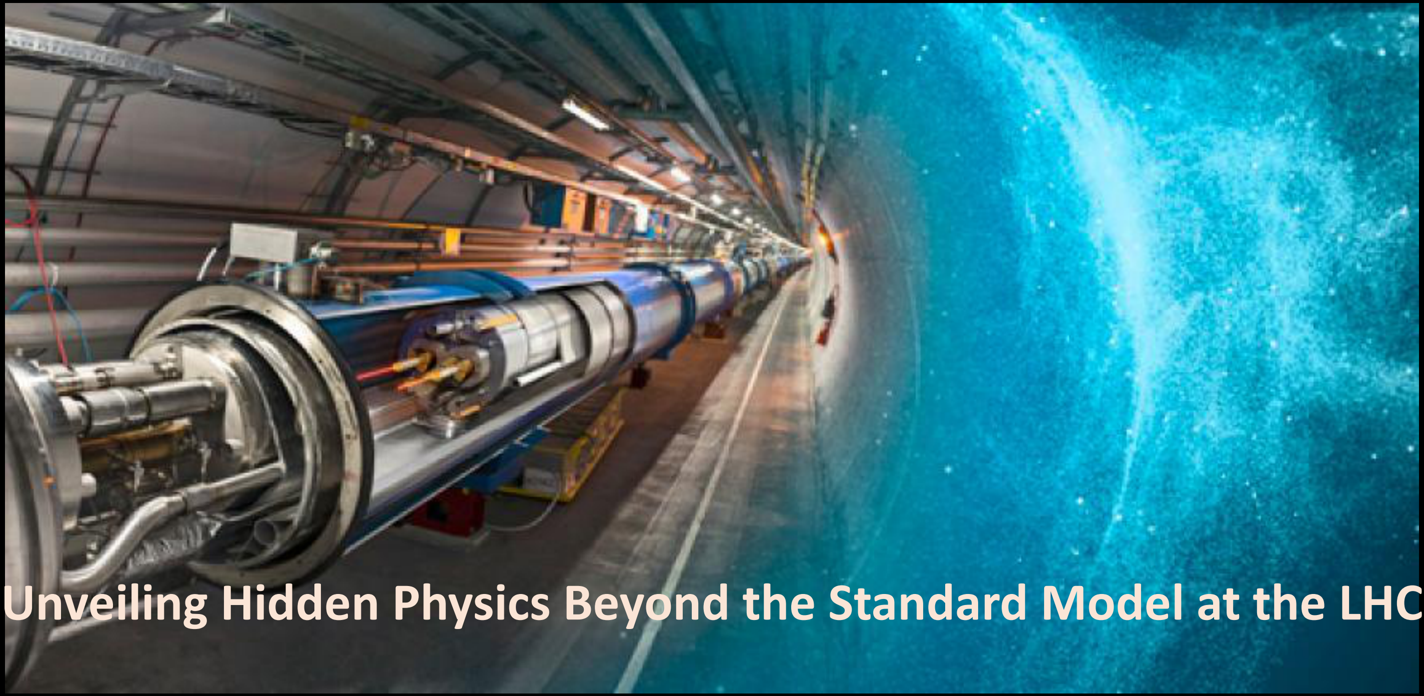
Overview of Anomalies

Bhupal Dev
Washington University in St. Louis



March 1, 2021

McDONNELL CENTER
FOR THE SPACE SCIENCES

The Era of Anomalies

- A growing list of "anomalies" — experimental results that conflict with the Standard Model but fail to overturn it for lack of sufficient evidence.
- Could be due to statistical fluctuations, systematic uncertainties, theoretical issues, or experimental error.
- Or breadcrumps to follow on the path toward new physics?
- A good driver of scientific creativity.

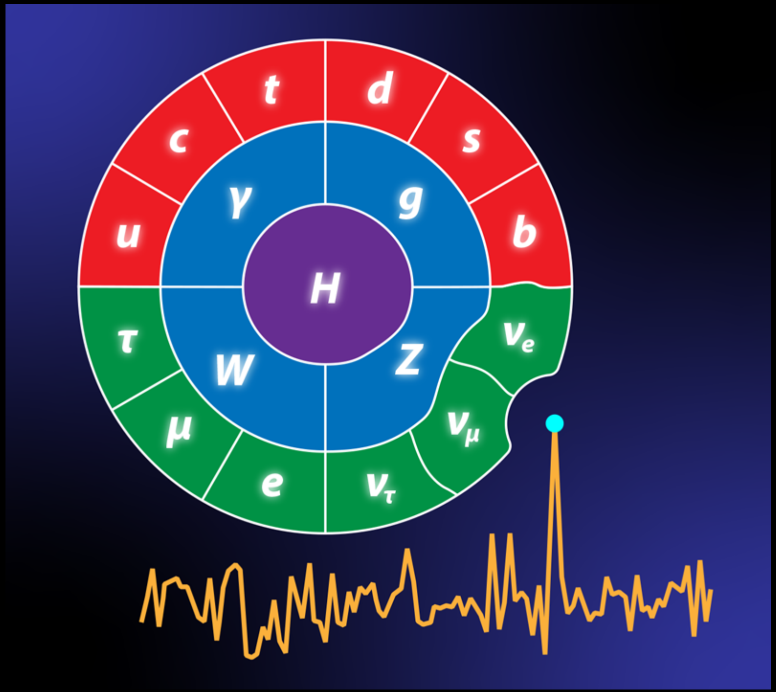


Figure credit: APS/Alan Stonebraker

Anomalies Workshop

You are welcome to attend Anomalies 2021 at IIT, Hyderabad (in July/August, most probably online)

Our goal is establish it as a mainstream annual workshop series. Need community support.

Ambulance-chasing: Is it really worth it?

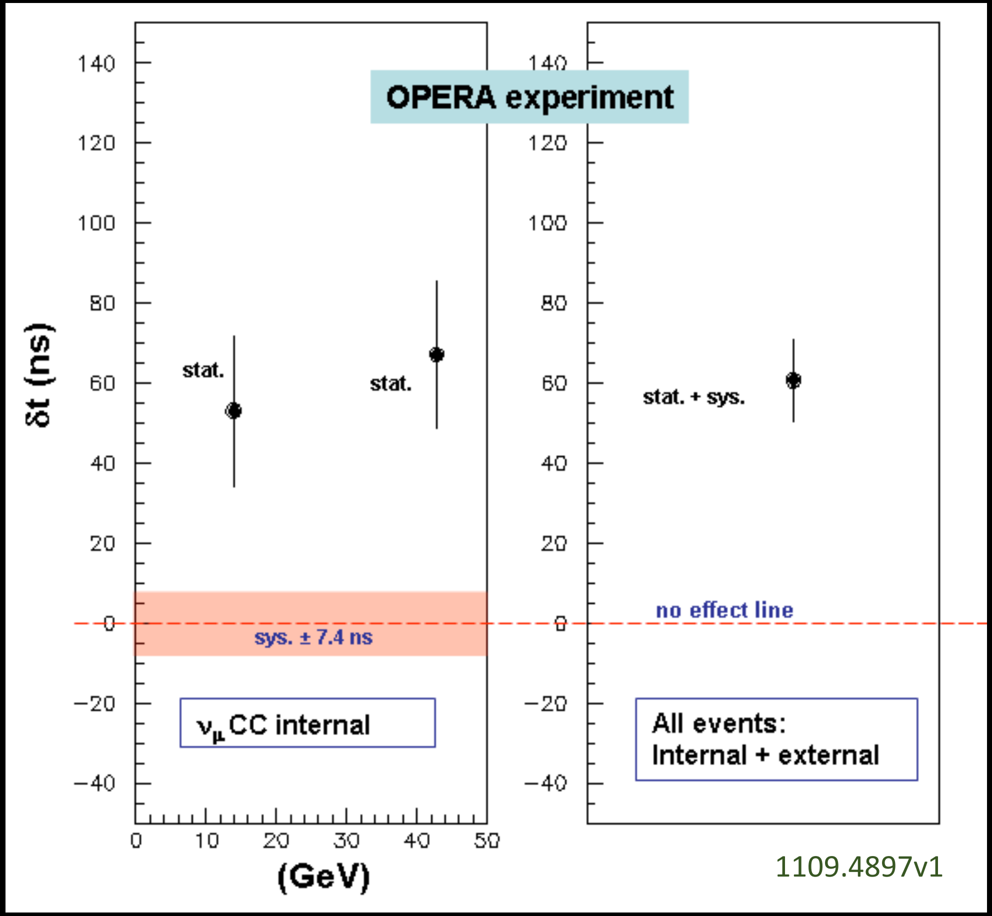
- Anomalies are mostly regarded with skepticism.
- Lack the grandeur of trying to solve big problems.
- Just about every anomaly in the past decades has disappeared over time.

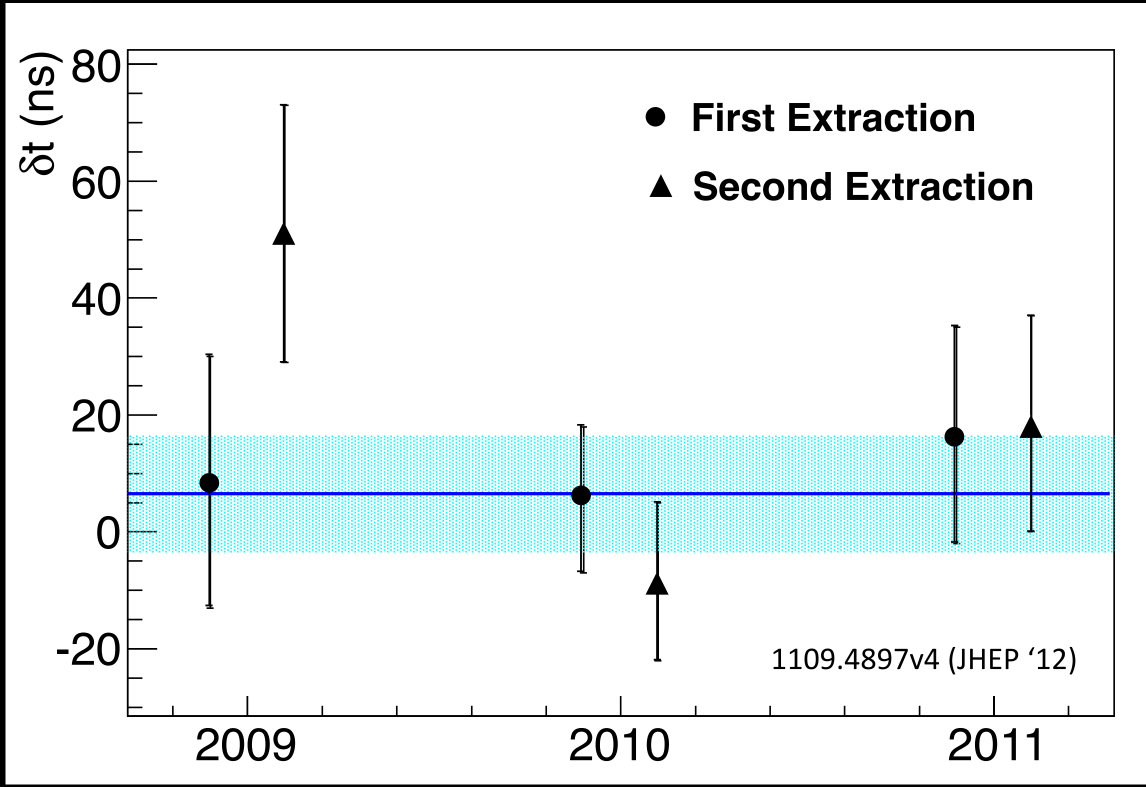
- But perhaps some anomaly might eventually turn out to be textbook material for future decades?
- Worthwhile hunting down blips in the data.
- Offer fresh challenges to experimentalists.
- A promising sandbox for theorists.
- Inspire new analysis methods and tools.

"It is better to work on a 2.6 σ signal than a 0 σ one."
— Ben Allanach (Cambridge)

Open-access data and more theory-experiment collaborations could play a crucial role.

Lessons from the Past: OPERA





$$(v - c)/c = (2.7 \pm 3.1\ (stat.)^{+3.4}_{-3.3}(sys.)) \times 10^{-6}.$$

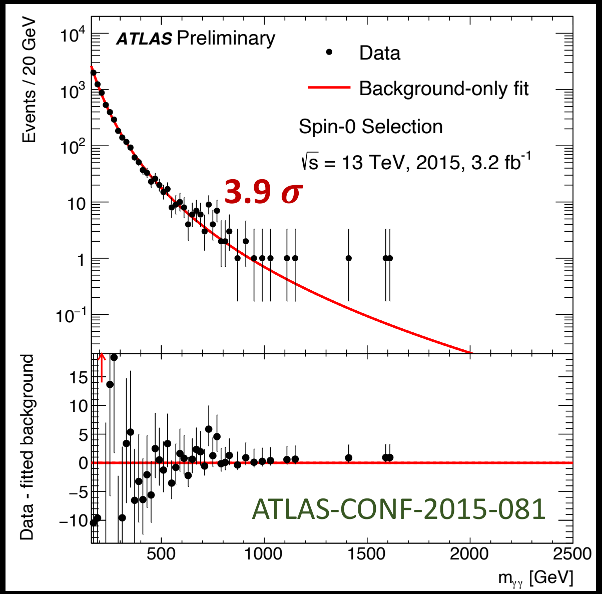
The corresponding relative difference of the muon neutrino velocity and the speed of light is:

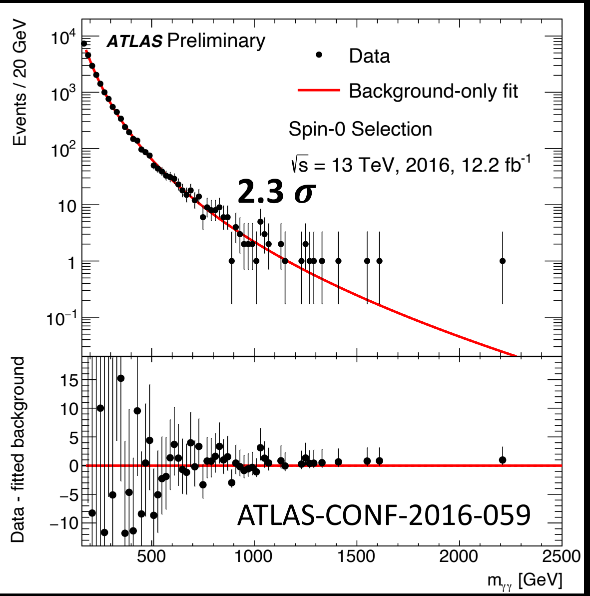
$$(v\text{-}c)/c = \delta t\,/(\mathrm{TOF'}_c - \delta t) = (2.48 \pm 0.28\ (\mathrm{stat.}) \pm 0.30\ (\mathrm{sys.})) \times 10^{-5}.$$

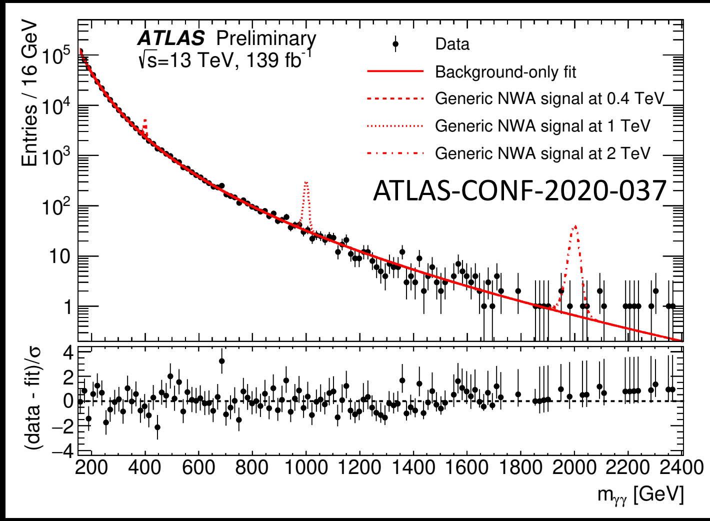
with an overall significance of 6.0 σ.

