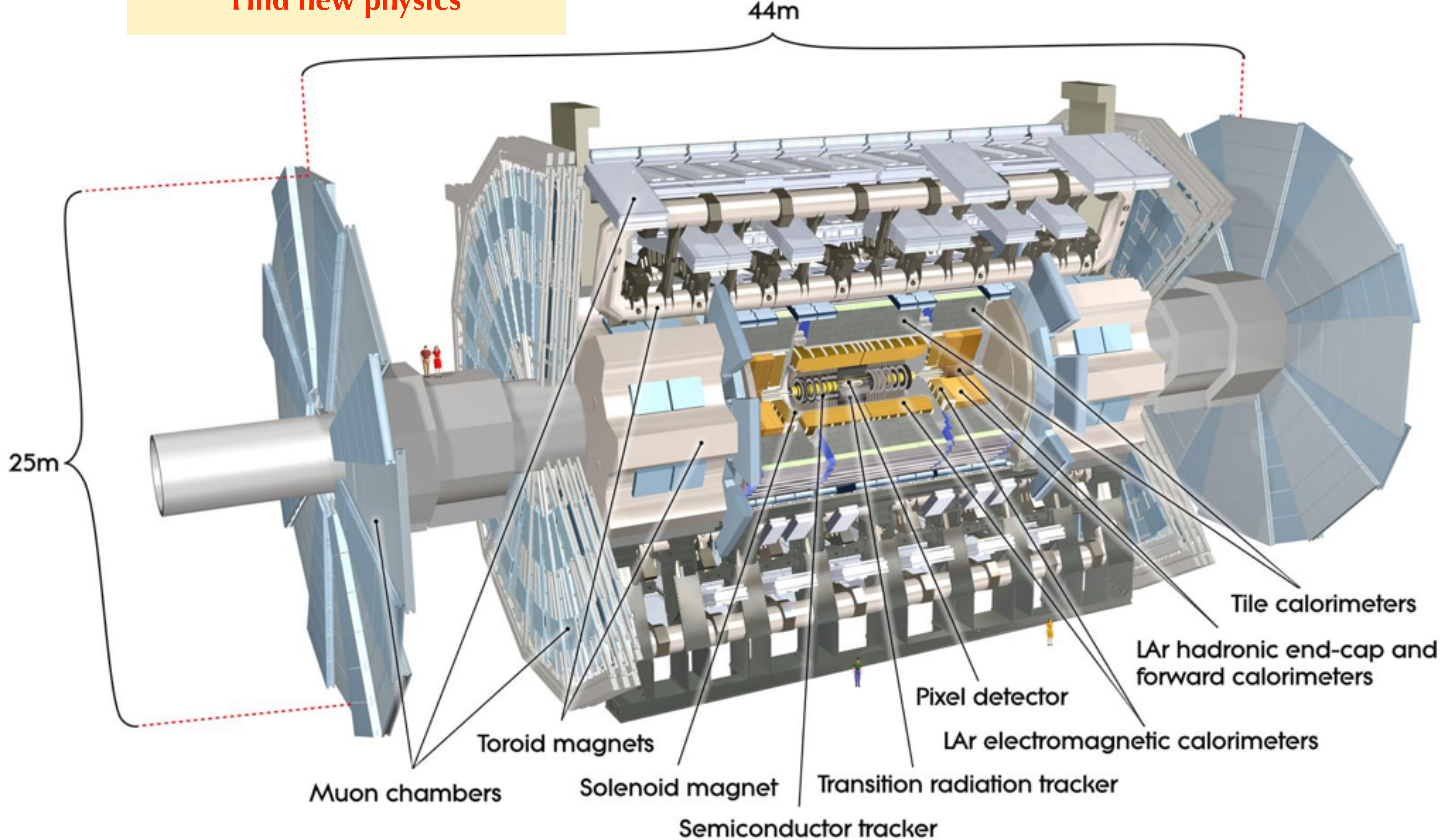
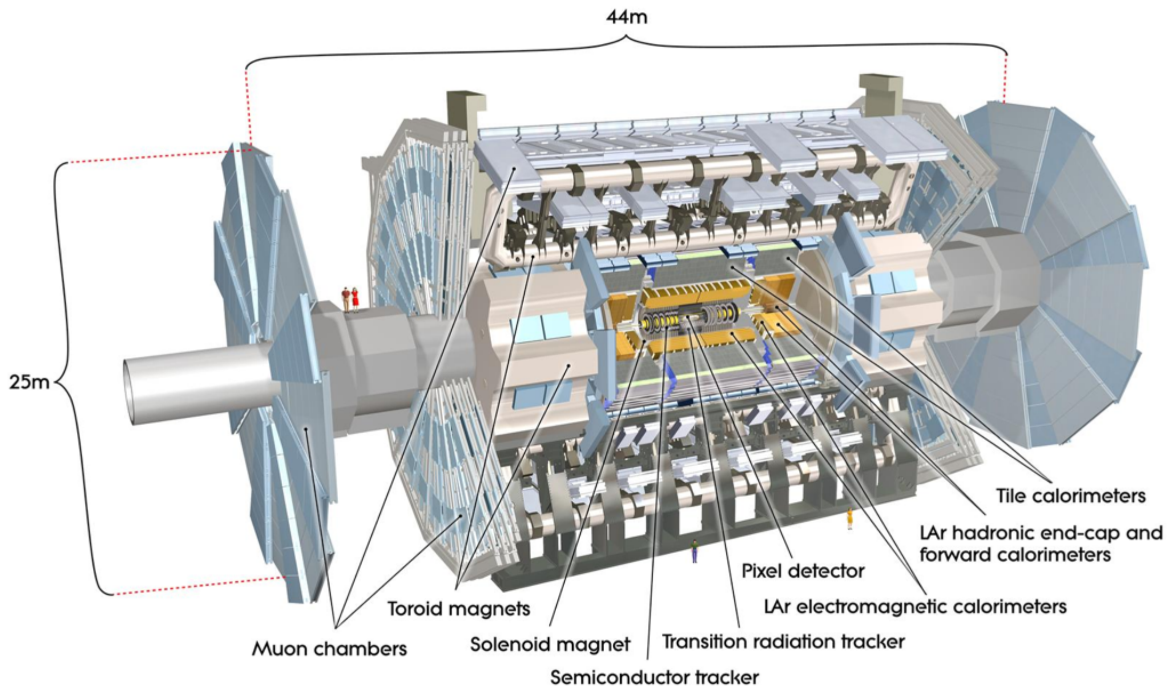
Avant-garde LHC:

Convincing the ATLAS Detector to Do Things it Wasn’t Designed to Do

James Beacham
Ohio State University

What the ATLAS detector *was* designed to do: Find new physics

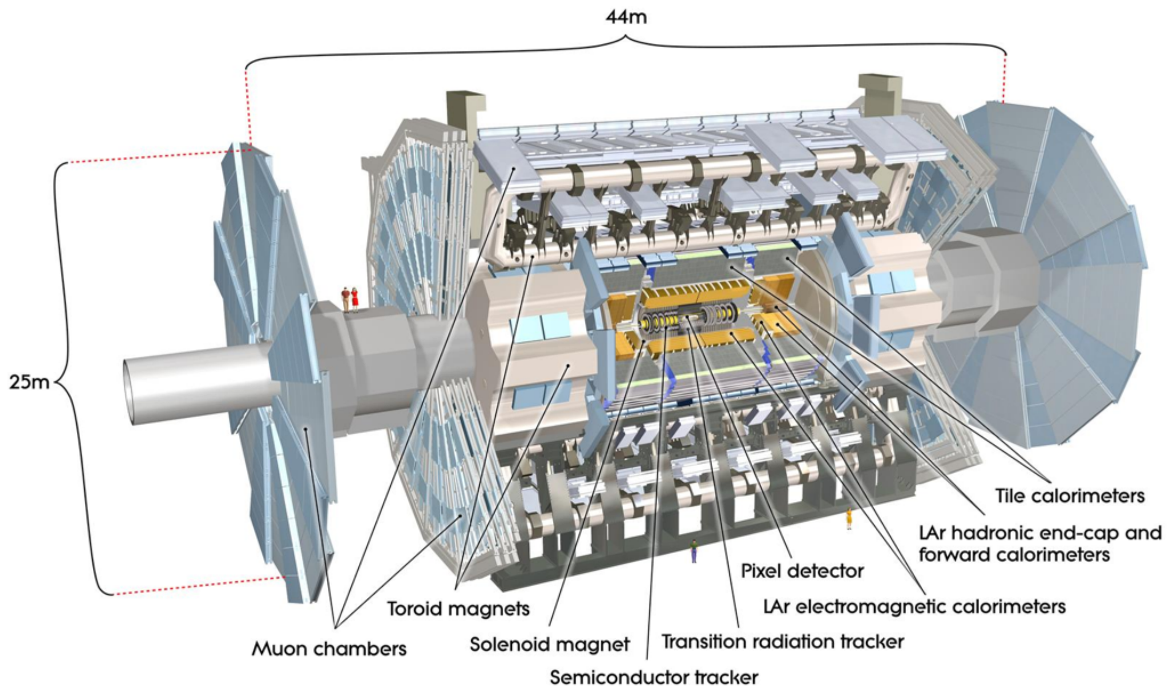




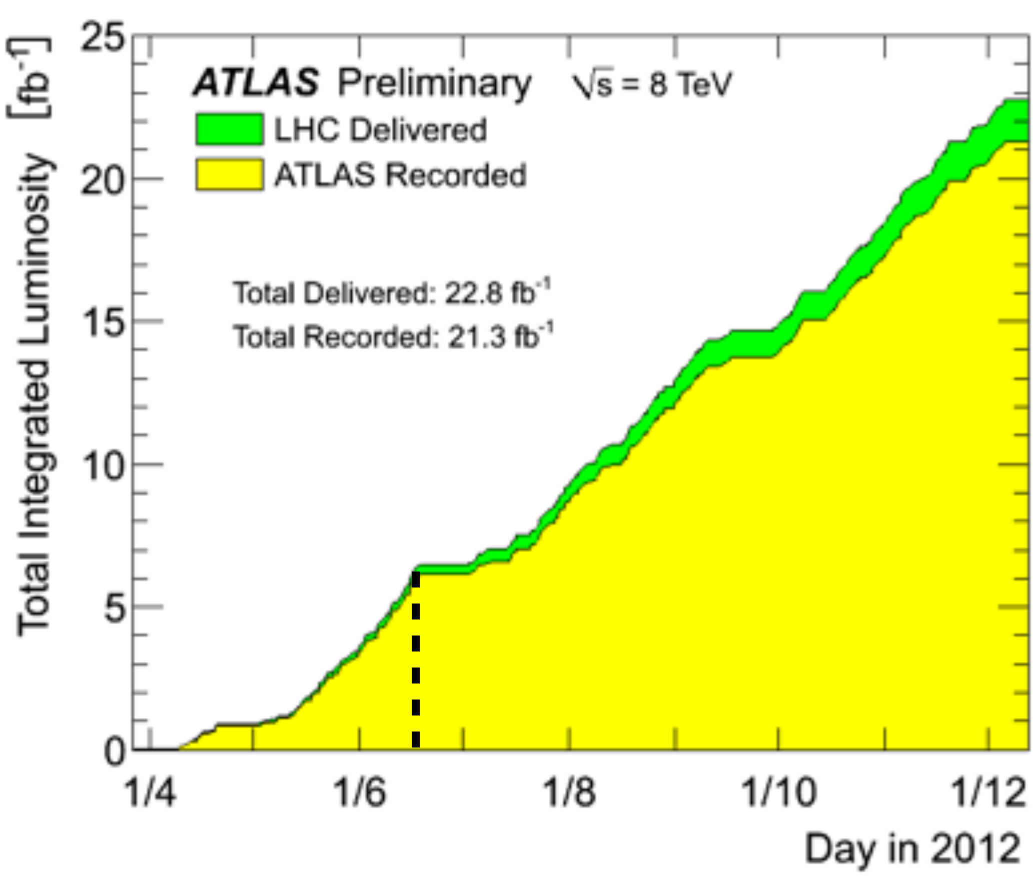
How do we find new physics with ATLAS?
It's a simple two-step process.

ATLAS

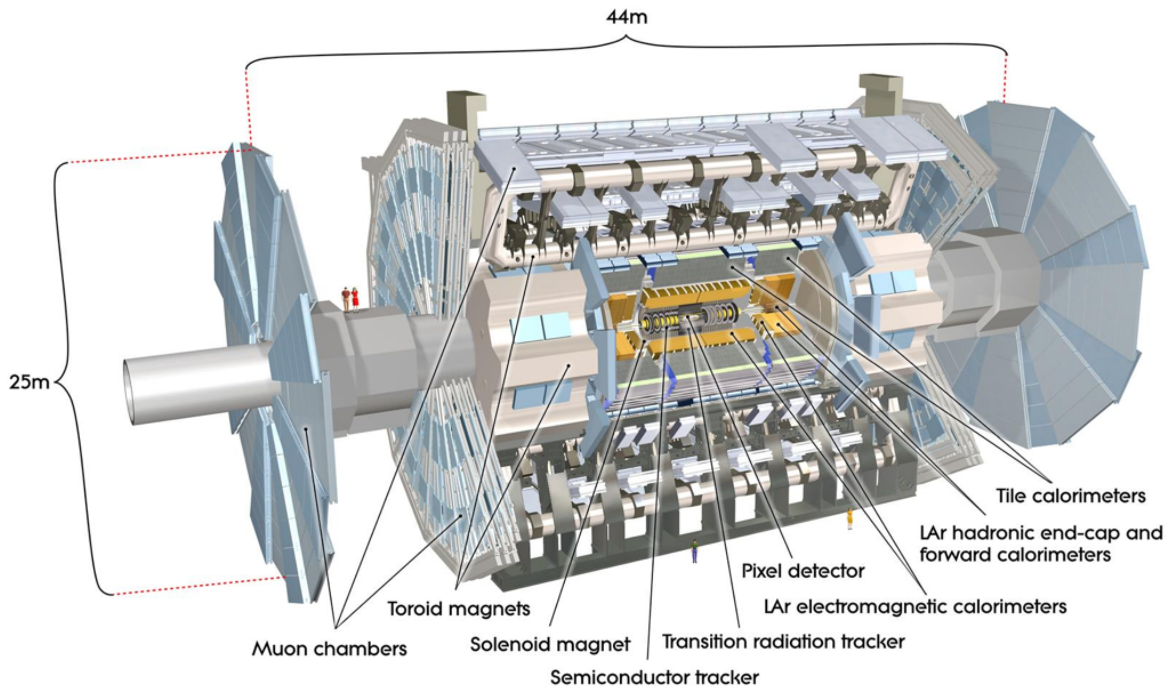
How do we find new physics with ATLAS?
It's a simple two-step process.



1) Take some data

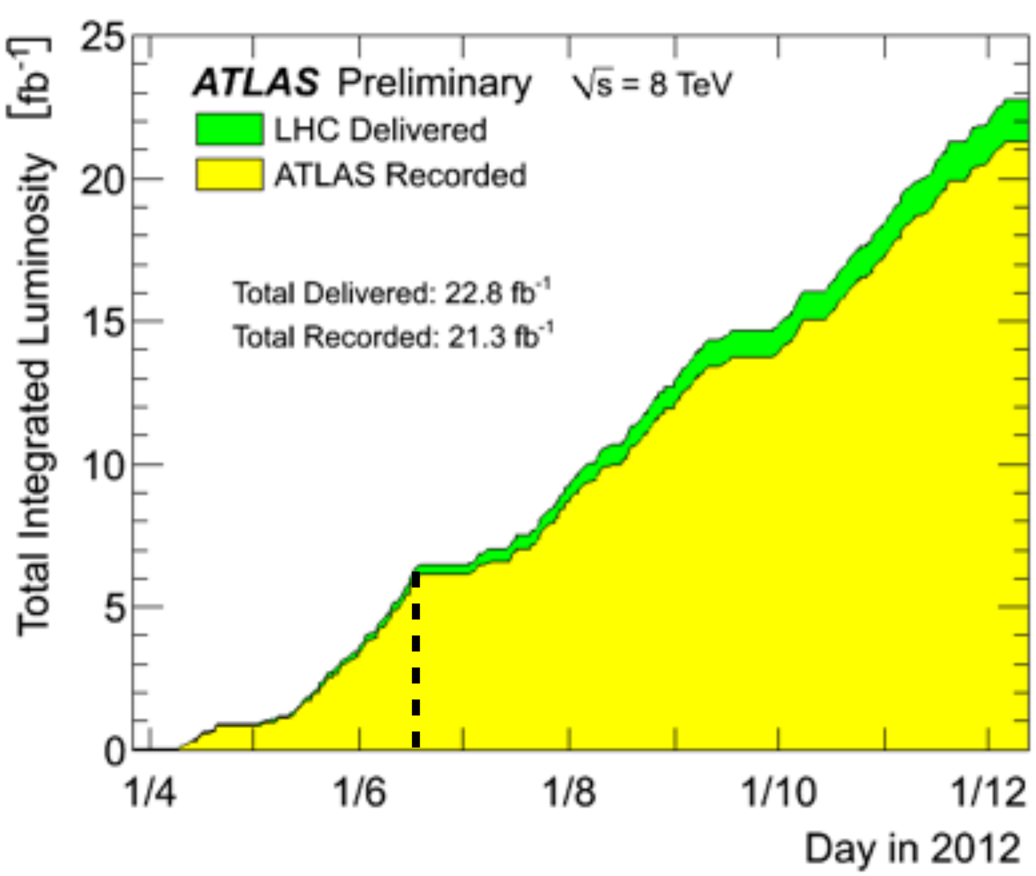


ATLAS

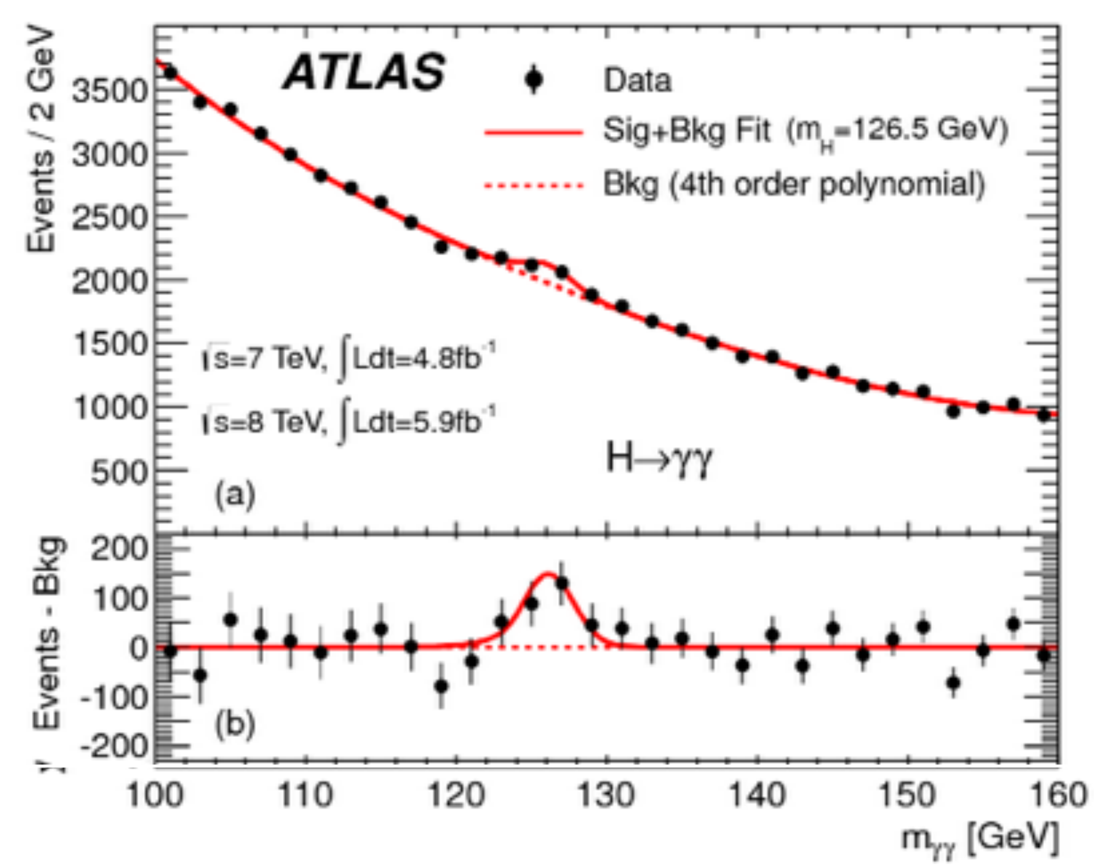


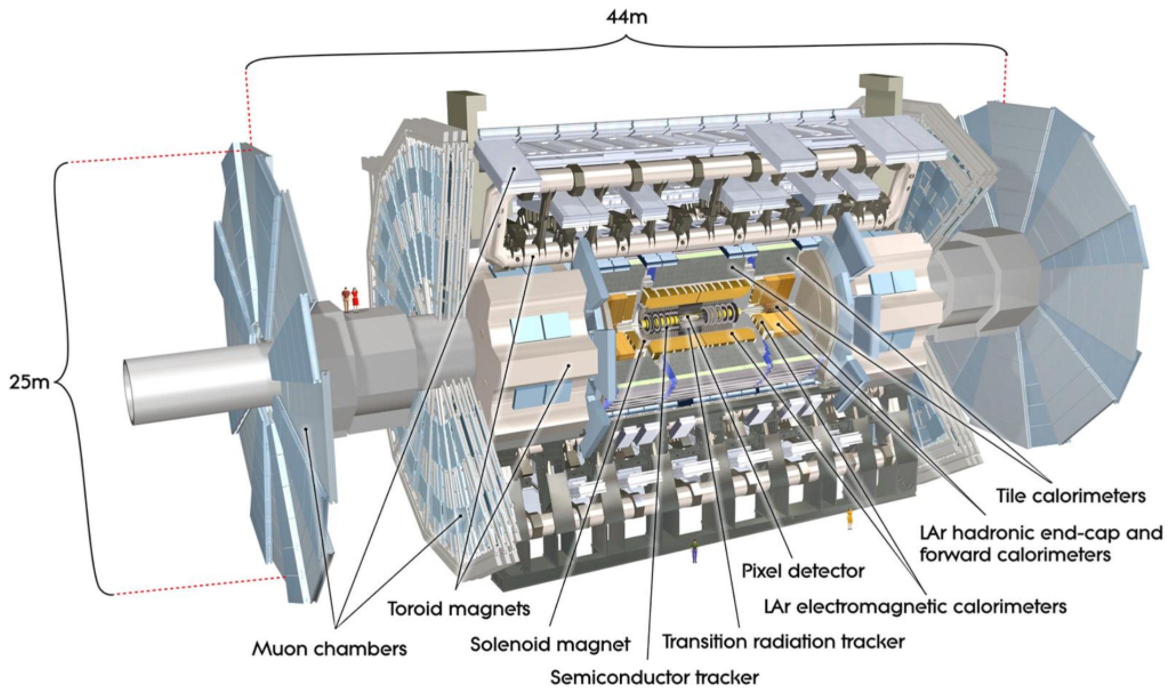
How do we find new physics with ATLAS?
It's a simple two-step process.

