# Dark Matter Searches in the Z(ll) +MET channel

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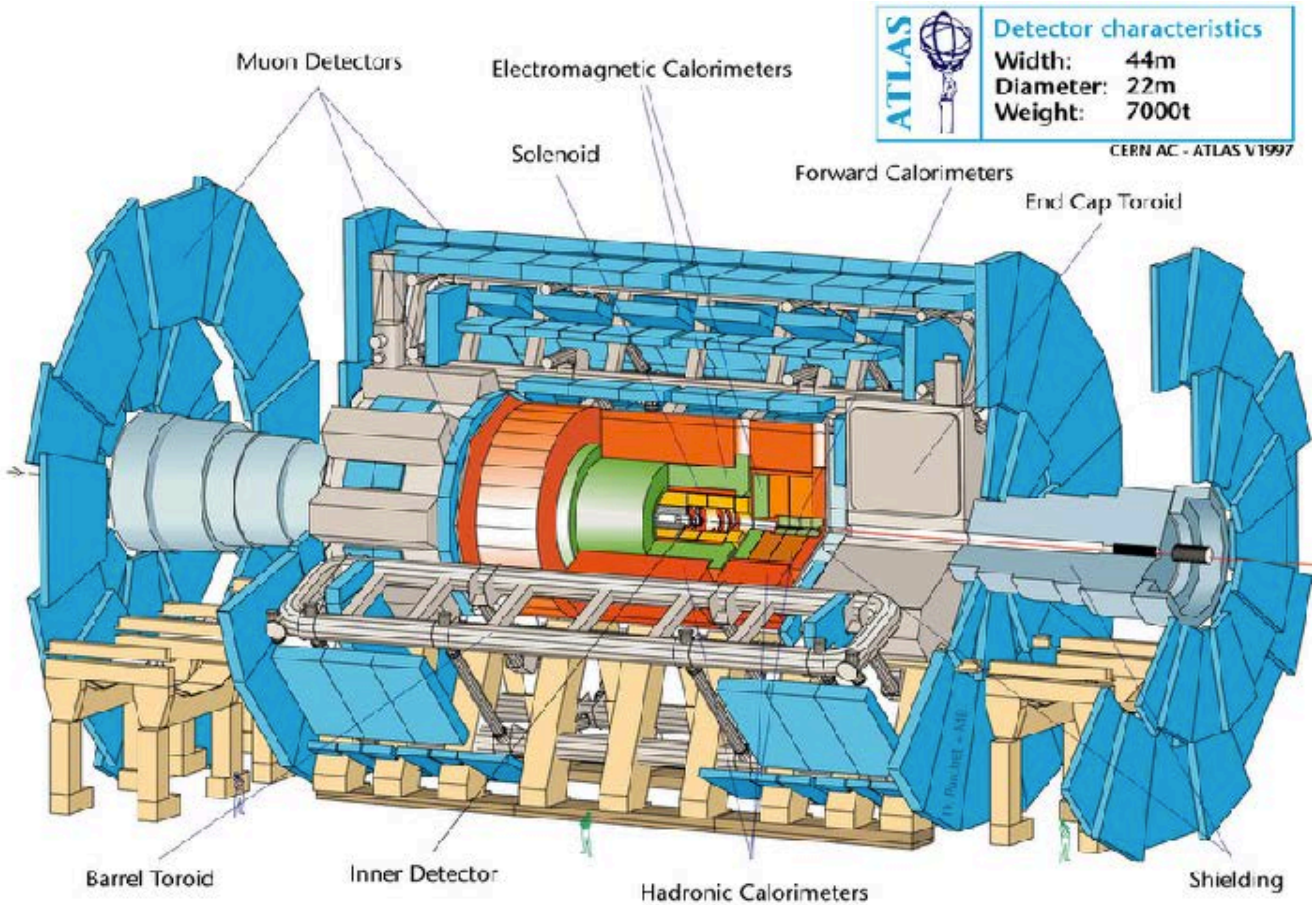
on Behalf of the ATLAS Experiment

ATLAS EXPERIMENT

University of Victoria

5, April 2018
Dark Matter @ LHC 2018

# ATLAS Experiment




- Analyze **13 TeV** proton-proton collisions collected by the ATLAS experiment during 2015 and 2016 of LHC Run-II.
- Collected events correspond to an integrated luminosity of **36.1 fb$^{-1}$**.

# Z(ll) + MET

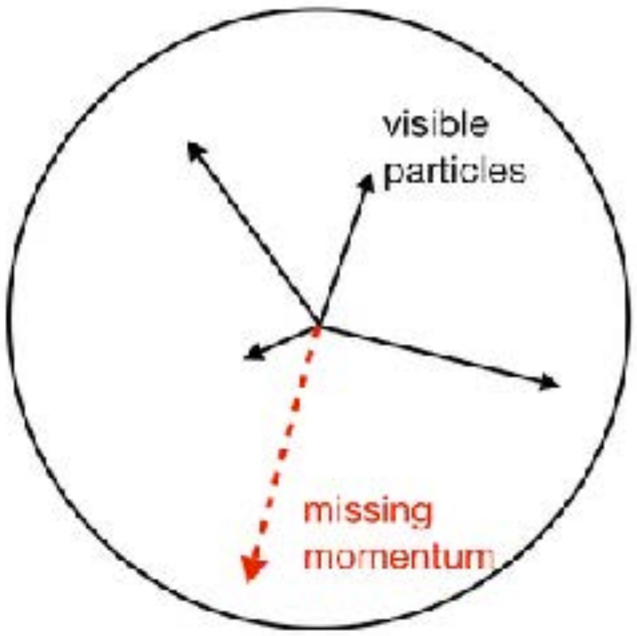
Search for DM through the presence of missing transverse momentum in the detector:

$E_T^{miss} = -\Sigma\, \vec{p}_T$ All Reconstructed Objects

†ATLAS definition also includes soft term for tracks not associated with a particle.

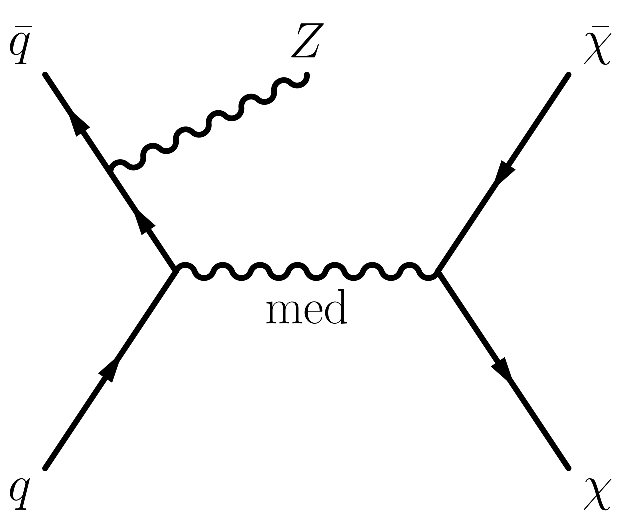
Missing Transverse Momentum Performance Paper (ATLAS 2018).

Neutrinos also produce $\mathbf{E_T^{miss}}$ and are a main source of background.

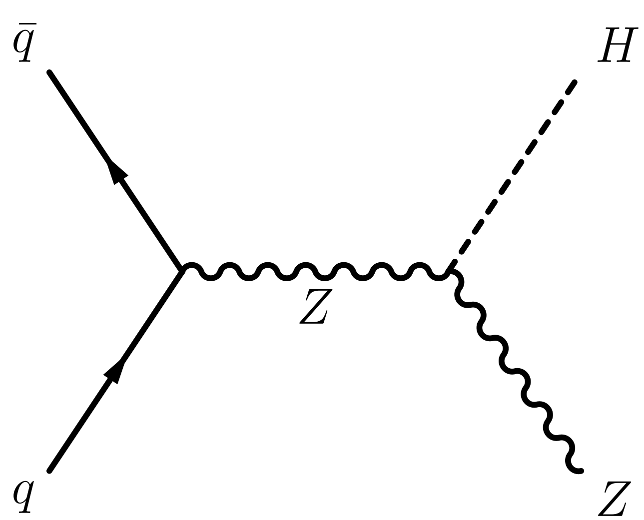



Sensitive to DM models where $p_T$ imbalance is created from DM production recoiled against a Z boson.

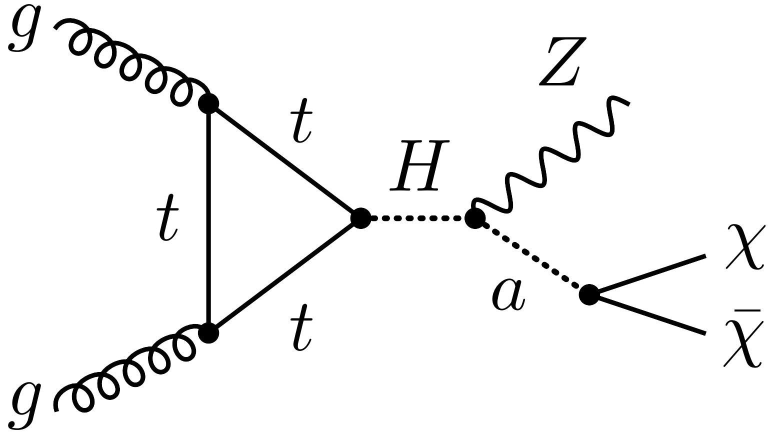
## Simplified Models




## Higgs Portal




## Pseudoscalar 2HDM



# Event Selection

**Triggers**:

- Low pT Triggers for isolated electrons (muons). Thresholds at 24 (20)† GeV.
- And high pT Triggers without an isolation requirement, 50 (60) GeV.

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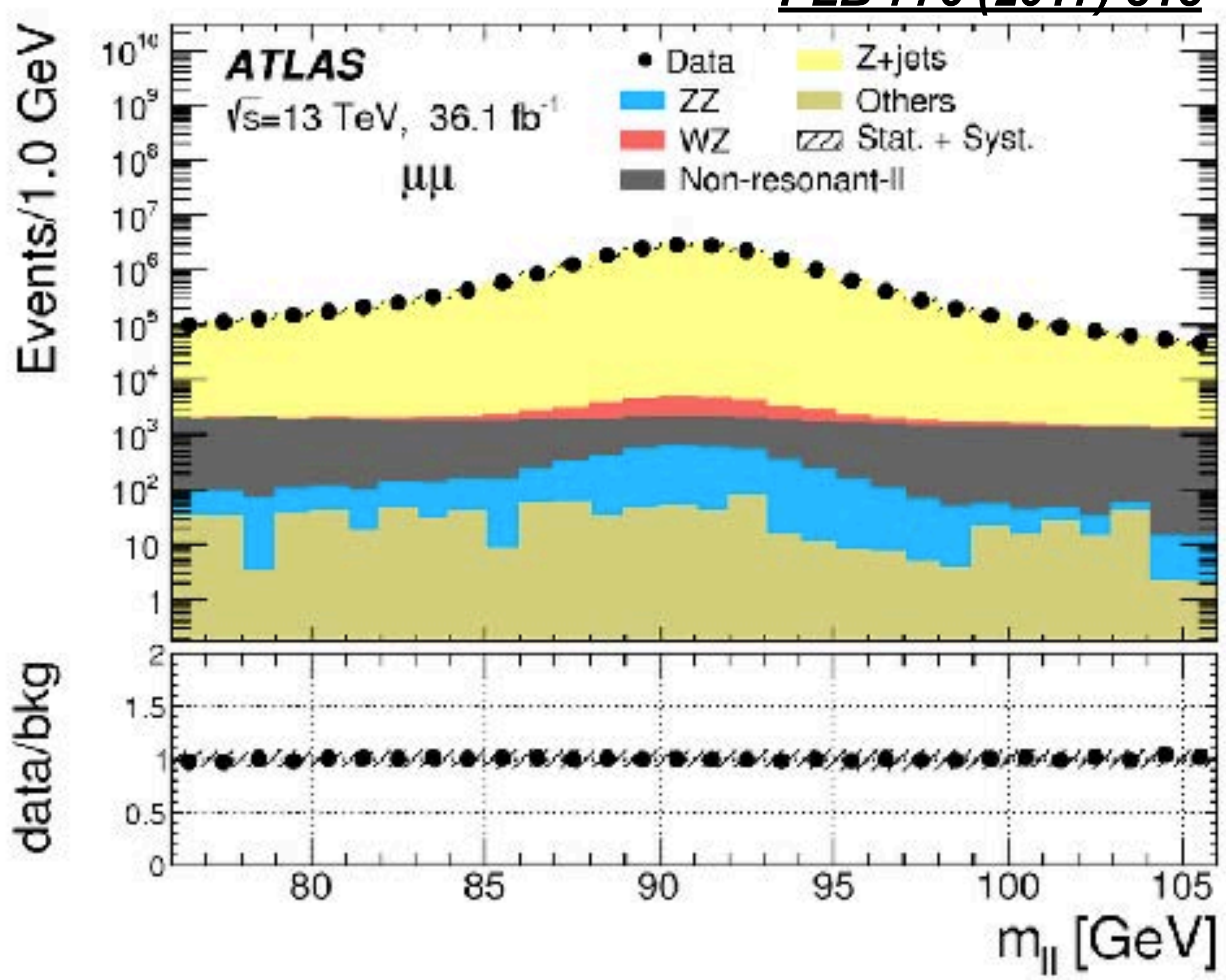


Distribution of data and background estimates following Z-window cut.

