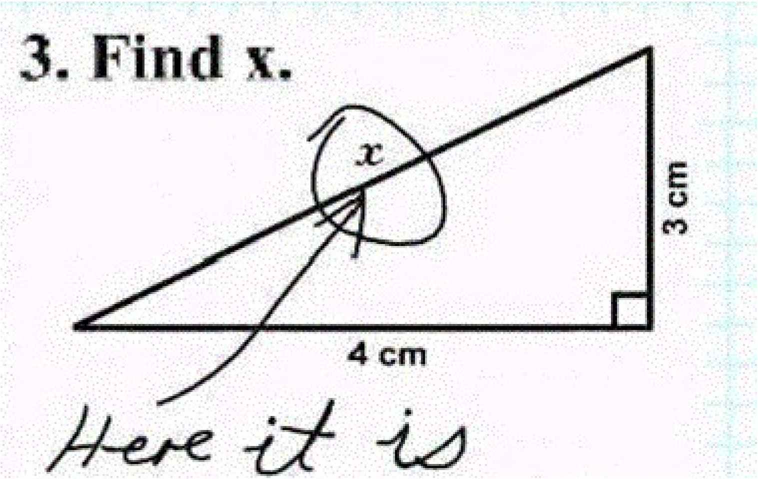


Simplified Models

Collider vs Non-collider

Phil Harris w/
C. Williams /V.Khoze/ M. Spannowsky

hep-ph/1411.0535

Comparing with Experiments

- Three classes of experiments can see DM
- Direct detection (DD)
  - Underground small background + small signal
  - LUX : Most sensitive for spin-independent
  - Picasso/Coupp/Simple : Most sensitive spin-dependent
- Indirect detection (ID)
  - Bounds are generally looser than DD
  - Fermi-LAT provides best bounds ($\gamma\gamma$ production)
- Collider experiments
  - CMS : the best detector
  - ATLAS : the cross check for CMS

Processes & Modeling

Vector

$$g_{\mathrm{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$$

EWK style coupling
(equal to all leptons)

Axial

$$g_{\mathrm{DM}} Z''_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$$

EWK style coupling
(equal to all leptons)

Scalar

$$g_{\mathrm{DM}} S\, \bar{\chi} \chi$$

Yukawa style coupling
(Mass based coupling)

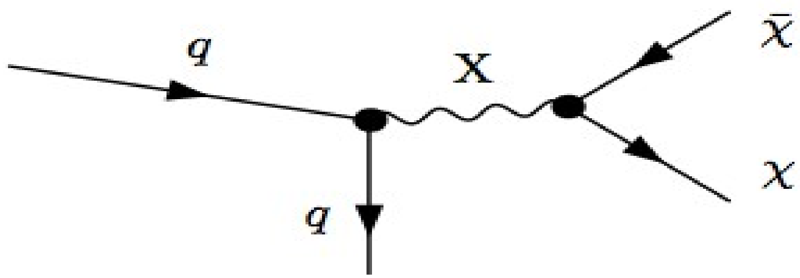
Pseudoscalar

$$g_{\mathrm{DM}} P\, \bar{\chi} \gamma^{5} \chi$$

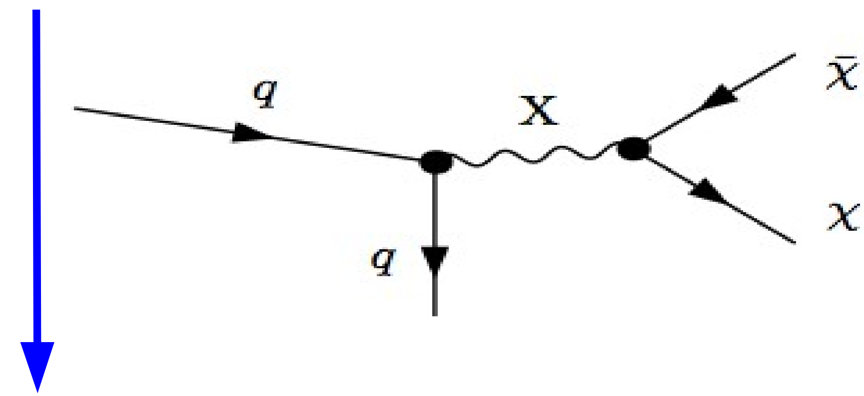
Yukawa style coupling
(Mass based coupling)

Direct Detection

Vector

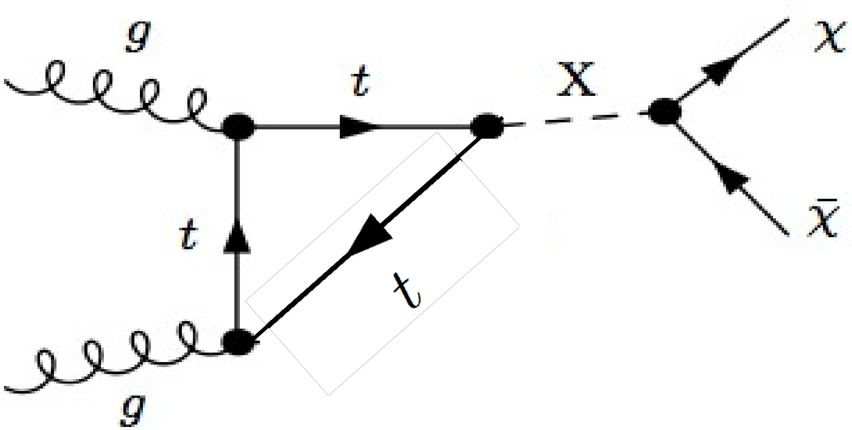


Axial

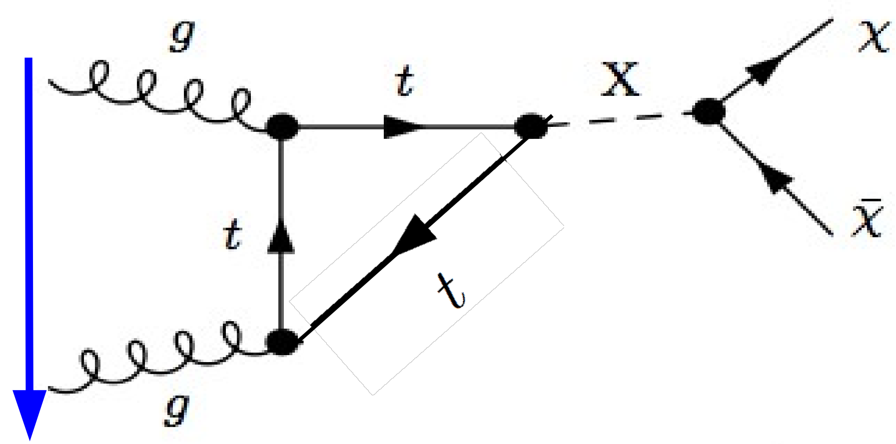


Spin-induced

Scalar

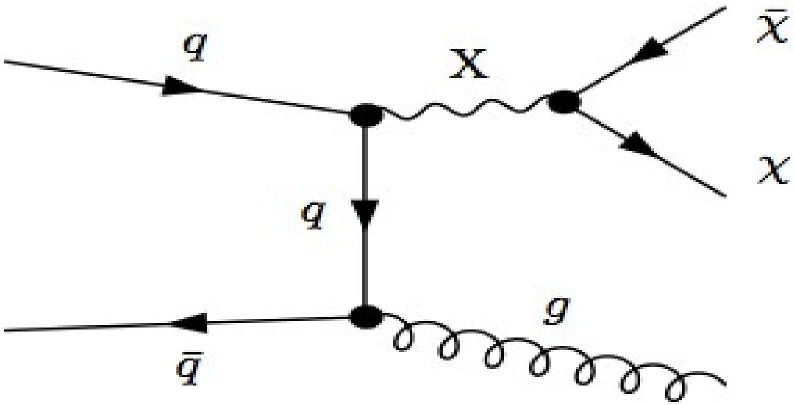


Pseudoscalar

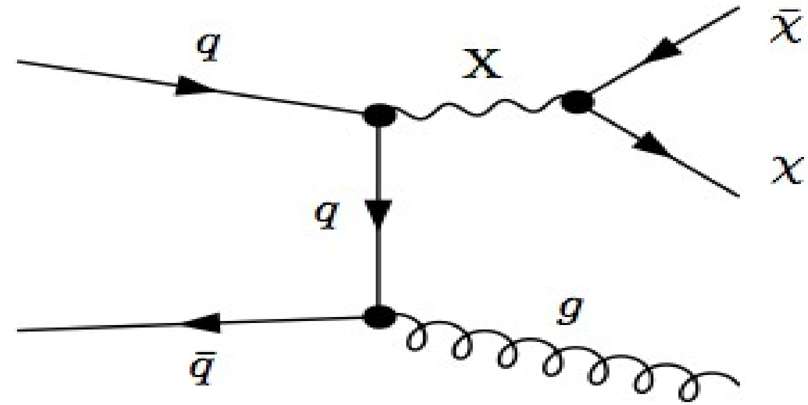


Collider detection

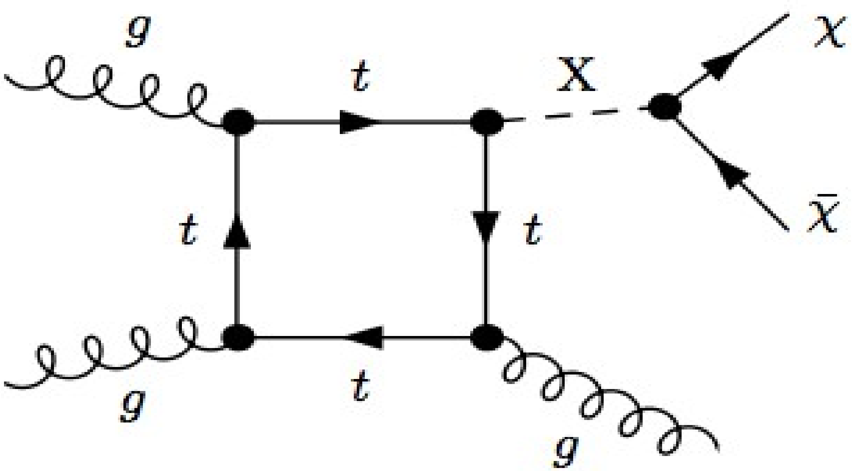
Vector



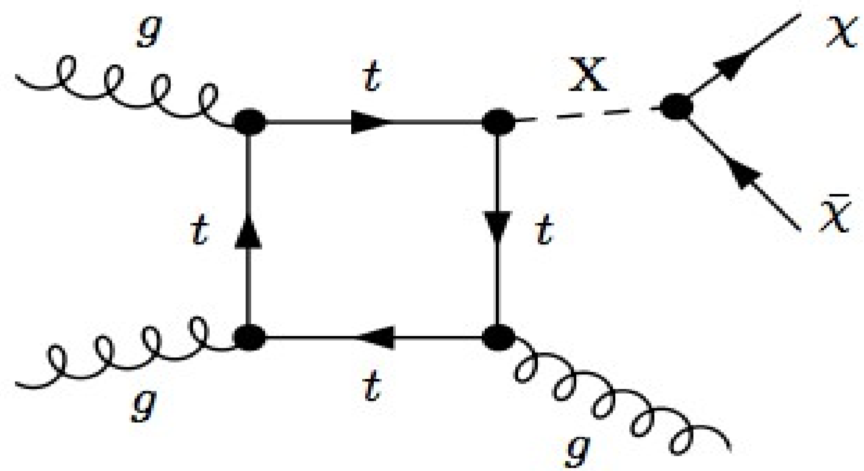
Axial



Scalar



Pseudoscalar



Only difference is one more vertex

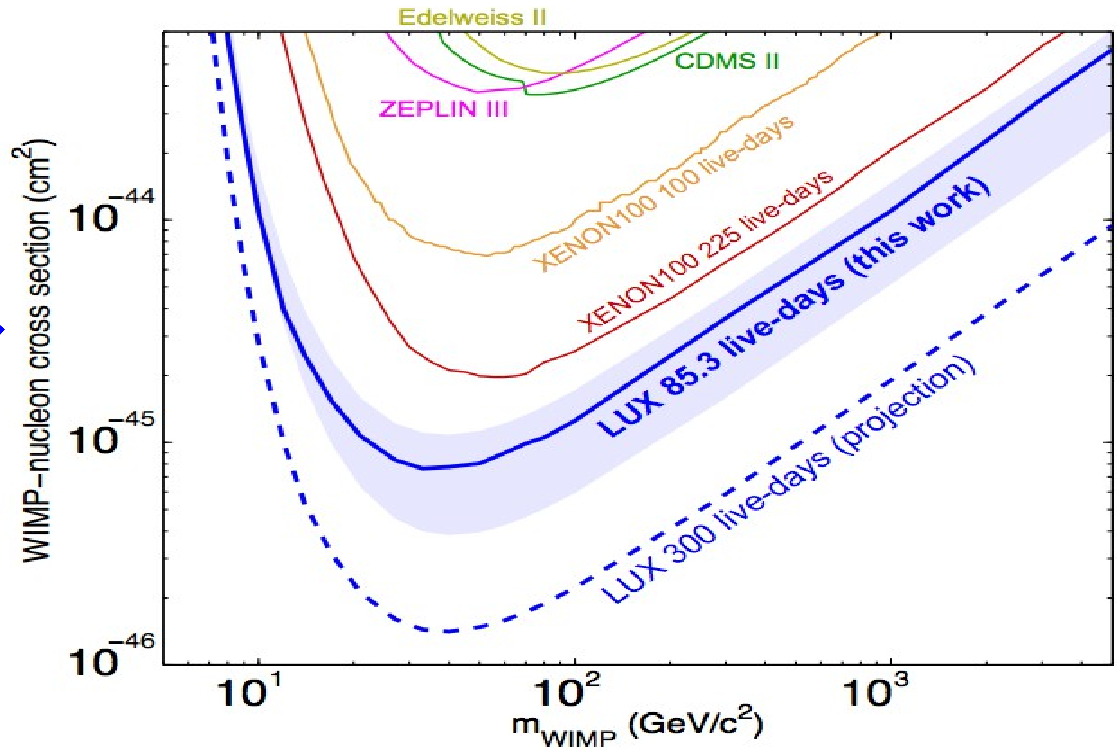
Direct Detection w/Simplified Models

- Direct detection :
  - Couplings and mediator all get merged into one

$$\sigma_{\chi p}^{DD} = C\,\boxed{\frac{g_{DM}^2 g_{SM}^2}{m_{MED}^4}}\,\rho^2 \qquad \rho = m_{DM} m_p / (m_{DM} + m_p)$$

No dependence on width (Γ)

σ_{eff}



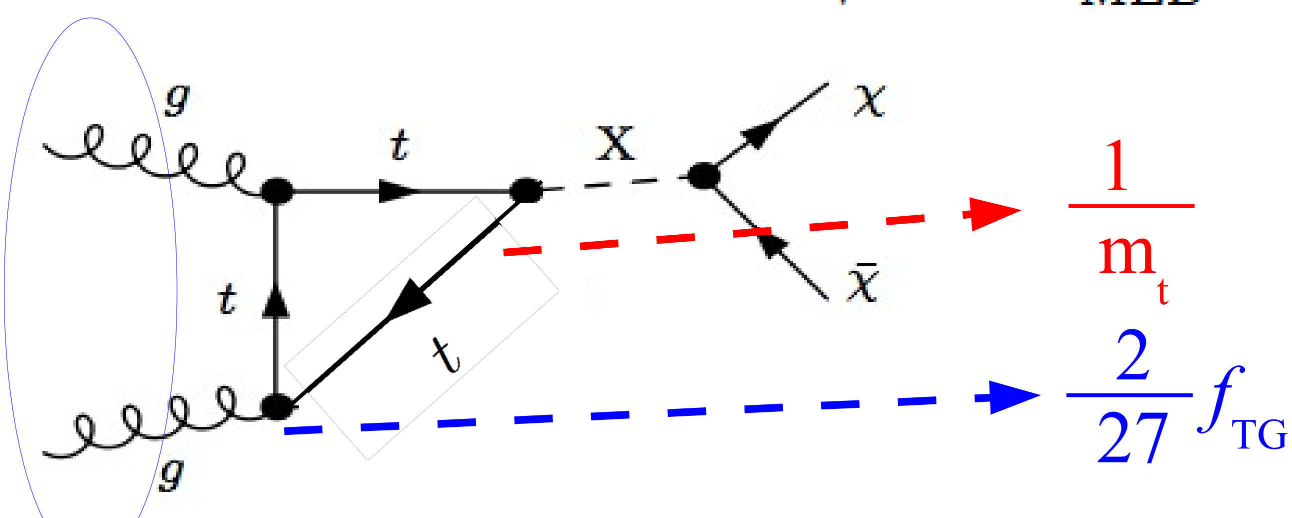
Two added degrees
1. Coupling ratio
2. Mediator mass

