Exotica Searches at LHC

B. de la Cruz (CIEMAT, Madrid)

On behalf of ATLAS and CMS Collaborations

5th Colombian Meeting
on High Energy Physics

2nd Dec 2020

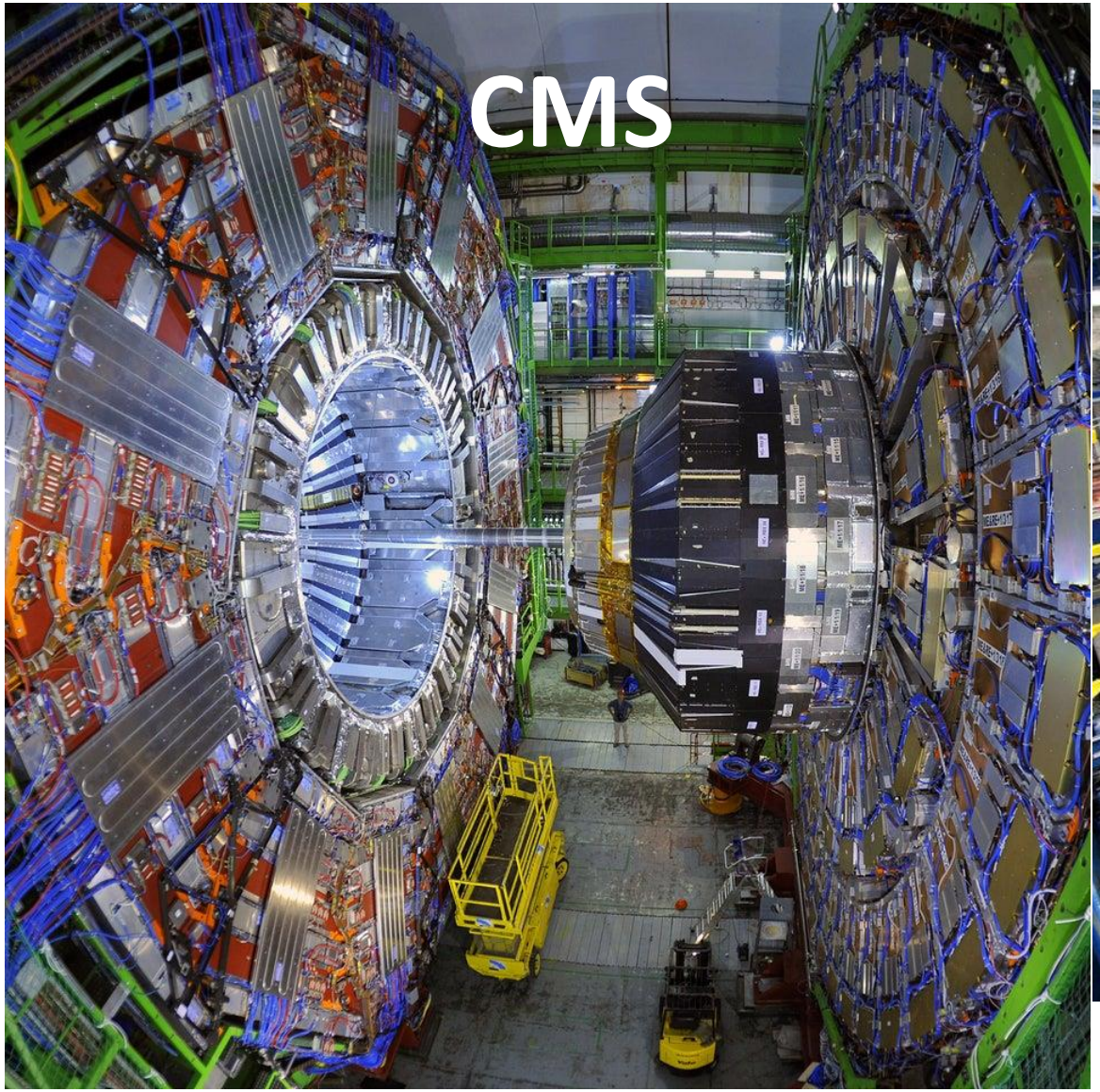
Searching

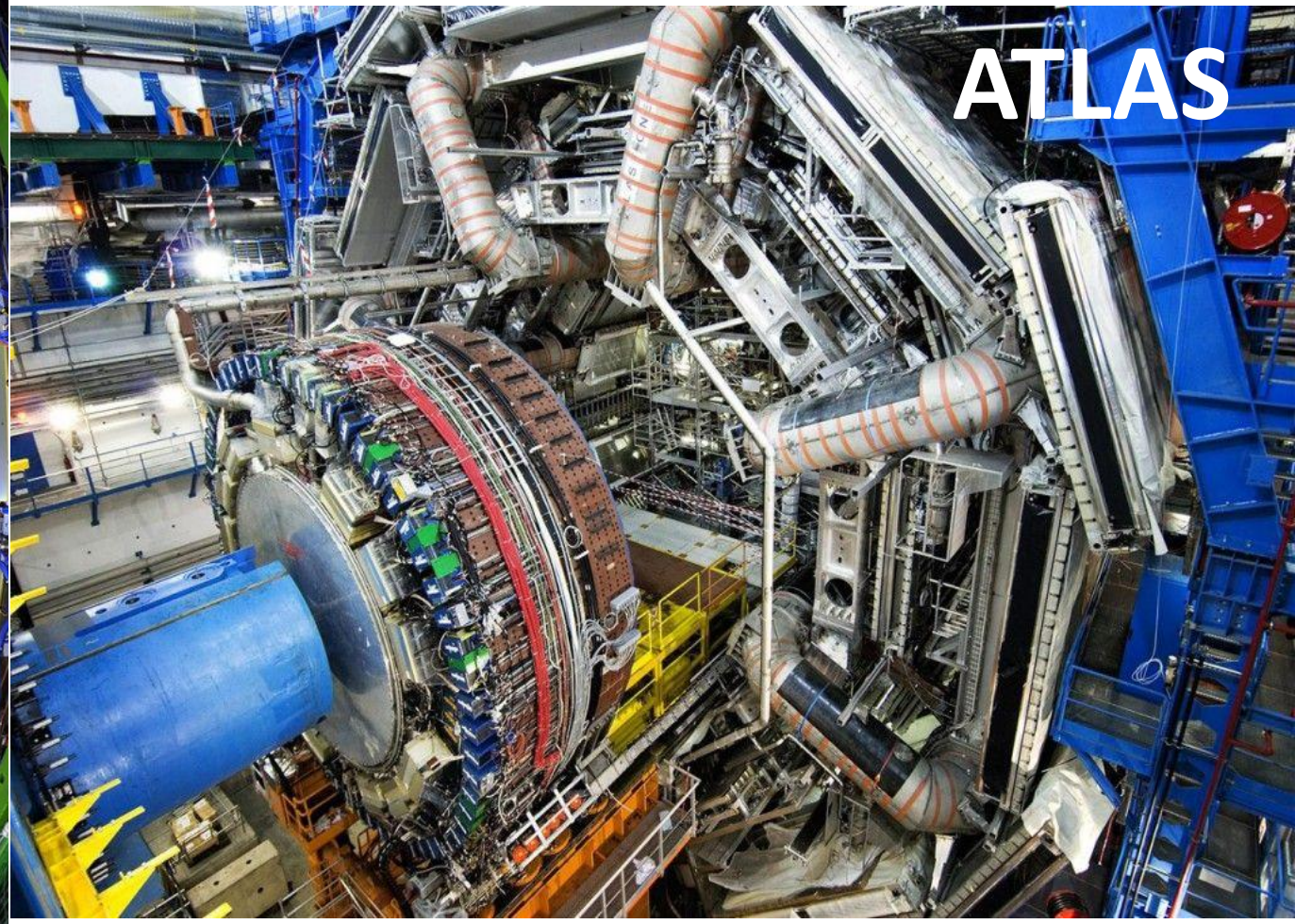
- Searches for new particles/interactions beyond SM is key in the present & future LHC scientific program
  - Characterization of Higgs properties & interactions, EW Symmetry Breaking mechanism is another basic pillar

- Possible scenarios:
  - New physics is at reach in the LHC → explore all posible signatures, driven or not, by theoretical models.
  - New physics at reach @LHC, but unnoticed in our detectors → smart ideas (long-lived, weird experimental signatures, explore intensity frontier…)
  - Beyond LHC reach, but still able to see deviations from SM predictions → EFT (Effective Field Theory approach)

All these aspects are pursued at LHC experiments: ATLAS and CMS

Experiments





We will review…

- Resonances:
  - Dijets
  - Dibosons
  - dileptons: Dark photon, LFV Z
  - Leptoquarks
  - Dark Matter (mediator)
- $\gamma\gamma$ collisions
- Conclusions

Disclaimer:

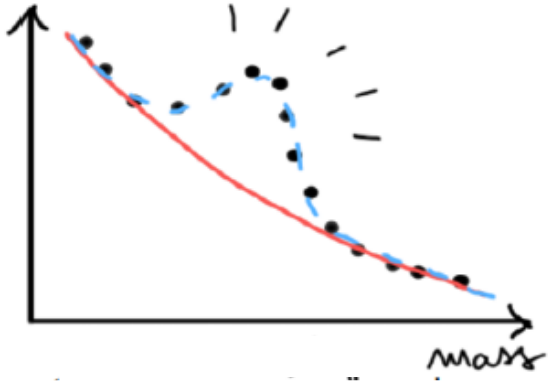
- concentrated on some of most recent topics and results by ATLAS & CMS with Full Run2 data (~140 fb^{-1})
- SUSY, Long-lived presented by Pablo… many other topics not covered in this talk

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

http://cms-results.web.cern.ch/cms-results/public-results/publications/Run2/index.html

N. Saoulidou

Resonances



- Historically, a “simple” way to discover new particles (clear experimental signature).
  - Carried out since LHC very beginning in Run1
- New particles predicted to decay into (coupled to) pairs of quarks/gluons (jets), leptons, bosons
  - addressing many BSM models (new gauge bosons, DM mediators, extra dimensions, gravitons, compositeness, …)
- Additionally, most searches are performed in model independent ways.
- Typically searched for in high-end tails of distributions (mass, pT, energy…) but renewed interest in exploiting these large datasets to also look for signals in the region $m_R < 1$ TeV and/or weakly coupled.
- Covering boosted regime of decay products in addition to resolved particles

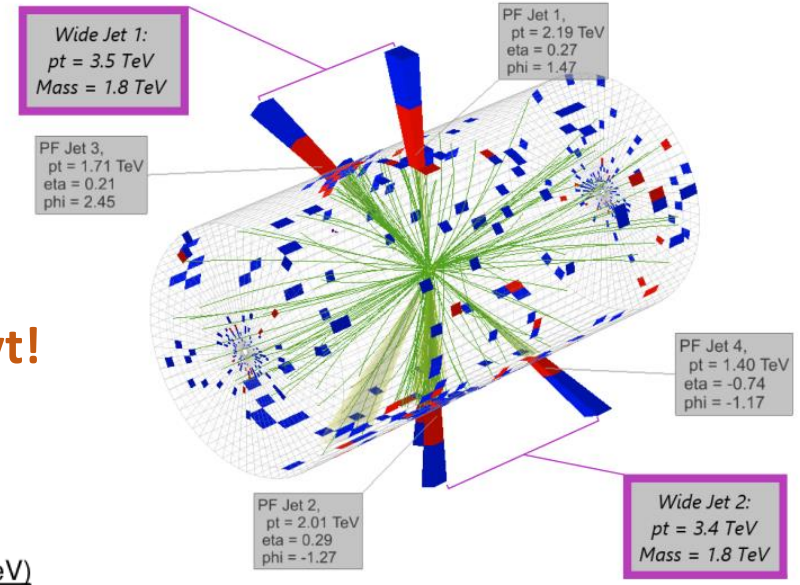
doi:10.1007/JHEP05(2020)033

High mass resonances in dijet evts

- Wide-jet algorithm: less sensitive to gluon radiation
- New data driven background prediction model:

ratio method (m_{jj} > 2.4 TeV) vs traditional fit with empirical function.

  - Use data CR with large $|\Delta\eta|$ between wide jets

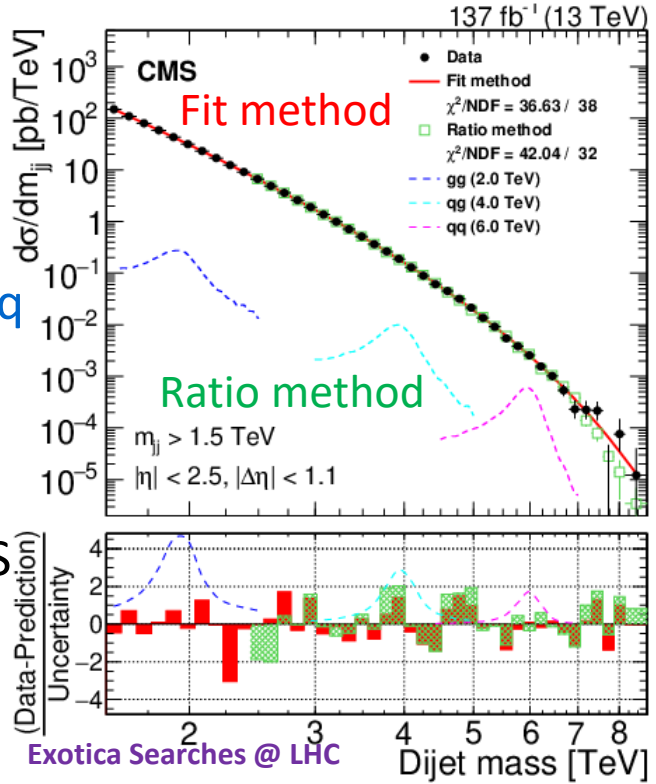


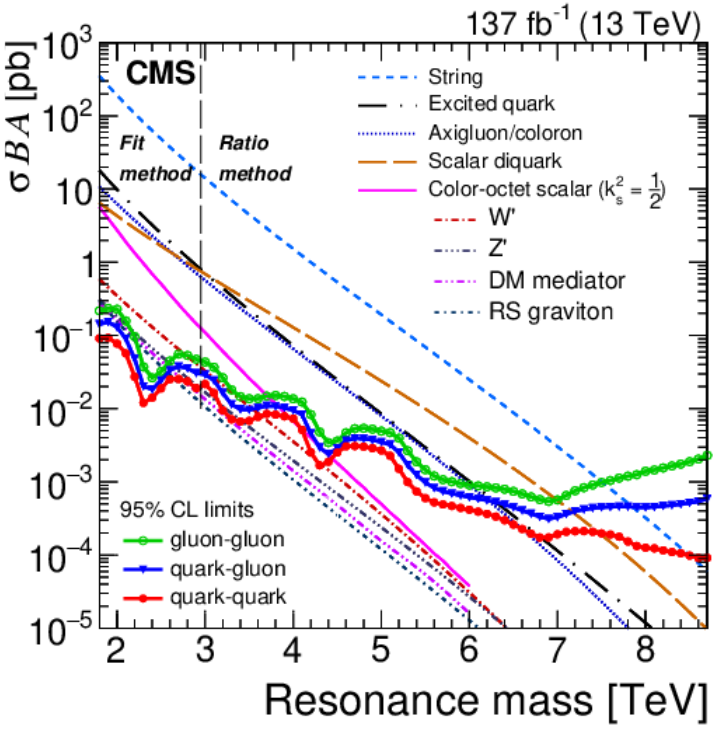
Peculiar evt!

- Independent of signal region→ less biased
- Less uncertainty on backgd at high mass
- More sensitive to wider signals

95% CL limits on many models assuming gg, qg, qq signal resonances from ~2.5 to 8 TeV:

  - broad resonances (widths up to 55% mass, for m_{jj} > 1.8 TeV)
  - Models: Gauge boons (W', Z'), DM mediators, RS graviton, q*, coloron, string