## Preselection

- Require <u>exactly</u> 2 SF OS leptons
- Lead (sublead) lepton $p_T$ > 30 (20) GeV
- Z window cut $| m_{\ell\ell} - m_Z | < 15$ GeV

## Highlighted Selection Cuts

- $E_T^{miss} > 90$ GeV and $E_T^{miss} / H_T > 0.6$
- $\Delta\varphi(p_T^{\ell\ell}, E_T^{miss}) > 2.7$
- $\Delta R_{\ell\ell} < 1.8$
- $|p_T^{\ell\ell} - p_T^{miss,jets})| / p_T^{\ell\ell} < 0.2$

†Depending on luminosity the electron trigger threshold is increased to 26 GeV.

# Backgrounds

**Background Estimates for Signal Region:**

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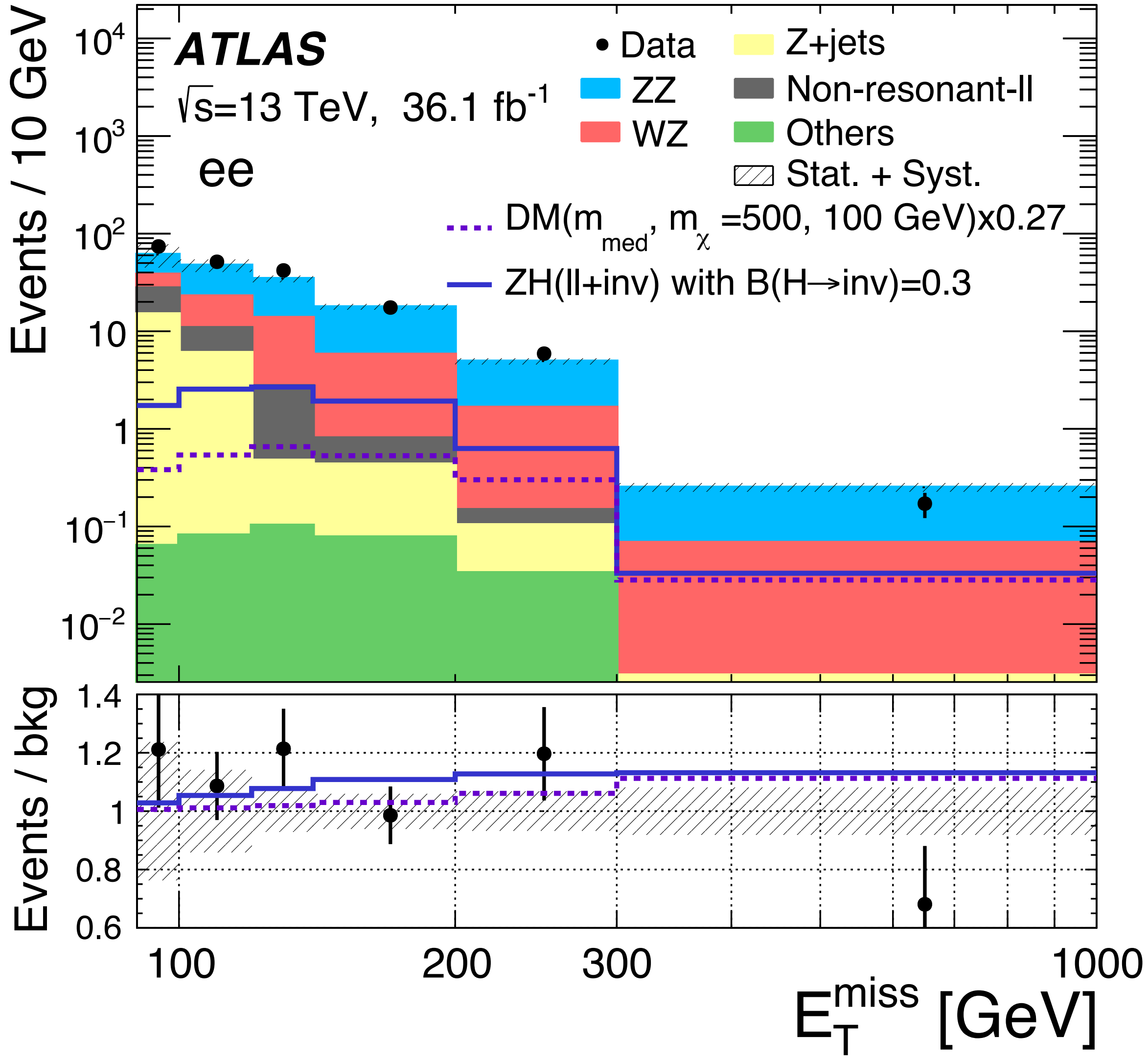


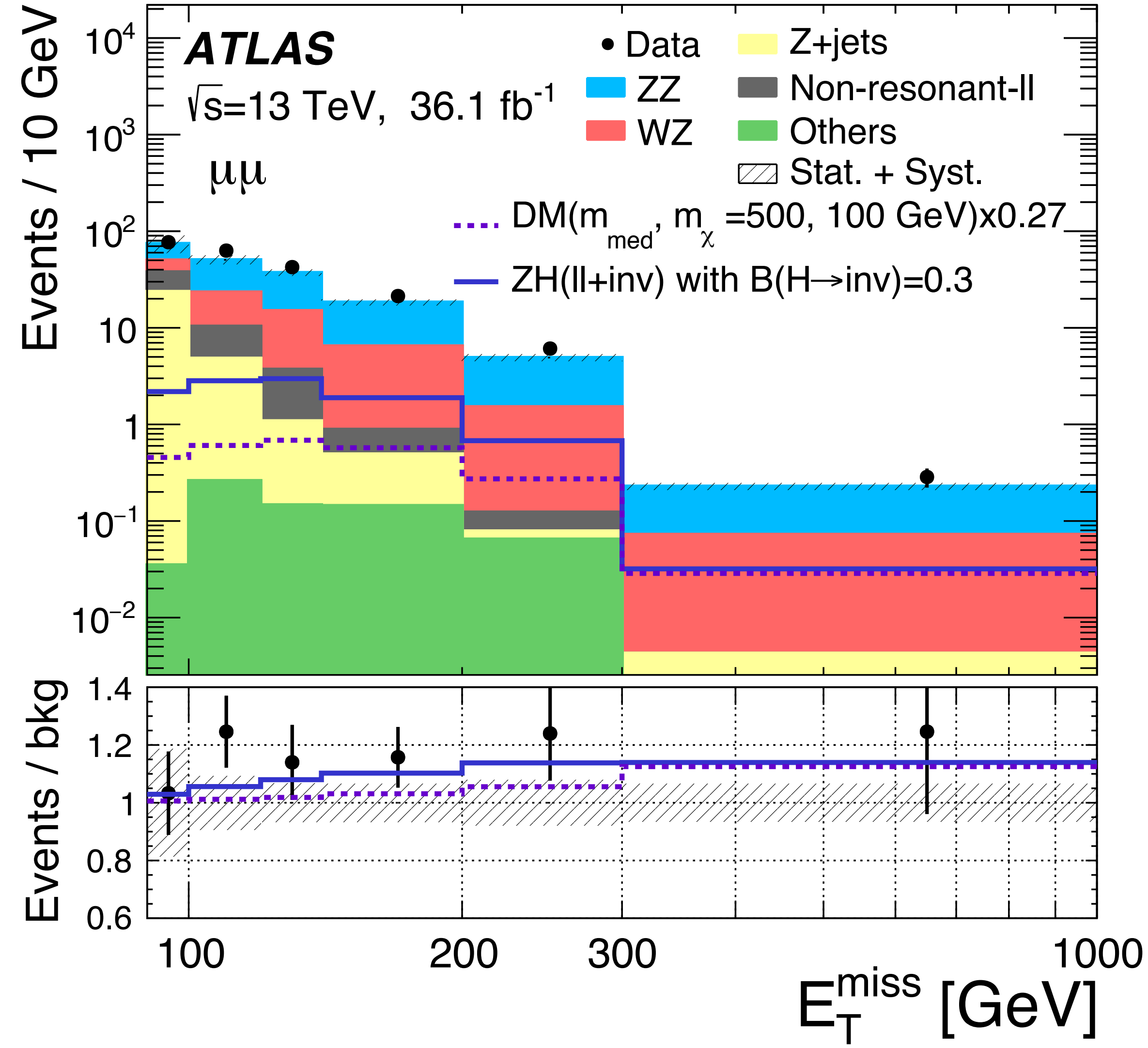


- Main background is ZZ production, with one Z→νν. Estimated with Monte Carlo.
- WZ background, (W→ℓν), where the lepton is lost or, in tau case hadronically decays. Shape modeled with MC, but normalized to data using WZ enriched control region.
- Non-resonant→ℓℓ background estimated with opposite sign eμ control region.
- Z+jets background, mis-reconstructed jets fake leptons, Z+jets background. Estimated using data driven ABCD method ($E_T^{miss}$ , $E_T^{miss}/H_T$).

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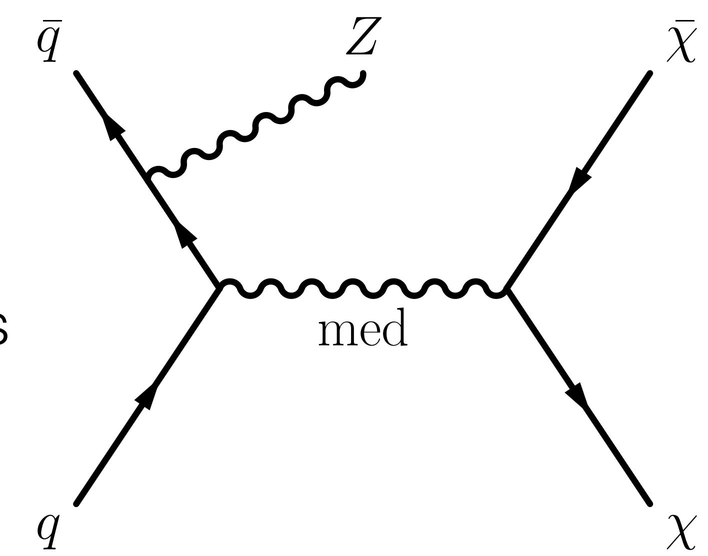
# DM Simplified Models

DM simplified models are distinguished by mediator type and coupling strengths:

**Mediator Types** - Vector, Axial-vector, Scalar, Pseudoscalar.

Simplified models have 6 free parameters:

- $g_q$ - mediator coupling to quarks
- $g_\ell$ - mediator coupling to leptons
- $g_\chi$ - mediator coupling to DM
- $M_{DM}$ - DM mass
- $M_{med}$ - Mediator mass
- $\Gamma_{med}$ - Mediator width




Following the recommendations of the DM Working Group, ATLAS studies two benchmark models:

- **A1** - Axial-vector model with $g_q$=0.25, $g_\ell$=0, $g_\chi$ =1
- **V1** - Vector model with $g_q$=0.25, $g_\ell$=0, $g_\chi$ =1

- $\Gamma_{med}$ is set using the minimal width formula.
- Results are shown as 2D exclusion plots in $M_{med}$ : $M_{DM}$.

# Axial-vector Model (A1)

95% confidence-level exclusion limits for the axial-vector model (A1):

**A1** - Axial-vector model with $g_q$=0.25, $g_\ell$=0, $g_\chi$ =1

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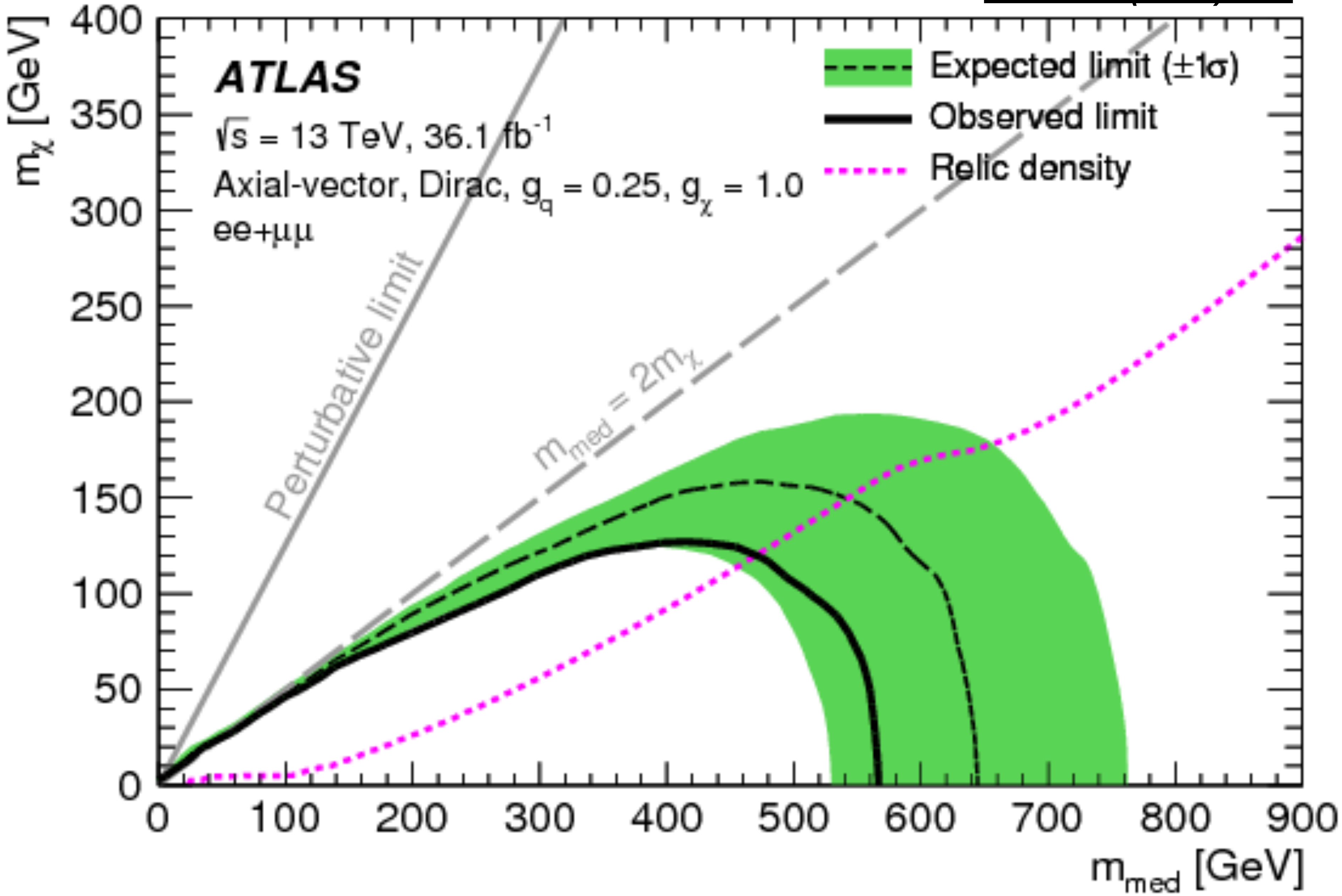