1) Take some data



2) Look for an excess of events above what you were expecting

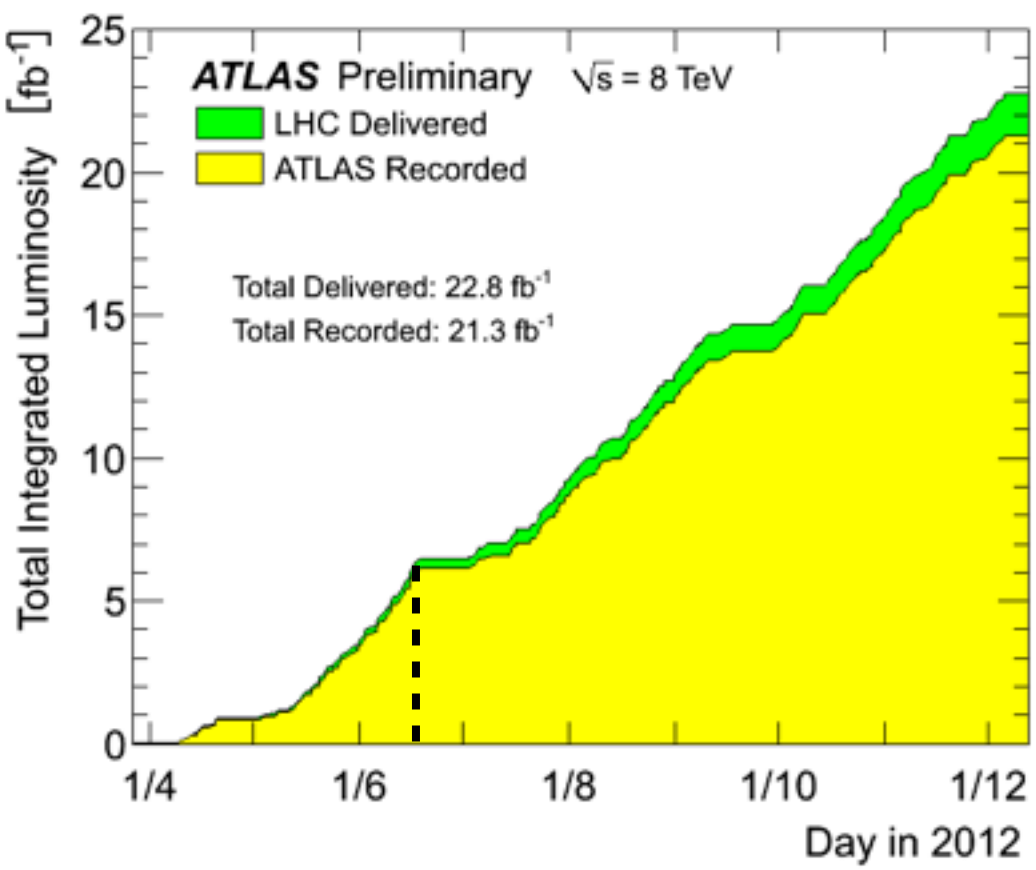




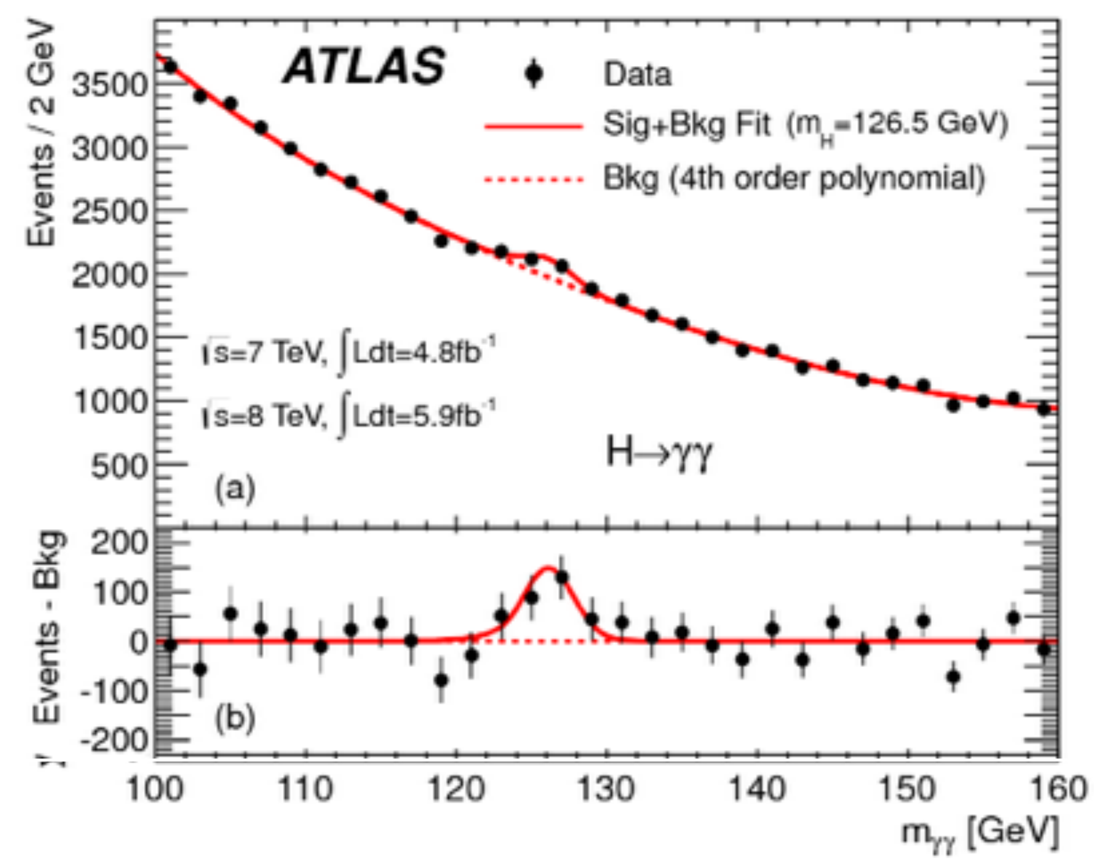
How do we find new physics with ATLAS?

It's an extremely complicated, multi-faceted effort involving thousands of people.

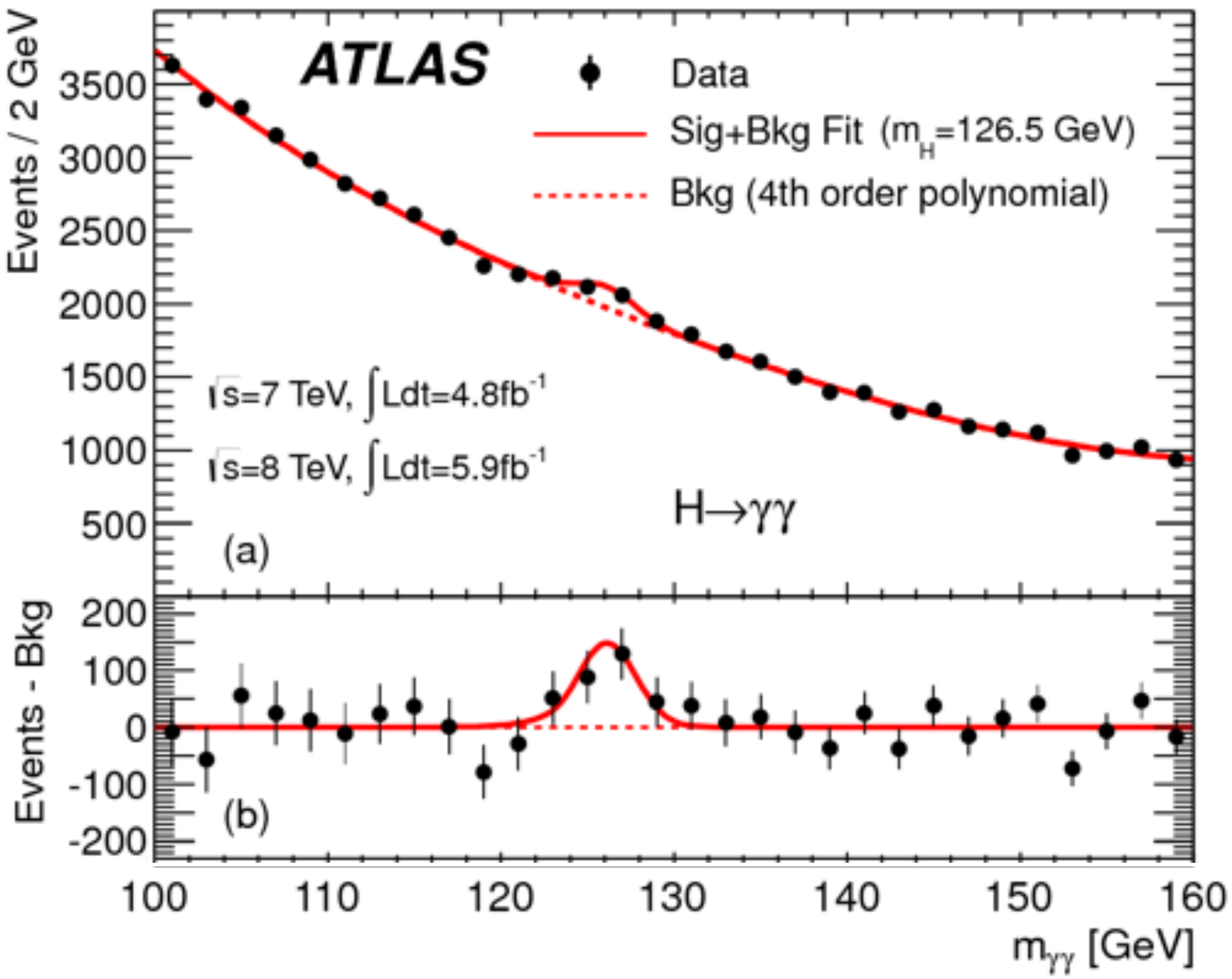
1) Take some data



2) Look for an excess of events above what you were expecting



Looking for an excess of events above what you were expecting



Example: Higgs boson discovery in the diphoton channel

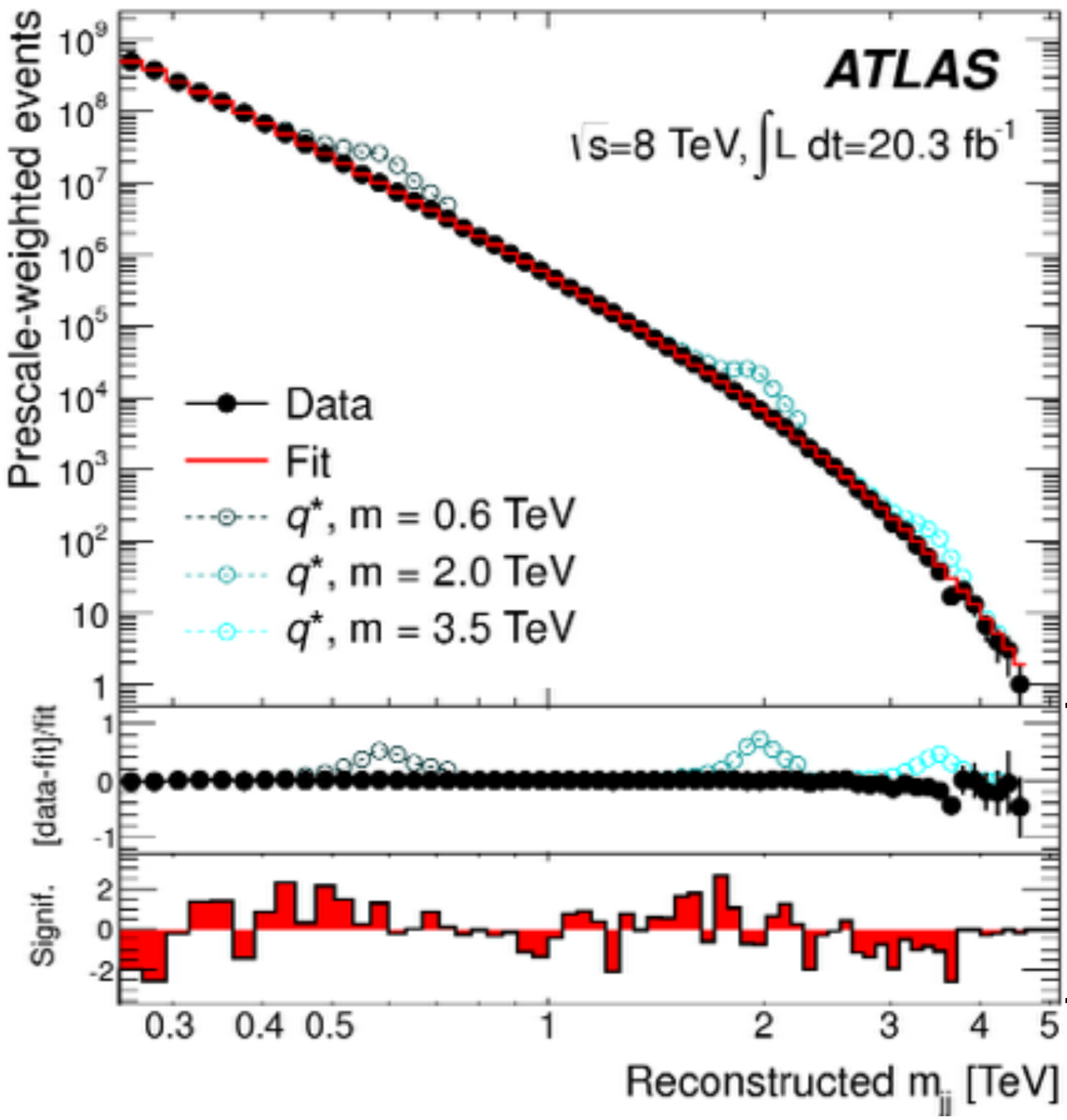
Take all events that contain two nicely-separated and well-identified photon candidates, measure their energies and momenta, work backwards to calculate the diphoton invariant mass, and then look for a bump

Overwhelmingly, this calculation gives you nothing new.

It gives you the overall background shape of Standard Model myy production, i.e., a measure of how the SM fluctuates when producing two-photon events over the allowed range of energies and momenta.

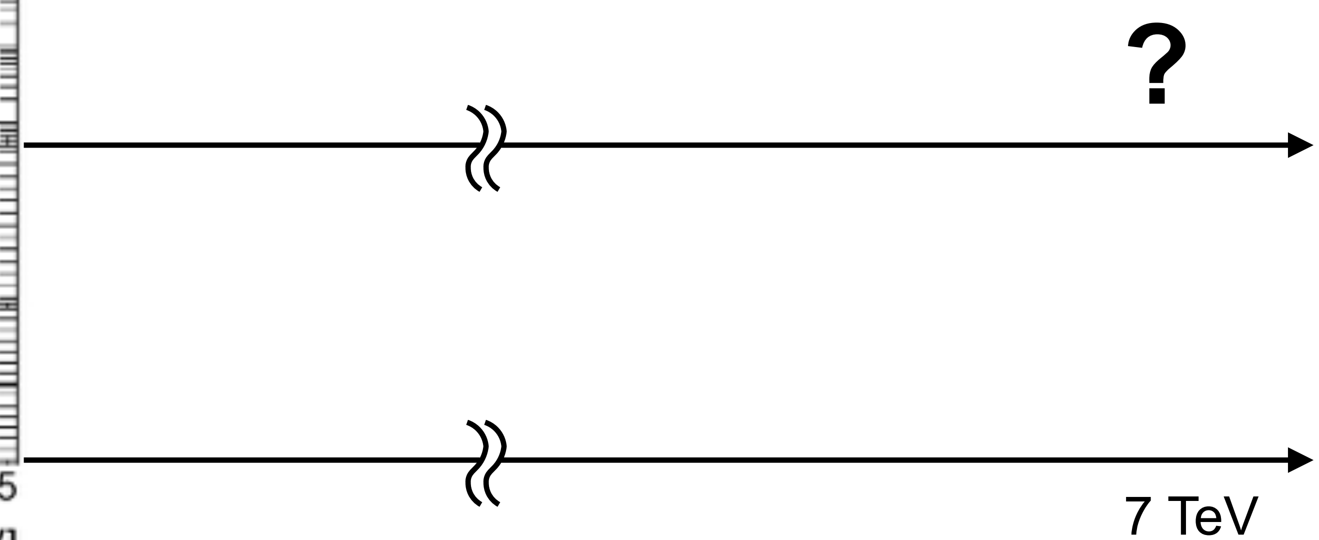
This is your background, and you must understand it to be able to conclude that you've seen a new particle like the Higgs.

Looking for an excess of events above what you were expecting



Another example: High-mass di-jet resonances

Same procedure as before, but look other places, such as at higher values of m_{jj}



This is what ATLAS is made for.

This is what 13 TeV is made for.

New high-mass particles could be just around the corner, in this high-mass region.

Squarks, gluinos, quantum black holes, new vector gauge bosons, extra Higgs bosons, as-yet unfathomed resonances, etc.

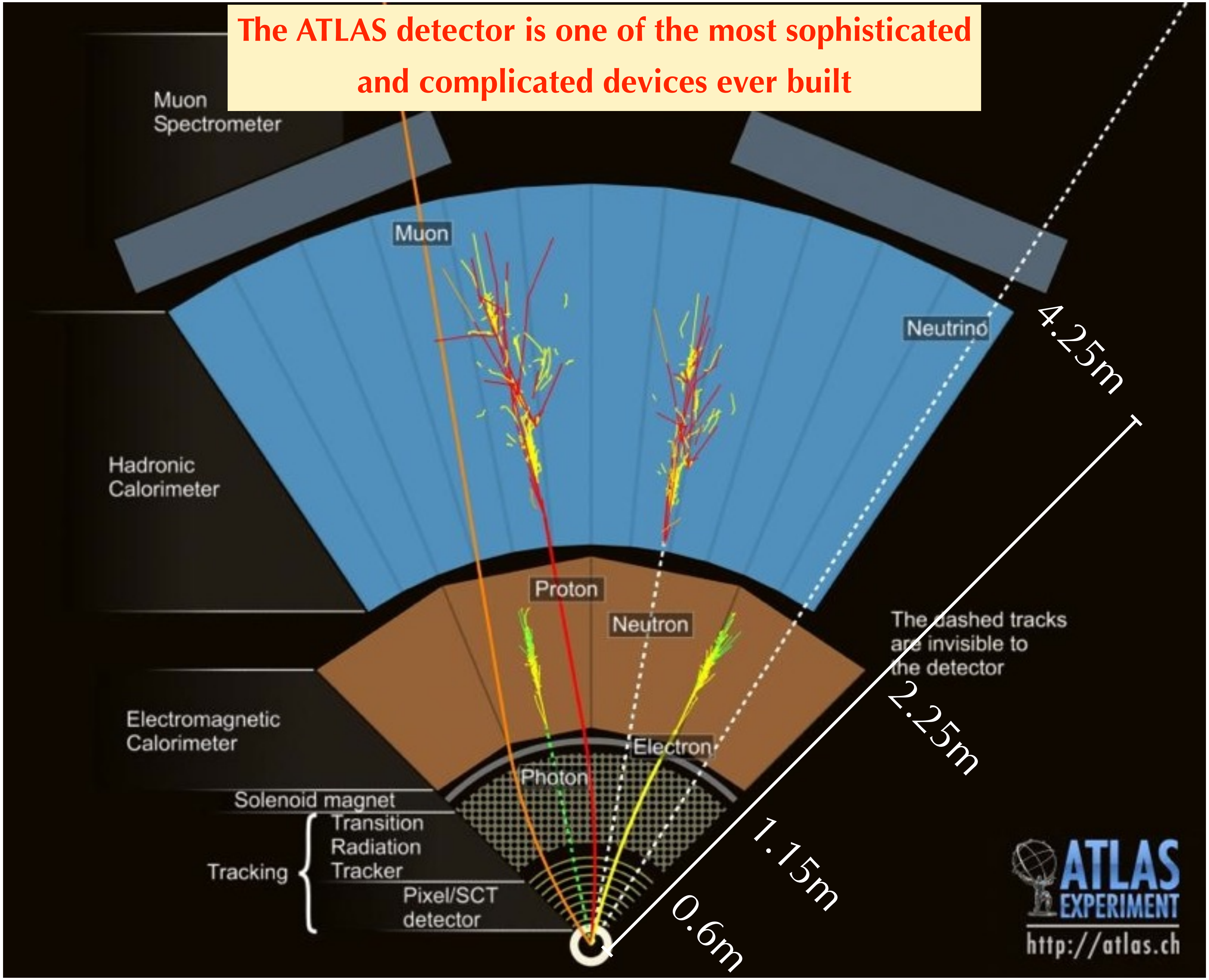
2015 IS GO TIME

Marquee LHC @ ATLAS

42nd & Broadway

Avant-garde LHC @ ATLAS

East Village Off-Off-Broadway



Designed to be sensitive to a wide range of new particles and phenomena that could help explain some of the most important open questions of physics

Successes:

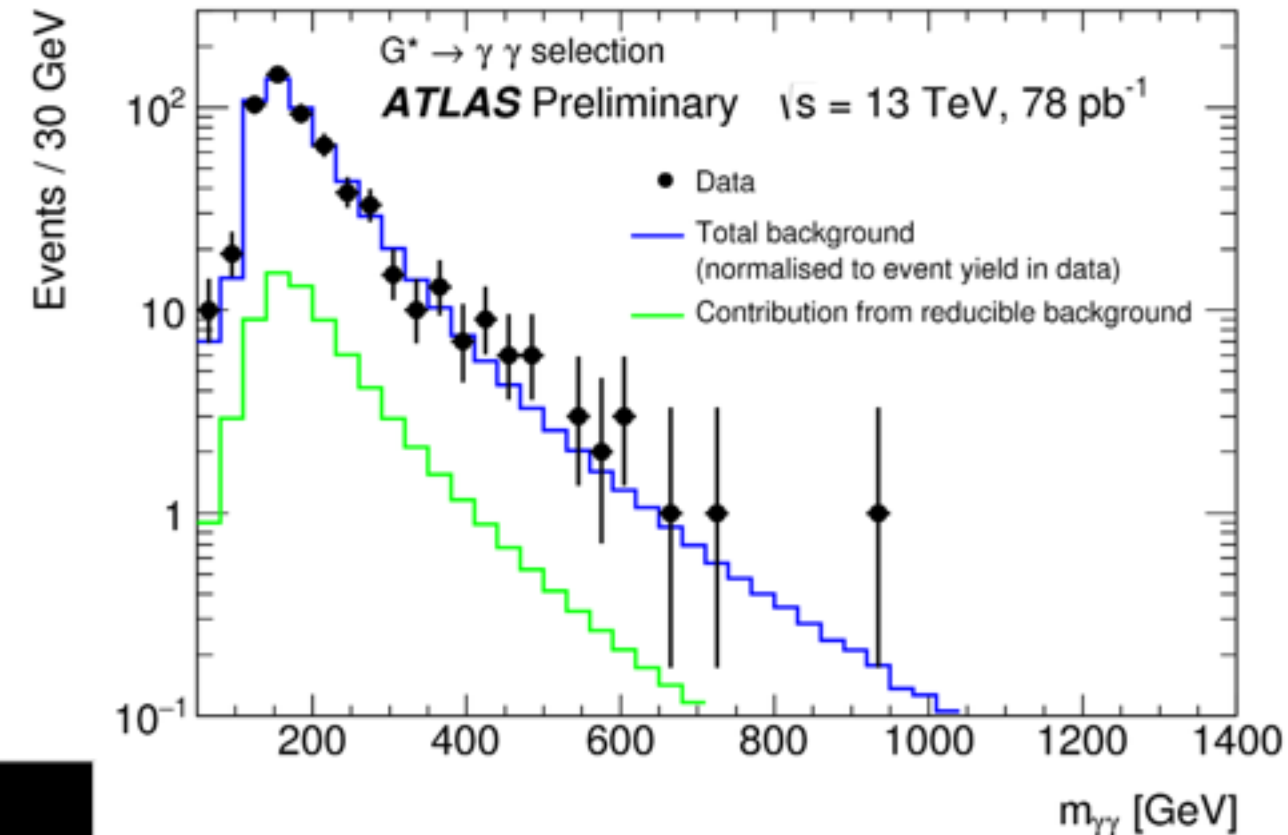
- Higgs discovery
- Measurement of some Higgs decay modes to increasingly good precision
- Strong exclusions on high-mass Z′/QBH and SUSY benchmarks

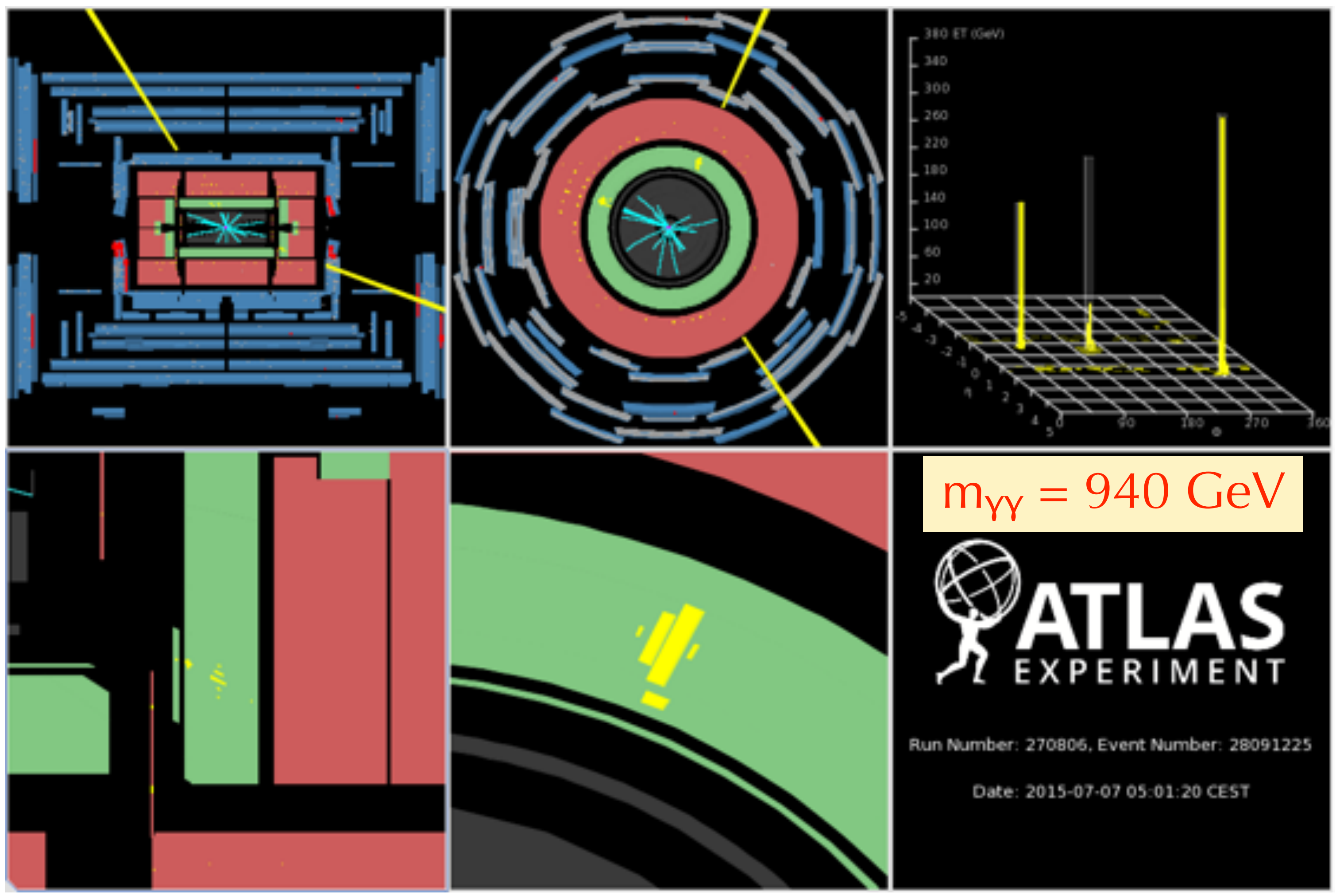
These successes only possible because of:

- Excellent particle ID (e.g., photons, jets)
- Great tracking
- Understanding and control of pile-up interactions and cosmic muon backgrounds