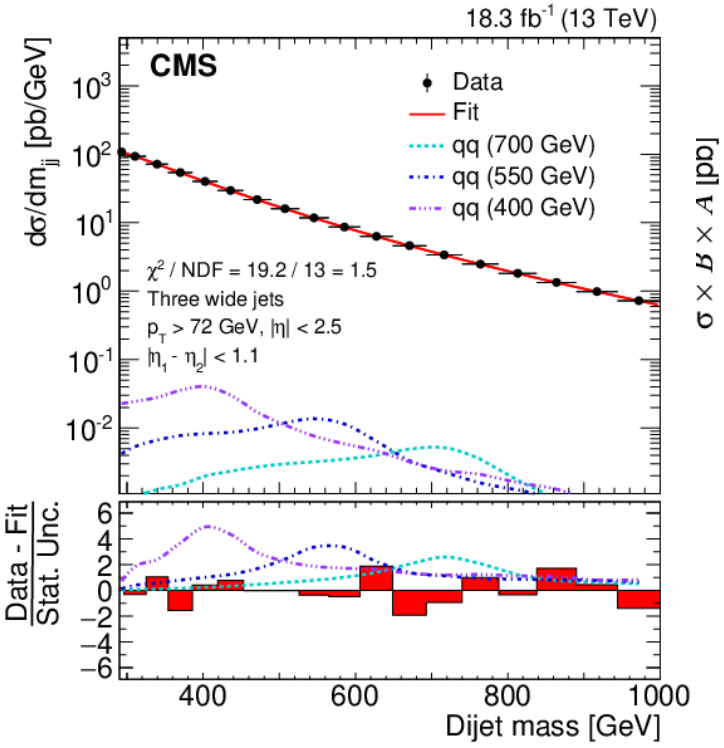


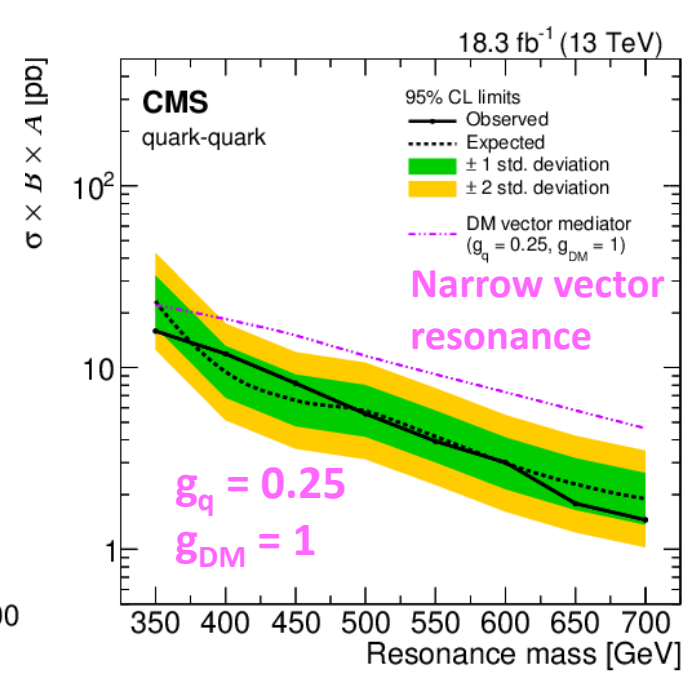


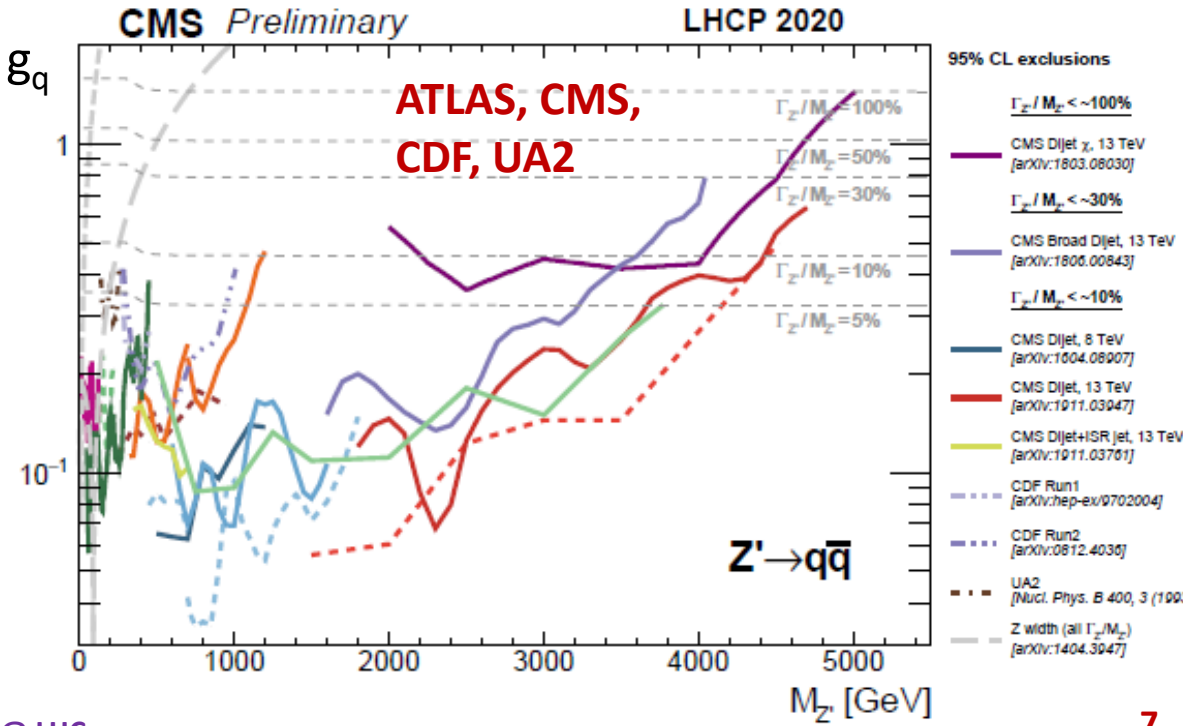
doi:10.1016/j.physletb.2020.135448

Exploring lower masses, scouting

- Extension to lower m_{jj} signal region, 350 - 700 GeV using "data scouting" technique [analysis at HLT level, allowing a higher rate, data format recorded ~0.5% of full evt size]
- Notice lower luminosity collected in 2016 data, while lower jet pT trigger thresholds (HT > 240 GeV)
- Improvement: use 3-wide-jet evts, jet p_T > 72 GeV, m_{jj} from 2 leading p_T jets.
- Values σxBxA [15 - 1.5] pb excluded at 95%CL in mass range. DM vector mediator benchmark point excluded





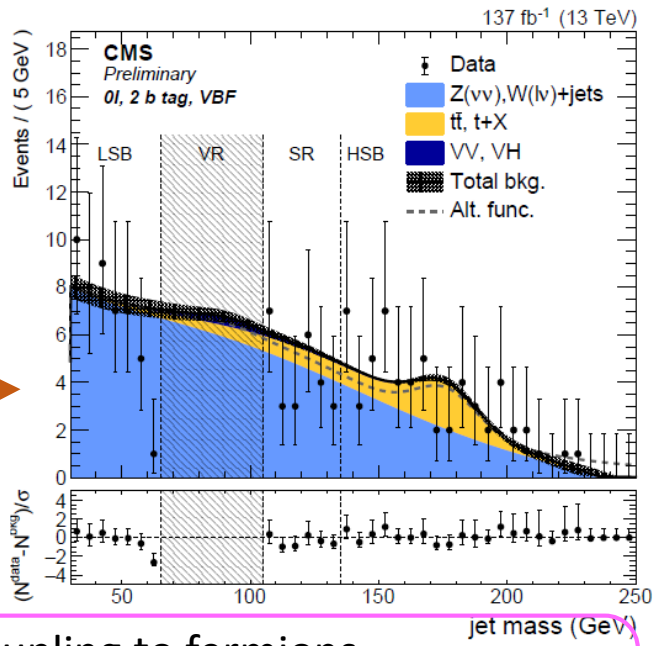


Dibosons: $Z' \rightarrow Z(ll, \nu\nu)H(bb)$

CMS-PAS-B2G-19-006

- Resonance coupling to bosons (V, γ, H). If fermiophobic, proceed through VBF process (for the first time included)
- H →bb as a fat jet, with substructure (boosted regime)
- Strategy: 12 categories: num (0, 2) & flavour of leptons (e,μ), b-tagged subjets (2, ≤1), presence of forward jets (VBF)
- M (Z → 2l), MT (Z → νν)

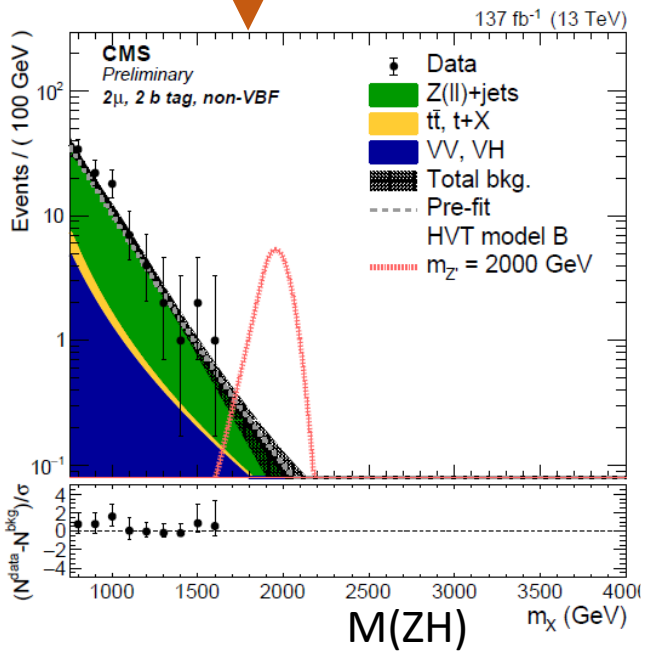
Fat-jet mass



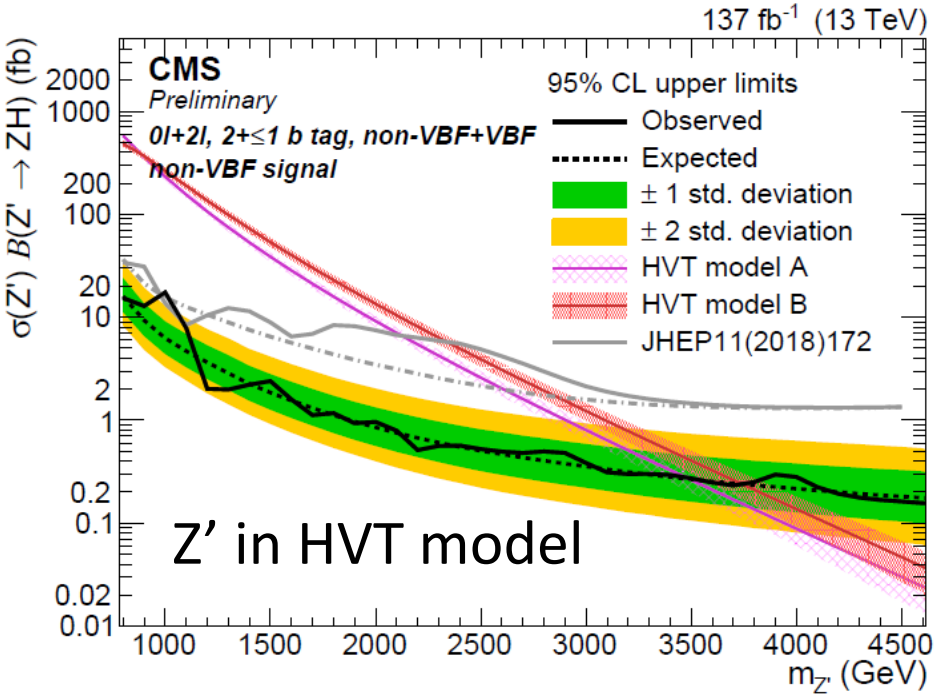
HVT model

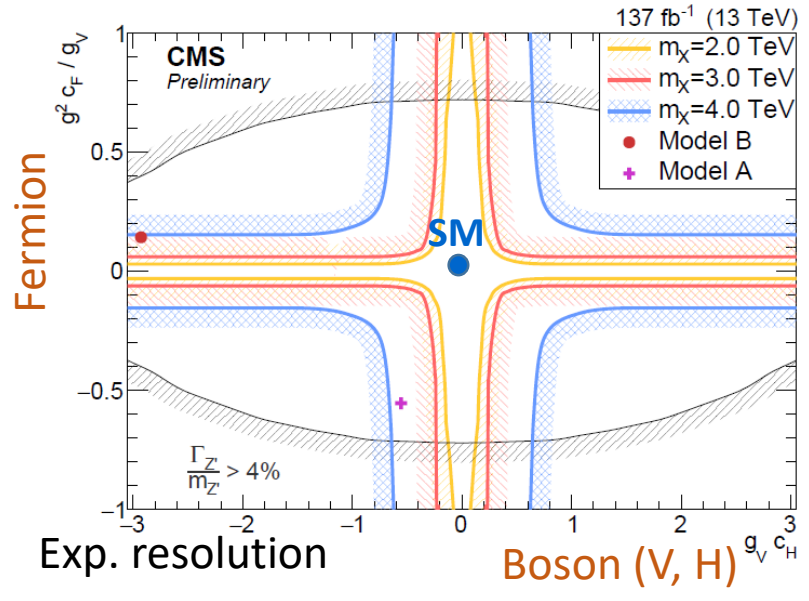
A: mainly coupling to fermions
B: fermionic couplings suppressed $C_F << C_V$
C: only coupling to bosons, $C_F = 0$. only VBF

M(ZH)



No exclusión for VBF processes (model C)



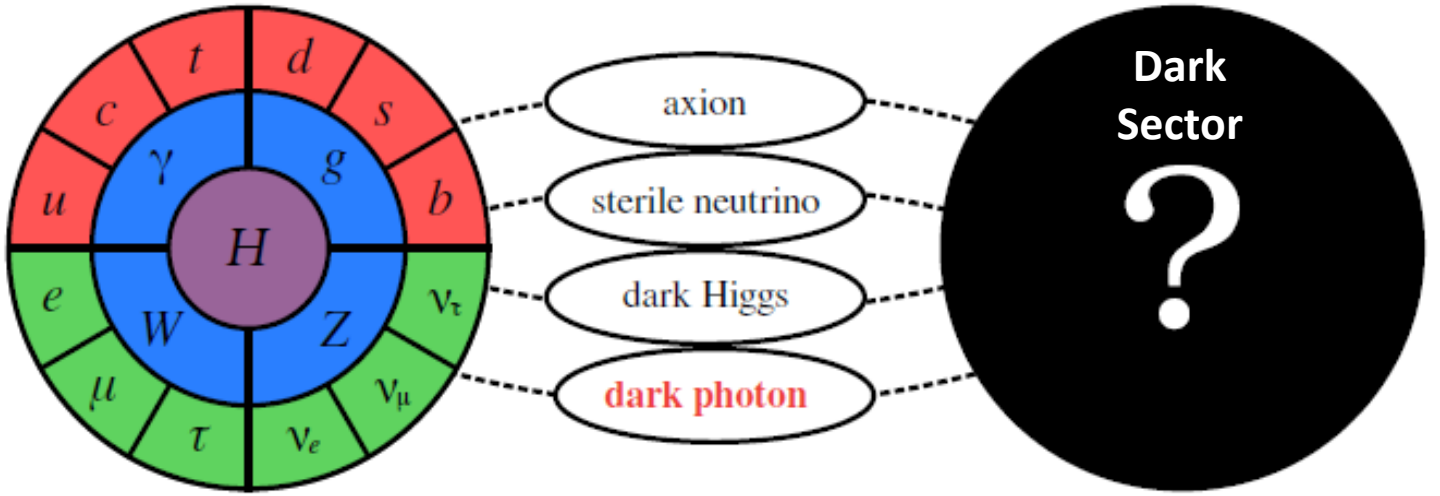


Dark Sectors

P. Ilten

- Entering the dark world…
  - Hypothetical “parallel” dark sector

- SM gauge group extension with a new gauge symmetry
  - new gauge bosons (dark photon/H, axion)
  - symmetry is broken, allowing for weak mixing with SM particles through kinetic mixing with hypercharge field of SM particles



$\epsilon \equiv g'/g$

g: γ - SM coupling
g’: A’ – Dark sector coupling

ϵ: γ - A’ coupling ≡ mixing = g’/g

➔

- A’ couples to SM matter as g·ϵ
- σ ∝ ϵ^2

Lagrangian extensión

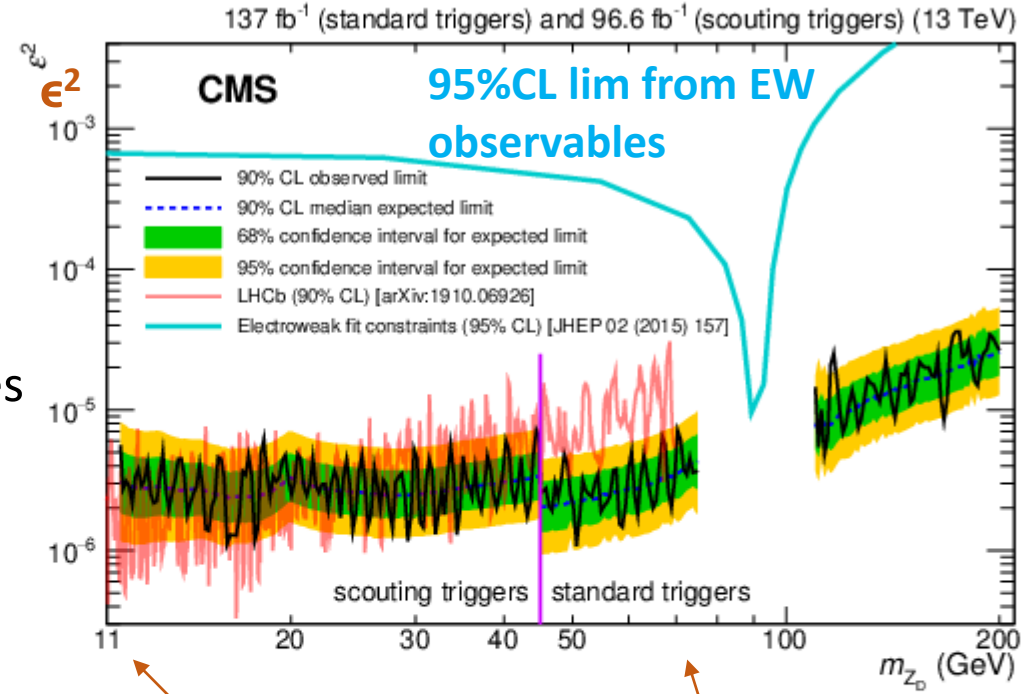
$L = L_{SM} + L_{mediator} + L_{DS}$

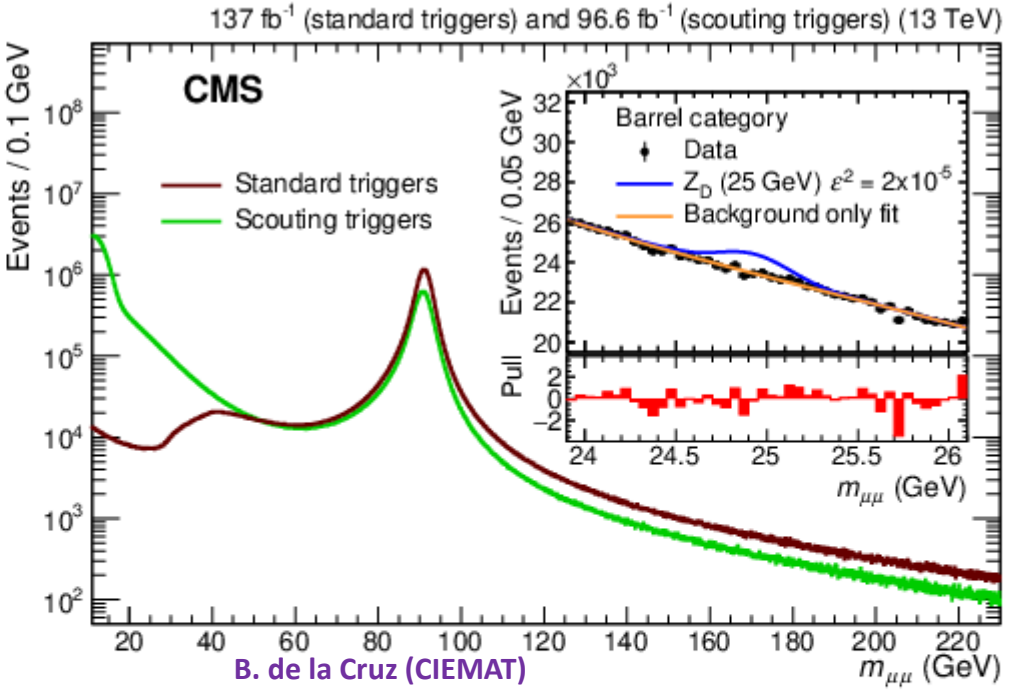
$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{{m_{A'}}^2}{2}A'_\mu A'^\mu + g_e J^\mu A_\mu + g g_e J^\mu A'_\mu$$

