Searches for Dark Matter with the ATLAS Detector

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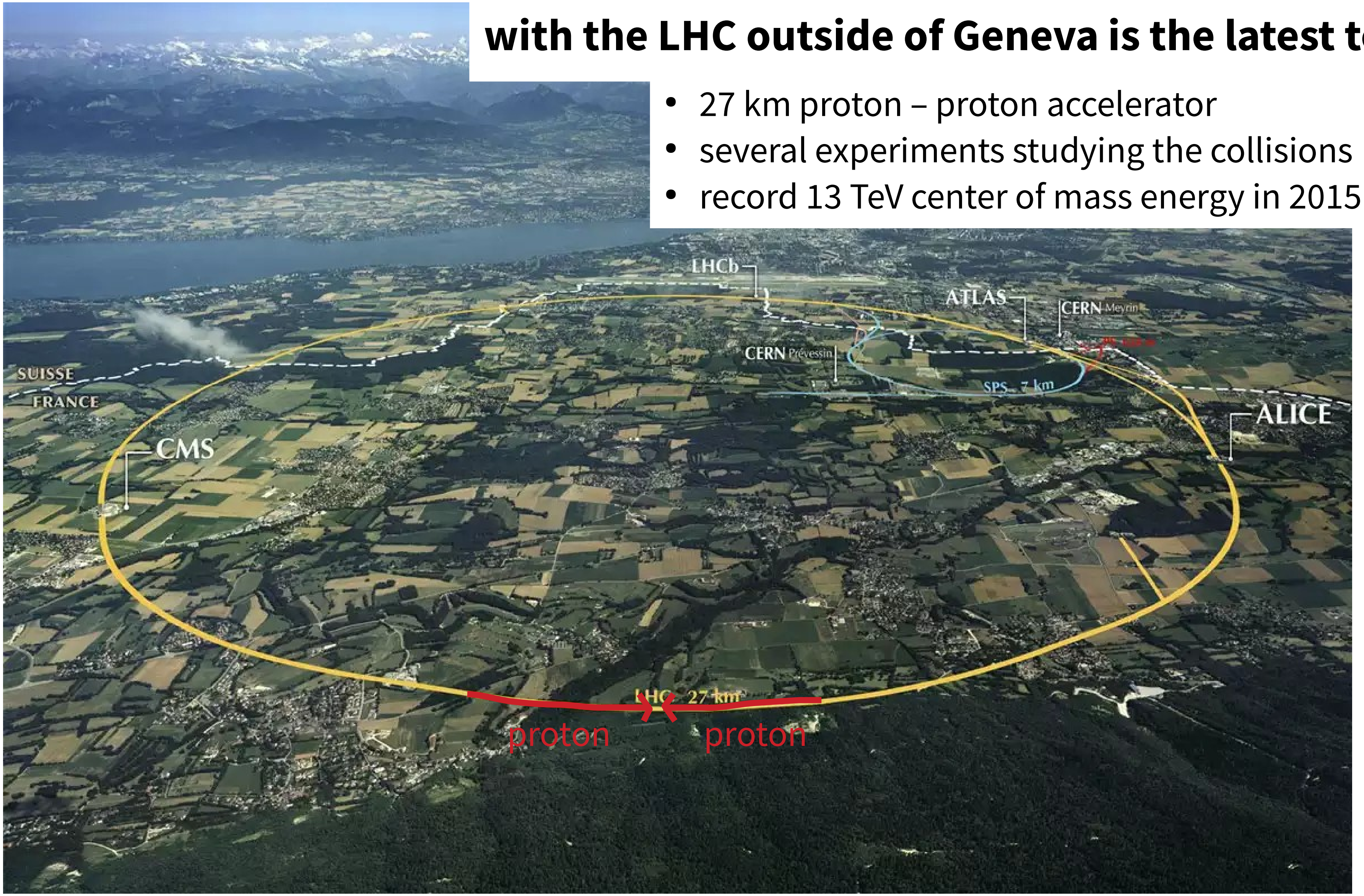
Physics 290e

Large Hadron Collider

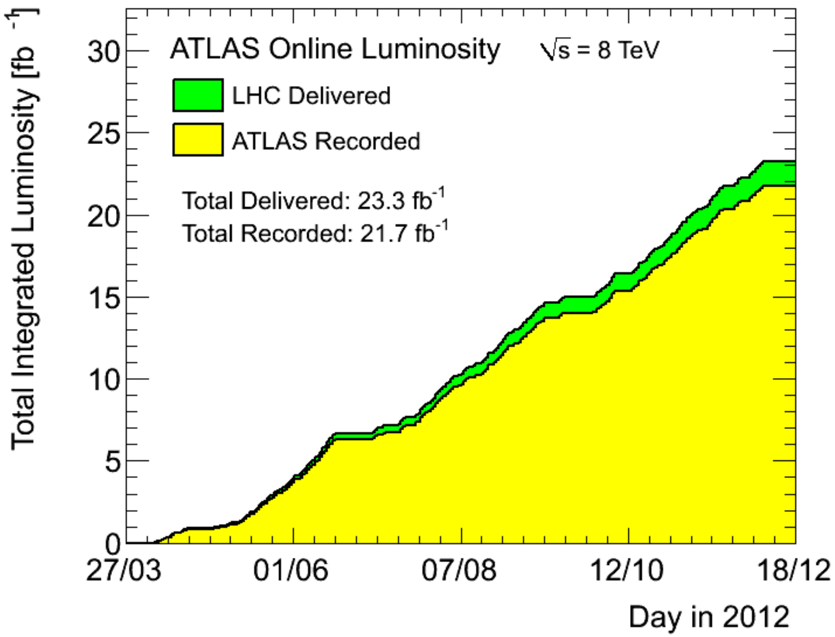
The Standard Model can be tested by smashing particles at high energies,

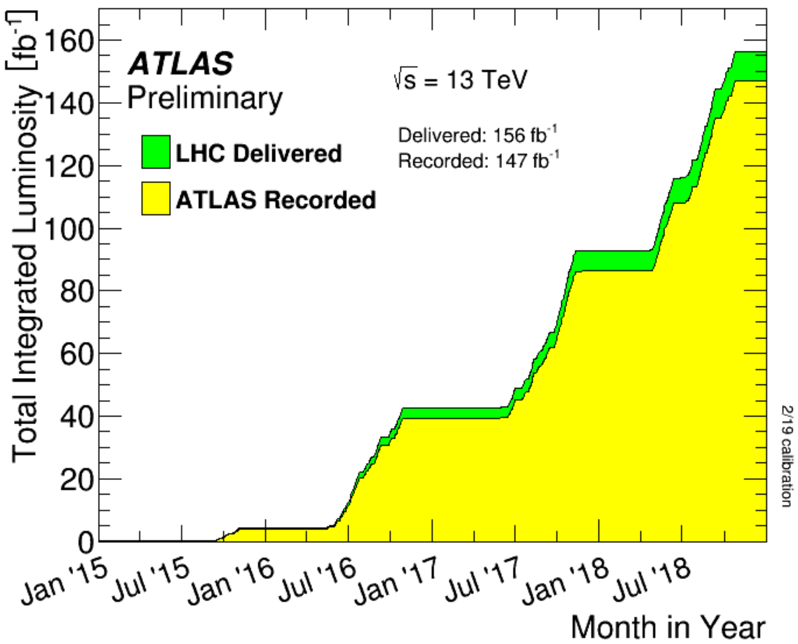
with the LHC outside of Geneva is the latest tool.

- 27 km proton – proton accelerator
- several experiments studying the collisions
- record 13 TeV center of mass energy in 2015!



Runs I and II





Run I

Higgs discovery!

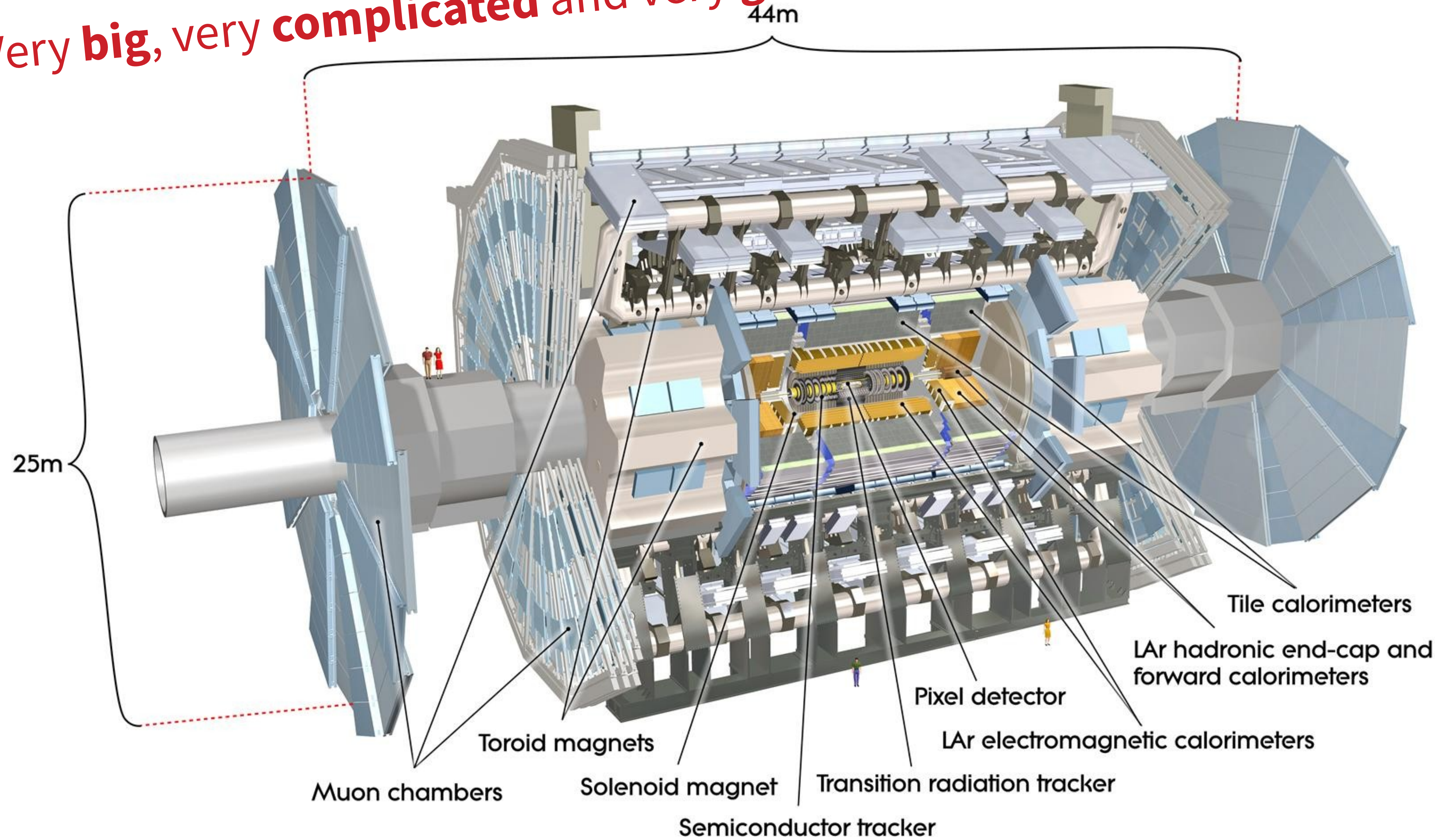
- First physics data at 7 TeV in 2011 (5.2 fb^{-1})
- Energy increased to 8 TeV in 2012 (21.7 fb^{-1})

Run II

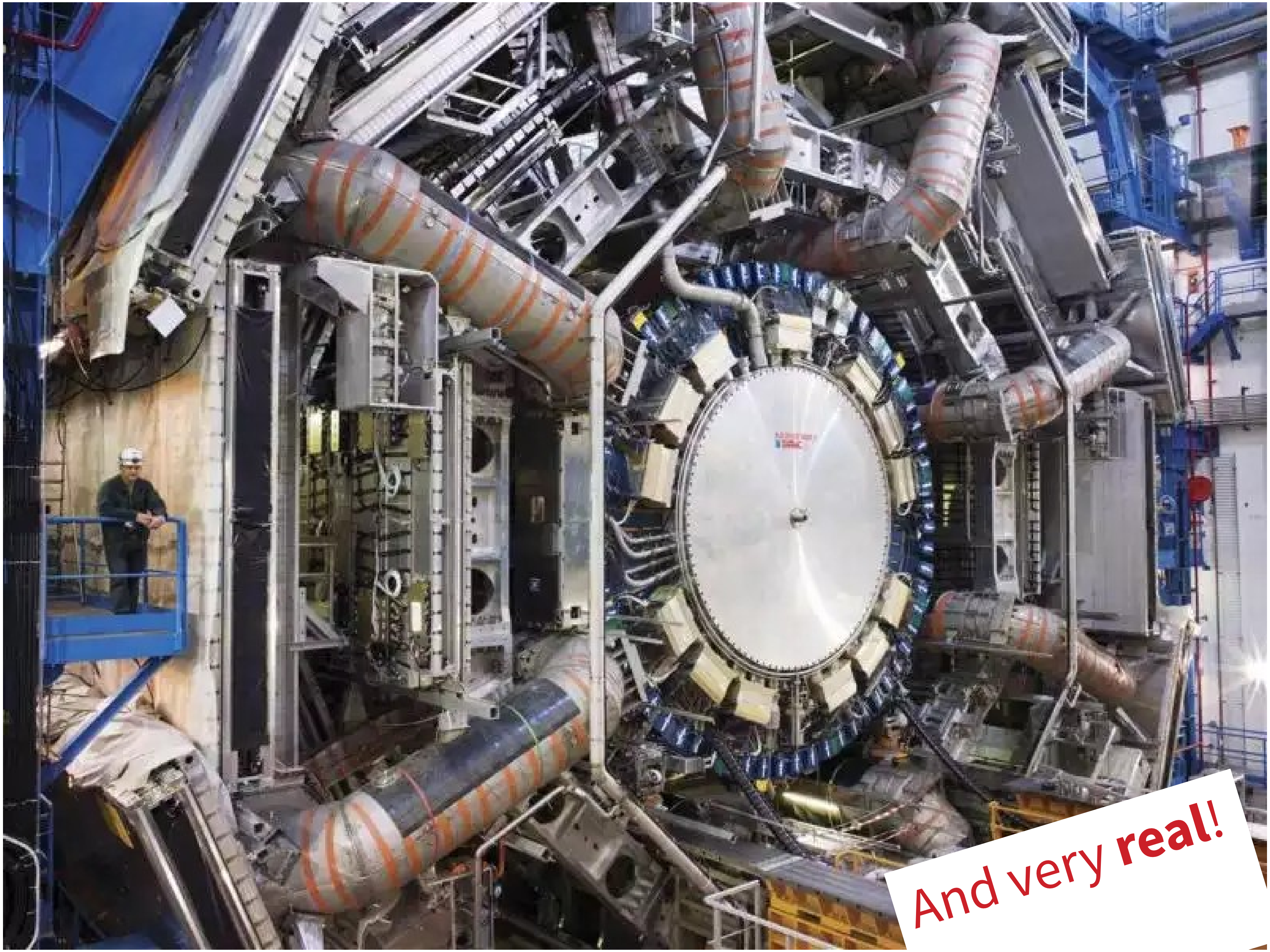
- Started running at 13 TeV in end of 2015 (3.2 fb^{-1})
- Finished in 2018 with 147 fb^{-1}

ATLAS Particle Detector

Very **big**, very **complicated** and very **general**!

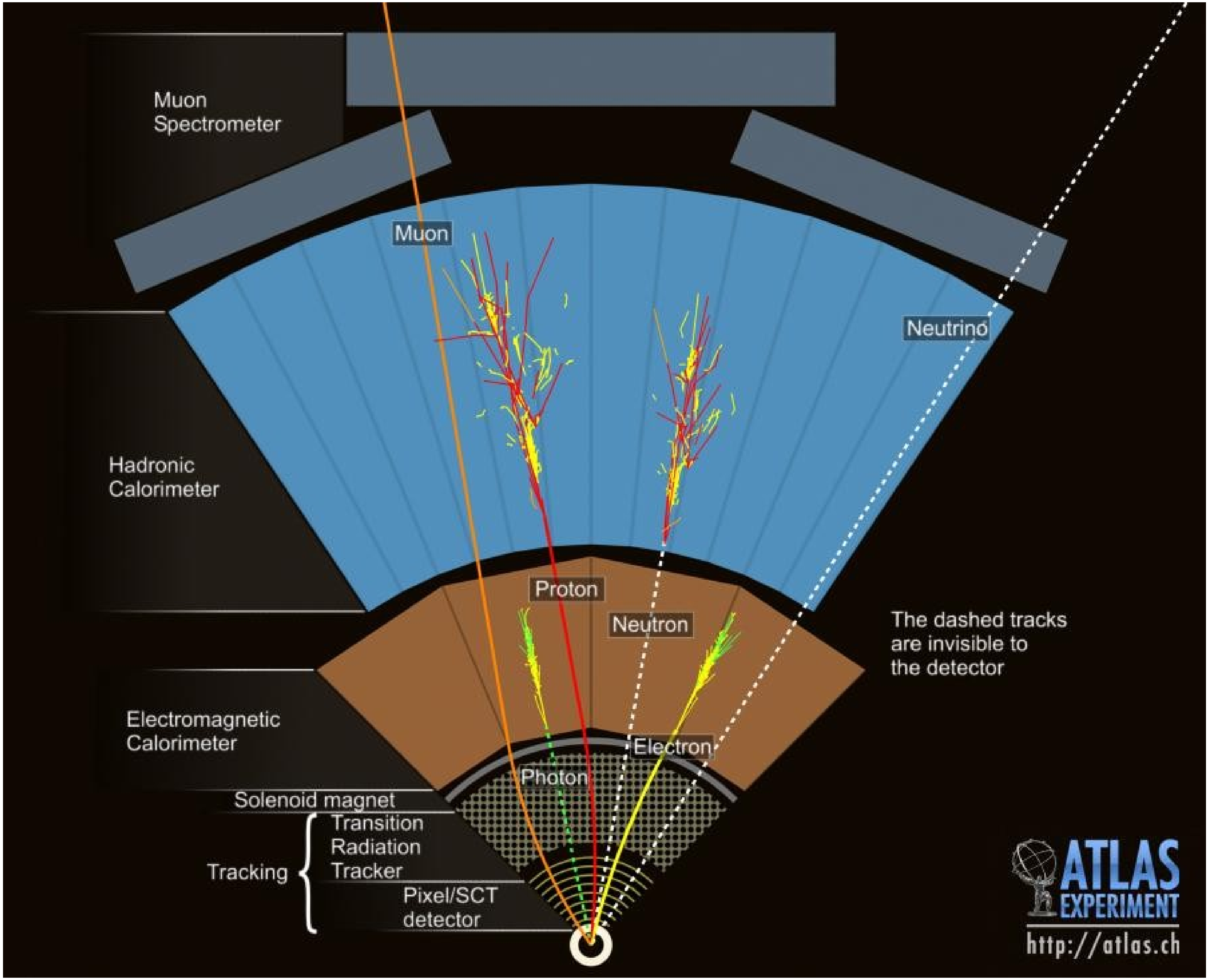


ATLAS Particle Detector

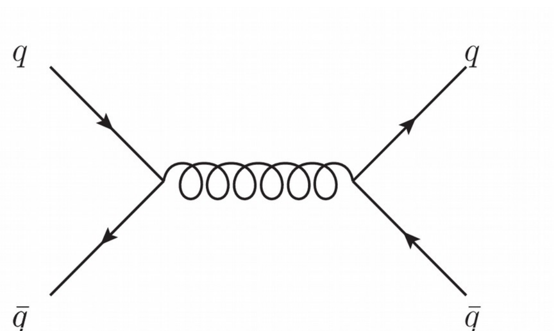


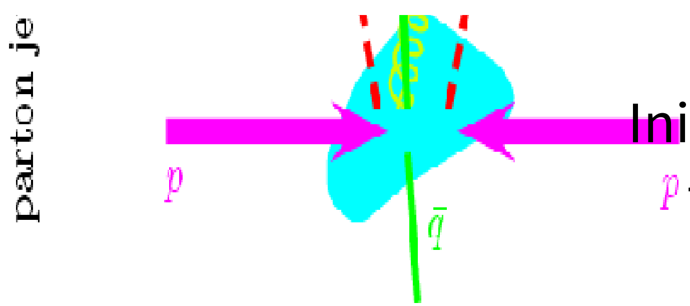
And very **real**!

