Source: https://commons.wikimedia.org/wiki/File:Shanghai_Pudong_Panorama_Jan_2_2014.jpg

High mass searches in CMS and ATLAS

Swagata Mukherjee

On behalf of the CMS and ATLAS Collaborations

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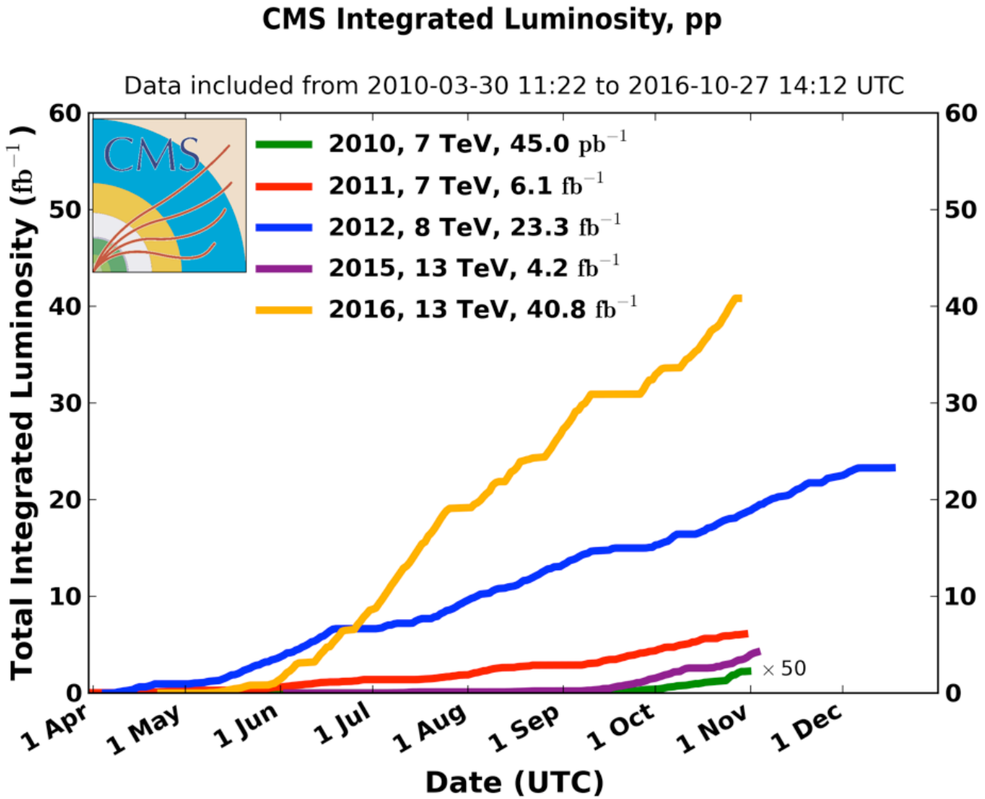
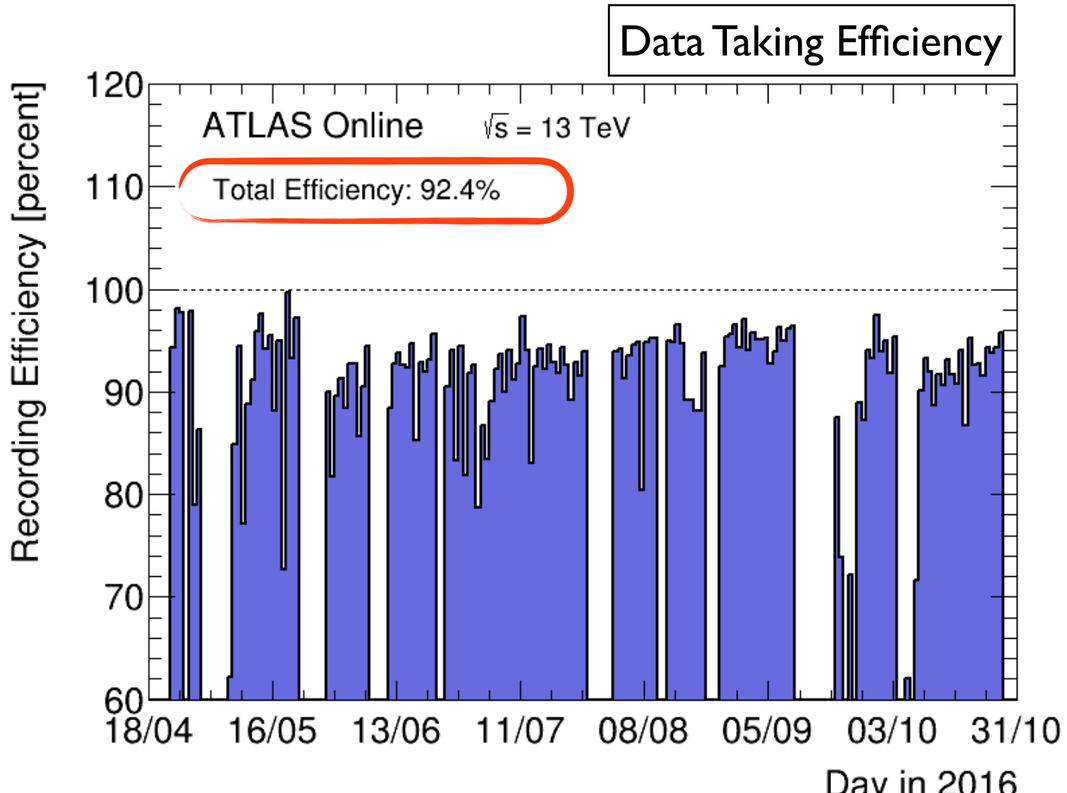
Introduction

- ~40 fb^{-1} in 2016.
  - Thanks to LHC, for a spectacular year!
  - ATLAS and CMS detectors performed well
- Large integrated luminosity (and high energy) give better sensitivity for searches

~10X more lumi than 2015 (13 TeV)

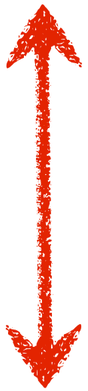
~2X more lumi than 2012 (8 TeV)





Plan of the talk

- Signature-based resonance searches
  - Di-jet, Di-jet+ISR, Pair-produced di-jets
  - Di-lepton
  - Di-photon
  - $Z\gamma$
- Searches targeting specific particles
  - W' (SSM)
  - W_R
  - Heavy Majorana Neutrino



various physics interpretations

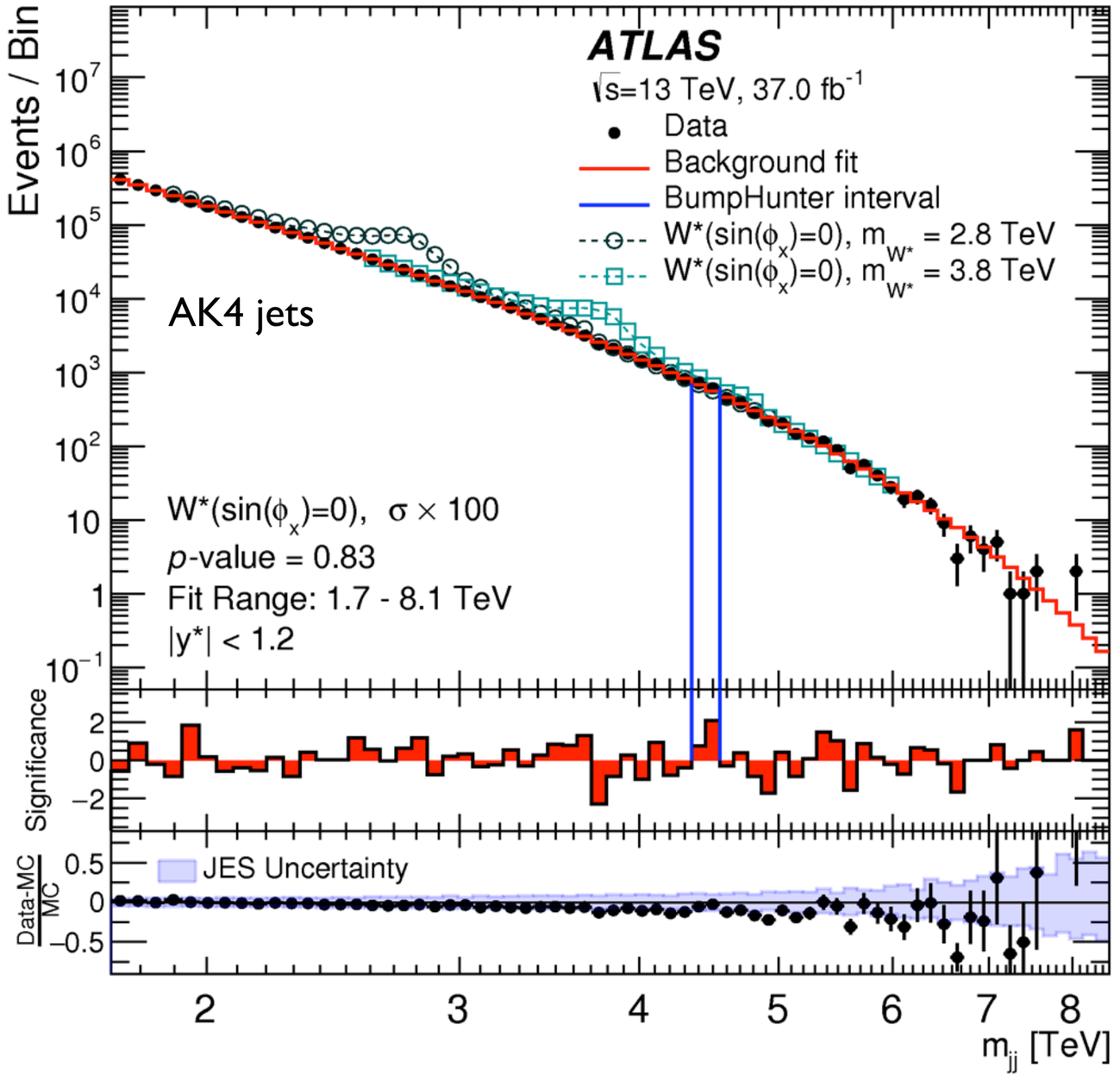
Di-jet

ATLAS : arxiv:1703.09127
CMS : PAS EXO-16-056

- Classic signatures to search for New Physics with strong interactions
- Due to trigger thresholds, standard dijet search at LHC explores higher masses (>1.5 TeV)

Di-jet **(≥1 b-tag)** search: similar strategy as the di-jet resonance search (ATLAS-CONF-2016-060)

No significant excess observed



Trigger: Single jet, pT>380 GeV
Offline selection: pT1(2)>440(60) GeV
Dijet mass resolution: 2.4% (2.0%) at 2 TeV (5 TeV)

Di-jet *Exploring low / intermediate mass with dijet*

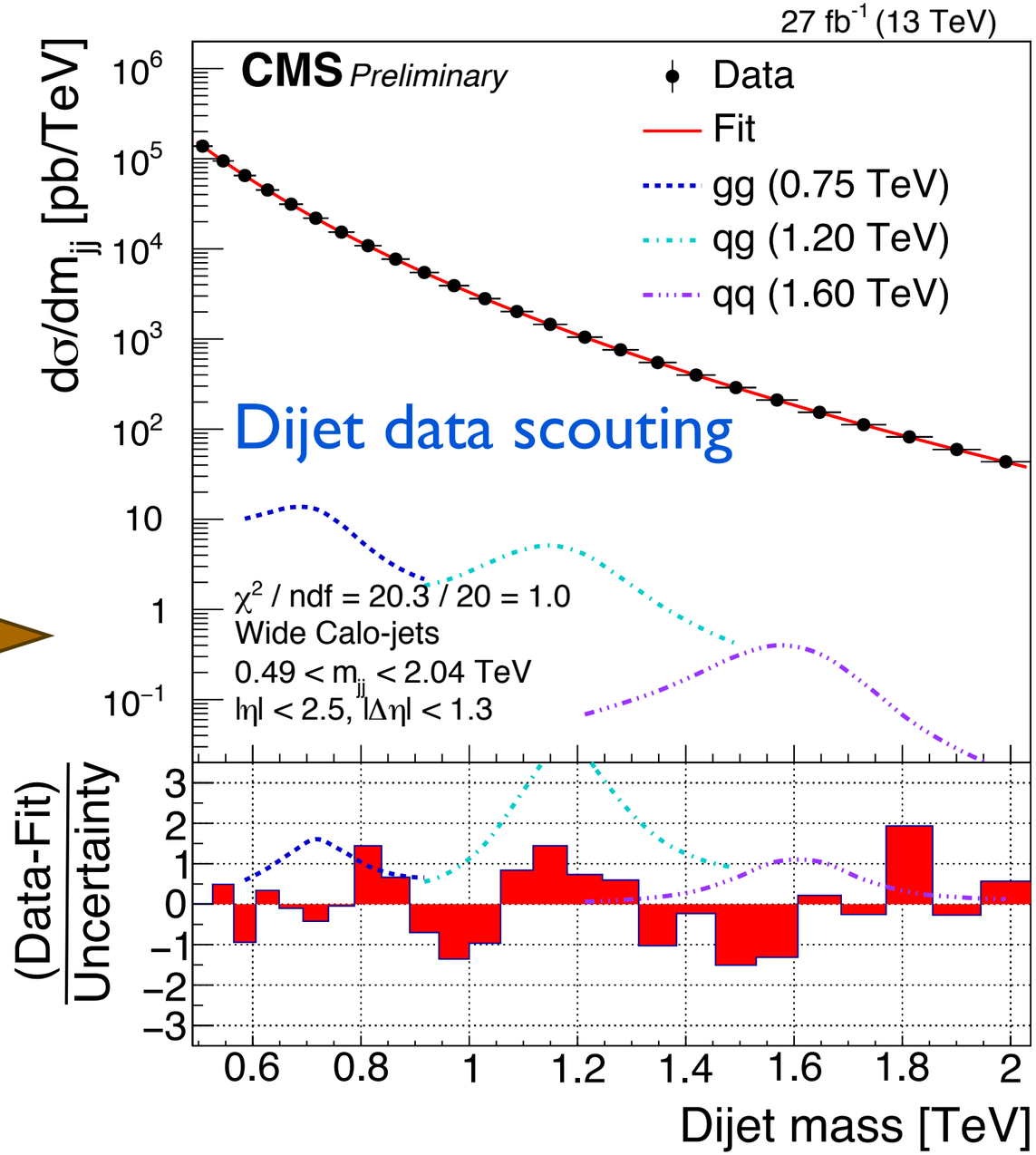
ATLAS-CONF-2016-030
CMS : PAS EXO-16-056

- Two ways to explore low or intermediate masses with dijet
  - **Dijet+ISR** → Use ISR jet to get above the trigger thresholds
  - **Data scouting** (trigger-level) analysis → based on low-threshold triggers writing only very limited information about the event