# Vector Model (V1)

95% confidence-level exclusion limits for the vector model (V1):

**V1** - Vector model with $g_q$=0.25, $g_\ell$=0, $g_\chi$ =1

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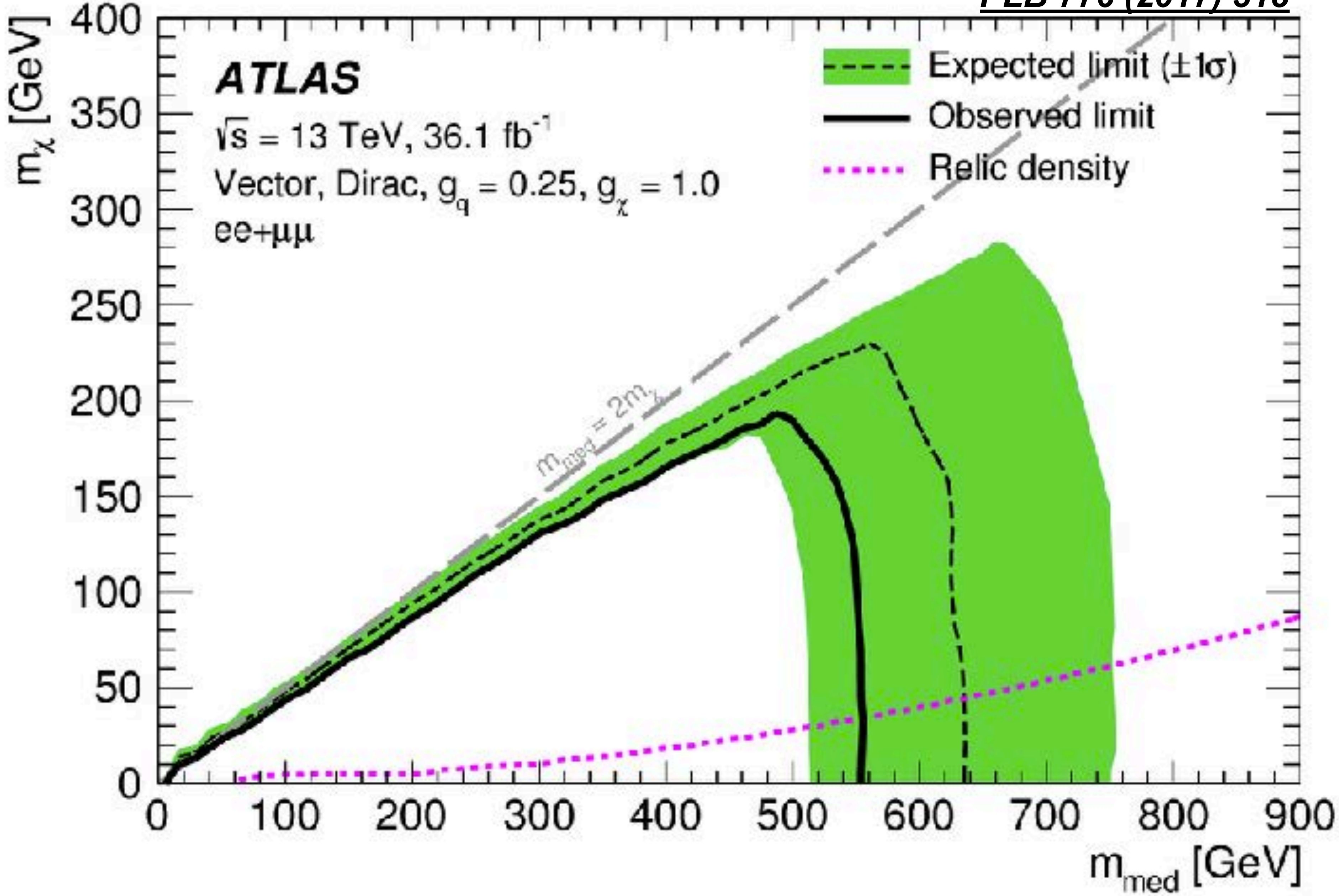

# Comparison to Direct Detection

Simplified models allow for comparison between direct detection experiments and colliders.

$$\sigma^0_{\mathrm{SD}} \approx 4.6 \times 10^{-41}\ \mathrm{cm}^2 \cdot \left(\frac{g_{\mathrm{DM}}\, g_q}{1}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

**Axial-vector model:**

Observed limits for Mono-Z(ll) search

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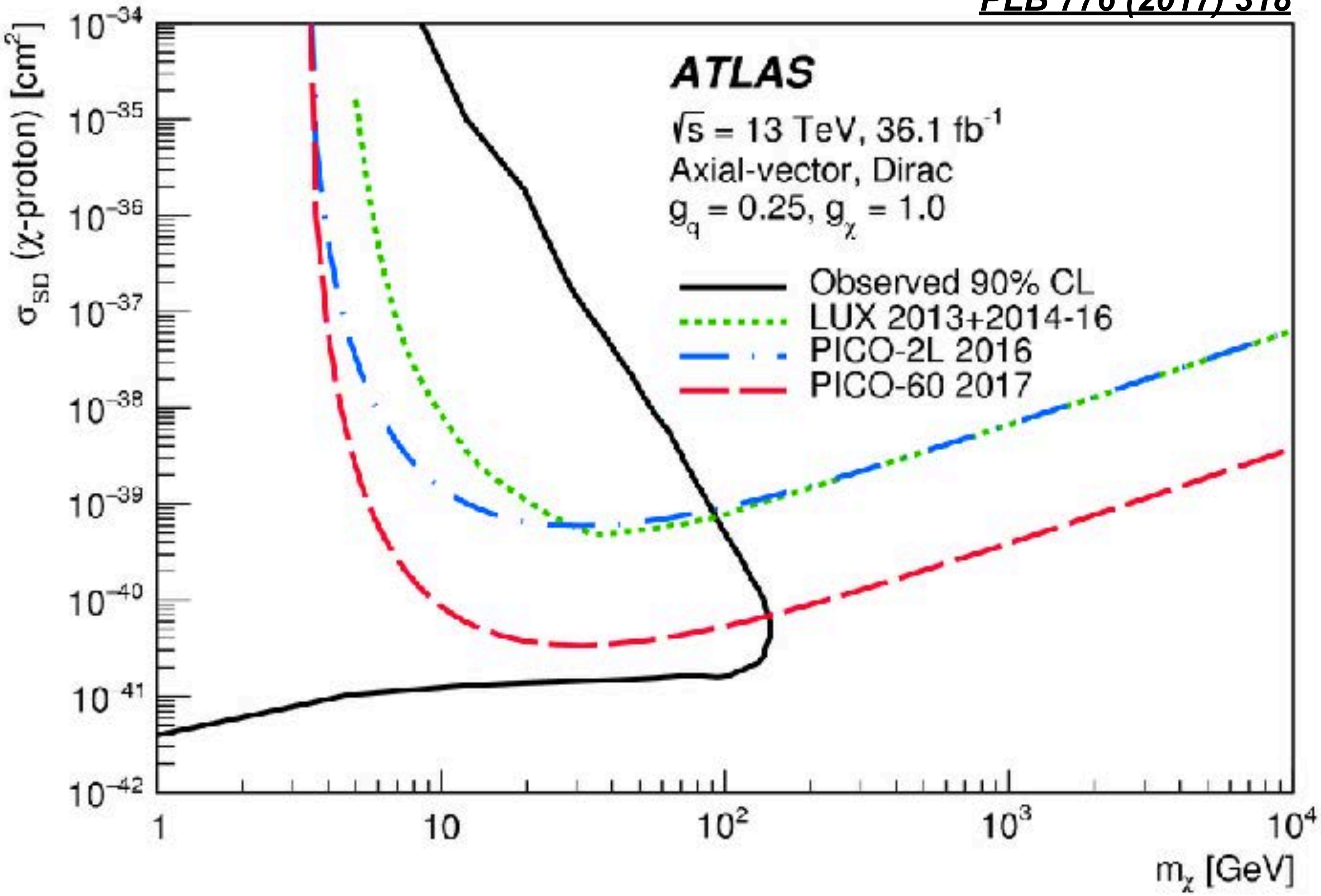


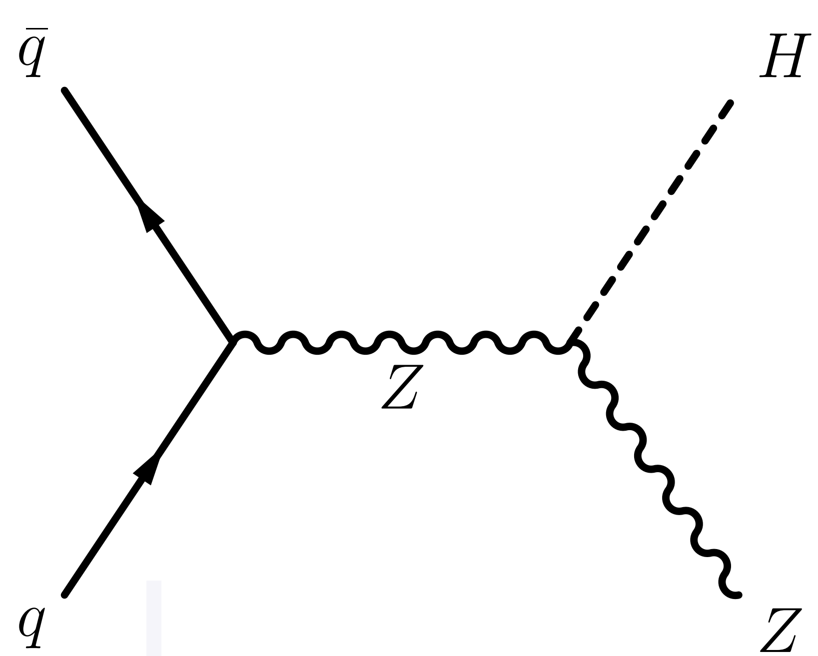

N.B. Collider limits are model dependent, and different couplings result in different limits.

# Invisible Higgs Decay

The Z(ll) + MET channel is sensitive to invisible decays of the Higgs boson. Assuming SM ZH production, ucan measure the branching fraction, B(H→inv).

The SM H→ZZ→νννν branching fraction is $1.06 \cdot 10^{-3}$, and observing a larger branching fraction is clear evidence of Beyond the SM physics.

