Searching for Exotic Hidden Signatures with ATLAS at the LHC

8 TeV Legacy
and
13 TeV Prospects

James Beacham (Ohio State)

ATLAS Dark Sector Workshop — Cosenza, Italy — 9 Feb. 2016

Outline

The LHC at 13 TeV so far

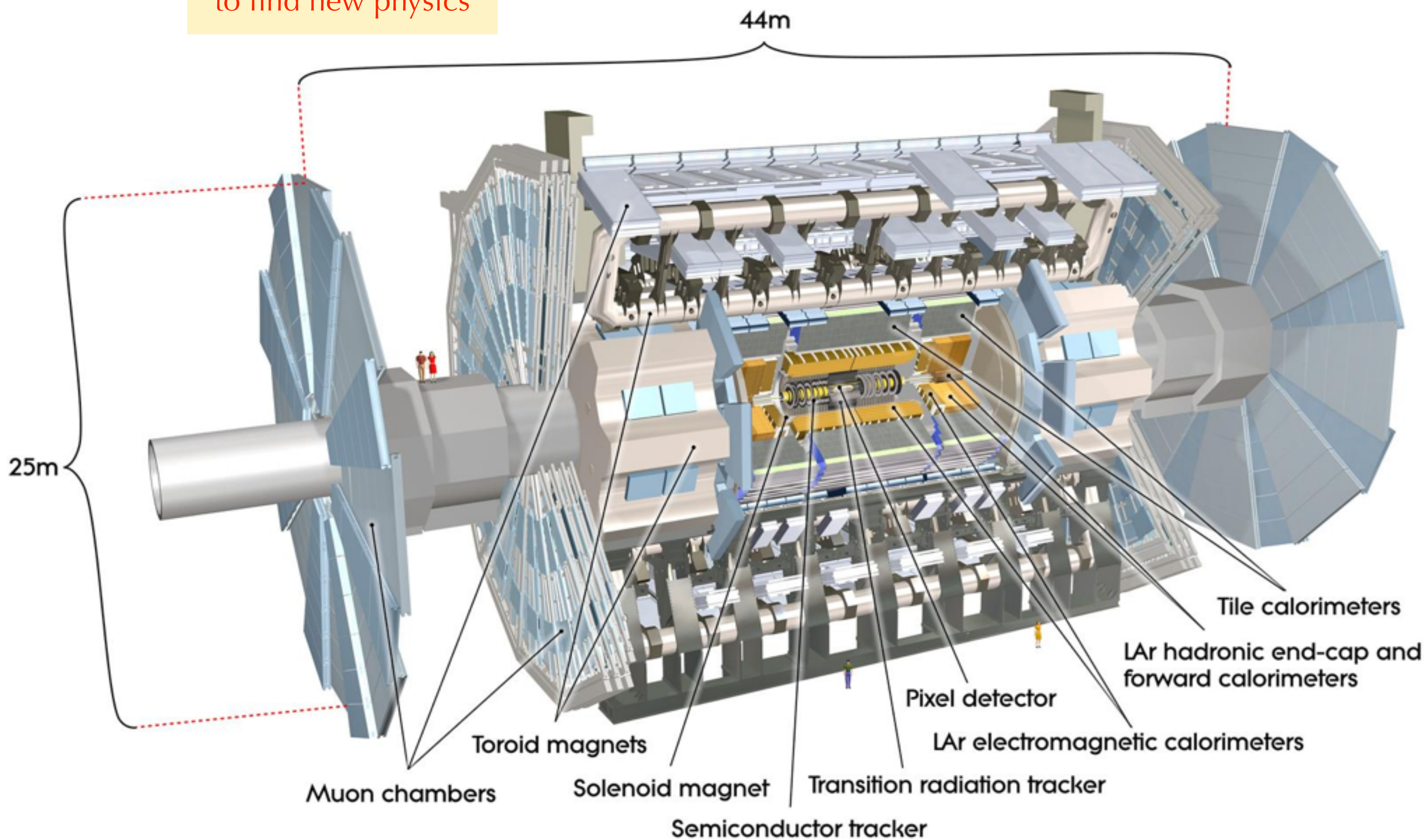
Dark / hidden sectors with ATLAS

ATLAS searches for unconventional signatures:
Run 1 results and Run 2 prospects

The LHC

ATLAS

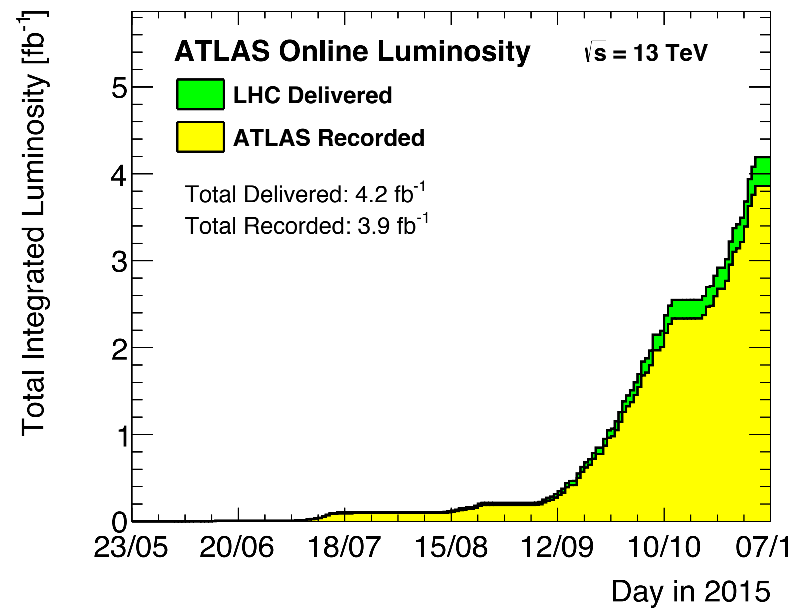
ATLAS was designed to find new physics

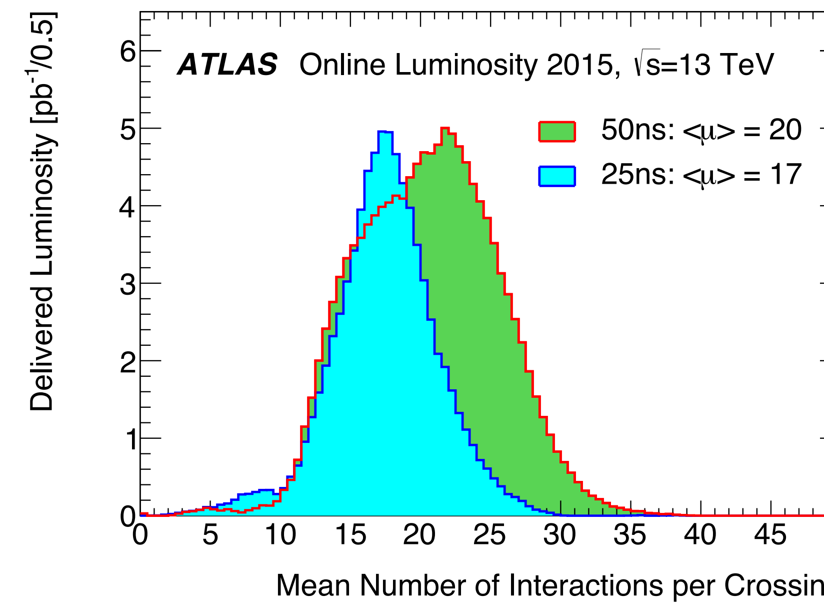


The LHC and ATLAS in Run 2

Unprecedented jump in center-of-mass energy, from 8 TeV to 13 TeV, allowing us to probe unexplored energy and mass regimes

First proton-proton collisions at 13 TeV in May 2015





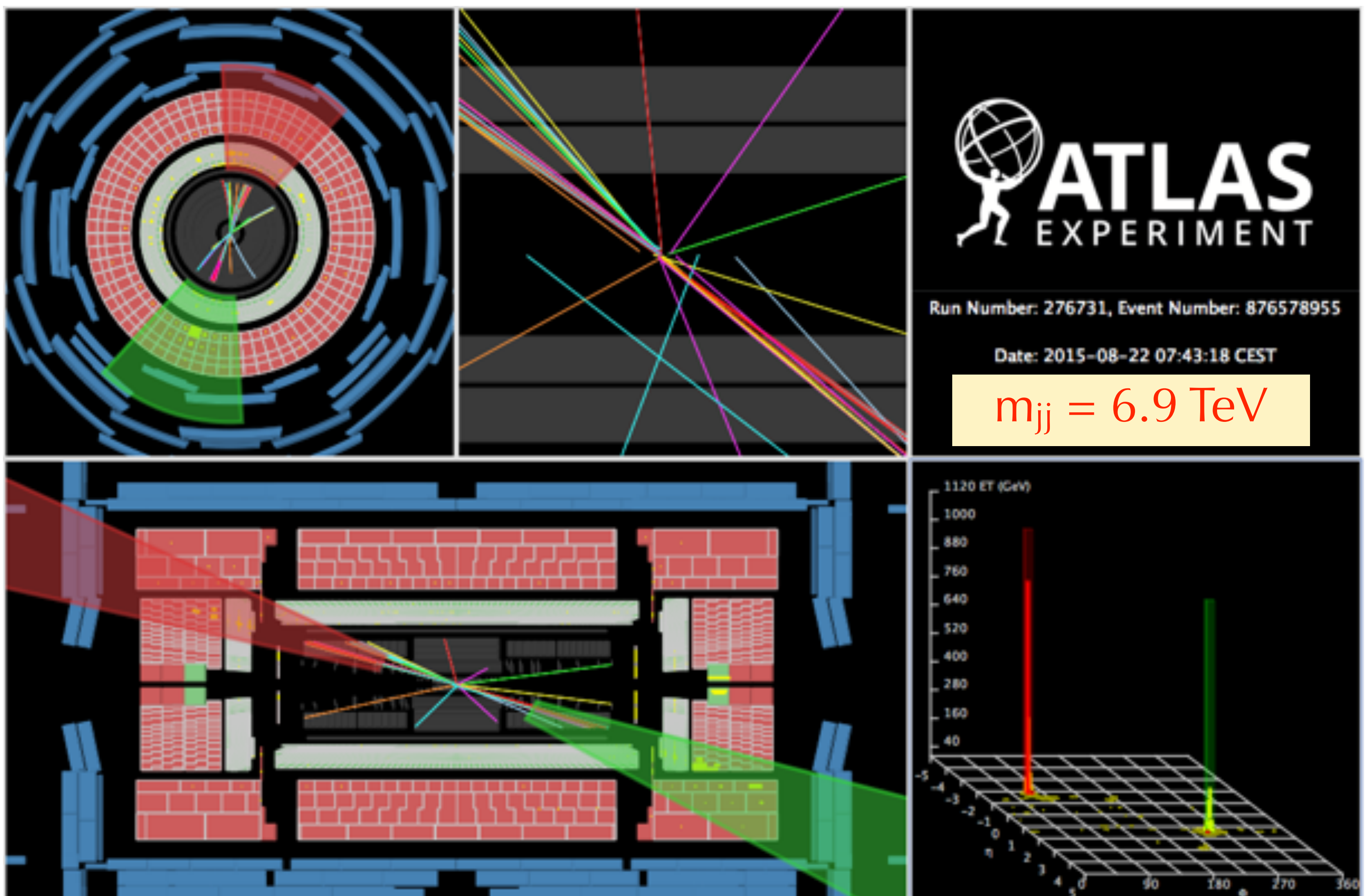
Long year of excellent ATLAS detector performance at 50 and 25ns bunch spacing

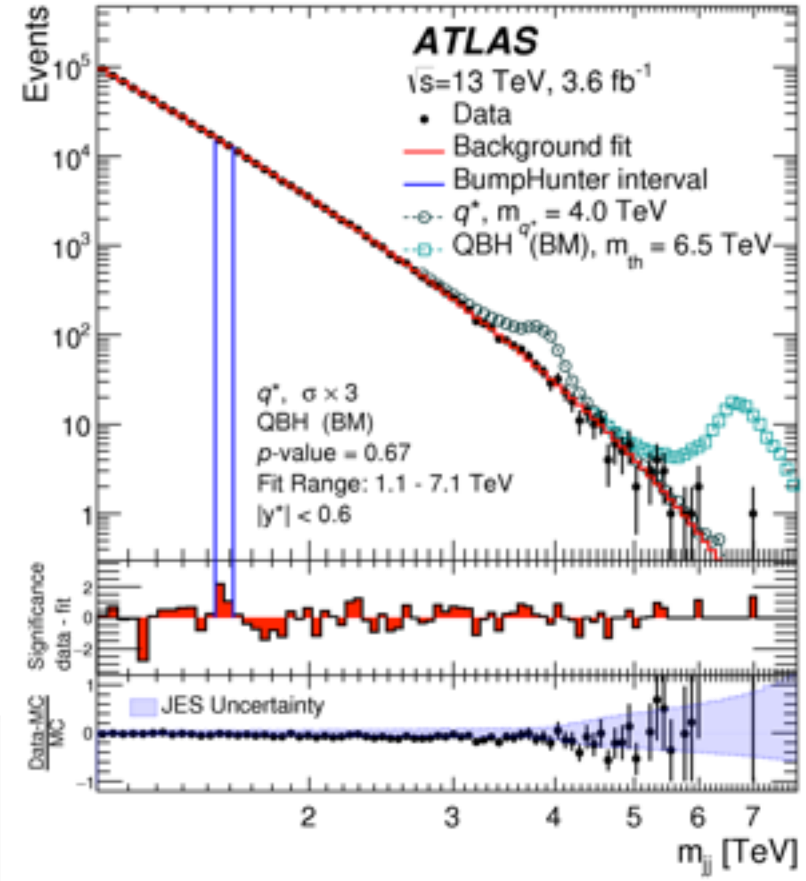
End-of-year seminar at CERN on 15 December 2015

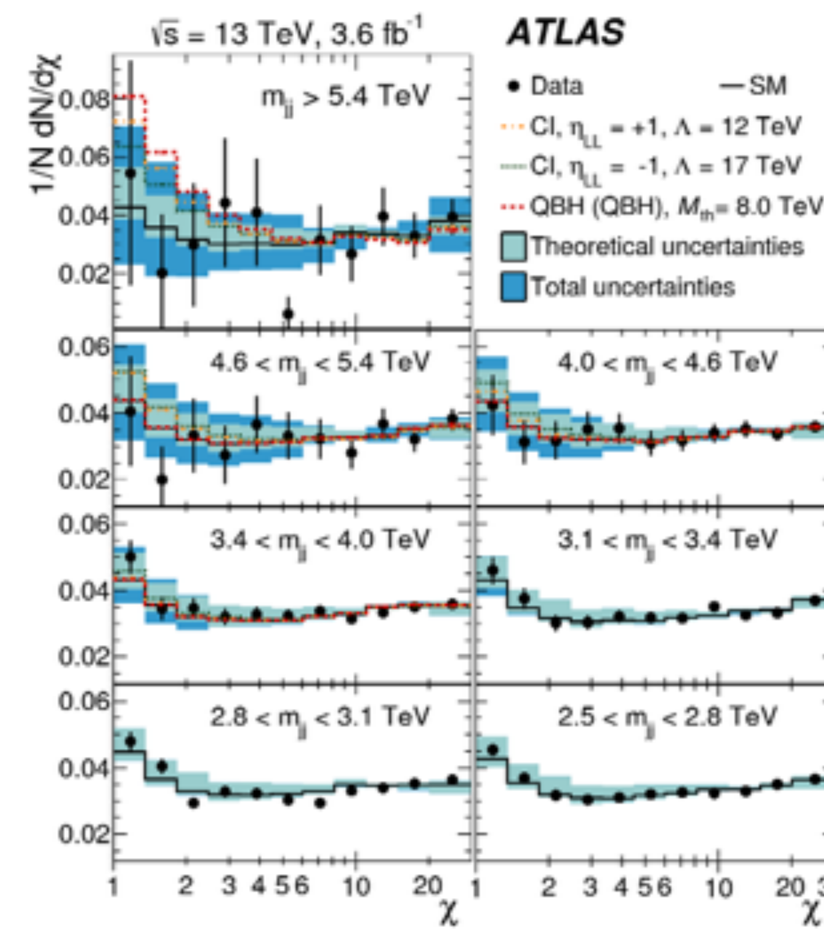
Uncharted territory:
Dijet resonances

High-p_T jets
at 13 TeV

PLB 754 (2016) 302-322

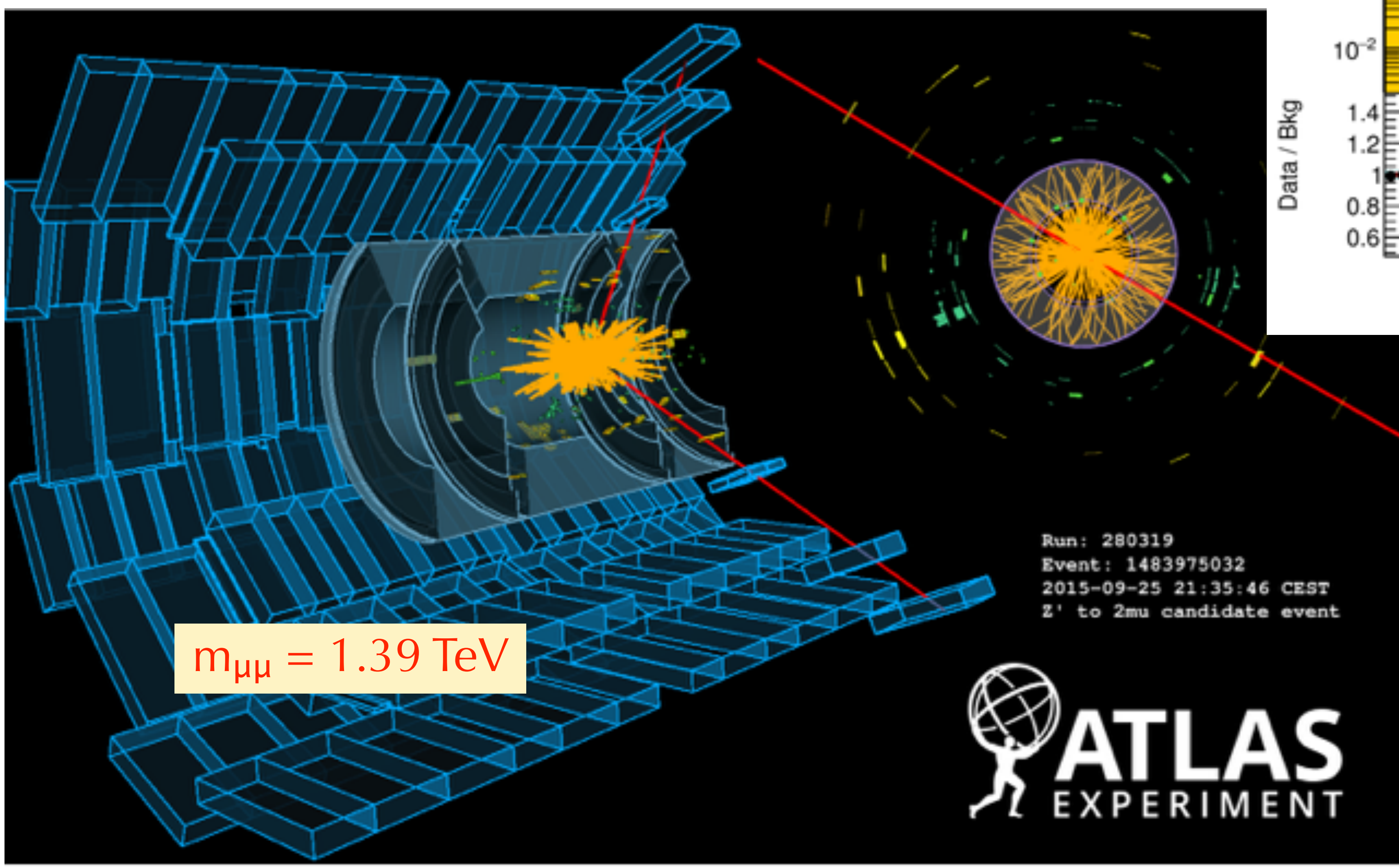




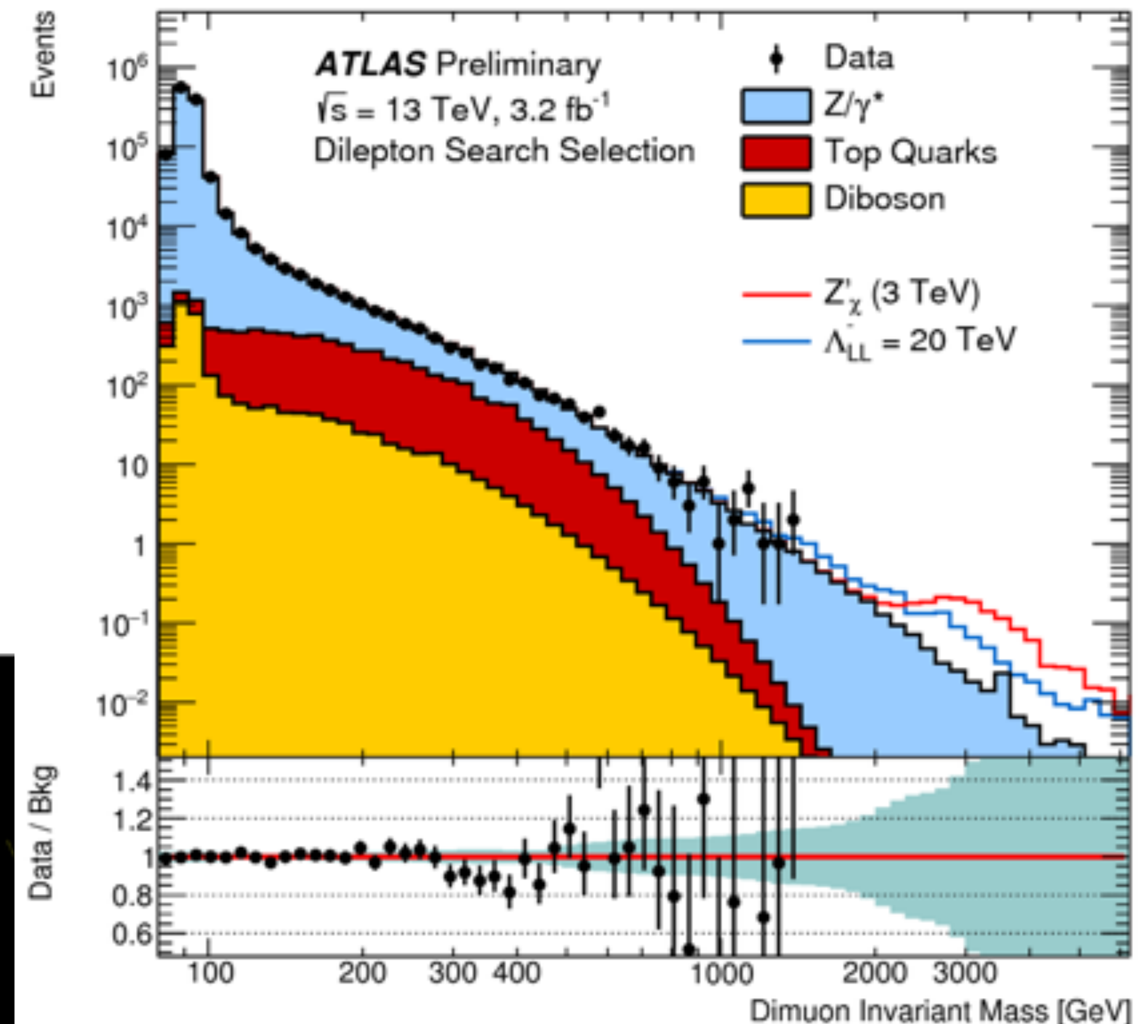


Uncharted territory:
Dilepton resonances

High-p_T
muon candidates
at 13 TeV



$m_{\mu\mu}$ = 1.39 TeV

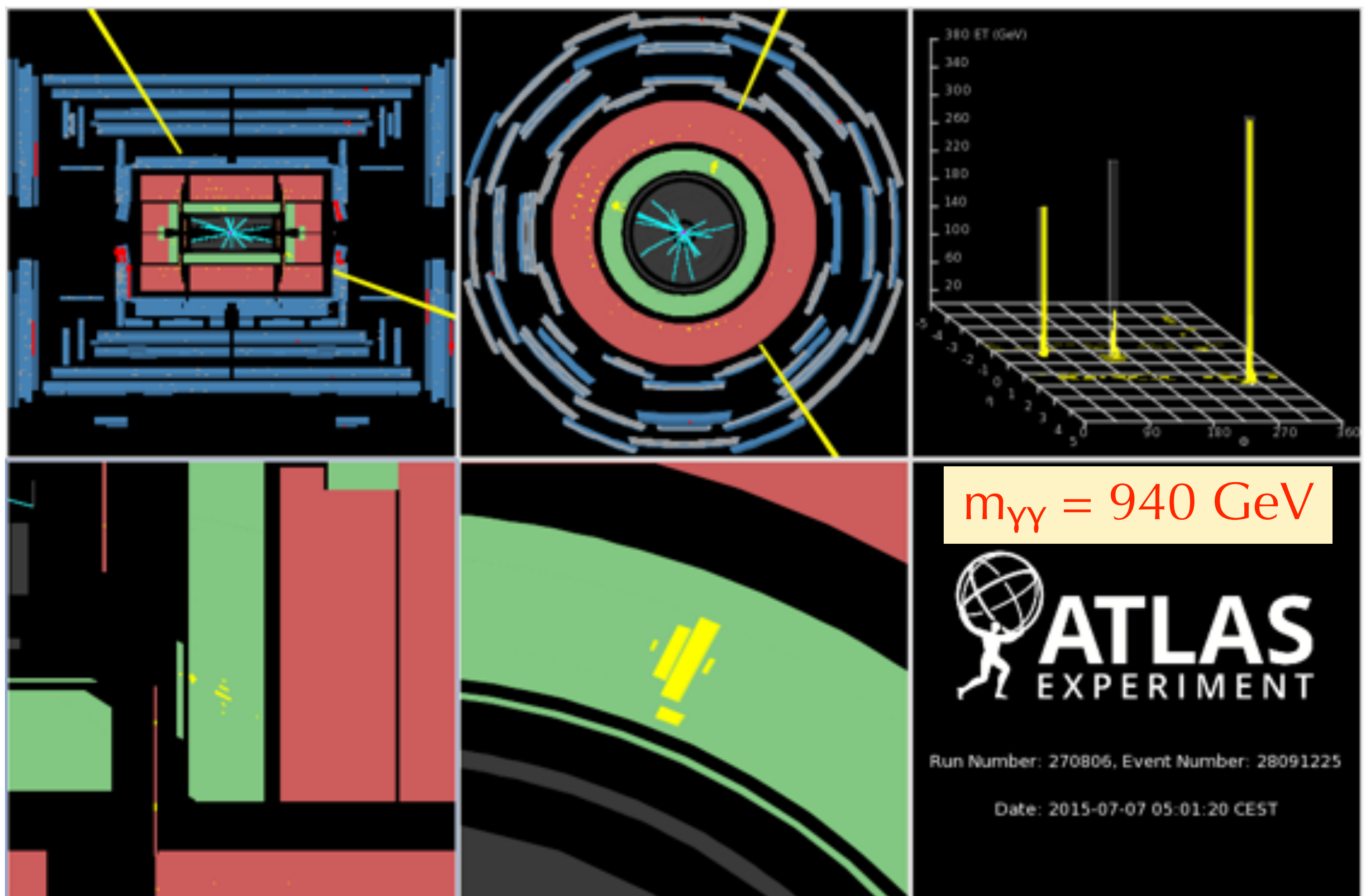


PLB 754 (2016) 302-322

ATLAS in LHC Run 2

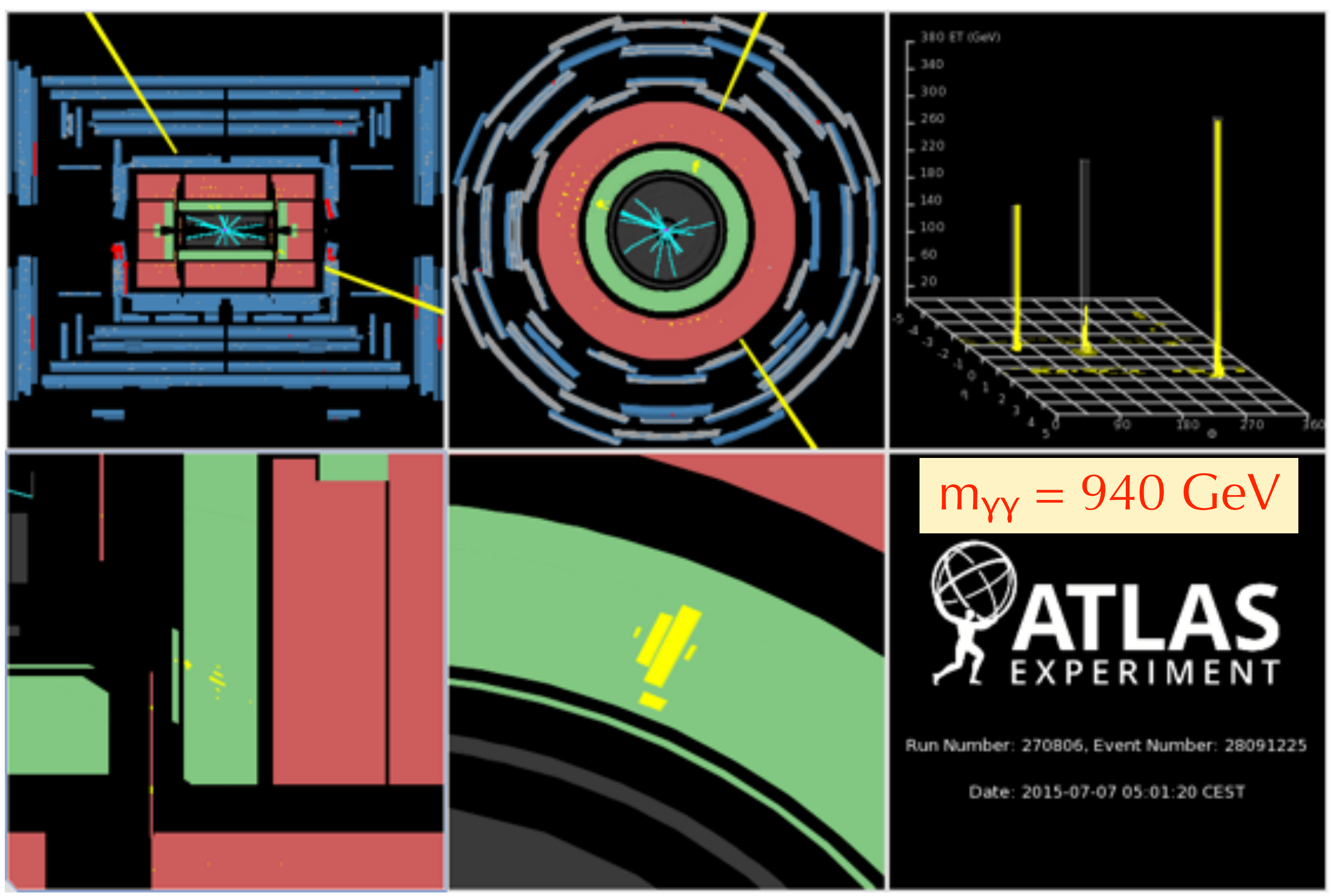
Uncharted territory:
Diphoton resonances

