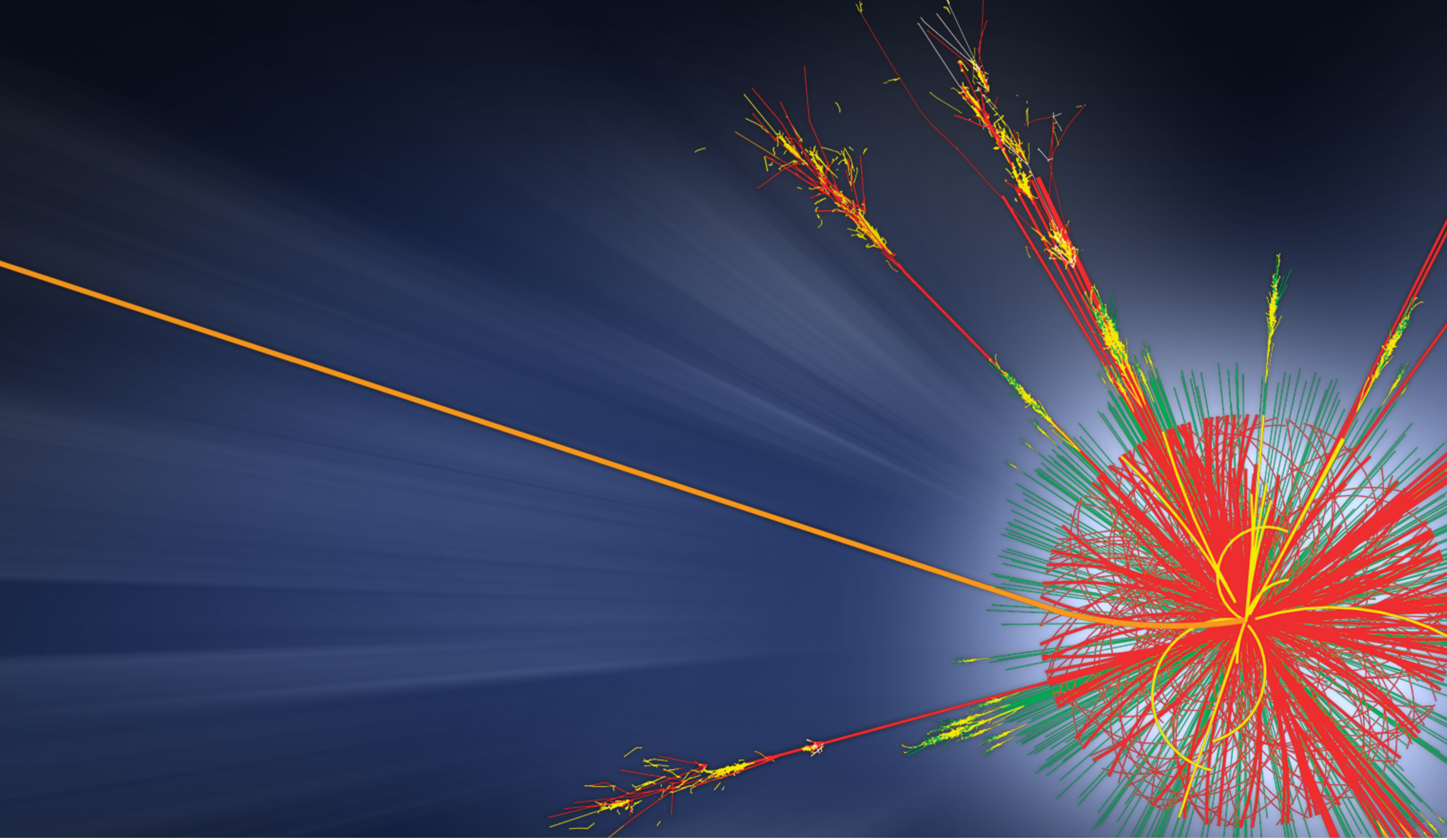
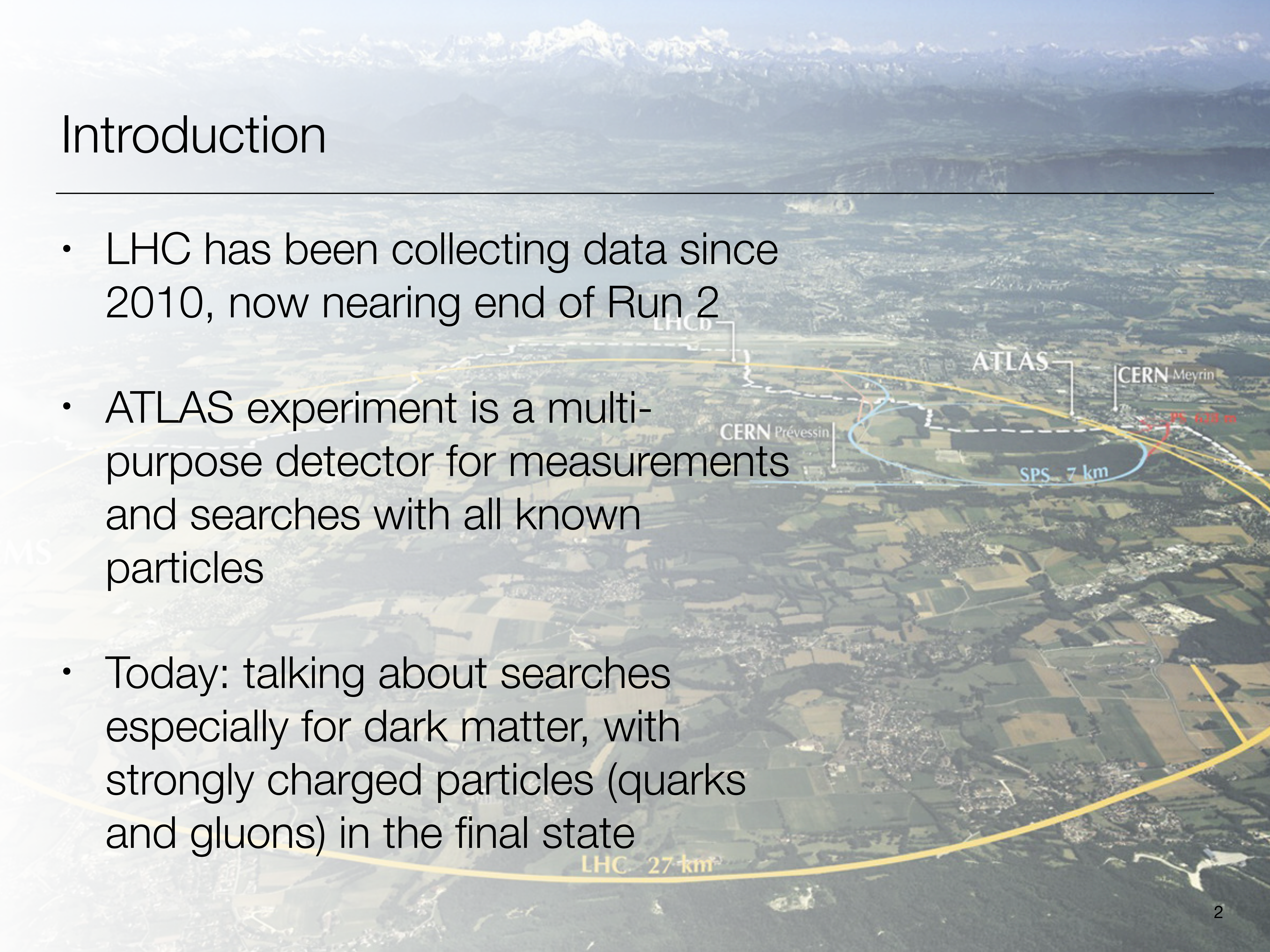


Searches for low-mass resonances using jets

Kate Pachal
Simon Fraser University

Introduction

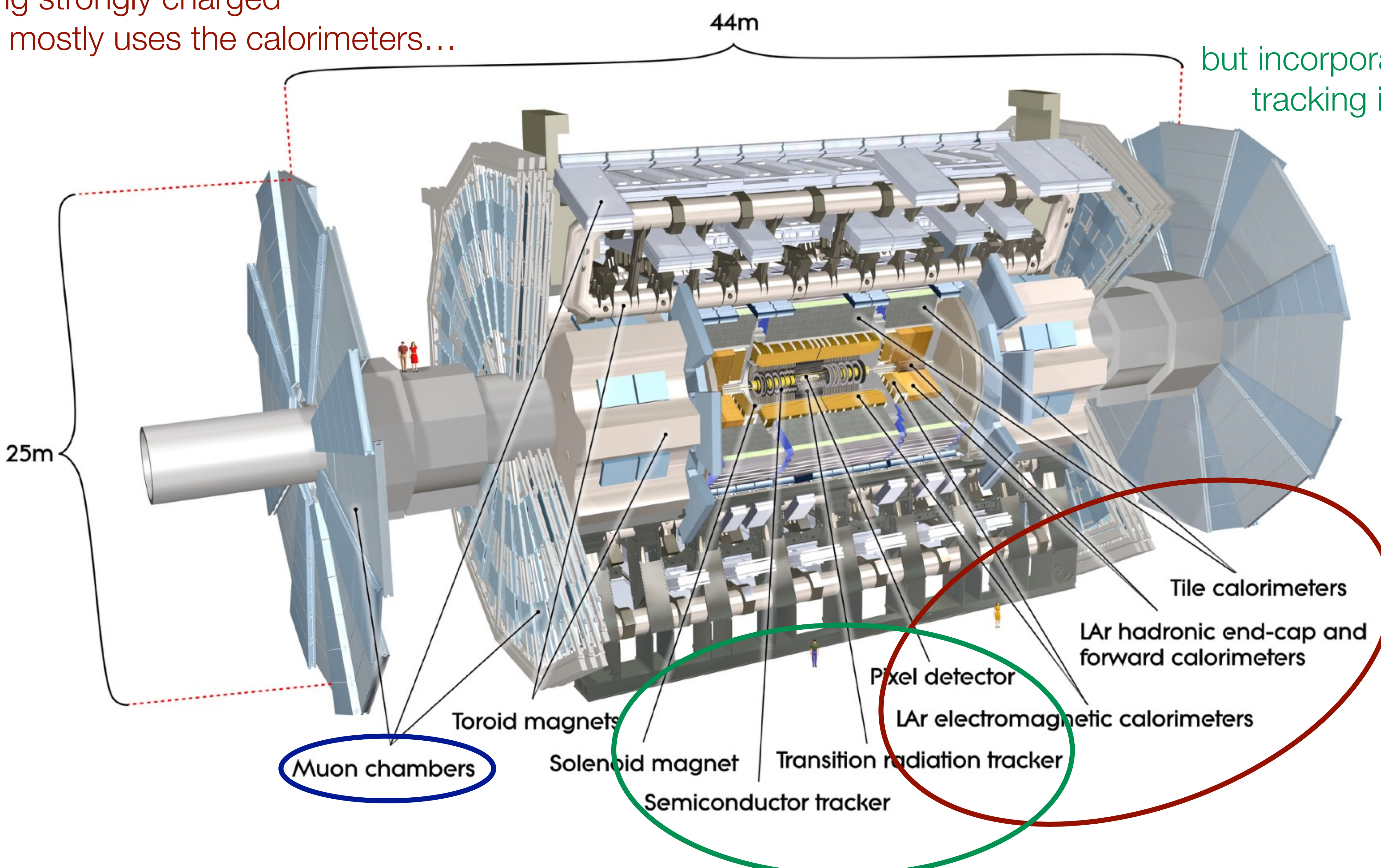
- LHC has been collecting data since 2010, now nearing end of Run 2
- ATLAS experiment is a multi-purpose detector for measurements and searches with all known particles
- Today: talking about searches especially for dark matter, with strongly charged particles (quarks and gluons) in the final state



The ATLAS Experiment

Measuring strongly charged particles mostly uses the calorimeters…

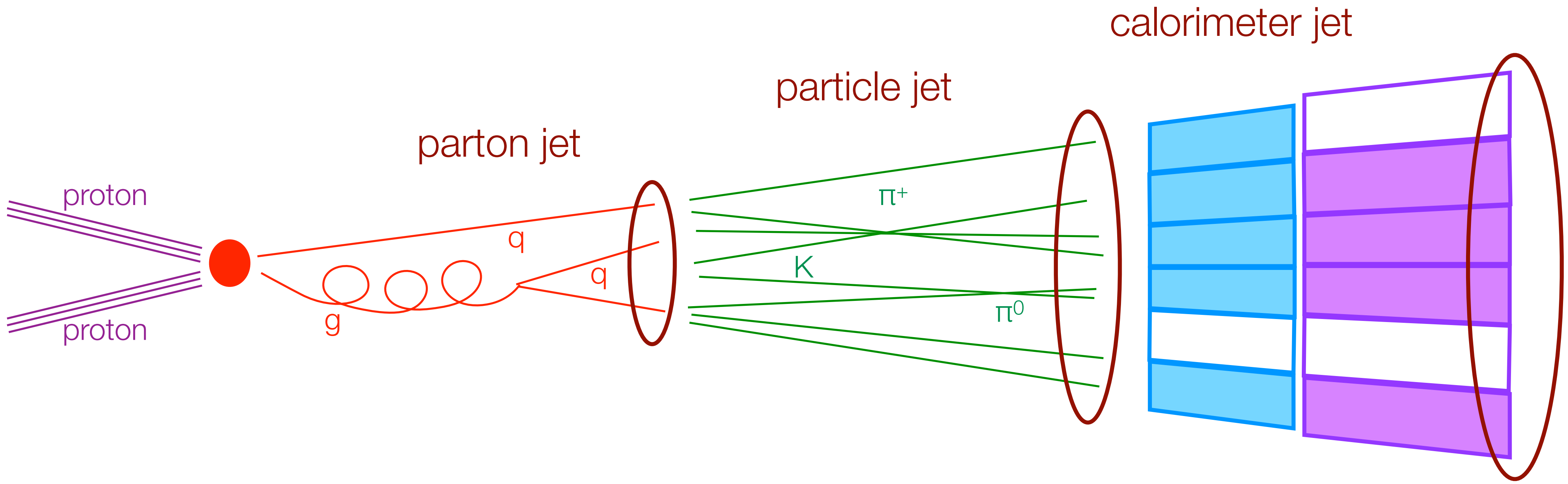
but incorporate some tracking info…



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 → **Origin Correction** → **Jet area based pile-up correction** → **Residual pile-up correction** →

Jet finding applied to topological clusters at EM or LCW scale

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

Function of event pile-up energy density and jet area

Function of μ and NPV applied to the jet at constituent scale

→ **Absolute EtaJES** → **Global sequential calibration** → **Residual in-situ calibration**

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

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

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

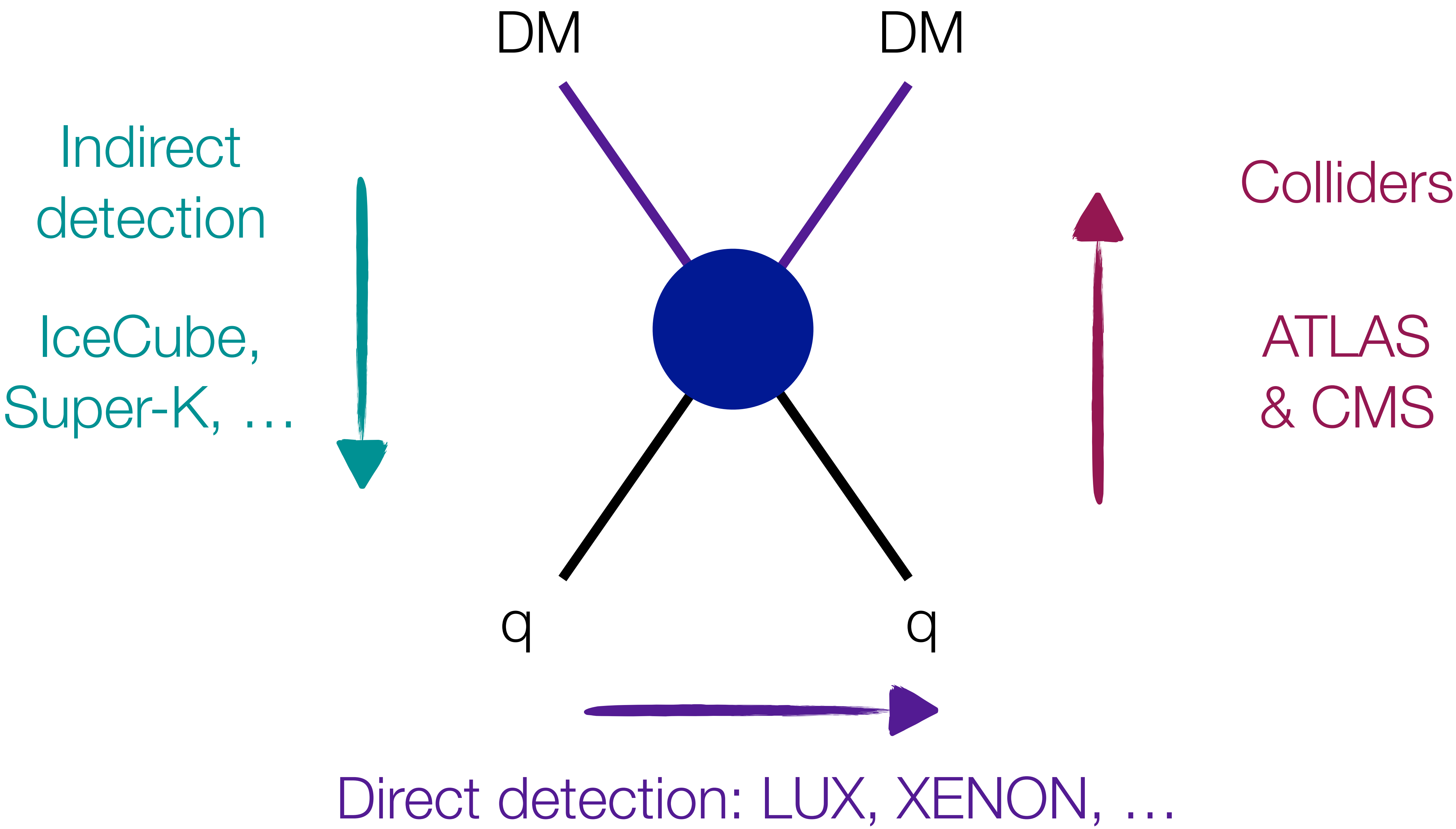
- Higgs discovery of 2012 marked last piece of the SM
- No meaningful deviations from SM predictions observed so far

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

Dark matter	What is it? Is it a particle?
Hierarchy problem	Why is gravity so weak? Can extra dimensions explain it?
Gauge unification	Is there a unified theory connecting fundamental forces?
Higgs fine-tuning	How do we account for large, fine-tuned Higgs mass corrections?
....	Why 3 generations? Why 4 forces? Matter-antimatter asymmetry?


