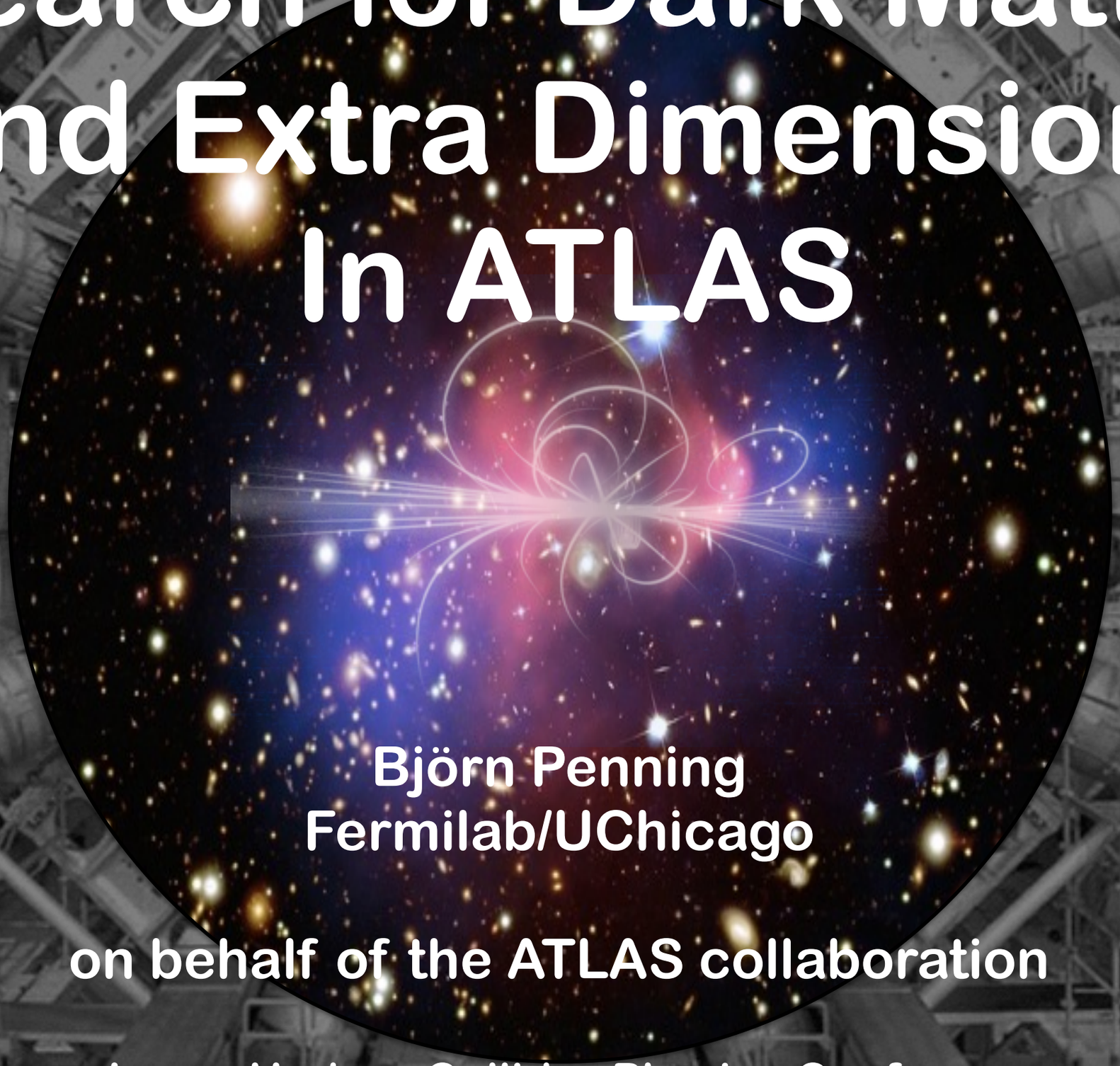
Search for Dark Matter and Extra Dimensions In ATLAS



Björn Penning
Fermilab/UChicago

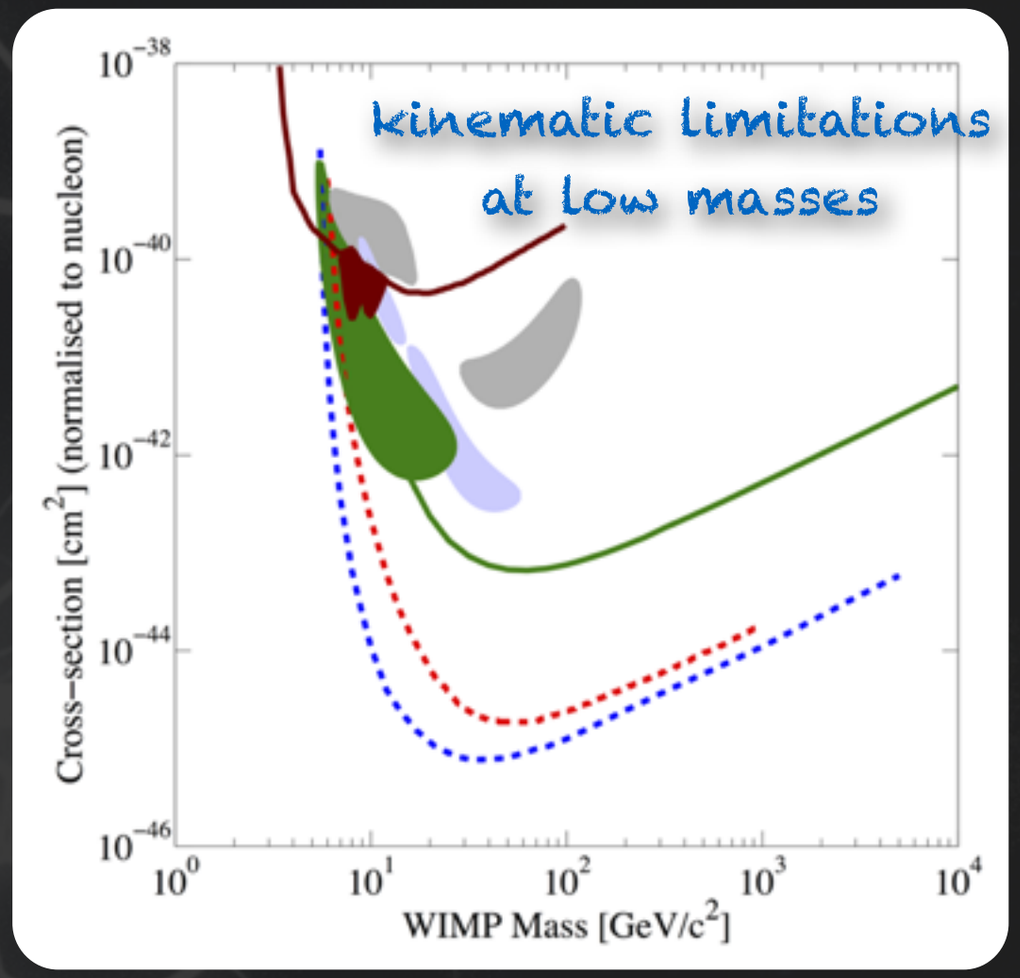
on behalf of the ATLAS collaboration

Large Hadron Collider Physics Conference
New York City, June 3rd, 2014

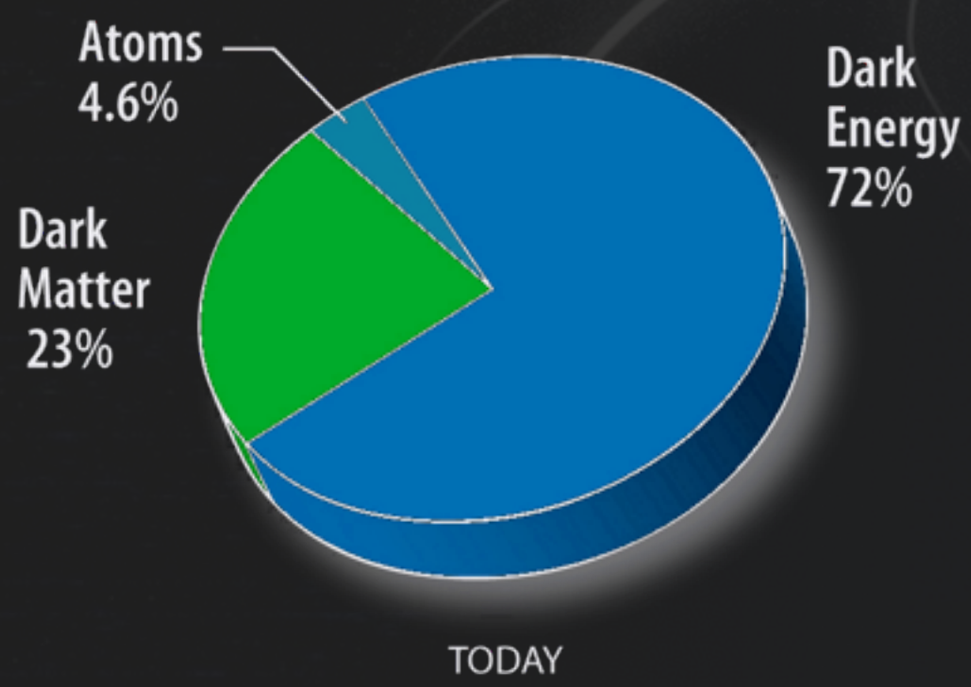
Why Dark Matter & Extra Dimension?

- Dark Matter (DM) firmly established signal of new physics
- DM likely to be 'non-baryonic cold dark matter'
- Global fit of cosmological parameters, ΛCDM:

  → $\Omega\Lambda \approx 0.68$, $\Omega DM \approx 0.27$, $\Omega b \approx 0.05$



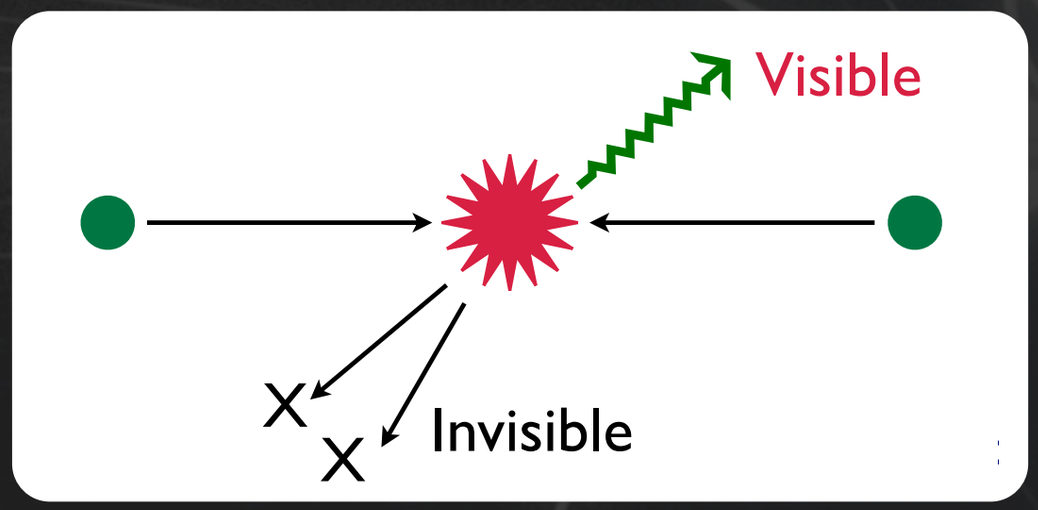
arXiv:1303.5062



- Underground dark matter searches measure nuclear recoil
- There may very well be more phenomena we do not yet understand
  → parametrize effective scales

Principle of Collider DM searches

- DM likely to be 'non-baryonic cold dark matter' → 'WIMP Miracle' → BSM physics
- Properties of low mass DM
  - Pair produced (stable)
  - Mediating particle (M*) not directly observed → Effective Field Theory (EFT)



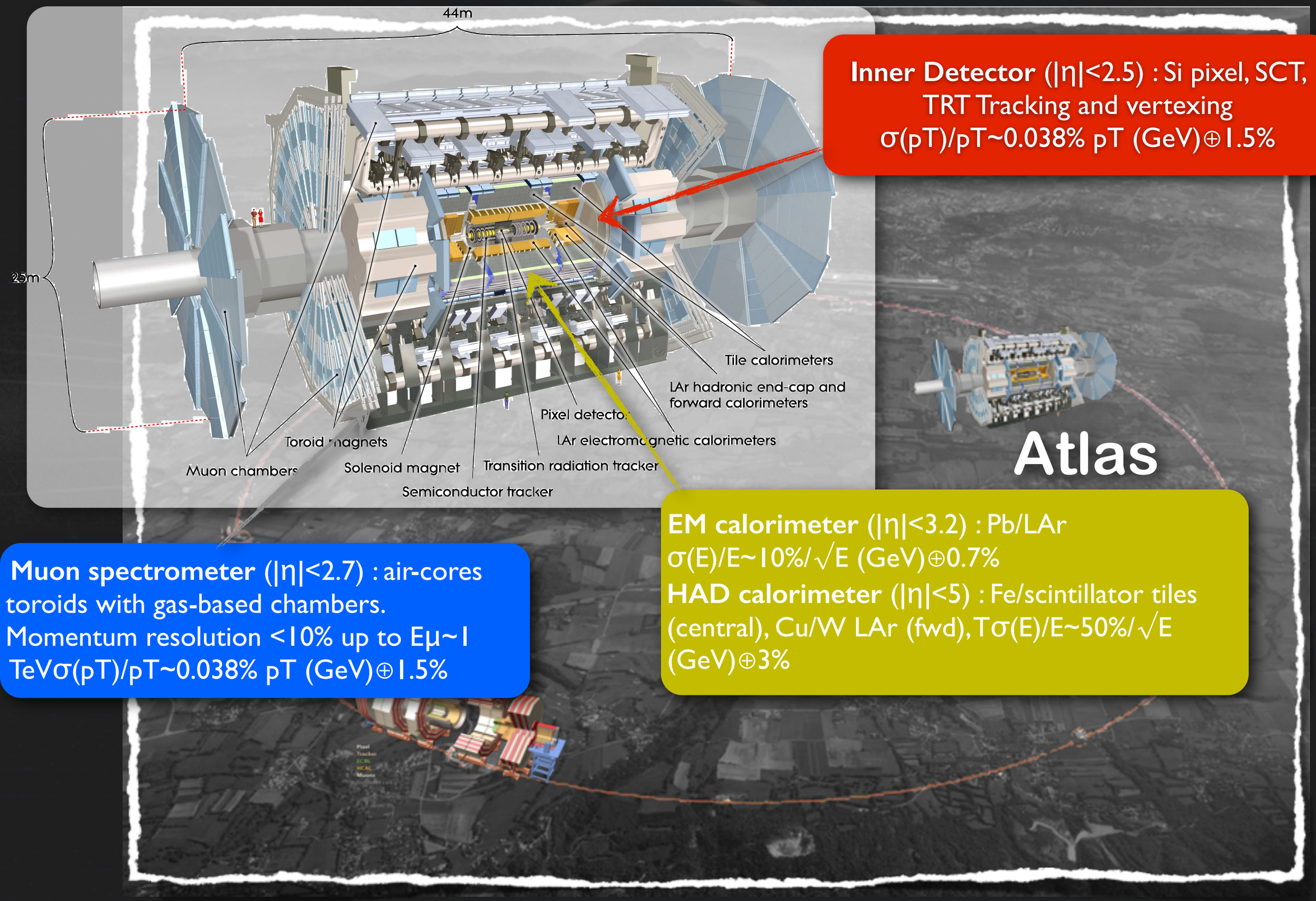
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

spin-independent spin-dependent

- Sensitive to spin-dependent and independent dark matter nucleon interactions and low masses

Ref: arxiv:1008.1783v2

The LHC & Atlas



Inner Detector (|η|<2.5) : Si pixel, SCT, TRT Tracking and vertexing
σ(pT)/pT~0.038% pT (GeV)⊕1.5%

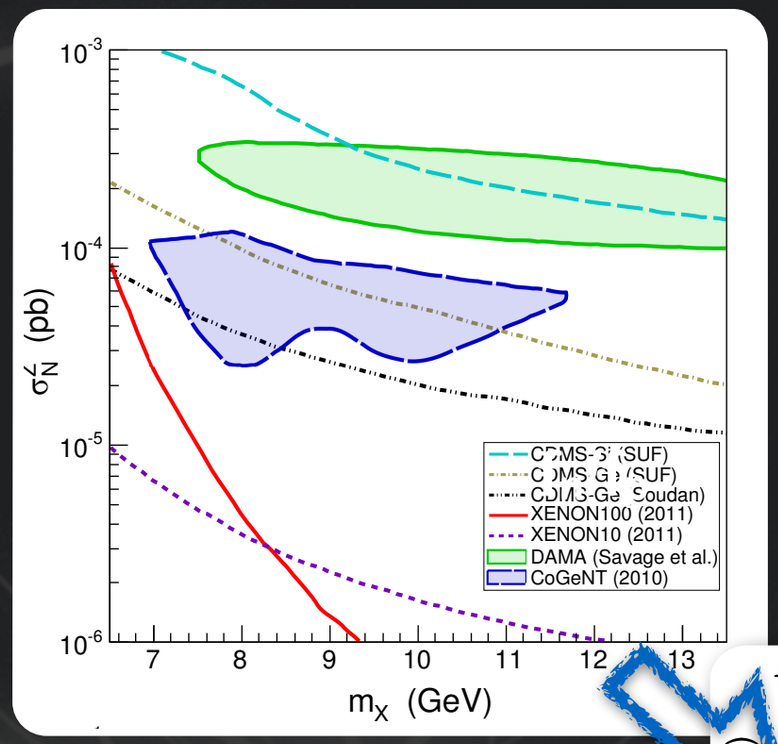
Muon spectrometer (|η|<2.7) : air-cores toroids with gas-based chambers.
Momentum resolution <10% up to Eμ~1 TeVσ(pT)/pT~0.038% pT (GeV)⊕1.5%

EM calorimeter (|η|<3.2) : Pb/LAr
σ(E)/E~10%/√E (GeV)⊕0.7%
HAD calorimeter (|η|<5) : Fe/scintillator tiles (central), Cu/W LAr (fwd), Tσ(E)/E~50%/√E (GeV)⊕3%

