Jets physics with ATLAS: From calorimeter clusters to searches for new phenomena

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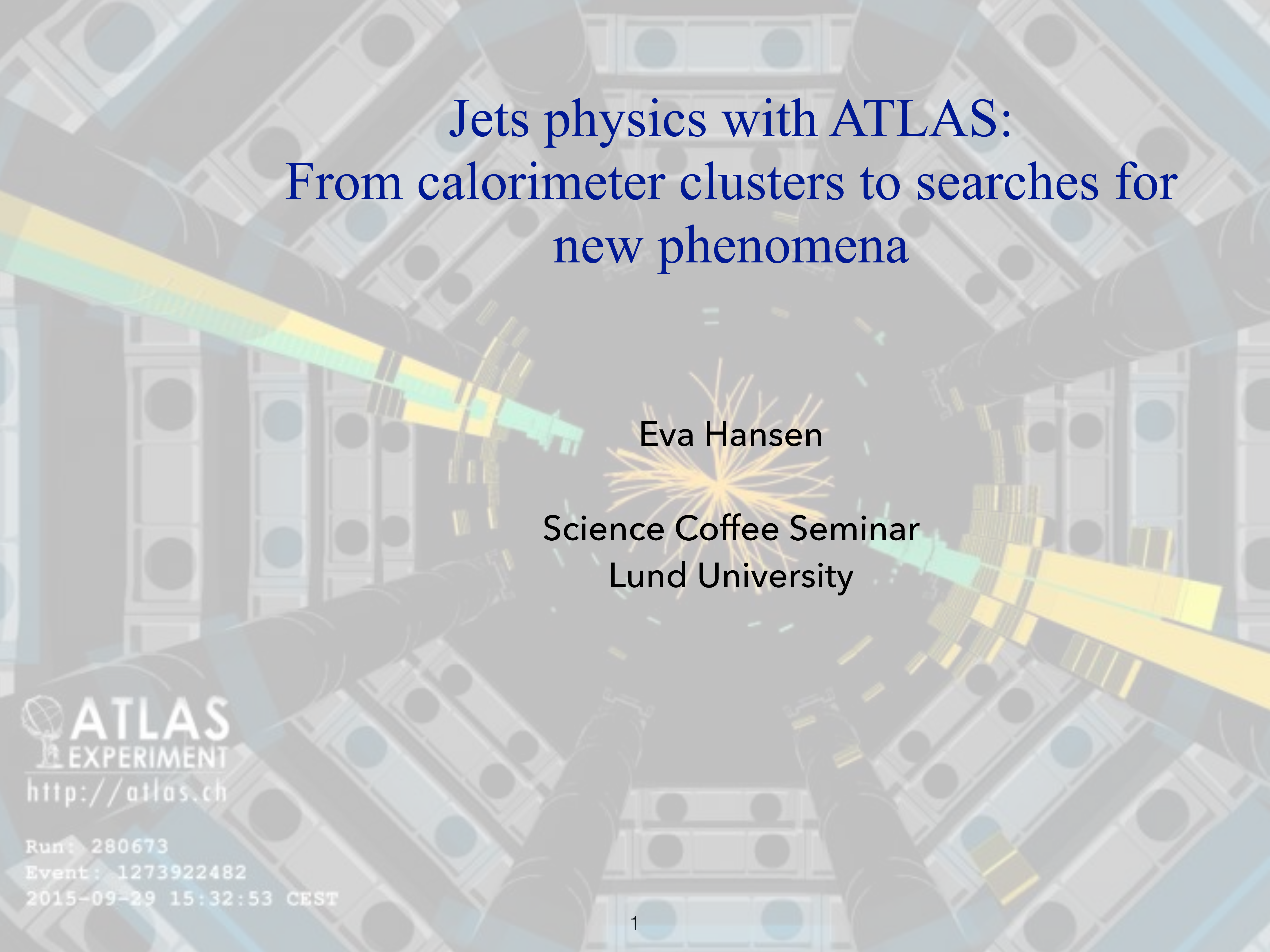
Science Coffee Seminar
Lund University



Logos

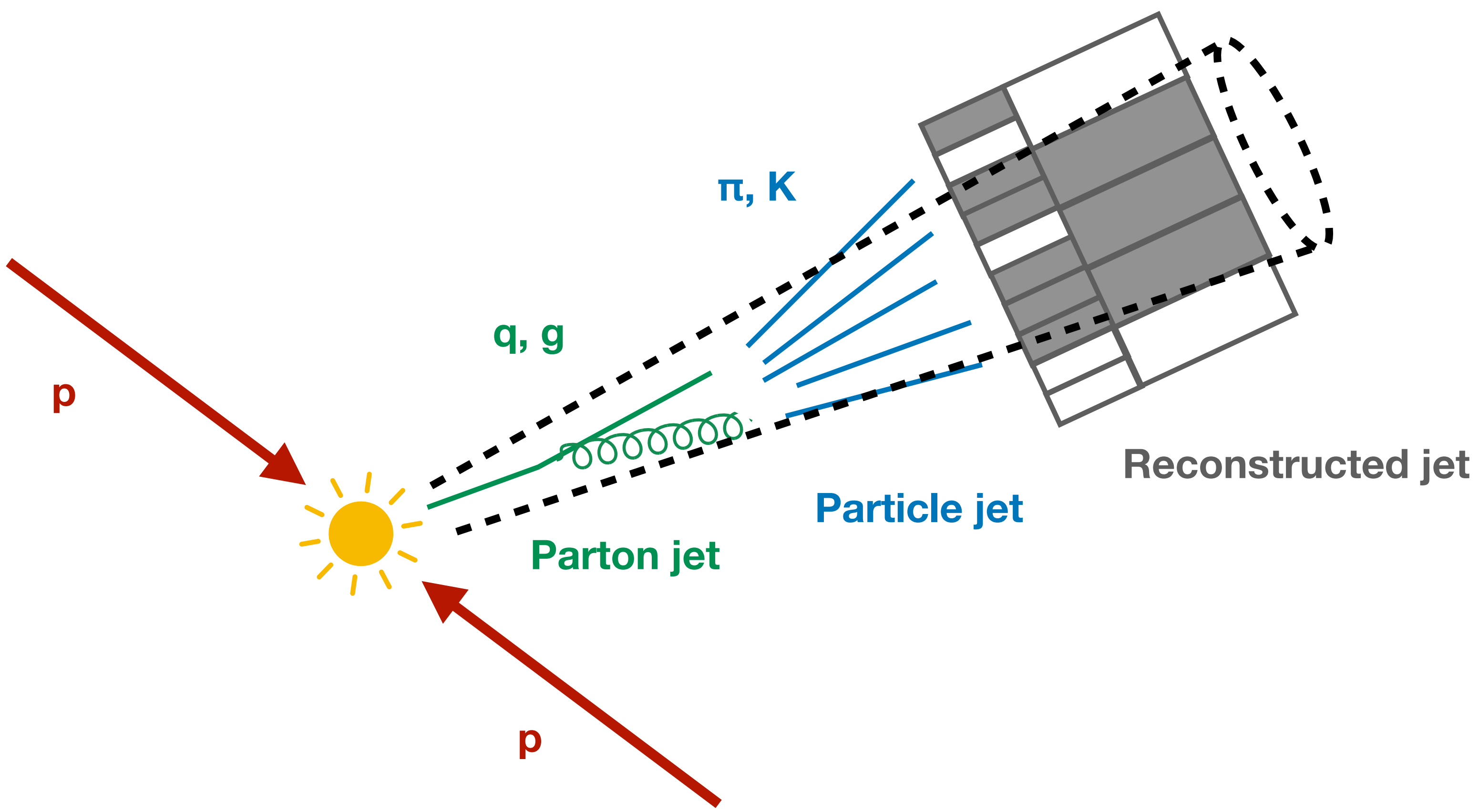
- Presented work carried out as a PhD student at Lund University
- … as part of the ATLAS collaboration
- Funded by the European Research Council via the DarkJets project
- Now employed at Manchester University
- … as part of the LHCb collaboration
- Funded by the European Research Council via the Beauty2Charm project

Overview

- Introduction
- Jet calibration in ATLAS
- Search for low-mass dijet resonances with the Trigger Level Analysis
- Search for “dark jet” resonances, arising from a confined hidden sector

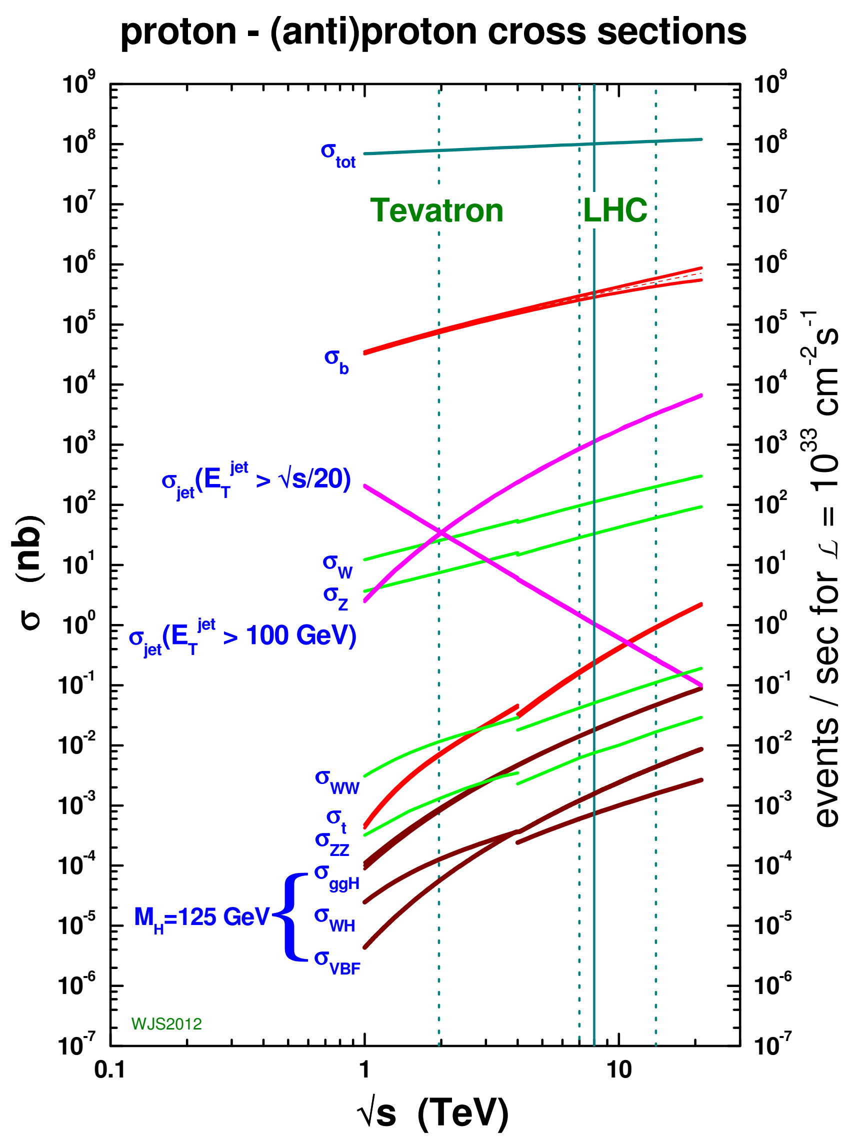
Introduction

- Jets: Collimates sprays of hadrons, arising from the showering and hadronisation of quarks or gluons
- In ATLAS, jets are reconstructed from energy deposits in the calorimeters and potentially tracks of charges particles
- Calibrated with a multi-step process to correct for various detector effects



Introduction

- Jets are useful probes of QCD at both soft and hard energy scales
- Produced in a variety of interesting final states at the LHC
  - Decays of Higgs bosons
  - Decays of new heavy particles in Standard Model extensions