Things we do fantastically well:
Diphoton resonances

13 TeV data

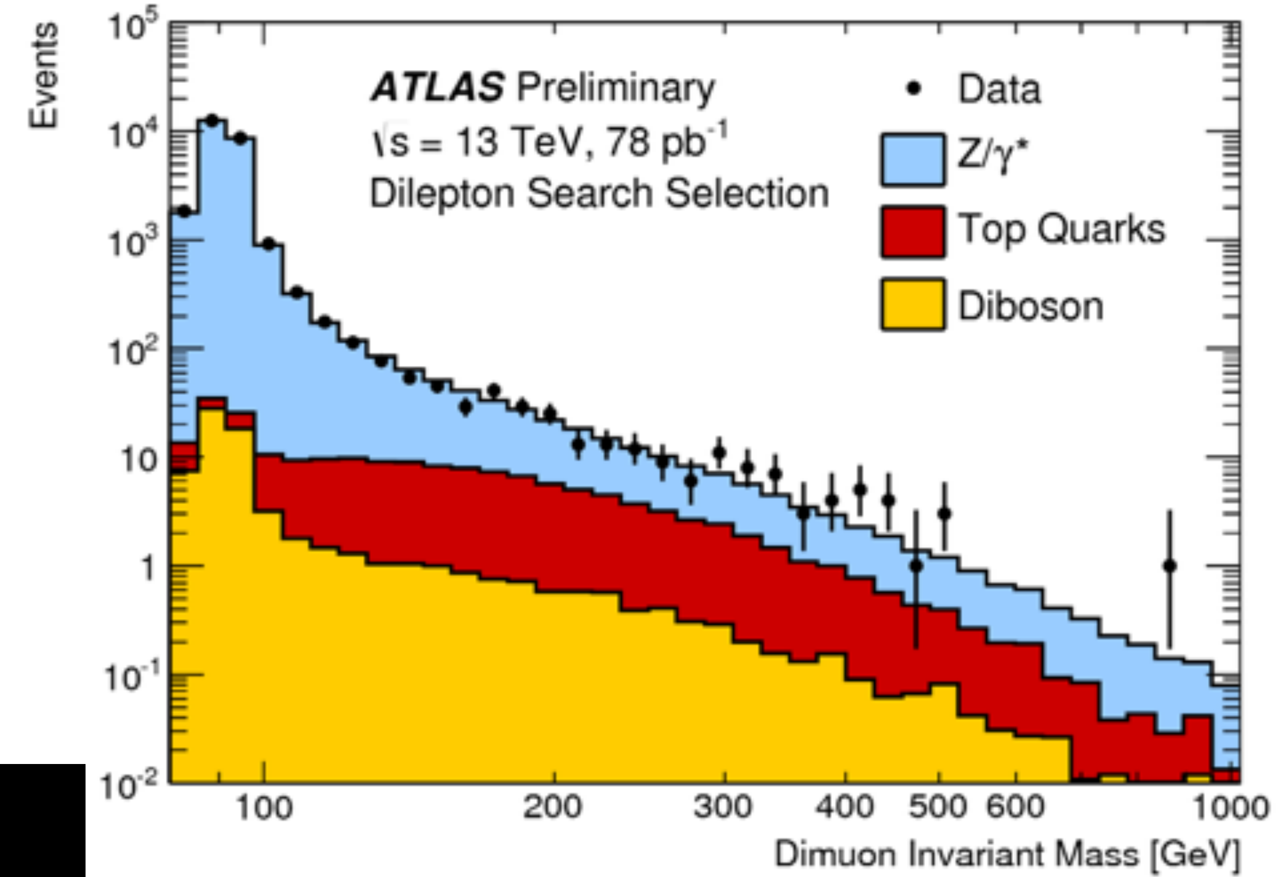


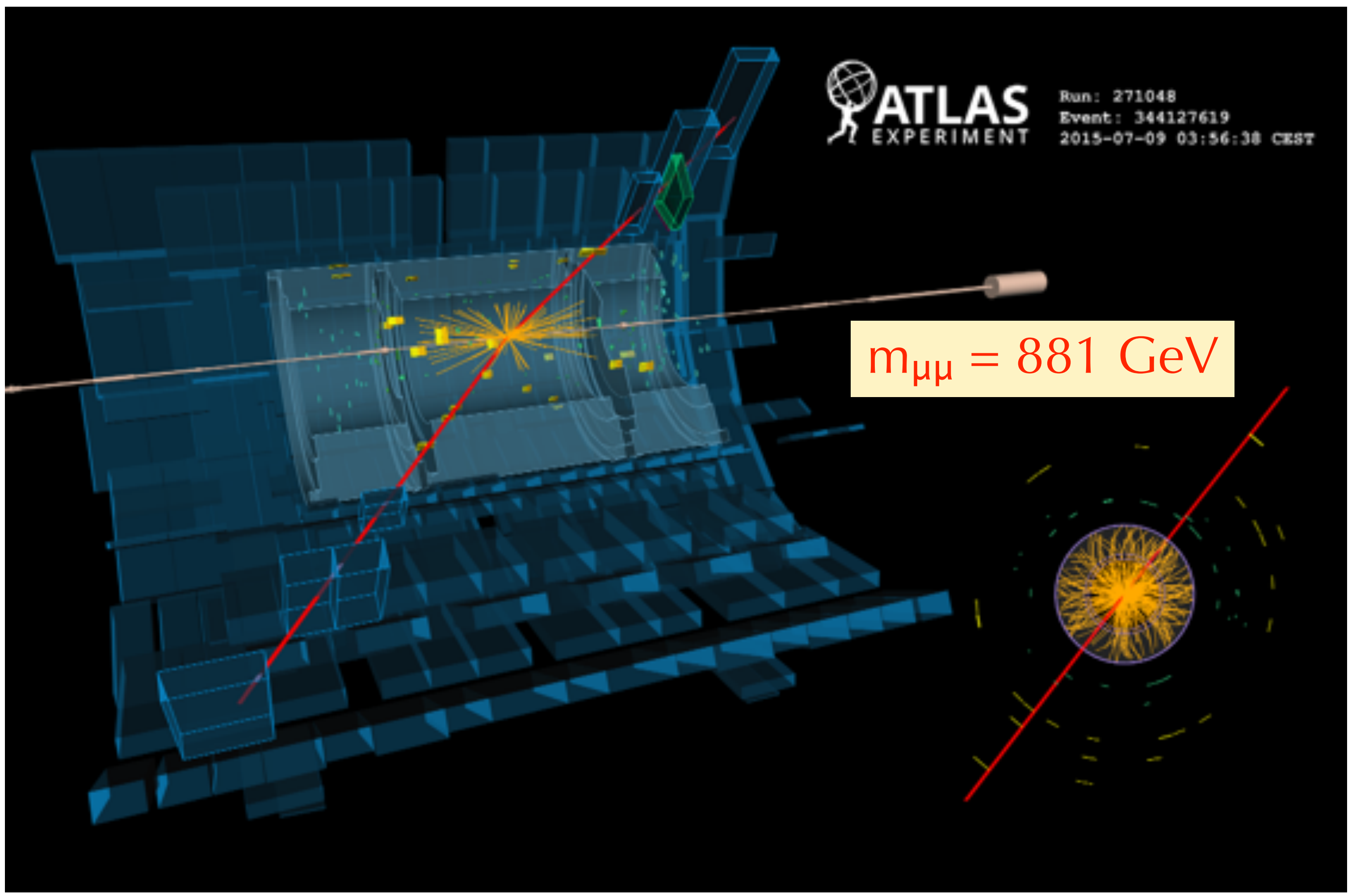


High-p_T, well-separated photon candidates

Things we do fantastically well:
Dilepton resonances

13 TeV data



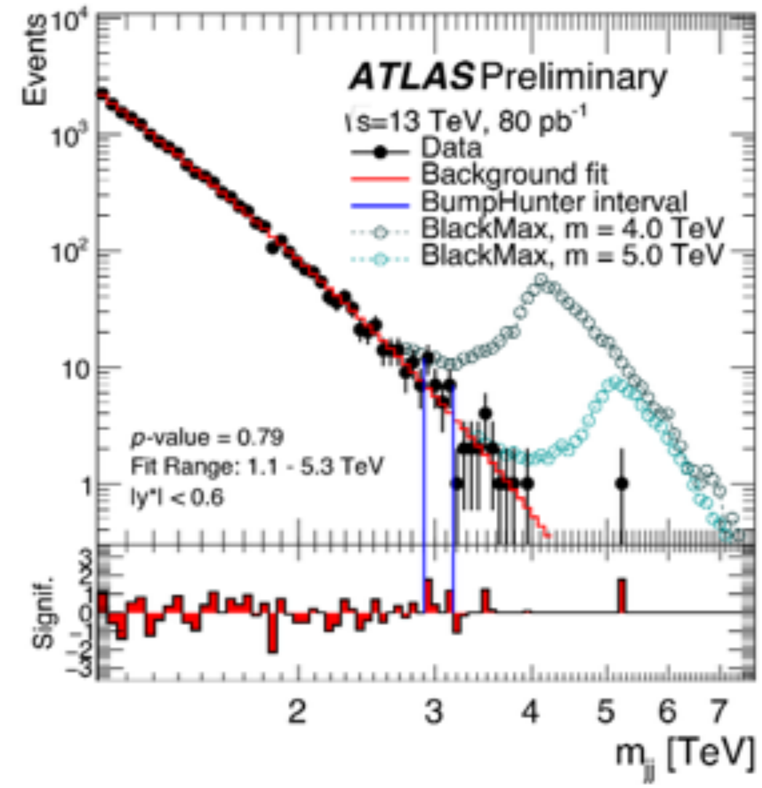


$m_{\mu\mu}$ = 881 GeV

High-p_T, well-separated muon candidates

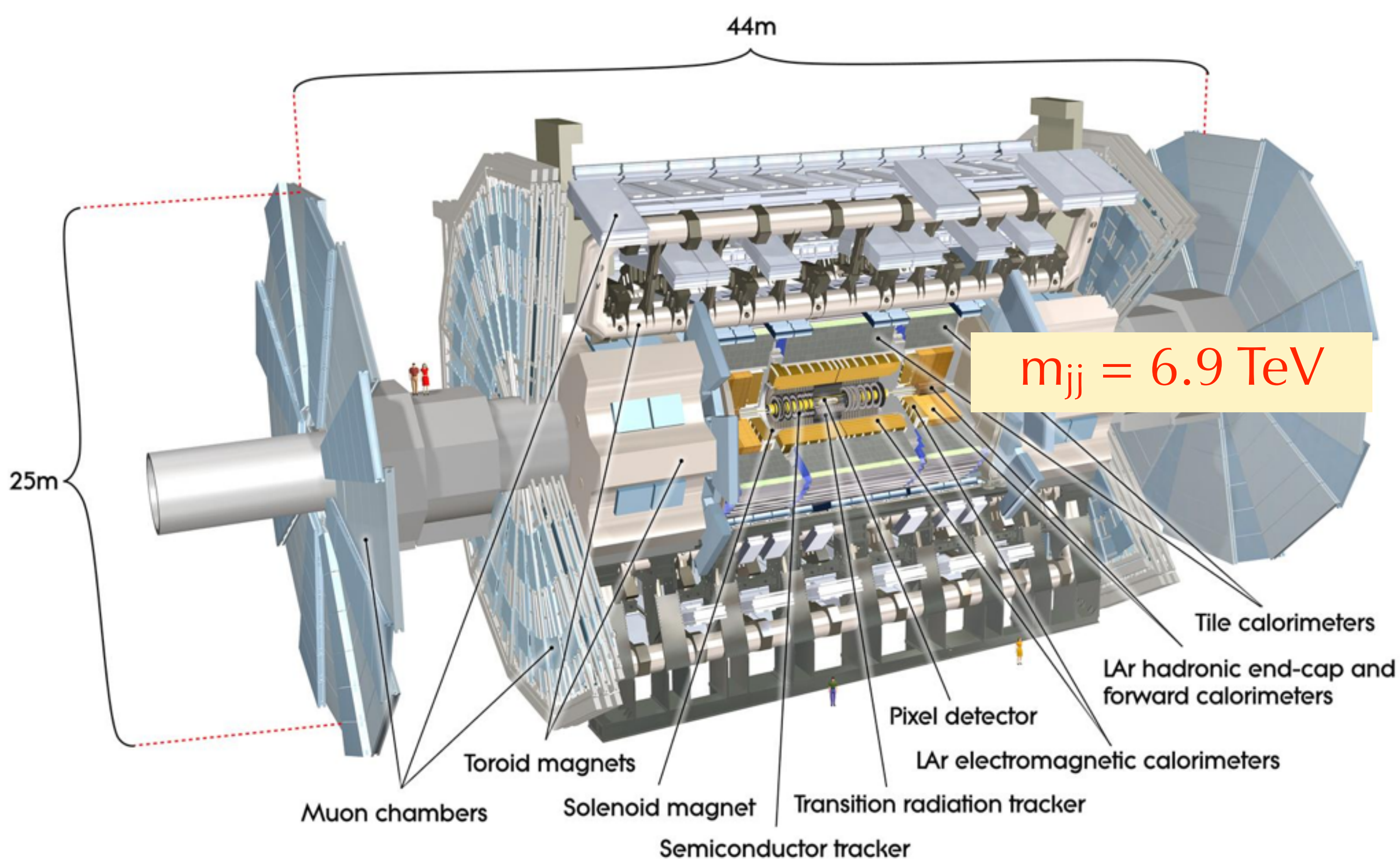
Things we do fantastically well:

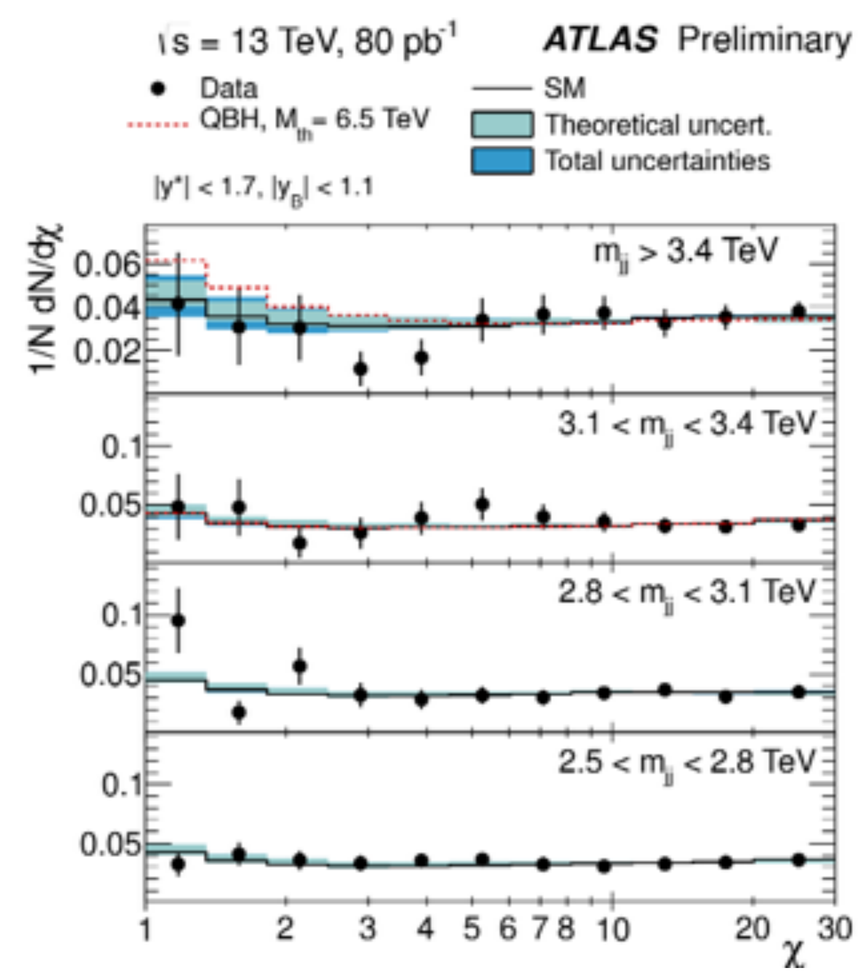
Dijet resonances



13 TeV data

High-p_T, well-separated jets





ATLAS is designed to be optimally sensitive to new high-mass particles using well-separated physics objects with excellent track-finding even in busy environments.

But.

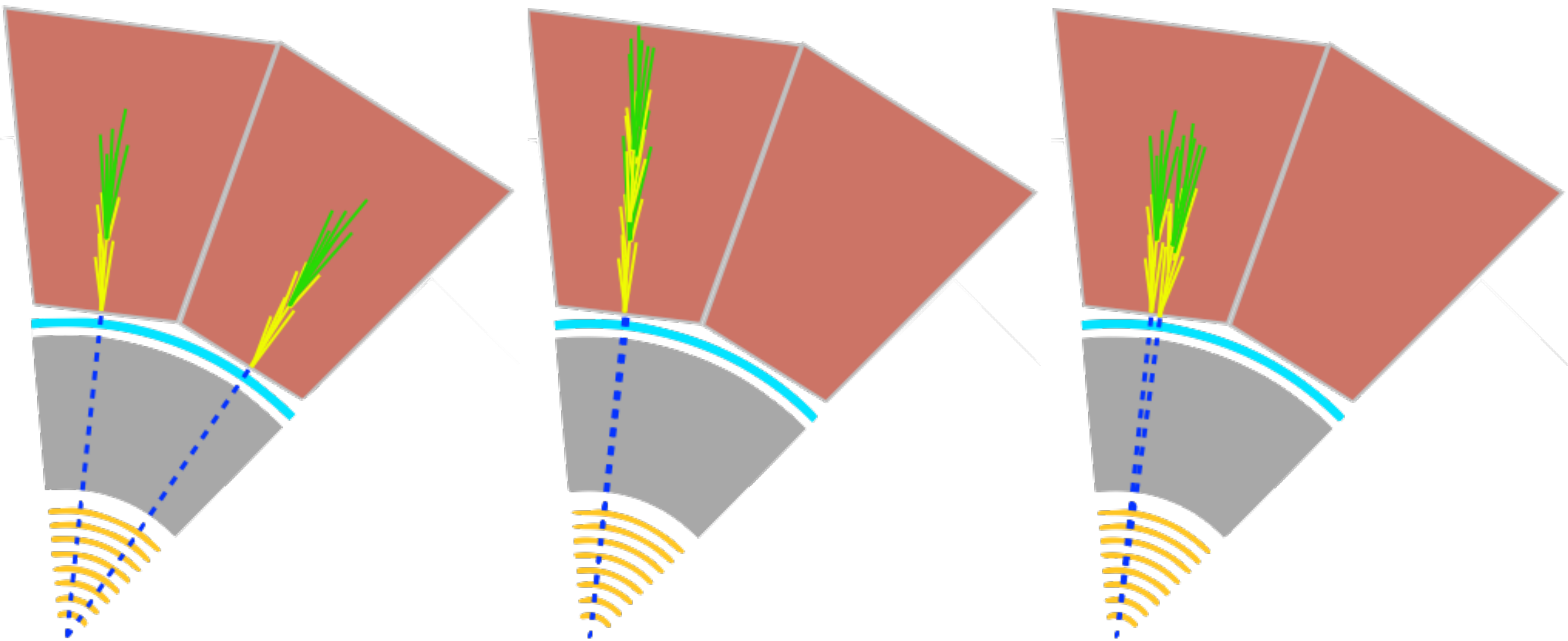
What about when the objects get close together and/or overlap?

$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

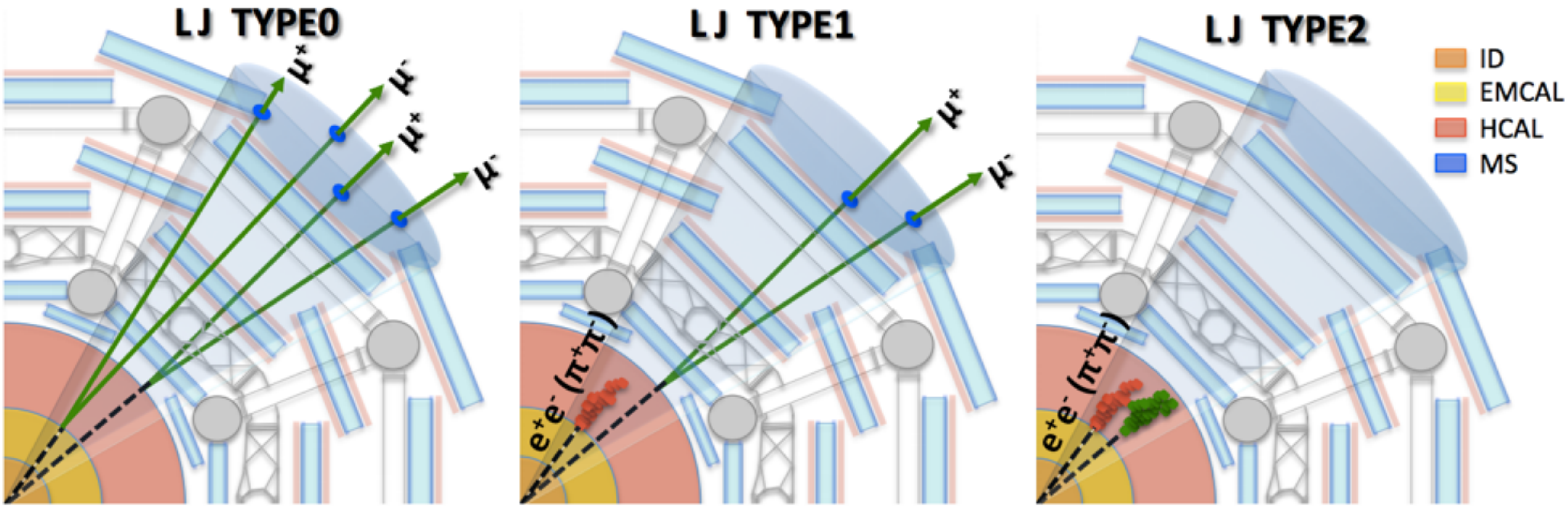
Two well-separated photons (!)

Two completely overlapping photons (!)

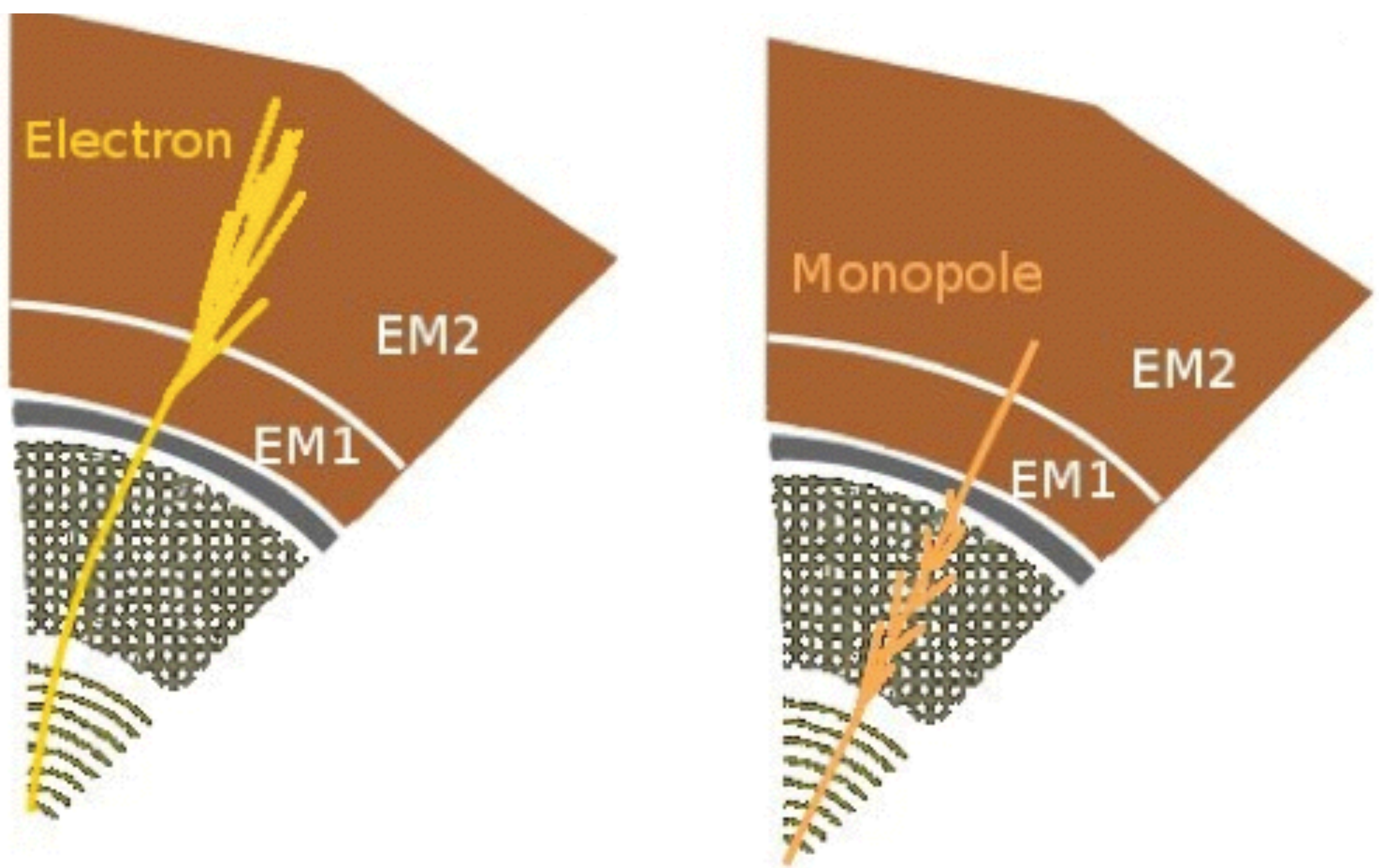
Two nearly-merged photons (?)