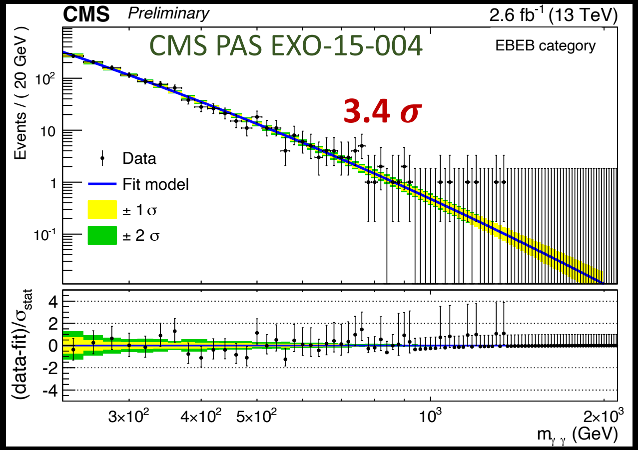
O(100) theory papers on "superluminal neutrinos."

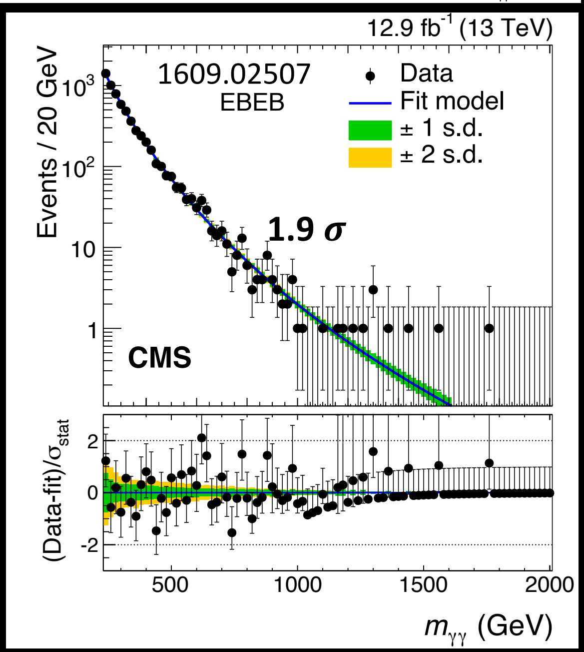
Lessons from the Past: 750 GeV Diphoton Excess

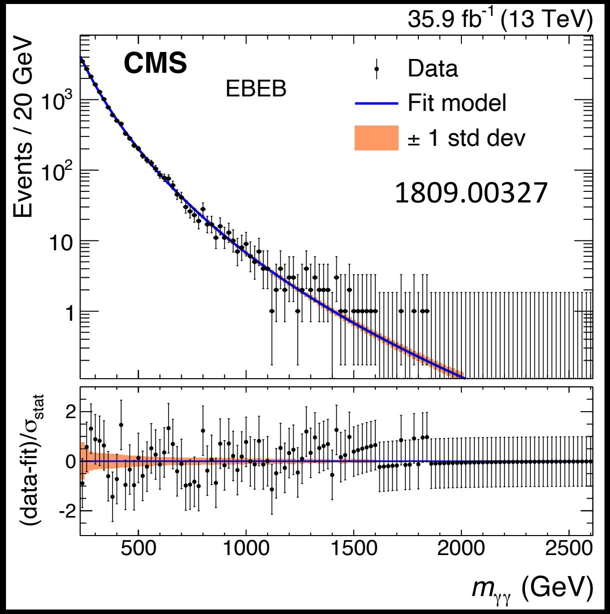






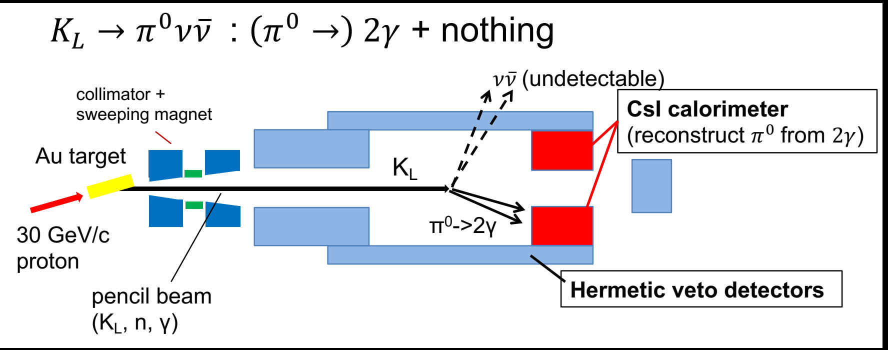


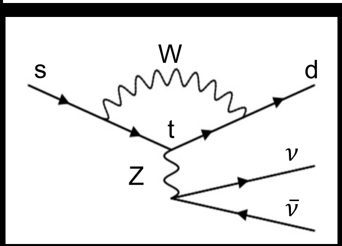




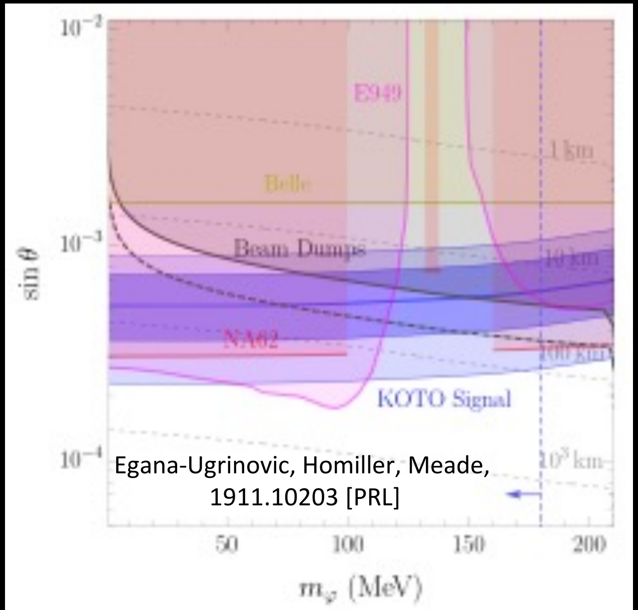
O(500) theory papers on “diphoton excess”

Lessons from the Past: KOTO Anomaly

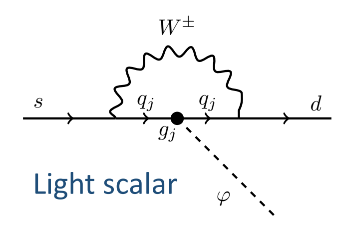


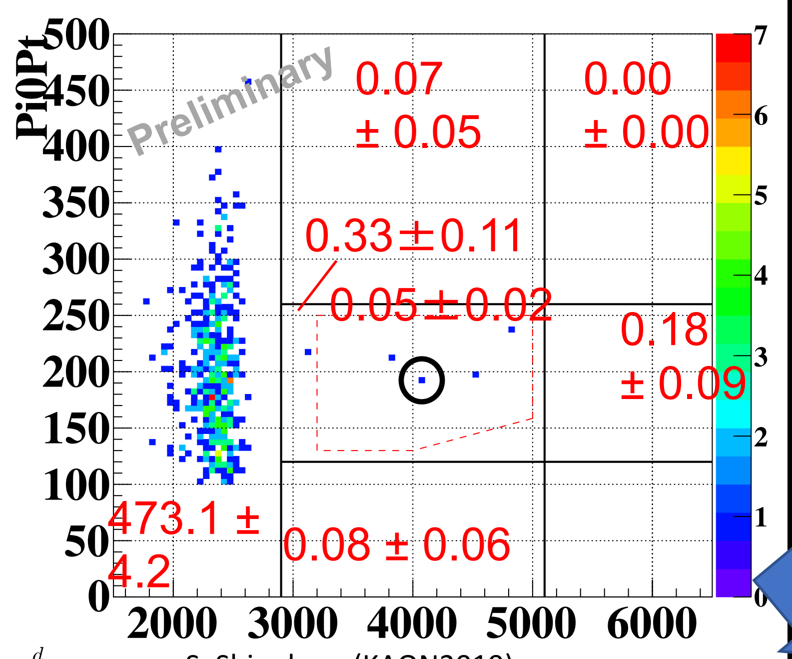


- FCNC : highly suppressed decay
  - BR (SM) : 3×10^{-11}
- Small theoretical uncertainty (~2%)
  - → Good probe for new physics search



Egana-Ugrinovic, Homiller, Meade, 1911.10203 [PRL]





S. Shinohara (KAON2019)

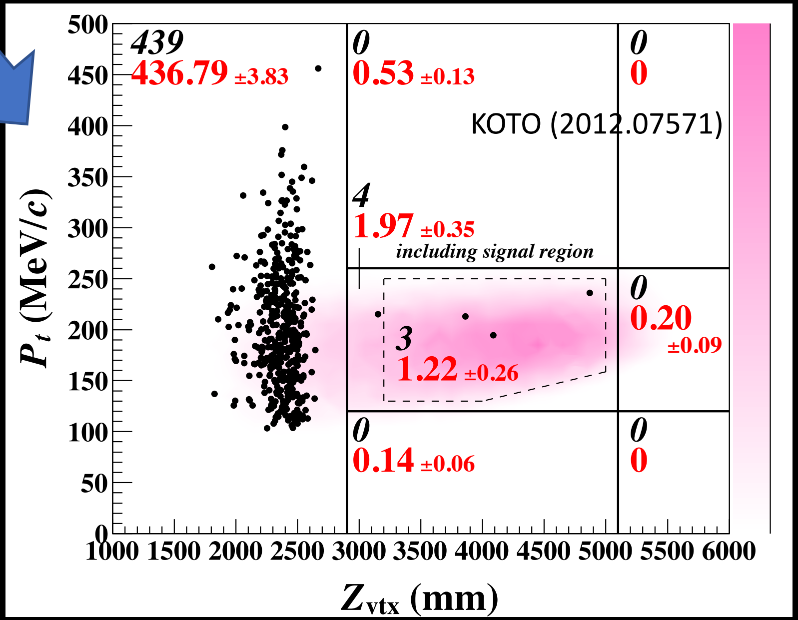
Consistency with GN bound?

$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) \leq 4.3\, \mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$$

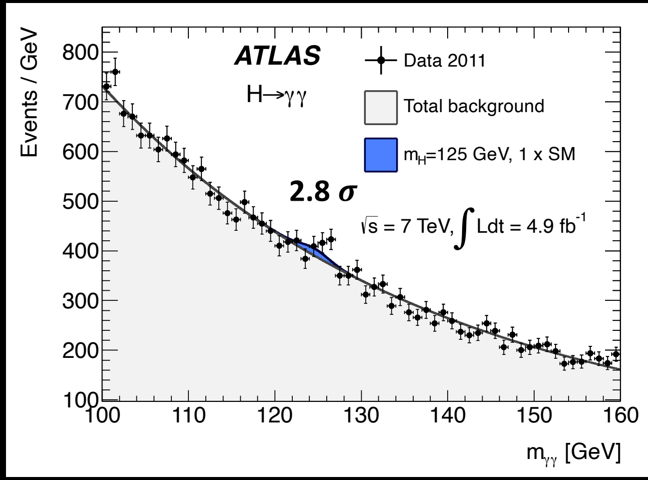
Grossman, Nir, hep-ph/9701313 [PLB]

See also
Kitahara, Okui, Perez, Soreq, Tobioka, 1909.11111 [PRL]
BD, Mohapatra, Zhang, 1911.12334 [PRD]
Liu, McGinnis, Wagner, Wang, 2001.06522 [JHEP]
Cline, Puel, Toma, 2001.11505 [JHEP]
He, Ma, Tandean, Valencia, 2002.05467 [JHEP]
Liao, Wang, Yao, Zhang, 2005.00753 [PRD]
Gori, Perez, Tobioka, 2005.05170 [JHEP]

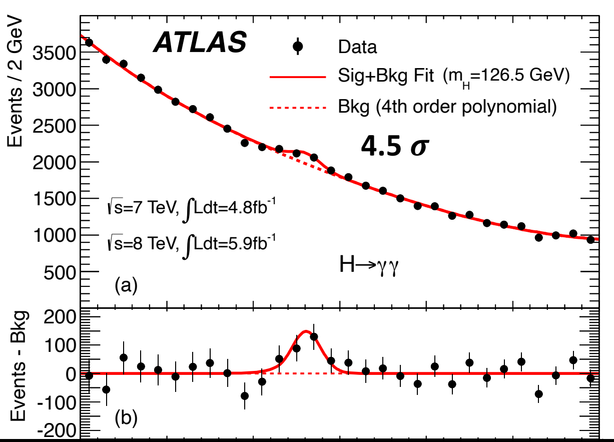
Conclusions and prospects With the 2016–2018 dataset, we obtained an SES of $(7.20 \pm 0.05_{\mathrm{stat}} \pm 0.66_{\mathrm{syst}}) \times 10^{-10}$ and observed three events in the signal region. We estimated the total number of background events to be 1.22 ± 0.26 with the two new background sources. The corresponding probability of observing three events is 13%. We conclude that the number of observed events is statistically consistent with the background expectation estimated after finding two new sources. Assuming Poisson statistics and considering uncertainties [32], we set an upper limit on the branching fraction of the $K_L \to \pi^0 \nu\bar{\nu}$ decay in this dataset to be 4.9×10^{-9} at the 90% C.L.



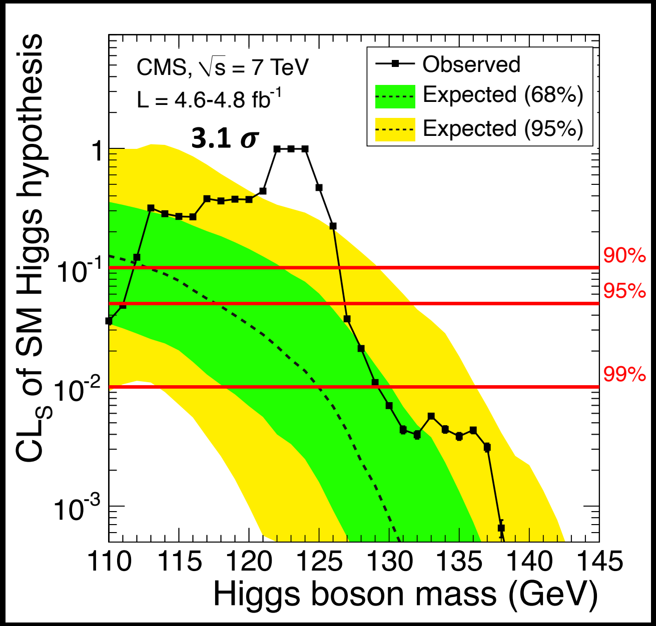
A Success Story



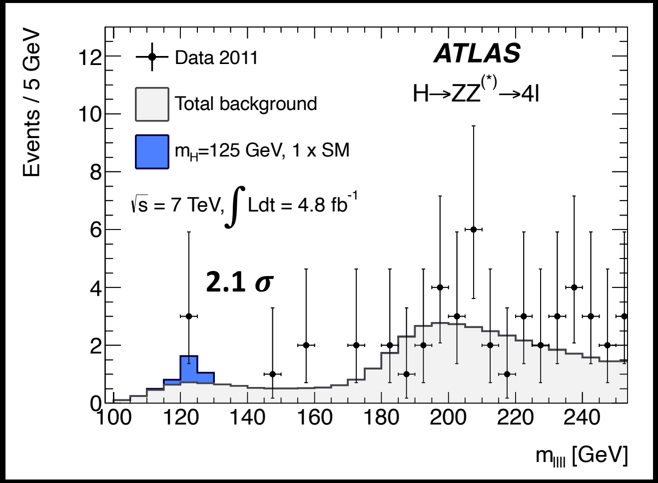
1207.0319 [PRD]



