EXOTICS AT THE LHC

Daniele del Re
Sapienza Università & INFN Sezione Roma

on behalf of the CMS, ATLAS and LHCb collaborations

Why Exotic Searches at LHC

UNANSWERED QUESTIONS

Several open issues implying Physics beyond Standard Model. Some examples:

1. **Why only three families of leptons and quarks?**
2. **Why four fundamental interactions and not one?**
   - unification is impossible even at very large energies
3. **Why only 5% of matter made of ordinary SM particles?**
   - what is dark matter?
4. **Why most massive particle“only” 200 times heavier than p?**
   - desert above 170 GeV

THE MEANING OF EXOTICS

1) Covering **all possible signatures** and be ready for the unexpected
2) Be as much **as model-independent as possible**
   - Use of **benchmark models to test the significance of the searches**
3) Search for **extremely high masses**
4) Go for **really exotic:**
   - Models with new interactions, quarks, leptons
   - Unconventional signatures
5) Find a **candidate for dark matter**
6) Explore **new analysis techniques** **to boost discovery** potential

- ***Hundreds of results and searches***
- *Here I provide the* ***global picture*** *and* ***focus*** *on* ***very recent or brand new results***

PLENTY OF LUMINOSITY TO PLAY WITH

Run1: ~30 fb^{-1} @ 7 - 8 TeV
- Discovery of Higgs boson
- Exploration of new physics

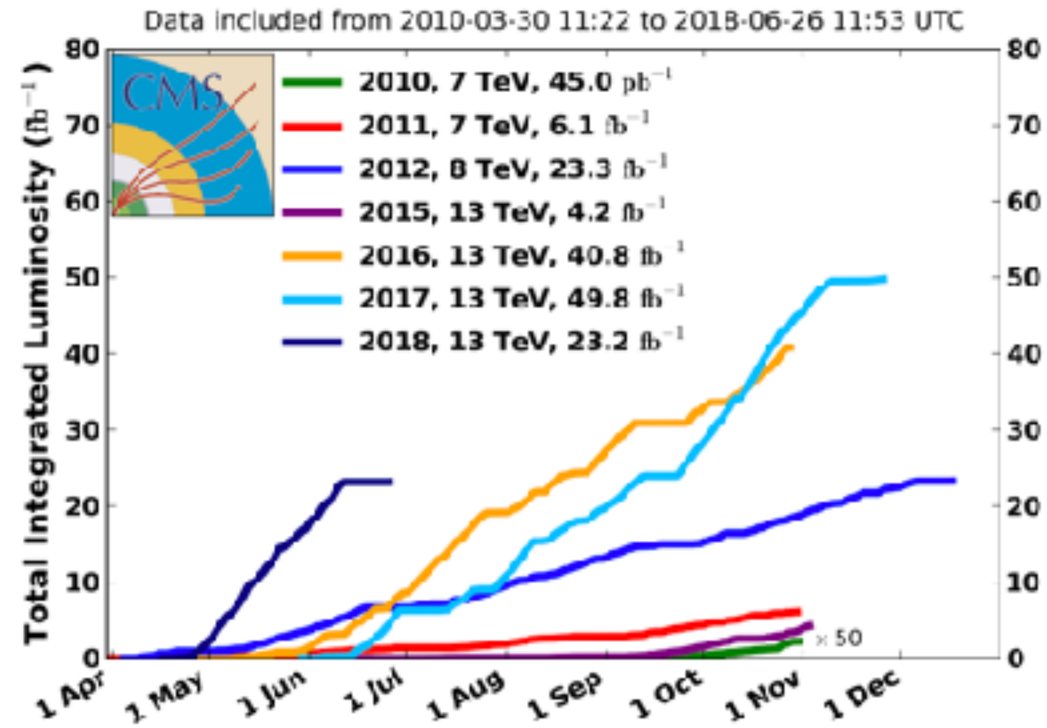
Run2:

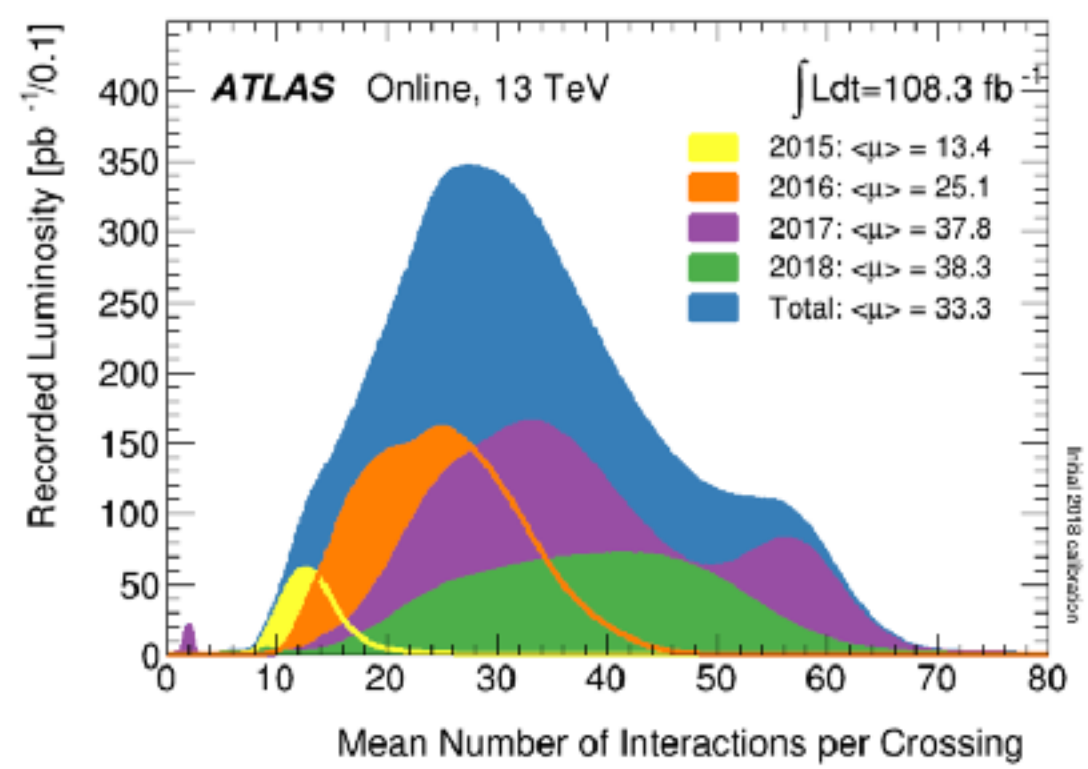
- **2015: ~4 fb^{-1} @ 13 TeV**
  - First look in new territory
- **2016: ~40 fb^{-1} @ 13 TeV**
  - Repeat 8 TeV program
- **2017: ~50 fb^{-1} @ 13 TeV**
  - Go deeper and detailed

statistics shown today

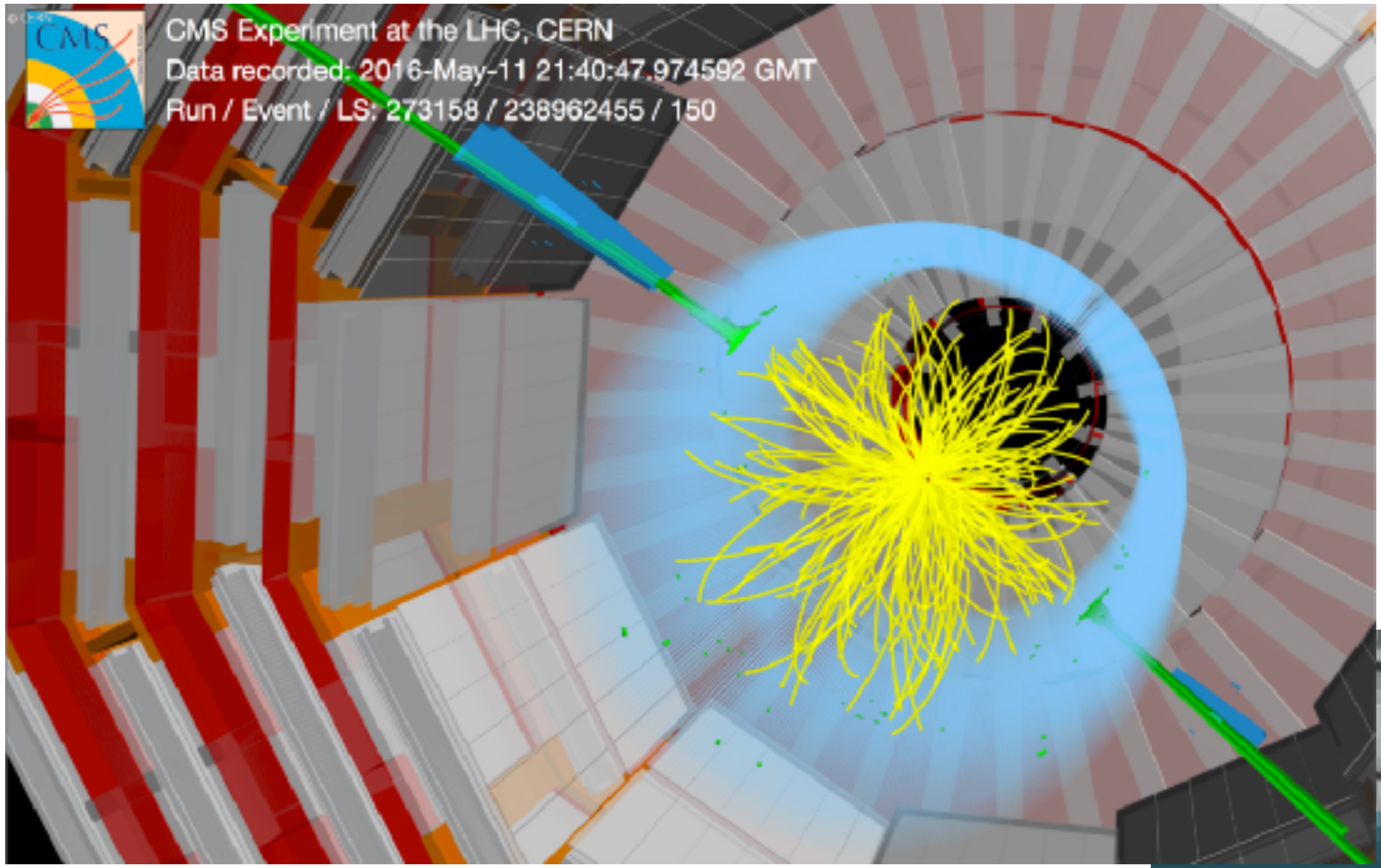
- **2018: ~20 fb^{-1} @ 13 TeV**
  - Ongoing: expect 60 fb^{-1}

Full Run2: ~150 fb-1



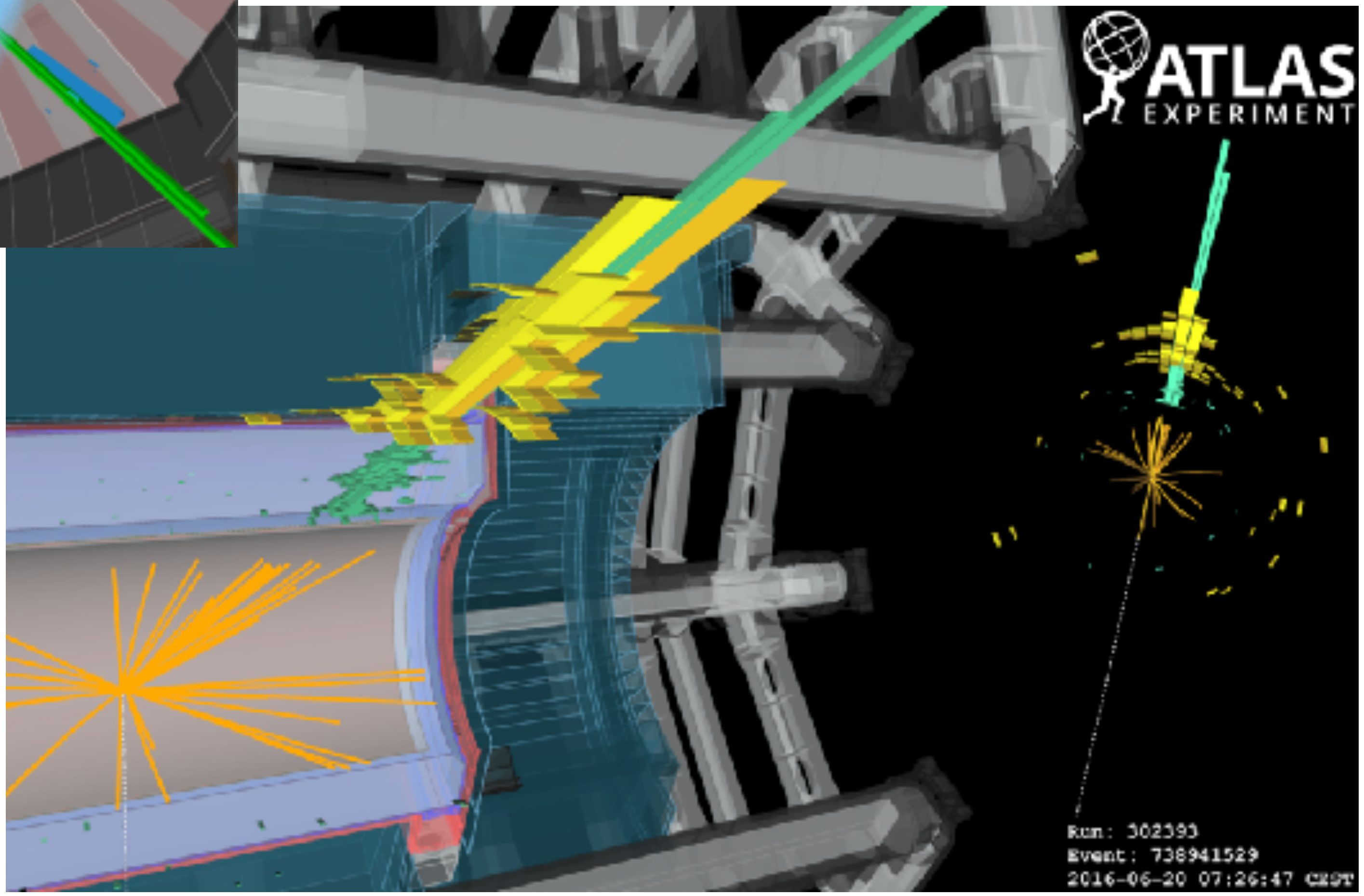


UNIQUE PLAYGROUND



Objects with huge energies

~ 1.7 TeV monojet event!

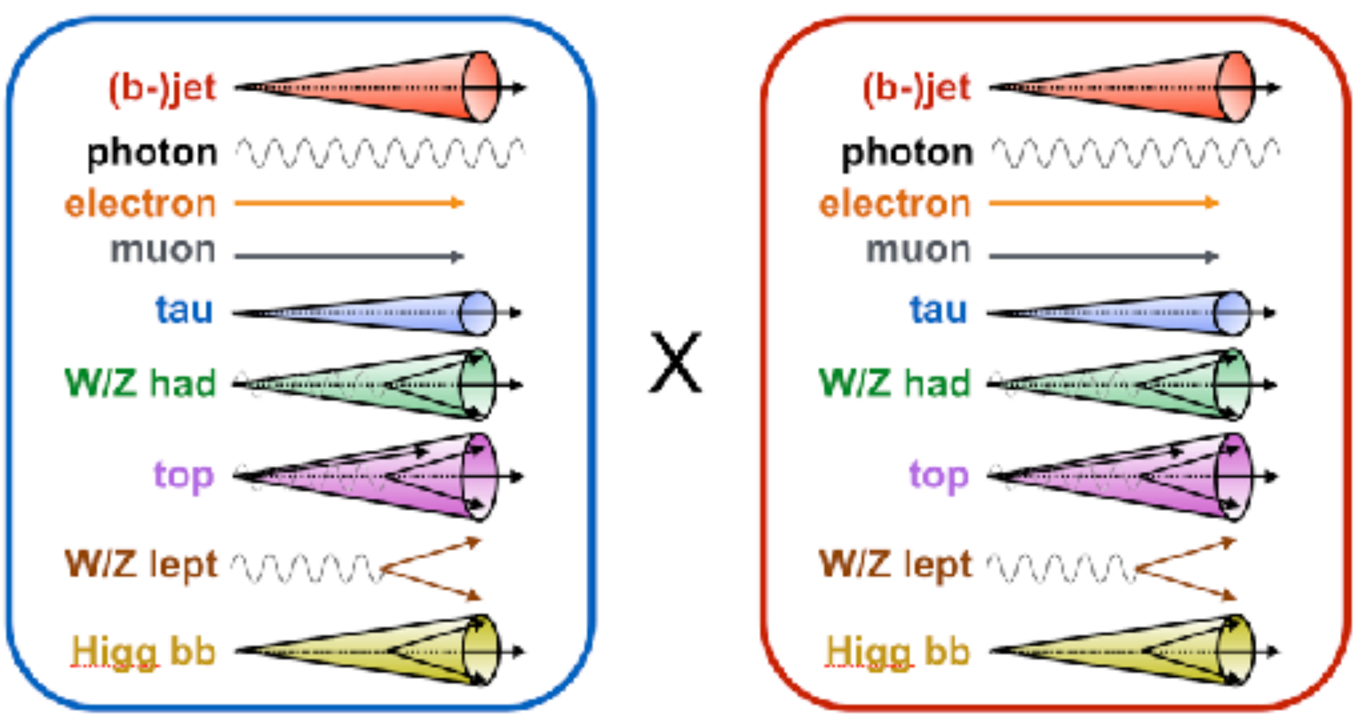


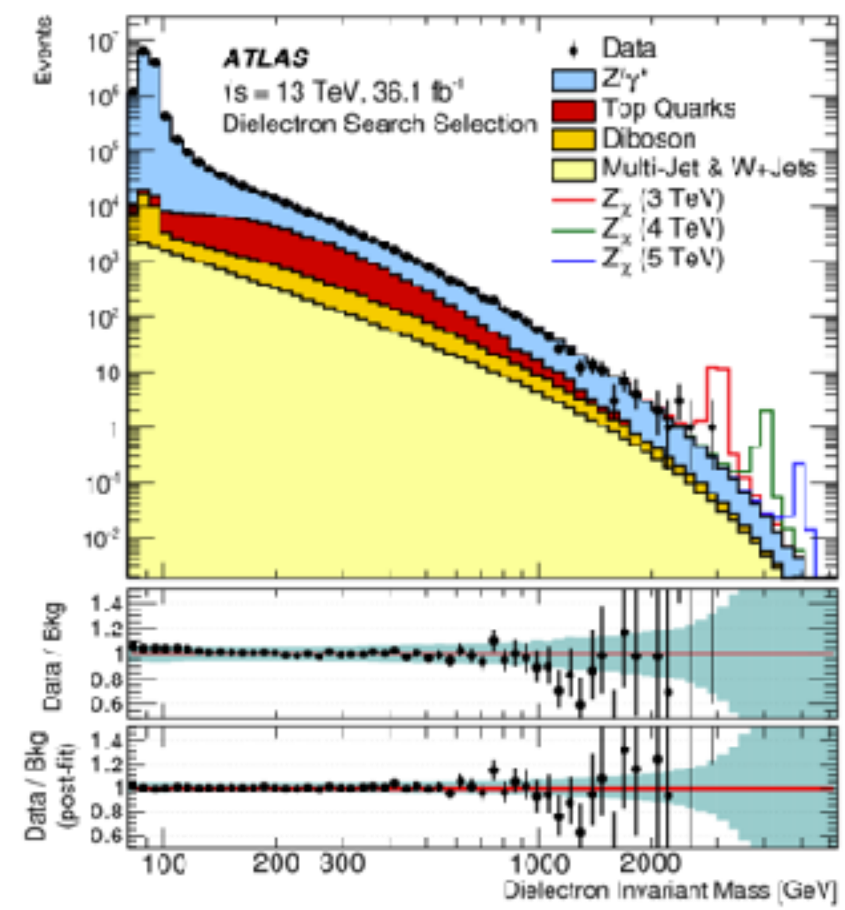
~ 8 TeV dijet event!

Deep understanding of detector for detailed searches

Resonances

- **Fully reconstructed resonances represent the simplest way to discover new particles**
  - striking and incontrovertible signature
  - small systematics, robust
- **Most of resonance searches are two-body**
- **Many possible combinations and channels explored**



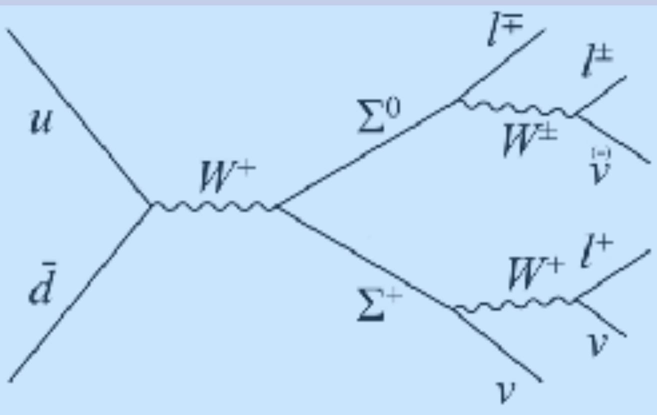


Specific Models for Specific Issues

Several models introduced to resolve issue in the Standard Model. Some examples

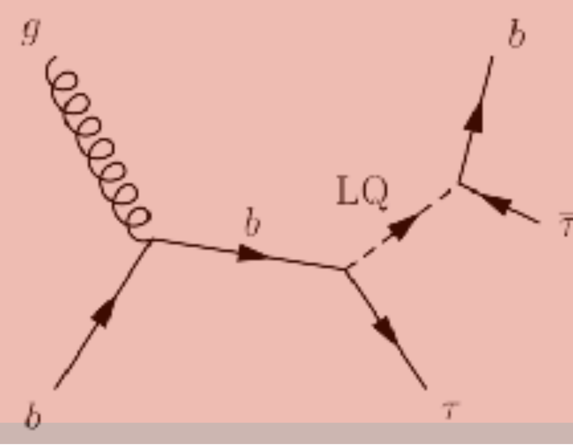
Explain light mass of the neutrinos:

- Seesaw Models:
  - Type III: introduces new heavy fermions, coupling to leptons, Higgs and V bosons



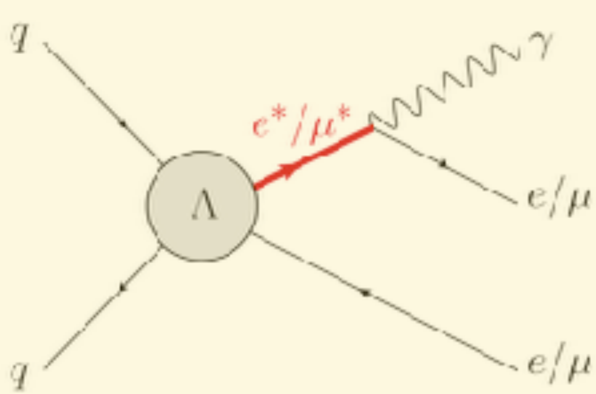
Why same number of generation for leptons and quarks:

- **leptoquarks** carry both lepton and baryon number
  - decay in lepton-jet



Why three generations of fermions and their **hierarchy:**

- **excited quarks, excited leptons**
  - resonant qγ/qg and lγ/Zγ states



Long-Lived and Unconventional

Long-lived (LL) and unconventional exotic particles with striking signatures **predicted by many extensions of the SM.**

Why LL?

small couplings

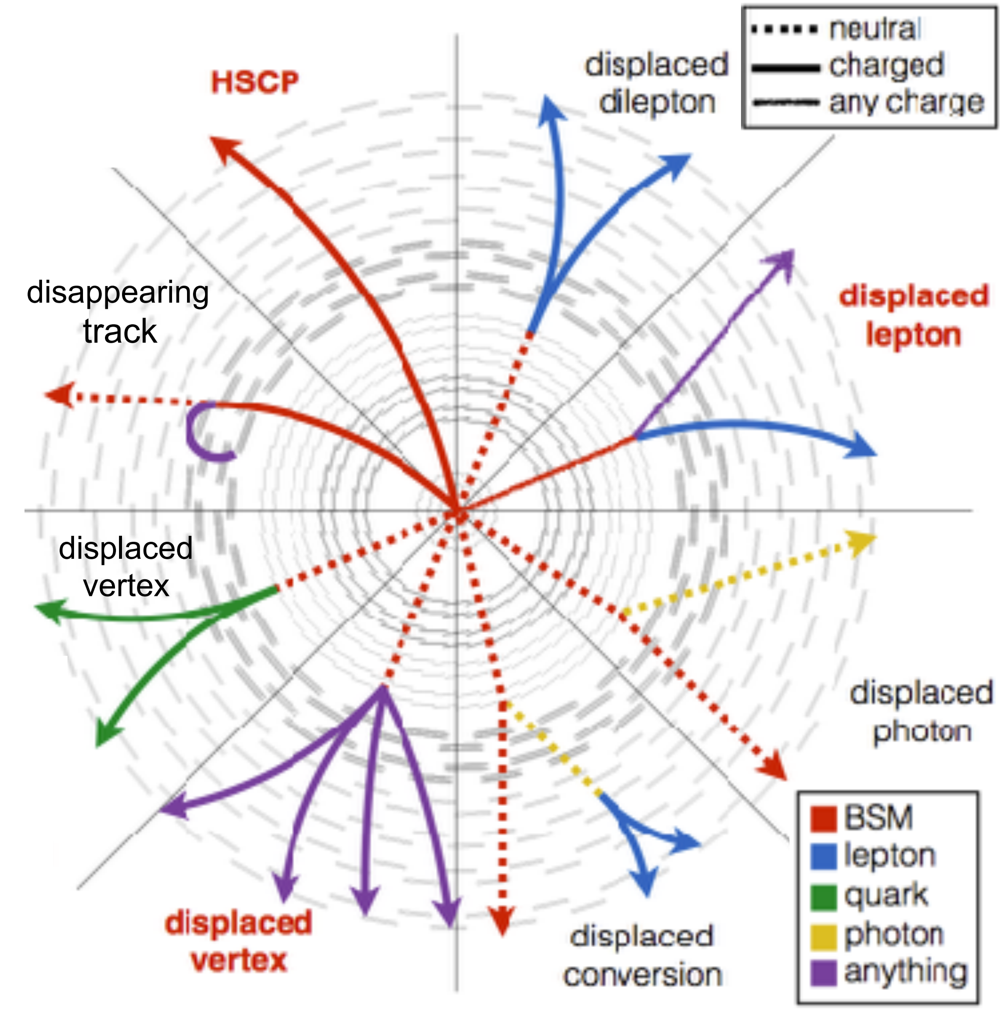
phase-space suppressed, small mass splitting

$$\Gamma = g^2 |A^2| \frac{\Phi}{M}$$

amplitude suppressed

Examples:

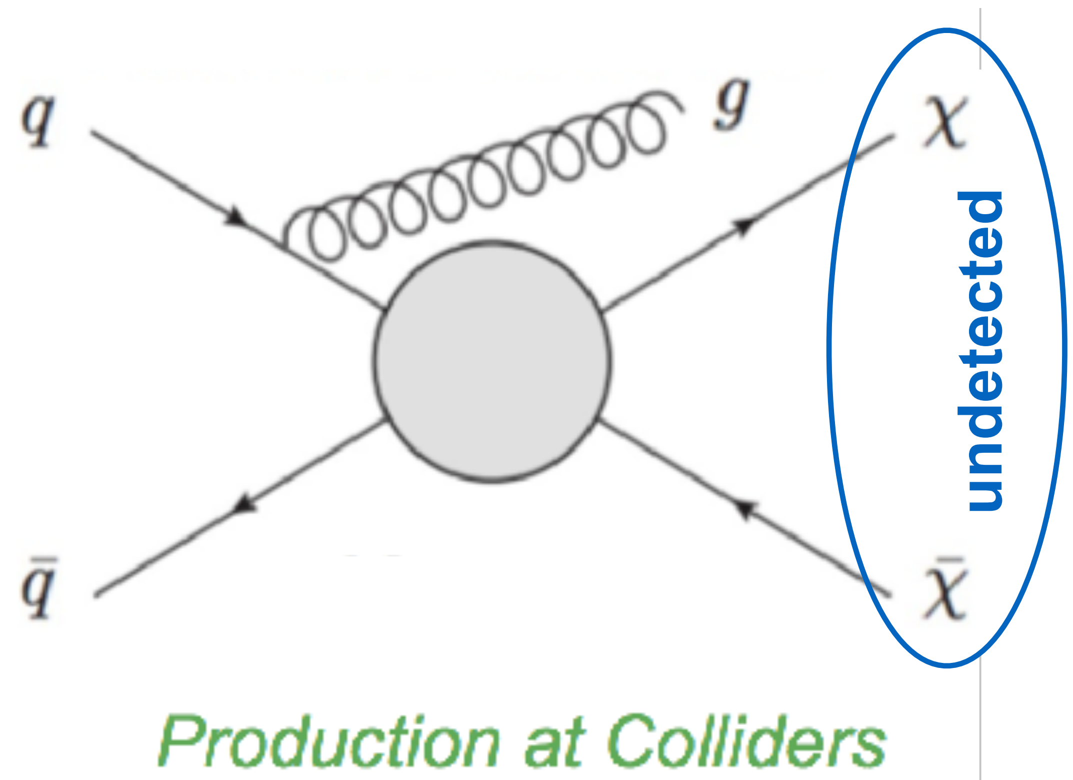
- **Heavy, long-lived, charged particles**
  - R-hadrons, Sleptons
- **Particles can decay in the detector after few cm**
  - neutralinos in GMSB, mass-degenerate gauginos, particles of an Hidden Sector



