Searches for low-mass resonances using jets

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Introduction

• LHC has been collecting data since 2010, now nearing end of Run 2.

• ATLAS experiment is a multi-purpose detector for measurements and searches with all known particles.

• Today: talking about searches especially for dark matter, with strongly charged particles (quarks and gluons) in the final state.
The ATLAS Experiment

Measuring strongly charged particles mostly uses the calorimeters…

but incorporate some tracking info…

and some muon info too!
Jets and how we use them

- What does a quark or gluon actually look like in a detector?

- Because strongly charged particles can’t exist alone, energy of a relativistic q or g converted to more particles: final state is a collimated shower of particles in the tracker & calorimeter

- No exact 1 to 1 correspondence between parton and jet (is a parton even real?), but we can use jets as a tool to tell us about strong processes in our initial collision
Calibrating jets

Why do we calibrate?

• Want to bring jets in data to same scale as “true” jets in simulations

• Account for dead regions of calorimeter, energy lost in “absorber” material, differences between EM and hadronic showers, …

We will see this again later!

EM or LCW constituent scale jets

Jet finding applied to topological clusters at EM or LCW scale

Origin Correction

Changes the jet direction to point to the primary vertex. Does not affect E.

Jet area based pile-up correction

Function of event pile-up energy density and jet area

Residual pile-up correction

Function of $\mu$ and NPV applied to the jet at constituent scale

Absolute EtaJES

Corrects the jet 4-vector to the particle level scale. Both the energy and direction are calibrated.

Global sequential calibration

Based on tracking and muon activity behind jets. Reduces flavour dependence and energy leakage effects.

Residual in-situ calibration

A final residual calibration is derived using in-situ measurements and is applied only to data
Motivating BSM physics [at the LHC]

The Standard Model has done remarkably well at withstanding experimental tests

- Higgs discovery of 2012 marked last piece of the SM
- No meaningful deviations from SM predictions observed so far

But still a lot of questions suggesting that BSM physics should be just around the corner!

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Dark matter

Cosmological evidence is the only positive confirmation of DM we currently have!

Current leading model is still WIMPs:
- Long lifetime
- No EM charge
- Correct relic density
Weak interactions possible
How do we look for dark matter?

Indirect detection: IceCube, Super-K, …

Direct detection: LUX, XENON, …

Colliders: ATLAS & CMS
Simplified dark matter models at ATLAS

What is that?

Common in Run 1

Current standard

Range of answers!

Moving this way

via DMF
Classic dark matter searches: mono-X

- Search for simplified-model DM mediator to MET plus any object on which to trigger
- Most sensitive is MET+jet but we also have MET+\gamma, MET+W/Z/h, …
What about other mediator decay products?

- Left: Classic MET+jet signature

- But: if you can make it from quarks, you can make quarks from it!
  - Allow $Z'$ mediator to decay back to two quarks and have a dijet final state signature with no missing energy
  
- No need for an ISR object, so higher cross section process
The high mass dijet analysis: a versatile search!

- **Invariant mass** of leading two jets in event is $m_{jj}$. If only SM, $m_{jj}$ is a smooth exponential distribution.

- Look for bumps on top! New particle of mass $M$ decaying to quarks or gluons -> bonus events at $M$.

- Use degree of bumpiness to set limits on **wide range of models** — black holes, $W'$ and $Z'$ mediators, excited quarks, scalar octets, etc. etc.
Dijet results

- Set limits on $Z'$ mediator in 2D plane: coupling to SM quarks vs $Z'$ mass
- With fit above, study events from 1.1 TeV to 8 TeV!
But what if we aren’t looking for high masses?

When we focus on pushing limits to higher masses, we treat this region as “excluded” - it’s not!

- “Exclusion” is a very model dependent statement
- Low mass resonances with small cross sections or BRs not actually strongly constrained
- At the start of Run II, leading limits were still from the Tevatron!
The ATLAS trigger system

Data leaves detector at 40 MHz: way more than we can process and store!

Hardware L1 trigger reduces flow to 100 kHz

Software HLT passes ~1 kHz: 40,000 x less

A perfect drop of physics!
Trigger prescales

- Sometimes there are just too many interesting events!
- Things with jets are an example.
  - At low $p_T$, way more interesting events than we can store! Throw some away.
- Easiest thing for analyses: search in events **above unprescaled trigger turn-on**.

![Diagram showing the relationship between jet $p_T$ and number of events, highlighting prescaling and unprescaled triggers.](image)
Combining triggers can get you something …

... but it isn’t great!

In 8 TeV we combined triggers to access $m_{jj} \sim 250$ GeV

But effective luminosity dropped so fast that CDF limits were still stronger

Effective luminosity vs. $m_{jj}$ for combination of prescaled triggers
Fancy Option 1: trigger level analysis!

