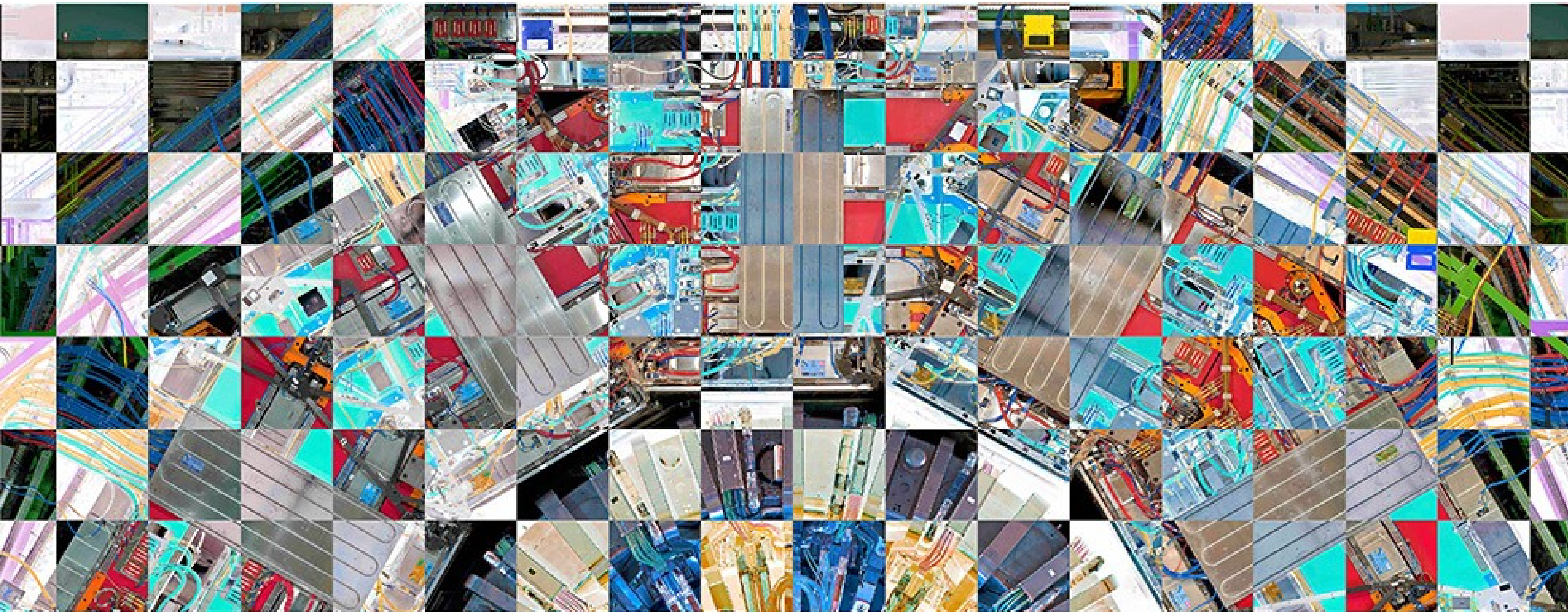


Chasing Dark Matter at the LHC

Part 1: Dark Matter at Collider and Non-hadronic Signatures

Livia Soffi & Valerio Ippolito (Harvard University)

VE RI TAS

Cornell University

ATLAS EXPERIMENT

CMS

What`s Next for Particle Physicists, Post-Higgs?

- **Four years ago**, exactly as **today**,

  we were all following an interesting seminar..

- **Today**, exactly as **four years ago**,

  we are still trying to answer many questions !!

Dark Matter:

→ 5x more prevalent than visible matter

→ nature unknown but could be made of particles

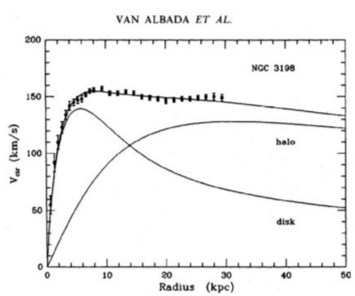
No discovery today (not yet)!

There is More Than Meets the Eye

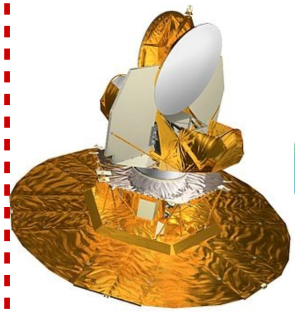
- F. Zwicky, **1933**:
  → **Masses of clusters of Galaxies**

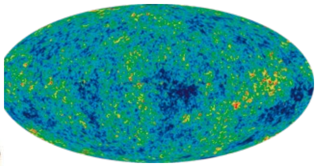
- Hubble Telescope, **1990s**-Today:
  → **Gravitational Lensing**

(time)



- V.Rubin et al., **1970s**:
  → **Galaxies Rotation Curves**





- WMAP, **2000-2010**:
  → **CMB**

...And many others: Large-Scale Structure Formation, BBN, Baryonic acoustic oscillation..

A Natural DM Candidate

- All evidence for dark matter so far is gravitational

  → **Non-Baryonic** → no electromagnetic or strong interaction
  → **Cold/Non-Relativistic/Massive**

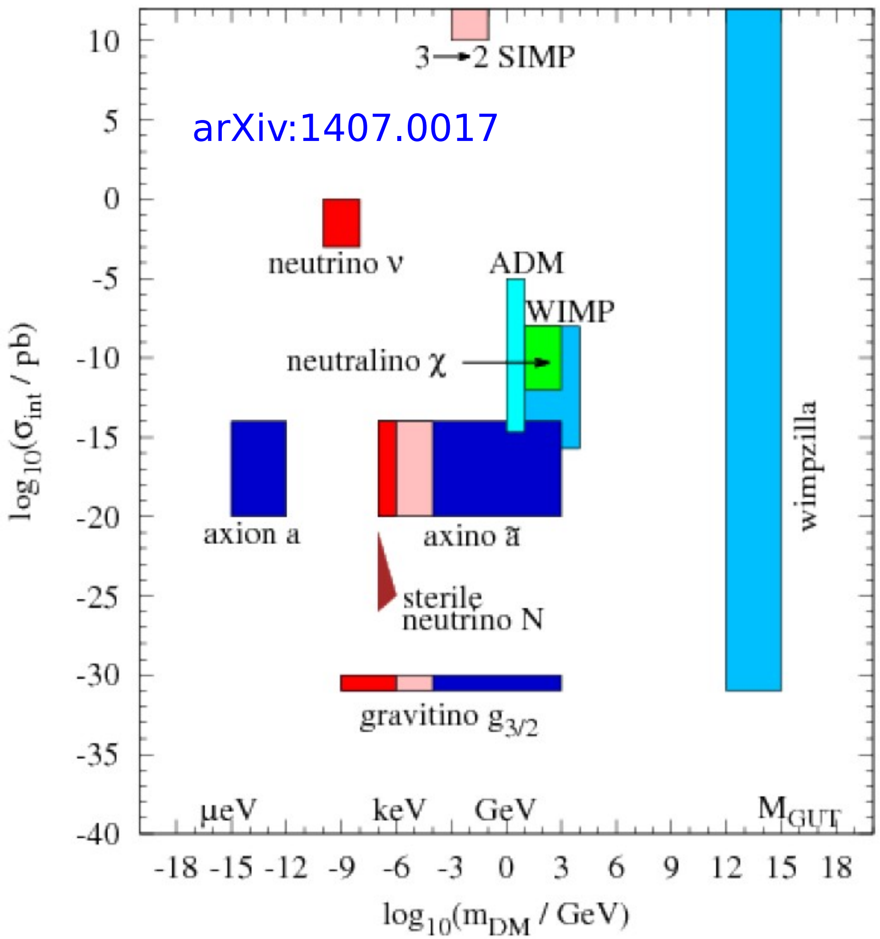
- Present day **DM density of 23%** explained assuming weak scale annihilation xsec

  → **DM as a thermal relic: WIMP**

- WIMPs arise 'naturally' in BSM-theories

- WIMP interactions with ordinary matter extremely rare

  → **Need sensitive detector**



When Theory Meets Experiments

Two Questions:

1. What channels should we be looking in?

Everywhere and with complementary strategies

When Theory Meets Experiments

Two Questions:

1. What channels should we be looking in?

Everywhere and with complementary strategies

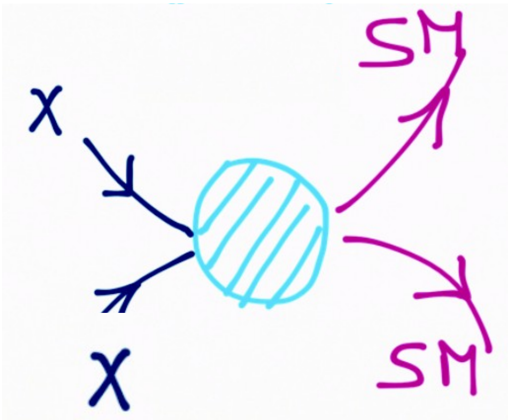
2. How do we interpret the results?

Fit results into theoretical models, and compare with other types of experimental evidence

Three Popular Strategies

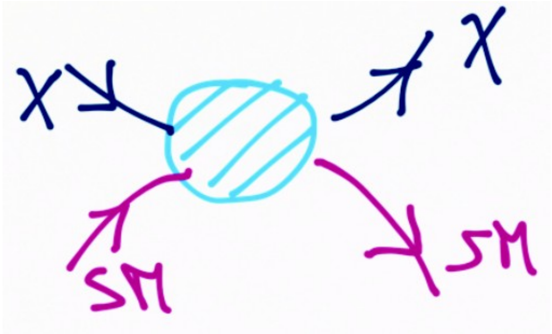
- Needs independent verification from non-astrophysical experiments

Indirect



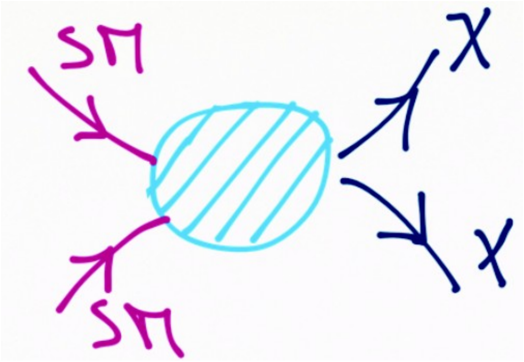
- AMS,IceCube

Direct



- XENON-100, DAMA, CoGeNT

Colliders

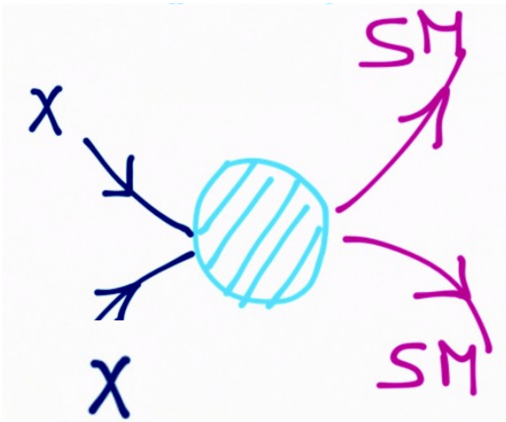


- Tevatron, LHC

Three Popular Strategies

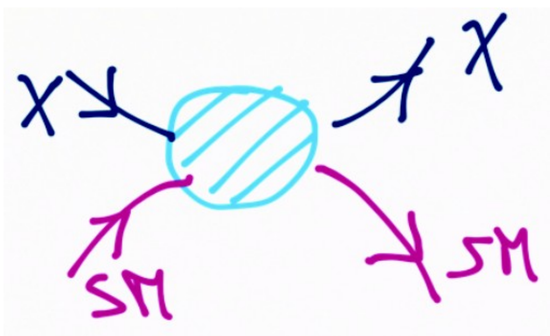
- Needs independent verification from non-astrophysical experiments

Indirect



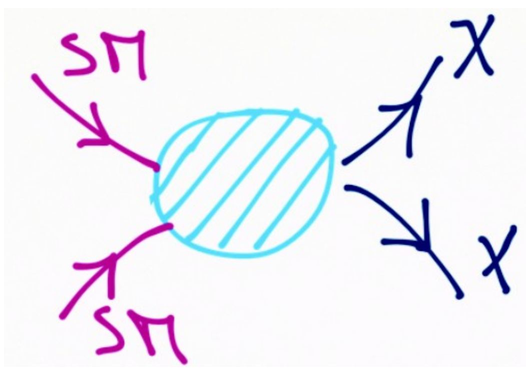
- Observe **annihilation products**
- **Low mass DM particles not accessible**
- Depends on DM density and annihilation model

Direct



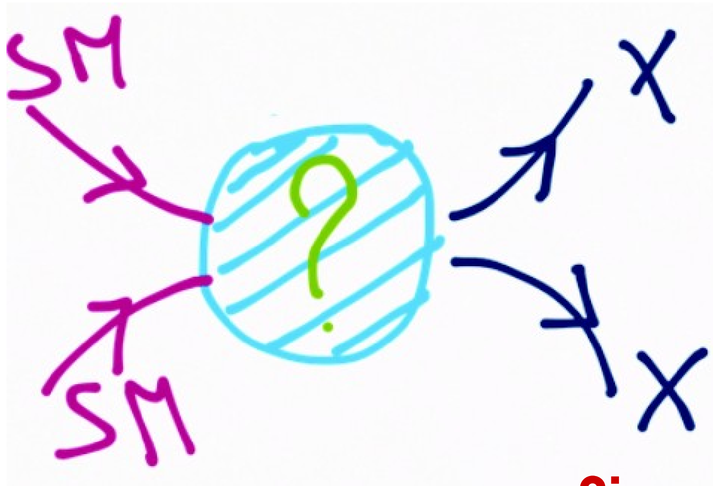
- **Dark Matter-nucleus scattering**
- Low mass DM particles not probed yet.
- Need **large detector masses**

