

Trigger-Level Analysis at ATLAS

↗ Phys. Rev. D 112, 092015 (2025)

Tobias Fitschen on behalf of the analysis team

19 June 2026

↗ HEP Seminar - Imperial College London



<https://doi.org/10.1103/15p2-bkg8>

PHYSICAL REVIEW D **112**, 092015 (2025)

Search for electroweak-scale dijet resonances using trigger-level analysis with the ATLAS detector in 132 fb^{-1} of pp collisions at $\sqrt{s} = 13 \text{ TeV}$

G. Aad *et al.**
(ATLAS Collaboration)

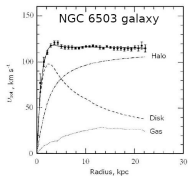


(Received 3 September 2025; accepted 14 October 2025; published 24 November 2025)

[arxiv:2509.01219](https://arxiv.org/abs/2509.01219) [aux material](#) [HepData](#)

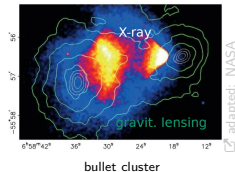
Abundant evidence for dark matter (DM) from astro physics and cosmology

Rotational curves

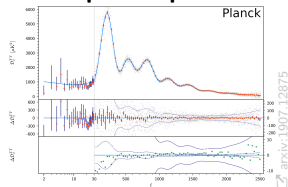


arxiv:0812.4005

Colliding galaxy clusters

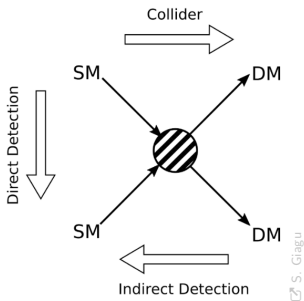


CMB power spectrum



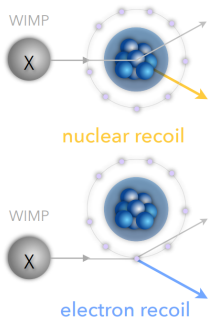
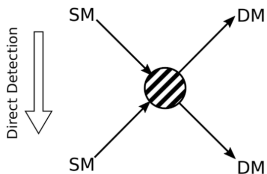
arxiv:1907.12875

So far DM evades detection as a particle



Direct detection

- Earth travels through galaxy's DM halo
- DM may rarely interact with atoms in large volumes of regular matter
- Goal: Measure signal of such interactions



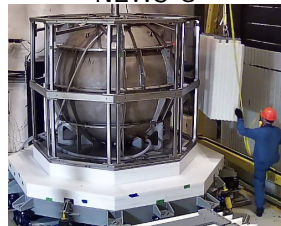
adapted: G. Fiorillo

Darkside 20k



50 tonnes of liquid Argon

NEWS-G

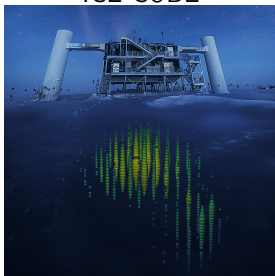
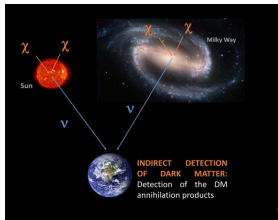
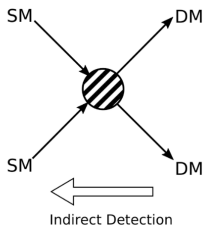


∅ = 135 cm copper sphere

snolab.ca/experiment/news-g

Indirect detection

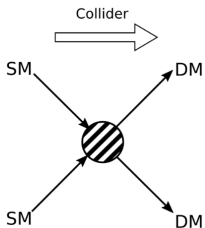
- DM may annihilate in regions with large abundance
 - Within galactic nuclei or stars
- Products (photons, neutrinos) may reach earth to be detected



neutrino observatory

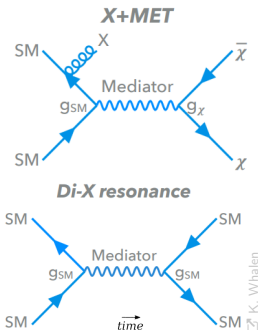


gamma ray telescope



Collider searches

- SM may interact with DM via mediator
- DM production: large missing energy (MET)
 - Together with SM product: $X + \text{MET}$
- $\text{SM} \rightarrow \text{BSM mediator} \rightarrow \text{SM}$
 - Di-X resonance search
 - This talk: Dij-jet resonance search

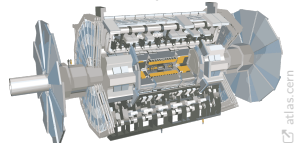


Large Hadron Collider (LHC)



$\sqrt{s} = 14 \text{ TeV } pp \text{ collider}$

ATLAS Experiment

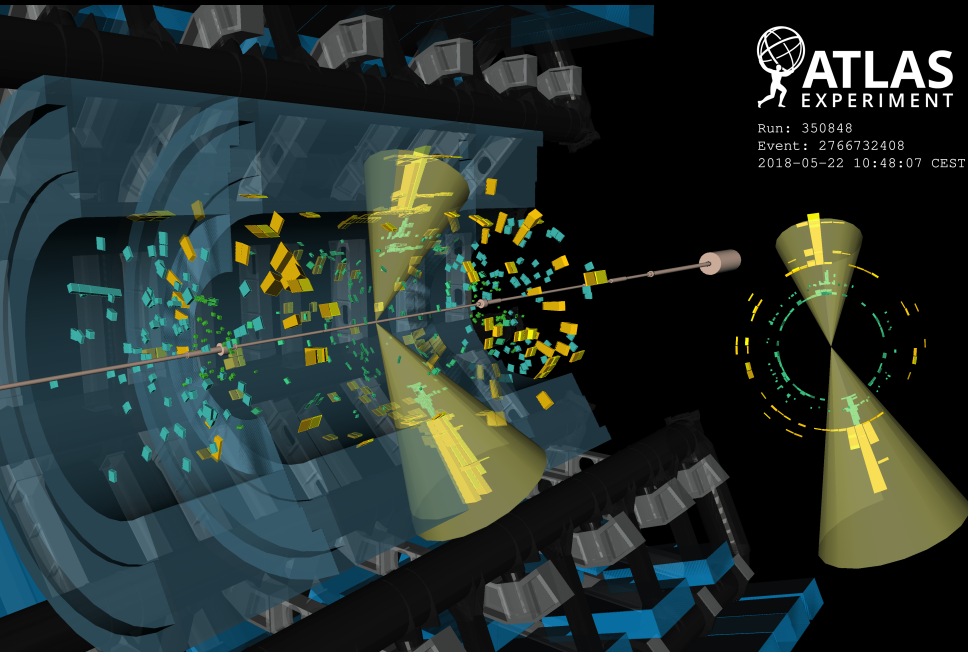


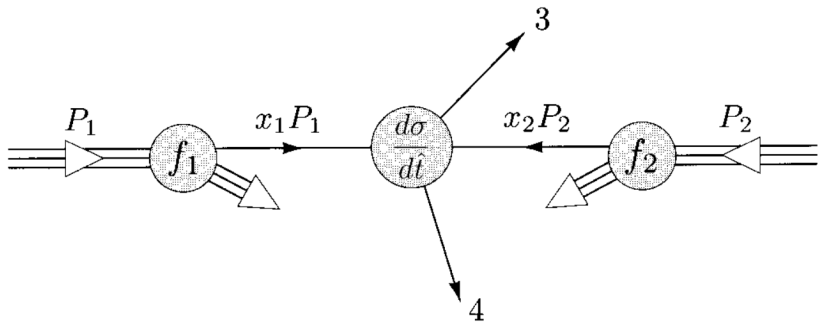
Particle detector at the LHC

Run: 350848

Event: 2766732408

2018-05-22 10:48:07 CEST





adapted from: Peskin & Schroeder

The total cross-section can be divided in 2 parts:

$$\frac{d^4\sigma}{dy_3 dy_4 d^2p_T} = \underbrace{x_1 f_1(x_1) x_2 f_2(x_2)}_{\text{proton PDFs}} \frac{1}{\pi} \underbrace{\frac{d\hat{\sigma}}{d\hat{t}}}_{\text{partonic cross section}} (1 + 2 \rightarrow 3 + 4)$$

Balanced transverse momenta $p_T^3 = p_T^4 \equiv p_T$

But rapidities may differ: $y_3 \neq y_4$ due to boost along beam axis ($x_1 \neq x_2$)

PDF: Probability to find parton with momentum fraction x in proton

→ dominates the shape of mass spectrum:

$$\frac{d\sigma}{dM^2} \propto \underbrace{x_1 f_1(x_1) x_2 f_2(x_2)}_{\text{proton PDFs}}$$

Dijet mass (parton level): $M = \sqrt{\hat{s}} = \sqrt{x_1 x_2} \sqrt{s}$

$\sqrt{\hat{s}}$: Parton CM energy (unknown)

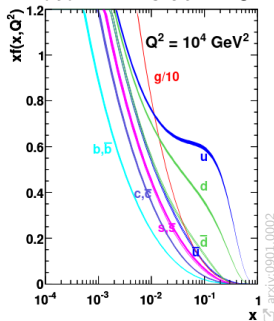
$\sqrt{s} = 13 \text{ TeV}$: LHC CM energy (Run 2)

High $M \rightarrow$ high $x_1, x_2 \rightarrow$ low $x_1 f(x_1), x_2 f(x_2)$

→ strongly suppressed by PDFs

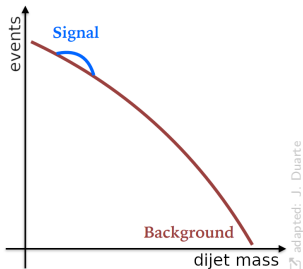
→ Steeply falling spectrum

Proton PDFs at NLO



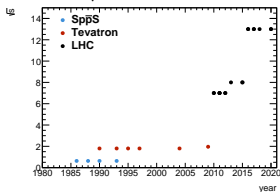
arXiv:0901.0002

Long history of dijet "bump hunts"
at hadron colliders

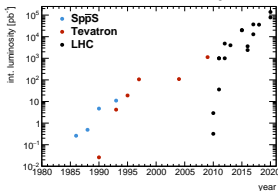


Expt.	Acc.	Year	\sqrt{s} [TeV]	$\int L dt$ [pb $^{-1}$]	m_{jj} range [TeV]	Ref.
UA1	Sp \bar{p} S	1986	0.63	0.26	0.07 - 0.3	ar1
UA1	Sp \bar{p} S	1988	0.63	0.49	0.11 - 0.3	ar2
CDF	Tevatron	1990	1.8	0.026	0.06 - 0.5	ar3
UA2	Sp \bar{p} S	1990	0.63	4.7	0.05 - 0.3	ar4
CDF	Tevatron	1993	1.8	4.2	0.14 - 1.0	ar5
UA2	Sp \bar{p} S	1993	0.63	11	0.05 - 0.3	ar6
CDF	Tevatron	1995	1.8	19	0.15 - 0.9	ar7
CDF	Tevatron	1997	1.8	106	0.18 - 1.0	ar8
D0	Tevatron	2004	1.8	109	0.18 - 1.2	ar9
CDF	Tevatron	2009	1.96	1130	0.18 - 1.3	ar10
ATLAS	LHC	2010	7	0.32	0.20 - 1.7	ar11
CMS	LHC	2010	7	2.9	0.22 - 2.1	ar12
ATLAS	LHC	2011	7	36	0.50 - 2.8	ar13
CMS	LHC	2011	7	1000	0.84 - 3.7	ar14
ATLAS	LHC	2011	7	1000	0.72 - 4.1	ar15
ATLAS	LHC	2012	7	1000	0.8 - 4.0	ar16
ATLAS	LHC	2012	7	4800	1.0 - 8.0	ar16
CMS	LHC	2013	8	4000	1.0 - 4.8	ar17
CMS	LHC	2015	8	19700	1.2 - 6.5	ar18
ATLAS	LHC	2015	8	20300	0.8 - 4.5	ar19
CMS	LHC	2016	13	2400	1.5 - 0.7	ar20
ATLAS	LHC	2016	13	3600	1.5 - 6.5	ar21
CMS	LHC	2017	13	12900	1.5 - 7.5	ar22
ATLAS	LHC	2017	13	37000	1.5 - 3.5	ar23
CMS	LHC	2018	13	36000	1.6 - 8.1	ar24
ATLAS	LHC	2020	13	139000	1.5 - 5.0	ar25
CMS	LHC	2020	13	77800	1.8 - 8.0	ar26

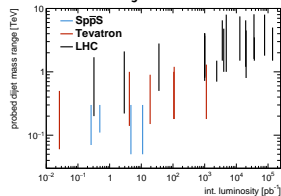
As \sqrt{s} increased...



so did the luminosity...

