The increasing complexity of searches for dark matter in ATLAS – from *Z* bosons to *b*-quarks, and beyond

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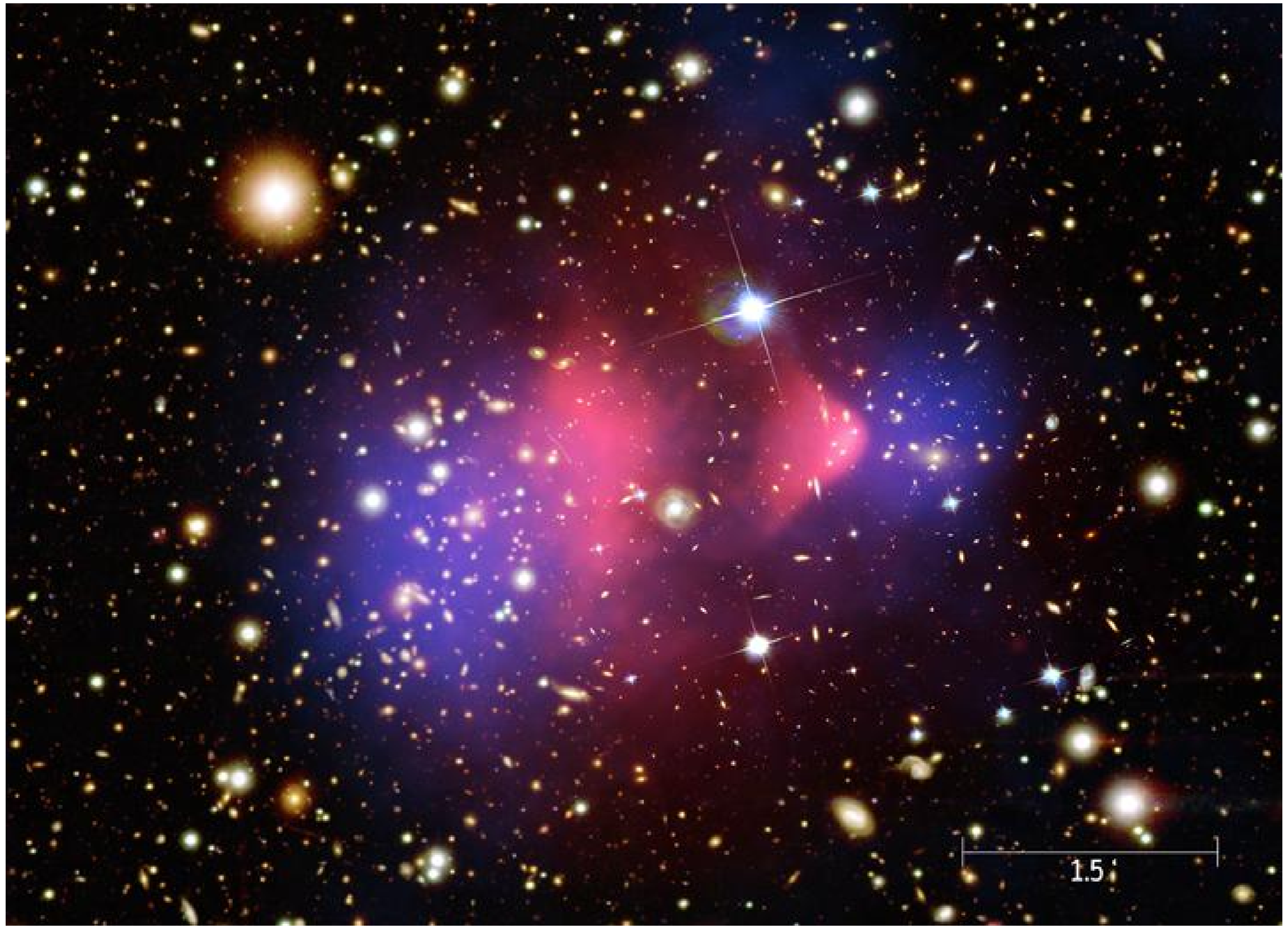
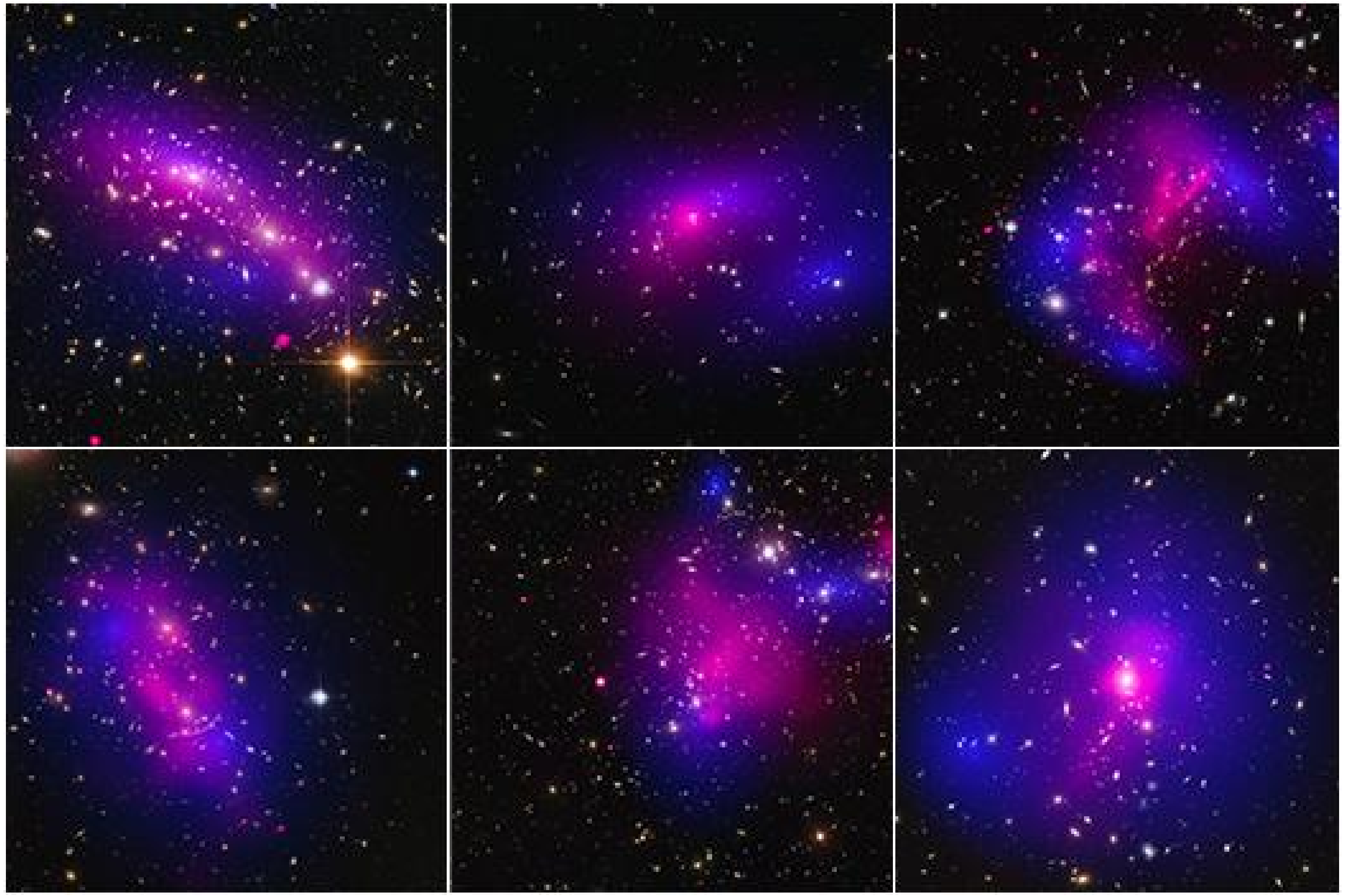
Are we sure about Dark Matter?

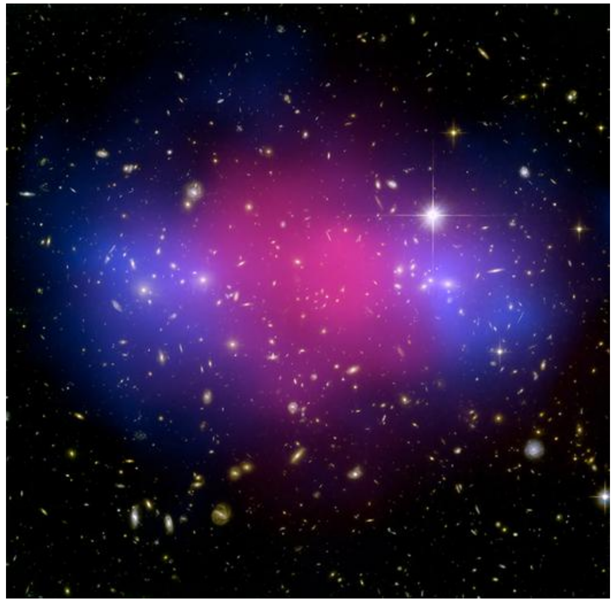


- The Bullet Cluster
- This is my least favourite evidence for dark matter in astronomy (sorry!)
- Can one example prove a systematic overabundance of material in the universe? Can it determine the nature of that material?

Bullet Cluster continued



http://chandra.harvard.edu/press/15_releases/press_032615.html



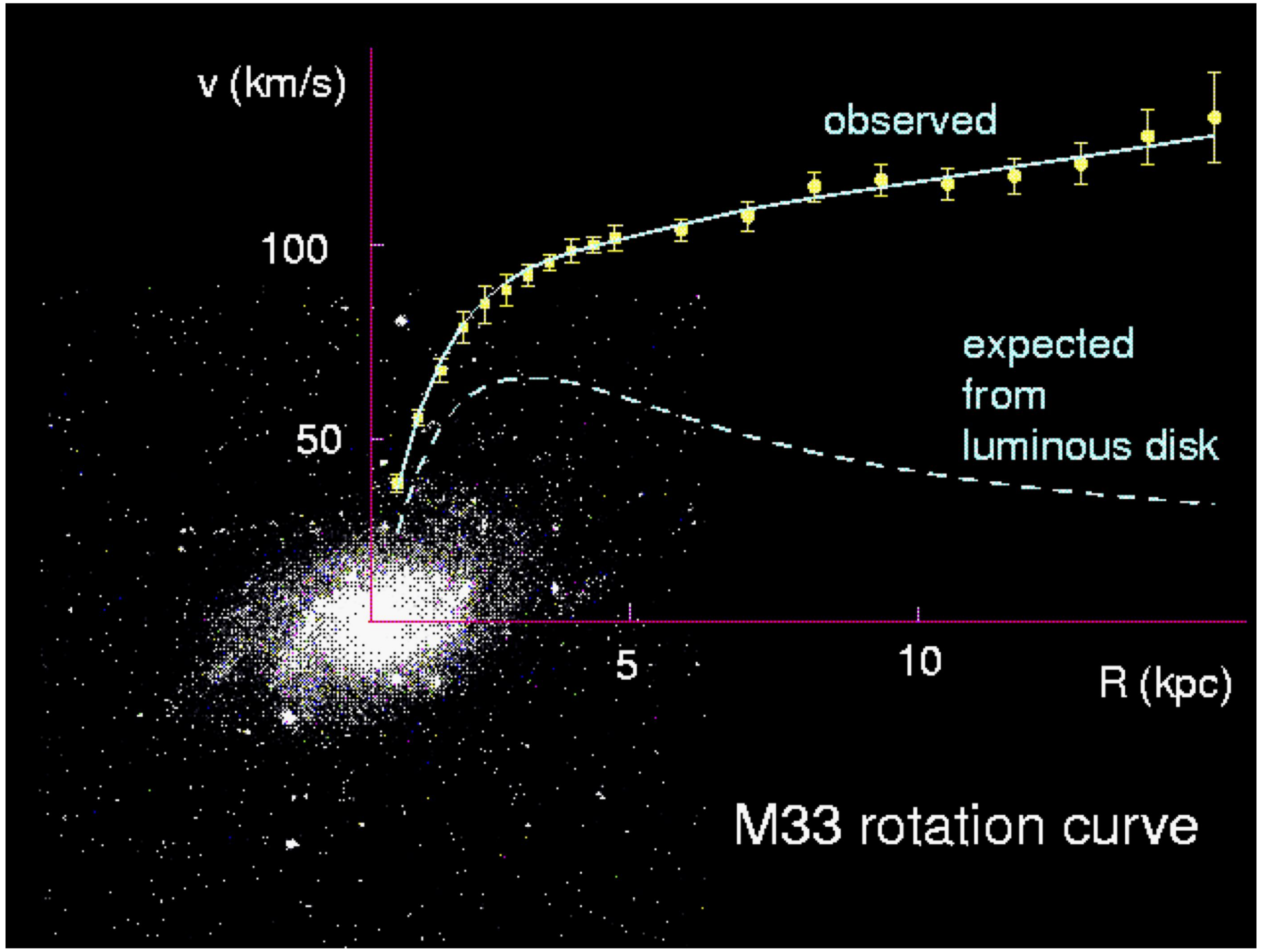
- Actually, there are a lot of colliding clusters like the bullet cluster.
- 72 similar clusters being studied by NASA & Chandra
- Giving a more systematic look at dark matter distributions on cluster scales

Galactic rotation curves

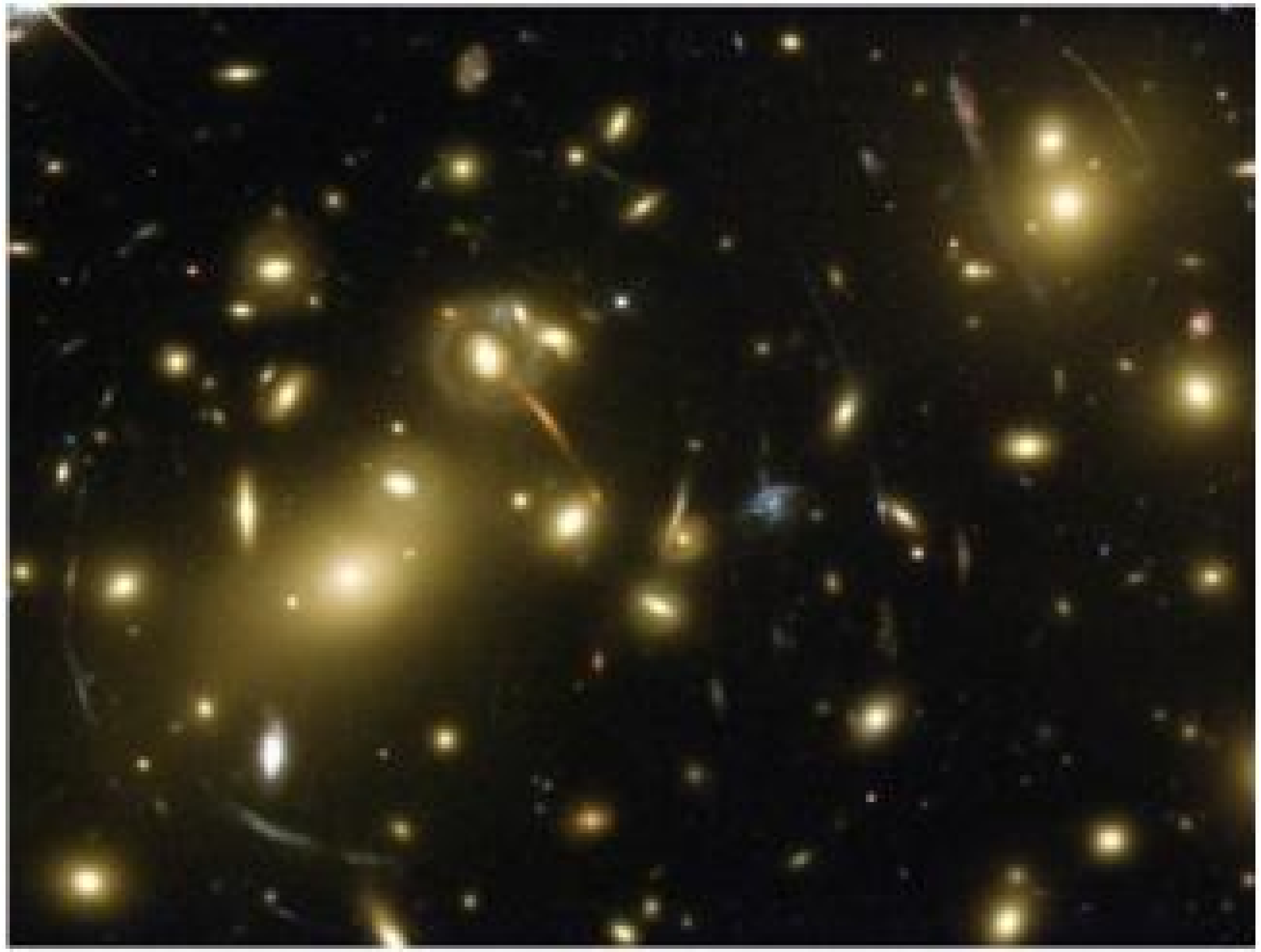
- As a random thought analogy:

  Think about riding your bike around a roundabout – the faster you go, the more grip (force) you need to keep you from being thrown out of the roundabout at a tangent.

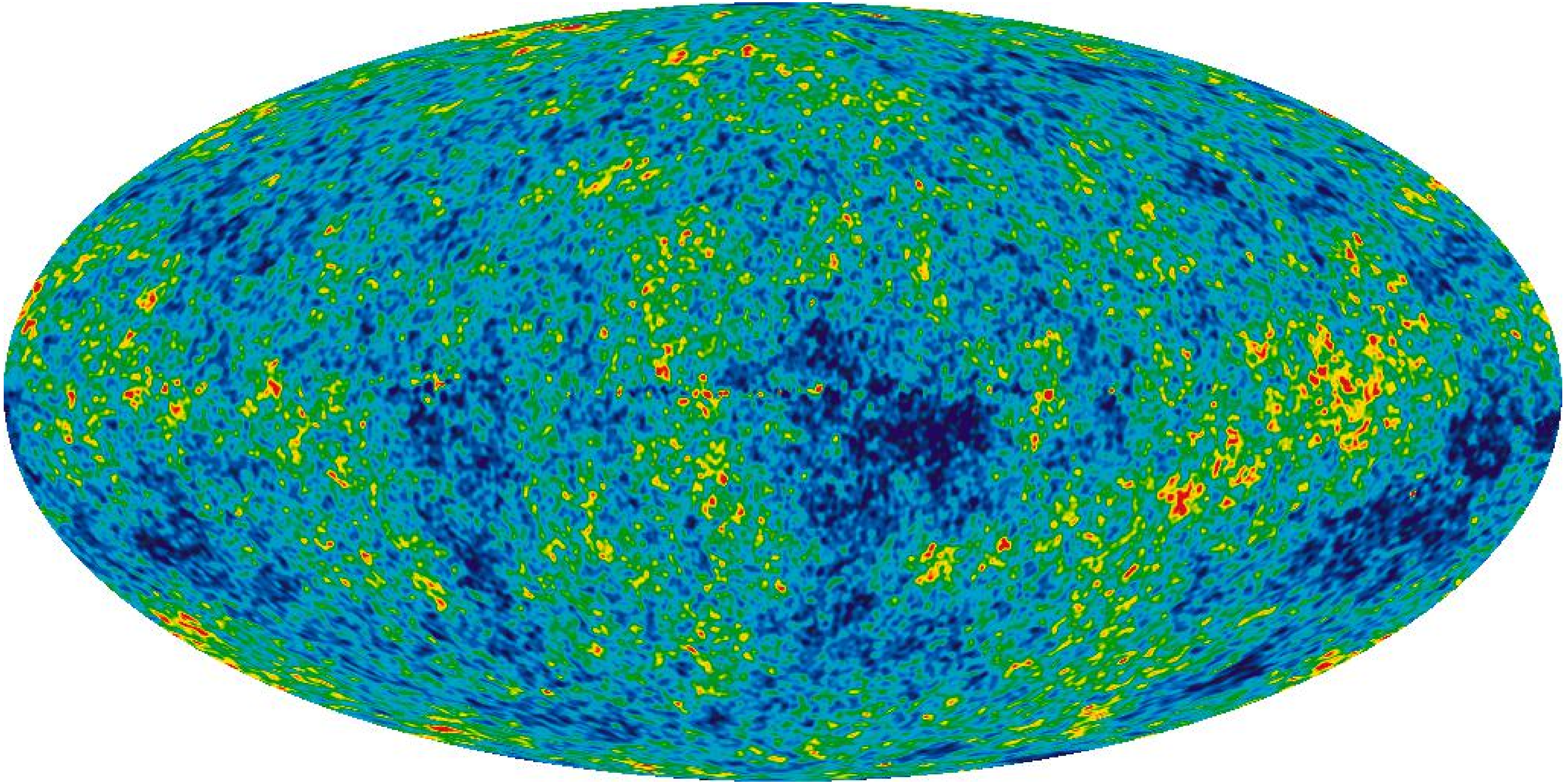
- If the stars are going that speed and not being hurled out of rotation, there is some extra force keeping them in there
- Much more mass from non-luminous matter than luminous material is indicated by the observations



