Existing anomalies @ CMS

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Hunting for new physics

- Precision measurements of SM processes
  - Understand SM backgrounds, look for deviations or anomalies
- Searches/measurements of rare SM processes
  - Take advantage of the large LHC datasets and look for (significant) enhancement from beyond-the-SM (BSM) particles

SM as a tool for discovery

- Direct searches for BSM particles
  - Go in new directions with new models, challenging topologies, enlarged parameter space ➔ innovate!

Explore new frontiers: Go beyond the SM

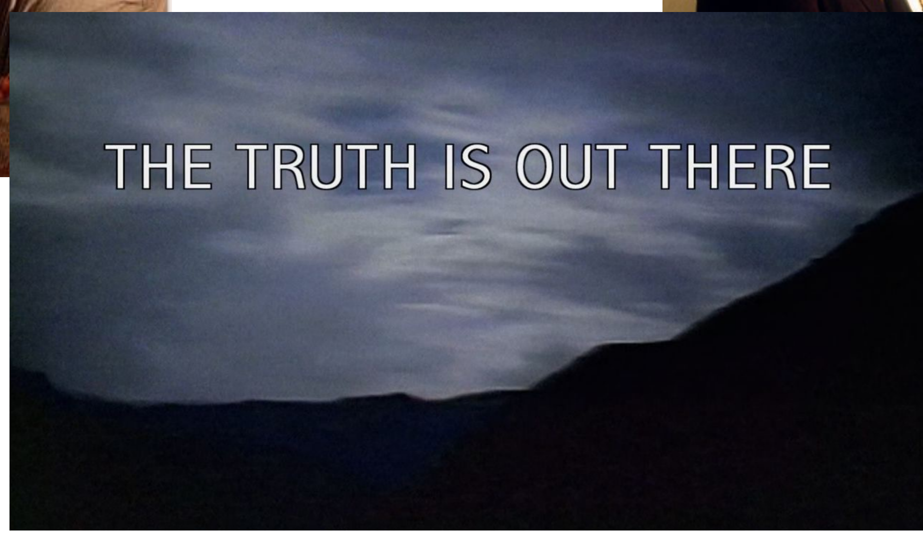
Take advantage of state-of-the-art analysis methods, data mining, machine learning, new technologies, upgraded detectors…

Achieved by…

Good collaboration between theorists and experimentalists!

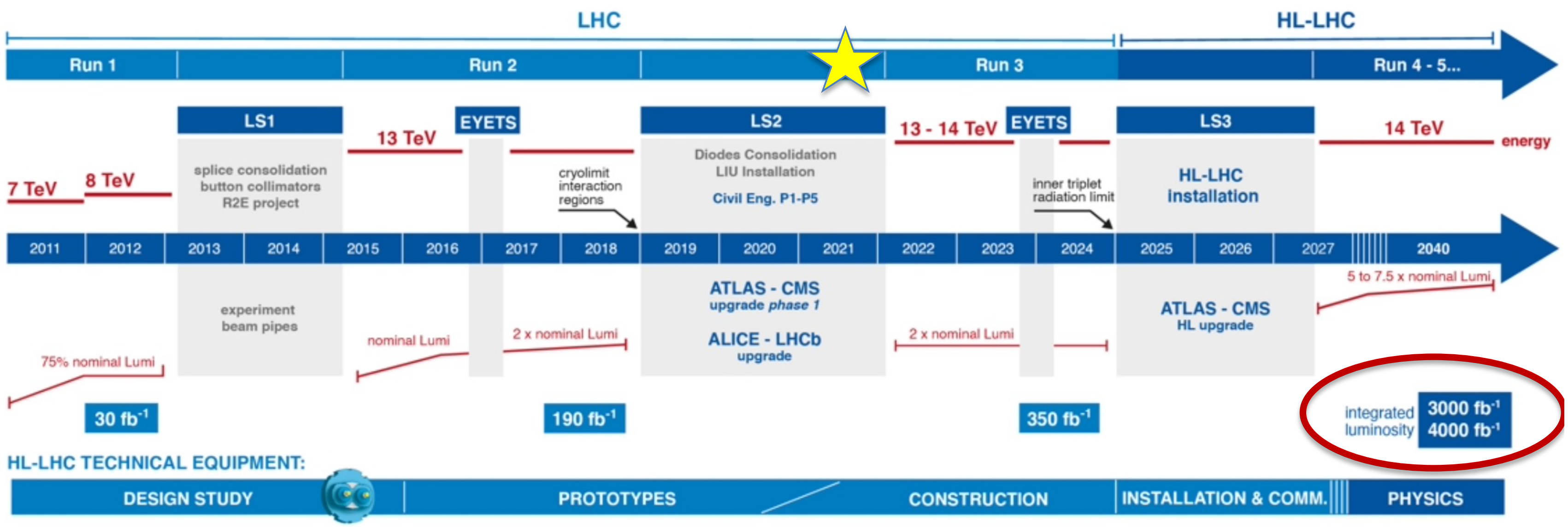
Theorist: comes up with (sometimes crazy) idea

Experimentalist: debunks theory



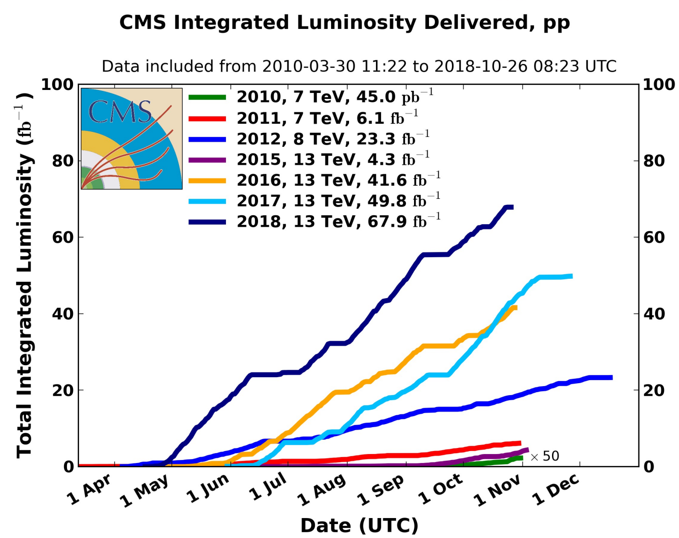
Inspired by P. Q. Hung @ Moriond EWK

LHC/HL-LHC Program

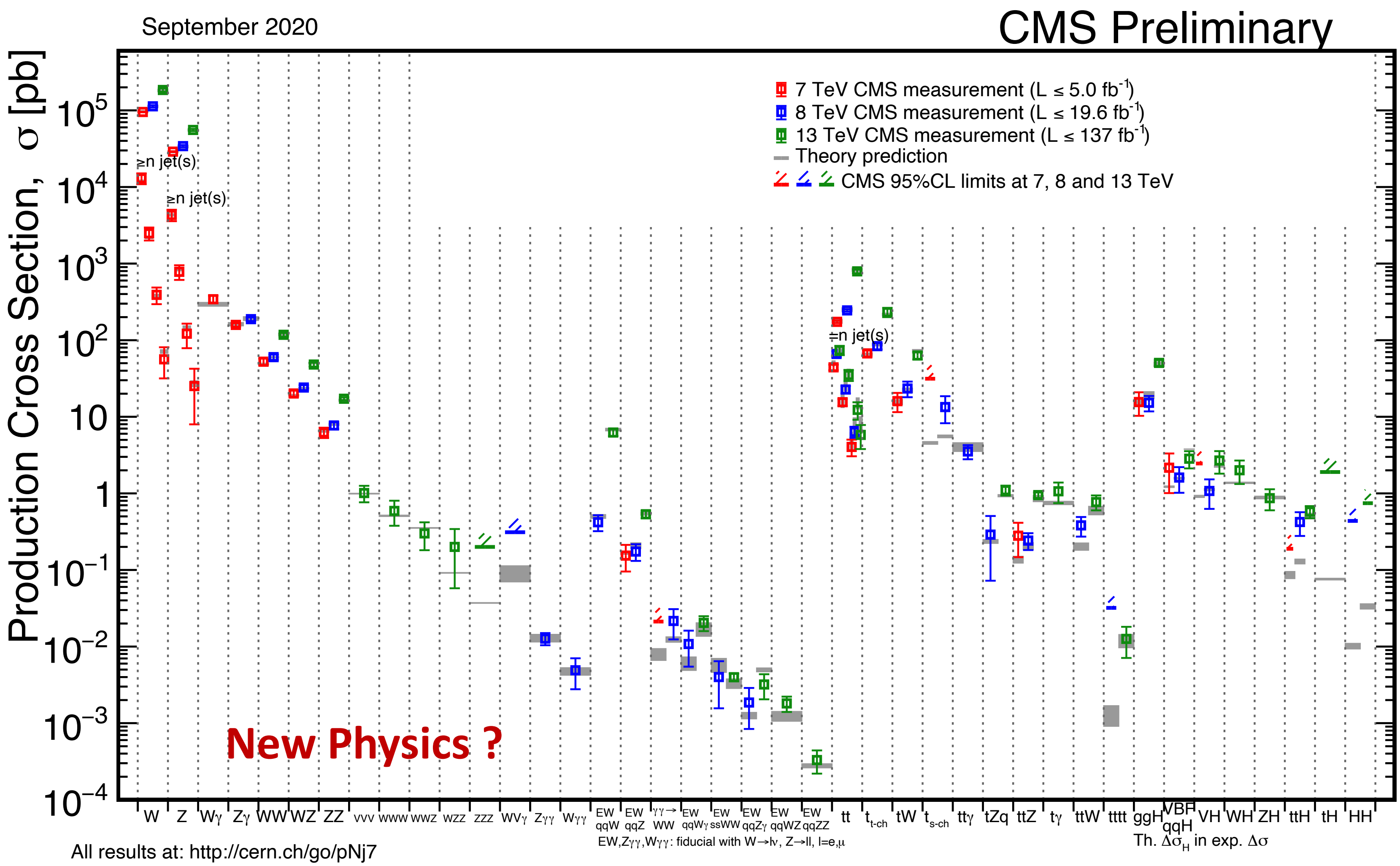


Excellent performance by the LHC and the experiments: ~140 fb^{-1} good for analysis during Run 2

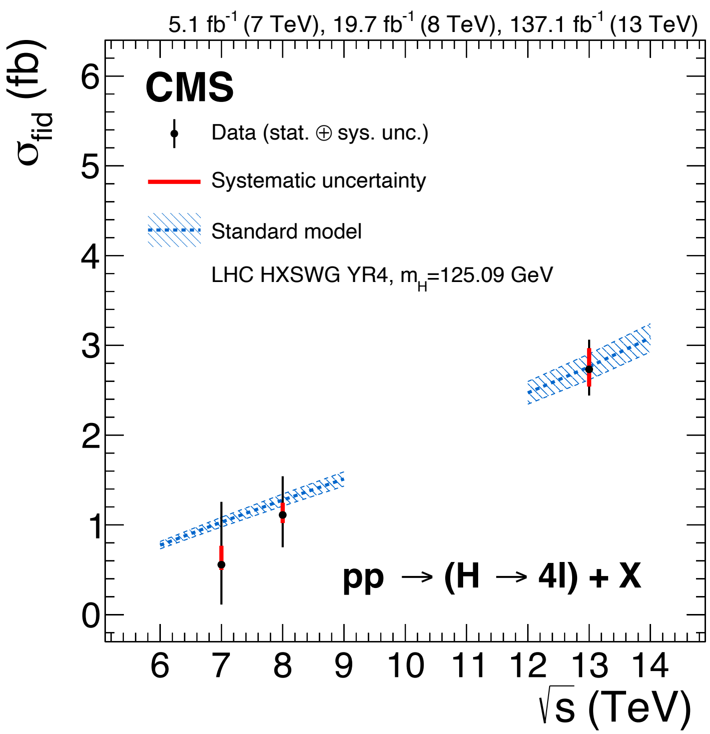
But 95% of the total LHC data still to come (and be studied)!

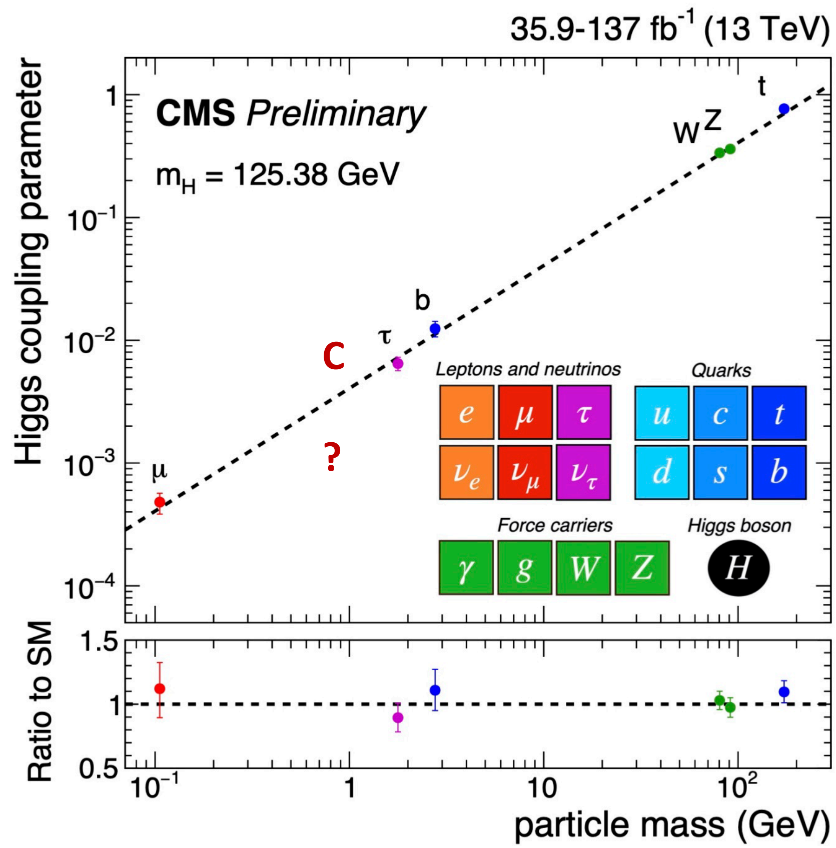


Standard Model reigns supreme



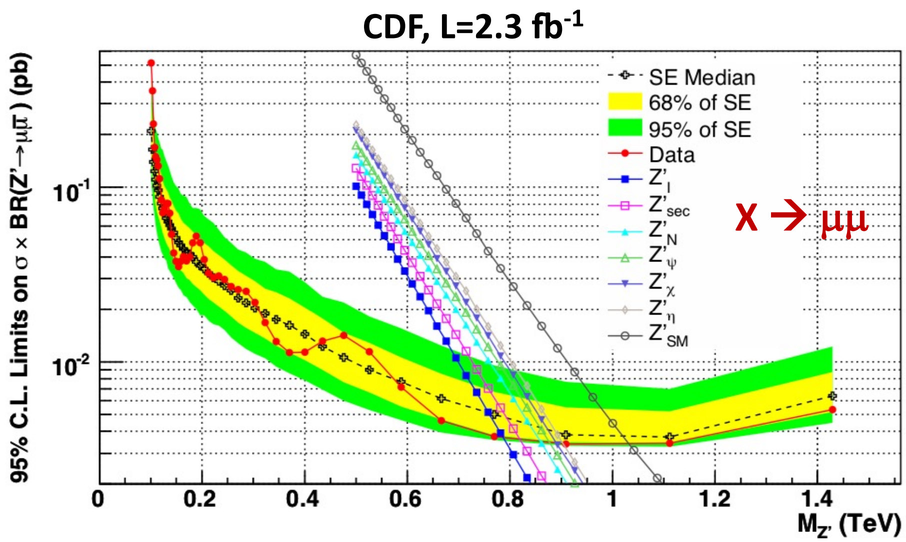
The legacy from Run 1 and Run 2



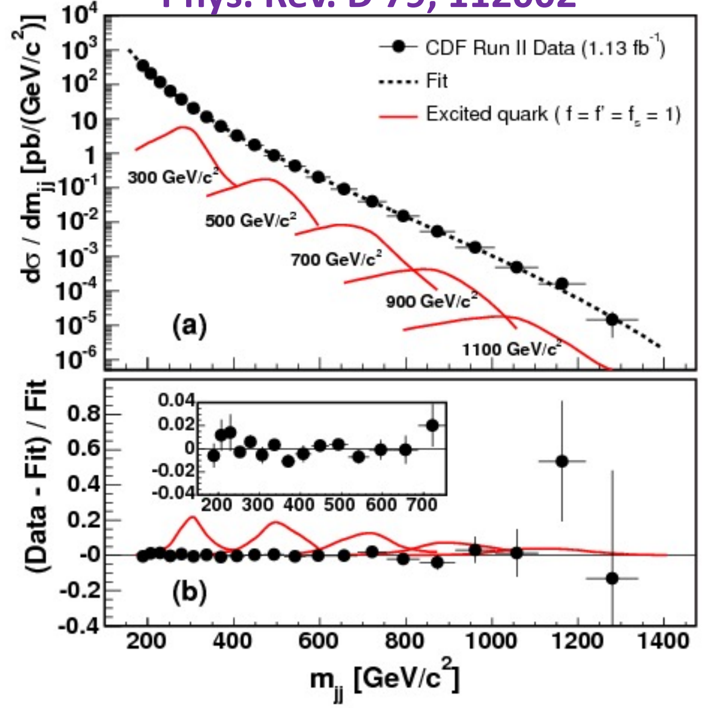


Exotic landscape ~10 years ago

PRL 102:091805,2009



Phys. Rev. D 79, 112002

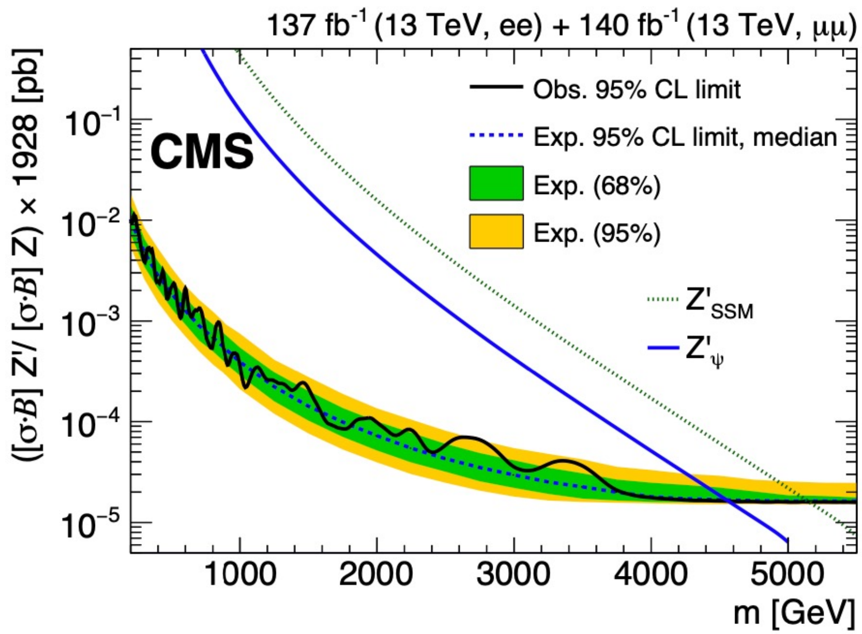


Searches for new massive resonances (di-leptons), di-jet resonances approaching ~ 1TeV

Exotic landscape circa 2021

Dilepton resonance search

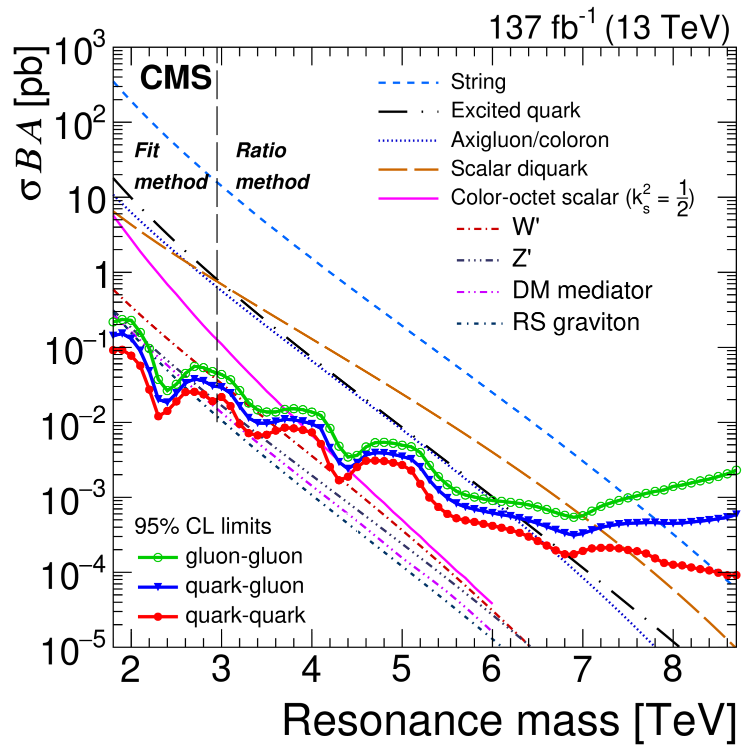
_arXiv:2103.02708



Excluding particles w/ mass ~5 TeV
i.e. > 5 times the reach from 10 years ago

Dijet resonance search

EXO-19-012



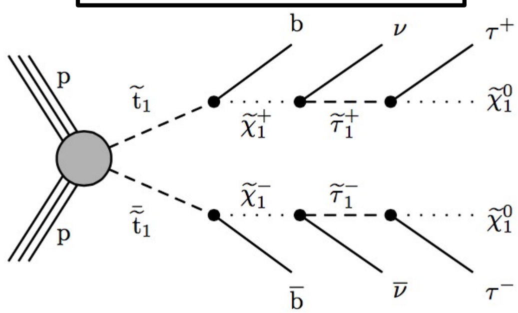
Focus now on complex topologies and weakly coupled phenomenon

Search strategies

Rich and diverse search landscape

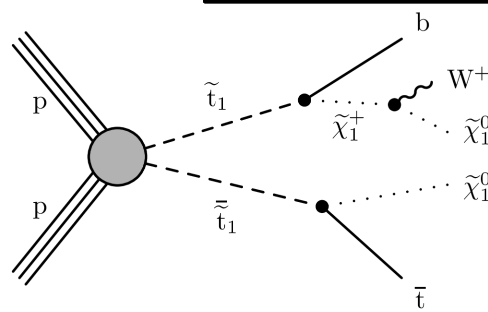
- Big inclusive searches complemented by dedicated searches that target gaps in coverage
- Incorporate machine learning for Higgs, b, charm, top tagging
- Improve lepton reconstruction/ID for low p_T leptons; improve analysis techniques

Longer decay chains

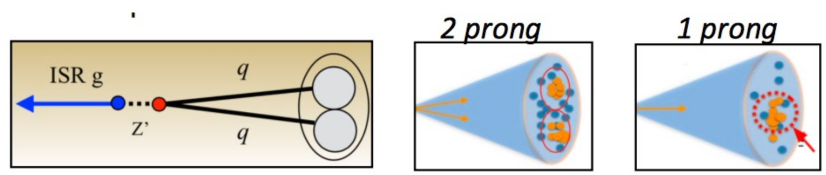


e.g. consider taus in stop decay chains (traditional searches veto taus or don't focus on them

Challenging topologies

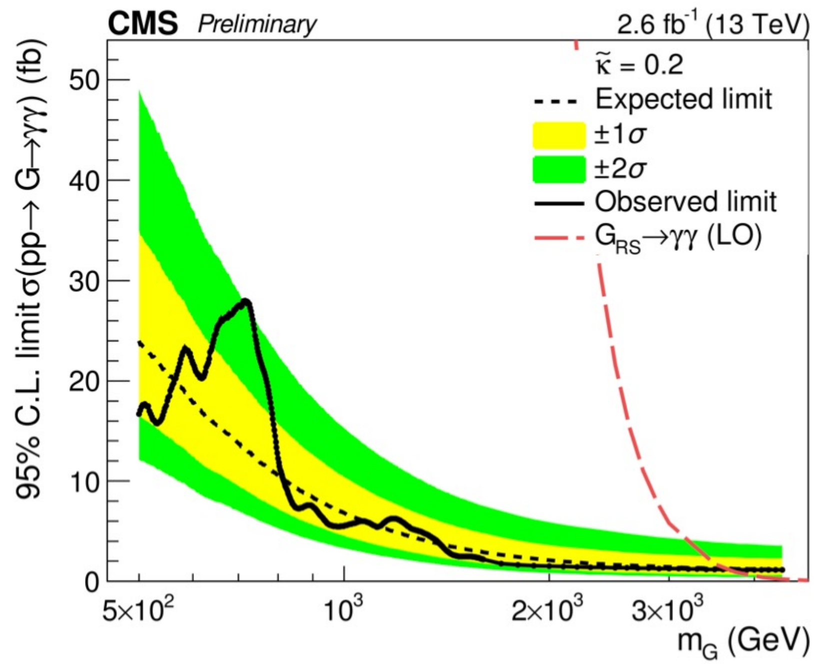


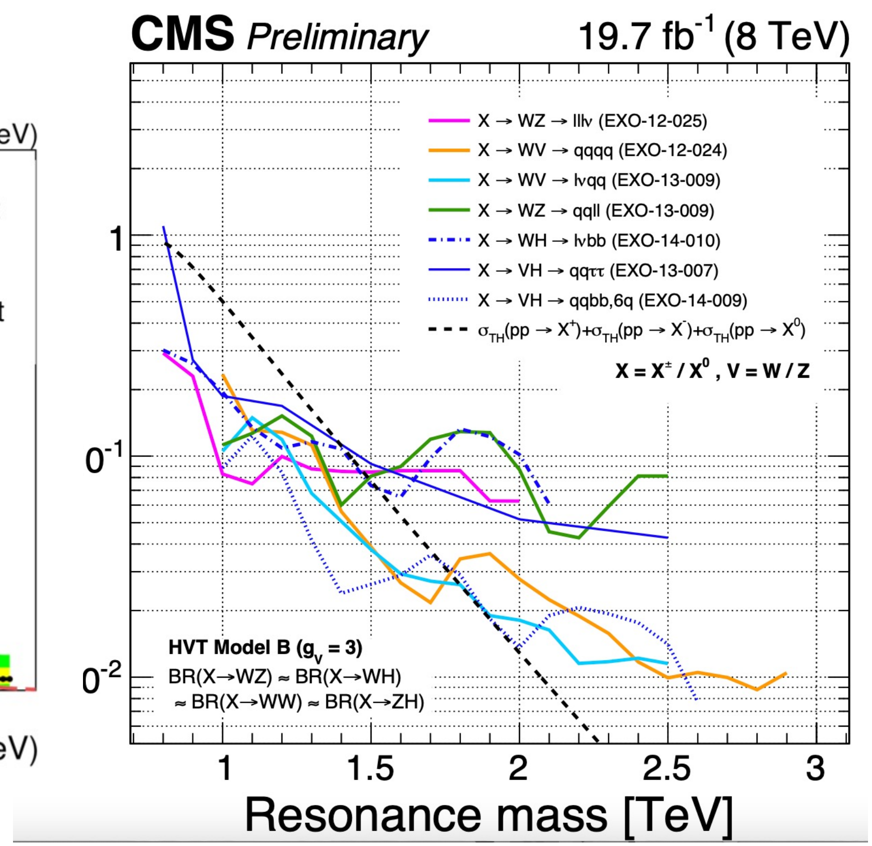
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim m_t$



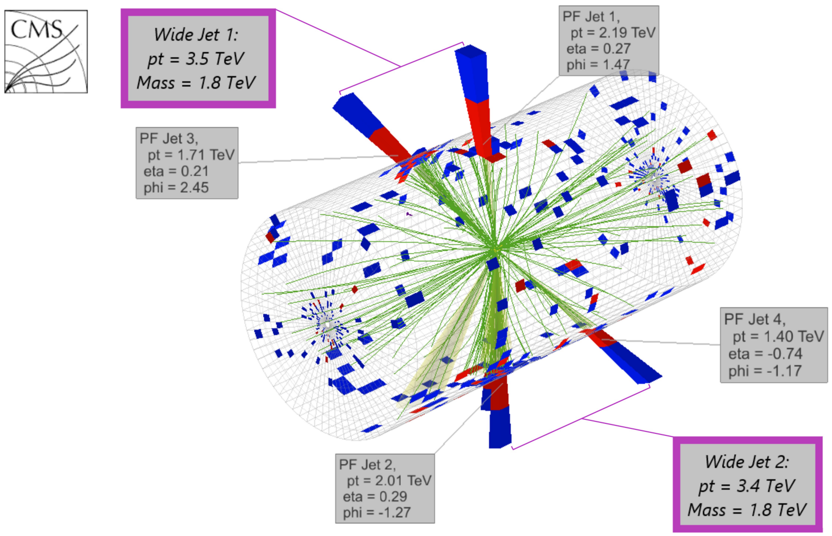
A lot of ground covered in Run 2; more luminosity awaits in Run 3

Run 1 and Run 2 legacy ?