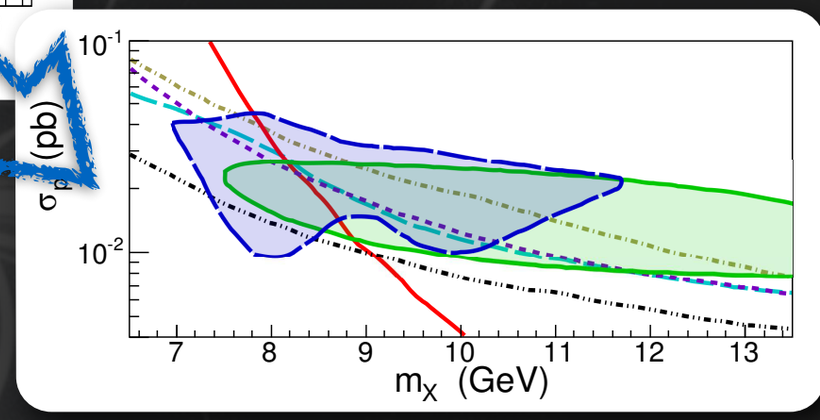
arXiv:1309.4017

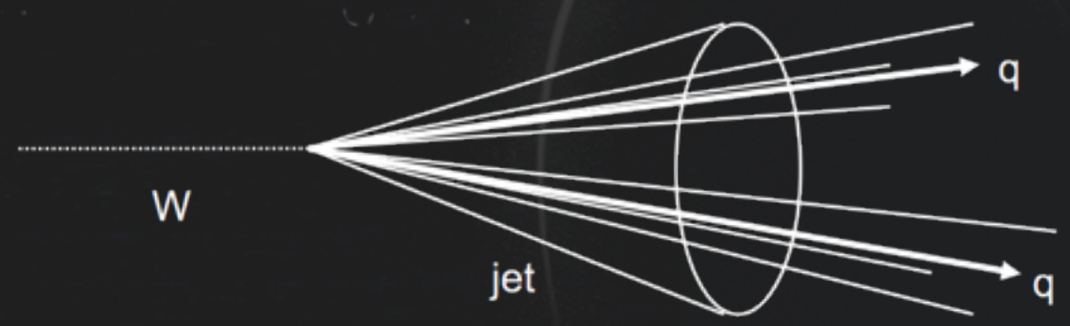
Dark Matter with W/Z

- Extending mono-jet/photon final states to new signatures
  - see Thursday's plenary talks
- W boson emission may become dominant for opposite sign couplings
- f_n/f_p = ratio of proton/neutron coupling
- For $-0.72 < f_n/f_p < -0.66$ DAMA- and CoGeNT, and XENON are consistent



f_n/f_p

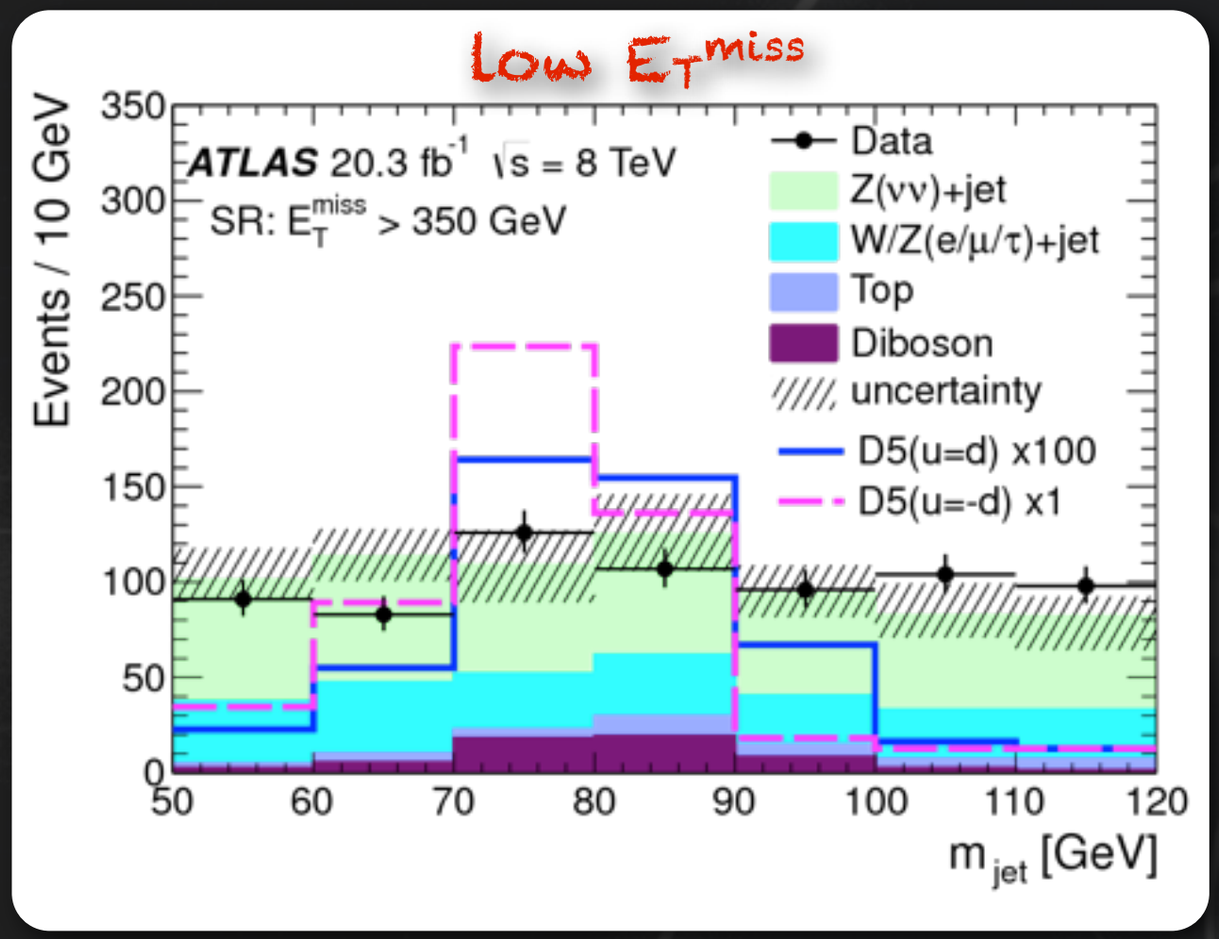


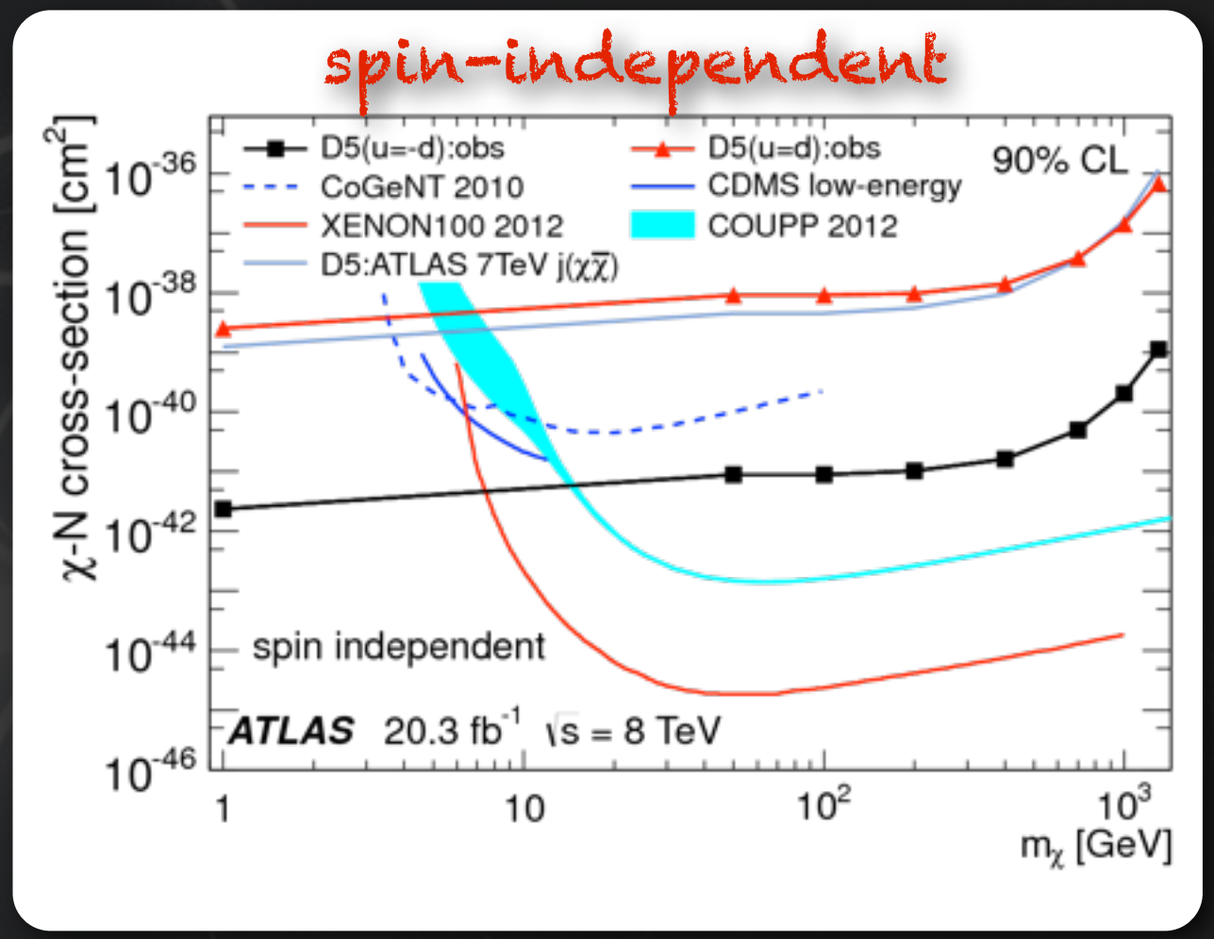


- Selection
  - 1 'fat jet', p_T>250 GeV (C.-A.)
  - maximal one dR=0.4 jet
  - separated from large radius jet and E_T^{miss}
  - Signal Regions: E_T^{miss}> 350, 500 GeV

Y. Bai, T. Tait; arXiv:1208.4361
Feng et al.; arXiv:1102.4331

Dark Matter with W/Z

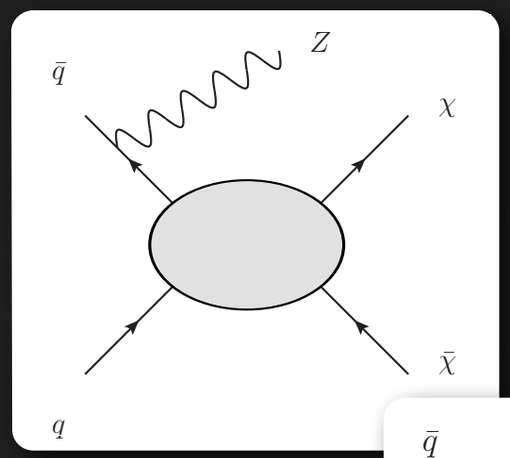


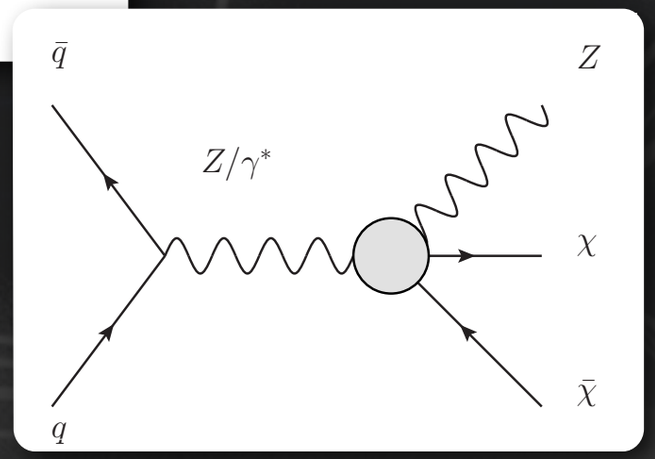


- Unfortunately no excess over SM found
- Converting into limits on WIMP-Nucleon scattering cross section
- Spin independent limits improve by three orders of magnitude if up/down have opposite sign
- See also ATLAS-CONF-2014-017 for W→lν channel

arXiv:1404.0051

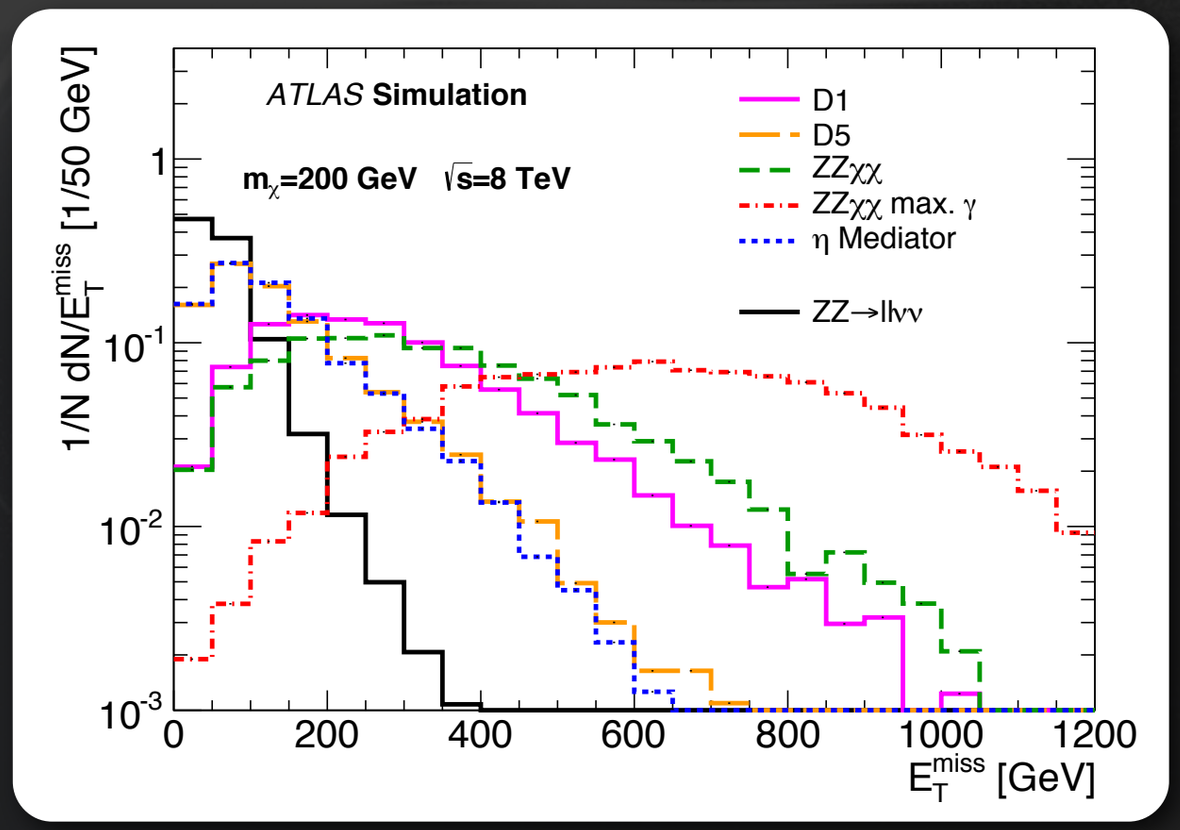
DM with Z (→ll)



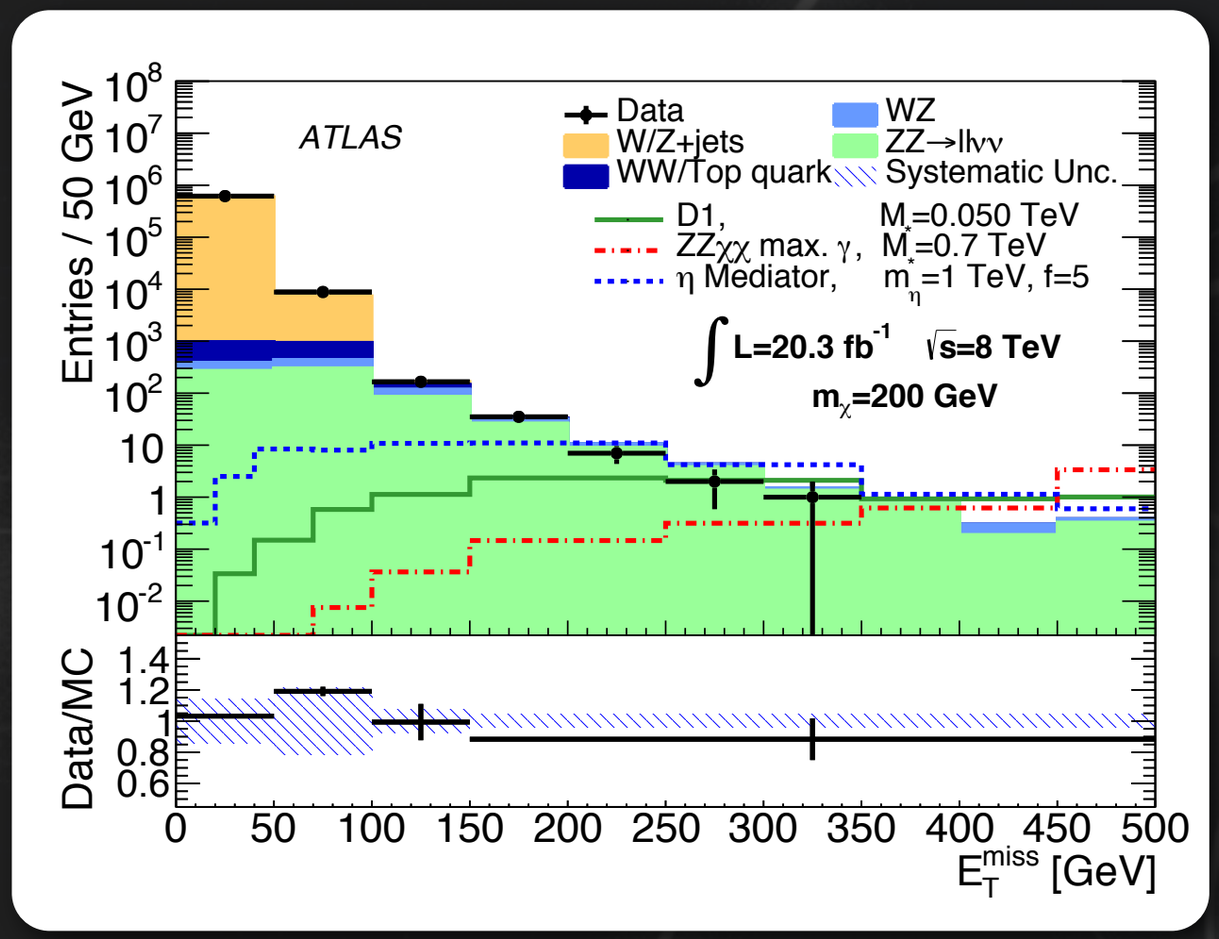


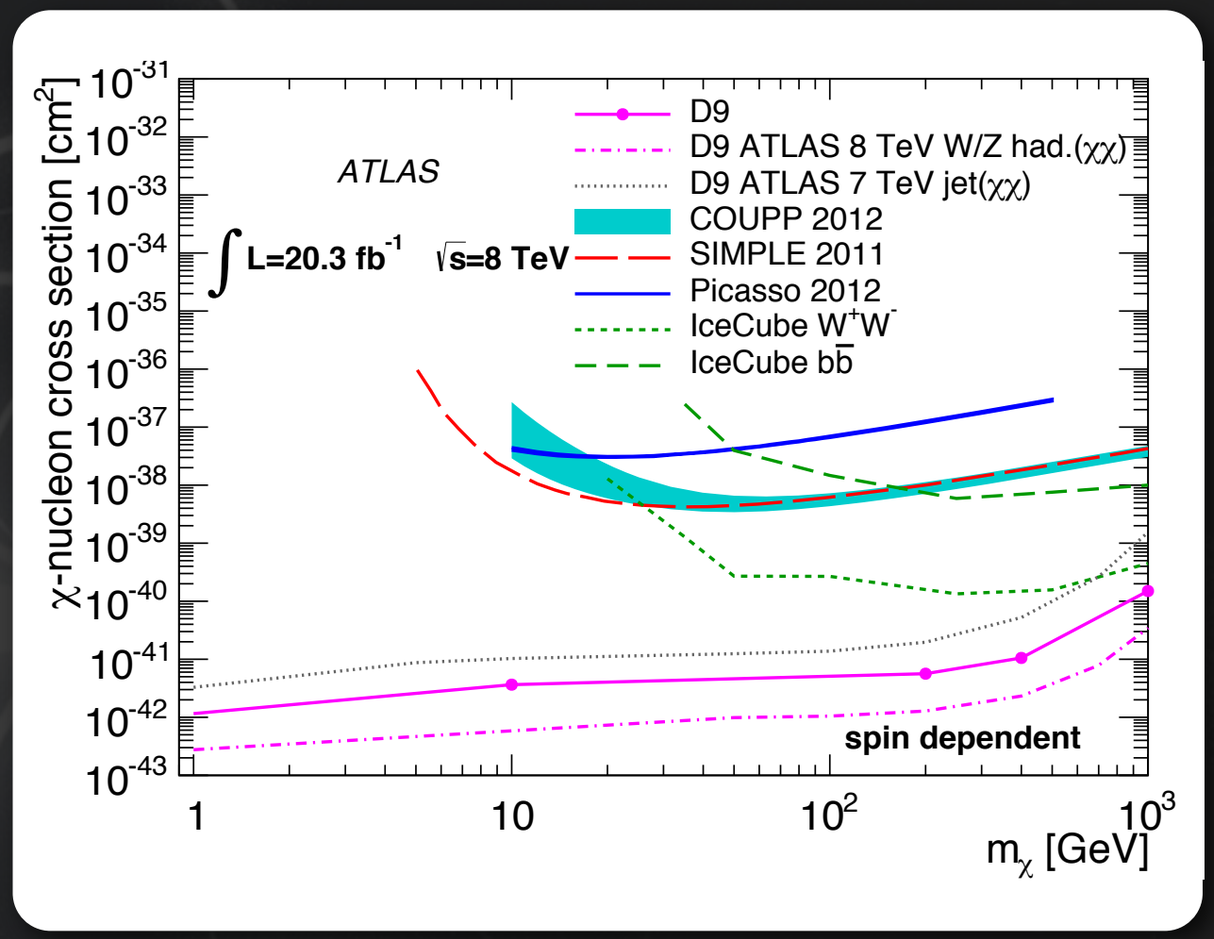
- Associated DM+Z production
- Consider EFT and UV complete models

