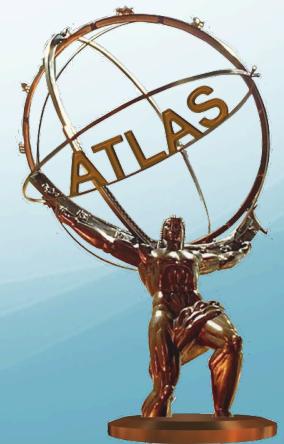


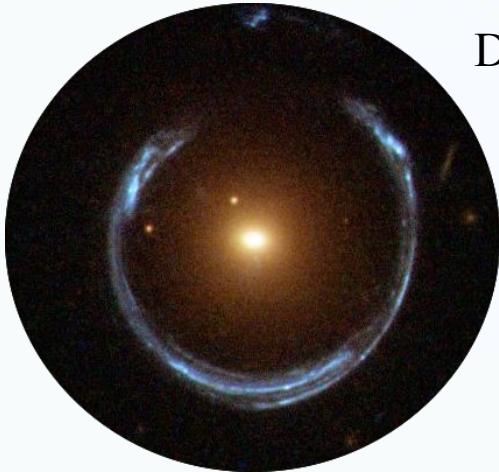
Run 2 ATLAS searches with fermions and jets

Jeff Dandoy (University of Chicago)
on behalf of the ATLAS Collaboration

LHCSki 2016
Tirol, Austria
April 10th – 15th



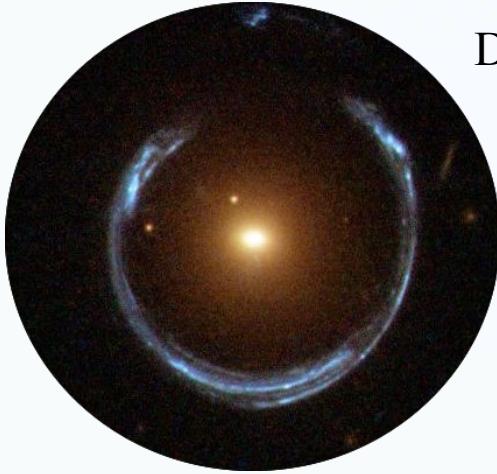
Motivation for New Physics



Dark Matter Evidence

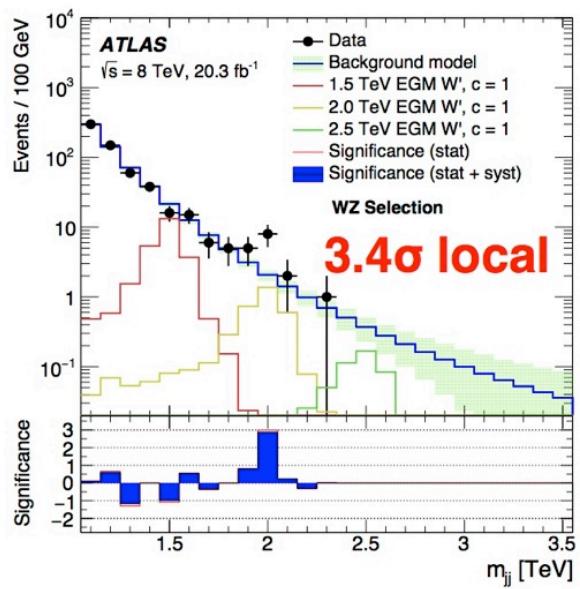
New physics could take the form of:
Dark Matter mediators – couple to SM

Motivation for New Physics



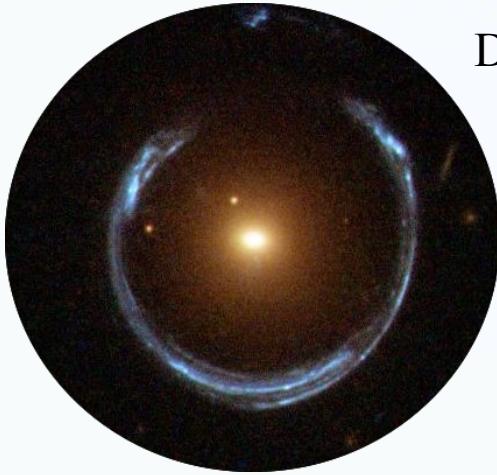
Dark Matter Evidence

Experimental Excesses



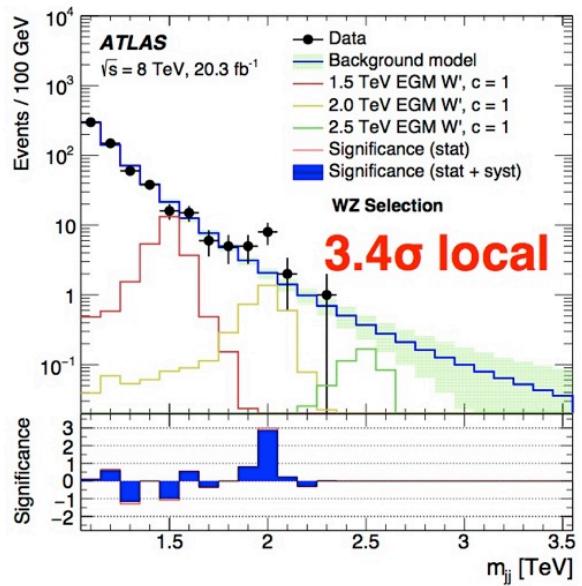
New physics could take the form of:
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Heavy Gauge Bosons – W' and Z'

Motivation for New Physics



Dark Matter Evidence

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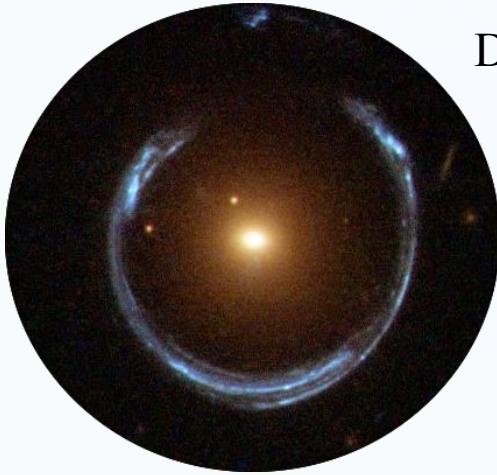


Hierarchy problem



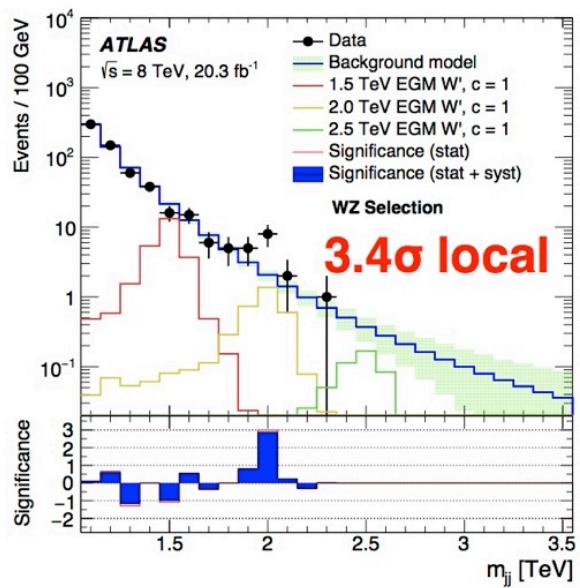
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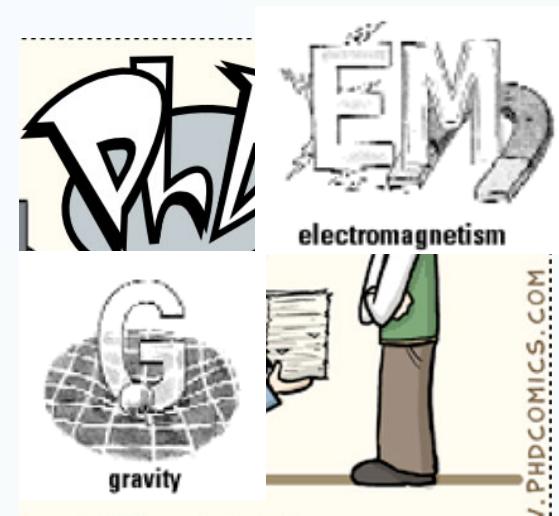


Dark Matter Evidence

Experimental Excesses

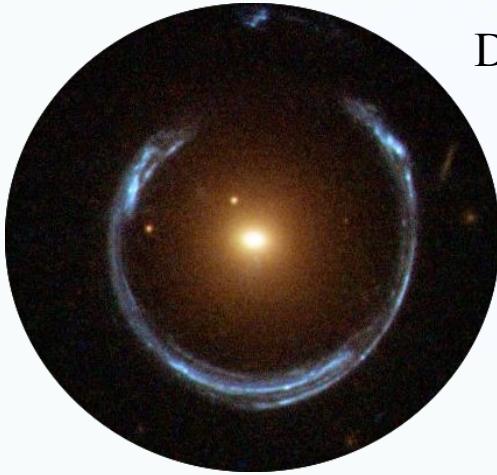


Hierarchy problem



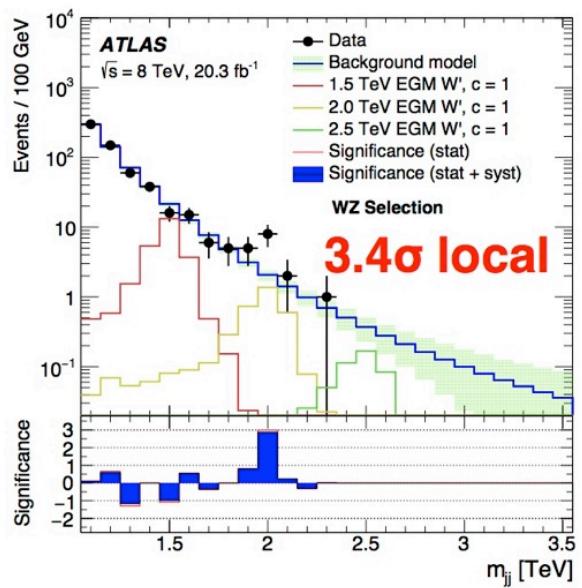
New physics could take the form of:
Dark Matter mediators – couple to SM
Heavy Gauge Bosons – W' and Z'
Grand Unification Theory – Z'
Extra dimensions - Quantum Black Holes

Motivation for New Physics

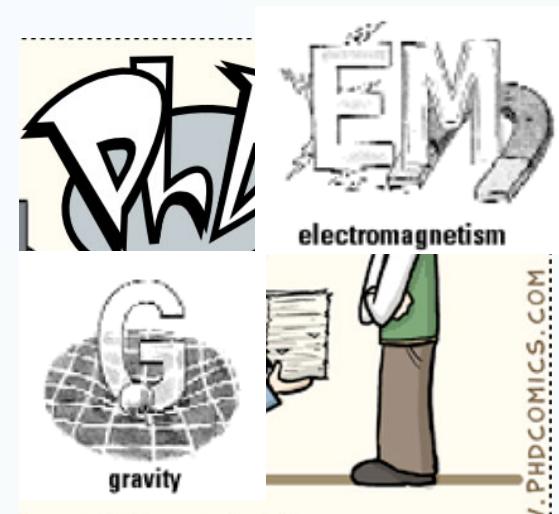
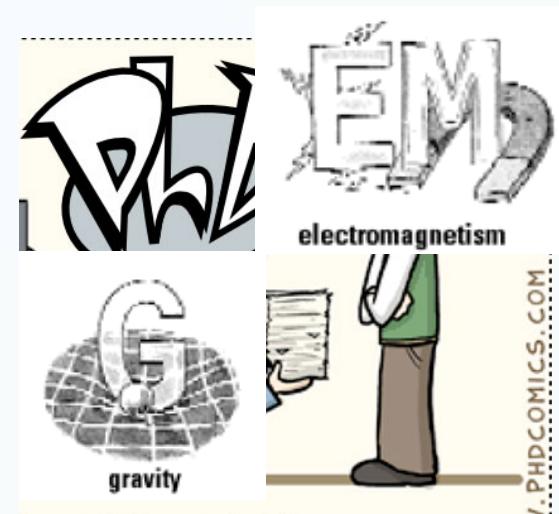


Dark Matter Evidence

Experimental Excesses



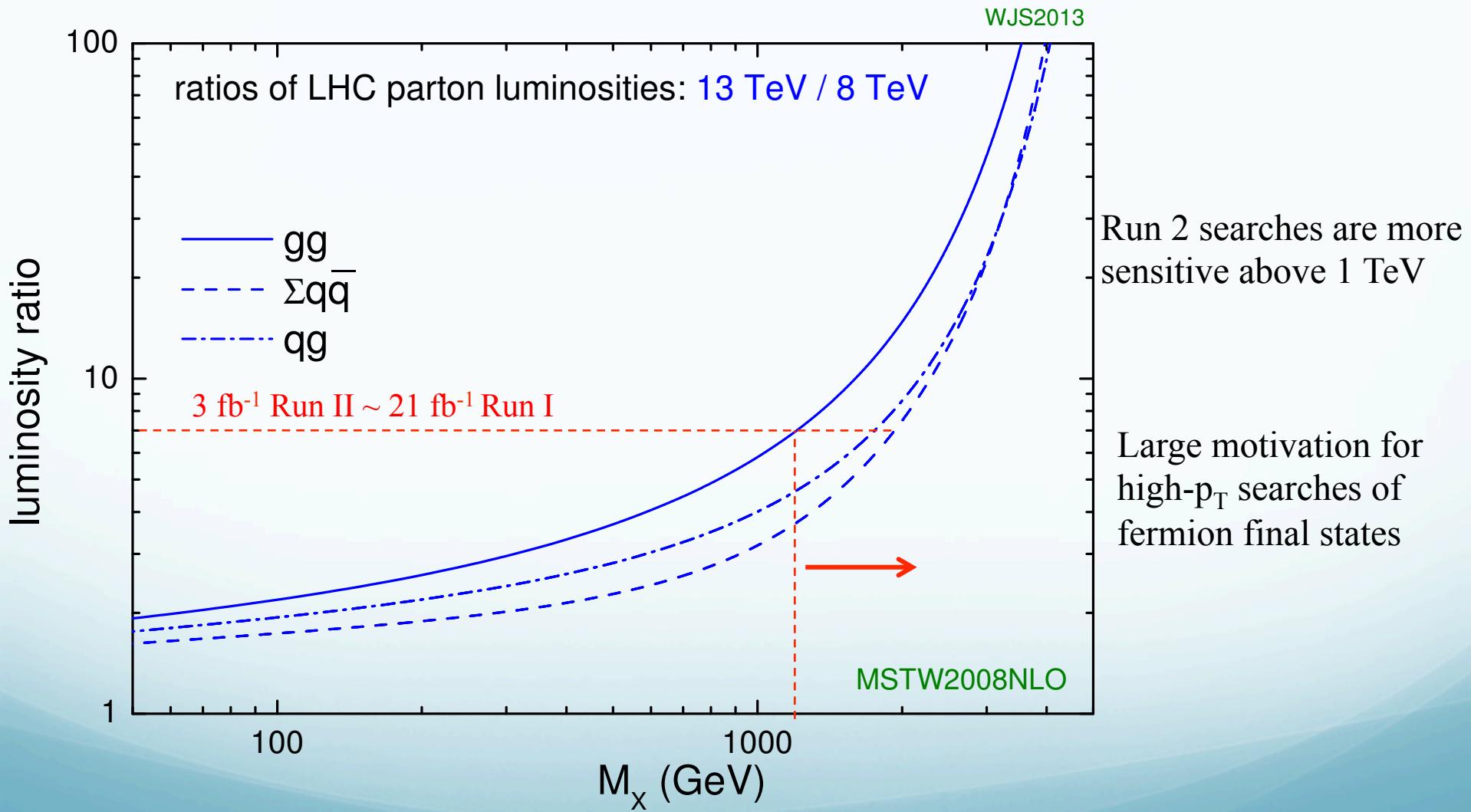
Hierarchy problem



New physics could take the form of:
Dark Matter mediators – couple to SM
Heavy Gauge Bosons – W' and Z'
Grand Unification Theory – Z'
Extra dimensions - Quantum Black Holes
Quark substructure – excited quarks
Contact Interactions above $\Lambda \sim 7 \text{ TeV}$
None of the above!