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

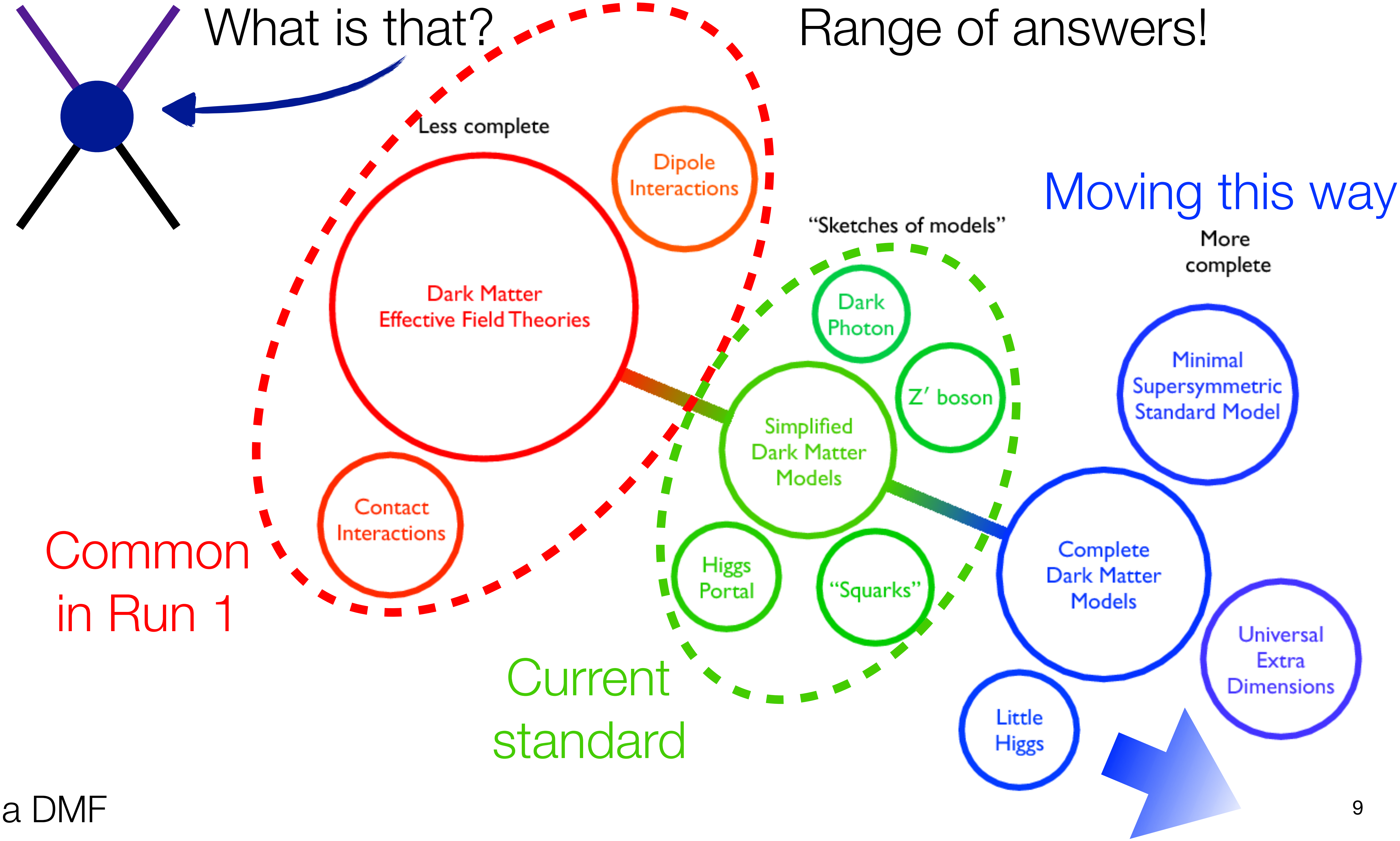
How do we look for dark matter?



Simplified dark matter models at ATLAS

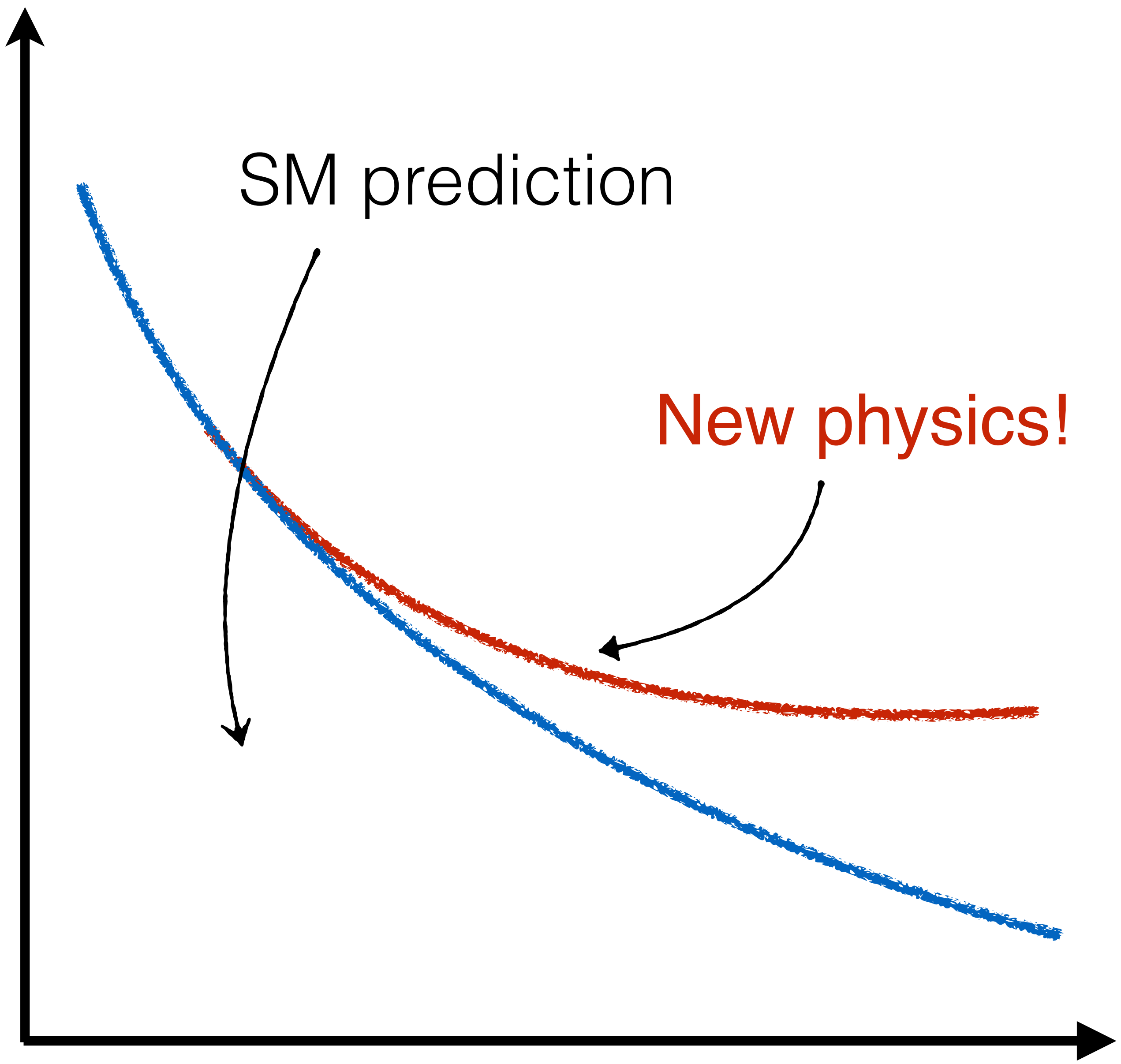
What is that?

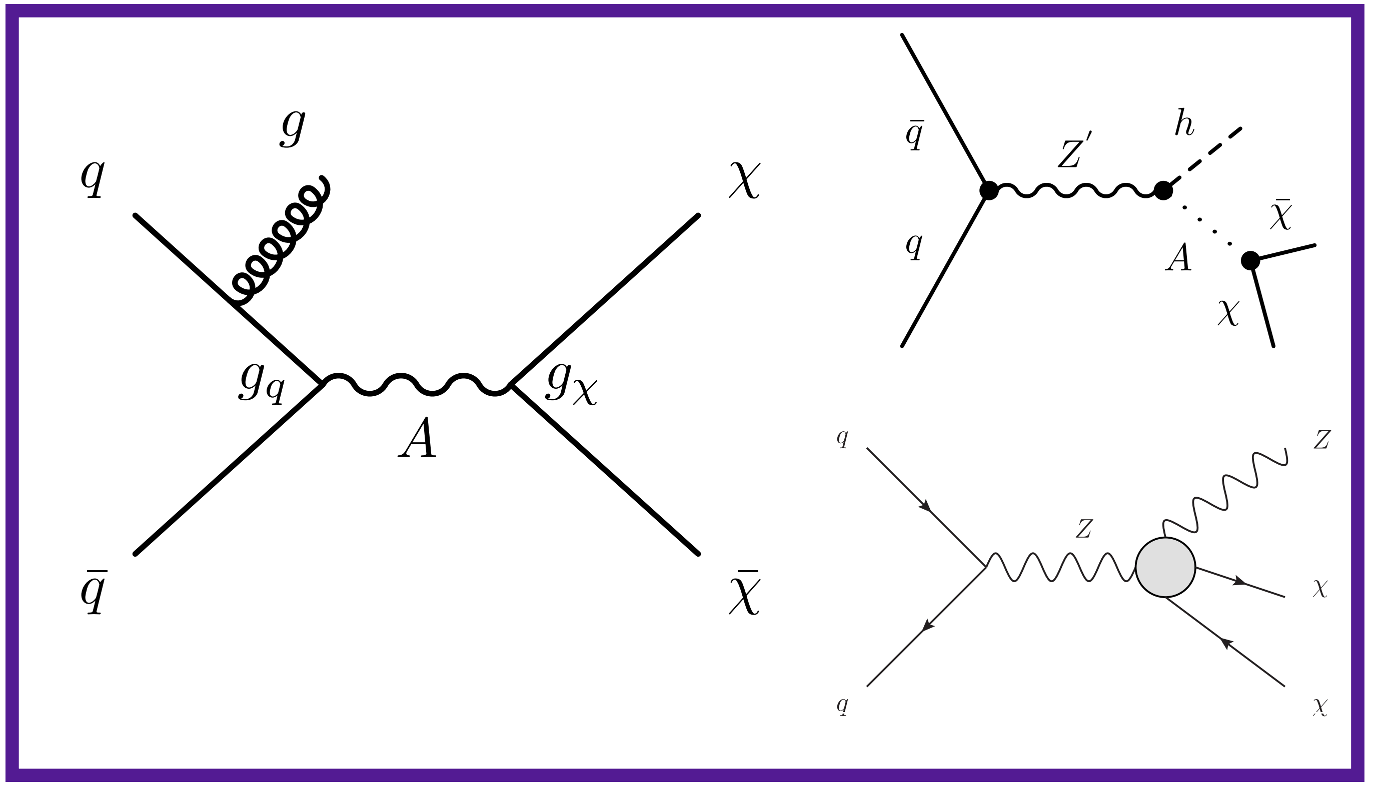
Range of answers!



via DMF

Classic dark matter searches: mono-X

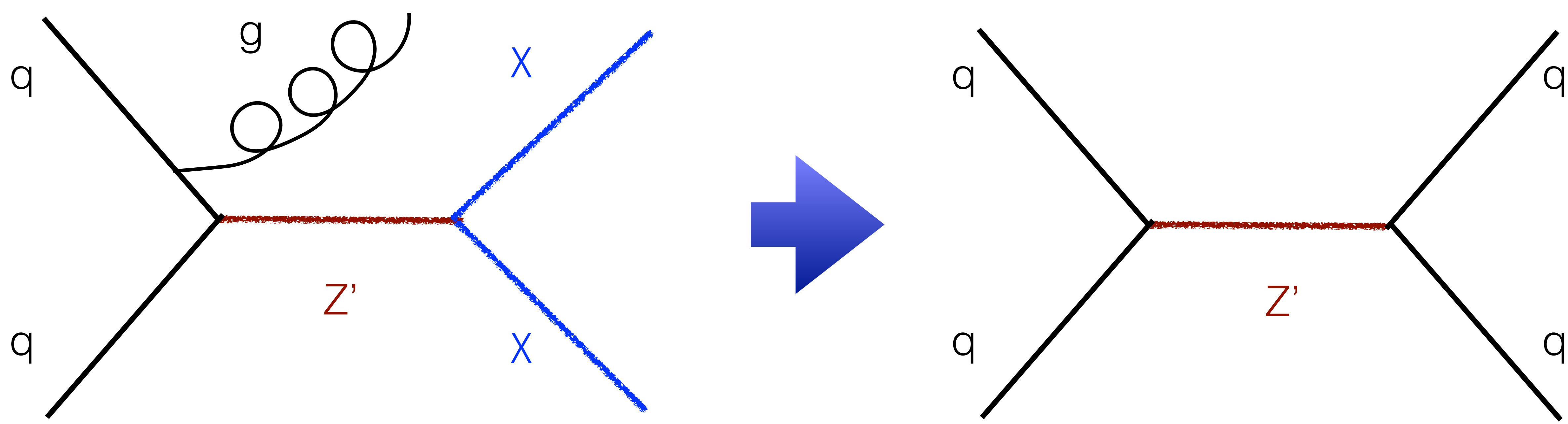


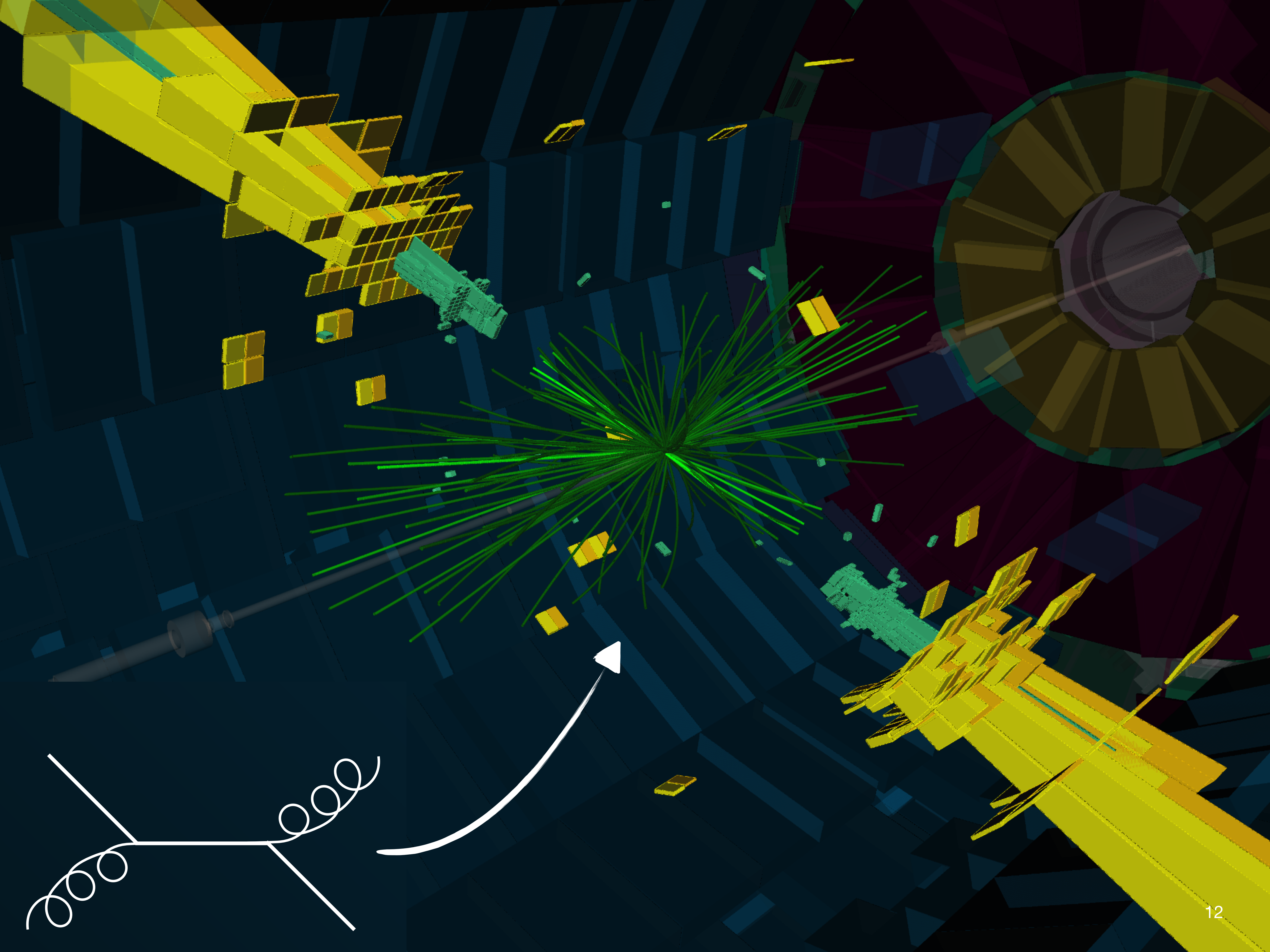


- Search for simplified-model DM mediator to MET plus any object on which to trigger
- Most sensitive is MET+jet but we also have MET+γ, MET+W/Z/h, …

What about other mediator decay products?

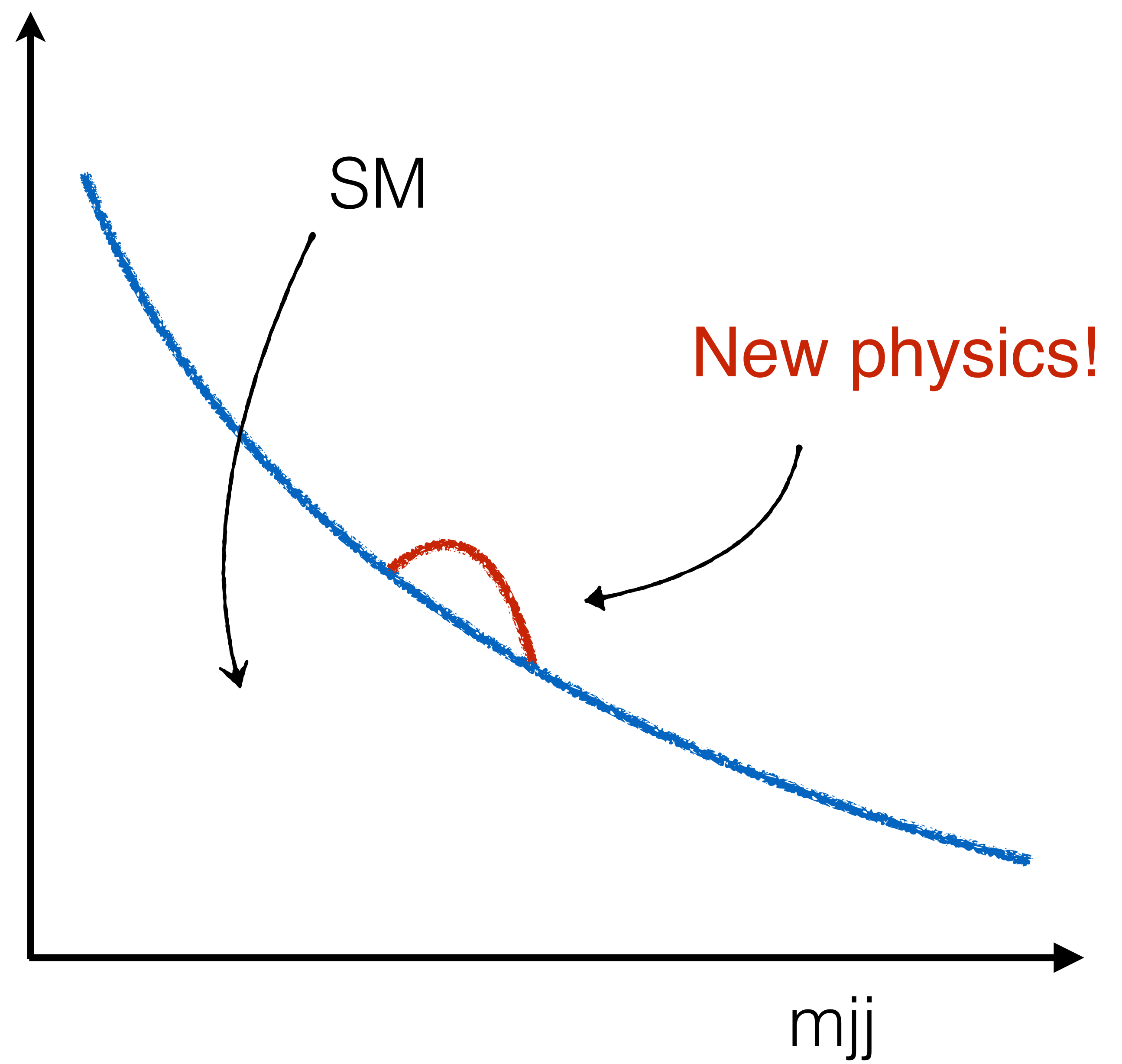
- Left: Classic MET+jet signature
- But: if you can make it from quarks, you can make quarks from it!
  - Allow Z’ mediator to decay back to two quarks and have a dijet final state signature with no missing energy
  - No need for an ISR object, so higher cross section process