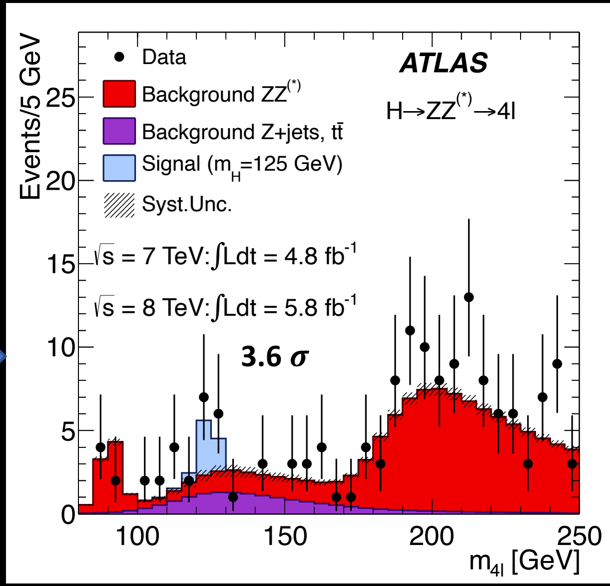
1207.7214 [PLB]



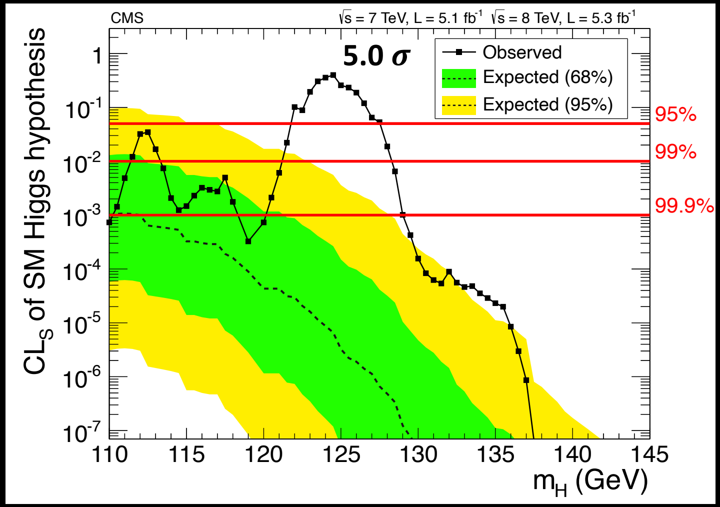
1202.1488 [PLB]



1207.0319 [PRD]

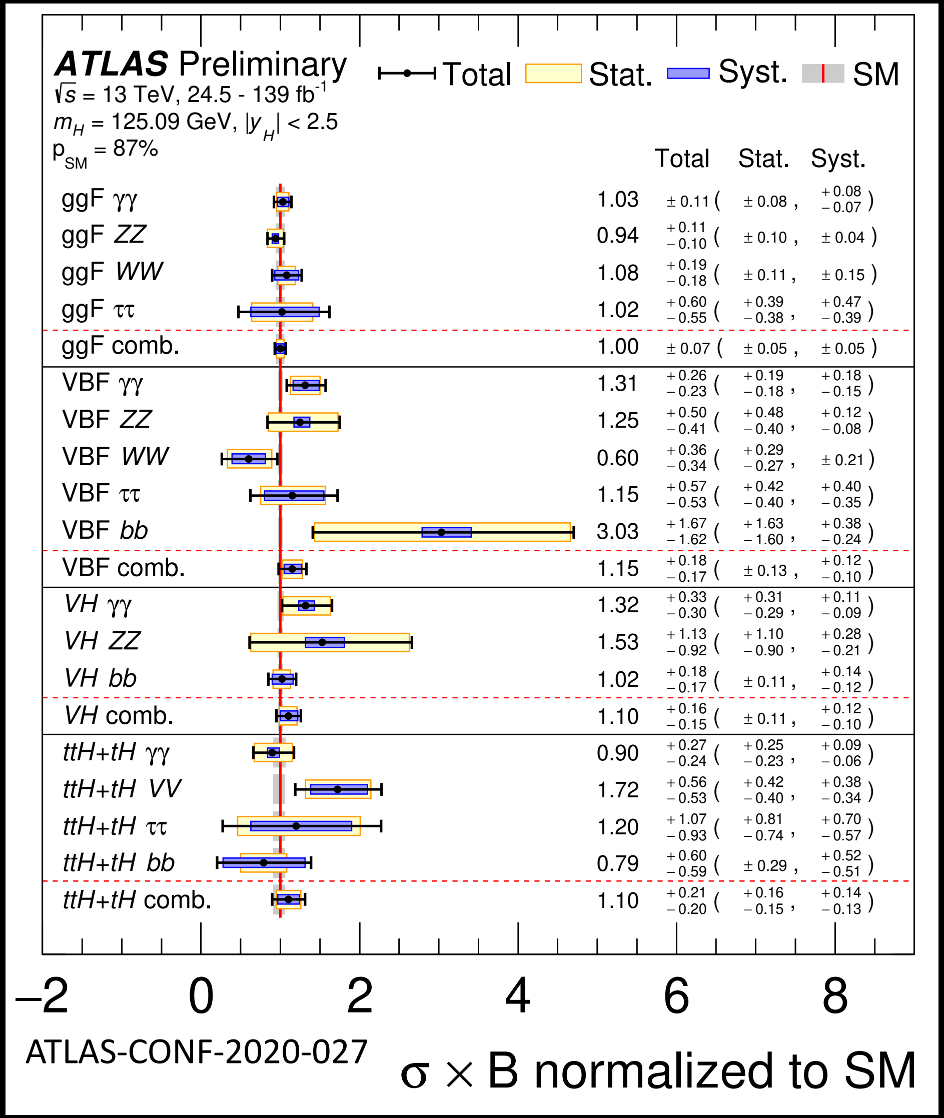


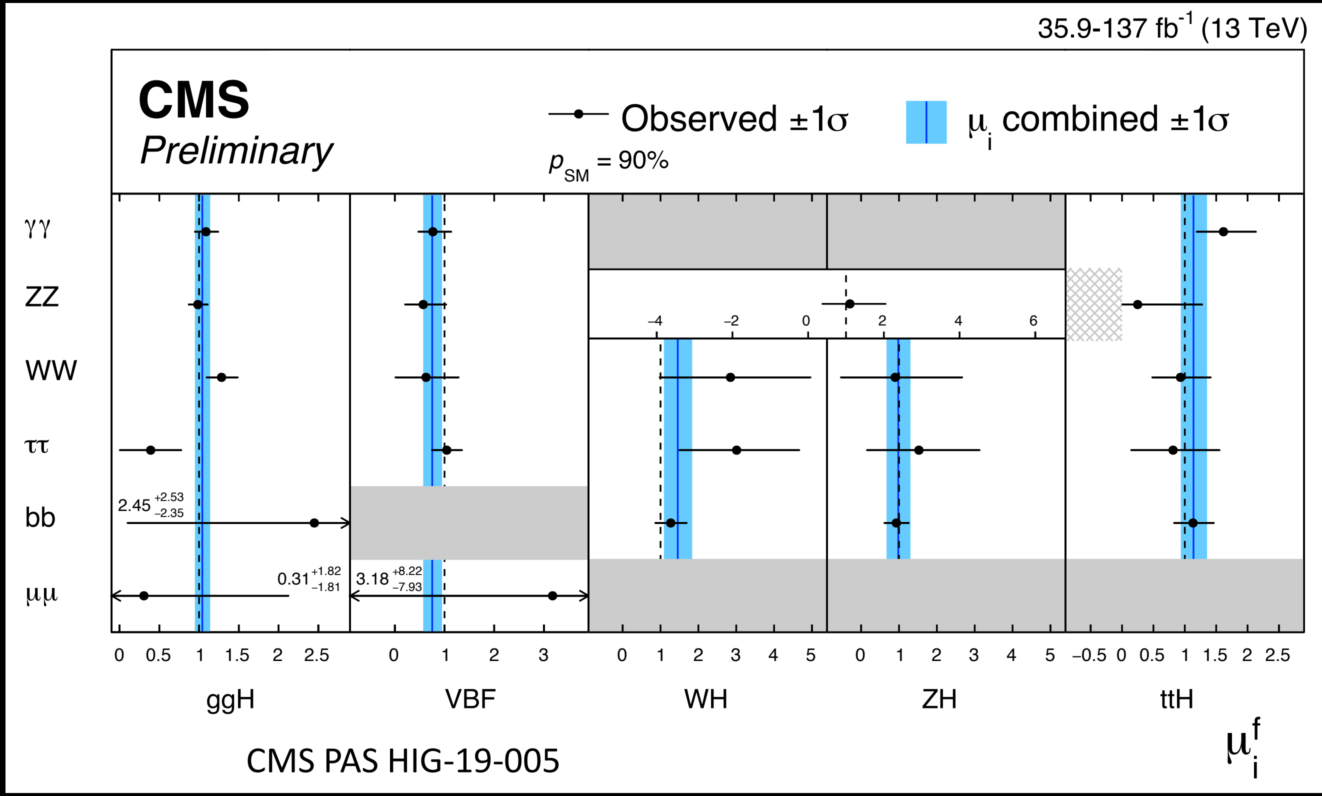
1207.7214 [PLB]



1207.7235 [PLB]

Understanding the Higgs Signal





Everything seems consistent with SM expectations.

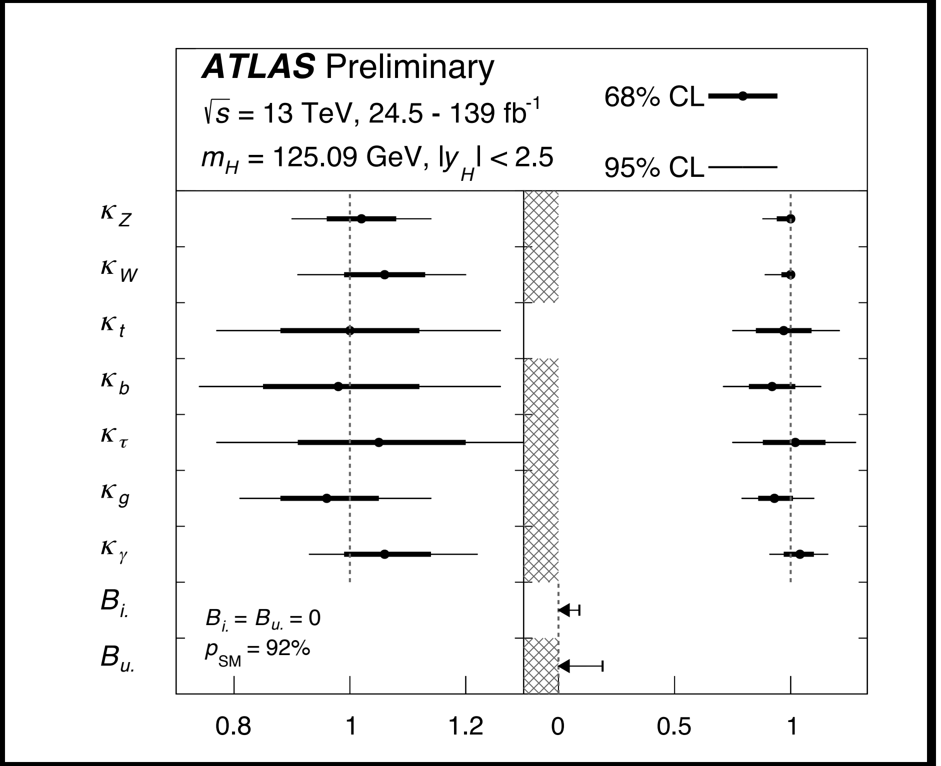
Interpretation beyond Signal Strength

- The κ-framework (1307.1347):
- Effective way to study modifications of Higgs couplings related to BSM physics.
- Devise similar techniques for studying other anomalies?
- Constrain a broad class of BSM scenarios, rather than fitting a single model.

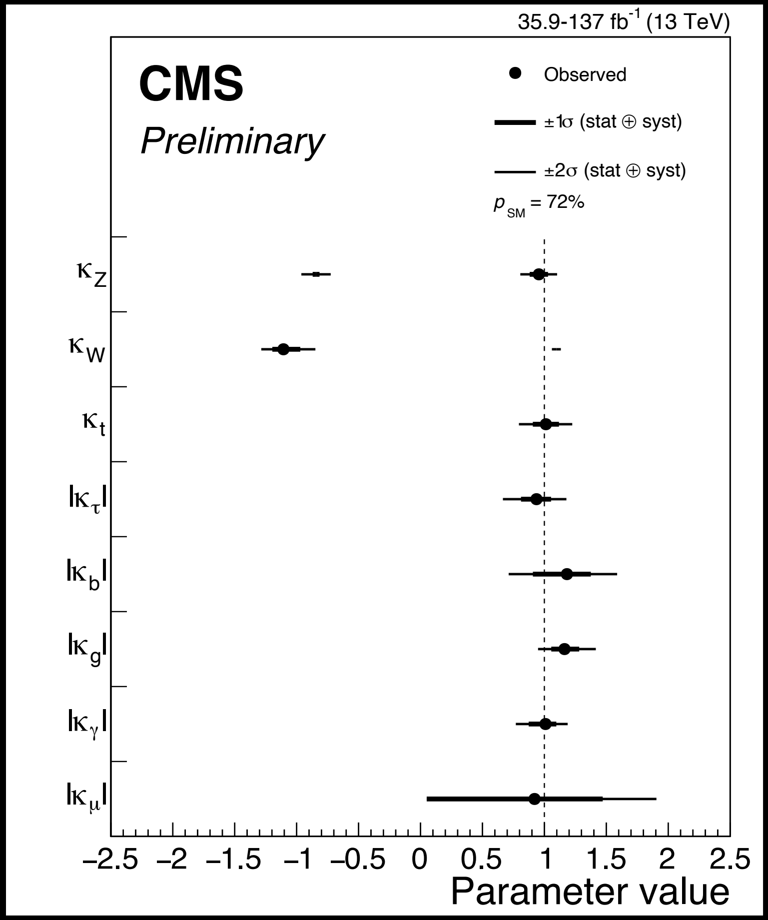
$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}.$$

$$\kappa_H^2(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \frac{\sum_j B_j^{\mathrm{SM}} \kappa_j^2}{(1 - B_{\mathrm{i.}} - B_{\mathrm{u.}})}.$$



ATLAS-CONF-2020-027



CMS PAS HIG-19-005

(Partial) List of Existing Anomalies

Anomaly	Significance	Reference
Multileptons@LHC	2-5 σ	1901.05300
LFUV in B-decays	2-5 σ	1909.12524
Muon g-2	3.7 σ	2006.04822
Cabibbo angle	~3 σ	PDG
LFUV in tau decay	~2 σ	PDG
LSND/MiniBooNE	6.1 σ	2006.16883
NOvA vs T2K	~2 σ	Neutrino 2020
IceCube HESE vs TG	~2 σ	2011.03545
ANITA upgoing events	~2 σ	2010.02869
Neutron lifetime	4.4 σ	PDG
^{8}Be transition	7.2 σ	1910.10459

Anomaly	Significance	Reference
DAMA/LIBRA	12.9 σ	1907.06405
Fermi-LAT GC excess	2-3 σ	1704.03910
AMS $e^{+}/\bar{p}$ excess	3-5 σ	Phys.Rep.894, 1
XENON1T e^{-}-recoil	2-3 σ	2006.09721
3.5 keV X-ray line	4 σ	2008.02283
511 keV gamma-ray line	58 σ	1512.00325
EDGES 21cm spectrum	3.8 σ	1810.05912
Primordial ^{7}Li problem	4-5 σ	1203.3551
Hubble tension	4.4 σ	2008.11284
NANOGRAV	>> 5 σ	2009.04496
Fast Radio Bursts	>> 5 σ	1906.05878

Should create and maintain an online repository for up-to-date information on anomalies.

