12th Vienna Central European Seminar on Particle Physics and Quantum Field Theory

PHYSICS AT LHC - RUN 2 Dec 01-02, 2016

Beyond Standard Model: Exotica (non-SUSY) experimental overview

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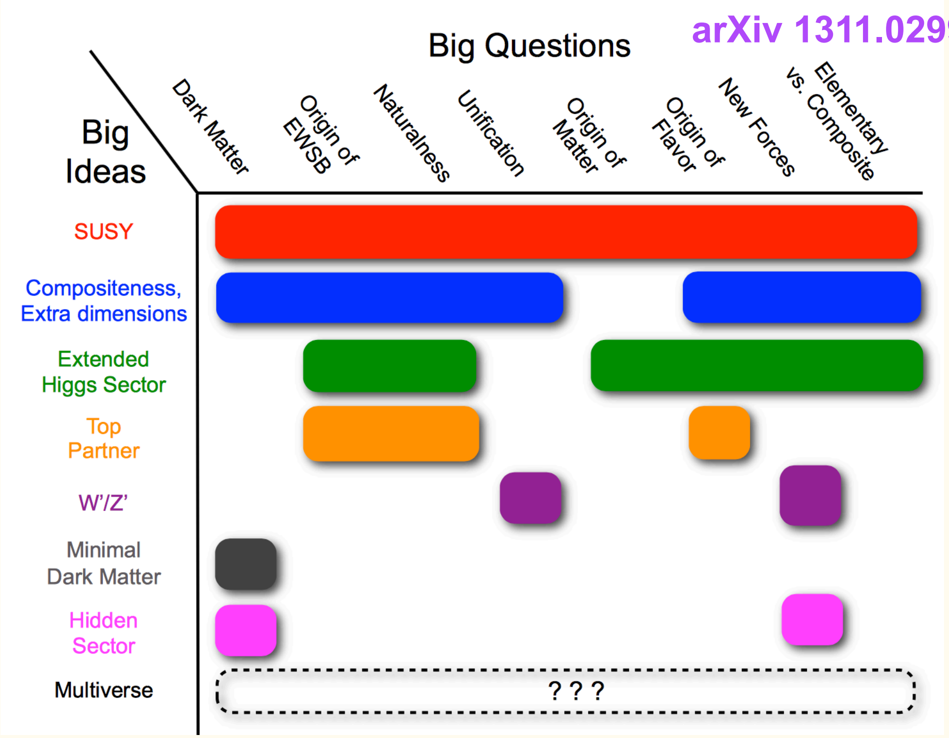
ATLAS

CMS Compact Muon Solenoid

Introduction

- Standard Model, despite of its success, leaves plenty of open questions
- Run 2 with almost twice the center-of-mass energy wrt. Run 1 brought a lot of expectation
- Main problem: we do not know where to look – have to look everywhere!
- Try to explore all possible signatures from simplest to most challenging

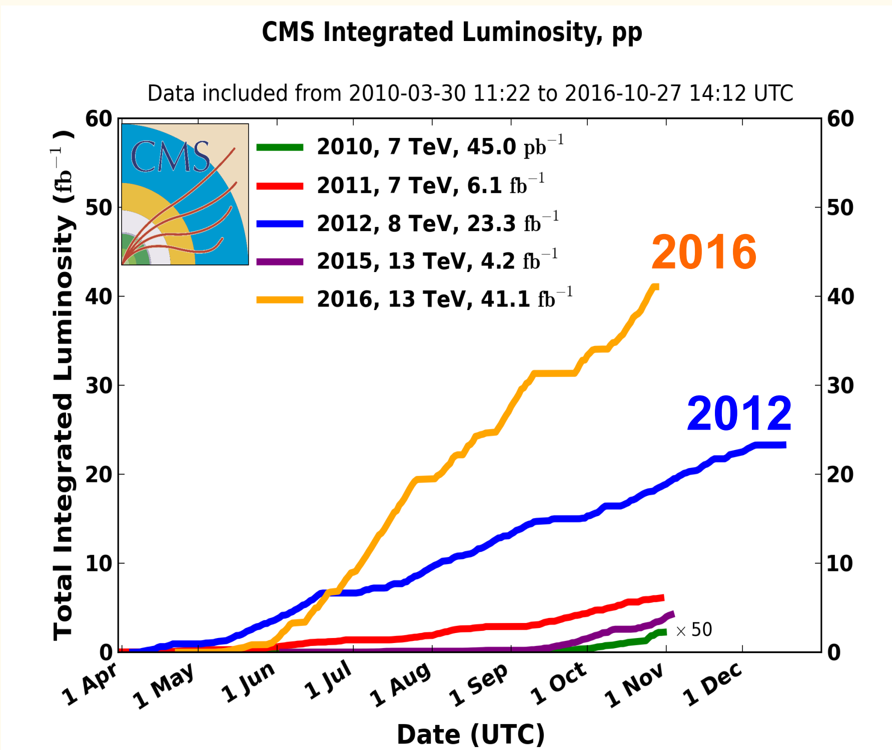
arXiv 1311.0299

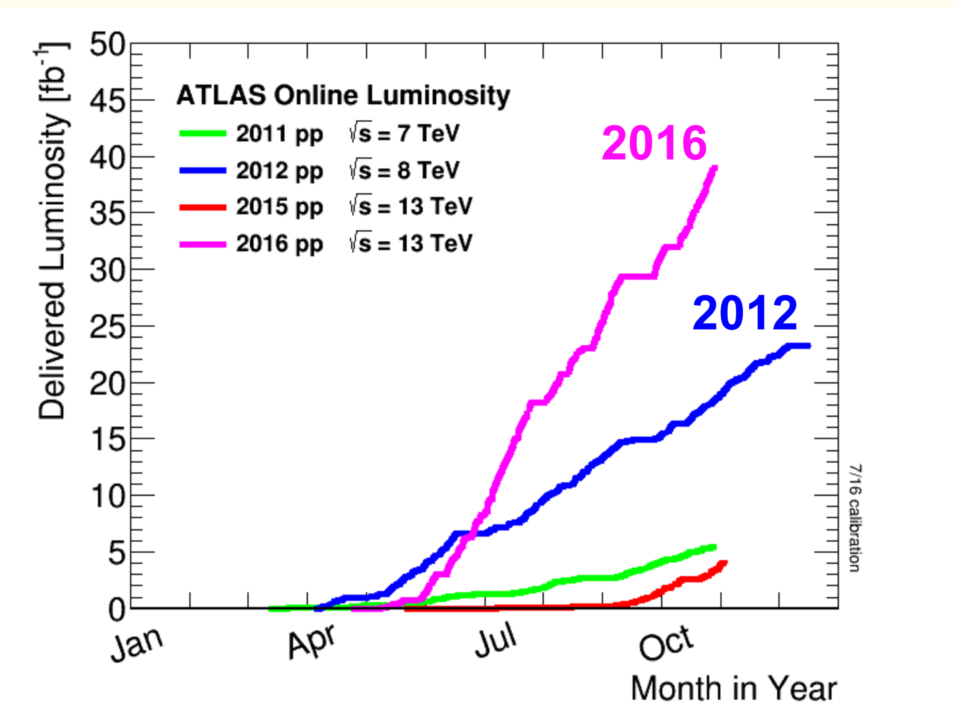


- Use existing models for guiding and as benchmarks
- Provide also model independent limits and sufficient information for reinterpretation

LHC Run 2

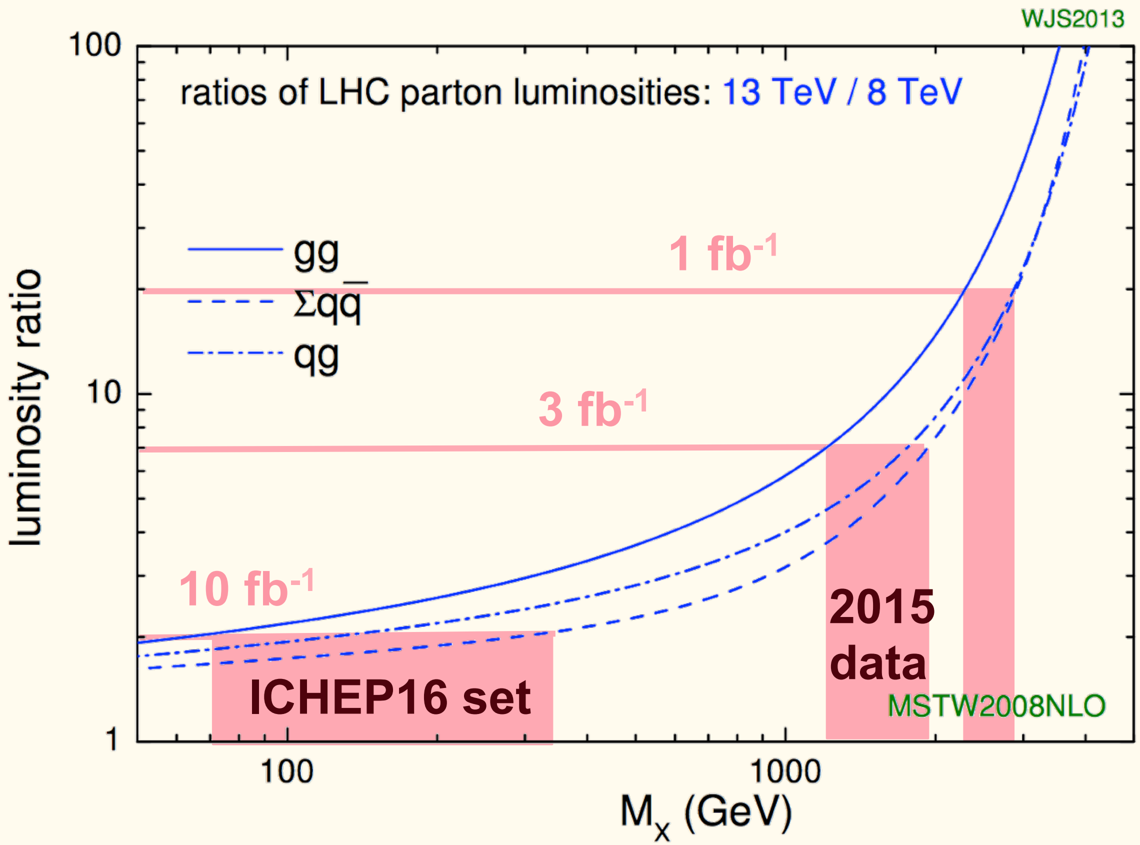
- **After a good but difficult first year, fantastic performance of LHC in 2016!**
- **From about 40 fb^{-1} pp collisions delivered, expect more than 35 fb^{-1} of certified data in 2016 in each ATLAS and CMS! Largest LHC dataset by far…**
- **Experiments performed very well despite of challenges for detectors, trigger, computing and analysis (e.g. pile up)**





Energy frontier and statistics

- The large **energy step** made the exploration exciting from the first inverse femtobarn
  - Some limits from Run 1 in a few TeV range
- Explored **simple signatures first**
- By now enough data to exceed Run 1 results by far in all mass ranges



~20 fb^{-1}

2012 | **LS1**

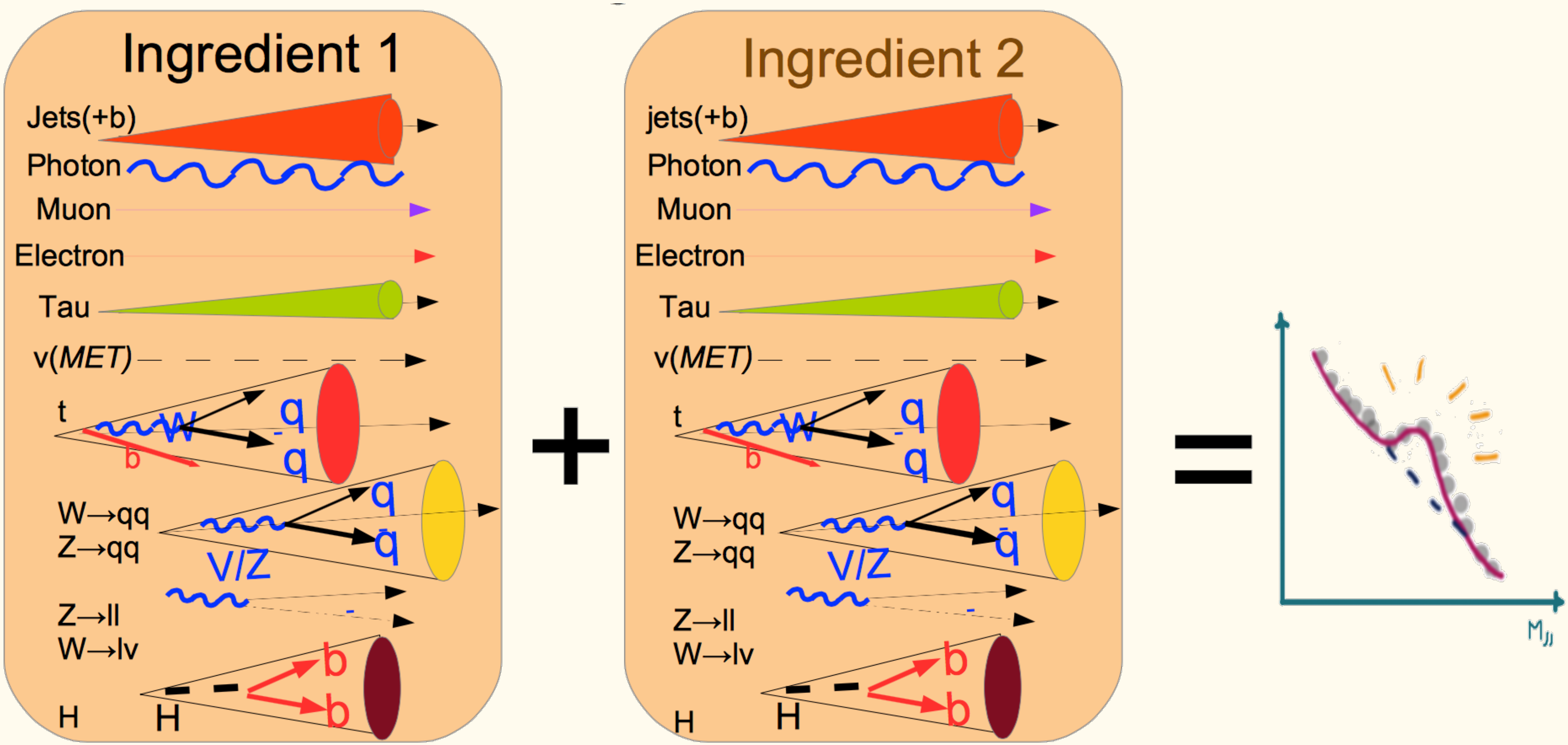
2015 | Currently analyzed dataset | **2016**

~3 fb^{-1} Winter conf. 16

~13 fb^{-1} Summer conf. 16

~35 fb^{-1}

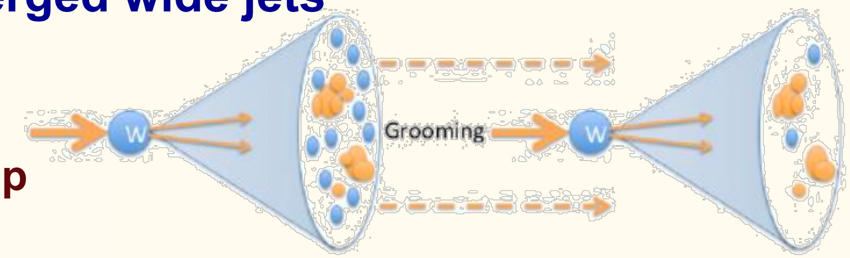
Resonance searches

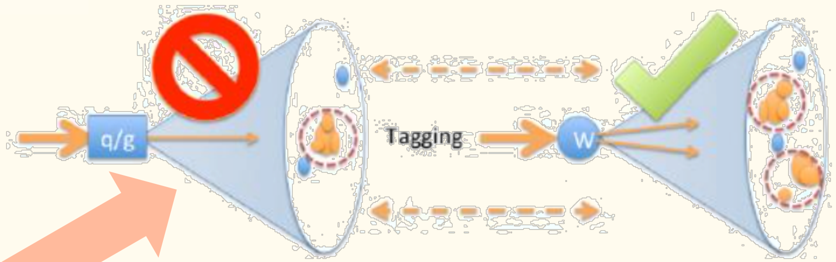


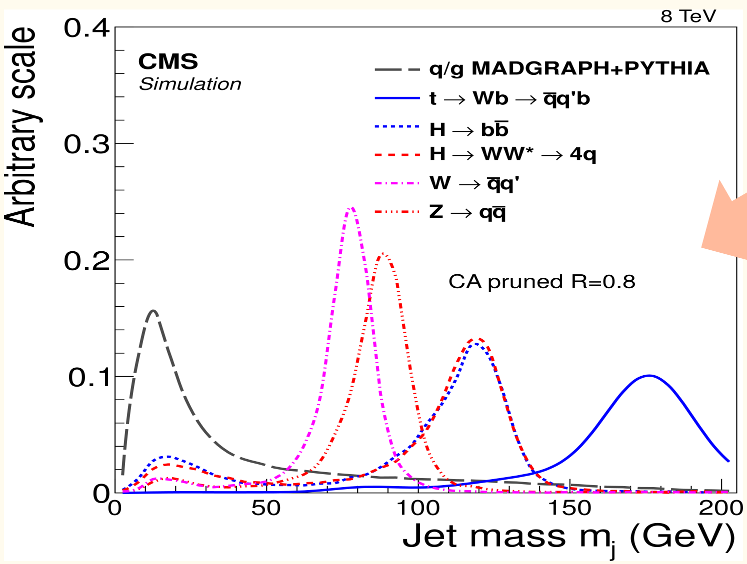
- Besides classical simple topologies, many complex signatures
  - Boosted topologies, jet substructure becoming a standard tool
- Many possibilities, but can be helpful e.g. to understand excesses

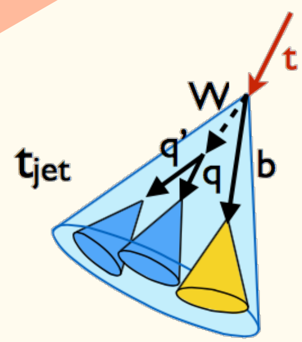
Jet substructure

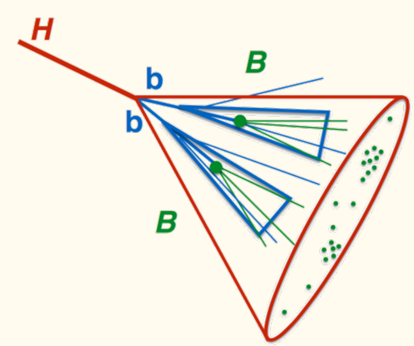
- Many searches explore final states with heavy bosons (W,Z,H) or top
- BRs to hadronic final states dominant; at a resonance mass of ≳ 1 TeV decay products get collimated into merged wide jets
- Grooming: remove soft components (underlying event, pile up, noise)
  - trimming, pruning, mass drop, soft drop
- W/Z/H/t tagging: based mainly on jet mass and subjettiness after grooming
- In addition, use subjet b-tagging (H,t)







