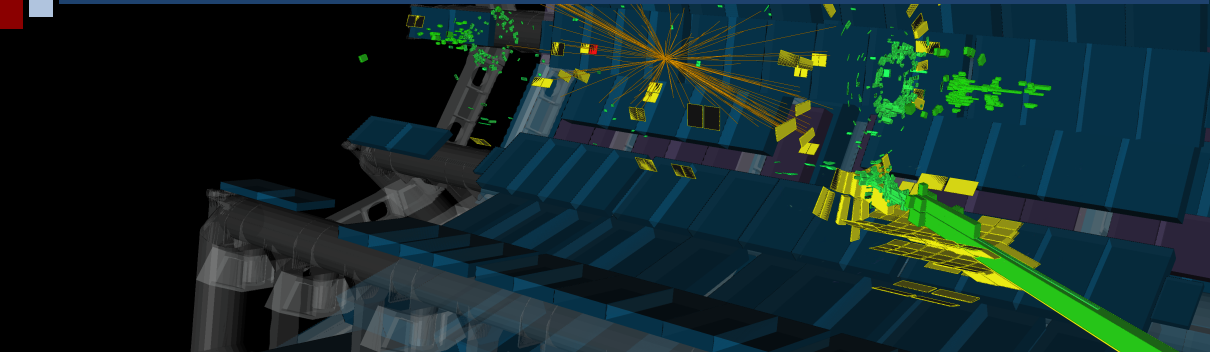
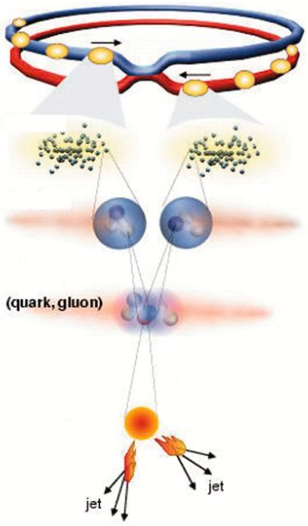
Istituto Nazionale di Fisica Nucleare

Matteo Bauce

Search for new physics in particle collisions at the ATLAS experiment



Particle colliders & Energy scale

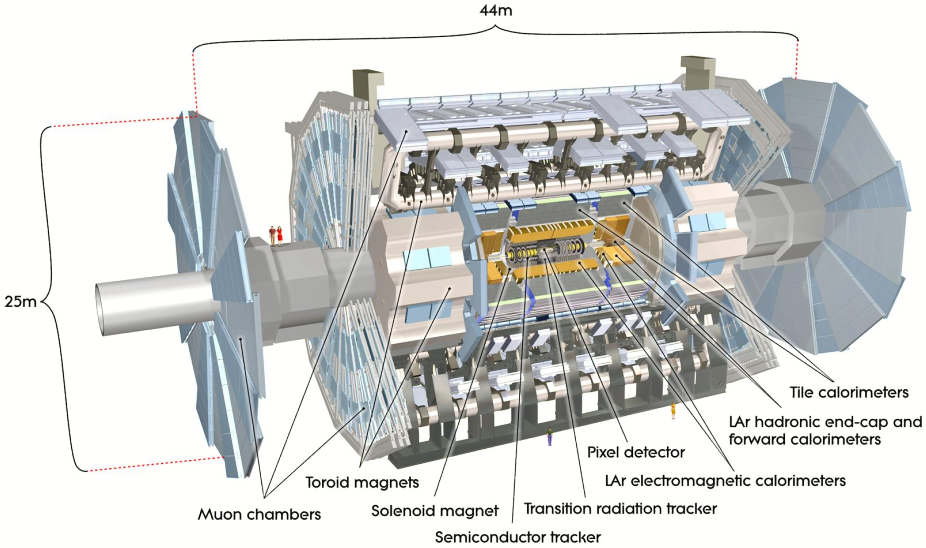


- High energy colliders have been powerful tools to study particle interactions to the *hardest* scales
- Probing smaller spatial scales and higher energy scales
- Two-fold: test predictions and explore the unknown

► LHC is the highest energy *pp* collider built to-date and can be used to deeply study fundamental particle properties

- $\sqrt{s}$= 7, 8, 13 TeV
- 40 MHz collision rate
- Max. peak luminosity 1.4 10^{34} $cm^{-2}s^{-1}$

The ATLAS detector



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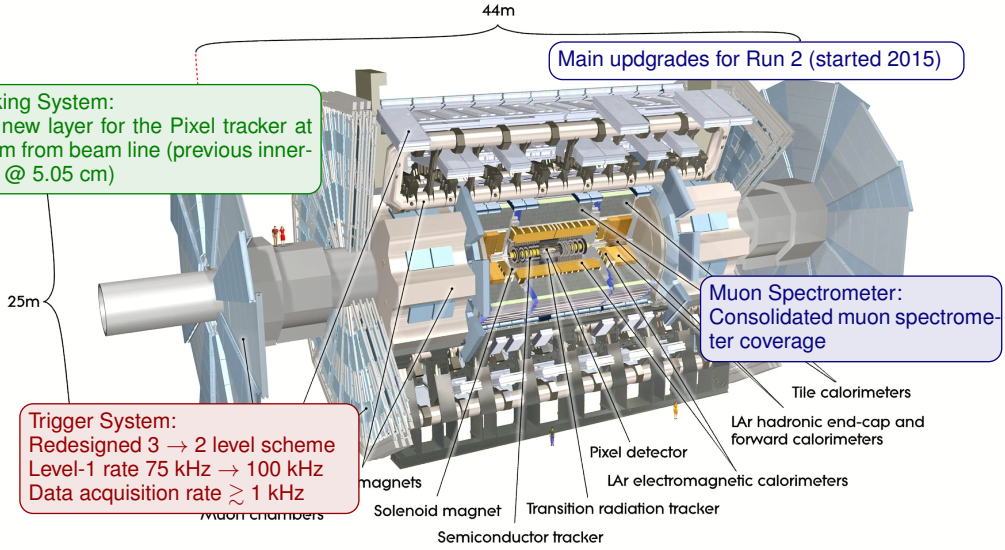
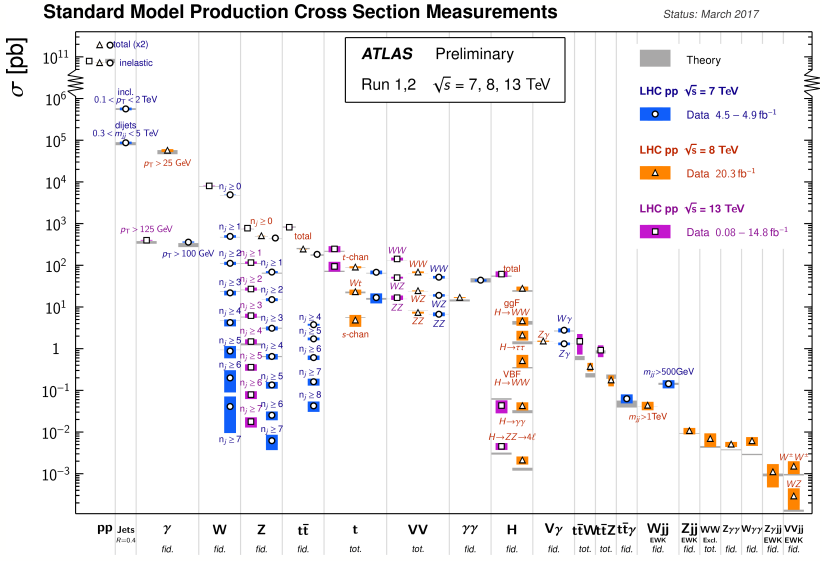
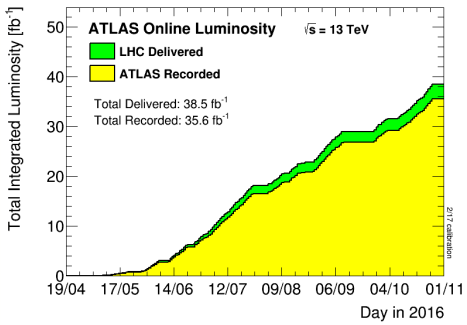


Precise SM measurements

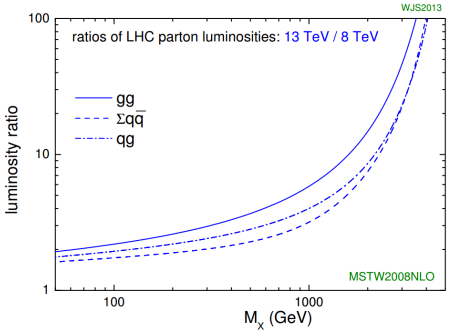


Why collecting more lumi?