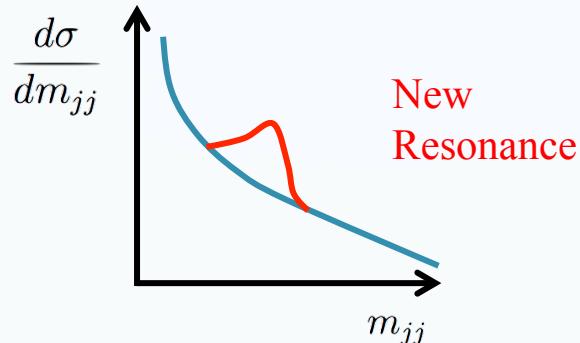
Run II Potential

Huge potential for discovering new physics at large masses

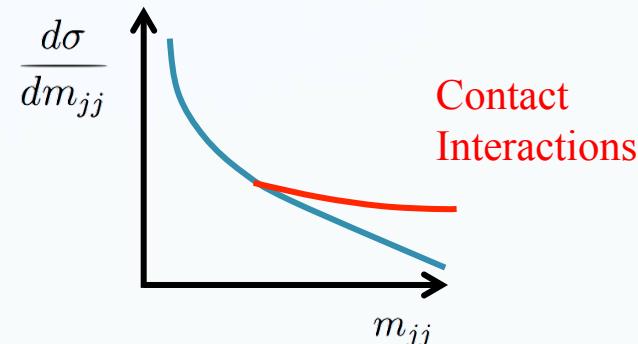


Search Strategies

Search for localized excesses
in mass distributions



Search for non-resonant
deviations from SM predictions



- QCD jet background modeled through **data-driven** techniques
 - Functional forms of dominant background in 0-lepton dijet and multijet searches
 - Fake leptons from jets or photons
- Lepton searches composed of several backgrounds involving real leptons modeled with **Monte Carlo**
 - Estimated individually, normalized to control regions in data
 - Extrapolated to high mass, low statistics regions

Dijet Resonance

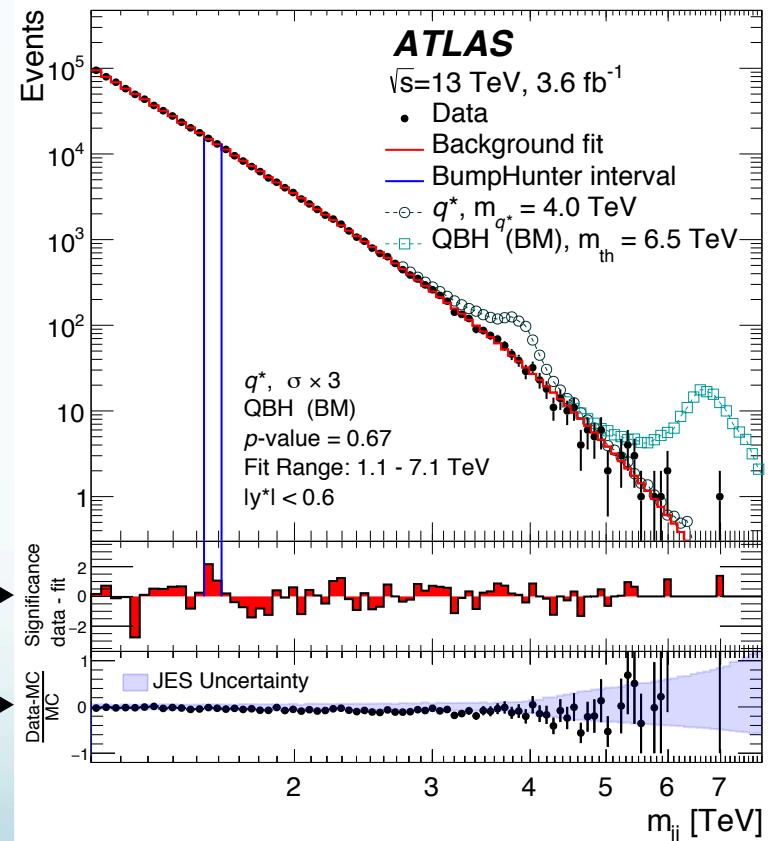
Search for central dijet excesses among falling QCD background

Data-driven background estimation

$$f(x) = p_1 \left(1 - \frac{x}{s}\right)^{p_2} \left(\frac{x}{s}\right)^{p_3}$$

Extensive 13 TeV data-MC comparisons

| Relevant Selections | |
|---------------------|---------------------------------------|
| high p_T | $p_T^{\text{lead}} > 440 \text{ GeV}$ |
| central | $m_{jj} > 1.1 \text{ TeV}$ |
| | $ y_1 - y_2 < 1.2$ |



Dijet Resonance

Search for central dijet excesses among falling QCD background

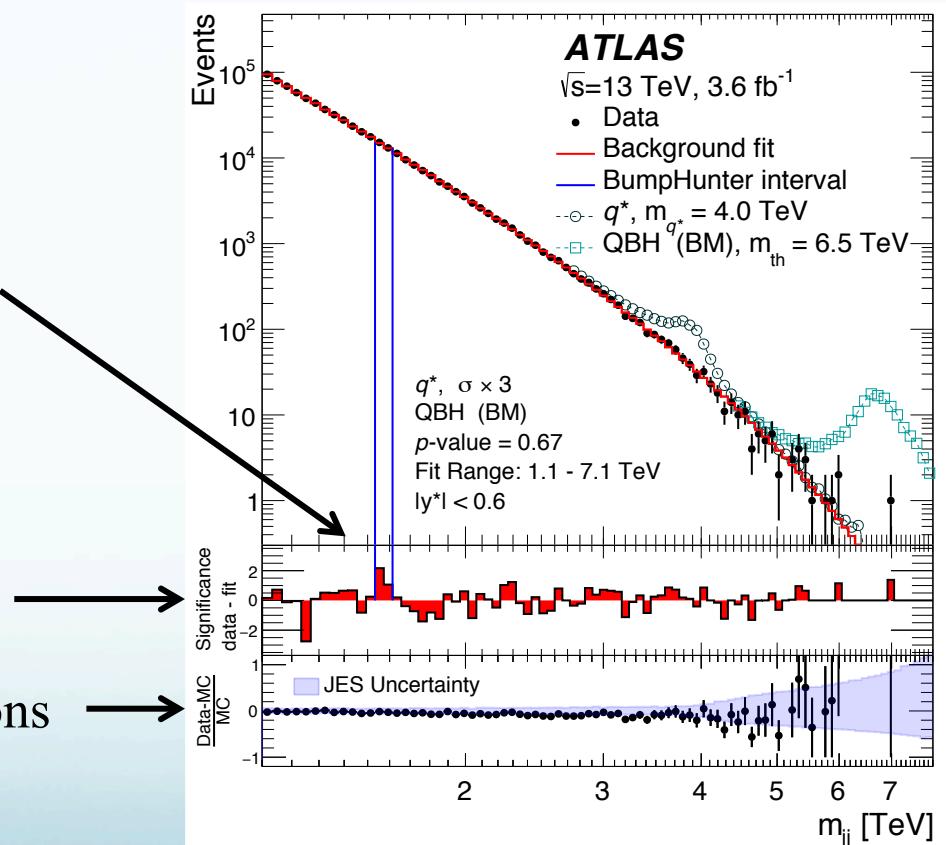
0.43 σ global significance
 $1.53 \rightarrow 1.61 \text{ TeV}$

Data-driven background estimation

$$f(x) = p_1 \left(1 - \frac{x}{s}\right)^{p_2} \left(\frac{x}{s}\right)^{p_3}$$

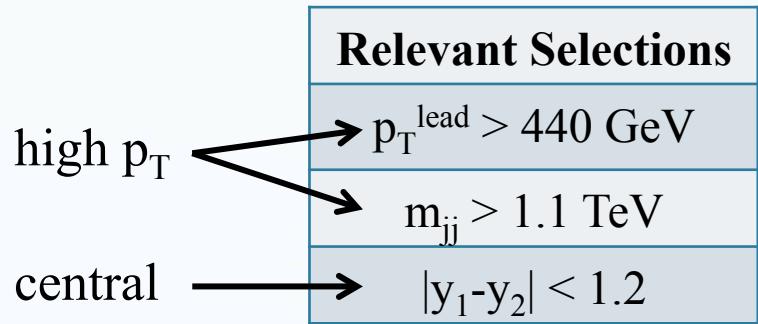
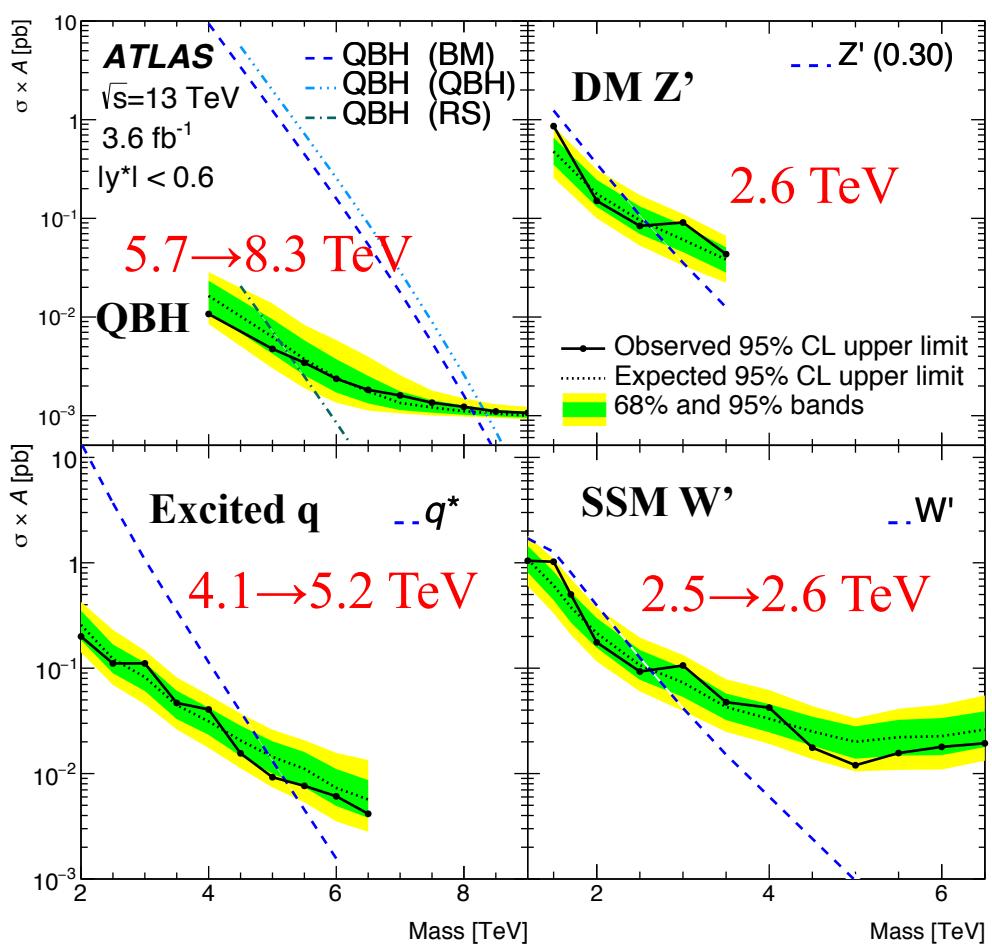
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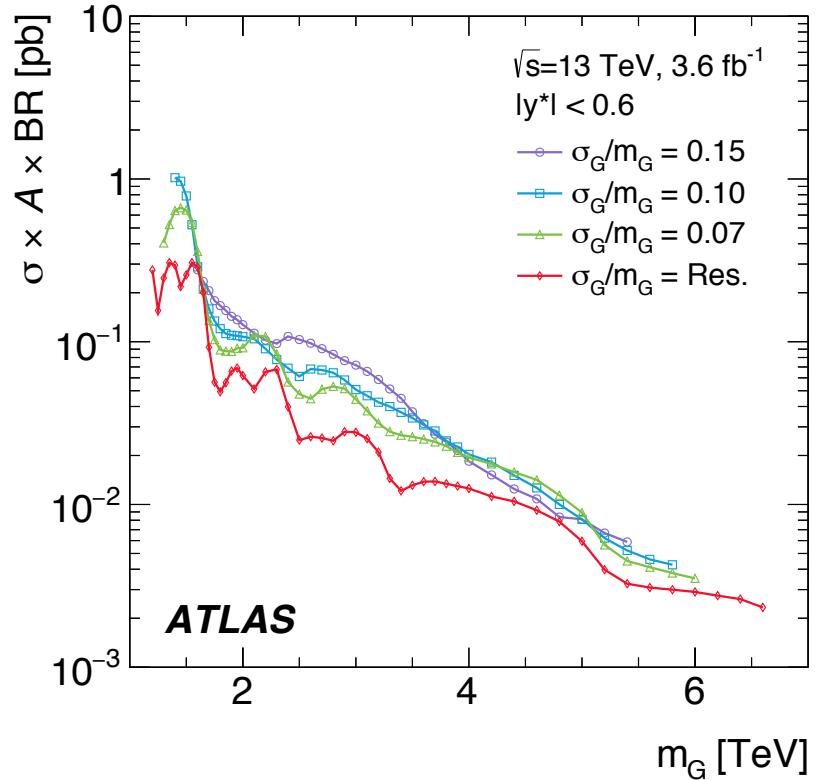


Dijet Resonance

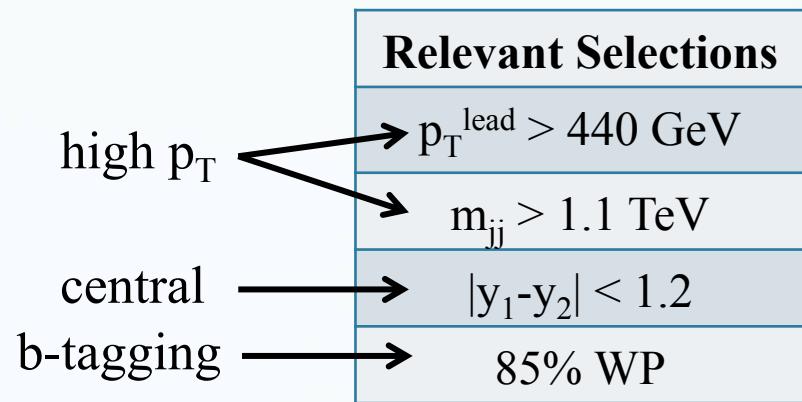
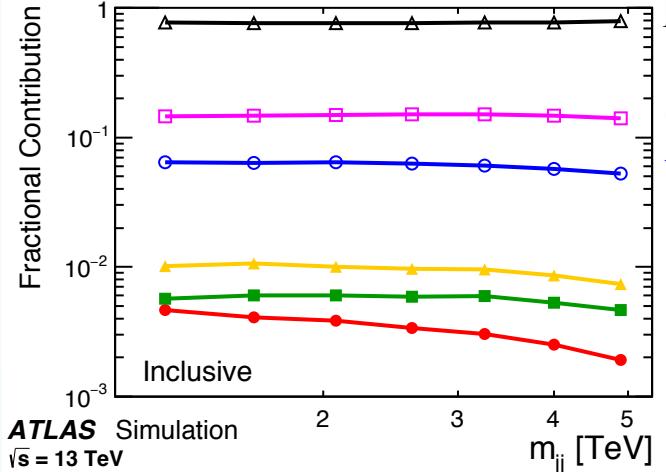
Stringent limits on several models