Translating to collider experiments gives us : m_{DM} and σ_{eff}

Direct Detection Cross sections

$$\rho = m_{\rm DM} m_p/(m_{\rm DM}+m_p)$$

- Vector $$\sigma^V_{\chi \rm p} = \frac{9}{\pi}\frac{g^2_{\rm DM} g^2_{\rm SM}\rho}{m^4_{\rm MED}}$$
- Axial $$\sigma^A_{\chi \rm p} = \frac{3}{\pi}\frac{g^2_{\rm DM} g^2_{\rm SM} a^2 \rho^2}{m^4_{\rm MED}} \qquad a = \Delta u + \Delta d + \Delta s \simeq 0.43$$
- Scalar $$\sigma^S_{\chi \rm p} = \frac{\rho^2}{\pi}\left|\frac{m_p}{m_t}\frac{g_t y_t \; g_\chi y_\chi}{m^2_{\rm MED}}\frac{2}{27}f_{\rm TG}\right|^2 \qquad f_{\rm TG} \simeq 0.9$$



Direct Detection Cross sections

$$\rho = m_{\rm DM} m_p / (m_{\rm DM} + m_p)$$

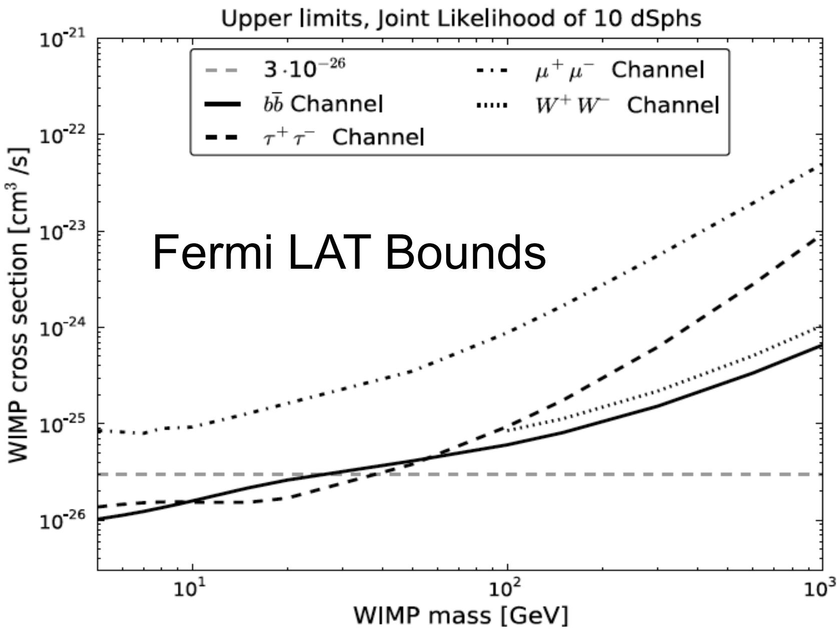
- Vector $$\sigma^V_{\chi p} = \frac{9}{\pi} \frac{g^2_{\rm DM} g^2_{\rm SM} \rho}{m^4_{\rm MED}}$$
- Axial $$\sigma^A_{\chi p} = \frac{3}{\pi} \frac{g^2_{\rm DM} g^2_{\rm SM} a^2 \rho^2}{m^4_{\rm MED}} \quad a = \Delta u + \Delta d + \Delta s \simeq 0.43$$
- Scalar $$\sigma^S_{\chi p} = \frac{\rho^2}{\pi} \left| \frac{m_p}{m_t} \frac{g_t y_t \; g_\chi y_\chi}{m^2_{\rm MED}} \frac{2}{27} f_{\rm TG} \right|^2 \quad f_{\rm TG} \simeq 0.9$$
- Pseudo-Scalar $$\sigma^{PS}_{\chi P} \sim \frac{c_q^2 \left[\Delta \tilde{q}^{(N)}\right]^2 \rho^4 \; v^2}{m_N^2 \, m^4_{MED}}.$$

No direct coupling to particles at rest
Direct detection with a pseudo-scalar is velocity suppressed*

Indirect Detection

- Indirect detection :
  - Gamma production from pair annihalation
  - Use this for pseudo-scalar bounds
- Pseudo-Scalar

$$\langle \sigma v \rangle^{P}_{\bar{b}b} = \frac{N_C}{2\pi} \frac{(y_b g_b)^2 (y_\chi g_\chi)^2 \, m^2_{\rm DM}}{(m^2_{\rm MED} - 4m^2_{\rm DM})^2 + m^2_{\rm MED}\Gamma^2_{\rm MED}} \sqrt{1 - \frac{m_b^2}{m_{DM}^2}}$$



enhanced sensitivity at $m_{\rm MED}=2m_{\rm DM}$

Constraint on σv gives
3 additional degrees:
1. coupling ratio
2. Width
3. Mediator mass

LHC Experiments

Collider Setup

- For this study :
  - Models were generated in MCFM
  - LO production of :
    - Vector
    - Axial
    - Scalar
    - Pseudo-Scalar
  - Have the ability to vary :
    - Couplings
    - Width
    - Mediator Mass
    - Dark Matter mass

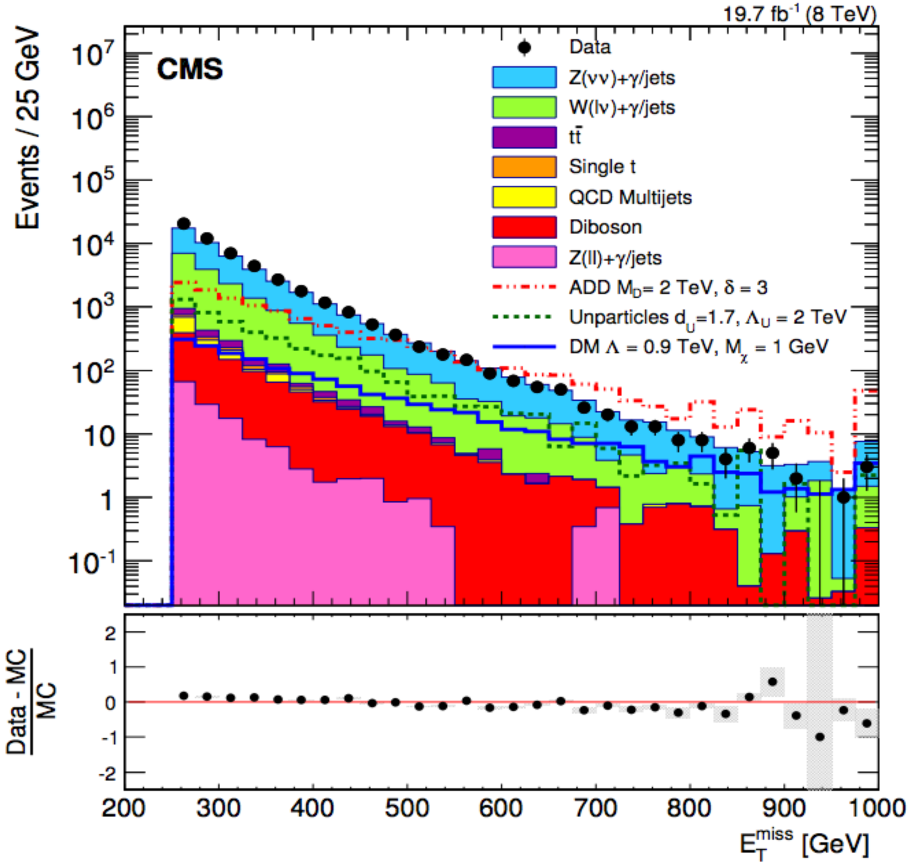
5 tunable parameters

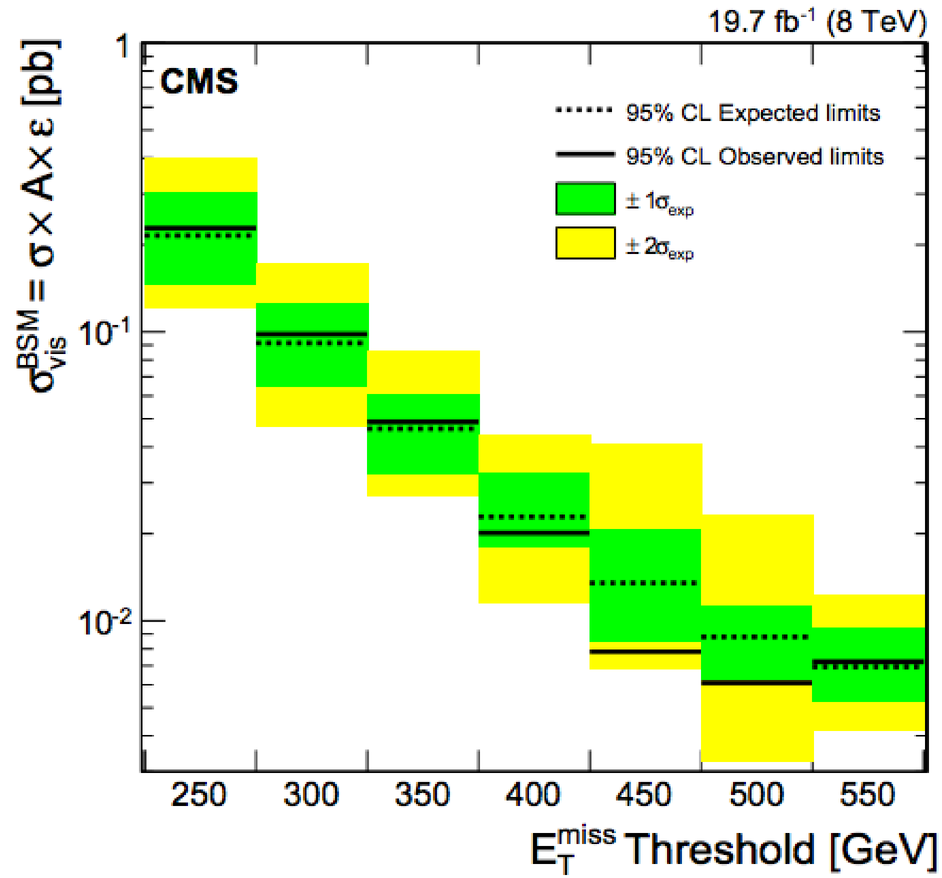
Setup cont'd

- All collider plots :
  - Generate samples with MCFM
  - Showered samples with Pythia 8
  - Smeared samples with parametric model
    - Model is tuned to CMS simulation
      - ~little bit better than Delphes (well validated)

- Extract limits with the current CMS analysis
  - Using the summer paper (EXO-12-048)
  - Validated with the CMS results to ~ few %

Analysis Setup

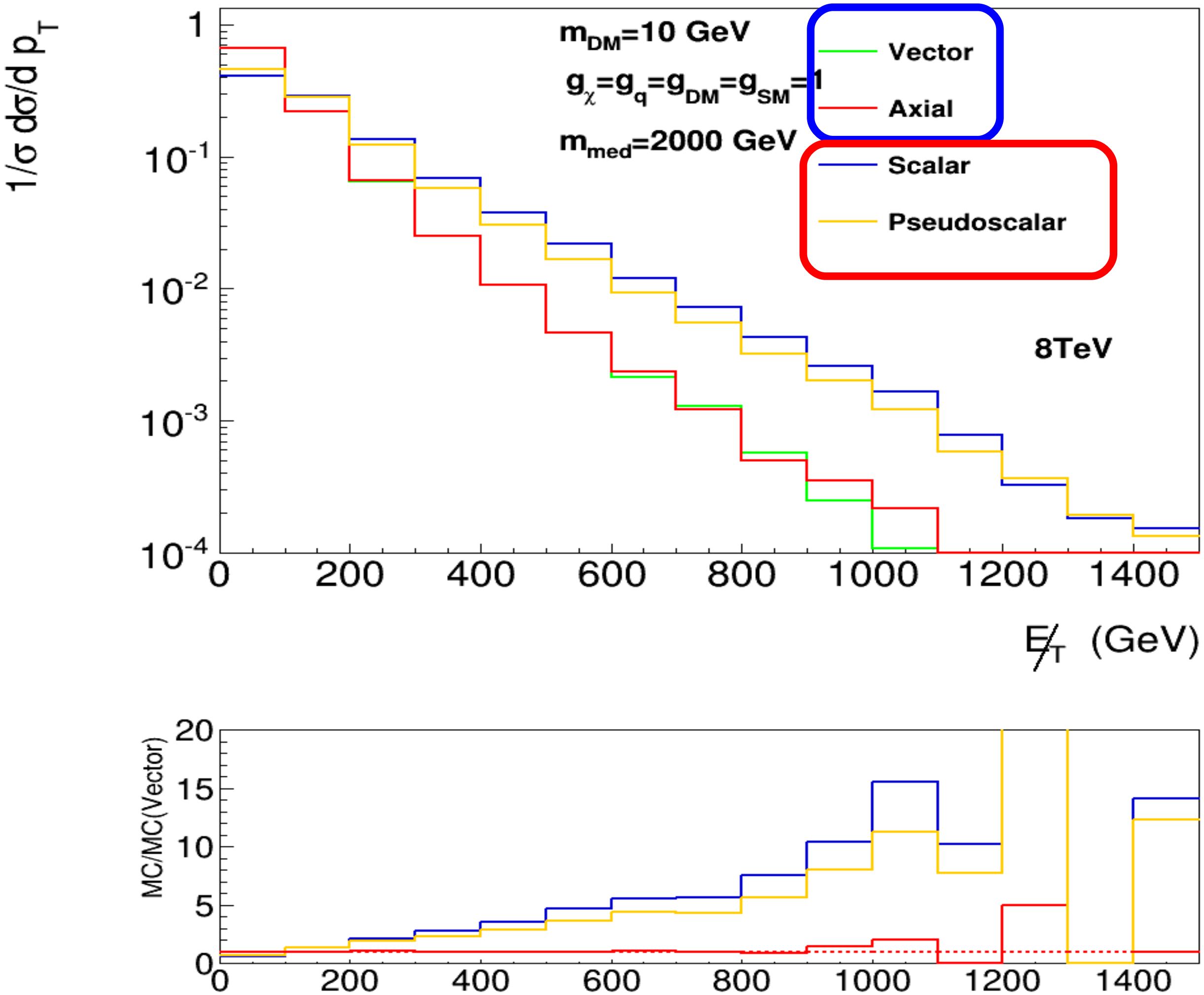




- Limit with full systematics @ 7 *MET* points
  - For a given DM model take limit with best *MET*
- 14 TeV => scale yields using MC & repeat

