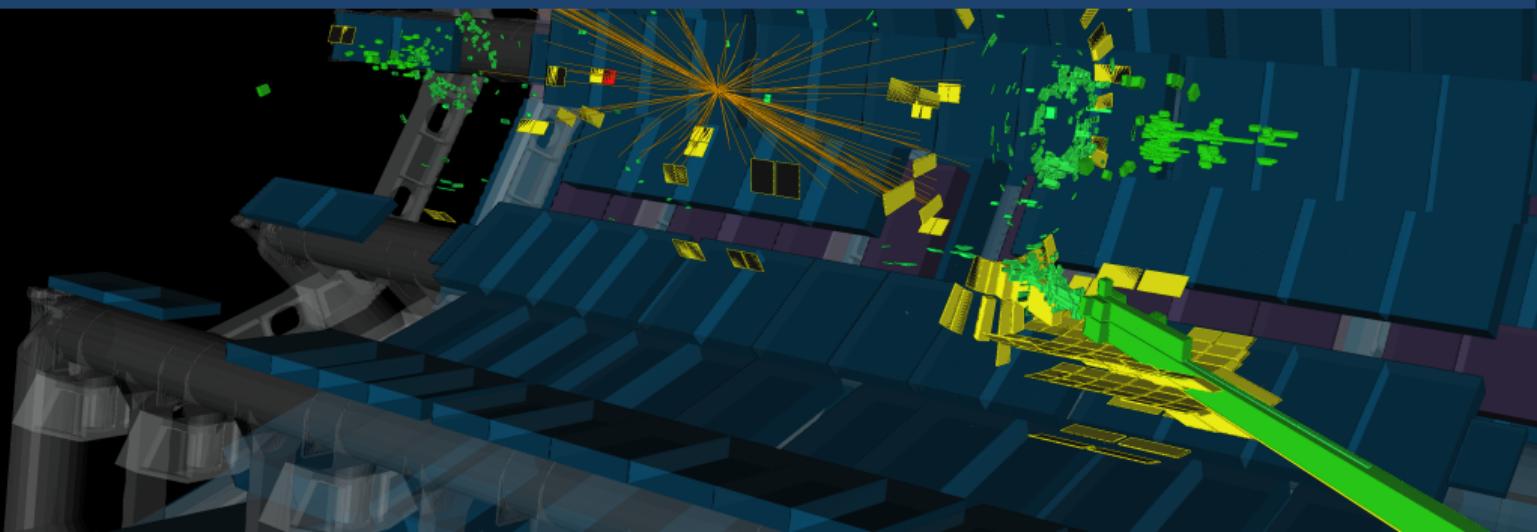
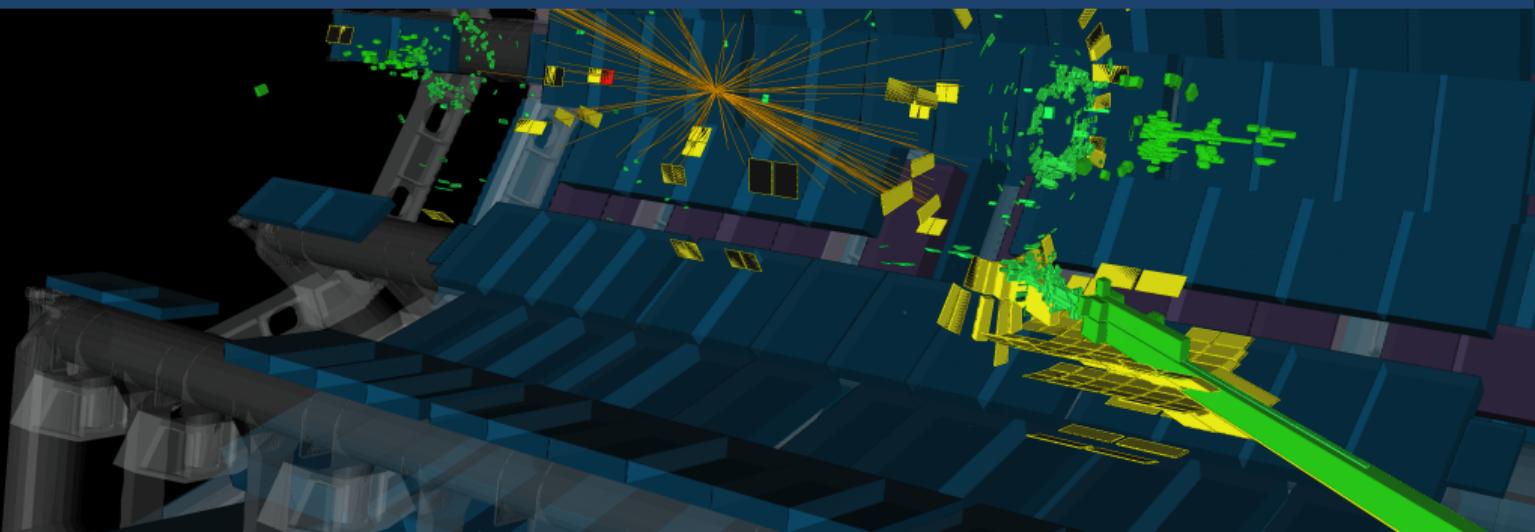


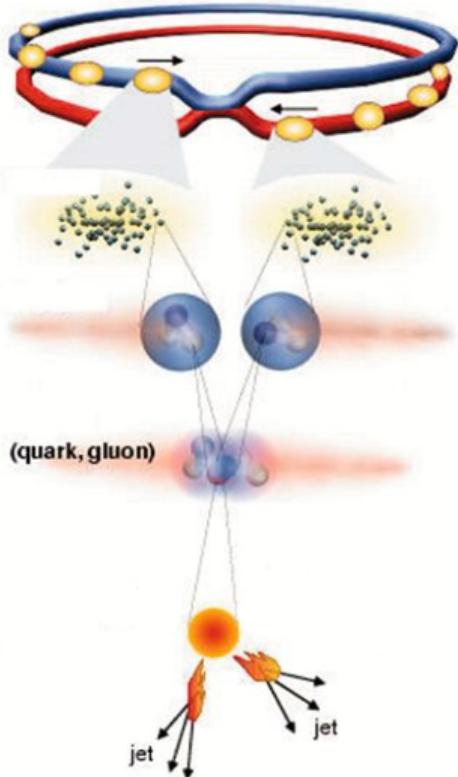
Matteo Bauce

Search for new physics in particle collisions at the ATLAS experiment



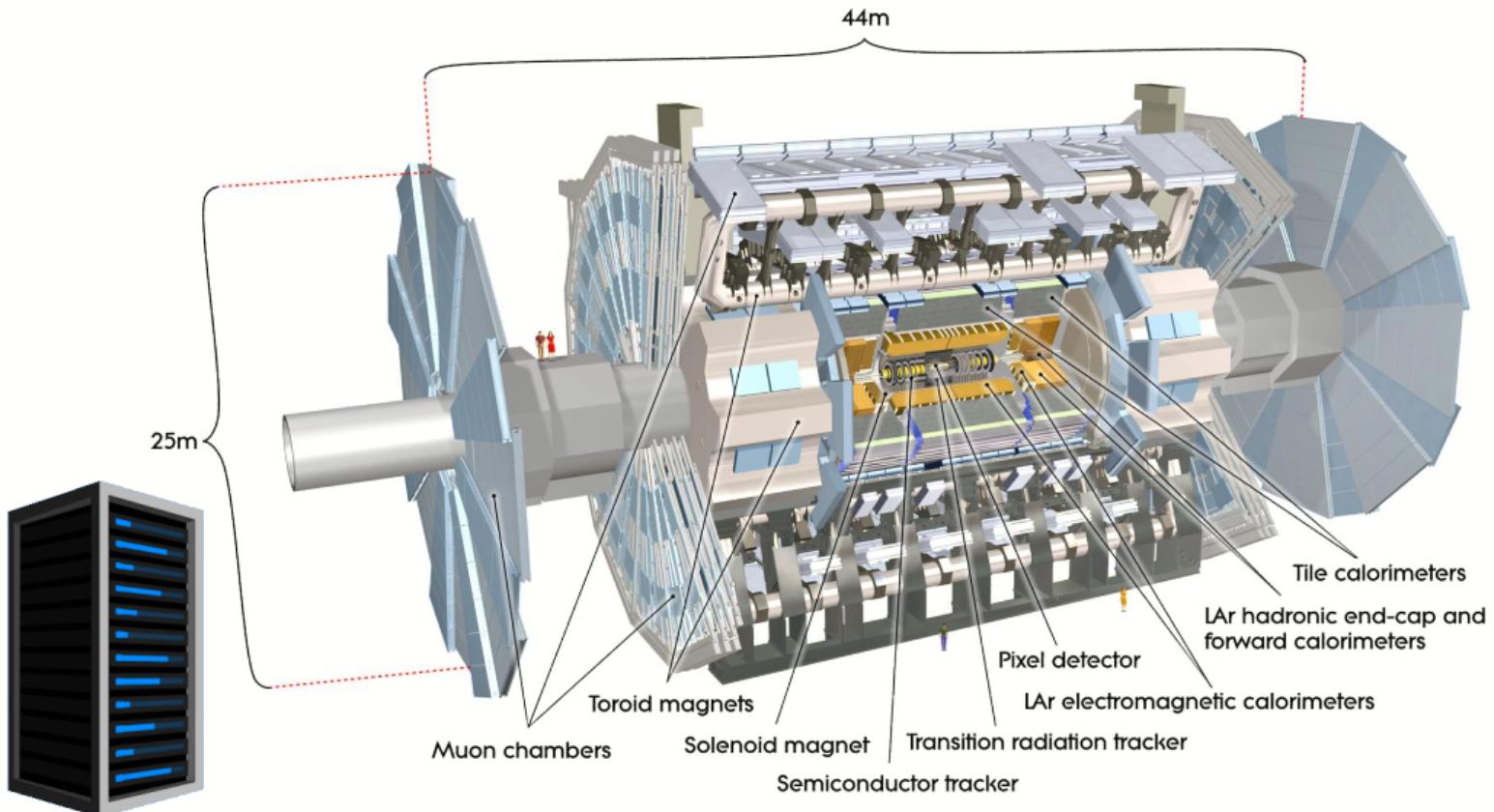
Search for new physics in *hadronic final states* at the ATLAS experiment



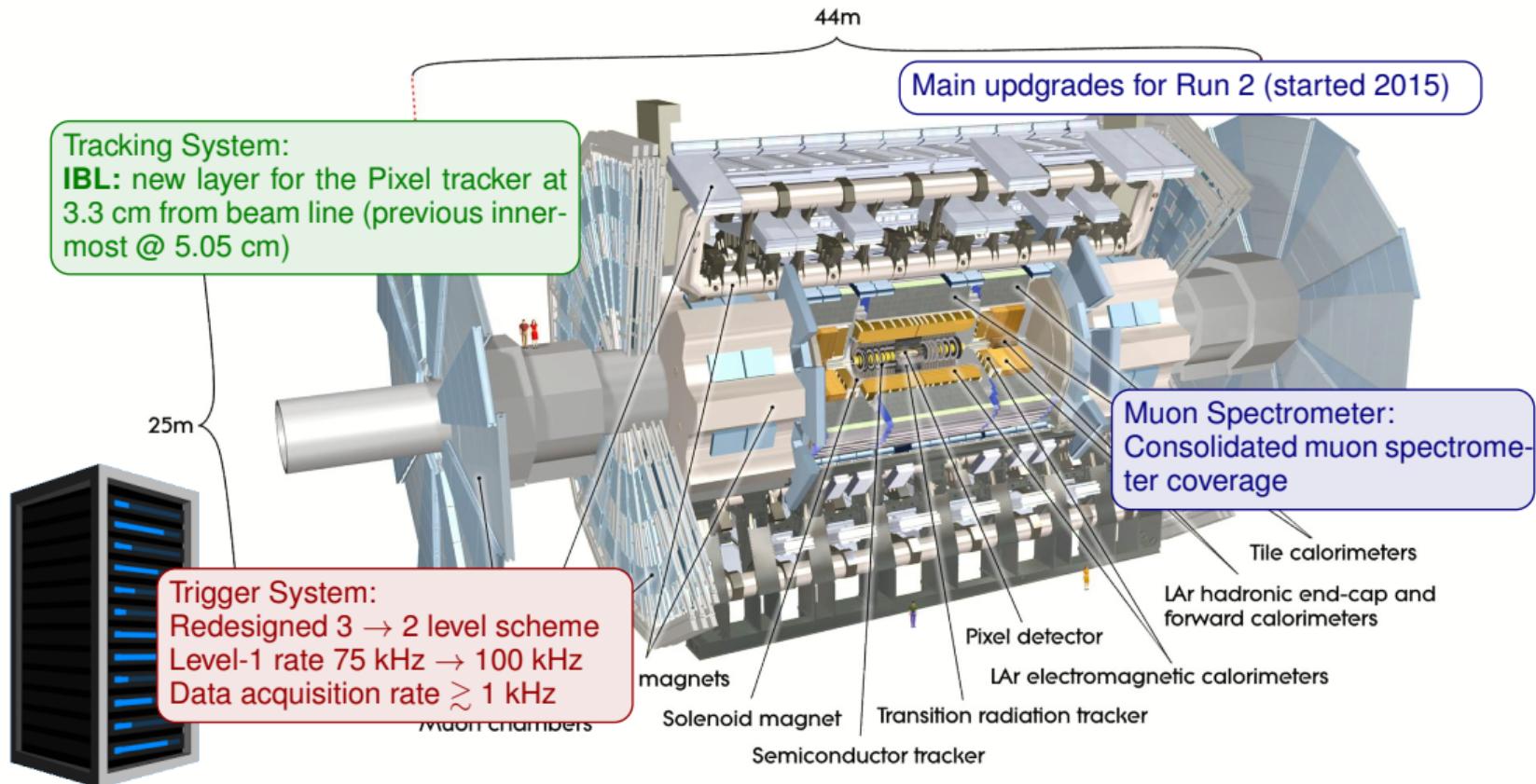


- High energy colliders are powerful tools to study particle interactions to the *hardest scales*
 - Probing smaller spatial scales and higher energy scales
 - Two-fold: test predictions and explore the unknown
- LHC is a discovery machine that can do precision physics
- $\sqrt{s} = 7$ (2010-'11), 8 (2012), 13 (since 2015) TeV
 - 40 MHz collision rate
 - Max. peak luminosity $1.4 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- The LHC Run 1 came along with a lot of precise measurements and some discoveries, the Run 2 can add new ones.

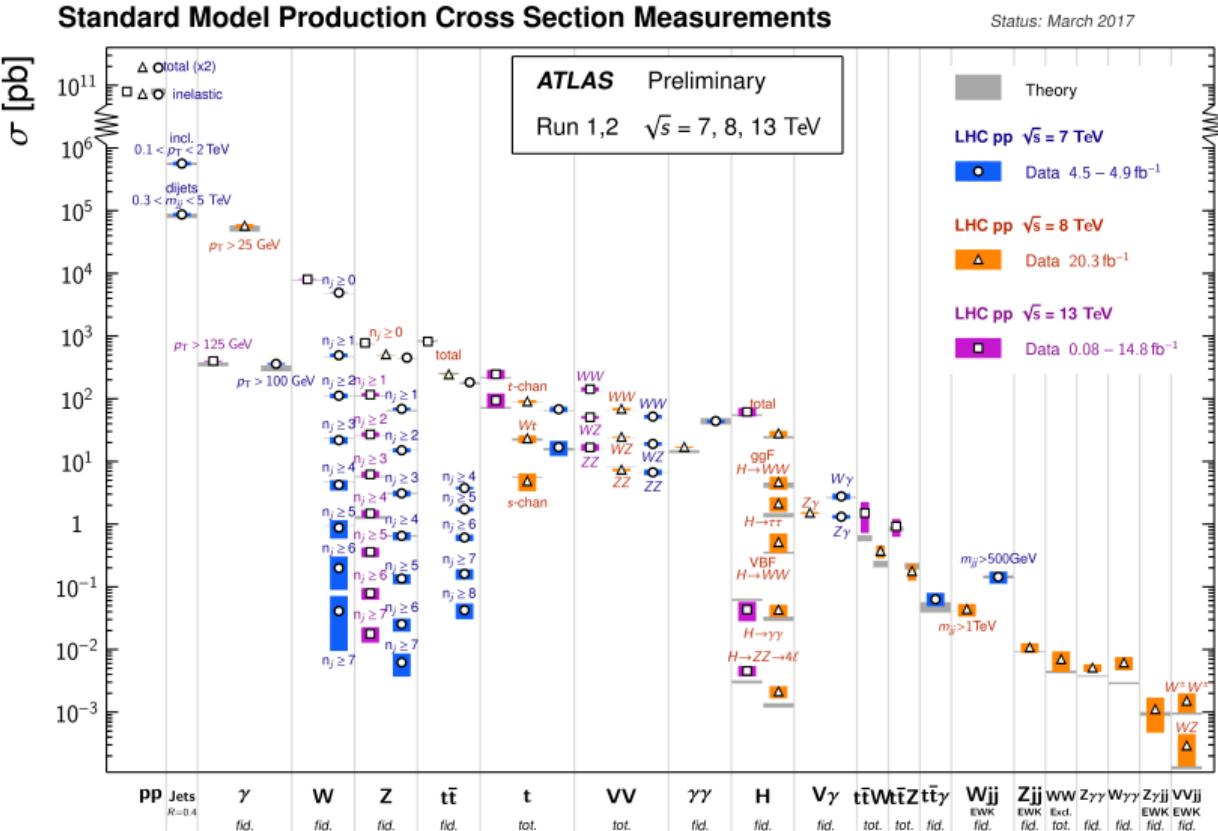
The ATLAS detector



The ATLAS detector

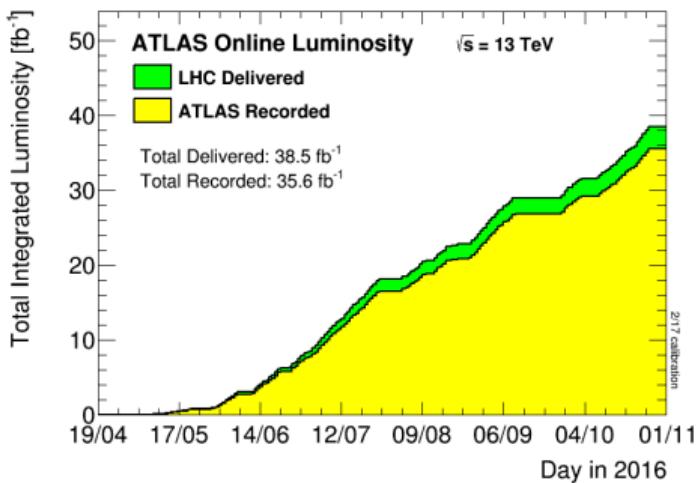


Precise SM measurements



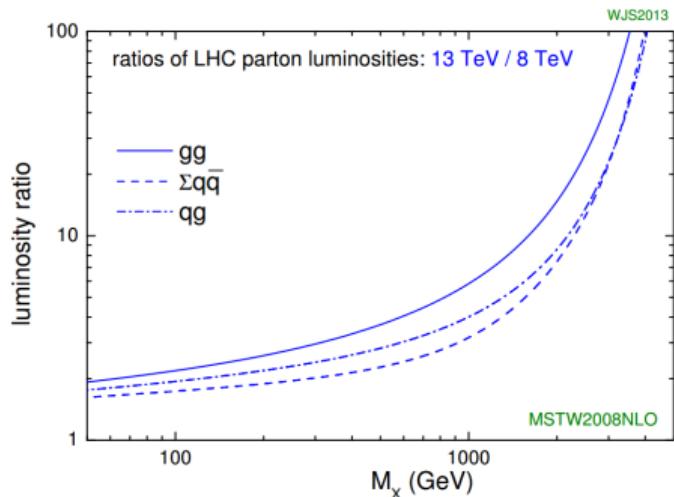
Why collecting more lumi?