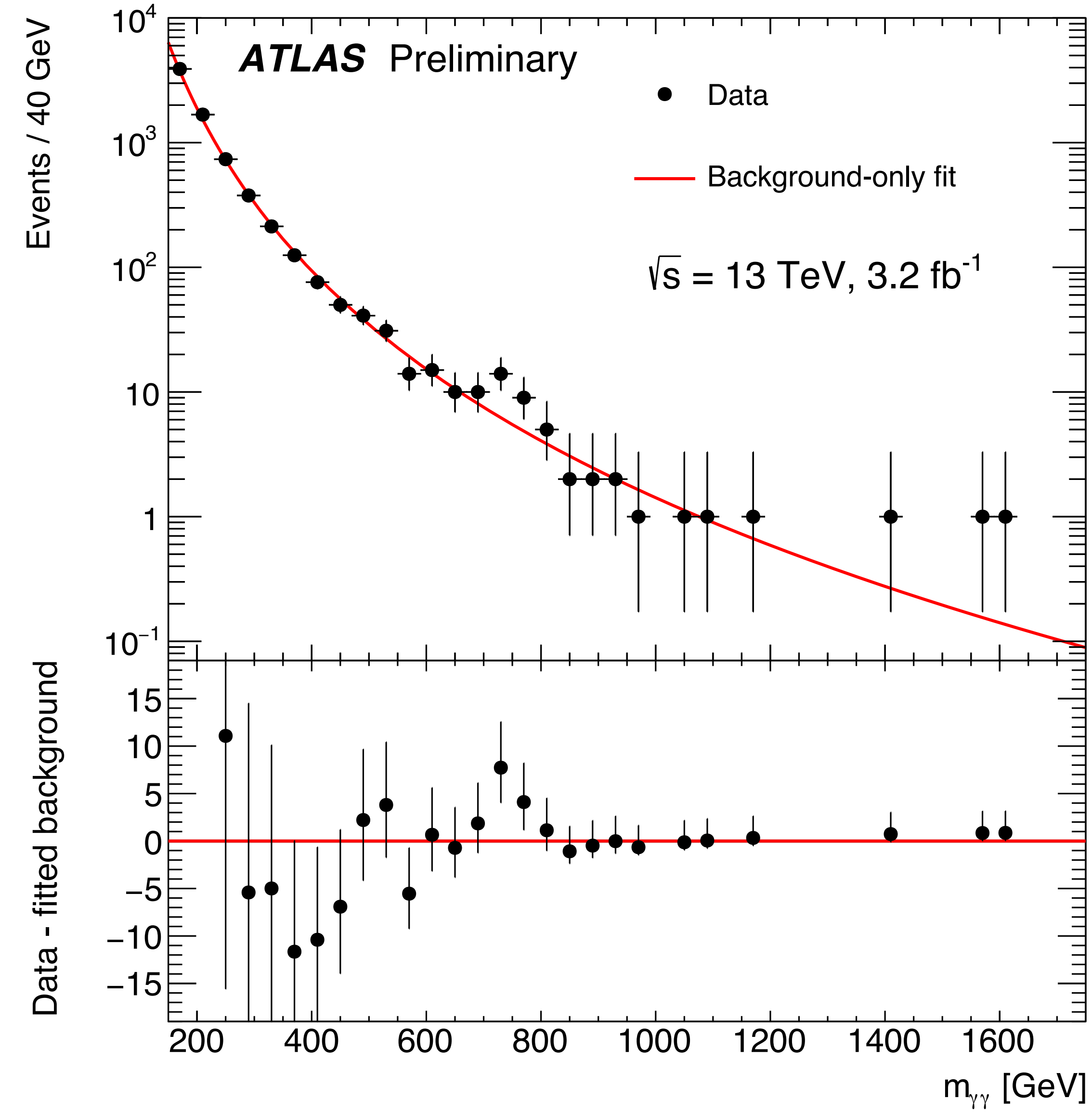
High-p_T
photon candidates
at 13 TeV



Uncharted territory:
Diphoton resonances

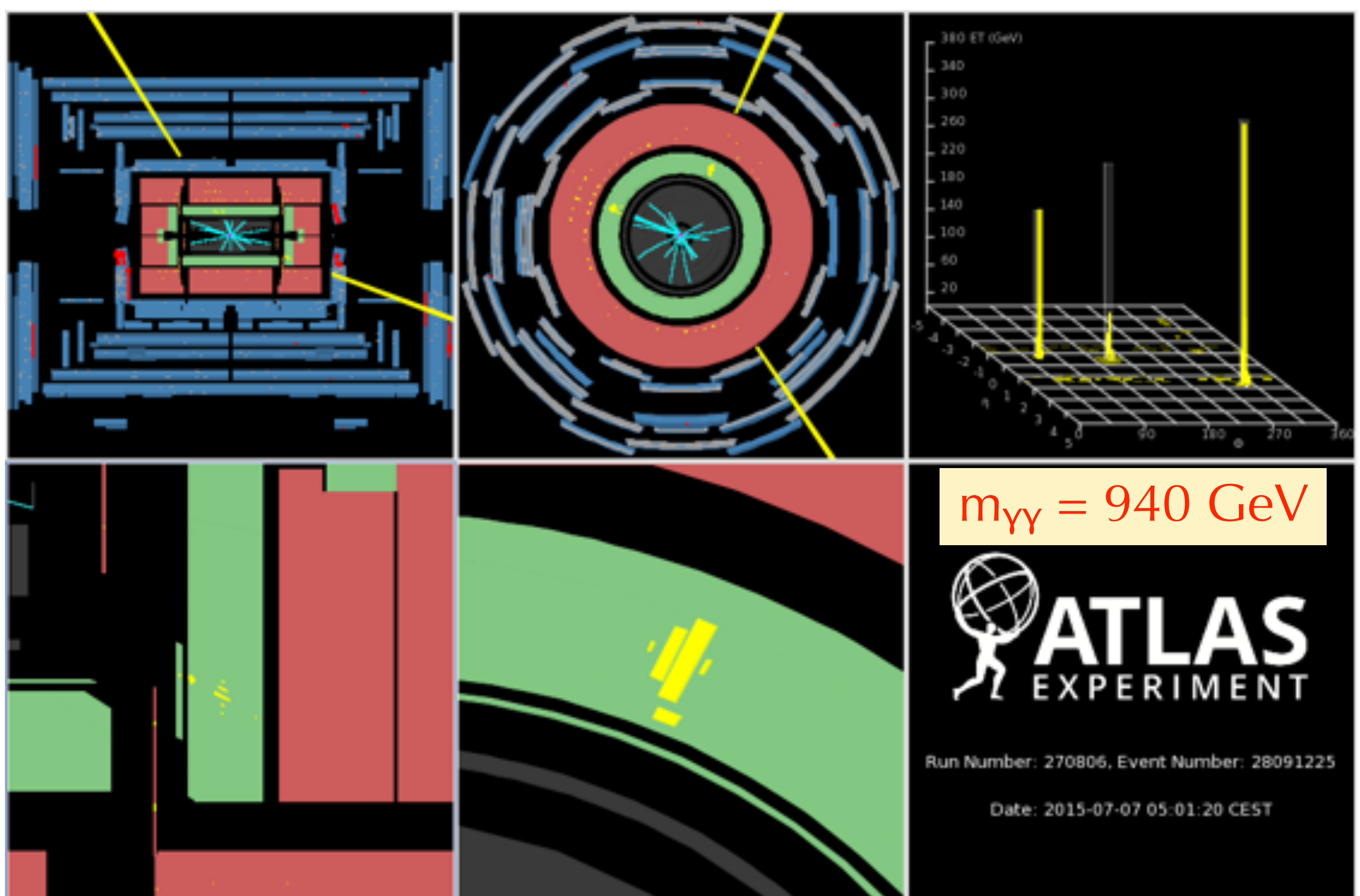
High-p_T
photon candidates
at 13 TeV

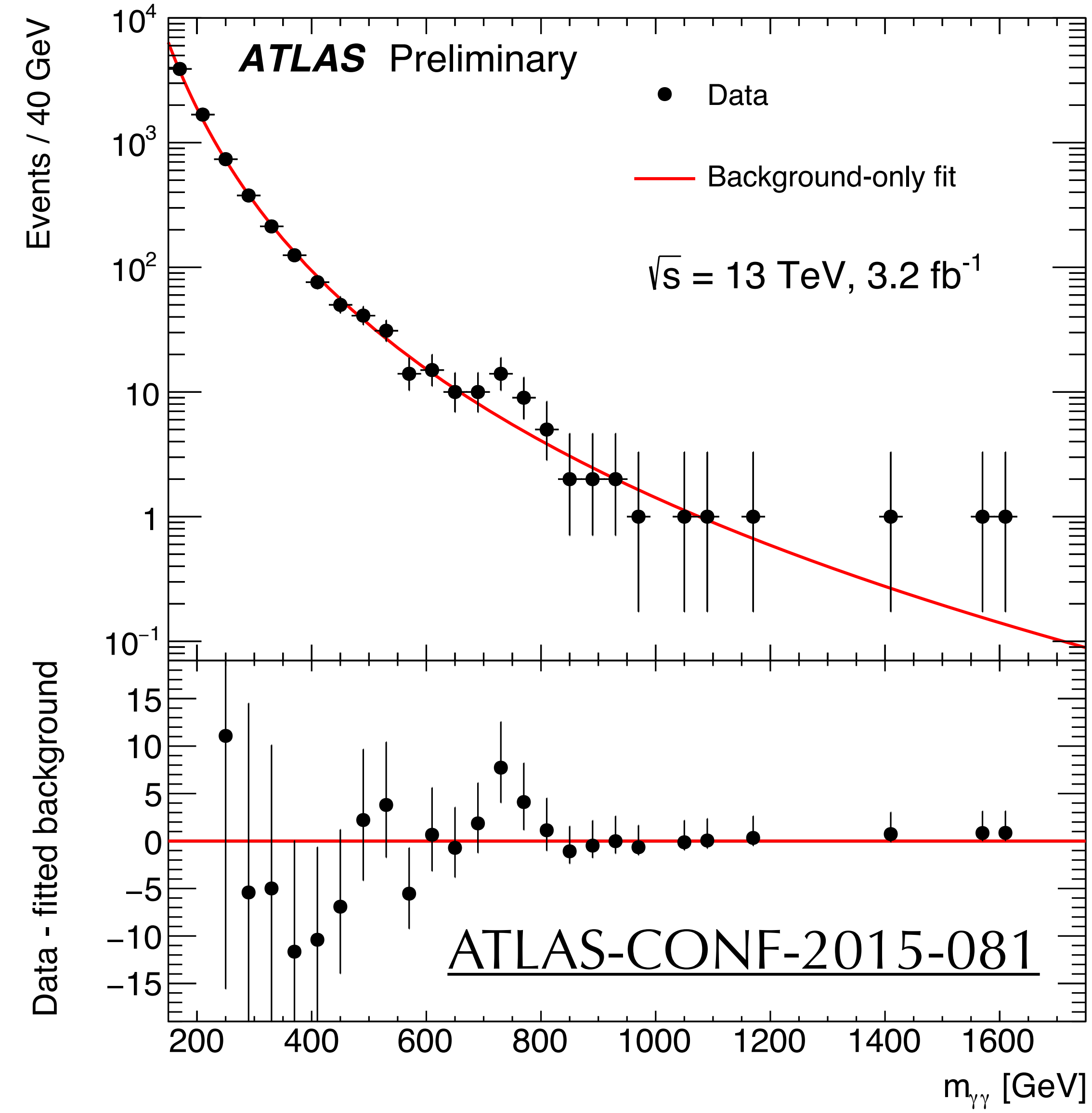




Uncharted territory:
Diphoton resonances

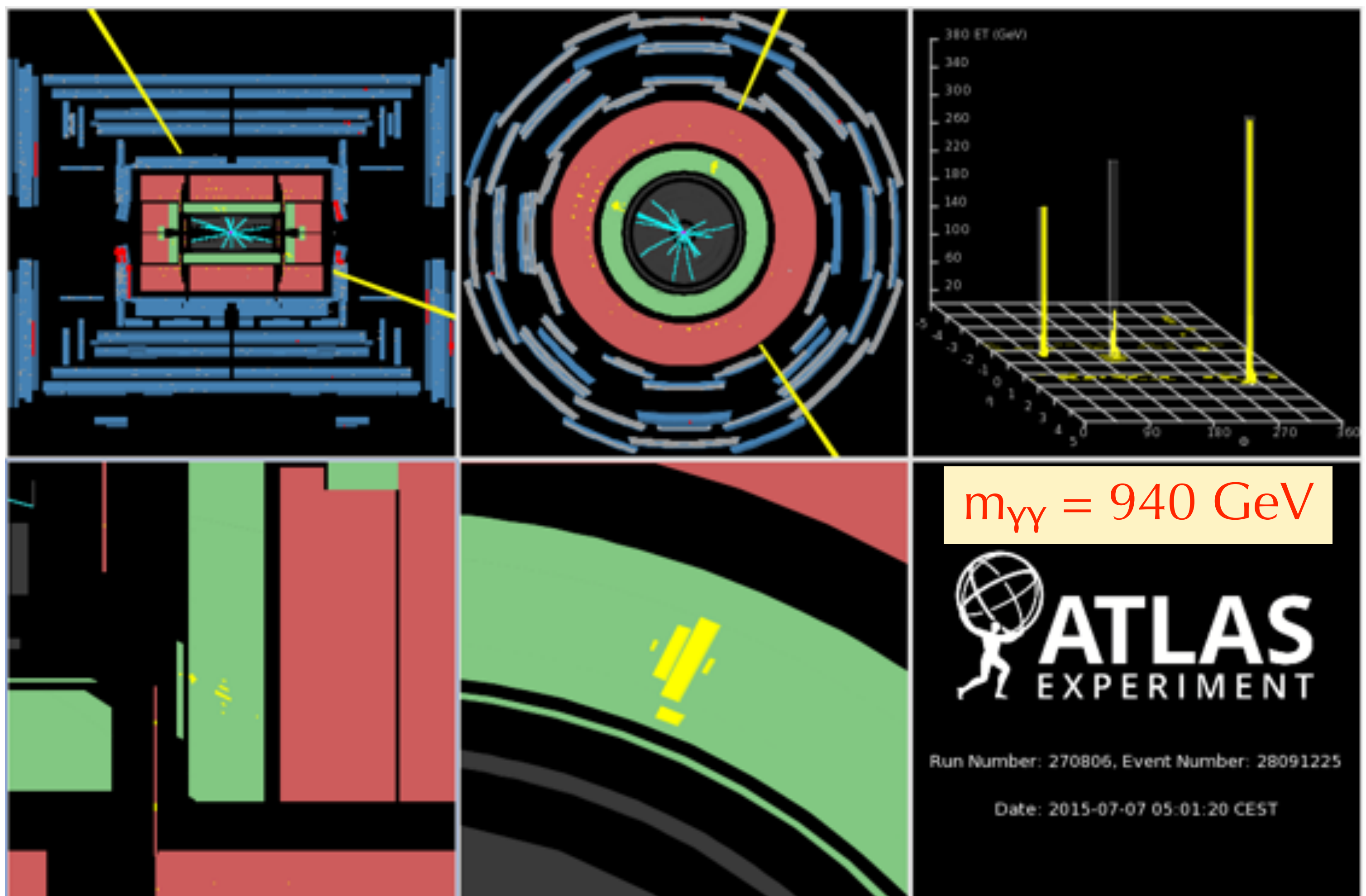
High-p_T
photon candidates
at 13 TeV

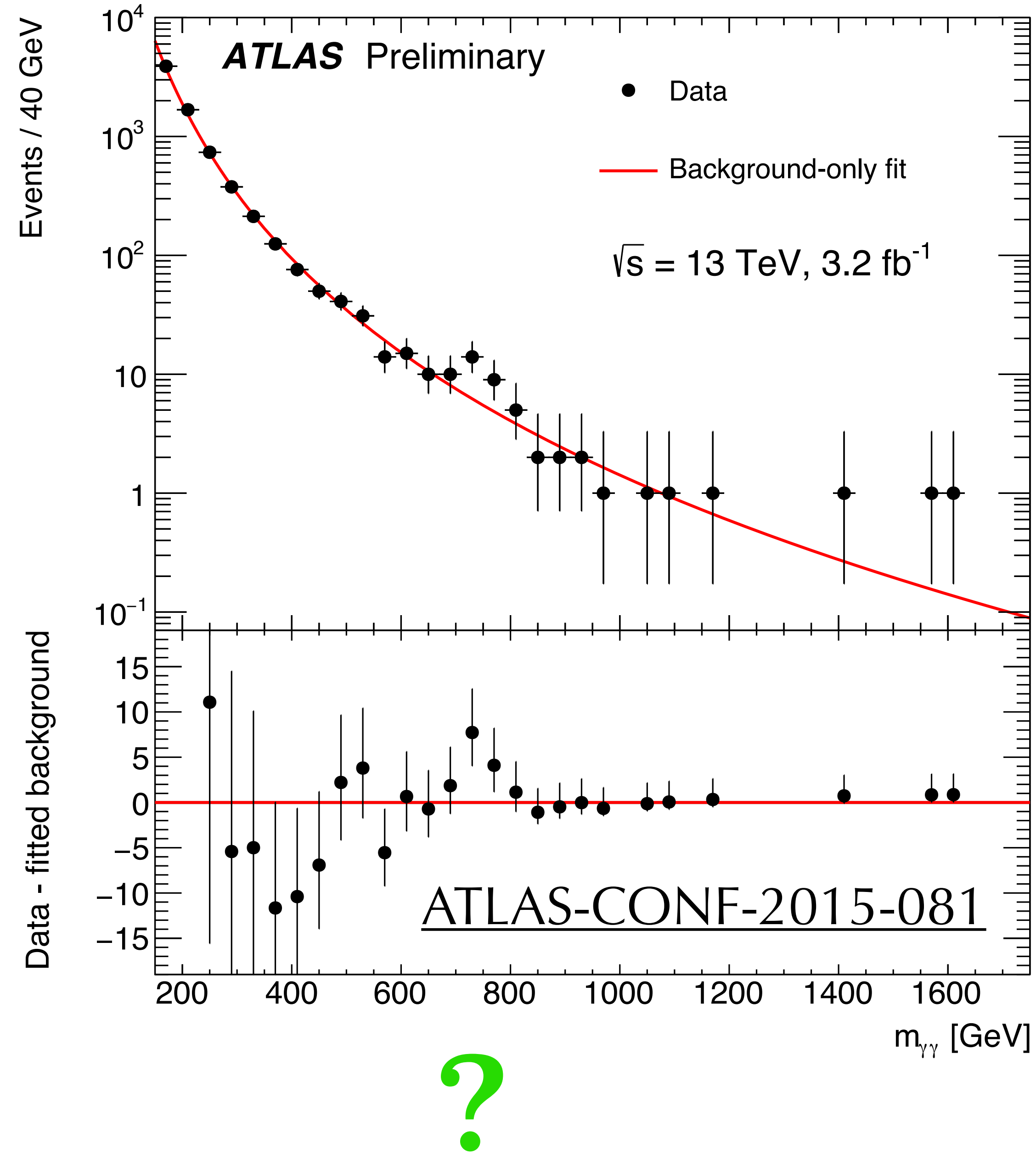




Uncharted territory:
Diphoton resonances

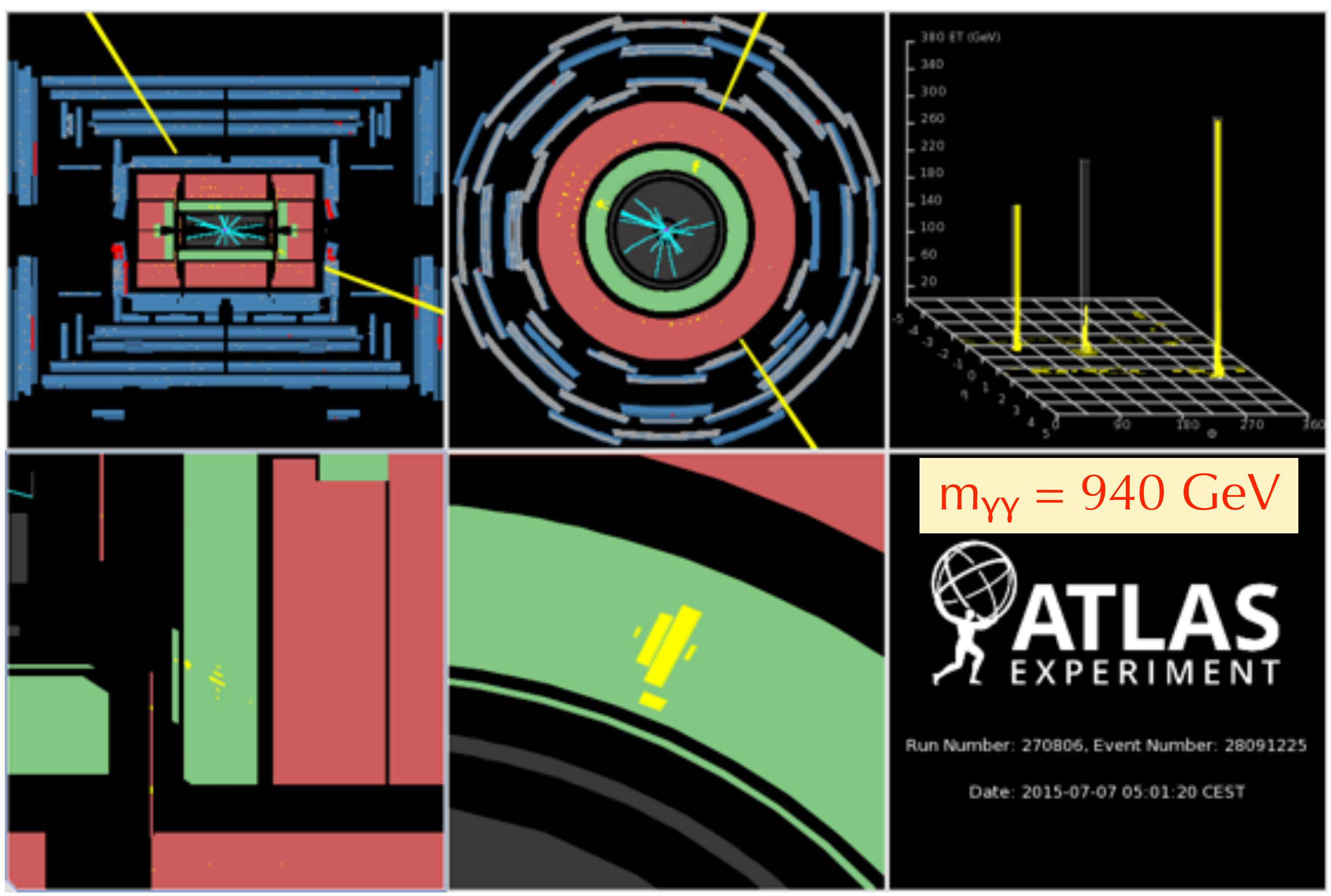
High-p_T
photon candidates
at 13 TeV

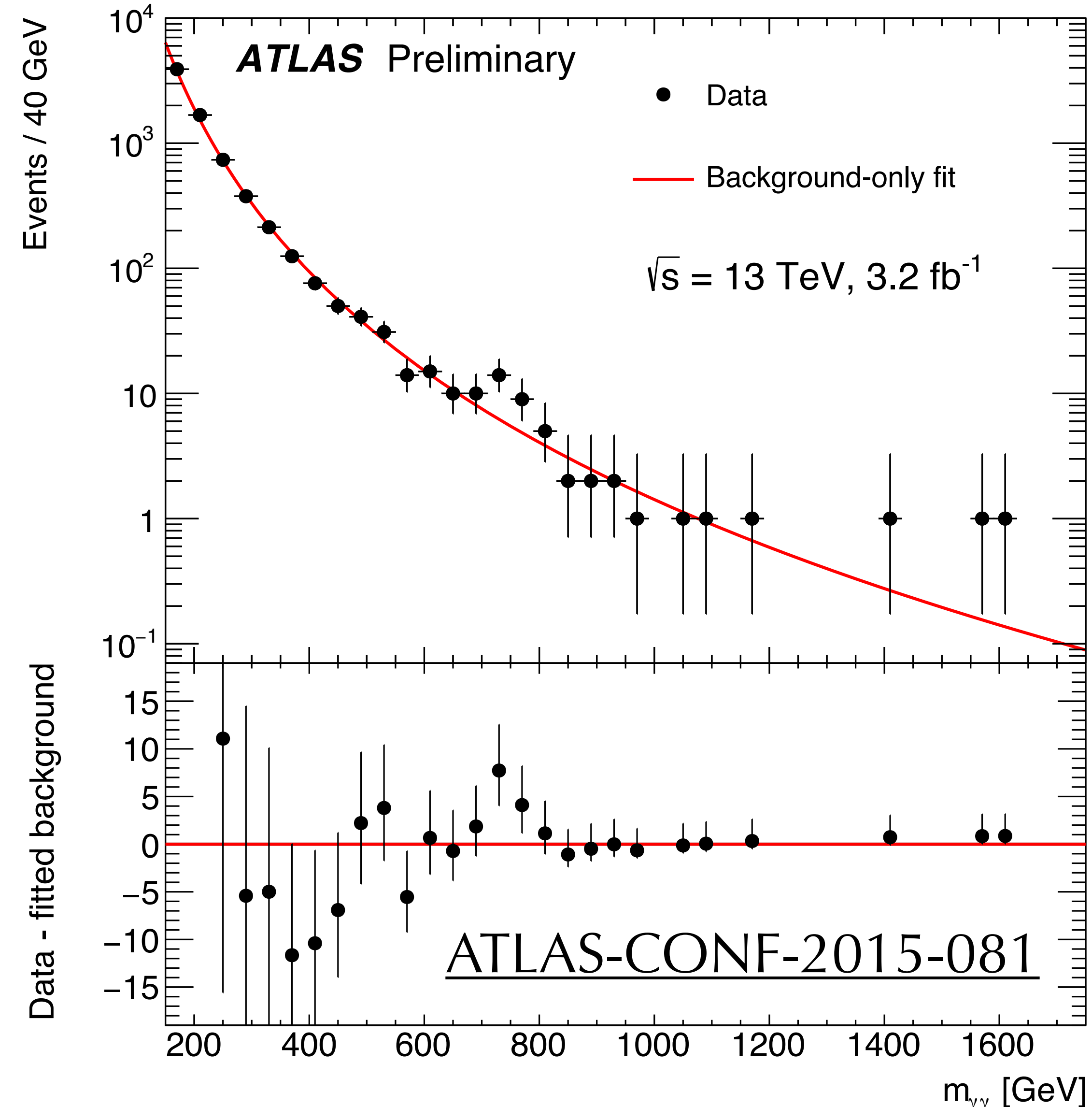




Uncharted territory:
Diphoton resonances

High-p_T
photon candidates
at 13 TeV

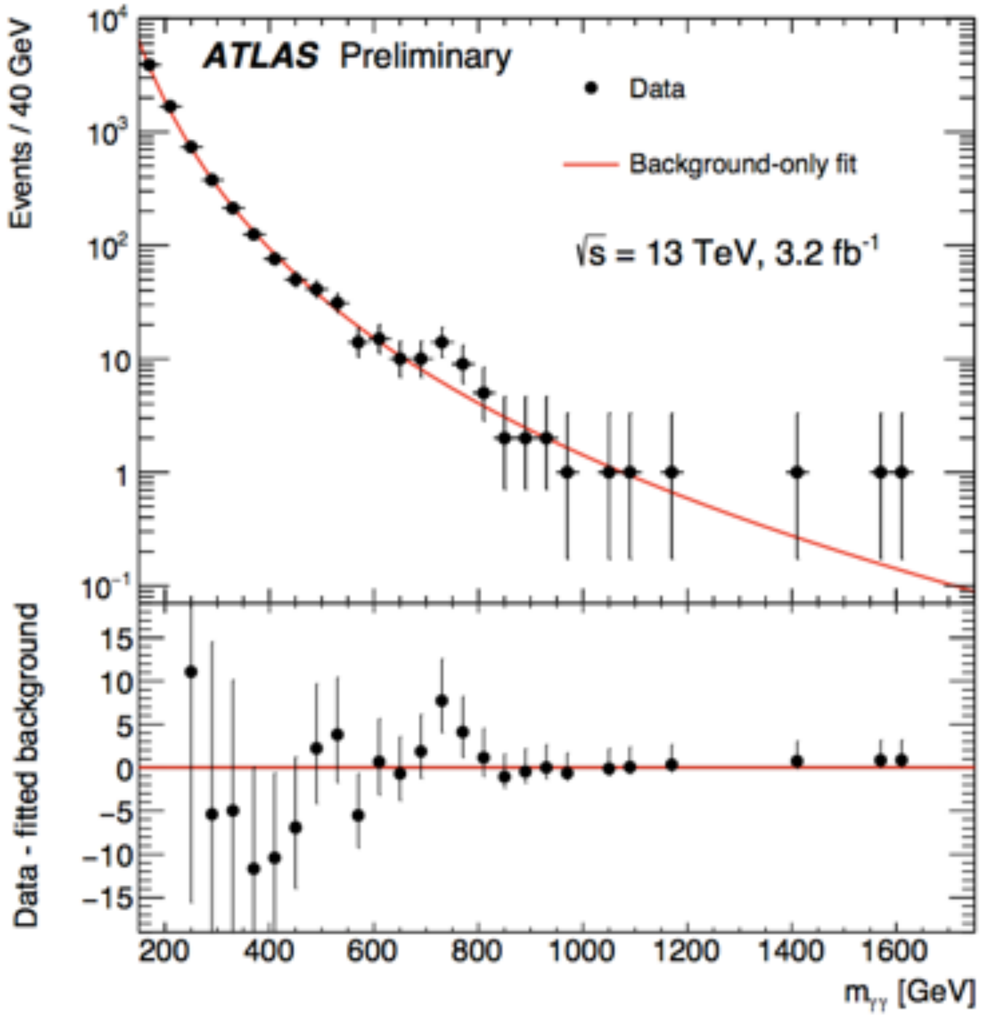


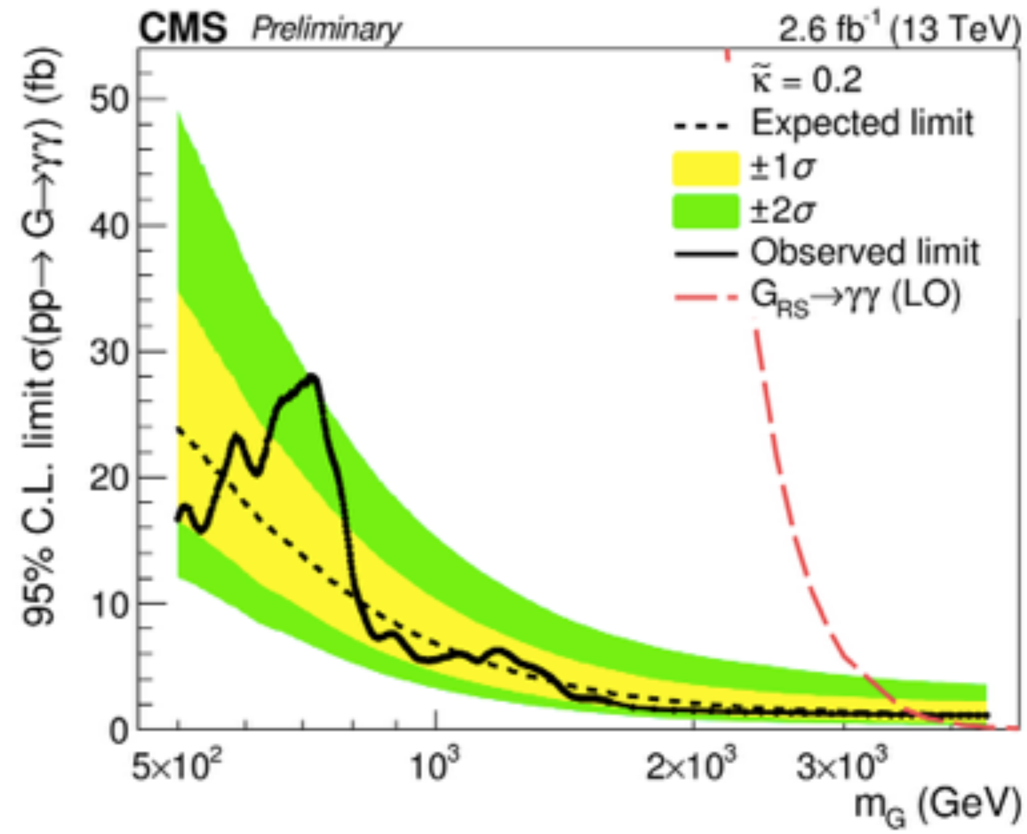


?

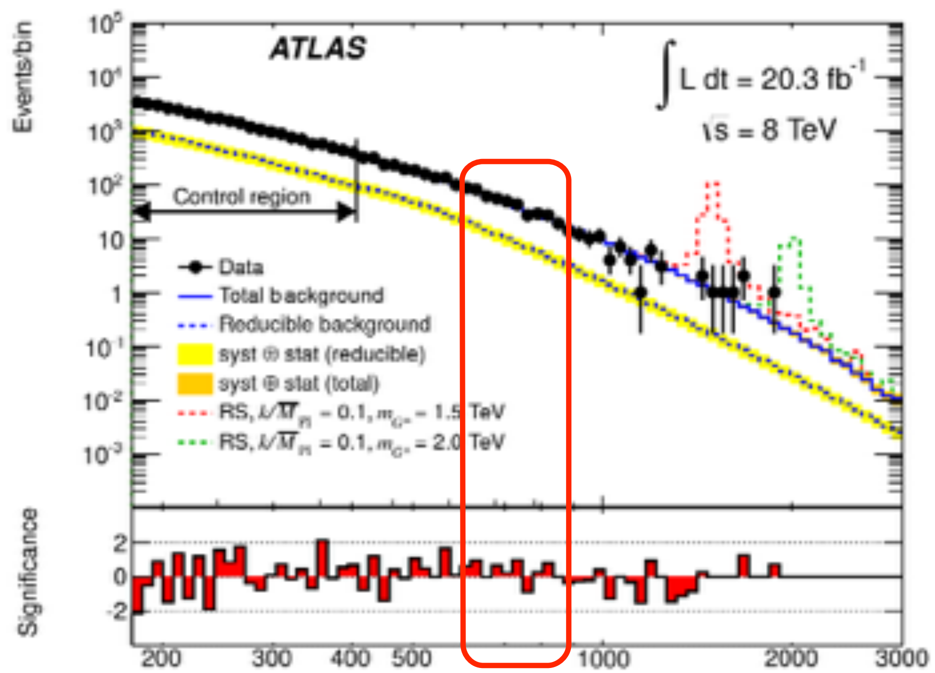
Ostensibly already-charted territory:
~2σ global excess at $m_{\gamma\gamma}$ ~ 750 GeV
with a similar excess seen by CMS

The LHC in Run 2





Fluctuation or new physics: Only more data will decide



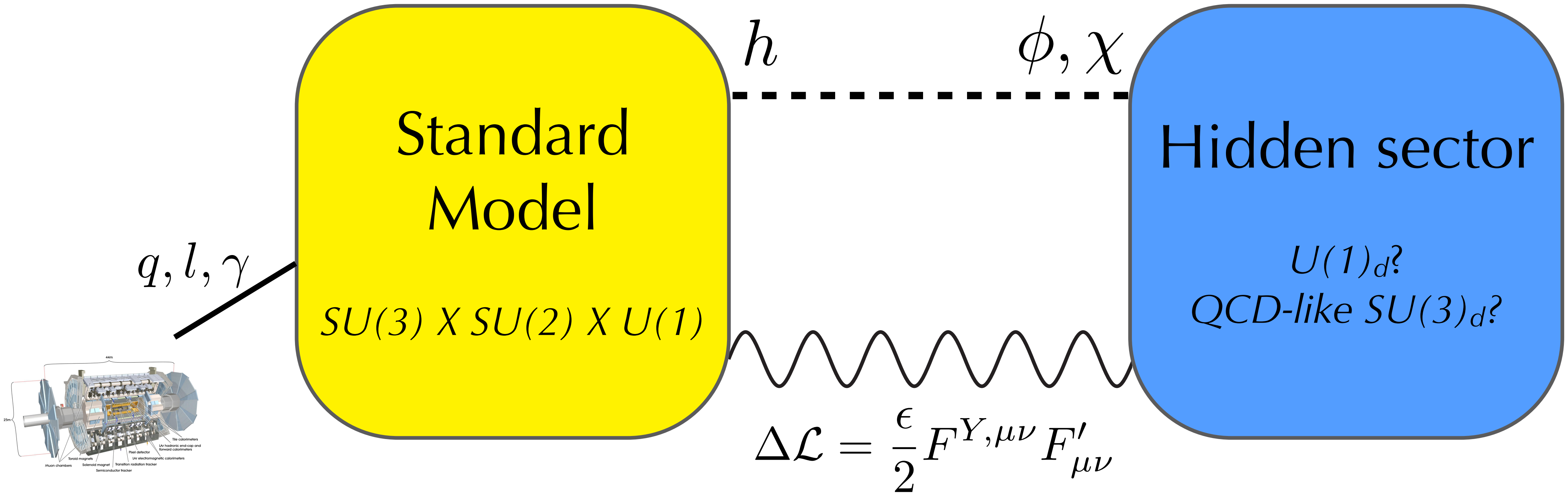
Run 1, 8 TeV

The lesson for those of us on ATLAS and CMS:
Expect the unexpected
and prepare to look everywhere

This is especially true for the future, when the LHC emphasis shifts from being a high-mass-discovery machine to being a high-luminosity machine

New physics may lie in dark or hidden sectors that require subtle, unconventional approaches to uncover

Dark / hidden sectors and you



The hidden sector can be simple (e.g., a single $U(1)_{dark}$) or more complicated, involving dark QCD sector / dark hadronization, dark matter candidates, etc.

Only a few allowed ways the hidden sector and the SM can talk to each other, and many of them yield rich, unconventional signatures at the LHC

