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

Flavor Physics and Flavor Anomalies
Beyond the Standard Model

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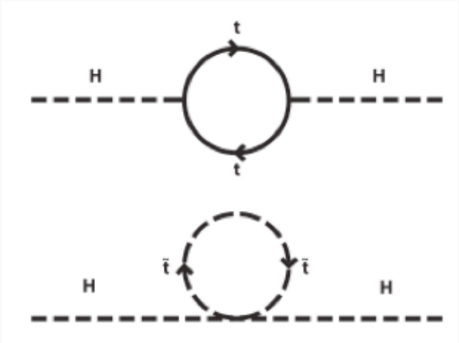
Quark Confinement and the Hadron Spectrum XII
Thessaloniki, Greece, 28 August - 4 September 2016
Based on work with M. Bauer, PRL 116 (2016) 141802 [arXiv:1511:01900]

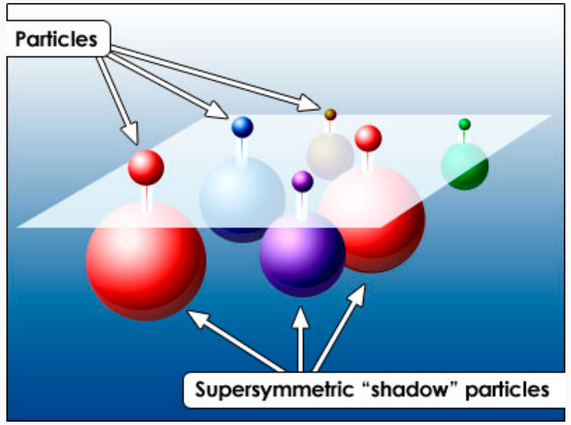
ERC Advanced Grant (EFT4LHC)
An Effective Field Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavor and Electroweak Symmetry Breaking

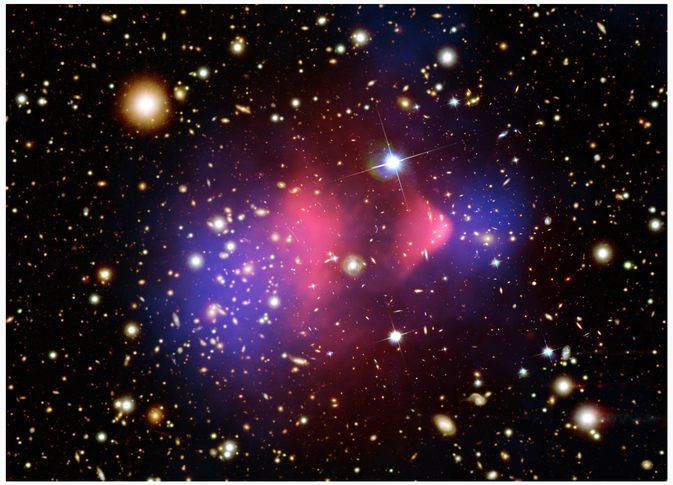
Mainz Institute for Theoretical Physics

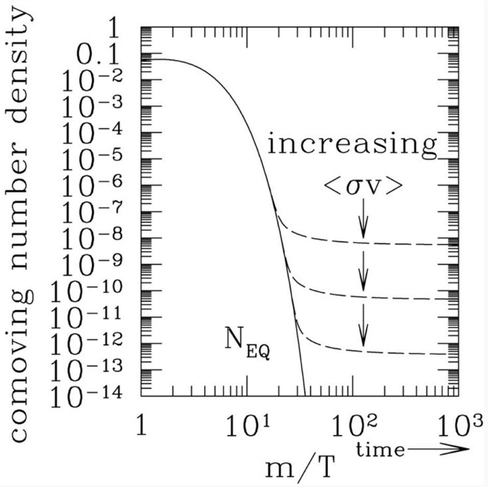
Is Nature natural?

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?

Overview

1 Hints for New Physics

2 Flavor Anomalies

~~3 Diphoton Resonance~~
~~(arXiv:1512:06828 with Martin Bauer)~~

4 Outlook

Many related talks during this conference:

- Thomas Blake (plenary TUE)
- M. Chrzaszcz, S. Jäger, L. Hofer, Z. Liu (parallel TUE)
- Round table presentations & discussion on TUE
  (M. Gersabeck, R. Zwicky, Z. Liu, T. Blake, L. Hofer, S. Jäger)

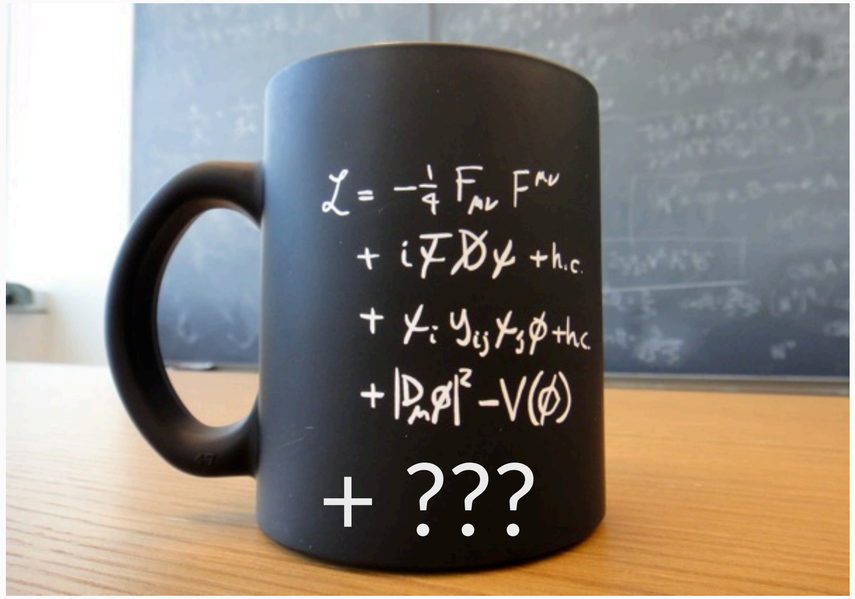
Hints for New Physics

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**
- (Disappearing) hints of new heavy resonances