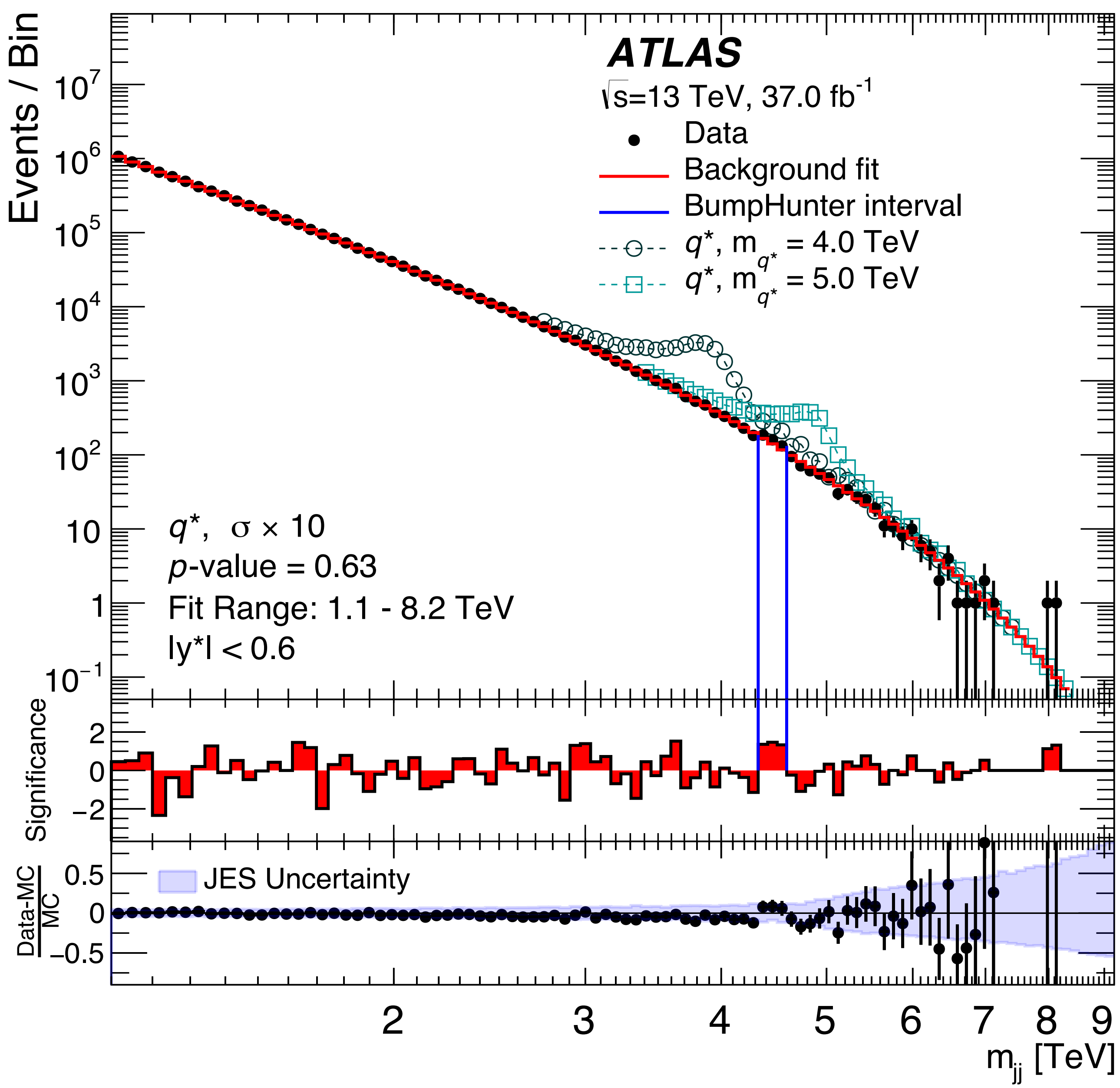


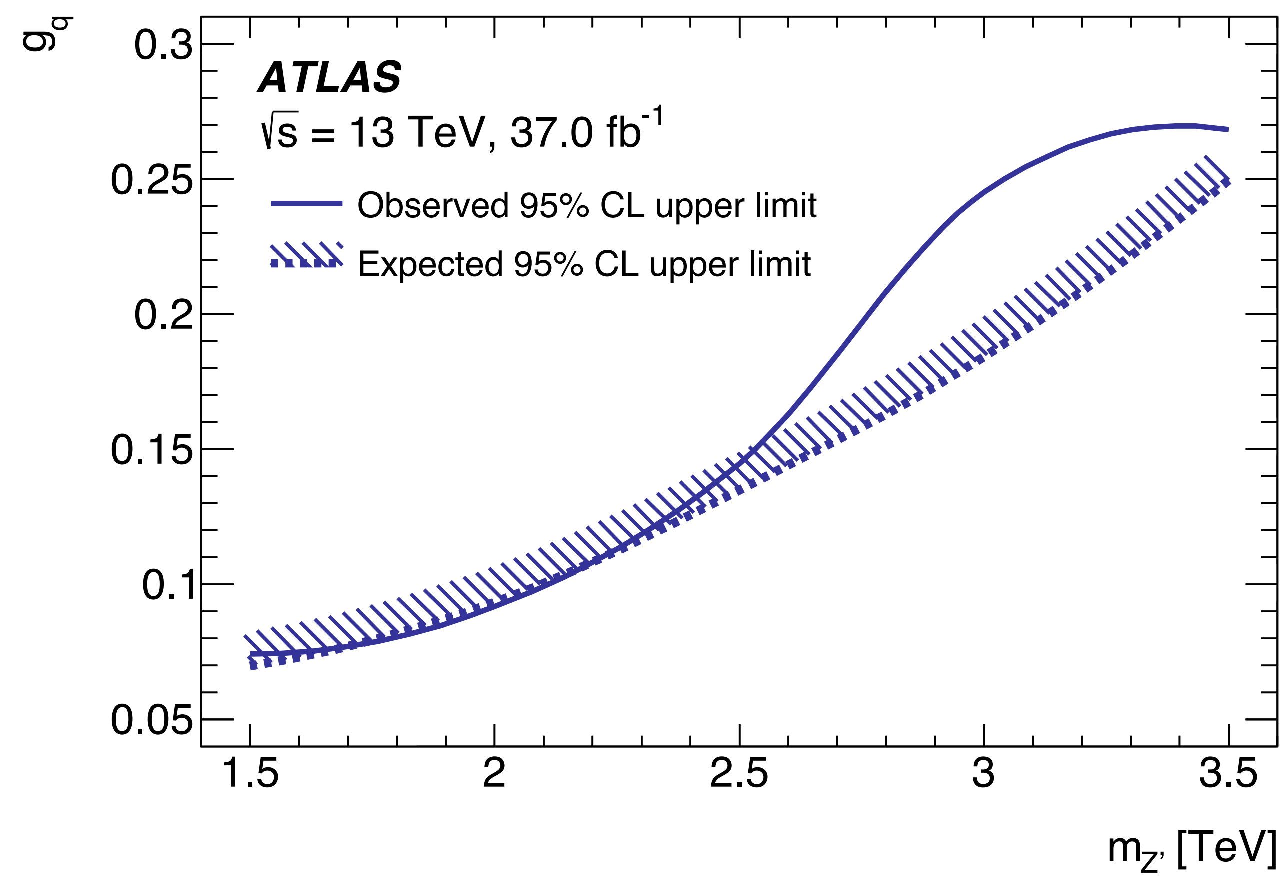
The high mass dijet analysis: a versatile search!

- **Invariant mass** of leading two jets in event is **mjj**. If only SM, mjj 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



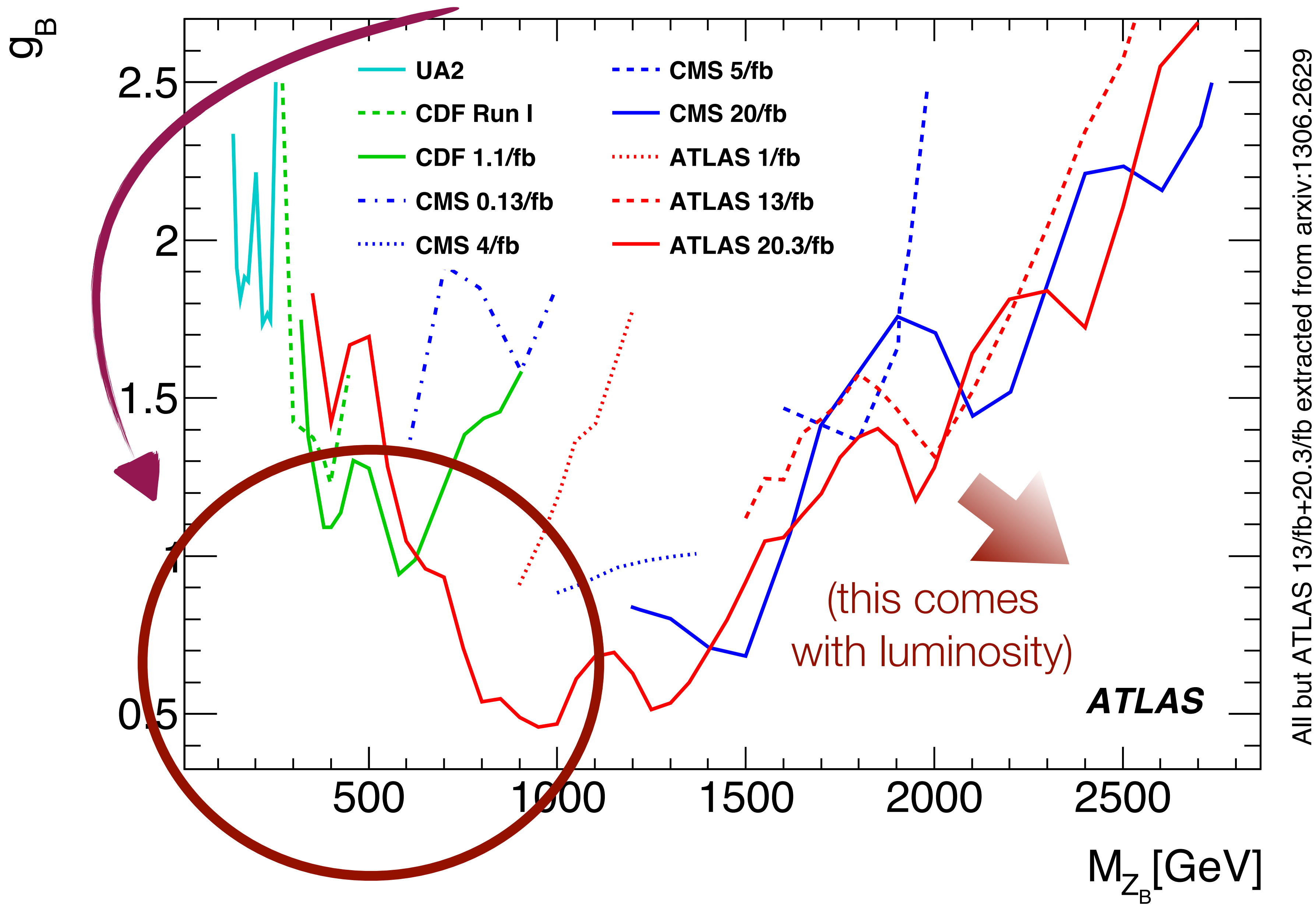


- Set limits on Z' mediator in 2D plane: coupling to SM quarks vs Z' mass

- 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!



Status at the beginning of Run II

- “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!

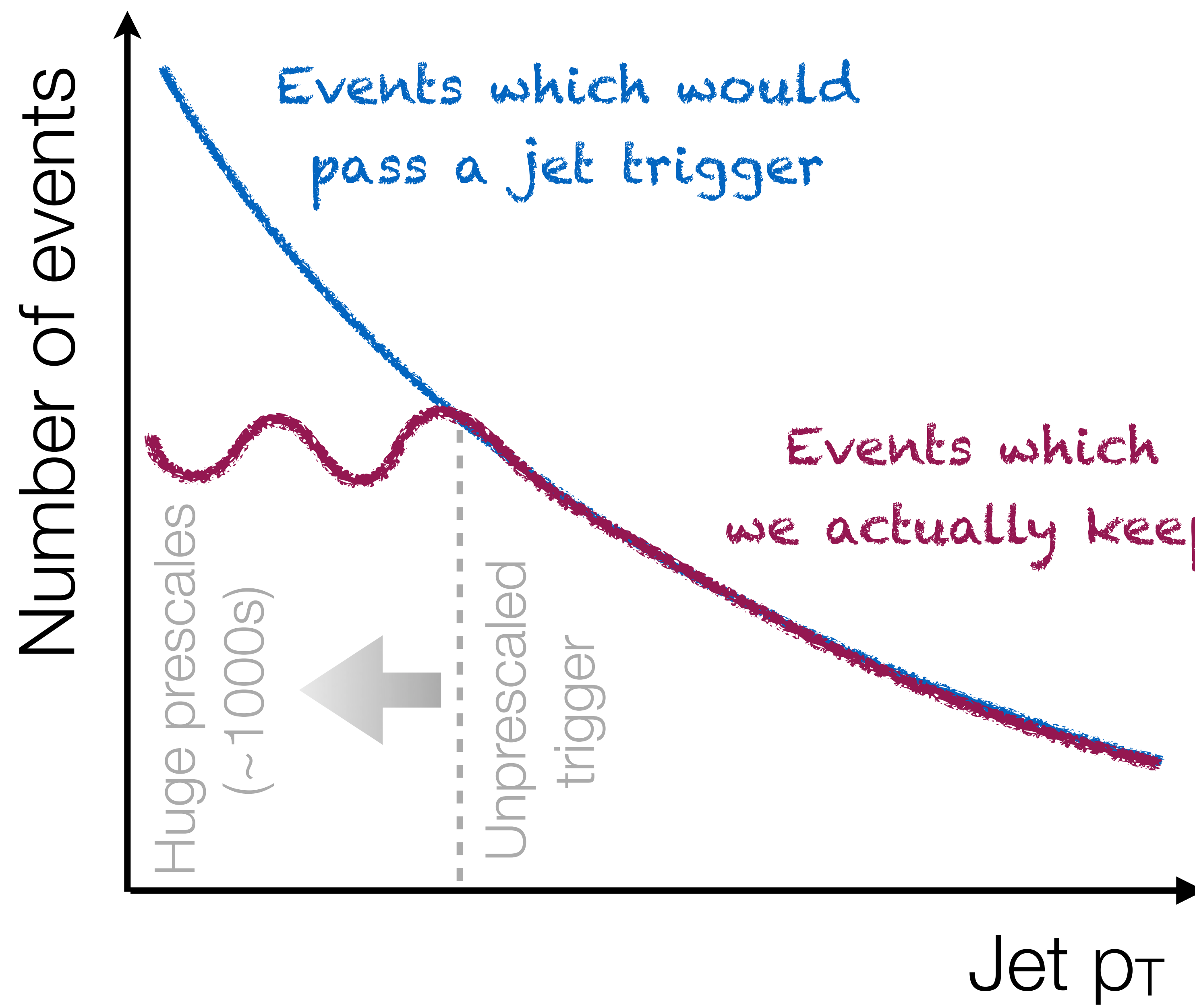
Hardware L1 trigger reduces flow to 100 kHz

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

A perfect drop of physics!

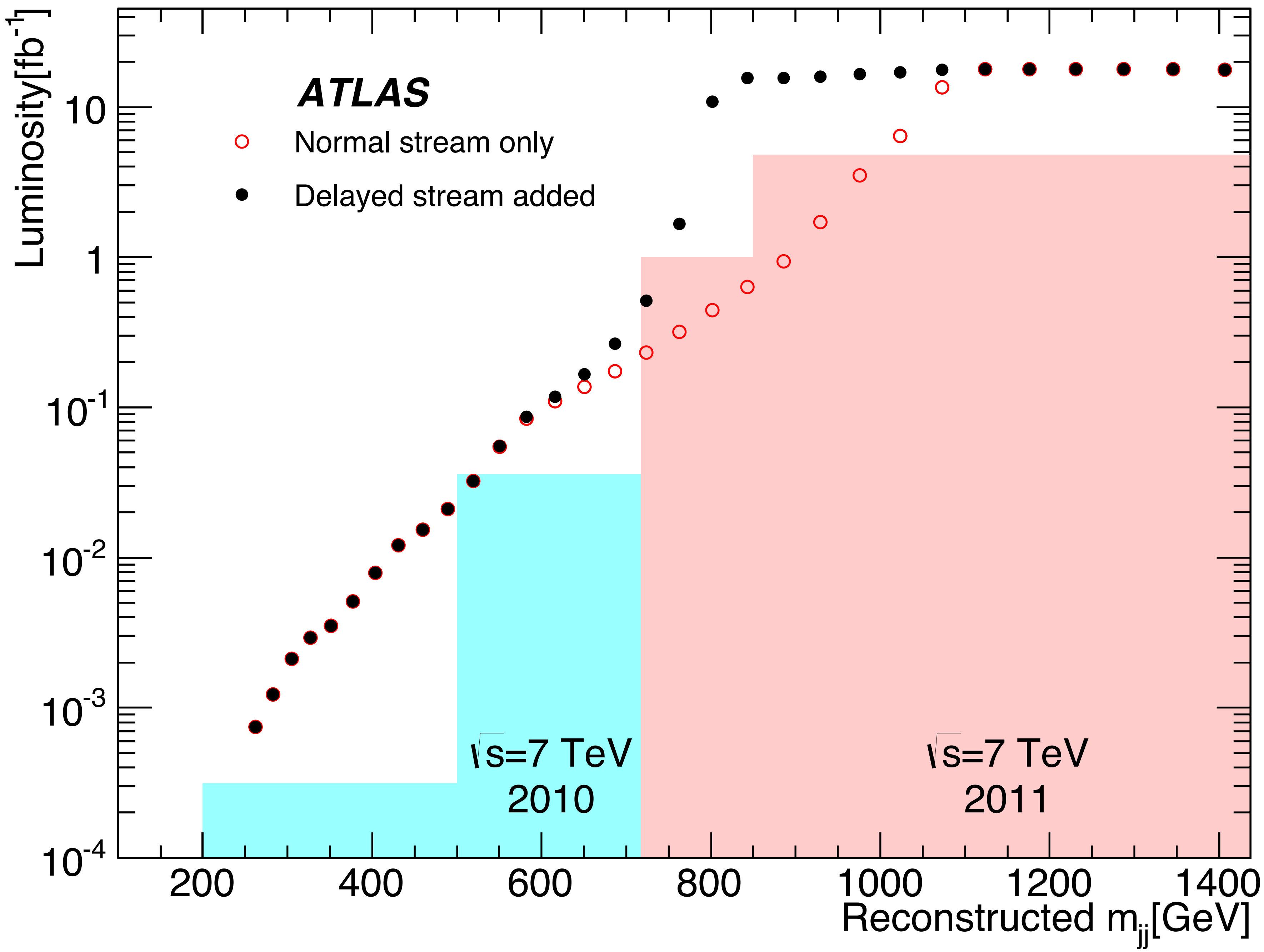
Trigger prescales

- 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.**



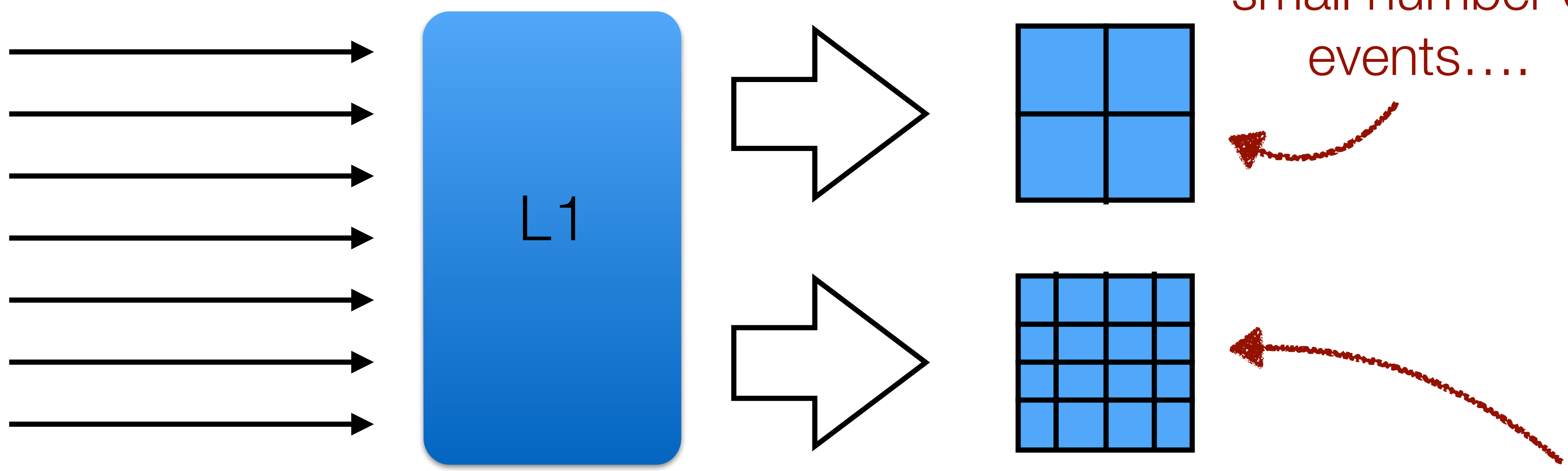
Combining triggers can get you something …