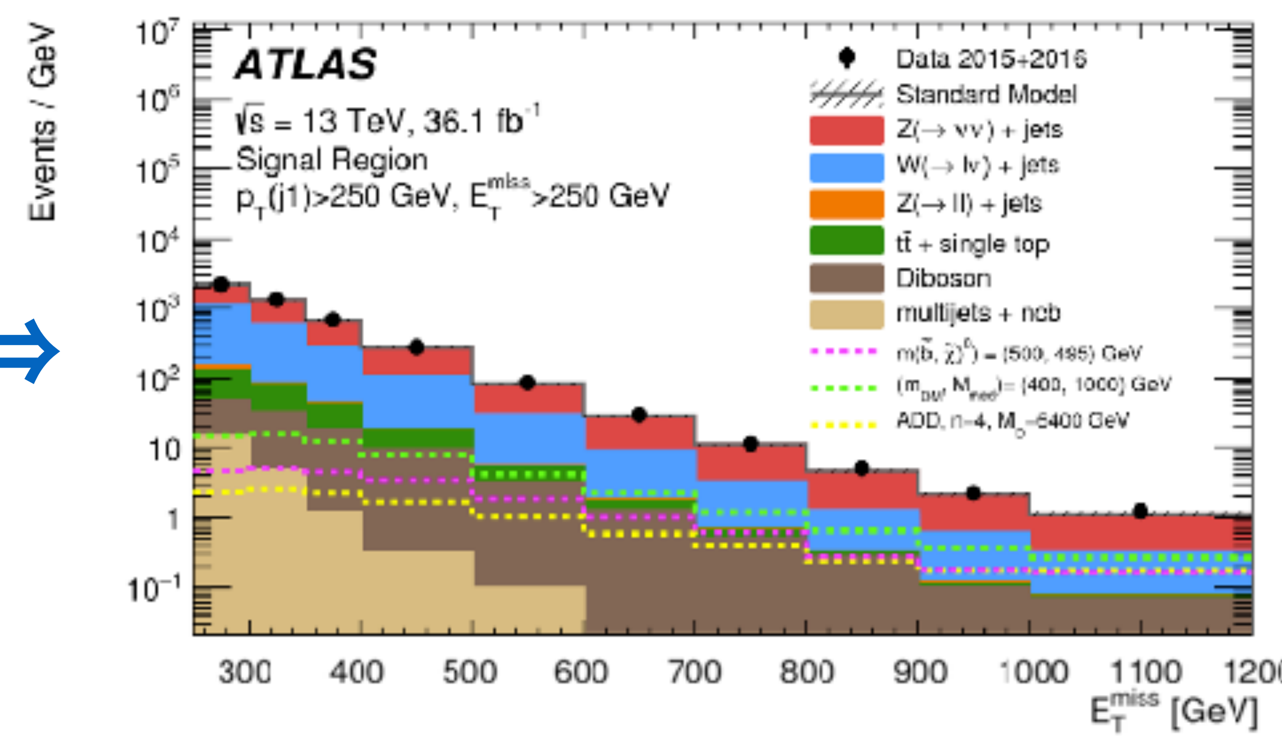
Credits: J. Antonelli

The Dark Matter

- **Look for weakly interacting new particles produced at LHC**
  - Dark Matter candidates!
- **Pair production at LHC**
  - DM candidates escape the detector (weekly interacting)
- **No peaks. Large Missing energy distribution**
- **Deep understanding of SM background and detectors**



missing energy



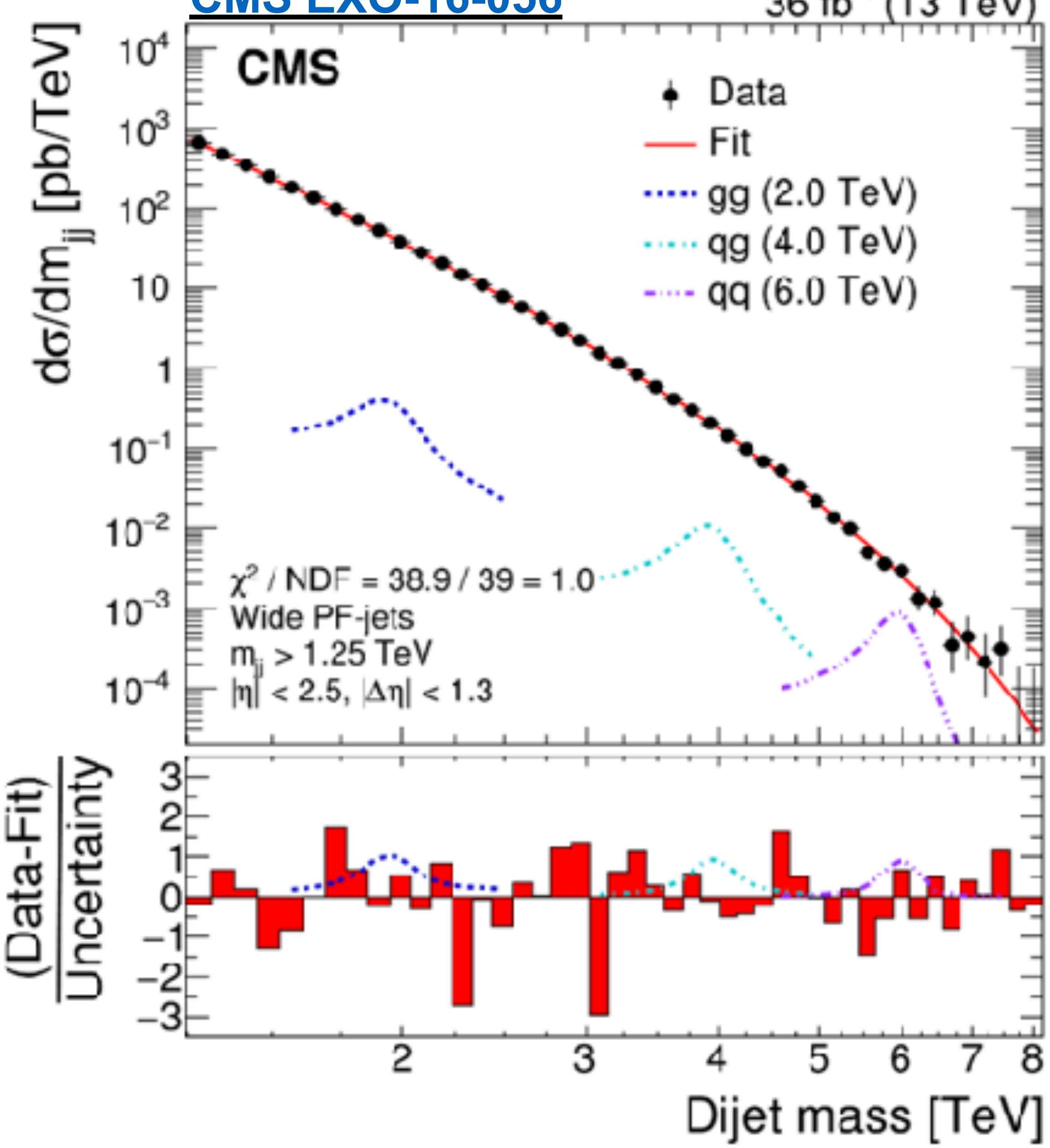
ATLAS : JHEP 01 (2018) 126

RESONANCES

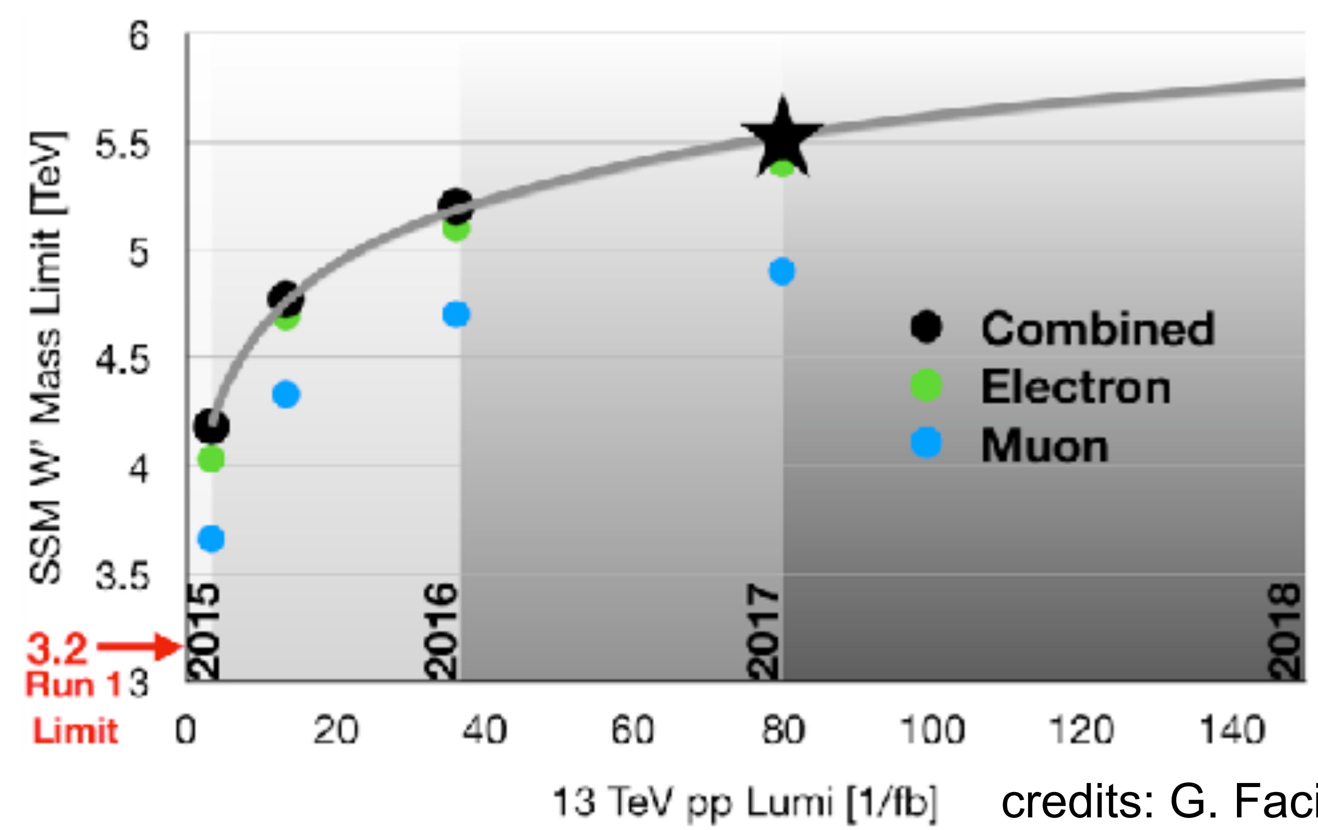
Extremely High Masses

- **Very strong limits now**
- Increasing statistics gives **no breakthrough anymore**

[CMS EXO-16-056]



examples	Mass Lower limit
String resonance (jj)	~ 8 TeV
Excited quark (jj)	~ 6 TeV
Z' (SSM) (ll)	~ 4.5 TeV
W' (SSM) (lν)	~ 5.5 TeV



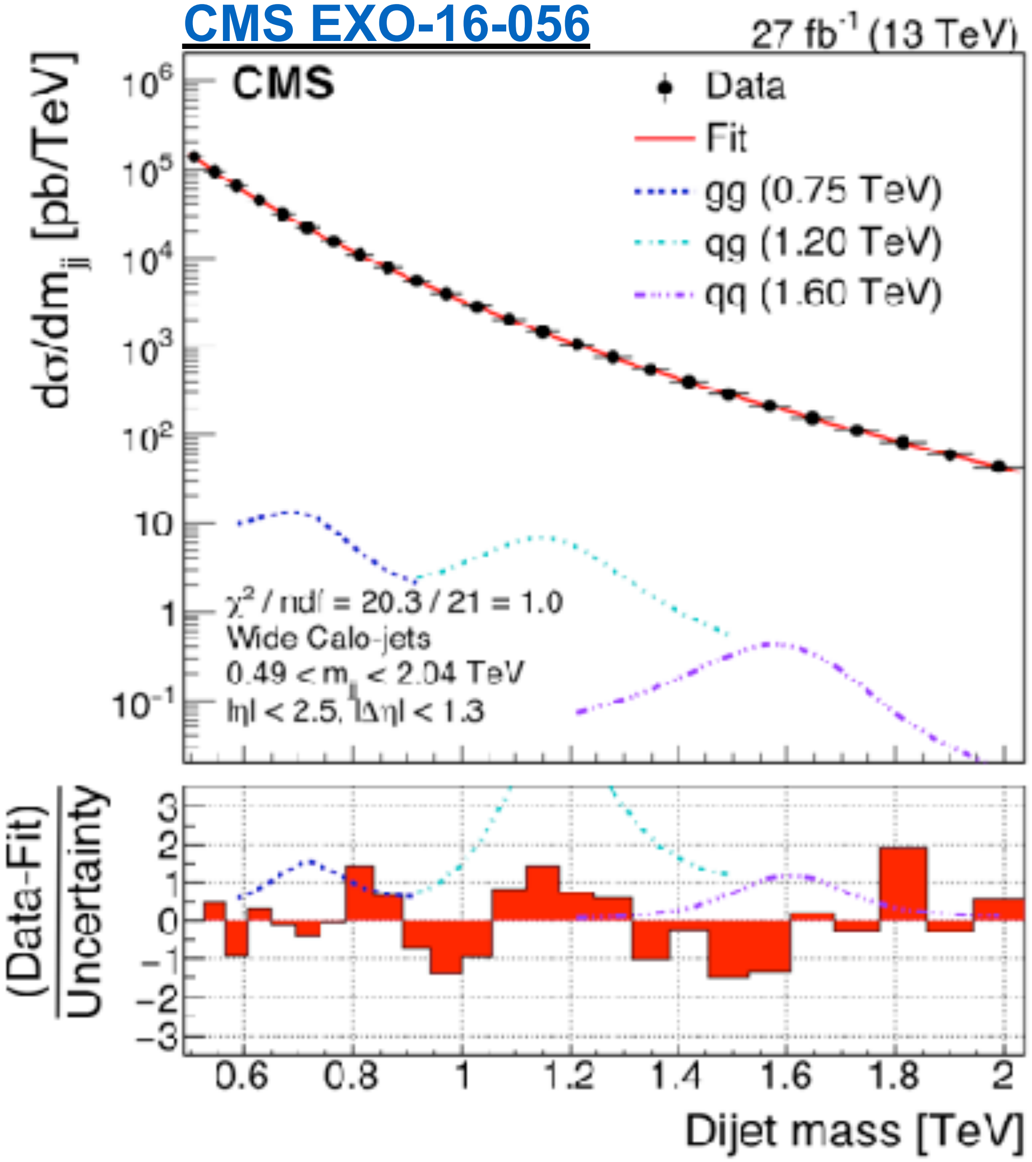
credits: G. Facini

DIJET: LOW AND INTERMEDIATE REGION

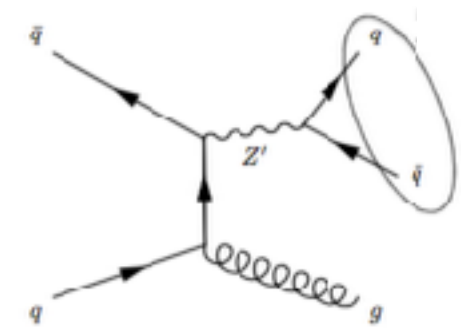
Extend the scope: look for **intermediate and low mass regions**

Save reduced event info and apply lower trigger thresholds

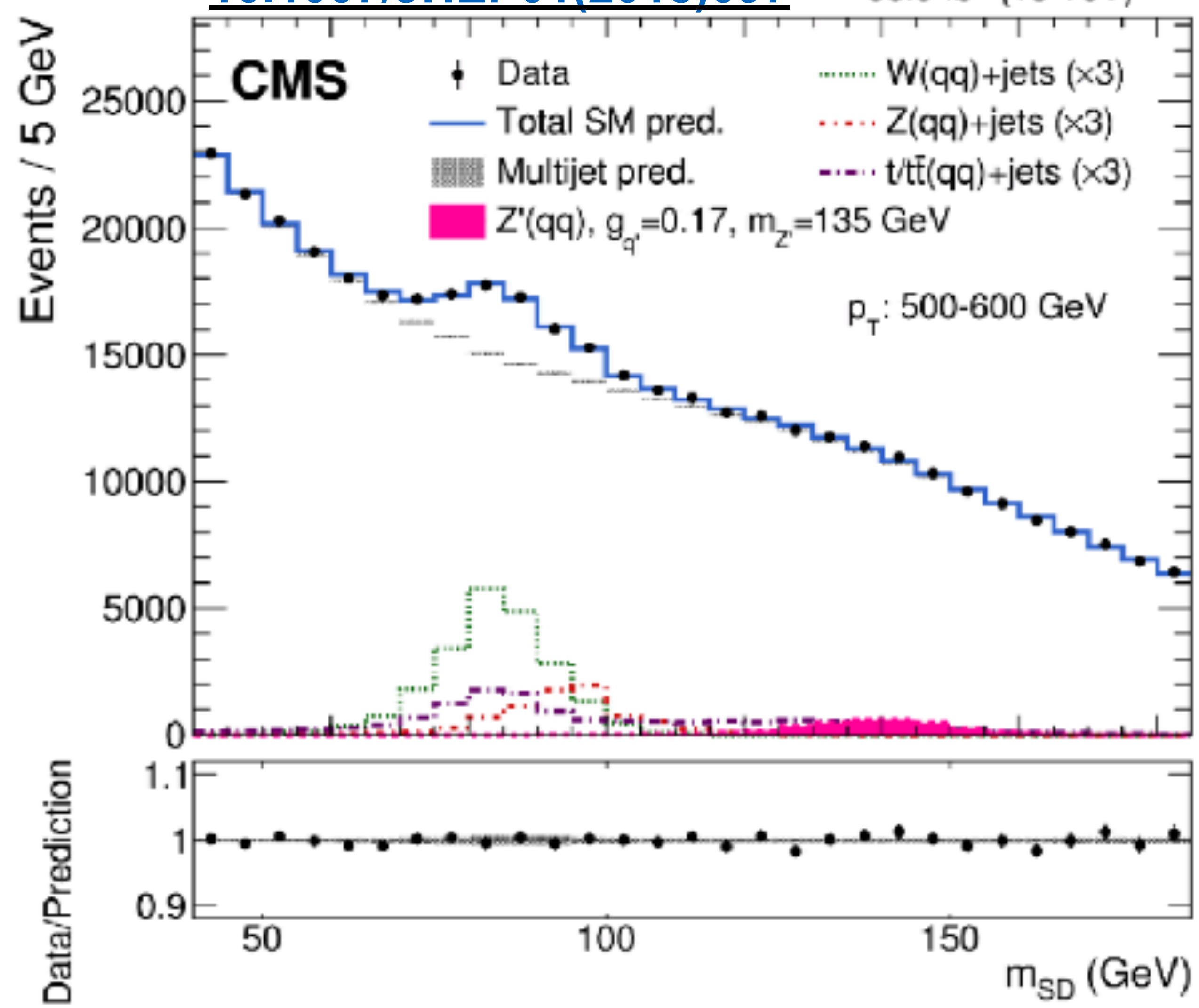
CMS EXO-16-056



Trigger events using ISR jet reconstruct dijet boosted topology

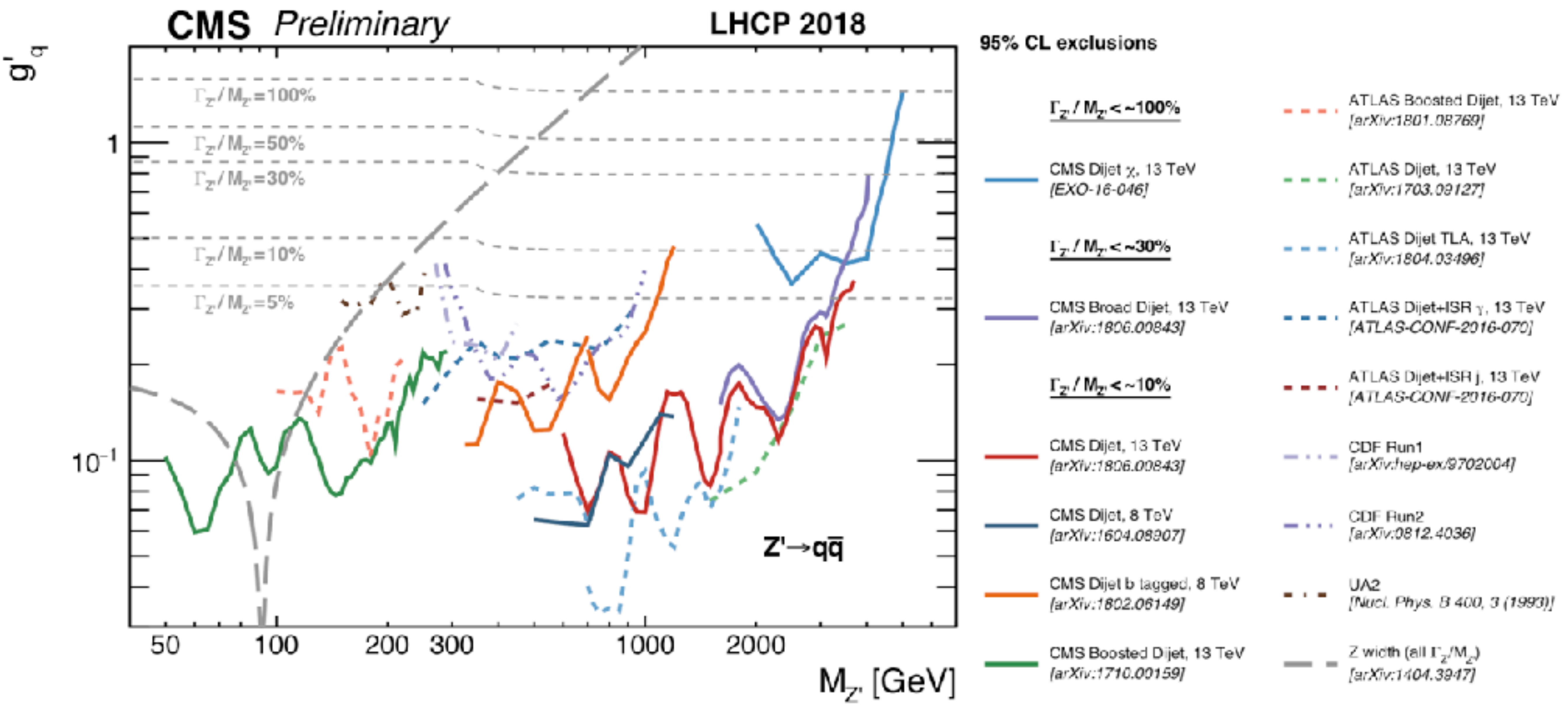


10.1007/JHEP01(2018)097



DIJET: COMBINED LIMITS

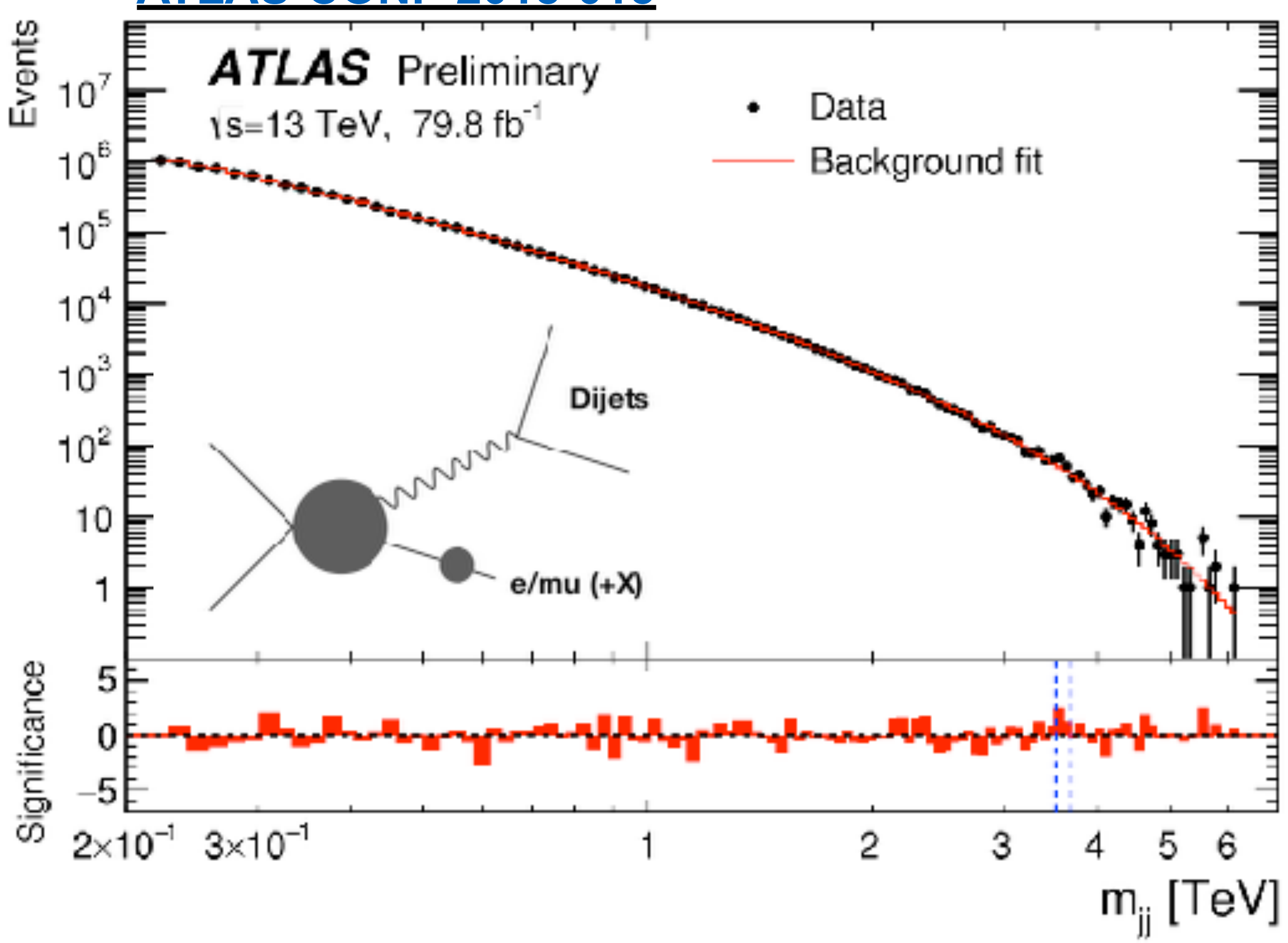
- **ATLAS and CMS limits on g_q ($\sigma \propto g_q^4$)**
  - covering the **whole range**. LHC now doing better than previous experiments everywhere