Model independent limits



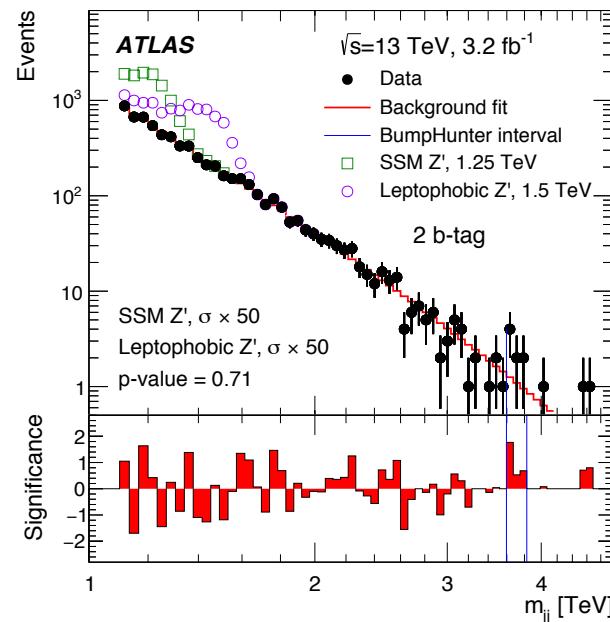
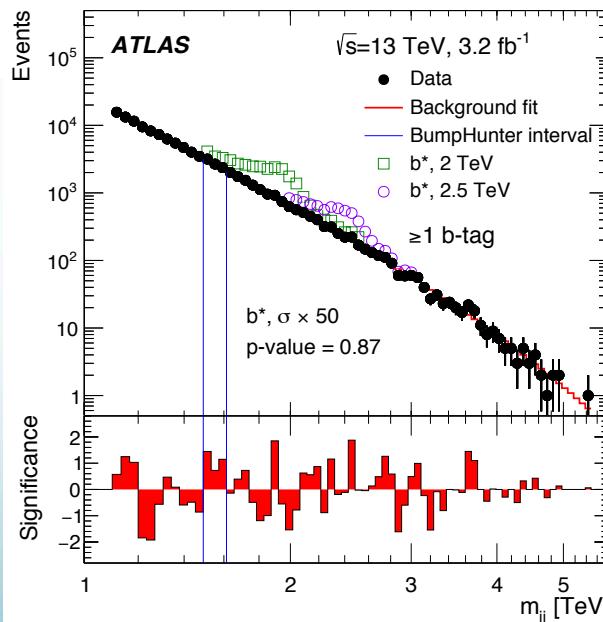
B-tagged Dijet Resonance



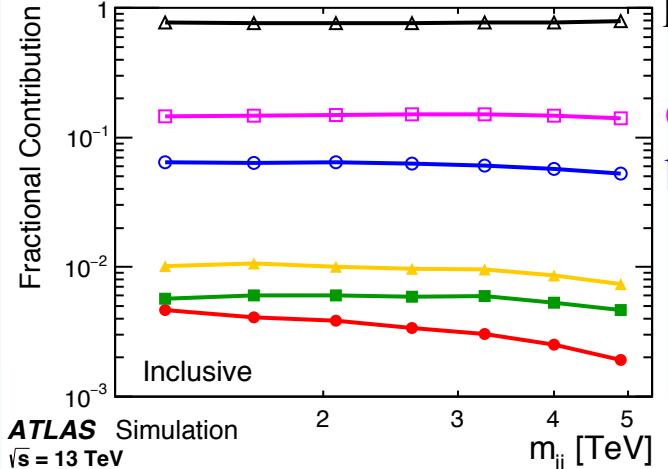
Rejection of dominant light flavor QCD background

1-tag region = b^*

2-tag region = Heavy Z'



B-tagged Dijet Resonance



2-tag
0.71 global p-value
 $3.60 \rightarrow 3.83 \text{ TeV}$

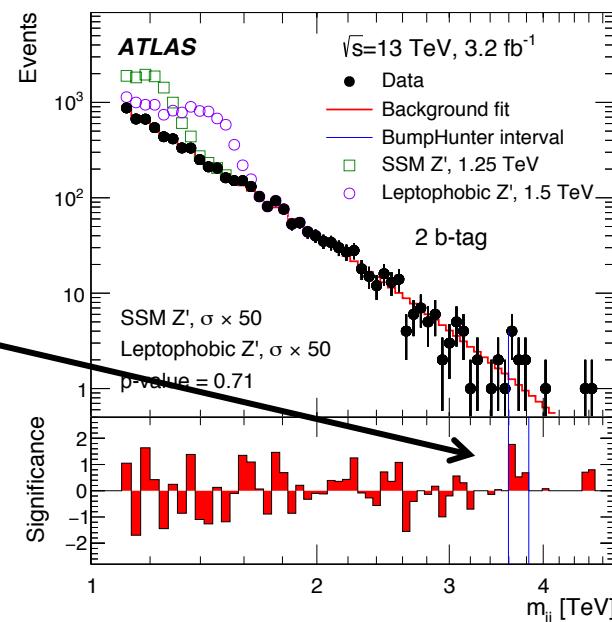
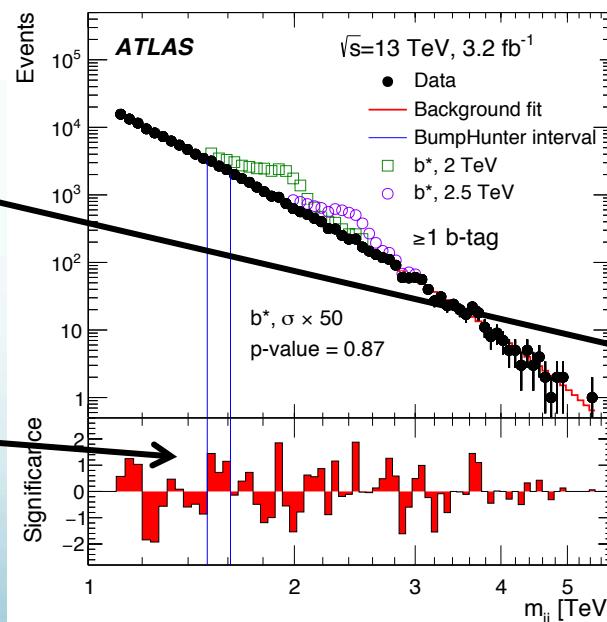
1-tag
0.87 global p-value
 $1.49 \rightarrow 1.61 \text{ TeV}$

| Relevant Selections | |
|---------------------|---------------------------------------|
| high p_T | $p_T^{\text{lead}} > 440 \text{ GeV}$ |
| central | $ y_1 - y_2 < 1.2$ |
| b-tagging | 85% WP |

Rejection of dominant light flavor QCD background

1-tag region = b^*

2-tag region = Heavy Z'

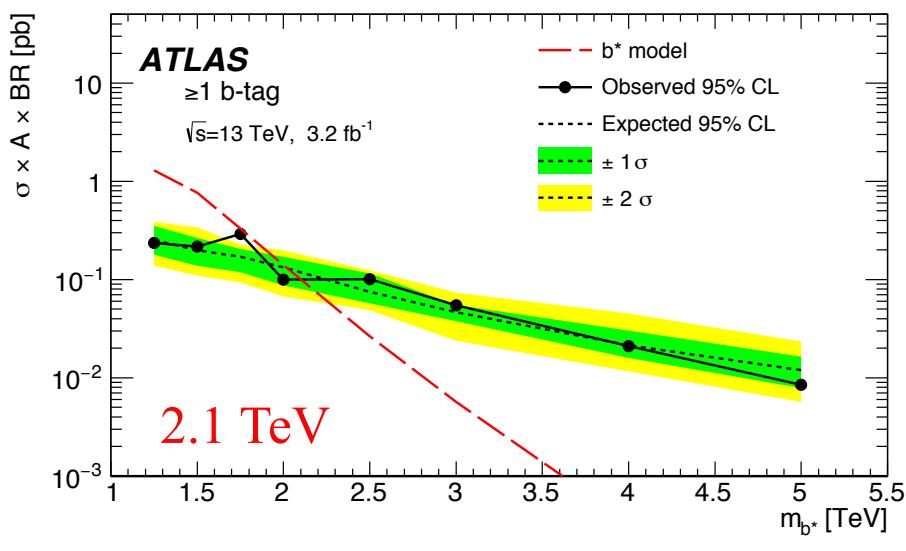


B-tagged Dijet Resonance

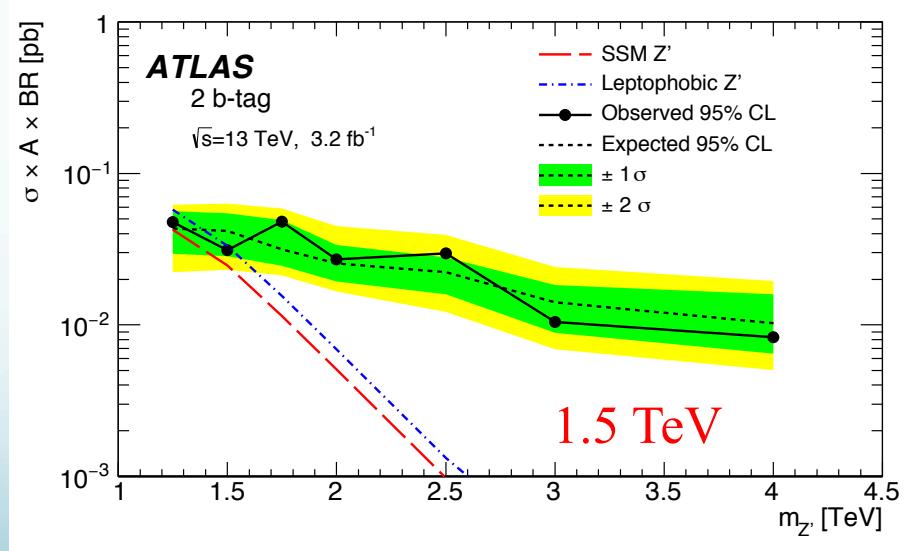
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| | 85% WP |

First b-tagged dijet limits from ATLAS!

1-tag region = b^*



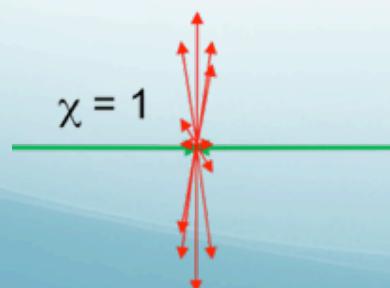
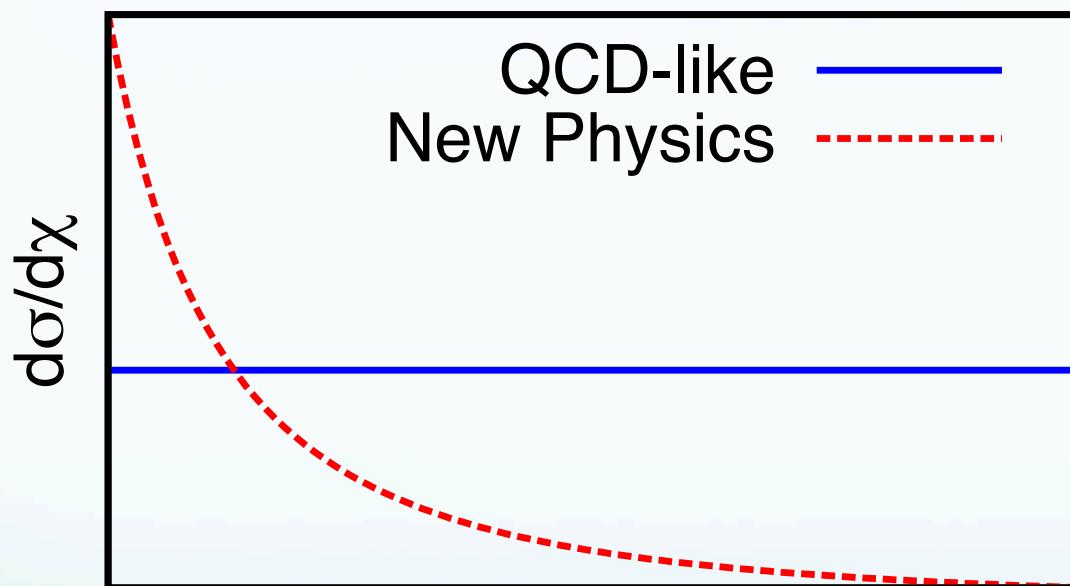
2-tag region = SSM/Leptophobic Z'



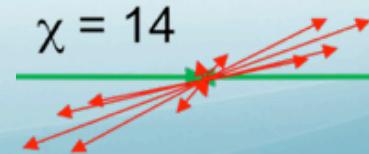
Dijet Angular

Search for deviations from QCD
in angular distribution of jets

| Relevant Selections | |
|---------------------|---------------------------------------|
| high p_T | $p_T^{\text{lead}} > 440 \text{ GeV}$ |
| central | $m_{jj} > 2.5 \text{ TeV}$ |
| boost | $ y_1 - y_2 < 3.4$ |
| | $ y_1 + y_2 < 2.2$ |

