Anomalies in Particle Physics

Anomaly:
something different, abnormal, peculiar, or not easily classified; deviation from the common rule

A selected

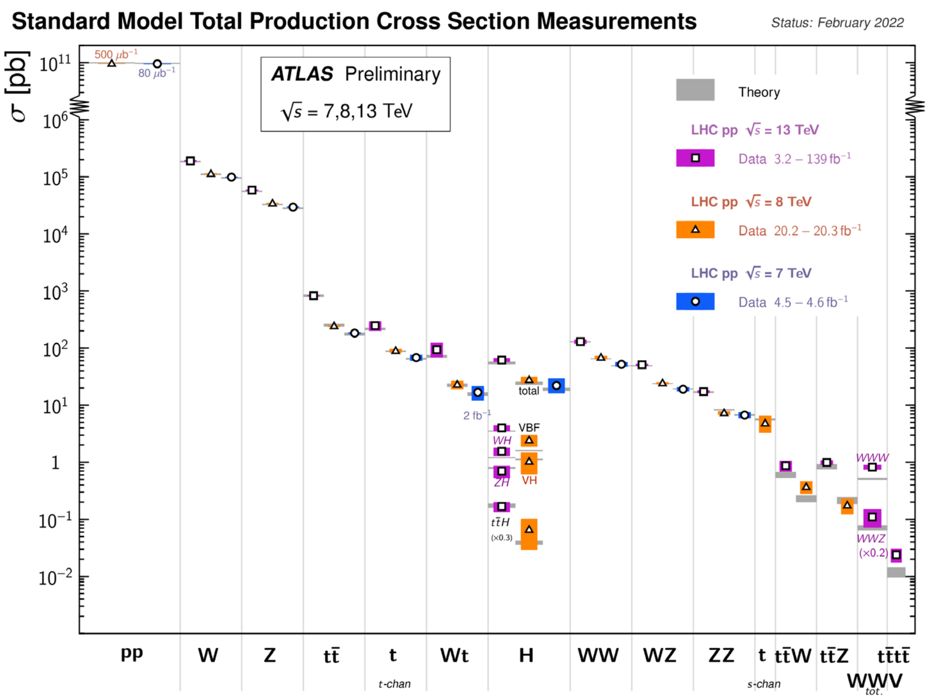
Deviations in measurements

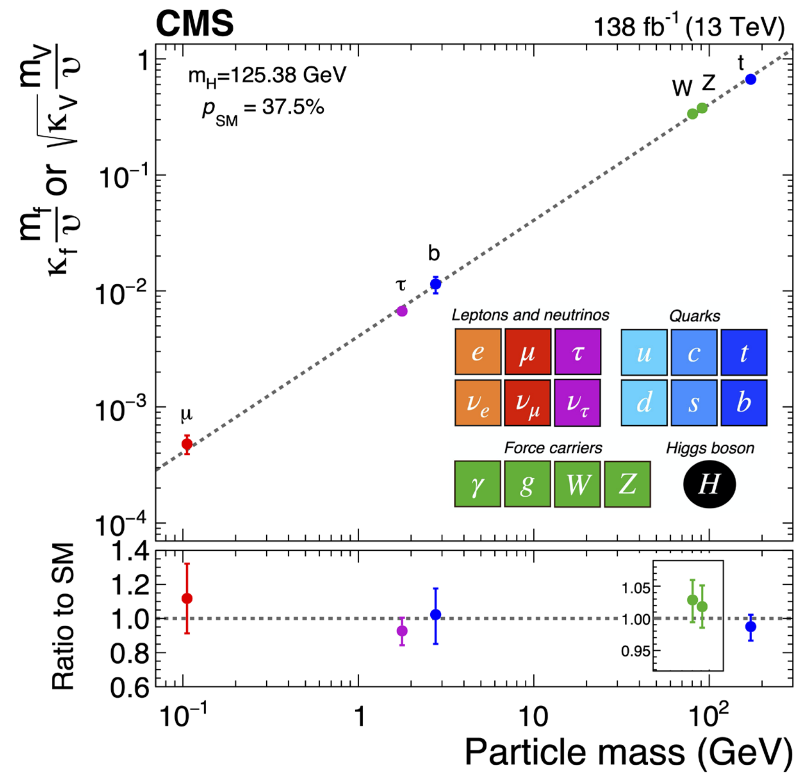
Excesses in searches at the LHC

Jianming Qian
University of Michigan

International Workshop on
the High Energy Circular Electron-Positron Collider
October 24-28, 2022

The Standard Model is live and well…





But it does not explain

the nature of dark matter, neutrino mass, matter-antimatter asymmetry, …

$\Rightarrow$ Call for BSM physics, unfortunately there is no prevailing theory nor experimental data tell us where the new physics will come from.

However, there are some measurement anomalies and search excesses.

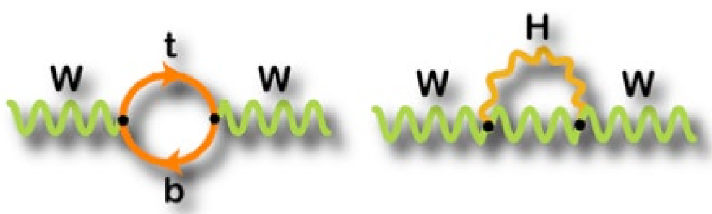
W Boson Mass

In the Standard Model, W boson mass can be calculated from a set of input parameters, such as α, G_F, α_s, $\sin^2\theta_W$, M_H, m_f,... most of these parameters have been measured with good precision.

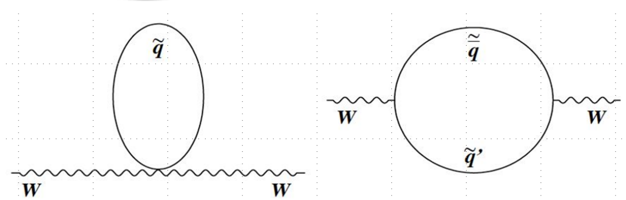
$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_W (1 - \Delta r)}$$

Δr summarizes the radiative corrections from the SM diagrams and potentially BSM contributions:

SM



BSM



Early this year, CDF reported the most precise single experiment measurement:

$$M_W = 80,433.5 \pm 9.4 \text{ MeV}$$

Science 376, 170 (2022)

W Boson Mass

Tevatron at Fermilab

$p\bar{p}$ collider @ $\sqrt{s} = 1.98$ TeV
$(1983 - 2011)$

Measurements from leptonic decays:

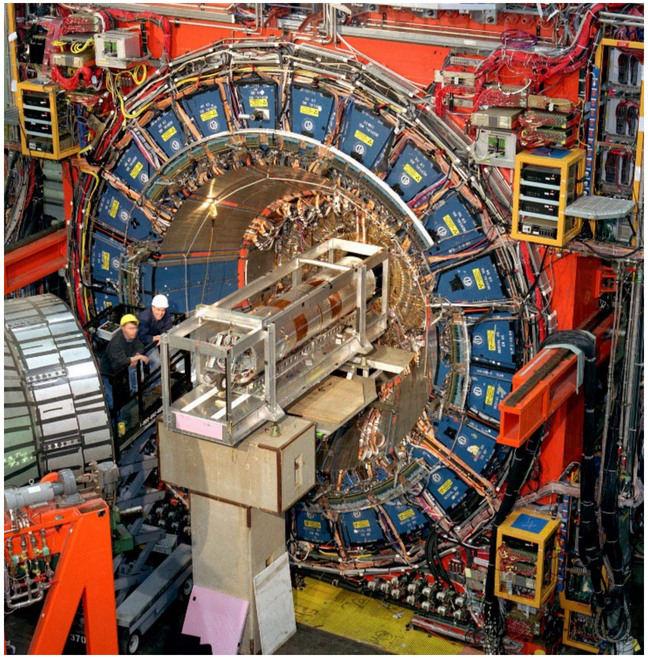
$$p\bar{p} \to W^{\pm} + X \to (e\nu/\mu\nu) + X$$

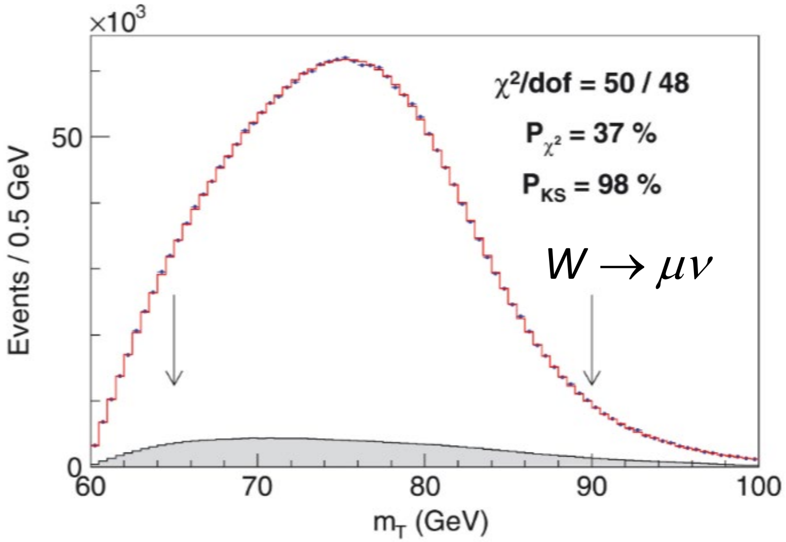
Transverse mass is the most insensitive quantity:

$$m_T^2 = 2E_T^{\ell} E_T^{\text{miss}} (1 - \cos\Delta\alpha)$$

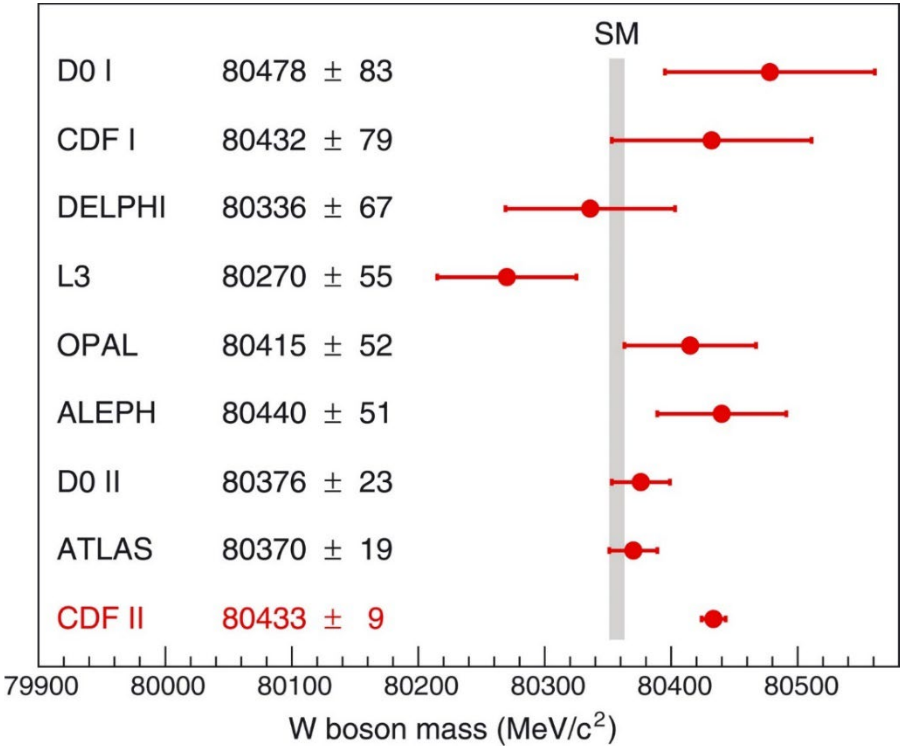
Lepton momentum is also sensitive to m_W.