- Using jets made with only trigger information, we save a lot of space!
- No tracks, no other objects, not even other calorimeter info outside the jets themselves.

Enormous amount of data read in at L1 trigger level

Can either store large amount of data for a small number of events….

… or small amount of data for many, many events

Fixed amount of bandwidth
How much does this approach actually help with data storage?

- Trigger level analysis has the highest stream rate of any HLT physics stream…

- … but makes up only a tiny fraction of the total HLT bandwidth!

- Due to very small event size
The luminosity gain in practice

3 orders of magnitude gain from j110 trigger

Below 800 GeV, increasing gain over all offline triggers
Event selection: kinematics

- 2 jets with $|\eta| < 2.8$
- $p_T^1 > 220$ GeV, $p_T^2 > 85$ GeV
- $y^* = (y_1 - y_2) / 2 < 0.6$ to optimise sensitivity
- Second signal region uses $y^* < 0.3$ to reach lower masses
- $m_{jj} > 520$ GeV (470 GeV) to remove trigger bias
- 3 leading jets pass cleaning (next slide)

QCD produces jets along the beamline…

… while most signals are fairly isotropic.
The biggest complication: customised jet calibration!

- Offline
  - Uncalibrated jets
  - Origin correction
  - Area pileup subtraction
  - Residual correction
  - MC JES
  - GSC
  - Custom GSC
  - Eta intercalibration
- Trigger-level jets
  - Data-driven cross calibration
  - In situ corrections
How well does it work?

Plot $m_{jj}$ for online and offline jets in each event with a prescaled low-$p_T$ trigger.

Response found to be within 1% with no $m_{jj}$ dependence!
New challenges in 2016!

- With 2015+2016 dataset and updated jet recommendations, discovered that extremely high statistical precision means sensitivity to small non-smoothnesses in calibration

- Developed new in situ combination and an uncertainty on the bump hunting process
Uncertainties on jet energy scale

- Uncertainty ~2x offline value, largely due to jet flavour (harder to distinguish without tracking information)

- New result in progress improves this with custom GSC including number of jet constituents in place of number of tracks
Searching for bumps on a smooth background

- Background estimate created by parameterising data distribution with a smooth fit
- Restricted range defined by fit shape
- Improvement to current analysis using a sliding window fit, allowing a fit to higher masses

No evidence of new physics!
Model-dependent TLA limits

Coupling vs. mass for Z' DM mediator

Start setting limits a little above start of fit, for sufficient stability

Upper limit constrained by fit challenges
Model-independent TLA limits

![Graph showing model-independent TLA limits](image)

This is how theorists can use the results to constrain other models.

Compare [my favourite model] to a Gaussian to get relevant width; extract limits.
News from the upcoming TLA result

- New results with ~10x the luminosity will be public next week for Moriond! Watch this space

- Sliding fit for background estimate allows us to look at higher mjj values

- Will be the first result with new smooth in situ calibration
Fancy Option 2: dijet + ISR analysis!

- Look for dijet + initial state radiation (jet or $\gamma$) events and trigger on the ISR object.
- Lower luminosity than TLA, and takes $\sigma$ hit from ISR requirement.
- But, gives access to even lower masses than TLA!
Event selection

- **Photon ISR channel**
  - Trigger: HLT_g140_loose
  - >= 2 selected jets, >= 1 (isolated) γ with $p_T > 150$ GeV
  - $y^* < 0.8$

- **Jet ISR channel**
  - Trigger: HLT_j380
  - >= 3 selected jets, lead jet $p_T > 430$ GeV
  - $y^* < 0.6$

A photon of 150 GeV can be $p_T$ balanced by two much softer jets.
Search phase results

• No new physics, again ...

• Photon channel offers greatest range but jet channel has higher statistics
Limits from dijet+ISR

All the way down to 200 GeV!

Short range but strong limit!

Not quite enough to connect with high-mass dijet: doing better this year!

And of course, Gaussian limits available too!
Dijet+ISR goodies to look forward to

• First paper is planned for 2015+2016+2017 data! Timeline this summer.

• Introducing 2-b-tagged channel!
  • Like di-b analysis, gain sensitivity for a democratic Z’ just from background suppression

• Better trijet channel fits!
  • Sliding window allows adaptation to background shape such that fit can be extended to higher mj" — ideally all the way to 1200 GeV

• Fancier triggers for photon ISR channel, allowing better sensitivities above 300 GeV
Going even lower: boosted dijet+ISR

- For even lower Z’ mass, decay products are very close together \( \rightarrow \) reconstruct as a large jet instead of two small jets. Use a tagger to distinguish signal from background based on substructure.

