Exotic Searches at ATLAS

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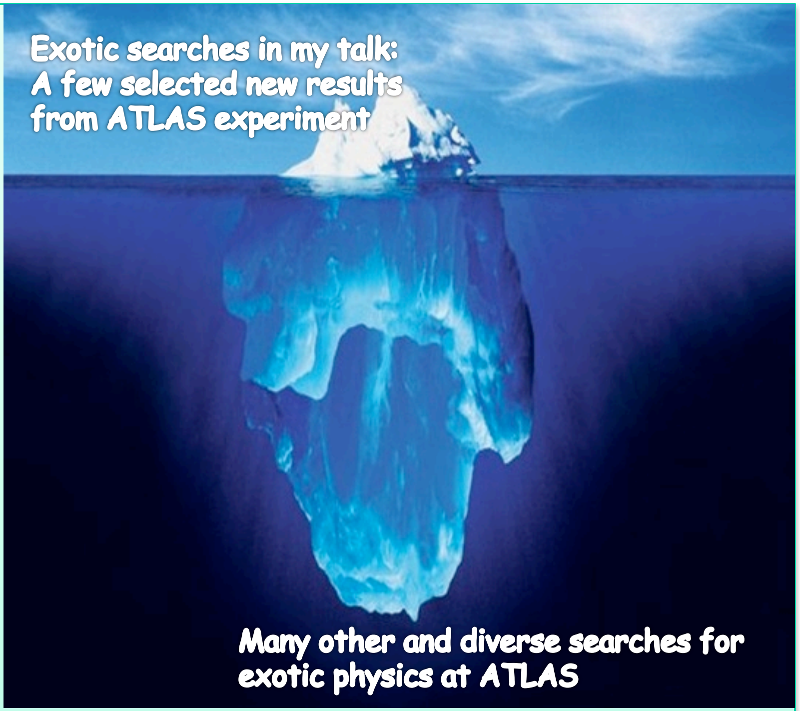
On behalf of the ATLAS Collaboration

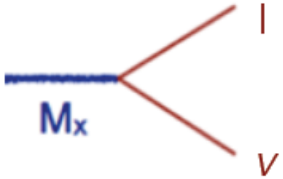
Introduction and Outline

- Exotic physics at ATLAS:
  - ✓ Searches for NP beyond the SM
    - Many well motived theories
  - ✓ Many diverse & broad topics
    - Large overlap with SYSY searches
- Outline of the talk:
  - ✓ Organized as signature based searches
    - High p_T lepton final state
    - Jet final states
    - SM boson final states
    - Unconventional signature

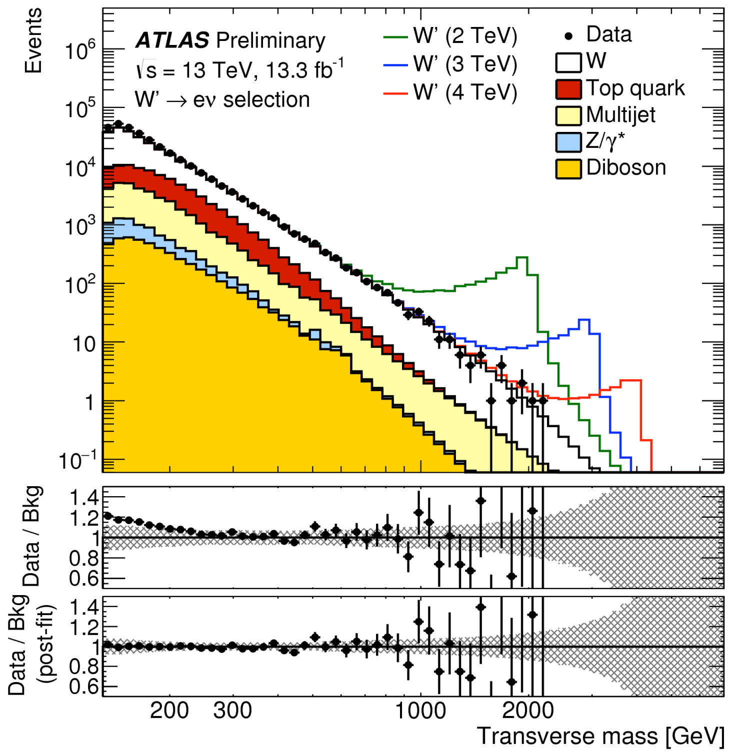


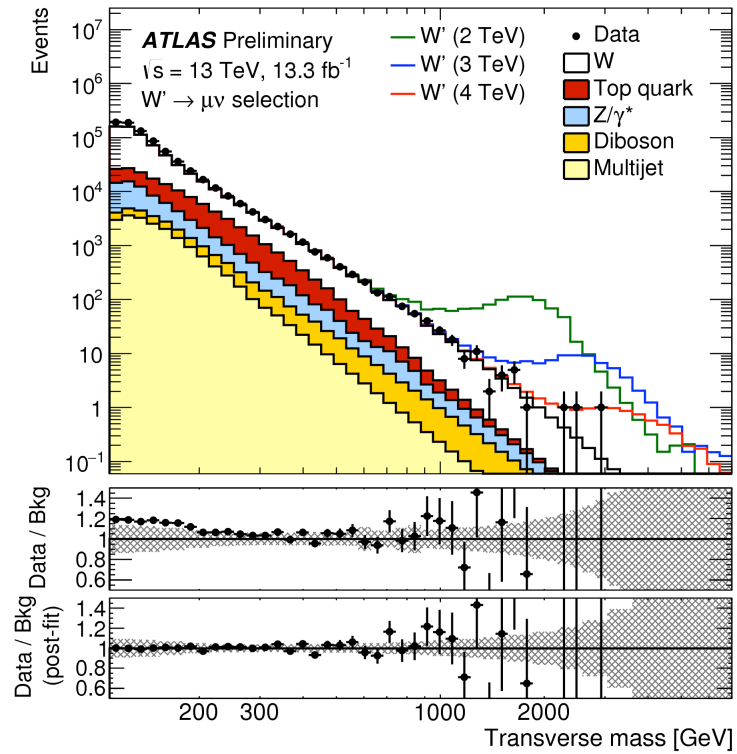
- Only a few selected new results from ATLAS
- Many new exotic results covered in other talks at this workshop
  - ✓ SUSY searches
  - ✓ Exotic Higgs beyond SM
  - ✓ Diboson resonances in llqq and vvqq final states
  - ✓ VBF WW->lvlv resonance search
  - ✓ HH->bbbb
  - ✓ Dark matter searches
- Focus in basic search strategy without too much details

Searches in high P_T lepton final states



Lepton + Miss E_T

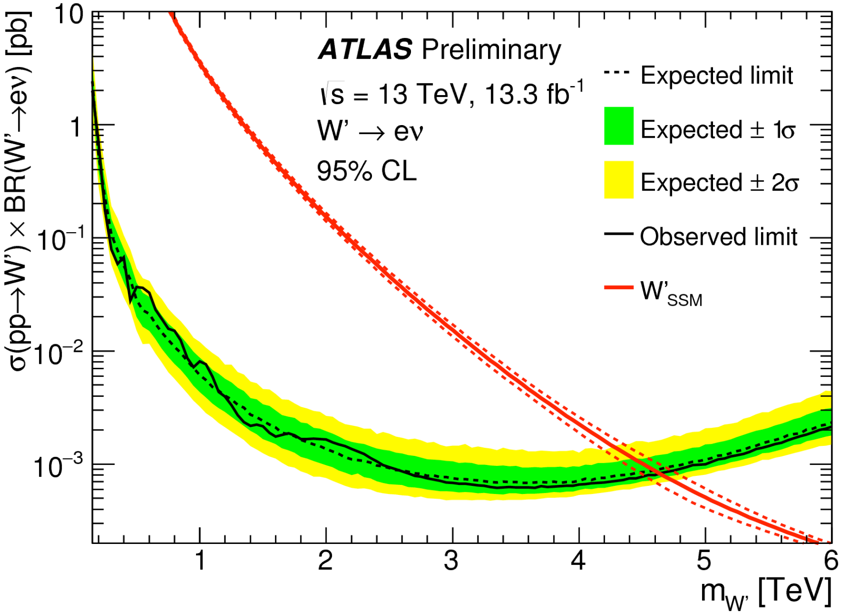


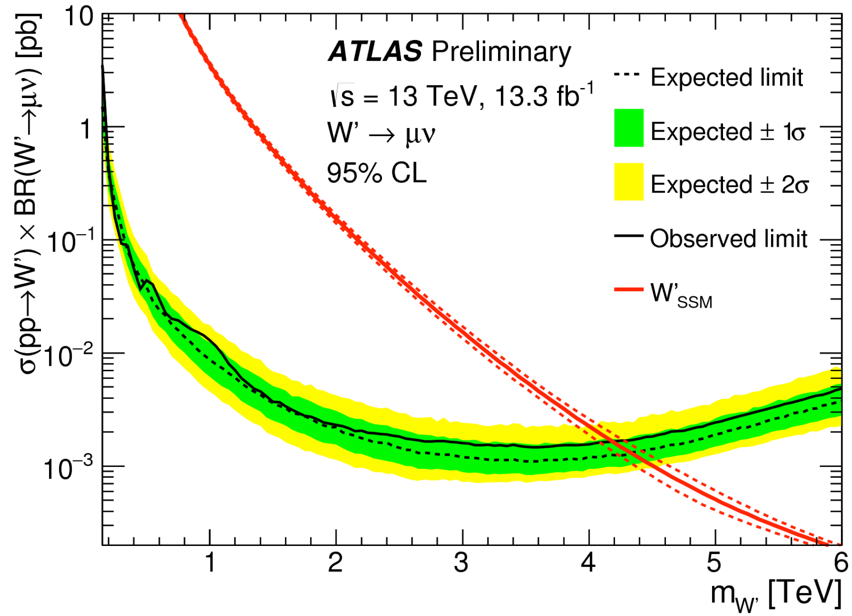


- W'->lnu: interpreted with a Sequential SM gauge boson with same coupling to fermion as SM
- Fit the transverse mass to look for peaking structure
- Background estimate:
  - ✓ SM production of W, top and diboson: MC simulation
  - ✓ Multijet background due to jet fake lepton: data driven matrix method
    - Measured lepton efficiency and fake (loosen lepton ID) rate from data
    - Infer true lepton and fake lepton numbers based on observed “good” & “fake” lepton numbers

$$m_T = \sqrt{2 p_T E_T^{miss} (1 - \cos\phi_{\ell\nu})},$$

Lepton + Miss E_T

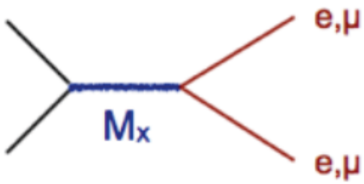




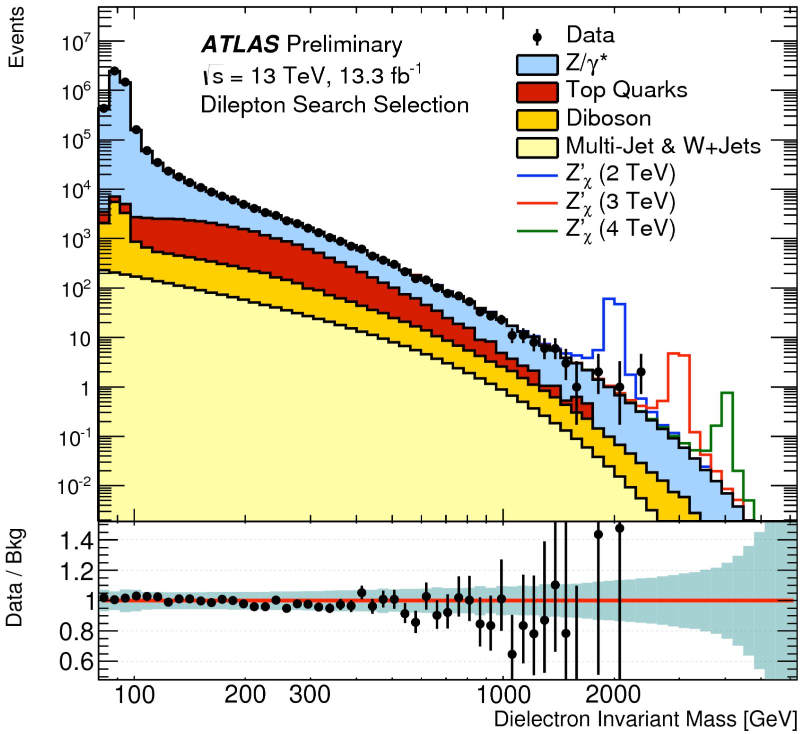
- No evidence of excesses
- Set production limits using profiled likelihood
  - ~ 500GeV better than 2015 analysis
- Dominant by statistical uncertainties
- Systematic uncertainties:
  - Dominated by multijet bg estimate
  - Significant error from PDF variation of W production