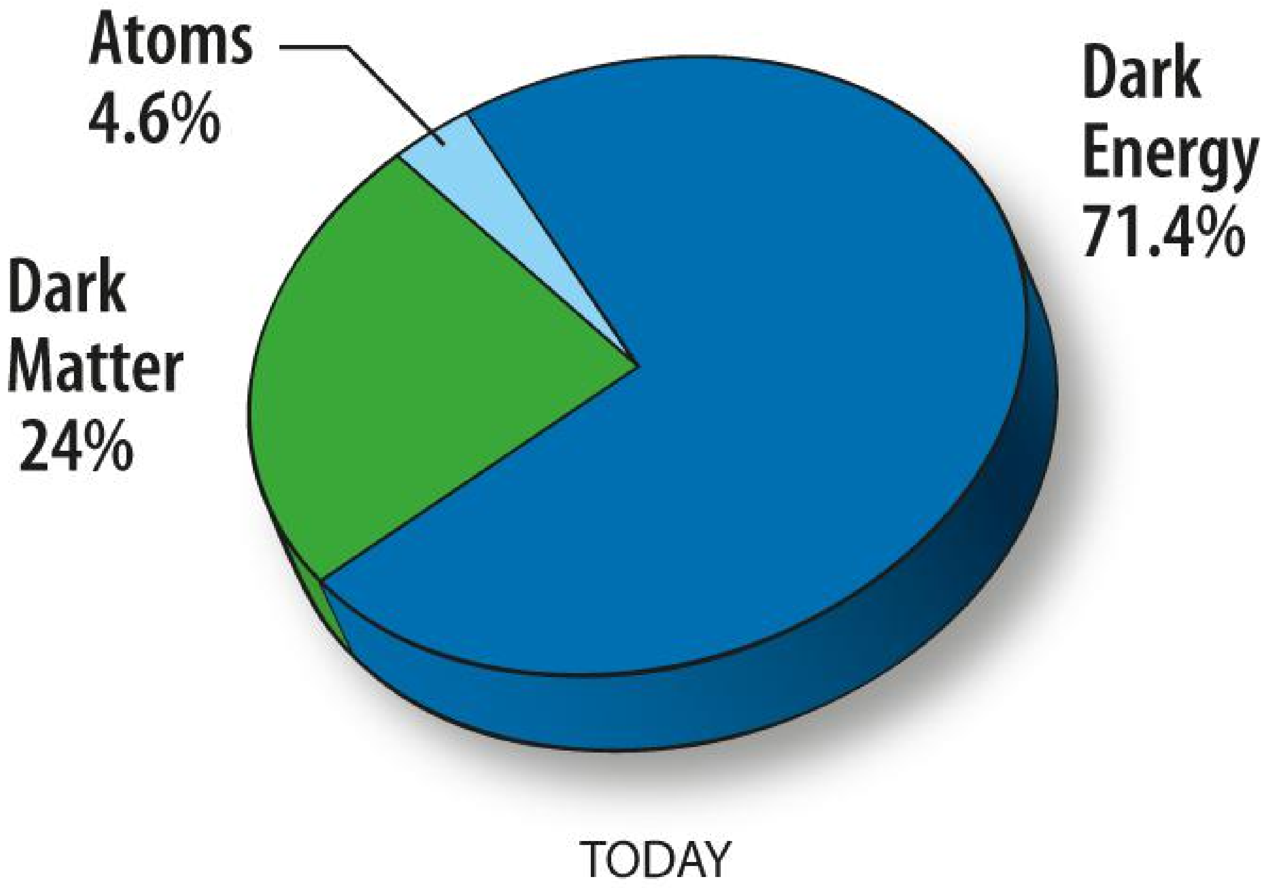
Galaxy Cluster lensing

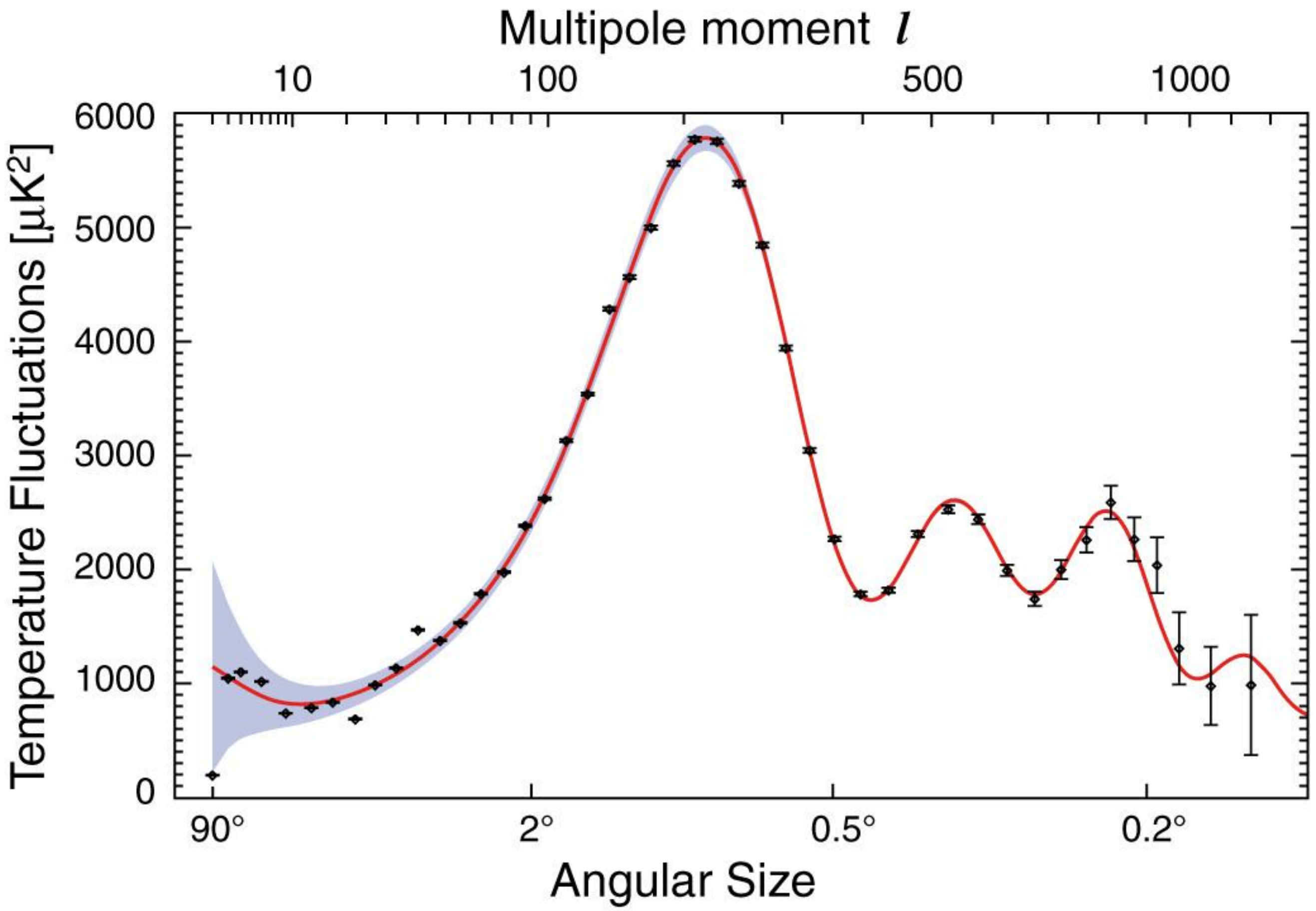


Large scale structure and the CMB

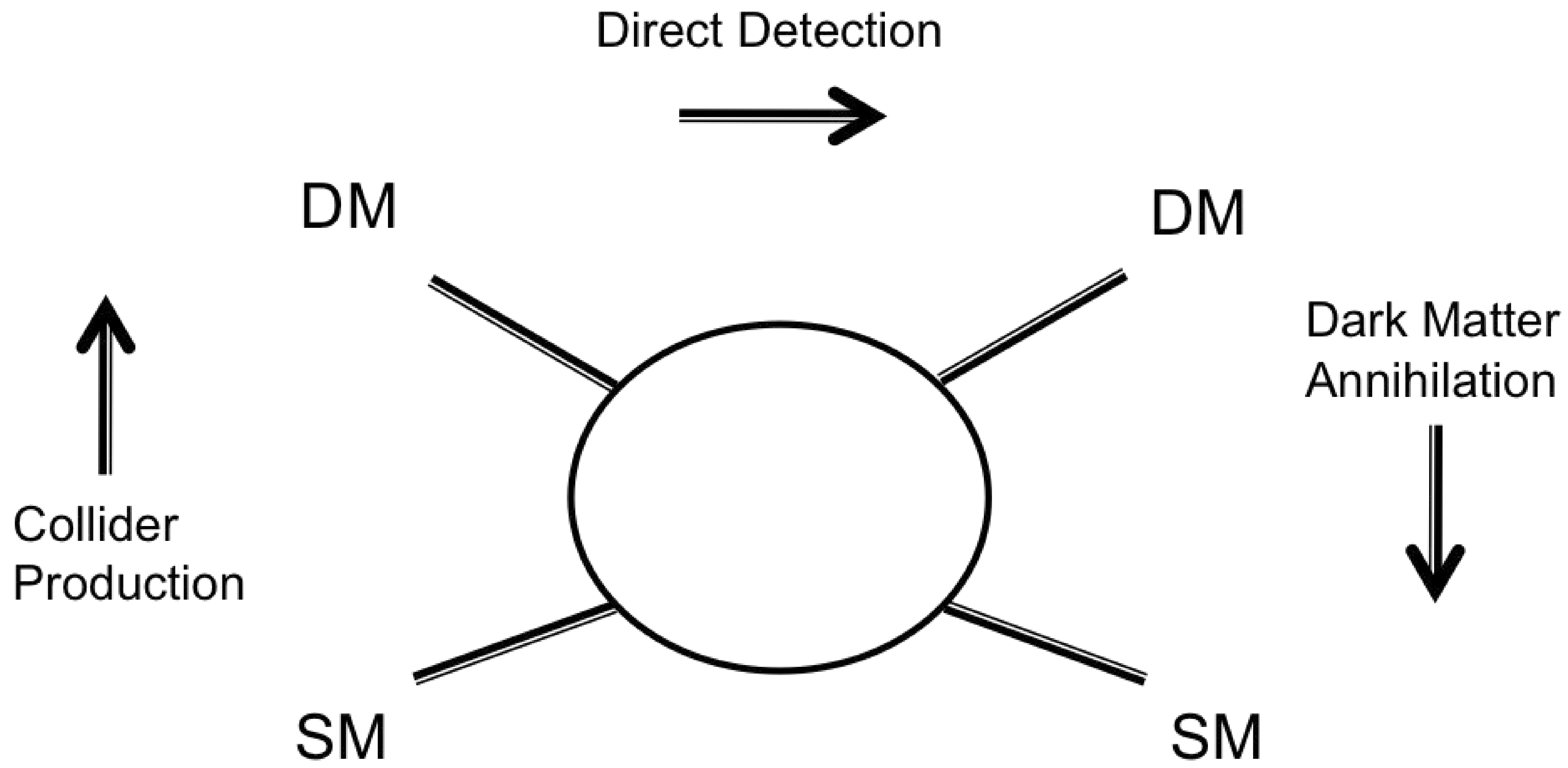


What does it all add up to?





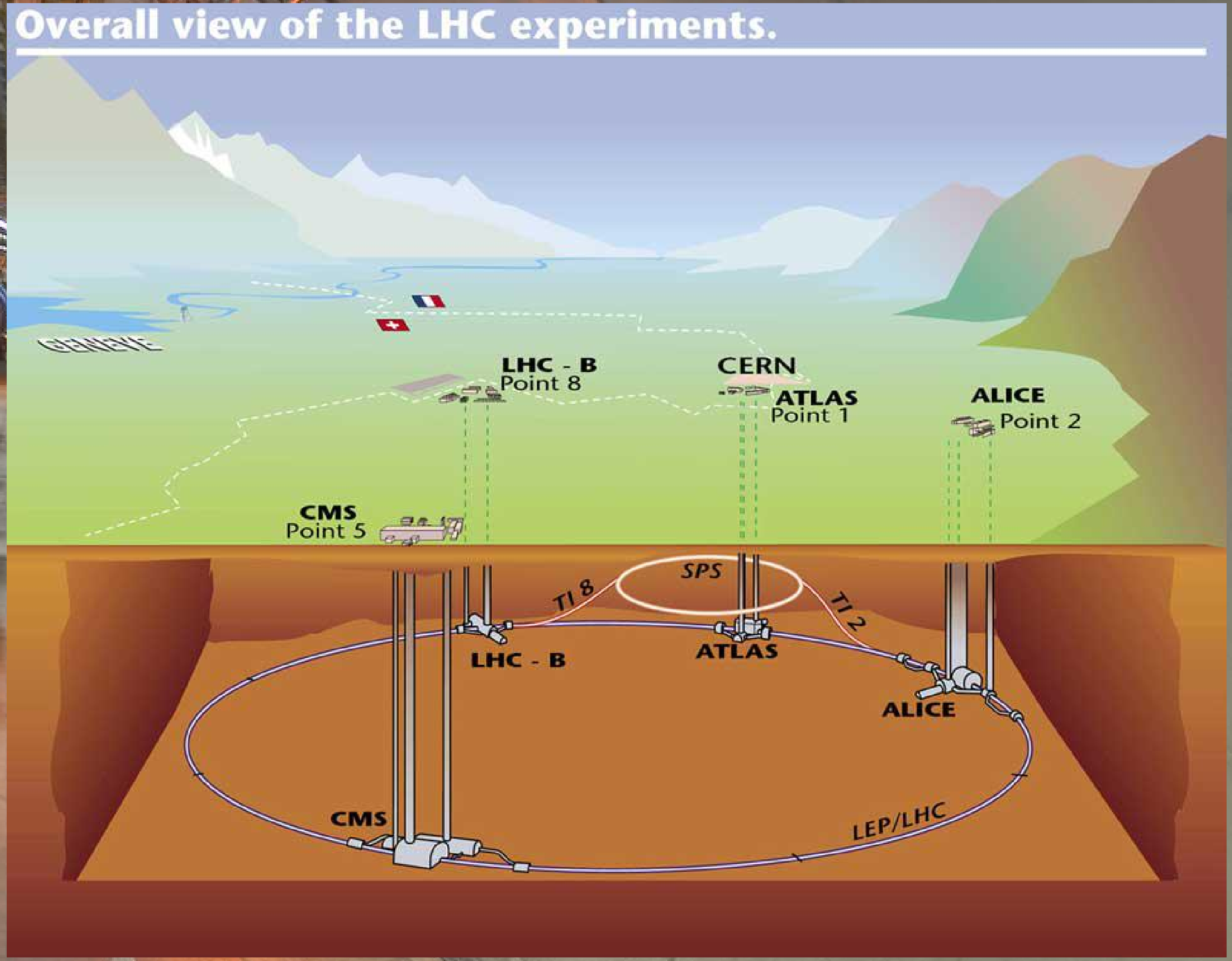
So what could Dark Matter be?



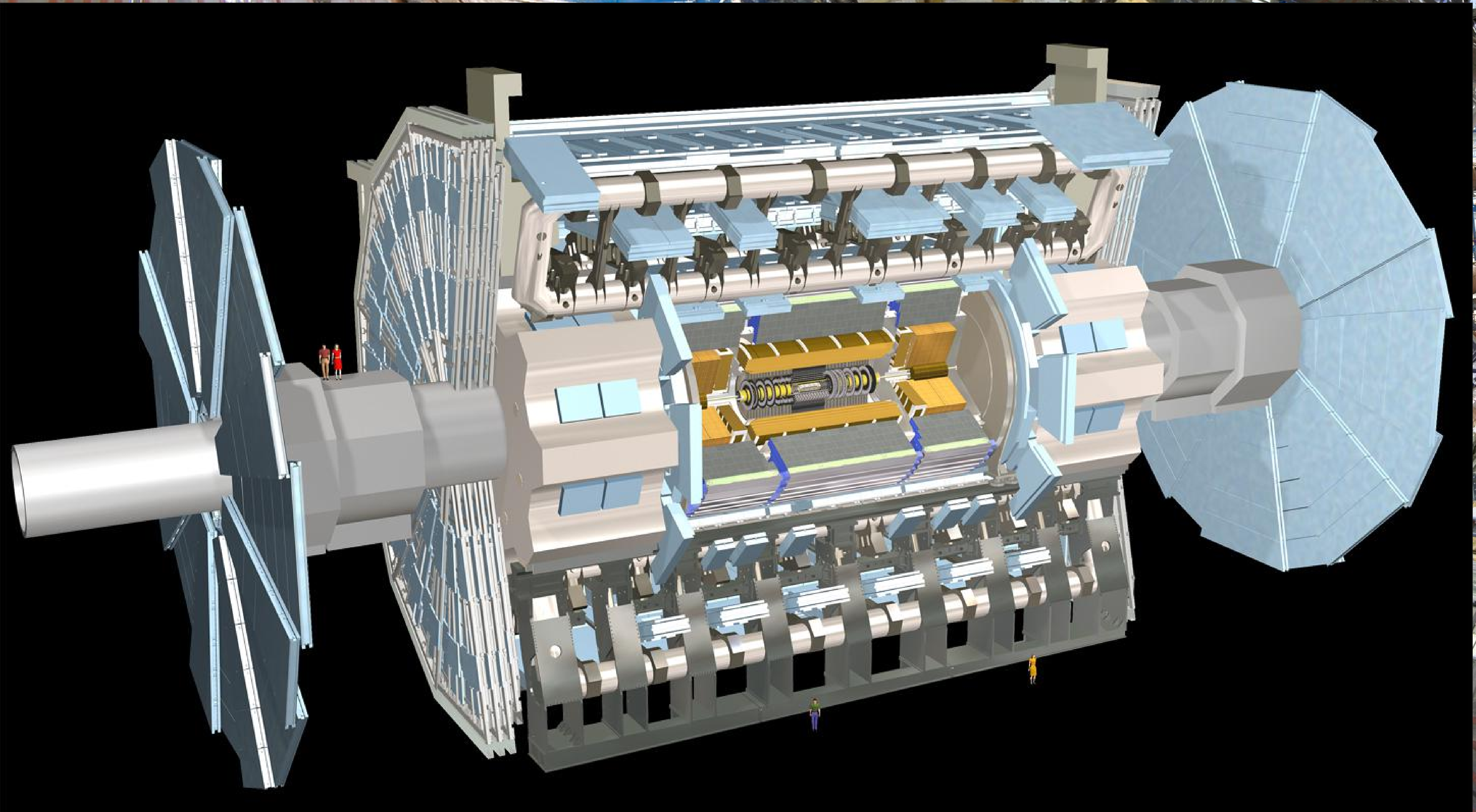
Disclaimer: I am a particle physicist

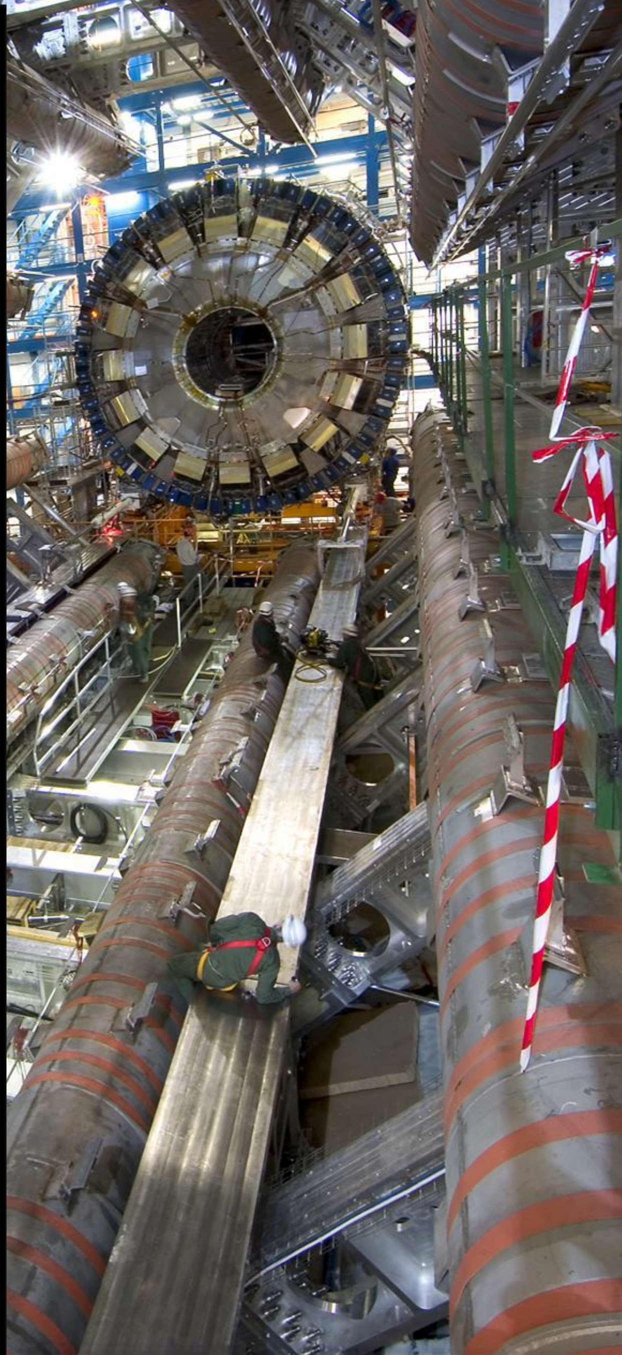
And I'm on ATLAS...

Experimental setup: the Large Hadron Collider



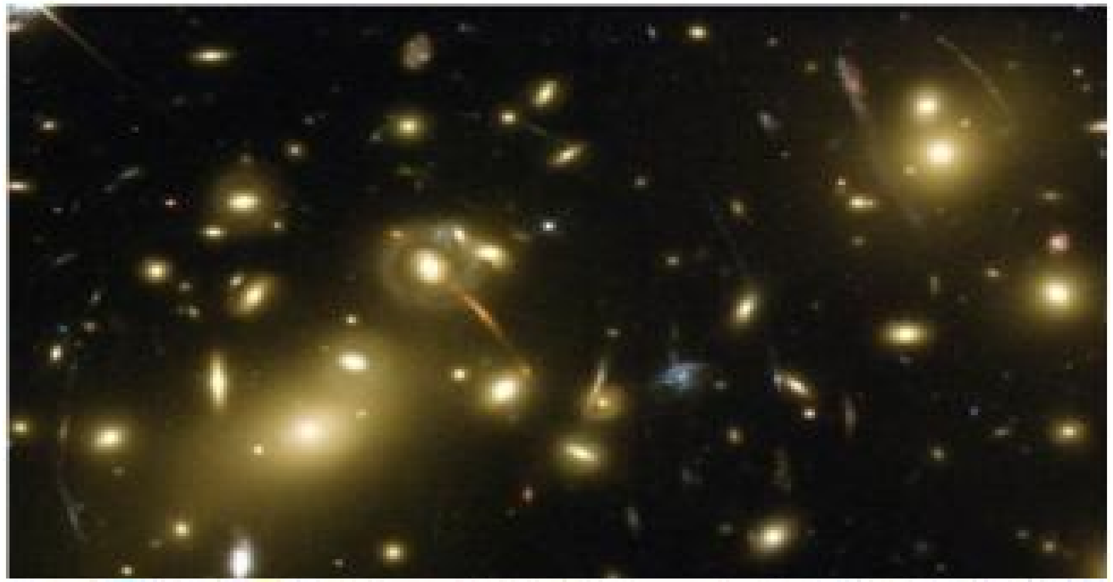
The detector I'm talking about today: ATLAS





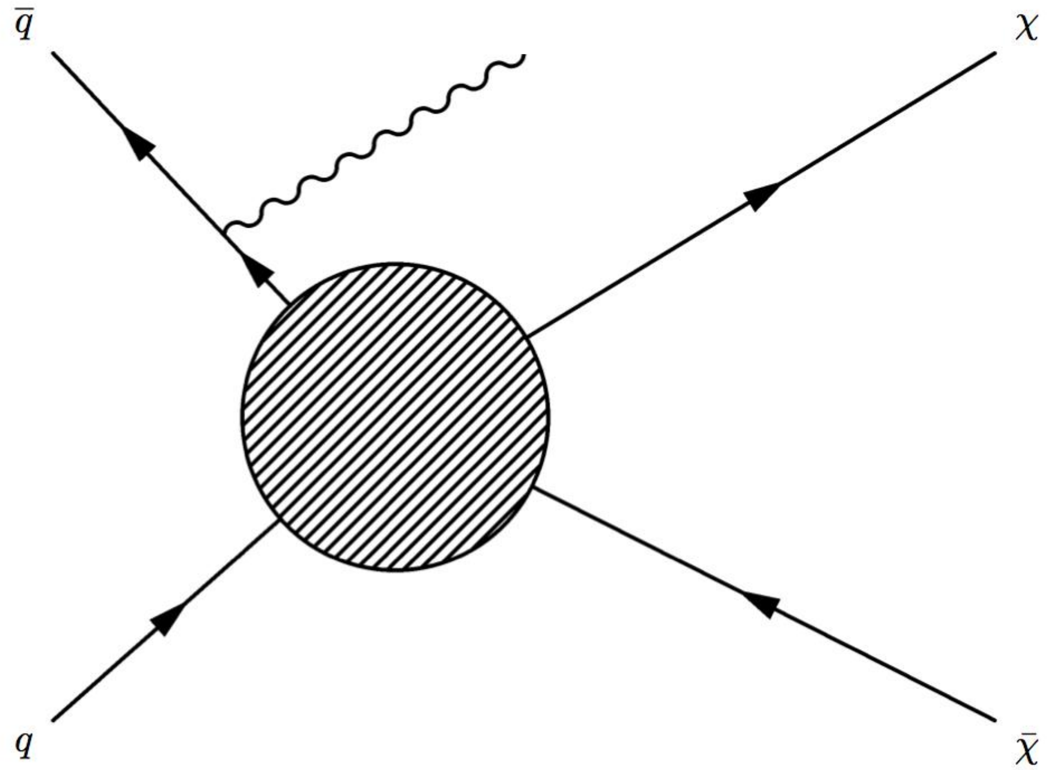
Summary of the big picture motivation

- Dark Matter: Unsolved problem
    - No Standard Model theory can explain it
    - Something beyond this theory clearly exists
- Astrophysical indicators
    - Cosmic Microwave Background
    - Gravitational lensing
    - Galaxy clusters
    - Galactic star motion
- Assume it interacts weakly with the Standard Model
    - Emission from galactic sources
    - Direct nuclear recoil underground
    - **Particle production in colliders**



Lets dive in...

An effective field theory model of dark matter



Benefits:

- A very simple but complete model
- The model is characterized by the energy, or mass scale

Limitations:

- Validity of model depends on momentum transfer in a collision being less than the mass scale of the model

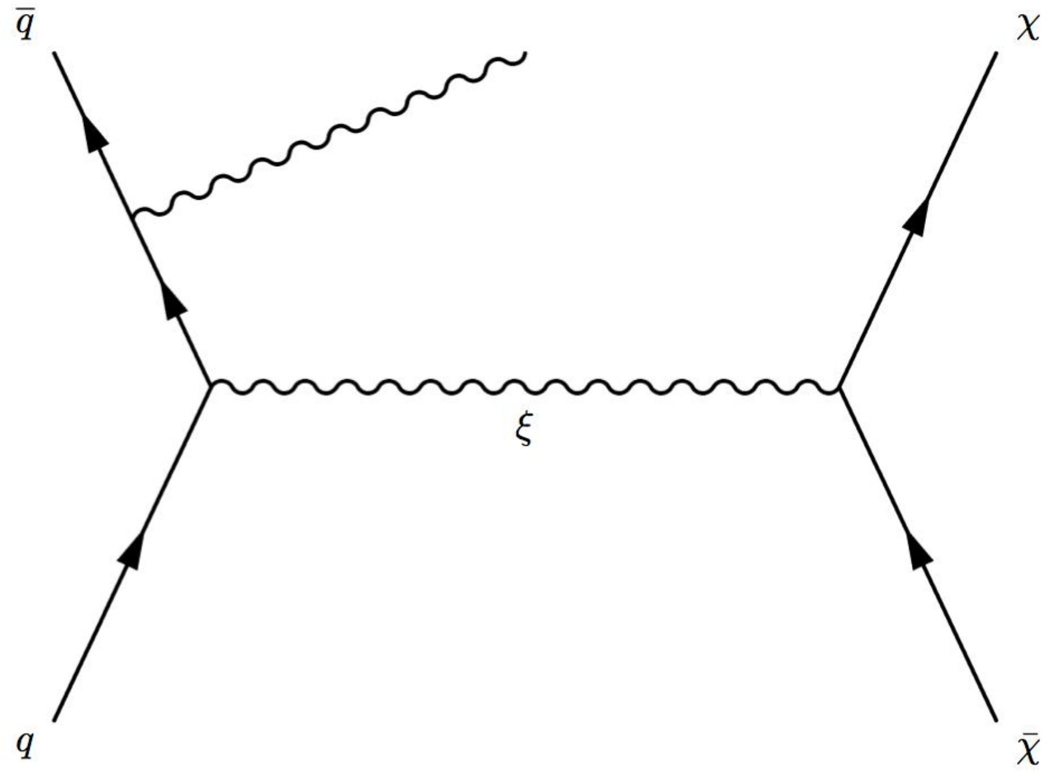
A simple mediator model of dark matter

Benefits:

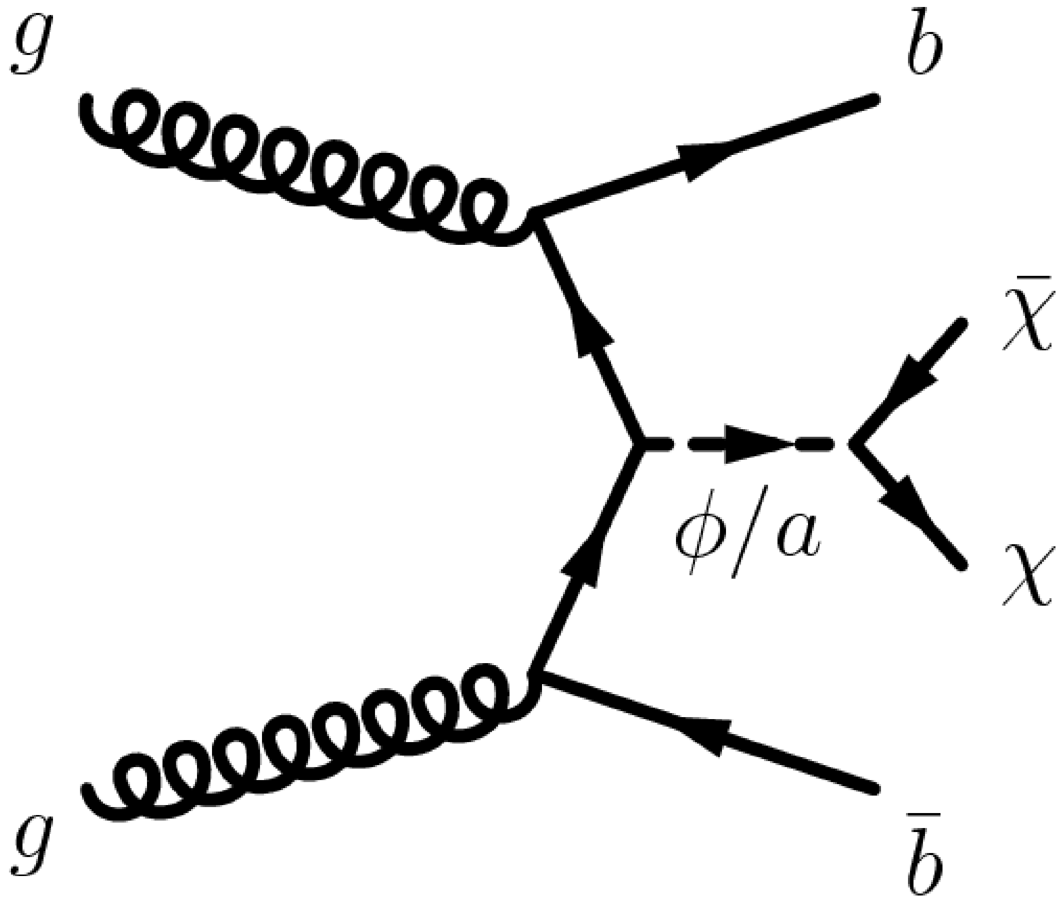
- Valid for LHC momentum transfers
- Provides a coherent model to compare results between different channels and experiments

Limitations:

- Several parameters to tune
- Not a physically complete theory, just a guideline



Another simple mediator model of dark matter



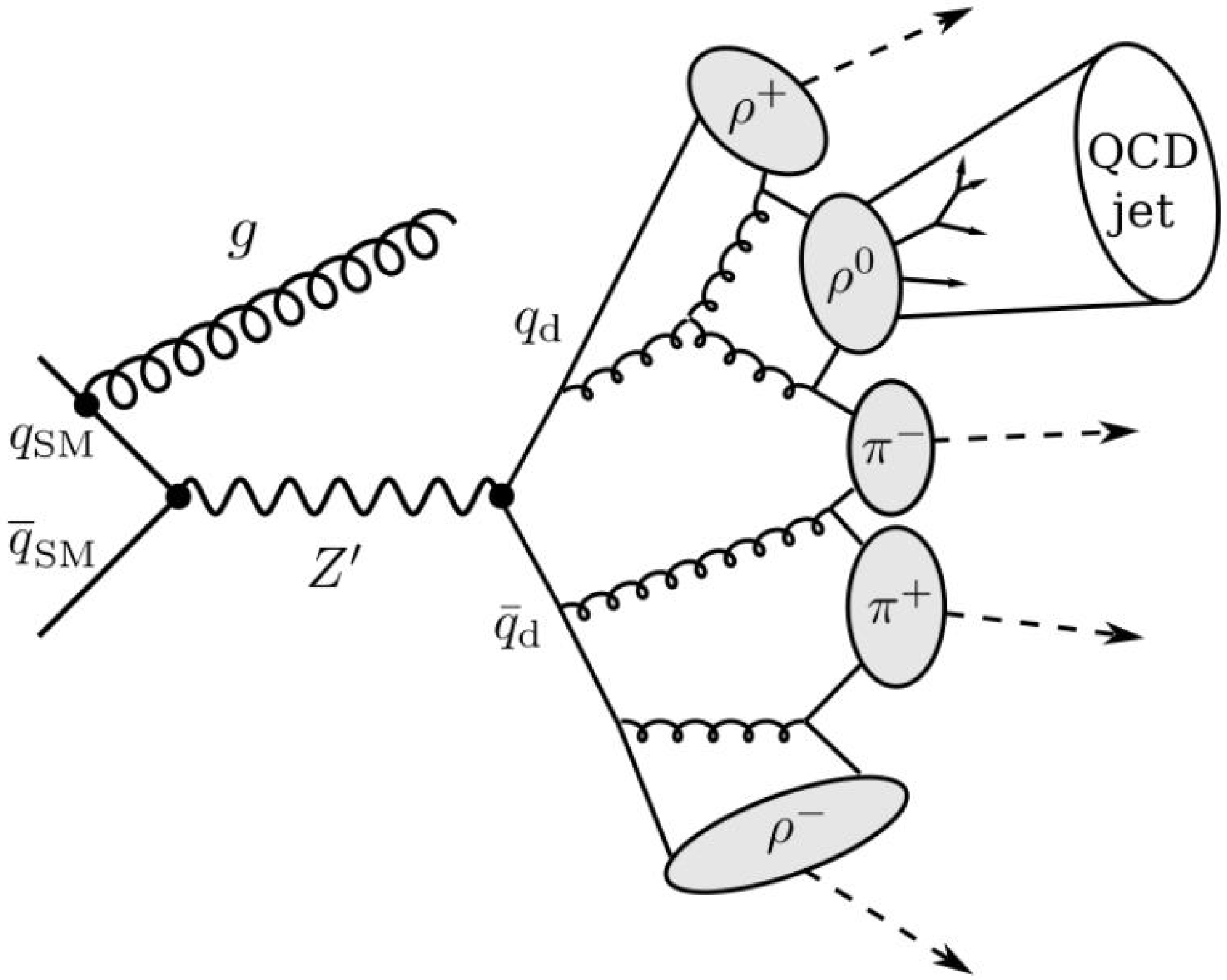
Similarities:

- Same number of parameters as the mono-X search
- The same coherent model allows comparison results with this different channel

Differences:

- Different signature in the detector
- Does not produce a resonance in the bb mass spectrum or MET spectrum

What about something messier?



