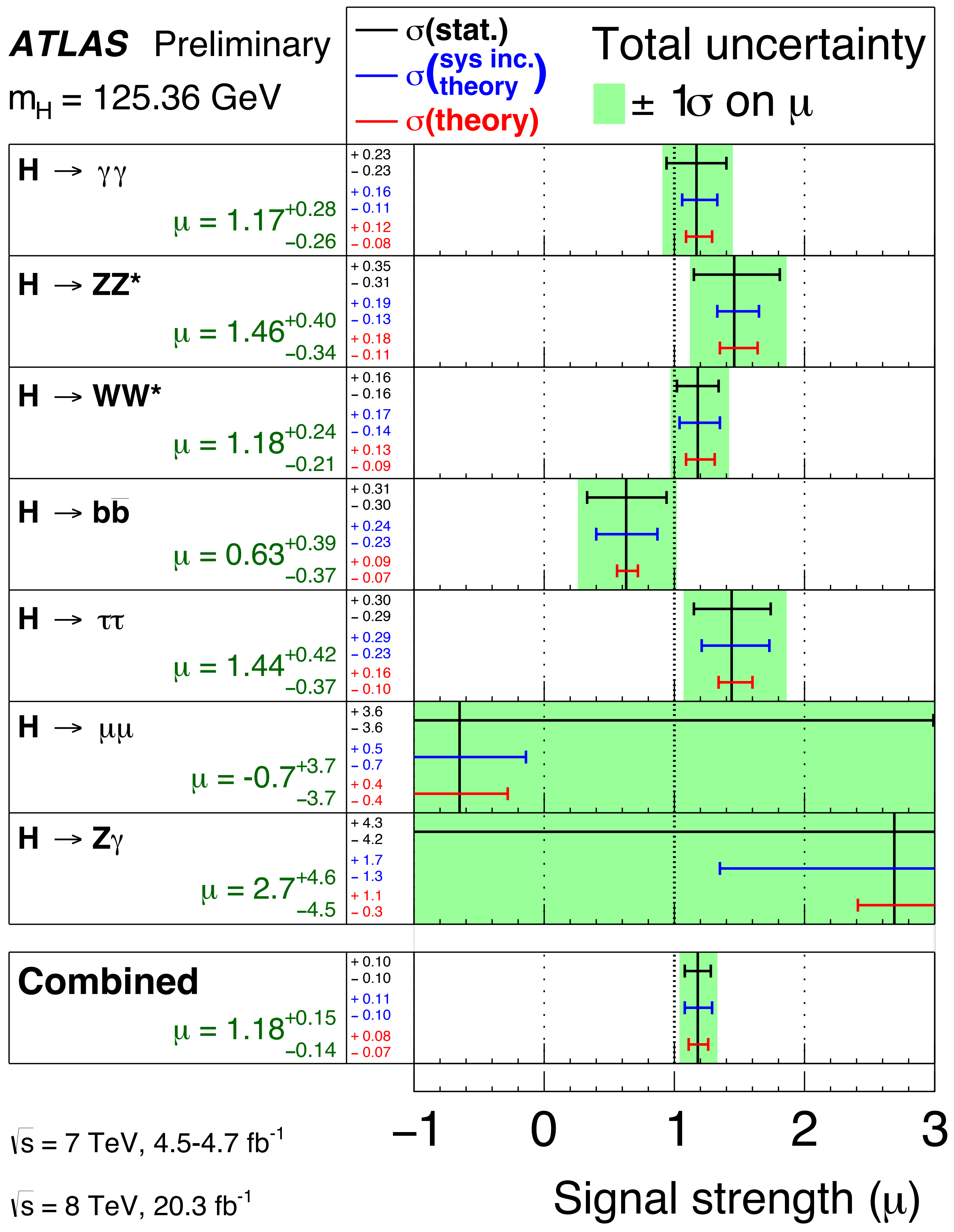


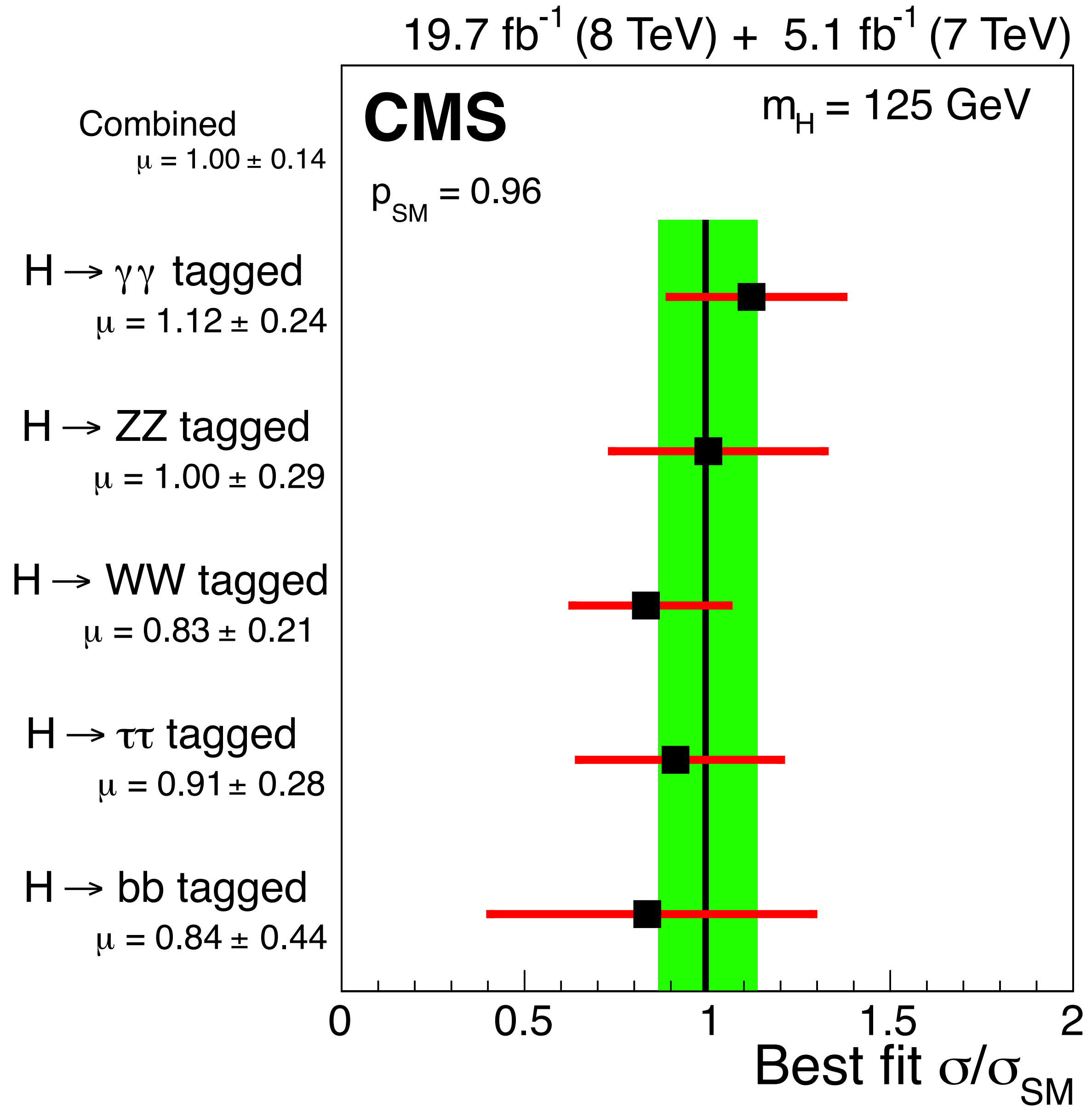
Is it the Higgs boson of the Standard Model?

Properties of the Higgs bosons:



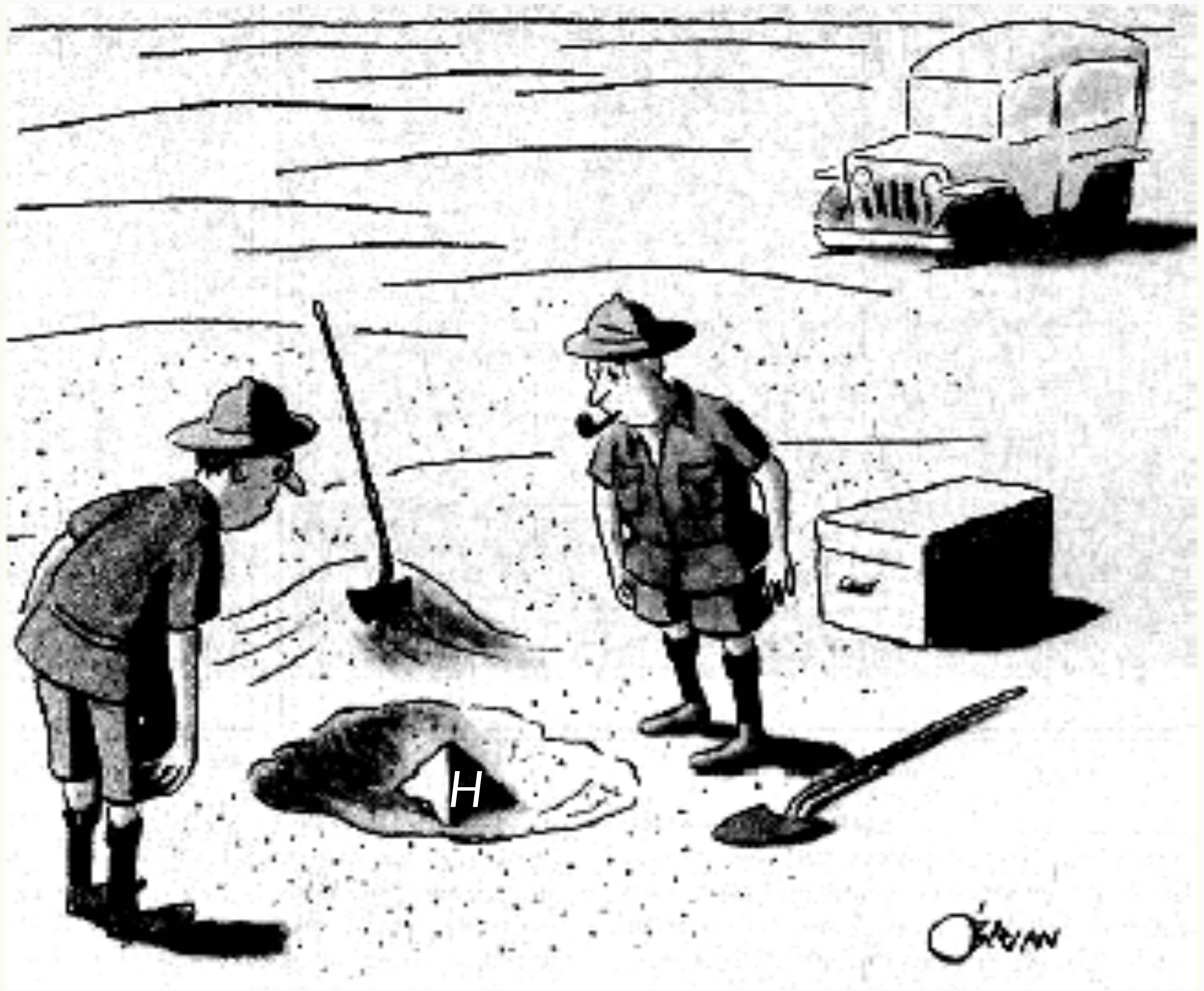
Higgs couplings are Standard Model-like within present experimental accuracy!





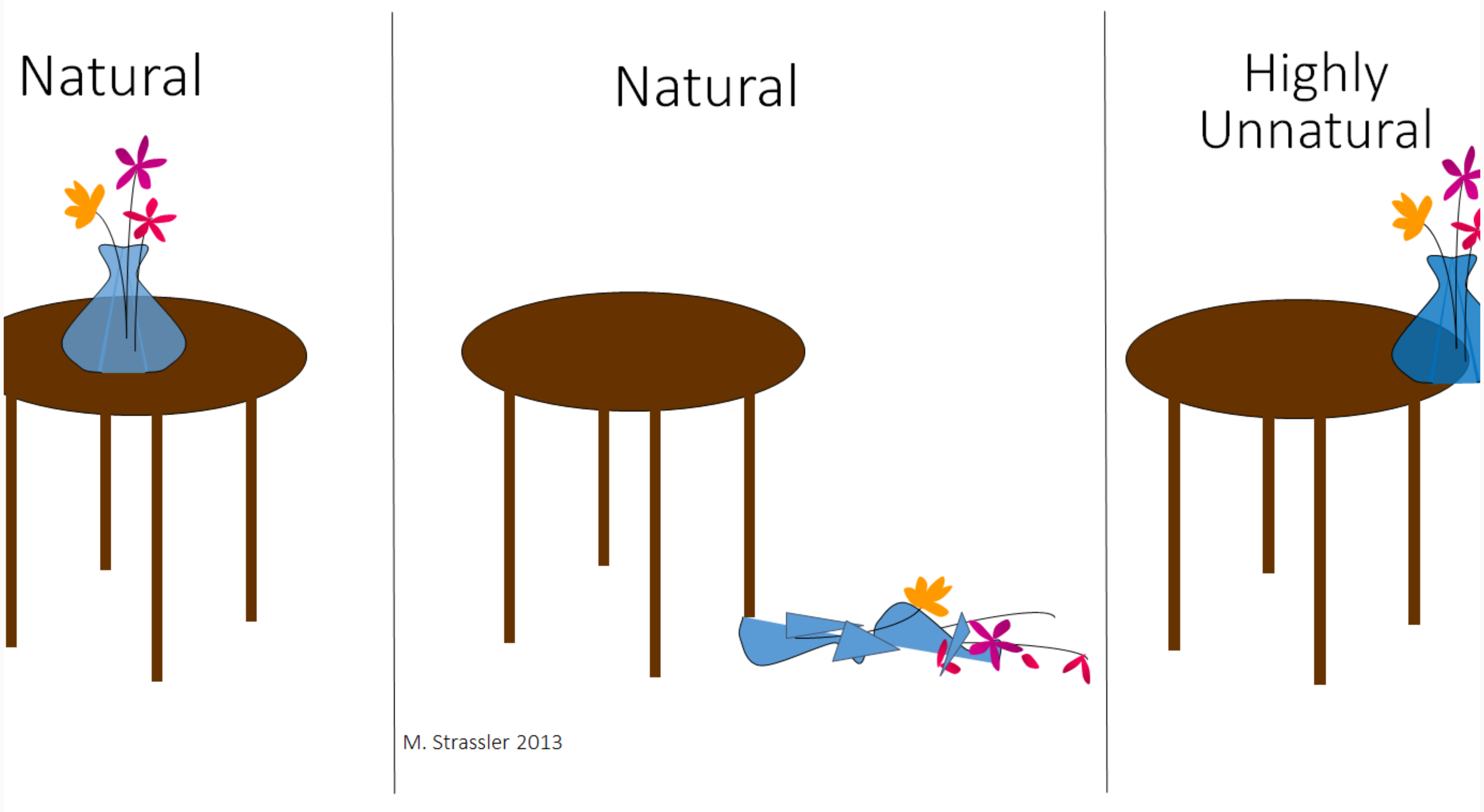
$$\mu = \frac{\sigma(pp \to H) \cdot \mathrm{BR}(H \to X)}{\sigma(pp \to H)_{\mathrm{SM}} \cdot \mathrm{BR}(H \to X)_{\mathrm{SM}}}$$

Is it the Higgs boson of the Standard Model?



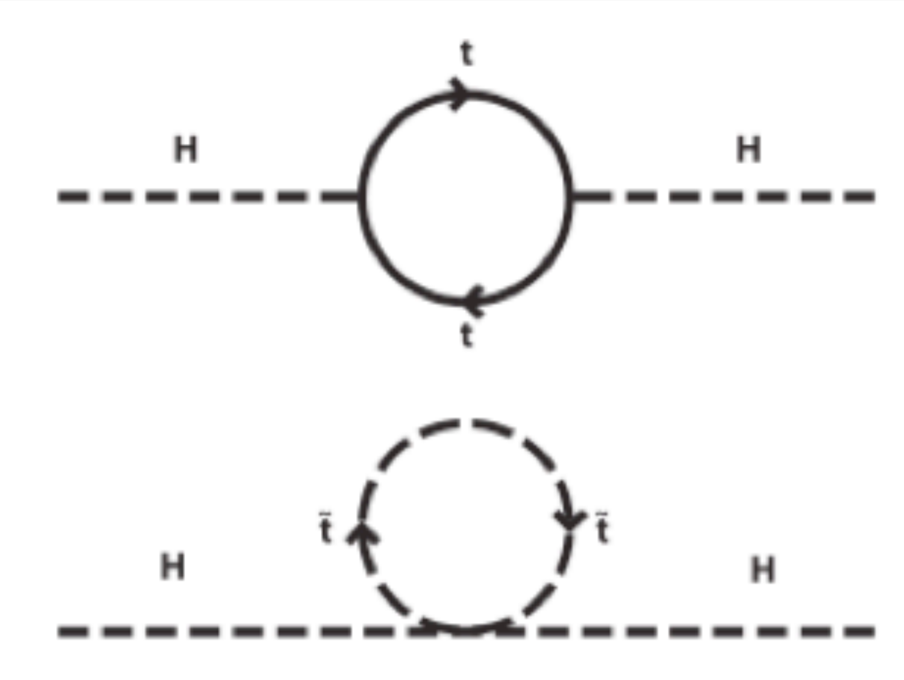
"This could be the discovery of the century.
Depending, of course, on how far down it goes."

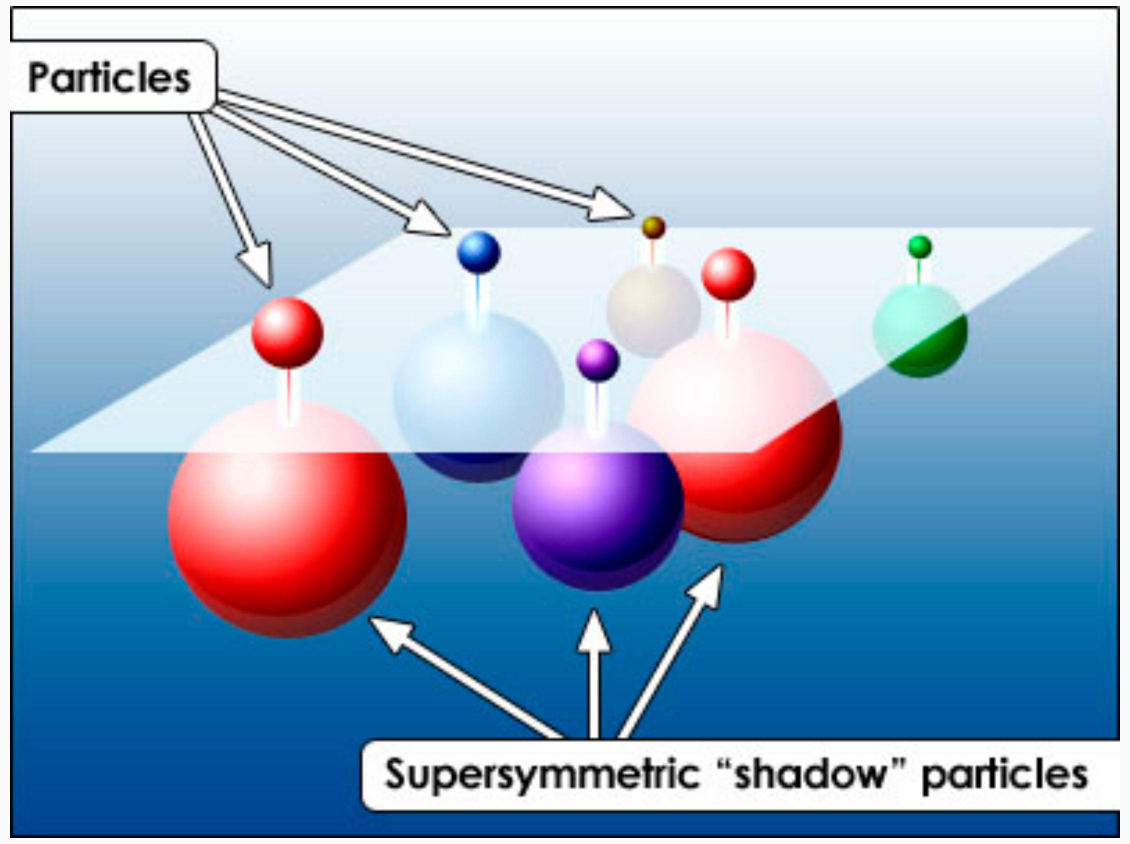
Is Nature natural?