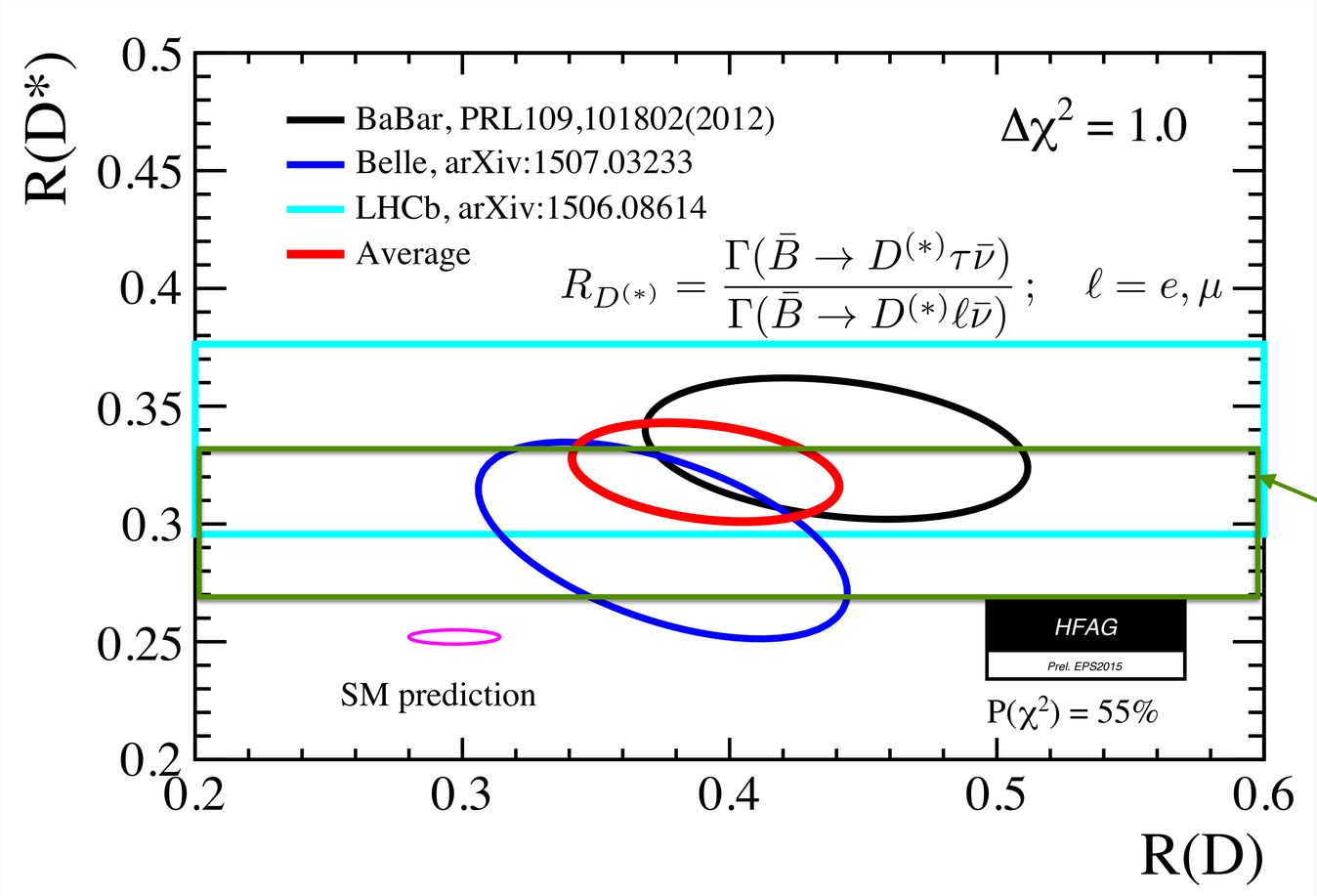


Anomalies in the flavor sector

$\sim 3.5\sigma$	$(g-2)_\mu$ 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 $\lvert V_{ub}\rvert$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$
$2-3\sigma$	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)

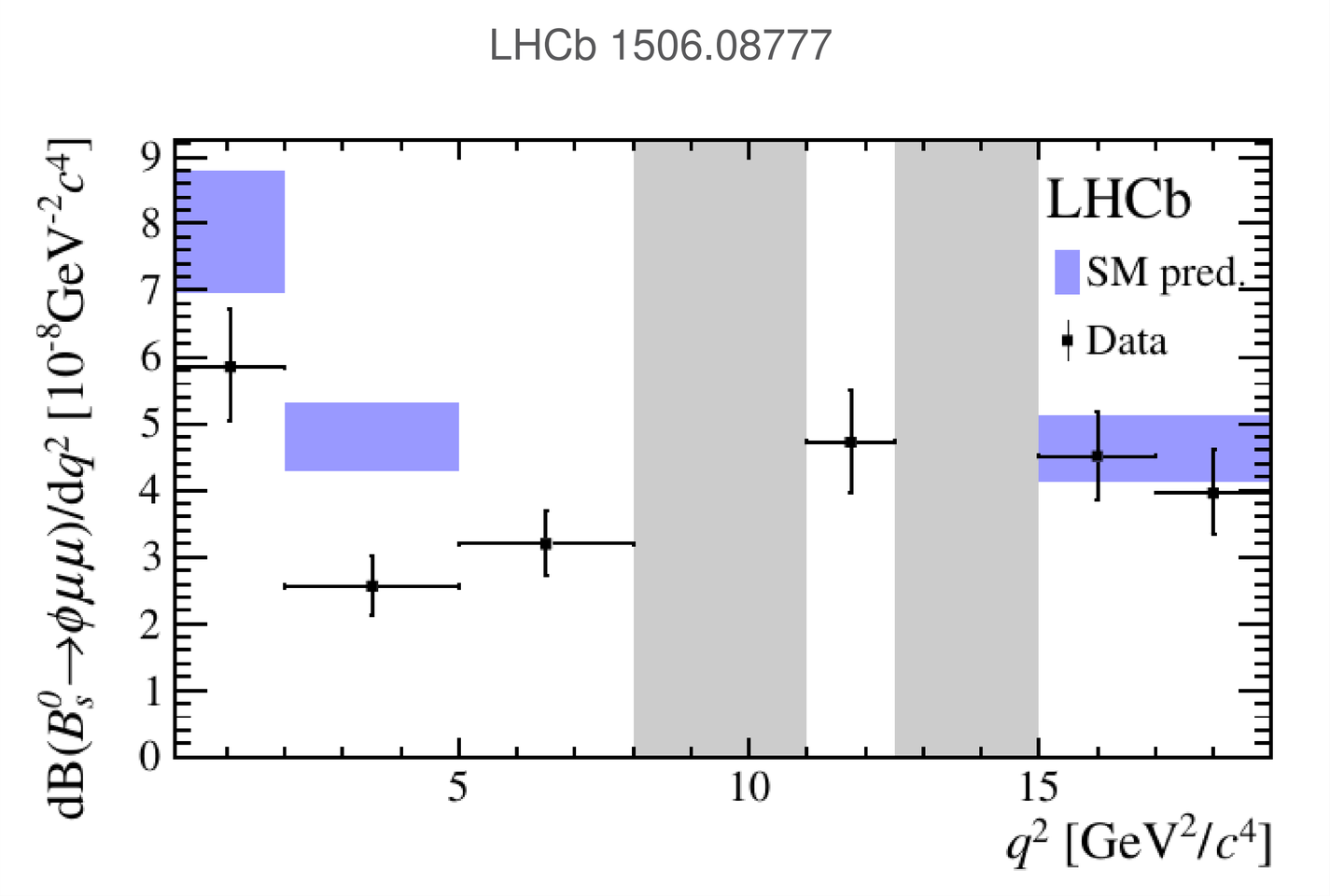
Flavor anomalies: Enhanced $B \to D^{(*)}\tau\nu$ rates