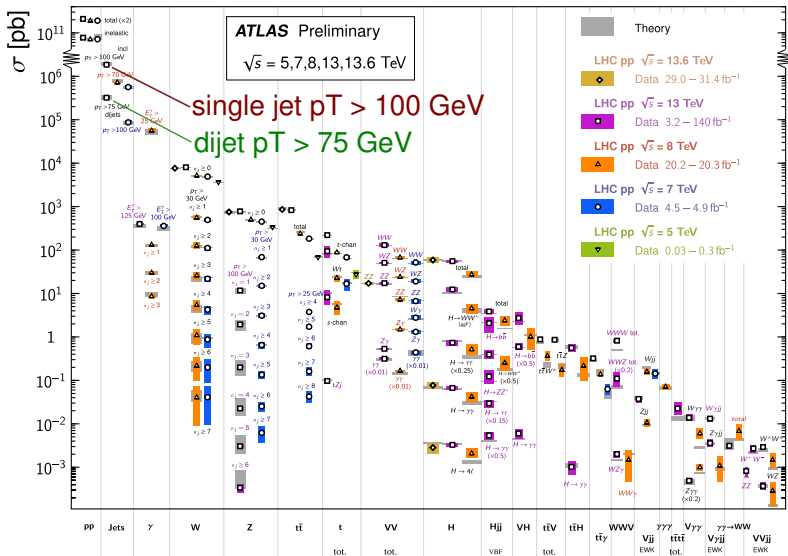


...and the dijet mass reach

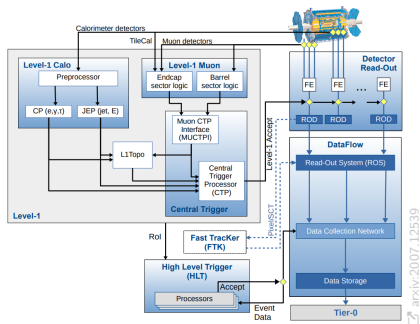


Standard Model Production Cross Section Measurements

Status: June 2024

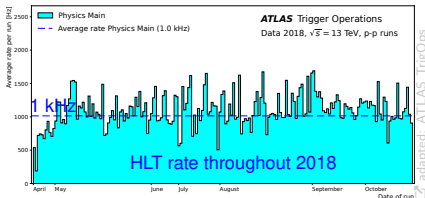


ATLAS Summary Plot

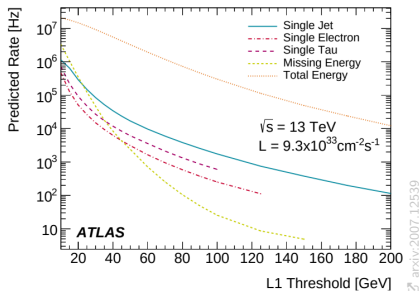


The ATLAS trigger system retains only a small fraction of the collisions

- Raw input: 30 MHz
- L1 hardware trigger: 100 kHz
- HLT software trigger: 1 kHz



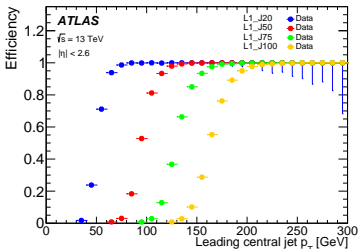
Predicted L1 rate vs p_T threshold



Many search targets lie at high p_T

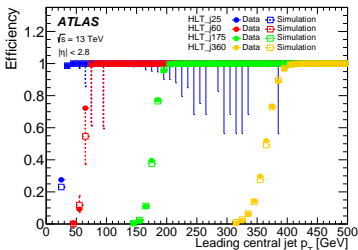
- Simple strategy: Pick a threshold and discard everything below
- Employed (better) strategy: Prescaling
 - Divide into multiple p_T thresholds with different "prescale factors" P
 - Retains only every P th event passing that threshold
 - Lower thresholds have larger prescale factors

L1 jet trigger efficiencies



arXiv:1611.09661

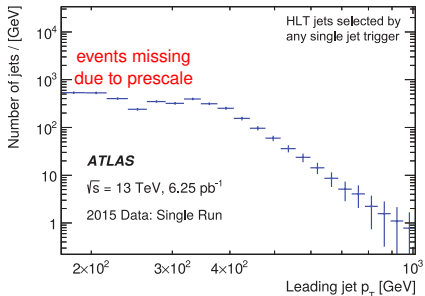
HLT jet trigger efficiencies



arXiv:1611.09661

- Multiple jet triggers at L1 and HLT
- With different p_T thresholds x :
 L1_J x and HLT_j x

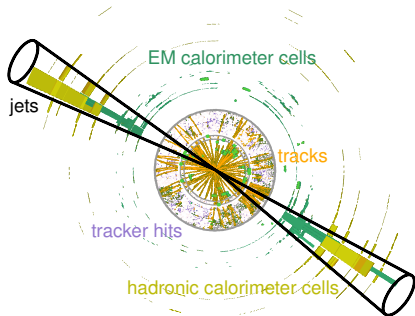
Resulting jet p_T after HLT



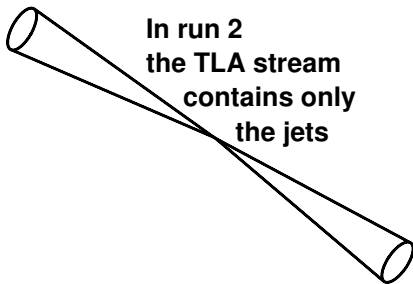
adapted: arXiv:1611.09661

Tapers out towards low p_T

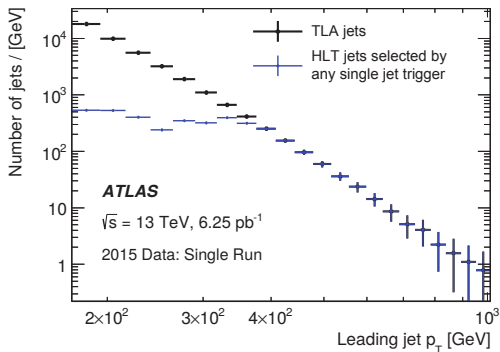
Physics Main Stream



TLA Stream



Lowest unprescaled HLT jet trigger: $p_T \gtrsim 400$ GeV



[arxiv:1611.09661](https://arxiv.org/abs/1611.09661)

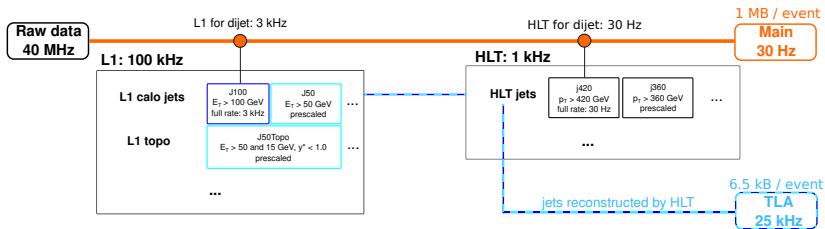
Which corresponds to a dijet mass of:

$$M = 4p_T^2 \cosh^2 y^* = 900 \text{ GeV}$$

$$\text{for } p_T = 400 \text{ GeV, } y^* = 0.6$$

For anything below that TLA outperforms Main

The **TLA** jet trigger stream runs in parallel to **Main**



The 1 kHz HLT rate limit is dictated by the readout bandwidth:

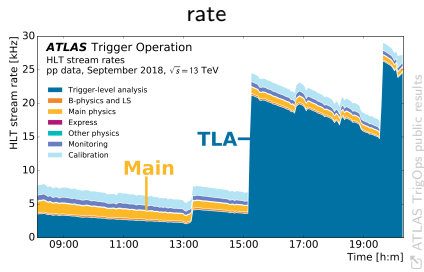
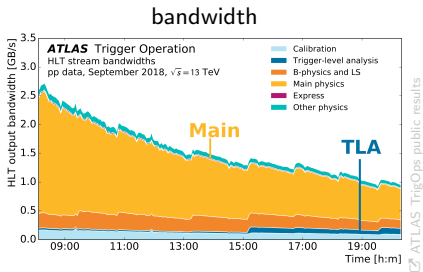
Bandwidth = rate \times event size

TLA greatly reduced event size ($\ll 1\%$ of Main)

→ Allows for much higher rate than Main

→ And all of it is jets!

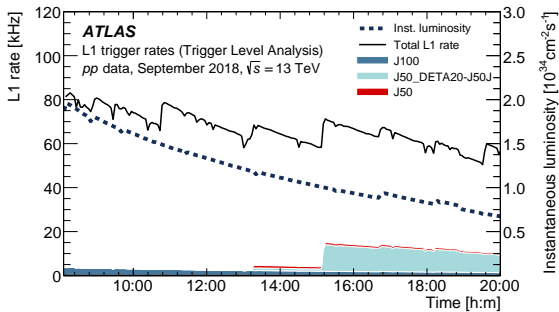
Trigger monitoring for one run in 2018:



- **Main**: 1kHz event rate
- **TLA**: Up to 25 kHz

There are two TLA datasets seeded by different L1 jet triggers:

- **J100**: 132 fb^{-1}
 - No prescale, active throughout all of Run 2
- **J50** (and **J50Topo**): 15 fb^{-1}
 - Prescaled, active at end of fills



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Decreasing luminosity at end of fill allows to enable higher rate triggers

- FPGA processors
- Allow kinematic cuts on combinations of objects
jets, taus, muons, missing E_T

J50_DELTA20-J50J (J50Topo):

→ Two L1 jets with:

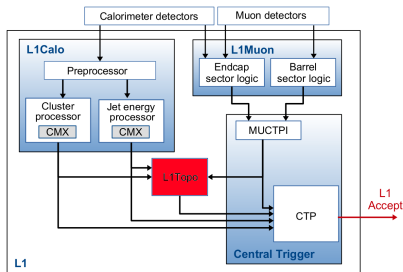
$$p_T^0 > 50 \text{ GeV} \ \& \ p_T^1 > 15 \text{ GeV}$$

and rapidity separation

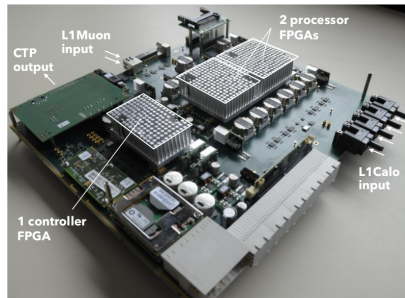
$$|y^*| = \frac{|y^1 - y^0|}{2} < 1$$

→ Similar to our analysis-level event selection

→ Especially suited for dijet

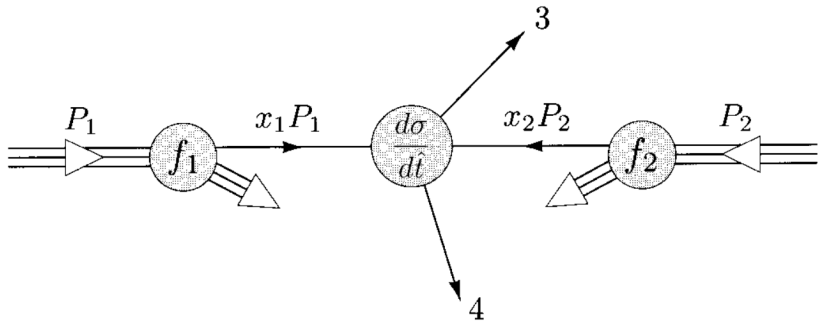


L1Topo module



adapted : arxiv:2509.01219

arxiv:2509.01219



adapted from: Peskin & Schroeder

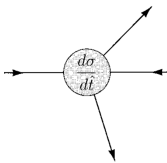
The total cross-section can be divided in 2 parts:

$$\frac{d^4\sigma}{dy_3 dy_4 d^2p_T} = \underbrace{x_1 f_1(x_1) x_2 f_2(x_2)}_{\text{proton PDFs}} \frac{1}{\pi} \underbrace{\frac{d\hat{\sigma}}{d\hat{t}}}_{\text{partonic cross section}} (1 + 2 \rightarrow 3 + 4)$$

Balanced transverse momenta $p_T^3 = p_T^4 \equiv p_T$

But rapidities may differ: $y_3 \neq y_4$ due to boost along beam axis ($x_1 \neq x_2$)

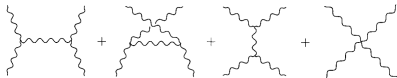
cross-section of hard process



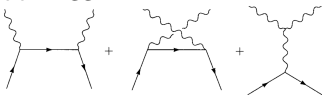
Each of the 4
partons can be
any type of quark
or gluon

Many subprocesses:

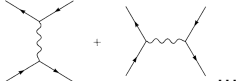
$gg \rightarrow gg$



$q\bar{q} \rightarrow gg$



$q\bar{q} \rightarrow q\bar{q}$



↑
time

Subprocess

$$\frac{\hat{s}^2}{\pi\alpha_s^2} \frac{d\hat{\sigma}}{d\hat{t}}(ij \rightarrow kl)$$

$q_1 q_2 \rightarrow q_1 q_2$

$$\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$

$q_1 \bar{q}_2 \rightarrow q_1 \bar{q}_2$

$$\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$

$qq \rightarrow qq$

$$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{\hat{u}\hat{t}}$$

$q_1 \bar{q}_1 \rightarrow q_2 \bar{q}_2$

$$\frac{4}{9} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$$

$q\bar{q} \rightarrow q\bar{q}$

$$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s}\hat{t}}$$

$q\bar{q} \rightarrow gg$

$$\frac{32}{27} \frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$$

$gg \rightarrow q\bar{q}$

$$\frac{1}{6} \frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}} - \frac{3}{8} \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2}$$