Colliders



- Laboratory **production of DM** particles
- Sensitive to **huge mass range**
- **Both spin-dependent and spin-independent couplings**

Describing Nature with Math



Effective Field Theories (EFTs)

- Largely model-independent
- Easy to compare results with those from direct detection experiments
- Suffer from validity issues at LHC energies

Simplified models

- Using explicit mediators
- More model-dependent
- Valid at all energies

LHC-DM Forum: Use simplified models when possible - still some EFT results for certain benchmark models

arXiv:1507.00966

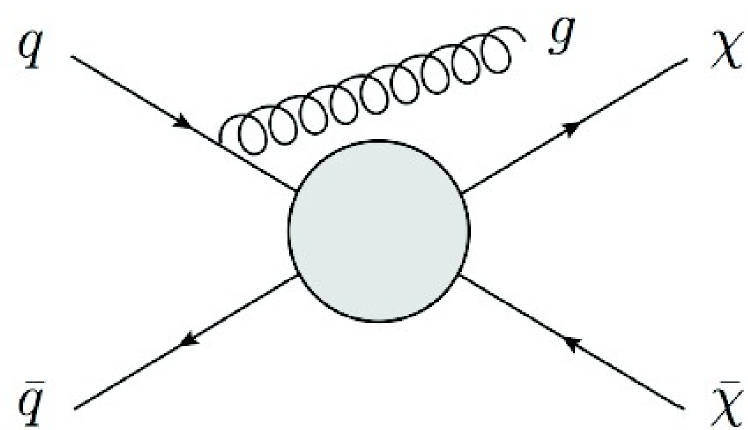
What Fermi has Taught Us: EFT

Assumptions:

- DM particle is only new state accessible to the collider
- **Mediator is heavy and can be integrated out**

  → contact interaction

$$\frac{g_q g_\chi}{q^2 - M^2} \xrightarrow{q^2 \ll M^2} \frac{1}{\Lambda^2} \qquad \Lambda^2 = \frac{M^2}{g_q g_\chi}$$



- Theory valid only if:

$$Q_{\text{transfer}} < M = \sqrt{g_\chi g_q}\Lambda < 4\pi\Lambda$$

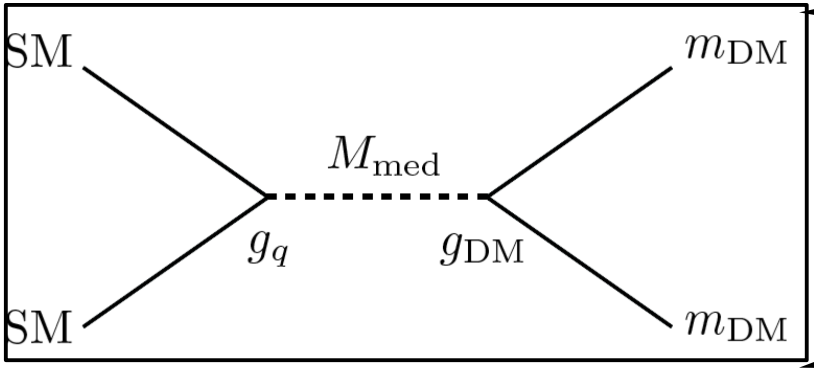
→ Parameter of interest is the contact interaction scale Λ

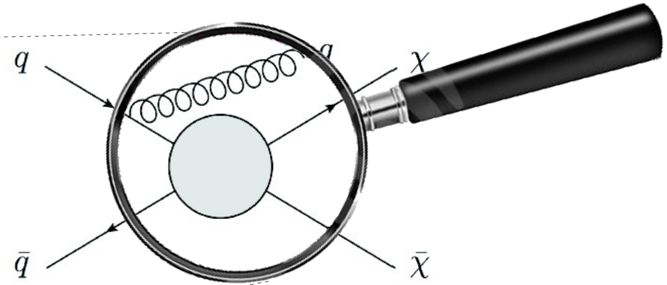
- **Vary Lorentz structure, spin assignments** to describe scalar, pseudoscalar, vector, axial vector and tensor interactions

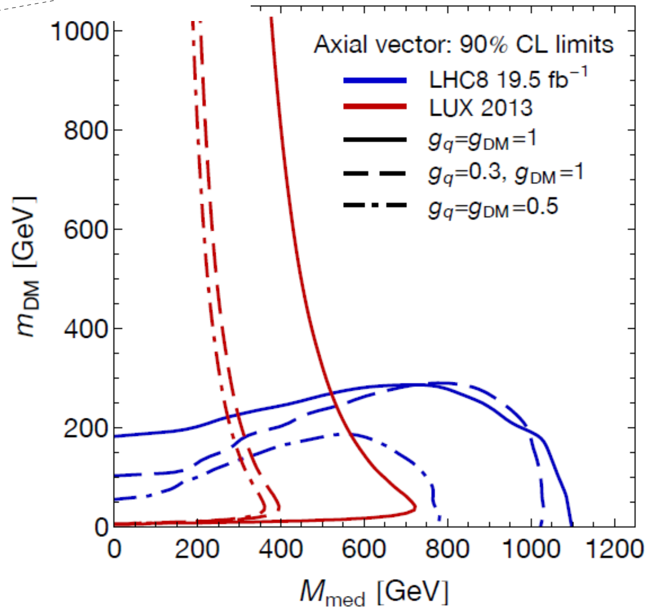
arXiv:1008.1783

Looking into the Details: Simplified Models

- Can truncate the EFT production when **$Q_{transfer}$ > M**
- This requires knowing the masses/couplings
- Turn a 1-D problem into a multi-dimensional one:







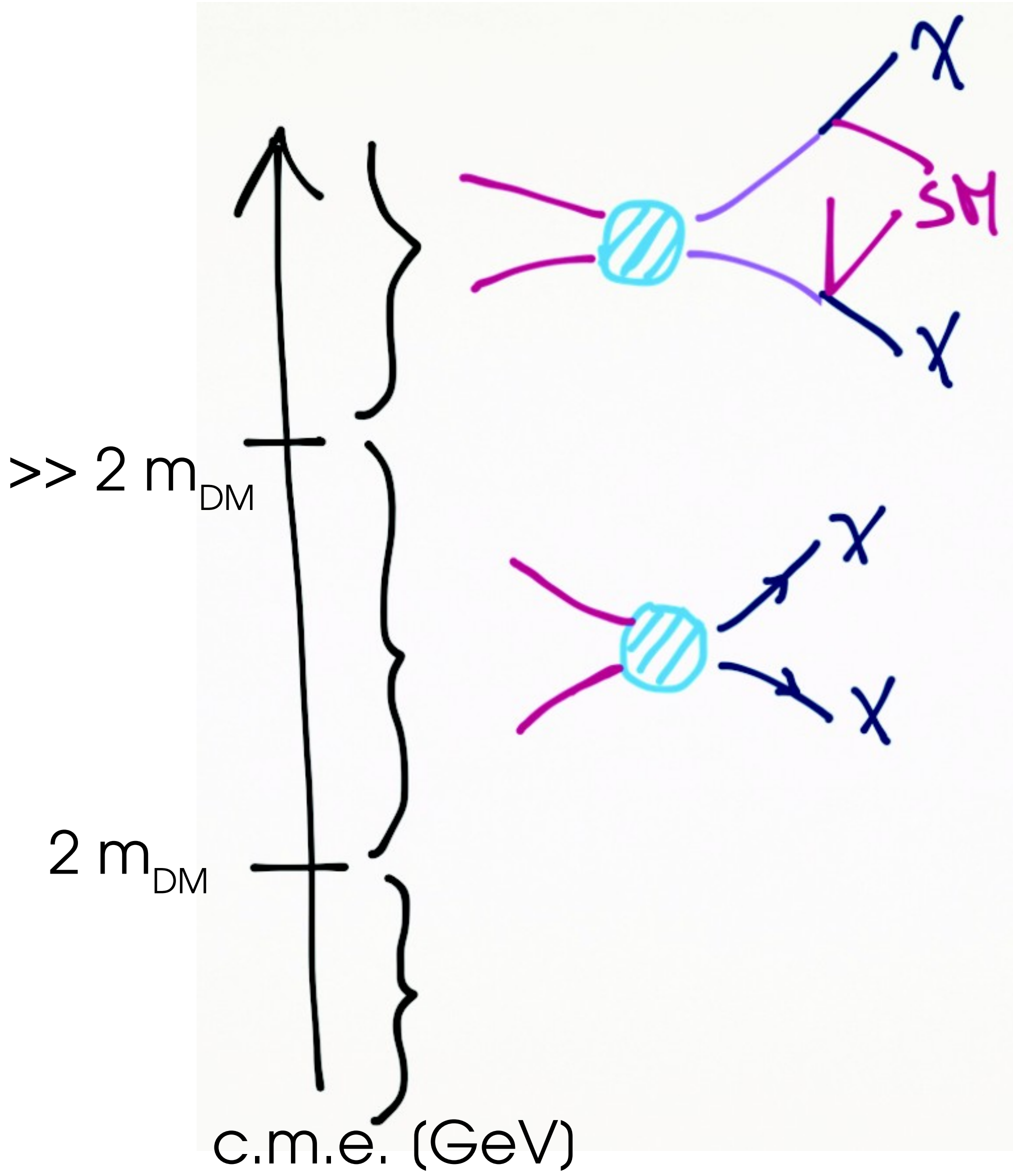
- Minimum 4 parameters: m_{DM}, M_{med}, g_q, g_χ

- Need to fix two parameters to show results

arXiv:1407.8257

Probing Dark Matter at the LHC

- Can probe a wide range of DM/SM interaction types in a wide energy range



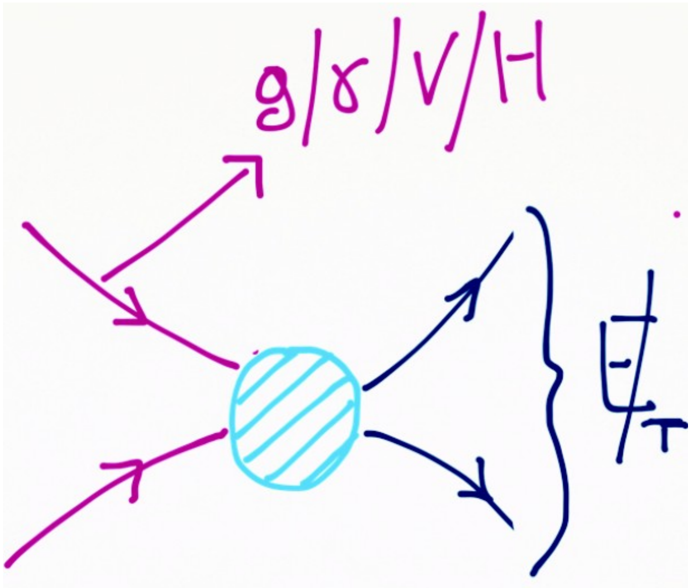
- Both direct and cascade production depending on the **partonic energy**
- DM particles **stable and weakly interacting** → escape detection
- How to "see" DM particles? → looking for "**missing energy**" **and additional SM radiation**
- **Generic signature:**

$$pp \rightarrow \not{E}_T + X$$

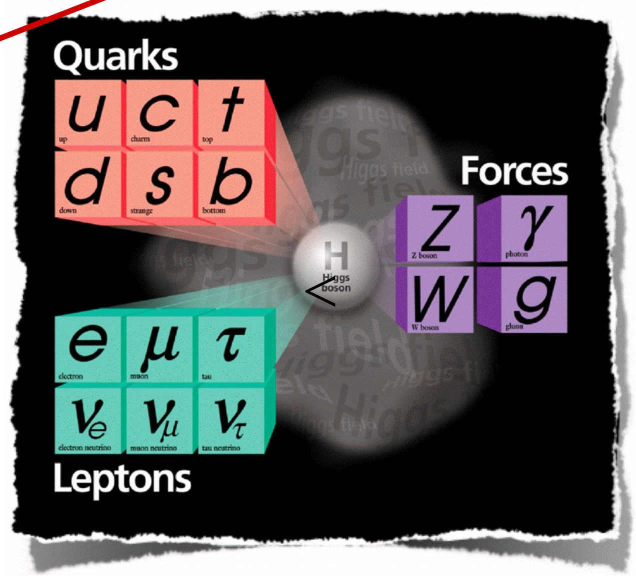
LHC Mono-X Searches

- A wide range of final states can be investigated exploiting the full potential of LHC experiments:

$$pp \rightarrow \not{E}_T + X$$

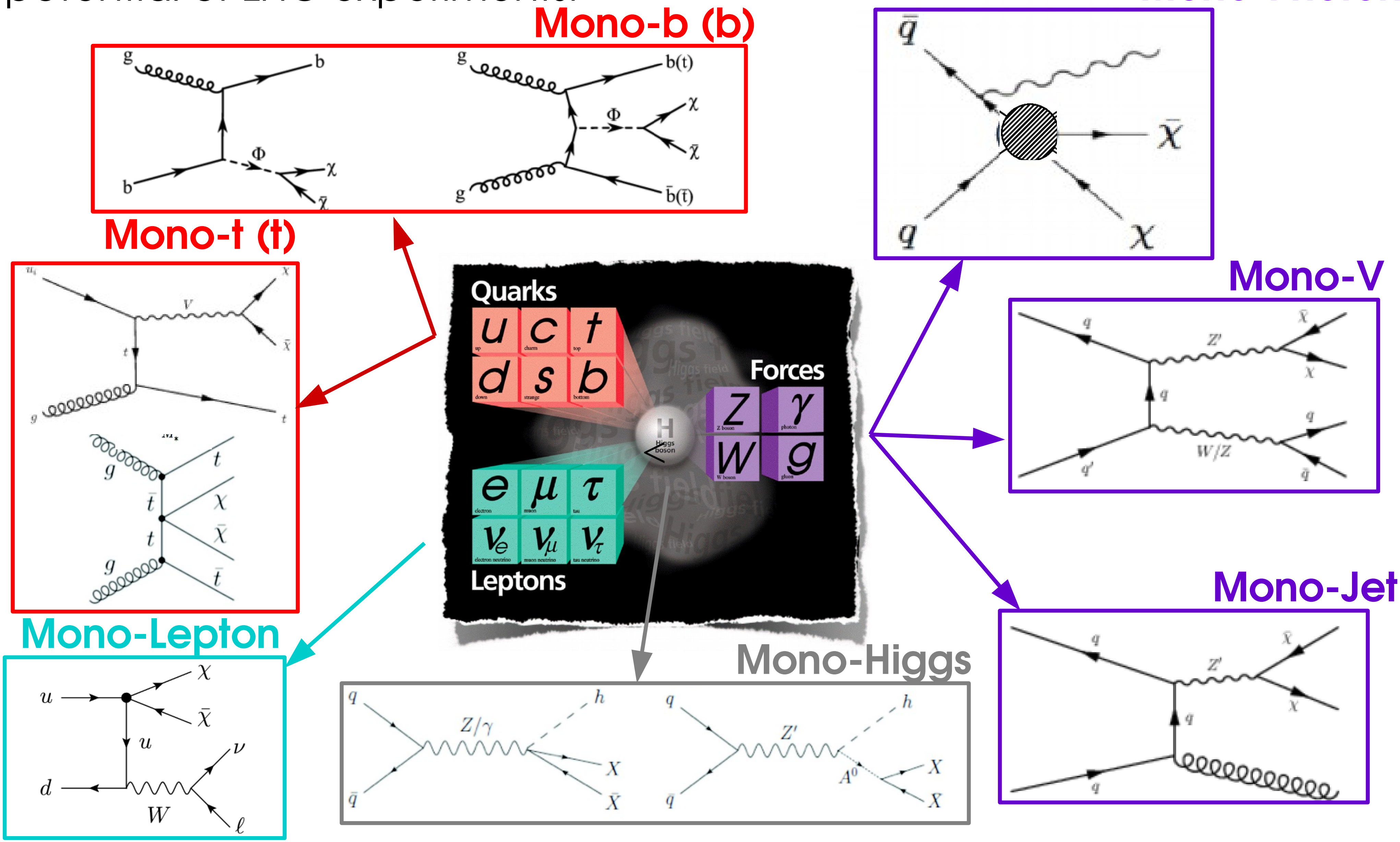


- **Any SM particle!!!**



LHC Mono-X Searches

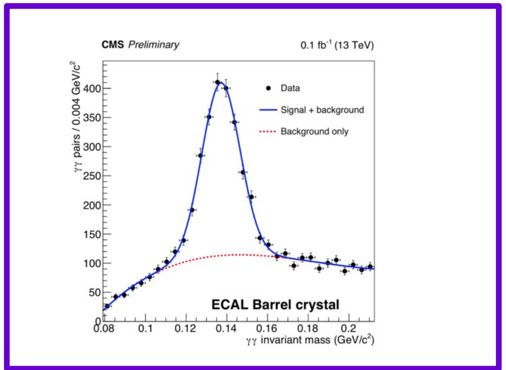
- A wide range of final states can be investigated using full potential of LHC experiments:



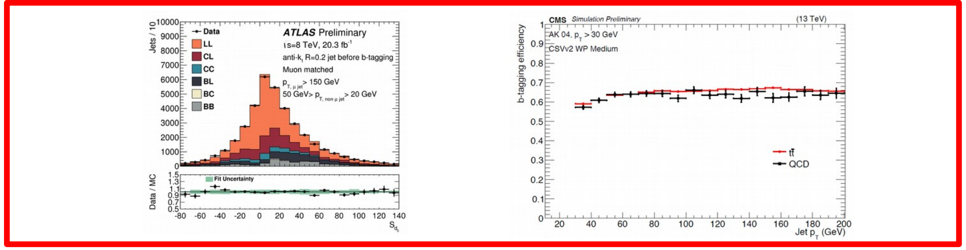
LHC Mono-X Searches

- A wide range of final states can be investigated using full potential of LHC experiments:

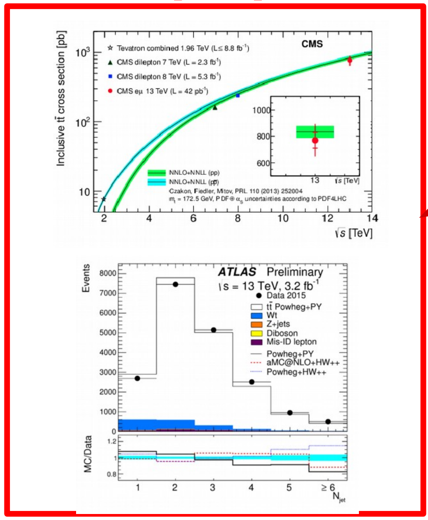
Photons

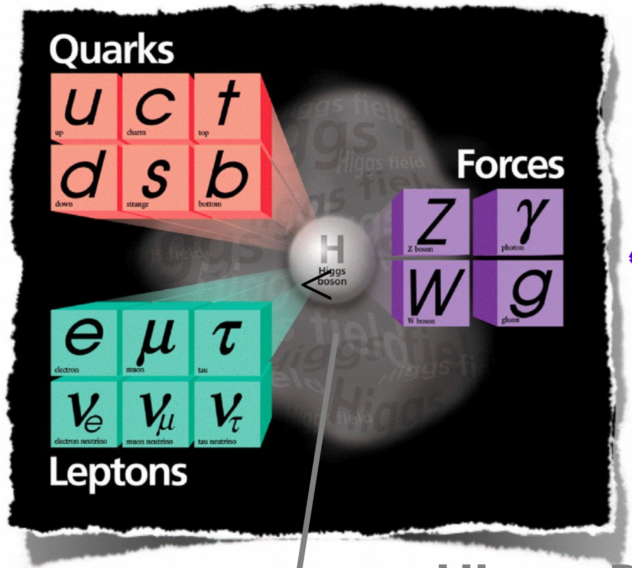


Bottom quarks

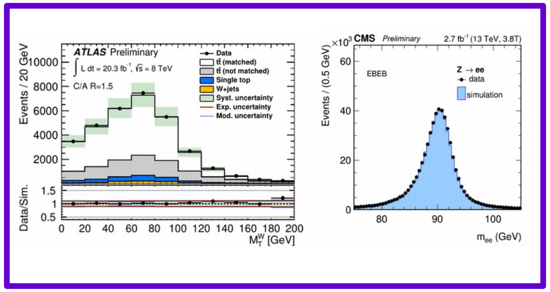


Top quarks

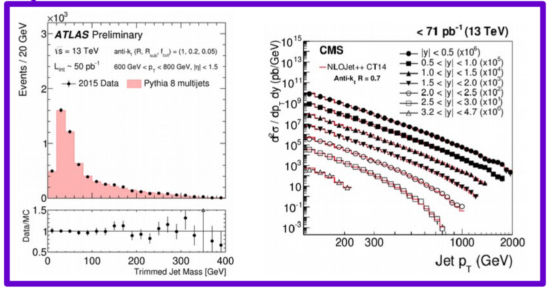




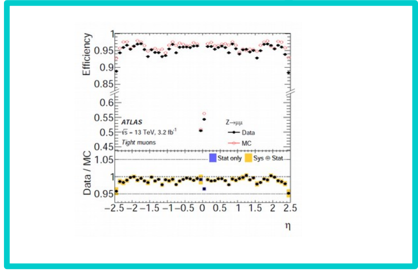
W/Z Bosons



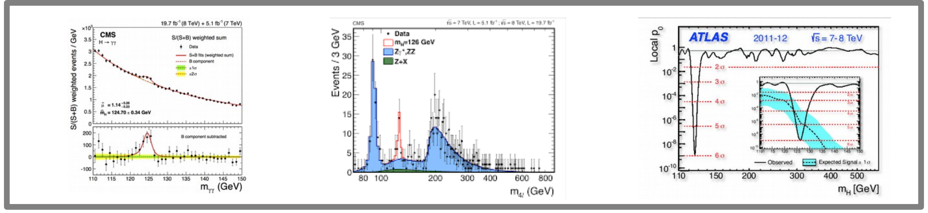
Jets



Leptons

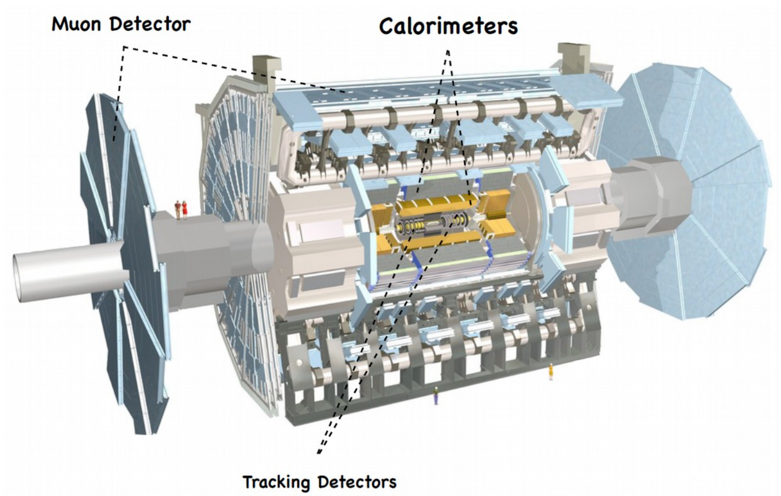


Higgs Boson

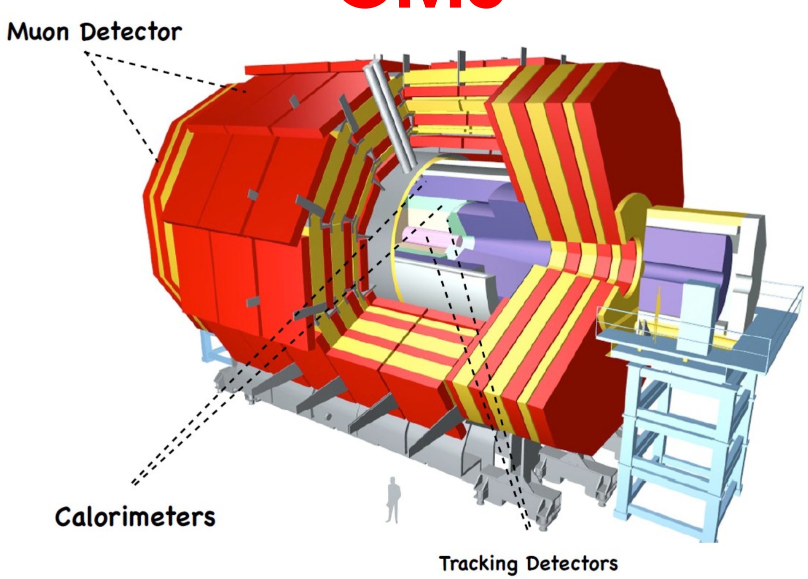


Multipurpose Detectors

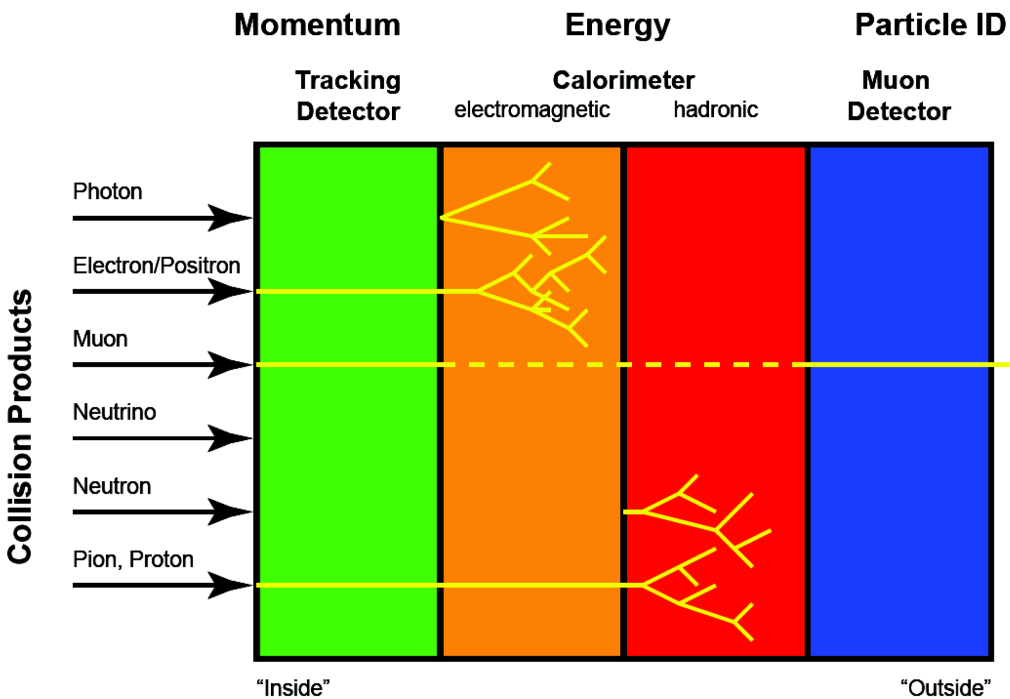
ATLAS



CMS



- Measure **all possible properties of all collision products**
- Combination of different detector types for momentum, energy, origin, type, …
- **Several subdetectors arranged like shells of an onion**