Model dependence & Kinematics

- Production model



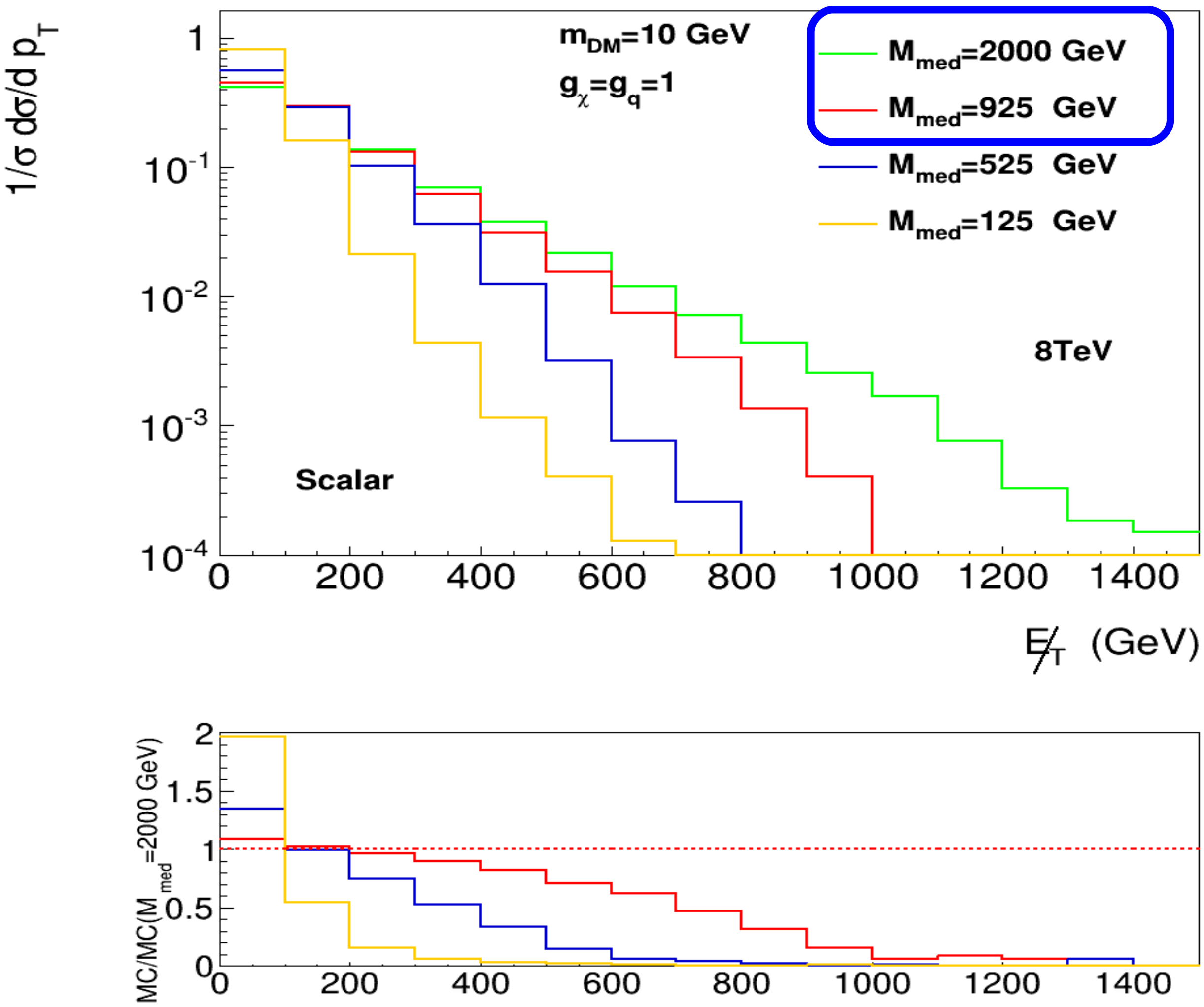
Quark initiated similar

Gluon initiated similar

Gluon initiated production has a higher p_T spectra

Model dependence & Kinematics

- Mediator model



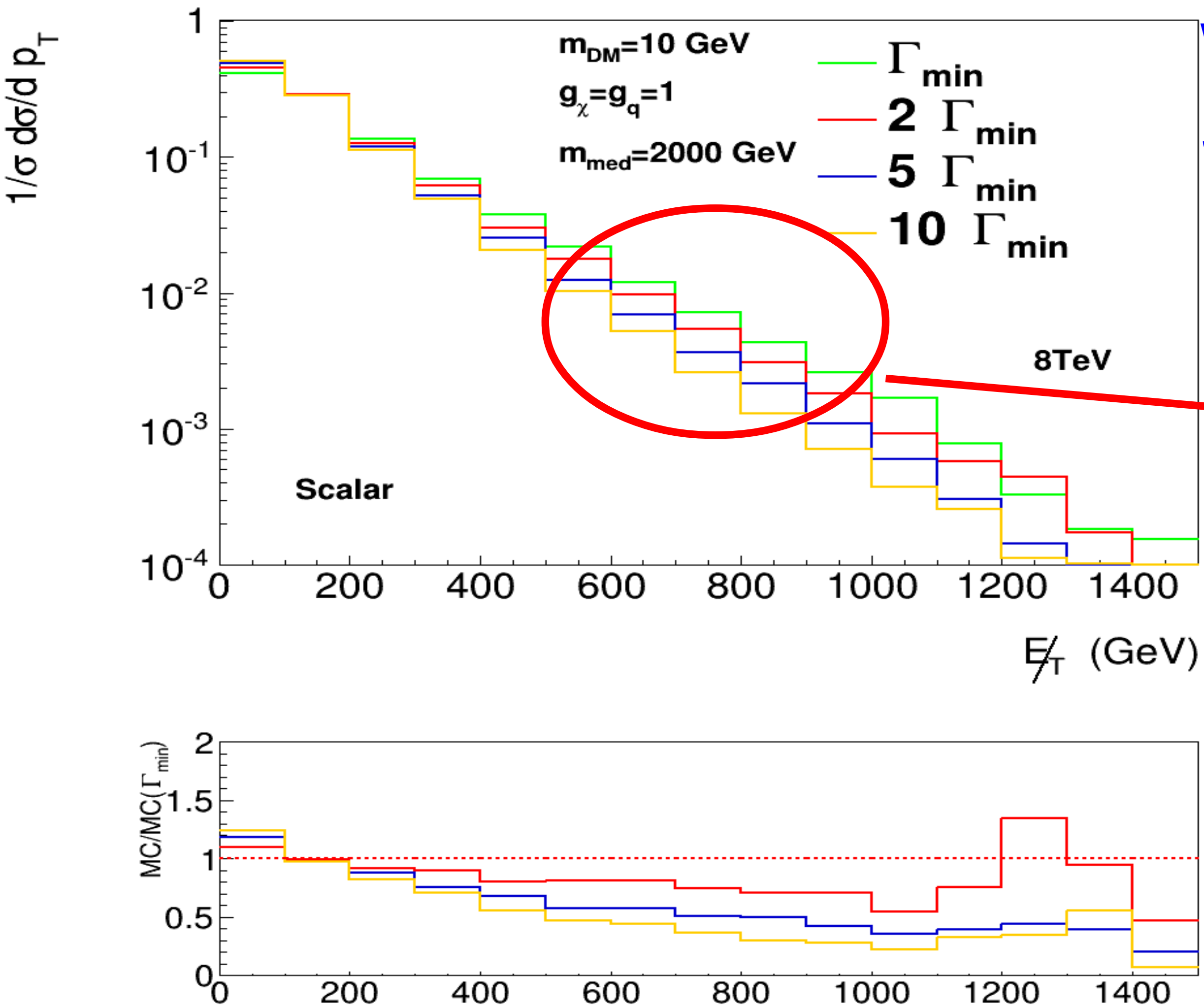
For mass > 1 TeV
Variation is reduced

Variation very similar
for axial/vector

Mediator mass : large effect on the change in sensitivity

Model dependence & Kinematics

- Width variation



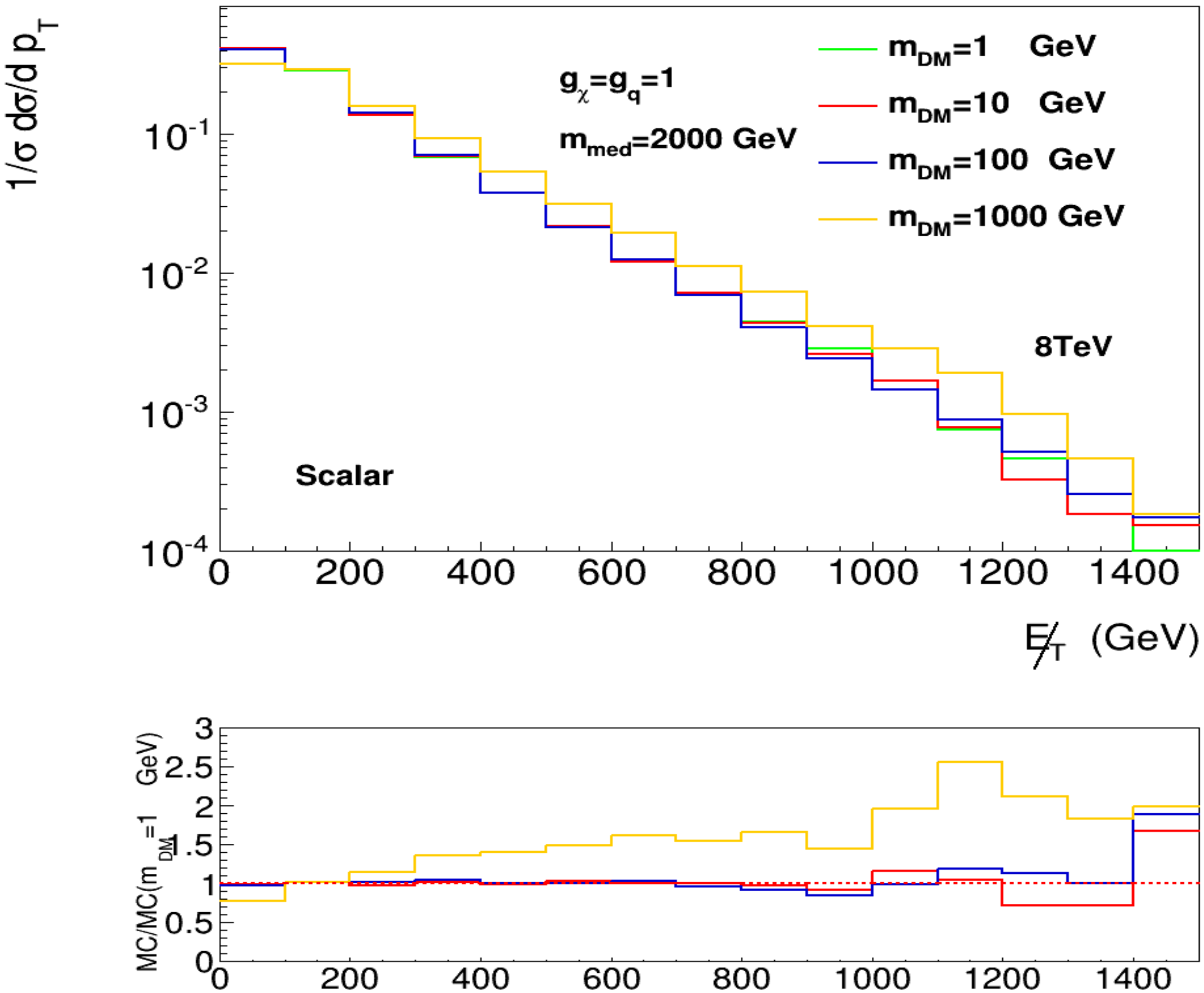
Width:
Substantial tail effects
Even when subdominant

Most sensitive region

Width can reduce sensitivity substantially

Model dependence & Kinematics

- Dark matter mass

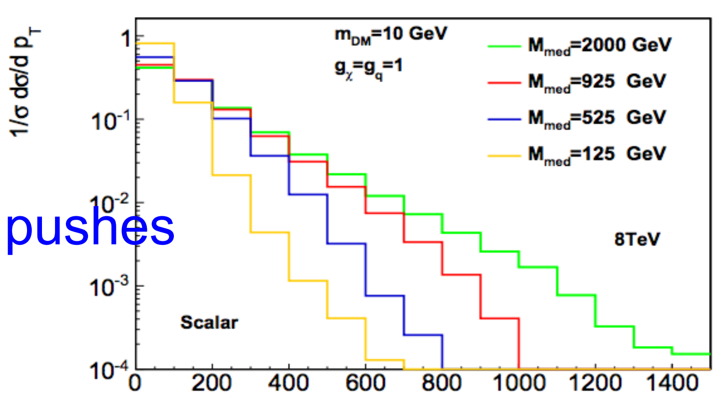


Not so important

Dark matter mass only matters when process ~off-shell

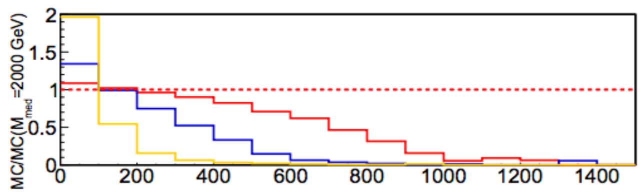
Executive Summary

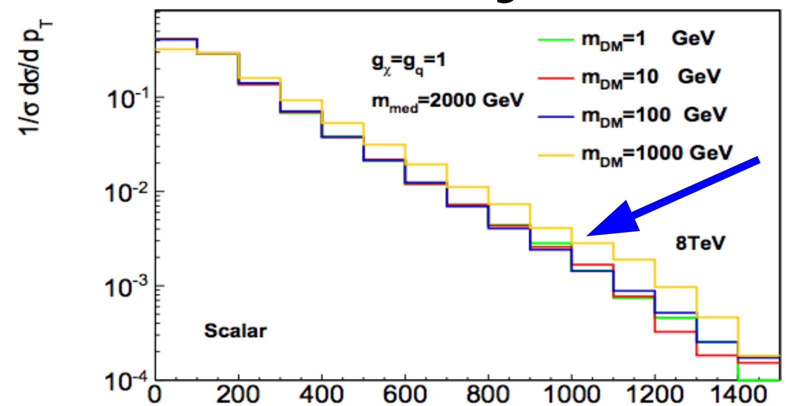
Mediator pushes p_T out



Mediator Mass

$\not{E}_T$ (GeV)

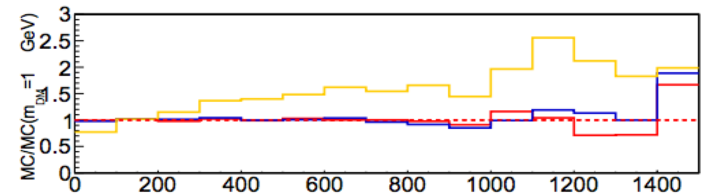




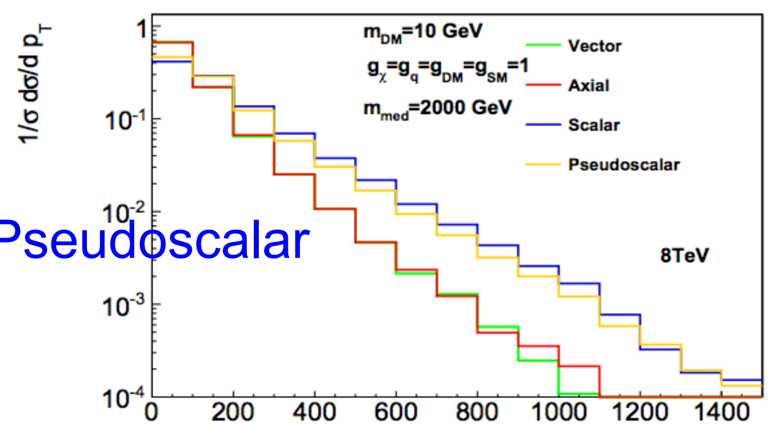
Off-shell Changes kinematics

Dark Matter Mass

$\not{E}_T$ (GeV)

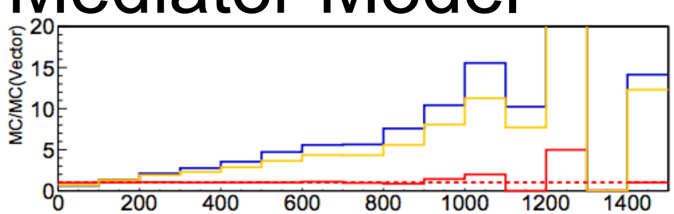


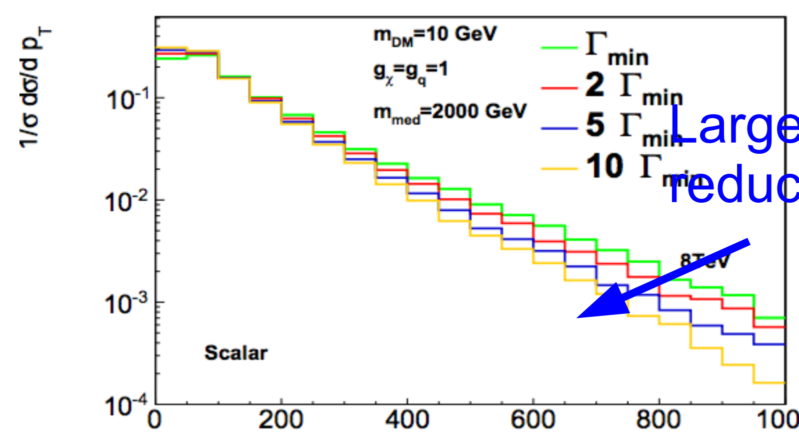
Scalar/Pseudoscalar Harder spectra



Mediator Model

$\not{E}_T$ (GeV)

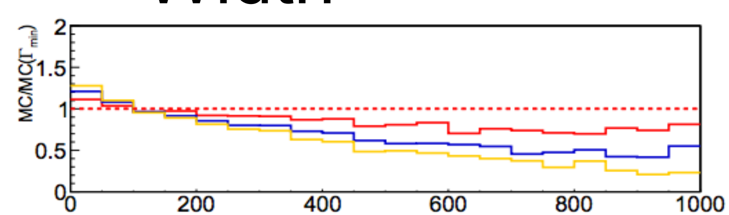




Larger width reduces sensitivity

Width

p_T leading Jet (GeV/c)