In particular, larger branching fractions are consistent with Higgs portal dark matter or Higgs decays to light neutralinos. (To be sensitive, must have $m_\chi < 0.5\, m_H$ )

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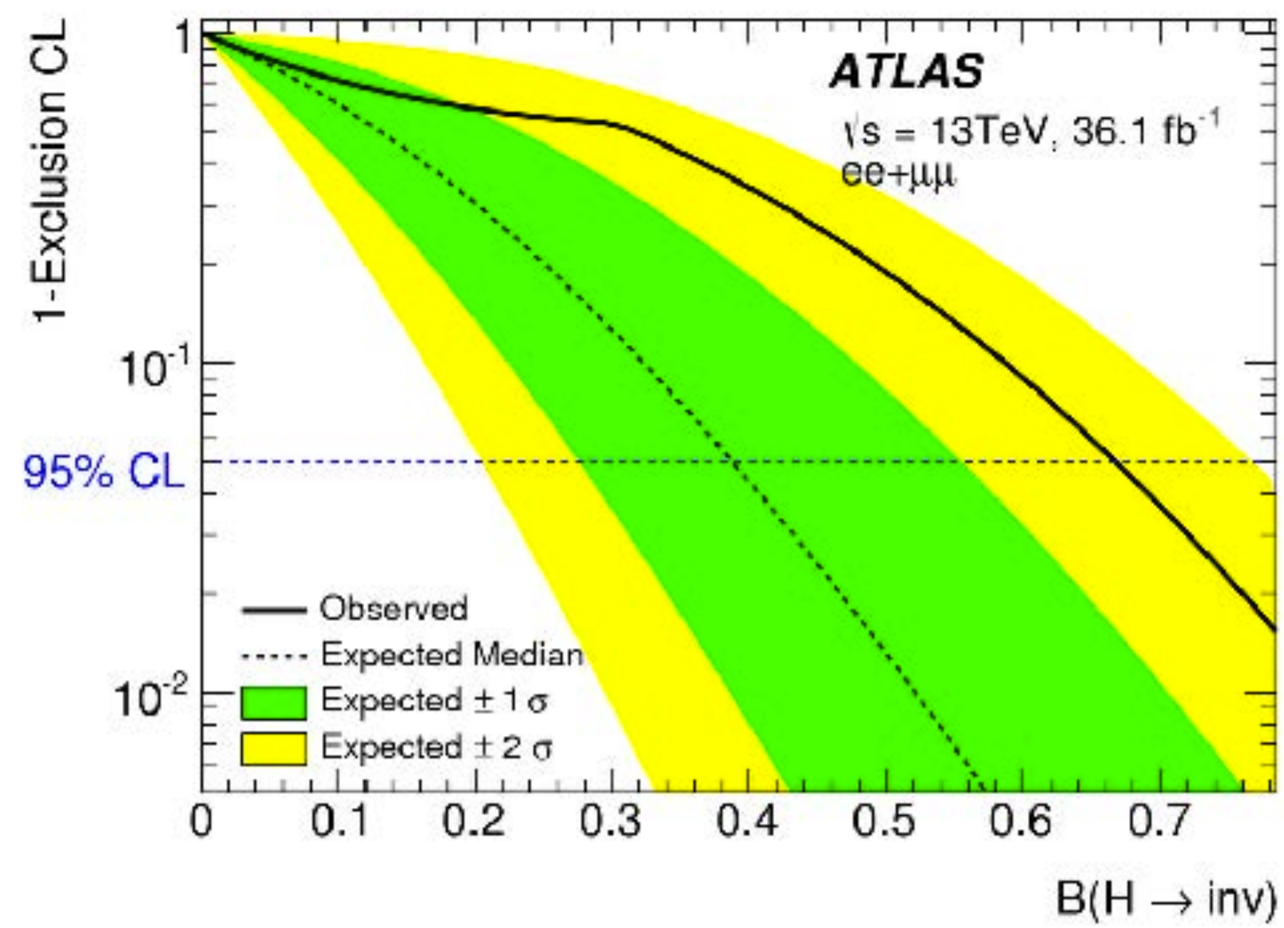
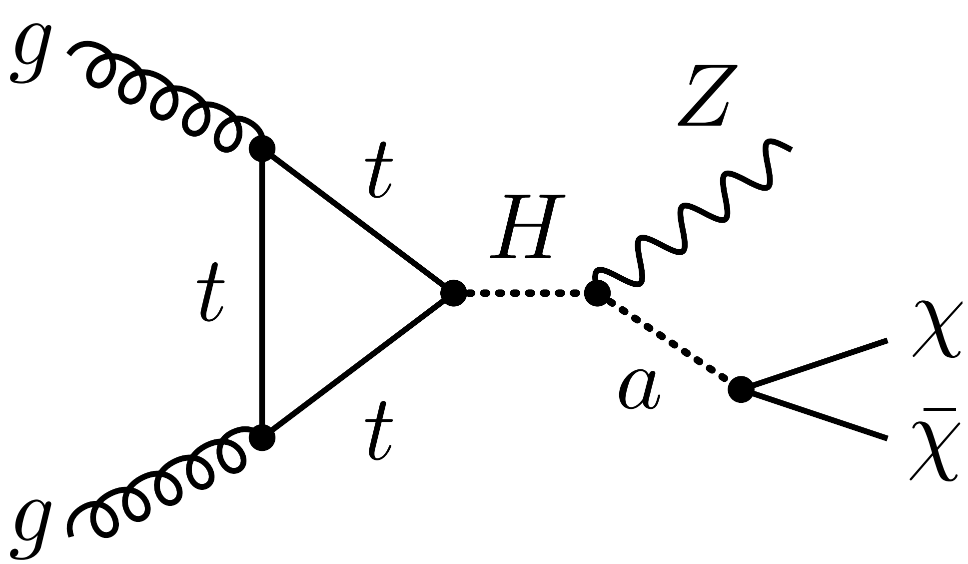
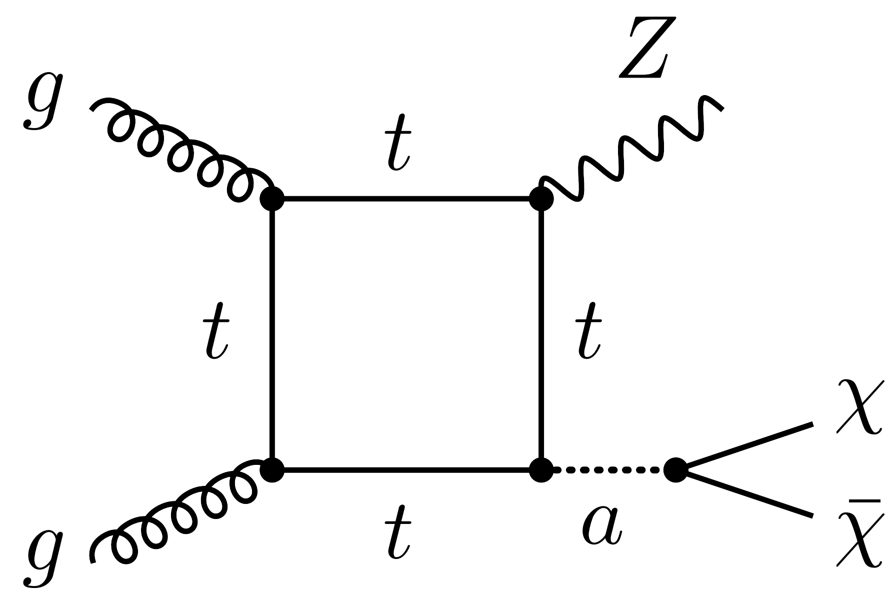


# Pseudoscalar Two Higgs Doublet Model

Feynman Diagrams for Mono-Z + MET production.




2HDMa model introduces 6 bosons:

h - light scalar, identified as SM Higgs

H - heavy scalar

$H^{\pm}$ - two heavy, charged scalars

A - heavy pseudoscalar

a - light pseudo scalar

} Mixture of 2HDM ($A_0$) and DM Mediator ($a_0$) pseudoscalars

Couples to DM and SM particles

Parameters:

mH, $mH^{\pm}$, mA, ma, $m_{\chi}$ - masses

$\sin(\theta)$ - a, A mixing angle

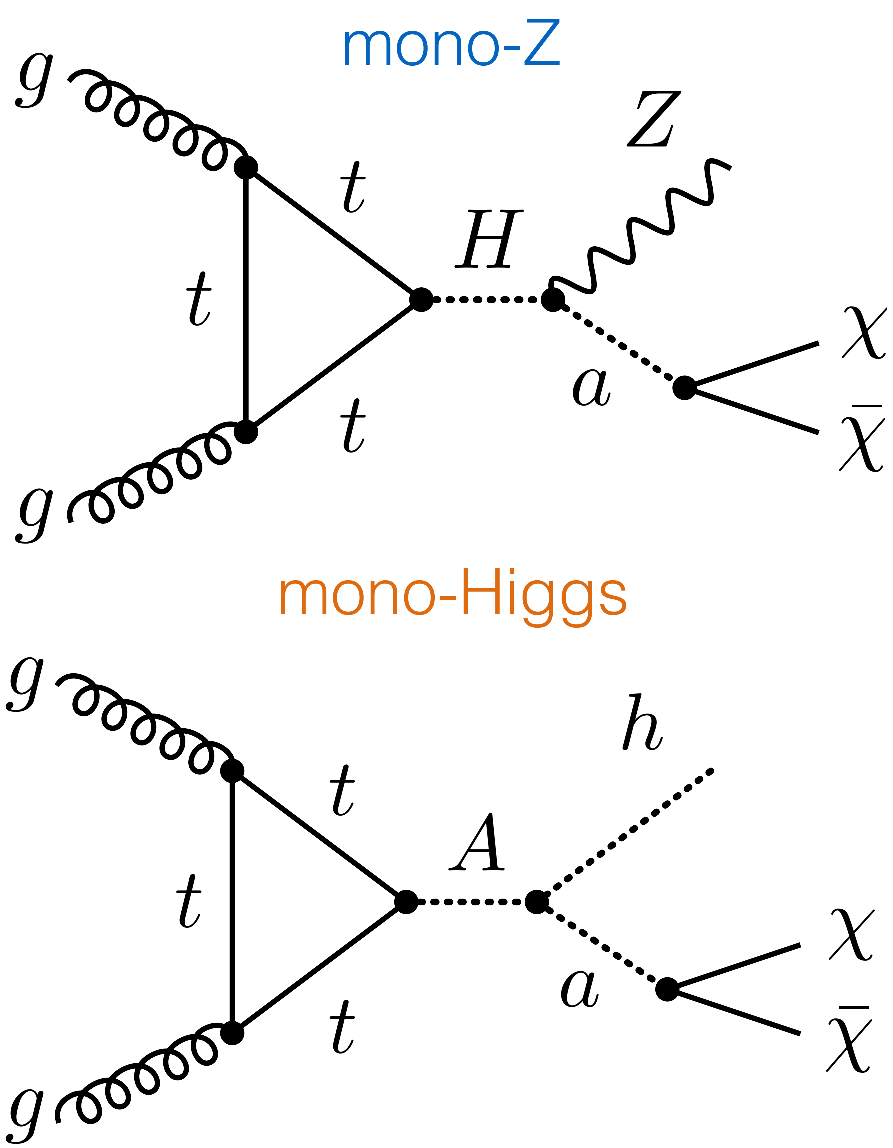
$\tan(\beta)$ - ratio of vacuum expectation values

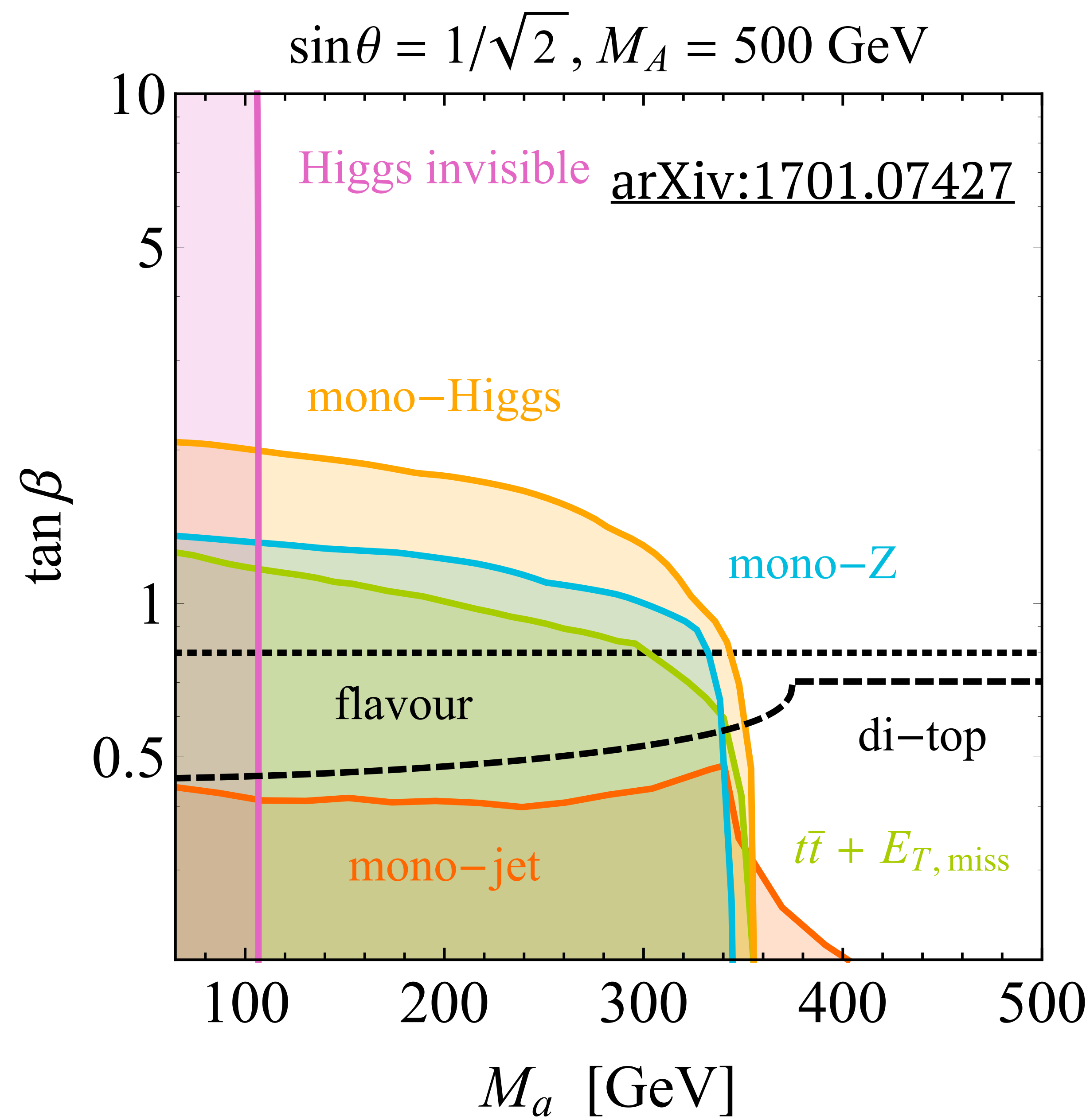
$\lambda_3$, $\lambda_{1p}$ , $\lambda_{2p}$ - quartic scalar couplings

$y_{\chi}$ - DM coupling

# Pseudoscalar Two Higgs Doublet Model

For 2HDMa, Mono-Z and Mono-Higgs channels are enhanced due to resonant production of heavy scalar (H) or heavy pseudoscalar (A) particles, can be more sensitive than Mono-Jet.