Belle: arXiv:1607:07923

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

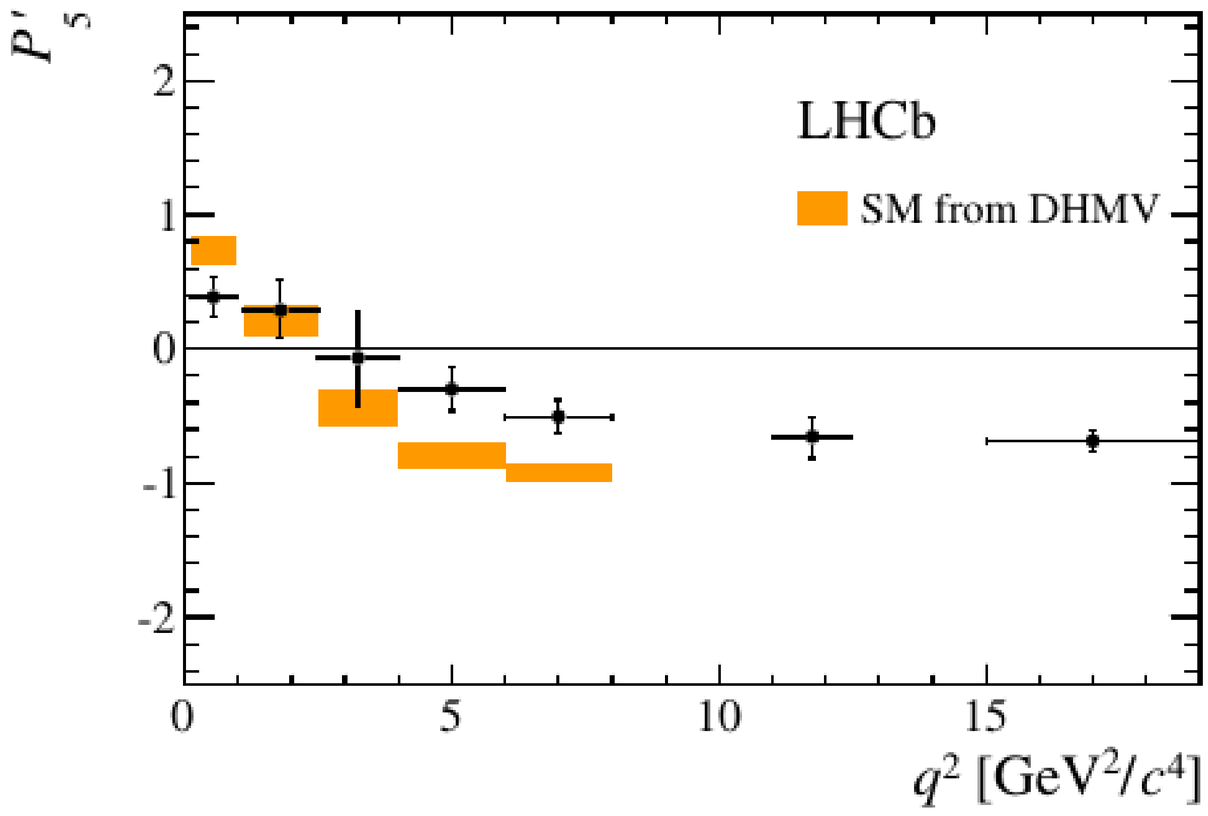
Flavor anomalies: Suppressed $B_s \to \Phi\, \mu^+\mu^-$ branching ratio



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

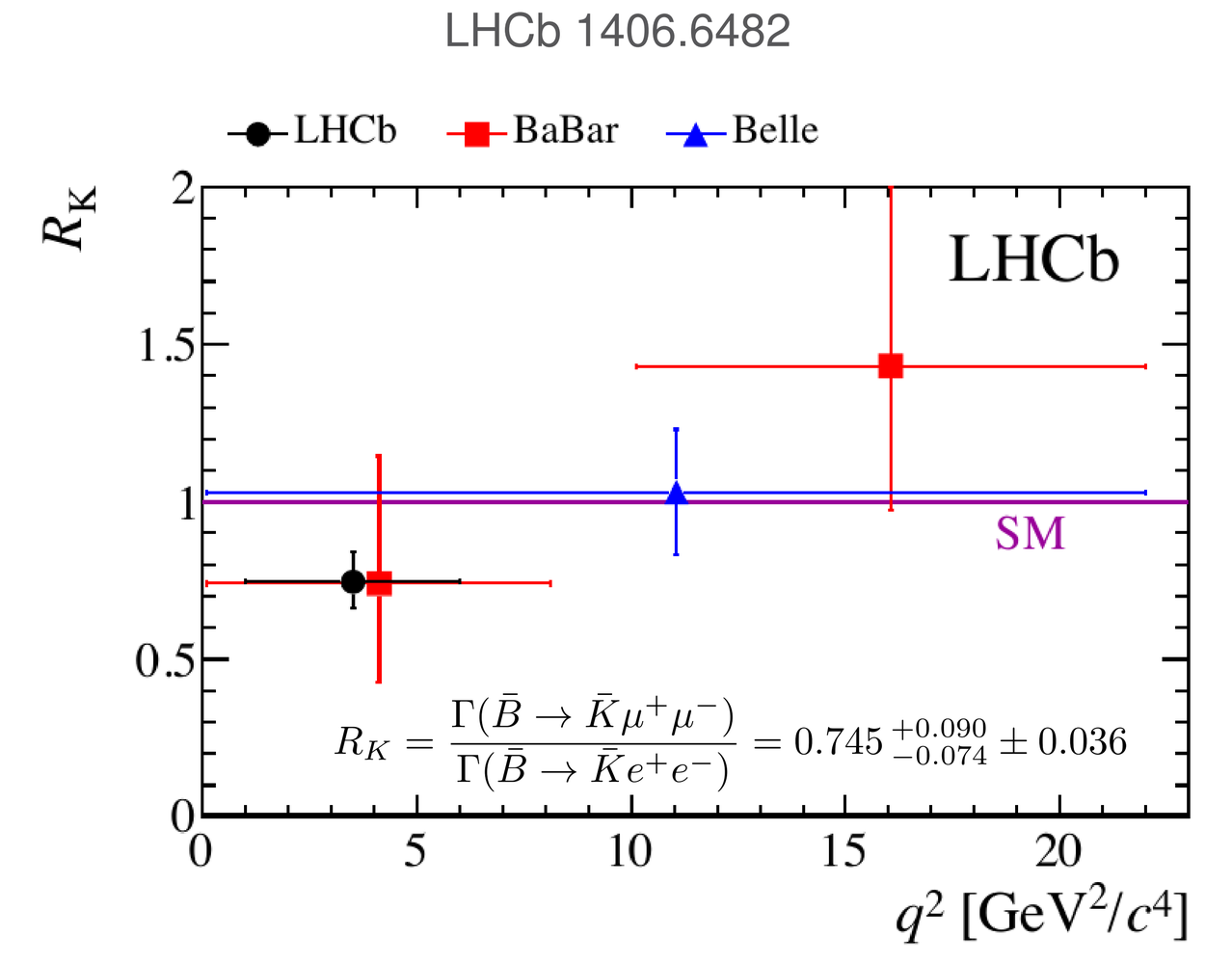


Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08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