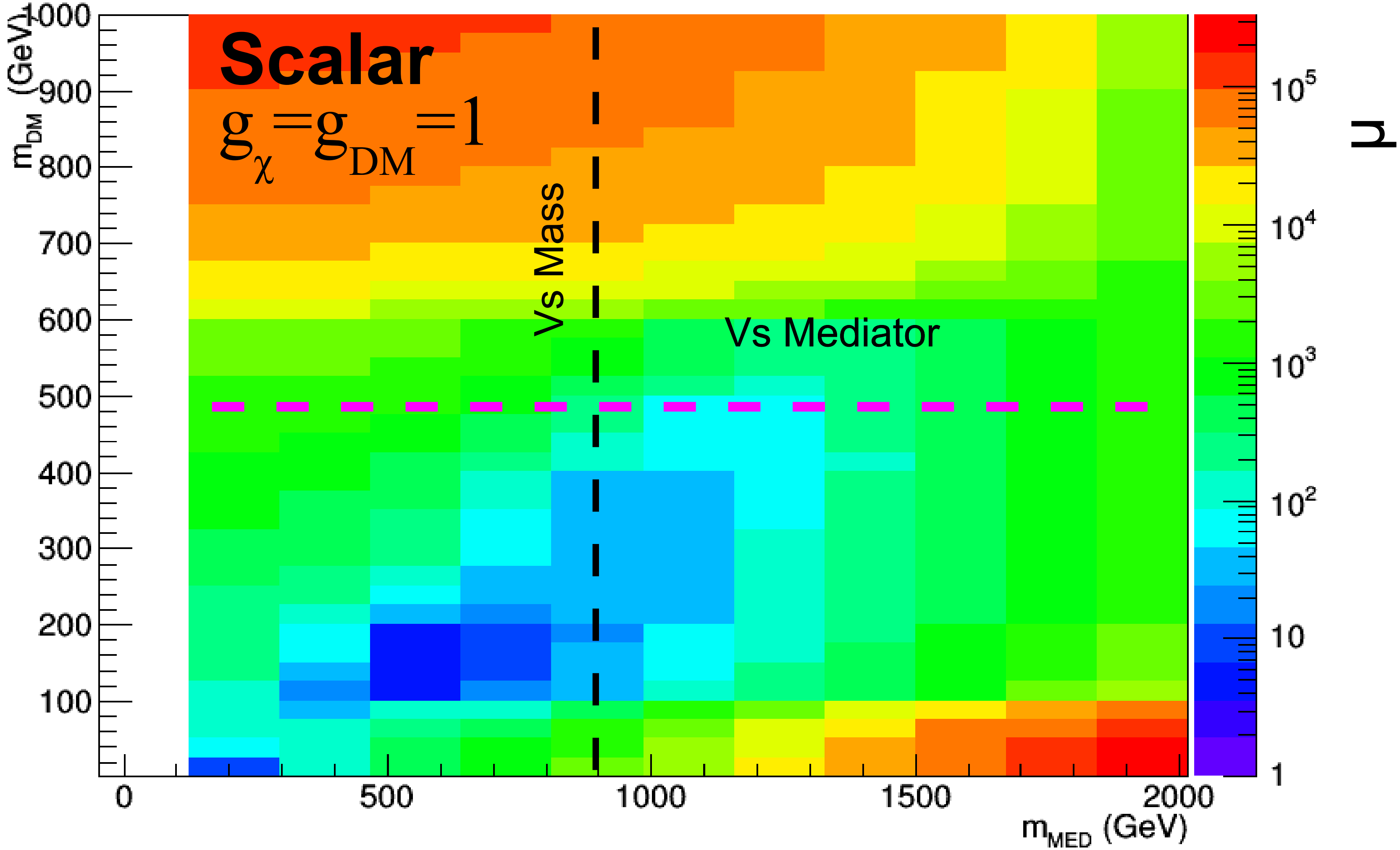


Dealing with Kinematic Variation

- For a discovery we want :
  - Maximal coverage of all possible shapes
  - Most essential parameters
    - Varying the process model
    - Varying the mediator
  - Choice of width
    - Bounded by detector limitations
  - Choice of DM mass
    - Effect is relatively small (not really needed)

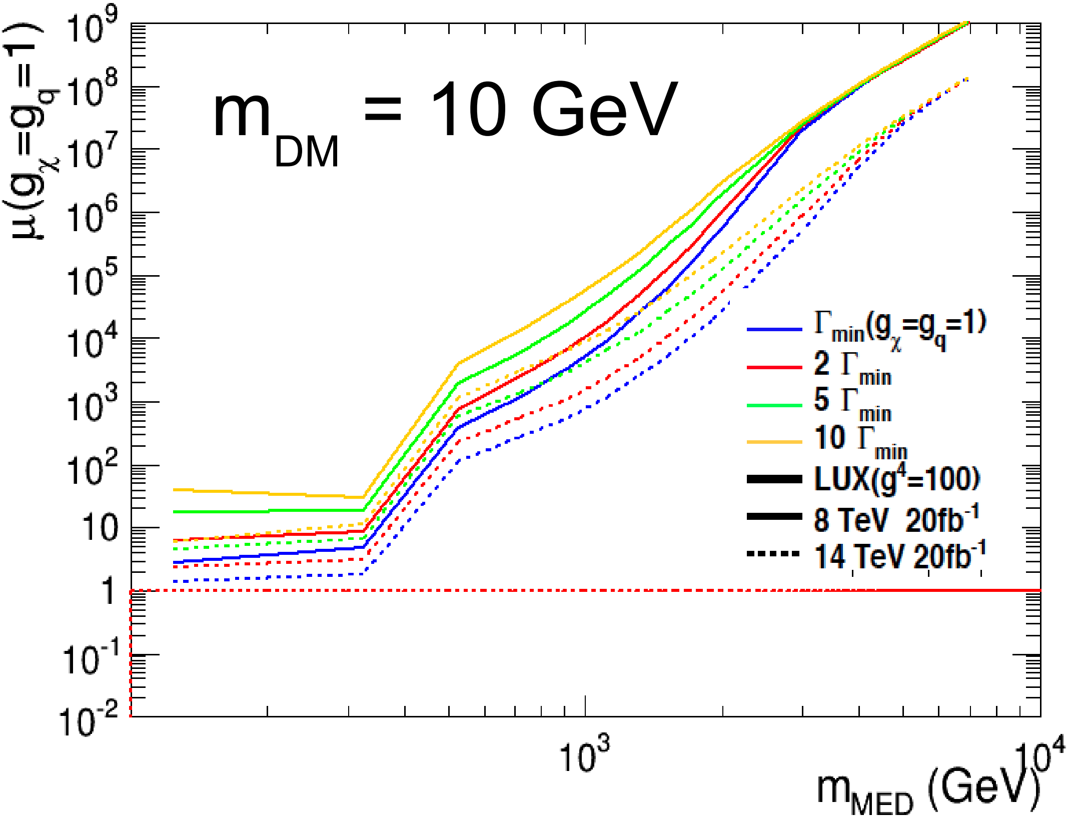
Limit Extraction

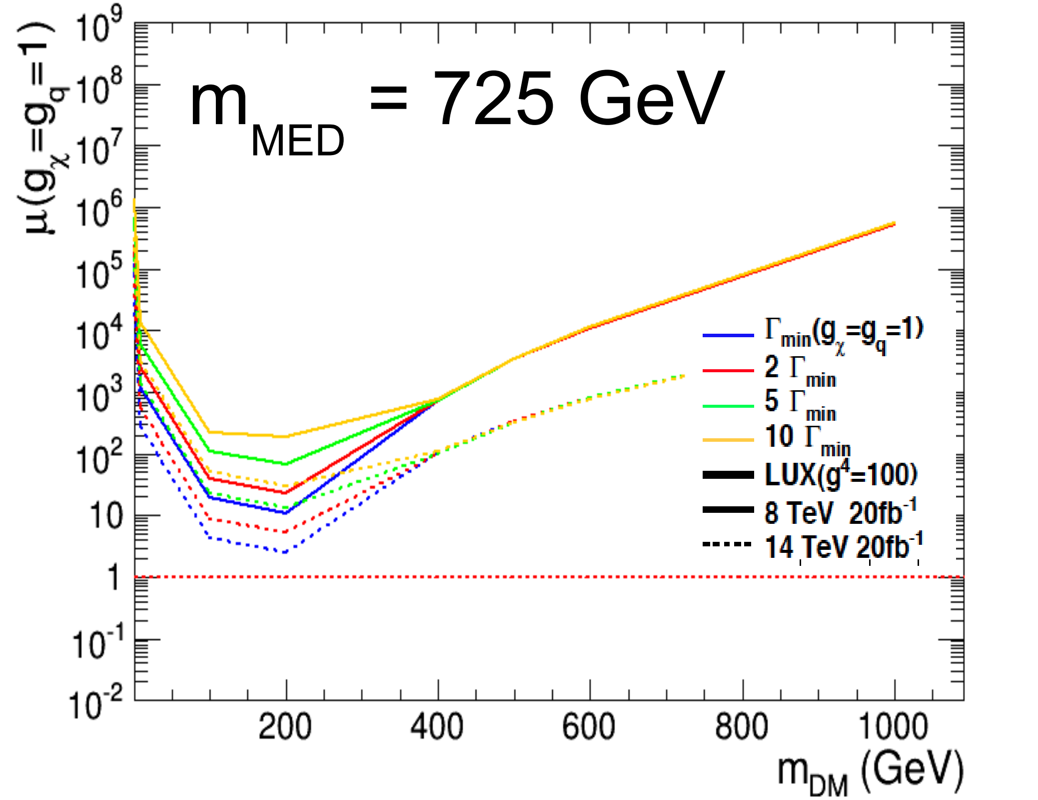
Each point is a MC => compute limit with each point



1D projections are the plots shown in the paper

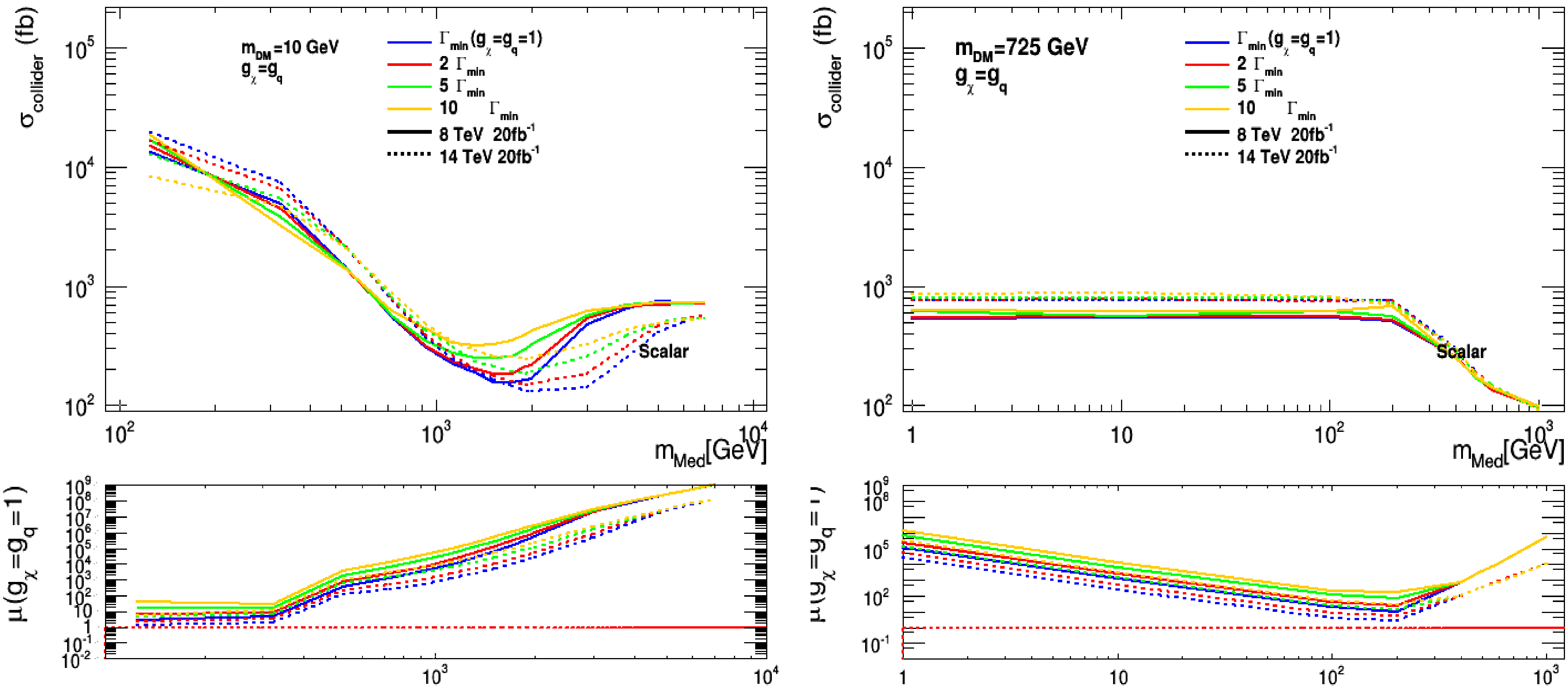
1D Limit Extraction





- Note collider limits are for a jet pT > 15 GeV
- Yukawa coupling reduces sensitivity @low mass

Translating into cross section



- Note collider limits are for a jet pT > 15 GeV
- Yukawa coupling reduces sensitivity @low mass

Collider vs Direct Detection

Vector

$$g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu \chi$$

Sensitive w/Direct Detection
Dominant bounds from LUX

Axial

$$g_{\rm DM} Z''_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$

Less Sensitive w/DD
Requires spin-dependent DD
Picasso/Coupp/Simple

Scalar

$$g_{\rm DM} S\, \bar{\chi}\chi$$

Less Sensitive w/DD
EFT coupling to gluons
Bounds still from LUX

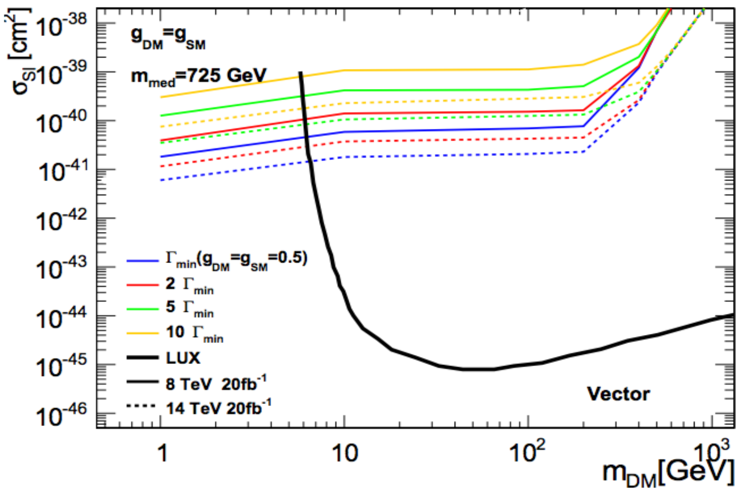
Pseudoscalar

$$g_{\rm DM} P\, \bar{\chi}\gamma^5 \chi$$

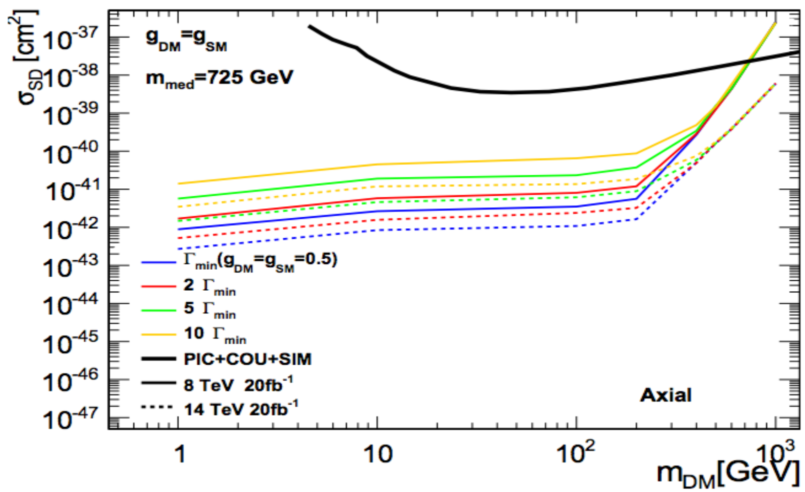
No bounds from DD
Only Cosmic bounds exist
FermiLAT reported bounds
Can yield Galactic x-rays