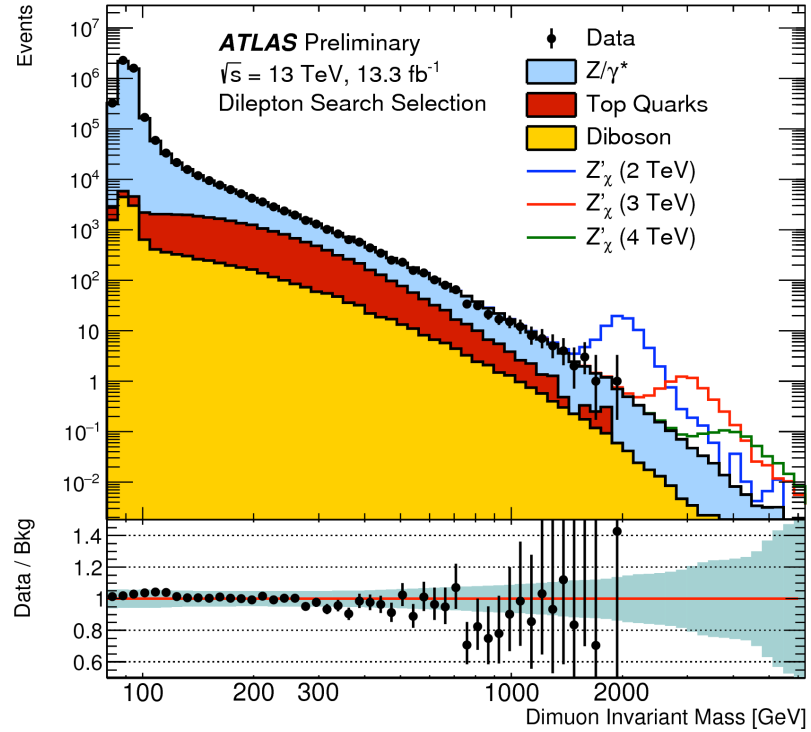
Decay	$m_{W'}$ lower limit [TeV] Expected	Observed
$W' \to e\nu$	4.44	4.42
$W' \to \mu\nu$	4.13	4.06
$W' \to \ell\nu$	4.62	4.59

Ref: ATLAS-CONF-2016-061
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-061/



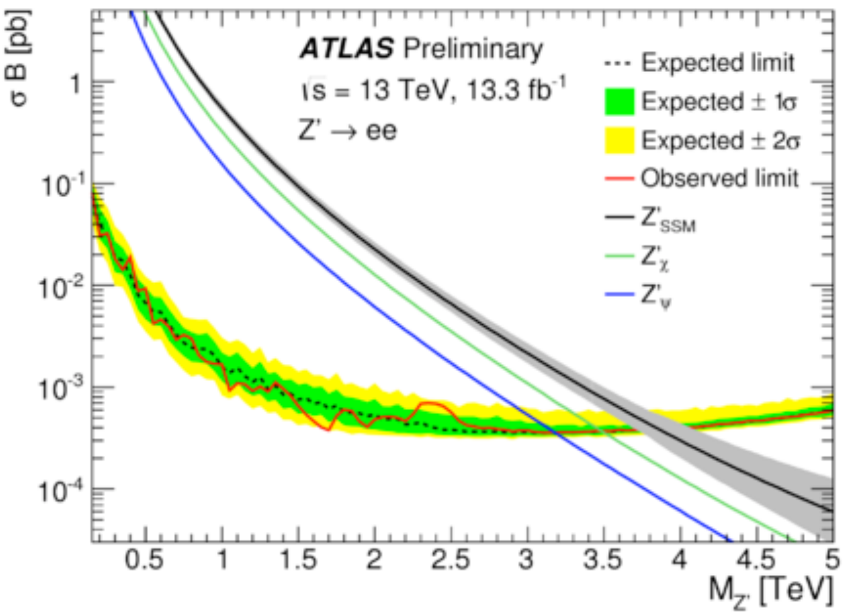
Narrow Di-Lepton Resonance

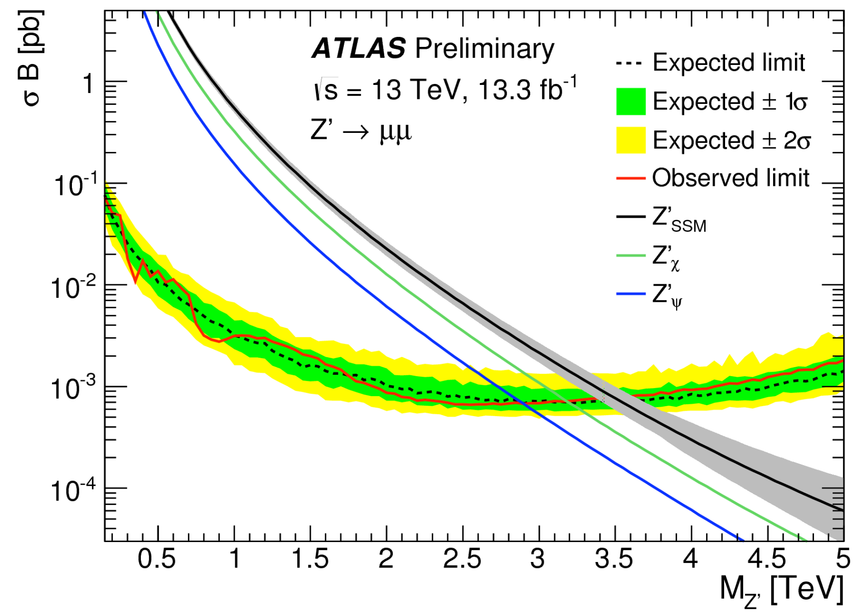




- Theory motivation: Additional a Gauge boson (SSM), Extra-dimension (RS graviton), E6 ……
- Fit the di-lepton invariant mass to look for peaking structure
- Background estimate:
  - ✓ MC for real 2 leptons from SM production: Z, top and diboson:
  - ✓ W+jets and multijet background due to jet fake lepton: data driven matrix method
    - Measured lepton efficiency and fake (loosen lepton ID) rate from data
    - Infer true lepton and fake lepton numbers based on observed "good" & "fake" lepton numbers

Narrow Di-Lepton Resonance





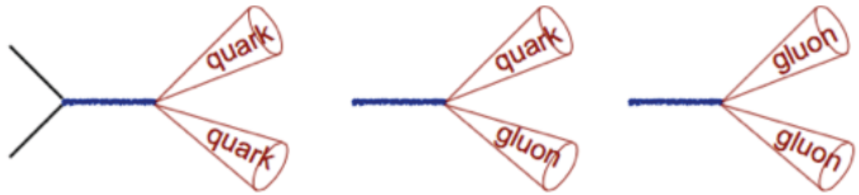
- No evidence of excesses
- Set production limits using profiled likelihood
  - ✓ ~ 400GeV better than 2015 analysis
- Dominant by statistical uncertainties
- Systematic uncertainties:
  - ✓ Dominated PDF variation of DY production

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	-	3.85	3.86	3.49	3.53	4.05	4.06
Z'_{χ}	1.2	0.50	3.48	3.49	3.18	3.19	3.66	3.67
Z'_{S}	1.2	0.63 π	3.43	3.44	3.14	3.14	3.62	3.61
Z'_{I}	1.1	0.71 π	3.37	3.37	3.08	3.08	3.55	3.55
Z'_{η}	0.6	0.21 π	3.25	3.25	2.96	2.94	3.43	3.42
Z'_{N}	0.6	-0.08 π	3.23	3.23	2.95	2.94	3.41	3.41
Z'_{ψ}	0.5	0 π	3.18	3.18	2.90	2.88	3.36	3.35

Ref: ATLAS-CONF-2016-045
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-045/

Searches in high P_T jets final states

Heavy resonance decaying to di-jets



- Particles in NP that can be produced in LHC will couple with partons in proton
  - ✓ Decaying to parton is dominant final states dominated
  - ✓ Possible large production cross section
  - ✓ Excited quarks, new heavy gauge bosons, quantum black holes and contact interaction
- Search Strategy: mass and angular distribution of the dijet events
  - ✓ Y*: half of the rapidity difference between 2 jets

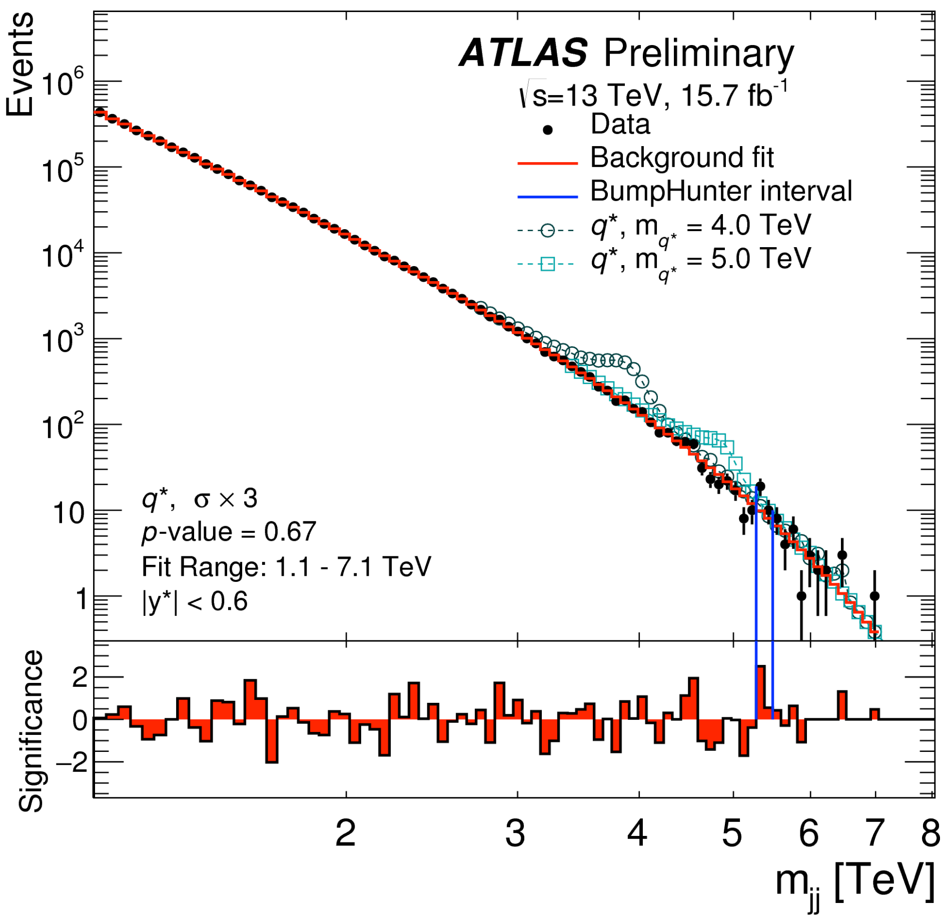
$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