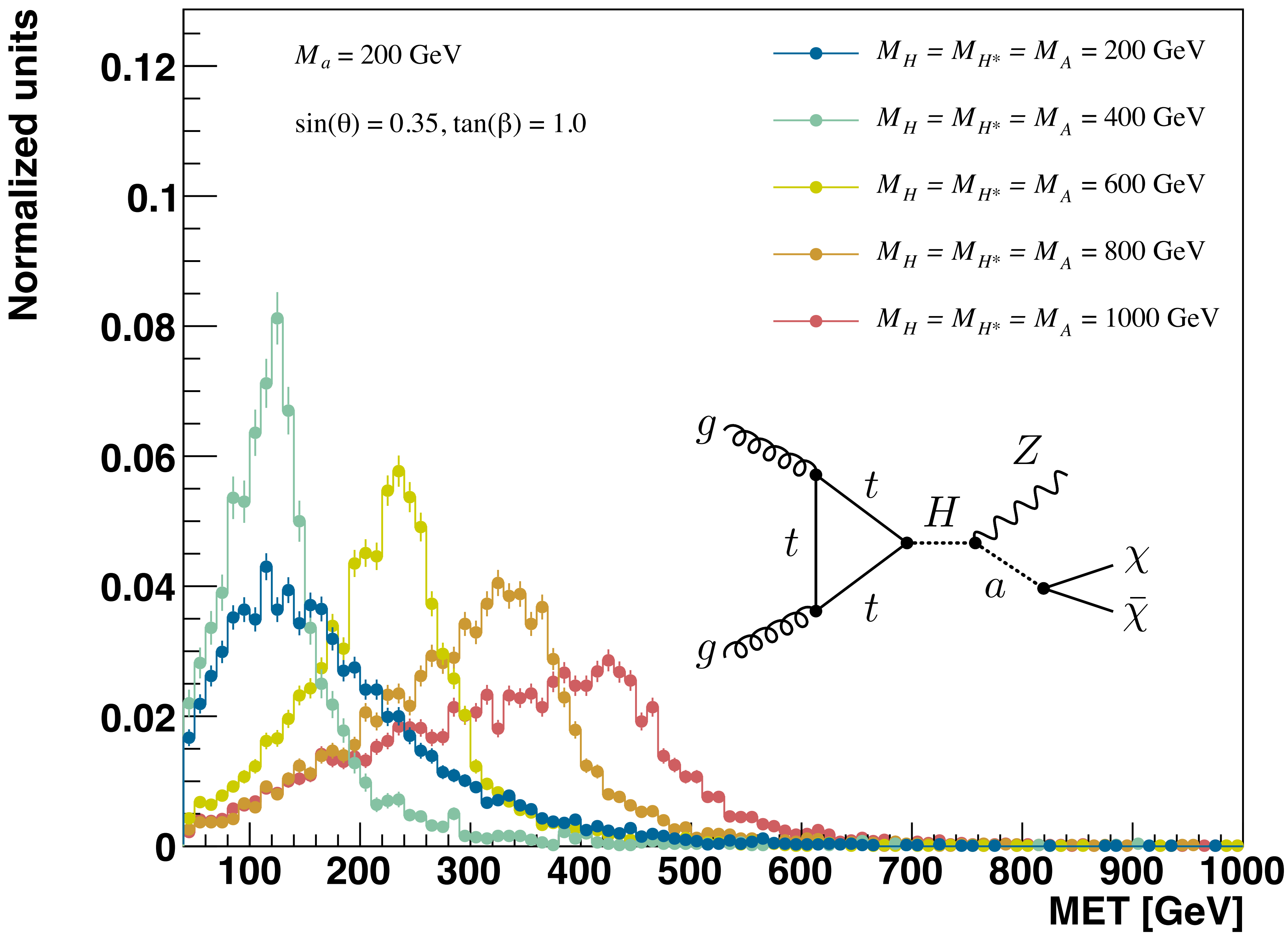




Study a subset of 2HDMa models with **mA =mH = mH±** (Mono-Z and Mono-Higgs channels complement each other.)

# Kinematic Dependence on Masses

For resonant production MET distribution is characterized by a Jacobian peak. Shape depends strongly on $M_H$ and $M_a$.

**Fixed parameters: sin(θ)=0.35, tan(β)=1.0, $m_\chi$=10 GeV**

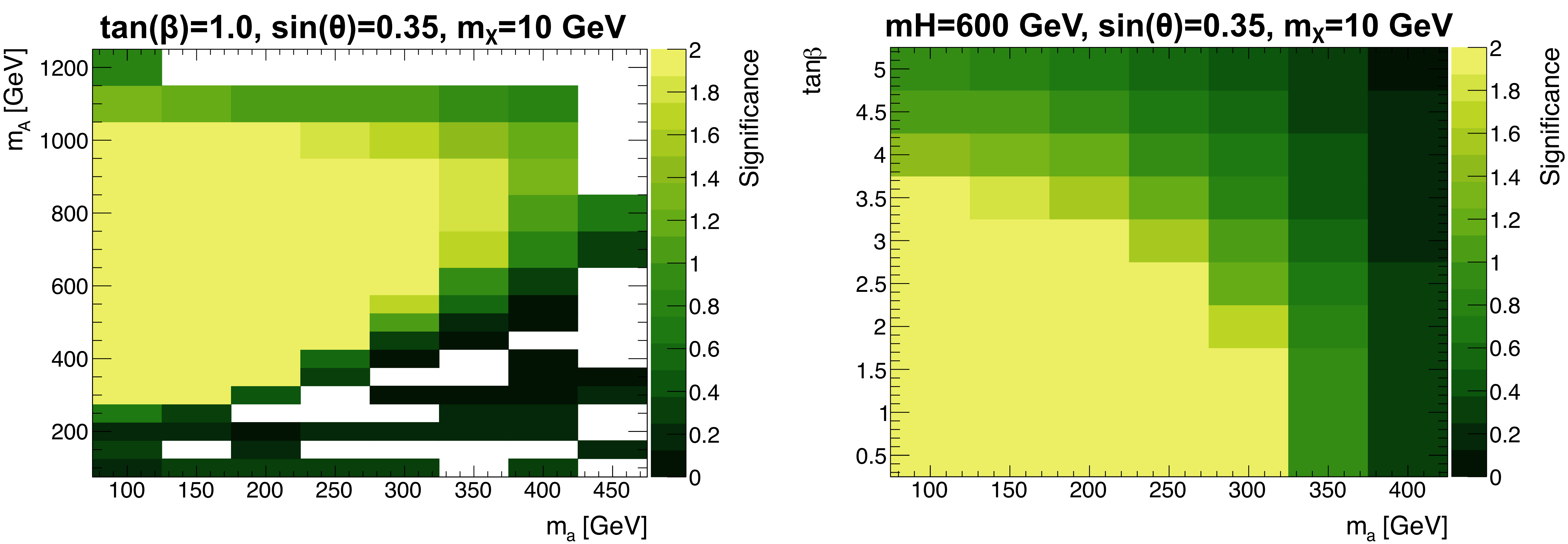



$$E_T^{miss,max} \approx \frac{\sqrt{(M_A^2 - M_a^2 - M_h^2)^2 - 4M_a^2 M_h^2}}{2M_A}$$

# Expected Significance (2HDMa)

## Mono-Z(ll): Truth-Level Significance

- Calculate significance using Asimov approximation for profile likelihood ratio (Cowan Paper). Per-bin significances summed in quadrature.
- Truth level cuts mirror Mono-Z(ll) (ATLAS) selection, background estimates taken from analysis, and conservative 10-20% background systematic per MET bin applied.
- Assume reconstruction efficiency of 75%.
- Exclude Phase Space with Significance > 2.




**DMWG Report** : https://indico.cern.ch/event/665524/contributions/2929794/attachments/1623601/2584712/DMWG_2HDM.pdf

# Conclusions

- Current ATLAS measurements of the Z(ll) + MET channel are consistent with SM predictions.
- Upper limits are placed on **Simplified Models** of DM, the **Invisible Branching Fraction** of the Higgs, and can be reinterpreted for the **pseudoscalar Two Higgs Doublet Model**.
- As LHC collects more data through Run-2, exclusion limits as well as the potential for discovery should continue to improve.

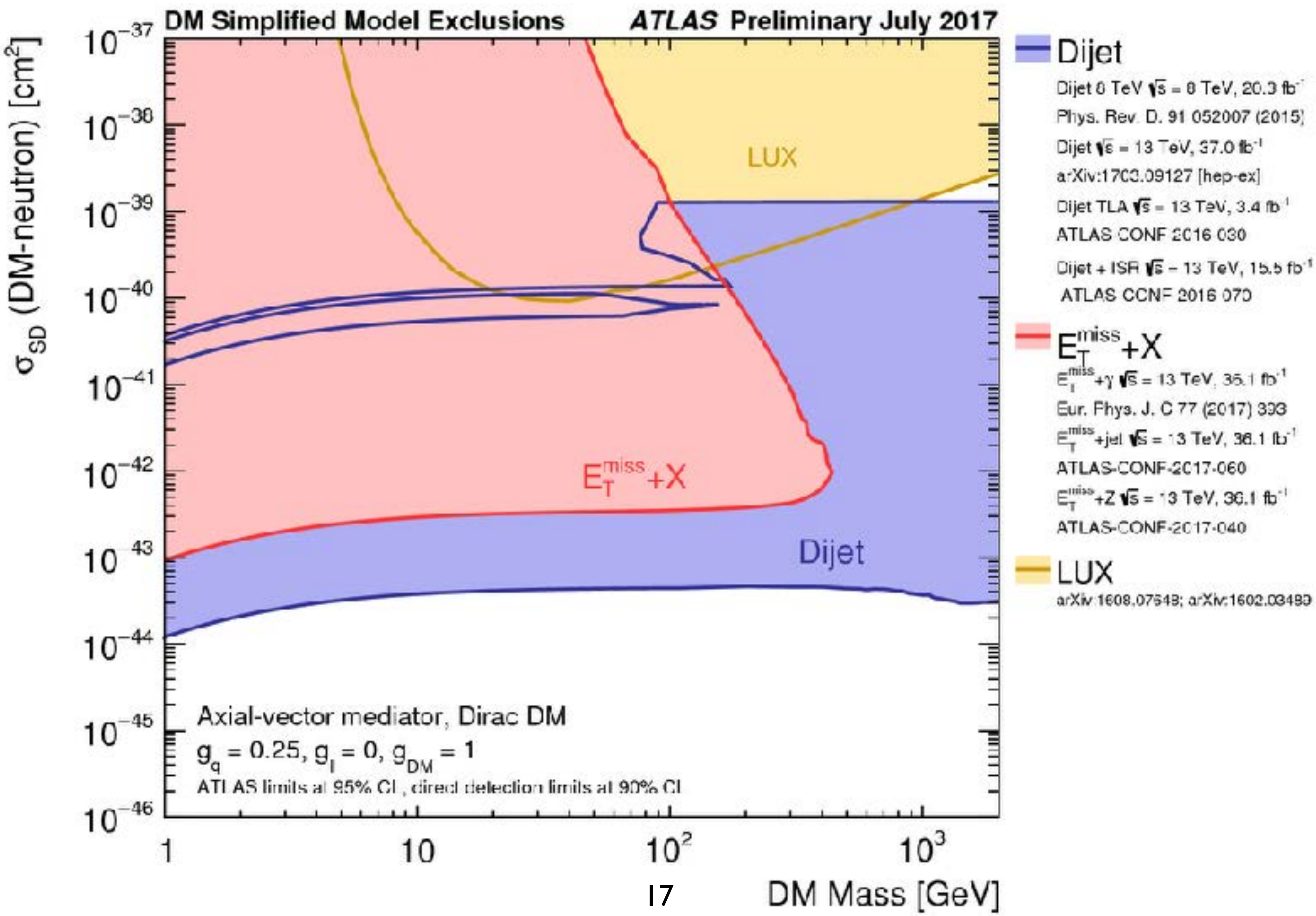
# Backup Slides

# Comparison to Direct Detection

Simplified models allow for comparison between direct detection experiments and colliders.