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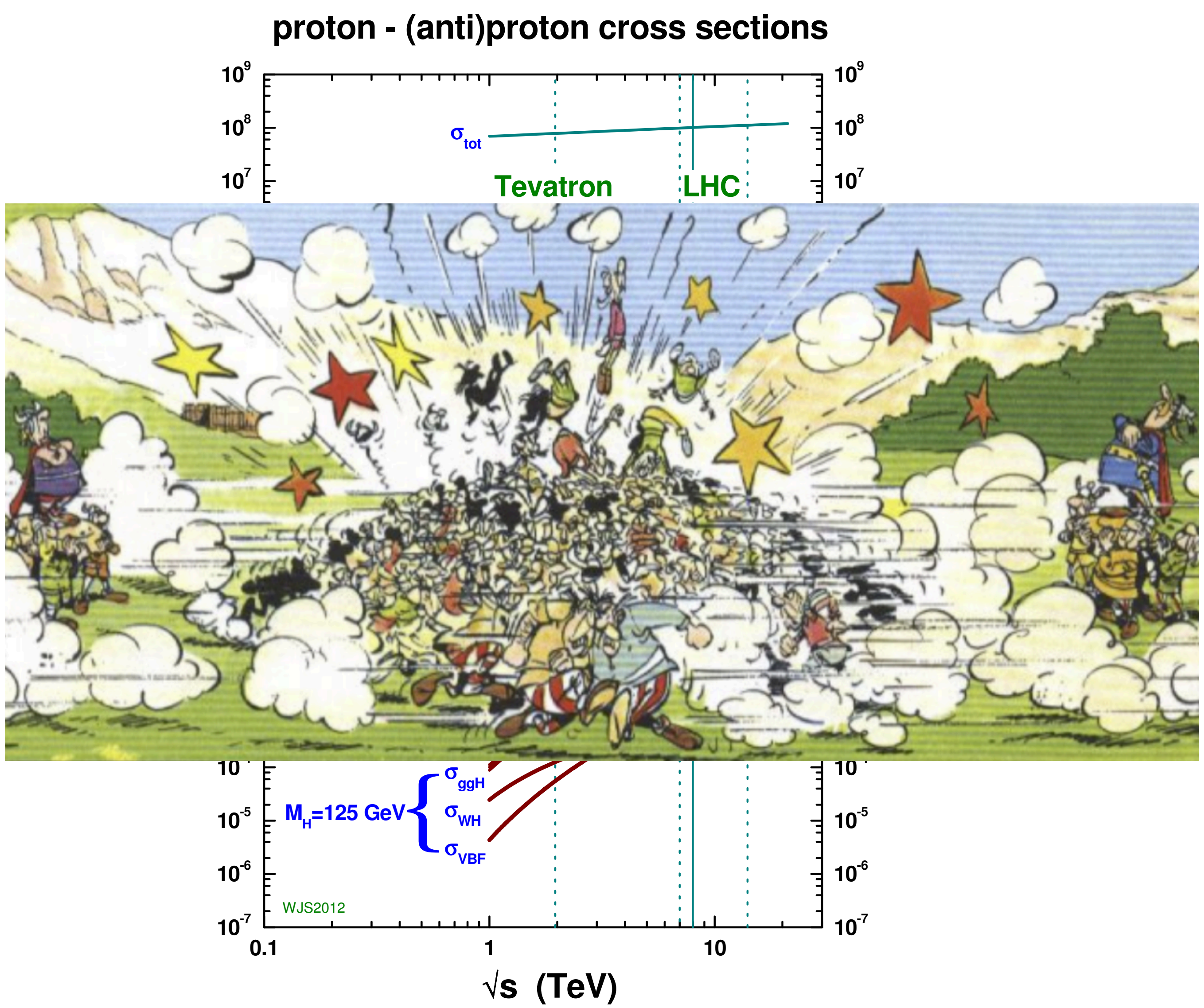
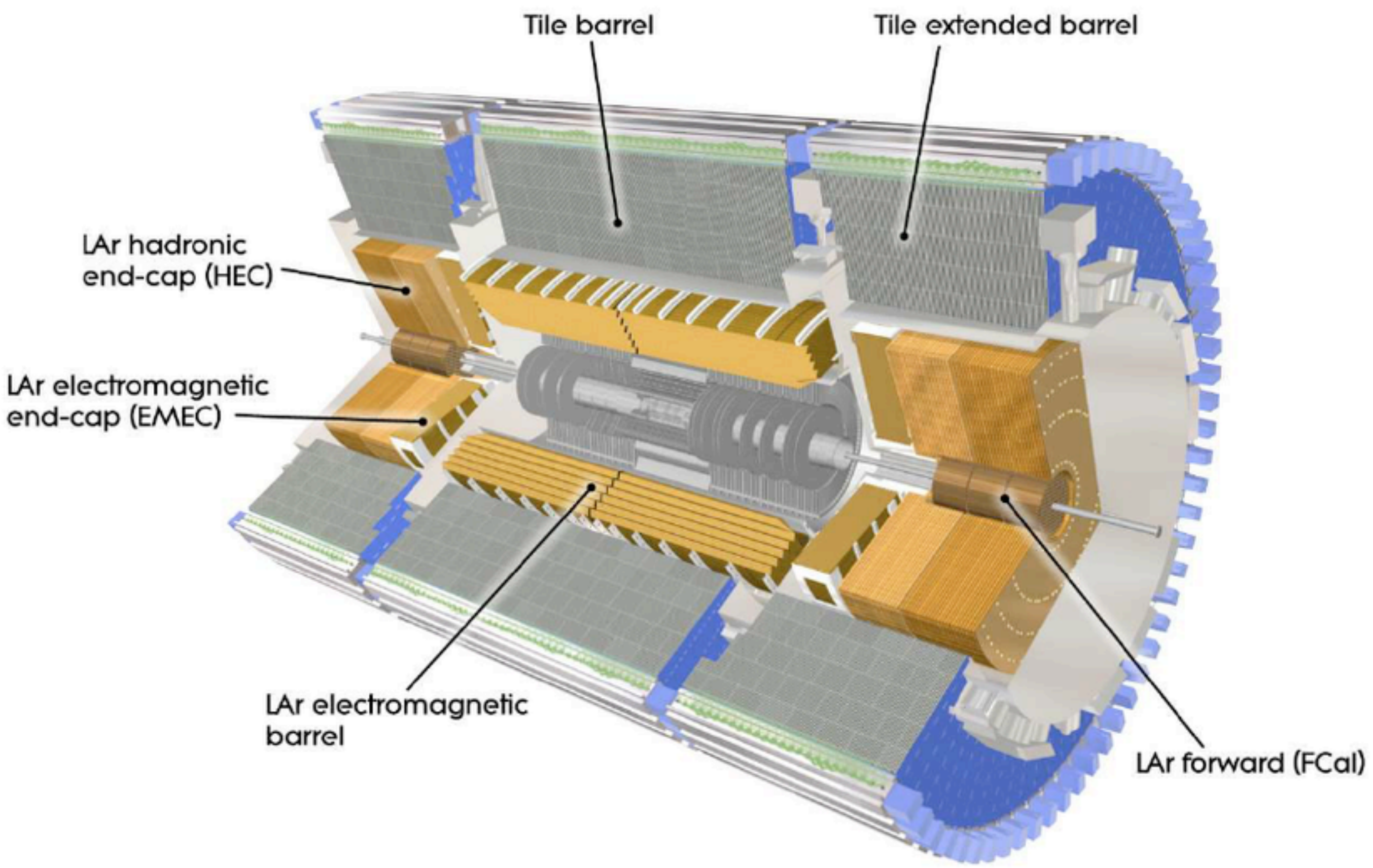


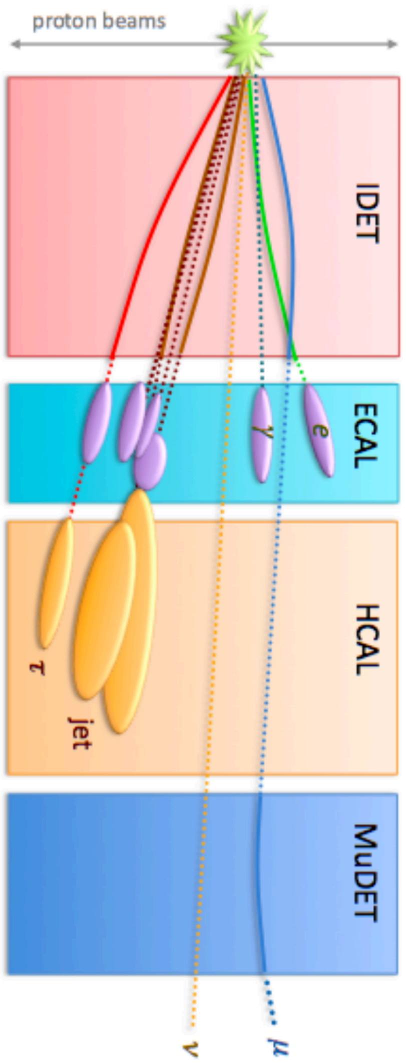
- Also abundant in uninteresting processes
  - Huge backgrounds
  - Pile-up
  - ➡ Detailed calibrations are important and challenging

Jet calibration in ATLAS

Jet measurement

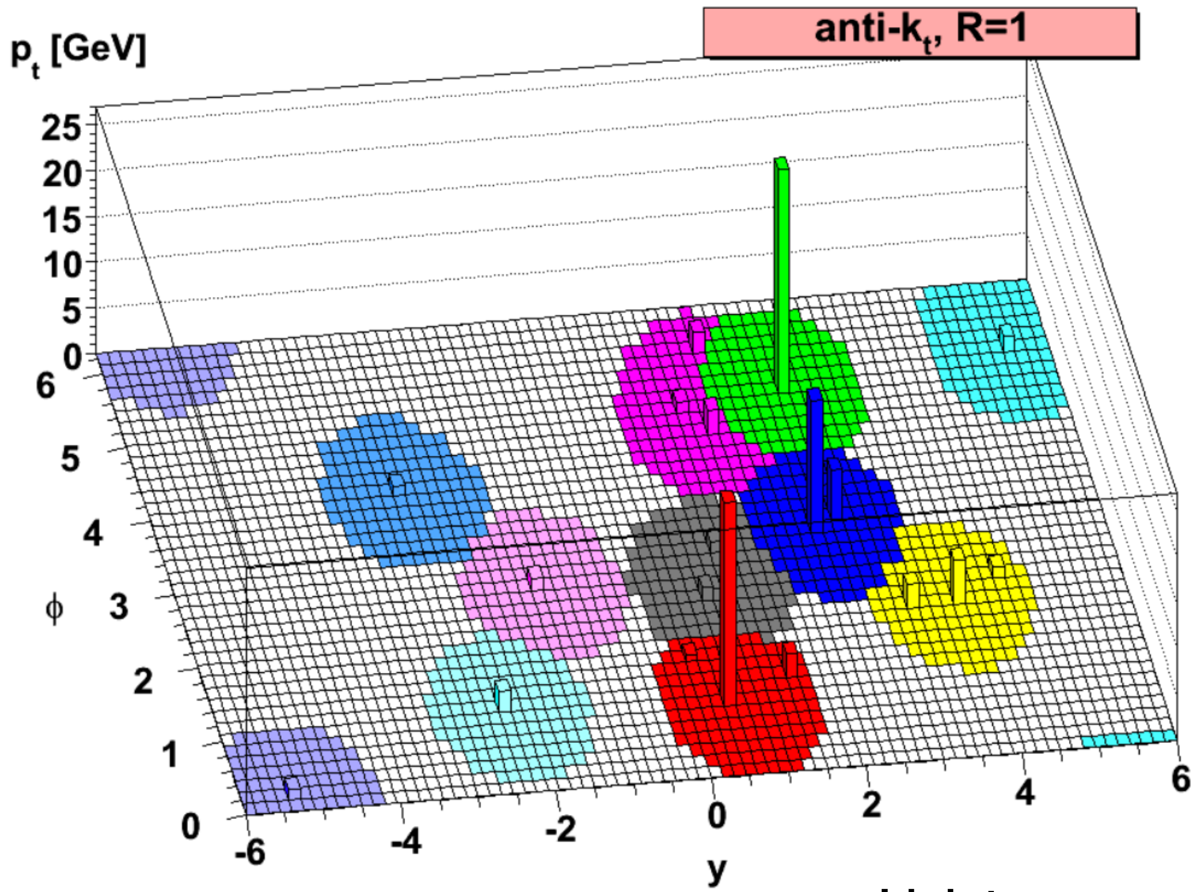
- Different sub-detectors allows us to reconstruct most particles efficiently
- Calorimeters provide the principal signals for jet measurement
- Inner detector adds precision p_T and direction information of charged particles
  - Vertex reconstruction, pile-up mitigation, and jet substructure





Jet reconstruction

- Sequential algorithms determine which cells are clustered in the jet
- A radius parameter *R* determines how wide the jet can get
- Primary jet definition in ATLAS relies on the anti-k_t algorithm