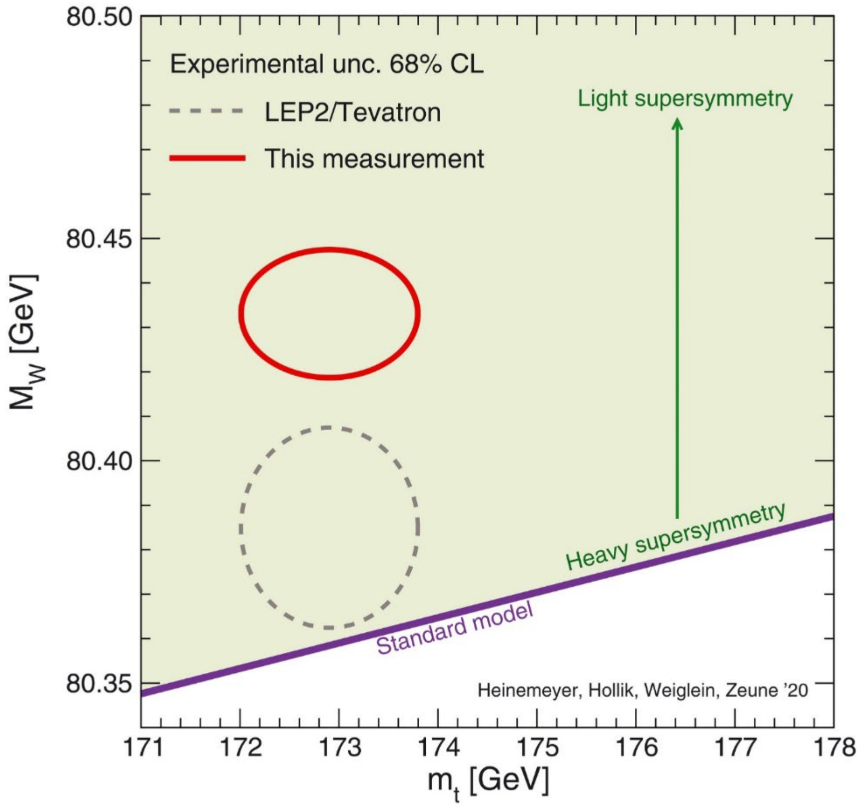
CDF Experiment





W Boson Mass





SM prediction: $M_W = 80{,}357 \pm 6$ MeV

Previous world average: $M_W = 80{,}379 \pm 12$ MeV

A discrepancy of $\sim 7\sigma$ between the measurement and the SM prediction.

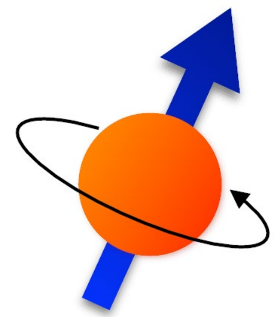
What's next? Independent measurements from ATLAS and CMS!

Muon g-2 Measurement

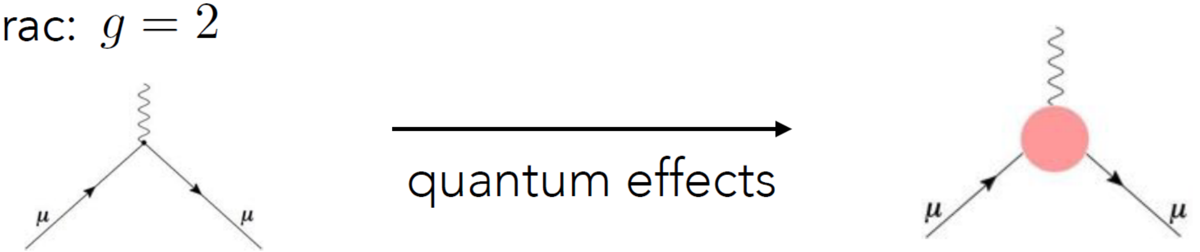
Muon is a spinning magnet with magnetic dipole moment

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S}$$

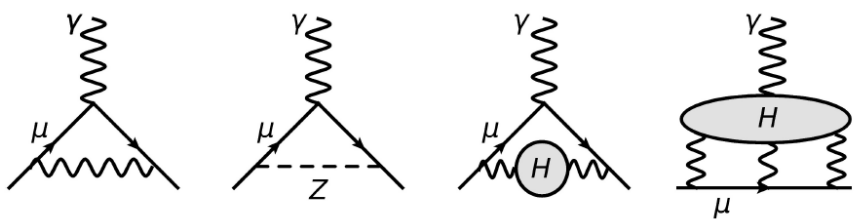
the "*g*"-factor can be calculated precisely in the SM



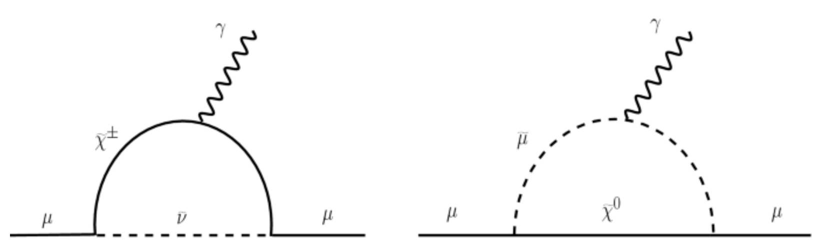
Dirac: $g = 2$



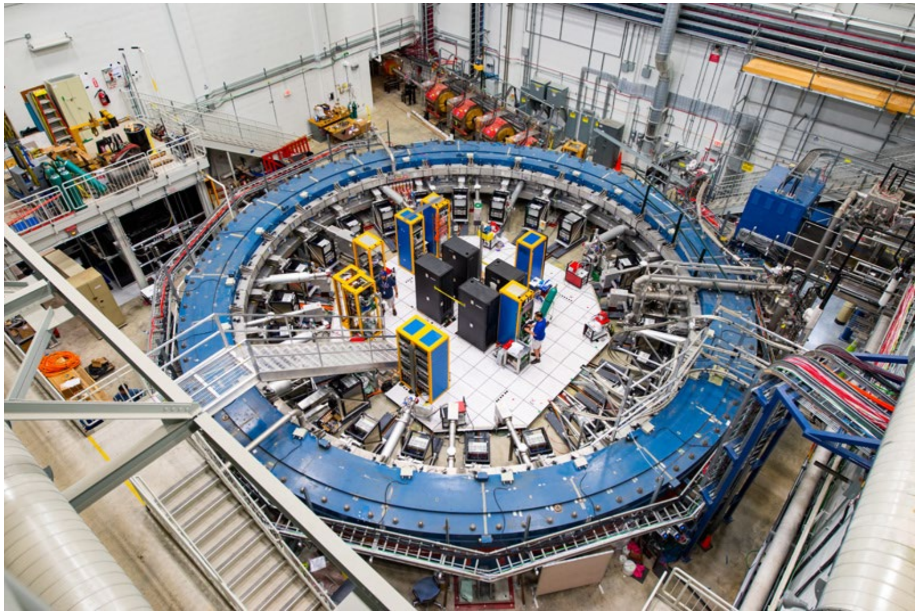
SM Contributions



BSM Contributions
(examples)



Muon g-2 Measurement



Fermilab g-2 experiment

Muon g-factor can be determined experimentally by measuring muon anomalous precession frequency in a storage ring $\Rightarrow$ g-2 experiment

Deviations from 2 is parameterized by the muon magnetic anomaly

$$a_\mu \equiv \frac{1}{2}\left(g_\mu - 2\right)$$

SM prediction:

$$a_\mu = 116{,}591{,}810(43)\times 10^{-11} \quad (0.37\ \text{ppm})$$

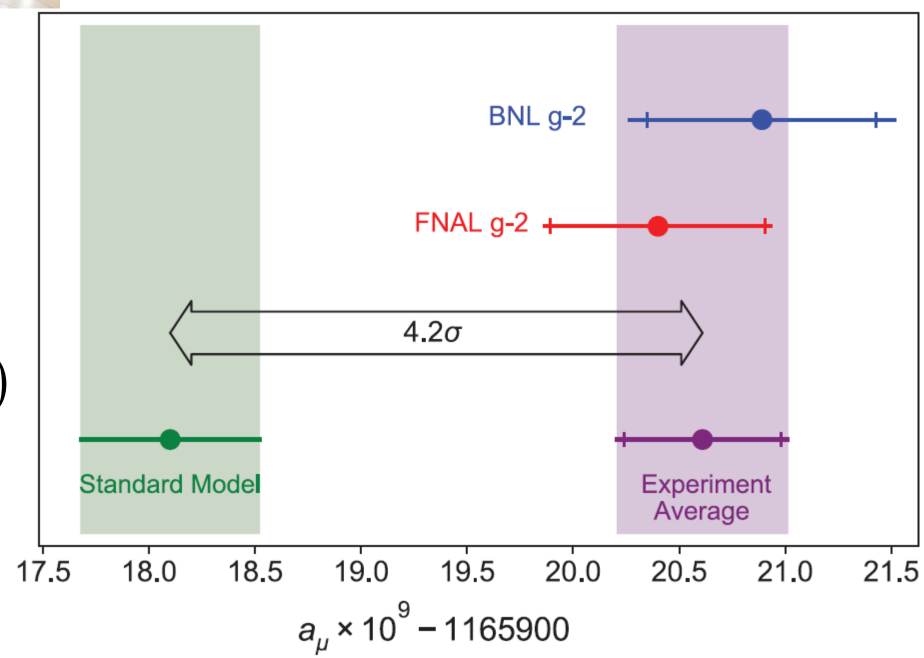
Fermilab measurement:

$$a_\mu = 116{,}592{,}040(54)\times 10^{-11} \quad (0.46\ \text{ppm})$$

Fermilab + BNL average:

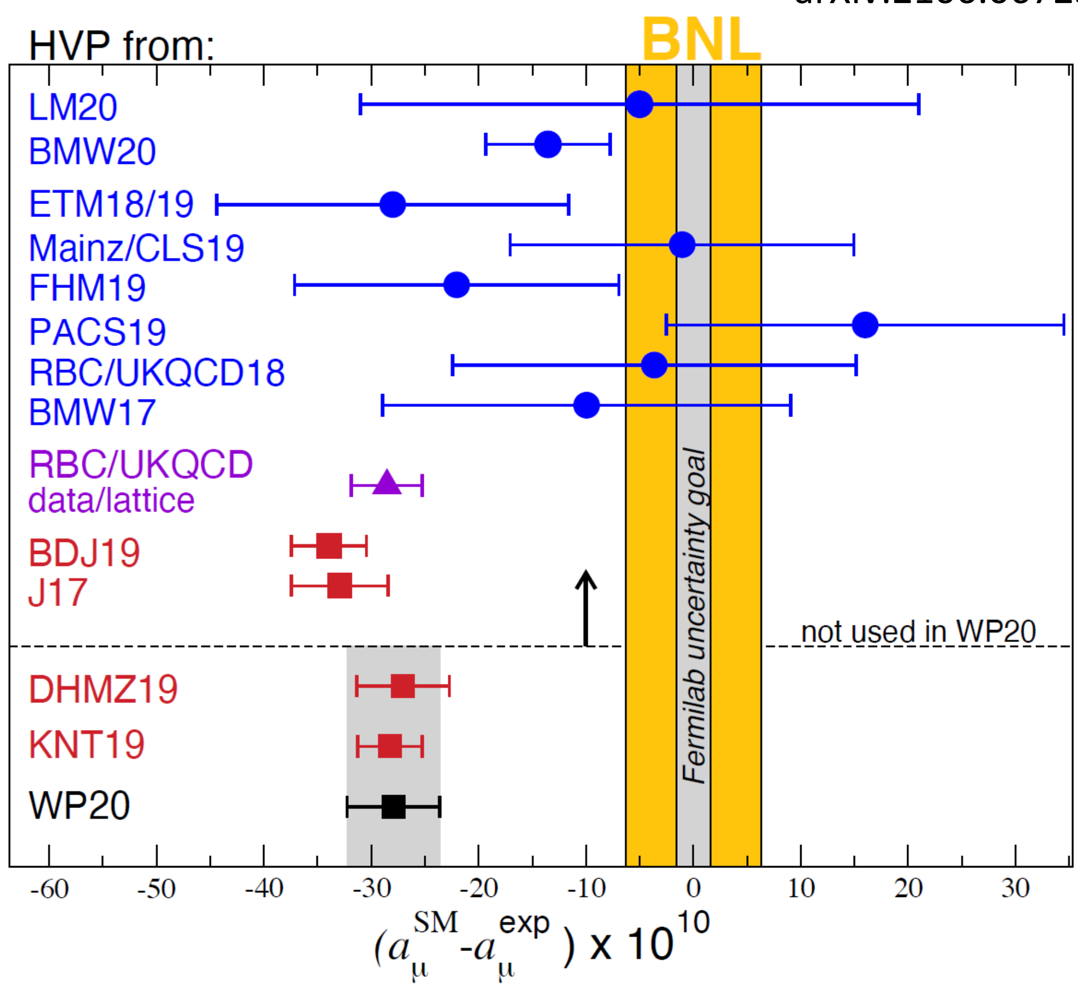
$$a_\mu = 116{,}592{,}061(41)\times 10^{-11} \quad (0.35\ \text{ppm})$$