- Increase accuracy of physics measurements
- Improve knowledge of searches' background contribution
- Investigate anomalies and deviations with respect to theory predictions
- Last-but-not-least: more sensible to smaller signals



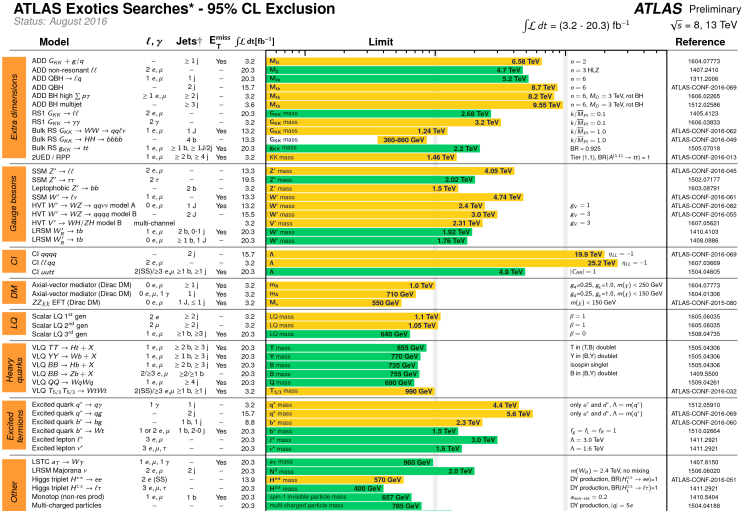
Why increasing energy?



- Since 2015 LHC restarted at a new center-of-mass energy: 13 TeV
- New phase-space accessible
- Larger cross section for high-mass particle production
- Signal/Background cross section ratio increased for many searches for new physics

$\sqrt{s}$ 8 $\rightarrow$ 13 TeV improved significantly the sensitivity of new physics searches in many signatures and theoretical models

What to look for?



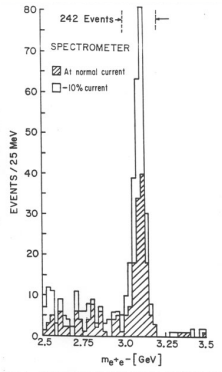
*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS pursued a large variety of searches, exploring complementary signatures.

No significant NP hints found so far at the TeV scale.

Notable resonances



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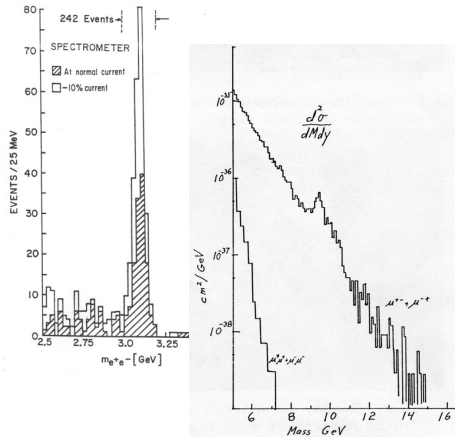

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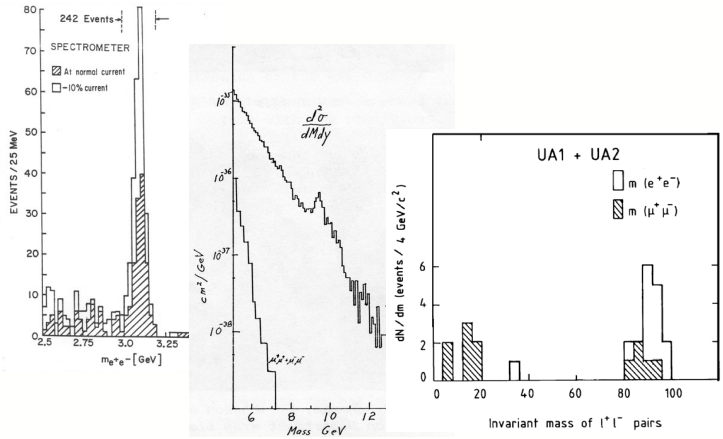

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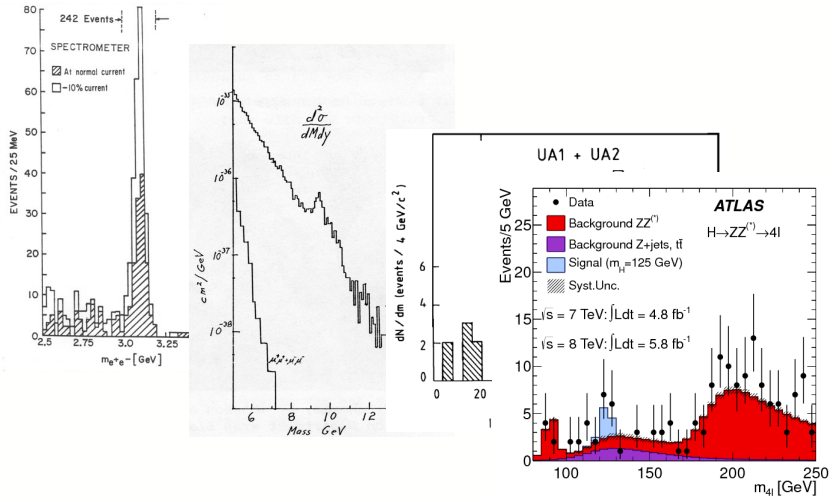
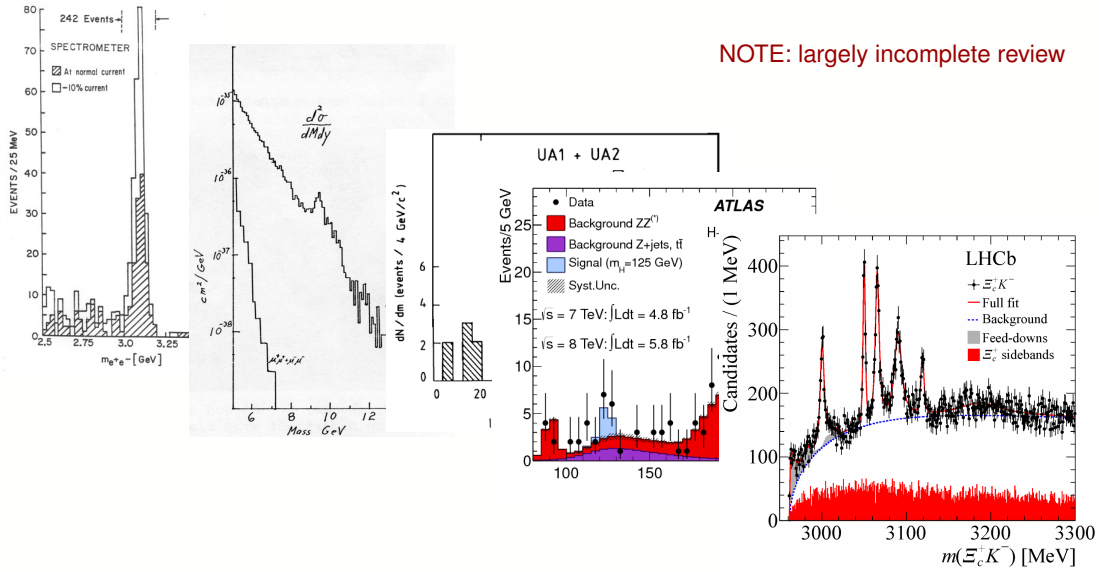
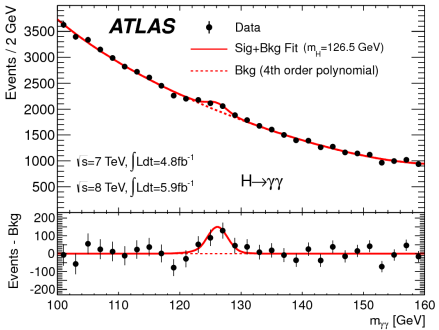