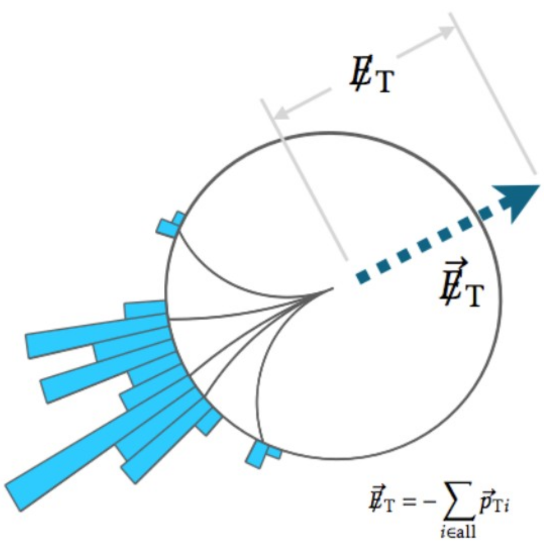


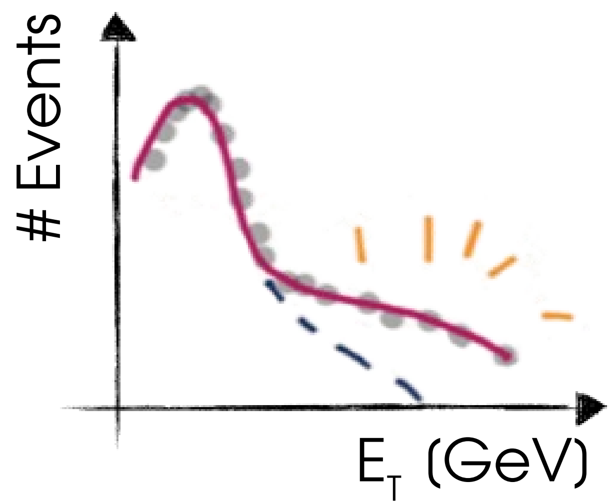
Measuring the Invisible

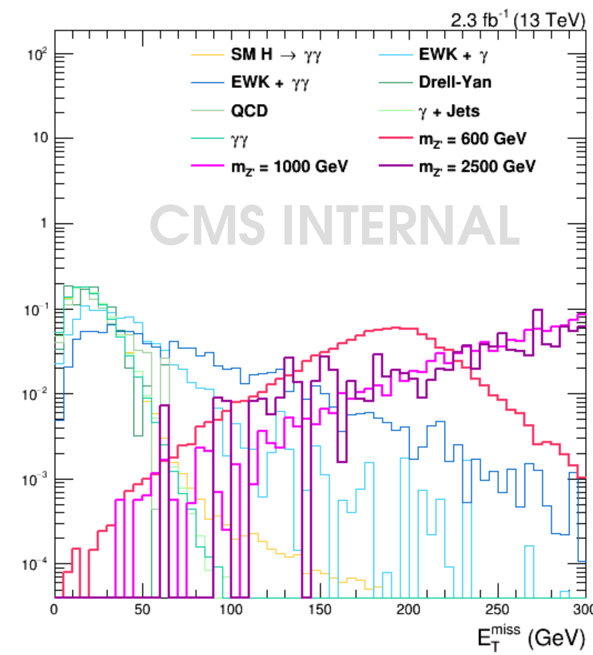
- MET caused by **particles escaping detection** and detector effects: noise, dead/hot cells

- MET $\rightarrow$ energy **imbalance in the plane transverse** to the colliding beams

$$\mathrm{MET} = \sqrt{\left(\sum_n E_x\right)^2 + \left(\sum_n E_y\right)^2}$$





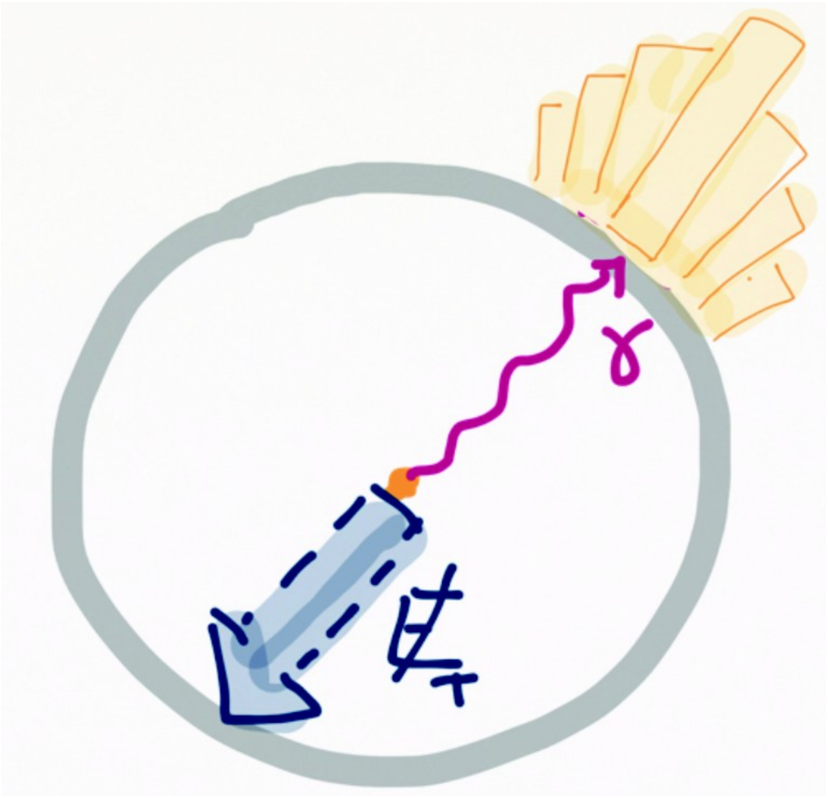


- SM process have no MET

- MET tail excess as hint of new -physics

Mono-Photon Search

<u>Signature:</u>
One high-P_T photon and large missing energy balanced in the transversal plan



CMS-PAS-EXO-16-014
arXiv:1604.01306

Photon Reconstruction and ID

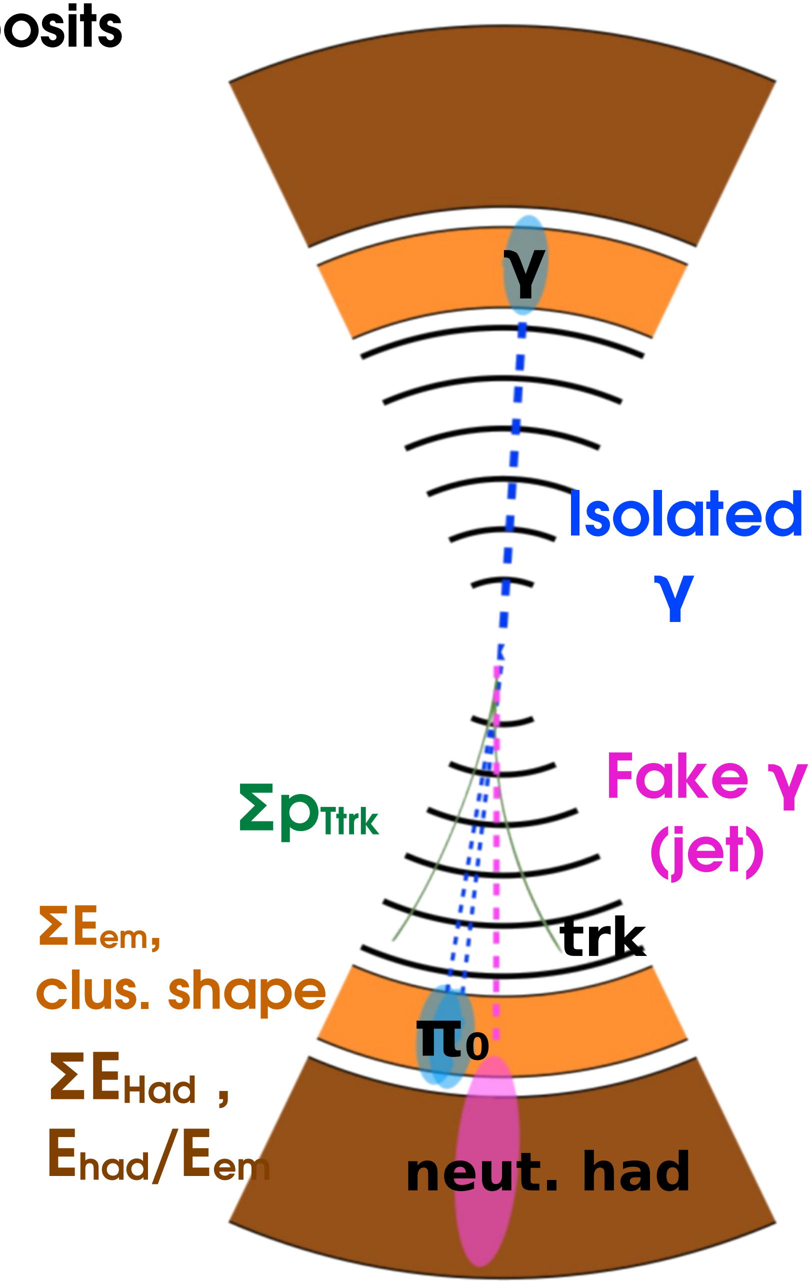
- Reconstruction from **clusters of energy deposits** in the electromagnetic calorimeter

- Data/MC **energy correction** obtained calibrating the detector w/ **Z→ ee events**

<u>Identification based on:</u>

Isolation	Shape
Isolated deposit with no track associated in the tracker	**Narrow circular energy deposit**

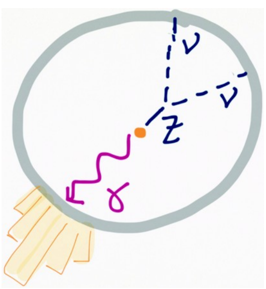
ATLAS LAr: :Longitudinal segmentation
→ Good Photon **Trajectory** Measurement
CMS ECAL: Homogenous Calorimeter
→ Good **Energy Resolution**

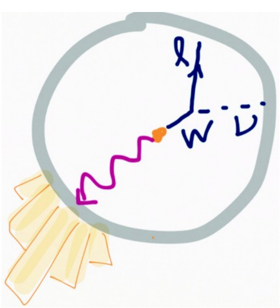


Background Contributions

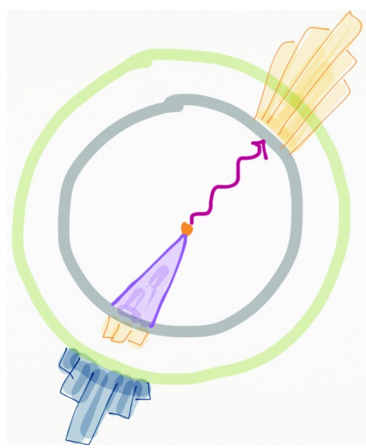
- All backgrounds extrapolated from orthogonal data samples.
- Normalization obtained via a simultaneous likelihood fit to the observed Yields

- **Z(νν)/W(lν) + γ → ~ 75%**

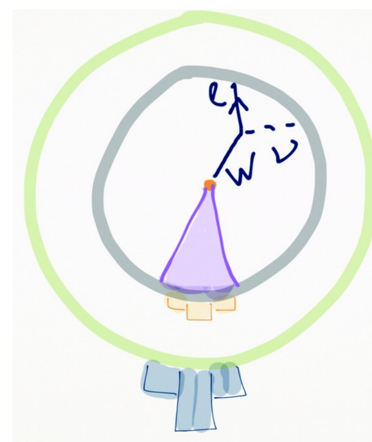




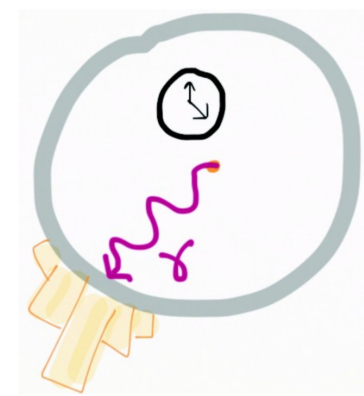
- **γ + jets/ Multi-jet**



- **Z/W+ jets**



- **Non-collision background**



<u>Reduced by:</u>

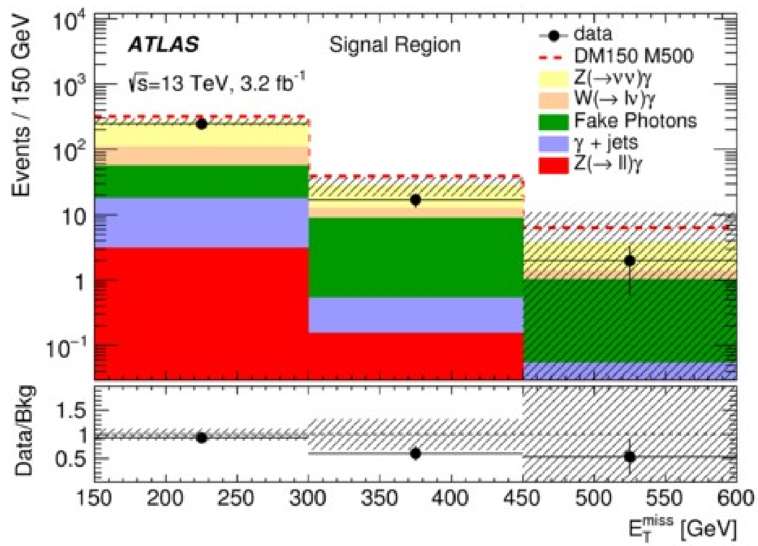
→ ΔΦ(MET, jet) && MET cut

→ Lepton Veto && Photon ID

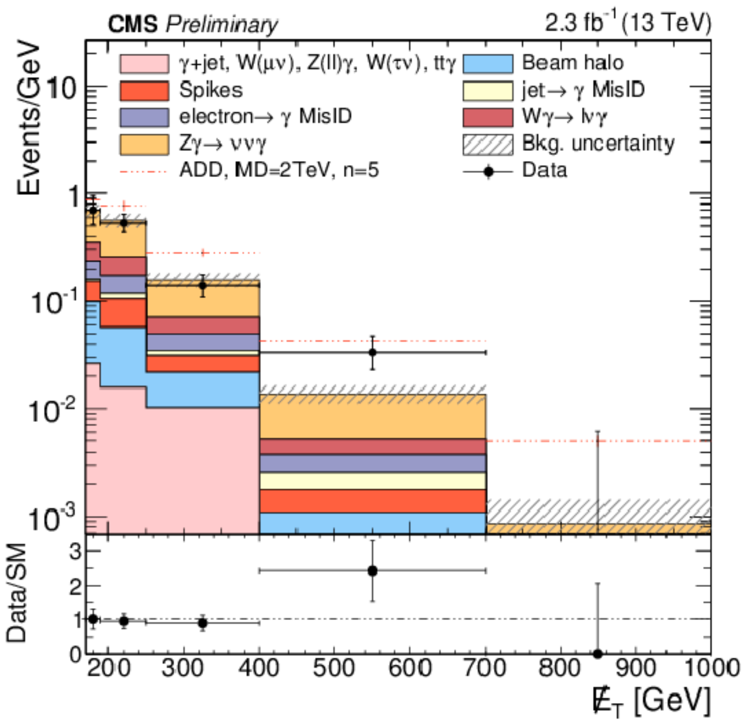
→ **time of cluster /trajectory**

Mono-Photon Energy Spectra

- Cut and count analysis in one SR bin: 264 events observed vs 295+/- 34 background events expected