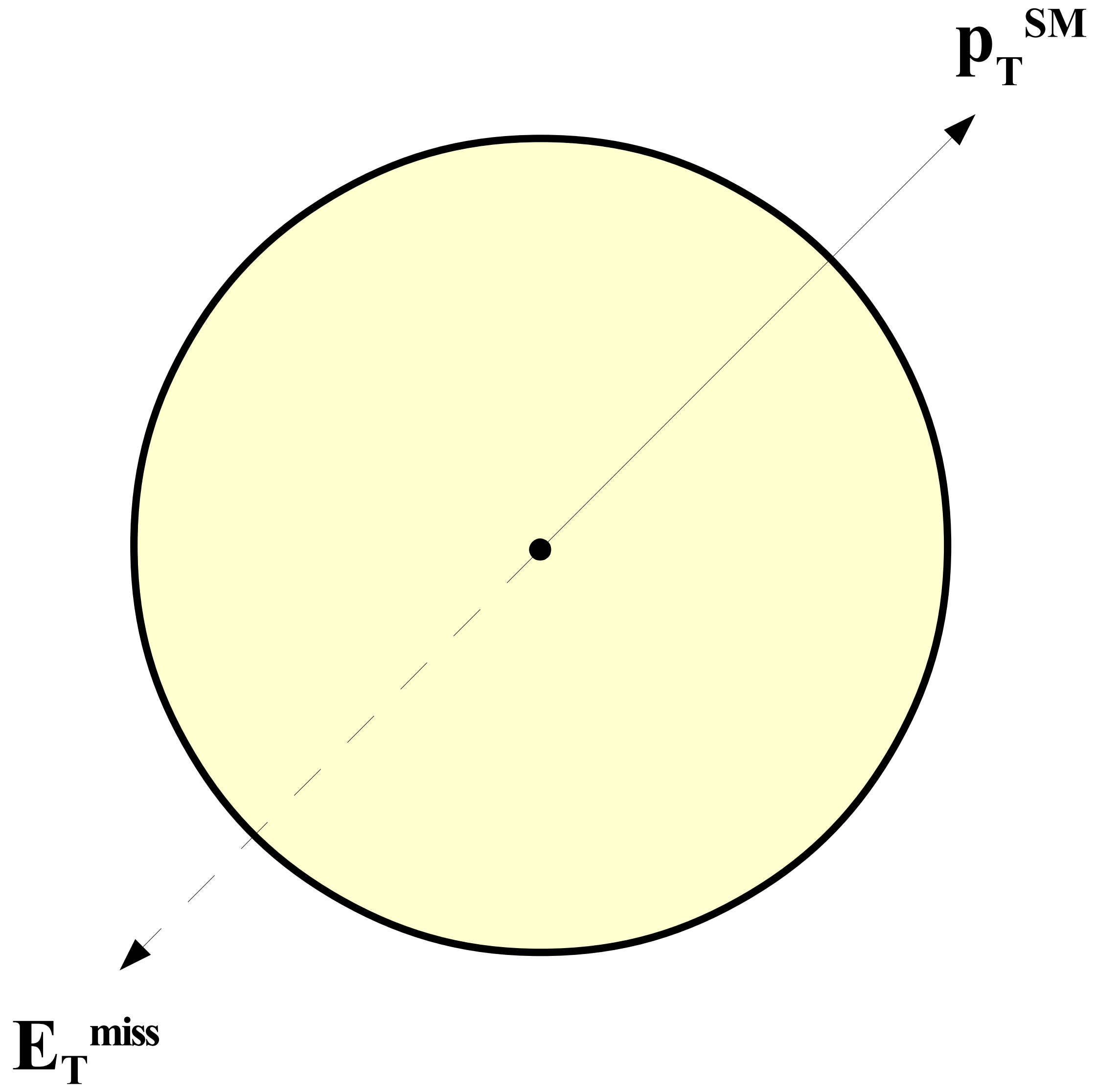
The idea

- What if the jets that we might normally throw away... are the ones that contain the new physics?
- Could produce a resonance spectrum, as it is an s-channel model
- However! It is very messy, hard to pick out from detector effects

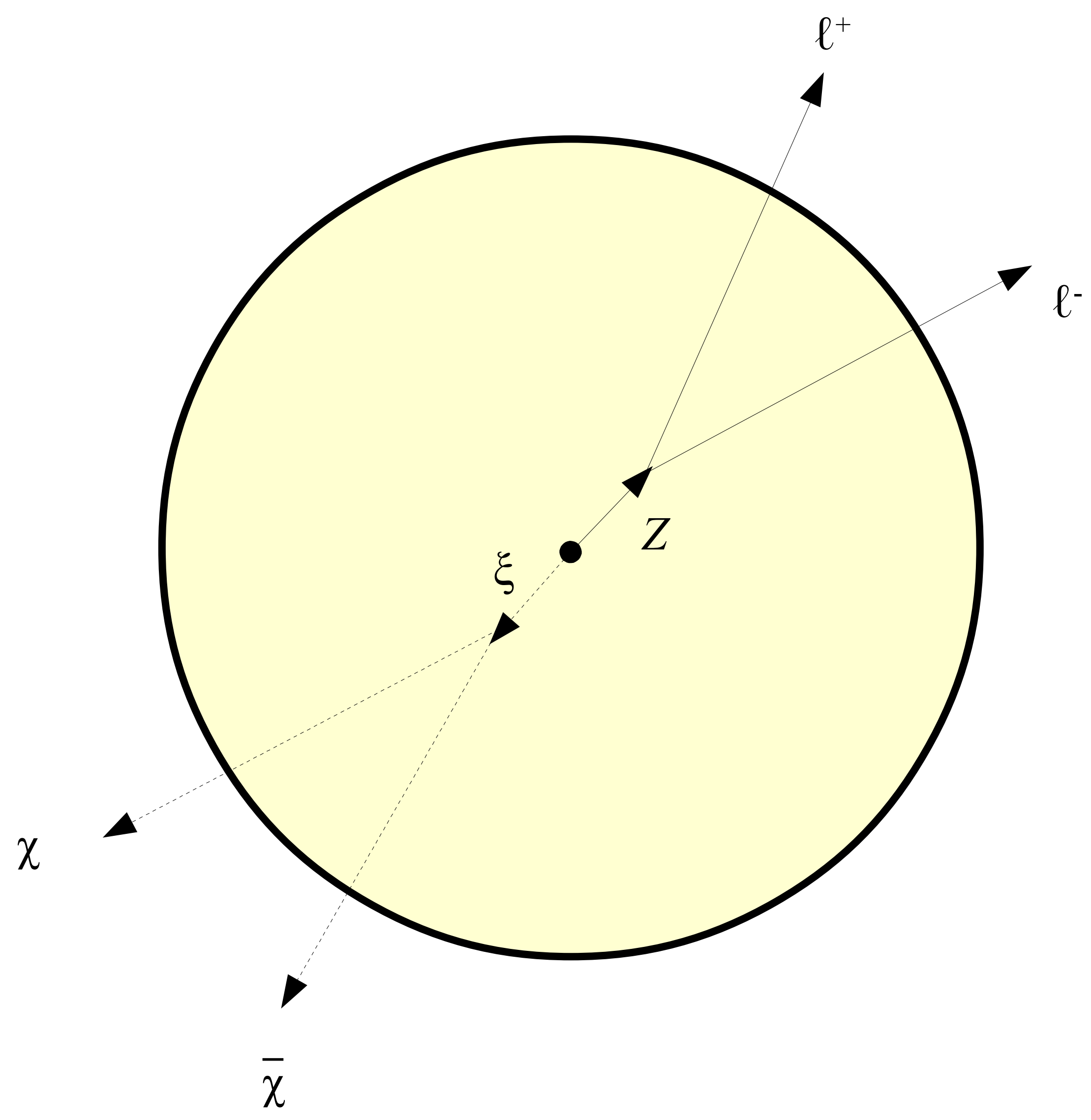
I will talk about this at the end

“Mono-X” searches

- Presence of dark matter inferred from momentum imbalance in the ATLAS detector
- Key variable is the magnitude of *missing momentum* $|\mathbf{E}_t^{miss}|$ transverse to beam direction, known as missing energy E_T^{miss}
- Suppression of *fake* E_T^{miss} through a proxy on its uncertainty: $E_T^{miss}/\sqrt{\Sigma E_T}$
- Large *separation* $\Delta\varphi$ required between $\mathbf{E}_T^{miss}$ and $\mathbf{p}_T^{SM}$
- Further separation between $\mathbf{E}_T^{miss}$ and hadronic activity guards against mismeasurement

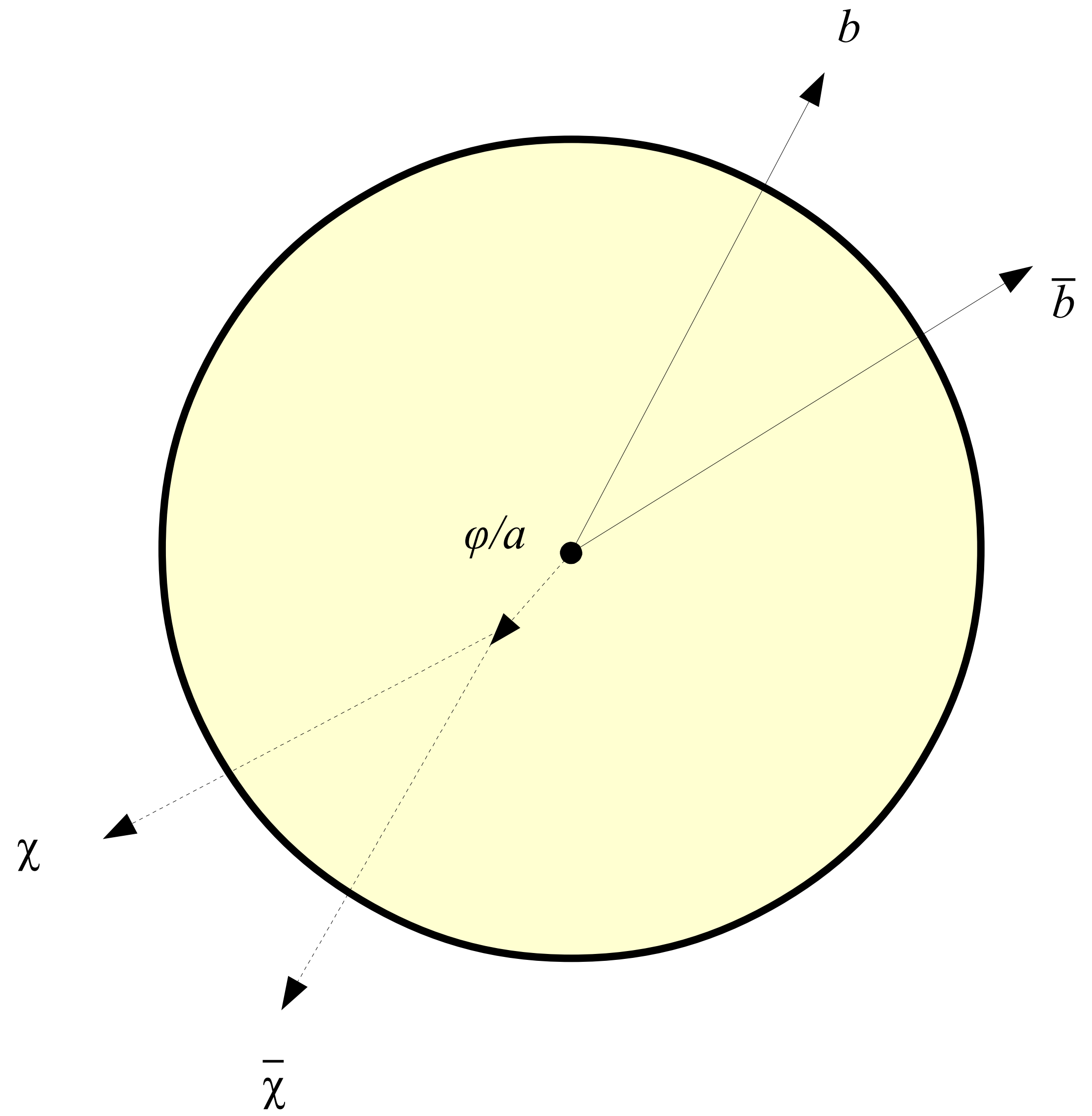


Dark matter in the detector



Mono-Z

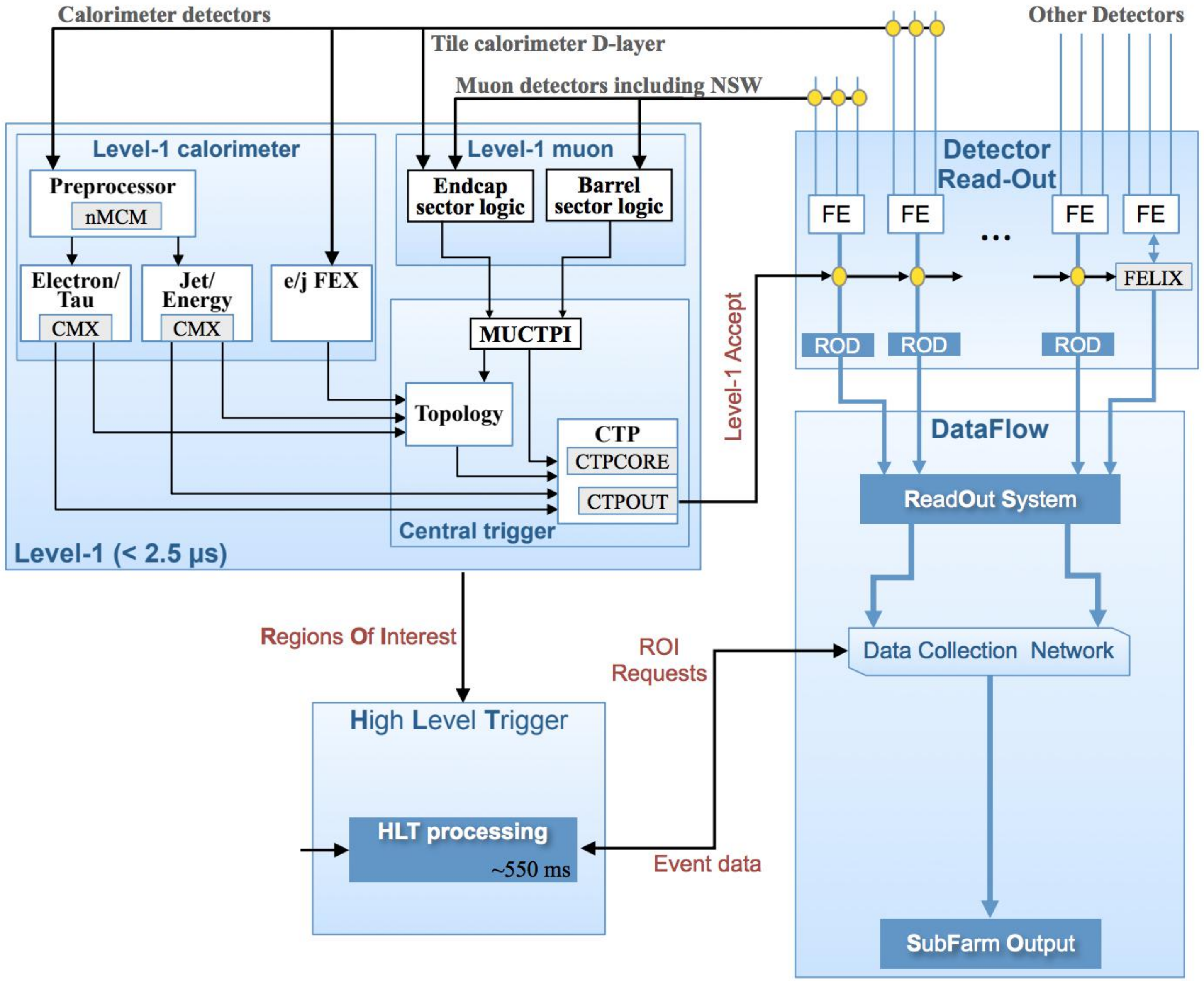
Dark matter in the detector



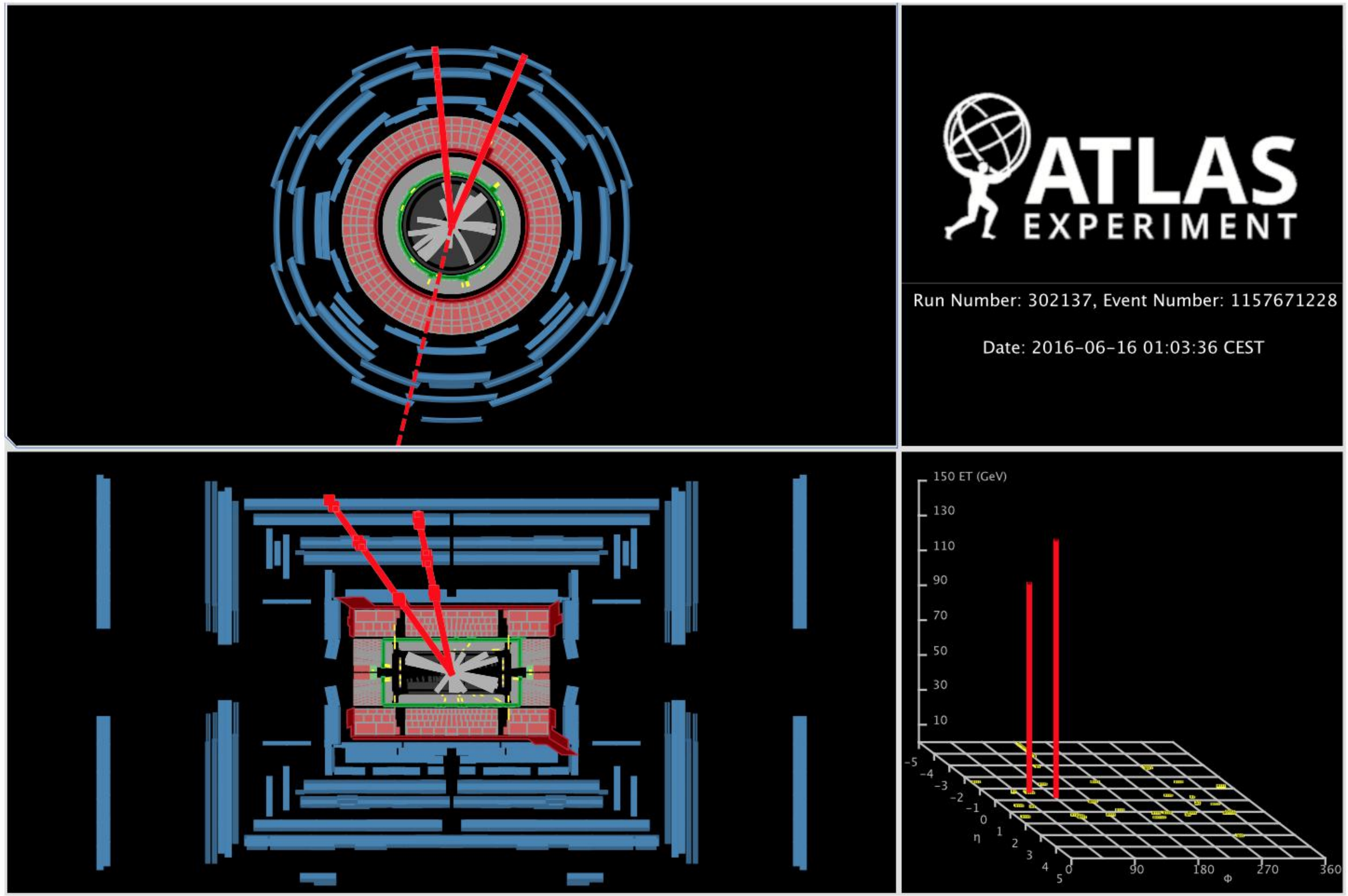
bbMET

Side note on triggering

How do we decide to actually analyse an event?



Potential dark matter event in ATLAS

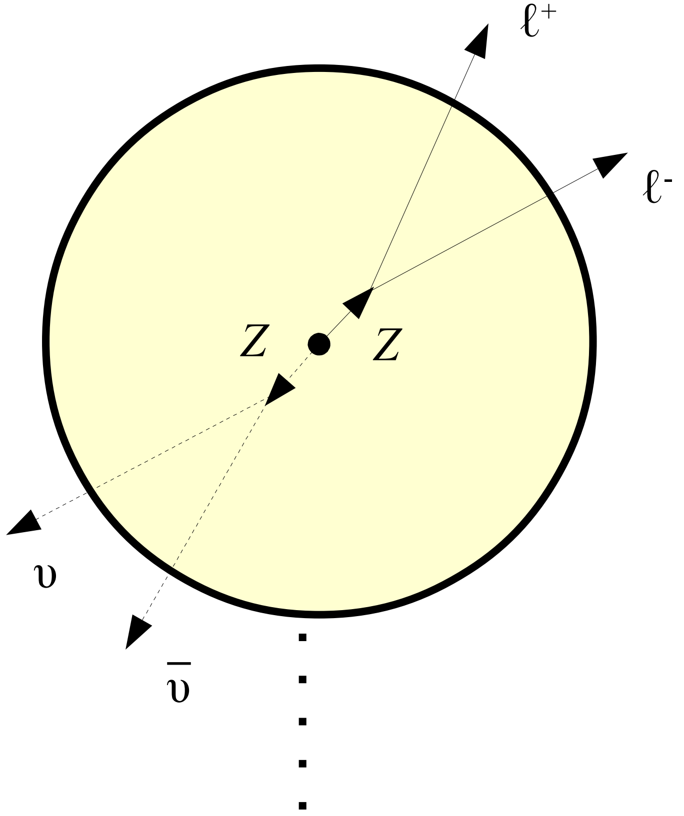


Link to Plot

Mono-Z

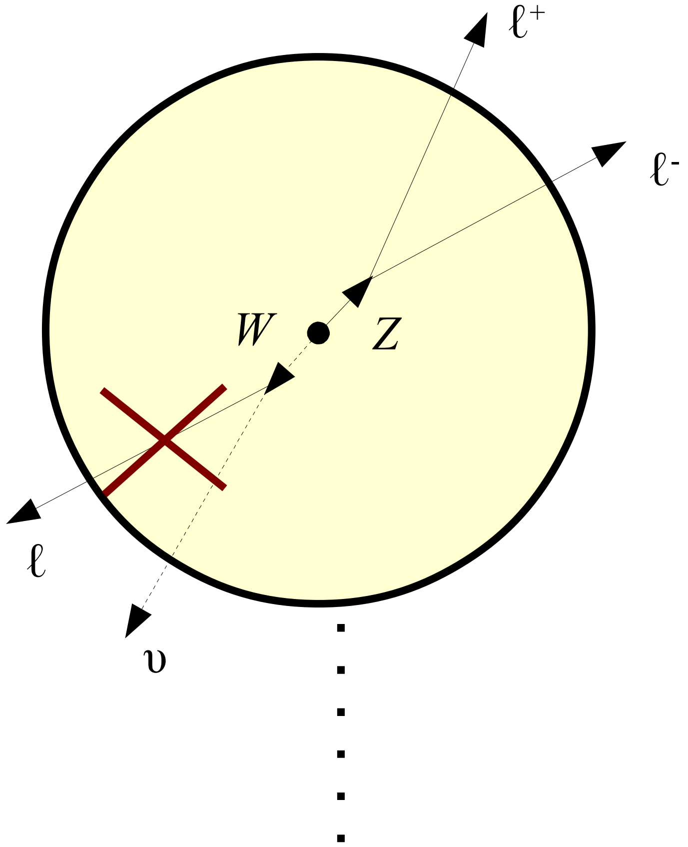
Standard Model in the detector: backgrounds to the analysis

ZZ



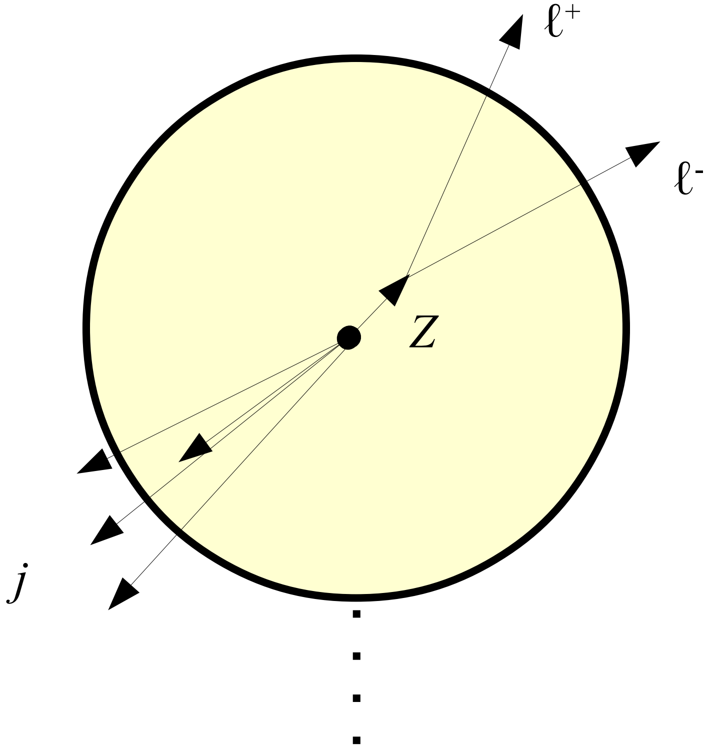
Estimated through MC
With NLO EW NNLO QCD