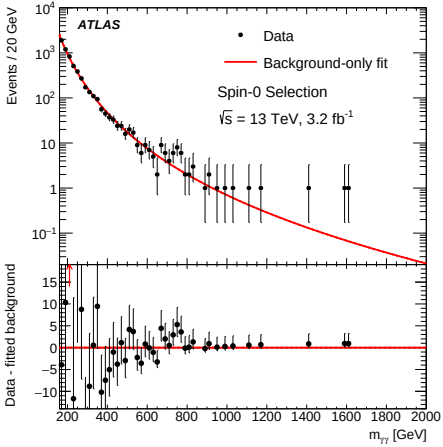
Notable resonances

NOTE: largely incomplete review

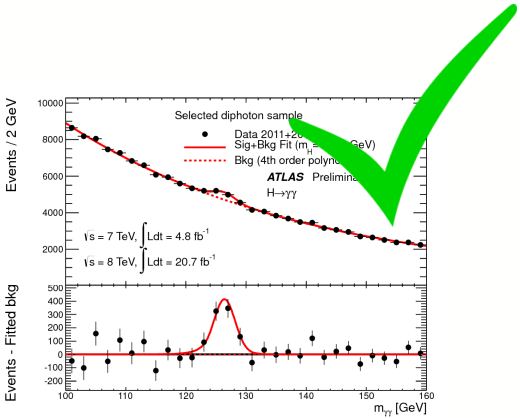


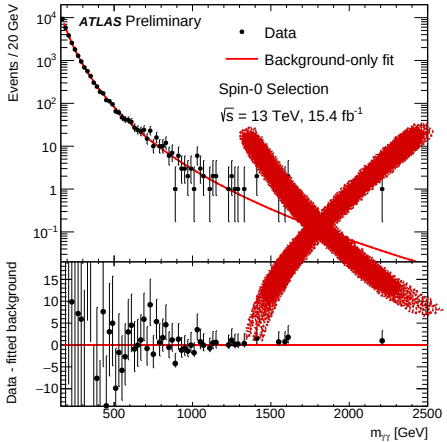
Is it that simple?





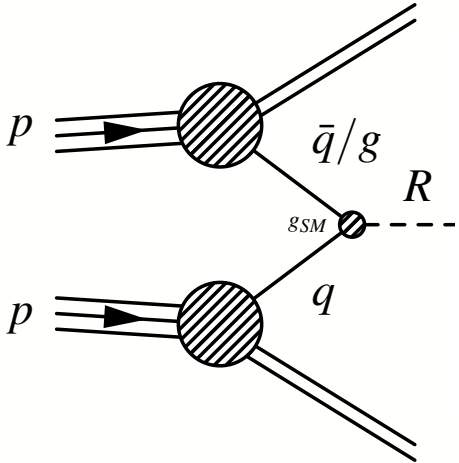
Is it that simple? No, it's not





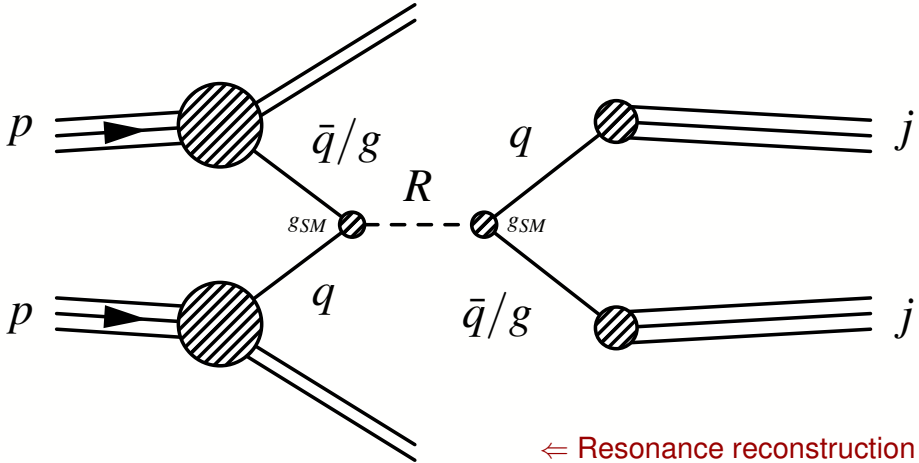
Search for a hadronic resonance: simplified approach

Resonance production $\Rightarrow$



Search for a hadronic resonance: simplified approach

Resonance production ⇒



⇐ Resonance reconstruction

Search for a hadronic resonance: simplified approach

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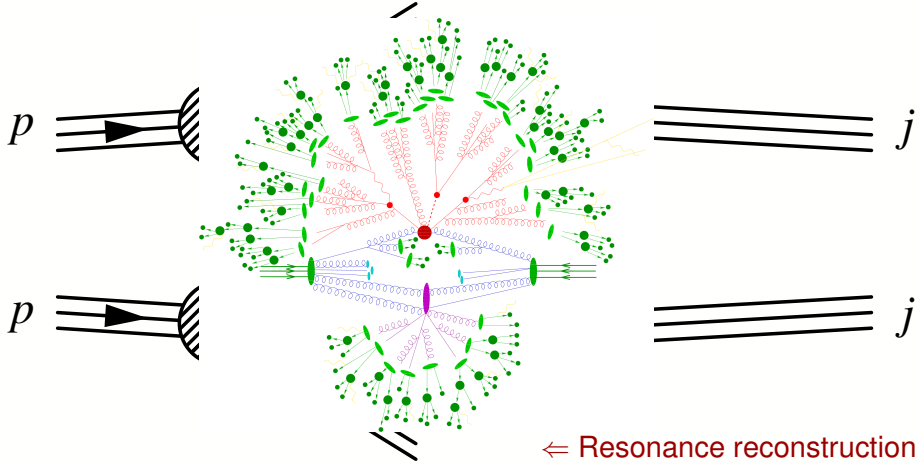
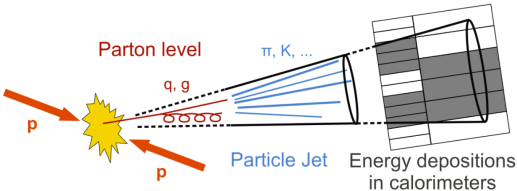
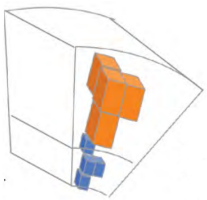