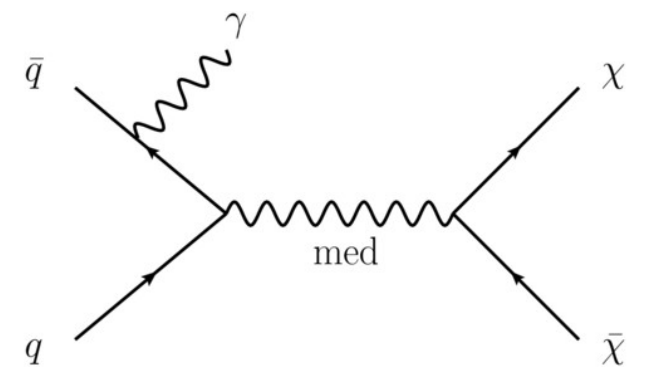


- Shape analysis in multi bin SR: 77 events observed vs 76+/- 8 background events expected

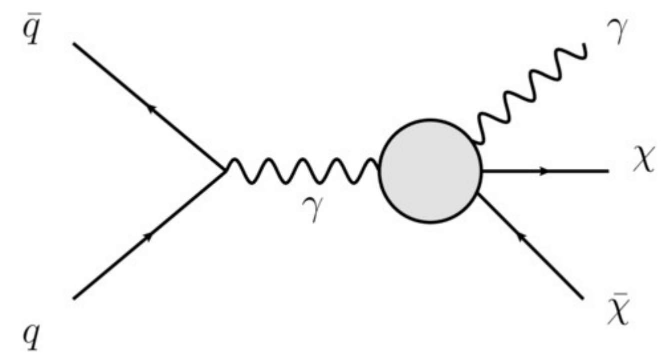


Models Interpretation for Mono-Photon Search

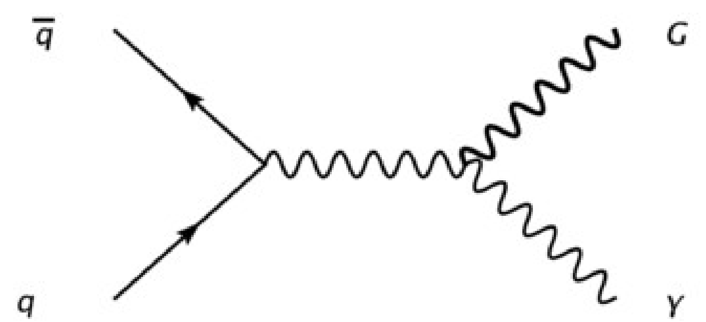
- **Simplied model** w/ fermion DM produced via s-channel mediator
  → m_{DM} m_{med}, g_q and g_{DM}



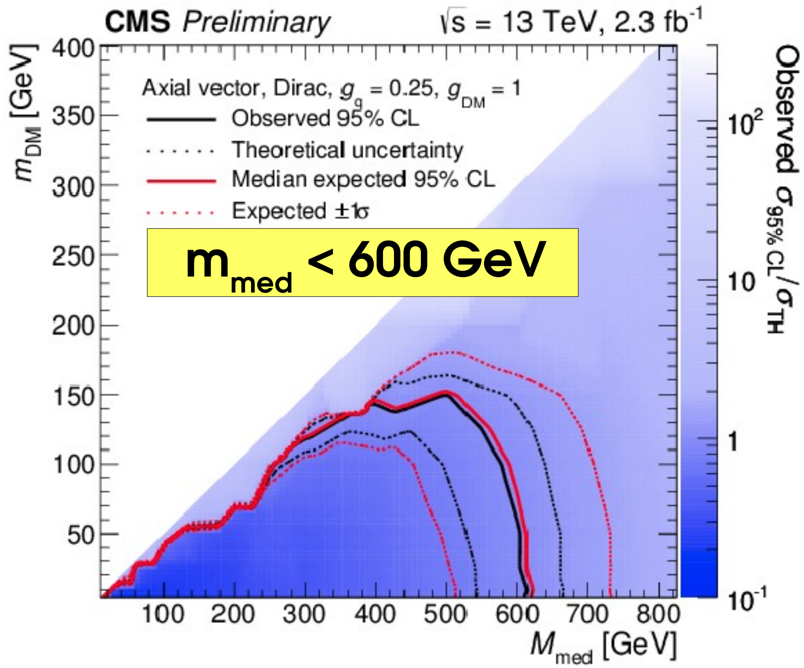
- A dimension-7 **EFT benchmark** with direct couplings between DM and electroweak bosons



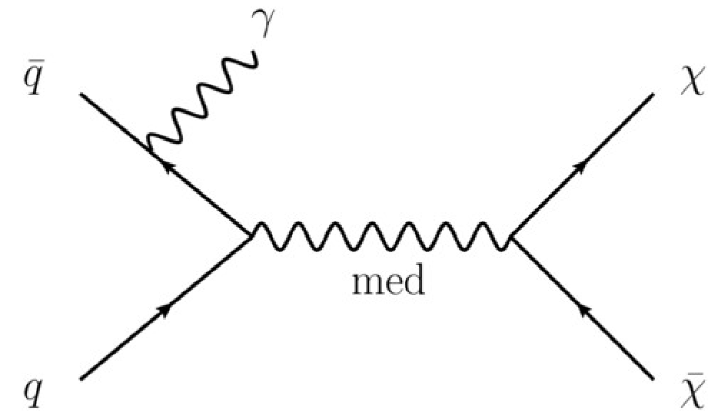
- **ADD model of LED**; stable gravitons would be invisible to the detector and could be produced in association with a photon