Outline

- LHC multilepton anomalies
- *B*-anomalies:
  - High-p_T LHC tests
  - A SUSY explanation
- Muon g-2:
  - Tests at LHC and future colliders
  - Leptophilic scalar
- LSND and MiniBooNE excess:
  - eV-scale sterile
  - Non-oscillatory new physics

(More details on LFUV anomalies → A. Crivellin's talk)

LHC Multilepton Anomalies

- Discrepancies in multi-lepton final states w.r.t. current MCs.
- Appear in corners of phase space dominated by different processes: Wt/tt, VV, ttV.
- Hard to explain with MC mismodelling of a particular process, e.g. $t\bar{t}$ production alone.

Data set	Reference	Selection
ATLAS Run 1	ATLAS-EXOT-2013-16 [41]	SS $\ell\ell$ and $\ell\ell\ell$ + b-jets
ATLAS Run 1	ATLAS-TOPQ-2015-02 [26]	OS $e\mu$ + b-jets
CMS Run 2	CMS-PAS-HIG-17-005 [42]	SS $e\mu$, $\mu\mu$ and $\ell\ell\ell$ + b-jets
CMS Run 2	CMS-TOP-17-018 [43]	OS $e\mu$
CMS Run 2	CMS-PAS-SMP-18-002 [44]	$\ell\ell\ell + E_T^{miss}$ (WZ)
ATLAS Run 2	ATLAS-EXOT-2016-16 [45]	SS $\ell\ell$ and $\ell\ell\ell$ + b-jets
ATLAS Run 2	ATLAS-CONF-2018-027 [46]	OS $e\mu$ + b-jets
ATLAS Run 2	ATLAS-CONF-2018-034 [47]	$\ell\ell\ell + E_T^{miss}$ (WZ)

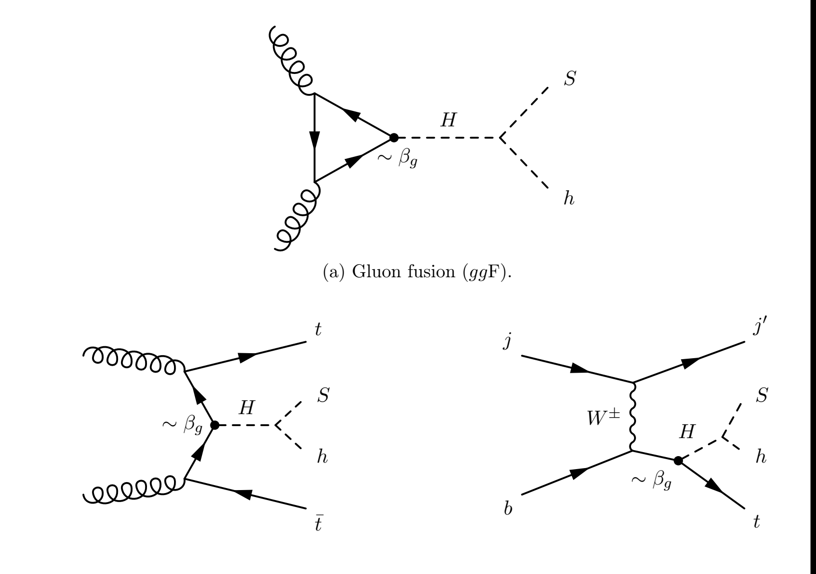
Final state	Characteristics	Dominant SM process
l^+l^- + jets, b-jets	m_{ll}<100 GeV, dominated by 0b-jet and 1b-jet	tt+Wt
l^+l^- + full-jet veto	m_{ll}<100 GeV	WW
$l^\pm l^\pm$ + b-jets	Excess with $N_\pm$>2, moderate H_T	ttV
$l^\pm l^\pm l$ + b-jets	Moderate H_T	ttV
$Z(\rightarrow l^+l^-)+l$	p_{TZ}<100 GeV	ZW

Buddenbrock, Cornell, Fang, Mohammed, Kumar, Mellado, Tomiwa, 1901.05300 [JHEP]

A Simple BSM Interpretation

Buddenbrock et al (1606.10674 [EPJC], 1711.07874 [JPG], 1901.05300 [JHEP])

- Can be interpreted with a simplified model where H→Sh, with h SM Higgs-like.
- Strengthens the need for precision Higgs measurements.
- E.g., distortion of Higgs p_T and rapidity.



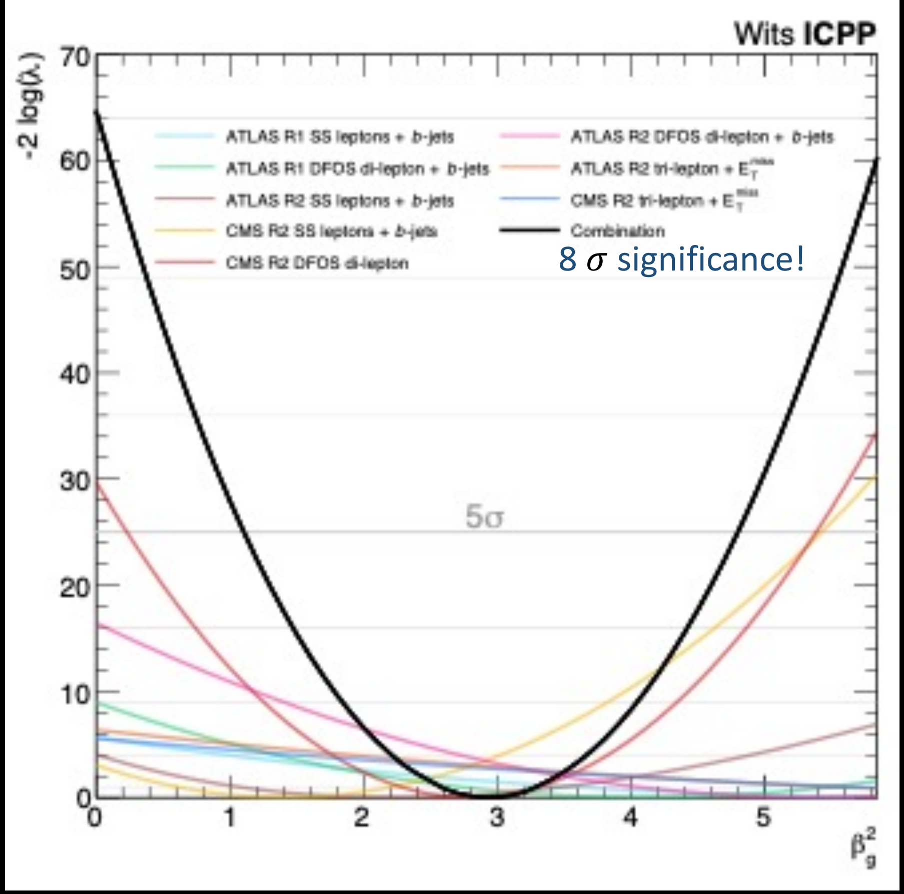
(a) Gluon fusion (ggF).

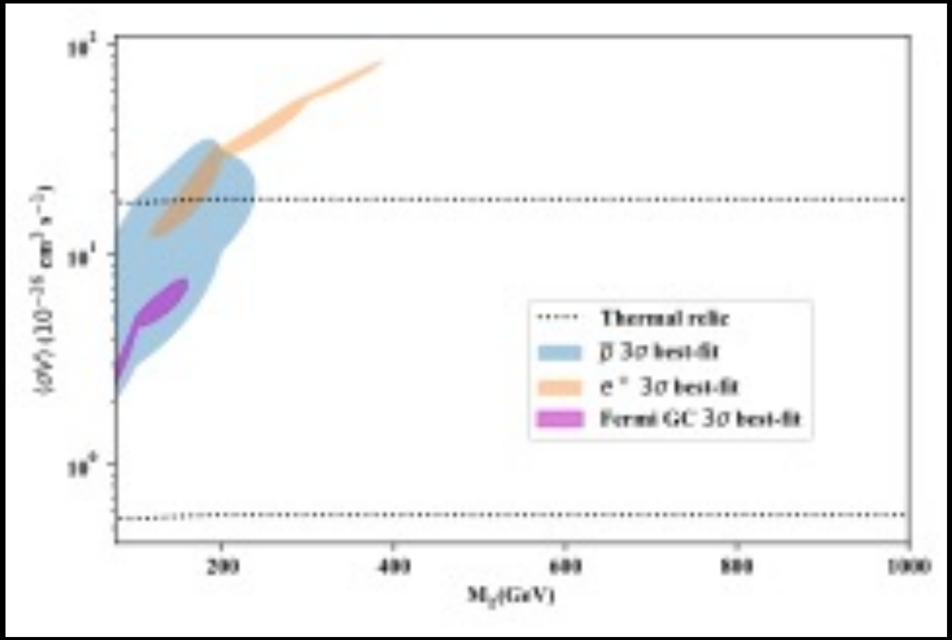
(b) Top pair associated production (ttH).

(c) Single top associated production (tH).

$$\mathcal{L}_{\rm int} \supset -\beta_g \frac{m_t}{v} t\bar{t}H + \beta_V \frac{m_V^2}{v} g_{\mu\nu} V^{\mu}V^{\nu}H.$$

$$\mathcal{L}_{HhS} = -\frac{1}{2} v \Big[\lambda_{hhS} hhS + \lambda_{hSS} hSS + \lambda_{HHS} HHS + \lambda_{HSS} HSS + \lambda_{HhS} HhS\Big],$$



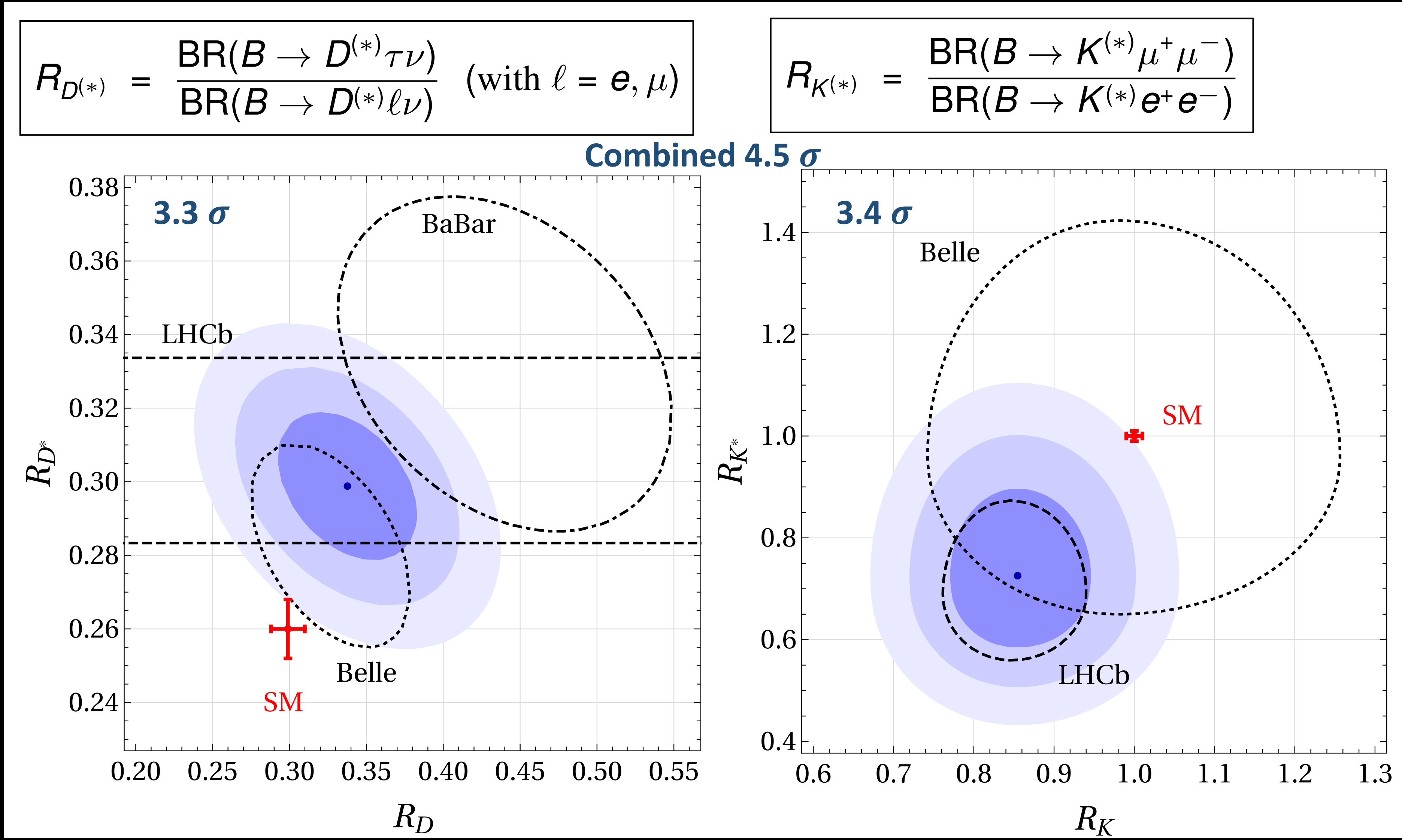


Beck, Temo, Malwa, Kumar, Mellado (2102.10596)