⇐ Resonance reconstruction

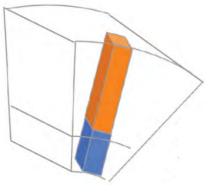
Jets: hadronic particle's signature



Topological Clusters

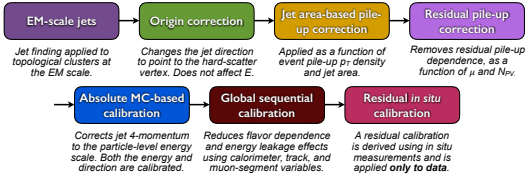


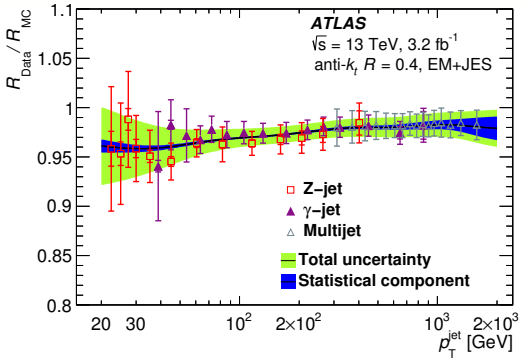
Calorimeter Towers



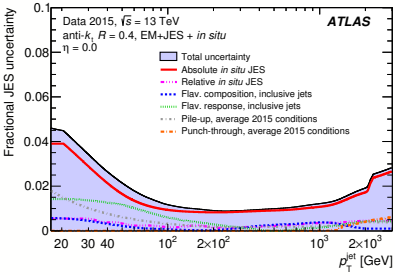
- Calorimeter jets from energy deposits
- Track jets from clusters of charged particles in the ID
- Anti-k_T, $\Delta R = 0.4$ clusterization algorithm
- Complex calibration procedure

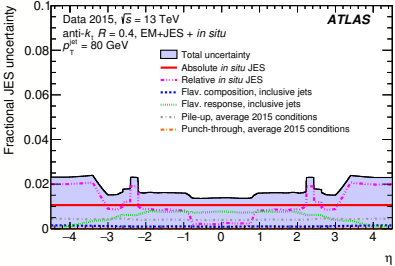
Detector calibration





η-p_T systematic uncertainties





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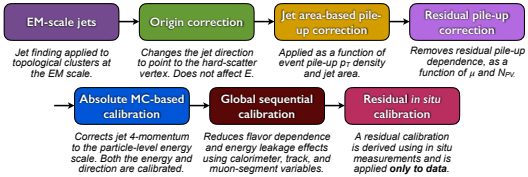
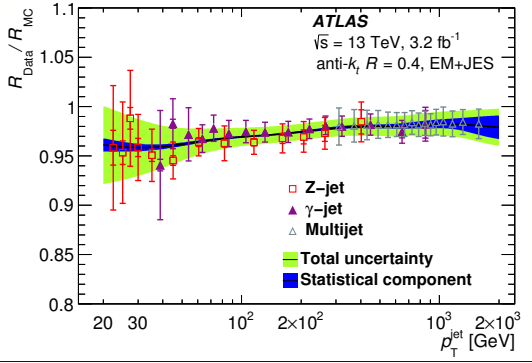
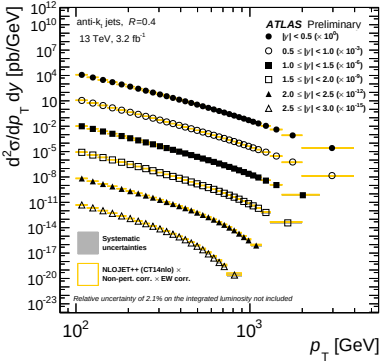
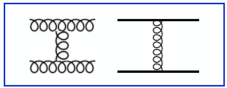


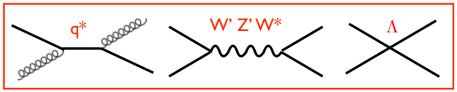


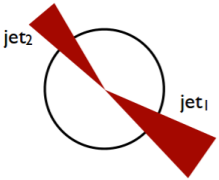
Double-differential inclusive jet cross section measurement



Search for dijet resonance







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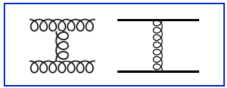

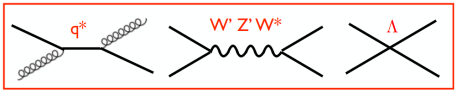

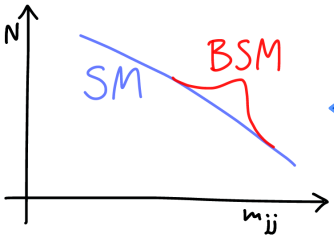

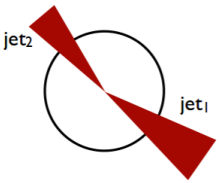

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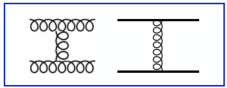

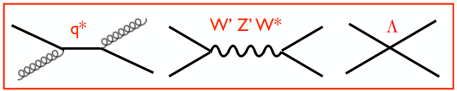

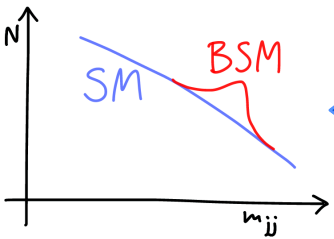

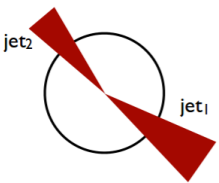

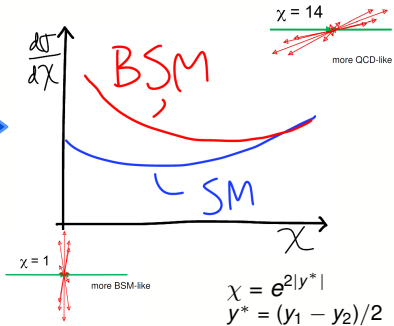

$\chi = e^{2|y^*|}$

$y^* = (y_1 - y_2)/2$

Simple event selection

- Single jet trigger - $p_T \geq 380$ GeV
- At least two jets in the event
- $p_T^{lead.(subl.)} \geq 440(50)$ GeV
- Small rapidity aperture $|y^*| < 0.6$
- Dijet invariant mass: $m_{jj} \geq 1.1$ TeV

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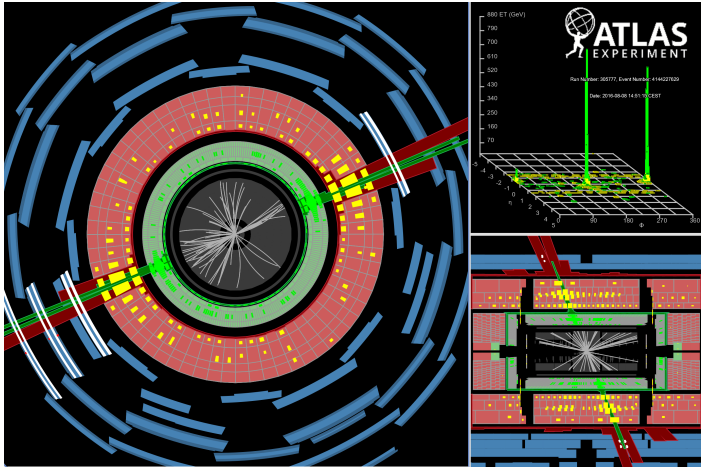

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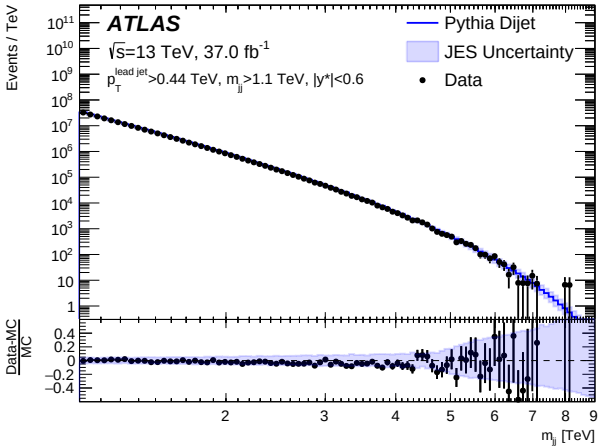
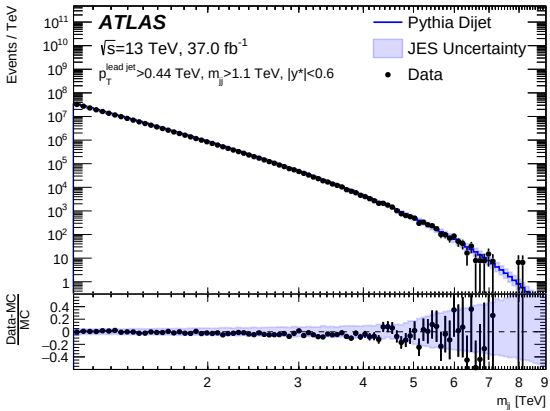