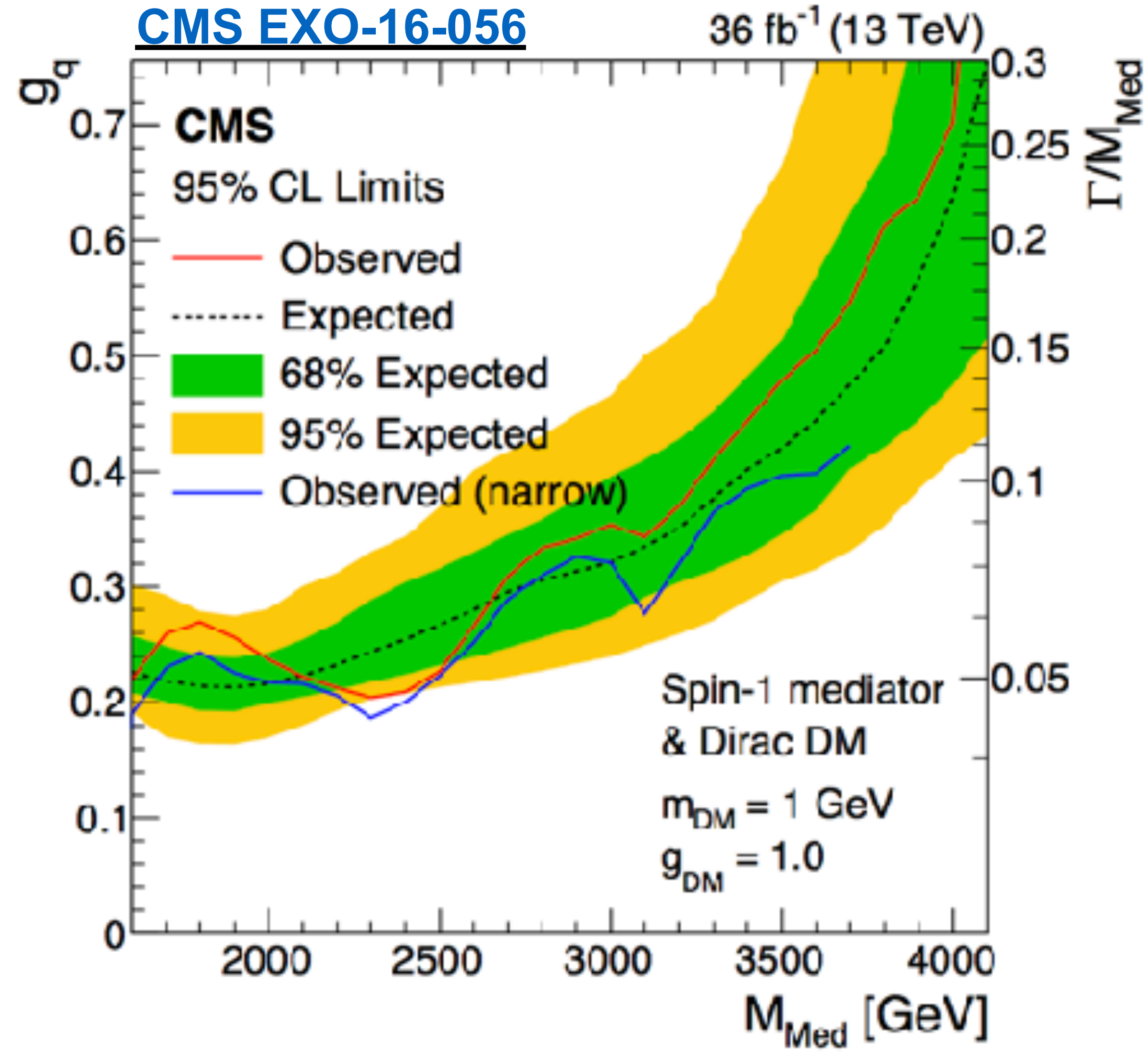
DIJET: BJETS, TAGS, WIDE RESONANCES

- **Extend dijet analysis**
  - **dijet in bb** (ATLAS: 1805.09299, CMS: EXO-17-024)
  - **extra event requirements** (high p_T lepton) to reduce E thresholds
  - **wide resonances,** important for dark matter reinterpretation

ATLAS-CONF-2018-015

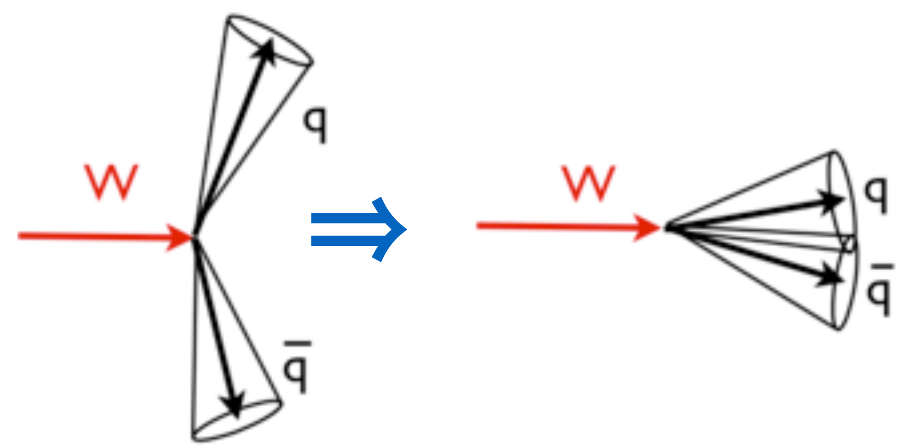


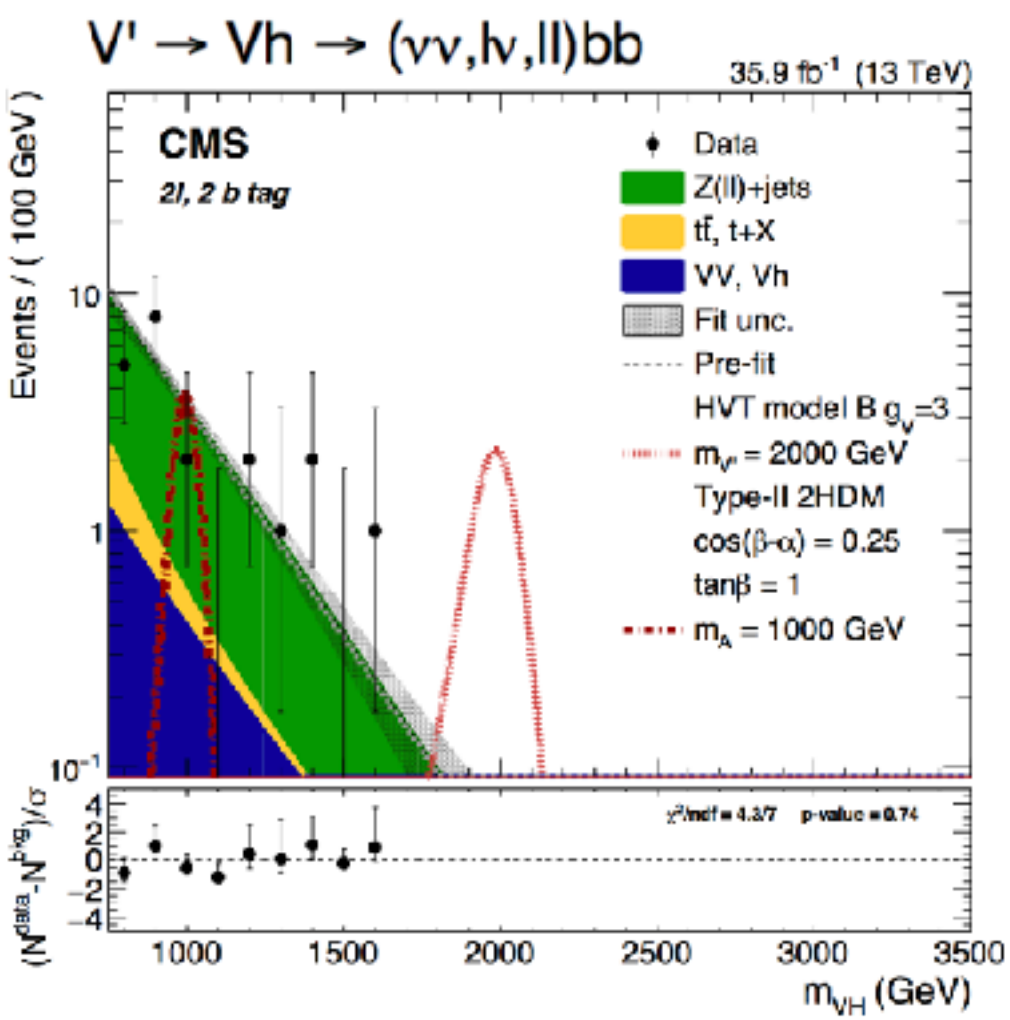
CMS EXO-16-056

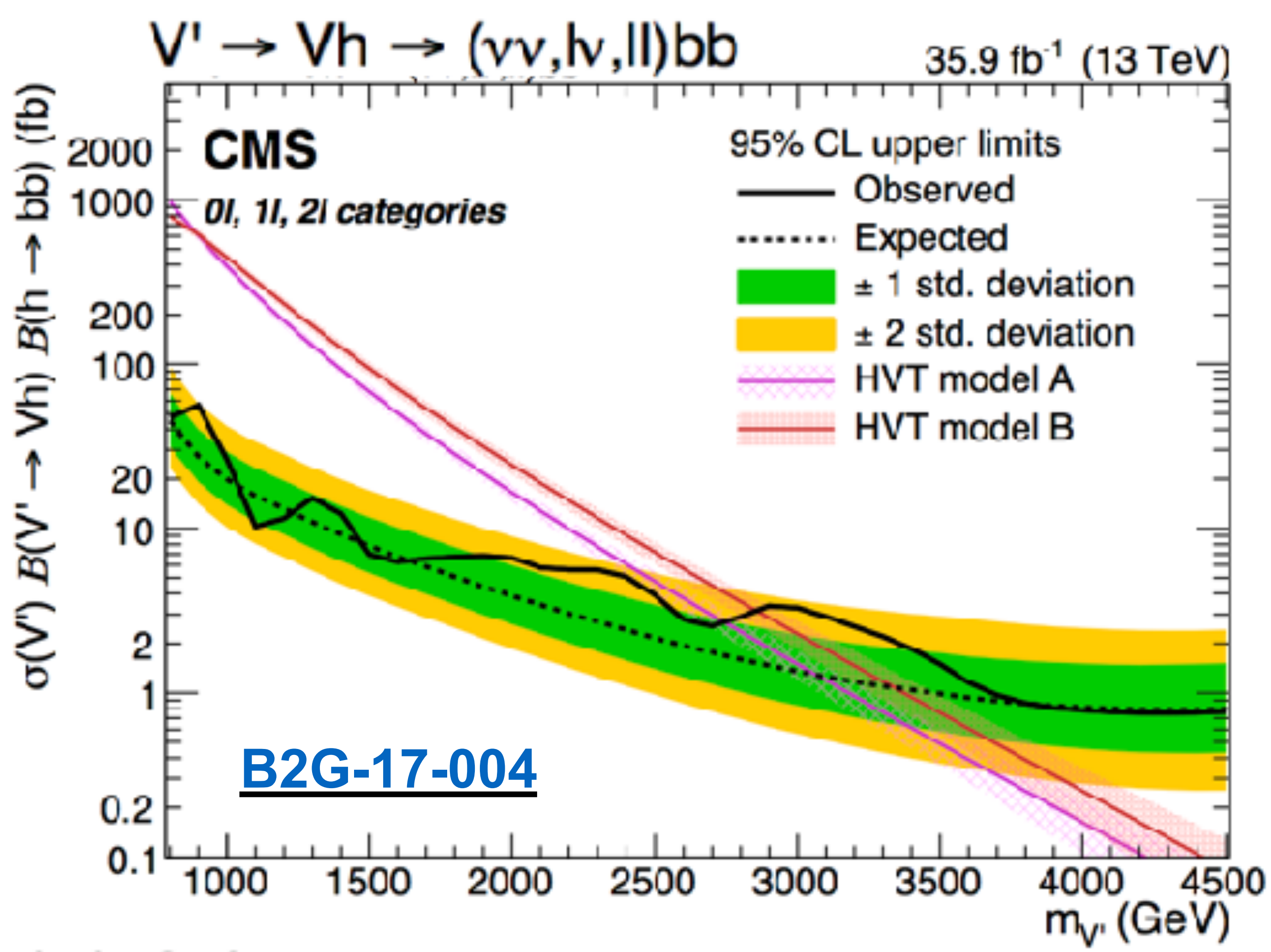


Exploiting Substructures

- Search for states decaying in **bosons and top quarks** in jets where states are **very boosted**
- At large boost **jets are merging**
- **Ad-hoc algorithms** to **reconstruct mass, reject QCD jets and subtract pileup**







EXPLOITING SUBSTRUCTURES

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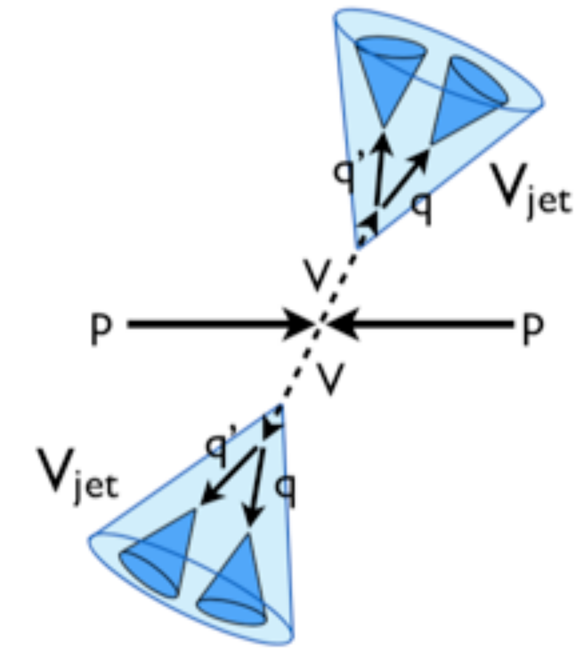
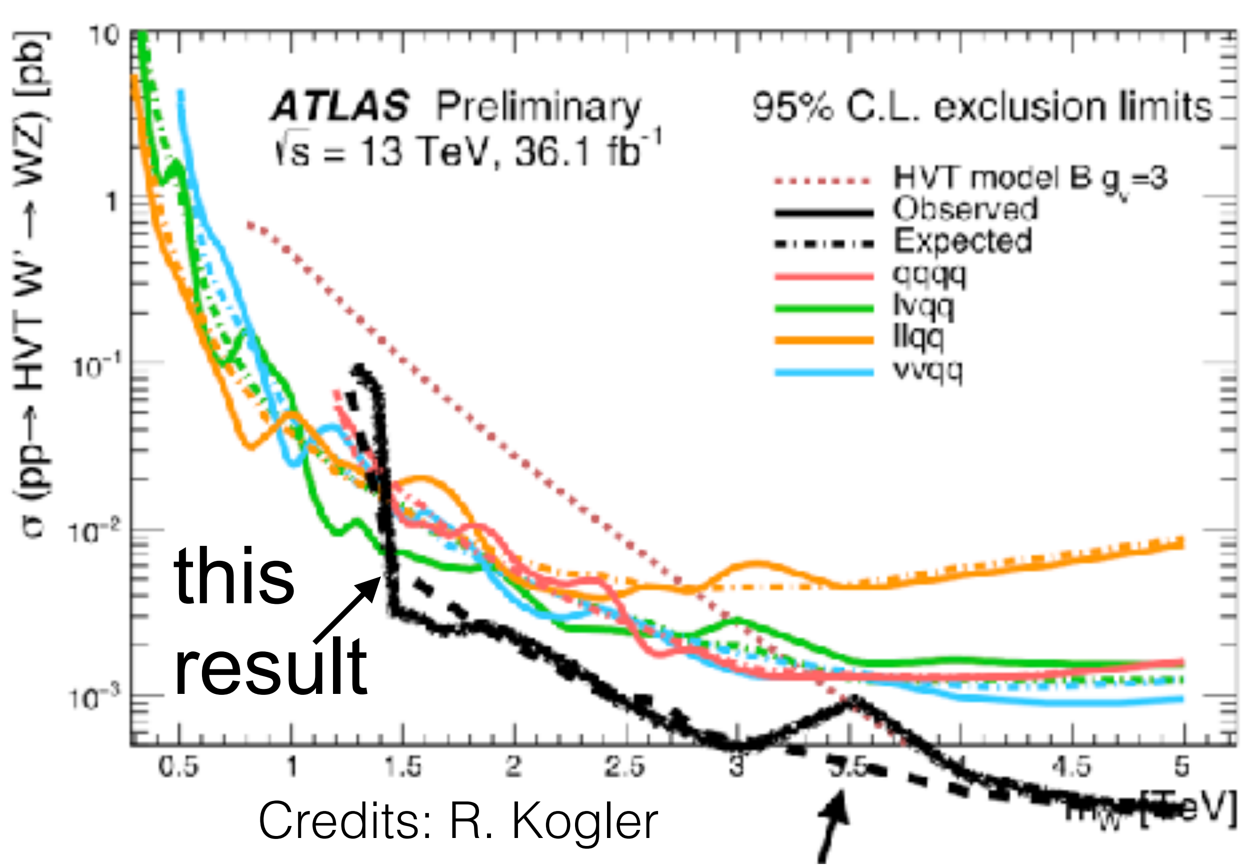
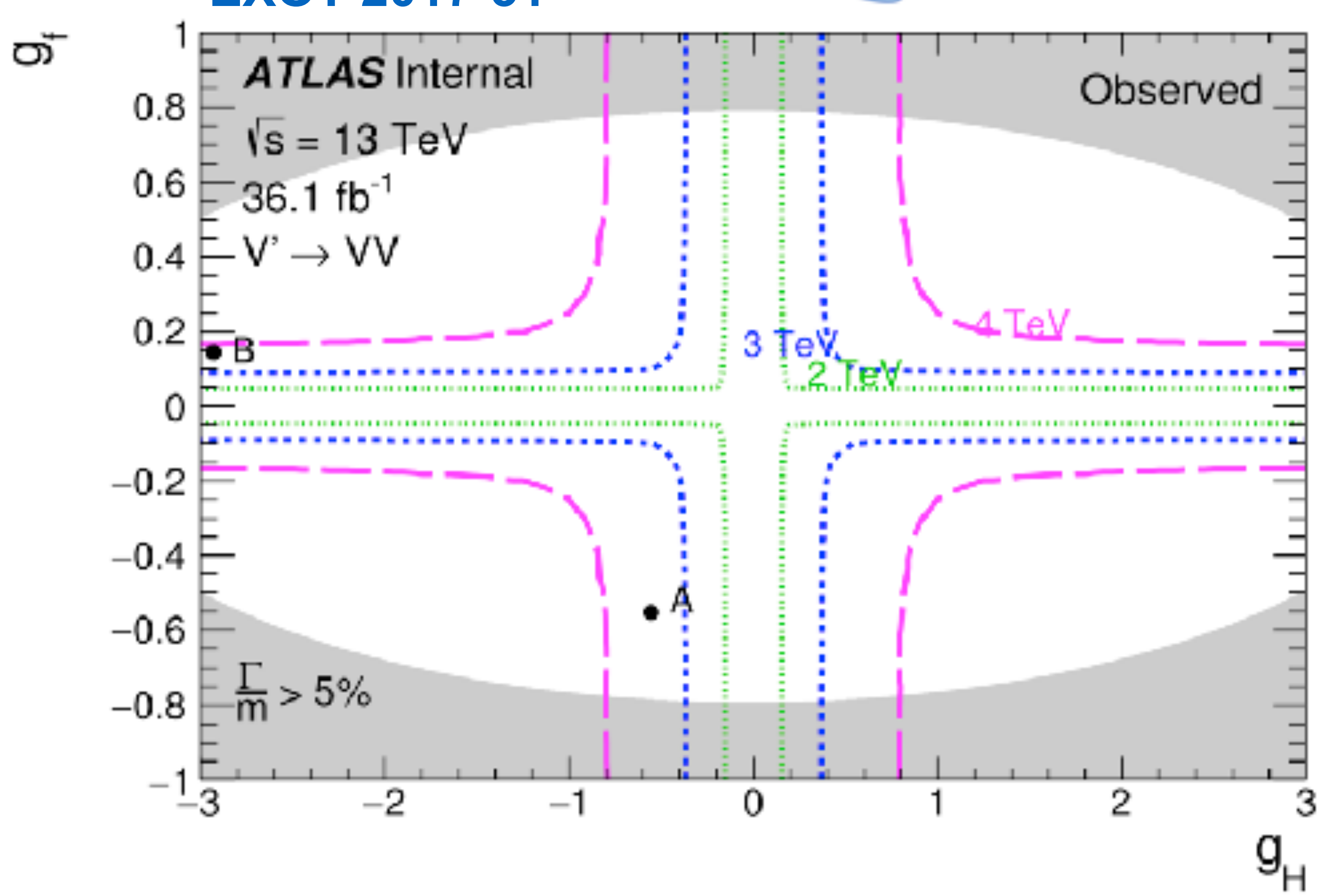


ATLAS-CONF-2018-016



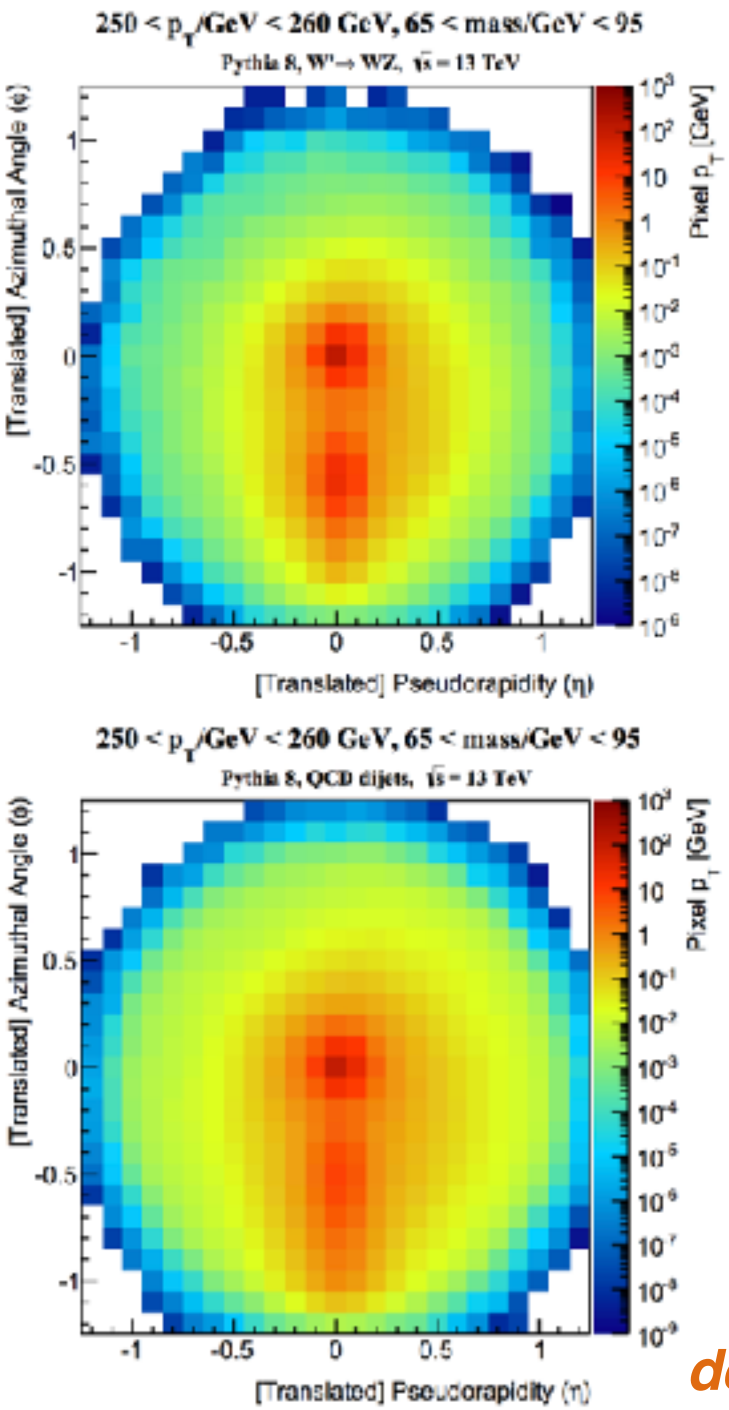
Credits: R. Kogler

EXOT-2017-31



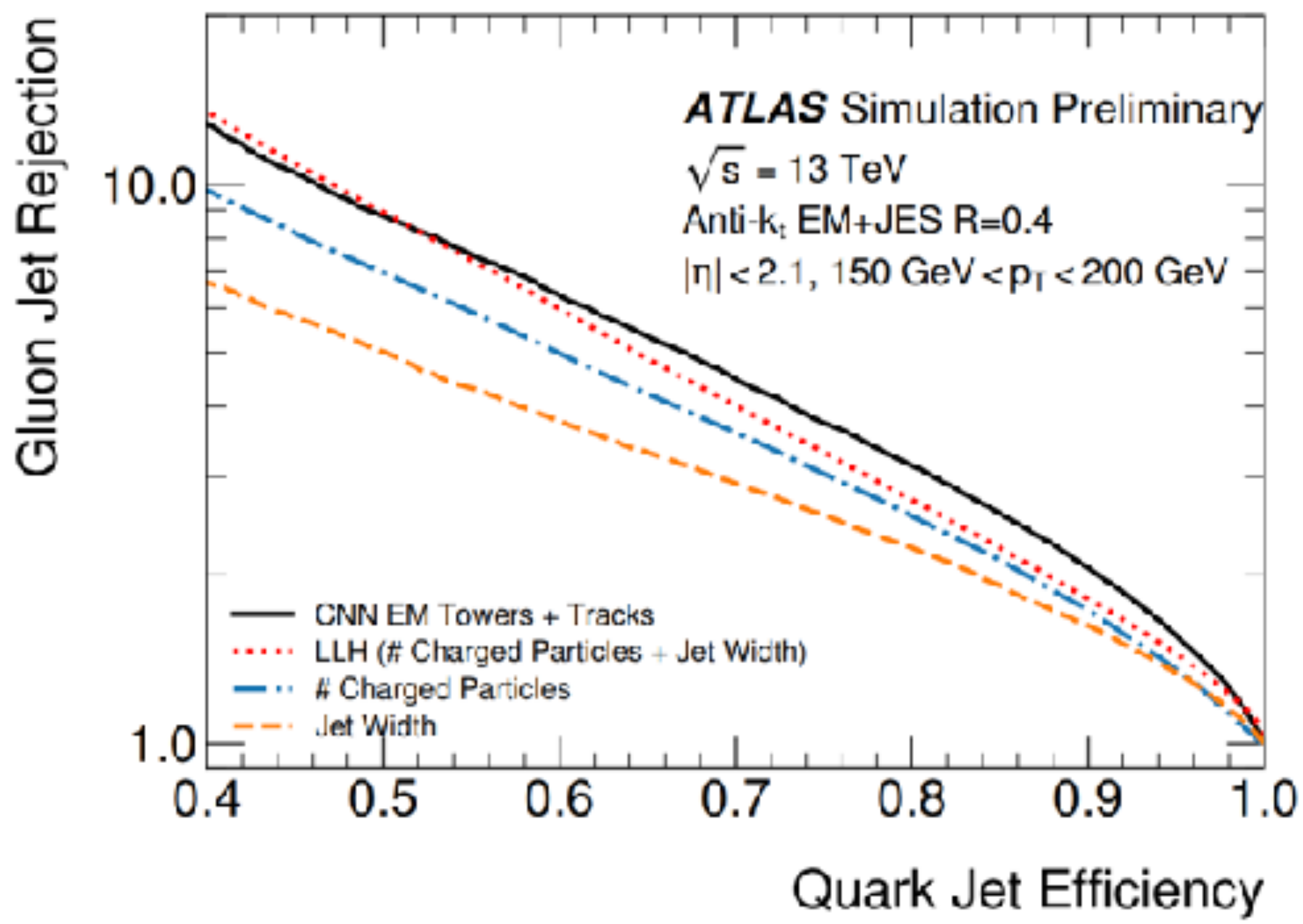
PERSPECTIVES AND IMAGES

- **Boosted jet variables** (substructures and flavor tagging) with **images, deep learning and more detailed algorithms**



[CMS-DP-2017-027]()

[ATLAS-PHYS-PUB-2017-017]()



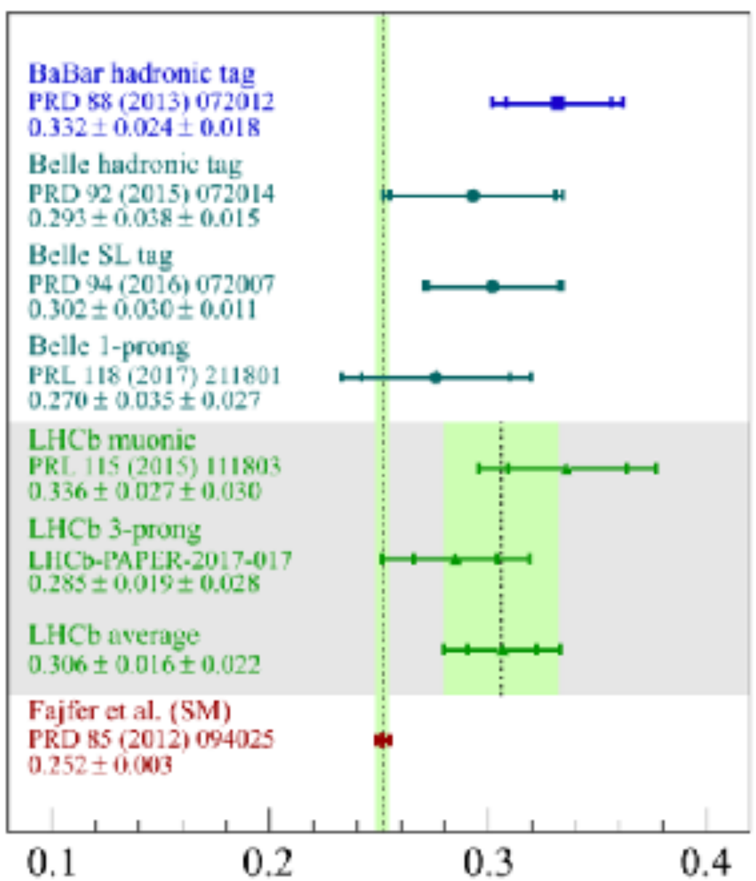
de Olivera, Kagan, Mackey, Nachman, Schwarzmann ‘15