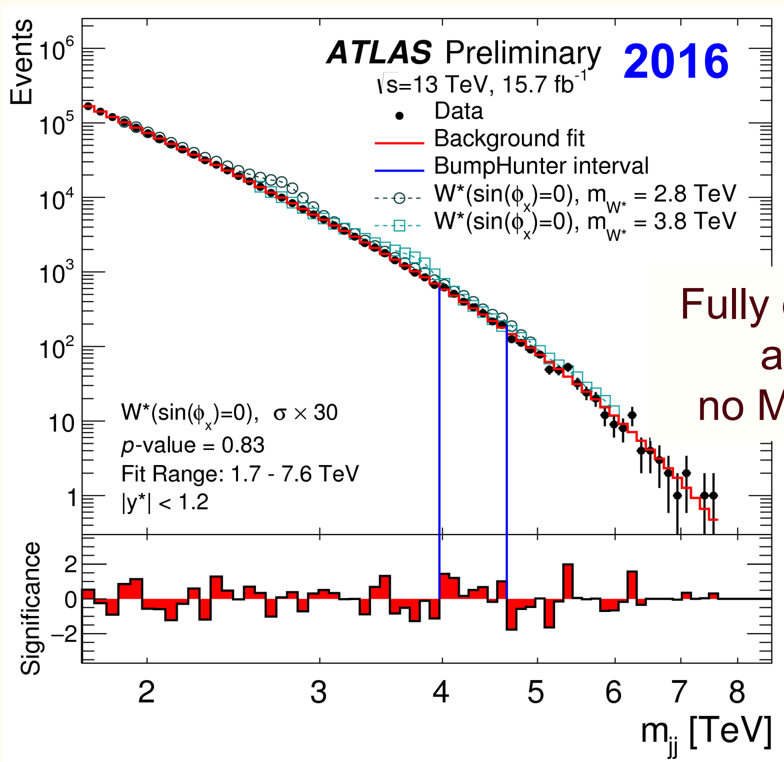




Dijets: high mass

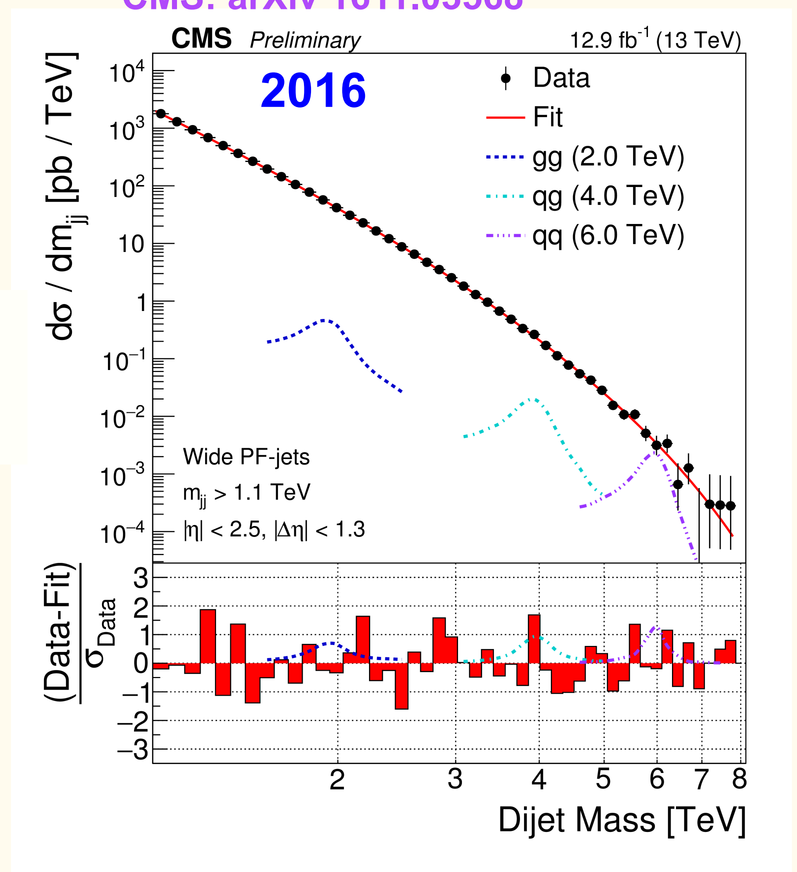
- **A resonance created at hadron collider practically must decay into two jets**
- **But large background – must be sufficiently narrow and abundant**
- **Highest mass limits at LHC – first signature to look at after an energy step**

ATLAS-CONF-2016-069



Fully data-driven analysis
no MC needed

CMS: arXiv 1611.03568



- **Highest mass events close to 8 TeV!**

Dijets: high mass

- **Spectacular improvement of limits wrt. Run 1:**

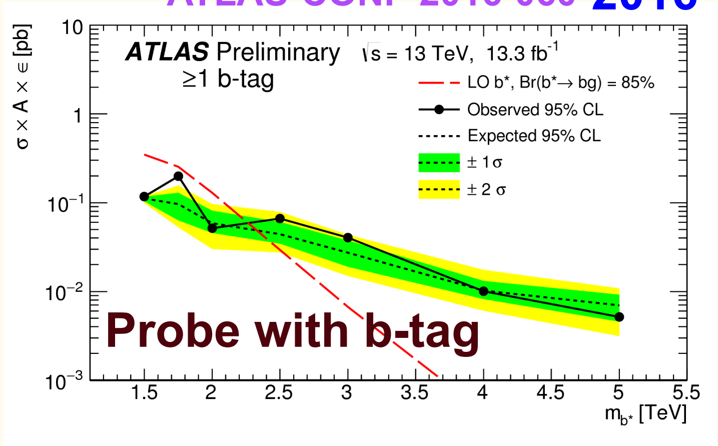
CMS: arXiv 1611.03568

Model	Final State	Observed (expected) mass limit [TeV] 12.9 fb^{-1} 13 TeV	2.4 fb^{-1} 13 TeV	20 fb^{-1} 8 TeV
String	qg	7.4 (7.4)	7.0 (6.9)	5.0 (4.9)
Scalar diquark	qq	6.9 (6.8)	6.0 (6.1)	4.7 (4.4)
Axigluon/coloron	$q\bar{q}$	5.5 (5.6)	5.1 (5.1)	3.7 (3.9)
Excited quark	qg	5.4 (5.4)	5.0 (4.8)	3.5 (3.7)
Color-octet scalar ($k_s^2 = 1/2$)	gg	3.0 (3.3)	—	—
W′	$q\bar{q}$	2.7 (3.1)	2.6 (2.3)	2.2 (2.2)
Z′	$q\bar{q}$	2.1 (2.3)	—	1.7 (1.8)
RS Graviton	$q\bar{q}$, gg	1.9 (1.8)	—	1.6 (1.3)

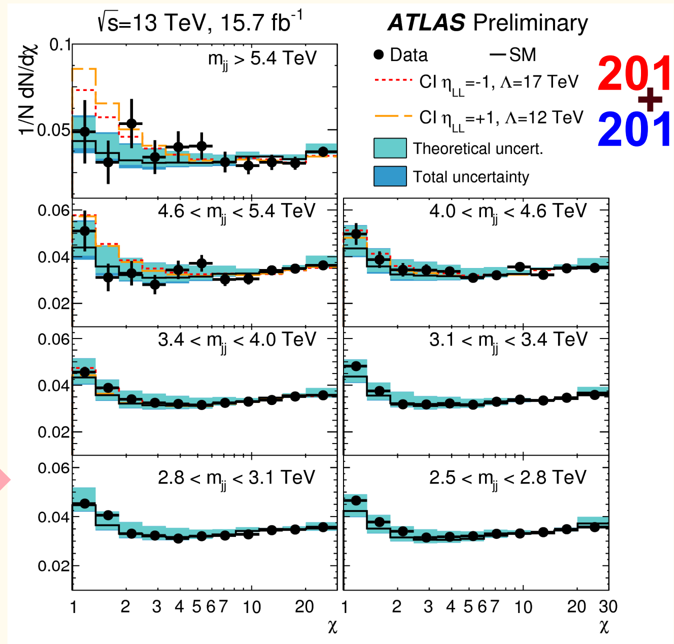
ATLAS-CONF-2016-069

Model	95% CL exclusion limit Observed	Expected
Quantum black holes, ADD (BLACKMAX generator)	8.7 TeV	8.7 TeV
Excited quark	5.6 TeV	5.5 TeV
W'	2.9 TeV	3.3 TeV
W^*	3.3 TeV	3.3 TeV
Contact interactions (η_{LL} =+1)	12.6 TeV	13.7 TeV
Contact interactions (η_{LL} =-1)	19.9 TeV	23.7 TeV

ATLAS-CONF-2016-060 **2016**



2015 + 2016



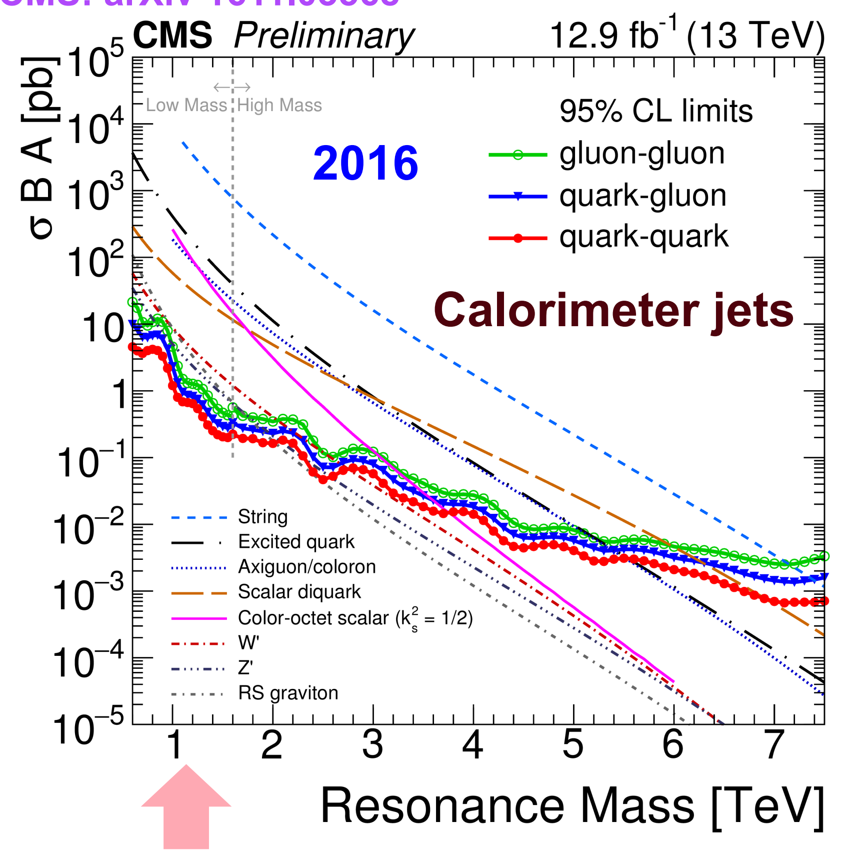
Explore angular distributions: $\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$

also CMS: EXO-15-009

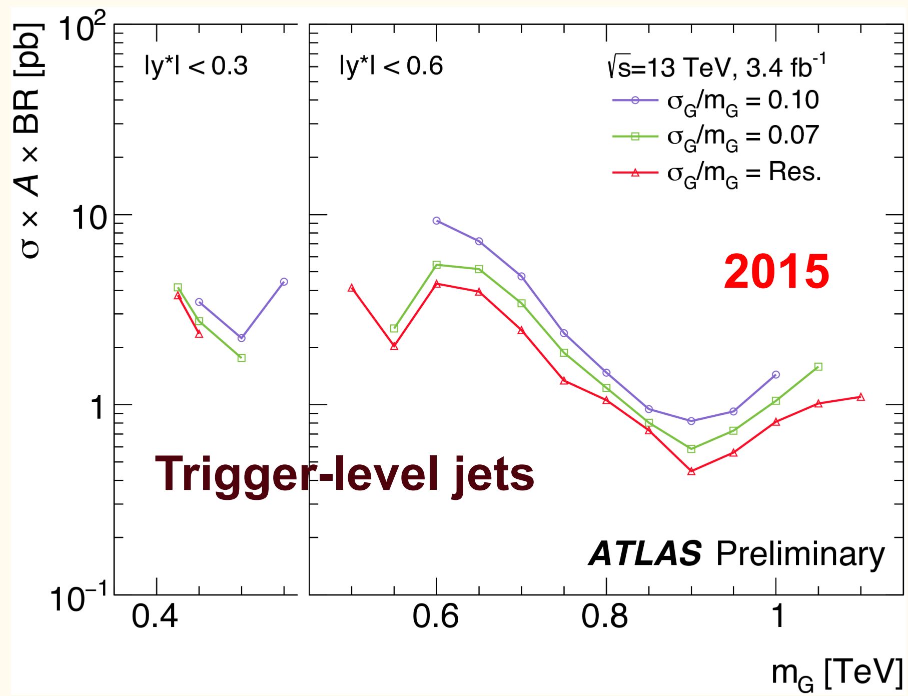
Dijets: low mass

- **Low mass edge of the classical dijet search is limited by trigger threshold**
- **Scouting technique: reducing the stored data volume per event allows for lower trigger threshold and higher rate!**

CMS: arXiv 1611.03568



ATLAS-CONF-2016-030

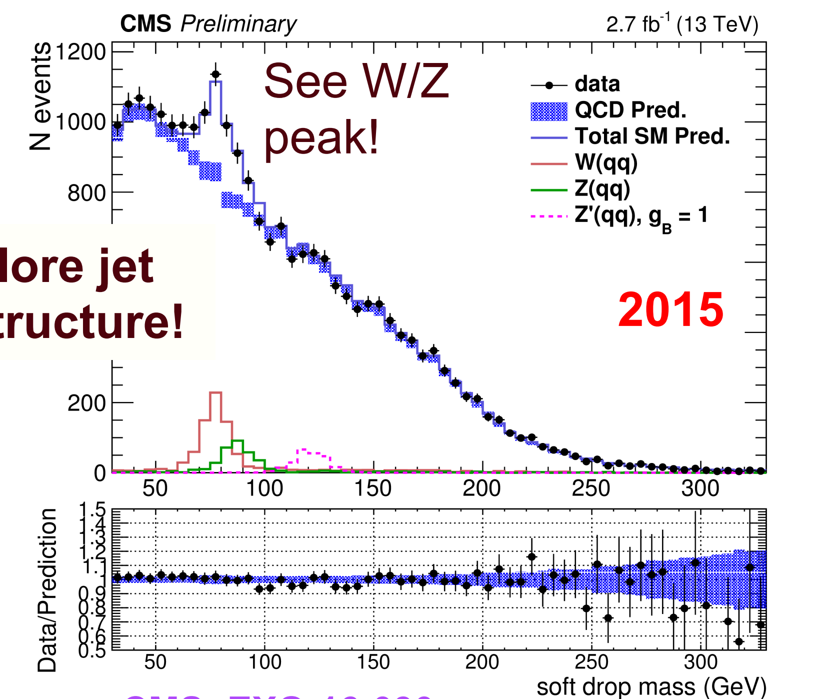


- **Extend sensitivity down to a few hundred GeV**

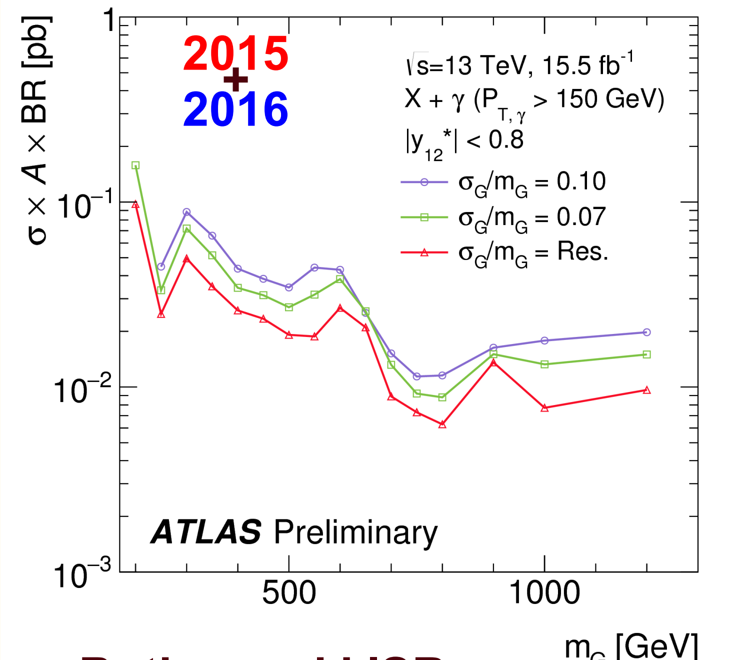
Dijets: even lower mass

- Use initial state radiation (as in Dark Matter or Compressed SUSY searches)!
- Other way to circumvent the trigger threshold, now at a cost of lower production rate

Explore jet substructure!

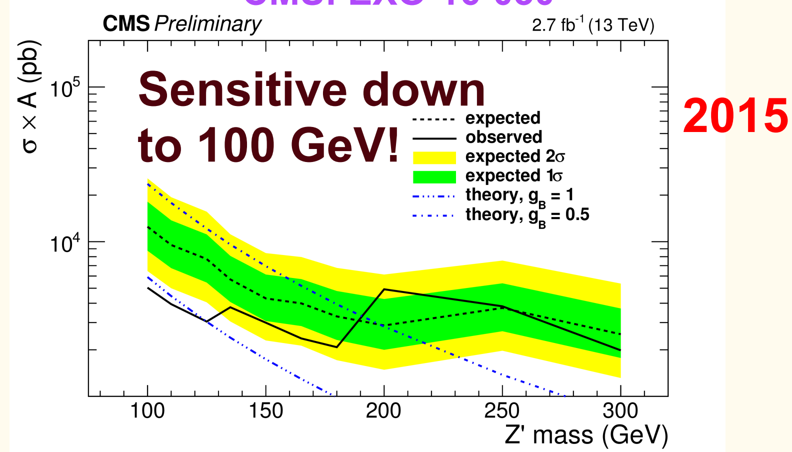


ATLAS-CONF-2016-070

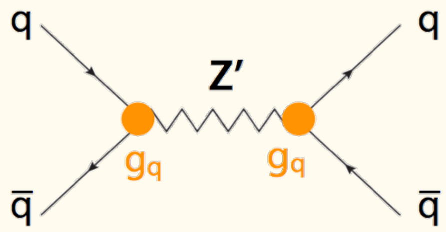


Both γ and j ISR

CMS: EXO-16-030

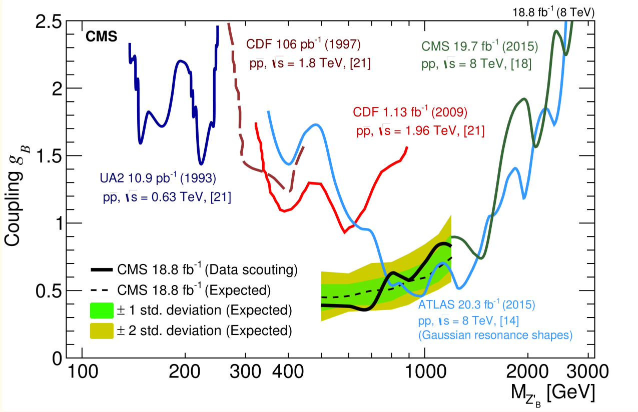


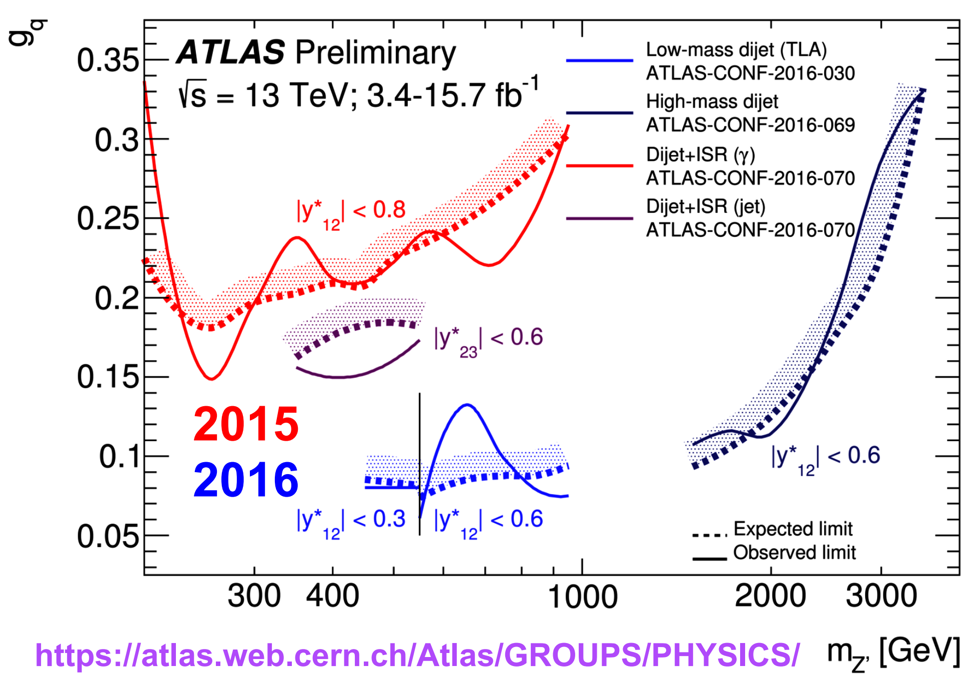
Dijets: big picture



- Convenient: express limits in terms of a coupling to a leptophobic resonance
  - ATLAS – CMS race to cover the vast territory
- Implication for DM!