Background estimation



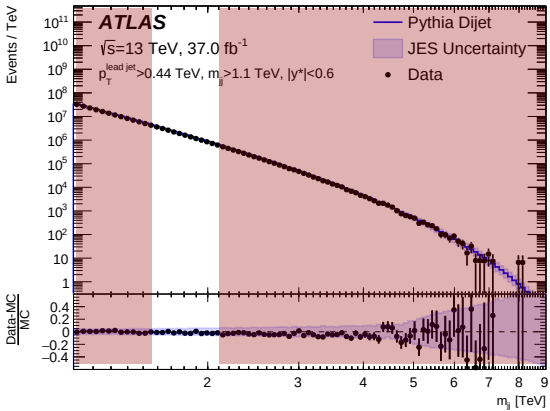
Fit a smoothly falling background with an analytical function to search for bumps

$$f(z) = p_1(1-z)^{p_2} z^{p_3 + p_4 \ln z} \qquad z = m_{jj}/\sqrt{s}$$

- Variable number of parameters needed
- Fit complexity increase with luminosity
  - more data - more parameters needed

Fit breaks when statistics increase!

Background estimation



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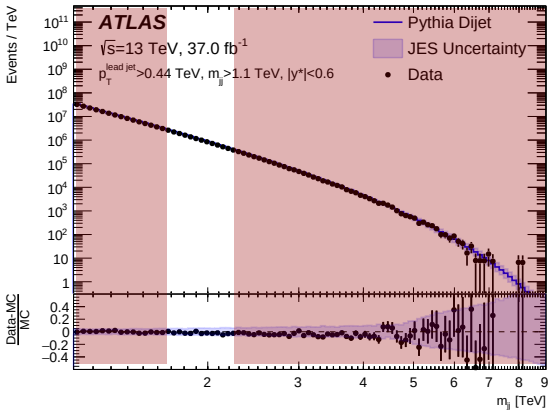
SWiFt: Sliding Window Fit

- Fit spectra in restricted regions (*window*)
- Slide the window centre bin-by-bin
- Fit with simpler function
- Extract background prediction at window center

Fit stable when increasing statistics!

Background estimation



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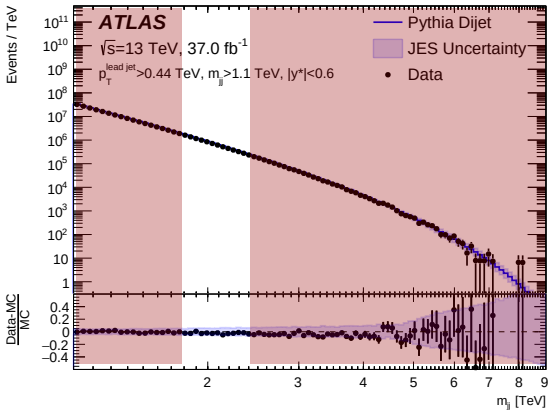

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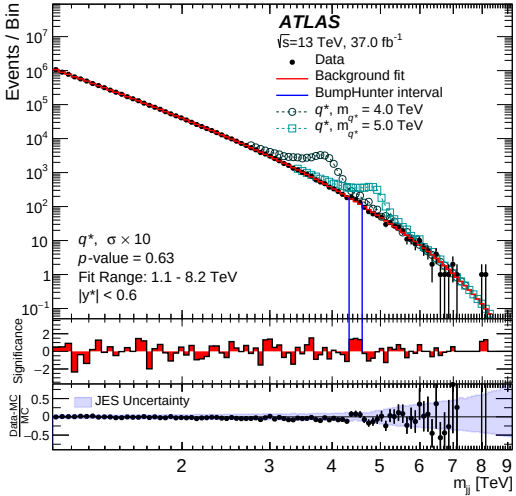
Search for a bump



BUMPHUNTER algorithm:

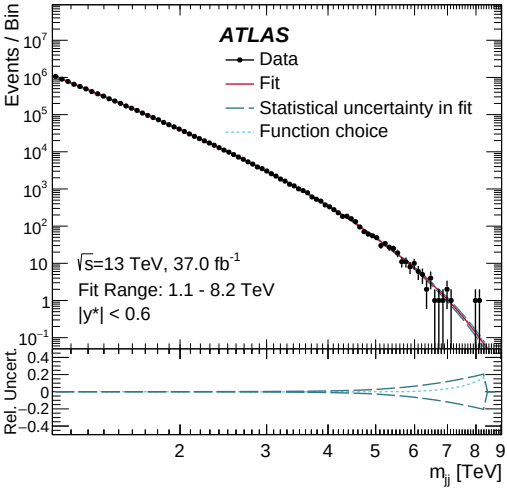
search for significant deviations with respect to background prediction

- exclude subsequent discrepant bins
- compare with background prediction

► No significant deviations with respect to SM background prediction: p-value = 0.63

► Use data to exclude New Physics contributions

Background prediction uncertainties



BUMPHUNTER algorithm:

search for significant deviations with respect to background prediction

- exclude subsequent discrepant bins
- compare with background prediction

► No significant deviations with respect to SM background prediction: p-value = 0.63

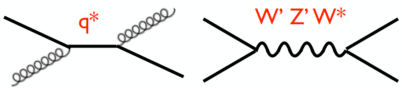
► Use data to exclude New Physics contributions

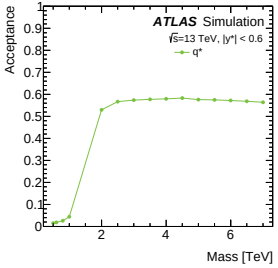
- Systematic uncertainties on fitted background
  - Fit parameter statistical uncertainties
  - Alternative fit function choice

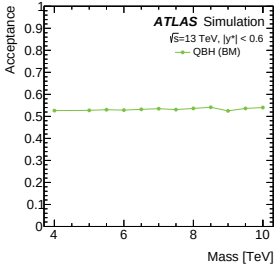
Benchmark signals

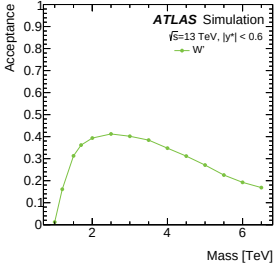
different benchmark signals
⇕
different shapes,
different acceptances

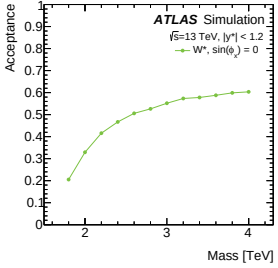
- Excited quarks : q^*
- Extra gauge bosons: Z', W', W^*
- Quantum Black Holes from ADD models







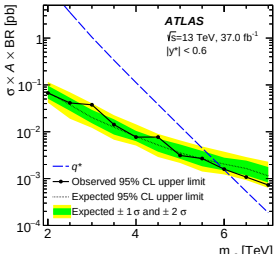


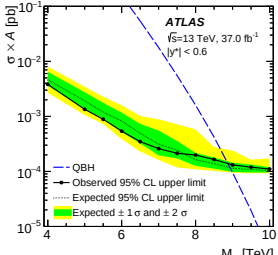


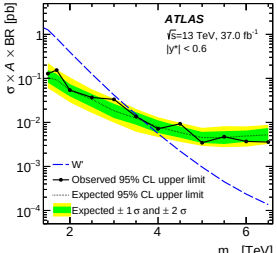
Limit extraction

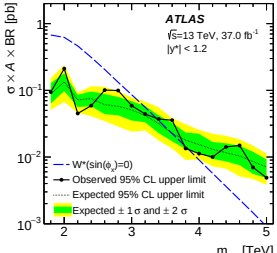
95% CL upper limit based on the full 2015+2016 collected dataset, 37 fb^{-1}

Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV









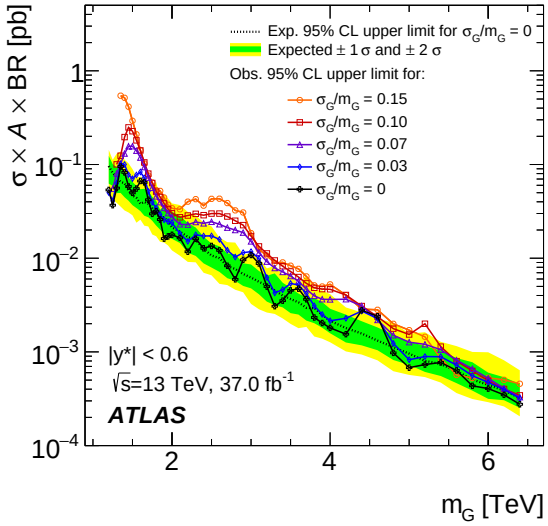
Generic signal interpretation

Jet energy folding

- Factorize detector effect on jet energy from the resonance intrinsic width
- Information provided at particle level

Generic gaussian signal

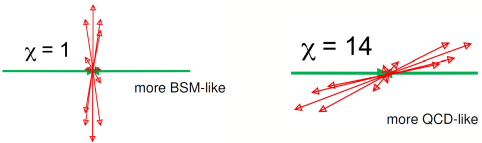
- Set limit on gaussian signal shape
- Useful for phenomenological reinterpretation of the results



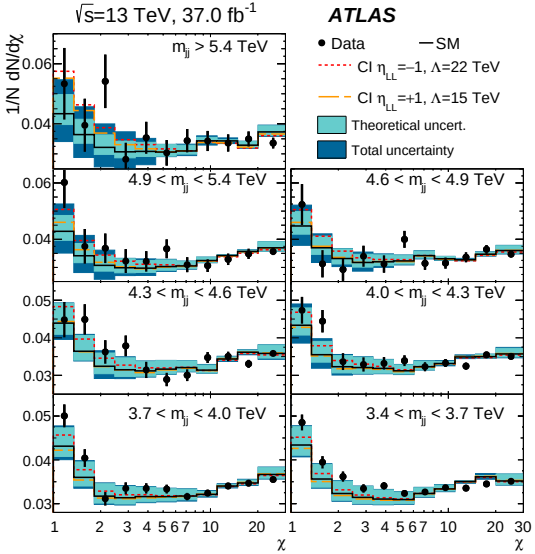
Dijet angular correlation

Explore dijet angular separation

$$\chi = e^{2|y^*|} \qquad |y^*| < 1.7 \qquad \frac{|y_1 + y_2|}{2} < 1.1$$



- Background prediction from MC simulation
  - include NLO QCD corrections
  - include LO EW corrections
- Theoretical uncertainties: pdf, factorization and renormalization scales
- Dominant experimental uncertainties: jet energy reconstruction (scale)



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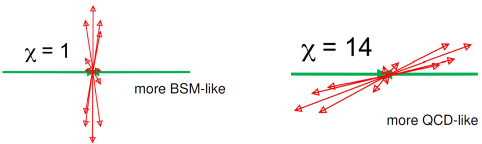

- Background prediction from MC simulation
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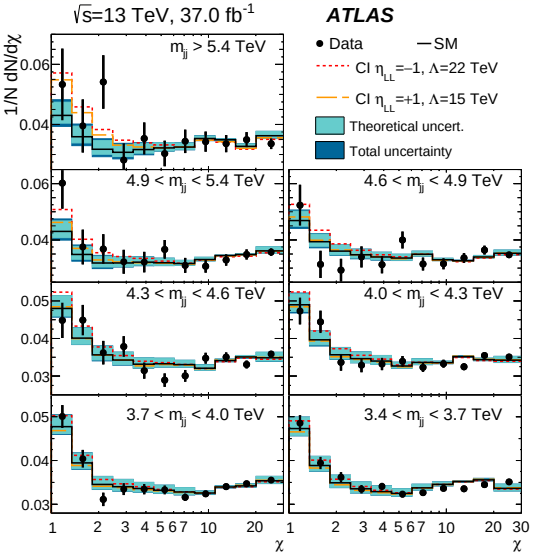
  - include LO EW corrections
- Theoretical uncertainties: pdf, factorization and renormalization scales
- Dominant experimental uncertainties: jet energy reconstruction (scale)
- Combined fit in different m_{jj} regions
  - constrain theo. and exp. uncertainties

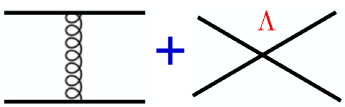


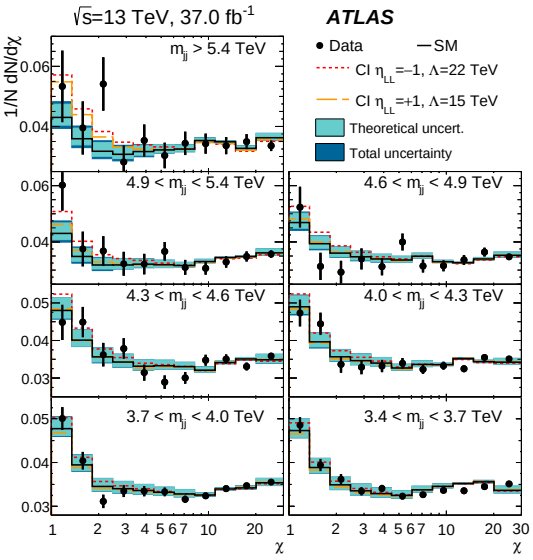
Dijet angular correlation

Contact Interaction contribution expected to modify χ distribution

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

- LL scenario as benchmark
- constructive/destructive interference with SM considered





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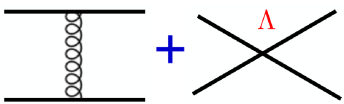
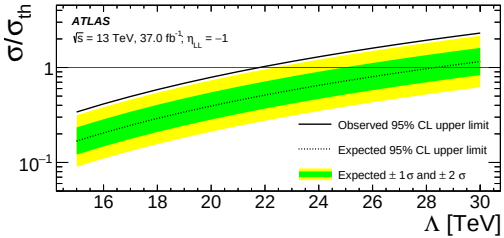
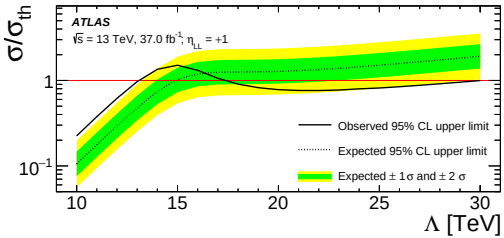


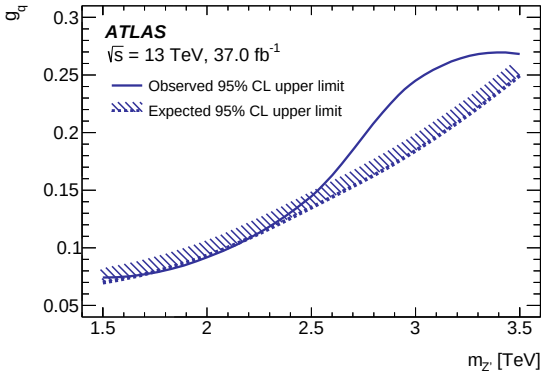
New physics scales Λ probed up to ∼30 TeV





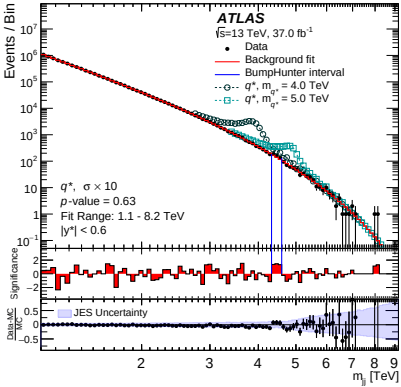
Dark Matter candidate model

- Standard Model U(1) extension:
  - leptophobic additional Z' boson
- Z' coupling to SM quarks determines its width
- Simple scenario for Dark Matter models (see next.)
- Constraint on the model on $m_{Z'}$ vs. g_q plane



► What happens at lower masses?