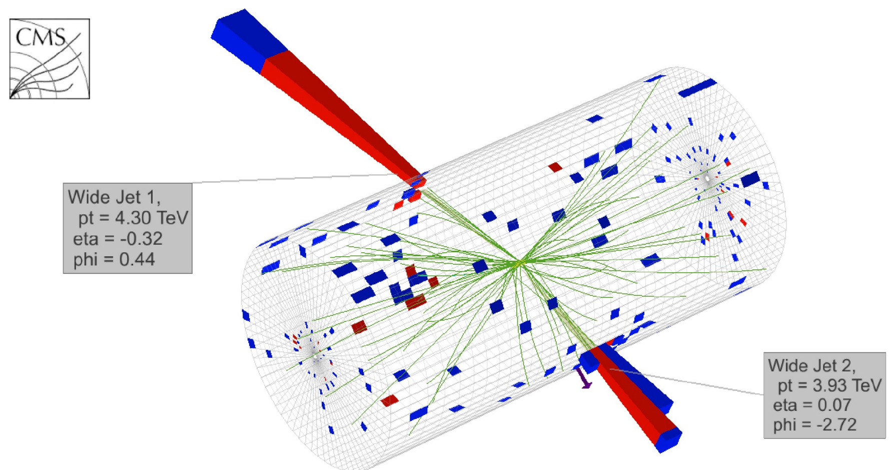


Exploring anomalies



~8 TeV dijet events

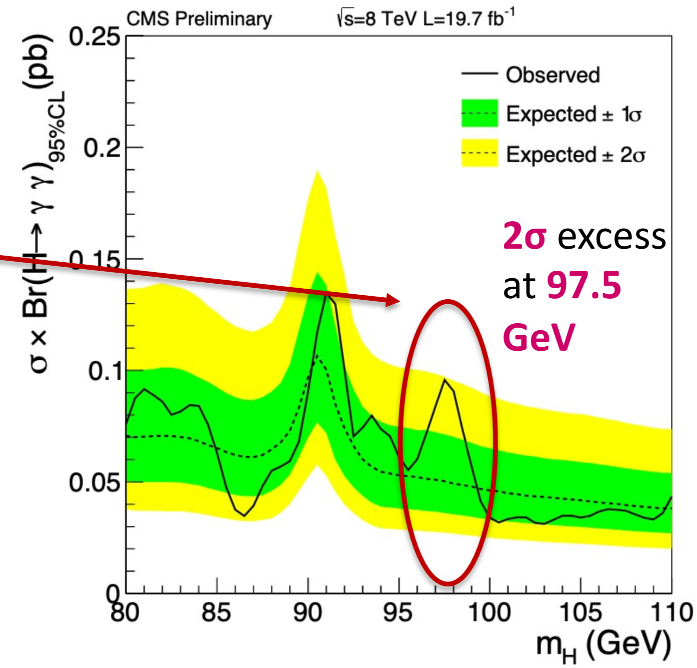
EXO-19-012



Dijet Mass = 8.4 TeV

Low-mass di-photon search

- Search for low-mass di-photon resonance in the 70 – 110 GeV mass range
- Dataset: 35.9 fb^{-1} @ 13 TeV (2016) + combination with Run 1 analysis
- Clean final state topology (2 isolated γ)
- Large smoothly decreasing background (continuum)
  - Reducible (jet-jet, γ-jet w/ jet faking photon)
  - Irreducible ($\gamma\gamma$)
- Based on standard H-> $\gamma\gamma$ analysis
  - Lower E_T, a bit more aggressive selection criteria
  - Edge of the trigger acceptance
  - Important Z → e+e- background (stricter electron veto, include DY in bkg model)

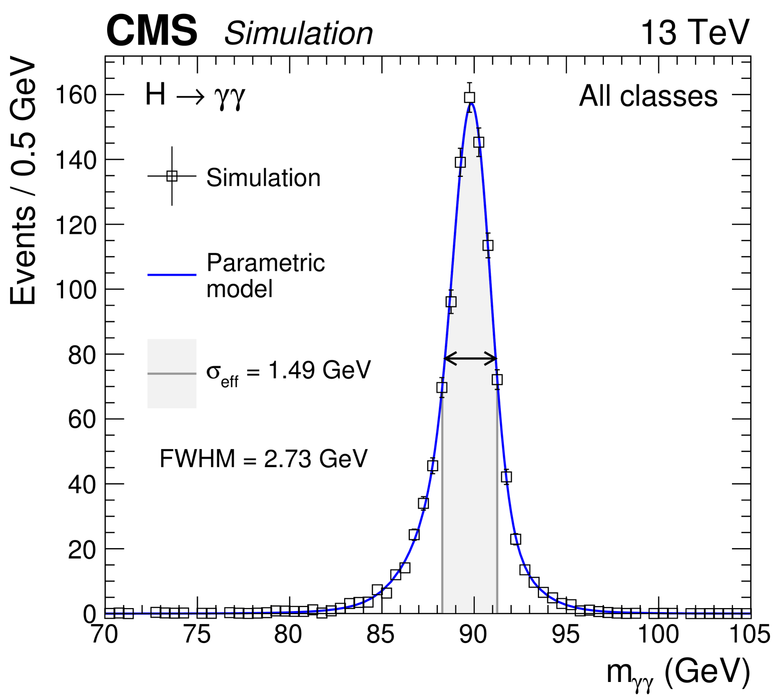


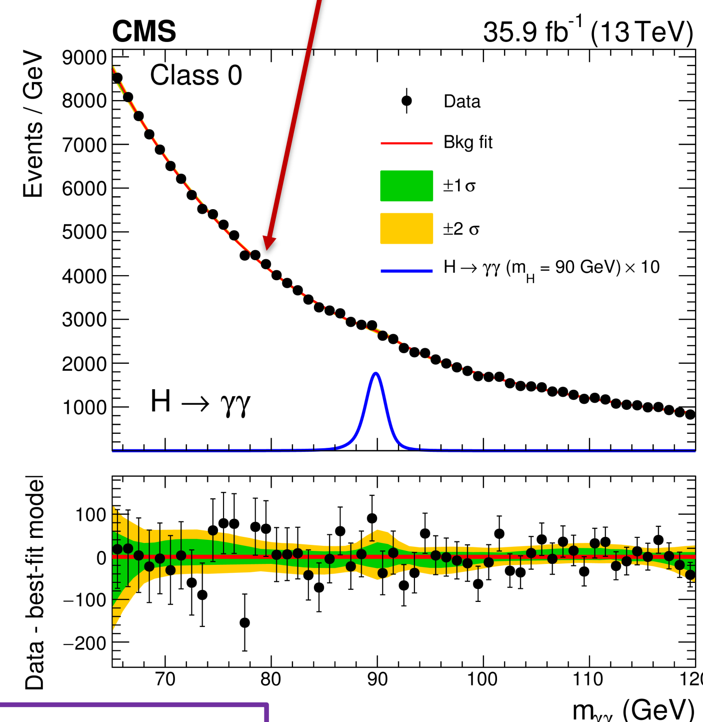
Run 1 analysis limited to 80 – 110 GeV range due to the trigger

Low-mass di-photon search

Signal
Parametric model extracted from **simulation : H→ γγ standard** samples for different higgs masses.

Background
Drell-Yan Parametric model extracted from **simulation : Z→e+e-**
Continuum background extracted from **data**





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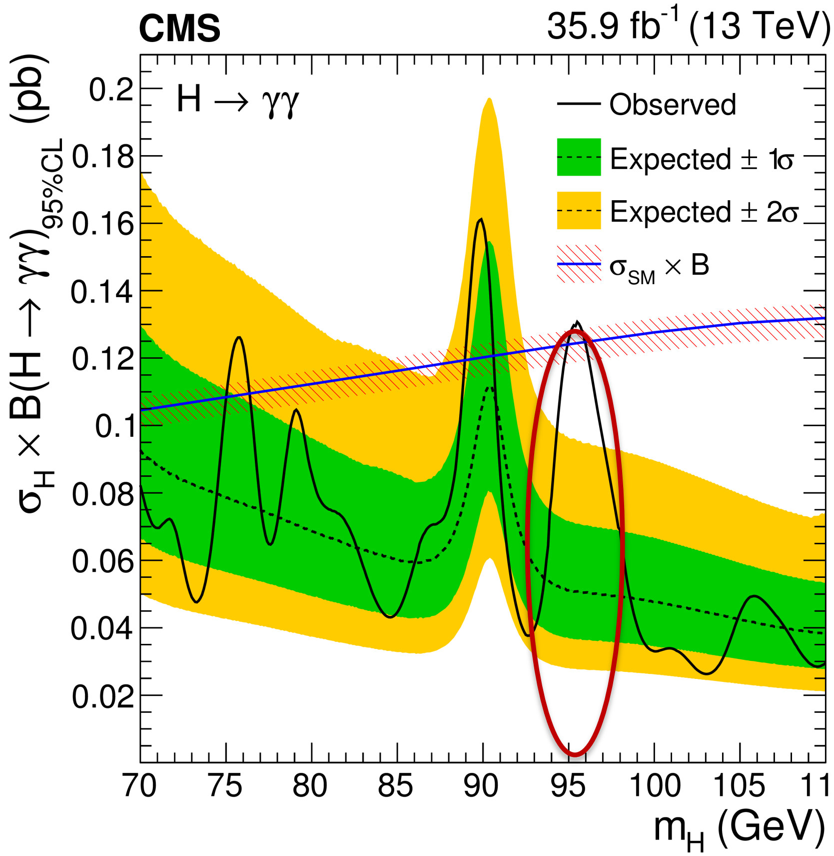
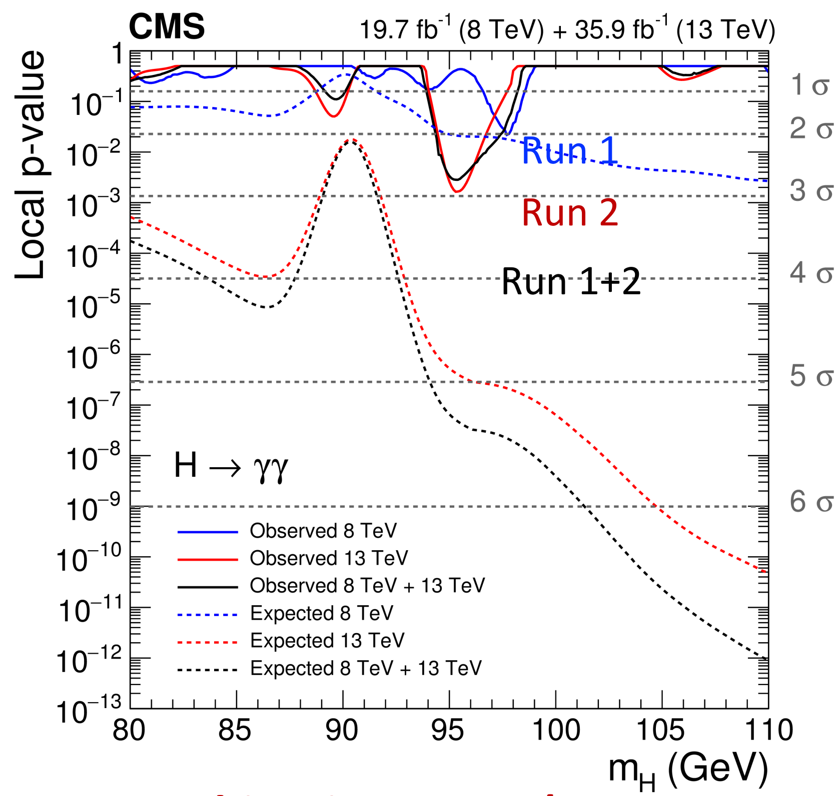
Low-mass di-photon search





2.90 σ (1.47 σ global) excess at **95.3 GeV**

Combination: 2.8 σ (1.3 σ global) excess at **95.3 GeV**

Analysis of the full Run 2 data ongoing

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Low mass search in μμbj

- Search for resonances in the 12 – 70 GeV mass range μμbj final state
- Dataset: 19.7 fb^{-1} @8 TeV, 35.9 fb^{-1} @ 13 TeV (2016)
- 2 mutually exclusive categories:
  - **SR1**: a b quark jet in the central region ($|\eta| \leq 2.4$) and at least one jet in the forward region ($|\eta| > 2.4$)
  - **SR2**: two jets in the central region, at least one of which is identified as a b quark jet, no jets in the forward region, and low missing transverse momentum

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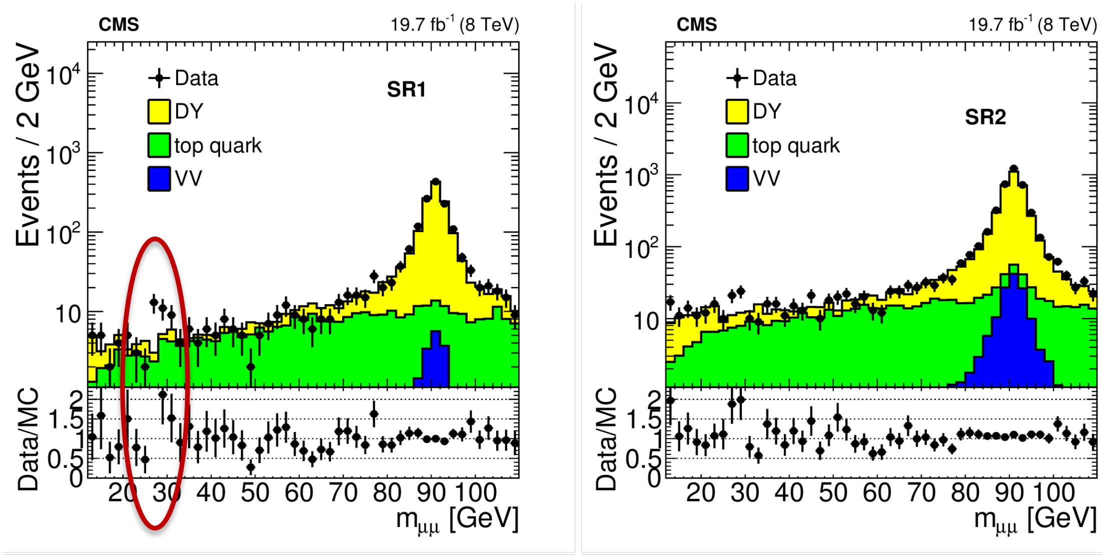
Event category	SR1 Additional forward jet	SR2 Additional central jet
Muons	OS, $p_T > 25\,\mathrm{GeV}, |\eta| < 2.1$	
$m_{\mu\mu}$	$m_{\mu\mu} > 12\,\mathrm{GeV}$	
b-tagged jet	$p_T > 30\,\mathrm{GeV}, |\eta| \leq 2.4$	
Additional jet	$p_T > 30\,\mathrm{GeV}, 2.4 < |\eta| < 4.7$	$p_T > 30\,\mathrm{GeV}, |\eta| \leq 2.4$
Jet veto	No other jets $p_T > 30\,\mathrm{GeV}, |\eta| \leq 2.4$	No jets $p_T > 30\,\mathrm{GeV}, 2.4 < |\eta| < 4.7$
p_T^{miss}	—	$<40\,\mathrm{GeV}$
$\Delta\phi(\mu\mu, \mathrm{jj})$	—	$>2.5\,\mathrm{rad}$

Low mass search in μμbj

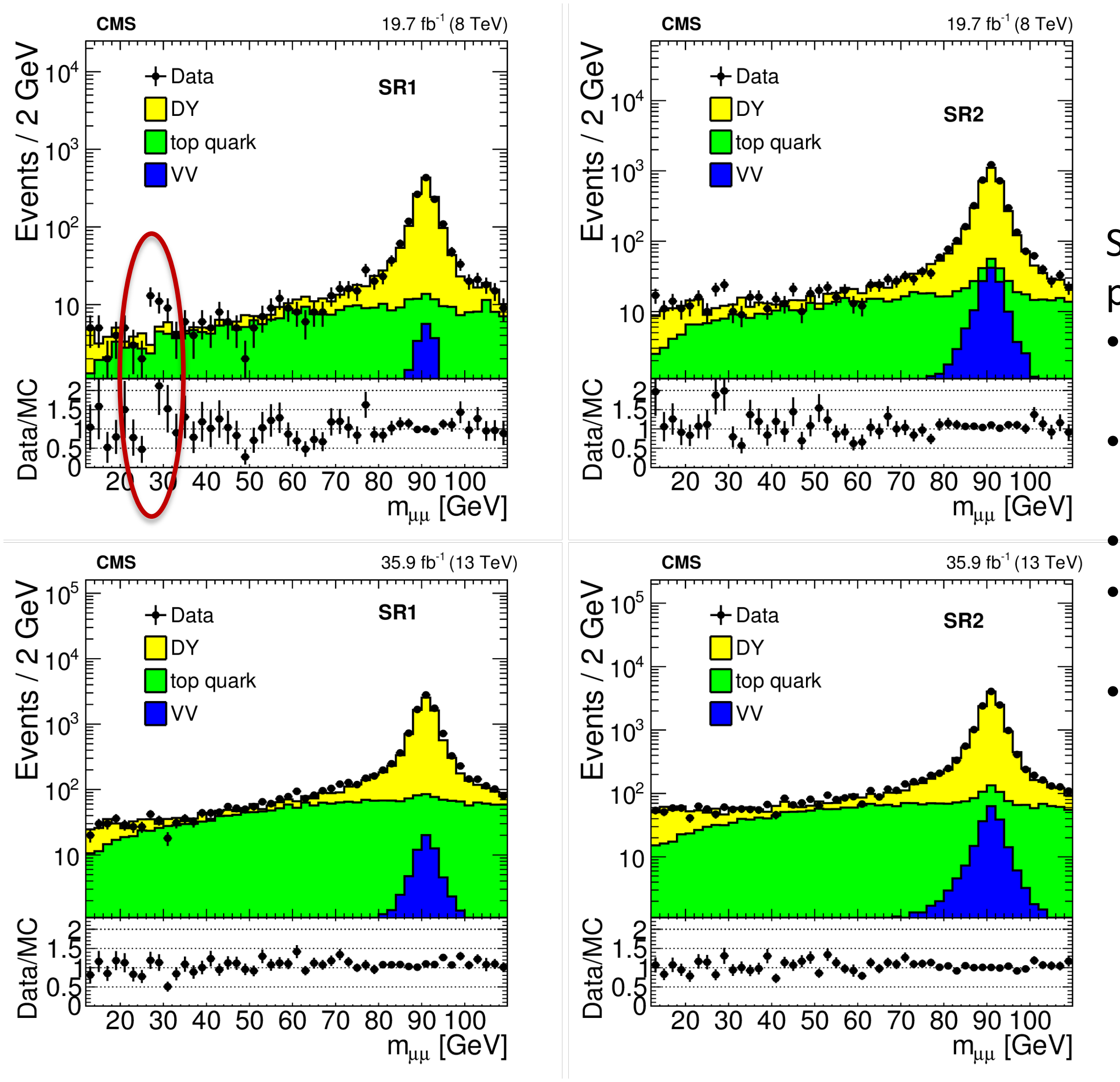


8 TeV

Several cross-checks performed:

- Relaxed, tighter b-tagging selection
- Removed muon isolation
- Different trigger
- Change veto jet selection (30--> 25 GeV)
- Dropped pileup jet ID criteria…

Low mass search in μμbj



8 TeV

Several cross-checks performed:

- Relaxed, tighter b-tagging selection
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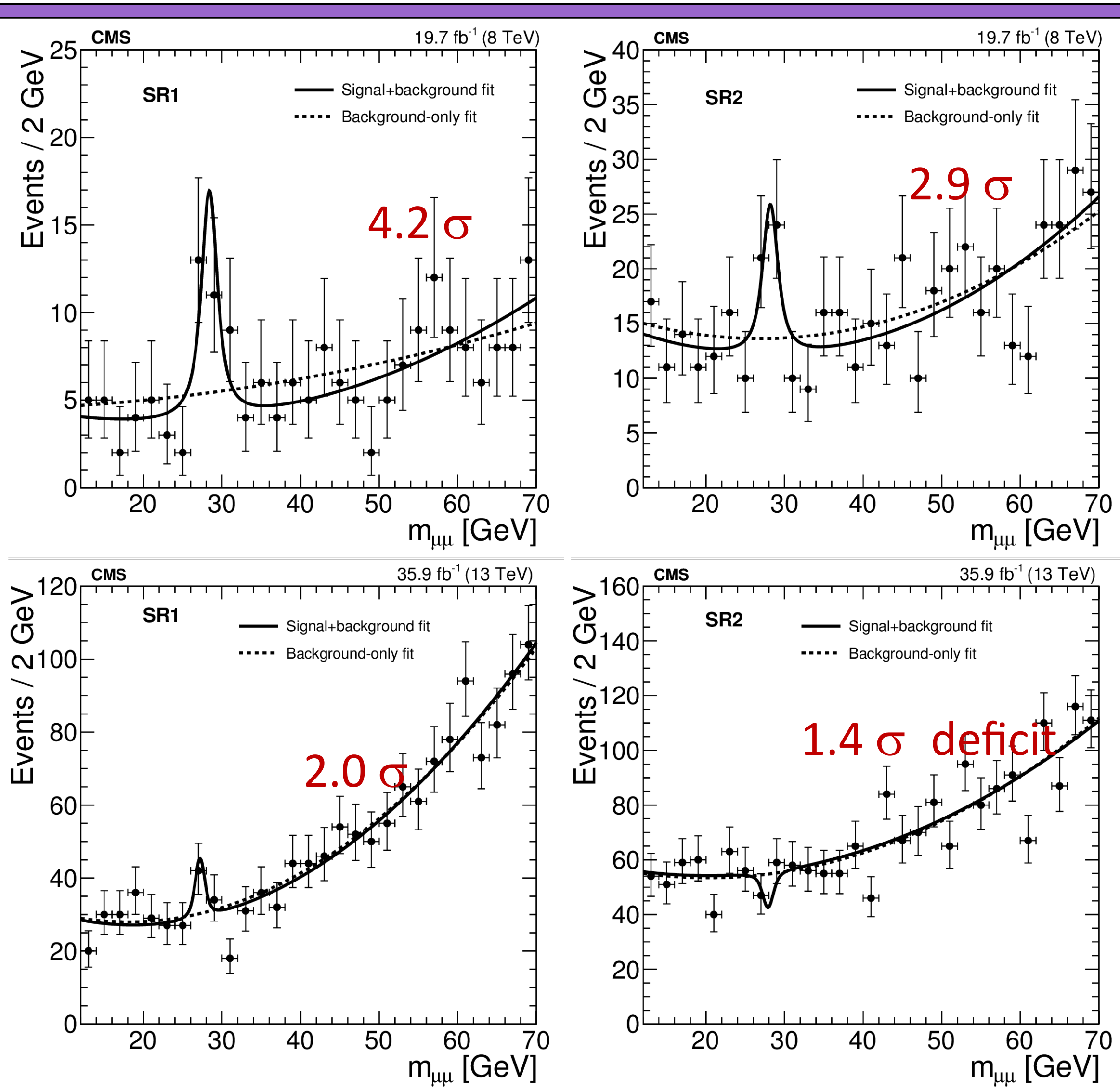
13 TeV