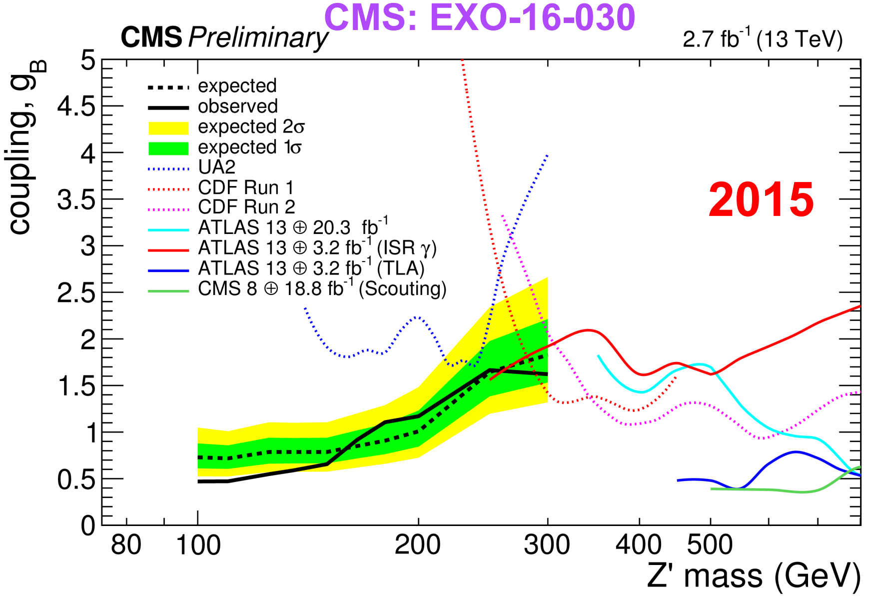
CMS: arXiv 1604.08907 **2012**





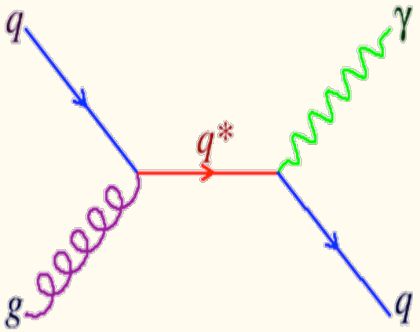
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

CMS: EXO-16-030

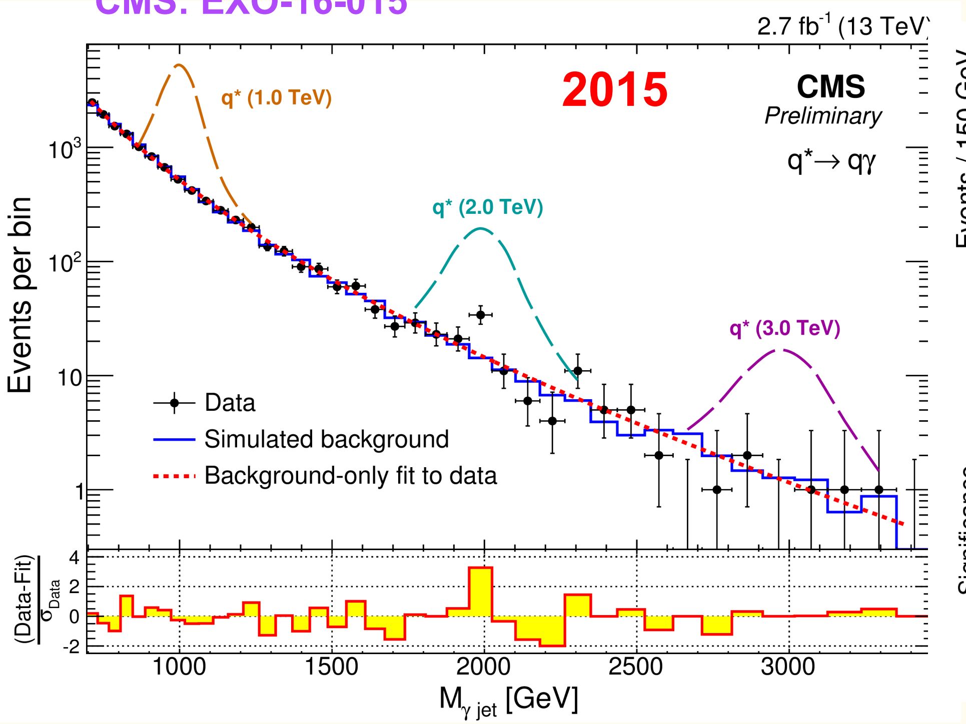


Photon + jet: a cousin of dijet

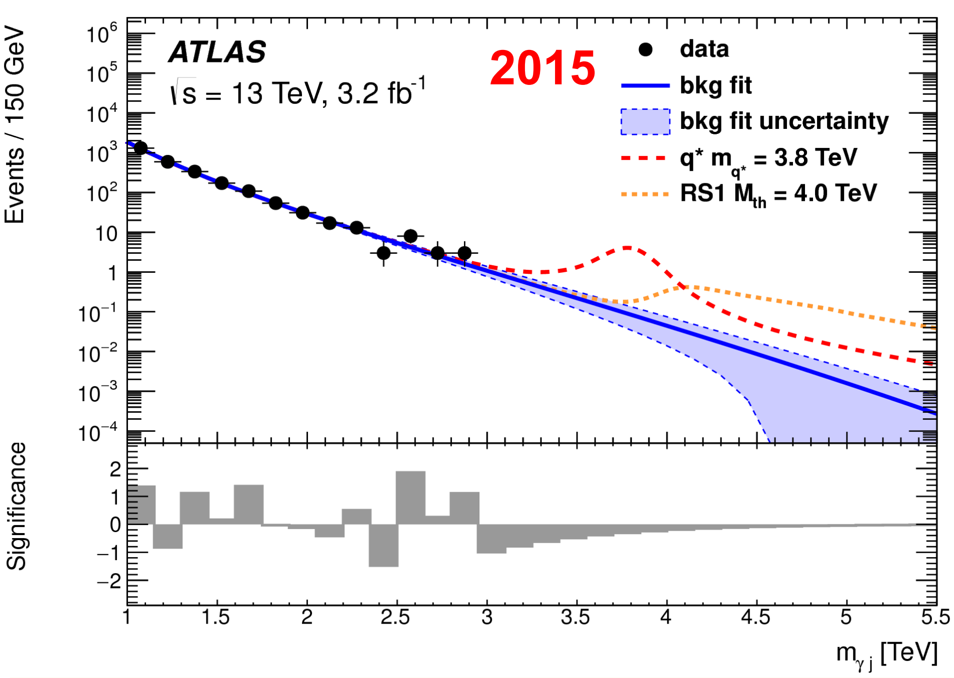
- **Very similar analysis as dijet – competitive e.g. in excited quark search**



CMS: EXO-16-015



ATLAS: JHEP03(2016)041

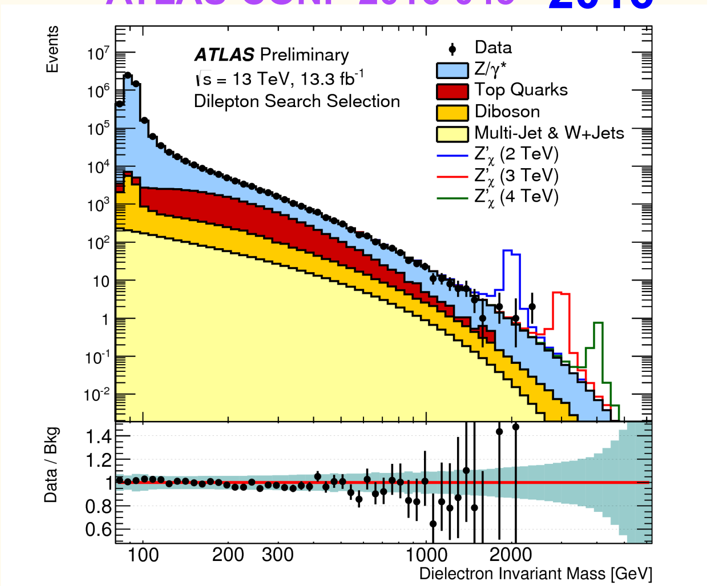


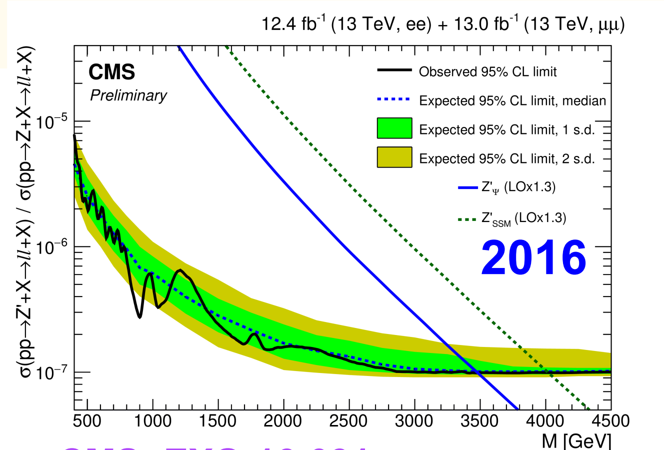
- **Excess at around 2 TeV in CMS 2015 data but not seen in ATLAS**

Dilepton

- **Golden channel, low background, relies on knowledge of SM DY spectrum**

ATLAS-CONF-2016-045 **2016**

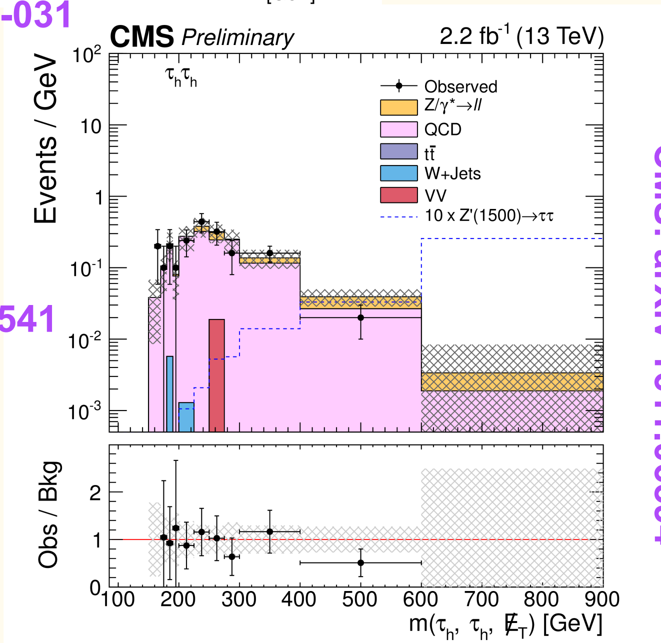




CMS: EXO-16-031

- **Limits on Z' (SSM) mass pushed above 4 TeV (Run 1: < 3 TeV)**

- **Many specific final states probed:**
  - **LFV** CMS: EXO-16-001, ATLAS: EPJC76(2016)541
  - **Same Sign** ATLAS-CONF-2016-051
  - **ττ**
- **More to come from 2016 data**



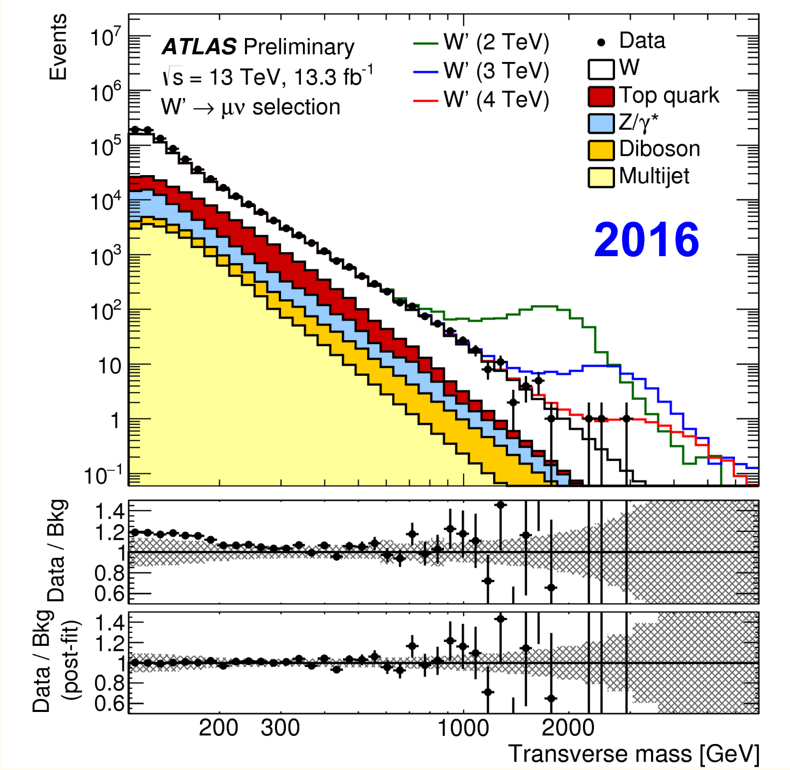
2015

CMS: arXiv 1611.06594

Lepton + neutrino

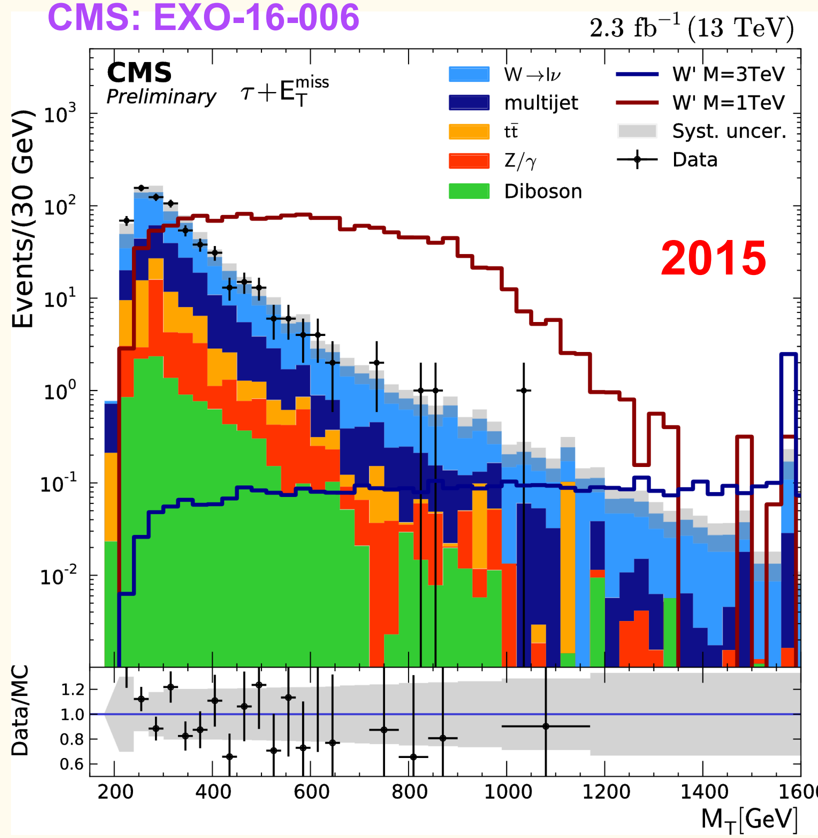
- **Similar to dilepton, but charged resonance, search in transverse mass**

ATLAS-CONF-2016-061

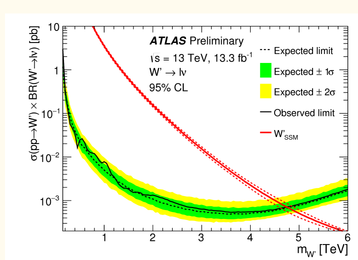


- **Analysis in tau channel:**

CMS: EXO-16-006



- **Limit on W' close to 5 TeV!**

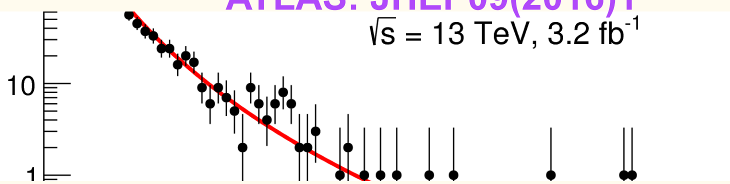


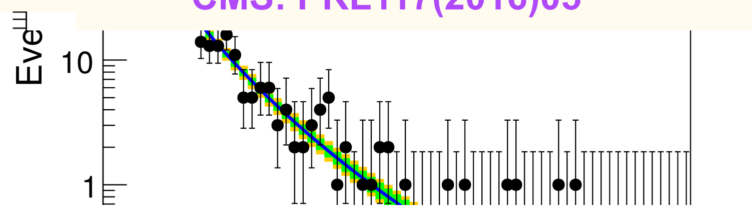
Diphotons: playmate of the year

- **The most popular excess since a long time: ATLAS – CMS match**
- **Has even a wikipedia entry:** https://en.wikipedia.org/wiki/750_GeV_diphoton_excess

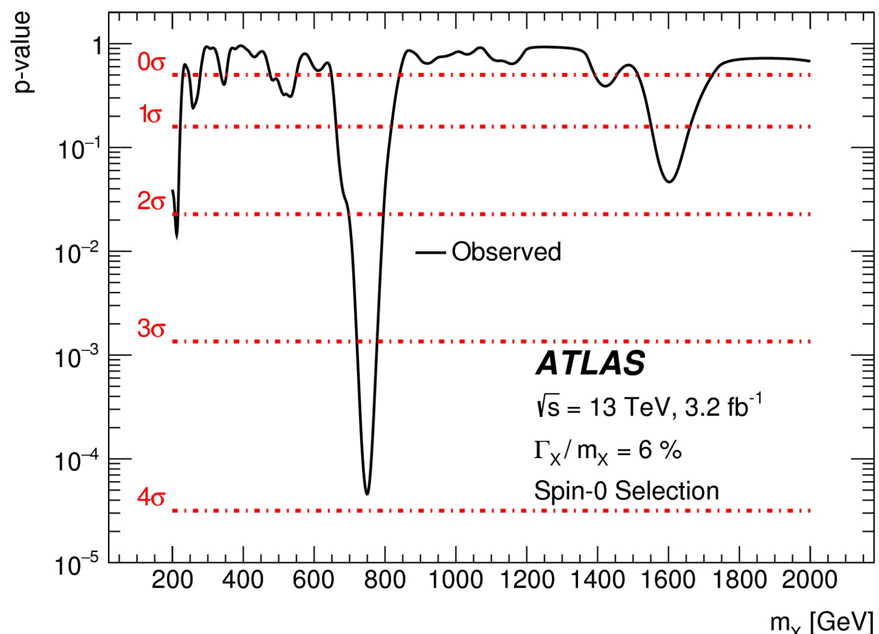
ATLAS: JHEP09(2016)1 | **CMS: PRL117(2016)05**

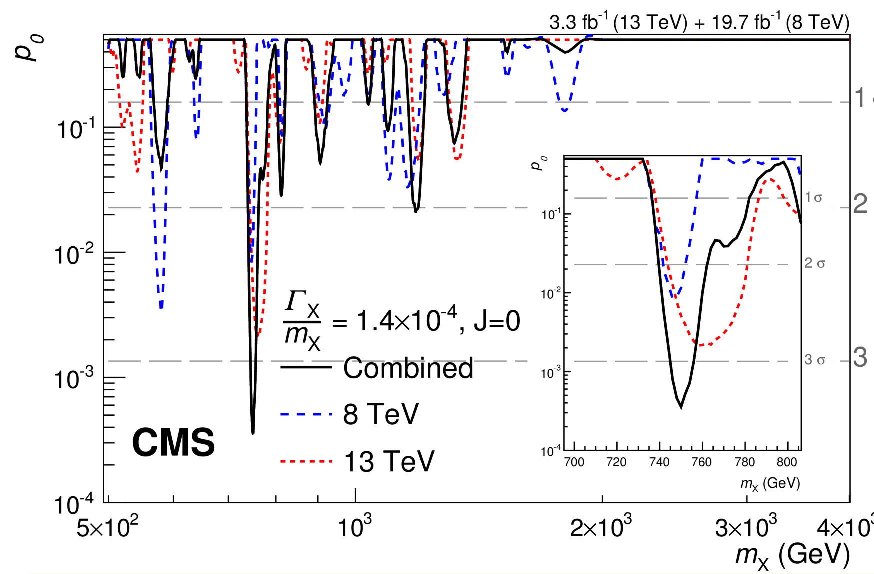
2015





2015



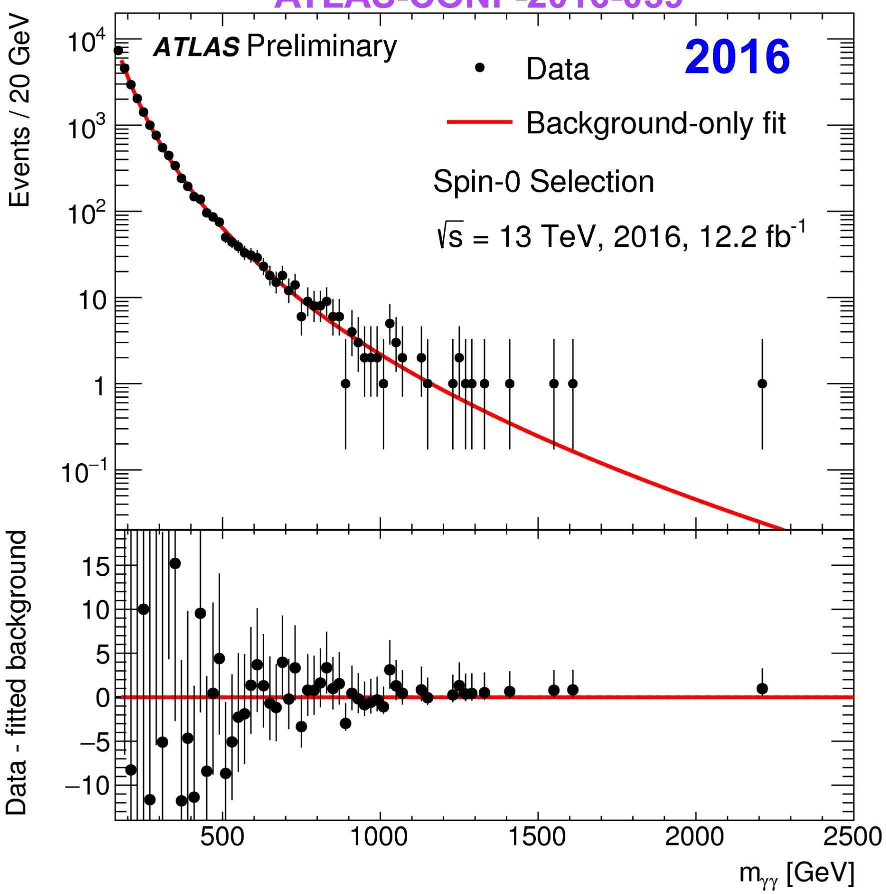


- **Looks compatible even though slightly different widths favored…**
- **Generated about 450 theoretical papers** (exceeded by large predictions of ambulance chasing)