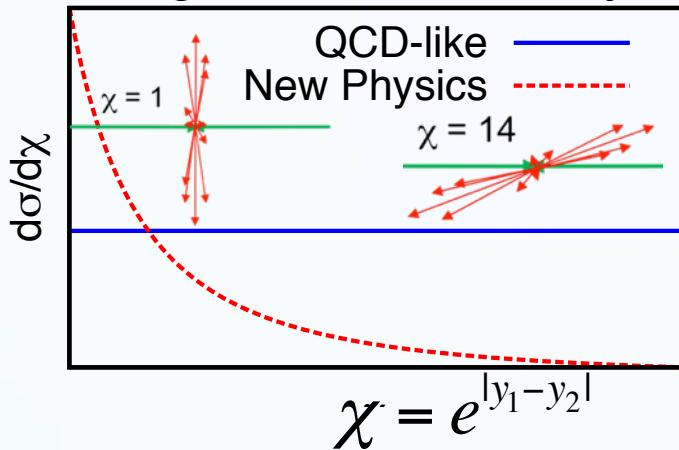


$$\chi = e^{|y_1 - y_2|}$$



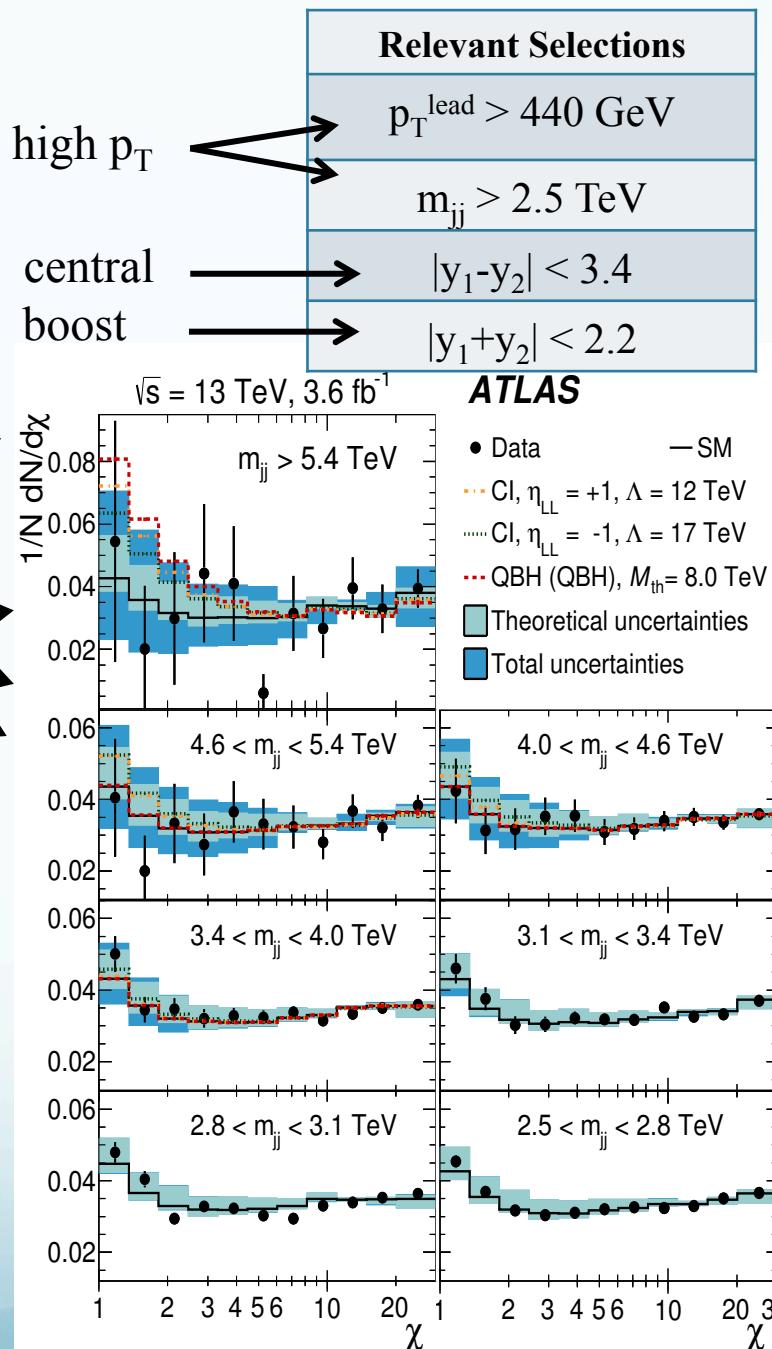
Dijet Angular

Search for deviations from QCD
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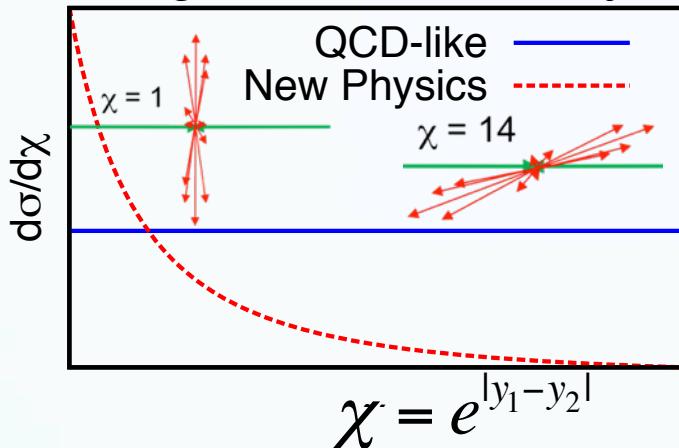
NLO+EW corrected
QCD background

binned in m_{jj}



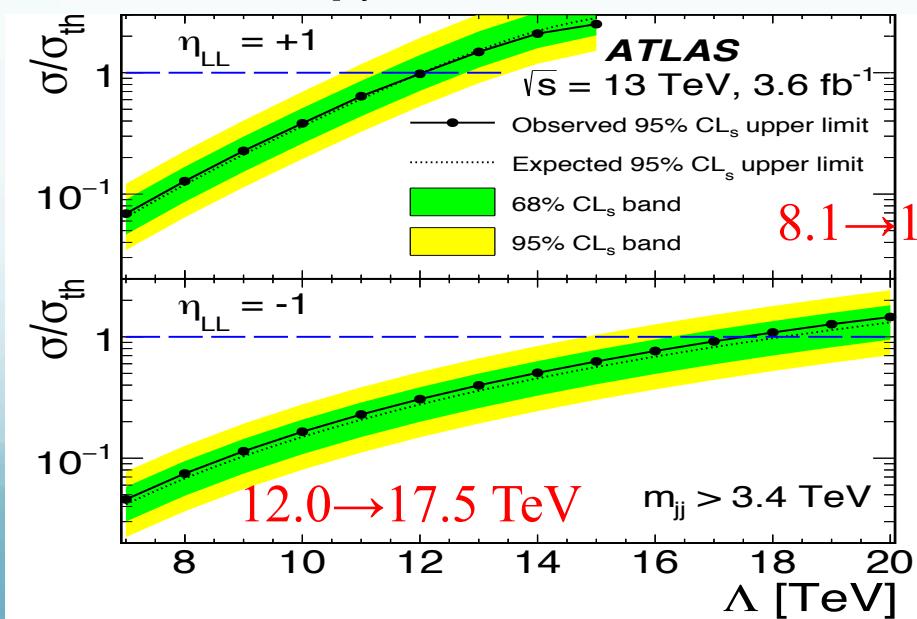
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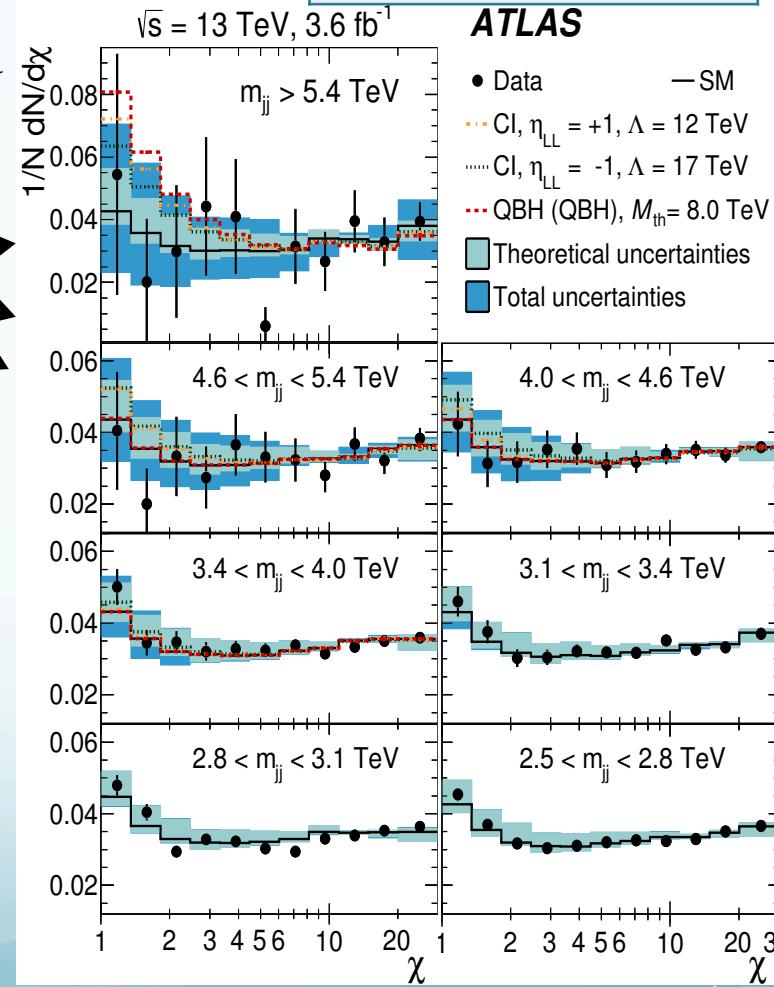


PLB
754 (2016)
302-322

LHCSki 2016

J. Dandoy

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|---------------------|--|
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4/12/16

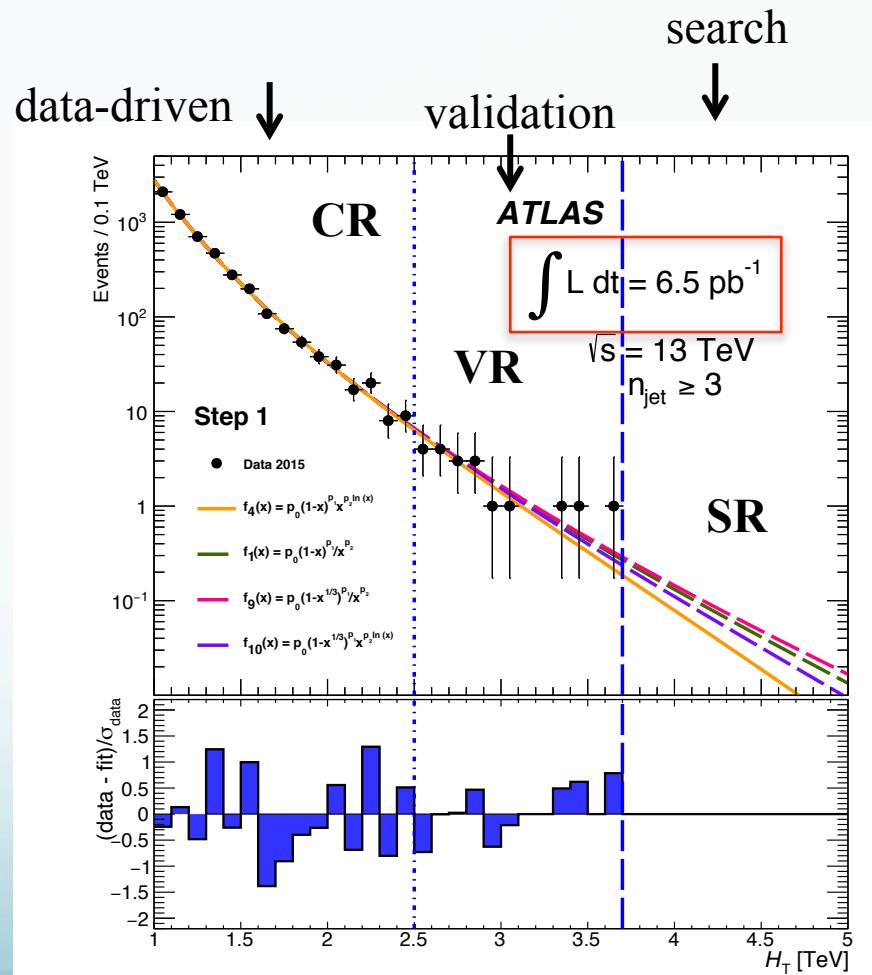
17

Multijet

Search $H_T = \sum p_T^{\text{jets}}$

Black hole produced $> M_D$ will decay into many particles following SM d.o.f.
→ Look for many jets!

| Relevant Selections | |
|---------------------|--|
| high p_T | $p_T^{\text{lead}} > 200 \text{ GeV}$ |
| many jets | $H_T > 1 \text{ TeV}$ |
| | $N_{\text{jets}} \geq 3 \rightarrow 8$ |

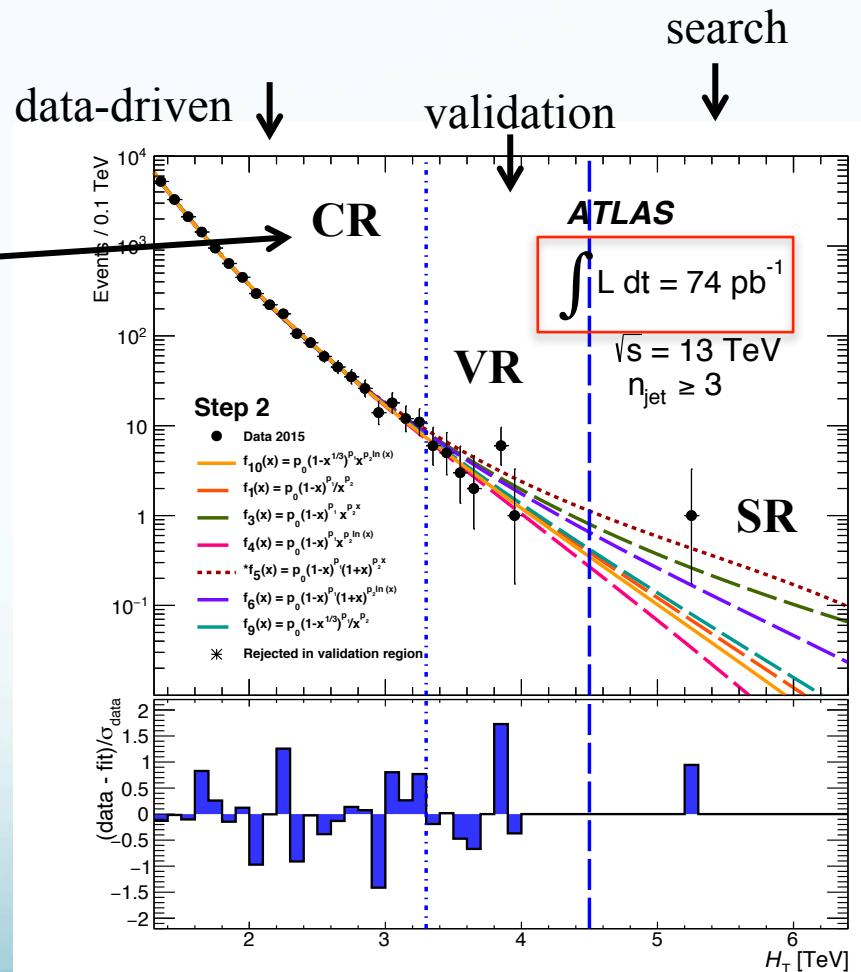
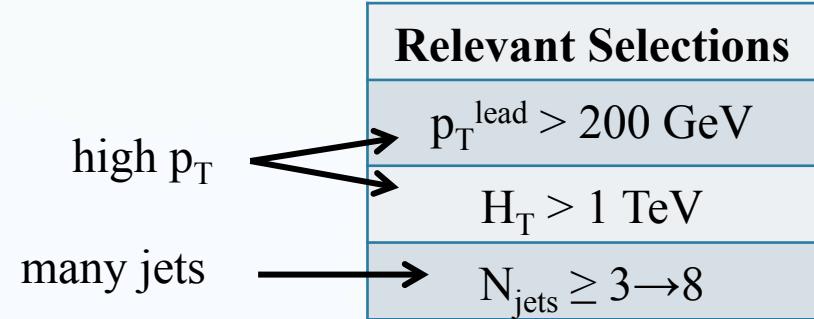
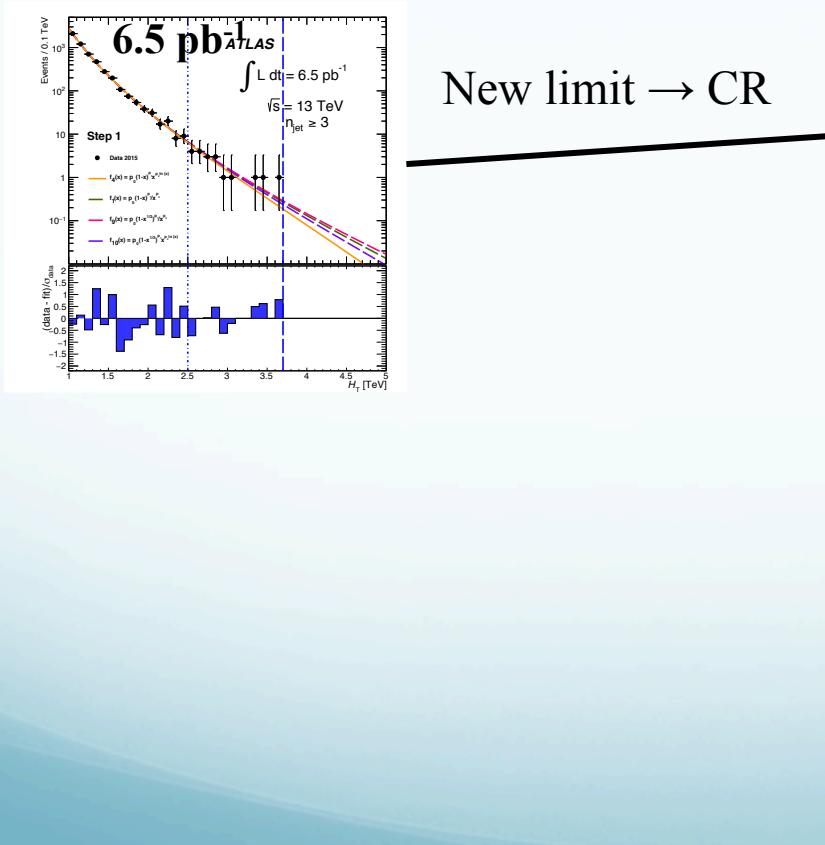


Multijet

Search $H_T = \sum p_T^{\text{jets}}$

Black hole produced $> M_D$ will decay into many particles following SM d.o.f.
→ Look for many jets!