$gq \rightarrow gq$

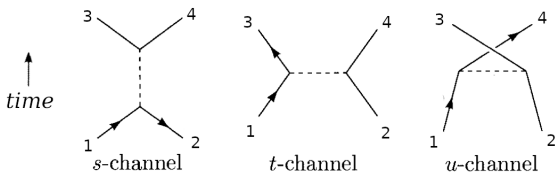
$$-\frac{4}{9} \frac{\hat{s}^2 + \hat{u}^2}{\hat{s}\hat{u}} + \frac{\hat{u}^2 + \hat{s}^2}{\hat{t}^2}$$

$gg \rightarrow gg$

$$\frac{9}{2} \left(3 - \frac{\hat{t}\hat{u}}{\hat{s}^2} - \frac{\hat{s}\hat{u}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2} \right)$$

$\hat{s}, \hat{t}, \hat{u}$: Mandelstam variables

The t-Channel Pole

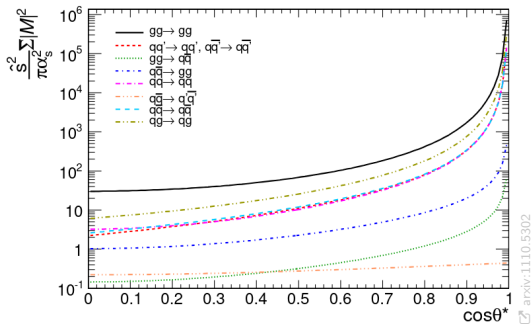


$$\hat{s} = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

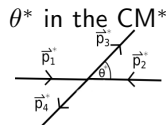
$$\hat{t} = (p_1 - p_3)^2 = (p_4 + p_2)^2$$

$$\hat{u} = (p_1 - p_4)^2 = (p_3 + p_2)^2$$

Determine the θ^* dependence for each subprocess:



With scattering angle



For massless partons:

$$\hat{s} = M^2 = \frac{4p_T^2}{\sin^2\theta^*}$$

$$\hat{t} = -\frac{\hat{s}}{2}(1 - \cos\theta^*)$$

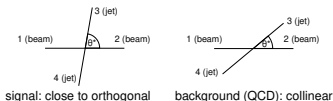
$$\hat{u} = -\frac{\hat{s}}{2}(1 + \cos\theta^*)$$

Most behave like Rutherford scattering: $\propto \frac{1}{(1 - \cos\theta^*)^2}$

BSM signals with resonant decays have very different $\cos\theta^*$ dependence:

relations from: arxiv:1110.5302

BSM model	$\frac{d\hat{\sigma}}{d\cos\theta^*}$
E_6 diquark, color octet scalars	constant
excited quarks	$\propto 1 + \cos^2\theta^*$
$W', Z',$ axigluon, coloron	$\propto 1 + \cos^2\theta^*$
RS graviton $gg \rightarrow G \rightarrow q\bar{q}$	$\propto 1 - \cos^4\theta^*$
RS graviton $gg \rightarrow G \rightarrow gg$	$\propto 1 + 6\cos^2\theta^* + \cos^4\theta^*$
RS graviton $q\bar{q} \rightarrow G \rightarrow q\bar{q}$	$\propto 1 - 3\cos^2\theta^* + 4\cos^4\theta^*$
QCD dijet	$1/(1 - \cos^2\theta^*)^2$



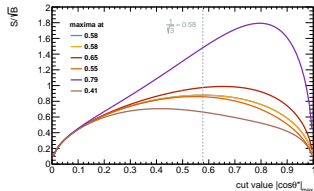
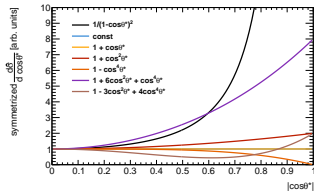
Allows to derive optimal $|\cos\theta^*|_{\max}$ cut for best S/\sqrt{B} :

$$S \propto \int_{-\cos\theta^*_{\max}}^{+\cos\theta^*_{\max}} \text{const } d\cos\theta^* = 2\cos\theta^*_{\max}$$

$$B \propto \int_{-\cos\theta^*_{\max}}^{+\cos\theta^*_{\max}} \frac{1}{(1 - \cos^2\theta^*)^2} d\cos\theta^* = \frac{2\cos\theta^*_{\max}}{1 - \cos^2\theta^*_{\max}}$$

$$\Rightarrow \frac{S}{\sqrt{B}} = \frac{2\cos\theta^*_{\max}}{\sqrt{\frac{2\cos\theta^*_{\max}}{1 - \cos^2\theta^*_{\max}}}} \rightarrow \text{maximum at } \cos\theta^*_{\max} = \frac{1}{\sqrt{3}}$$

$$\cos\theta^* = \tanh y^* \Rightarrow \text{best } y^* \text{ cut: } \tanh^{-1} \frac{1}{\sqrt{3}} \approx 0.66$$



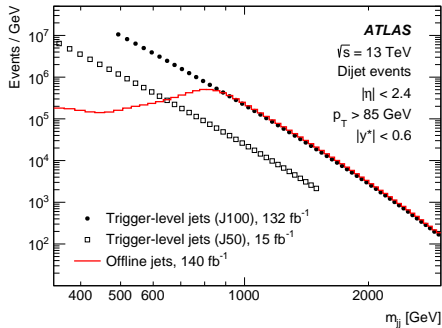
TLA Run 2 TLA dataset has:

- > 60 billion events in J100
- > 40 billion in J50 (overlaps with J100)
- For comparison: All of Physics Main in Run1 & 2 combined:
 \approx 25 billion events ([↗ source](#))

	cutflow	J50 dataset	J100 dataset
	initial	40 763 638 635	62 285 765 243
$ \eta^{0,1} < 2.4$, veto $1.0 < \eta^{0,1} < 1.6$		17 640 375 792	27 460 791 144
$p_T^{0,1} > 85$ GeV		7 261 455 769	15 827 611 199
$ y^* < 0.6$		3 964 040 080	8 348 429 622
trigger: J50(Topo) or J100		2 666 093 601	5 549 390 857
J50: $m_{jj} > 344$ GeV		351 223 259	—
J100: $m_{jj} > 481$ GeV		—	765 234 799

↗ HepData:161624

After Event selection: > 0.3 & > 0.7 billion events



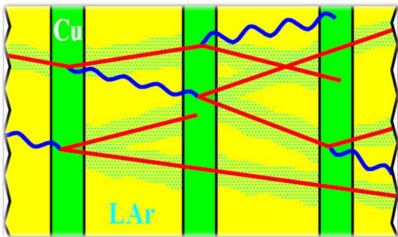
Phys. Rev. D 112, 092015

- Advantage over **offline** (physics main) dataset at $m_{jj} \ll 1 \text{ TeV}$

Getting the jet energy right demands calibration

The ATLAS calorimeter

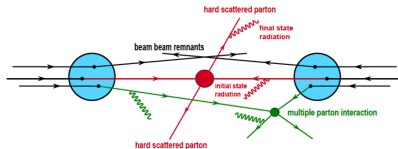
- Non-compensating:
 - Different response to EM and hadronic signals
- Sampling:
 - Not all material is active



© P. Loch

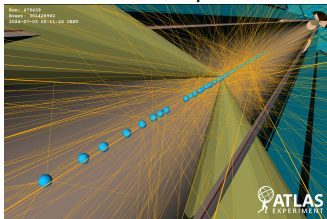
Additional effects from collisions

Underlying event



© O. Kepka

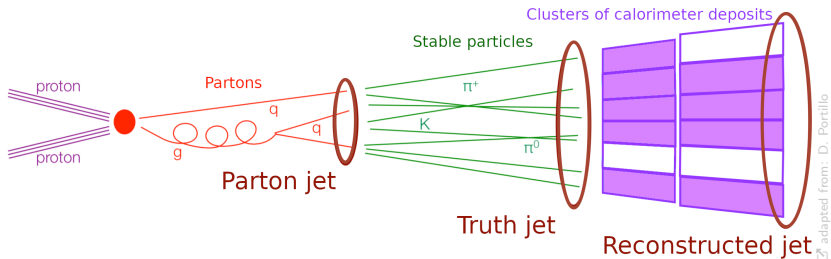
Pileup



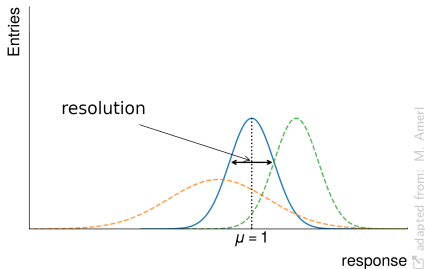
© ATLAS Public Event Display

(dijet event at $\mu = 65$)

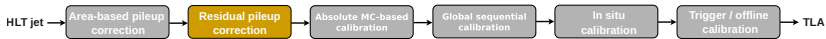
... and many more effects ...



- ΔR -match isolated reco to truth jets in MC
- Response $\frac{p_T^{\text{reco}}}{p_T^{\text{truth}}}$
- Gaussian fit determined mode of distribution
- Resolution: Width of response distribution



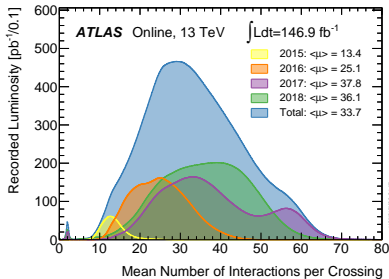
→ Calibration factor: Inverse of response binned in e.g. p_T , η etc



Residual pileup correction

- After area-based correction residual pileup dependencies remain
- Offline: Corrected for two pileup-estimators:
 - N_{PV} : Number of primary vertices
 - μ : Average number of interactions per bunch crossing

μ throughout Run 2



$$p_T^{\text{res}} = p_T^{\text{area}} - \alpha \frac{\partial p_T}{\partial N_{PV}} (N_{PV} - 1) - \beta \frac{\partial p_T}{\partial \mu} \mu$$

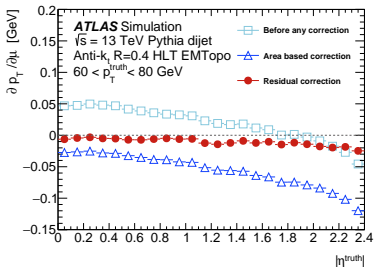
- TLA: Good closure achieved with regards to μ term
- NPV term not possible for trigger jets due to lack of tracking in TLA



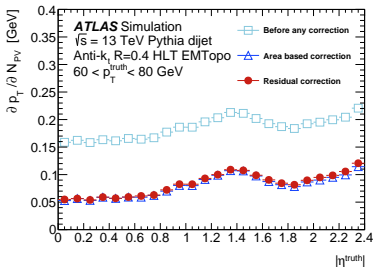
μ dependence

N_{PV} dependence

Trigger-Level

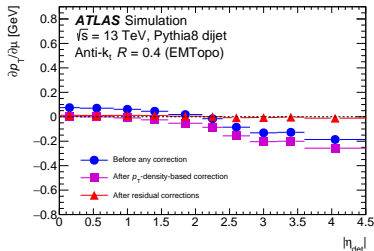


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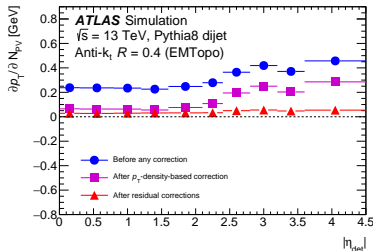


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Offline



JETM-2018-05



JETM-2018-05



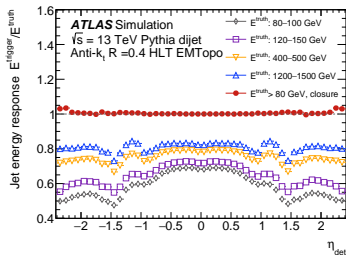
Absolute MC-based calibration

- Performs bulk of response calibration
- Corrects according to response measured in MC
- Small angular correction to η
- Response binned in E , η fitted with functional form:

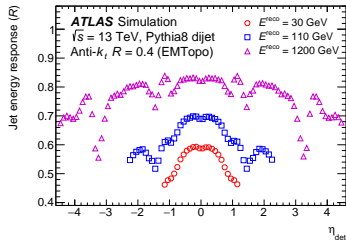
$$\mathcal{F}_{JES}(E^{\text{truth}}) \sum_{i=0}^{N_{\text{max}}} a_i (\ln E^{\text{truth}})^i$$

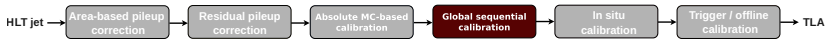
- Calibration factors from numerical inversion
- Excellent closure of E across η