Overcome trigger-bandwidth limitation

No significant excess observed

Trigger: HT > 250 GeV, Offline selection: p_T > 30 GeV, $|\eta| < 2.5$



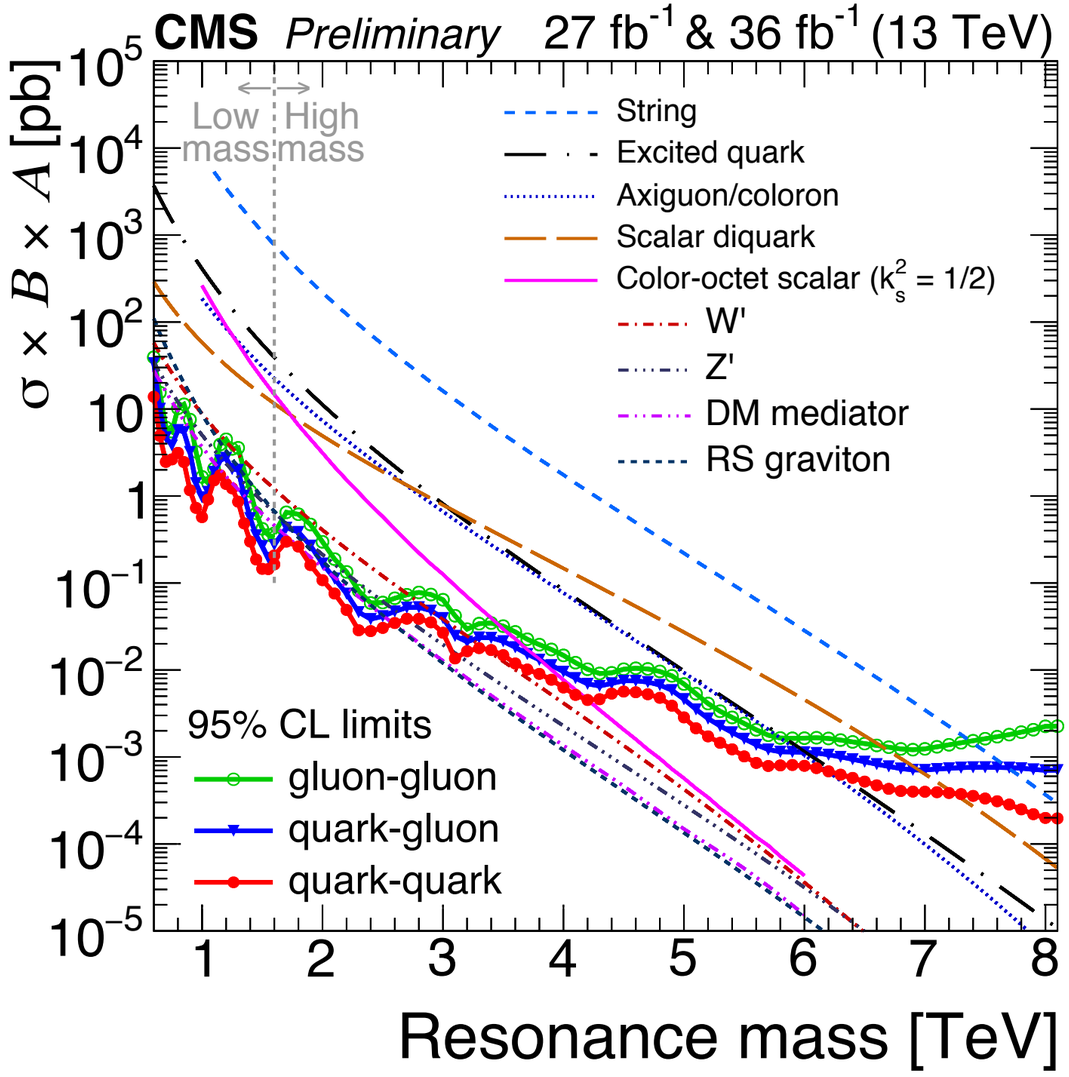
Di-jet

Dijet search sensitive to many BSM scenarios

ATLAS : arxiv:1703.09127
CMS : PAS EXO-16-056

Model	Observed exclusion
Quantum black hole	8.9 TeV
W'	3.6 TeV
Z'(g_q=0.2)	2.9 TeV
q*	6.0 TeV
String Resonance (Regge excitations) arXiv:0808.0497	7.7 TeV
Scalar di-quark (Superstring inspired E_6 models)	7.2 TeV
Coloron	6.1 TeV
RS gravitin (k/M_{Pl}=0.1)	1.7 TeV

.... and more



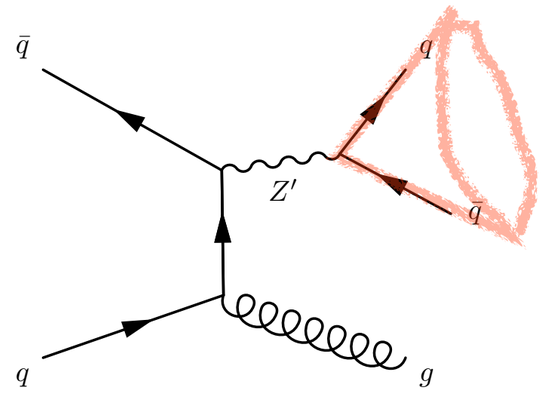
Mass limits improved by several hundred GeV compared to 2015 results

ATLAS : ATLAS-CONF-2016-070
CMS : PAS-EXO-17-001

Di-jet + ISR *Exploring low mass with dijet*

ATLAS : Resolved dijet + ISR photon/jet

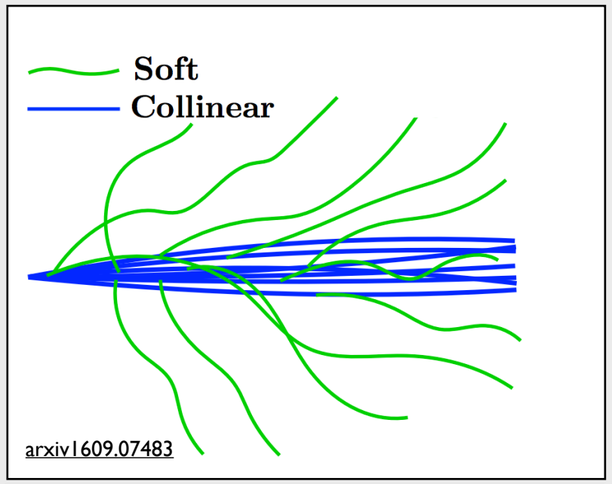
CMS : Merged dijet + ISR jet



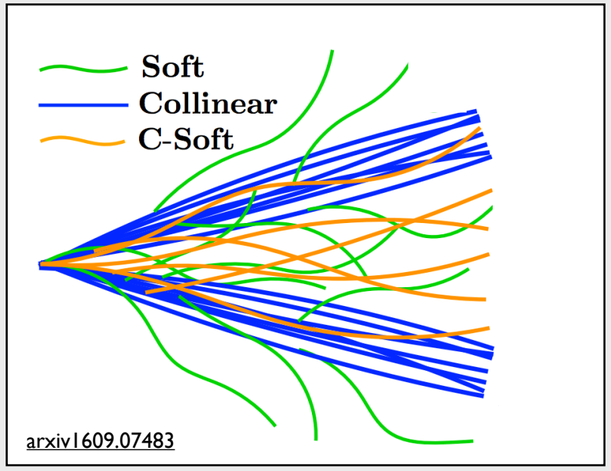
2-prong fat-jet

Novel jet-substructure techniques used

1-prong jet
QCD background



2-prong jet
Signal



2 steps

- Get rid of softer components in jet (from UE or pile-up)
  - "Grooming"
    - Pruning
    - Trimming
    - **Soft-drop**

  Better mass resolution expected after grooming
- Substructure identification
  - "Tagging"
    - N-subjettiness
    - **Energy correlation function**

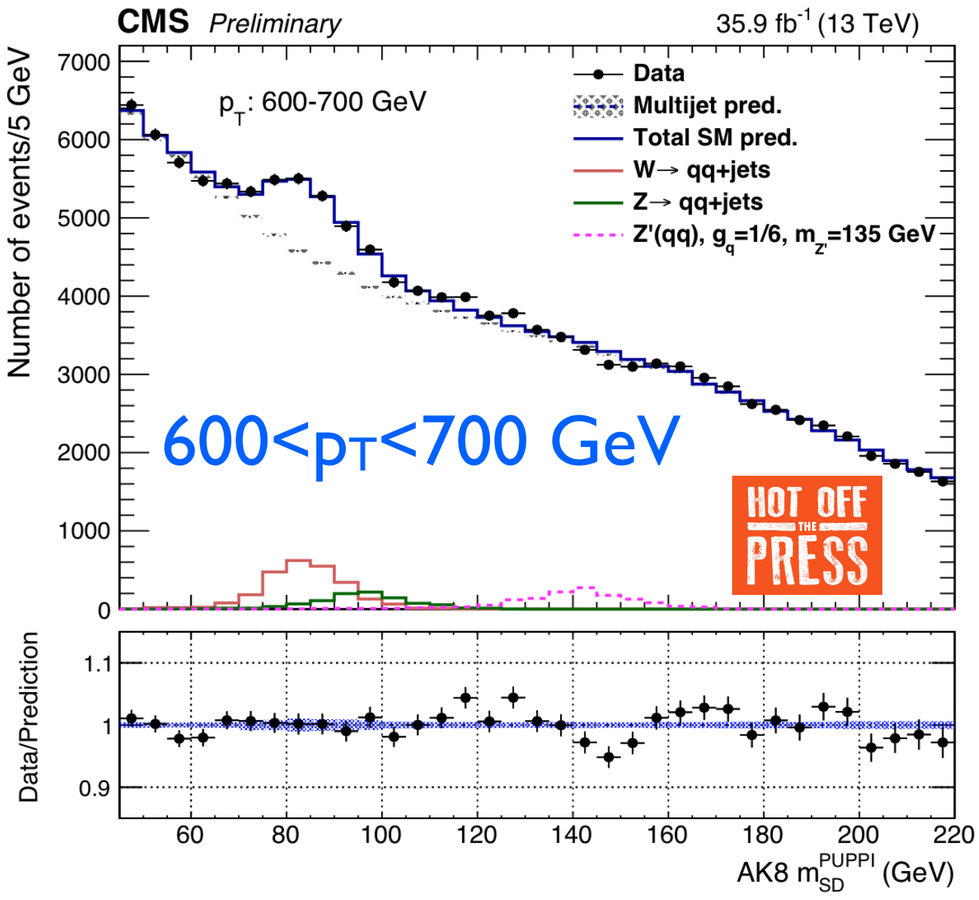
Di-jet + ISR *Exploring low mass with dijet*

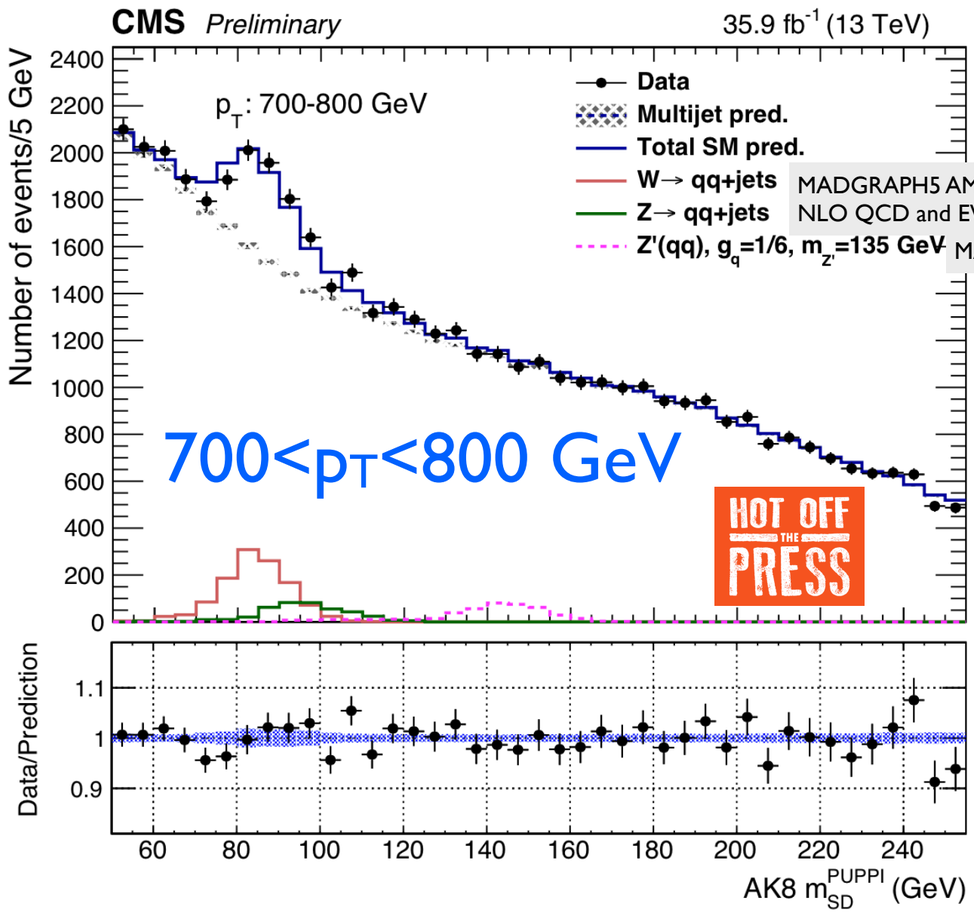
ATLAS : ATLAS-CONF-2016-070
CMS : PAS-EXO-17-001