Usual Plots

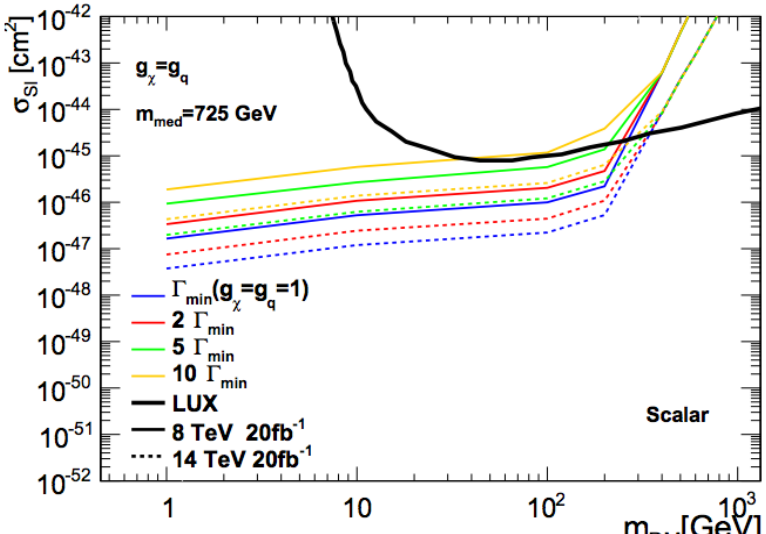
Vector



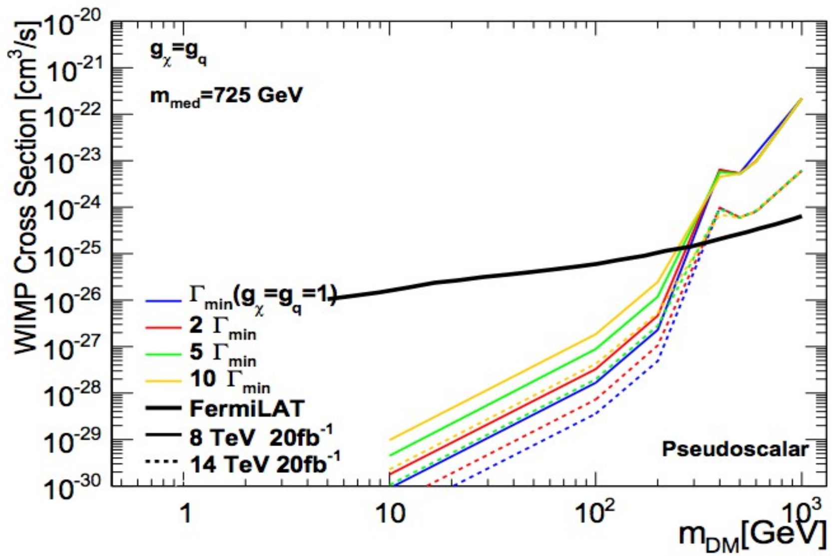
Axial



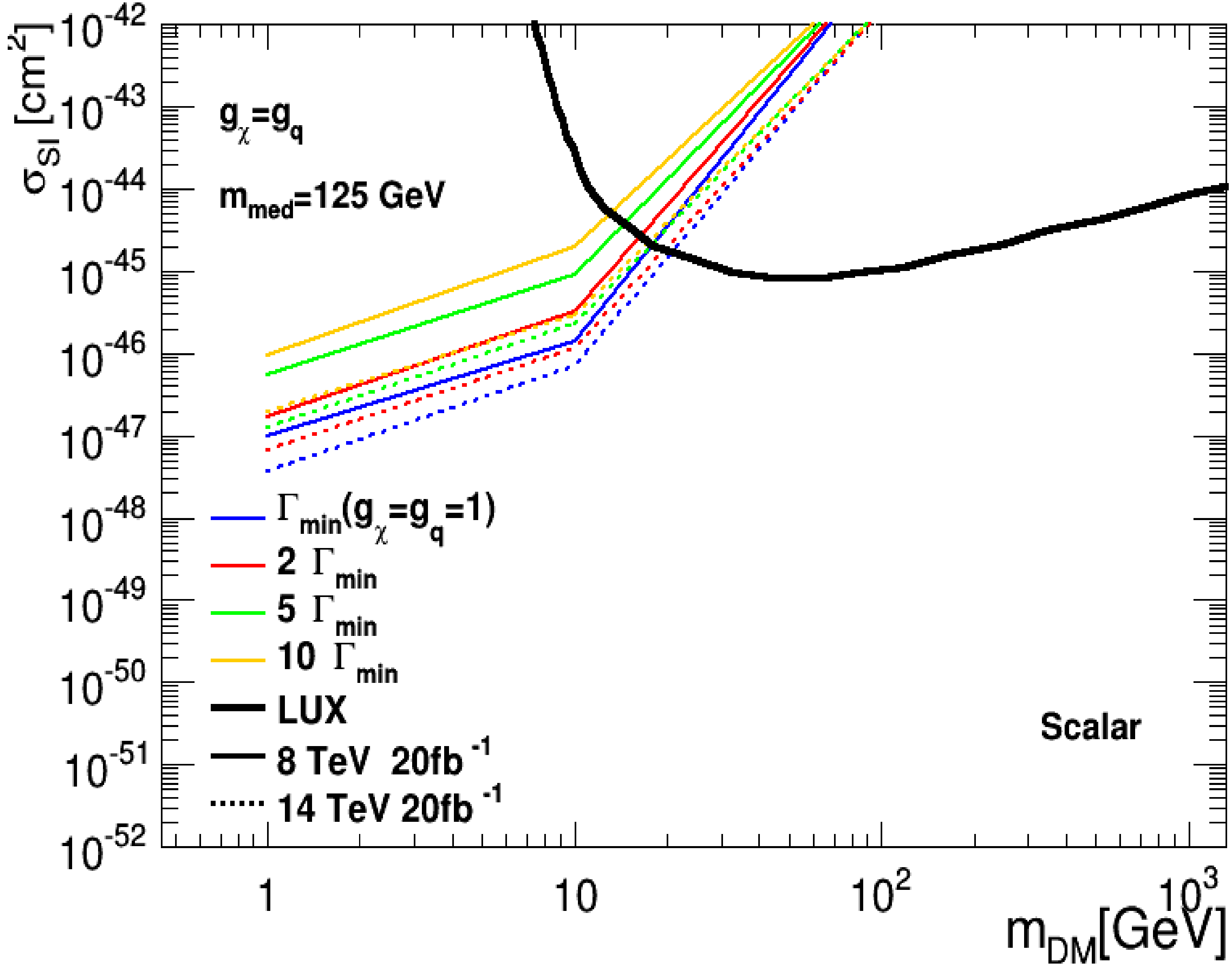
Scalar



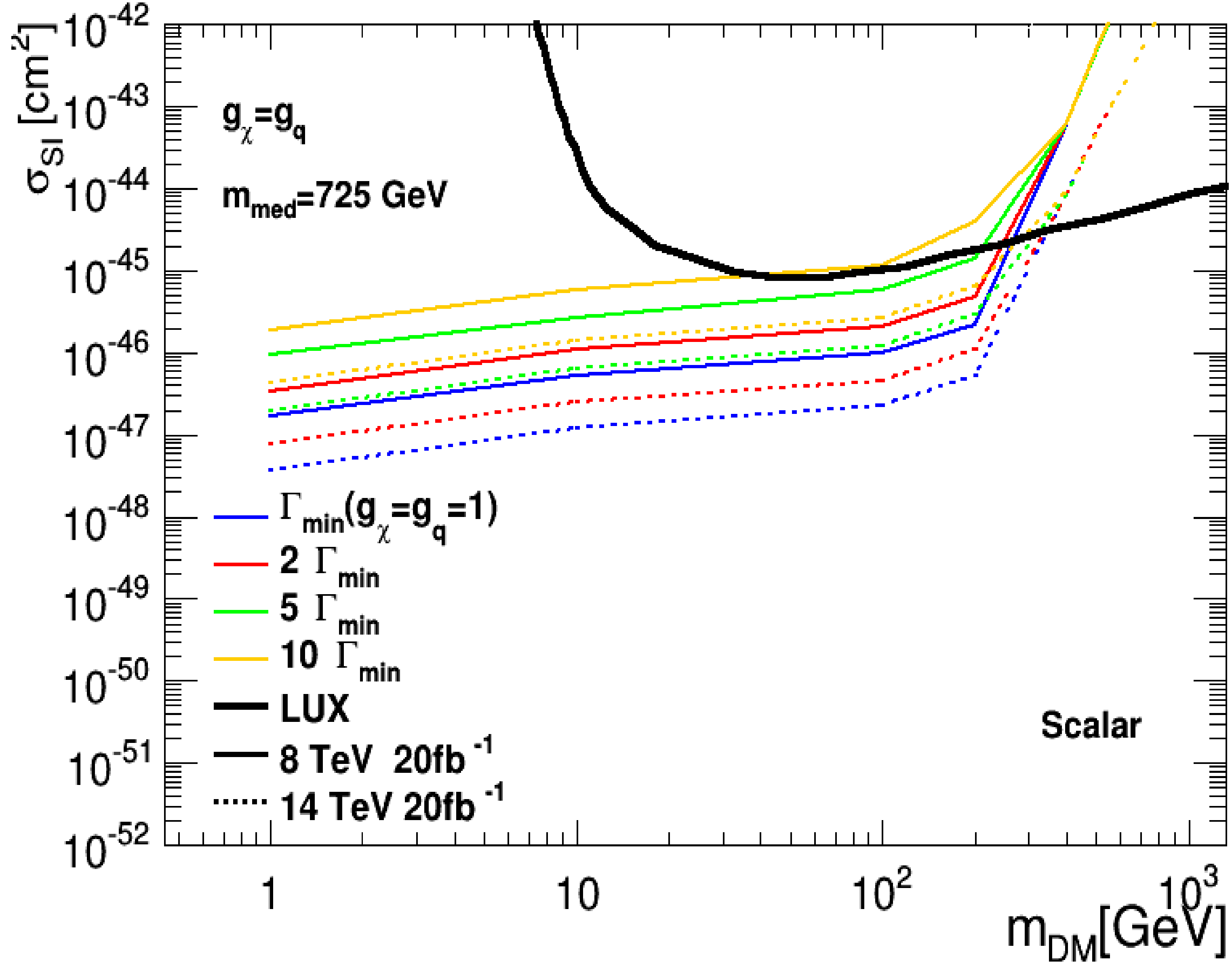
Pseudoscalar



Usual Plots

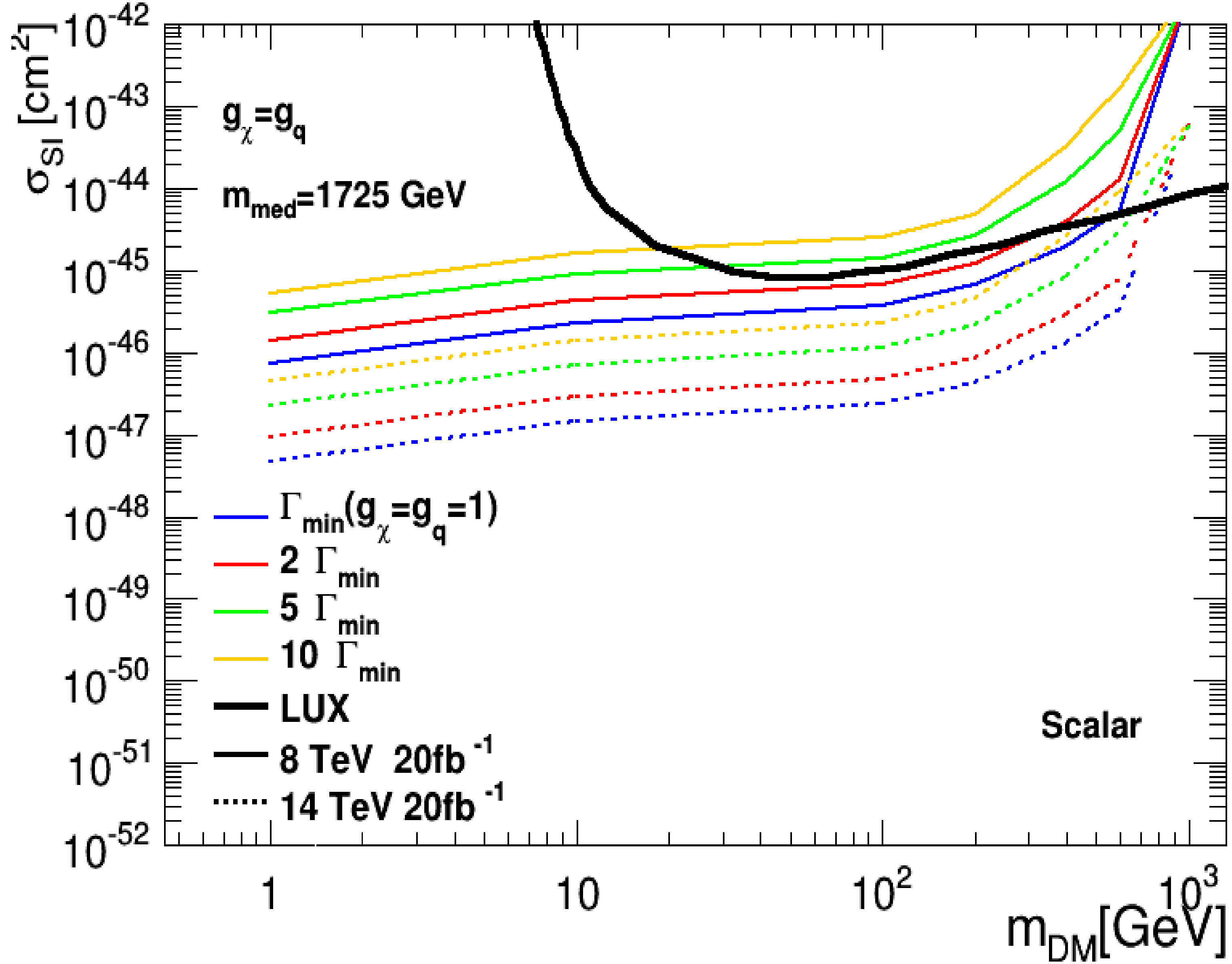

σ_{SI} [cm^2]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-52}
$g_\chi = g_q$
m_{med}=125 GeV
$\Gamma_{min}(g_\chi = g_q = 1)$
2 Γ_{min}
5 Γ_{min}
10 Γ_{min}
LUX
8 TeV 20fb $^{-1}$
14 TeV 20fb $^{-1}$
Scalar
1
10
10^2
10^3
m_{DM}[GeV]

Usual Plots

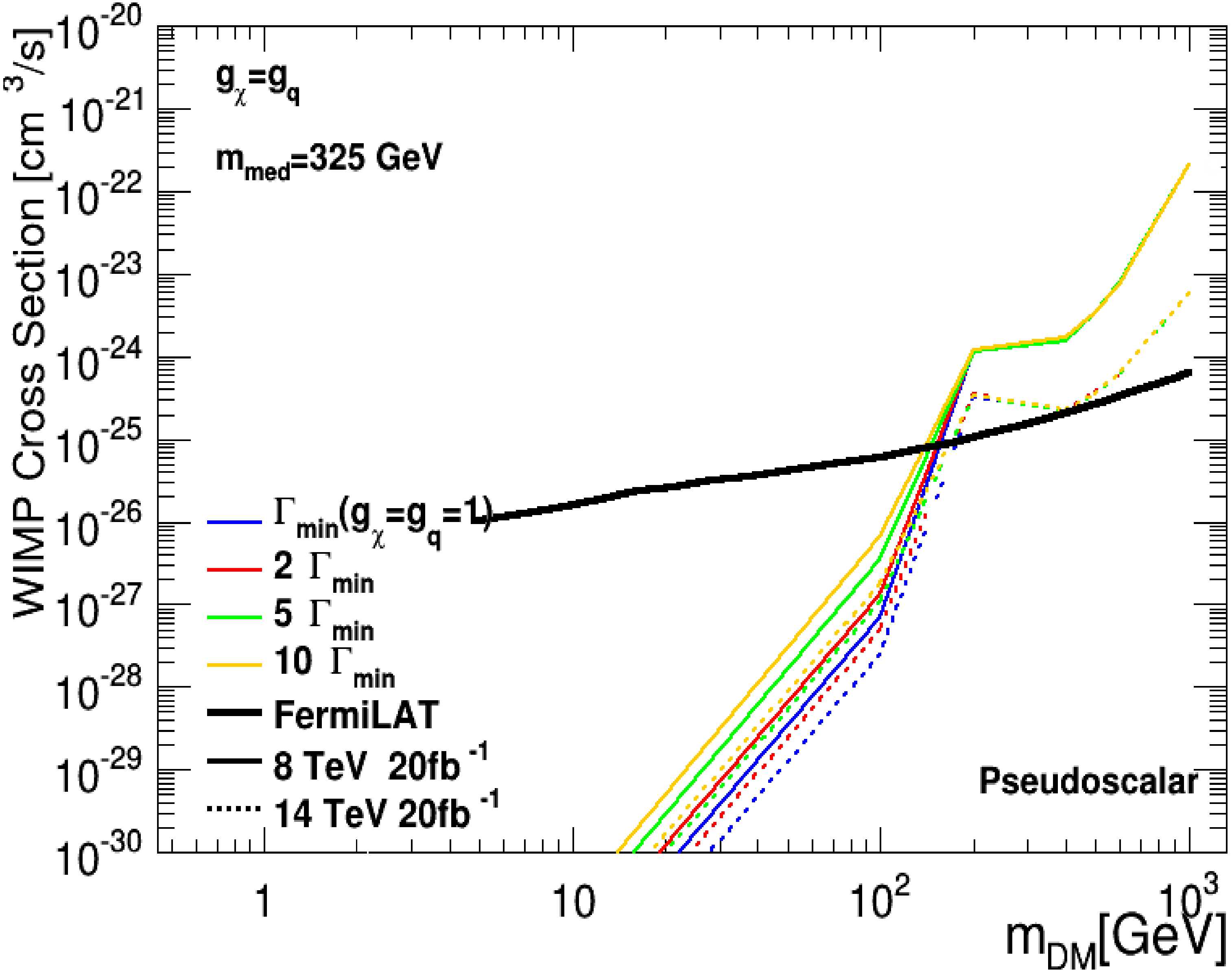


σ_{SI} [cm^2]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-52}
$g_\chi = g_q$
m_{med}=725 GeV
$\Gamma_{min}(g_\chi = g_q = 1)$
2 Γ_{min}
5 Γ_{min}
10 Γ_{min}
LUX
8 TeV 20fb $^{-1}$
14 TeV 20fb $^{-1}$
Scalar
1
10
10^2
10^3
m_{DM}[GeV]