Altmannshofer, Straub (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. $B \to K\,e^+e^-$



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

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

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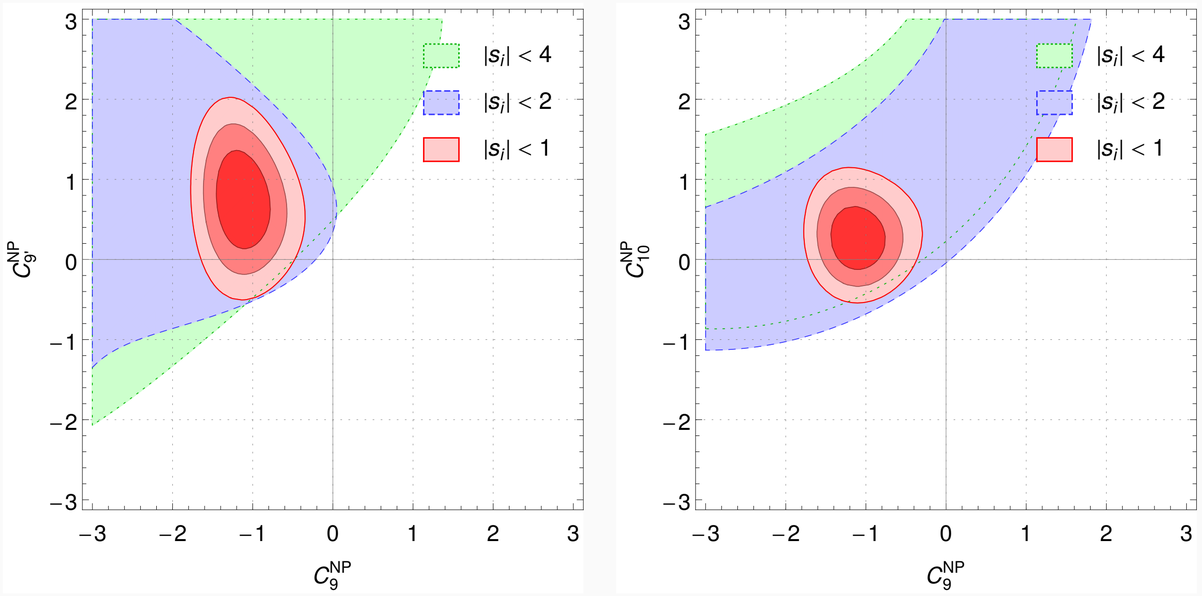

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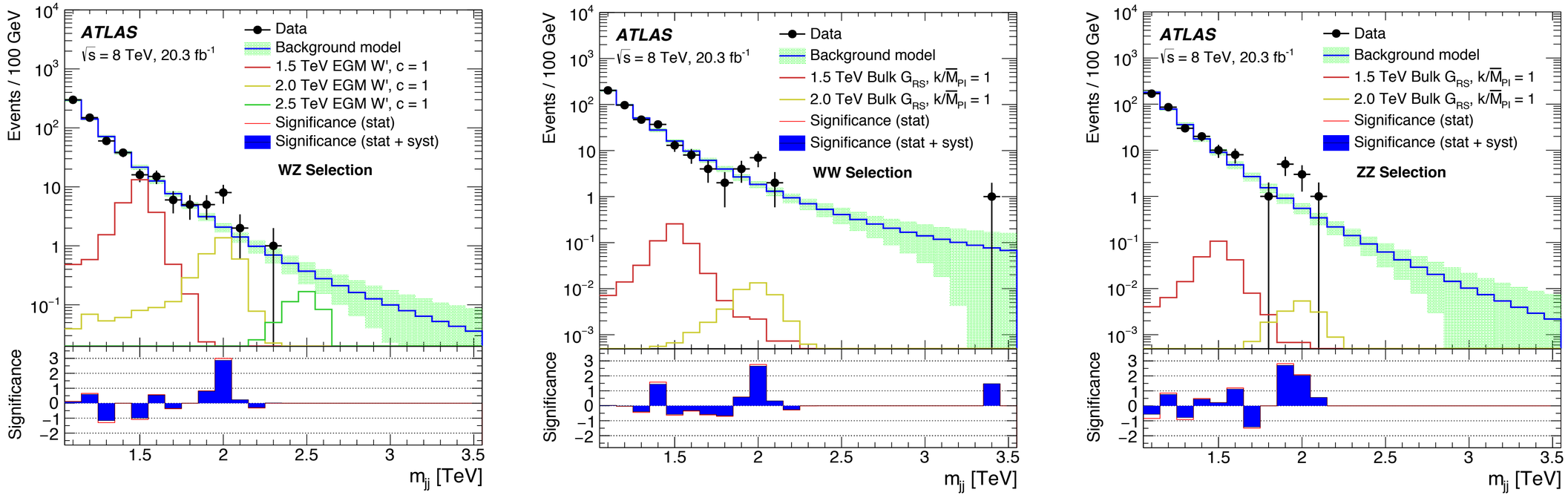
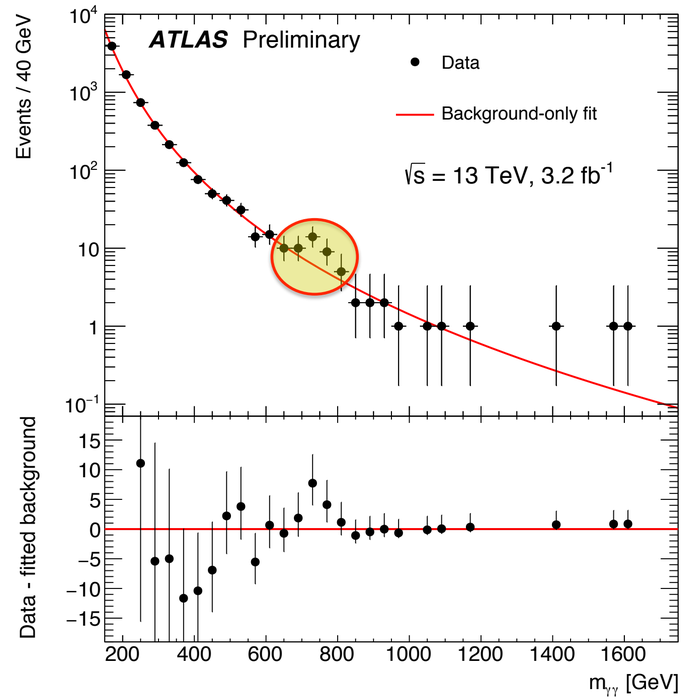
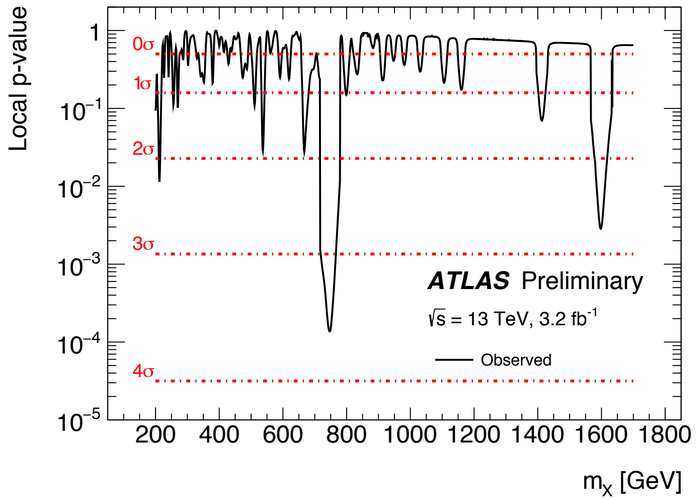
A new diboson resonance near 2 TeV in Run-I ?