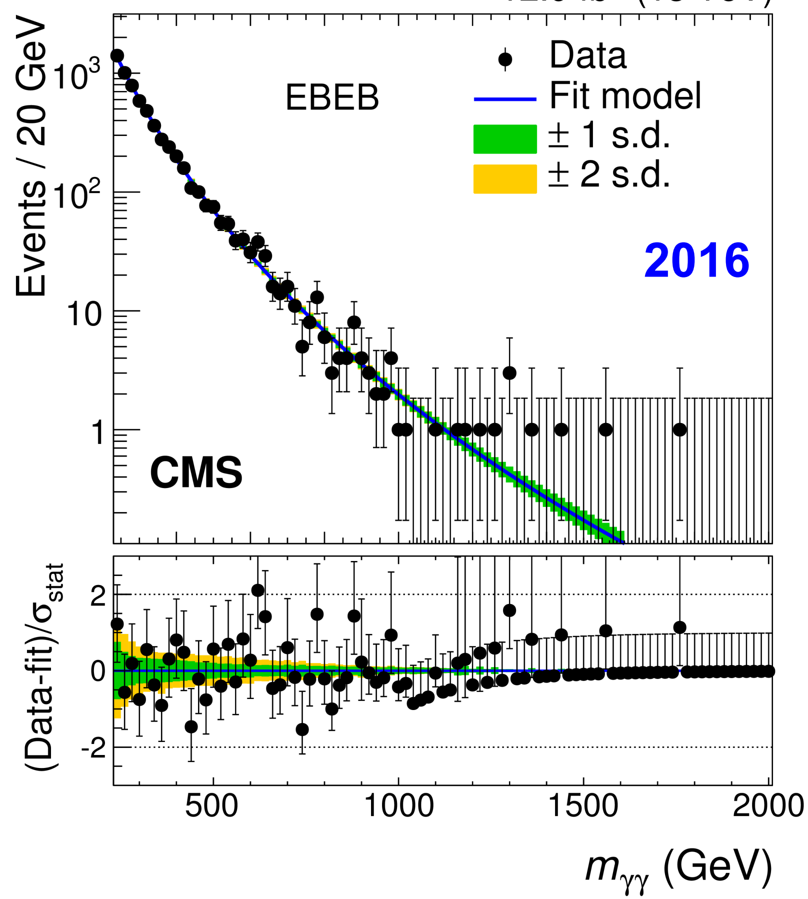
Diphotons: add statistics

- **2016 data do not confirm the excess**

ATLAS-CONF-2016-059



CMS: arXiv 1609.02507

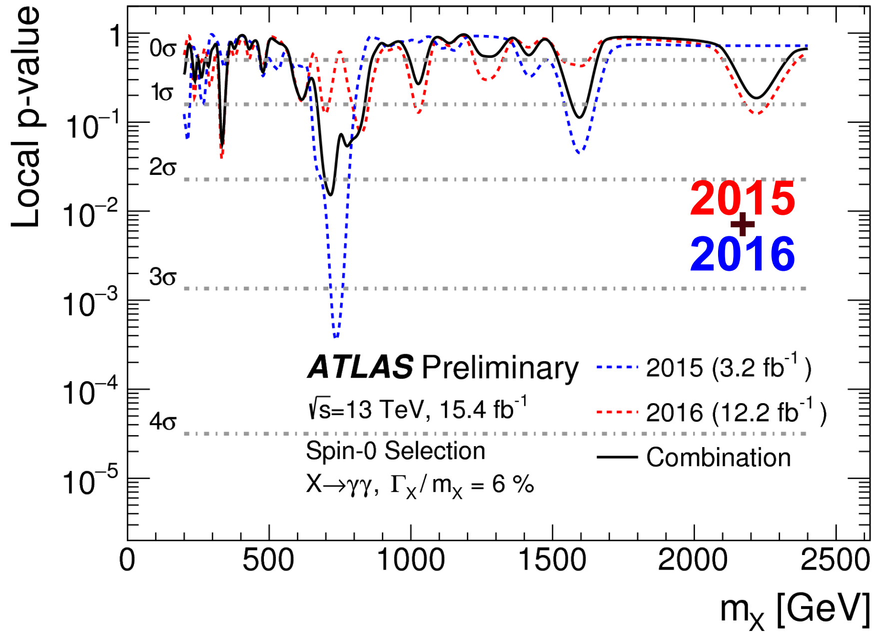


- **Limit on RS graviton ($k/M_{Pl} = 0.1$) almost 4 TeV (Run 1: 2.7 TeV)**

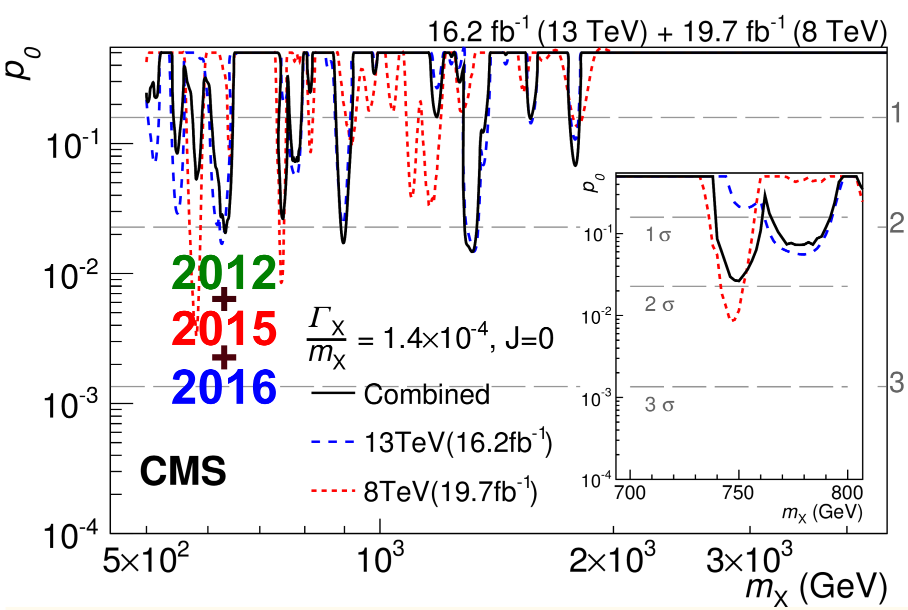
Diphoton excess: resume

- **Combining 2015 and 2016 samples, the deviations with largest significance appear at masses outside of the 700 – 800 GeV range in both experiments**

ATLAS-CONF-2016-059



CMS: arXiv 1609.02507



- **Highest excess in the 700 – 800 GeV range at M = 710 GeV:**

  2.3 σ local and < 1 σ global

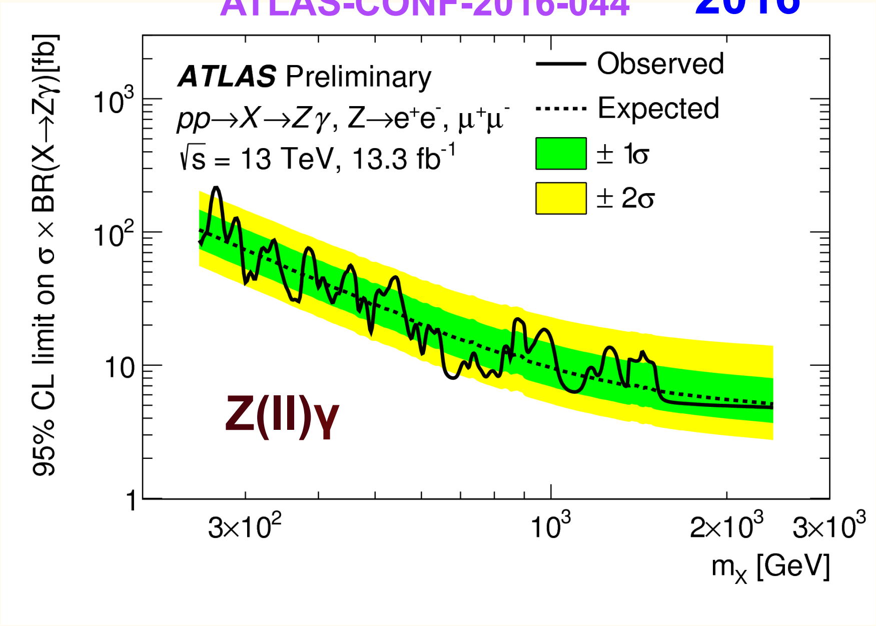
- **Highest excess in the 700 – 800 GeV range still at M = 750 GeV:**

  1.9 σ local and < 1 σ global

Zγ: a cousin of diphotons

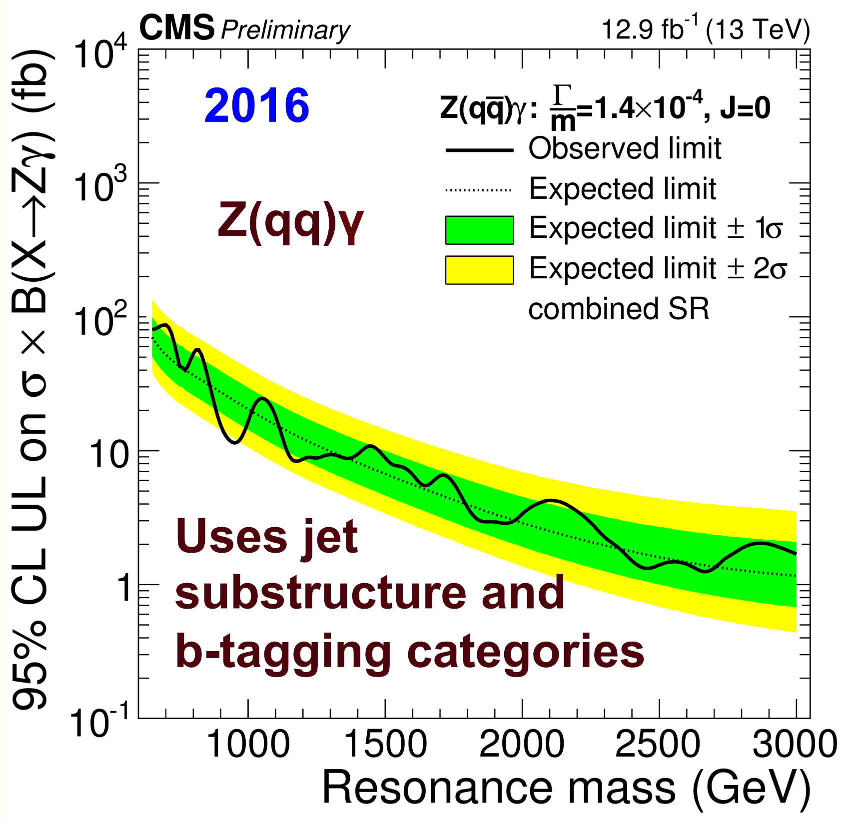
- **Interest boosted by the 750 GeV excess**
- **Leptonic channel has better sensitivity at lower masses – less background**
- **Hadronic channel better at high mass**

ATLAS-CONF-2016-044 **2016**



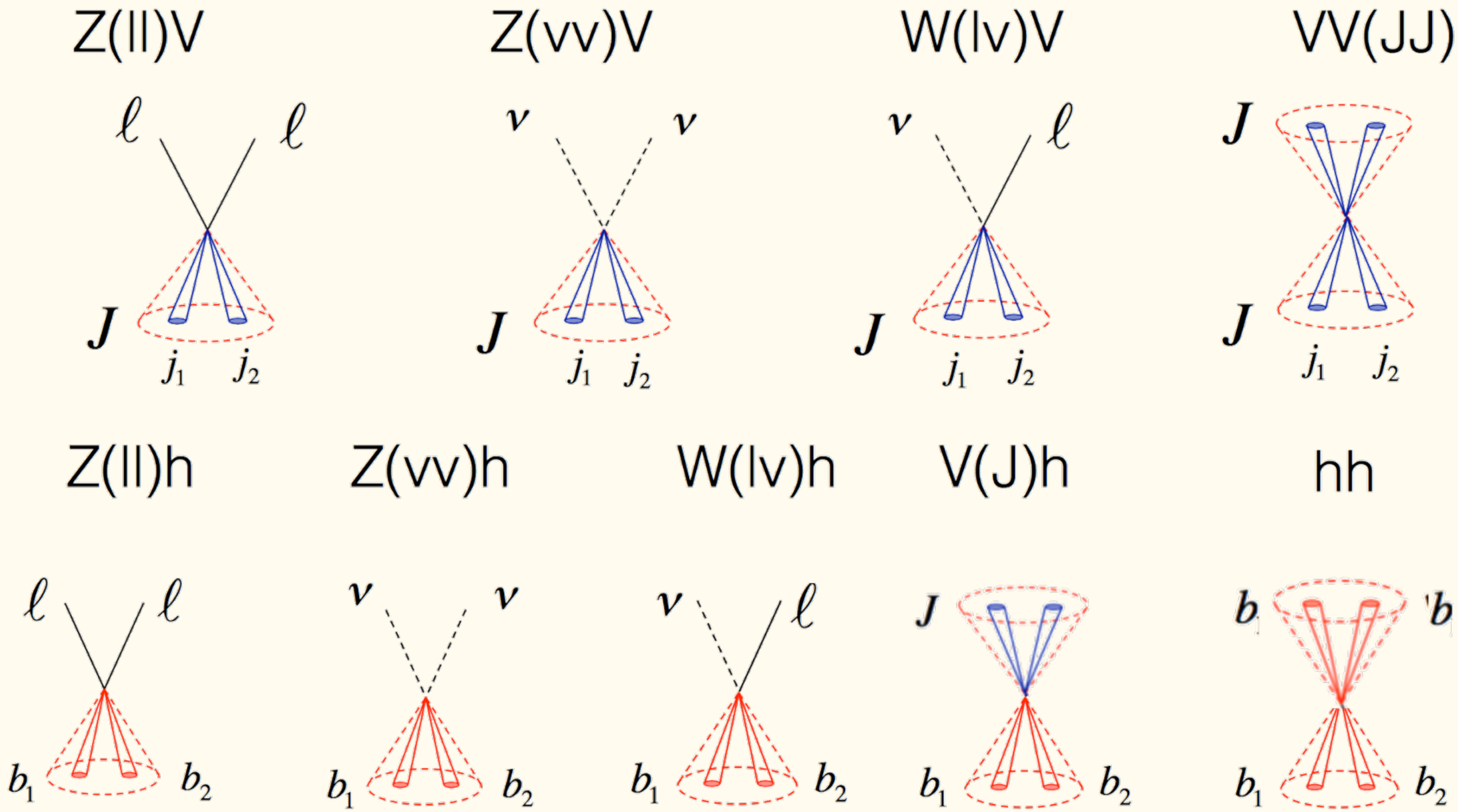
Also: CMS: EXO-16-034

CMS: EXO-16-035



Dibosons: VV/Vh/hh

- **Large variety of competitive final states – balance background vs. BR**
- **Extensively relies on and pushes forward jet substructure techniques**
- **Higgs is becoming integral part of the suite**

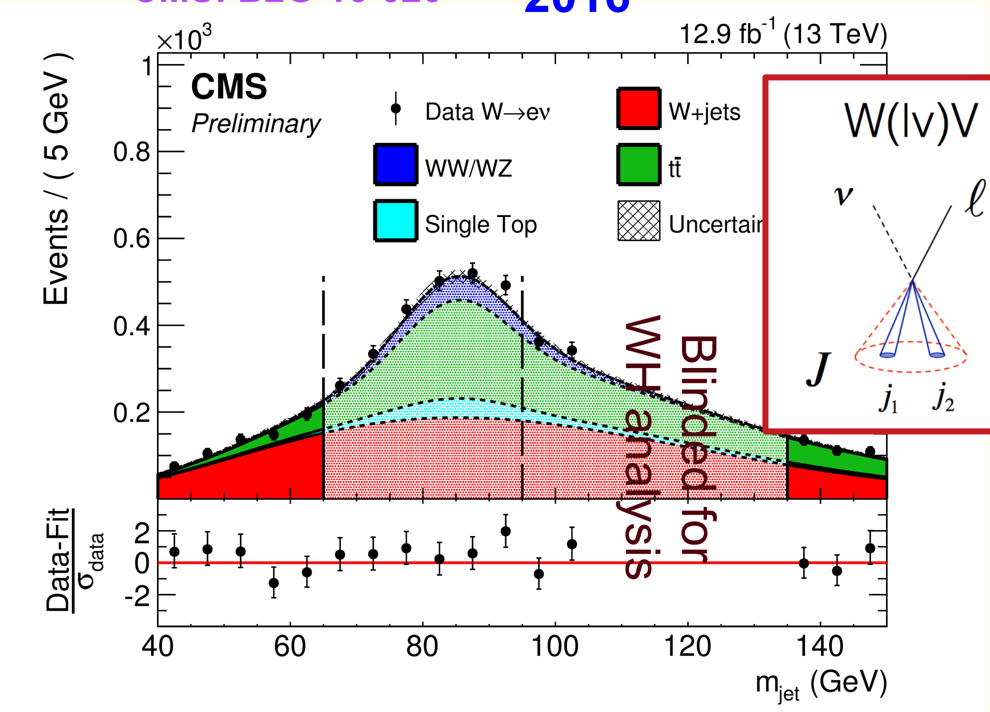


Dibosons: performance

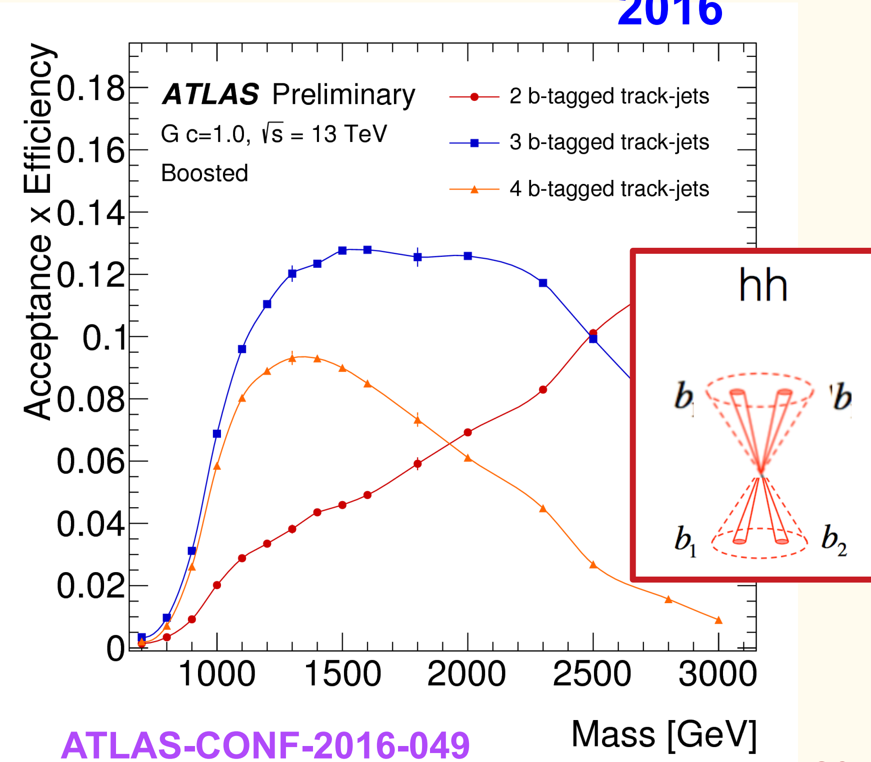
- Jet substructure performance is studied and calibrated using tt samples – source of boosted Ws.
- Background estimated using jet mass sidebands