CMS : Merged dijet + ISR jet
Probes masses >50 GeV

ATLAS : Resolved dijet + ISR photon/jet
Probes masses >200 GeV

Classify events according to p_T of fat-jet



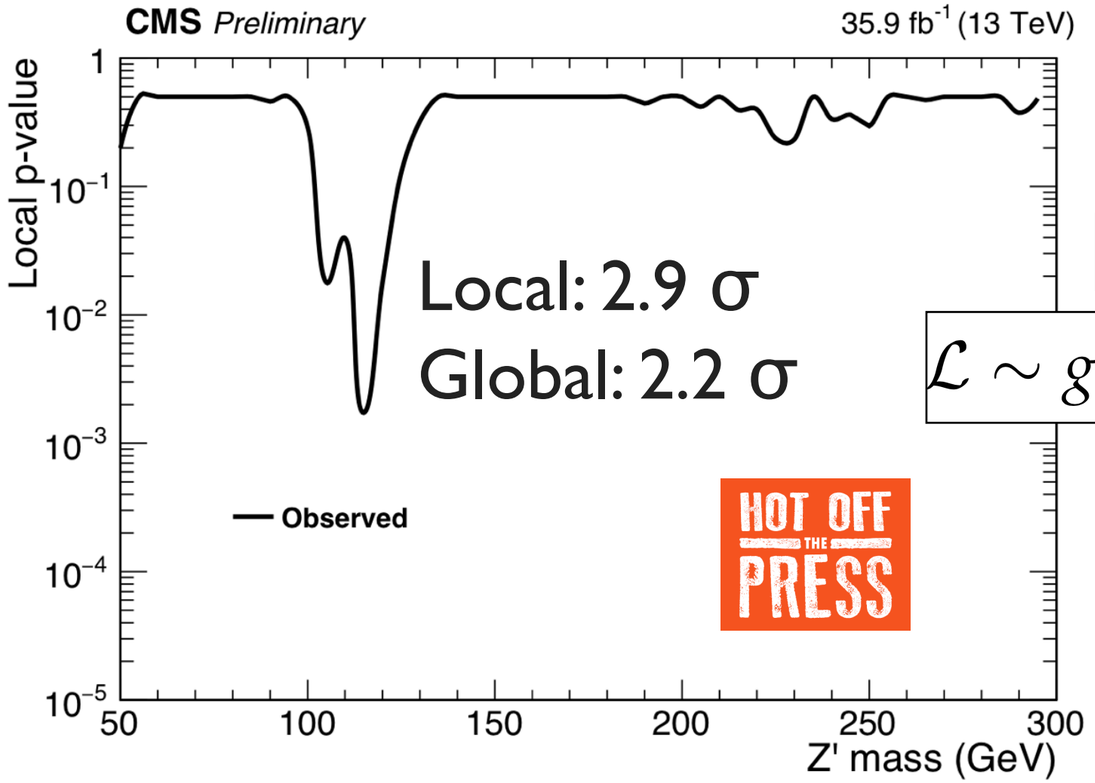


MADGRAPH5 AMC@NLO, MLM
NLO QCD and EWK corrections applied
MADGRAPH5 AMC@NLO

Overall good data/MC agreement.
Mild excess ~115 GeV in CMS

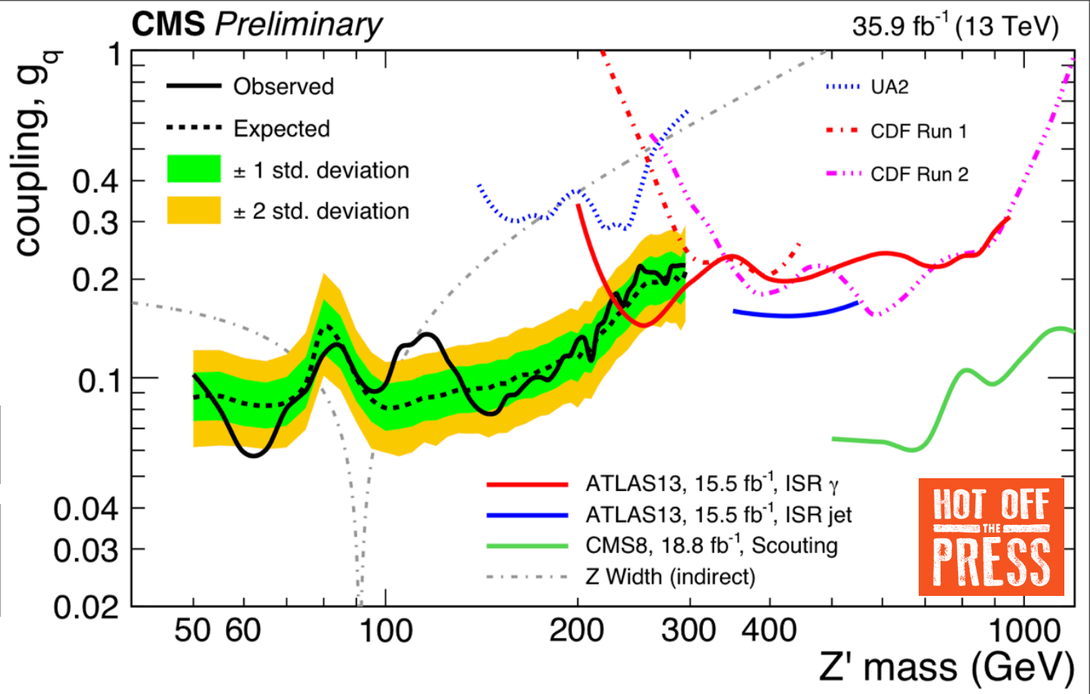
Offline Selection:
Fat jet pT>500 GeV, $|\eta|<2.5$
$-5.5 < \rho < -2$
N21<0

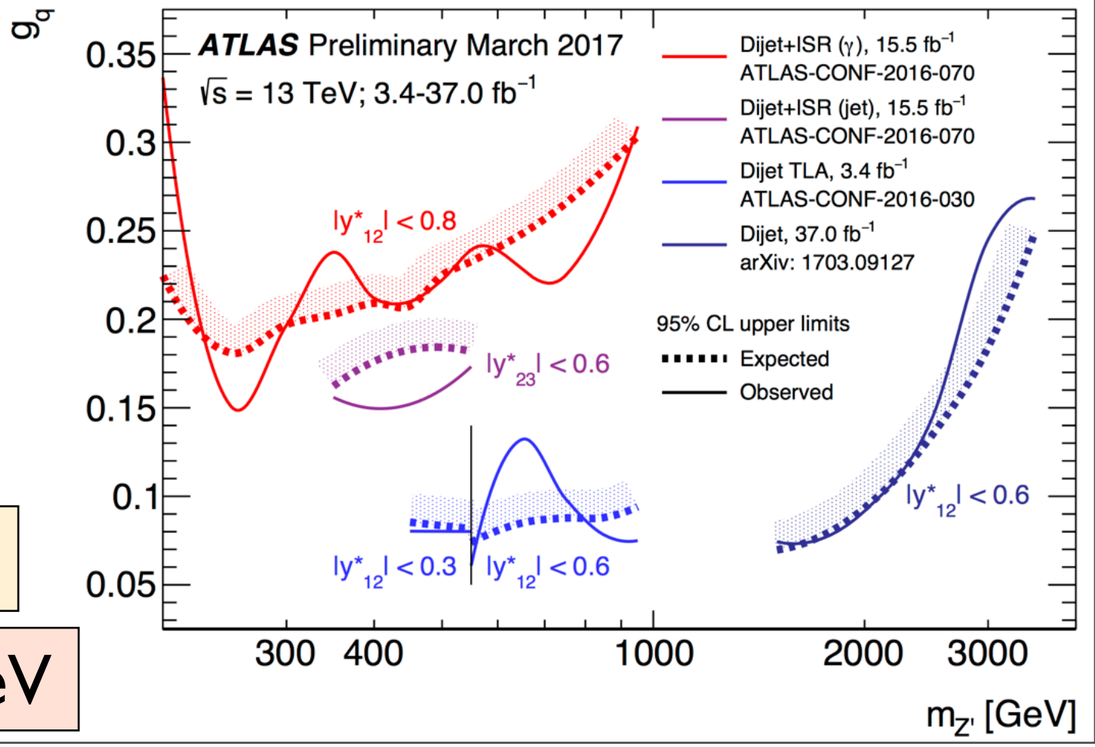
Di-jet + ISR *Exploring low mass with dijet*



ATLAS-CONF-2016-070
CMS : PAS-EXO-17-001

$$\mathcal{L} \sim g_q Z'_{B,\mu} \bar{q} \gamma^\mu q$$





Mild excess. Not statistically significant

➥Limits on g_q as a function of the Z' mass

CMS provides stringent limits in **50-200** GeV

ATLAS provides strong constraint above 200 GeV

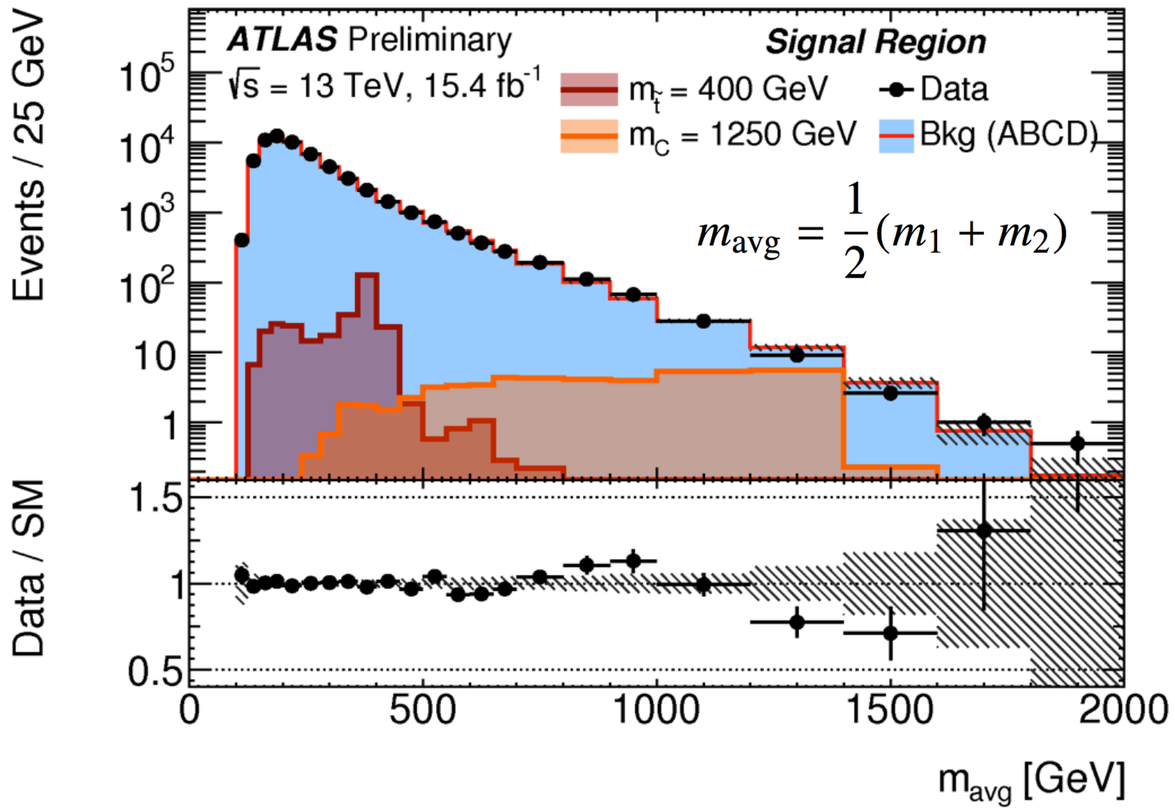
ATLAS : ATLAS-CONF-2016-084
CMS : PAS EXO-16-029 (2015)

4-jets *Search for pair-produced dijet resonances*

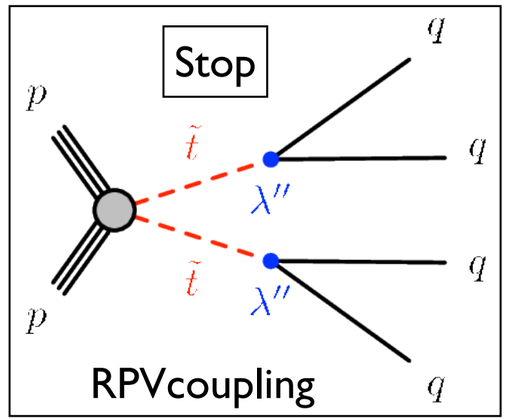
ATLAS : Resolved resonances

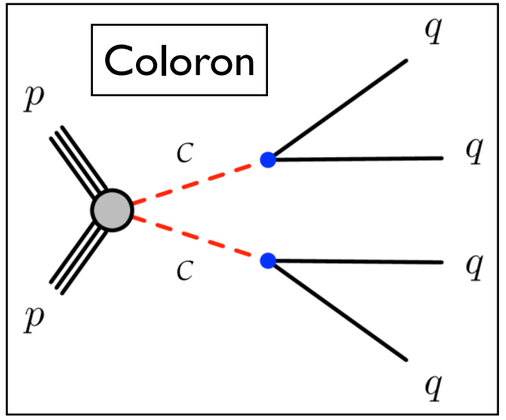
CMS : Boosted resonances (merged jets)

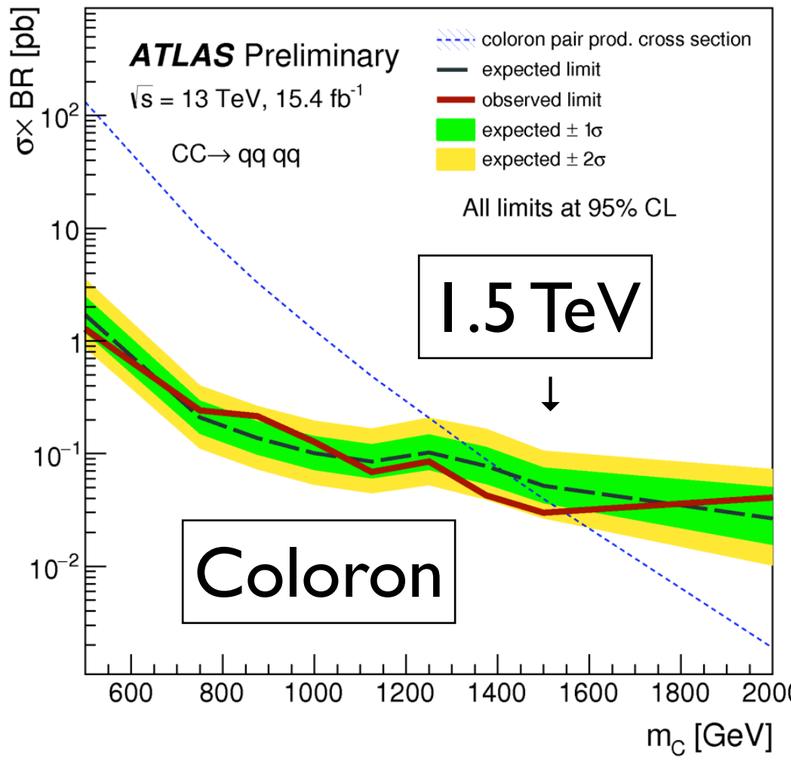
- Pruning and N-subjettiness



No significant excess observed







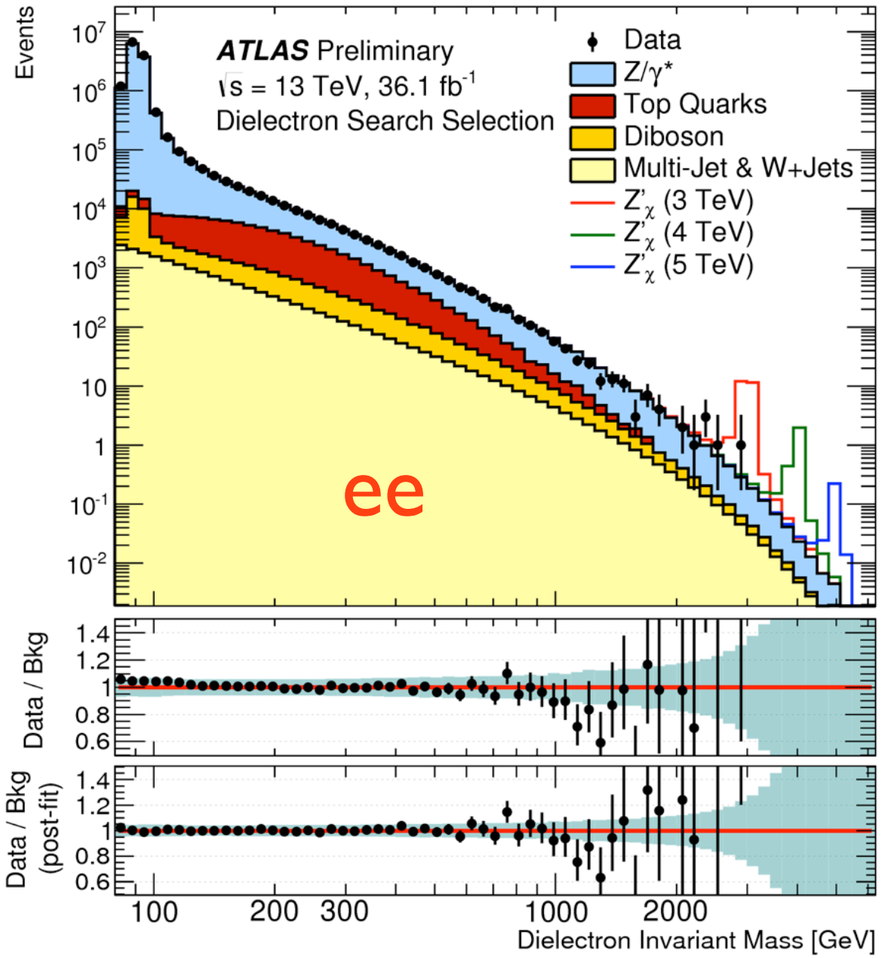
CMS probed masses down to 80 GeV

Stop exclusion: (250-405 GeV) and (445-510 GeV)

Dilepton (ee / μμ)

ATLAS : ATLAS-CONF-2017-027
CMS : PAS EXO-16-031

Search for narrow resonances in M_{ll} distributions above SM background



No significant excess observed

Same search also performed in τ channels (enhanced coupling to third generation). CMS : JHEP 02 (2017) 048, 2015 data, ATLAS : EXOT-2014-05, 2012 data