Trigger-Level



Offline

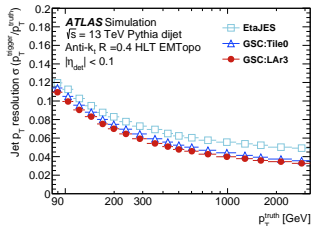




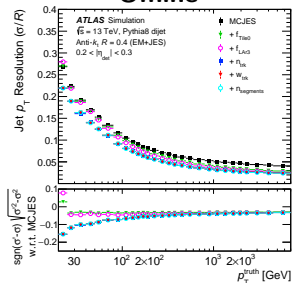
Global sequential calibration

- Improves resolution
- While leaving response unchanged
- Idea: Different populations of jets have higher/lower response
- Correcting them individually towards the mean improves overall resolution
- Only 2 out of the 5 GSC variables are available in TLA
- But they are the main contributors
- Missing: Track- and muon-based variables: n_{trk} , w_{trk} , n_{segments}
- Still: Considerable improvement in resolution from TLA GSC

Trigger-Level

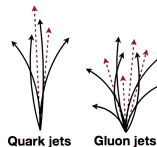


Offline

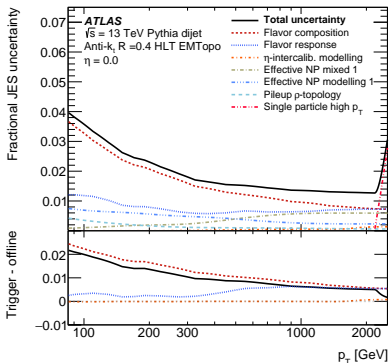




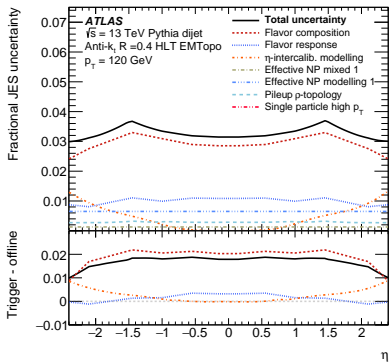
- Quark- and gluon-initiated jets differ in response
- Lack of tracking in TLA does not allow for q/g-sensitive GSC steps: n_{trk} (number of tracks), w_{trk} (track-width)
- Rederived flavour-composition and -response uncertainty



adapted from: J. Babbar



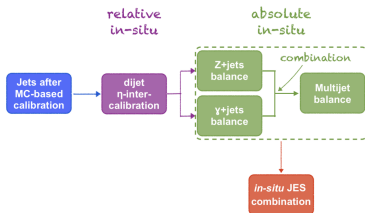
Phys. Rev. D 112, 092015



Phys. Rev. D 112, 092015



- All previous steps are applied to MC and data
- In situ: only applied to data
- Corrects for residual differences in data/MC



Relative in situ calibration

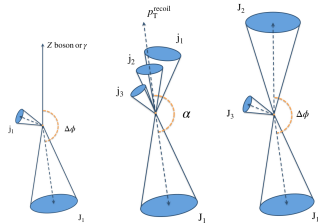
- Use well measured central jets to constrain forward jet momenta

Absolute in situ calibration

- Use balance of jets against well measured objects (photons, multiple jets)
- Factors derived for offline jets also used for trigger jets

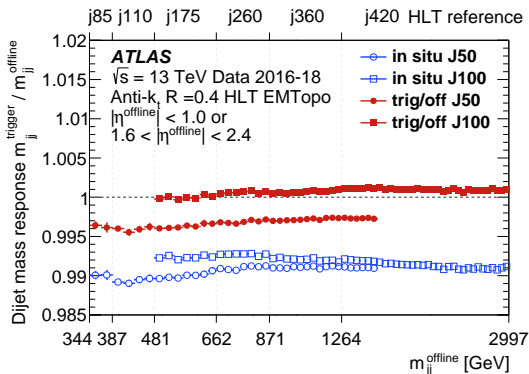
Relative *in-situ* JES: correct jets with $|\eta| > 0.8$ to the same energy scale as $|\eta| < 0.8$

Absolute *in-situ* JES: correct jets with $|\eta| < 0.8$ to a precise reference object





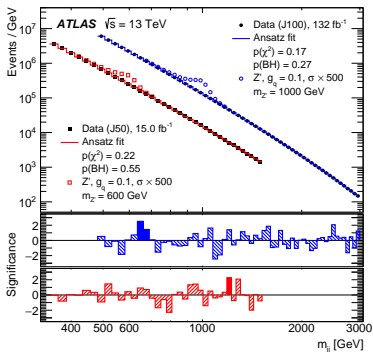
Trigger/offline jet correction brings trigger jets to offline scale



- Allows use of most uncertainties derived for offline jets
- Derived independently for each year (2016, 2017, 2018) and dataset (J50, J100) to compensate for different pileup conditions
- Excellent closure within 5 per-mille both in m_{jj} and in p_T

Data-driven background estimate

- With dijet m_{jj} functional form
- Observed m_{jj} spectrum consistent with bkg-only hypothesis
- Bump-Hunter identifies most significant excess at 650 GeV
 - Global BH p-value: 0.27



$$f(x) = \underbrace{p_1(1-x)p_2 x \sum_{i=3}^N p_i \log^{(i-3)}(x)}_{\text{dijet function}} \underbrace{\left(1 + \sum_{j=1}^{n_{\text{sys}}} \theta_j \sum_{k=1}^5 c_{jk} x^k \right)}_{\text{jet systematics}} \quad \text{with } x = \frac{m}{\sqrt{s}}$$

$$f(x) = \left[\text{dijet function plot} \right] \times \left(1 + \theta_1 \times \left[\text{jet systematics plot 1} \right] + \theta_2 \times \left[\text{jet systematics plot 2} \right] + \dots \right)$$

© F. Barcels

→ Tests following ATLAS' ["Recommendations for the Modeling of Smooth Backgrounds"](#)

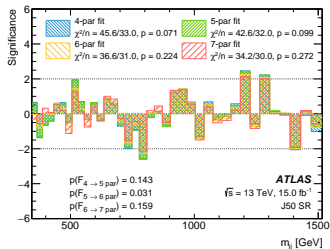
F-test

- Used to determine number of parameters N in fit function
- Choose N for which $N + 1$ does not significantly improve goodness-of-fit p -value by > 0.05
- Resulting choice:
 $\rightarrow N = 6$ both in J50 and J100

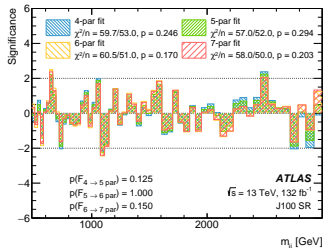
Additional tests (backup)

- Spurious signal
- Signal injection
- Coverage

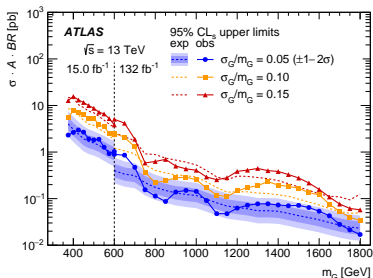
J50



J100

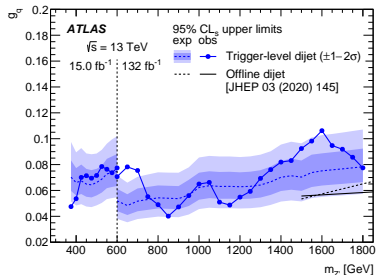


Gaussian



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Z'



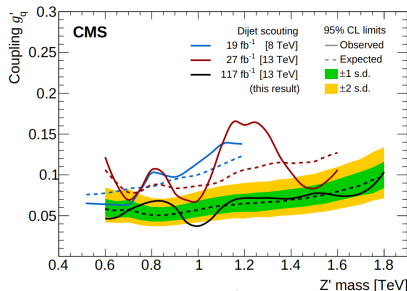
Phys. Rev. D 112, 092015

- Limits on Z' and Gaussian resonances (5%, 10%, 15% width)
- Starting at 375 GeV
- Most significant excess at 650 GeV for Z' (3.4 σ local, 2.2 σ global)

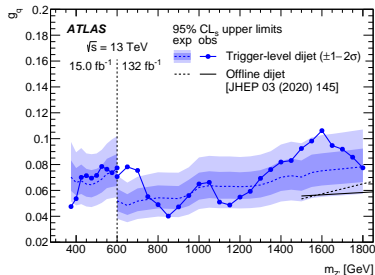
CMS recently presented their full Run 2 dijet scouting analysis

- [arxiv:2510.21641](https://arxiv.org/abs/2510.21641)
- ATLAS TLA \approx CMS Scouting
- Limits compatible with us at > 600 GeV
- Do not set limits below 600 GeV
where ours uses J50 dataset
- CMS published multiple data scouting analyses before

CMS



ATLAS



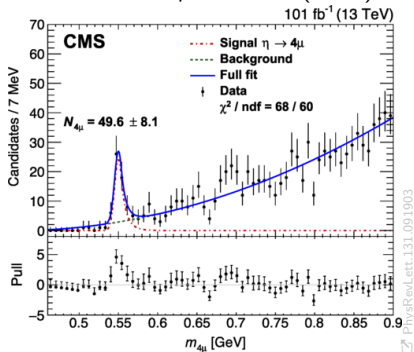
[arxiv:2510.21641](https://arxiv.org/abs/2510.21641)

[arxiv:2510.21641](https://arxiv.org/abs/2510.21641)

TLA / Data Scouting publications

experiment	signature	mass range [GeV]	publication
ATLAS	dijet	450-1800	↗ PRL 121 (2018) 081801
	dijet	375-1800	↗ Phys. Rev. D 112, 092015 (2025)
CMS	dijet	600-1800	↗ arxiv:2510.21641
	dijet	500-900	↗ CMS-PAS-EXO-11-094
	dijet	500-800	↗ PRL 117 (2016) 031802
	dijet	600-1600	↗ PLB 769 (2017) 520
	dijet	600-1600	↗ JHEP 08 (2018) 130
	pair of 3j	200-700	↗ Phys. Rev. D 99, 012010
	dijet + ISR jet	350-700	↗ PLB 805 (2020) 135448
	LLP→di- μ	10-50	↗ Phys. Rev. 124, 131802
	LLP→di- μ	0.6-50	↗ JHEP 04 (2022) 062
	multi- μ ($\eta \rightarrow 4\mu$)	0.45-40	↗ CMS-PAS-BPH-22-003
	L1-DS heavy LLP di- μ	1000-7000	↗ arxiv:2601.20063
di- τ	20 - 60	↗ arxiv:2605.25103	

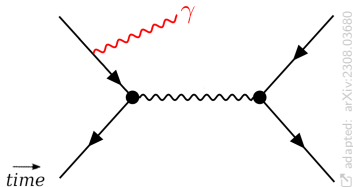
CMS multi- μ , 13 TeV (2022)



- 101 fb⁻¹ (2017 & 2018)
- First $\eta \rightarrow 4\mu$ observation!

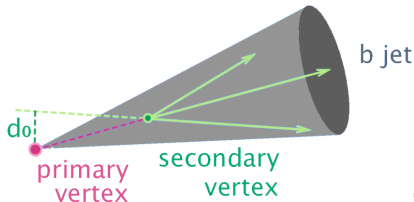
Initial State Radiation (ISR)

Trigger on ISR (γ or jet) instead



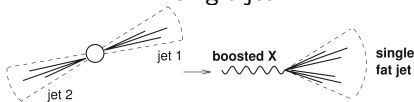
b-tagging

b-initiated jets are much less abundant



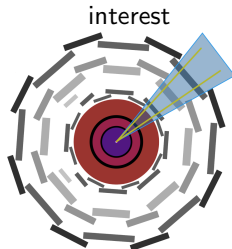
Boosted large-R jets

Reconstruct highly collimated dijets in single jet



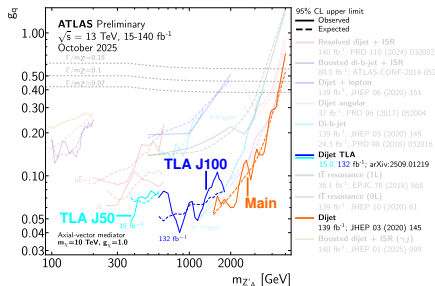
Partial Event Building (PEB)