Particle Identification



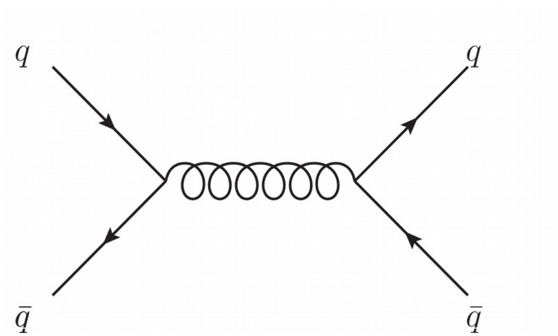
Jets



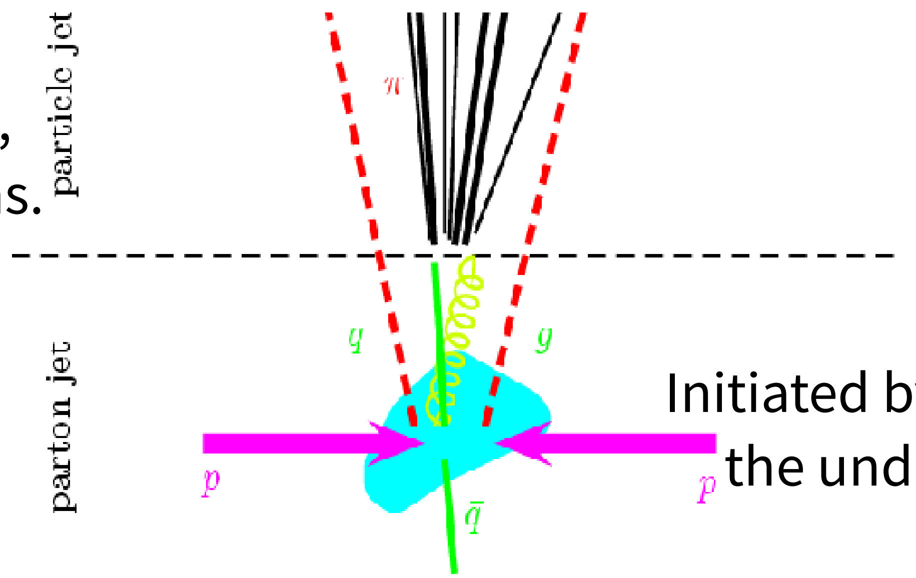


Initiated by quarks and gluons in the underlying process.

Jets



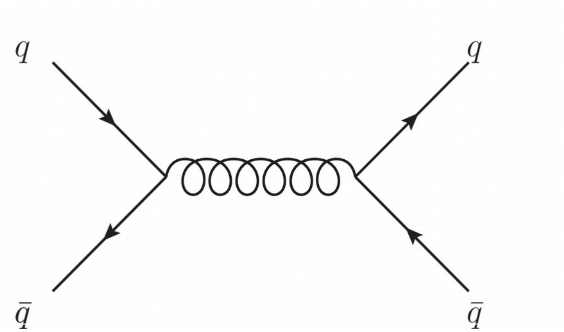
Due to color confinement,
partons turn into hadrons.

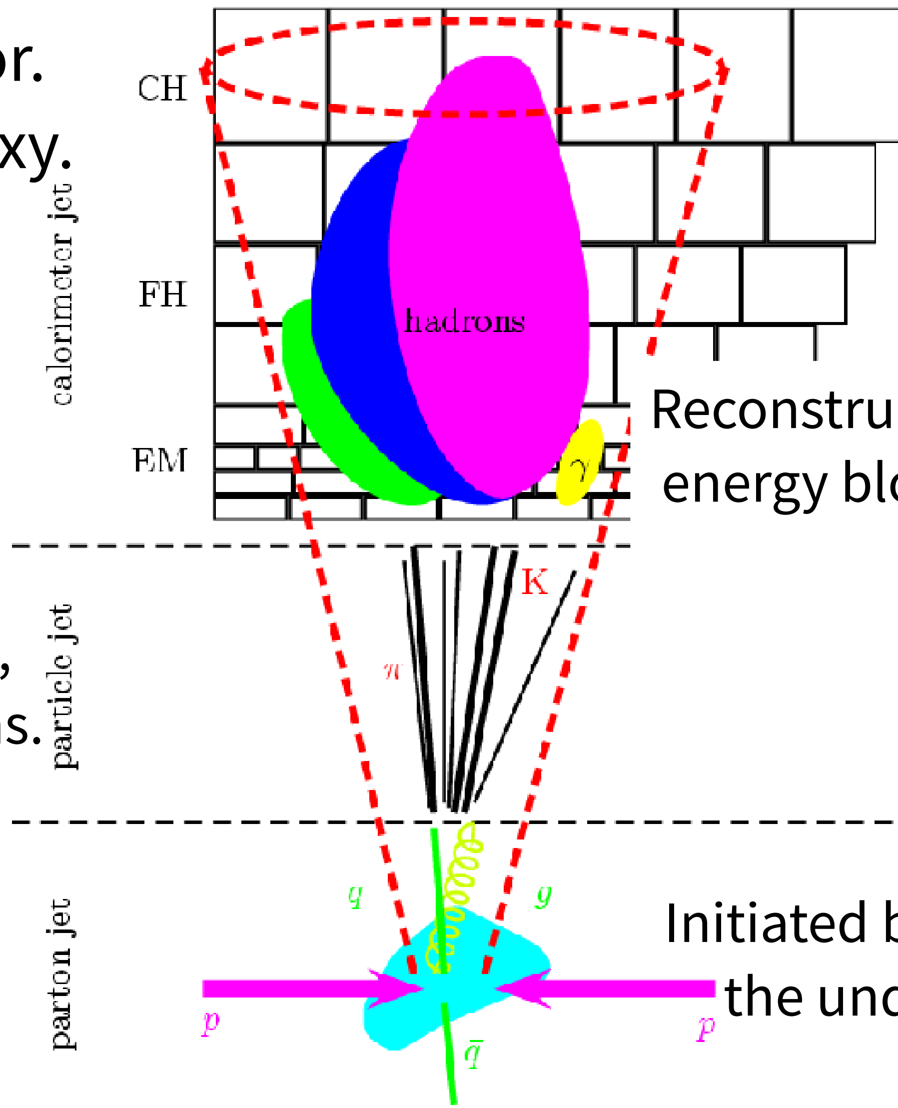


Initiated by quarks and gluons in the underlying process.

Jets

Cannot see quarks/gluons directly in the detector. Jets are used as a proxy.



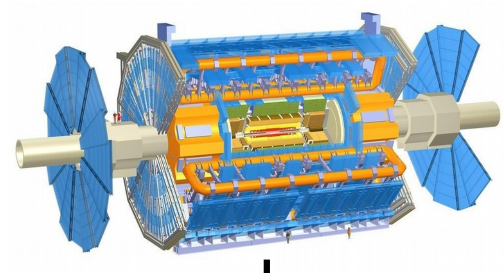


Reconstructed as jets from energy blobs in the calorimeter.

Due to color confinement, partons turn into hadrons.

Initiated by quarks and gluons in the underlying process.

ATLAS Trigger



40 MHz — *(50 TB/s)*

Cannot write every collision to disk!!!
Must be smart about what events are saved.

Hardware-based
- custom boards
- simple jets, EM objects, ME_T
- no tracking!

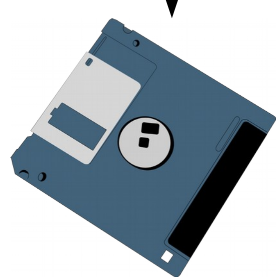
Level 1 — 2.5 μs

100 kHz — *(150 GB/s)*

High Level Trigger — ~ seconds

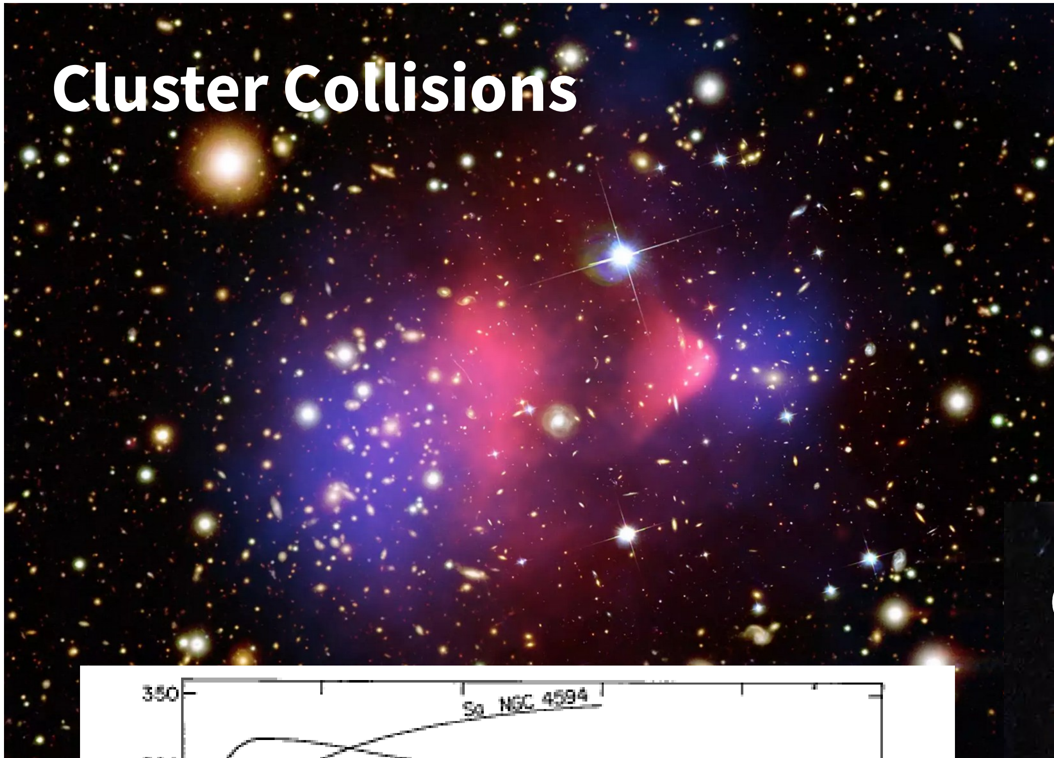
Software-based
- big computing farm
- offline-like reconstruction and calibration for calorimeter
- simple tracking

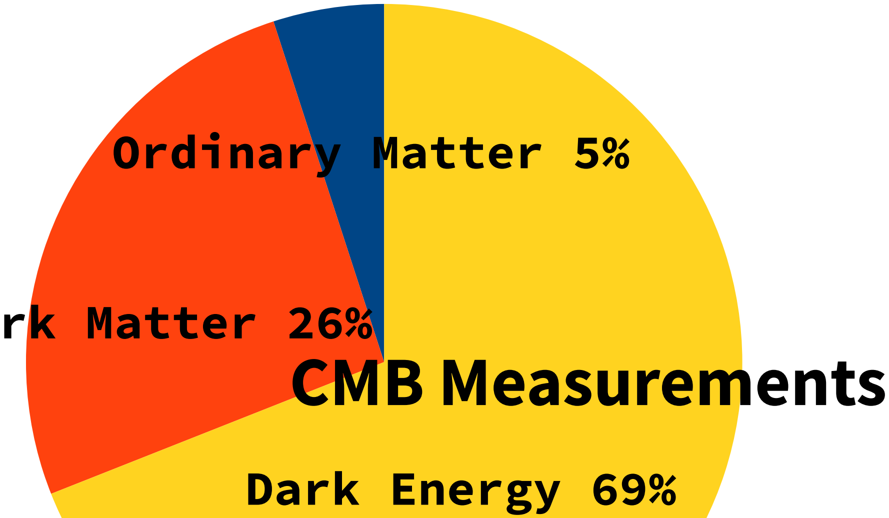
1 kHz — *(GB/s)*

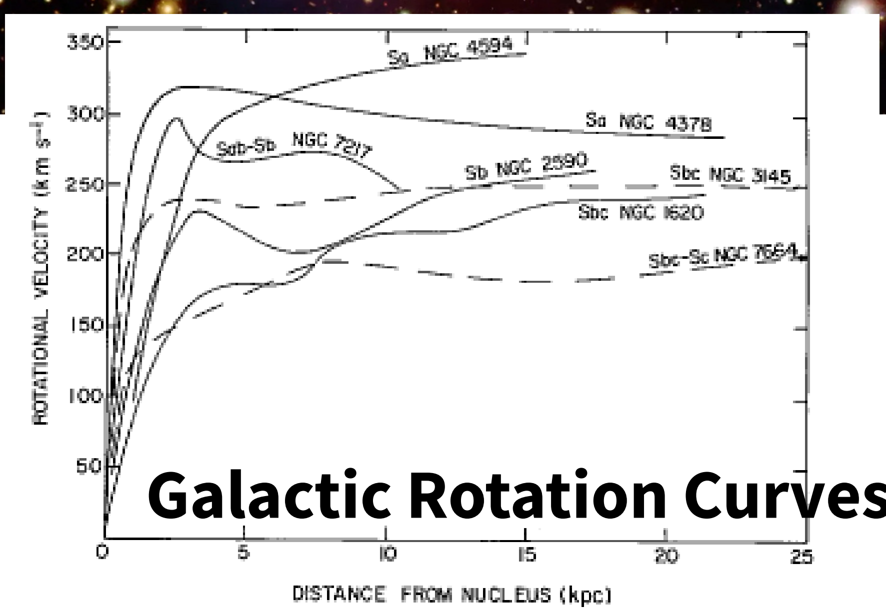


Example *unprescaled* triggers:
- 380 GeV jet (32 Hz)
- 140 GeV photon (20 Hz)
- 110 GeV ME_T (10 Hz)

Why Dark Matter?



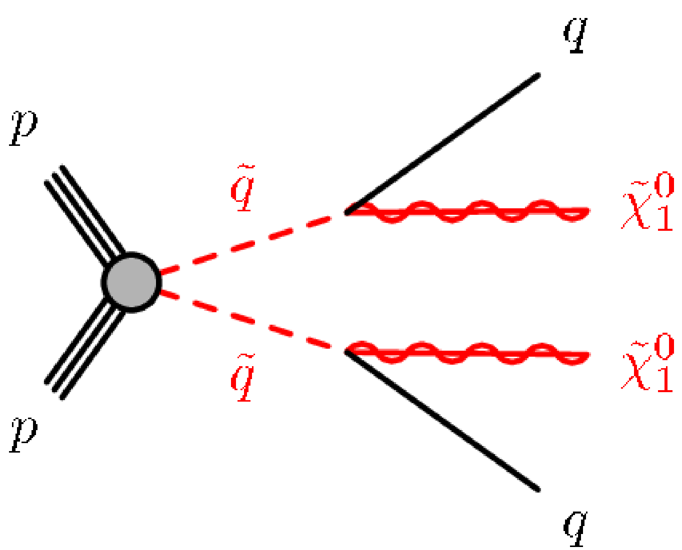




Dark Matter Models at the LHC

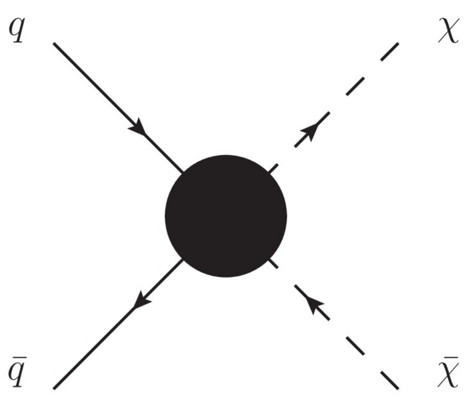
Two approaches to a benchmark model

Part of Larger Model (ie: SUSY)



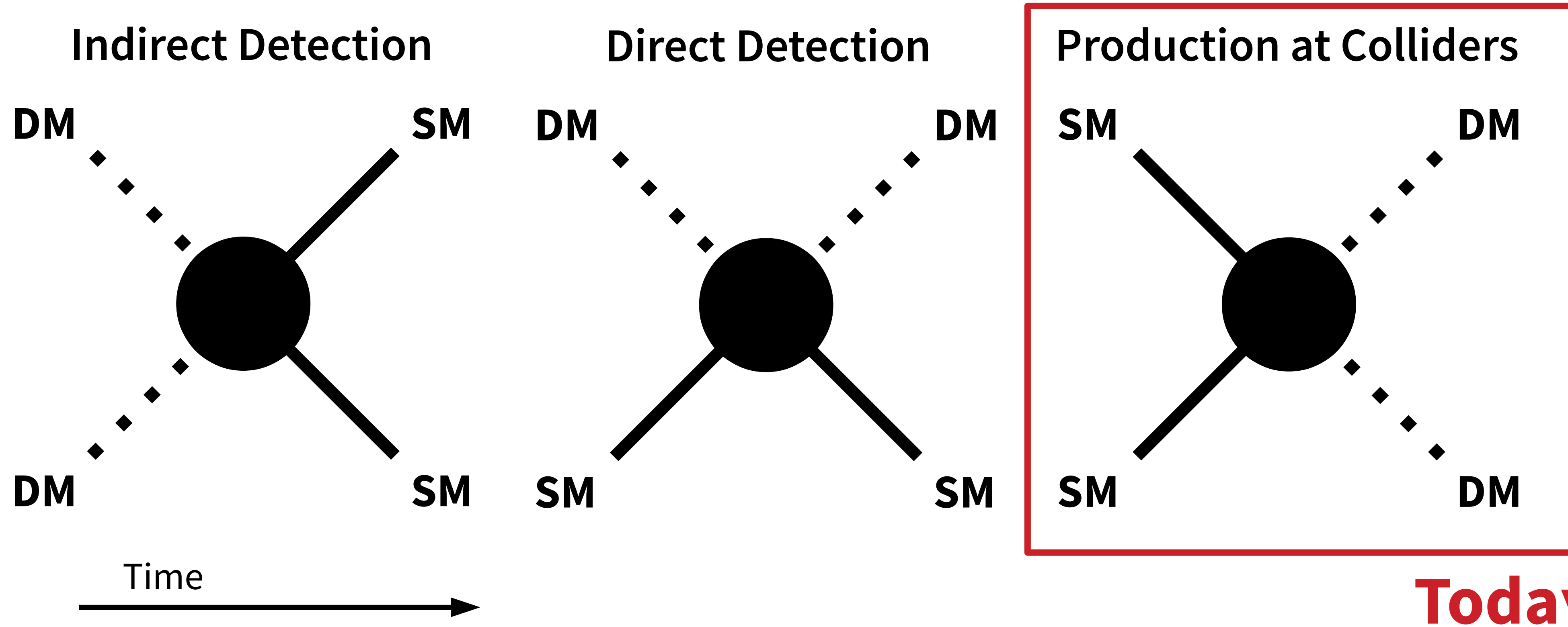
- valid over large energy range
- many parameters

Simplified Model



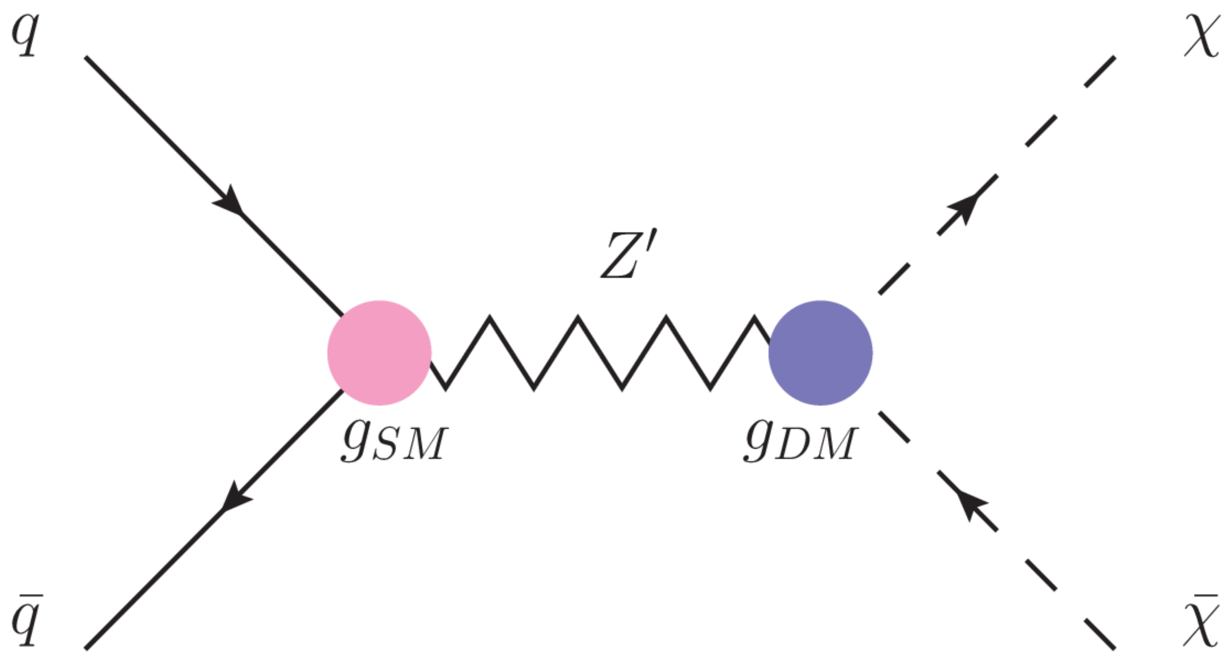
- valid only at certain energies (EFT)
- few parameters as possible

Searching For Dark Matter



Today

Mediator-Based Dark Matter Model

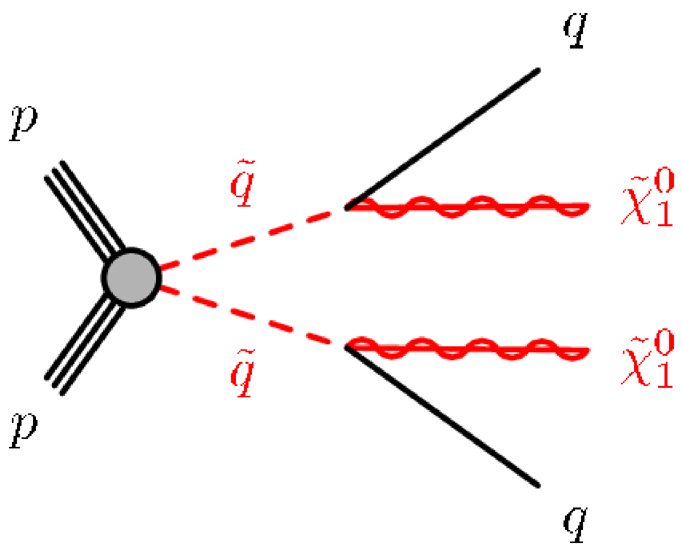


- **Common model used by all searches and all LHC experiments**
  - An (spin ?) mediator (mass m_R) couples to Dark Matter (mass m_{DM})
  - Independent couplings to quarks (g_{SM}) and Dark Matter (g_{DM})