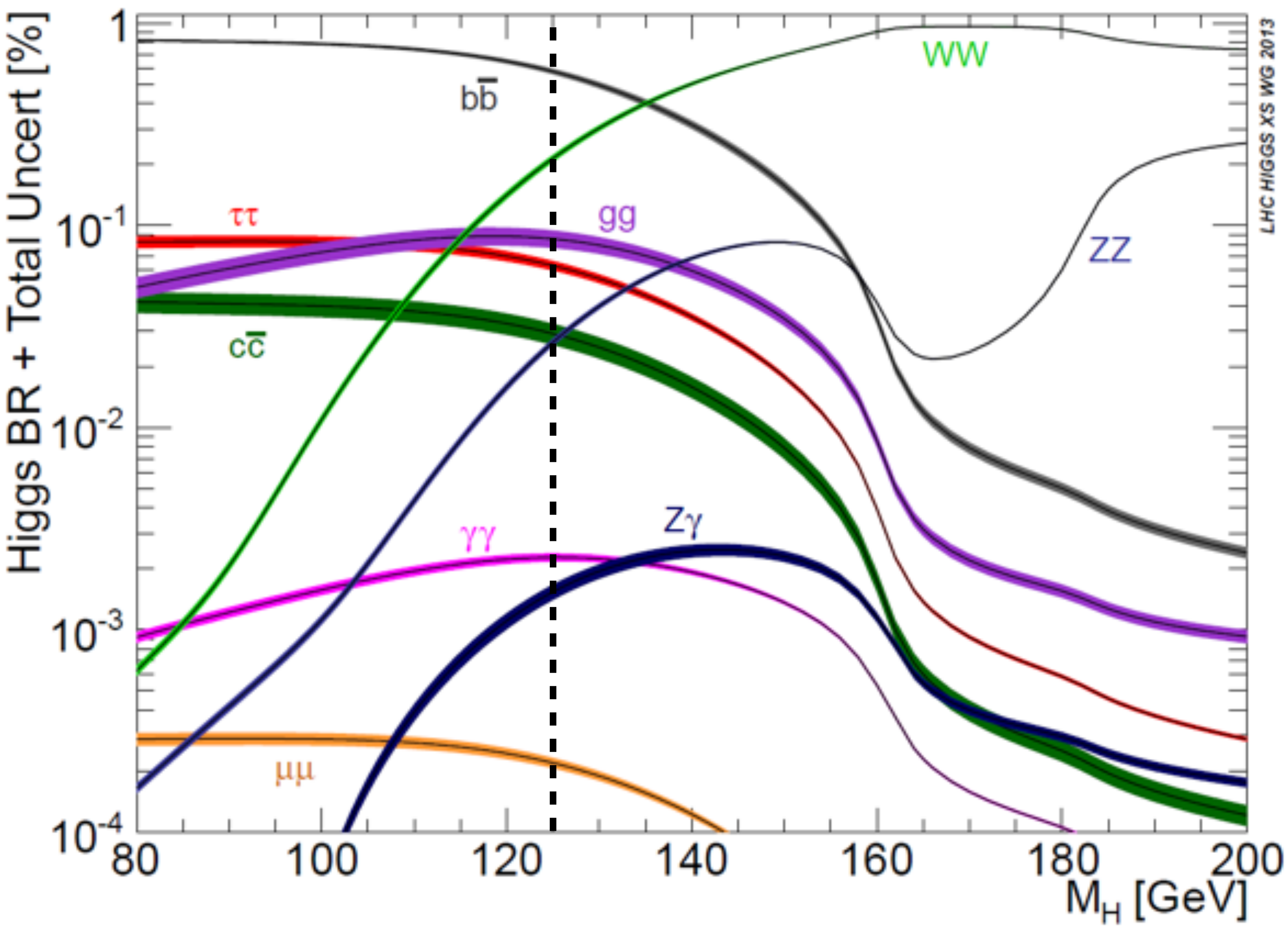
What about long-lived particles that decay
ONLY in the outer detector components?

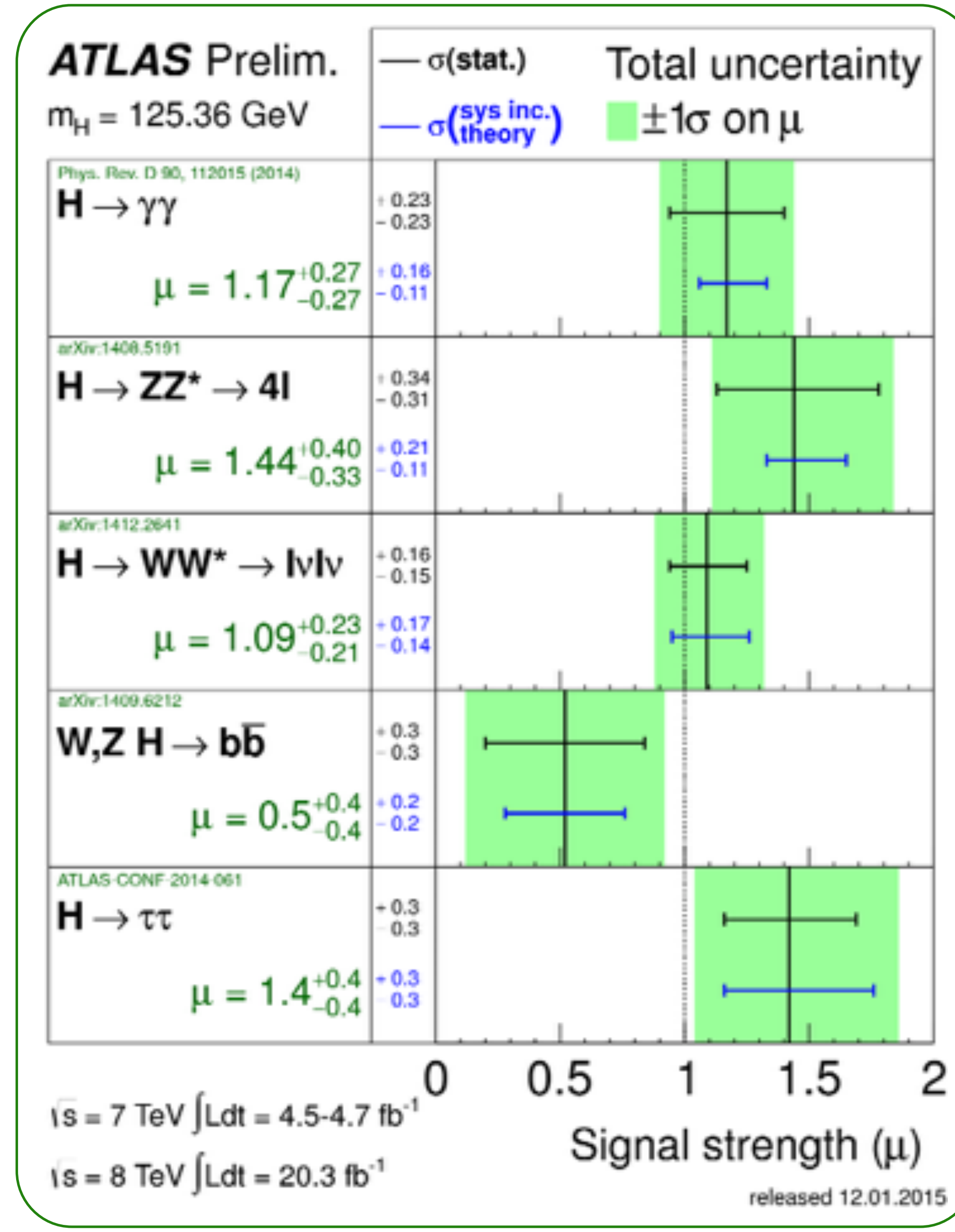


What about highly-ionizing particles that suffer high energy loss through ionization along trajectory?



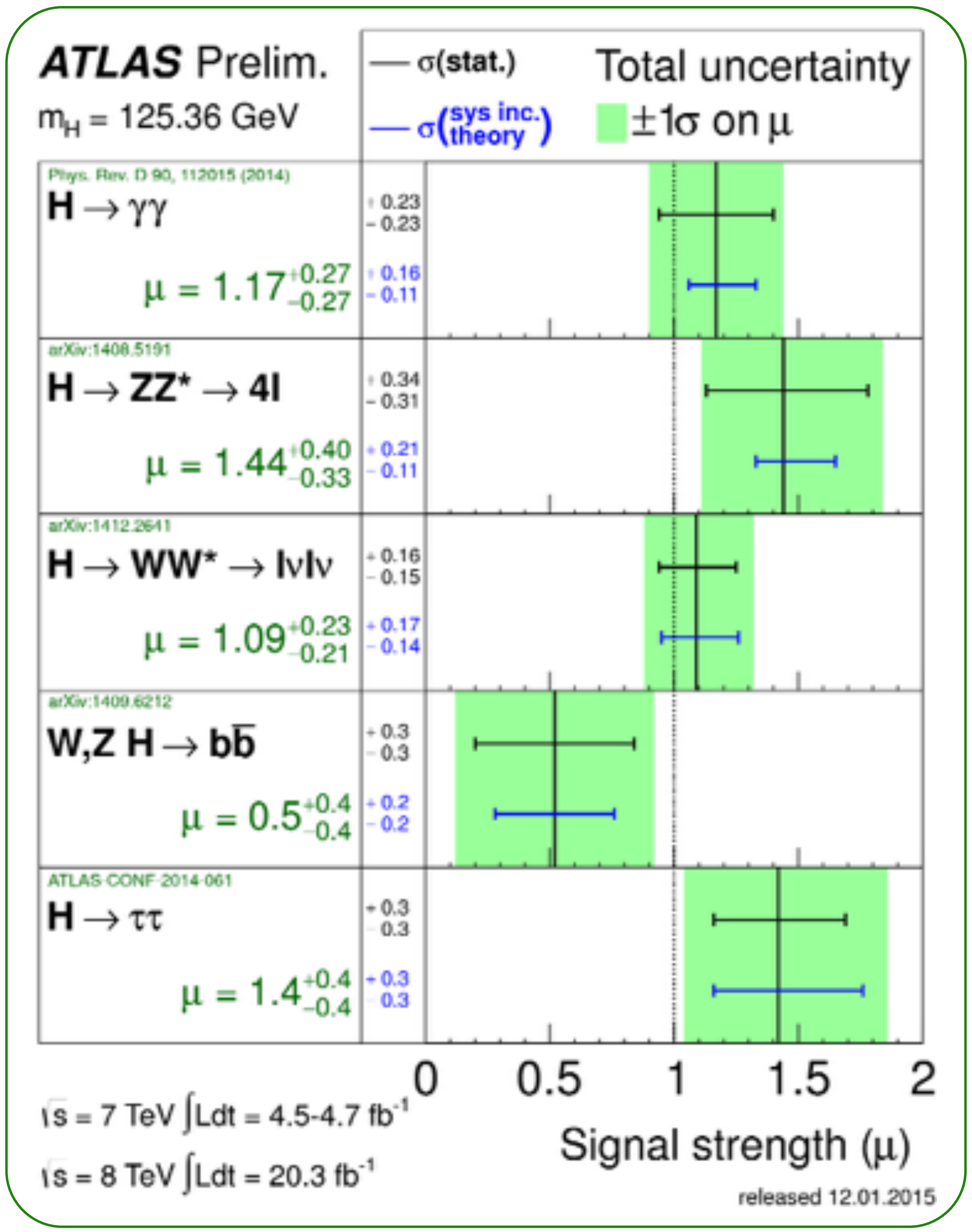
What about low-mass particles that can take up a sizable fraction of the total Higgs width?



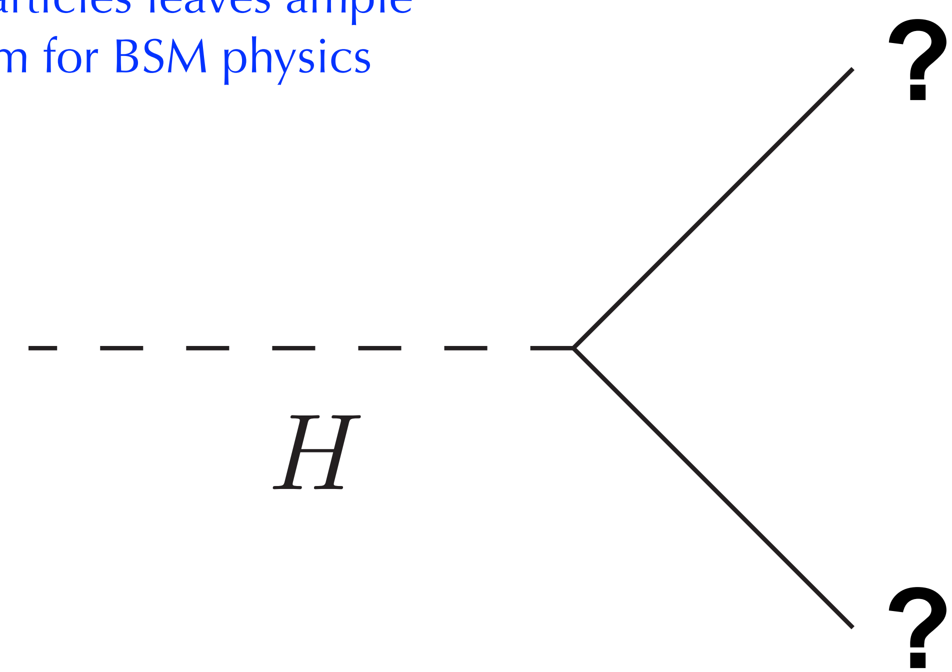


How Standard is the Higgs?

What about low-mass particles that can take up a sizable fraction of the total Higgs width?

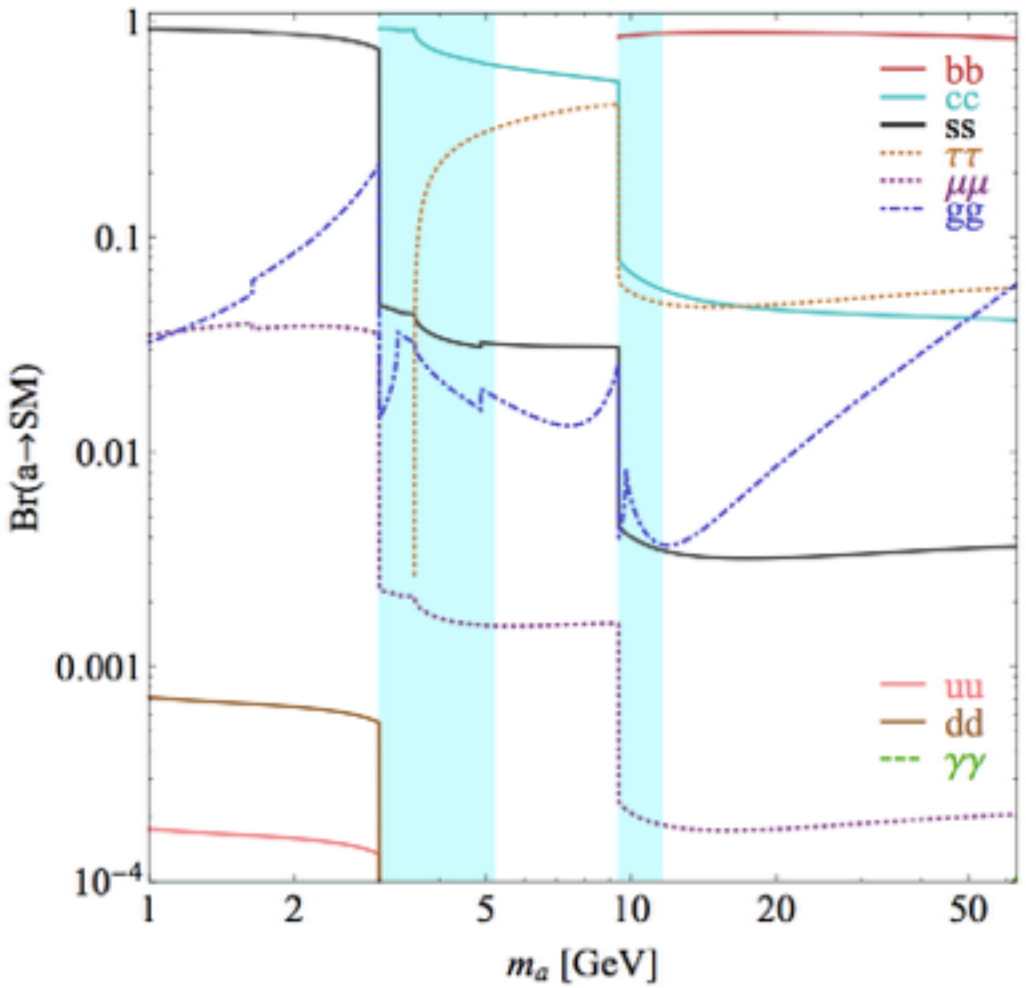


Current precision of measurements of couplings to SM particles leaves ample room for BSM physics



Some fits predict branching ratio of Higgs to invisible could be as large as 20 to 40%

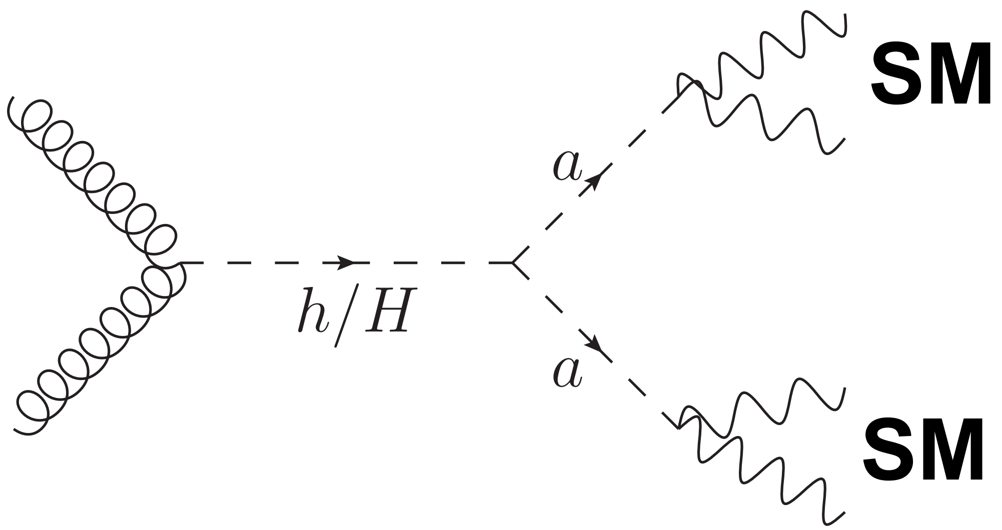
What about low-mass particles that can take up a sizable fraction of the total Higgs width?



Example:
2HDM+S with
Type 1 Yukawa couplings

Simple extension to the SM gauge group of a new light (pseudo)scalar that couple to both the Higgs and SM particles

Yields a rich set of resonant decay topologies



H —> aa —> 2μ2τ

H —> aa —> 2μ2b

H —> aa —> 4γ

etc.

Survey of the unconventional

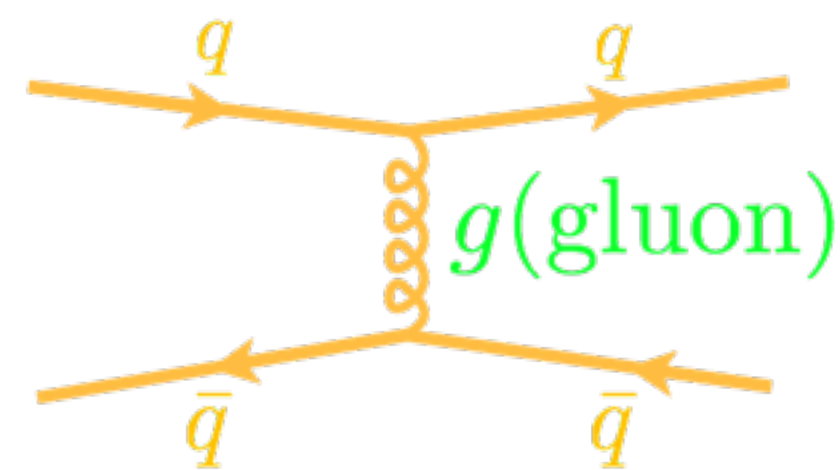
- Dark photons: Prompt and displaced lepton-jets
- Hidden valley pions: Displaced jets
- Magnetic monopoles: Highly ionizing particles (HIPs) / high electric charge objects (HECOs)
- Multi-charged particles
- Non-standard Higgs bosons and new vector gauge bosons: Three or more photons…

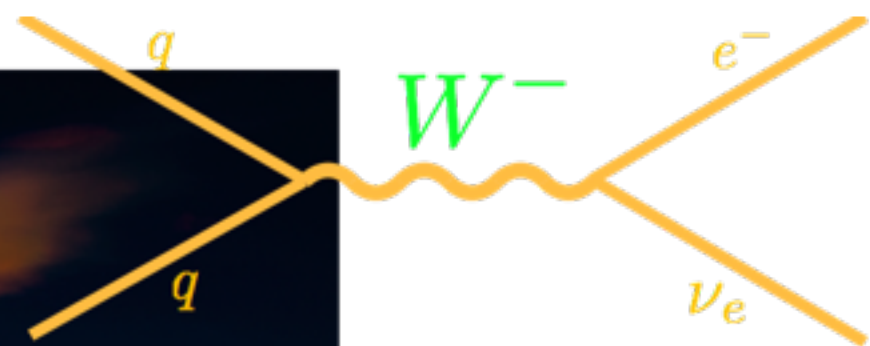
  … and the photon-beyond

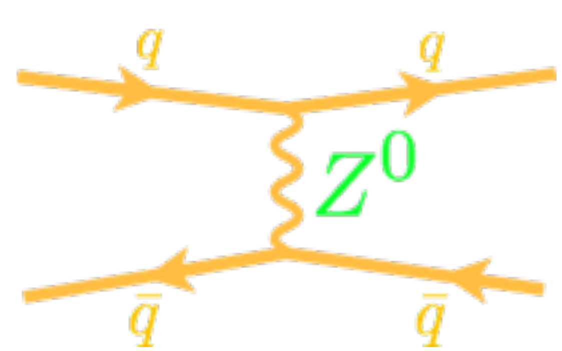
Forces that we care about at the LHC

1) Electromagnetism

2) Strong



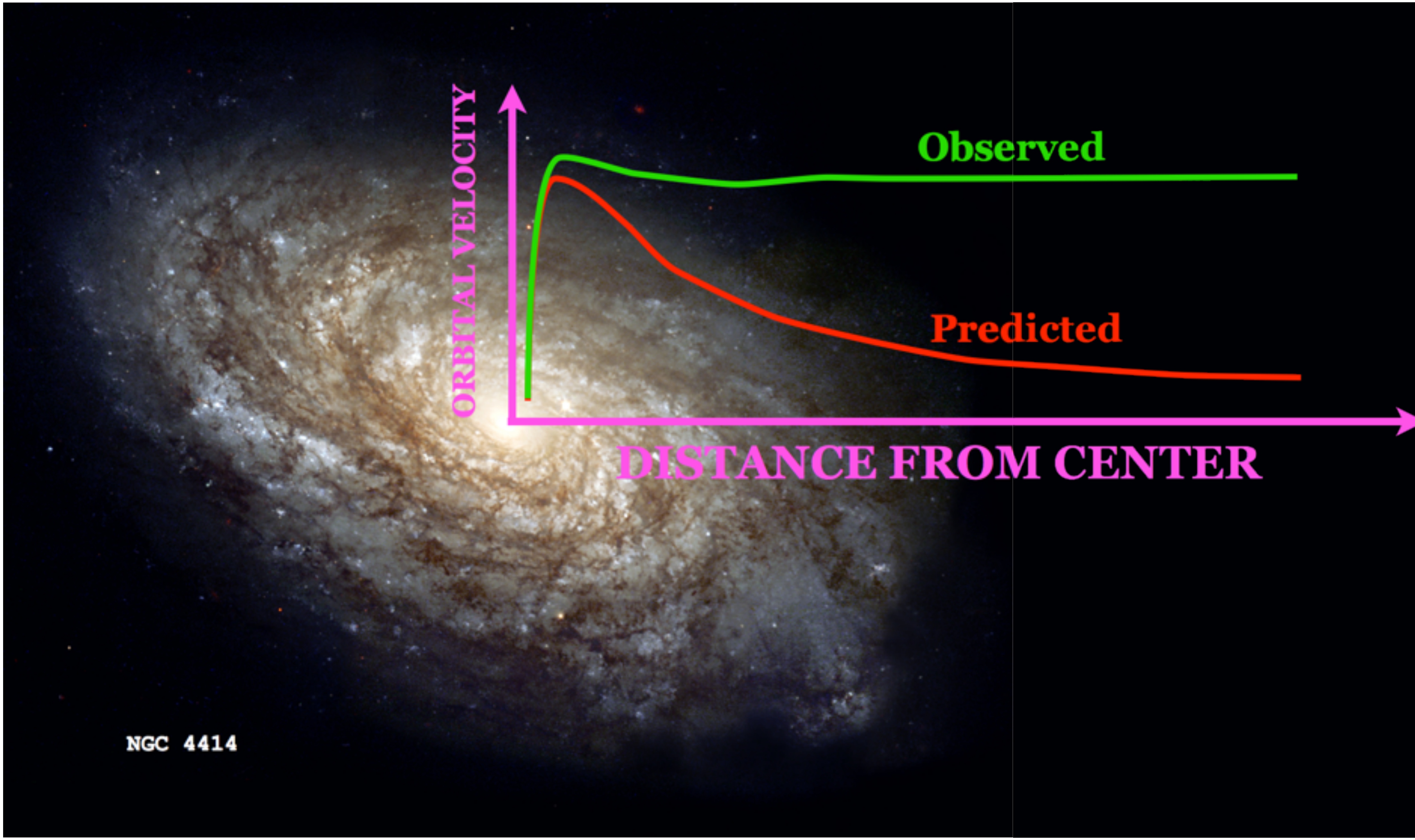




But is that it?