ATLAS

Benchmark SSM Z' and E_6-motivated Z' models

Model	Width [%]	θ_{E_6} [Rad]	Lower limits on $m_{Z'}$ [TeV]					
			ee		$\mu\mu$		$\ell\ell$	
			Obs	Exp	Obs	Exp	Obs	Exp
Z'_{SSM}	3.0	-	4.3	4.3	4.0	3.9	4.5	4.5
Z'_{χ}	1.2	0.50 π	3.9	3.9	3.6	3.6	4.1	4.0
Z'_{S}	1.2	0.63 π	3.9	3.8	3.6	3.5	4.0	4.0
Z'_{I}	1.1	0.71 π	3.8	3.8	3.5	3.4	4.0	3.9
Z'_{η}	0.6	0.21 π	3.7	3.7	3.4	3.3	3.9	3.8
Z'_{N}	0.6	-0.08 π	3.6	3.6	3.4	3.3	3.8	3.8
Z'_{ψ}	0.5	0 π	3.6	3.6	3.3	3.2	3.8	3.7

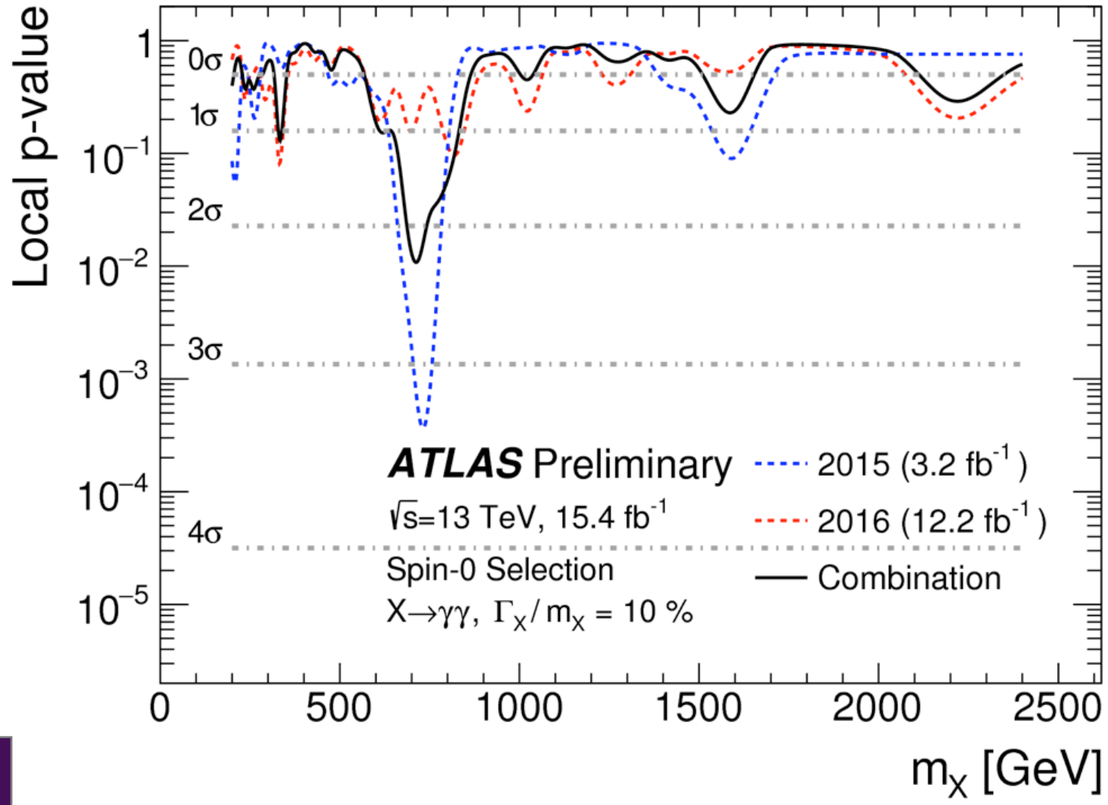
+other Z' interpretations

SSM Z': 2015 limit improved by ~1.2 TeV

ATLAS also provides lower limits on contact interaction energy scale

γγ

ATLAS : ATLAS-CONF-2016-059
CMS : Phys. Lett. B 767 (2017) 147



Sizable excess observed by CMS and ATLAS at 750 GeV in 2015 data

Excess not confirmed with 4 times more data in 2016

CMS

Width	Scenario	RS graviton coupling	RS graviton exclusion
Narrow (0.014%)	Detector resolution dominates	0.01	1.95 TeV (except 1.75-1.85 TeV)
Intermediate (1.4%)	Detector resolution and resonance width comparable	0.1	3.85 TeV
Broad (5.6%)	Resonance width dominates	0.2	4.45 TeV

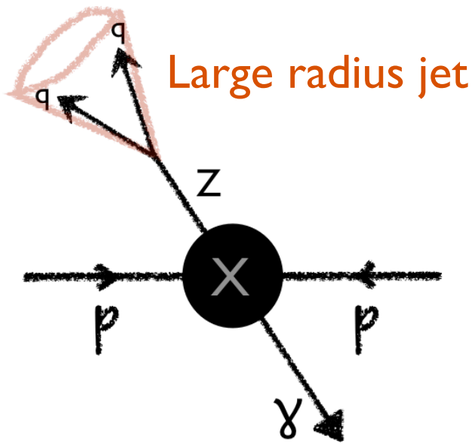
Most stringent limits on RS graviton

Z(qq/ll)γ

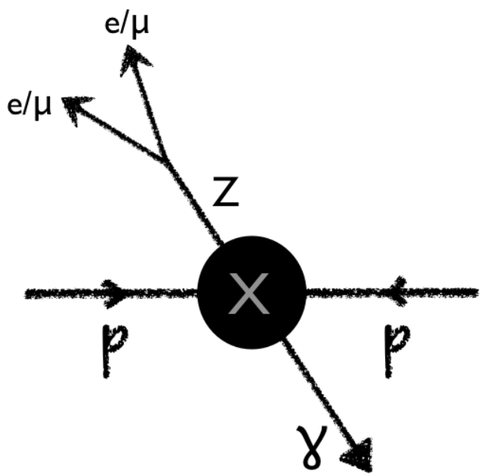
ATLAS : Coming out soon
CMS : PAS EXO-17-005

Bump search in M(Zγ) spectrum in Z→ll and Z→qq channels

Cross-check diphoton excess in 2015



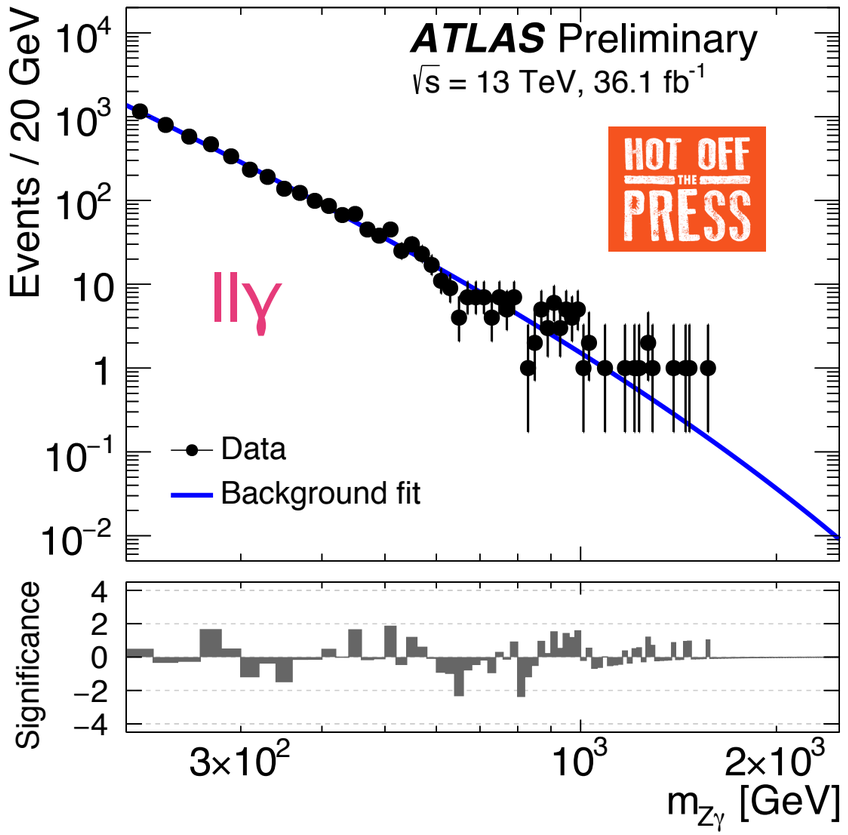
Large radius jet



Fat jet pT>200 GeV and |η| < 2.0
Photon |η| < 1.44
b-tag: medium (70%,2%), loose (85%,15%)

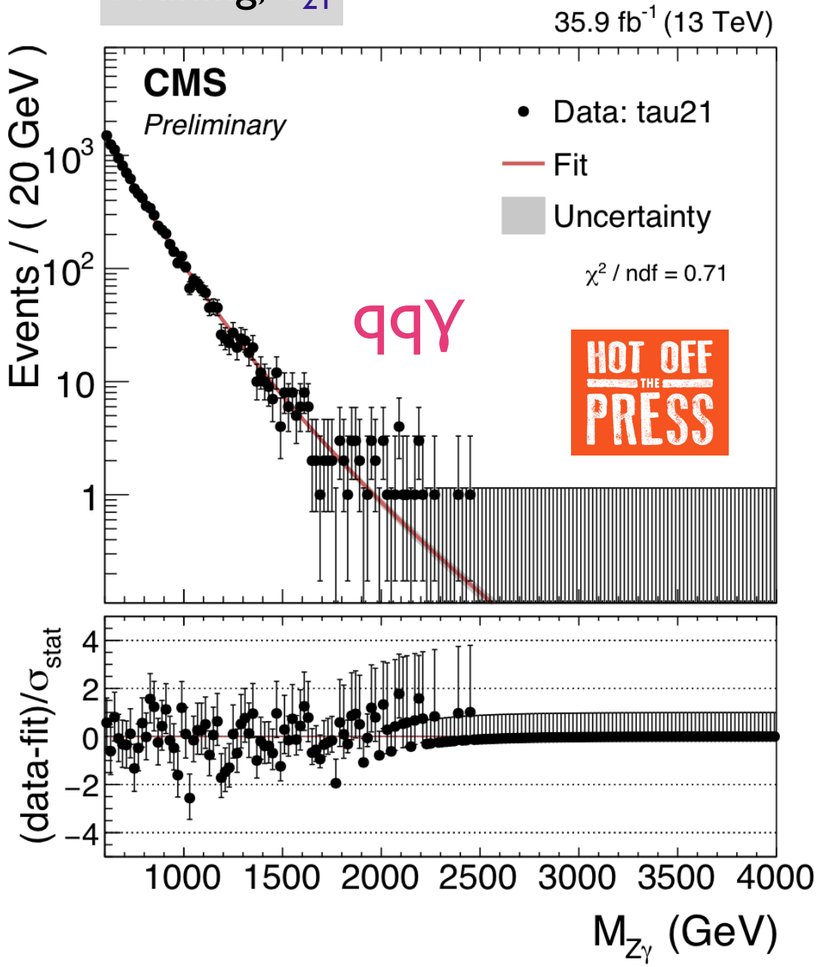
Event Categories (qqγ CMS)