Low mass search in μμbj

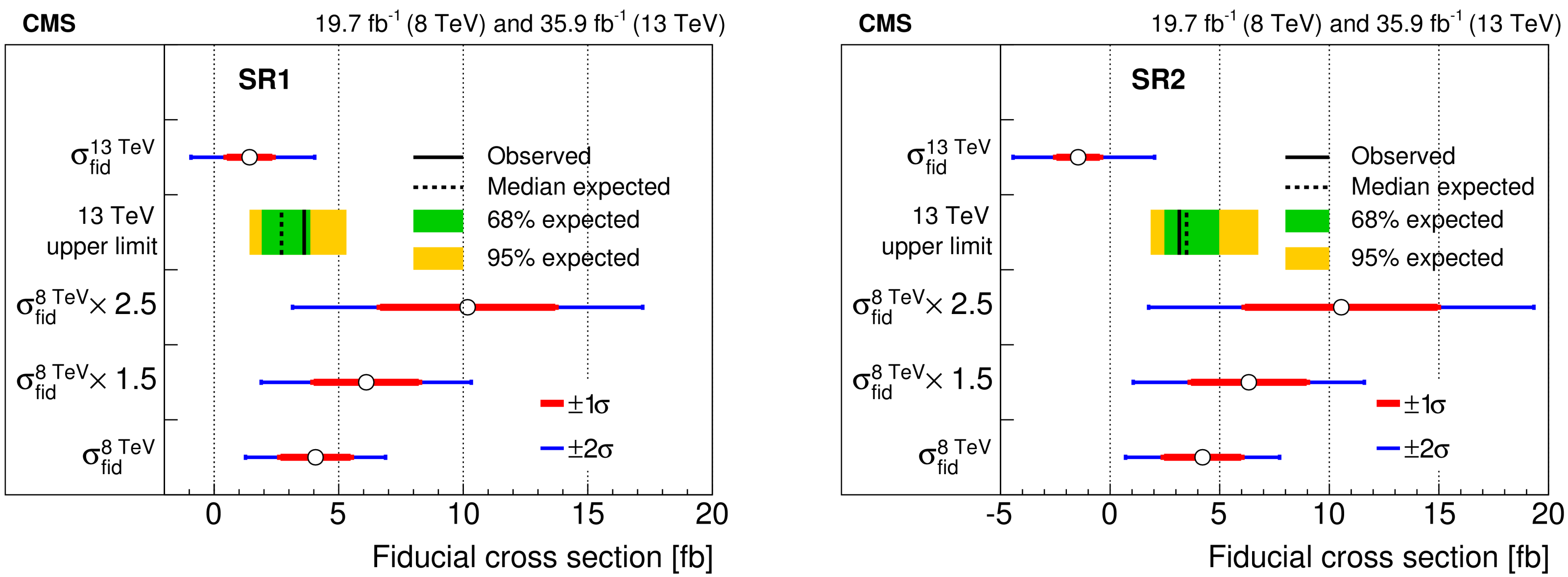


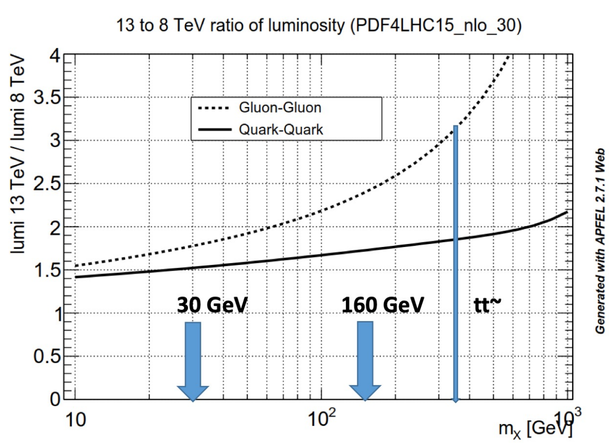
8 TeV

Local significances

13 TeV

Compatibility of 8 and 13 TeV results



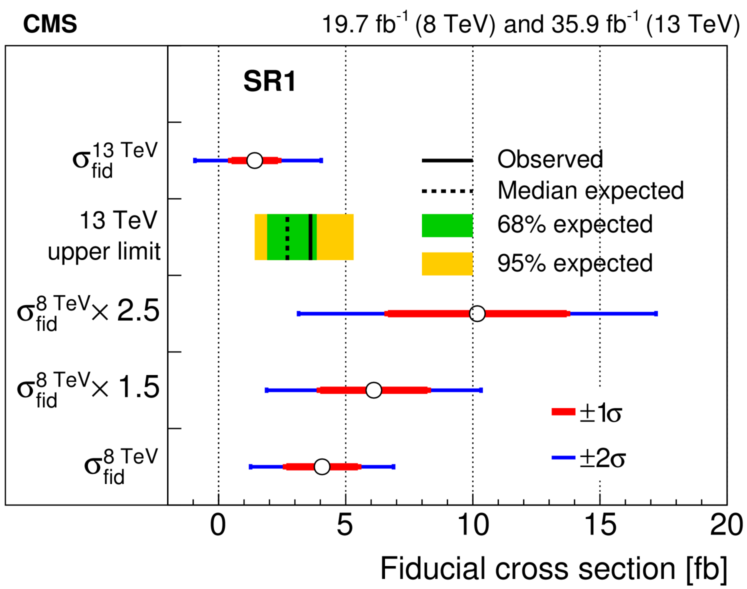


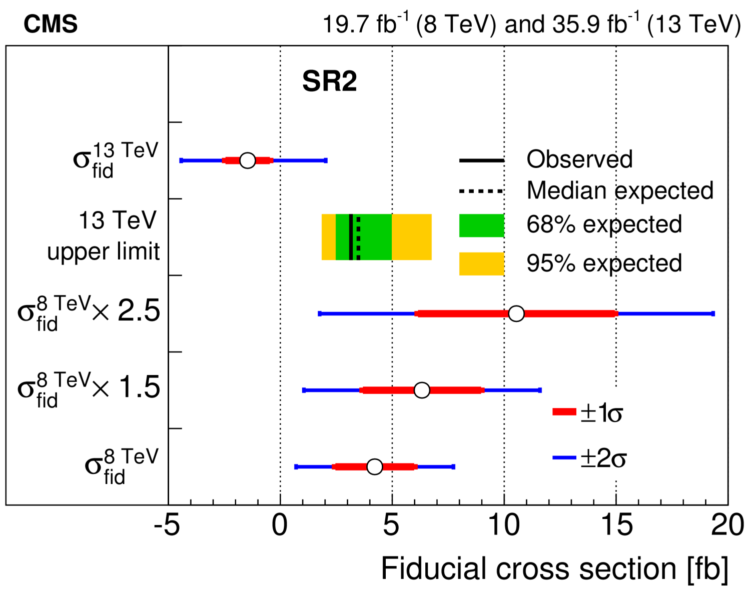
If we assume an increase of the signal cross-section (e.g. by a factor of 1.5), the 8 and 13 TeV results are compatible within 2 σ

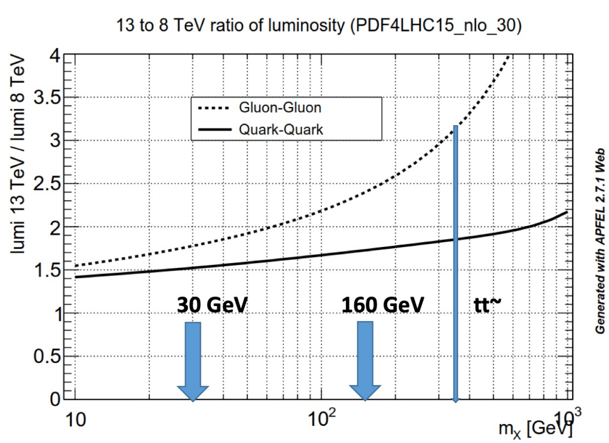
Assumes same signal efficiency at 8 and 13 TeV; signal acceptance could be different.

Also, a big increase in the pileup jets at 13 TeV in the forward region (➔ reduction of signal in SR2 due to forward jet veto)

Compatibility of 8 and 13 TeV results



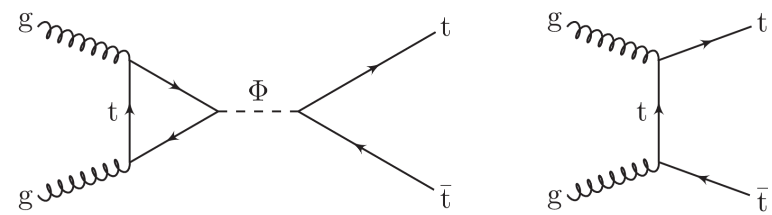




Need to check with full Run 2 dataset!

Heavy Higgs to ttbar

- gg→ A/H → ttbar in 400-750 GeV, relative width Γ/m = {0.5-25}%
- Dataset: 35.9 fb^{-1} @ 13 TeV (2016)
- ℓ+jets and $\ell\ell$ channel
- Statistical analysis using 2D binned distributions of m_{tt} and angular observables



Strong interference with SM ttbar

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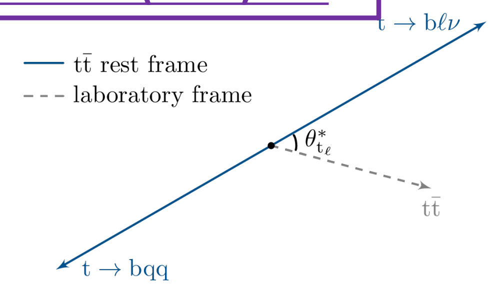
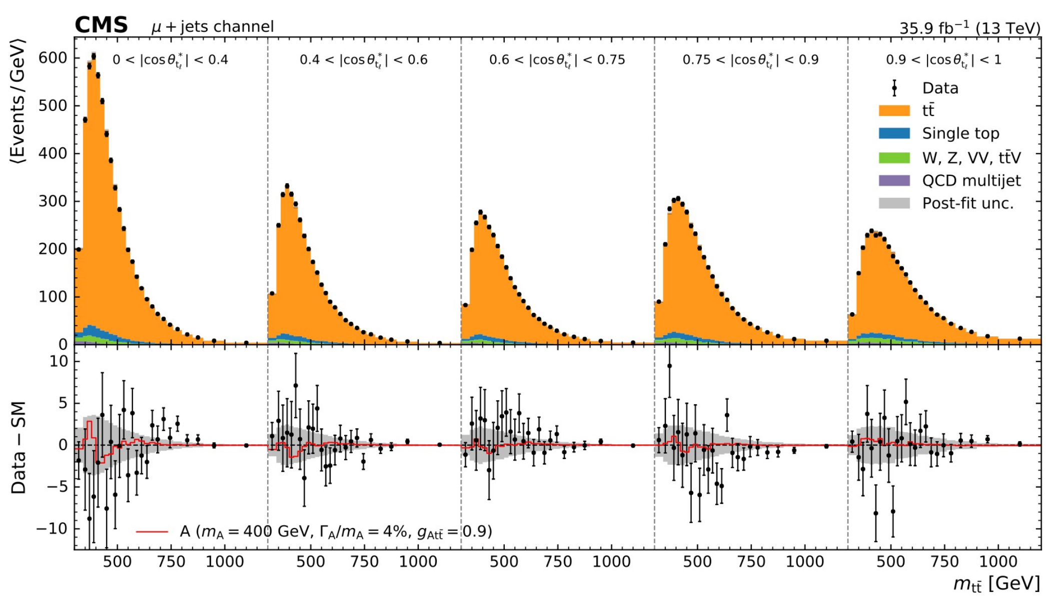
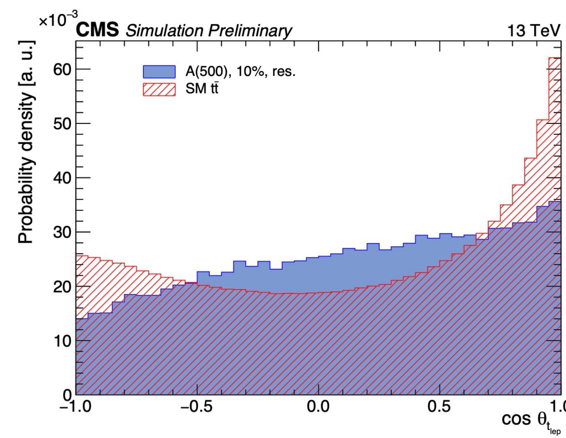






Heavy Higgs to ttbar

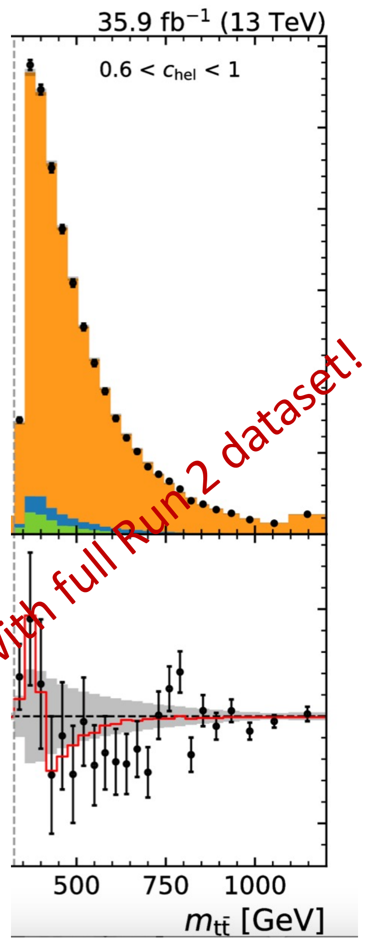
Model independent limits also set on the coupling strength modifier

Excess at A=400 GeV (local 3.5 σ, global 1.9σ)

Γ/m=4%

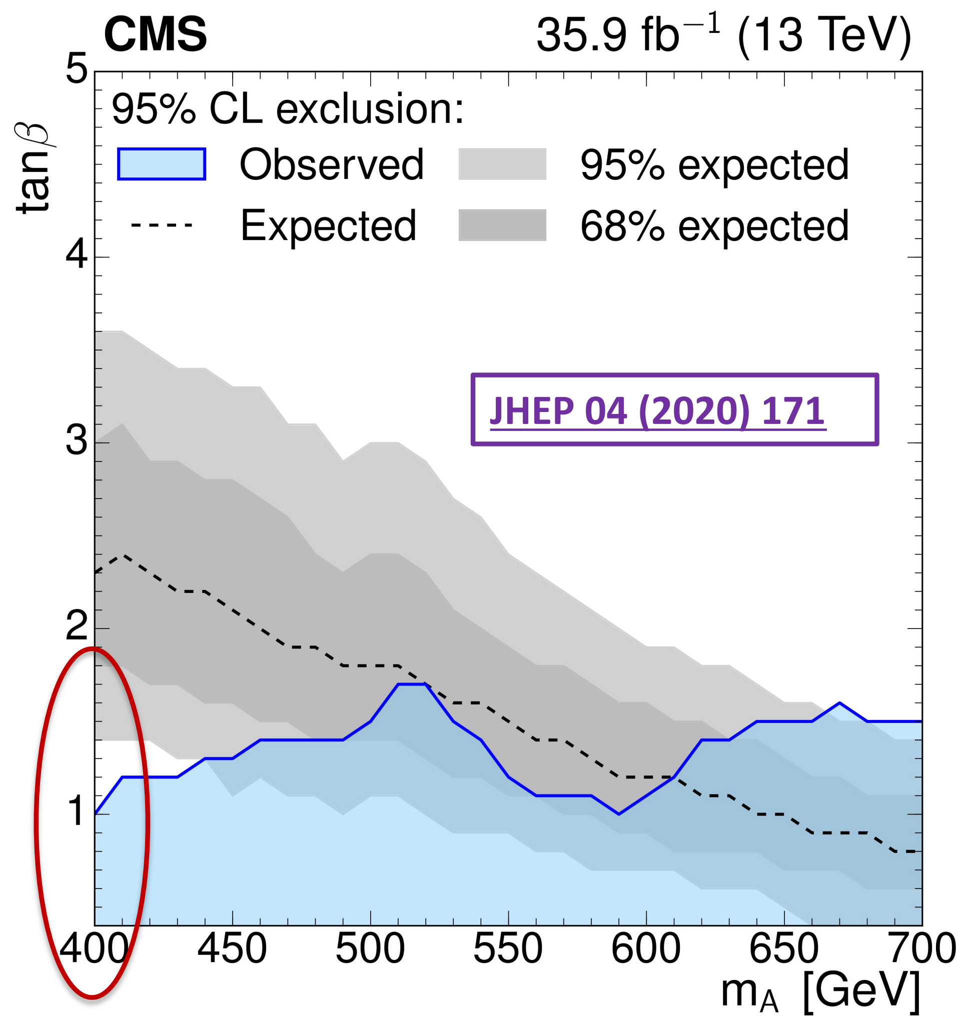
[ℓℓ channel]

Higher-order EWK corrections to SM ttbar production ?



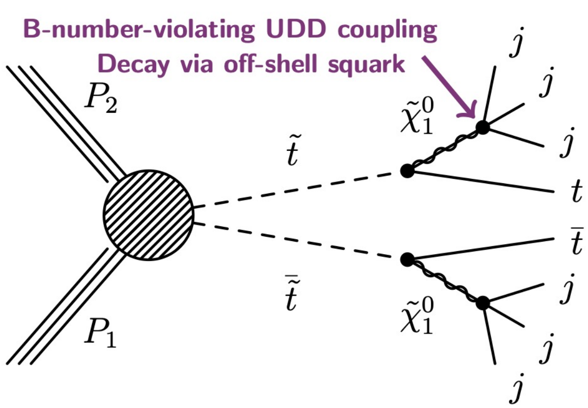
Need to check with full Run 2 dataset!

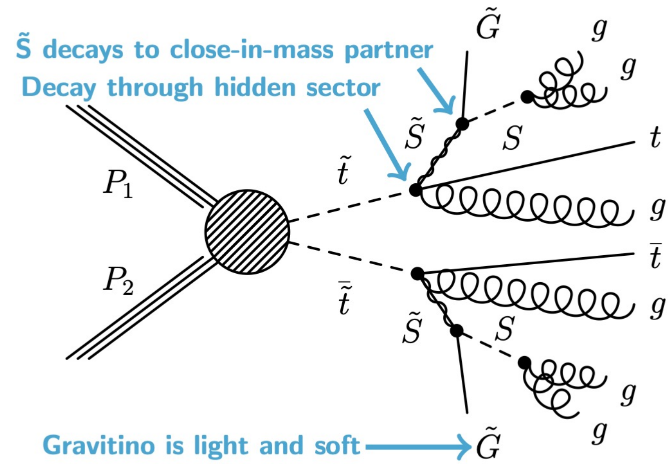
Limits interpreted within hMSSM



Pair production of stops decaying to top quarks and light flavor jets

- Explore a complementary phase-space to the "traditional" high-MET SUSY searches and focus on low-MET signatures of top squark decays.





arXiv:2102.06976

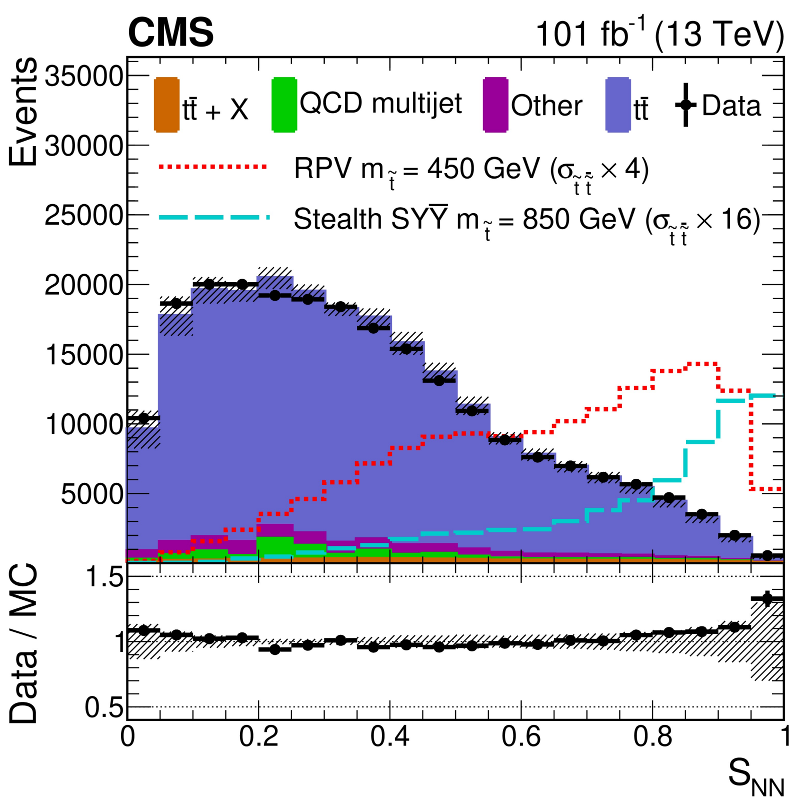
- The primary topology feature of the signal is high jet multiplicity.
  - >= 7 jets, H_T >300 GeV, >1 bjet

No MET requirement

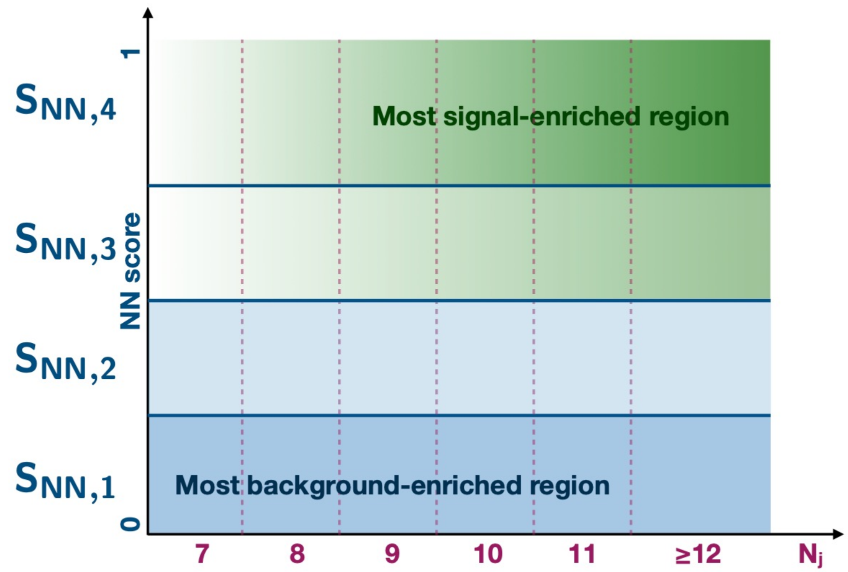
- Requiring one lepton helps reduce QCD background.
- Jet multiplicity is hard to model at high multiplicity, so rely on data and fit the Njets distribution.

Pair production of stops decaying to top quarks and light flavor jets

Train a neural network (NN) to discriminate signal from irreducible $\bar{t}t$ + jets background, while being uncorrelated with Njets.



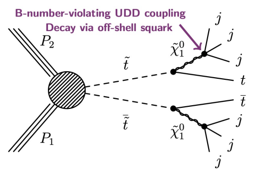
Events are grouped into 4 bins of S_{NN} and 6 bins of Njets

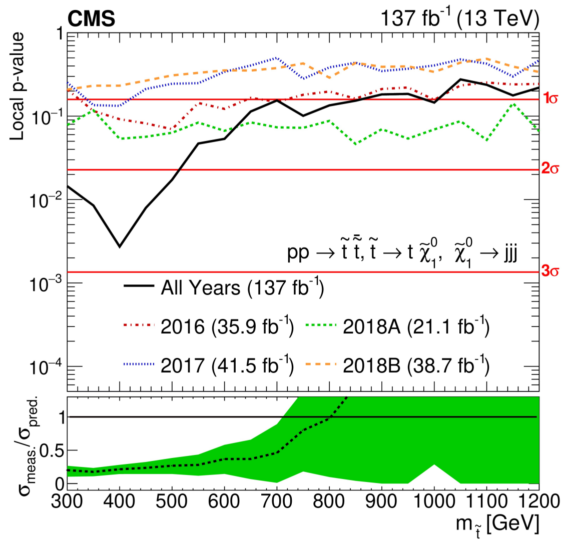


$\bar{t}t$ parameterized shape ⇒ same for all S_{NN} bins.

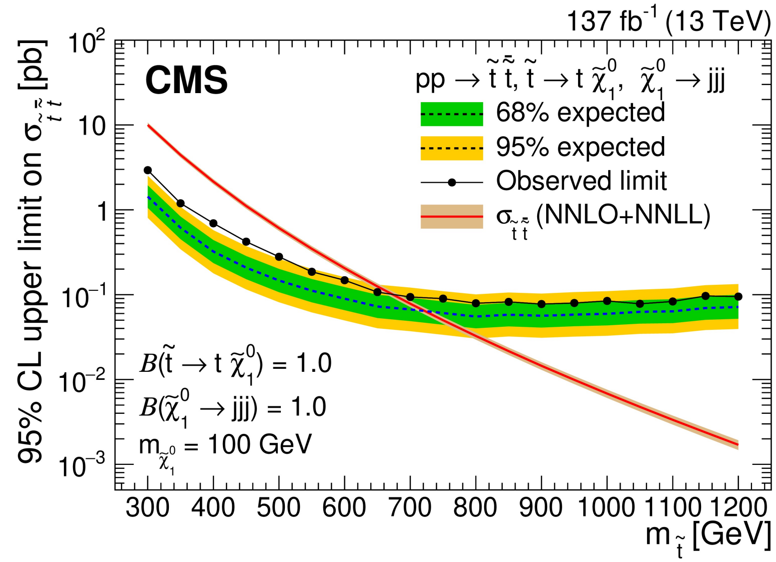
- QCD estimate from control region.
- TTX ($\bar{t}t$ + X) backgrounds ⇒ from simulation.
- Other backgrounds (diboson, triboson, etc.) ⇒ from simulation.