Dark Matter Models at the LHC

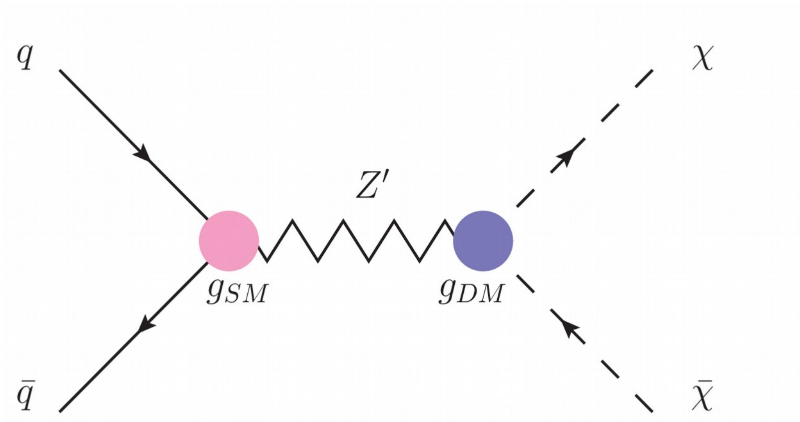
Two approaches to a benchmark model

Part of Larger Model (ie: SUSY)



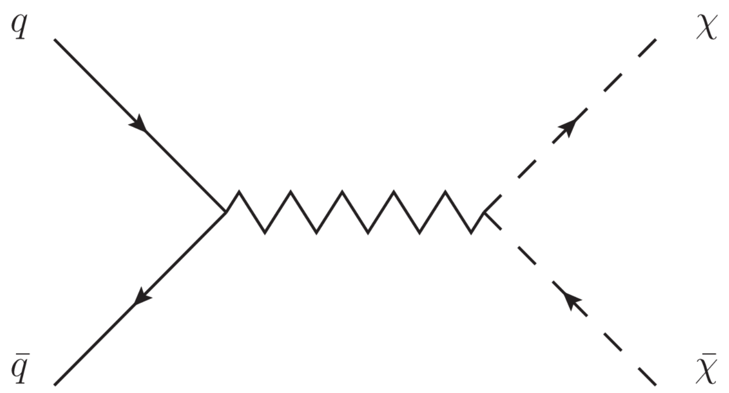
- valid over large energy range
- many parameters

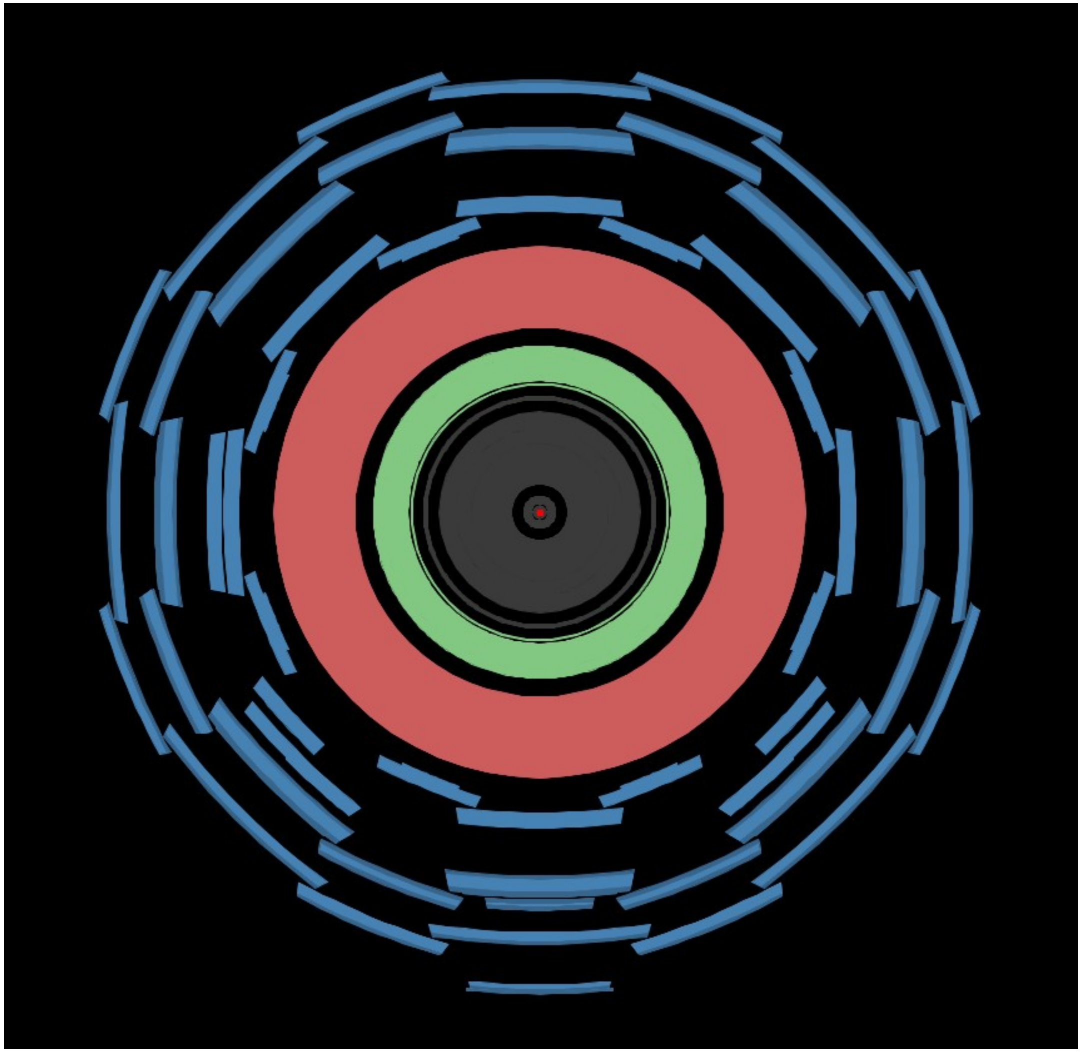
Simplified Model



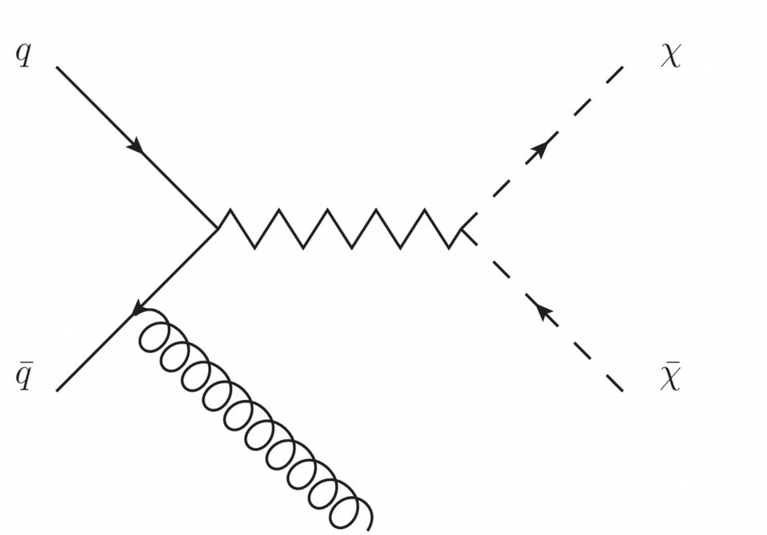
- valid only at “low” energies
- few parameters as possible

Detecting Dark Matter in ATLAS

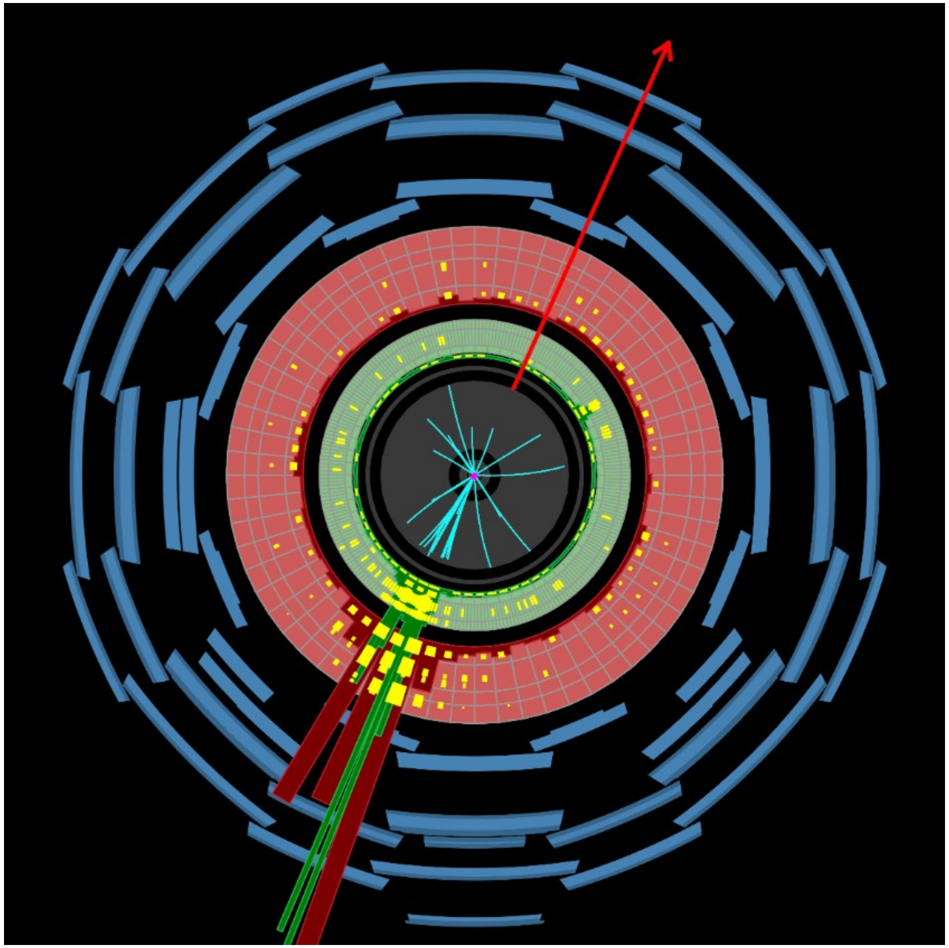




Detecting Dark Matter in ATLAS



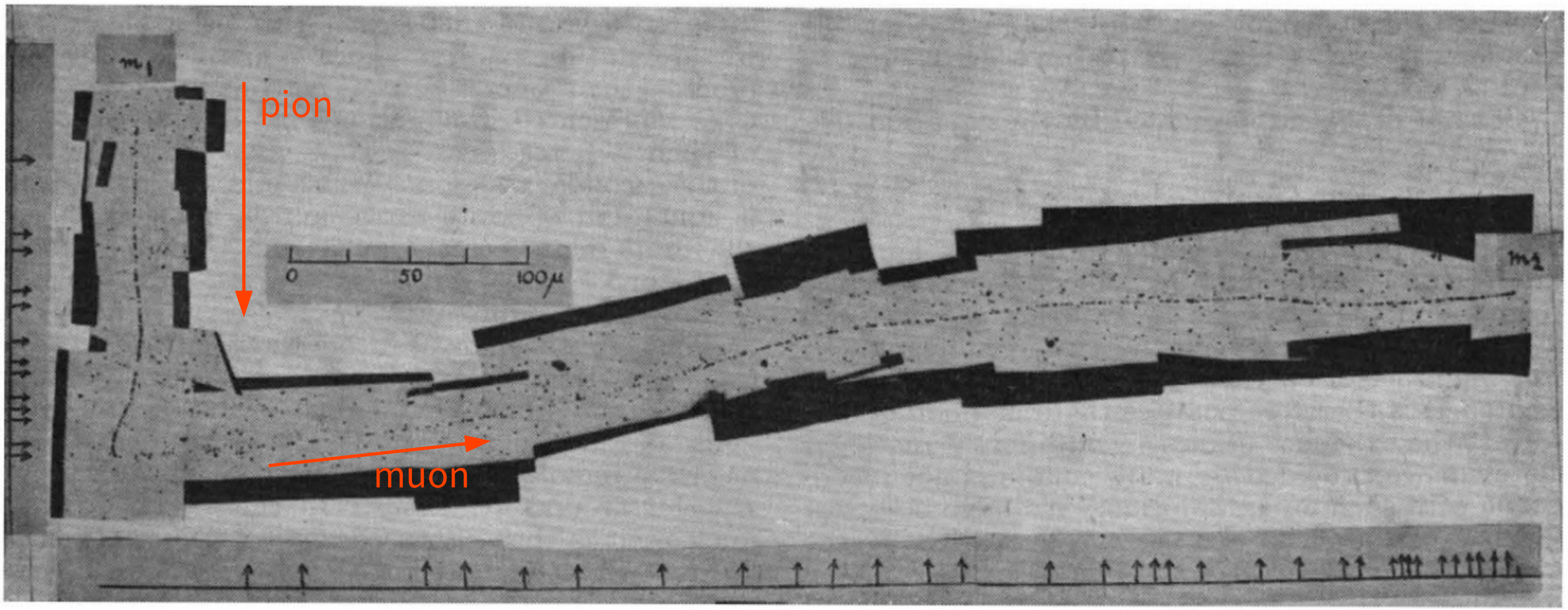
X = gluon, photon, Higgs...



Require production of mediator in association with *X*.

- Dark Matter will have momentum imbalance in the transverse plane.
- Called Mono-*X* searches

Early Example of Missing Energy



Nature 159, 694-697 (1947)

Missing Transverse Energy

$$\vec{E}_T^{\text{miss}} = \boxed{-\vec{p}_T^{\,e} - \vec{p}_T^{\,\mu} - \vec{p}_T^{\,\tau} - \vec{p}_T^{\,\gamma} - \vec{p}_T^{\,\text{jet}}} \boxed{- \vec{p}_T^{\,\text{soft}}}$$

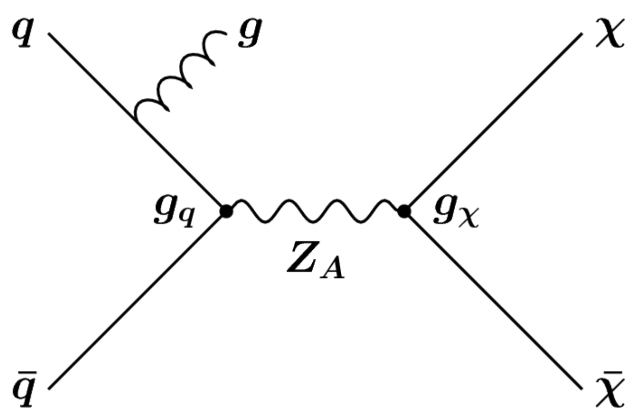
Hard term: Reconstructed particles with best calibration

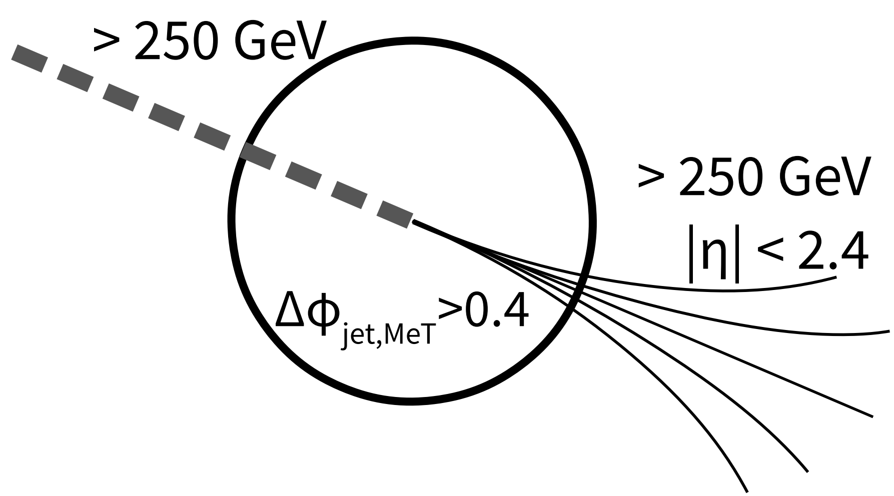
Soft Term: From tracks not matched to any other objects

Sources of Missing Energy (Backgrounds)

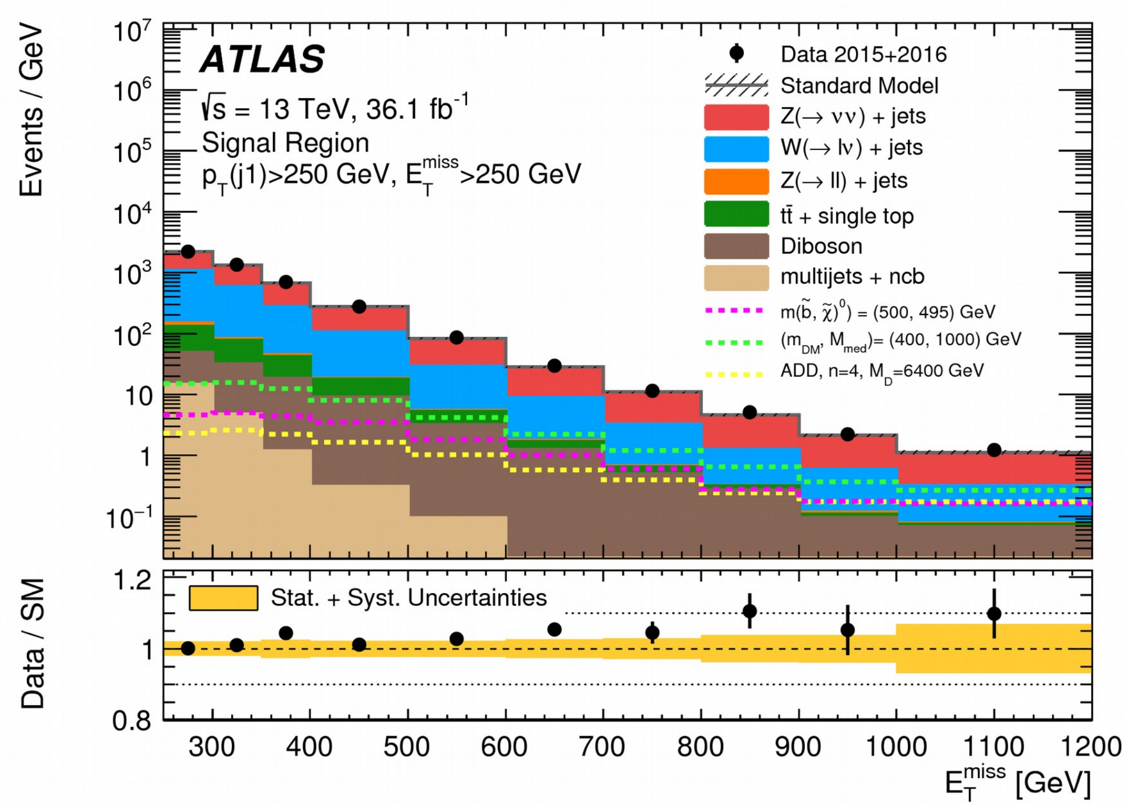
- **"Real" missing energy**
  - Z→νν is the largest "irreducible" background (looks like a Z'→DM decay!)
  - W→lν where the lepton is not reconstructed
  - Laptonic decays of top quarks
- **Detector effects**
  - We do not model every single cable and crack
  - Hard to estimate from simulation
- **Non-Collision Backgrounds**
  - Muons created from ineslastic beam-gas interactions with collimators
  - Cosmic-rays
  - Calorimeter noise

Mono-Jet EXOT-2016-27



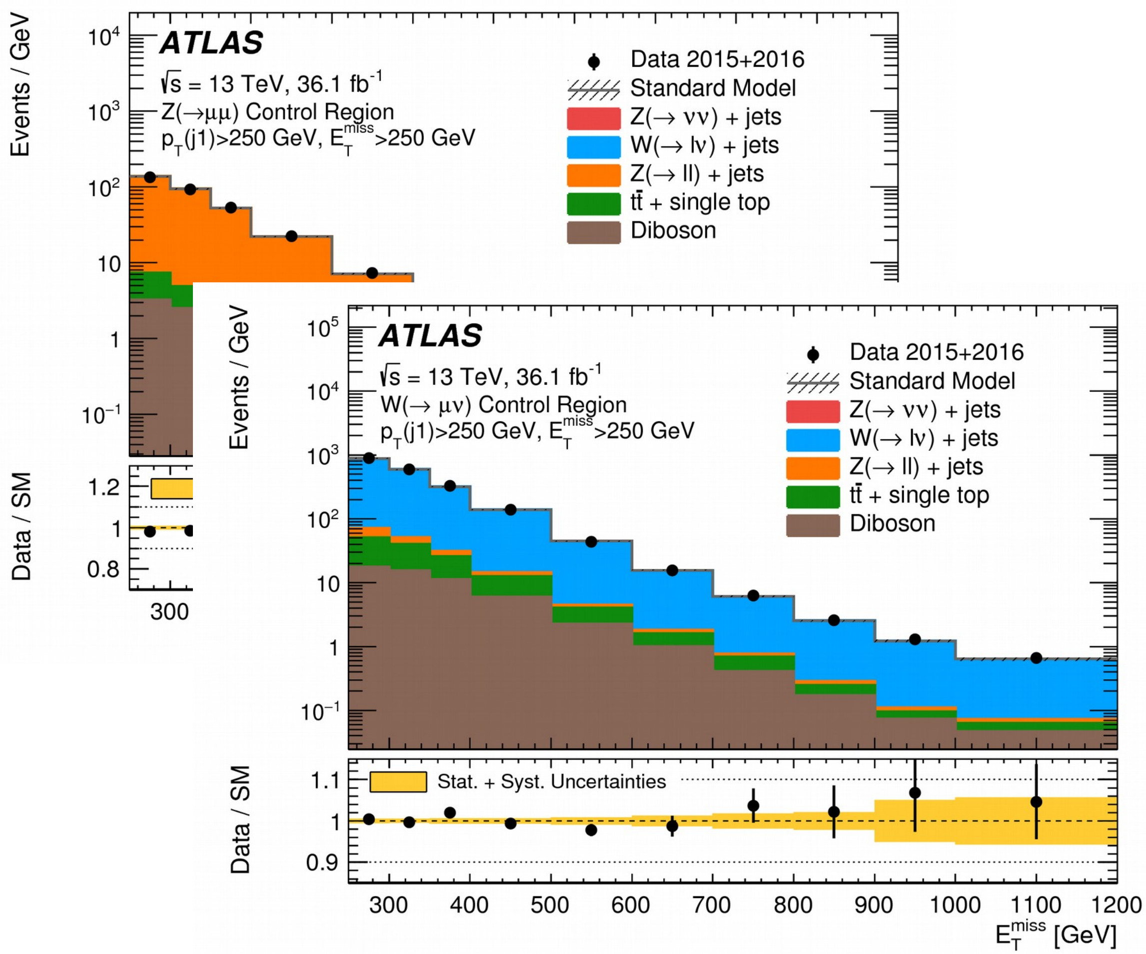


- **Triggers on missing energy**
  - Jet trigger (other choice): ~500 GeV
- **Data-driven background estimation**
  - Simutenous fit of Control Regions
  - Binned in ME_T



Modelling Z→νν Background

- **Z→μμ is the same as Z→νν, if you remove the muons!**
  - Same with W→lν, and has very high statistics.