arXiv:2104.03281



Muon g-2 Measurement

arXiv:2106.06723



What's next?

More data from Fermilab, ultimate design goal to reach 0.14 ppm, improved theoretical calculations

Coincidence?

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Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

B. Abi *et al.* (Muon $g-2$ Collaboration)

Phys. Rev. Lett. **126**, 141801 – Published 7 April 2021

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HOME > SCIENCE > VOL. 376, NO. 6589 > HIGH-PRECISION MEASUREMENT OF THE W BOSON MASS WITH THE CDF II DETECTOR

RESEARCH ARTICLE | PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

CDF COLLABORATION†‡, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, [...] S. ZUCCHELLI +389 authors Authors

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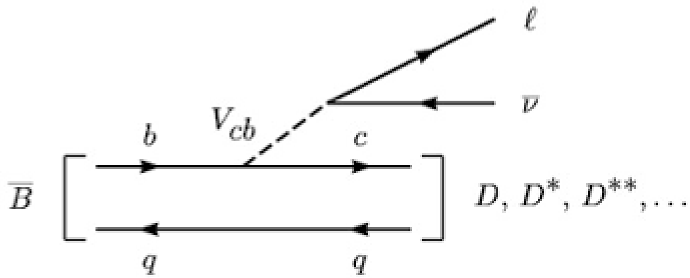
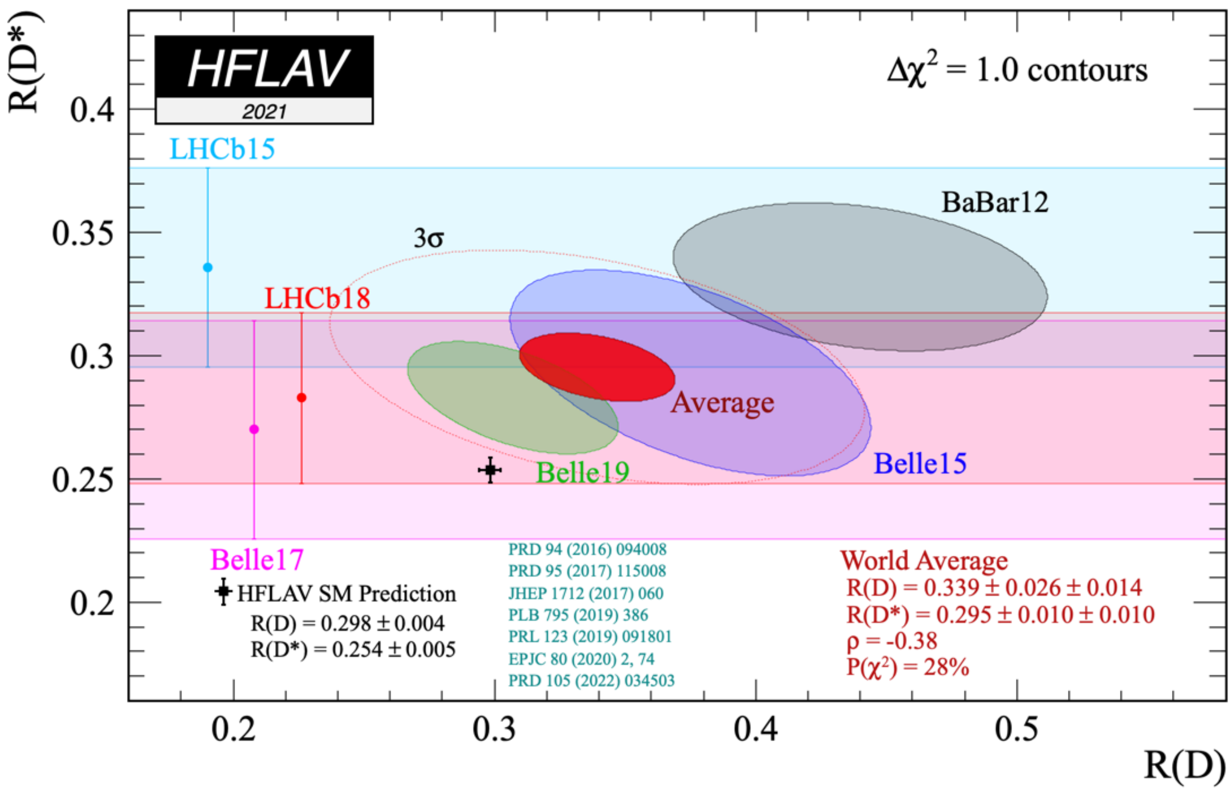
What's in store for April 7, 2023?

Lepton Flavor Universality in B Decays



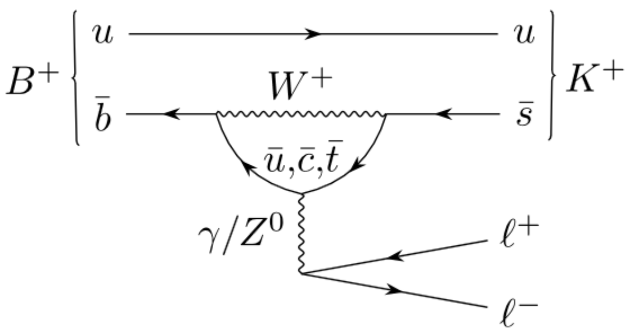
Test of the $\tau/(e,\mu)$ universality

$$R(D)=\frac{BR(B\to D\tau\nu)}{BR(B\to D\ell\nu)},\qquad R(D^*)=\frac{BR(B\to D^*\tau\nu)}{BR(B\to D^*\ell\nu)}$$



A $\sim 3\sigma$ discrepancy between the SM prediction and the average.

Lepton Flavor Universality in B Decays



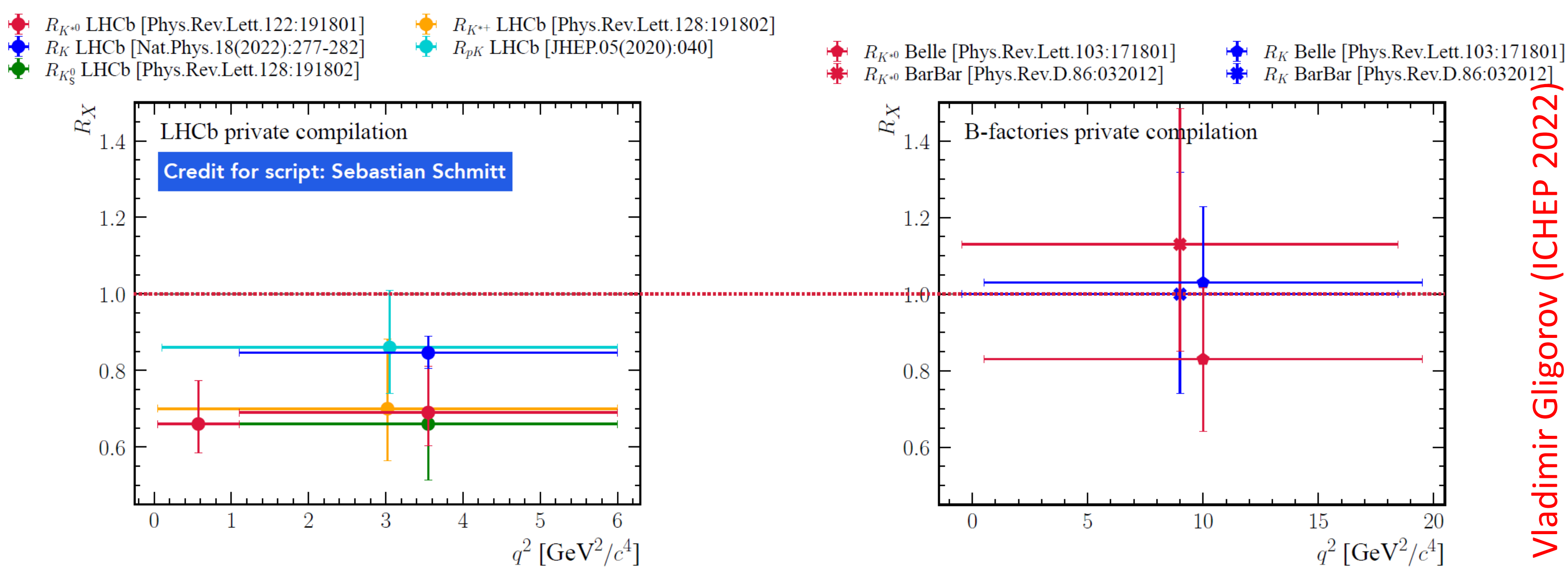
Test of the e/μ universality

$$R_K = \frac{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^+ \to K^+ \mu^+ \mu^-\right)}{\mathrm{d}q^2} \mathrm{d}q^2}{\int_{1.1\ \mathrm{GeV}^2}^{6.0\ \mathrm{GeV}^2} \frac{\mathrm{d}\mathcal{B}\left(B^+ \to K^+ e^+ e^-\right)}{\mathrm{d}q^2} \mathrm{d}q^2}$$

LHCb result shows a $\sim 3.1\sigma$ discrepancy with the LFU. B factory measurements consistent with the LFU, but with large uncertainties.