WZ



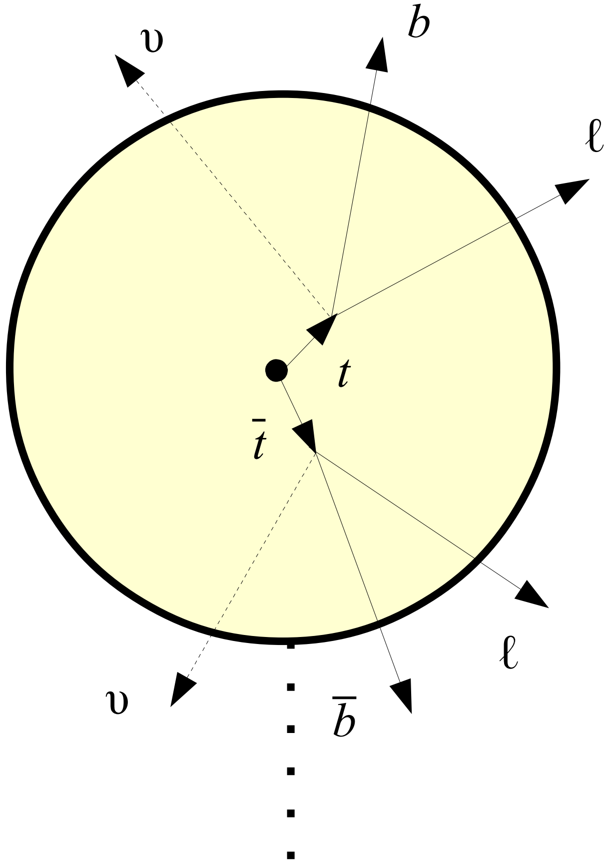
Estimated through
Third lepton control region

$Z + \text{jets}$



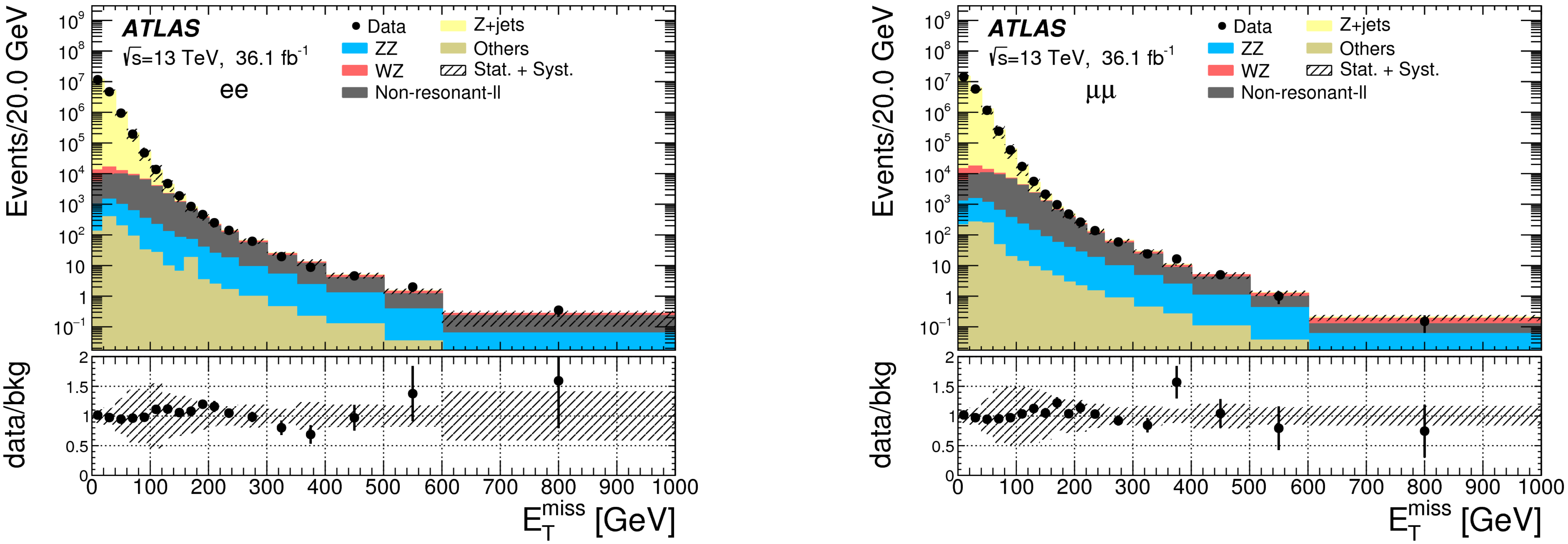
Estimated through
ABCD control region

Non-resonant $\ell\ell$
e.g. tt, WW, Wt

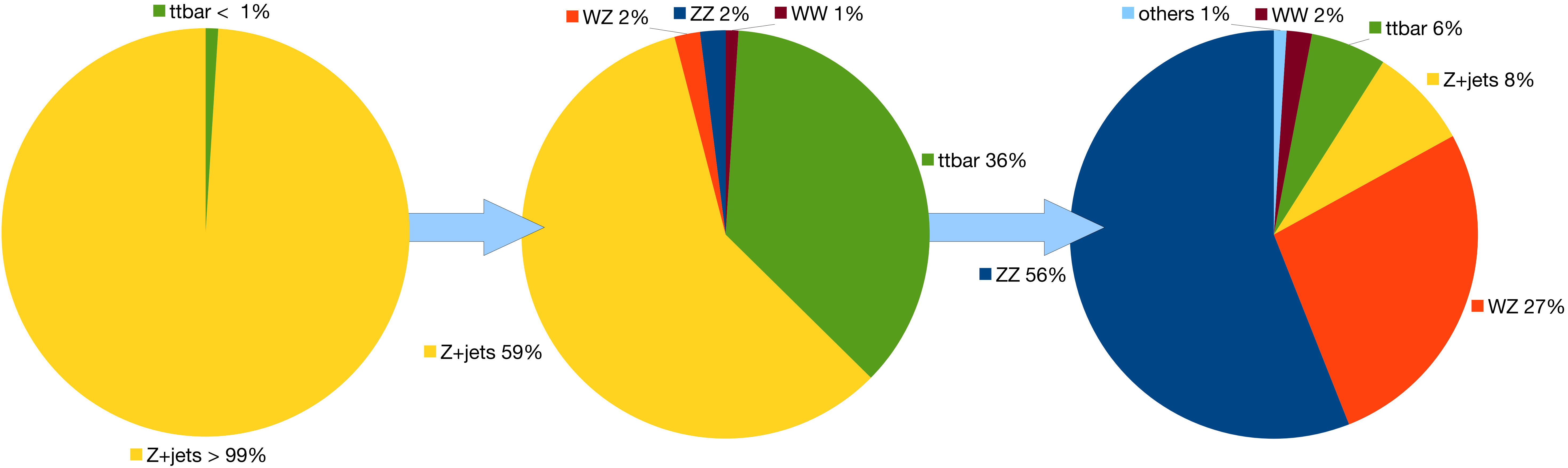


Estimated through an
opposite flavour control region

Background composition: before signal region cuts are applied



Changing background composition and reducing total number of events



Select events with a *Z* → Require presence of missing energy → Final signal selection

Estimating the background: *ZZ*

- Background is entirely estimated from Monte Carlo, using Powheg generators
  - POWHEG + Pythia8
    - $qq \rightarrow ZZ \rightarrow$ llll
    - $qq \rightarrow ZZ \rightarrow$ vvvv
    - $qq \rightarrow ZZ \rightarrow$ llvv
  - POWHEGgg2vv + Pythia8
    - $gg \rightarrow ZZ \rightarrow$ llvv

- *ZZ* is the dominant background (approximately 2/3 of total)
- *ZZ* is an irreducible background, it has the same signature as the signal
- Theoretical uncertainties for *qq*:
  - QCD scale variation and PDF variation impact evaluated using POWHEG internal weights $\rightarrow \sim 4\%$
  - NNLO/NLO QCD k-factor evaluated as a function of m_{ZZ}
  - NLO EW corrections
- Theoretical uncertainties for *gg*:
  - NLO/LO QCD flat k-factor = 1.7 ± 1.0

Estimating the background: *WZ*

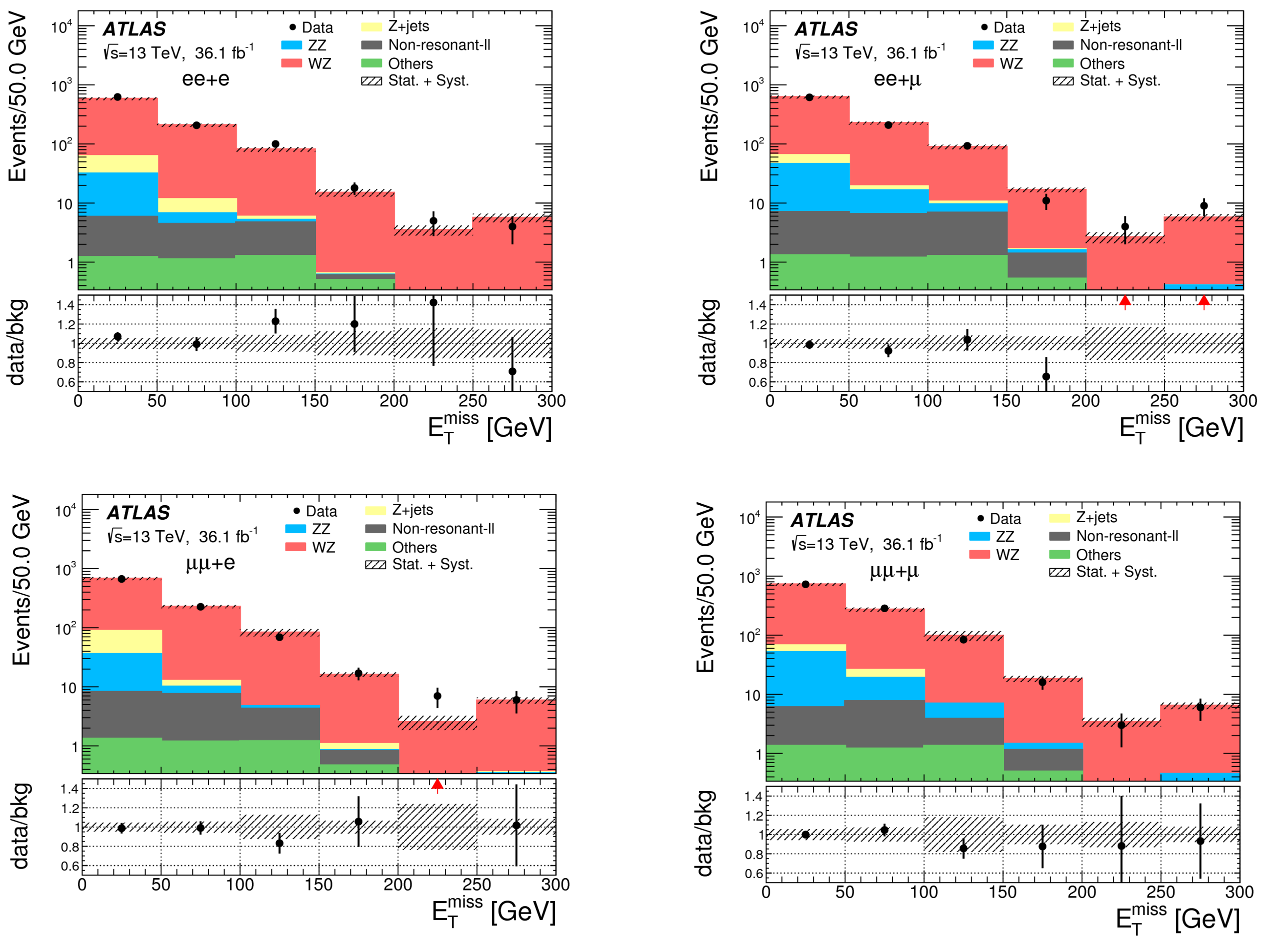
Three lepton control region

- Require a third lepton with $p_T > 20$ GeV
- Define the transverse mass, m_T^W, of the *W* boson with the E_T^{miss} and the 3rd lepton
- Require the $m_T^W > 60$ GeV
- Veto on any *b*-jets to remove ttbar contamination
- Theory and experimental systematics

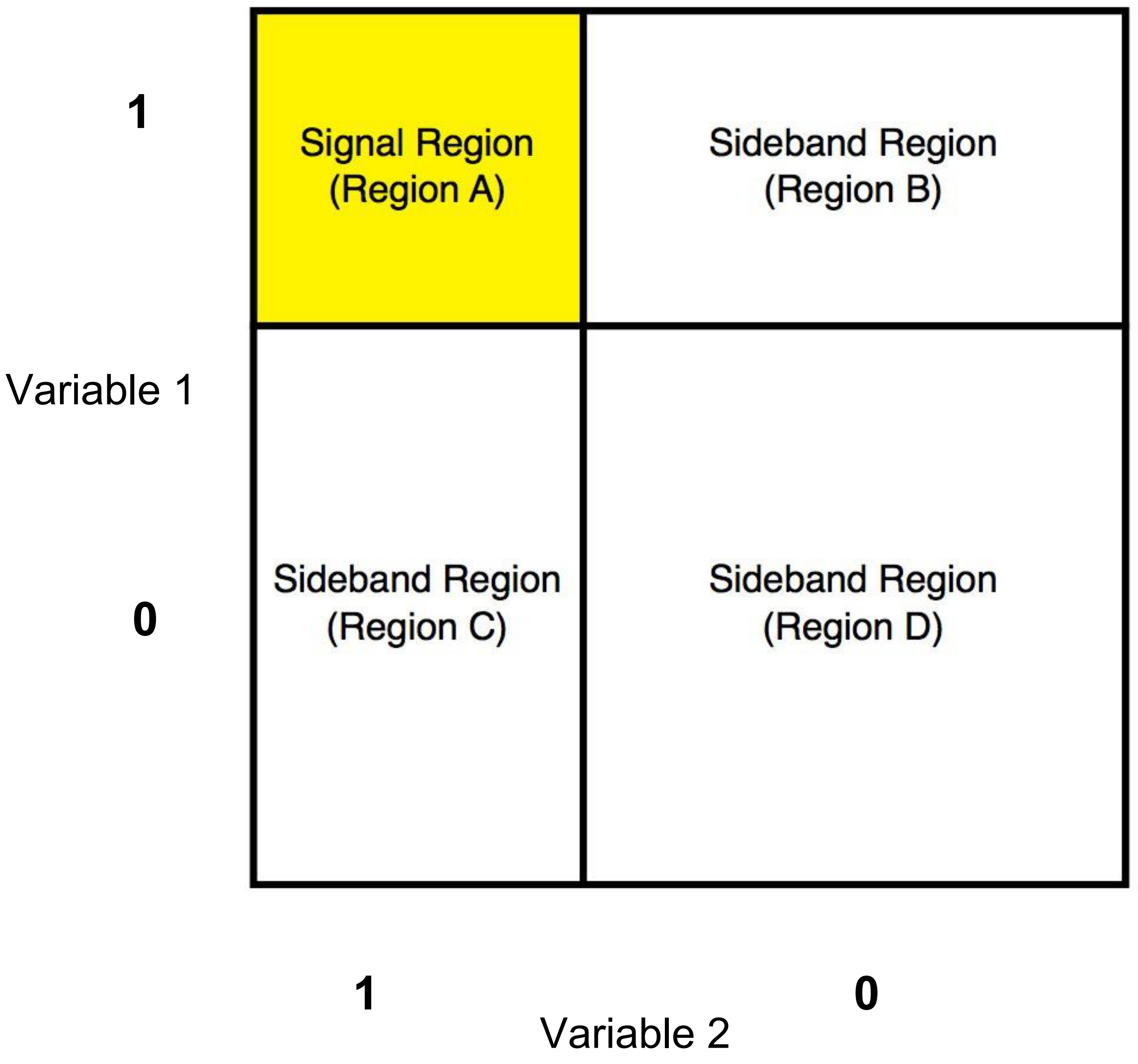
Data / MC:

ee+*e* ratio	=	1.39 ± 0.05
ee+μ ratio	=	1.25 ± 0.05
μμ+*e* ratio	=	1.26 ± 0.06
μμ+μ ratio	=	1.28 ± 0.04
Average	=	**1.29 ± 0.03**

$$N_{WZ}^{\mathrm{SR}} = N_{WZ,\,\mathrm{MC}}^{\mathrm{SR}} \times \frac{N_{\mathrm{data}}^{\ell_3} - N_{\mathrm{non}\text{-}WZ,\,\mathrm{MC}}^{\ell_3}}{N_{WZ,\,\mathrm{MC}}^{\ell_3}}$$



Estimating the background: $Z +$ jets



- This background estimated by the ABCD method
- A combination of analysis variables used to define the four regions
  - Variable 1 = $E_T^{miss} > 90$ && $E_T^{miss}/H_T > 0.6$
  - Variable 2 = $\Delta R(l,l) < 1.8$ && fracpt < 0.2 && $\Delta\varphi(Z, E_T^{miss}) > 2.7$ && $n_{b\text{-jets}} == 0$
- Cuts reversed to enhance $Z +$ jets contributions, with loose cuts added to Variable 2 to minimize correlation
- The systematic uncertainty estimated from the correlation bias, MC subtraction, and from ratio cross-checks

$$N_A^{est} = N_C^{obs,sub} \times \frac{N_B^{obs,sub}}{N_D^{obs,sub}}$$

Estimating the background: non-resonant $\ell\ell$

- Opposite flavour ($e + \mu$) control region
- Exploiting the fact that these backgrounds have a flavour symmetry of ee:$\mu\mu$:$e\mu$ = 1:1:2
- Control region defined with same selection as the signal region aside from lepton flavour
- Systematics estimated from efficiency factor, background subtraction, and differences in data/MC shape and various cut steps

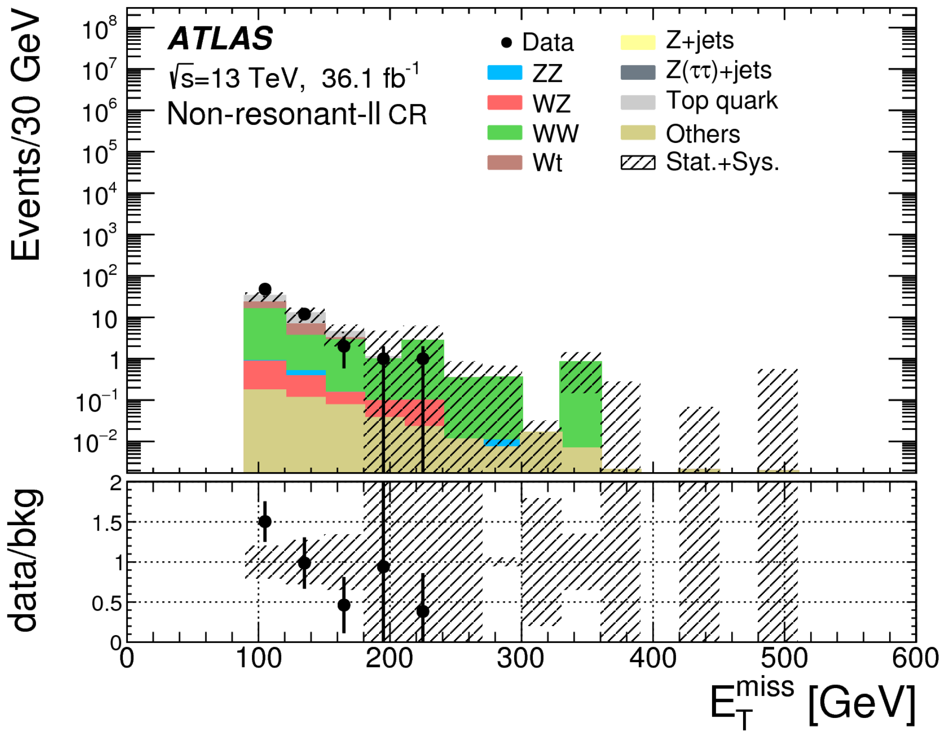
Contributions from: $WW/tt/Wt/Z(\to\tau\tau)$

$$N^{e\mu}_{SRee} = \frac{1}{2} \times \epsilon \times N^{data,sub}_{e\mu}$$

$$N^{e\mu}_{SR\mu\mu} = \frac{1}{2} \times \frac{1}{\epsilon} \times N^{data,sub}_{e\mu}$$

$$\epsilon^2 = \frac{N_{ee}}{N_{\mu\mu}}$$

Efficiency measurement difference is measured in bins of η and p_T



$$N^{data,sub}_{e\mu} = N^{data}_{e\mu} - N^{MC}_{sub}$$

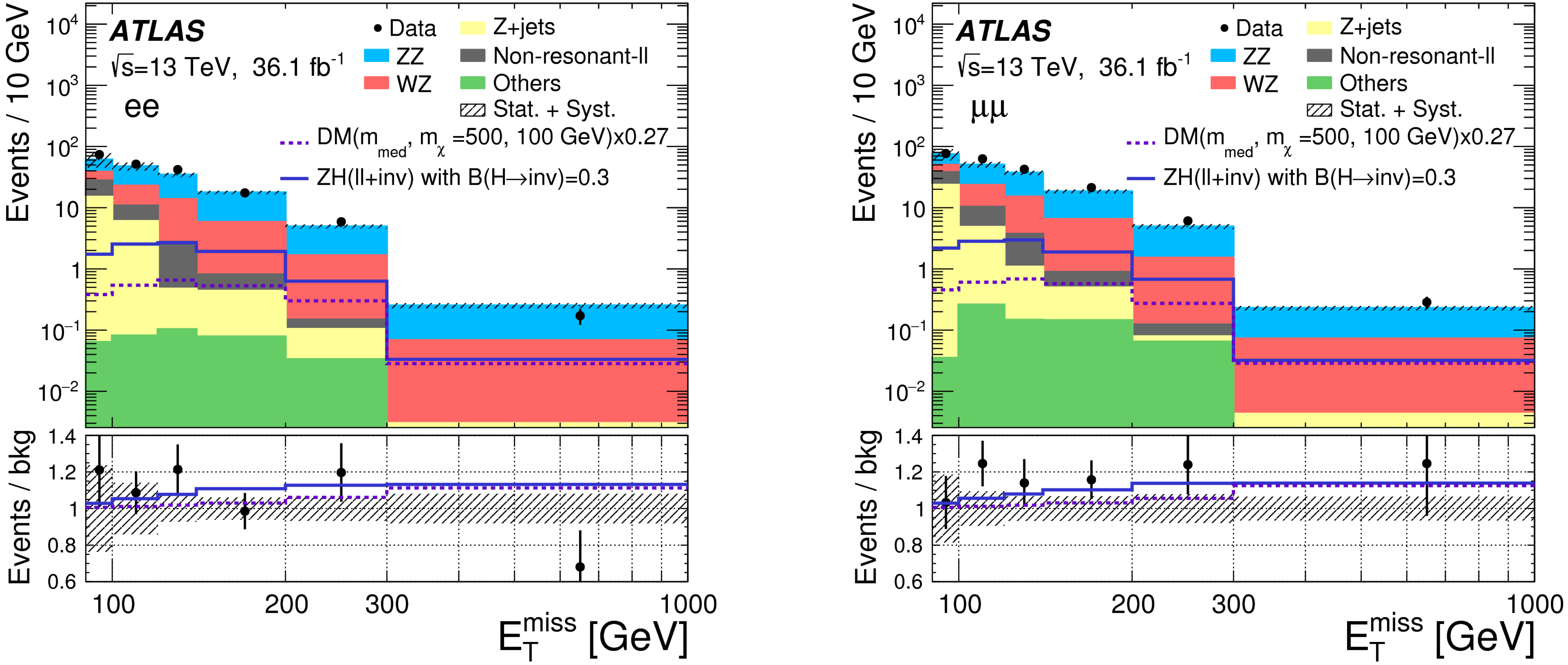
Other minor backgrounds are estimated in MC and are subtracted from the data

Estimating the background: 'others' and final numbers

- Fake factor method used to estimate this background
- One of the leptons is required to be 'bad' (faked from a jet) leading to large $W+$ jets contribution
- The good lepton is used as a tag, and the bad lepton is used as a probe
- Other background contributions are subtracted
- Systematics are assessed by studying the difference when applying this method to MC samples of $W+$ jets vs $Z+$ jets

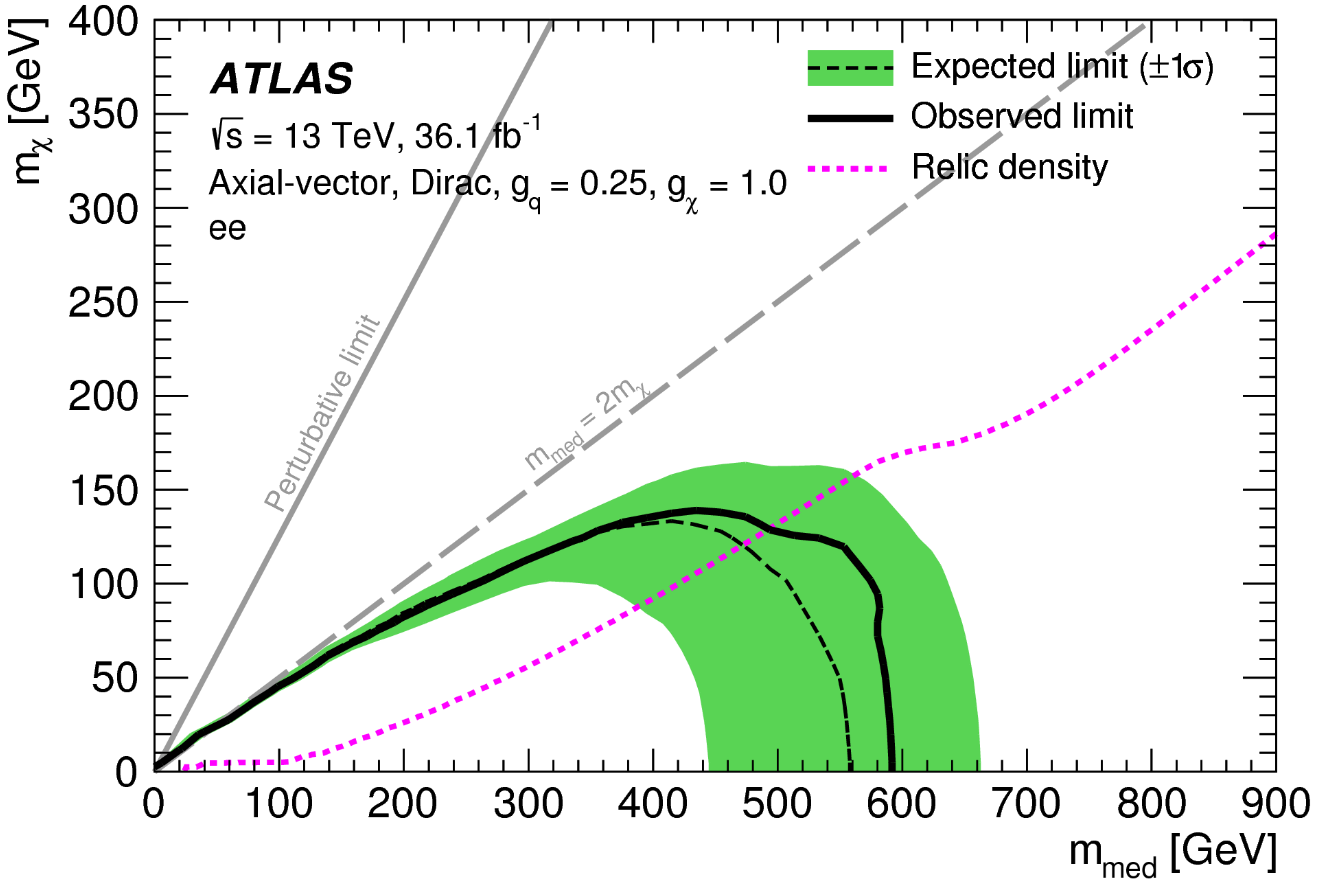
	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_T > 30$ (20) GeV
Third lepton veto	Veto events if any additional lepton with $p_T > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
E_T^{miss} and E_T^{miss}/H_T	$E_T^{miss} > 90$ GeV and $E_T^{miss}/H_T > 0.6$
$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss})$	$\Delta\phi(\vec{p}_T^{\ell\ell}, \vec{E}_T^{miss}) > 2.7$ radians
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.8$
Fractional p_T difference	$\left\|p_T^{\ell\ell} - p_T^{miss,jets}\right\|/p_T^{\ell\ell} < 0.2$
b-jets veto	$N(b\text{-jets}) = 0$ with b-jet $p_T > 20$ GeV and $\|\eta\| < 2.5$