- b-tagged: Two b-tagged subjets
- anti b-tagged: Further categorized by τ_{21}



Jet-substructure techniques used

Pruning, τ_{21}

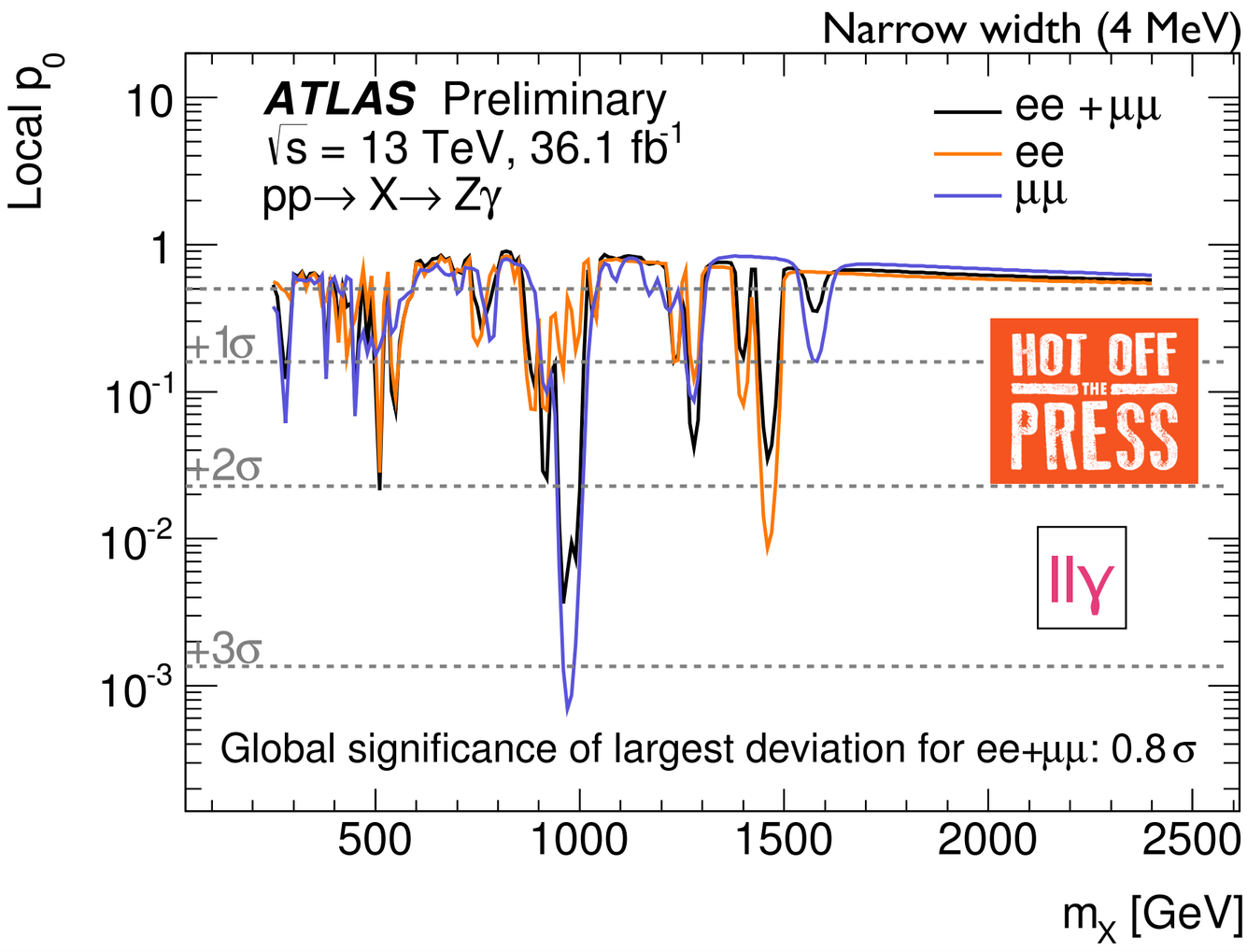


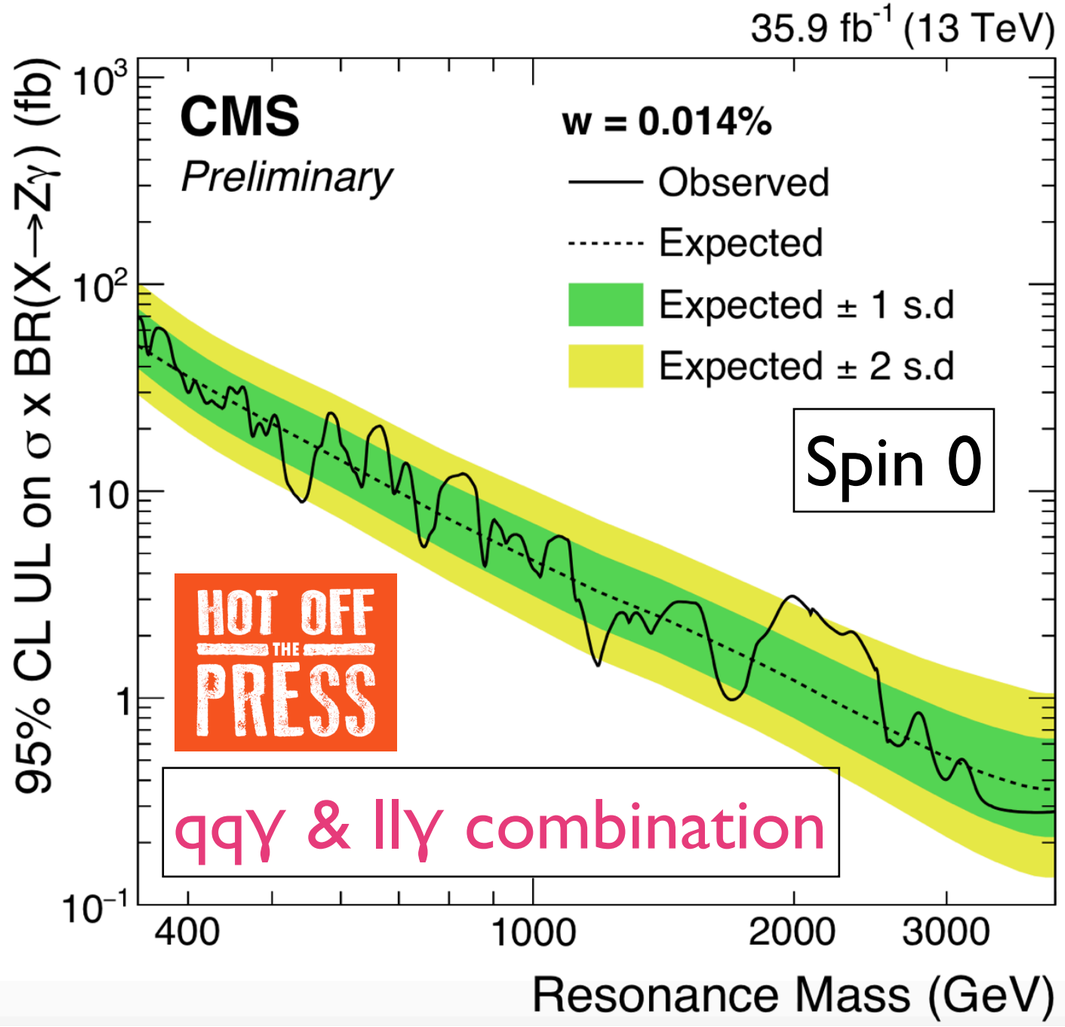
No significant excess found. Slight over-fluctuation ~1 TeV in ATLAS in μ channel only

Z(ll/qq)γ

ATLAS : Coming out soon
CMS : PAS EXO-17-005

- Zγ→qqγ: Higher branching ratio. Good at high mass
- Zγ→llγ: Lower trigger threshold, low background. Good at low mass





Plan of the talk

- Signature-based resonance searches
  - Di-jet, Di-jet+ISR, Pair-produced di-jets
  - Dilepton
  - Diphoton
  - Zγ

various physics interpretations

- **Searches targeting specific particles**
  - W' (SSM)
  - W_R
  - Heavy Majorana Neutrino

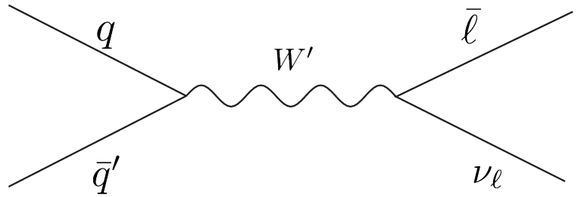
ATLAS : ATLAS-CONF-2017-016
CMS : arXiv:1612.09274 (Submitted to PLB)

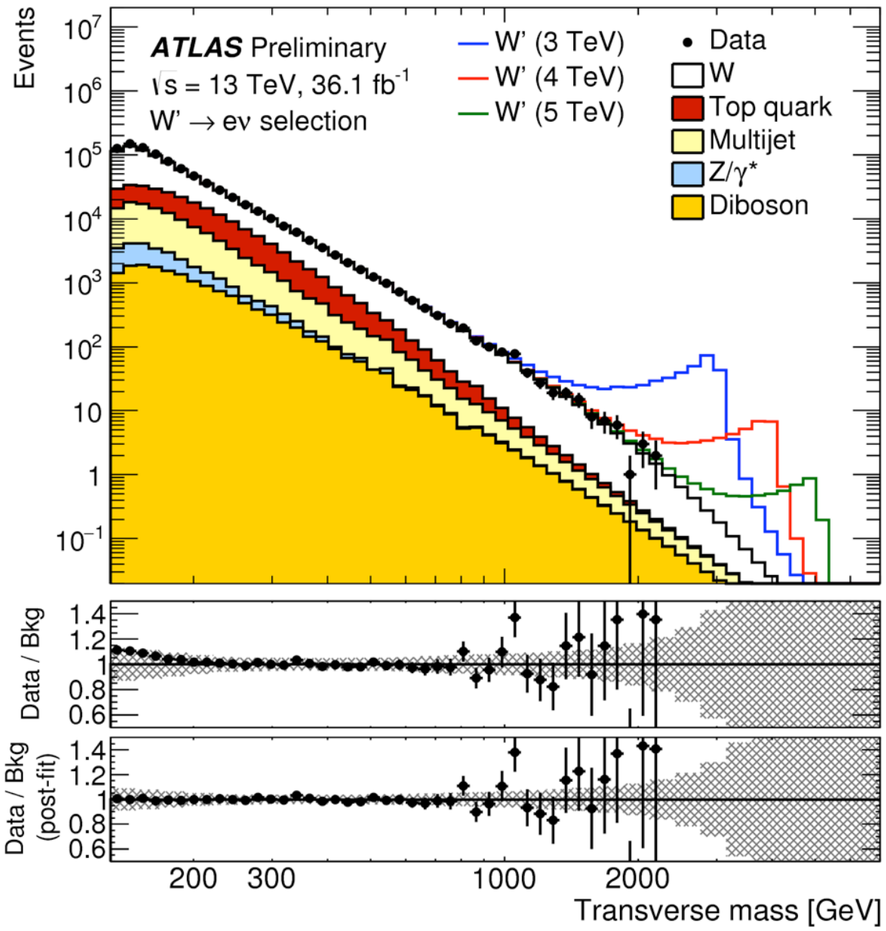
W'→e/μ+ν

Search for deviations from background in transverse mass distribution : $M_T = \sqrt{2p_T^l E_T^{miss}(1-\cos[\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,miss})])}$

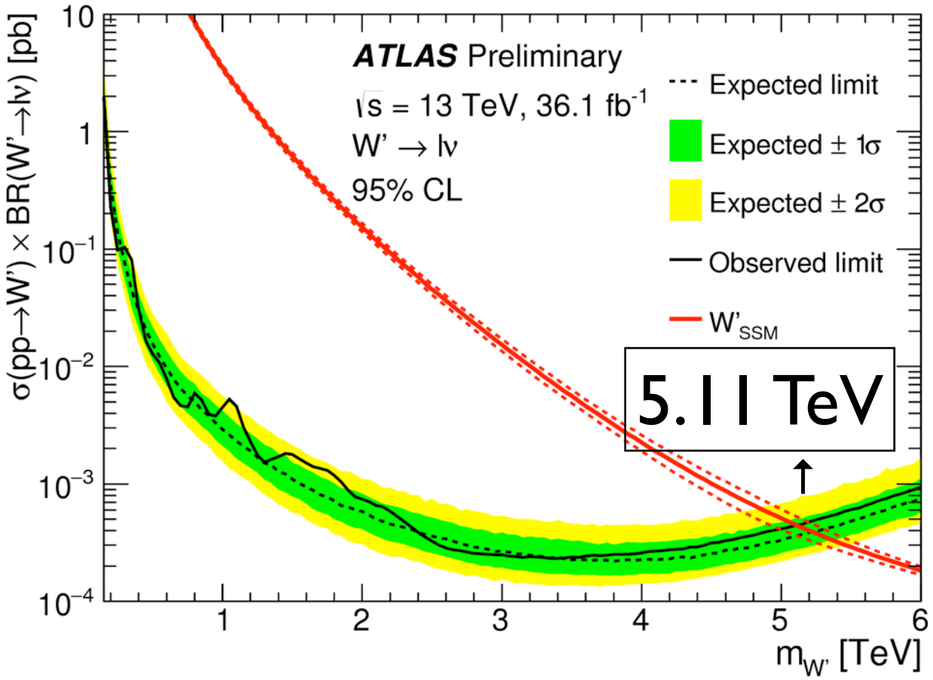
Benchmark: Sequential Standard Model (SSM)

W': Heavy replica of SM W





No significant excess observed



SSM W': 2015 limit improved by ~1 TeV

CMS also provides Model Independent limit

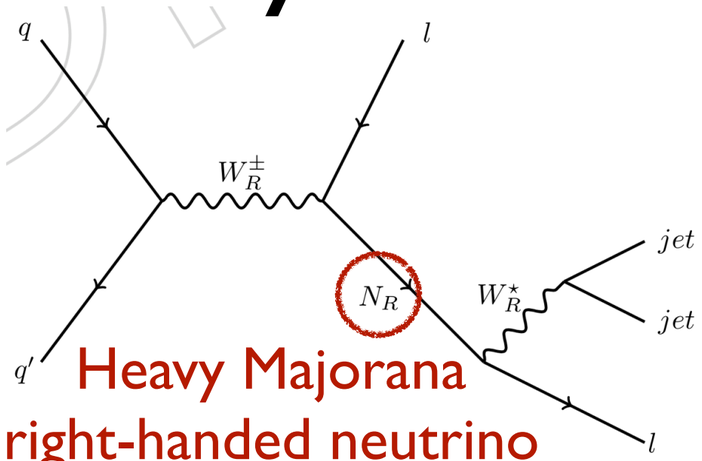
- Same search in **τ** channel.
  - Enhanced coupling to third generation in some models.
    - CMS 13 TeV (2015) PAS EXO-16-006

Heavy neutrino and W *leptons+jets*

CMS PAS EXO-16-045

2015

HOT OFF THE PRESS



Heavy Majorana right-handed neutrino

Final states: eejj / μμjj

Cut and count analysis

8 TeV(CMS): 2.8σ excess in eejj channel ~2.1 TeV

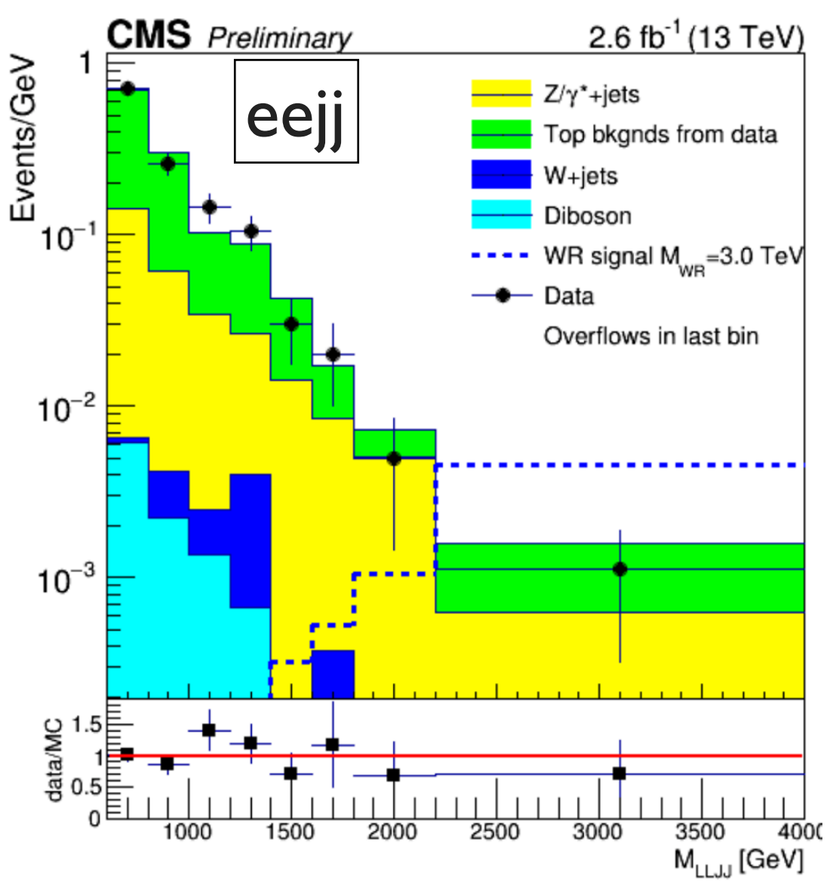
Eur. Phys. J. C 74 (2014) 3149

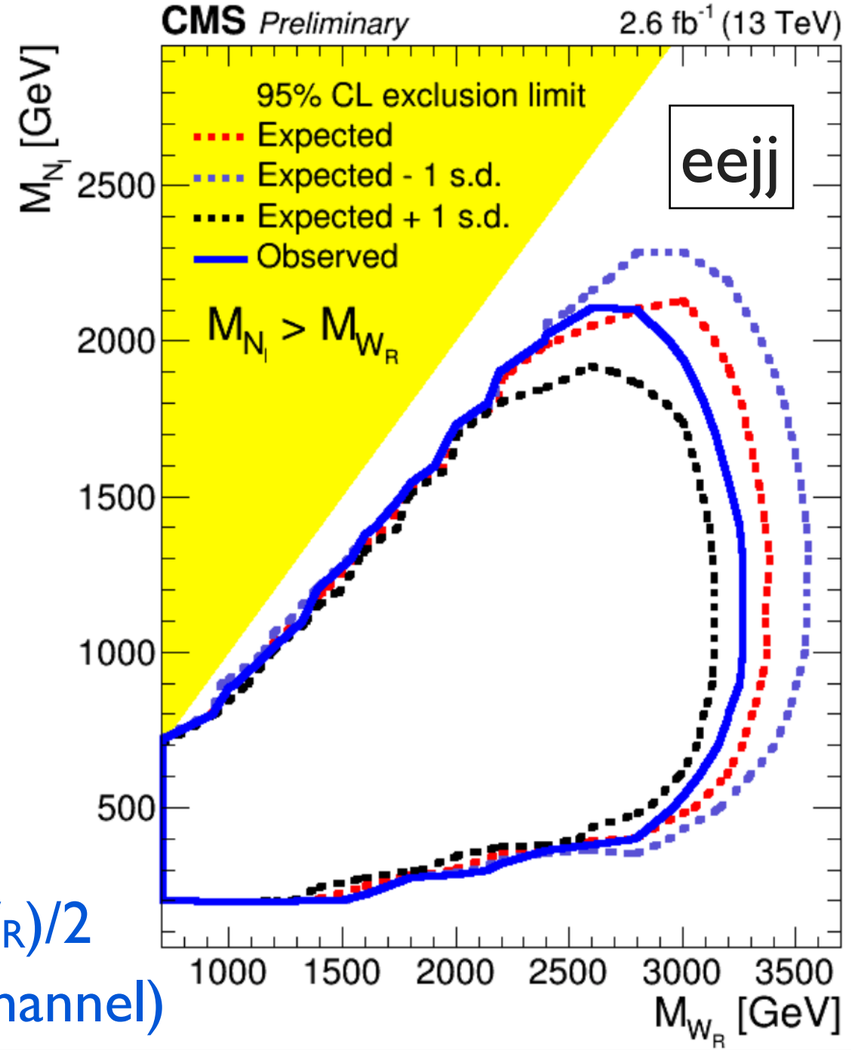
8 TeV excess not confirmed

No significant excess observed

$M(N_R)>M(W_R)$ not accessible (kinematic constraint)