Dark photons

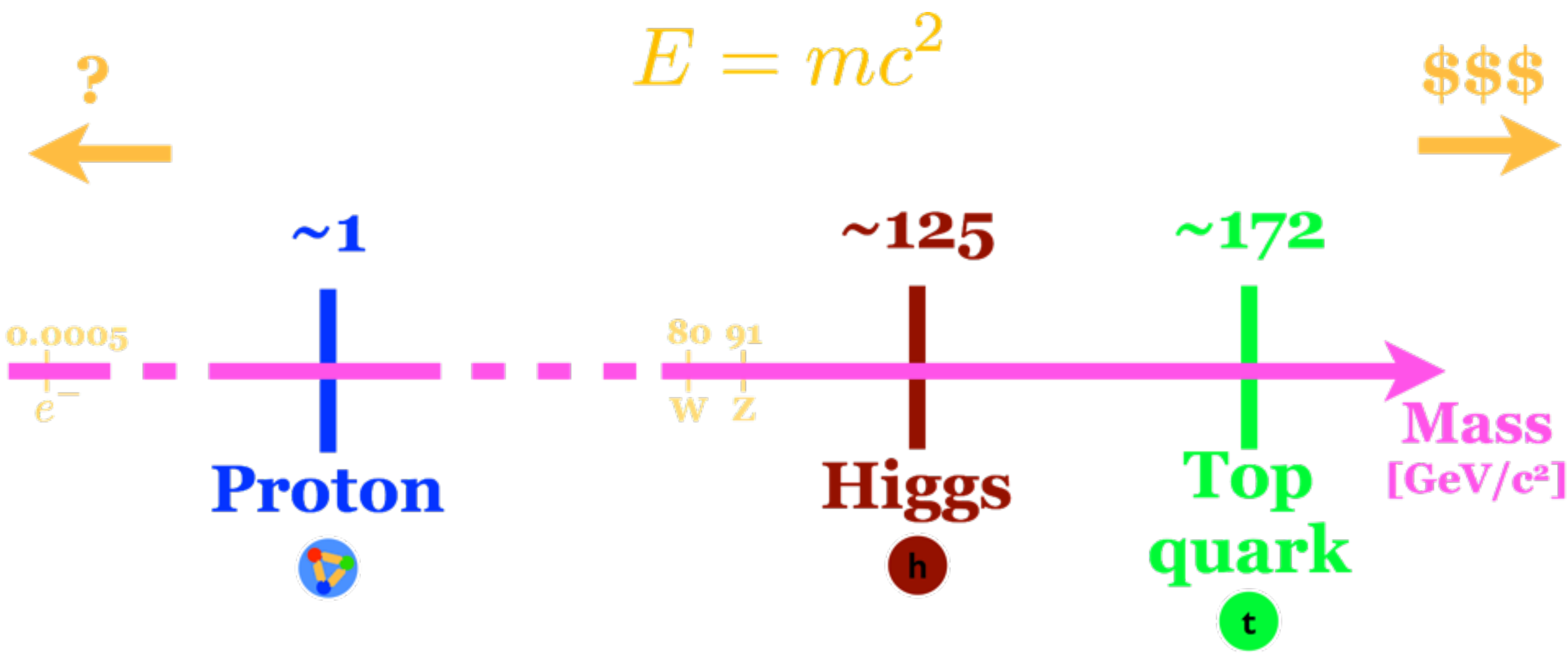
But is that it? Probably not.



But hasn't particle physics been around for a long time?

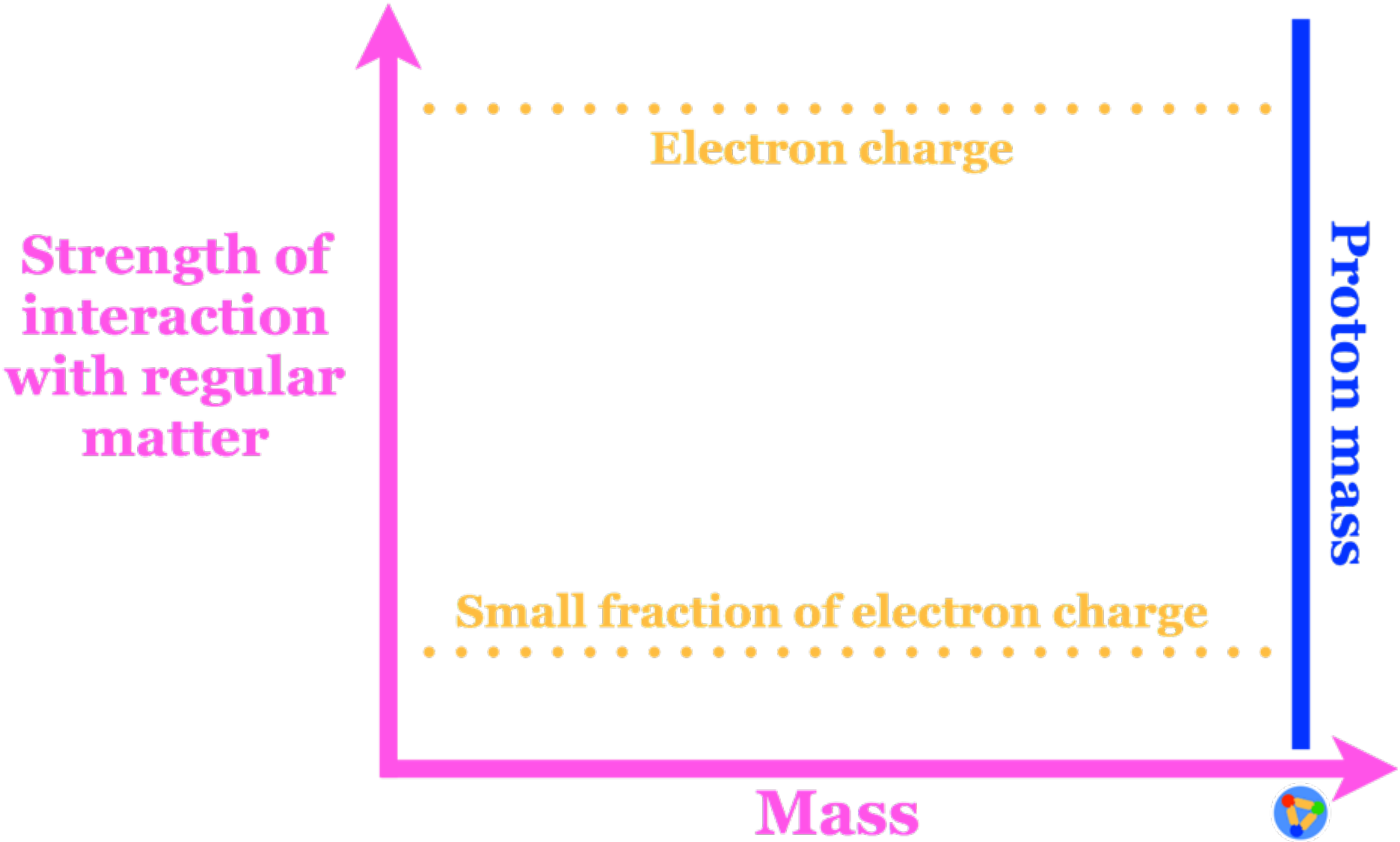
How could we have missed new forces?

One way: The gauge bosons associated to these forces are super massive.



Dark photons

Another way: The gauge bosons have a very small mass…



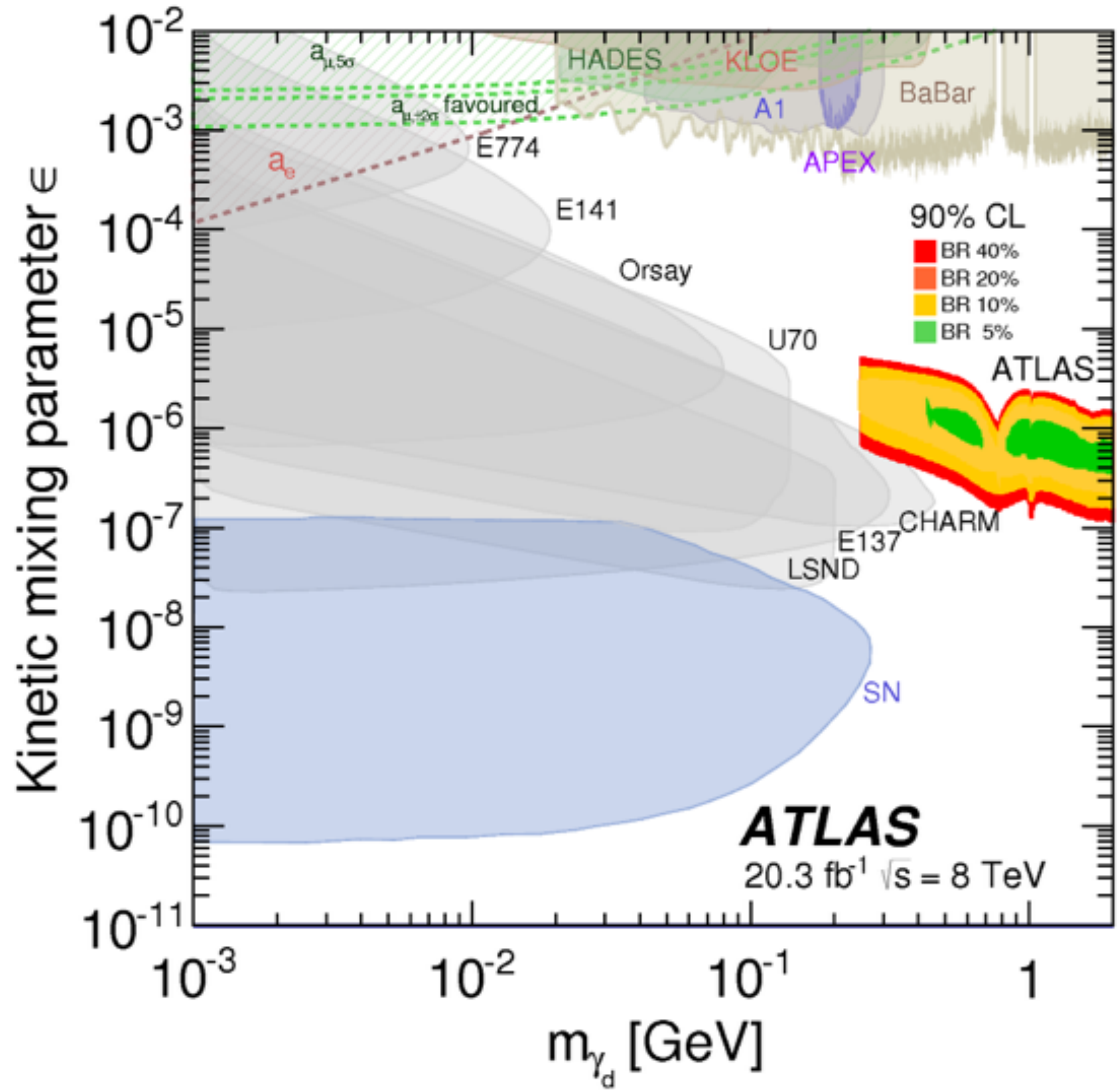
…and couple *very slightly* to Standard Model particles.

Another way: The gauge bosons have a very small mass…

…and couple *very slightly* to Standard Model particles.

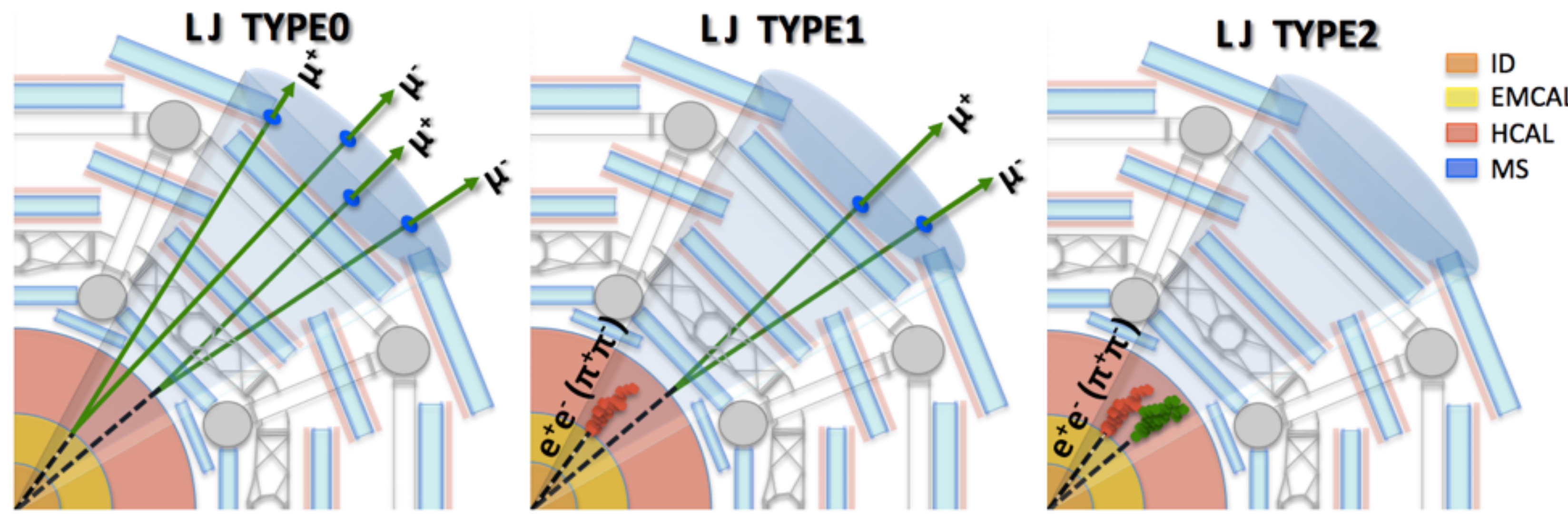
It turns out that this is a very good place for collider experiments to look for an explanation for dark matter anomalies. Previously only the purview of fixed target facilities, the LHC is now getting in on the action…

…via *lepton-jets*.

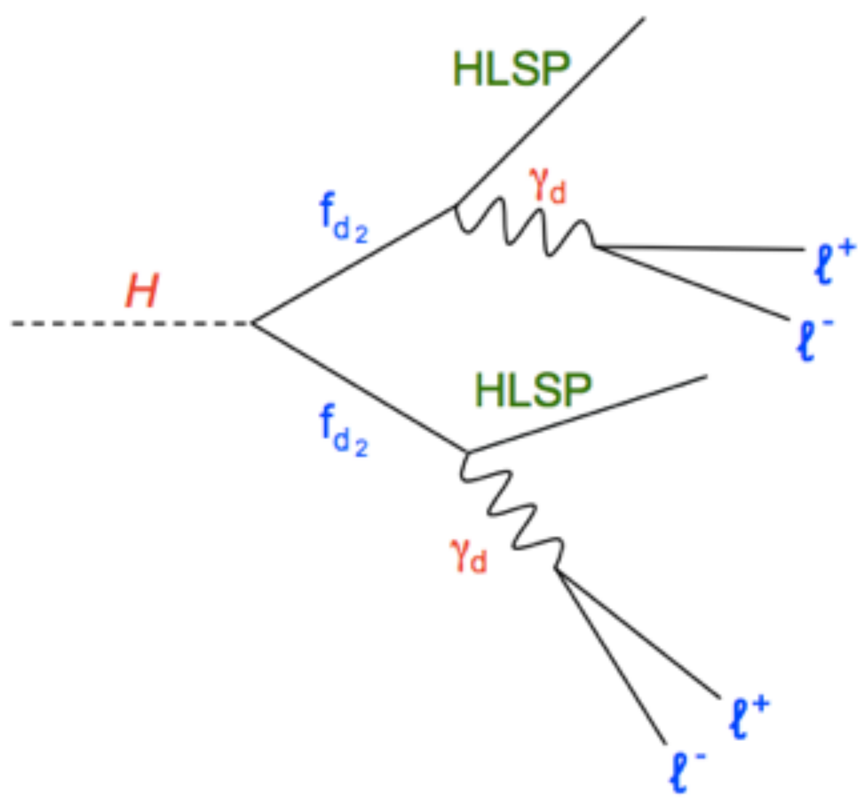


What happens when muons and/or electrons are right on top of each other in the detector?

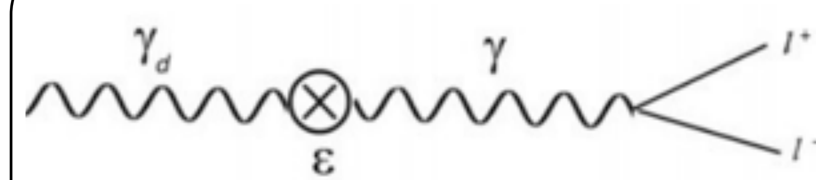
- Highly collimated groupings of leptons: **lepton-jets;** distinct LHC signature
- Standard muon ID benefits from isolation; here need dedicated clustering algorithm with a cone of ΔR



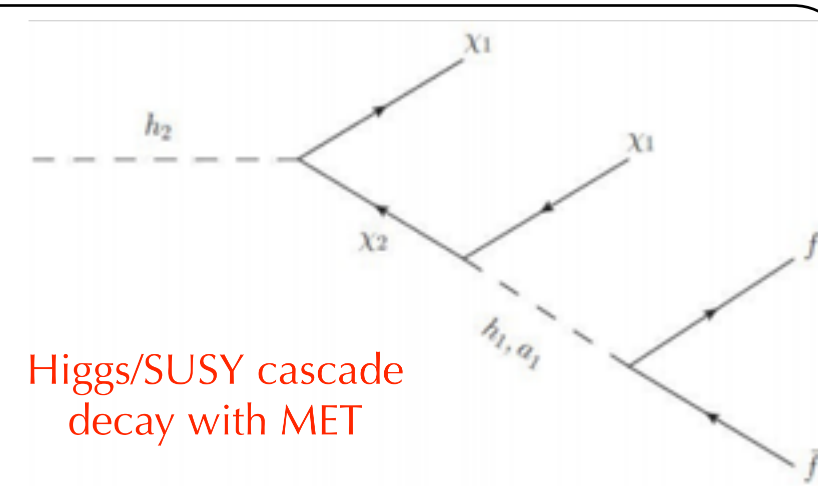
Model-independent search for lepton-jet objects, with a few benchmark signal interpretations



Dark/hidden sector coupled to SM Higgs and leptons via very light dark sector particles



Kinetic mixing portal



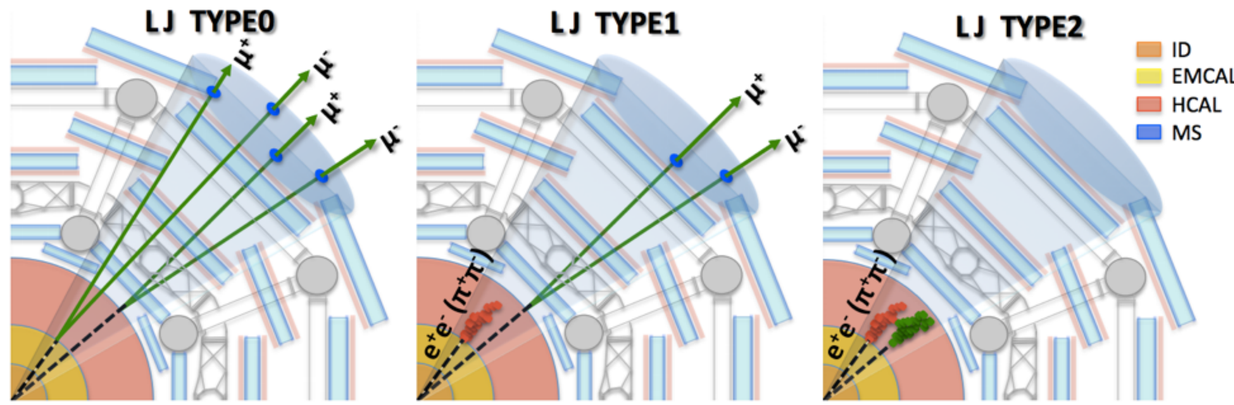
Higgs/SUSY cascade decay with MET

Prompt and displaced lepton-jets

Displaced — 8 TeV

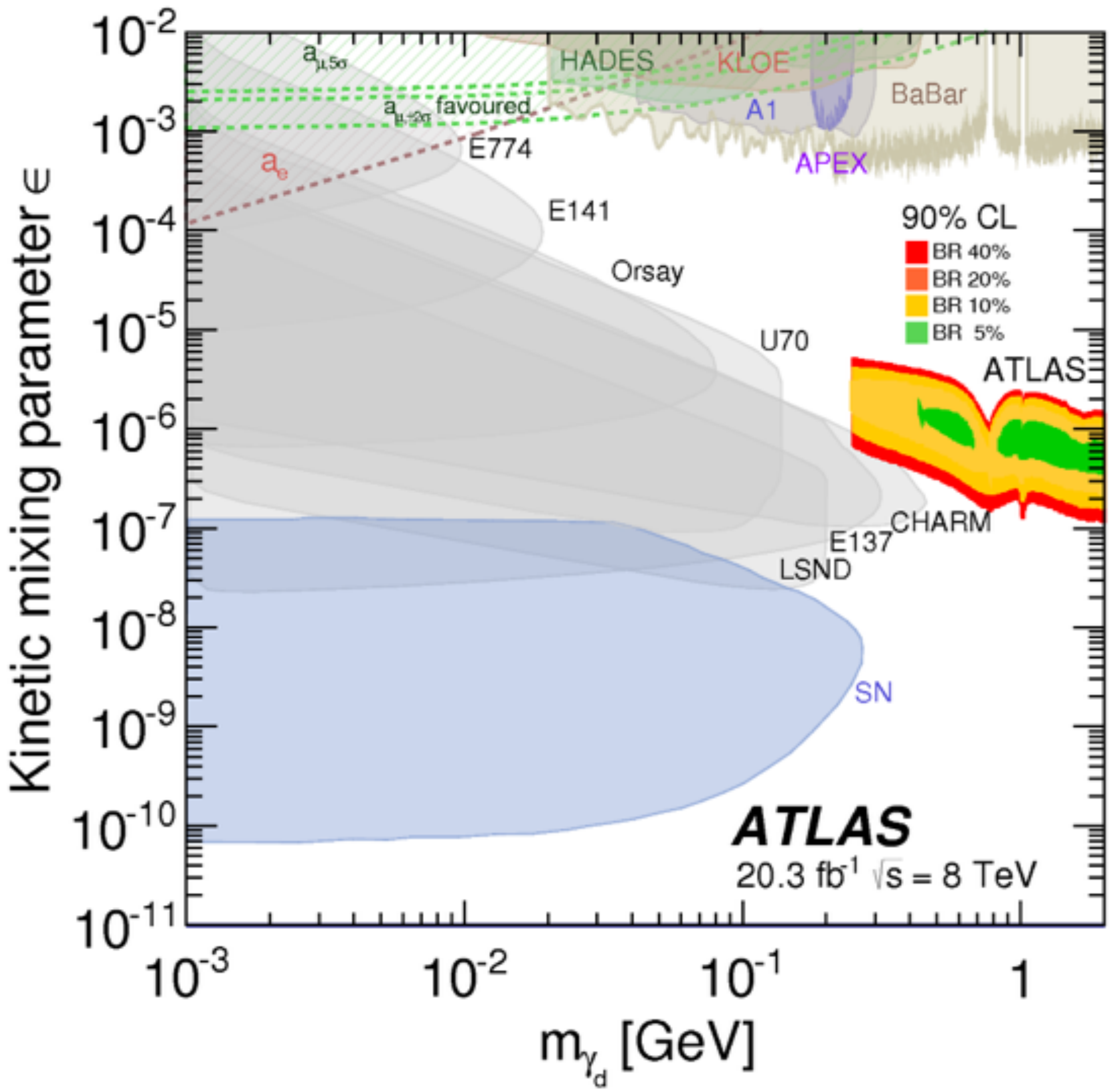
Three separate types of lepton-jet definitions considered

Cosmic backgrounds important



ATLAS: JHEP11(2014)088

Weak interaction ==> non-negligible dark photon lifetime

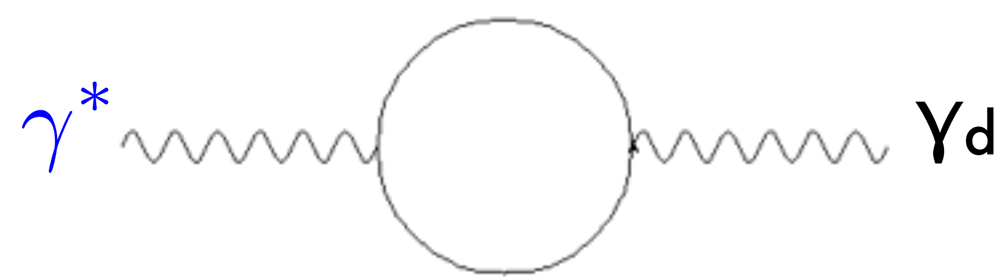


Kinetic mixing

Holdom, Phys.Lett. B166 (1986) 196

- Lagrangian contains a term

$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} \qquad \alpha'/\alpha = \epsilon^2$$



Effective coupling of dark photon to SM EM charge

Run 2 developments:

- Recover muon reconstruction efficiency for nearby muons and extend mass reach higher
- Investigate non-prompt electron LJs reconstructed as converted photons

What happens when a long-lived particle decays to hadronic jets far from the interaction point?

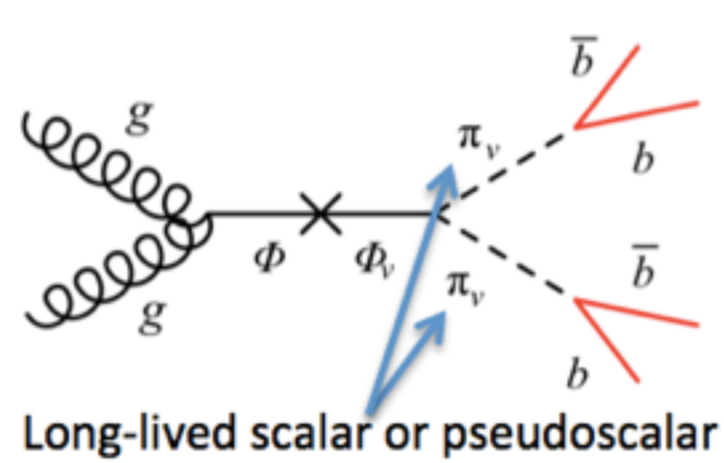
- Out-of-the-box jet reconstruction assumes inner detector tracking and pointing to common primary vertex, as well as nice calorimeter clusters, etc.