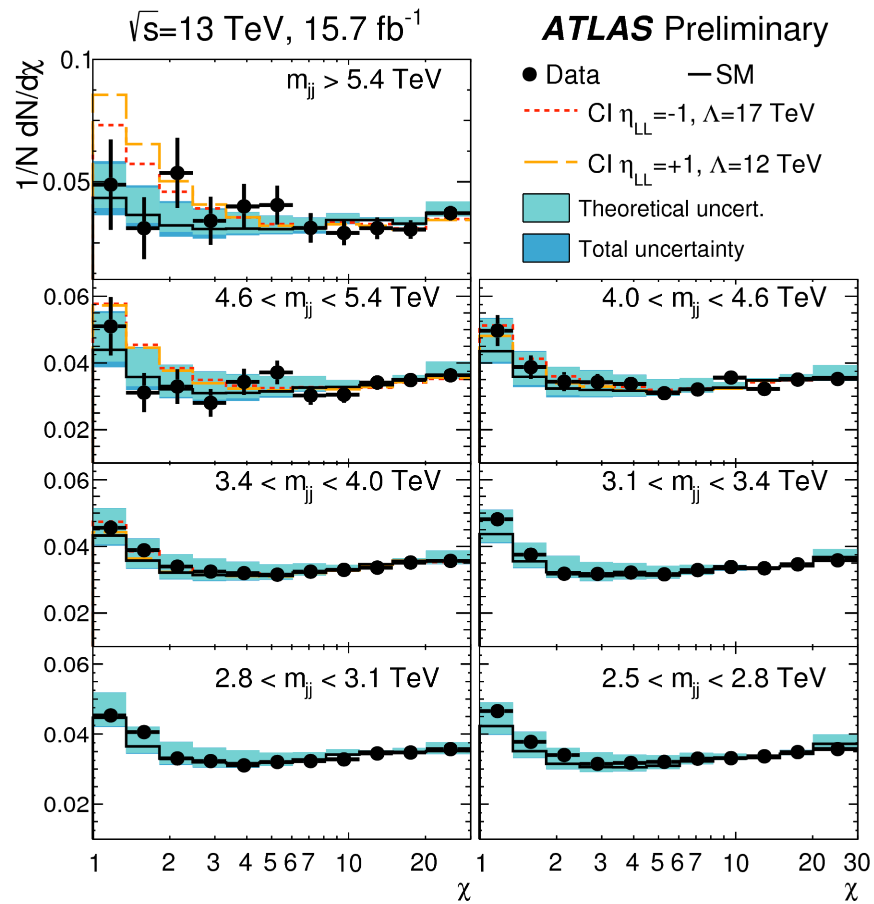
- Event selection
  - ✓ Single jet trigger with p_T>380GeV: ~ 99.5% efficiency for selected offline events
  - ✓ Leading (sub-leading jet) with p_T>440 (60) GeV
- Resonance search using m_{jj} distribution
  - ✓ Empirical analytical function to describe SM background
    - Used in dijet m_{jj} searches at lower collision energies
    - Test with MC simulated events with additional free parameters/functions

$$f(z) = p_1(1-z)^{p_2} z^{p_3}$$

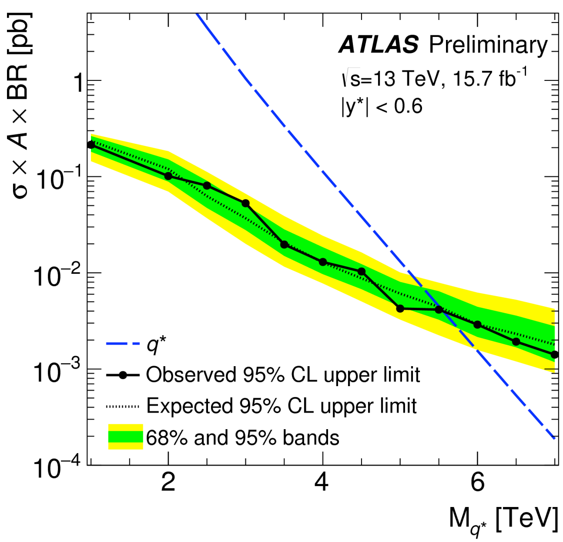
  - ✓ z=m_{jj}/sqrt(s), parameter p_1, p_2 and p_3 fitted from data
- Resonance search using angular distribution: dN/dχ
  - ✓ Background distribution modeled from MC simulated events

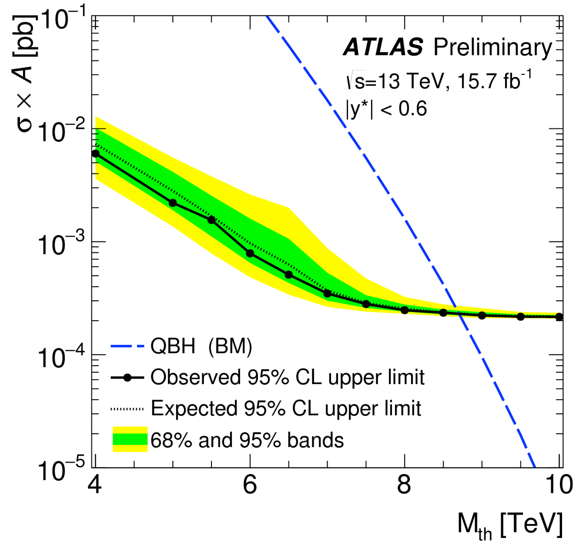
Heavy resonance decaying to di-jets



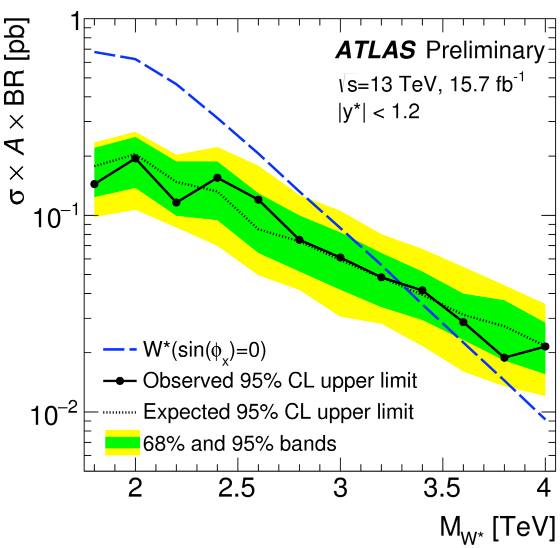


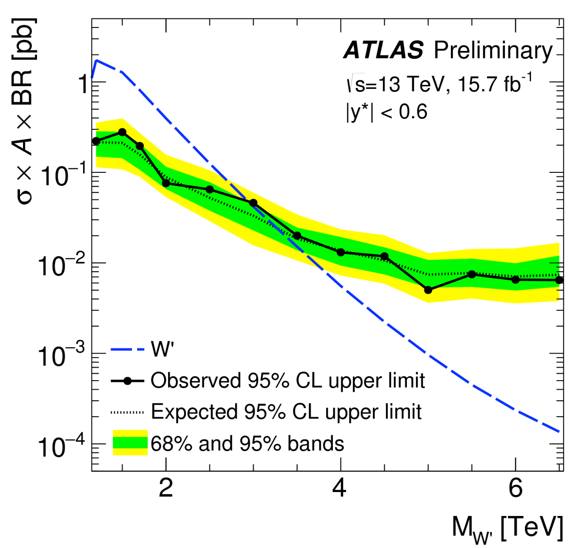
Heavy resonance decaying to di-jets





Model	95% CL Exclusion limit	
	Observed 13 TeV	Expected 13 TeV
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



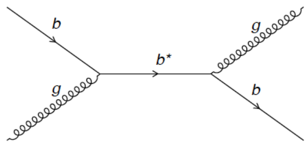


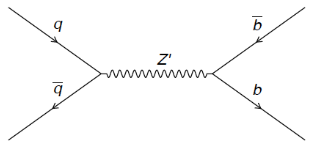
- Upper limits 15% improvement over 2015 13TeV data
- For contact interaction:
  - ✓ Assume η_{RR}=0 and η_{RL}=0

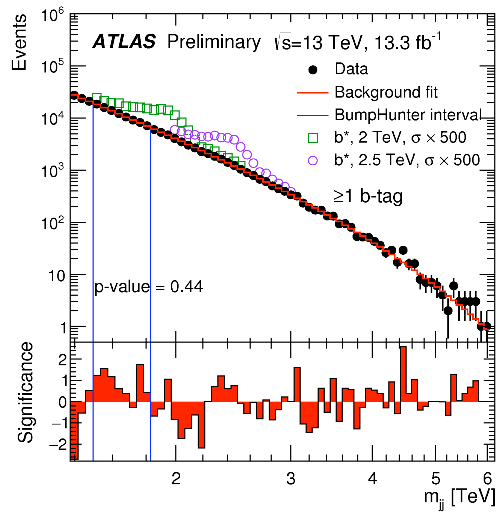
$$L_{qq} = \frac{2\pi}{\Lambda^2}[\quad \eta_{LL}(\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L) + \eta_{RR}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_R\gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R\gamma^\mu q_R)(\bar{q}_L\gamma_\mu q_L)],$$

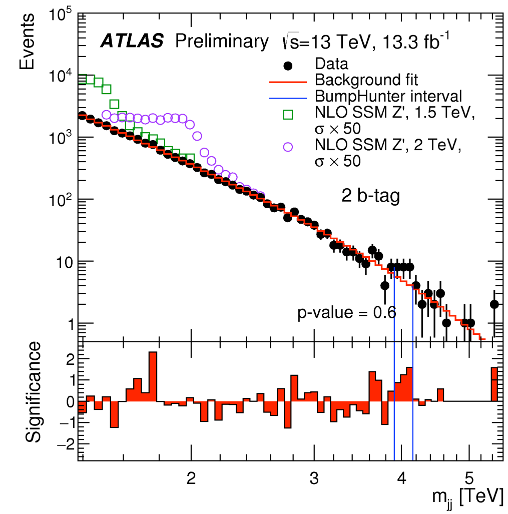
Ref: ATLAS-CONF-2016-069
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-069/

Heavy Resonance on b-jet final state



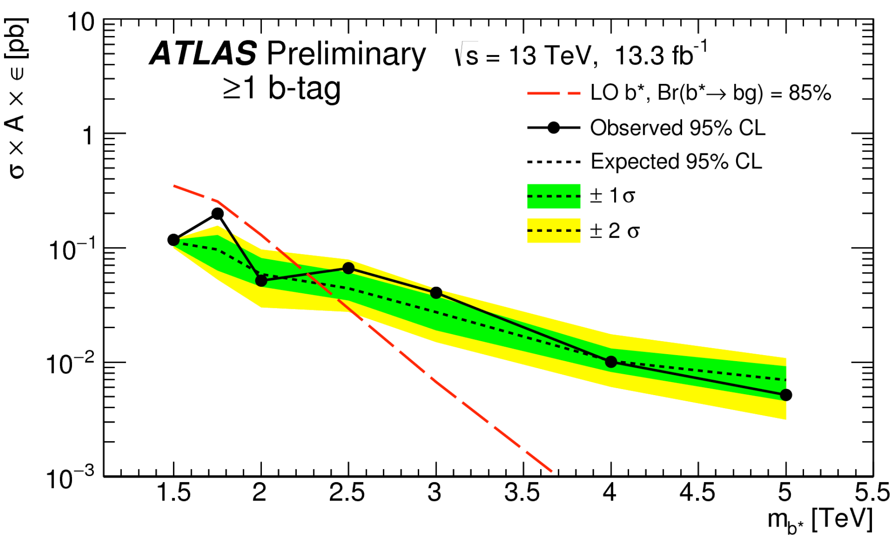


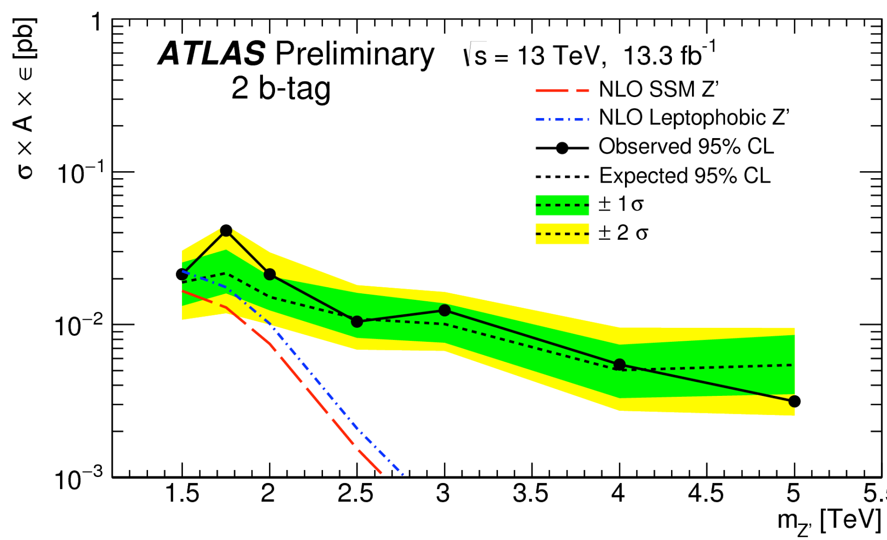




- ➢ Empirical analytical function to model background distribution
  - ✓ $x=m_{jj}/sqrt(s)$, parameters fitted from data