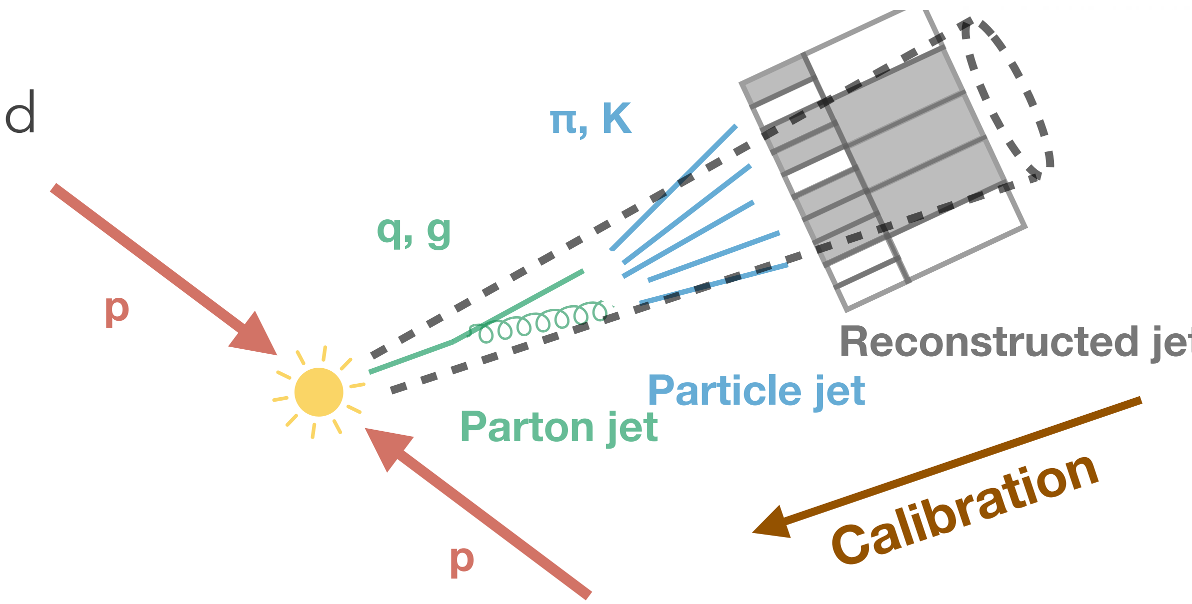


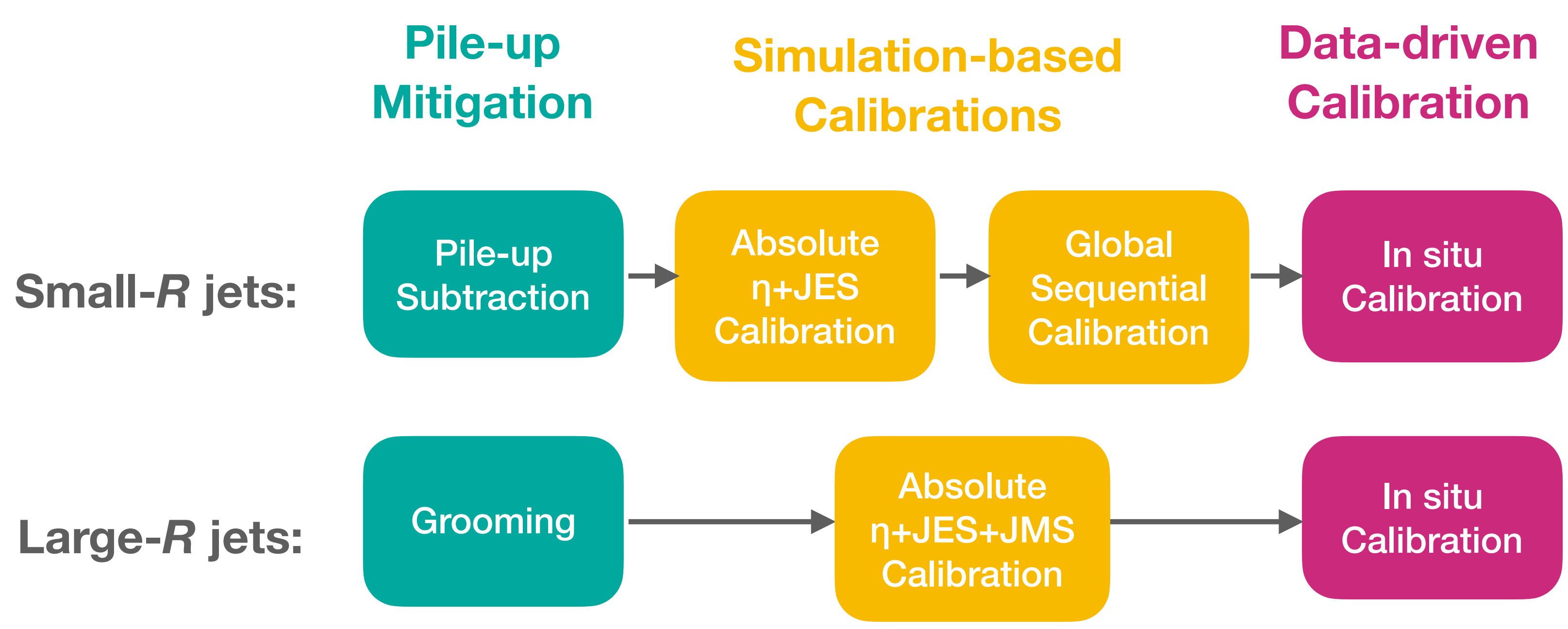
Link to paper

- **Small-*R* jets: R = 0.4**
  - Contains most of the radiation from quark/gluon jets
- **Large-*R* jets: R = 1.0**
  - Captures hadronic decays of heavy, boosted objects (W/Z/top etc.)

Jet calibration

- The reconstruction translates the measured detector signals to jet properties
  - p_T, direction, mass
- The calibration corrects the translation for various detector effects
- Consists of several steps, derived separately for small- and large-*R* jets



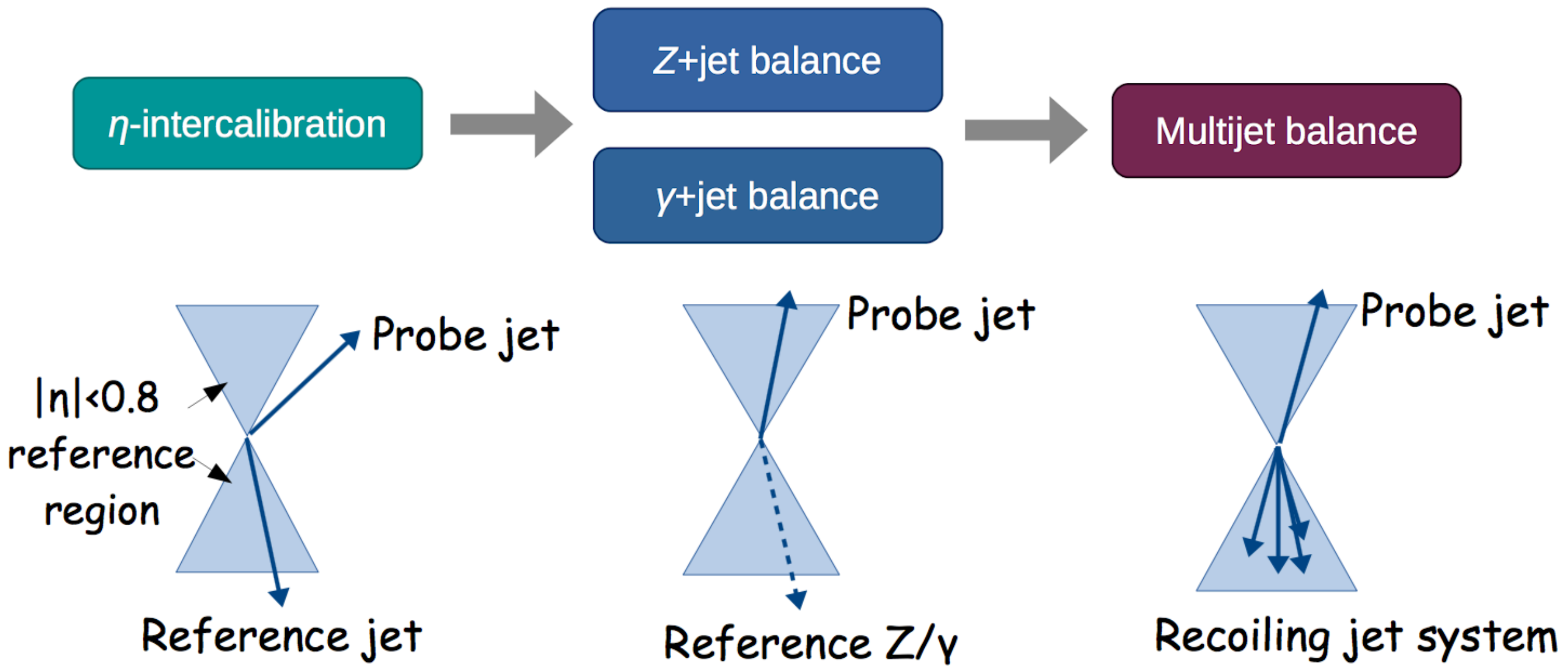


In situ JES calibration

- Last step of the Jet Energy Scale calibration chain is data-driven
- Corrects for potential differences between p_{T} response in data and MC
- Uses events where the jet recoils against a well-calibrated reference object

$$Response = R = \left\langle p_T^{jet} / p_T^{ref} \right\rangle$$

$$Correction\,factor = \frac{R_{MC}}{R_{data}}$$



Combination of *in situ* measurements

- Fours sets of measurements are combined to give a smooth calibration curve across the p_T spectrum
  - Each set of measurements is interpolated with splines
  - Combined by taking the weighted average in small bins of p_T
  - Weights are determined by the total uncertainty on each measurement
  - All uncertainties are propagated to the final, combined curve

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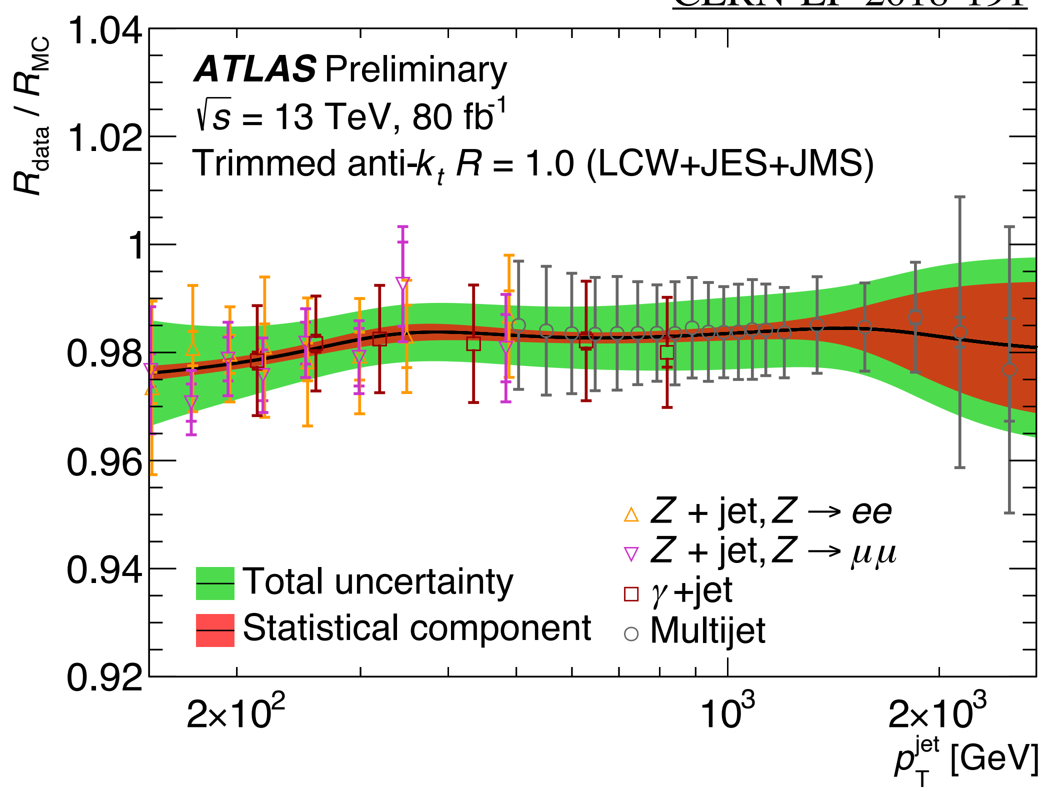

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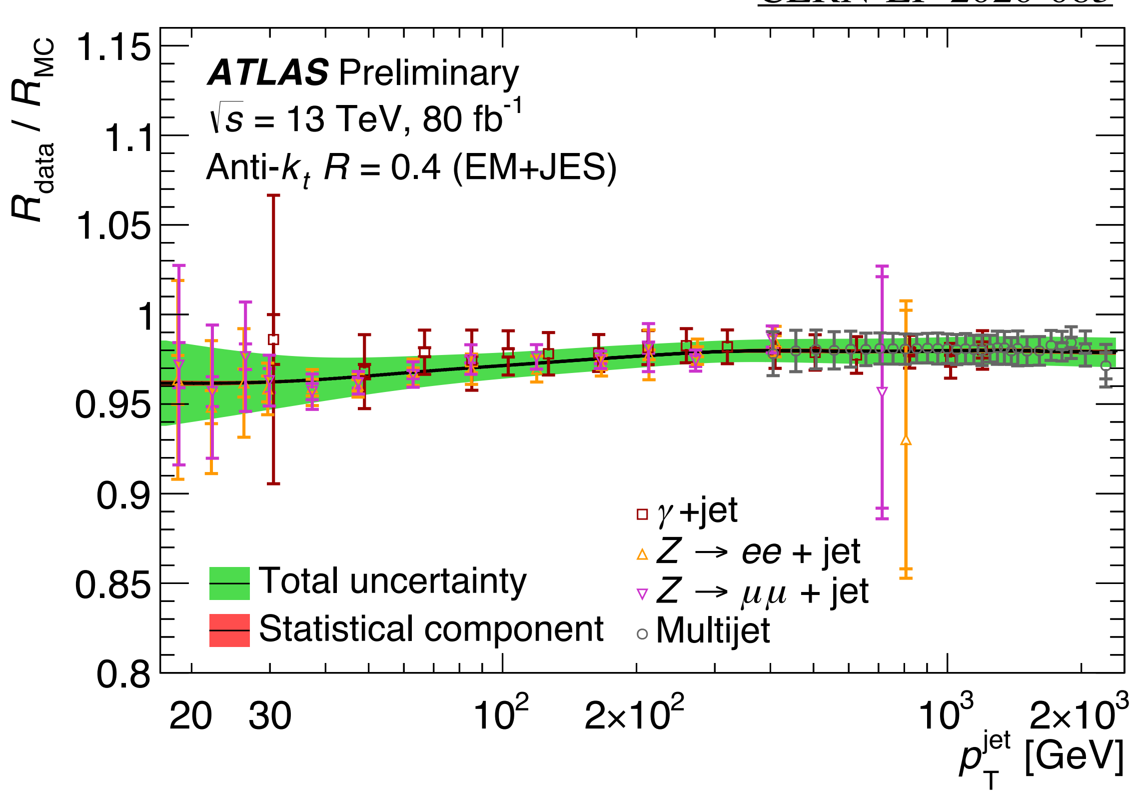
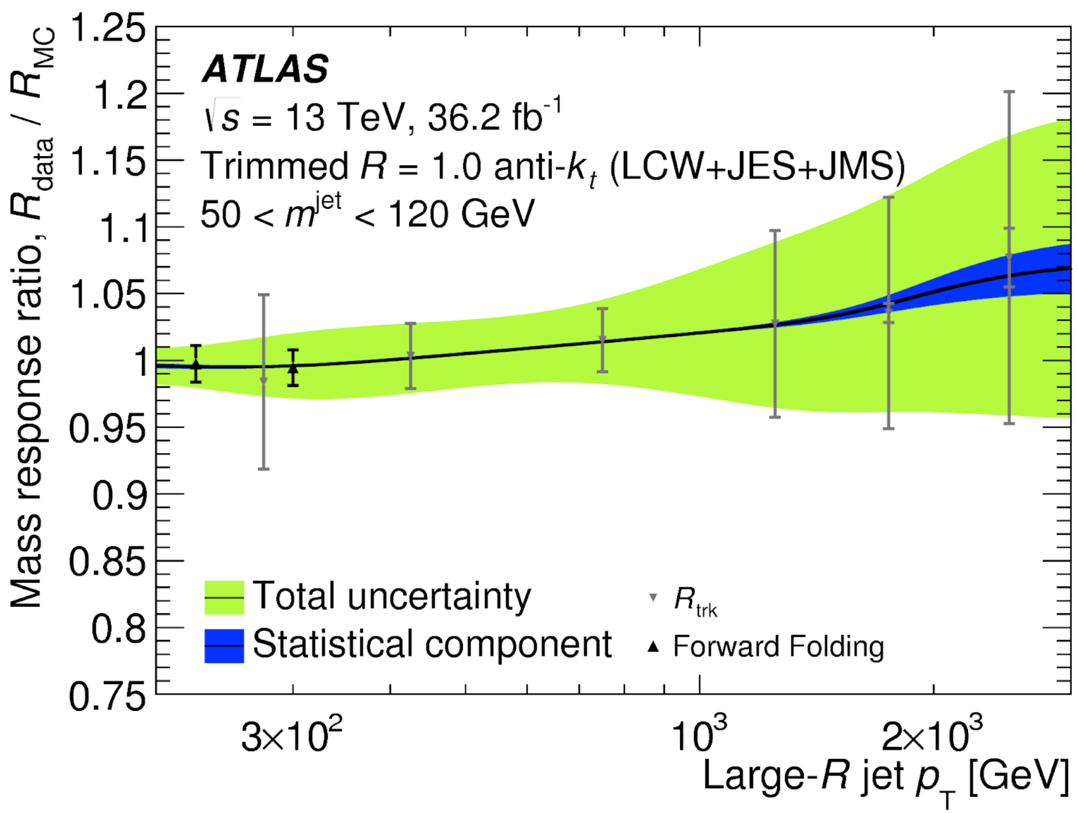