Bootstrap Procedure

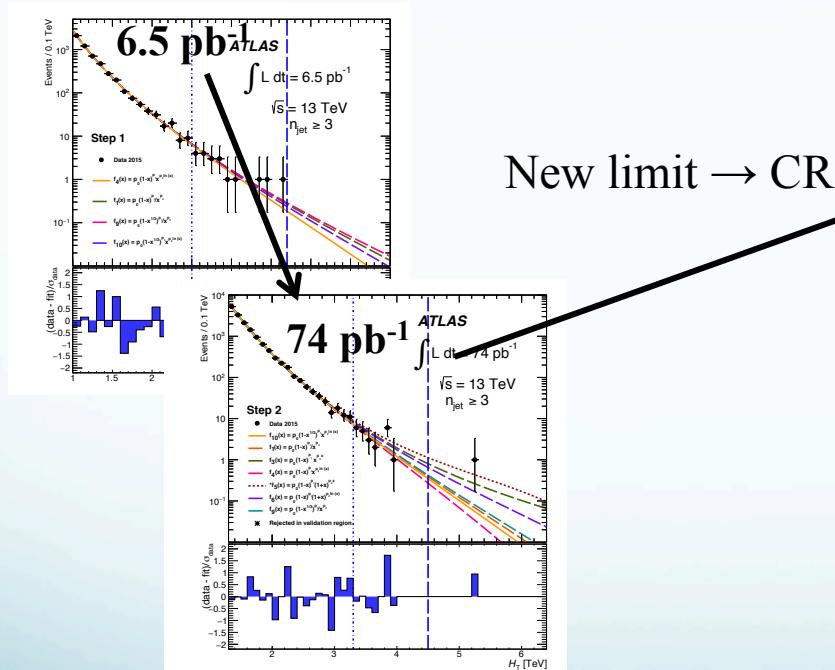


Multijet

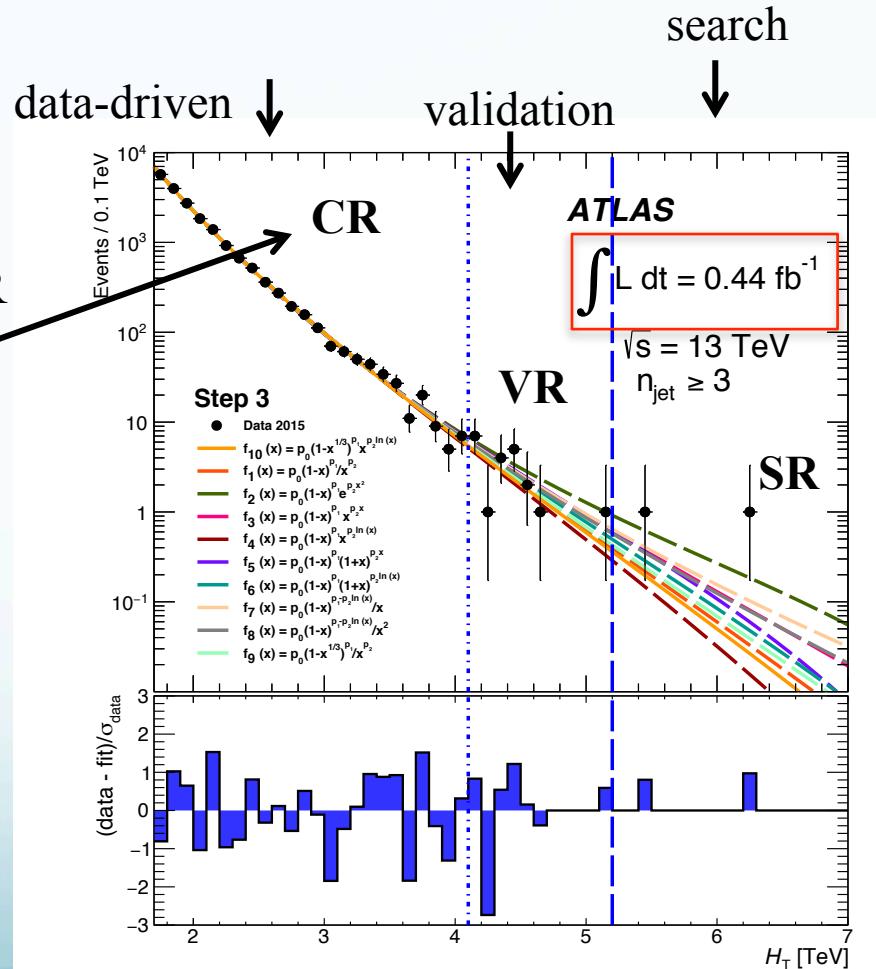
Search $H_T = \sum p_T^{\text{jets}}$

Black hole produced $> M_D$ will decay into many particles following SM d.o.f.
→ Look for many jets!

Bootstrap Procedure



New limit → CR

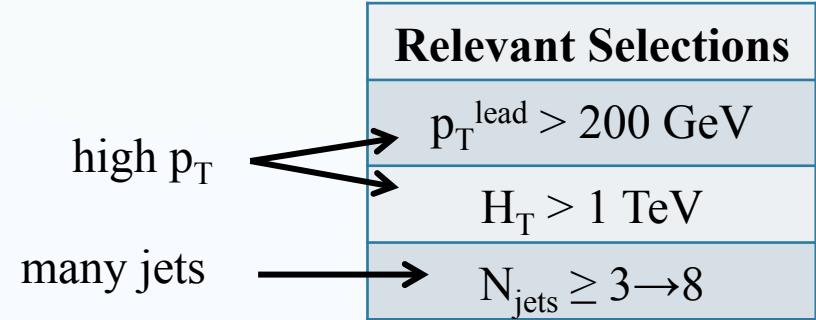
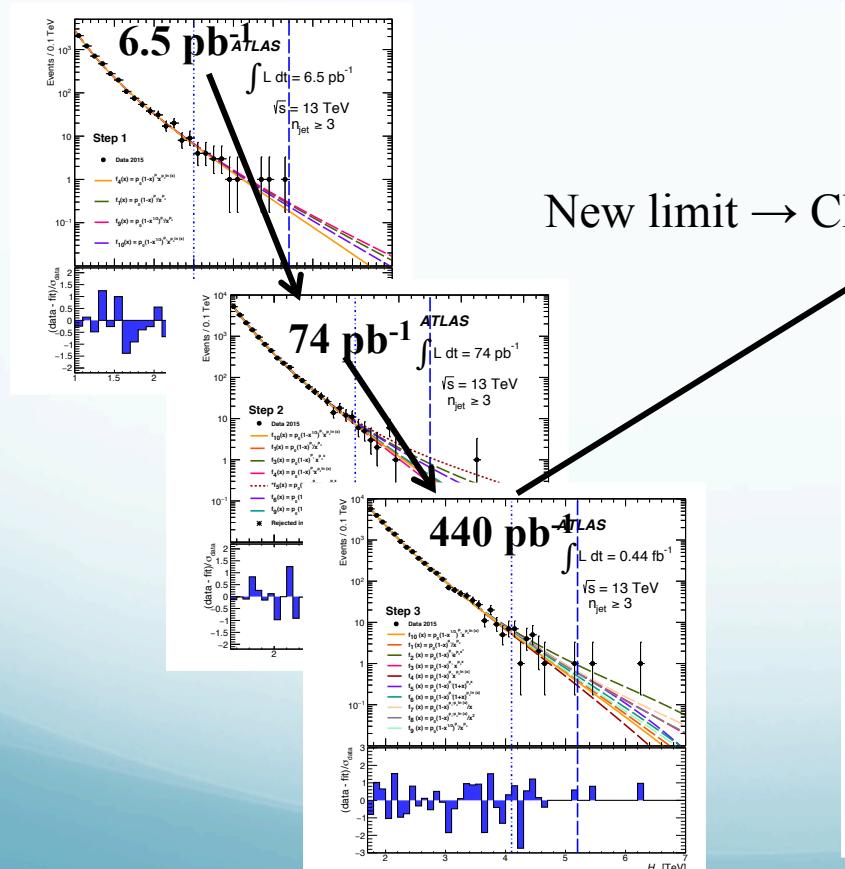


Multijet

Search $H_T = \sum p_T^{\text{jets}}$

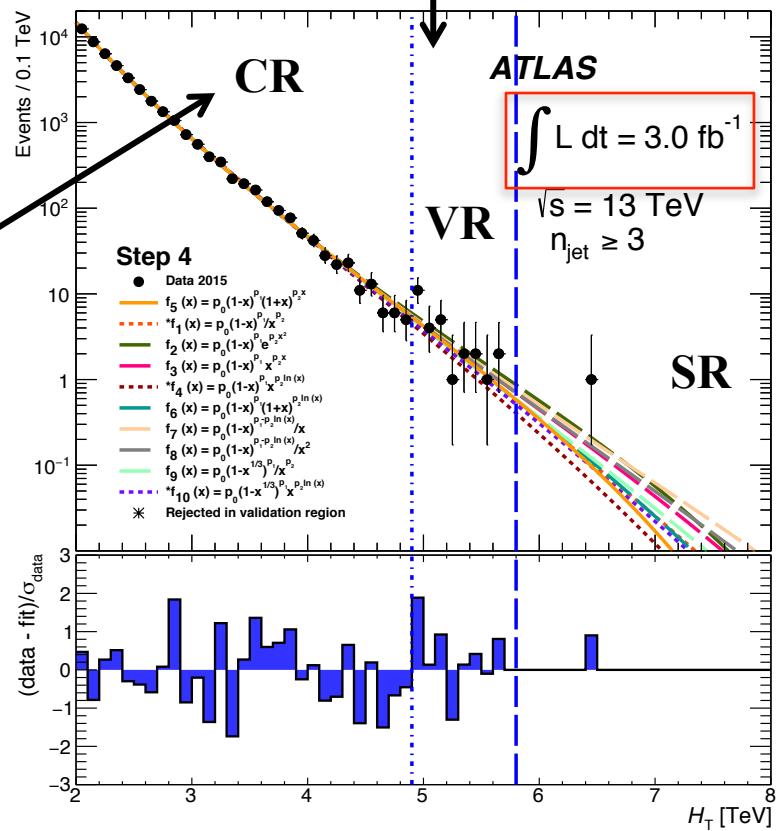
Black hole produced $> M_D$ will decay into many particles following SM d.o.f.
→ Look for many jets!

Bootstrap Procedure

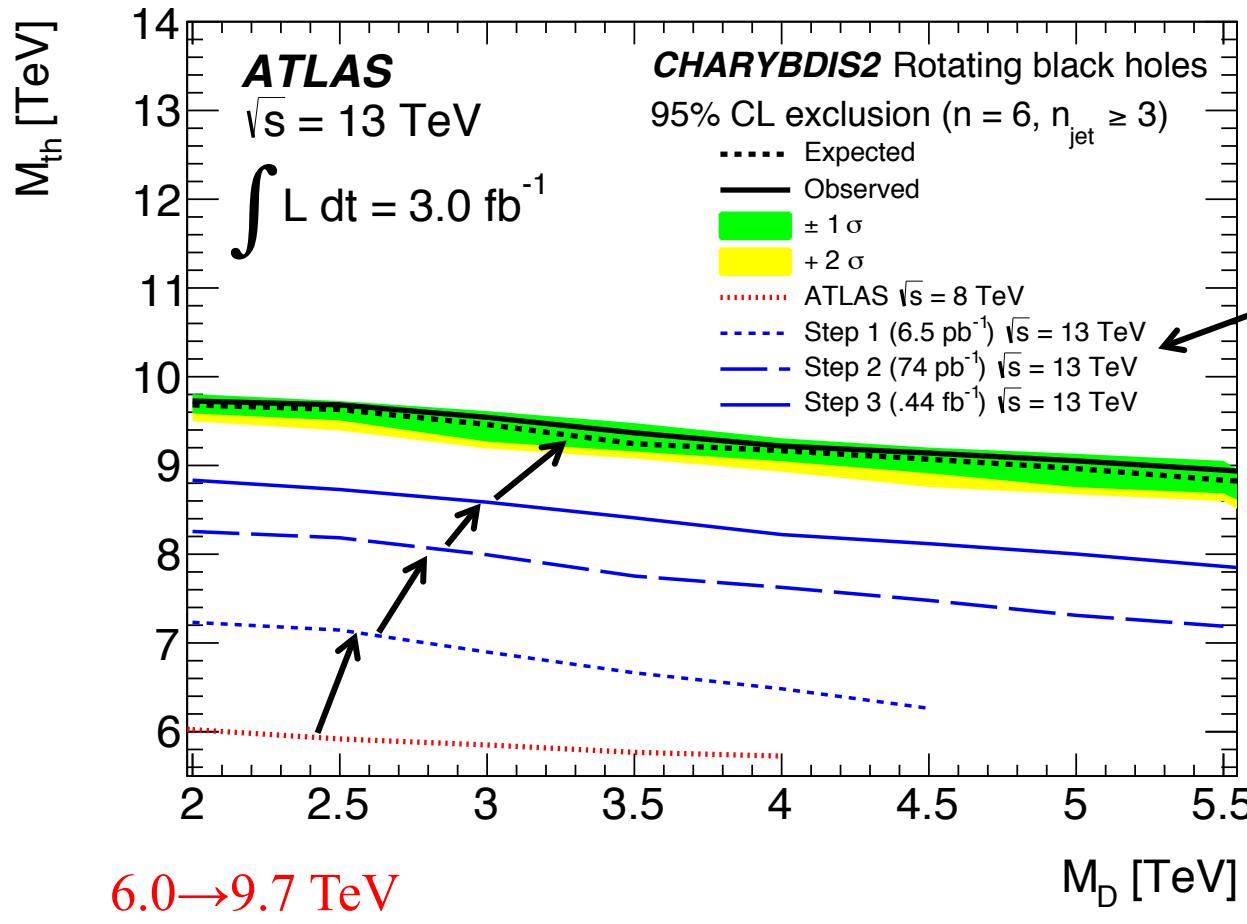


$$f(x) = p_0(1-x)^{p_1}(1+x)^{p_2}x^x$$

search
↓
data-driven ↓
validation ↓



Multijet



high p_T

many jets

| Relevant Selections |
|--|
| $p_T^{\text{lead}} > 200 \text{ GeV}$ |
| $H_T > 1 \text{ TeV}$ |
| $N_{\text{jets}} \geq 3 \rightarrow 8$ |

Black hole limits set at various:

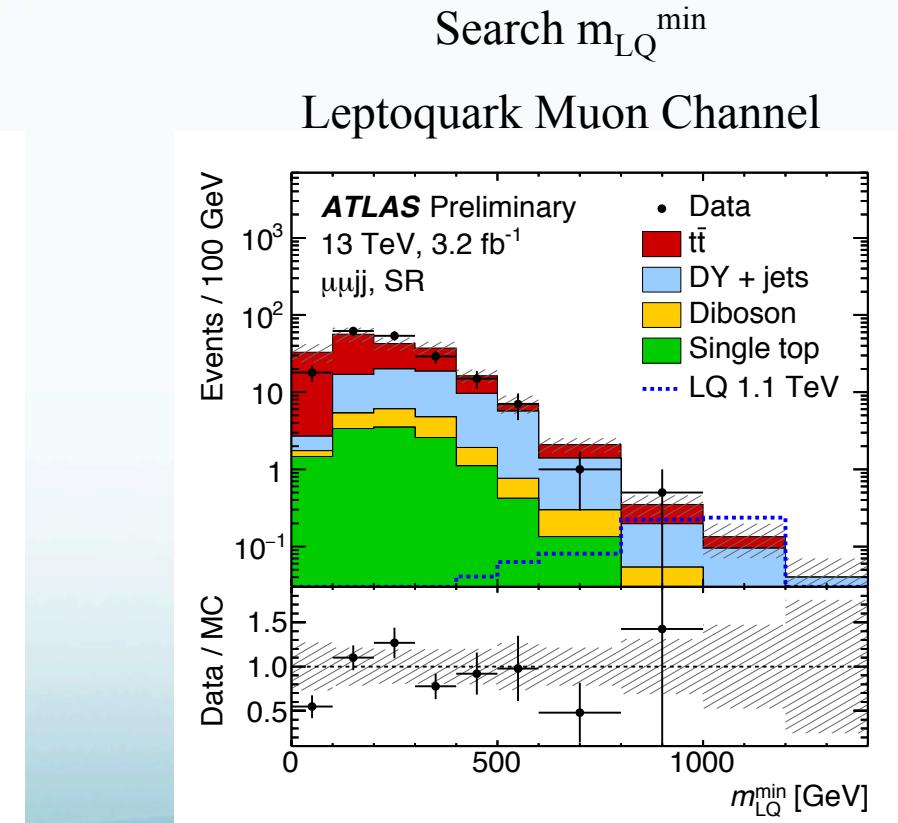
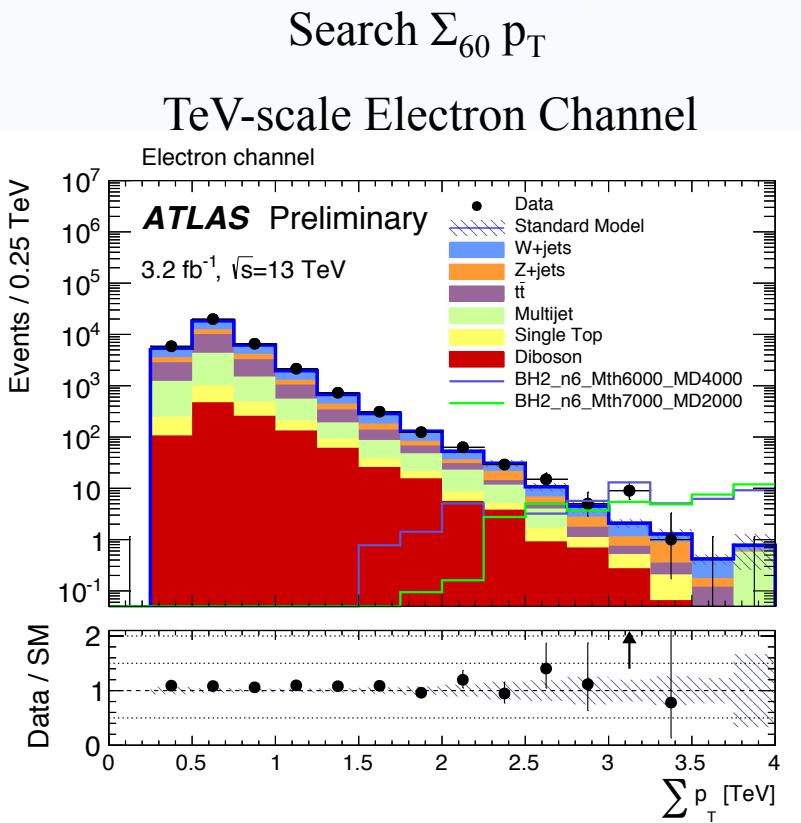
- Bootstrap stages
- y • Production threshold M_{Th}
- x • True Planck scale M_{D}
- N dimensions (not shown)

Lepton + Jets

Black holes decay democratically
 Leptoquark pair production
 → look for leptons and jets

| TeV-scale | Leptoquark |
|--|---|
| lep+jets → 3 jet/e/ μ $p_T > 100 \text{ GeV}$ | $e\bar{e}jj / u\bar{u}jj$ $m_{ll} > 130 \text{ GeV}$ |
| Signal Region → $\sum_{60} p_T > 2 \text{ TeV}$ | $\Sigma p_T > 600 \text{ GeV}$ |

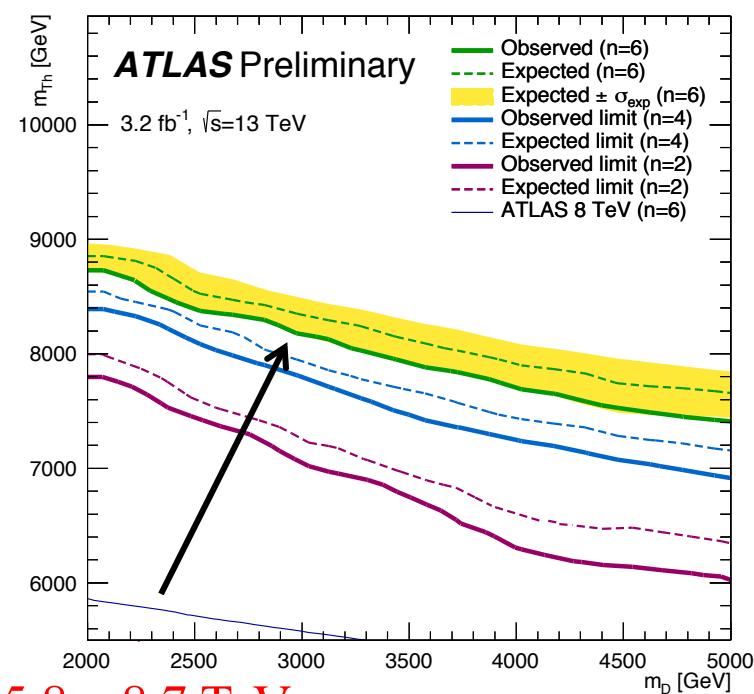
MC estimation of individual backgrounds, normalized to lower p_T control regions



Lepton + Jets

| TeV-scale | Leptoquark |
|--|-----------------------------------|
| lep+jets → 3 jet/e/ μ $p_T > 100$ GeV | eejj / uujj $m_{ll} > 130$ GeV |
| Signal Region → $\Sigma_{60} p_T > 2$ TeV | $\Sigma p_T > 600$ GeV |

Black hole limits set at various
 M_{Th} , M_D , and N dimensions



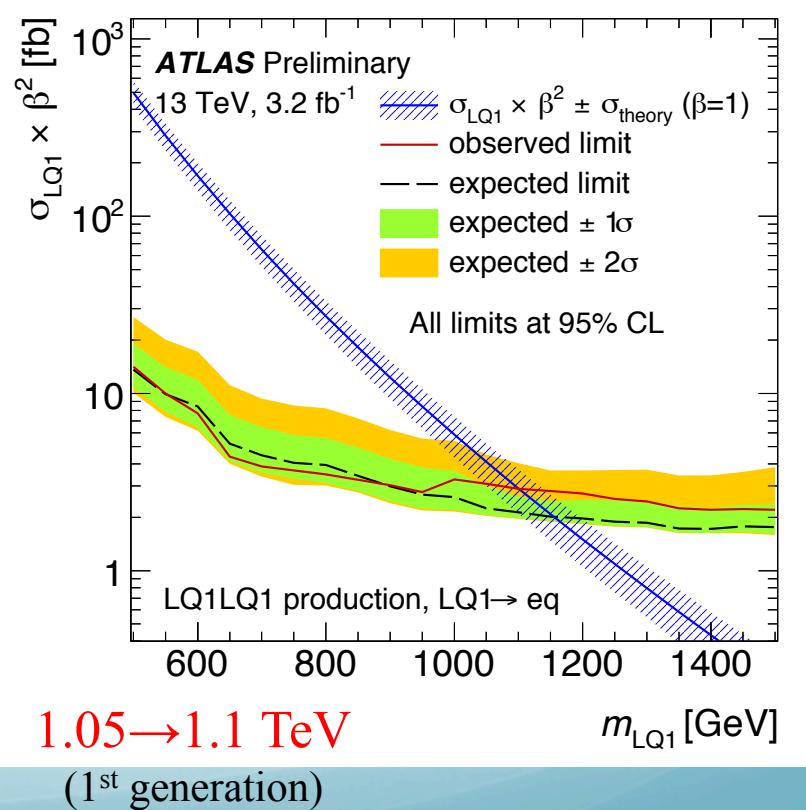
$5.8 \rightarrow 8.7 \text{ TeV}$
 $(n=6, M_D=2 \text{ TeV})$

ATLAS-CONF-2016-006

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Leptoquark limits set for first
and second generation decays



4/12/16

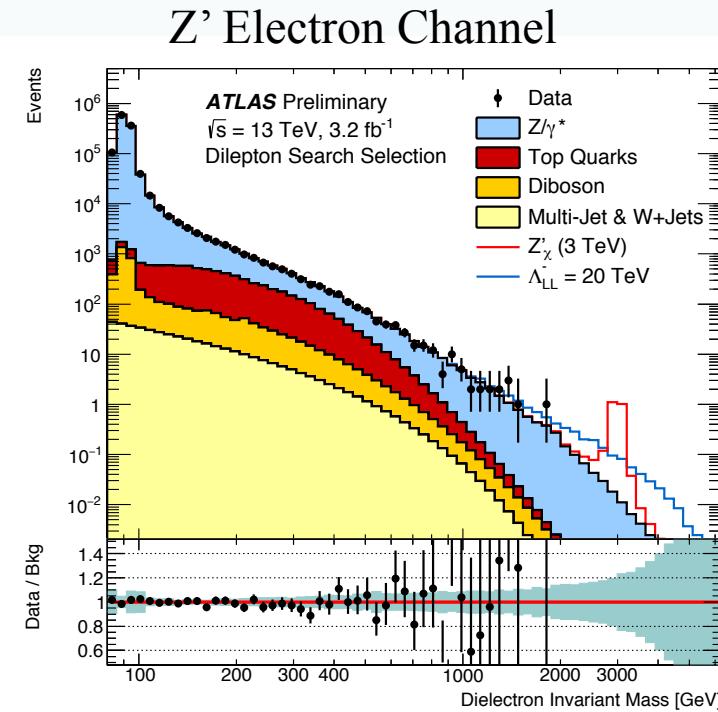
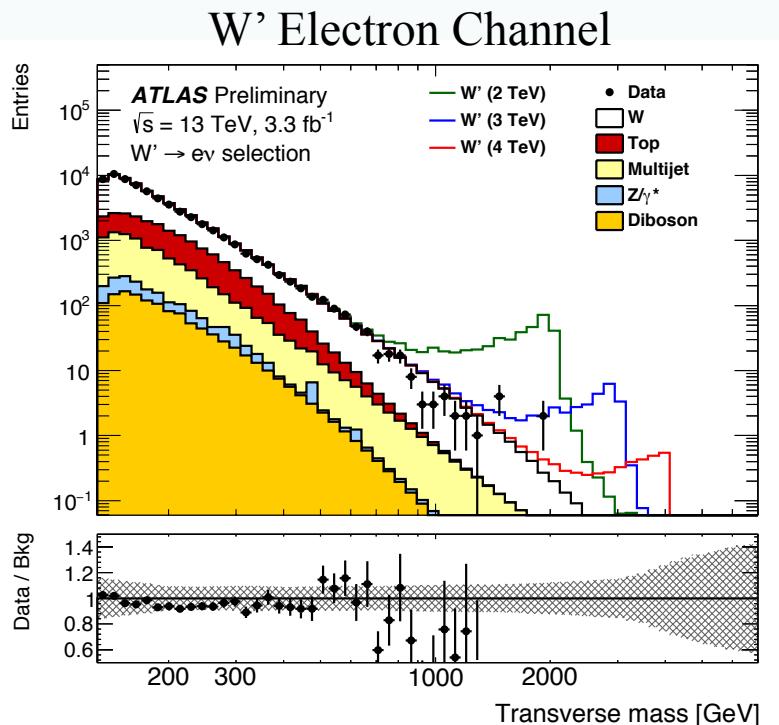
24

W' and Z' Searches

| | W' | Z' |
|----------|---|---|
| W/Z-like | 1 $\mu(e)$ $p_T > 55 (65)$ GeV $E_T^{\text{miss}} > 55 (65)$ GeV | 2 $\mu(e)$ $p_T(E_T) > 30$ GeV opposite charge μ |
| not W/Z | $m_T > 110 (130)$ GeV | $M_{ll} > 120$ GeV |

- SSM W' / Z' may have similar couplings and decay modes as the SM partners
- Search invariant mass (Z') or transverse mass (W') distributions
- Drell-Yan (W & Z/y*) dominant background

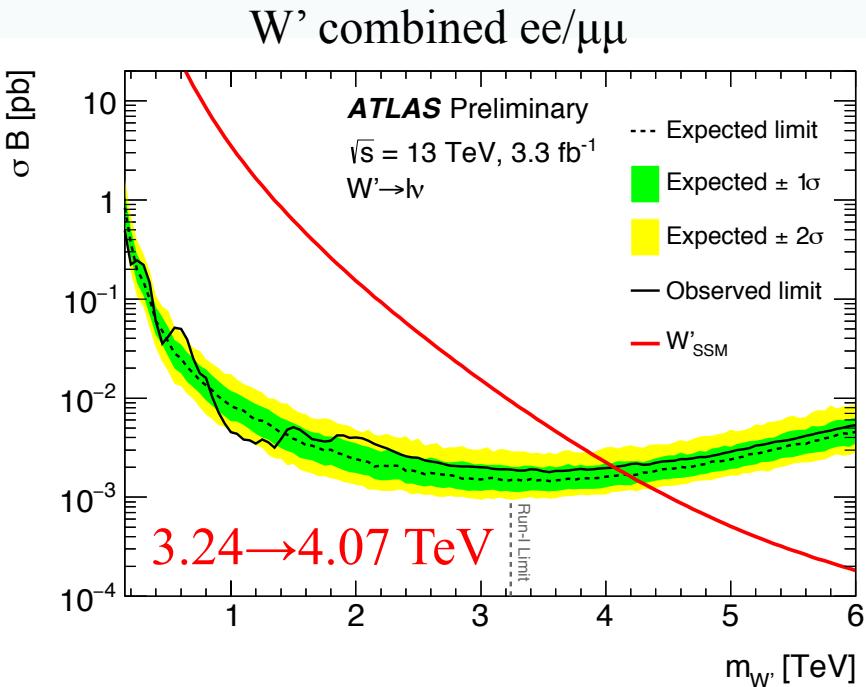
$$m_T = \sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi_{\ell\nu})}$$



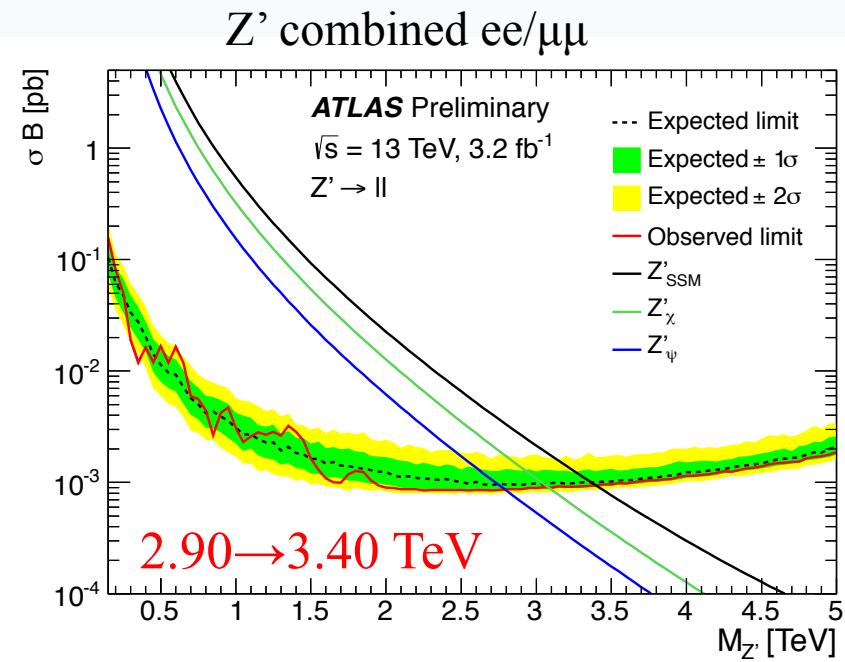
W' and Z' Searches

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| not W/Z | $M_T > 110 (130)$ GeV | $M_{ll} > 120$ GeV |