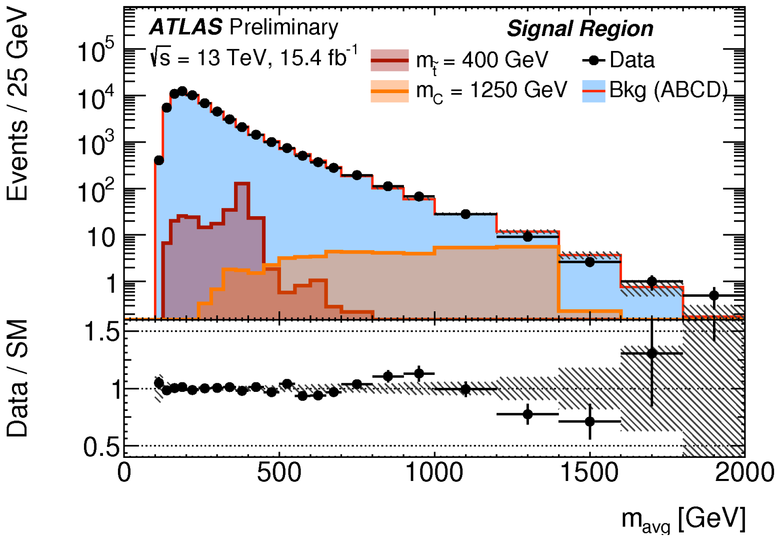
$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4(\ln x)+p_5(\ln x)^2}$$





Ref: ATLAS-CONF-2016-060
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-060/

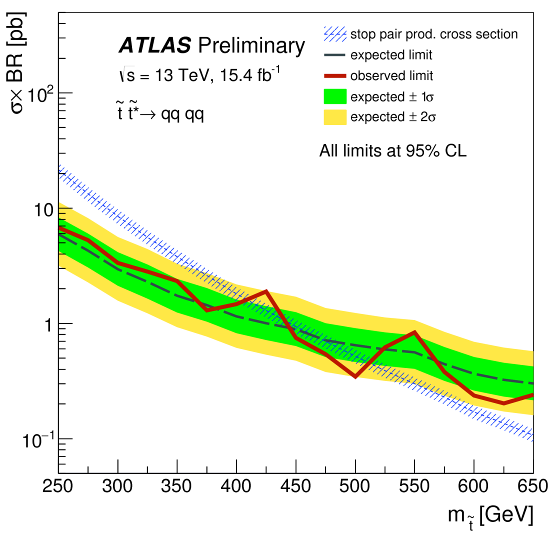
Pair Produced Resonance

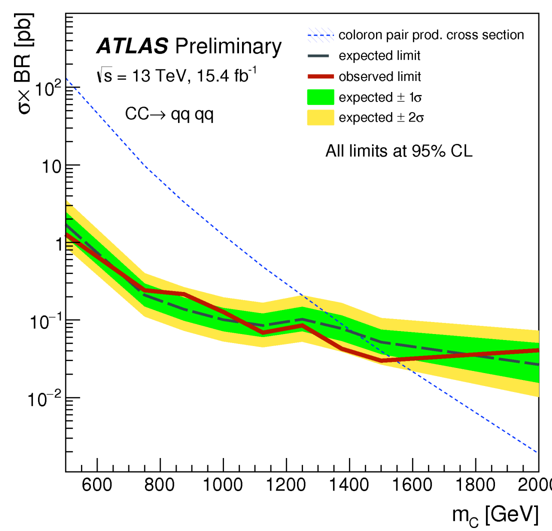


- New particles produced in pair
  - ✓ SUSY, massive color octet resonances
- Event selection:
  - ✓ 4 leading jets with pT>120GeV
  - ✓ Choose 2 jet pairs with

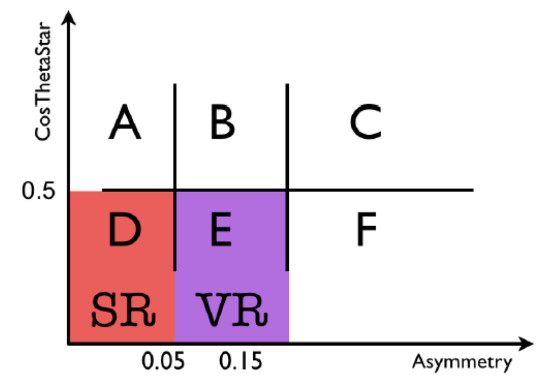
$$\Delta R_{\min} = \sum_{i=1,2} |\Delta R_i - 1.0|$$

  - ✓ Averaged mass to distinguish signal from bg
- Background modeling
  - ✓ Using control samples from data
  - ✓ Validated using data and MC





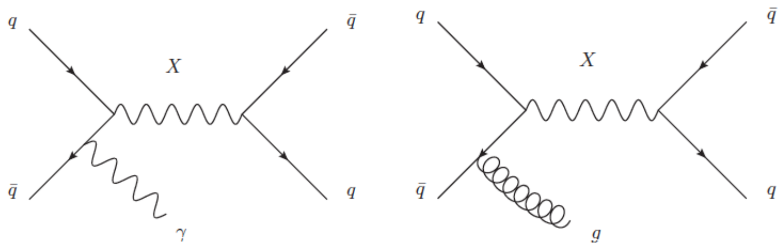
Theta: resonance pair production angle in the center-of-mass frame with respect to the beamline

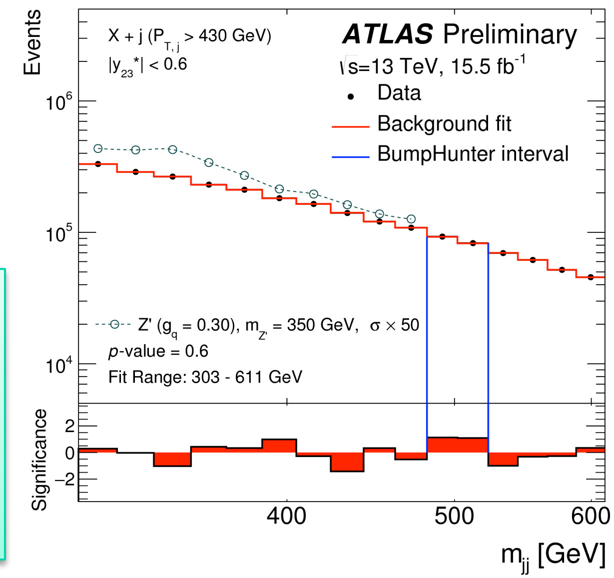


$$\mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2}$$ Mass asymmetry between 2 pairs

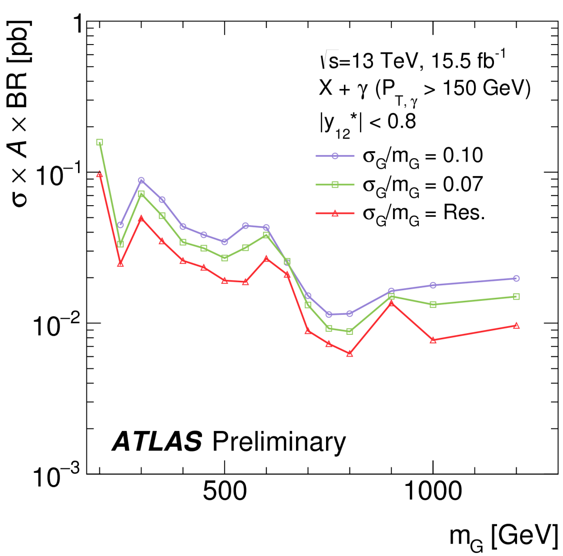
Ref: ATLAS-CONF-2016-084
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-084/

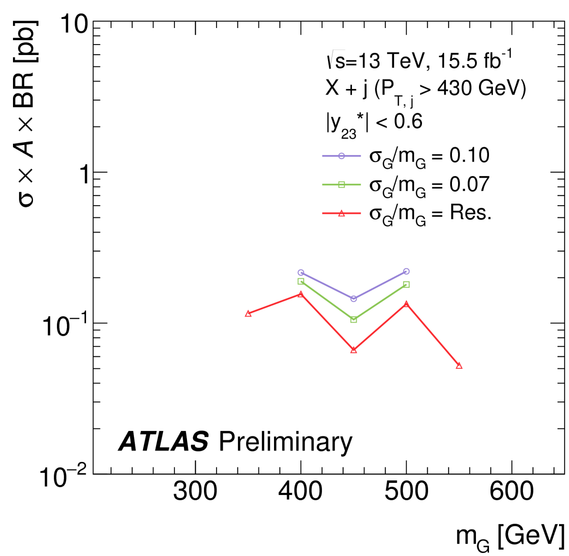
Light Resonance with ISR

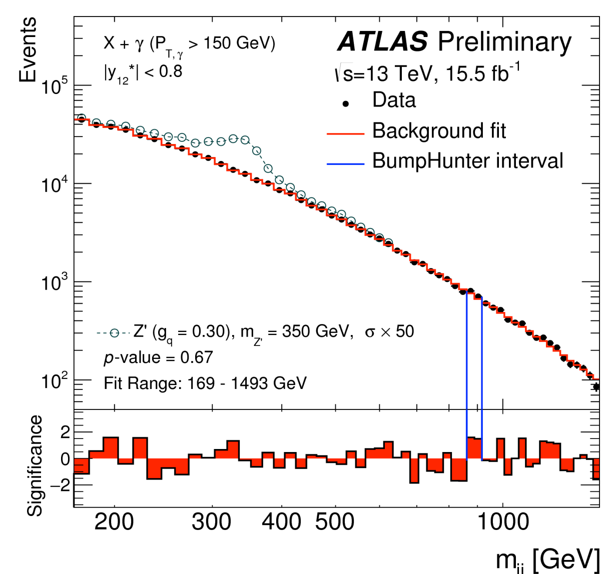




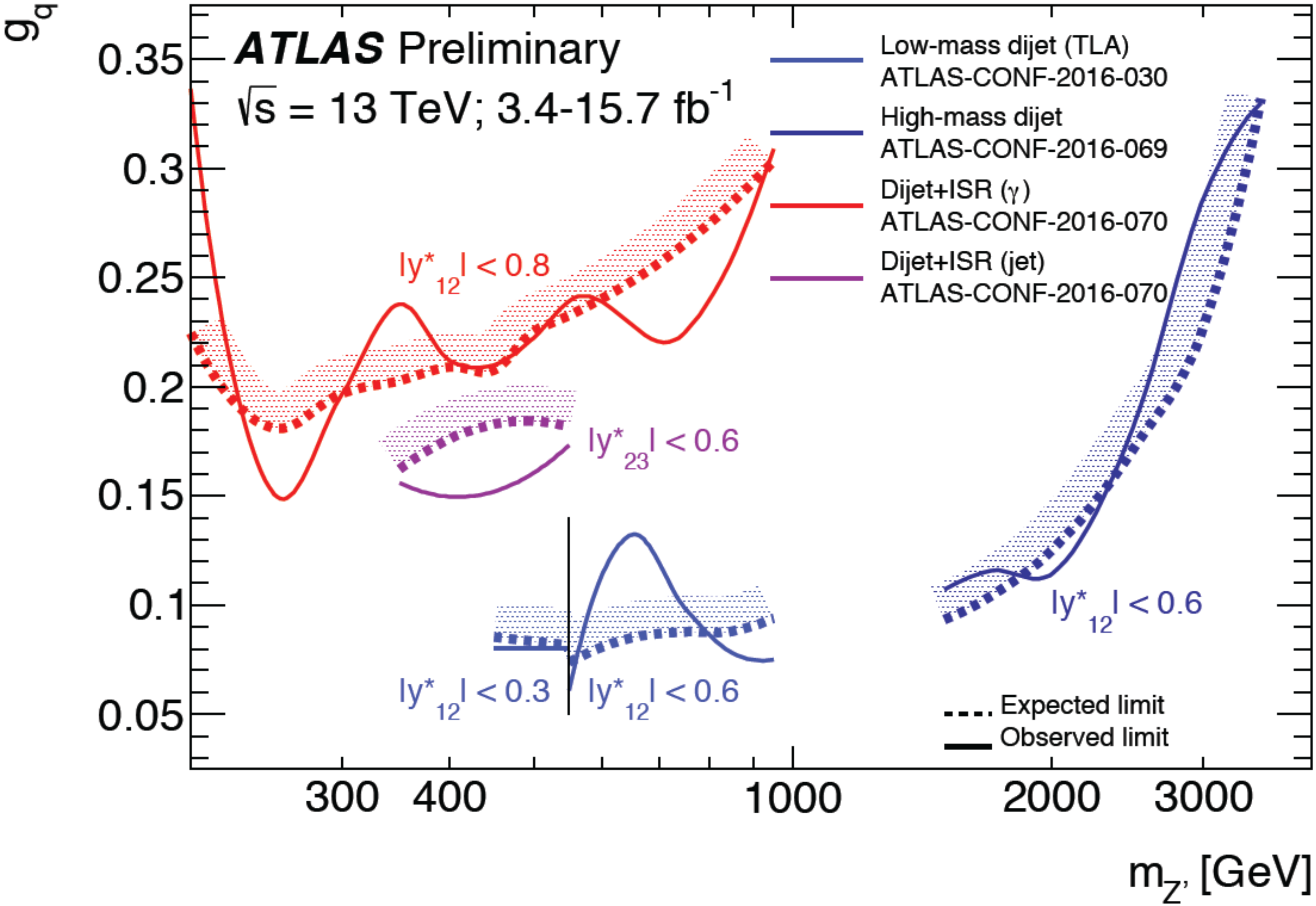
- Light resonance recoiled via a high p_T ISR photon/gluon
- Event selection:
  - ✓ At least a photon with p_T>150GeV + 2 jets or
  - ✓ Leading jet with p_T>430GeV + 2 subleading jets
- Background modeling:
  - ✓ Empirical analytical function Similar to di-b jets analysis