- **… but it isn't great!**
- In 8 TeV we combined triggers to access mjj ~250 GeV
- But effective luminosity dropped so fast that CDF limits were still stronger



Effective luminosity vs. mjj
for combination of prescaled triggers

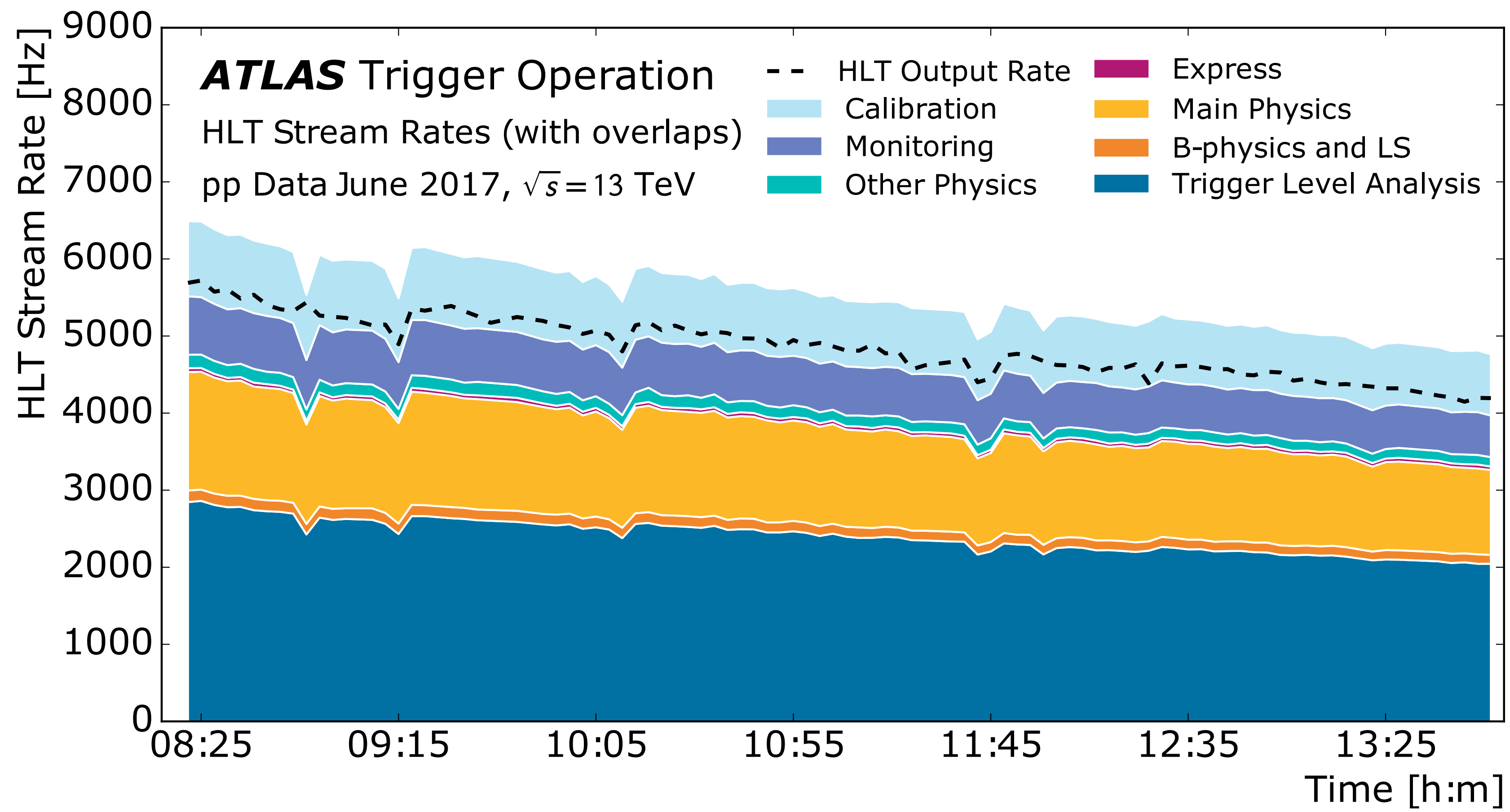
Fancy Option 1: trigger level analysis!

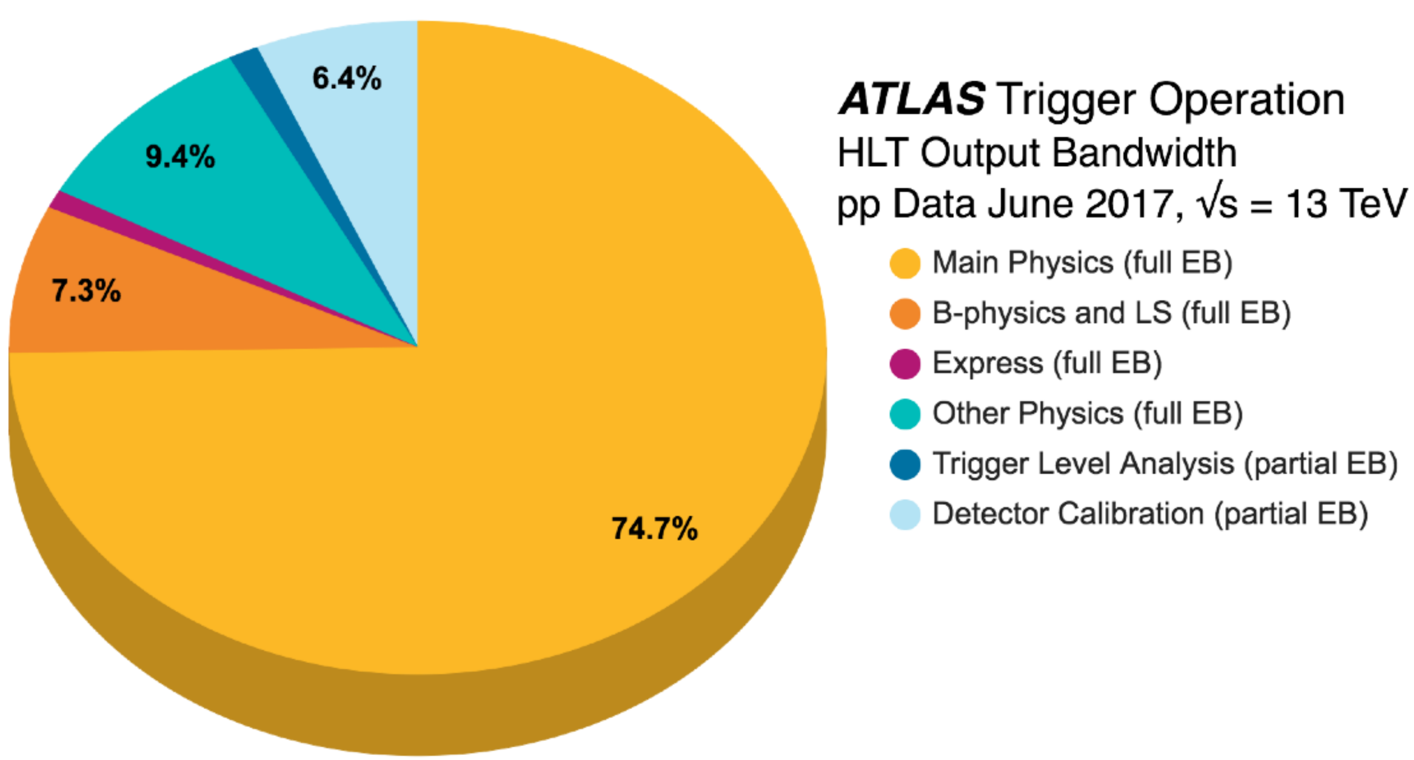


- Using jets made with only trigger information, we save a lot of space!
- No tracks, no other objects, not even other calorimeter info outside the jets themselves.

How much does this approach actually help with data storage?

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

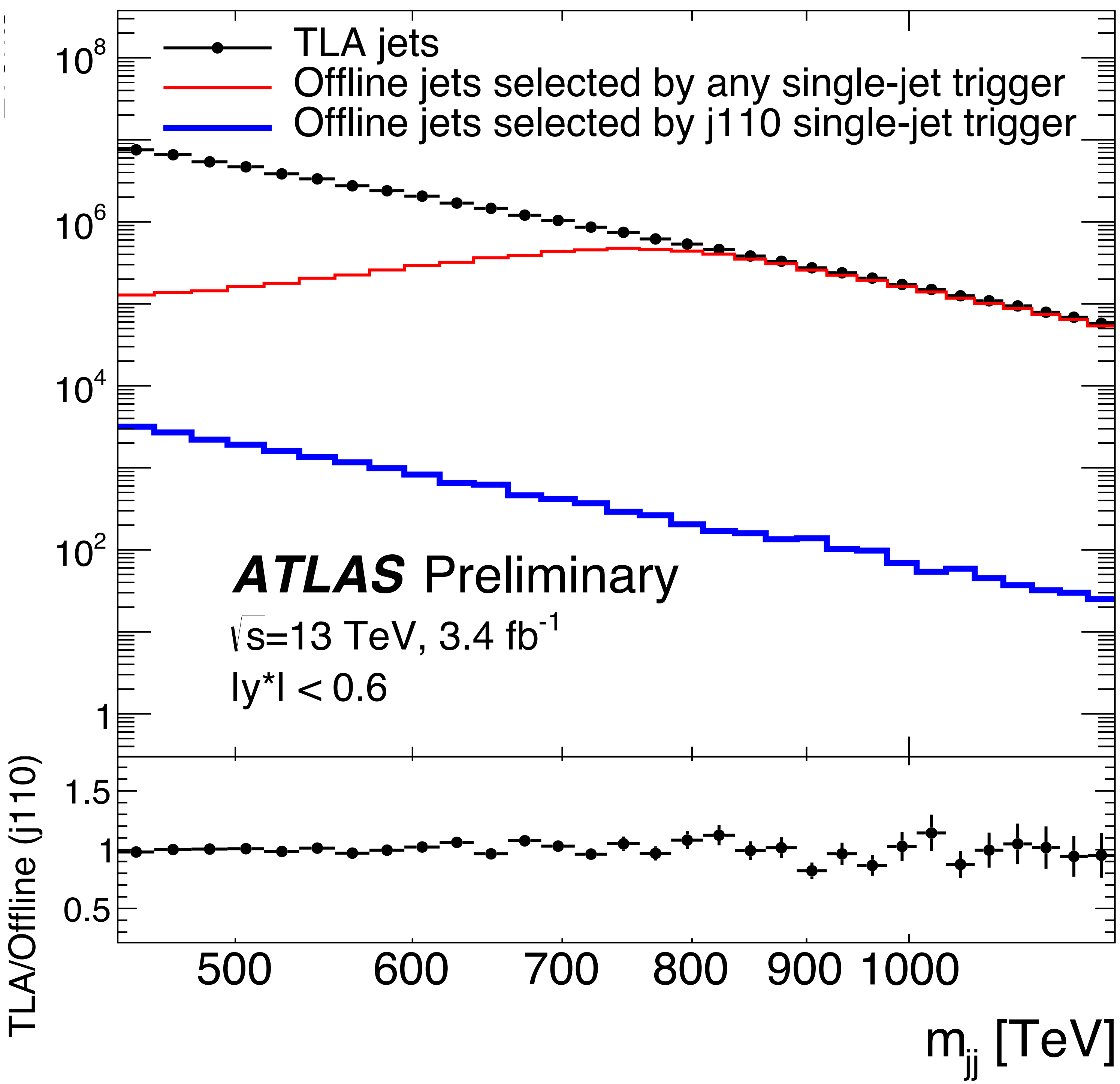




- … but makes up only a tiny fraction of the total HLT bandwidth!

- Due to very small event size

The luminosity gain in practice

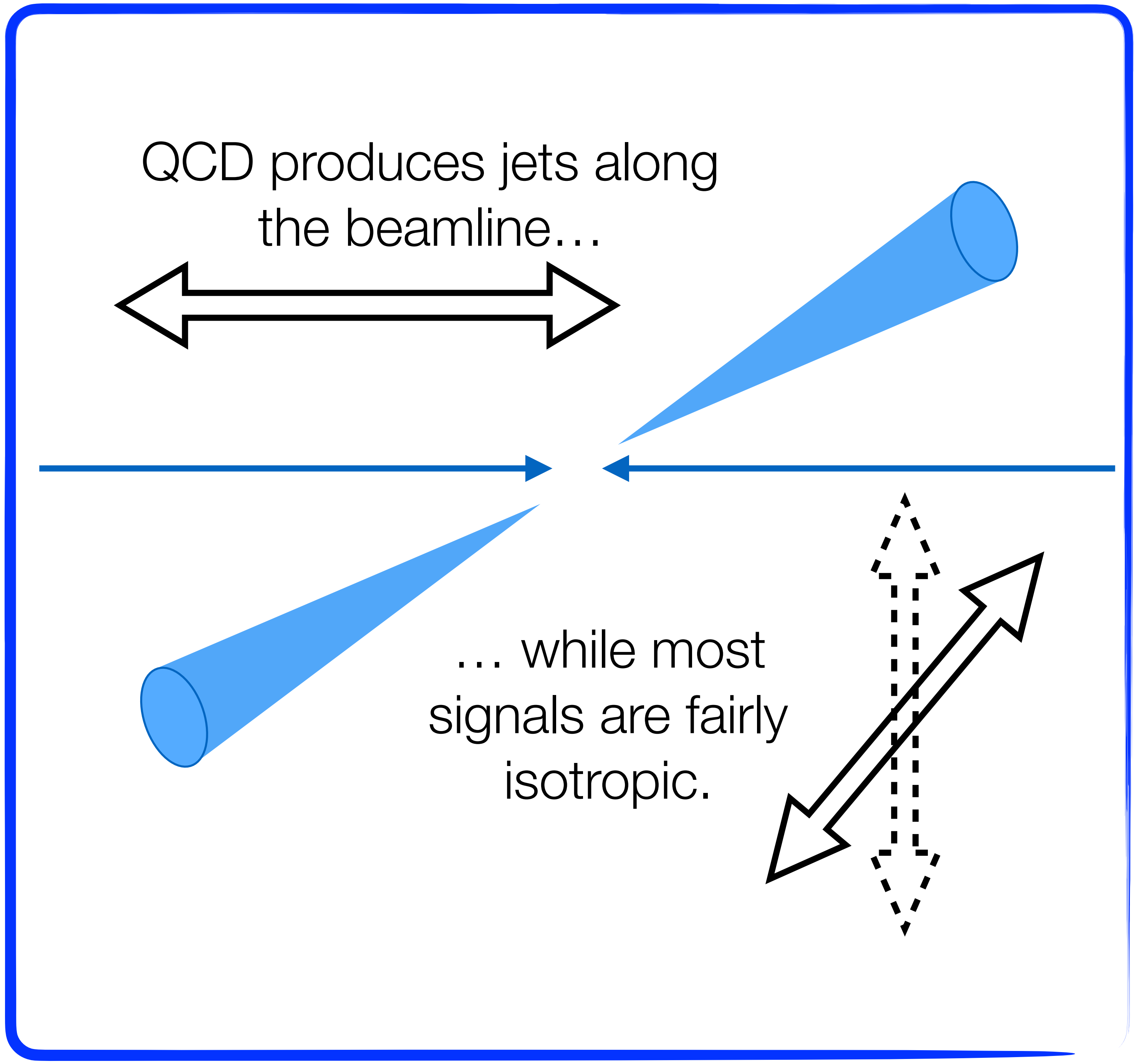


3 orders of magnitude gain from j110 trigger

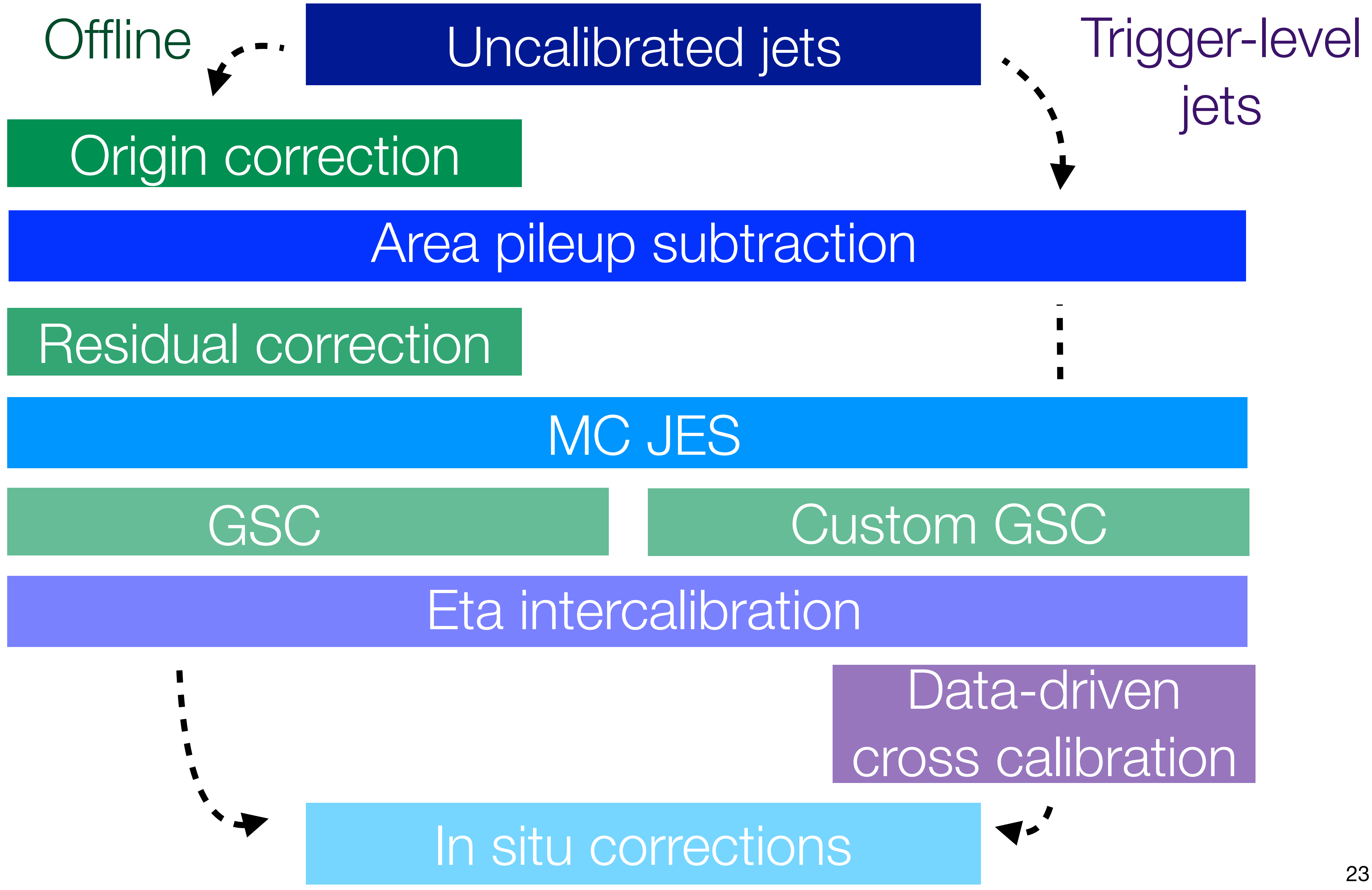
Below 800 GeV, increasing gain over all offline triggers