In-situ JMS calibration

- Two methods are used for the Jet Mass Scale calibration of large-*R* jets
- Forward folding:
  - Semi-leptonic *tt* events with one hadronically decaying *W*
  - Fits the W and top mass peaks to get mass scale and resolution
- R_{trk} method:
  - Uses tracker information as a proxy for independent measure of the mass scale



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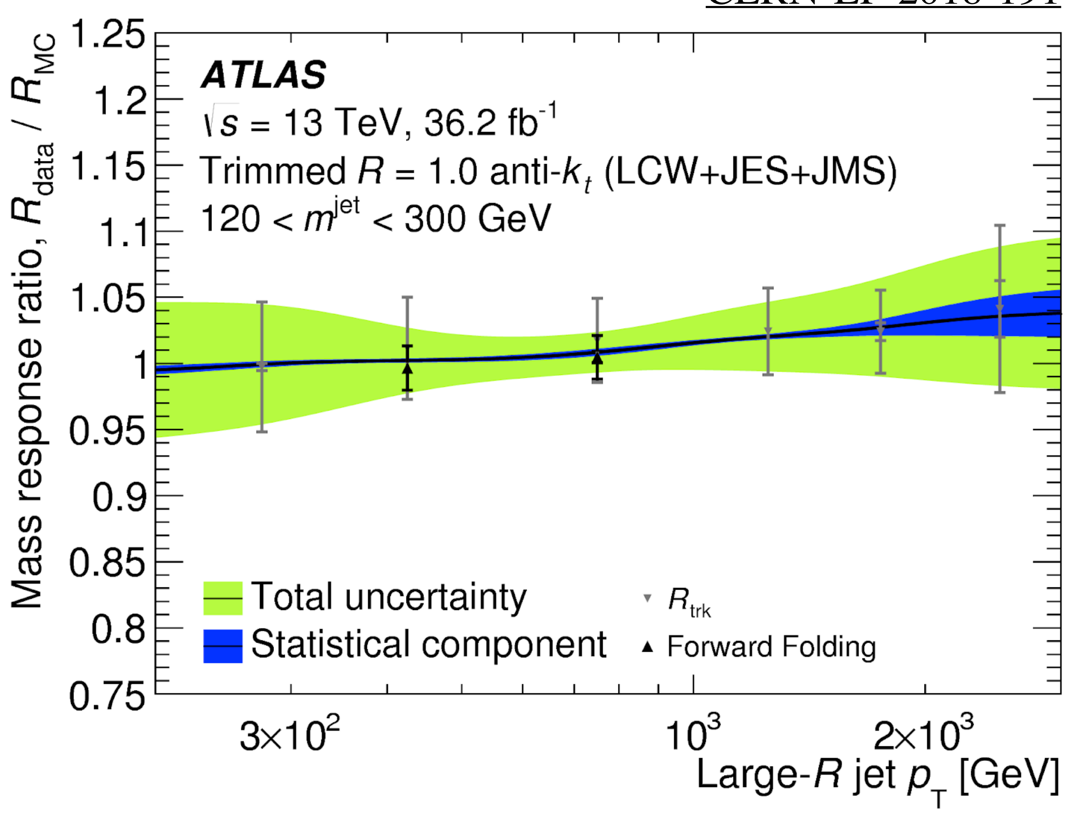


With well-measured and calibrated jets, we can look for new physics phenomena:

Unknown dijet resonance?
Jets obeying a different kind of QCD?

Search for Dark Jet Resonances

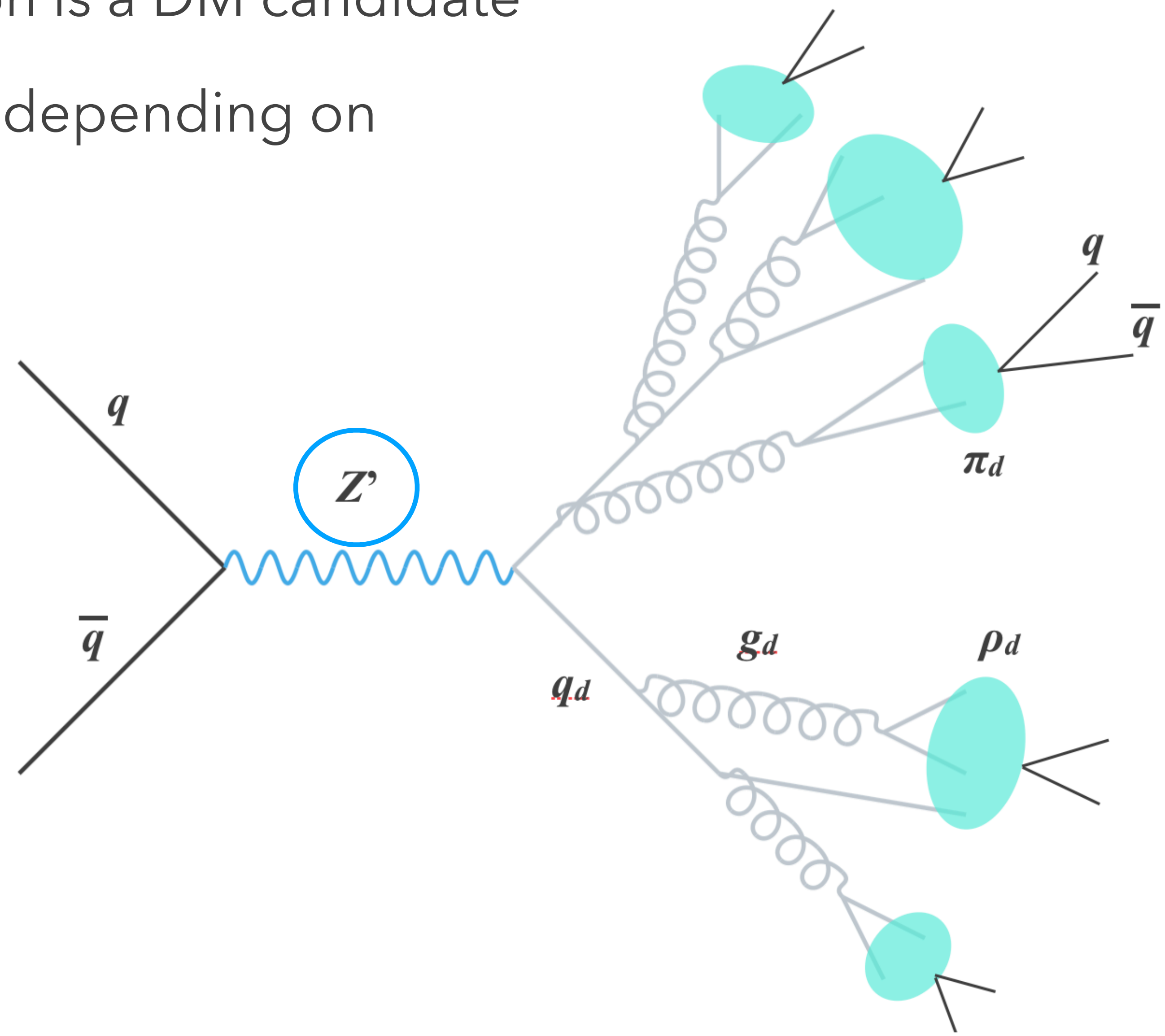
Motivation

- Hidden particle sectors arise from various theories of BSM physics
- Confined hidden sectors ("dark QCD") are particularly well motivated
  - Can provide a composite Dark Matter candidate
  - Can explain the similar DM and baryon abundance by asymmetric production
    - Requires a mediator linking the hidden sector to the SM

Image credit: EAGLE Project

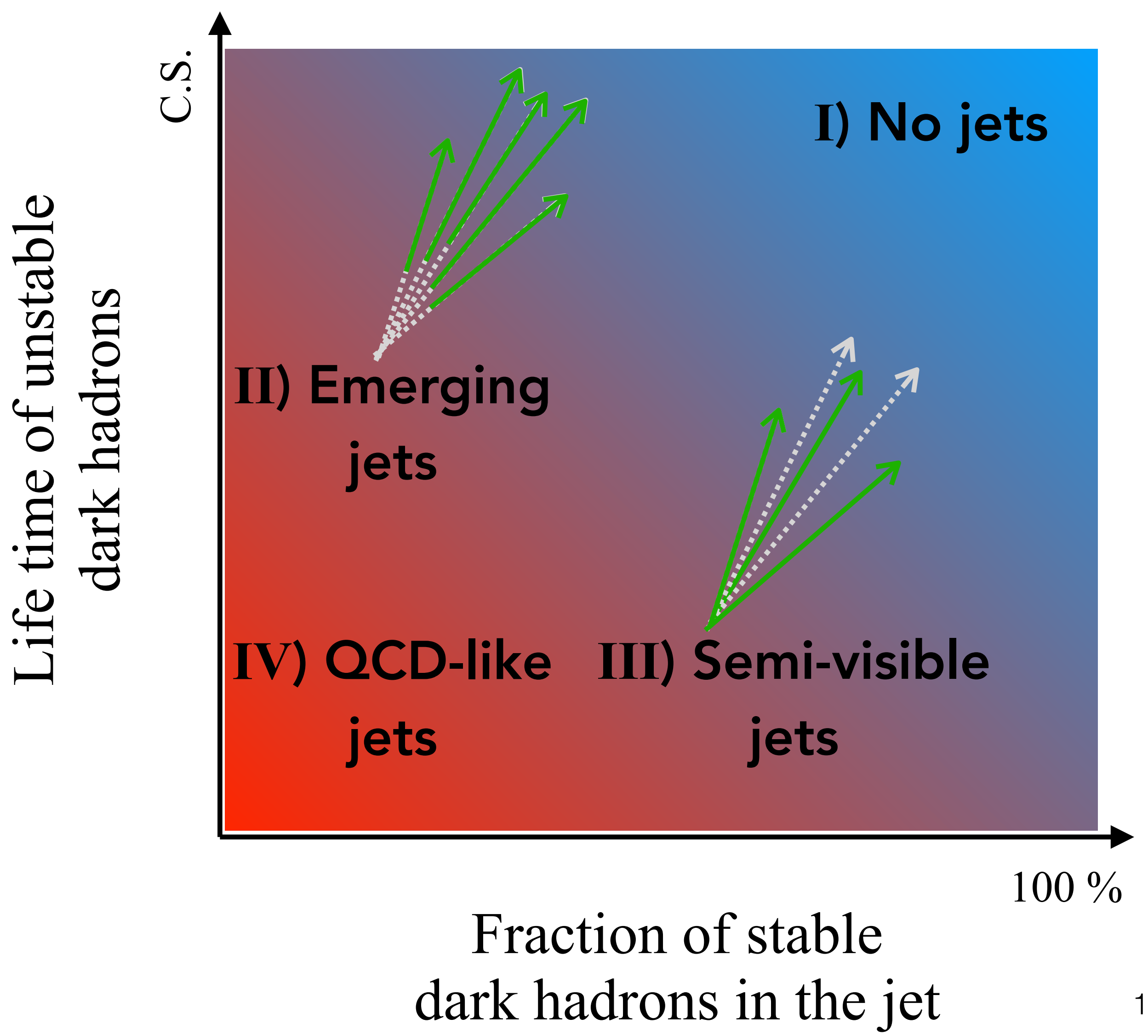
Dark QCD

- If the mediator is a vector boson **Z′**, it decays to two dark quarks
- They shower and hadronize according to the dark sector
- Some or all dark hadrons may decay back to SM particles
  - The lightest stable dark hadron is a DM candidate
- Can result in various signatures depending on specific model parameters