Save full data but only in region of interest



Multiple techniques (and combinations) are needed to span the full mass range

Expt.	Year	\sqrt{s} [TeV]	$\int L dt$ [pb^{-1}]	m_{jj} range [TeV]	Ref.	technique
UA1	1986	0.63	0.26	0.07 - 0.3	<i>or</i> 1	
UA1	1988	0.63	0.49	0.11 - 0.3	<i>or</i> 2	
CDF	1990	1.8	0.026	0.06 - 0.5	<i>or</i> 3	
UA2	1990	0.63	4.7	0.05 - 0.3	<i>or</i> 4	
CDF	1993	1.8	4.2	0.14 - 1.0	<i>or</i> 5	
UA2	1993	0.63	11	0.05 - 0.3	<i>or</i> 6	
CDF	1995	1.8	19	0.15 - 0.9	<i>or</i> 7	
CDF	1997	1.8	106	0.18 - 1.0	<i>or</i> 8	
D0	2004	1.8	109	0.18 - 1.2	<i>or</i> 9	
CDF	2009	1.96	1130	0.18 - 1.3	<i>or</i> 10	
ATLAS	2010	7	0.32	0.20 - 1.7	<i>or</i> 11	
CMS	2010	7	2.9	0.22 - 2.1	<i>or</i> 12	
ATLAS	2011	7	36	0.50 - 2.8	<i>or</i> 13	
CMS	2011	7	1000	0.84 - 3.7	<i>or</i> 14	
ATLAS	2011	7	1000	0.72 - 4.1	<i>or</i> 15	
ATLAS	2012	7	1000	0.8 - 4.0	<i>or</i> 16	
ATLAS	2012	7	4800	1.0 - 8.0	<i>or</i> 17	
CMS	2013	7	5000	1.0 - 4.0	<i>or</i> 18	b-tagged
CMS	2013	8	4000	1.0 - 4.8	<i>or</i> 18	
CMS	2015	8	19700	1.2 - 6.5	<i>or</i> 19	
ATLAS	2015	8	20300	0.8 - 4.5	<i>or</i> 20	
CMS	2016	8	18800	0.5 - 0.8	<i>or</i> 21	scouting
CMS	2016	13	2400	1.5 - 0.7	<i>or</i> 22	
ATLAS	2016	13	3200	1.1 - 5.0	<i>or</i> 23	b-tagged
ATLAS	2016	13	3600	1.5 - 6.5	<i>or</i> 24	
CMS	2017	13	12900	0.6 - 1.5	<i>or</i> 25	scouting
CMS	2017	13	12900	1.5 - 7.5	<i>or</i> 25	
ATLAS	2017	13	37000	1.5 - 3.5	<i>or</i> 26	
ATLAS	2018	13	29300	0.45 - 1.8	<i>or</i> 27	TLA
ATLAS	2018	13	36100	0.57 - 7.0	<i>or</i> 28	b-tagged
CMS	2018	13	36000	1.6 - 8.1	<i>or</i> 29	
CMS	2018	13	27000	0.6 - 1.6	<i>or</i> 30	scouting
CMS	2018	13	19700	0.325 - 1.2	<i>or</i> 31	b-tagged
ATLAS	2019	13	36100	0.1 - .22	<i>or</i> 32	boosted + ISR (γ, j)
ATLAS	2020	13	139000	1.5 - 5.0	<i>or</i> 33	
CMS	2020	13	77800	1.8 - 8.0	<i>or</i> 34	
CMS	2020	13	18300	0.35 - 0.7	<i>or</i> 35	ISR j
CMS	2023	13	138000	1.8 - 2.4	<i>or</i> 36	b-tagged
ATLAS	2025	13	140000	0.2 - 0.65	<i>or</i> 37	ISR (γ, j)
ATLAS [†]	2025	13	132000	0.375 - 1.8	<i>or</i> 38	TLA
CMS*	2025	13	117100	0.6 - 1.8	<i>or</i> 39	scouting

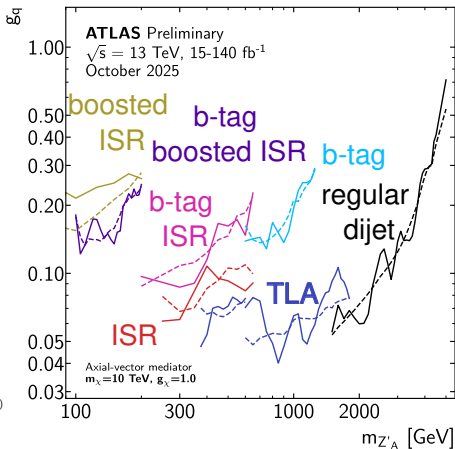


ATLAS-PHYS-PUB-2025-041

*:preliminary, †: this publication

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UA1	1986	0.63	0.26	0.07 - 0.3	ar1	
UA1	1988	0.63	0.49	0.11 - 0.3	ar2	
CDF	1990	1.8	0.026	0.06 - 0.5	ar3	
UA2	1990	0.63	4.7	0.05 - 0.3	ar4	
CDF	1993	1.8	4.2	0.14 - 1.0	ar5	
UA2	1993	0.63	11	0.05 - 0.3	ar6	
CDF	1995	1.8	19	0.15 - 0.9	ar7	
CDF	1997	1.8	106	0.18 - 1.0	ar8	
D0	2004	1.8	109	0.18 - 1.2	ar9	
CDF	2009	1.96	1130	0.18 - 1.3	ar10	
ATLAS	2010	7	0.32	0.20 - 1.7	ar11	
CMS	2010	7	2.9	0.22 - 2.1	ar12	
ATLAS	2011	7	36	0.50 - 2.8	ar13	
CMS	2011	7	1000	0.84 - 3.7	ar14	
ATLAS	2011	7	1000	0.72 - 4.1	ar15	
ATLAS	2012	7	1000	0.8 - 4.0	ar16	
ATLAS	2012	7	4800	1.0 - 8.0	ar17	
CMS	2013	7	5000	1.0 - 4.0	ar18	b-tagged
CMS	2013	8	4000	1.0 - 4.8	ar18	
CMS	2015	8	19700	1.2 - 6.5	ar19	
ATLAS	2015	8	20300	0.8 - 4.5	ar20	
CMS	2016	8	18800	0.5 - 0.8	ar21	scouting
CMS	2016	13	2400	1.5 - 0.7	ar22	
ATLAS	2016	13	3200	1.1 - 5.0	ar23	b-tagged
ATLAS	2016	13	3600	1.5 - 6.5	ar24	
CMS	2017	13	12900	0.6 - 1.5	ar25	scouting
CMS	2017	13	12900	1.5 - 7.5	ar25	
ATLAS	2017	13	37000	1.5 - 3.5	ar26	
ATLAS	2018	13	29300	0.45 - 1.8	ar27	TLA
ATLAS	2018	13	36100	0.57 - 7.0	ar28	b-tagged
CMS	2018	13	36000	1.6 - 8.1	ar29	
CMS	2018	13	27000	0.6 - 1.6	ar30	scouting
CMS	2018	13	19700	0.325 - 1.2	ar31	b-tagged
ATLAS	2019	13	36100	0.1 - .22	ar32	boosted + ISR (γ, j)
ATLAS	2020	13	139000	1.5 - 5.0	ar33	
CMS	2020	13	77800	1.8 - 8.0	ar34	
CMS	2020	13	18300	0.35 - 0.7	ar35	ISR j
CMS	2023	13	138000	1.8 - 2.4	ar36	b-tagged
ATLAS	2025	13	140000	0.2 - 0.65	ar37	ISR (γ, j)
ATLAS†	2025	13	132000	0.375 - 1.8	ar38	TLA
CMS*	2025	13	117100	0.6 - 1.8	ar39	scouting

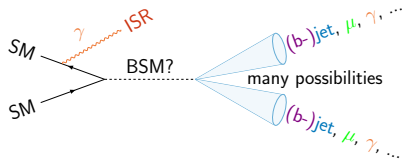


*:preliminary, †: this publication

Expt.	Year	\sqrt{s} [TeV]	$\int Ldt$ [pb^{-1}]	m_{jj} range [TeV]	Ref.	technique
UA1	1986	0.63	0.26	0.07 - 0.3	<i>ar1</i>	
UA1	1988	0.63	0.49	0.11 - 0.3	<i>ar2</i>	
CDF	1990	1.8	0.026	0.06 - 0.5	<i>ar3</i>	
UA2	1990	0.63	4.7	0.05 - 0.3	<i>ar4</i>	
CDF	1993	1.8	4.2	0.14 - 1.0	<i>ar5</i>	
UA2	1993	0.63	11	0.05 - 0.3	<i>ar6</i>	
CDF	1995	1.8	19	0.15 - 0.9	<i>ar7</i>	
CDF	1997	1.8	106	0.18 - 1.0	<i>ar8</i>	
D0	2004	1.8	109	0.18 - 1.2	<i>ar9</i>	
CDF	2009	1.96	1130	0.18 - 1.3	<i>ar10</i>	
ATLAS	2010	7	0.32	0.20 - 1.7	<i>ar11</i>	
CMS	2010	7	2.9	0.22 - 2.1	<i>ar12</i>	
ATLAS	2011	7	36	0.50 - 2.8	<i>ar13</i>	
CMS	2011	7	1000	0.84 - 3.7	<i>ar14</i>	
ATLAS	2011	7	1000	0.72 - 4.1	<i>ar15</i>	
ATLAS	2012	7	1000	0.8 - 4.0	<i>ar16</i>	
ATLAS	2012	7	4800	1.0 - 8.0	<i>ar17</i>	
CMS	2013	7	5000	1.0 - 4.0	<i>ar18</i>	b-tagged
CMS	2013	8	4000	1.0 - 4.8	<i>ar18</i>	
CMS	2015	8	19700	1.2 - 6.5	<i>ar19</i>	
ATLAS	2015	8	20300	0.8 - 4.5	<i>ar20</i>	
CMS	2016	8	18800	0.5 - 0.8	<i>ar21</i>	scouting
CMS	2016	13	2400	1.5 - 0.7	<i>ar22</i>	
ATLAS	2016	13	3200	1.1 - 5.0	<i>ar23</i>	b-tagged
ATLAS	2016	13	3600	1.5 - 6.5	<i>ar24</i>	
CMS	2017	13	12900	0.6 - 1.5	<i>ar25</i>	scouting
CMS	2017	13	12900	1.5 - 7.5	<i>ar25</i>	
ATLAS	2017	13	37000	1.5 - 3.5	<i>ar26</i>	
ATLAS	2018	13	29300	0.45 - 1.8	<i>ar27</i>	TLA
ATLAS	2018	13	36100	0.57 - 7.0	<i>ar28</i>	b-tagged
CMS	2018	13	36000	1.6 - 8.1	<i>ar29</i>	
CMS	2018	13	27000	0.6 - 1.6	<i>ar30</i>	scouting
CMS	2018	13	19700	0.325 - 1.2	<i>ar31</i>	b-tagged
ATLAS	2019	13	36100	0.1 - .22	<i>ar32</i>	boosted + ISR (γ, j)
ATLAS	2020	13	139000	1.5 - 5.0	<i>ar33</i>	
CMS	2020	13	77800	1.8 - 8.0	<i>ar34</i>	
CMS	2020	13	18300	0.35 - 0.7	<i>ar35</i>	ISR j
CMS	2023	13	138000	1.8 - 2.4	<i>ar36</i>	b-tagged
ATLAS	2025	13	140000	0.2 - 0.65	<i>ar37</i>	ISR (γ, j)
ATLAS [†]	2025	13	132000	0.375 - 1.8	<i>ar38</i>	TLA
CMS*	2025	13	117100	0.6 - 1.8	<i>ar39</i>	scouting

Multiple techniques (and combinations) are needed to span the full mass range

Run 3 ATLAS TLA



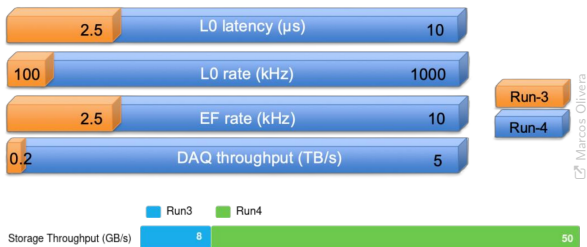
- Track-assisted jets (Pflow)
- More objects (not just jets)
- Partial Event Building
- Flavour-tagging

(see ATLAS Phase II Trigger Technical Design Report)

*:preliminary, †: this publication

ATLAS at the HL-LHC: L1 \rightarrow L0, HLT \rightarrow Event Filter (EF)

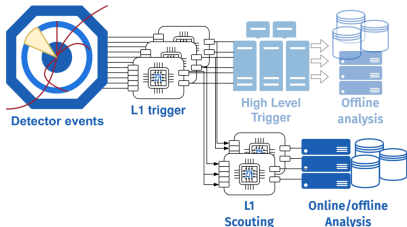
- HL-LHC increases rates by
 - L1 \rightarrow L0: $\times 10$
 - HLT \rightarrow EF: $\times 4$
- And throughput:
 - DAQ by $\times 50$
 - Storage by $\times 7$



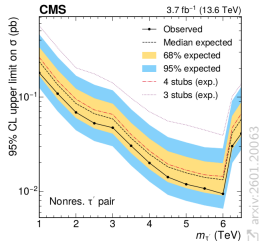
- Great opportunity for TLA to recover losses from L0 to EF:
 - Run 3: HLT/L1 = 2.5%
 - Run 4: EF/L0 = 1.0%

(source: [ATLAS Phase II Trigger Technical Design Report](#))

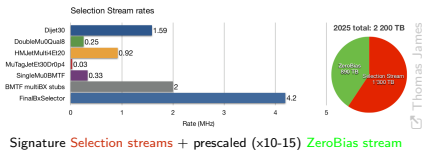
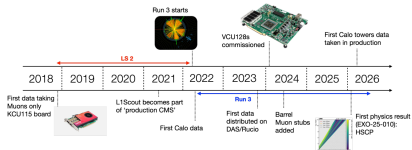
- CMS is committed to ambitious TLA (scouting) programme
- Including L1-scouting at the full 40 MHz (trigger-less)