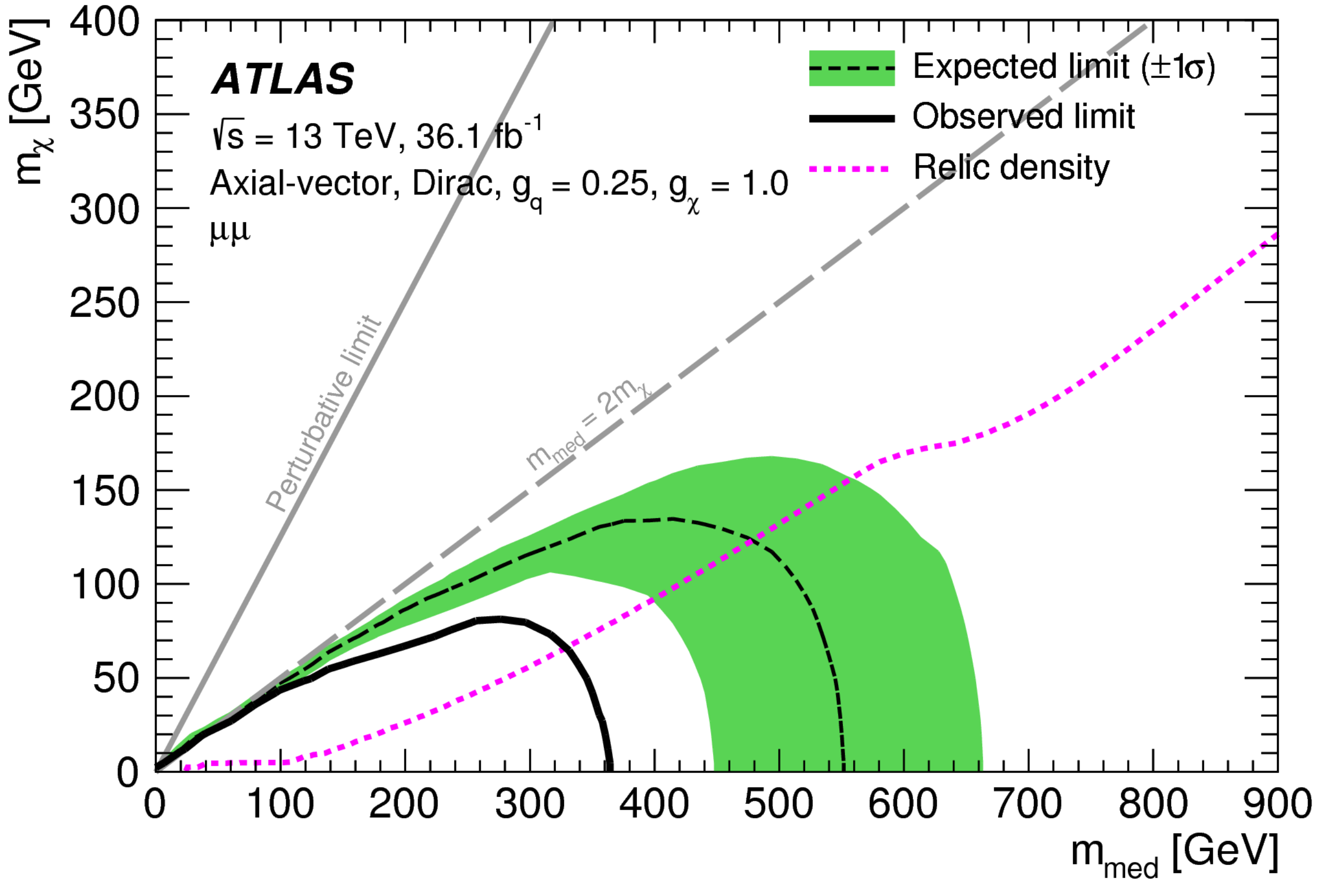
Selections applied and backgrounds estimated



Results and interpretation (1)

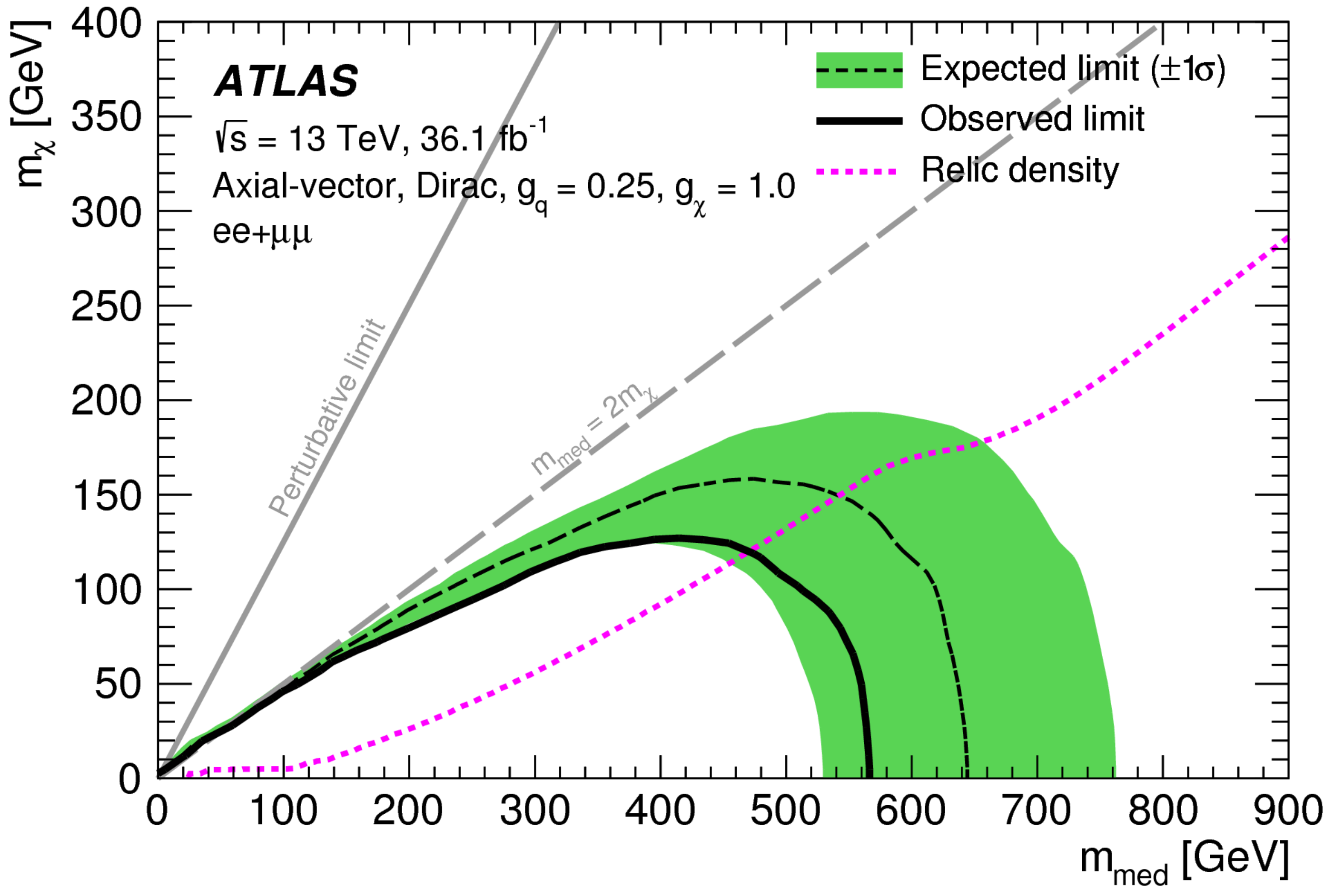
No statistically significant signal was found beyond the Standard Model expectation
→ Limits are determined for a set of axial-vector mediated dark matter samples



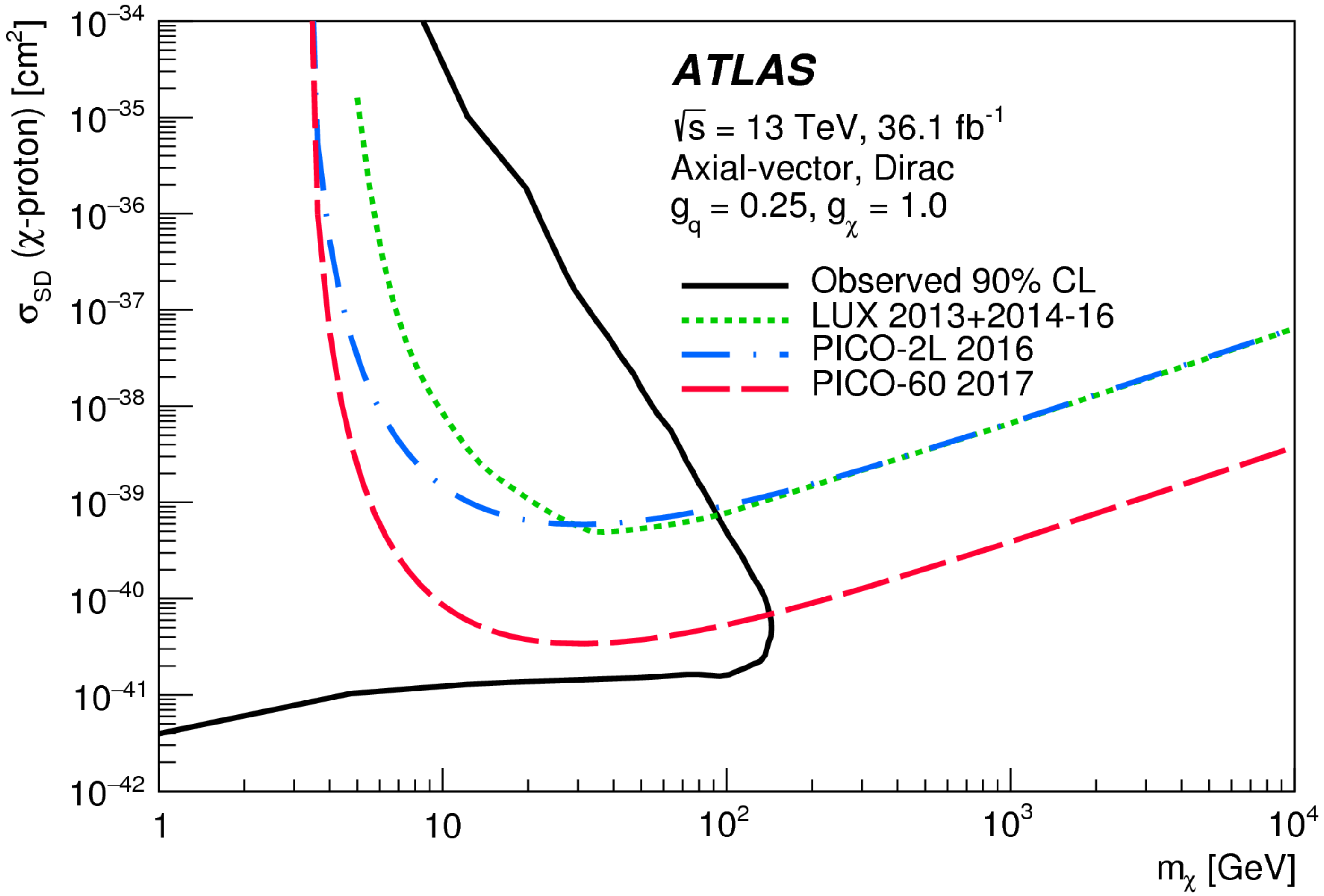


Results and interpretation (2)

Combination

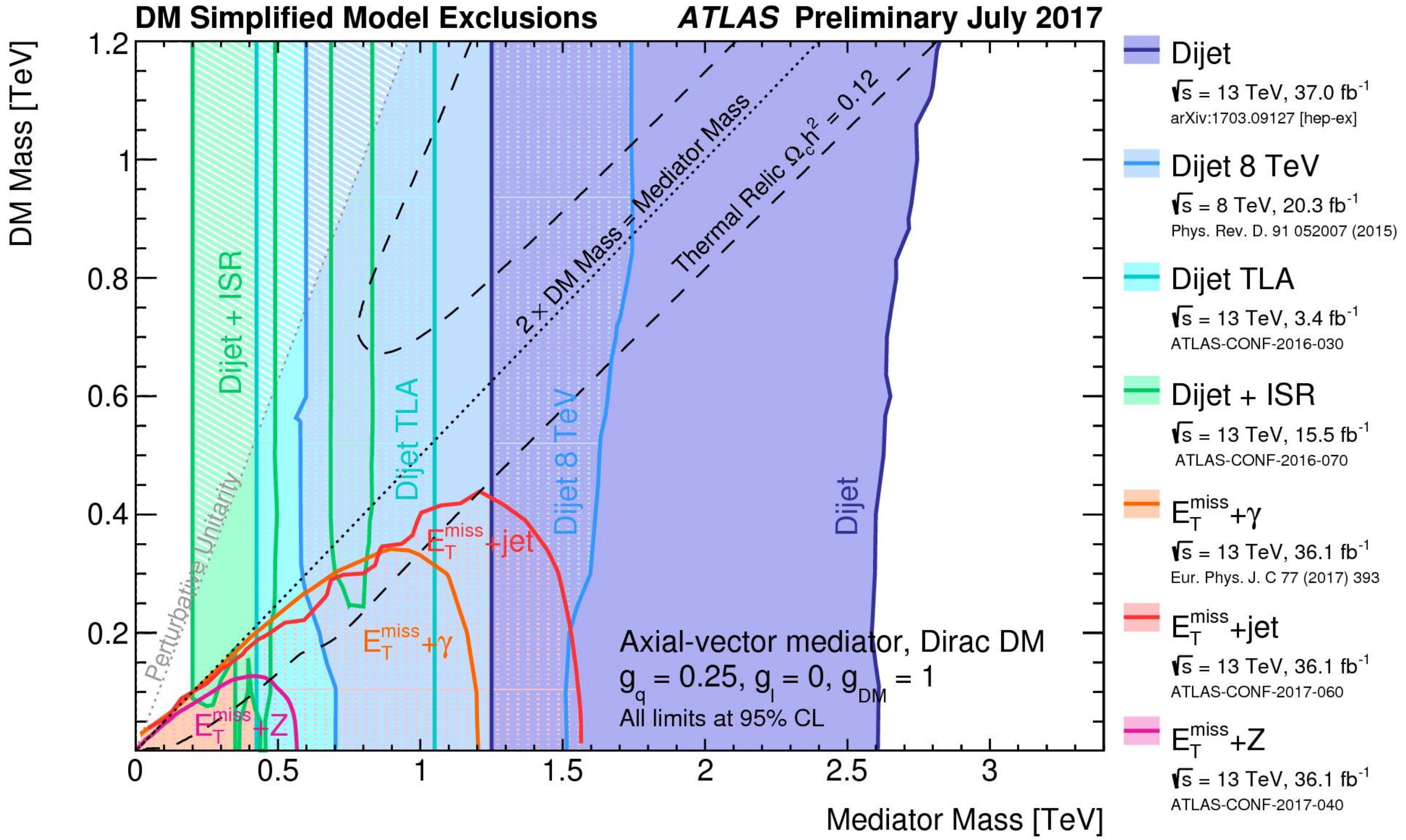


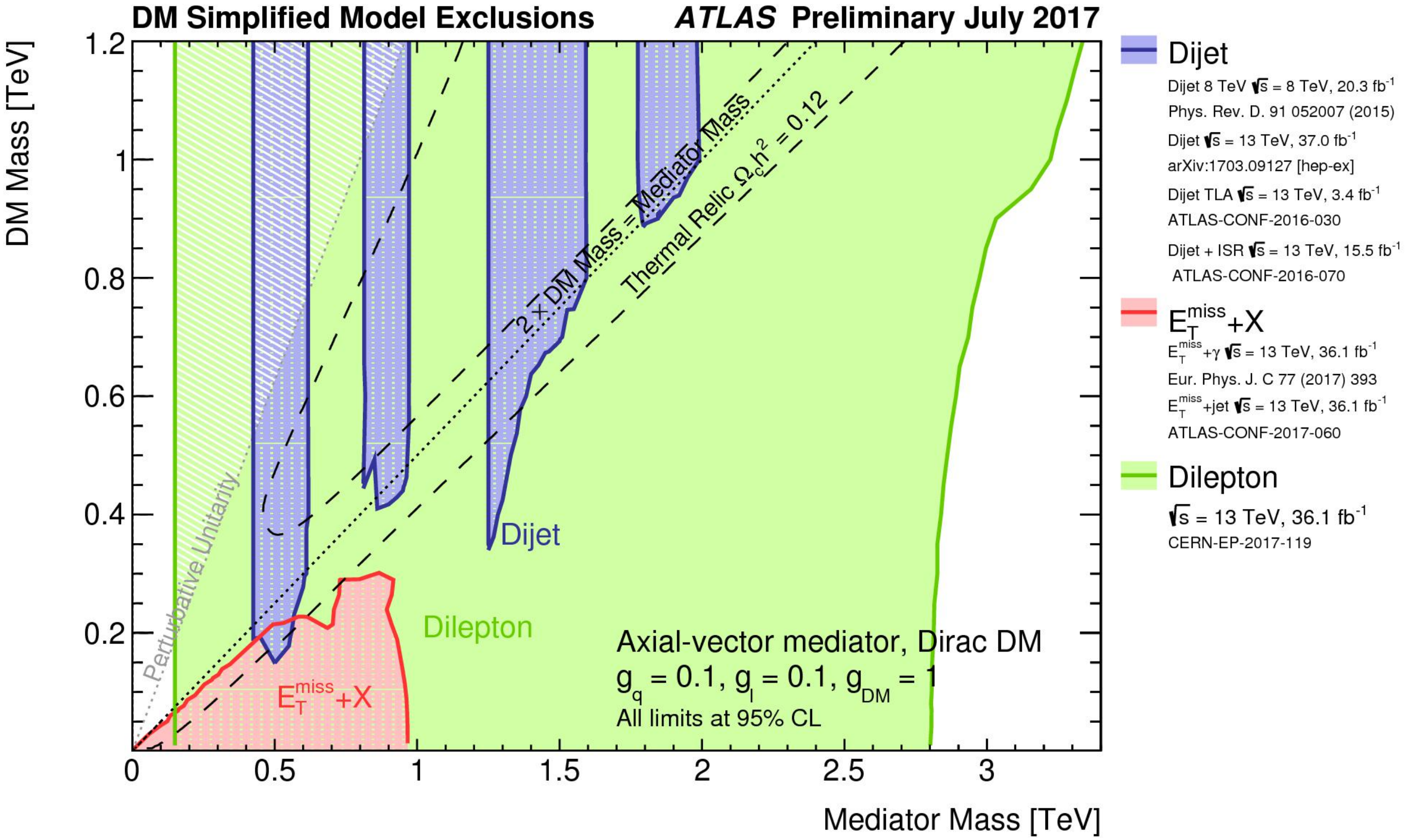
Comparison to direct detection



Combinations: mediator-DM mass plane

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/



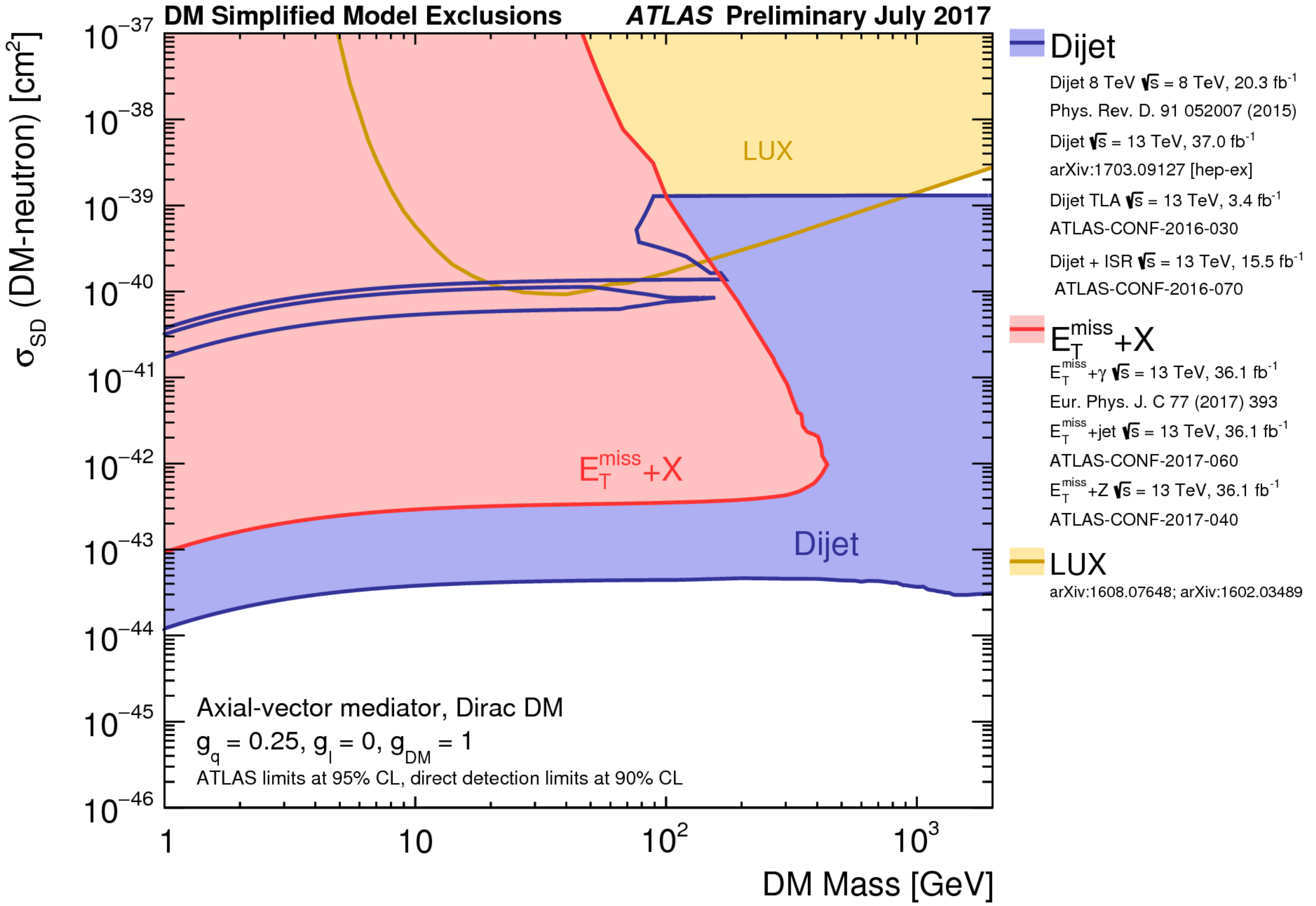


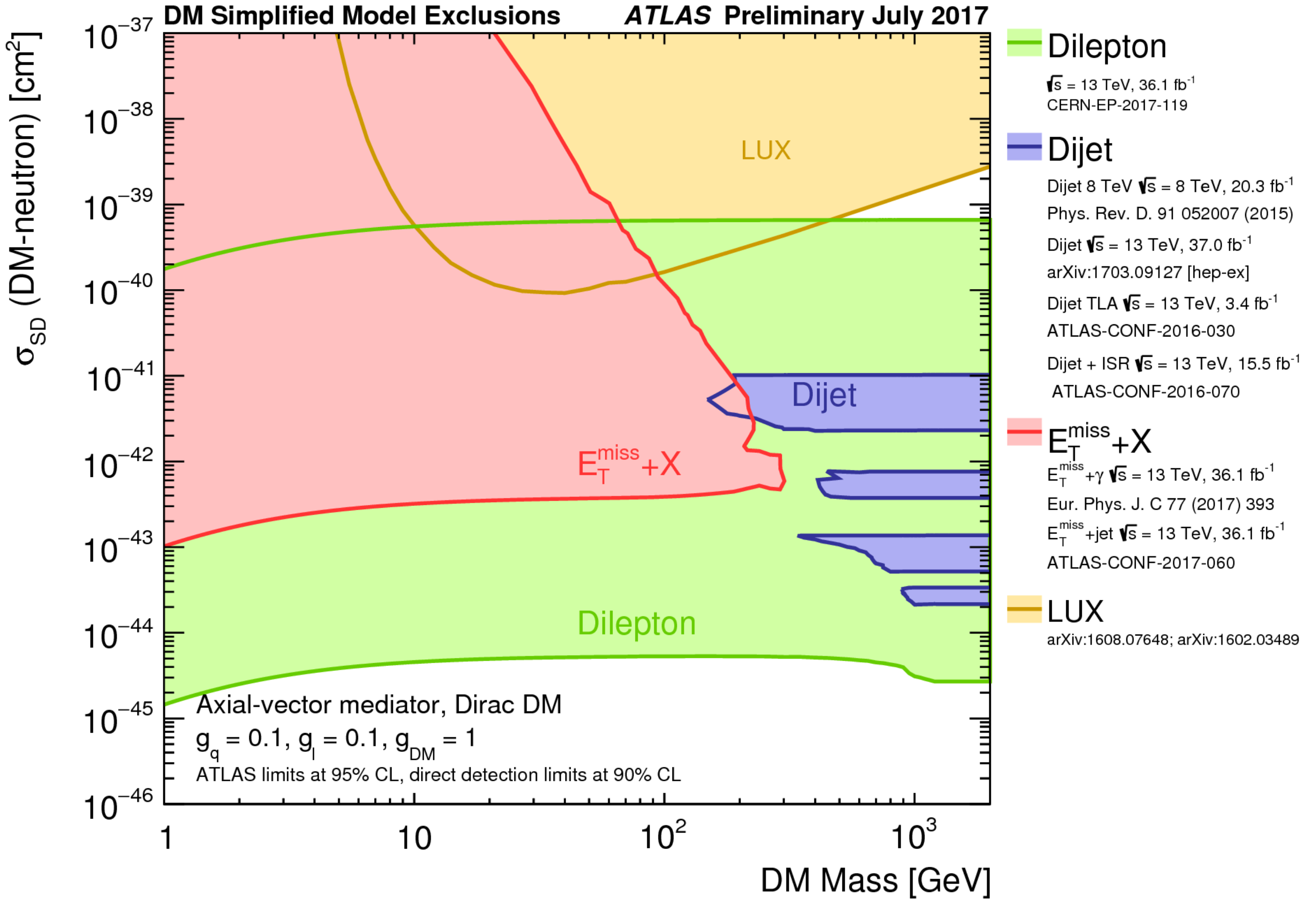
- Axial vector mediators with **no leptonic coupling**s, only mediators coupling to quarks and dark matter.
- *Dijet* analyses place the most stringent limits