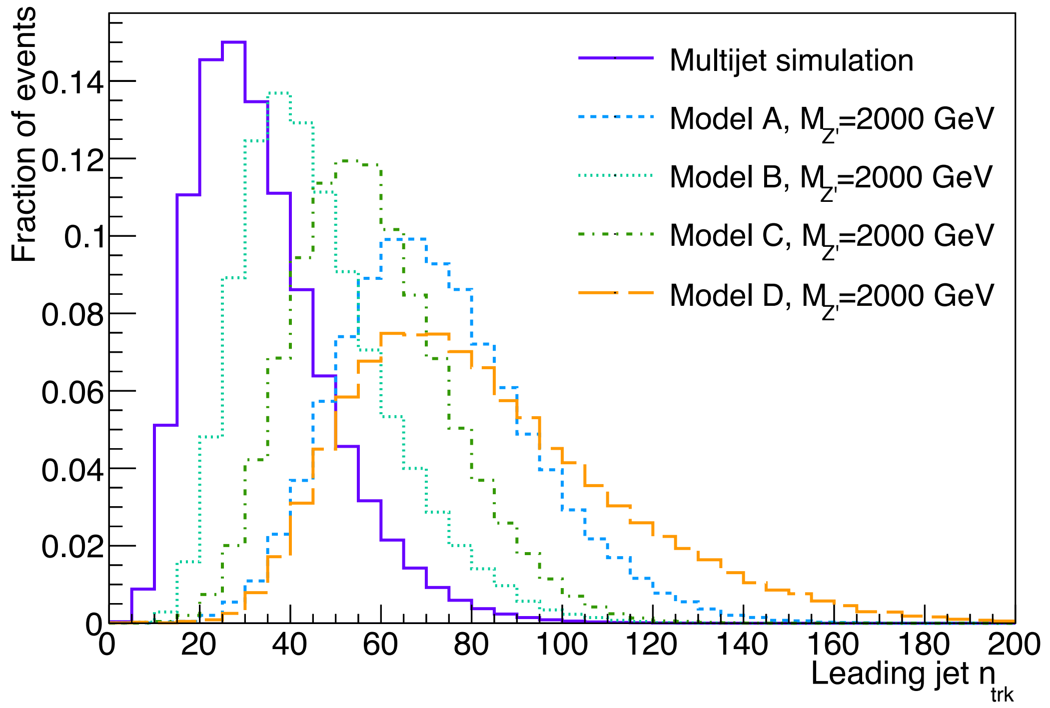
Benchmark signal models

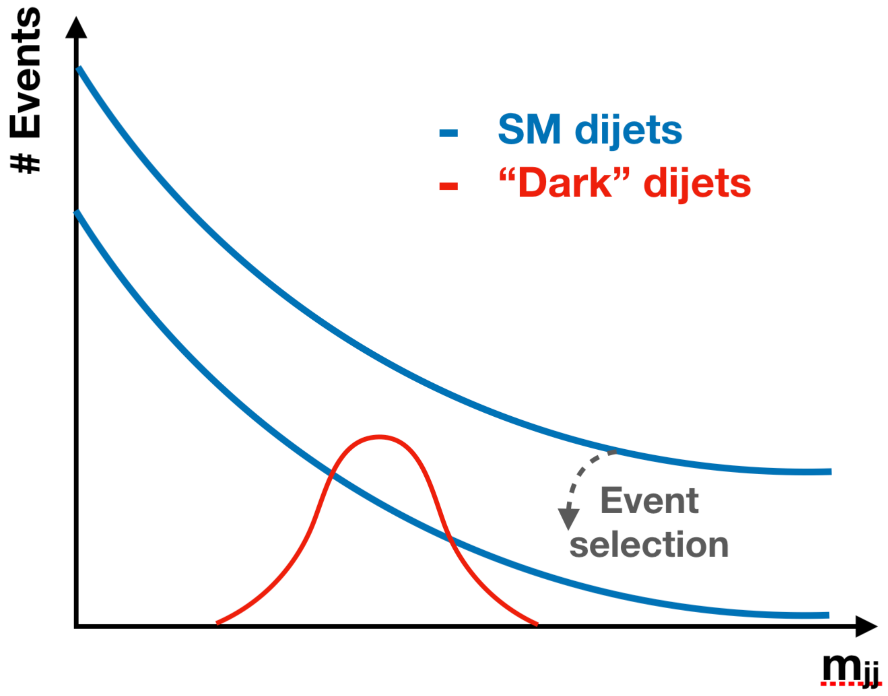
- Composition of visible and invisible particles in the jet depend on the dark QCD parameters
- Targeting QCD-like jets: All dark hadrons decay promptly to SM particles
  - Forms a **"dark jet"**
  - No dark matter candidate
- Four models implemented with Pythia Hidden Valleys
  - All have larger confinement scales than SM QCD
  - Give wider jets with larger particle multiplicity
  - Based on arXiv:1712.09279v3



Analysis strategy

- Two large-*R* jets are reconstructed
  - Dominant background is SM dijet events
- Signal region based on number of charged tracks associated with the jet, n_{trk}
- Main analysis variable is the invariant dijet mass, m_{JJ}
  - Signal: Peaks around the mediator mass
  - Background: Smoothly falling spectrum

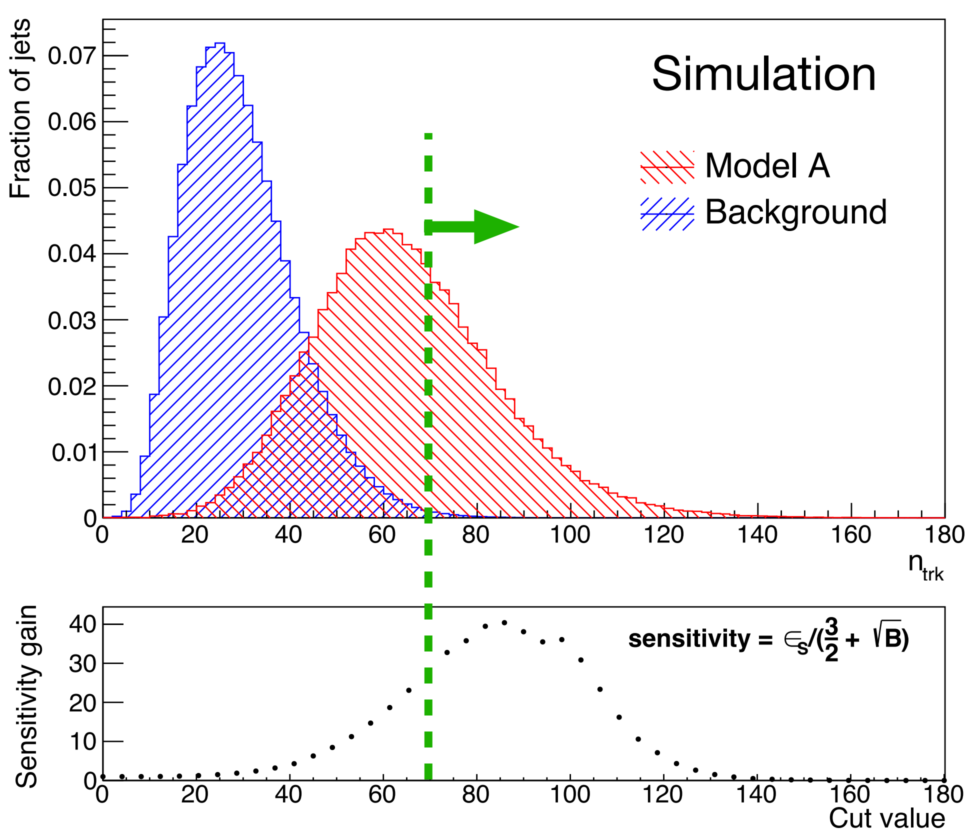


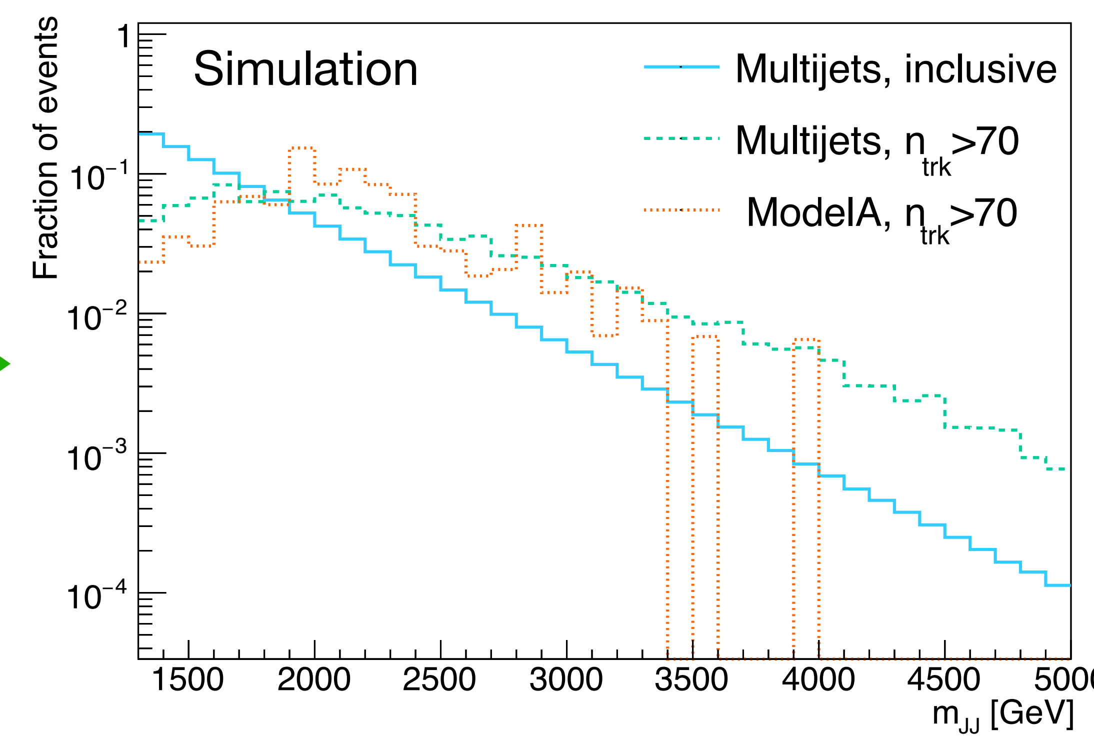


- **Shape analysis:** Compare the shape of the m_{JJ} spectrum to background expectation
  - Look for a bump
- Analysis still ongoing, "blinded"
  - Can not show data in the signal region

Challenge of the strategy

- Best sensitivity is obtained with a very strict cut on n_{trk}
- Such a cut sculpts the background dijet mass spectrum
  - Makes resonance bump finding impossible





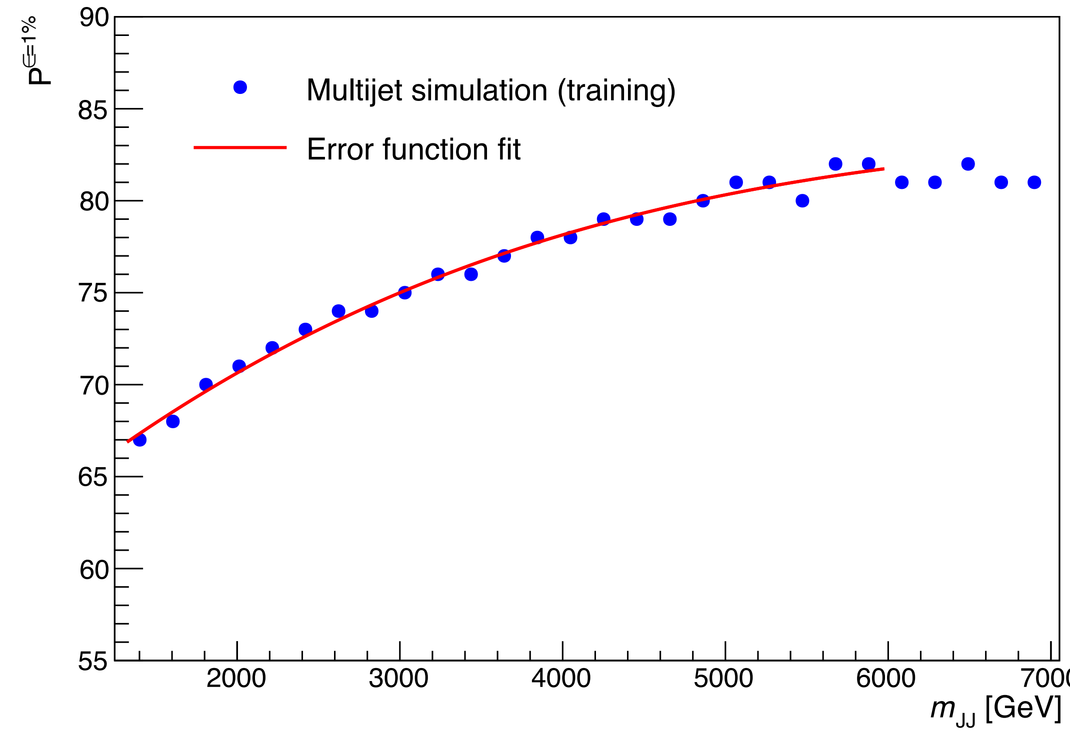
Fixed-efficiency regression

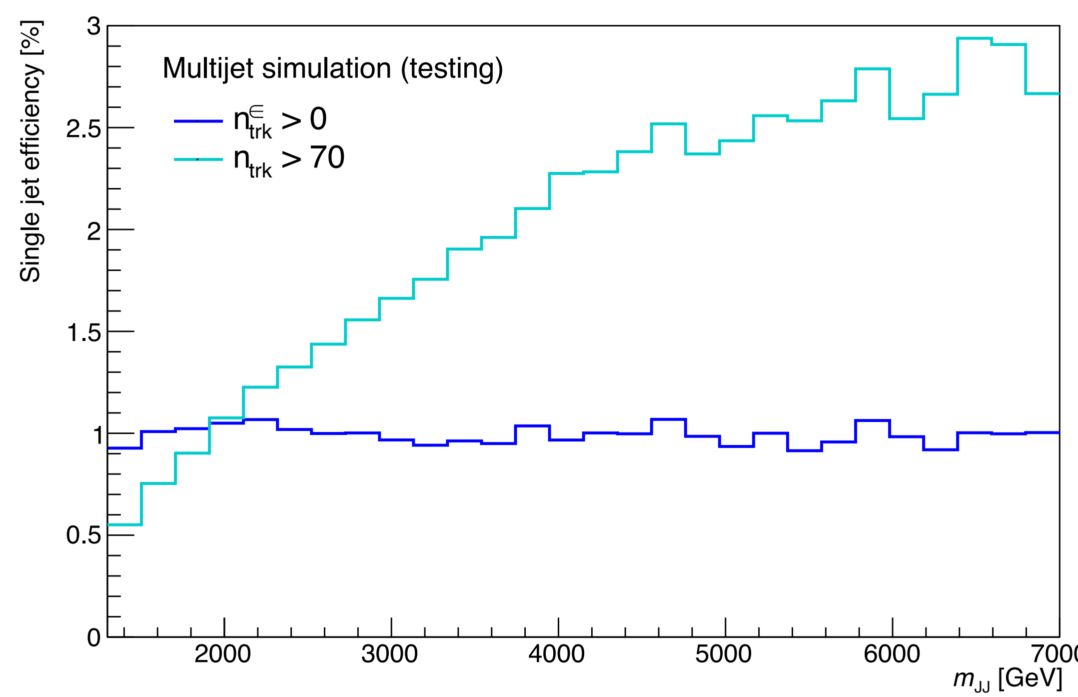
- Instead of a flat cut on n_{trk}, we use a cut that enforces ~constant efficiency across m_{JJ}
  - Similar method used by CMS: CERN-EP-2017-235
  - Tested for W-tagging in ATLAS: ATL-PHYS-PUB-2018-014
- In practice, a new variable is defined:
  1. Choose the desired single jet background efficiency ε (here ε=1 %)
  2. Evaluate the "percentiles" p^{ε} bin by bin:
     - Which cut value on n_{trk} gives the desired background efficiency of ε?
  3. Fit the points to an error function:

$$y = a \cdot \mathrm{erf}(b \cdot (x + c))$$

  4. For each jet, a new variable is defined:

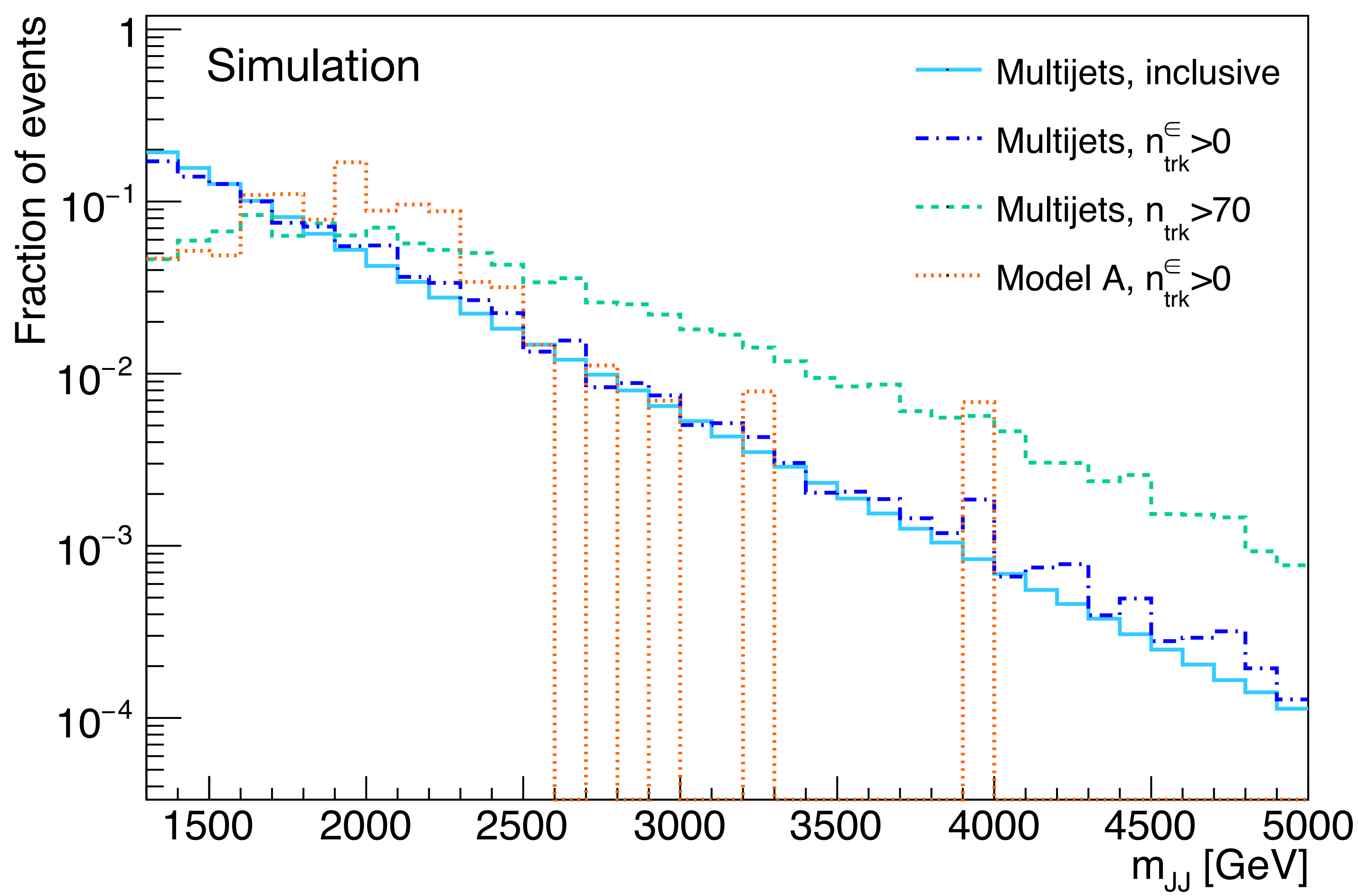
$$n^{\epsilon}_{\mathrm{trk}} = n_{\mathrm{trk}} - p^{\epsilon}(m_{\mathrm{JJ}})$$





Fixed efficiency regression

- Requiring $n_{trk}^{\varepsilon} > 0$ should give a smoothly falling background distribution in the signal region
- Performance tested with simulated multi-jet events:

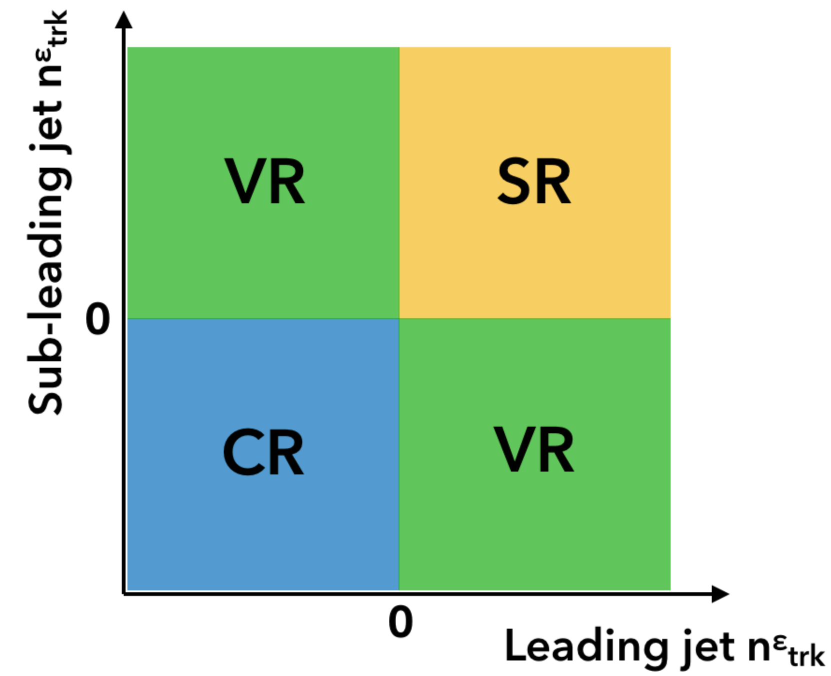


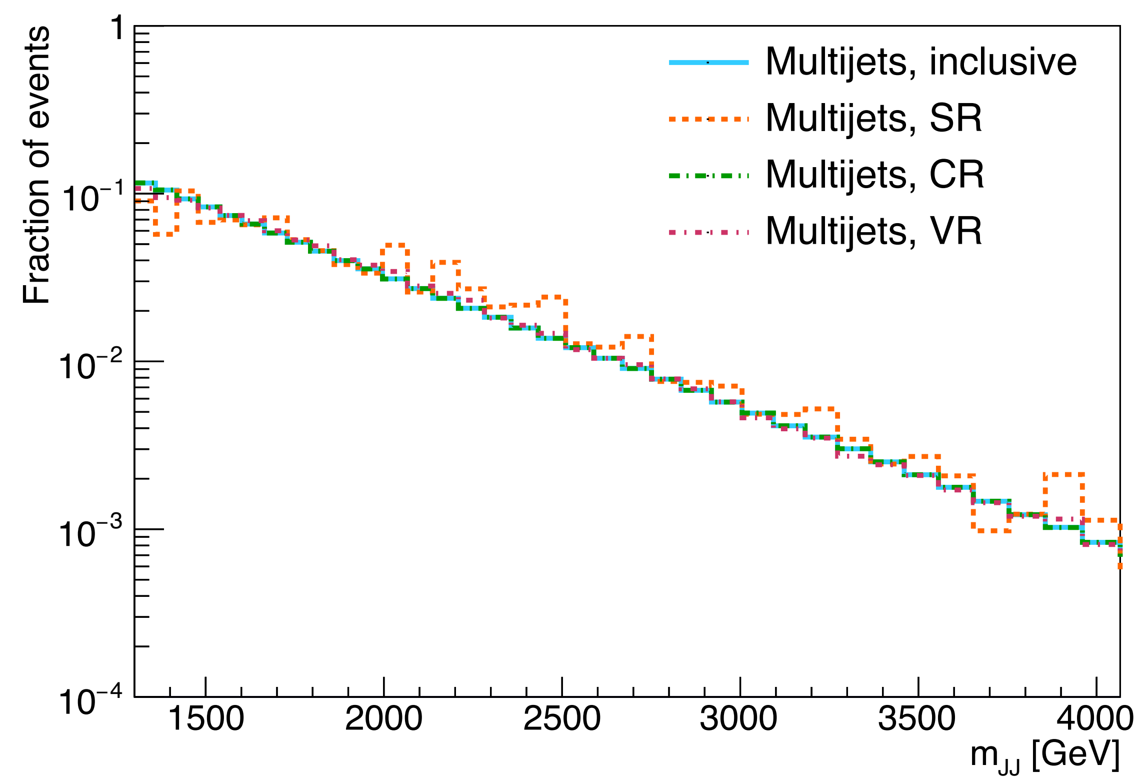
Background estimation

- Background contribution estimated by a parametric fit to data

$$\frac{\mathrm{d}N}{\mathrm{d}x} = p_1(1-x)^{p_2+\zeta p_3}x^{p_3}$$

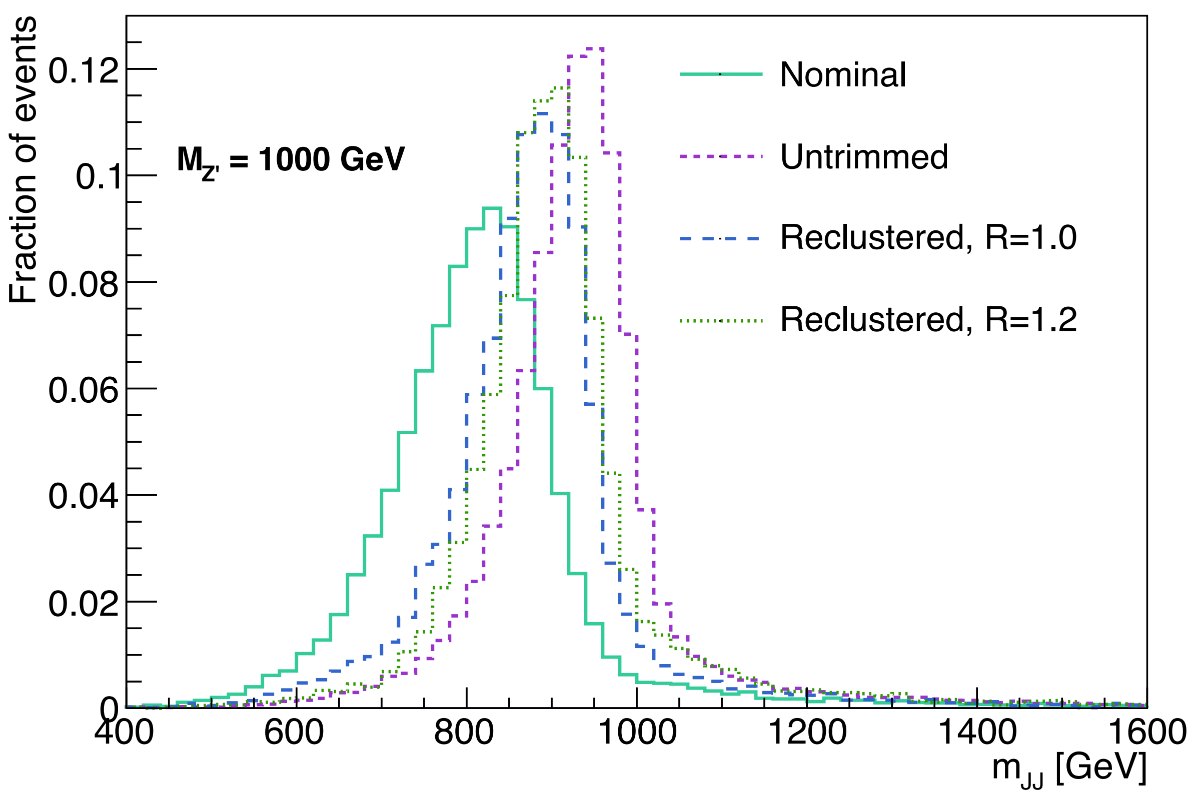
- To test and validate the method, we use MC and data in regions with less signal contamination
- Shape parameters will be determined in the control region (CR)
- Requires background distribution shape to be very similar in all regions
- Ongoing: Iteratively testing background estimation method and improving the signal region definition





Outlook

- Ongoing analysis:
  - Validating background description
  - Estimating systematic uncertainties