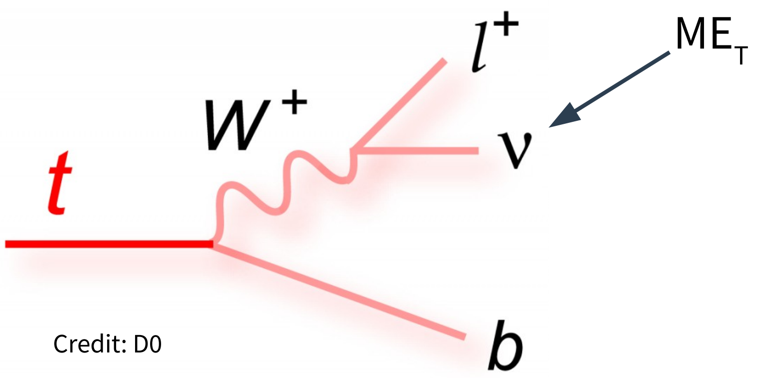
Taken from Monte Carlo:

- Ratio between Z→νν vs Z→μμ vs W→lν
- General shape of ME_T distribution

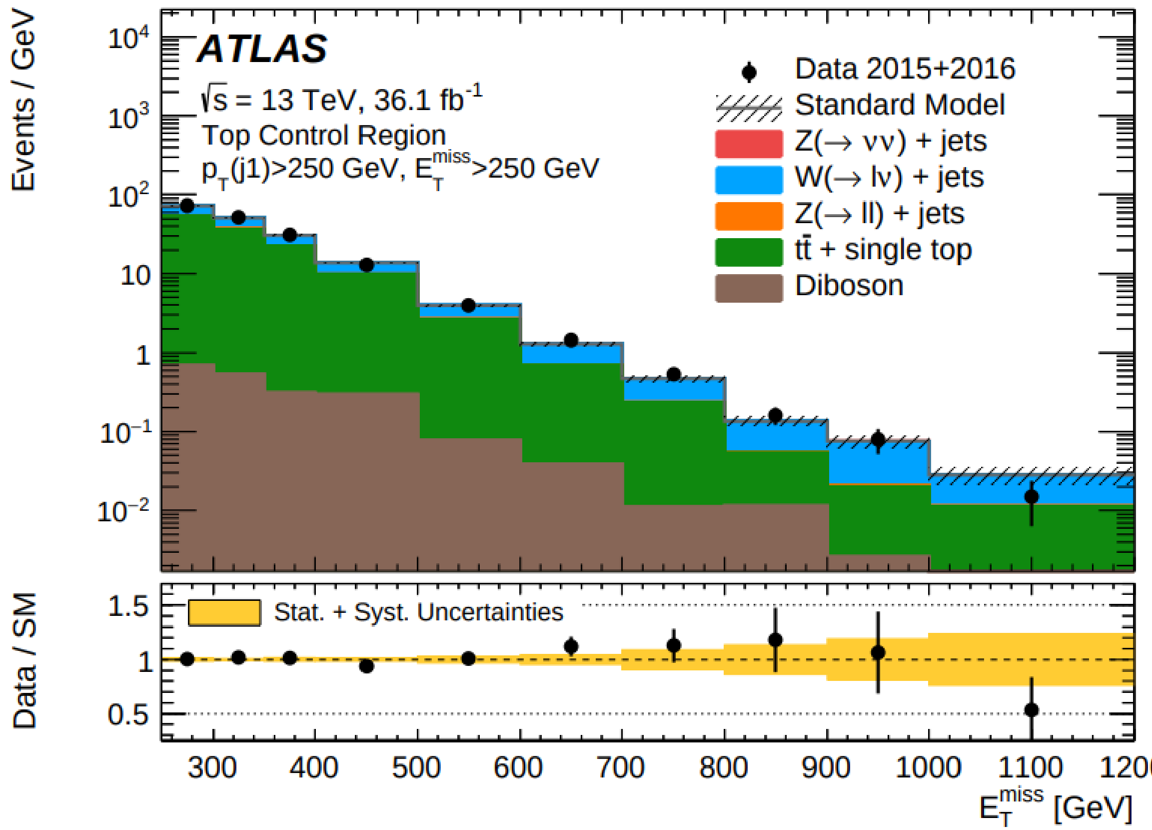
Taken from Data:

- Overall normalization of Z/W processes
- Contraint of systematics governing ME_T shape via bin-by-bin nuisance parameters

Top Background



Credit: D0

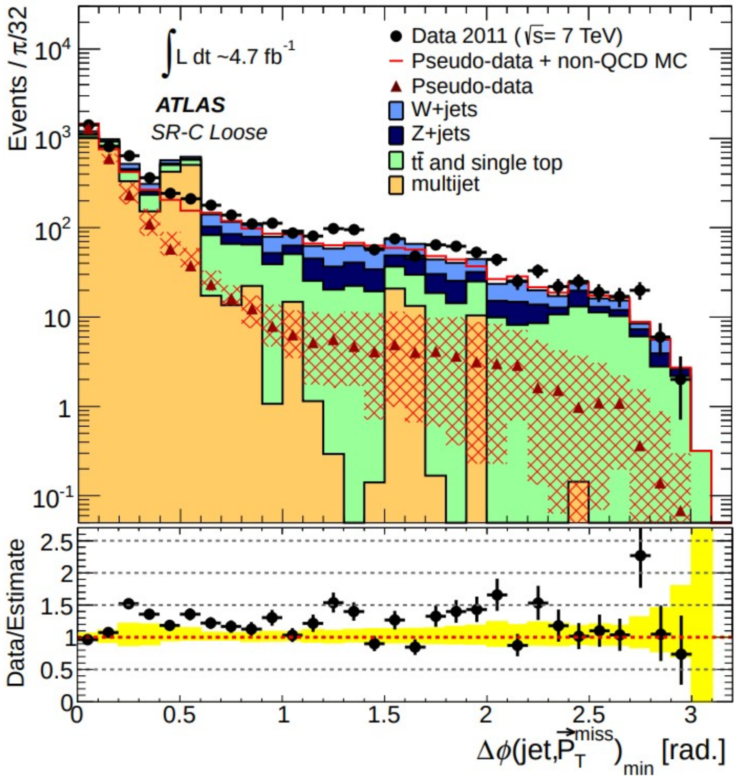


- **Control Region for all processes with a top quark**
  - Presence of a single muon
  - Require W-like transverse mass $m_T = \sqrt{2p_T^{\ell}p_T^{\nu}[1-\cos(\phi^{\ell}-\phi^{\nu})]}$
  - Presence of b-quark
- **Included in the simultaneous fit**

Multi-Jet Background

- **Comes from calorimeter effects**
  - "Truth" distribution of high ME_T and low ME_T jets is the same
- **Estimated using the Jet Smearing Method**

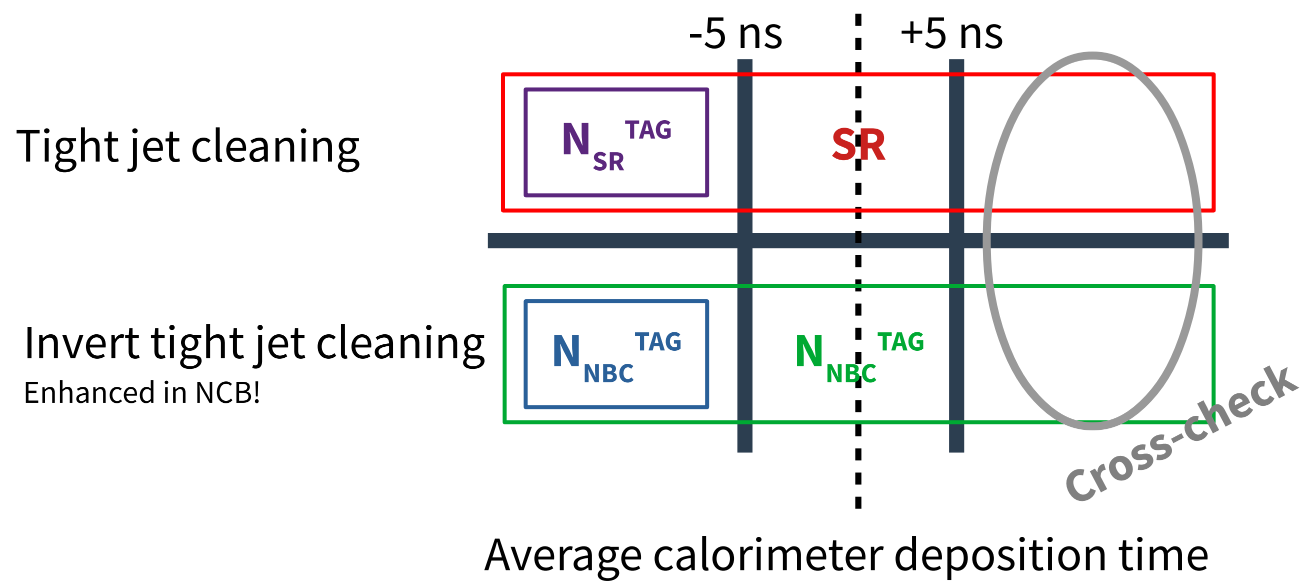
1) Take "*well-measured*" low-ME_T jets
2) Smear with jet response function
   - Initial estimate from MC (truth vs detector simulated jets)
   - Modify using functions by testing on data
     - dijet for the Gaussian core
     - trijet for the non-Gaussian tails
3) Invert $\Delta\phi_{j,MET}$ cut for normalization

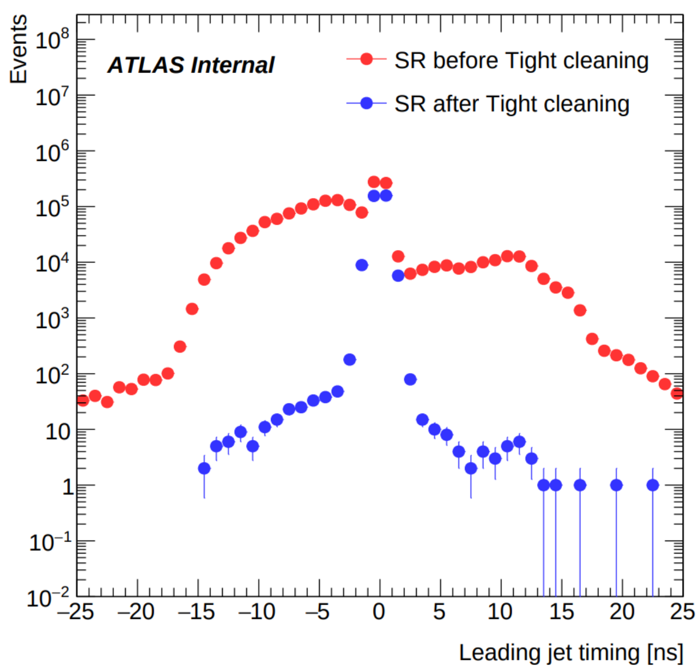


Non-Collision Backgrounds

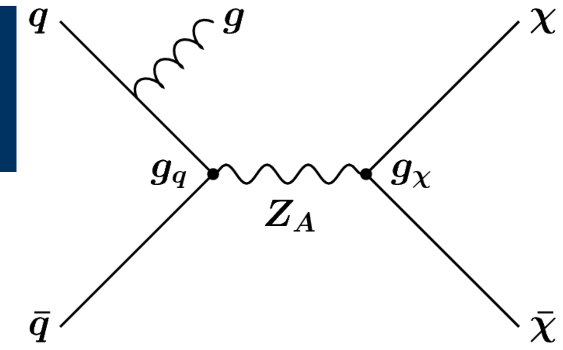
- **Greatly reduced by very tight "jet cleaning" cuts**
- **Estimated by inverting cleaning and selecting out-of-time jets**
  - Also known as the ABCD method

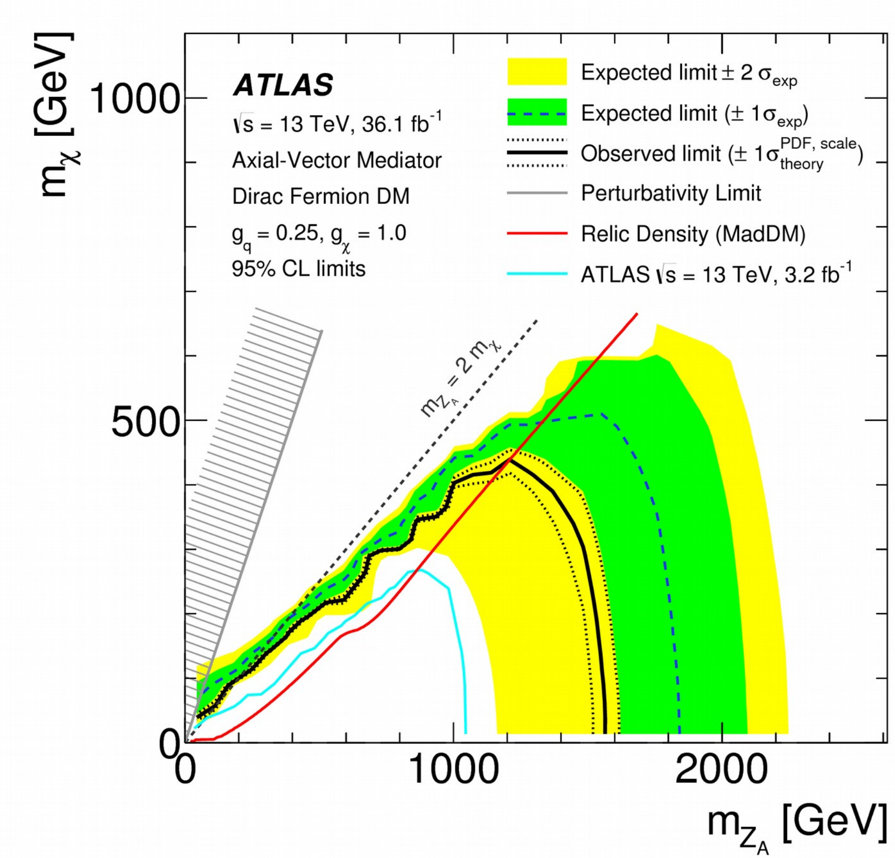
$$N_{SR}^{TAG} / N_{SR} = N_{NBC}^{TAG} / N_{NBC}^{TAG}$$