But unconventional means significant customization and non-standard ATLAS methods

This involves inspiring the ATLAS detector to do things it wasn't designed to do

Unconventional signatures as a window to dark / hidden sectors

- Prompt and displaced lepton-jets via dark photons
- Displaced, non-collimated leptons via dark photons and dark Zs
- Higgs-to-four-leptons via Z_{dark}
- Higgs-to-four-SM particles via intermediate (pseudo)scalars with prompt decays
- Displaced vertices / hadronic jets
- Emerging jets
- Long-lived, heavy neutral leptons
- Multi-charged particles

ATLAS searches not covered here (for lack of time):

- SUSY R-parity-violating scenarios that yield long-lived particles
- Dark matter / mono-X searches

U(1) extension of the Standard Model

Old-school idea

- Holdom, Phys.Lett. B166 (1986) 196
- Galison, Phys.Lett. B136 (1984); Manohar
- Later revisitation / developments by many

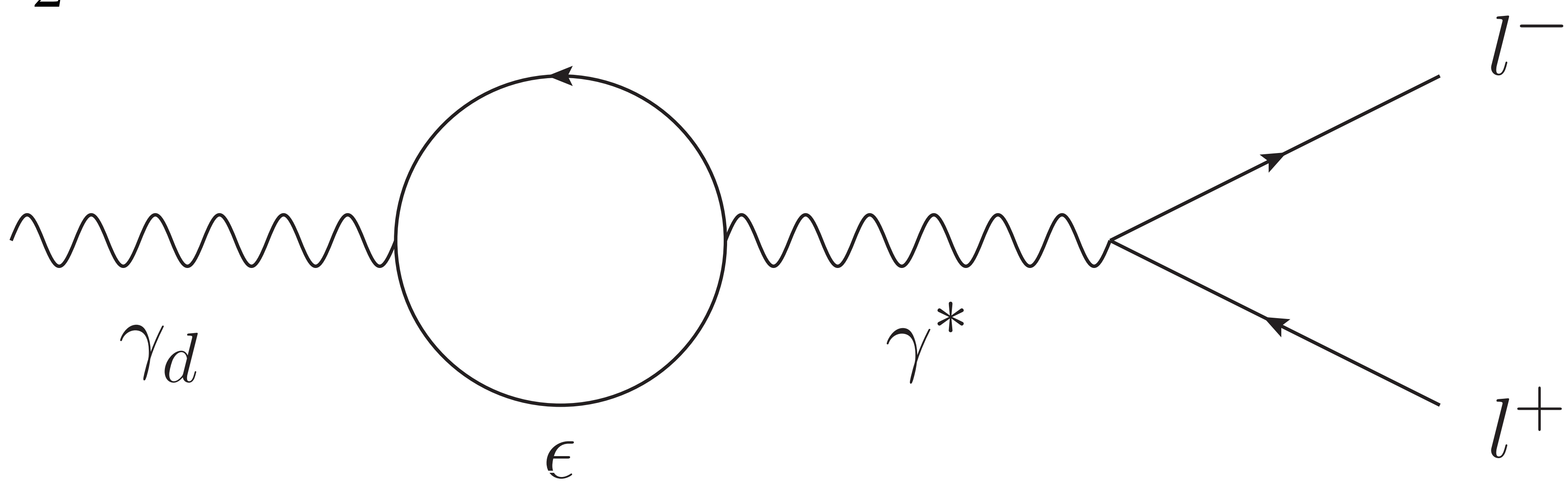
γ_d

Dark photon
A′
Heavy photon
Z_{dark}
Hidden photon
U-boson
etc.

Kinetic mixing

- Lagrangian contains a term

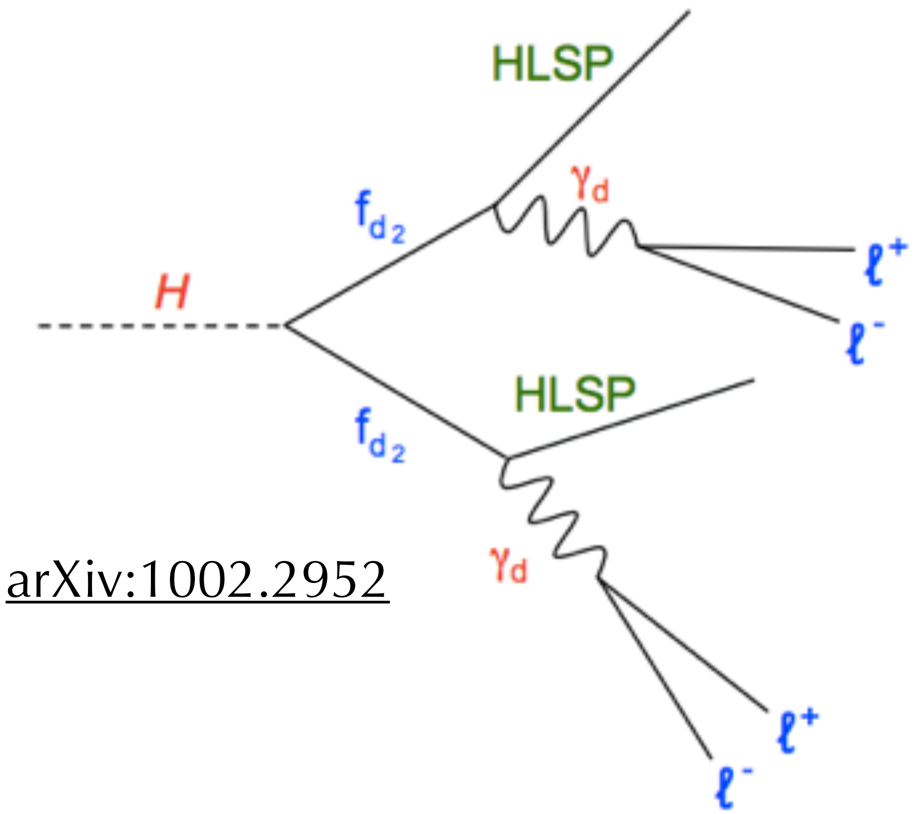
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$



But dark photons at the LHC are not usually this simple…

Dark photons at the LHC

Highly collimated groupings of leptons: *lepton-jets*; distinct LHC signature



arXiv:1002.2952

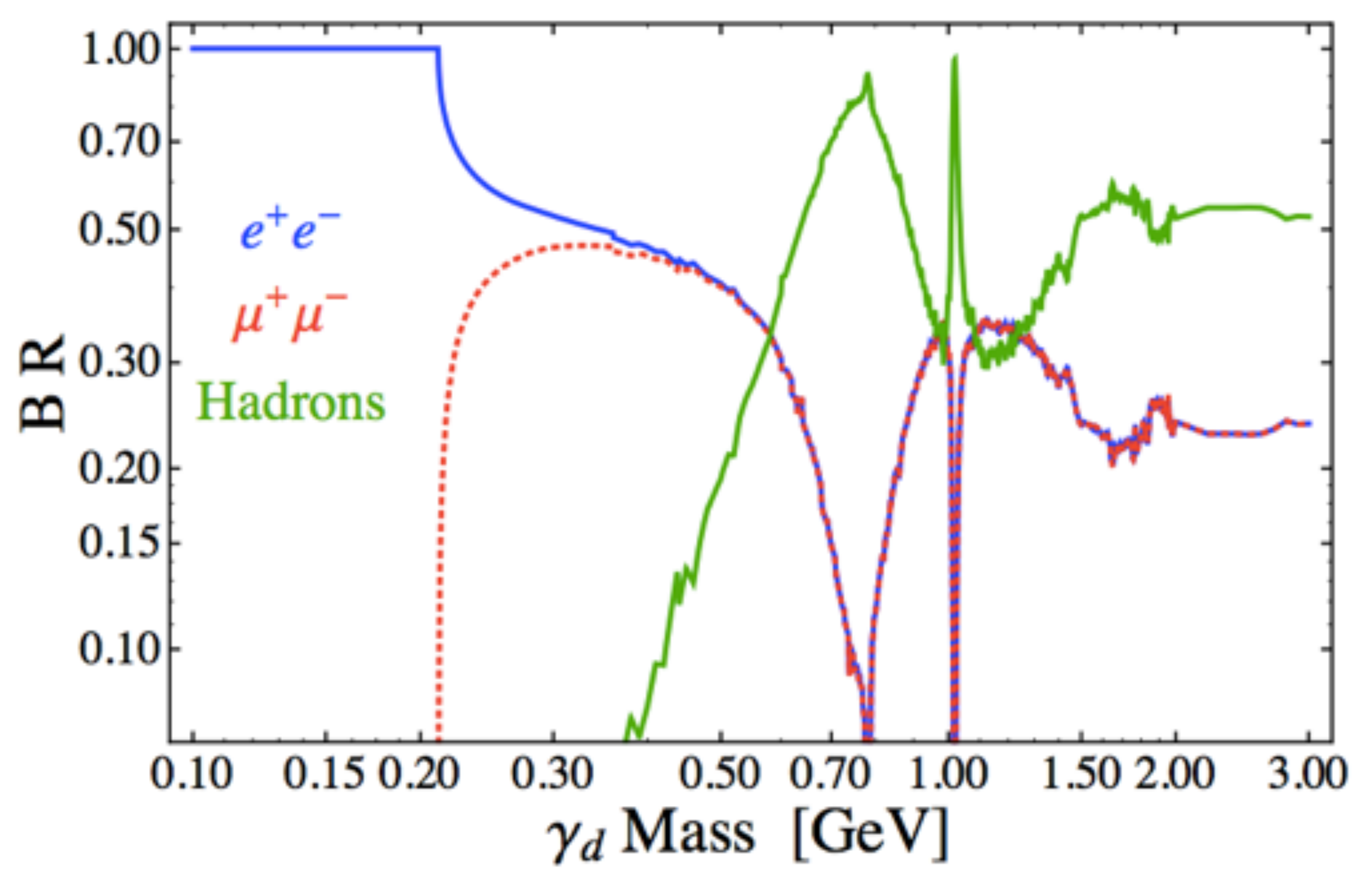
One viable LHC realization:

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

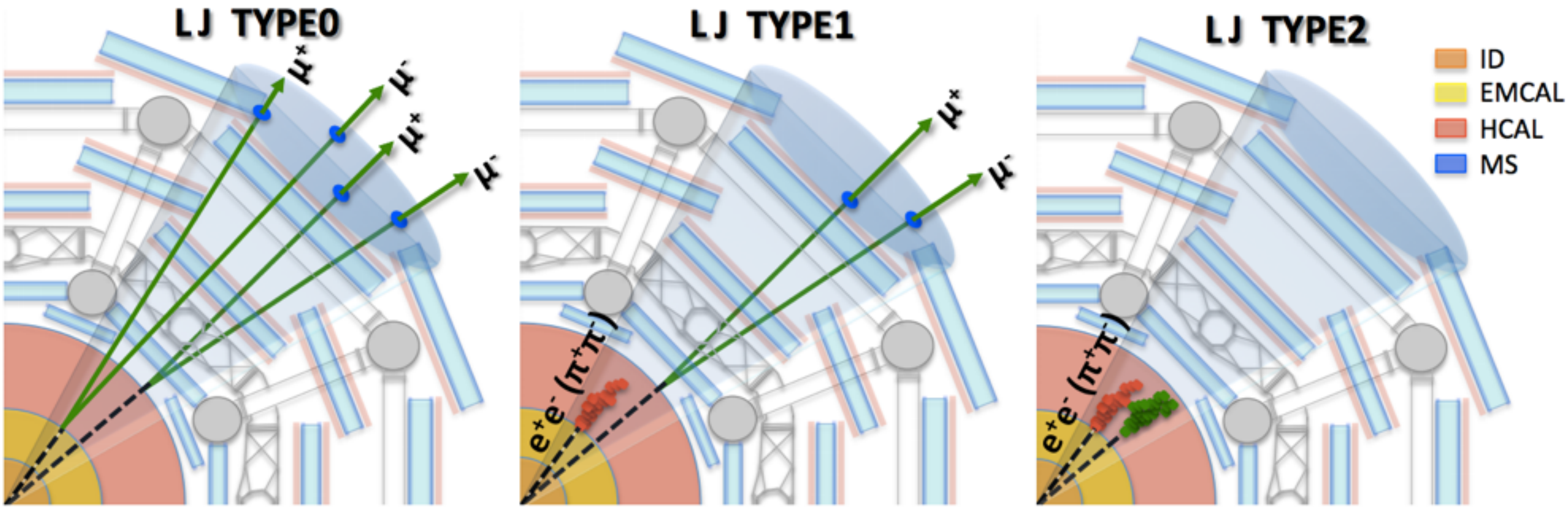
Low-mass dark photons can be produced via cascade decays of heavier states

Low-mass
—> large boost
—> collimated decay products

Leptonic decays prominent over wide (low) mass range



Why are lepton-jets difficult in ATLAS?