Ref: ATLAS-CONF-2016-070 https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-070/



g_q
ATLAS Preliminary
√s = 13 TeV; 3.4-15.7 fb^-1
Low-mass dijet (TLA)
ATLAS-CONF-2016-030
High-mass dijet
ATLAS-CONF-2016-069
Dijet+ISR (γ)
ATLAS-CONF-2016-070
Dijet+ISR (jet)
ATLAS-CONF-2016-070
|y*12| < 0.8
|y*23| < 0.6
|y*12| < 0.3
|y*12| < 0.6
|y*12| < 0.6
Expected limit
Observed limit
0.35
0.3
0.25
0.2
0.15
0.1
0.05
300
400
1000
2000
3000
m_Z' [GeV]

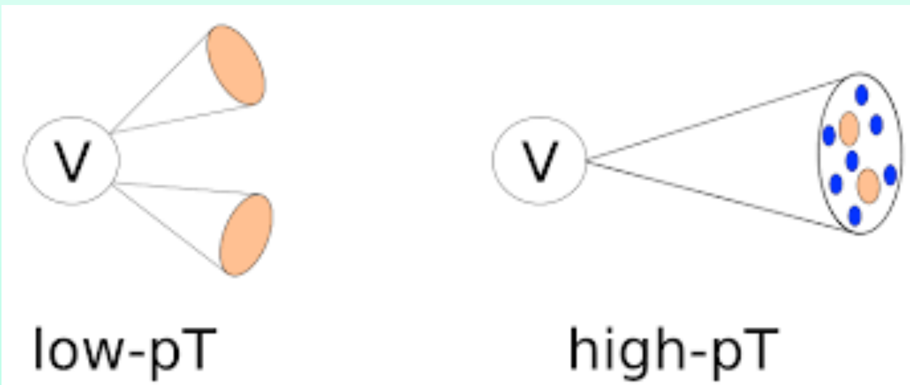
Searches in SM Boson Final states

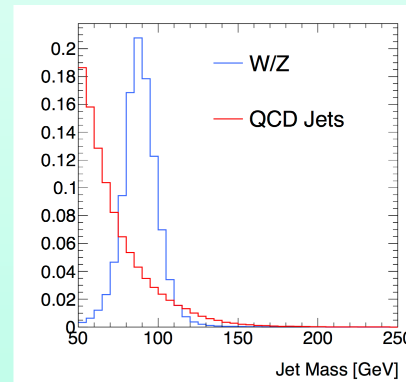
Resonance decaying to SM Bosons

- Most NP models predict heavy resonance (~ TeV) decay into W/Z/H:

$$T' \to Wb, \quad X \to WW, WZ, ZZ, WH, ZH$$

  - ✓ Boosted (high p_T) jets in the final decay states
  - ✓ The hadronic decay product are highly collimated

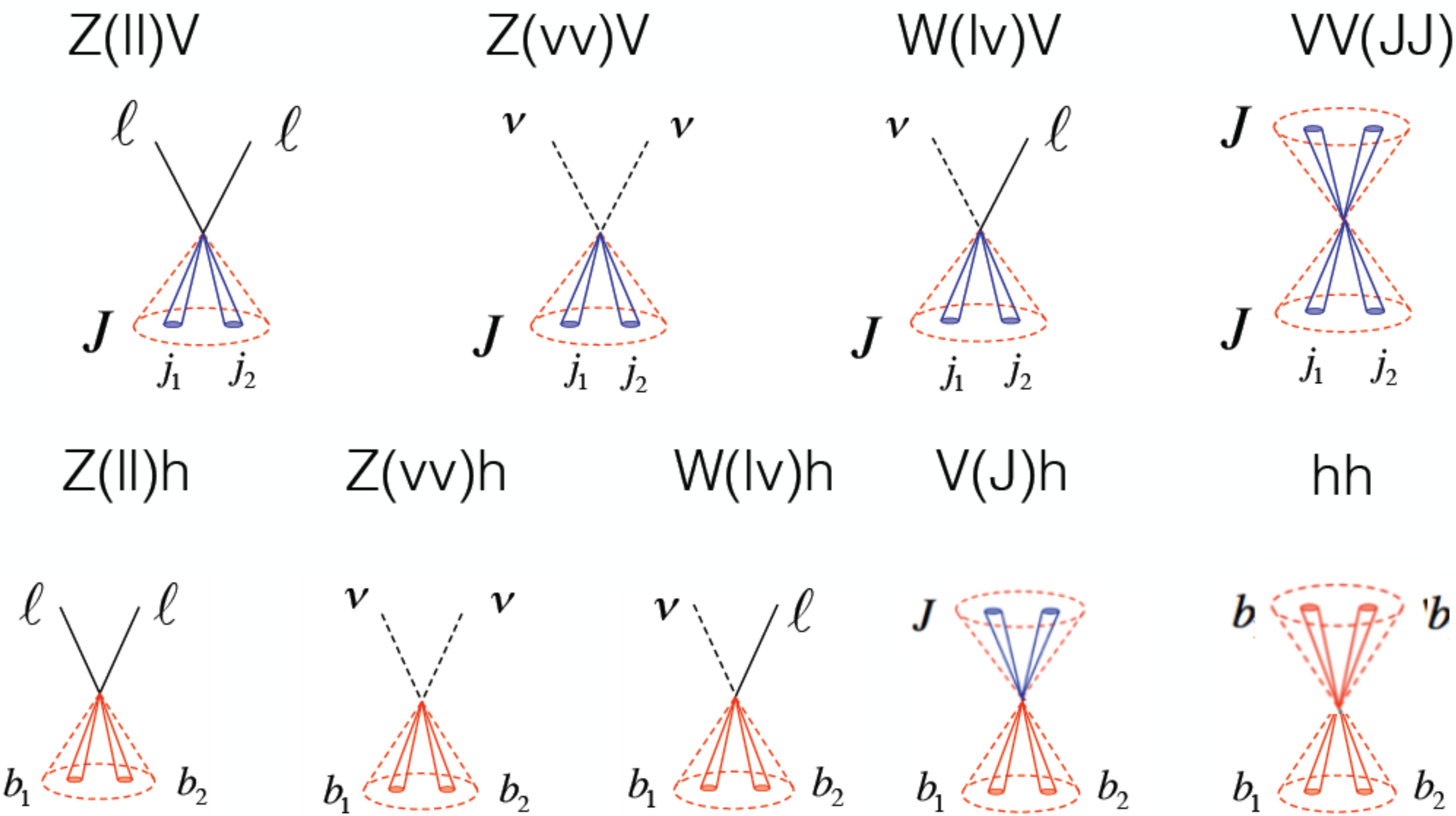




- Traditional jet reco. relying on one-to-one jet-to-parton assignment not adequate
- Solution: reconstruct multi quarks in a single jet (**boosted W/Z/H/Top jet**)
  - ✓ 2 quarks for W/Z decay, 3 quarks for top decay
  - ✓ Better (only way) to search for certain NP models

- How to identify the boosted W/Z/H/top
  - ✓ Jet mass
  - ✓ Jet substructure: exam the energy cluster distribution in the single jet

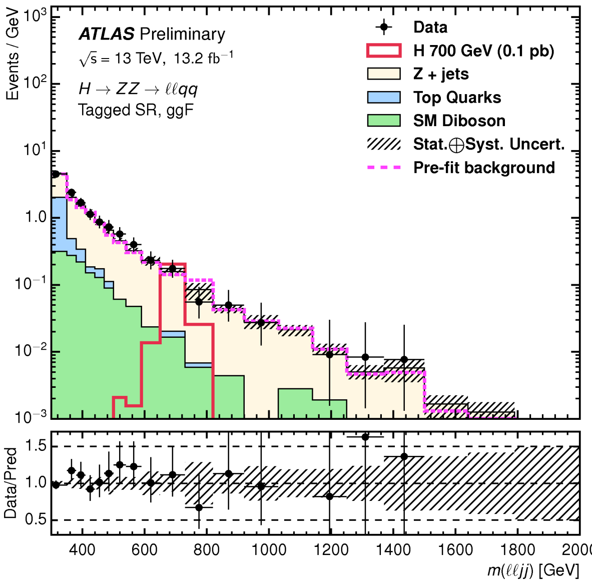
X->VV (V=W,Z,H) Resonance Searches

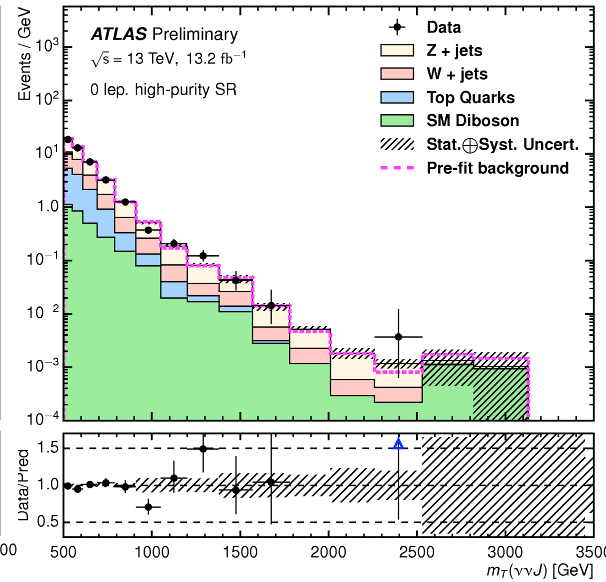


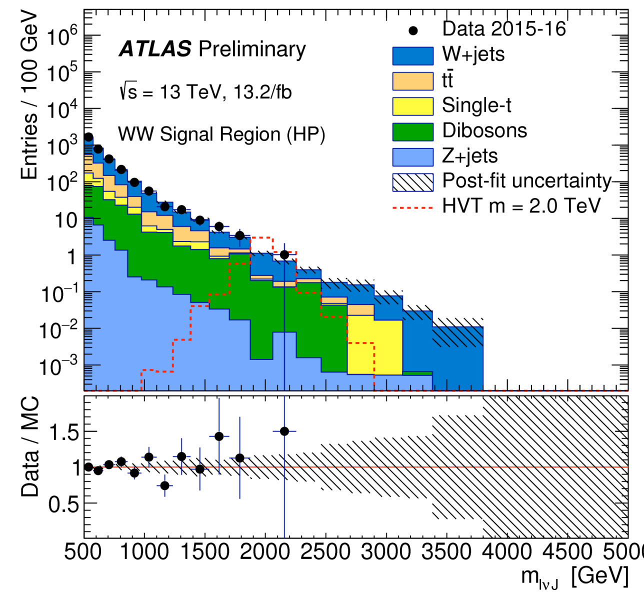
- Many searches in VV final states
  - ✓ Similar analysis strategy: boosted jet for hadronically decaying V
- Some detailed discussion on event selection & analysis in the talk by Steven Patrick