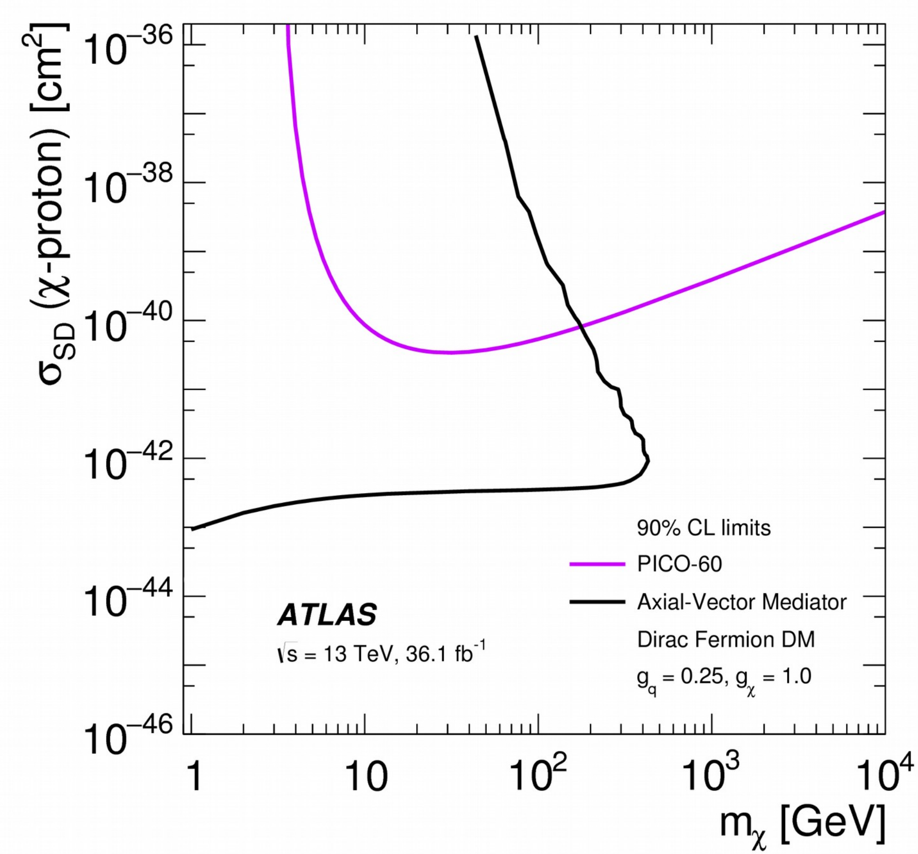




Mono-jet Limits







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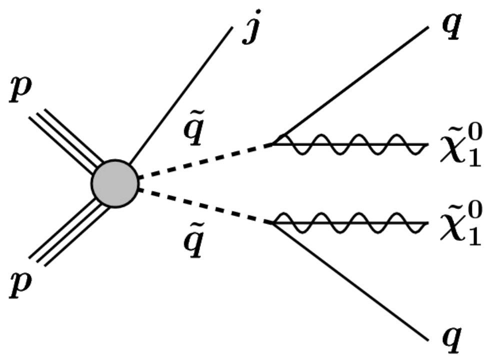
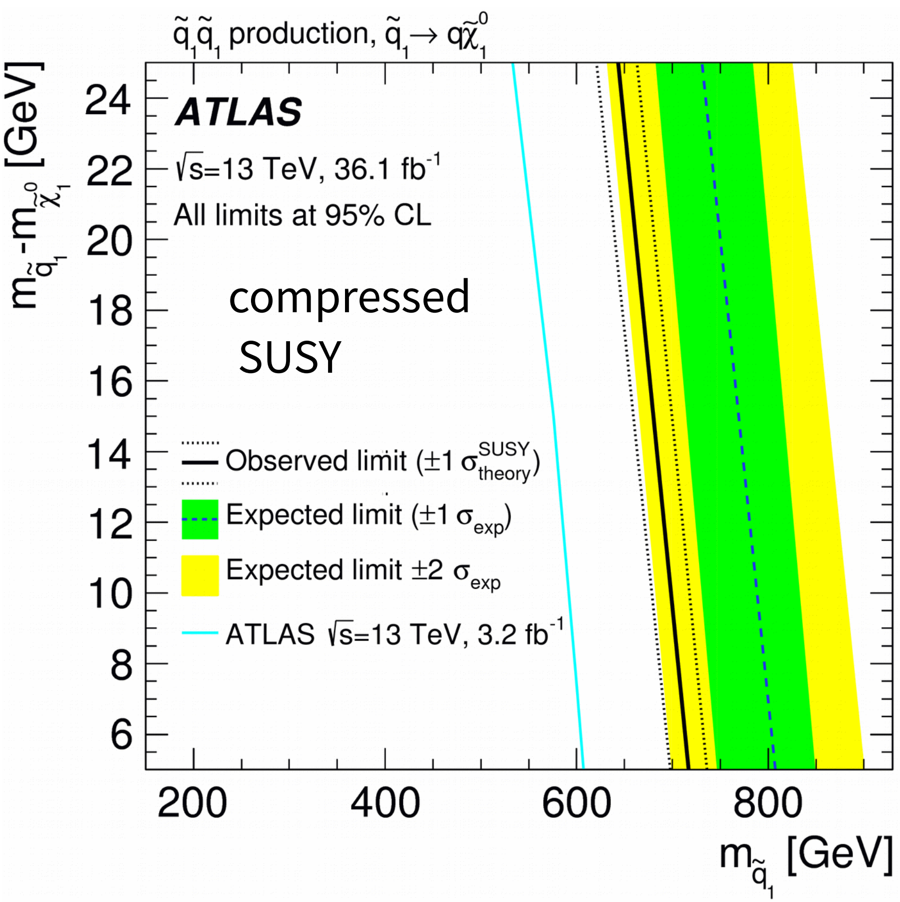
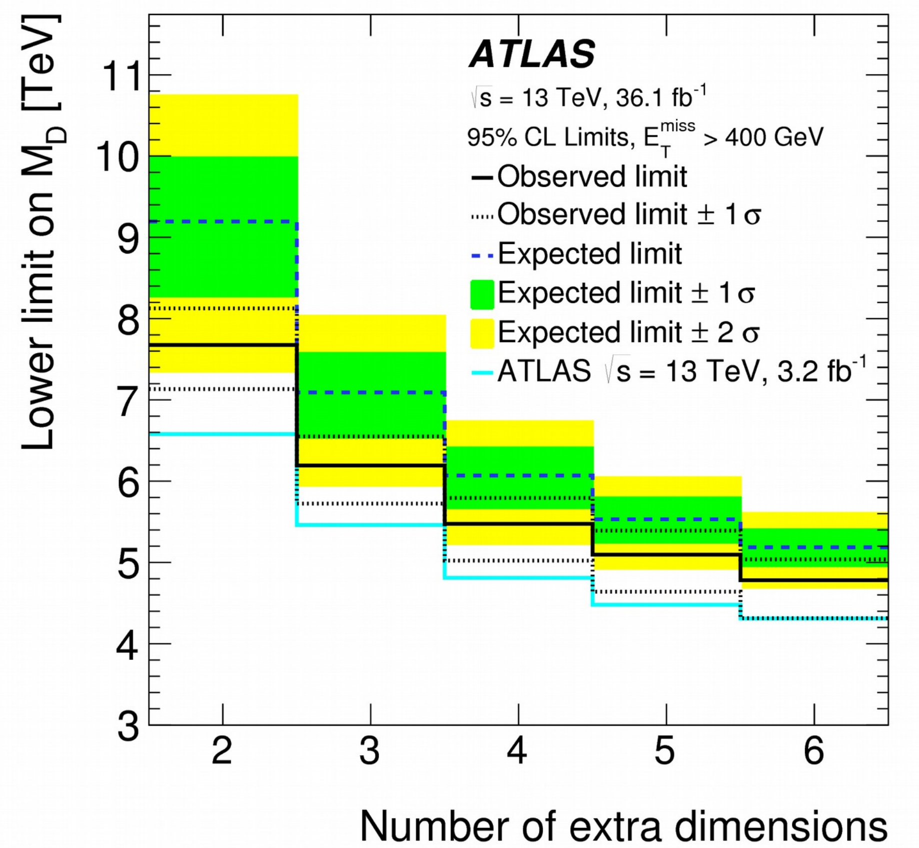
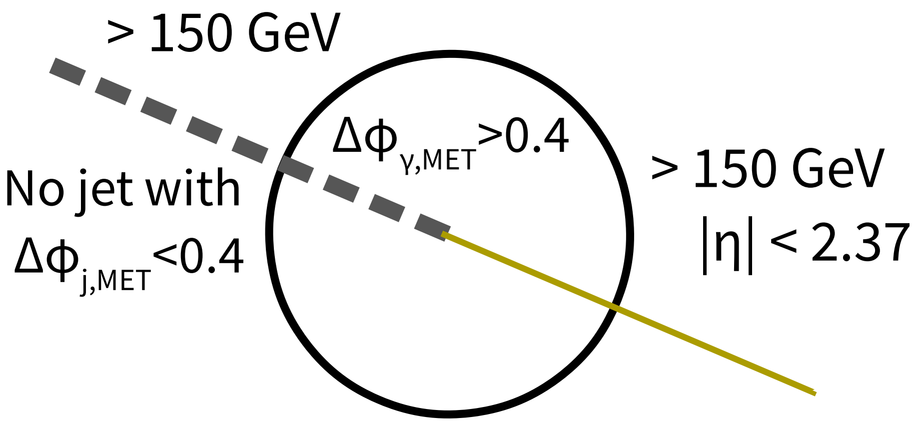


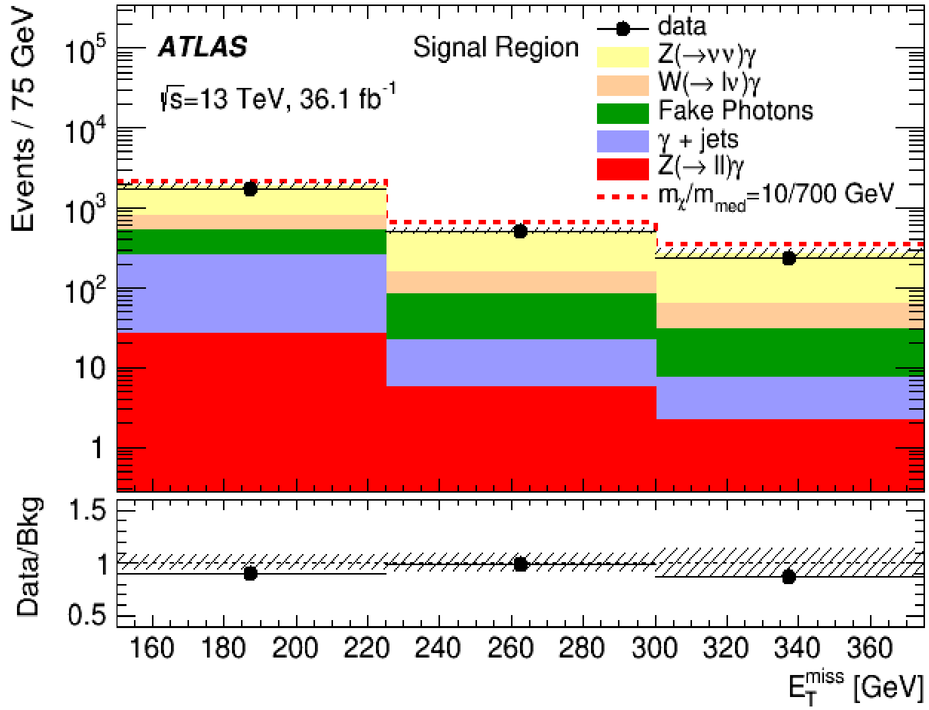




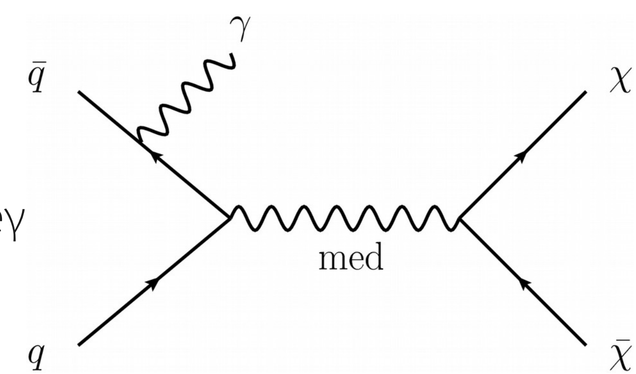
Mono-photon

EXOT-2016-32





- **Z/W background k-factors estimated via simultaneous fits to Z/W control regions**
  - Same as in mono-jet!
- **Data-driven estimation for fake photons**
  - Miss-ID'ed electrons estimated from Z→ee sample misidentified as Z→eγ
  - Miss-ID'ed jets estimated using ABCD method



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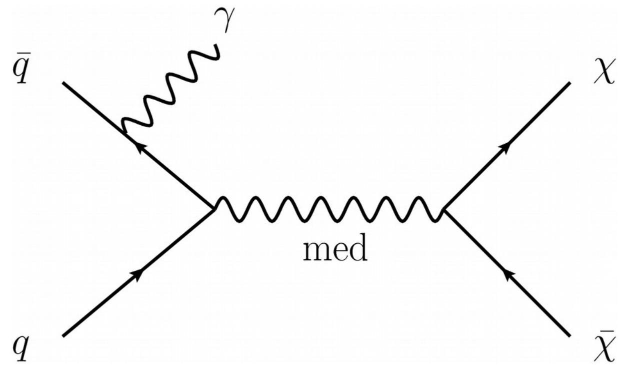
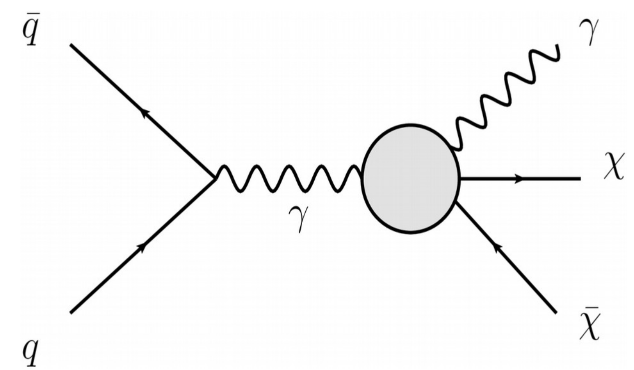
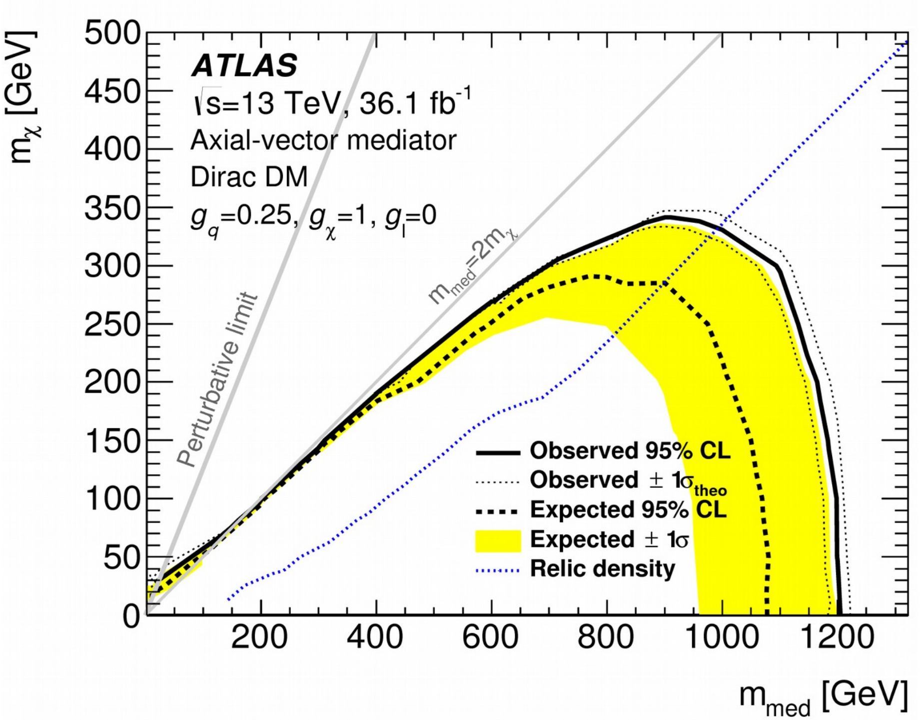
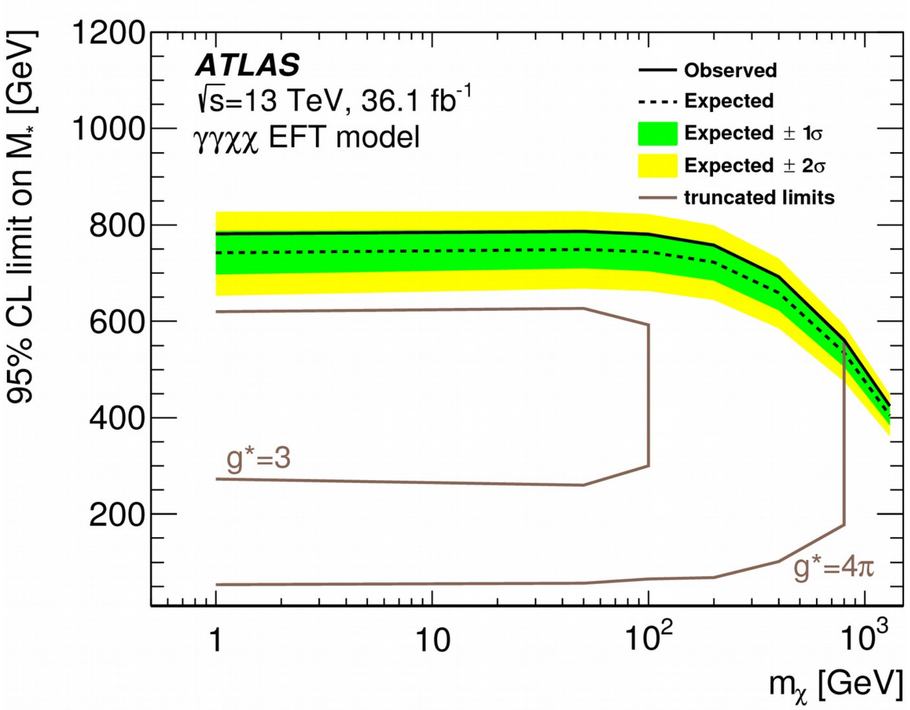




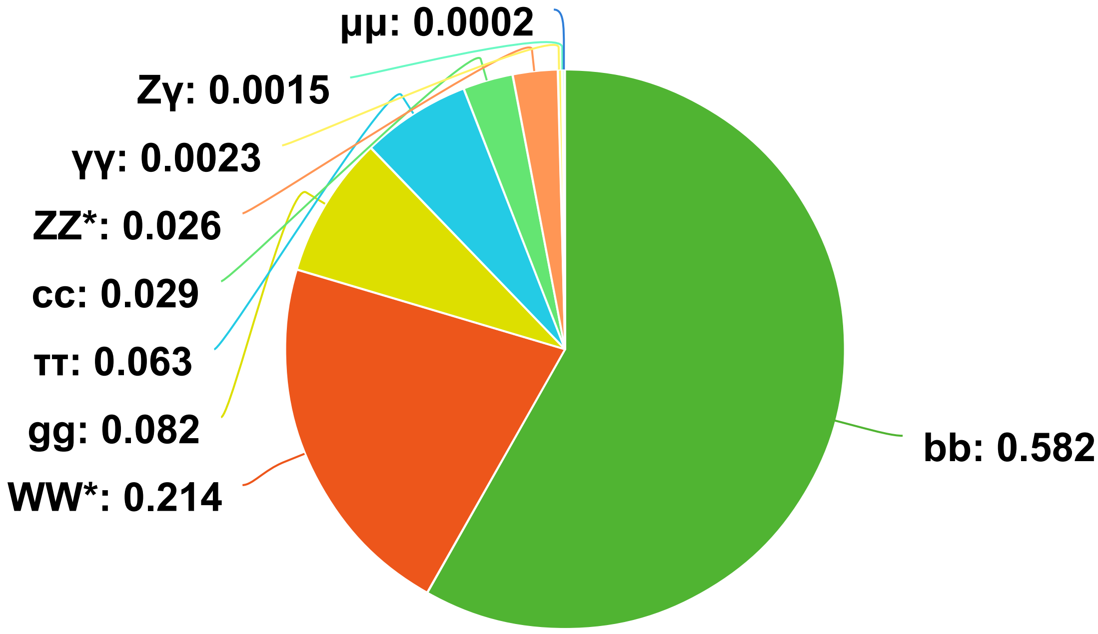




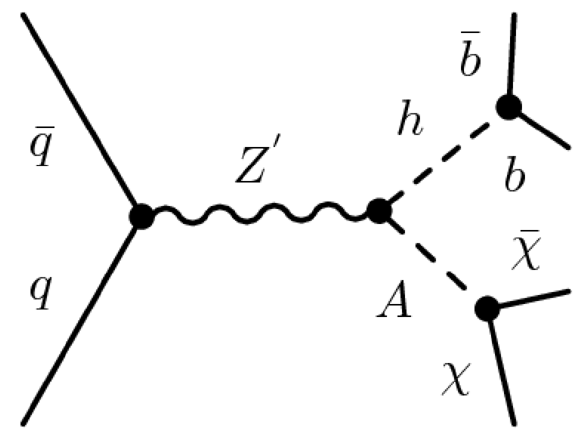
Mono-Higgs

Higgs is slowly turning from “new particle” into a tool.

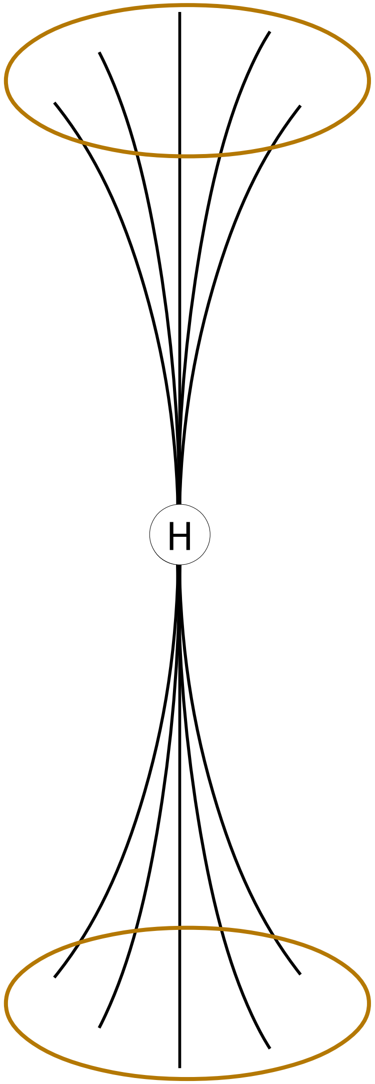
Higgs Branching Fractions



Z' Embedded inside Type II 2HDM

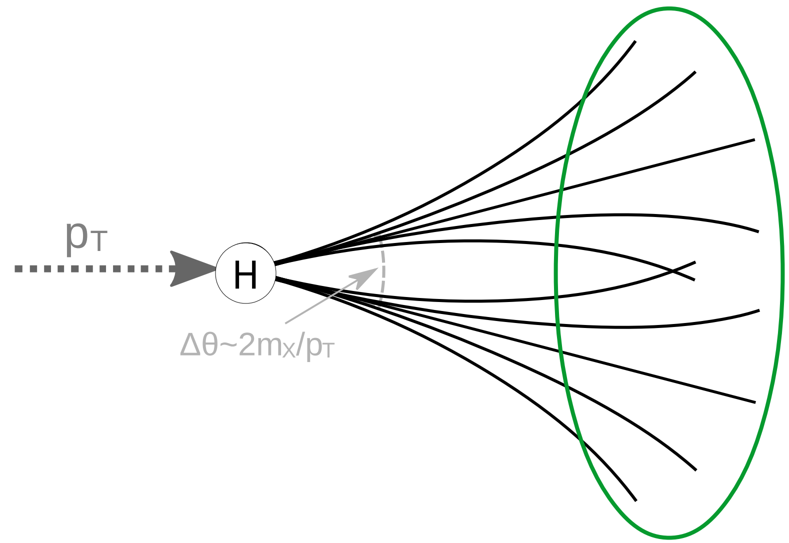


What are boosted objects?



A hadronically decaying particle *X* at rest can be reconstructed using two anti-K_T R=0.4 jets.

But if *H* is boosted, then anti-k_T R=0.4 will not be able to resolve two separate jets.

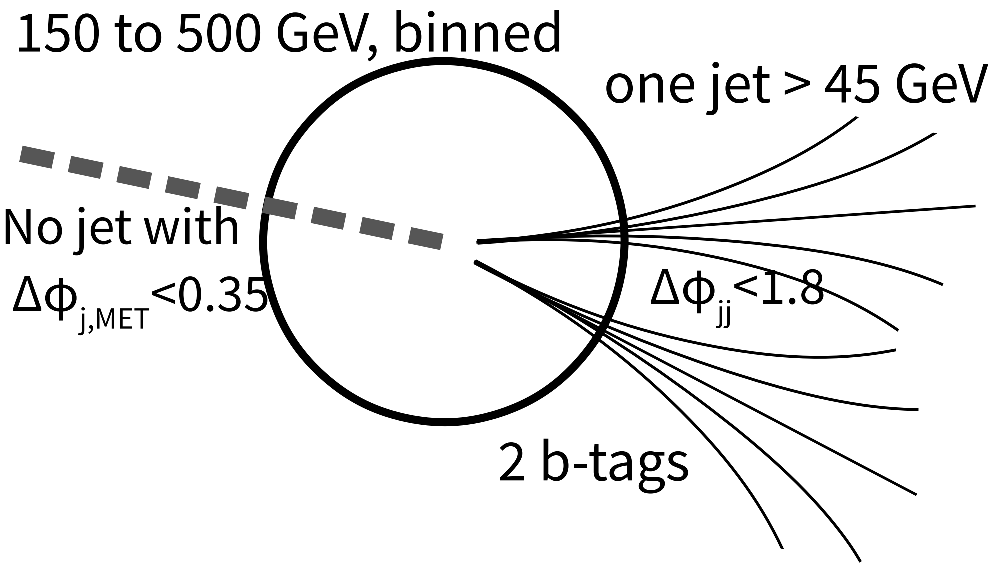


Solution: reconstruct a single **large-R** jet and look at the radiation pattern of the constituents (substructure).