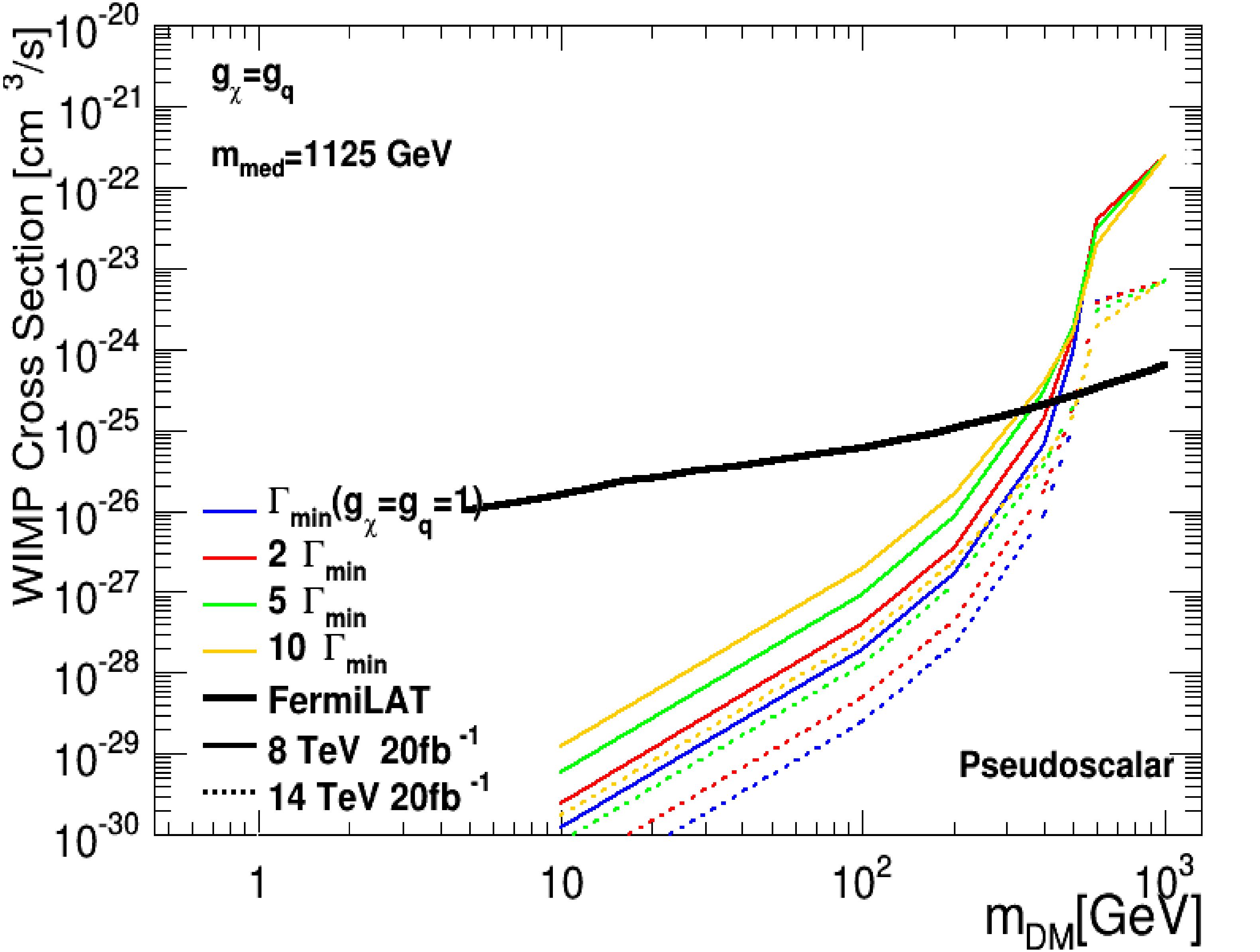
Usual Plots


σ_{SI} [cm^2]
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-51}
10^{-52}
$g_\chi = g_q$
m_{med}=1725 GeV
$\Gamma_{min}(g_\chi = g_q = 1)$
2 Γ_{min}
5 Γ_{min}
10 Γ_{min}
LUX
8 TeV 20fb^{-1}
14 TeV 20fb^{-1}
Scalar
1
10
10^2
10^3
m_{DM}[GeV]

Usual Plots

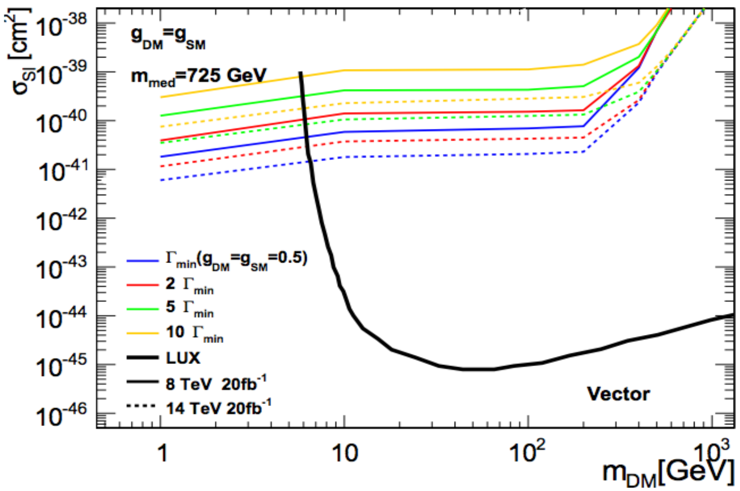

$g_\chi = g_q$
m_{med}=325 GeV
$\Gamma_{min}(g_\chi = g_q = 1)$
$2\ \Gamma_{min}$
$5\ \Gamma_{min}$
$10\ \Gamma_{min}$
FermiLAT
8 TeV 20fb $^{-1}$
14 TeV 20fb $^{-1}$
Pseudoscalar
WIMP Cross Section [cm ^{3}/s]
m_{DM}[GeV]
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
1
10
10^2
10^3

Usual Plots

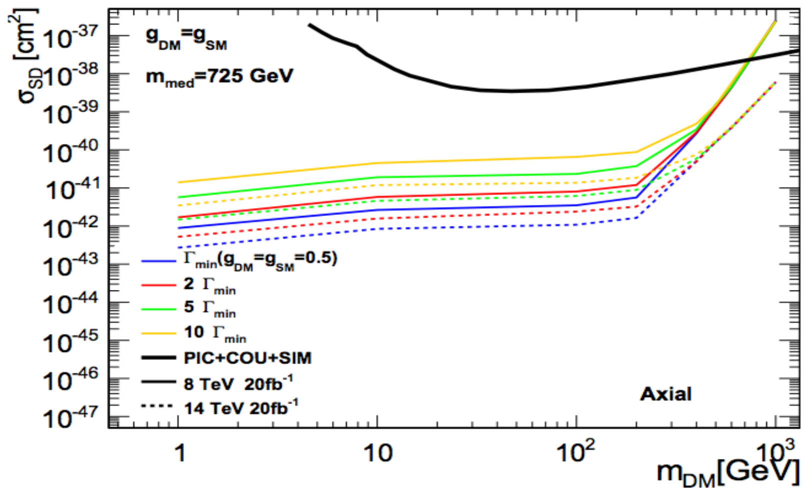

$g_\chi=g_q$
m_{med}=1125 GeV
$\Gamma_{min}(g_\chi=g_q=1)$
2 Γ_{min}
5 Γ_{min}
10 Γ_{min}
FermiLAT
8 TeV 20fb $^{-1}$
14 TeV 20fb $^{-1}$
Pseudoscalar
WIMP Cross Section [cm ^{3}/s]
m_{DM}[GeV]