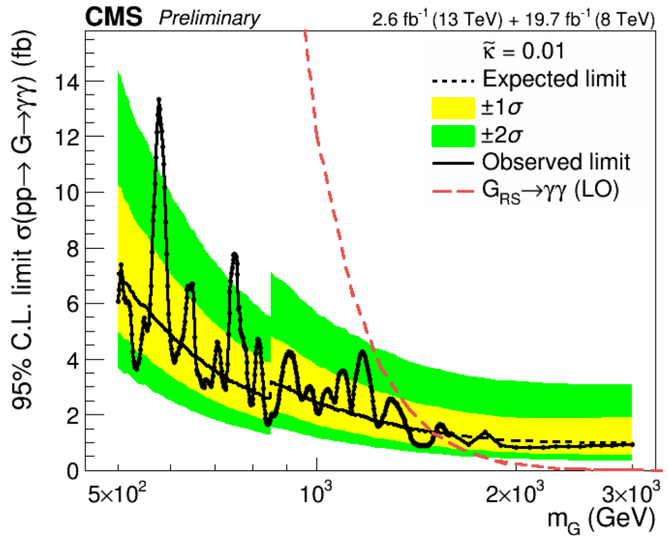


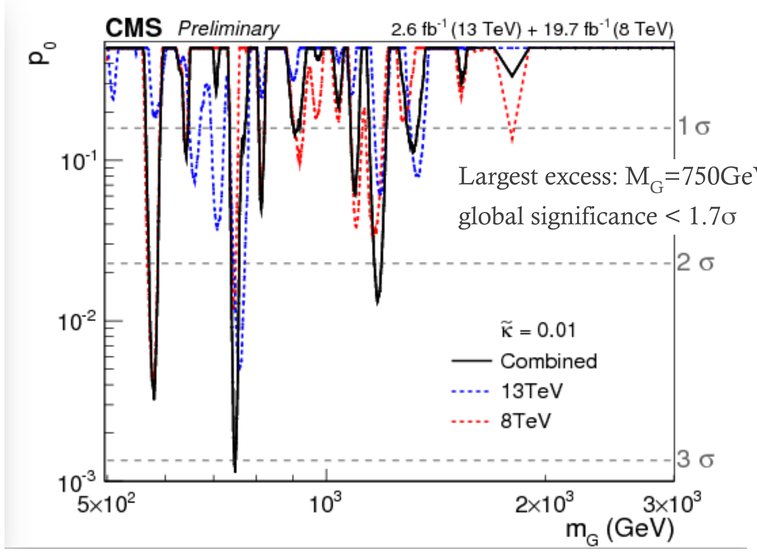
A new diphoton resonance near 750 GeV in Run-II ?





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

One Leptoquark to Rule them All

Based on work with M. Bauer, PRL 116 (2016) 141802 [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:

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

After rotation to the mass basis, we have:

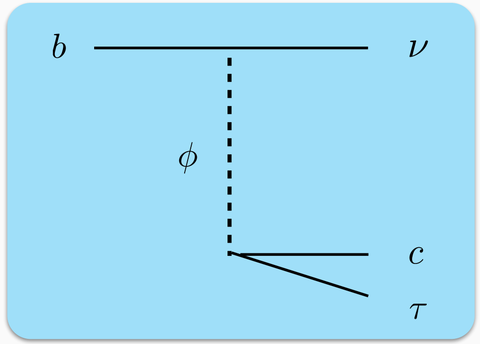
$$\mathcal{L}_\phi \ni \bar{u}_L^c\boldsymbol{\lambda}_{ue}^L e_L\,\phi^* - \bar{d}_L^c\boldsymbol{\lambda}_{d\nu}^L\nu_L\phi^* + \bar{u}_R^c\,\boldsymbol{\lambda}_{ue}^R e_R\,\phi^* + \text{h.c.}$$

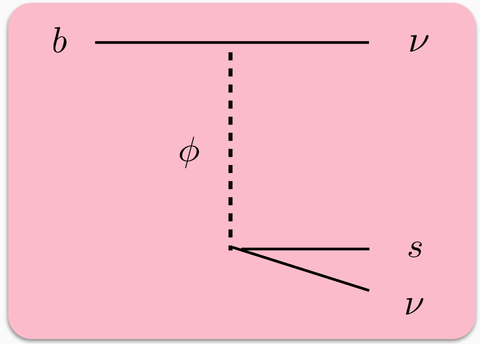
with:

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

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.:





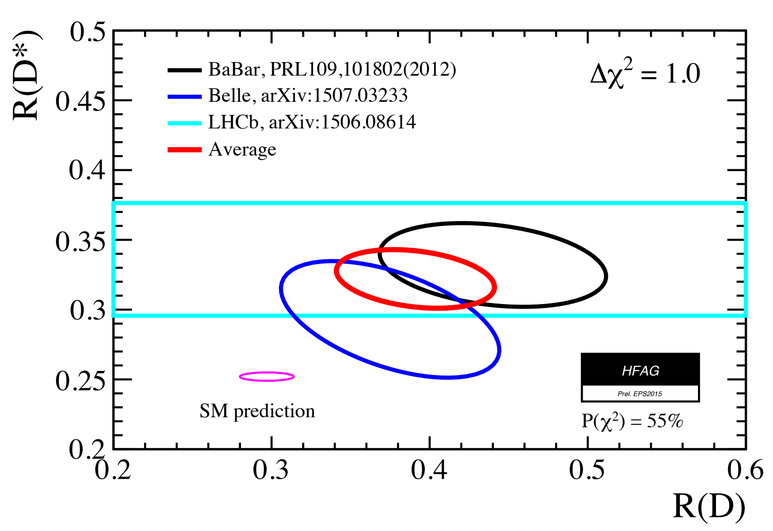
Will need:

$$\lambda_{ue}^L = V_{\text{CKM}}^*\lambda_{d\nu}^L U_e \approx \begin{pmatrix} \bullet & \cdot & \cdot \\ \cdot & \bullet & \cdot \\ \cdot & \cdot & \bullet \end{pmatrix}$$

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

$$\lambda_{ue}^R \sim \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix}$$