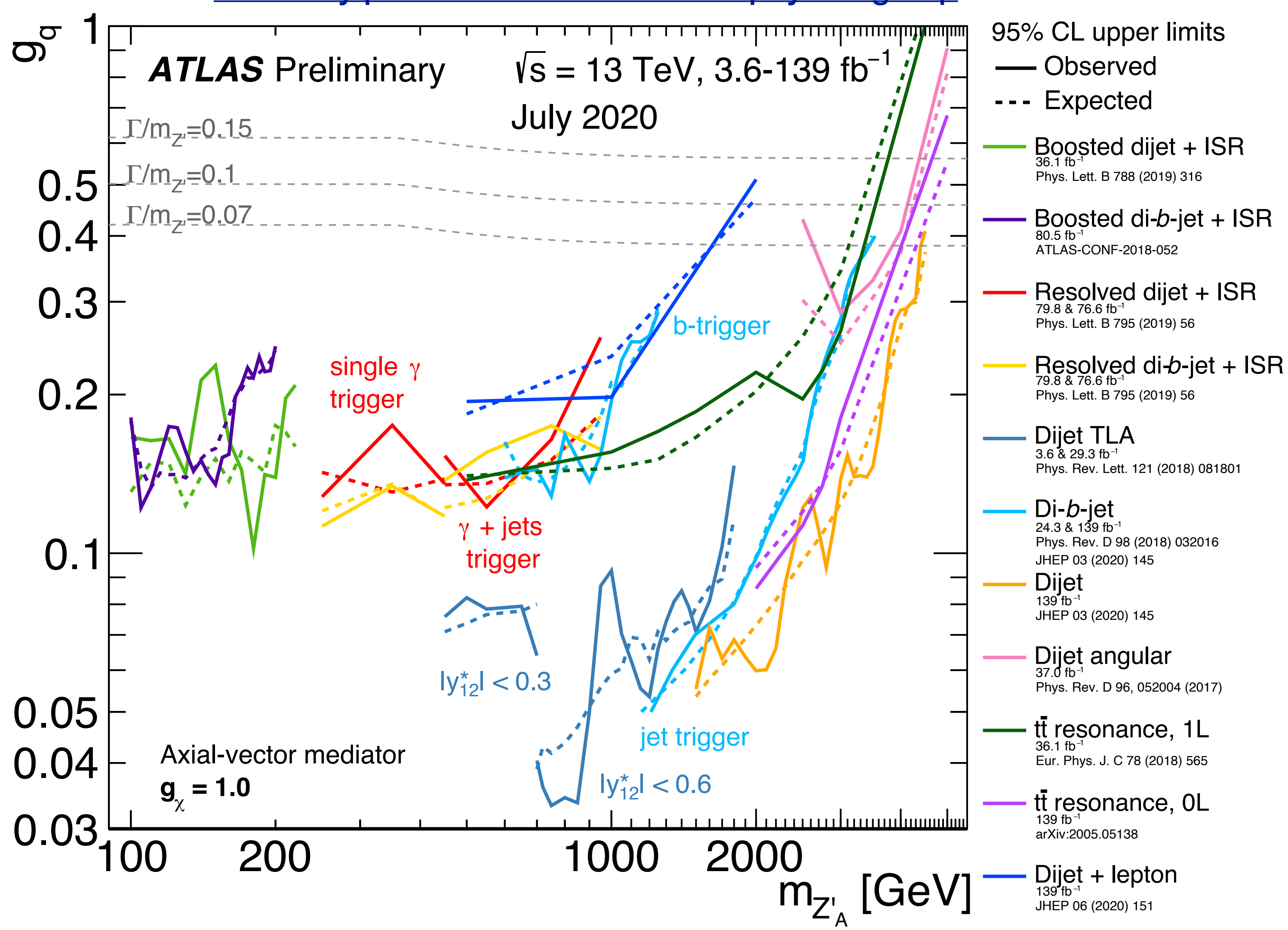
- Future analyses:
  - Jet definition:
    - Improve mass resolution for signal jets
  - Multivariate analyses:
    - Broaden the search to more signatures

Search for low-mass dijet resonances with trigger-level analysis

Motivation

- "Low-mass" refers to the electroweak TeV scale
  - Home town of *Z*, *W*, Higgs, and top - **should be thoroughly studied!**
- Two-body resonances historically fruitful (J/psi, Z, Higgs)
  - Key-component of the ATLAS search program
  - Well-covered for most decays
- Dijet searches constrained to higher masses due to threshold on jet triggers (p_T < 380 GeV)

Summary plots from ATLAS Exotics physics group



Trigger constraints

- Limits on bandwidth means low-p_T jet triggers must be *prescaled*
  - Standard analysis would not make use of the full statistical power available by the LHC
- Solution: A separate data stream which stores more events, but much less information on each:
  - All trigger-level jets with $p_T > 20$ GeV are stored
  - 0.5 % the size of a full event
- Similar techniques used in LHCb (Turbo stream) and CMS (Data scouting)

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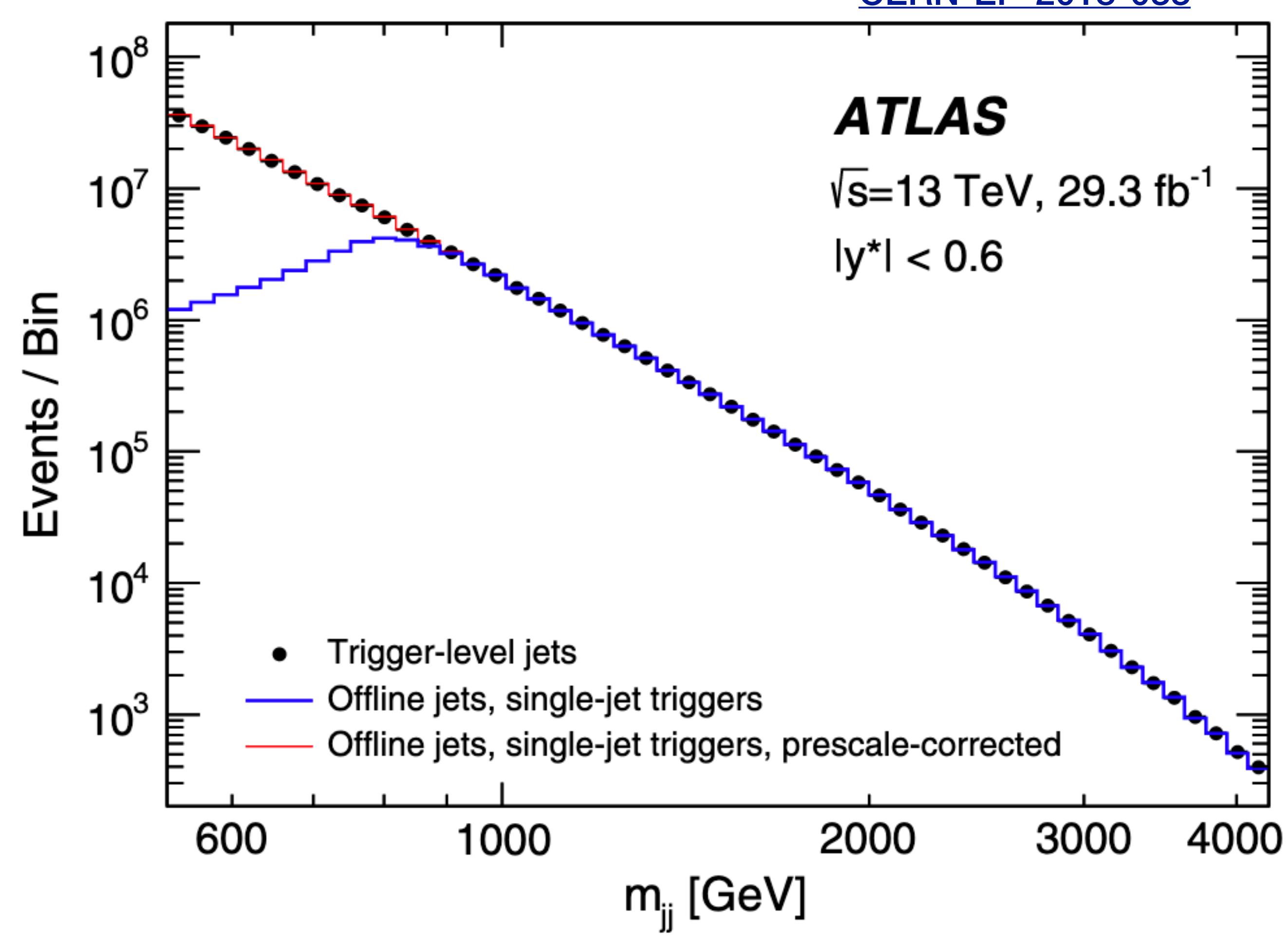
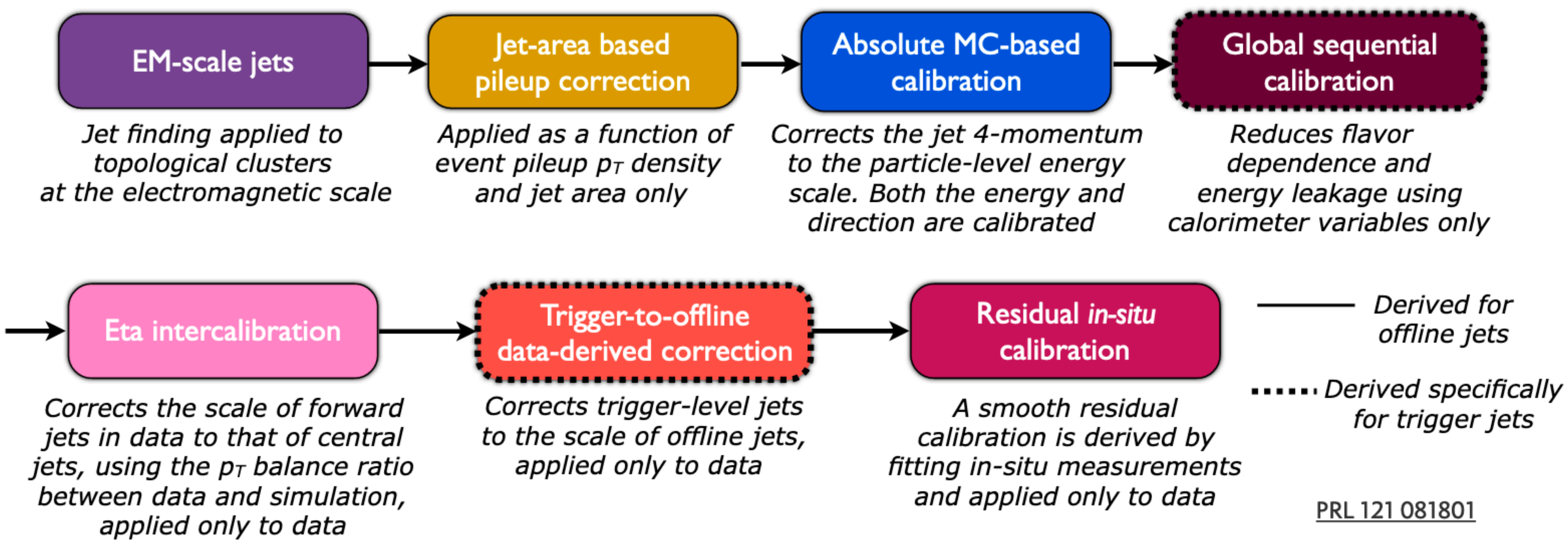


Analysis strategy

- Jets are reconstructed at the trigger-level using anti-k_t, R=0.4
- Cover a wider mass range by studying two selections:
  - L1 trigger $E_T > 75$ GeV and angular cut of $|y^*| < 0.3$
  - L1 trigger $E_T > 100$ GeV and angular cut of $|y^*| < 0.6$
- **Shape analysis:** Look for a small “bump” in the invariant mass spectrum
  - Should be smoothly falling according to the Standard Model
- Background described by a sliding-window fit
  - The functional form is evaluated at the centre bin of each window

Challenges of the strategy

- No track reconstruction at trigger level
  - Pile-up suppression more difficult
  - Requires separate reconstruction and calibration
- Background from SM dijet events expected to be huge compared to possible signal
  - Sensitive to fluctuations in the jet energy calibration



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Alternative in-situ combination

- Spline-based combination not ideal for analyses that rely on very smooth background distribution
- Alternative method based on a polynomial fit
- Gives similar uncertainty, but reduces the risk of features in the calibration curve, which can propagate to the final distribution