- Event selection:
  - Single- or Dilepton Trigger
  - m(ll) within Z window
  - E_T^{miss} and $p_T(ll)$ well separated
  - Central production: $|\eta(ll)|<2.5$
  - Balanced: $|p_T(ll)-E_T^{miss}|/p_T(ll)<0.5$
  - 4 SRs: E_T^{miss}>150, 250, 350, 450 GeV



DM with Z (→ll)



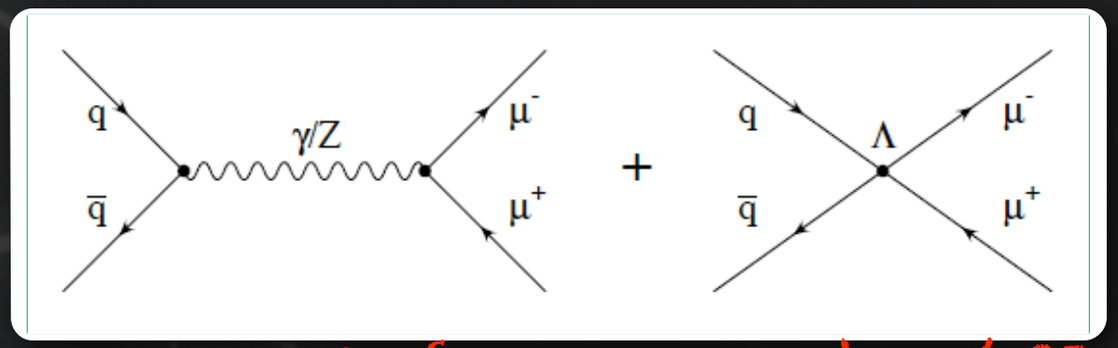


- Unfortunately **no excess** over SM found
- Converting into **limits on WIMP-Nucleon** scattering cross section
- Also limits on coupling strength in **mediator mass - DM** plane are presented

Extending to ADD & general CI

ATLAS-CONF-2014-30

- Extend dilepton selection to **high masses** m_{ll}>80 GeV and **allow inclusive final states** (jets and leptons)
- Consider **EFT** and UV complete model
- **Contact Interaction (CI)**: Search using **COS Θ ≷ 0** and **m_{ll}=[400,…4500] GeV**

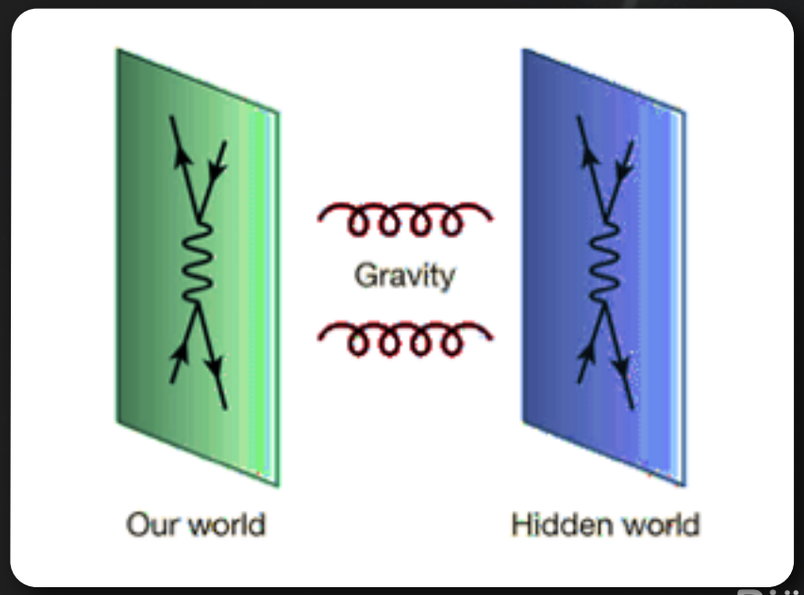


Interference 'pure' CI

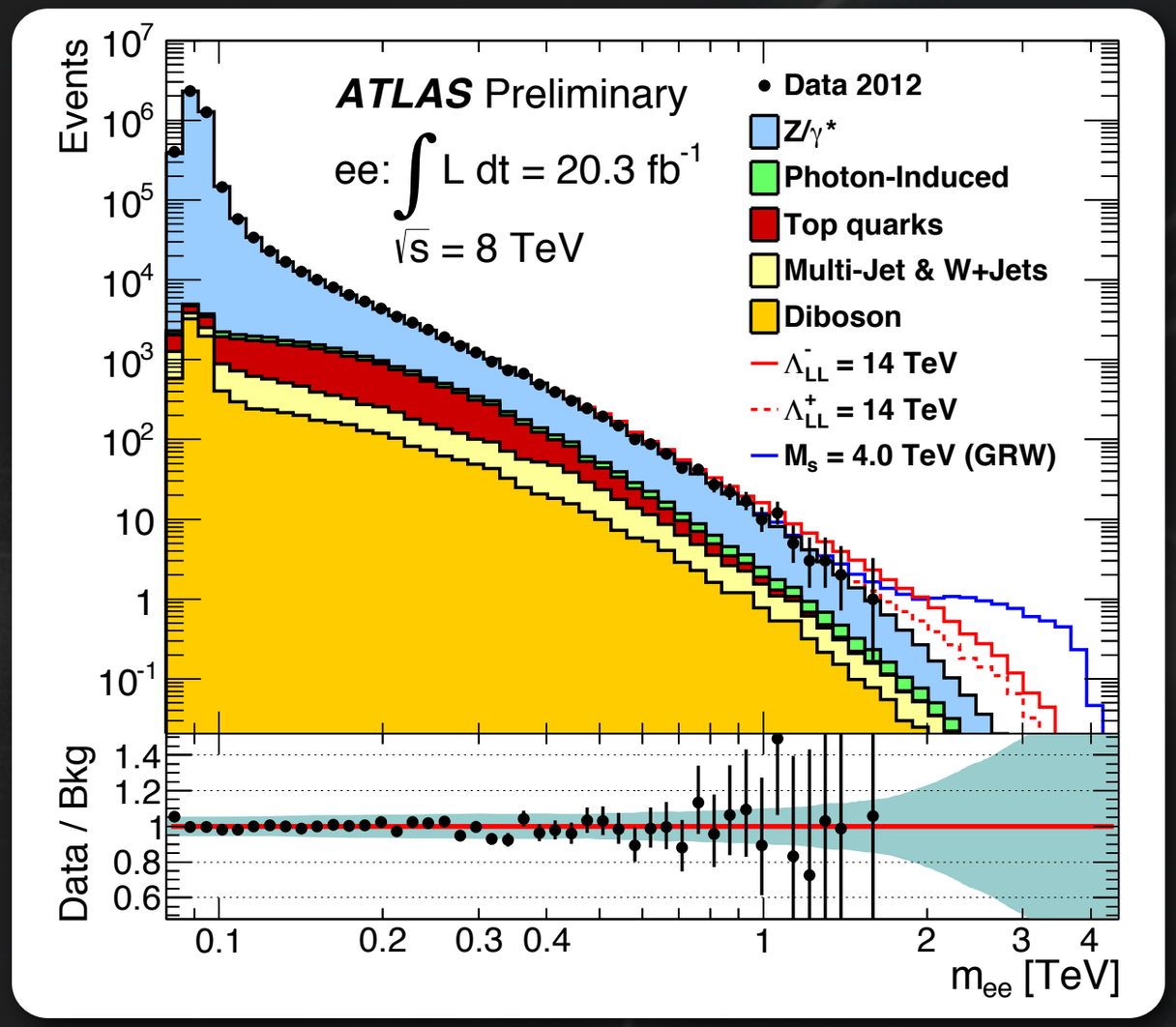
CI & DY

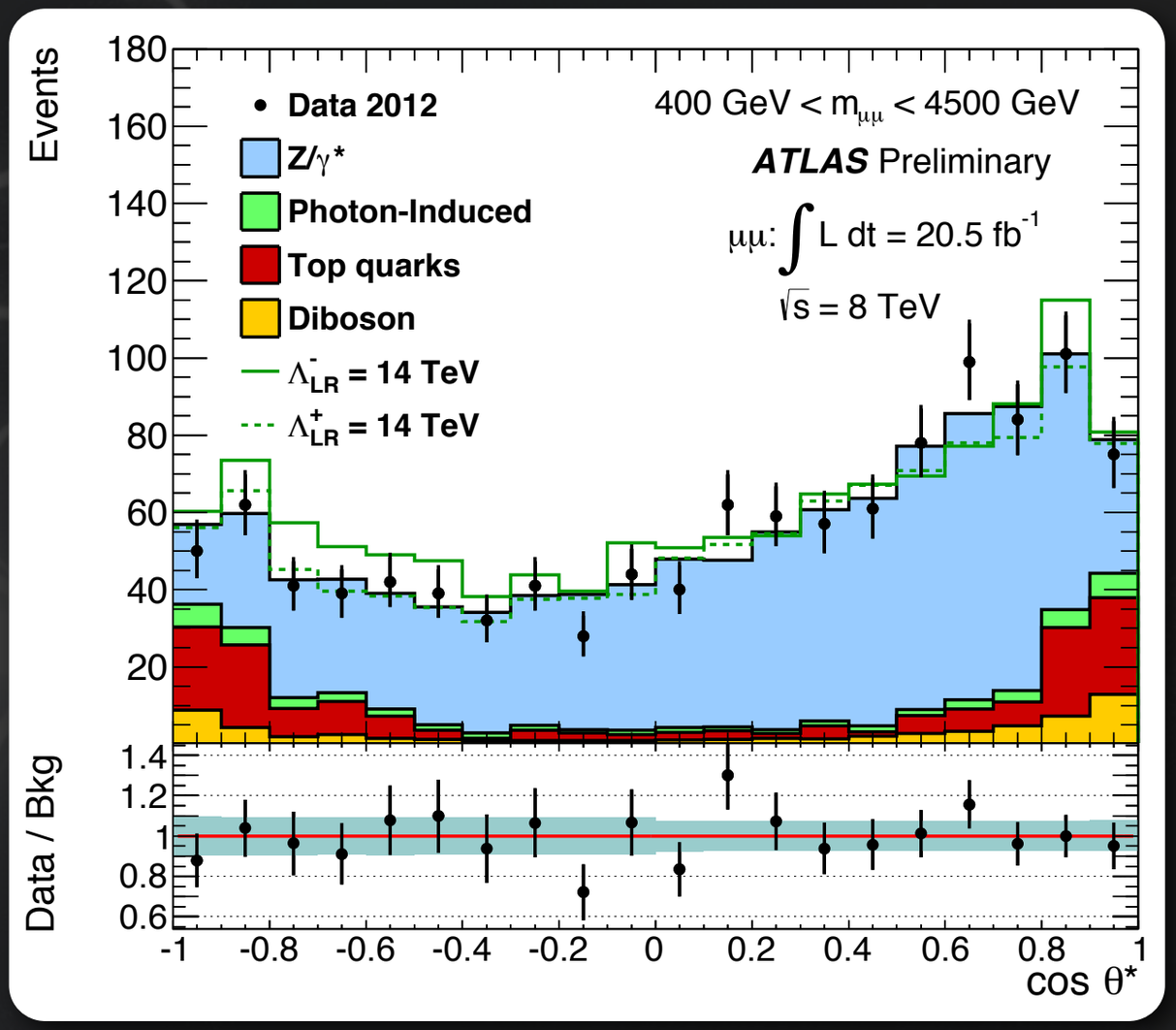
$$\frac{\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{LL}\frac{F_I(m_{\ell\ell})}{\Lambda^2} + \frac{F_C(m_{\ell\ell})}{\Lambda^4}$$

- **Models of large extra dimensions**: provide solution to hierarchy problem
- **Arkani-Hamed, Dimopoulos, Dvali (ADD)**
  - Gravity propagates in **(4+n)-dim bulk space**
  - SM fields confined to 4d
- Propagation of LED results in Kaluza-Klein Modes
- As well DM signal candidate but at higher energies
- Search using **m_{ll}>1900 GeV**



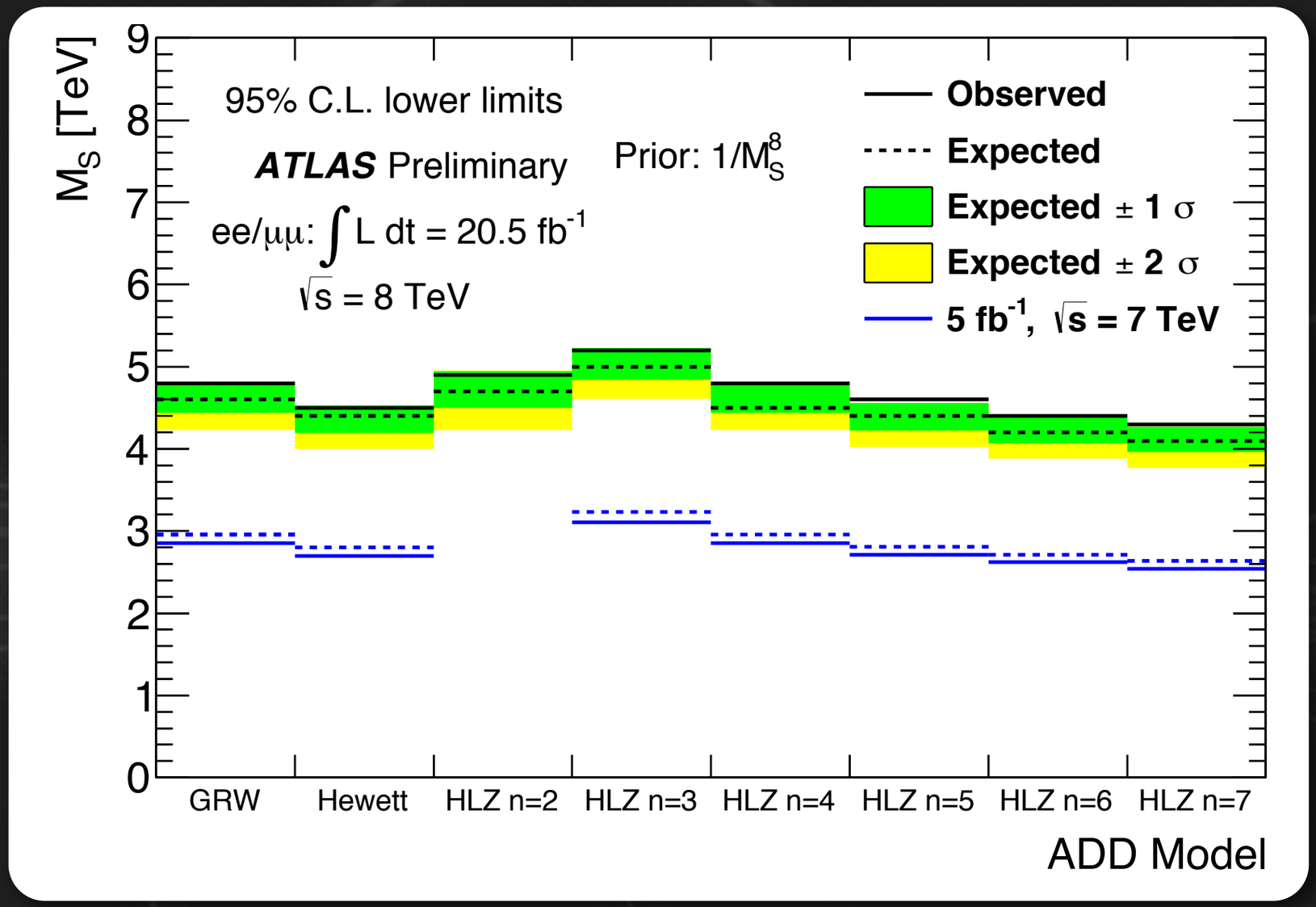
Extending to ADD and general CI





- Discriminating variables agree well

Extending to ADD and general CI



- **Good agreement** is observed between both, data and background model in mass and A_{FB} distributions
- Setting **best limits** on various ADD models

BH→l+jets

M_D

$$M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n$$

- LED may lower Gravity scale to EW scale
- Grav. scale $M_D << M_{Pl}$; if $M_D \sim$ TeV
  → strong production of mini Black Holes (BH) at LHC
- DM produced at $M_{th} \sim 2 \times M_D$
- Different BH evolution and decay modes considered
  - Gravitons
  - Hawking Radiation

→ approaching M_D → 'Final burst' remnants (high mult. states)

Generator	Angular Mom.	Description	n considered
CHARYBDIS	Non-rotating	Black holes: High multiplicity remnant	2, 4, 6
	Rotating	Black holes: High multiplicity remnant	2, 4, 6
	Rotating	Black holes: Low multiplicity remnant	2, 4, 6
	Rotating	Production loss model (gravitons)	2, 4, 6
CHARYBDIS	Non-rotating	String balls	6
	Rotating	String balls	6
BLACKMAX	Non-rotating	Black holes: High multiplicity remnant	2, 4, 6
	Rotating	Black holes: High multiplicity remnant	2, 4, 6
	Non-rotating	Black holes with graviton	2, 4, 6
	Rotating	10% Production loss model (photons)	2, 4, 6
	Rotating	Lepton number conservation	4