NEW LEPTONS, NEW QUARKS

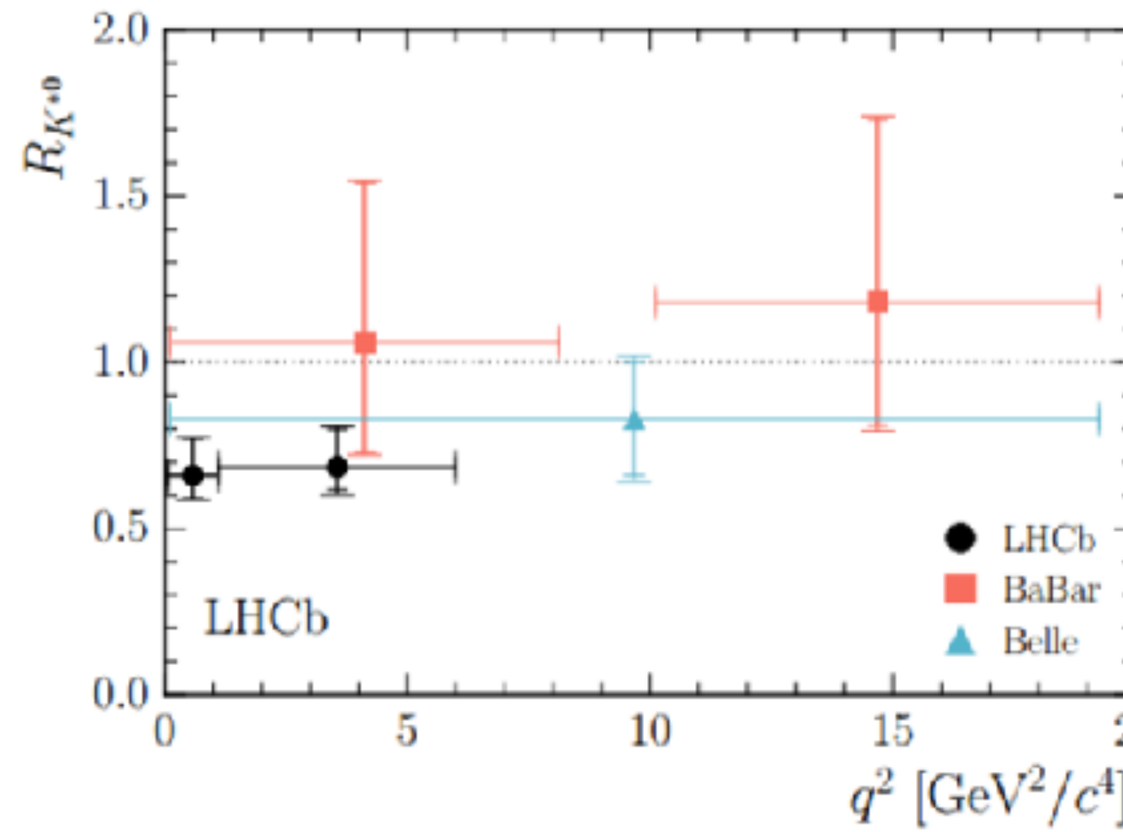
LEPTOQUARKS AND ANOMALIES

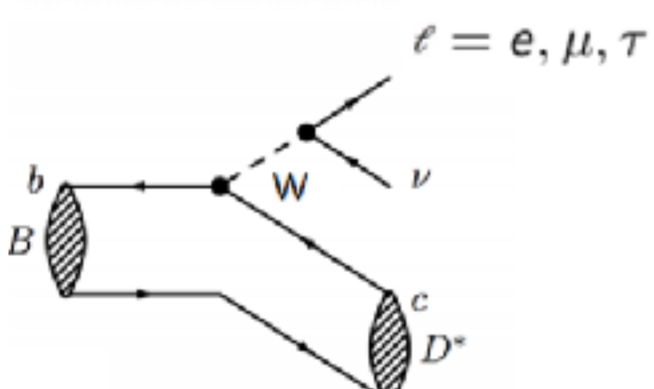
Anomalies in B decays explained with leptoquark contributions

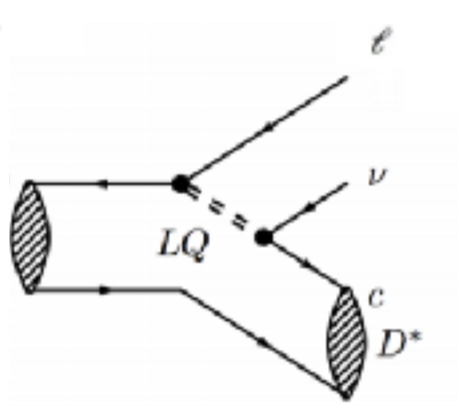
$$R_{D^{(*)}}^{\tau/\ell} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}$$

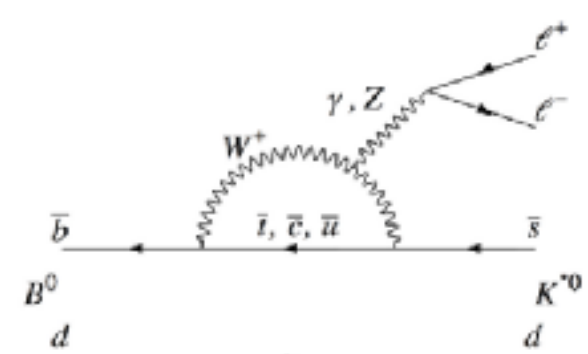


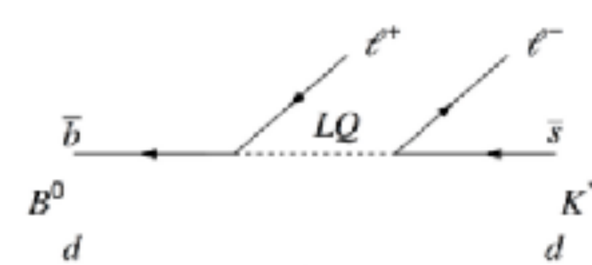
$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$





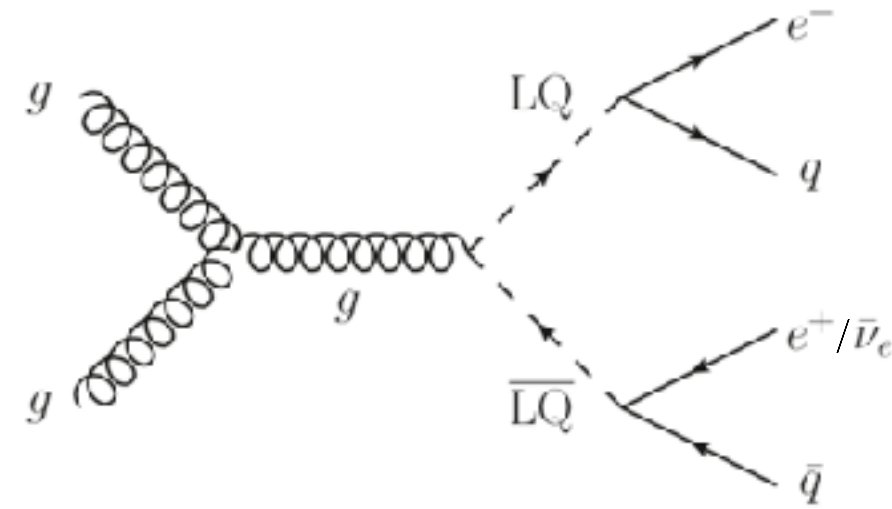


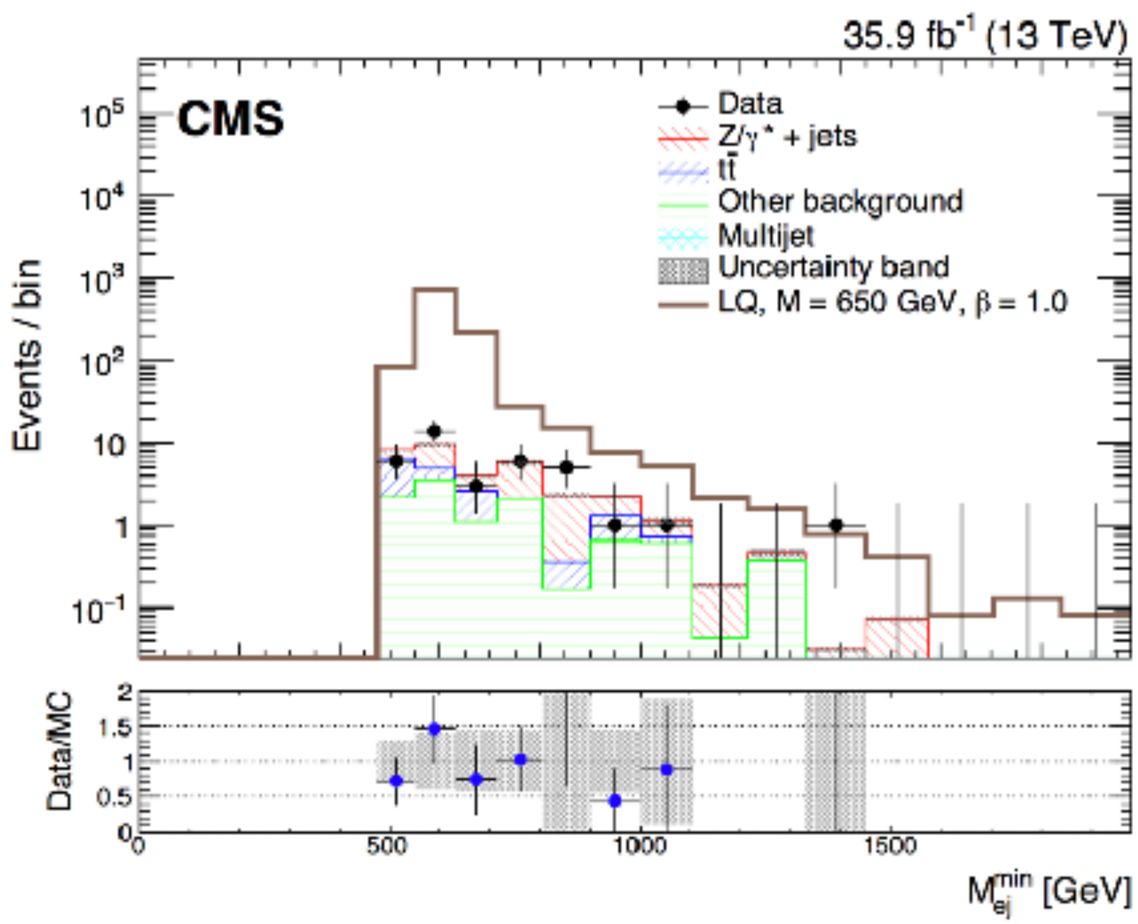




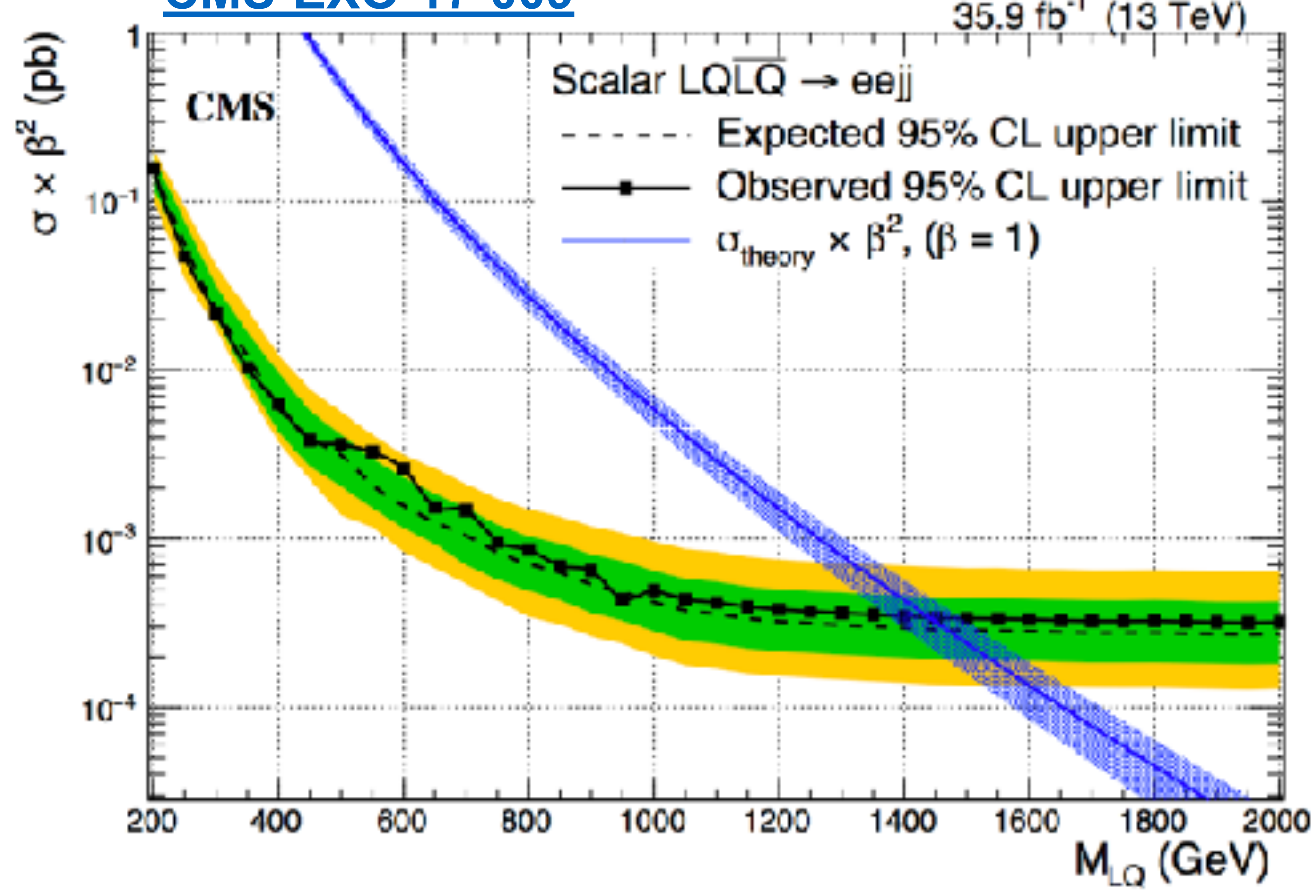
RECENT LQ RESULTS: LQ1 PAIRS

- Leptoquarks **produced in pairs**
- **2e - 2jets, ev - 2jets** final states
- Selection based on **visibile momentum, minimum m(e-jet) and m(ee)/m(ev), MET**
- mass **limits @ ~ 1.2 - 1.45 TeV**



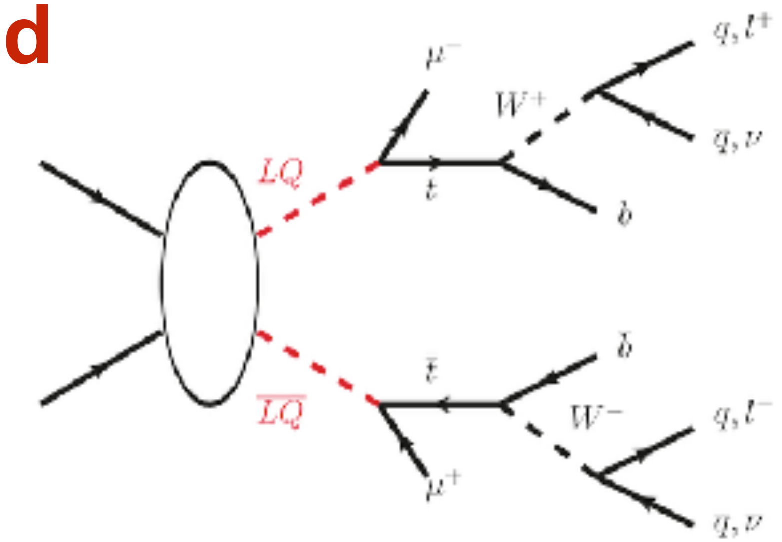


[CMS-EXO-17-009]

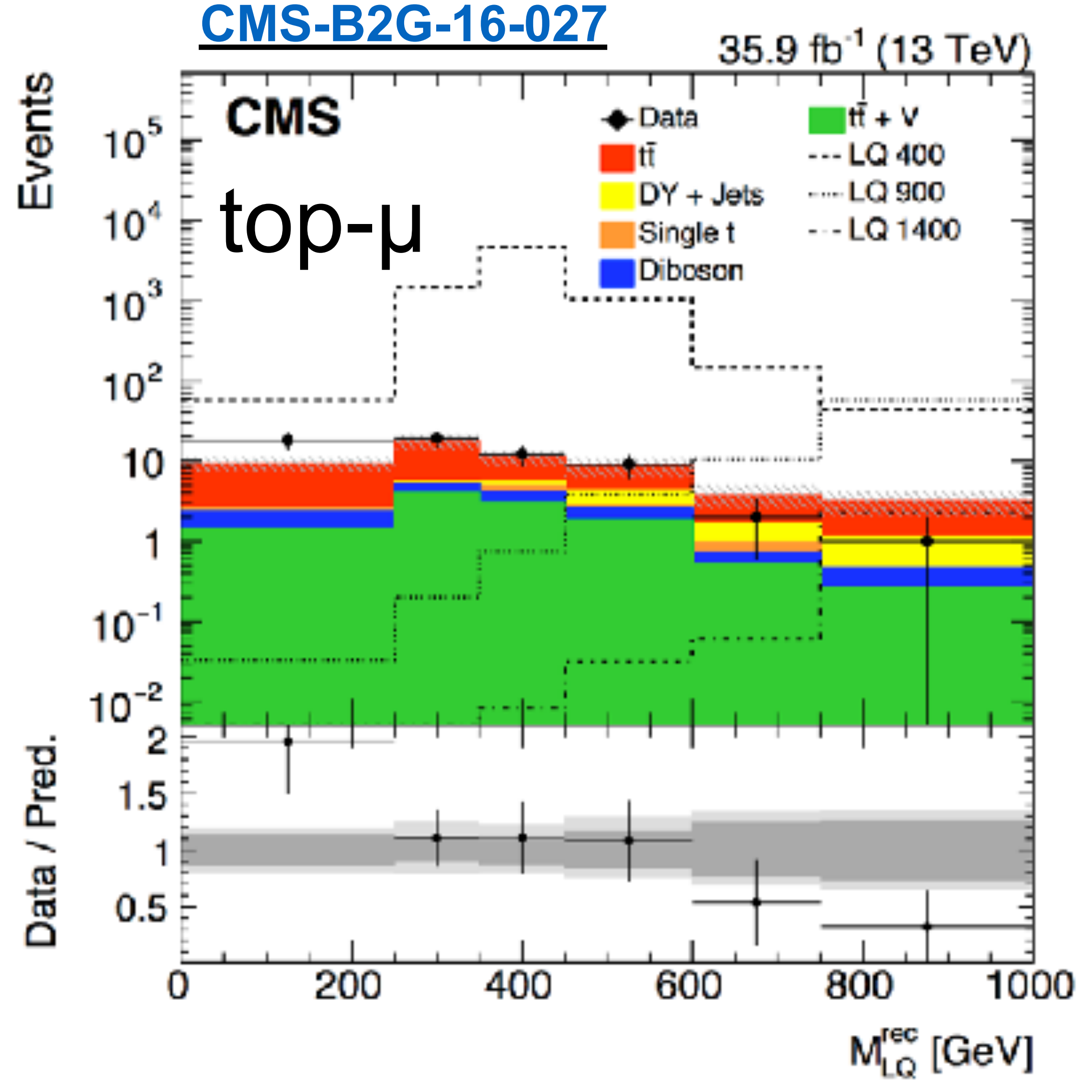


Recent LQ Results: LQ3 Pairs

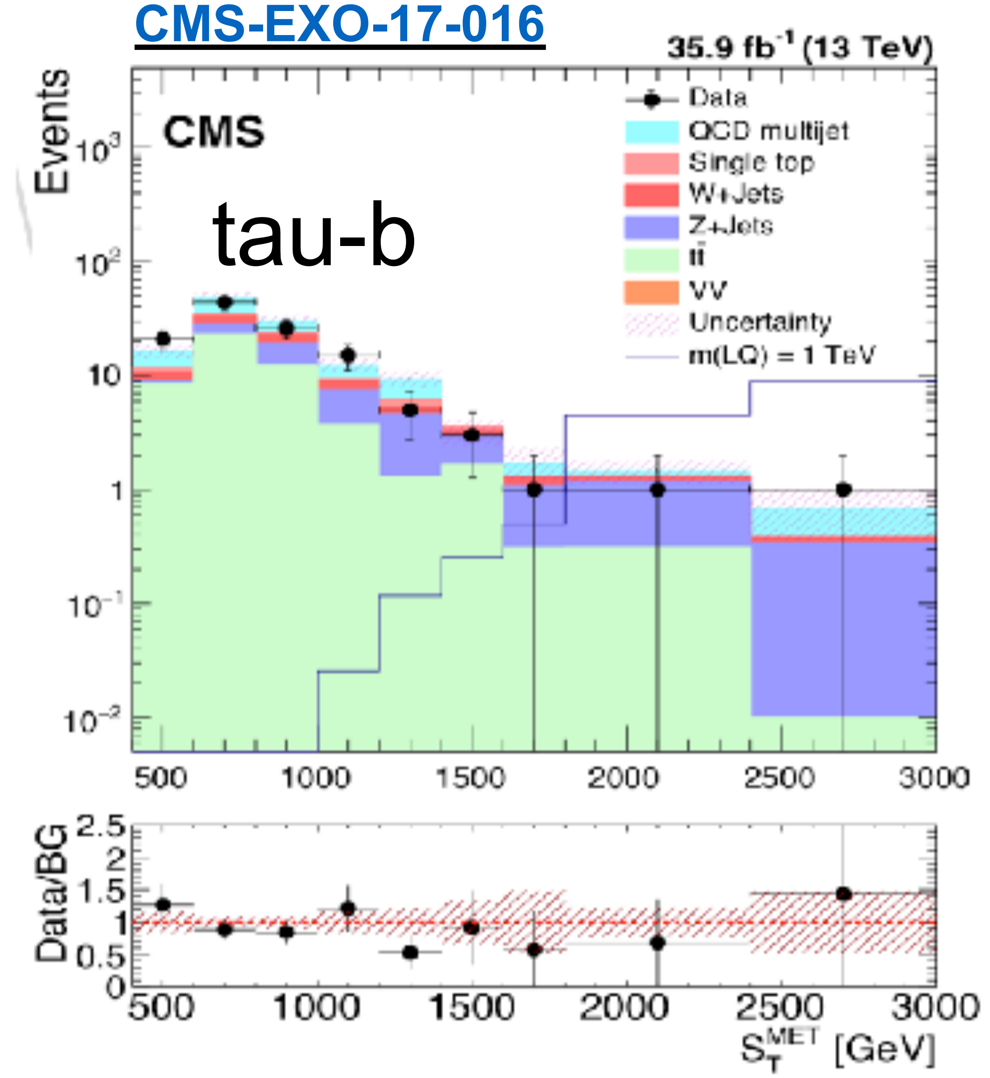
- Leptoquarks **decaying to top-μ and tau-b and produced in pairs**
- mass **limits**
  - top-μ: **1.45 TeV**
  - tau-b: **1.02 TeV**