LHCb (arXiv:2103.11769)

$$R_K = 0.846^{+0.042}_{-0.039}\,(\mathrm{stat.})^{+0.013}_{-0.012}\,(\mathrm{syst.})$$

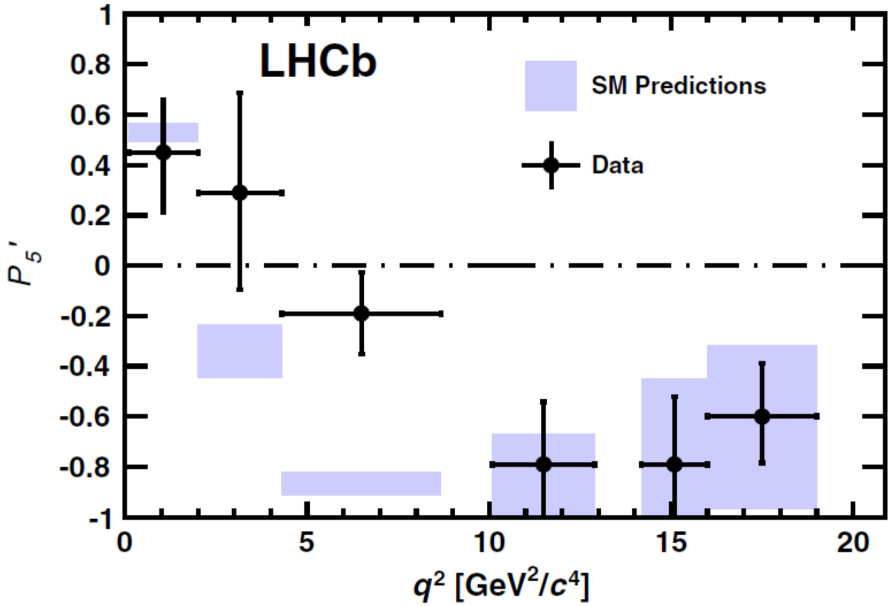


Vladimir Gligorov (ICHEP 2022)

Angular Analyses of $B \to K^* \mu^+ \mu^-$ Decays

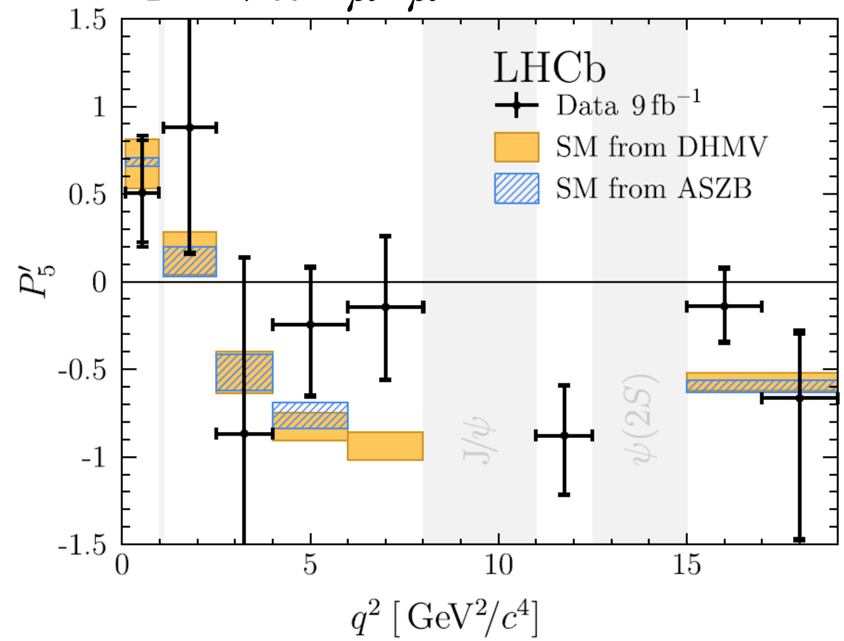
Form-factor-independent CP-averaged angular observable P_5'

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



LHCb: PRL 111, 19180 (2013)

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



LHCb: PRL 126, 161802 (2021)

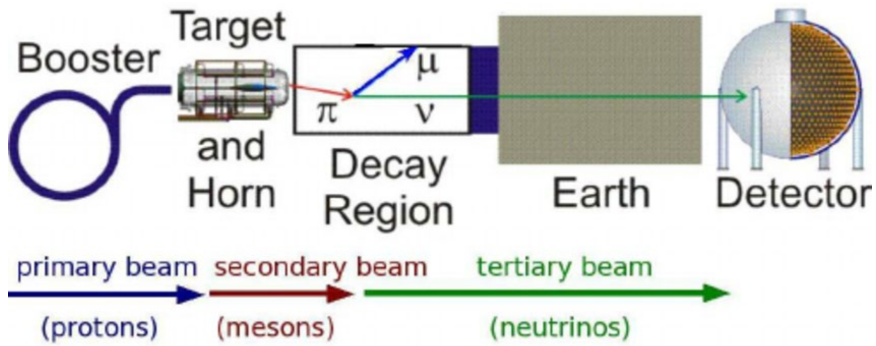
Deviations from the SM predictions are at $\sim$4-5σ level

(See review arXiv:1704.05340)

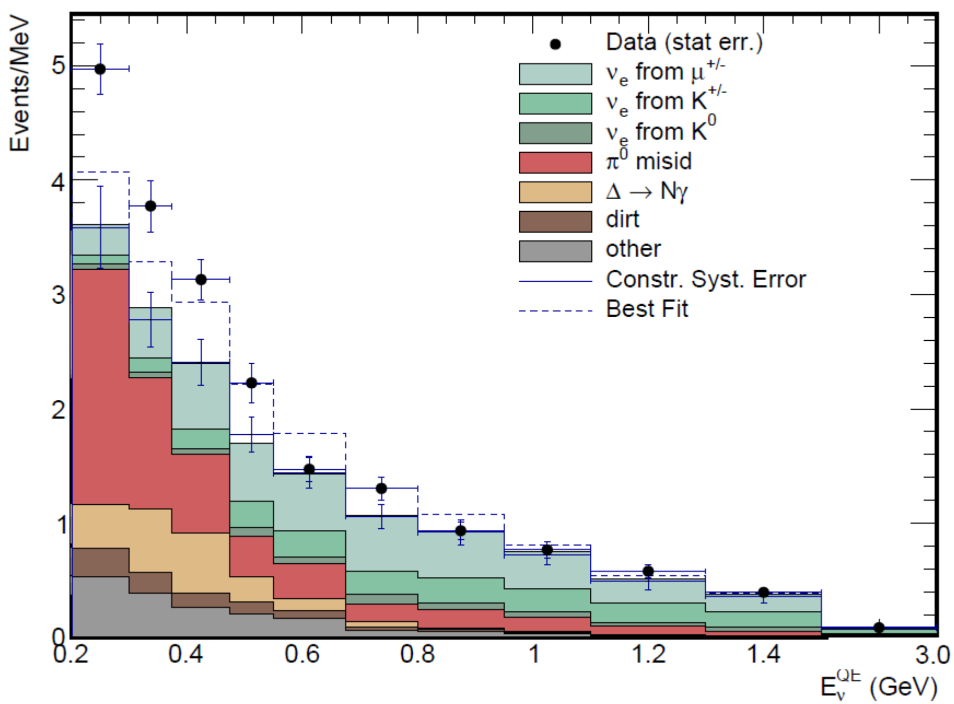
Low Energy Electron Neutrino Anomaly

Short baseline

$\nu_\mu \rightarrow \nu_e$ appearance



arXiv:1805.12028



Low energy ν_e excess with significances:

4.7σ MiniBooNE alone,

6.0σ combined with LSND

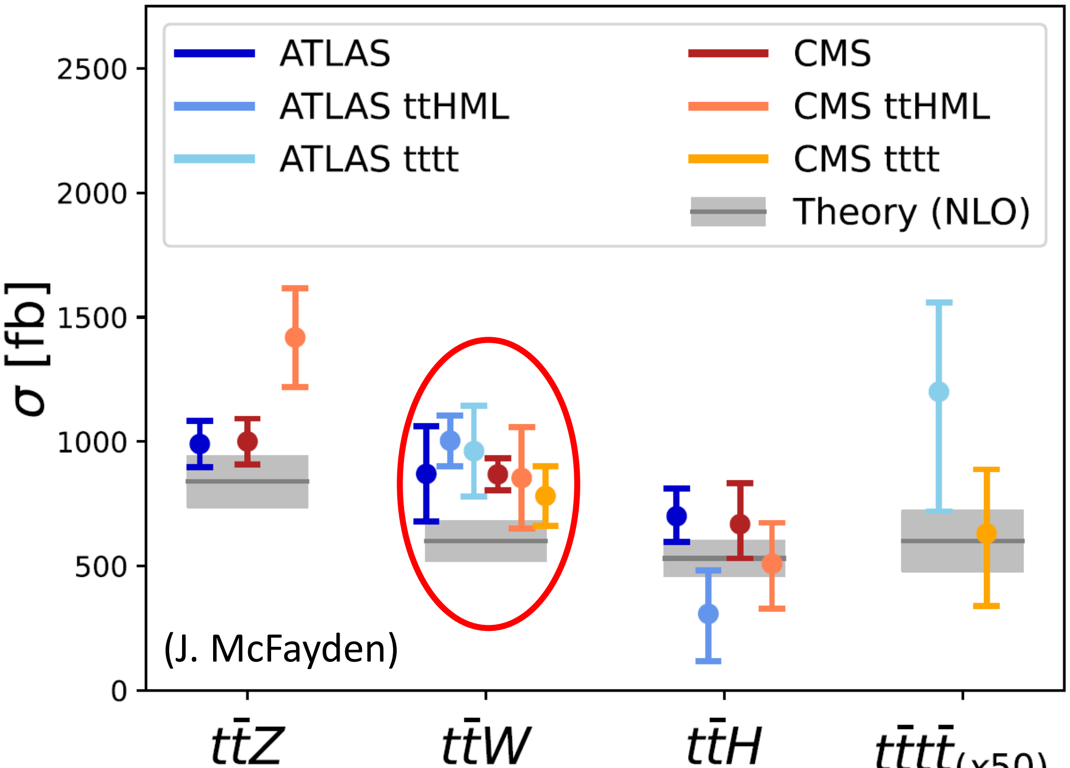
Inconsistent with the 3 light neutrino species

Sterile neutrino explanation ruled out by MicroBooNE (arXiv:2110.14054)

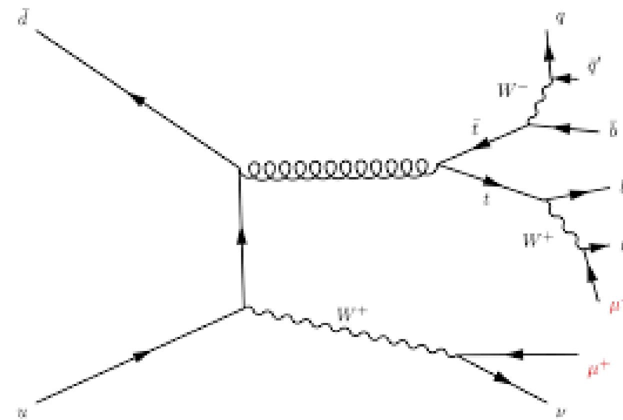
ttW Measurements at the LHC

in the SSML final state
(Same-Sign dilepton and MultiLepton)

Tension with the SM prediction at $\sim 3\sigma$ level
Consistently 30%+ high



arXiv:1908.06463 (CMS)
arXiv:2007.14858 (ATLAS)

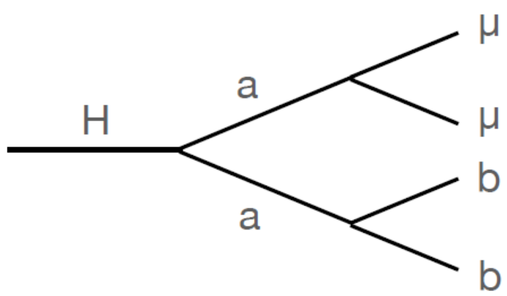


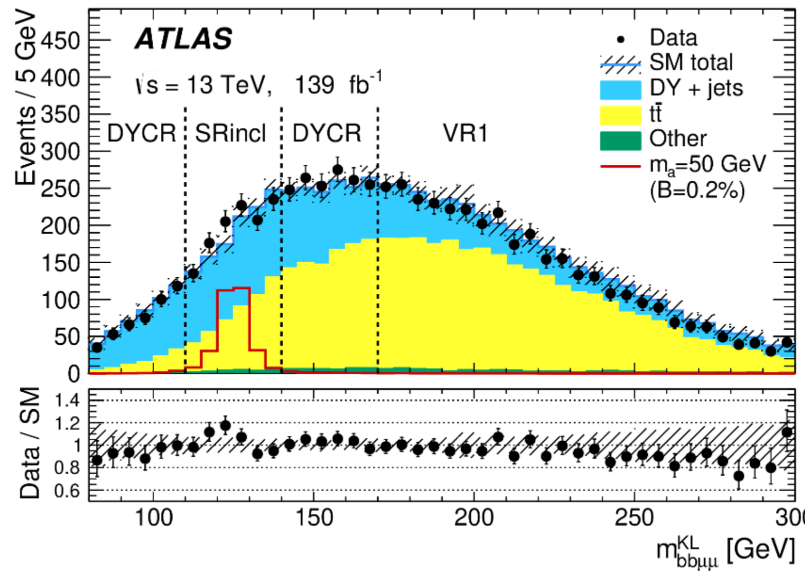
- $t\bar{t}$ measurements agree with the SM;
- $t\bar{t}W$ is an electroweak process (on top of $t\bar{t}$)

Why it is interesting?