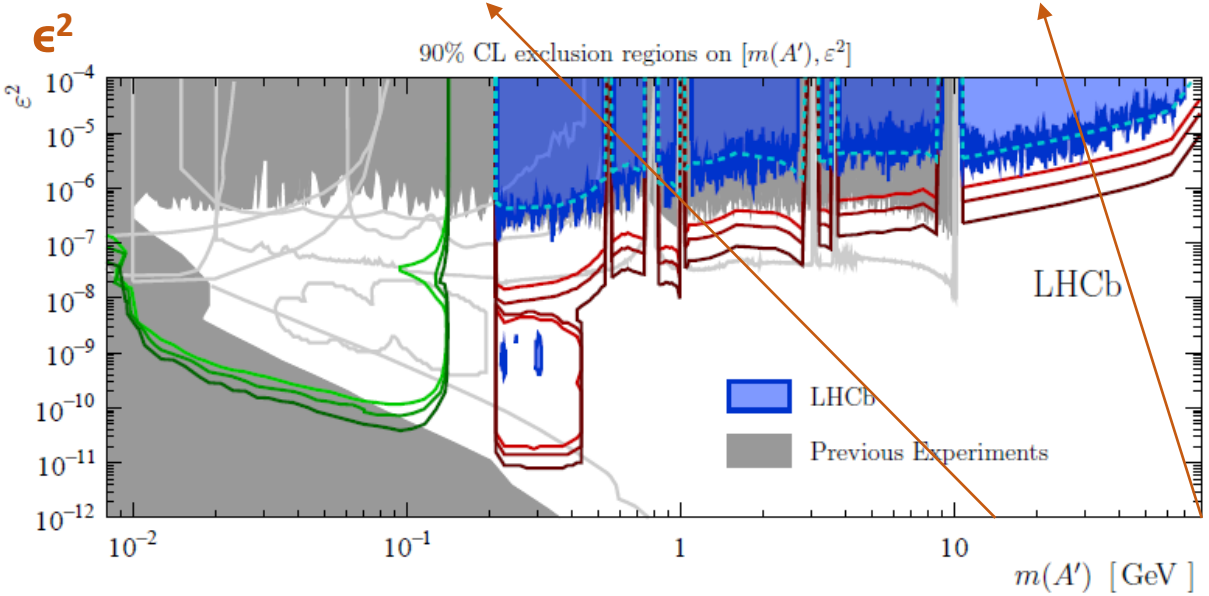
Resonances to leptons: Dark photons

arXiv:1910.06926
10.1103/PhysRevLett.124.131802

- Search for narrow light dimuon resonances with $m_{\mu\mu} > 11.5$ GeV
- Data from "scouting" for $11.5 < m_{\mu\mu} < 45$ GeV
- 95% CL limits on σBA interpreted in terms of ϵ^2, kinetic mixing coefficient
- Dark photons excluded in ~30–75 and 110–200 GeV mass ranges
- Constraints from LHCb results extended for A' mass > 45 GeV





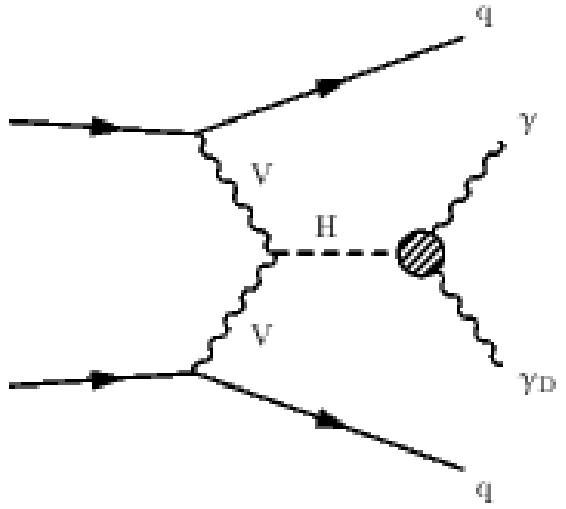


CMS extending excluded region

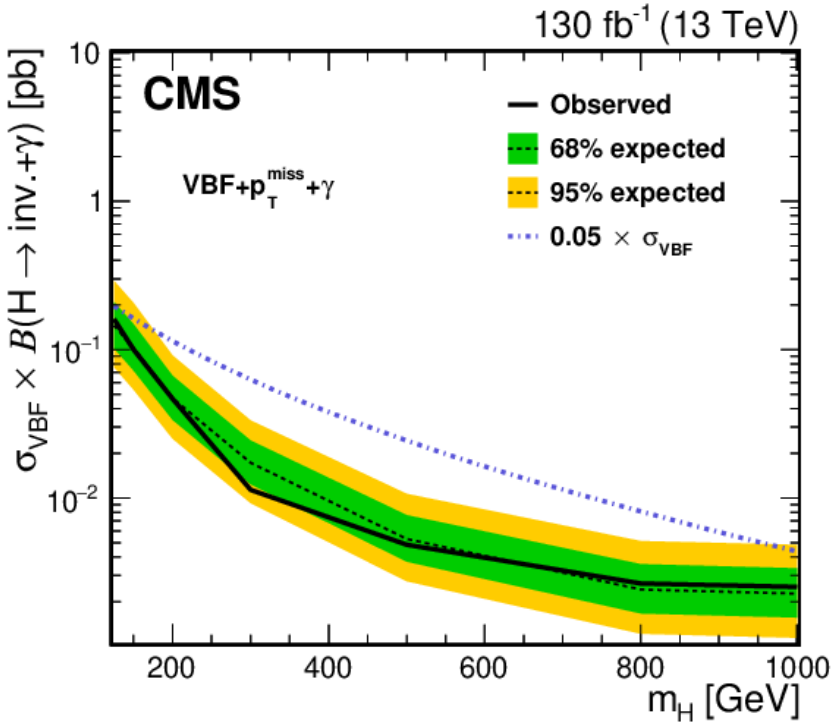
Dark photons, $H \rightarrow \gamma\gamma_D$

arXiv:2009.14009

- H produced in VBF process. Semivisible decay. First search of this kind.
  - pure ggH or ZH already published
- Additionally motivated by "loose" constraint of H → invisible particles
- VBF channel sensitive to exotic H decays (low SM background).
- Independent model limits placed for a wide mass rage, 125-1000 GeV (potential non-SM bosons)
- Dominant backgd from W/Z($\nu\nu$)+jets, γ+jets, then W/Z+γ, obtained from simulation and normalized using CR in data.
- Dedicated VBF+γ trigger (2016), combination of γ+ MET triggers (2017/18)
- Binned fit using $m_T(\gamma, \text{MET})$
- BF of Higgs decay excluded at 95%CL



VBF		ZH		VBF+ZH	
Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)	Obs. (%)	Exp. (%)
3.4	$2.7^{+1.2}_{-0.8}$	4.6	$3.6^{+2.0}_{-1.2}$	2.9	$2.1^{+0.9}_{-0.6}$



Charged LFV: $Z \rightarrow (e/\mu)+\tau$

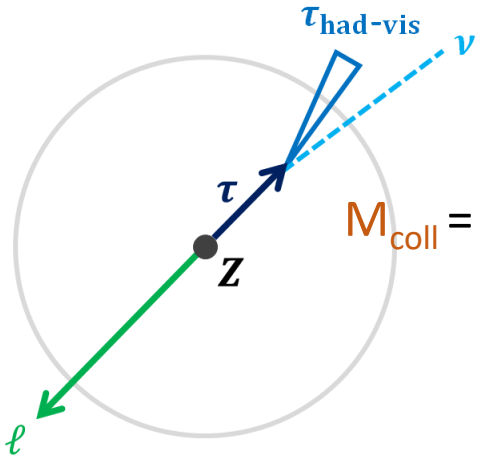
arXiv:2010.02566

- Charged lepton number conserved in weak interactions, though neutrinos violate it in their oscillations.
  - Unknown mechanism (that makes Weak int violate LFV)
  - Finding LFV in charged lepton sector would be sign of new physics (Heavy Neutral Lepton models)
- Search for $Z \rightarrow e\tau$ and $Z \rightarrow \mu\tau$. Large (8×10^9) Z sample
  - less constrained than $e\mu$ (see arxiv 1207.4894)
  - hadronic decay of τ, improved tau Id NN
- Backgrounds: $Z \rightarrow \tau\tau$ and W+jets (fakes)
- Novel use of NN classifiers, $Z \rightarrow l\tau$ correctly selected in 98% cases.
- Results on Full Run2 combined with Run1 ones

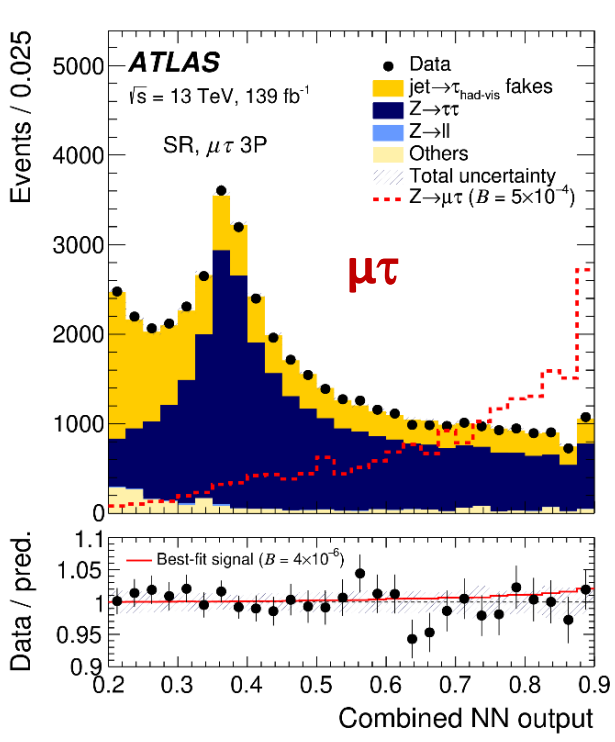
$BR(Z \rightarrow e\tau) < 8.1\ (8.1) \times 10^{-6}$ obs (exp)

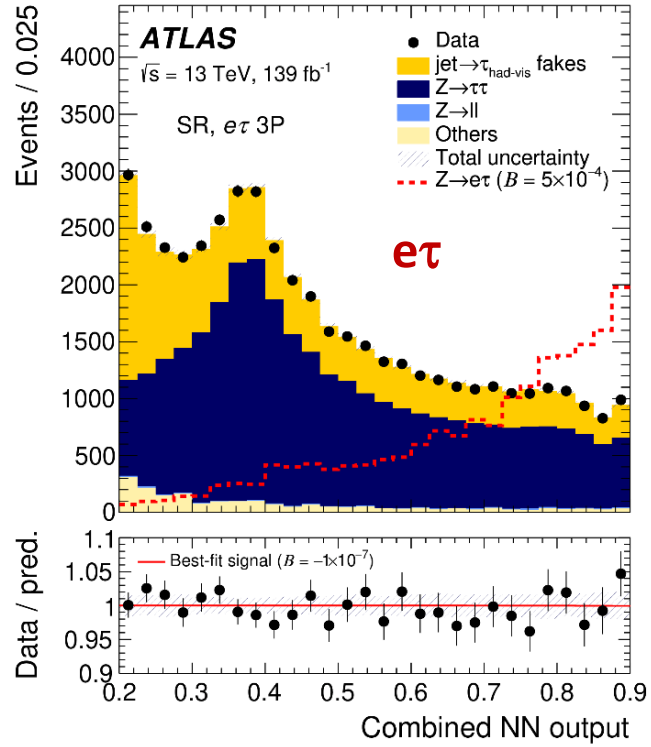
$BR(Z \rightarrow \mu\tau) < 9.5\ (6.1) \times 10^{-6}$ obs (exp)

superseding LEP values from 20 years ago



M_{coll} = τ visible products + collinear ν





Leptoquarks: LQ →t+(e/μ)

arXiv:2010.02098

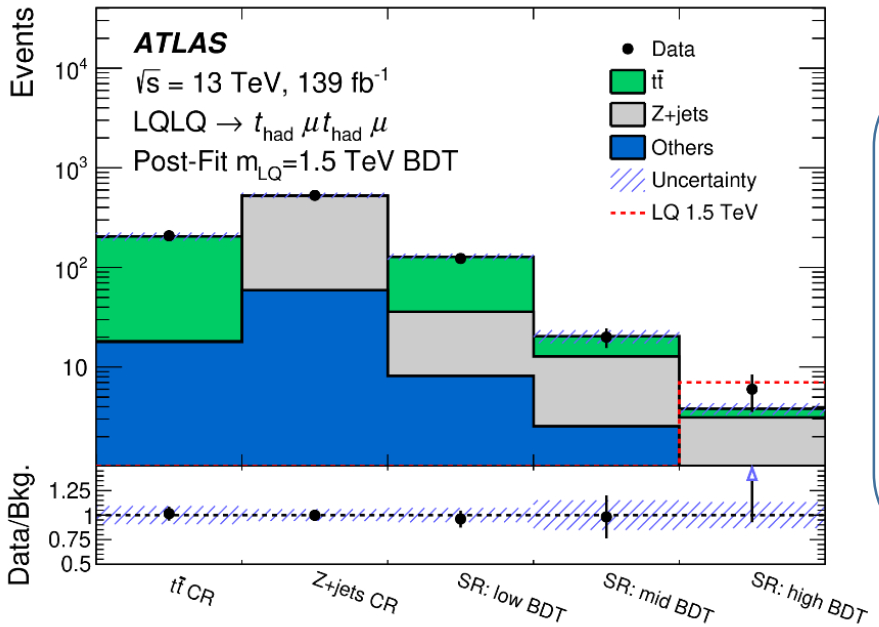
- Colour-triplet bosons that create symmetry between quark and lepton sectors
- Arising in GUT, RPV SUSY, ….can be scalar/vector, with fractional charge, coupling to both quarks and leptons
- Provide atractive explanation of recent hints of possible lepton-flavour-universality violation from observed B meson decay anomalies in BaBar, Belle, LHCb
- In this channel, previous CMS study with 2016 data excluded $m_{LQ} < 1420$ GeV for BF(LQ→ tμ)=1

Experimentally: pair produced LQ, 2 leptons + 2 large-R jets (boosted tops)

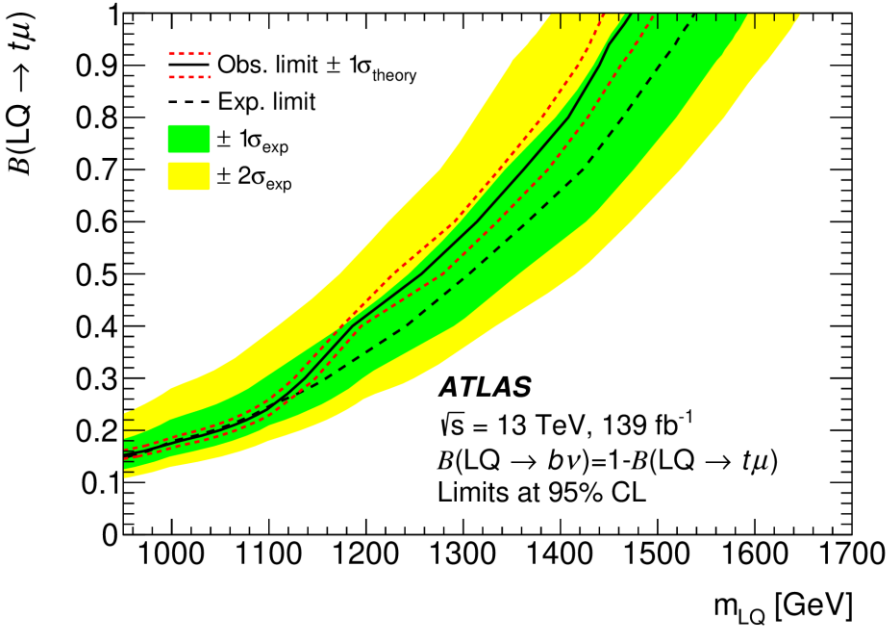
BDT [kinematic variables and jet substructure] to classify signal-like or backgd-like evts in SR

Main bckgds, tt, Z+jets, normalization from CR

Fit of BDT score + backgd contribution in CR, separately for tμ and te channels. No significant excess found

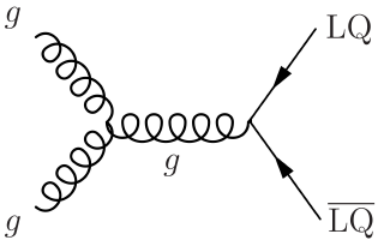


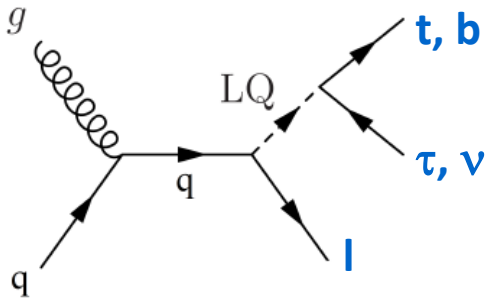
95%CL limits
$m_{LQ} < 1480$ GeV for
BF(LQ→ te)=1
and
$m_{LQ} < 1470$ GeV for
BF(LQ→ tμ)=1



Leptoquarks: LQ →3rd gen fermions

CMS-PAS-EXO-19-015

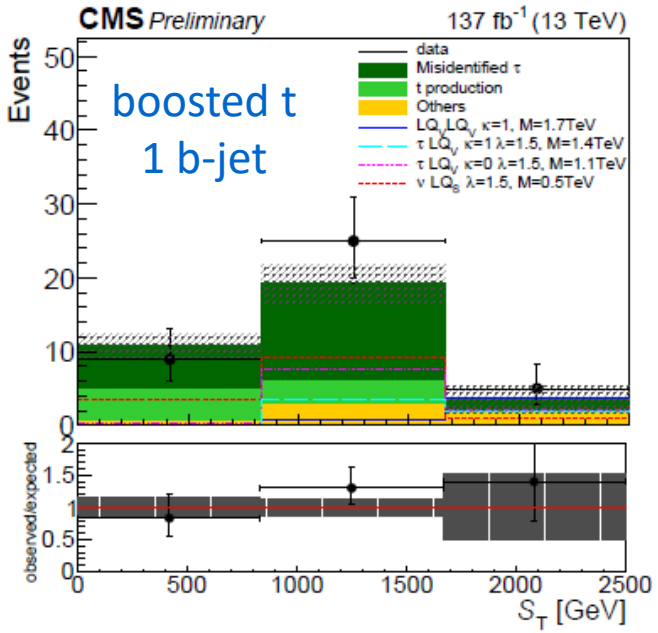


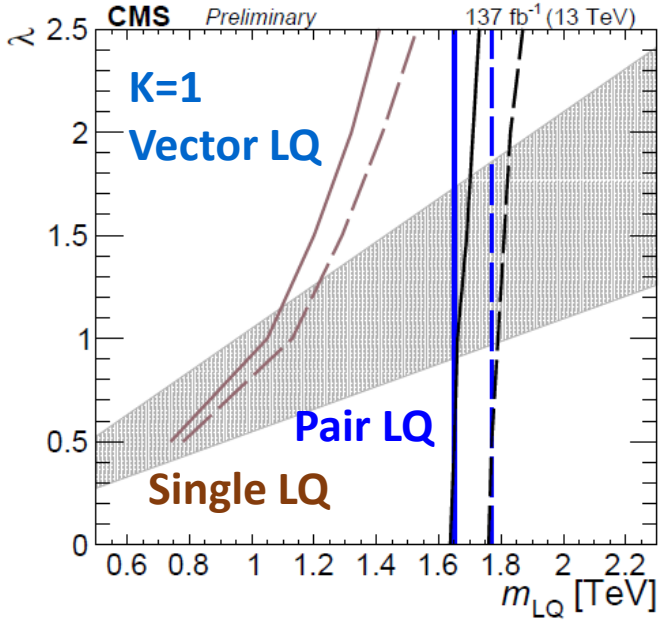


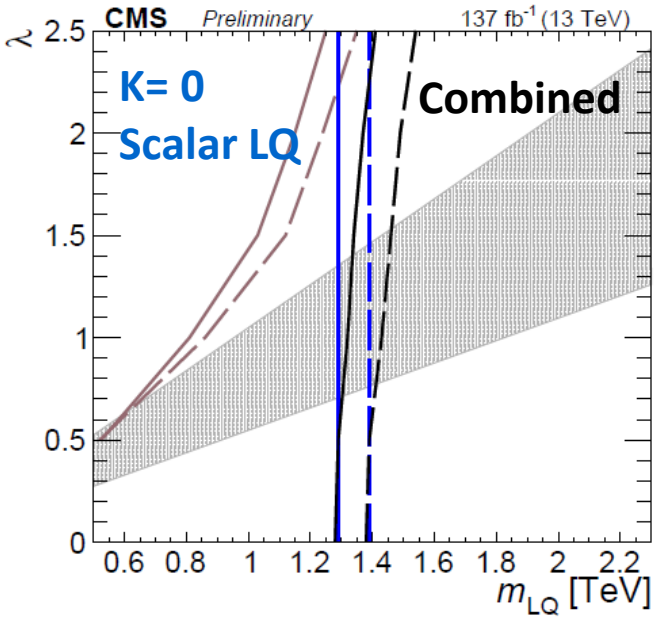
- Experimental study of final states ττνb and ττν give access to pair or singly produced LQ
- LQ → tτ, bν, tν, or bτ
- inclusive hadronic decays of t and τ, and boosted top quark signature for the first time
- ST variable in 4 categories: nb-jet=1, ≥2; resolved/boosted top quark
- 95% CL limits on $m_{LQ} > 0.98$-1.73 TeV, depending on λ and LQ spin.
  - most stringent limits to date on LQ for BF() = 0.5 to each lepton-quark pair.