- In hh searches, number of b-tags increases the signal purity but the efficiency decreases with resonance mass
- Use b-tag categories to cover the whole mass range

CMS: B2G-16-020 **2016**



2016

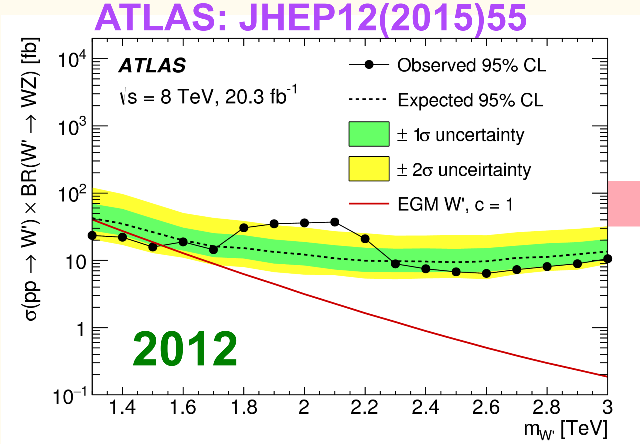


ATLAS-CONF-2016-049

Dibosons: Run 1 excess

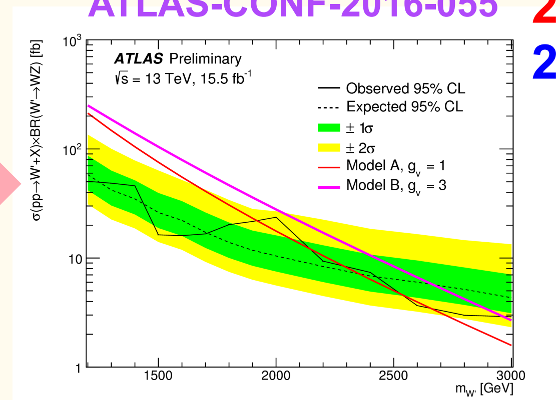
- **The most popular excess from Run 1: moderate excesses only in some channels (mainly all-hadronic) both in ATLAS and CMS around 1.8 – 2 TeV**

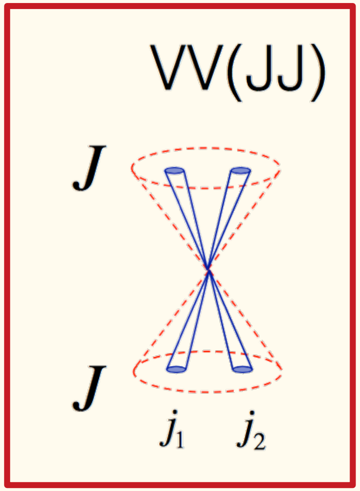
ATLAS: JHEP12(2015)55



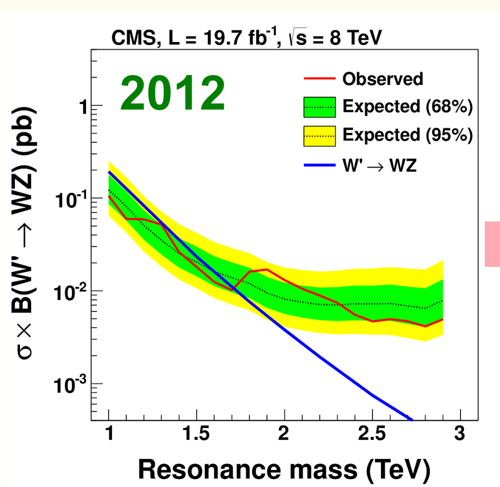
ATLAS-CONF-2016-055

2015 + 2016

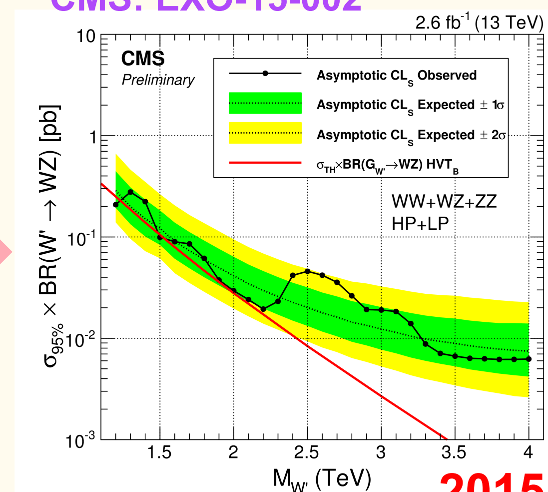




CMS: JHEP08(2014)173



CMS: EXO-15-002



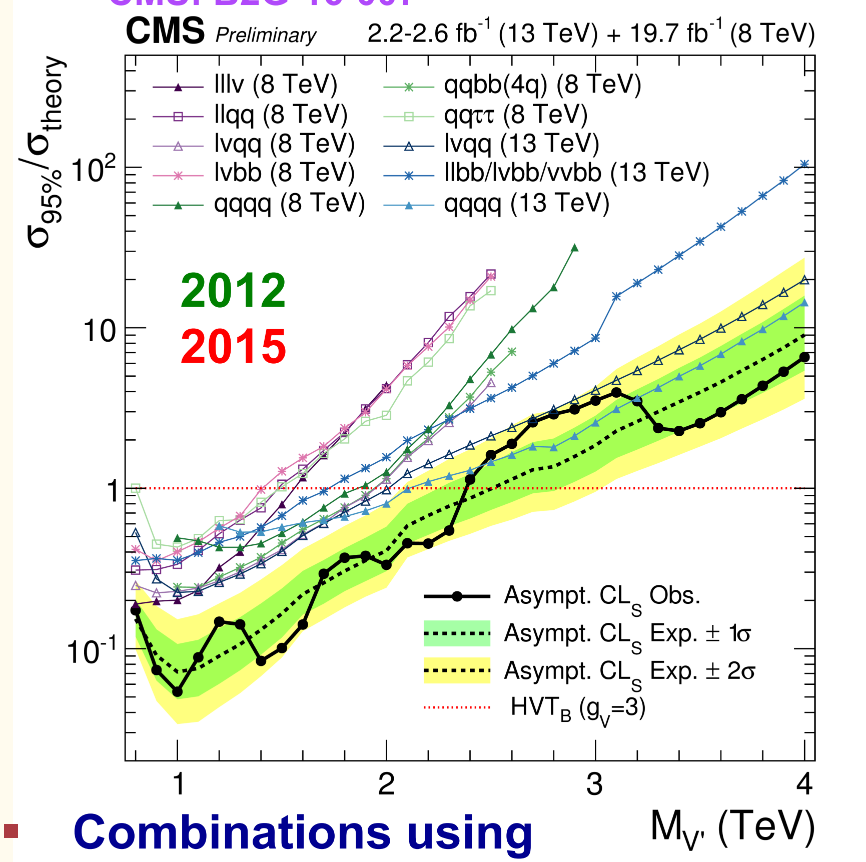
2015

- **Excess not confirmed in Run 2 data…**

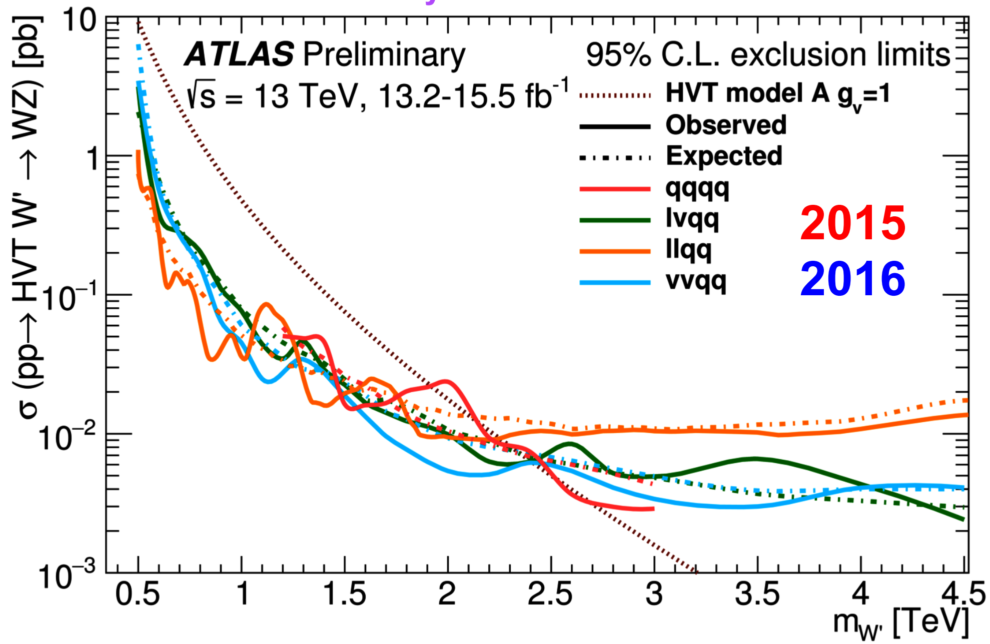
Dibosons: status

- **Many competing channels: spin-1 interpretation using Heavy Vector Triplet simplified model with two benchmarks, A and B (fermiophobic)**

CMS: B2G-16-007



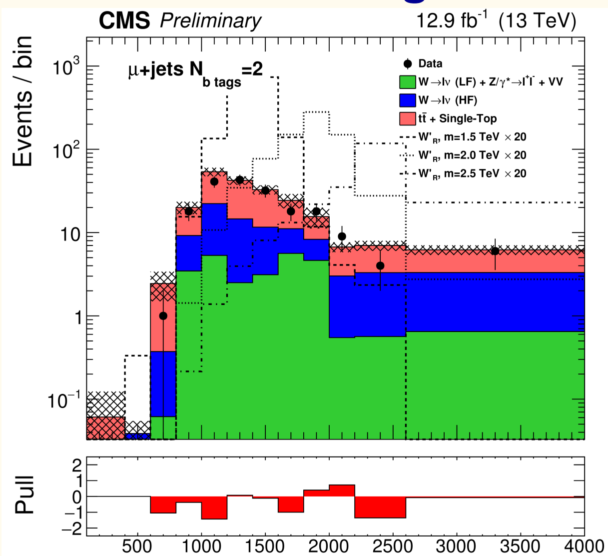
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html



- **Combinations using appropriate final states: W'➔WZ/WH, Z'➔WW/ZH, V'➔WV/VH, G_{bulk}➔VV**
- **Exclusion limits for HVT W' or Z' between 2 – 3 TeV**
- **Limit for bulk RS Graviton (k/M_{Pl}=1) at 1.2 TeV**

tb resonance

- **Very competitive esp. in the search for massive right handed W'_R**
- **Much lower background than simple dijet**

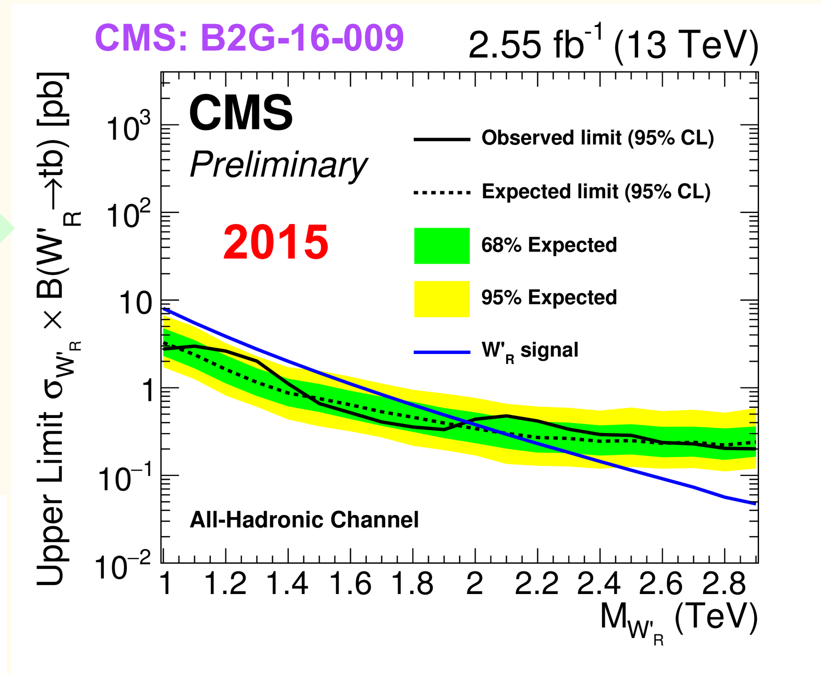


2016

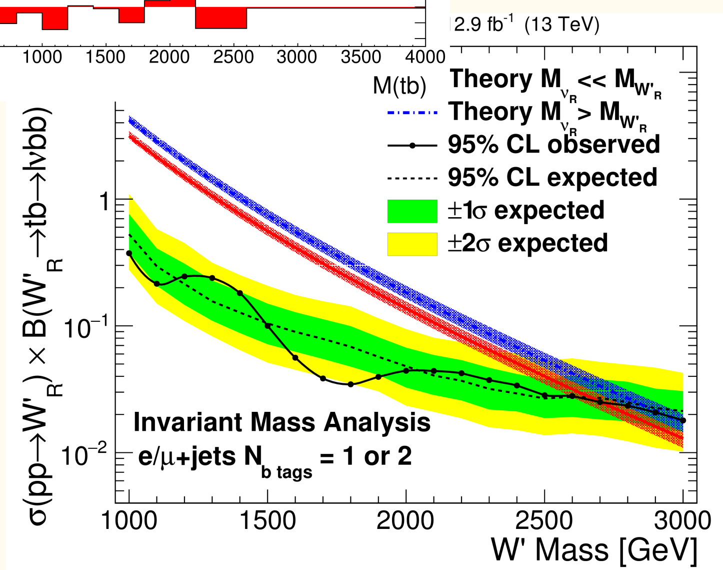
Channel:

hadronic

leptonic



CMS: B2G-16-017

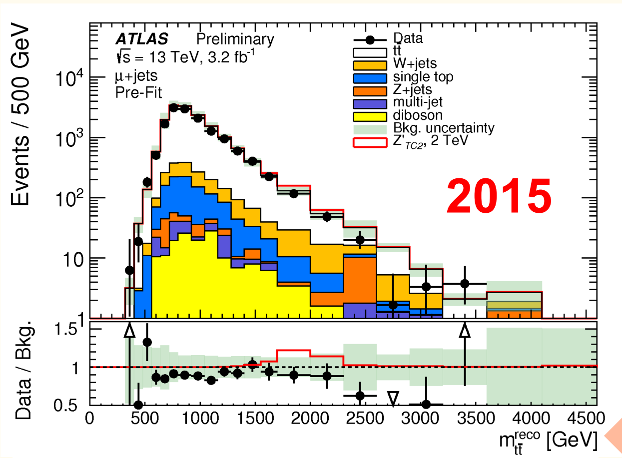


- **With 2016 data limits are pushed up to almost 3 TeV**

tt resonance

- **Serach for leptophobic Z', RS gluon or other resonances with enhanced coupling to tt**

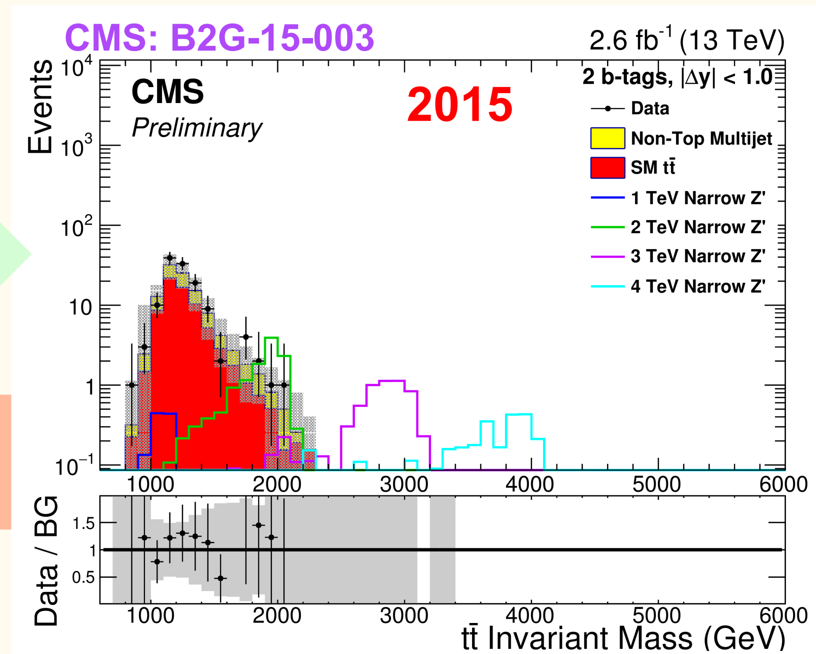
ATLAS-CONF-2016-014

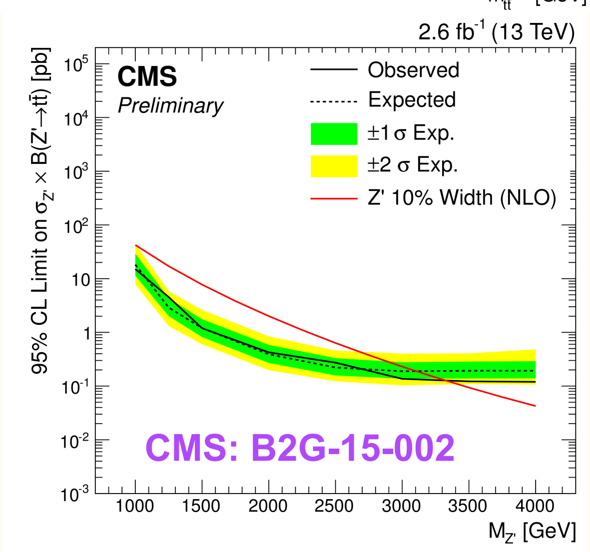


Channel:

All-hadronic

Semi-leptonic

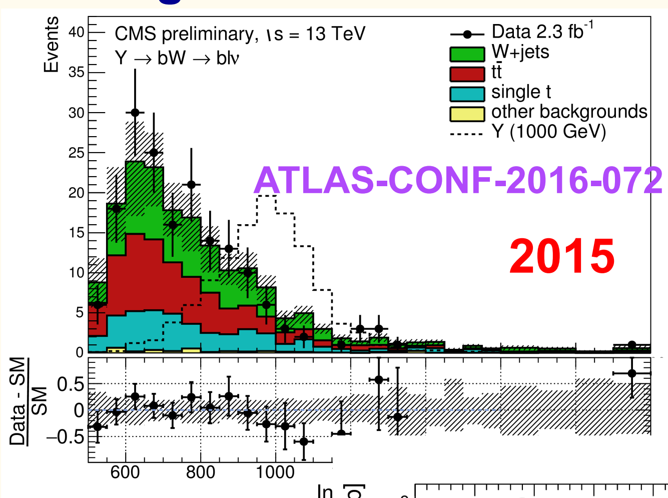


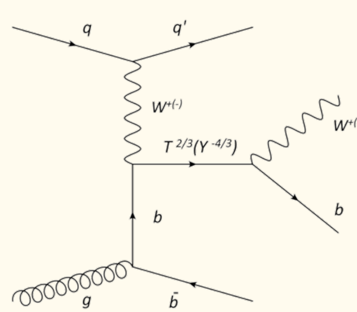


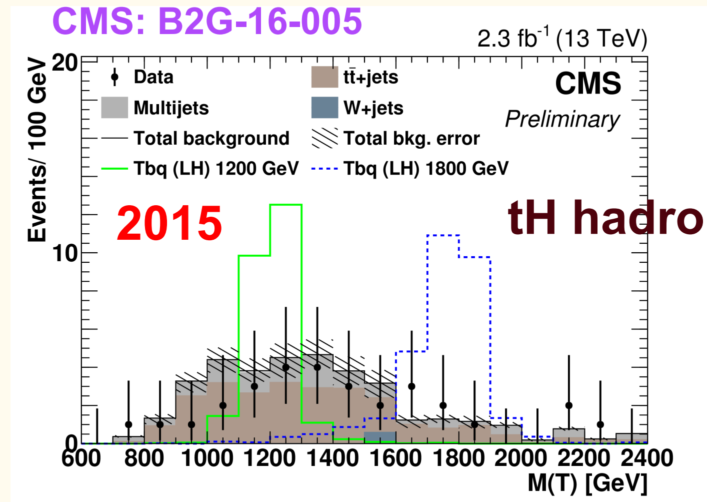
- **With 2015 data limits for leptophobic Z' range between 2 – 4 TeV depending on the width**
- **RS gluon limits around 3 TeV**