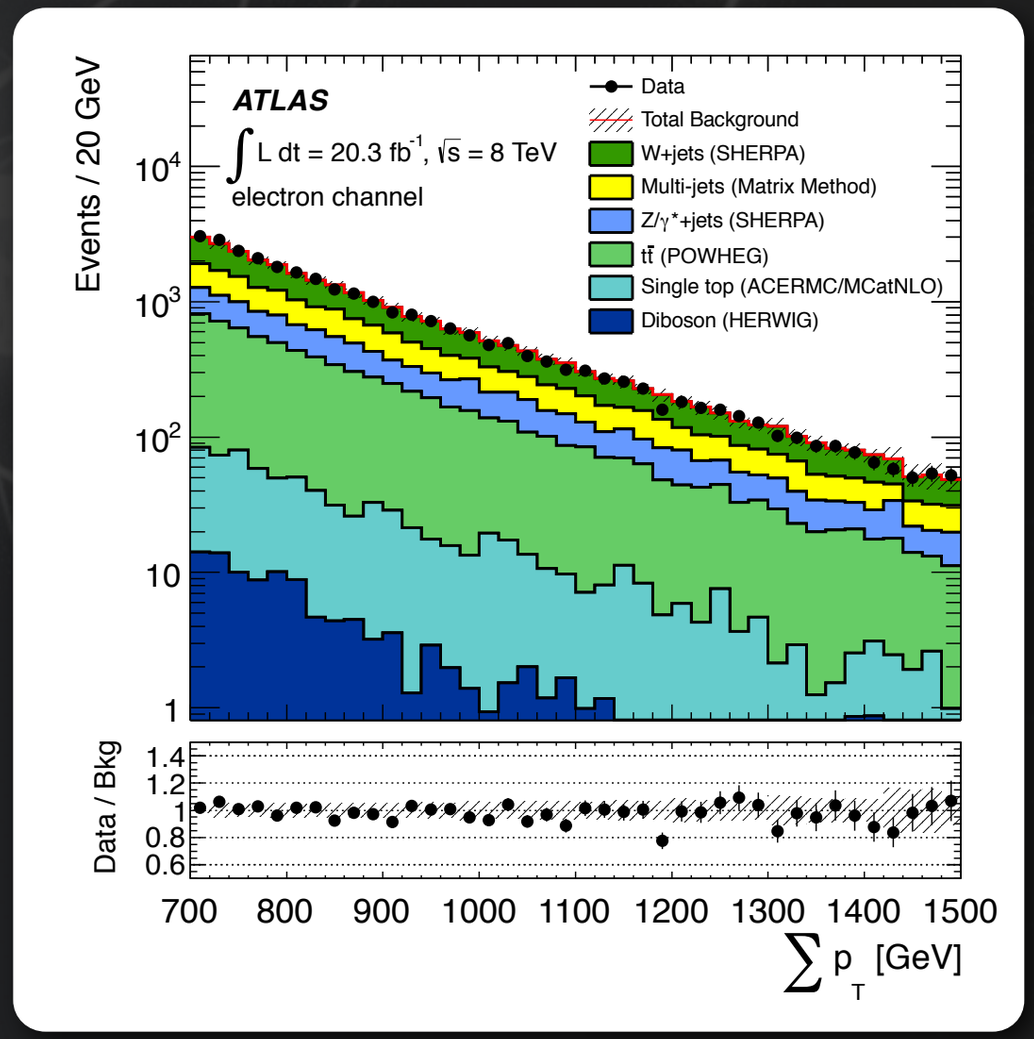
arXiv:1405.4254

BH→l+jets

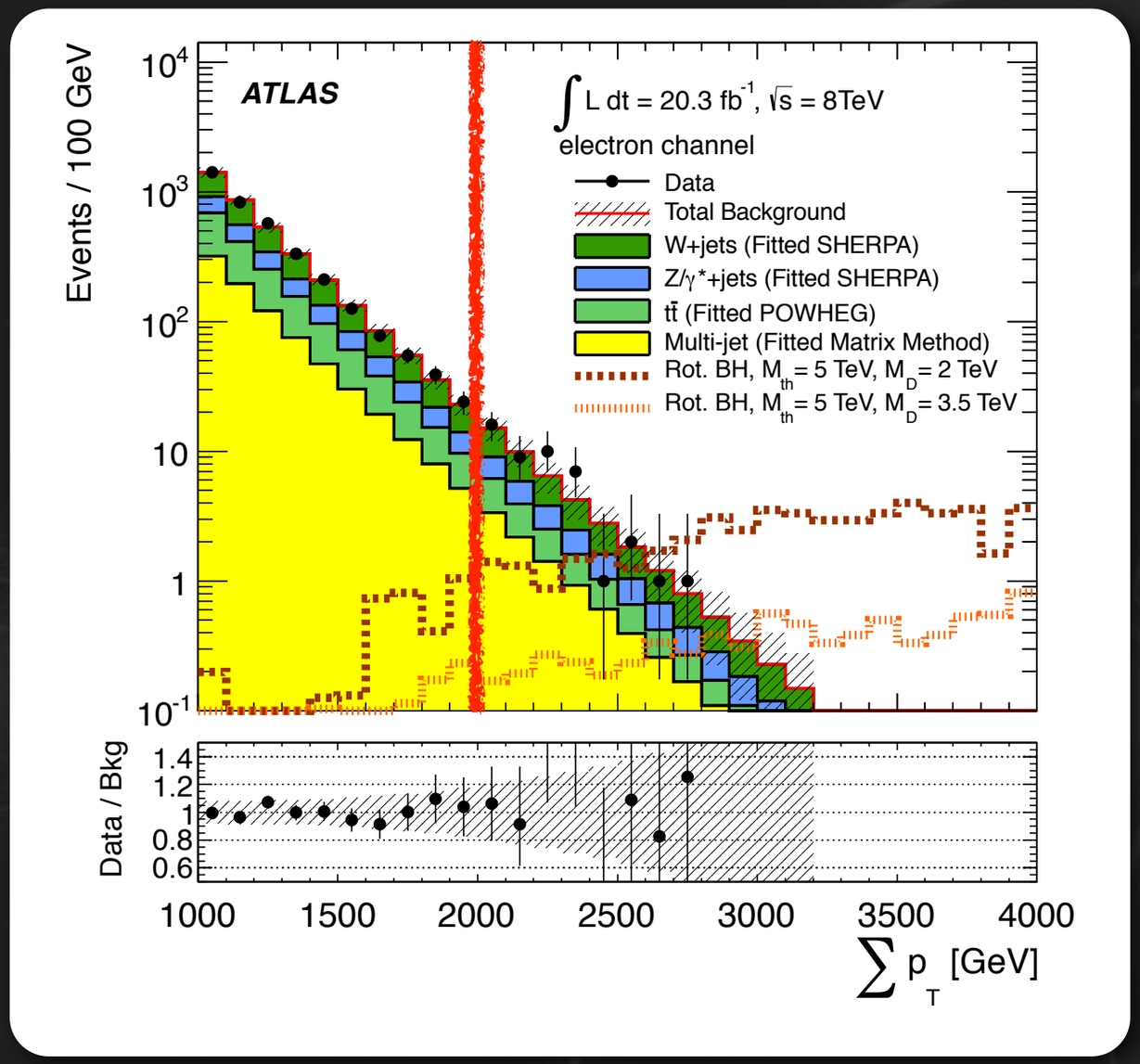
- Further extend this signature by requiring only one lepton, and large jet multiplicities (>2 high p_T final state objects)

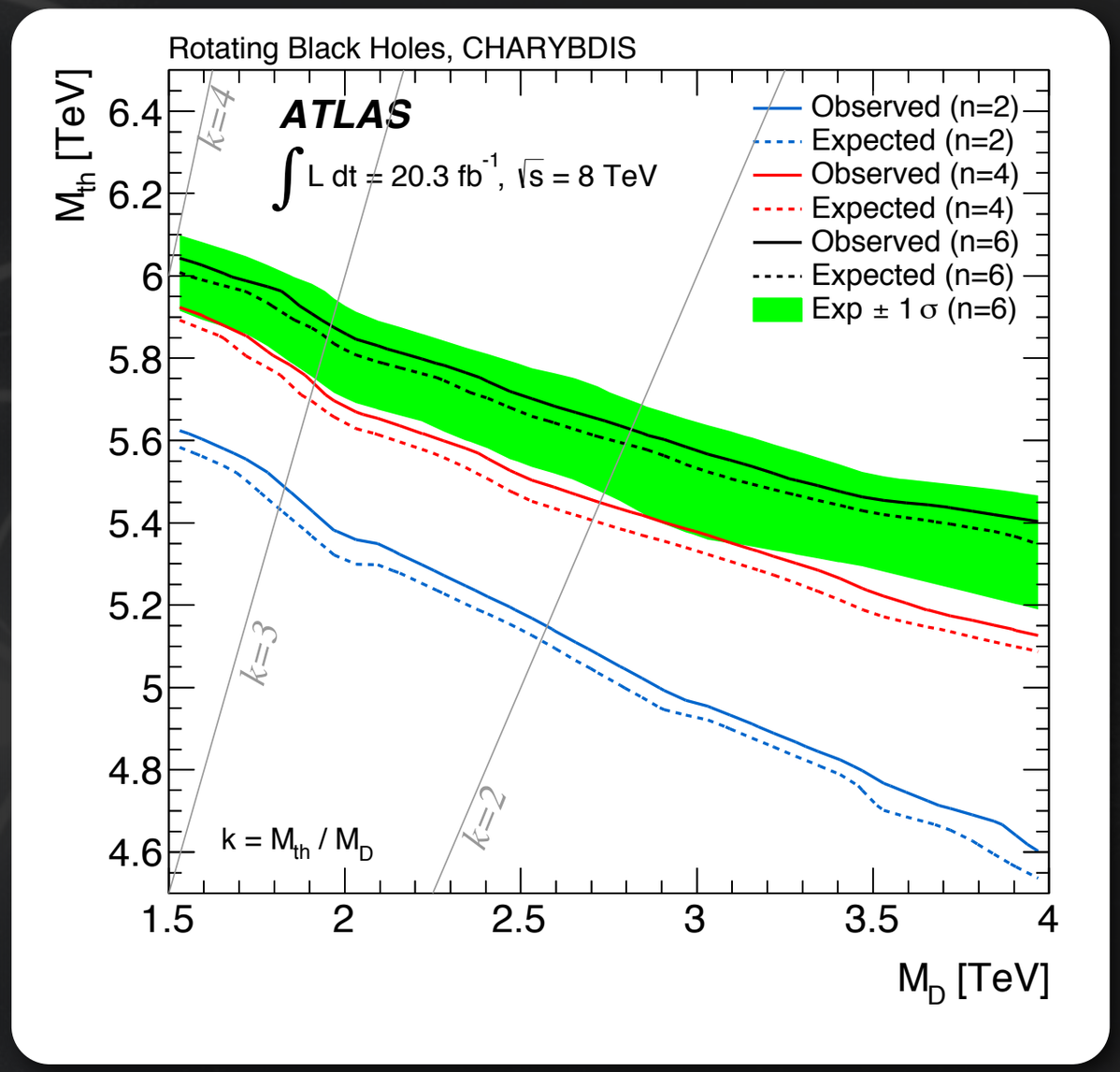
$$\sum p_{\mathrm{T}} = \sum_{i=\mathrm{objects}} p_{\mathrm{T},i}$$

- Signal selection:
  - $\sum p_T > 2000$ GeV
  - At least three objects with p_T>100 GeV
  - At least one lepton with p_T>100 GeV
- Using MC and data driven methods for background
- Interpolate via analytical function to very high p_T



BH→l+jets

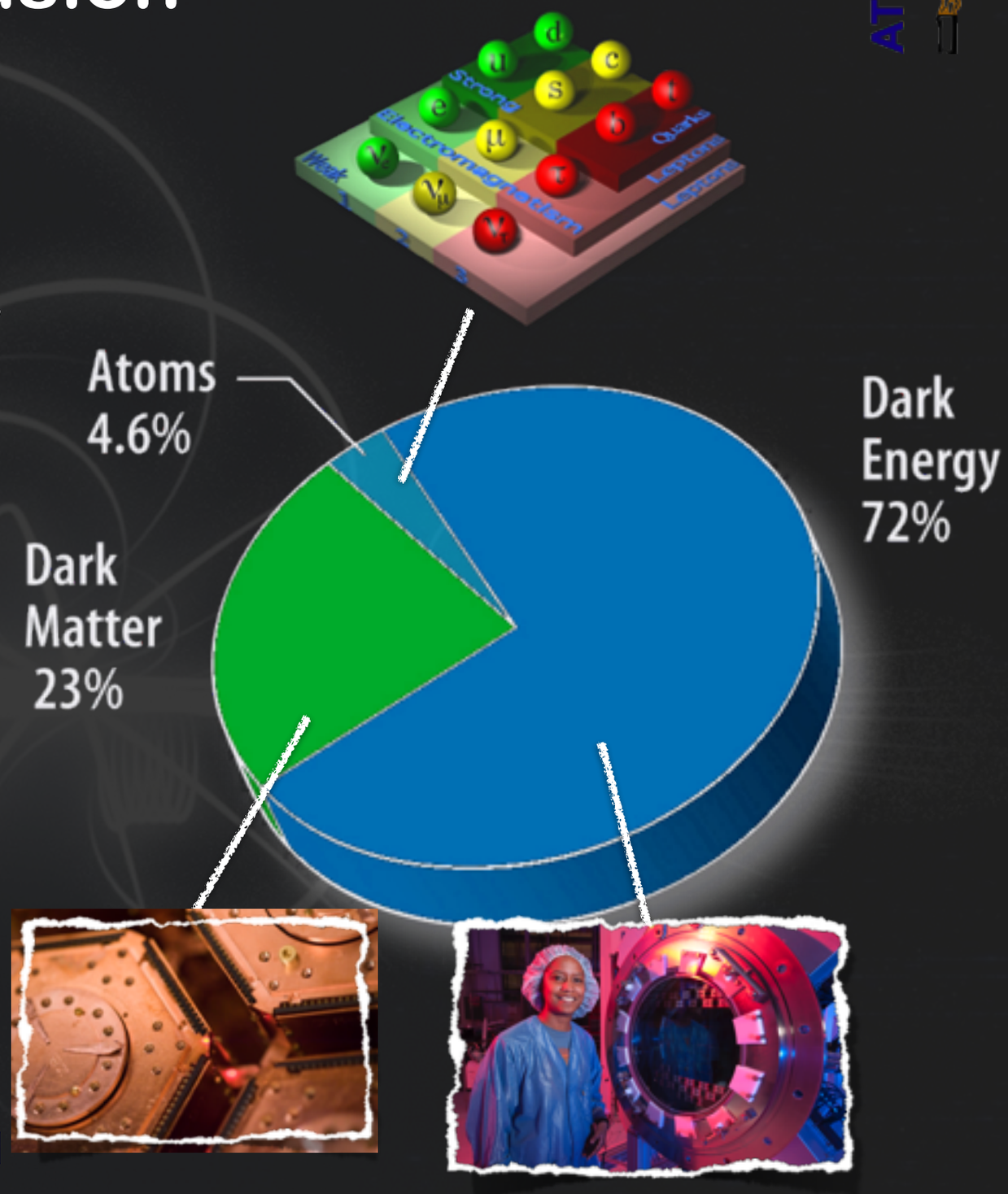




- Limits agree again well expectation
- Limits are set on wide range of black hole and string ball models
- Strongest existing bounds along with CMS

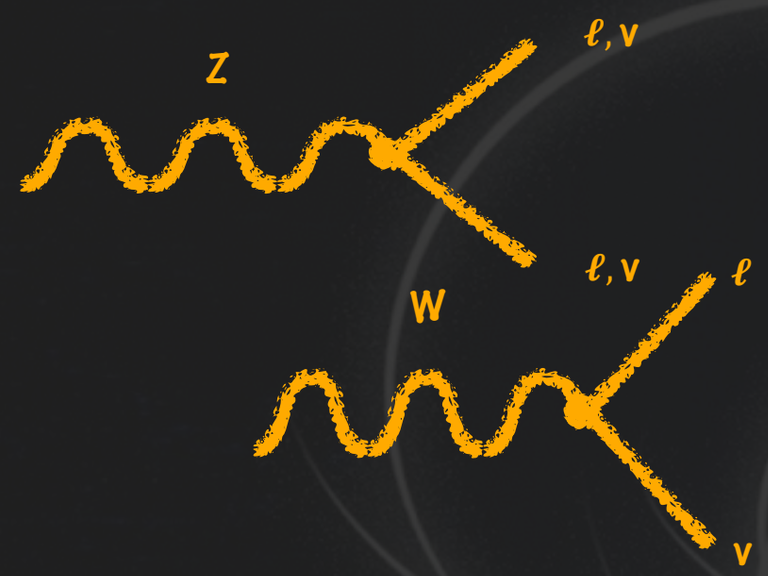
Conclusion

- At the LHC make a strong statement regarding ‘cosmological’ phenomena
- Using Effective Theories to explore new Frontiers
- Extending DM searches to unexplored low mass region
- Set strongest bounds on Extra Large Dimensions and Microscopic Black Holes
- Extending these analyses to new final states and probing wider phase space
- Use of new experimental tools (boosted jets)
- Looking forward to even higher energies