DM coupling to S

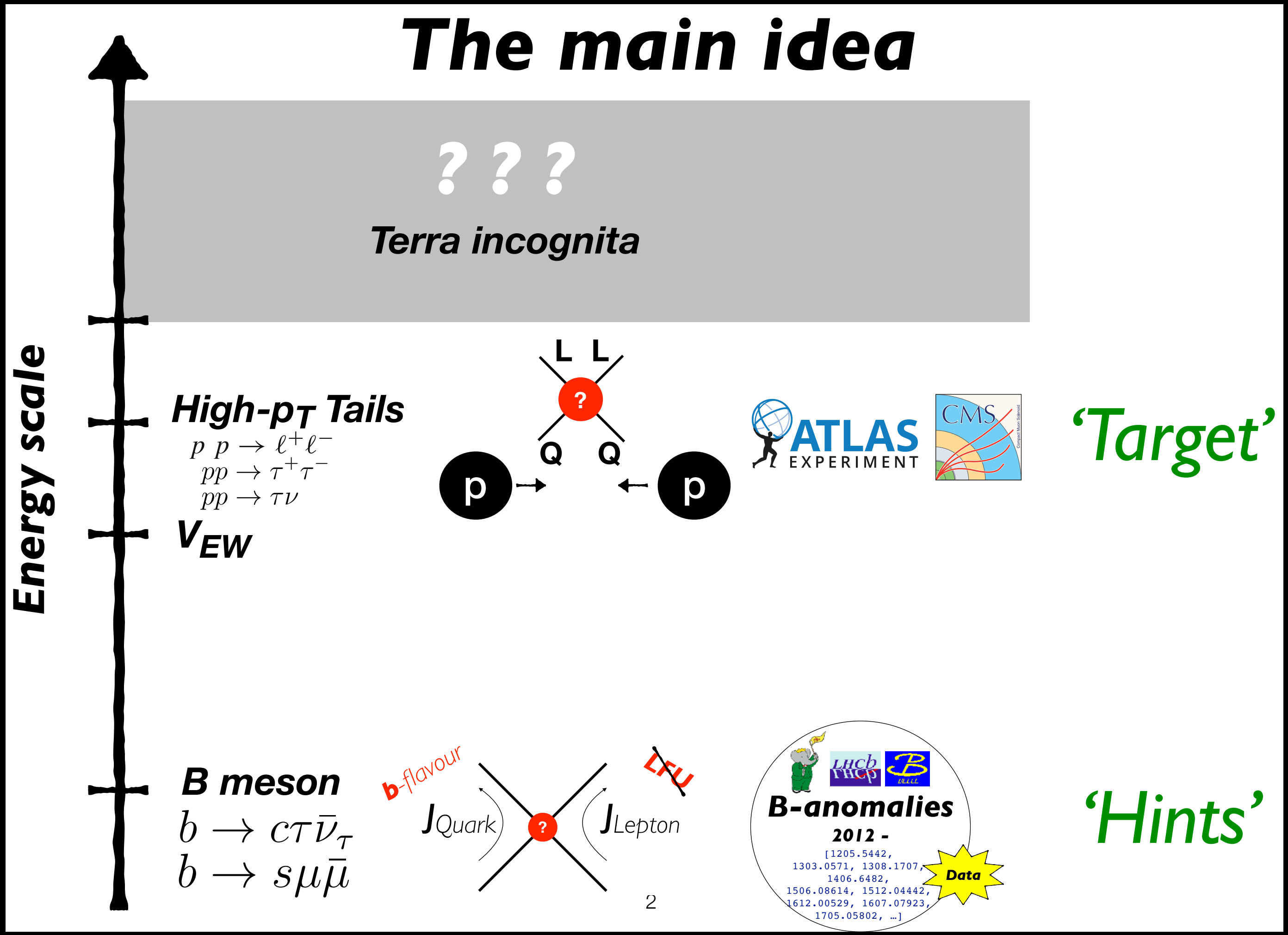
LHC-astro complementarity

B-anomalies

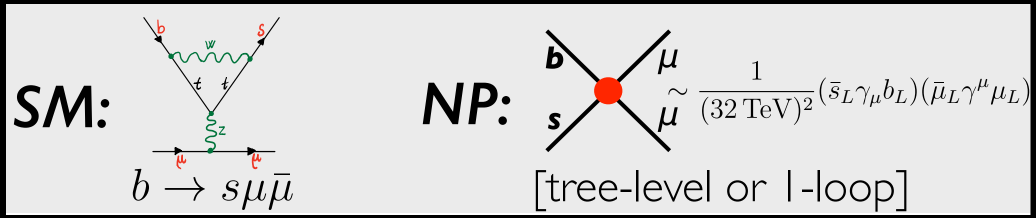


Altmannshofer, BD, Soni, Sui, 2002.12910 [PRD], updated from HFLAV '19

High-p_T LHC Tests

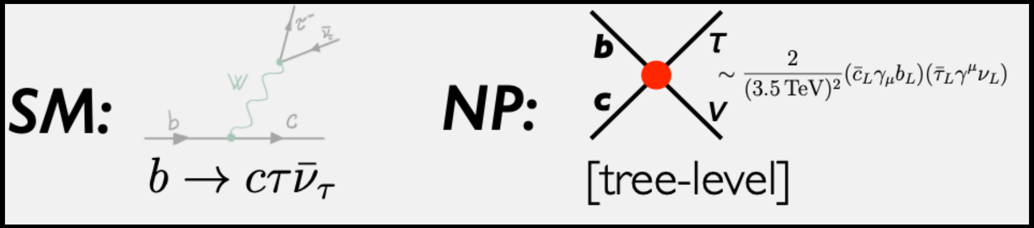


A. Greljo, CERN Implications Workshop 2018



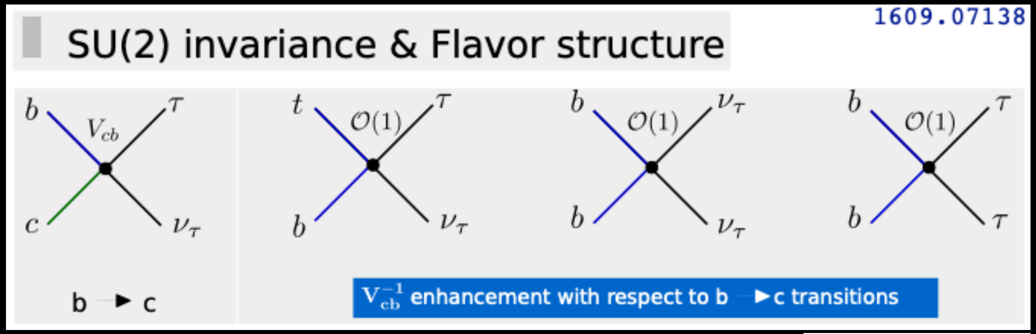
Greljo, Marzocca (1704.09015 [EPJC])

$pp \to \ell^+\ell^-$



$pp \to \tau\nu$ inclusive

Greljo, Camalich, Ruiz-Alvarez (1811.07920 [PRL])



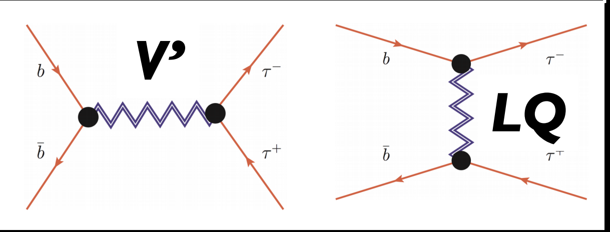
Faroughy, Greljo, Kamenik (1609.07138 [PLB])

Large!

$pp \to \tau^+\tau^-$

EFT validity $\hat{s} \lesssim M_X^2$

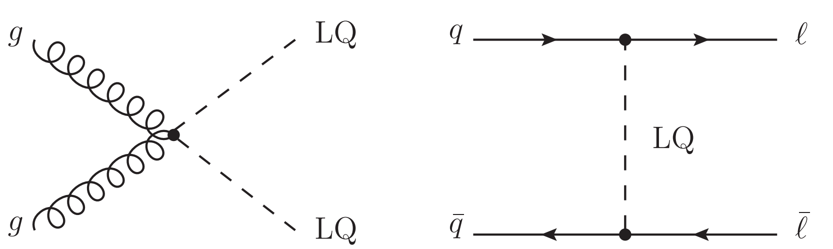
Simplified models

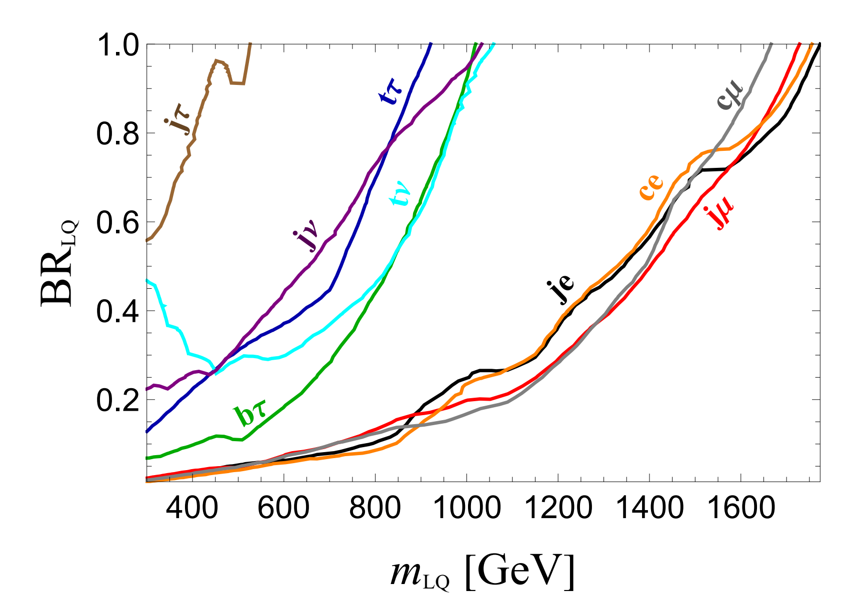


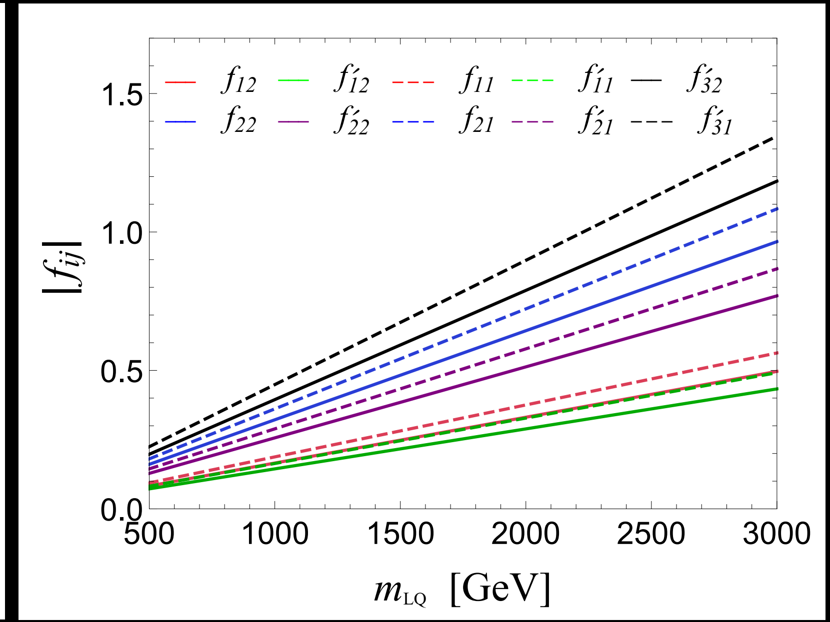
Dilepton Limits on Leptoquarks

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

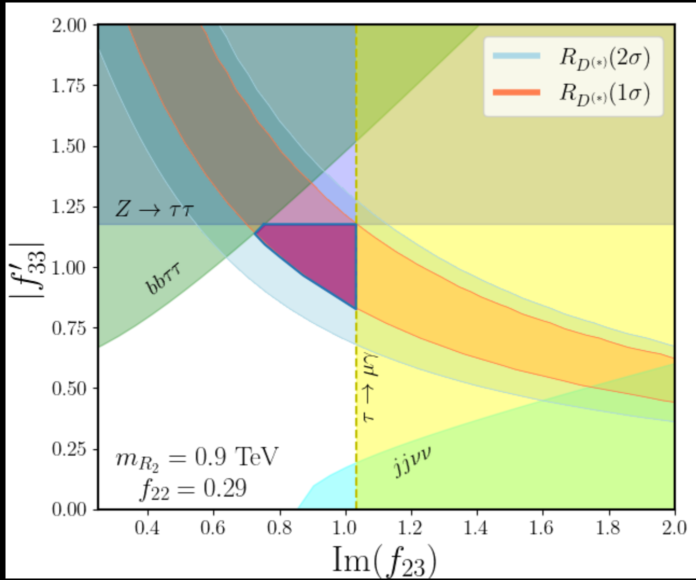
Angelescu, Becirevic, Faroughy, Sumensari, 1808.08179 [







Babu, BD, Jana, Thapa (2009.01771 [JHEP])



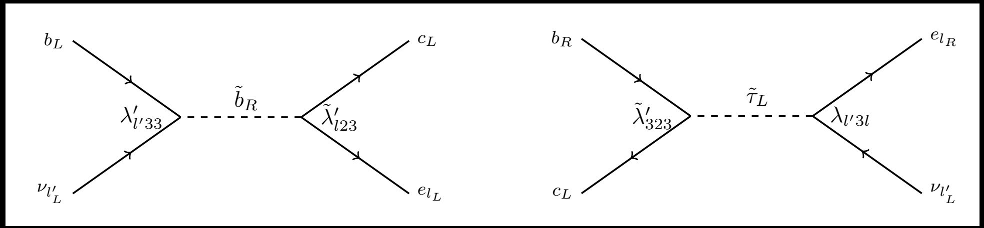
Non-resonant dilepton searches at LHC severely restrict the allowed LQ parameter space for B-anomalies.

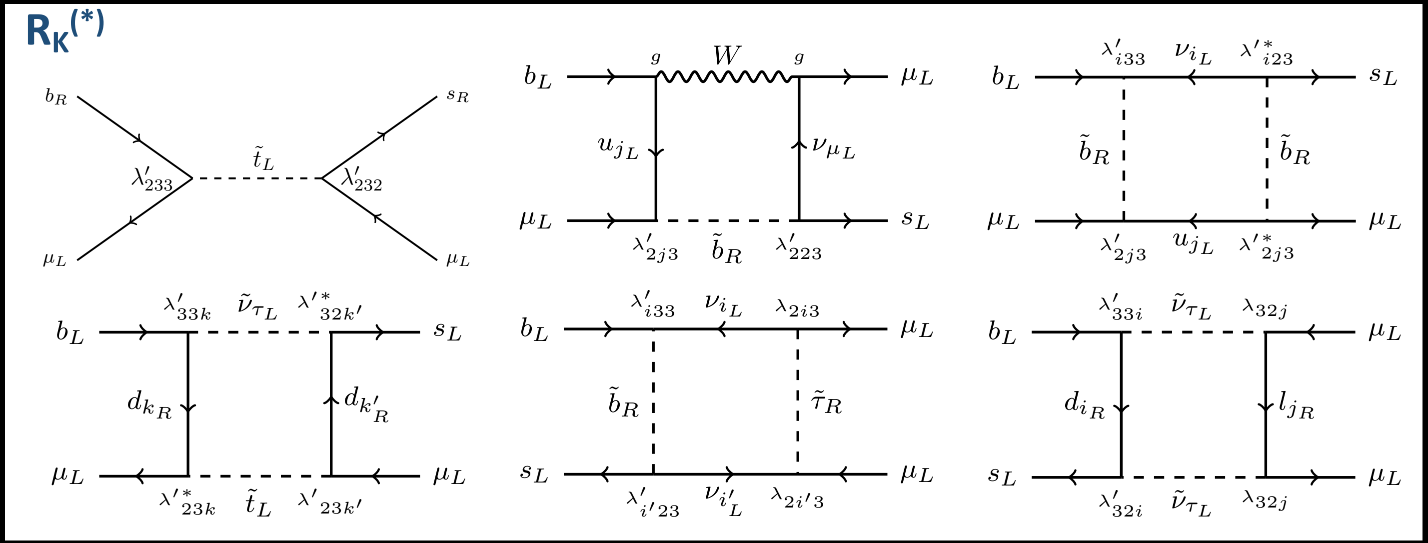
B-anomalies in RPV SUSY

$$\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\widetilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \widetilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \widetilde{d}^{*}_{kR}\bar{\nu}^{c}_{iL}d_{jL} - \widetilde{e}_{iL}\bar{d}_{kR}u_{jL} - \widetilde{u}_{jL}\bar{d}_{kR}e_{iL} - \widetilde{d}^{*}_{kR}\bar{e}^{c}_{iL}u_{jL}\right] + \text{H.c.}$$

$$\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}\left[\widetilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \widetilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \widetilde{e}^{*}_{kR}\bar{\nu}^{c}_{iL}e_{jL} - (i \leftrightarrow j)\right] + \text{H.c.}$$