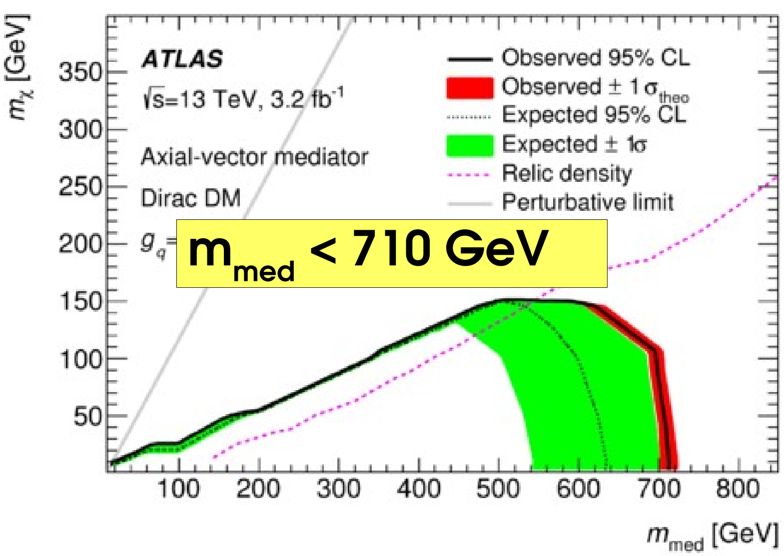
Mono-Photon Search – Simplified Model



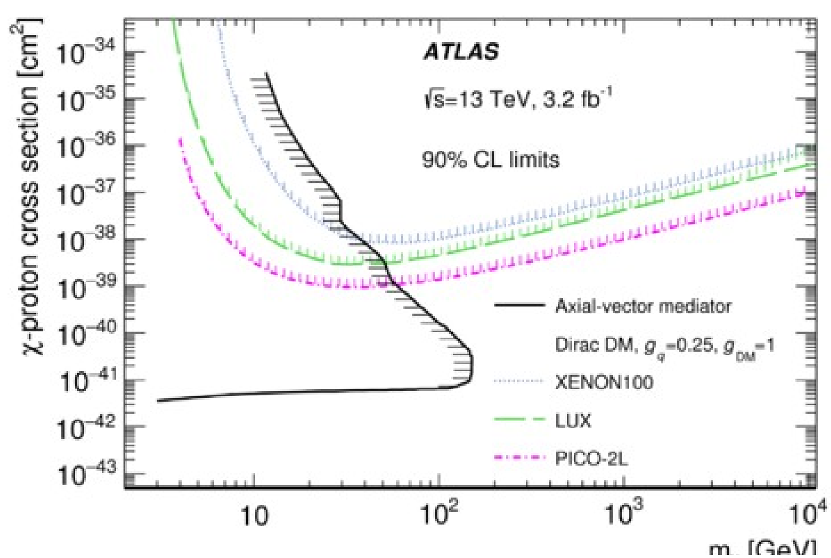
m$_{med}$ < 600 GeV



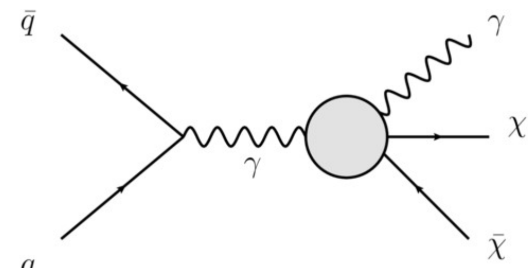
< 10^{-41} cm^2 for m$_{DM}$ ~ 150 GeV

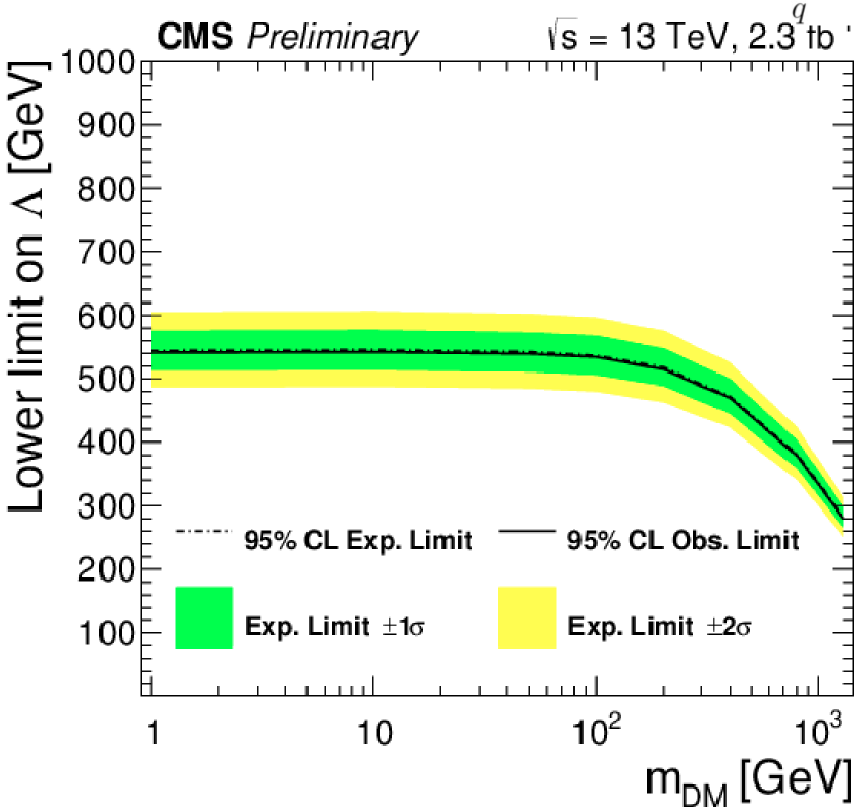


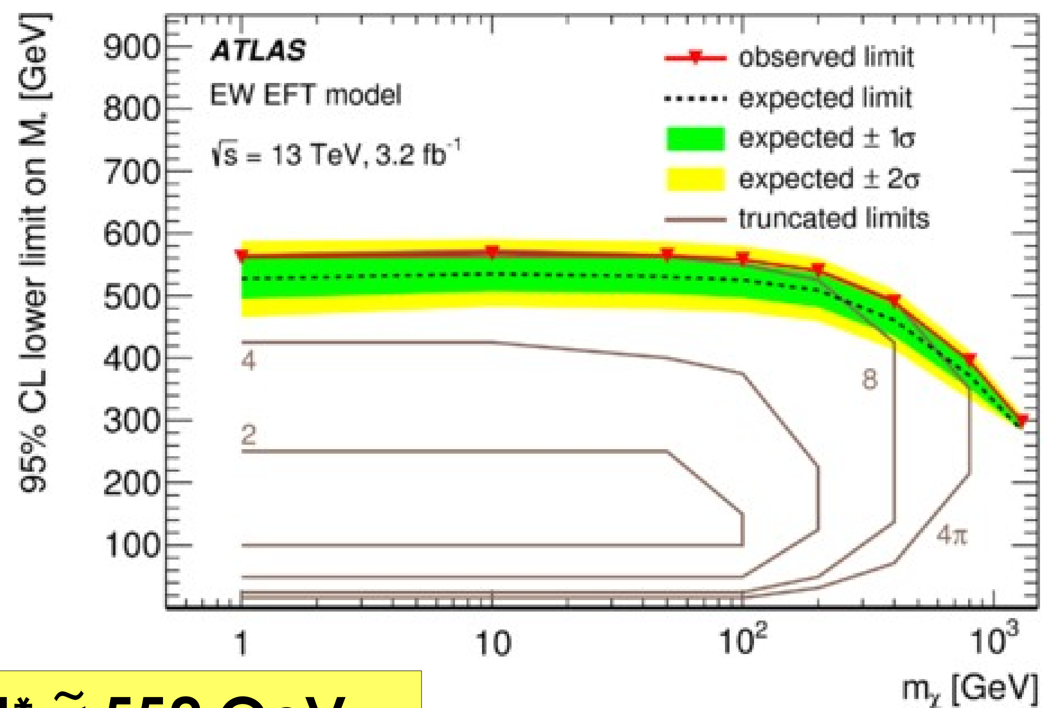
m$_{med}$ < 710 GeV



Mono-Photon Search- EFT



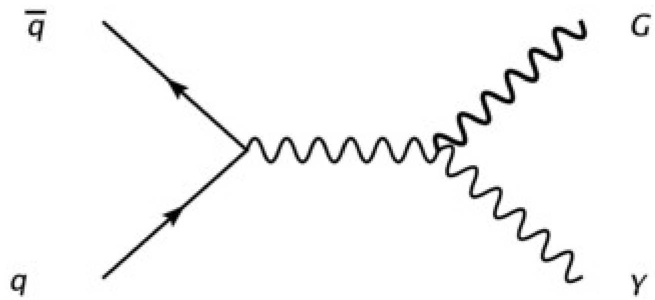


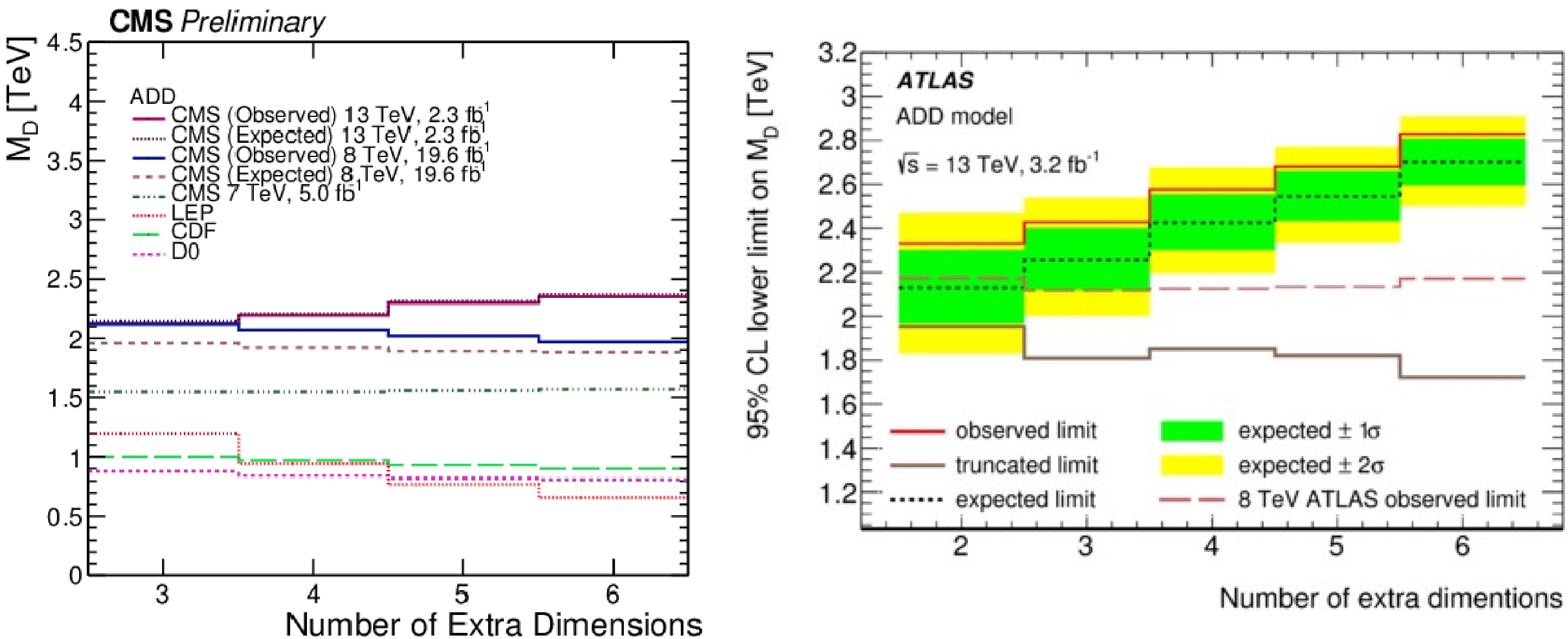


M* ≳ 550 GeV

- Upper limits placed on the production cross section, then translated into the lower limits on the suppression mass scale

Mono-Photon Search - ADD

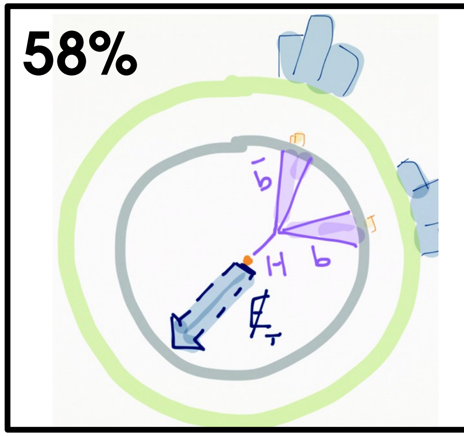


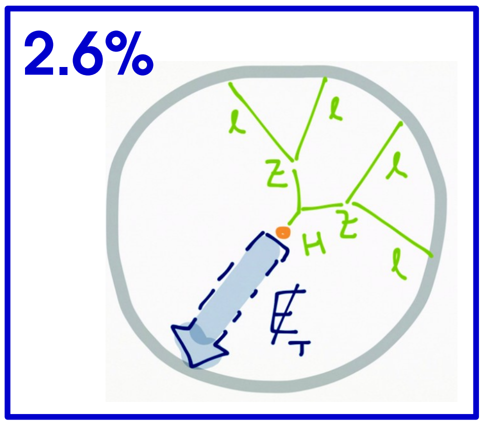


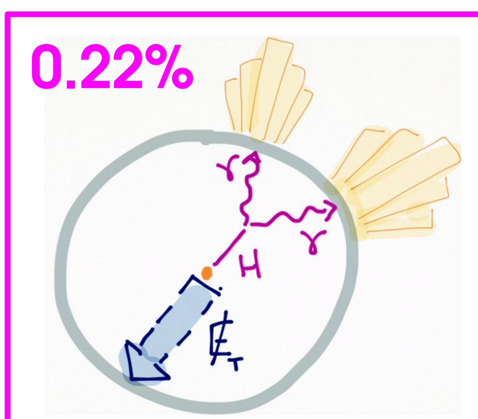
M_D < 2-3 TeV for n=2-6

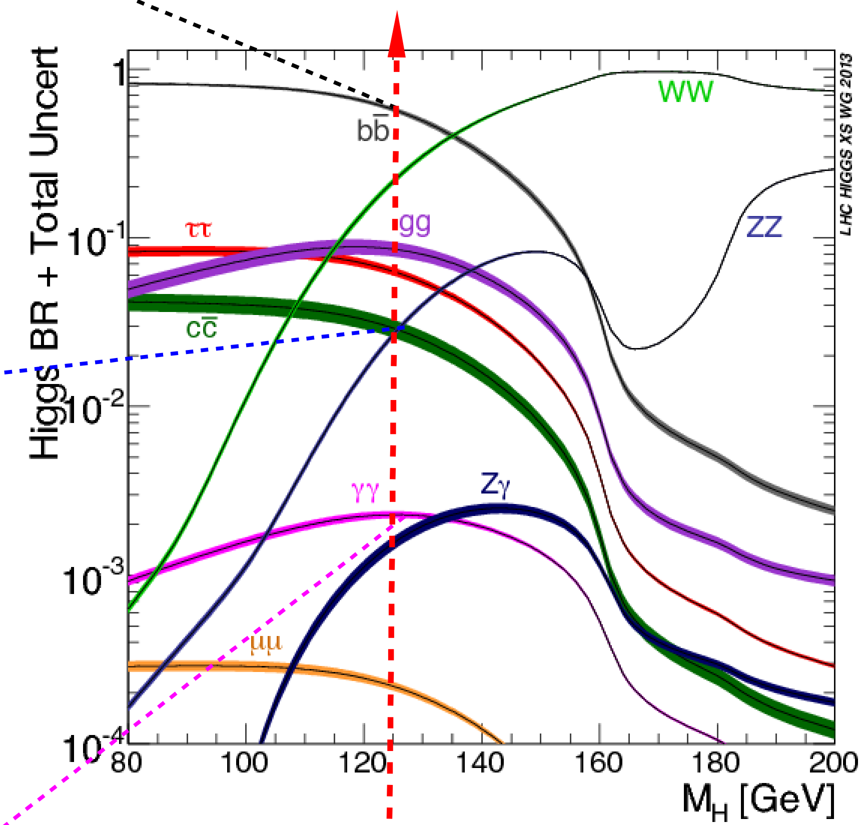
Higgs Portal to Dark Matter

<u>Signature:</u>
Large missing energy and a SM Higgs Boson balanced in the transversal plan







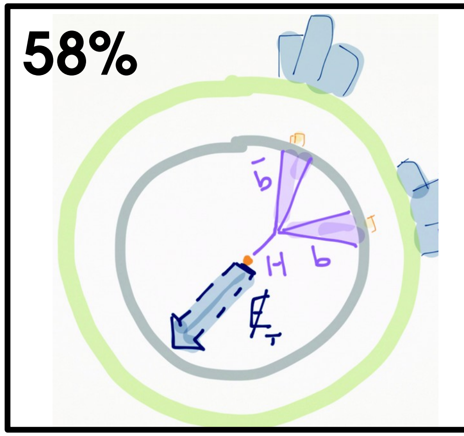


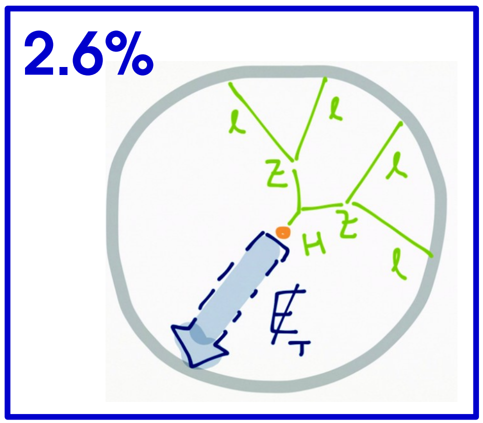
CMS-PAS-EXO-16-011
CMS-PAS-EXO-16-012
ATLAS-CONF-2016-011
ATLAS-CONF-2016-019