Demonstrated capability in Run 3 with first L1-Scouting paper:
Slow LLPs via muon stubs reconstructed across multiple bunch-crossings



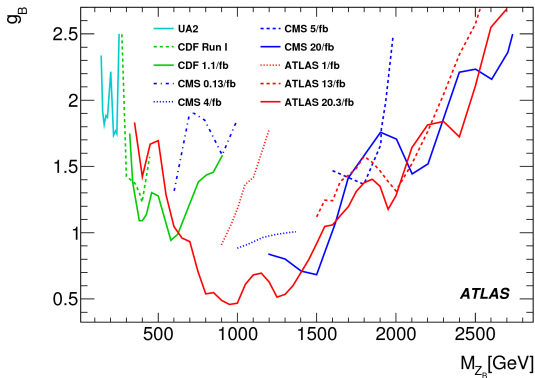
CMS L1-Scouting demonstrator boards operational since end of Run 2



- **TLA is a great tool to increase physics reach**
- **With very limited cost on bandwidth**
- **Great potential in Run 3 and beyond**
- **Unconventional analyses expose you to many aspects of the experiment**

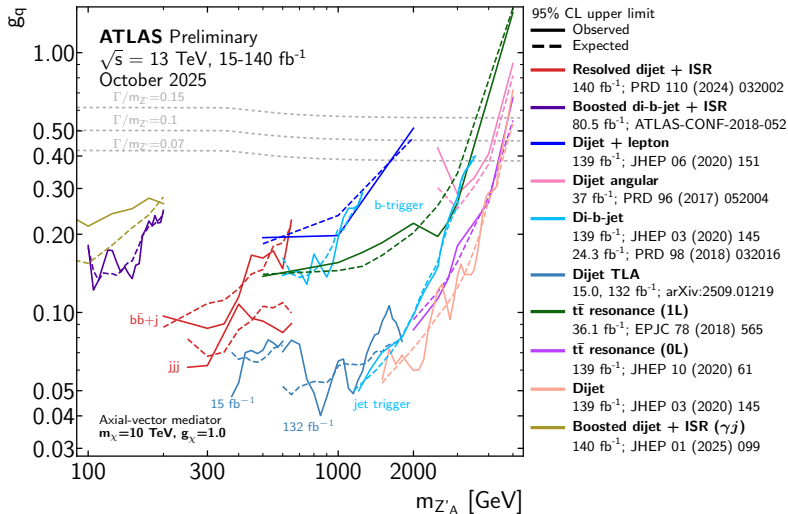
Appendix

Before the start of Run 2 (2015)

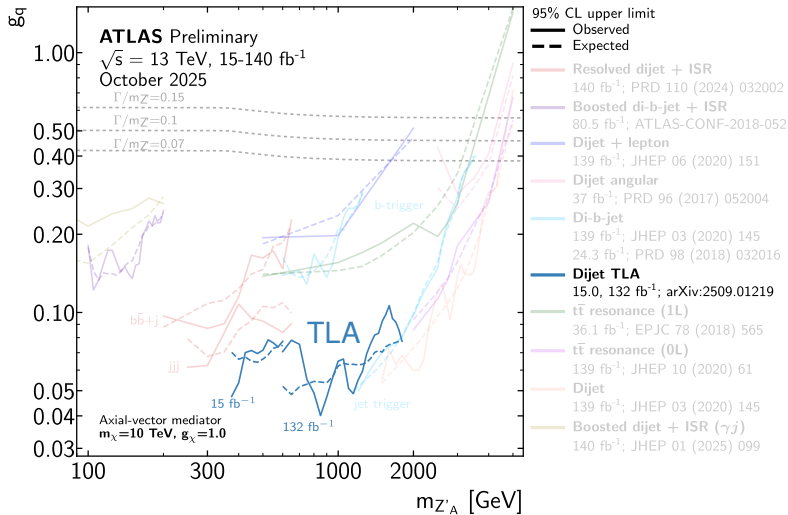
(simplified model: Z' coupling to baryon number)

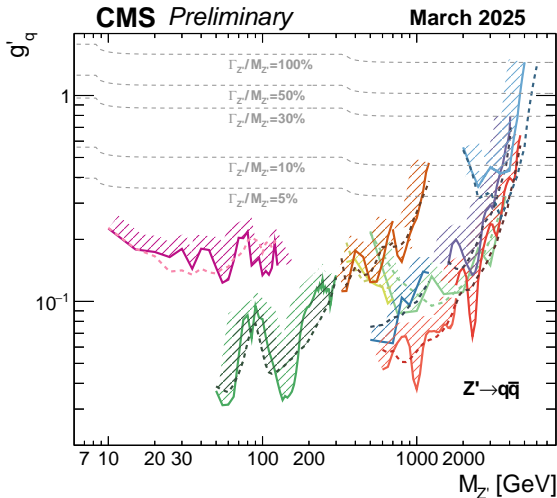
$S\bar{p}\bar{p}S$ (UA2) and Tevatron (CDF) probed up to 1 TeV
 LHC (ATLAS, CMS) pushed towards high mass, but were not able to compete at low mass

Limit Comparison



Limit Comparison





95% CL exclusions

Observed

Expected

$\Gamma_Z/M_Z < \sim 5\%$

$t\bar{t}$ resonance, (JHEP 2019, 031)
35.9 fb⁻¹, 13 TeV

$\Gamma_Z/M_Z < \sim 10\%$

Boosted dijet+ γ (PRL 123, 231803)
35.9 fb⁻¹, 13 TeV

Boosted dijet (EXO-24-007)
138 fb⁻¹, 13 TeV

Dijet+ISR jet (PLB 805, 135448)
18.3 fb⁻¹, 13 TeV

Dijet b-tagged (PRL 120, 201801)
19.7 fb⁻¹, 8 TeV

Dijet scouting (PRL 117, 031802)
19.7 fb⁻¹, 8 TeV

Dijet scouting (EXO-23-004)
117 fb⁻¹, 13 TeV

Dijet (JHEP 2020, 033)
138 fb⁻¹, 13 TeV

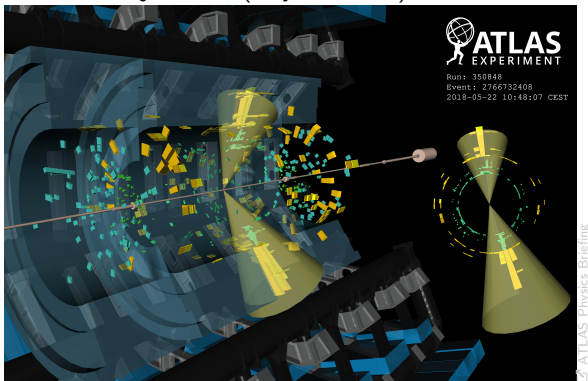
$\Gamma_Z/M_Z < \sim 30\%$

Broad dijet (JHEP 2018, 130)
35.9 fb⁻¹, 13 TeV

$\Gamma_Z/M_Z < \sim 100\%$

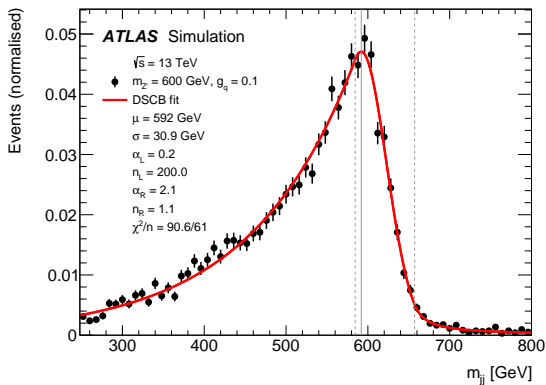
Dijet χ (EPJC 78, 789)
35.9 fb⁻¹, 13 TeV

Event with 356 GeV dijet mass (Physics Main), recorded on 22 May 2018

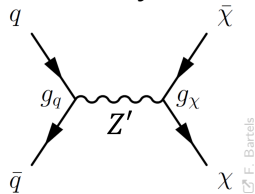


- Physics Main event contains many objects:
 - Energy deposits in the calorimeter, tracks, ...
- The corresponding TLA event only has the jets (yellow cones)
- It is rare to retain such a low mass dijet event in Physics Main
- In the TLA Dataset these events are abundant

Z' signal distributions for various $m_{Z'}$ described by double sided Crystal Ball functions

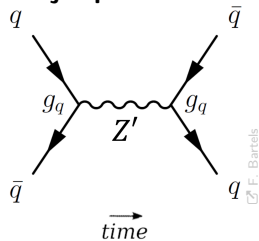


Direct decay to DM



© F. Bartels

Dijet production



© F. Bartels

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Additionally performed all fits with generic gaussian signal models of various masses and width

Various trigger chains for different physics categories
 Jet triggers are only a small fraction of the 1 kHz HLT rate

2015 L1 rate	
Category	Rate [kHz]
Single MU	10.2
Multi MU	19.8
Single EM	13.8
Multi EM	15.3
Single JET	5.6
Multi JET	3.9
E_T^{miss}	0.5
TAU	12.0
Combined (inclusive)	6.5

TRIG-2016-01

2015 HLT rate	
Category	Rate [Hz]
Single Muon	132
Single Electron	194
Multi Lepton	79
Single Jet	76
Multi Jet	62
b -jet	146
E_T^{miss}	210
Tau	72
Photon	68
B -physics	144
Combined (inclusive)	107
Combined Lepton	21
Combined E_T^{miss}	31
Combined Jet	93
Main Physics Stream	1163

TRIG-2016-01

Differences in Offline and Trigger-Level jet calibration

Pile-up correction → Absolute EtaJES → Global sequential → Data correction

Pile-up correction

- jet area
- residual μ
- residual N_{PV}

Absolute EtaJES

- E correction
- η correction

Global sequential

- Tile0
- LAr3
- n_{trk}^{1000}
- w_{trk}
- $n_{segments}$

Data correction

- η -intercalibration
- absolute in situ
- trigger/offline

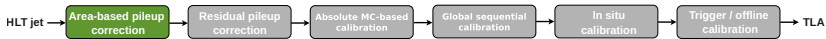
applied by HLT

derived custom

not applied

same as offline

newly introduced



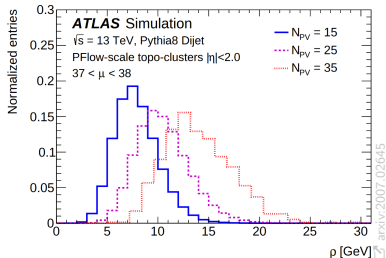
Area-based pileup correction

- Removes bulk of the pileup
- Pileup density ρ : Per-event measure for amount of pileup
- Jet area A : Estimator for jet's catchment area
- Combination gives estimate for how much of a jet's p_T is from pileup

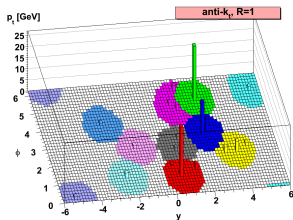
$$p_T^{\text{area}} = p_T^{\text{init}} - \rho A$$

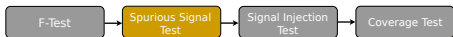
- Already applied within the HLT itself

ρ distributions for various number of vertices N_{PV}



Jet area of anti-k_T jets

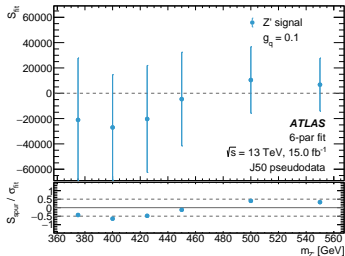




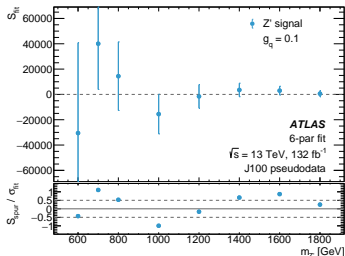
Spurious signal test

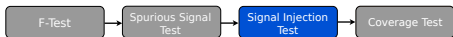
- Add signal with Gaussian-constrained amplitude to the signal+background fits
- Spurious signal = difference between fitted and expected signal yield
- Determined for each mass point and used as uncertainty
- On order of half the stats uncertainty for most signals considered

J50



J100

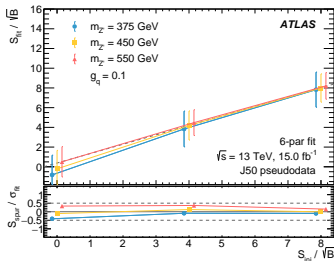




Signal injection test

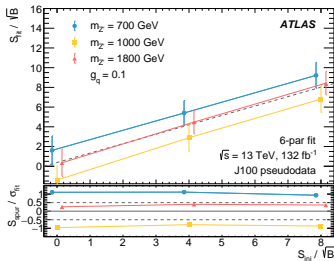
- Similar to spurious signal test
- Difference: Inject \sqrt{B} events
- B : Integral of background-only fit within full-width-half-maximum of signal mass
- 100 toy experiments per signal hypothesis
- Goal: linear trend in S_{fit}/\sqrt{B} vs S_{inj}/\sqrt{B}