$R_D^{(*)}$

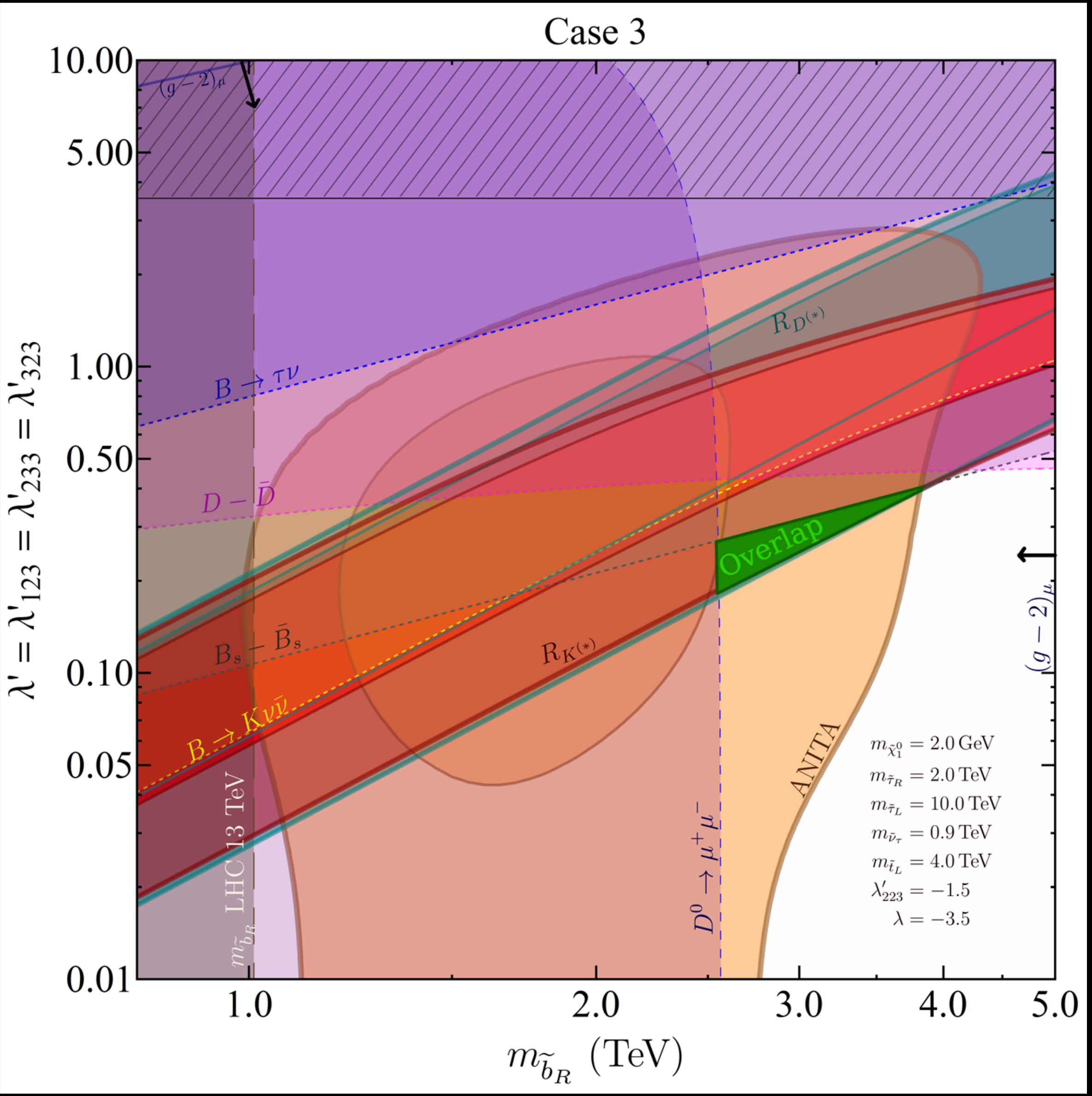




Work within RPV3 framework: RPV SUSY with light 3rd-generation sfermions. (Altmannshofer, BD, Soni, 1704.06659 [PRD])

Motivated by Higgs naturalness arguments. (Brust, Katz, Lawrence, Sundrum, 1110.6670 [JHEP]; Papucci, Ruderman, Weiler, 1110.6926 [JHEP])

B-anomalies (+Muon g-2+ANITA) in RPV3 SUSY



Flavor-violating decay mode	λ,λ' dependence	RPV3 Prediction			Current experimental bound/measurement
		Case 1	Case 2	Case 3	
$\tau \to \mu\phi$	$\lambda'_{332}\lambda'_{232},\ \lambda_{323}\lambda'_{322}$	1.9×10^{-15}	3.8×10^{-10}	2.6×10^{-12}	$< 8.4 \times 10^{-8}$ [201]
$\tau \to \mu KK$	$\lambda'_{332}\lambda'_{232},\ \lambda_{323}\lambda'_{322}$	1.2×10^{-17}	2.4×10^{-12}	2.9×10^{-13}	$< 4.4 \times 10^{-8}$ [202]
$\tau \to \mu K^0_s$	$\lambda'_{332}\lambda'_{231},\ \lambda'_{312}\lambda_{323}$	4.5×10^{-19}	8.7×10^{-12}	3.1×10^{-13}	$< 2.3 \times 10^{-8}$ [203]
$\tau \to \mu\gamma$	$\lambda'_{333}\lambda'_{233},\ \lambda_{133}\lambda_{123}$	1.3×10^{-10}	1.3×10^{-8}	2.4×10^{-10}	$< 4.4 \times 10^{-8}$ [204]
$\tau \to \mu\mu\mu$	$\lambda_{323}\lambda_{322}$	1.7×10^{-11}	1.2×10^{-9}	1.2×10^{-11}	$< 2.1 \times 10^{-8}$ [205]
$B_{(s)} \to K^{(*)}(\phi)\mu\tau$	$\lambda'_{333}\lambda'_{232},\ \lambda'_{233}\lambda'_{332},\ \lambda'_{332}\lambda_{323}$	4.1×10^{-9}	1.2×10^{-7}	2.2×10^{-10}	$< 2.8 \times 10^{-5}$ [206]
$B_s \to \tau\mu$	$\lambda'_{333}\lambda'_{232},\ \lambda'_{233}\lambda'_{332},\ \lambda'_{332}\lambda_{323}$	4.4×10^{-10}	1.3×10^{-8}	2.3×10^{-11}	$< 3.4 \times 10^{-5}$ [207]
$b \to s\tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.4×10^{-7}	2.8×10^{-8}	1.3×10^{-13}	N/A
$B \to K^{(*)}\tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.7×10^{-6}	4.2×10^{-8}	9.6×10^{-12}	$< 2.2 \times 10^{-3}$ [208]
$B_s \to \tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.7×10^{-8}	3.0×10^{-9}	1.4×10^{-14}	$< 6.8 \times 10^{-3}$ [209]
$b \to s\mu\mu$	$\lambda'_{233}\lambda'_{232},\ \lambda'_{332}\lambda_{232}$	5.9×10^{-9}	3.2×10^{-8}	8.8×10^{-9}	4.4×10^{-6} [210]
$B_s \to \mu\mu$	$\lambda'_{233}\lambda'_{232},\ \lambda'_{332}\lambda_{232}$	4.1×10^{-11}	6.5×10^{-11}	1.8×10^{-11}	3.0×10^{-9} [211]

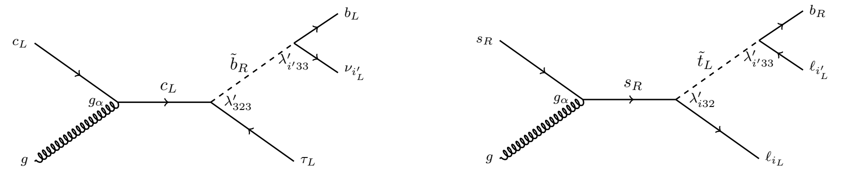
Altmannshofer, BD, Soni, Sui, 2002.12910 [PRD]

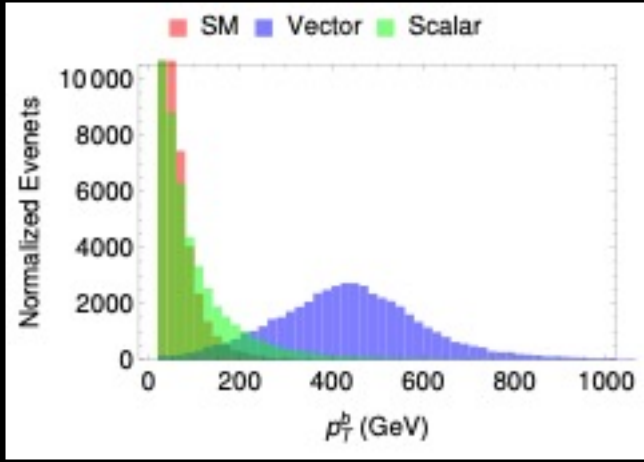
High-p_T LHC Tests

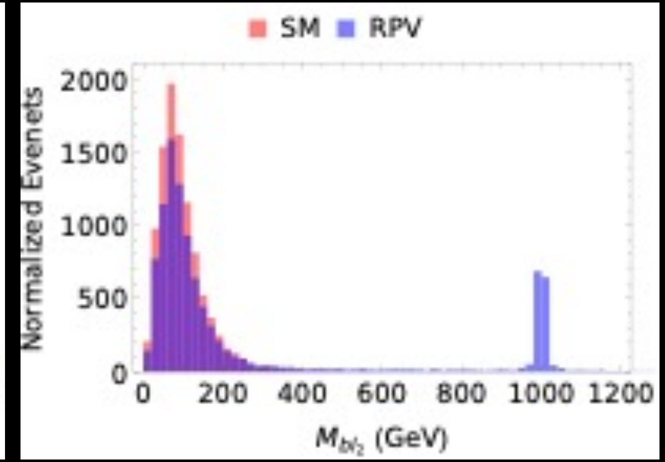
$$R_{D^{(*)}} \; : \mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu)$$

$$R_{K^{(*)}} \; : Q^{\ell}_{9(10)} = (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu(\gamma_5)\ell)$$

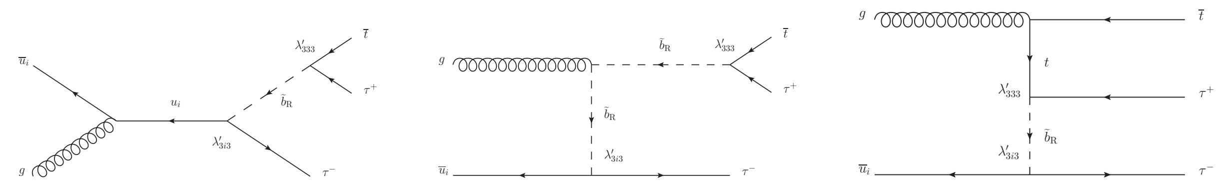
Crossing symmetry: $b \to c\tau\nu$ leads to $gc \to b\tau\nu$, and $b \to s\ell\ell$ leads to $gs \to b\ell\ell$.





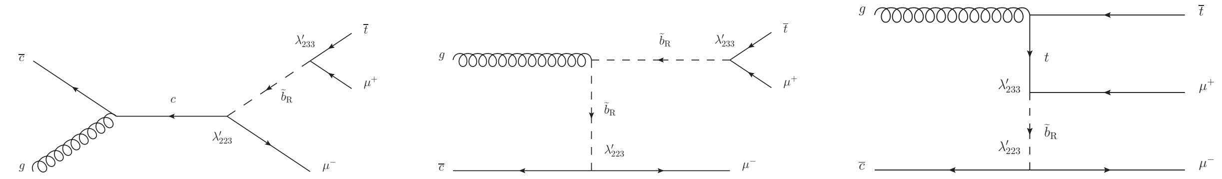


Altmannshofer, BD, Soni, 1704.06659 [PRD]; Altmannshofer, BD, Soni, Sui, 2002.12910 [PRD]



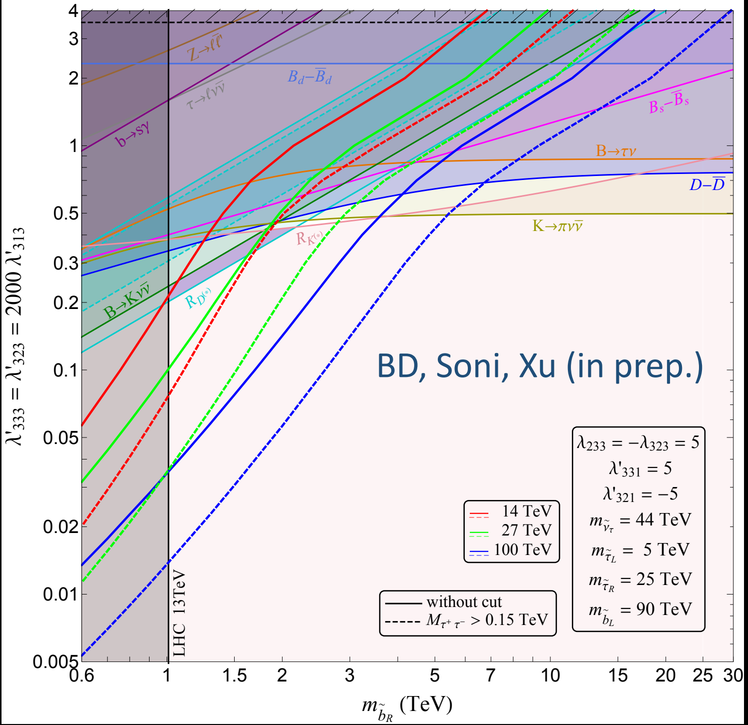
(a) (b) (c)

Figure 1: Feynman diagrams for the signal process $pp \to \bar{t}\tau^+\tau^-$



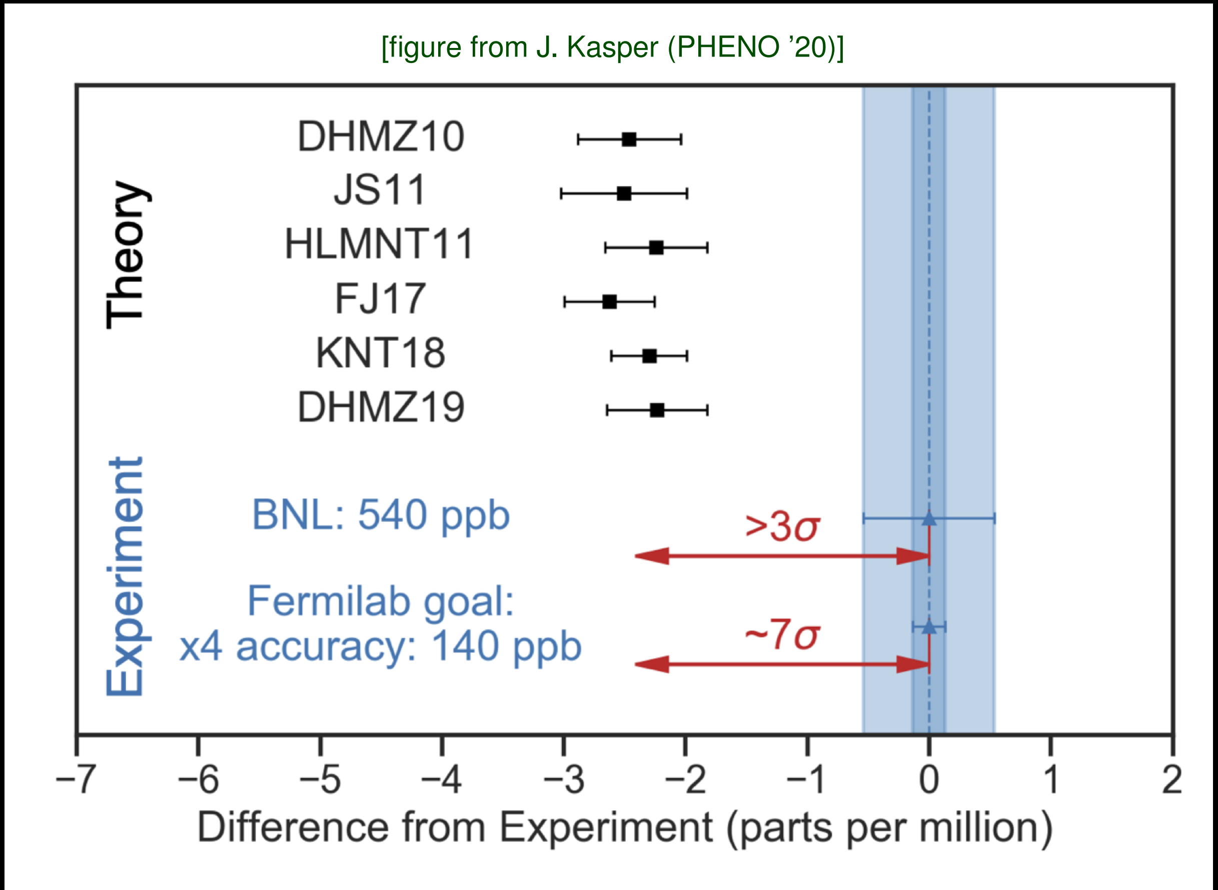
(a) (b) (c)

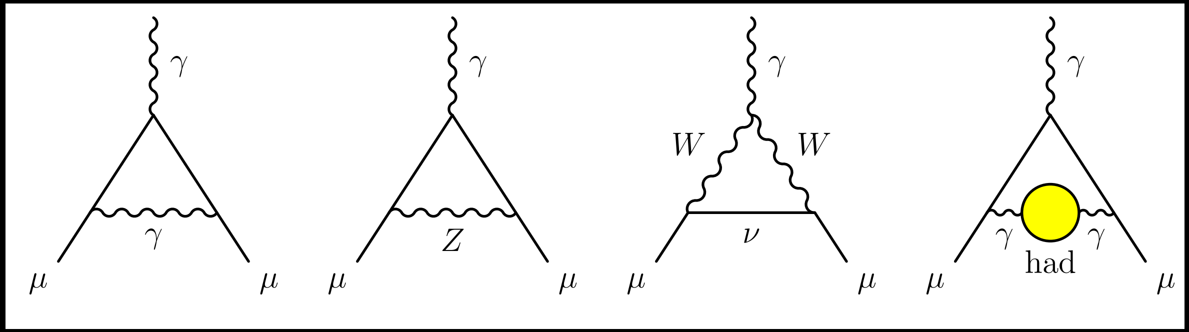
Figure 2: Feynman diagrams for the signal process $pp \to \bar{t}\mu^+\mu^-$



Can test the RPV3 solution to B-anomalies at HL-LHC.