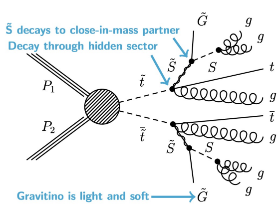
Pair production of stops decaying to top quarks and light flavor jets

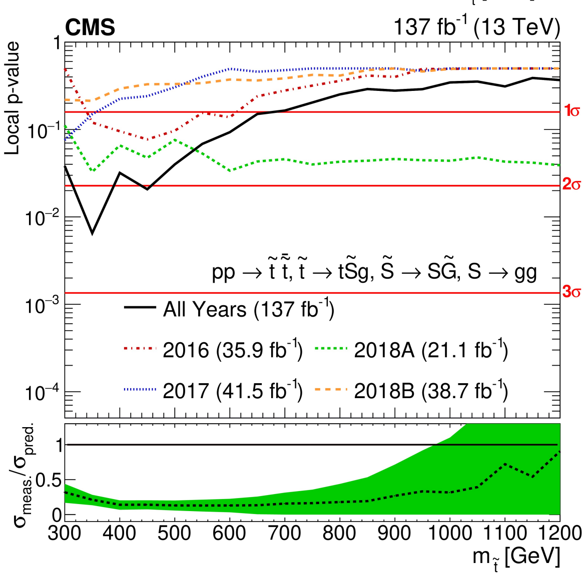




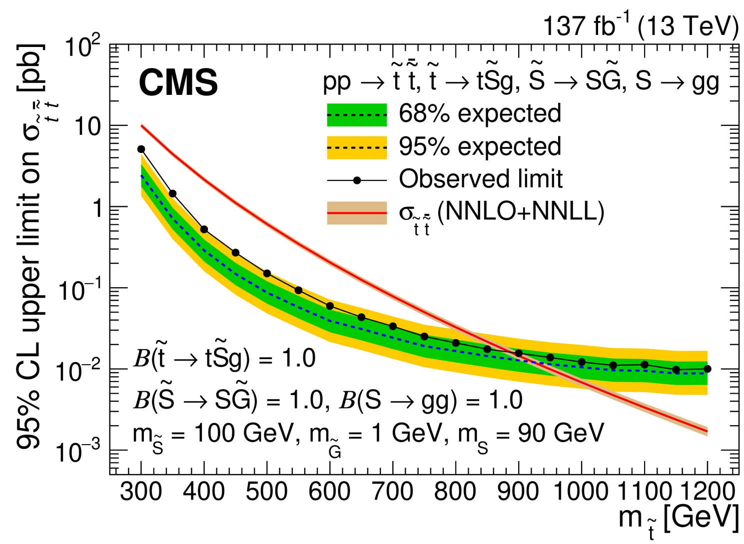
~2.8σ local significance at 400 GeV







~2.5σ local significance at 400 GeV



Search for exotic Higgs decays

Search for $h \to a_1 a_1 \to \mu^+\mu^- b\bar{b}$

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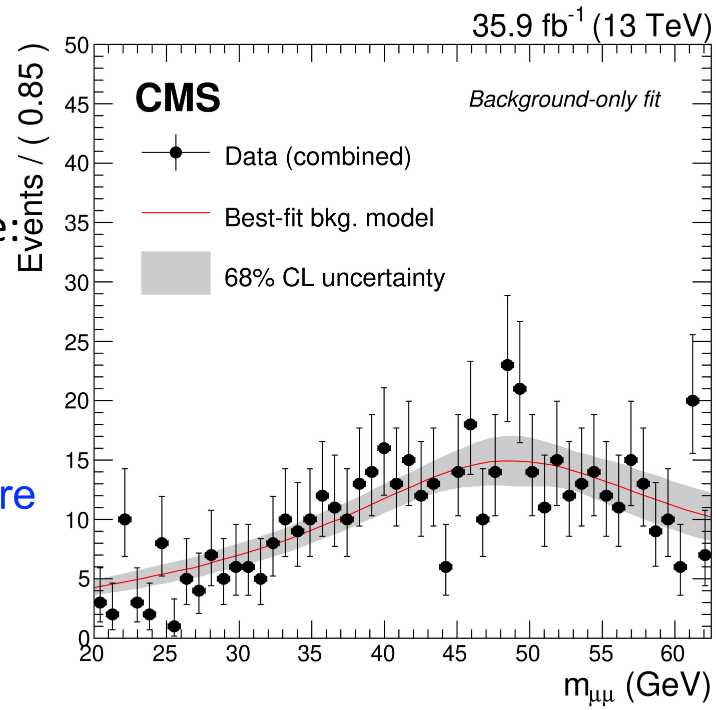
- Require 2 isolated muons with $p_T > 20, 9$ GeV
- 2 jets with $p_T > 20, 15$ GeV,
- MET < 60 GeV
- B-tag categories (Tight, Medium, Loose)

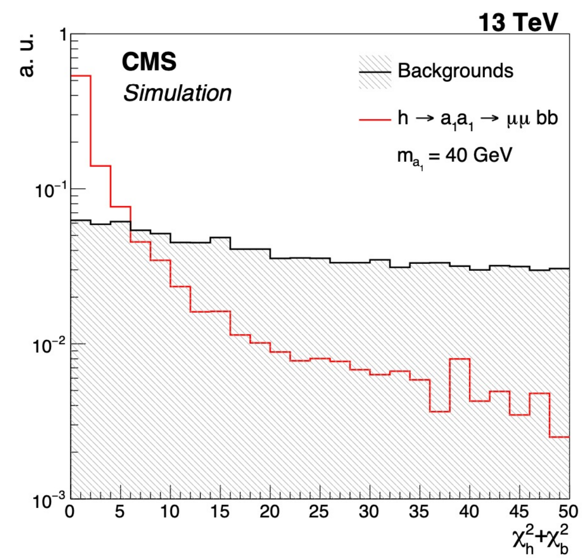
$$\chi^2 = \left(\frac{m_{bb} - m_{\mu\mu}}{\sigma_{bb}}\right)^2 + \left(\frac{m_{bb\mu\mu} - 125}{\sigma_{bb\mu\mu}}\right)^2 < 5$$

Sensitive variable: dimuon mass

below 20 GeV
b's merge ->
Need substructure techniques

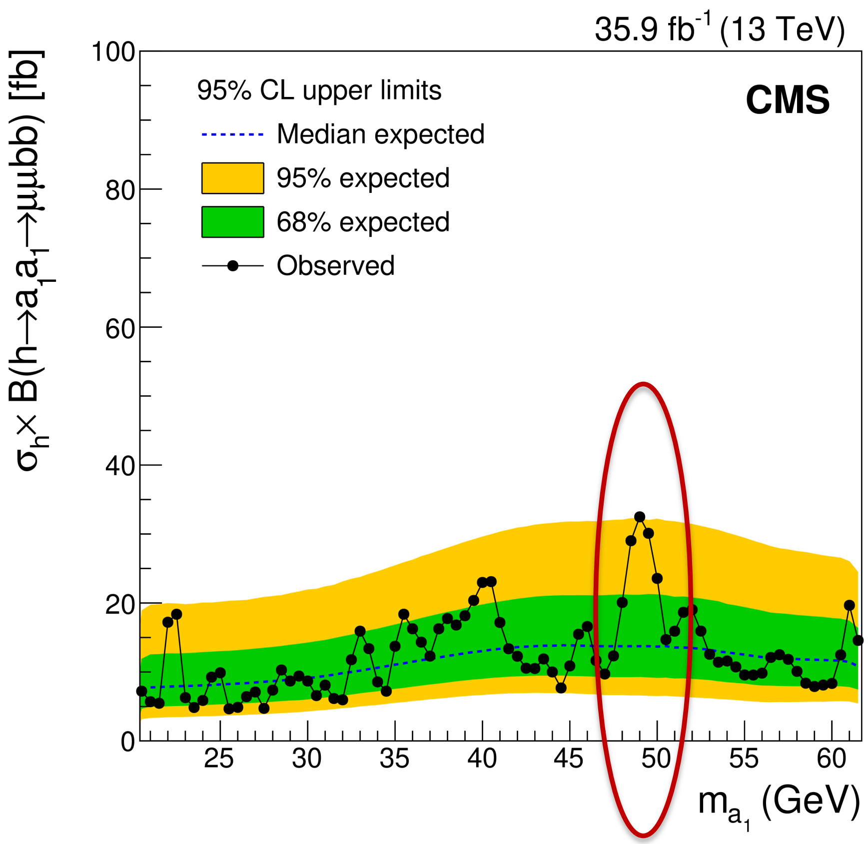


~$m_H/2$

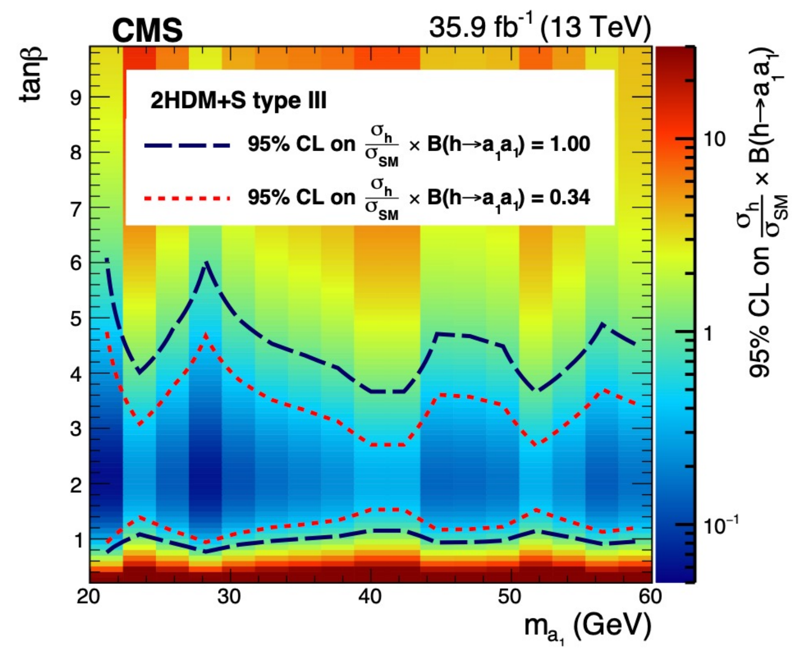


Search for exotic Higgs decays

Limits Br(H→μμbb) ~ (1-7)x10^{-4}



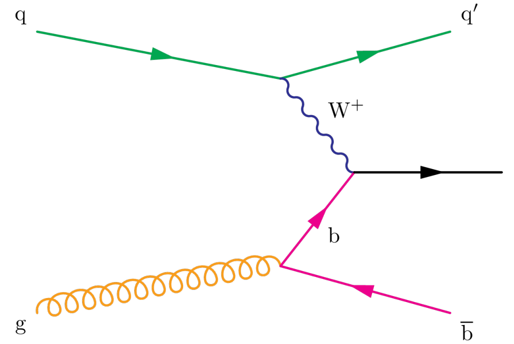
Model is needed to get to Br(H→aa)

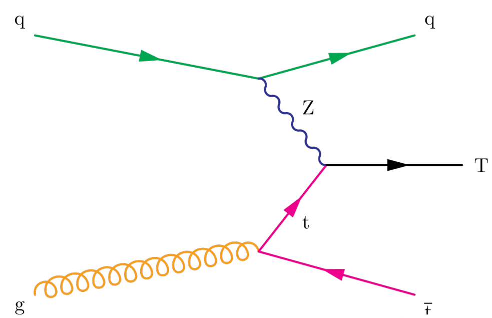


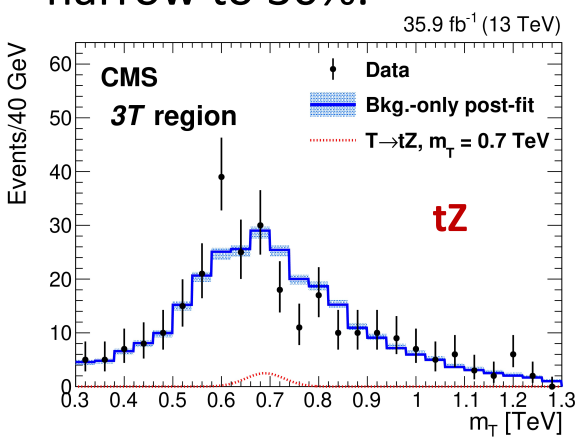
Need to check with full Run 2 dataset!

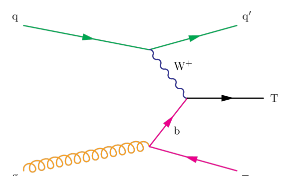
Single VLQ T → tH/Z

- Vector-like quark search : one top + H/Z
- All-hadronic final state
  - first constraints on T → tZ using hadronic decays of the Z boson with this production mode.
- Low mass search:
  - 0.6 – 1.2 TeV; >=5 narrow jets (resolved), 5-jet invariant mass signature, at least 3 b-tagged jets
- High mass:
  - > 1.0 TeV, boosted, 2 fat jets
- Explore T quark fractional widths ranging from narrow to 30%.



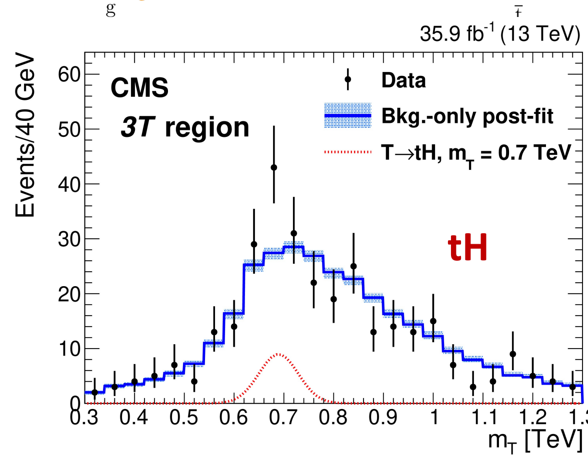




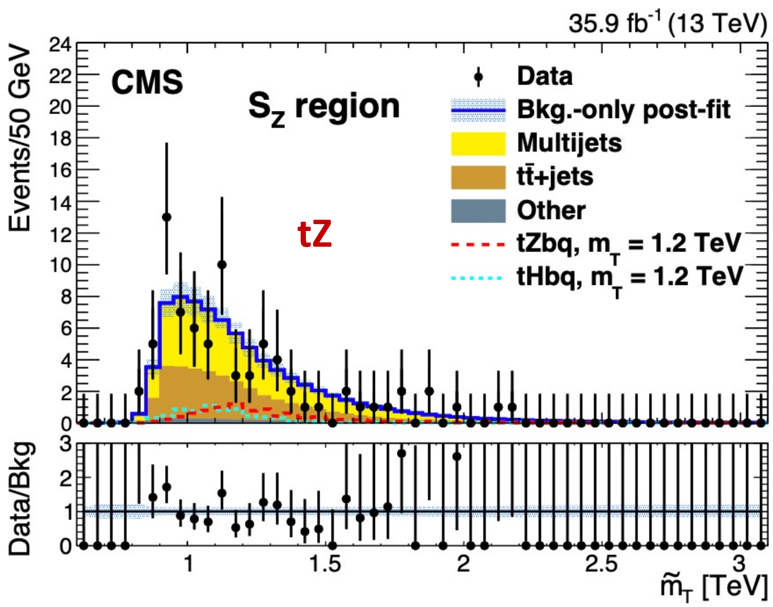


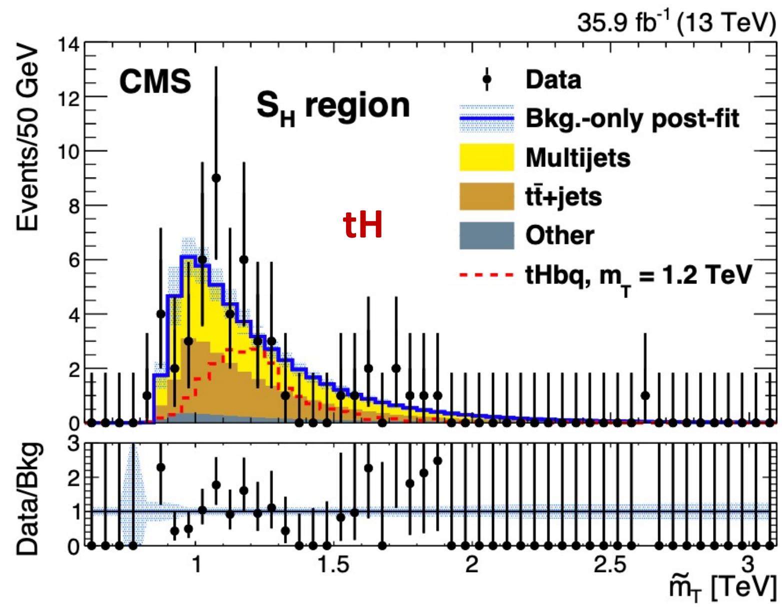
Low-mass analysis:

Backgrounds from control regions in data



Single VLQ T → tH/Z



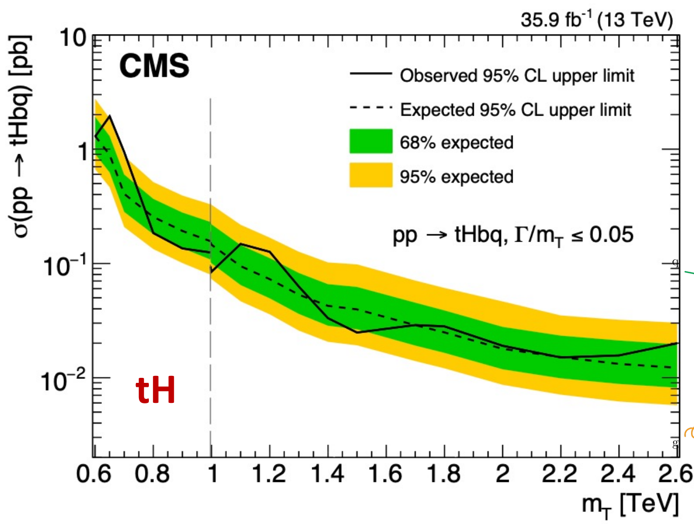


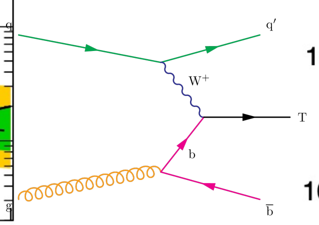
High-mass analysis:
ttbar from simulation, QCD background
from control regions in data

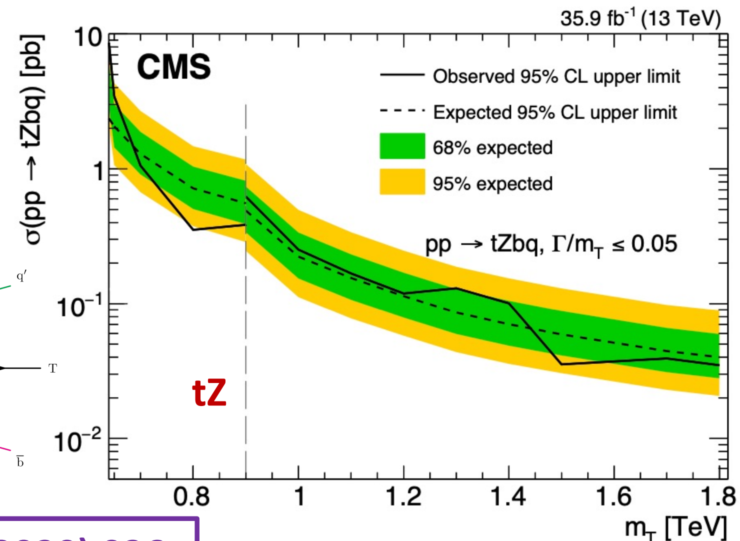
Upper limits are set on the cross sections for the two production modes (pp → Tbq and pp → Ttq) with the two decay modes (tH and tZ) as well as their sum (tH+tZ), for four width values.

pp → Tbq: T singlet model with $\kappa_W = \kappa_H = \kappa_Z$
pp → Ttq, (TB) doublet model with $\kappa_H = \kappa_Z$ and $\kappa_W = 0$

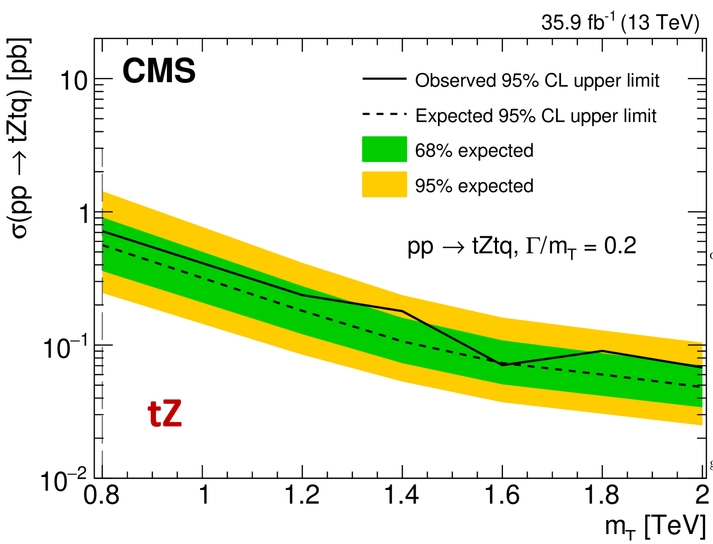
Single VLQ T → tH/Z

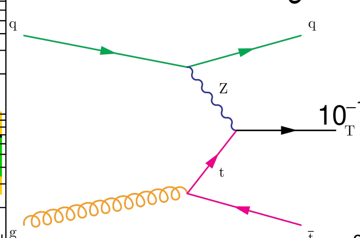


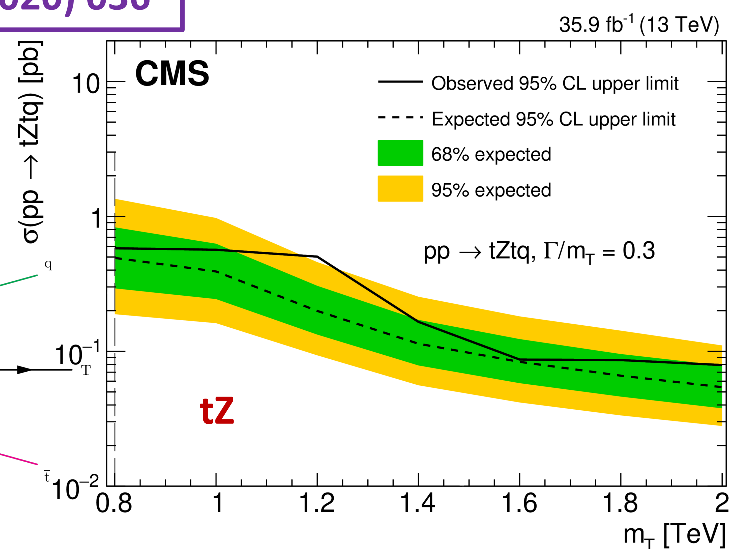




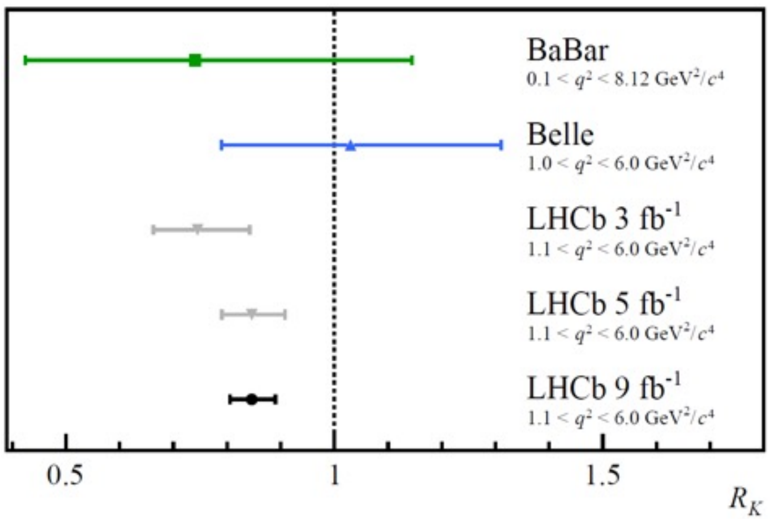
JHEP 01 (2020) 036

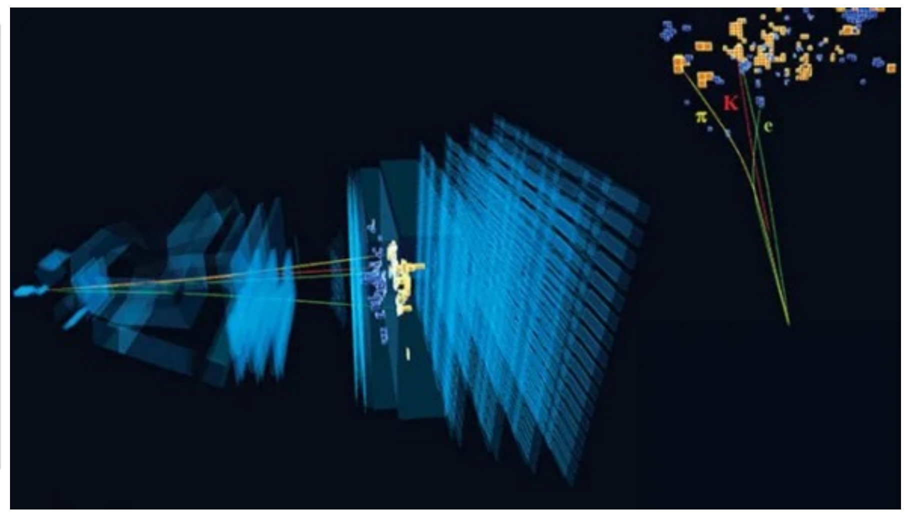






Going after the flavor anomalies

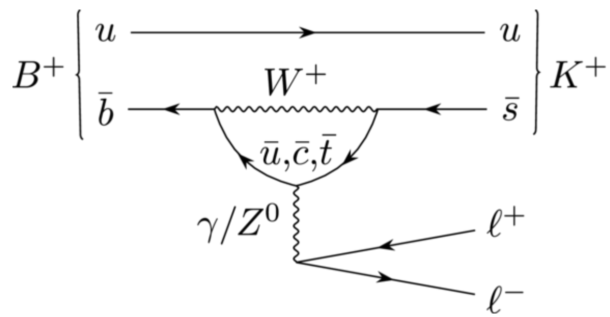




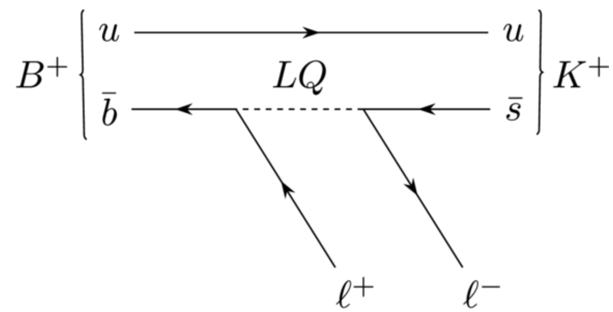
Searches for leptoquarks

Renewed interest in leptoquark searches, particularly 2nd & 3rd generation

SM

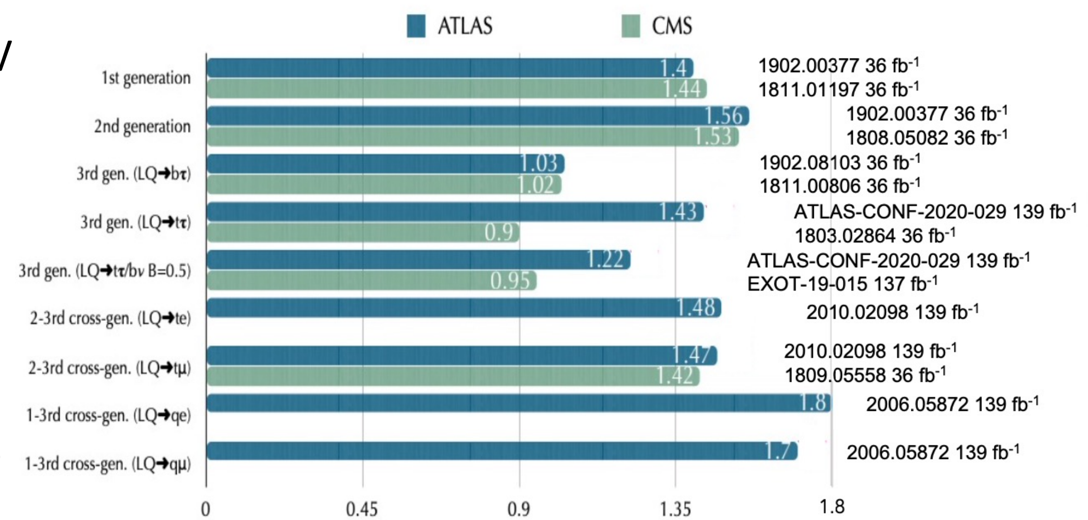


BSM



Many channels starting to push sensitivity above the TeV scale, favored by B physics anomalies