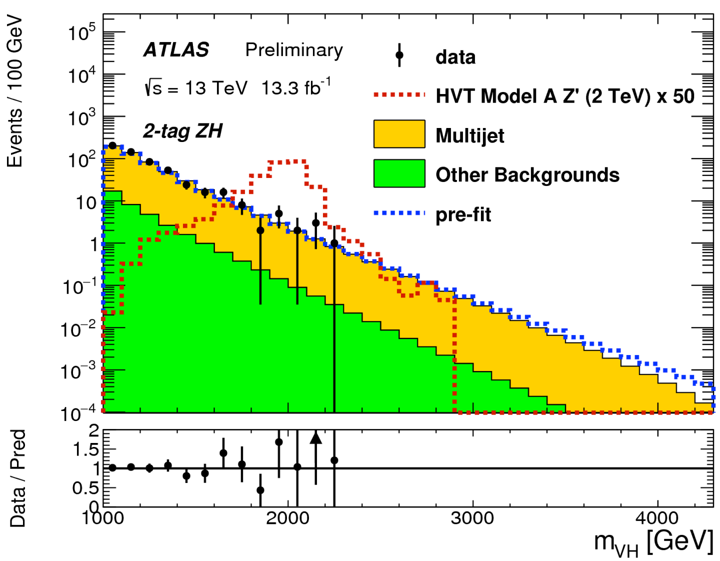
X->VV (V=W,Z,H) Resonance Searches

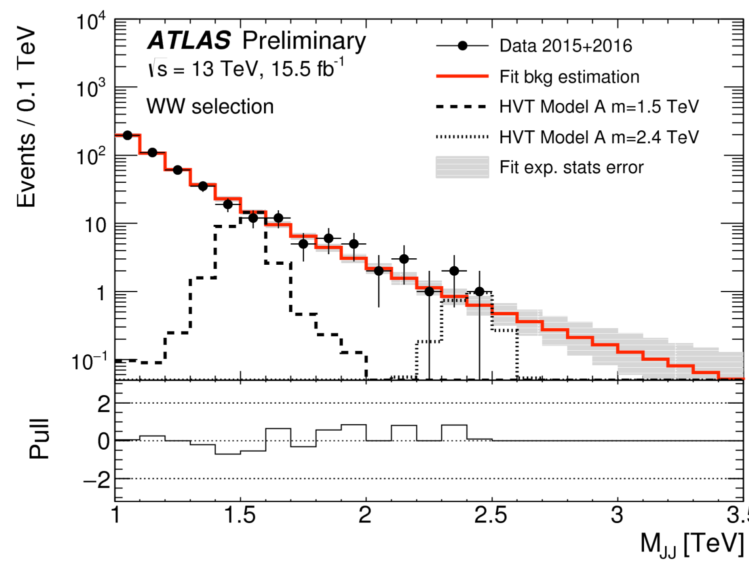
A few selected distribution shown here





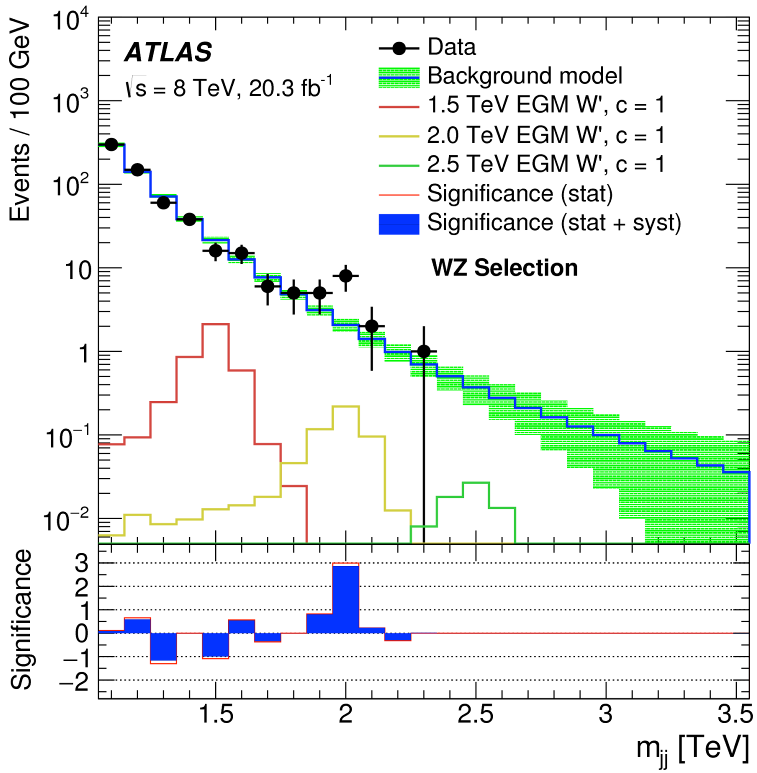


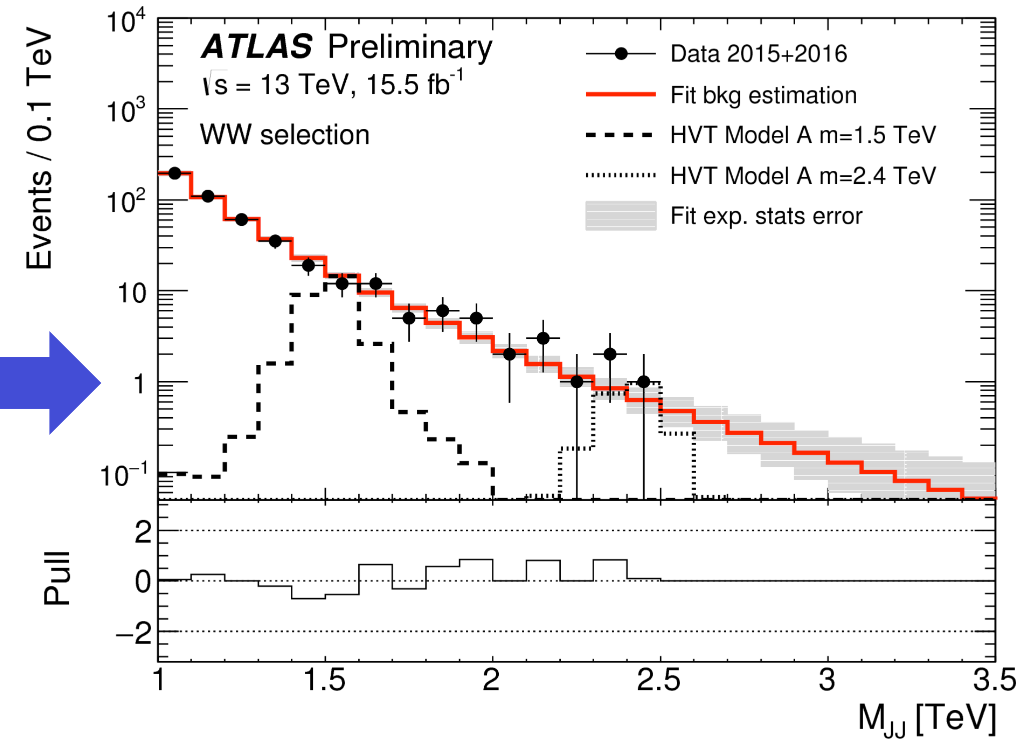




Ref:
ATLAS-CONF-2016-083
ATLAS-CONF-2016-055
ATLAS-CONF-2016-062
ATLAS-CONF-2016-088

Comparison between Run 1 & 2 results

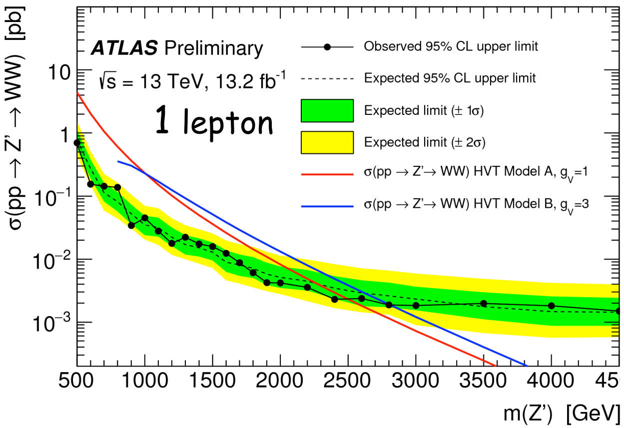


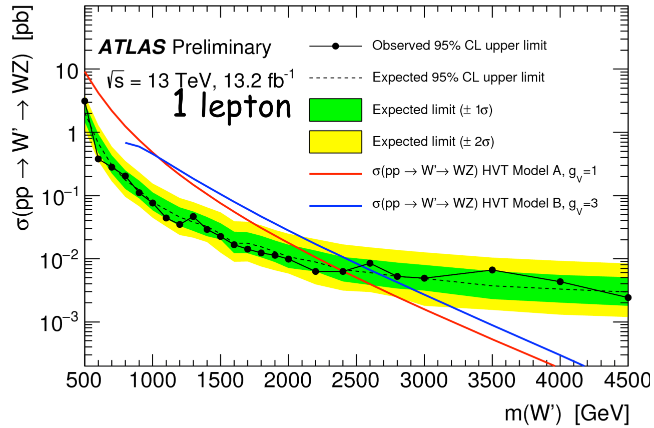


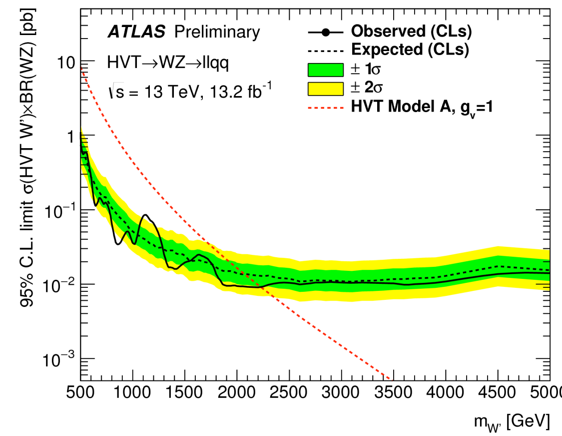
- Run 1 excess: 2TeV, 3.4 sigma (local), 2.5 sigma (Global)
- Not confirmed in Run 2 (2015 + 2016 13 TeV data)

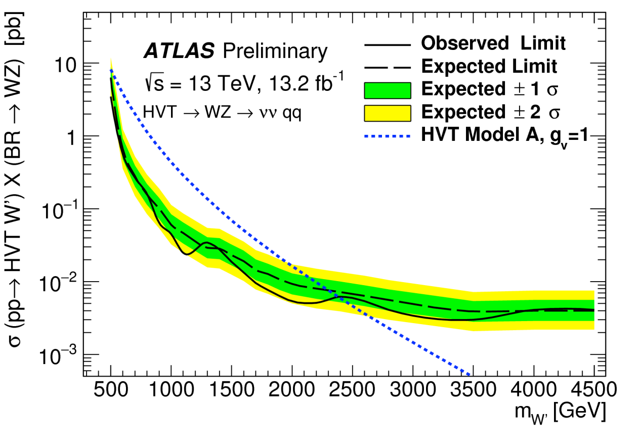
X->VV (V=W,Z,H) Resonance Searches

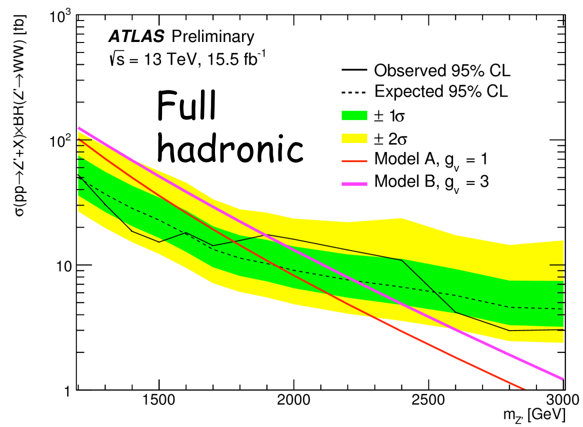
A few selected exclusion limits shown here