Boson – heavy quark resonance: VLQ

- Vector-like quark: most natural extension of the quark sector
- In Run 1 the focus on QCD pair production of VLQs
- The EWK production of single VLQ becomes dominant at high mass
- Large multitude of final states including Higgs boson

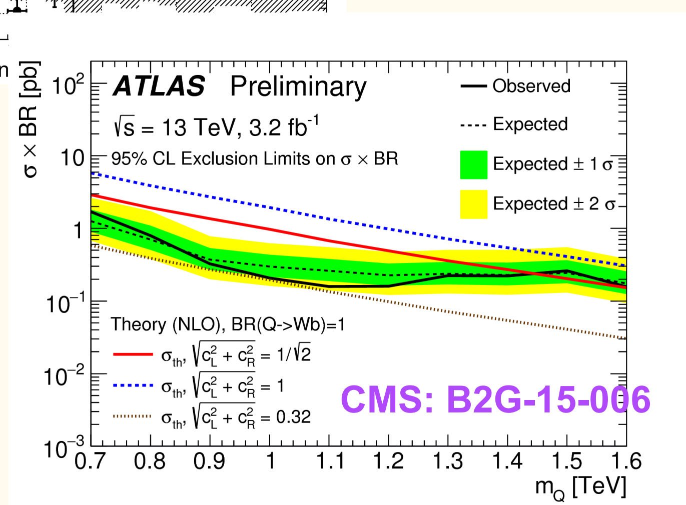






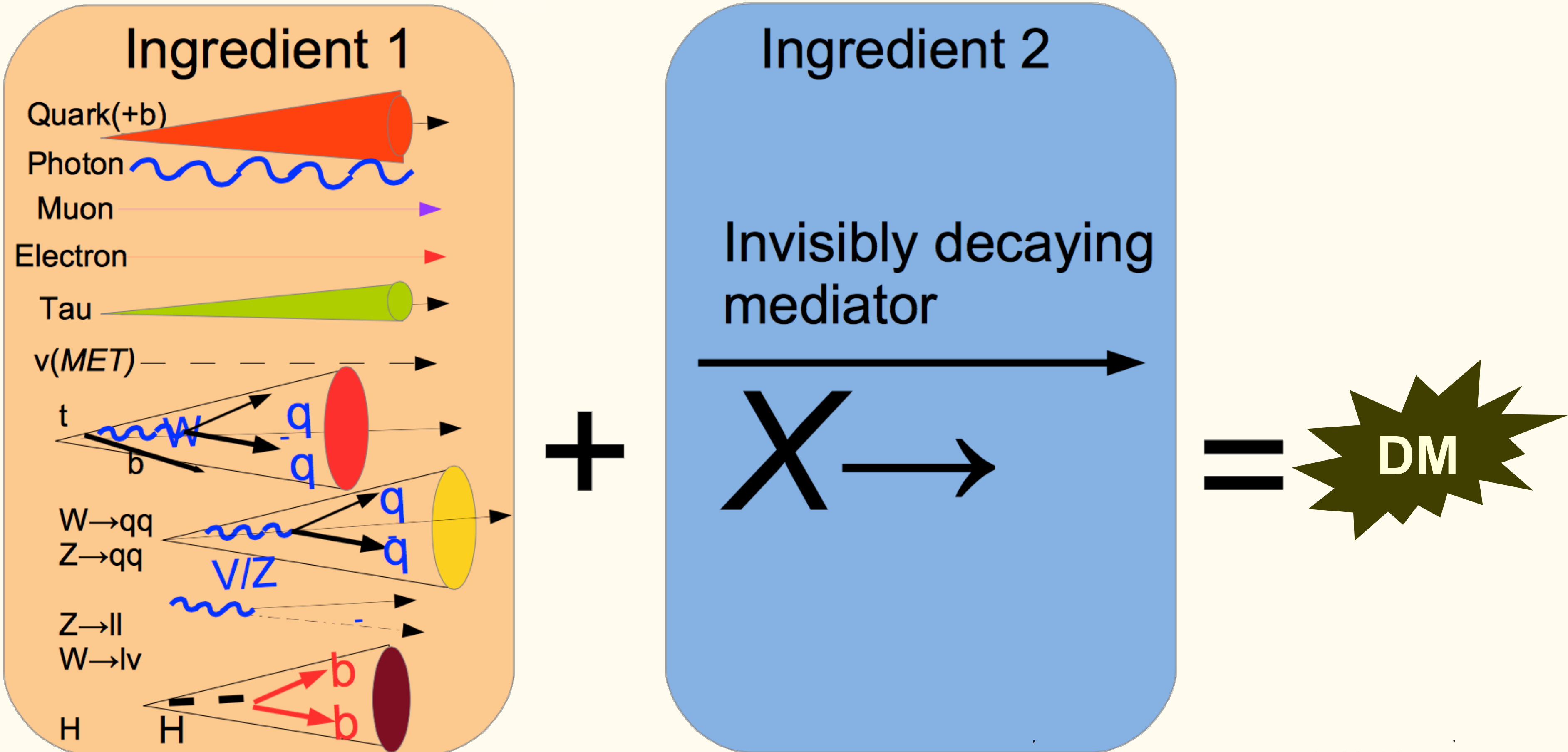
bW leptonic

2015

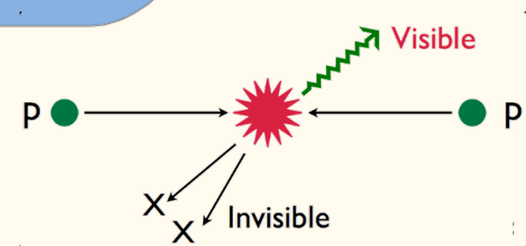


- Limits up to 1.5 TeV depending on coupling
- Run 1 limits ranged between 600 - 900 GeV

Dark Matter searches



- **Missing transverse energy (MET) back-to-back to a visible recoil (e.g. ISR)**



DM search boom

- …converted to reality:

ATLAS DM searches at ICHEP 2016

Analysis	Dataset	Public link
Production search:		
E_T^{miss}+jet	2015	Paper: EXOT-2015-03
$E_T^{miss}+\gamma$	2015	Paper: EXOT-2015-05
$E_T^{miss}+Z(\to \ell\ell)$	2015+2016	Note: ATLAS-CONF-2016-056
$E_T^{miss}+W/Z(\to qq)$	2015	Paper: EXOT-2015-08
$E_T^{miss}+H(\to bb)$	2015	Note: ATLAS-CONF-2016-019
$E_T^{miss}+H(\to \gamma\gamma)$	2015+2016	Note: ATLAS-CONF-2016-087
$E_T^{miss}+H(\to \ell\ell\ell\ell)$	2015	Note: ATLAS-CONF-2015-059
E_T^{miss}+b-jets	2015+2016	Note: ATLAS-CONF-2016-086
$E_T^{miss}+t\bar{t}\ (0\ell)$	2015+2016	Note: ATLAS-CONF-2016-077
$E_T^{miss}+t\bar{t}\ (1\ell)$	2015+2016	Note: ATLAS-CONF-2016-050
$E_T^{miss}+t\bar{t}\ (2\ell)$	2015+2016	Note: ATLAS-CONF-2016-076

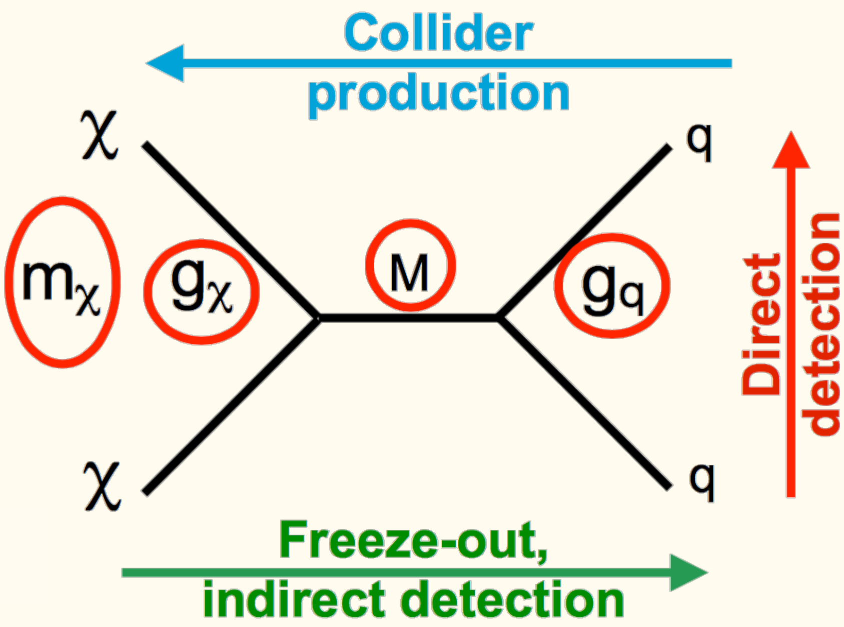
- A lot of new results in 2016 Summer conferences and a lot more to come…

CMS DM searches at ICHEP 2016

X	Dataset	CMS Documentation
jet or V (hadronic)	2016, 12.9 fb	EXO-16-037
photon	2016, 12.9 fb	EXO-16-039
Z (ll)	2015, 2.3 fb	EXO-16-010
Z (ll)	2016, 12.9 fb	EXO-16-038
Higgs (bb)	2015, 2.3 fb	EXO-16-012
Higgs (γγ)	2015, 2.3 fb	EXO-16-011
tt (semilep+had)	2015, 2.2 fb	EXO-16-005
t (hadronic)	2016, 12.9 fb	EXO-16-040

DM: Run 2 strategy

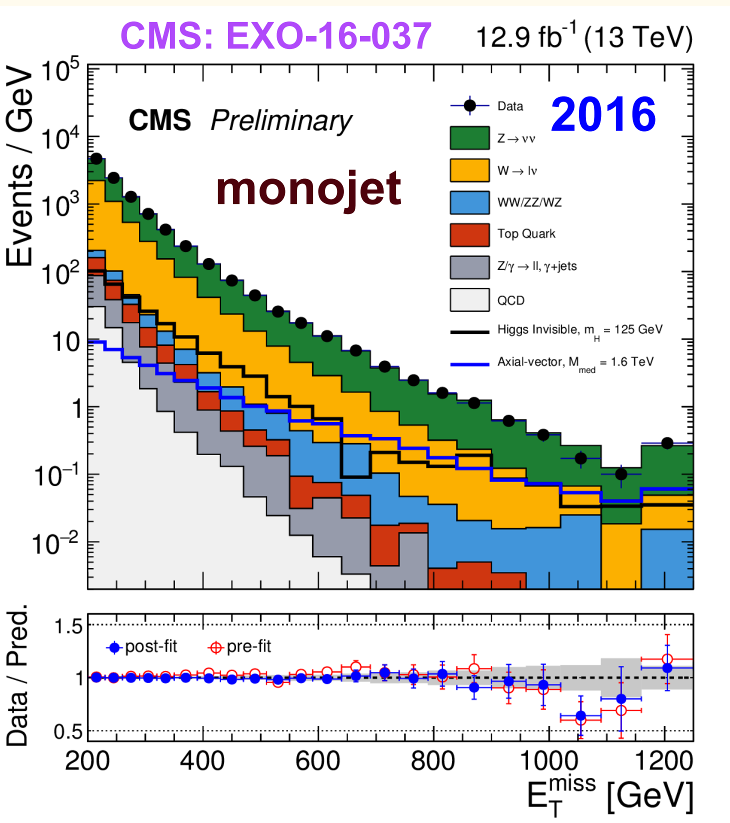
- After Run 1 a big step forward in defining the strategy of interpretation: ATLAS/CMS DM Forum (arXiv 1507.00966) and LHC DM WG (arXiv 1603.04156)
- Concerns about the Run 1 Effective Field Theory approach overcome using a Simplified Model with a single mediator
- Parameter space extended to four parameters: DM and mediator mass and mediator couplings to DM and SM
- Defined reasonable benchmarks respecting existing constraints and allowing to compare the results between ATLAS and CMS

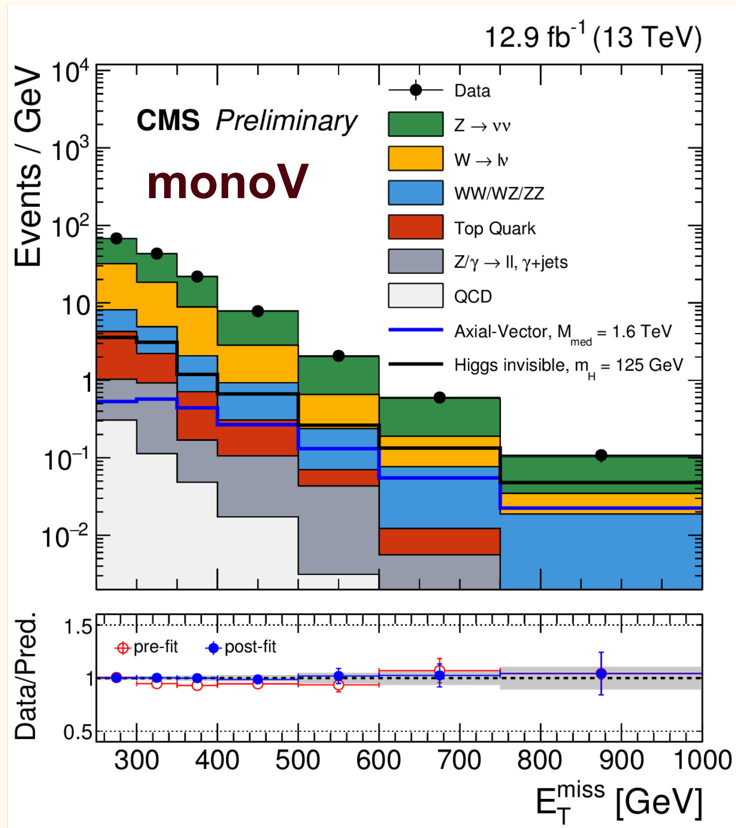


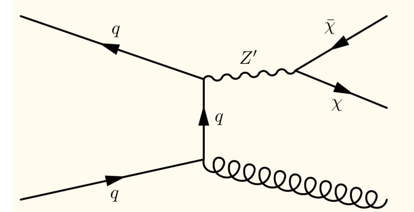
- Recommendations have been made on how to represent the results and how to compare to Direct/Indirect Detection experiments
- Focus on spin-0 and spin-1 mediators with reasonable choice of couplings (minimal width); representation in m_{DM}-M_{med} plane (a la SUSY)

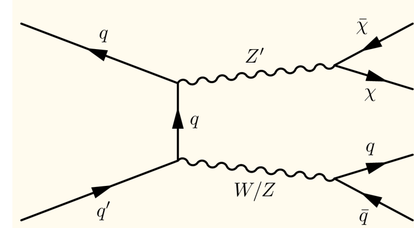
Monojet/V

- **Flagship DM collider search analysis**
- **Build on experience from Run 1**
- **Combines simple jet and boosted V-tagged jet signatures**
- **Main bkg. Z(vv)+j estimated using various control samples (esp. γ+jets)**



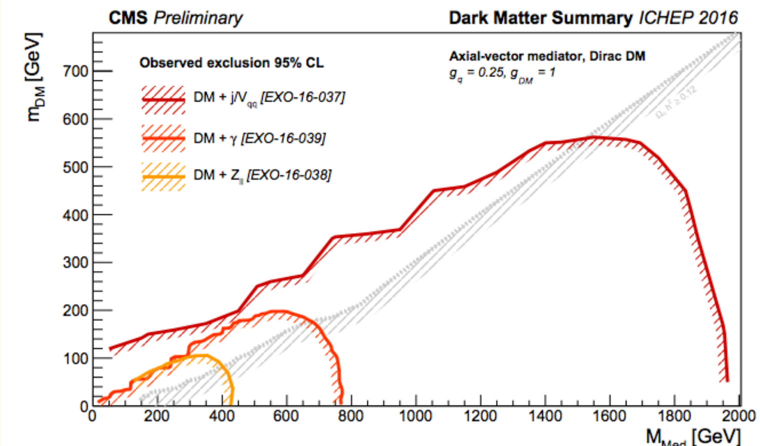


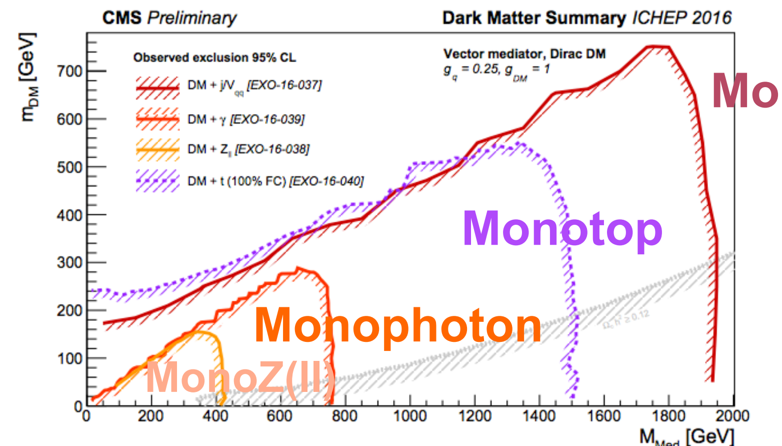




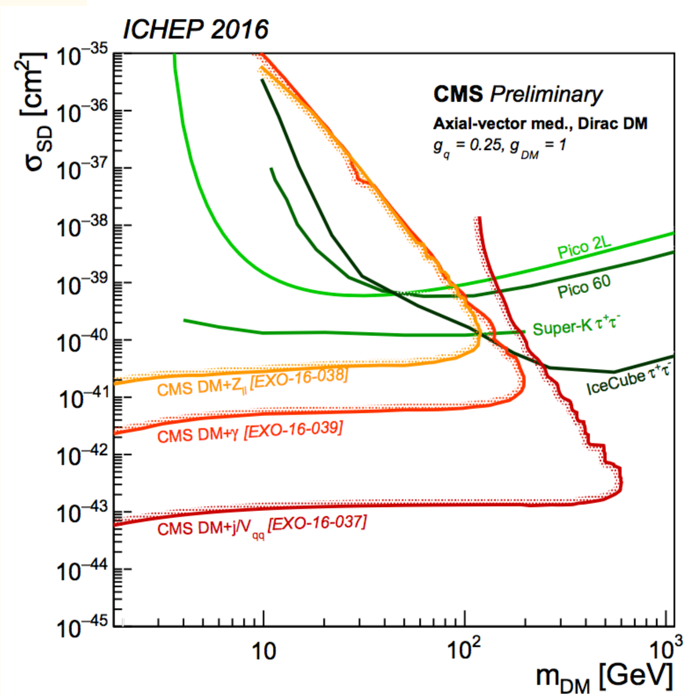
MonoX reach

Axial-vector mediator **2016** **Vector mediator**

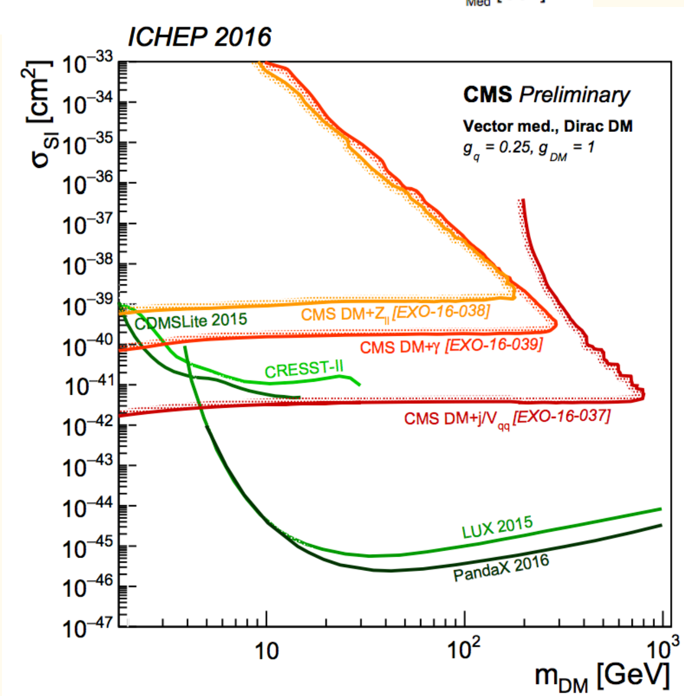




CMS: DP-2016/057

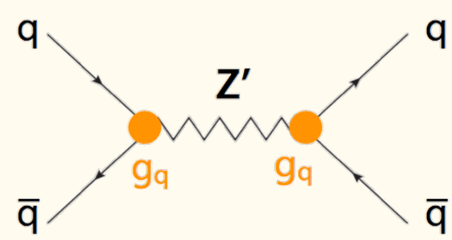


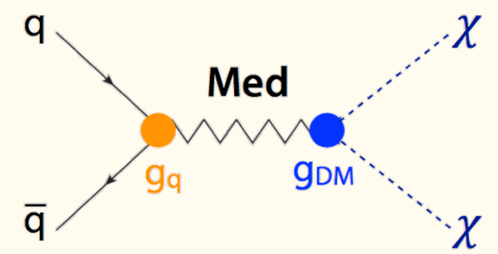
Collider searches complementary to DD exp. for axial-vector mediator models and vector mediator with low m_{DM}