Challenges the idea of what a "good" lepton is

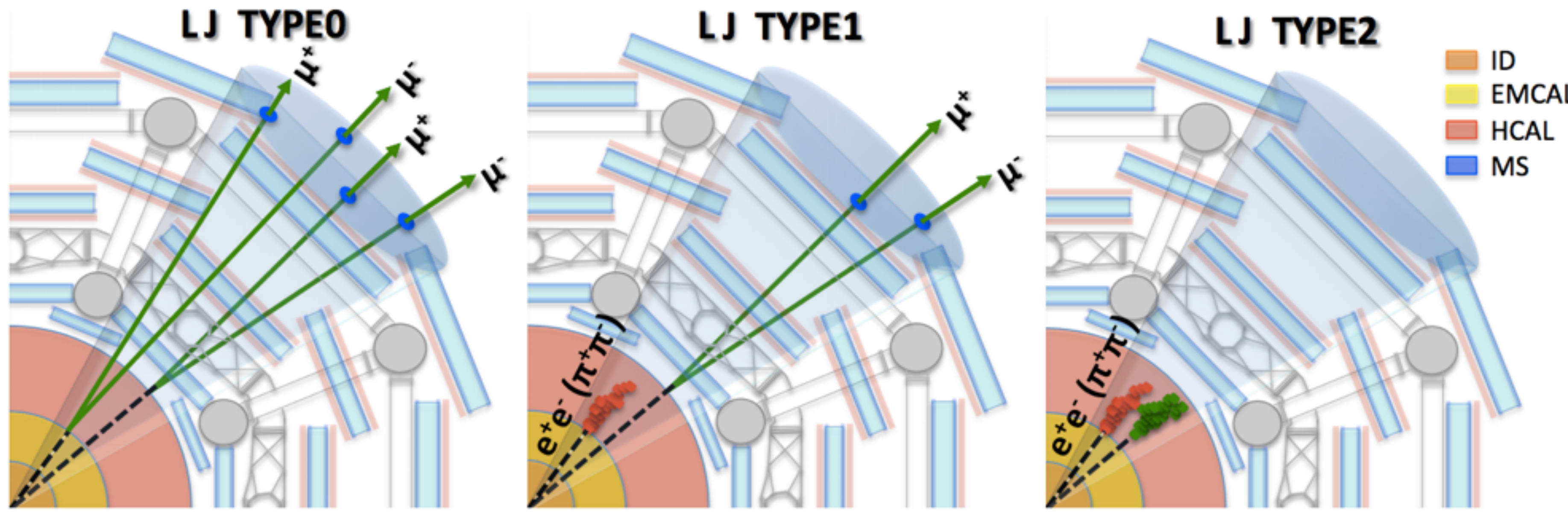
Muon triggers and ID / reconstruction in ATLAS have been optimised for some degree of isolation, spoiled with a very-nearby muon

Similar challenges with electrons

Primary vertex information, of primary importance for most searches, not useful for displaced decays

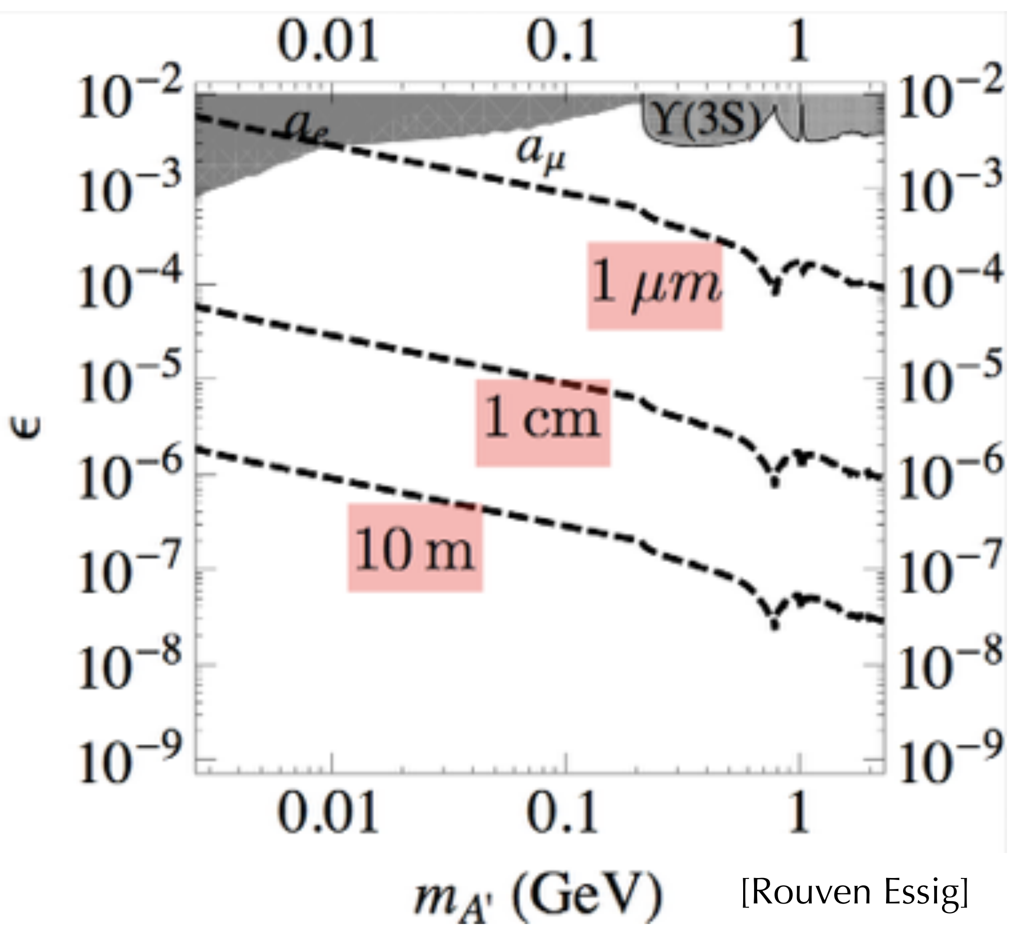
Prompt and displaced lepton-jets at ATLAS

Standard muon ID benefits from isolation; here need dedicated clustering algorithm with a cone of ΔR



Three separate types of lepton-jet definitions considered

Cosmic backgrounds important

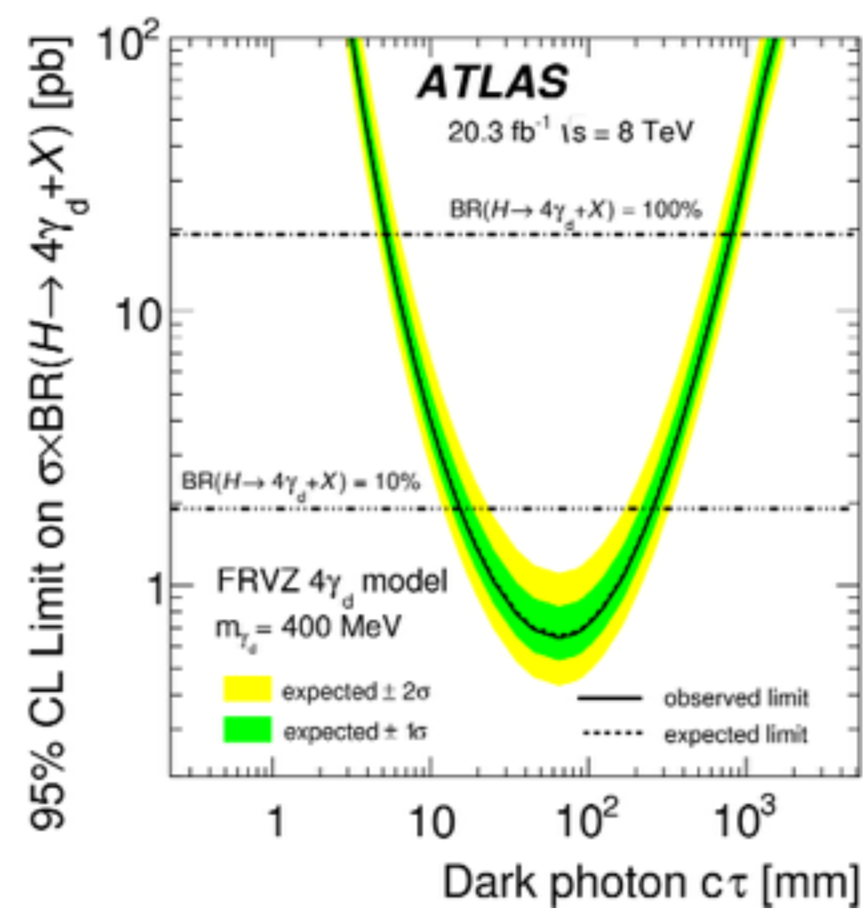


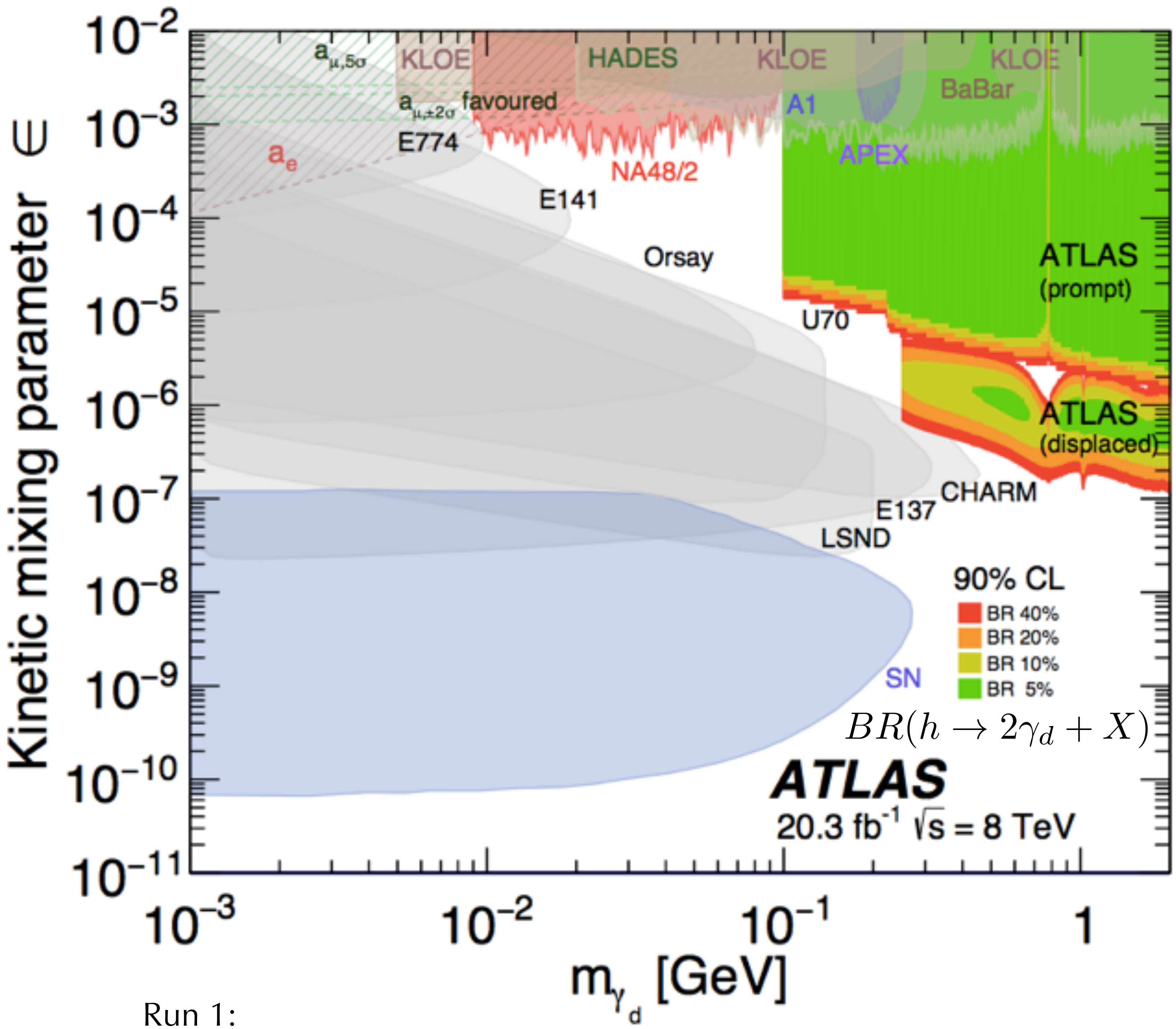
[Rouven Essig]

Weak interaction ==> non-negligible dark photon lifetime

Search for both prompt and displaced decays

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





Run 1:
JHEP11(2014)088
arXiv:1511.05542

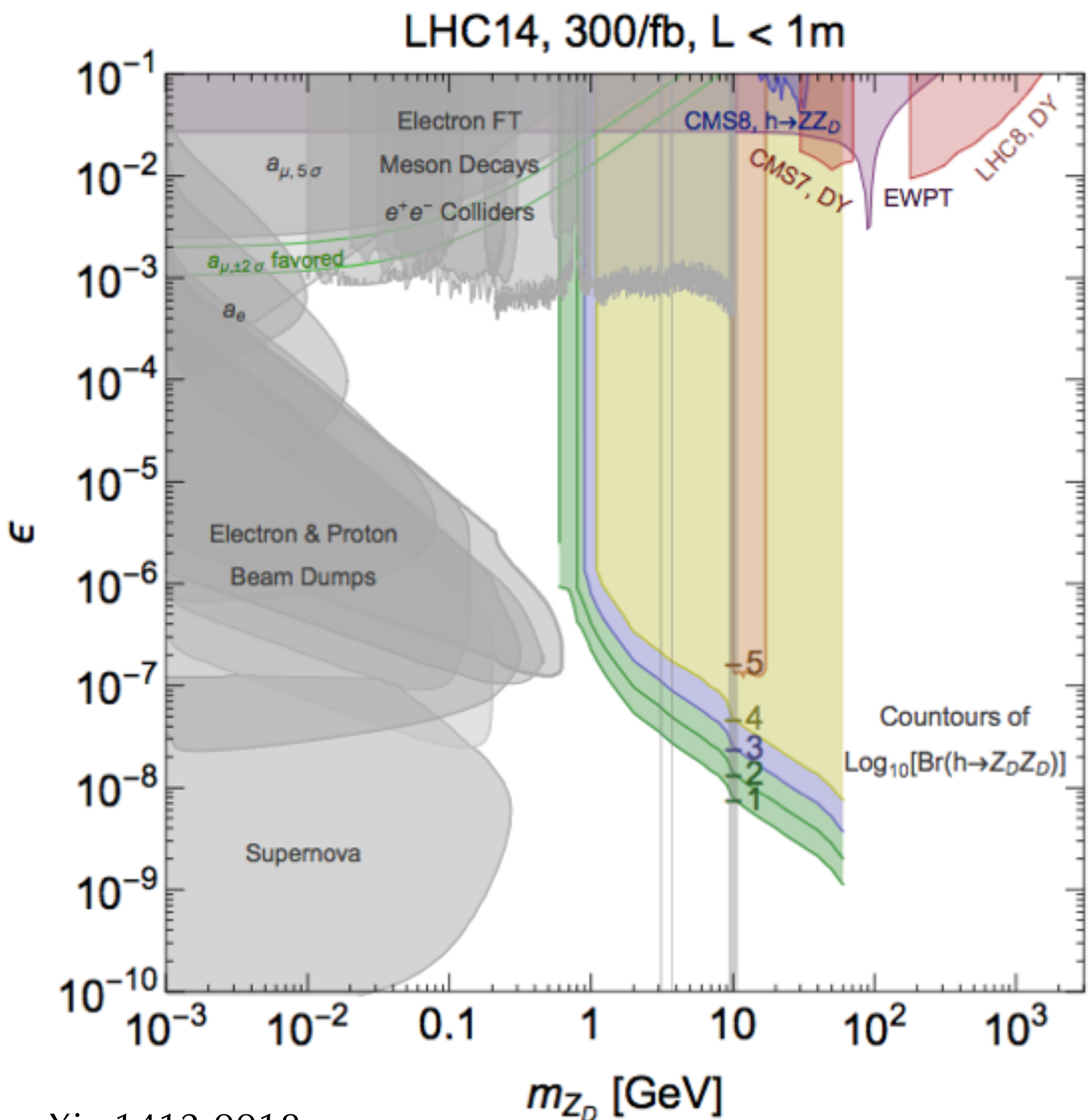
Run 2 prospects

Displaced:

- Expect to exceed Run 1 sensitivity with 3-4 fb^{-1} at 13 TeV
- New narrow-scan muon triggers greatly improve signal efficiency
- Recover muon reconstruction efficiency for nearby muons and extend mass reach higher
- Investigate non-prompt electron LJs reconstructed as converted photons

Prompt:

- Focus on larger dataset for an end-of-2016 result



arXiv:1412.0018

Further run 2 prospects

For non-prompt decays of dark photons / dark Zs with higher masses, the leptonic decay products can be displaced but non-collimated

"Good" muons in ATLAS require tracks in both the inner tracking volume and the muon spectrometer; "combined" muons

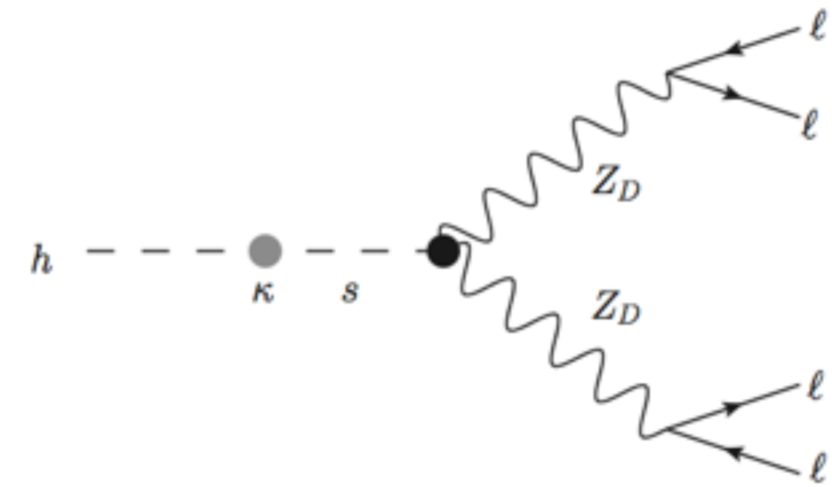
Instead use MS-only "tracklets" and match to a common MS vertex

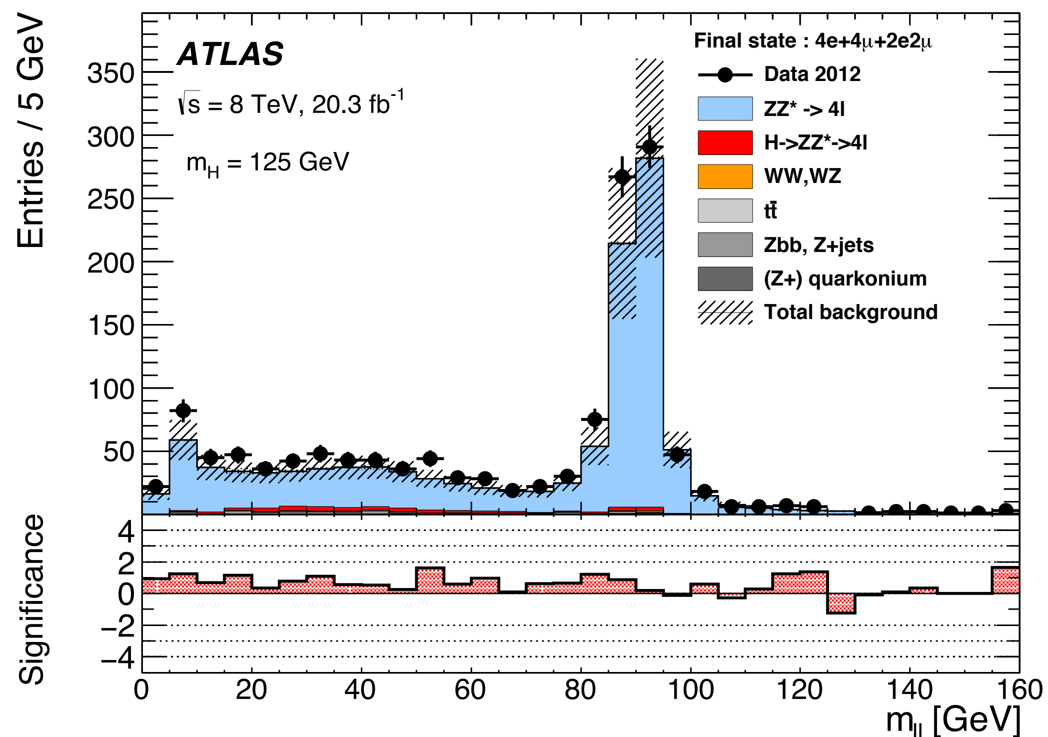
Model-independent searches for such topologies will be a priority in ATLAS Run 2

Higher mass hidden gauge bosons: $H \rightarrow Z_{(d)}Z_d \rightarrow 4l$

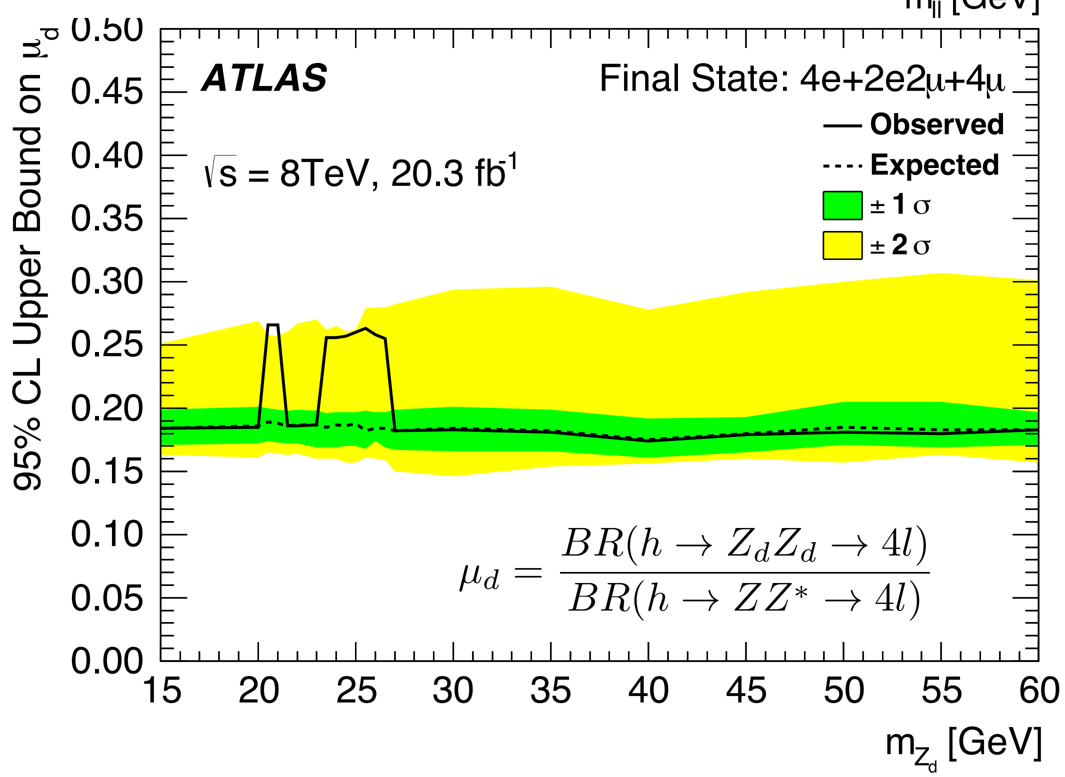
Run 1: PRD 92 092001

Dedicated search in ATLAS Higgs-to-four-leptons events





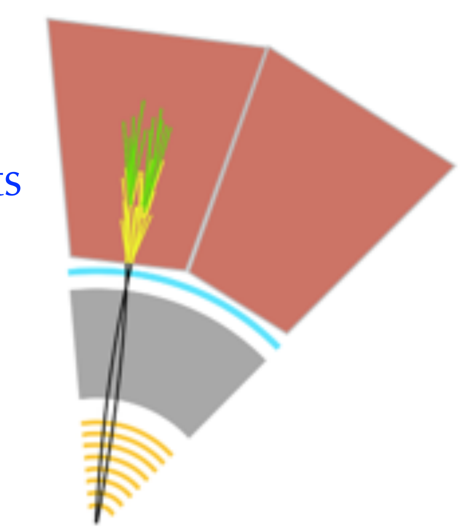
Z_dZ_d: keep events with a unique quadruplet where the mass difference between the 2 dilepton system $|m_{12}-m_{34}|$ is minimal; then apply a Z-veto and a J/ψ and ϒ veto



$$\mu_d = \frac{BR(h \to Z_d Z_d \to 4l)}{BR(h \to ZZ^* \to 4l)}$$

Run 2 developments:

- Lower mass reach in m_{Zd}
  - Lower mass ==> close together decay products
    - Muons ==> lepton-jet-like
    - Electrons ==> Need new approach
- Investigate higher Higgs masses
- Investigate adding some Z_d decay channels

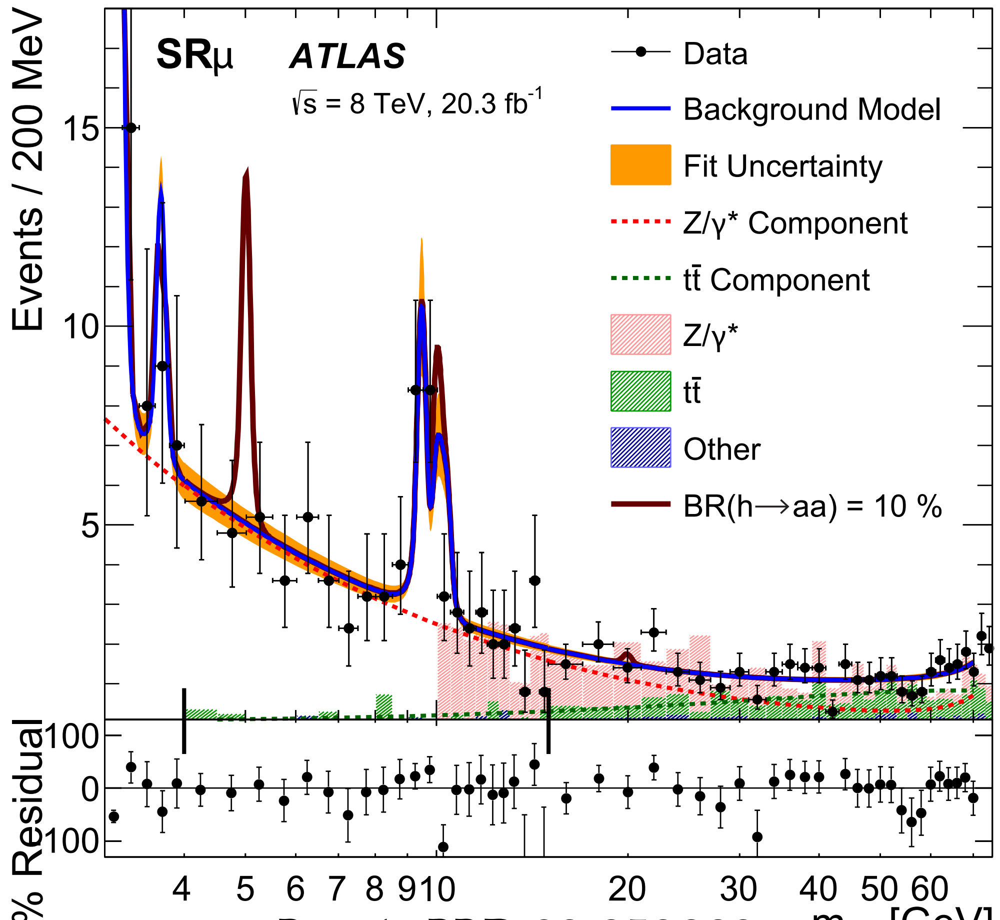


Run 2 sensitivity:

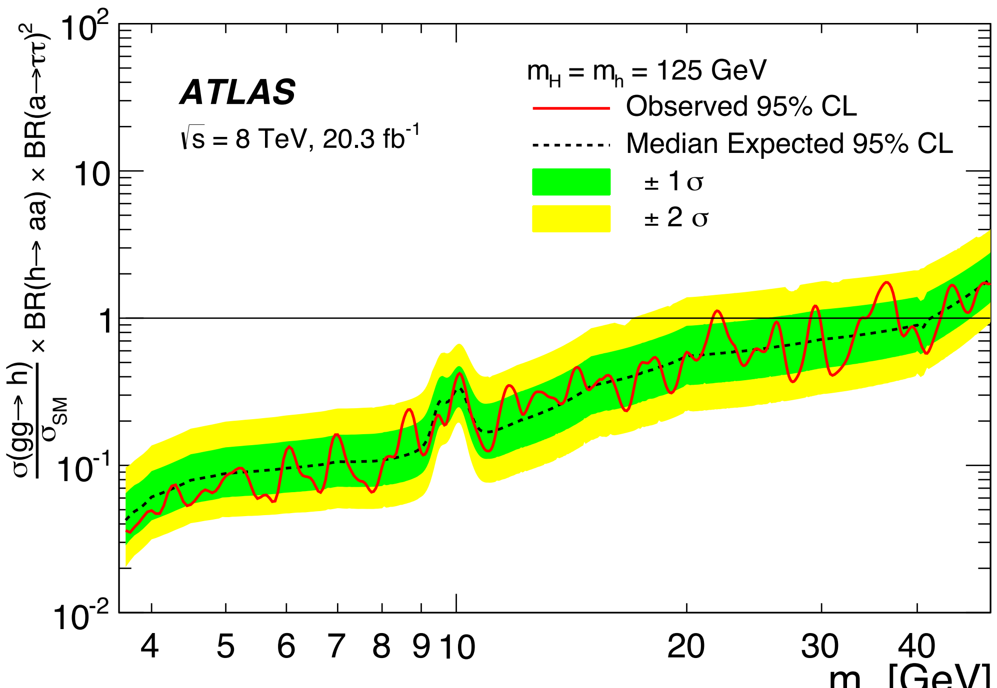
- Benefit from increased Higgs production cross section
- Expect to improve upon Run 1 results with ~10 fb^{-1} at 13 TeV

H ⟶ aa(ss) ⟶ 4SM (or 2SM+X)

H —> aa —> 2μ2τ

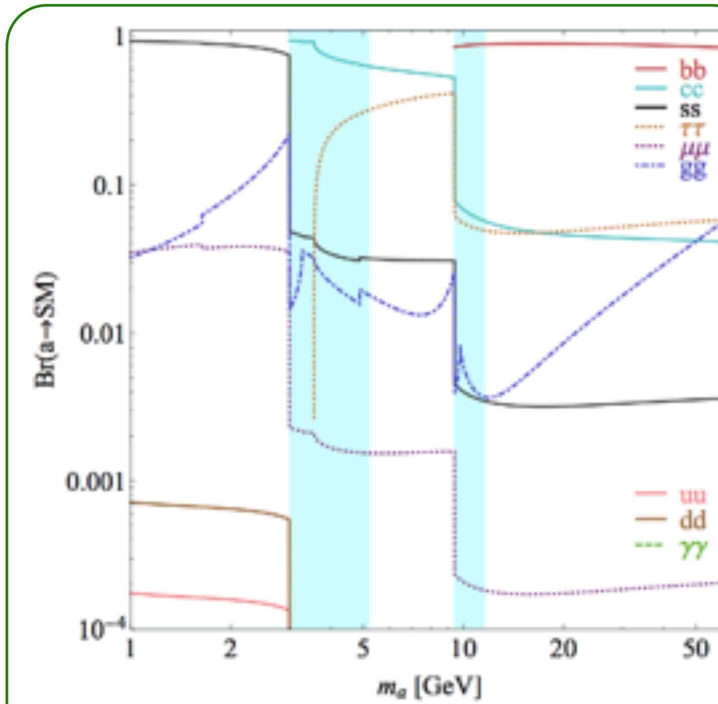


Run 1: PRD 92 052002



Extended Higgs sectors with relatively light (pseudo)scalars (*a*)*s* from hidden sectors

Given the limit to the expected precision with which we can ever measure the couplings of h125 to SM particles at the LHC, h —> aa searches remain possibly our best window into the dark sector



Example:
2HDM+S with
Type 1 Yukawa couplings

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

Run 2 prospective searches for h125 and m_H > 125 GeV:

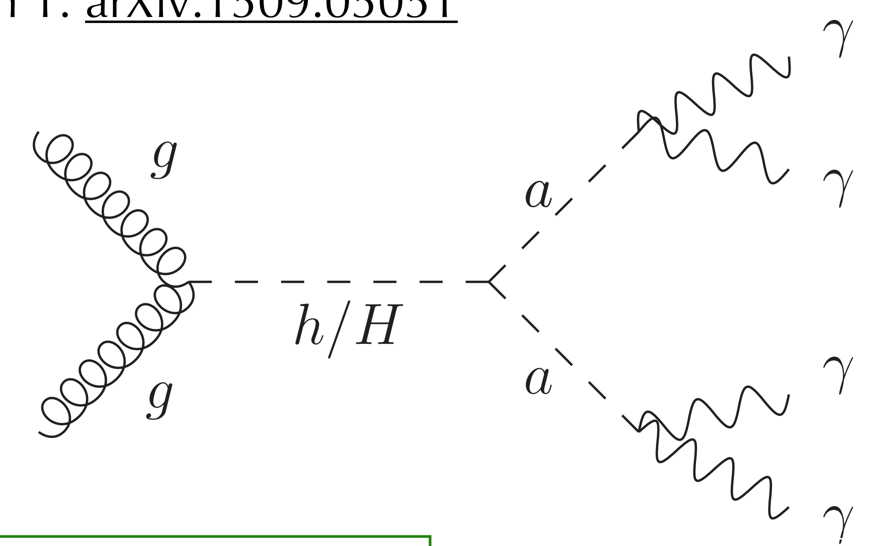
- h —> aa —> 2μ2τ
- h —> aa —> 4b
- h —> aa —> 2b2μ
- h —> aa —> 2b+MET
- h —> aa —> 4τ
- h —> aa —> 4γ

Speaking of that last one…

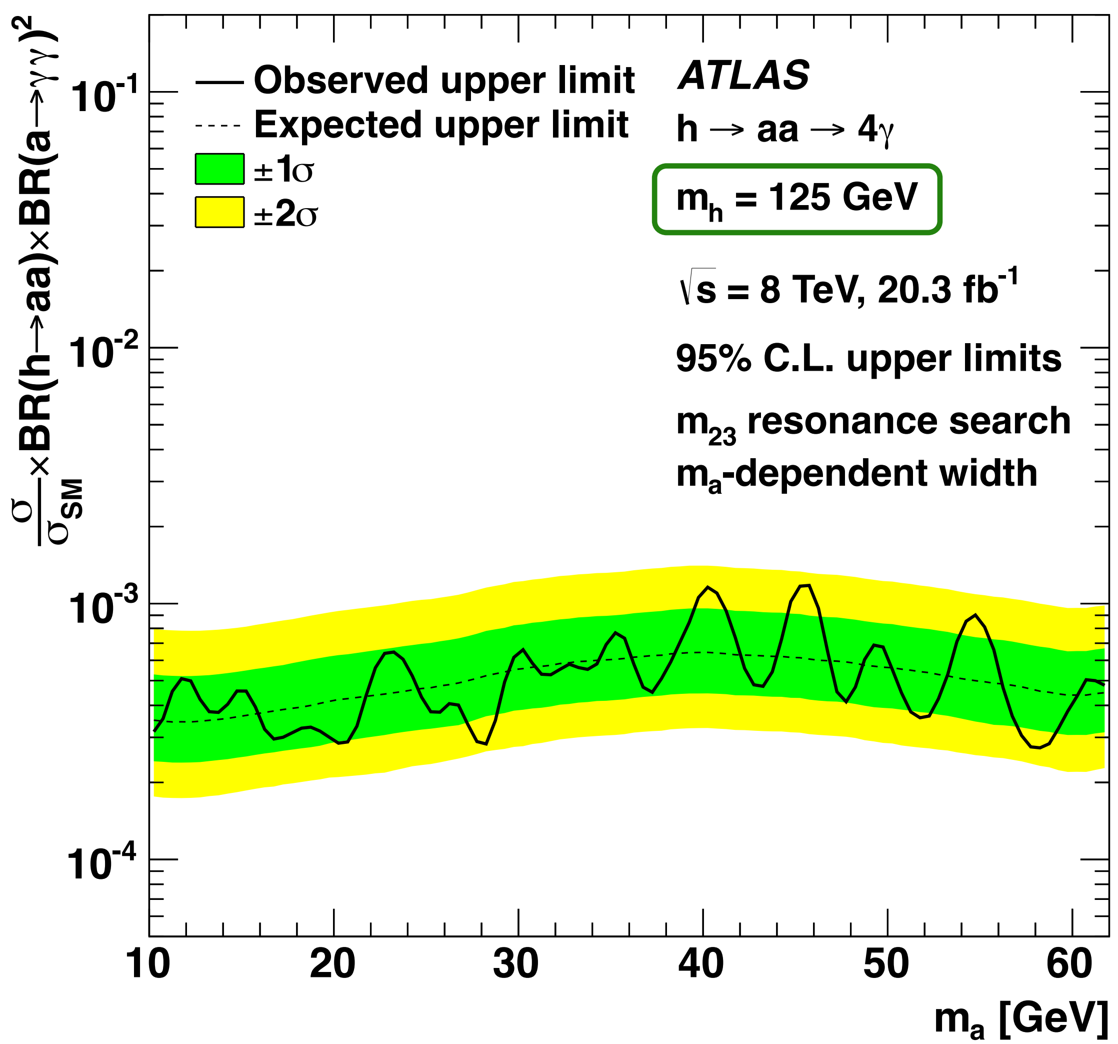
General search for new phenomena in inclusive three-photon events at 8 TeV

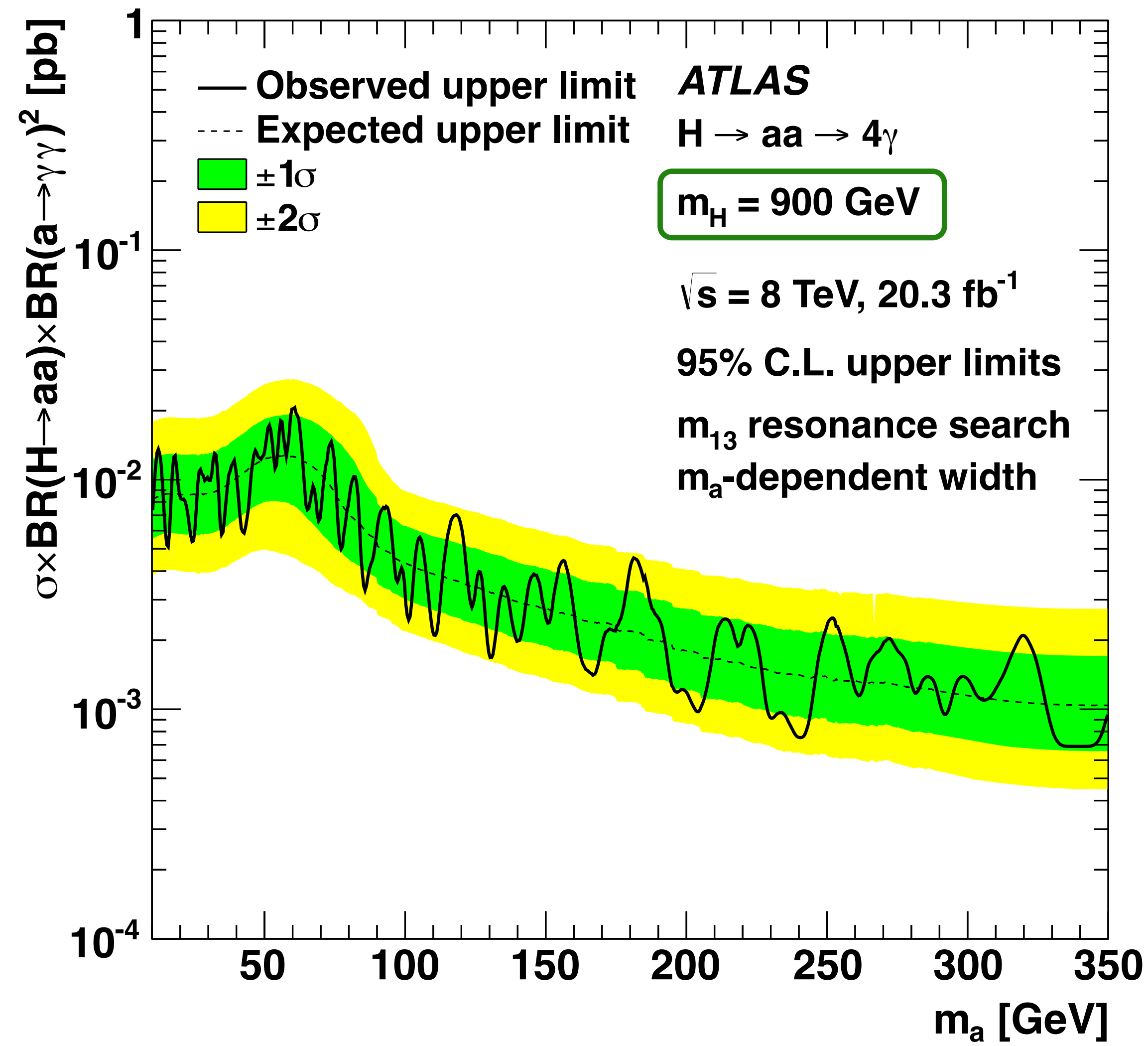
Run 1: arXiv:1509.05051

- Low-p_T photon requirements: > 22, 22, and 17 GeV
- Photon ID limitations for low-p_T, nearly-merged photons ($\Delta R < 0.15$)
- Resonance searches in 2γ and 3γ mass spectra



One of the main benchmarks: H —> aa —> 4γ

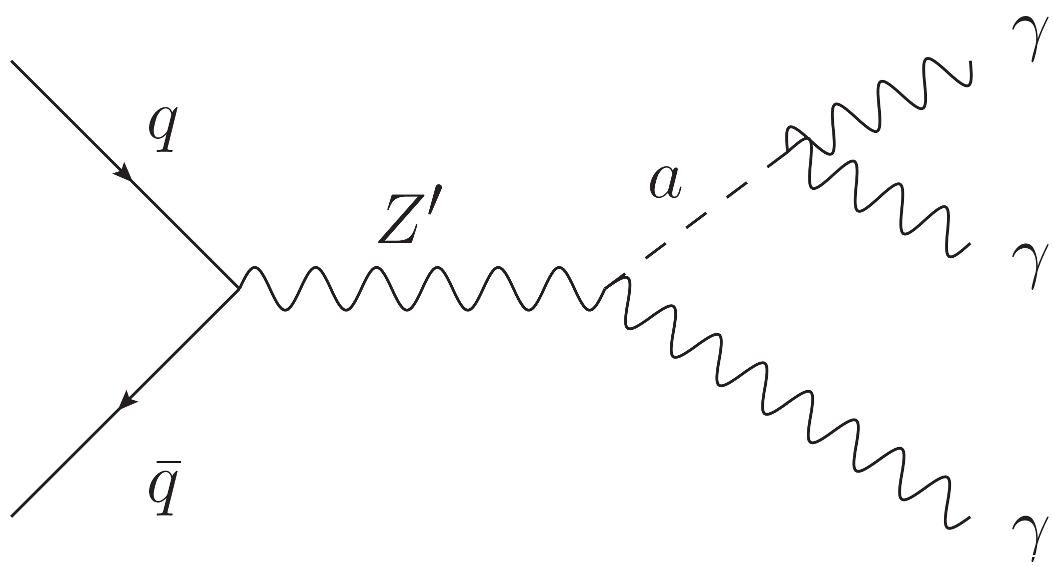


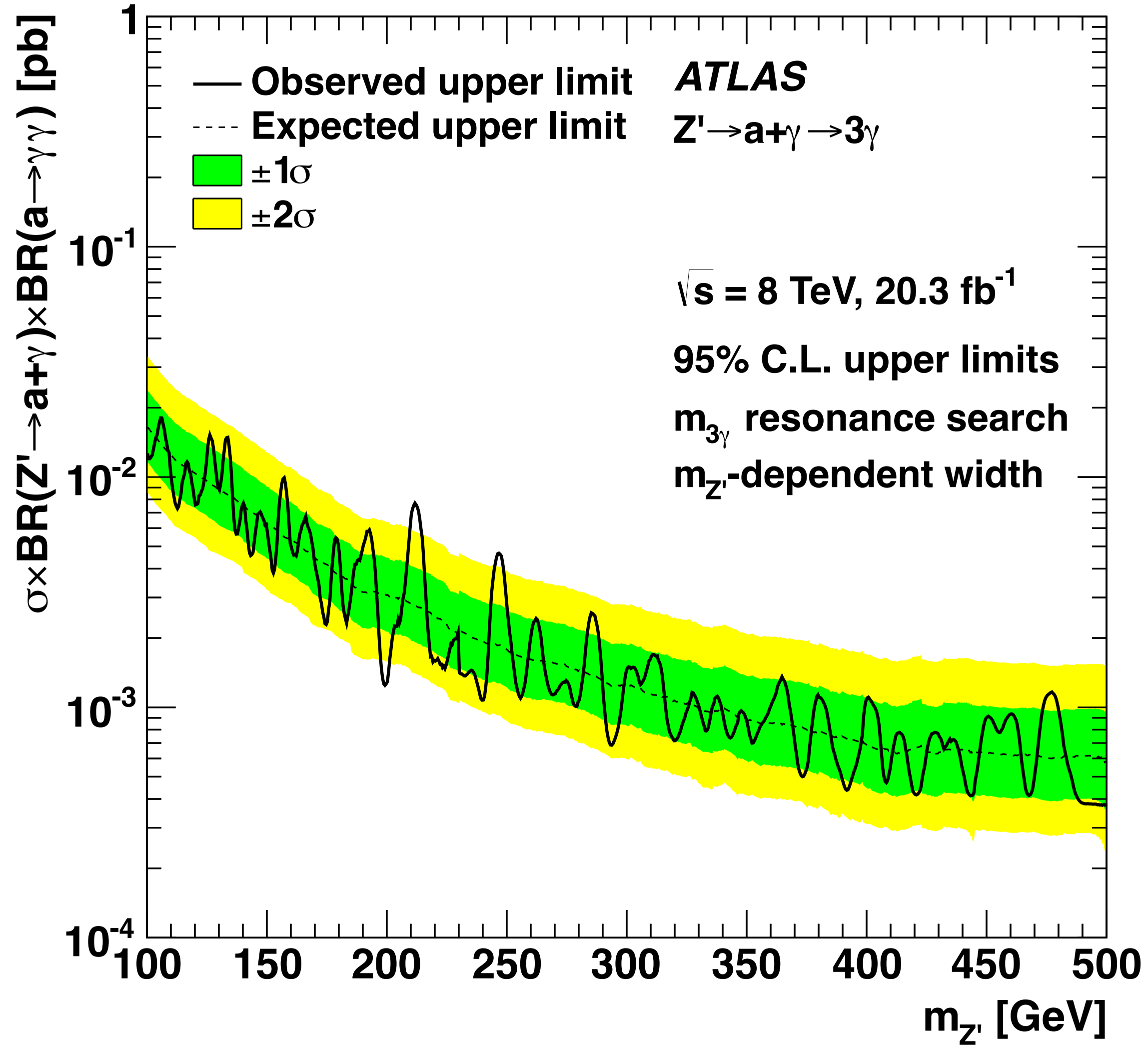


General search for new phenomena in inclusive three-photon events at 8 TeV

Run 1: arXiv:1509.05051

Z′ —> a+γ —> 3γ





Both H —> aa —> 4γ and Z′ —> a+γ —> 3γ have implications for $m_{\gamma\gamma}$ = 750 GeV

- Very low m_a leads to highly-collimated photon pairs from multi-photon events that can yield a “diphoton” final state in ATLAS
- Run 1 search utilized separated, isolated photons

Standard isolation calculated based on some fixed cone size

Real photons have narrower shower shapes than jets

Lots of extra energy in the cone ==> jet faking a photon

Distinguish photons from jets-faking-photons by requiring stringent isolation

—> Straightforward for high mass diphoton resonance searches

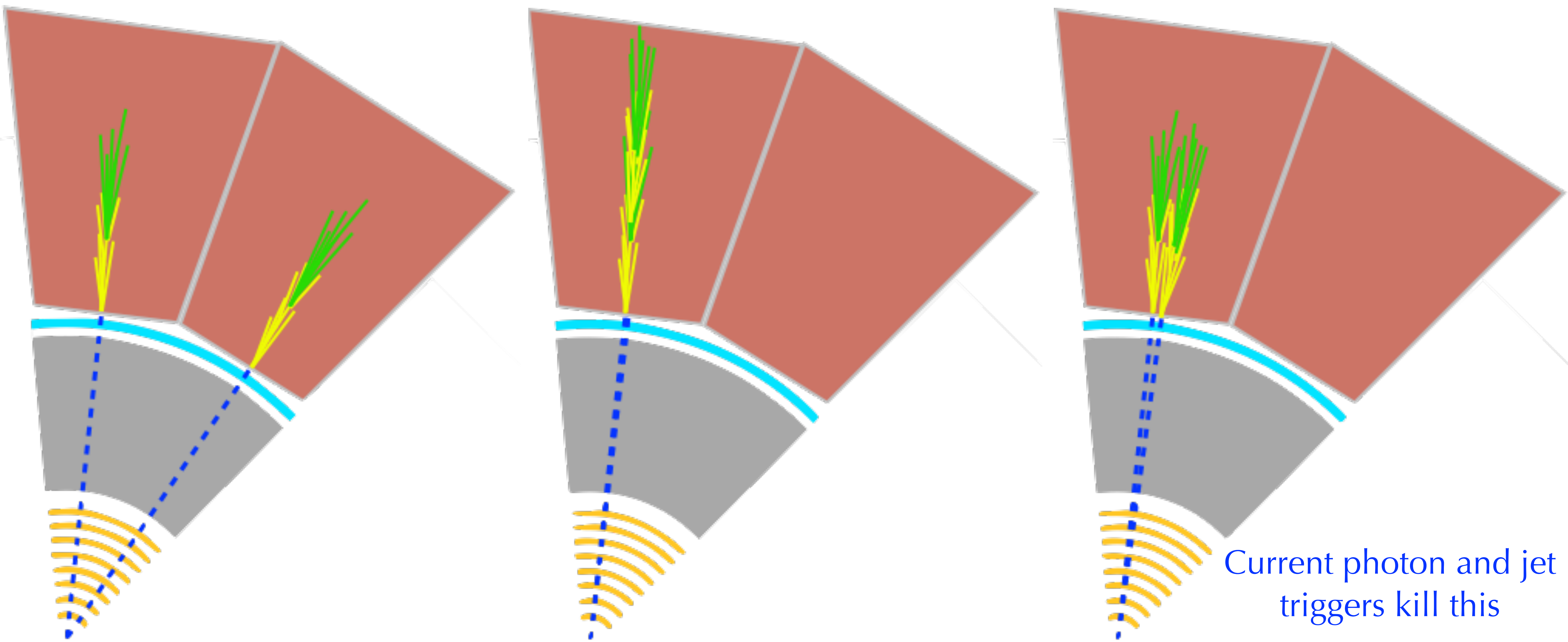
—> Challenge arises for low-mass resonances with low-p_T photons or highly boosted states

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

Two well-separated photons (!)

Two completely overlapping photons (!)

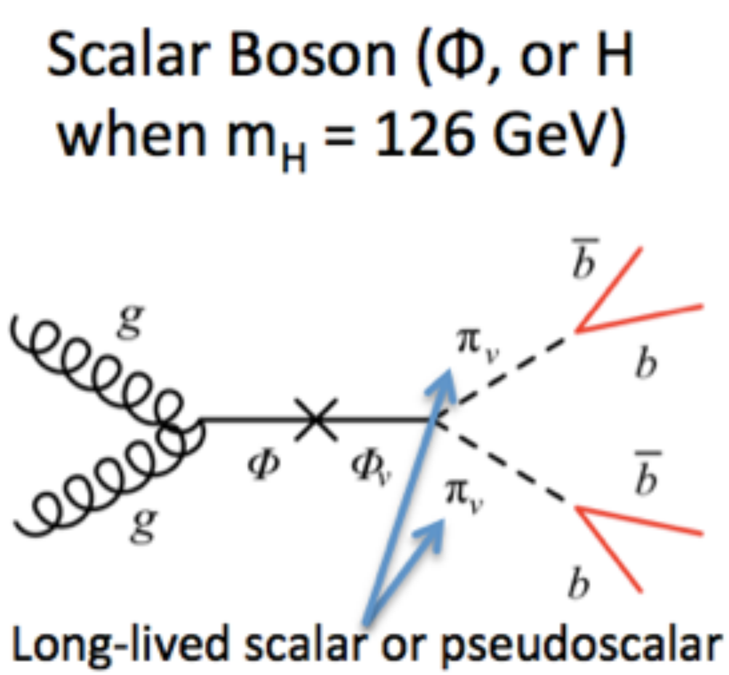
Two nearly-merged photons (?)