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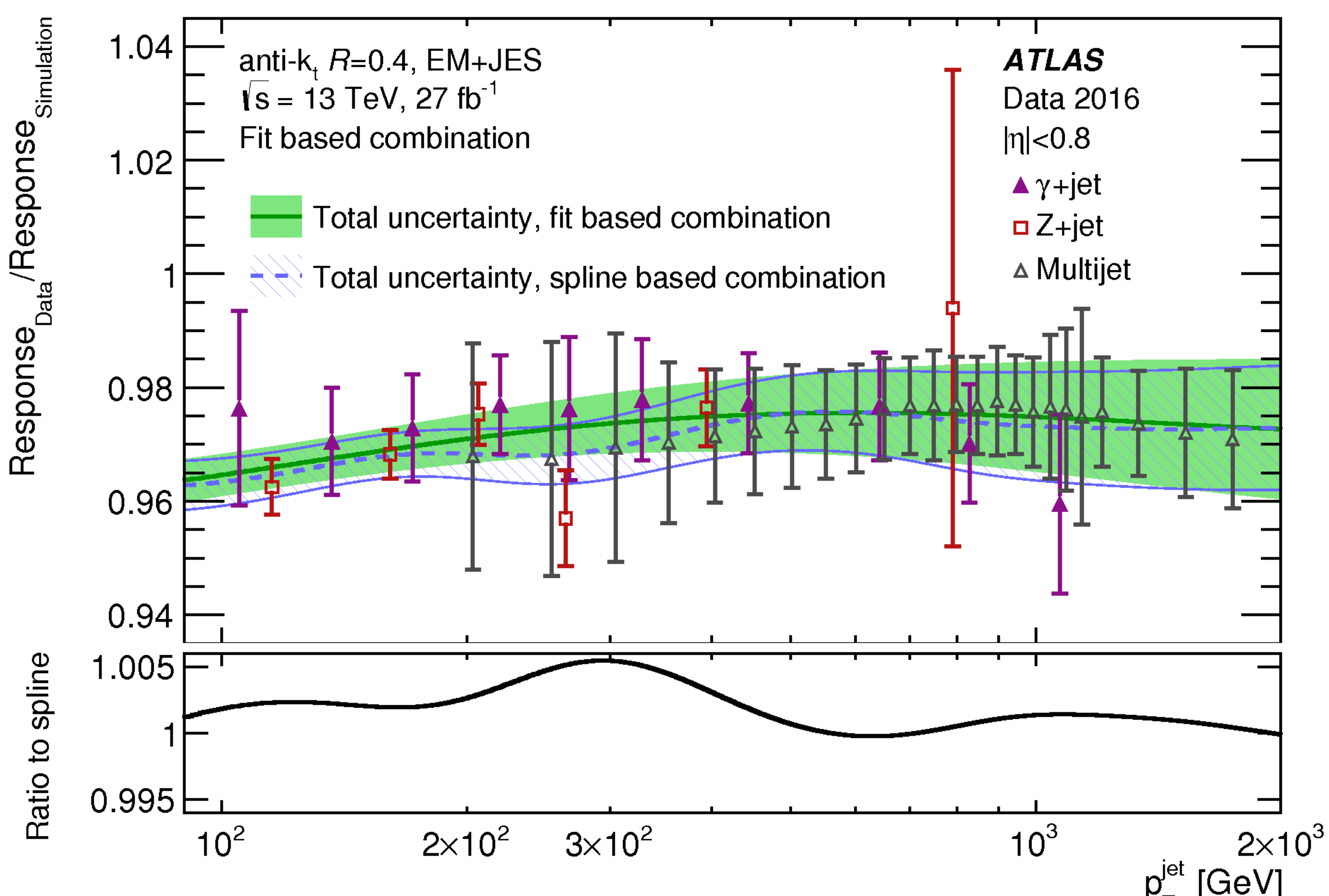

Results and interpretation

- No evidence of any localised excess
- Limits set on a simplified dark-matter model with a leptophobic *Z′*
  - and on a generic Gaussian shaped signal
- Sensitivity improved by a factor of 2 compared to pre-LHC and previous ATLAS results

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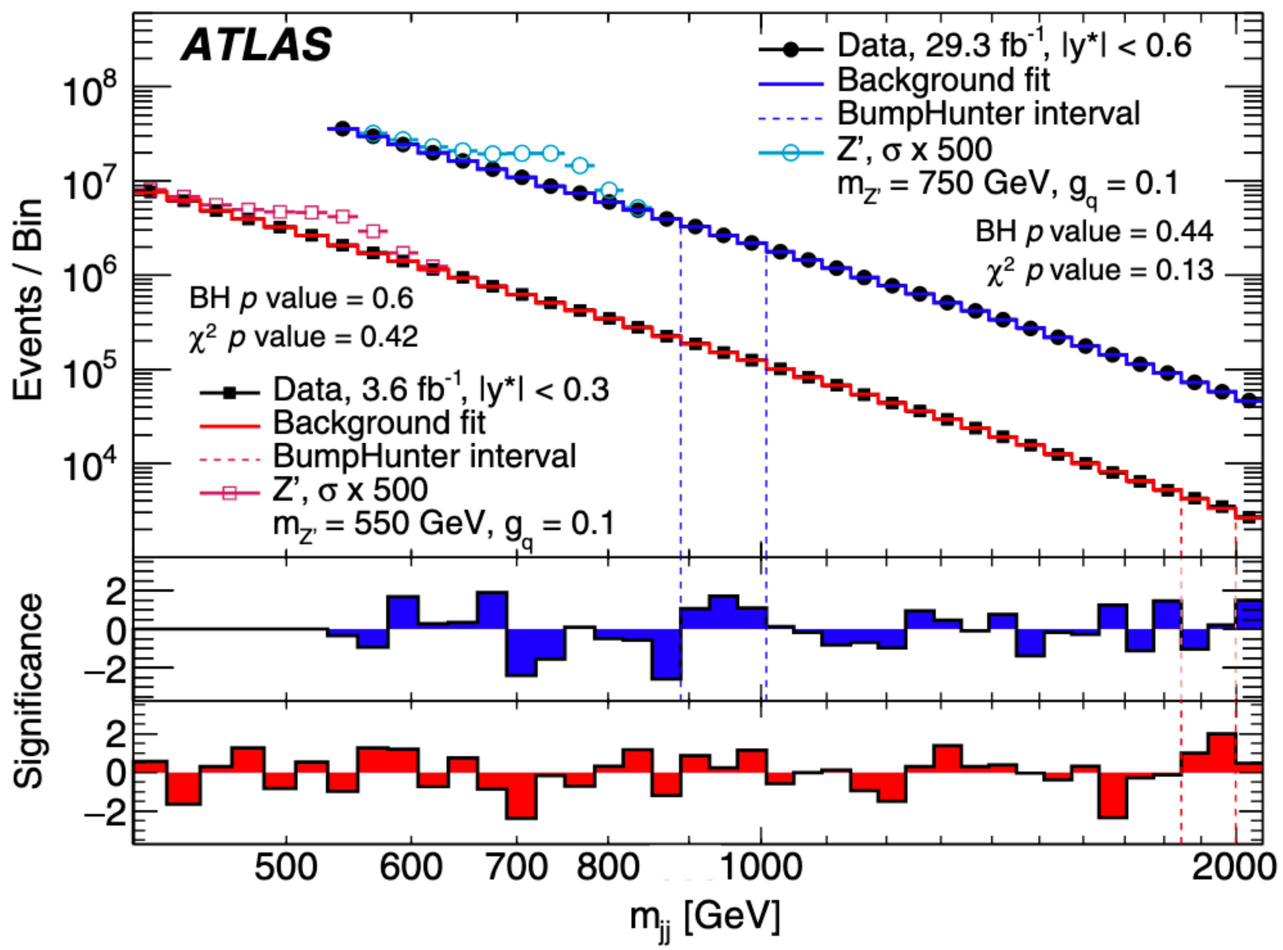
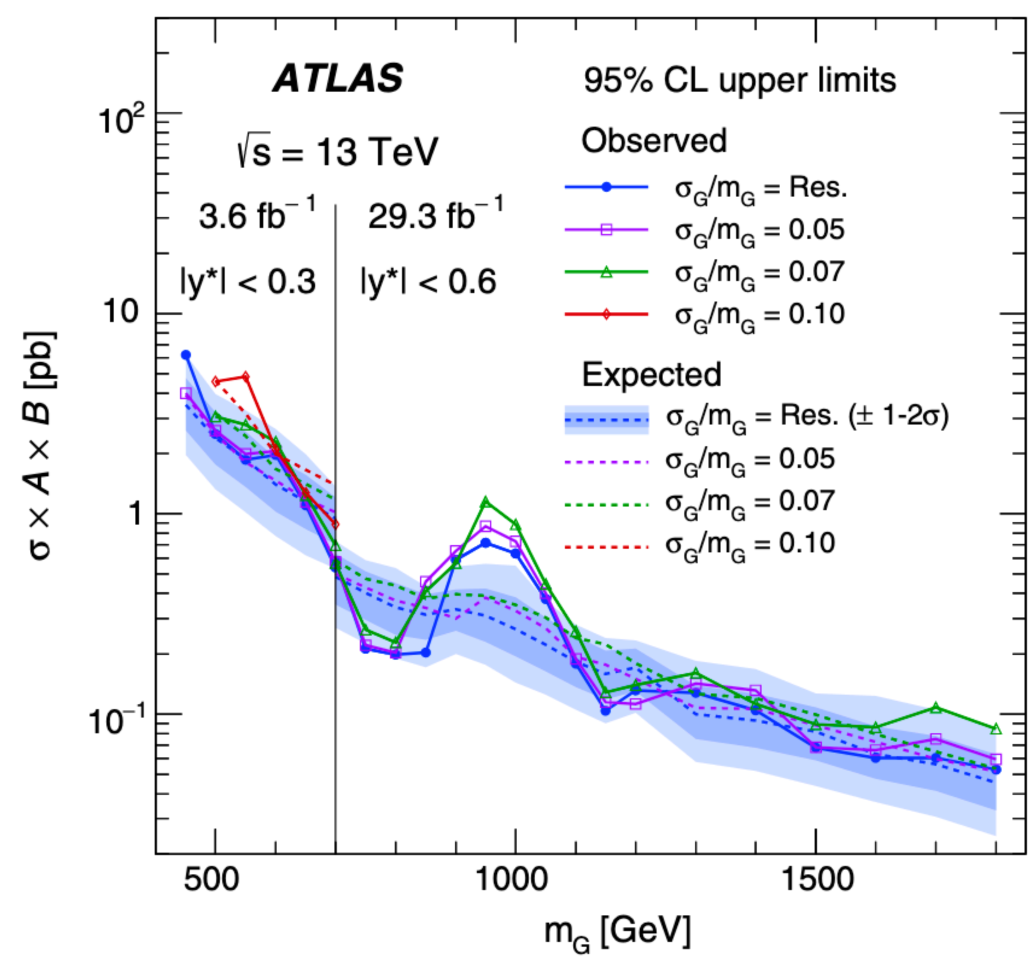
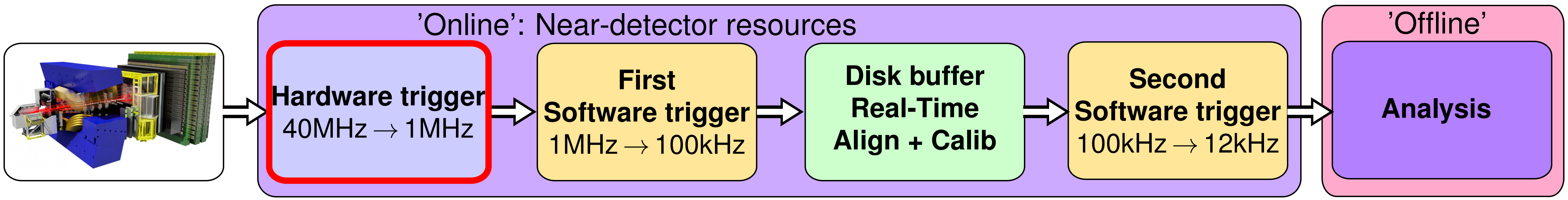




Segue to LHCb RTA



- A similar data-taking approach of the TLA is widely used by the LHCb
- High signal rates requires more data analysis to be done at the trigger-level (Real-time analysis) in order to store only relevant object

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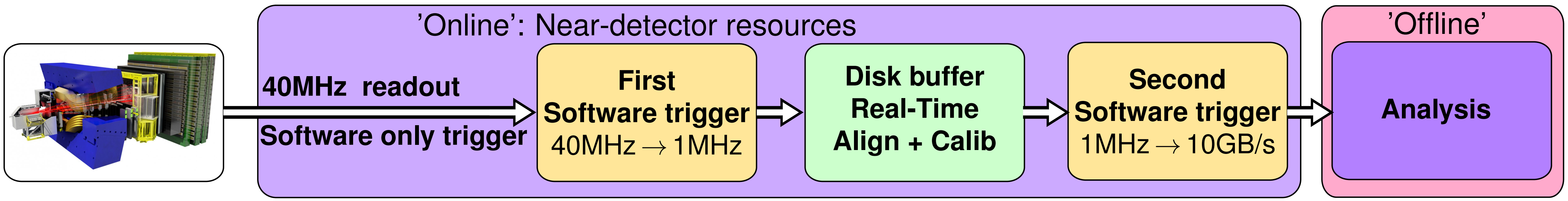
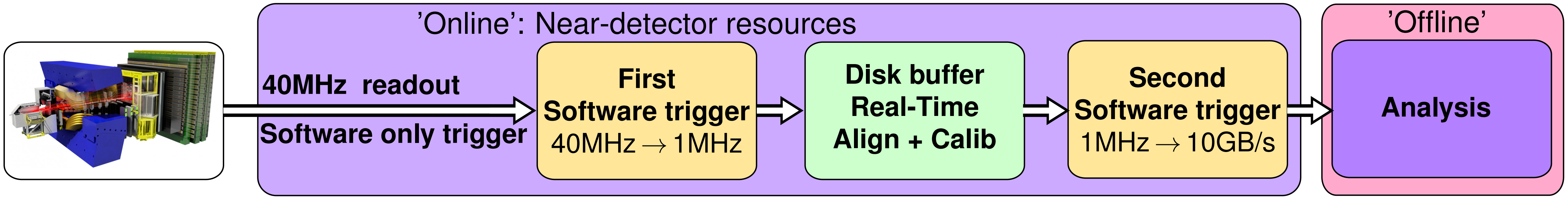


- A similar data-taking approach of the TLA is widely used by the LHCb
- High signal rates requires more data analysis to be done at the trigger-level (Real-time analysis) in order to store only relevant object
- In Run 3 LHCb will run at five times the collision rate of Run 2
  - Even more sophisticated analyses necessary at trigger level
  - Hardware trigger replaced by software
- Now working to get the second software trigger ready for Run 3
  - Providing support for storing for objects to be analysed offline

Segue to LHCb RTA



More about the LHCb trigger from Conor Fitzpatrick next week!

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Summary

Summary

- **My PhD work revolved around jets - how they are calibrated and how they can be used in searches for new physics phenomena**
  - The jet energy and mass scale calibrations have been described with focus on the data-driven *in situ* methods
  - A search for low-mass dijet resonance using trigger-level jets was presented
    - Improves constraints on the possible mass down to 450 GeV
  - The search for a heavy resonance decaying to two large-radius jets is still ongoing
    - Demonstrates the feasibility of searching for confined hidden sectors with jet substructure
    - Implemented a technique for defining an event selection that does not distort the final background distribution
- **Carrying experiences especially from the TLA with to my current work on LHCb**