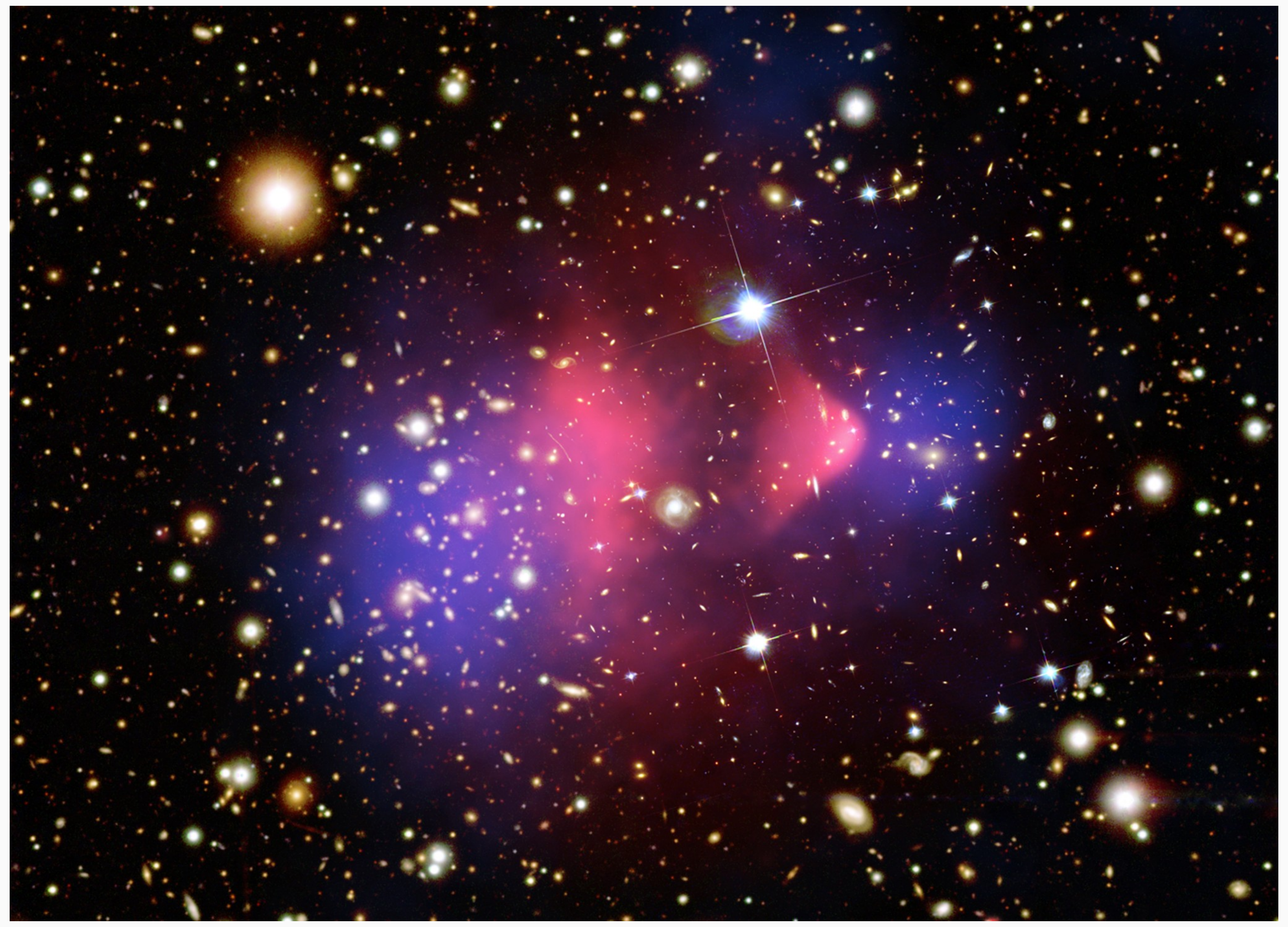


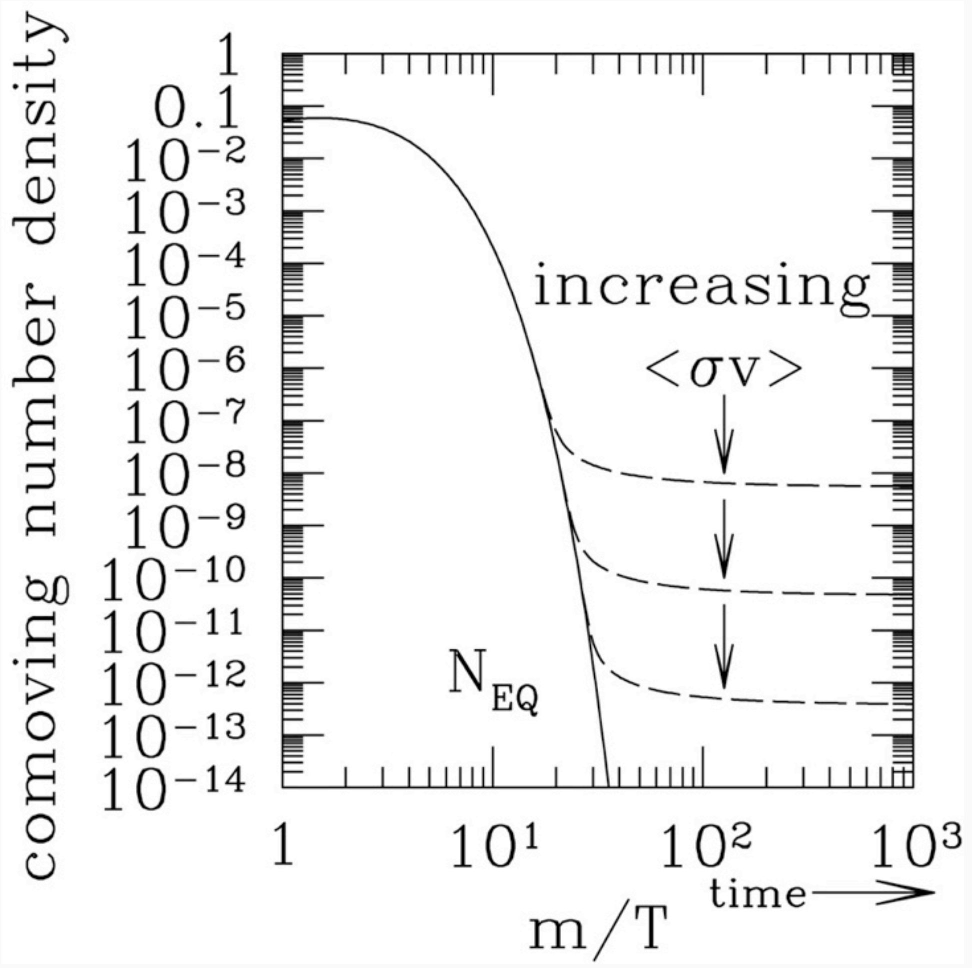
Is Nature natural?

Hierarchie problem suggested that a "natural" theory of electroweak symmetry breaking should contain new colored particle near the weak scale





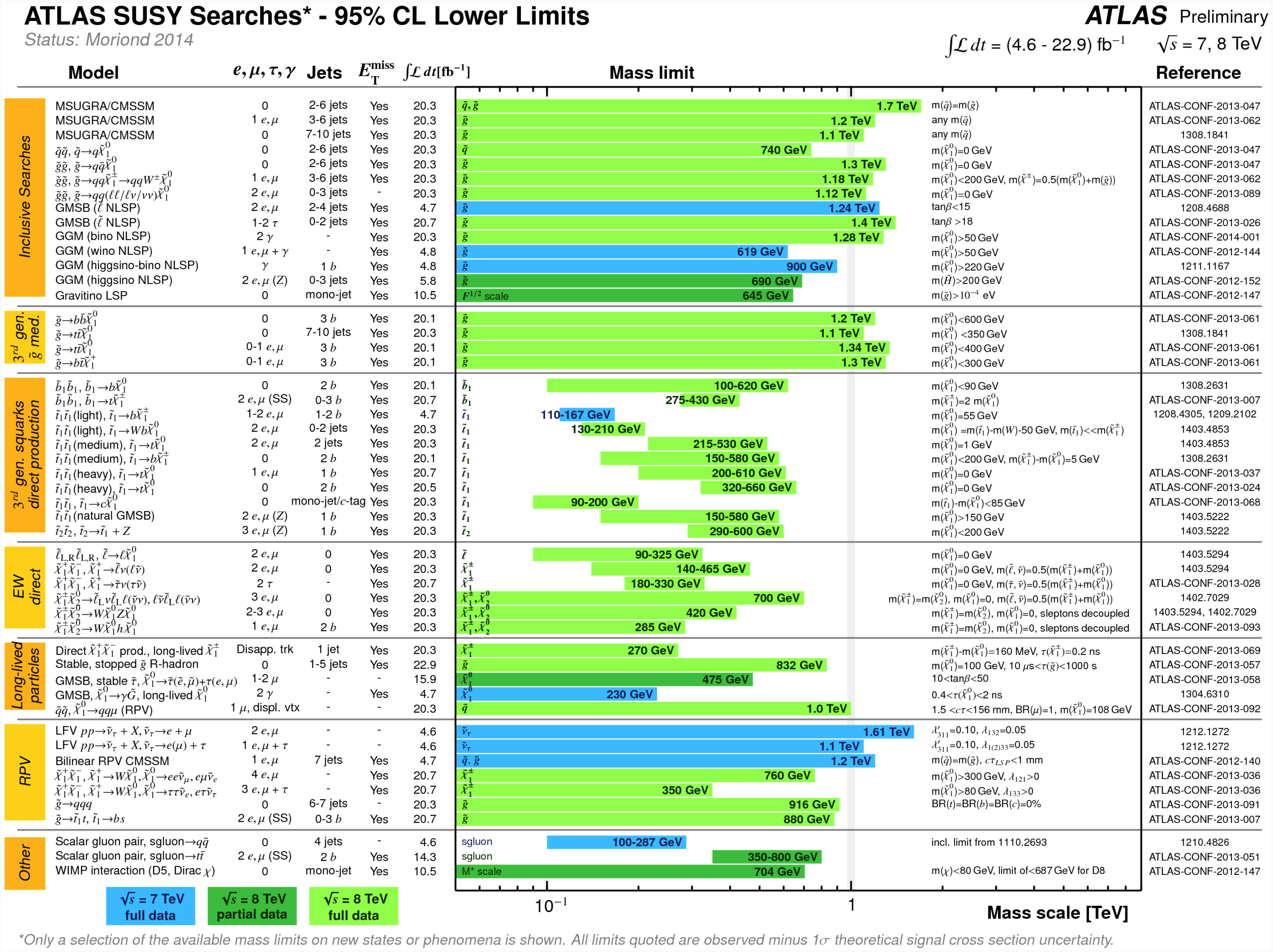


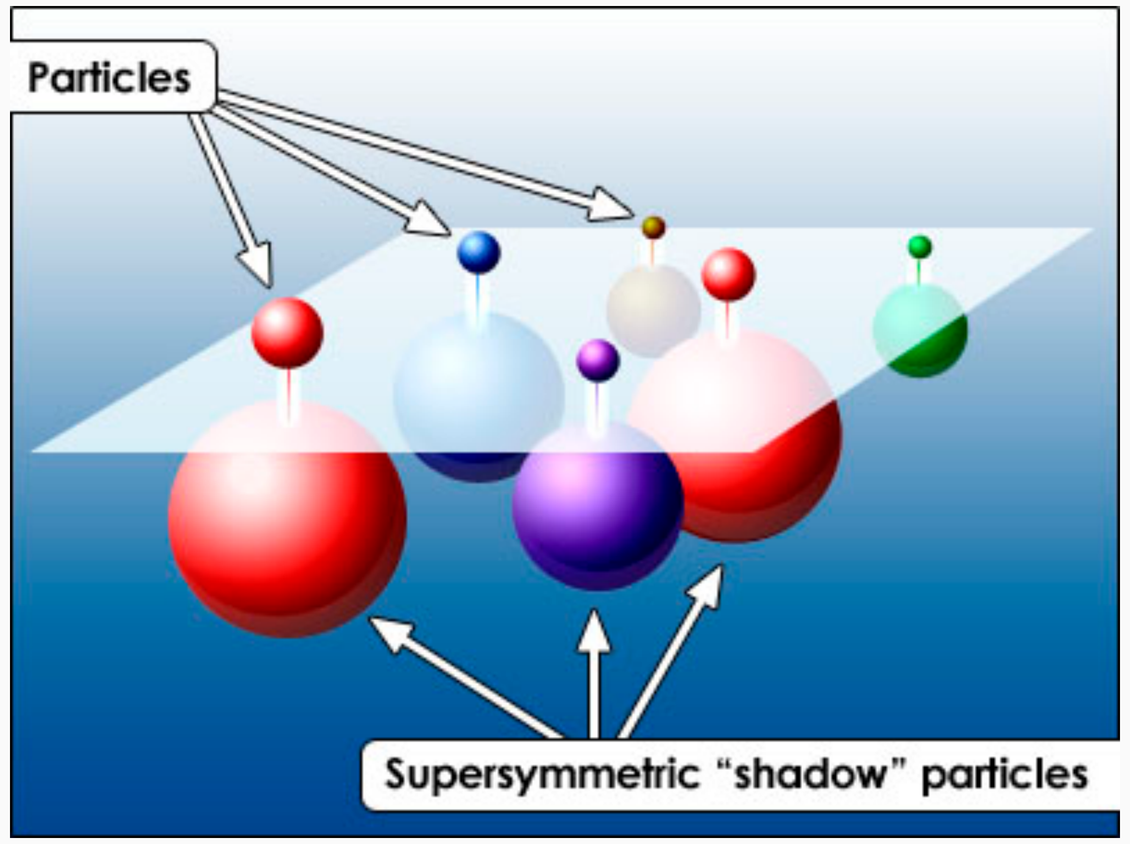


Existence of dark matter suggested that there should be new weakly interacting particles near the weak scale (WIMP miracle)

Where are they?

Is Nature natural?





Where are they?

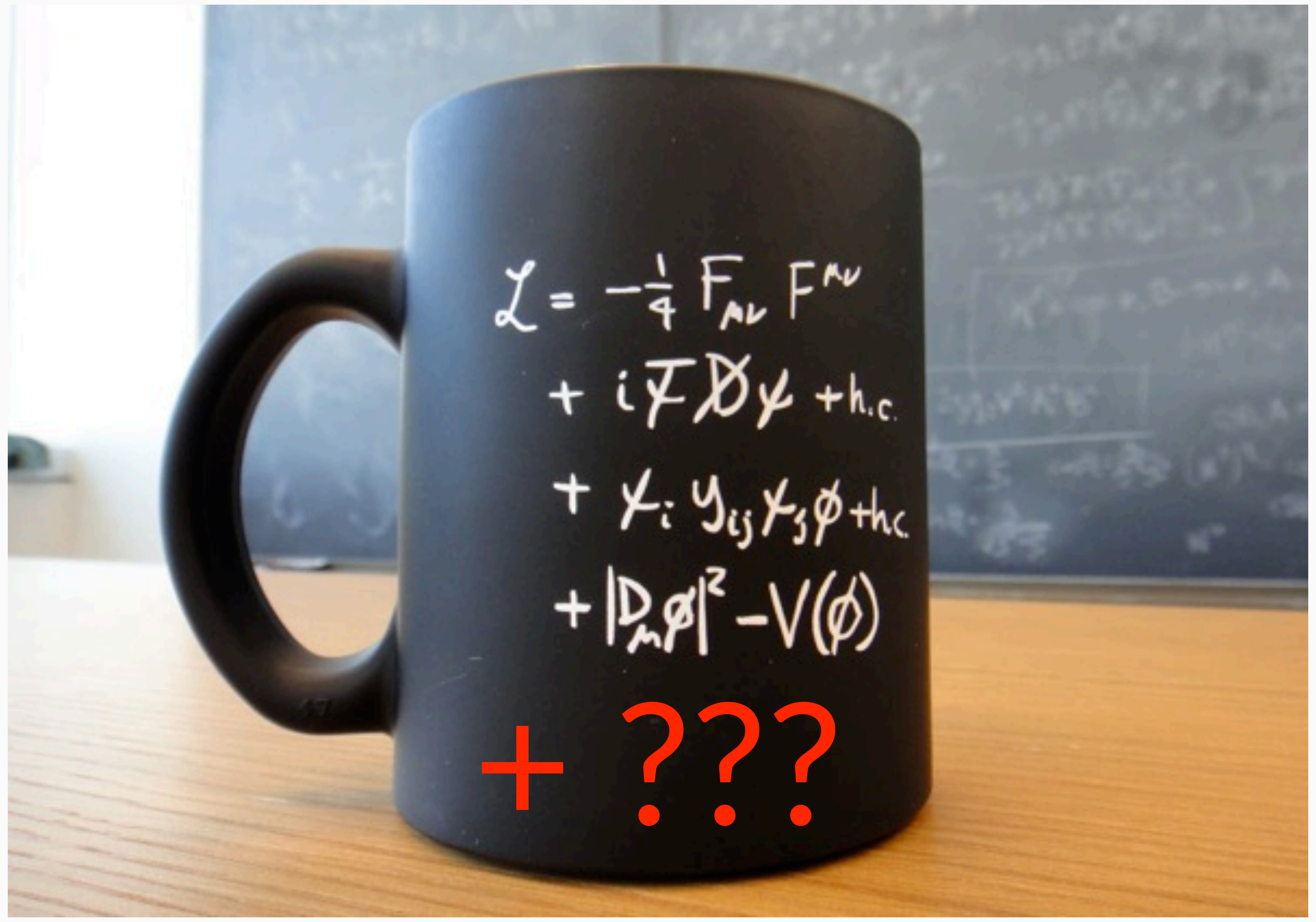
Hints for New Physics

Dark matter, flavor anomalies and diboson resonances

On the verge of another discovery?