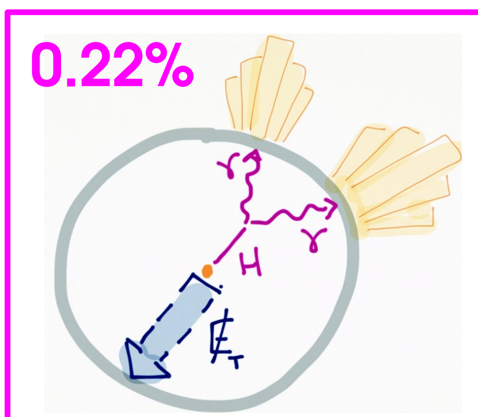
Higgs Portal to Dark Matter

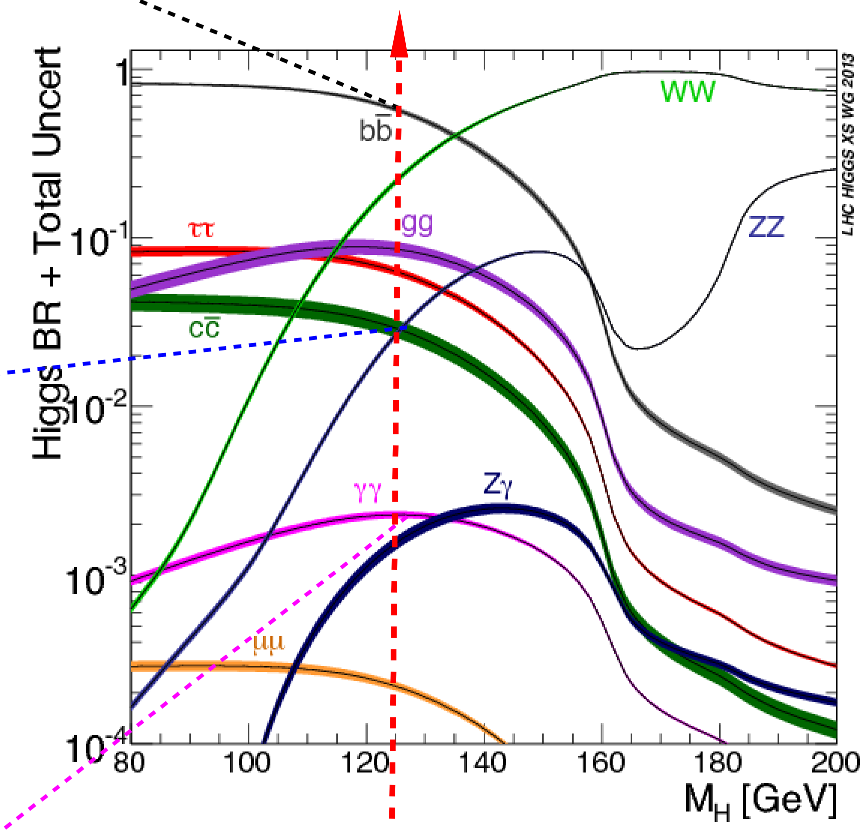
Signal Over Background Ratio

Branching Fraction



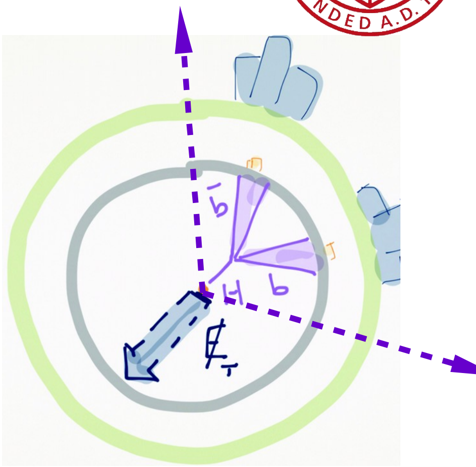






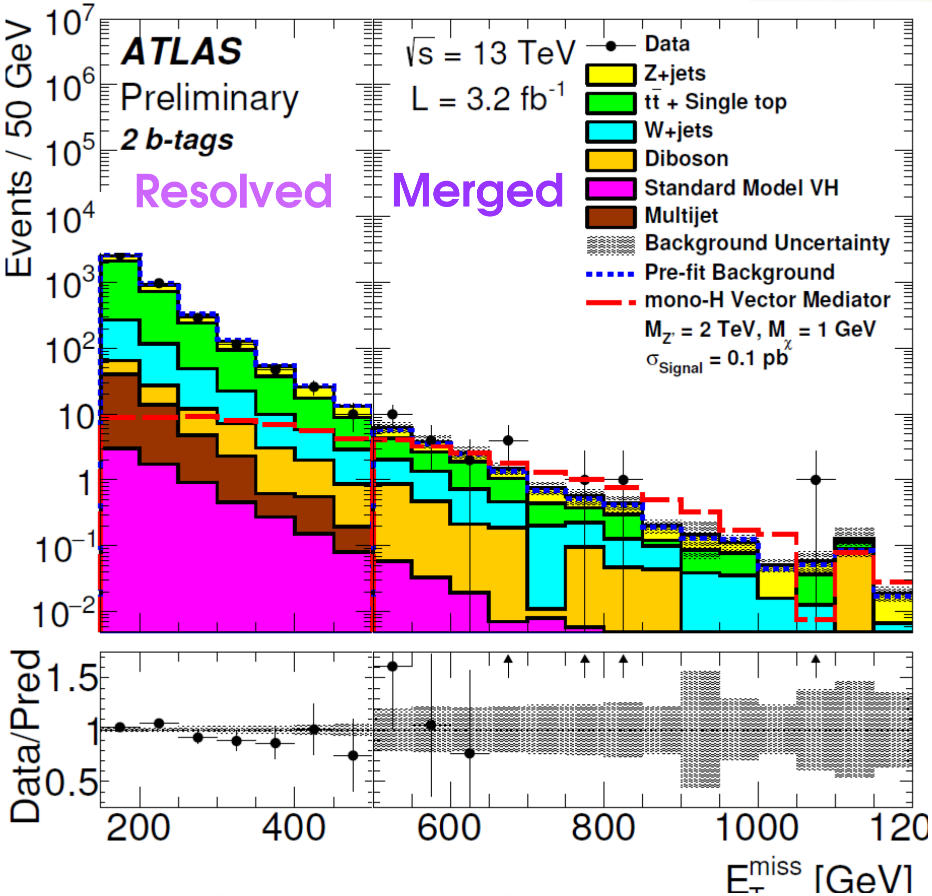
Mono-Higgs to bb

- High-p_T bb system with either **a pair of small radius jets**, or a **single large-radius jet with substructure**
- No identified, isolated muons or electrons
- Classification in terms of **# b-tagged jets**



- Signal Enhanced by:

  $\Delta\Phi$(MET, H) > 120°



- Two kinematic regions:

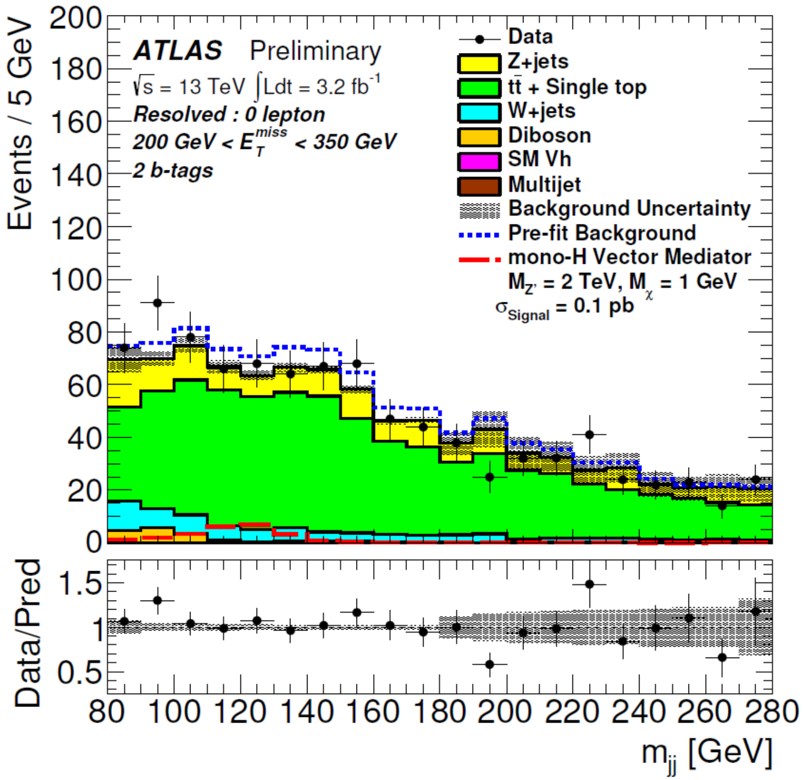
  MET **< 500 GeV**

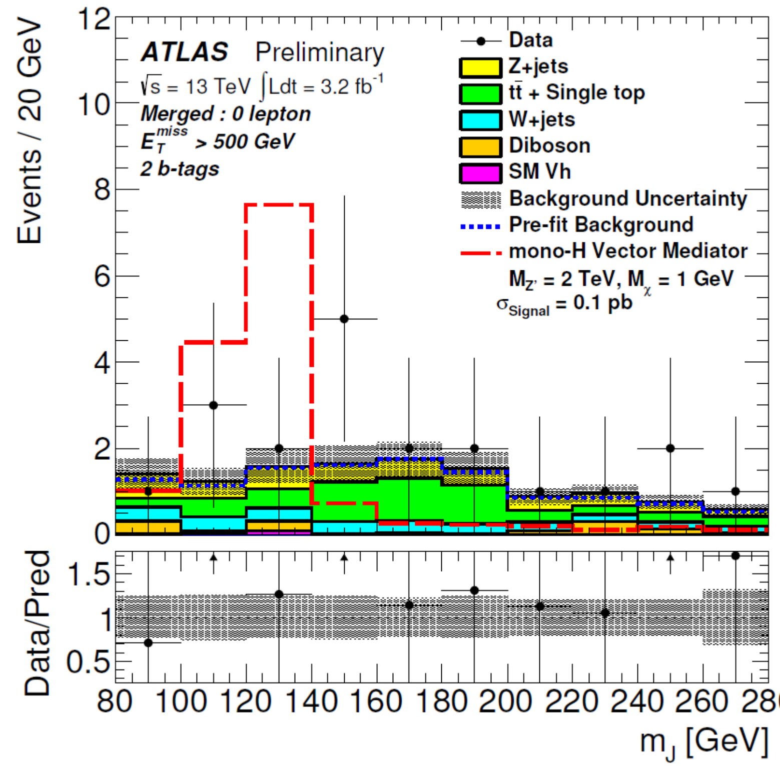
  → Resolved: Two small jets

  MET **> 500 GeV**

  → Merged: One "fat" jet

Mono-Higgs to bb Mass Spectra





- Dominant backgrounds:

→ SM W/Z + jets: 15-65%

→ $t\bar{t}$: 45-80%

=>CR in data w/ #1/#2 leptons

- Other backgrounds:

→ VV, Vh, single-top: < 15%

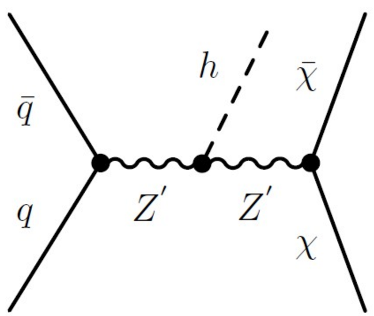
=> Simulation

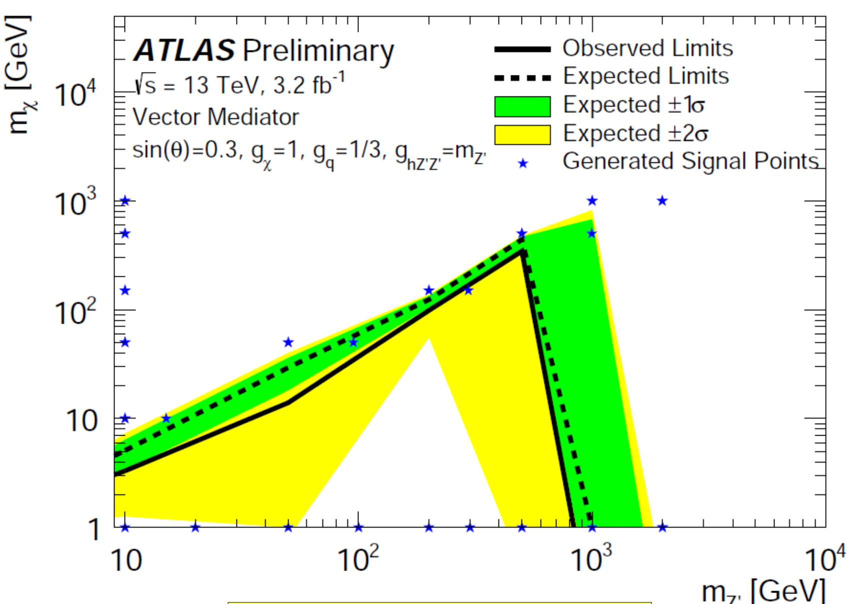
→ Multi-jet: < 2% (resolved)

=> CR in data inverting min |ΔΦ(MET, jet)| cut

Mono-Higgs to bb Results

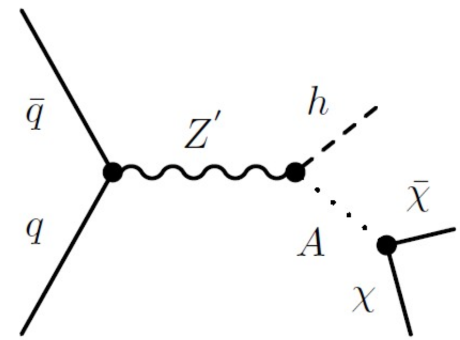
- Simplified model with a Z^0 gauge boson mediating the SM-DM interaction