Warrants investigation of new/more complicated final states or model phase space (e.g. bigger couplings/widths)



Searches adding and using 2017+2018 data in progress

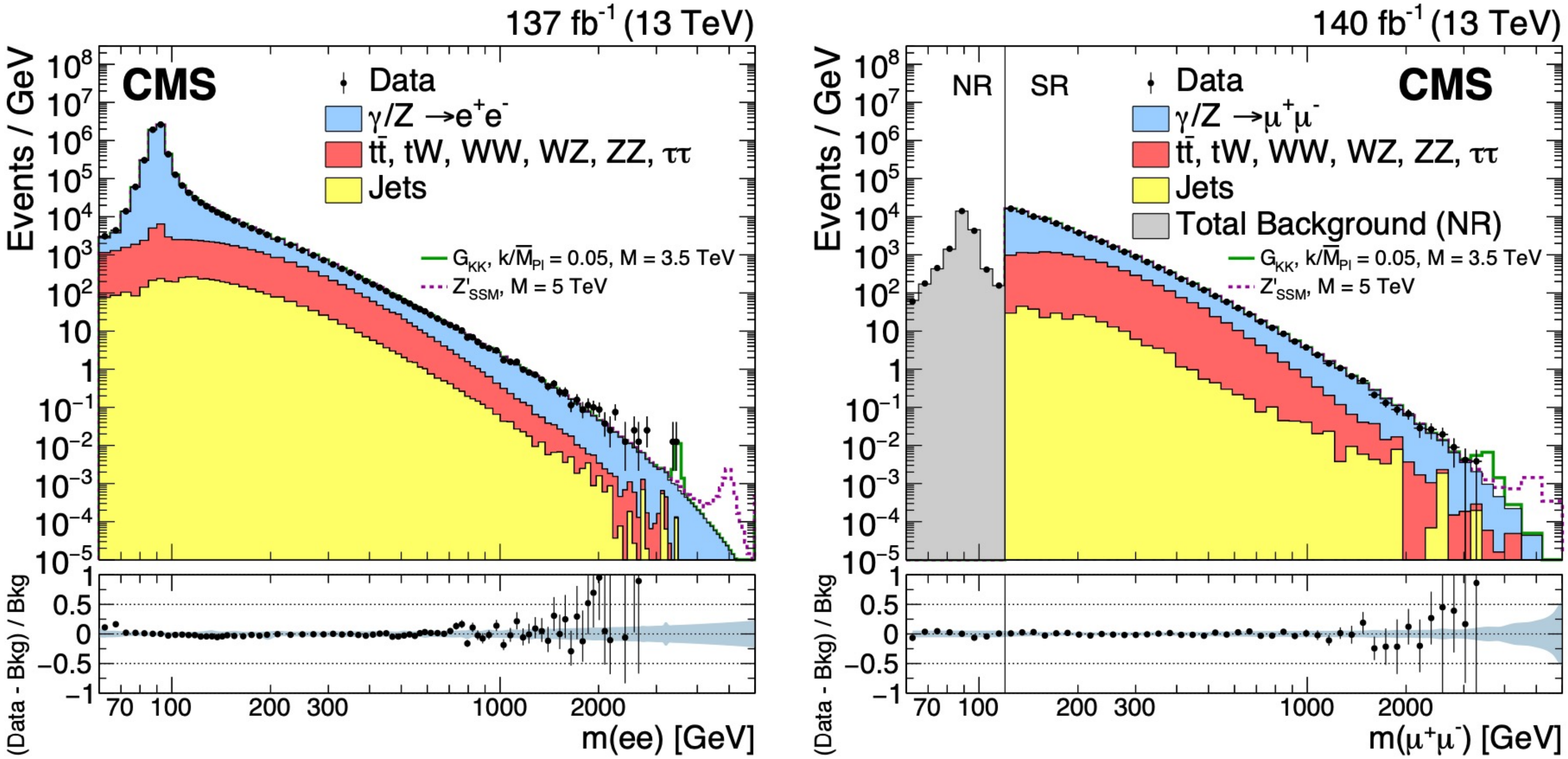
summary of observed lower limits on scalar LQ mass (TeV)

Moriond 2021 summary

32

Exploring lepton flavor anomalies

arXiv:2103.02708



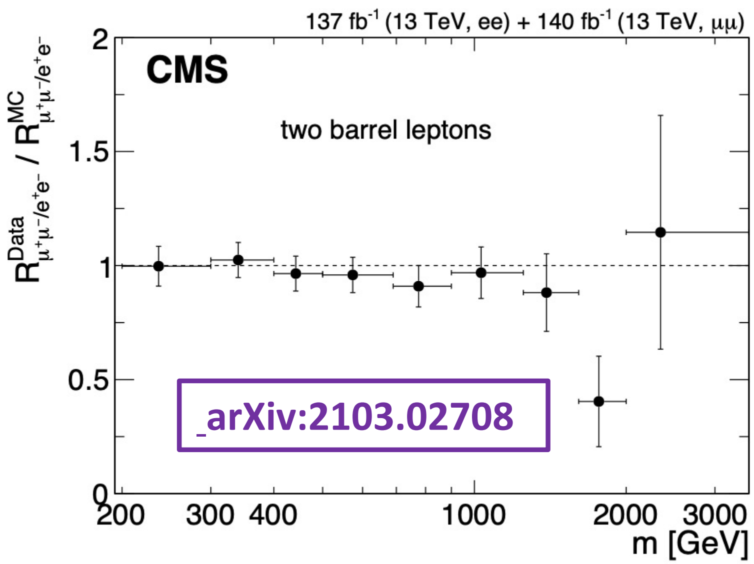
Four events are observed with mass above 3 TeV, two each in the ee and dimuon channels. Masses are 3.35 and 3.47 TeV in the ee channel and 3.07 and 3.34 TeV in the dimuon channel.

Exploring lepton flavor anomalies

Lepton universality is tested at TeV scale by comparing the ee & μμ mass spectra!

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$

LFU ➔ ratio is unity

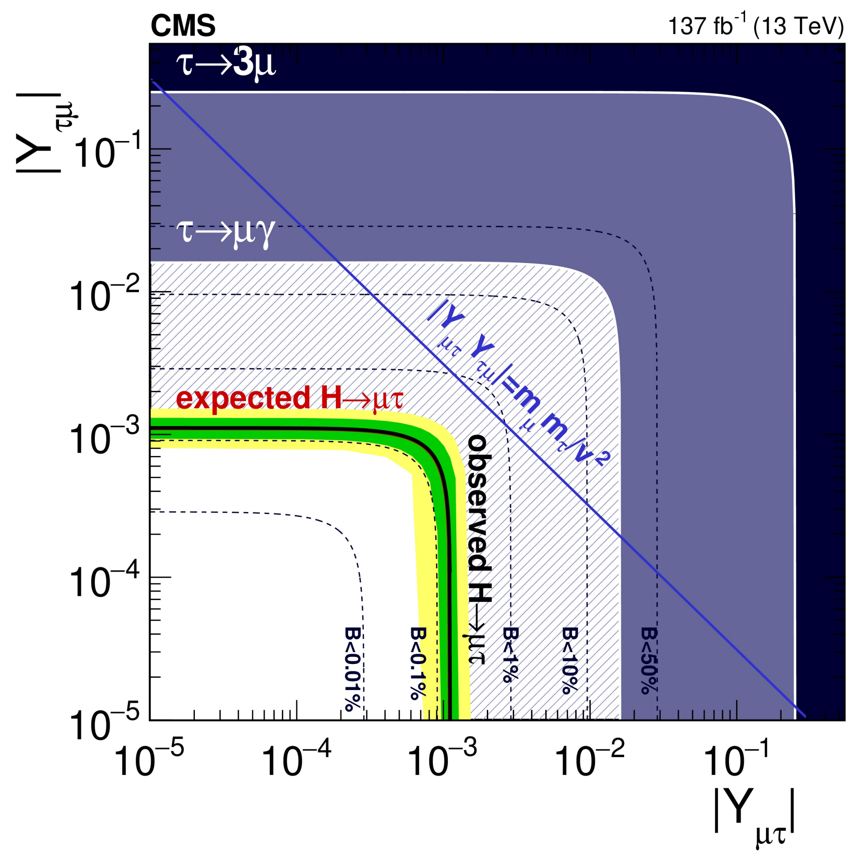


Good agreement with this expectation observed up to 1.5 TeV.

LFV decays of the Higgs

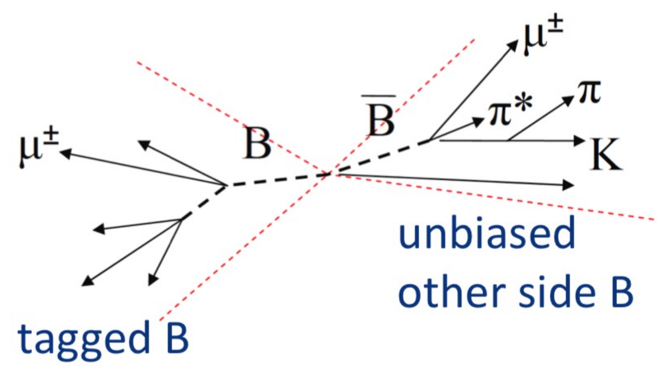
Search for $\boldsymbol{h \to e\tau}$ and $\boldsymbol{h \to \mu\tau}$

CMS-PAS-HIG-20-009



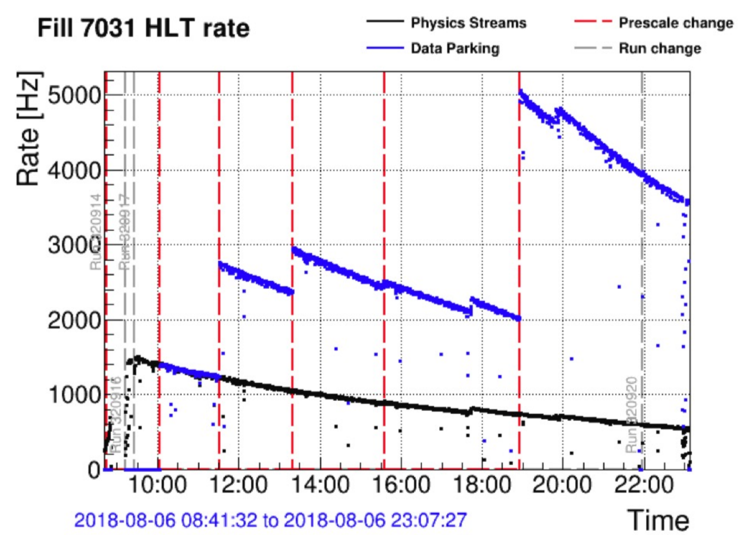
Data parking and B physics

- During Run 2, CMS stored a large unbiased B hadron sample by tagging on the "opposite-side" B
  - 12 B events recorded
  - Up to 6 kHz additional rate to tape



- Data was "parked" (→ no prompt reconstruction) and processing delayed to times of lower load on the computing system

- Potential resource for investigating B flavor anomalies and searches for other exotic phenomena



Analyses ongoing – stay tuned!

Summary & Outlook

- The ~11 years of LHC operation has been one amazing ride!
  - Discovery of the Higgs boson
    - Now using the Higgs as a tool for discovery
  - Huge amounts of BSM parameter space ruled out
  - At the same time, innovative strategies for triggering, data-taking and analysis are providing access to previously unexplored territory!
  - Some interesting excesses – being pursued with full Run 2 datasets (and Run 3 starting next year)
  - Tantalizing hints of new physics in the flavor sector

- An exciting time to develop and implement new ideas
  - Go in directions where no one has gone before!

- <u>**95% of the total LHC data still to come (and be studied)!**</u>


CMS Experiment at the LHC, CERN
Data recorded: 2015-Sep-28 06:09:43.129280 GMT
Run / Event / LS: 257645 / 1610868539 / 1073
I WANT TO BELIEVE

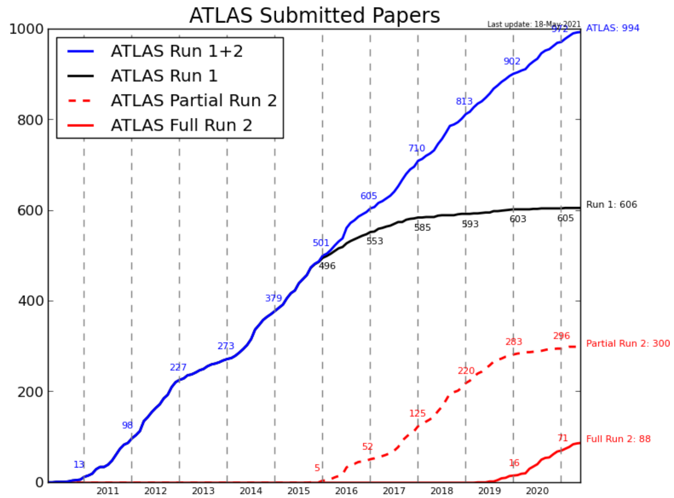
Existing Anomalies In The Current ATLAS Run 2 Dataset

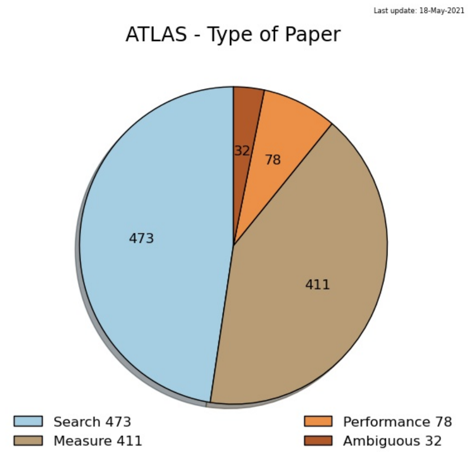
Simone Pagan Griso

May 21st, 2021
New Physics from Precision at High Energies - KITP

Introduction

- Vast physics program of measurements, searches for new physics and performance papers





- Each containing often a large number of signal regions / observables
- A number large enough that > 3σ statistical fluctuations are expected to occur
  — Although systematics play an important role and are often not as Guassian as we'd like

Introduction

- Despite large number of searches and measurements, most of the abstracts contain

> is carried out on 139 fb^{-1} of proton–proton collision data at $\sqrt{s}$ = 13 TeV collected by the ATLAS detector at the LHC between 2015 and 2018. No significant deviation from the Standard Model background prediction is observed. Mass-dependent exclusion limits at the 95% confidence level are drawn on the single production cross-section of a vector-like B quark

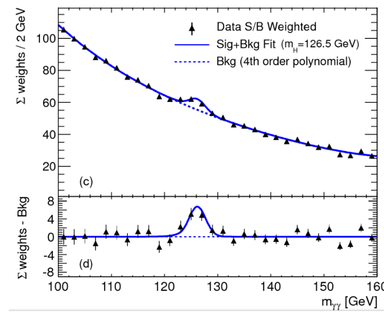
> data-taking periods. The search is conducted by examining the reconstructed invariant or transverse mass distributions of Wh and Zh candidates for evidence of a localised excess in the mass range of 220 GeV up to 5 TeV. No significant excess is observed and the results are interpreted in terms of constraints on the production cross-section times branching fraction

> volumes and are compared with theoretical predictions at different levels of precision, based on a χ^2/ndf and p-value computation. Overall, good agreement is observed between the unfolded data and the predictions.

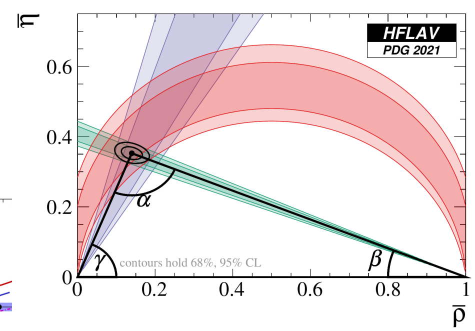
- However, a small number of anomalies have been observed…
  - … some are gone with more data,
  - … some persist or appeared in the full run 2 dataset,
  - … some are direct evidence of physics we don't fully understand (just maybe not necessarily beyond-SM)
- Tracking them allows to plan at the best for the future dataset increase and R&D needs

Type of anomalies

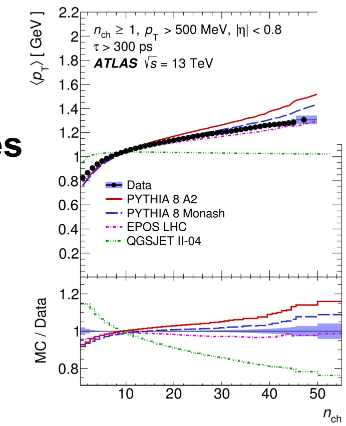
- **Anomalies in direct searches**
  - — Bump-hunting
  - — Partially reconstructed final states



- **Anomalies in indirect searches**
  - — Rare SM phenomena enhanced by BSM
  - — Comparison of sensitive observables with SM predictions
  - — Consistency within SM



- **Measurements of “poorly-known” SM processes**
  - — e.g. non-perturbative regimes, measurements with much better experimental than theoretical accuracy, ...



← Likely the longest-living discrepancy in the LHC dataset :)

Type of anomalies

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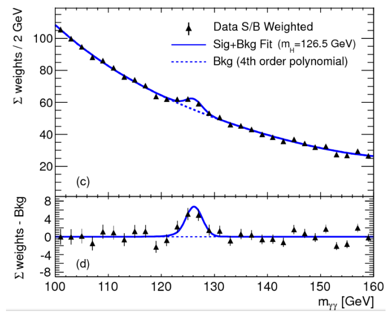

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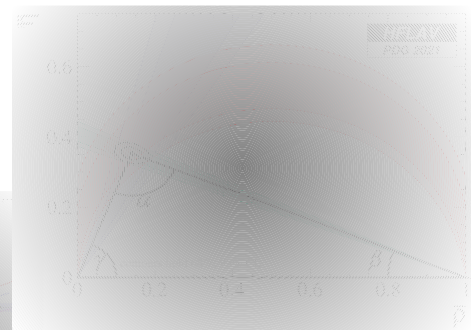

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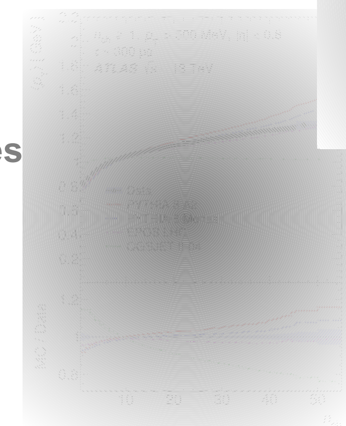


← Likely the longest-living discrepancy in the LHC dataset :)

Bump Hunting

- Fully reconstructed BSM candidate final state
  - Measure candidate mass
  - Explore angular correlations to gather information on the particle's properties
- Large trial factor when scanning the full kinematic available region with good mass resolution

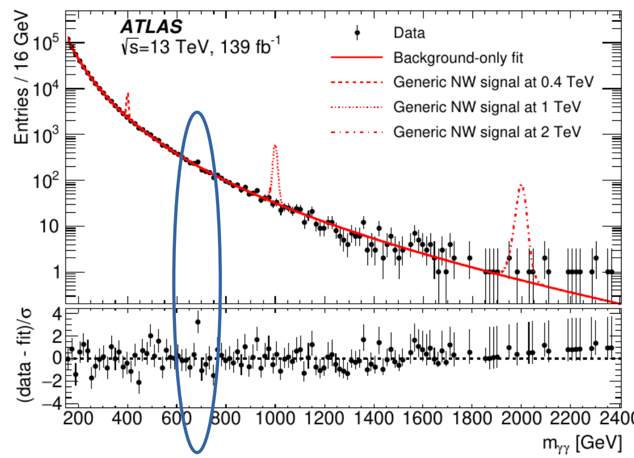
$$p_{global} = 1 - (1 - p_{local})^N$$

(only valid for N ~equal significance regions)

γγ resonance arXiv:2102.13405

- Look for spin-0 and spin-2 resonances
  - Scan mass, width (spin-0) or coupling (spin-2)
- Two high p_T isolated photons (> 35,25 GeV)
  - E_T / $m_{\gamma\gamma}$ > 0.3 (0.25) for (sub-)leading E_T photon
- Smooth background from non-resonant γγ
- Most significant excess for $m_{\gamma\gamma}$ ~ 684 GeV

  local significance: 3.3 σ
  global significance: 1.3 σ } narrow-width results
- Good example of large trial factor

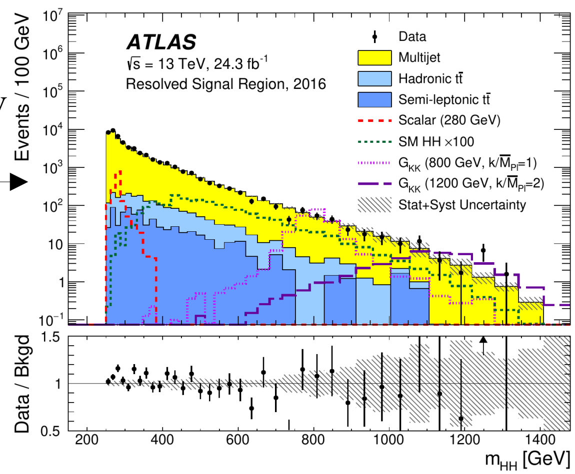


Other heavy scalar searches

36 fb^{-1} HH (→ 4b) resonance arXiv:1804.06174

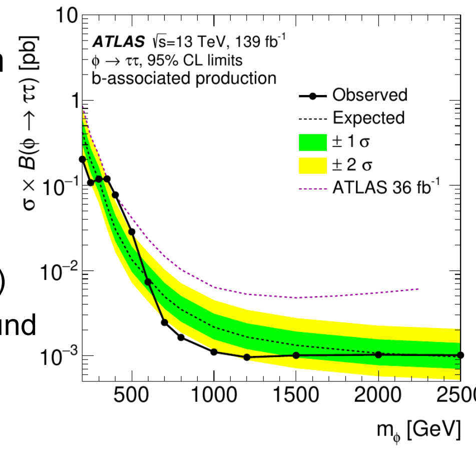
- 4 b-tagged jets required with kinematic selections to enhance expected signal
  - — Boosted (>0.8 TeV) and Resolved analyses
- Most significant excess at M~280 GeV
  - — **local(global) significance: 3.6σ (2.3σ)**

- Expected signal mass resolution @ 280 GeV ~ 9 GeV
- 2016 data only →
  - 2015 data looks compatible with background-only
- Leading systematic from data-driven multijet background



A → ττ arXiv:2002.12223 139 fb^{-1}

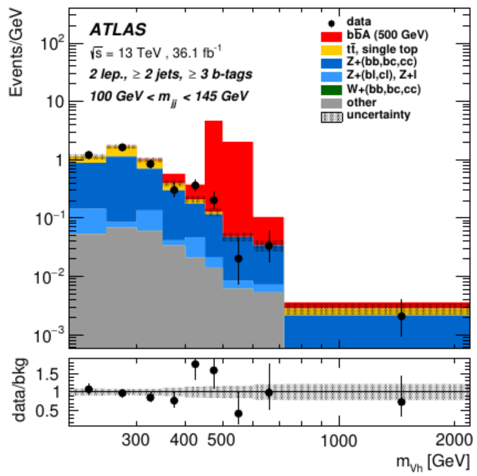
- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ final states
- Explores gluon-fusion and b-associated production (MSSM inspired)
- Most significant excess ~ 400 GeV
  - — 2.2σ gluon-fusion
  - — 2.7σ bbH prod.