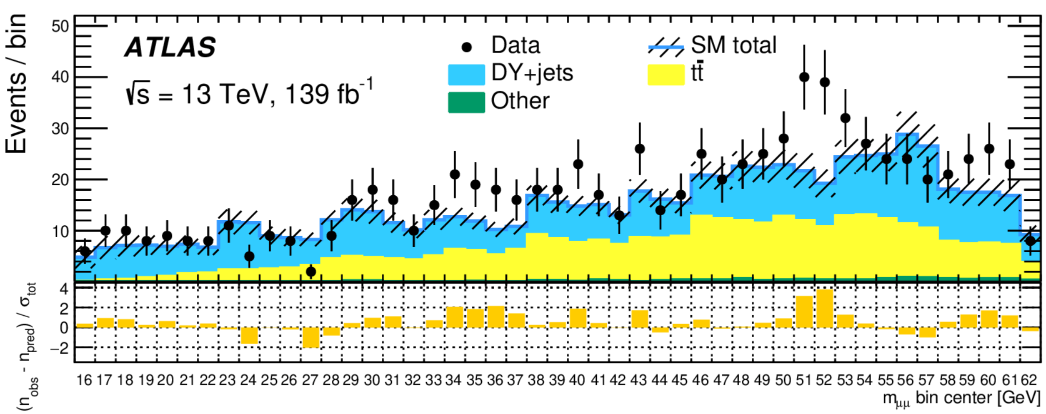
SSML events are also generic signatures of the production of heavy particles which decay electroweakly (W/Z bosons in cascade)

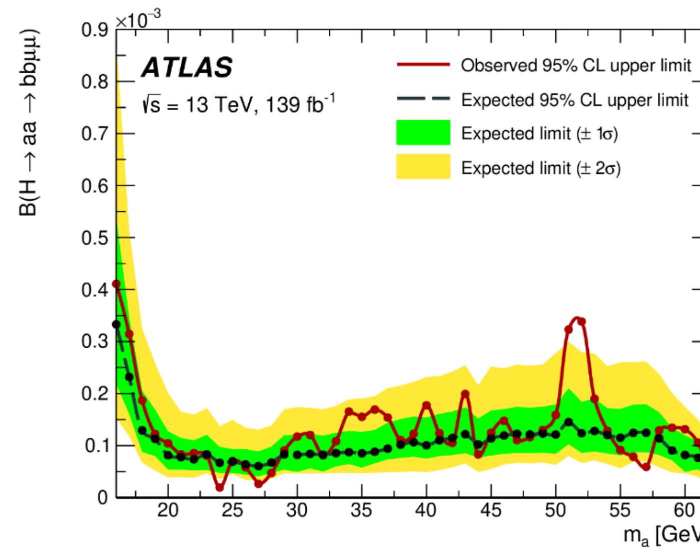
Search for h→*aa*→bbμμ





Scan m_a at steps in 1 or 1.5 GeV steps, requiring $m_{\mu\mu} \approx m_{bb}$ and consistent with m_a, search for excess in $m_{bb\mu\mu}$ distribution at m_H.





arXiv:2110.00313

Largest excess at $m_a = 52$ GeV:

local (global) significance of $3.3(1.7)\sigma$

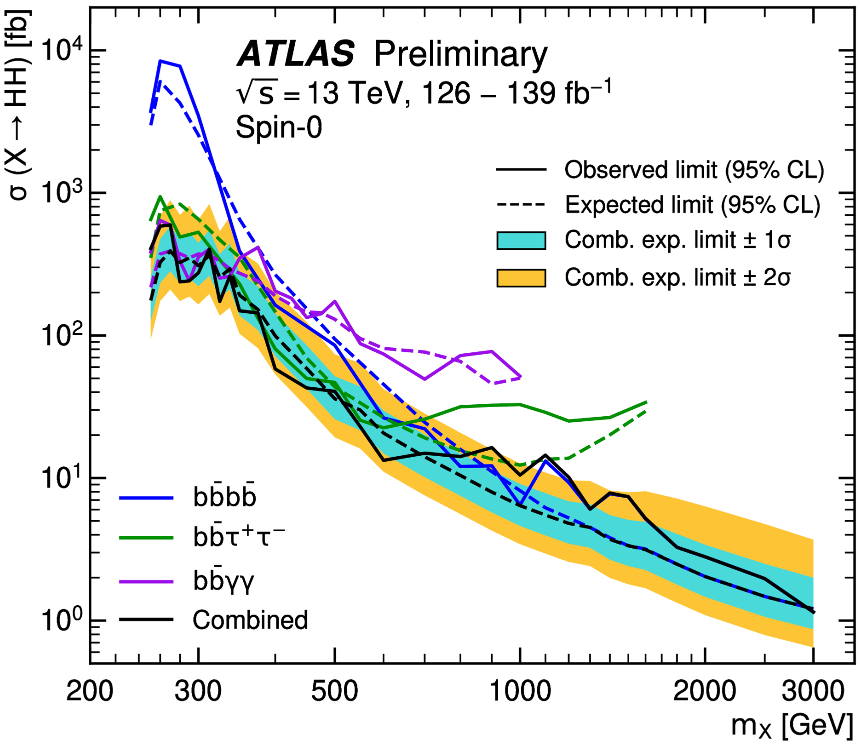
Combined search for X→hh

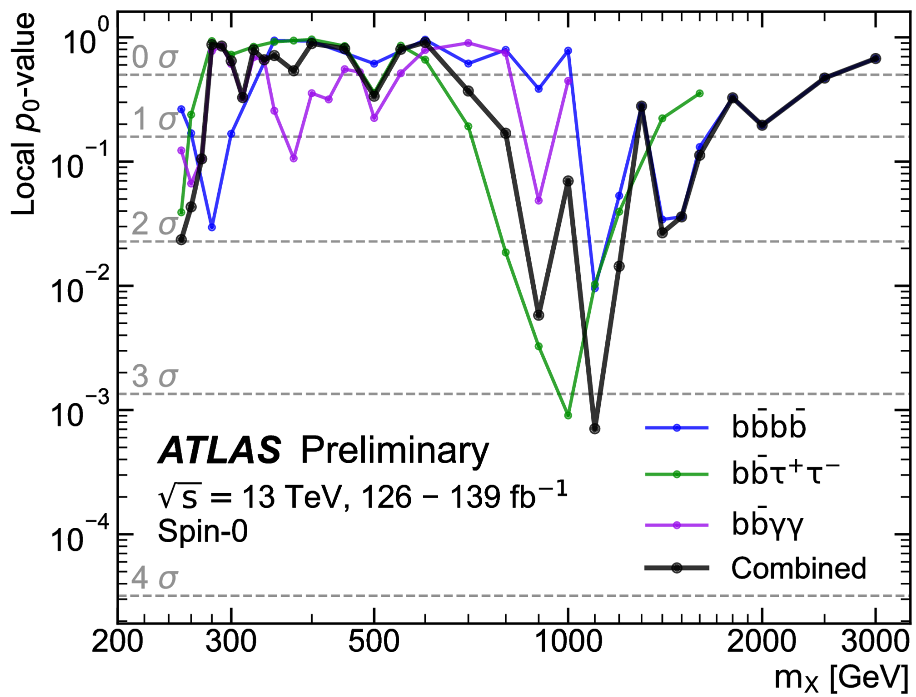
Decay channel sensitivities:

$bb\gamma\gamma$: mass low, $bb\tau\tau$: intermediate mass, $bbbb$: high mass

Most significant excess at $\sim$1.1 TeV: 3.2 $(2.1)\sigma$ local (global)

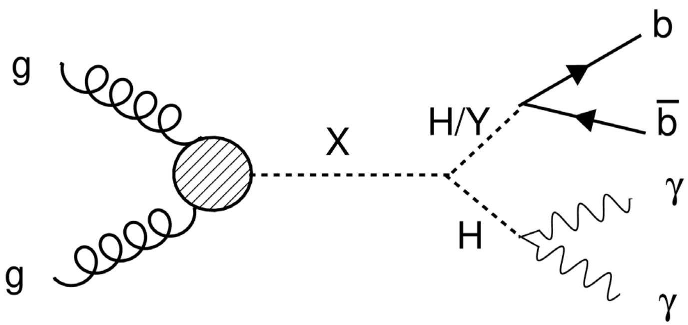
mostly from the excess observed in the $bb\tau\tau$ channel