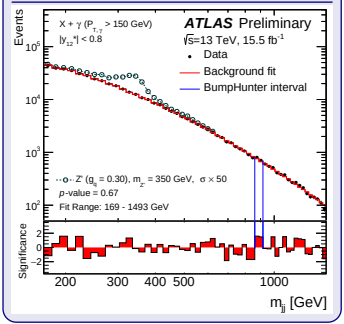
Complementary dijet searches

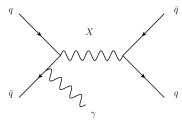


- What happens at lower masses?

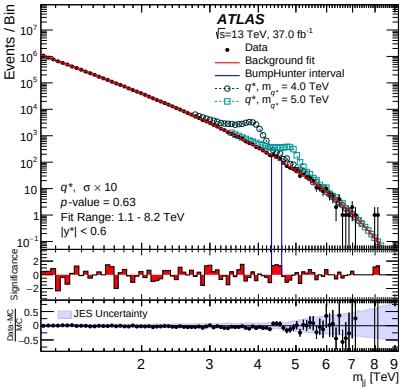
Complementary dijet searches

dijet + γ





Select events with an additional high-$p_T\gamma(g)$ from ISR



Complementary dijet searches

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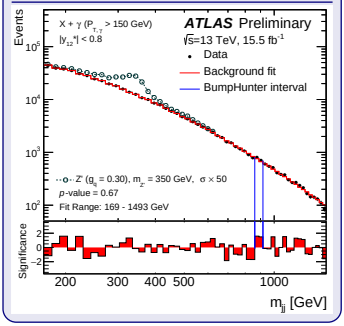

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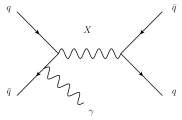
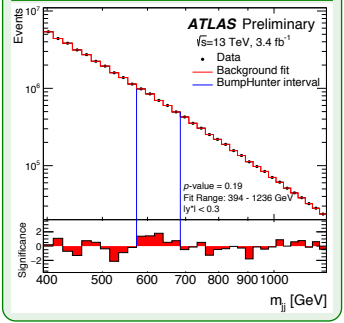
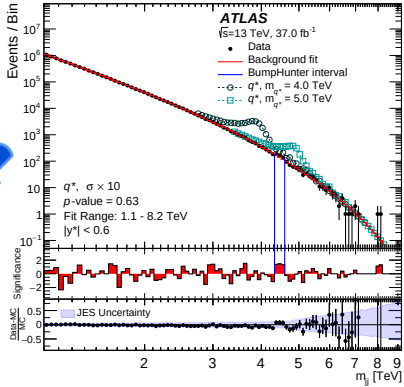


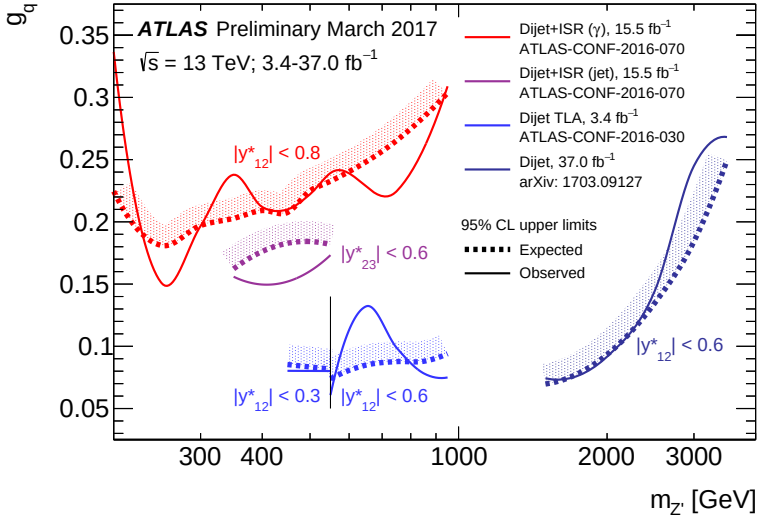
Trigger Level Analysis



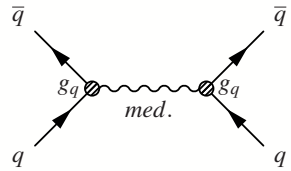


Dedicated trigger stream with partial event reconstruction (jet only)

Z' combined interpretation



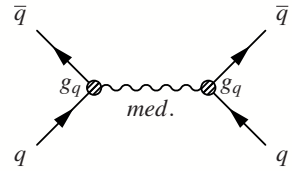
- Why Z' extension is good for Dark Matter?

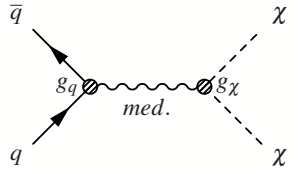


$$\mathcal{L}_{\mathcal{AV}} = g_q \sum_{q=u,d,c,s,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q$$

- Extend the SM with an axial-vector mediator Z' [U(1)-like]

▶ Why Z' extension is good for Dark Matter? A good simplified model

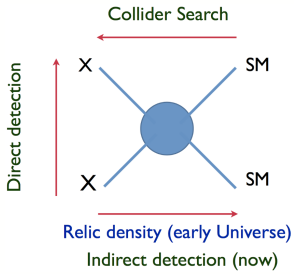




$$\mathcal{L}_{\mathcal{AV}} = g_q \sum_{q=u,d,c,s,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma^5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$$

4 pars : $[g_q, g_\chi, m_\chi, M_{med}]$

- Extend the SM with an axial-vector mediator Z' [U(1)-like]
- Add a Dirac fermion WIMP candidate (χ)
- couple Z' to χ
- This is a simple model, different ones can be considered
  - details in 1507.00966[hep-ex] and 1503.05916[hep-ph]



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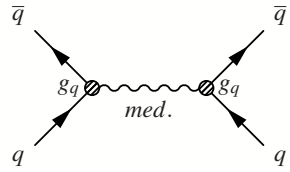

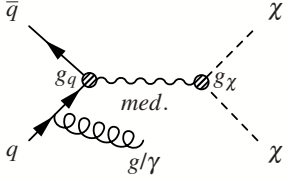

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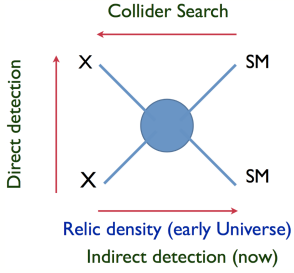
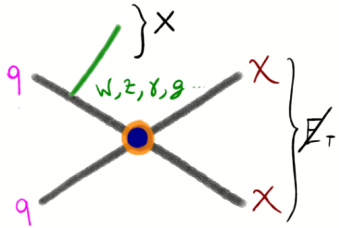
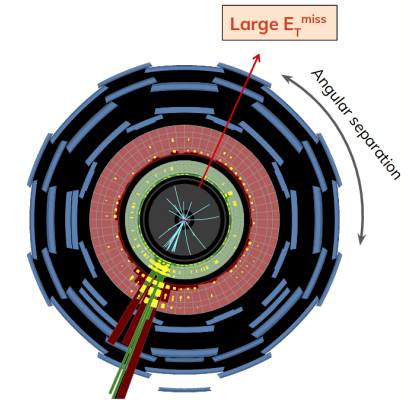