- Be sensible to smaller hints of new physics
- Increase accuracy of known processes' measurements
- Improve knowledge of searches' background contribution
- Investigate anomalies and deviations with respect to theory predictions



► During Run 2 already collected more data than in Run 1

Why increasing energy?



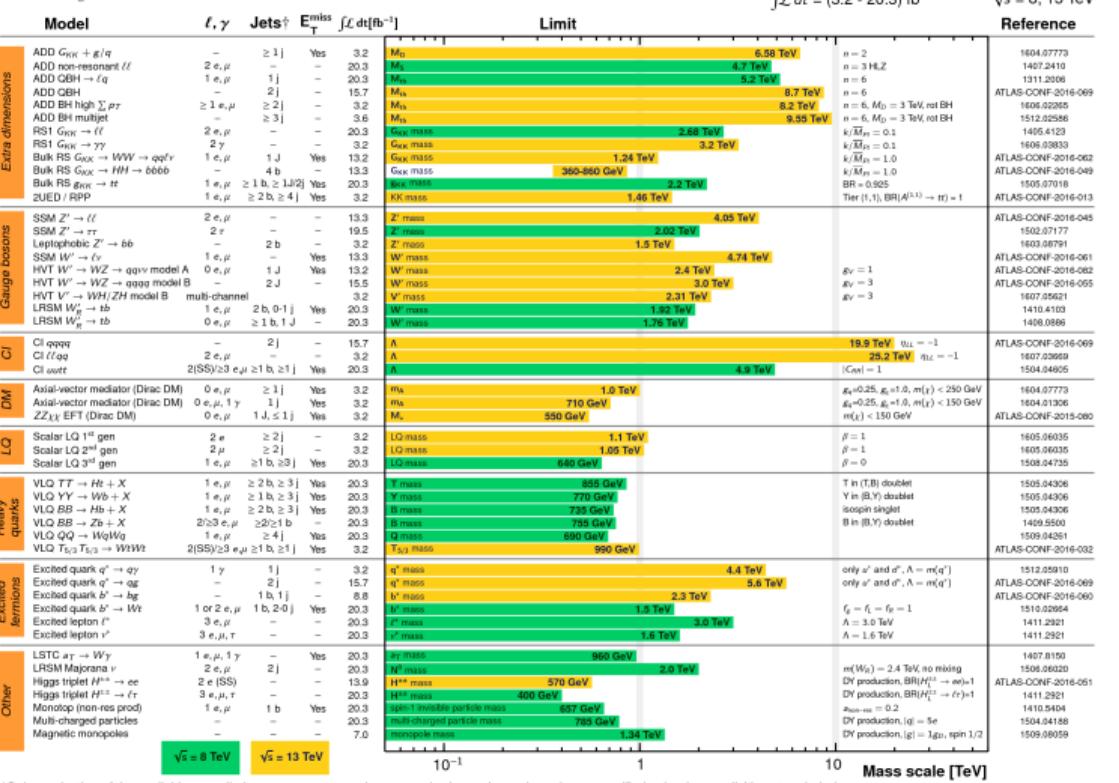
- Since 2015 LHC restarted at a new center-of-mass energy: 13 TeV
- New phase-space accessible
- Larger cross section for high-mass particle production
- Signal/Background cross section ratio increased for many searches for new physics

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

What to look for?

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016



*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.

- Simple signatures:
model independent, fast searches, start of a run
- Complex signatures:
model specific, need more statistics

What to look for?

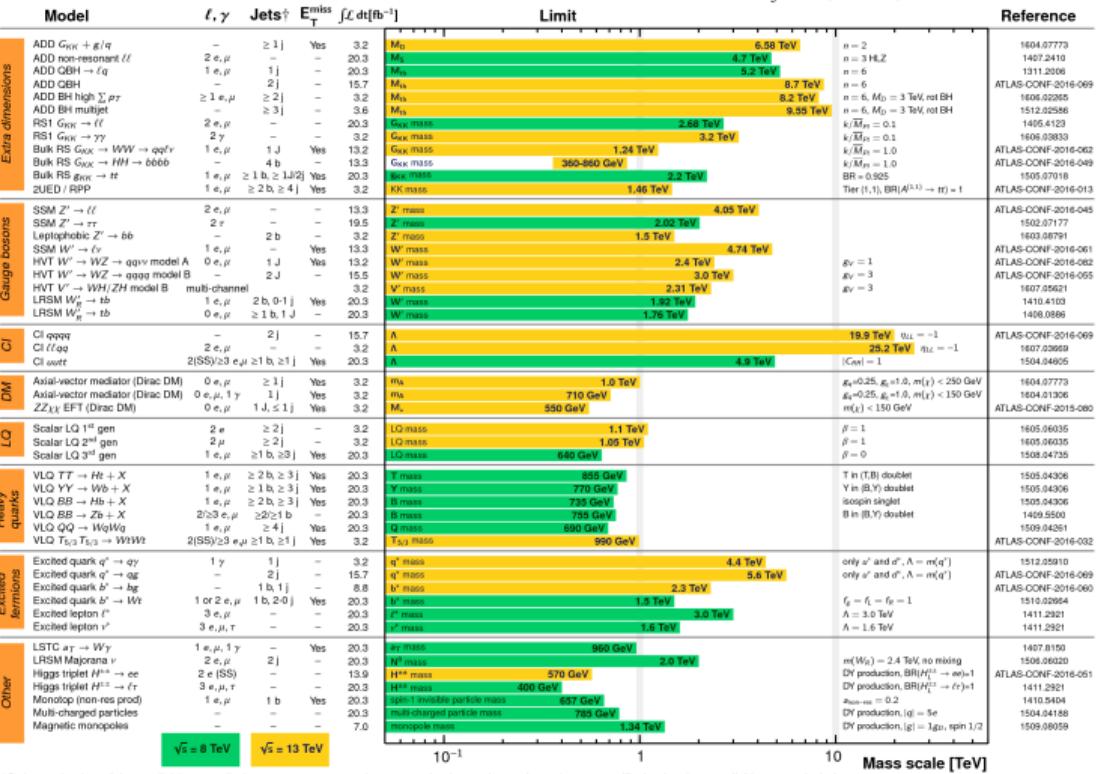
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\sqrt{s} = 8, 13 \text{ TeV}$

$$\int \mathcal{L} dt = (3.2 - 20.3) \text{ fb}^{-1}$$



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

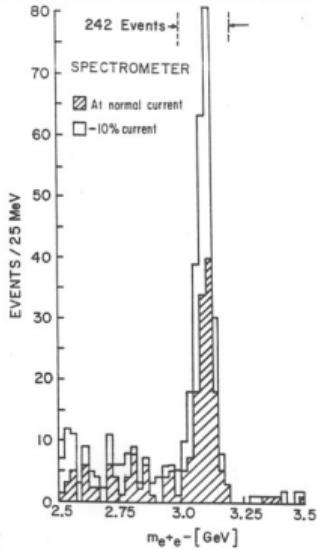
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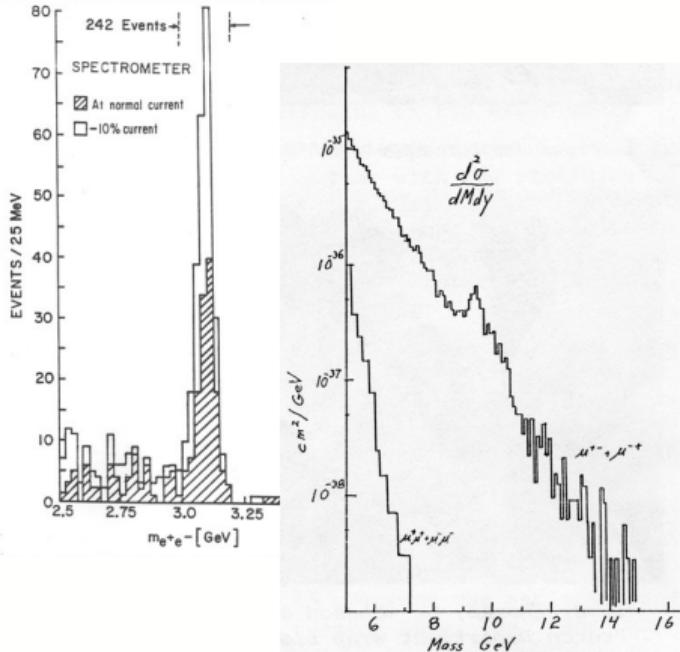
Expect the unexpected



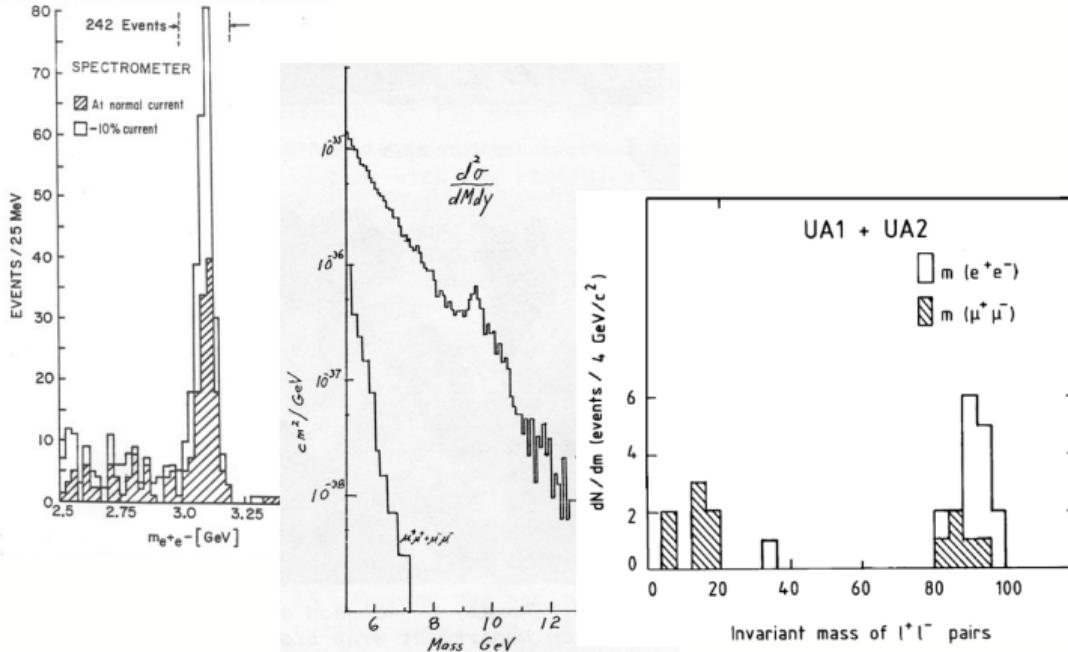
New physics hints: notable signatures



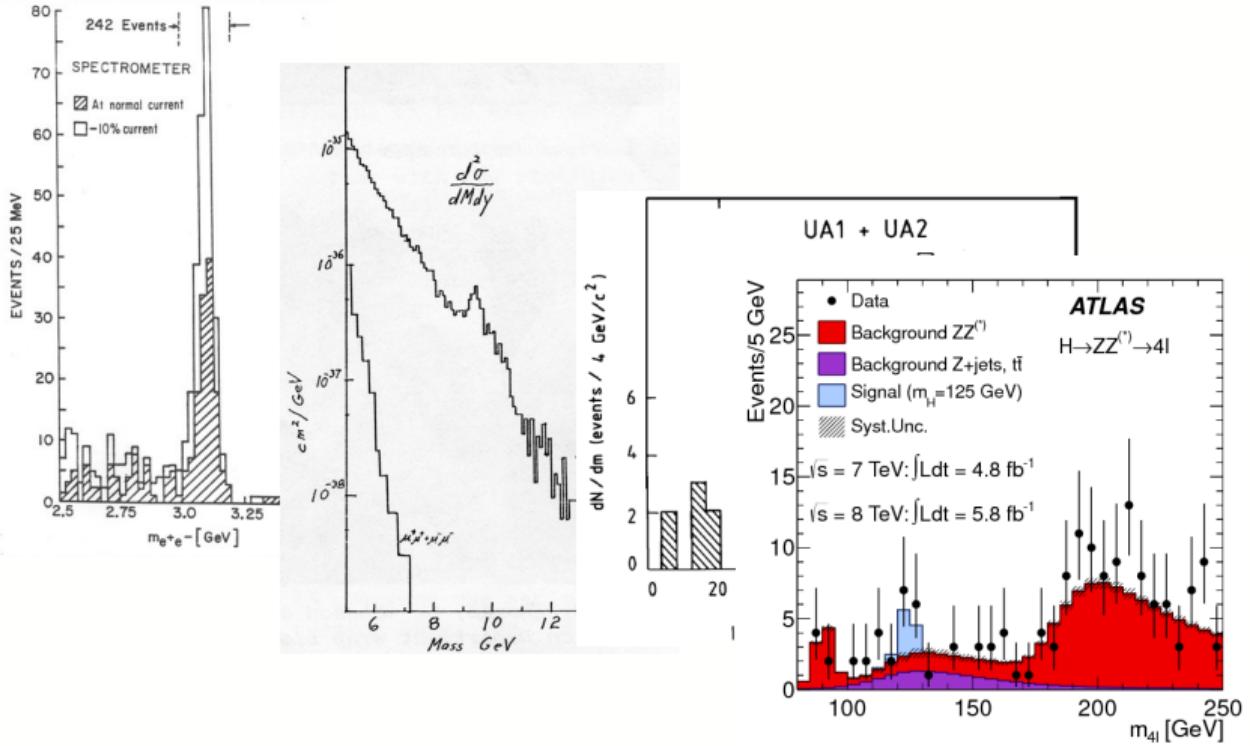
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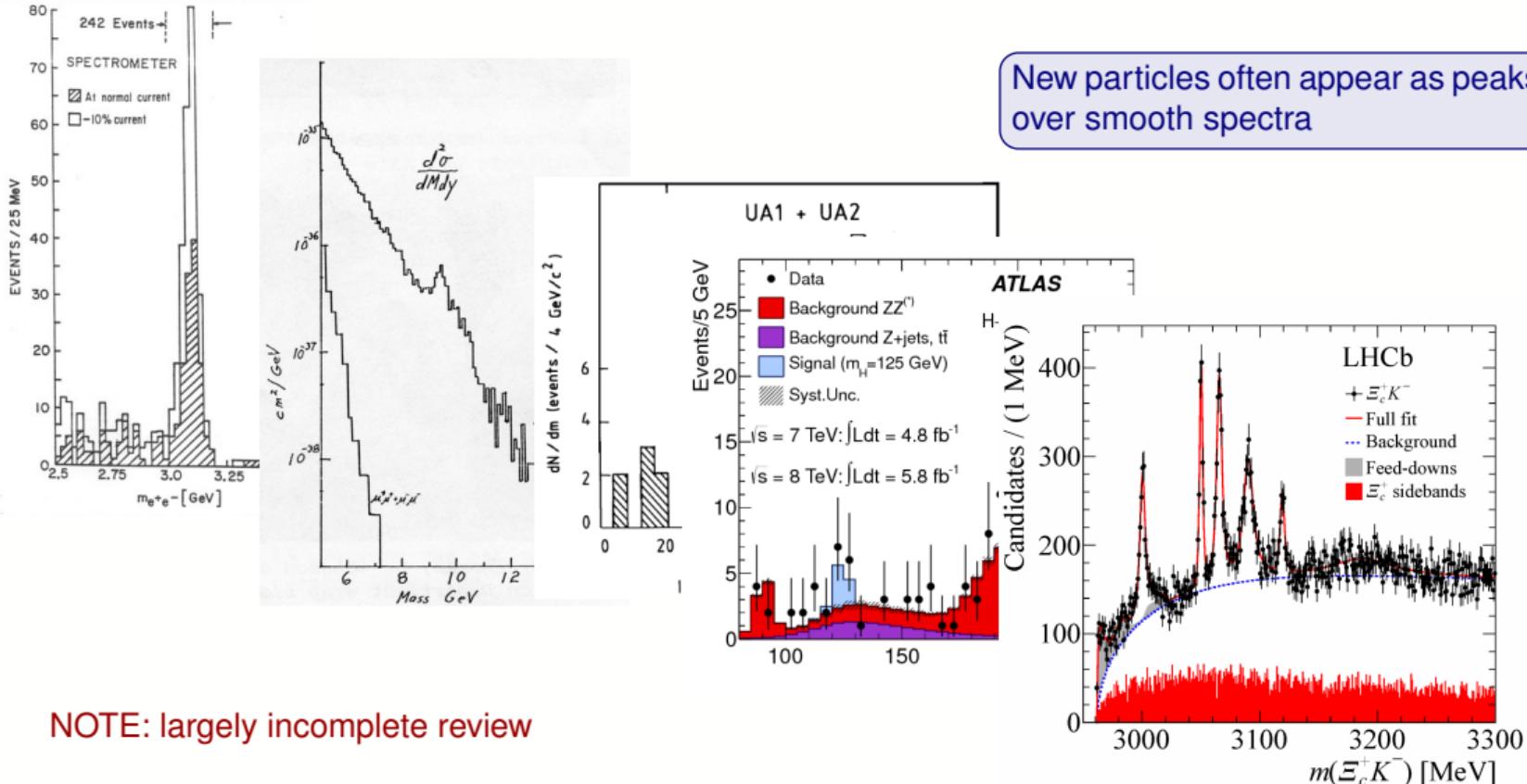
New physics hints: notable signatures