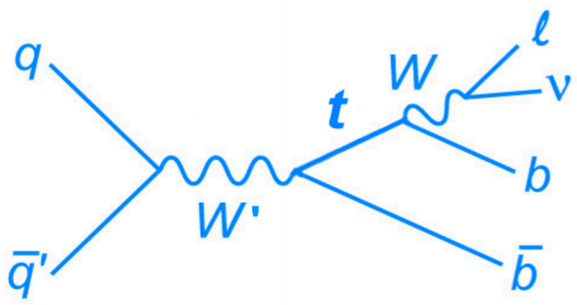
Left-right symmetric extension of SM
(Explain SM neutrino masses through seesaw mechanism)





- W_R mass limit, assuming $M(N_R)=M(W_R)/2$
  - **3.5 / 3.3 TeV** (Electron / Muon channel)

W'→t+b *lepton+jets+MET*

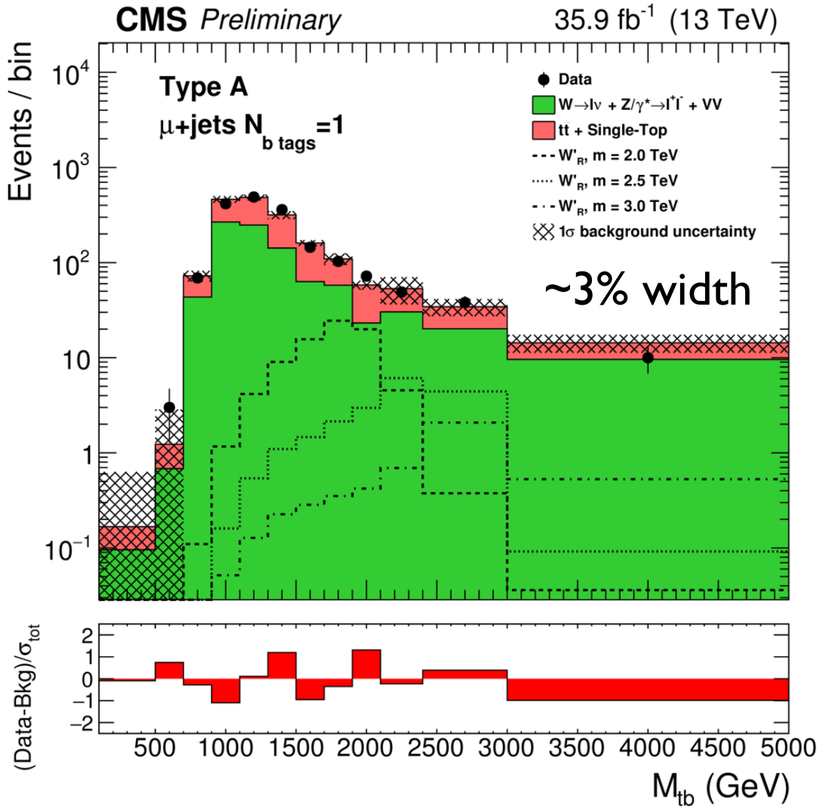


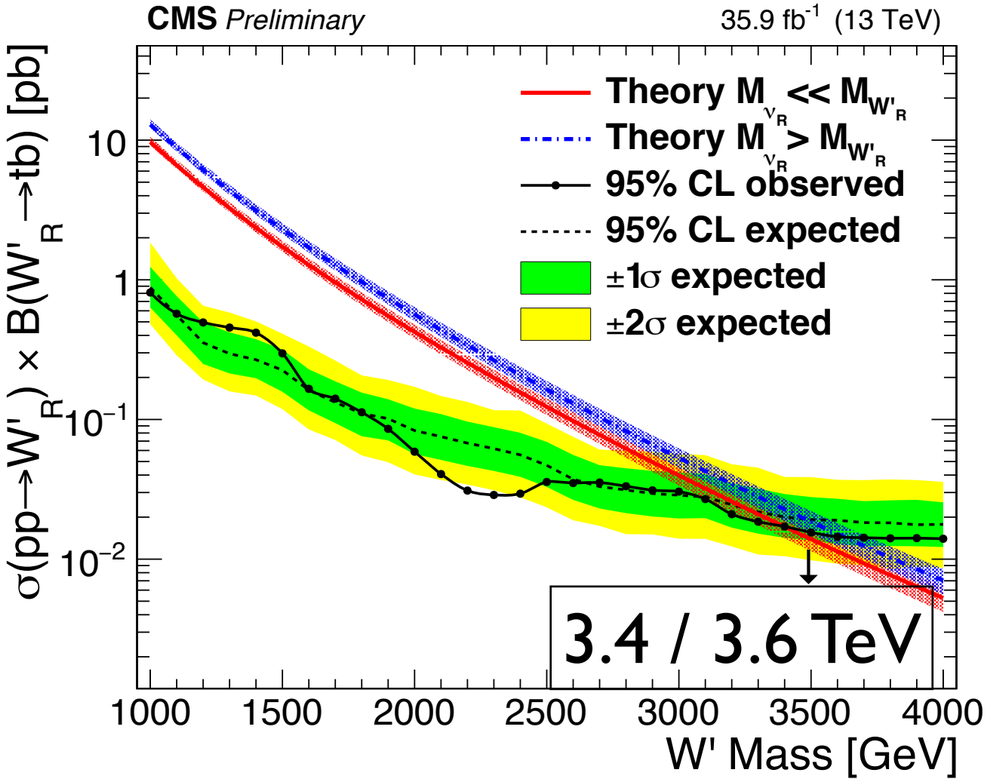
Coupling to 3rd generation quark enhanced in some models

- Final state : One lepton, ≥2 jets and MET
- 8 independent signal regions according to
  - lepton flavour (e or μ)
  - number of b-tagged jets (1 or 2)
  - top p_T and dijet p_T (Type A or Type B)

$M(N_R)>M(W_R)$ is accessible

No significant excess observed

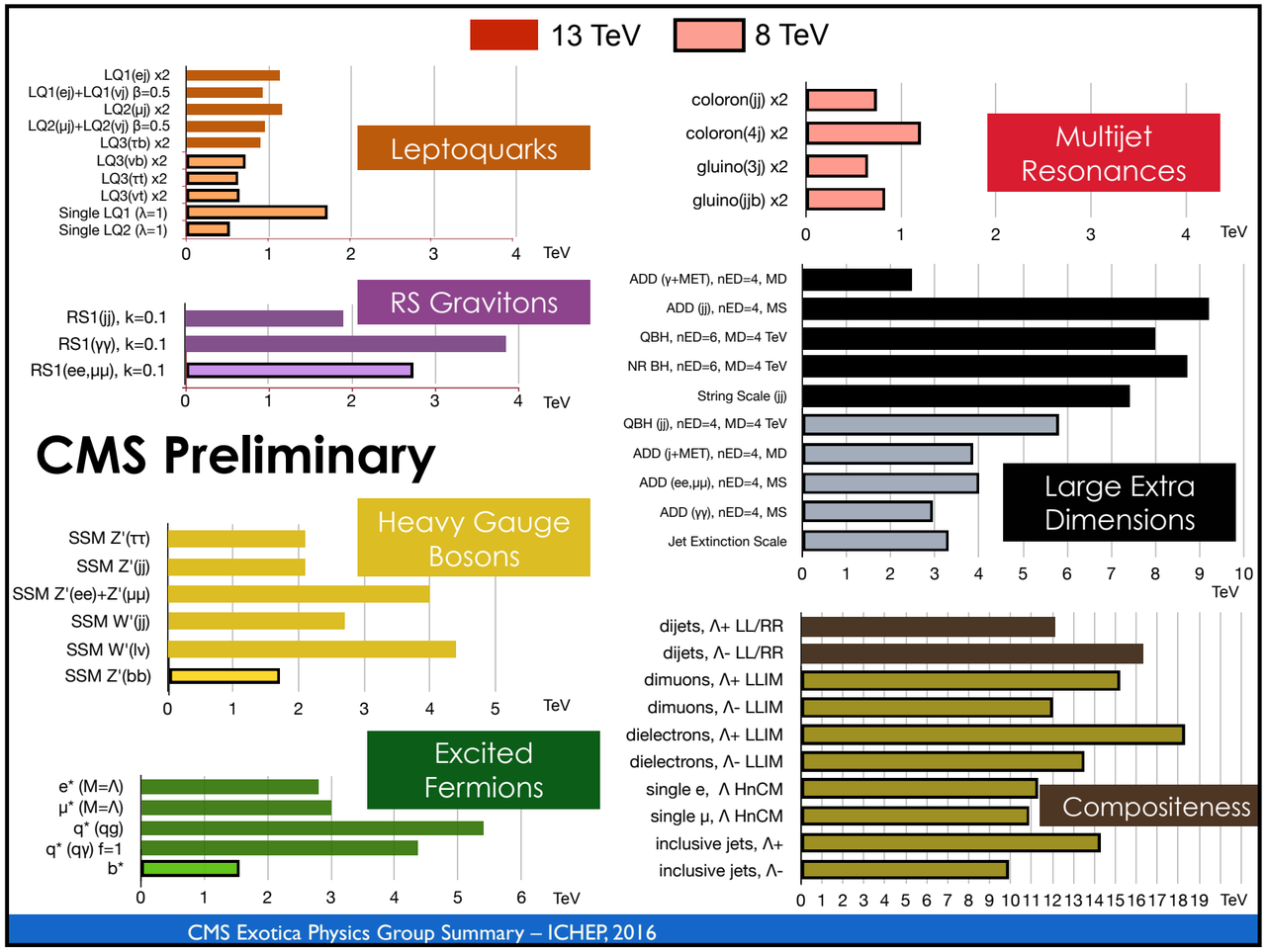


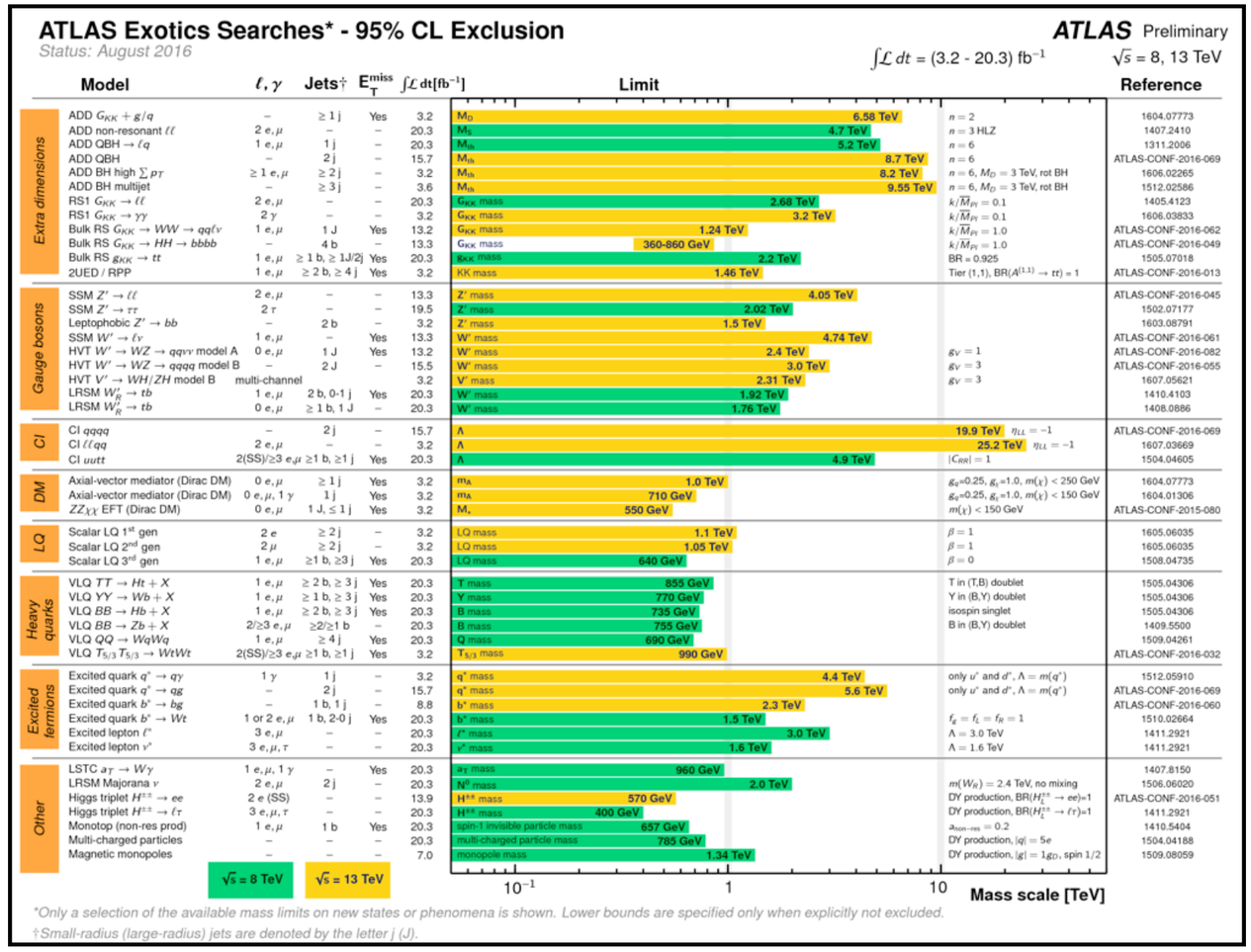


- Type B:
  - pT(top)>650 GeV
  - pT(j1+j2)>700 GeV
- Type A: other

2015 limit improved by ~1.1 TeV

And many more...