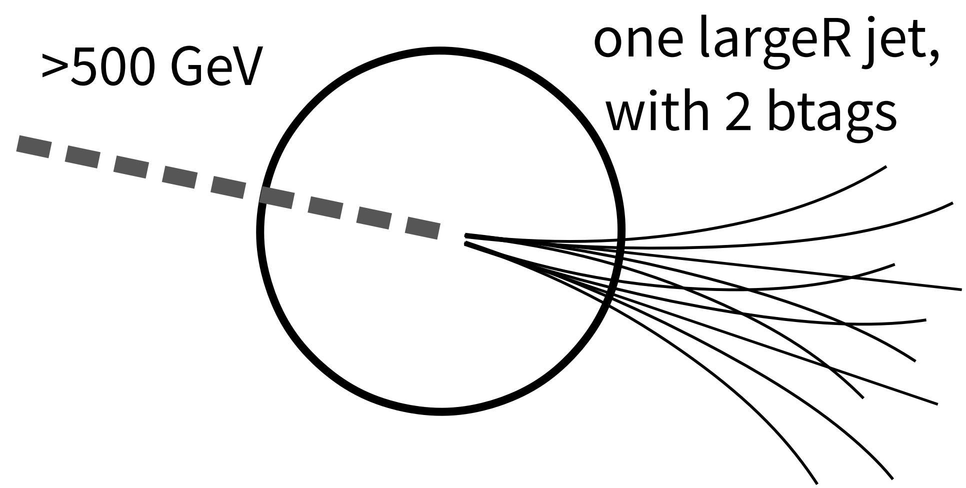
- Invariant mass of constituents?
- How many hard prongs?
- How many b-tagged track jets?

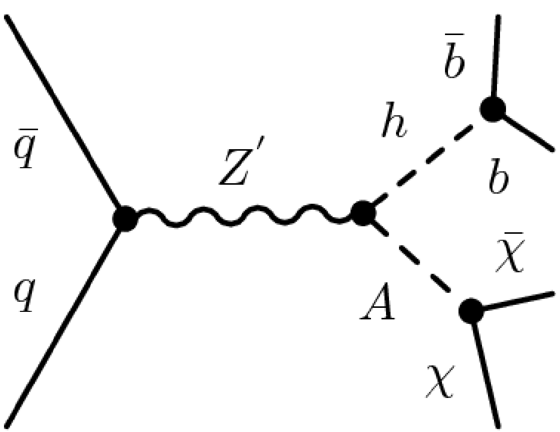
Mono+H(→bb) ATLAS-CONF-2018-039

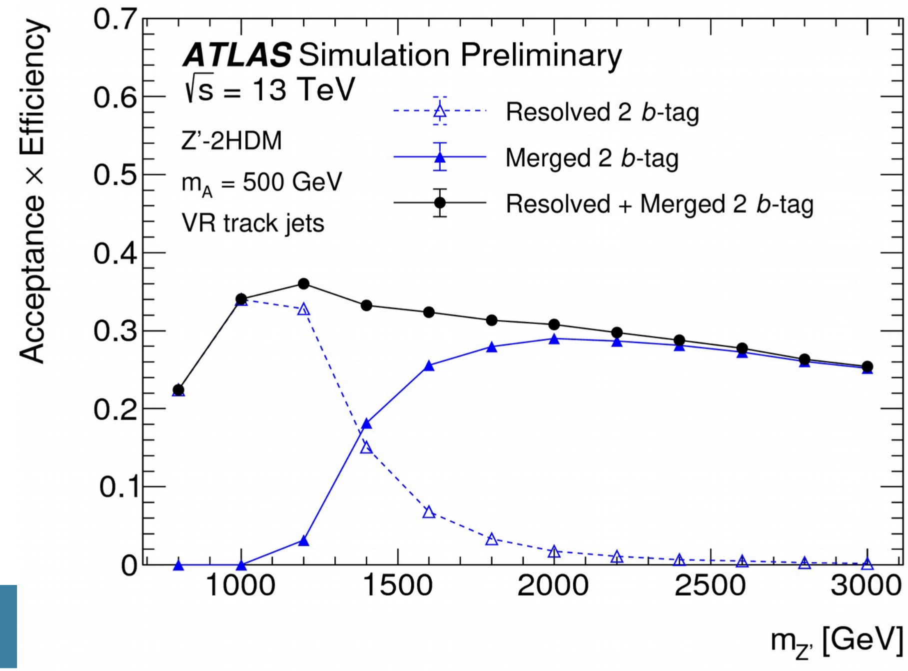
Resolved



Merged

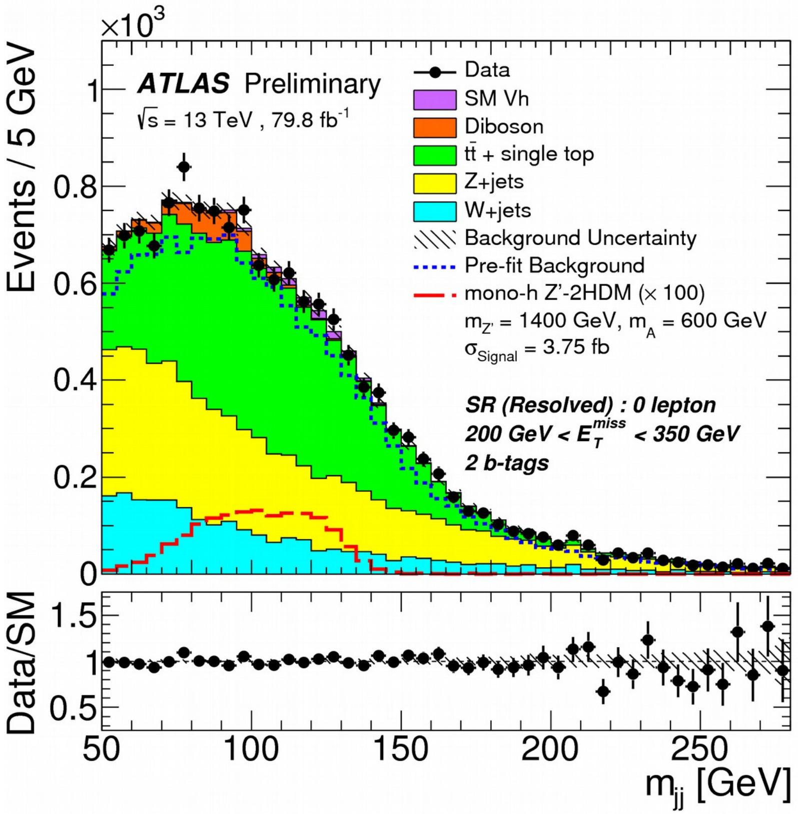


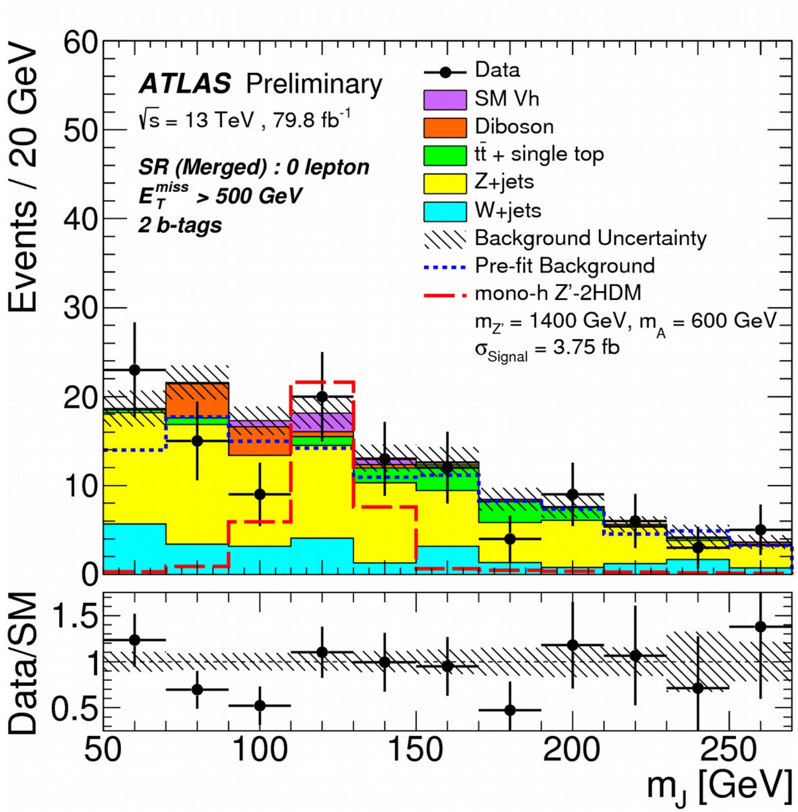




Background Estimation

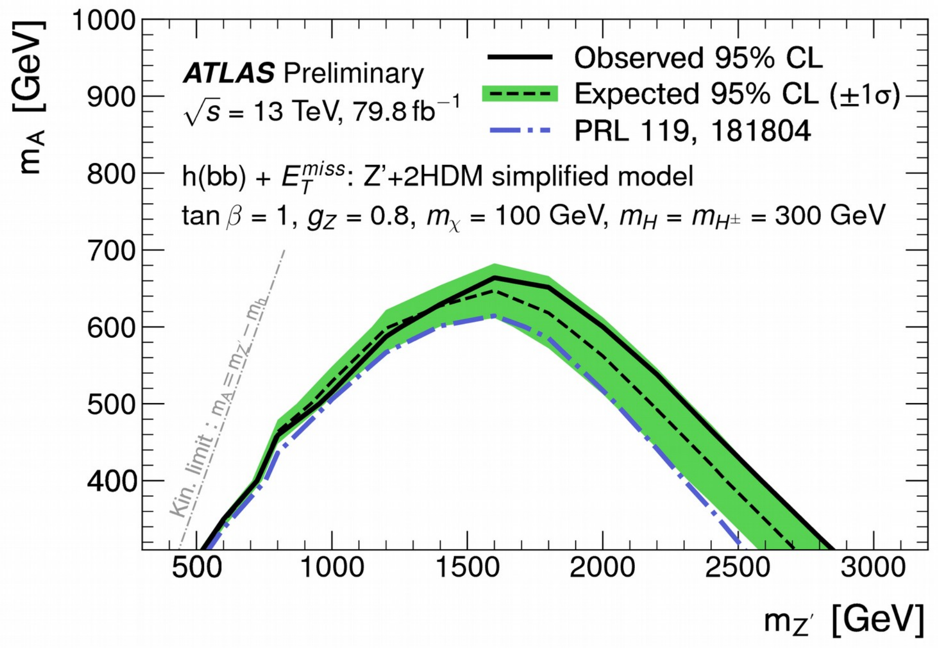
- Top and Z/W+jet estimated using usual lepton Control Regions
- Multijet background estimated by inverting $\Delta\phi_{j,MET}$<0.35 cut
- Final fit is in the invariant jet mass (signal = bump at 125 GeV)

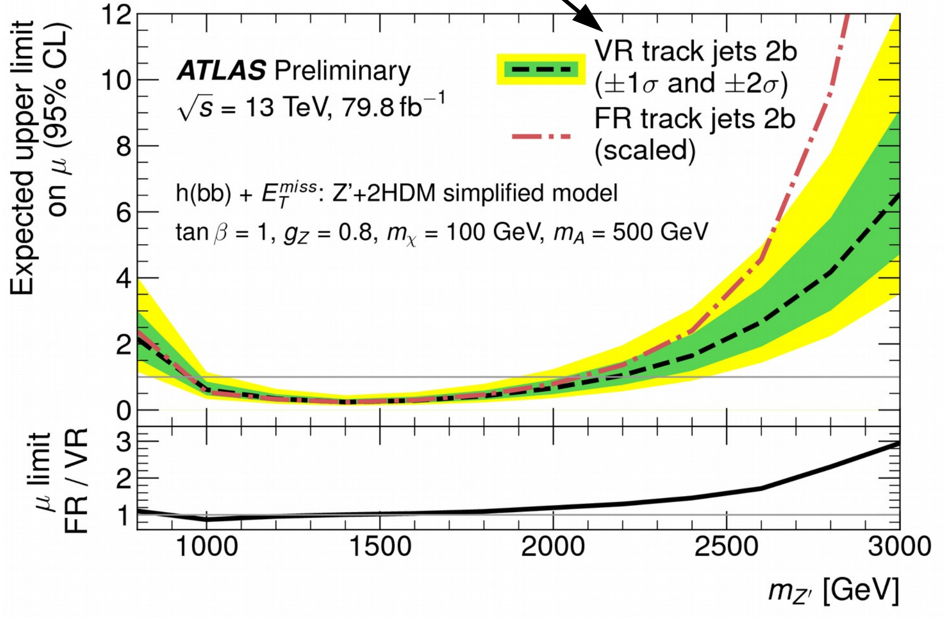




Mono+H(→bb) Limits

Variable **R**adius jets are a **new** substructure tool that modifies jet radius as a function of p_T

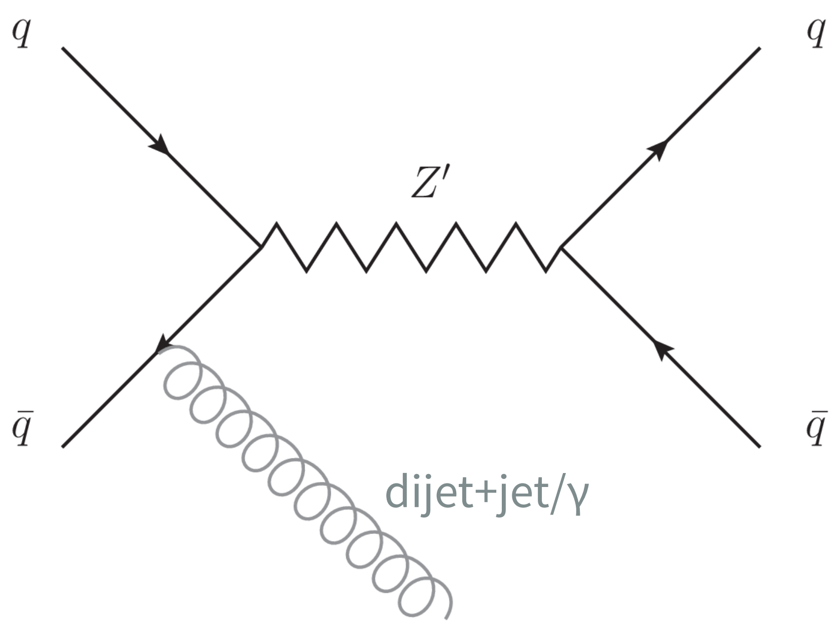




Dijet Resonance Search

Search directly for Z’ via decay into quarks!

Constrains DM model, but does not confirm it.



Three strategies:

- **High mass dijet, m_{jj}>1 TeV**
  - Limited by 500 GeV single jet trigger
- **Trigger Level dijet, m_{jj}>500 GeV**
  - Limited by 200 GeV Level-1 single jet trigger
- **Dijet+ISR, m_{jj}>100 GeV**
  - Lower cross-section due to high energy of ISR

Non-Resonant Background Model

- **Data-driven background model**
  - Model smoothly falling background with a smoothly falling function

$$c_0(1-x)^{c_1} x^{c_2 + c_3 \ln x + c_4 \ln x^2 + c_5 \ln x^3}, x = \frac{m_{jj}}{\sqrt{s}}$$

- **What functions to use?**
  - Fitting non-resonant background is an industry in itself!
  - Single function, sliding window, decomposition, Gaussian processes…
- **How many parameters are enough?**
  - 3 parameter, 4 parameter, 5 parameter, 6 parameter
  - Choice depends on luminosity

Search Phase – Bump Hunter

Algorithm for finding a generic excess

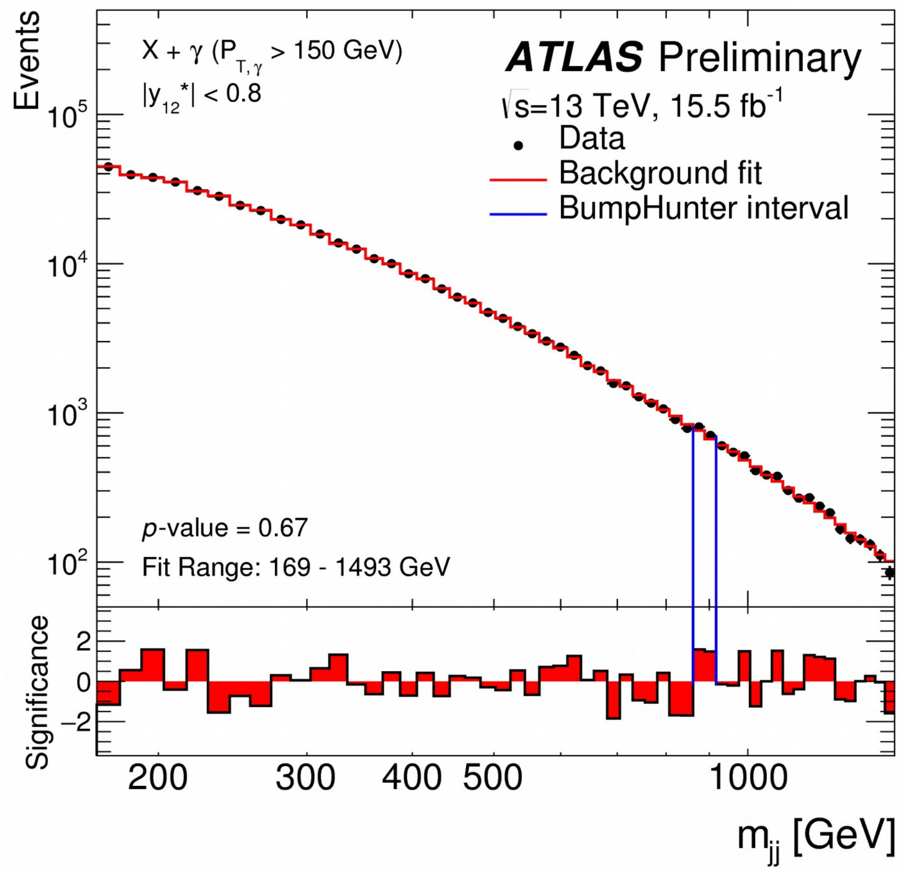
1) Fit m_{jj} spectrum

2) Locate range with largest discrepancy (using Poisson statistics)

- Size ranging from two histogram bins to half of range
- Refit m_{jj} blinded spectrum if local probability of discrepant region is low

3) Throw toys using background model to estimate distribution of discrepant regions

- Used to gauge the global significance of the "signal"



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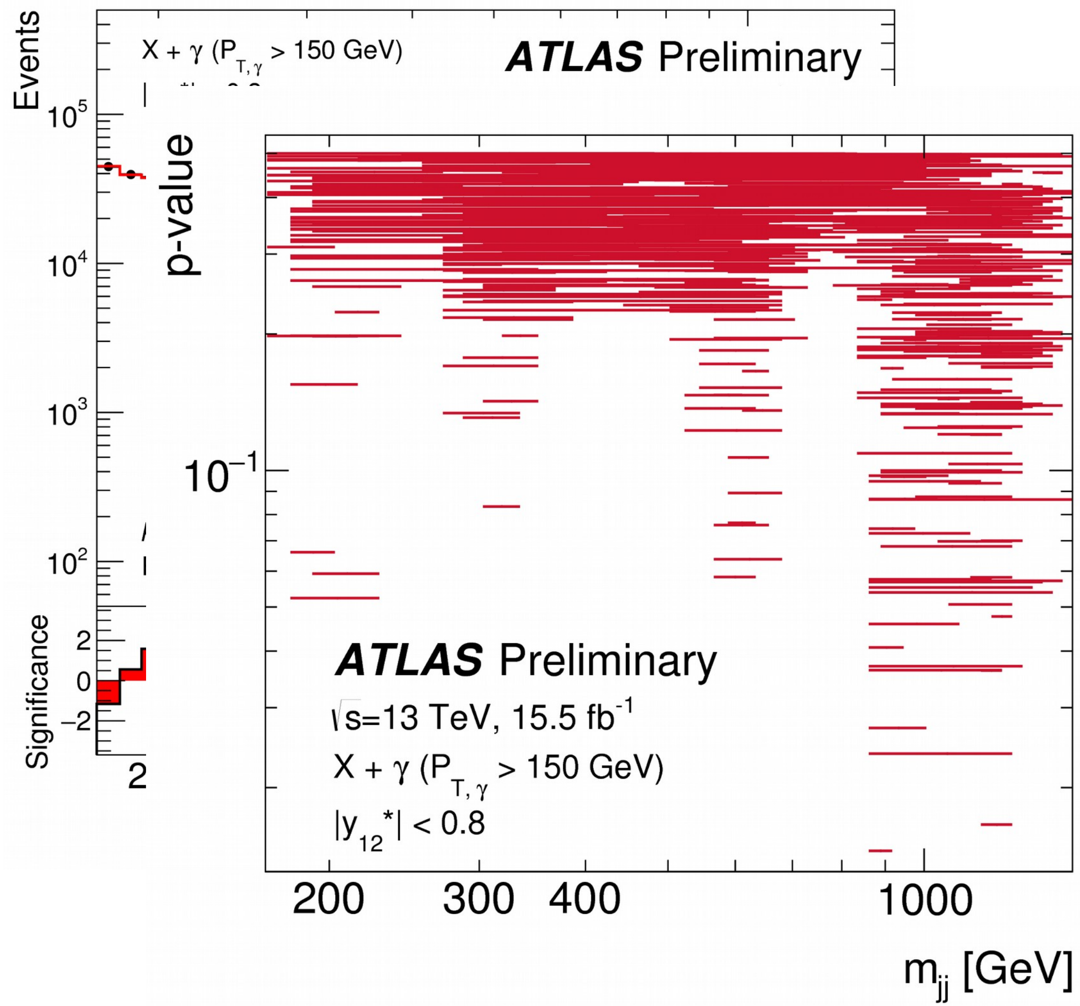