- Lots of challenges in the background estimate! Extrapolate from data CR which does not pass tagging requirements. 1 estimate per signal point.

- Can extend limits as low as 100 GeV! (Then we run into W & Z…)

\[\text{Events / GeV} \]

\[10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7\]

\[\text{Jet mass [GeV]} \]

\[50, 100, 150, 200, 250, 300\]

\[\text{ATLAS} \]

\[\sqrt{s} = 13 \text{ TeV}, \ 36.1 \text{ fb}^{-1}\]

\[\text{Photon channel}\]

\[\text{SR Data / est.} \]

\[0.98, 0.99, 1.00, 1.01, 1.02\]

\[\text{Events / GeV} \]

\[10^6, 10^7\]

\[\text{Jet channel}\]

\[\text{SR Data / est.} \]

\[0.9, 1.0, 1.1\]
Outstanding challenges for the full Run II analyses

• **Background estimates**
  
  • Sliding window fit is not a complete solution! The narrower the window the more susceptible to spurious signals. Causing serious issues in current TLA
  
  • Several new proposals are under investigation

• **Smoothness** — from calibrations, b-tagging, etc
  
  • Several analyses discovered non-smoothness introduced by calibrations, tagging, etc
  
  • Developing uncertainty handling for smoothness issues - will be more robust next time
Putting it all together ….

\[ \sqrt{s} = 13 \text{ TeV}; \, 3.4-37.0 \, \text{fb}^{-1} \]

\[ g_\sigma \]

**ATLAS** Preliminary March 2017

**Filling in that low-mass hole!**

(No boosted results yet)
What does this tell us about DM?

- Depends a lot on the assumptions we make!
- Take an axial-vector mediator à la arXiv: 1703.05703
- Top: $g_L = 0.1$, bottom: $g_L = 0.0$
- Strong constraints from dijet family!
Comparing collider limits to the rest of the field

DM Simplified Model Exclusions
ATLAS Preliminary July 2017

\( \sigma_{SI} \) (DM-nucleon) [cm\(^2\)]

10\(^{-37}\) -- 10\(^{-48}\)

DM Mass [GeV]

1 -- 10^3

Vector mediator, Dirac DM
\( g_q = 0.25, \ g_l = 0, \ g_{DM} = 1 \)

ATLAS limits at 95% CL, direct detection limits at 90% CL

Dijet
Dijet 8 TeV \( \sqrt{s} = 8 \) TeV, 20.3 fb\(^{-1}\)
Dijet \( \sqrt{s} = 13 \) TeV, 37.0 fb\(^{-1}\)
arXiv:1703.09127 [hep-ex]
Dijet TLA \( \sqrt{s} = 13 \) TeV, 3.4 fb\(^{-1}\)
ATLAS-CONF-2016-030
Dijet + ISR \( \sqrt{s} = 13 \) TeV, 15.5 fb\(^{-1}\)
ATLAS-CONF-2016-070

\( E_T^{miss} + X \)
\( E_T^{miss} + \gamma \) \( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1}\)
\( E_T^{miss} + \text{jet} \) \( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1}\)
ATLAS-CONF-2017-060
\( E_T^{miss} + Z \) \( \sqrt{s} = 13 \) TeV, 36.1 fb\(^{-1}\)
ATLAS-CONF-2017-040

CRESST II
arXiv:1509.01515v1

XENON1T
arXiv:1705.06655v2

PandaX
arXiv:1607.07400

LUX
Comparing collider limits to the rest of the field

- Axial vector mediators, spin dependent limits
What else can we say with low-mass dijet limits?

A “real” version of this plot will be public in 5 days!

Stop mass

More RPC-like

More RPV 1L

Stop 0L, Stop 1L

RPV 1L

High-mass dijet + TLA

forbidden

More RPV-like
The roadmap forward

• How can we **improve resonance searches**? Going to get both a lot harder and less immediately rewarding in Run III

  • In the pipeline: Combine both ideas today into **trigger level dijet+ISR**

  • **FTK** allowing pileup discrimination in trigger jets will make lower $p_T$ jetty analyses possible

• Intensify searches for more **unusual models/signatures**

  • Less over-simplified DM models? Long lived particles?

  • Make interesting new (unintended) use of the detector to target uncovered possibilities
The BSM landscape at 13 TeV

Looked under most of the obvious rocks …

… time to start getting more exotic?
Thanks! Any questions?
Event selection: everything beyond kinematics

• Key part of ATLAS analysis is cleaning and quality checks: don’t want any corrupted data or fake jets

• In TLA, we are missing a lot of relevant quantities!
  • Ignore cuts which remove less than 0.01% of data, as long as they have no shape bias
  • Some event criteria can be removed later by timestamp
  • 5/6 jet cleaning criteria still available: ignore the last, subject to careful validation