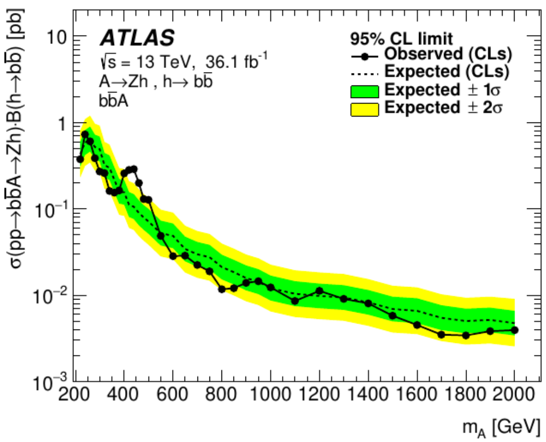


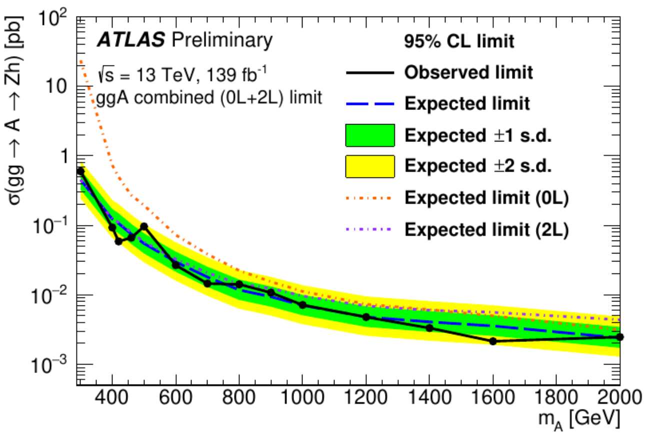
- Mostly statistically limited (>600 GeV)
- Fake tau background dominates at low masses

A → V H(bb)

- Leptonic V decay, resolved or boosted H → bb reconstruction
- Analysis shows an interesting excess with 36 fb^{-1} of data in the ZH → llbb signal region
  - **Local significance: 3.6σ, Global significance: 2.4σ**
  - Driven by the 3 b-tags region (associated bbA production)
- Similar run-2 result looking for A → ZH → llbb (only 1,2 b-tag regions) → mild excess but difficult to compare fairly







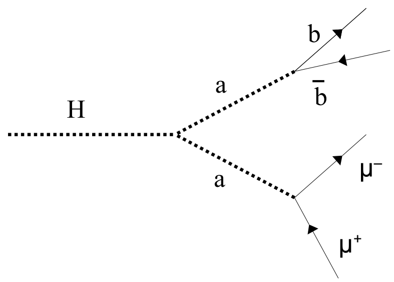
H → aa → bbμμ

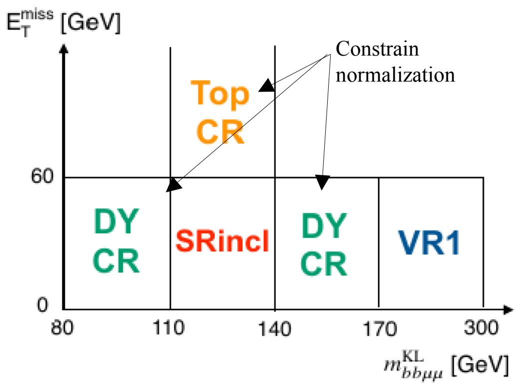
139 fb^{-1}

Mar 25th, 2021

ATLAS-CONF-2021-009

- Balance of clean final state and high branching ratio
  - Single (p_T^{μ} > 27, 5 GeV) / di-lepton (p_T^{μ} > 15, 15 GeV) triggers
  - Two b-tagged jets (p_T > 20 GeV, ε^b=77%)
- Kinematic constrained applied via likelihood fit
  - Much poorer m_{bb} resolution → $m_{\mu\mu}$ to constrains b-jet energy scale
  - Four-body mass required to be consistent with Higgs mass
- Boosted-Decision-Tree to enhance background suppression
  - Based on kinematic likelihood, mass combinations and angular information





- Main background from Drell-Yan + heavy-flavor and ttbar
  - ttbar: kinematic (shape) from simulation
  - DY: kinematic (shape) from 0 b-tag region
    - Kinematics corrected for 2 vs 0 b-tags via BDT-based event reweighting to better match all kinematic properties

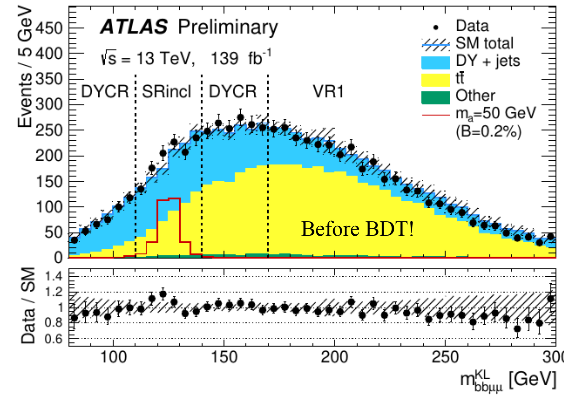
consistent with CMS result!

H → aa → bbμμ

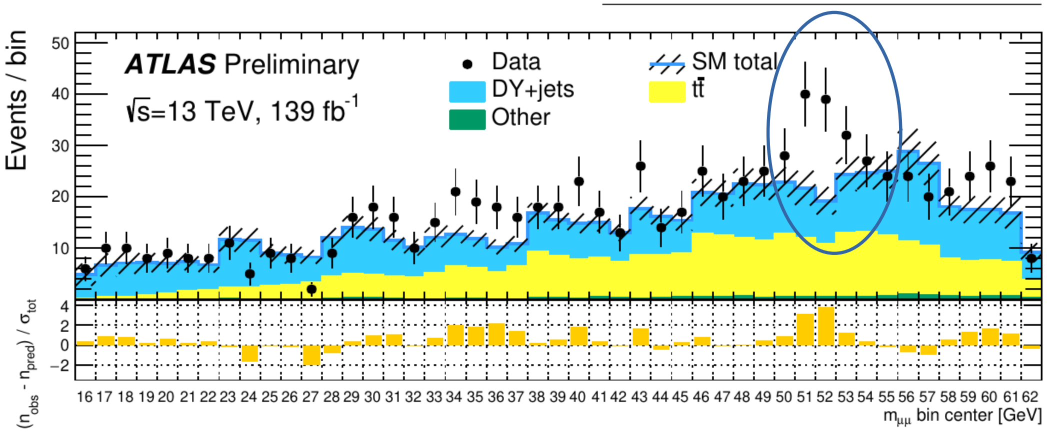
139 fb⁻¹

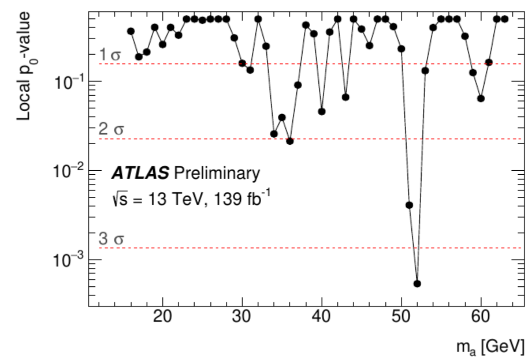
Mar 25th, 2021
ATLAS-CONF-2021-009

- Good shape agreement in side-bands of candidate m_H →
- Selection-BDT individually trained for each $m_{\mu\mu}$ hypothesis
- Largest discrepancy at $m_{\mu\mu} \sim 52$ GeV
  - **Local significance: 3.3σ**
  - **Global significance: 1.7σ**
- Statistically-dominated!



$m_{\mu\mu}$ bin [GeV]	[34-36]
Observed events	19
Total background	11.9 ± 1.6





CMS: multi-b excess as well?!

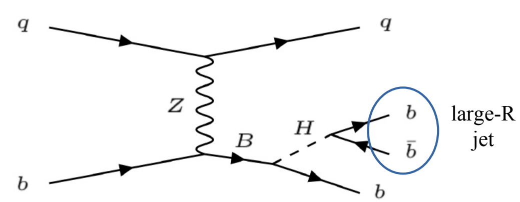
B → bH(bb)

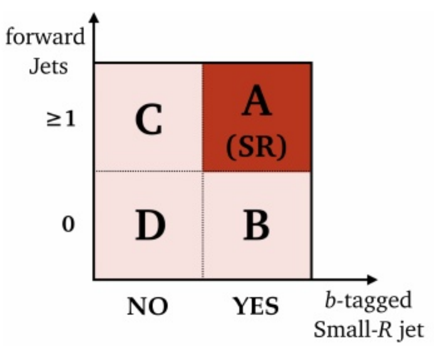
139 fb^{-1}

Apr 6th, 2021

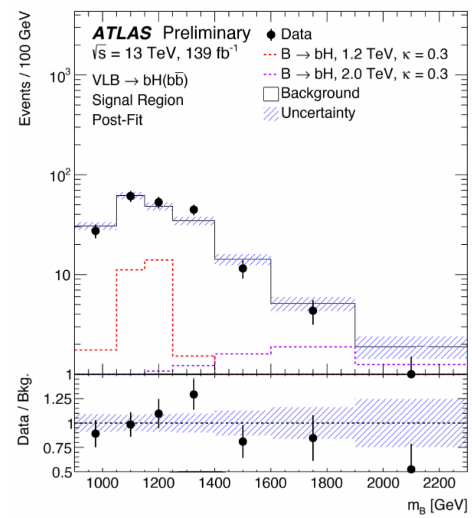
ATLAS-CONF-2021-018

- Targets single-production of vector-like quarks (B)
- H → bb reconstructed as single large-R jet (p_T > 480 GeV)
  - — Track-jets matched to large-R jet used for b-tagging
  - — One or two b-tagged sub-jets: ε^b=70%, ε^c=10%, ε^{light}=0.25%
- In total, requires (two) three identified b-jets
  - — Isolated b-jet away from Higgs candidate and p_T > 480 GeV
  - — Note: explicit veto of events with isolated high p_T lepton





- Data-driven multi-jet background
- Mass of B candidate as final discriminant
  - — Quite poor mass resolution
- Largest excess at m ~ 1.3 TeV
  - — **Local significance ~ 1.9σ**
- Systematic uncertainty play an important role, but limited by statistics in background "B" region

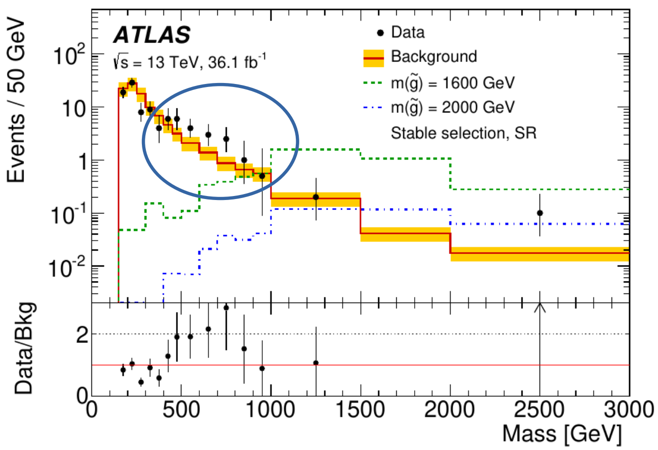


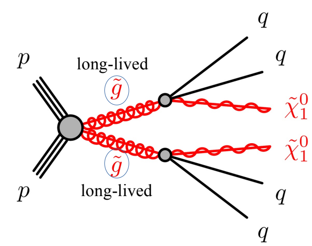
(Meta-)stable charged particles

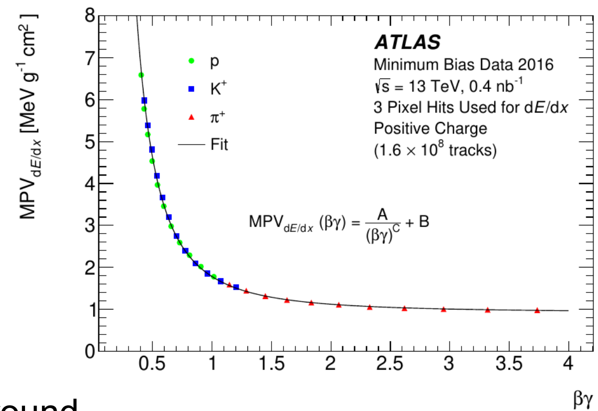
36 fb^{-1}

arXiv:1808.04095

- Charged, massive BSM particle with macroscopic lifetime
  - — Heavily ionizing in the pixel detector → measure dE/dx → βγ
  - — Inner tracker → particle momentum p
- Final discriminant: mass M ~ p / βγ
- Select events with large MET
  - — used for triggering
  - — common to many BSM signatures







- Data-driven background
- Cut-and-count in pre-determined mass windows
  - — Determined based on expected resolution, which is largely model-independent – driven by σ(p), σ(dE/dx)
- Interesting excess at M ~ 600 GeV
  - — **Local significance: 2.4 σ** (little trial factor)
  - — Resolution compatible with expectations (not shown)
- Partial dataset → expect follow up w/ Run 2 data!

Partially-reconstructed final states

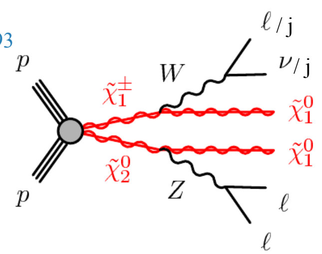
- Often results in final states with large MET → great for trigger/background suppression
  — trial-factor either small or due to large number of optimized signal regions
- Relies on fine control of backgrounds' kinematic (often in tails) to extract the signal

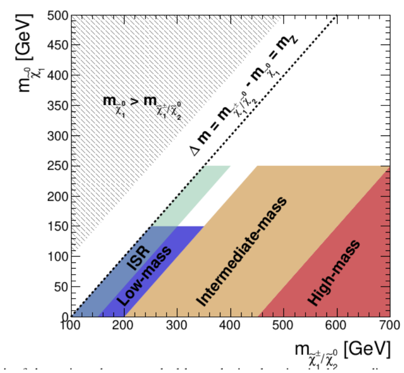
36 fb^{-1} $\chi_1^{\pm}\chi_2^0 \rightarrow$ **2/3L + MET** arXiv:1806.02293

- Recursive Jigsaw technique
- Includes boosted region to probe compressed scenarios

Signal region	SR3ℓ_ISR
Total observed events	12
Total background events	3.9 ± 1.0
Other	$0.06^{+0.19}_{-0.06}$
Triboson	0.08 ± 0.04
Fit output, *VV*	3.8 ± 1.0
Fit input, *VV*	3.4

3.0σ (local)





arXiv:1912.08479
ATLAS-CONF-2020-015

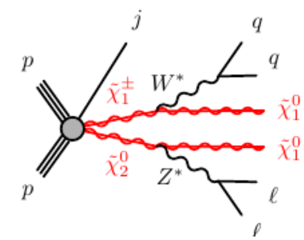
139 fb^{-1}

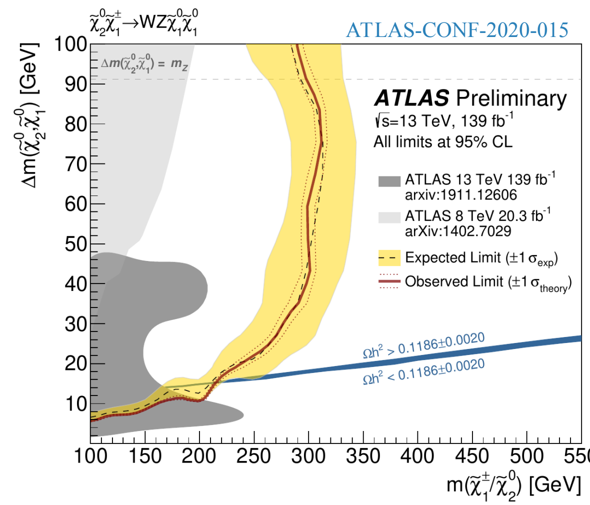
- Using more standard kinematic to map similar features
  — Reproduced the excess in 36/fb
  — Excess not confirmed
- Latest iteration released recently:
  — largest excess ~2.3σ in a targeted offshell-Z signal region
  — sensitivity to exclude

$\chi_1^{\pm 0}\chi_2^0 \rightarrow$ 2/3L + MET

- Dedicated analysis for compressed scenarios
  - Very soft leptons: $p_T^e > 4.5$, $p_T^\mu > 3$ GeV
  - Isolated track to recover unidentified leptons as low as 1-2 GeV
- Several signal regions optimized for:
  - Production (direct EWKinos, VBF, sleptons)
  - MET and m(ll) bins
- Excess with **local significance 2.7σ** in EWKino search

- However, the same region is also probed by the most recent result focused on "regular" 2L/3L signature and does not confirm it
  - Clear benefit in overlapping sensitivity within the final state and parameter space probed



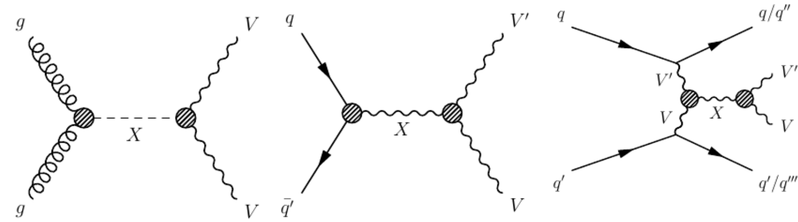


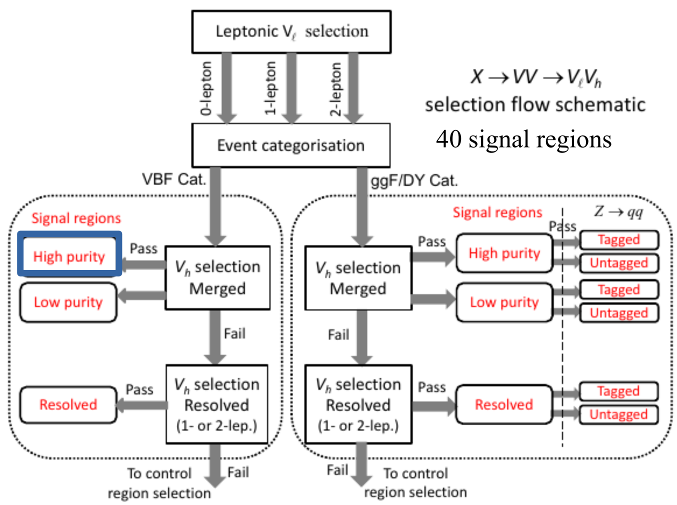
VV → ll/lν/νν jj

139 fb^{-1}

arXiv:2004.14636

- Probes several production modes
  - Classified using recursive NN
- Boosted hadronic V decays reconstructed as single large-R jet





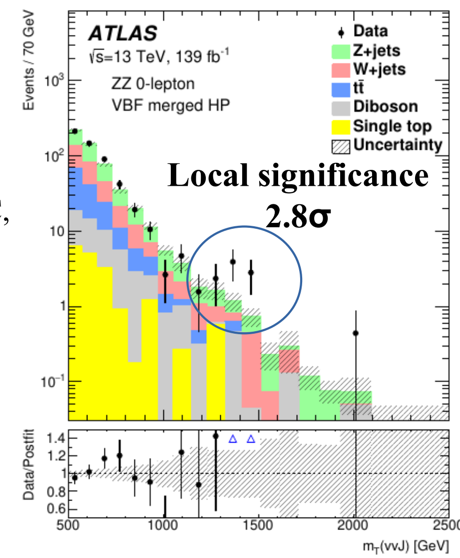
$X \to VV \to V_\ell V_h$

selection flow schematic

40 signal regions

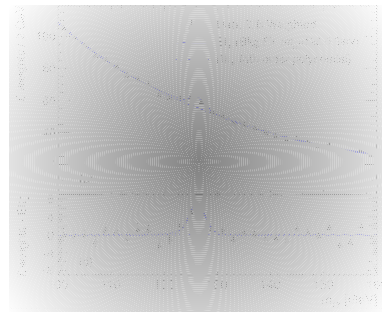
VBF – ZZ → νν

- Large MET
- High/Low-Purity via jet substructure (D_2)
- W/Z+jet background from MC, normalized in dedicated Crs
  - Sherpa as baseline
  - Scale variations, MG5 comparison
- Largest systematics:
  - Large-R jet response
  - MC statistics
  - W/Z+jets modeling
- Excess stat. limited



Type of anomalies

- **Anomalies in direct searches**
  - — Bump-hunting
  - — Partially reconstructed final states



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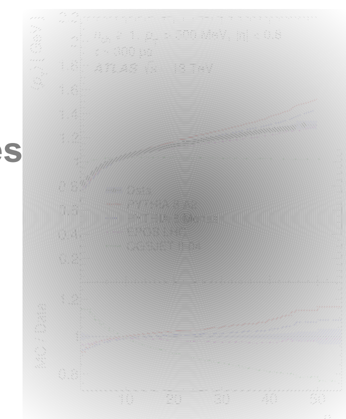
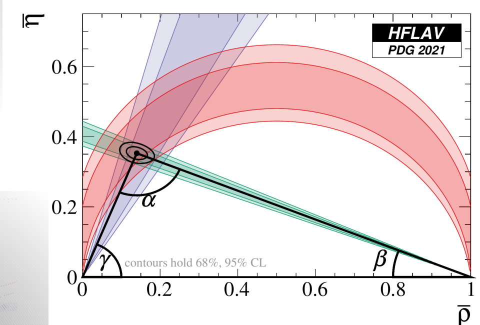
  - — Comparison of sensitive observables with SM predictions
  - — Consistency within SM





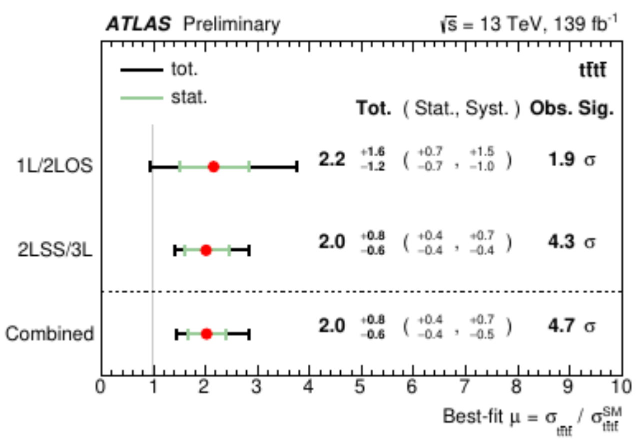
- **Measurements of “poorly-known” SM processes**
  - — e.g. non-perturbative regimes, measurements with much better experimental than theoretical accuracy, …

← Likely the longest-living discrepancy in the LHC dataset :)

Rare SM processes

139 fb^{-1} **Four tops production** ATLAS-CONF-2021-013

- σ^{SM}(tttt) ~12 fb
- Systematics play a dominant role
  - Signal modeling
  - tt+h.f. background
- Need data + theory improvements!

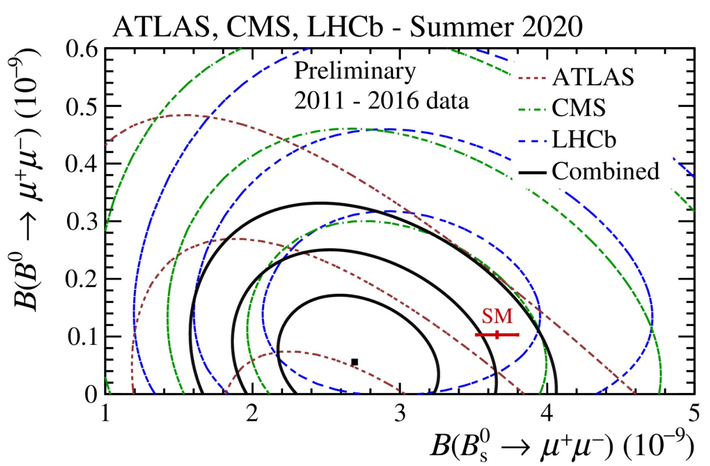


$B^0_{(s)} \rightarrow \mu\mu$ ATLAS-CONF-2020-049 139 fb^{-1}

- Tiny SM expectation

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

- Recent ATLAS+CMS+LHCb combination
  - 2.4σ compatibility w/ SM for $B_s \rightarrow \mu\mu$



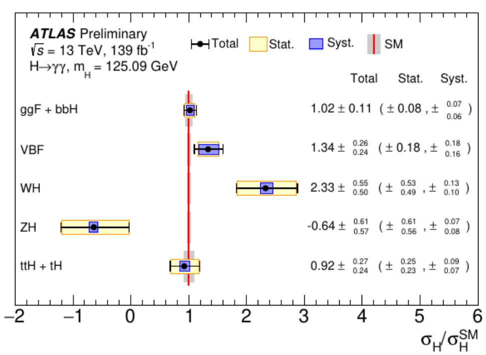
Precision measurements

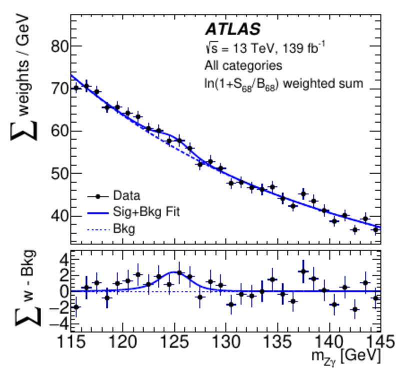
- Probe consistency of the SM and very sensitive to e.g. loop-induced BSM contributions

139 fb^{-1} Higgs couplings

ATLAS-CONF-2021-013
HIGG-2018-42

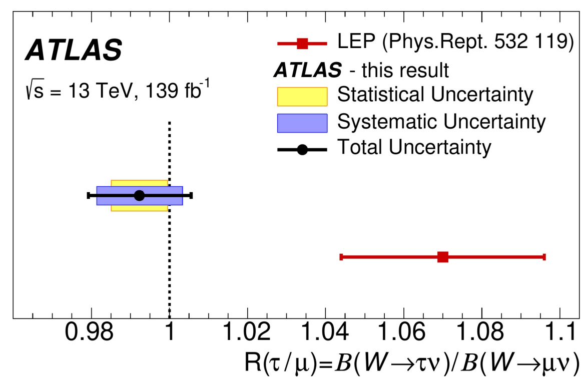
- Higgs production and decay modes
- H → γγ mode:
  - **slight tension: 1.9σ** (global fit)
  - WH and WZ highly correlated (-41%)
- H → Zγ: 2.2σ “expected” excess.. towards observation!





W → τν / W → μν arXiv:2007.14040 139 fb^{-1}

- Lepton universality test
- Large W sample from top decays
  - eμ, μμ final states
- Probe unbiased muon (trigger on other lepton)
- Using muon impact parameter to distinguish muons promptly produced or from tau decay



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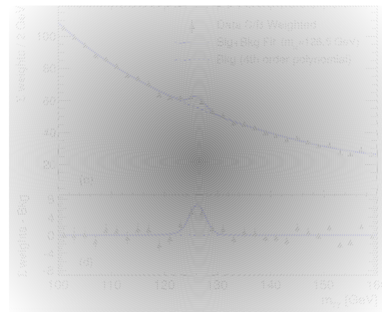

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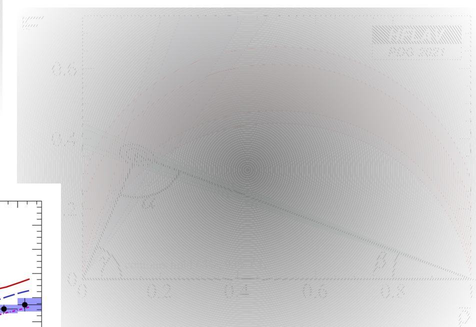

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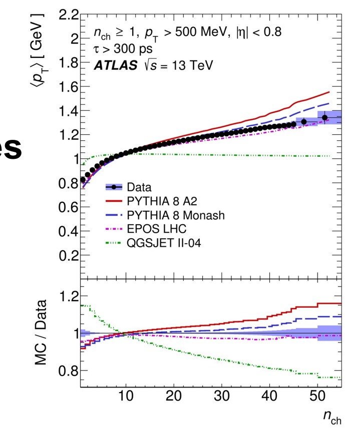


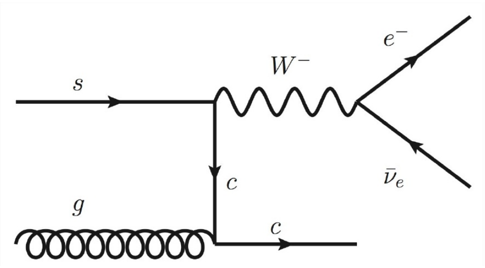
← Likely the longest-living discrepancy in the LHC dataset :)

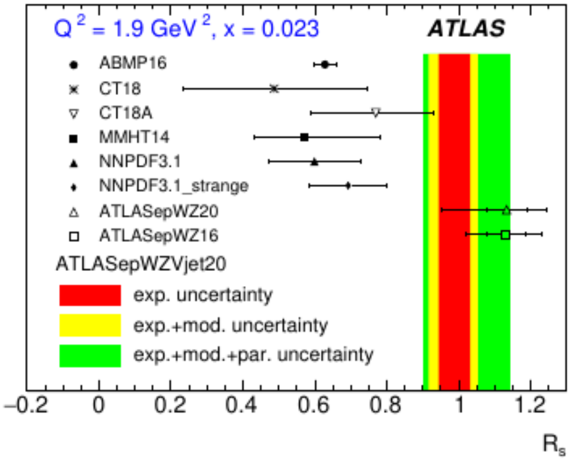
Proton's Strange PDF

7,8 TeV

arXiv:1402.6263
arXiv:2101.05095

- LHC precision measurements on W/Z+jets constraint proton's PDF
  - — HERA data instrumental to our knowledge of PDF, but can't distinguish e.g. flavor of sea-quark $\bar{d}$ vs $\bar{s}$
  - — Usually combined with previous collider and low-energy experiments
- Particularly interesting puzzle on strange PDF, characterized by $R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$,
  - — Strange PDF usually assumed suppressed from neutrino CC scattering with charm ($R_s < 1$)
  - — ATLAS fit on generic W/Z+jets suggest an "unsuppressed" *s* vs *d* ($R_s \sim 1$)
  - — ATLAS 7 TeV W+charm → confirms unsuppression
  - — CMS 7+13 TeV result points to the "usual" suppression
- New analyses under way to clarify this puzzle!