Limits set on SSM W' in electron, muon, and combined channels



Limits similarly set on Z'_SSM , E_6 models ($Z'_\psi \rightarrow Z'_\chi$), and contact interactions



ATLAS-CONF-2015-063

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ATLAS-CONF-2015-070

4/12/16

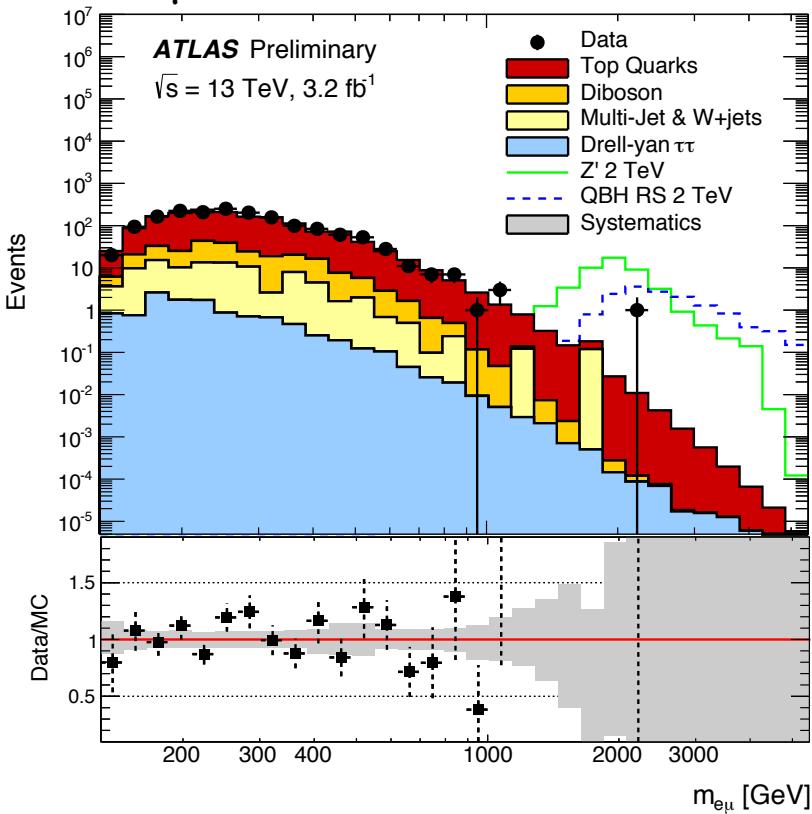
Lepton Number Violation

SSM Z' and QBH models can allow for lepton-number violating decays

| Relevant Selections | |
|---------------------|---------------------------------|
| opposite flavour | → e and μ of $p_T > 65$ GeV |
| back-to-back | → $\Delta\Phi(e,\mu) > 2.7$ |

→ $e\mu$ final states

$e\mu$ invariant mass distribution



Highly suppressed backgrounds

Top (diboson) MC extrapolated to low statistics region beyond $m_{e\mu} > 600$ (400) GeV

Search for excesses above 600 GeV

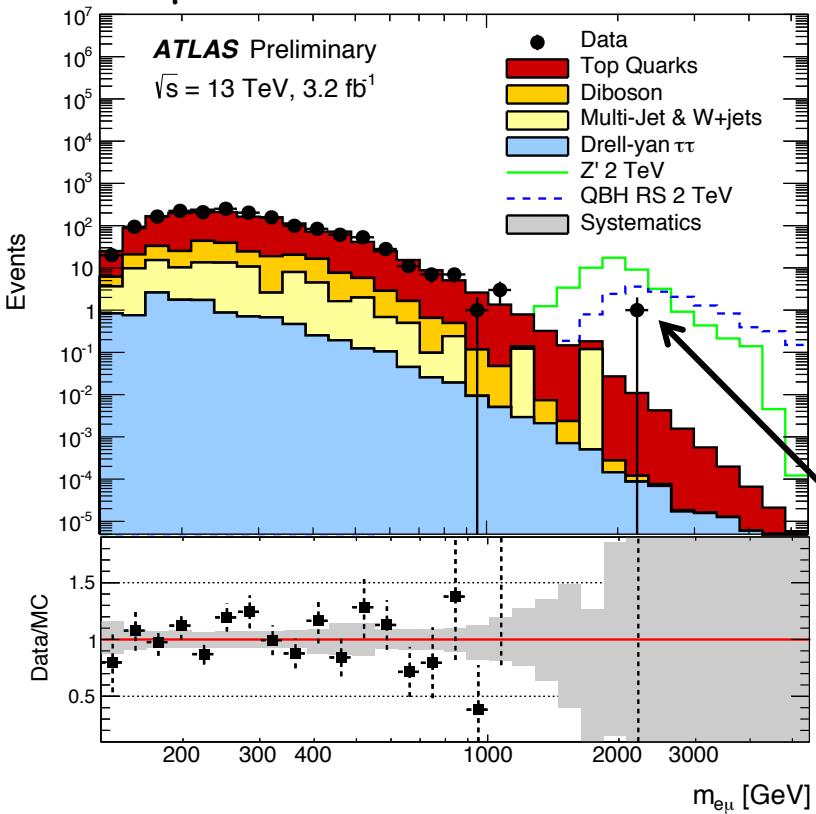
Lepton Number Violation

SSM Z' and QBH models can allow for lepton-number violating decays

| Relevant Selections | |
|---------------------|---------------------------------|
| opposite flavour | → e and μ of $p_T > 65$ GeV |
| back-to-back | → $\Delta\Phi(e,\mu) > 2.7$ |

→ $e\mu$ final states

$e\mu$ invariant mass distribution



Highly suppressed backgrounds

Top (diboson) MC extrapolated to low statistics region beyond $m_{e\mu} > 600$ (400) GeV

Search for excesses above 600 GeV

1.7 σ local excess at 2.1 TeV

Lepton Number Violation

| Relevant Selections | |
|---------------------|---------------------------------|
| opposite flavour | → e and μ of $p_T > 65$ GeV |
| back-to-back | → $\Delta\Phi(e,\mu) > 2.7$ |

Improvement to limits in $e\mu$ channel:

QBH (n=1)

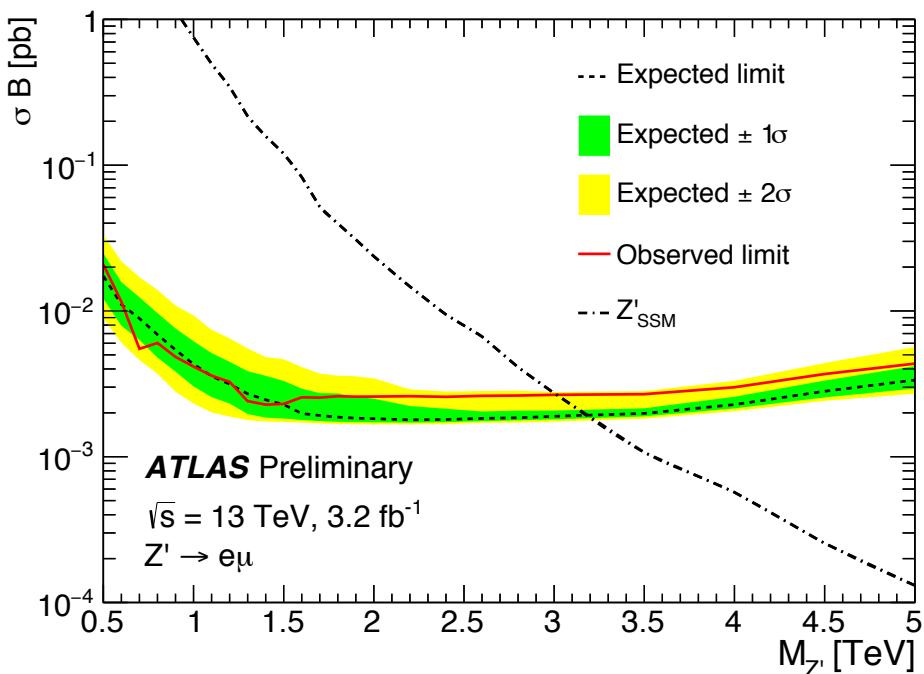
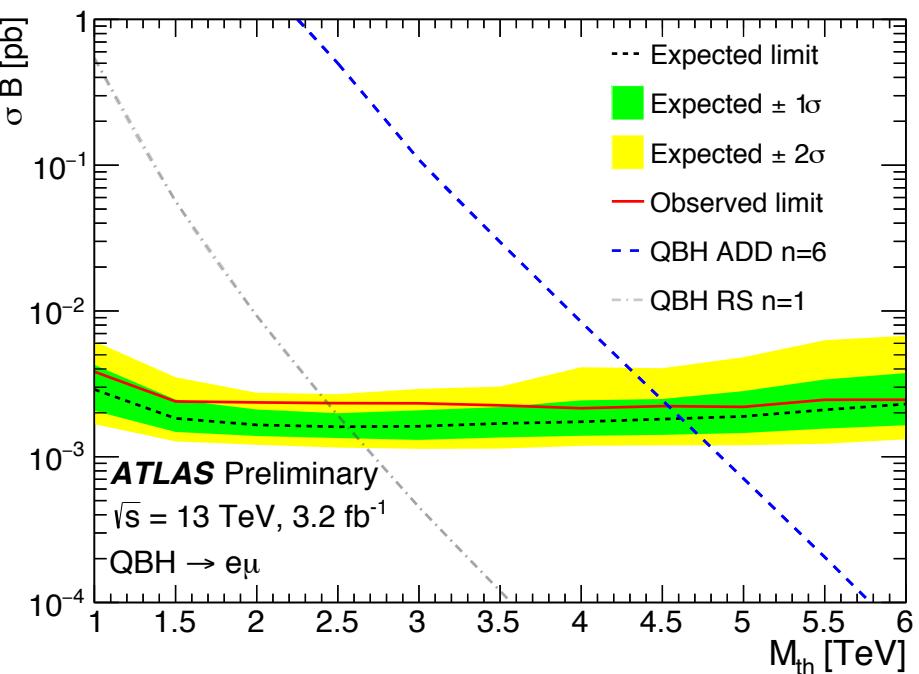
2.44 TeV

QBH (n=6)

4.54 TeV

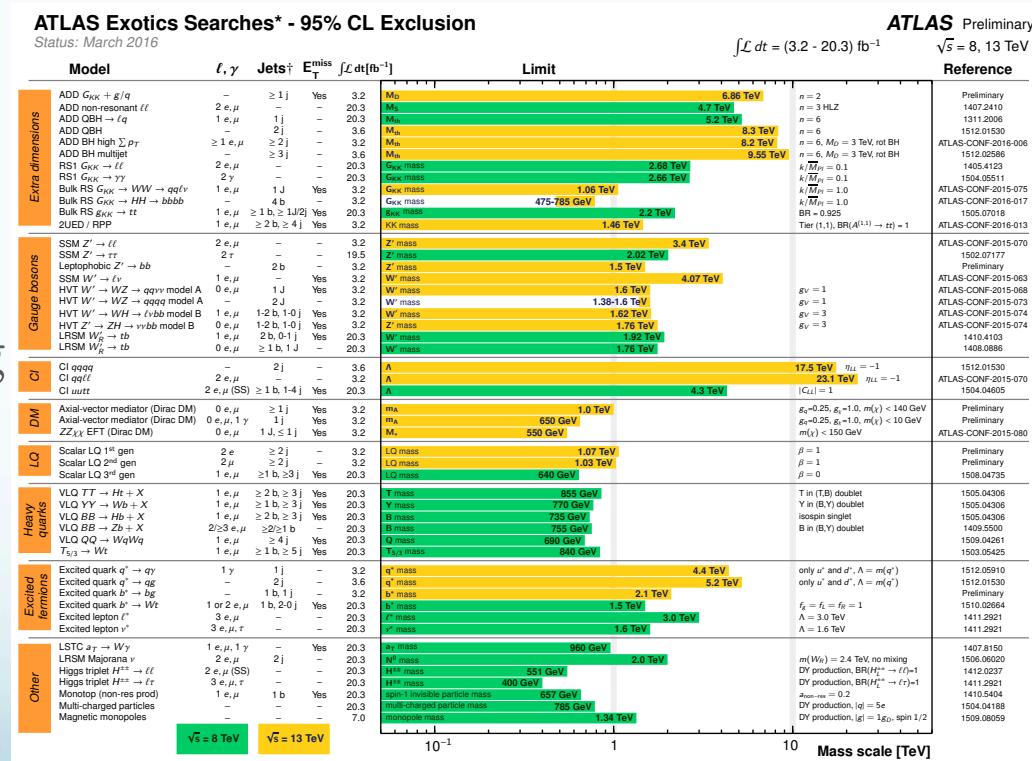
SSM Z'

2.5→3.01 TeV



Conclusion

- Several analyses using high p_T jets and leptons have set stringent limits on theoretical models and generic Gaussian resonances
 - Significant improvement over Run I due to parton luminosity scaling
- 2016 will bring $\sim 10x$ more data, significantly increasing our mass reach
- Innovative analyses probing masses < 1 TeV through ISR, b-jet triggers, and trigger level analyses
- Interesting physics ahead!