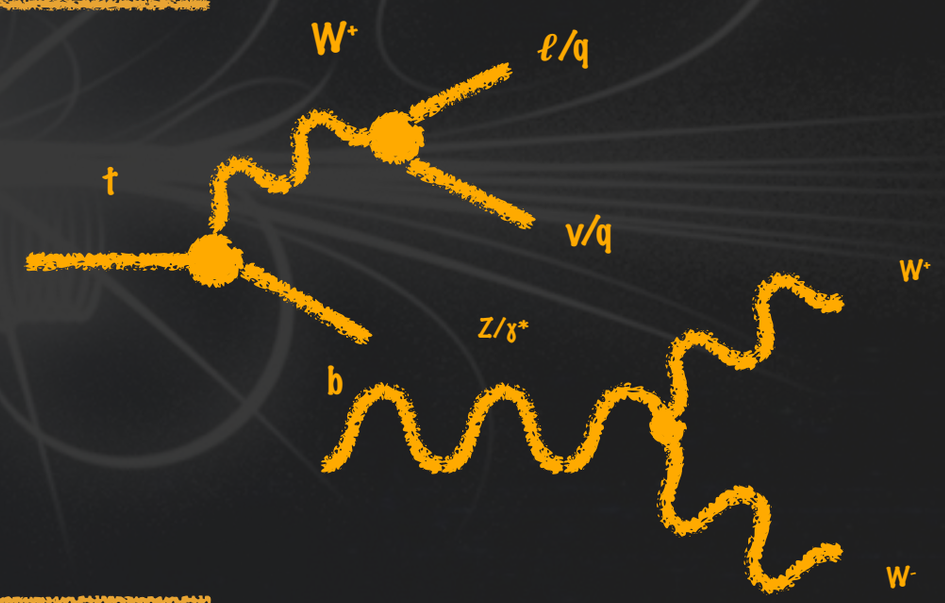


Backup

Typical Collider Backgrounds



V+jets: Data driven or MC with data corrections

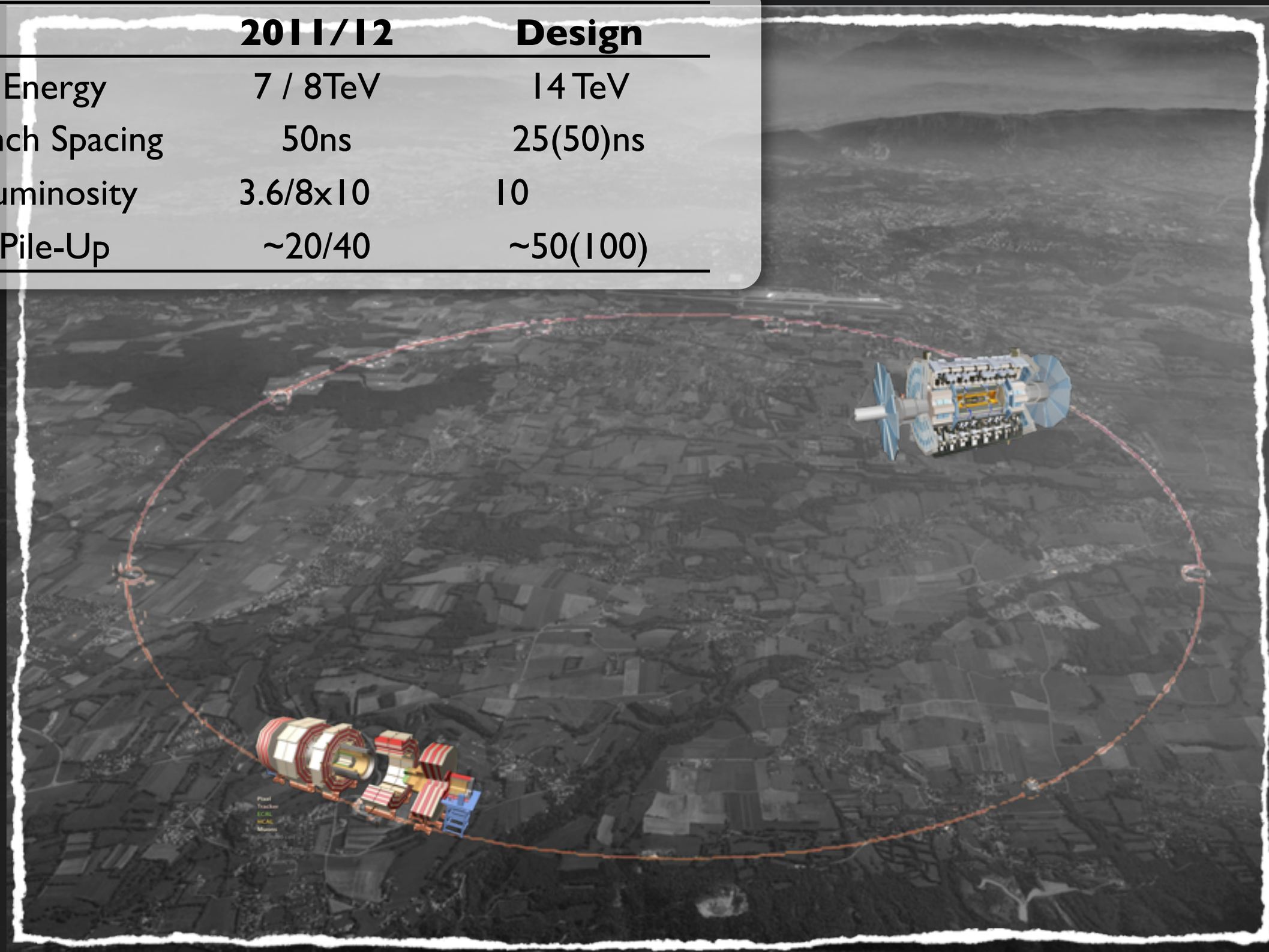


Diboson, Single Top, Top Pair: Simulations

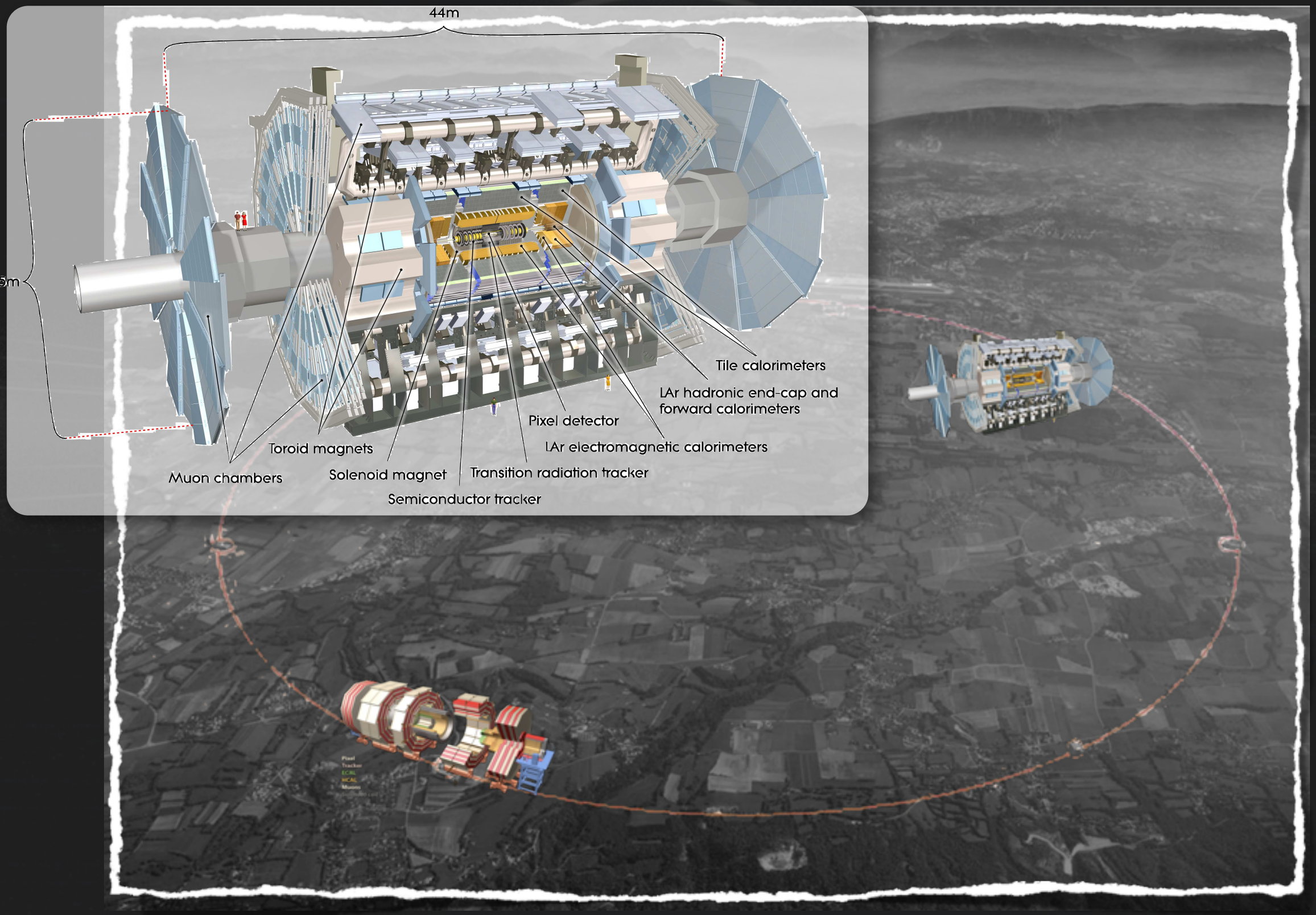
Multijet: Data driven

The LHC & ATLAS

	2011/12	Design
Energy	7 / 8TeV	14 TeV
Bunch Spacing	50ns	25(50)ns
Luminosity	3.6/8x10	10
Pile-Up	~20/40	~50(100)

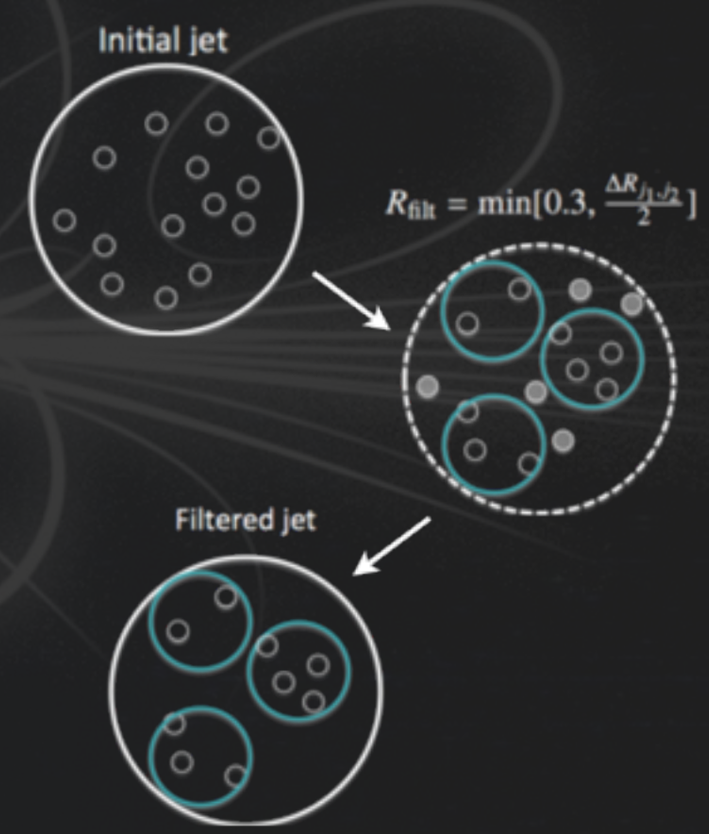


The LHC & ATLAS



Dark Matter with W/Z

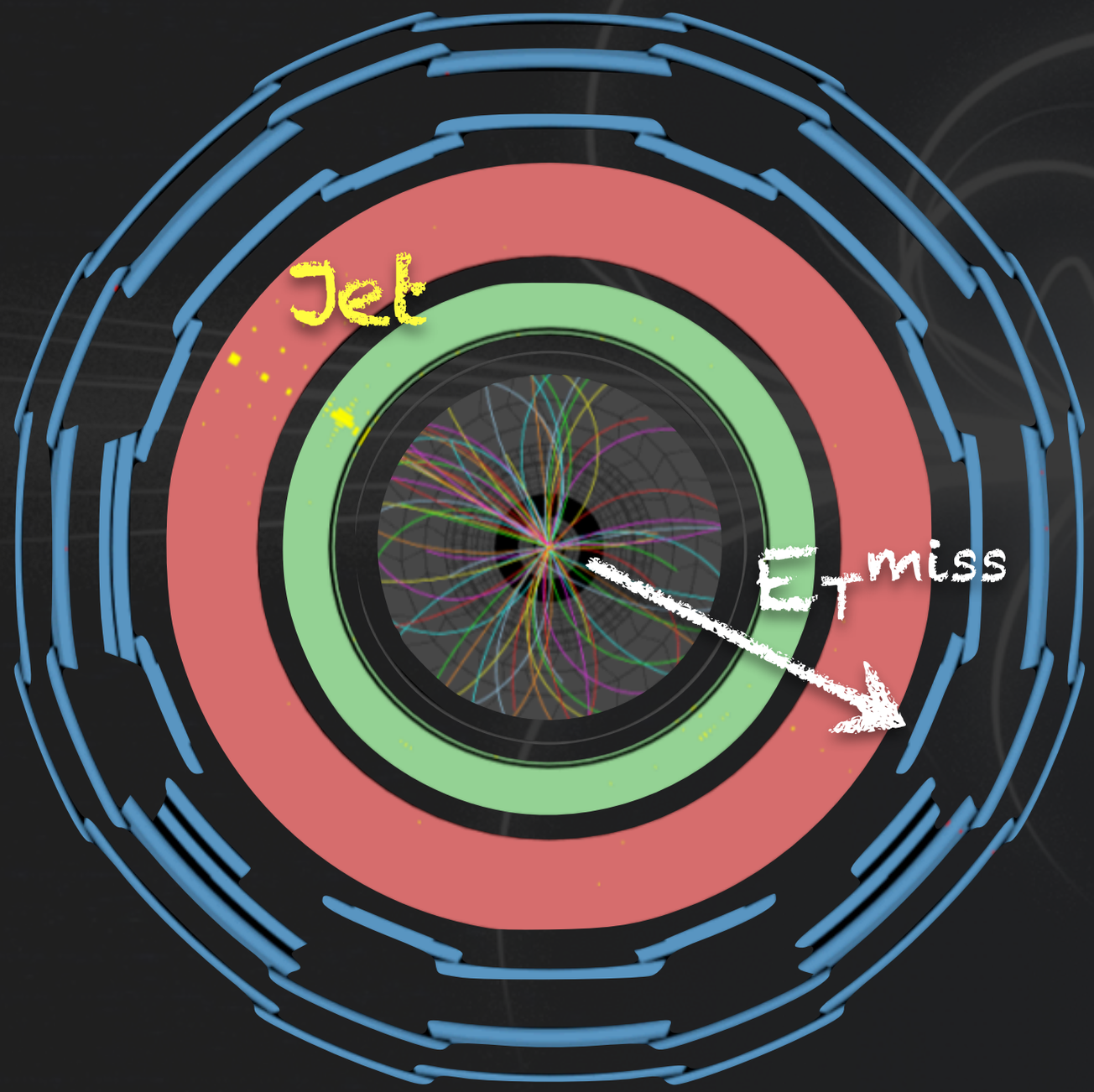
- **Jets boosted**, reconstructed as single large radius jet
- Using '**Cambridge-Aachen**' algorithm for jet reconstruction
  - p_T>250 GeV, |η|<1.2
  - 50 GeV < M_{jets}< 120 GeV
  - √(y)<0.4, where √(y)<min(p_T^1, p_T^2)
    $\Delta R_{1,2}$ / M_{jets}
    (balancing of two leading subjets)



Example of Present Searches

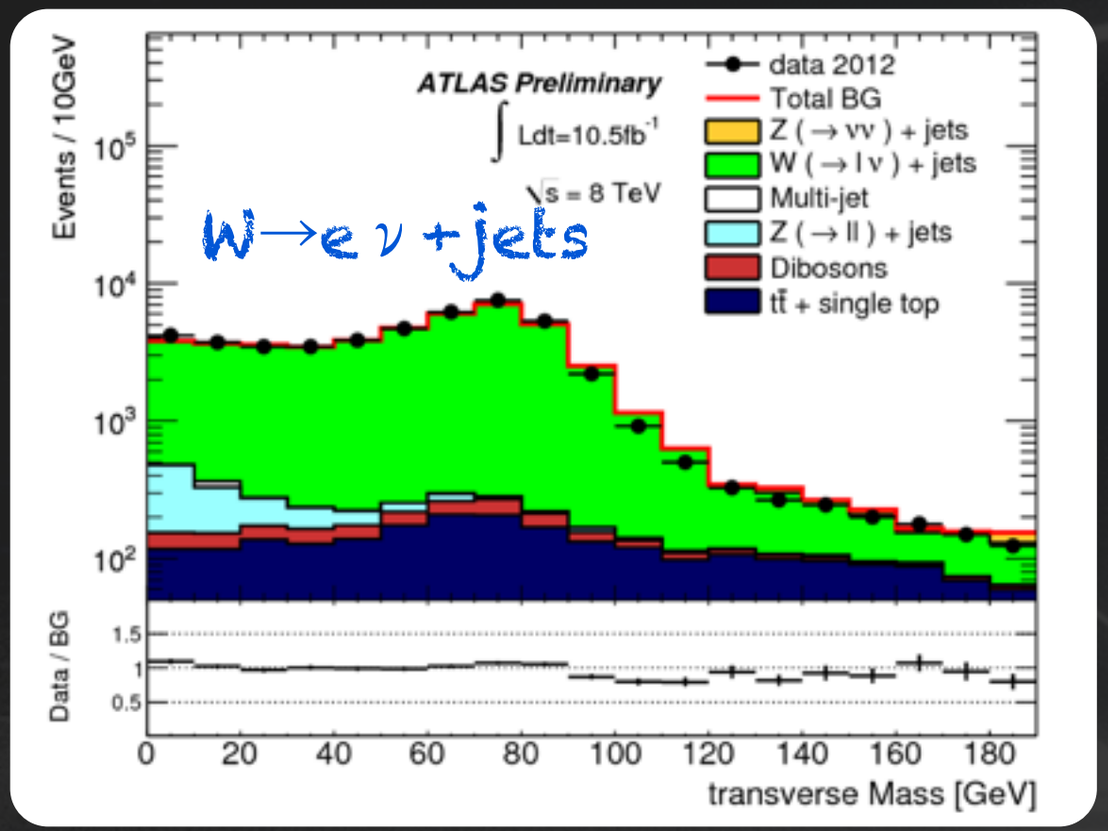
- **Mono-jet**

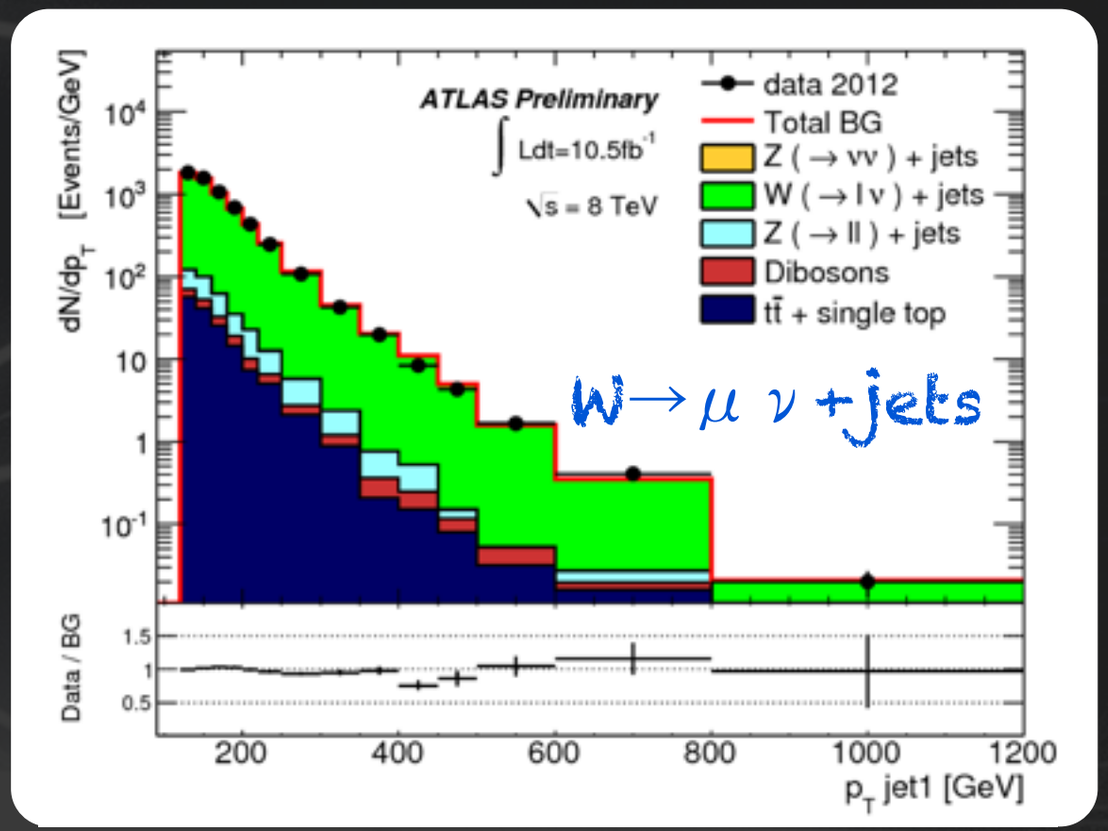
Selection Requirements

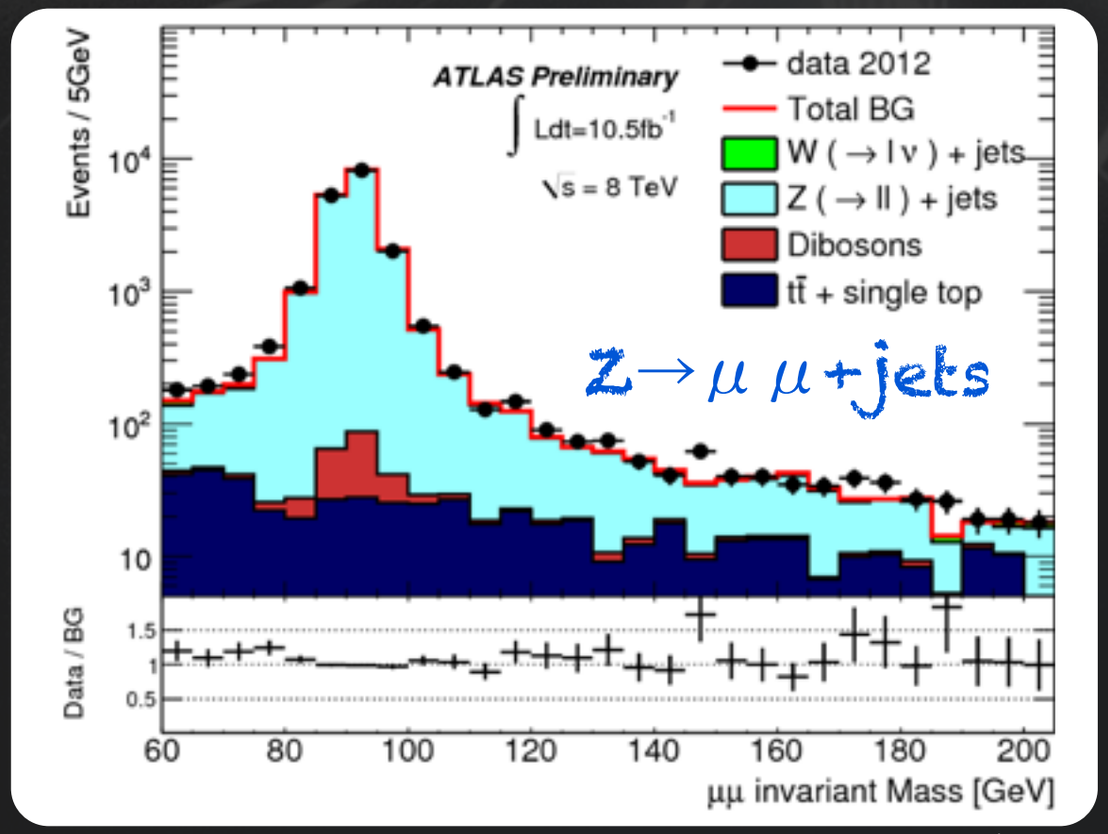


- E_T^{miss} trigger
- Monojet (8 TeV, 10.5 fb^{-1})
  - E_T^{miss} , p_T(jet) > 120, 220, 350, 500 GeV
  - 1 or 2 jets
  - $|\Delta\varphi(E_T^{miss}, j_2)|>0.5$
- ATLAS-CONF-2012-147