Lepton Anomalous Magnetic Moment





$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP,\,LO} + a_\mu^{\rm HVP,\,NLO} + a_\mu^{\rm HVP,\,NNLO} + a_\mu^{\rm HLbL} + a_\mu^{\rm HLbL,\,NLO} = 116\,591\,810(43) \times 10^{-11}\,.$$

Aoyama et al, 2006.04822

$$\Delta a_\mu := a_\mu^{\rm exp} - a_\mu^{\rm SM} = 279(76) \times 10^{-11}$$

3.7 σ discrepancy

$$a_\mu^{\rm exp} = 116\,592\,089(63) \times 10^{-11}$$

BNL, hep-ex/0602035

New results coming soon from Fermilab!

Similar anomaly earlier reported in electron sector:

$$\Delta a_e^{\rm Cs} \equiv a_e^{\rm exp\ (Cs)} - a_e^{\rm SM} = (-8.7 \pm 3.6) \times 10^{-13}$$

2.4 σ

Parker, Yu, Zhong, Estey, Mueller, 1812.04130 (Science)

Recent development:

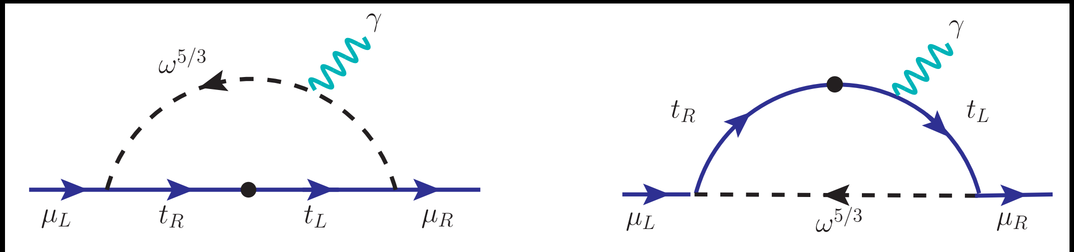
$$\Delta a_e^{\rm Rb} \equiv a_e^{\rm exp\ (Rb)} - a_e^{\rm SM} = (4.8 \pm 3.0) \times 10^{-13}$$

1.6 σ

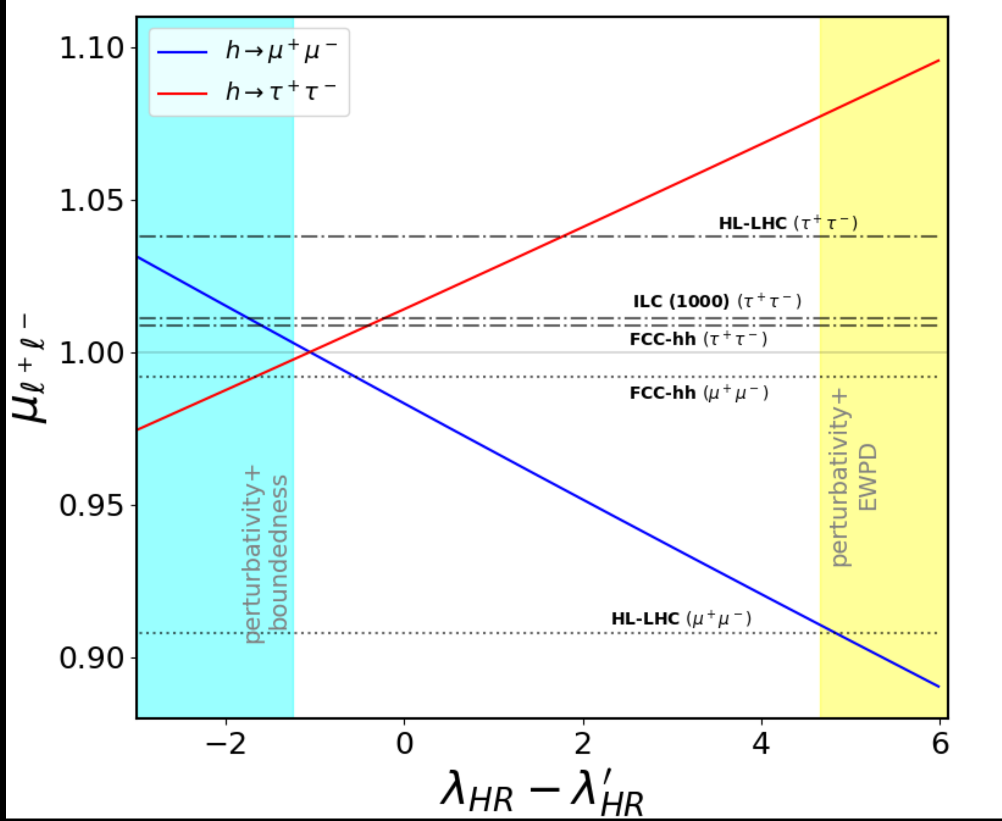
Morel, Yao, Clade, Guellati-Khelifa, Nature 588, 61 (2020)

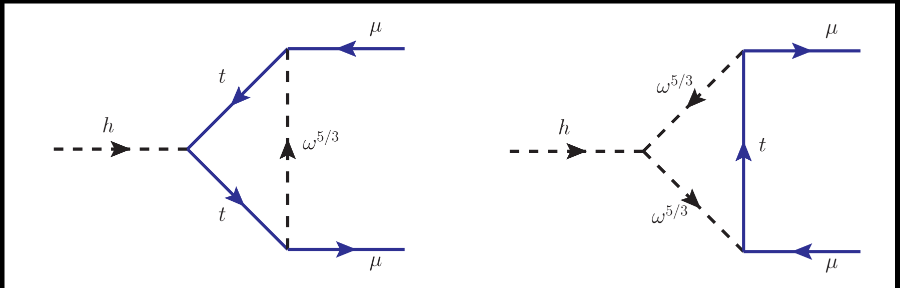
But Cs and Rb measurements of $\alpha_{\rm em}$ now disagree by more than 5 σ!

Chiral Enhancement from LQ Loop



$$\Delta a_\ell = -\frac{3}{16\pi^2}\frac{m_\ell^2}{m_{R_2}^2}\sum_q\Big[\left(|f_{q\ell}|^2+|(V^\star f')_{q\ell}|^2\right)\left(Q_qF_5(x_q)+Q_SF_2(x_q)\right) -\frac{m_q}{m_\ell}\mathrm{Re}[f_{q\ell}\,(V^\star f')^\star_{q\ell}]\left(Q_qF_6(x_q)+Q_SF_3(x_q)\right)\Big]$$





Connection with Higgs decay to dileptons

Crivellin, Mueller, Saturnino, 2008.02643

$$\mu_{\mu^+\mu^-} \equiv \frac{\mathrm{BR}(h\to\mu^+\mu^-)}{\mathrm{BR}(h\to\mu^+\mu^-)_{\mathrm{SM}}} = \left|1-\frac{3}{8\pi^2}\frac{m_t}{m_\mu}\frac{f_{32}(V^\star f')^\star_{32}}{m_{R_2}^2}\left\{\frac{m_t^2}{8}\mathcal{F}\left(\frac{m_h^2}{m_t^2},\frac{m_t^2}{m_{R_2}^2}\right)+v^2\left(\lambda_{HR}-\lambda'_{HR}\right)\right\}\right|^2$$

$$\mathcal{F}(x,y) = -8+\frac{13}{3}x-\frac{1}{5}x^2-\frac{1}{70}x^3+2(x-4)\log y\,.$$

Depends on quartic couplings $\lambda_{HR}(H^\dagger H)(R_2^\dagger R_2)+\lambda'_{HR}(H^\dagger\tau_a H)(R_2^\dagger\tau_a R_2)$

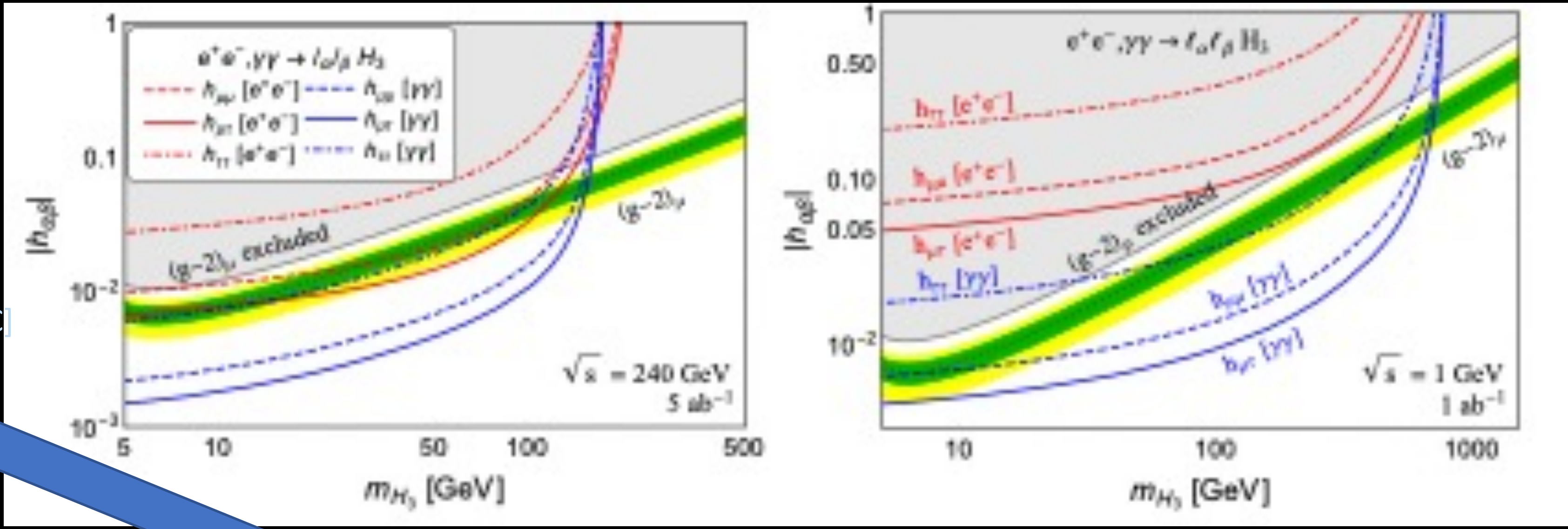
Leptoquark solution to muon g-2 can be tested in precision Higgs data at LHC and future colliders.

Babu, BD, Jana, Thapa, 2009.01771 [JHEP]

Leptophilic Scalar

BD, Mohapatra, Zhang, 1711.08430 [PRL]; 1803.11167 [PRD]

Future lepton colliders an ideal place to probe leptophilic scalar interpretation of muon g-2.

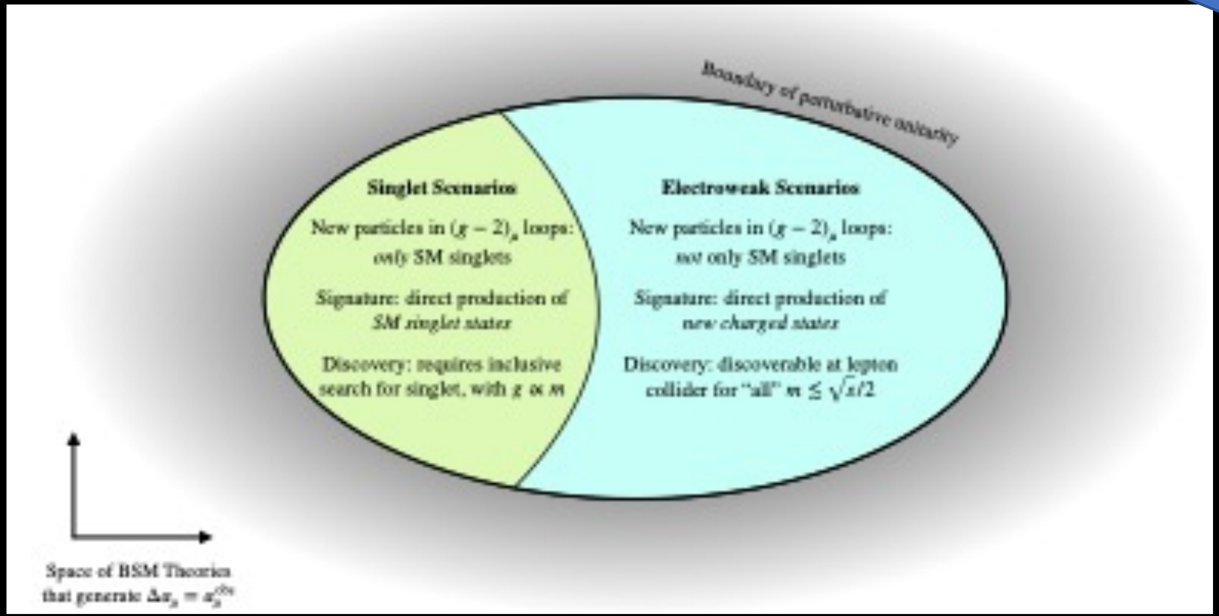


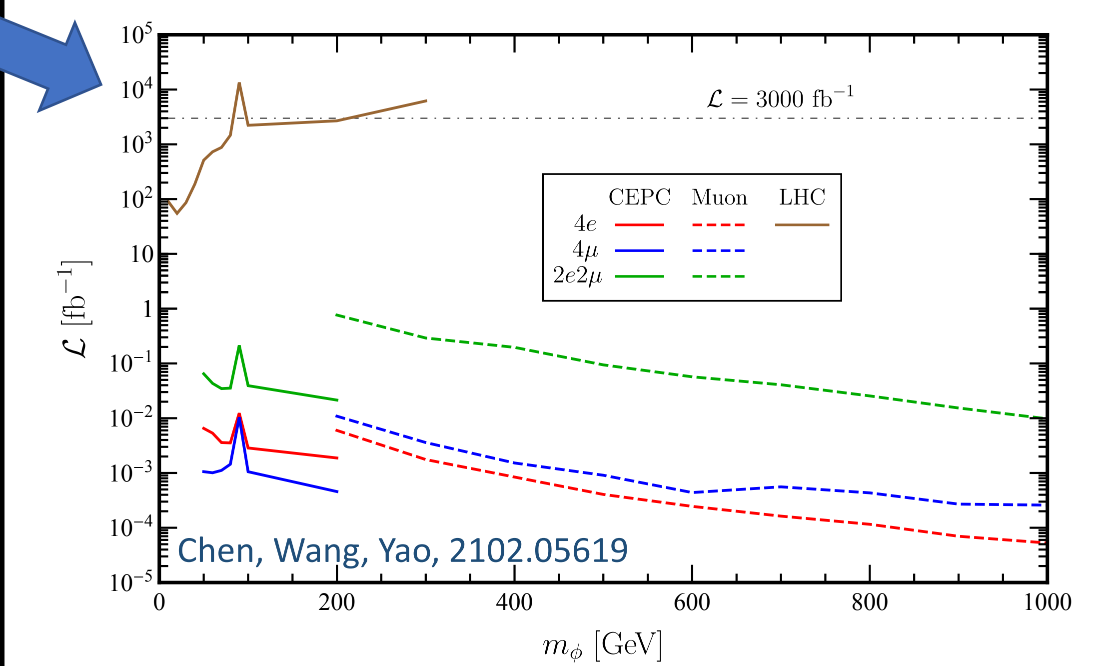
Connection to multilepton anomalies@LHC

Sabatta, Cornell, Kumar, Mellado, Ruan, 1909.03969 [CPC]