While we have not observed any of the expected faces of new physics, there exist several tantalizing hints of effects which cannot be explained by the Standard Model

- Dark matter
- Neutrino masses and mixings
- Anomalous magnetic moment of the muon
- **Various anomalies in the flavor sector**
- **Hints for new heavy resonances from the LHC**



Anomalies in the flavor sector

$\sim 3.5\sigma$ $(g-2)_\mu$ anomaly

$\sim 3.5\sigma$ non-standard like-sign dimuon charge asymmetry

$\sim 3.5\sigma$ enhanced $B \to D^{(*)}\tau\nu$ rates

$\sim 3.5\sigma$ suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$

$\sim 3\sigma$ tension between inclusive and exclusive determination of $|V_{ub}|$

$\sim 3\sigma$ tension between inclusive and exclusive determination of $|V_{cb}|$

$2-3\sigma$ anomaly in $B \to K^*\mu^+\mu^-$ angular distributions

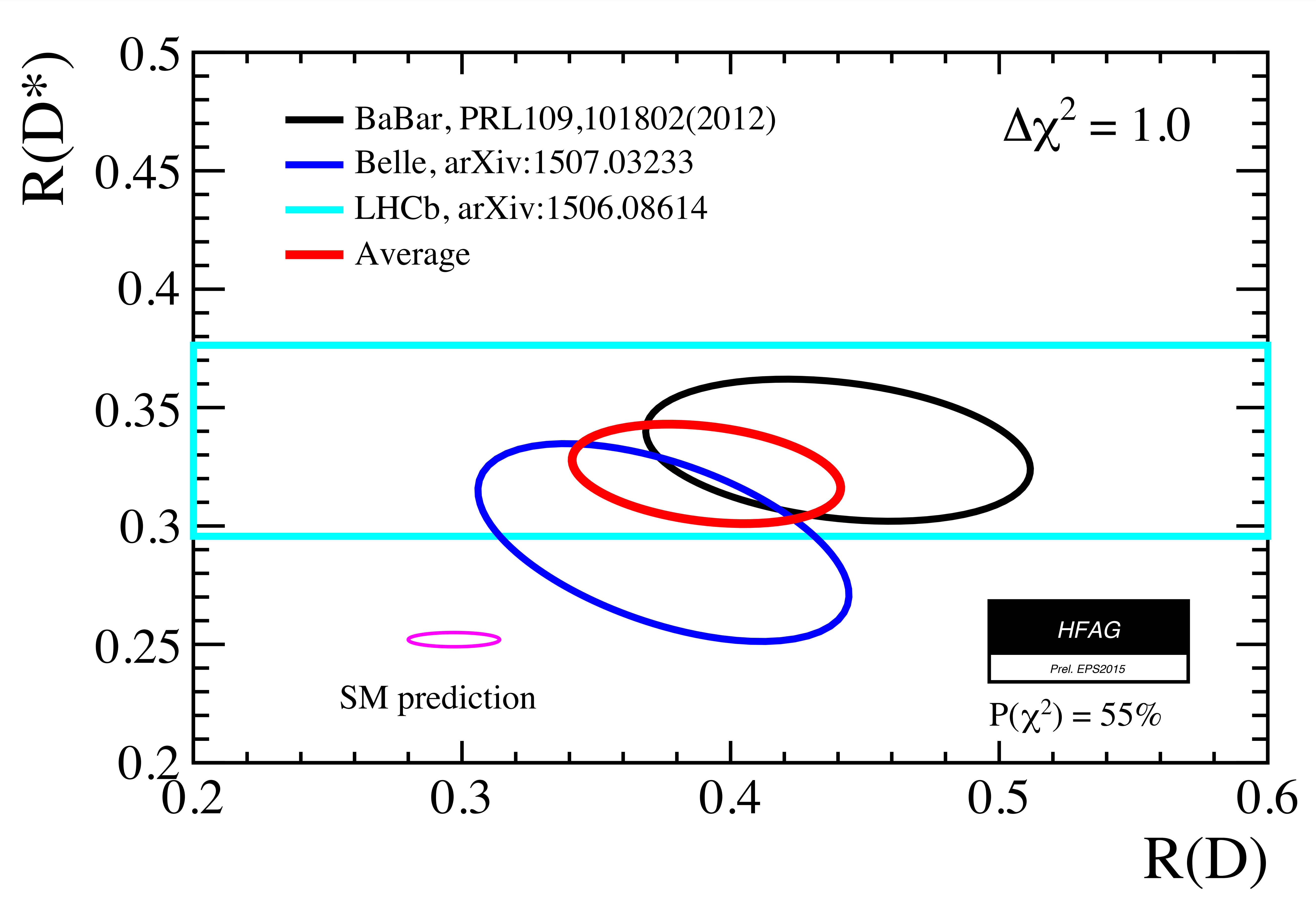
$2-3\sigma$ SM prediction for ϵ'/ϵ below experimental result

$\sim 2.5\sigma$ lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$

$\sim 2.5\sigma$ non-zero $h \to \tau\mu$

(Wolfgang Altmannshofer, Aspen Winter Conference on Particle Physics 2016)

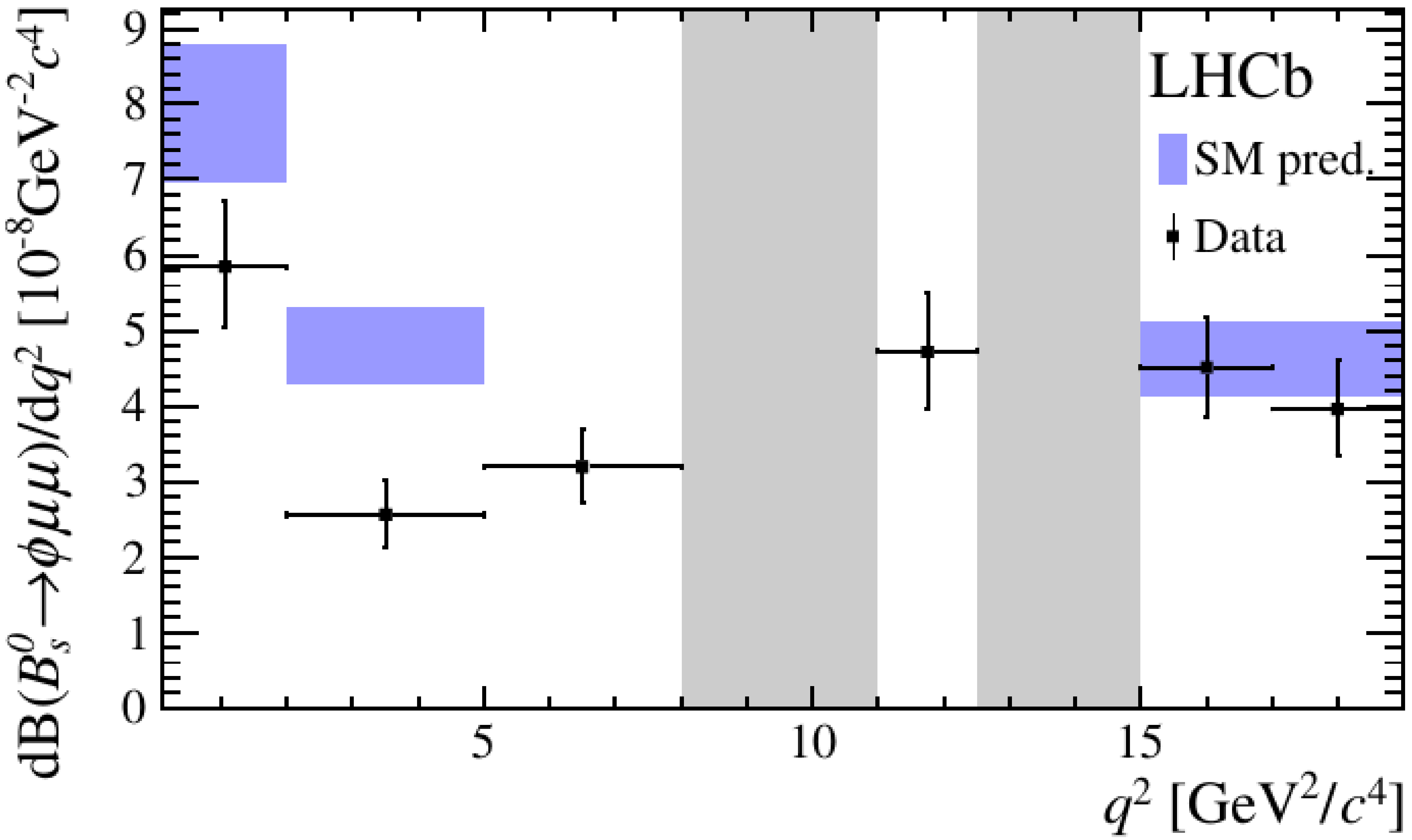
Flavor anomalies: Enhanced $B \to D^{(*)}\tau\nu$ rates



Semileptonic decays with tau leptons are 3.5σ higher than SM prediction!

Flavor anomalies: Suppressed $B_s \to \Phi \mu^+ \mu^-$ branching ratio

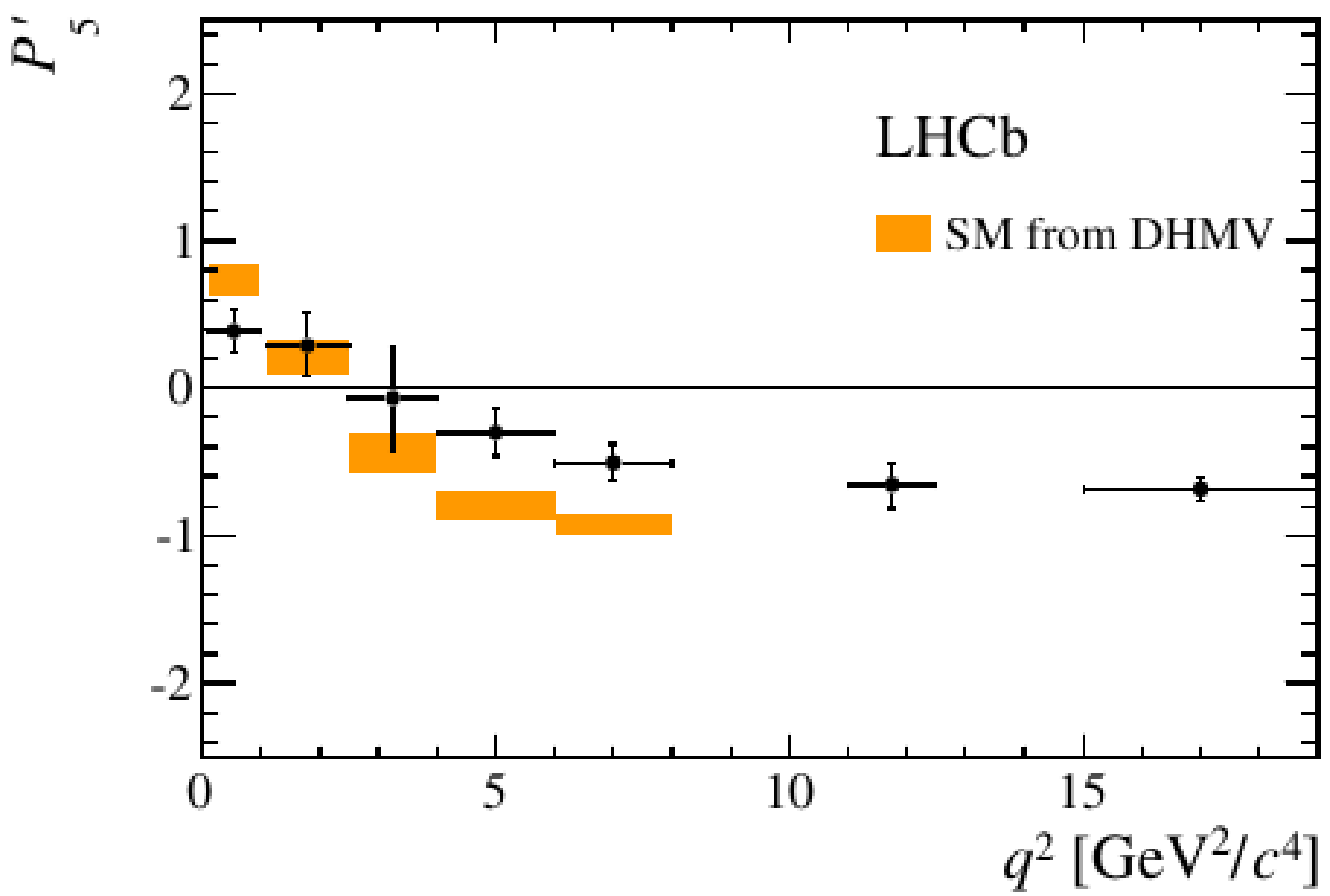
LHCb 1506.08777



Branching ratio in region 1 GeV^2 < q^2 < 6 GeV^2 is 3.5σ lower than SM prediction!

Flavor anomalies: $B \to K^* \mu^+ \mu^-$ angular distributions

LHCb 1512.04442



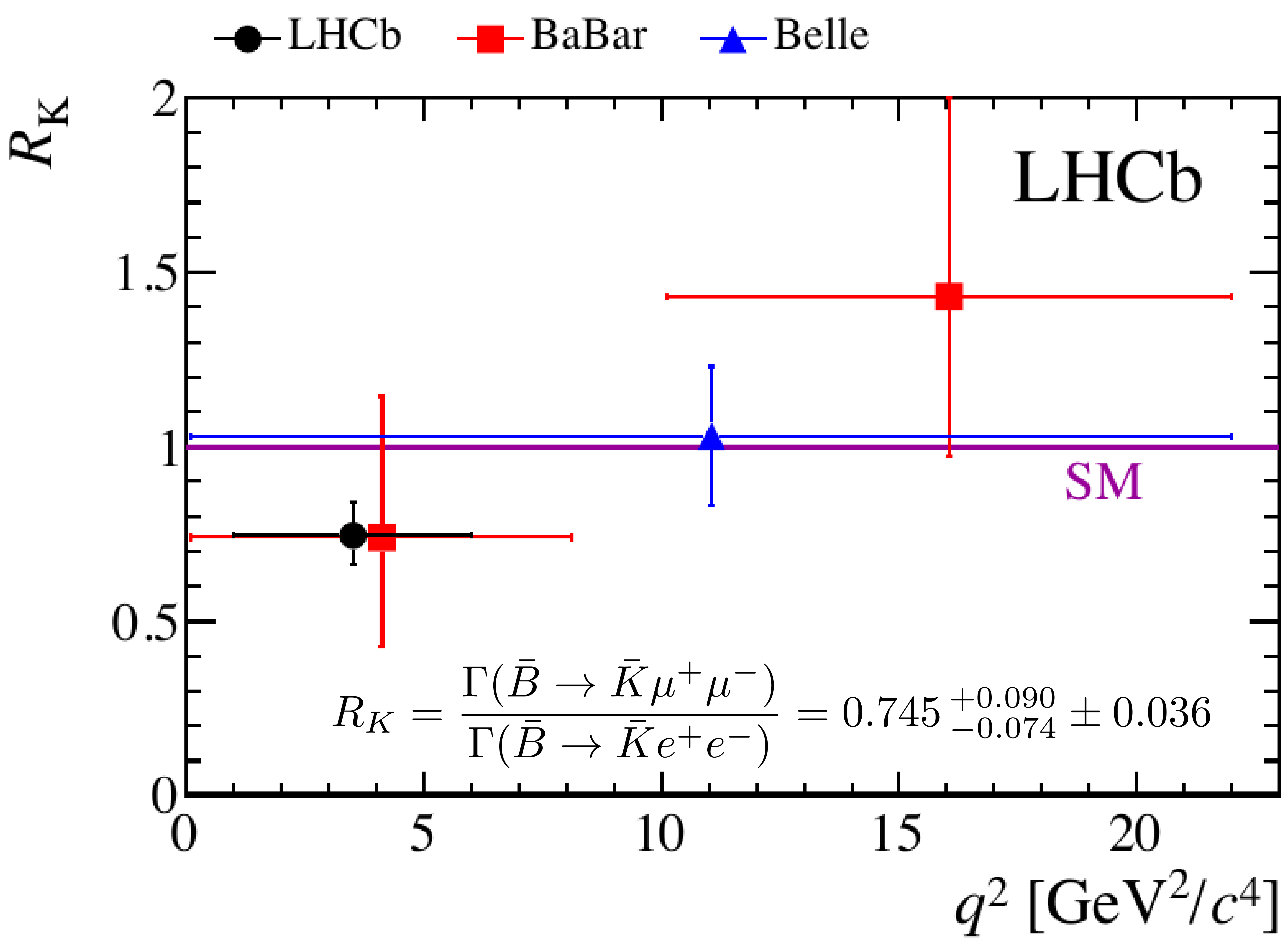
Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[2, 4.3]	0.81 ± 0.02	0.26 ± 0.19	ATLAS	+2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	[4, 6]	0.74 ± 0.04	0.61 ± 0.06	LHCb	+1.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	[4, 6]	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	−2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P'_5	[1.1, 6]	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	−2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P'_5	[4, 6]	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	−2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{dBR}{dq^2}$	[4, 6]	0.54 ± 0.08	0.26 ± 0.10	LHCb	+2.1
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[0.1, 2]	2.71 ± 0.50	1.26 ± 0.56	LHCb	+1.9
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{dBR}{dq^2}$	[16, 23]	0.93 ± 0.12	0.37 ± 0.22	CDF	+2.2

Altmannshofer, Sraub (arXiv:1503:06199)

2.8σ deviation in q^2 bin between [4, 6] GeV^2 (3.0σ in bin [6, 8] GeV^2) !

Flavor anomalies: $B \to K\,\mu^+\mu^-$ vs. $B \to K\,e^+e^-$

LHCb 1406.6482



2.6σ hint for a violation of lepton flavor universality!