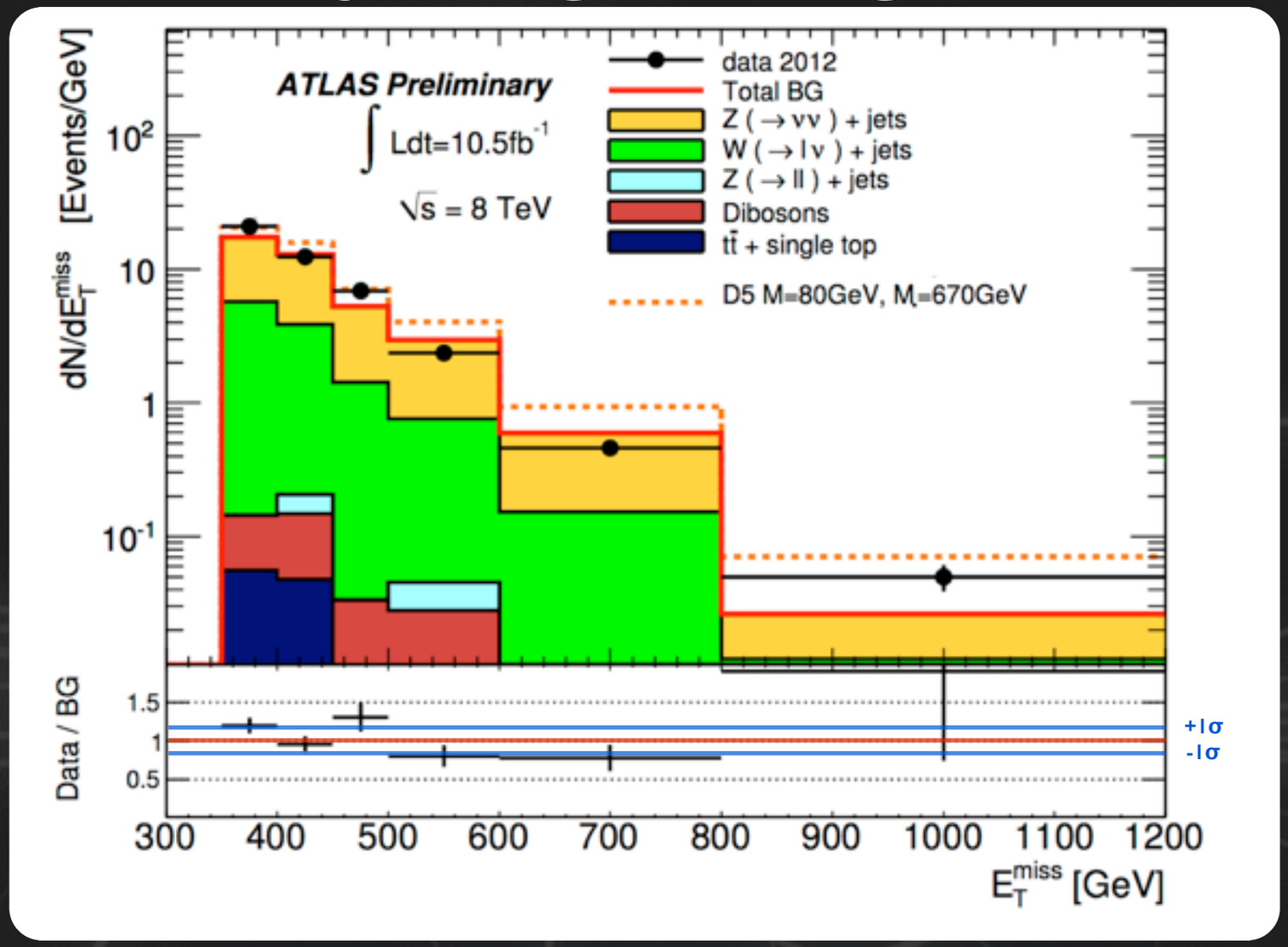
Validation Regions







Monojet Signal Region



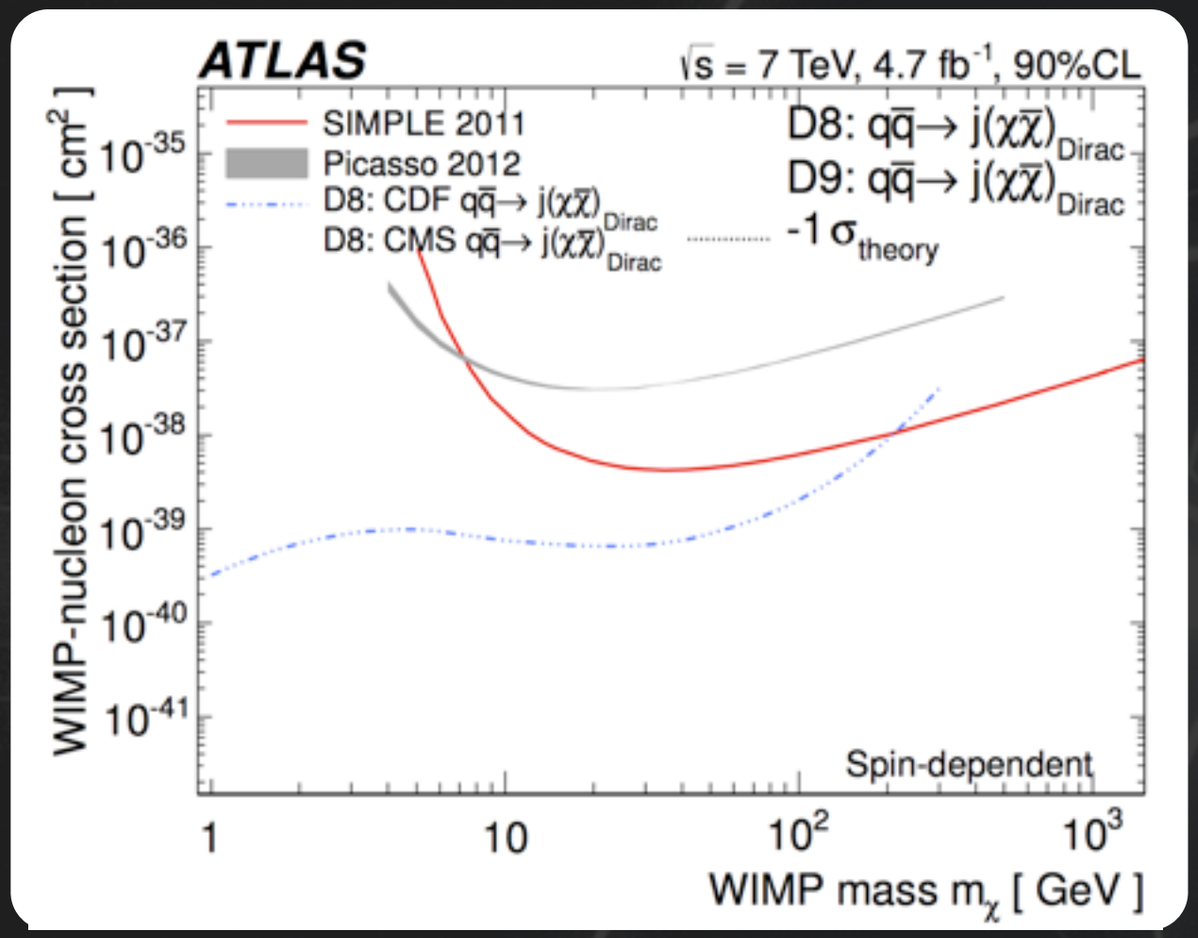
Yield

Exp. Bkgd	2180 +/- 171
Data	2353

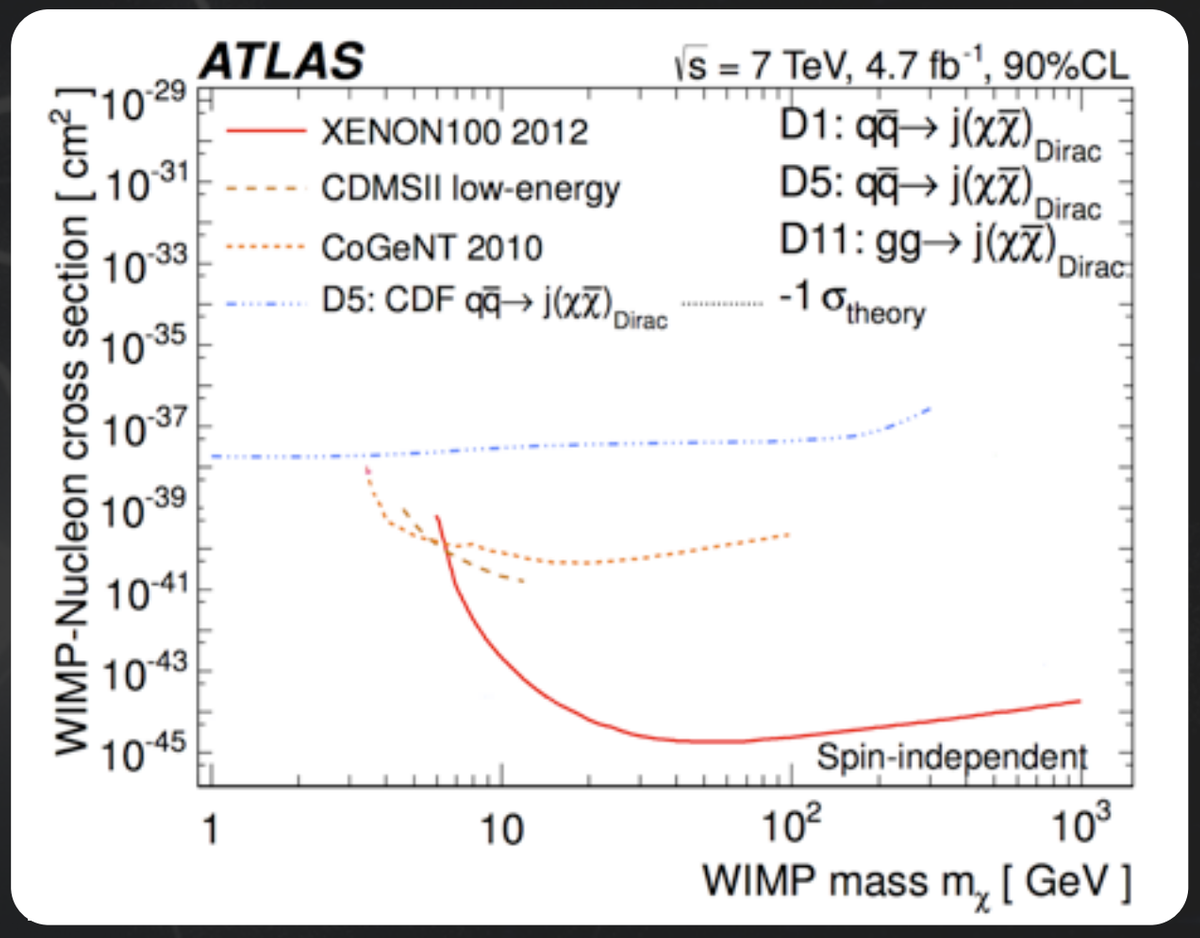
- Expected and observed number of events agree
- Set limits on coupling strength of heavy mediator

Direct Detection Limits

spin-dependent

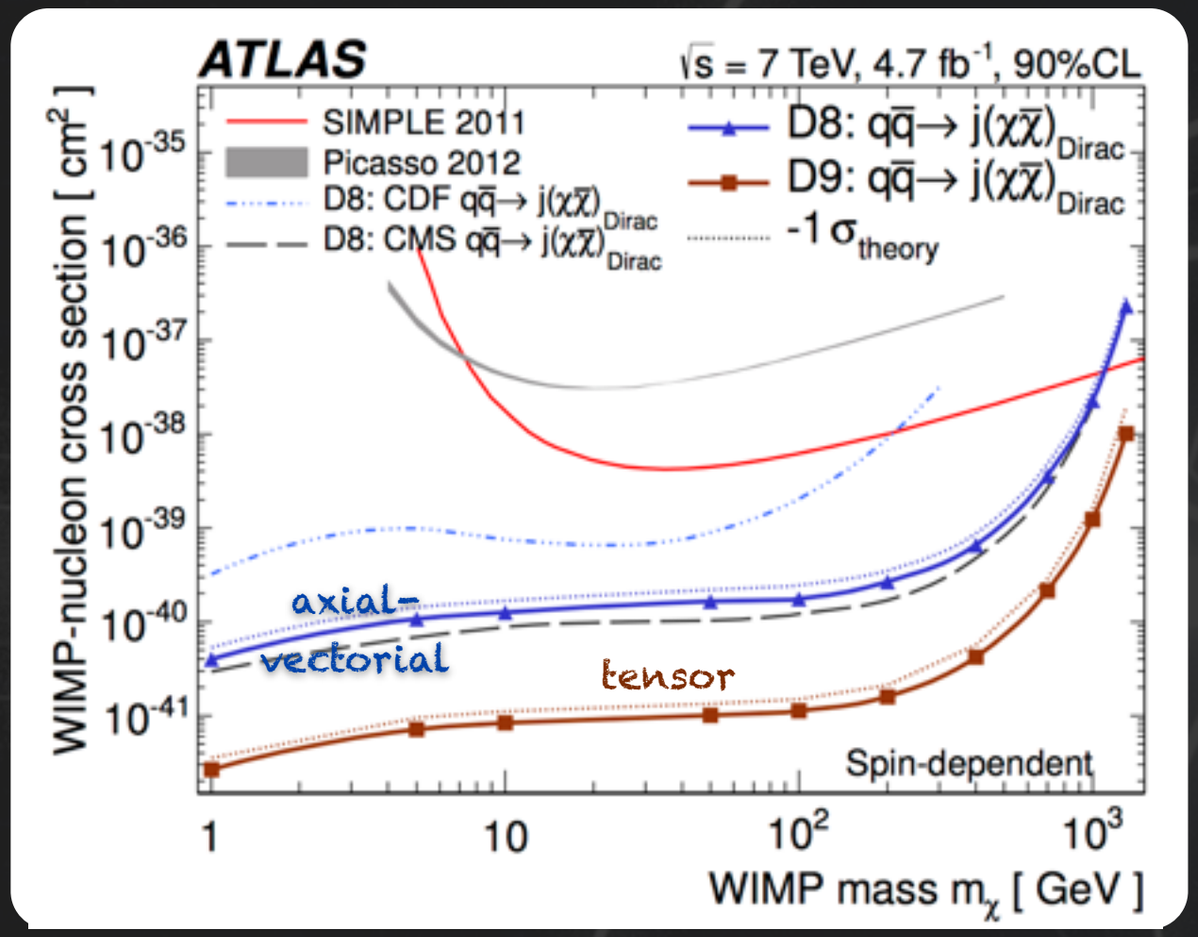


spin-independent

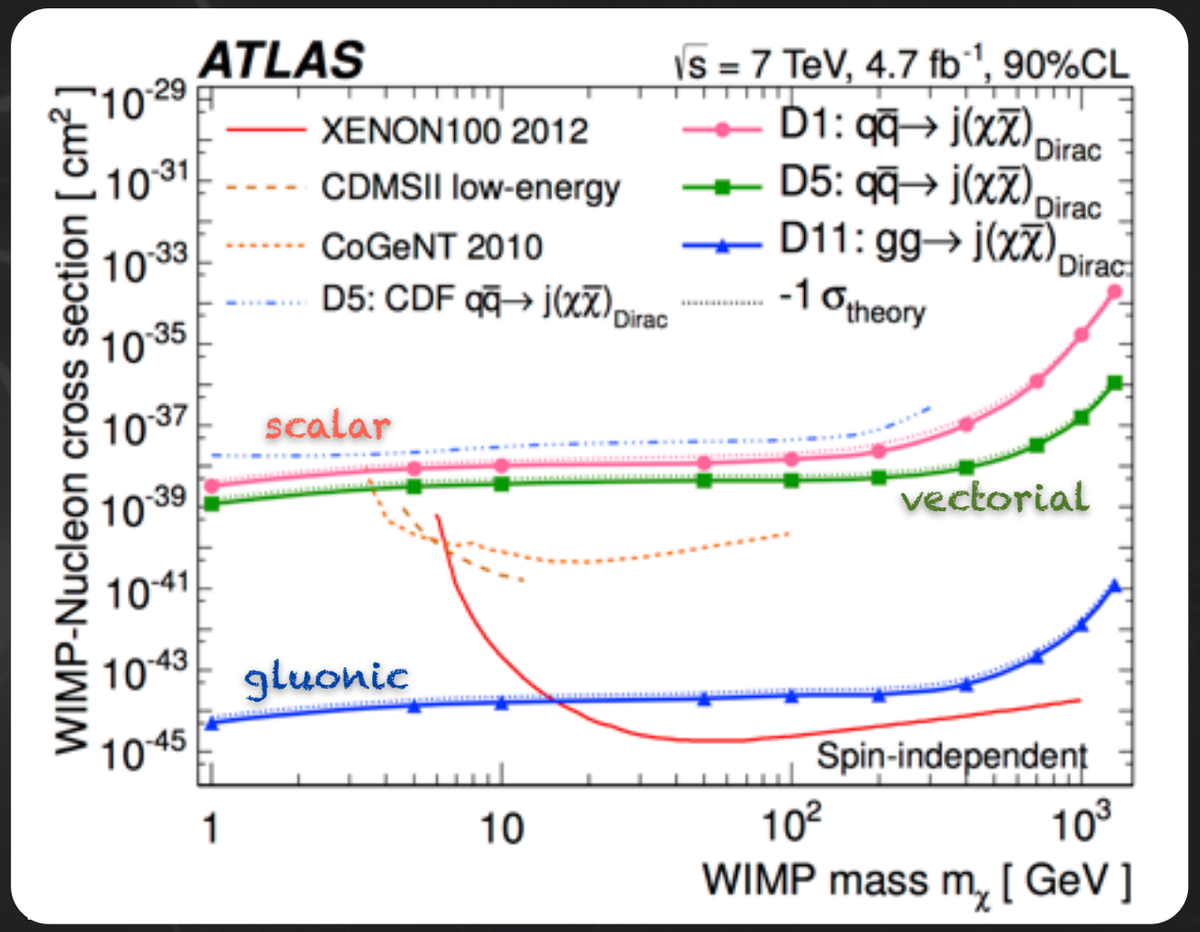


Direct Detection Limits

spin-dependent



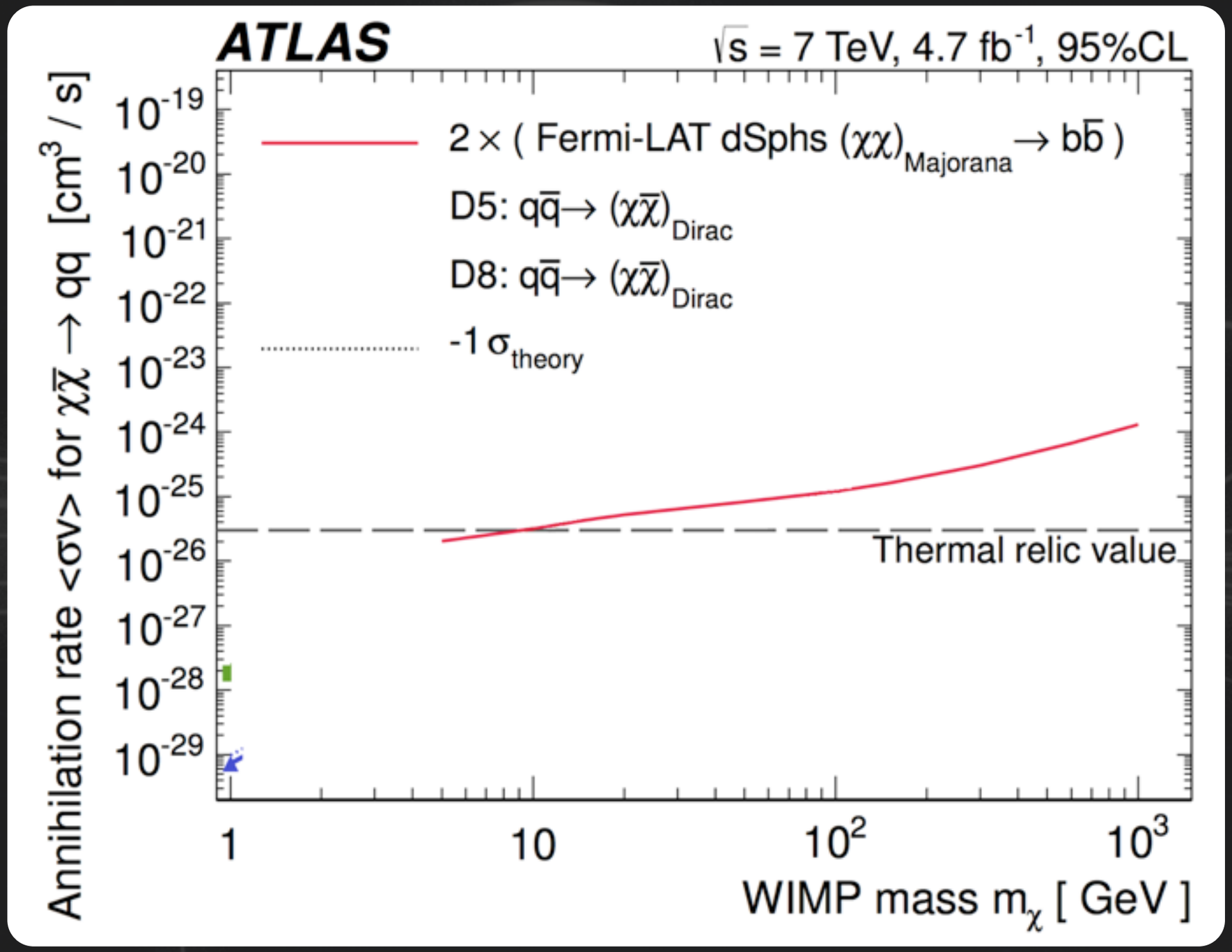
spin-independent



- **Spin-Dependent** (SIMPLE, Picasso)
  Atlas limits stronger for axial vector (D8) and tensor (D9) couplings