CMS-B2G-16-027

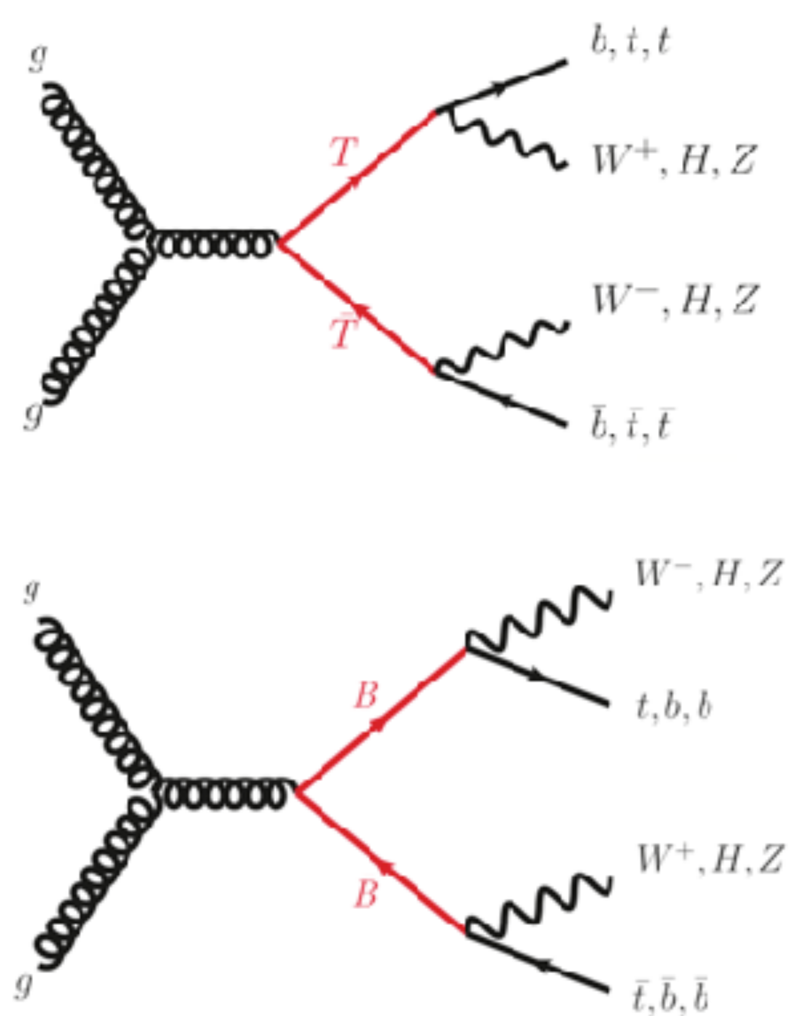


CMS-EXO-17-016

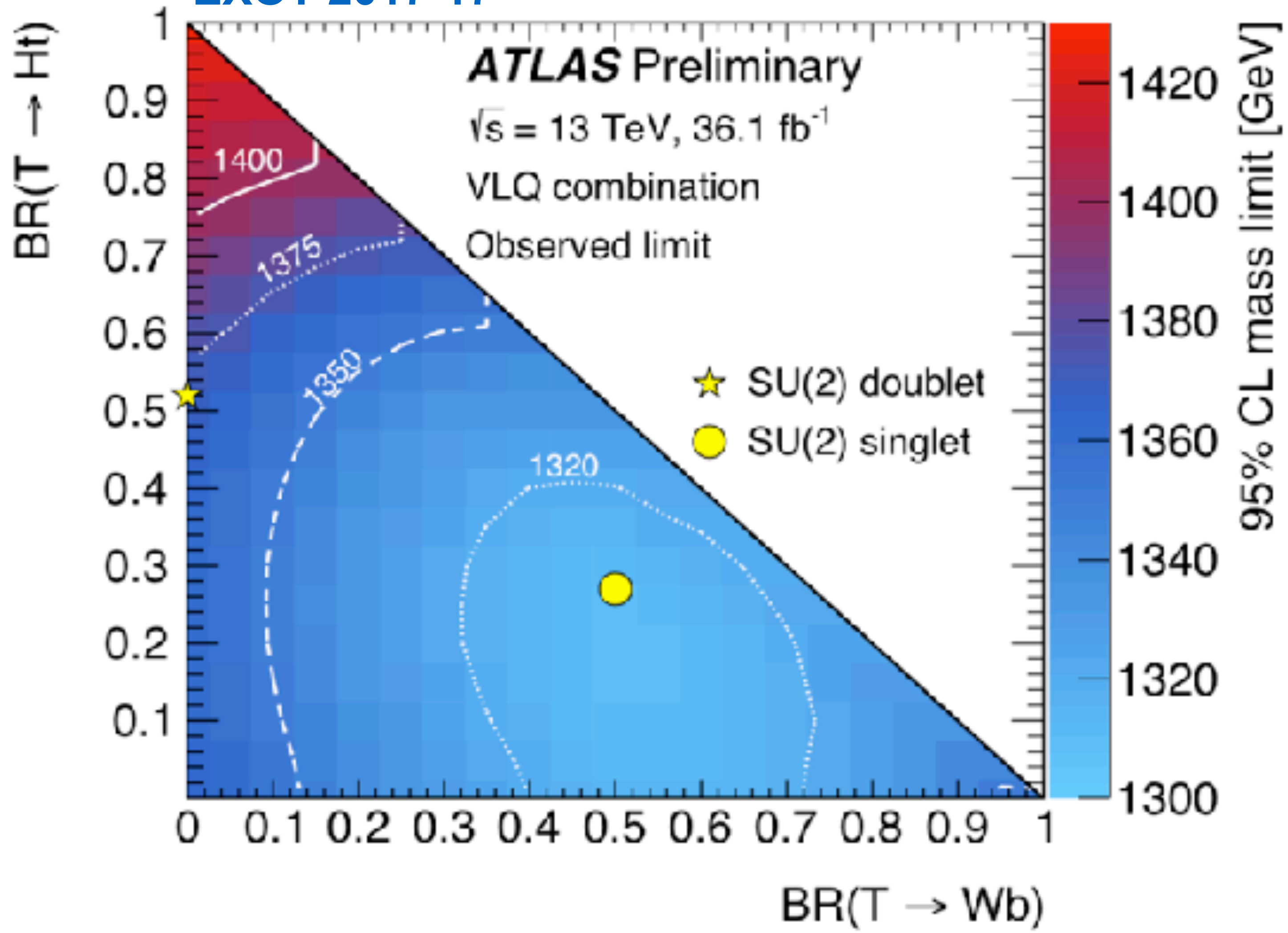


VECTOR-LIKE QUARKS

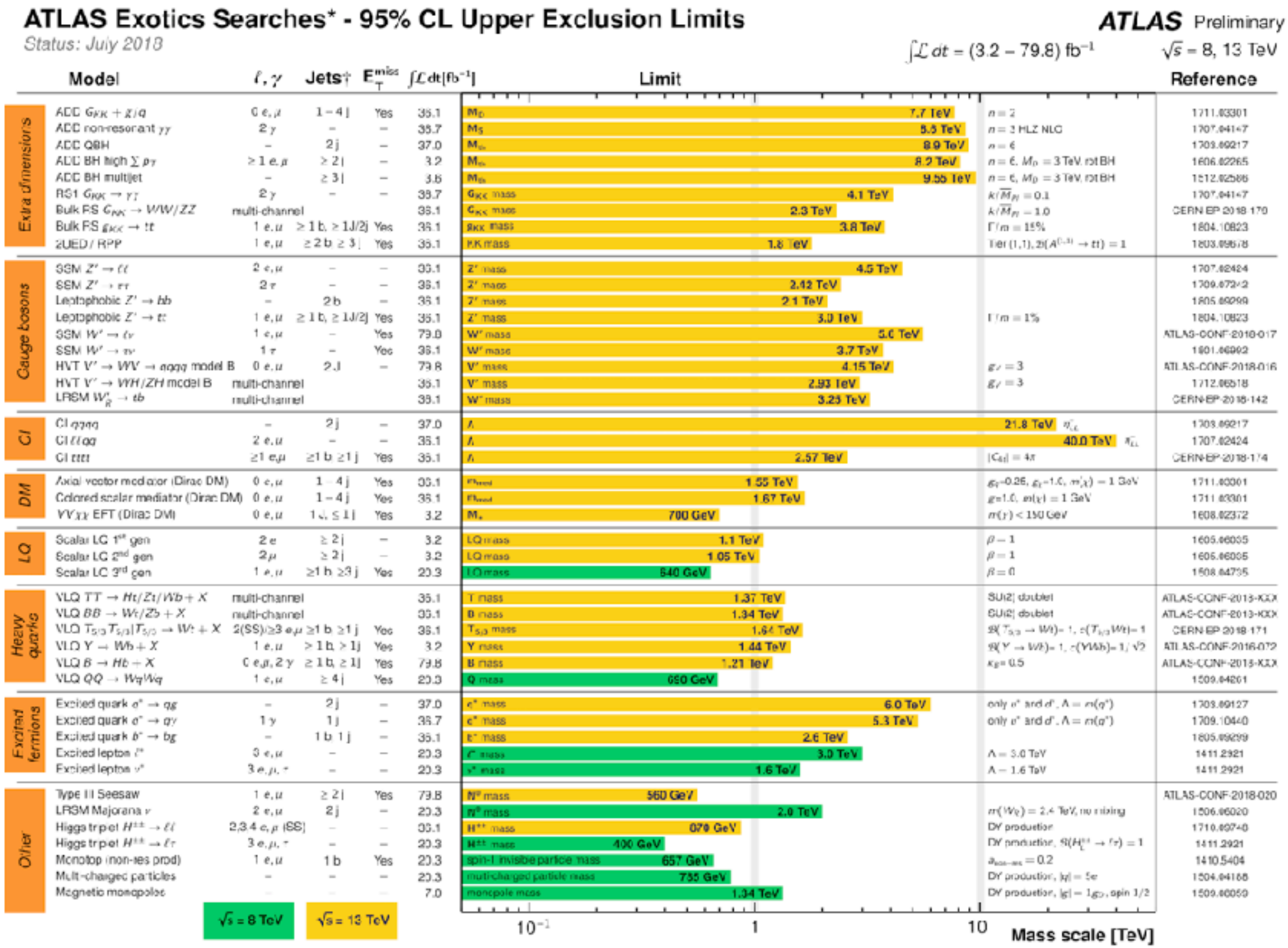
- Search of **T (q=2/3) and B (q=-1/3)** VLQ with, decaying to **W,H,Z and t,b** produced in **pairs**
- Recent **combination of several final states**
- **Limits at the level of 1.3-1.4 TeV**



EXOT-2017-17



Mass Reach



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

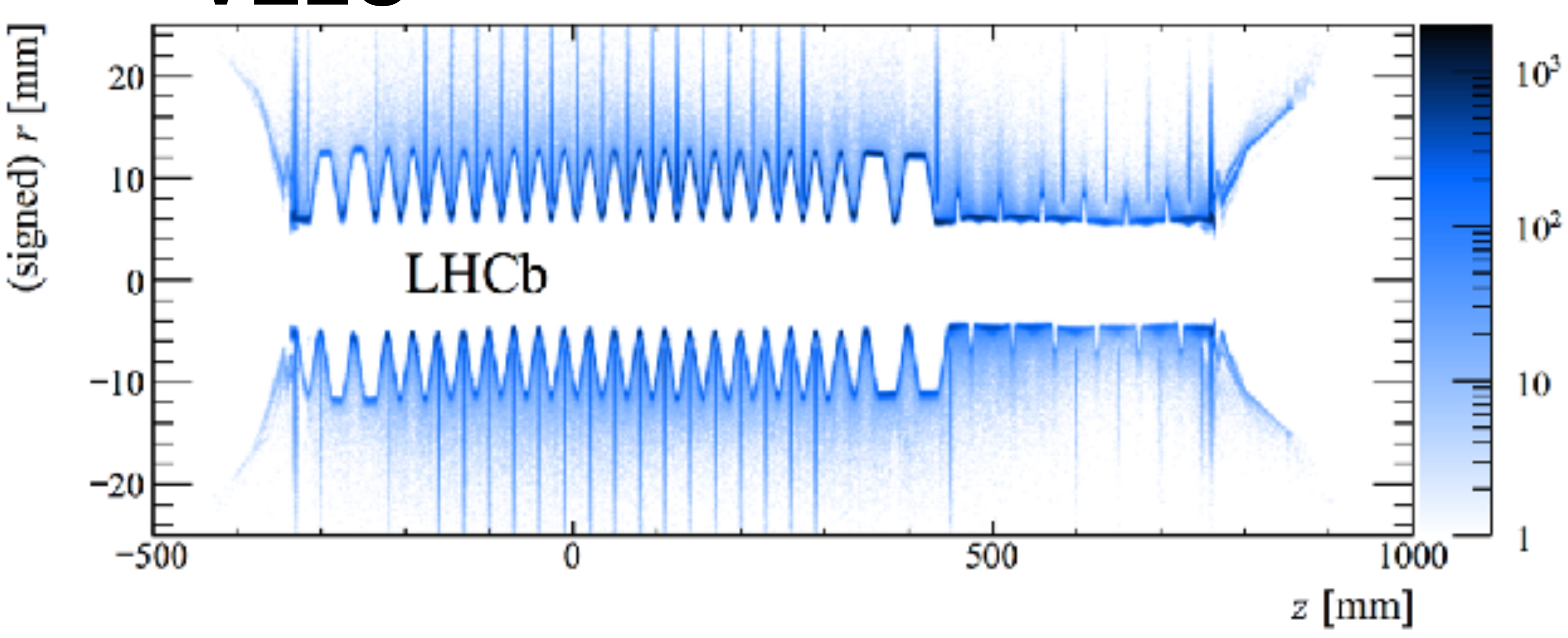
LONG-LIVED SIGNATURES

UNDERSTANDING DETECTORS

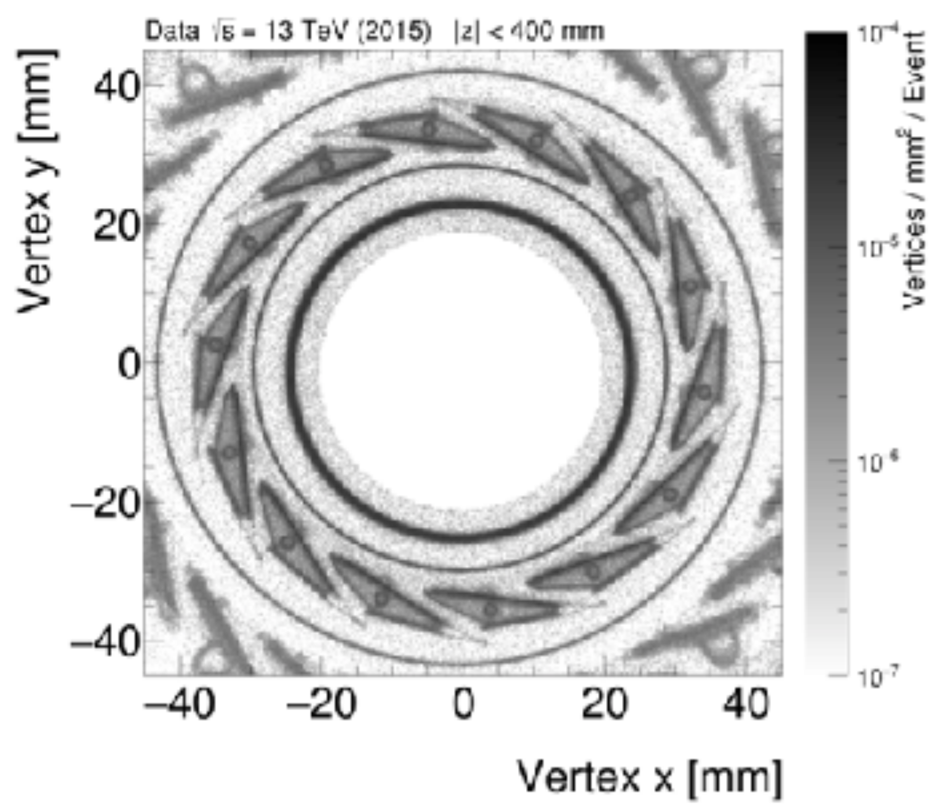
when the going gets tough, the tough get going

- **Detector-based exotic signatures require:**
  - dE/dx, TOF, displaced vertex, disappearing tracks, stopped particles
- **Specific control samples to model exotic signature in detector:**
  - LL signatures like detector noise. Deep knowledge of detector.

VELO

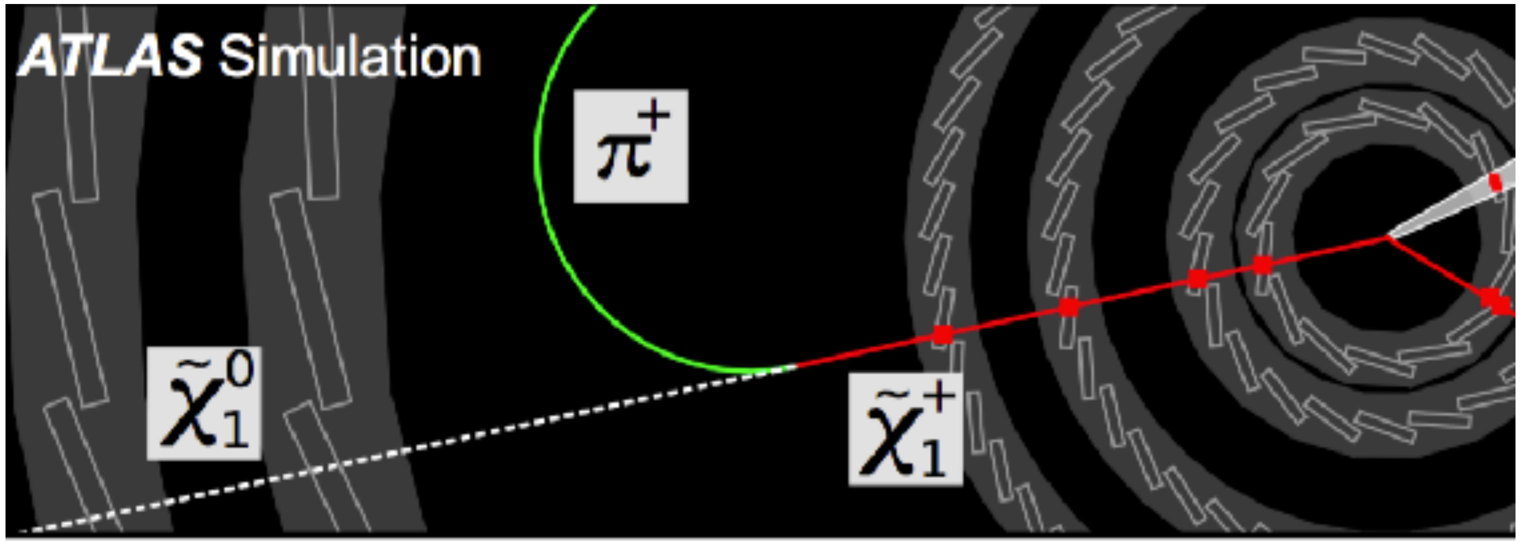


inner detector

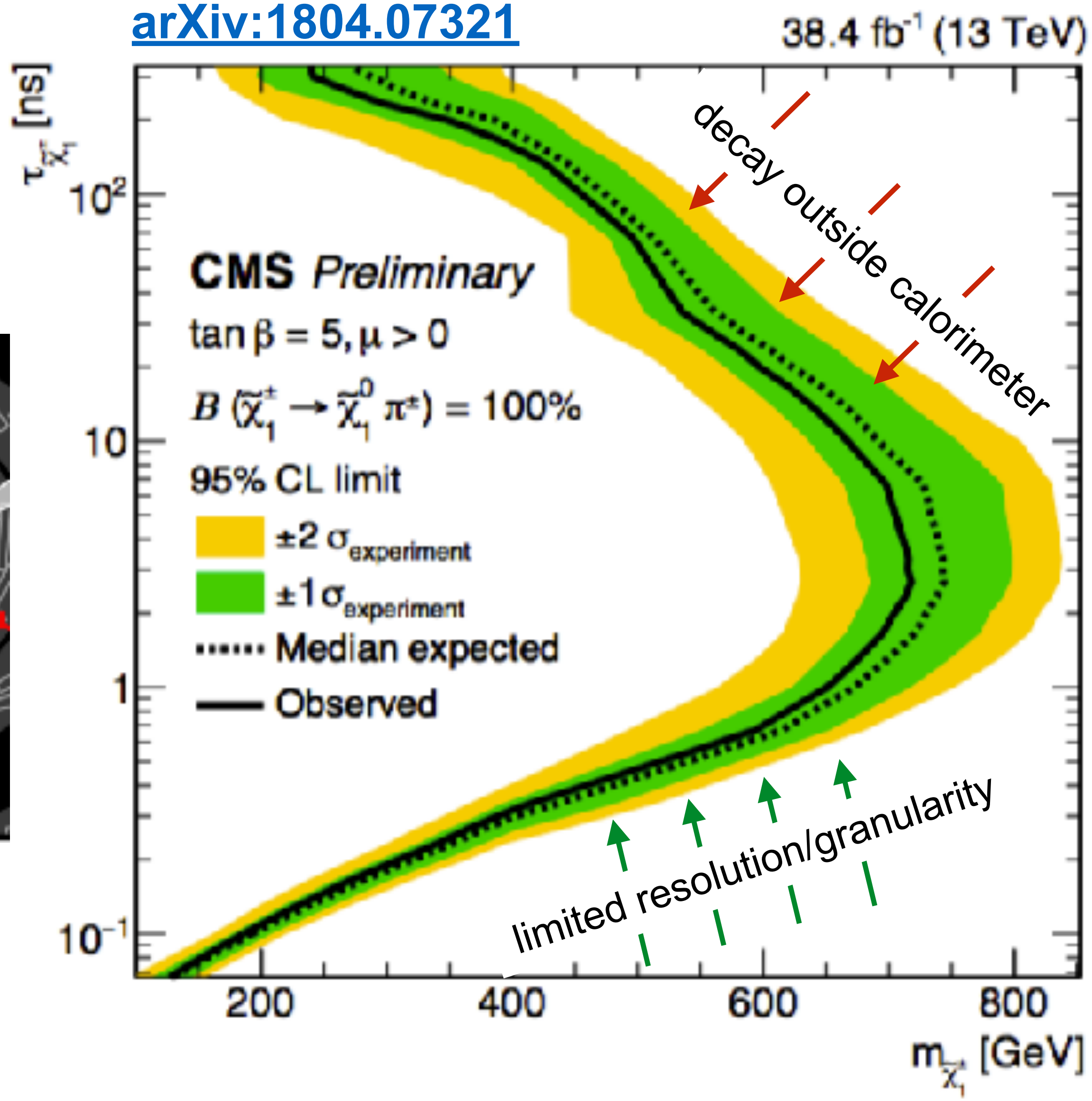


DISAPPEARING STUFF

- **Isolated track with**
  - **missing hits in the outer layers** of the tracker
  - **little energy in associated calorimeter deposits**
  - **no** associated hits **in muon detectors**.
- **Require Missing ET**
  - typical of SUSY events



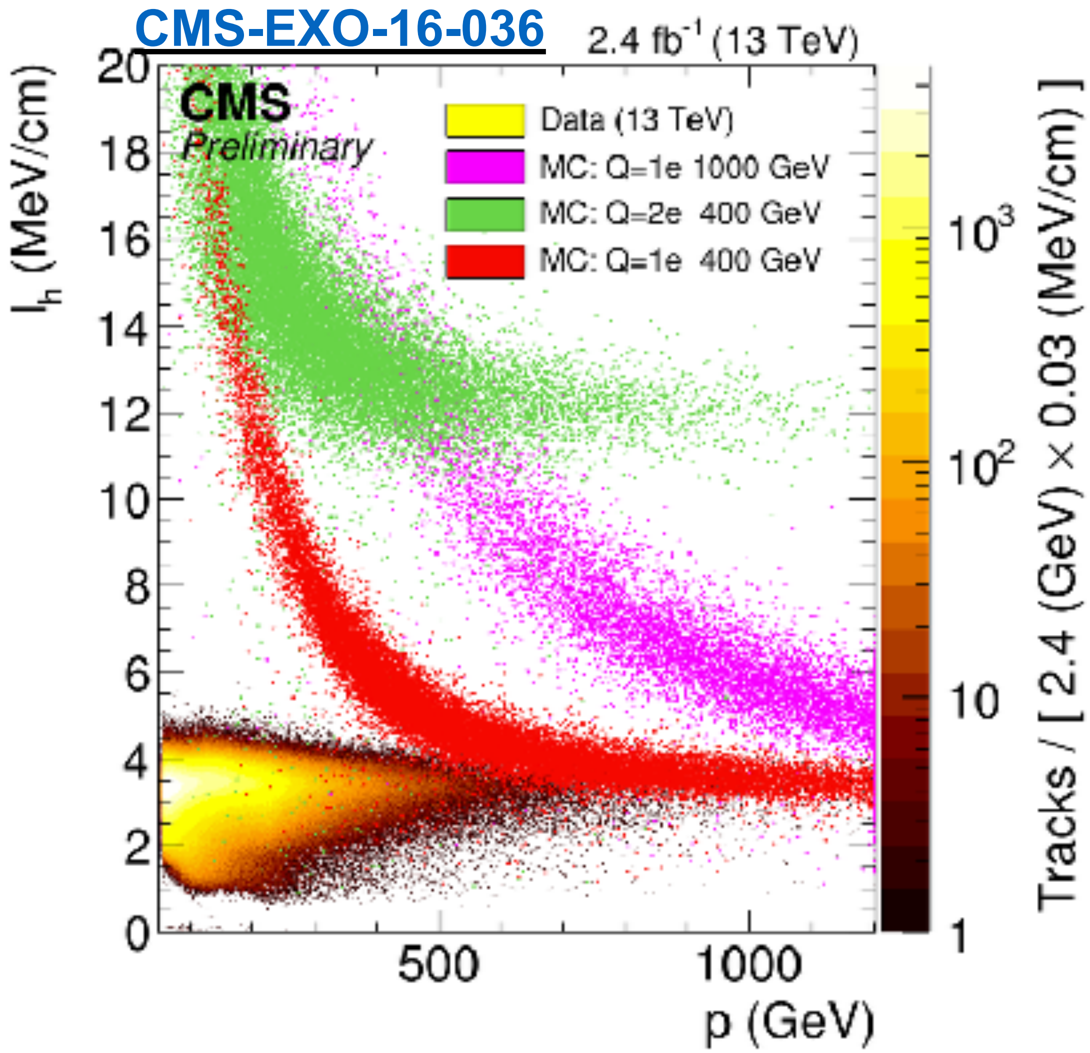
arXiv:1804.07321

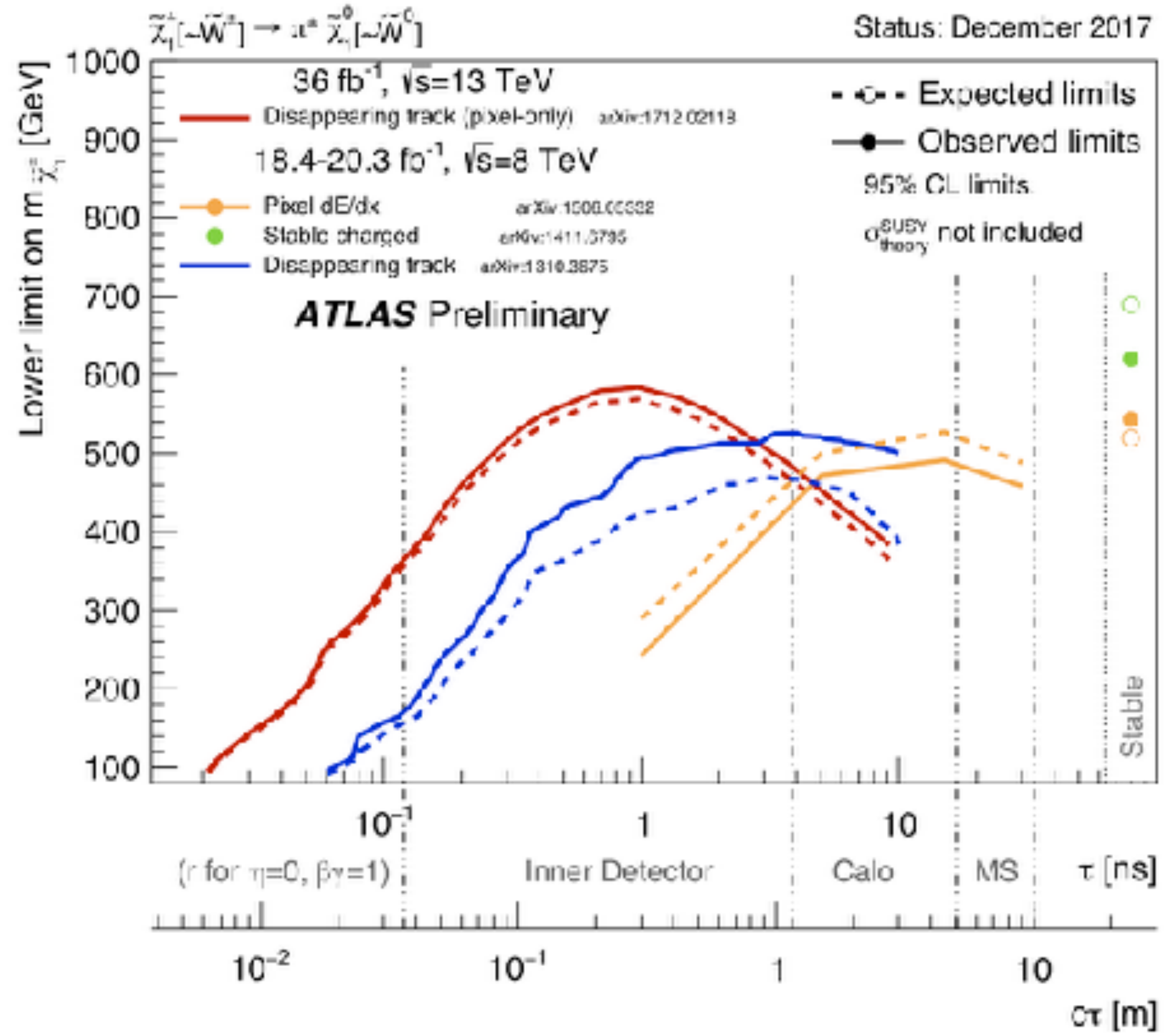


STABLE STUFF

- **Heavy Stable Charged Particles, e.g. slepton (slow moving muon-like particle)**
  - **dE/dx**: large ionization left in tracker detectors by high mass R-hadrons or sleptons (enhanced if charge ≠ 1)
  - **slow moving** high mass stable charged particles identified using **timing measured in muon system**

CMS-EXO-16-036

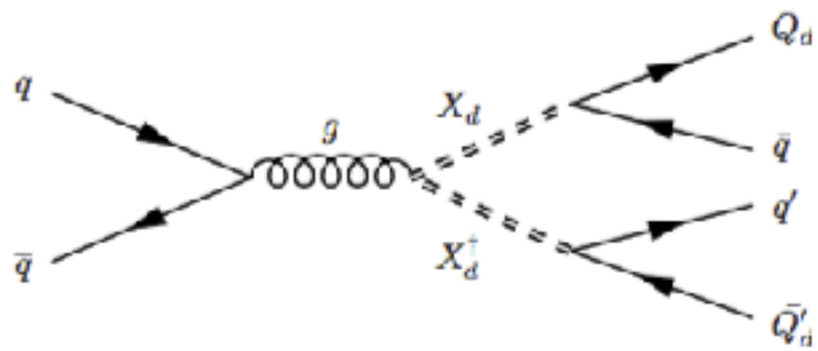




EMERGING STUFF

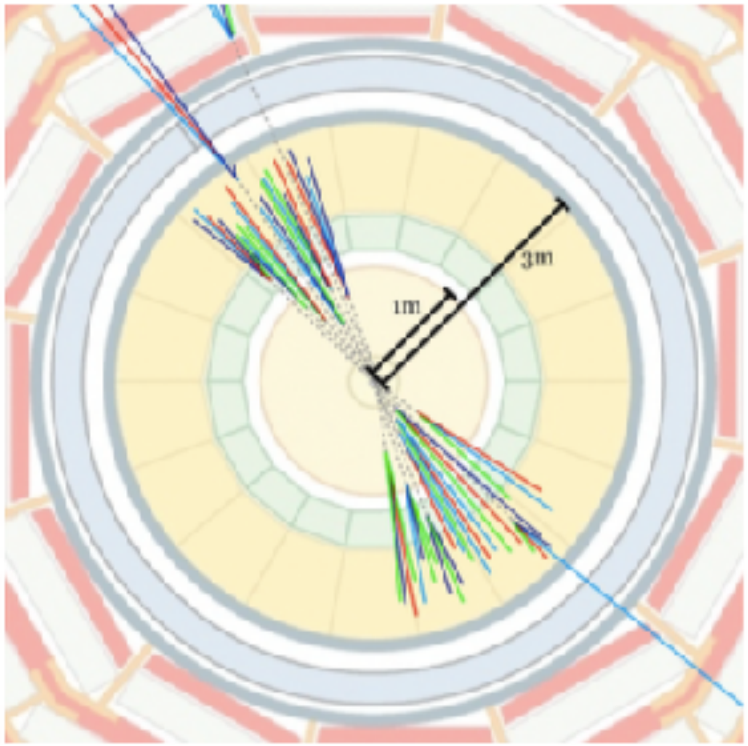
Dark QCD (dark matter candidate)