Flavor anomalies — reason for excitement

The flavor anomalies in rare *B*-meson decays are:

- in many cases statistically significant
- seen by more than one experiment
- provide a **coherent picture** when interpreted in terms of new physics contributions to one or two operators in the effective weak Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i O_i$$

Coefficient	Best fit	1σ	3σ	Pull$_{\text{SM}}$
$\mathcal{C}_7^{\text{NP}}$	-0.02	$[-0.04, -0.00]$	$[-0.07, 0.04]$	1.1
$\mathcal{C}_9^{\text{NP}}$	-1.11	$[-1.32, -0.89]$	$[-1.71, -0.40]$	4.5
$\mathcal{C}_{10}^{\text{NP}}$	0.58	$[0.34, 0.84]$	$[-0.11, 1.41]$	2.5
$\mathcal{C}_{7'}^{\text{NP}}$	0.02	$[-0.01, 0.04]$	$[-0.05, 0.09]$	0.7
$\mathcal{C}_{9'}^{\text{NP}}$	0.49	$[0.21, 0.77]$	$[-0.33, 1.35]$	1.8
$\mathcal{C}_{10'}^{\text{NP}}$	-0.27	$[-0.46, -0.08]$	$[-0.84, 0.28]$	1.4
$\mathcal{C}_9^{\text{NP}} = \mathcal{C}_{10}^{\text{NP}}$	-0.21	$[-0.40, 0.00]$	$[-0.74, 0.55]$	1.0
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.69	$[-0.88, -0.51]$	$[-1.27, -0.18]$	4.1
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.09	$[-1.28, -0.88]$	$[-1.62, -0.42]$	4.8

Descotes-Genon, Hofer, Matias, Virto (arXiv:1510:04239)

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{9'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad \mathcal{O}_{10'} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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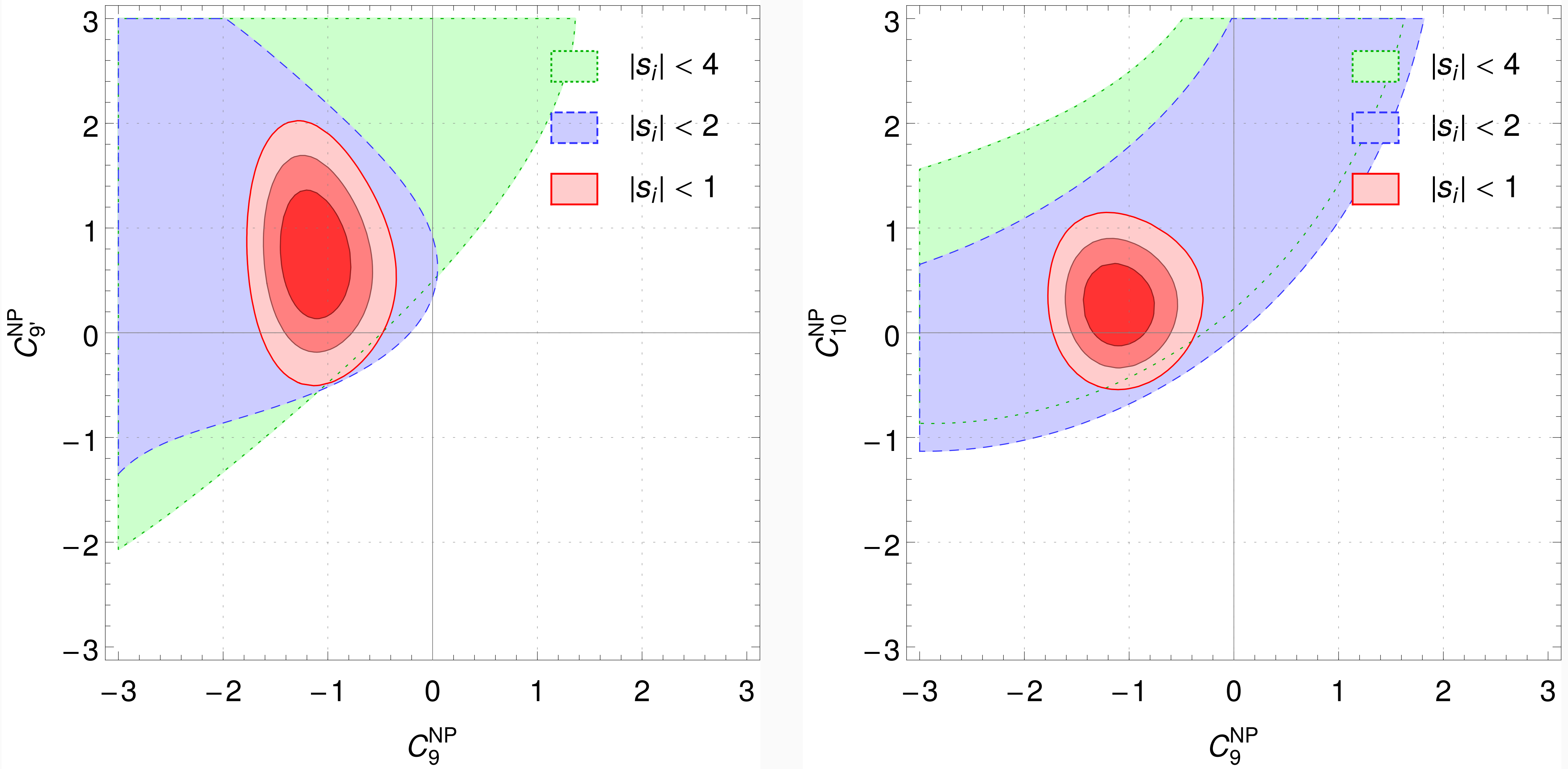

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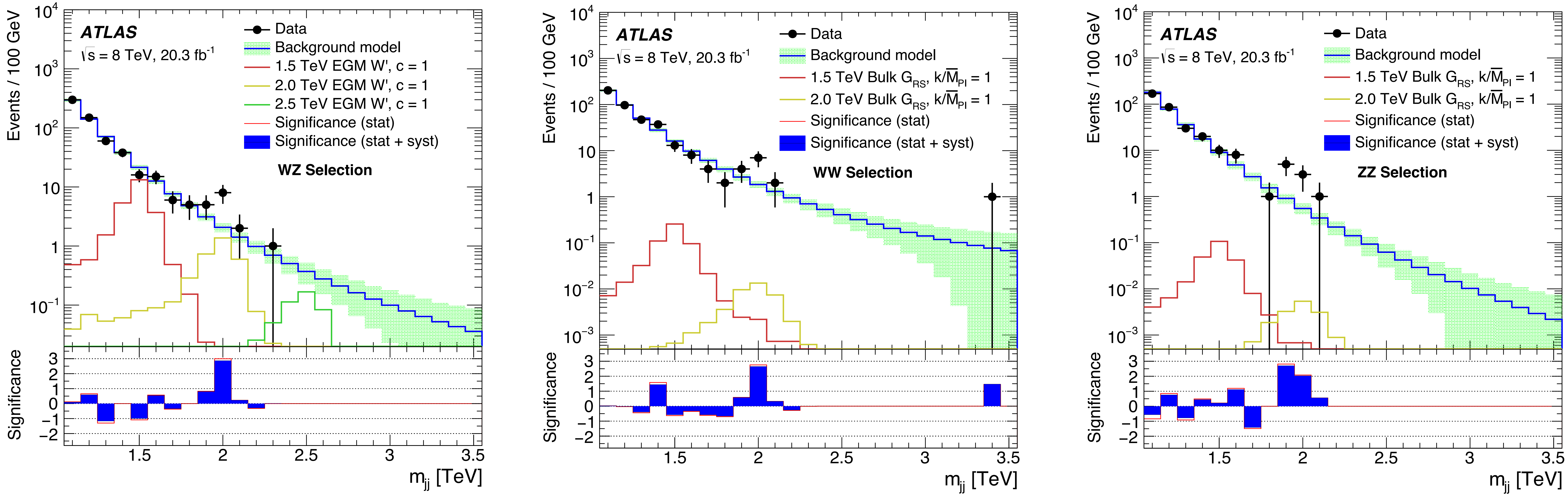
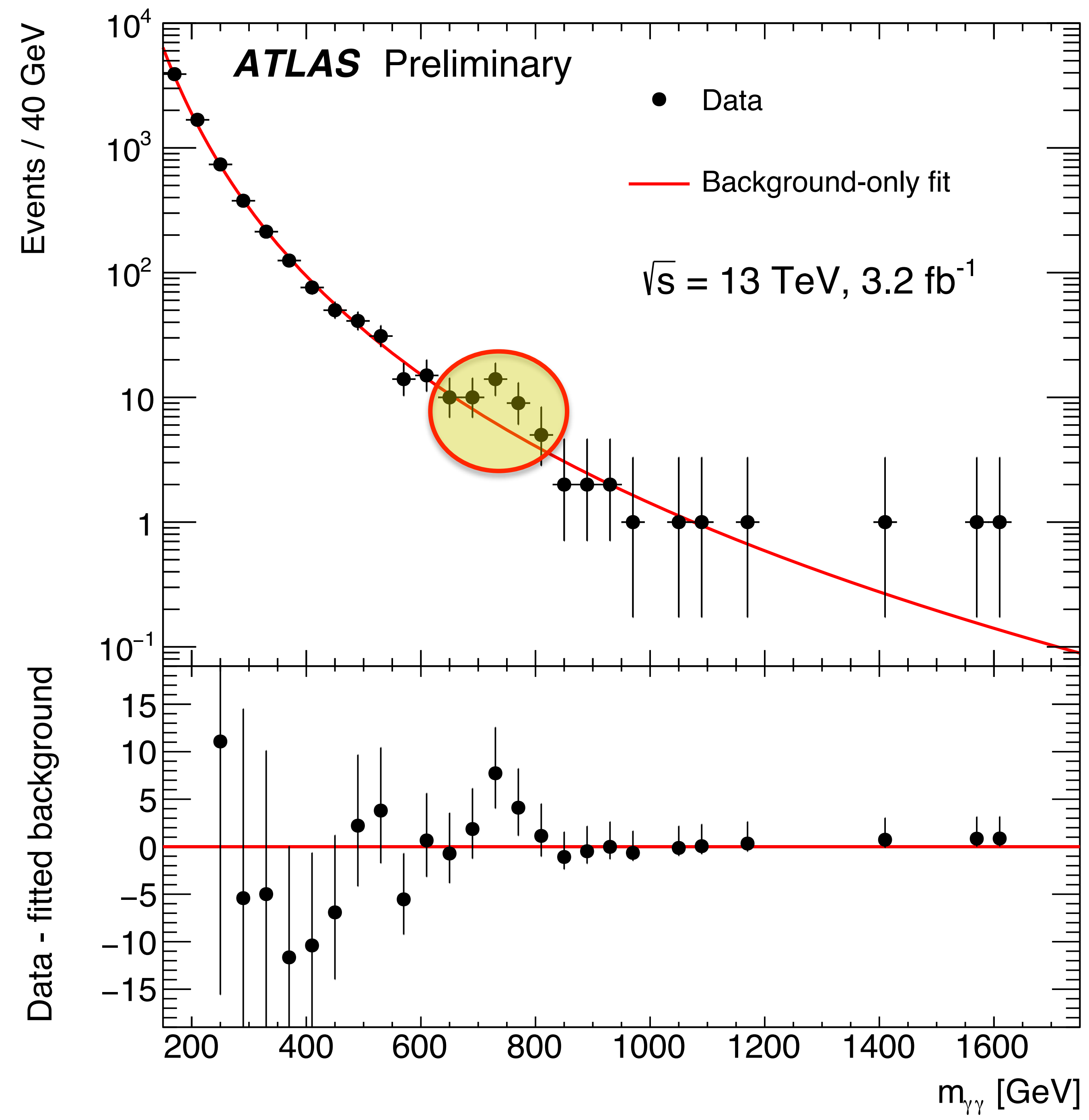
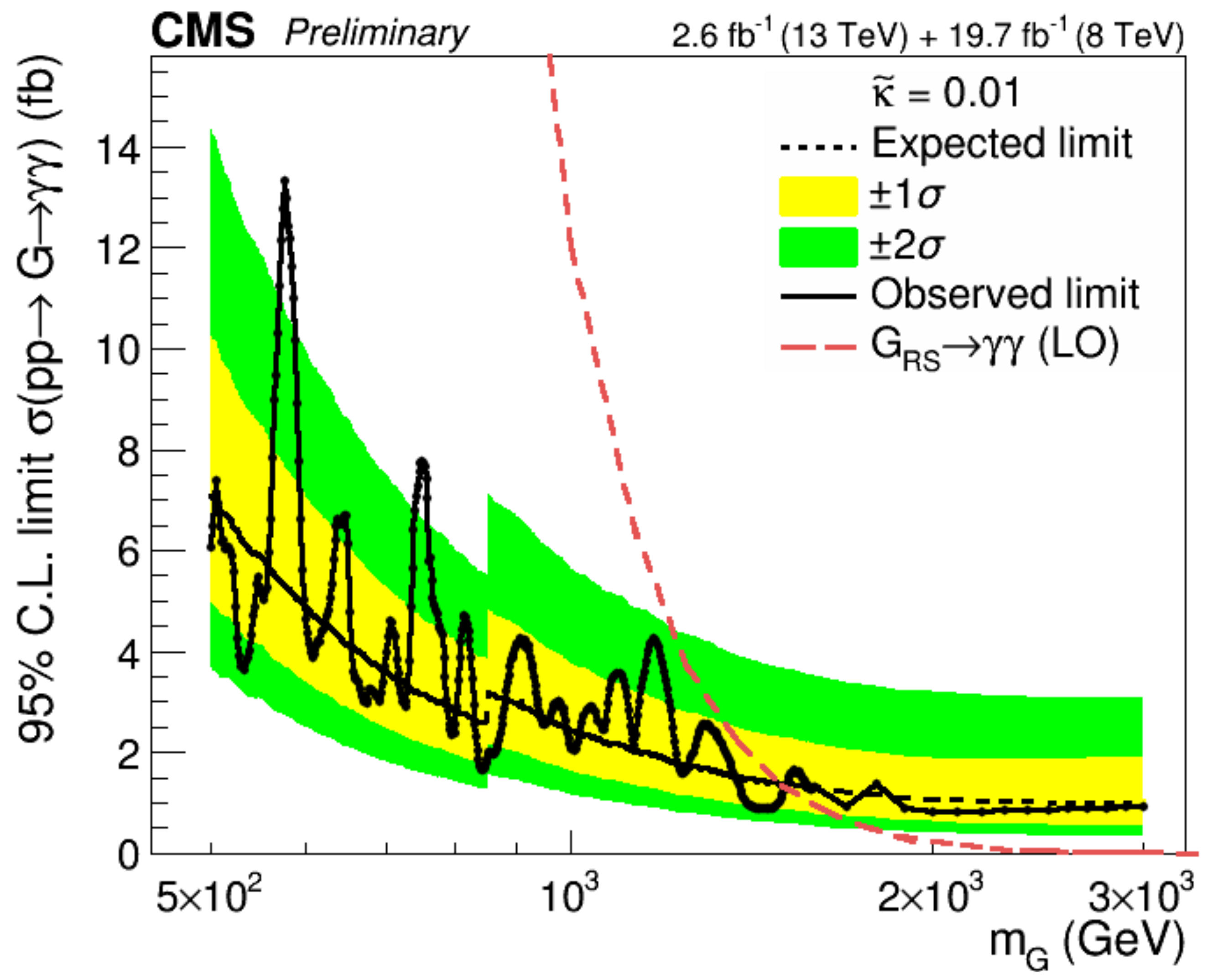
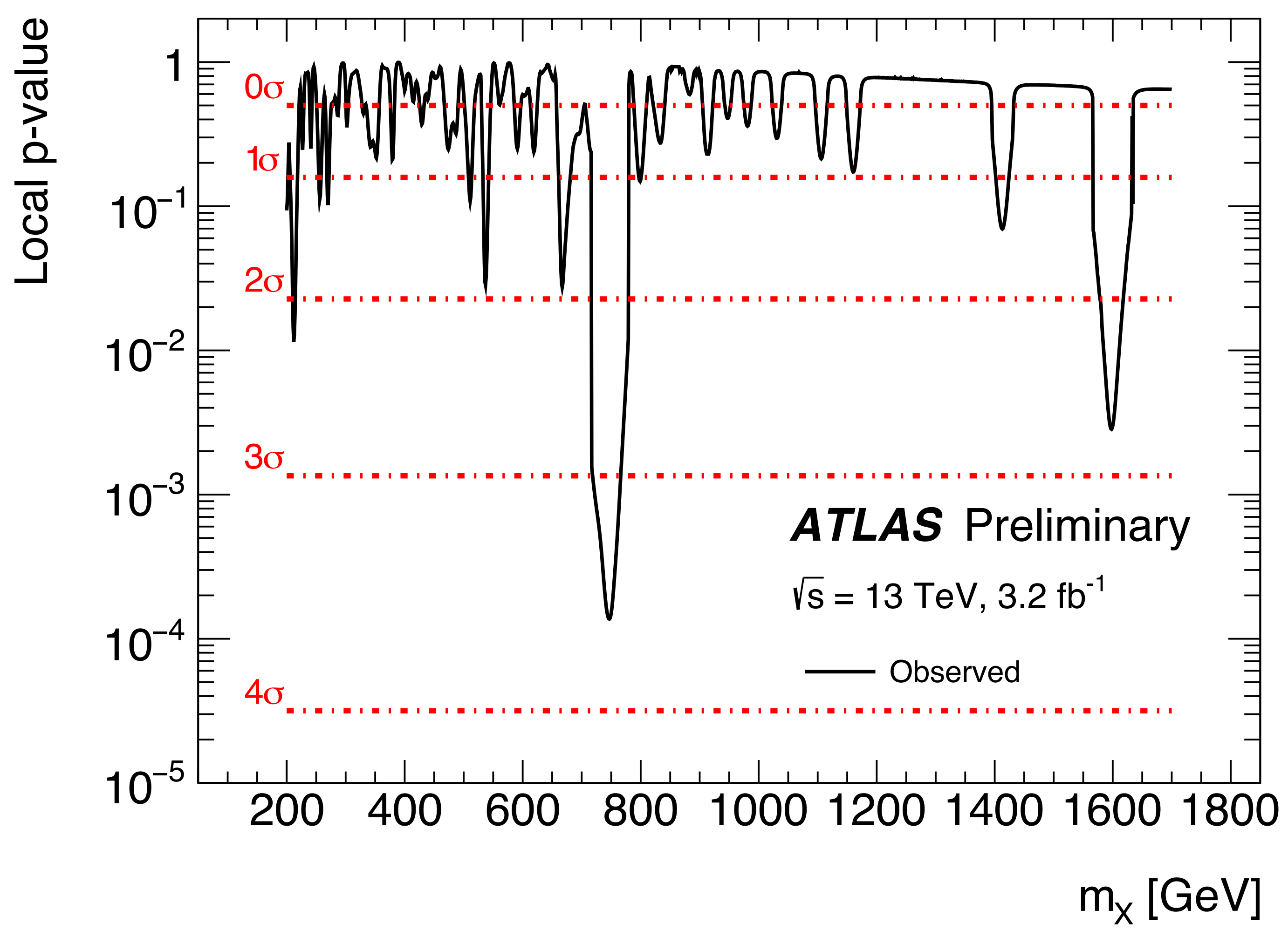
A new diboson resonance near 2 TeV in Run-I ?



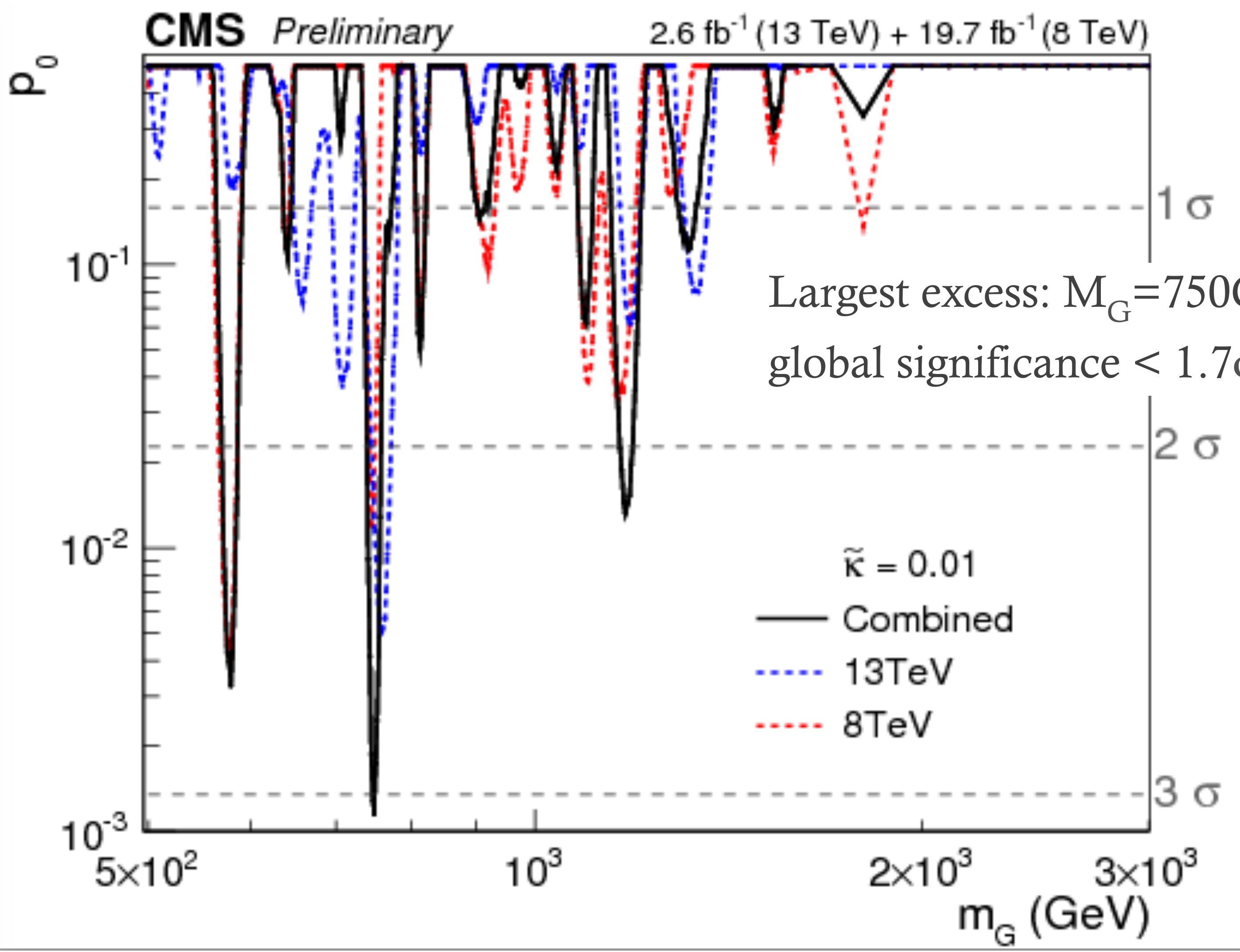
A new diphoton resonance near 750 GeV in Run-II ?