Event selection: kinematics

- 2 jets with $|\eta| < 2.8$
- $p_{T1} > 220$ GeV, $p_{T2} > 85$ GeV
- $y^* = (y_1 - y_2)/2 < 0.6$ **to optimise sensitivity**
- Second signal region uses $y^* < 0.3$ **to reach lower masses**
- mjj > 520 GeV (470 GeV) to remove trigger bias
- 3 leading jets pass cleaning (next slide)



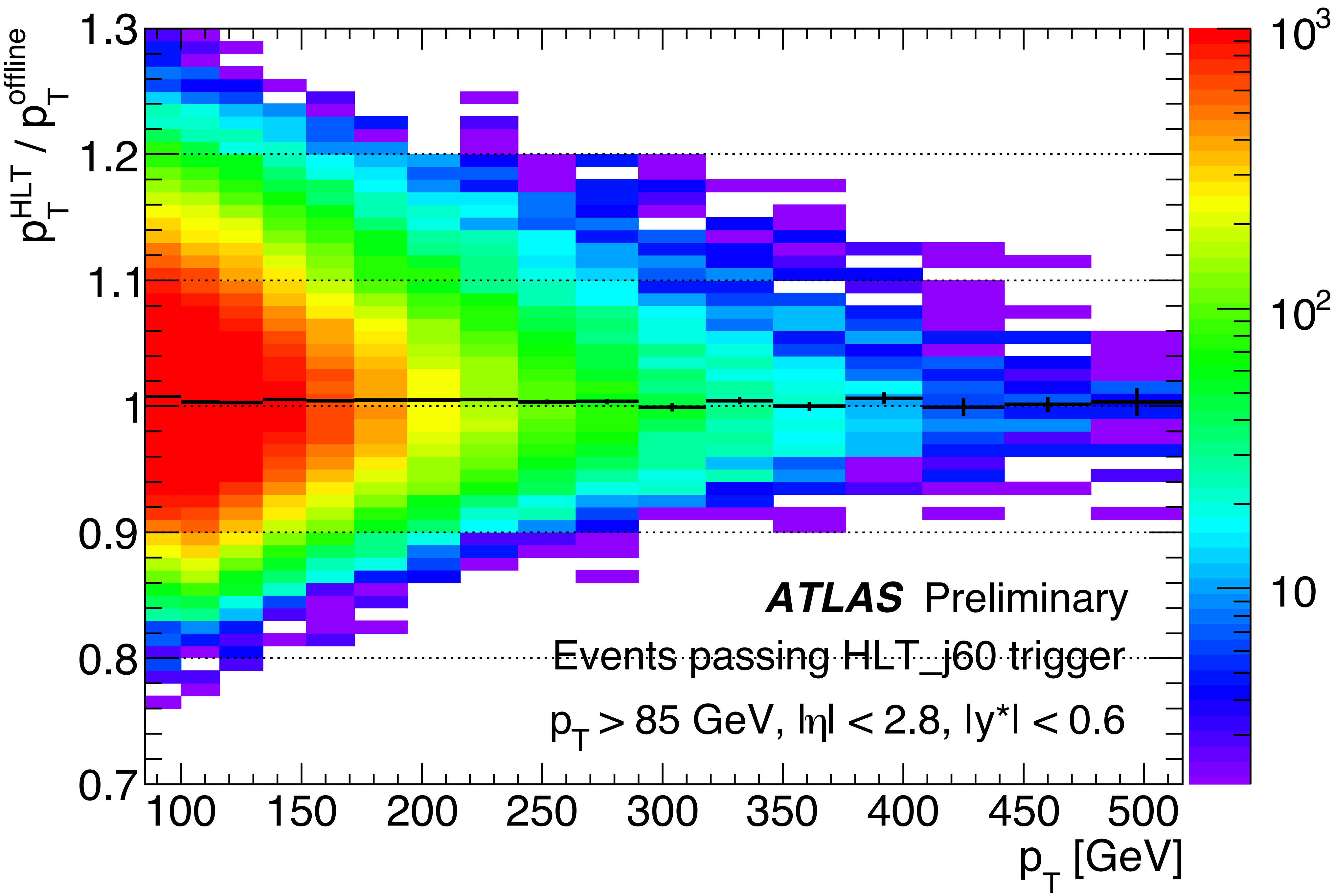
The biggest complication: customised jet calibration!



How well does it work?

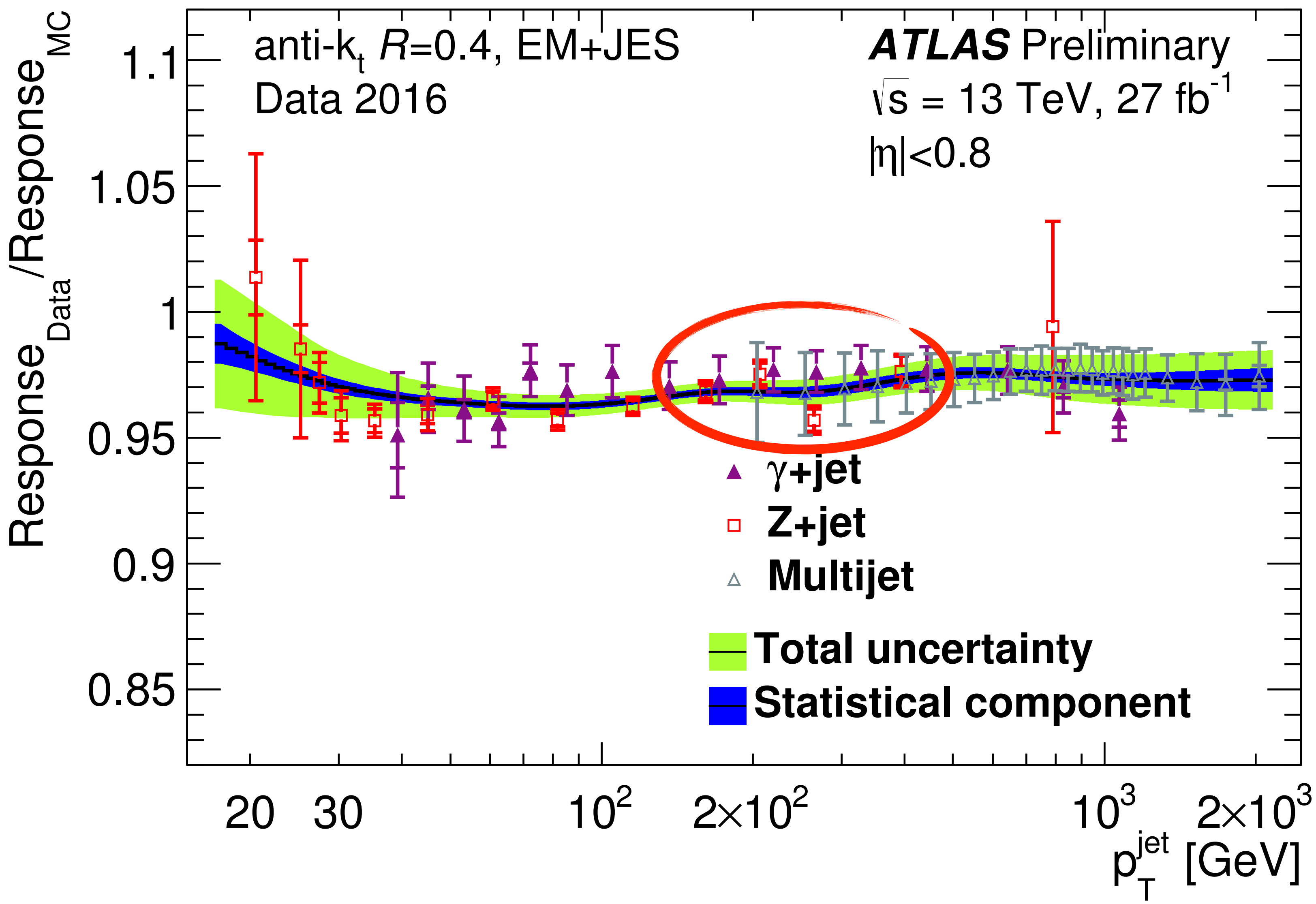
Plot mjj for online and offline jets in each event with a prescaled low-pT trigger.

Response found to be within 1% with no mjj dependence!



New challenges in 2016!

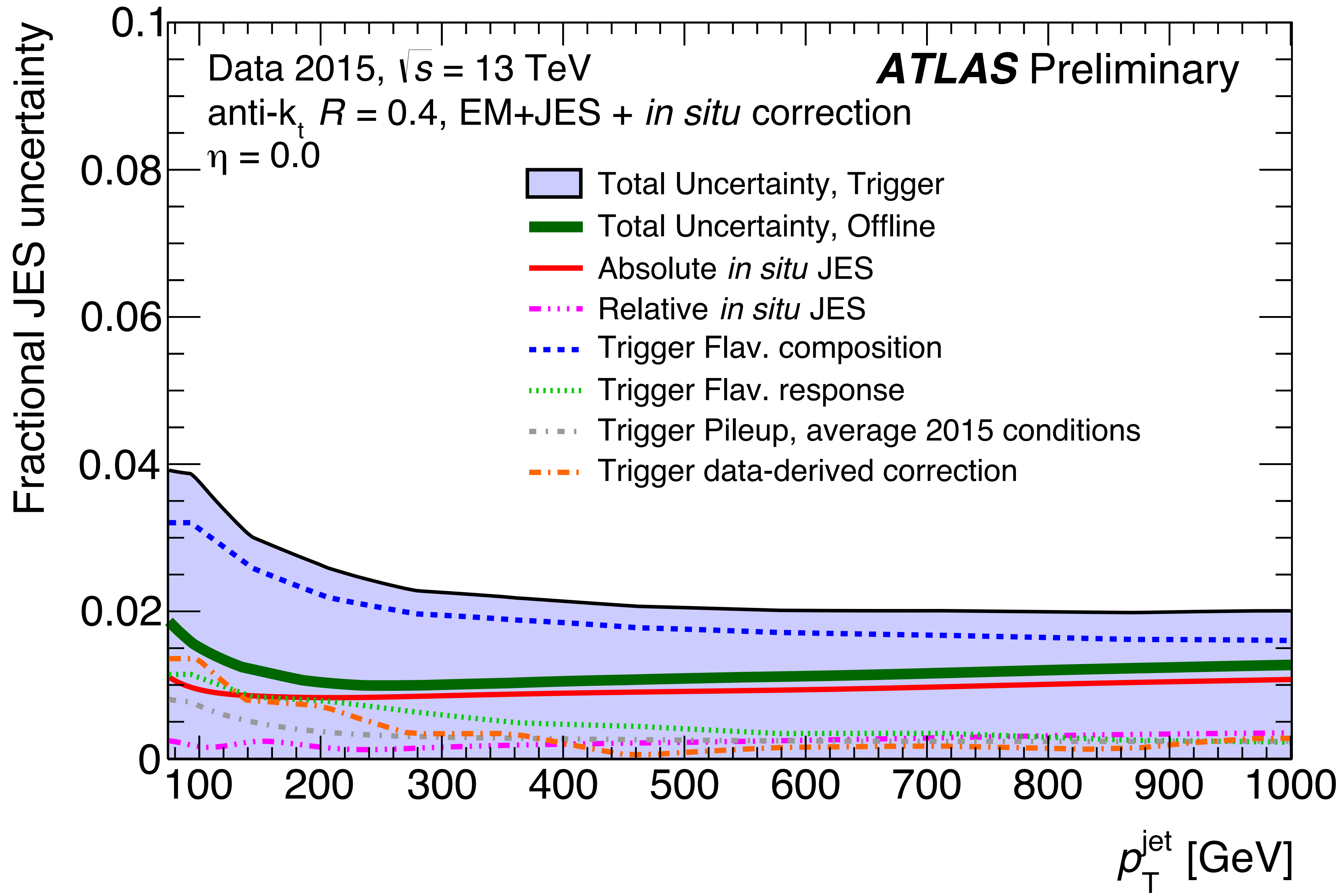
- With 2015+2016 dataset and updated jet recommendations, discovered that **extremely high statistical precision** means sensitivity to **small non-smoothnesses in calibration**



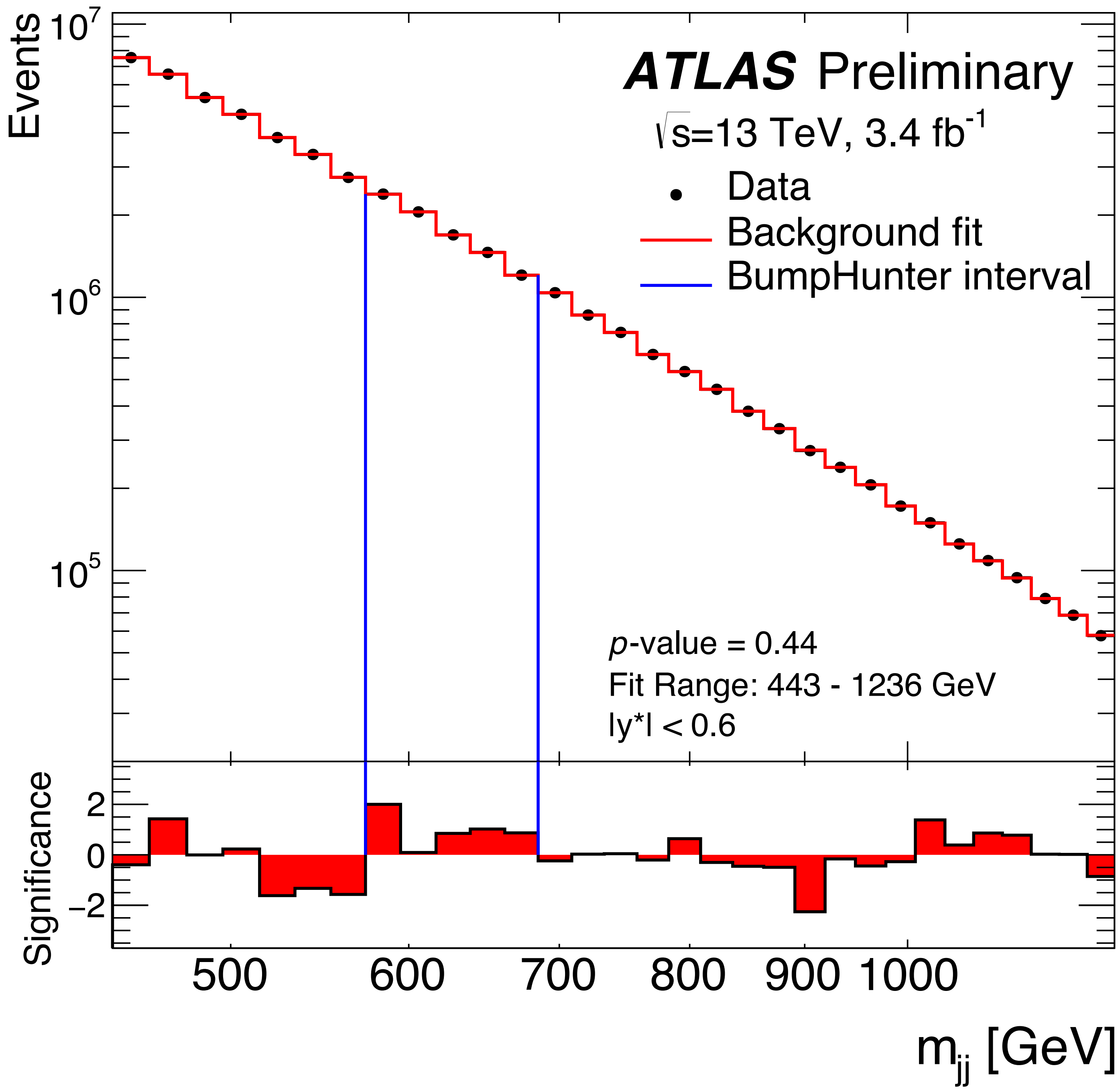
- Developed new in situ combination and an uncertainty on the bump hunting process

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

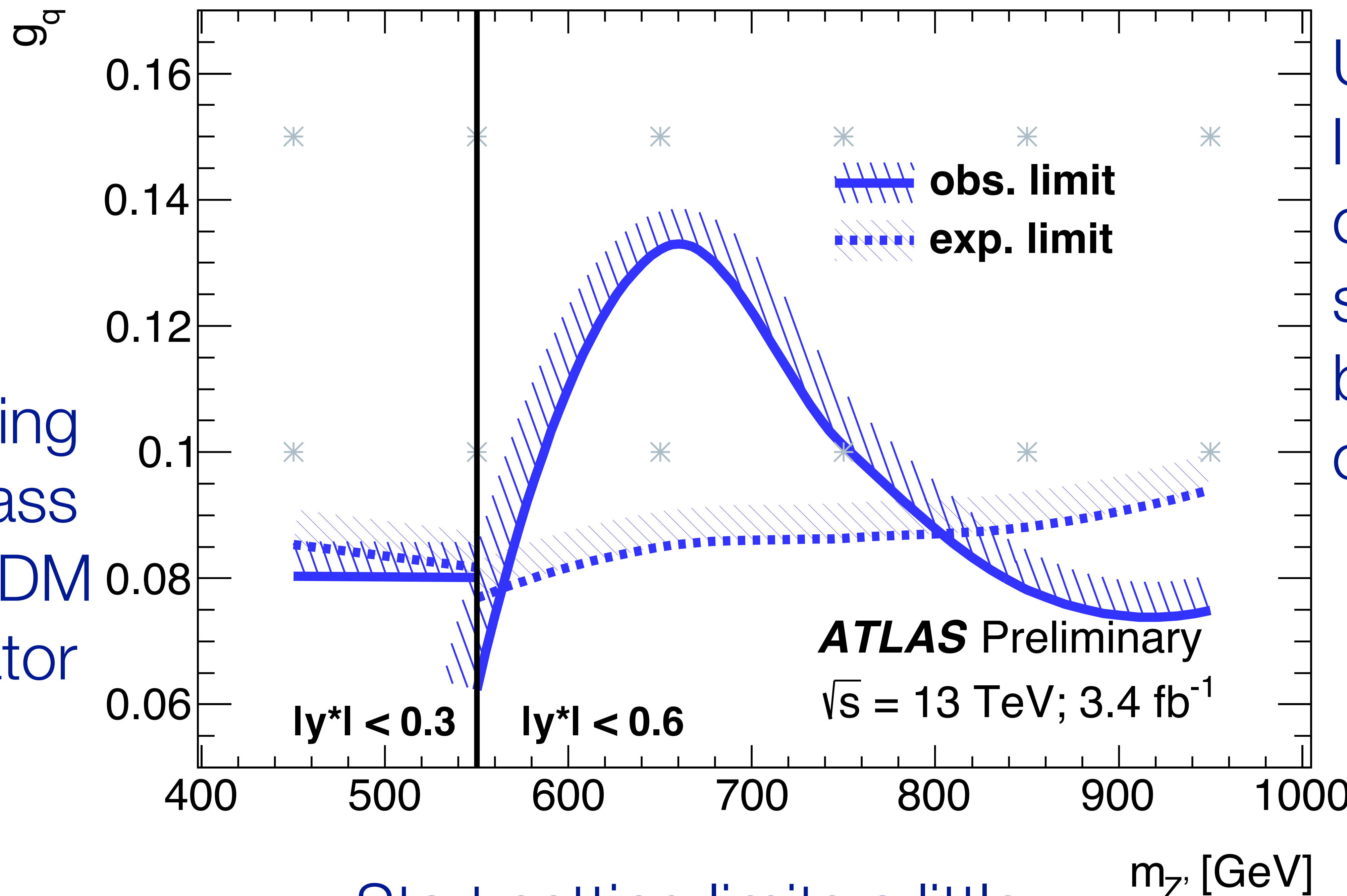


No evidence of new physics!