Usual Plots

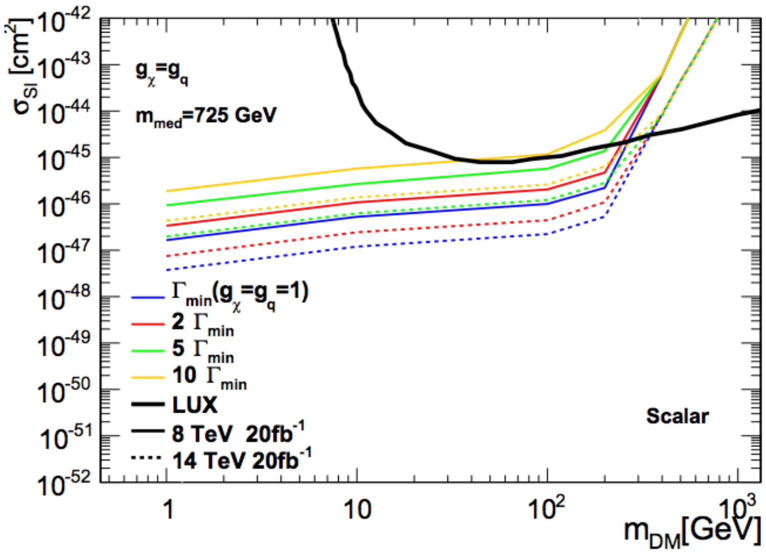
Vector



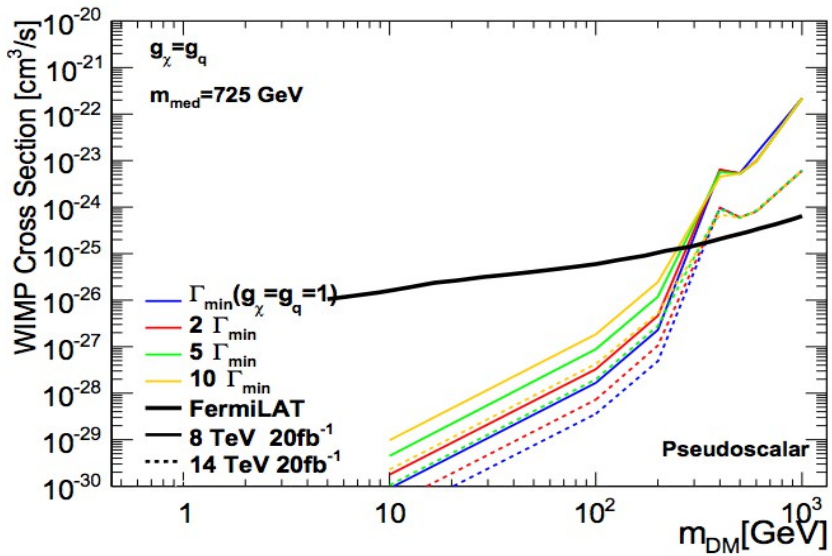
Axial



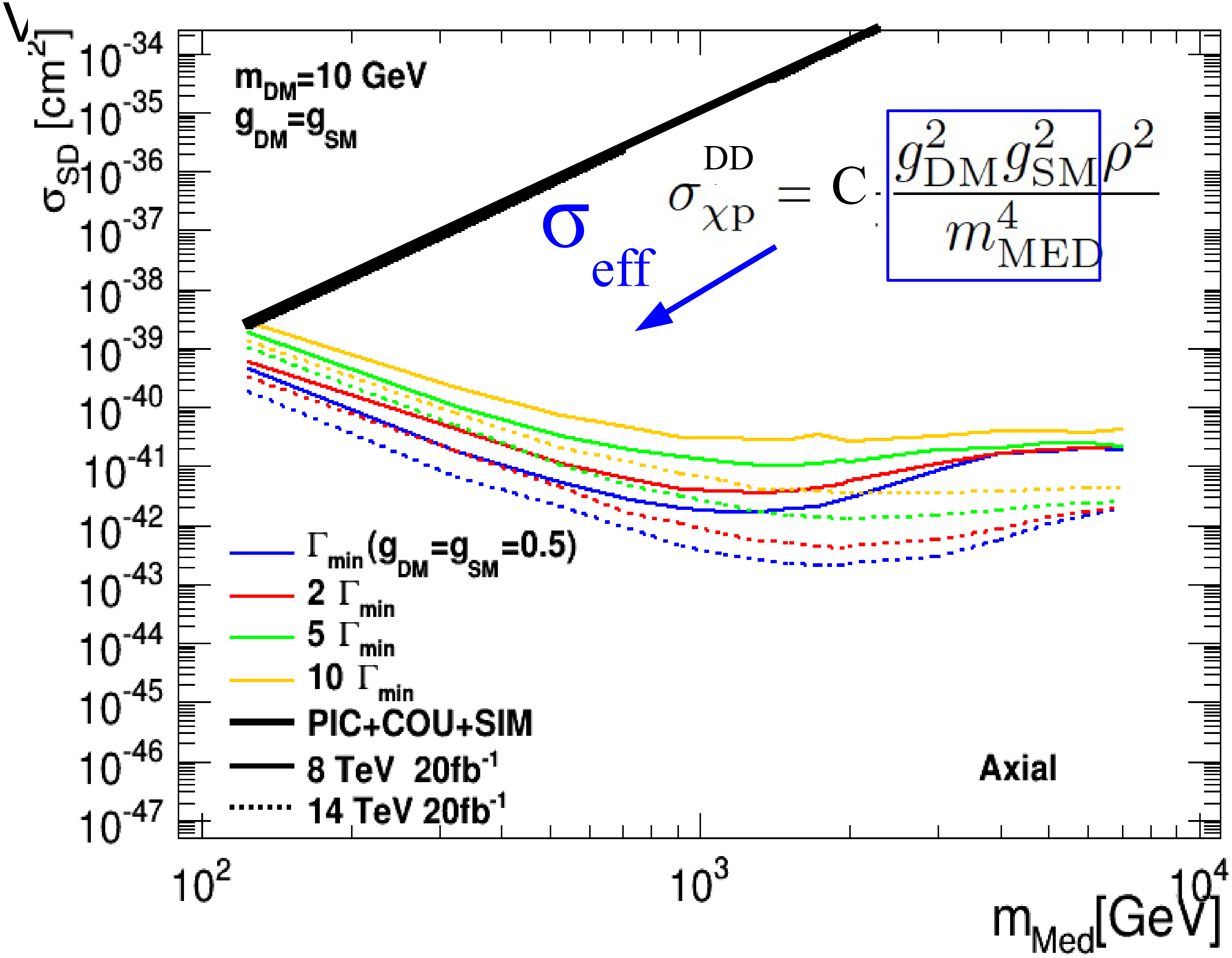
Scalar



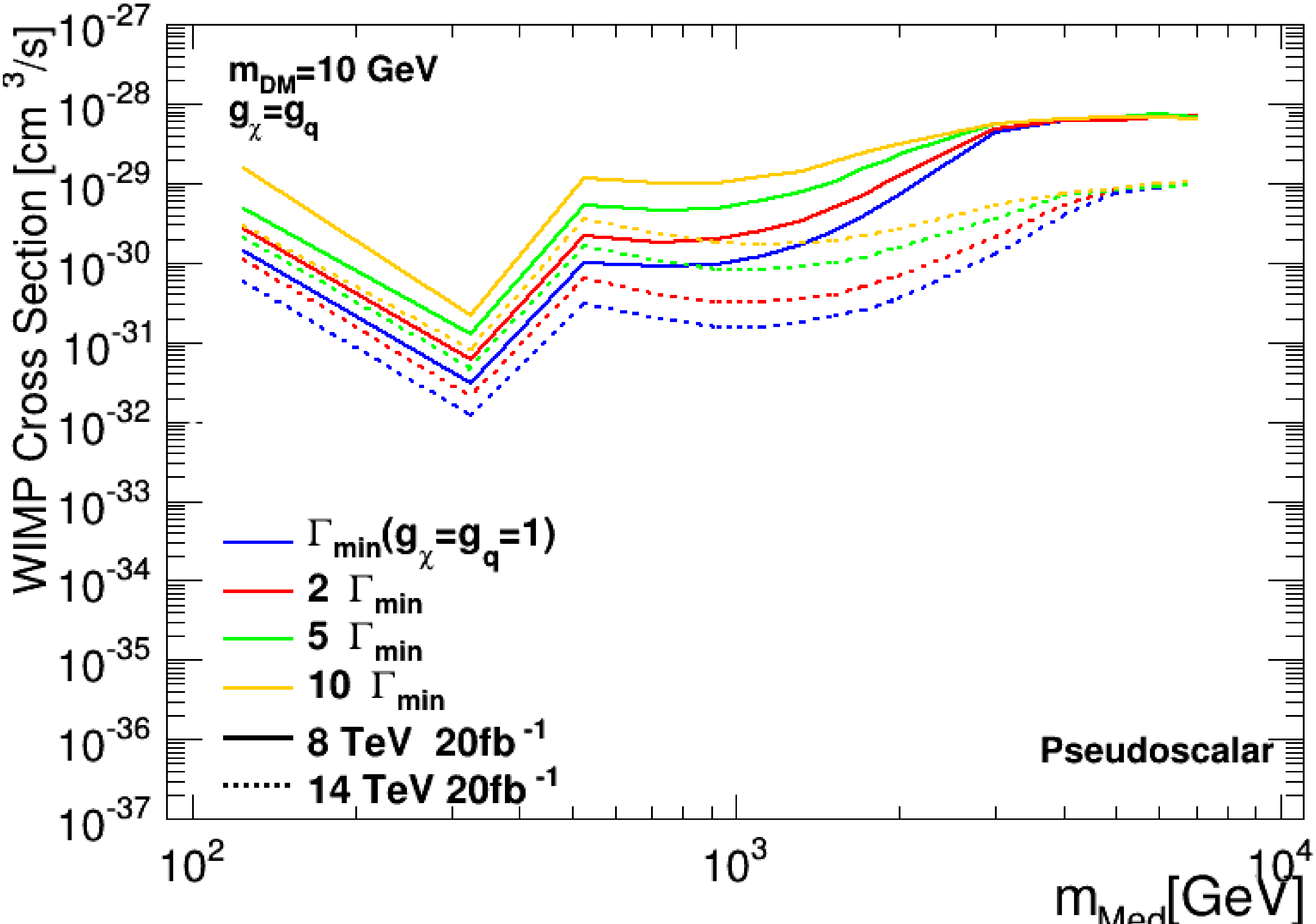
Pseudoscalar



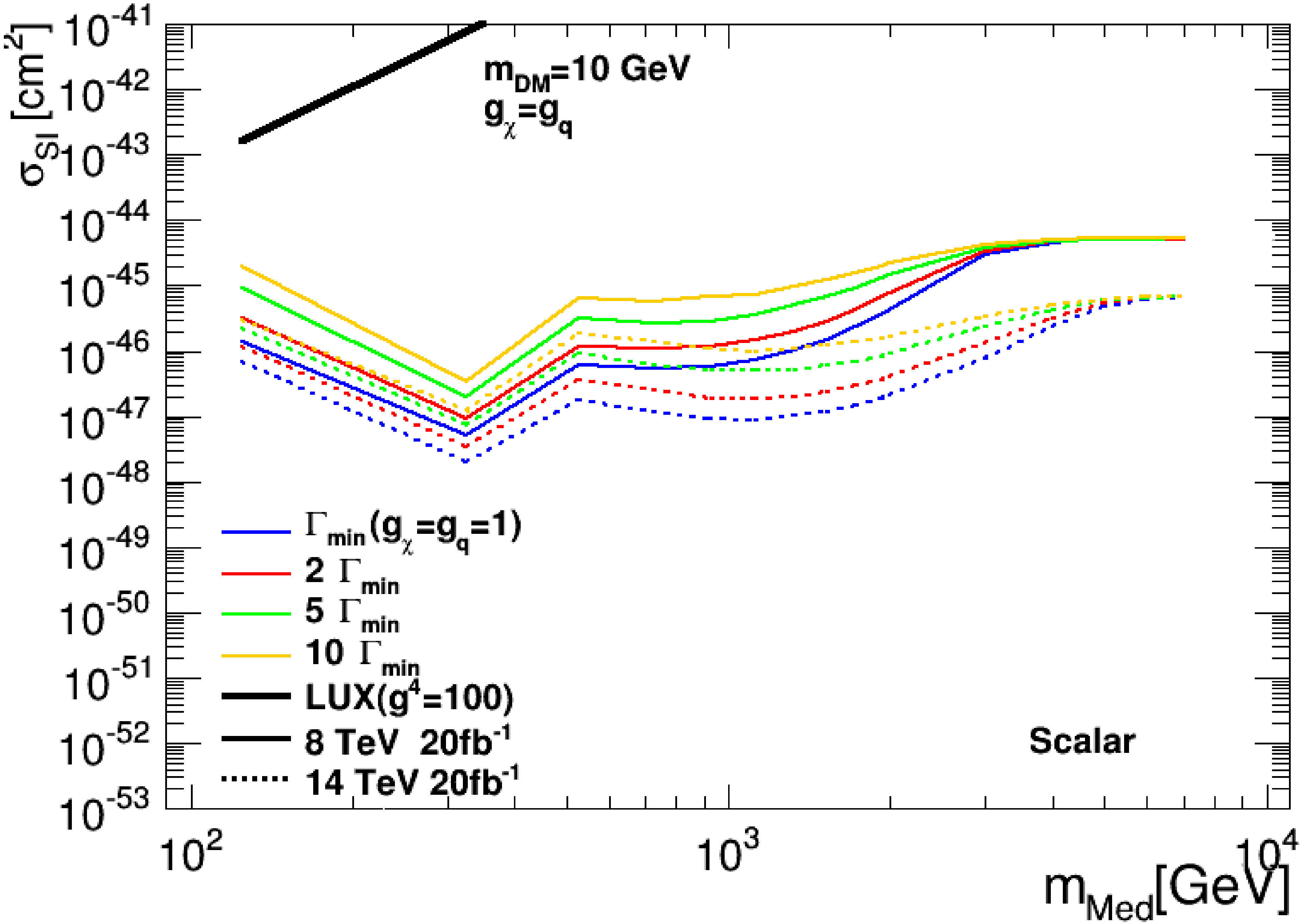
Mediator Plots



Mediator Plots

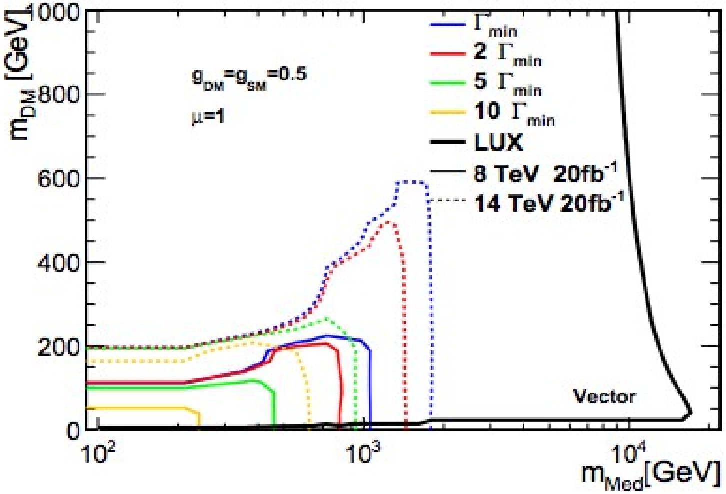


Mediator Plots

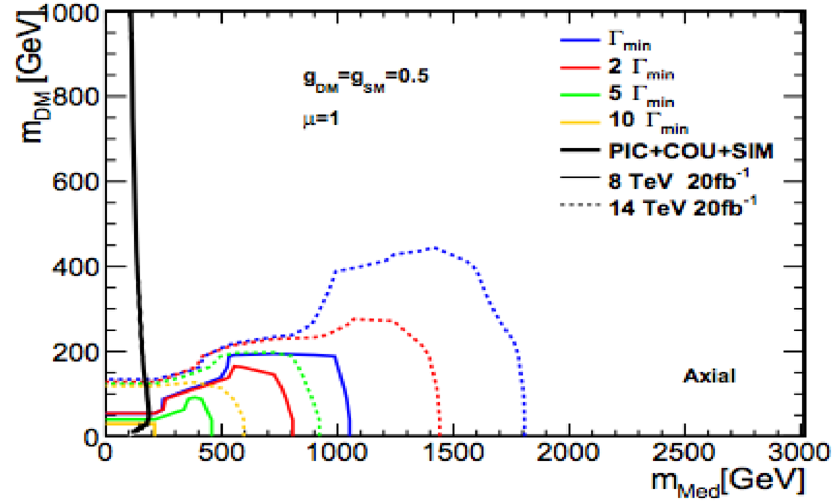


Mass Bounds vs DD/ID

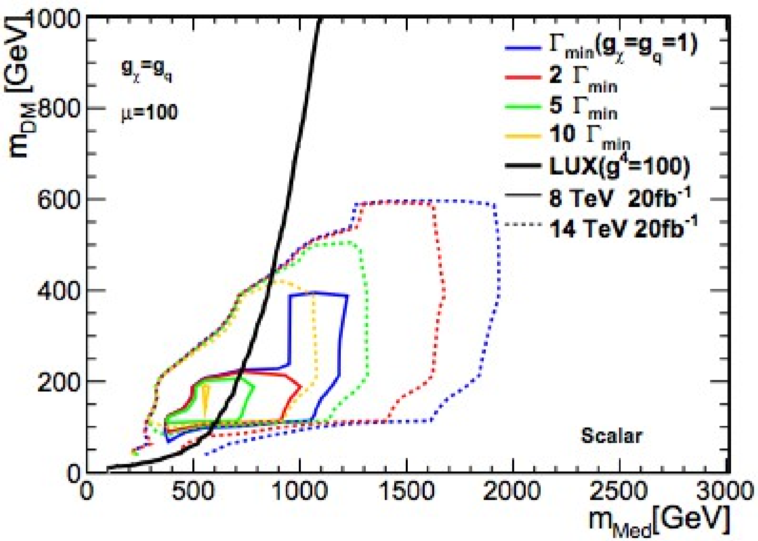
Vector



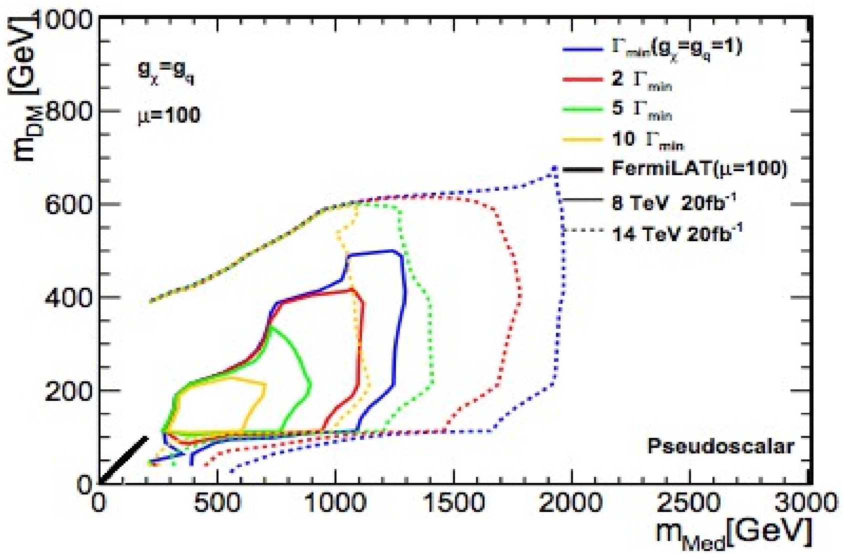
Axial



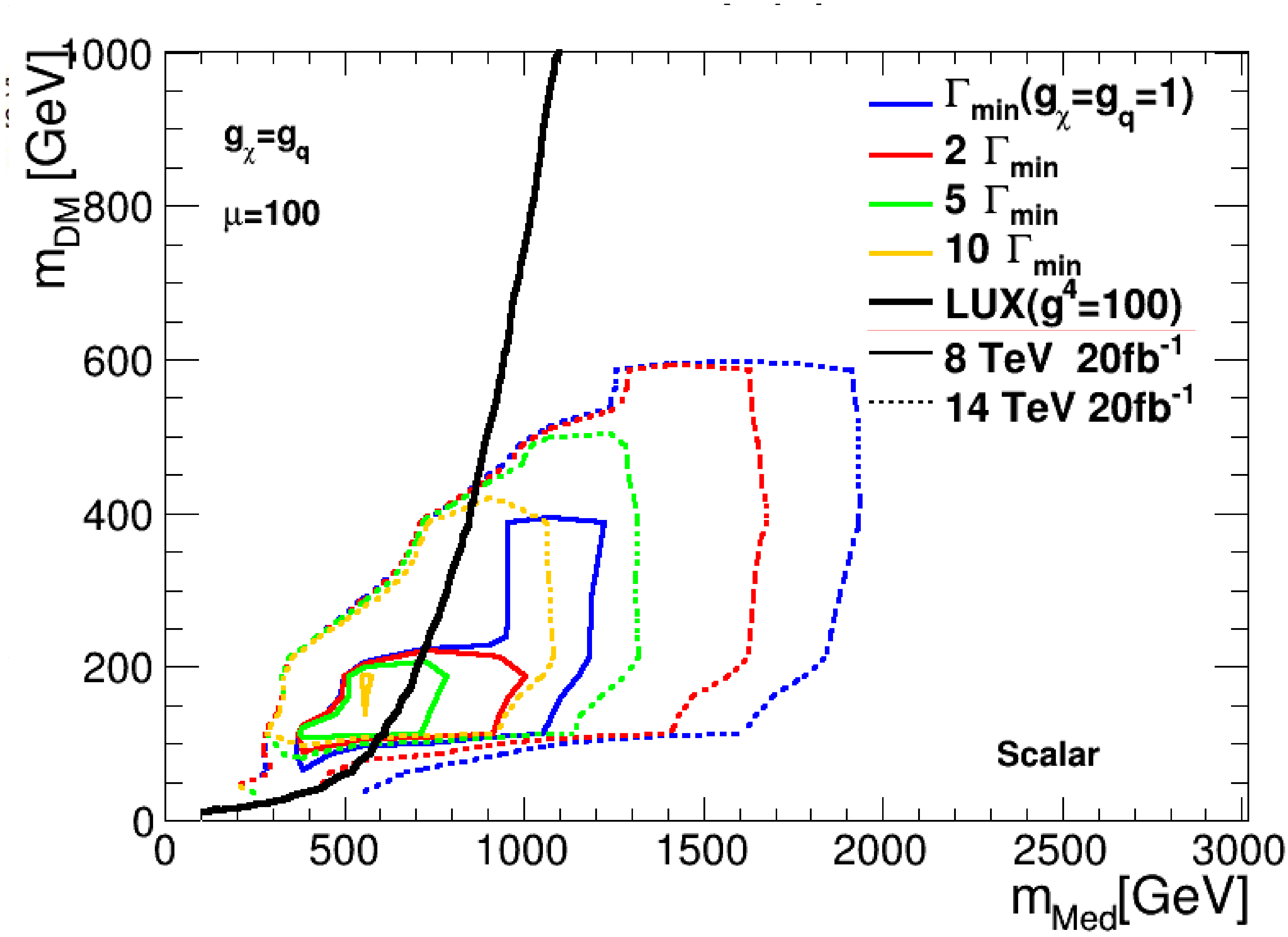
Scalar



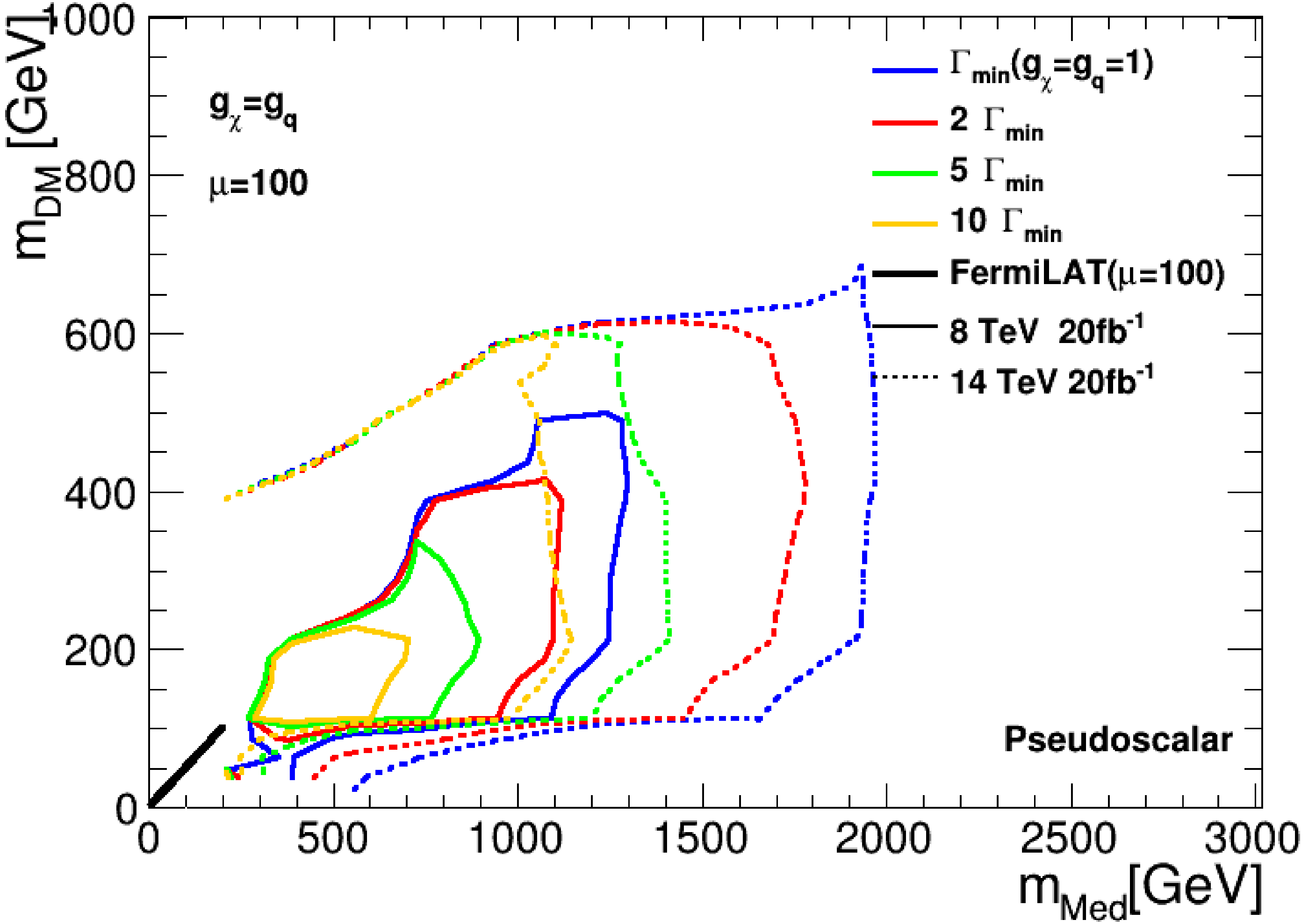
Pseudoscalar



Mass Bounds vs DD/ID



Mass Bounds vs DD/ID



Conclusions

- Take home messages from the arxiv paper
  - Interpretation differs for each Vector/Axial/Scalar/Pseudo
    - Simplified scheme for understanding these
  - Mediator mass has a large impact on kinematics
  - Scanning the dark matter mass is not so important
  - MinWidth assumption not always true (can & should vary)
    - Will have real effects on the physics interpretation

- Moving ahead : Questions
  - What needs to be done to keep the presentation simple?
  - What can be done for a consistent picture?

Processes & Modeling