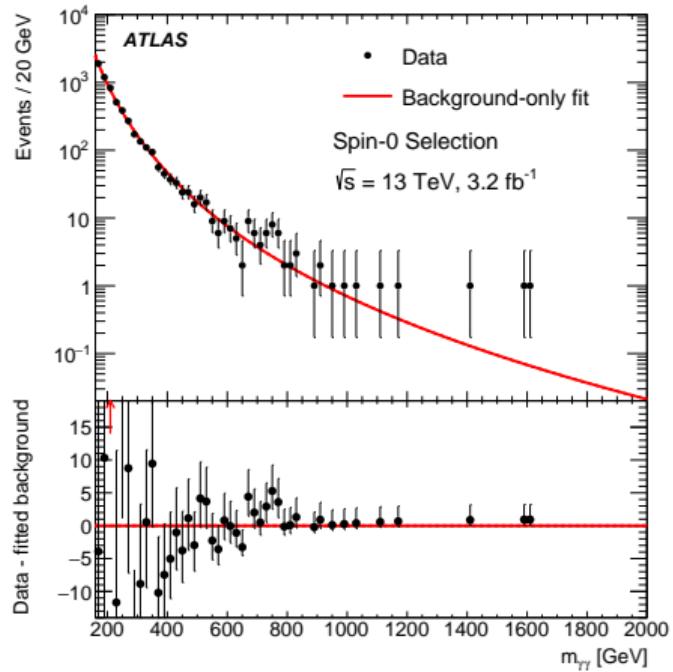
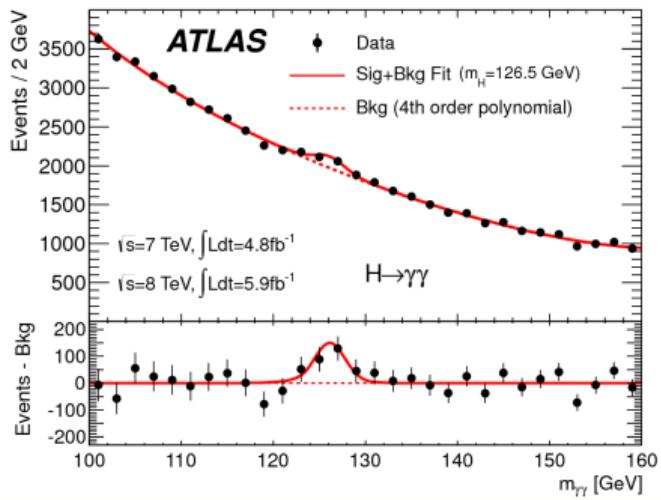
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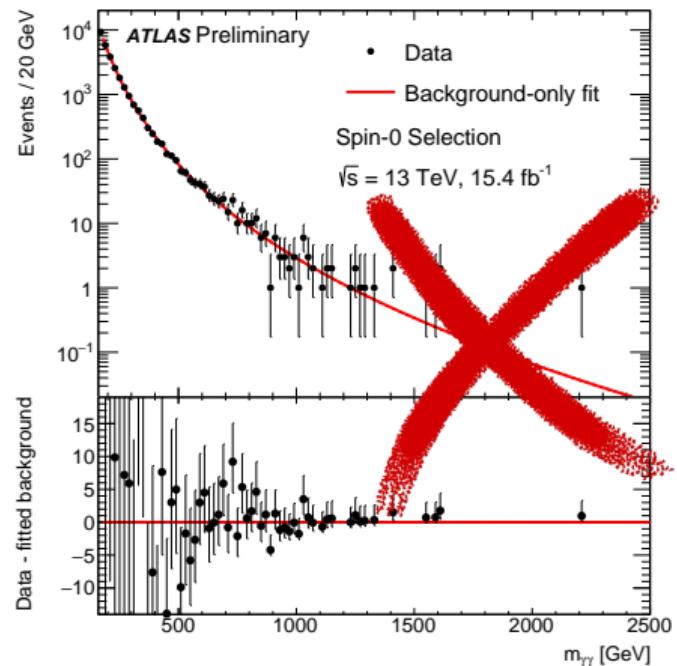
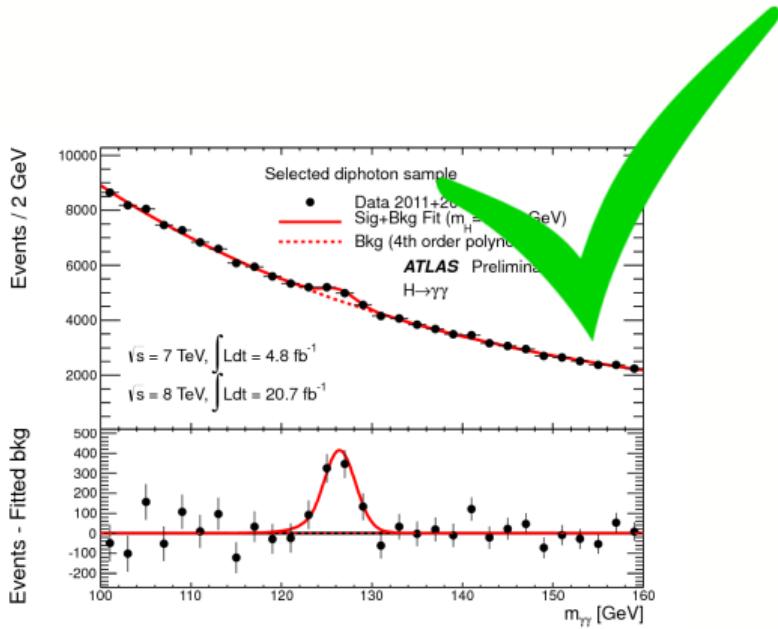
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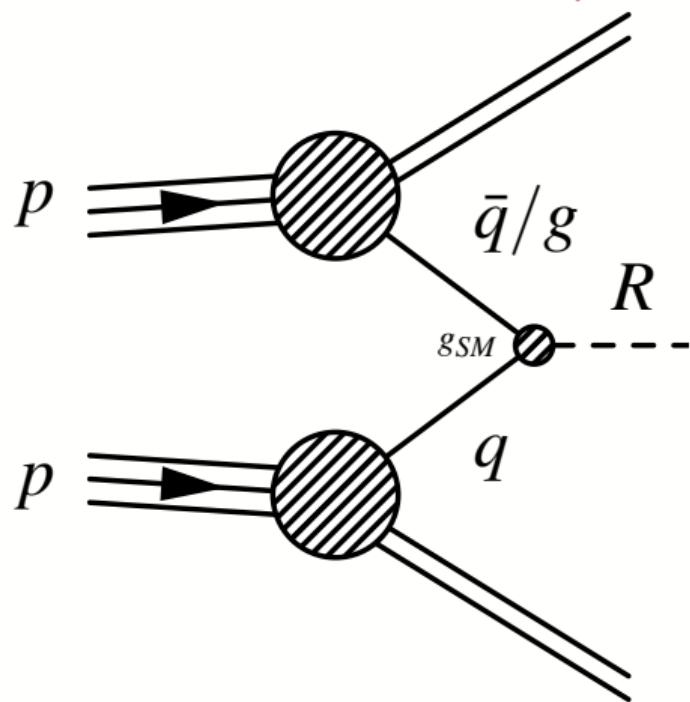
Is it that simple?

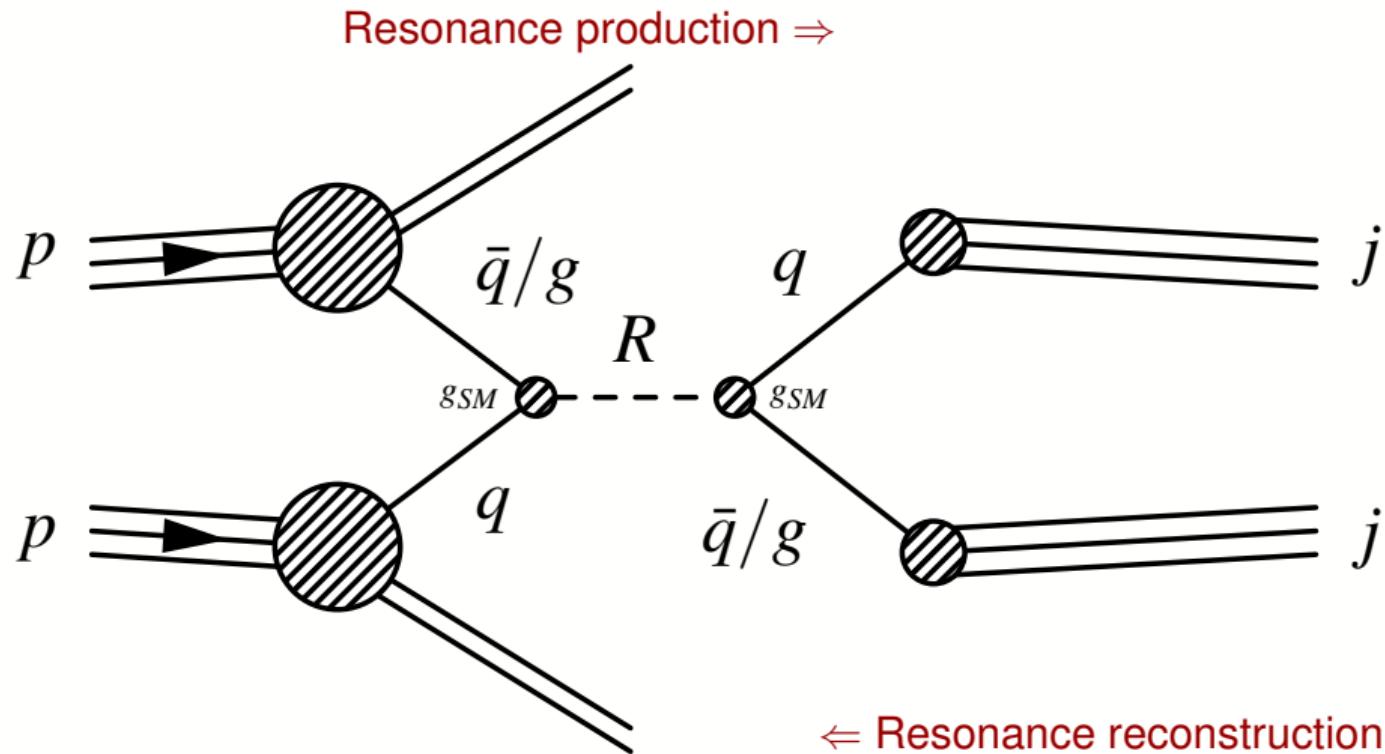


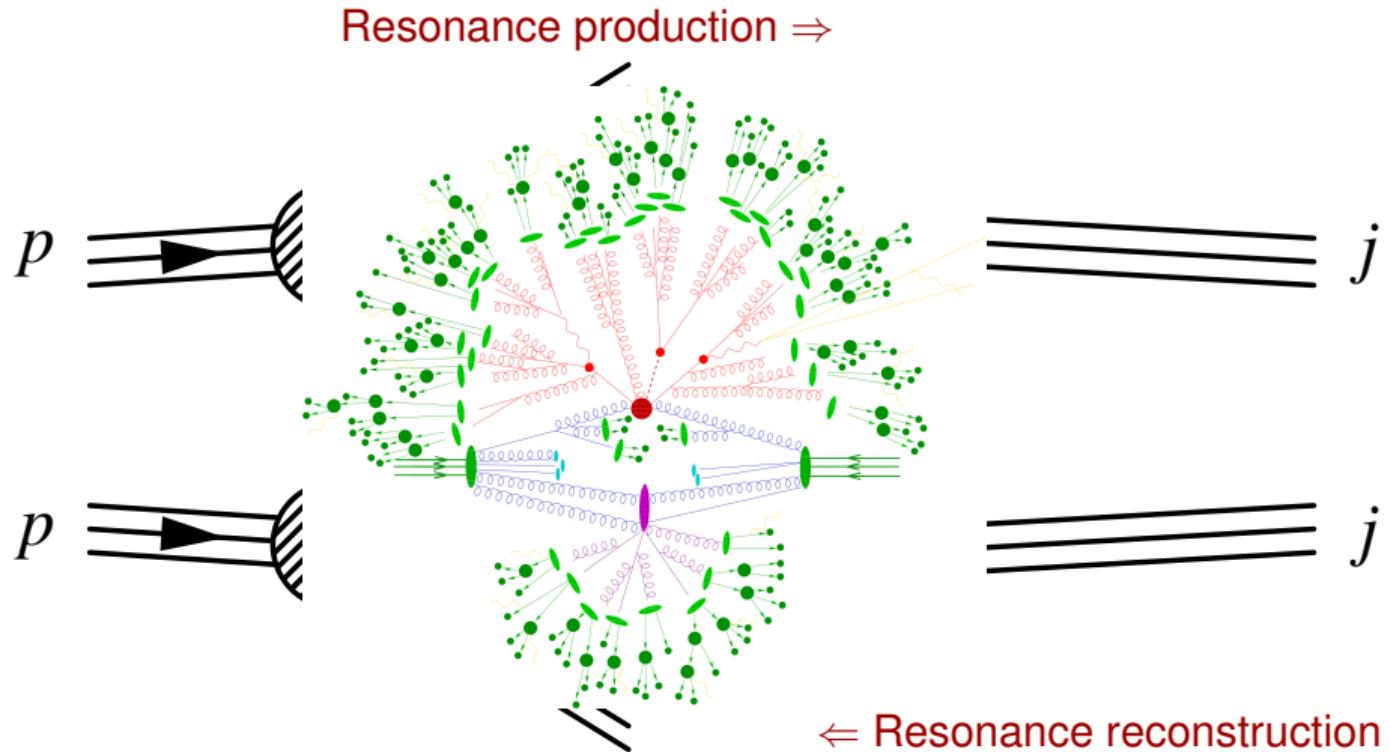
Is it that simple? No, it's not

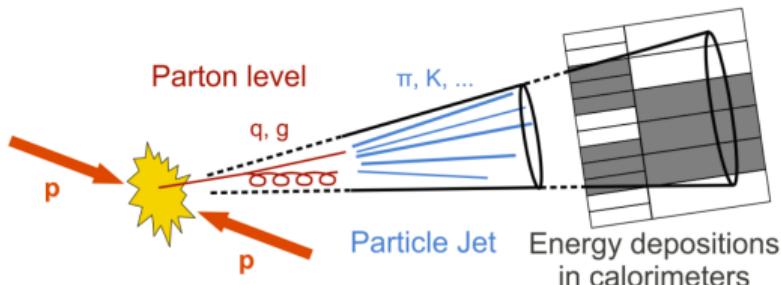


Resonance production \Rightarrow

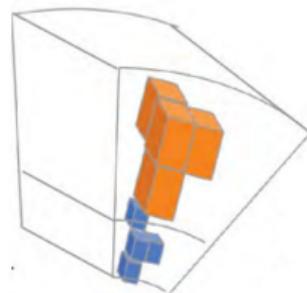






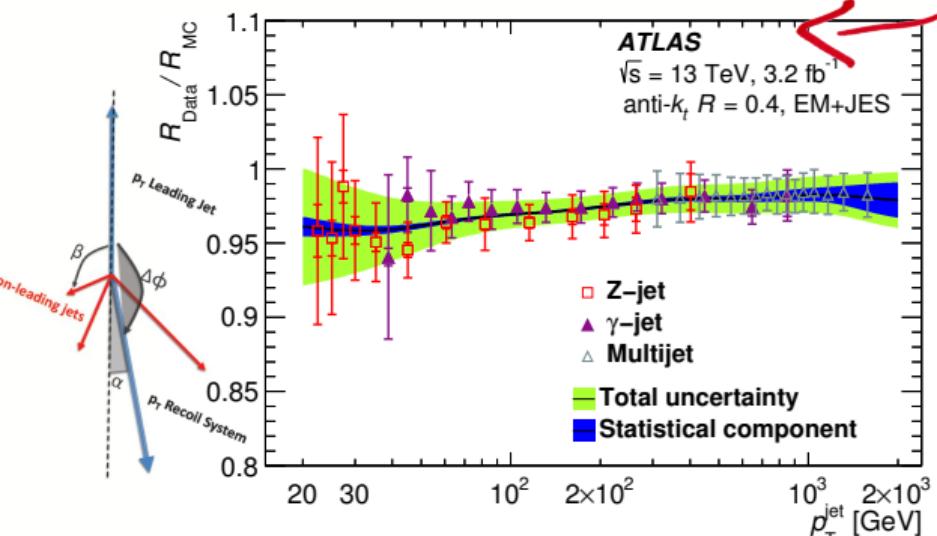
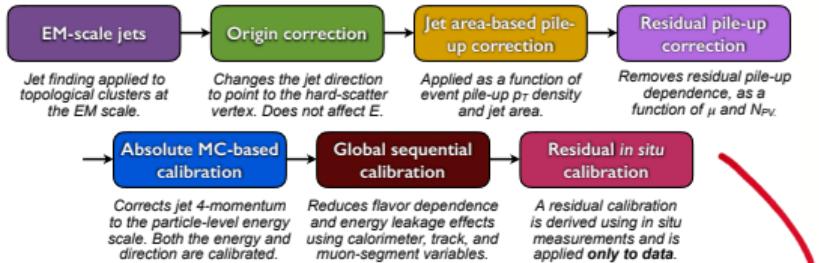


Topological Clusters

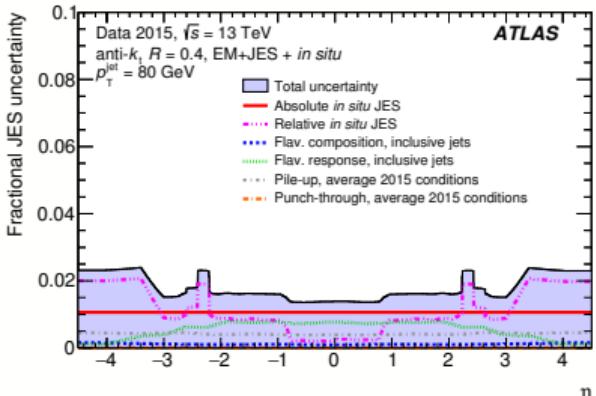
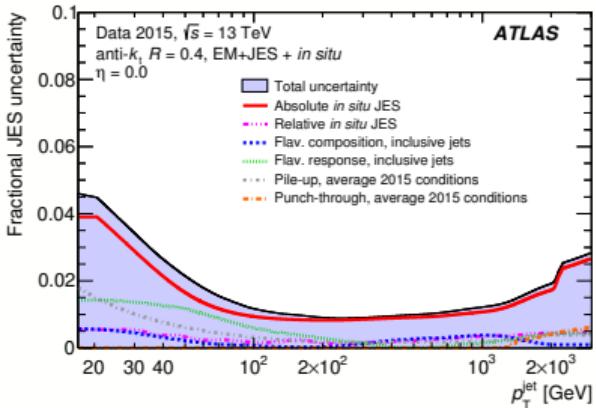


- Calorimeter jets from energy deposits
- Track jets from clusters of charged particles in the ID
- Anti- k_T , $\Delta R = 0.4$ clusterization algorithm
- Complex calibration procedure
- Boosted topologies for close-by jets
 - ▶ large- R jets, jet grooming, jet substructure, ...

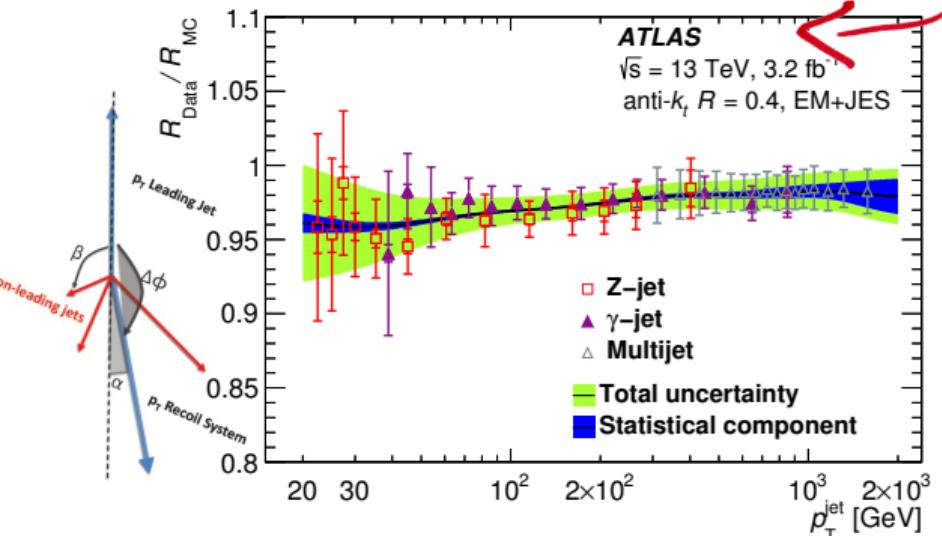
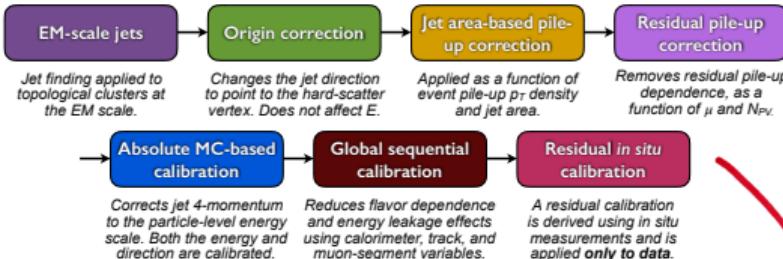
Detector calibration



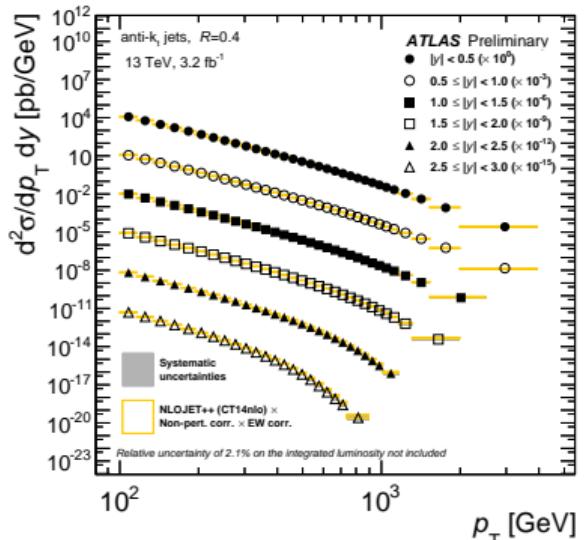
η - p_T systematic uncertainties



Detector calibration

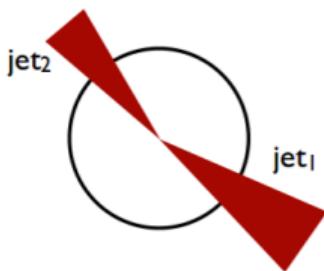
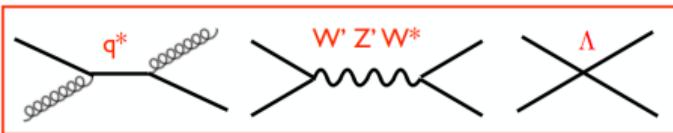
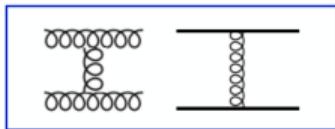