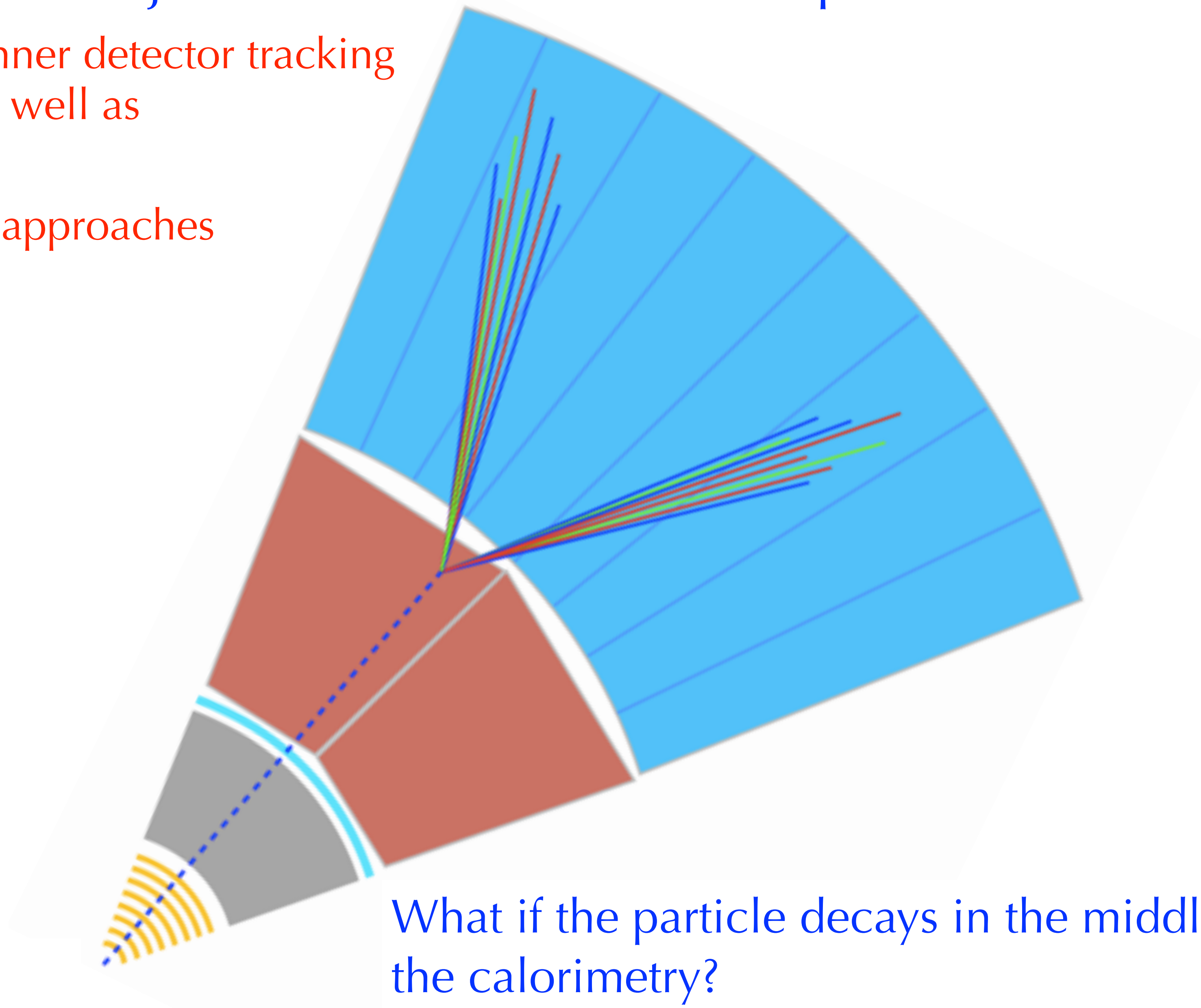


Current photon and jet triggers kill this

Long-lived particles decaying 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.
- Displaced jets confound the standard jet ID approaches





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

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

CalRatio: Pair of jets decaying in the HCal

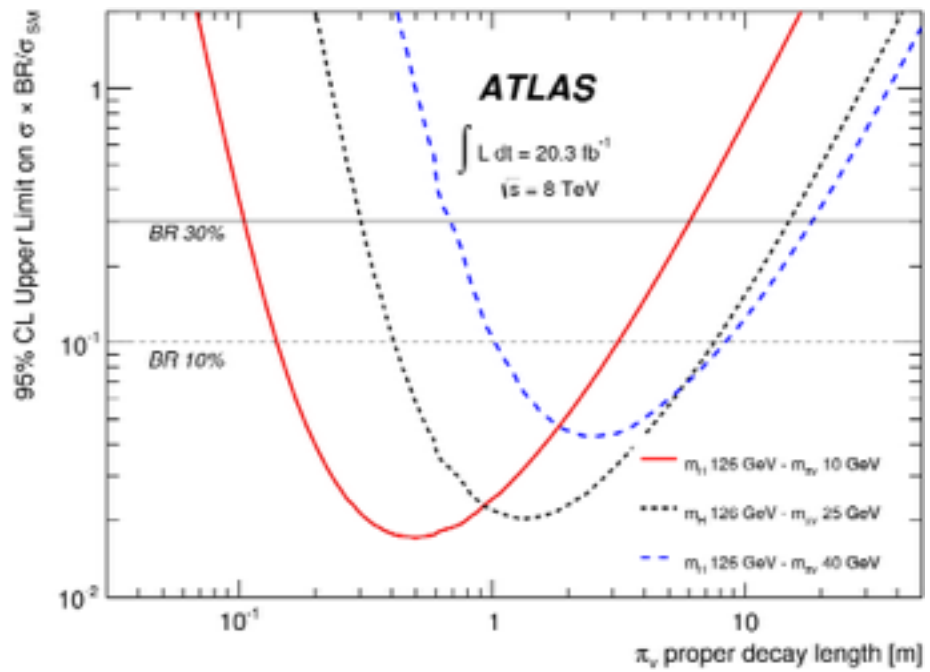
- A narrow radius
- No ID tracks pointing towards the jet
- Large energy deposit in the HCal with little to no energy in the ECal
- Primary background from SM multijets

Run 1 results

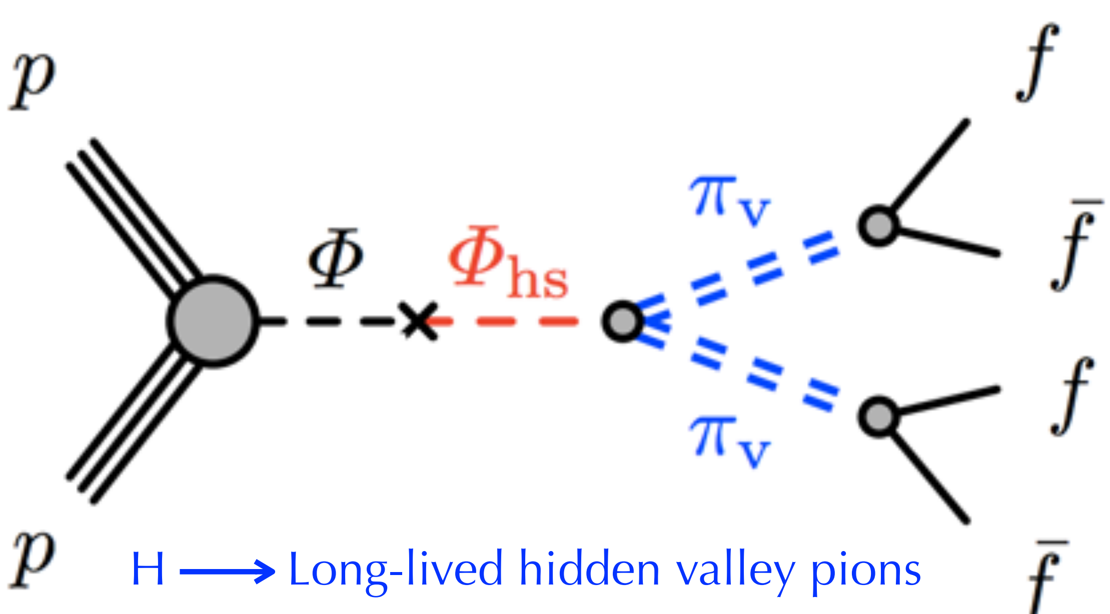
Run 1: PLB 743 (2015) 15-34

DJs in the hadronic calorimeter

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



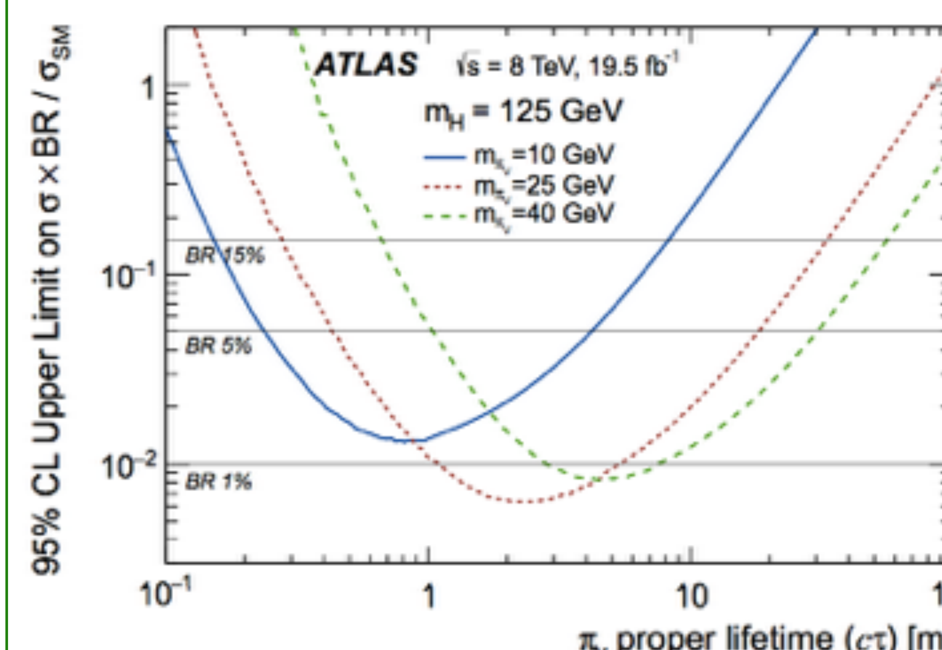
Dedicated CalRatio trigger (also used by other long-lived particle searches)



Run 1: PRD92 (2015) 1, 012010

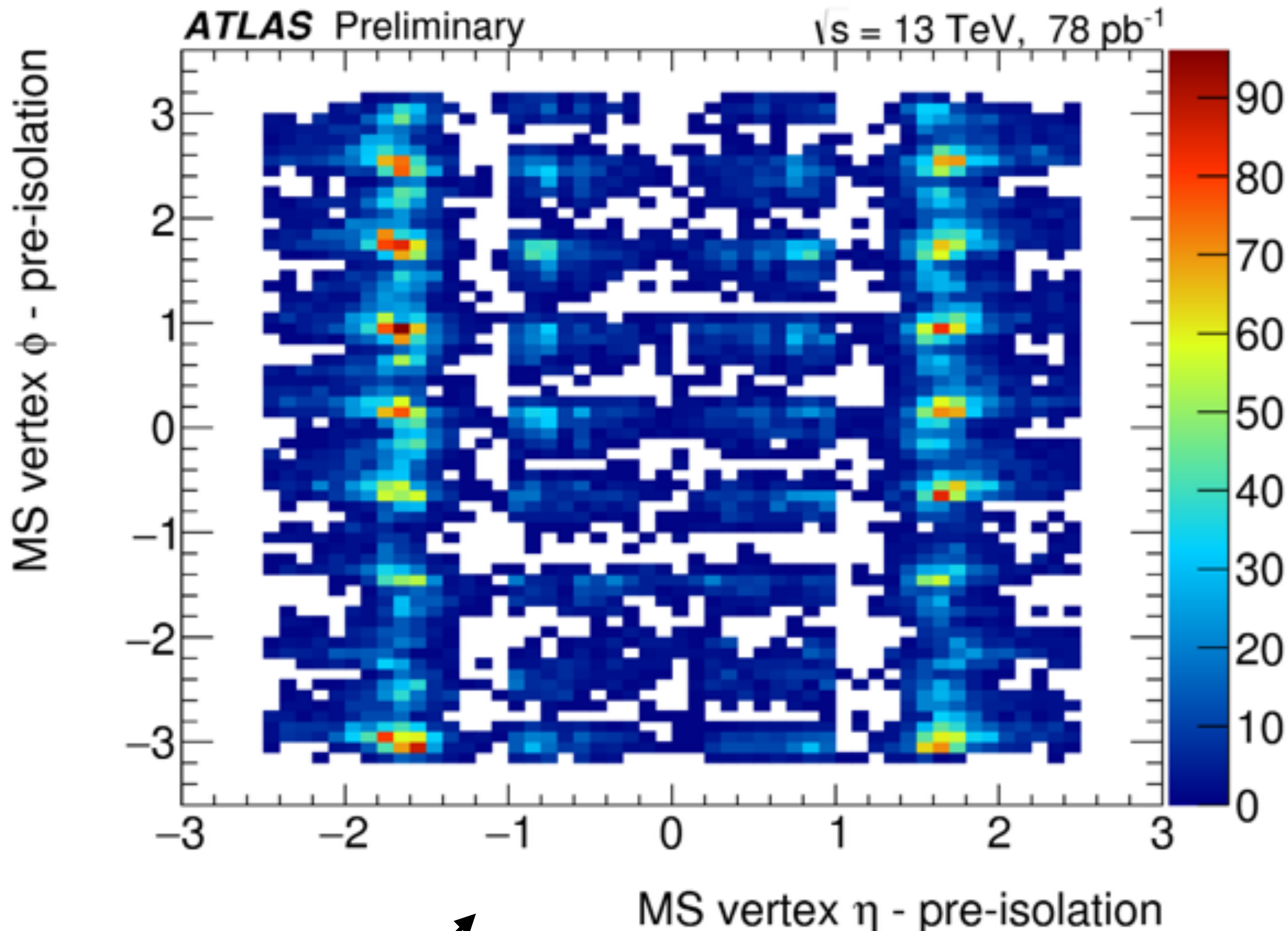
DJs in the ID or muon spectrometer

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



Run 2 prospects

- Major improvements for triggers, signal jet ID, trackless SM multi-jet background rejection
- Exceed Run 1 sensitivity for most benchmark scenarios with 2015+2016 data
- Adding multiple new model interpretations currently unconstrained



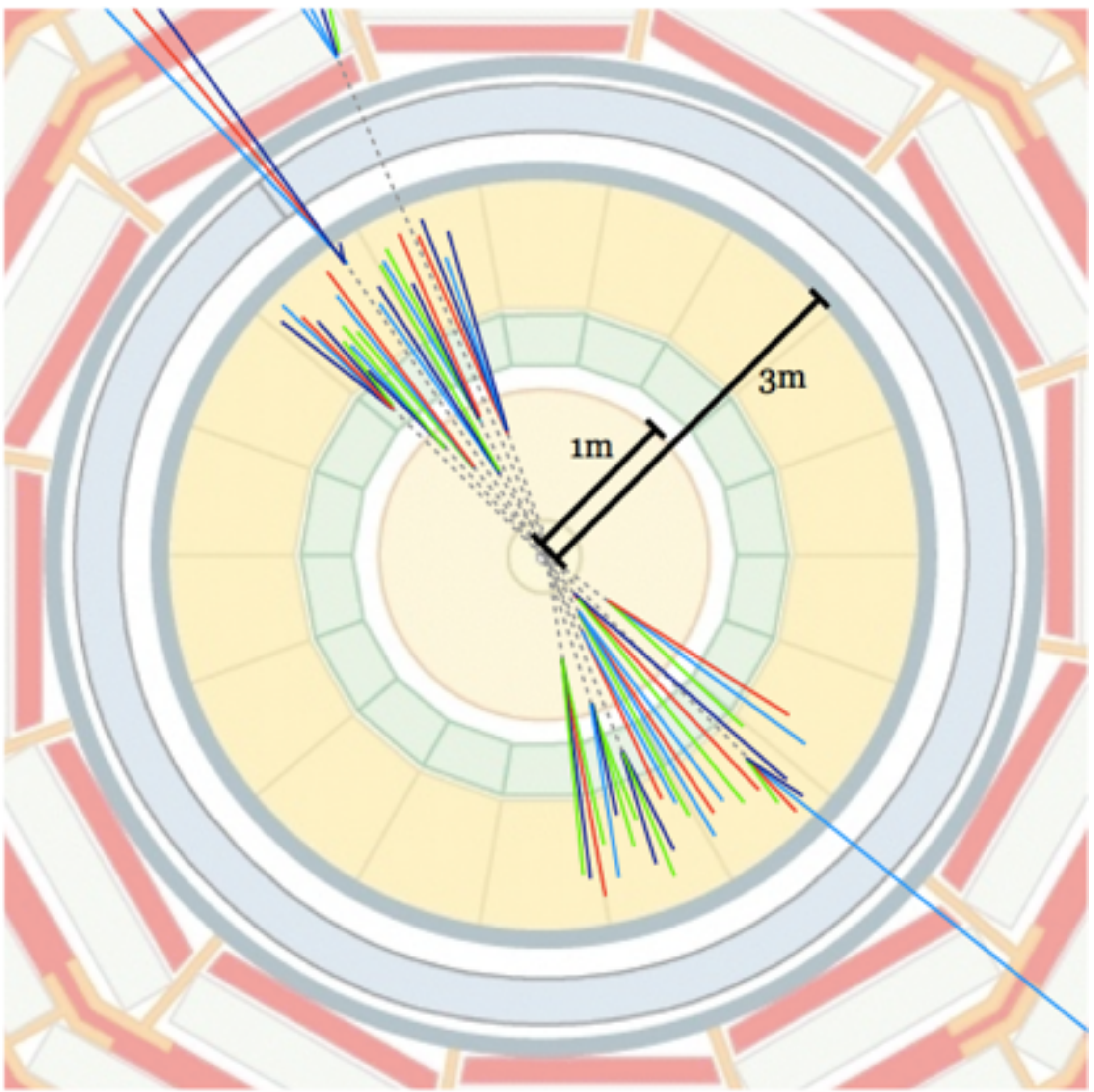
MS-only vertexing algorithms work like a charm in Run 2

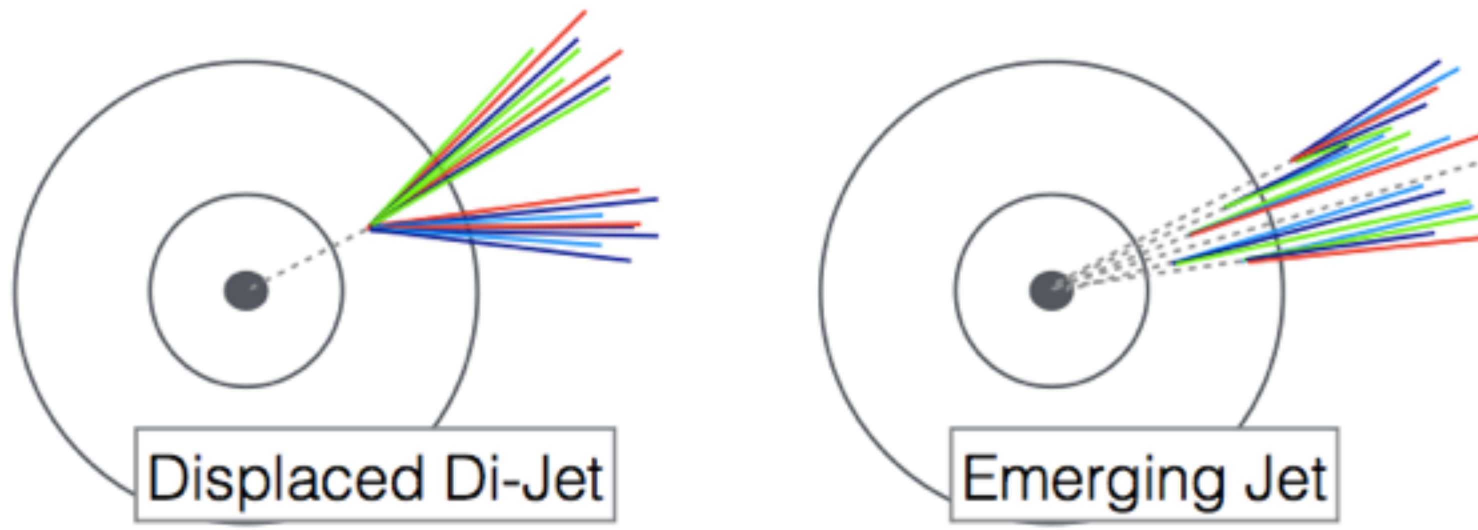
Emerging jets

NEW IN ATLAS FOR RUN 2

A novel LHC signature where dark or hidden sector quarks decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object. Pair-produced dark quarks then give rise to **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but to **emerging jets**.

arXiv:1502.05409





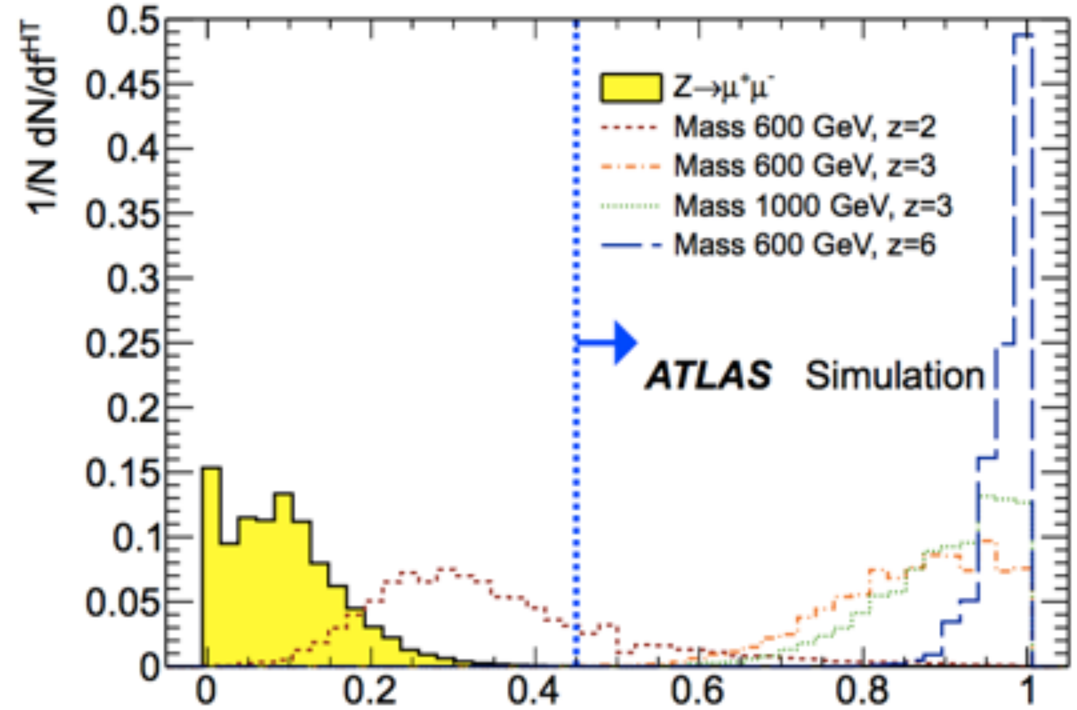
Requires custom emerging jet ID and background rejection

Aiming for late summer result, to be updated for full 2015+2016 dataset

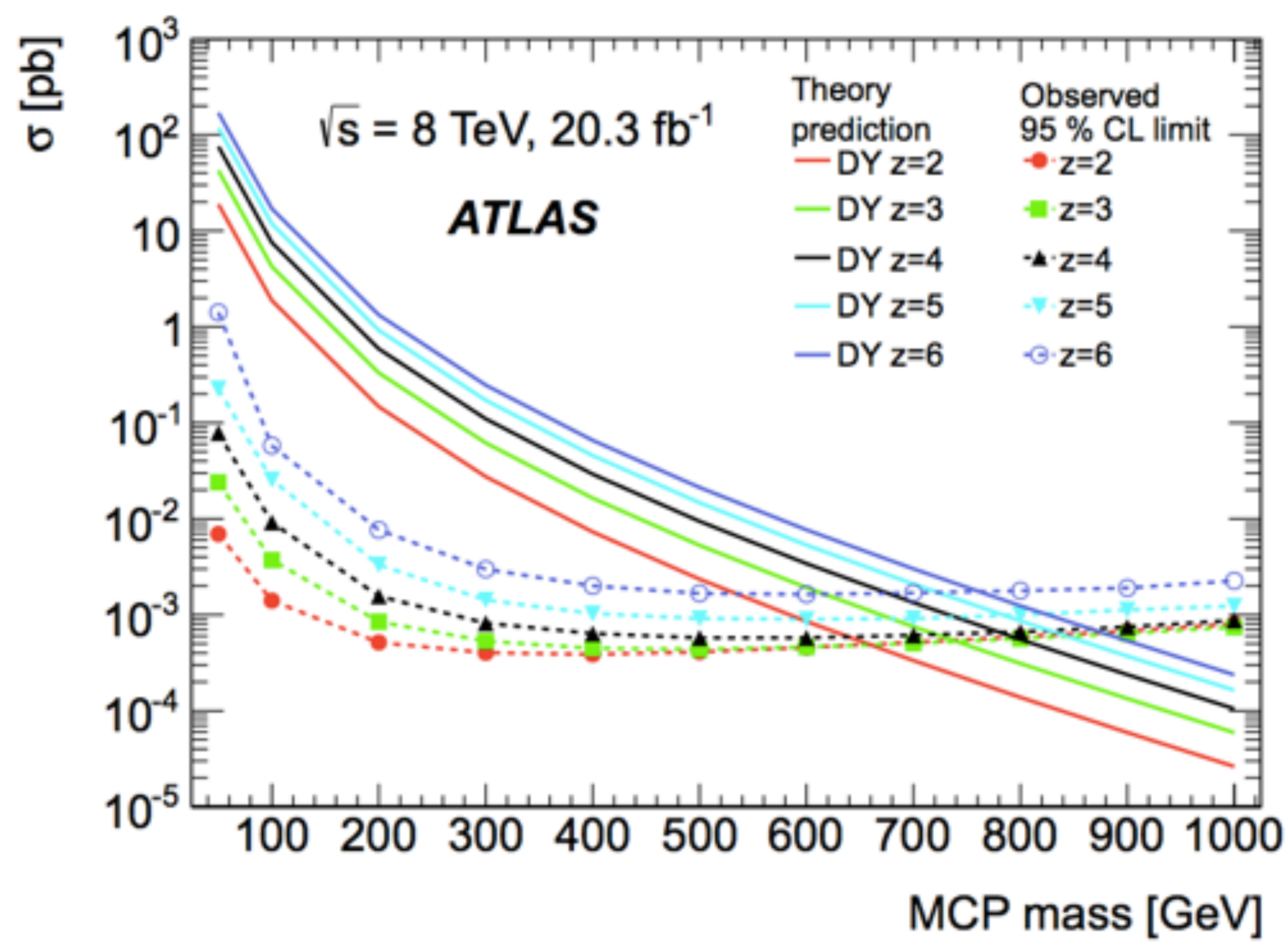
Multi-charged particles

Search for long-lived (ATLAS-stable) multi-charged particles (MCPs) with $2e < |q| < 6e$

- Highly ionizing, muon-like signature
- MCPs lose an anomalously high amount of energy per distance in all subdetectors
- Doubly-charged particles appear in models (almost-commutative model, walking technicolor) that can have implications for composite dark matter



Run 1 (8 TeV): EPJC (2015) 75:362



Drell-Yan pair-production of MCPs
Use muon and MET triggers and look for muon-like tracks with high dE/dx along trajectories in subdetectors

Run 1 at 8 TeV exclusions:

m_{MCP} < 650-800 GeV (charge-dependent)

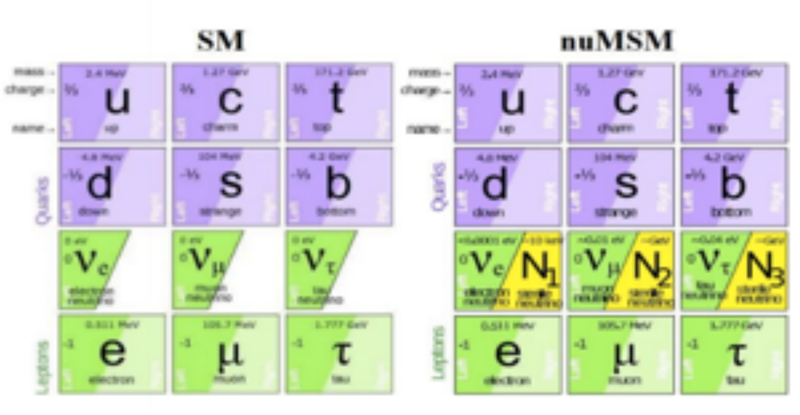
Run 2 at 13 TeV, preliminary sensitivity estimates with 2015 and projected 2016 datasets:

m_{MCP} < 900-1100 GeV (charge-dependent)