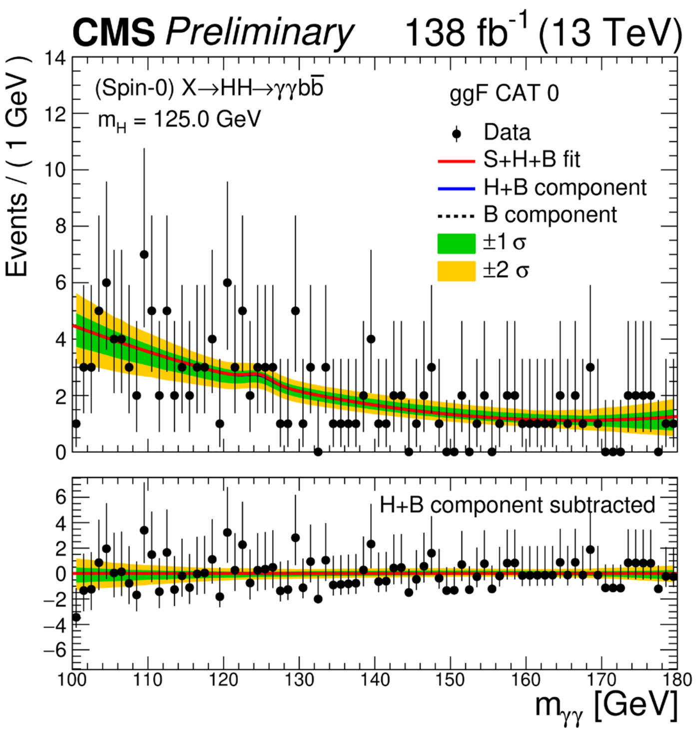
ATLAS-CONF-2021-052

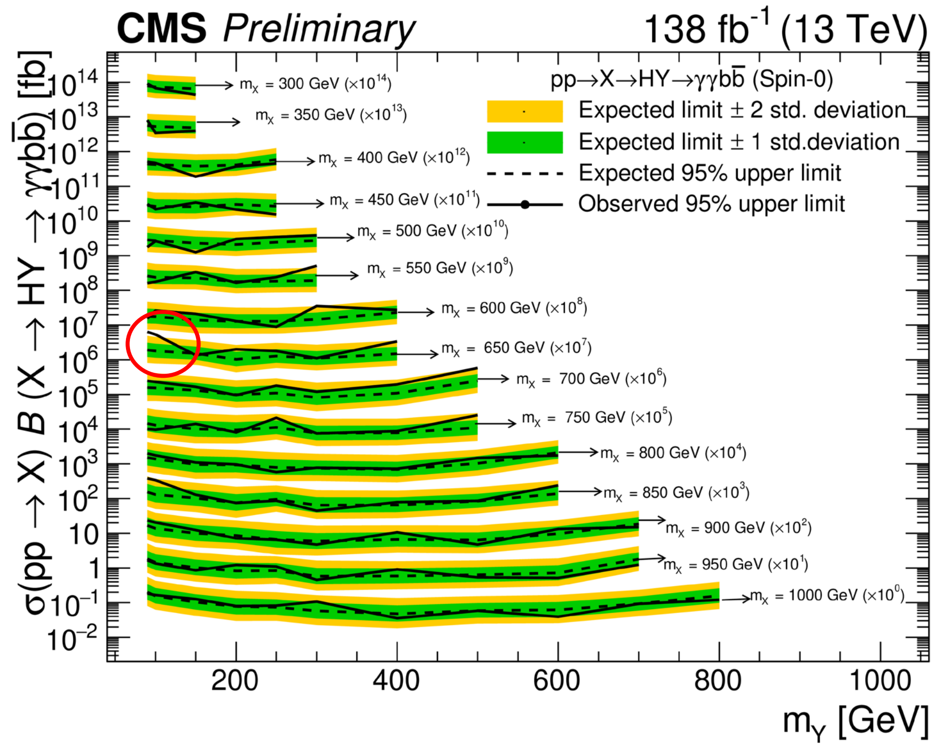
Search for X→h(Y)h→bbγγ



CMS extended the analysis to include another resonance: $Y \to bb$

2D fit to $(m_{\gamma\gamma}, m_{jj})$ to extract the signal

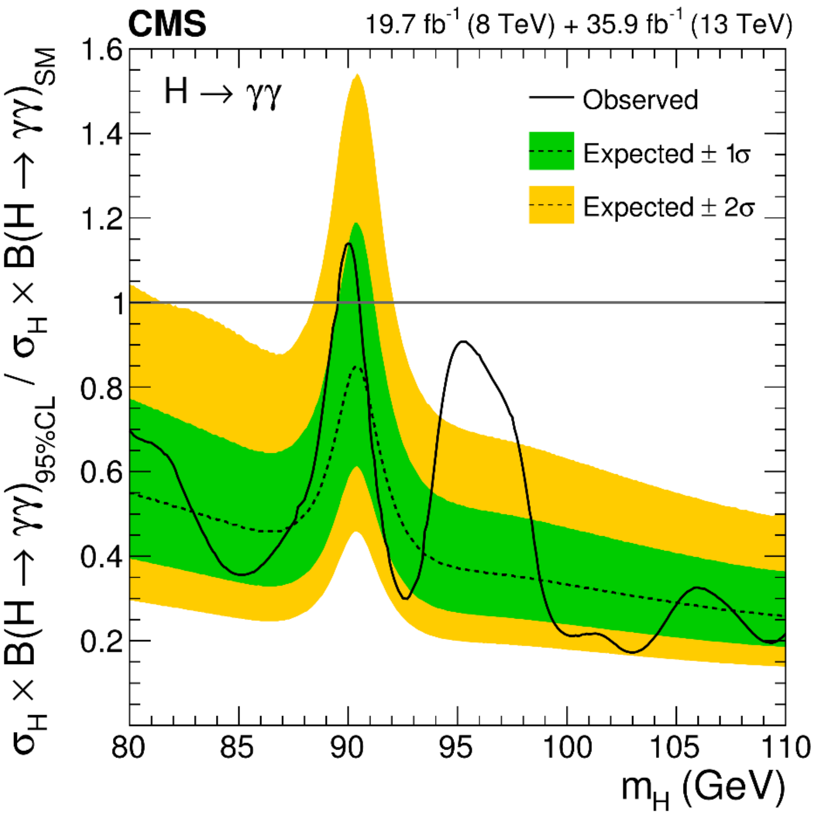


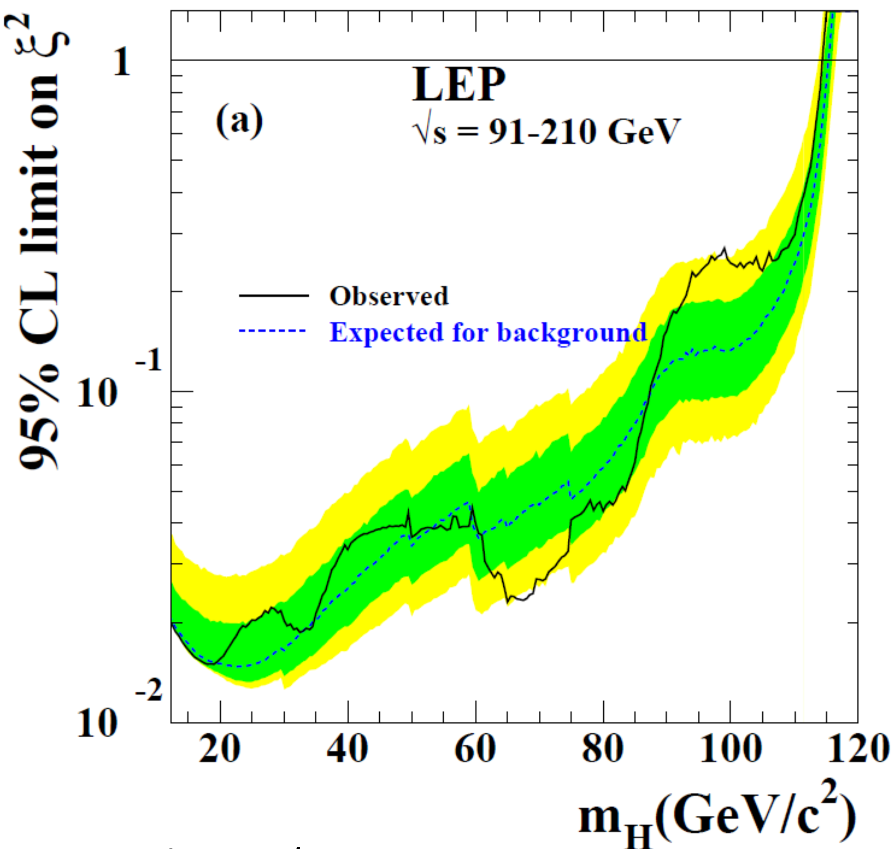


CMS-PAS-HIG-21-011

Largest excess at $(m_X, m_Y) = (650, 90)$ GeV: local (global) significance of 3.8 (2.8)σ

The “96 GeV Excesses” at the LHC





CMS: arXiv:1811.08459

hep-ex/0306033

Run 1 + Run 2 (partial) data,
Local excess $\sim 3\sigma$

In the same mass region of the $\sim 2\sigma$ excess observed at LEP

See theoretical speculation: arXiv:2003.05422 (Biekotter et al.)
Eagerly waiting for update from CMS and results from ATLAS.

Search for $H \to WW$

Signal model:

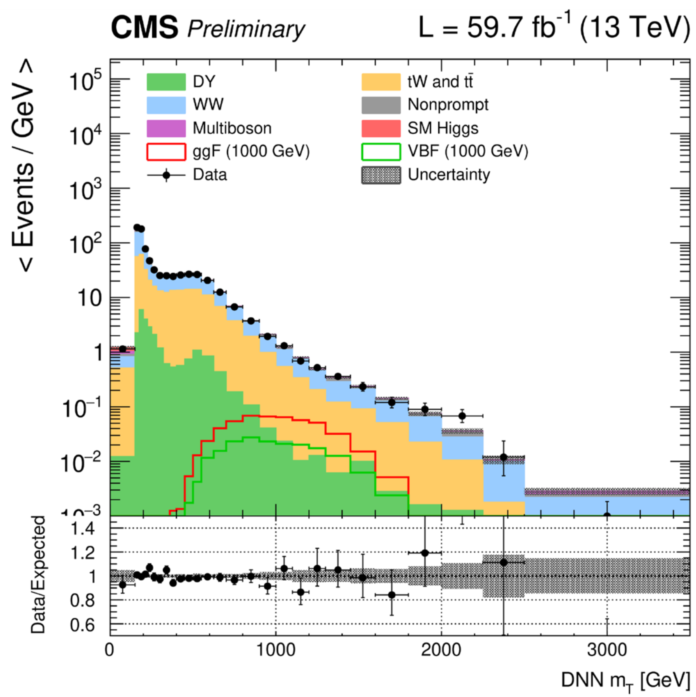
both ggF and VBF production with the varying fraction,

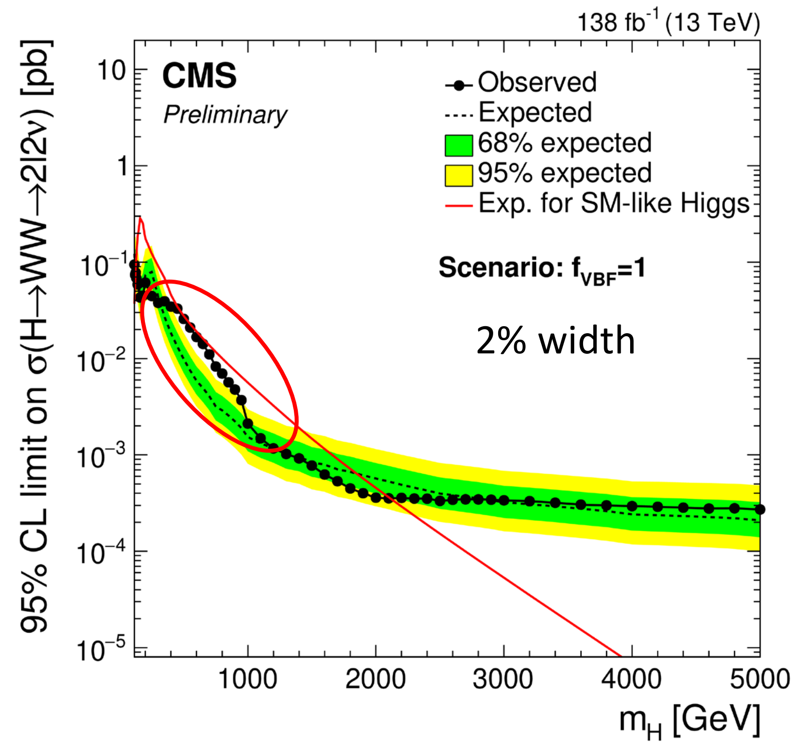
resonance width from 0.1-10%, including interference for $m_H > 300$ GeV

Analysis:

Final states considered: ee, $\mu\mu$, and $e\mu$

mass sensitive DNN as the final discriminant

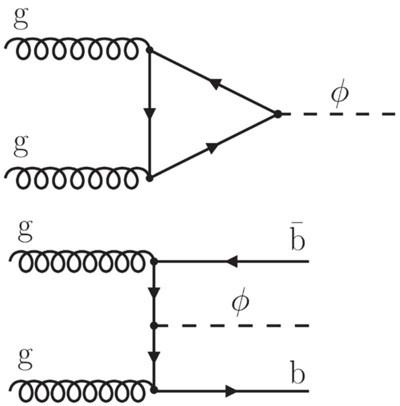




CMS-PAS-HIG-20-016

Largest excess at $m_H = 650$ GeV for $f_{VBF} = 1$: local (global) significance of $3.8(2.6)\sigma$