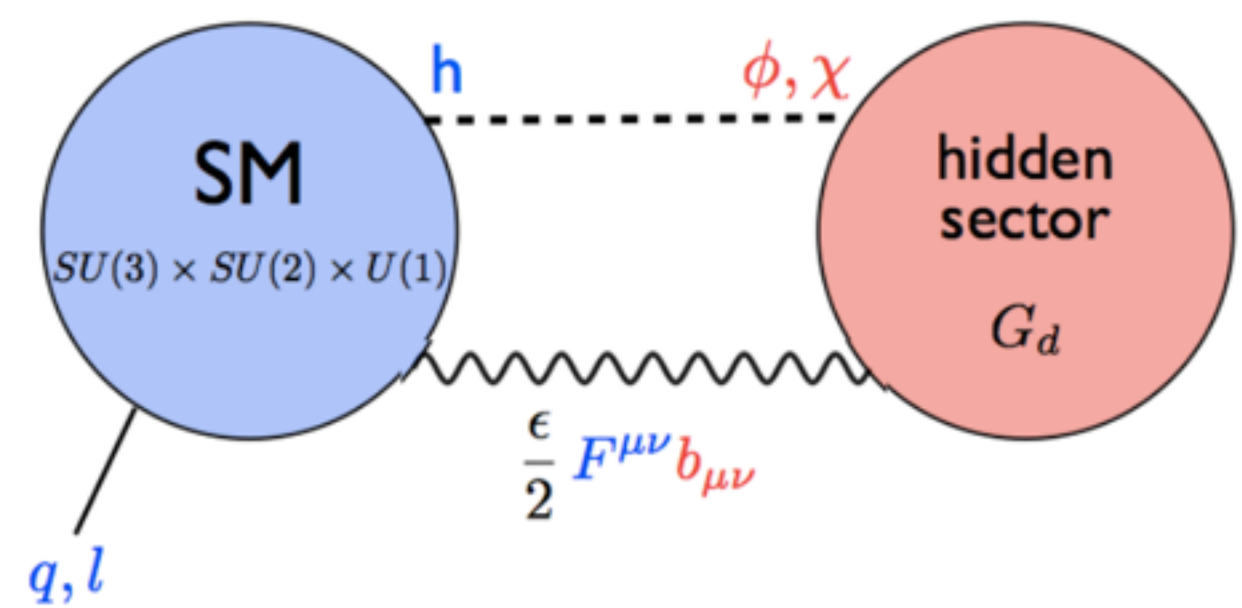
What if the particle decays in the middle of the calorimetry?

CalRatio: Pair of jets decaying in the HCal
- A narrow radius
- No ID tracks pointing towards the jet
- Large energy deposit in the HCal with little to no energy in the ECal
- Primary background from SM multijets

What if the particle decays in the inner detector but at a sizable distance from the nominal interaction point OR decays all the way out in the muon spectrometer?

MS-ID: Two or more jets in the ID and/or MS





See *Exotic Decays of the 125 GeV Higgs Boson* for an exhuastive roundup: arXiv:1312.4992

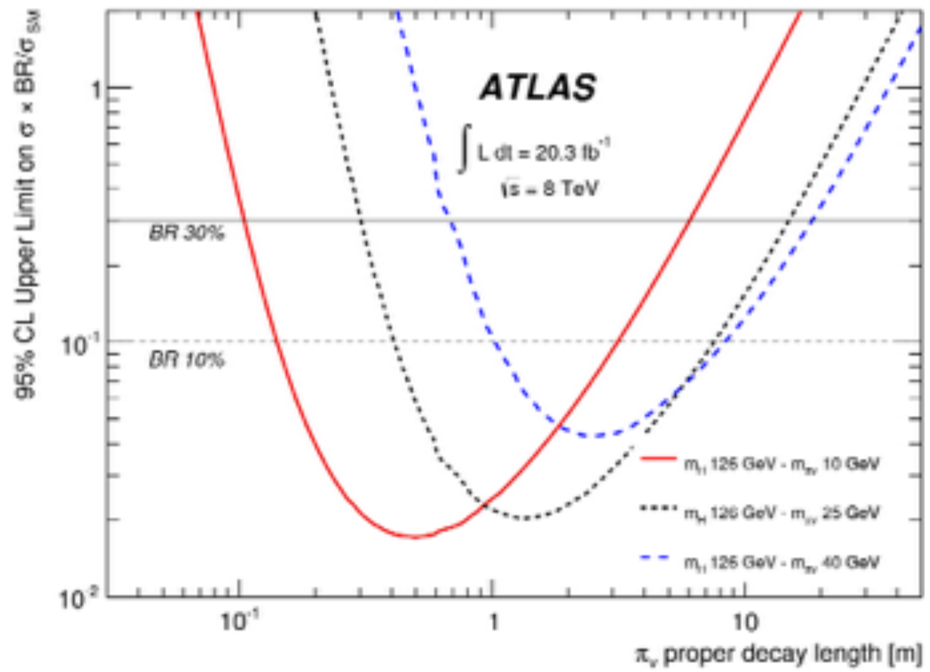
INFN Rome, UMass Amherst, U. Washington

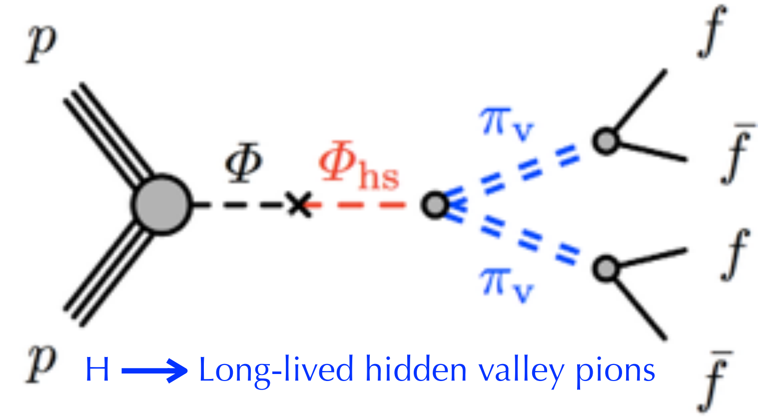
Displaced vertices/hadronic jets

ATLAS: PLB 743 (2015) 15-34

DJs in the hadronic calorimeter

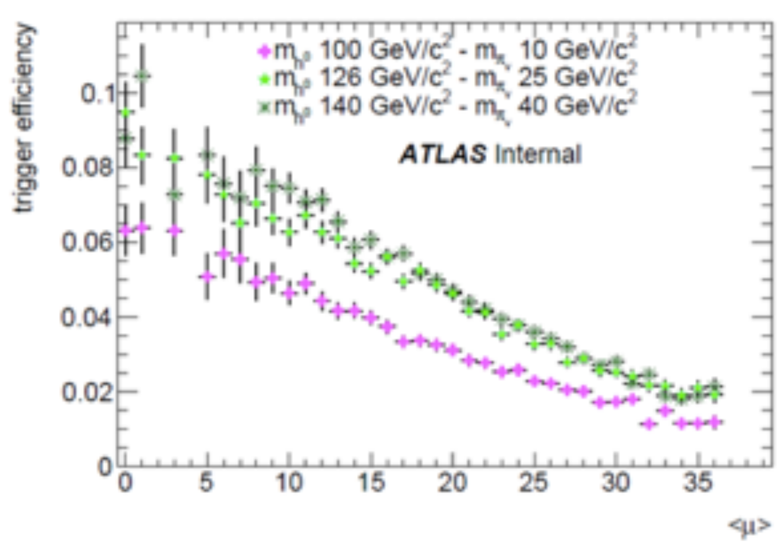
Pair of jets decaying in the HCal, no ID tracks pointing towards the jet





Run 2 challenges

- Pileup tracks ruin jet track isolation criteria
  ==> Trigger modifications underway (z0 cut)

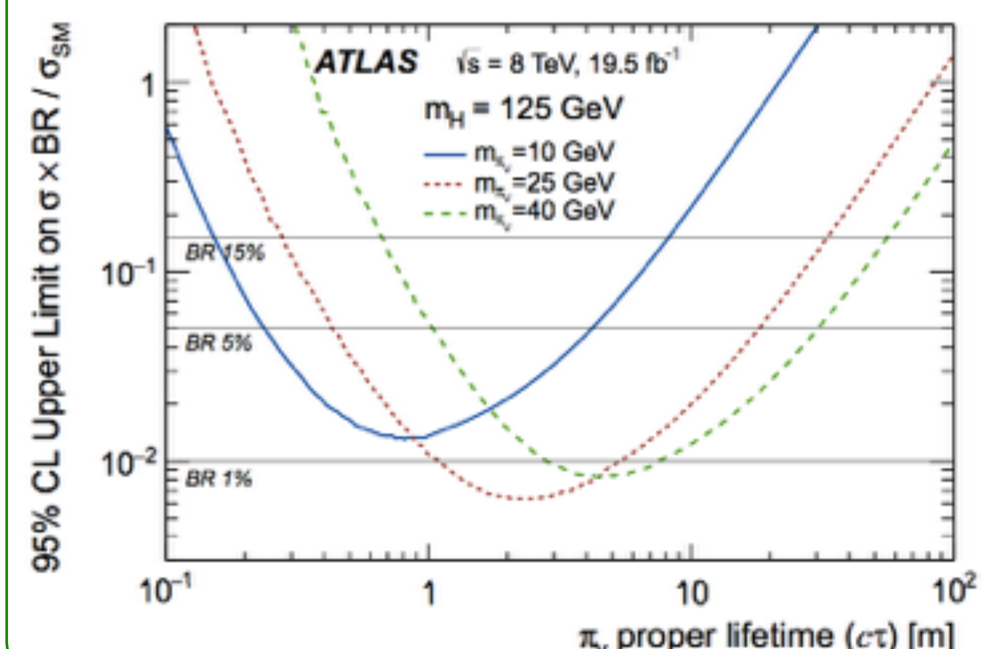


- Other track-related quantities for signal jet and trackless SM multi-jet backgrounds

ATLAS: PRD92 (2015) 1, 012010

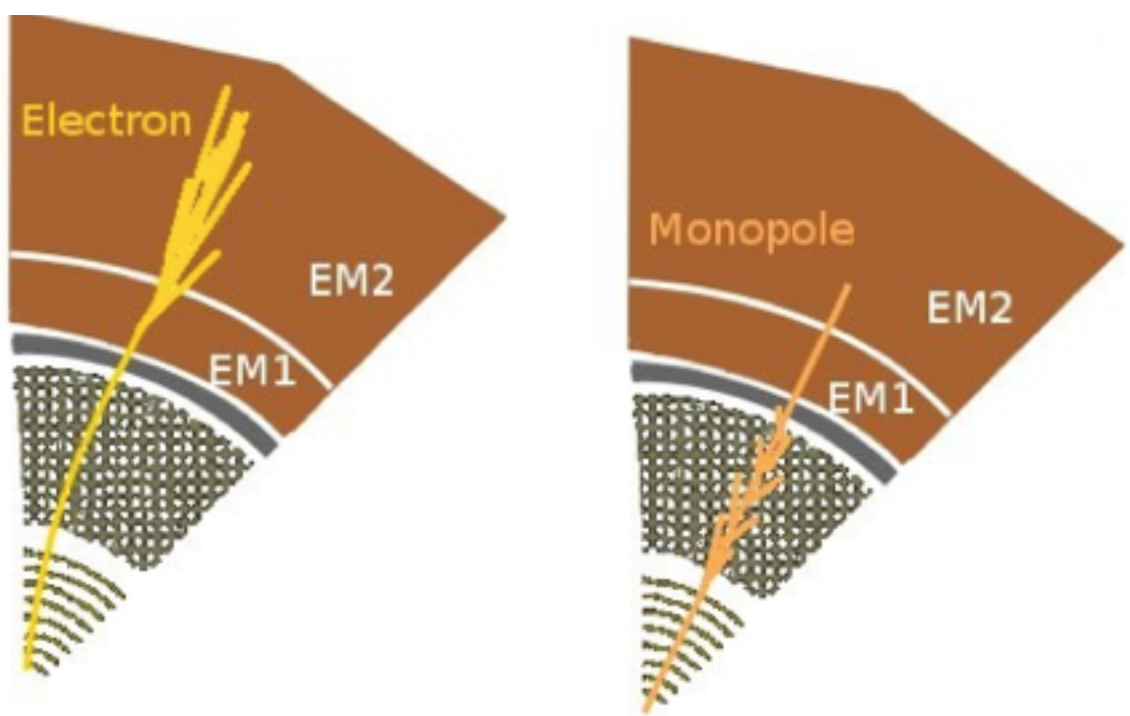
DJs in the ID or muon spectrometer

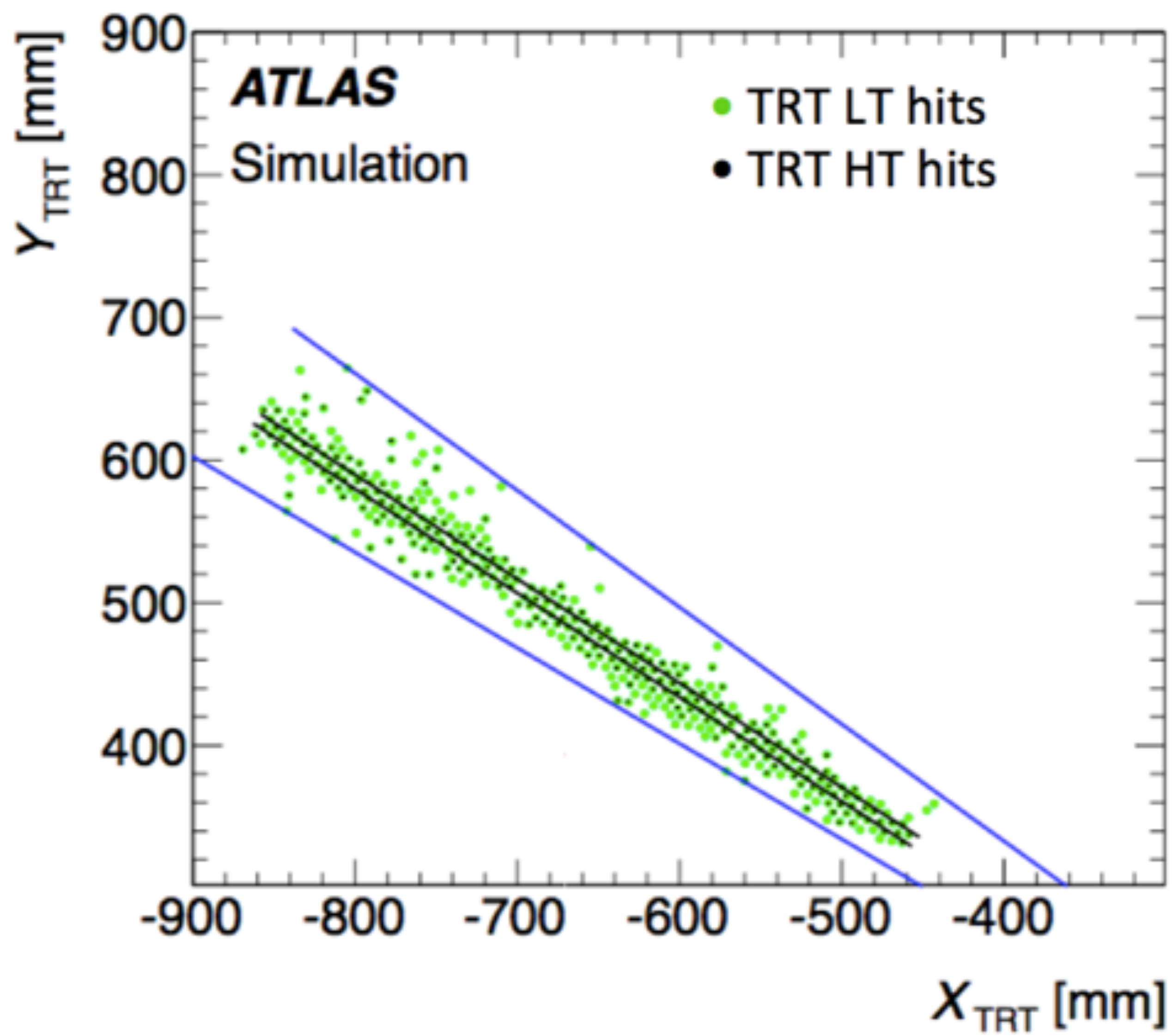
Five topologies defined by combinations of muon and jet + E_T^{miss} triggers



What happens when the charged particle you seek refuses to behave like a charged particle?

- Very high electric charge
- Not a track but a road of high-threshold hits in the tracker without an electron-like energy deposit



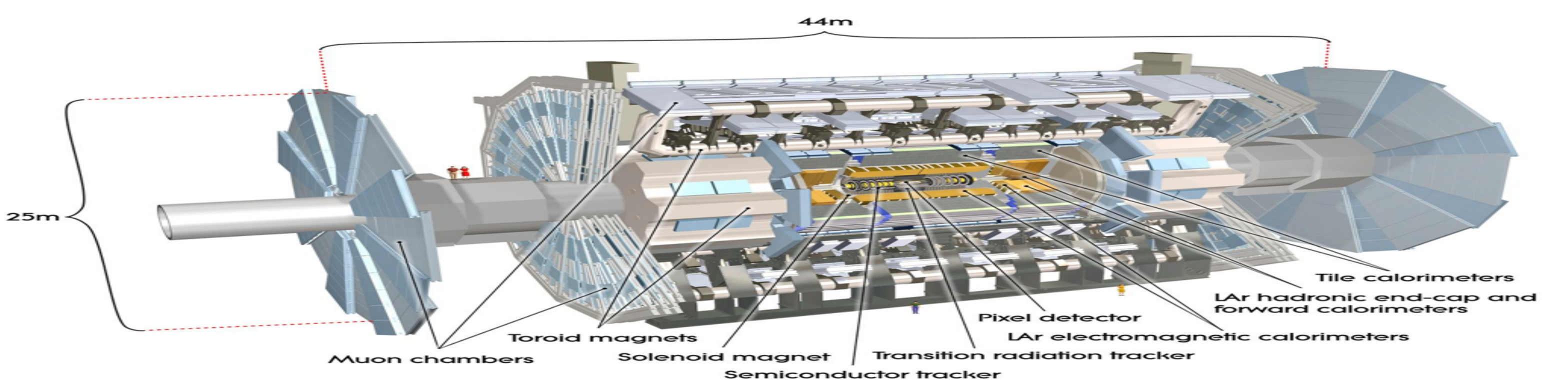


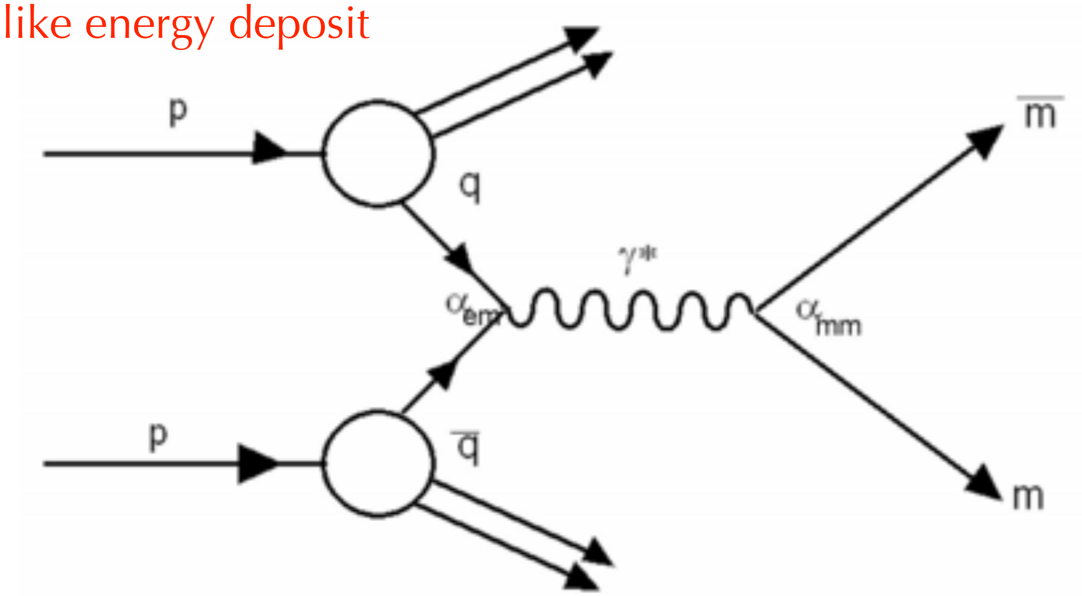
Search is sensitive to general high-electric-charge objects (HECOs)

- High ionization energy loss along trajectory
- Very high charge —> stopping, electron-like, but *not* electrons

What's an example of something that behaves like this?

- Magnetic monopoles
- Not a track but a road of high-threshold hits in the tracker without an electron-like energy deposit





HIP ionization in the TRT exceeds the high level threshold producing high-threshold (HT) hits

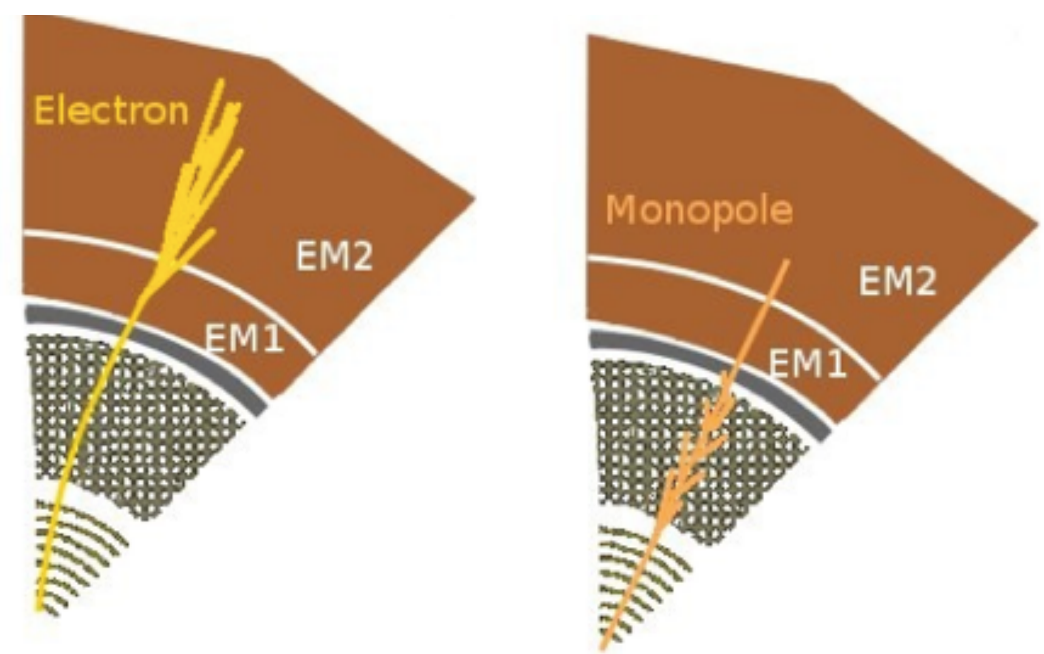
δ-electrons deposit a few keV in the straw where they were produced and neighbouring straws producing TRT HT hits

A swath of TRT HT hits is the signature of a HIP in the TRT; his affects the use of track reconstruction

Narrow calorimeter cluster due to absence of electromagnetic cascade

HIPs stop early in the LAr EM calorimeter making the energy deposited in the presampler and EM1 of great importance to this search

Wendy Taylor



Monopoles don't play nicely with our standard ATLAS analysis framework

$$\frac{d\vec{p}}{dt} = g\vec{B}$$

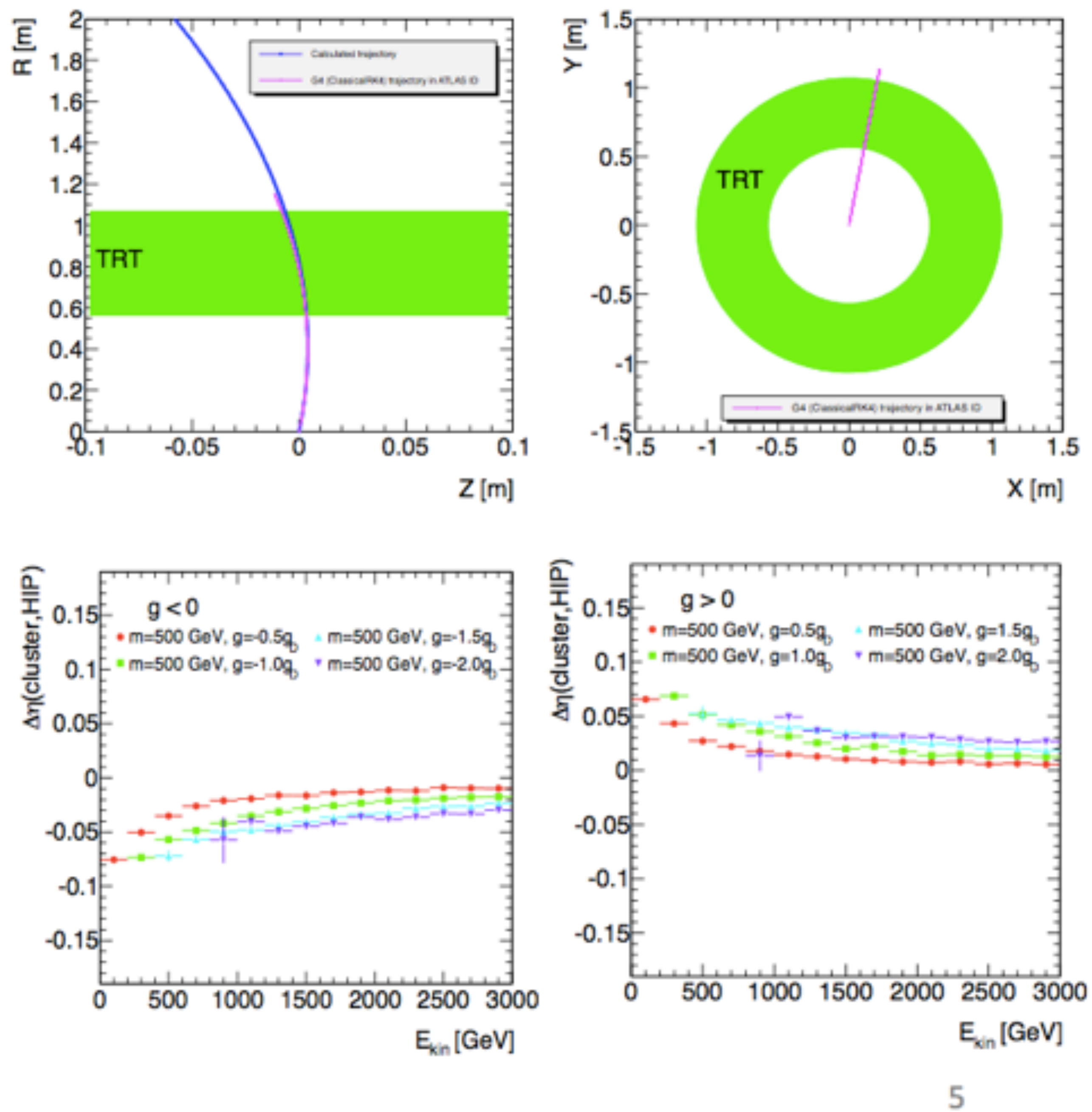
Monopole trajectory bends in the r-z plane