- Axial vector mediators with **small leptonic couplings** and mediators coupling to quarks and dark matter.
- *Dilepton* analyses place the most stringent limits

Combinations: comparison to direct detection

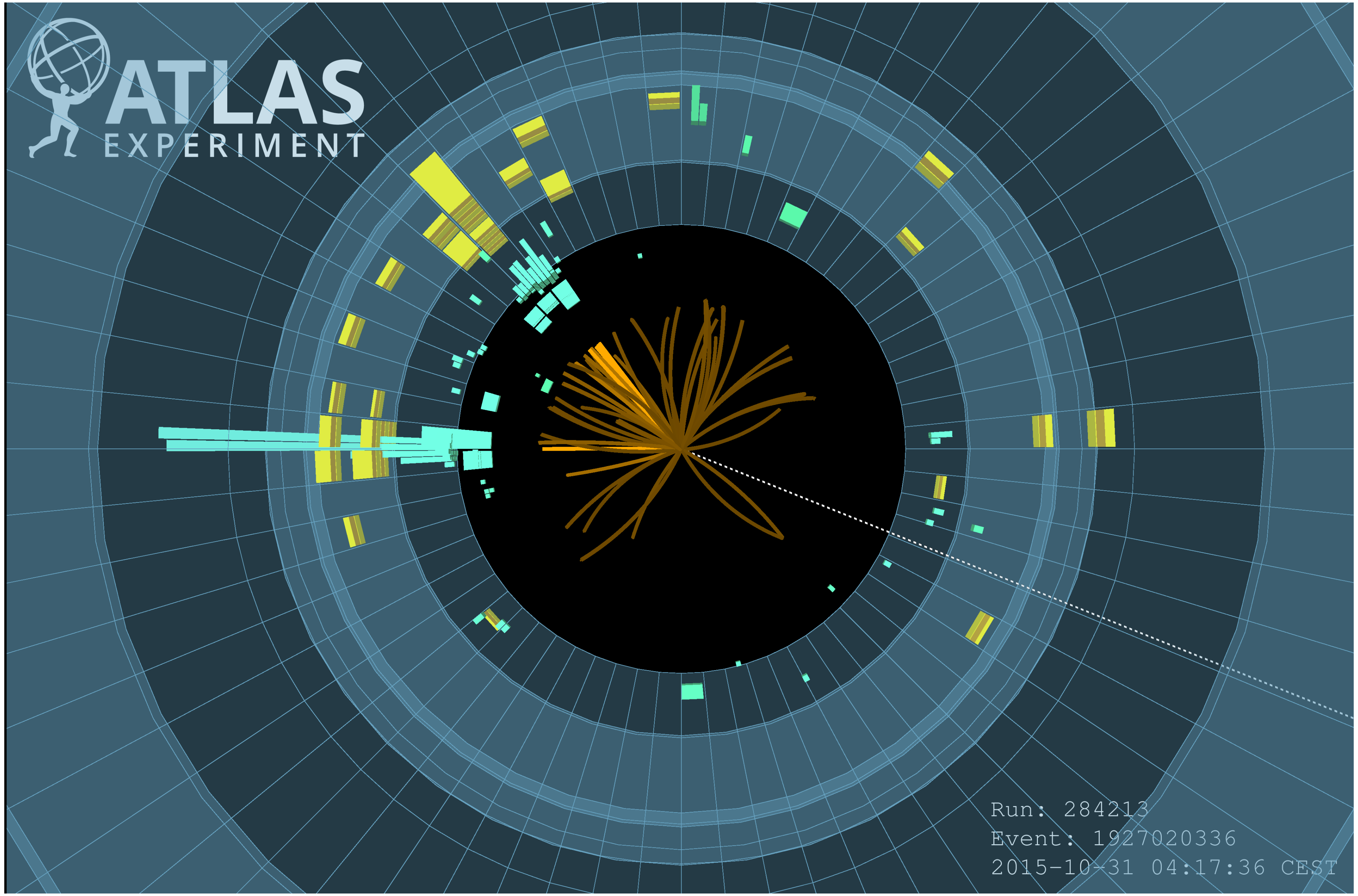
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/





bb+MET

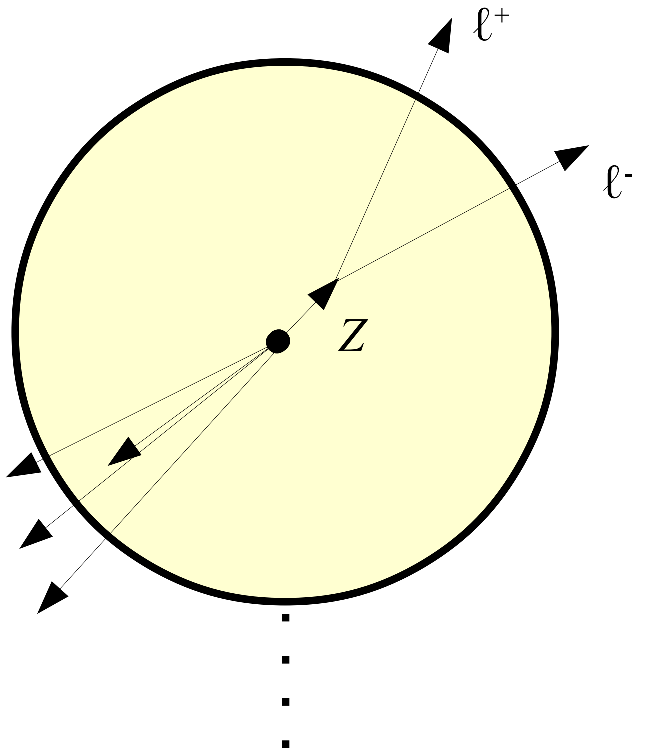
Potential dark matter + b-quarks



Link to Plot

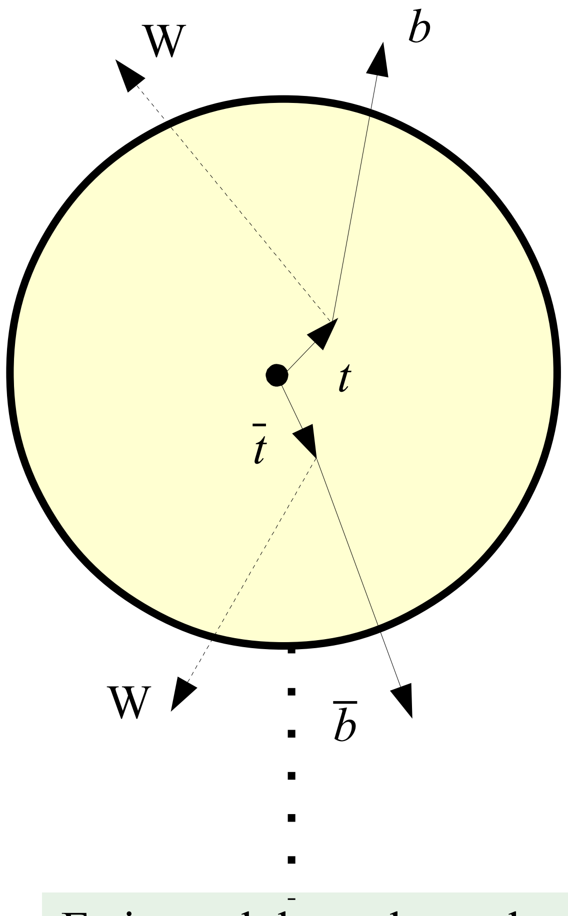
Standard Model in the detector: backgrounds to the analysis

$Z + \text{jets}$



Estimated through dedicated control region

$t\bar{t}$



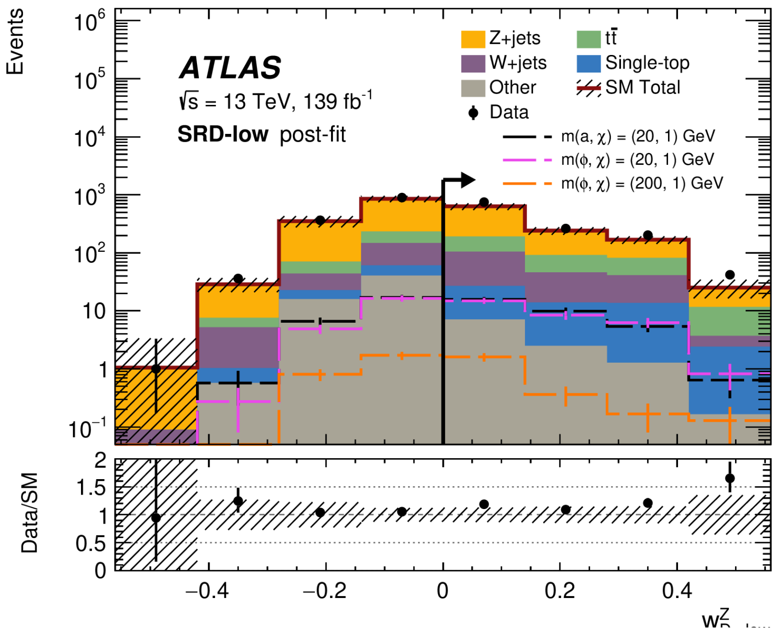
Estimated through another control region

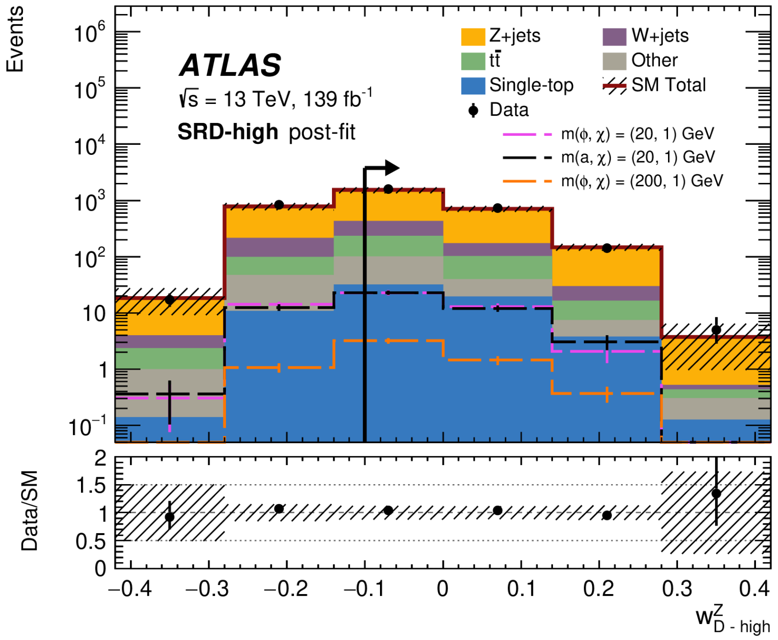
+ Others (single t, W+jets, diboson, tt+V)

Boosted decision tree

- Trained on uncorrelated discriminating variables.
- Signals separated into low and high masses for training
- Weights applied to events based on training

Mediator	Mediator mass (GeV)	NLO cross section (pb)	Rel. Unc. (%)
ϕ & a	10	29	60
ϕ & a	20	14	42
ϕ & a	50	3.2	30
ϕ & a	100	0.69	20
ϕ & a	200	$93 \cdot 10^{-3}$	13
ϕ & a	300	$22.7 \cdot 10^{-3}$	8.8
a	500	$1.5 \cdot 10^{-3}$	10.0
ϕ	500	$1.9 \cdot 10^{-3}$	10.0





Some specific selection criteria

Variable		SRD-low	SRD-high	CRzD-low	CRzD-high	VRzD-low	VRzD-high
Trigger plateau		$(p_T(j_1) - 20\text{ GeV})(E_T^{miss} - 160\text{ GeV}) > 5000\text{ GeV}^2$					
N_{jets}		2–3					
$N_{b\text{-jets}}$		≥ 2					
$p_T(j_1)$	[GeV]	> 100					
$p_T(j_2)$	[GeV]	> 50					
$\min[\Delta\phi(\text{jet}_{1-3}, \mathbf{p}_T^{miss})]$	[rad]	> 0.4					
$\mathcal{S}$		> 7					
$p_T(j_1)/H_T$		> 0.7					
Number of baseline leptons		0		2		0	
Number of high-purity leptons		–		2 SFOS		–	
$p_T(\ell_1)$	[GeV]	–		> 27		–	
$p_T(\ell_2)$	[GeV]	–		> 20		–	
$m_T(\ell, \mathbf{p}_T^{miss})$	[GeV]	–		> 20		–	
$m_{\ell\ell}$	[GeV]	–		[81, 101]		–	
$\tilde{E}_T^{miss}$	[GeV]	–		> 180		–	
E_T^{miss}	[GeV]	> 180		< 100		> 180	
$w^{tt}_{\text{D-low}}$		> 0	–	–		> 0	–
$w^{Z}_{\text{D-low}}$		> 0	–	> 0	–	[−0.2, 0]	–
$w^{W}_{\text{D-low}}$		> 0	–	–		> 0	–
$w^{tt}_{\text{D-high}}$		–	> 0	–		–	> 0
$w^{Z}_{\text{D-high}}$		–	> -0.1	–	> -0.1	–	[−0.3, −0.1]
$w^{W}_{\text{D-high}}$		–	> -0.05	–		–	> -0.05

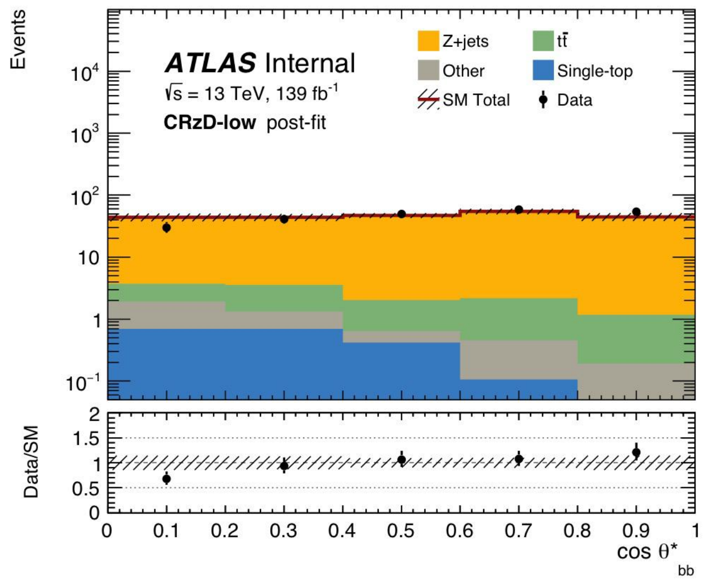
Key separation variable between irreducible background and signal

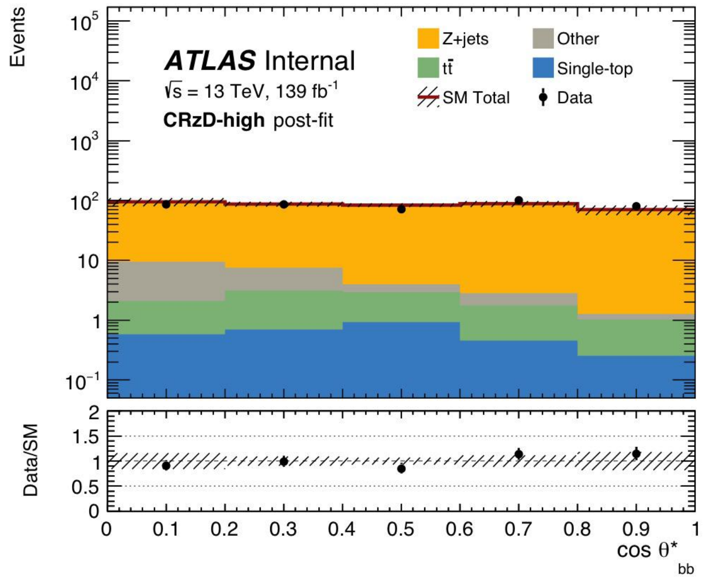
$$\delta^- = \Delta\phi(\mathrm{j}, \vec{p}_T^{miss}) - \Delta\phi_{bb},$$
$$\delta^+ = |\Delta\phi(\mathrm{j}, \vec{p}_T^{miss}) + \Delta\phi_{bb} - \pi|.$$

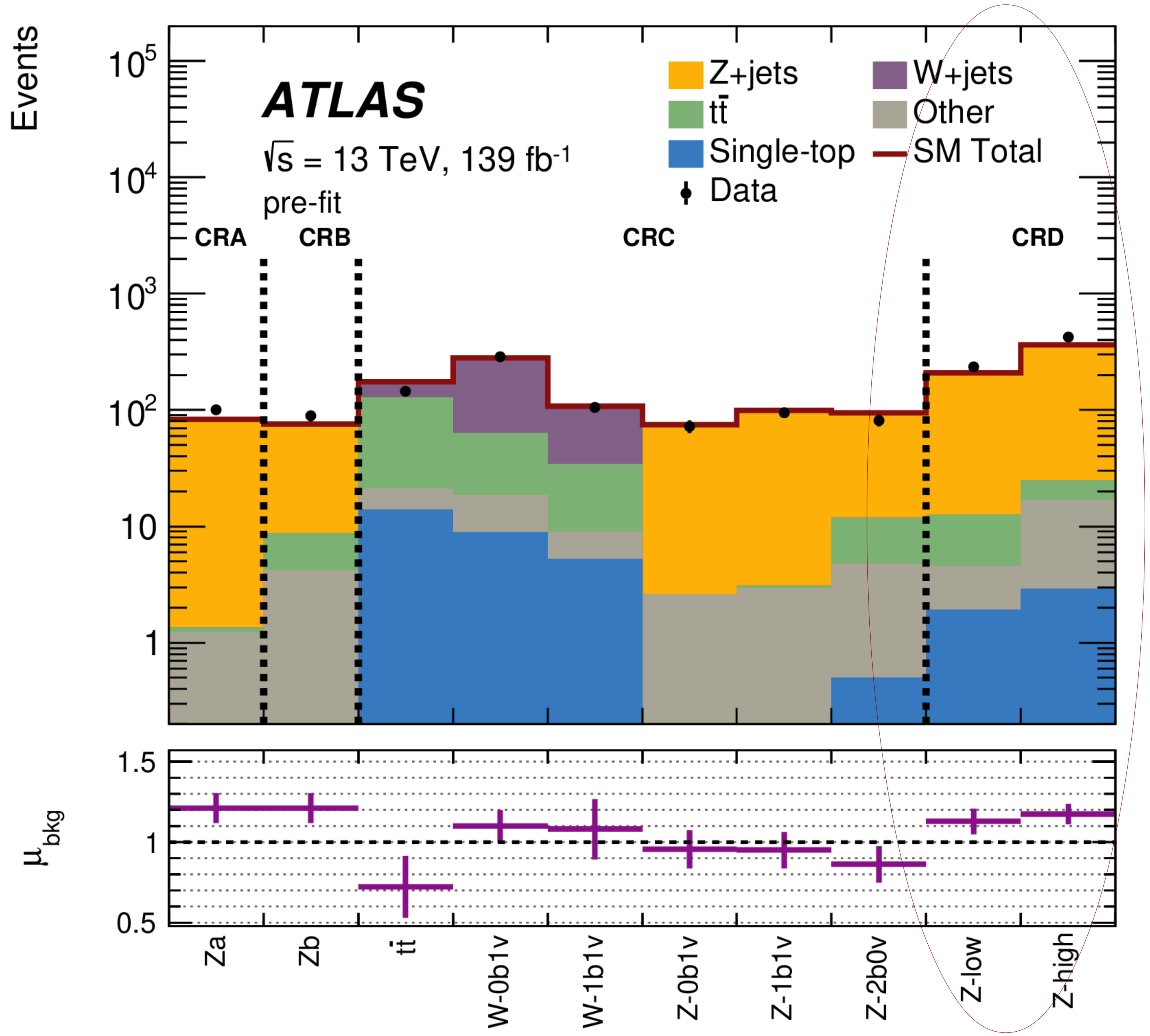
Variable of interest: Exploits differences between scalar/pseudoscalar