- **O(TeV) heavy mediators** in **dark pion (mass ~GeV)**, lifetime 1 to 1000 mm

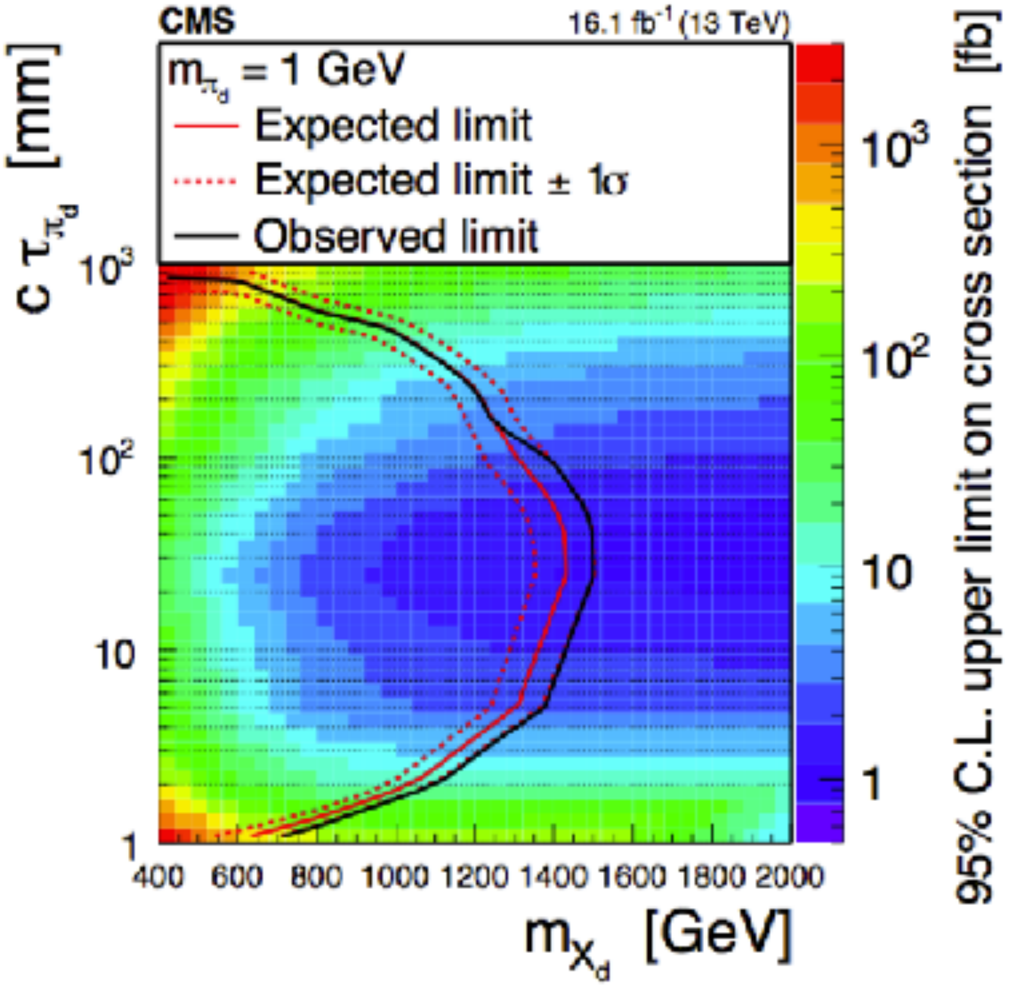


- **Signature**: 2 SM jets and 2 emerging jet
  - emerging jet selected by exploiting the displacement of tracks in jet

JHEP05(2015)059
arXiv:1502.05409

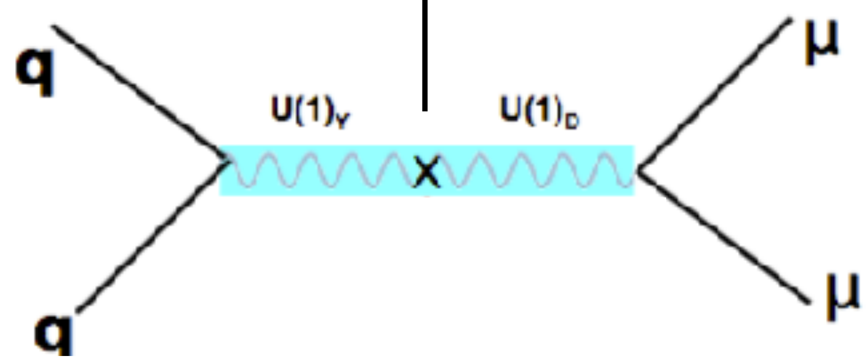


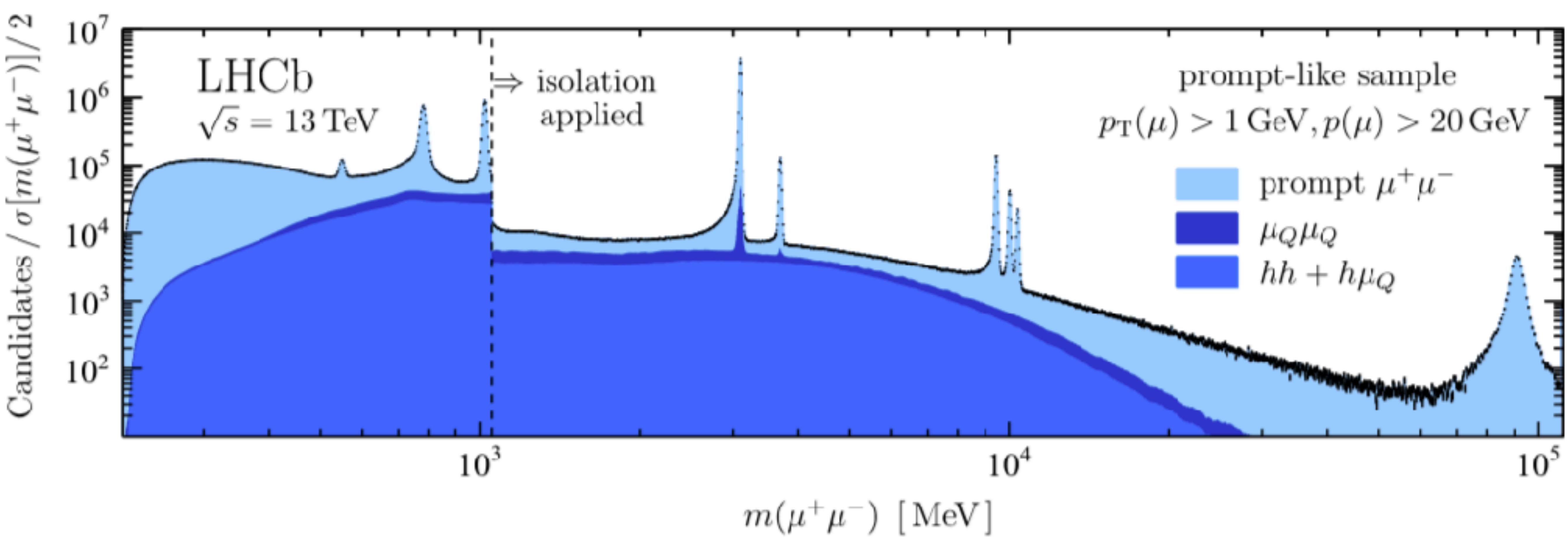
CMS-EXO-18-001



DARK PHOTON (LHCB)

- **Dark matter** may interact **via a new dark force**
- **Dark photon couples to SM via kinetic mixing:** $\frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu}$
- Depending on ε **A' prompt or long-lived**
- **Search for dimuon resonance:**
  - prompt or displaced events

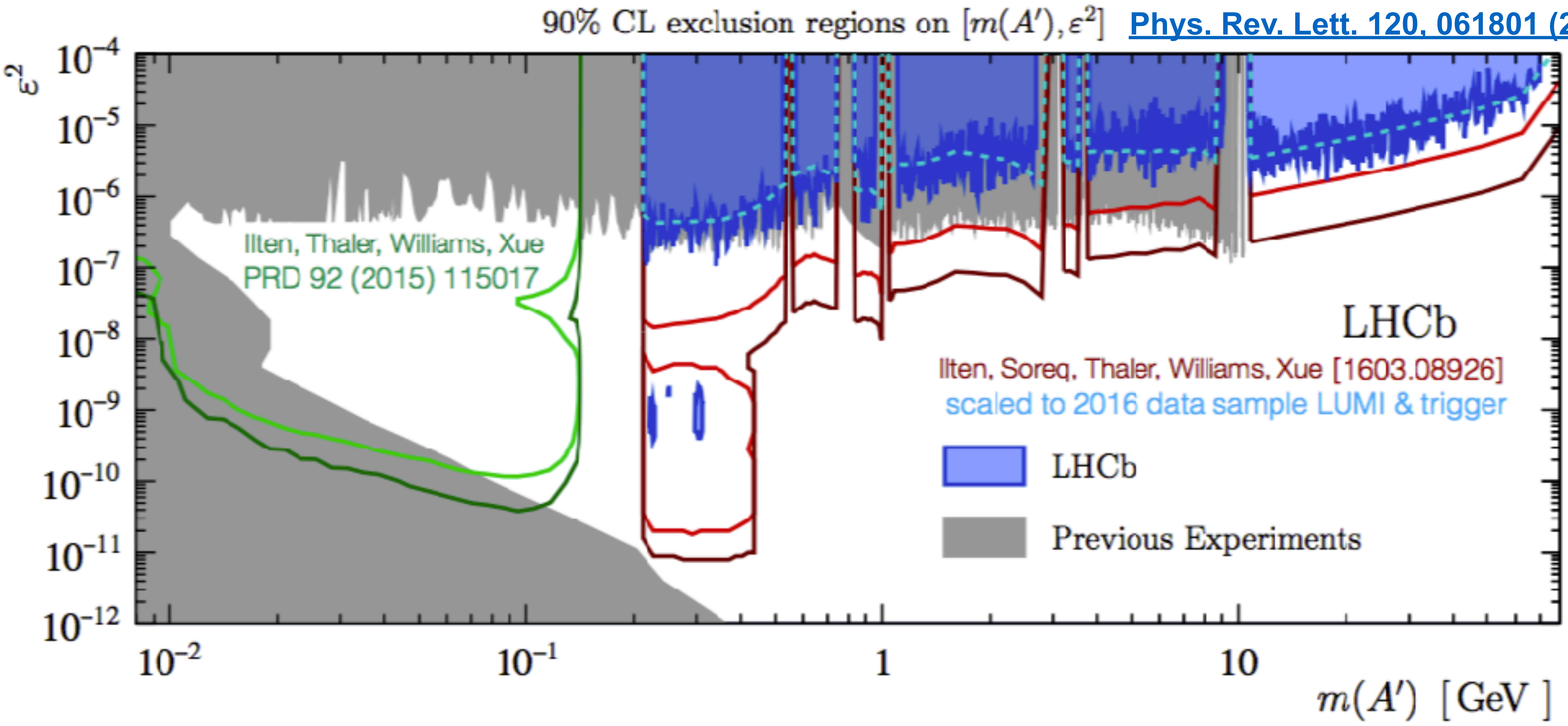




Dark Photon (LHCb)

- Limits **competitive to B factories**
- **Only** experiments to put constraint **above 10 GeV**
- Red and green curves show the **predictions from LHC Run 3**

Phys. Rev. Lett. 120, 061801 (2018)

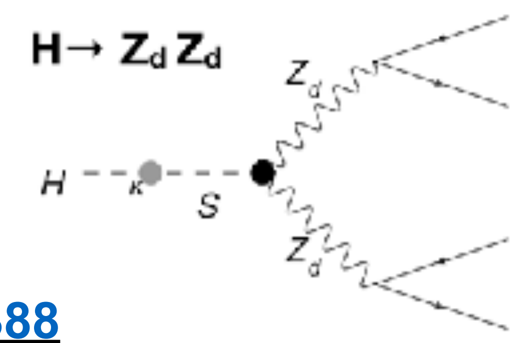


DARK PHOTON (ATLAS)

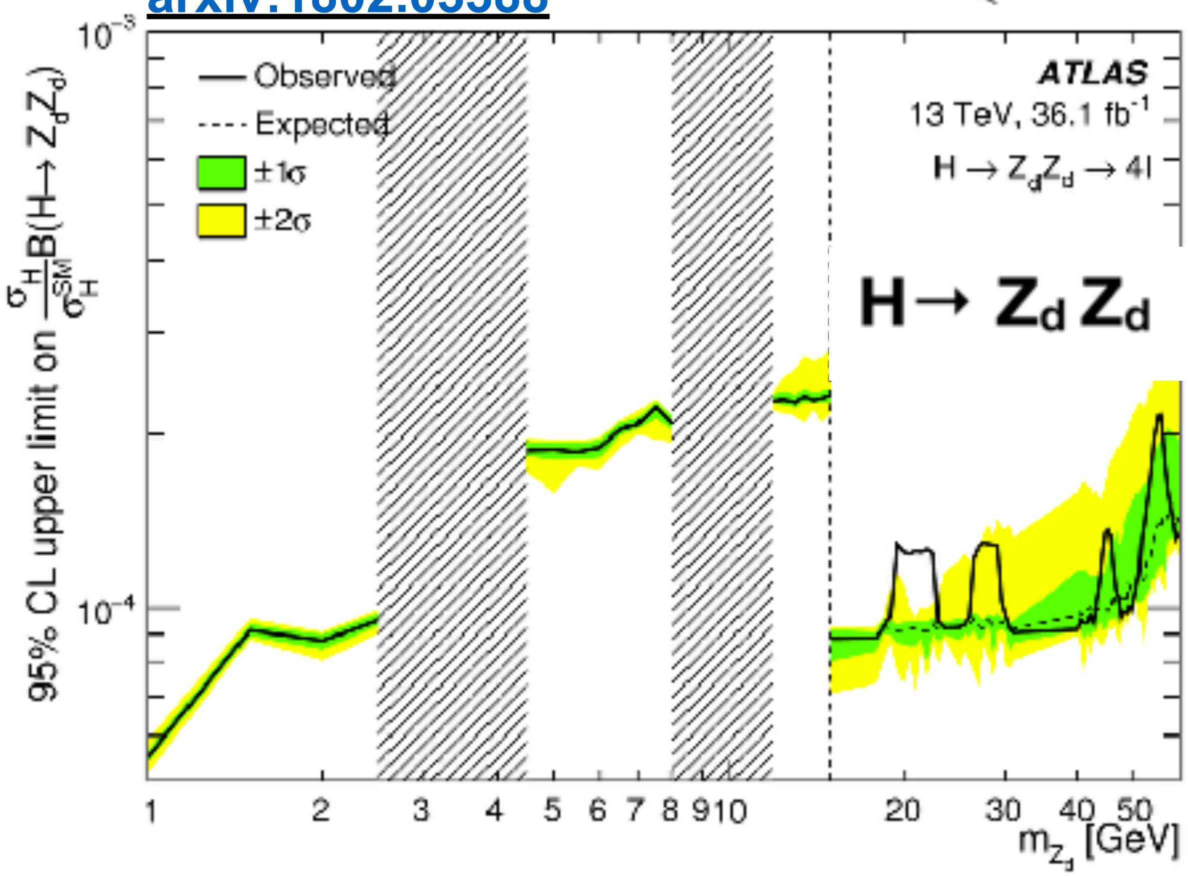
Two recent analyses:

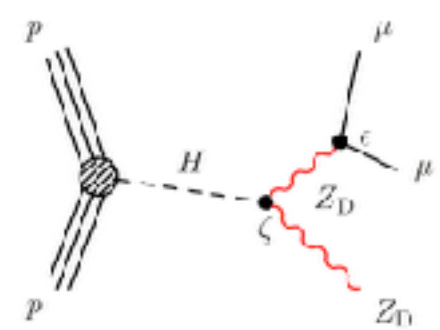
1) **Four prompt leptons.** Require Higgs mass and use of m(ll).

2) **Two displaced muons.** Displaced vertex and use of m(μμ)

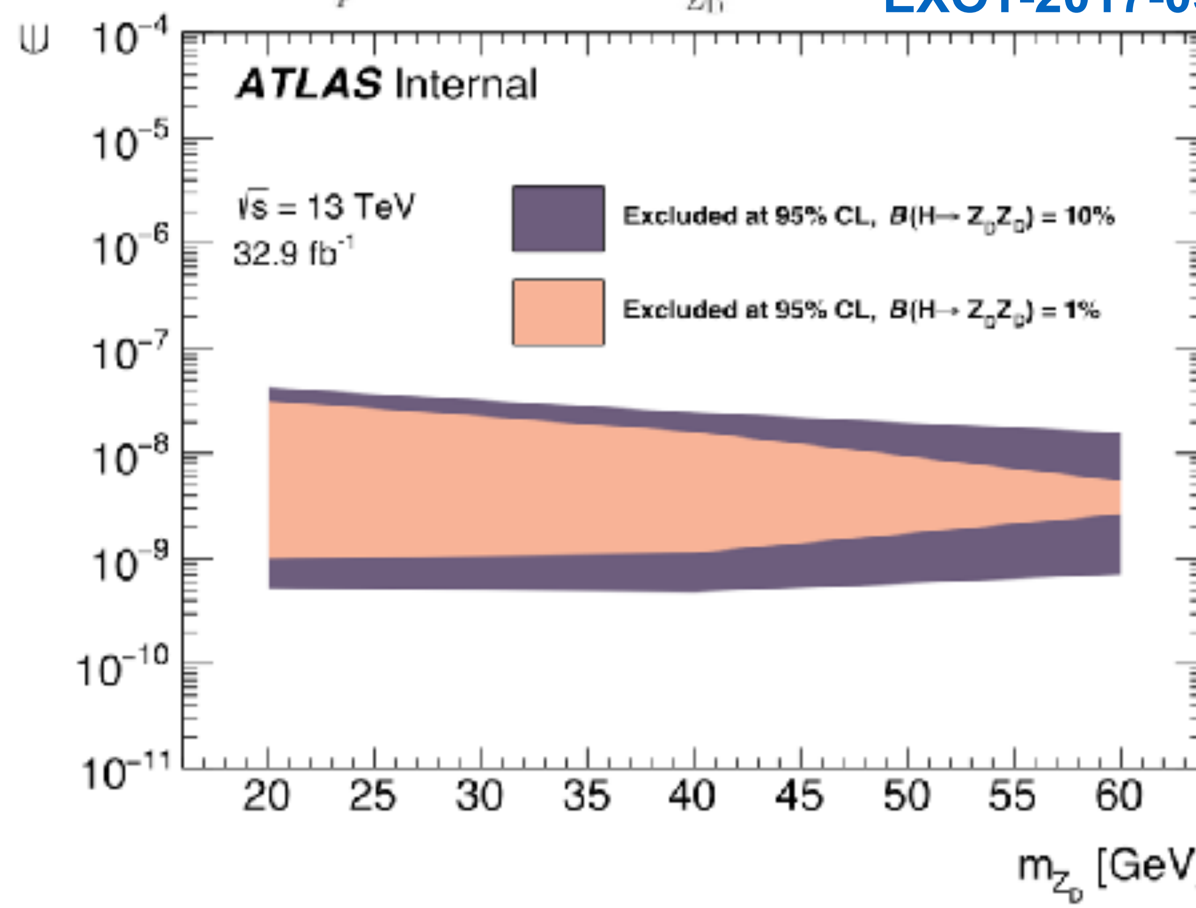


arxiv:1802.03388





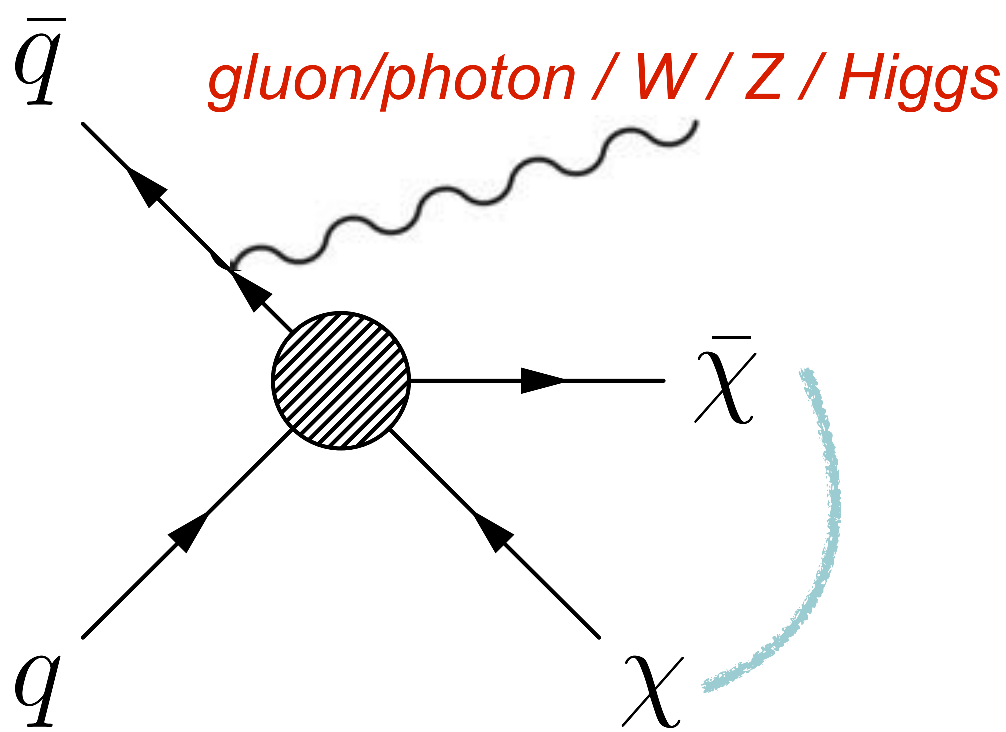
EXOT-2017-03



DARK MATTER

Dark Matter Search at LHC

- **EW bosons and gluons can be radiated by initial partons**
- **Presence of high energy photon/W/Z/Higgs or jet(s) *in addition* to large missing transverse energy**
- **Gluon radiation at higher rate than EW bosons**
  - strong interaction vs. electromagnetic

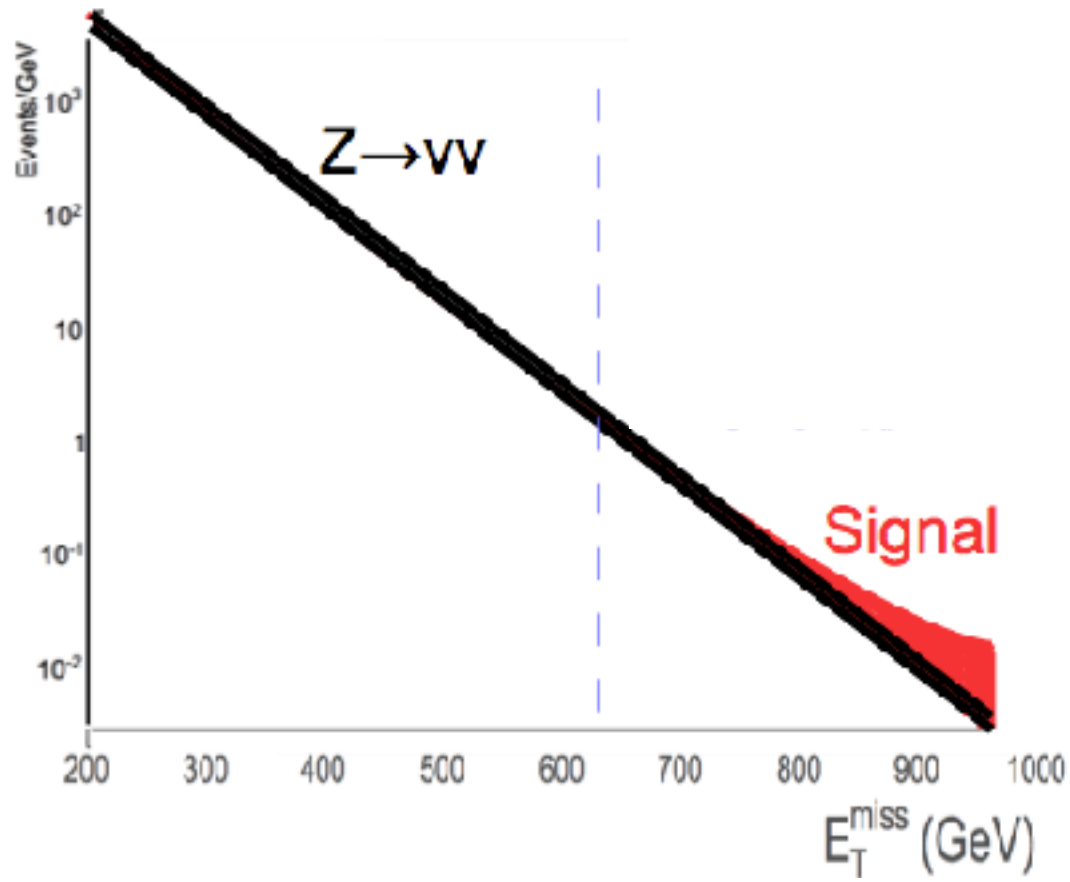


jet/γ/W/Z/H + MET

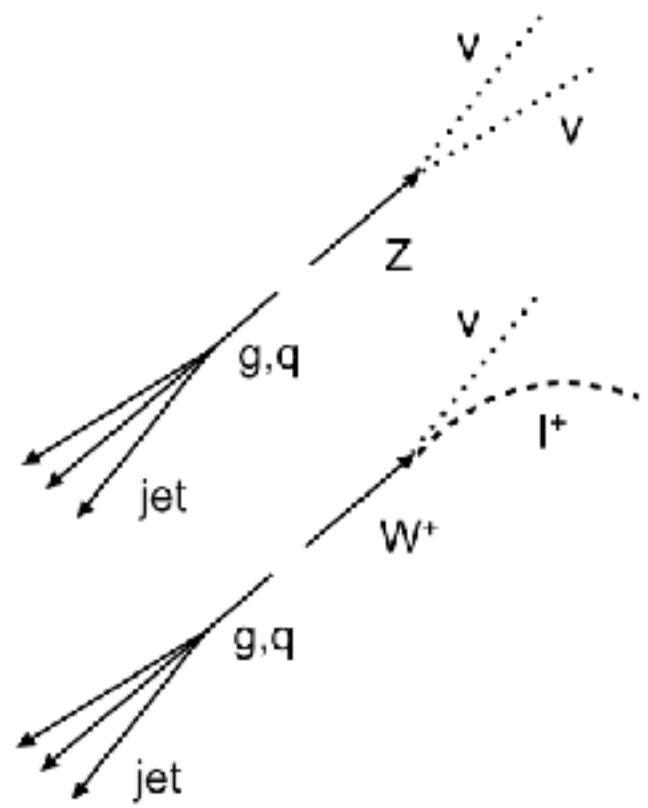
- **mono-jet**
  - strongest constraints
- **mono-photon**
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- **mono-W/Z leptonic**
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- **mono-W/Z hadronic**
  - larger statistics with larger background
- **tt+MET/bb+MET and mono-top**
  - more complicated experimentally
  - powerful in some scenarios
- **mono-Higgs**

DM @ LHC: Analysis Strategy

- **Use MET shape** to extract signal contribution
- **Similar shape for signal and background**
  - Signal harder

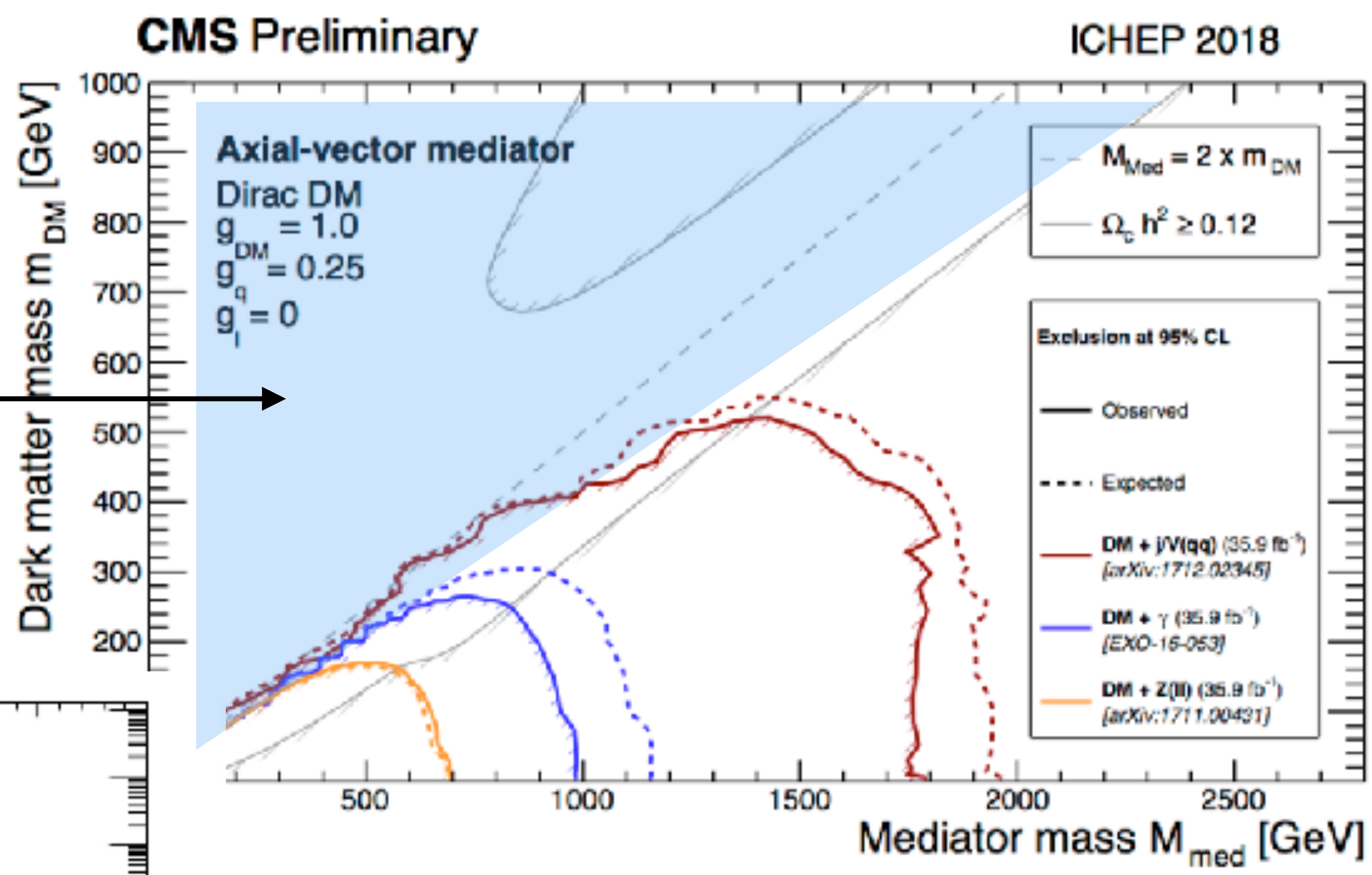


- **Background modeling very important**
- **Main contributions (monojet example)**
  - **Z(νν)+jet**
  - **W(lν)+jet**, where charged lepton is not reconstructed