Standard ATLAS inner tracking doesn't work

- Cannot use any standard objects (e.g., electrons)
- Need access to TRT hit information (**not** just "hits on tracks")

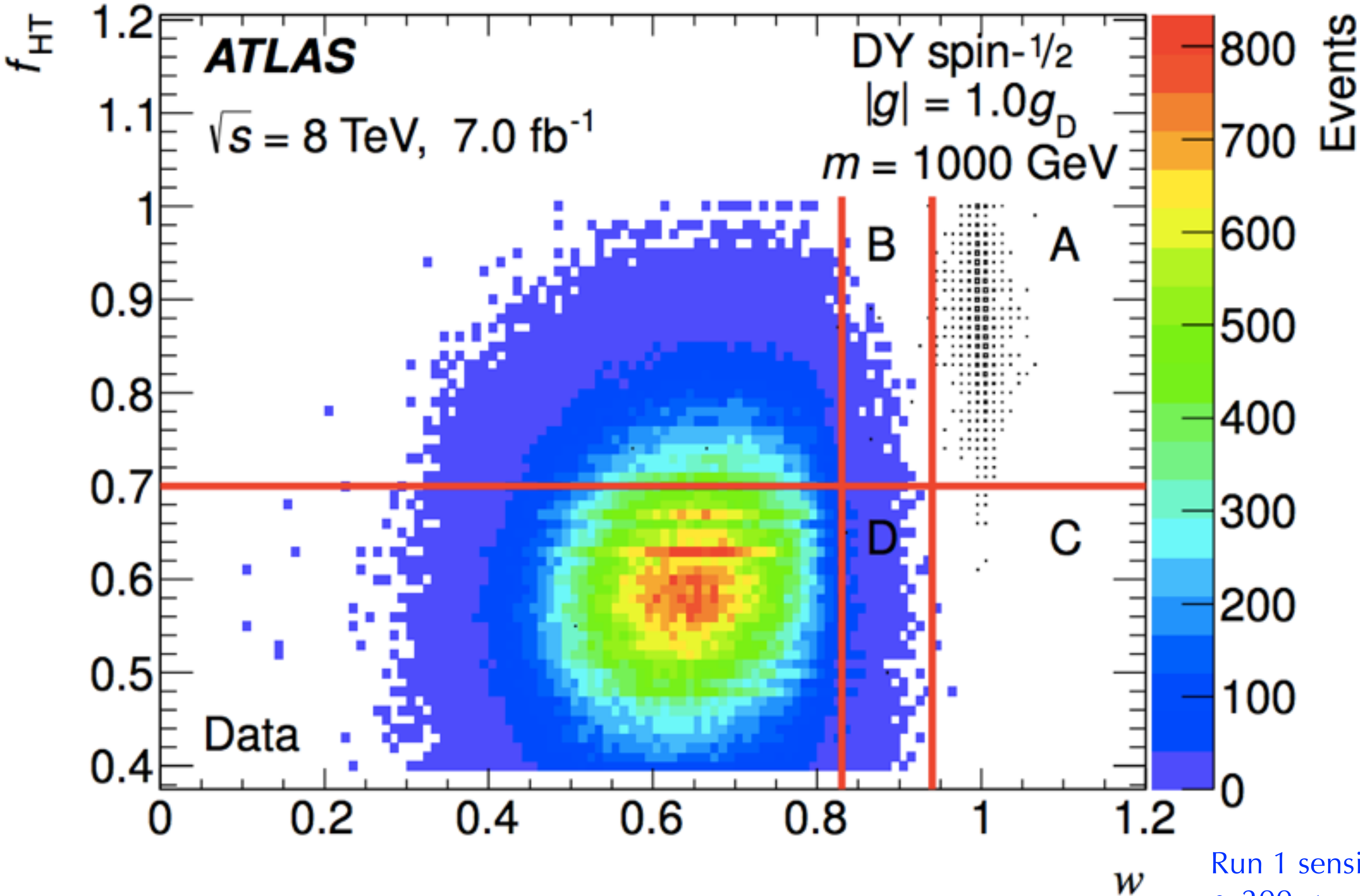
Search required an completely custom-made trigger to be designed, commissioned and implemented midway through Run 1

- Final 8 TeV paper is with ~7/fb, not the ~20/fb of the full Run 1



Wendy Taylor

Run 1 results: No magnetic monopole observed

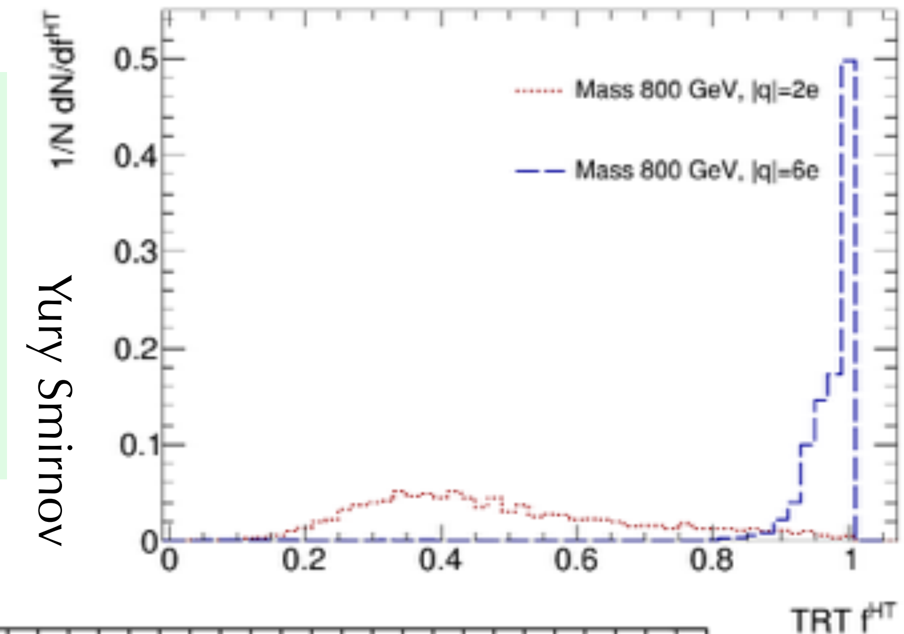


Run 1 sensitivity
- 200 < m_{HECO} < 2500 GeV
- 0.5 < $|g_D|$ < 2
- 10 < $|z|$ < 60

Run 1 (8 TeV): arXiv:1509.08059

What happens when the charged particle you seek refuses to behave like a charged particle — muon-like version?

- Search for long-lived highly ionizing heavy particles with high electric charges (|q| = 2e, 3e, 4e, 5e, & 6e) mainly by their ionization losses;
- Analysis ingredients: muon and MET triggers + muon-like tracks with high dE/dx along their trajectories in all subsystems;

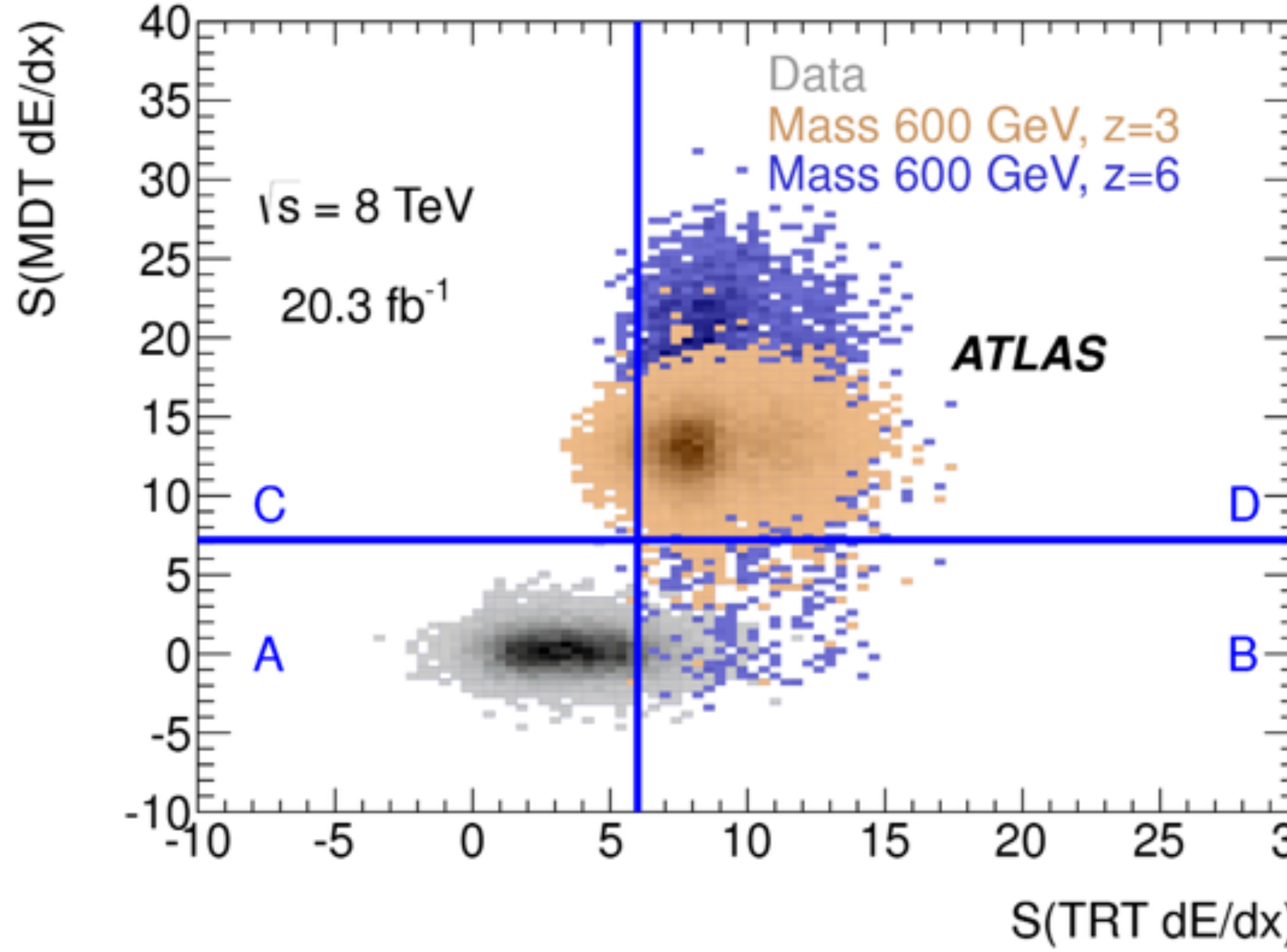


Walking technicolor, doubly-charged Higgses, composite dark matter, etc.

Signal particles have a muon-like signature, losing an anomalously high amount of energy per distance in all subdetectors

Look for events with a pair of multi-charged particles, for |q| = {2,3,4,5,6}e

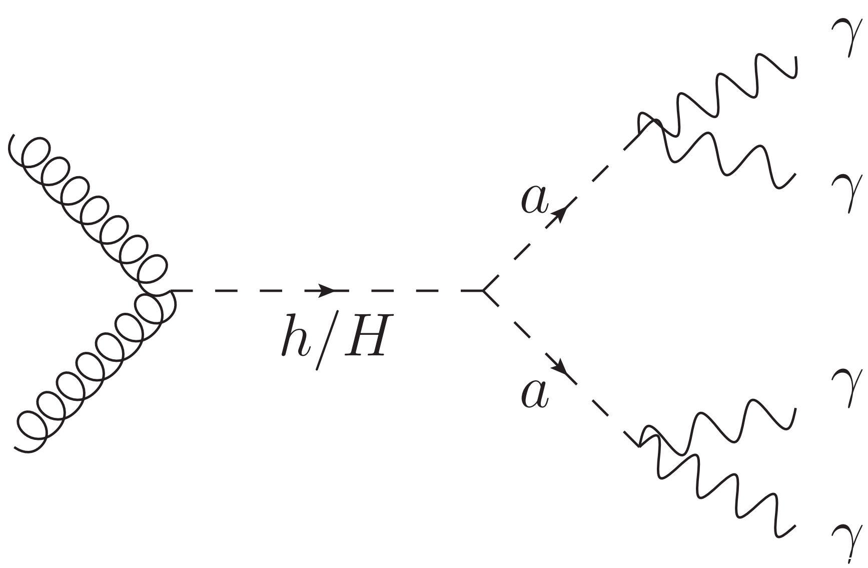
$50 < m_{MCP} < 1000$ GeV (8 TeV)



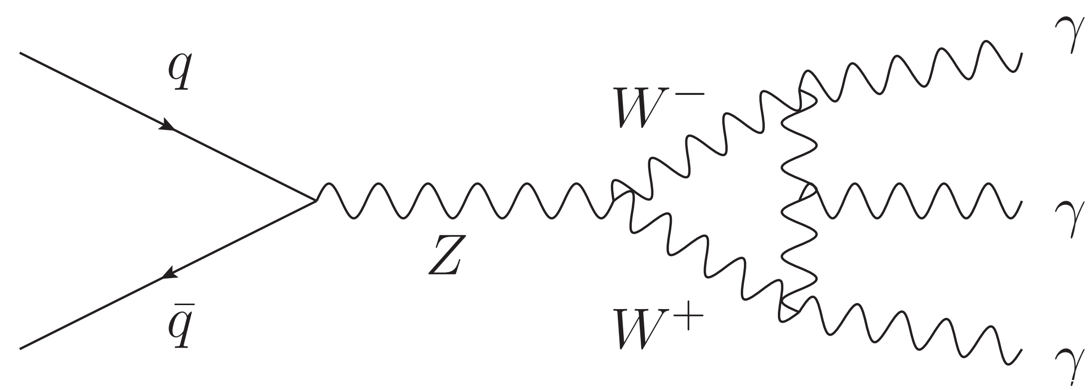
Run 1 (8 TeV): [EPJC 75 (2015) 8, 362]

What happens when you're looking for too many low-energy photons?

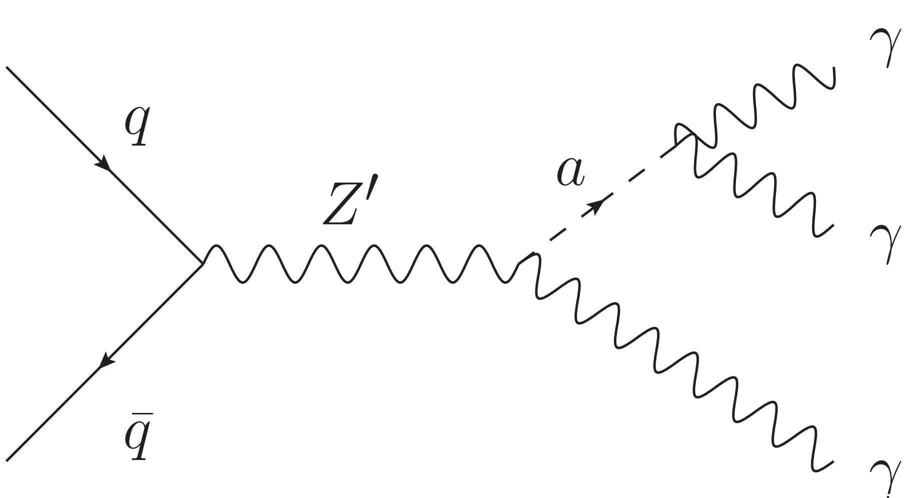
- Standard methods of estimating jet backgrounds break down
- Photon ID needs to be augmented for nearly-merged photons



BSM Higgs decays



Rare Z decays



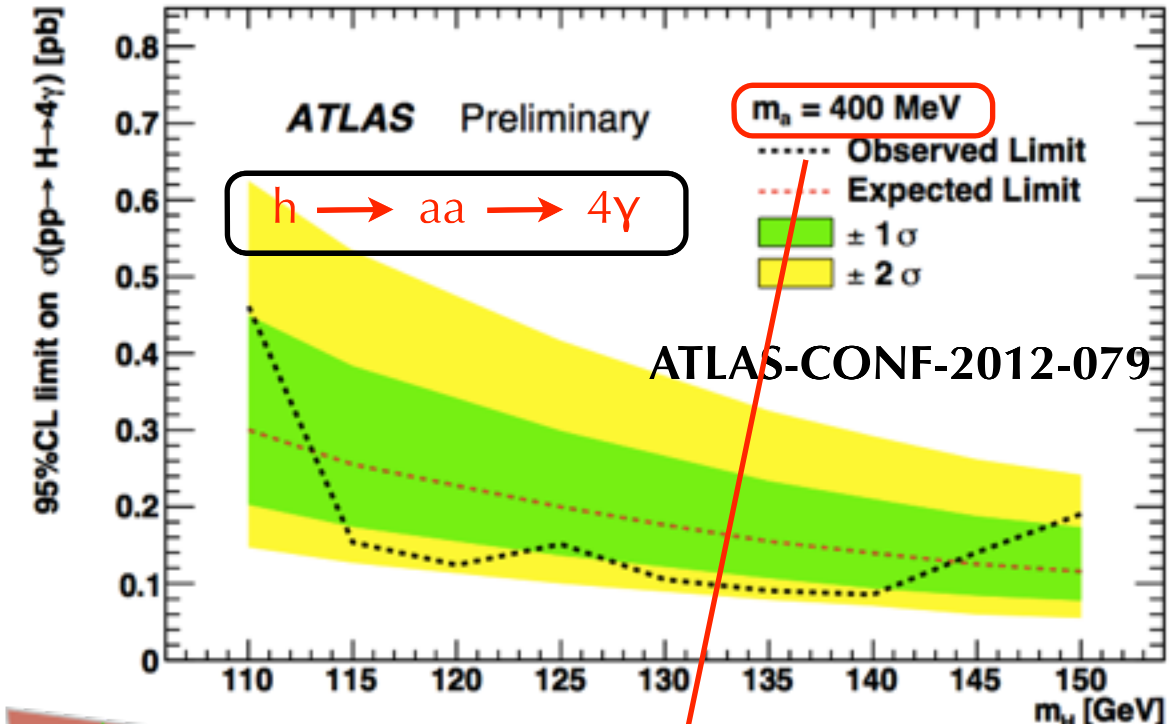
Z′ to photons

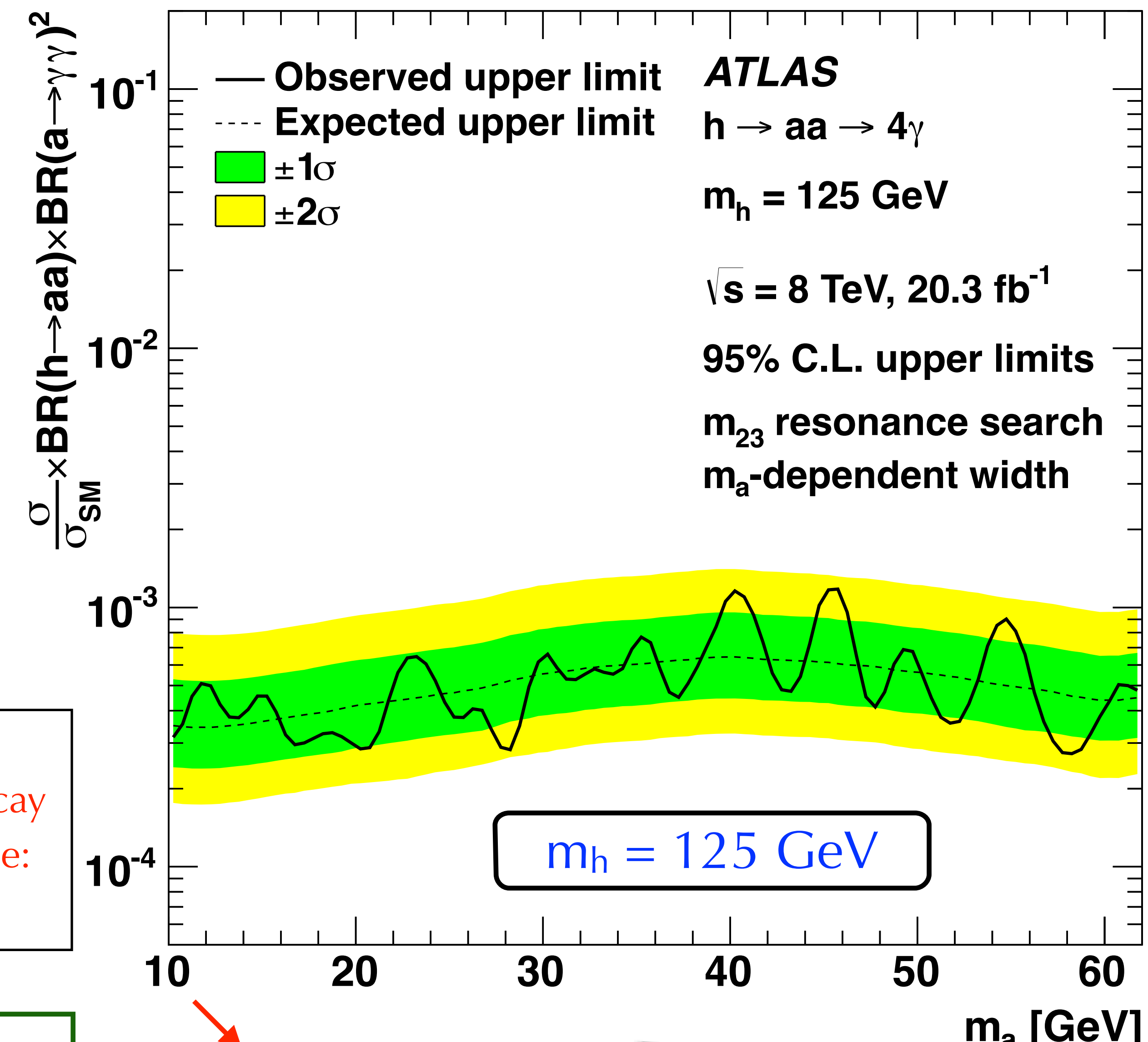
How to find new physics here

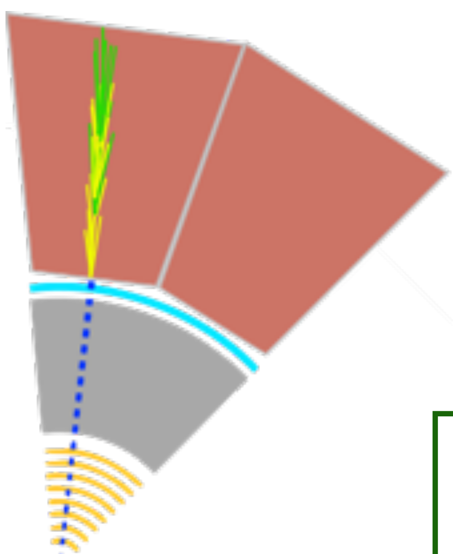
- **Number-counting (look for an overall excess of events) in inclusive signal region, Z —> 3γ signal region, and fiducial kinematic region**
  - Most general results on fiducial cross section for new phenomena
- **Resonance searches in 2/3γ mass spectra**
  - Search for local excesses corresponding to detector mass resolution

Multi-photon signatures

Limited sensitivity at medium-low-mass two-photon resonances



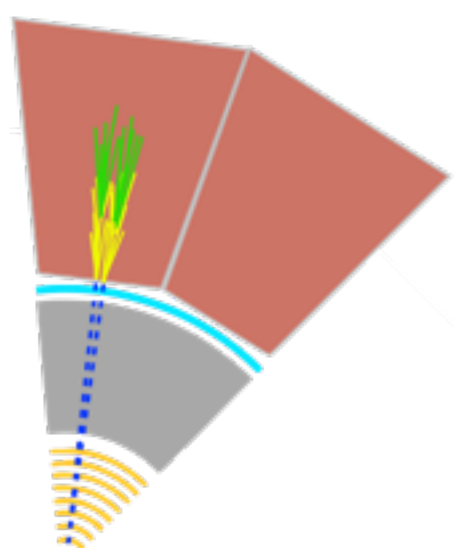




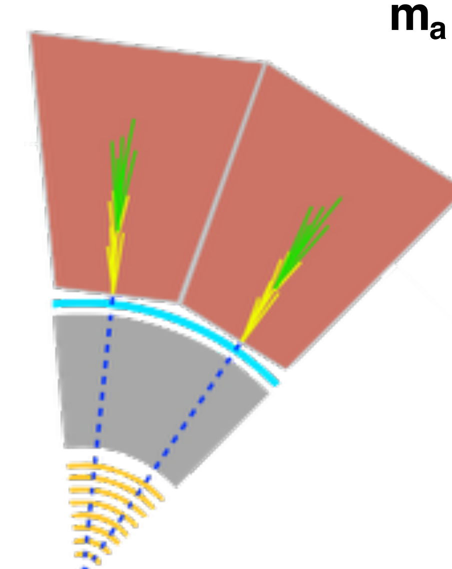
Highest limit for $m_a \sim$ 400 MeV

Rule-of-thumb:
Opening angle of decay products of X particle:
$\Delta R \sim 2 * m_X / p_{T,X}$