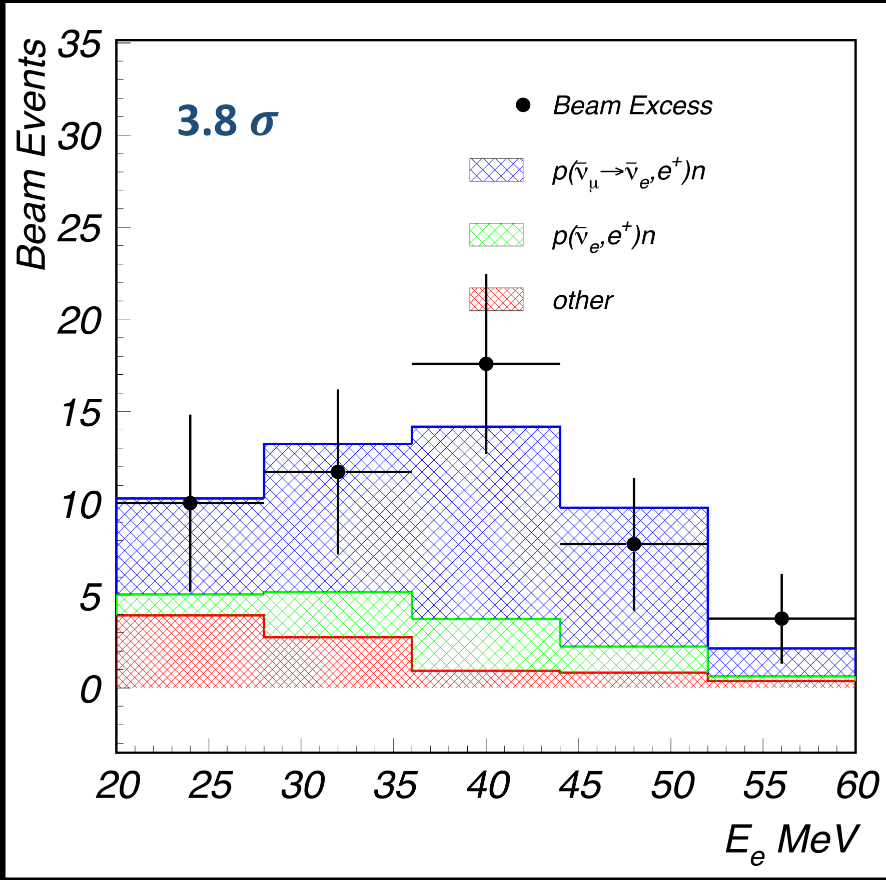
No-lose theorem at muon collider

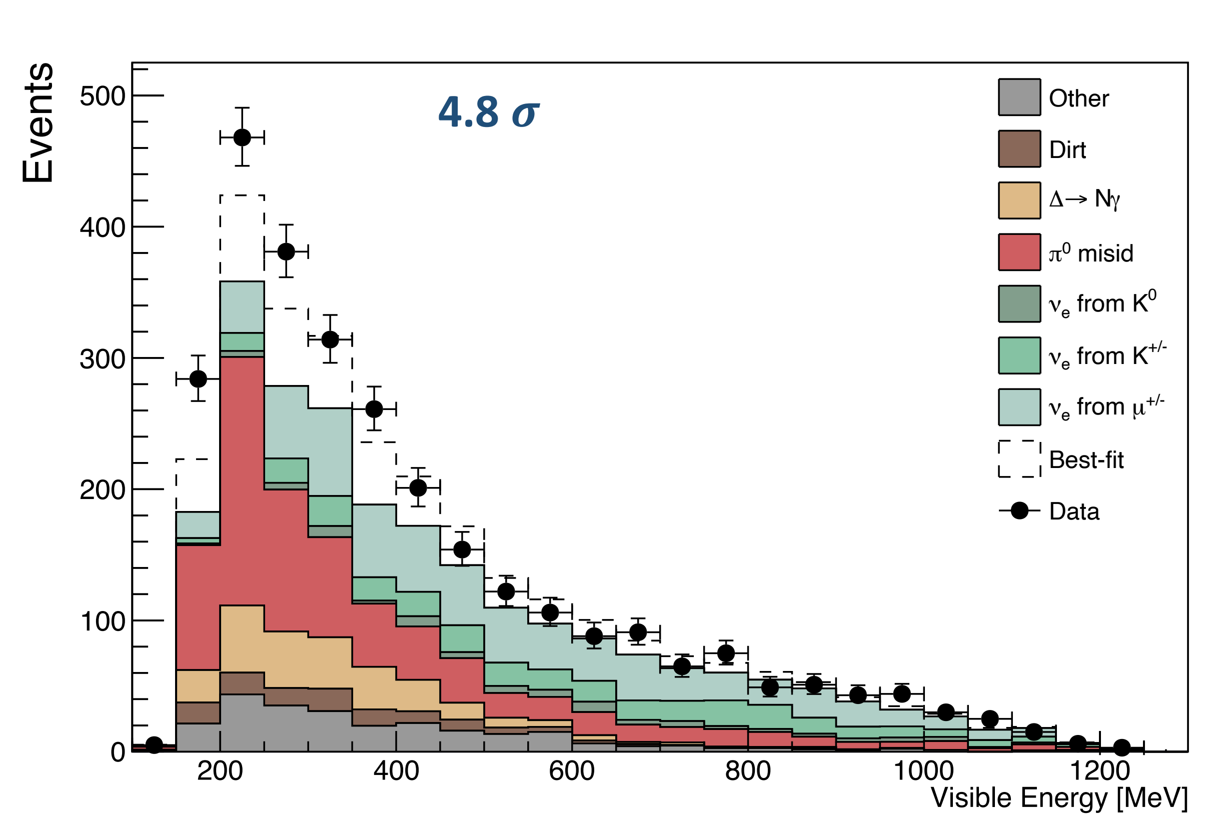
Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; 2101.10334





LSND and MiniBooNE Anomalies





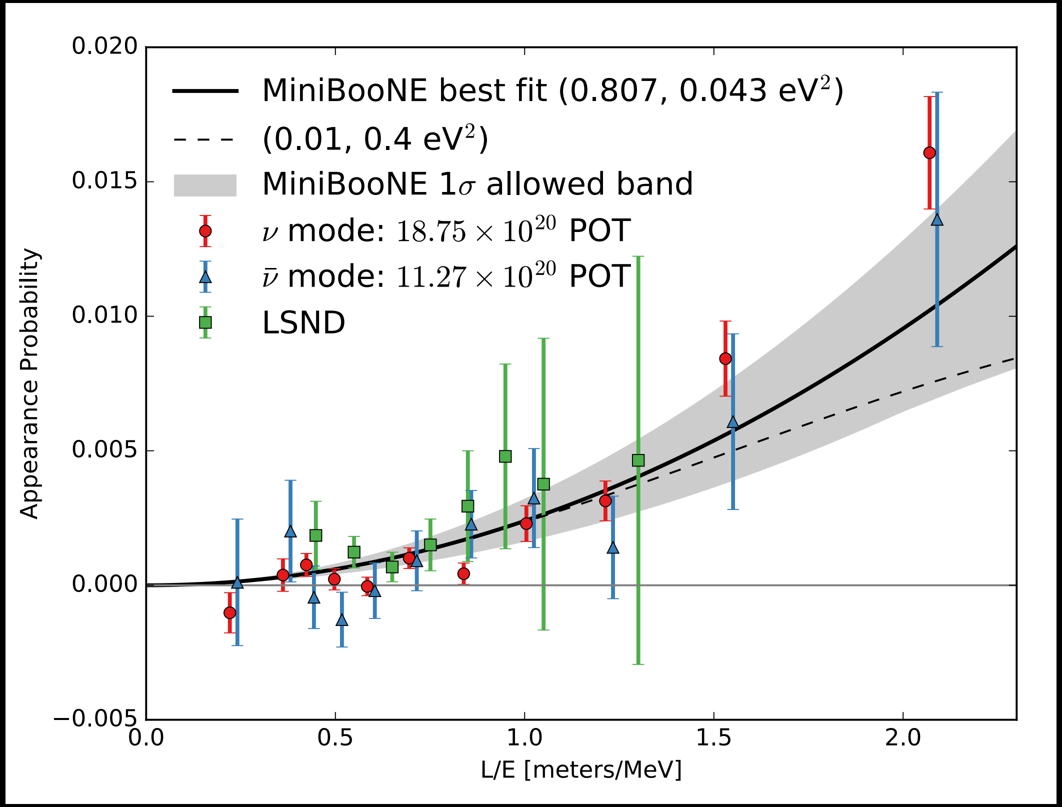
LSND, hep-ex/0104049 [PRD]

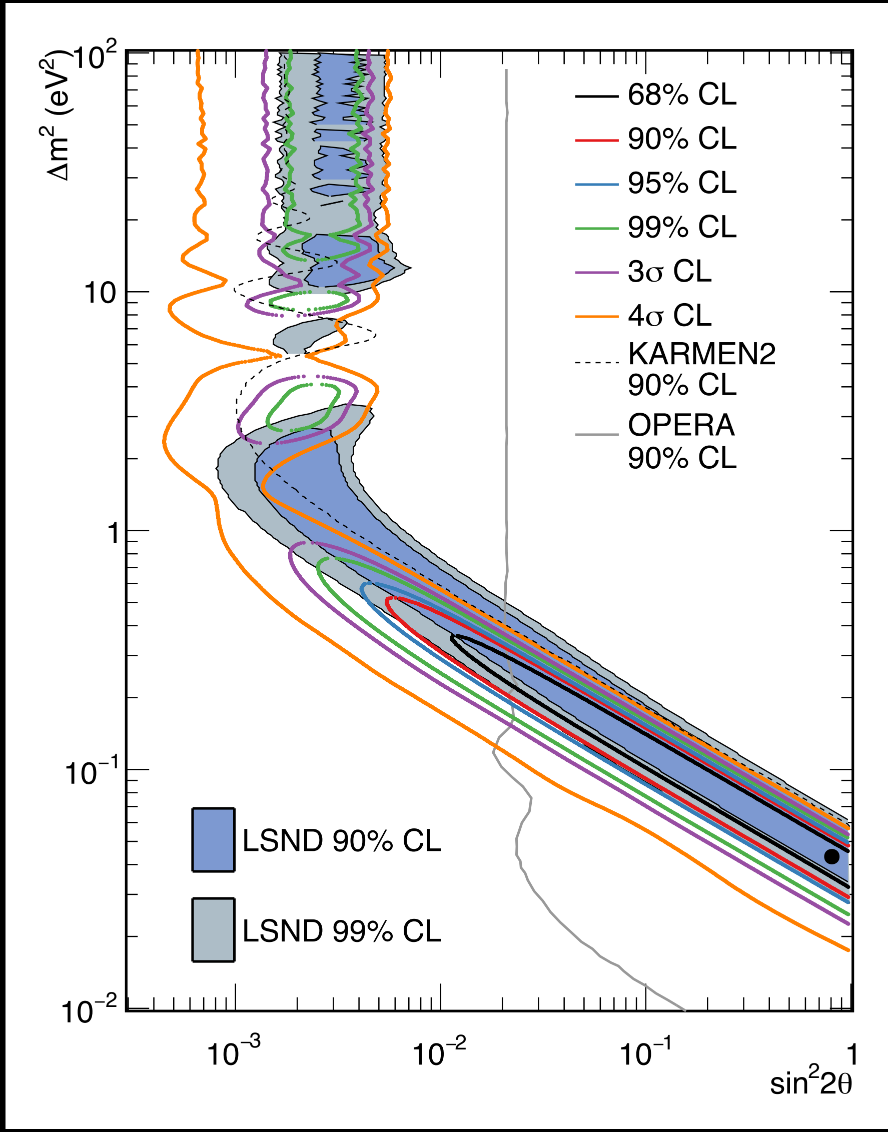
Confirmed in MiniBooNE, 1805.12028 [PRL]; 2006.16883

Completely different neutrino energies, neutrino fluxes, reconstructions, backgrounds, and systematics.

Need some exotic model beyond the three-neutrino paradigm.

eV-scale Sterile Neutrino?



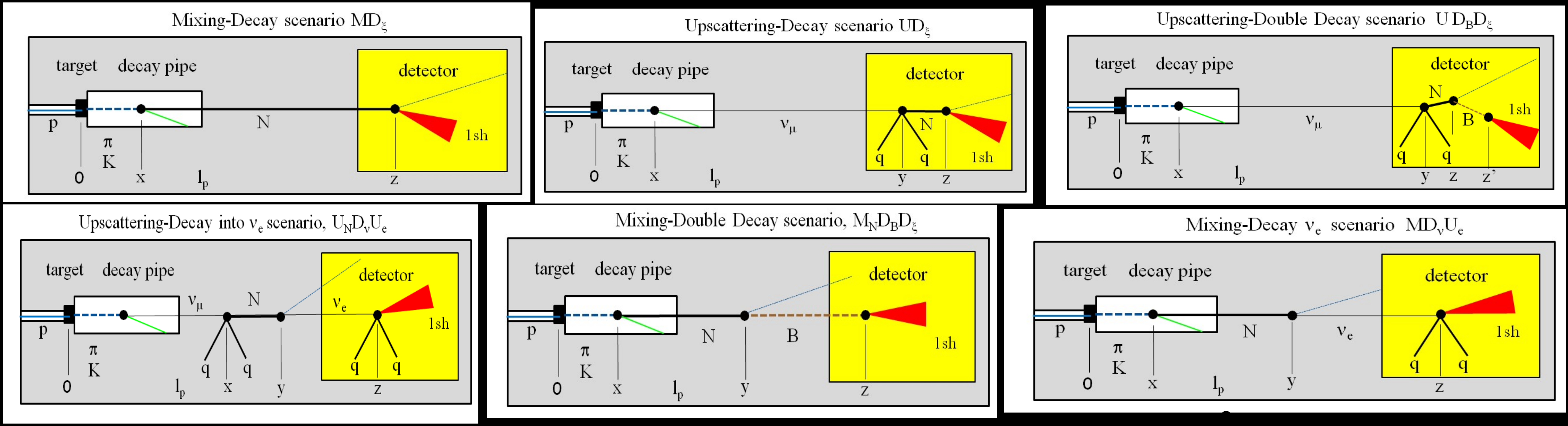


Combined significance of 6.1 σ

More data to come from MicroBooNE and JSNS^2

MiniBooNE, 2006.16883

Non-Oscillatory Explanation



Brdar, Fischer, Smirnov, 2007.14411

MiniBooNE excess can be directly connected to expected excesses in other experiments (T2K ND280, MINERvA, NOvA, PS-191, NOMAD, CHARM-II).

Still some allowed parameter space.

Heavy right-handed neutrino can be connected to neutrino mass via seesaw.

Conclusion

- More conspicuous paths to “new physics” have remained stubbornly out of reach.
- Look for inspiration from anomalies as possible alternative routes.
- Worth investing time and effort, even though the future is uncertain.
- Need coherent community effort, active theory-experiment collaborations and open-access data to raise the status of anomalies (from “taboo” to mainstream physics).
- Need to find BSM scenarios that fit the anomalous data naturally without too much finagling. May not be your favorite model.
- Make concrete predictions that can be tested.