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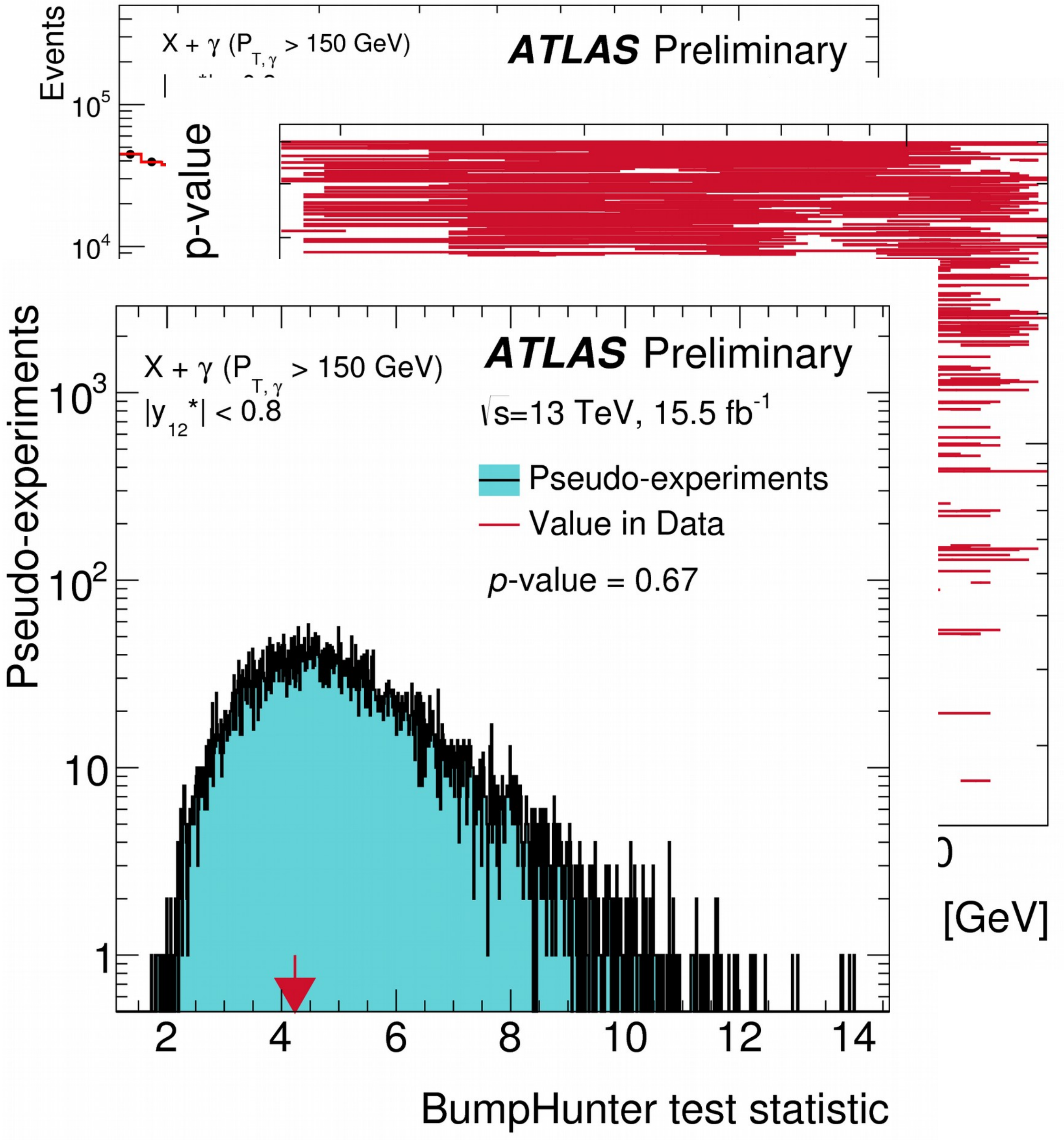

Search Phase – Bump Hunter

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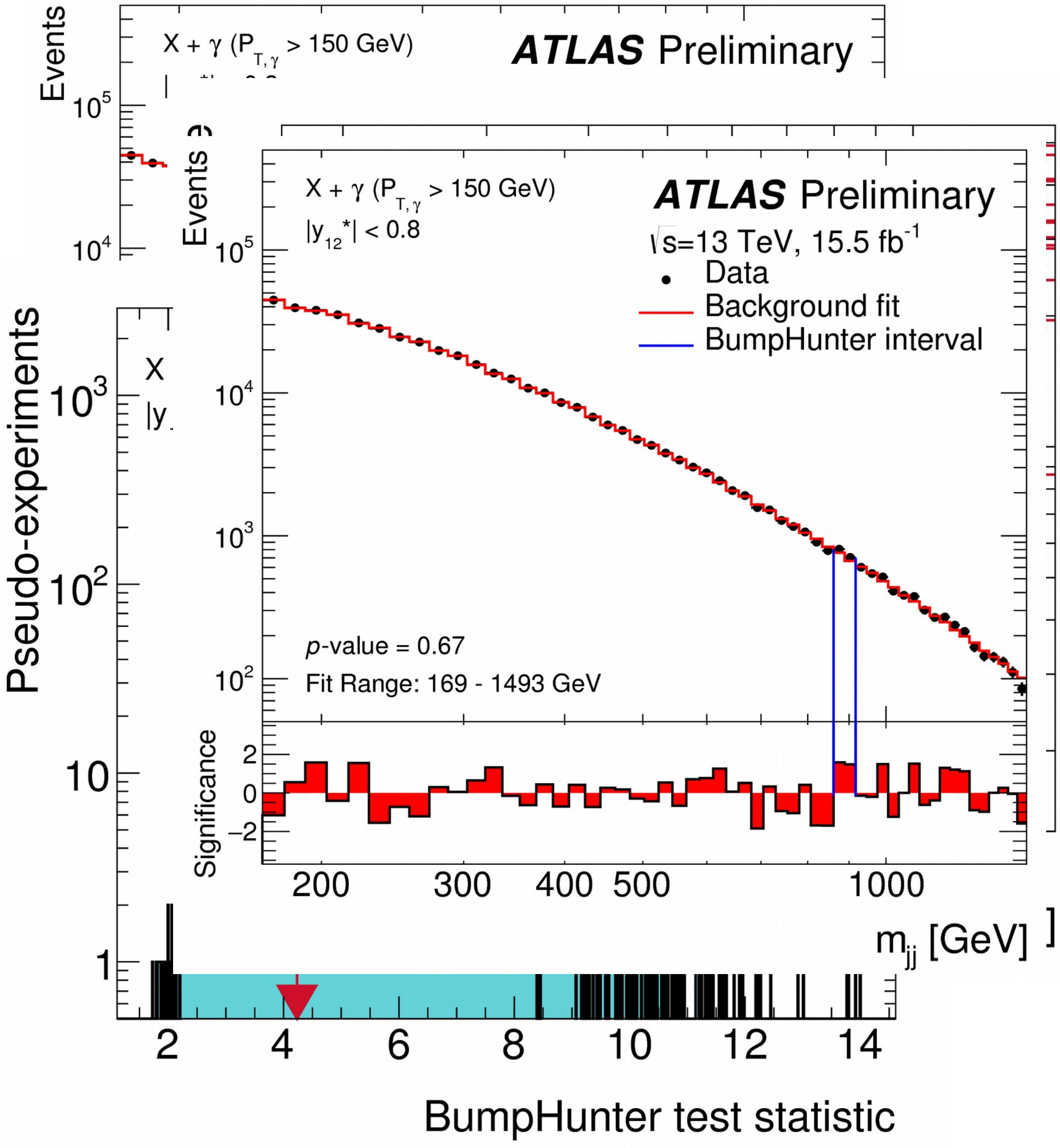
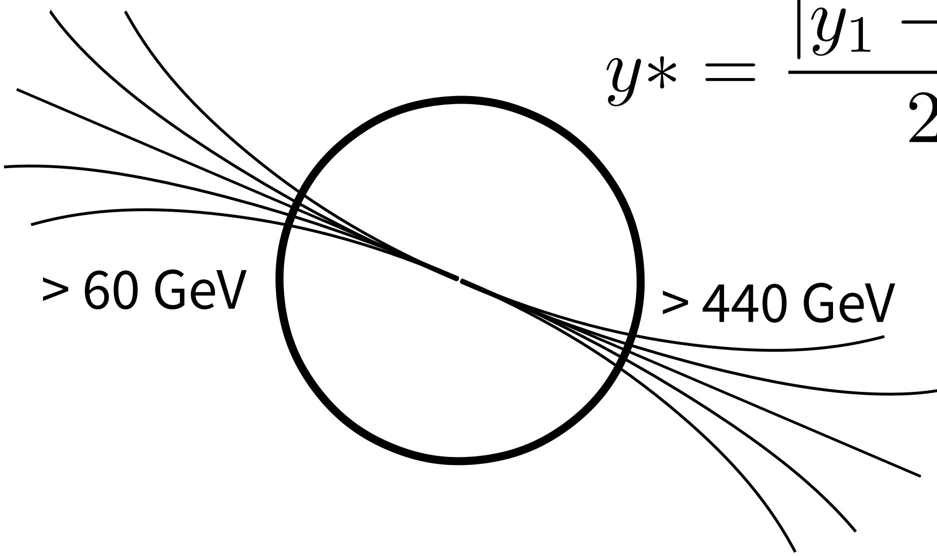
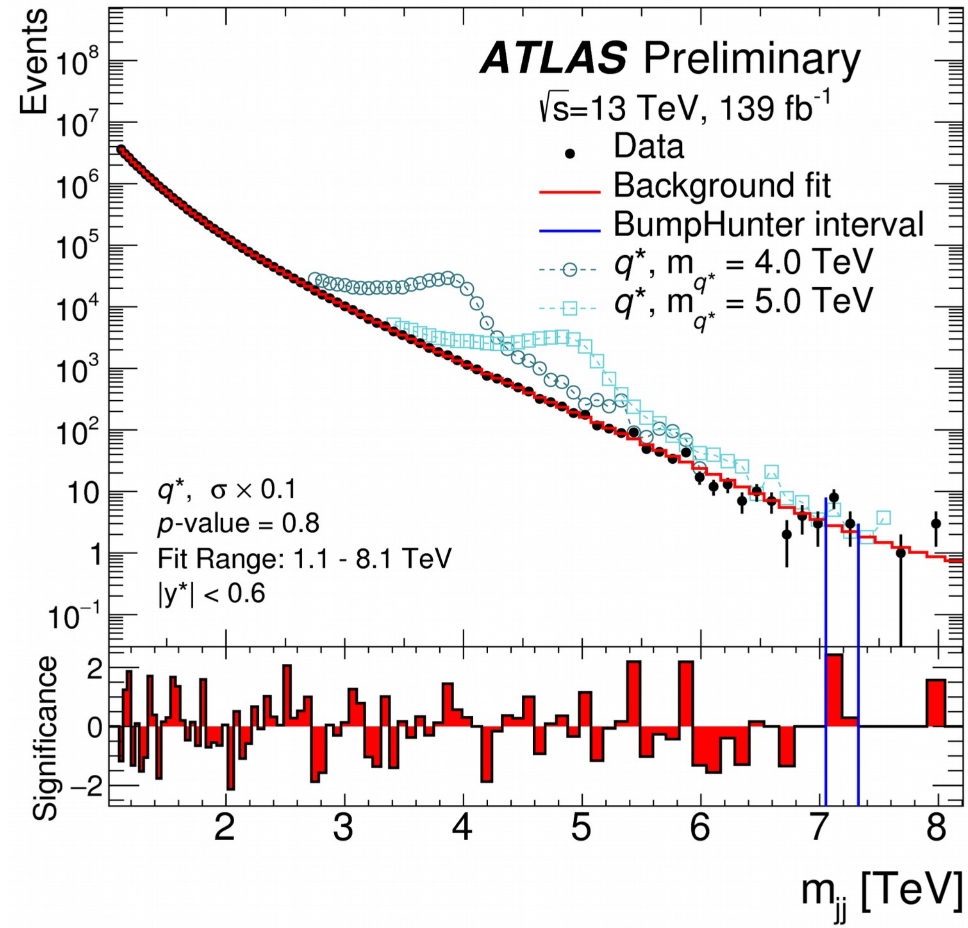


High Mass Dijets

ATLAS-CONF-2019-007



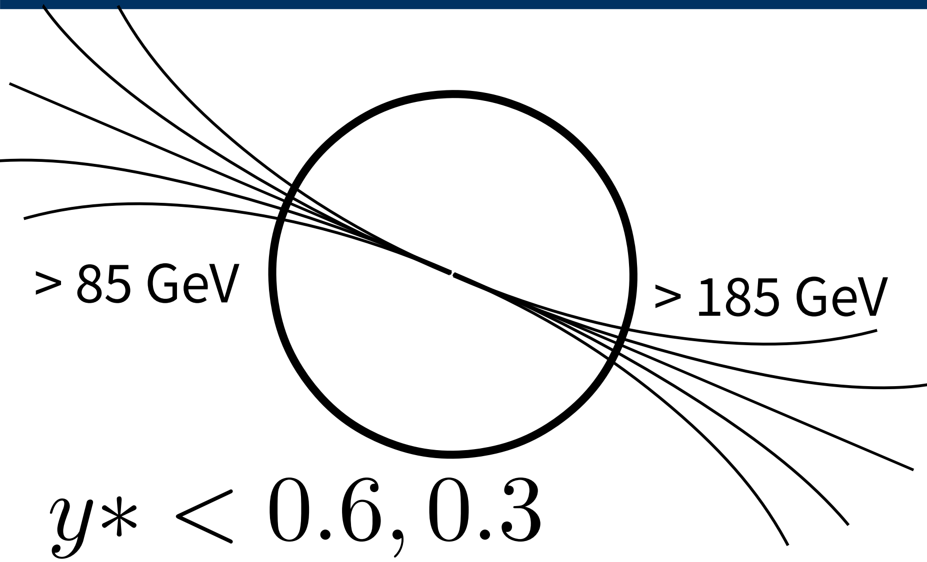
$$y* = \frac{|y_1 - y_2|}{2} < 0.6$$



- **Most energetic event has m_{jj}=8 TeV!**
- **Several benchmark models**
  - Z', W', q*, quantum black holes

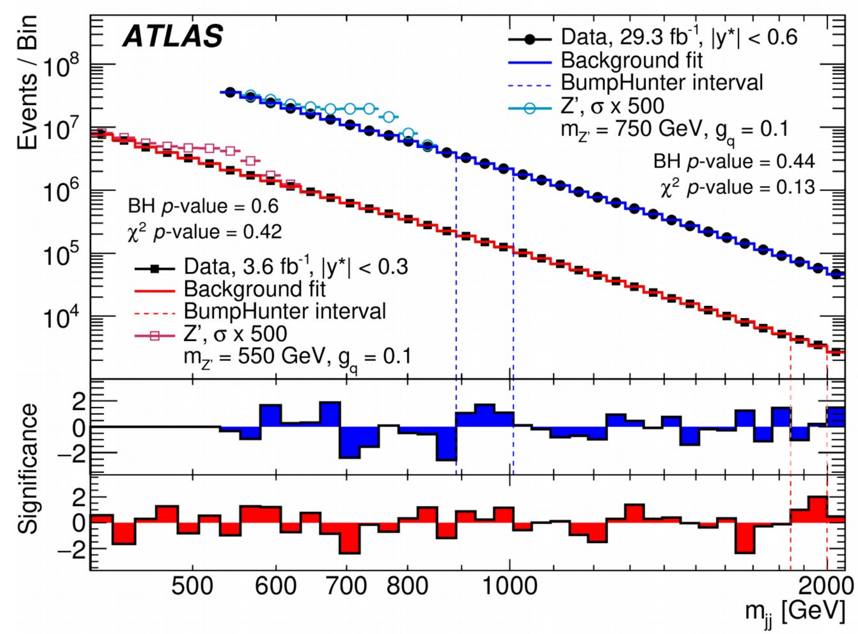
Trigger Level Dijet

EXOT-2016-20

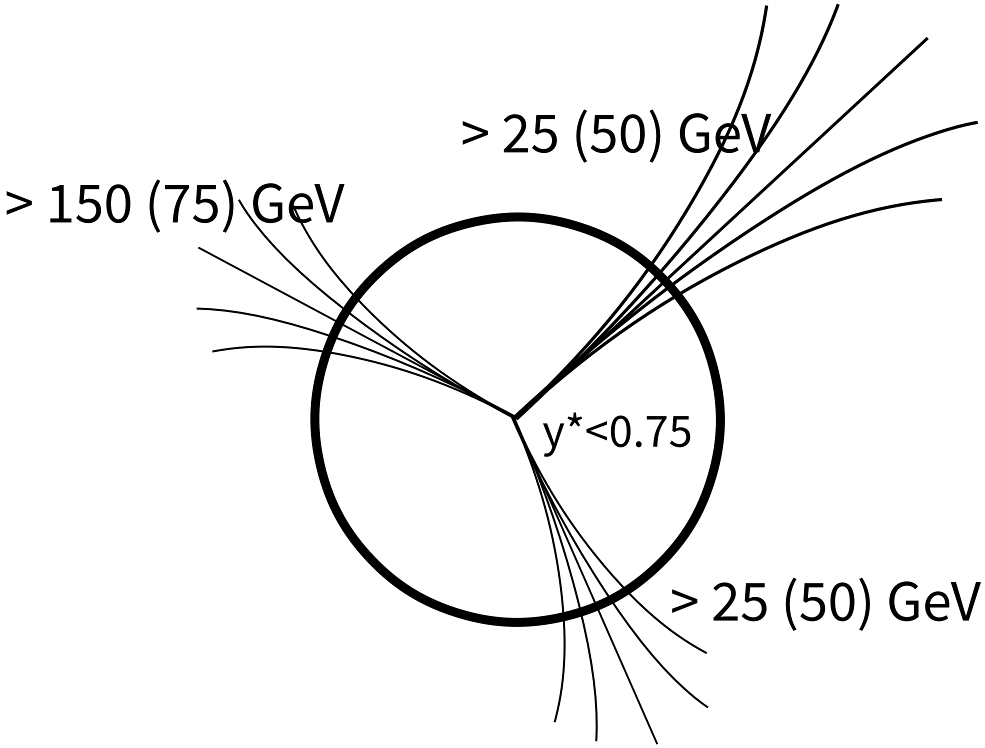


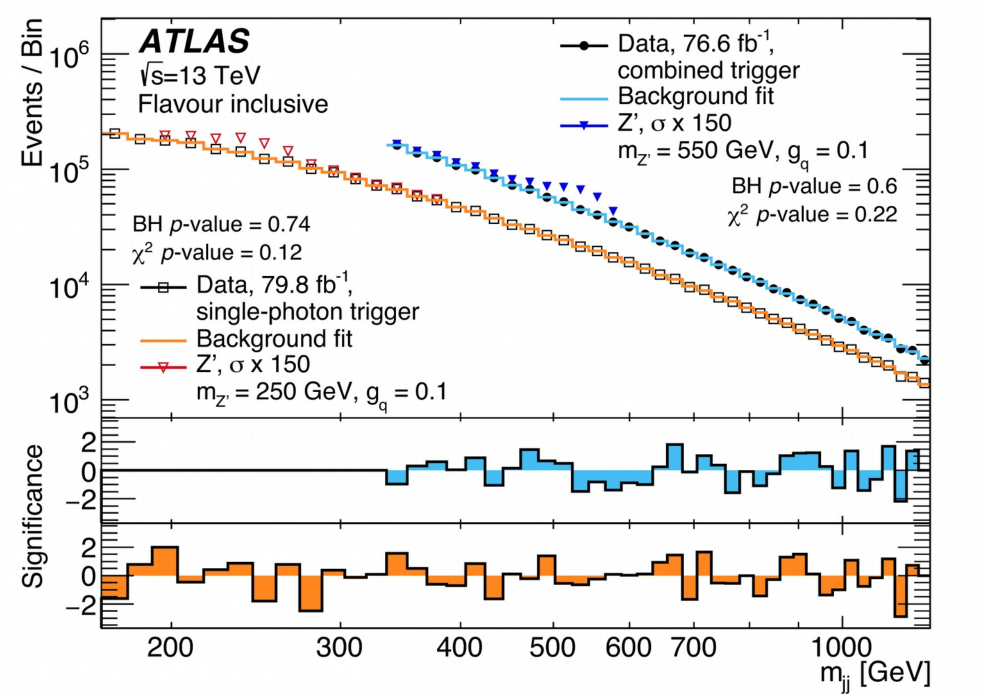
$$y* < 0.6, 0.3$$

- **2 kHz event rate, but only 100 MB/s**
  - Rest of ATLAS: 1 kHz event rate, 1 GB/s output
- **About million events in each bin!**
  - Quite a challenge to fit with a single function
- **Lower masses reach with tighter y* cut**