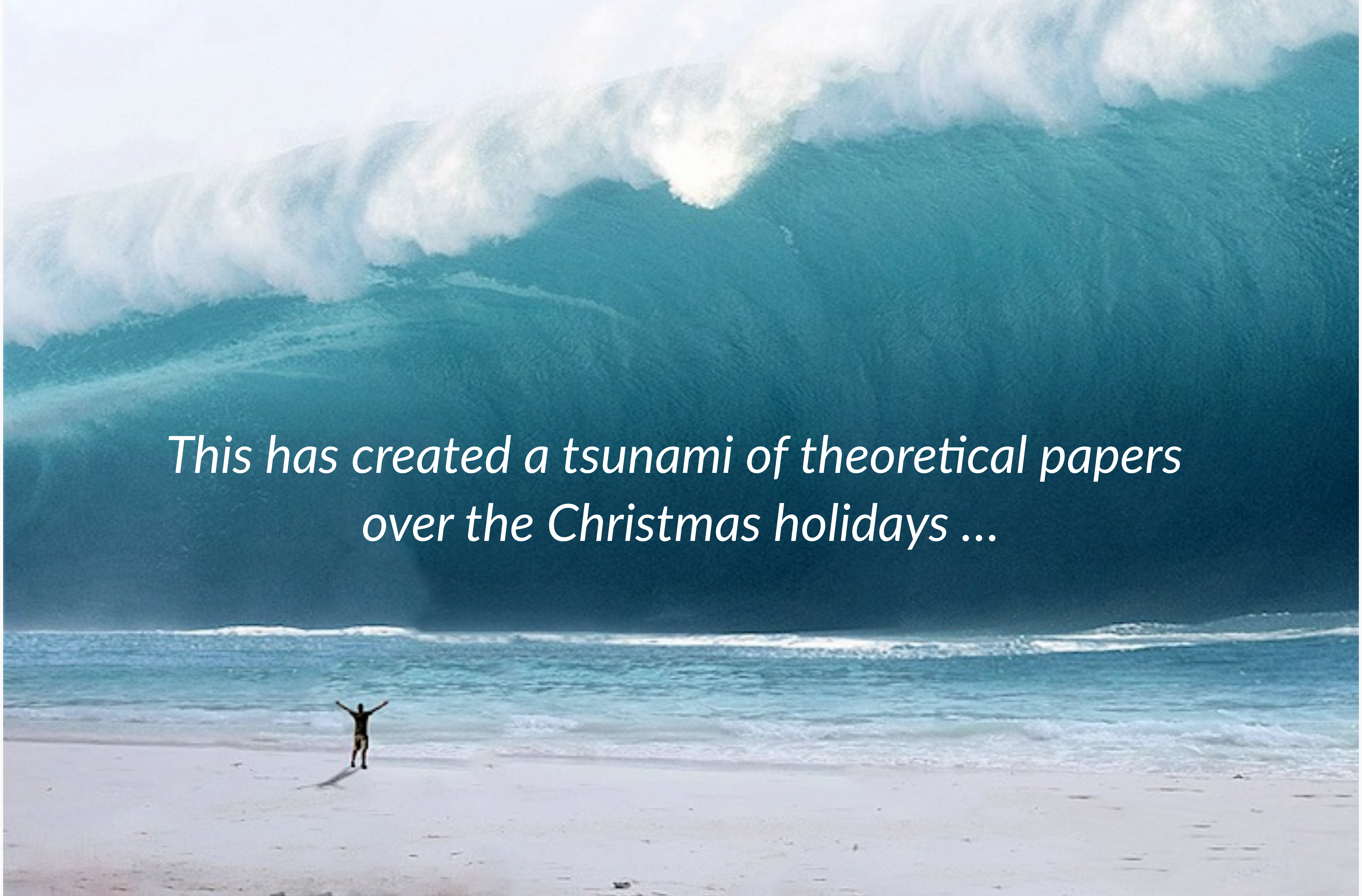




Excess at 750 GeV		
	Local	Global
NWA	3.6σ	2.0σ
Γ ~ 45 GeV	3.9σ	2.3σ



Largest excess: M_G=750GeV, local significance 3σ
global significance < 1.7σ


This has created a tsunami of theoretical papers
over the Christmas holidays …

High Energy Physics – Phenomenology

How the $\gamma\gamma$ Resonance Stole Christmas

Nathaniel Craig, Patrick Draper, Can Kilic, Scott Thomas

(Submitted on 24 Dec 2015)

The experimental and theoretical implications of heavy di-gauge boson resonances that couple to, or are comprised of, new charged and strongly interacting matter are investigated. Observation and measurement of ratios of the resonant di-gauge boson channels WW, ZZ, $\gamma\gamma$, $Z\gamma$, and gg in the form of di-jets, provide a rather direct -- and for some ratios a rather robust -- probe of the gauge representations of the new matter. For a spin-zero resonance with the quantum numbers of the vacuum, the ratios of resonant WW and ZZ to $\gamma\gamma$ channels, as well as the longitudinal versus transverse polarization fractions in the WW and ZZ channels, provide extraordinarily sensitive probes for possible mixing with the Higgs boson, while di-Higgs and di-top resonant channels, hh and tt, provide somewhat less sensitivity. We present a survey of possible underlying models for di-gauge boson resonances by considering various limits for the mass of the new charged and strongly interacting matter fields as well as the confinement scale of new hyper-gauge interactions under which they may also be charged. In these limits, resonances may be included as elementary weakly coupled spin-zero states or can correspond to hyper-glueballs, hyper-onia, or pseudo-scalar hyper-mesons. For each of these cases, we make predictions for additional states that could be resonantly or pair-produced and observed at the Large Hadron Collider or in future collider experiments. Heavy di-gauge boson resonances can provide a unified explanation for a number of small discrepancies and excesses in reported data from the Large Hadron Collider.

Comments: 30 pages, 4 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Report number: UTTG-28-15
Cite as: arXiv:1512.07733 **[hep-ph]**
(or arXiv:1512.07733v1 **[hep-ph]** for this version)

Submission history

From: Nathaniel Craig [view email]
[v1] Thu, 24 Dec 2015 07:13:23 GMT (352kb,D)

One Leptoquark to Rule them All

Part I: Flavor anomalies

Based on a collaboration with Martin Bauer (arXiv:1511:01900)

A minimal leptoquark model

We add a single leptoquark $\phi \sim (\mathbf{3},\mathbf{1})_{-1/3}$ to the Standard Model, with couplings:

$$\begin{aligned}\mathcal{L}_\phi &= (D_\mu\phi)^\dagger D_\mu\phi - M_\phi^2\,|\phi|^2 - g_{h\phi}\,|\Phi|^2|\phi|^2 \\ &\quad + \bar{Q}^c\boldsymbol{\lambda}^L i\tau_2 L\,\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}^R e_R\,\phi^* + \text{h.c.}\end{aligned}$$

After rotation to the mass basis, we have:

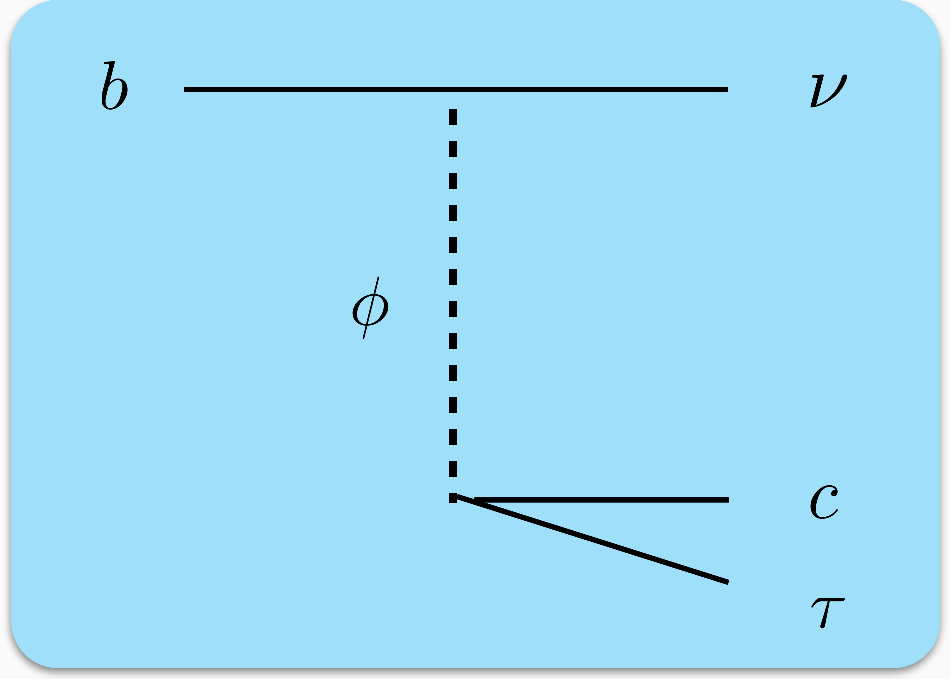
$$\mathcal{L}_\phi \ni \bar{u}_L^c\boldsymbol{\lambda}_{ue}^L e_L\,\phi^* - \bar{d}_L^c\boldsymbol{\lambda}_{d\nu}^L\nu_L\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}_{ue}^R e_R\,\phi^* + \text{h.c.}$$

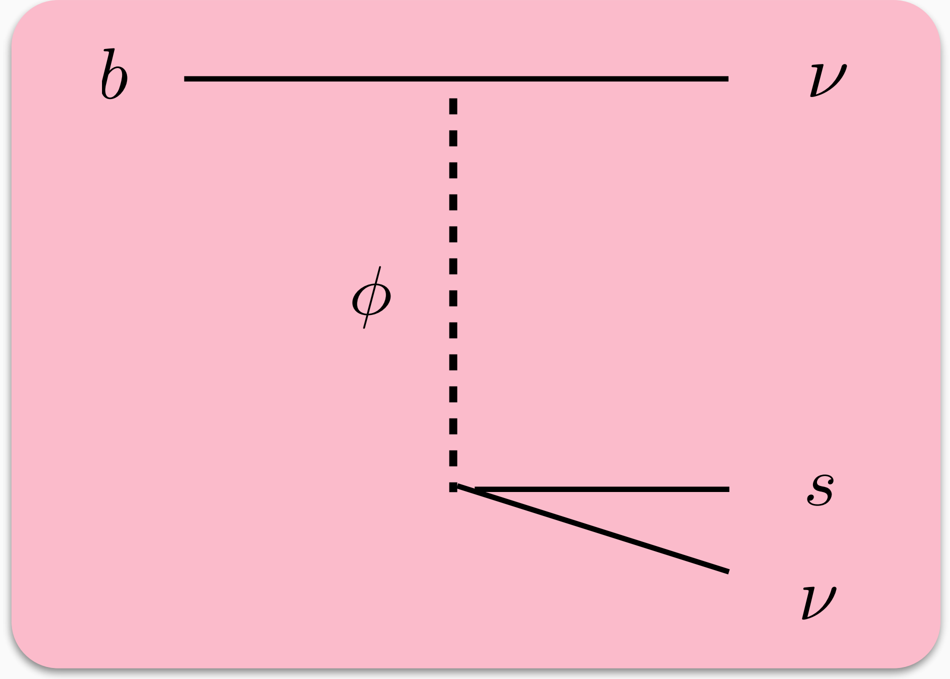
with:

$$\boldsymbol{V}_{\text{CKM}}^T\,\boldsymbol{\lambda}_{ue}^L = \boldsymbol{\lambda}_{d\nu}^L\boldsymbol{U}_e$$

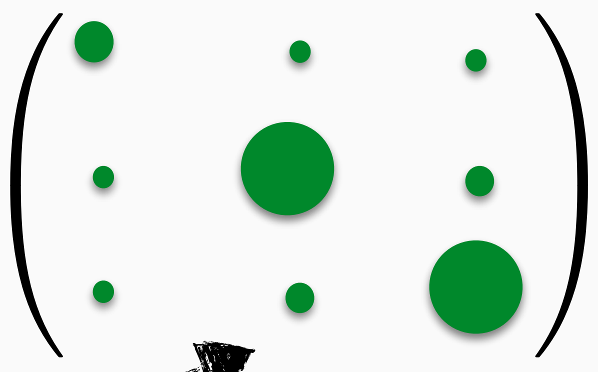
UV completion: ϕ could be the right-handed sbottom of a split SUSY model, with left-handed couplings derived from the R-parity violating terms in the superpotential (expect $|\lambda^R| \ll |\lambda^L|$)

At tree level, this gives rise to e.g.:

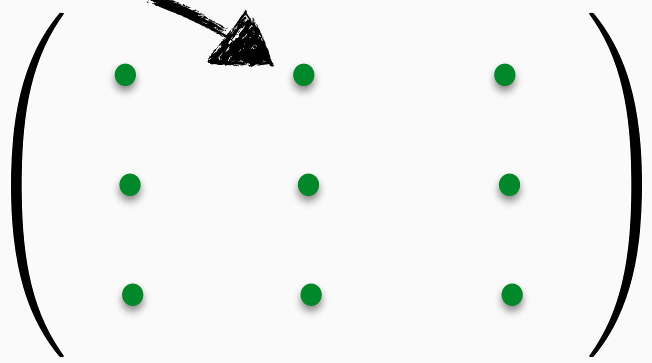




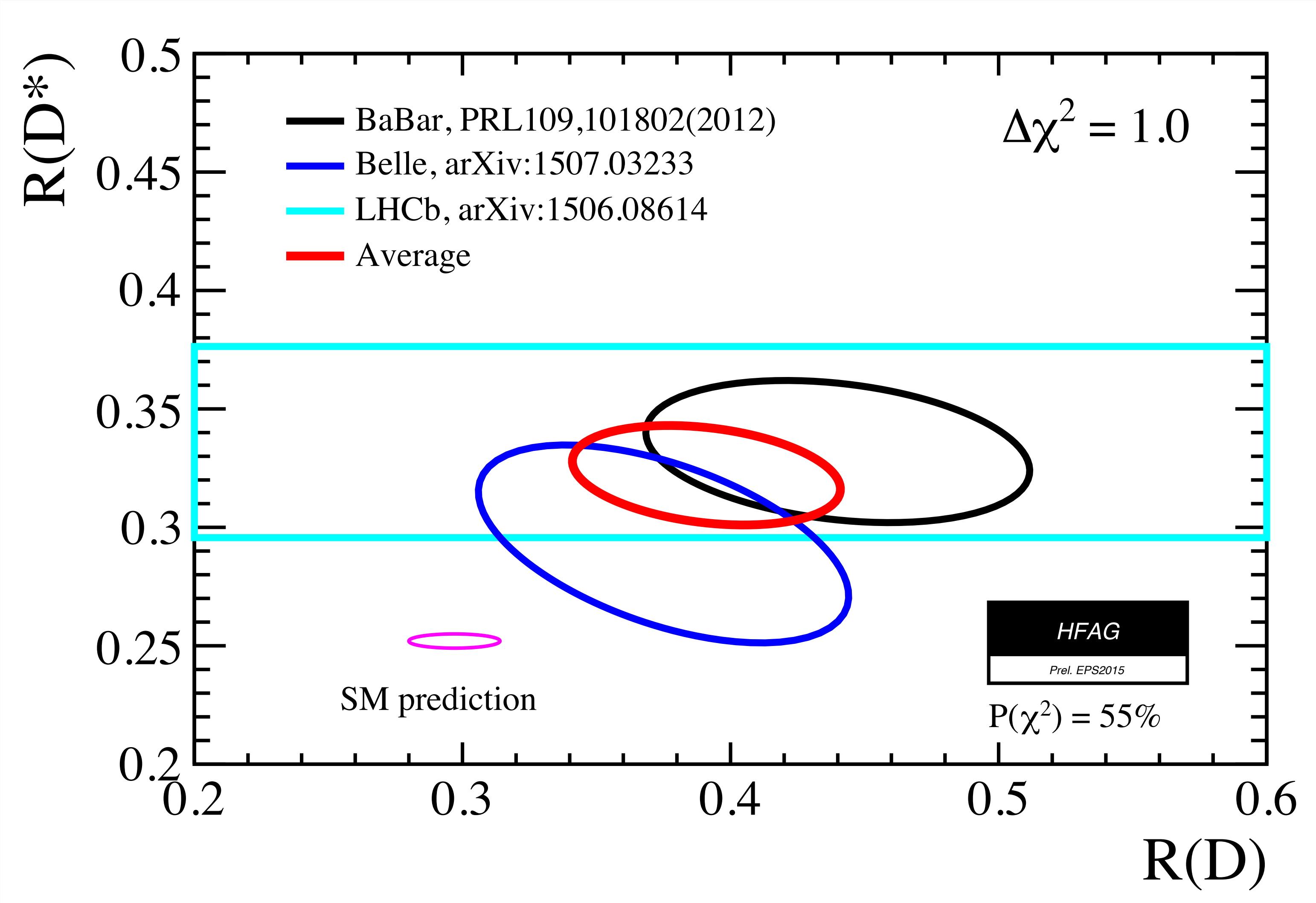
Will need:

$\lambda_{ue}^L = V_{\text{CKM}}^*\lambda_{d\nu}^L U_e \approx$ 

$10^{-1} - 10^{-3}$

$\lambda_{ue}^R \sim$ 

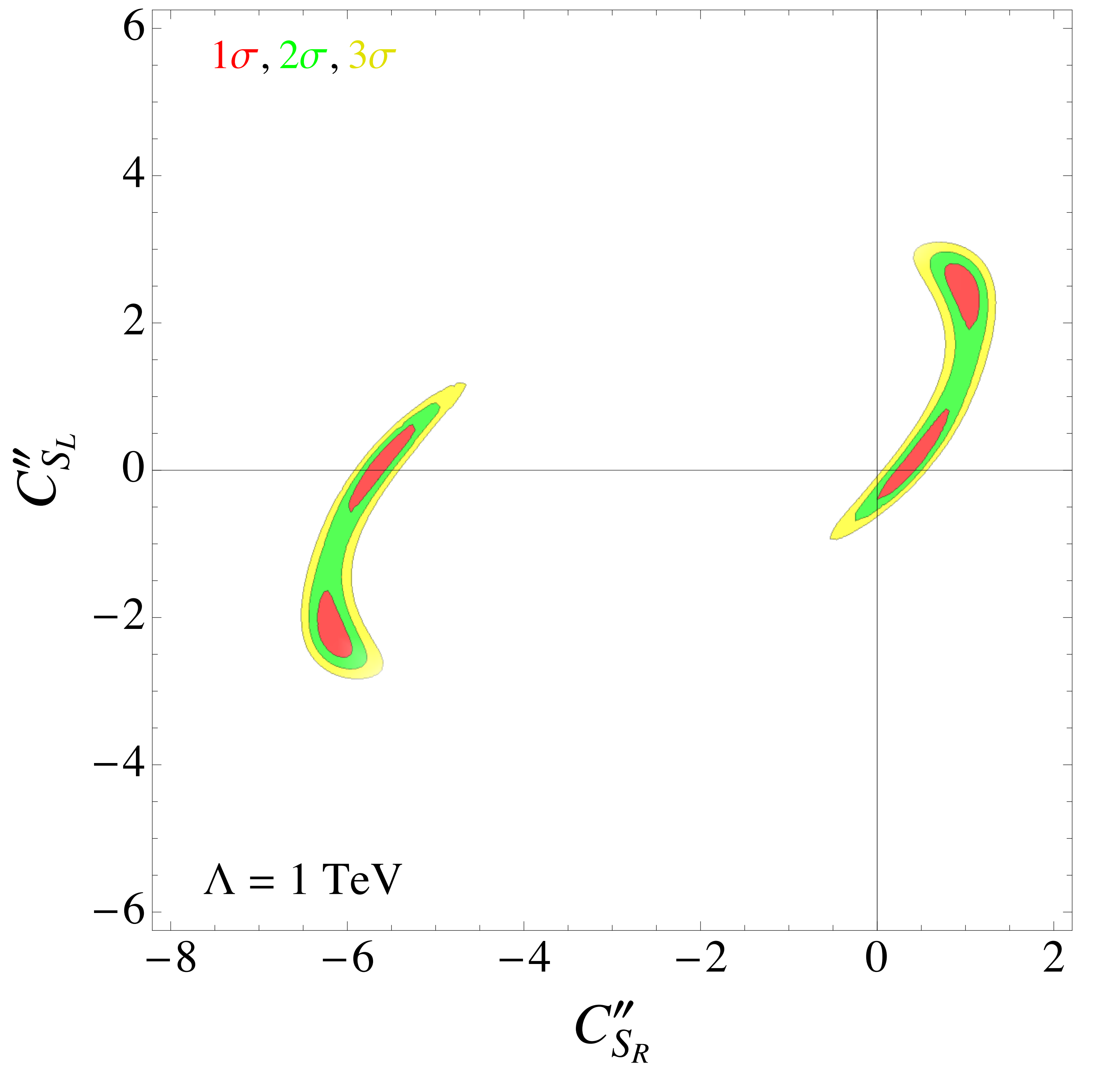
Explanation of the enhanced $B \to D^{(*)}\tau\nu$ rates



Semileptonic decays with tau leptons are 3.5σ higher than SM prediction!