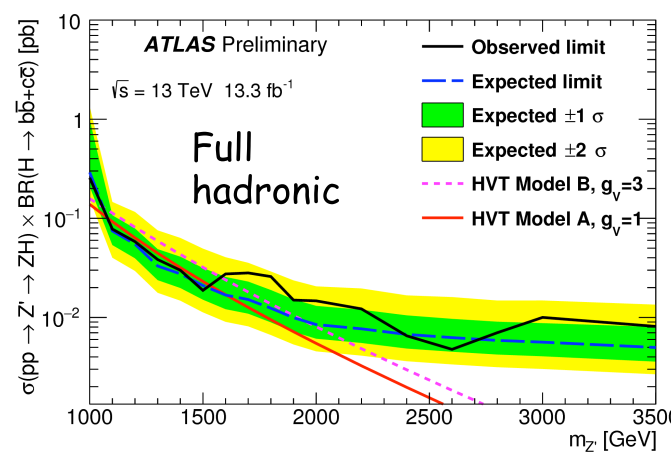






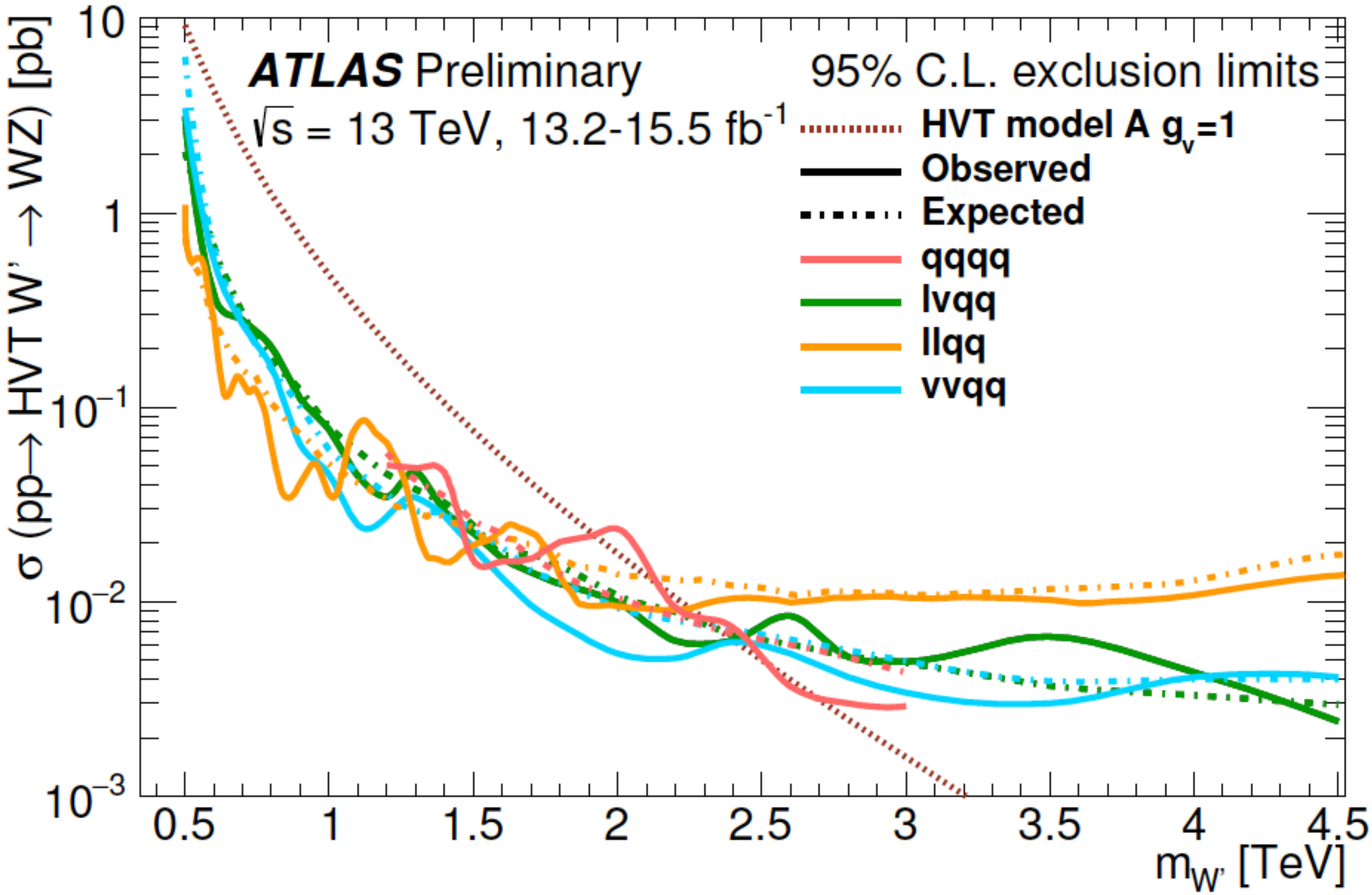






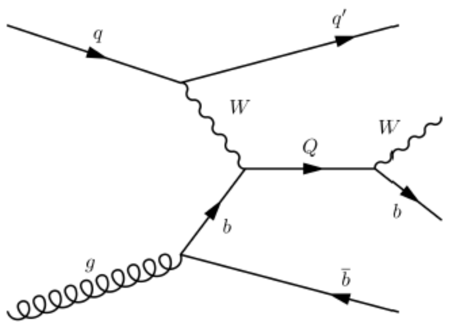
- Limits on other theoretical models as well: Graviton …
- Similar sensitivity in different final states
- Probe heavy mass at the TeV scale
- Still limited by statistical uncertainties

X->VV (V=W,Z,H) Resonance Searches

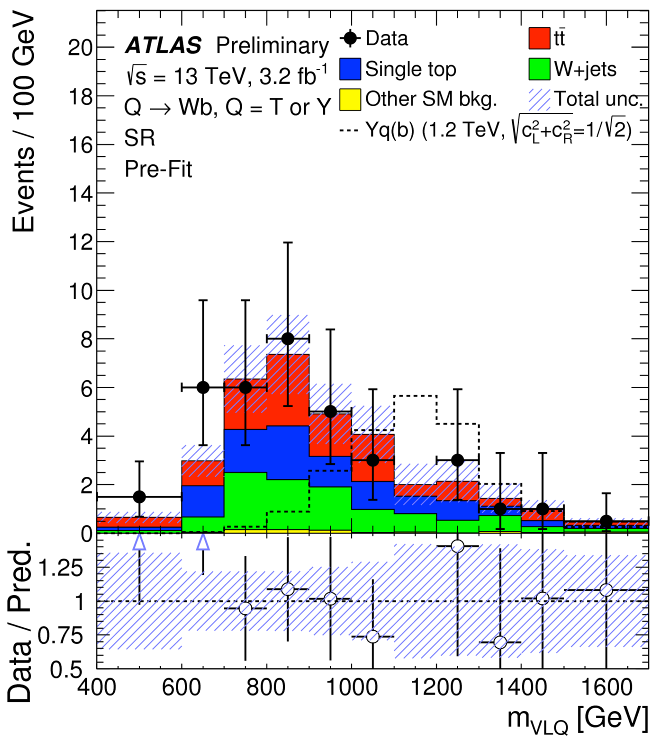


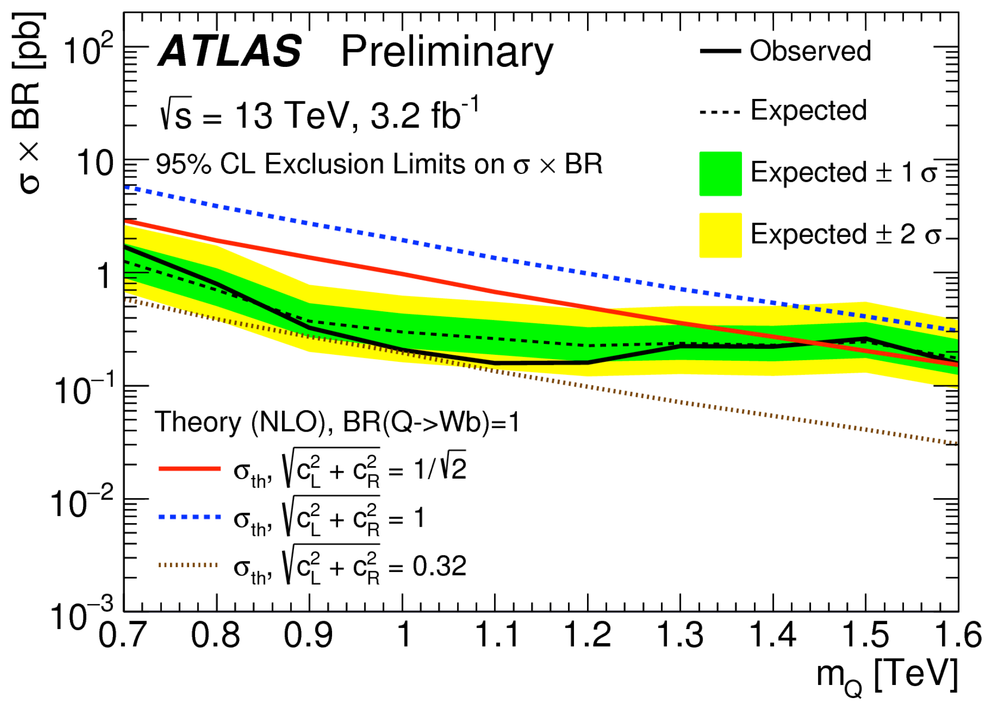
- RS graviton mass limit up to 2 TeV
- HVT W' mass limit up to 2.4 TeV

Wb Resonance



- Vector-like Q quark decaying to Wb
  - ✓ Leptonically decaying W
  - ✓ At least 1 forward jets
  - ✓ Full reconstruction of Q mass
- Background modeling
  - ✓ SM W+jets, top, diboson from MC
    - Constrained using control data
  - ✓ Multijets: data driven estimate



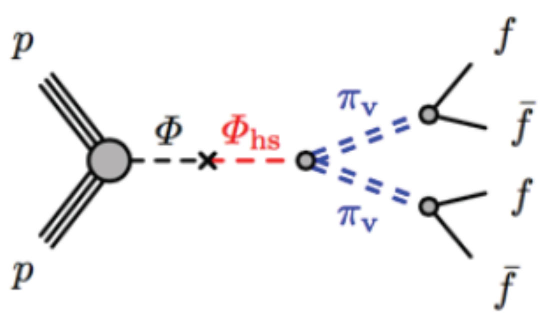


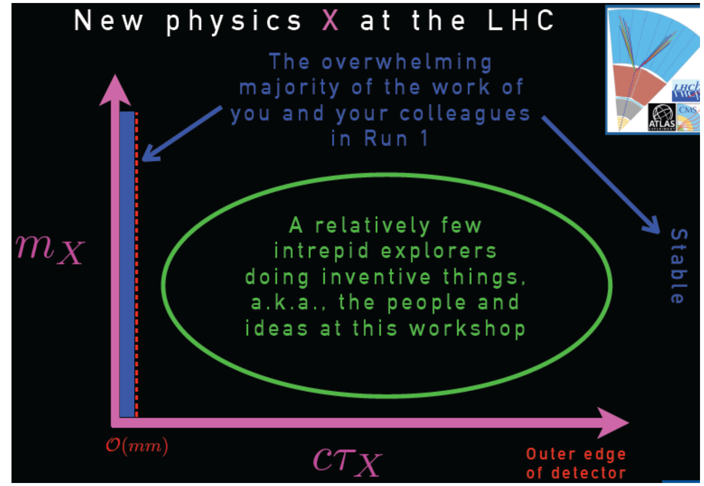
Ref: ATLAS-CONF-2016-072
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-072/

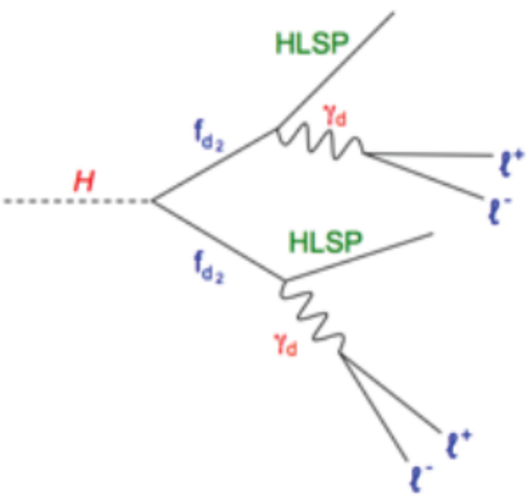
Unconventional Signature

Displaced Lepton Jets

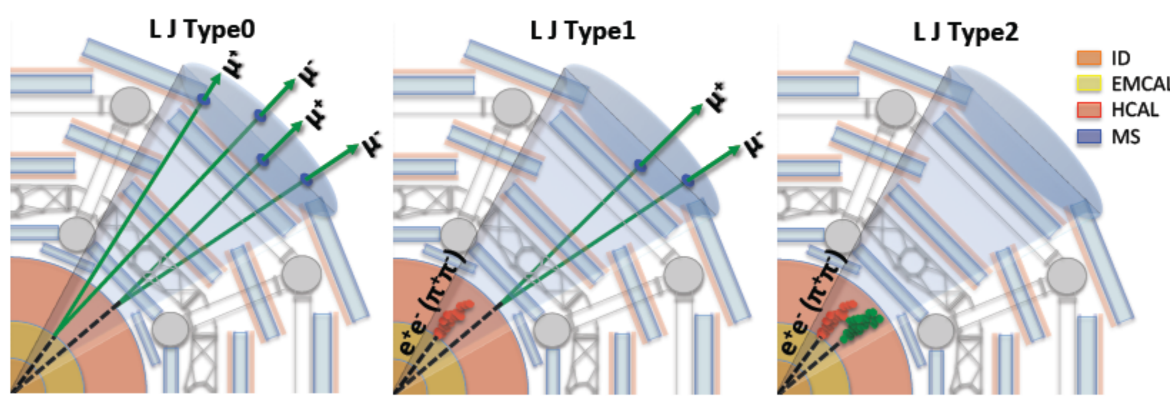
- Long lived neutral particles predicted by Hidden sector/Dark sector that don't couple directly with the SM