- **Spin-Independent** (XENON100, CDMSII, CoGent)
  Atlas limits stronger for scalar (D1) and vector (D5) at low m_χ

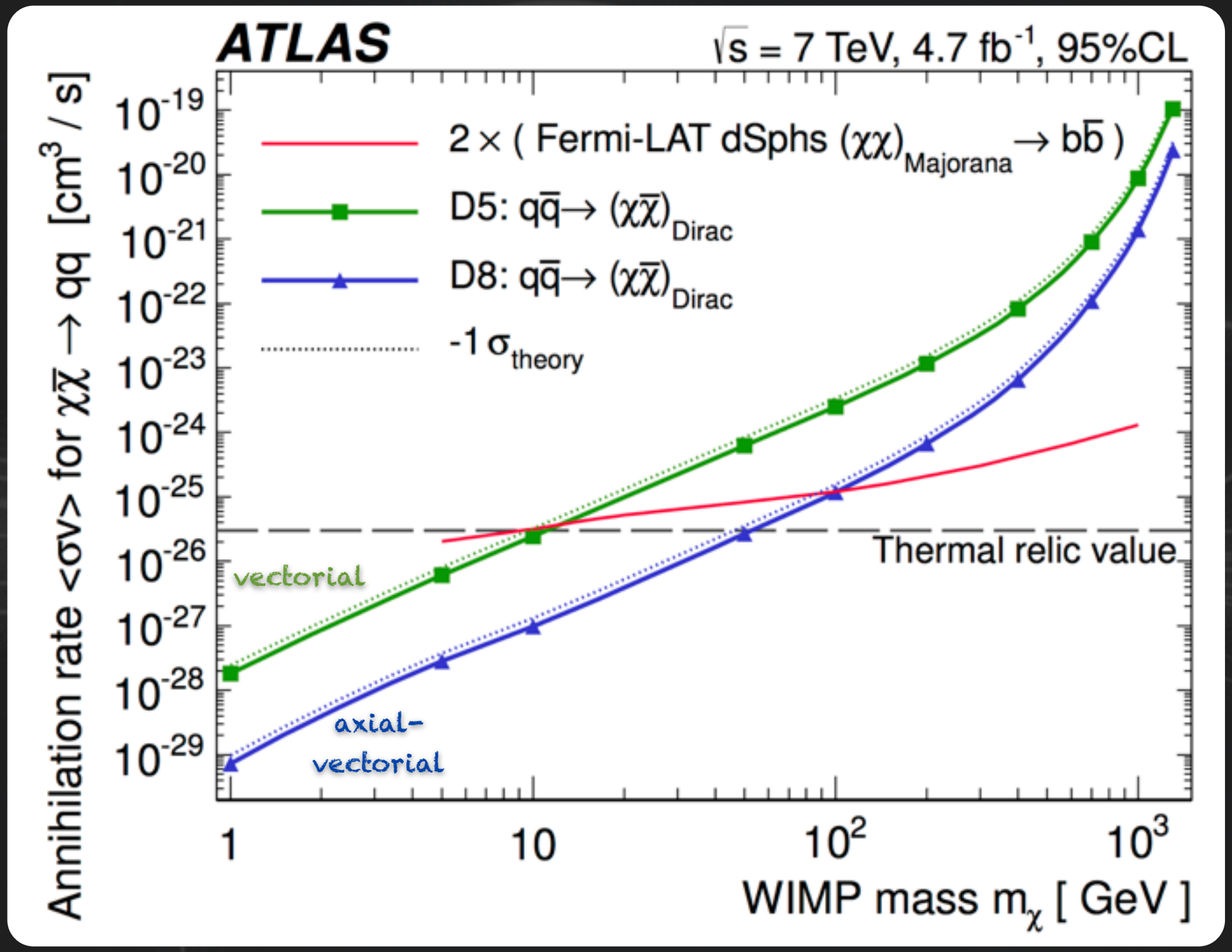
Indirect Detection Limits



- Comparing to annihilations from galactic high energy gamma ray observations by **FERMI LAT**

1109.4398v1, Fox et al.

Indirect Detection Limits

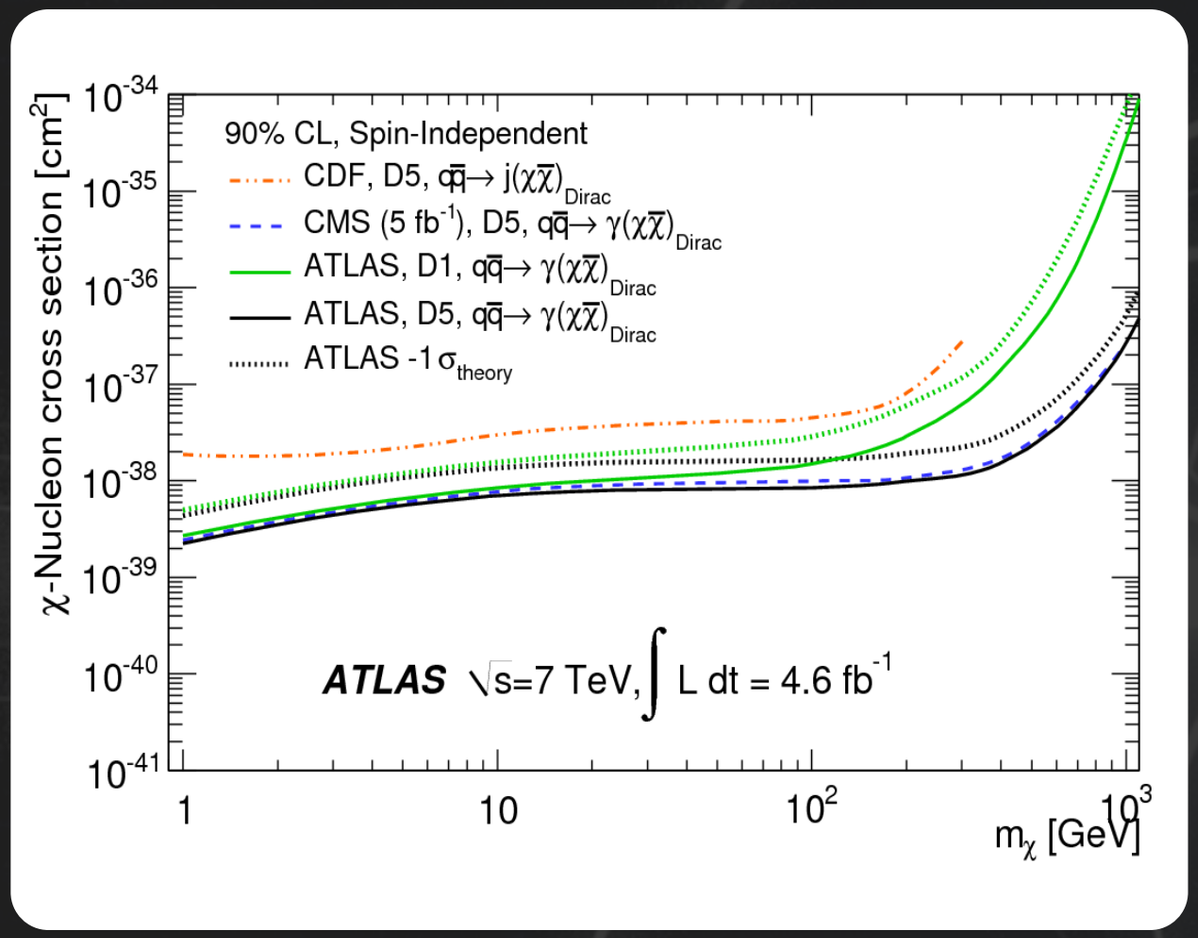


- Comparing to annihilations from galactic high energy gamma ray observations by **FERMI LAT**

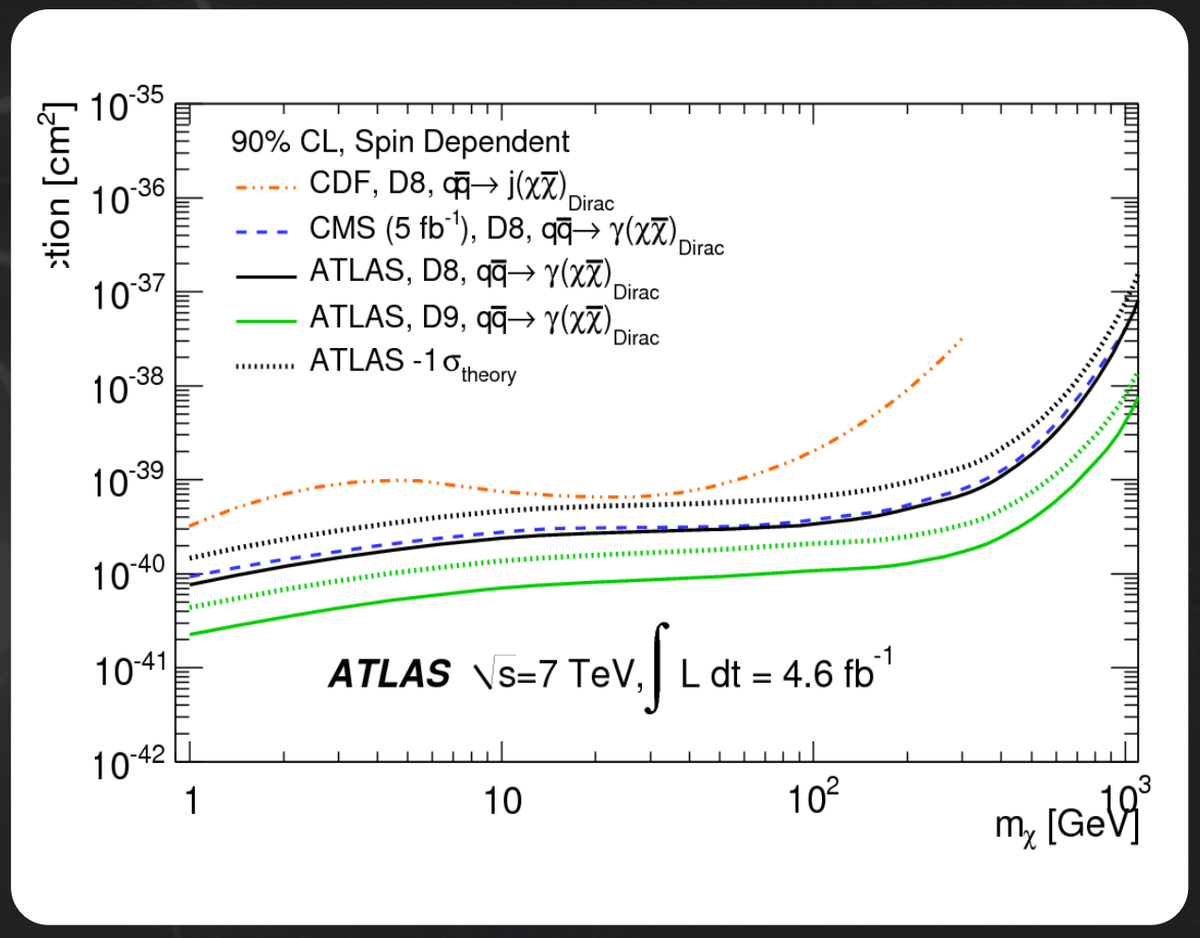
1109.4398v1, Fox et al.

Monophoton limits

spin-dependent

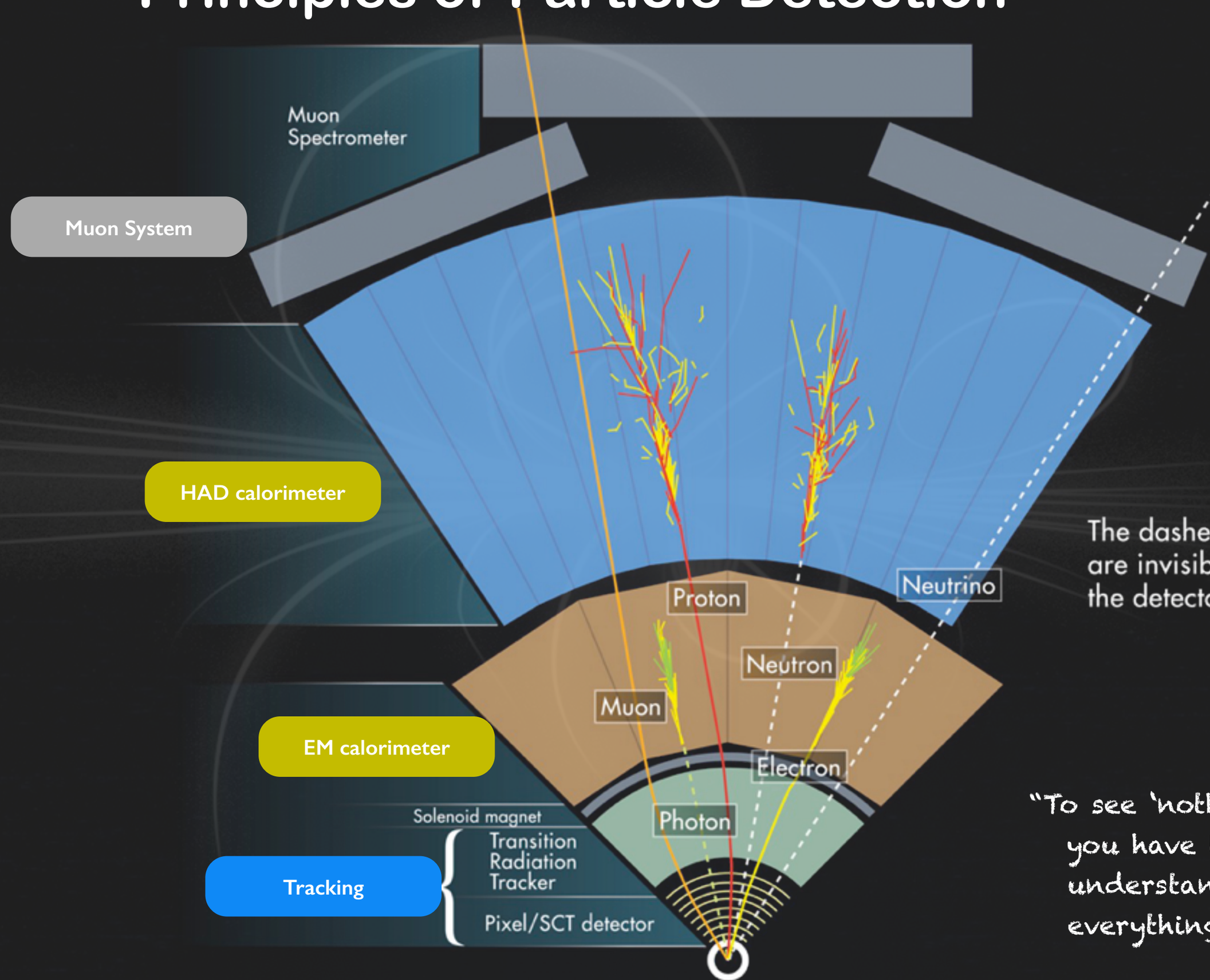


spin-independent



- **Cross sections for mono-photon suppressed** by ratio of strong and electromagnetic fine structure constants as well as a color factor
- **Relative size of excesses** in mono-photon vs. mono-jets is sensitive to whether the operator dominating the signal involves up or down quarks, due to their different electric charges
- Some operators (e.g. gg) **won't produce mono-photon** signals