- 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

Model-dependent TLA limits

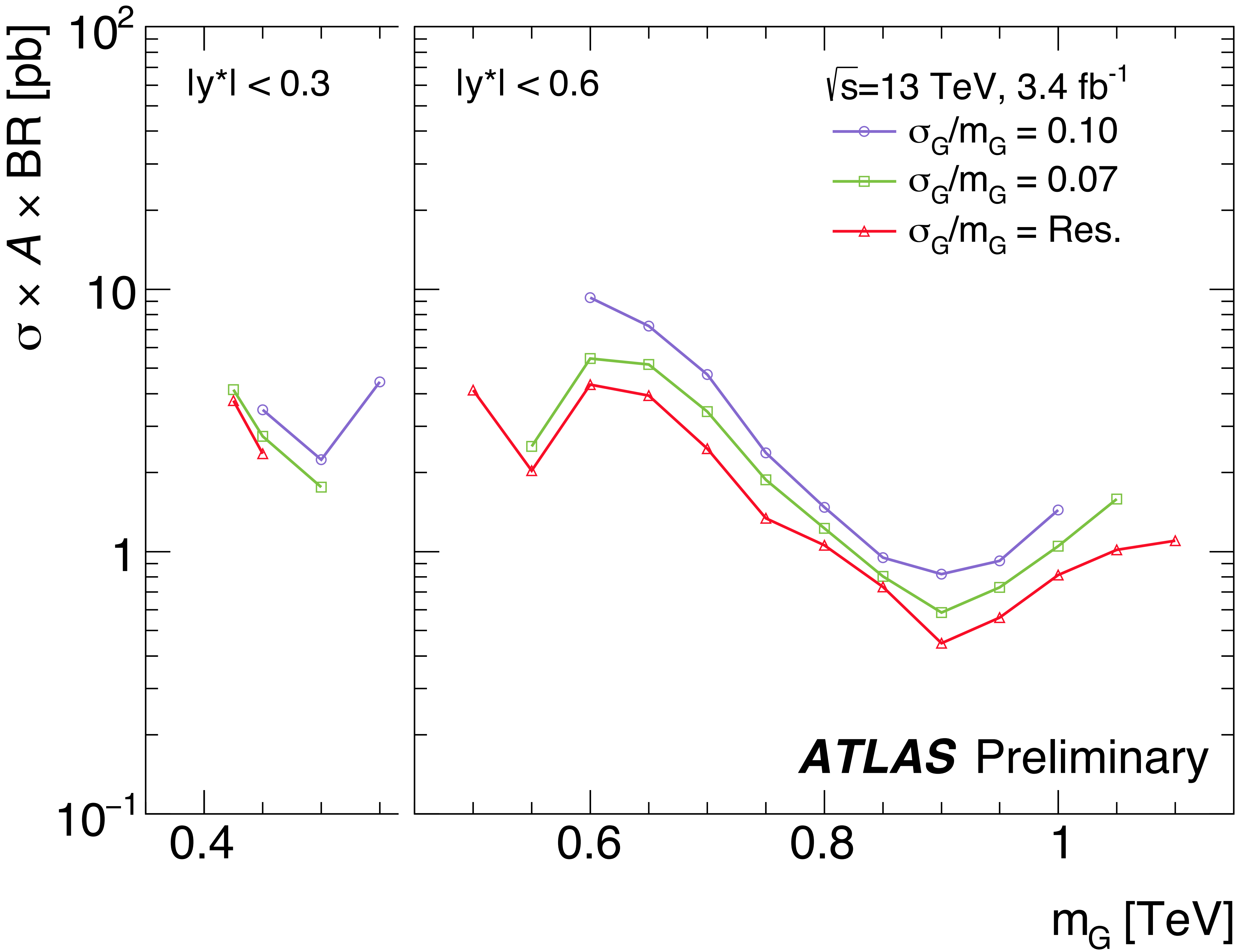
Coupling vs. mass for Z' DM mediator



Upper limit con-strained by fit challenges

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

Model-independent TLA limits



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

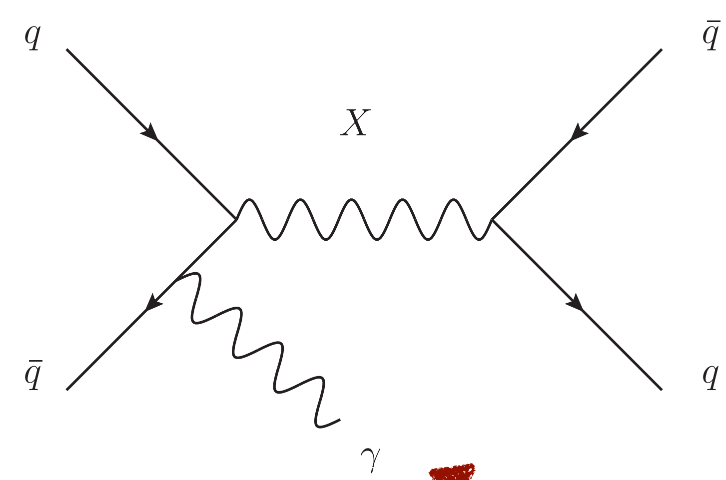
Compare [my favourite model] to a Gaussian to get relevant width; extract limits

News from the upcoming TLA result

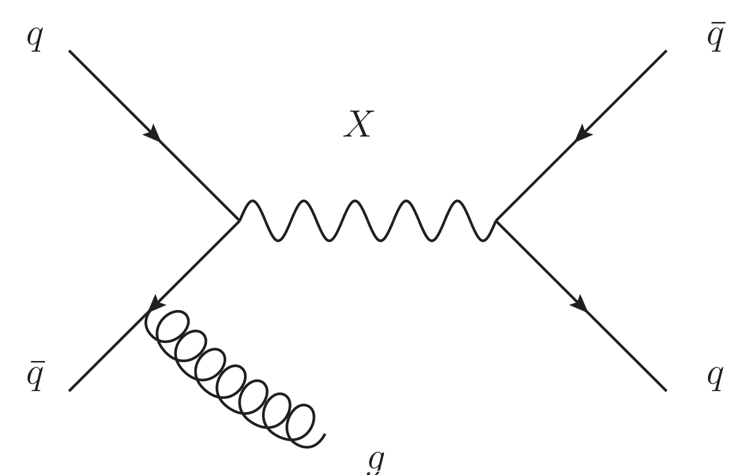
- New results with ~10x the luminosity will be public next week for Moriond! Watch this space
- Sliding fit for background estimate allows us to look at higher mjj values
- Will be the first result with new smooth in situ calibration

Fancy Option 2: dijet + ISR analysis!

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

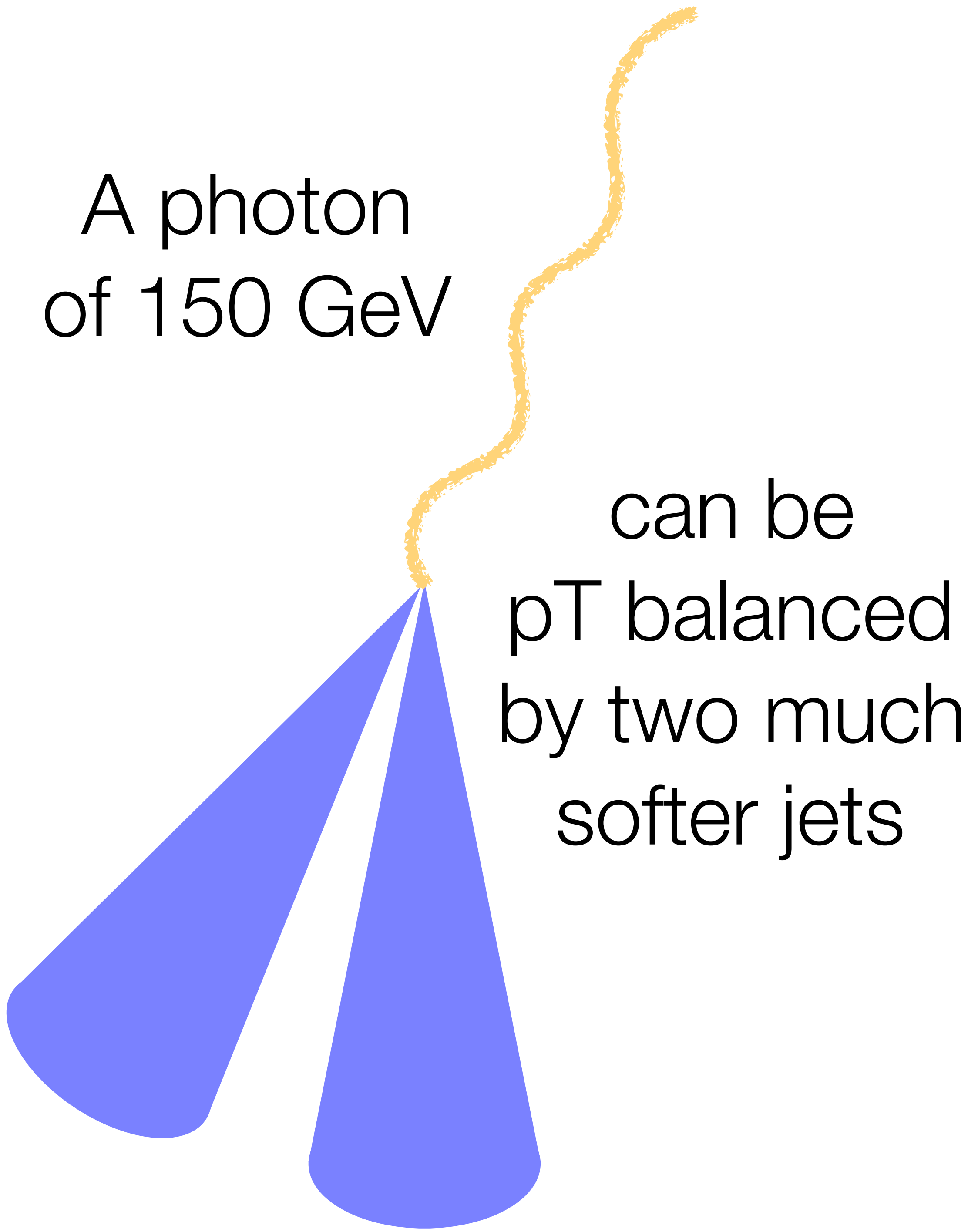


Search from 200 GeV using lowest unprescaled single photon trigger



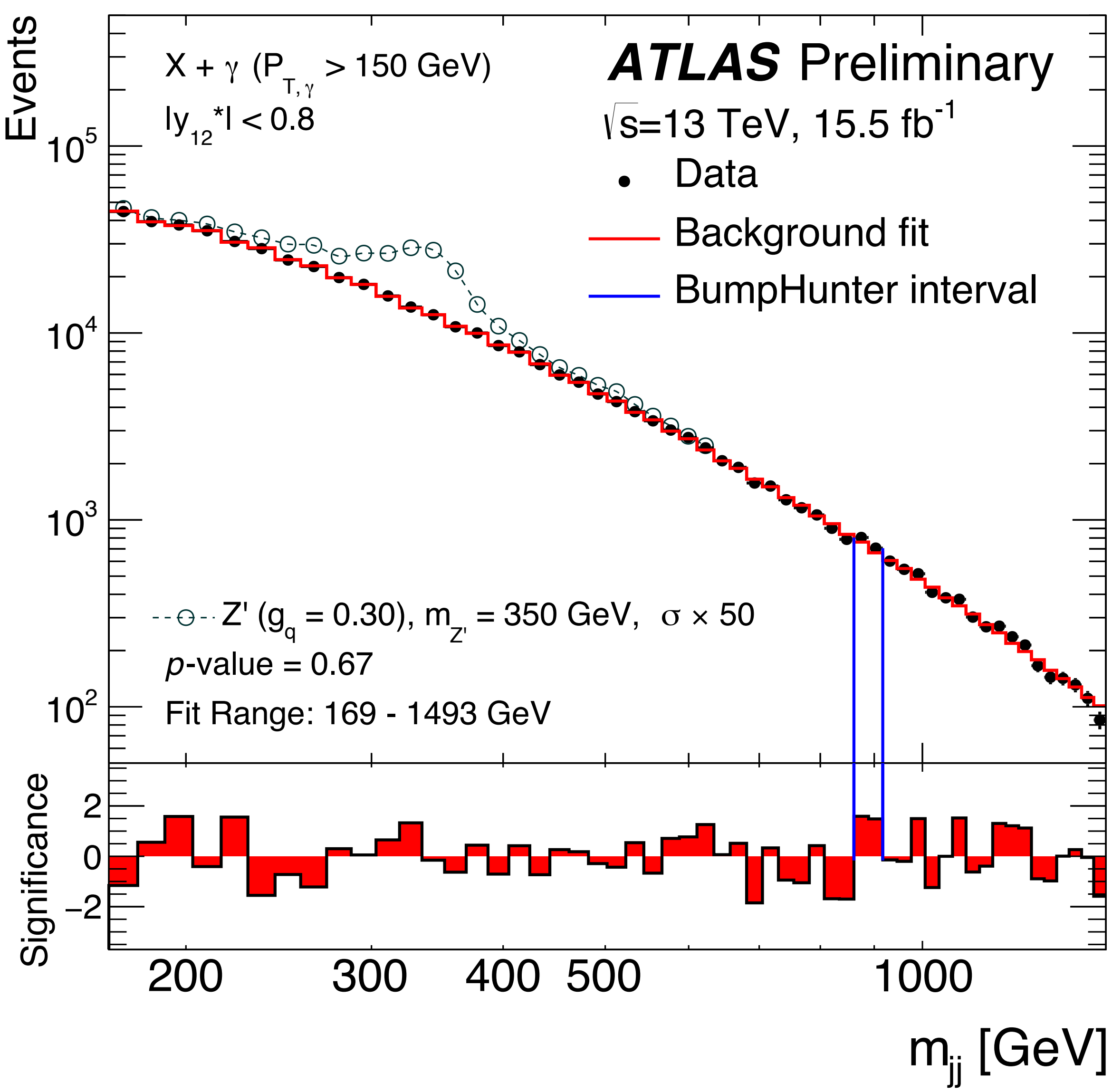
…and from 300 GeV using lowest unprescaled single jet trigger