All results available here :

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

CMS : http://cms-results.web.cern.ch/cms-results/public-results/publications/

Conclusion & Outlook

- Wide program for high mass search.
  - No hint of New Physics so far.
  - Stringent limits on BSM scenarios.
  - Development / extensive use of novel techniques
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    - Jet substructure, identify boosted topologies
- Surprises can come from low mass also !
  - Keep searching there
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  - In run-2 expect ~120-150 fb^{-1}
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Conclusion & Outlook

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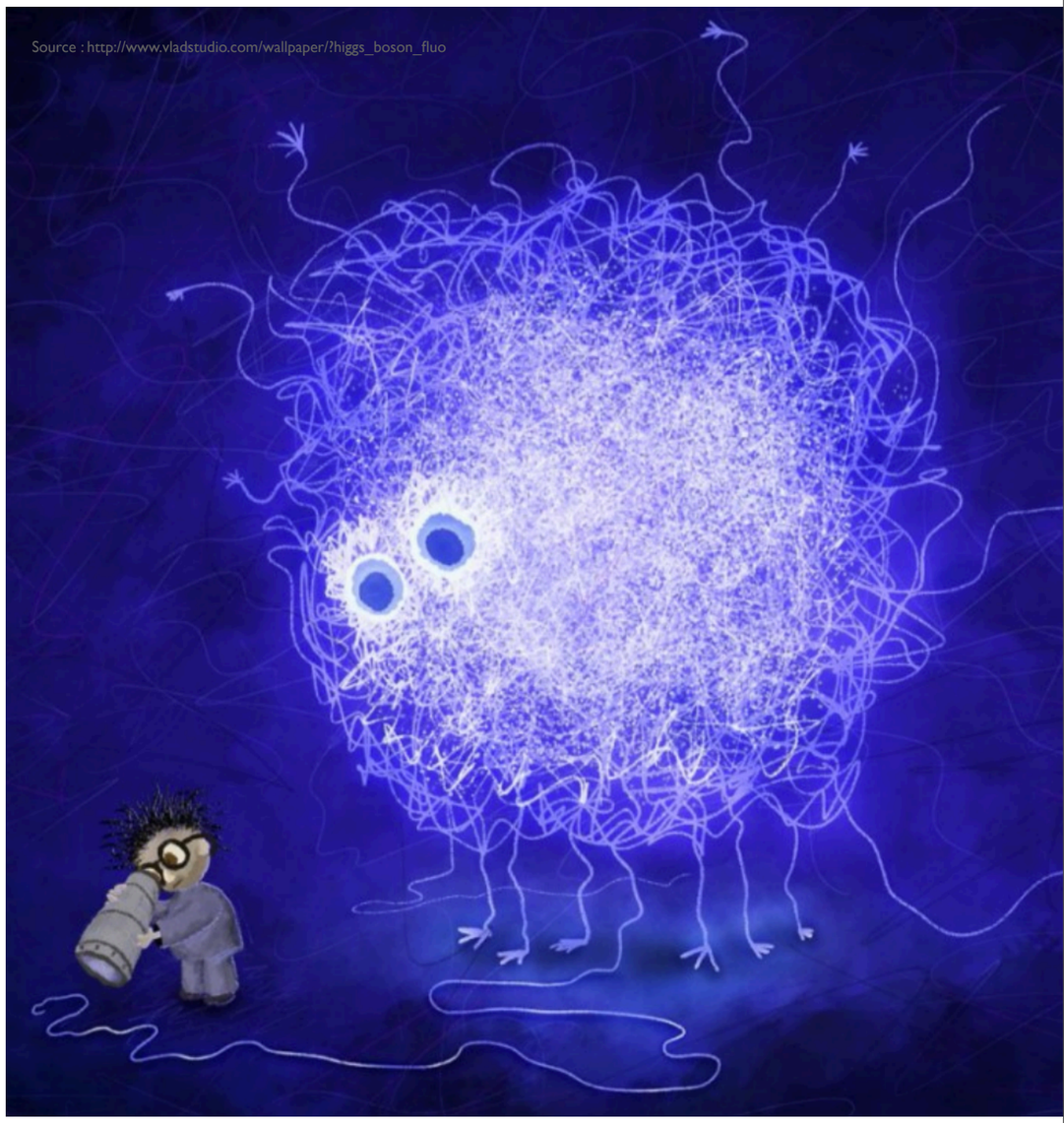
- We are still at the beginning of a long journey, so *stay tuned !*



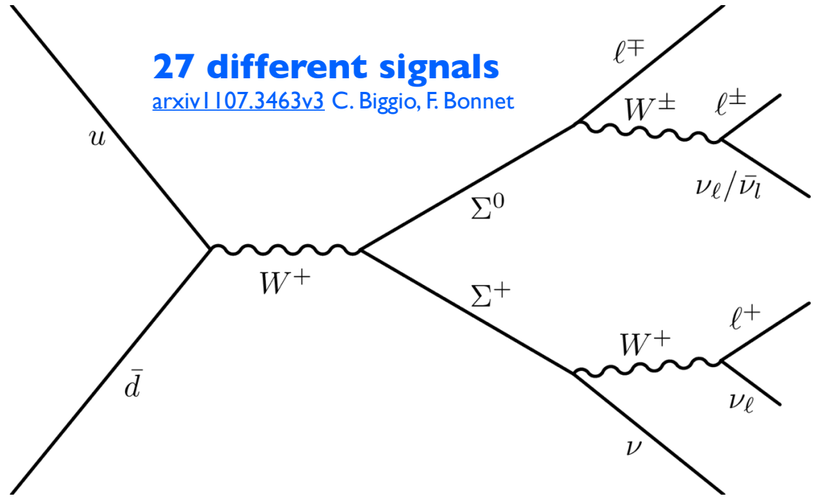
Extra Slides

CMS-PAS-EXO-17-006

Heavy Fermions *Multi-lepton*

Seesaw mechanism aims to explain ν masses

- Type III Seesaw: Pair-production of heavy fermions
- Heavy fermion → W/Z/H + lepton
- $\Sigma^{\pm}$ and Σ^{0} degenerate in mass
- Σ → lepton decays flavor democratic $V_e = V_\mu = V_\tau = 10^{-6}$

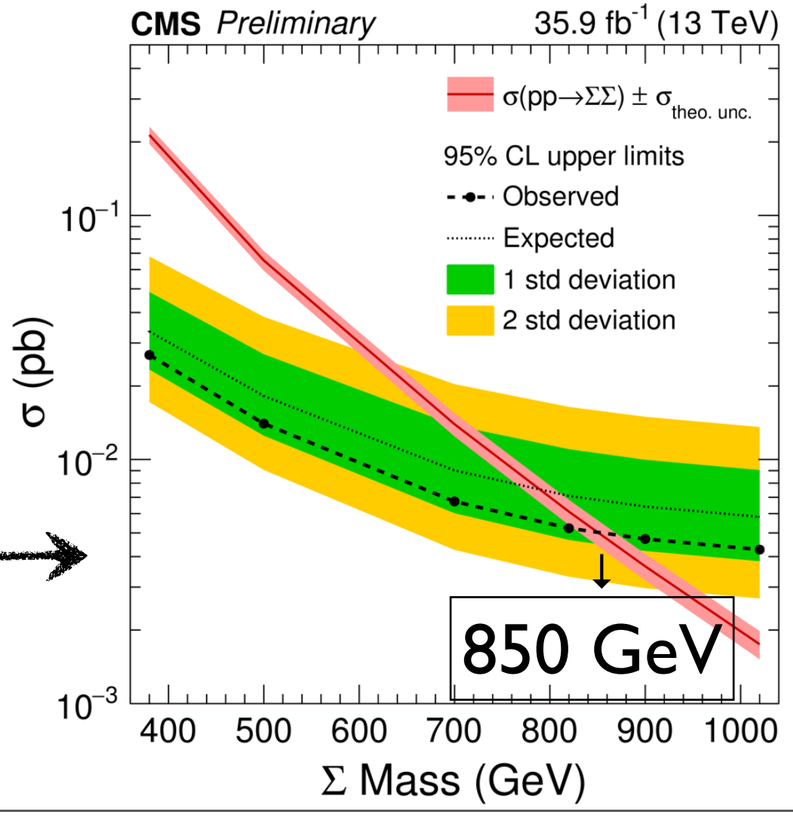


48 orthogonal signal regions based on

- Number of leptons in final state (eg. 3, ≥4)
- Number of OSSF lepton-pair (eg. 1,2)
- Invariant mass of OSSF lepton-pair (on Z-peak etc.)

No significant excess observed

Upper limits on the cross section sum for production of heavy fermion pairs



2015 limit improved by ~420 GeV

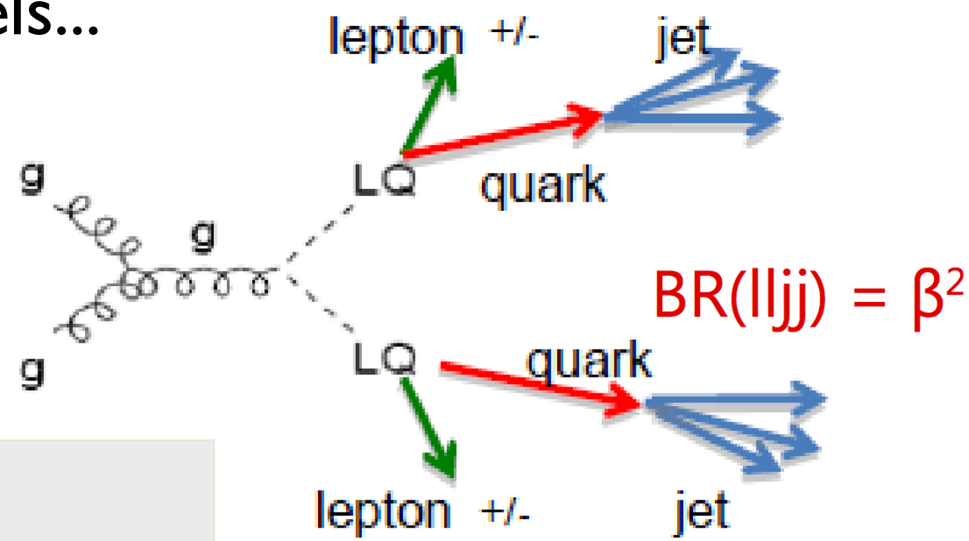
ATLAS Seesaw search (2012, 8 TeV): arxiv:1506.01839 (Published in PRD)

CMS arXiv:1703.03995
CMS PAS EXO-16-043
CMS PAS EXO-16-007
ATLAS NJP 18 (2016) 093016

Leptoquarks (LQ) *leptons+jets*

Arise in many models, eg. GUT, compositeness models...

- Search for pair-produced scalar LQs
- LQ have both baryon and lepton numbers
  - decay to lepton+quark (same generation)



BR(lljj) = β^2

1st and 2nd generation LQ

- Final state: eejj / μμjj
- CMS: Cut-and-count counting analysis
  - Cuts on S_T, $M_{\ell\ell}$, $M_{min}(\ell,j)$ optimised for each signal mass
- ATLAS: Look for excess in $M_{min}(\ell,j)$ distribution

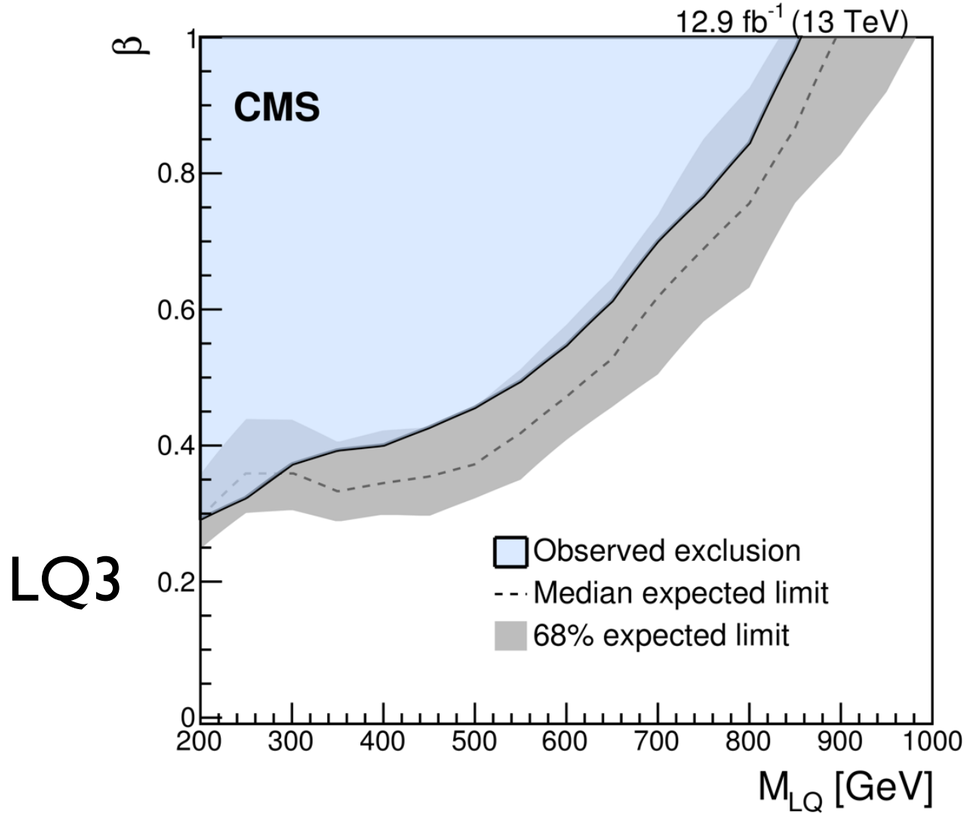
3rd generation LQ

- Final state: $\tau_\ell\tau_h$, ≥2 jets (≥1 b-tagged)
- Look for excess in S_T distribution

S_T: Scalar sum of pT of $\ell\ell$jj (and MET)

No significant excess observed

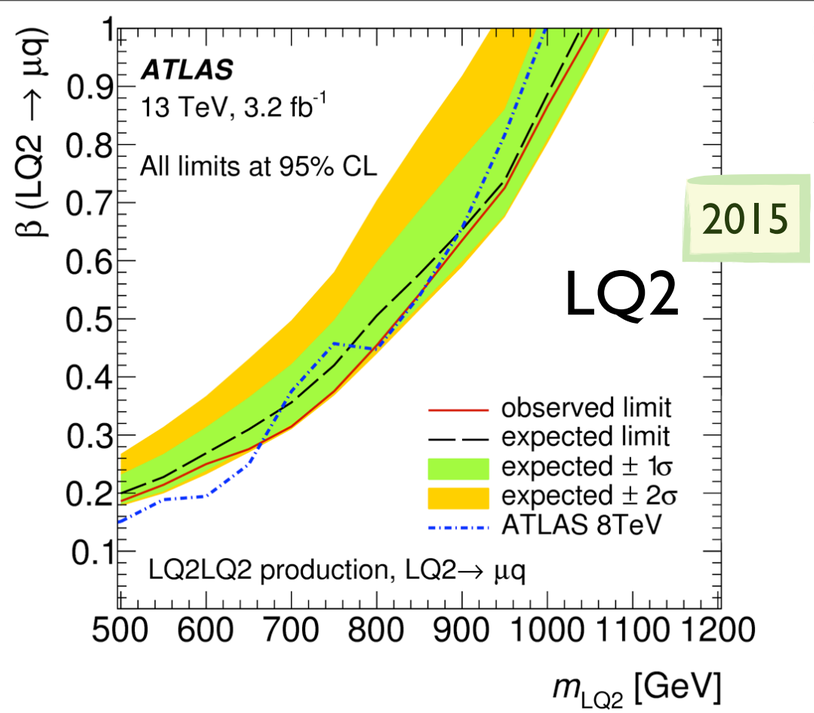
Leptoquarks (LQ) *leptons+jets*



LQ3

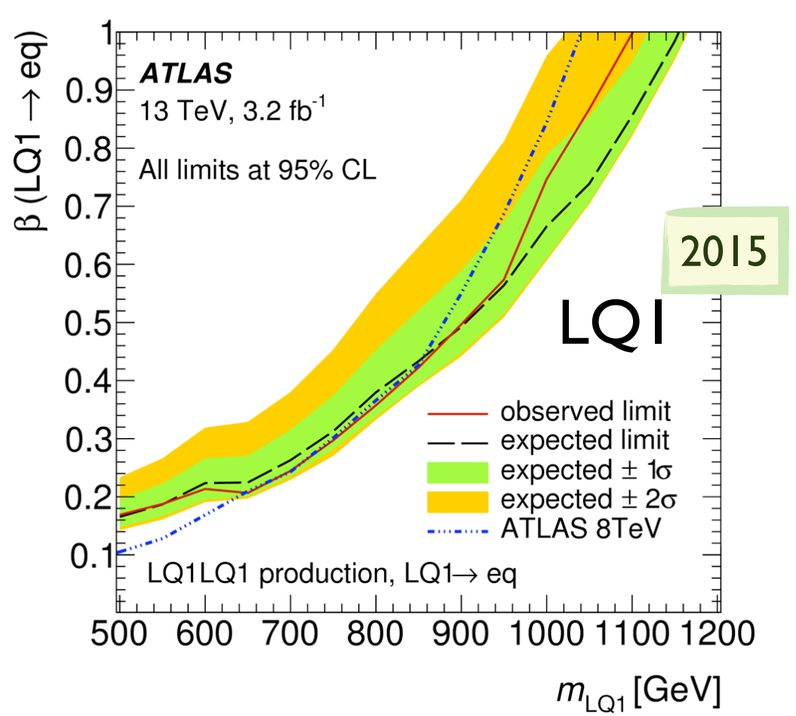
LQ generation	Exclusion limit β=1
LQ1	1130 GeV 2015
LQ2	1165 GeV 2015
LQ3	850 GeV

CMS arXiv:1703.03995
CMS PAS EXO-16-043
CMS PAS EXO-16-007
ATLAS NJP 18 (2016) 093016



2015

LQ2



2015

LQ1

Z’

E6
-> SO(10) × U(1)ψ
-> SU(4) × SU(2)L × SU(2)R × U(1)ψ
-> SU(3)C × U(1)B–L× SU(2)L × SU(2)R × U(1)ψ

Z’B–L Z’$_{3R}$

E6
-> SO(10) × U(1)ψ
-> SU(5) × U(1)χ × U(1)ψ

Z’ψ and Z’χ -> they can mix

4 jets

Coloron : massive color octet resonances. They arise in a wide range of theories, including axigluon, Topcolor, and vector-like confinement models, as scalar partners of a Dirac gluino in SUSY and Kaluza-Klein excitations of the gluons.