$$\cos\theta^*_{bb} = \left|\tanh\left(\frac{\Delta\eta_{bb}}{2}\right)\right|$$

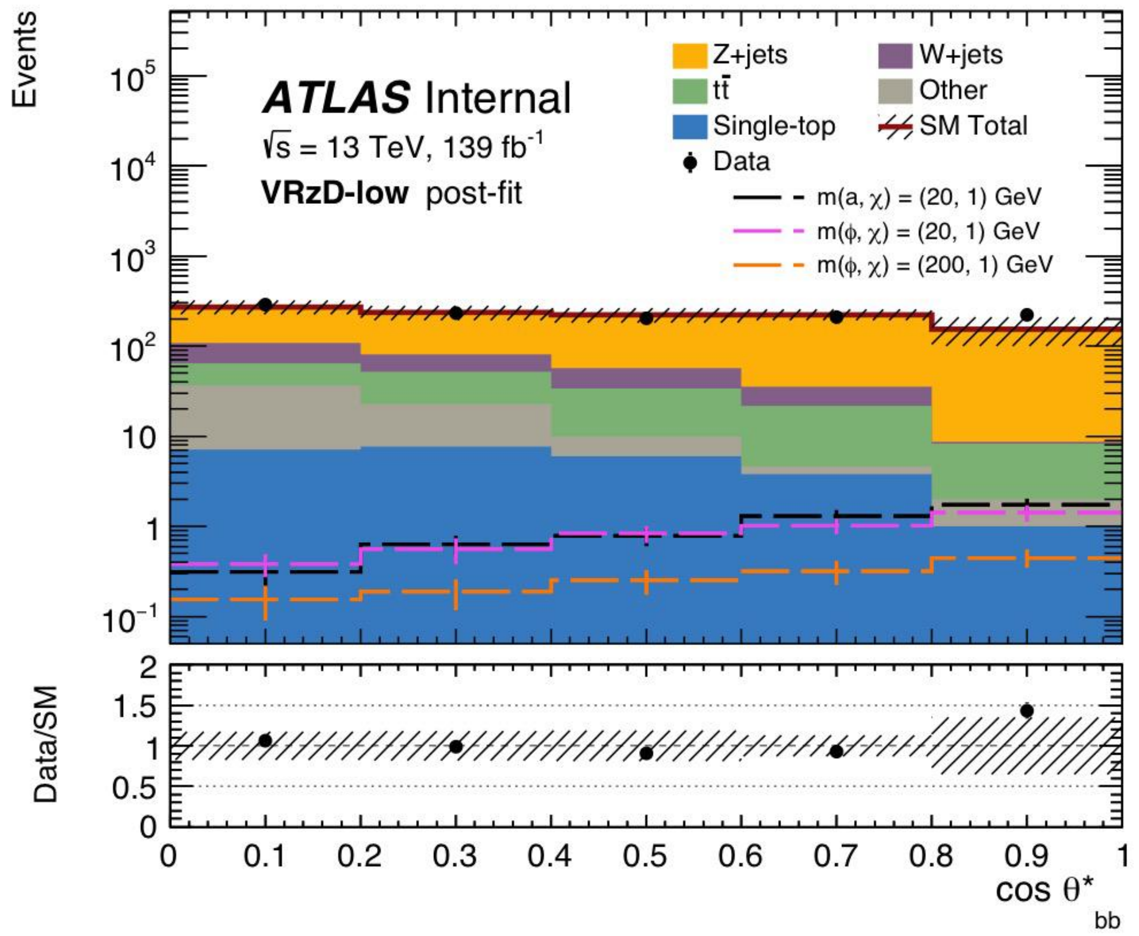
Background estimation and fitting

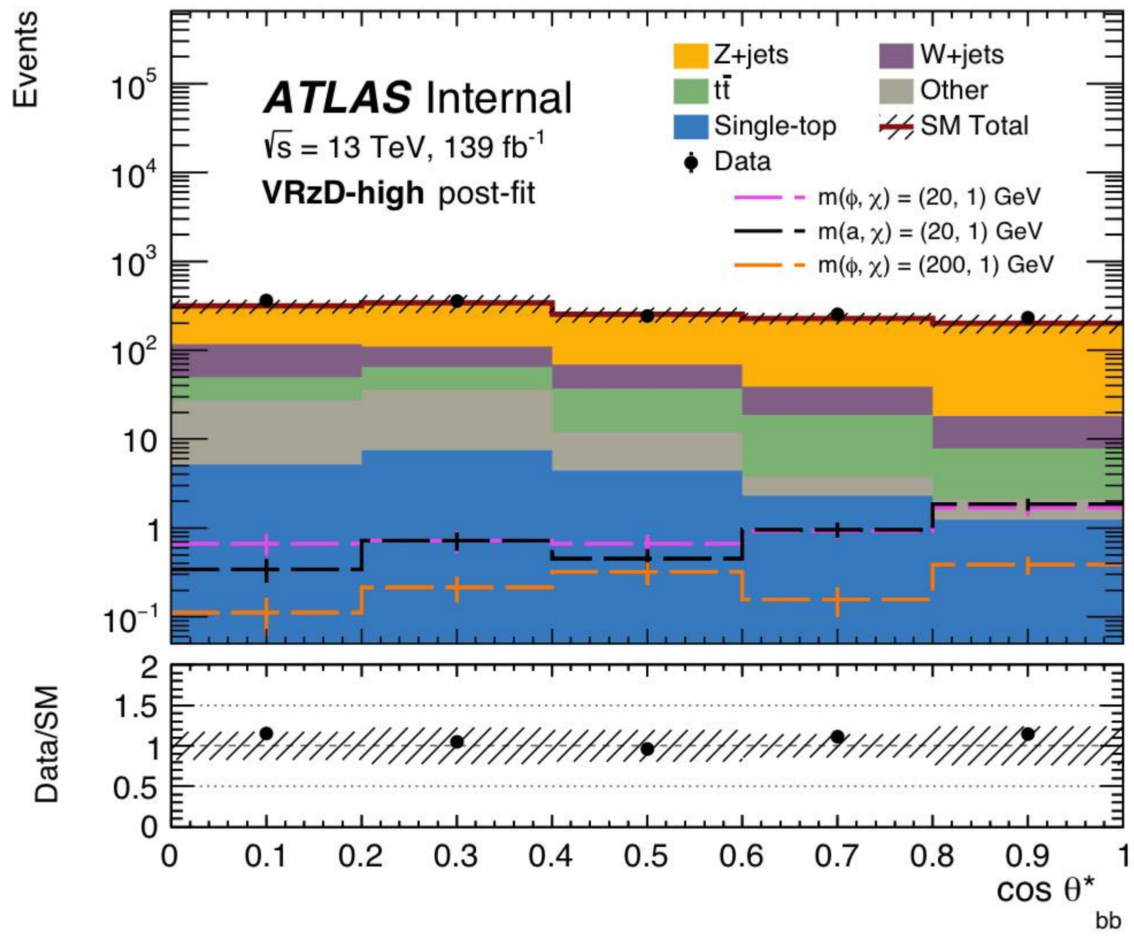




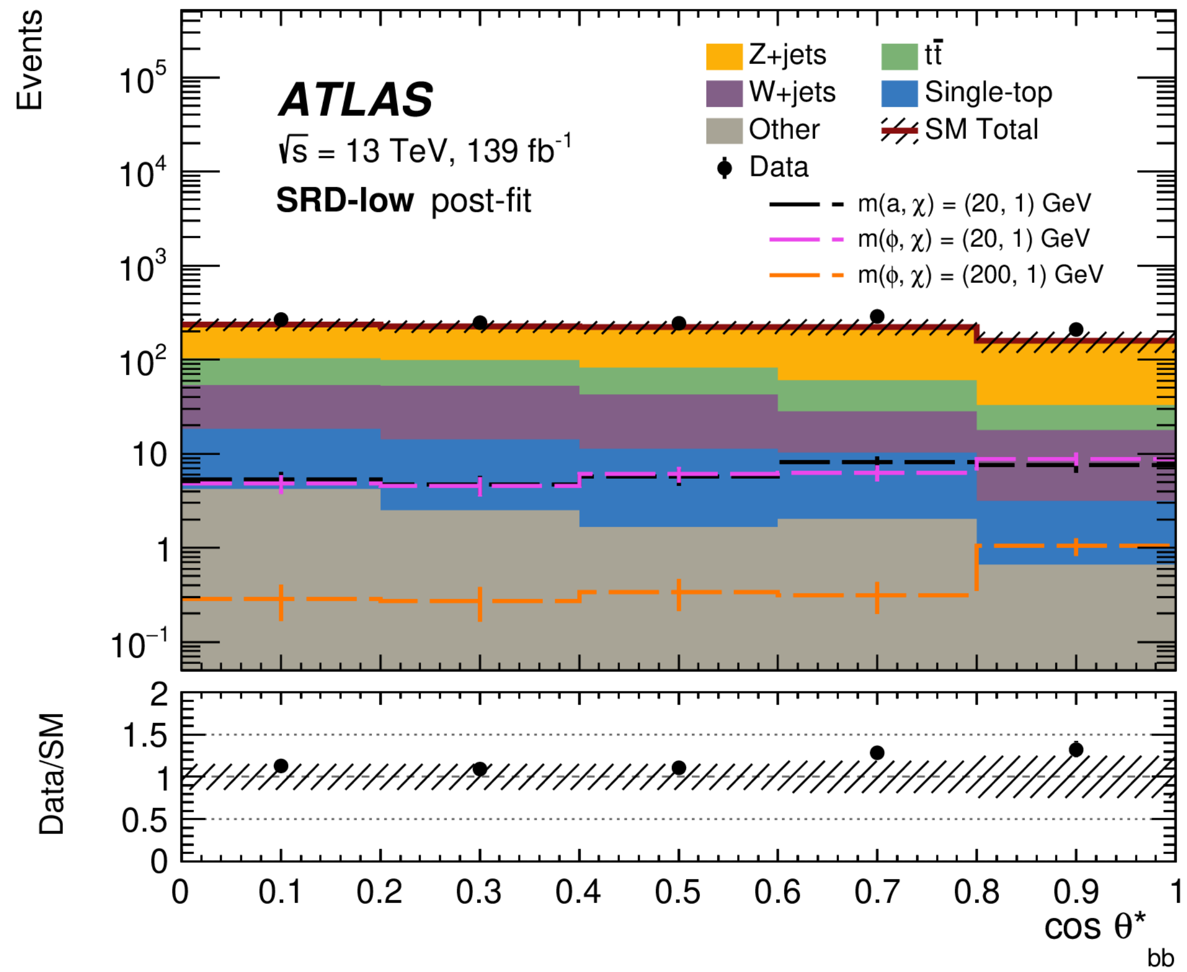


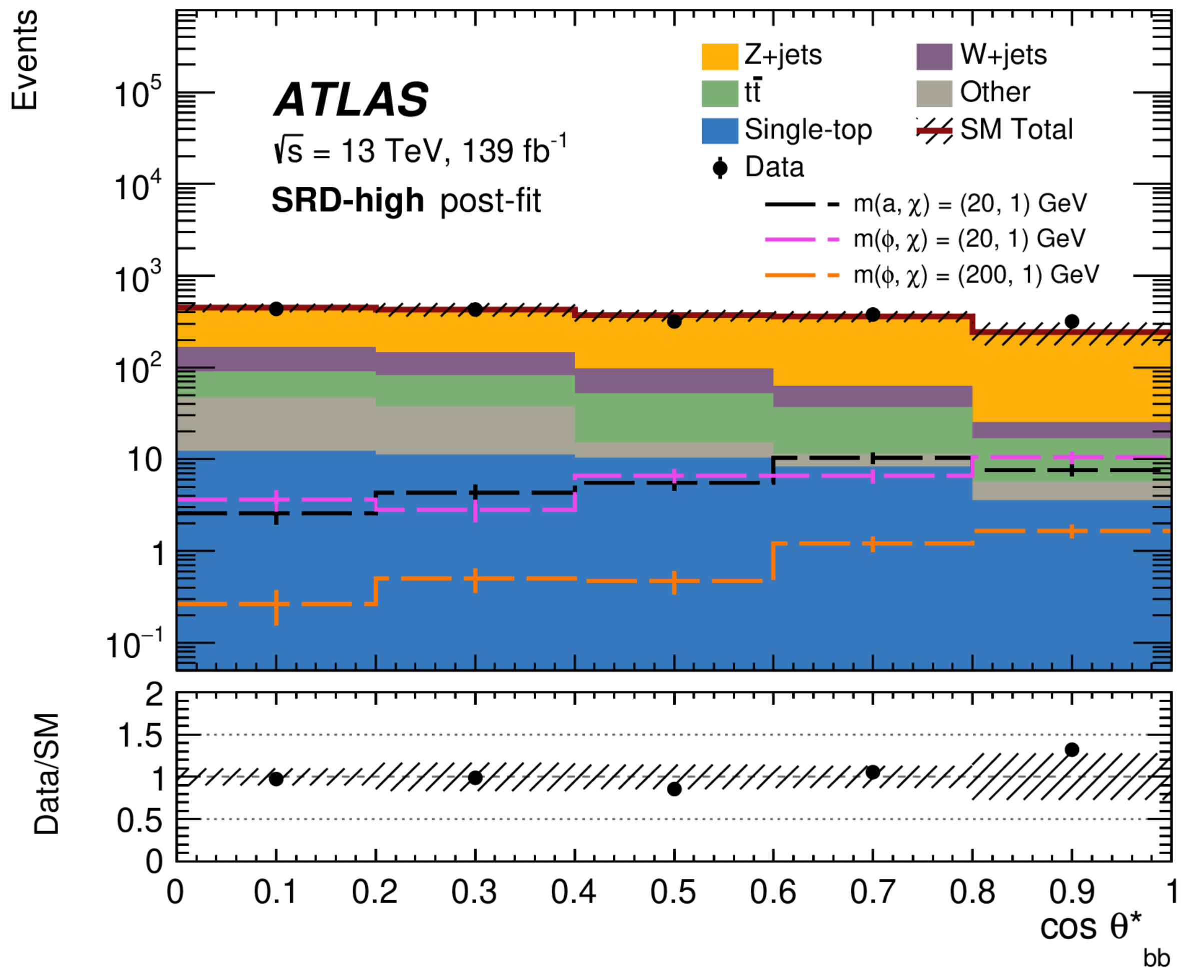
Validation of the fit





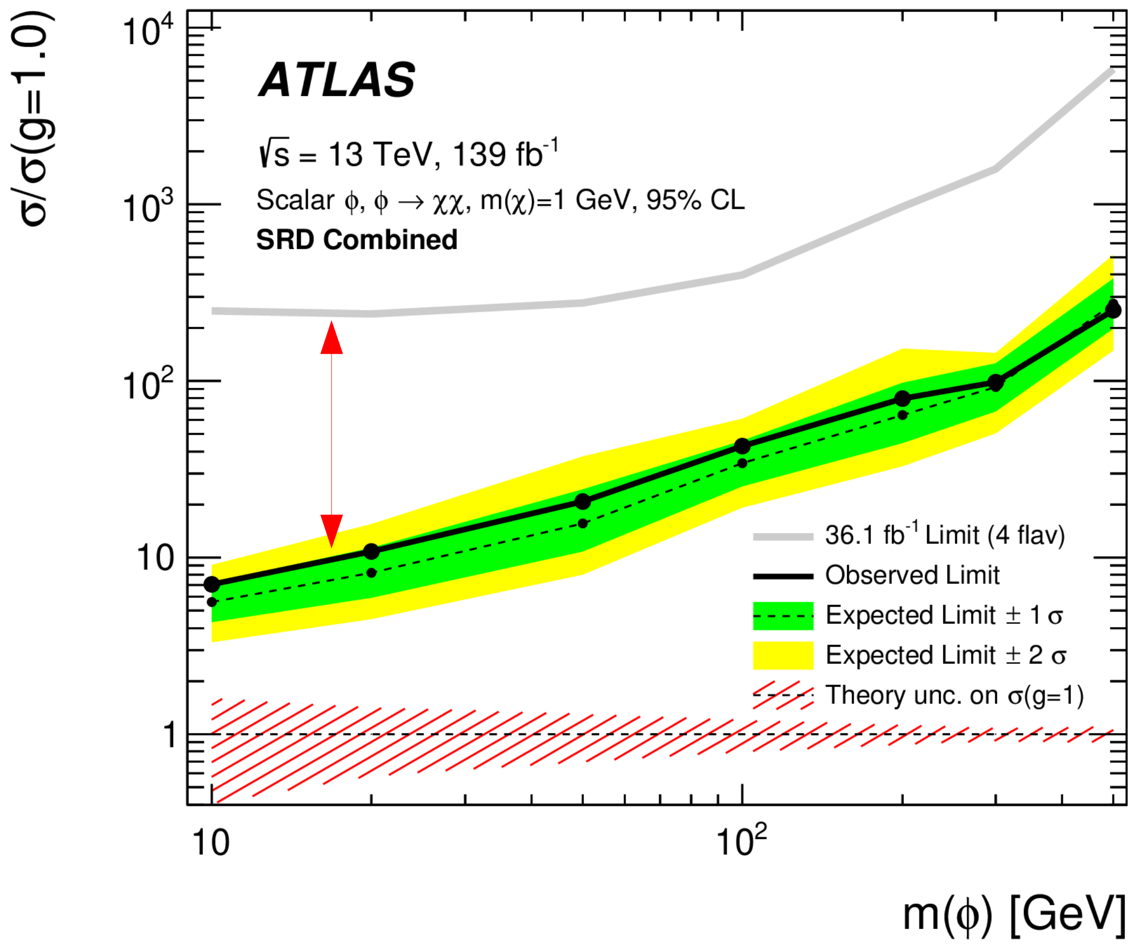
Final results

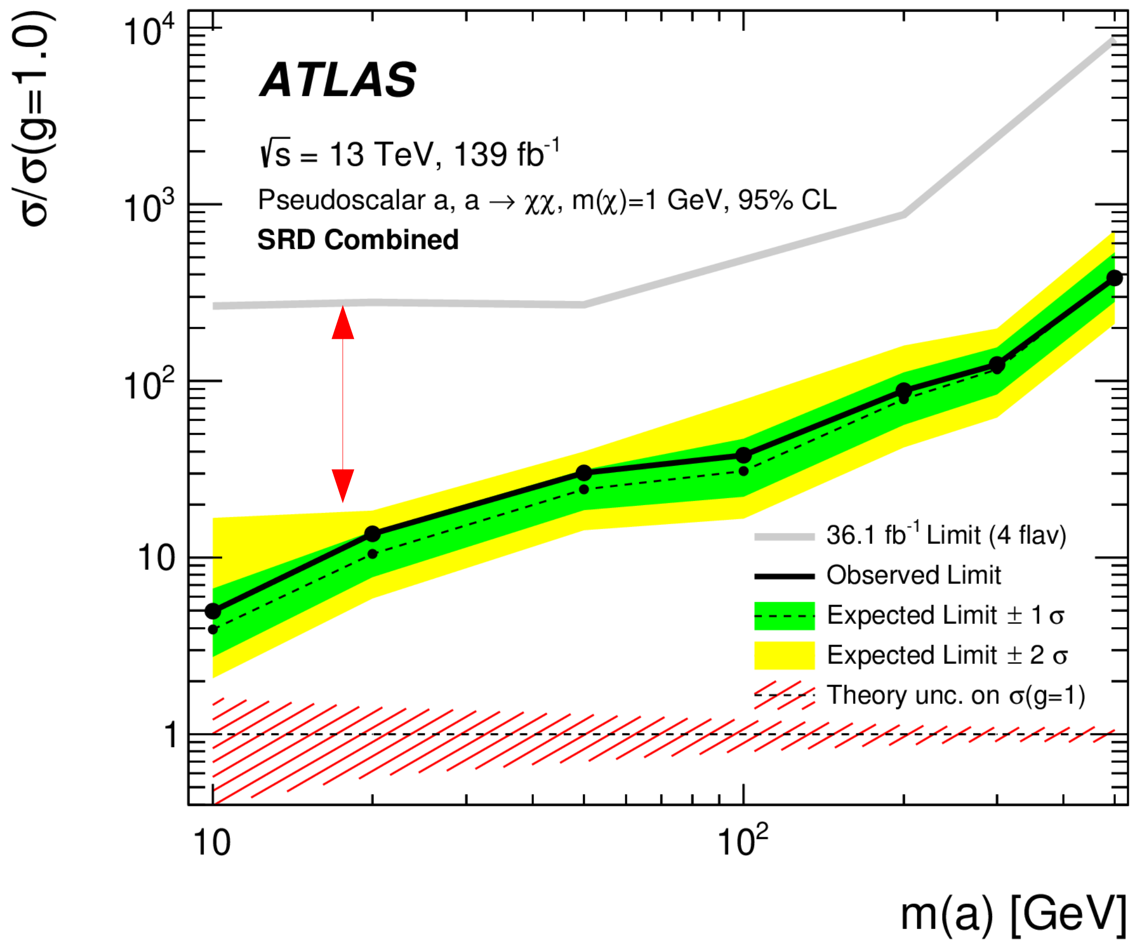




Signal channel	Obs.	SM exp.	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_B	$p(s=0)$ (Z)
SRD-low	497	381 ± 76	1.8	250	155^{+65}_{-60}	0.91	0.07 (1.48)
SRD-high	320	242 ± 66	1.4	195	140^{+48}_{-44}	0.82	0.13 (1.13)

Limit plots

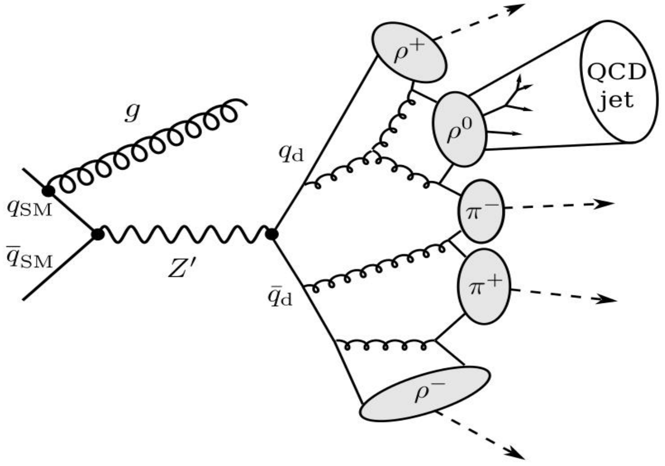

ATLAS
√s = 13 TeV, 139 fb-1
Scalar ϕ, ϕ → χχ, m(χ)=1 GeV, 95% CL
SRD Combined
36.1 fb-1 Limit (4 flav)
Observed Limit
Expected Limit ± 1 σ
Expected Limit ± 2 σ
Theory unc. on σ(g=1)
σ/σ(g=1.0)
m(ϕ) [GeV]


ATLAS
√s = 13 TeV, 139 fb-1
Pseudoscalar a, a → χχ, m(χ)=1 GeV, 95% CL
SRD Combined
36.1 fb-1 Limit (4 flav)
Observed Limit
Expected Limit ± 1 σ
Expected Limit ± 2 σ
Theory unc. on σ(g=1)
σ/σ(g=1.0)
m(a) [GeV]

Dark and semi-visible jets

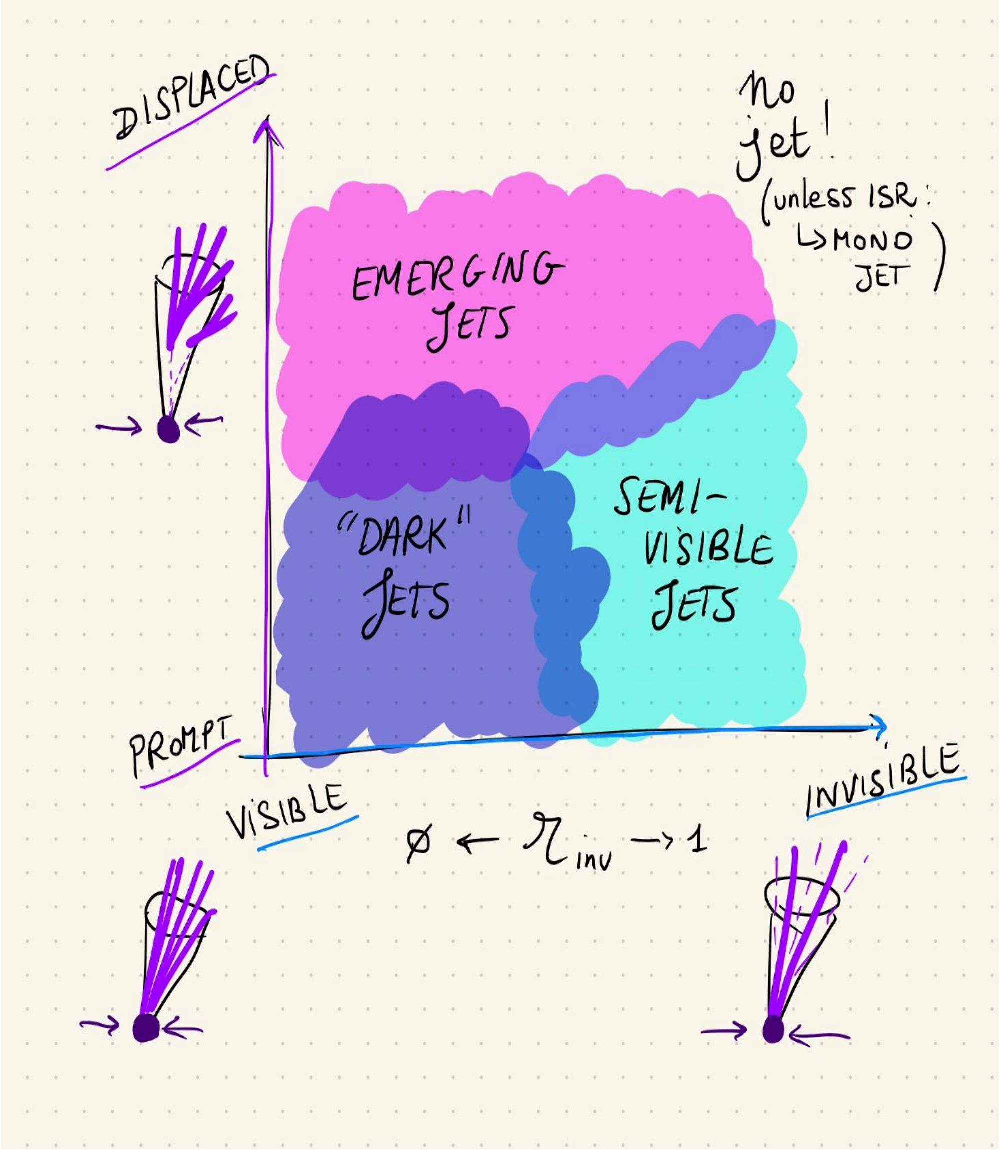
Dark sector phenomenology

- Semi-visible jets motivation
  - Complex, prompt signature that has the unusual signature of jets aligned with missing ET
  - Dark hadrons decaying in a QCD-like fashion, fully (**dark jets**) or partially back to visible sector (**semi-visible jets: SVJ**)

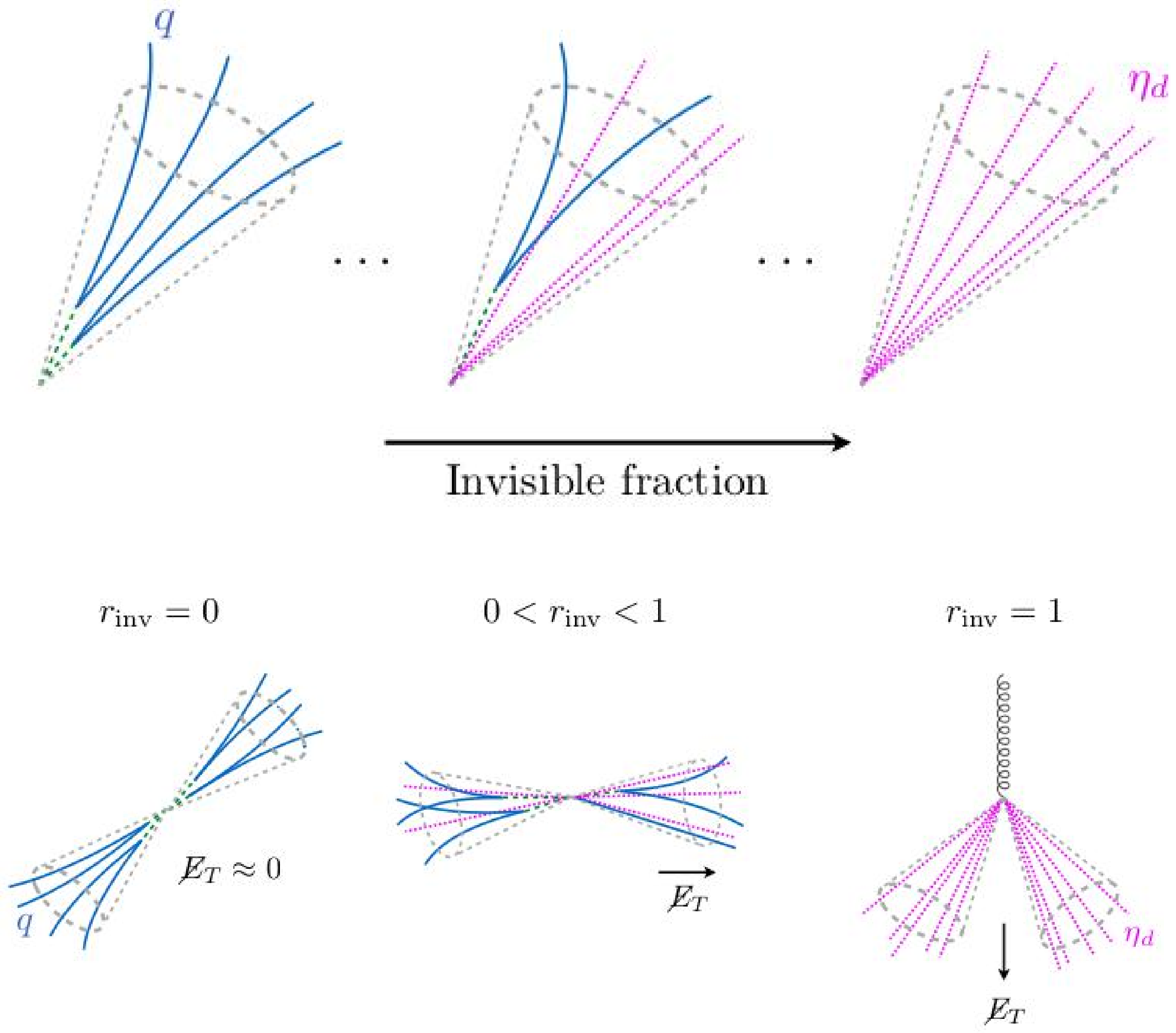


Hard scatter either via Madgraph or via Pythia's Z'

Showering using Pythia Hidden Valley module

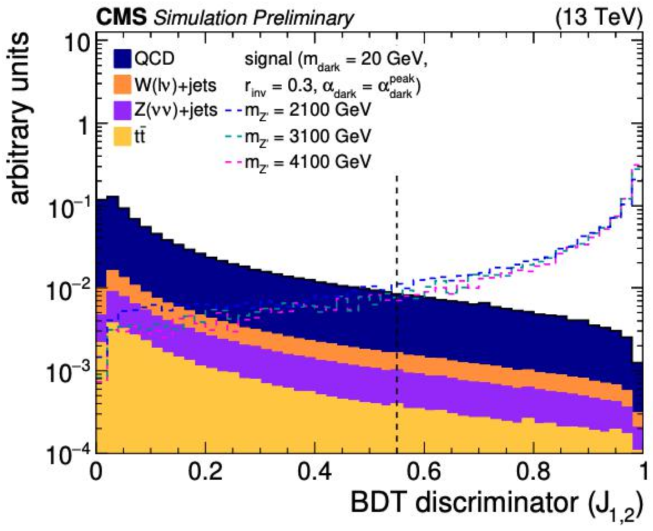


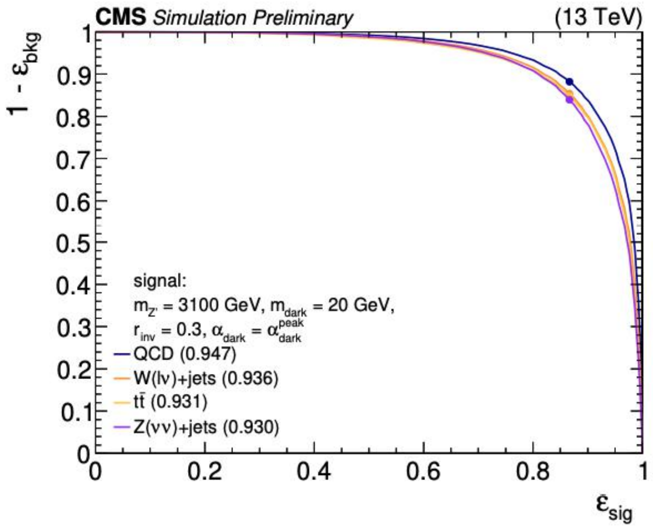
Semi-visible jets phenomenology

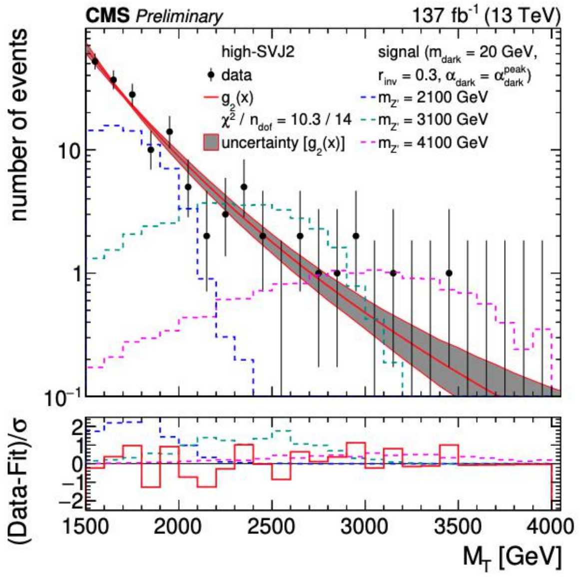


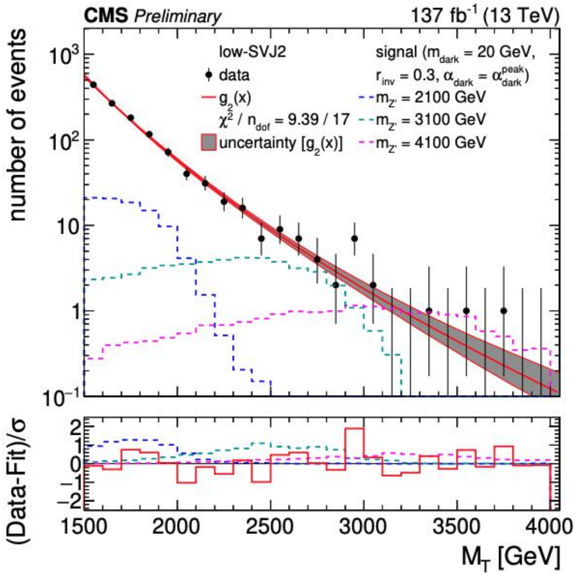
- r_{inv} is the fraction of stable (invisible/dark-matter-like) particles inside the jet
- This fraction determines event topology and the analysis strategy
    - r_{inv}=0: dark jets analysis
    - r_{inv}=1: mono-X search
    - $0 < r_{inv} < 1$: SVJ
        - t-channel
        - s-channel
- No publications in ATLAS! One from CMS!