Lowest limit for m_a = 10 GeV

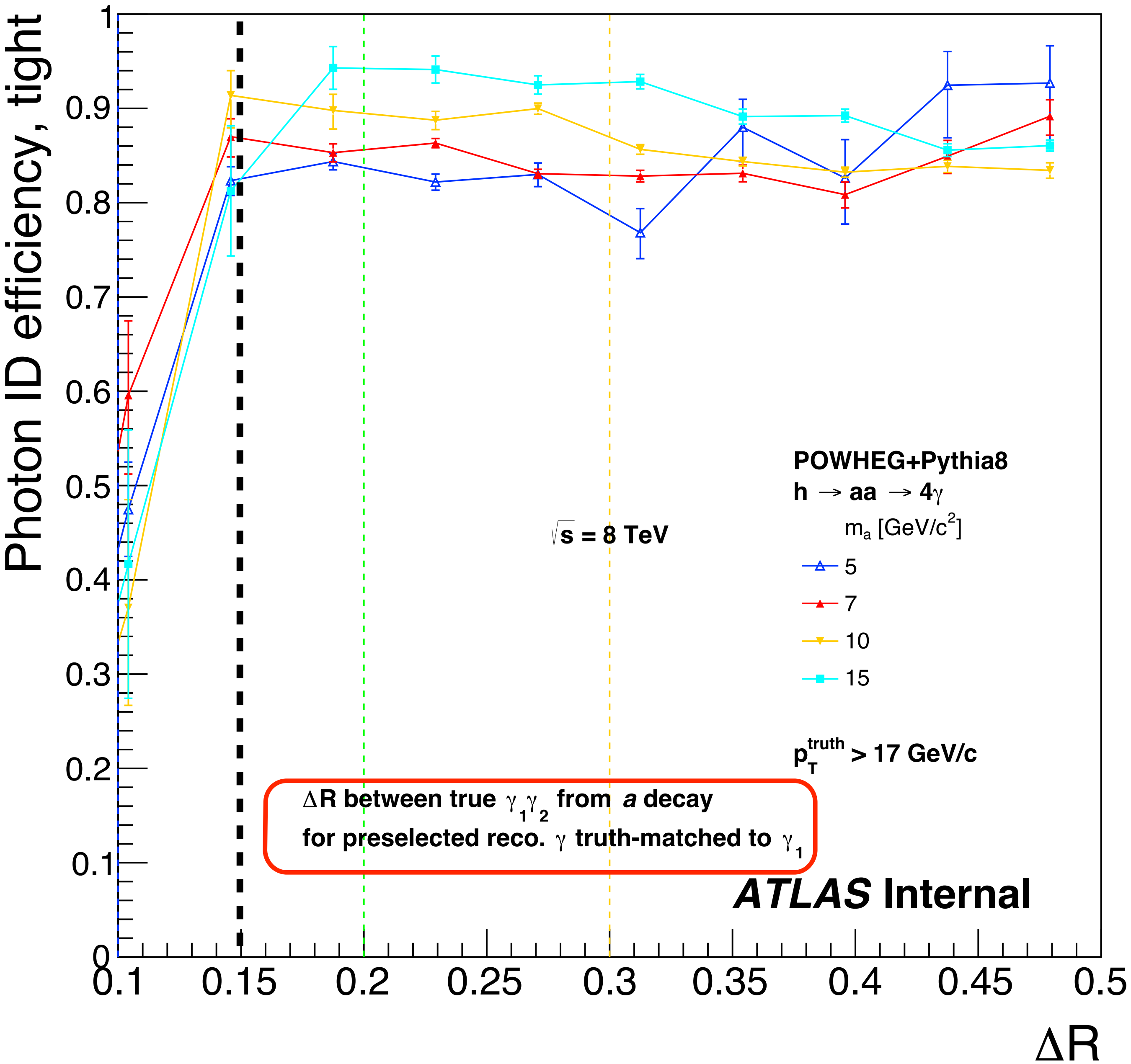


Gap in the search for this BSM Higgs decay, where the two photons are nearly-merged

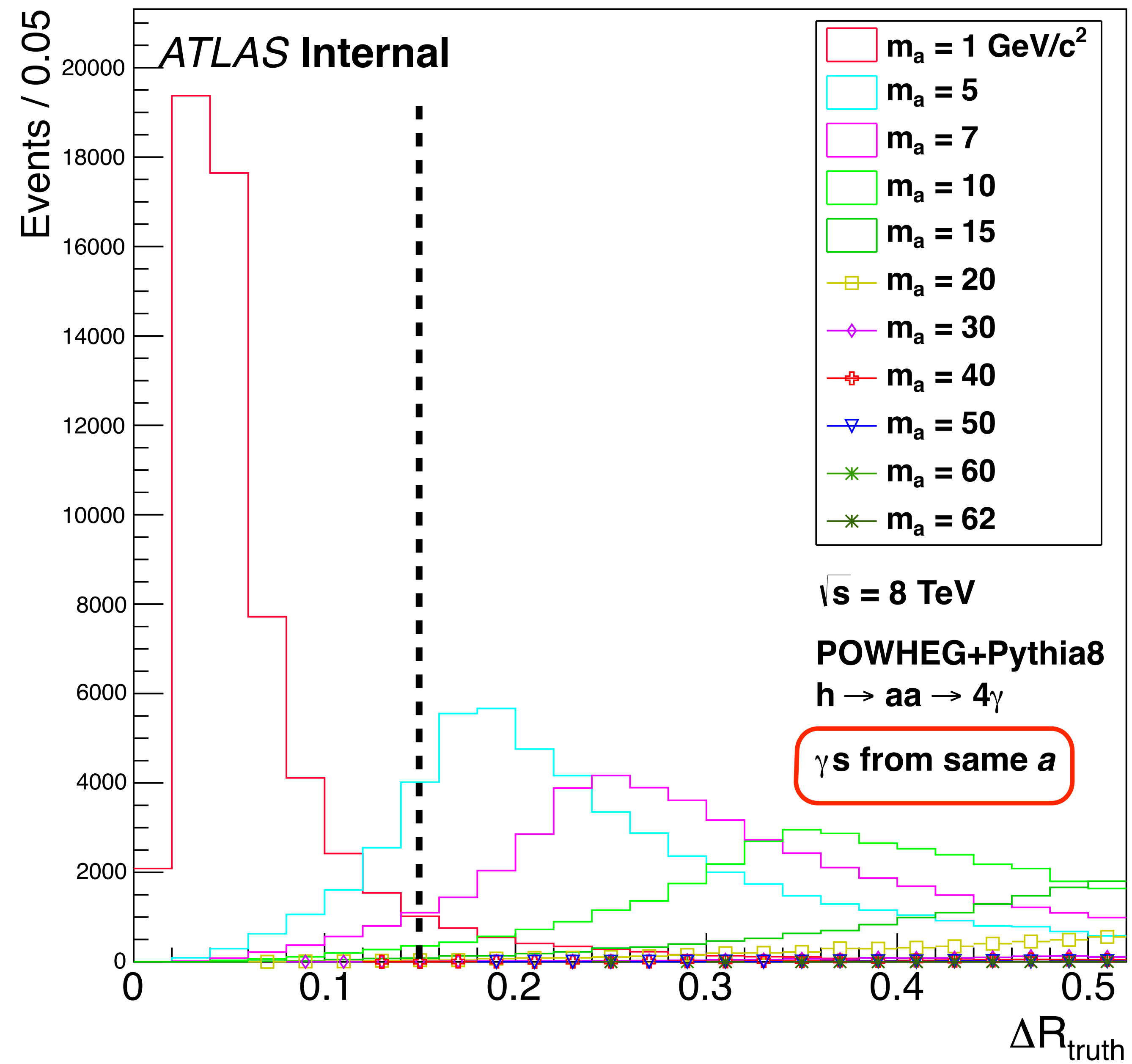


Multi-photon signatures

h ⟶ aa ⟶ 4γ



m_h = 125 GeV



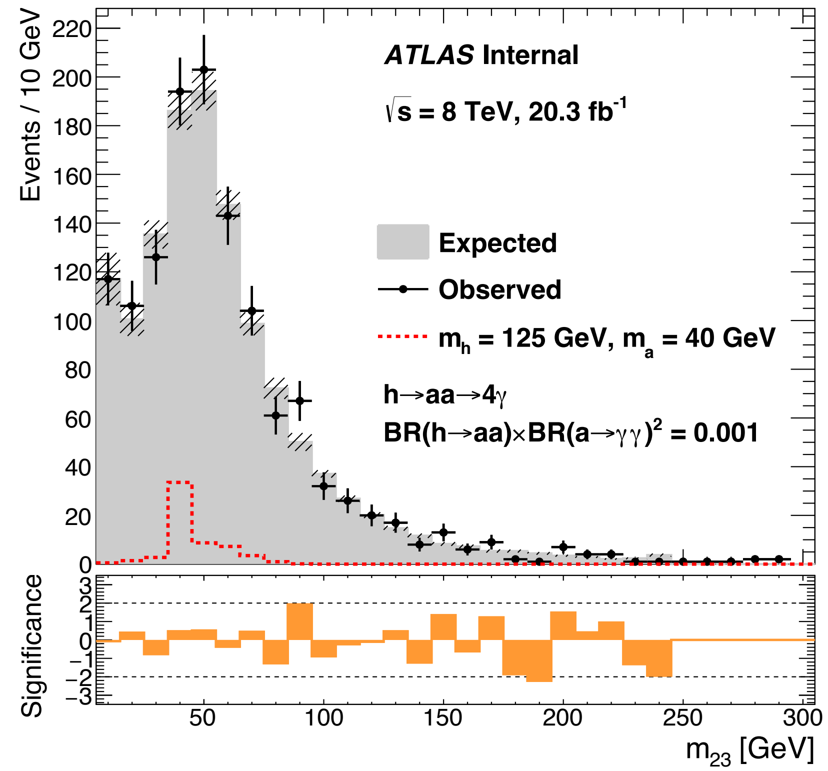
Motivates requirement of **ΔR > 0.15** for all pre-selected photons; sacrifice sensitivity at low m_a

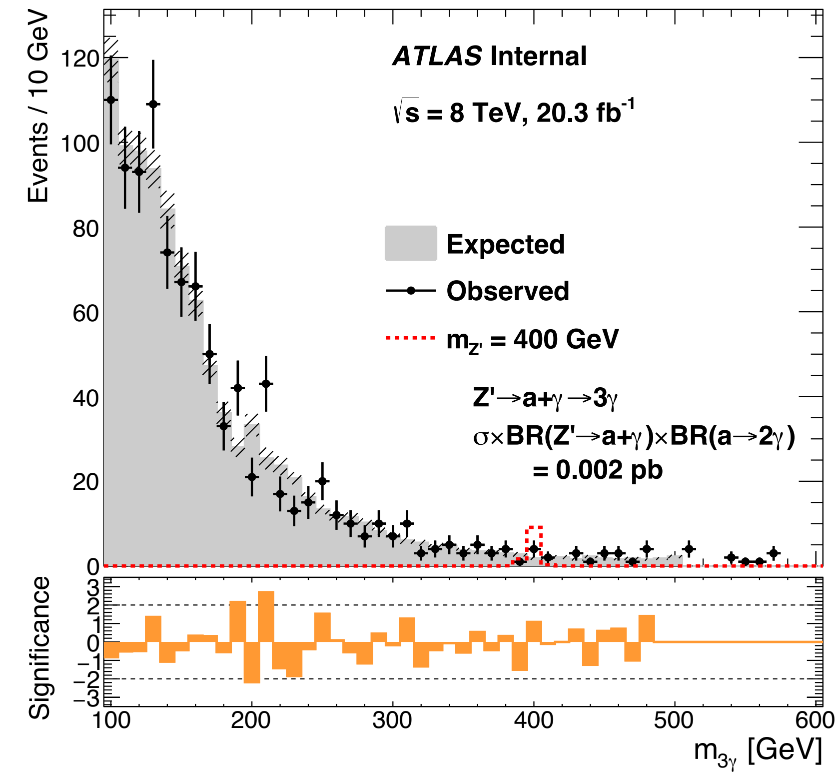
Rule-of-thumb:
Opening angle of decay products of X particle:
$\Delta R \sim 2 m_X / p_{T,X}$

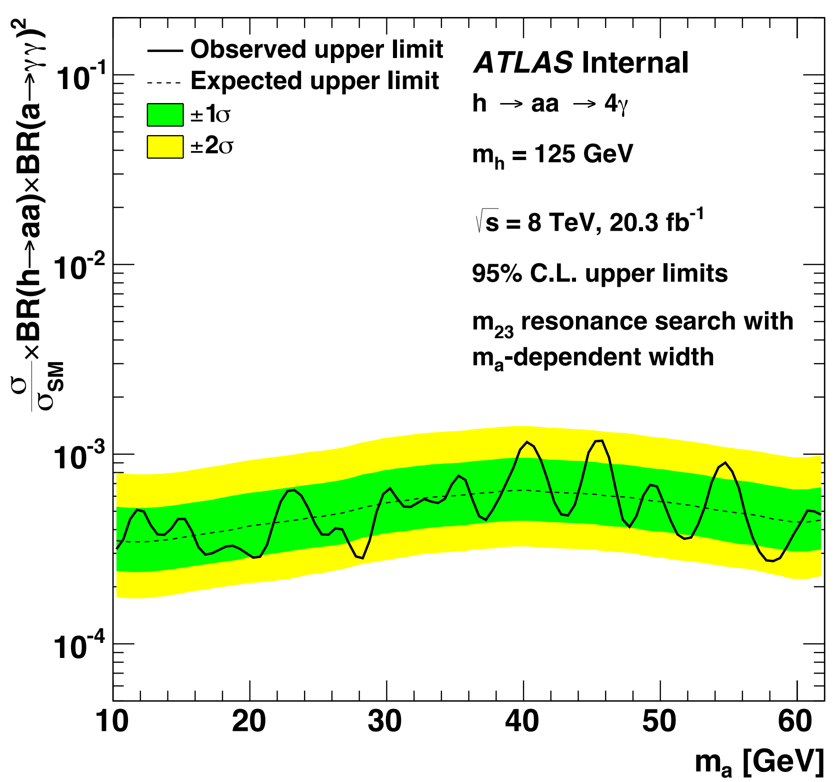
5x7 cluster ==>
<ΔR> = 0.15
New approach needed for nearly-merged regime

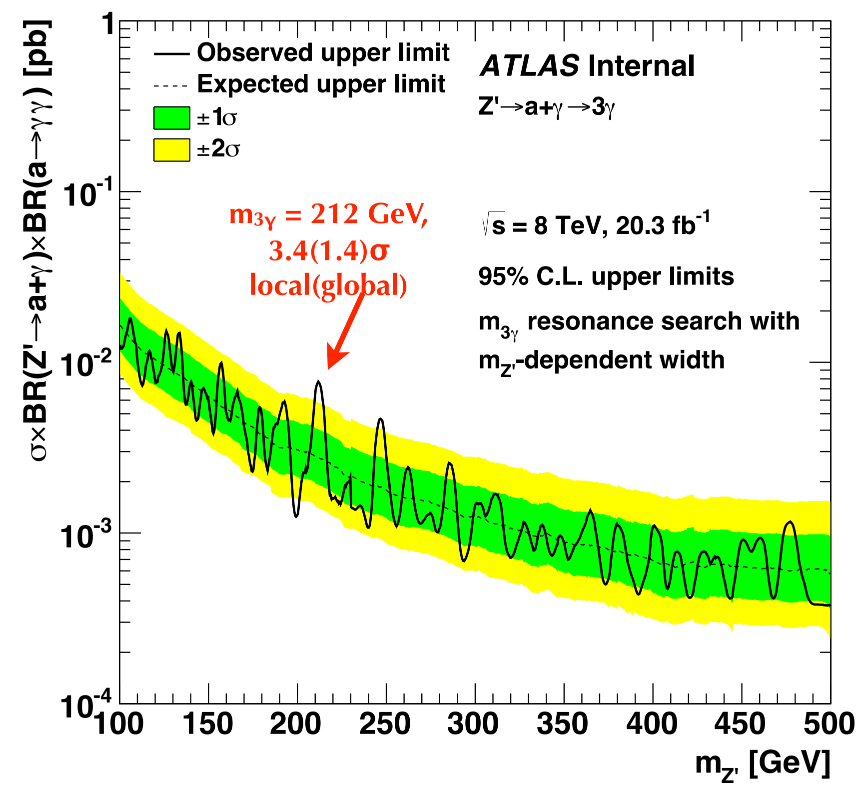
m_{23}

$m_{3\gamma}$


ATLAS Internal
√s = 8 TeV, 20.3 fb-1
Expected
Observed
mh = 125 GeV, ma = 40 GeV
h→aa→4γ
BR(h→aa)×BR(a→γγ)² = 0.001
Events / 10 GeV
Significance
m23 [GeV]


ATLAS Internal
√s = 8 TeV, 20.3 fb-1
Expected
Observed
mZ' = 400 GeV
Z'→a+γ→3γ
σ×BR(Z'→a+γ)×BR(a→2γ)
= 0.002 pb
Events / 10 GeV
Significance
m3γ [GeV]


Observed upper limit
Expected upper limit
±1σ
±2σ
ATLAS Internal
h → aa → 4γ
mh = 125 GeV
√s = 8 TeV, 20.3 fb-1
95% C.L. upper limits
m23 resonance search with
ma-dependent width
σ/σSM×BR(h→aa)×BR(a→γγ)²
ma [GeV]


Observed upper limit
Expected upper limit
±1σ
±2σ
ATLAS Internal
Z'→a+γ→3γ
m3γ = 212 GeV,
3.4(1.4)σ
local(global)
√s = 8 TeV, 20.3 fb-1
95% C.L. upper limits
m3γ resonance search with
mZ'-dependent width
σ×BR(Z'→a+γ)×BR(a→γγ) [pb]
mZ' [GeV]

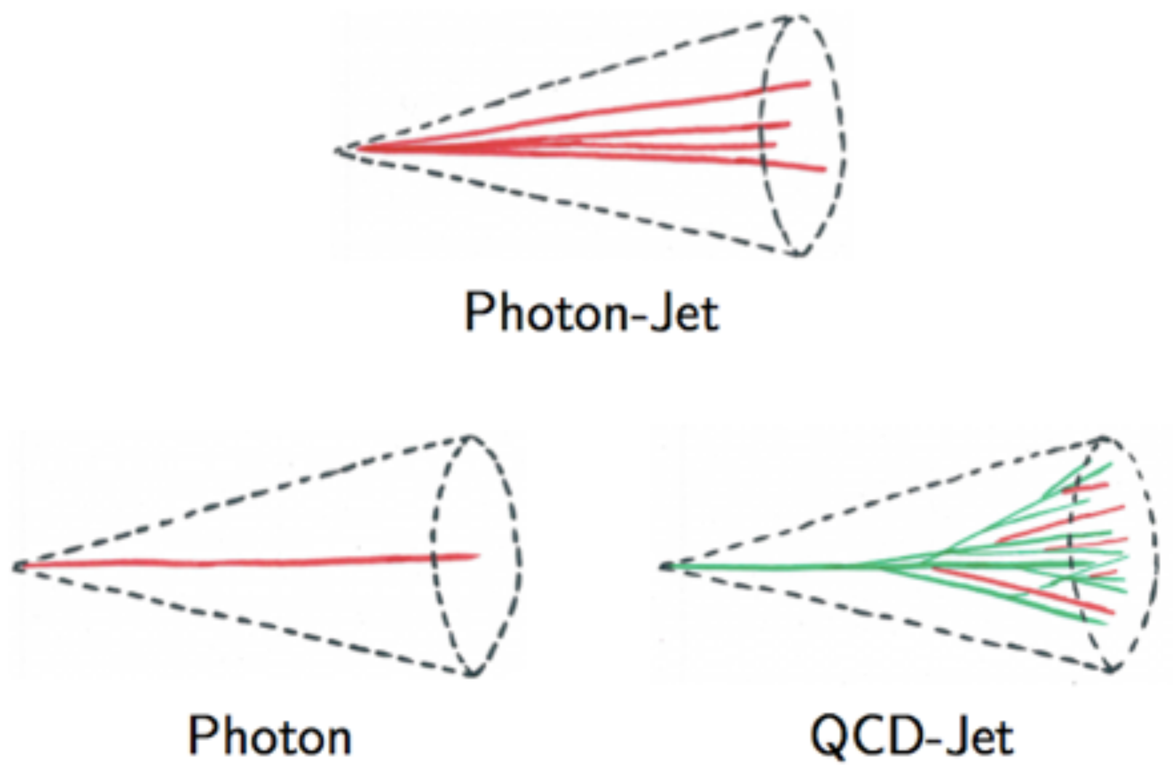
Avant-avant-garde

Renewed interest in vertex reconstruction in the ID

- New efforts on retracking in 2016
- New group dedicated to improving out-of-the-box tracking software

Nearly-merged regime for photons and electrons

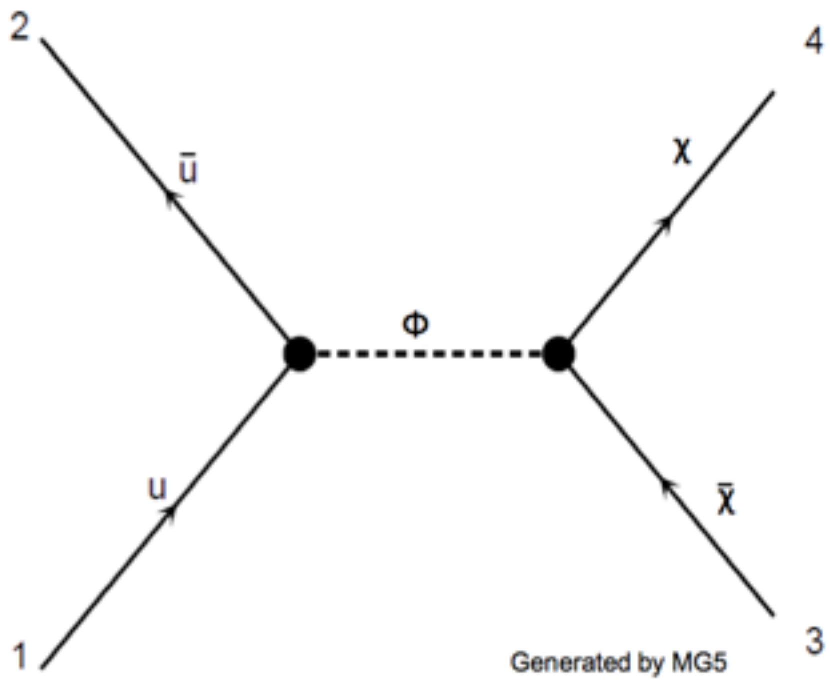
- Keen need in Run 2 multi-photon and $Z_d Z_d$ analyses, as well as other analyses in other groups
- Need a dedicated photon-jets analysis



Jakub Scholtz

Reinterpretation of existing analyses for SIMP dark matter models [example]

- SIMP signature: Trackless dijets with low EM ratio

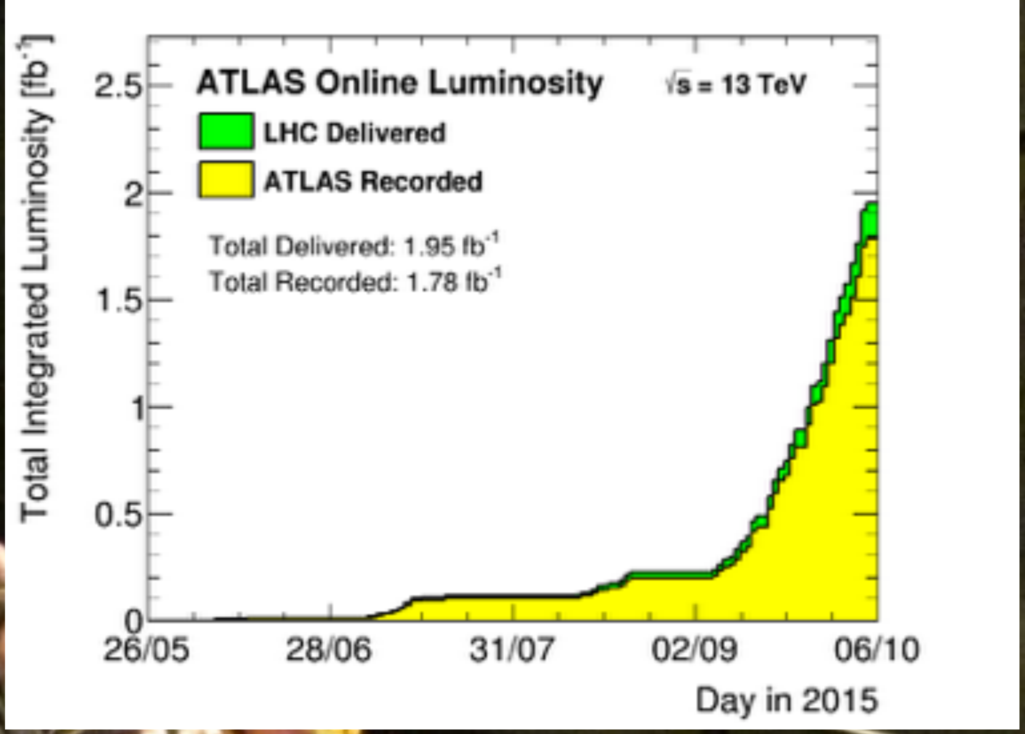


Emerging jets [arXiv]

- Excellent dark matter-related search
- Lots of interest in the theory community

Avant-garde LHC @ ATLAS

The LHC at 13 TeV is a burst forward into the unknown; there's no ace-in-the-hole (a source of electroweak symmetry breaking — the Higgs)



The marquee searches (resonant di-X) are fantastic showcases for what we can do with the highest energy humans have ever used in a collider experiment

However, many more new possible signatures currently unexplored

These avant-garde searches are the home to new methods, innovations, boundary-pushing techniques, many of which may become standard later

Particle physics is necessarily collaborative today. The few thousand names on a discovery paper for low-mass, very-hard-to-detect dark photons will all be well-deserved

Everyone benefits from the give-and-take between the high-profile and the avant-garde

END

A final word on motivation.

A final word on motivation.

Where the new physics might be?

A final word on motivation.

Where the new physics might be?

It's not up to you.

A final word on motivation.

Where the new physics might be?

It's not up to you.

We're experimentalists: Look everywhere.

A final word on motivation.

Where the new physics might be?

It's not up to you.

We're experimentalists: Look everywhere.

END