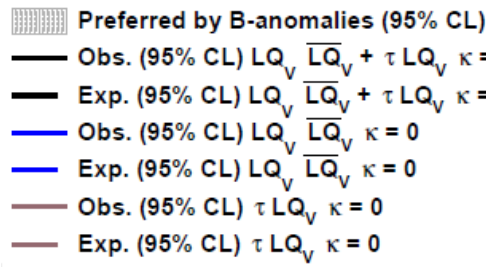
These results probe the parameter space preferred by the B-physics anomalies in several models and exclude relevant portions.

λ: LQ-l-q vertex coupling



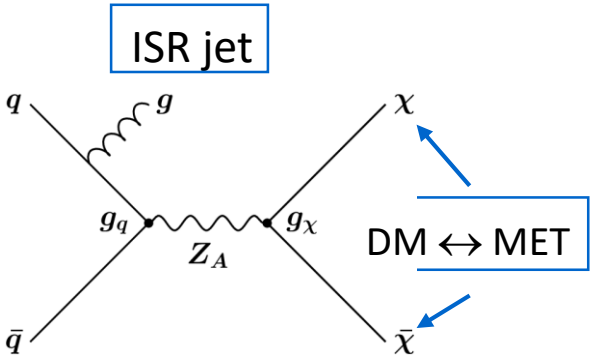






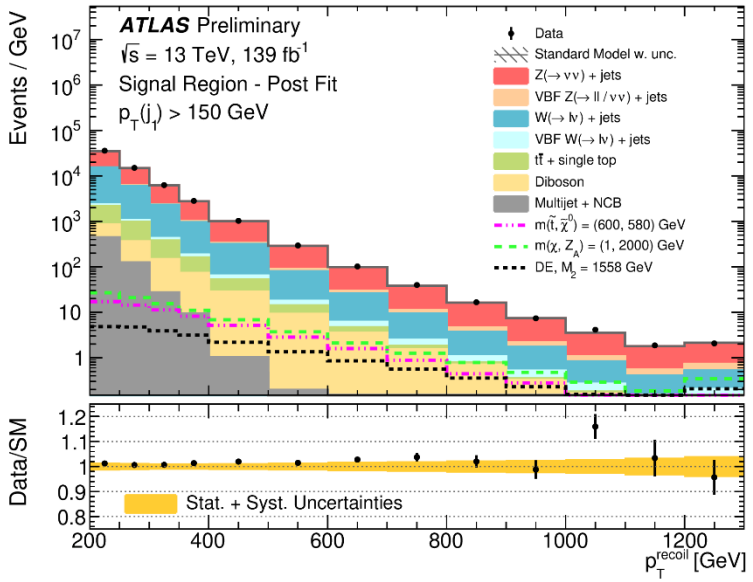
Dark matter: Jet+MET (Monojet)

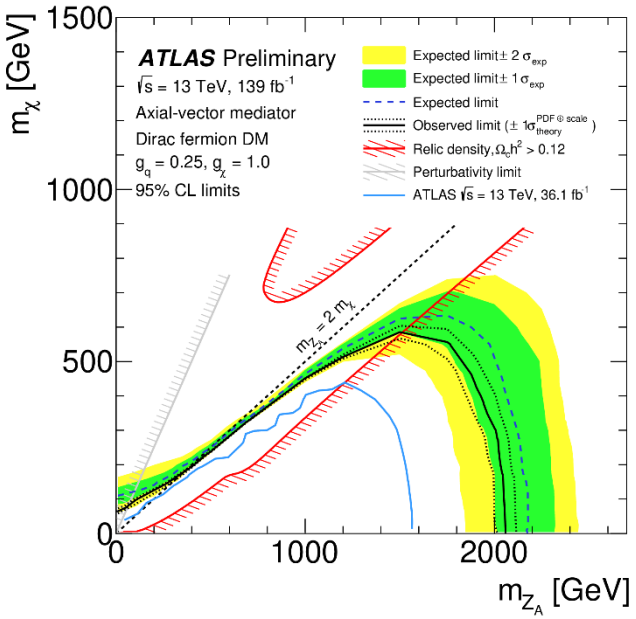
- Understanding DM is one of the main motivations for BSM searches at LHC
- Relevant experimental signature: jet (ISR) + MET signalling presence of DM particles. Other searches focus on photon, vector boson, H…
- Additionally, Compressed SUSY, Axion, new scalars in Dark Energy models addressed

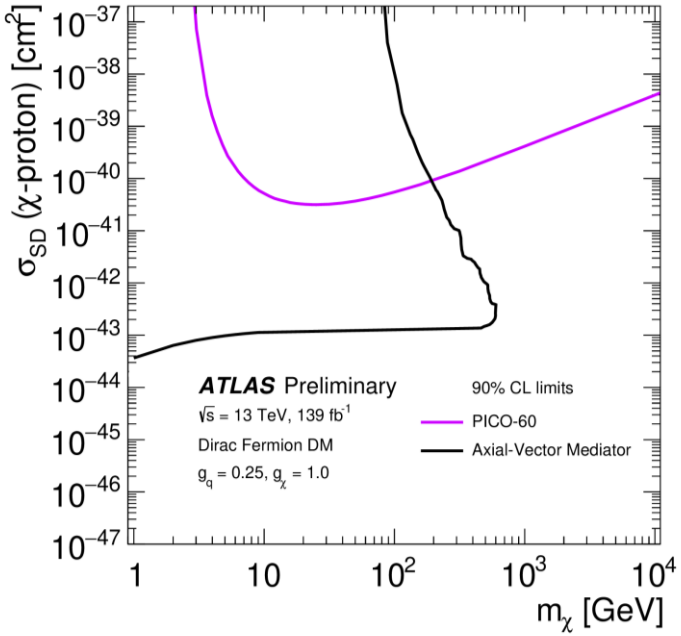


Experimentally:
- Jet E_T>150 GeV , MET > 200 GeV
- SR defined on MET ranges, inclusive or exclusive, backgrounds defined in CR regions
- Fit simultaneously in SR and CRs
- Mediator masses < 2 TeV excluded for low DM mass

Parameters
M_{med}, M_χ
g_q, g_χ, g_l



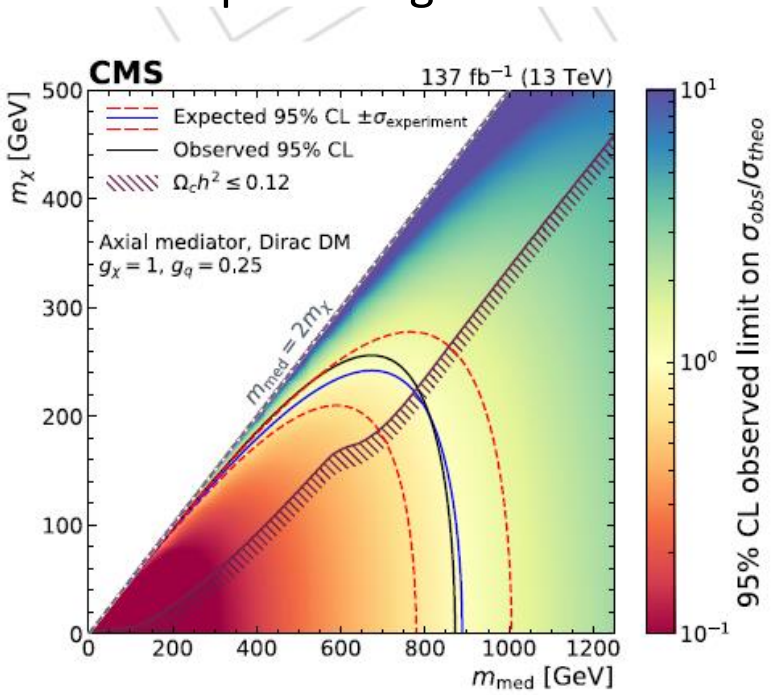


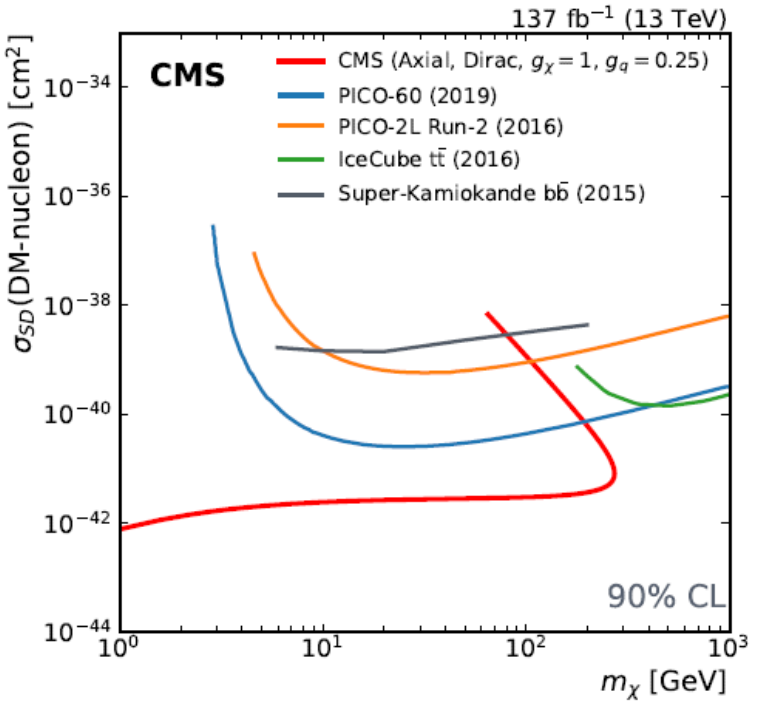


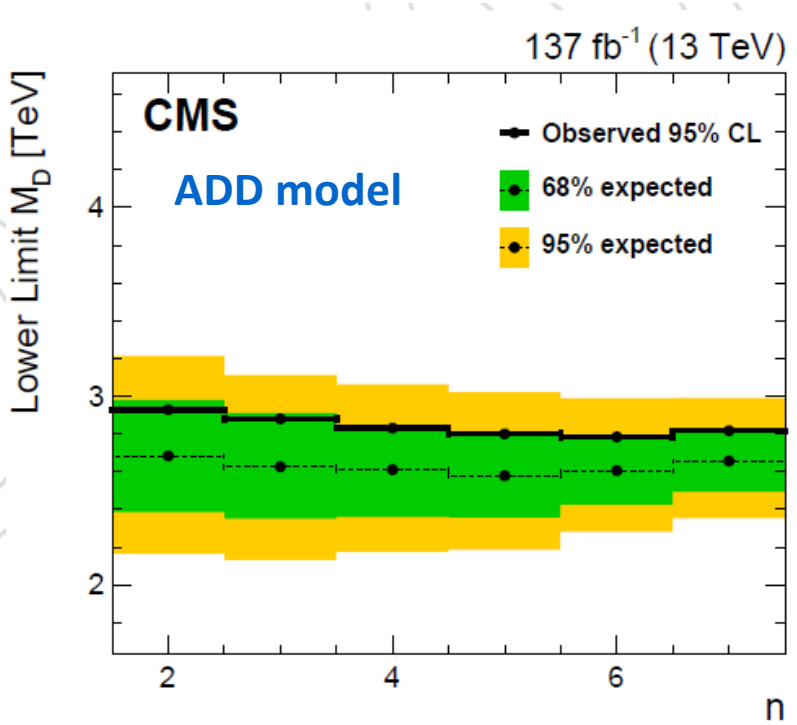
Dark matter: Z(ll)+MET

arXiV:2008.04735

- $Z(l^+l^-)$ recoiling to MET (DM, invisible particles)
- Rich in interpretations!: simplified DM models with vector/axial-vector mediators and DM a Dirac fermion, H invisible decays, 2HDM
- Outside DM, unparticles and large extra dimensions: $qq \rightarrow Z + G$, $M_{Pl}^2 \approx M_D^{n+2} R^n$ M_D = Fundamental Planck scale in n+4 space-time
- Main backgrounds dibosons and top processes, from simulation and CR. Veto 3rd lepton and hadronic activity
- Simultaneous fit of MET in SR and CR + uncertainties
- Clean and promising channel



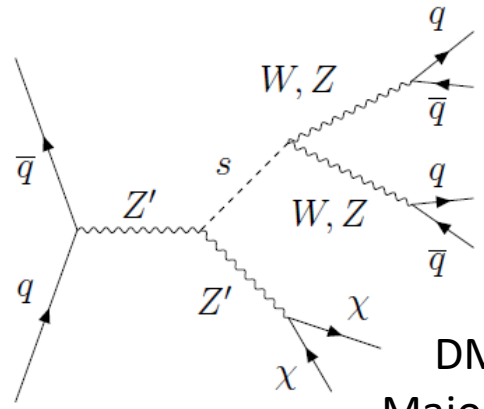




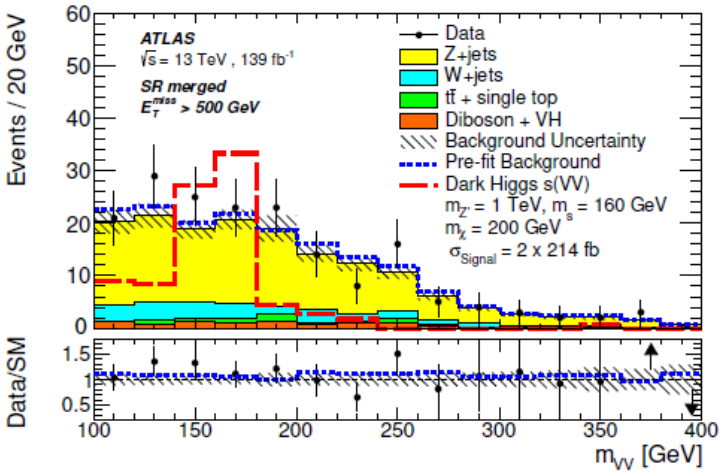
Dark matter: associated with resonant VV

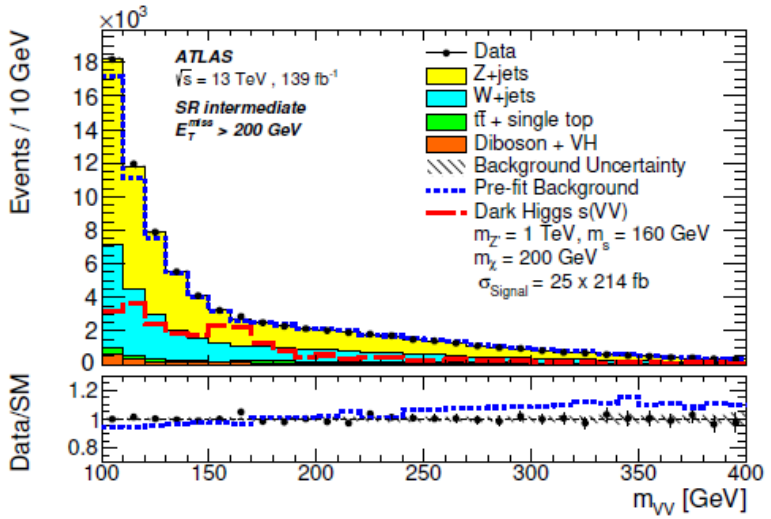
EXOT-2020-40-paper

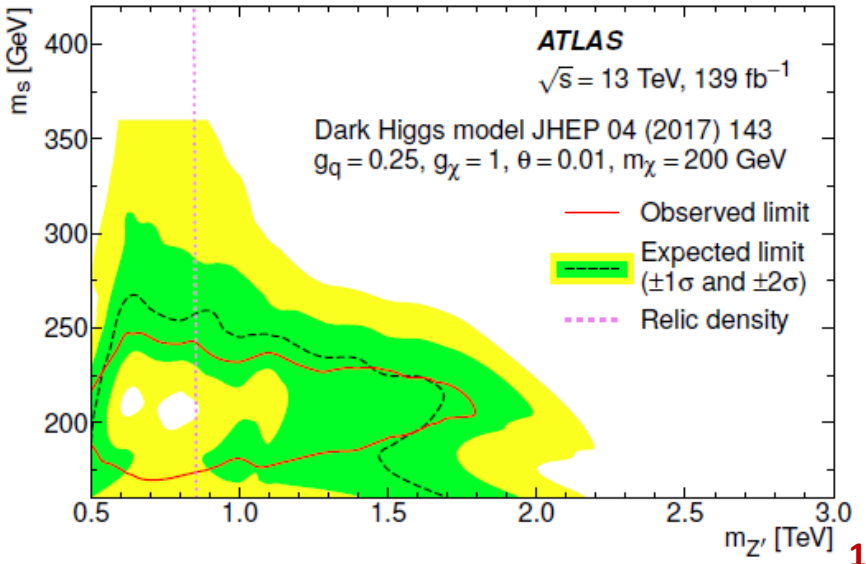
- DM (mediator) recoils to a dark Higgs, s, decaying to V(qq)V(qq) (V=W, Z). First study of this signature
- Refined track reclustering algorithm, improving resolution on jet substructure for s → V(qq) V(qq). MET> 200 GeV
- SR splitted in merged and intermediate according to boosted or not jet topologies, with 4-prong substructure.
- Exclusion contours in ($M_{Z'}$ - m_s) plane derived