Double-differential inclusive jet cross section measurement

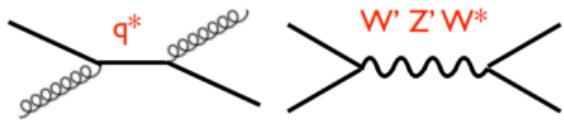
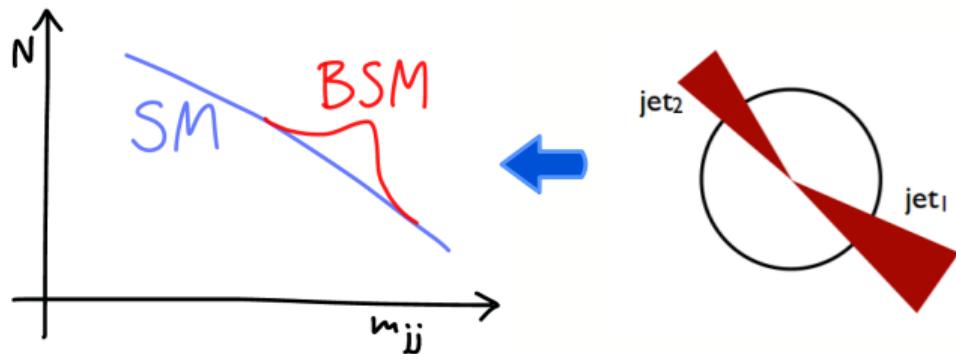
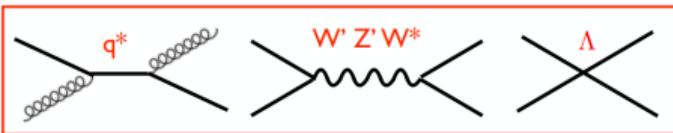
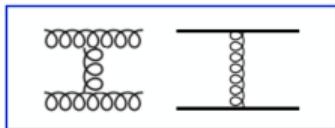


Good agreement in the full p_T and rapidity ranges

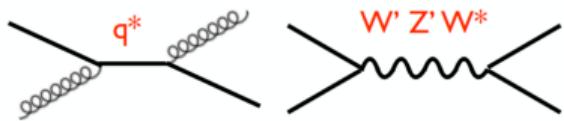
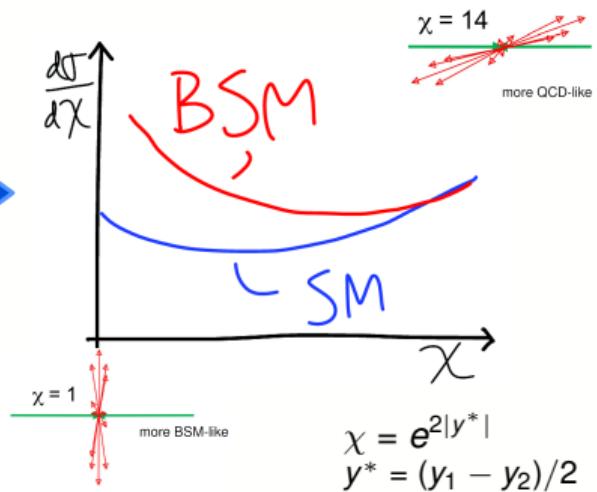
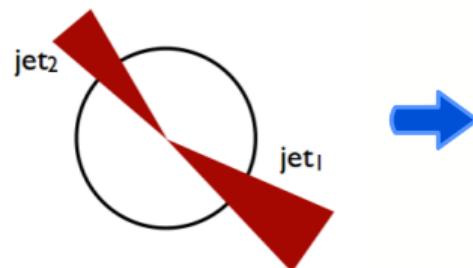
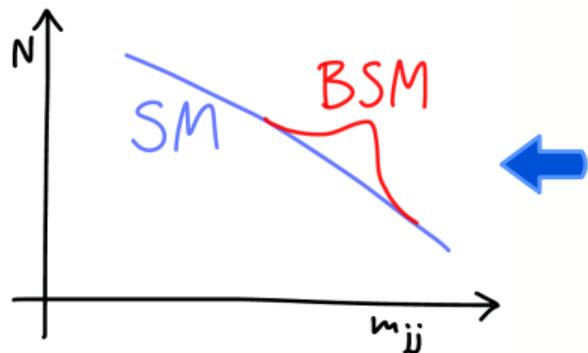
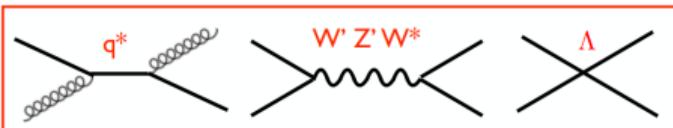
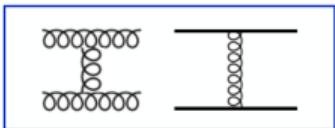
Search for dijet resonance



Search for dijet resonance



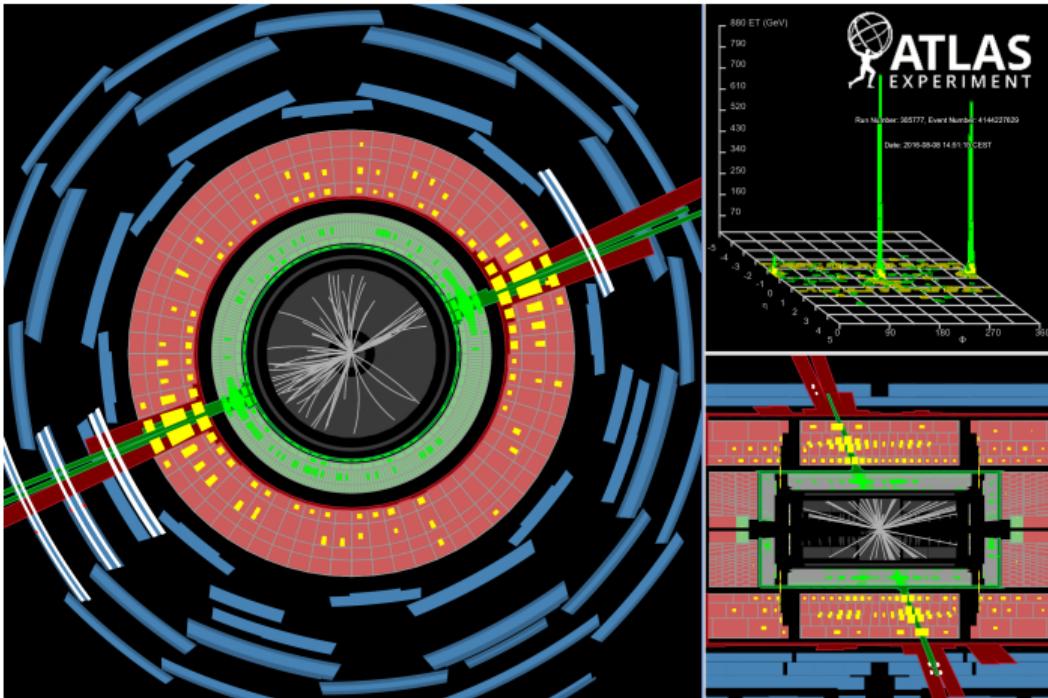
Search for dijet resonance



- Single jet trigger - $p_T^{online} \geq 380$ GeV
- At least two jets in the event
- $p_T^{lead.(subl.)} \geq 440(50)$ GeV
- Central events: $|y^*| < 0.6$
 - ▶ looking for s-channel resonances
- Dijet invariant mass: $m_{jj} \geq 1.1$ TeV
 - ▶ trigger constraint to avoid turn-on effects

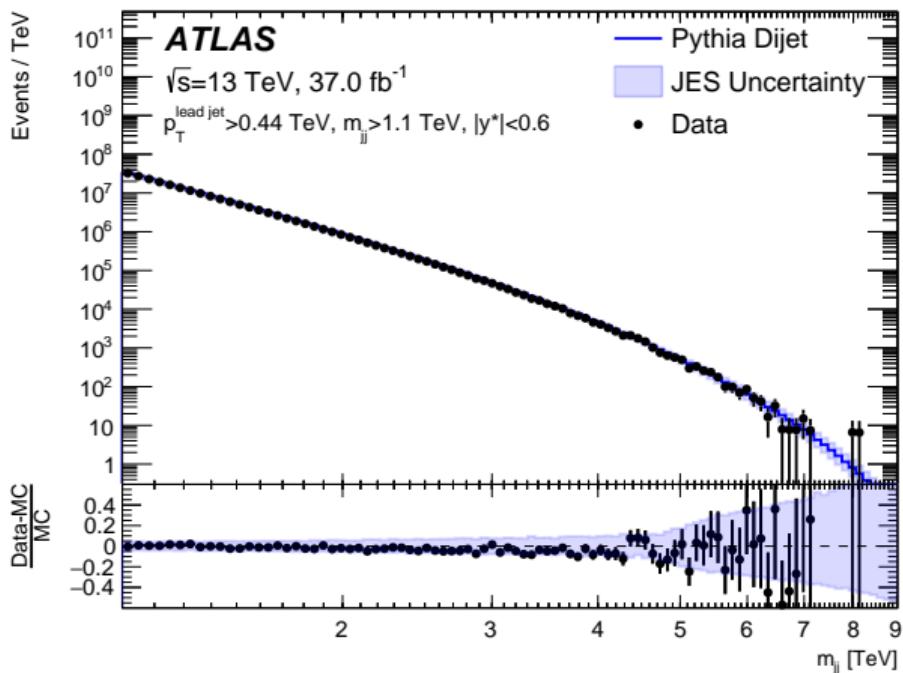
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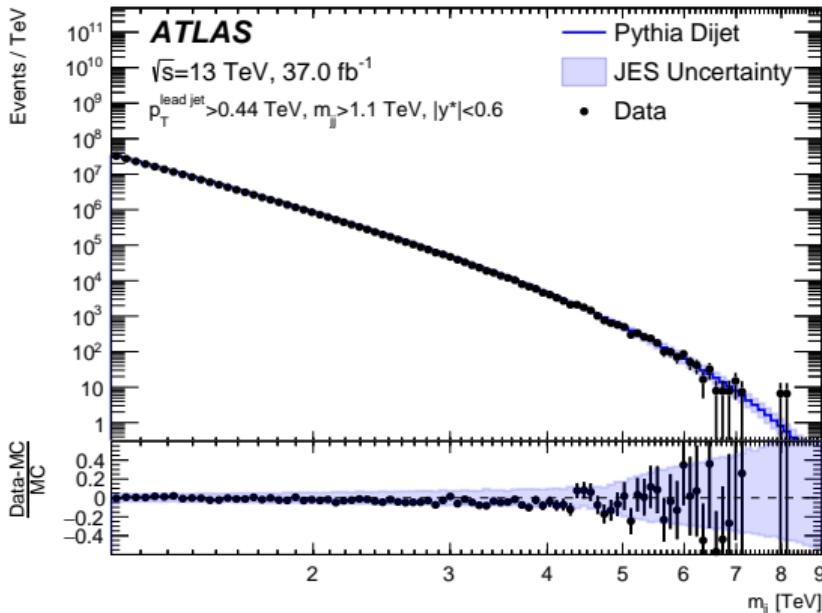
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Background estimation

↓ Monte Carlo simulation unable to reproduce QCD background at the precision needed



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

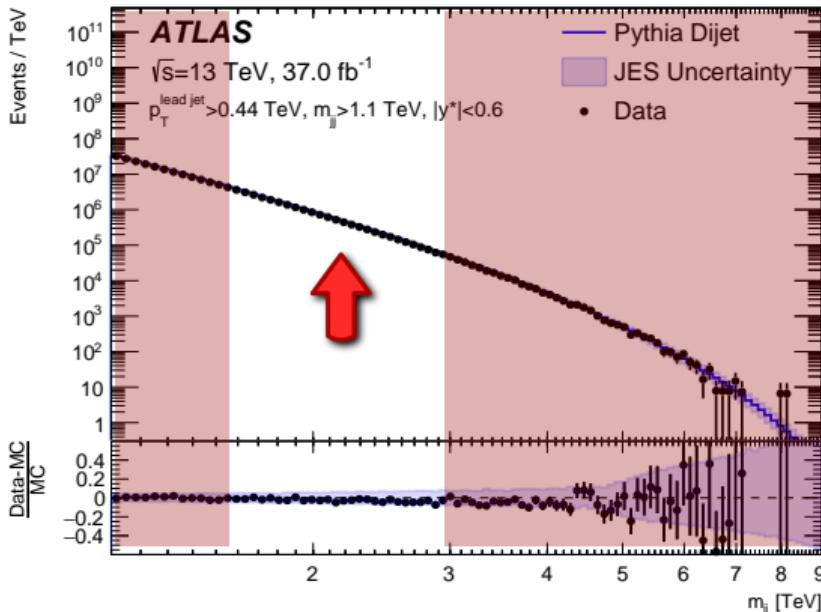
$$f(z) = p_1 \cdot (1 - z)^{p_2} \cdot z^{p_3 + p_4 \ln z} \quad z = m_{jj}/\sqrt{s}$$

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

Fit breaks when statistics increase!

Background estimation

↓ Monte Carlo simulation unable to reproduce QCD background at the precision needed



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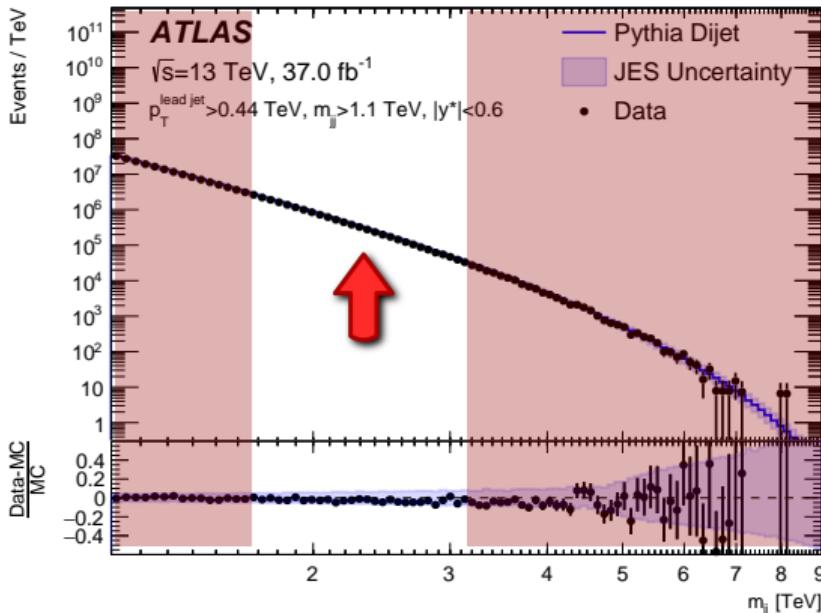
SWiFt: Sliding Window Fit

- 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!

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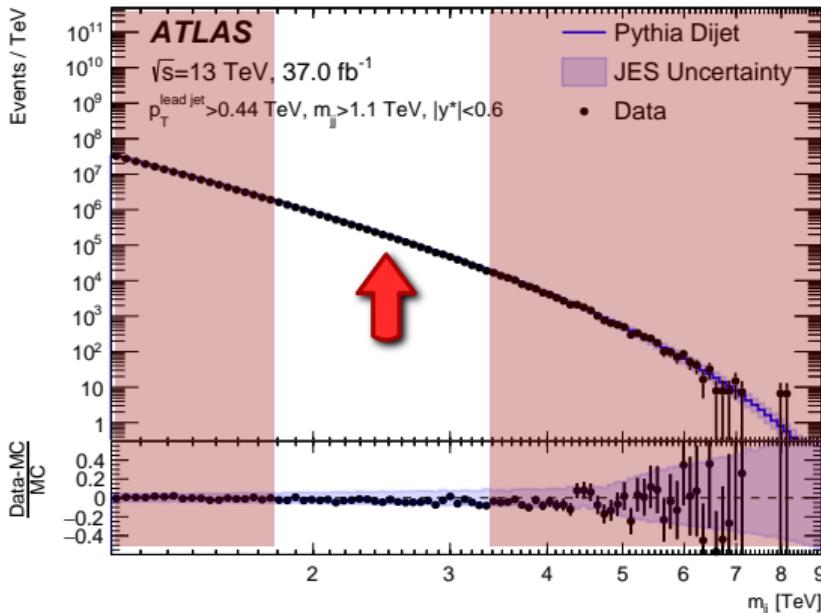
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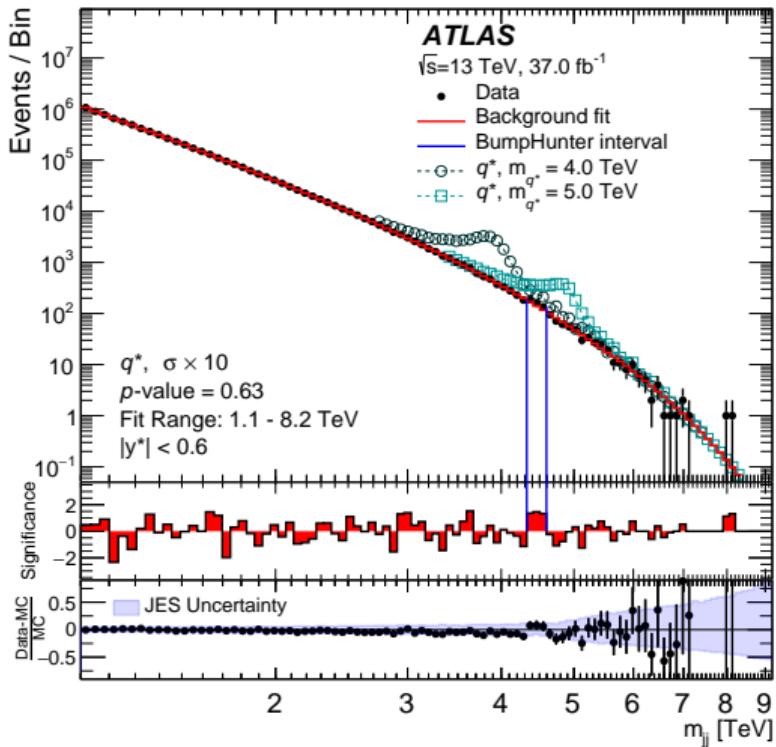
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Search for a bump