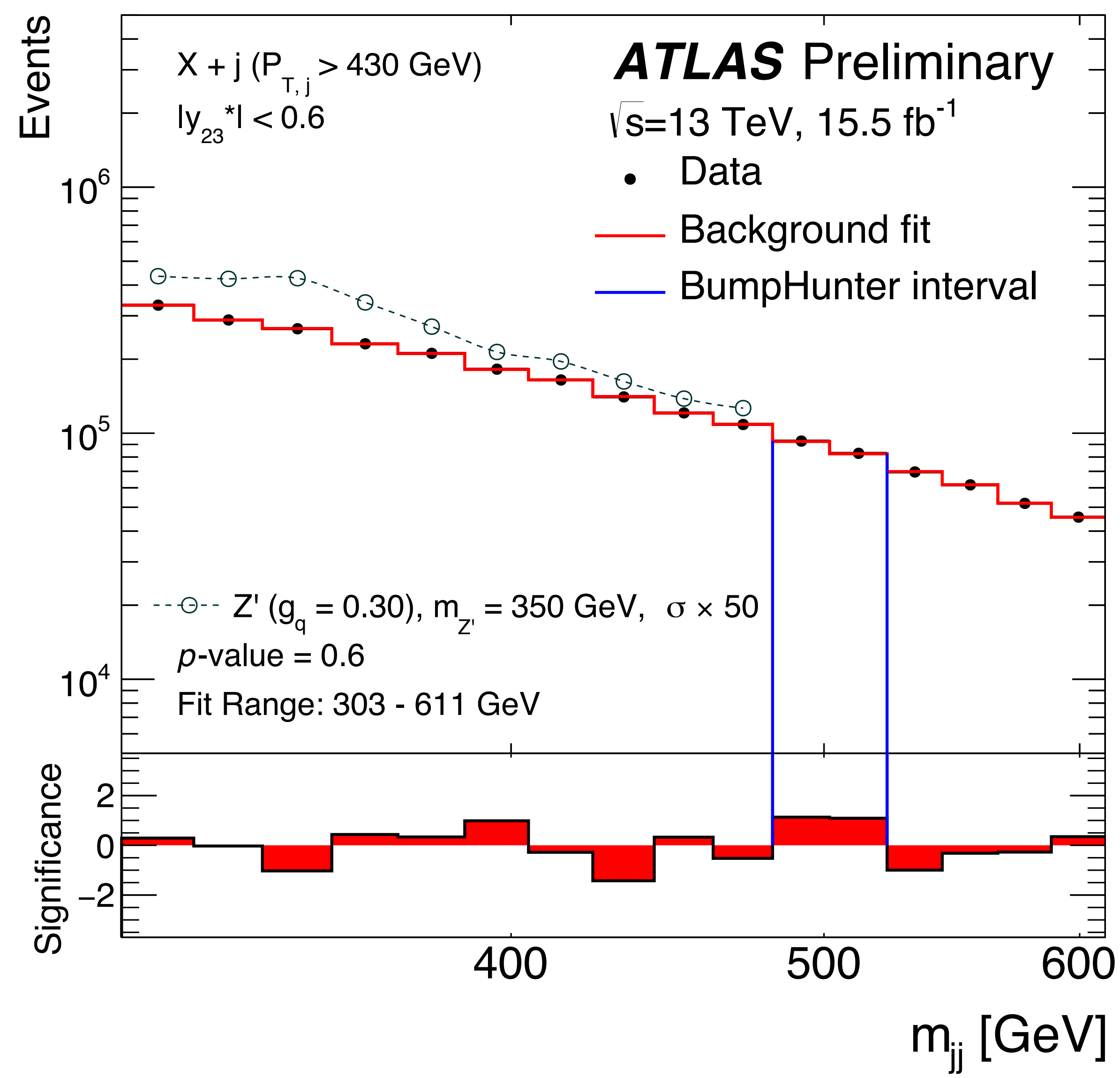
Event selection



- **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
  - $y^* < 0.6$

Search phase results

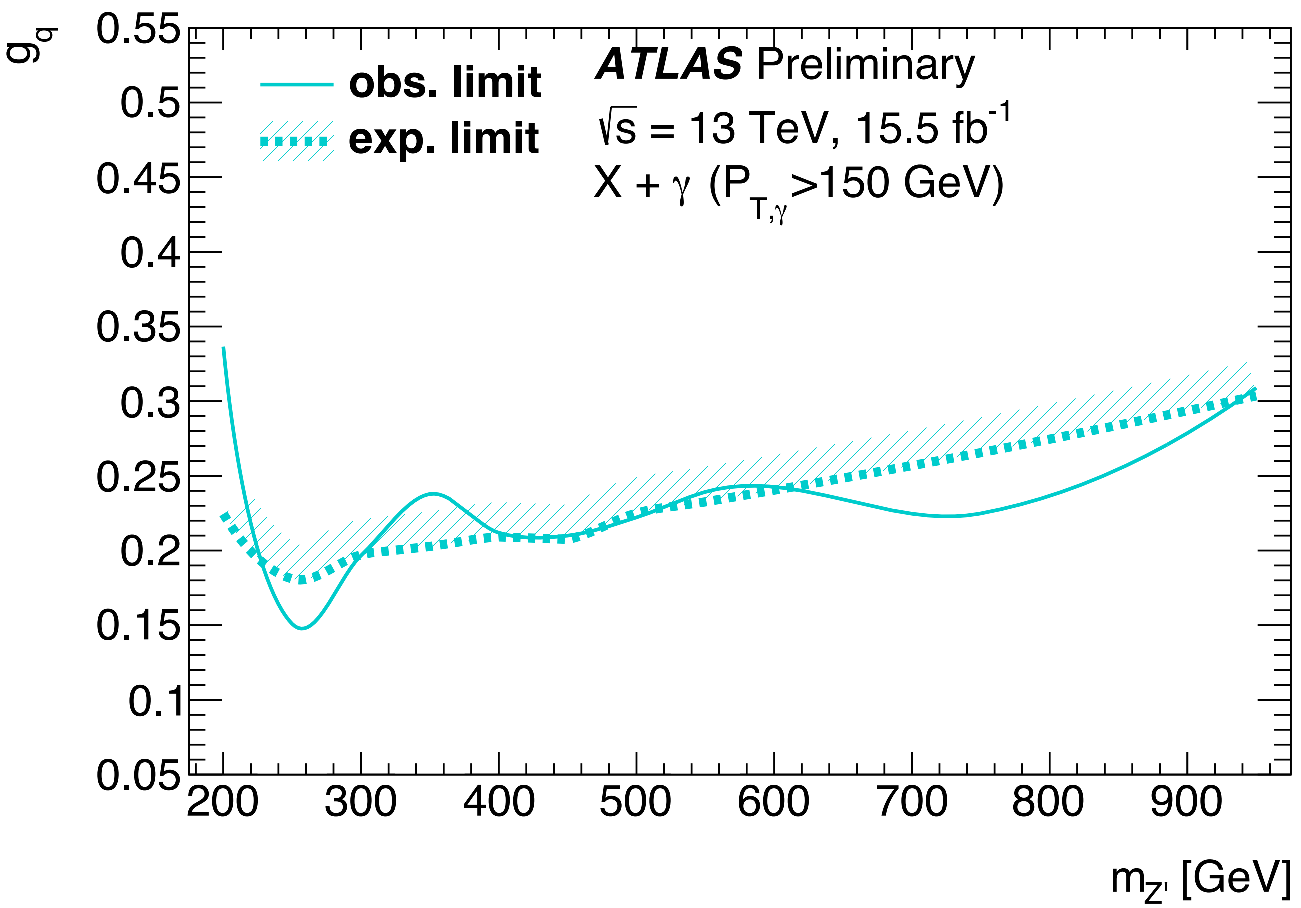


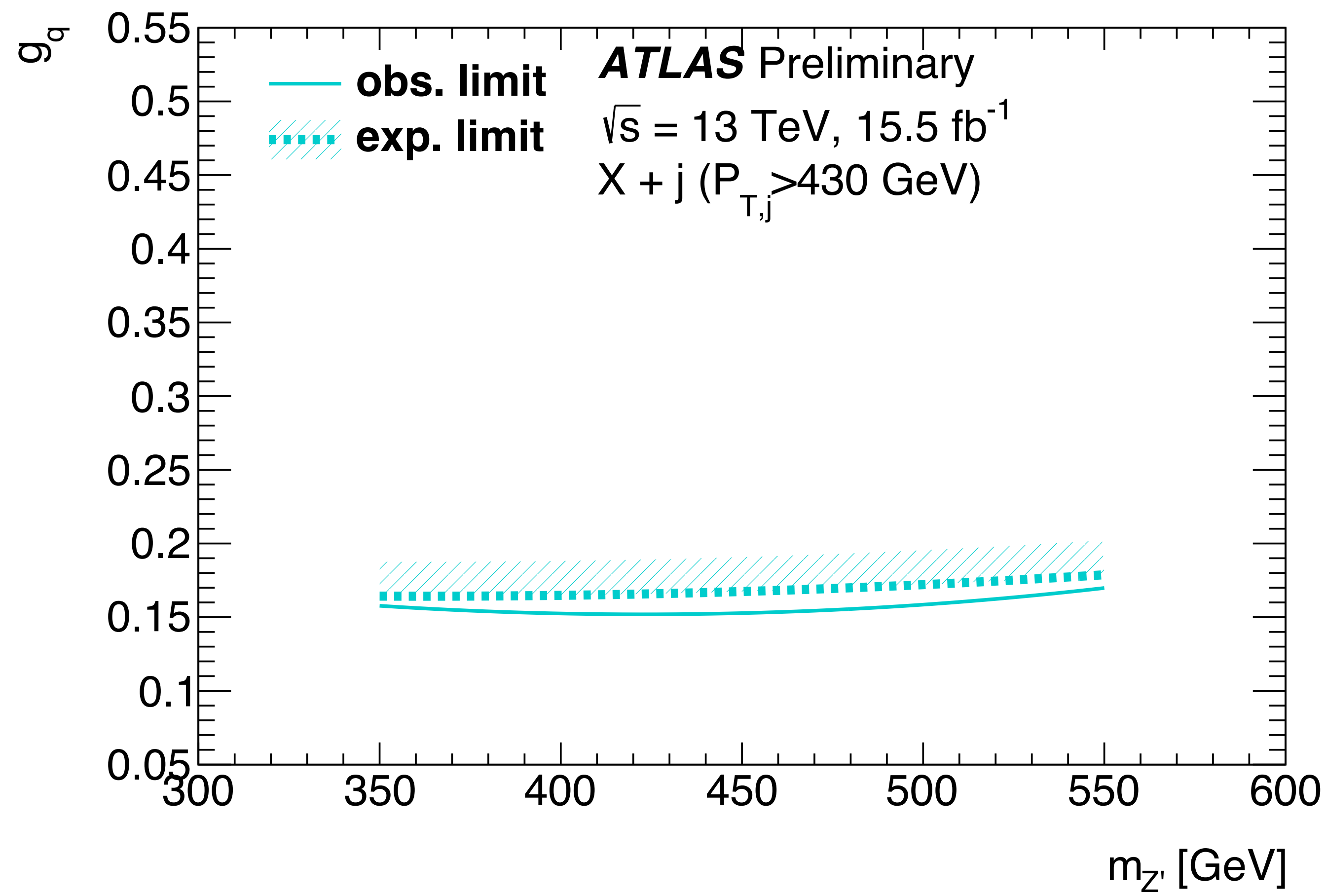


- No new physics, again …
- Photon channel offers greatest range but jet channel has higher statistics

Limits from dijet+ISR

And of course, Gaussian limits available too!





All the way down to 200 GeV!

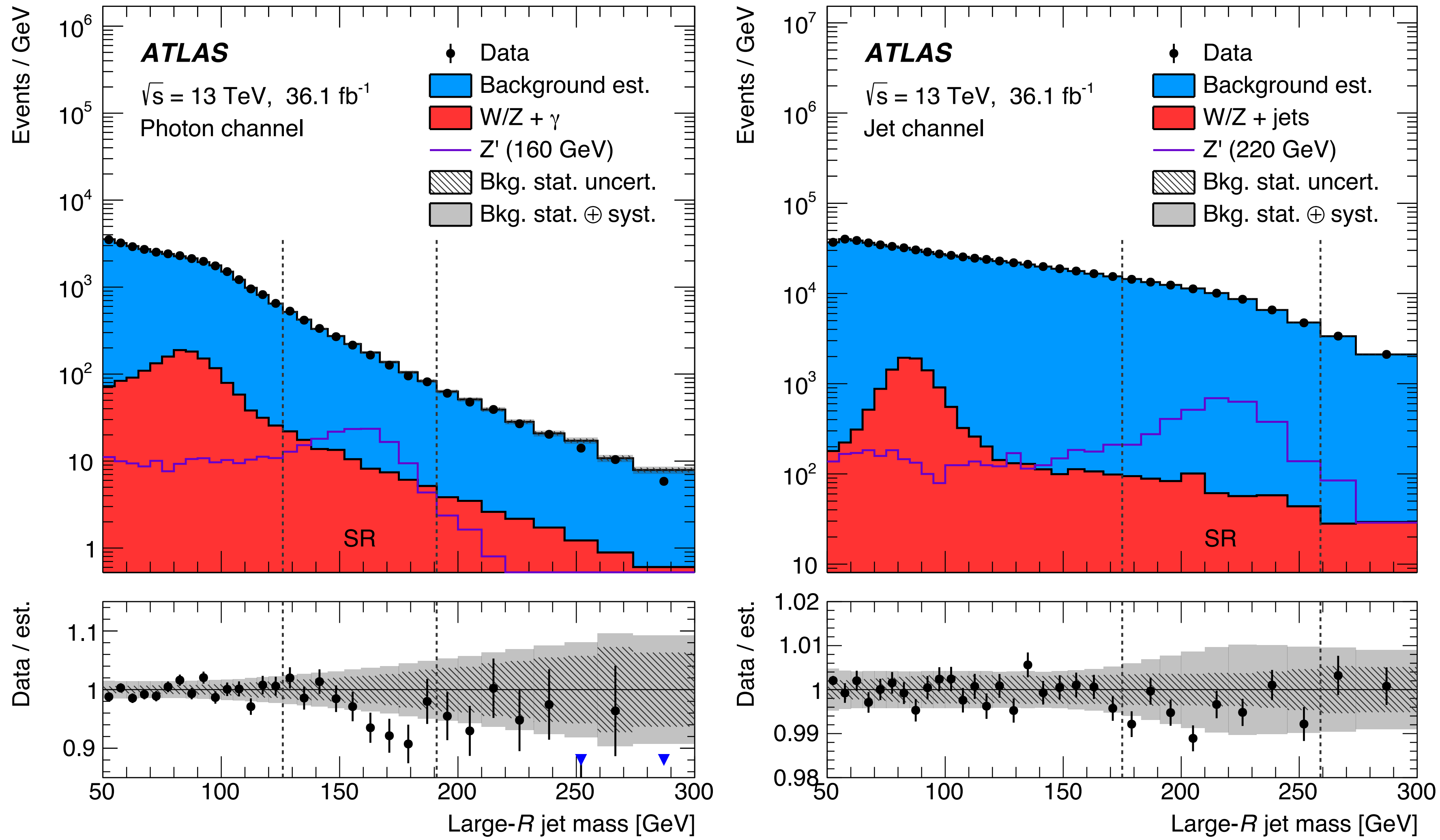
Short range but strong limit!

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

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 mjj — 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

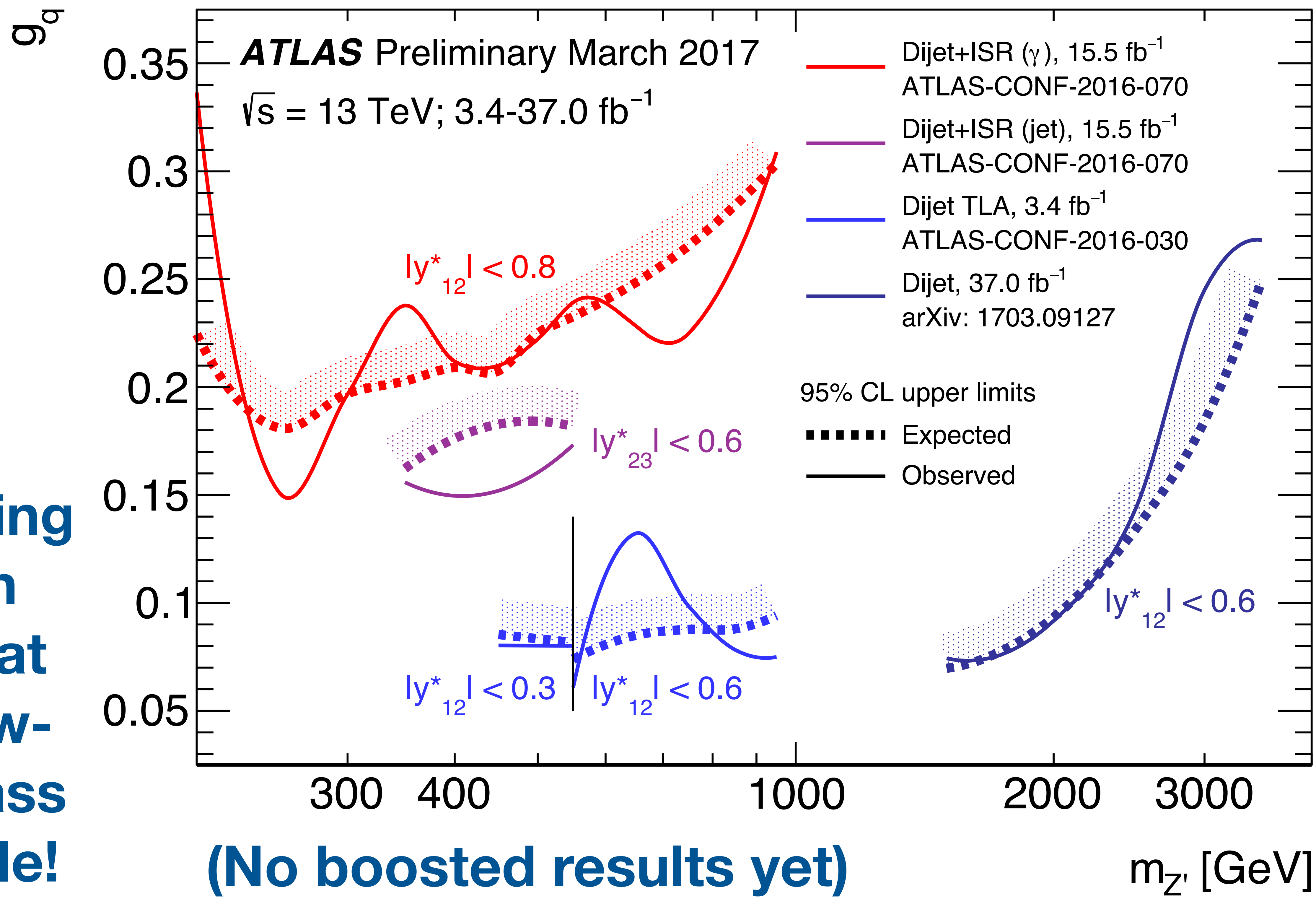


- For even lower Z' mass, decay products are very close together → reconstruct as a large jet instead of two small jets. Use a tagger to distinguish signal from background based on substructure
- Lots of challenges in the background estimate! Extrapolate from data CR which does not pass tagging requirements. 1 estimate per signal point.
- Can extend limits as low as 100 GeV! (Then we run into W & Z…)

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 ….