DM, Majorana







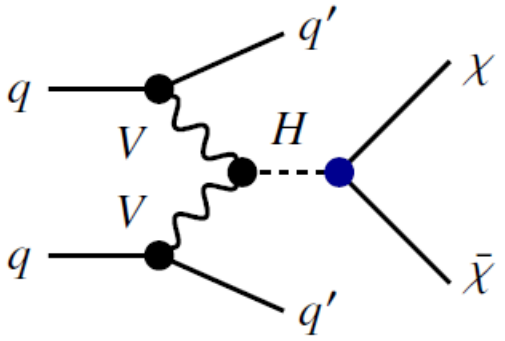
Dark matter: combining info

ATLAS-CONF-2020-008

ATLAS-CONF-2020-052

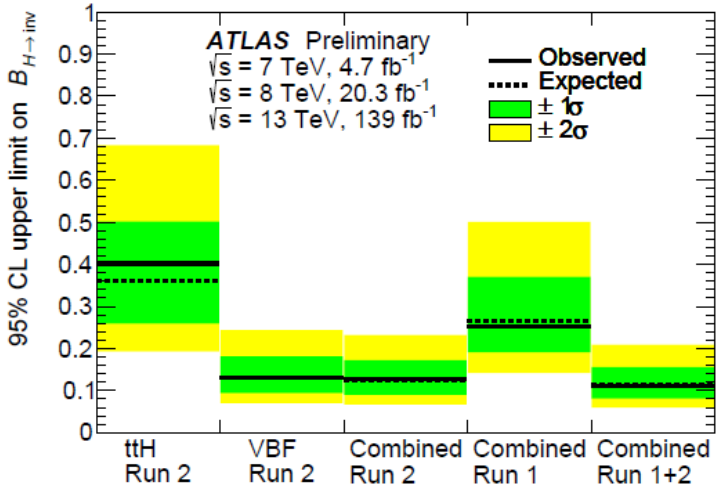
Sensitive and promising channel explored by ATLAS: VBF+MET

Using the Higgs boson to search for DM

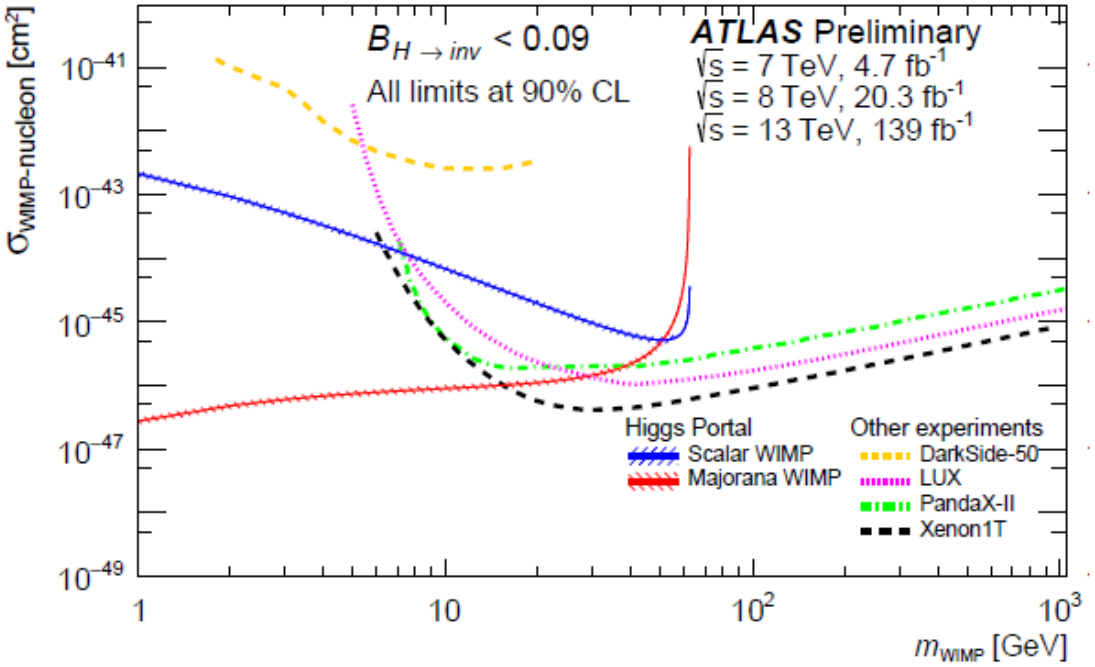


Partial combination of analyses for Run1 and 2

Using VBF + ttH channels in Run2

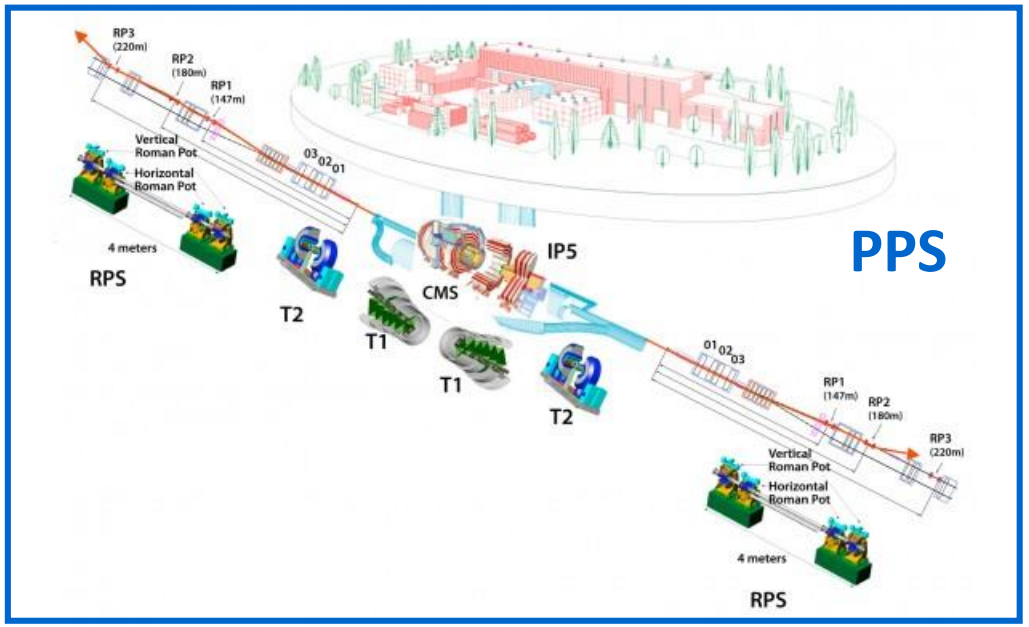


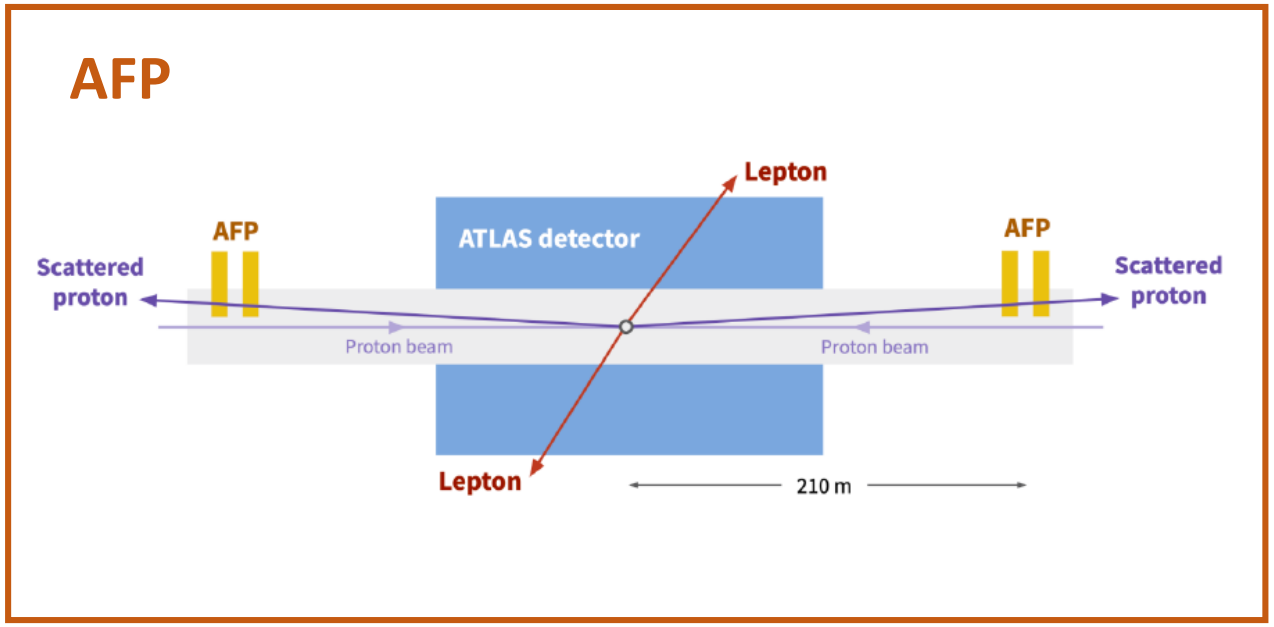
BF (H → inv) < 0.11 (0.11 exp) @ 95% CL



γγ collisions

- Extending searches beyond LHC pp collisions, using LHC as photon collider, γγ
- ATLAS & CMS furnished with very forward detectors: Proton Precision Spectrometer (PPS) in CMS, ATLAS Forward Proton Spectrometer (AFP) in ATLAS.



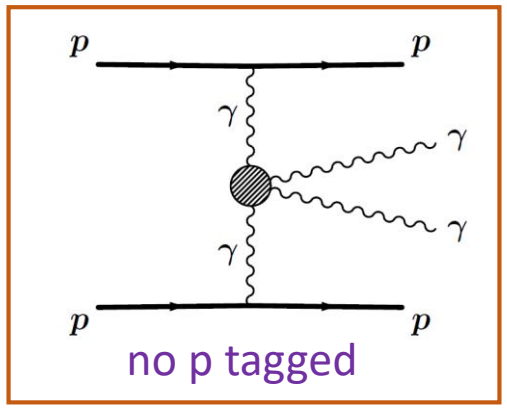


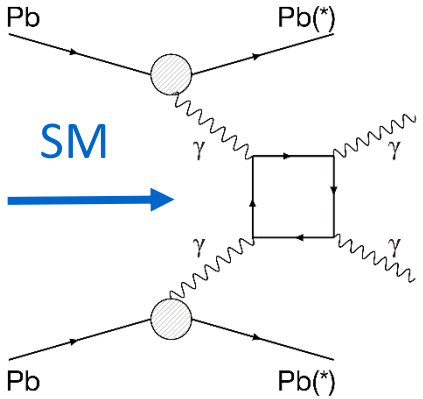
- Profit from photon flux emitted by charged particles.
- Scales with Z^2 ➔ γγ collisions strongly enhanced in PbPb vs pp collisions
- Exploitation of initial colliding systems, pp, pPb and PbPb
- Mass range explored dependent on initial colliding system and requirement of protons being tagged

$\gamma\gamma \rightarrow \gamma\gamma$ in PbPb @ $\sqrt{s_{NN}}$=5.02TeV

arXiv:2008.05355

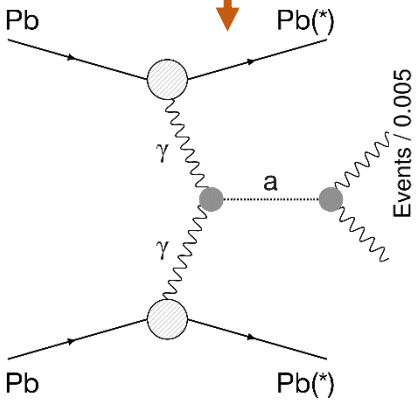
Evidence for "light-by-light" scattering already set by ATLAS and CMS few years ago



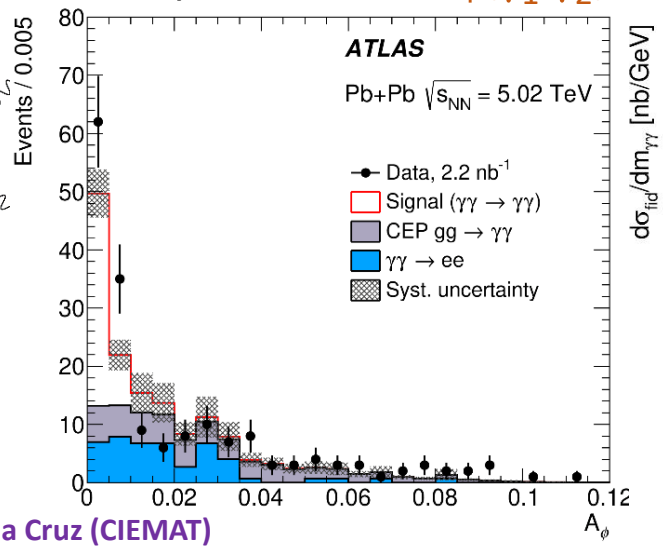


- Proceed through one-loop box diagram (SM) or it may involve new particles (NP).
- **ALP**: Axion Like Particle, neutral candidate coupling to photons, forming narrow resonances.
- Possible existence in several orders of magnitude in mass.
- Constraints in γ-coupling vs ALP mass, assuming BF(ALP$\rightarrow \gamma\gamma$) = 1

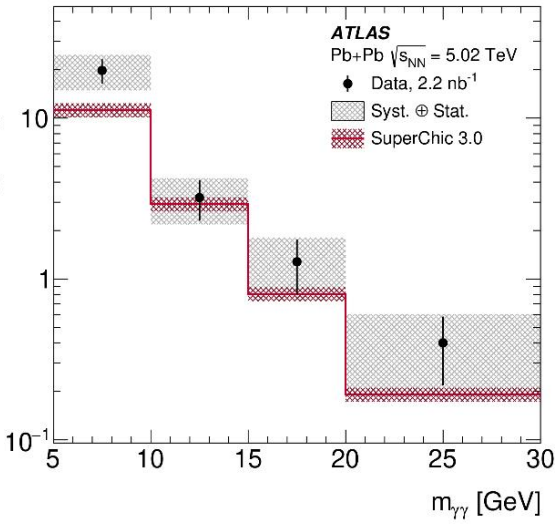
NP

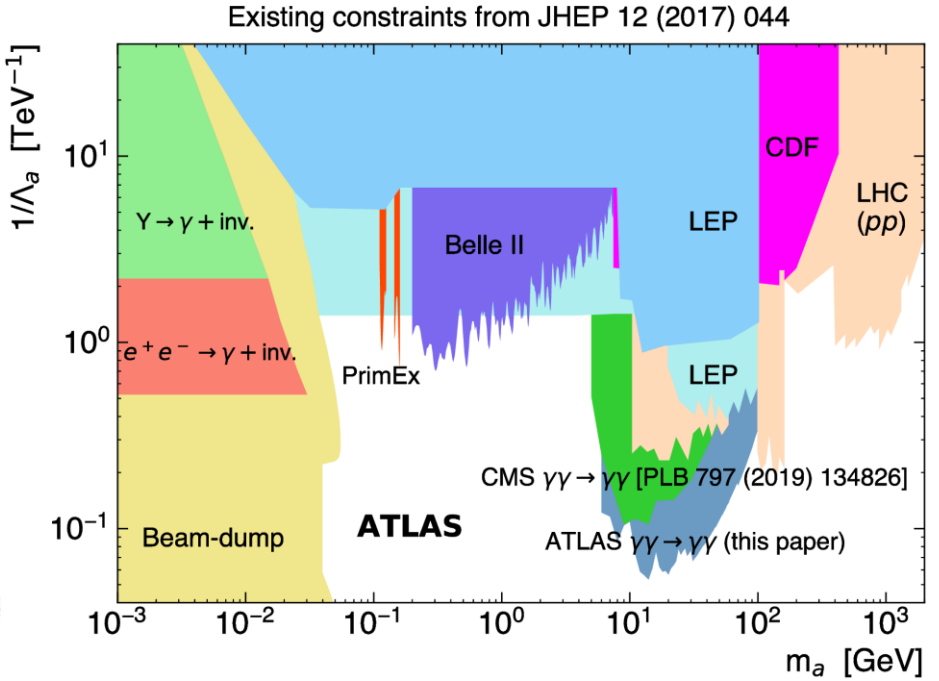


Acoplanarity, A_ϕ between photons: π-$\Delta\phi(\gamma_1,\gamma_2)$



Diphoton mass, $m_{\gamma\gamma}$



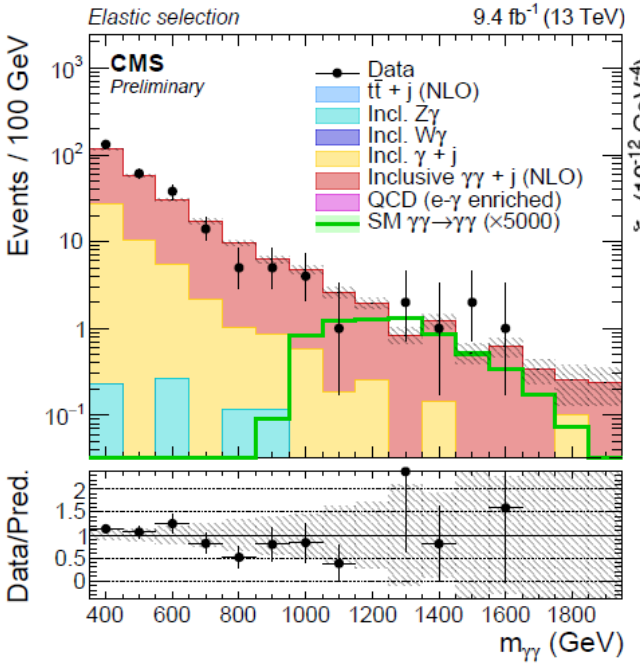


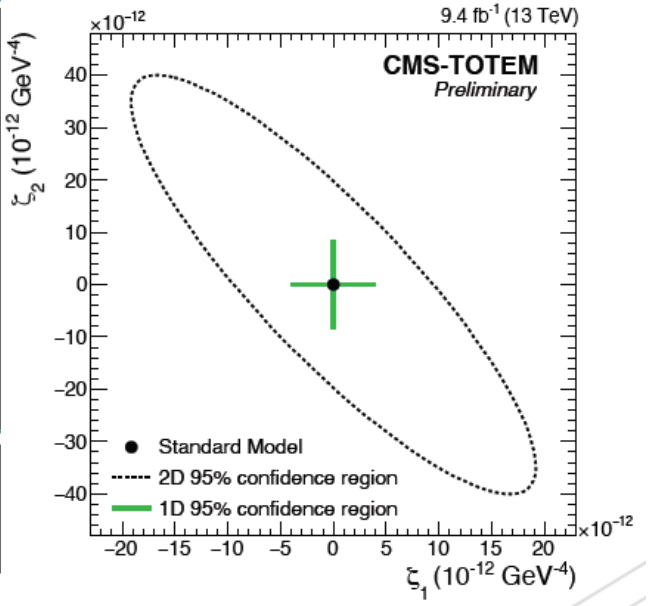
$\gamma\gamma \rightarrow \gamma\gamma$ in pp, at high mass