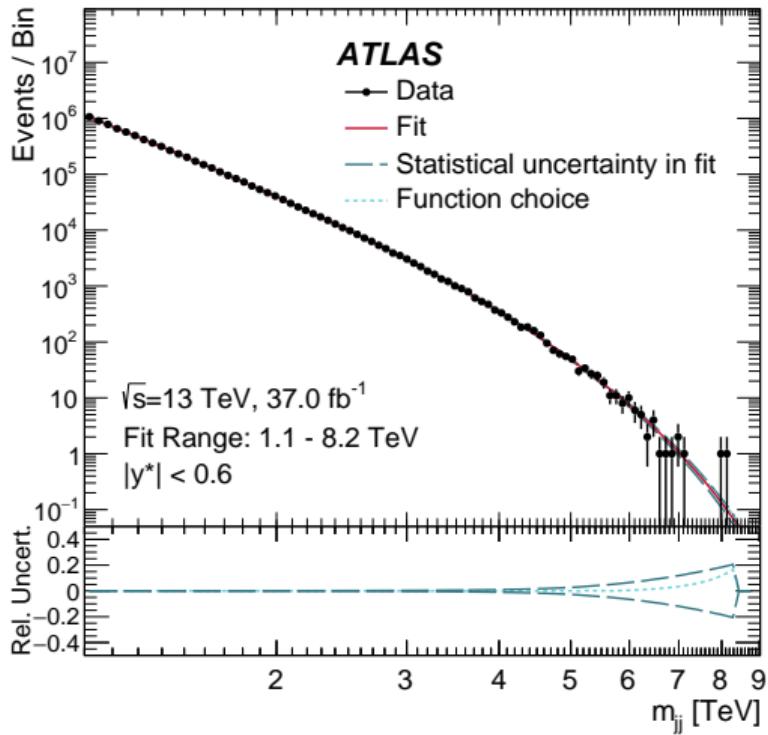
BUMPHUNTER algorithm:

search for a *peak* on top of predicted background

- search for significantly discrepant subsequent bins
- exclude them, refit and compare data with new background prediction

► No significant deviations with respect to SM background prediction: $p\text{-value} = 0.63$

Search for a bump



BUMPHUNTER algorithm:

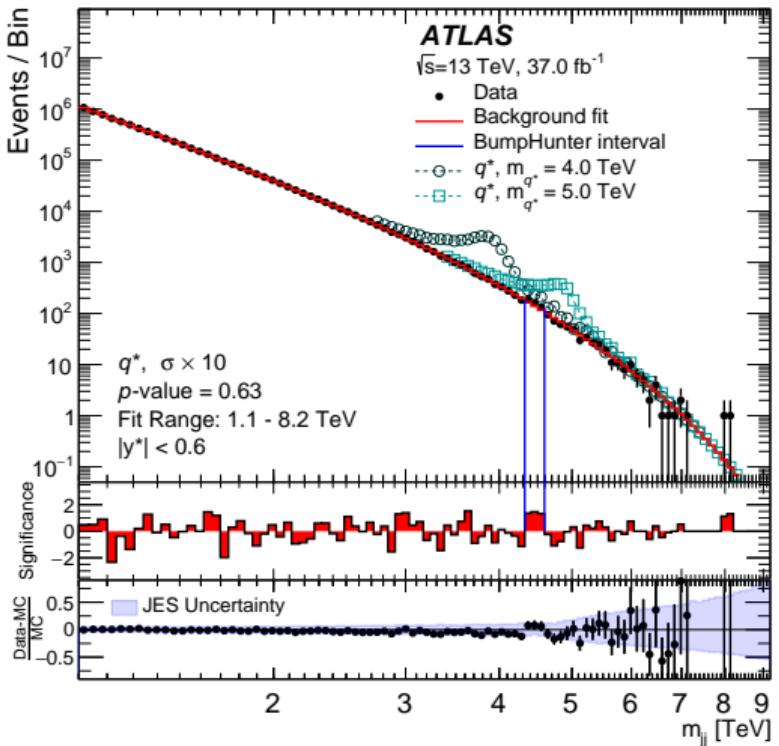
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 - Fit parameter statistical uncertainties
 - Alternative fit function choice

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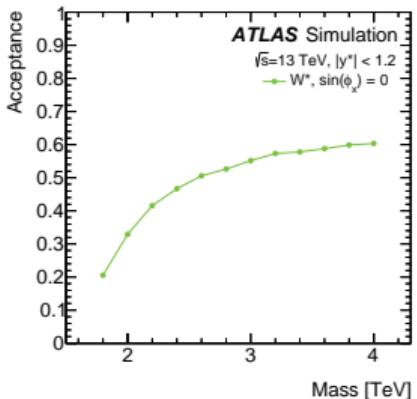
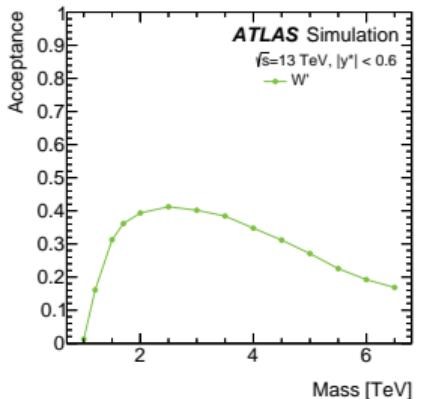
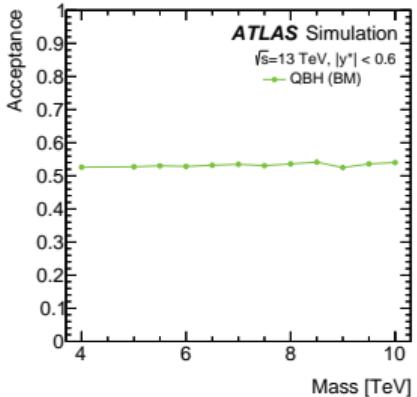
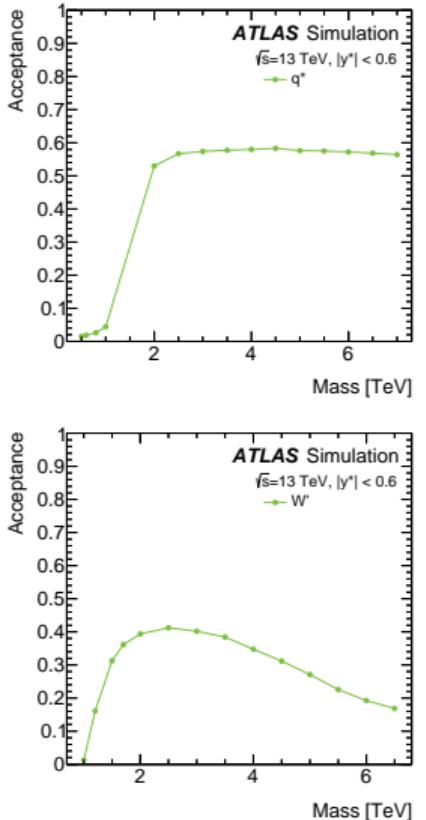
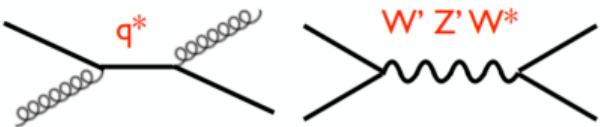
- Systematic uncertainties on fitted background
 - Fit parameter statistical uncertainties
 - Alternative fit function choice

► Use data to **exclude new physics contributions**

Benchmark signals

different benchmark signals
 \Updownarrow
different shapes,
different acceptances

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



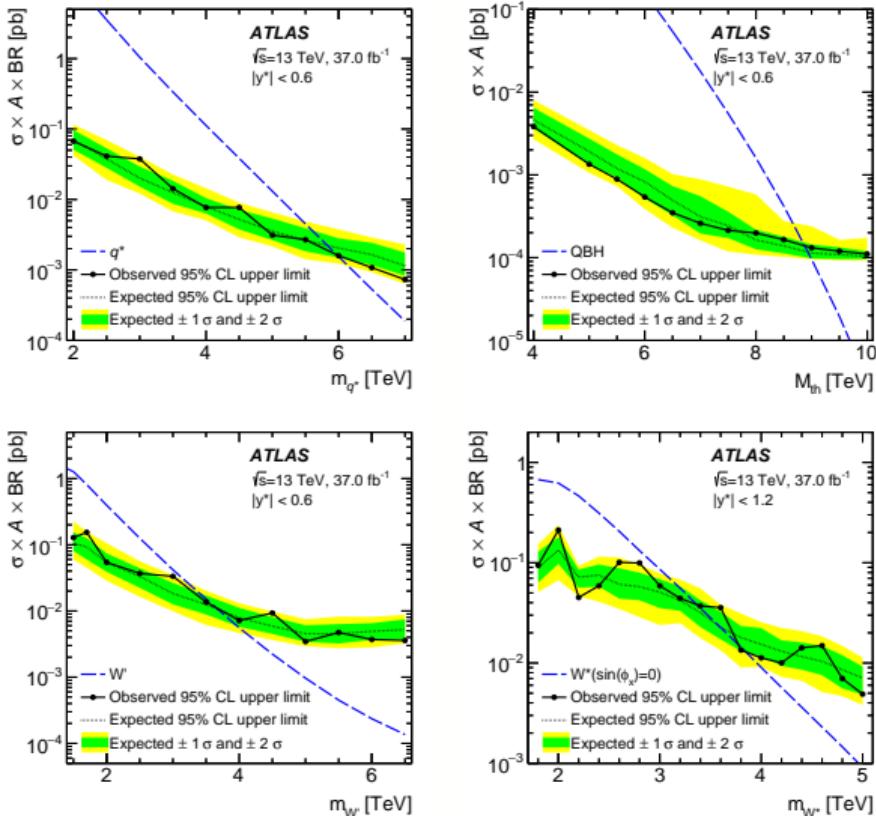
Limit extraction

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

Model	95% CL exclusion limit		
	Run 1	Observed	Expected
Quantum black hole	5.8 TeV	8.9 TeV	8.9 TeV
W'	2.5 TeV	3.6 TeV	3.7 TeV
W^*	1.8 TeV 3.77 TeV – 3.85 TeV	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	4.1 TeV	6.0 TeV	5.8 TeV

► 40-50% improvements with respect to Run 1

W^* re-optimized → 90% improvement

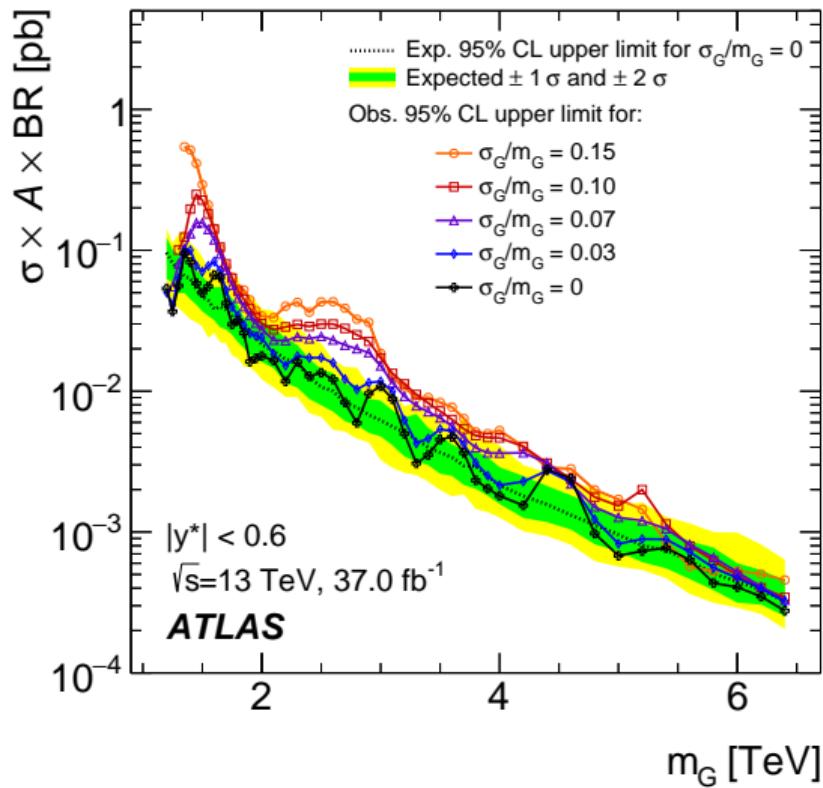


Generic gaussian signal

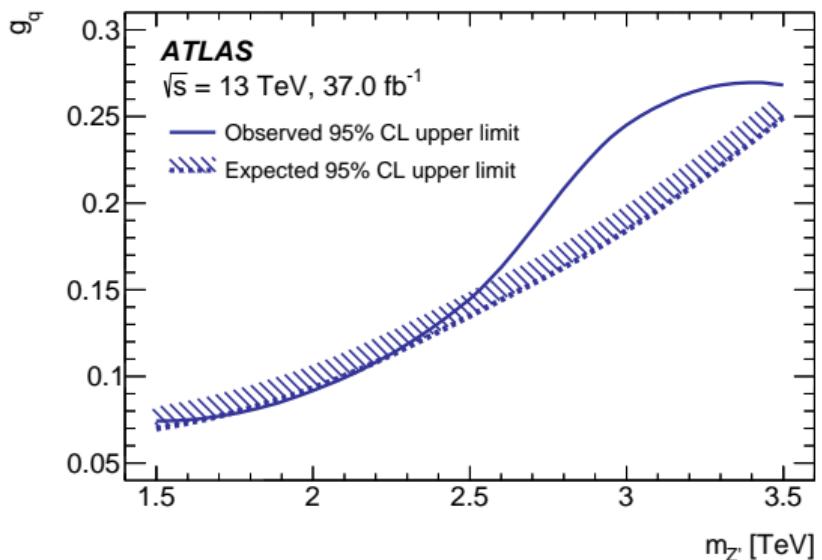
- Set limit on gaussian signal shape
- Useful for phenomenological reinterpretation of the results

Jet energy folding

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

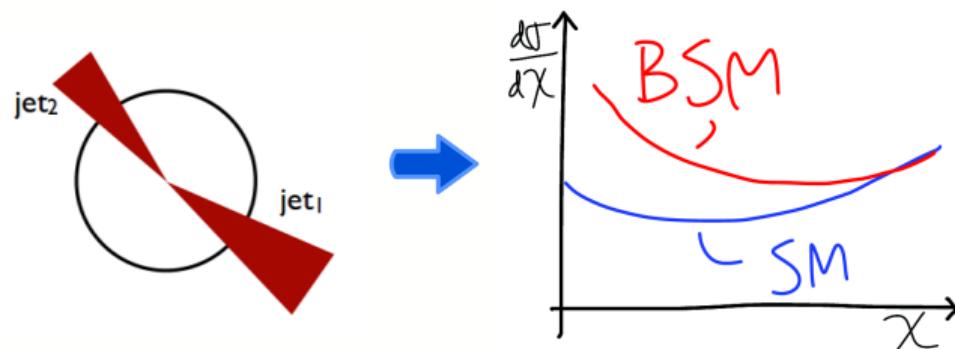


- Standard Model U(1) extension:
 - ▶ leptophobic additional Z' boson
- Z' coupling to SM quarks determines its width
- Simple scenario for Dark Matter models (see next.)
- Constraint on the model on $m_{Z'}$ vs. g_q plane



What if new physics is not a narrow resonance?

- Too wide to be seen in m_{jj}
- At a too high scale



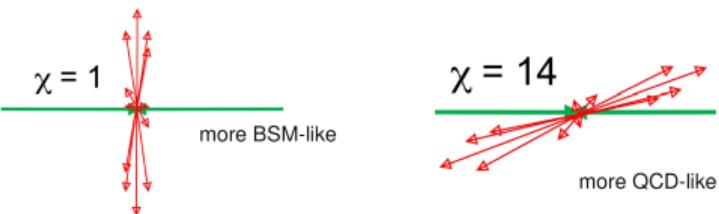
$$\chi = e^{2|y^*|}$$
$$y^* = (y_1 - y_2)/2$$



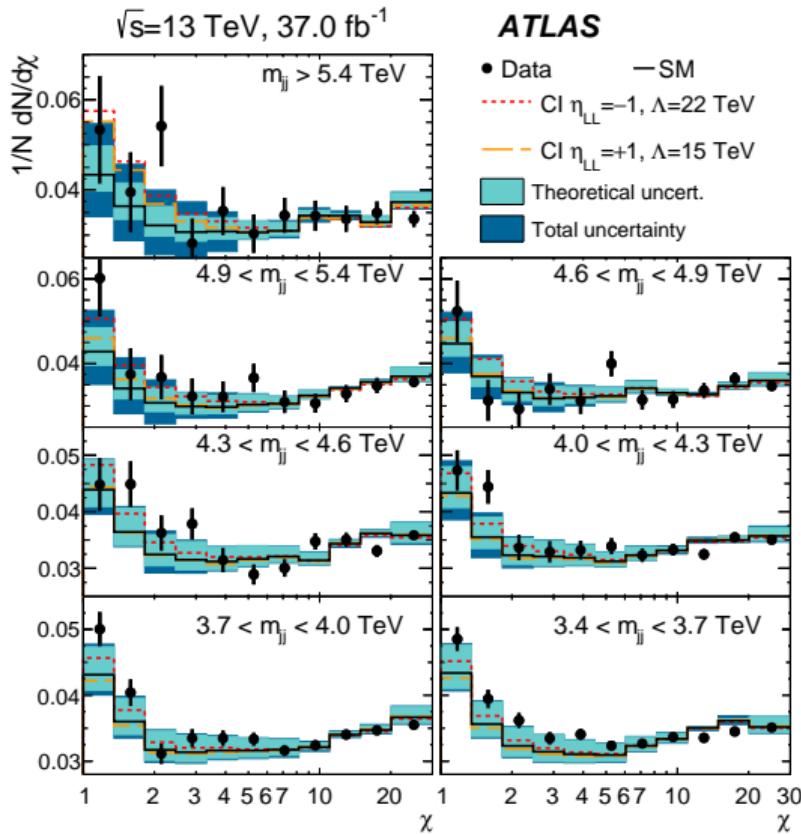
Dijet angular correlation

Explore dijet angular separation

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



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



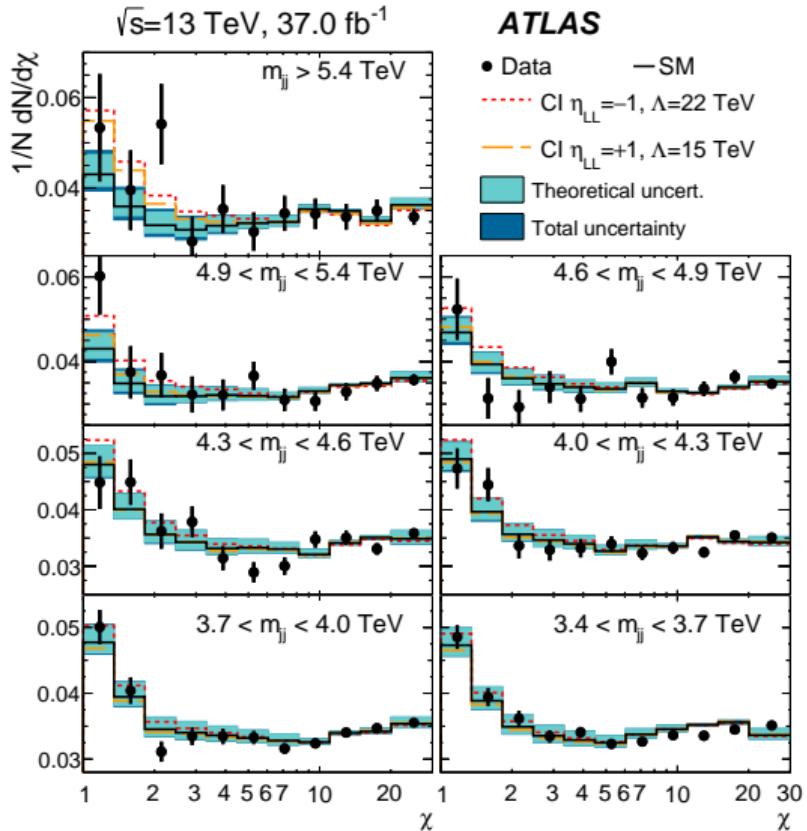
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 - ▶ include NLO QCD corrections
 - ▶ include LO EW corrections
- Theoretical uncertainties: pdf, choice of factorization and renormalization scales
- Dominant experimental uncertainties: jet energy reconstruction (scale)
- **Combined fit in different m_{jj} regions**
 - ▶ constrain theo. and exp. uncertainties