Conclusions

- Yes, no striking sign of beyond-SM physics yet in the Run 2 LHC dataset

- I've tried to review a few of the most interesting anomalies we currently have in our dataset
  - Some will need Run 3 data to clarify
  - Some can be clarified with ongoing full Run 2 dataset analysis

- We should not forget that we have plenty of measurements that clearly point to physics we haven't fully mastered, and they can be important in our understanding of LHC data!

BACKUP

Statistical fluctuations don't have a sign..

- EWK Zjj (deficit)

Wilson coefficient	Includes $\|\mathcal{M}_{d6}\|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

Existing Anomalies In The Current ATLAS Run 2 Dataset

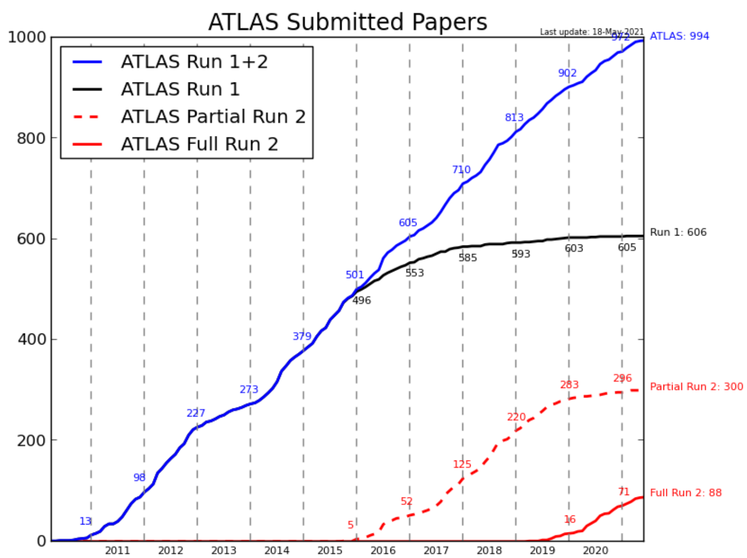
Simone Pagan Griso

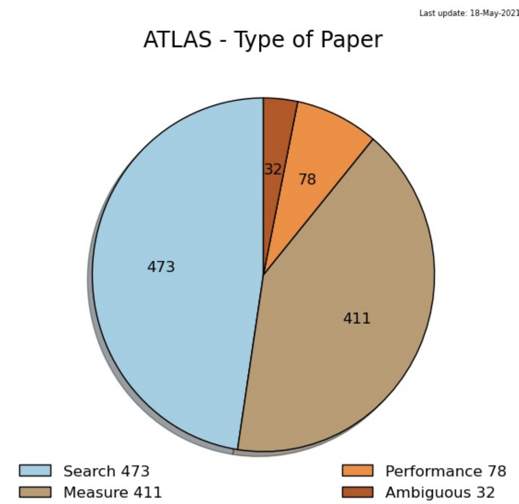
May 21st, 2021

New Physics from Precision at High Energies - KITP

Introduction

- Vast physics program of measurements, searches for new physics and performance papers





- Each containing often a large number of signal regions / observables
- A number large enough that > 3σ statistical fluctuations are expected to occur
  — Although systematics play an important role and are often not as Guassian as we'd like

Introduction

- Despite large number of searches and measurements, most of the abstracts contain

> is carried out on 139 fb^{-1} of proton–proton collision data at $\sqrt{s}$ = 13 TeV collected by the ATLAS detector at the LHC between 2015 and 2018. No significant deviation from the Standard Model background prediction is observed. Mass-dependent exclusion limits at the 95% confidence level are drawn on the single production cross-section of a vector-like B quark

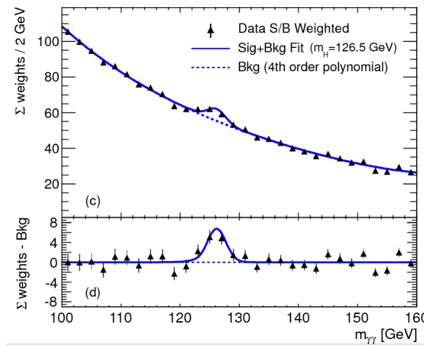
> data-taking periods. The search is conducted by examining the reconstructed invariant or transverse mass distributions of Wh and Zh candidates for evidence of a localised excess in the mass range of 220 GeV up to 5 TeV. No significant excess is observed and the results are interpreted in terms of constraints on the production cross-section times branching fraction

> volumes and are compared with theoretical predictions at different levels of precision, based on a χ^2/ndf and p-value computation. Overall, good agreement is observed between the unfolded data and the predictions.

- However, a (not-so) small number of anomalies have been observed…
  - … some are gone with more data,
  - … some persist or appeared in the full run 2 dataset,
  - … some are direct evidence of physics we don't fully understand (just maybe not necessarily beyond-SM)
- Tracking them allows to plan at the best for the future dataset increase and R&D needs

Type of anomalies

- **Anomalies in direct searches**
  - Bump-hunting
  - Partially reconstructed final states



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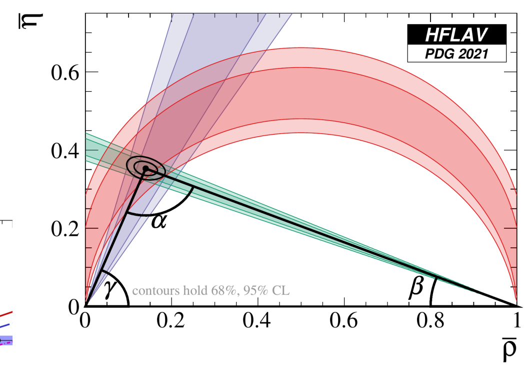

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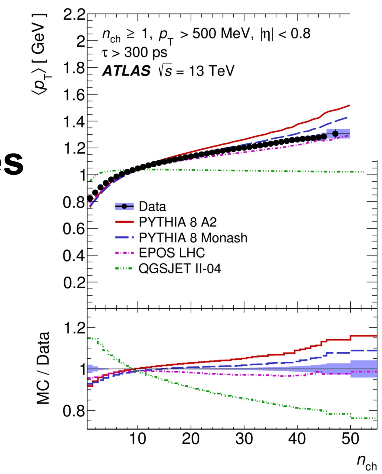
  - e.g. non-perturbative regimes, measurements with much better experimental than theoretical accuracy, ...



← Likely the longest-living discrepancy in the LHC dataset :)

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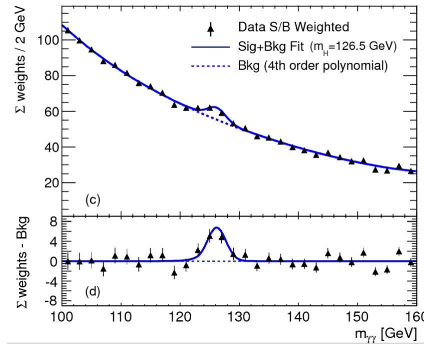

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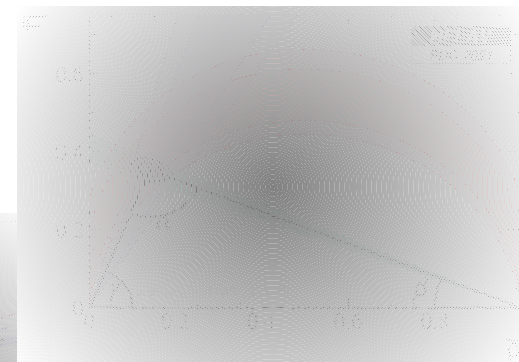

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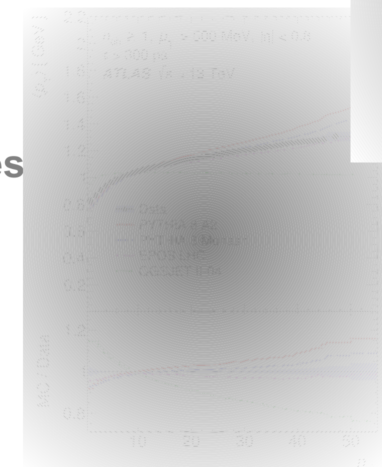

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Bump Hunting

- Fully reconstructed BSM candidate final state
  - — Measure candidate mass
  - — Explore angular correlations to gather information on the particle's properties

- Large trial factor when scanning the full kinematic available region with good mass resolution

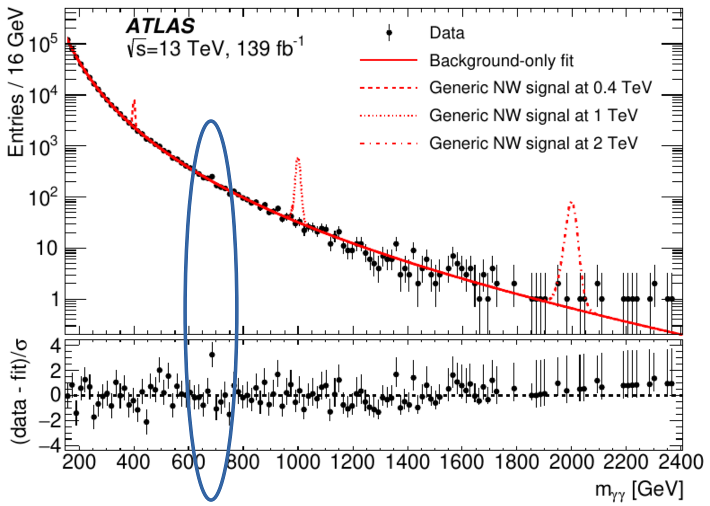
$$p_{global} = 1 - (1 - p_{local})^N$$

(only valid for N ~equal significance regions)

γγ resonance arXiv:2102.13405

- Look for spin-0 and spin-2 resonances
  - — Scan mass, width (spin-0) or coupling (spin-2)
- Two high p_T isolated photons (> 35,25 GeV)
  - — E_T / $m_{\gamma\gamma}$ > 0.3 (0.25) for (sub-)leading E_T photon
- Smooth background from non-resonant γγ
- Most significant excess for $m_{\gamma\gamma}$ ~ 684 GeV

  local significance: 3.3 σ
  global significance: 1.3 σ } narrow-width results
- Good example of large trial factor

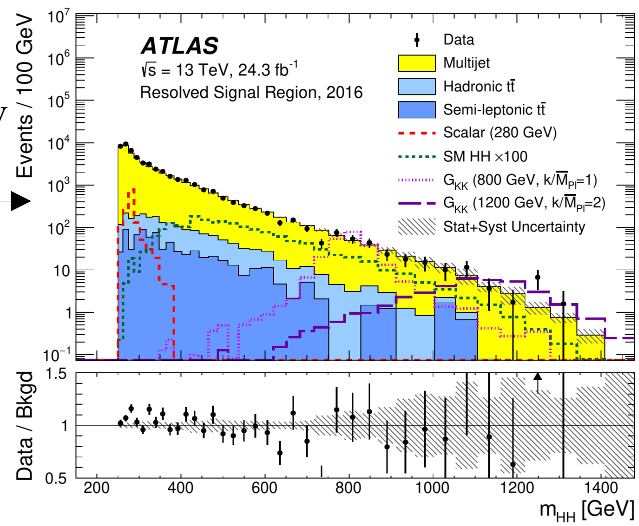


Other heavy scalar searches

36 fb^{-1} **HH (→ 4b) resonance** arXiv:1804.06174

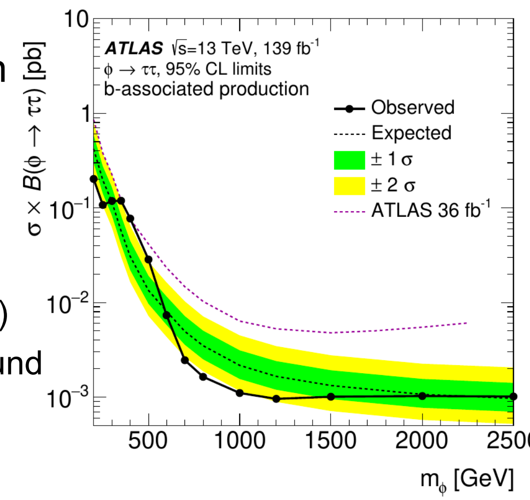
- 4 b-tagged jets required with kinematic selections to enhance expected signal
  - — Boosted (>0.8 TeV) and Resolved analyses
- Most significant excess at M~280 GeV
  - — **local(global) significance: 3.6σ (2.3σ)**

- Expected signal mass resolution @ 280 GeV ~ 9 GeV
- 2016 data only →
  - 2015 data looks compatible with background-only
- Leading systematic from data-driven multijet background



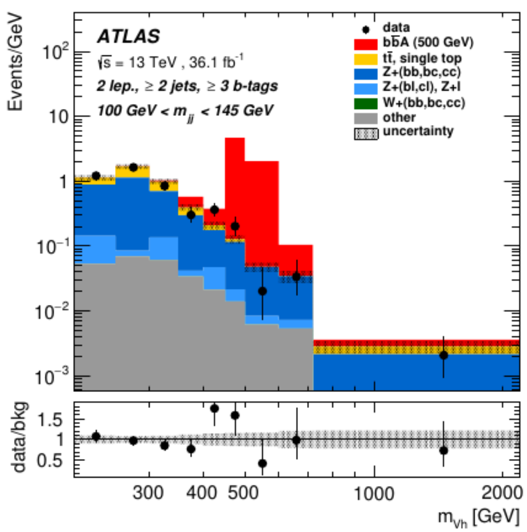
A → ττ arXiv:2002.12223 139 fb^{-1}

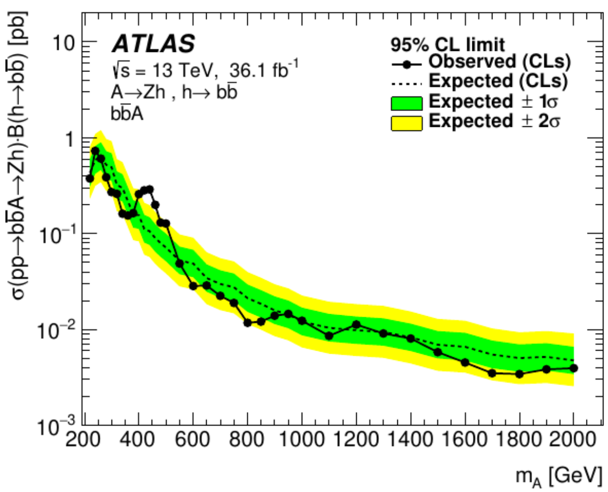
- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ final states
- Explores gluon-fusion and b-associated production (MSSM inspired)
- Most significant excess ~ 400 GeV
  - — 2.2σ gluon-fusion
  - — 2.7σ bbH prod.
- Mostly statistically limited (>600 GeV)
- Fake tau background dominates at low masses

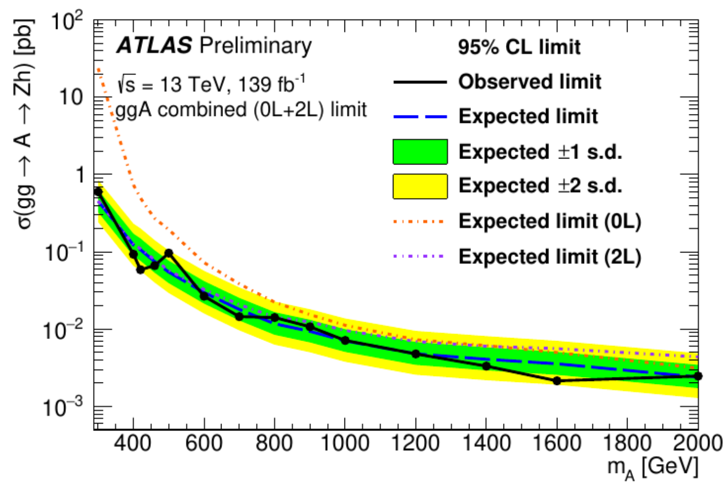


A → V H(bb)

- Leptonic V decay, resolved or boosted H → bb reconstruction
- Analysis shows an interesting excess with 36 fb^{-1} of data in the ZH → llbb signal region
  - — **Local significance: 3.6σ, Global significance: 2.4σ**
  - — Driven by the 3 b-tags region (associated bbA production)
- Similar run-2 result looking for A → ZH → llbb (<u>only 1,2 b-tag regions</u>) → mild excess but difficult to compare fairly



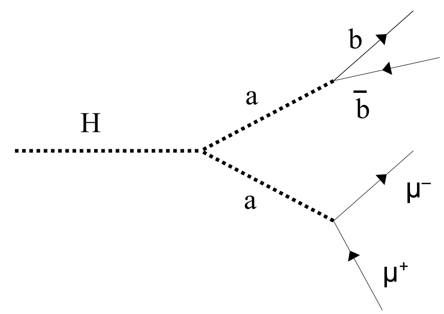


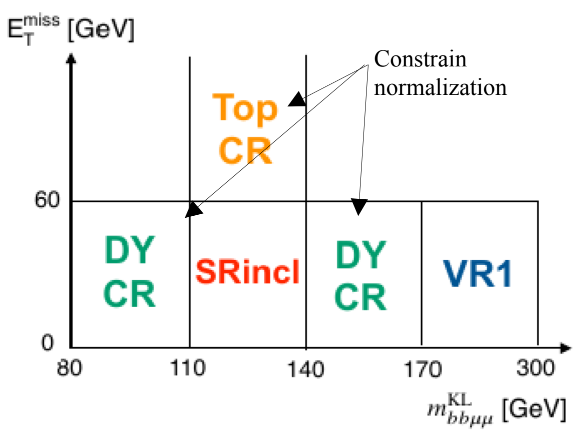


$H \rightarrow aa \rightarrow bb\mu\mu$

139 fb^{-1}
Mar 25th, 2021
ATLAS-CONF-2021-009

- Balance of clean final state and high branching ratio
  — Single (p_T^{μ} > 27, 5 GeV) / di-lepton (p_T^{μ} > 15, 15 GeV) triggers
  — Two b-tagged jets (p_T > 20 GeV, ε^{b}=77%)
- Kinematic constrained applied via likelihood fit
  — Much poorer m_{bb} resolution → $m_{\mu\mu}$ to constrains b-jet energy scale
  — Four-body mass required to be consistent with Higgs mass
- Boosted-Decision-Tree to enhance background suppression
  — Based on kinematic likelihood, mass combinations and angular information





- Main background from Drell-Yan + heavy-flavor and ttbar
  - ttbar: kinematic (shape) from simulation
  - DY: kinematic (shape) from 0 b-tag region
    - Kinematics corrected for 2 vs 0 b-tags via BDT-based event reweighting to better match all kinematic properties

~ consistent with CMS result?

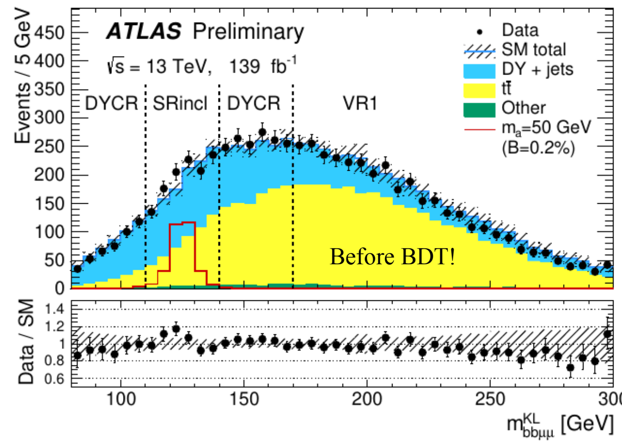
H → aa → bbμμ

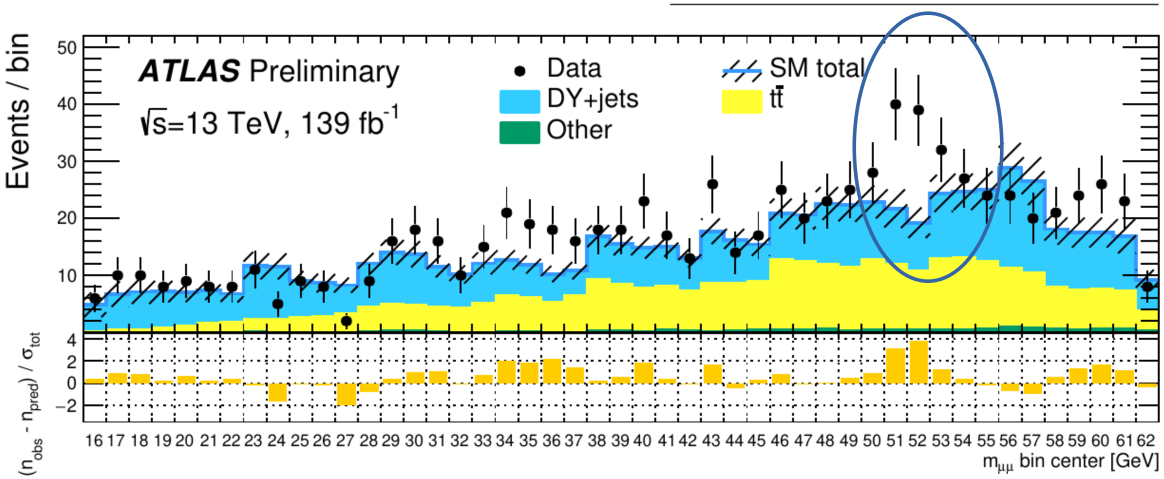
139 fb^{-1}

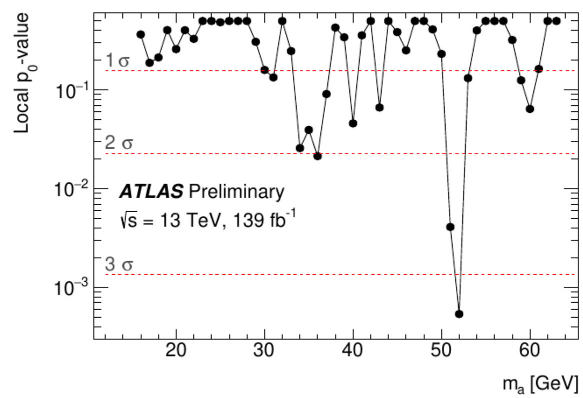
Mar 25th, 2021
ATLAS-CONF-2021-009

- Good shape agreement in side-bands of candidate m_H →
- Selection-BDT individually trained for each $m_{\mu\mu}$ hypothesis
- Largest discrepancy at $m_{\mu\mu}$ ~ 52 GeV
  - — **Local significance: 3.3σ**
  - — **Global significance: 1.7σ**
- Statistically-dominated!

$m_{\mu\mu}$ bin [GeV]	[34-36]
Observed events	19
Total background	11.9 ± 1.6







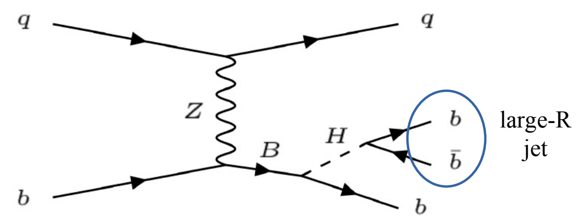
CMS: multi-b excess as well?!