CMS-PAS-EXO-18-014

- Exclusive evts, central detector "empty", but 2 γ
- Correlate presence of 2 intact protons in PPS with 2 back to back high p_T photons in Tracker+ECAL system
- Correlate protons and photons (momentum conservation) in mass and rapidity
- Main backgd from wrong pairing of PU p with γ in evt

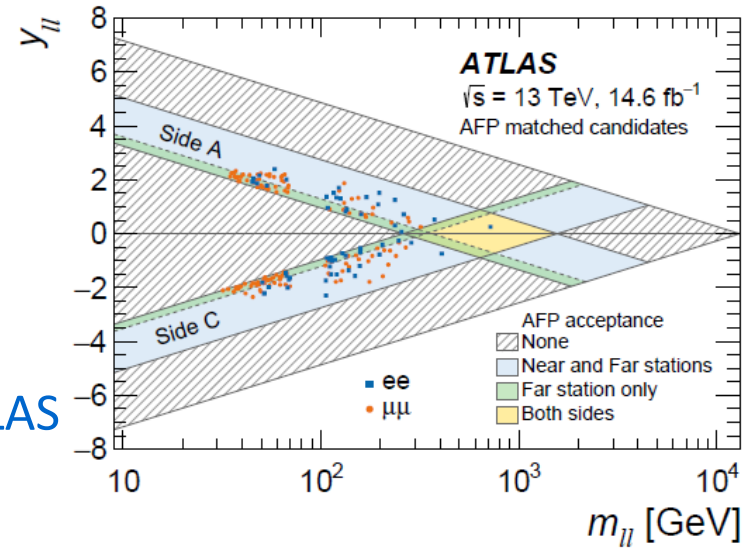
No deviation. Set limits on photon quartic couplings



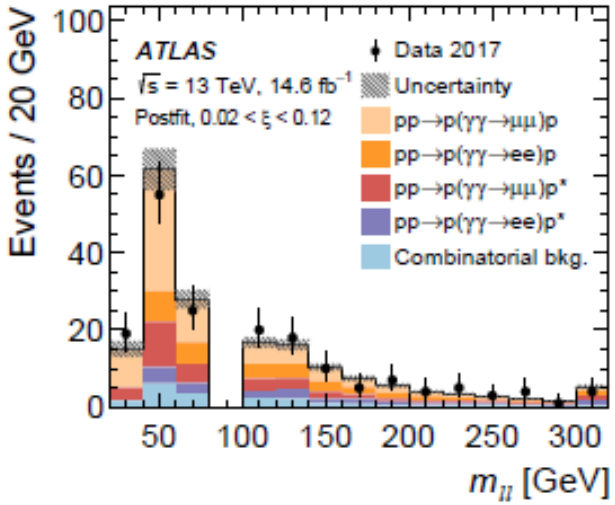


Similarly, ATLAS pp initial system, $\gamma\gamma \rightarrow l^+l^-$

- In intermediate mass region
- Correlate fraction of momentum loss by protons with that inferred from lepton kinematics.
- First cross section measurement in $\gamma\gamma$ collisions using protons tagged in AFP spectrometer in ATLAS
- Good agreement with SM expectations



arxiv:2009.14537



Summary

Overwhelming number of searches addressed with Full Run2 data collected by LHC experiments

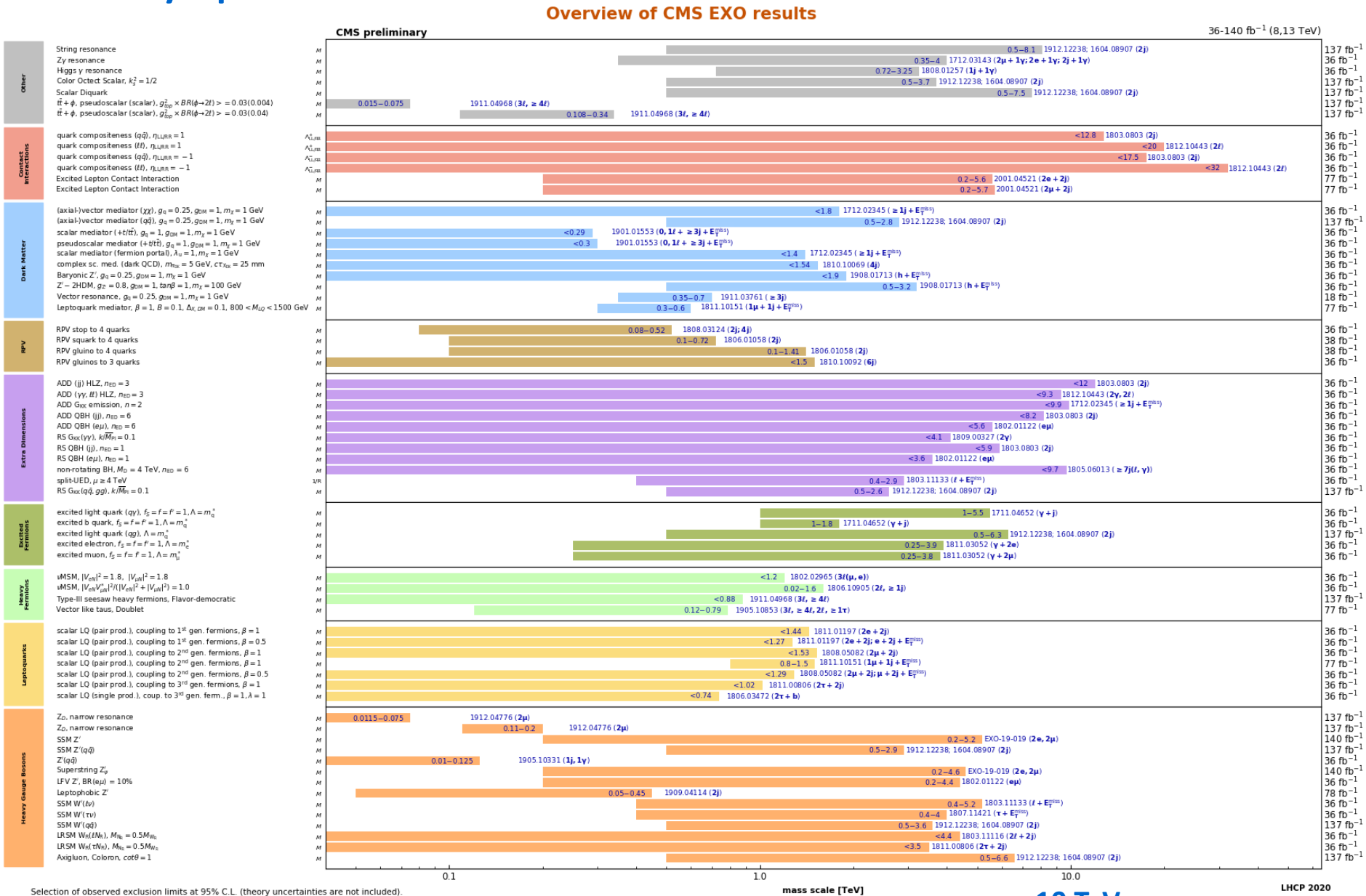
- Many of them repetition from previous analyses at $\sqrt{s}$=7 and 8 TeV and combined with their results
- Many others are new, building on latest, smarter ideas and procedures
- Exploting several input collision systems: pp, pPb, PbPb, …. and $\gamma\gamma$!!
- Paying attention to the highest mass regions, but also the low coupling realms

And still… No New Physics signal observed

Many Run2 analyses still ongoing, to be released in the coming months.
Run3 ahead of us, with possibly increase in $\sqrt{s}$ and for sure enlarging our collected datasets

Searches will go on, pushing the limits, improving upon new reconstruction techniques, and extending to phase spaces with challenging experimental signatures, in the hope to get some signal or clear deviation from SM.

Summary plot

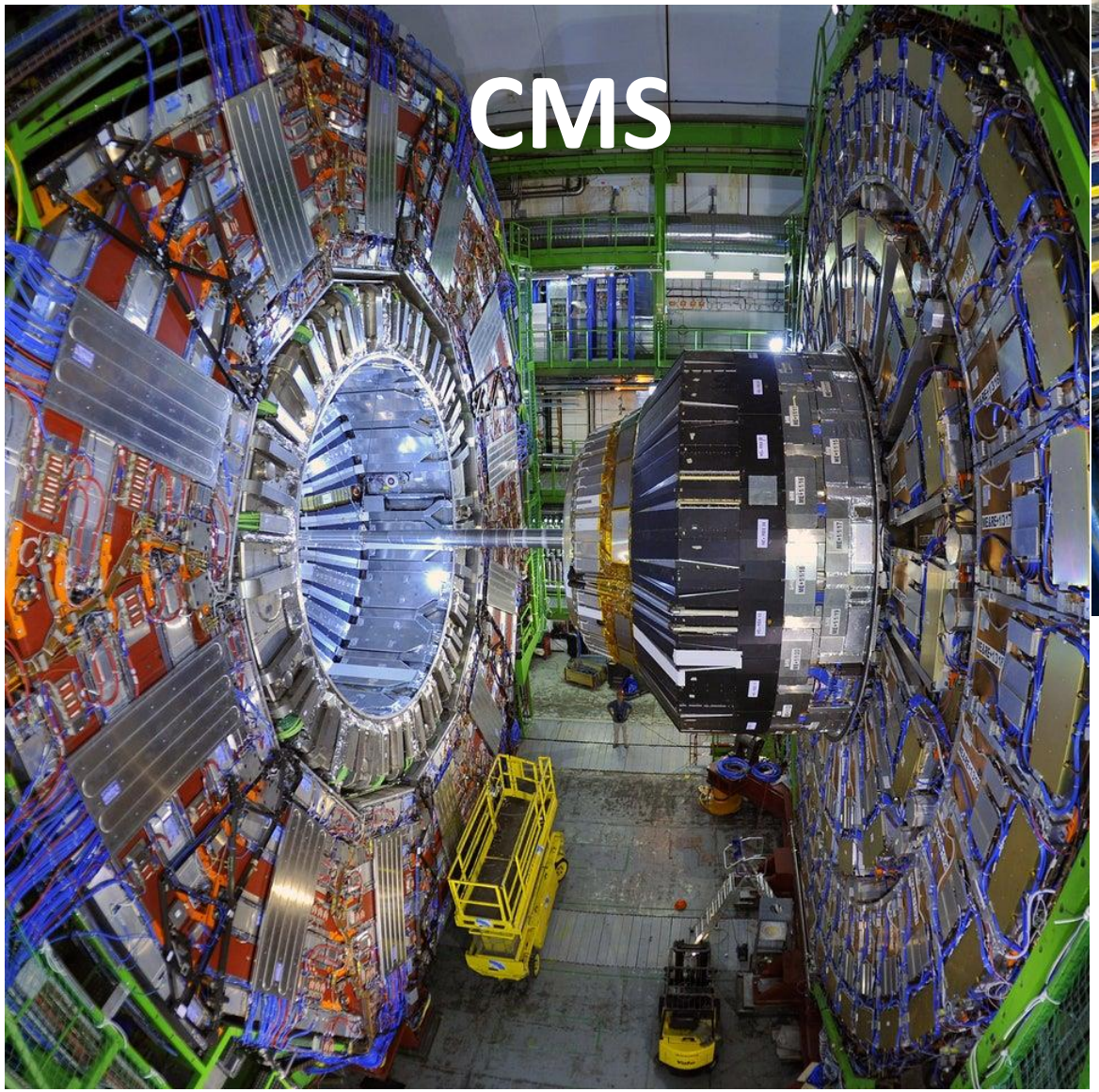


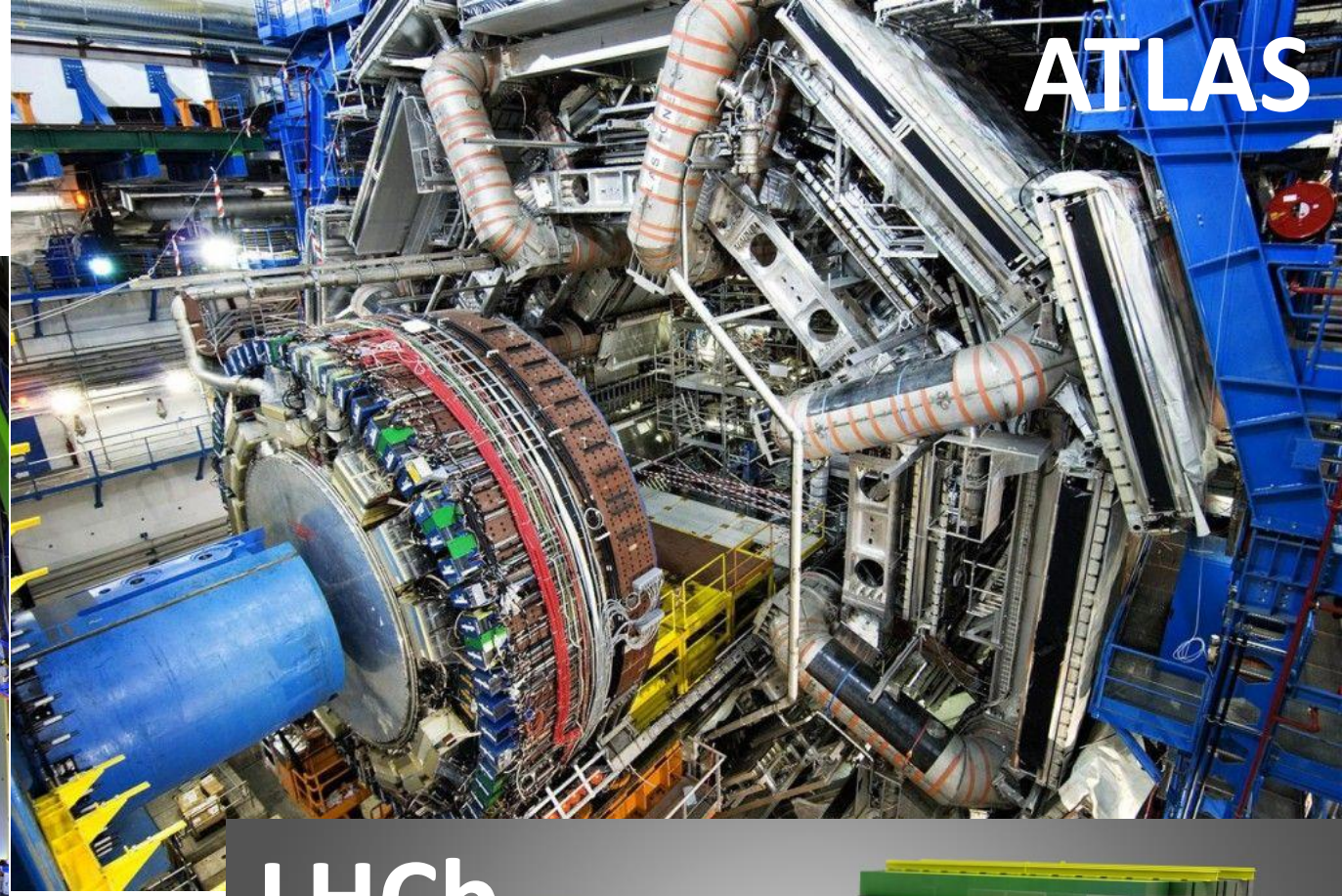
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

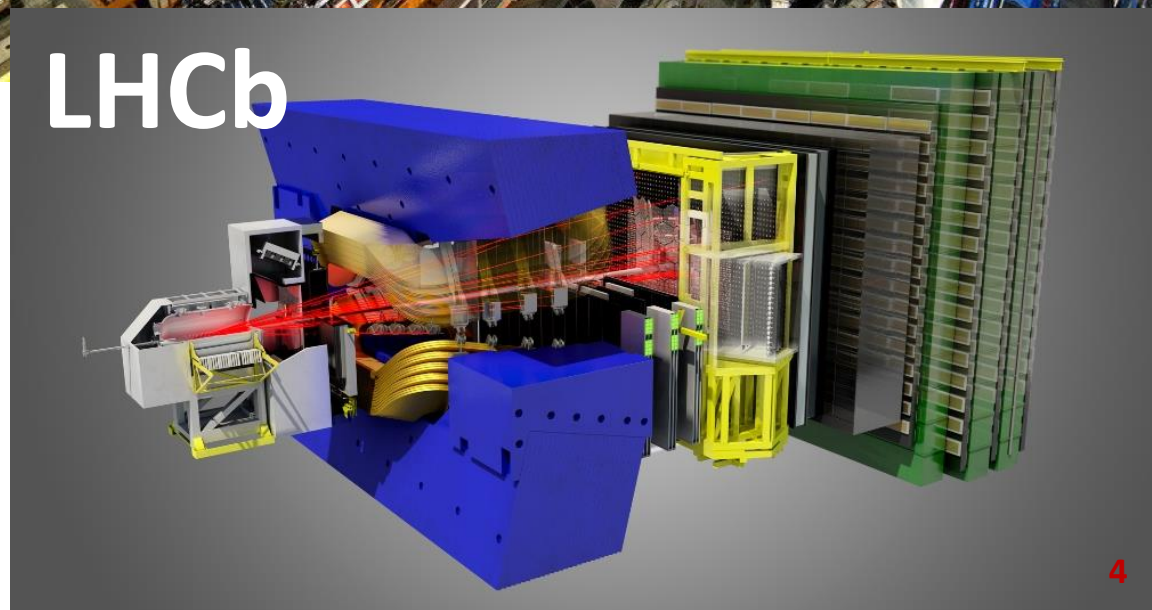
Thank you for your attention!