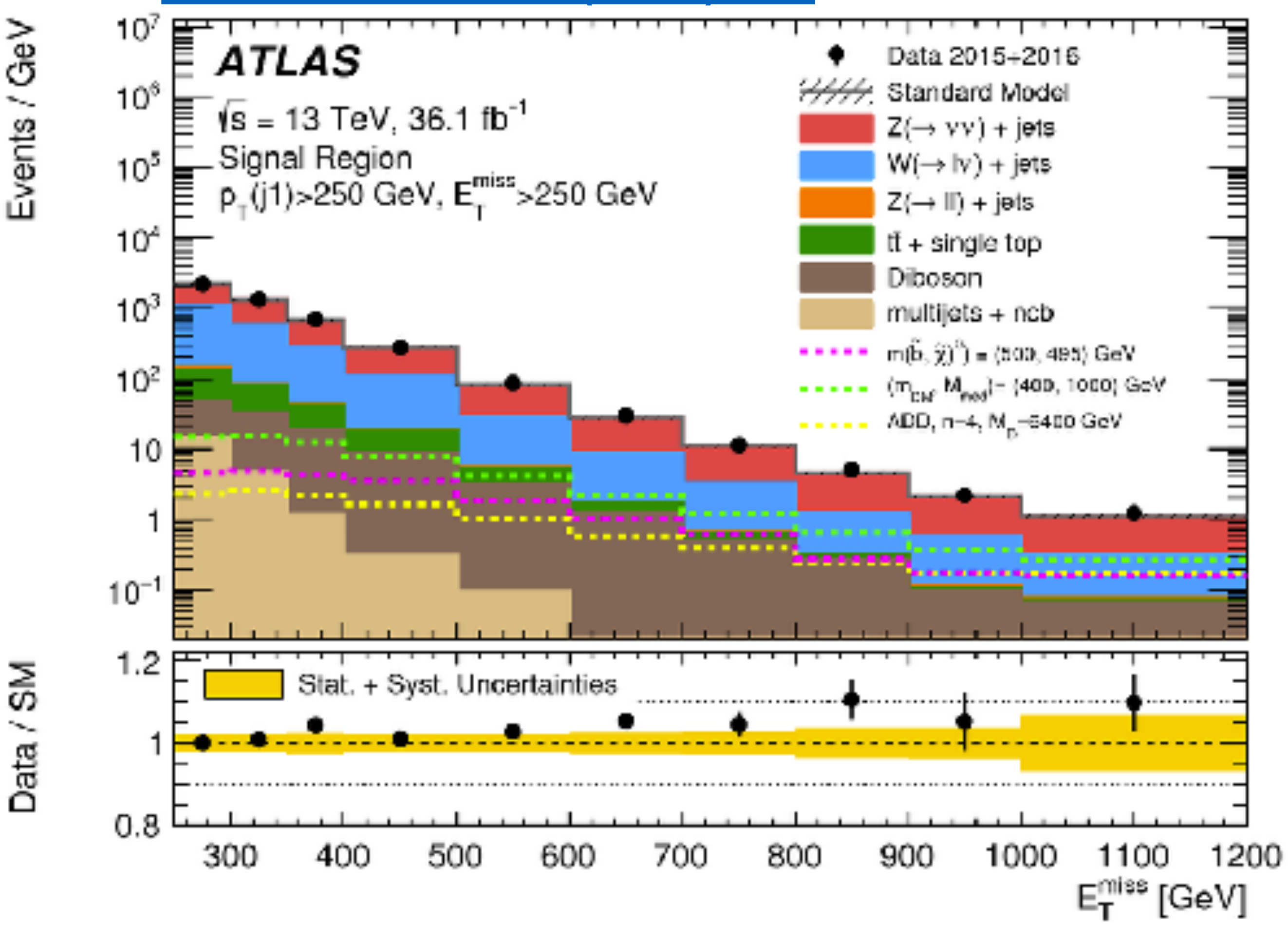


SPIN-1: MONOJET, MONOPHOTON, MONOZ

no sensitivity
for off-shell mediator



[ATLAS : JHEP 01 (2018) 126]



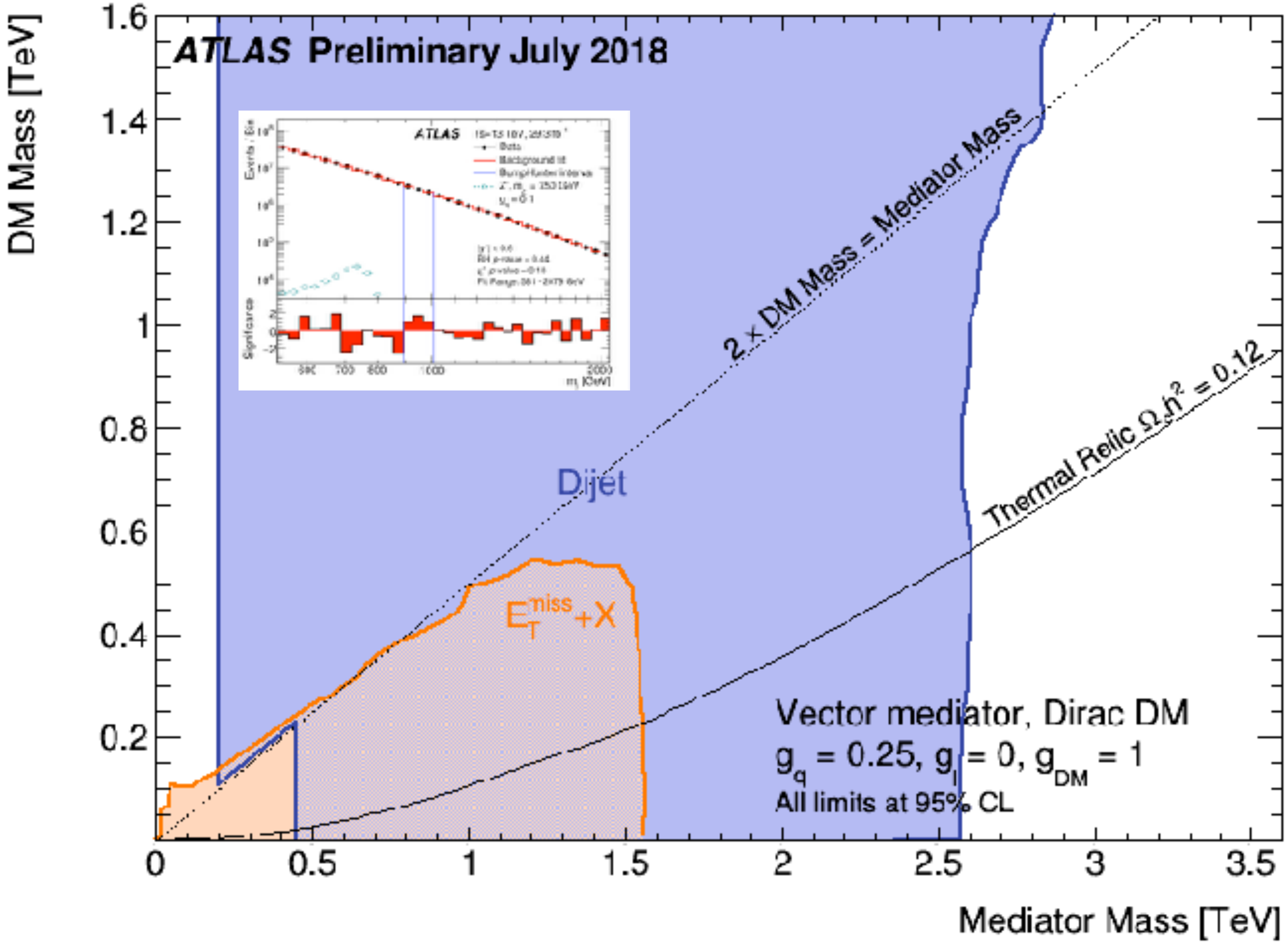
Background extraction:

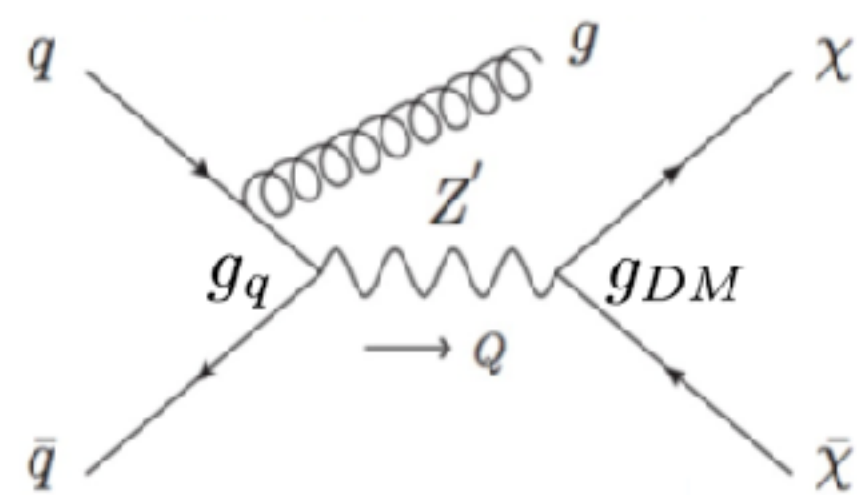
- Use of Z(ll)+jet, W(lν)+jet, γ+jet control samples (see 1705.04664)

Uncertainty on bkg estimate from 2 to 10%

MEDIATOR SEARCHES AND DM: SPIN-1

- By fixing couplings limits on mediators cross section **translated into DM production cross section**





$$\sigma = K' \frac{g_q^2 g_{DM}^2}{M^4 \Gamma_{med}}$$

g_q = coupling to SM

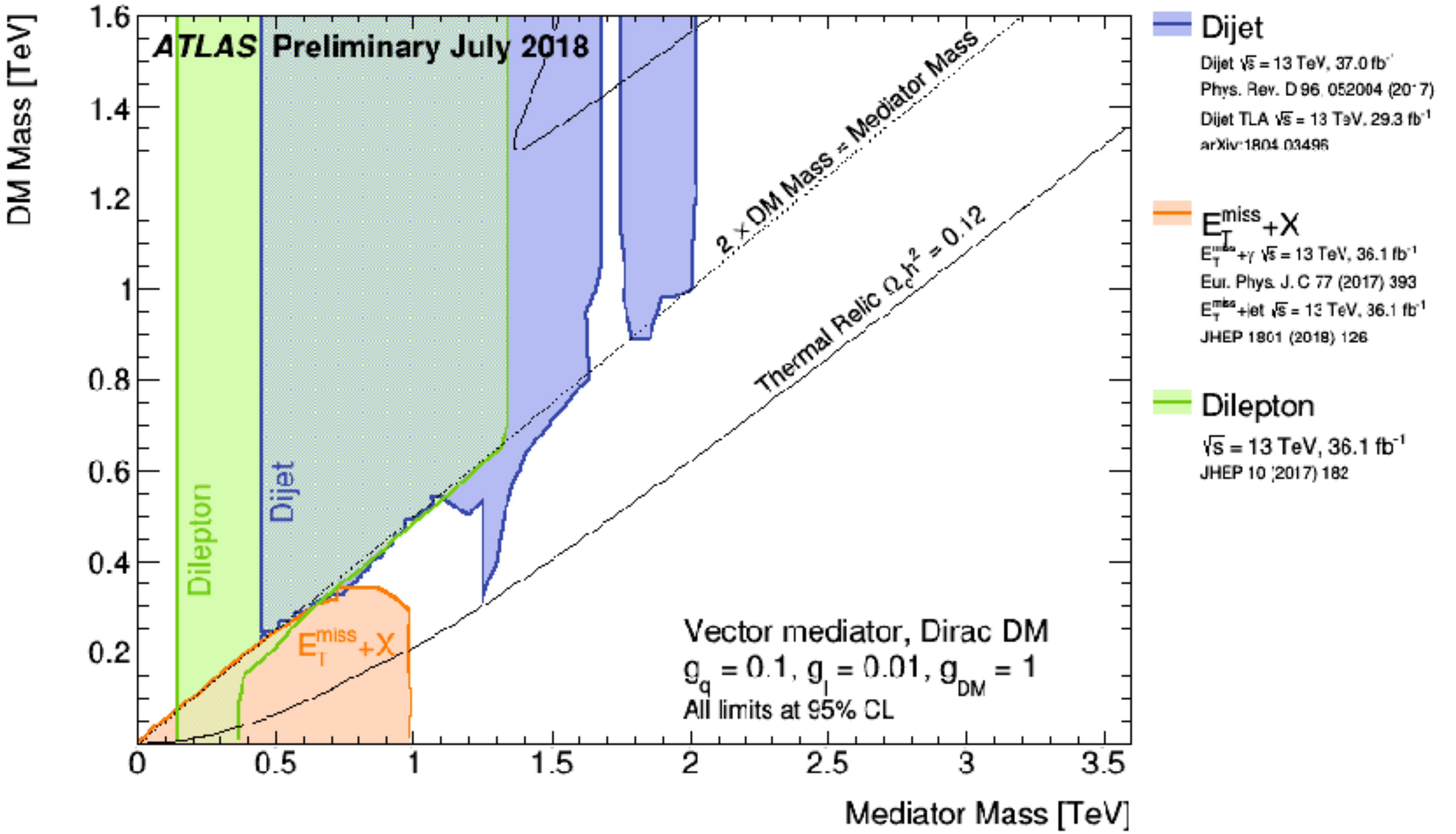
g_{DM} = coupling to DM

M = mediator mass

Γ_{med} = mediator width

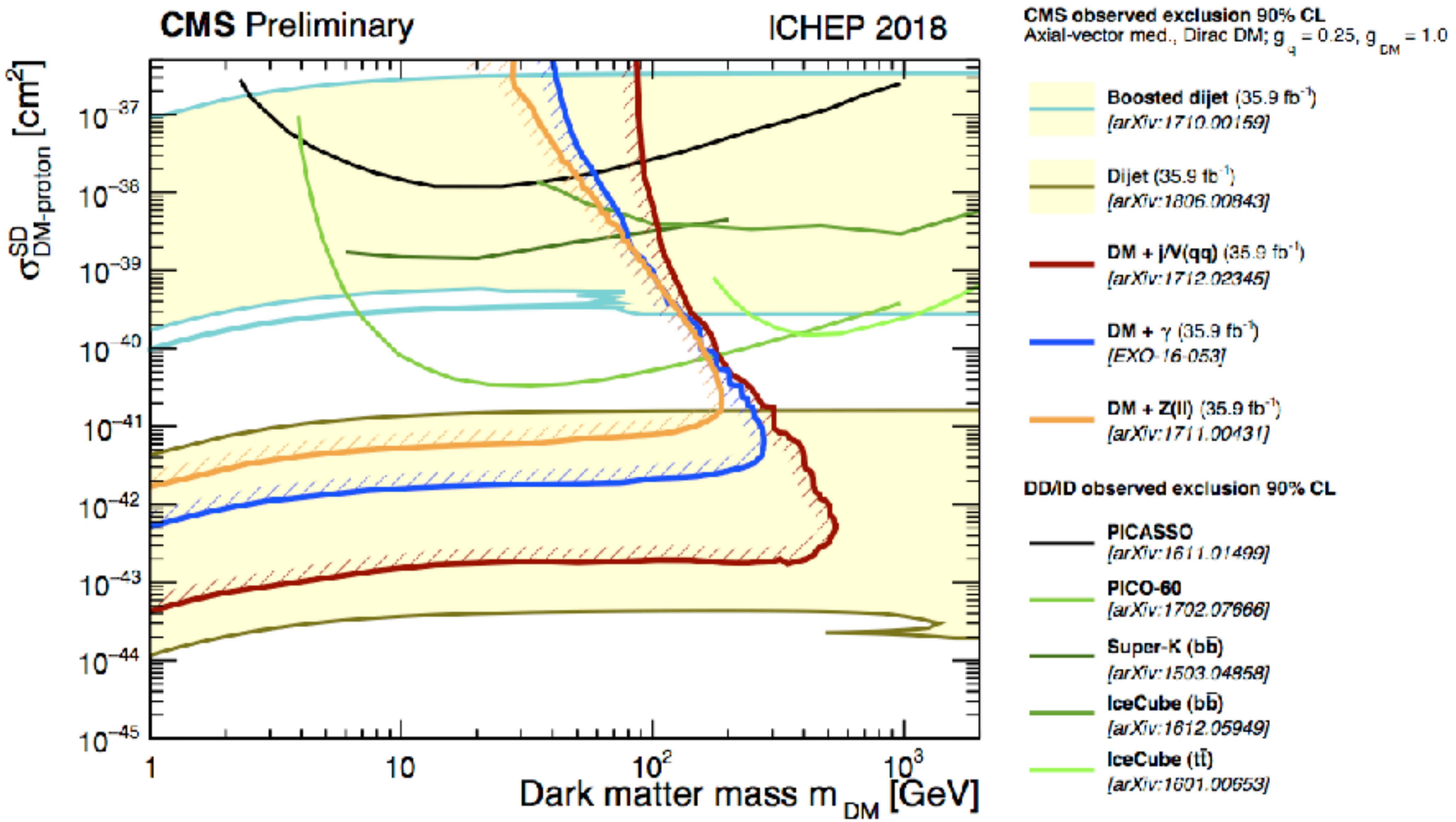
MEDIATOR SEARCHES AND DM: SPIN-1

- By fixing couplings limits on mediators cross section **translated into DM production cross section**



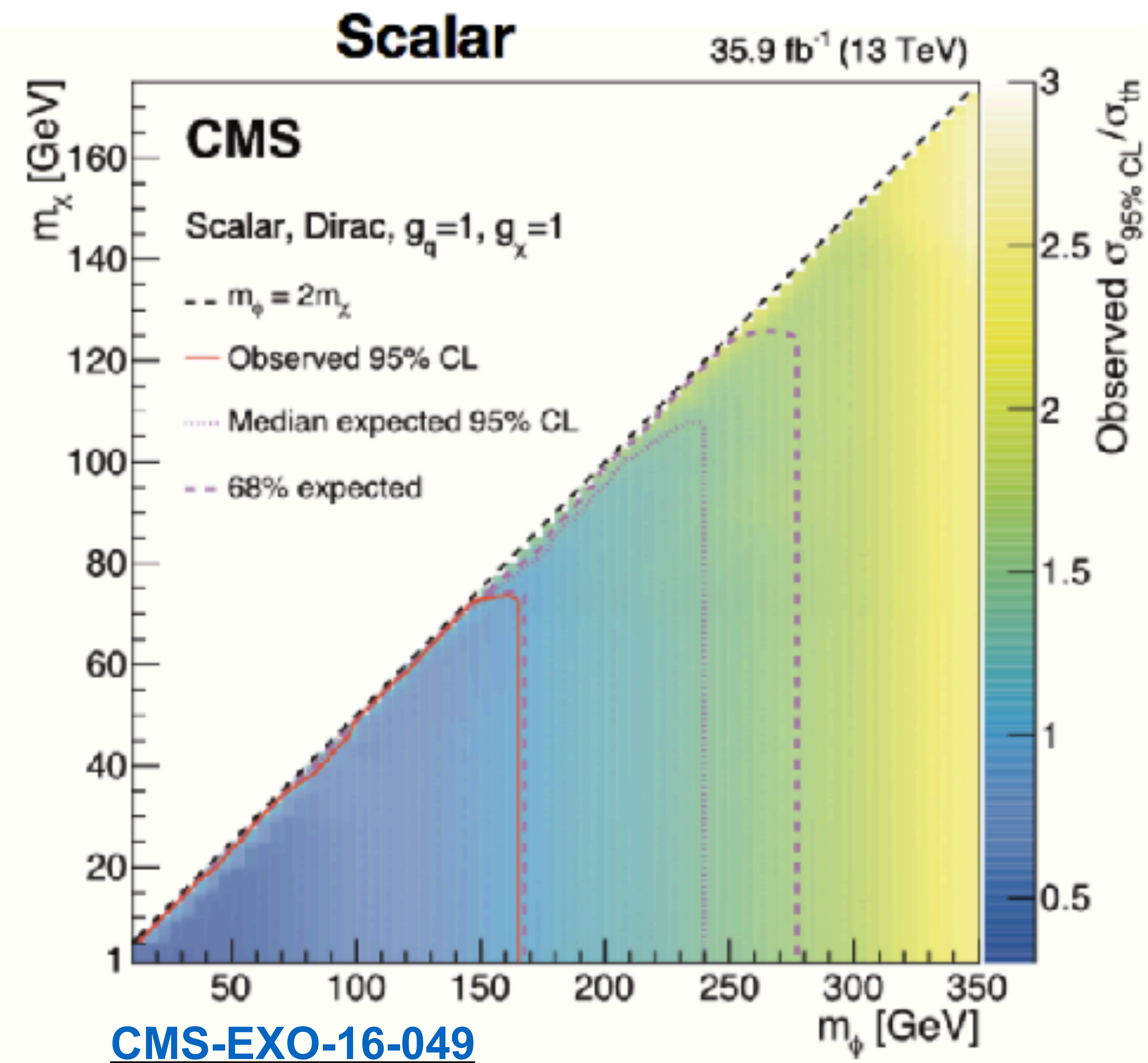
MEDIATOR SEARCHES AND DM: SPIN-1

- By fixing couplings limits on mediators cross section **translated into DM production cross section**

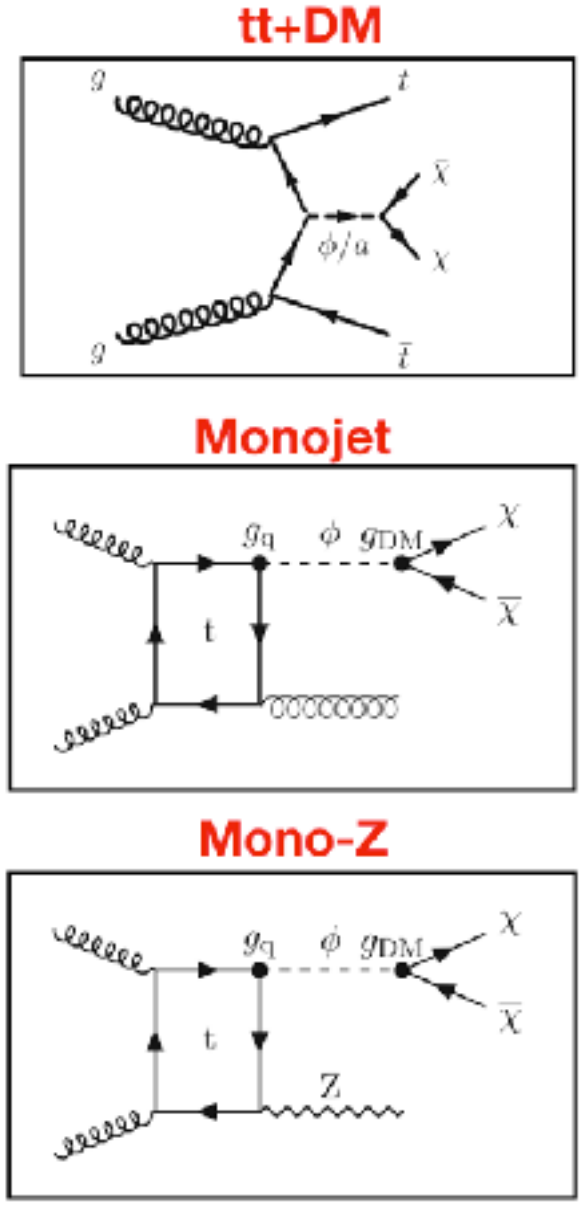


SPIN-0

- In case of **spin-0 mediator**, **final states with top quarks are favored** (coupling proportional to quark mass)
- For **tt+MET** analysis use of **final states with b jets and leptons** from W decays in **different categories**



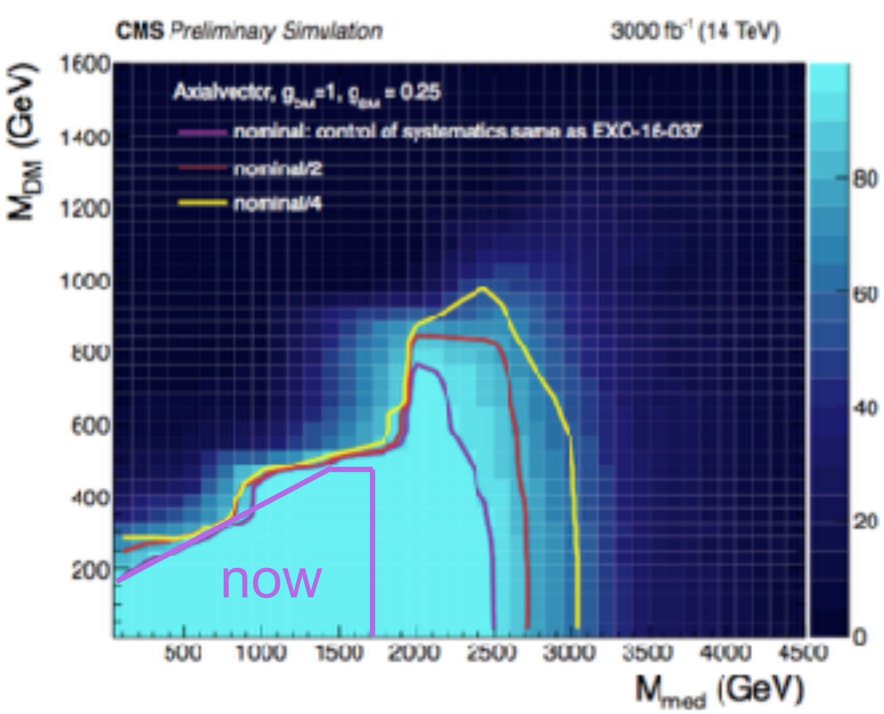
CMS-EXO-16-049



LONGER TERM

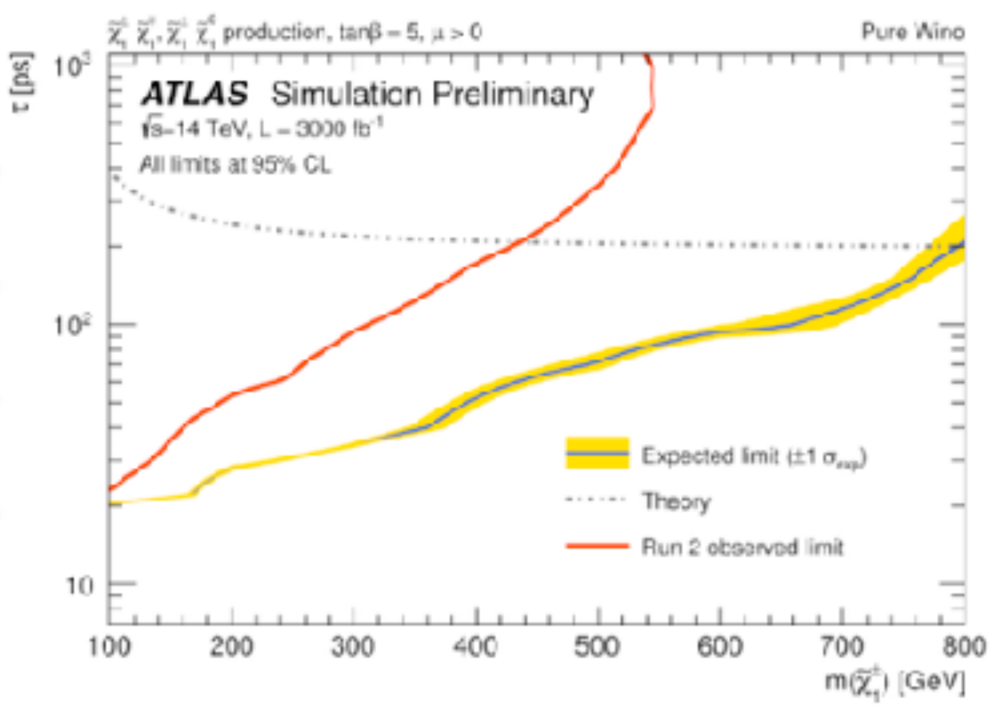
- **Many searches** (in particular intermediate masses and long lived) **largely improve with larger luminosities**
- **HL-LHC with 3 ab^{-1} will extend discovery potential**