J50



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J100

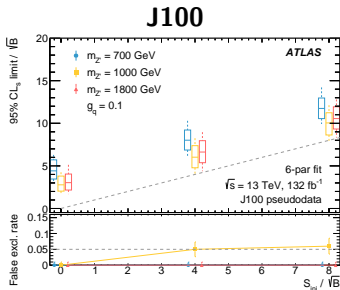
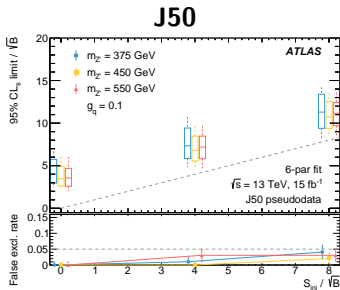


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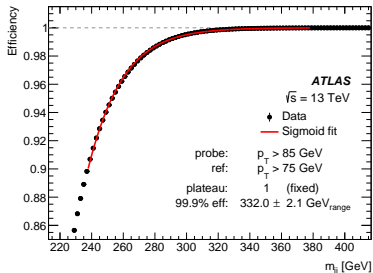
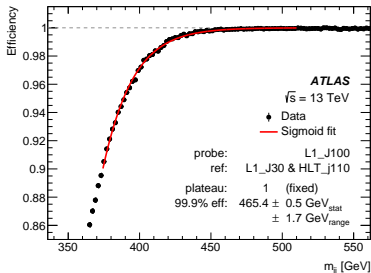
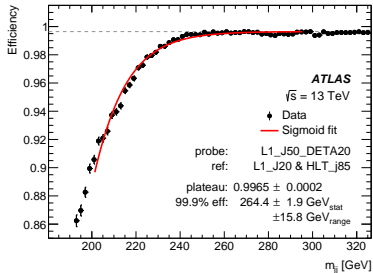
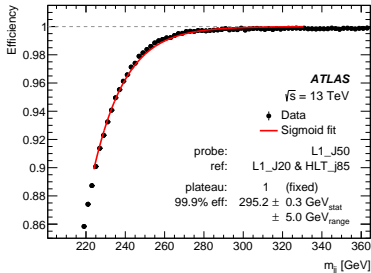


Coverage test

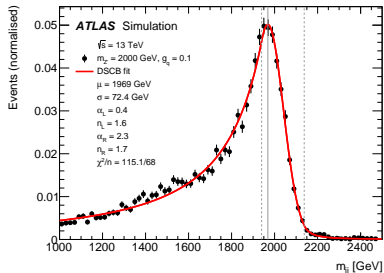
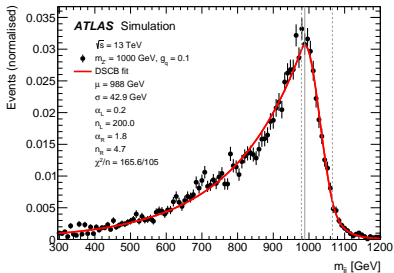
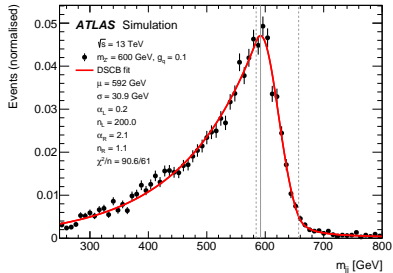
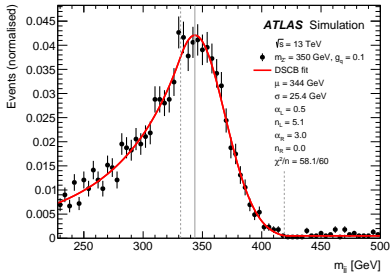
- Final results are 95 % C_{LS} upper limits
- In at most 5% of toy datasets a limit stronger than the number of injected signal events should be derived
 - Else: undercoverage
- Even with largest spurious signals proper coverage was found
- Systematic uncertainty properly covers fit bias

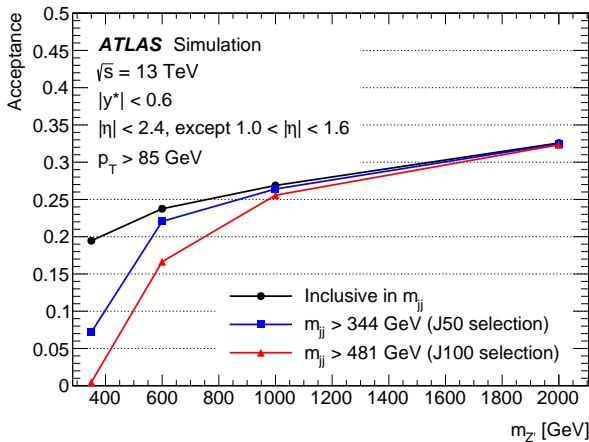


Trigger Efficiencies



Z' Signal Shapes



Z' signal acceptance with respect to m_{jj} 

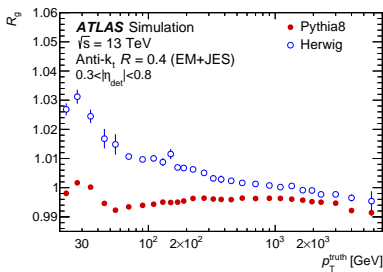
The flavour uncertainties were re-derived as in Ref. [50],

$$\sigma_{\text{response}}^{\text{flavour}} = f_g \sigma_{R_g}, \quad (6)$$

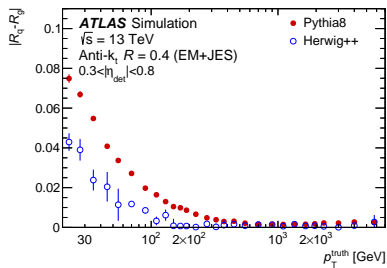
$$\sigma_{\text{composition}}^{\text{flavour}} = \frac{\sigma_{f_g} |R_q - R_g|}{f_g R_g + (1 - f_g) R_q}, \quad (7)$$

where R_q and R_g are the fraction of light quarks and gluons which were measured in PYTHIA 8 dijet simulated events. The gluon response modelling uncertainty σ_{R_g} was obtained as the maximum difference of the gluon response using PYTHIA 8, HERWIG [63, 64], or SHERPA [65, 66] simulated events. The gluon fraction f_g was set to a constant value of 50% with a conservative estimate on its uncertainty of $\sigma_{f_g} = 100\% f_g$. All other components were derived in bins of jet p_T and η . The flavour uncertainties are the dominant jet uncertainties and mainly arise due to the lack of tracking information which, for the offline jet calibration, is key to aligning the response of quark- and gluon-initiated jets [50].

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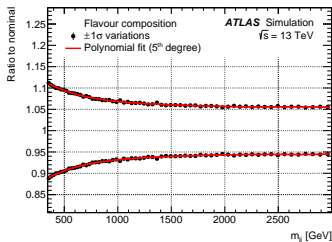


JETM-2018-05



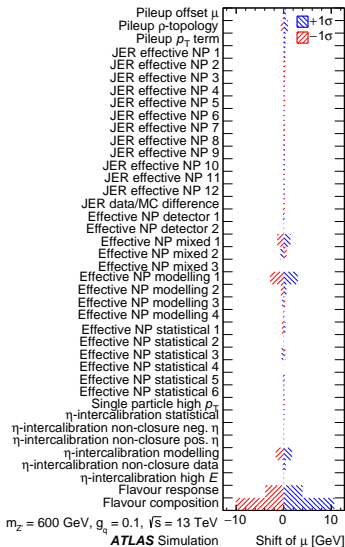
JETM-2018-05

- All offline jet systematics applied to trigger jets
- Plus uncertainty from spurious signal test
- Re-derived flavour systematics have highest impact on signal mean μ (8 – 20 GeV)
- Pulls on signal width σ negligible (< 1 GeV)



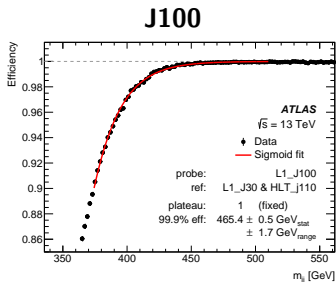
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Impact on signal mean μ

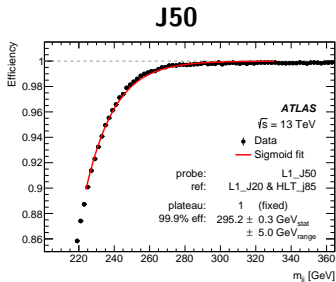


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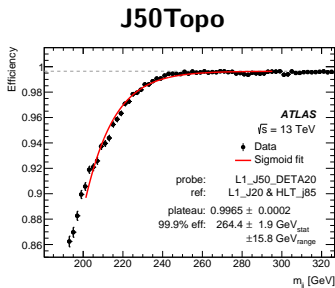
- Turnon: Efficiency of trigger when compared to other trigger with lower threshold
- Used here to determine starting points of m_{jj}
- To avoid kinematic sculpting of m_{jj} spectrum by inefficiencies



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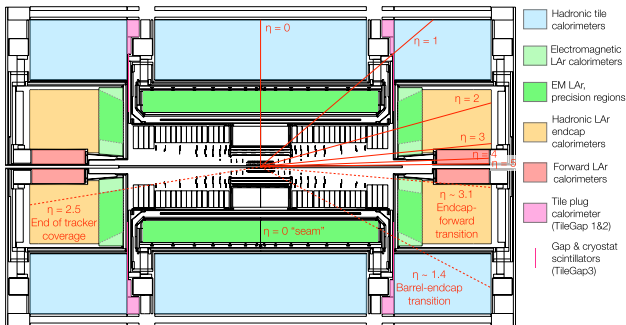


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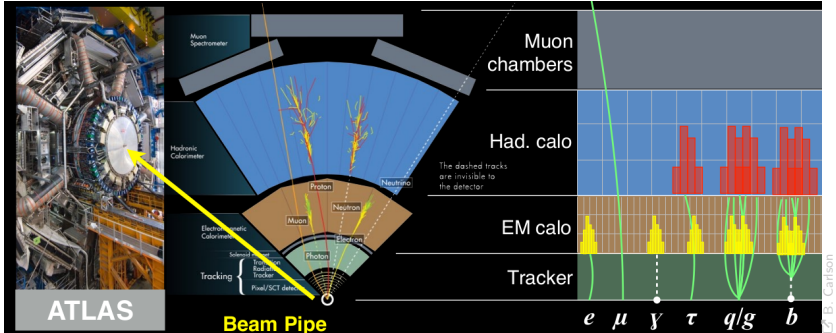
Phys. Rev. D 112, 092015

Tile gap veto: exclude event if any of $1.0 < |\eta^{0,1}| < 1.6$



arxiv:2007.02645

- Narrow region between hadronic calorimeters instrumented only by a thin set of gap and cryostat scintillators
- Due to lack of tracking in Run 2 TLA stream, unable to perform stable calibration here
- Excluded after discussion with JetEtMiss and Exotics conveners



At low p_T the tracker p_T resolution

$$\sigma\left(\frac{1}{p_T}\right) = 0.036\% \cdot p_T \oplus 1.3\%$$

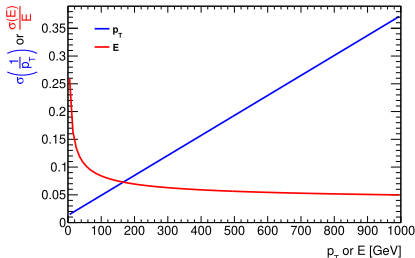
is better than the calorimeter E resolution

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3.4\% \oplus \frac{1\%}{E}$$

[source](#)

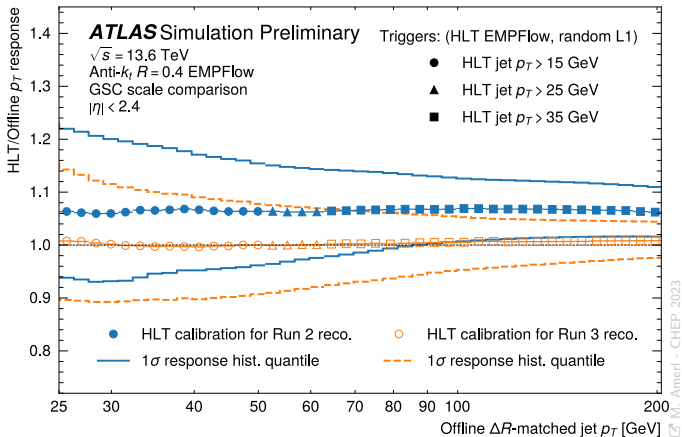
- Run 2: Only EMTopo (calo only) jets in TLA stream
- Run 3: Full-scan tracking \rightarrow ParticleFlow jets

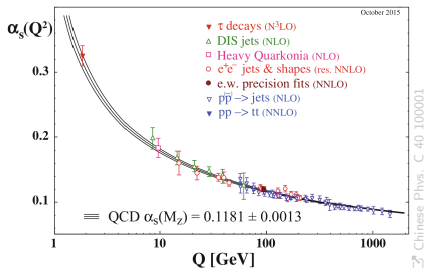
Jet definitions used in Run 3 rely on calo+track information