Backup

Experiments at LHC

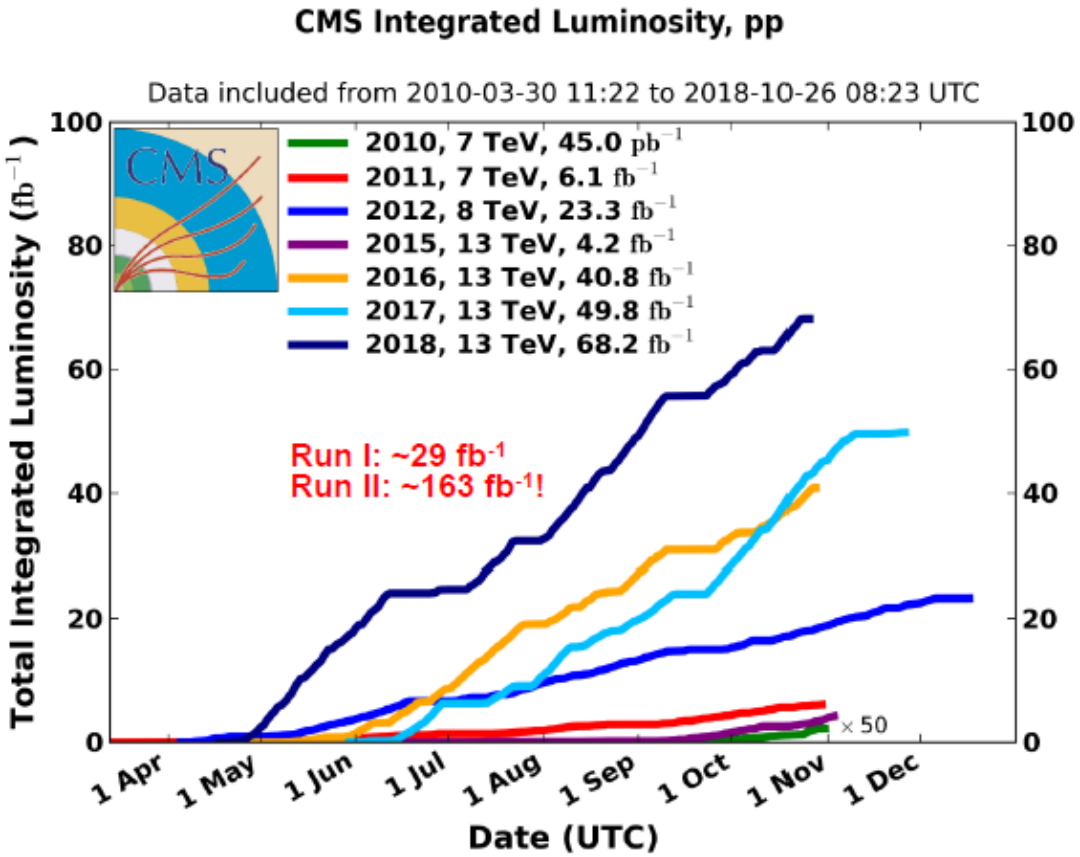


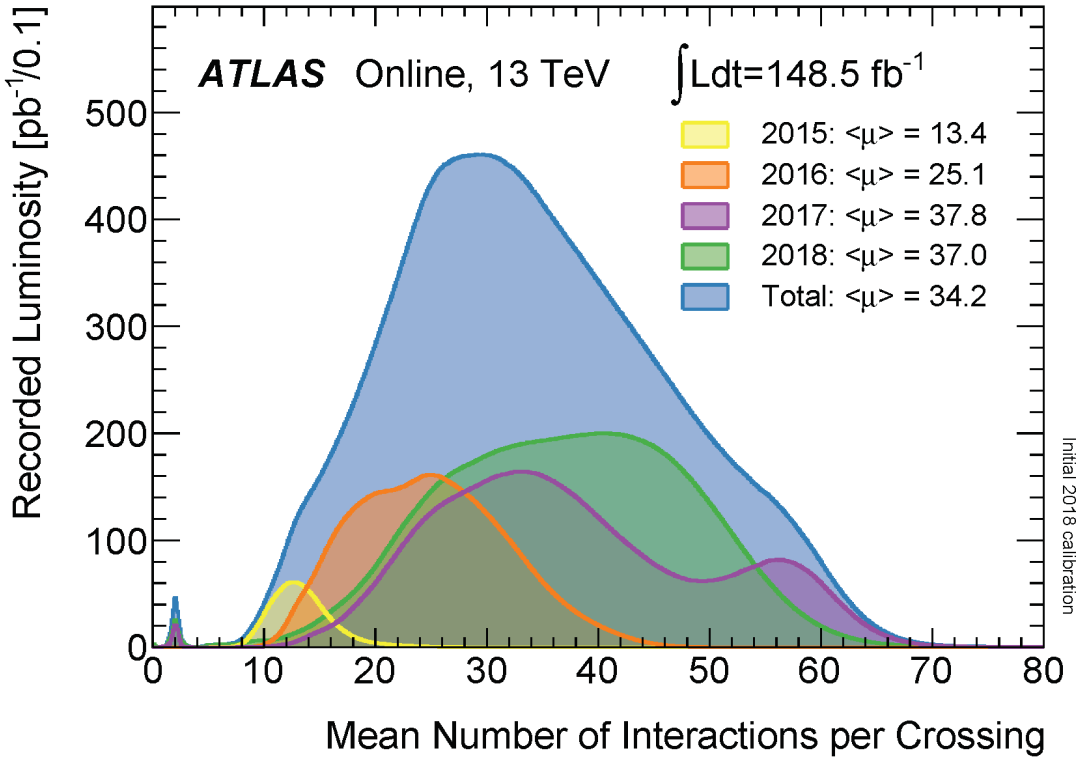




Datasets

- Full Run2 dataset (2016-17-18) ≈ 140 fb^{-1}
- Pile-Up Conditions: pp interactions per crossing, varying among years,25-38





Where we stand with SM

The SM is a wonderful guide, but not “the theory” describing our universe (small & big scales)

Experimental facts for BSM

- Nature of non-barionic DM
- Matter/Antimatter asymmetry in universe / CP Violation
- Dark Energy

….

Theoretical shortcomings pointing to BSM

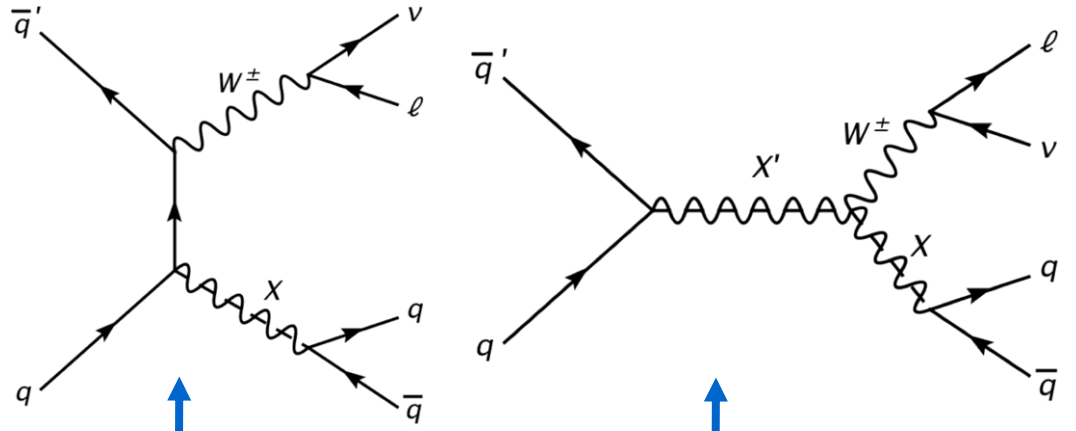
- Quantum Gravity description
- Unification of gauge couplings? (why so different)
- Mass/energy hierarchy:$M_{Planck}/M_{EW} \sim 10^{15}$
- ….

Exploring lower masses, association

10.1007/JHEP06(2020)151

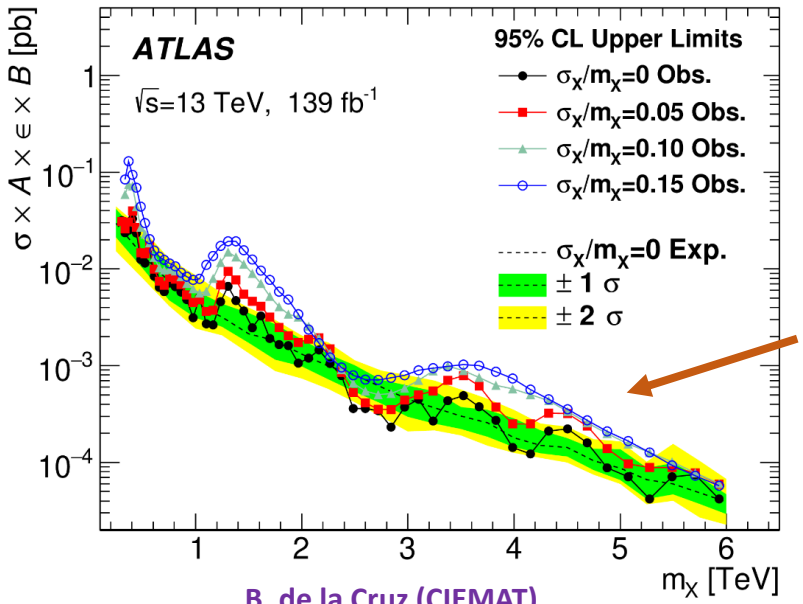
- Dijet resonance + lepton in the evt
  - Lepton used for triggering
  - Better sensitivity due to lower background
  - Previous analyses: lepton → γ, jet

- Test of new models and production modes (eg. association with EWK bosons, DM mediator, others).
  - Generic search, model independent, as a function of resonance mass and width

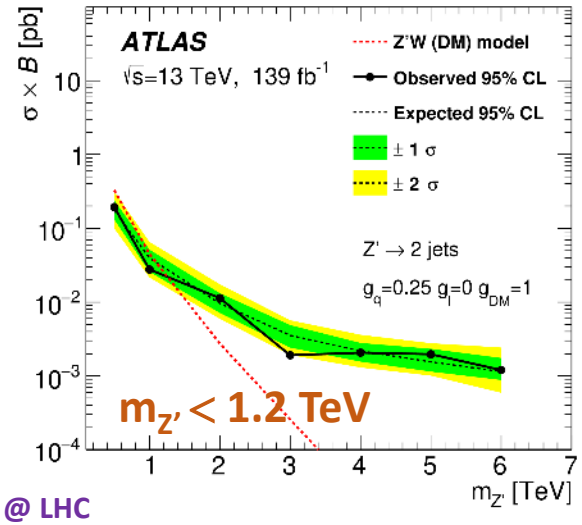


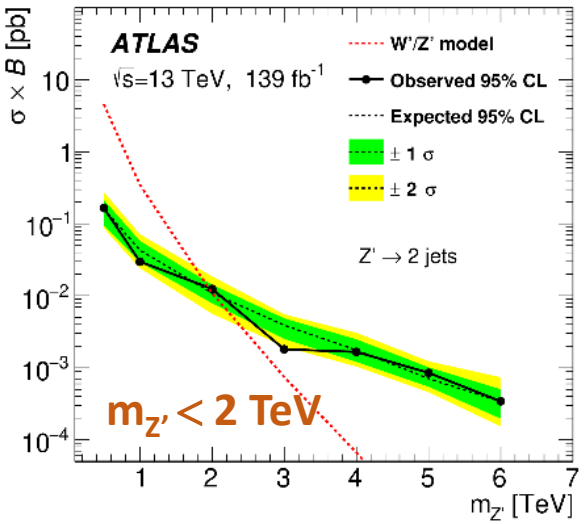
Z' leptophobic DM mediator
Simplified DM Model

W' → Z' W
Sequential Standard Model



Assuming Gaussian-shaped signals with σ_{eff} in [100-0.1] fb





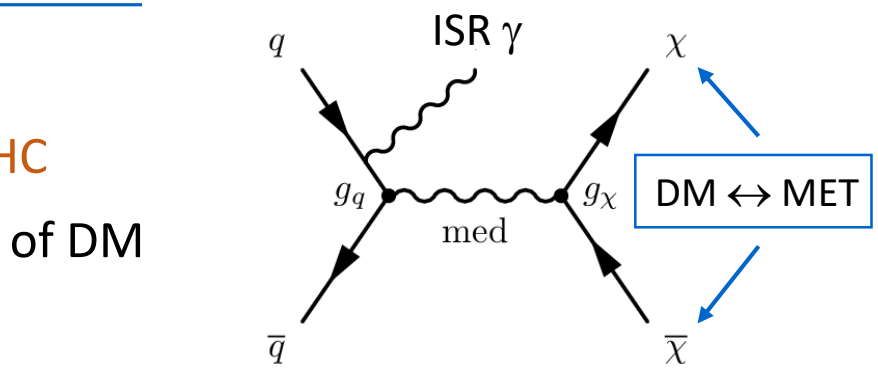
Dark matter: γ+MET

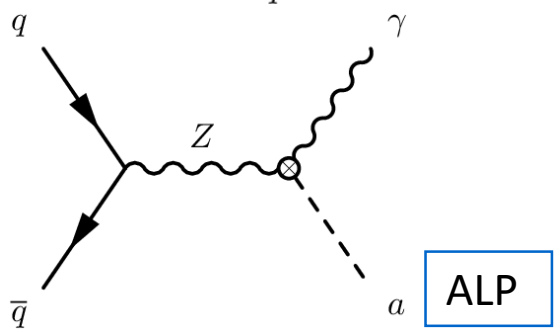
arXiv:2011.05259

- Understanding DM is one of the main motivations for BSM searches at LHC
- Relevant experimental signature: photon (ISR) + MET signalling presence of DM particles. Other searches focus on jet (also b, t), vector boson, H…
- Alternatively, ALP production in EFT extension of SM lagrangian

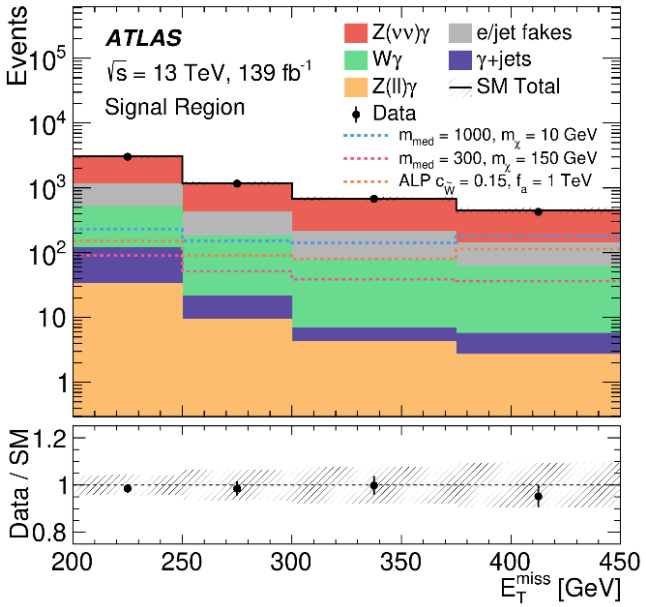
Experimentally: ▫ Photon E_T>150 GeV , MET > 200 GeV

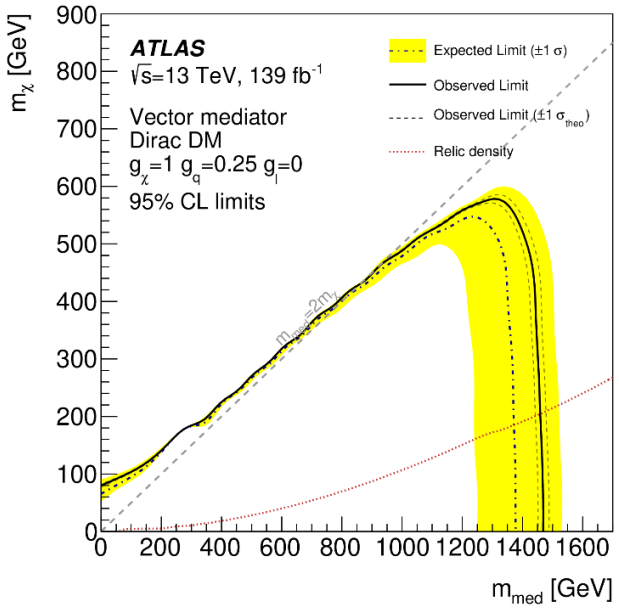
- SR defined on MET ranges, inclusive or exclusive
- Backgrounds defined in CR, ported to SR with normalization factors
- Fit simultaneously in SR and CRs

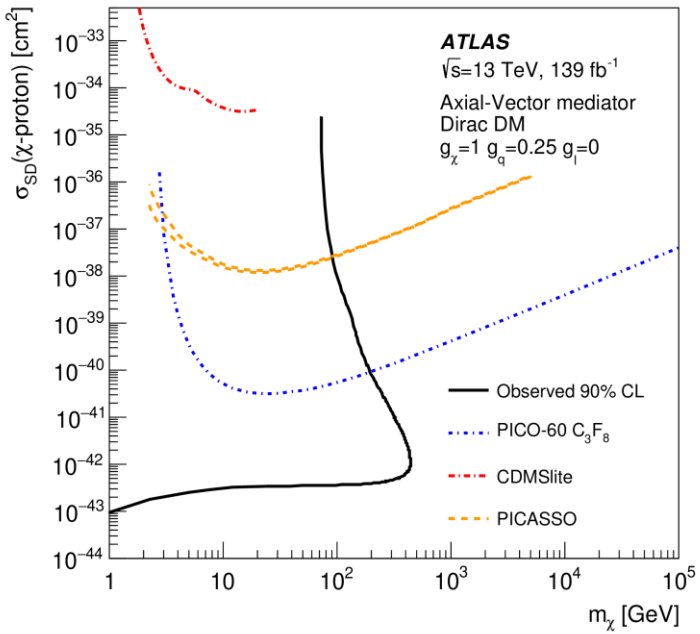




Parameters
M_{med}, M_χ
g_q, g_χ, g_l







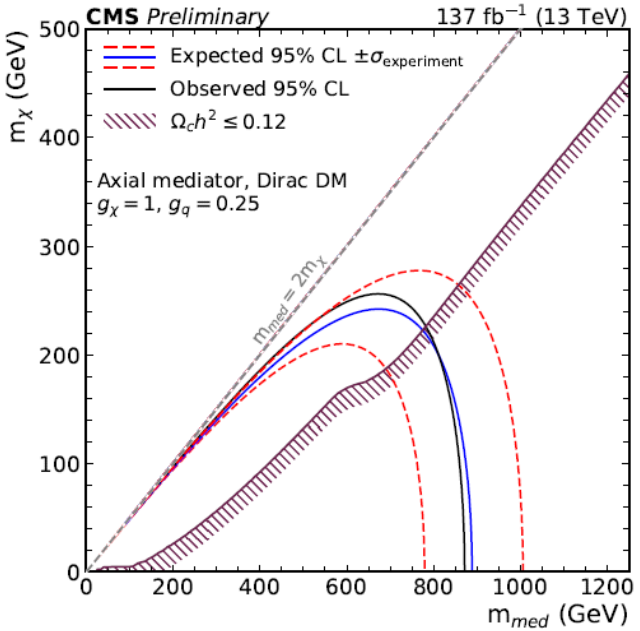
Dark matter: Z(ll)+MET

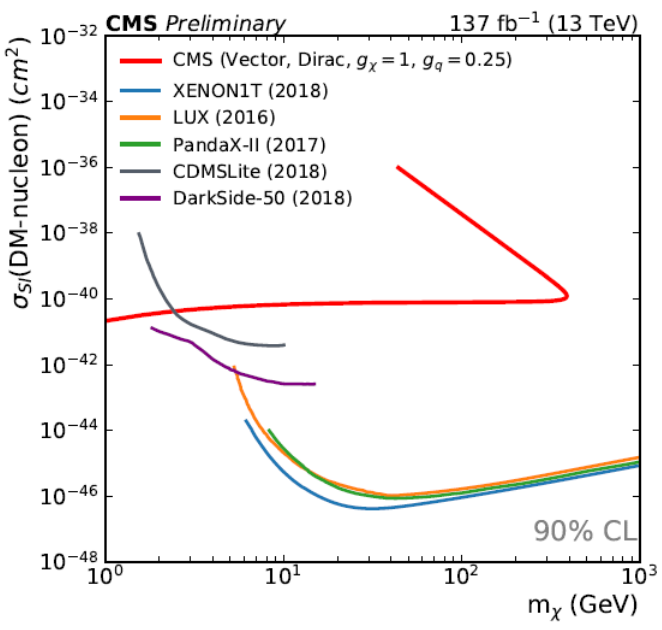
arXiV:2008.04735

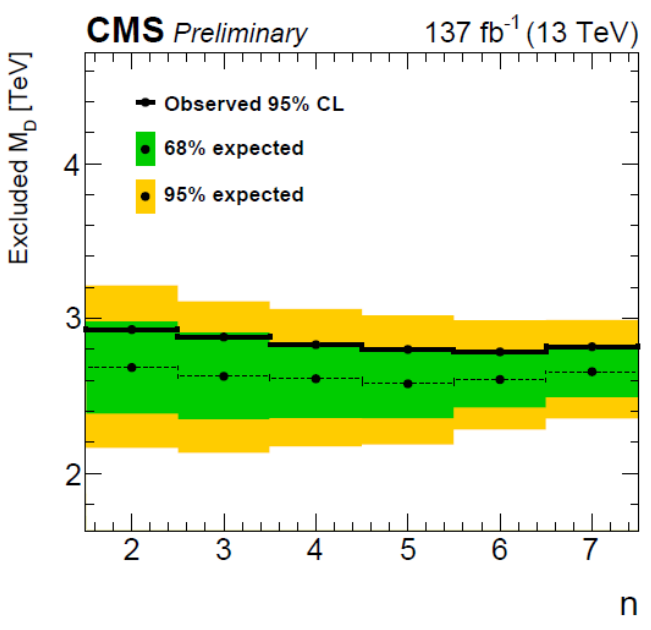
- $Z(l^+l^-)$ recoiling to MET (DM, invisible particles)
- Rich in interpretations!: simplified DM models with vector/axial-vector mediators and DM a Dirac fermion, H invisible decays, 2HDM
- Outside DM, large extra dimensions and unparticles
- Main backgrounds dibosons and top processes, from simulation and CR
- Reduced contribution thanks to 3rd lepton and hadronic activity vetos (only up to 1 jet)
- Simultaneous fit of MET in SR and CR + uncertainties