Dijet angular correlation

Explore dijet angular separation

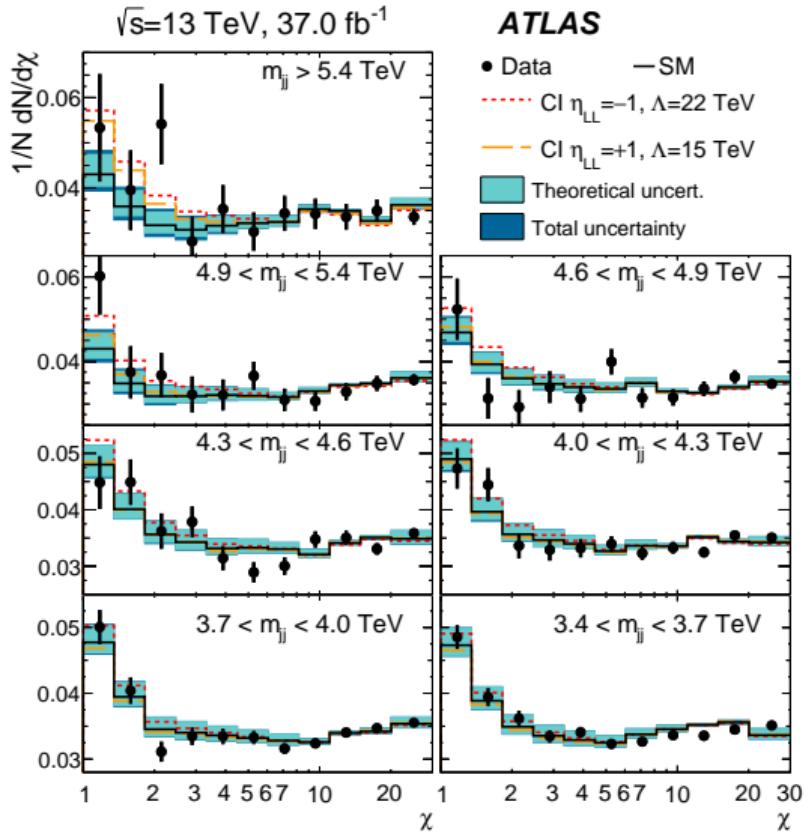
$$\chi = e^{2|y^*|} \quad |y^*| < 1.7 \quad \frac{|y_1 + y_2|}{2} < 1.1$$



- Background prediction from MC simulation

► $\chi(m_{jj})$ introduced in Run 2 search,
toward a full 2D analysis:

- The factorization of the energy scale
- Double ratio reconstruction
- Combined fit in different m_{jj} regions
 - constrain theo. and exp. uncertainties



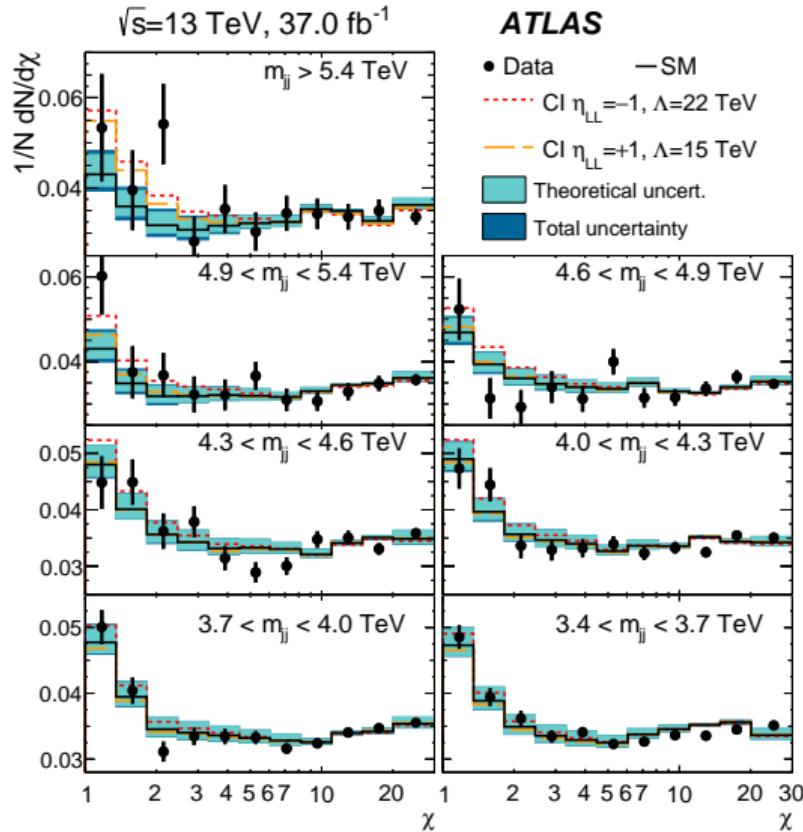
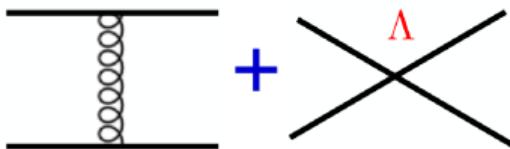
Dijet angular correlation

The logo of the National Institute of Nuclear Physics (INFN) of Italy, featuring the letters INFN in blue with a curved swoosh.

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

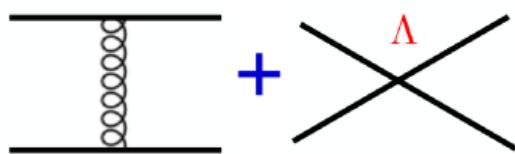


Dijet angular correlation

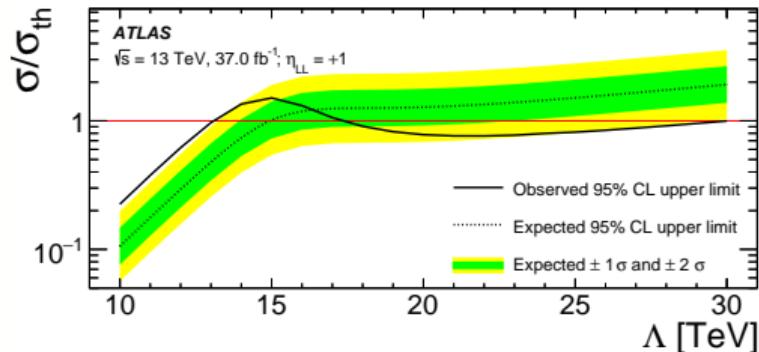
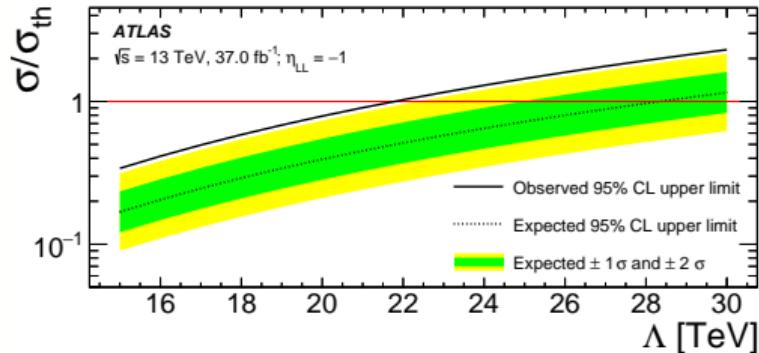
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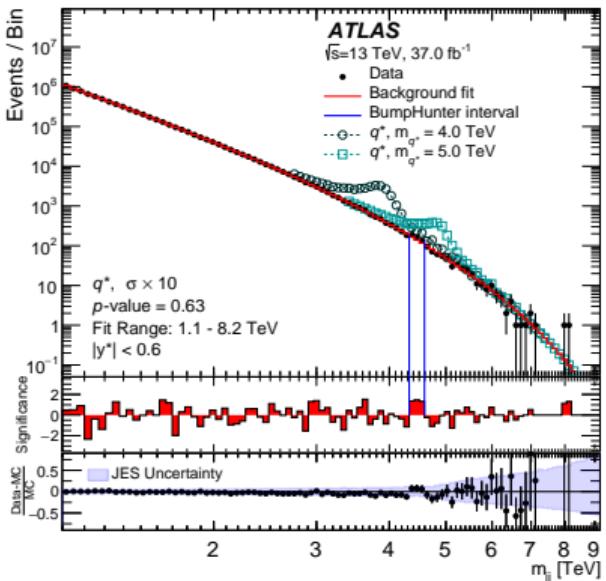


New physics scales Λ probed up to ~ 30 TeV



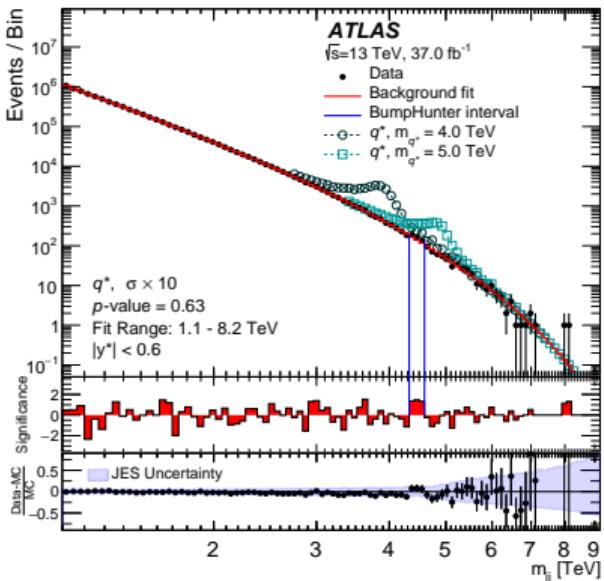
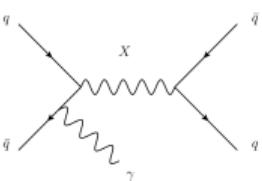
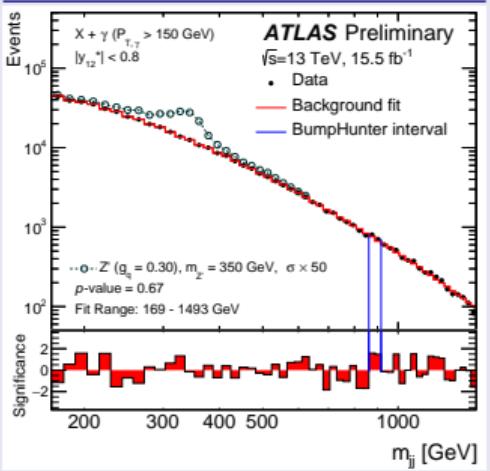
- What happens at lower masses?

Recorded data rate
 =
 event rate \times event size
 =
 too large...



Complementary dijet searches

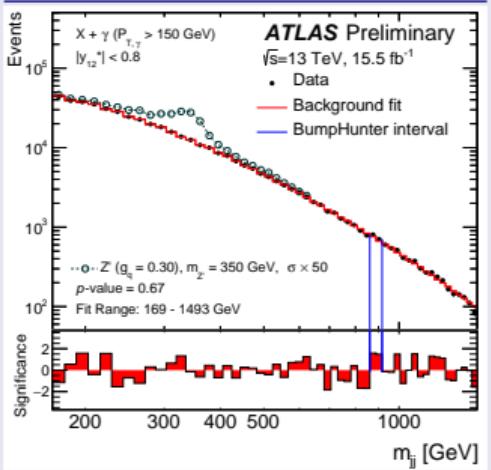
dijet + γ



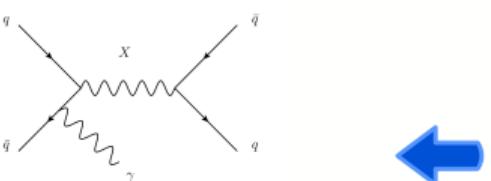
Select events with an additional high- $p_T \gamma(/g)$ from ISR

Complementary dijet searches

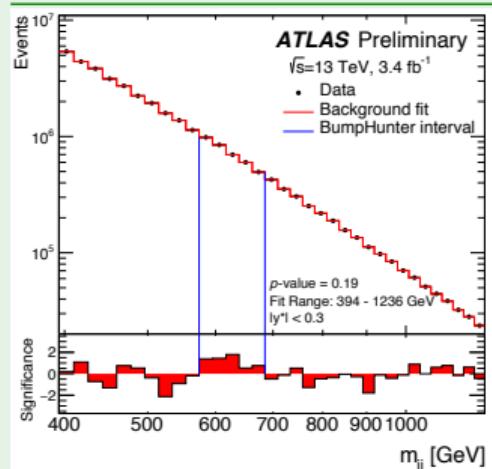
dijet + γ



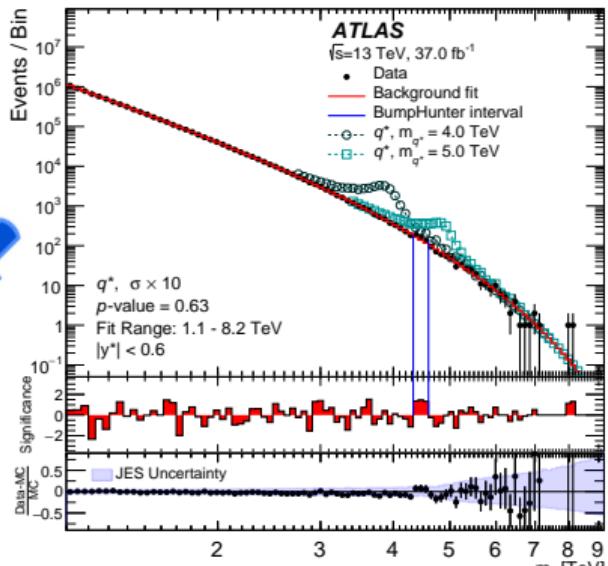
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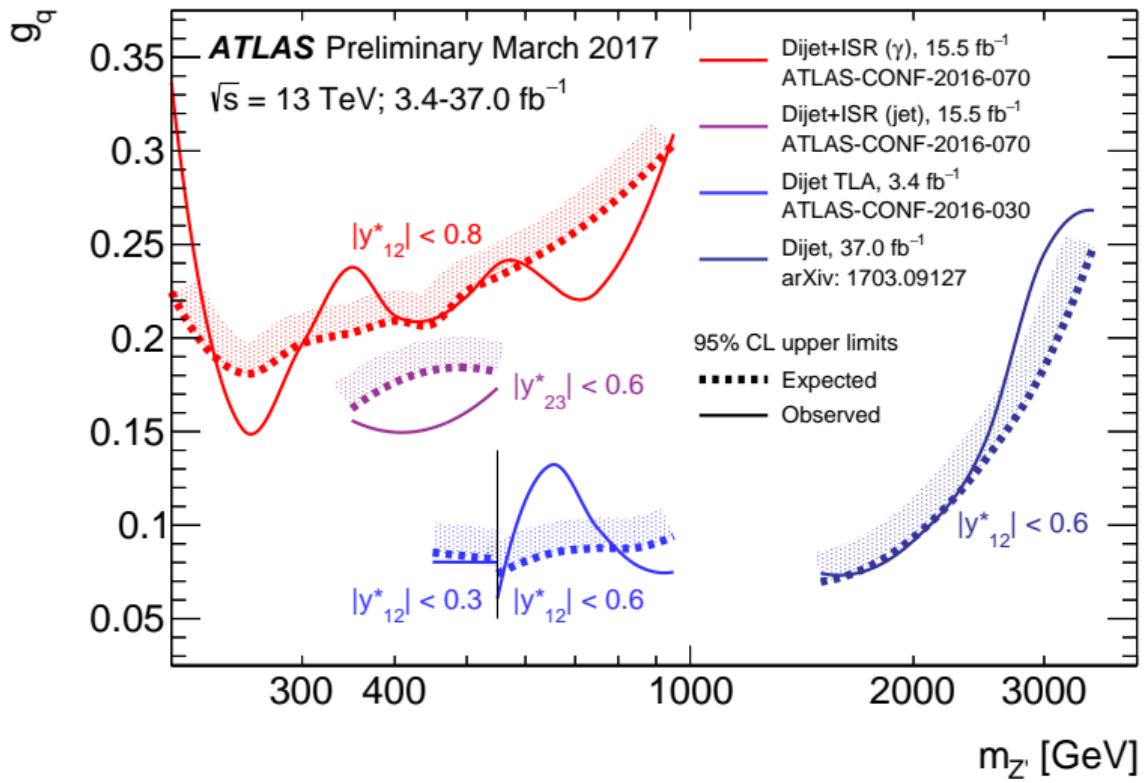
Trigger Level Analysis



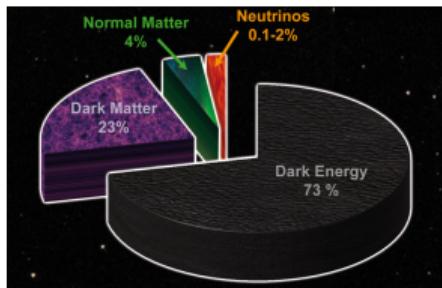
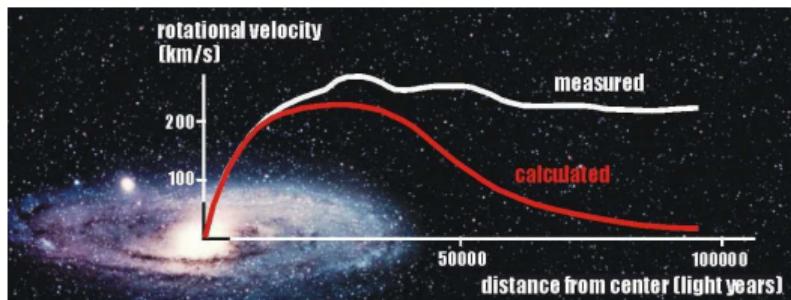
Dedicated trigger stream with partial event reconstruction (jet only)

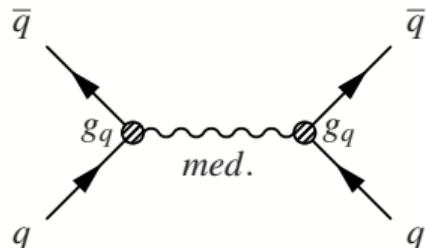


Z' combined interpretation



Dark Matter - from cosmology to colliders

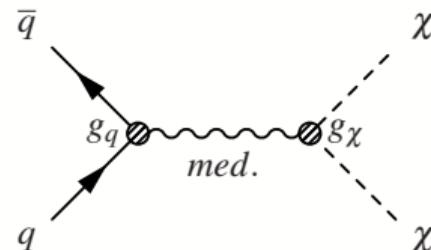
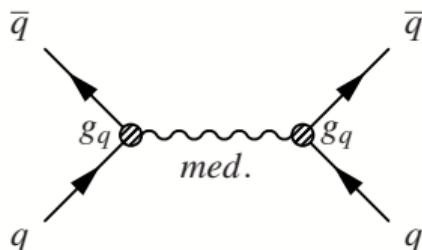


► Why Z' extension is good for Dark Matter?