Model-independent operator analysis:

$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb}\, \mathcal{O}_{V_L} + \frac{1}{\Lambda^2} \sum_i C_i^{(\prime,\prime\prime)}\, \mathcal{O}_i^{(\prime,\prime\prime)}$$

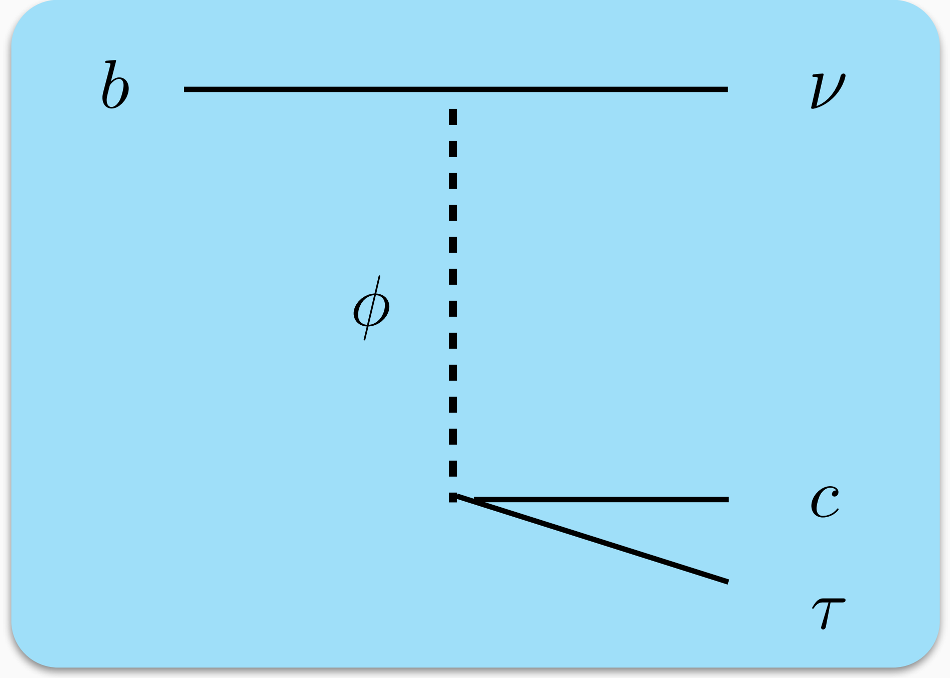


$$\boxed{\begin{aligned} \mathcal{O}''_{S_L} &= (\bar{\tau} P_L c^c)(\bar{b}^c P_L \nu) \\ \mathcal{O}''_{S_R} &= (\bar{\tau} P_R c^c)(\bar{b}^c P_L \nu) \end{aligned}}$$

Freytsis, Ligeti, Rudermann (arXiv:1506:08896)

Explanation of the enhanced $B \to D^{(*)} \tau \nu$ rates

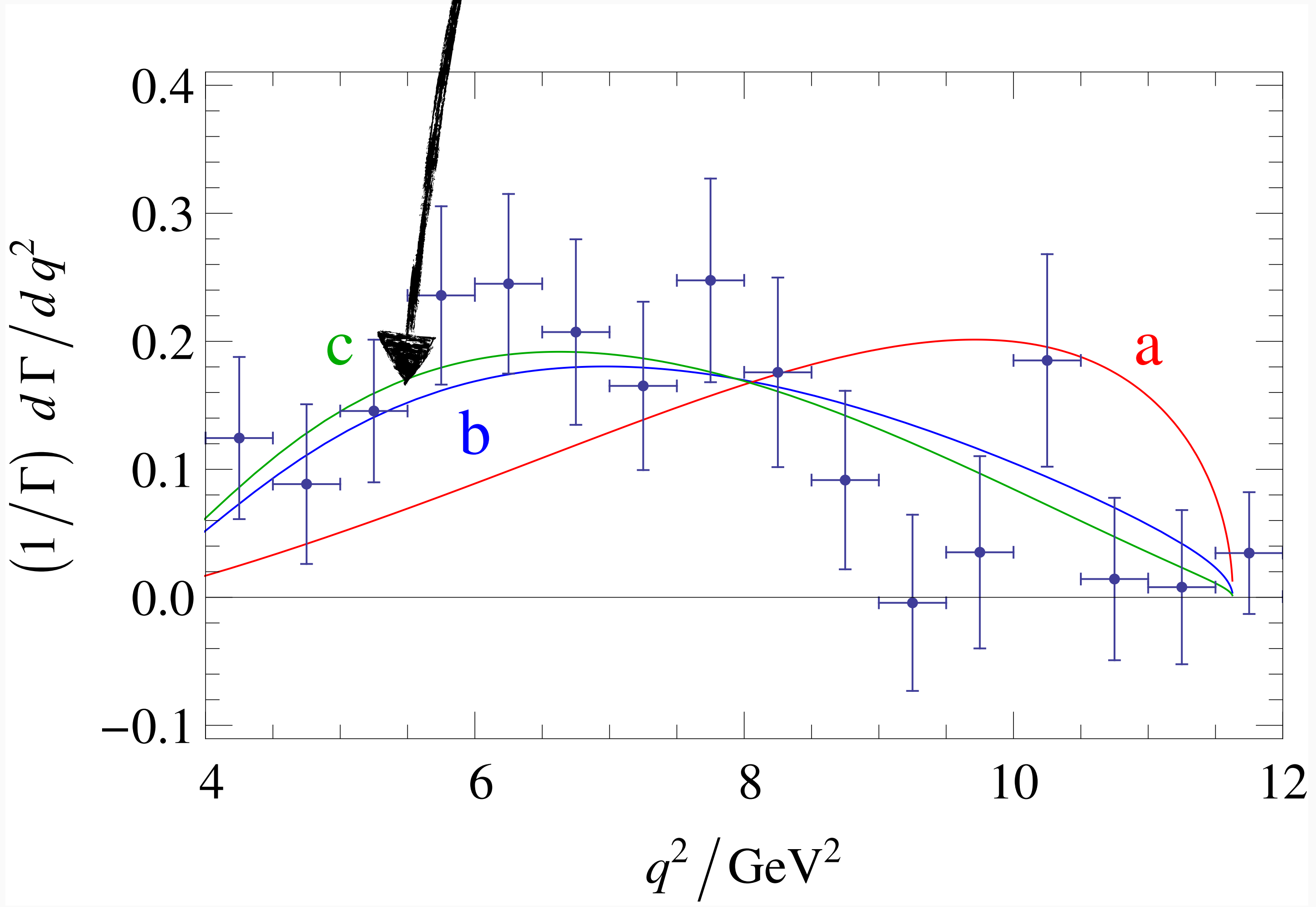
Leptoquark contribution:



$$\frac{\lambda_{c\tau}^{L*}\,\lambda_{b\nu_\tau}^{L}}{M_\phi^2} \approx \frac{0.35}{\text{TeV}^2} \quad = C''_{S_R}$$

$$\frac{\lambda_{c\tau}^{R*}\,\lambda_{b\nu_\tau}^{L}}{M_\phi^2} \approx -\frac{0.03}{\text{TeV}^2} \quad = C''_{S_L}$$

q^2 distribution:



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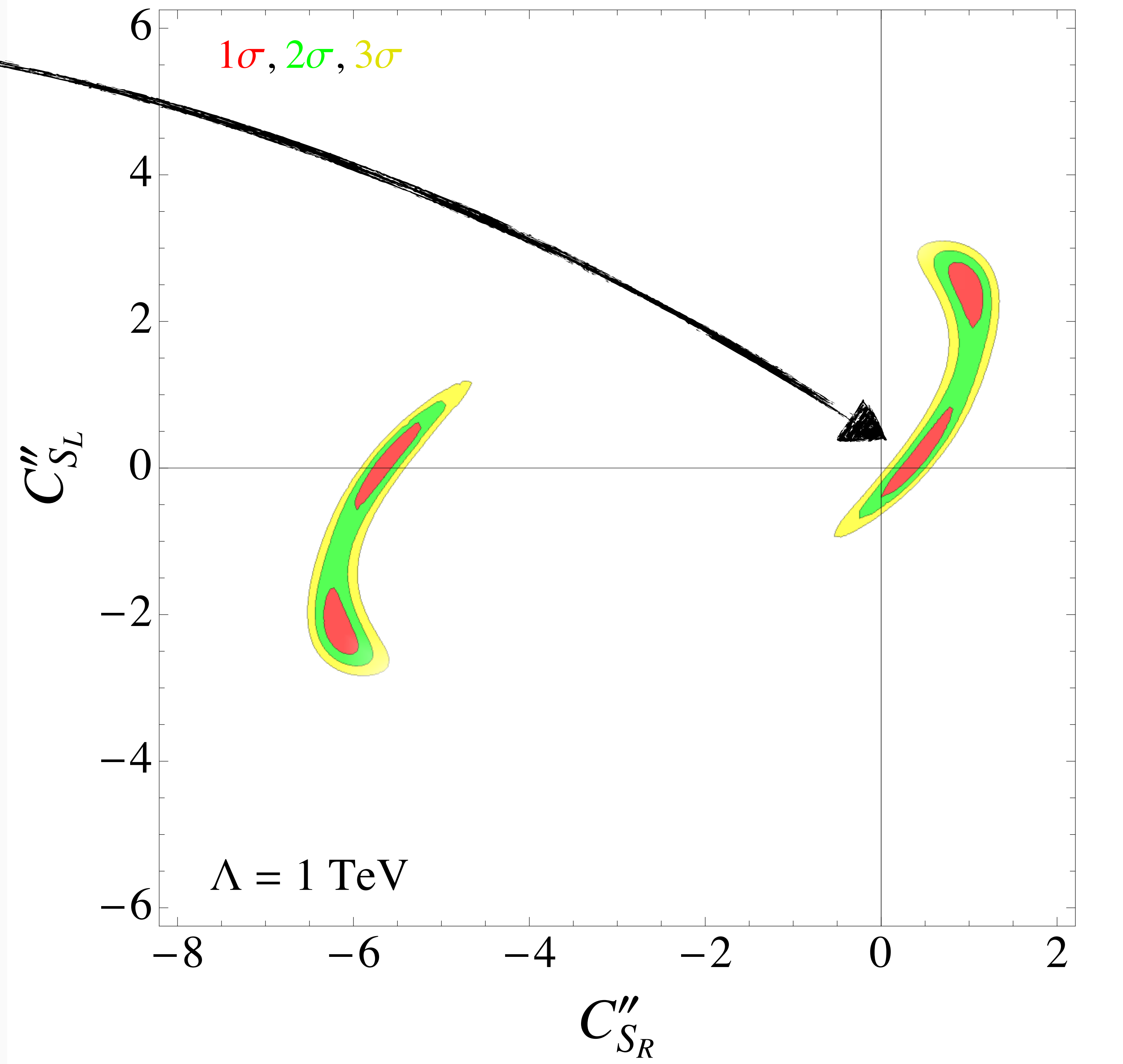
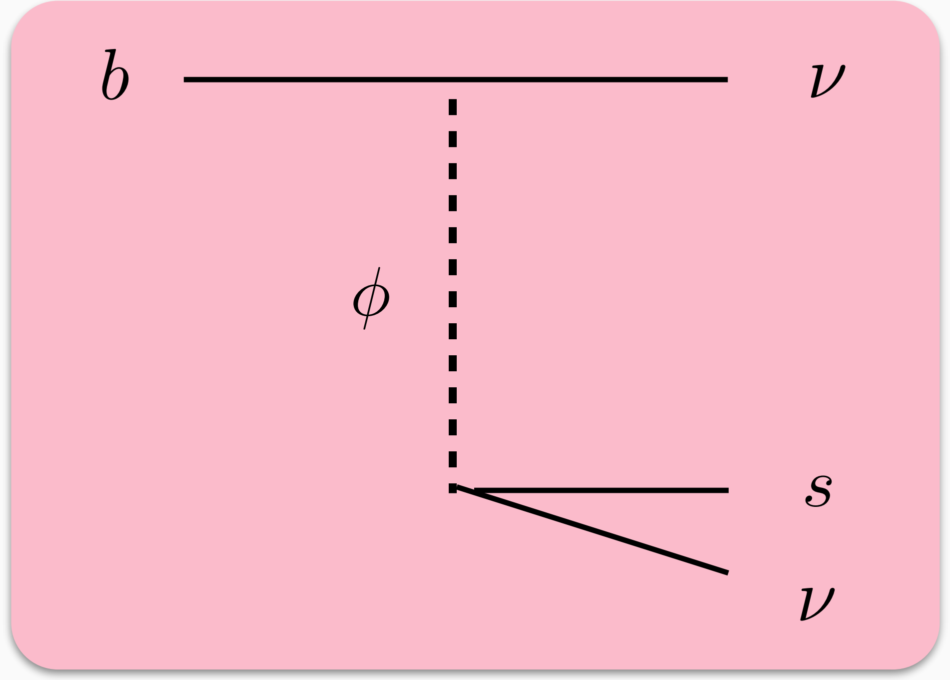


$$\mathcal{O}''_{S_L} = (\bar\tau P_L c^c)(\bar b^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar\tau P_R c^c)(\bar b^c P_L \nu)$$

Freytsis, Ligeti, Rudermann (arXiv:1506:08896)

Bound from $B\to K^{(*)}\nu\nu$ rates

Leptoquark contribution:



$$\mathcal{L}_{\text{eff}}^{(\phi)} = \frac{1}{2M_\phi^2}\,\lambda^{L*}_{s\nu_i}\lambda^{L}_{b\nu_j}\,\bar{s}_L\gamma_\mu b_L\,\bar{\nu}^i_L\gamma^\mu\nu^j_L$$

Interference with SM yields for $R_{\nu\bar{\nu}} = \Gamma/\Gamma_{\text{SM}}$:

$$R_{\nu\bar{\nu}}^{(\phi)} = 1 - \frac{2r}{3}\,\text{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*} + \frac{r^2}{3}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bb}\left(\lambda^L\lambda^{L\dagger}\right)_{ss}}{\left|V_{tb}V_{ts}^*\right|^2}$$

with:

$$r = \frac{s_W^4}{2\alpha^2}\,\frac{1}{X_0(x_t)}\,\frac{m_W^2}{M_\phi^2} \approx 1.91\,\frac{\text{TeV}^2}{M_\phi^2}$$

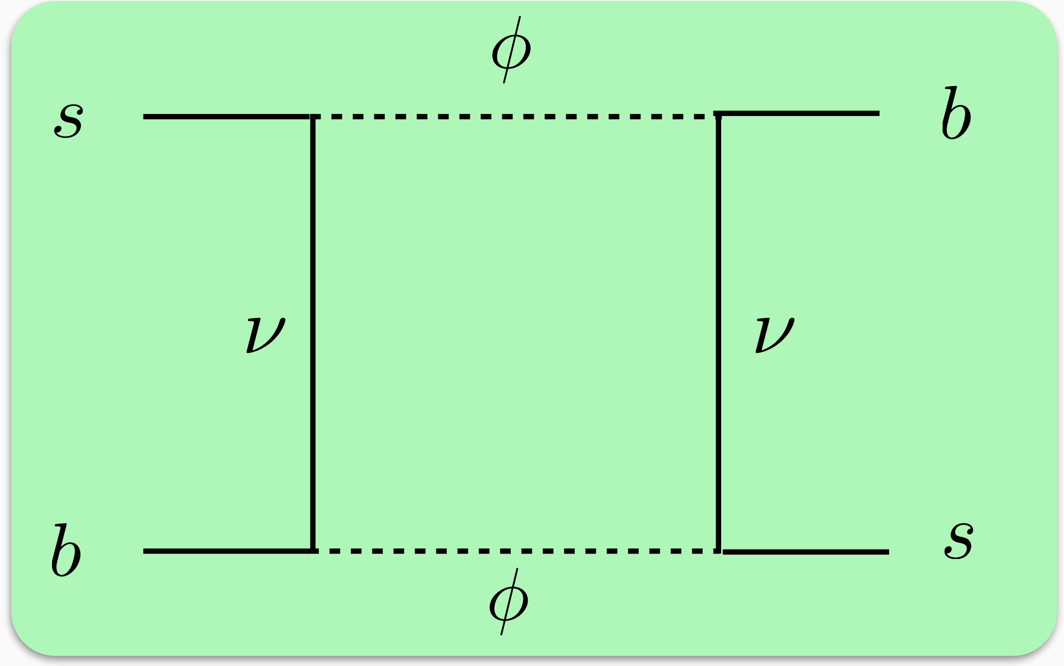
$$\left(\lambda^L\lambda^{L\dagger}\right)_{bs} = \sum_i \lambda^L_{b\nu_i}\,\lambda^{L*}_{s\nu_i}$$

Current BaBar bound $R_{\nu\bar{\nu}} < 4.3$ @ 90% CL implies:

$$\boxed{-\frac{1.2}{\text{TeV}^2} < \frac{1}{M_\phi^2}\,\text{Re}\,\frac{\left(\lambda^L\lambda^{L\dagger}\right)_{bs}}{V_{tb}V_{ts}^*} < \frac{2.3}{\text{TeV}^2}}$$

Constraints from B_s mixing and $B \to X_s \gamma$

Leptoquark contribution:



Correction to SM mixing amplitude:

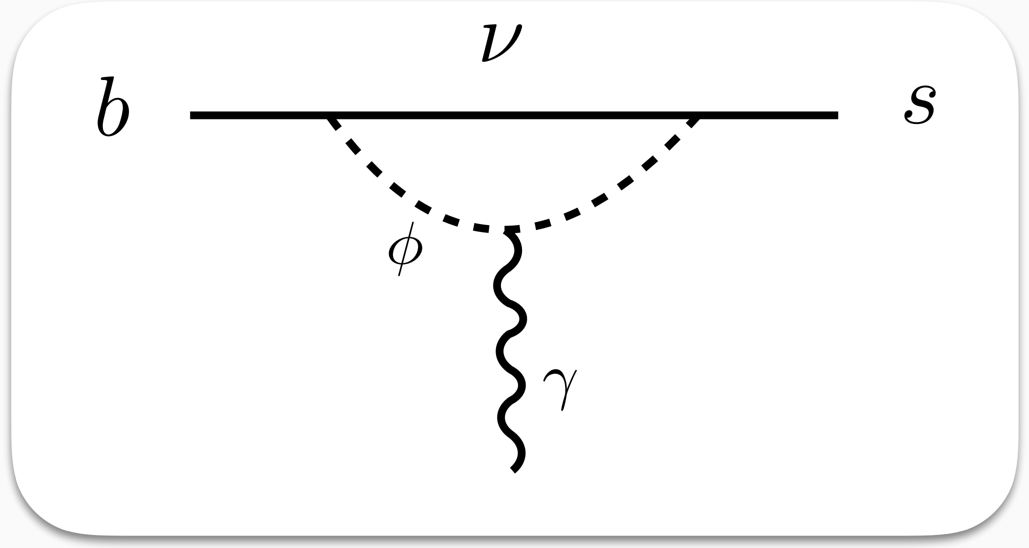
$$C_{B_s}^{(\phi)}\, e^{2i\phi_{B_s}^{(\phi)}} = 1 + \frac{1}{g^4 S_0(x_t)} \frac{m_W^2}{M_\phi^2} \left[\frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*} \right]^2$$

Best fit value:

$$\boxed{\frac{1}{M_\phi} \frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*} \approx \frac{1.87 + 0.45i}{\text{TeV}}}$$

Bona *et al.*, UT*fit* collaboration (arXiv:0707.0636)

Leptoquark contribution:

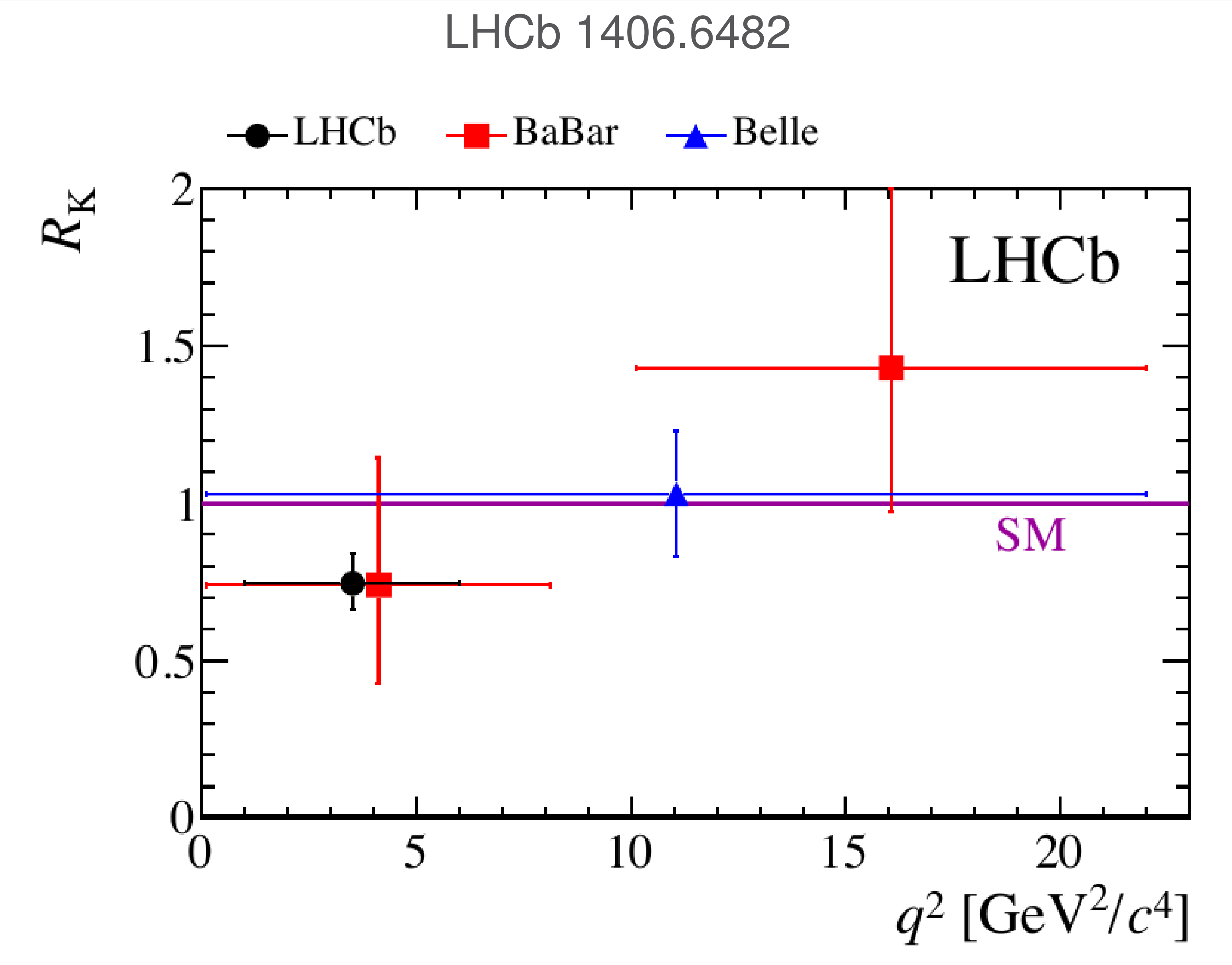


Correction to SM amplitude:

$$C_{7\gamma} = C_{7\gamma}^{\text{SM}} + \left(\frac{v}{12 M_\phi} \right)^2 \frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*}$$

Correction to branching ratio of order 1% or less, below current level of sensitivity

Explanation of the R_K and $B \to K^* \mu^+ \mu^-$ anomalies



2.6σ hint for a violation of lepton flavor universality!

Model-independent operator analysis:

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

with:

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

Take new linear combinations:

$$\mathcal{O}_{LL}^\ell \equiv (\mathcal{O}_9^\ell - \mathcal{O}_{10}^\ell)/2\,, \quad \mathcal{O}_{LR}^\ell \equiv (\mathcal{O}_9^\ell + \mathcal{O}_{10}^\ell)/2$$
$$\mathcal{O}_{RL}^\ell \equiv (\mathcal{O}_9'^\ell - \mathcal{O}_{10}'^\ell)/2\,, \quad \mathcal{O}_{RR}^\ell \equiv (\mathcal{O}_9'^\ell + \mathcal{O}_{10}'^\ell)/2$$

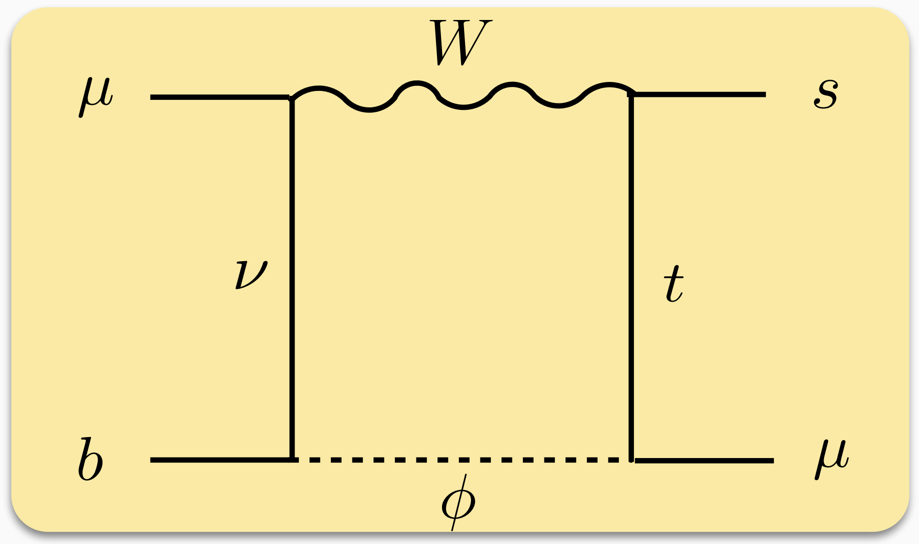
A good fit is obtained for:

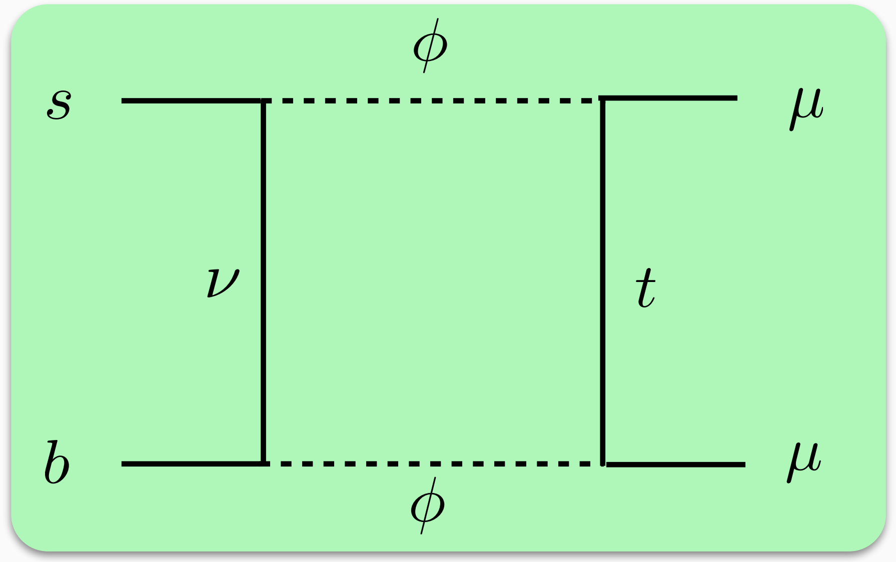
$$\boxed{C_{LL}^\mu \simeq -1\,, \quad C_{ij}^\mu = 0 \text{ otherwise}}$$

Hiller, Schmaltz (arXiv:1408.1627)

Explanation of the R_K and $B \to K^* \mu^+ \mu^-$ anomalies

Leptoquark contributions:





Contributions to Wilson coefficients:

$$C_{LL}^{\mu(\phi)} = \frac{m_t^2}{8\pi\alpha M_\phi^2} \left|\lambda_{t\mu}^L\right|^2 - \frac{1}{64\pi\alpha} \frac{\sqrt{2}}{G_F M_\phi^2} \boxed{\frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*}} (\lambda^{L\dagger}\lambda^L)_{\mu\mu}$$

$$C_{LR}^{\mu(\phi)} = \frac{m_t^2}{16\pi\alpha M_\phi^2} \left|\lambda_{t\mu}^R\right|^2 \left[\ln \frac{M_\phi^2}{m_t^2} - f(x_t)\right] - \frac{1}{64\pi\alpha} \frac{\sqrt{2}}{G_F M_\phi^2} \frac{(\lambda^L \lambda^{L\dagger})_{bs}}{V_{tb} V_{ts}^*} (\lambda^{R\dagger}\lambda^R)_{\mu\mu}$$

Best fit values can be obtained for:

$$\boxed{\sqrt{\left|\lambda_{u\mu}^L\right|^2 + \left|\lambda_{c\mu}^L\right|^2 + \left(1 - \frac{0.77}{\hat{M}_\phi^2}\right)\left|\lambda_{t\mu}^L\right|^2} > 2.36}$$

Model-independent operator analysis:

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

with:

$$\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

Take new linear combinations:

$$\mathcal{O}_{LL}^\ell \equiv (\mathcal{O}_9^\ell - \mathcal{O}_{10}^\ell)/2\,, \quad \mathcal{O}_{LR}^\ell \equiv (\mathcal{O}_9^\ell + \mathcal{O}_{10}^\ell)/2$$
$$\mathcal{O}_{RL}^\ell \equiv (\mathcal{O}_9'^\ell - \mathcal{O}_{10}'^\ell)/2\,, \quad \mathcal{O}_{RR}^\ell \equiv (\mathcal{O}_9'^\ell + \mathcal{O}_{10}'^\ell)/2$$

A good fit is obtained for:

$$\boxed{C_{LL}^\mu \simeq -1\,, \quad C_{ij}^\mu = 0 \text{ otherwise}}$$

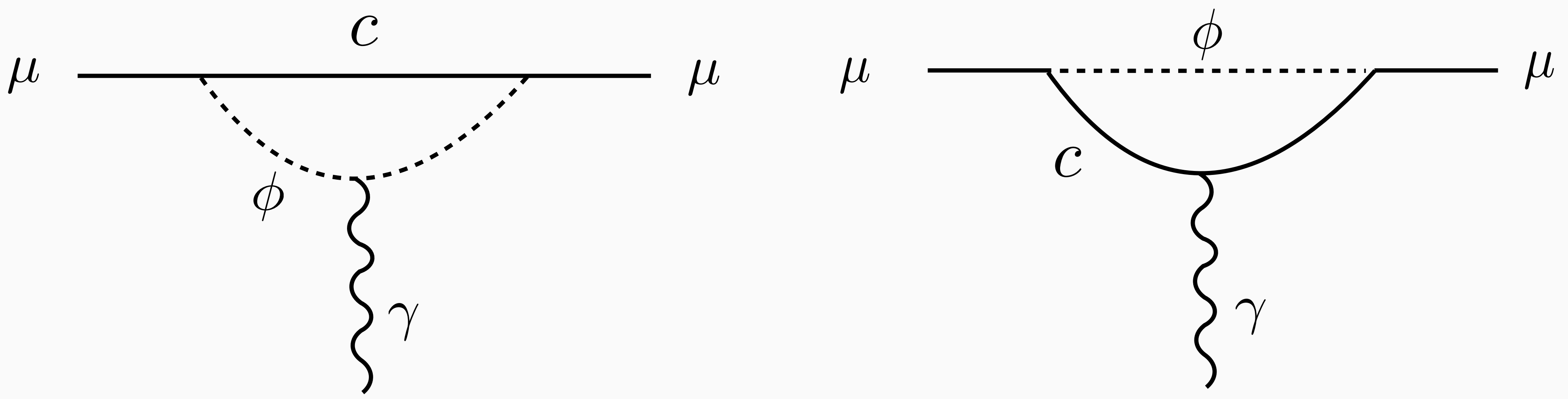
Hiller, Schmaltz (arXiv:1408.1627)

Other observables

With a modest right-handed coupling

$$|\lambda_{c\mu}^{R}| \sim 0.03$$

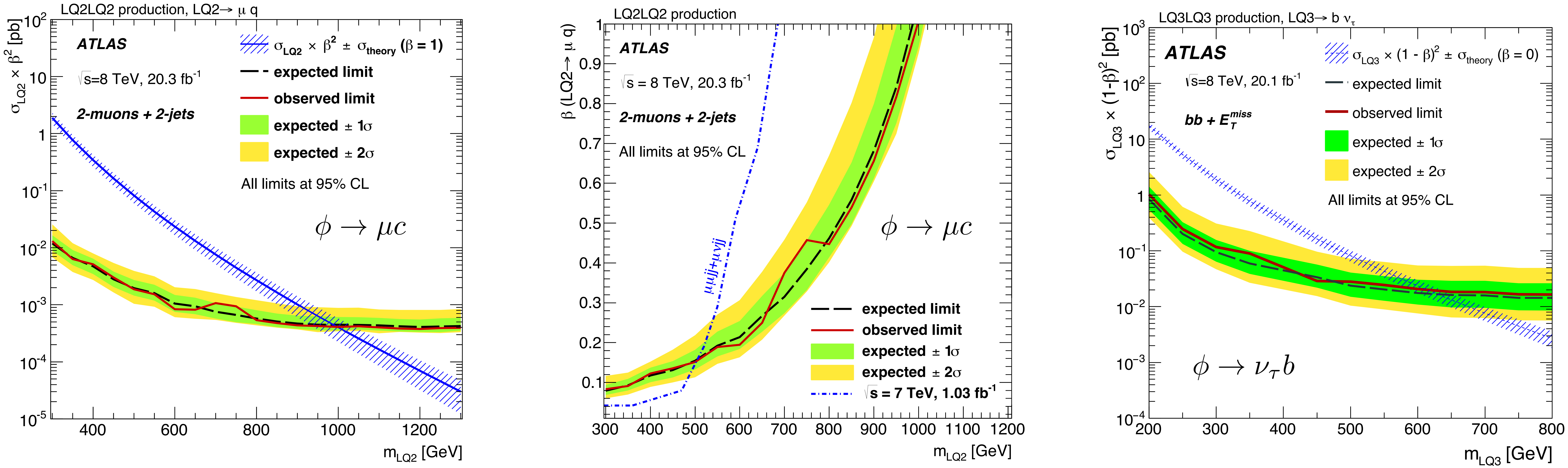
our model can explain the **anomalous magnetic moment** of the muon!