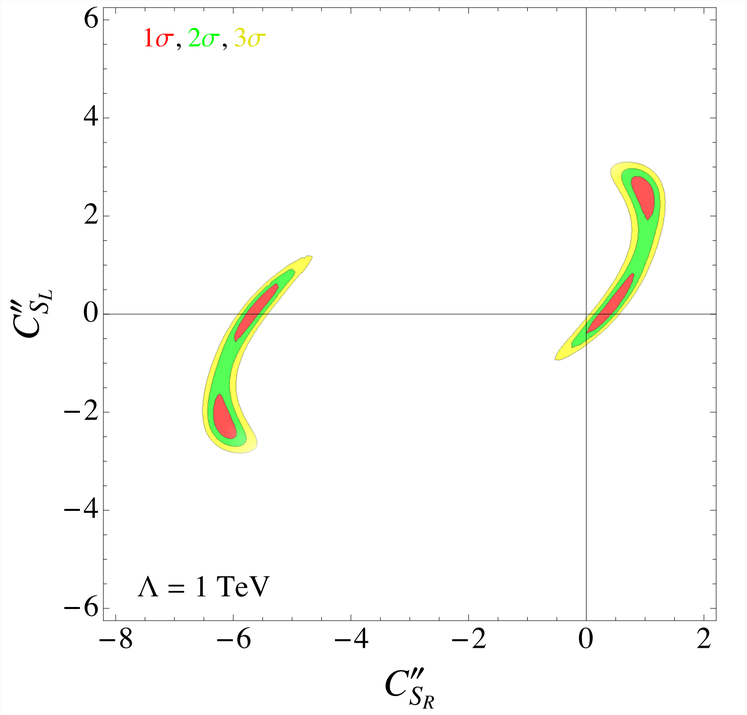
Explanation of the enhanced $B \to D^{(*)}\tau\nu$ rates



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

Model-independent operator analysis:

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

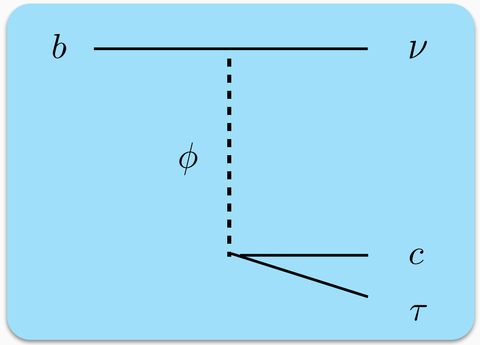


$$\mathcal{O}''_{S_L} = (\bar{\tau} P_L c^c)(\bar{b}^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar{\tau} P_R c^c)(\bar{b}^c P_L \nu)$$

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

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

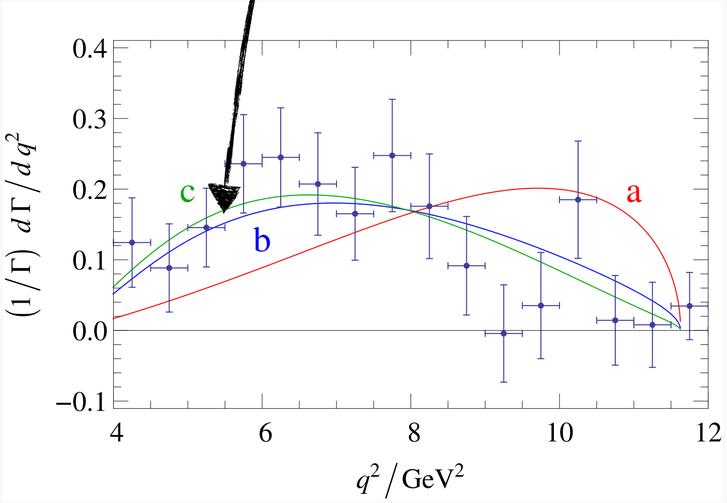
Leptoquark contribution:



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

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

q^2 distribution:



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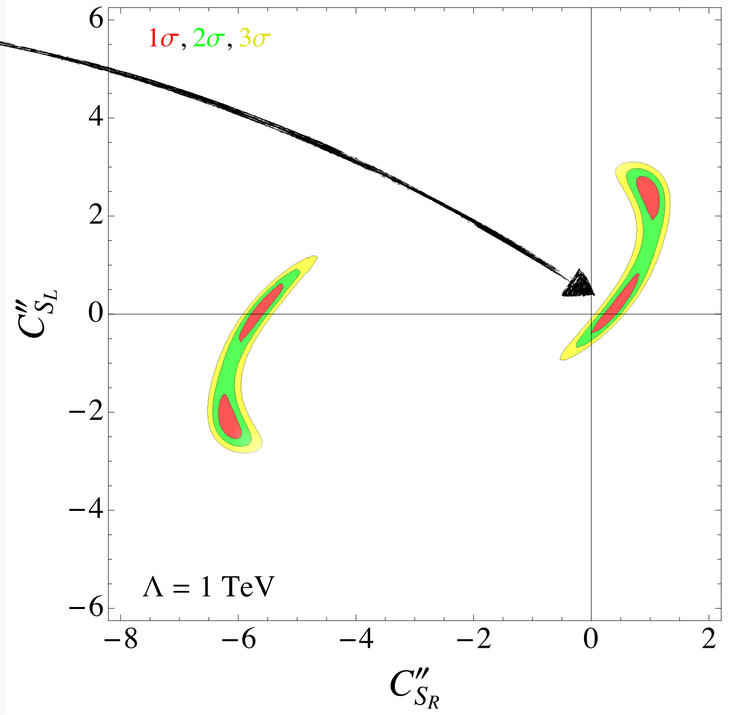
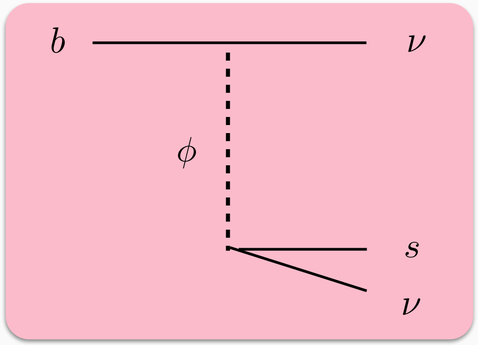


$$\mathcal{O}''_{S_L} = (\bar\tau P_L c^c)(\bar b^c P_L \nu)$$
$$\mathcal{O}''_{S_R} = (\bar\tau P_R c^c)(\bar b^c P_L \nu)$$

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

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

Leptoquark contribution:



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

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

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

with:

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

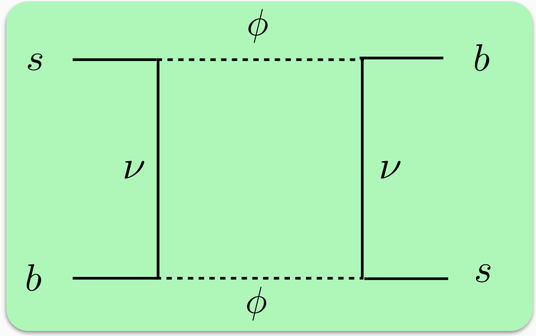
$$\left(\lambda^L\lambda^{L\dagger}\right)_{bs} = \sum_i \lambda^L_{b\nu_i}\,\lambda^{L*}_{s\nu_i}$$

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

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

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

Leptoquark contribution:



Correction to SM mixing amplitude:

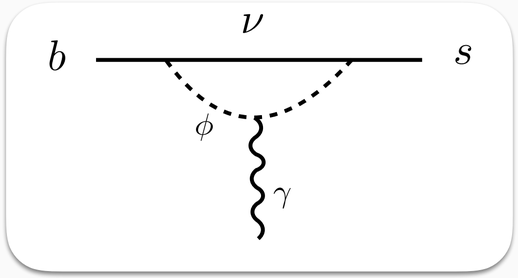
$$C_{B_s}^{(\phi)} e^{2i\phi_{B_s}^{(\phi)}} = 1 + \frac{1}{g^4 S_0(x_t)} \frac{m_W^2}{M_\phi^2} \left[\frac{\left(\lambda^L \lambda^{L\dagger}\right)_{bs}}{V_{tb} V_{ts}^*} \right]^2$$

Best fit value:

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

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

Leptoquark contribution:

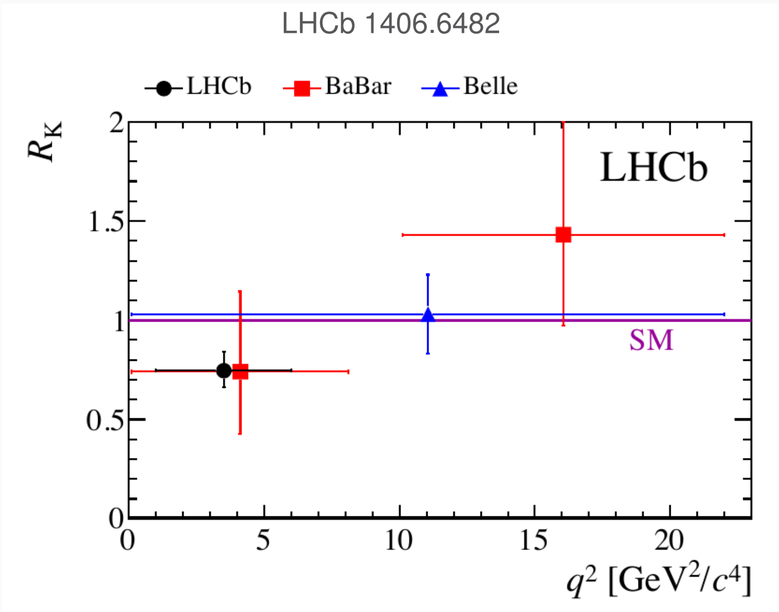


Correction to SM amplitude:

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

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



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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:

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

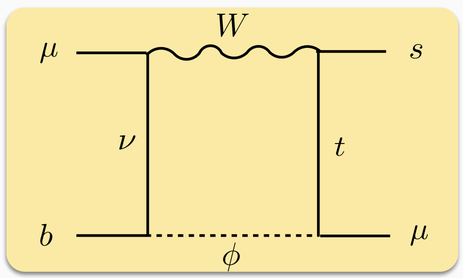
A good fit is obtained for:

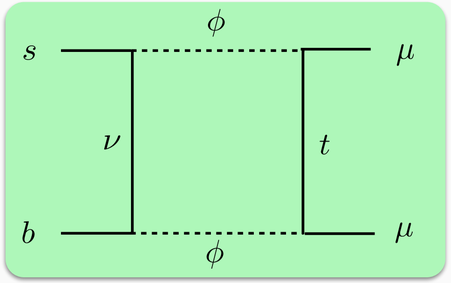
$$\boxed{C_{LL}^\mu \approx -1\,, \qquad C_{ij}^\mu \approx 0 \text{ otherwise}}$$

Hiller, Schmaltz (arXiv:1408.1627)

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

Leptoquark contributions:





Contributions to Wilson coefficients:

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

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

Best fit values can be obtained for:

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

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:

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

Take new linear combinations:

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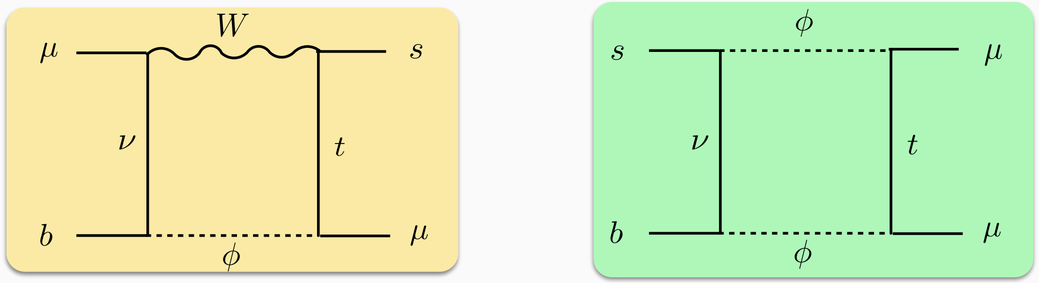

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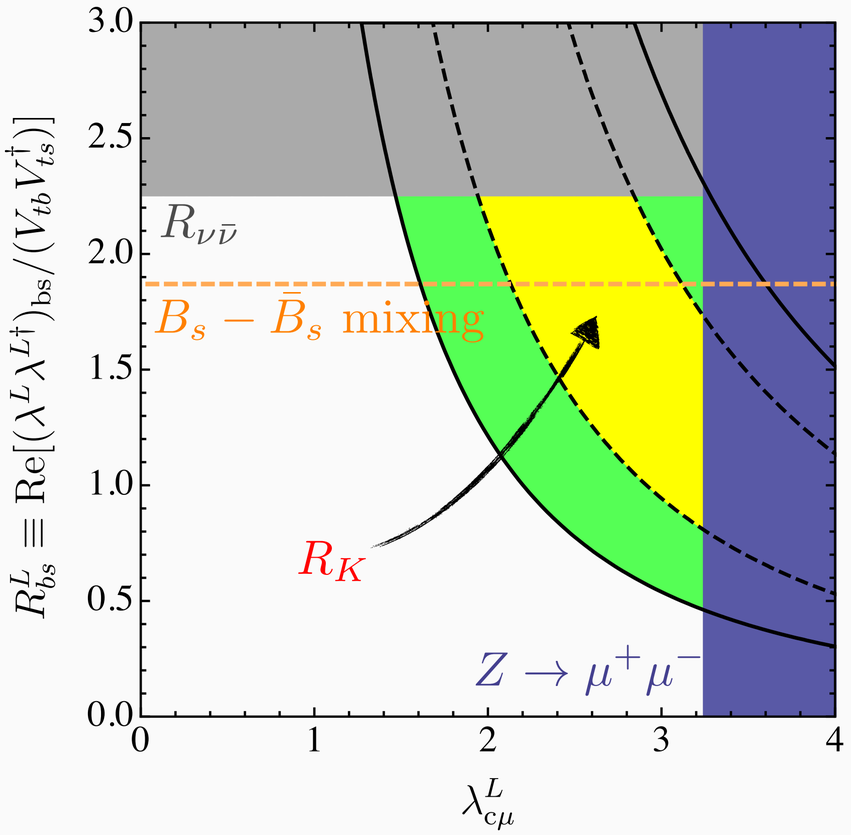
Allowed parameter space for $M_\phi = 1$ TeV:

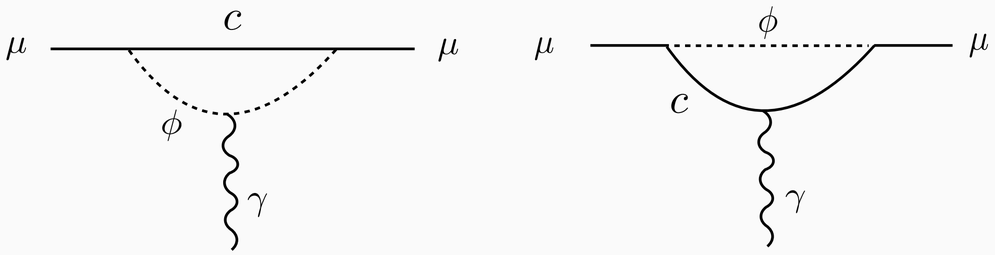


Other observables

With a modest right-handed coupling

$$|\lambda^R_{c\mu}| \sim 0.03$$

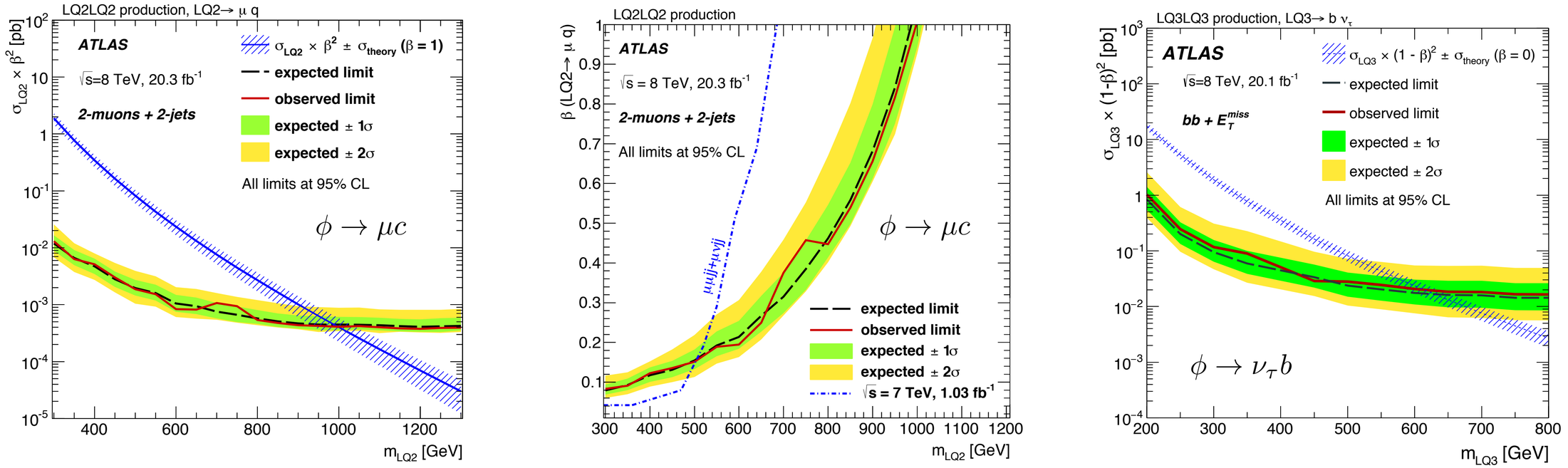
our model can explain the **anomalous magnetic moment** of the muon!



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 $\tau \to \mu\gamma$
- ...

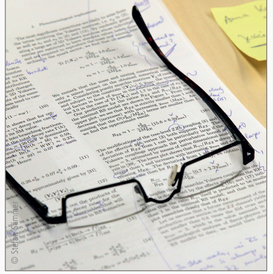
Collider bounds



Outlook

One the verge of another discovery?

- The discovery of the Higgs boson has opened a new era in exploration of fundamental structures of Nature
- While precision Higgs measurements make a compelling mid-term physics case, the future of our field will likely depend on a discovery of some truly “new” physics
- The flavor anomalies give us hope that such a discovery may be within reach of present experiments



Mainz Institute for Theoretical Physics

ACTIVITIES 2017

SCIENTIFIC PROGRAMS JGU CAMPUS MAINZ

Amplitudes: Practical and Theoretical Developments
Fabrizio Caola **CERN**, Herbert Gangl **Univ. Durham**, Jaroslav Trnka **UC Davis**, Johannes Henn, Stefan Müller-Stach, Stefan Weinzierl **JGU**
February 6-17, 2017

Quantum Vacuum and Gravitation: Testing General Relativity in Cosmology
Manuel Asorey **Univ. Zaragoza**, Emil Mottola **LANL**, Ilya L. Shapiro **Fed. Univ. Juiz de Fora**, Andreas Wipf **Univ. Jena**
March 13-24, 2017

Low-Energy Probes of New Physics
Peter Fierlinger, Martin Jung **TU Munich**, Susan Gardner **Univ. Kentucky**
May 2-24, 2017

The TeV Scale: A Threshold to New Physics?
Csaba Csaki **Cornell**, Christophe Grojean **DESY**, Andreas Weiler **TU Munich**, Pedro Schwaller **JGU**
June 12-July 7, 2017

Diagrammatic Monte Carlo Methods for QFTs in Particle-, Nuclear-, and Condensed Matter Physics
Christof Gattringer **Univ. Graz**, Dean Lee **North Carolina State Univ.**, Shailesh Chandrasekharan **Duke Univ.**
September 18-29, 2017

TOPICAL WORKSHOPS JGU CAMPUS MAINZ

Quantum Methods for Lattice Gauge Theories Calculations
Ignacio Cirac **MPI for Quantum Optics**, Simone Montangero **Univ. Ulm**, Peter Zoller **Univ. Innsbruck**
February 6-10, 2017, Schloss Waldthausen

Women at the Intersection of Mathematics and High Energy Physics
Sylvie Paycha **Univ. Potsdam**, Kasia Rejzner **Univ. York**, Katrin Wendland **Univ. Freiburg**, Gabriele Honecker **JGU**
March 6-10, 2017

Geometry, Gravity and Supersymmetry
Vicente Cortés **Univ. Hamburg**, José Figueroa-O'Farrill **Univ. Edinburgh**, George Papadopoulos **King's College London**
April 24-28, 2017

Foundational and Structural Aspects of Gauge Theories
Claudio Dappiaggi **Univ. Pavia**, Marco Benini **Univ. Potsdam**, Klaus Fredenhagen **Univ. Hamburg**
May 29-June 6, 2017

Supernova Neutrino Observations: What can we learn and do?
Hans-Thomas Janka **MPI for Astrophysics**, Georg Raffelt **MPI for Physics**, Lutz Köpke, Michael Wurm **JGU**
October 9-13, 2017

MITP SUMMER SCHOOL

Joachim Kopp, Felix Yu, Anna Kaminska, Maikel De Vries, Matthias Neubert **JGU**
August 2017, Erbacher Hof Mainz

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Mainz Institute for Theoretical Physics
PRISMA Cluster of Excellence
Johannes Gutenberg-Universität Mainz, Germany

Thank you!

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

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