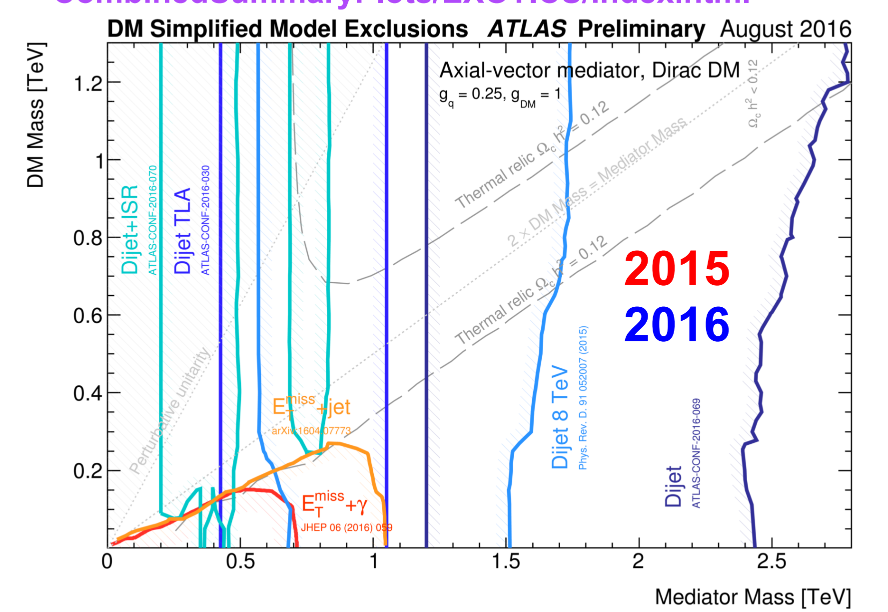
DM vs. resonance search

- **Comparison of exclusions from various dijet searches and DM searches**
- **Here, the benchmark is a leptophobic axial-vector mediator with g_q=0.25 and g_{DM}=1**

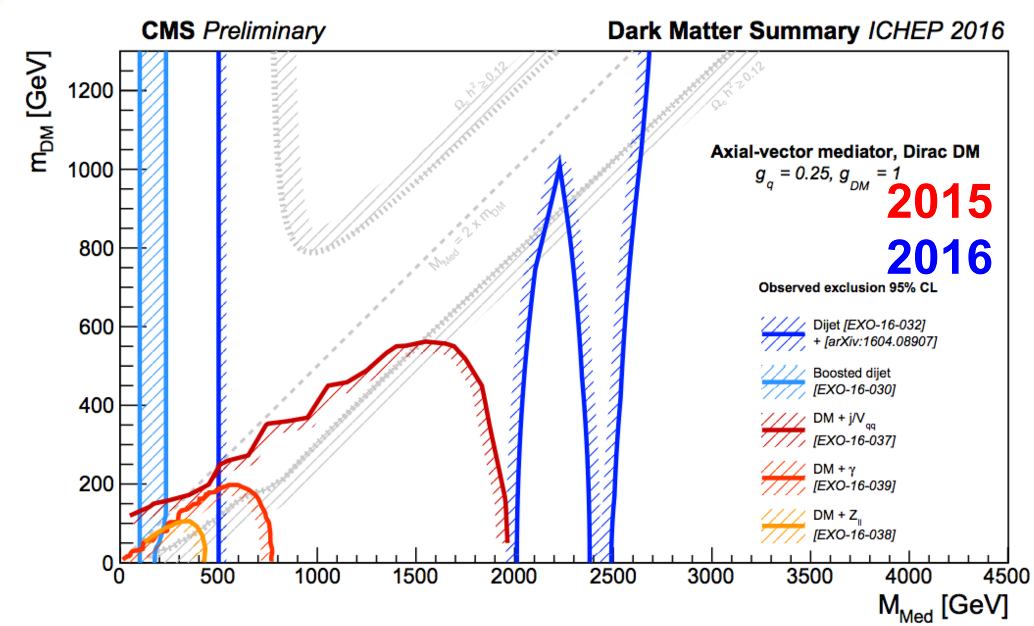




https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

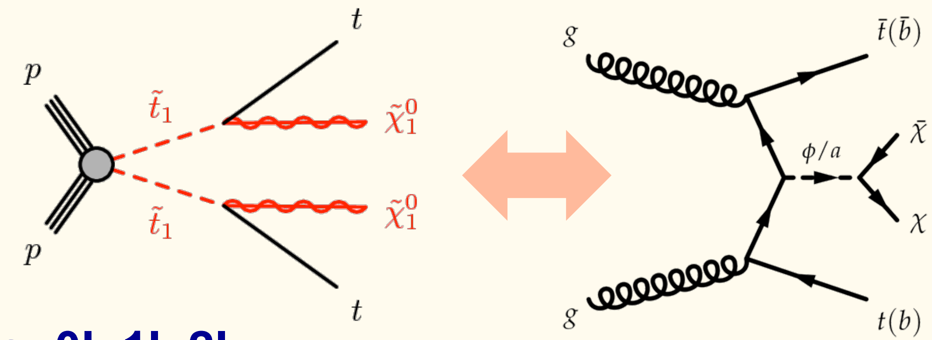


CMS: DP-2016/057

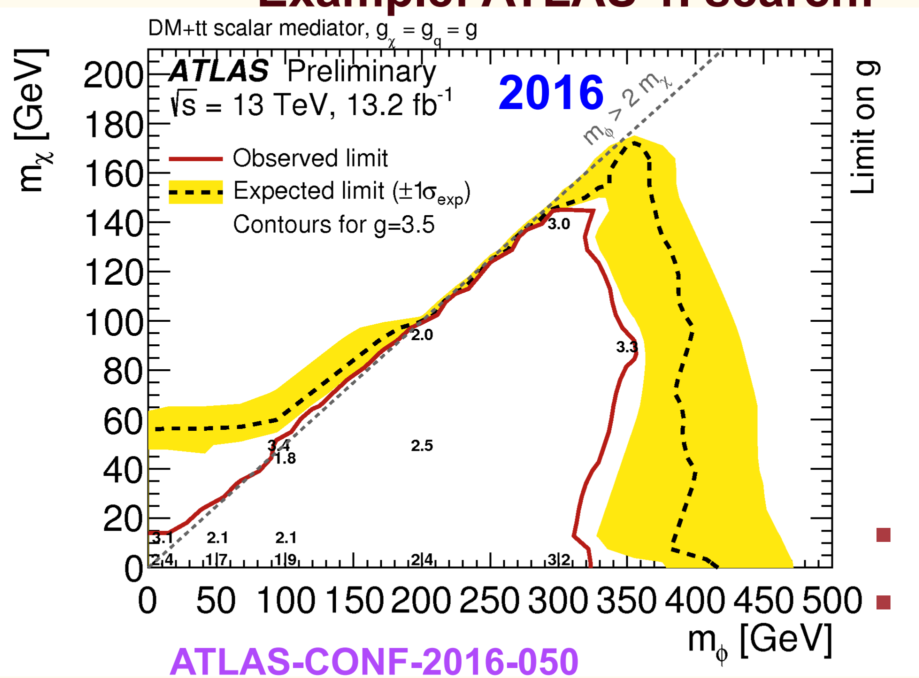


DM + tt

- **Particularly suitable for DM searches with (pseudo-)scalar mediator**
- **Typical SUSY signature – recycle SUSY analyses**
- **Good sensitivity in all channels: 0l, 1l, 2l**

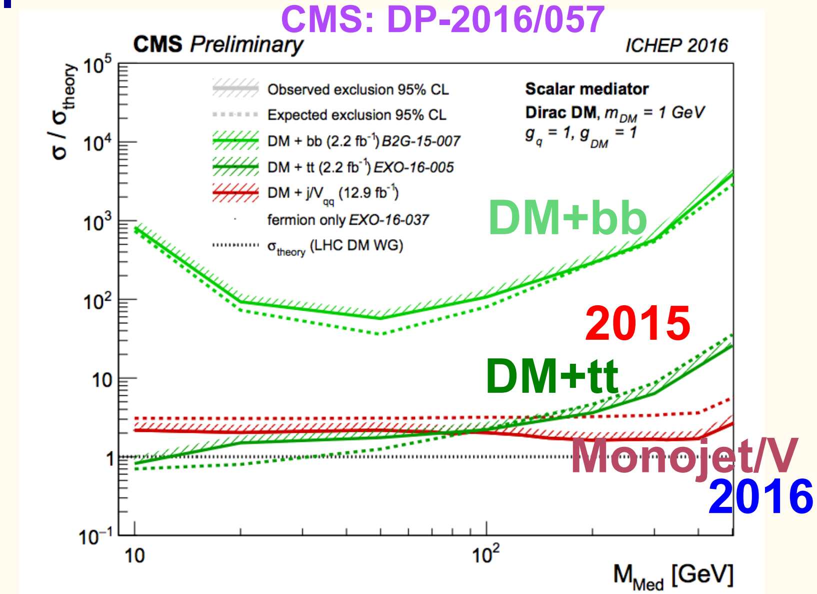


Example: ATLAS 1l search:



ATLAS-CONF-2016-050

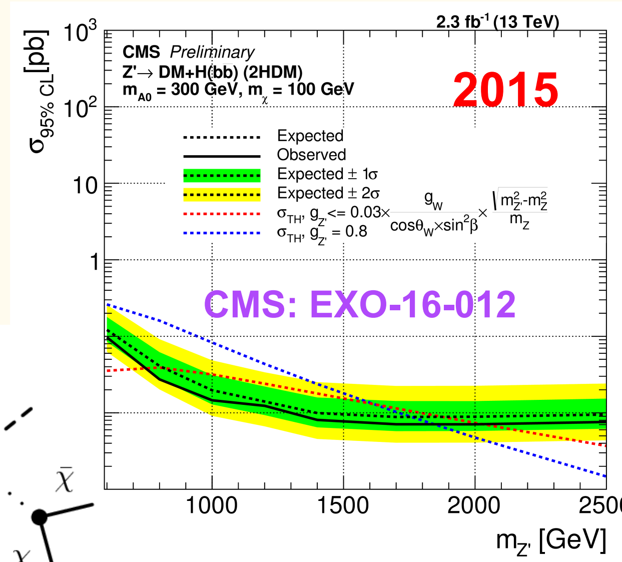
CMS: DP-2016/057



- **Specific DM tuning could be beneficial**
- **CMS 2015 DM+tt analysis as good as 2016 monojet/V for (pseudo-)scalar**

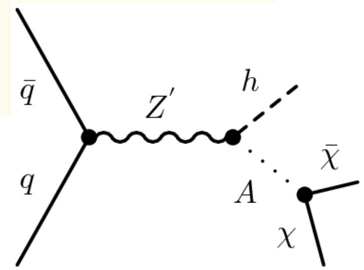
Mono-Higgs

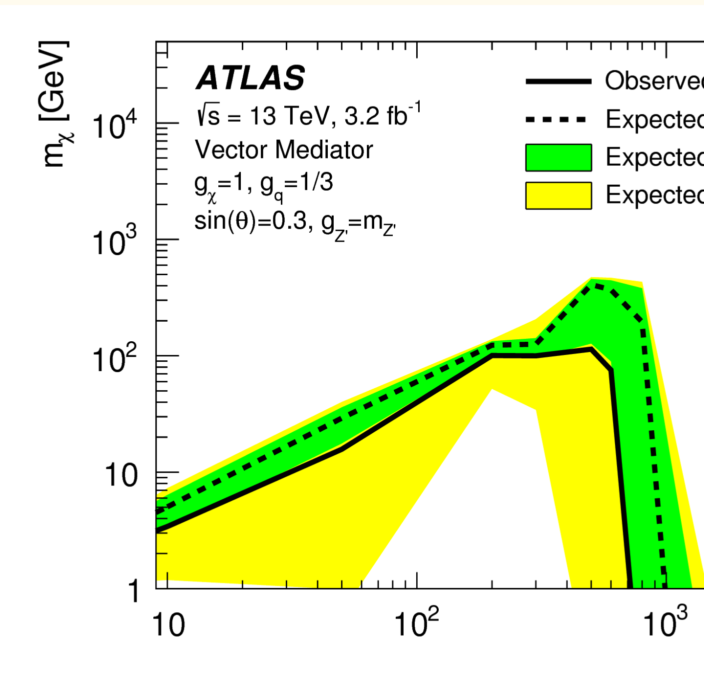
- **Mono Higgs signature is complementary to traditional DM searches – Higgs ISR Yukawa-suppressed**
- **Models: 2HDM or Higgs radiated by a vector mediator**
- **Most sensitive channel: h(bb)+DM**

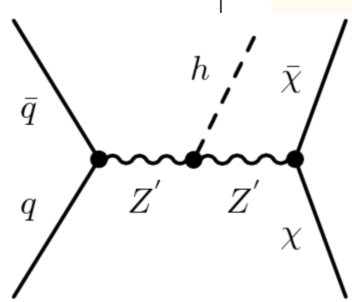


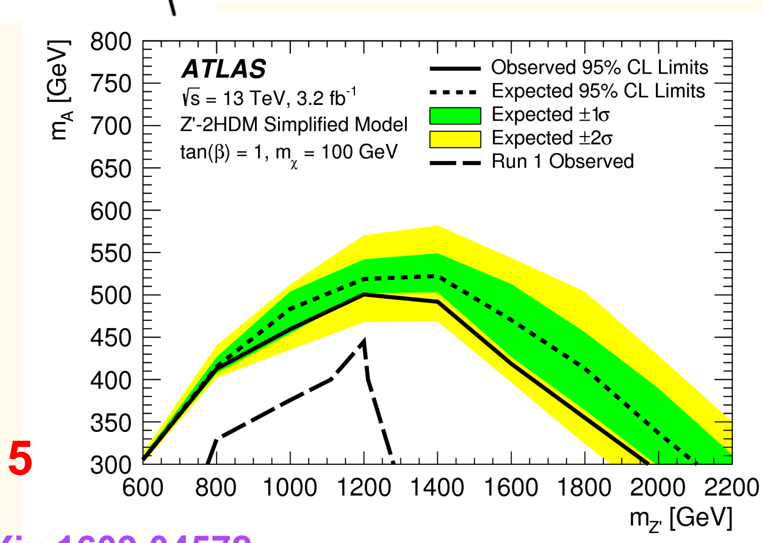
2015

CMS: EXO-16-012







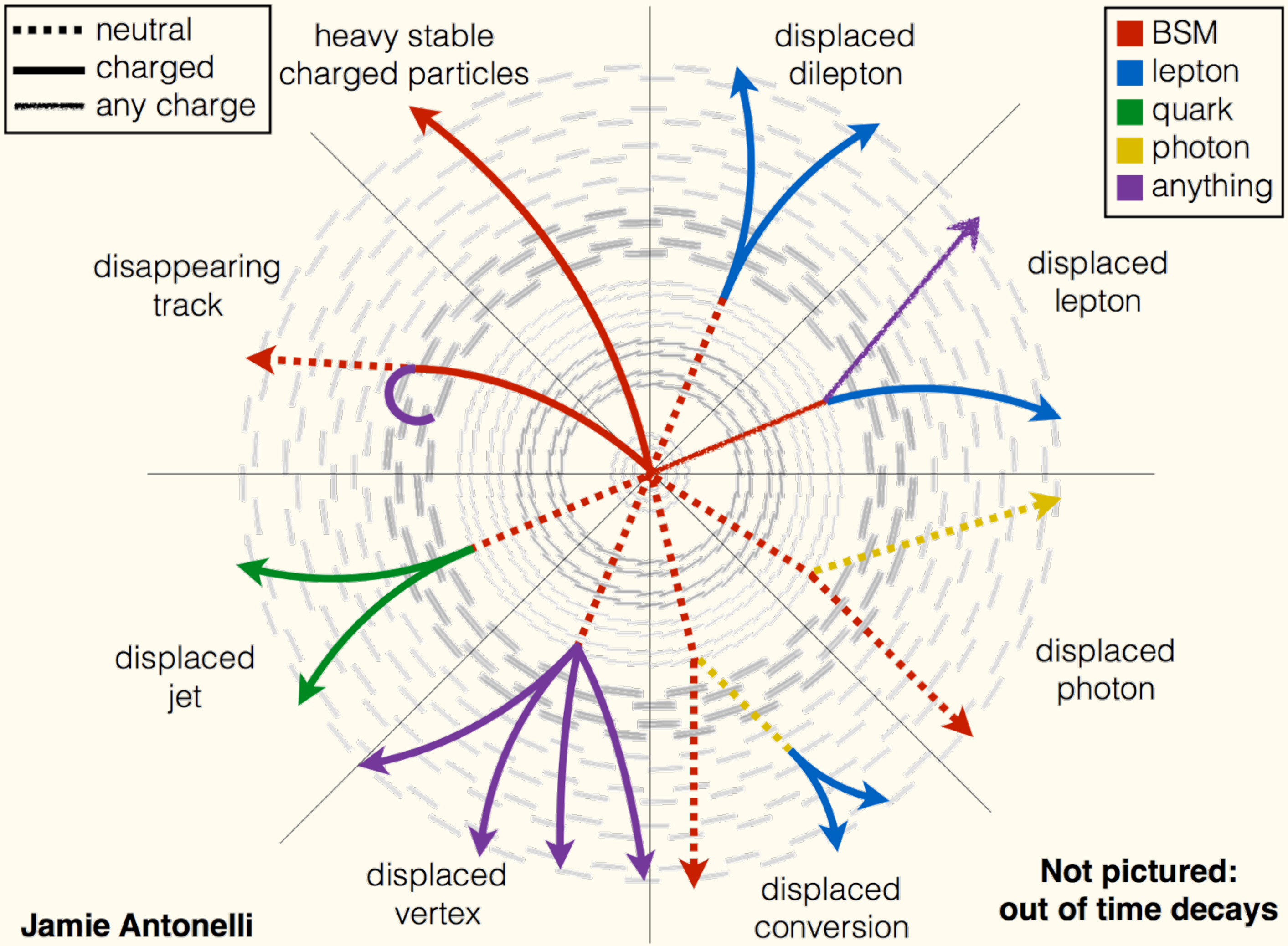


2015

ATLAS: arXiv 1609.04572

Displaced/delayed objects

- **Signature to search for long-lived particles: weak couplings (Hidden Valley, GMSB), small mass gaps (Stealth SUSY, AMSB), weakly broken symmetries (RPV SUSY) etc.**