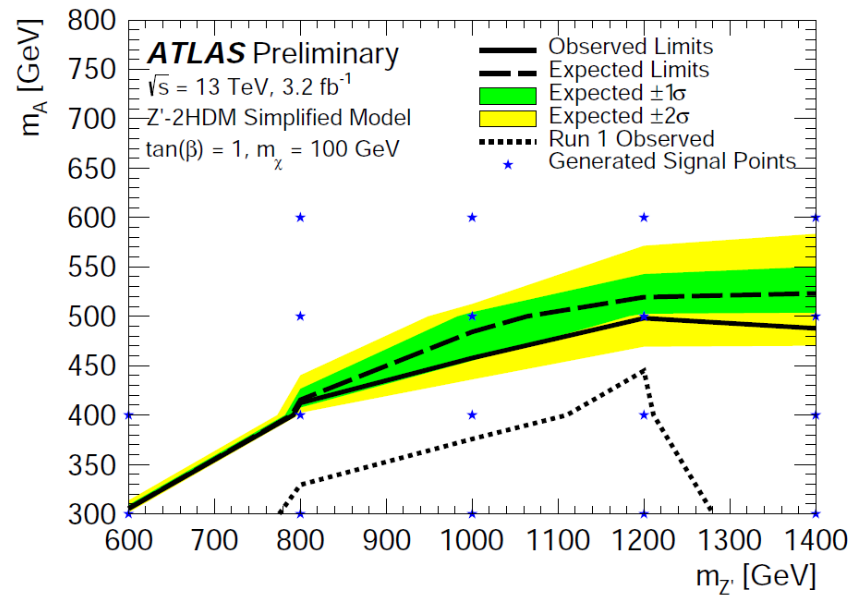




$M_{Z`}$ < 900 GeV

- Two-Higgs-doublet model



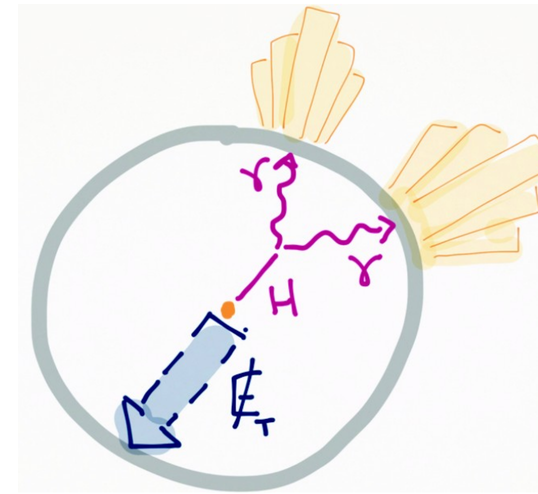


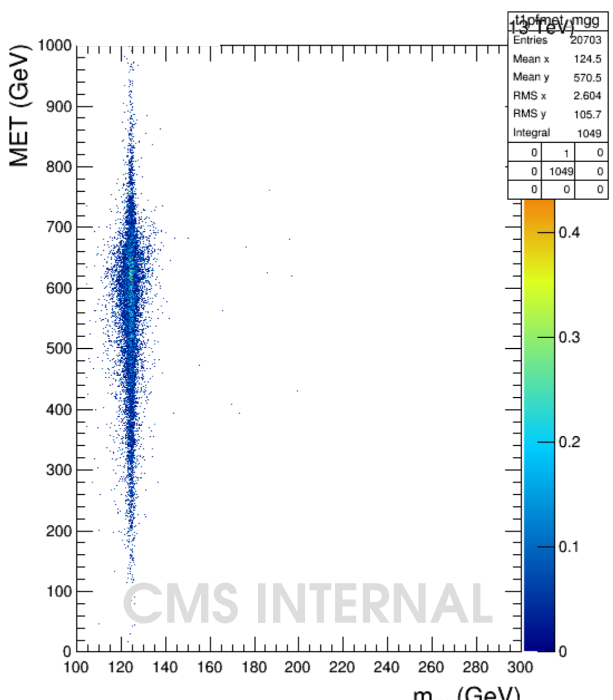
$M_{Z`}$ < 1400 GeV m_A < 500 GeV

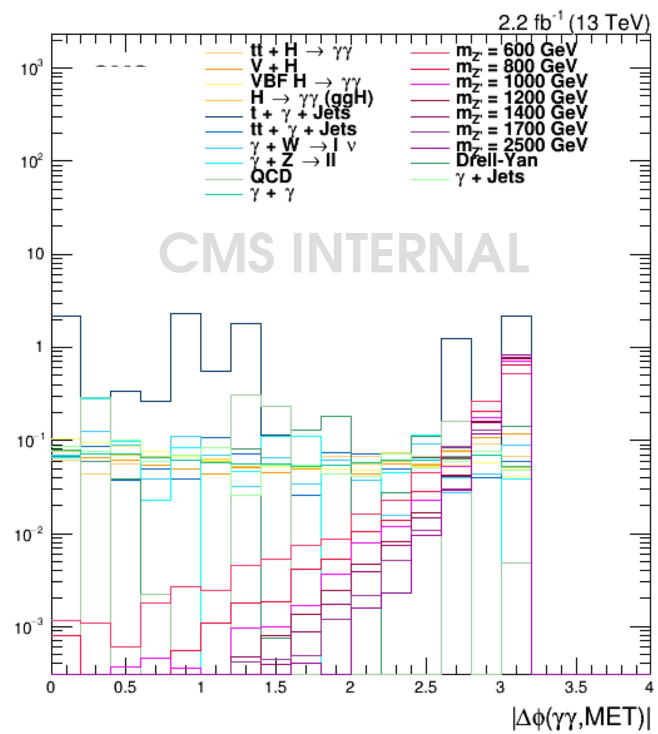
- Results from CMS not yet public but similar analysis strategy and sensitivity

Mono-Higgs to γγ

- Select the highest-pT diphoton pair in the event
- Signal Region defined as:
  → **High MET and $m_{\gamma\gamma}$ around 125 GeV**
- Signal Enhanced requiring Met and H to be b2b
  → ΔΦ(MET, H) > 2.7 rad

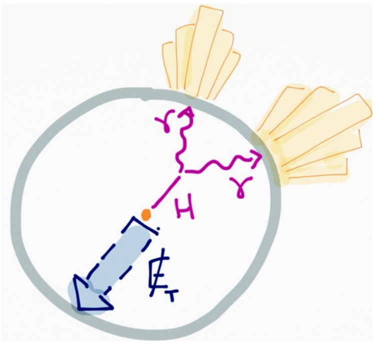




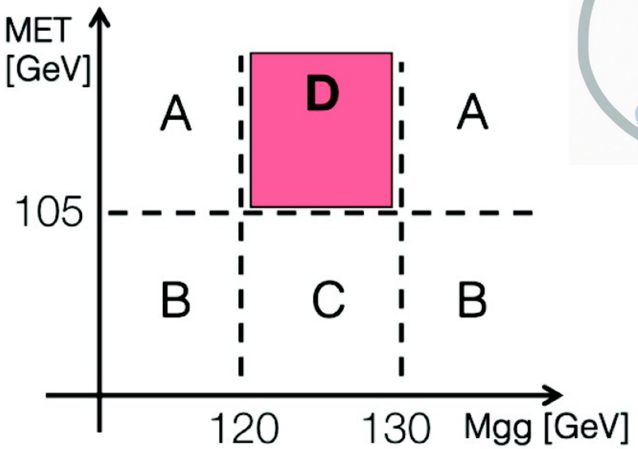


Mono-Higgs to γγ

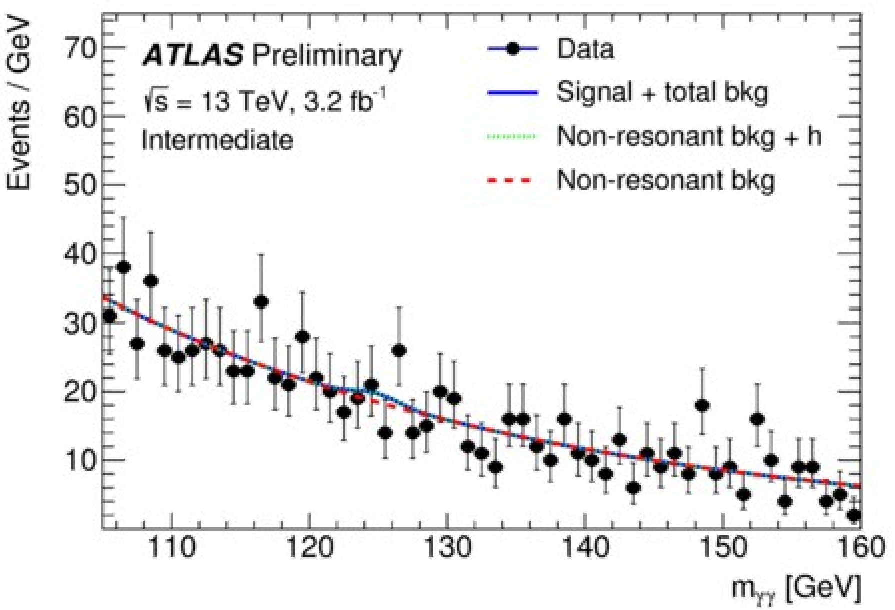
- ATLAS and CMS follow two different analysis strategies:



→ **CMS**: **Cut and Count** approach using a 2-D ABCD method w/ MET and $m_{\gamma\gamma}$ (not yet public)

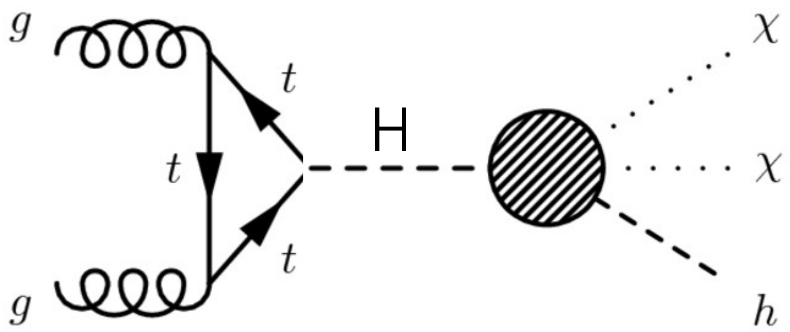


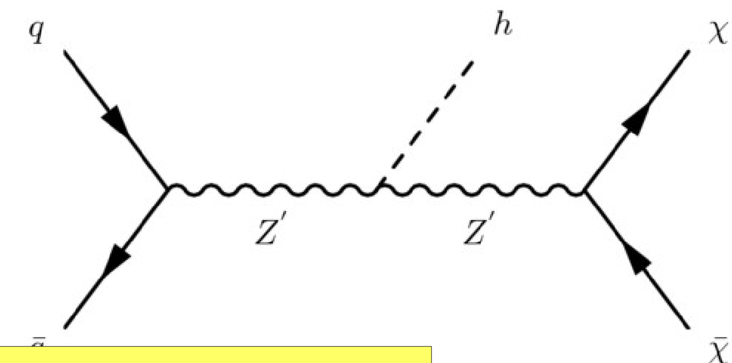
→ **ATLAS**: Categorize events in terms of pT $_{\gamma\gamma}$ and MET and perform **shape analysis** fitting directly data w/ a signal+background model



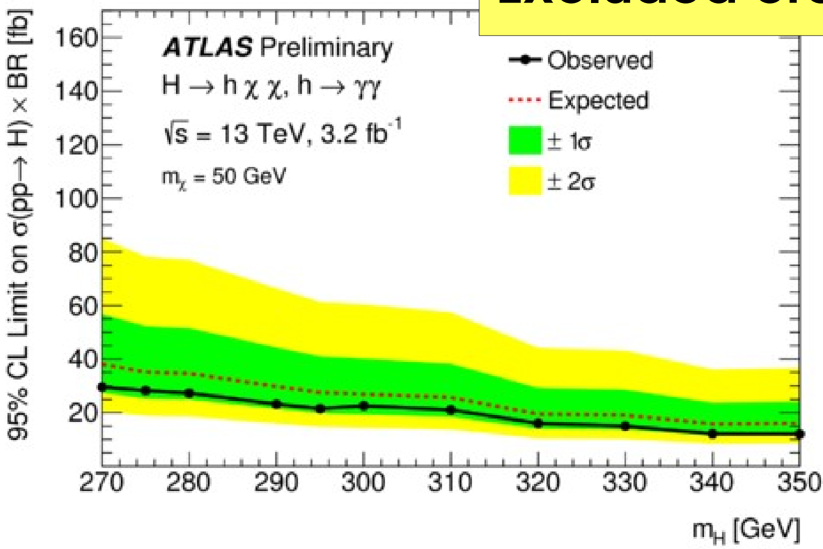
Mono-Higgs to γγ

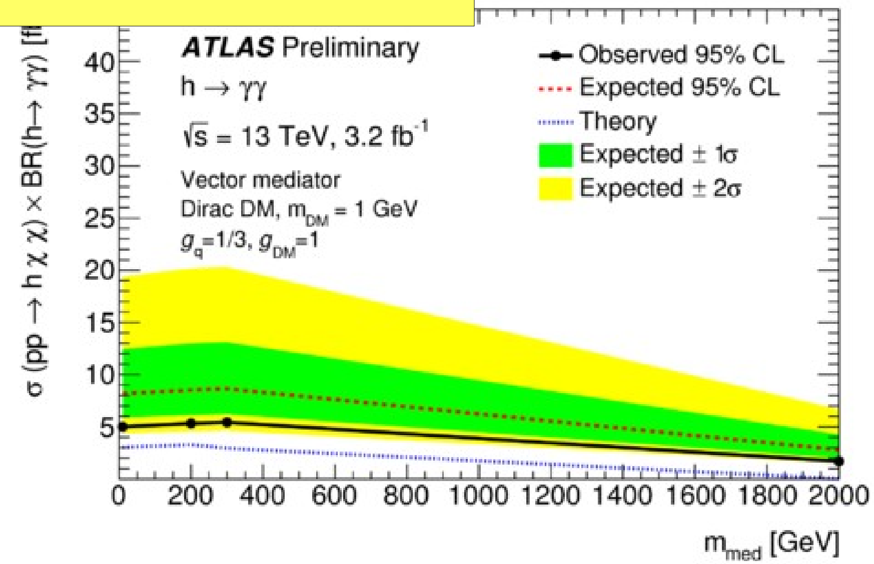
- ATLAS results on DM+ H→γγ presented in terms of **EFT and simplified model**





Excluded cross-sections X BR < 5-25 fb





- CMS results under approval process this week. Only simplified model. Roughly 10% better.

This is not the Full Picture...

- Investigate all the **DM-SM particles interactions** fundamental to elucidate the nature of DM particle and its properties
- **Collider searches** provide complementary information on DM to be integrated with results from direct and indirect experiments
- **Non hadronic channels** benefit from clean signatures but suffer from relatively small statistics
- **Mono-Jet/Mono-V** signals: statistic enhanced from strong couplings → large discovery power
- **Not only mono-X** signatures can be interpreted in terms of DM results...

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… Many other new LHC results to be discussed in the next 30' with Valerio :)