Run 3 HLT jet calibration performance derived within dijet+ISR TLA

TLA work benefits the wider collaboration





Partonic cross section further
contributes to falling: $\propto \frac{d\hat{\sigma}}{d\hat{t}} \propto \frac{\alpha_s^2}{\hat{s}^2}$

High $M \rightarrow$ high $Q^2 \rightarrow$ low α_s

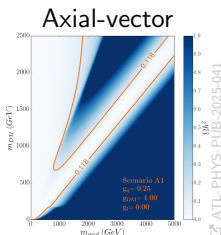
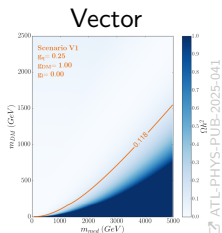
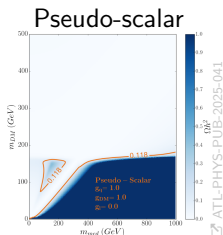
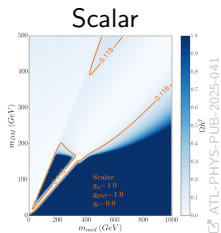
p_T falls too but not quite as steeply:

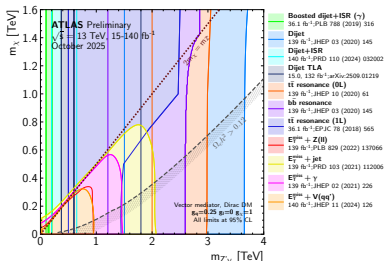
$$M = \hat{s} = 4p_T^2 \cosh^2 y^*$$

$$\Rightarrow p_T \propto \sqrt{M}$$

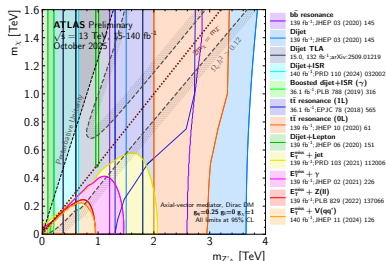
Result: M distribution is steeply falling (up to $\propto M^{-10}$) with non-trivial but smooth shape

Mediator	Spin	Parity	Coupling
Scalar (S)	0	even	$g_S S \bar{\psi}\psi$
Pseudo-scalar (P)	0	odd	$g_P P \bar{\psi}i\gamma_5\psi$
Vector (V)	1	odd	$g_V V_\mu \bar{\psi}\gamma^\mu\psi$
Axial-vector (A)	1	even	$g_A A_\mu \bar{\psi}\gamma^\mu\gamma_5\psi$



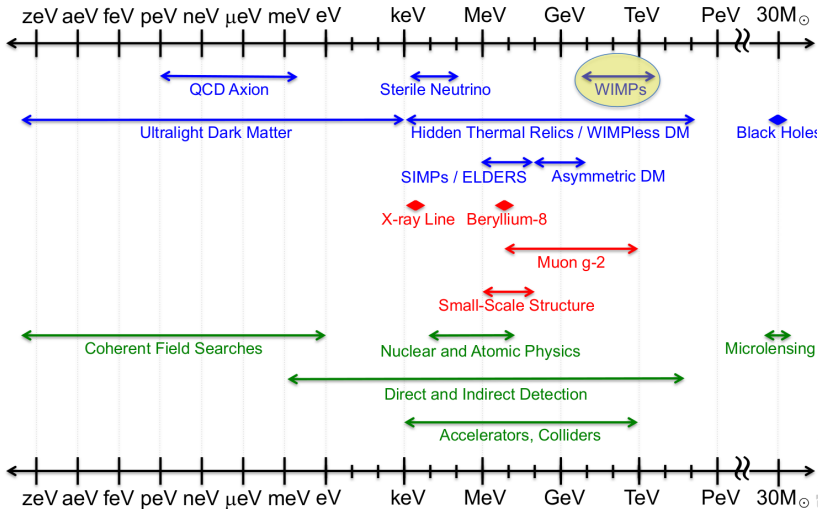


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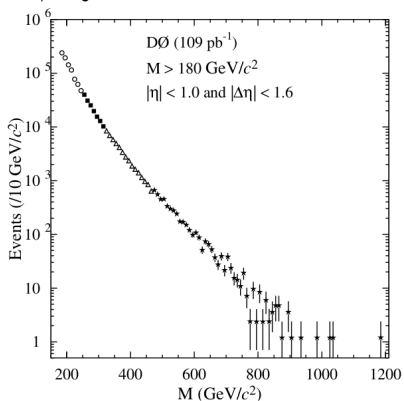


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DM Landscape

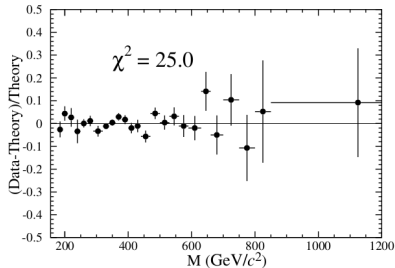


DØ dijet mass search in 2004:



arXiv:hep-ex/0308033

Agrees well with NLO QCD calculation

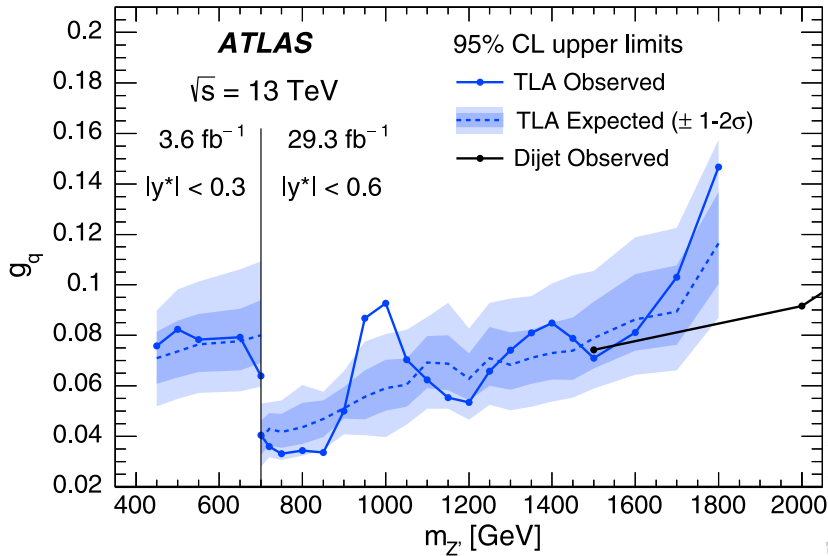


arXiv:hep-ex/0308033

Appendix

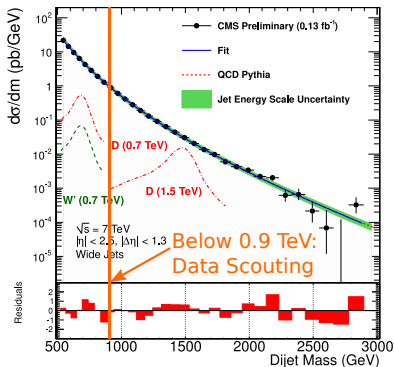
TLA Publications

experiment	signature	mass range [GeV]	publication
ATLAS	dijet	450-1800	☞ PRL 121 (2018) 081801
	dijet	375-1800	☞ Phys. Rev. D 112, 092015 (2025)
CMS	dijet	600-1800	☞ arxiv:2510.21641
	dijet	500-900	☞ CMS-PAS-EXO-11-094
	dijet	500-800	☞ PRL 117 (2016) 031802
	dijet	600-1600	☞ PLB 769 (2017) 520
	dijet	600-1600	☞ JHEP 08 (2018) 130
	pair of 3j	200-700	☞ Phys. Rev. D 99, 012010
	dijet + ISR jet	350-700	☞ PLB 805 (2020) 135448
	LLP \rightarrow di- μ	10-50	☞ Phys. Rev. 124, 131802
	LLP \rightarrow di- μ	0.6-50	☞ JHEP 04 (2022) 062
	multi- μ ($\eta \rightarrow 4\mu$)	0.45-40	☞ CMS-PAS-BPH-22-003
	L1-DS heavy LLP di- μ	1000-7000	☞ arxiv:2601.20063
di- τ	20 - 60	☞ arxiv:2605.25103	



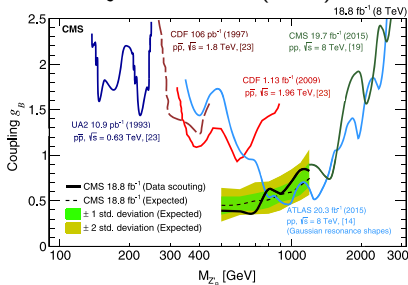
CMS equivalent to TLA: Data Scouting

First use: dijets @ 7 TeV (2013)



CMS-PAS-EXO-11-094

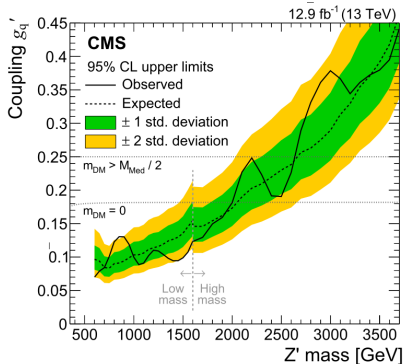
dijets @ 8 TeV (2016)



PRL 117 (2016) 031802

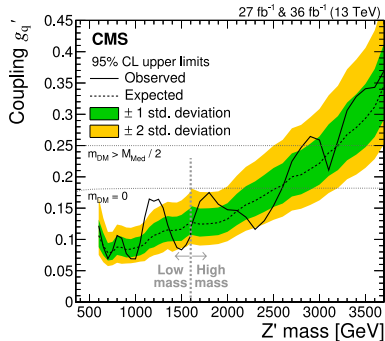
- TLA used to extend limits from 0.9 down to 0.5 TeV

dijets @ 13 TeV (2017)



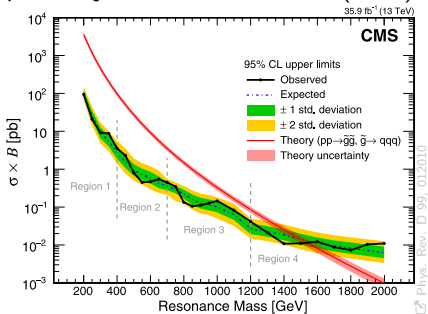
- 12.9 fb⁻¹
- 0.6-1.6 TeV

dijet @ 13 TeV (2018)



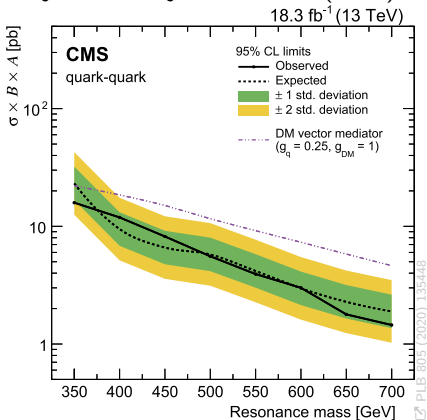
- 27 fb⁻¹
- 0.6-1.6 TeV

pair of 3j resonances @ 13 TeV (2019)



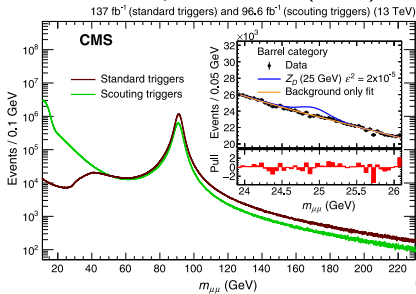
- $H_T > 410$ GeV from $p_T > 20$ GeV jets
- DS: 0.2-0.7 TeV

dijets + ISR jet @ 13 TeV (2020)



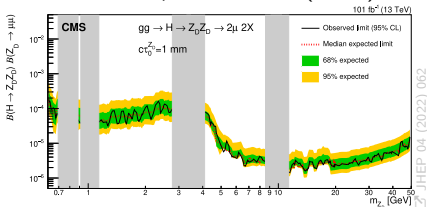
- 18.3 fb⁻¹
- 350-700 GeV

LLP \rightarrow di- μ @ 13 TeV (2020)



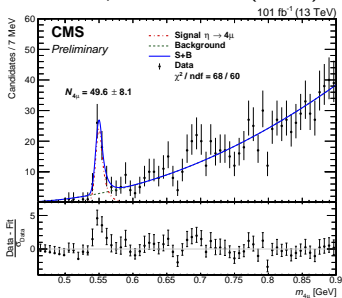
- 96.6 fb⁻¹ (2017 & 2018)
- **DS** advantage kicks in <50 GeV

LLP \rightarrow di- μ @ 13 TeV (2022)



- 101 fb⁻¹ (2017 & 2018)
- E.g. Dark photon Z_D down to sub-GeV range

multi- μ @ 13 TeV (2022)



☐ CMS-PAS-BPH-22-003

- 101 fb⁻¹ (2017 & 2018)
- DS in < 40 GeV range
- First $\eta \rightarrow 4\mu$ observation