EXOT-2018-05

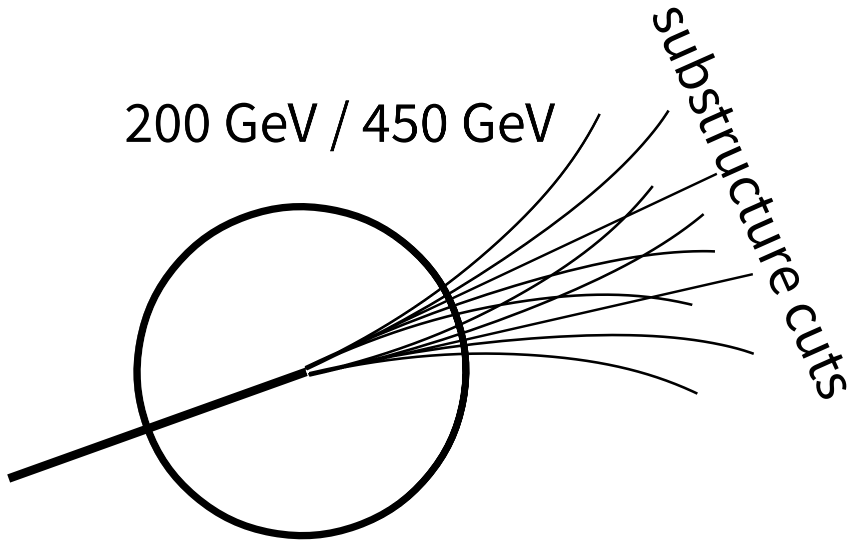


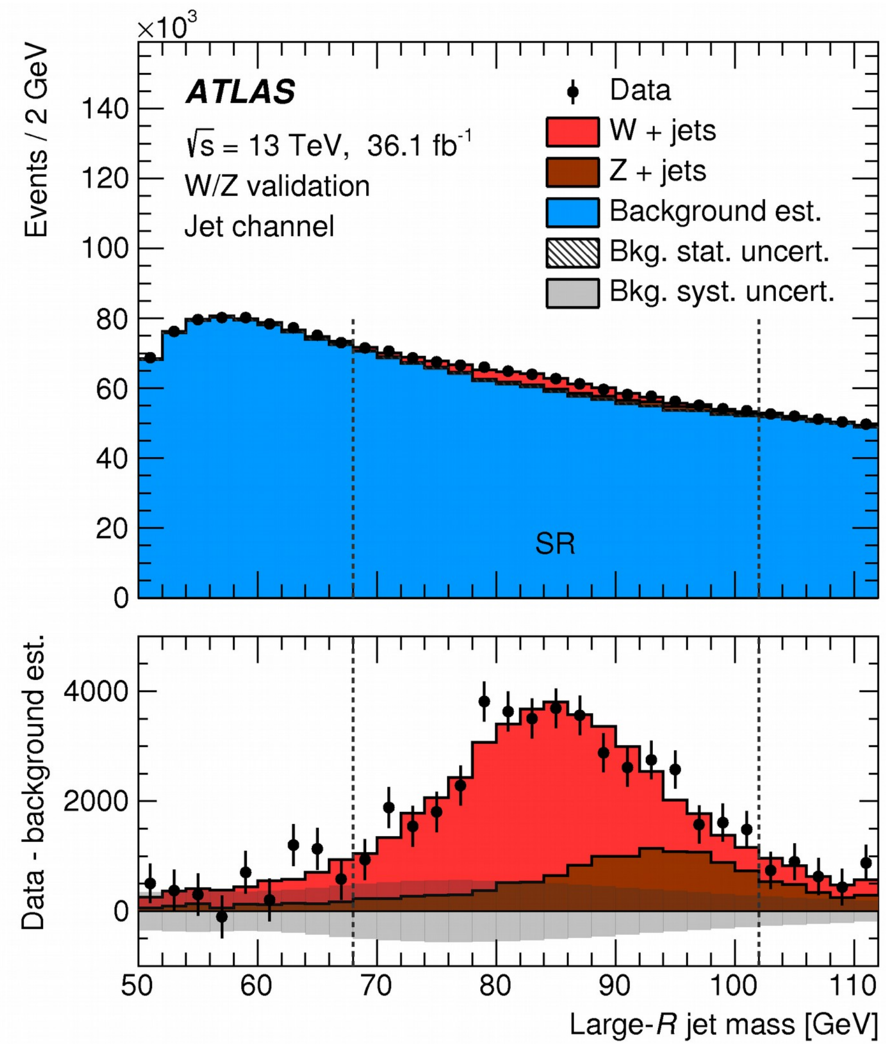


- **Two trigger strategies**
  - Single photon (150 GeV)
  - Photon (75 GeV) + 2 jets (50 GeV)

Boosted Dijet+ISR

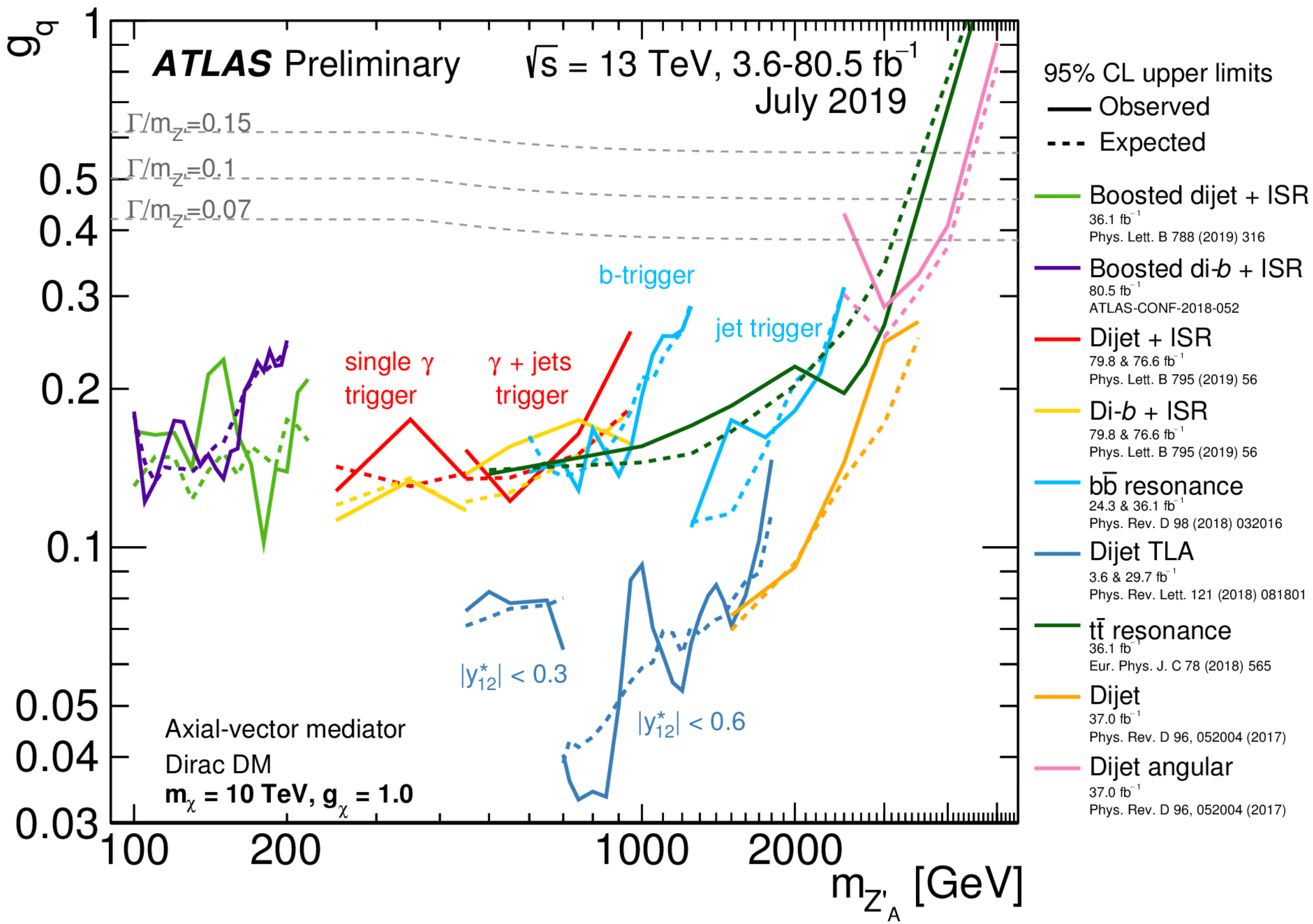
EXOT-2017-01



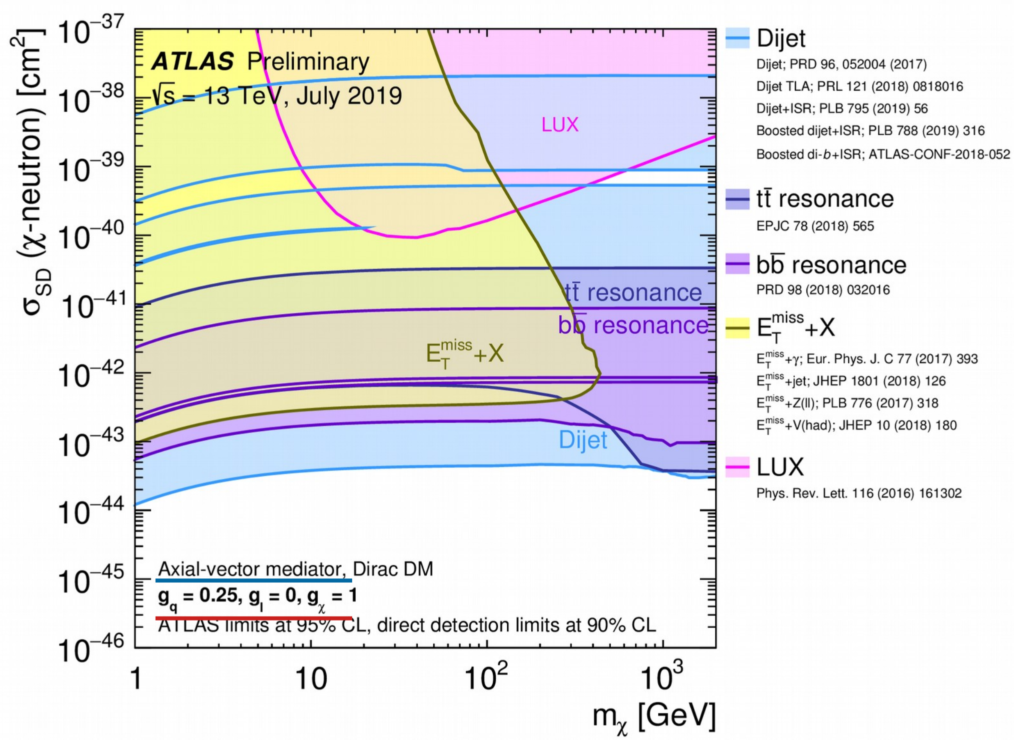


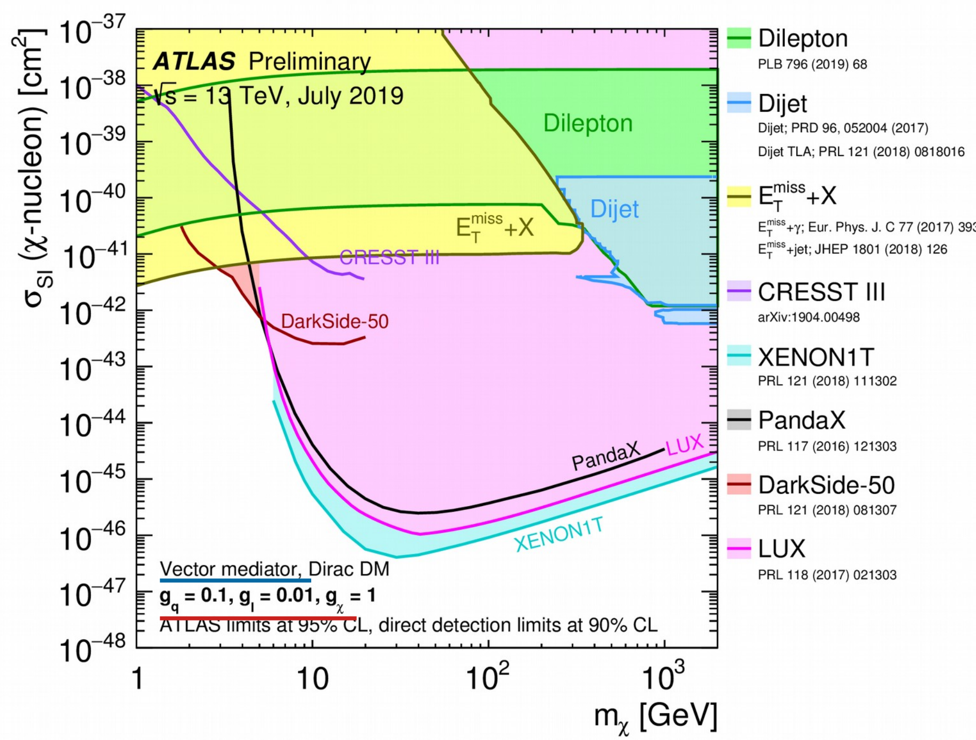
- **ISR could be photon or jet**
- **Tries to count number of subjets in signal jet (substructure)**
- **Background estimation by inverting substructure cuts**

Resonance Search Results



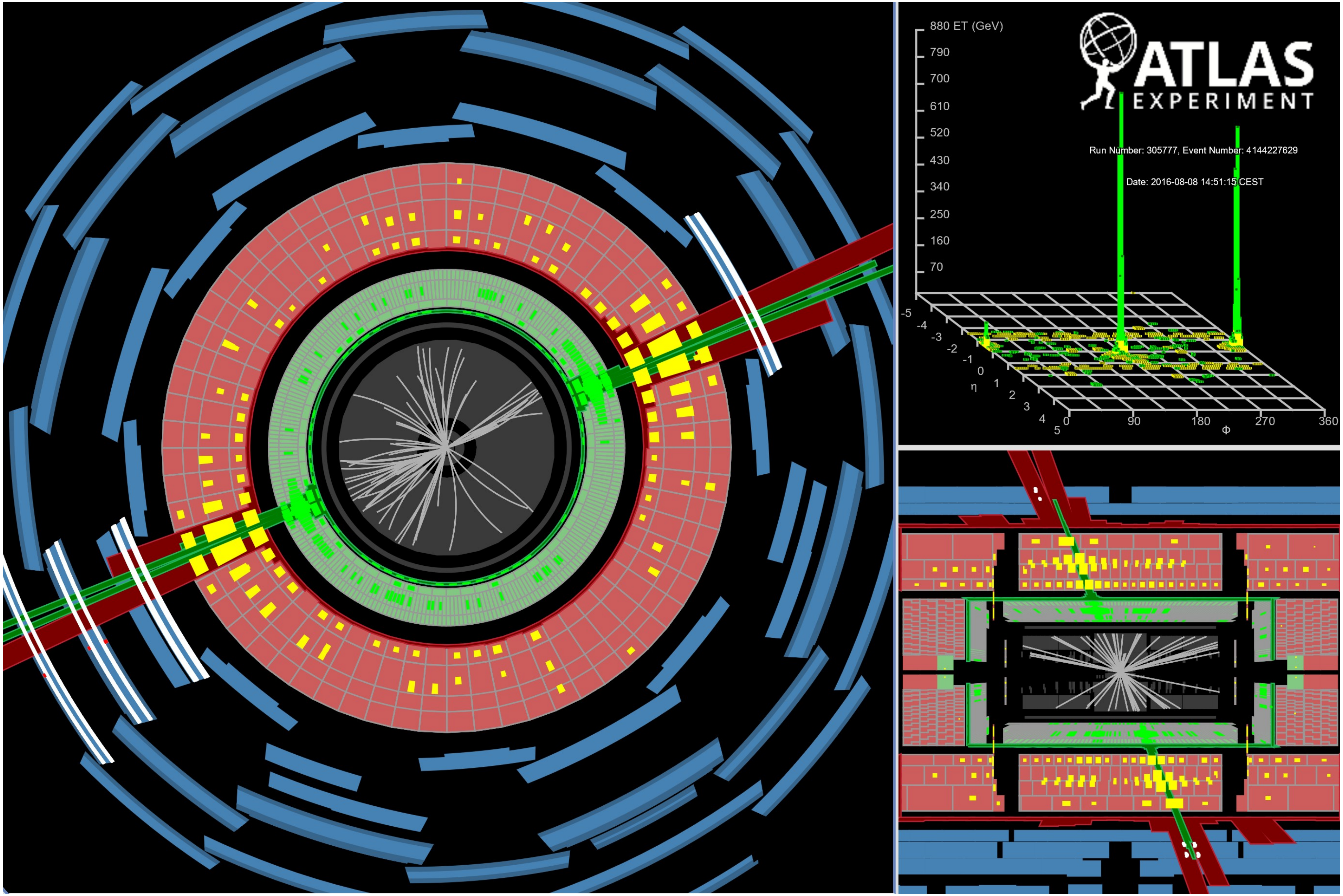
Summary Plot



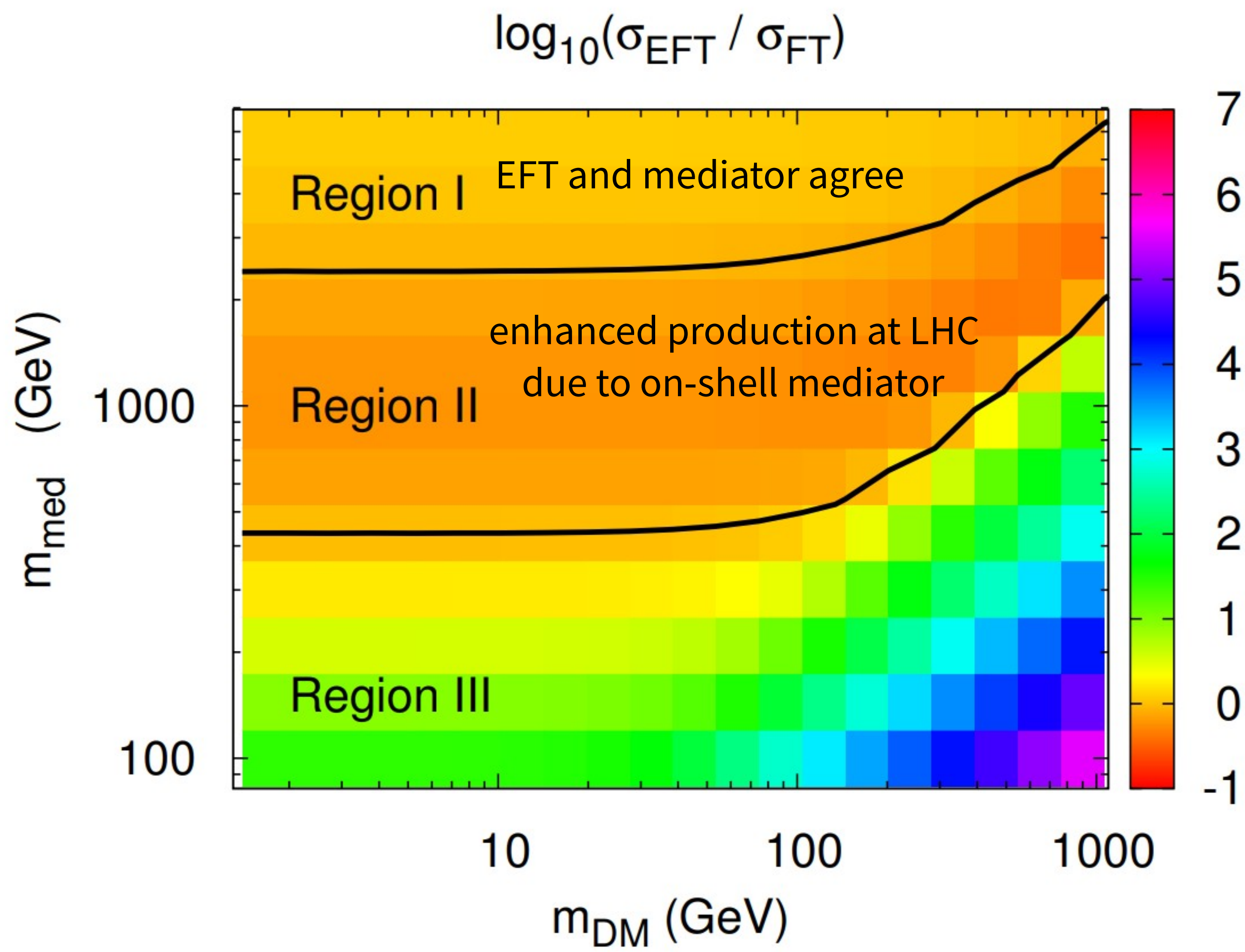


The size of excluded region depends on the coupling values and type.

Highest Energy Event In ATLAS



Why Mediator-Based Models?



Source: arXiv:1308.6799