Run II limits beat Run I in many channels

Backup

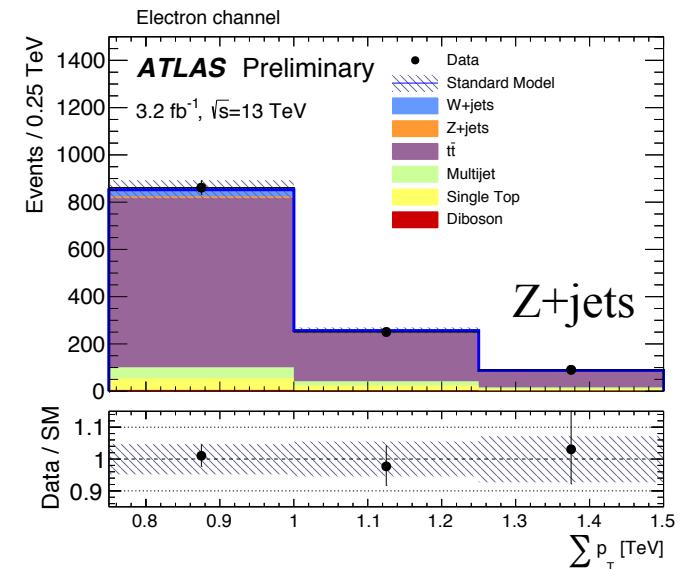
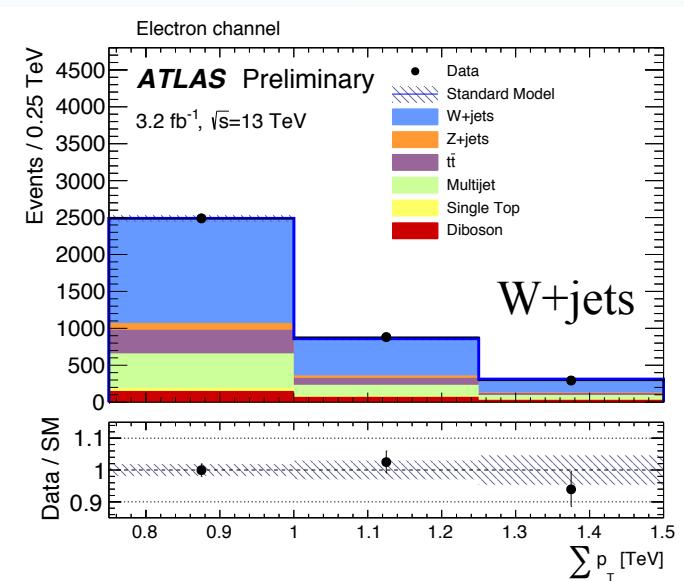
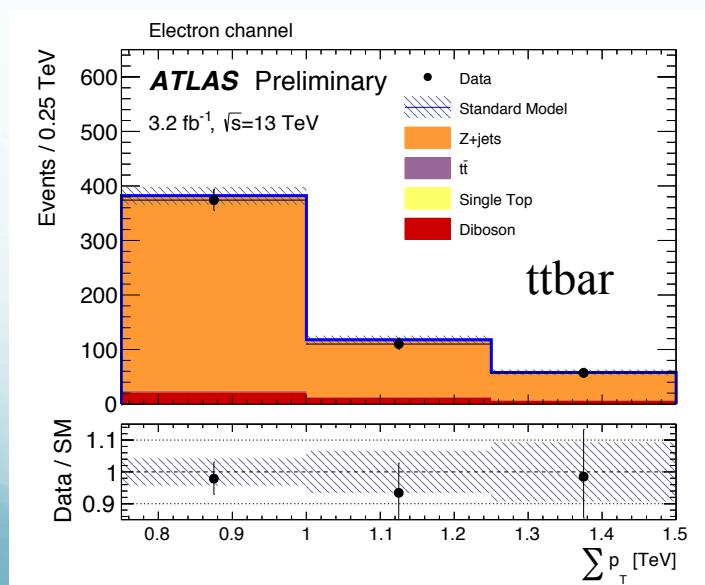
Control Regions: TeV-Scale

| Cut | Control Regions | | |
|-------------------------|--|-------------------|------------|
| | $Z + \text{jets}$ | $W + \text{jets}$ | $t\bar{t}$ |
| $\sum p_T$ | 750–1500 GeV | | |
| Number of Objects | The event must contain at least 3 objects (leptons or jets) with $p_T > 60$ GeV. | | |
| Leading lepton | The event must contain a leading electron or muon of good quality, isolated and with $p_T > 60$ GeV. | | |
| m_{ll} | 80 – 100 GeV | n/a | |
| E_T^{miss} | n/a | > 60 GeV | n/a |
| Number of leptons | exactly 2, opposite sign same flavour | exactly 1 | |
| Number of b-tagged jets | n/a | exactly 0 | > 1 |
| Number of jets | n/a | | > 3 |

Control Regions: TeV-Scale

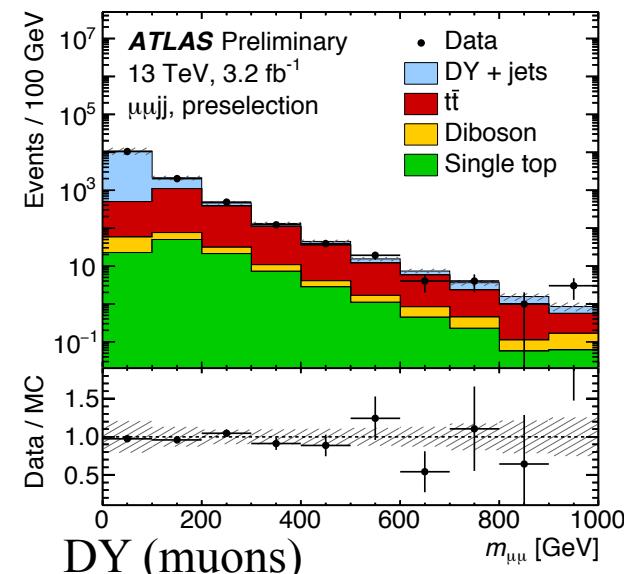
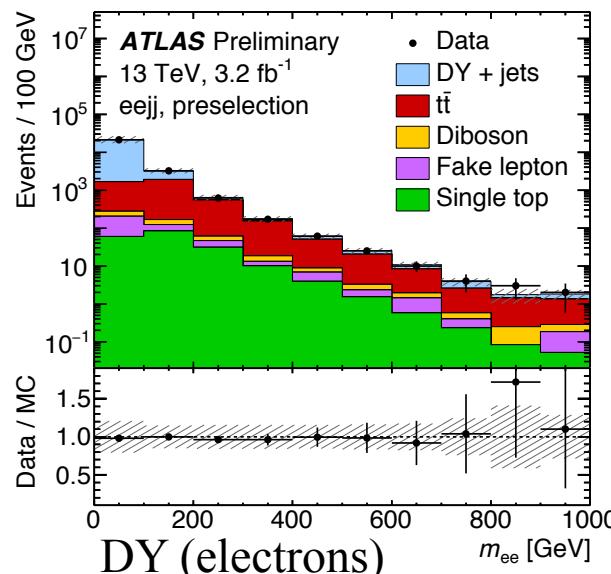
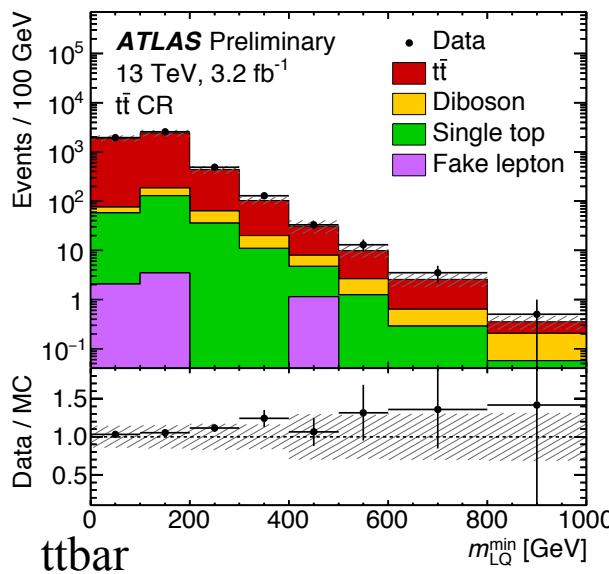
Σp_T distributions for W+jets (0.81), Z+jets (1.01), and ttbar (0.95) control regions

Single top and diboson normalization
is taken from MC
Multijet background is data-driven



Control Regions: Leptoquark

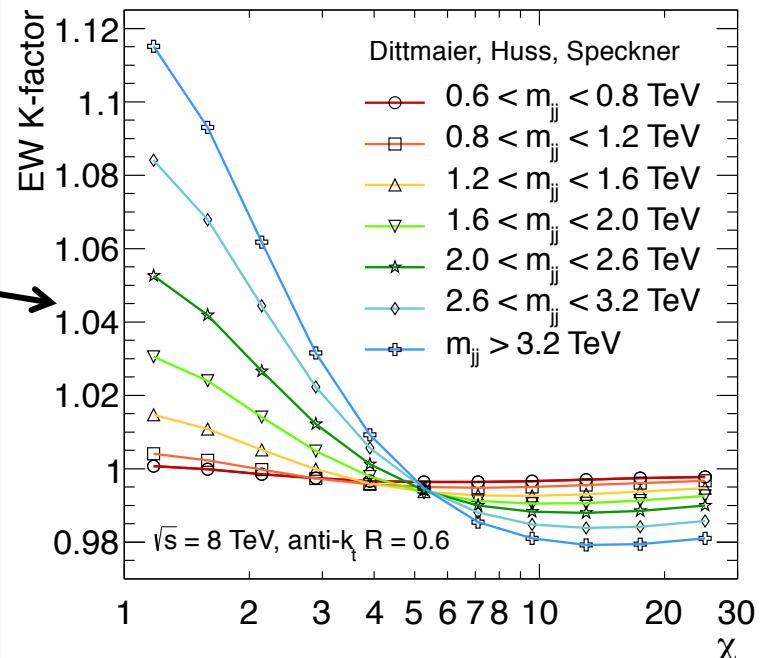
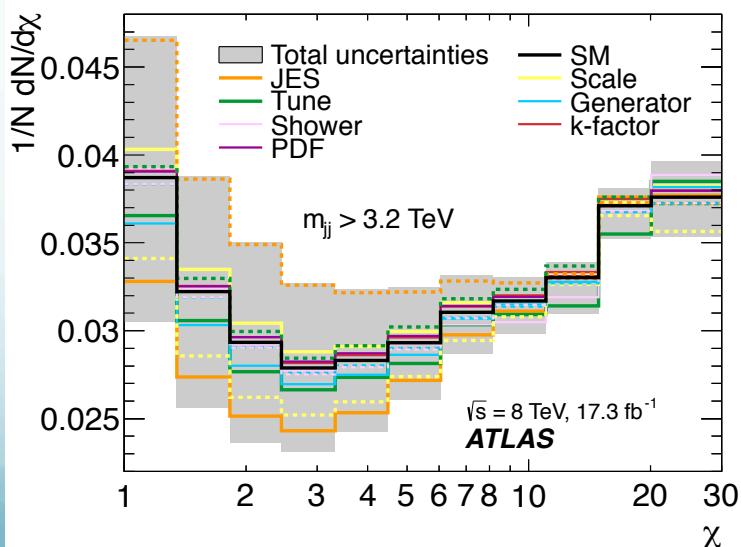
- Drell-Yan + jets:
 - Exactly 2 same-flavor leptons with $70 < m_{\parallel} < 110$ GeV
- ttbar:
 - Exactly 1 muon and 1 electron
- Single top, diboson, and $Z \rightarrow \tau\tau + \text{jets}$ taken from MC



Dijet Angular NLO MC Prediction

Background estimate using LO Pythia8

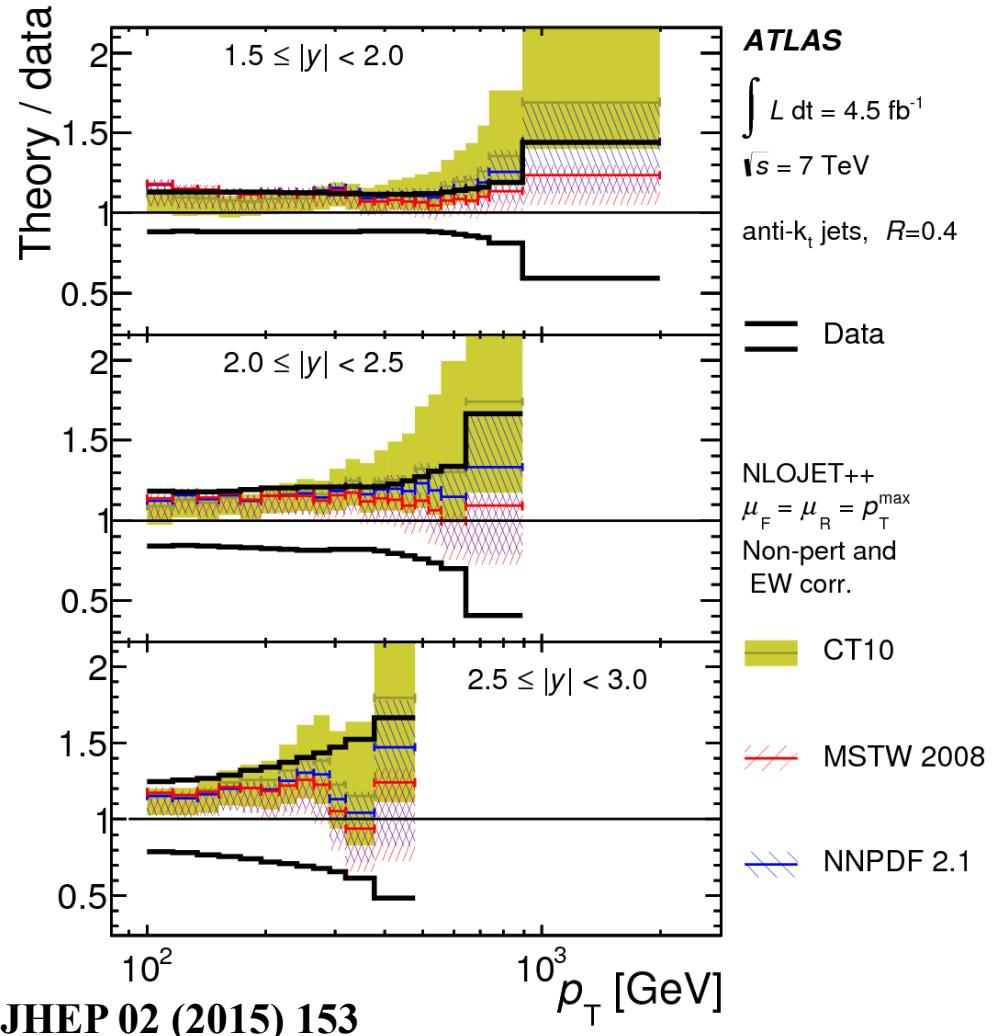
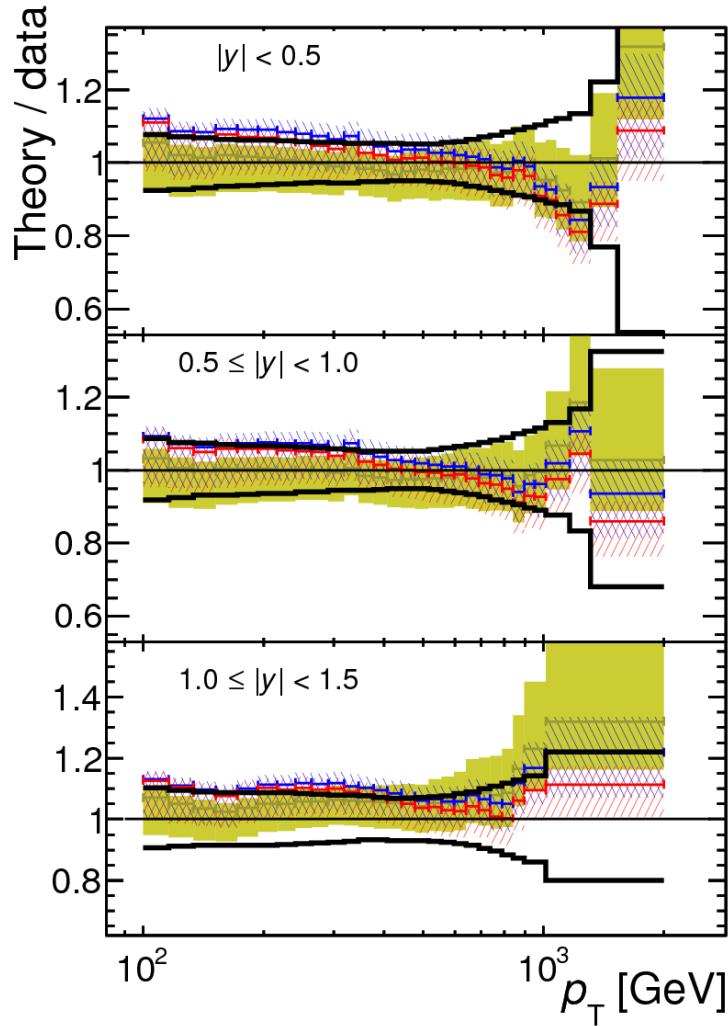
Derived NLOJet++ and **Electroweak** corrections



Systematic Uncertainties
Low mass: Renormalization and factorization scales
High mass: Jet Energy Scale

NLO p_T Comparisons

Large p_T shape PDF uncertainties, but roughly similar across η regions



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