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

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

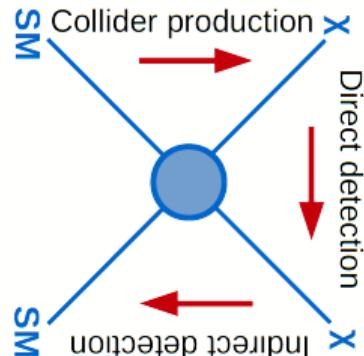
► Why Z' extension is good for Dark Matter? **A good simplified model**



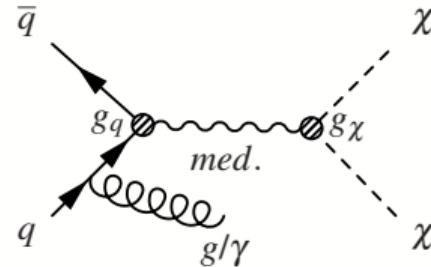
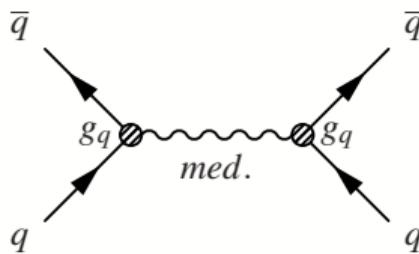
$$\mathcal{L}_{AV} = \sum_{q=u,d,c,s,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$

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]



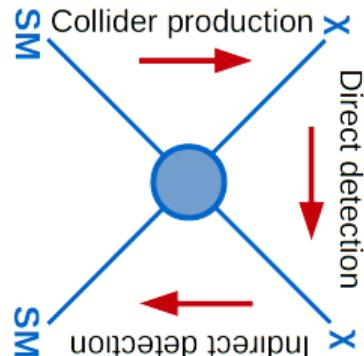
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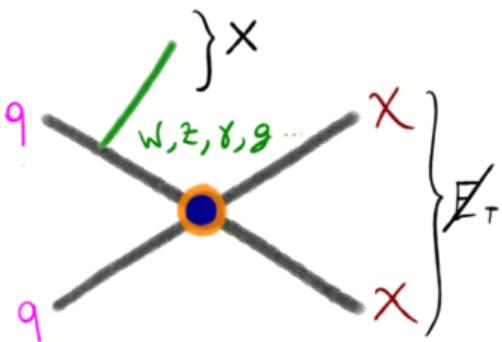
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4 pars : [g_q , g_χ , m_χ , M_{med}]

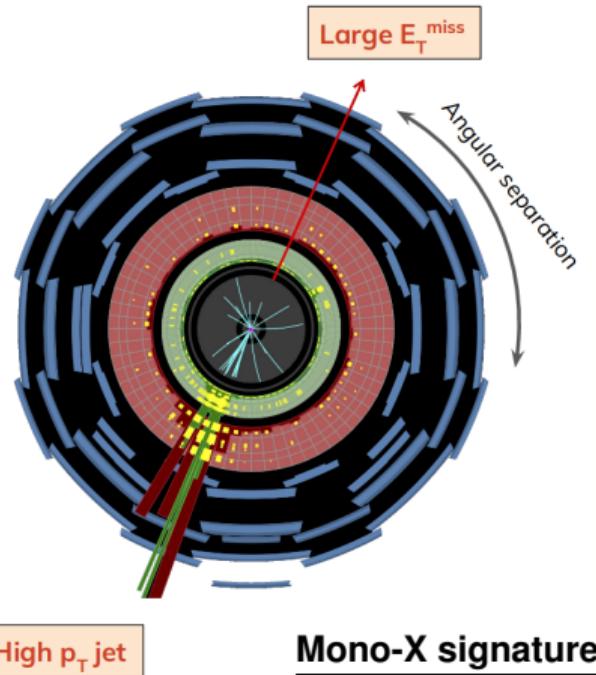
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- This is a simple model, different ones can be considered
 - details in 1507.00966[hep-ex] and 1503.05916[hep-ph]



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

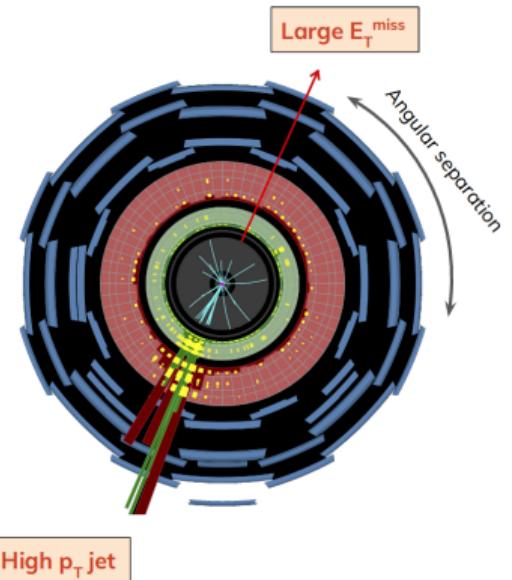


- WIMP (χ) invisible in the detector
- Identify the event through a recoiling object: W, Z, γ, g, b
- Production of large unbalanced energy in the transverse plane, \cancel{E}_T
- Peculiar back-to-back event topology



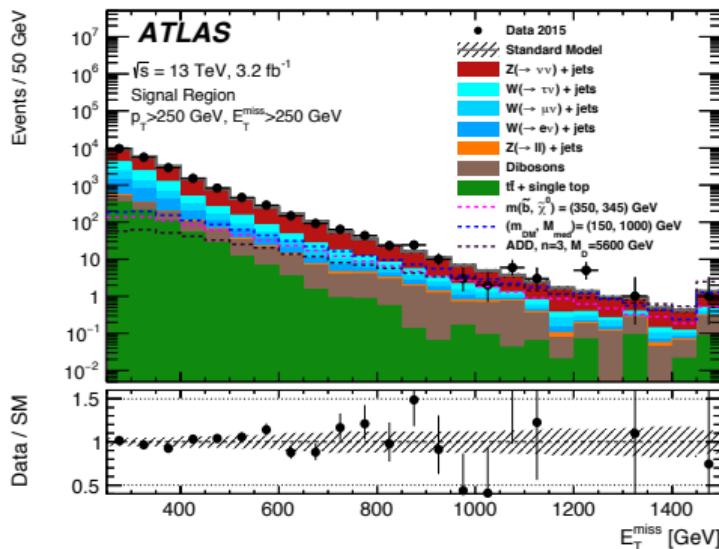
Mono-X signatures

Mono-jet search



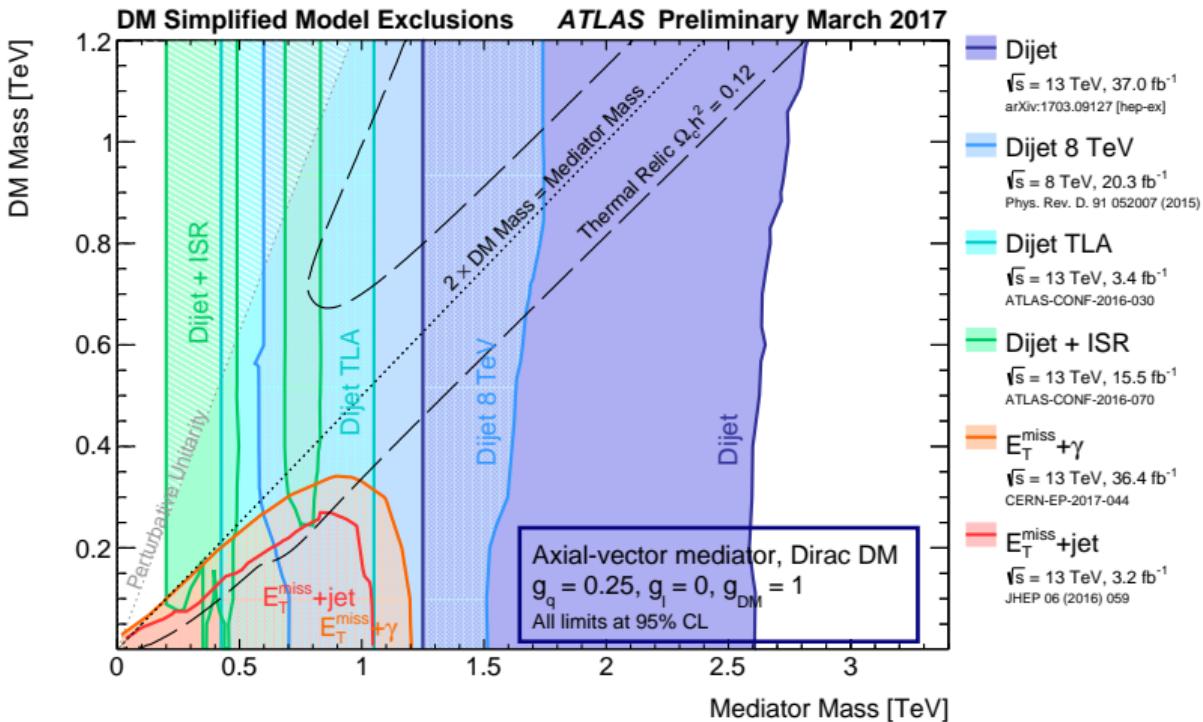
- Dominant irreducible $Z \rightarrow \nu\bar{\nu}$ +jets background
(not the only one, unfortunately)

- Constrain subdominant background in dedicated control regions
- Simultaneous fit of E_T -distribution in signal and control regions
- Similar approach for mono-photon search



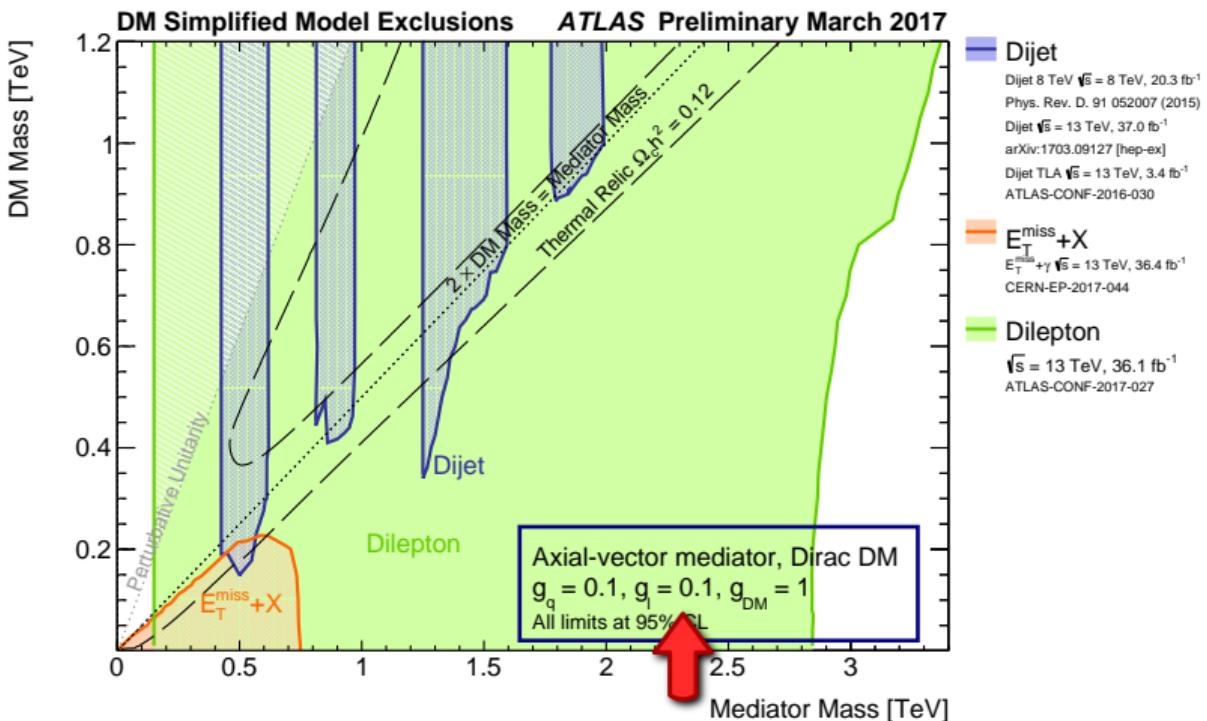
Dark Matter combined interpretation

- For relatively large coupling g_q dijet constraints are strong

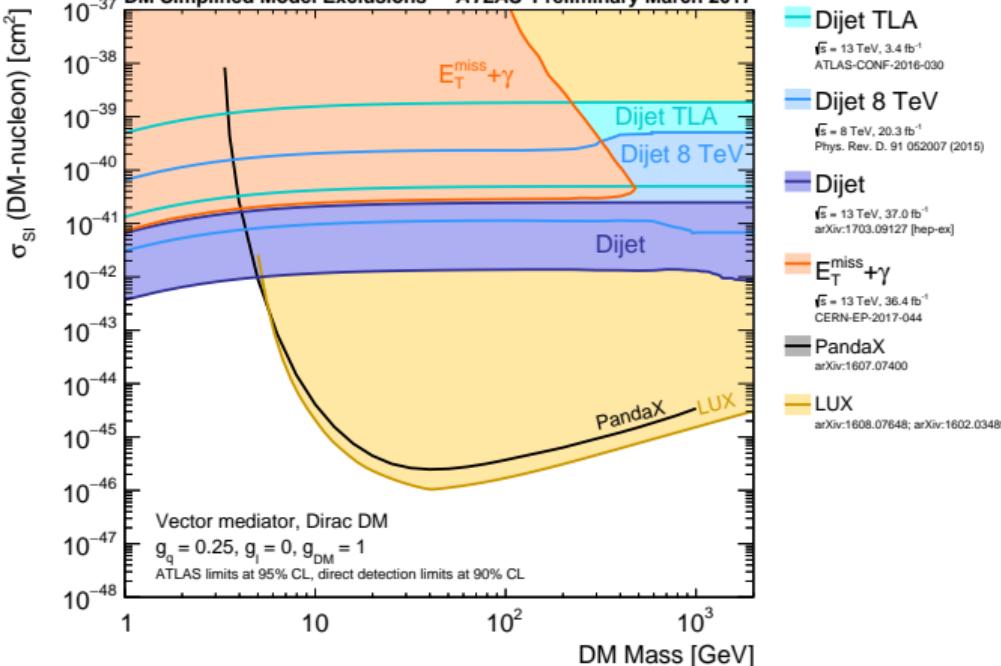


Dark Matter combined interpretation

- 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 constrain the parameter space



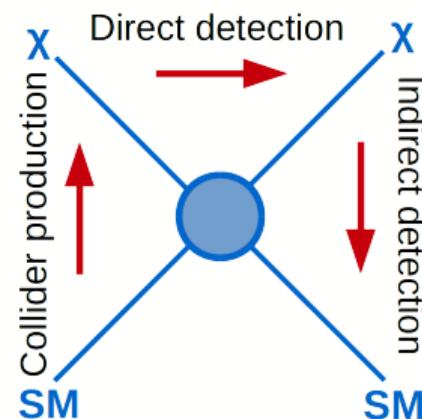
Comparison with Direct Detection



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

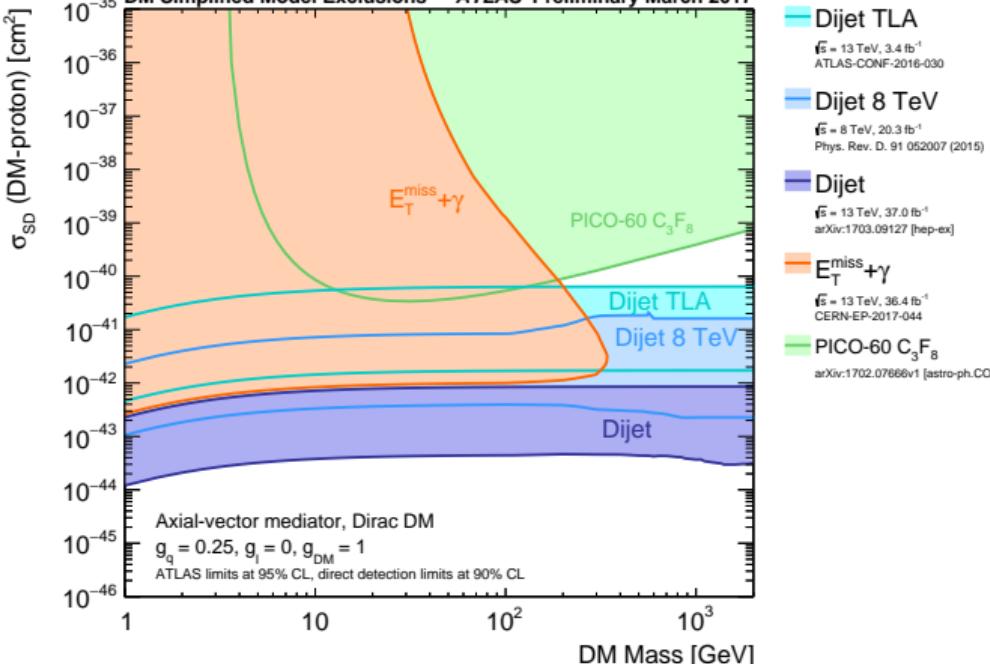
$$\sigma_{SI}^0 = \frac{9g_{DM}^2 g_q^2 \mu_n^2 \mu_\chi^2}{\pi m_{med.}^4}$$

(details in hep-ph:1407.8257)



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

Comparison with Direct Detection

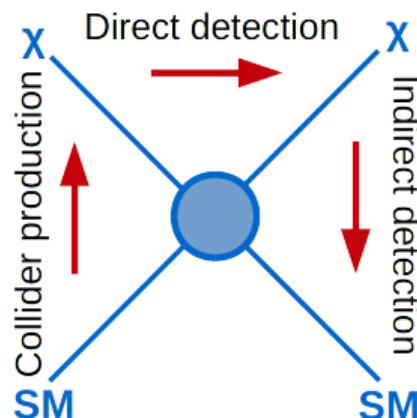


Good sensitivity for low-mass DM candidates (i.e. $< 10 \text{ GeV}$)

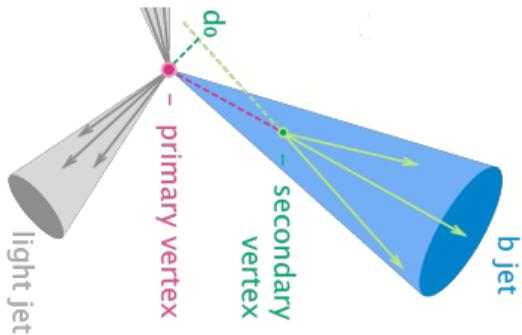
► $(m_\chi, m_{\text{med.}})$ exclusion converted into cross section limits

$$\sigma_{SD}^0 = \frac{3g_{\text{DM}}^2 g_q^2 (\Delta_u + \Delta_d + \Delta_s)^2 \mu_{n\chi}^2}{\pi m_{\text{med.}}^4}$$

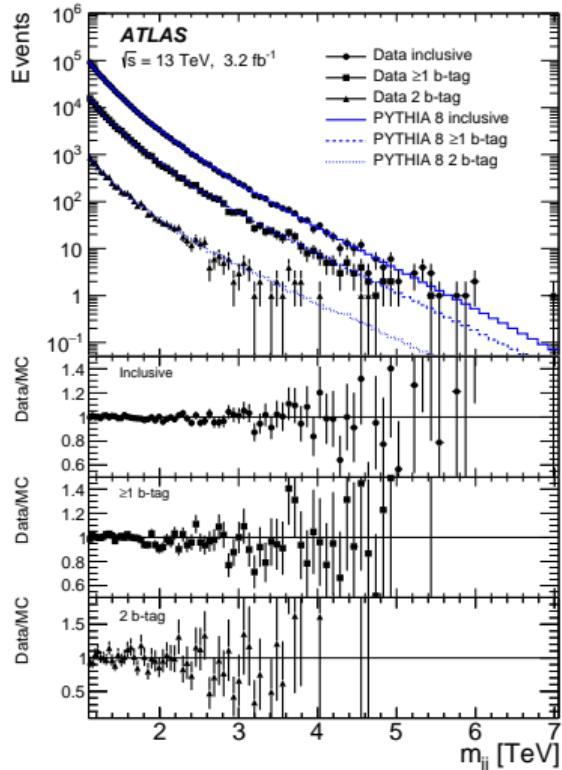
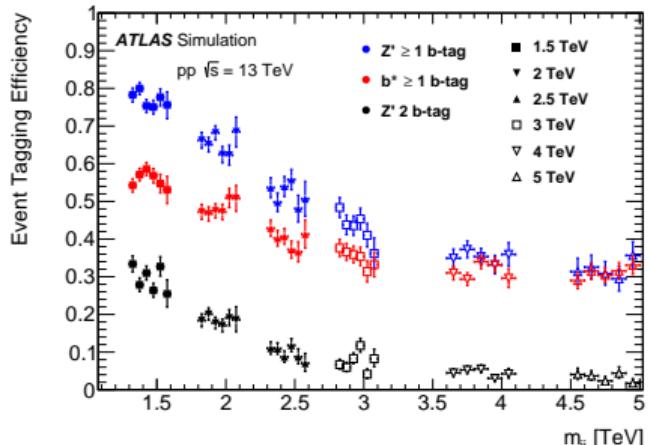
(details in hep-ph:1407.8257)