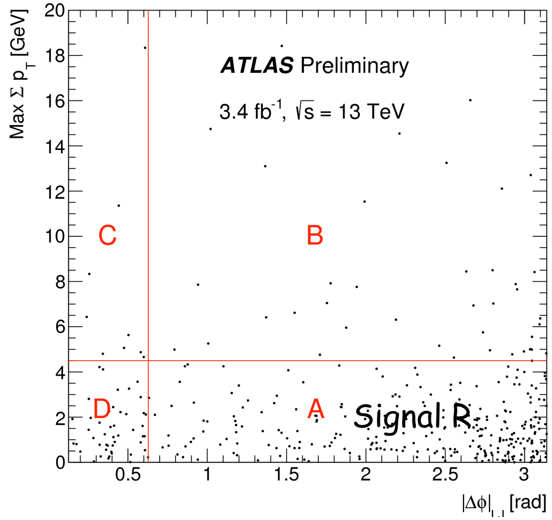




- Displaced jet: narrow jets with litter energy deposition in the EM calorimeter, and no inner detector tracks
- Lepton jet: collinear jet-like structure containing leptons/pions



Displaced Lepton Jets

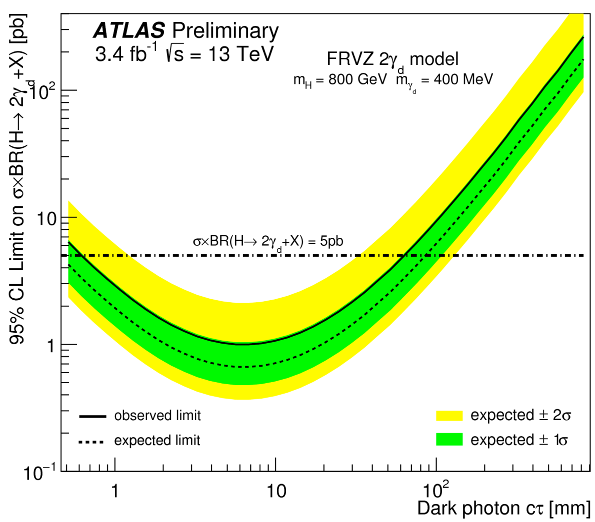


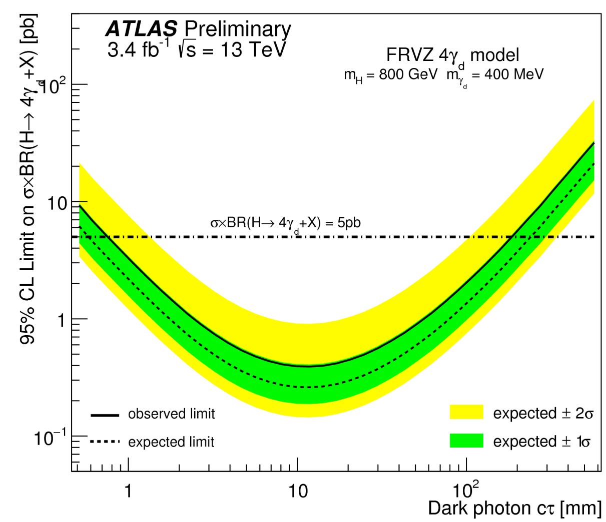
$|\Delta\phi|$ between the two reconstructed LJs

- ➢ Counting analysis: data driven approach to estimate background (ABCD method)

Category	Observed events	Expected background
All events	285	231 ± 12 (stat) ± 62 (syst)
Type2–Type2 excluded	46	31.8 ± 3.8 (stat) ± 8.6 (syst)
Type2–Type2 only	239	241 ± 41(stat) ± 65(syst)

FRVZ model	m_H (GeV)	Excluded $c\tau$ [mm]
Higgs $\rightarrow 2\gamma_d + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\rightarrow 4\gamma_d + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\rightarrow 2\gamma_d + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\rightarrow 4\gamma_d + X$	800	$0.8 \leq c\tau \leq 186$

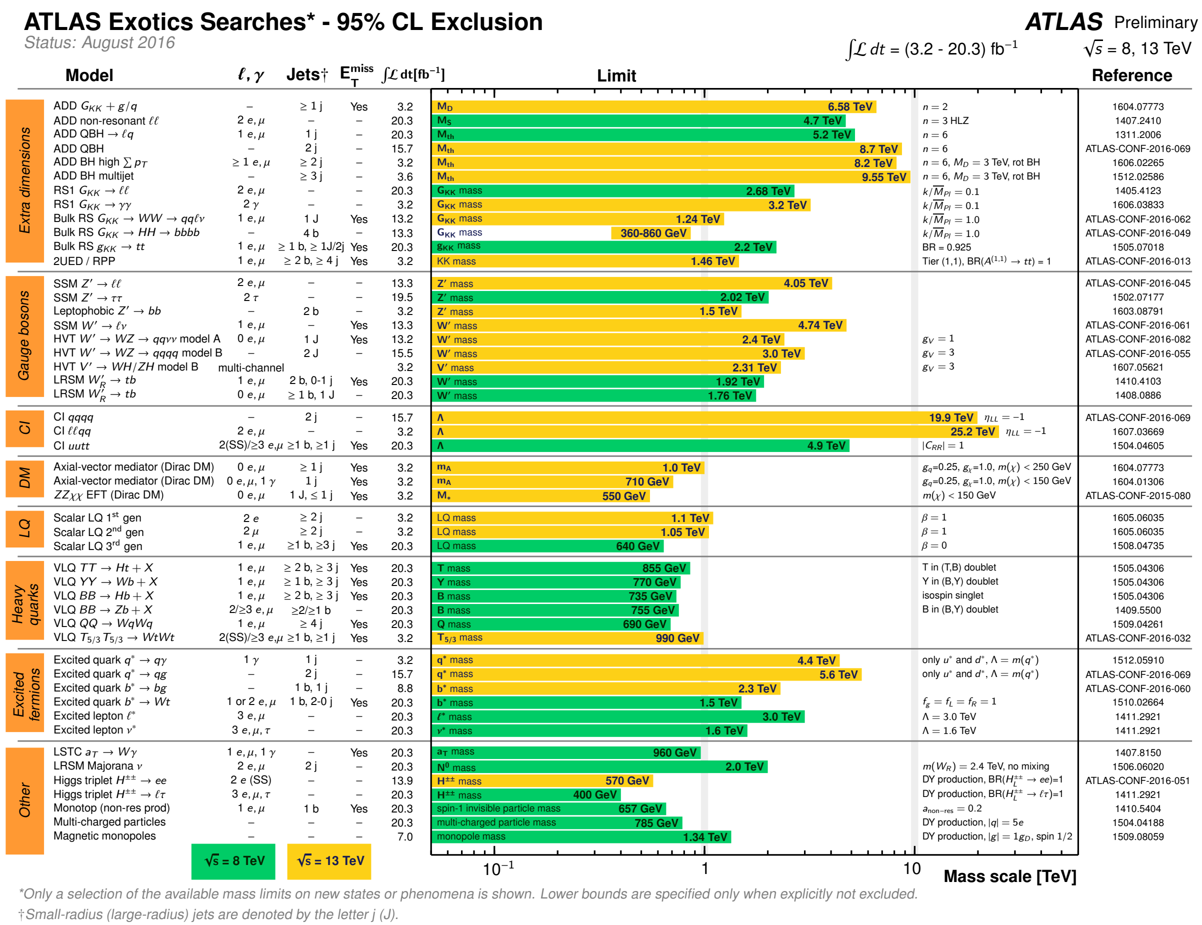




Ref: ATLAS-CONF-2016-042
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-042/

Conclusion

- Very broad and rich exotic physics program at ATLAS
  - ✓ Only a few selected new results were reported here
  - ✓ Start to probe many possible new particles/NP scenario at TeV scale
  - ✓ Strong constraint for some NP scenario
- Current results still dominated by statistical limitation
  - ✓ Expect significant better physics reach with more data (HL-LHC)



Backup

The ATLAS Detector

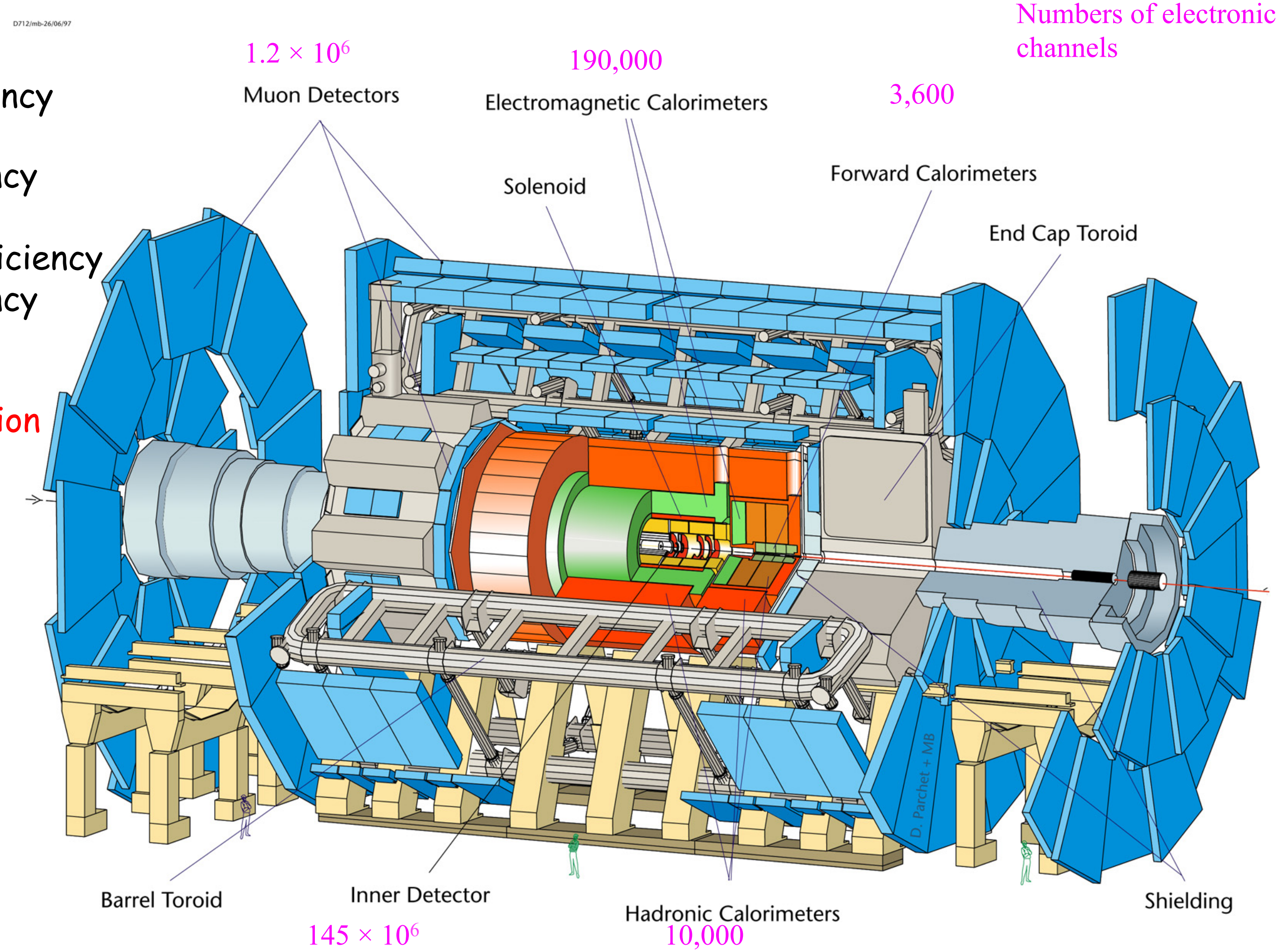
e: ~75 – 90% efficiency

muon: ~90% efficiency

b tagging: ~57% efficiency
~ 0.2% fake efficiency
from light jets

Efficiency & resolution dependents on the selection criteria

Numbers of electronic channels



46 m long, Overall weight: 7000 Tons

Excellent reconstruction efficiency and resolution:
Electron, muon, track, jets, b-tagging & missing transverse energy