No sensitivity yet to scalar/pseudoscalar mediators with $g_q = g_\chi = 1$

B(H → invisible) < 29% (25^{+9}_{-7})% obs (exp) for SM H (125 GeV). Combined with previous CMS values, B < 19%



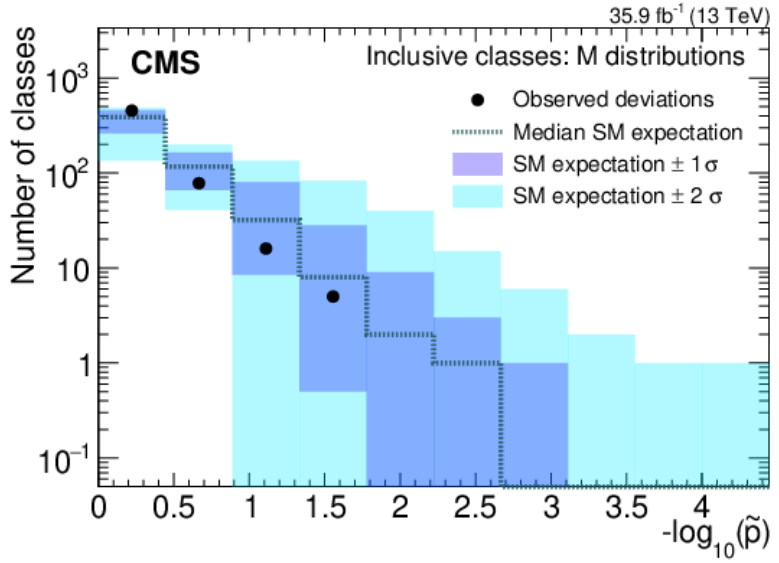


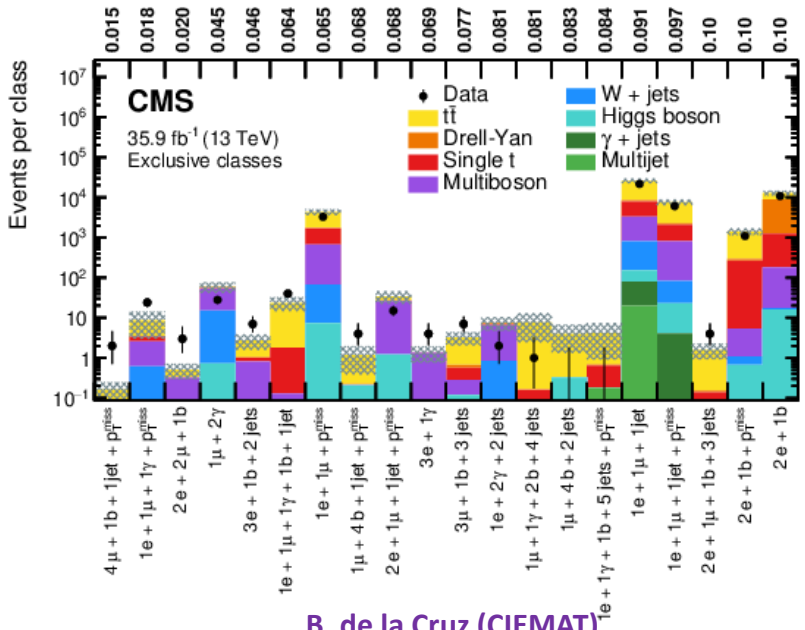


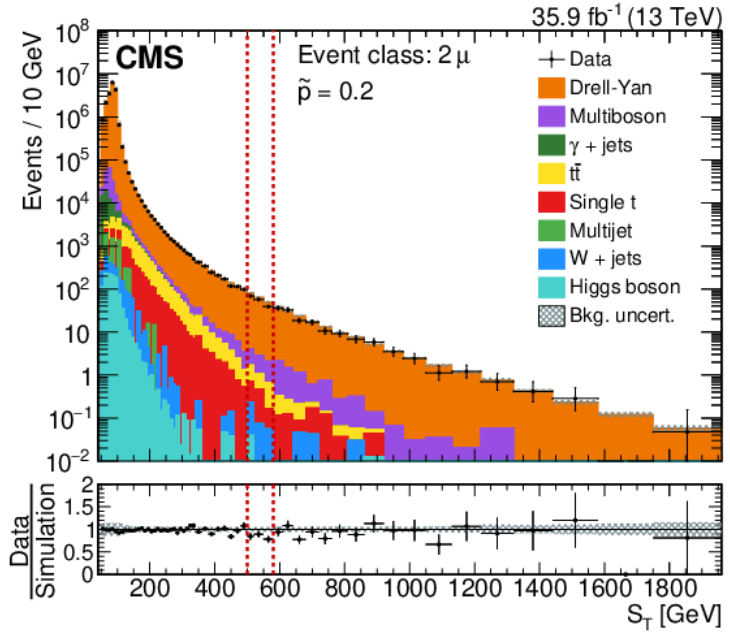
Wide search: MUSIC (Model Unspecific Search in CMS)

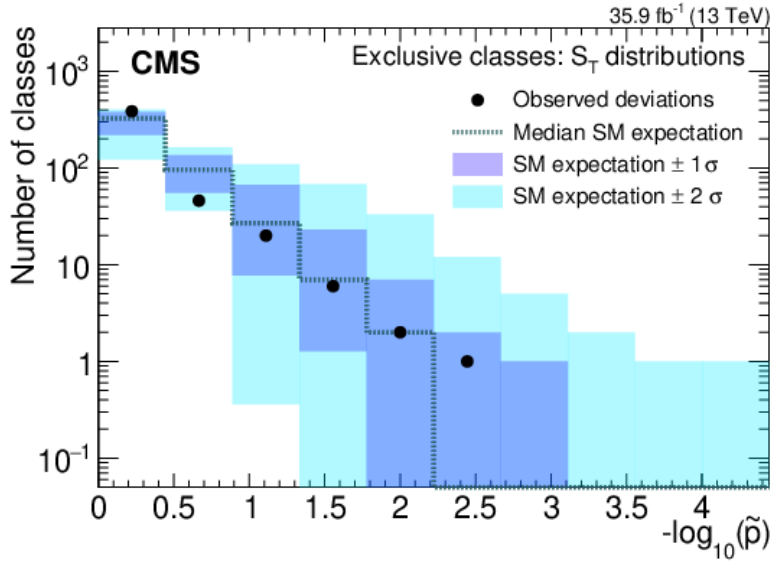
arXiv:2010.02984

- No significant deviation in the p-value distribution for data
- Lowest p-value for global evt yield is 0.015, for 4μ + 1b + 1jet + MET category
- Lowest p̃-value (0.0038) found in ST distrib. for 3e + 1b + 2jets (local p-value for ST [340-540] is 0.00053









Wide search: MUSIC (Model Unspecific Search in CMS)

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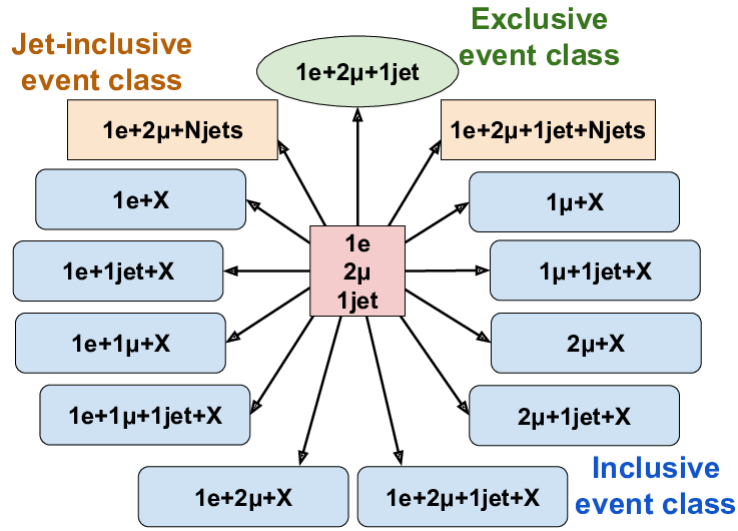
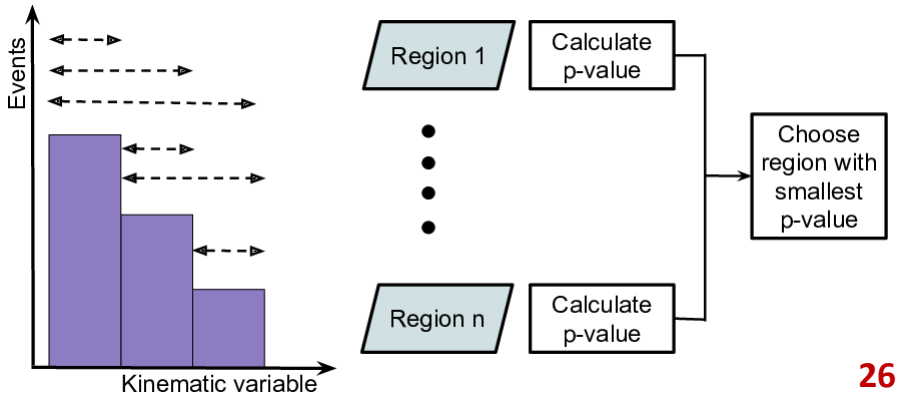


- Look for deviations wrt SM prediction in a large number of inclusive/exclusive event categories, based on e/μ/γ/(b)-jet multiplicity and low/high MET (<>100 GeV)
- Assess data/MC agreement in total evt yield and for distributions of MET, ST (sum of pT for physics objects), M/MT
- Focus on evts with ≥ 1 e / μ
- SM predictions entirely from simulations
- Technically:
  - Compute p-value in data, P_{data}
  - Select region of interest (ROI) as that with smallest p-value in combination of adjacent bins.
  - Compute global p̃-value: $\tilde{p} = \frac{N^{SM}_{pseudo\ exp.}(p_{min} < p^{data}_{min})}{N^{SM}_{pseudo\ exp.}}$

$$P_{data} = \begin{cases} \sum_{i=N_{data}}^{\infty} C \cdot \int_0^{\infty} d\lambda \exp\left(-\frac{(\lambda - N_{SM})^2}{2\sigma^2_{SM}}\right) \cdot \frac{e^{-\lambda}\lambda^i}{i!} & \text{if } N_{data} \geq N_{SM} \\ \sum_{i=0}^{N_{data}} G \int_0^{\infty} d\lambda \exp\left(-\frac{(\lambda - N_{SM})^2}{2\sigma^2_{SM}}\right) \cdot \frac{e^{-\lambda}\lambda^i}{i!} & \text{if } N_{data} < N_{SM} \end{cases}$$

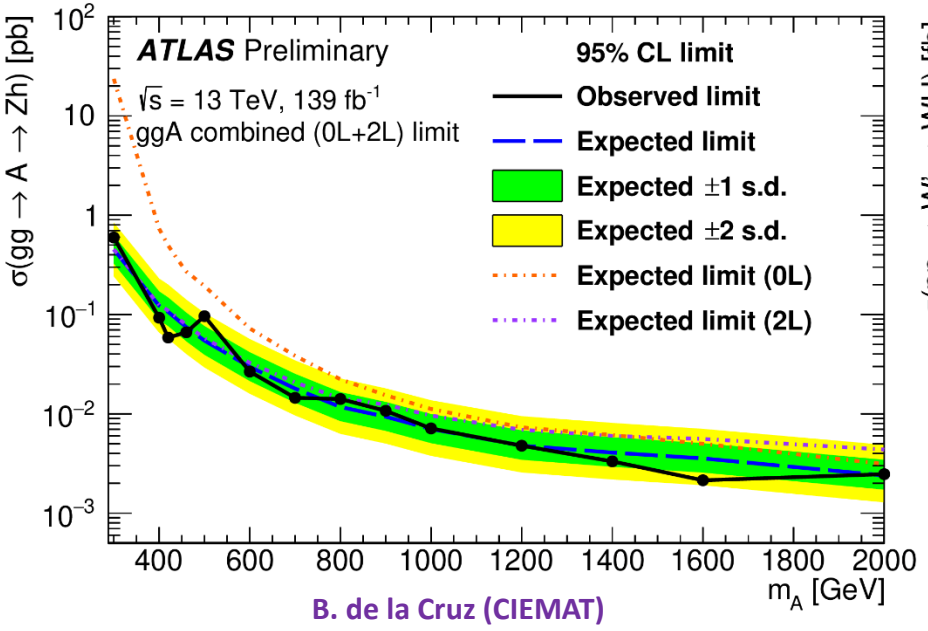


Dibosons:Z' → Z(ll, νν)H(bb)

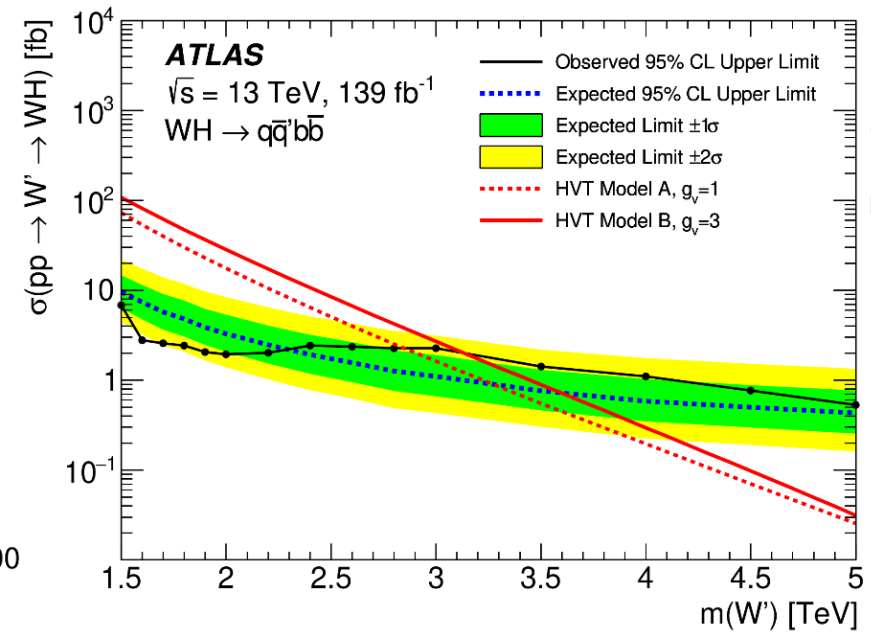
ATLAS-CONF-2020-043
arXiv:2007.05293

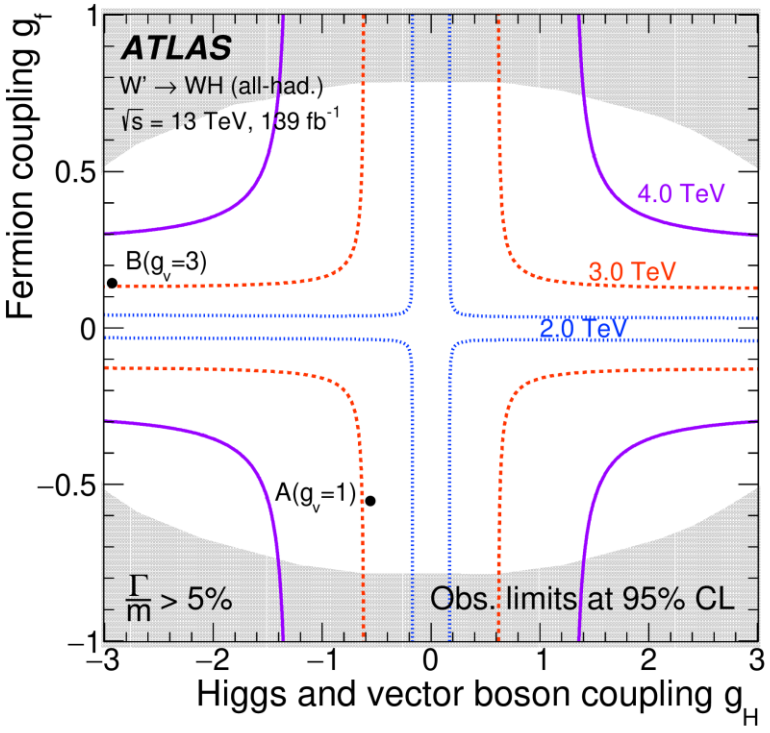
- Same final state as CMS, enlarging to lower R masses, 0.3 TeV to 5 TeV
- Probe Z' HVT model and generic CP-odd scalar boson, A from 2HDM (in a reduced mass range, up to 2 TeV)
- Several improvements at reco performance and selection optimization wrt previous ATLAS pub.
  - No inclusión of VBF, but resolved and boosted regimes.
- Similar results obtained in an all hadronic final state qqbb, this time in WH and ZH.

semileptonic channel



all hadronic channel





$\gamma\gamma \rightarrow WW$ in pp

arxiv:2010.04019

- Process sensitive to anomalous gauge boson interactions
- Observation of the process and Cross section measured
- Consistent with theoretical predictions.
  - useful input for constraints on anomalous quartic $\gamma\gamma WW$ interactions