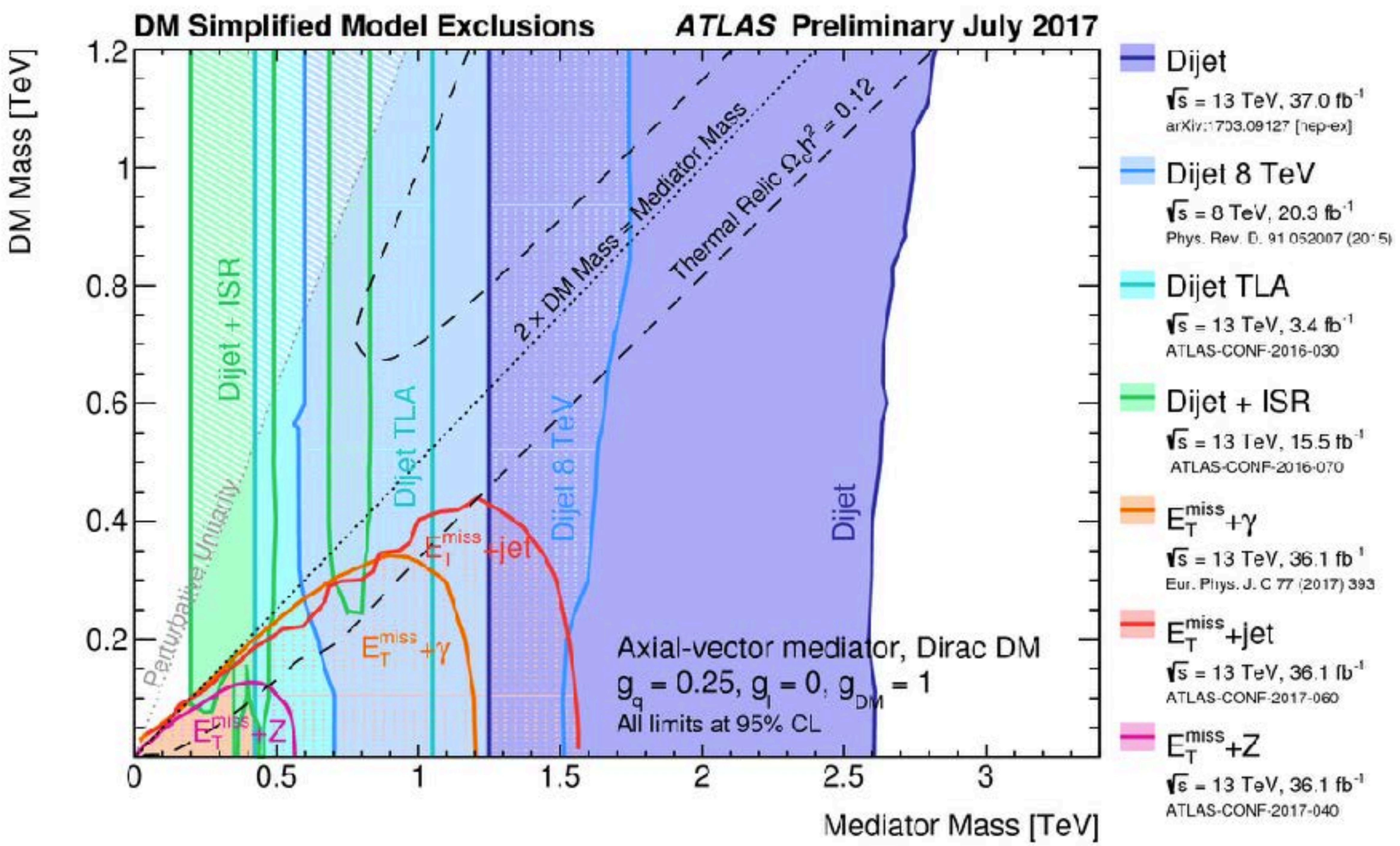
**Axial-vector model:**

$$\sigma^0_{\rm SD} \approx 4.6 \times 10^{-41}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$



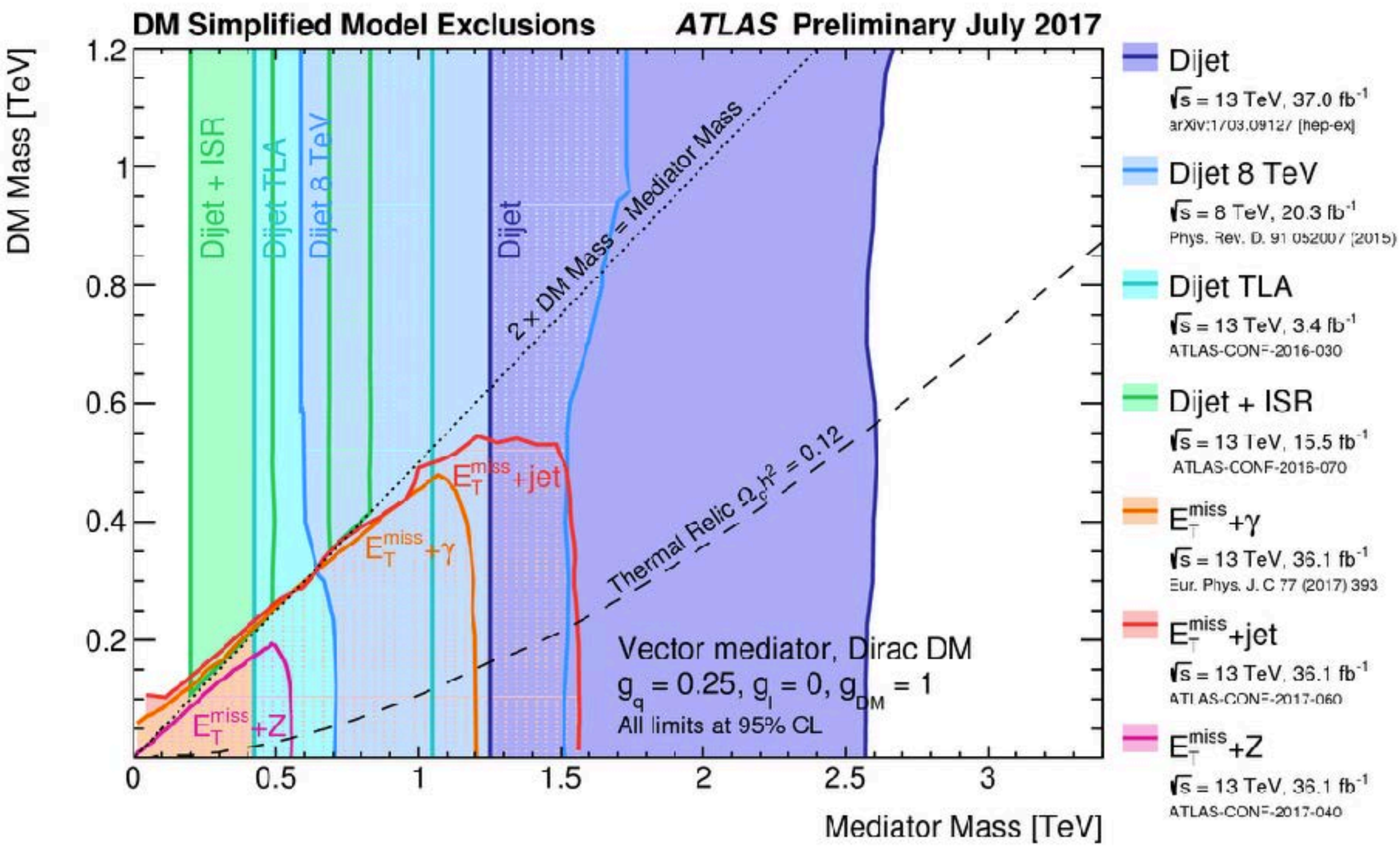
# Exclusion Limits

**Axial-vector mediator (A1):**



# Exclusion Limits

**Vector mediator (V1):**



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Observed limits for Mono-Z(ll) channel.

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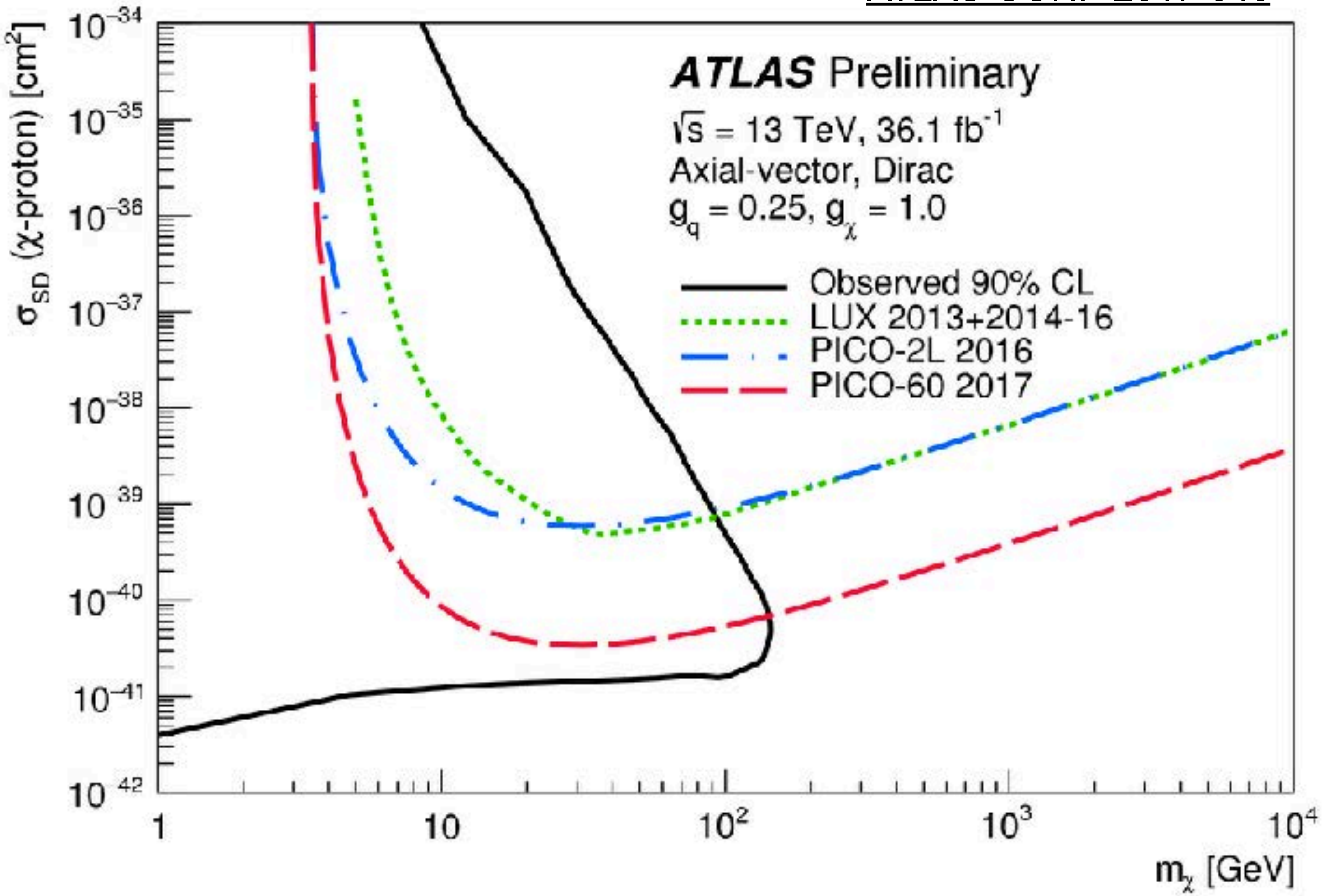
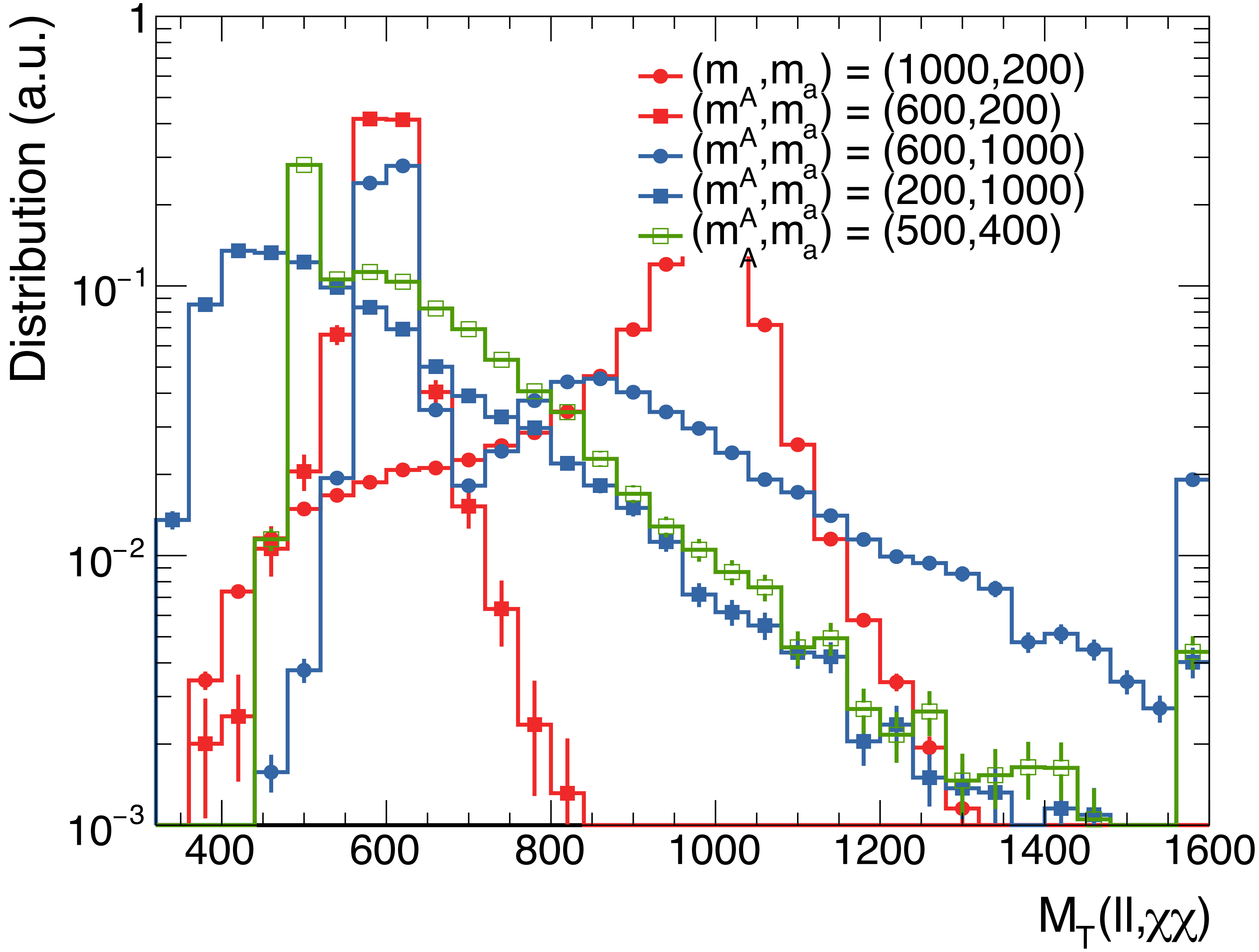