Without much fine-tuning, our model survives the bounds from:

- rare D-meson decays such as $D \to \mu\mu$
- precision data on Z-boson couplings to muons
- rare decays of the tau lepton, such as $\tau \to \mu\gamma$
- …

Collider bounds



One Leptoquark to Rule them All

Part II: The diphoton resonance S(750)

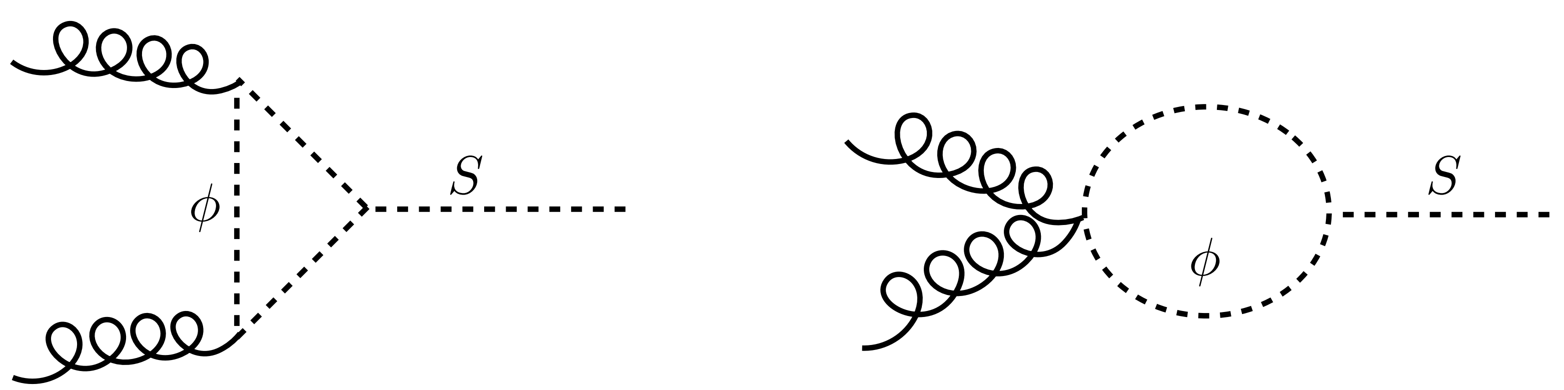
Based on a collaboration with Martin Bauer (arXiv:1512:06828)

Leptoquark-initiated production of S(750)

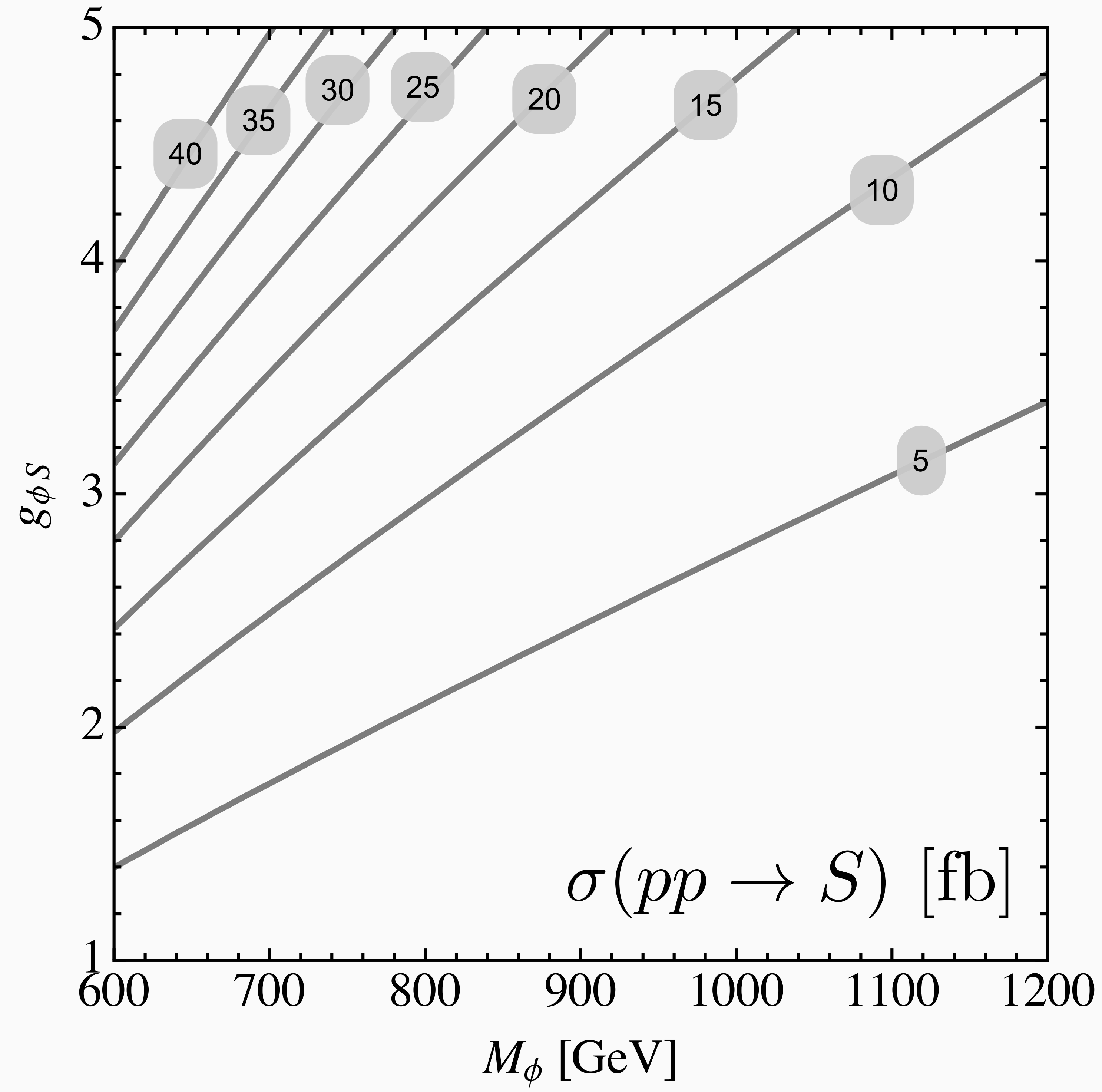
A new resonance S which is a singlet under the Standard Model gauge group naturally has a portal coupling to the scalar leptoquark ϕ

$$\mathcal{L} = g_{\phi S} M_\phi S\, \phi^\dagger \phi$$

This will unavoidably give rise to the production of S in gluon fusion at the LHC:



$$\sigma(pp \to S) = \frac{\pi}{s} \left[\frac{\alpha_s}{192\pi} \frac{g_{\phi S} M_S}{M_\phi} A_0(\tau_\phi) \right]^2 K_{gg}\, ff_{gg}(M_S^2/s)$$



If the $S \to \gamma\gamma$ branching fraction can be made sufficiently large, this can explain the observed rate:

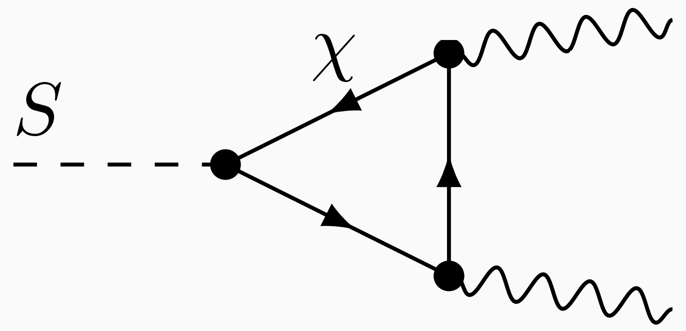
$$\sigma(pp \to S)\, \mathrm{Br}(S \to \gamma\gamma) = (4.4 \pm 1.1)\, \mathrm{fb}$$

Diphoton decay of S(750)

The diphoton decay via leptoquark loops yields too small a branching fractions (~$2\cdot 10^{-4}$)

Obtaining an enhanced diphoton rate requires introducing new color-neutral, vector-like fermions χ:

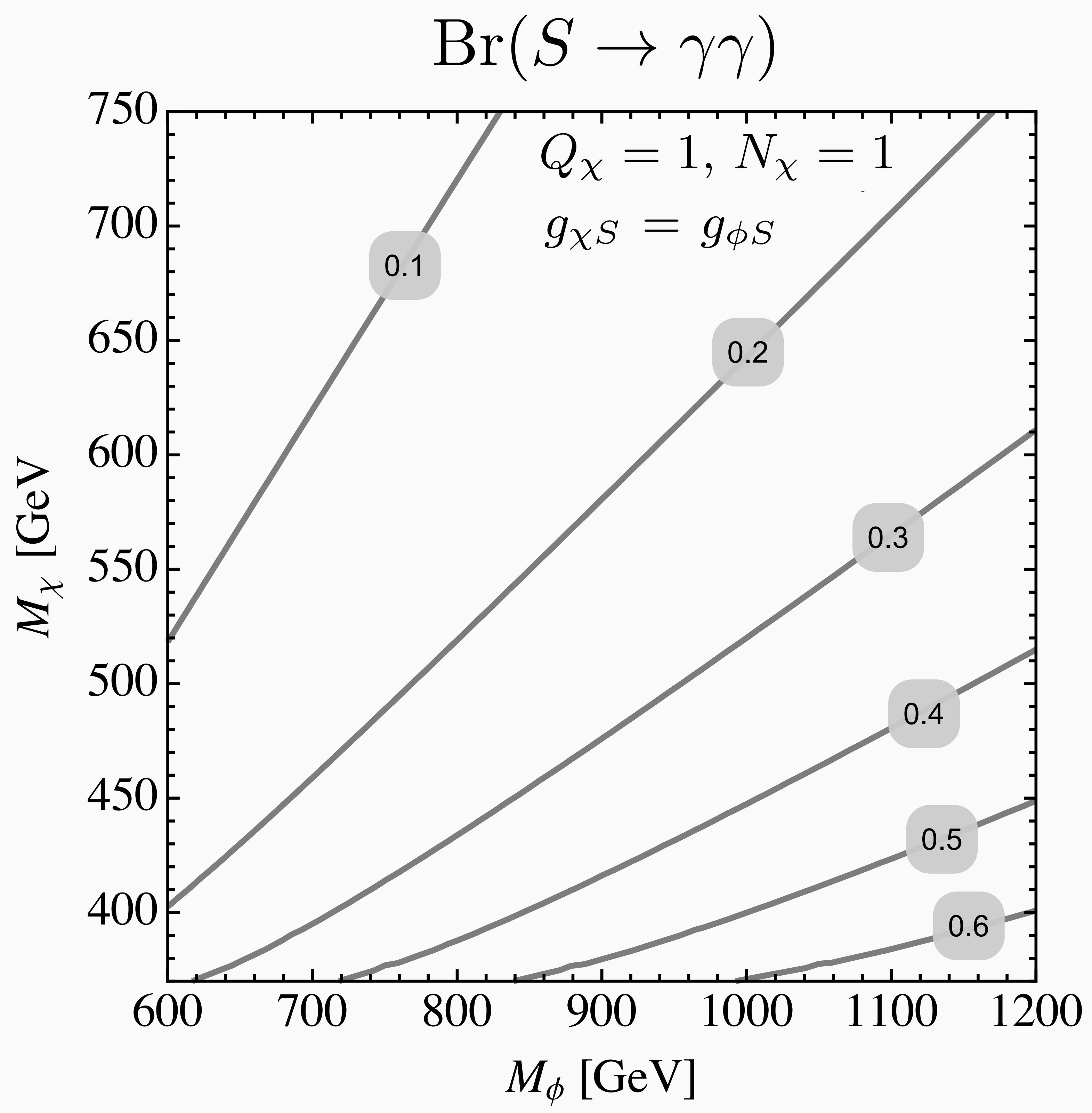
$$\mathcal{L} = g_{\chi S}\, S\, \bar{\chi}\, \chi$$



This yields the ratio:

$$\frac{\Gamma(S \to \gamma\gamma)}{\Gamma(S \to gg)} = \frac{32 N_\chi^2 Q_\chi^4}{K_{gg}} \left(\frac{g_{\chi S}}{g_{\phi S}}\, \frac{\alpha}{\alpha_s} \right)^2 \frac{\tau_\phi}{\tau_\chi} \left| \frac{A_{1/2}(\tau_\chi)}{A_0(\tau_\phi)} \right|^2$$

If χ is a member of a multiplet, its neutral partner χ_0 can be a **dark matter** candidate!



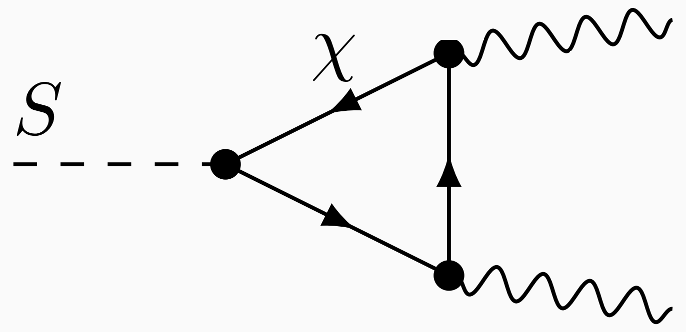
The $S \to \gamma\gamma$ branching fraction can be further enhanced by increasing the electric charge of χ, its multiplicity (dark color) or the ratio $g_{\chi S}/g_{\phi S}$

Diphoton decay of S(750)

The diphoton decay via leptoquark loops yields too small a branching fractions (~2·10^{-4})

Obtaining an enhanced diphoton rate requires introducing new color-neutral, vector-like fermions χ:

$$\mathcal{L} = g_{\chi S}\, S\, \bar{\chi}\, \chi$$



This yields the ratio:

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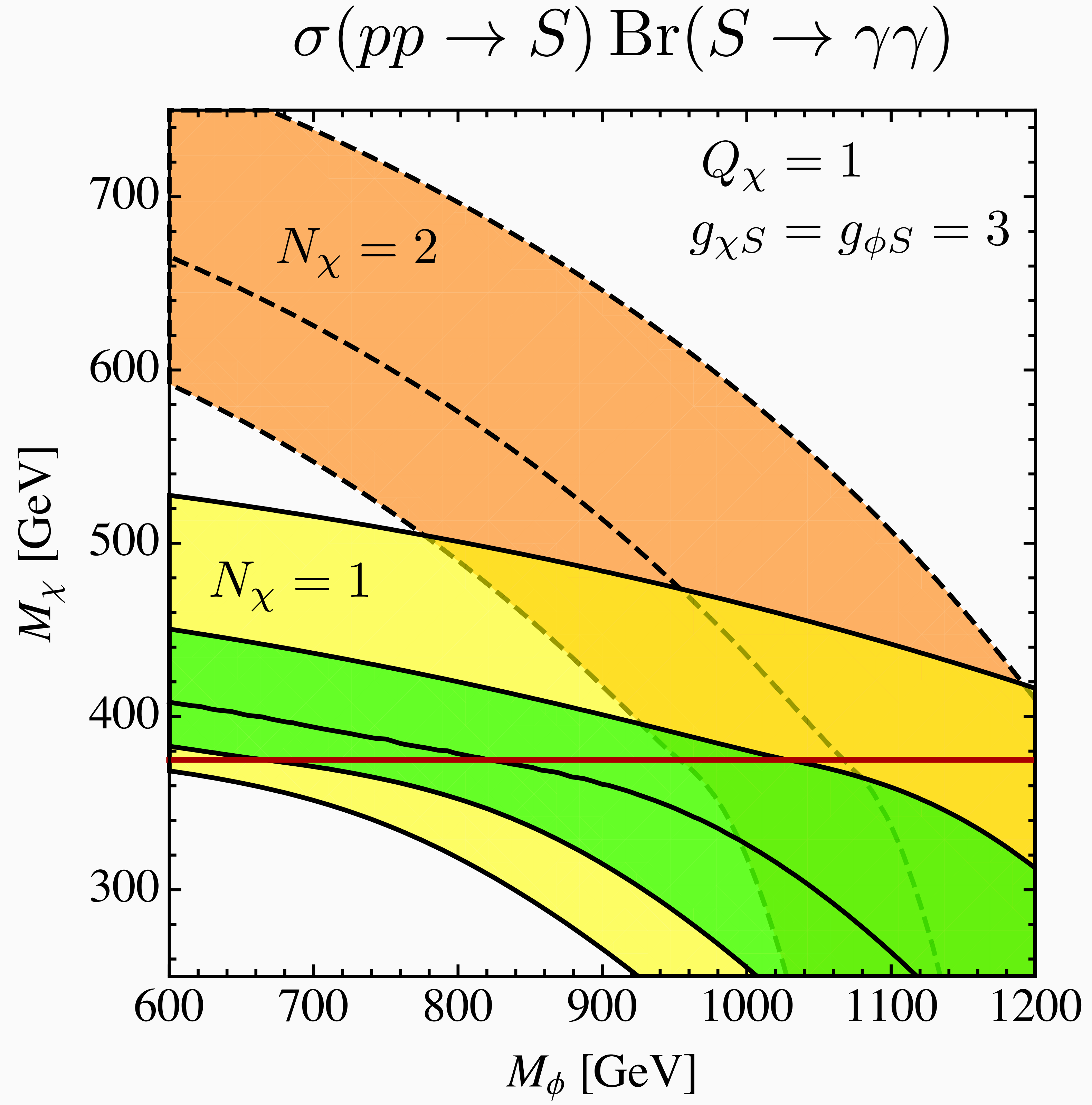
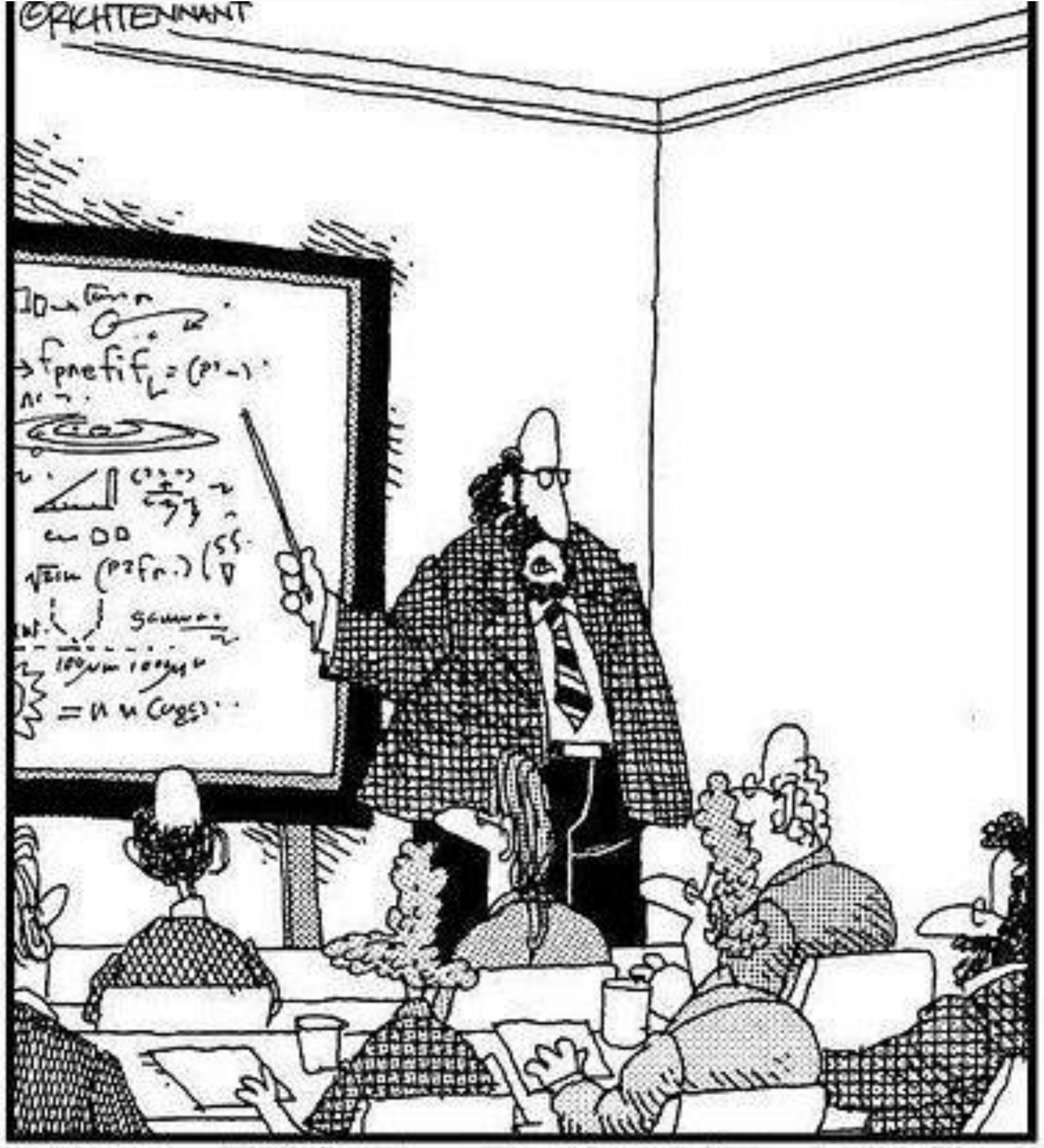


Parameter space in which the experimental rate

$$\sigma(pp\to S)\,\mathrm{Br}(S\to\gamma\gamma) = (4.4 \pm 1.1)\,\mathrm{fb}$$

is reproduced in our model



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

Outlook

One the verge of more discoveries?

- Discovery of the Higgs boson has opened a new era in exploration of fundamental structures of Nature
- Growing number of anomalies – both at the precision frontier and the energy frontier – give us confidence that the Standard Model may soon be cracked

Thank you!

ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

Mainz Institute for Theoretical Physics