Dark Matter



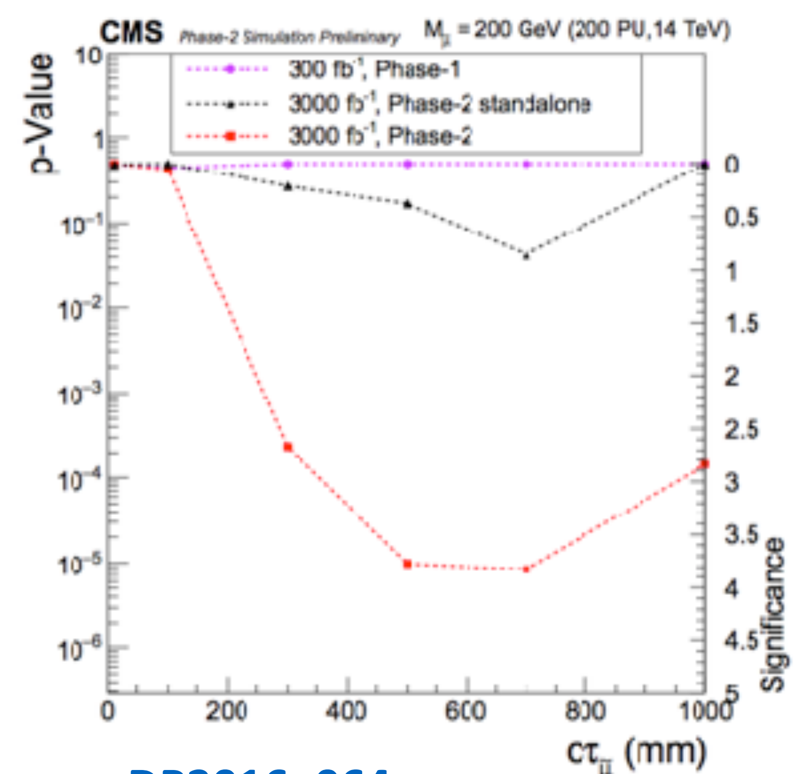
[CMS-TDR-016]

Disappearing tracks



Pixel TDR

Displaced μ



[DP2016_064]

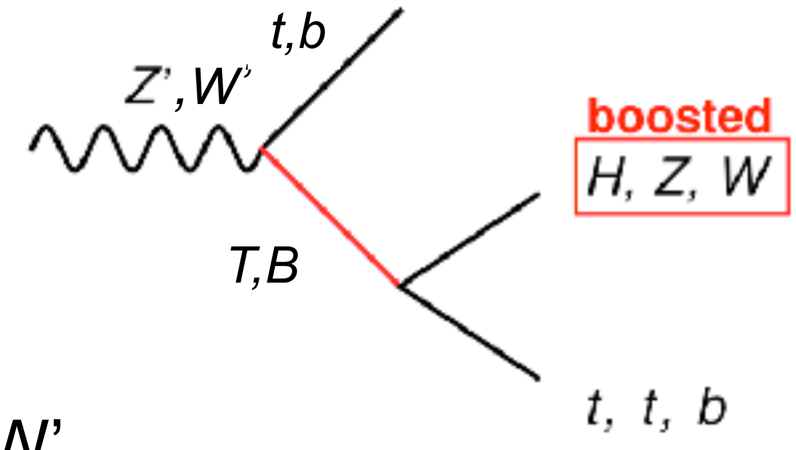
CONCLUSIONS

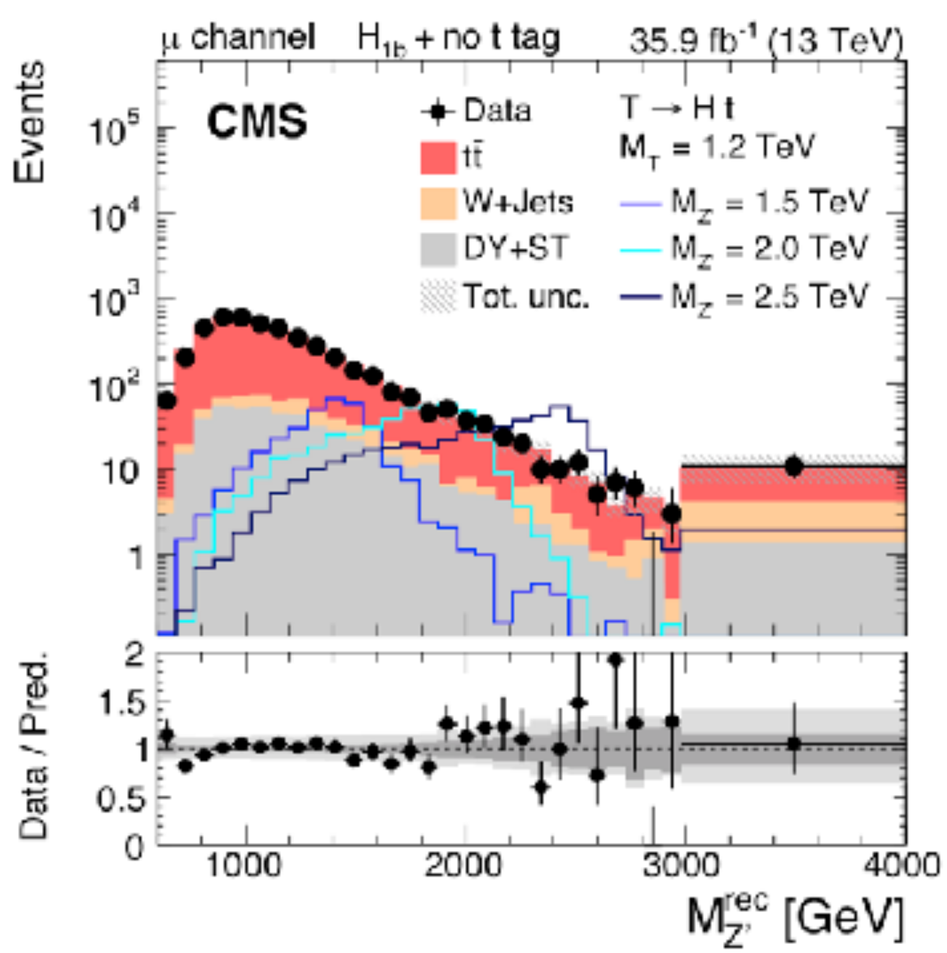
- **Coherent and rich program of Exotics searches at LHC**
- **Several different signatures and models** are tested, e.g.
  - High mass resonances
  - Long-lived
  - Dark Matter
- **No sign of new physics yet**
- Expect **moderate improvements for extremely high mass** searches in future
- **Several new approaches and analysis techniques** target low/ intermediate mass region and new signatures
- **There is still plenty of room to search for new physics in the Exotics land at the LHC**

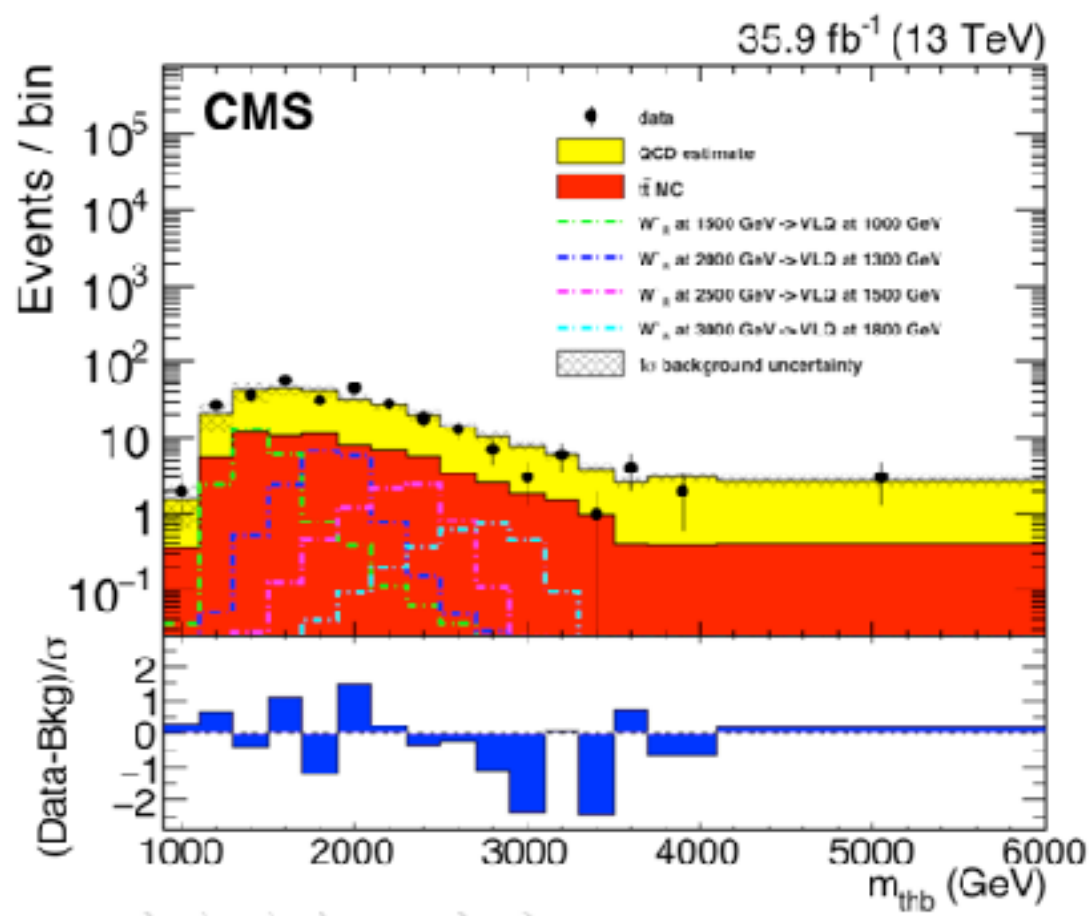
BACKUP

Resonances in Vector Like Quarks

- **Vector-like T quark models solve hierarchy problem:** new heavy partner of top in loop
- Search of **resonances in T/B + t/b with VLQ decaying to H(bb)t, H(bb)b or Z(bb)t**
  - substructures to reconstruct H, Z and top
- **Limits on Z'/W' depend on m(T) and m(B)**
  - @ 1.5 -2.5 TeV level for Z', cross section vs mass for W'

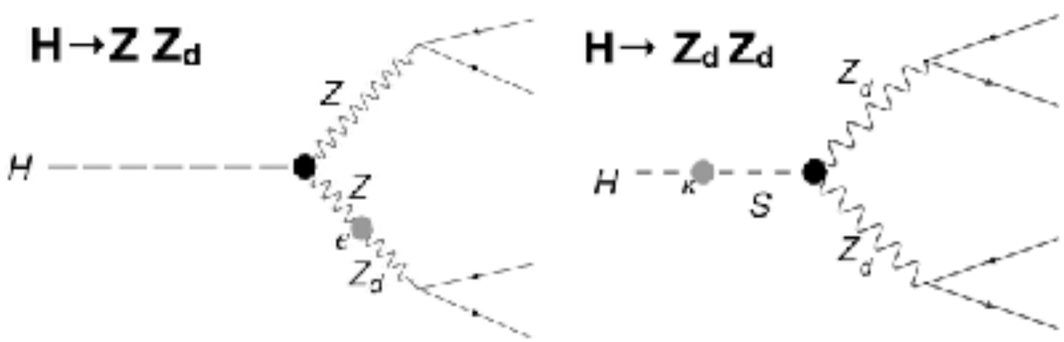


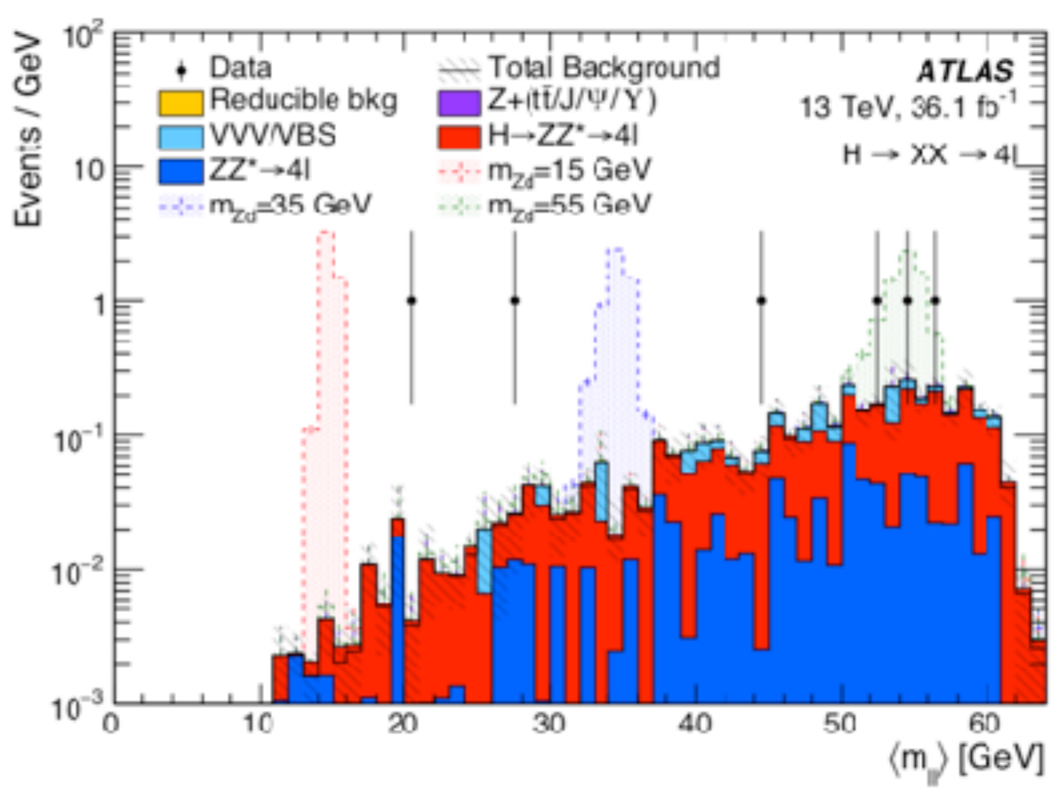




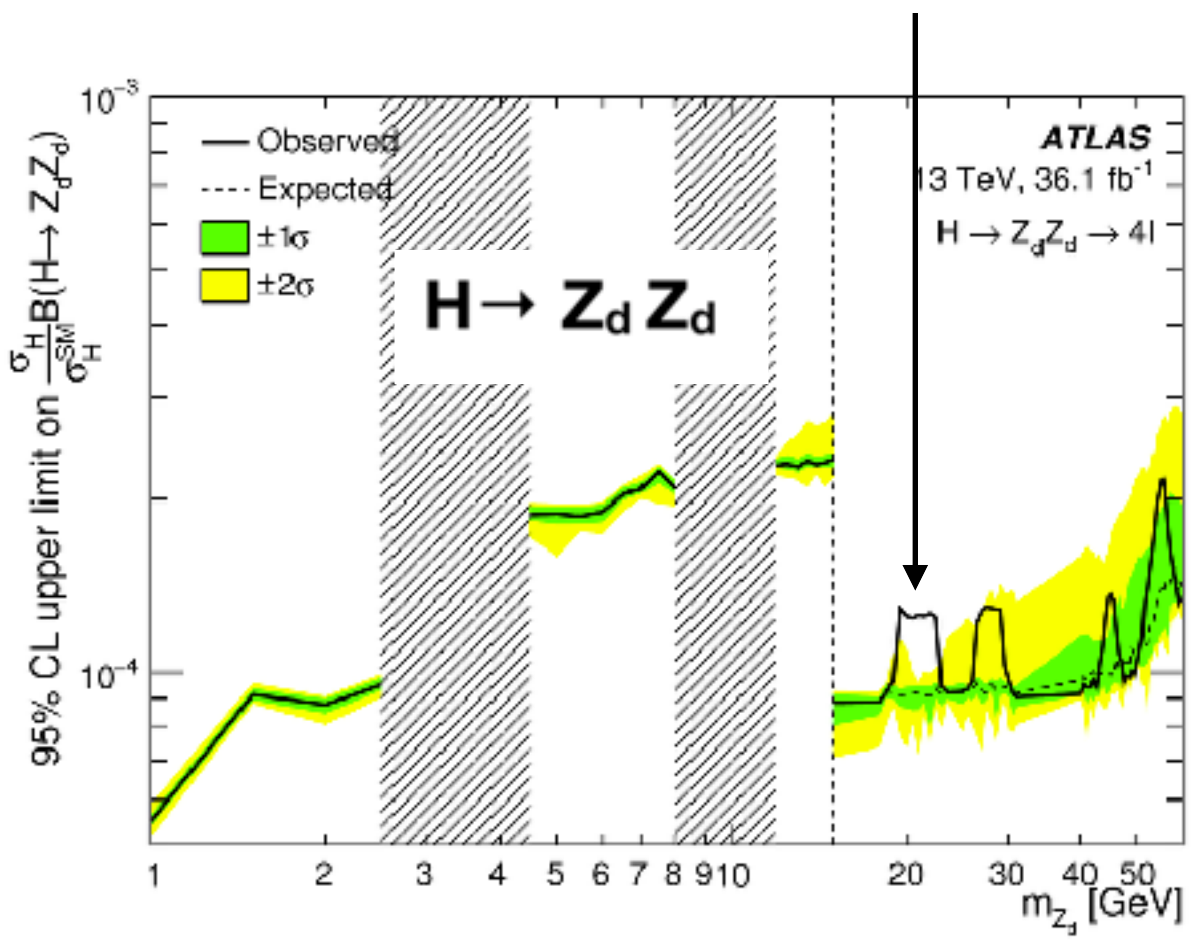
DARK PHOTON (ATLAS)

- Here **1) Z mixes with dark Z** and **2) H mixes with dark Higgs**
- **Reconstruct four leptons, m(4l) = m(H)**
  - for **1)** require **m(ll) = m(Z)**, search fo peak in other ll combination
  - for **2)** search for peak in **average mass** of two ll combinations

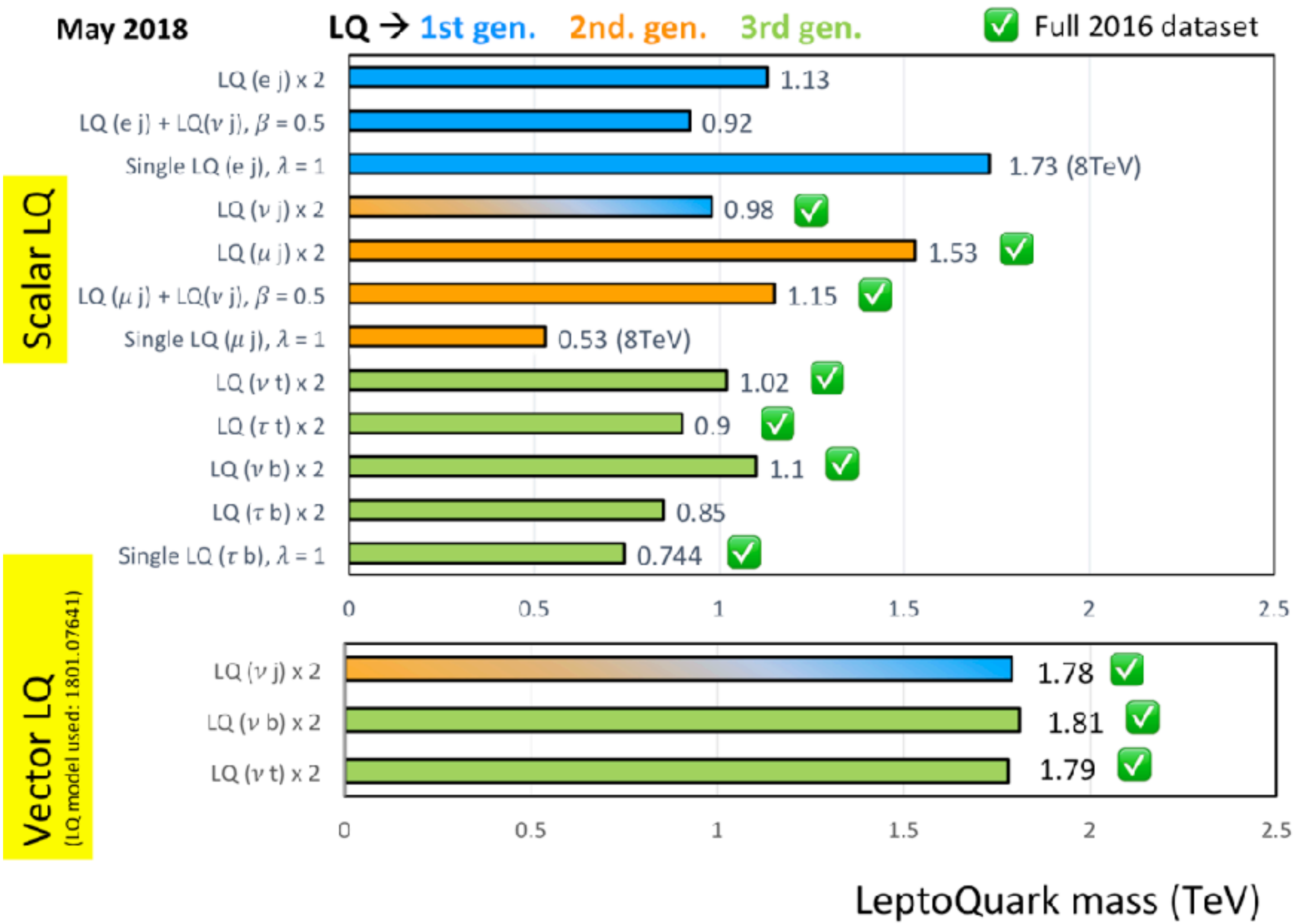




3.2 σ excess

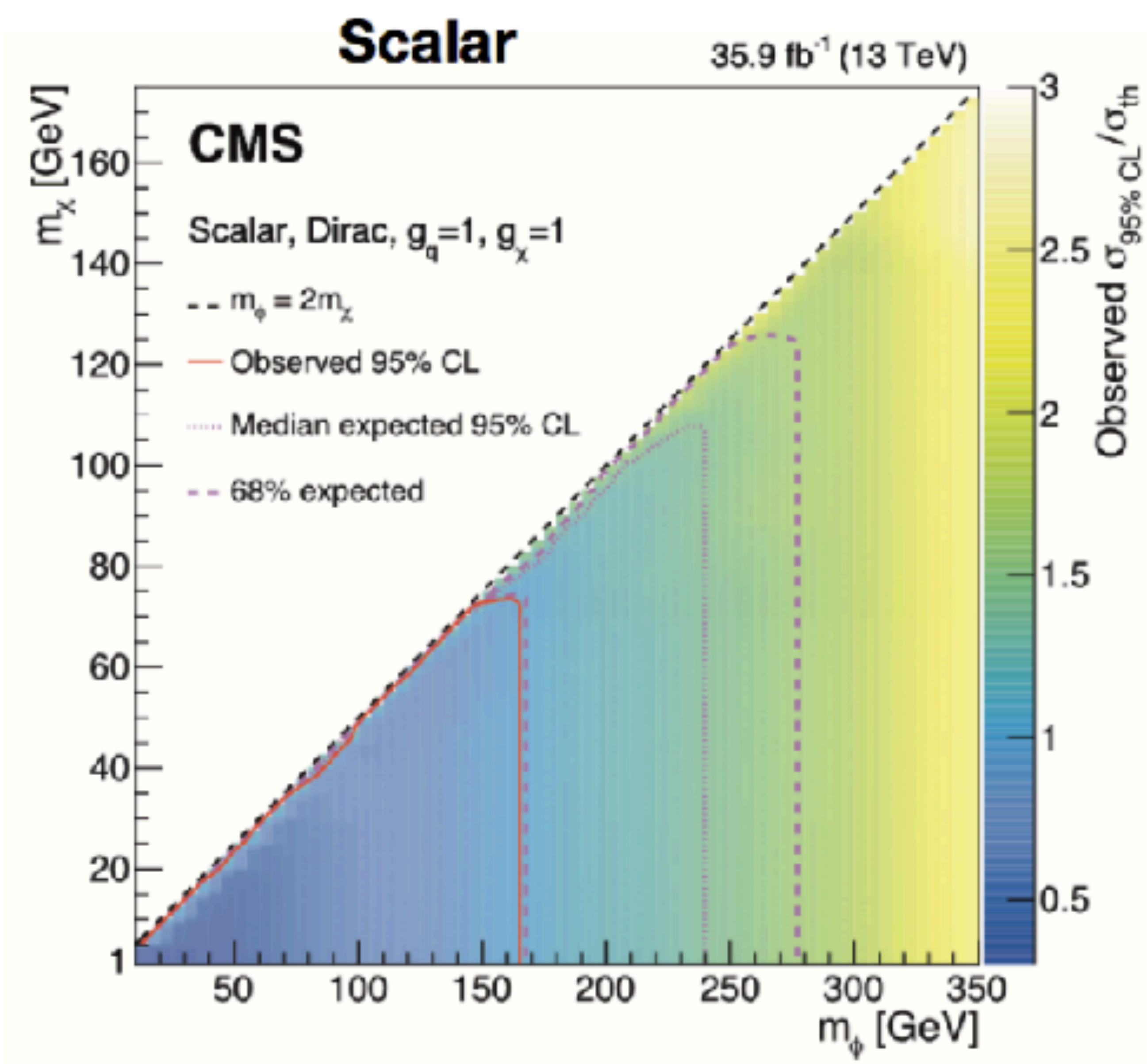


LQ SUMMARY

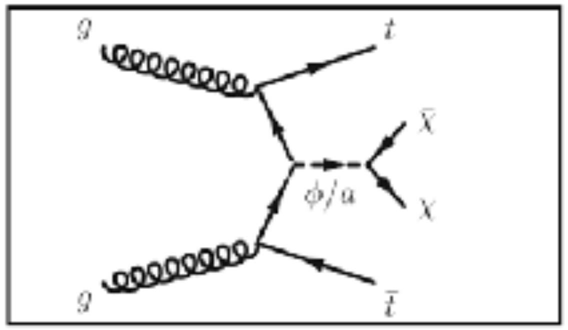

May 2018
LQ → 1st gen. 2nd. gen. 3rd gen.
Full 2016 dataset
Scalar LQ
LQ (e j) x 2
1.13
LQ (e j) + LQ(ν j), β = 0.5
0.92
Single LQ (e j), λ = 1
1.73 (8TeV)
LQ (ν j) x 2
0.98
LQ (μ j) x 2
1.53
LQ (μ j) + LQ(ν j), β = 0.5
1.15
Single LQ (μ j), λ = 1
0.53 (8TeV)
LQ (ν t) x 2
1.02
LQ (τ t) x 2
0.9
LQ (ν b) x 2
1.1
LQ (τ b) x 2
0.85
Single LQ (τ b), λ = 1
0.744
0
0.5
1
1.5
2
2.5
Vector LQ
(LQ model used: 1801.07641)
LQ (ν j) x 2
1.78
LQ (ν b) x 2
1.81
LQ (ν t) x 2
1.79
0
0.5
1
1.5
2
2.5
LeptoQuark mass (TeV)

SPIN-0

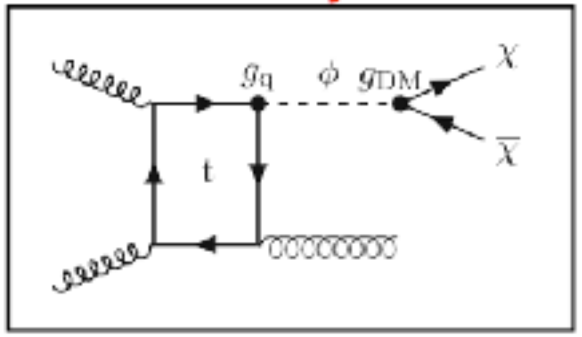
- In case of **spin-0 mediator**, **final states with top quarks are favored** (coupling proportional to quark mass)
- For **tt+MET** analysis use of **final states with b jets and leptons** from W decays in **different categories**



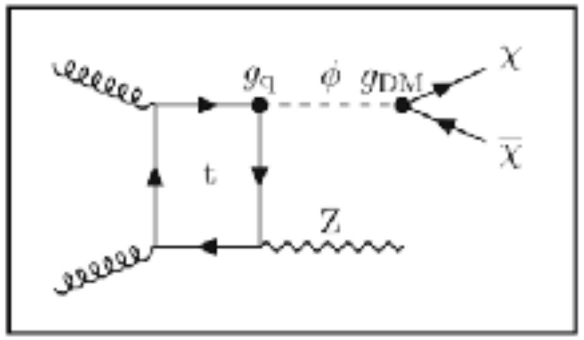
tt+DM



Monojet



Mono-Z



DIJET: GO WIDER

- **Dijet data reinterpreted considering wide resonances**
  - makes the background fits and possible biases more critical
  -