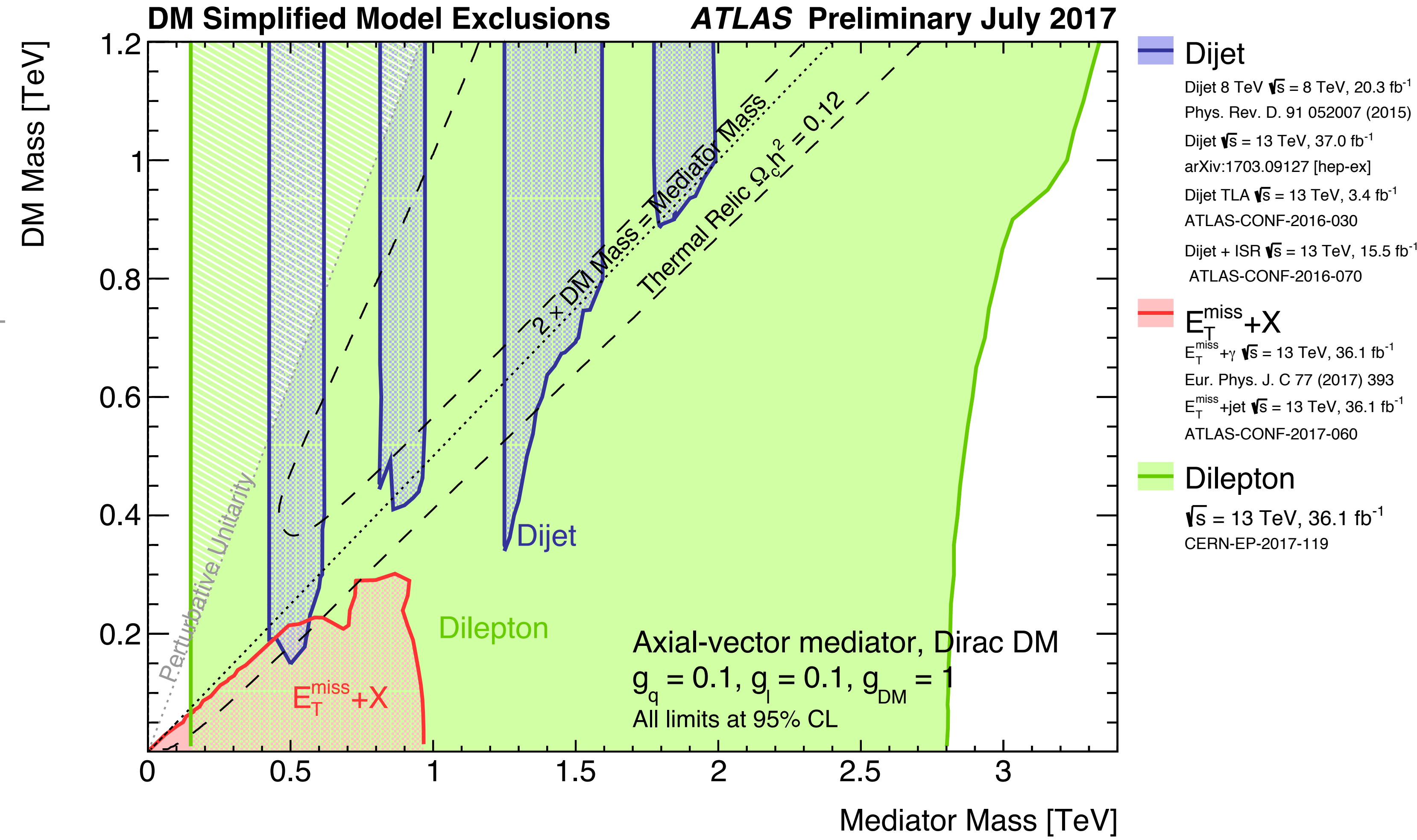


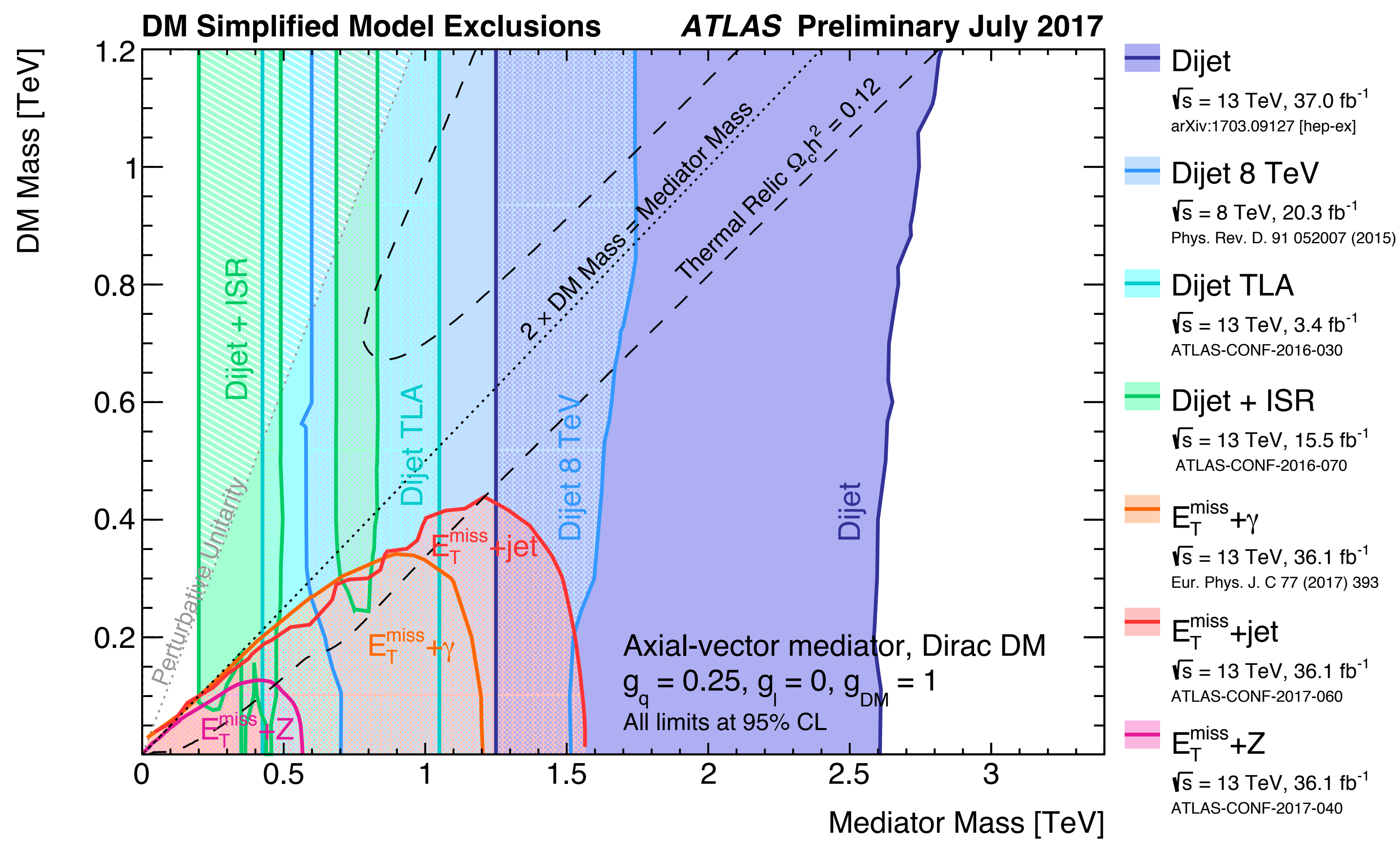
Filling in that low-mass hole!

(No boosted results yet)

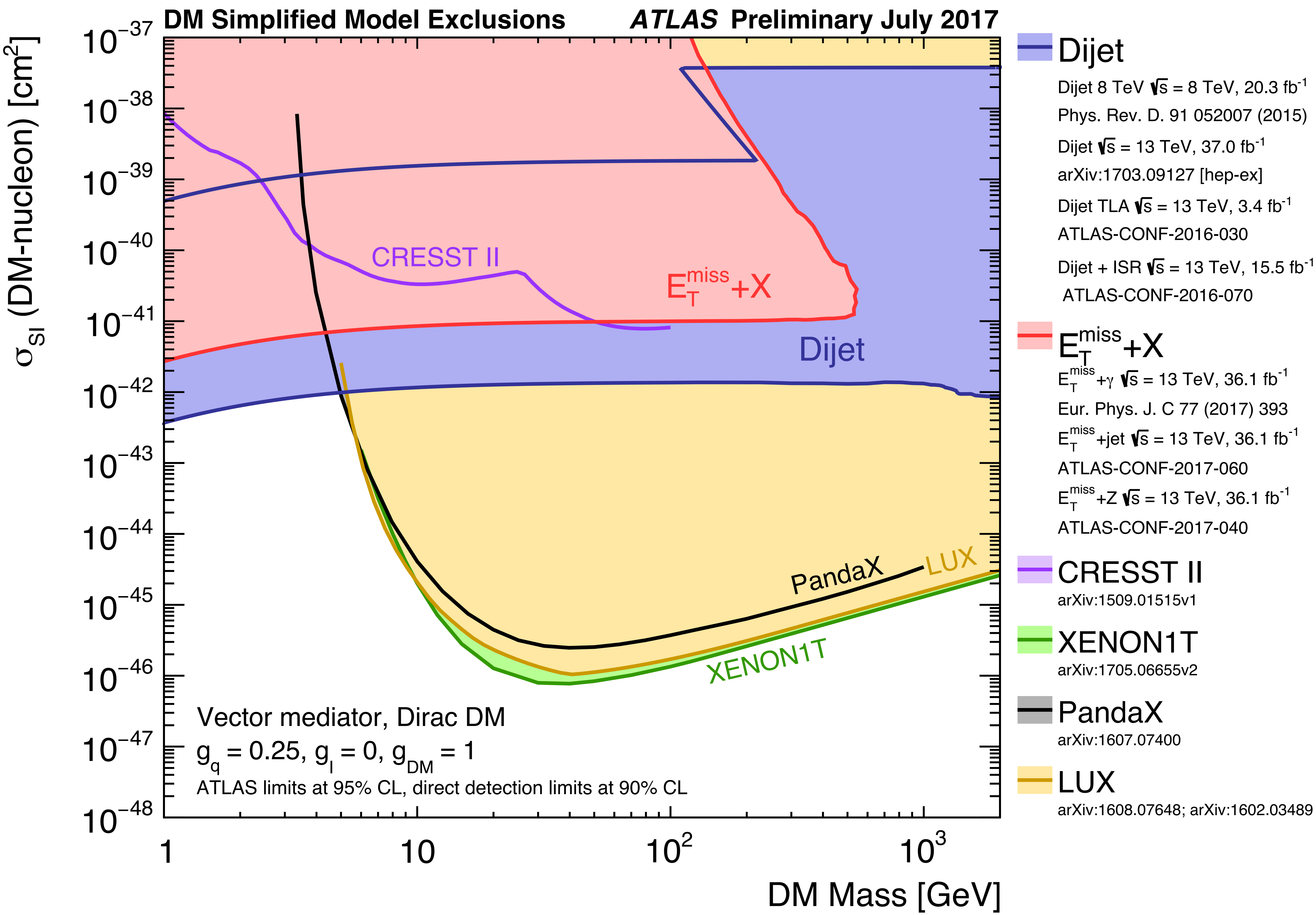
What does this tell us about DM?

- 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!

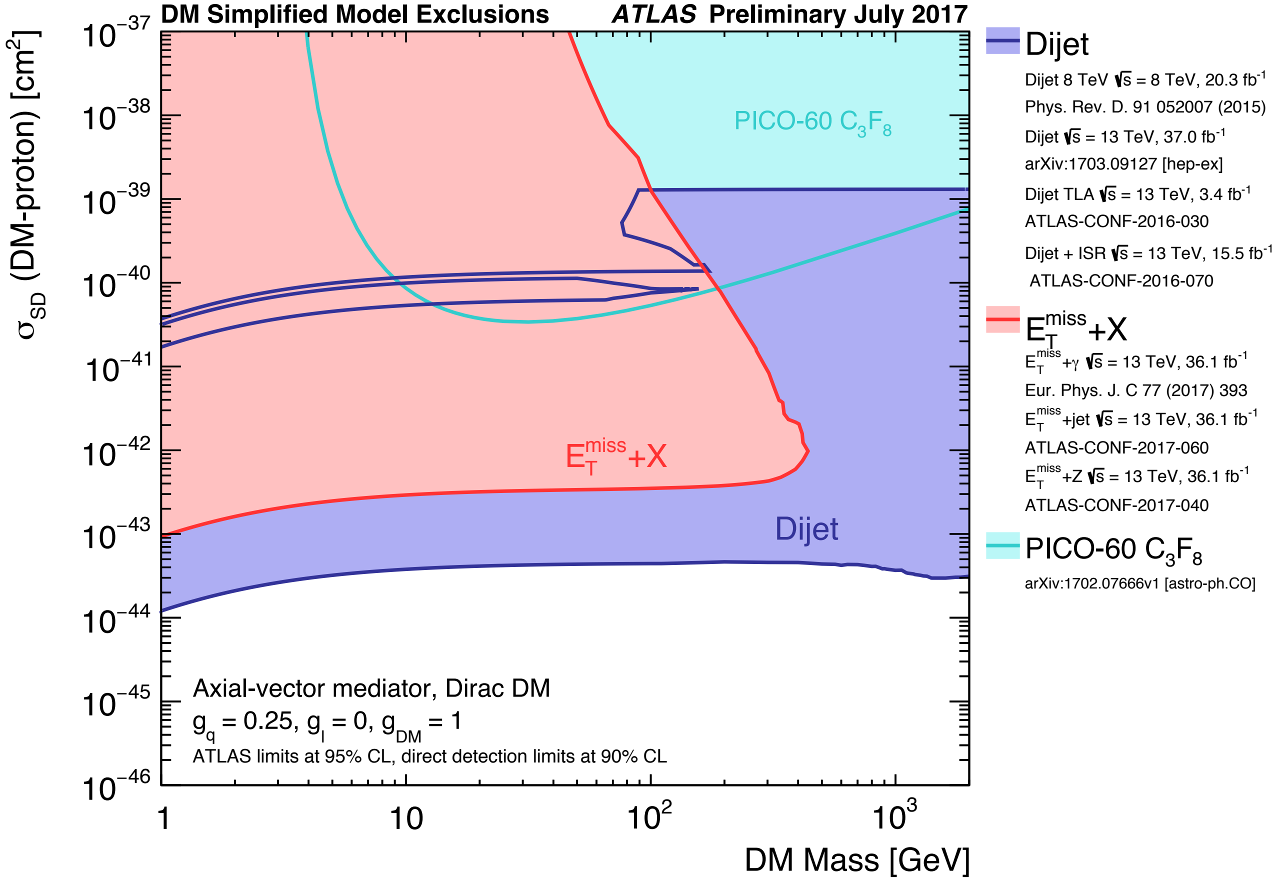


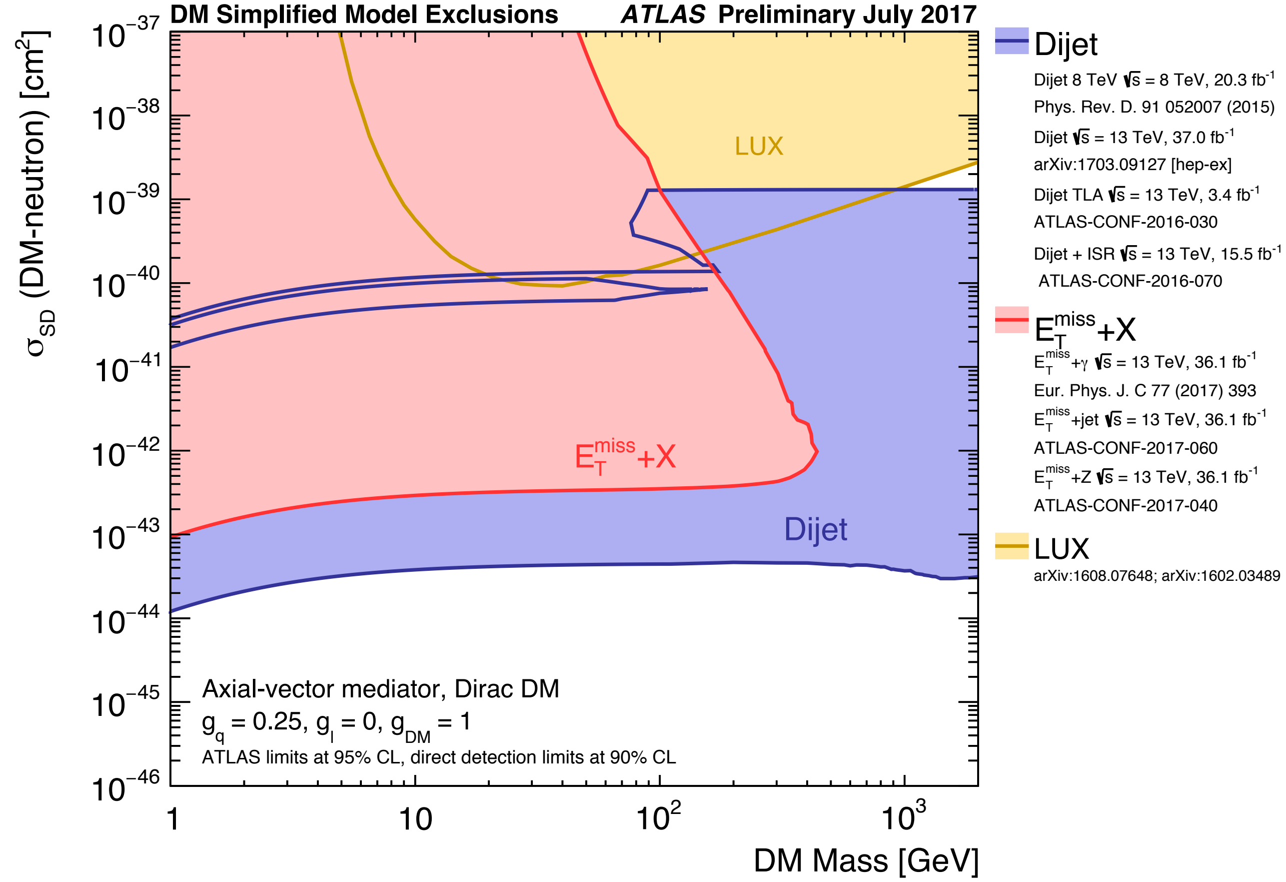


Comparing collider limits to the rest of the field



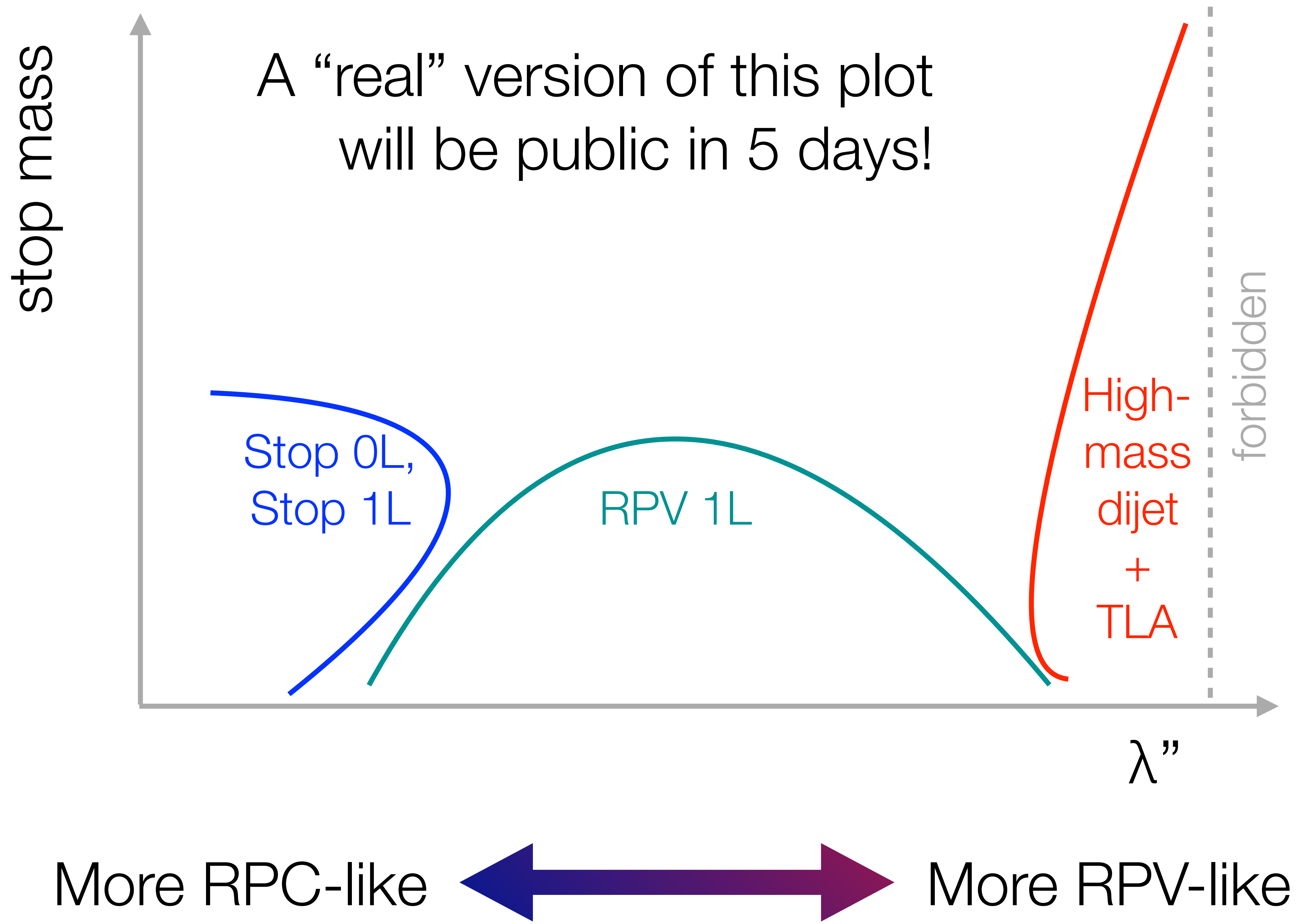
Comparing collider limits to the rest of the field





- Axial vector mediators, spin dependent limits
- Left: DM-proton cross section. Right: DM-neutron cross section.

What else can we say with low-mass dijet limits?



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