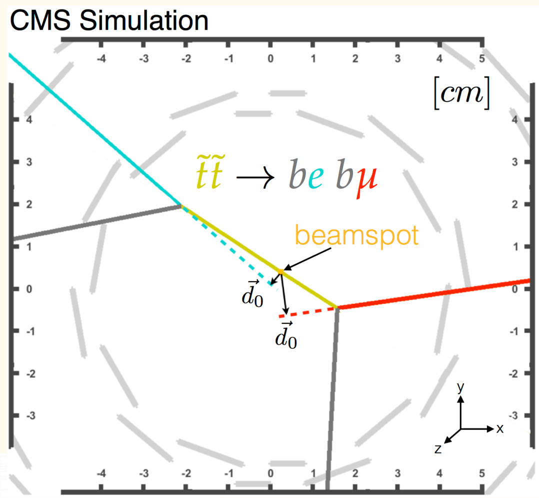


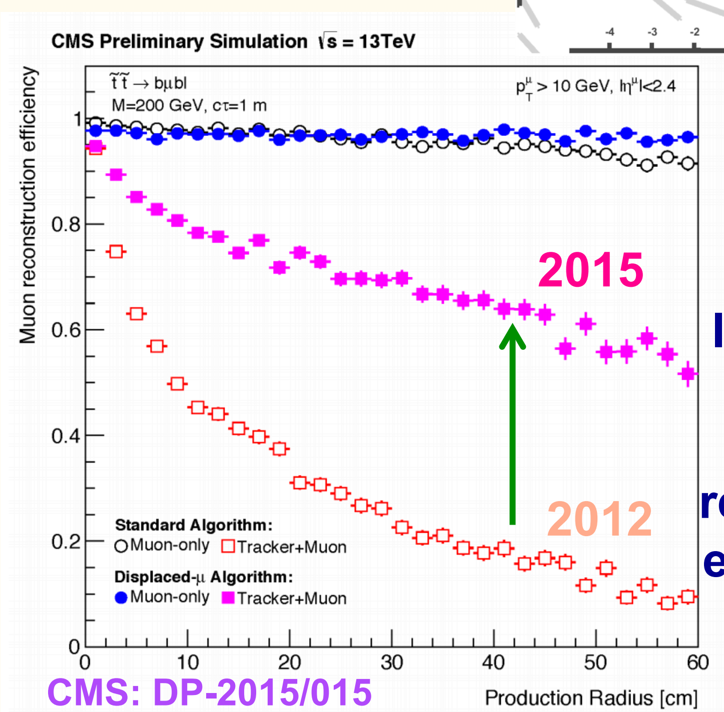
Not pictured: out of time decays

Jamie Antonelli

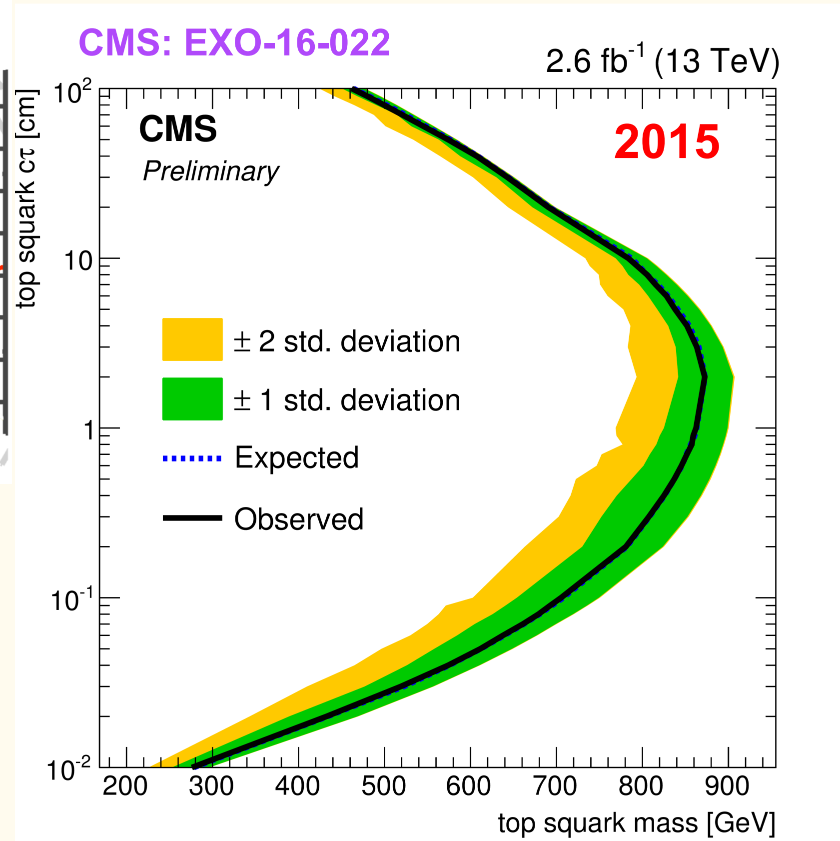
Displaced eμ

- Interpret as RPV stop decaying to b + lepton
- Select events with large e and μ impact parameter





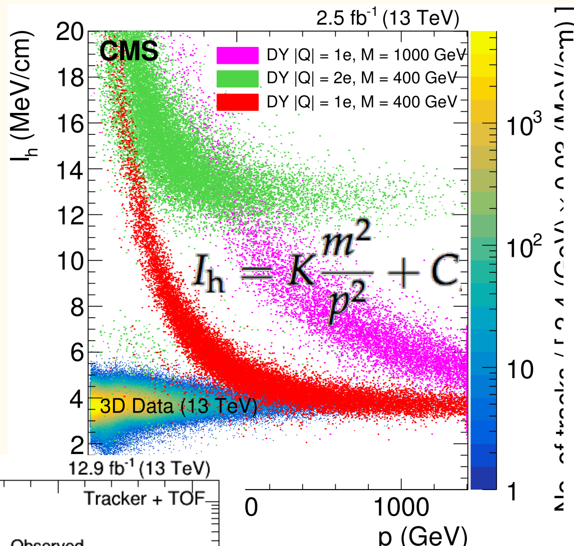
Improvement in displaced muon reconstruction efficiency wrt. Run 1

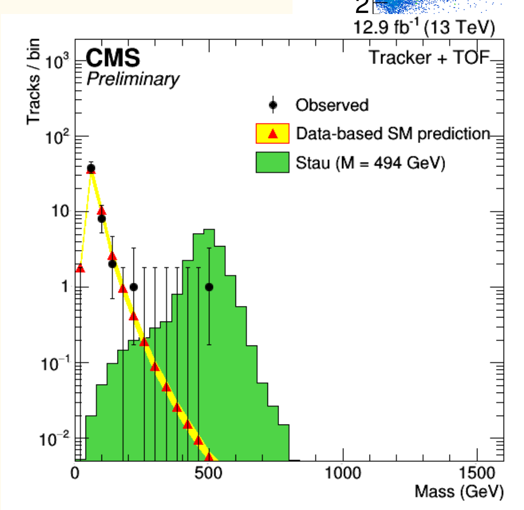


- Cover four orders of magnitude in cτ (up to 1m)
- Limits slightly improved wrt. Run 1 already with 2015 data

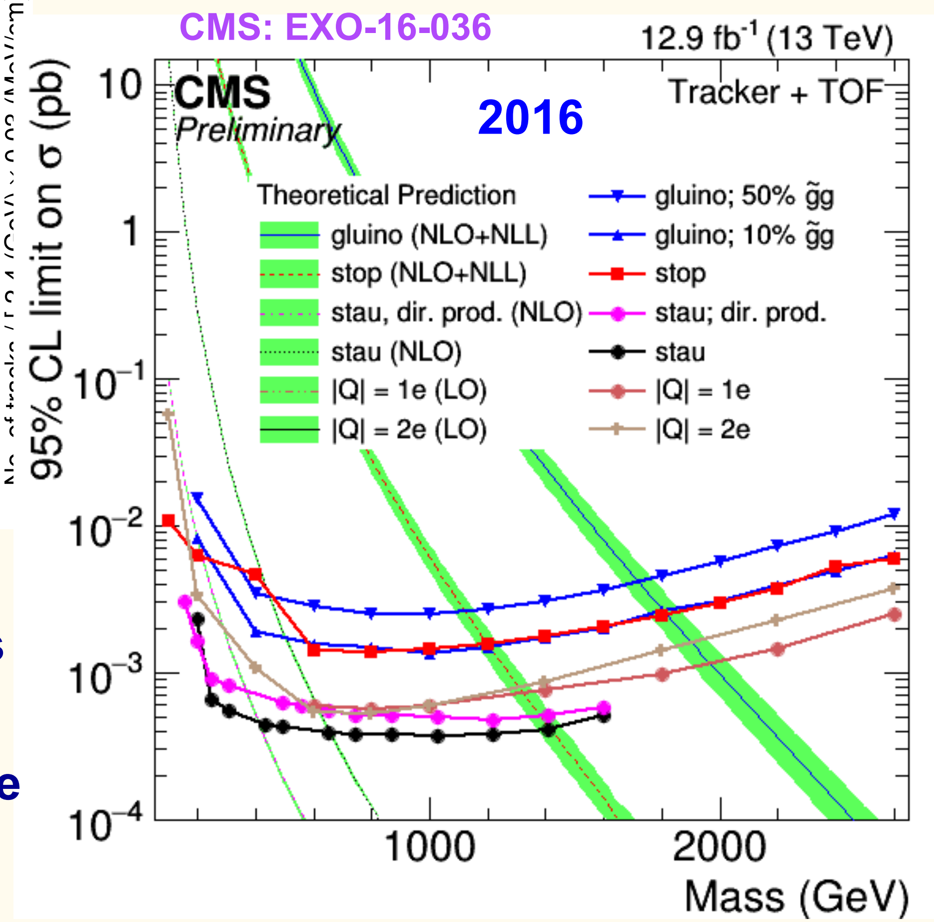
HSCP

- **Heavy stable charged particle: slow massive particle discriminated from background mainly through energy loss (dE/dx) and time of flight (ToF)**
  - **Tracker: dE/dx**
  - **Muon system: ToF**



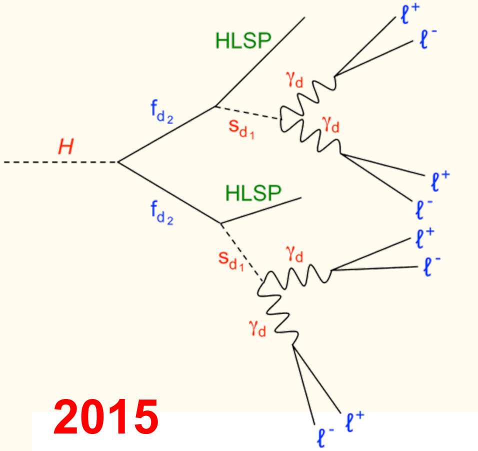


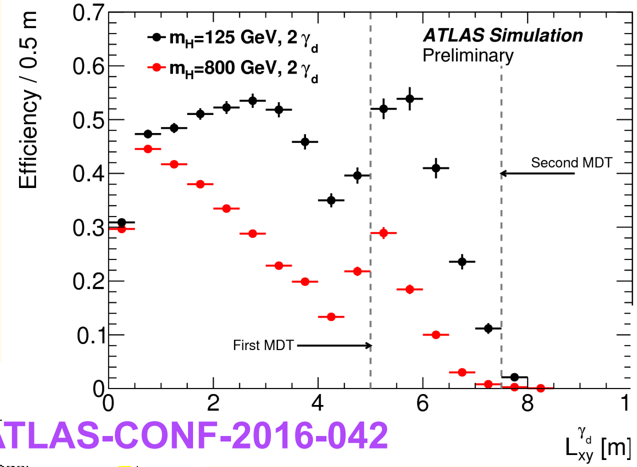
Benchmarks:
- **R-hadrons**
- **Staus**
- **Lepton-like fermions**

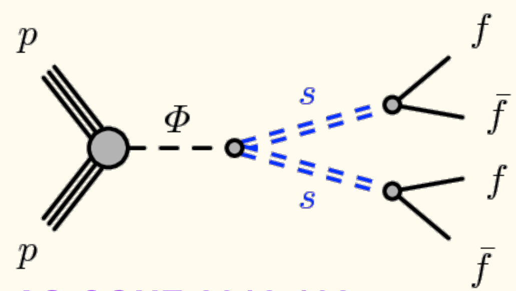


Displaced lepton and hadron jets

- **Neutral long-lived Hidden Valley particles with scalar communicator**
- **Signature: collimated lepton or hadron jets with displaced origin**







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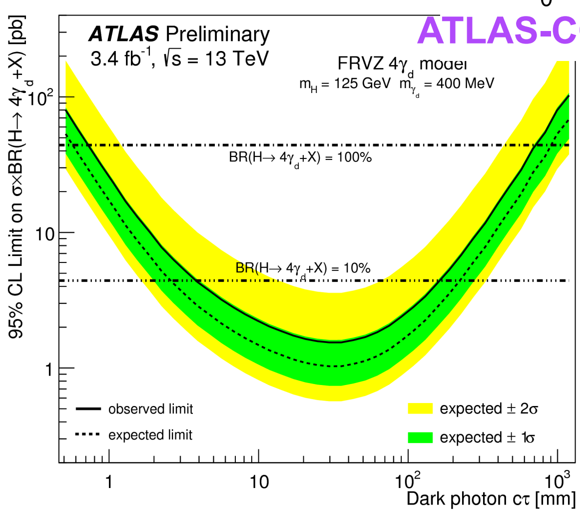
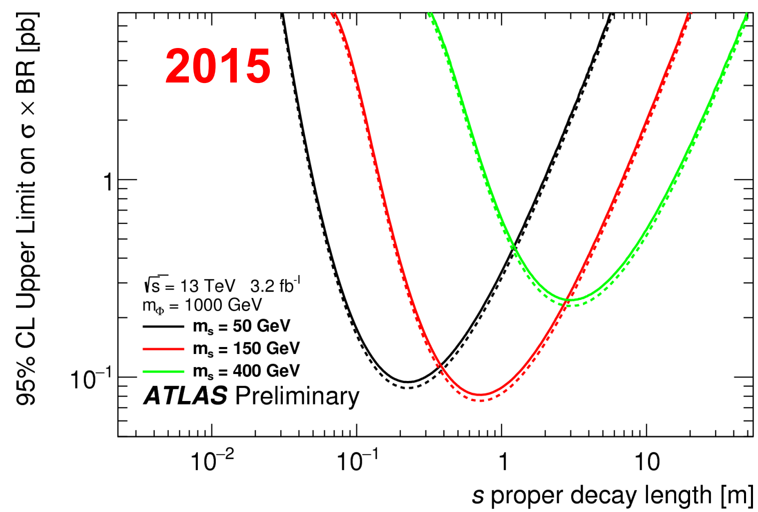
2015



ATLAS-CONF-2016-042

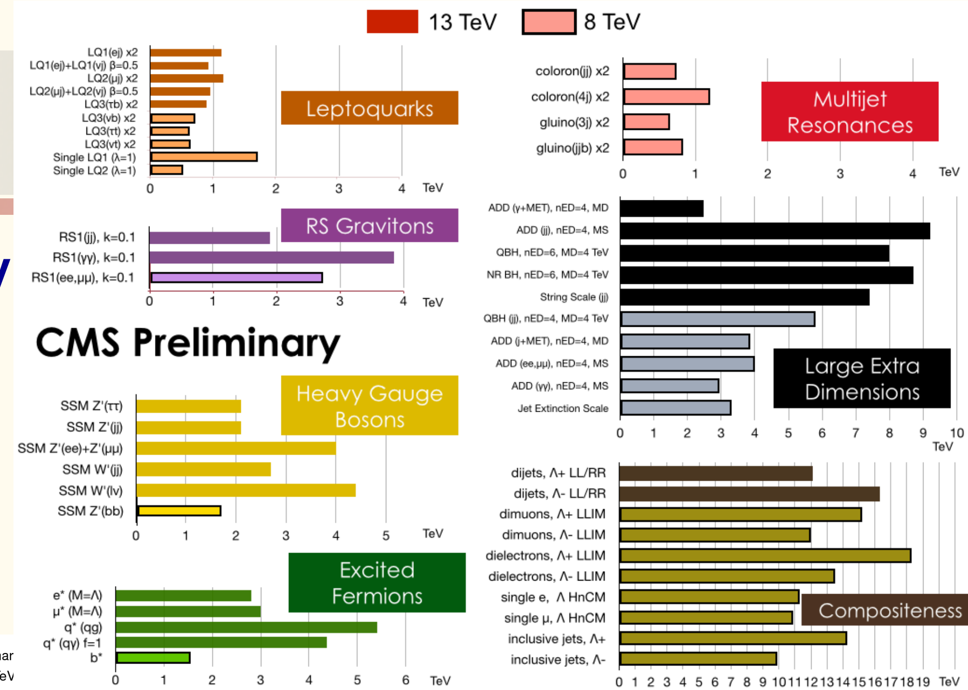
- **Improved trigger, reconstruction and analysis techniques**
- **Sensitivity better than Run 1 already with 2015 data**

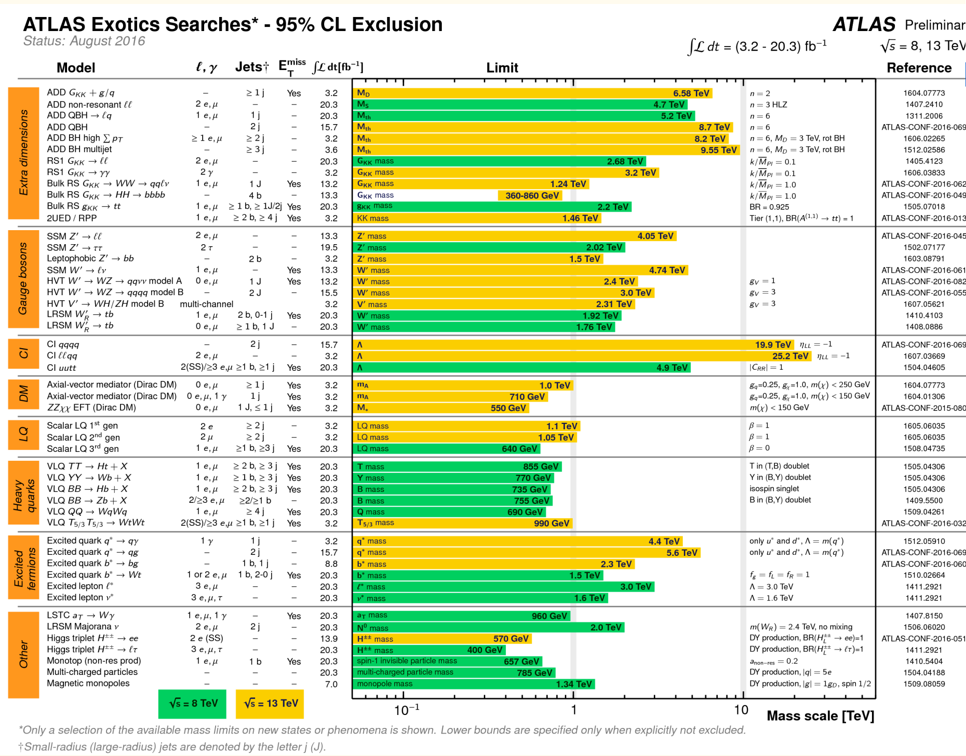
2015

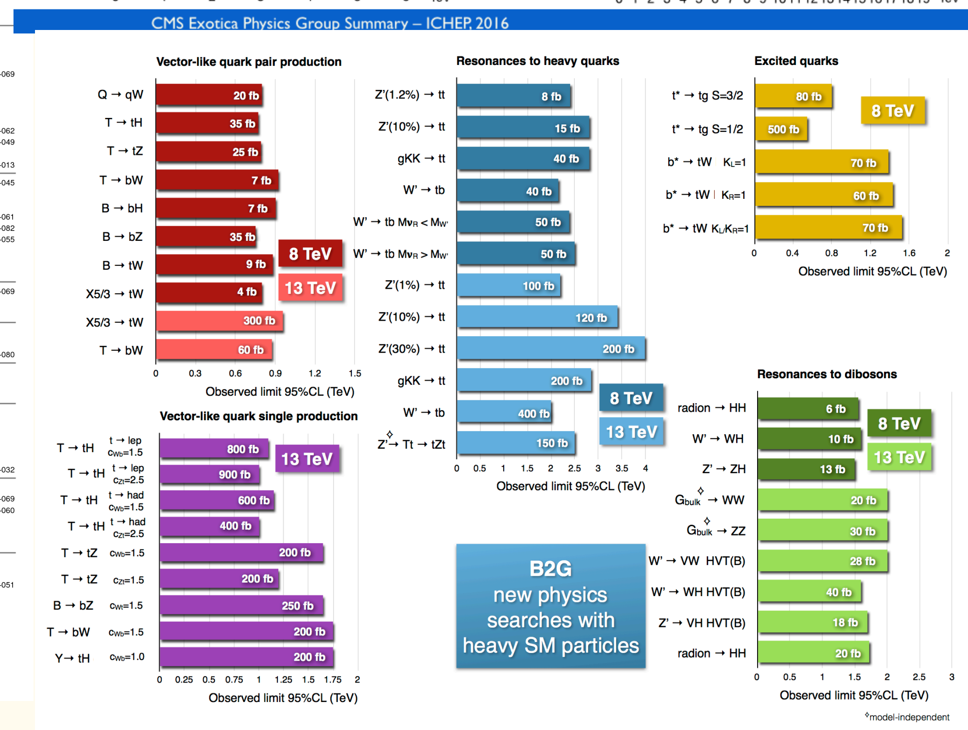


Run 2 status

- This talk was only a selection – many more results from Run 2 available: leptoquarks, seesaw, l*, heavy neutrino, BHs, TeV-gravity etc.
- The process of superseding Run 1 results is not yet complete







Summary

- Huge amount of results from Run 2 in the field of exotic searches
- Unfortunately, all old and intermediate excesses were unconfirmed and no new ones are on the horizon
- Clearly, this 13 TeV tree has no low hanging fruits…

Summary

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Summary

- Huge amount of results from Run 2 in the field of exotic searches
- Unfortunately, all old and intermediate excesses were unconfirmed and no new ones are on the horizon
- Clearly, this 13 TeV tree has no low hanging fruits – but it does not mean it has no fruits at all!
- Other searches, exploring more challenging signatures are coming up
- More than twice the data shown is being analyzed and more is to come in the next years (100x with HL-LHC)

- Next rendezvous: winter conferences 2017