Search for H→ττ



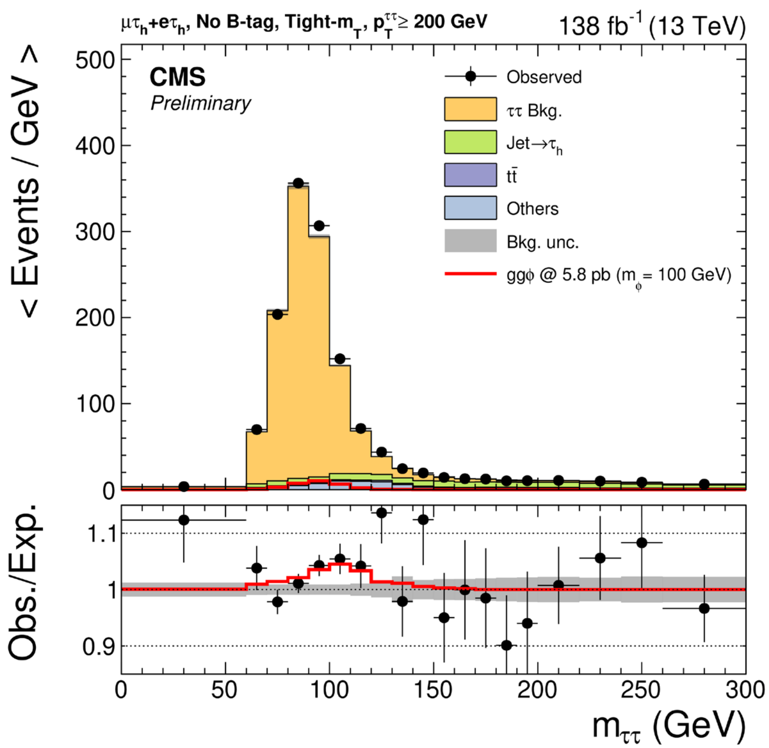
Signal model: $gg\phi$ and $bb\phi$ production

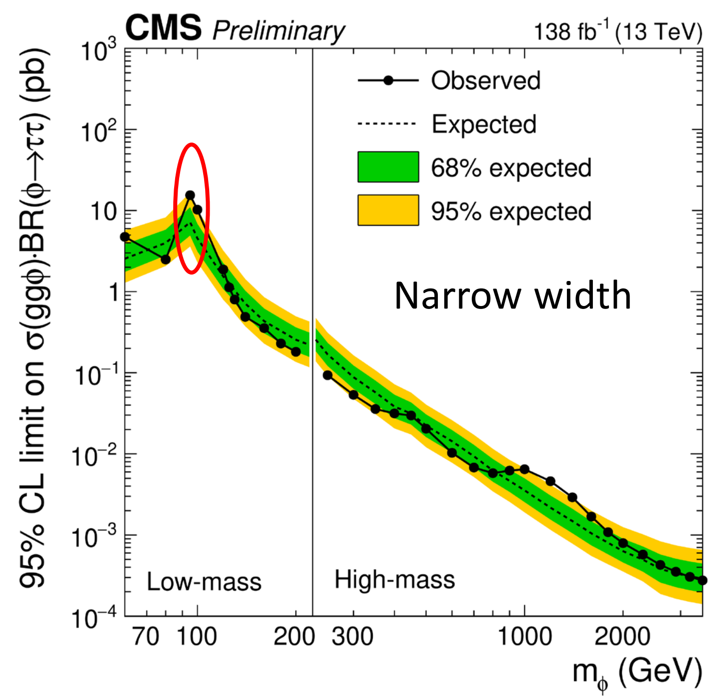
Analysis:

Final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$,

b-tagging for $gg\phi$ and $bb\phi$ separation,

Discriminant: $m_{\tau\tau}$ for low mass and m_T^{tot} for high mass





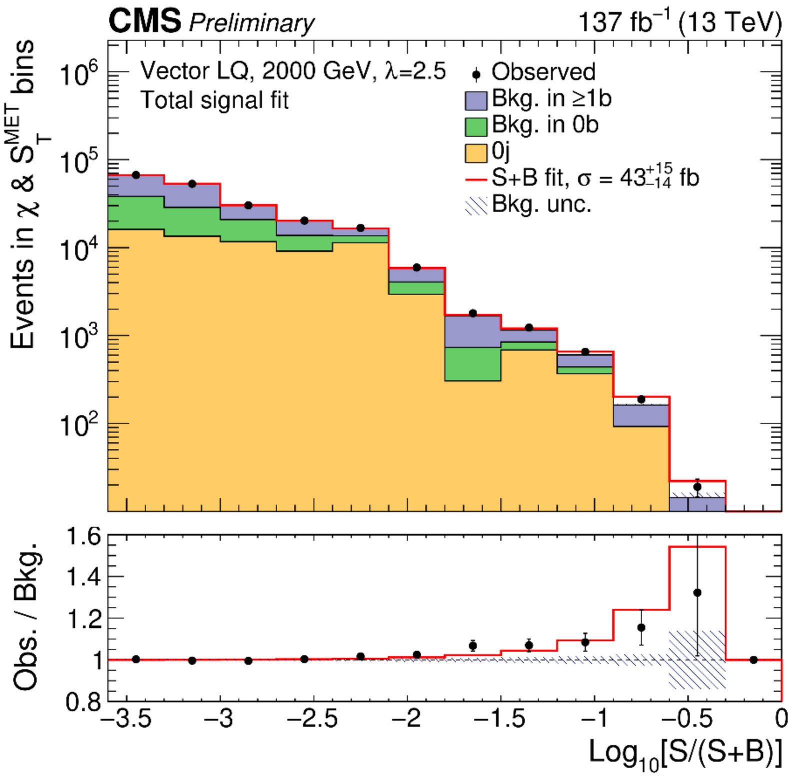
CMS-PAS-HIG-21-001

Largest excess at $m_H = 100$ GeV:

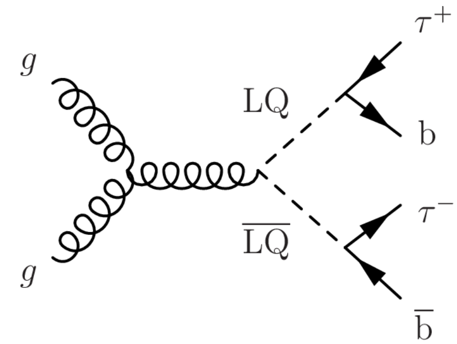
local (global) significance of $3.1(2.7)\sigma$

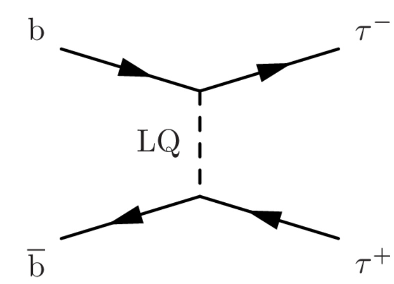
Search for Leptoquarks

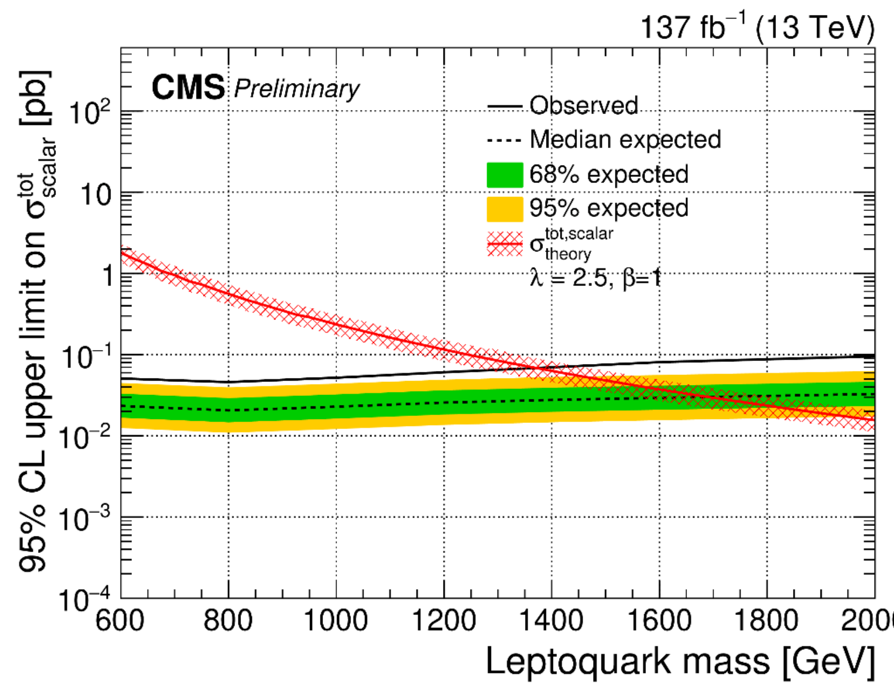
Leptoquark (LQ) is a possible explanation of the LFU violation, see *e.g.* arXiv:1609.07138



CMS-PAS-EXO-19-016







An excess of $\sim 3\sigma$ over a wide LQ mass (dominated by the non-resonant search)

Heavy Long-Lived Charged Particle

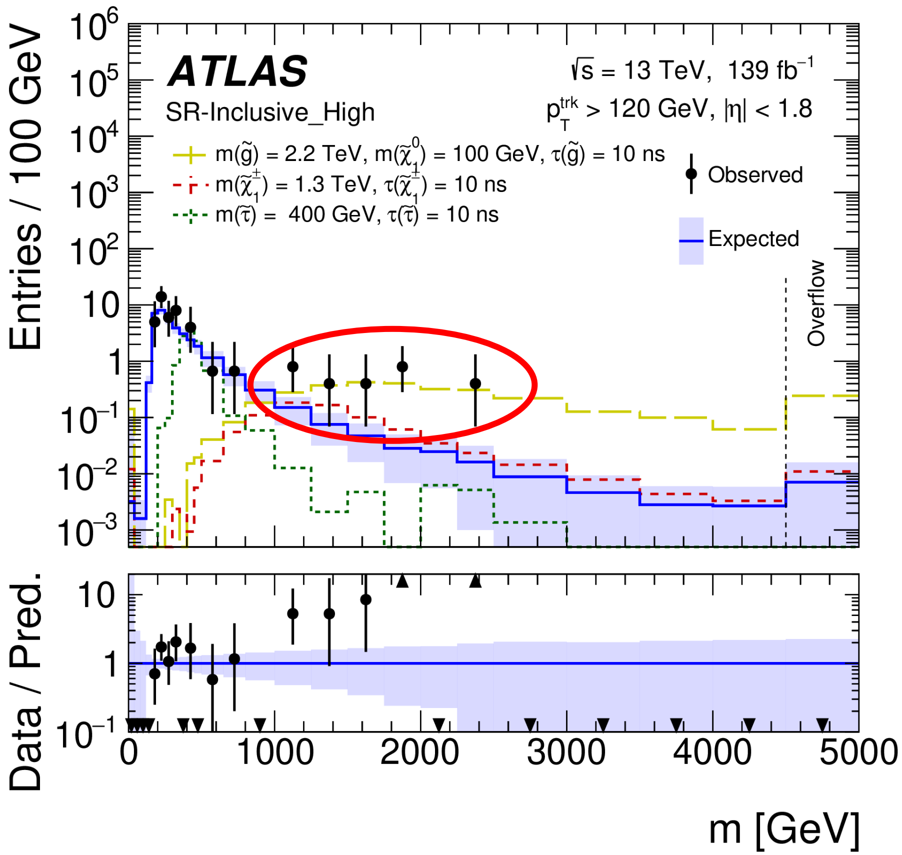
For non-relativistic charged particles

$$\frac{dE}{dx} \sim \frac{1}{(\beta\gamma)^2} \sim \left(\frac{m}{p}\right)^2 \Rightarrow$$

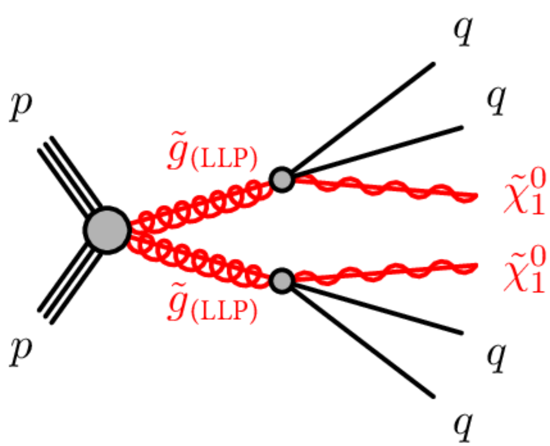
Estimate particle mass from dE/dx and momentum measurement.

dE/dx measurement from the pixel detector with $r \sim 13$ cm, sensitive to particles with lifetime down to ~ 1 ns

arXiv:2205.06013



Example model



In samples with large E_T^{miss}, observed an excess of events with large dE/dx, corresponding to a local (global) significance of 3.6 (3.3)σ.