Long-lived, heavy neutral lepton

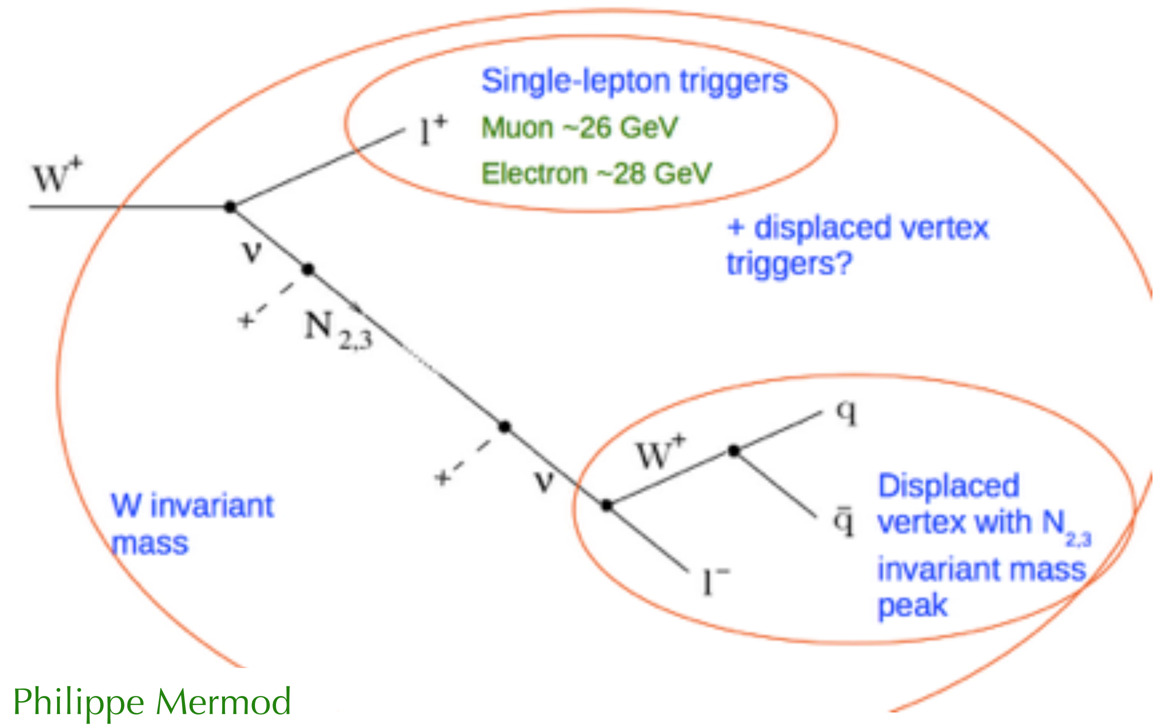
NEW IN ATLAS FOR RUN 2

The neutrino Minimum Standard Model (νMSM)
Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)



N_1 stable dark matter
$N_{2,3}$ long-lived,
mass in 0.2-100 GeV range

Main signature in ATLAS



Philippe Mermod

Simple addition of right-handed terms to the lagrangian

- Three right-handed neutrinos, with no other new particles

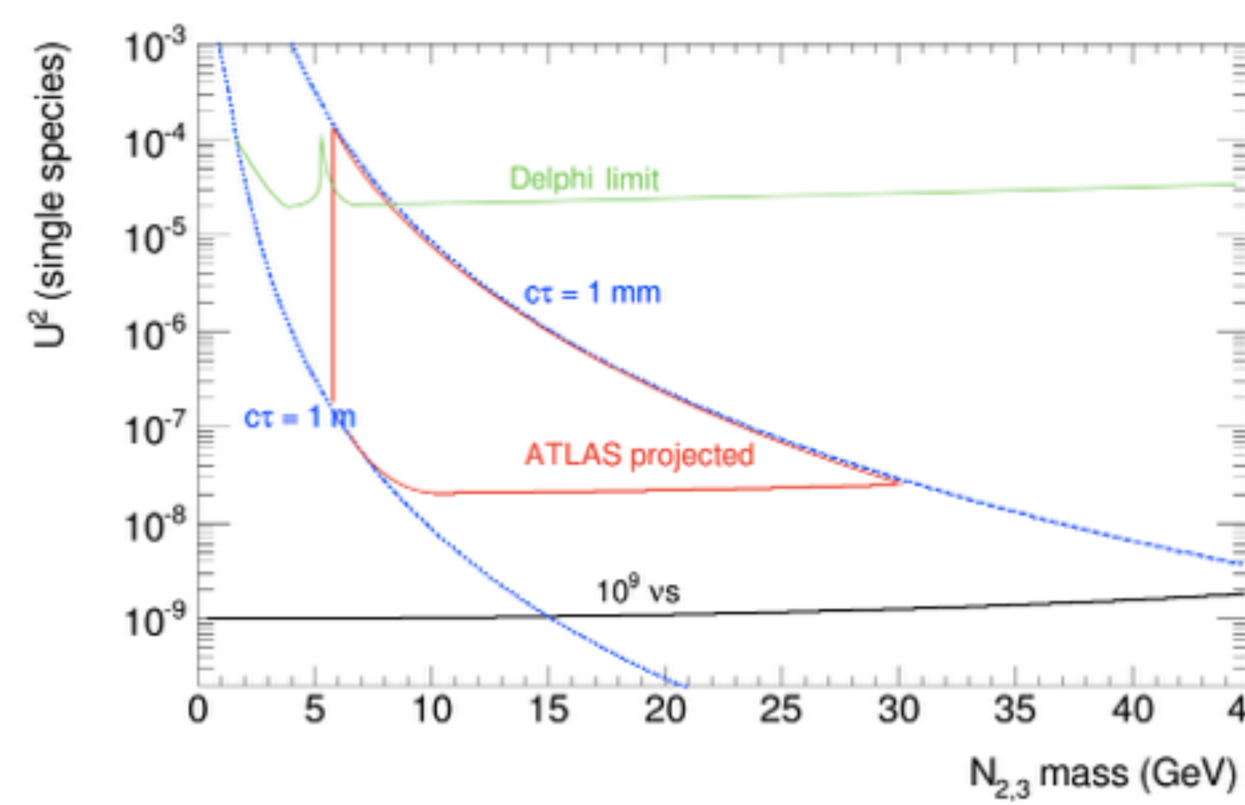
Explains neutrino masses and accommodates dark matter and the matter-antimatter asymmetry

Direct searches for $N_{2,3}$

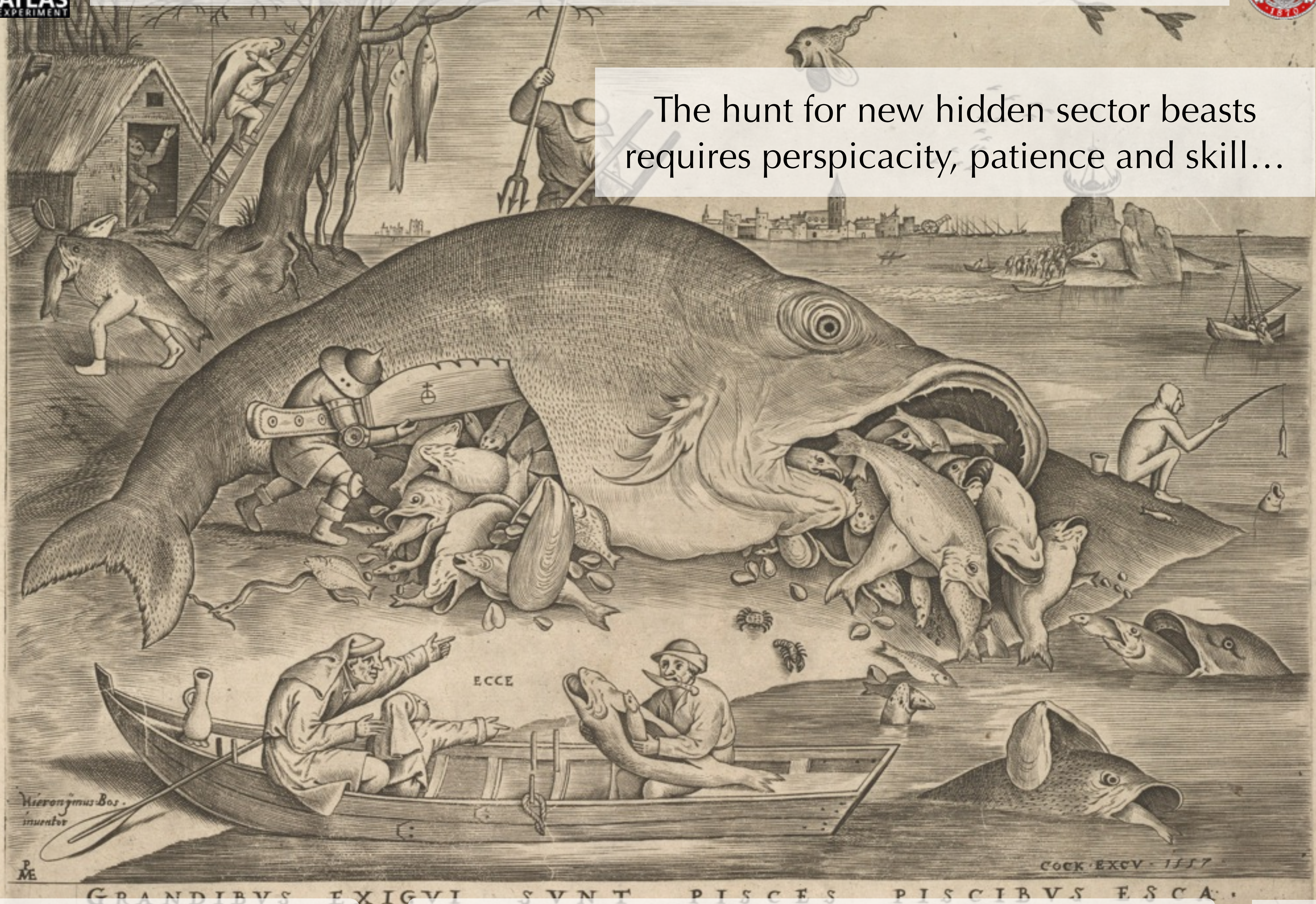
- To probe small mixing with ordinary neutrinos requires high statistics (10^9 from Ws in Run 2)
- Tiny mixing / long lifetime (10^{-11} - 0.1 s) allowed by observations and cosmology

==> displaced vertices in ATLAS

assuming 50 fb⁻¹ @ 14 TeV

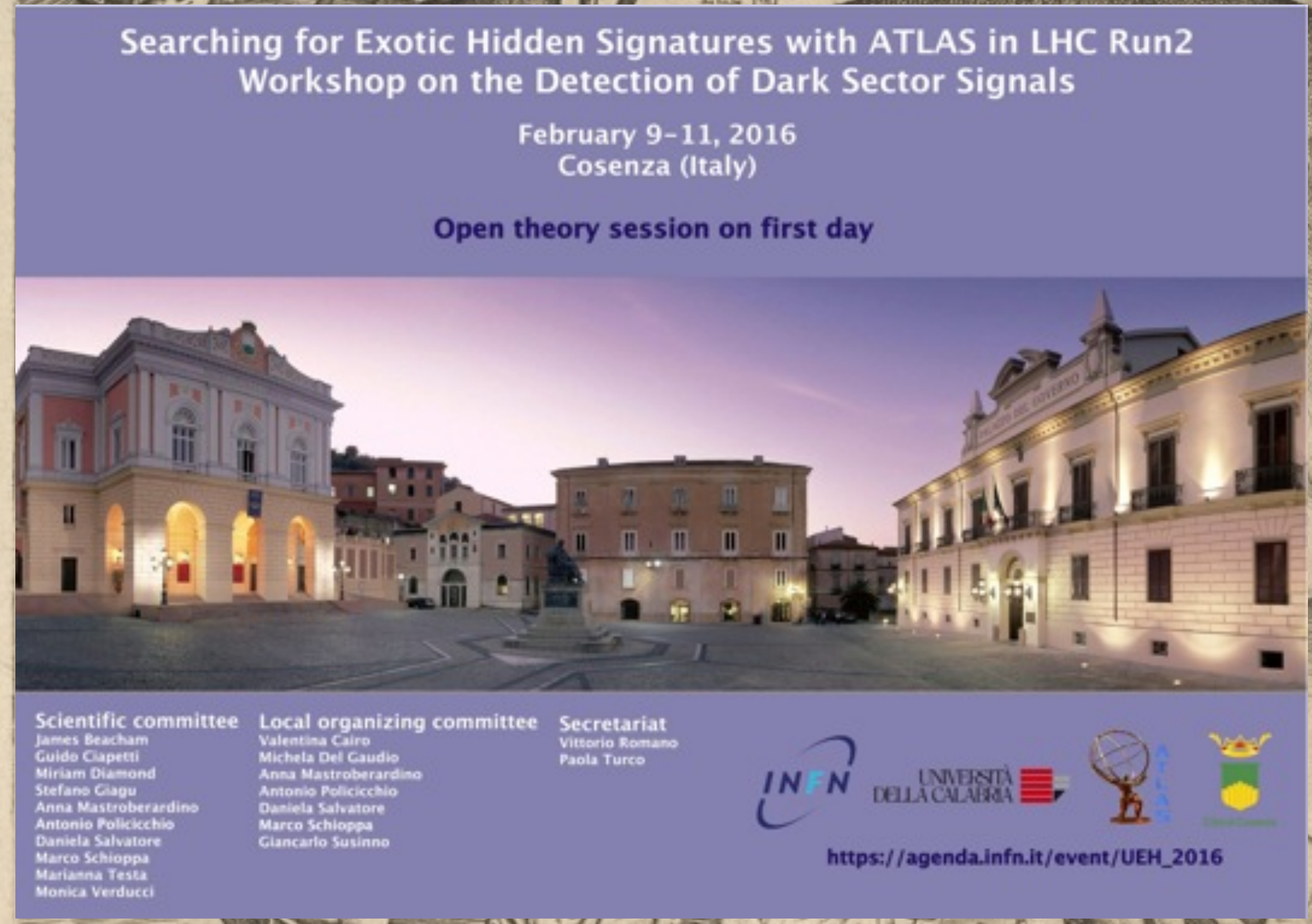


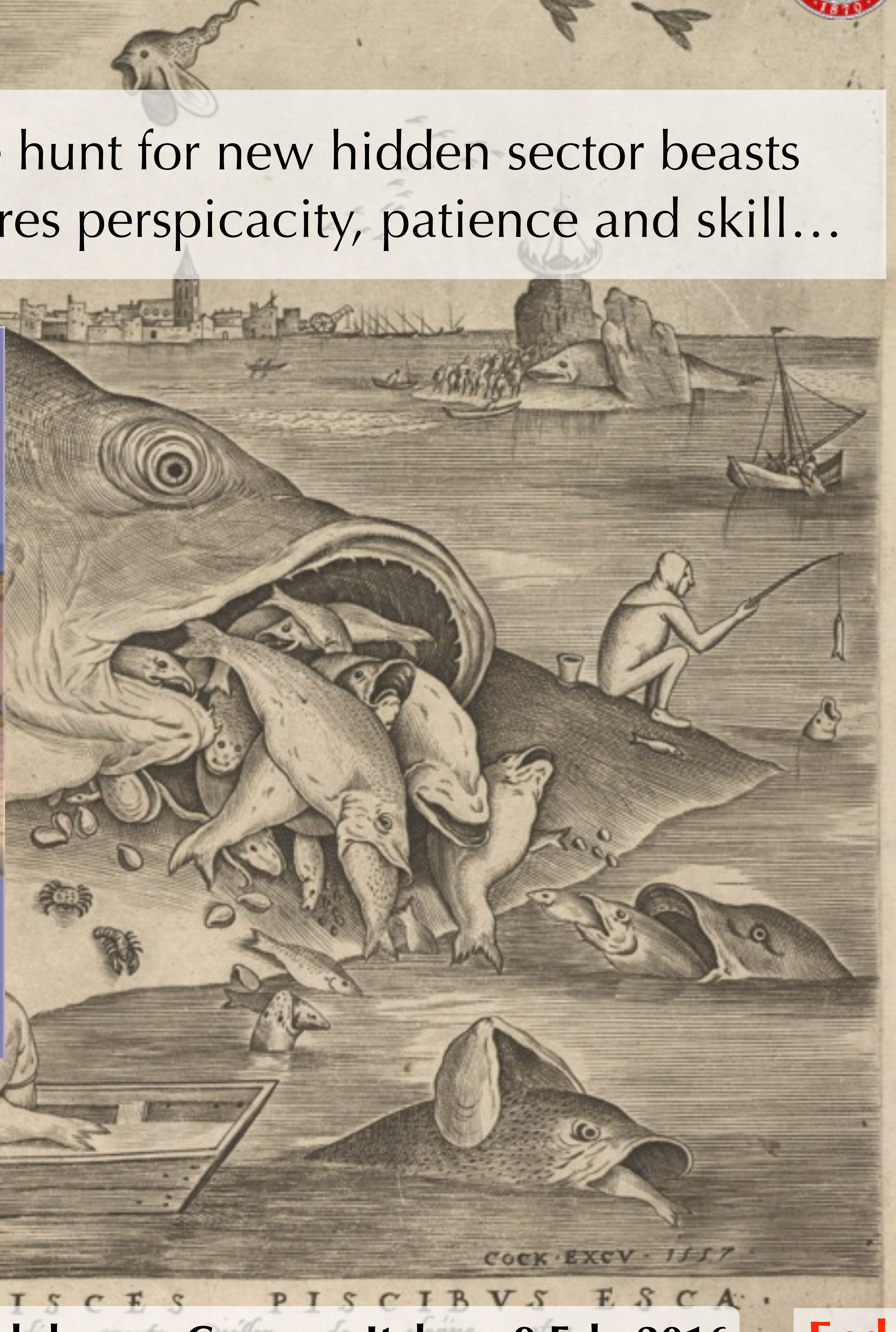
The hunt for new hidden sector beasts requires perspicacity, patience and skill…



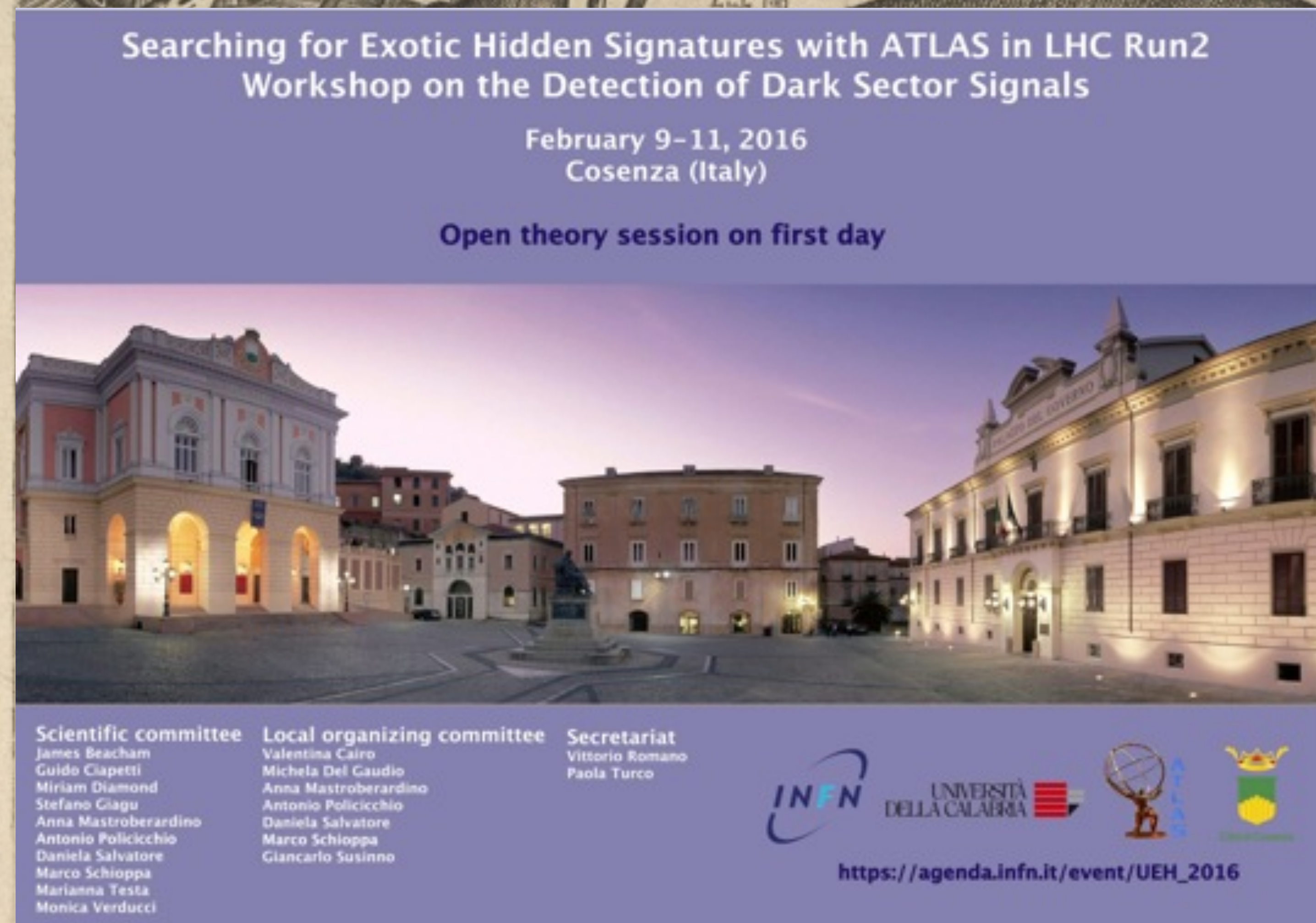
Dark / hidden sectors with ATLAS in LHC Run 2

The hunt for new hidden sector beasts requires perspicacity, patience and skill…





The hunt for new hidden sector beasts requires perspicacity, patience and skill…



Searching for Exotic Hidden Signatures with ATLAS in LHC Run2
Workshop on the Detection of Dark Sector Signals

February 9-11, 2016
Cosenza (Italy)

Open theory session on first day

Scientific committee
James Beacham
Guido Ciapetti
Miriam Diamond
Stefano Giagu
Anna Mastroberardino
Antonio Policicchio
Daniela Salvatore
Marco Schioppa
Marianna Testa
Monica Verducci

Local organizing committee
Valentina Cairo
Michela Del Gaudio
Anna Mastroberardino
Antonio Policicchio
Daniela Salvatore
Marco Schioppa
Giancarlo Susinno

Secretariat
Vittorio Romano
Paola Turco

INFN UNIVERSITÀ DELLA CALABRIA

https://agenda.infn.it/event/UEH_2016

…and planning.
Here's to an excellent workshop.

Backups

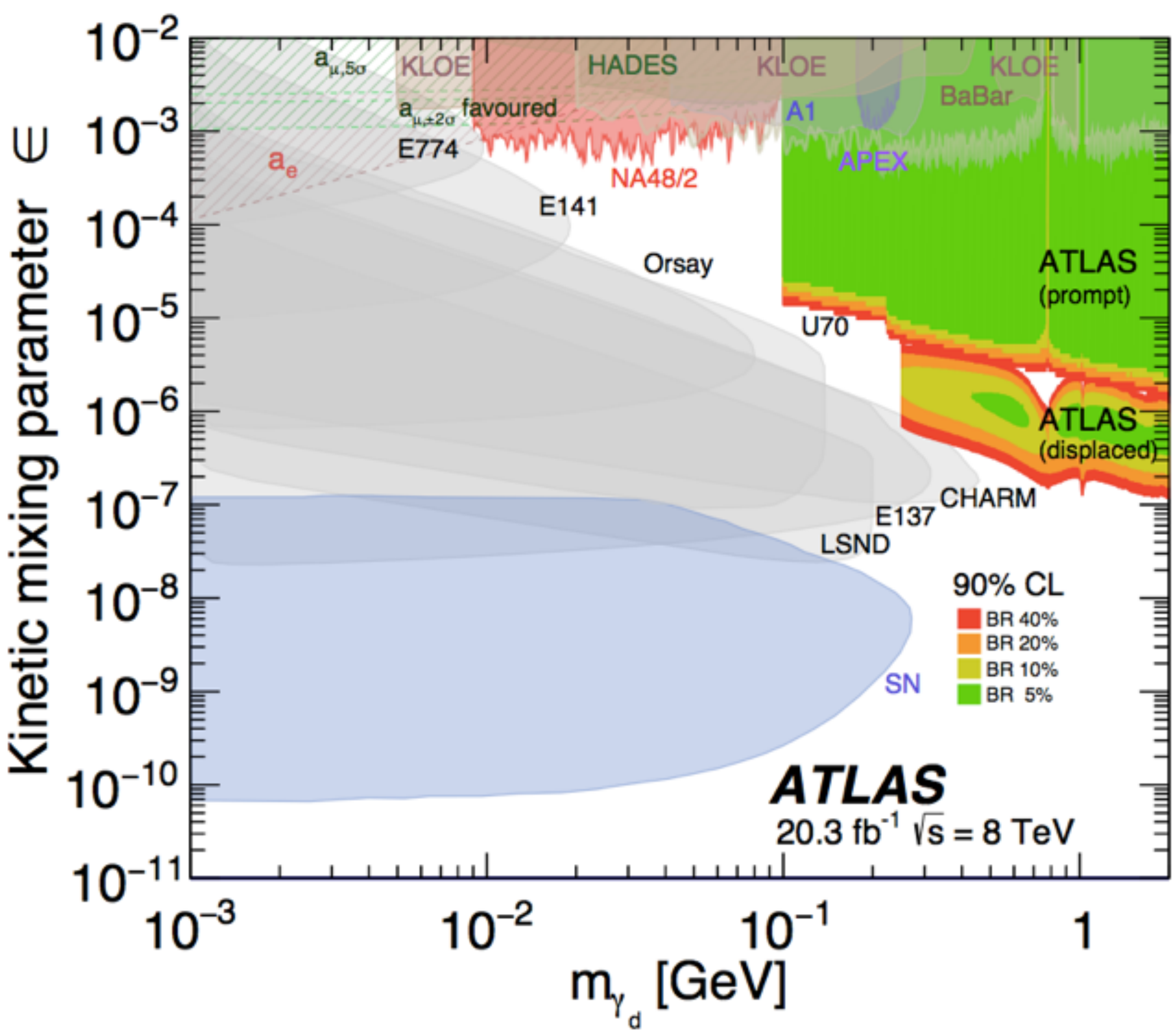
Prompt and displaced lepton-jets at the LHC