Results on SVJ from CMS

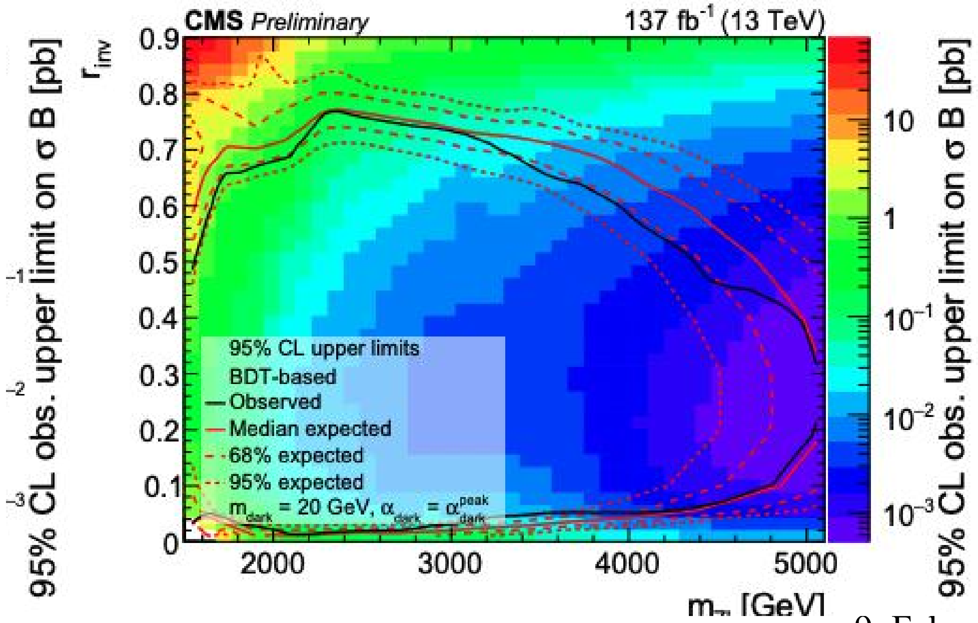






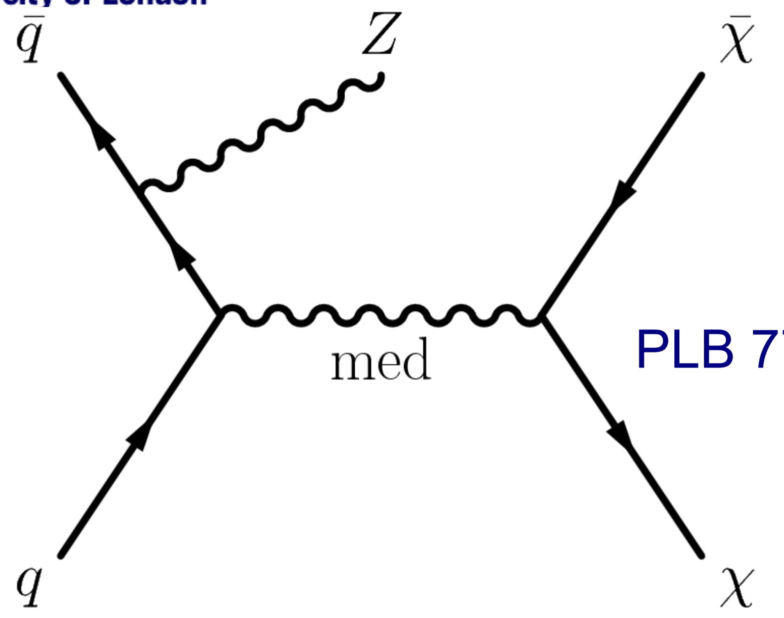


- BDT used on substructure to discriminate from QCD
- However, a cut-and-count approach also published, as the BDT relies too much on the model itself
- Limits set on r_{inv} between 0.05 and 0.7 and between 1.5 and 5 TeV mediator mass



summary

Recap! Mono-Z(ll)



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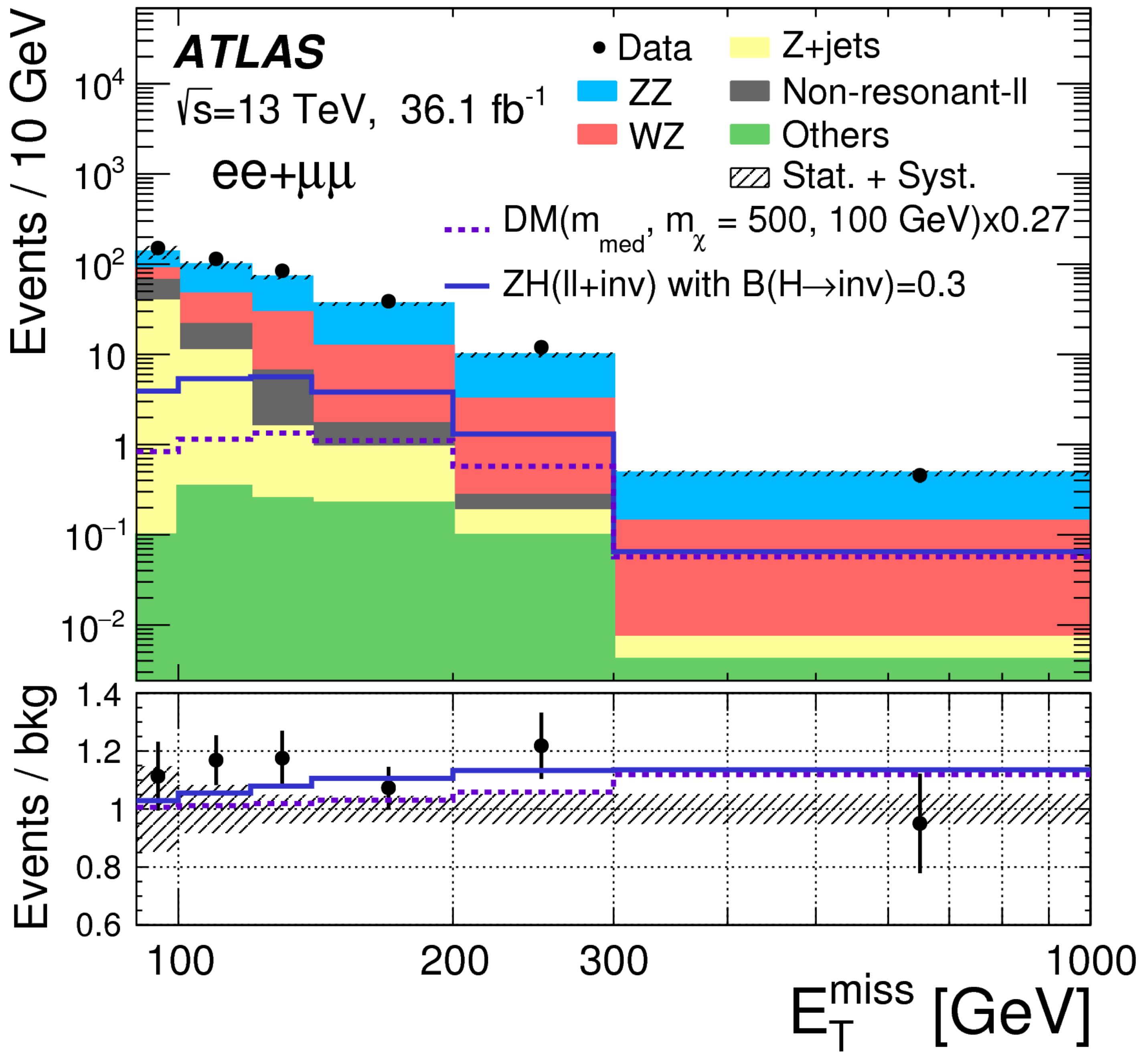
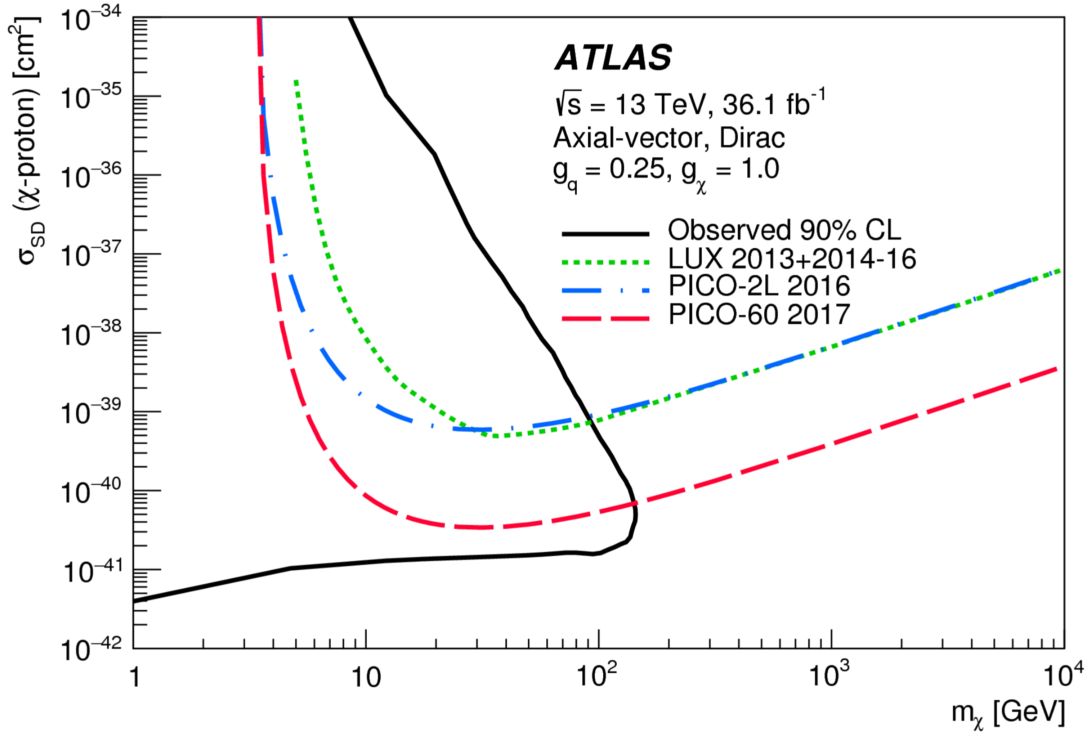


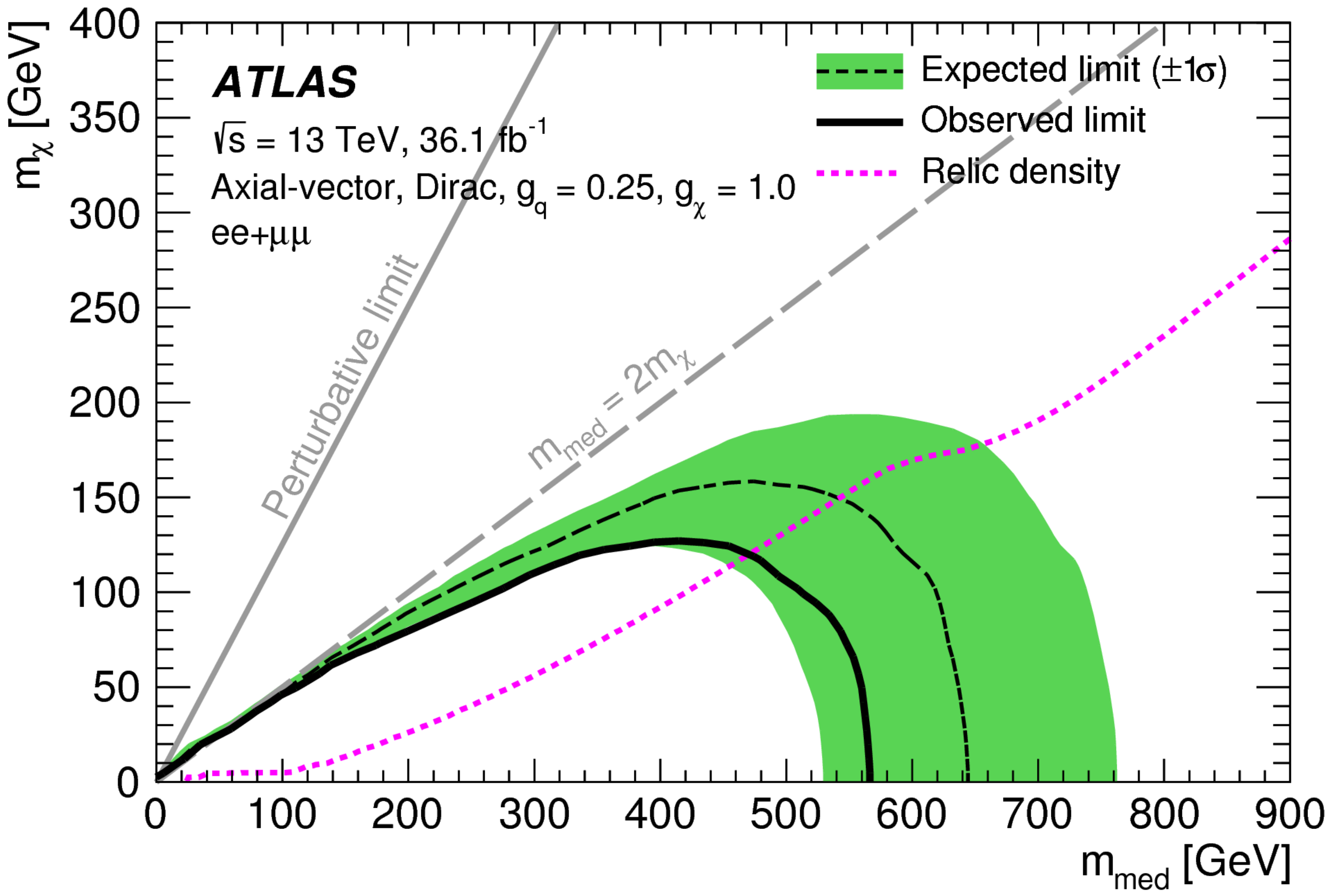
Dataset: 36.1 fb^{-1} (2015+2016)

- Event selection highlights
  - $E_T^{miss} > 90$ GeV
  - B-jet veto, third lepton veto
- Main backgrounds & estimation:
  - ZZ(→ llvv)
  - WZ(→ llvl), Z(→ ll,) ll non-resonant

Mono-Z(ll) results

- Two signal regions:
  - final states with ee
  - final states with μμ
- Limits are set on the mediator mass to about 550 GeV





Recap! bb+MET

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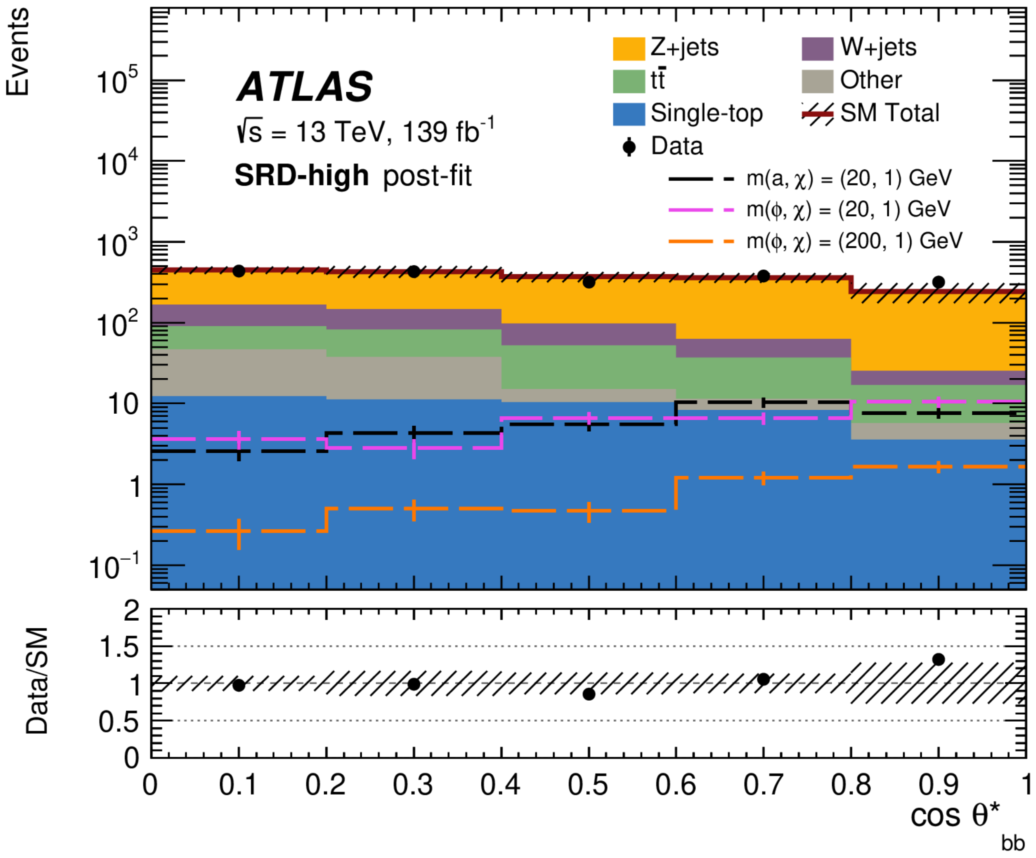
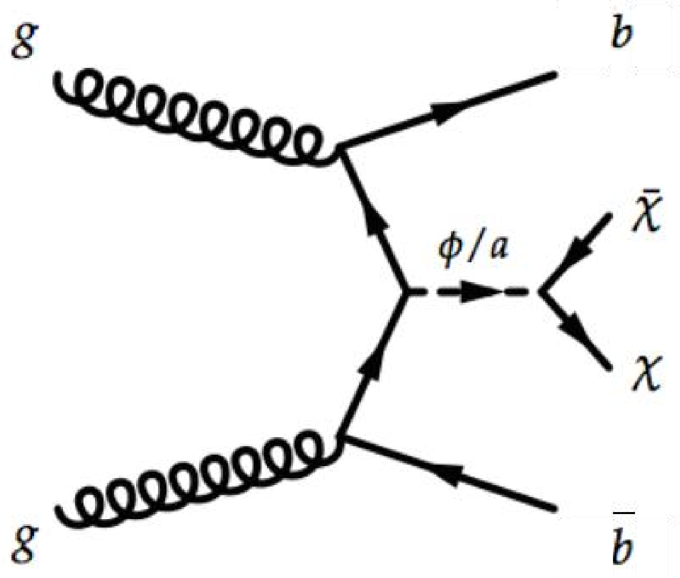
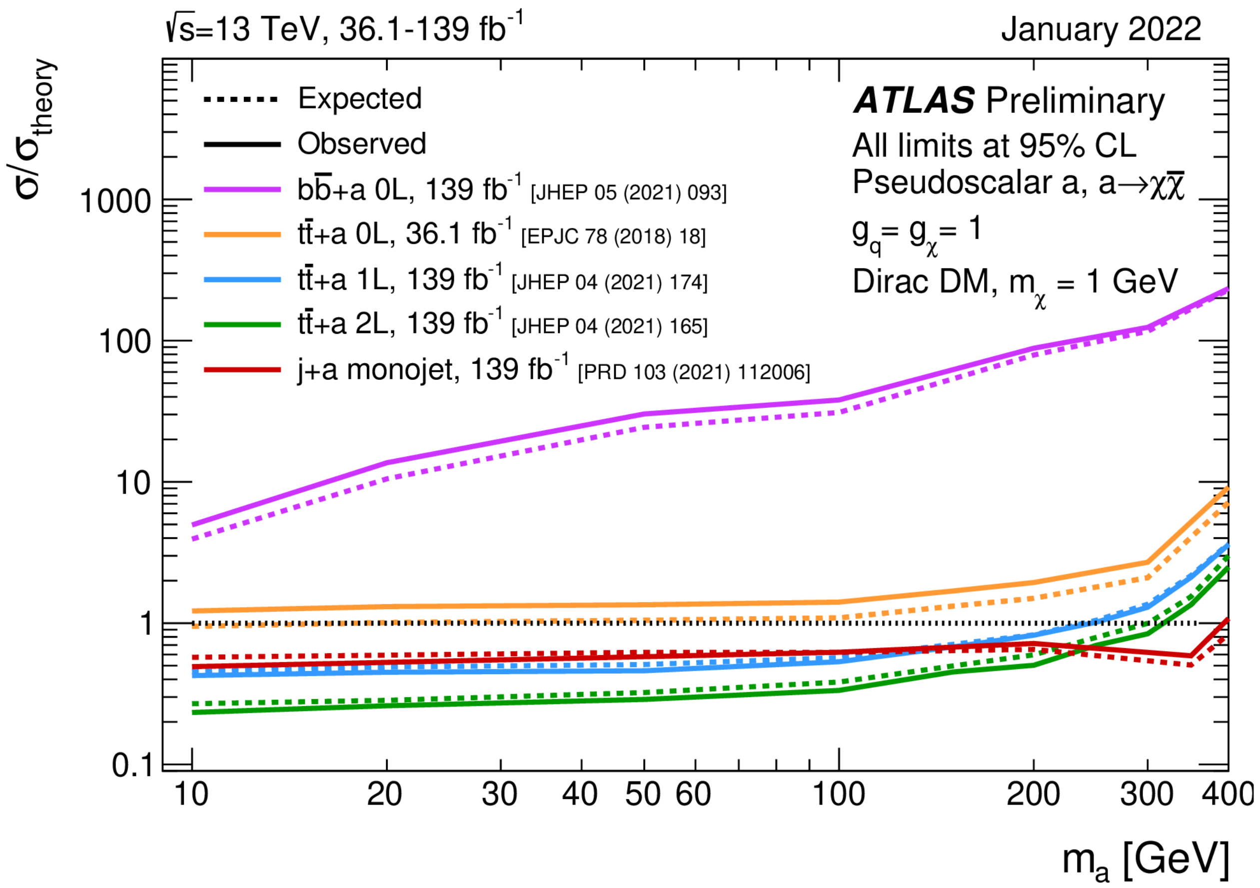


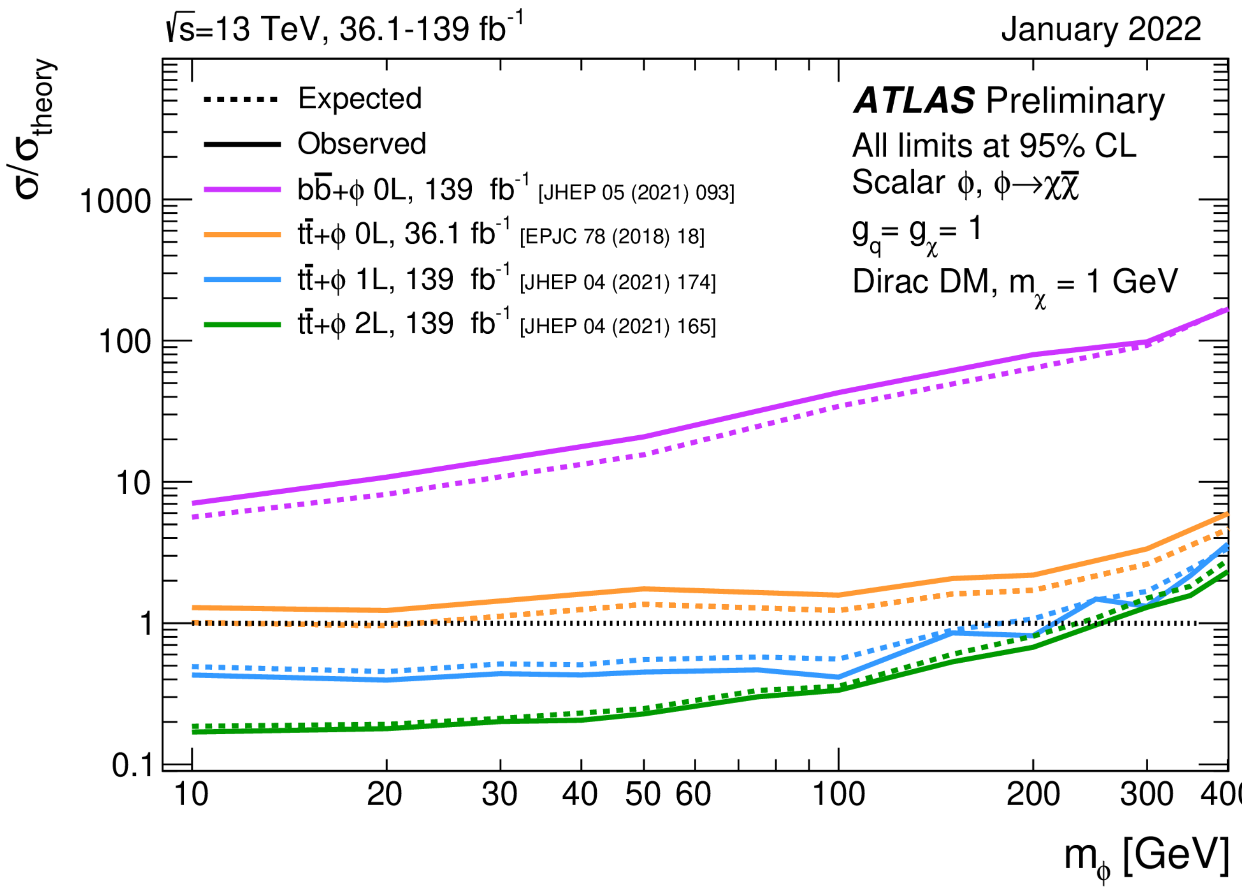


Dataset: 139 fb^{-1} (2015-18)

- Event selection highlights
  - Two b-tagged jets, imbalanced in p_T
  - $E_T^{miss} > 180$ GeV
  - Lepton veto
- Backgrounds & estimation:
  - Z(→ νν)+HV jets, Top, W+jets
  - BDT provides background separation
  - Backgrounds fit simultaneously in CR

MET + bb results in context





- Best limits are for the lowest mass mediators – 10 GeV.
- Models are excluded at better than 10x SM expectation

Summary and Outlook

- Search for new physics with a final states of $Z(\rightarrow \ell\ell) + E_T^{miss}$ and $bb + E_T^{miss}$ have both yielded no discoveries, but allowed limits to be set on the same dark matter interpretation.
    - Mono-Z search published in *Physics Letters B - 776 (2017) 318*
    - bb+MET search published in the *Journal for High Energy Physics 05 (2021) 093*
        - Public combination plots in *ATL-PHYS-PUB-2021-045*
    - Reinterpretations of the data in these searches could be made in context of new theoretical models
- Important and fun to search for **dark matter** in context of of what we might be missing
    - The data we have already recorded could hold the key...
- Lots more data to come in Run-3, plus updated versions of these searches, and a whole lot of new ideas

backup

Validity of collider comparisons with direct detection

Two kinds of nucleon-DM interactions:

- Spin independent direct detection searches are enhanced by mass of the nucleus squared
- Spin dependent direct detection searches depend on the spin of the nucleus

$$\sigma_{\mathrm{SI}} \simeq 6.9 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2$$

Vector

$$\sigma^{\mathrm{SD}} \simeq 2.4 \times 10^{-42}\ \mathrm{cm}^2 \cdot \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\mathrm{GeV}}\right)^2$$

Axial vector

Two key assumptions:

- That all SM quarks couple equally to the mediator
- That there is a single variant of dark matter in the universe for the direct detection searches to probe

$$\mu_{n\chi} = m_n m_{\mathrm{DM}}/(m_n + m_{\mathrm{DM}})$$