M. Redi et al., Strong Signatures of Right-Handed Compositeness, JHEP 08 (2013) 008, arXiv: 1305.3818.

Many tools available to identify boosted topologies

- **Grooming** (remove pileup contamination)
  - Trimming (arXiv:0912.1342)
  - Filtering (arXiv:0802.2470)
  - Pruning (arXiv:0903.5081)
  - Soft-drop (arXiv:1402.2657)
- **Substructure "Tagging"**
  - N-subjettiness (arXiv:1108.2701)
  - Energy correlation functions (arXiv:1609.07483)

"**soft drop declustering**", recursively removes soft wide-angle radiation from a jet.
The soft drop algorithm depends on two parameters—
a soft threshold zcut and
an angular exponent β—with the β = 0 limit corresponding roughly to the (modified) mass drop procedure. The β = 0 limit is particularly interesting, since it is not only "Sudakov safe" but also largely insensitive to the value of the strong coupling constant.

Recluster the jet constituents using the Cambridge-Aachen (C/A) algorithm to form a pairwise clustering tree with an angular-ordered structure.

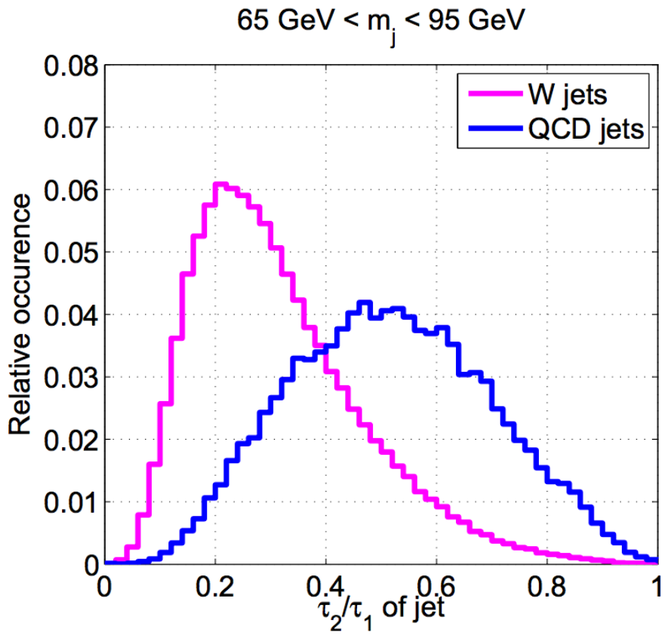
Given a jet of radius R0 with only two constituents, the soft drop procedure removes the softer constituent unless

$$\text{Soft Drop Condition:} \quad \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta},$$

N-subjettiness

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \left\{ \Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k} \right\}.$$

$$d_0 = \sum_k p_{T,k} R_0,$$



(a)

Pruning

$$z \equiv \min(p_{T_1}, p_{T_2})/p_{T_p}, \qquad \theta \equiv \Delta R_{12}.$$

1. Rerun the jet algorithm on the set of initial protojets from the original jet, checking for the following condition in each recombination $1, 2 \to p$:

$$z < z_{\text{cut}} \qquad \text{and} \qquad \Delta R_{12} > D_{\text{cut}}. \tag{3}$$

2. If this condition is met, do not merge the two protojets 1 and 2 into p. Instead, discard the softer protojet and proceed with the algorithm. The resulting jet is the *pruned* jet.

Energy correlation functions (arXiv:1609.07483)

used in dijet+ISR search

2-point, 3 point energy correlation functions

$$e_2^{(\beta)} = \sum_{1 \le i < j \le n_J} z_i z_j \, \theta_{ij}^{\beta} \,,$$

$$e_3^{(\beta)} = \sum_{1 \le i < j < k \le n_J} z_i z_j z_k \, \theta_{ij}^{\beta} \theta_{ik}^{\beta} \theta_{jk}^{\beta} \,,$$

Assumption β=1

$$z_i \equiv \frac{p_{Ti}}{\sum_{j \in \text{jet}} p_{Tj}} \,, \qquad \theta_{ij}^2 \equiv R_{ij}^2 = (\phi_i - \phi_j)^2 + (y_i - y_j)^2 \,,$$

$$N_i^{(\beta)} = \frac{2 e_{i+1}^{(\beta)}}{\left(1 e_i^{(\beta)}\right)^2} \,;$$

defined without respect to subjet axes, and therefore exhibit improved behavior compared to N-subjettiness, particularly in the transition to the unresolved region, where the definition of subjet axes becomes ambiguous

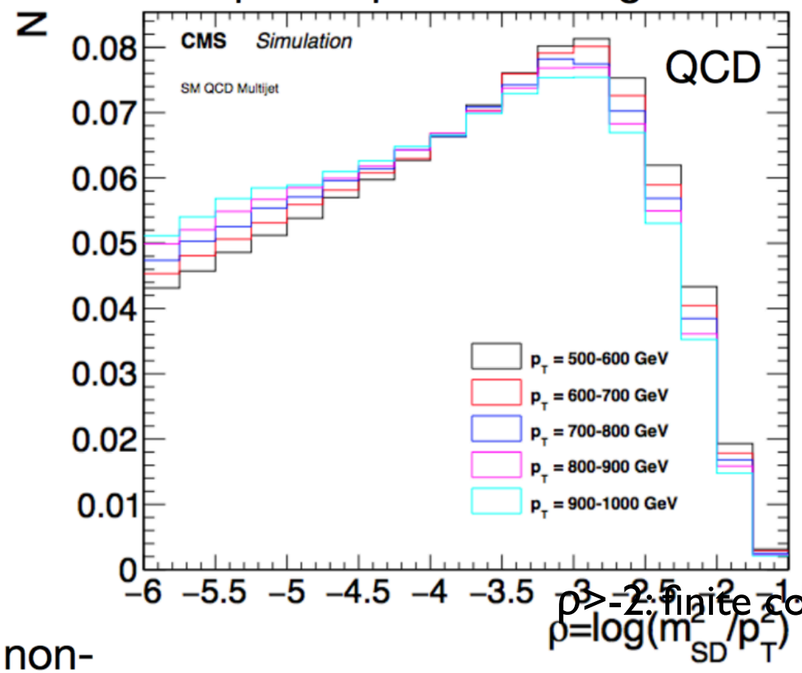
Dijet+ISR

Triggers:
AK8PFJet360_TrimMass30
AK8PFHT700_TrimR0p1PT0p03Mass50
PFHT[800,900]
PFHT650_WideJetMJJ[900,950]DEtaJJ1p5
PFJet450
AK8DiJet280_220_TrimMass30_Btag020

Lepton veto:
- 0 "loose" and isolated muons, electrons pT > 10 GeV
- 0 taus, pT > 18 GeV, $|\eta| < 2.3$

Jets Kinematic Selection:
- AK8 Jets - PUPPI inputs: pT>500 GeV, $|\eta| < 2.5$, tight jet ID
- Soft drop jet mass (m_{SD}) + Puppi-SD corrections (AN-16-215)
- Jet rho defined as $\rho = \ln(m_{SD}^2/pT^2) = 2\ln(m_{SD}/pT)$
  - $-5.5<\rho<-2$

Helpful to predict background!



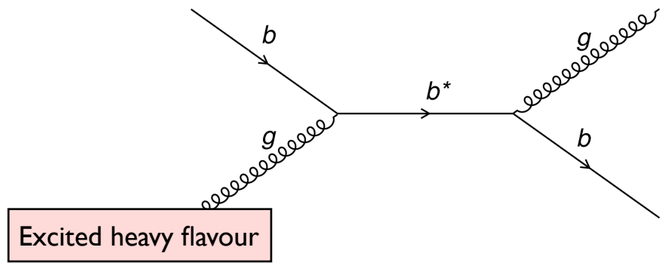
ρ>-2: finite cone effects

ρ<-5.5: non-perturbative effects

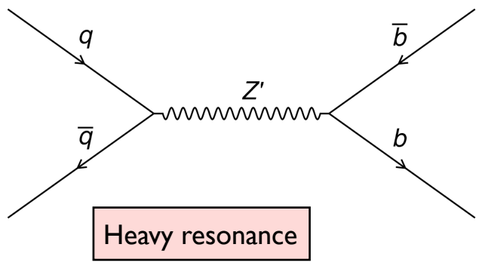
Di-jet (≥ 1 b-tag)

ATLAS-CONF-2016-060

Many BSM scenarios predict resonances decaying to b-quark(s)



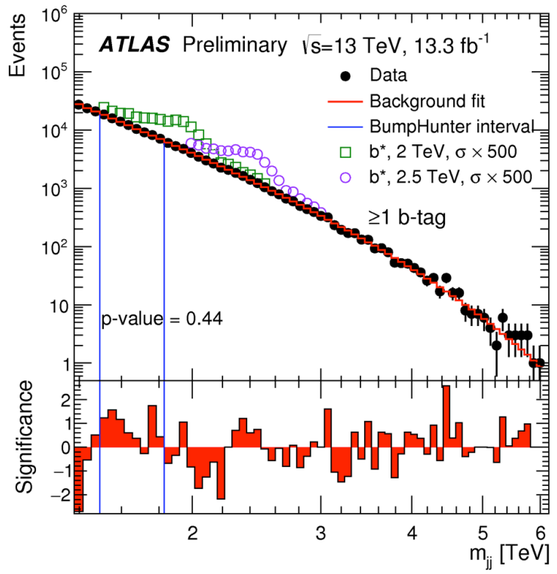
Excited heavy flavour



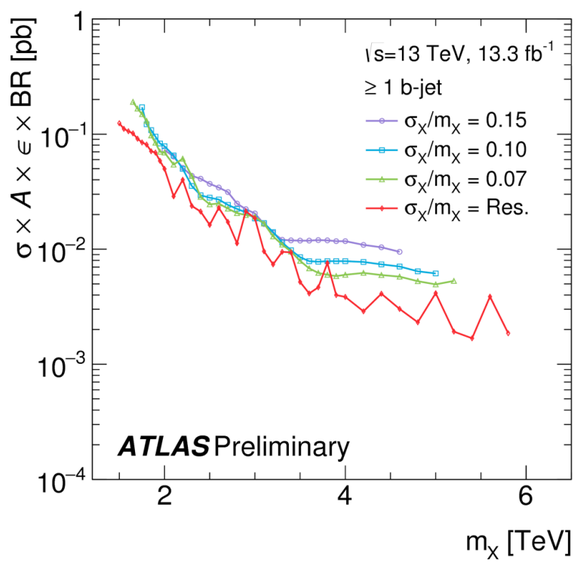
Heavy resonance

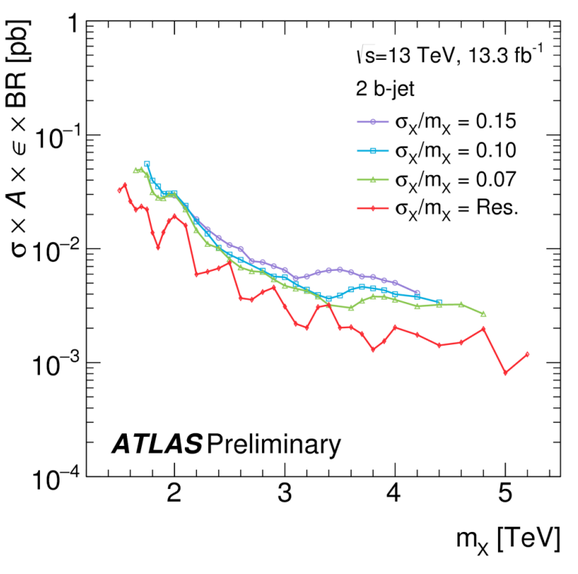
Follows similar strategy as the di-jet resonance search

No significant excess observed



Limits on generic gaussian shapes





Dilepton (ee / μμ)

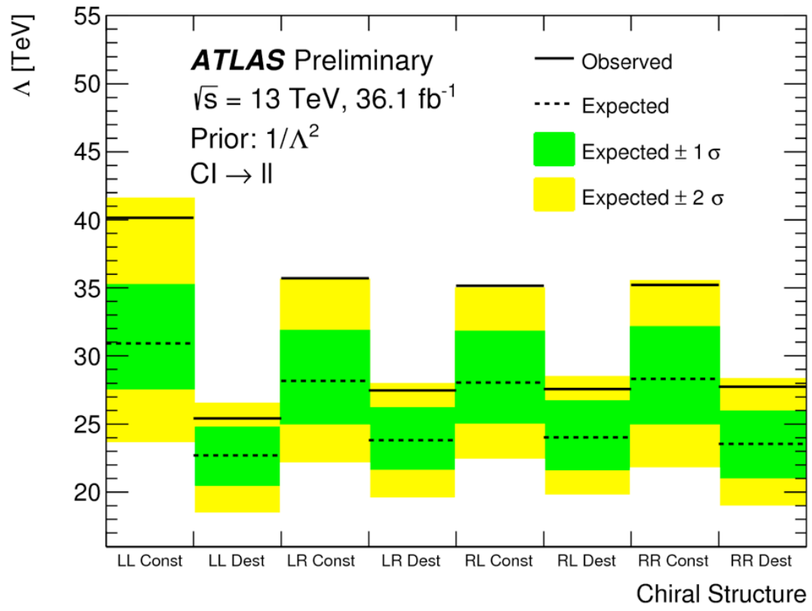
ATLAS : ATLAS-CONF-2017-027
CMS : PAS EXO-16-031

The results can also be interpreted as limits on quark-lepton compositeness and reach 25-40 TeV

ATLAS

Minimal Z' models

Model	γ'	$\tan\theta_{\text{Min}}$	Lower limits on $m_{Z'_{\text{Min}}}$ TeV			
			ee		$\mu\mu$	
			Obs	Exp	Obs	Exp
Z'_{χ}	$\sqrt{\frac{41}{24}}\sin\theta_{\text{Min}}$	$-\frac{4}{5}$	3.7	3.7	3.4	3.3
Z'_{3R}	$\sqrt{\frac{5}{8}}\sin\theta_{\text{Min}}$	-2	4.0	3.9	3.6	3.6
Z'_{B-L}	$\sqrt{\frac{25}{12}}\sin\theta_{\text{Min}}$	0	4.0	4.0	3.6	3.6



- Other dilepton searches : Lepton flavour violating eμ/eτ/μτ channels
  - CMS : PAS EXO-16-001, 2015 data, 13 TeV (eμ)
  - ATLAS : EXOT-2015-20, 2015 data, 13 TeV (eμ/eτ/μτ)