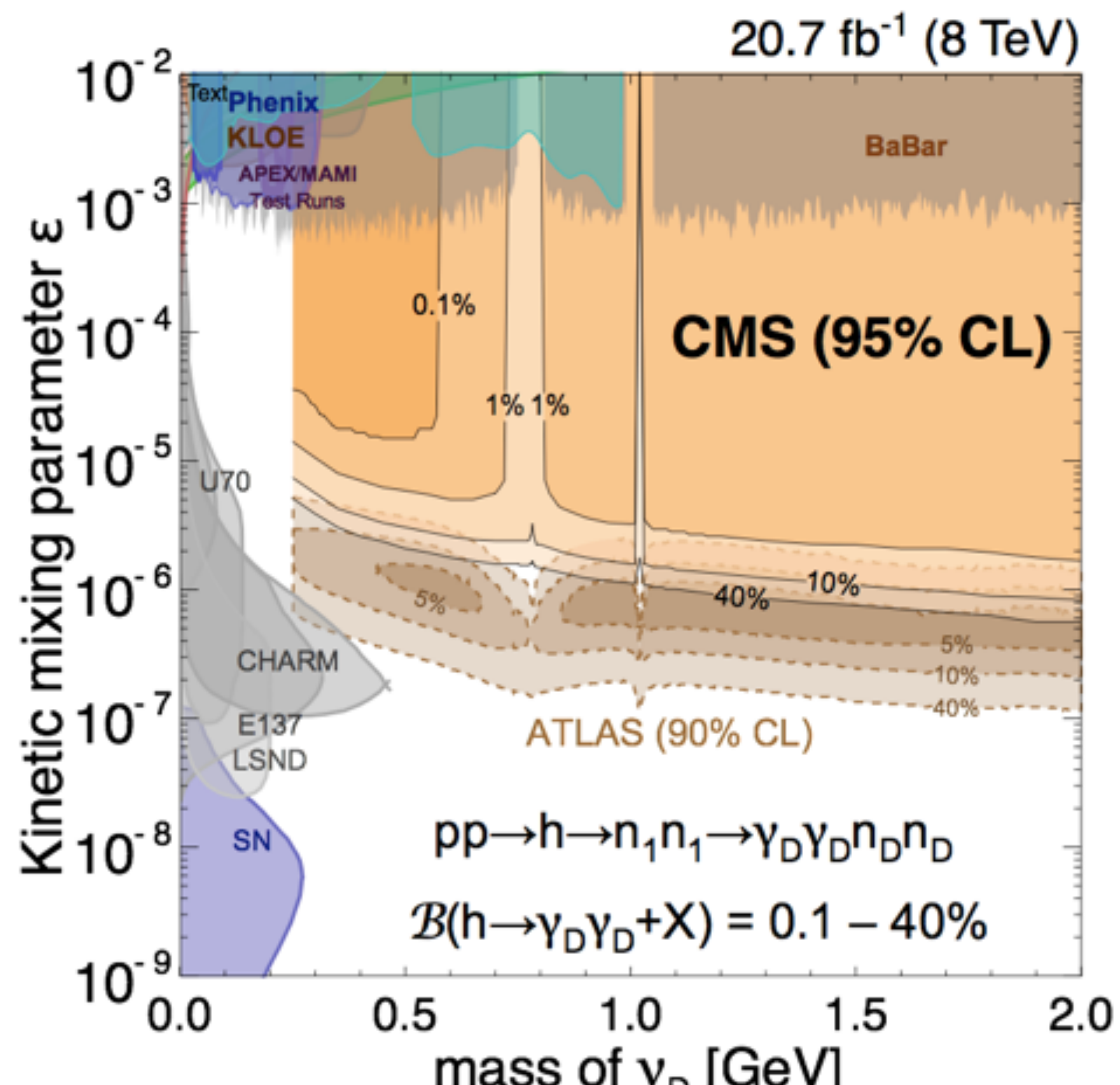
ATLAS: JHEP11(2014)088
arXiv:1511.05542

CMS: arXiv:1506.00424

ATLAS lepton-jets

CMS dark photon interpretation of H —> aa —> 4μ

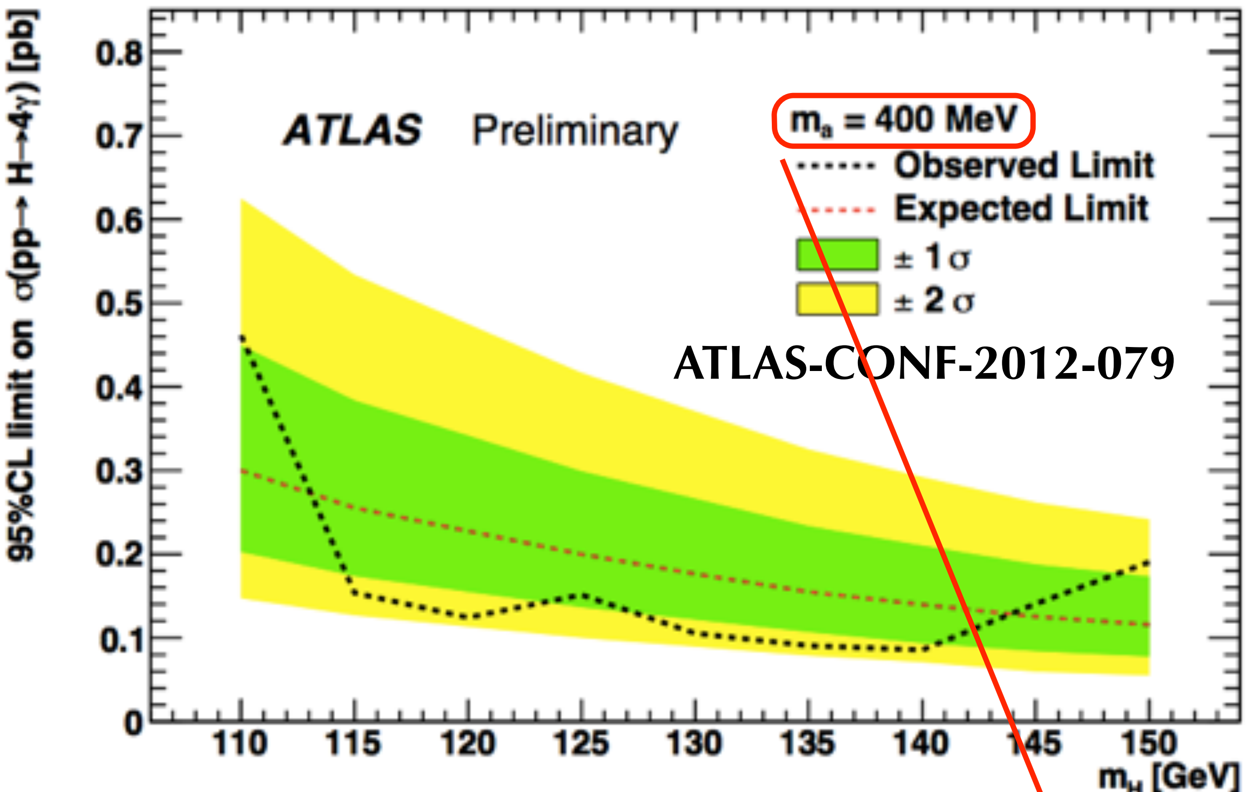


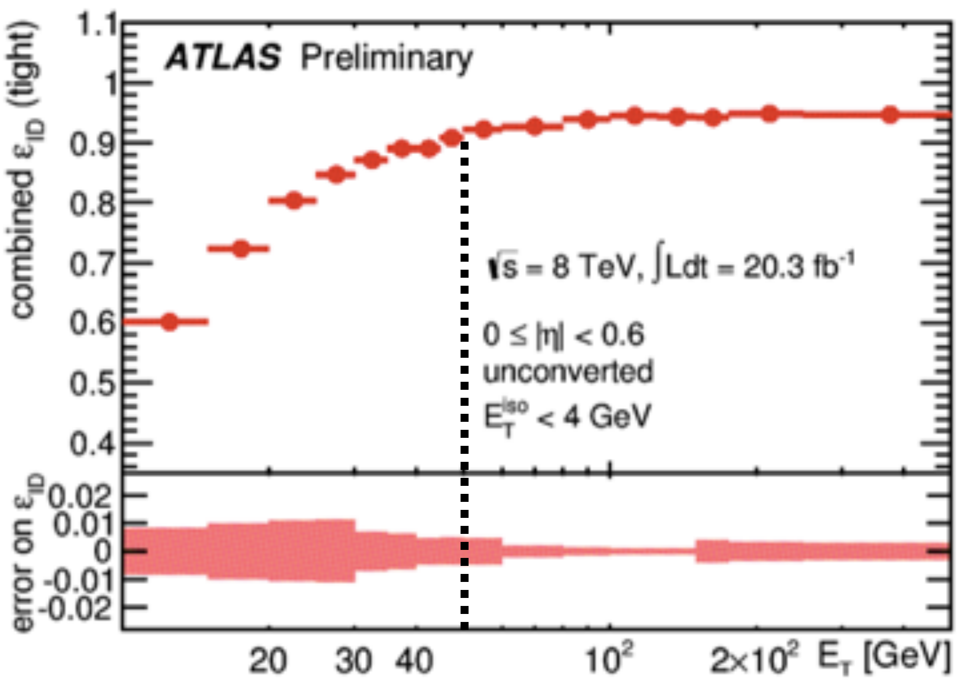


Parameter space getting squeezed

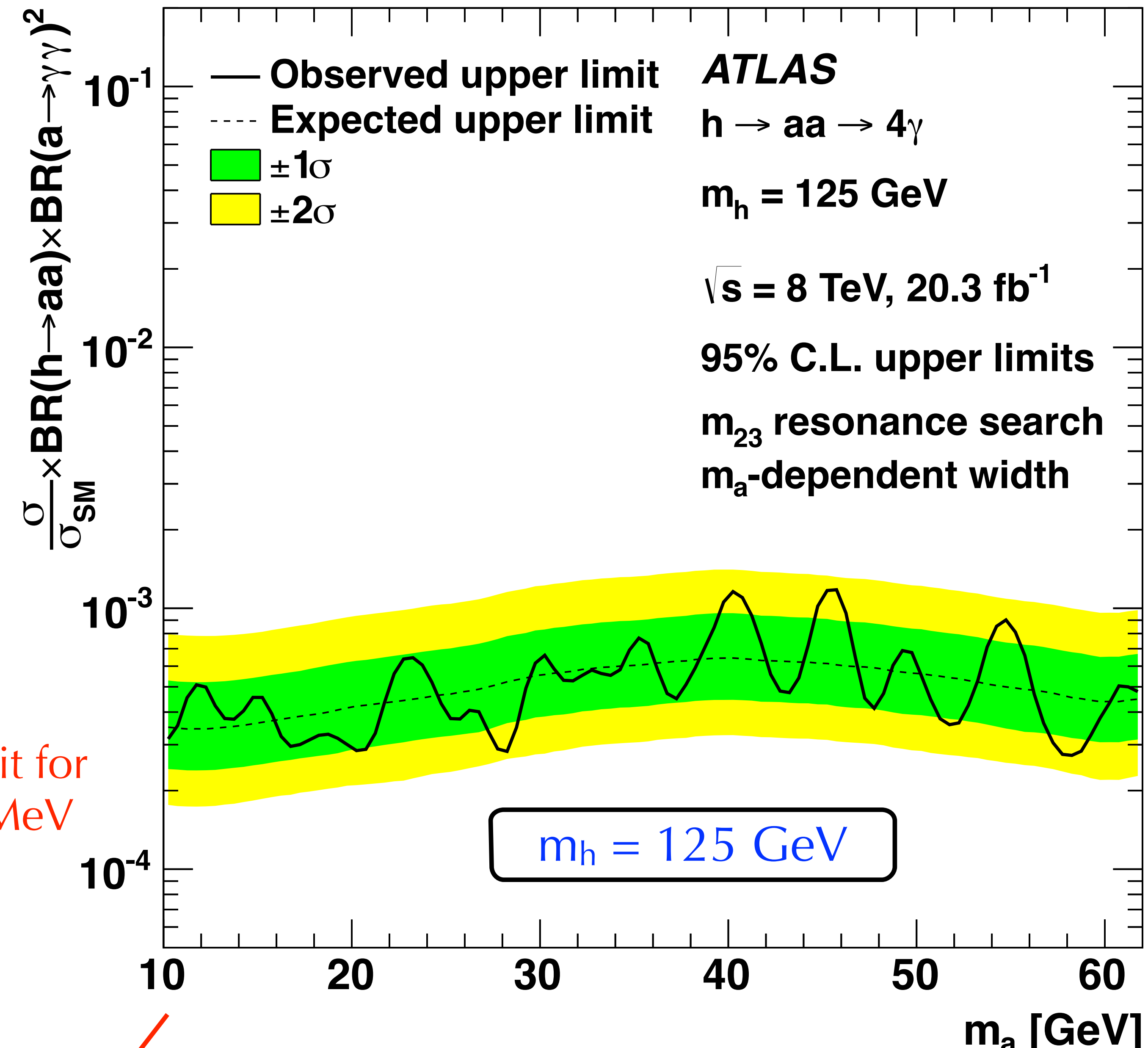
Limited sensitivity at medium-low-mass two-photon resonances

$h \longrightarrow aa \longrightarrow 4\gamma$





Highest limit for m_a ~ 400 MeV

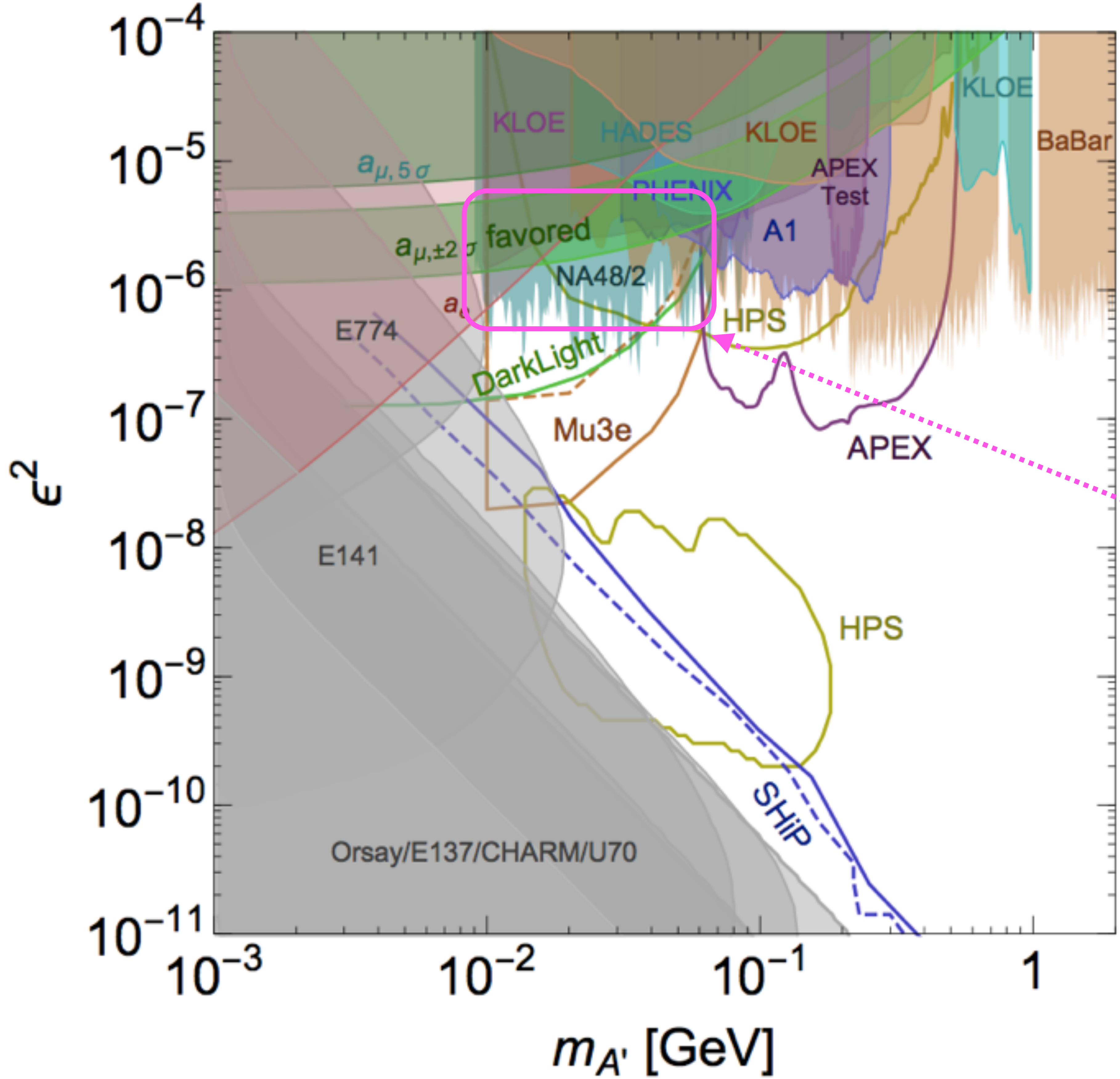


m_h = 125 GeV

Lowest limit for m_a = 10 GeV

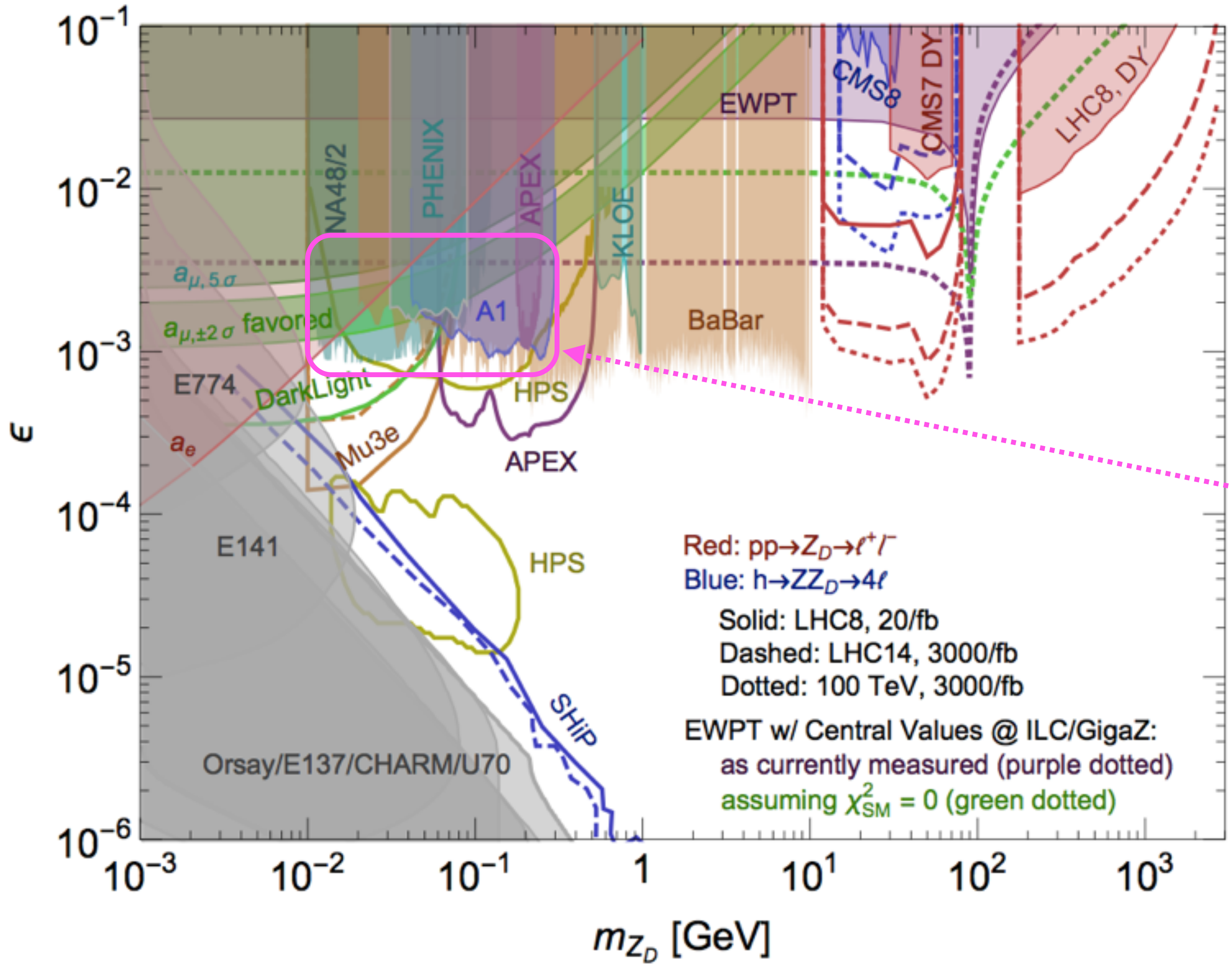
Gap in the search for this BSM Higgs decay

Similar limitations for higher m_H and the Z′ —> a+γ —> 3γ case



Recent results disfavor γ_d —> SM solution to muon g-2 (also beam dump reinterpretation)

γ_d —> invisible a stronger possibility



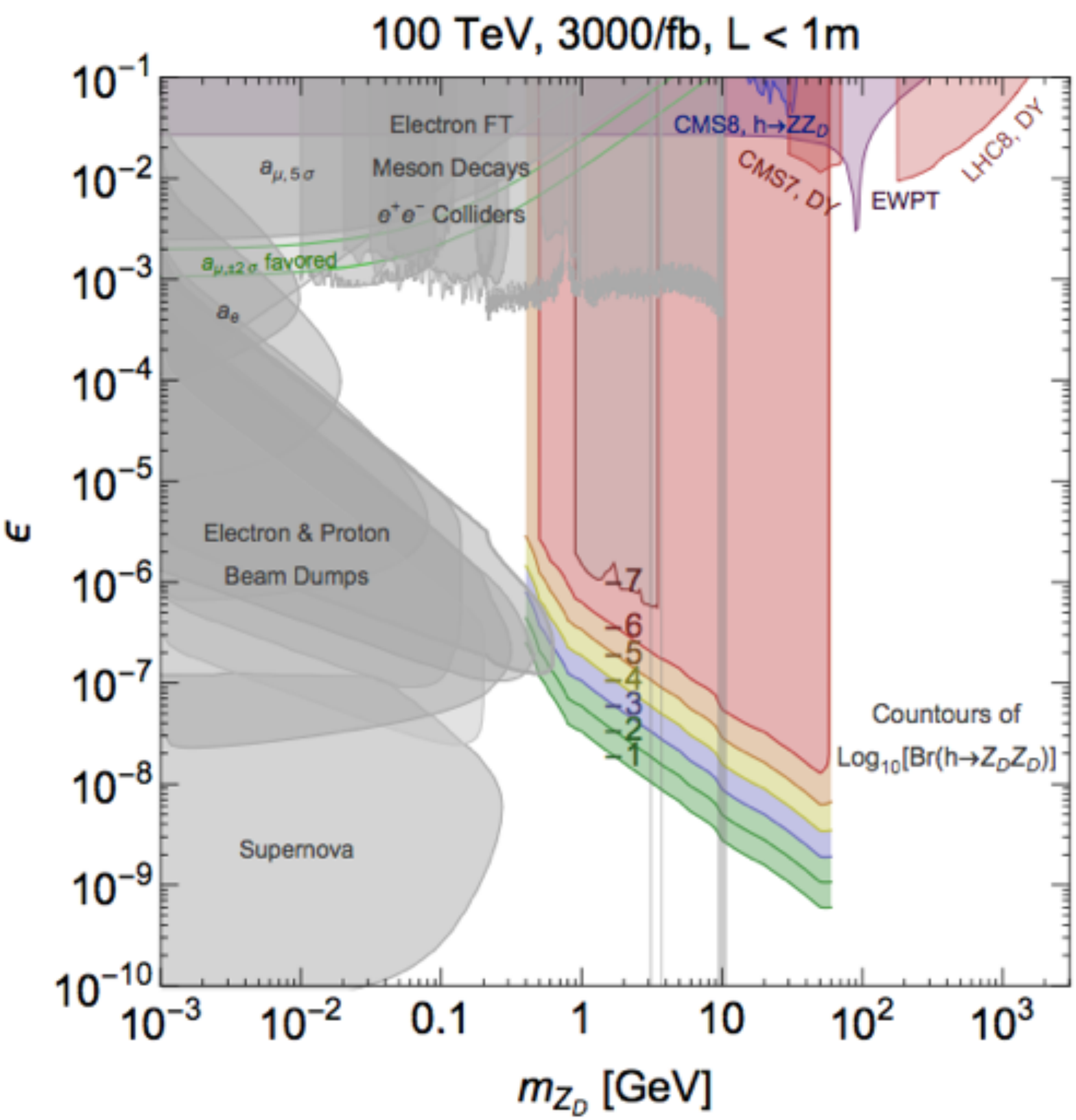
Recent results disfavor γ_d —> SM solution to muon g-2 (also beam dump reinterpretation)

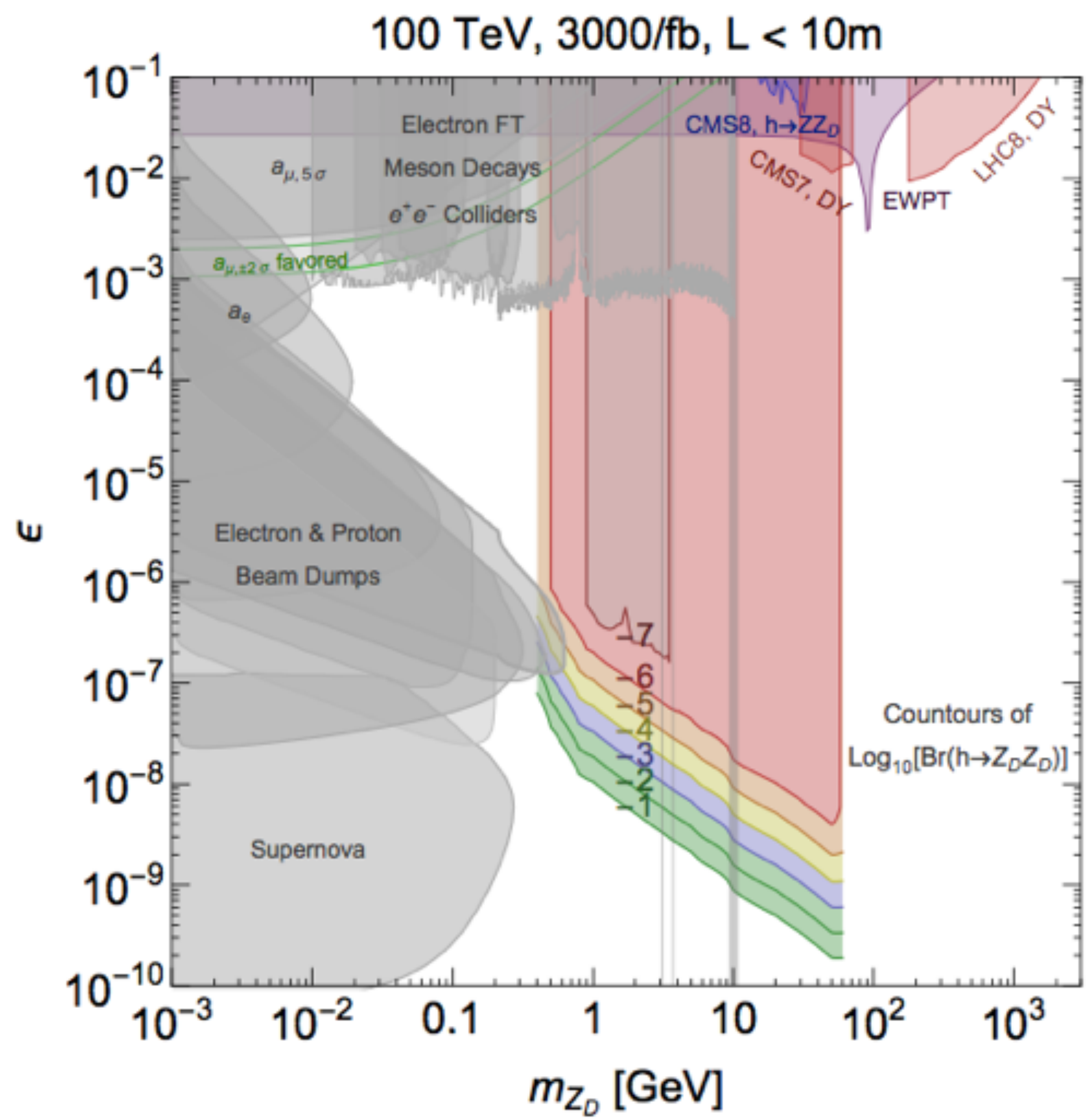
γ_d —> invisible a stronger possibility

Extend our thinking to higher masses

arXiv:1412.0018

The future: FCC





Higgs mixing with displaced decays

arXiv:1412.0018