# Transverse Mass Distibution for 2HDMa

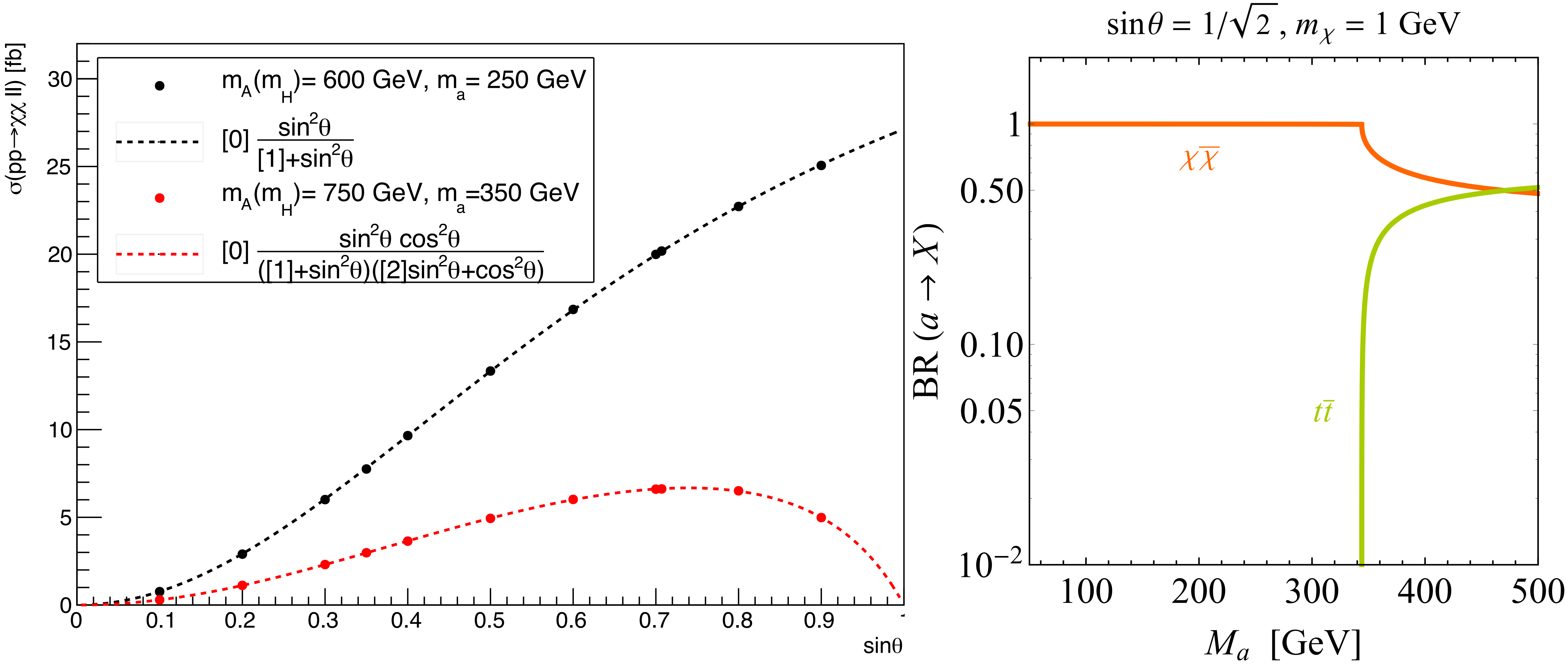
Transverse mass distribution for 2HMDa model. For resonant production, has characteristic shape.




$$M_T^2 = m_1^2 + m_2^2 + 2\left(E_{T,1}E_{T,2} - \vec{p}_{T,1}\cdot\vec{p}_{T,2}\right)$$

## Dependence of cross section on tan(β), $M_\chi$ , and sin(θ):

- Cross Section decreases with increasing tan(β).
- Is flat as a function of $M_\chi$, but drops steeply for $2M_\chi > Ma$.
- sin(θ) dependence is interesting. For Ma < 350 GeV, mixing angle only impacts branching fraction of H→aZ and is strictly increasing. For Ma > 350 GeV, decay of the mediator to tt becomes accessible (increasing with sin(θ) ) leading to a turnover point.

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# Object and Event Selection

## Single Lepton Triggers

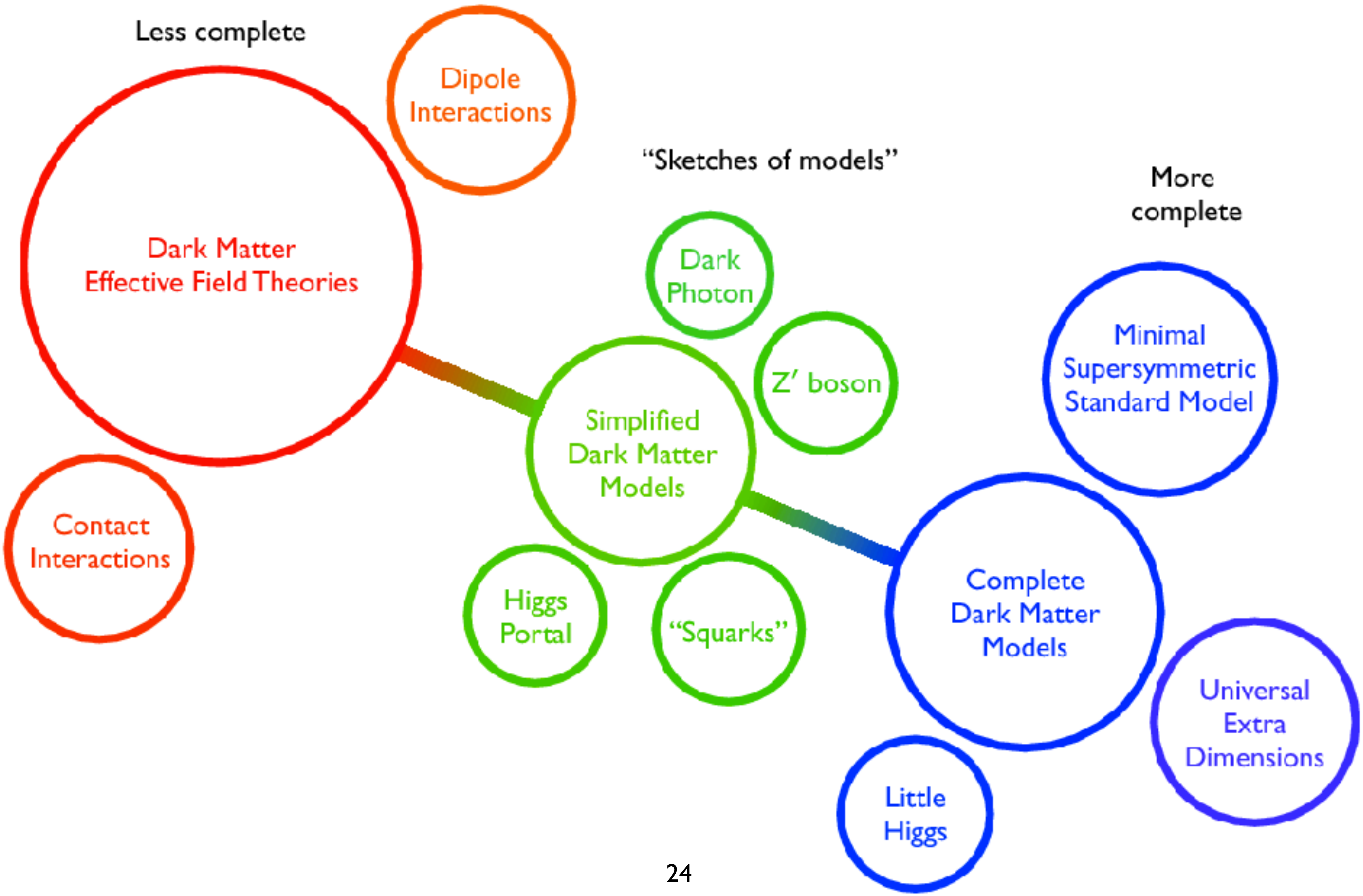
- Low, pT Triggers for isolated electrons (muons). Thresholds at 24 (20)- 26 GeV.
- And high, pT Triggers without an isolation requirement, 50 (60) GeV.

## Mono-Z(ll) Selection

- Electrons: isolated, pT > 7 GeV , $|\eta| < 2.47$
- Muons: isolated pT > 7 GeV, $|\eta| < 2.5$
- $E_T^{miss} = - \Sigma$ All reconstructed particles†
- Require <u>exactly</u> 2 opposite sign leptons with lead pT > 30 GeV and sublead pT > 20 GeV.
- Z-window cut ( $76 < m_{\ell\ell} < 106$ GeV)
- $E_T^{miss} > 90$ GeV and $E_T^{miss} / H_T > 0.6$.
- $\Delta\varphi(p_T^{\ell\ell}, E_T^{miss}) > 2.7$
- $\Delta R_{\ell\ell} < 1.8$
- Fractional $p_T$ difference : $|p_T^{\ell\ell} - p_T^{miss,jets}) > 2.7 | / p_T^{\ell\ell} < 0.2$
- B jet veto

†And soft tracks not associated with a particle.

# Dark Matter Models

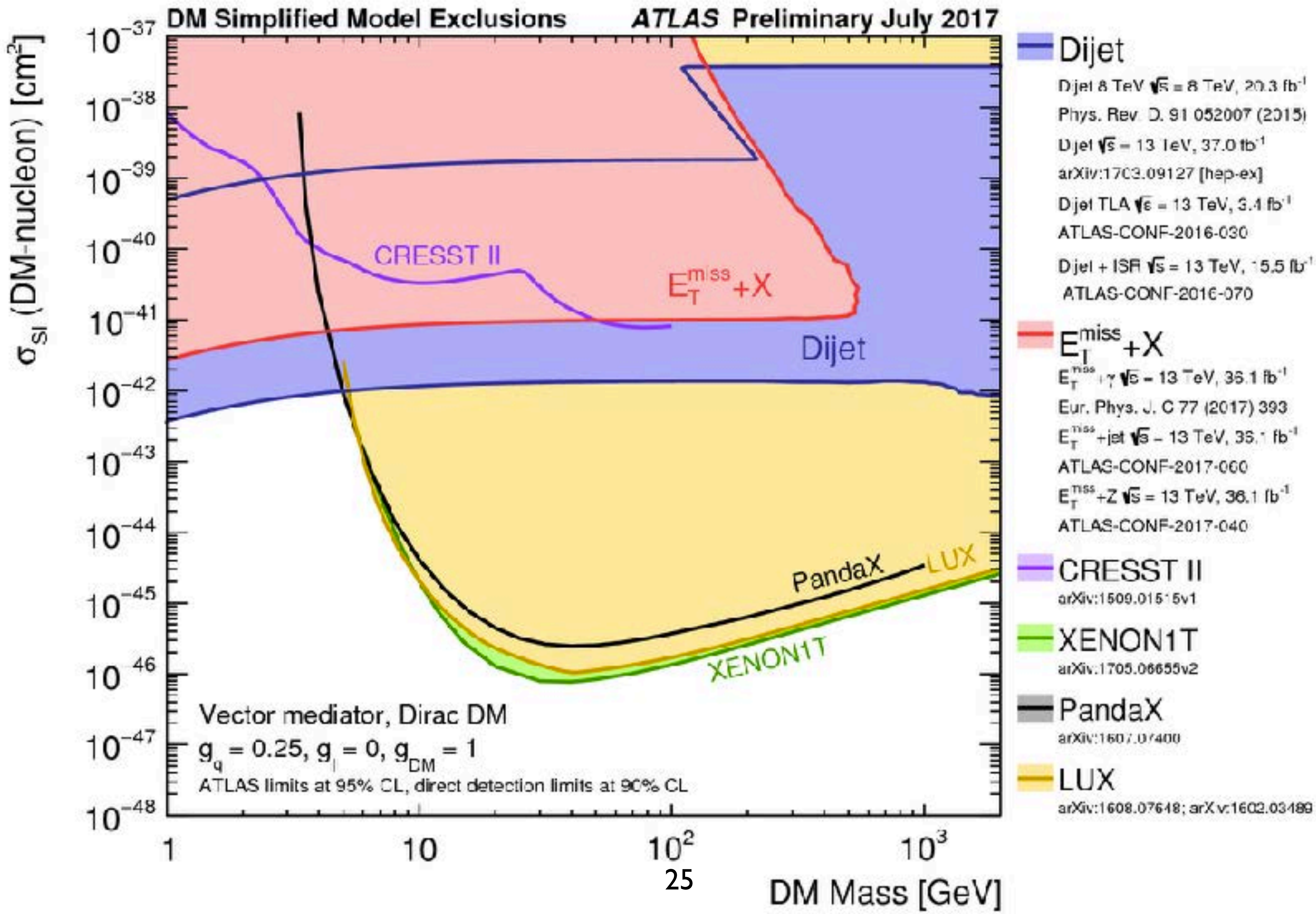


# Comparing to Direct Detection

Simplified models allow for comparison between direct detection and collider results:

**Vector model:**

$$\sigma^0_{\rm SI} \approx 1.1 \times 10^{-39}\ {\rm cm}^2 \cdot \left(\frac{g_{\rm DM}\, g_q}{1}\right)^2 \left(\frac{1\ {\rm TeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2$$



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# Comparing to Direct Detection

Simplified models allow for comparison between direct detection and collider results:

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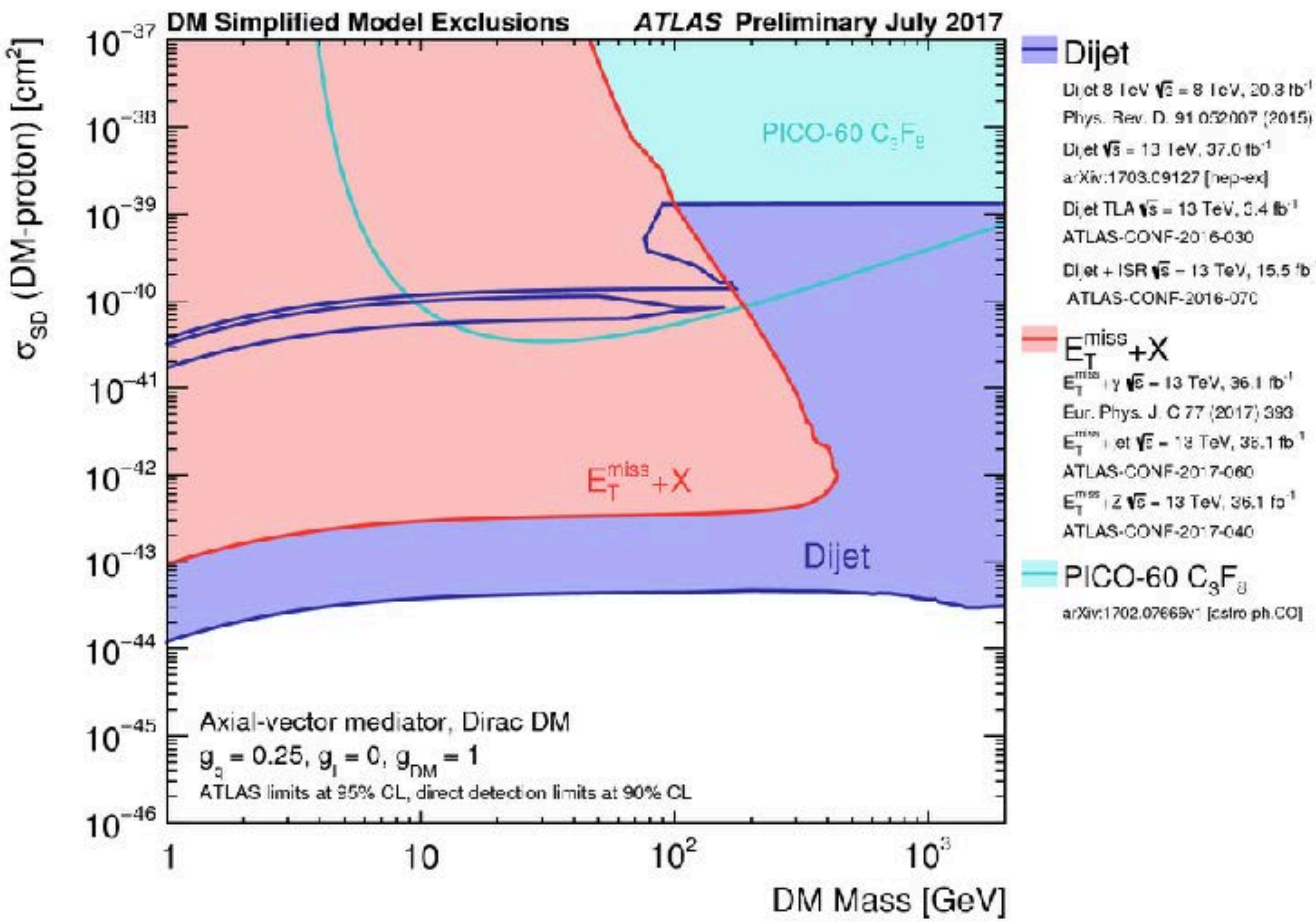


# Significance Caluculation

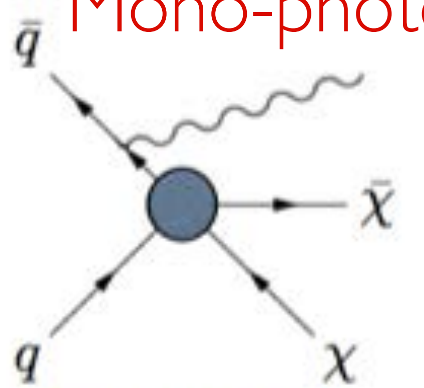
- (Cowan Paper)

$$Z'_{bin} = \sqrt{2 \cdot \left( (s+b) \ln[\frac{(s+b)(b+\sigma_b^2)}{b^2 + (s+b)\sigma_b^2}] - \frac{b^2}{\sigma_b^2} \ln[1 + \frac{\sigma_b^2 s}{b(b+\sigma_b^2)}] \right)}$$

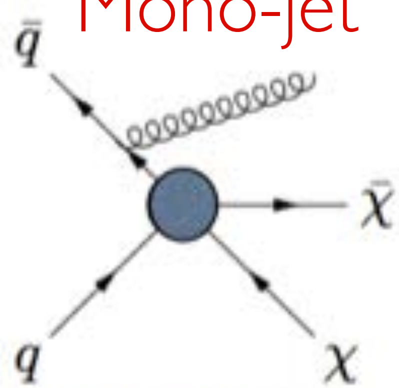
# Mono-X Searches

Mono-X searches look for $p_T$ imbalances created from DM production recoiled against a detectable particle.

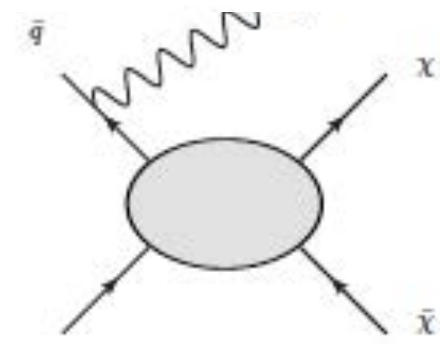
Mono-photon



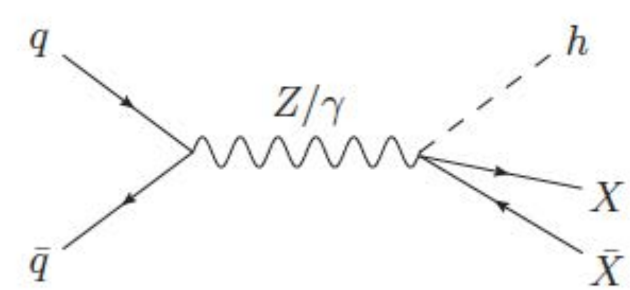

Mono-jet



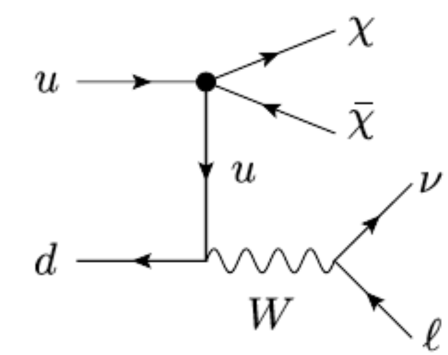

Mono-Z




Mono-Higgs




Mono-W



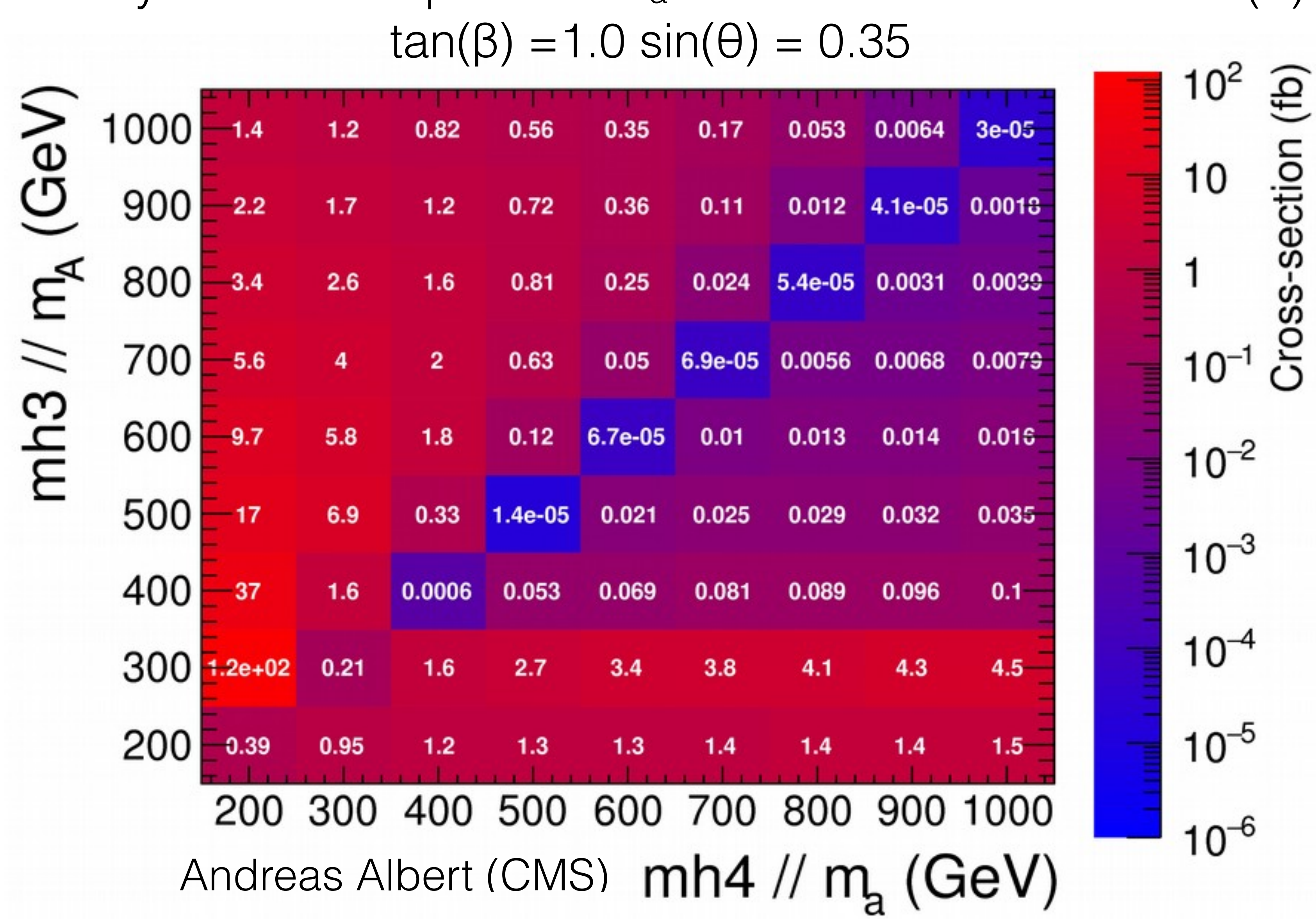

†And soft tracks not associated with a particle.

# Cross Sections

MadGraph + Pythia generators were used to simulate 2HDMa events and calculate cross sections at LO, g g > xd xd~ l+ l-

**Dependence of cross section on $m_H$ and $m_a$:**

- Destructive interference for $m_H = m_a$.
- For $m_A$, $m_a$ > 350 GeV, cross sections decrease as pseudoscalars can also decay to ttbar. Impact on $m_a$ is minimized for small sin(θ).

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