Search for what you don't see: mono-X

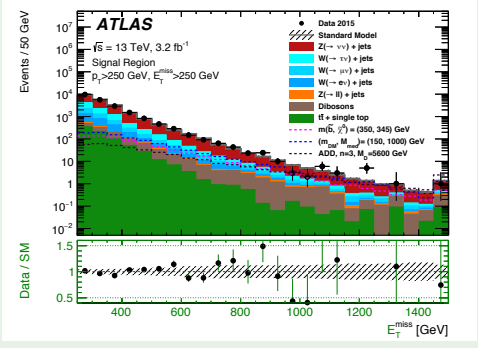


- Weakly Interactive Massive Particle (χ) invisible in the detector
- Production of large unbalanced energy in the transverse plane, $\not{E}_T$
- Identified the event through a recoiling object: W, Z, γ, g, b
- Peculiar back-to-back event topology



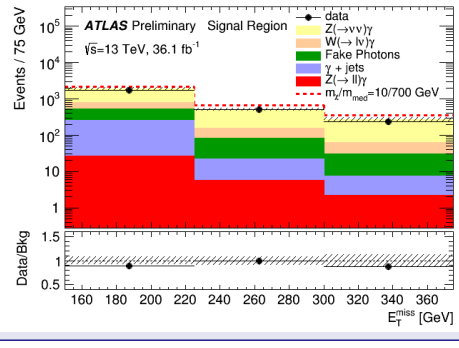
Mono-jet

- Dominant irreducible $Z \to \nu\overline{\nu}$+jets background
- Constrain subdominant background in dedicated CR
- Simultaneous fit of $\not{E}_T$distribution in signal and control regions



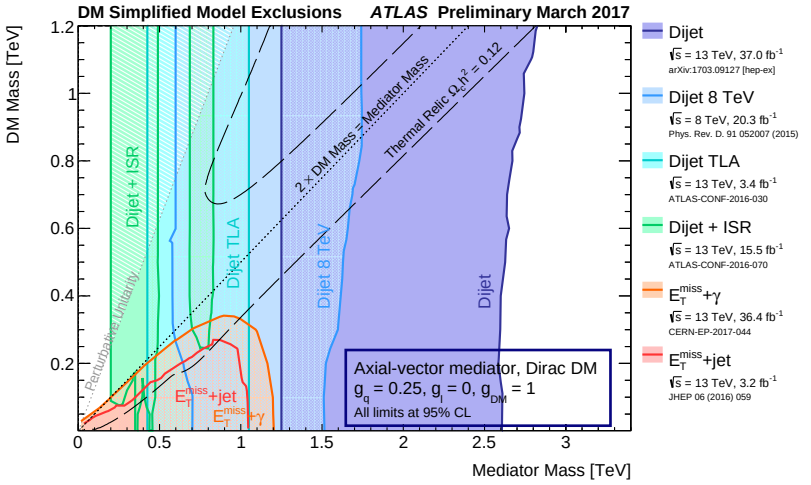
Mono-photon

- Fake photon irreducible background estimated from data
- Subdominant $Z/W/jet+\gamma$ background normalized in CR
- Non-negligible background from fake photons (jets)
- Independent background normalization in different $\not{E}_T$bins



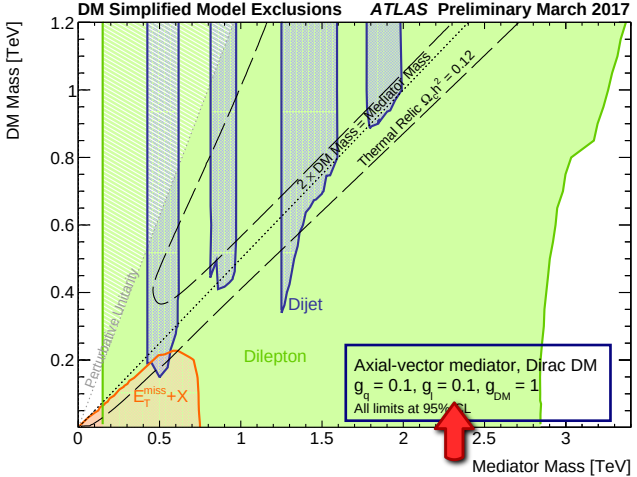
Dark Matter combined interpretation

- For relatively large coupling g_q dijet constraints are strong

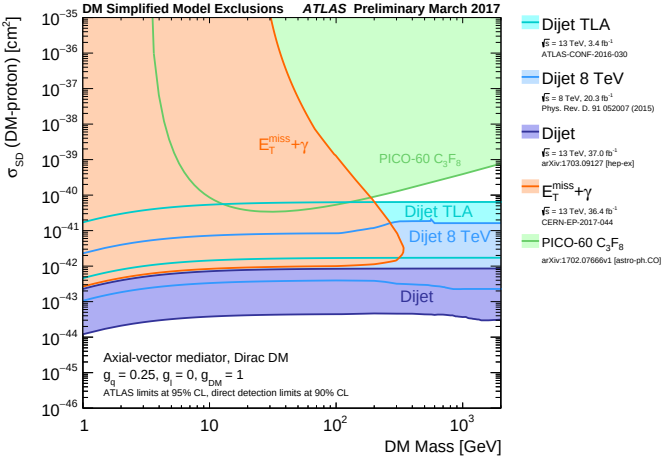


Dark Matter combined interpretation

- For relatively large coupling g_q dijet constraints are strong
- As g_q gets weaker dijet searches are complementary to mono-X
- For $g_l \neq 0$ dilepton searches largely contraint the parameter space



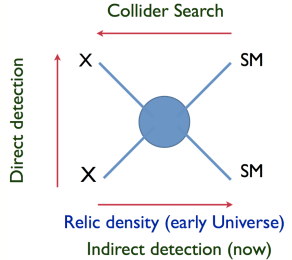
Comparison with Direct Detection



► $(m_\chi, m_{med.})$ exclusion converted into cross section limits

$$\sigma^0_{SD} = \frac{3 g^2_{DM} g^2_q (\Delta_u + \Delta_d + \Delta_s)^2 \mu^2_{n\chi}}{\pi m^4_{med.}}$$

(details in hep-ph:1407.8257)



Good sensitivity for low-mass DM candidates (i.e. <10 GeV)

Future prospects? [...]

Conclusions

BACKUP

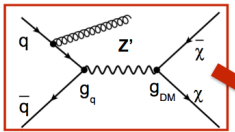
Multijet signatures, di-*b*-jets

Diphoton, γ-jet, mono-γ

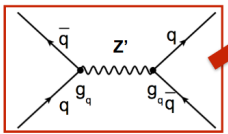
DM simplified models

- **DM simplified model** for **spin-1 mediator** is equivalent to the **leptophobic Z'** explored in **dijet searches**
- **Difference:** the addition of a **DM candidate** modifies the **total width** of the **mediator**

Monojet production



Dijet production



Mediator Width

$$\Gamma_{\mathrm{AV}}^{\mathrm{tot}} = \Gamma_{\mathrm{AV}}^{\chi\bar{\chi}} + 3 \times \sum_{q=u,d,s,c,b,t} \Gamma_{\mathrm{AV}}^{q\bar{q}}$$

$$\Gamma_{\mathrm{AV}}^{q\bar{q}} = \frac{g_q^2 M_{\mathrm{med}}}{4\pi}\left(1 - 4\frac{m_q^2}{M_{\mathrm{med}}^2}\right)^{3/2}$$

$$\Gamma_{\mathrm{AV}}^{\chi\bar{\chi}} = \frac{g_{\mathrm{DM}}^2 M_{\mathrm{med}}}{12\pi}\left(1 - 4\frac{m_{\mathrm{DM}}^2}{M_{\mathrm{med}}^2}\right)^{3/2}$$

Interesting scenarios

m_{MED} >> m_{DM}: the relative branch fraction of monojet and dijet is proportional to $N_c N_q g_{SM}^2/g_{DM}^2$

g_{SM} << g_{DM}, g_{DM} ~ 1: narrow resonance but BR monojet larger than dijet one

g_{DM} >> g_{SM}, g_{DM} > 1: resonance not narrow anymore BR monojet larger than dijet one

$2m_{DM}$ >> m_{MED}: no partial width into dark matter so the Z' model reduces to the standard one used in dijet searches