Summary

There are a number of anomalies, with tensions over 3σ with the SM predictions, particularly in flavor physics. Could they be signs for BSM physics?

Extensive programs in searching for both non-SM decays of the 125 GeV Higgs boson and for additional Higgs bosons or other resonances. There are a few excesses here and there that need to be followed up in new data, but no strong evidence for BSM physics so far.

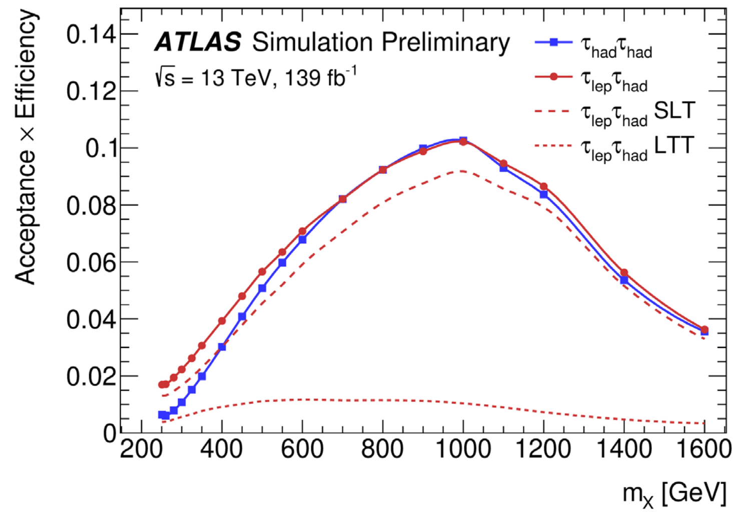
More data, improved measurements, searches in related processes or final states are crucial to ascertain the natures of these anomalies. Also important to search in unusual places…

Additional Slides

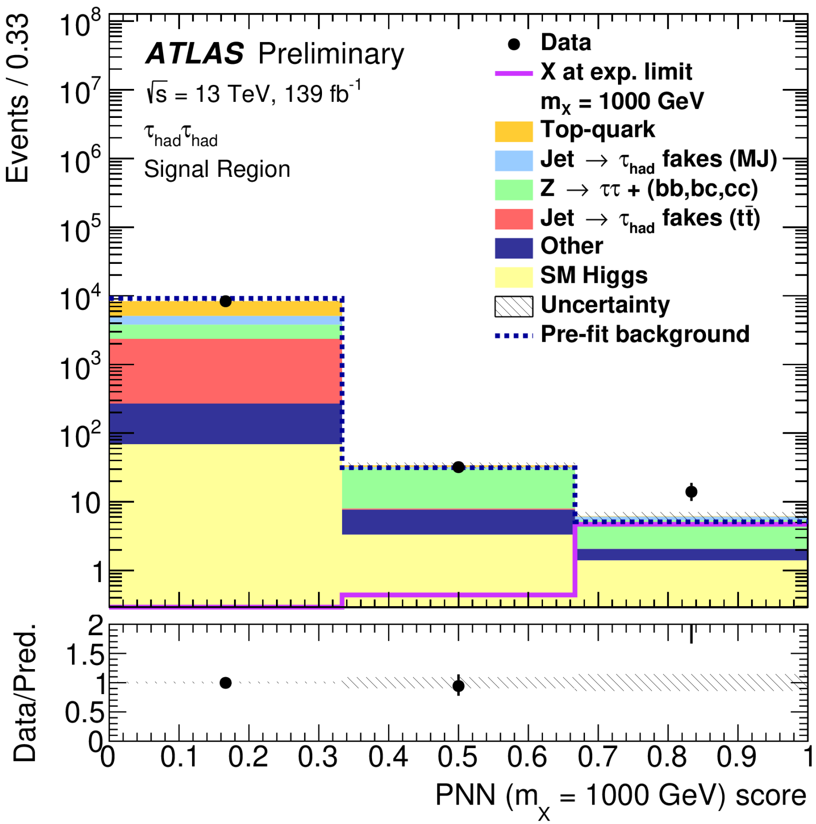
Search for X→hh→bbττ

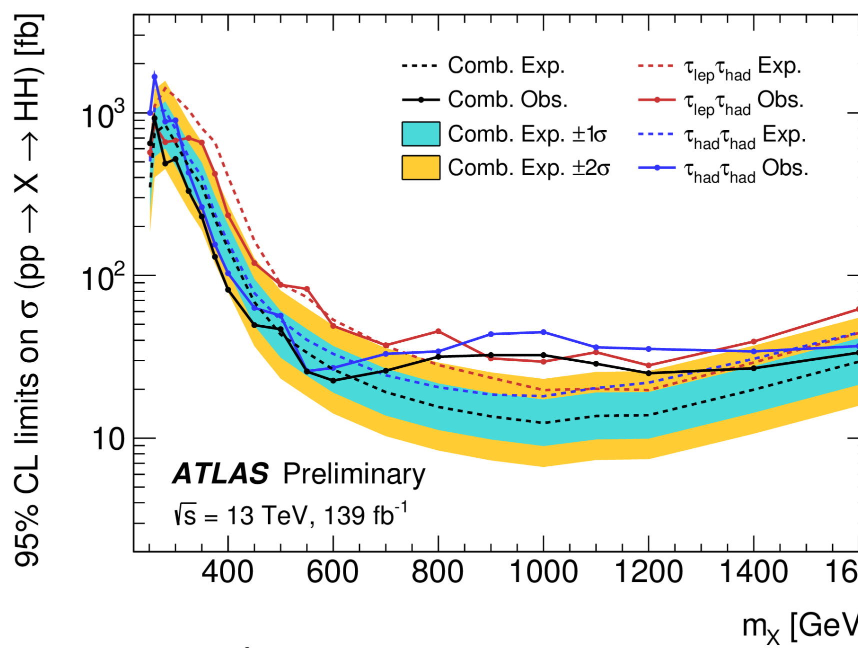
Final states: $bb\tau_h\tau_h$, $bb\tau_\ell\tau_h$

Resolved, losing efficiencies at large m_X



Parameterized NN for S-B separation
and S extraction





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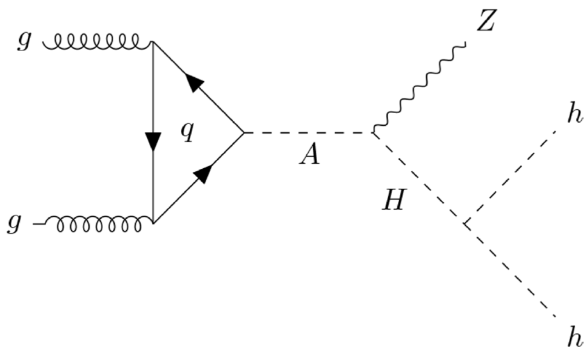
Broad excess at ~ 1 TeV:
local (global) significance 3.0 (2.0)σ

Search for A→ZH→Zhh

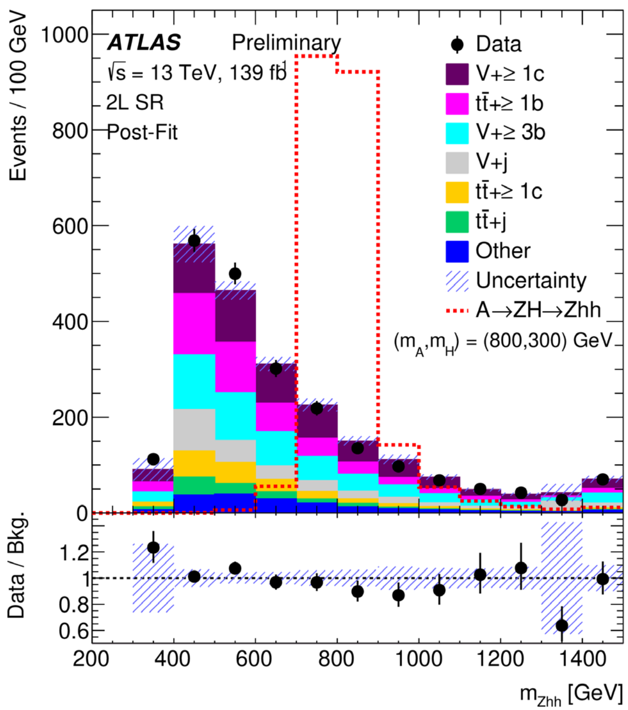
Signal models: 2HDM, NW H and A width up to 20%
Signatures: 4 resonances, full reconstruction

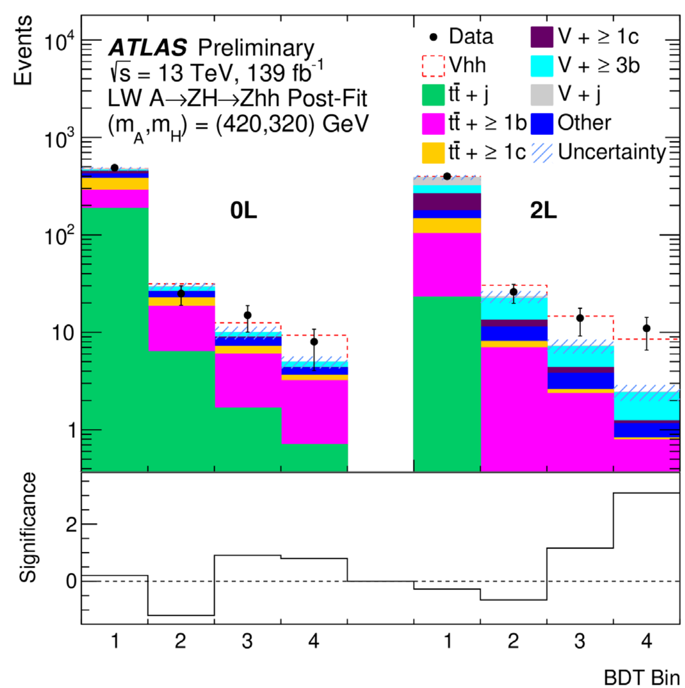
Main backgrounds: Z+jets
BDT for S-B separation and S extraction



Largest excess for a large-width (20%) A

Observed (expected) significance of 3.8 (2.8)σ at $(m_A, m_H) = (420, 320)$ GeV





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