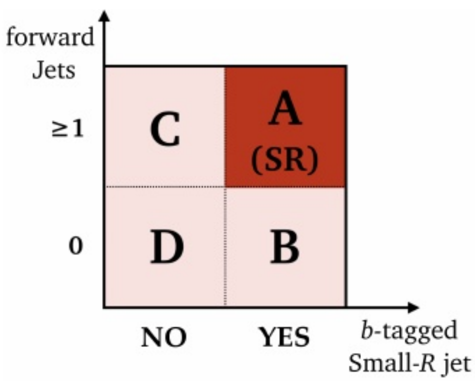
B → bH(bb)

139 fb^{-1}

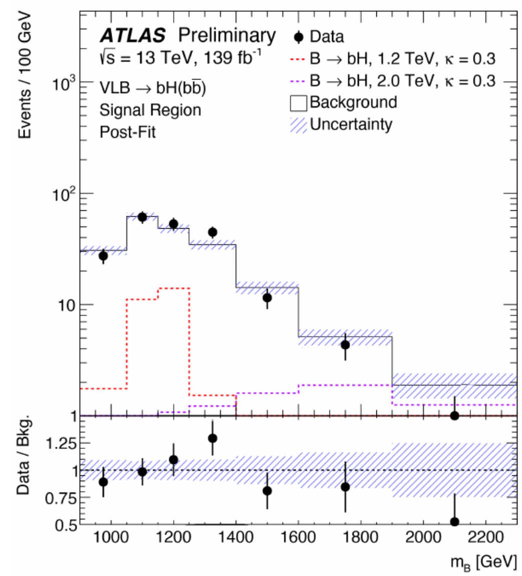
Apr 6th, 2021
ATLAS-CONF-2021-018

- Targets single-production of vector-like quarks (B)
- H → bb reconstructed as single large-R jet (p_T > 480 GeV)
  - — Track-jets matched to large-R jet used for b-tagging
  - — One or two b-tagged sub-jets: ε^b=70%, ε^c=10%, ε^{light}=0.25%
- In total, requires (two) three identified b-jets
  - — Isolated b-jet away from Higgs candidate and p_T > 480 GeV
  - — Note: explicit veto of events with isolated high p_T lepton





- Data-driven multi-jet background
- Mass of B candidate as final discriminant
  - — Quite poor mass resolution
- Largest excess at m ~ 1.3 TeV
  - — **Local significance ~ 1.9σ**
- Systematic uncertainty play an important role, but limited by statistics in background "B" region

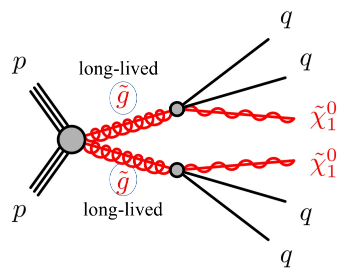


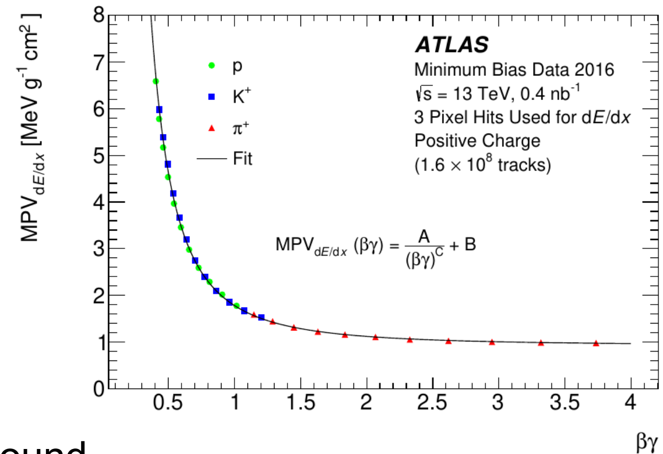
(Meta-)stable charged particles

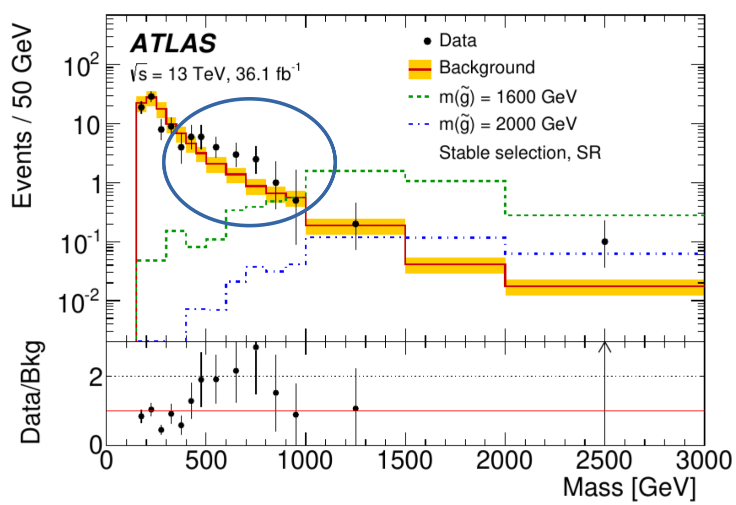
36 fb^{-1}

arXiv:1808.04095

- Charged, massive BSM particle with macroscopic lifetime
  - — Heavily ionizing in the pixel detector → measure dE/dx → βγ
  - — Inner tracker → particle momentum p
- Final discriminant: mass M ~ p / βγ
- Select events with large MET
  - — used for triggering
  - — common to many BSM signatures







- Data-driven background
- Cut-and-count in pre-determined mass windows
  - — Determined based on expected resolution, which is largely model-independent – driven by σ(p), σ(dE/dx)
- Interesting excess at M ~ 600 GeV
  - — **Local significance: 2.4 σ** (little trial factor)
  - — Resolution compatible with expectations (not shown)
- Partial dataset → expect follow up w/ Run 2 data!

Partially-reconstructed final states

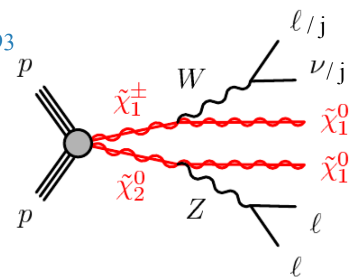
- Often results in final states with large MET → great for trigger/background suppression
  - — trial-factor either small or due to large number of optimized signal regions
- Relies on fine control of backgrounds' kinematic (often in tails) to extract the signal

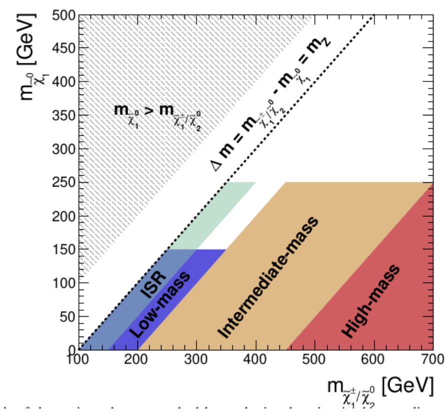
36 fb^{-1} $\chi_1^\pm \chi_2^0 \rightarrow$ **2/3L + MET** arXiv:1806.02293

- Recursive Jigsaw technique
- Includes boosted region to probe compressed scenarios

Signal region	SR3ℓ_ISR
Total observed events	12
Total background events	3.9 ± 1.0
Other	$0.06^{+0.19}_{-0.06}$
Triboson	0.08 ± 0.04
Fit output, VV	3.8 ± 1.0
Fit input, VV	3.4

3.0σ (local)





arXiv:1912.08479
ATLAS-CONF-2020-015

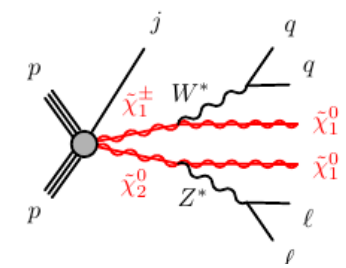
139 fb^{-1}

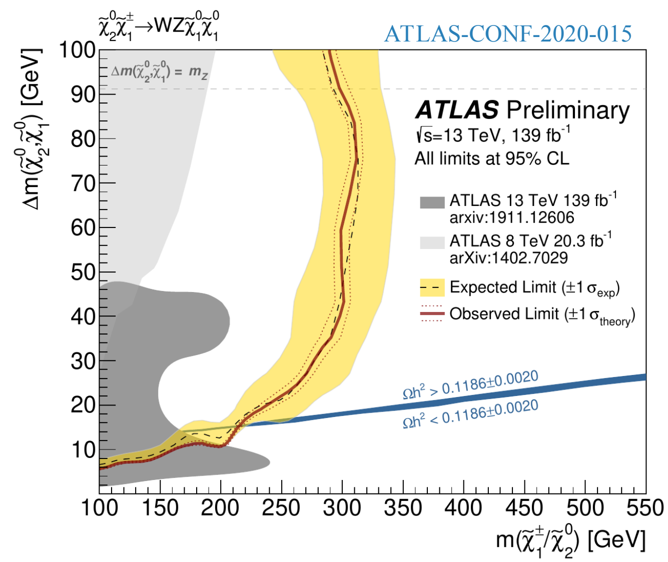
- Using more standard kinematic to map similar features
  - — Reproduced the excess in 36/fb
  - — Excess not confirmed
- Latest iteration released recently:
  - — largest excess ~2.3σ in a targeted offshell-Z signal region
  - — sensitivity to exclude

$\chi_1^{\pm 0}\chi_2^0 \rightarrow$ 2/3L + MET

- Dedicated analysis for compressed scenarios
  - Very soft leptons: $p_T^e > 4.5$, $p_T^\mu > 3$ GeV
  - Isolated track to recover unidentified leptons as low as 1-2 GeV
- Several signal regions optimized for:
  - Production (direct EWKinos, VBF, sleptons)
  - MET and m(ll) bins
- Excess with **local significance 2.7σ** in EWKino search

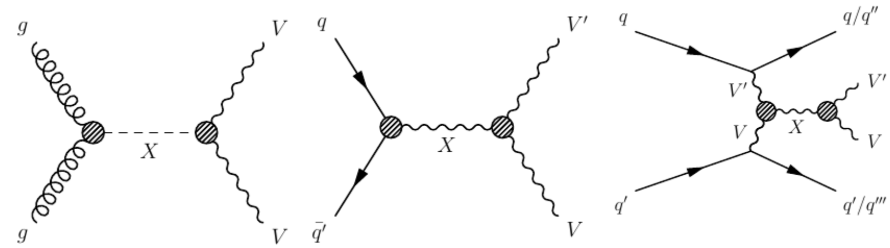
- However, the same region is also probed by the most recent result focused on "regular" 2L/3L signature and does not confirm it
  - Clear benefit in overlapping sensitivity within the final state and parameter space probed

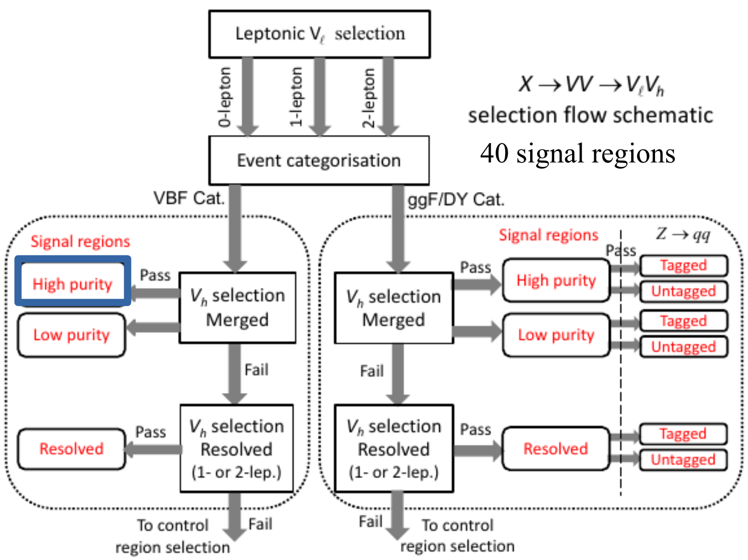




VV → ll/lν/νν jj

- Probes several production modes
  - Classified using recursive NN
- Boosted hadronic V decays reconstructed as single large-R jet

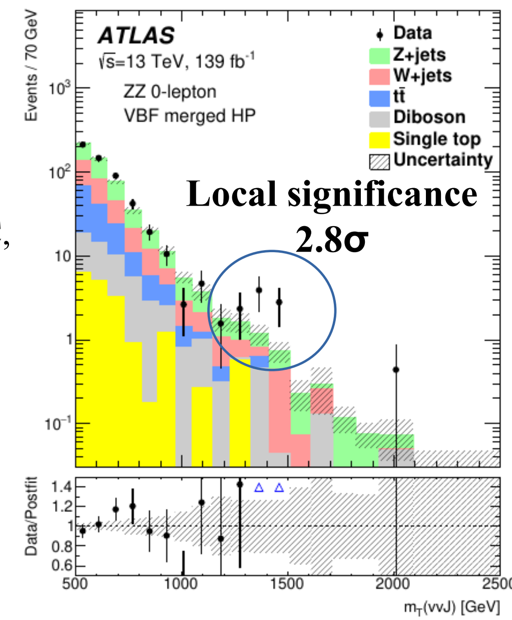




$X \to VV \to V_\ell V_h$
selection flow schematic
40 signal regions

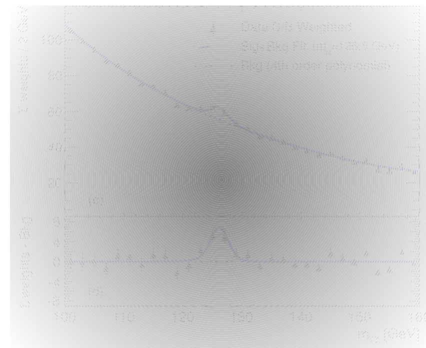
VBF – ZZ → νν

- Large MET
- High/Low-Purity via jet substructure (D_2)
- W/Z+jet background from MC, normalized in dedicated Crs
  - Sherpa as baseline
  - Scale variations, MG5 comparison
- Largest systematics:
  - Large-R jet response
  - MC statistics
  - W/Z+jets modeling
- Excess stat. limited

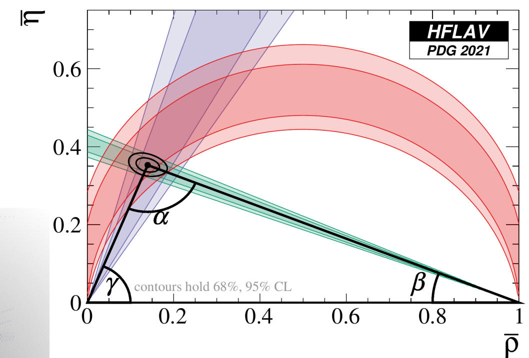


Type of anomalies

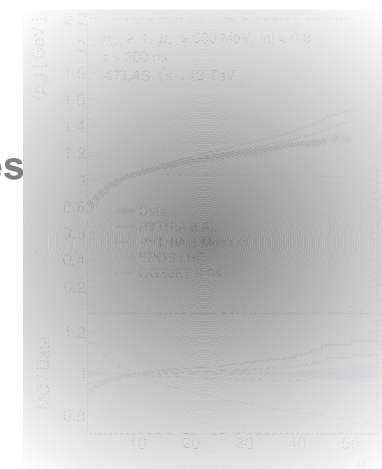
- **Anomalies in direct searches**
  - Bump-hunting
  - Partially reconstructed final states



- **Anomalies in indirect searches**
  - Rare SM phenomena enhanced by BSM
  - Comparison of sensitive observables with SM predictions
  - Consistency within SM



- **Measurements of "poorly-known" SM processes**
  - e.g. non-perturbative regimes, measurements with much better experimental than theoretical accuracy, …

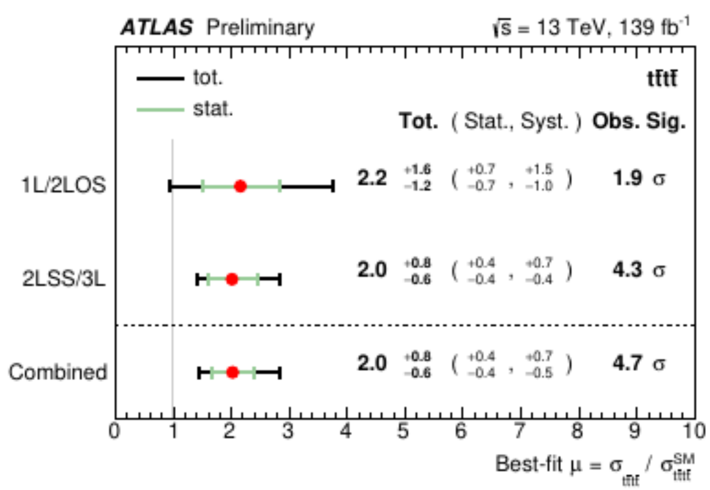


← Likely the longest-living discrepancy in the LHC dataset :)

Rare SM processes

139 fb^{-1} **Four tops production** ATLAS-CONF-2021-013

- σ^{SM}(tttt) ~12 fb
- Systematics play a dominant role
  - Signal modeling
  - tt+h.f. background
- Need data + theory improvements!

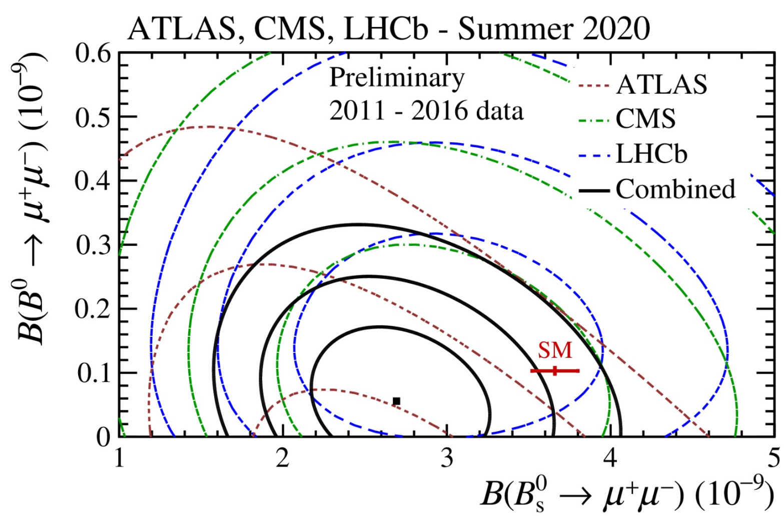


$B^0_{(s)} \rightarrow \mu\mu$ ATLAS-CONF-2020-049 139 fb^{-1}

- Tiny SM expectation

$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

- Recent ATLAS+CMS+LHCb combination
  - 2.4σ compatibility w/ SM for $B_s \rightarrow \mu\mu$

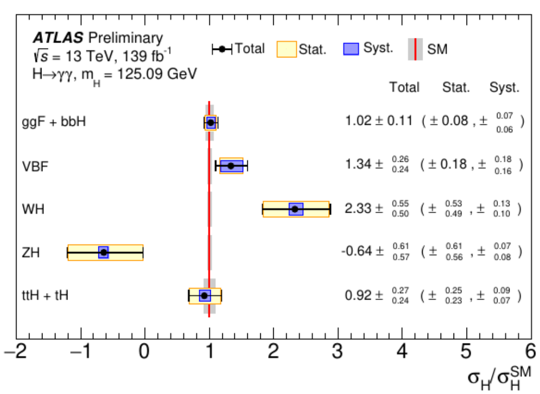


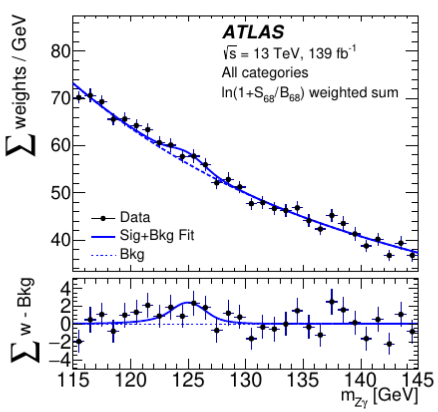
Precision measurements

- Probe consistency of the SM and very sensitive to e.g. loop-induced BSM contributions

139 fb^{-1} Higgs couplings ATLAS-CONF-2021-013 HIGG-2018-42

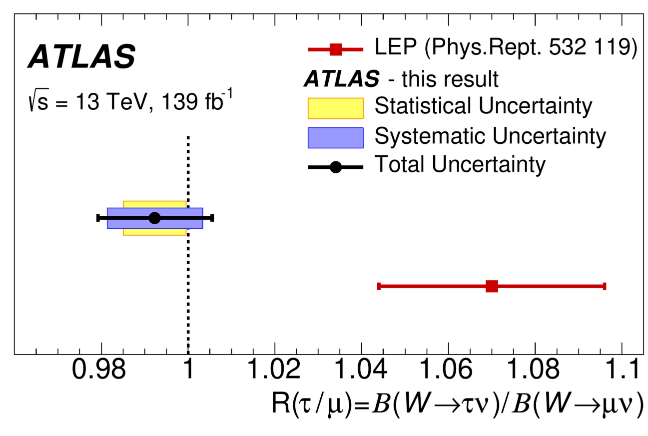
- Higgs production and decay modes
- H → γγ mode:
  - **slight tension: 1.9σ** (global fit)
  - WH and WZ highly correlated (-41%)
- H → Zγ: 2.2σ "expected" excess.. towards observation!





W → τν / W → μν arXiv:2007.14040 139 fb^{-1}

- Lepton universality test
- Large W sample from top decays
  - eμ, μμ final states
- Probe unbiased muon (trigger on other lepton)
- Using muon impact parameter to distinguish muons promptly produced or from tau decay



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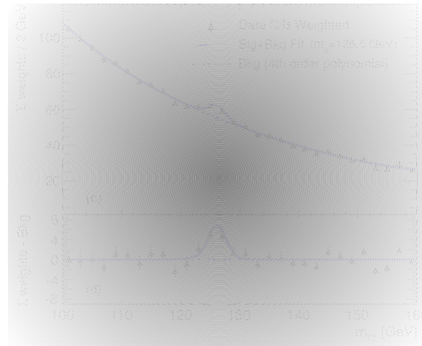

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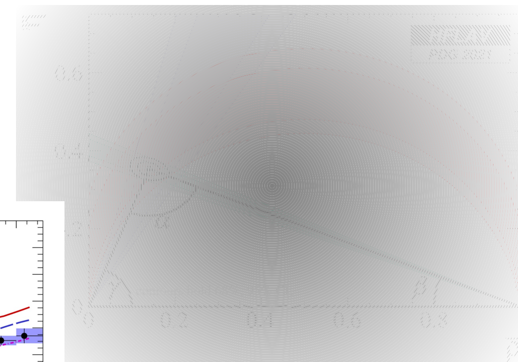

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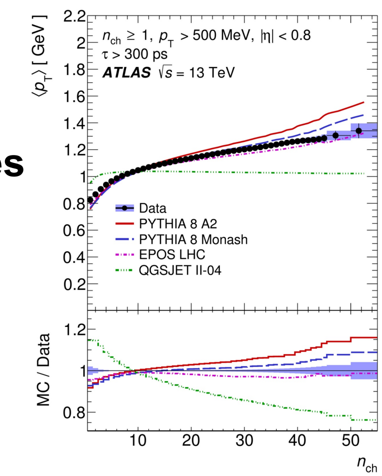


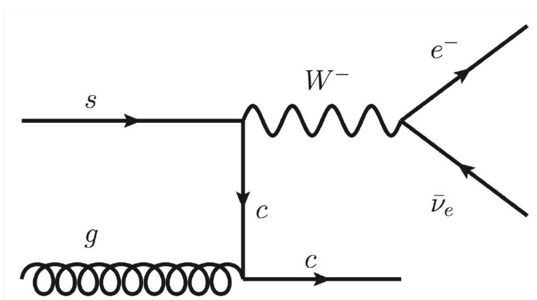
← Likely the longest-living discrepancy in the LHC dataset :)

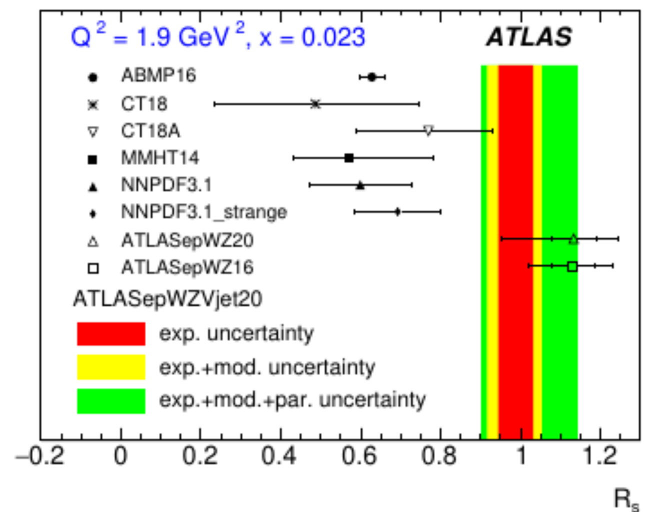
Proton's Strange PDF

7,8 TeV

arXiv:1402.6263
arXiv:2101.05095

- LHC precision measurements on W/Z+jets constraint proton's PDF
  - — HERA data instrumental to our knowledge of PDF, but can't distinguish e.g. flavor of sea-quark $\bar{d}$ vs $\bar{s}$
  - — Usually combined with previous collider and low-energy experiments
- Particularly interesting puzzle on strange PDF, characterized by $R_s = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$,
  - — Strange PDF usually assumed suppressed from neutrino CC scattering with charm ($R_s < 1$)
  - — ATLAS fit on generic W/Z+jets suggest an "unsuppressed" *s* vs *d* ($R_s \sim 1$)
  - — ATLAS 7 TeV W+charm → confirms unsuppression
  - — CMS 7+13 TeV result points to the "usual" suppression
- New analyses under way to clarify this puzzle!



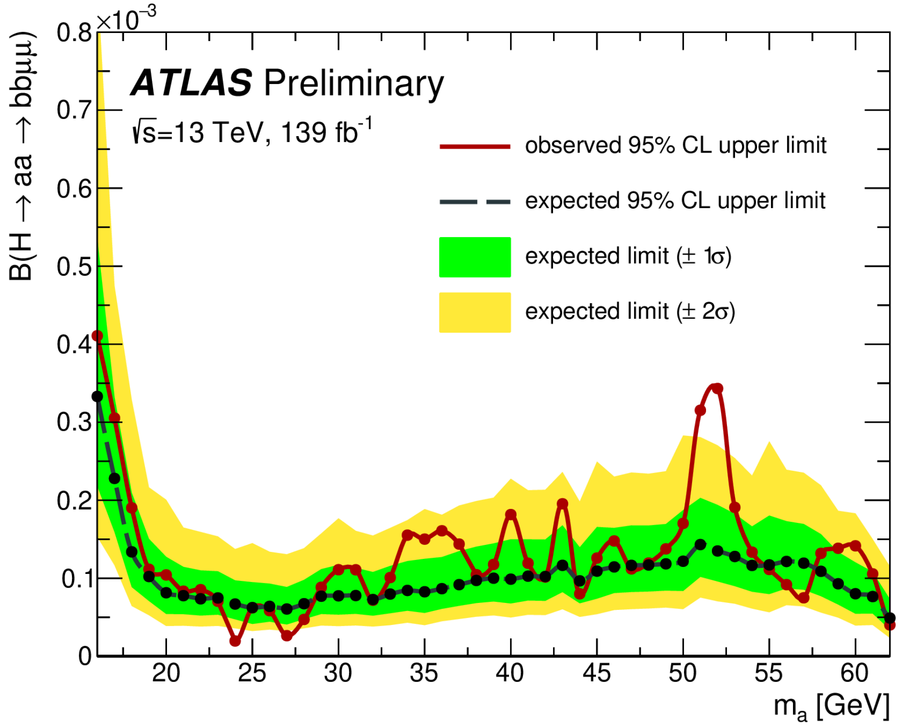


Conclusions

- Yes, no striking sign of beyond-SM physics yet in the Run 2 LHC dataset

- I've tried to review a few of the most interesting anomalies we currently have in our dataset
  - Some will need Run 3 data to clarify
  - Some can be clarified with ongoing full Run 2 dataset analysis

- We should not forget that we have plenty of measurements that clearly point to physics we haven't fully mastered, and they can be important in our understanding of LHC data!



ATLAS Preliminary
√s=13 TeV, 139 fb⁻¹
observed 95% CL upper limit
expected 95% CL upper limit
expected limit (± 1σ)
expected limit (± 2σ)
B(H → aa → bbμμ)
×10⁻³
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20
25
30
35
40
45
50
55
60
m_a [GeV]

BACKUP

Statistical fluctuations don't have a sign..

- EWK Zjj (deficit)

Wilson coefficient	Includes $\|\mathcal{M}_{\mathrm{d6}}\|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%