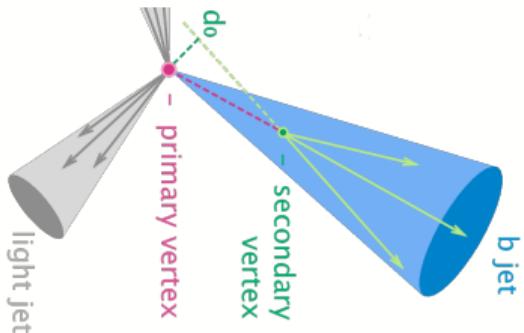
Ongoing and future searches: di-*b*-jets



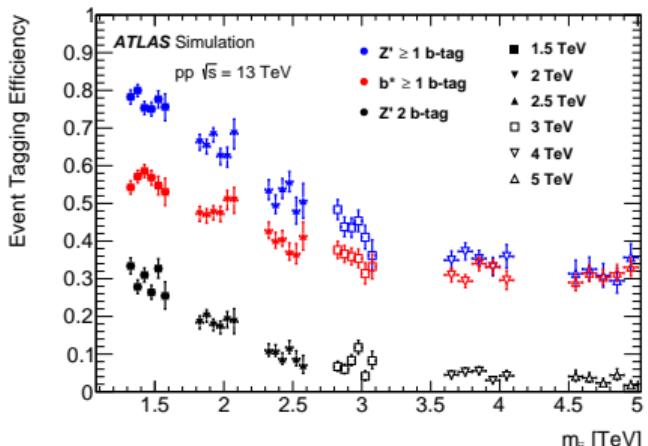
Identification of jets from heavy-flavor quarks: *b*-tagging



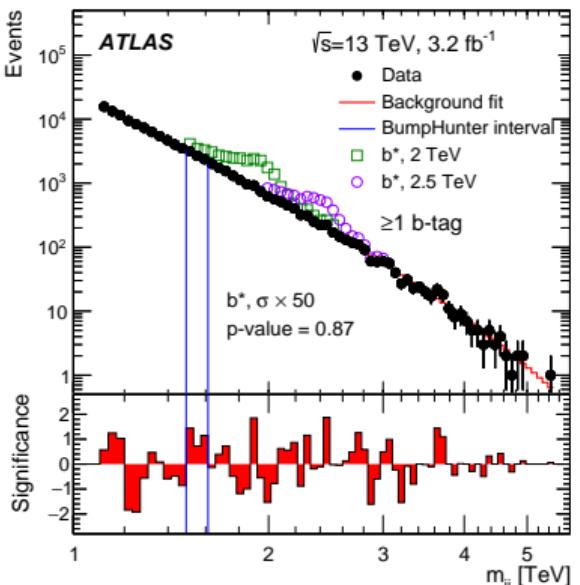
Ongoing and future searches: di-*b*-jets



Identification of jets from heavy-flavor quarks: *b*-tagging



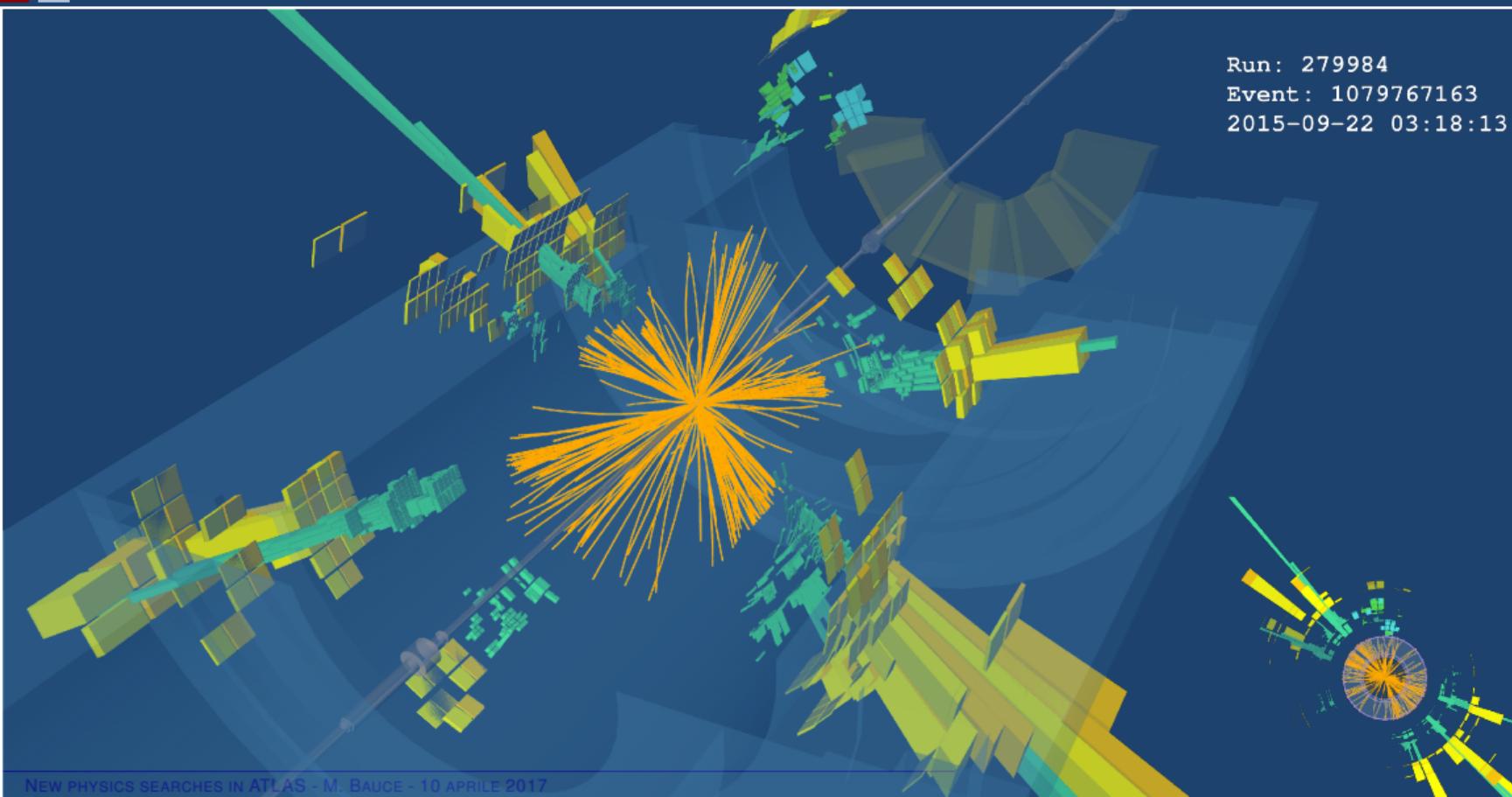
Resonances can be sought into the smoothly falling spectrum



► Search will benefit from the increasingly available statistics

Ongoing and future searches: peculiar multi-jet signatures

Run: 279984
Event: 1079767163
2015-09-22 03:18:13 CEST

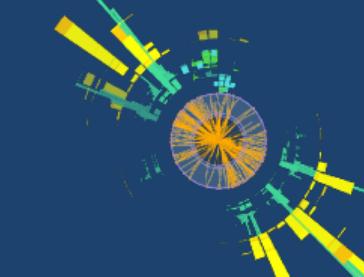
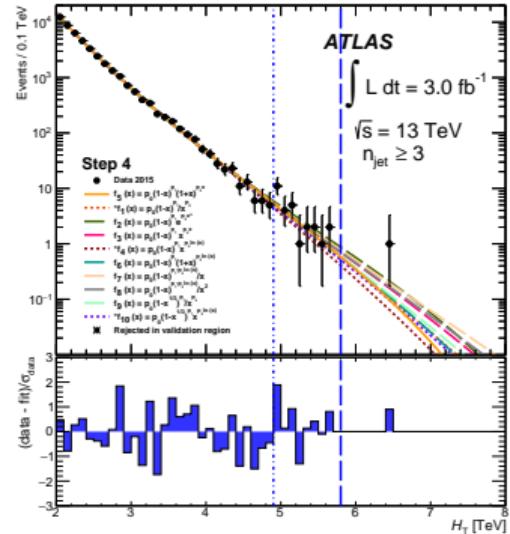
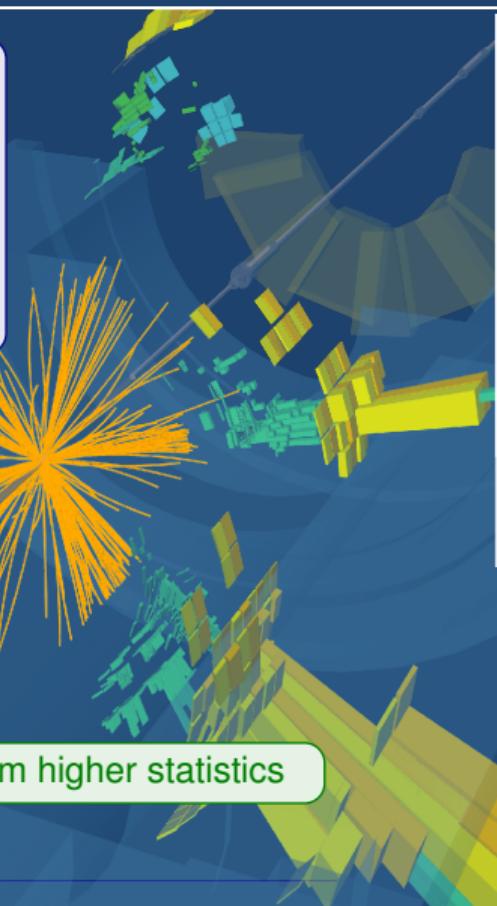


Ongoing and future searches: peculiar multi-jet signatures

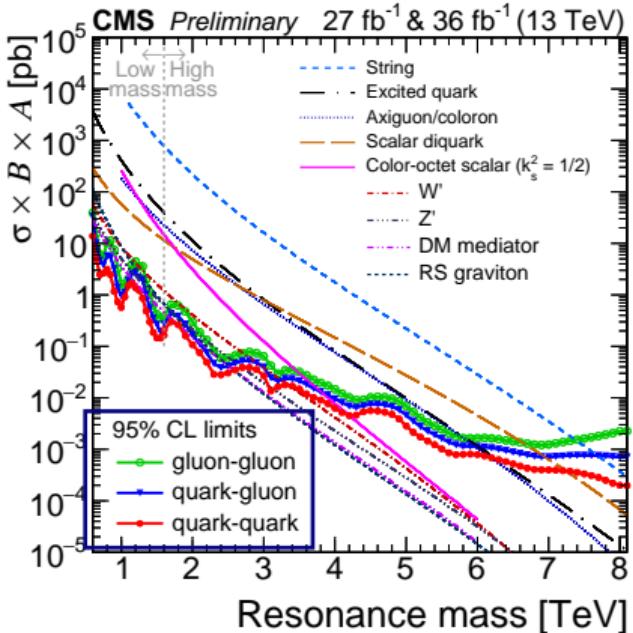
Many-jet events open opportunities to search for peculiar signatures:

- inclusive multijet searches
- double resonance cascades:
 $Y \rightarrow X X \rightarrow jj + jj$
- Three-jet resonances: $Y \rightarrow jjj$

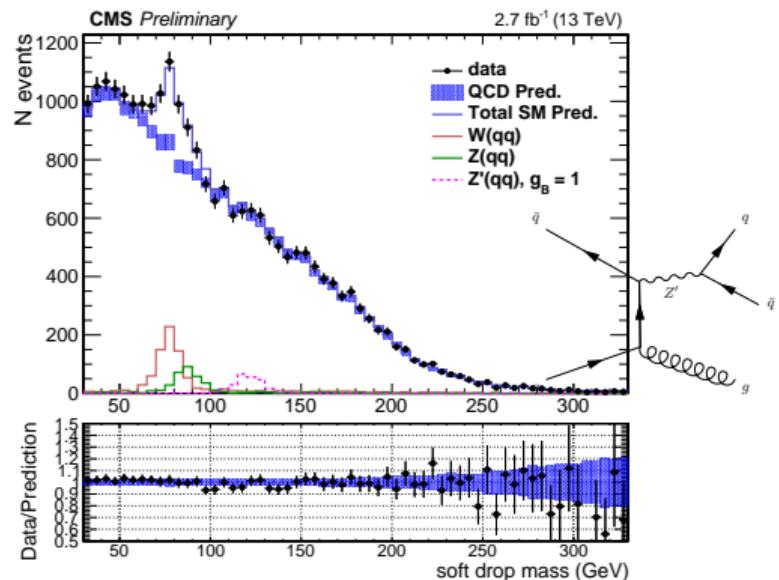
This searches will benefit from higher statistics



Learn from your *neighbors*



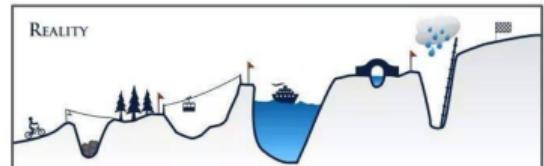
Distinguish composition
of dijet final states



Boosted topologies in low-mass region

- 13 TeV collisions provided by the LHC are an unprecedented dataset to search for new physics
- Striking signatures are promptly explored - unfortunately no new physics hints so far
- The search will continue until the end of Run 2 in 2018
 - expect to collect 100 fb^{-1} of data by then
 - ▶ Run 3, 2021-2023, possibly at 14 TeV, will collect $\sim 300 \text{ fb}^{-1}$
- Systematic and coordinated searches will continue in the upcoming years to explore uncharted territories

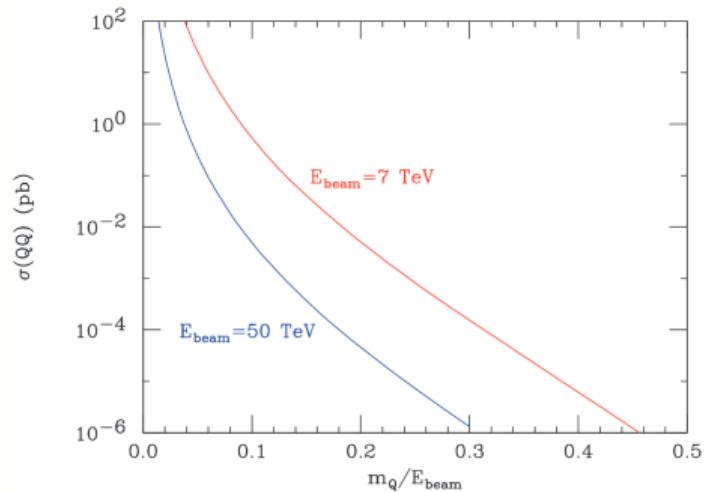
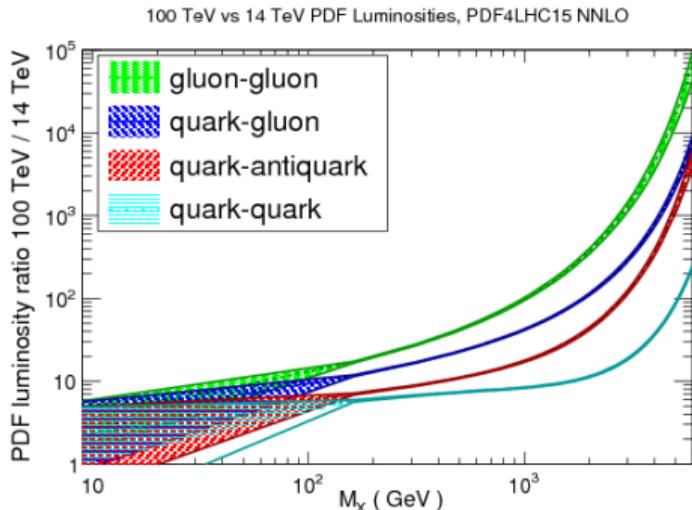
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BACKUP

Luminosity vs. Energy

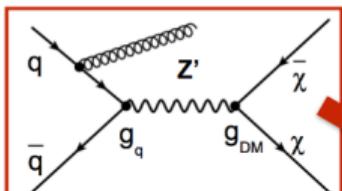
- Increased collision energy is the ultimate way to increase the mass reach
- The cross section to produce states of mass M a fixed fraction of E_{beam} decreases as $1/S$
- To fully exploit higher-energy collider, its luminosity should scale as $\sim S$



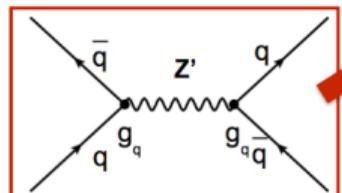
- Besides acceleration challenges, dealing with huge amount of pileup will be a major issue

- 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

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

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

Interesting scenarios

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

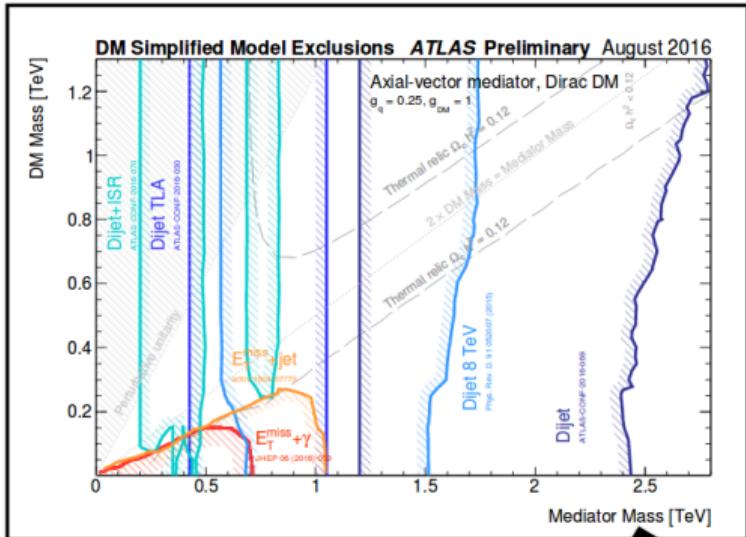
$g_{\text{SM}} \ll g_{\text{DM}}, g_{\text{DM}} \sim 1$: narrow resonance but BR monojet larger than dijet one

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

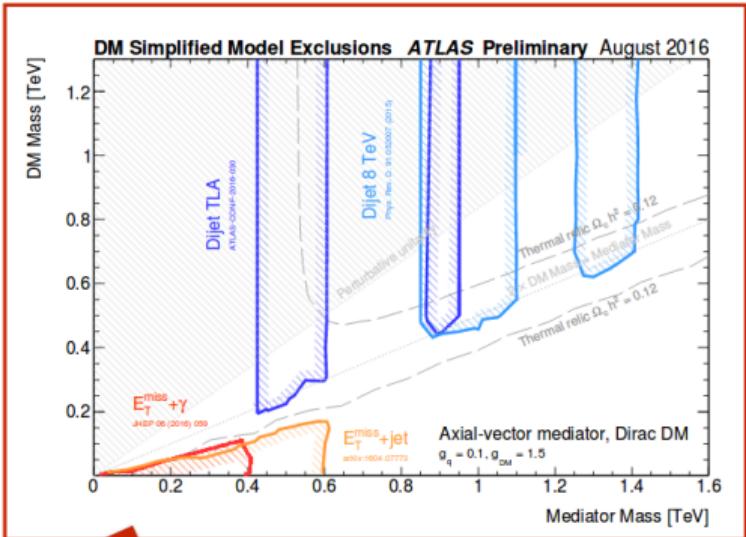
$2m_{\text{DM}} \gg m_{\text{MED}}$: no partial width into dark matter so the Z' model reduces to the standard one used in dijet searches

DM Coupling choice

$g_{\text{SM}} = 0.25, g_{\text{DM}} = 1$



$g_{\text{SM}} = 0.10, g_{\text{DM}} = 1.5$



For “relatively large” quark coupling (g_{SM}) → **dijet constraints are very strong**

As g_{SM} gets weaker compared to g_{DM} → **dijet constraints becomes complementary to mono-X**

Constraining power in the off-shell region remains strong