Principles of Particle Detection



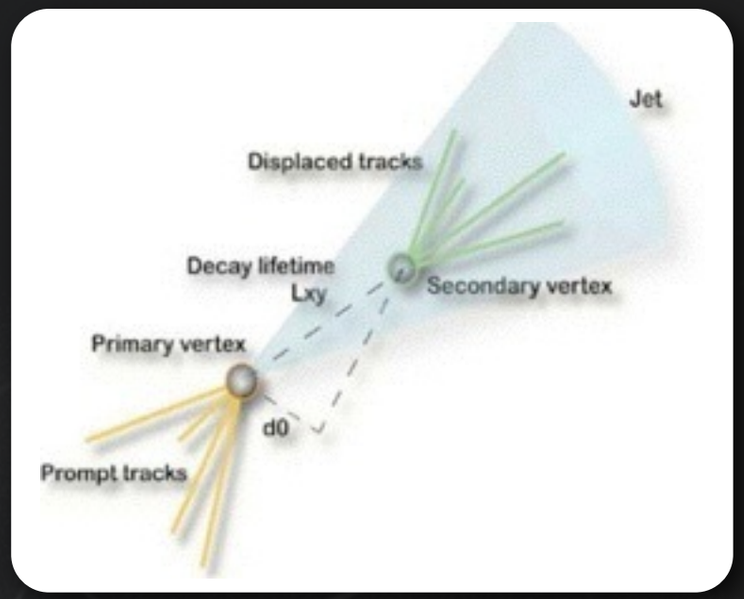
1 m

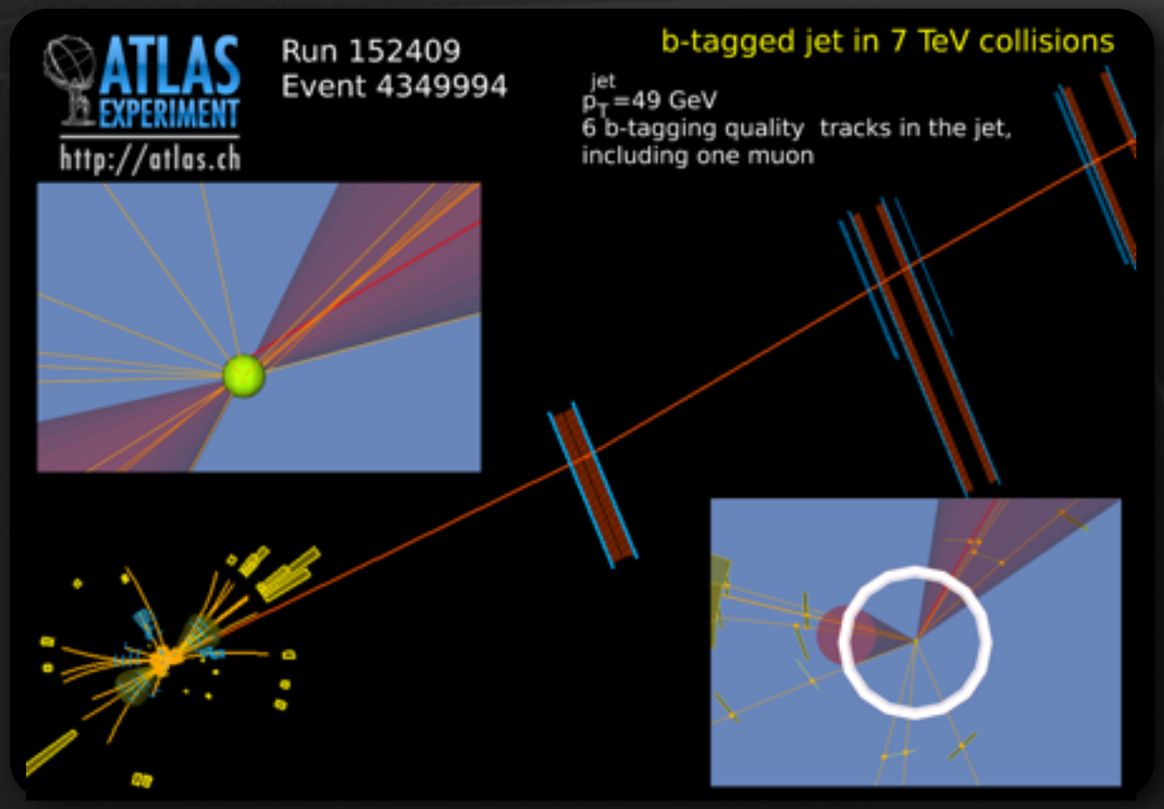
The dashed tracks are invisible to the detector

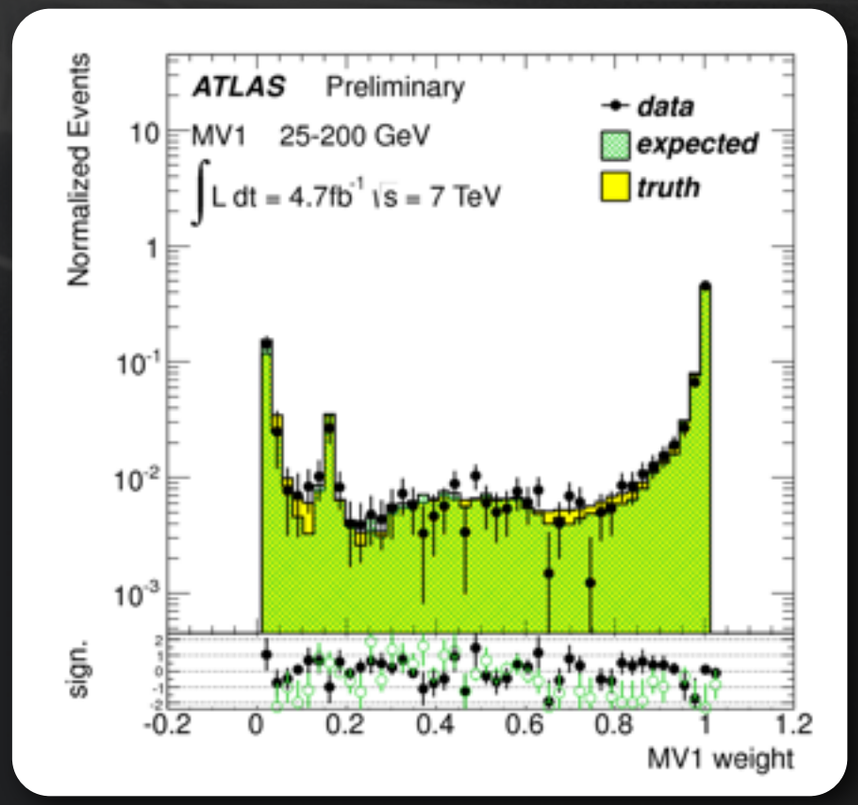
"To see 'nothing' you have to understand everything."

b-tagging in ATLAS

- Long life-time of b/c-hadrons → displaced vertex
- ATLAS uses multivariate method, exploiting information of displaced vertex, track impact and PV association probability
- Typically 50-60% efficient for 0.5-1.5% fake rate

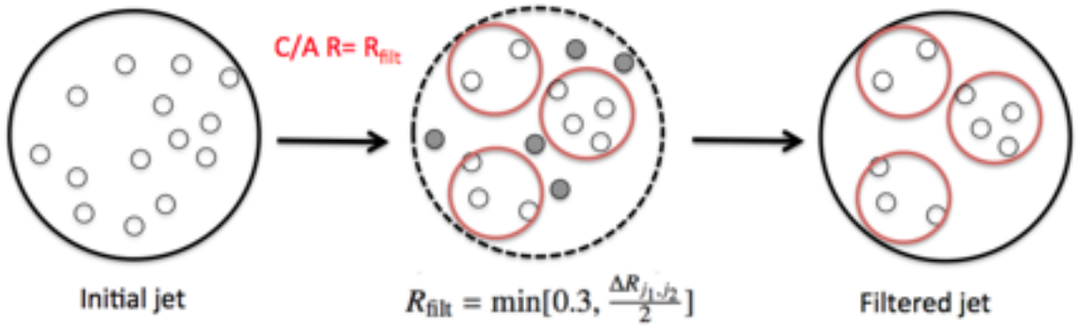




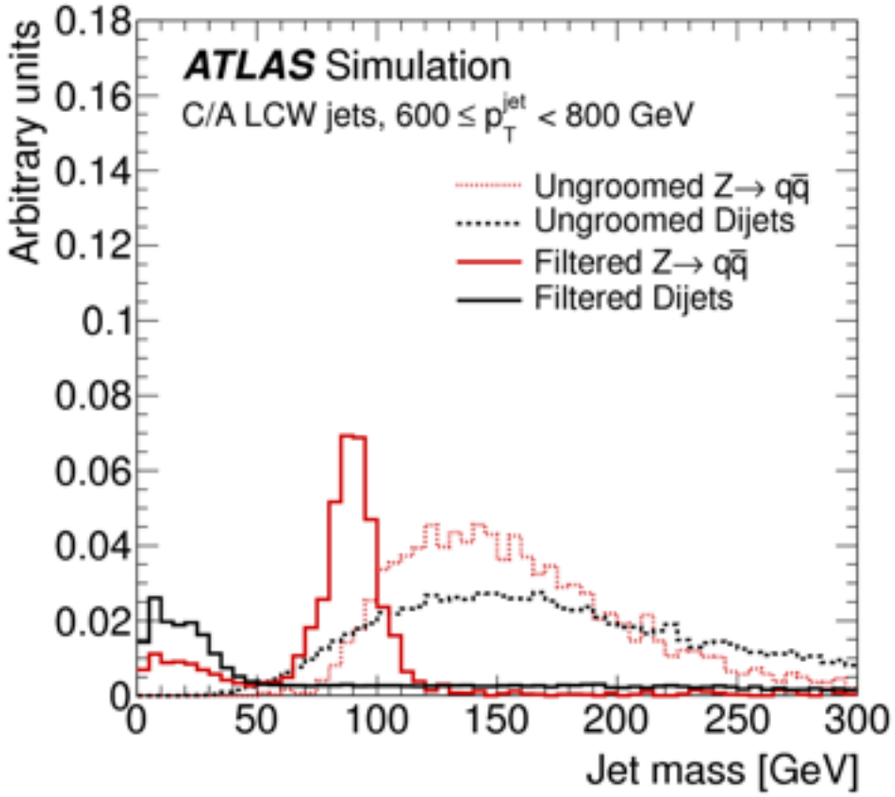


C/A Jets

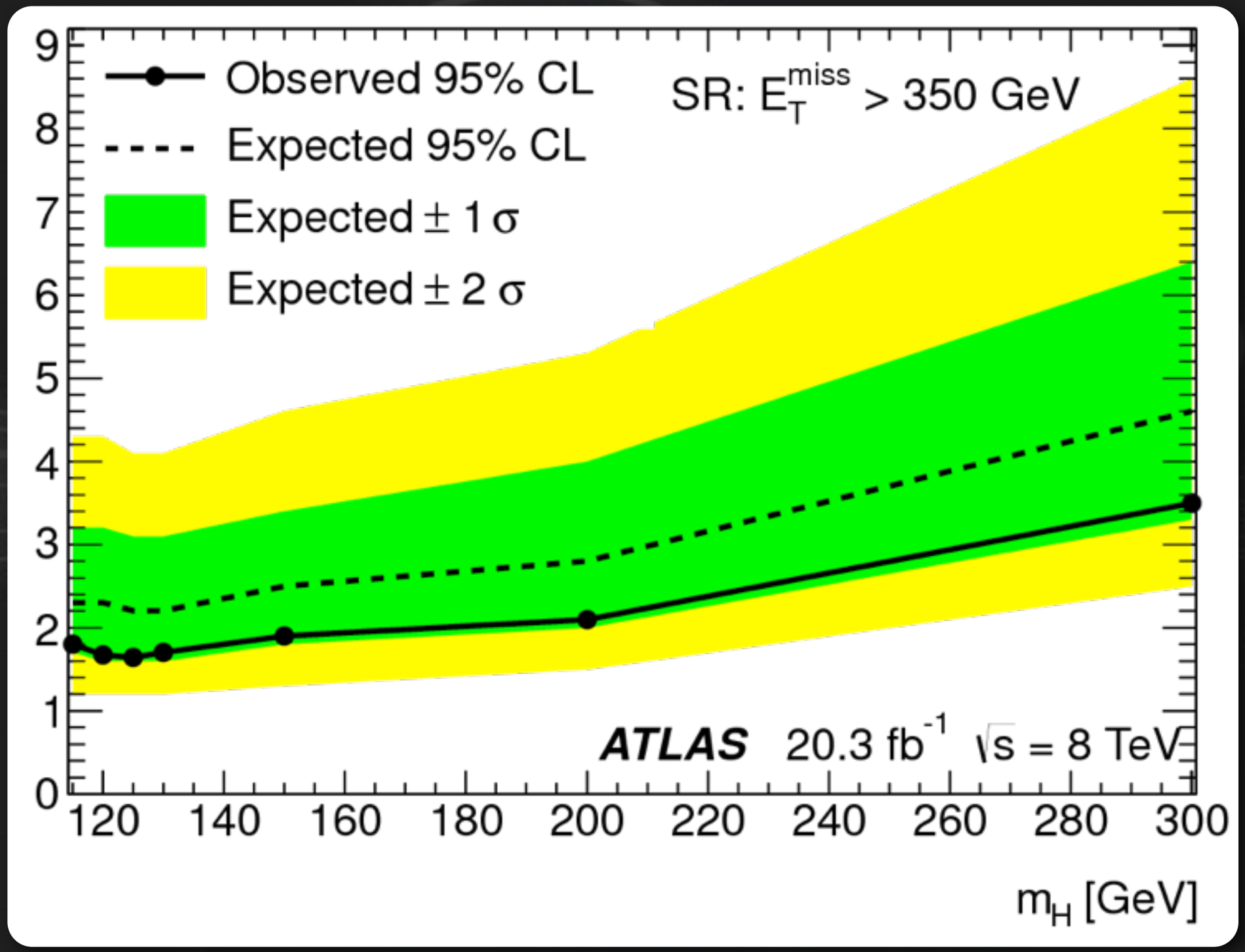
- For highly boosted objects objects, decay products have narrow dR distribution
- To recover efficiency & resolution:
  - Use a single large R Cambridge/Aachen jet encompassing all decay products
  - Revert last step of clustering and look for two low mass, symmetric sub-jets
  - Recluster constituents of sub-jets, keep 3 hardest new sub-jets
- Process greatly improves jet mass measurement, QCD separation



arXiv:1306.4945



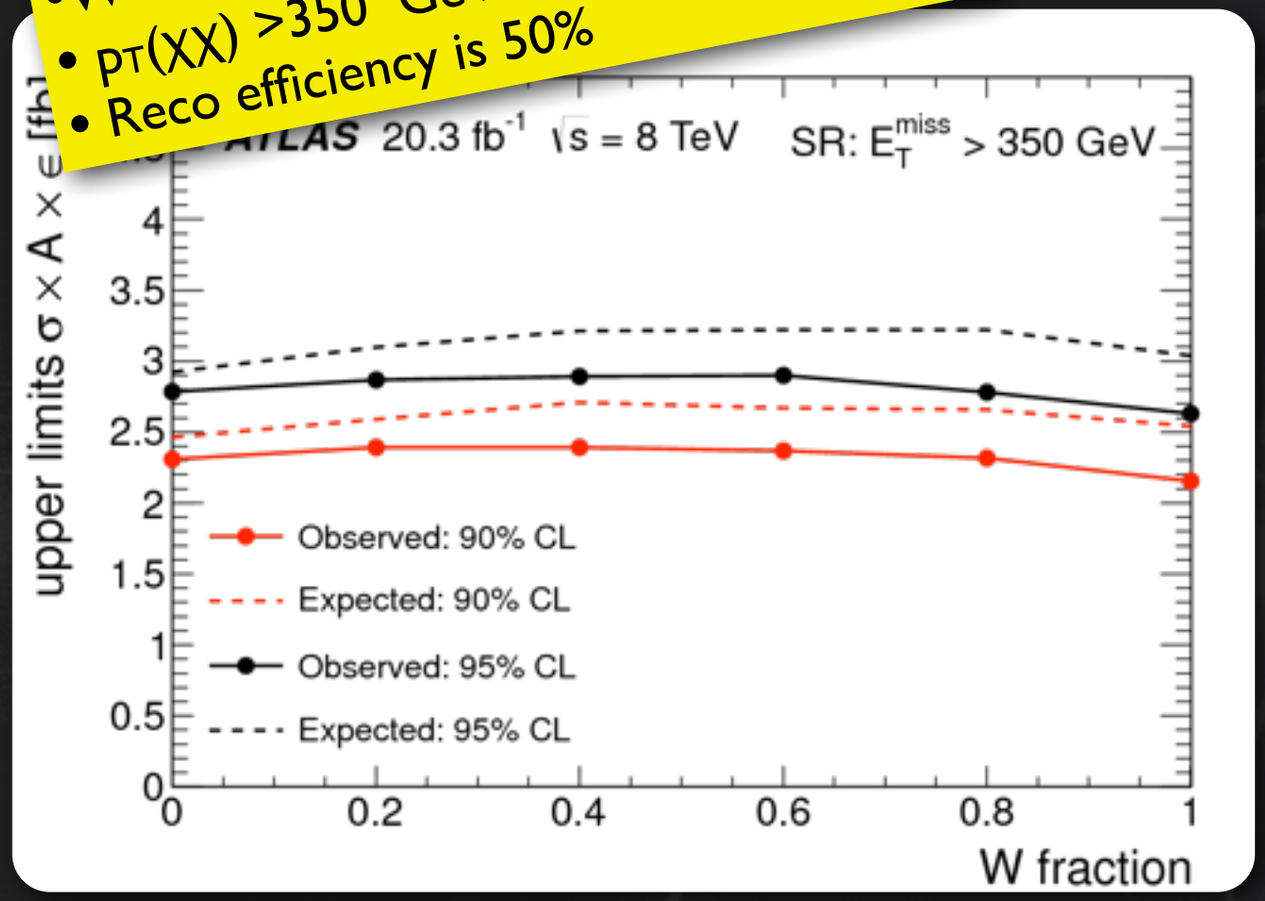
Limits on H→inv.

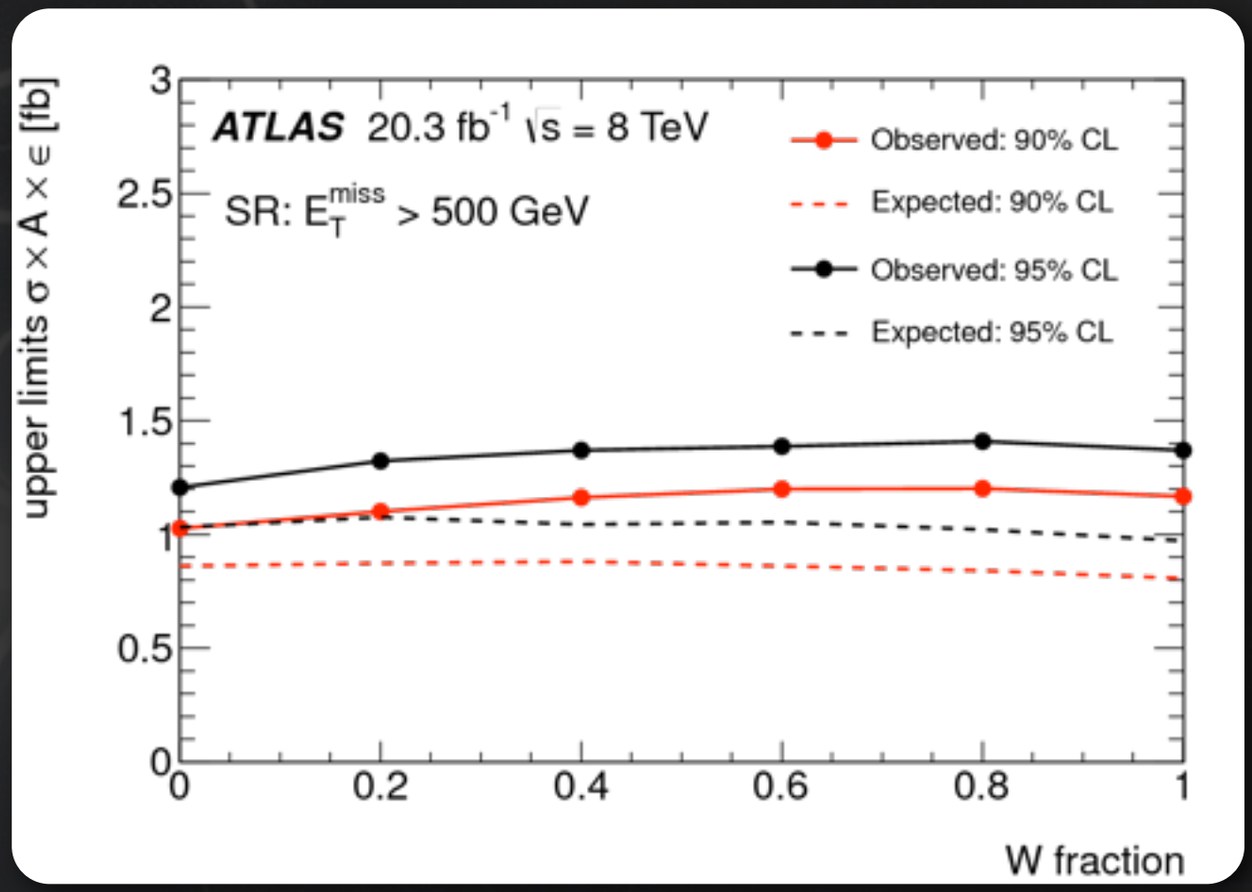


Limits on Higgs→inv

Model independent limits

Fiducial regions:
- W or Z p_T>250GeV, |eta|<1.2, $\sqrt{y} > 0.4$
- p_T(XX) >350 GeV or 500 GeV
- Reco efficiency is 50%





Model independent limits as function of W-boson fraction