Vector

$$g_{\mathrm{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi$$

$$\Gamma^V_{f\bar{f}} = \frac{g_f^2(m_{\mathrm{MED}}^2 + 2m_f^2)}{12\pi m_{\mathrm{MED}}}\sqrt{1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}}$$

Axial

$$g_{\mathrm{DM}} Z''_\mu \bar{\chi}\gamma^\mu \gamma^5 \chi$$

$$\Gamma^A_{f\bar{f}} = \frac{g_f^2(m_{\mathrm{MED}}^2 - 4m_f^2)}{12\pi m_{\mathrm{MED}}}\sqrt{1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}}$$

Scalar

$$g_{\mathrm{DM}} S \bar{\chi}\chi$$

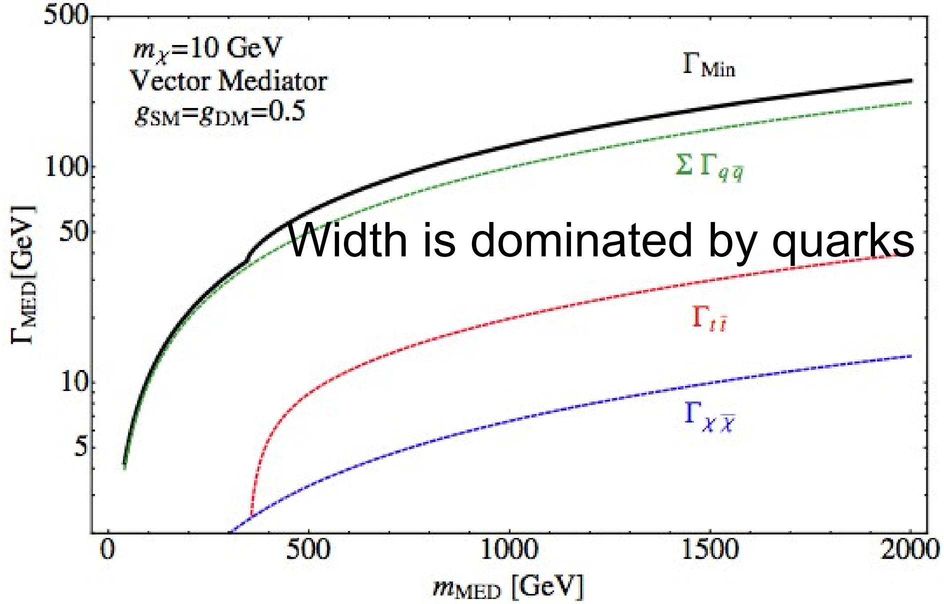
$$\Gamma^S_{f\bar{f}} = \frac{g_f^2 m_f^2 m_{\mathrm{MED}}}{8\pi v^2}\left(1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}\right)^{\frac{3}{2}}$$

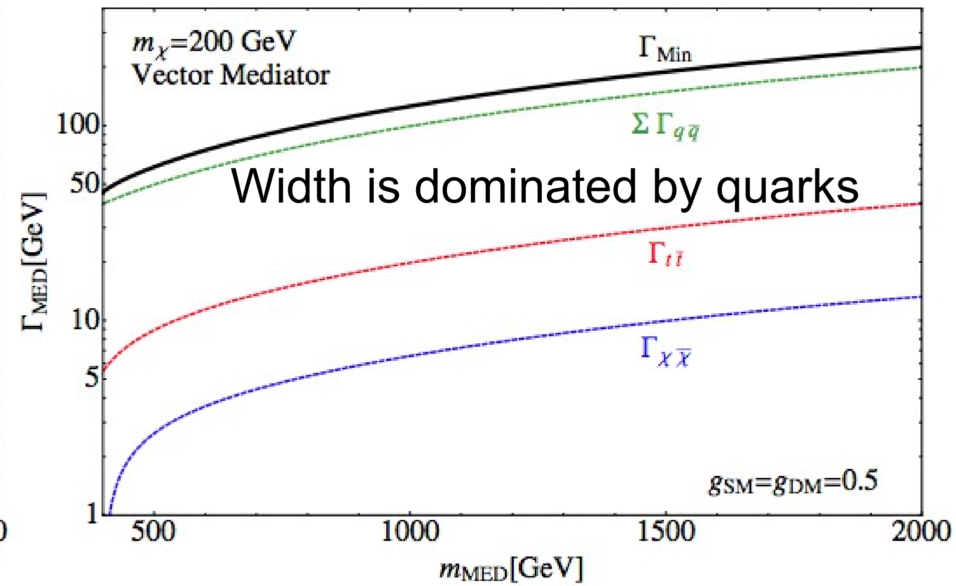
Pseudoscalar

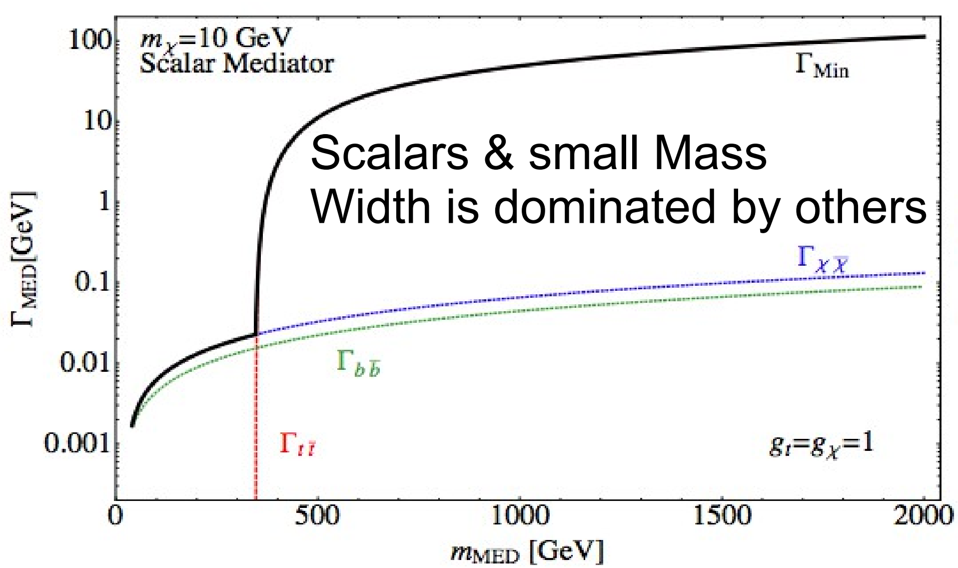
$$g_{\mathrm{DM}} P \bar{\chi}\gamma^5 \chi$$

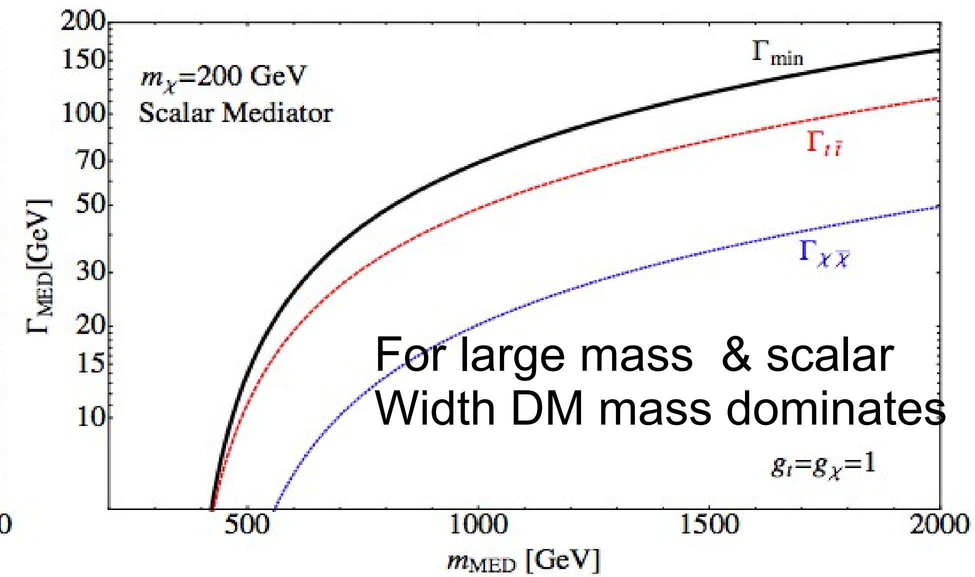
$$\Gamma^P_{f\bar{f}} = \frac{g_f^2 m_f^2 m_{\mathrm{MED}}}{8\pi v^2}\left(1 - \frac{4m_f^2}{m_{\mathrm{MED}}^2}\right)^{\frac{1}{2}}$$

Meaning of Width



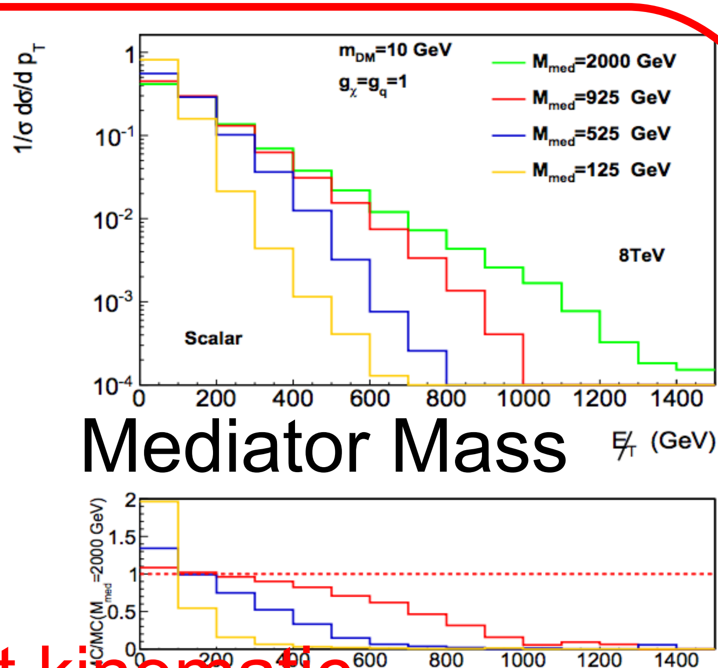




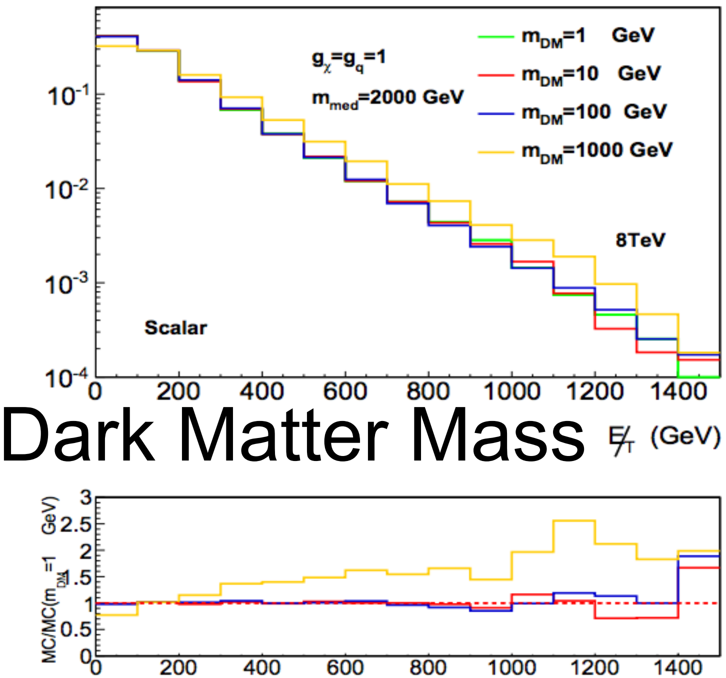


Kinematic Variation

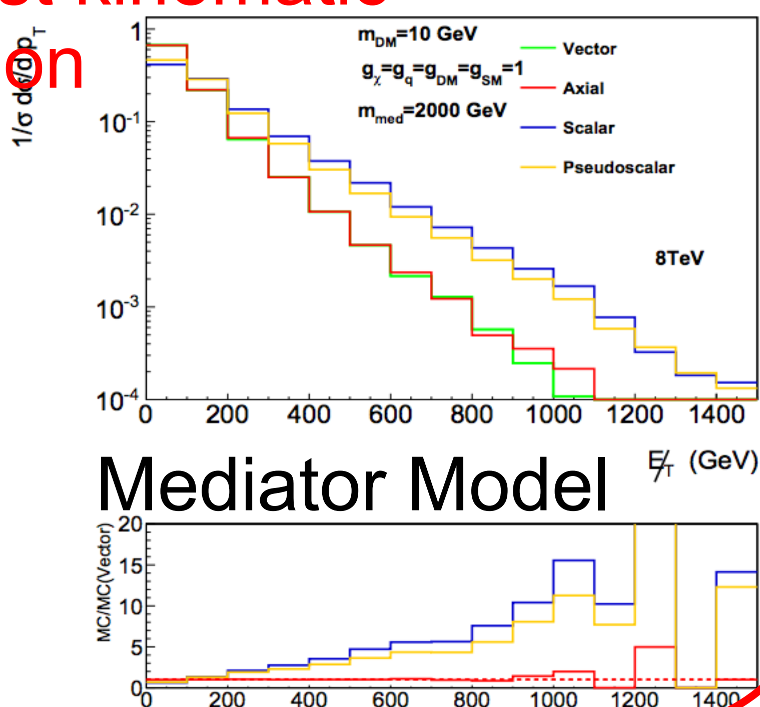
Largest kinematic variation



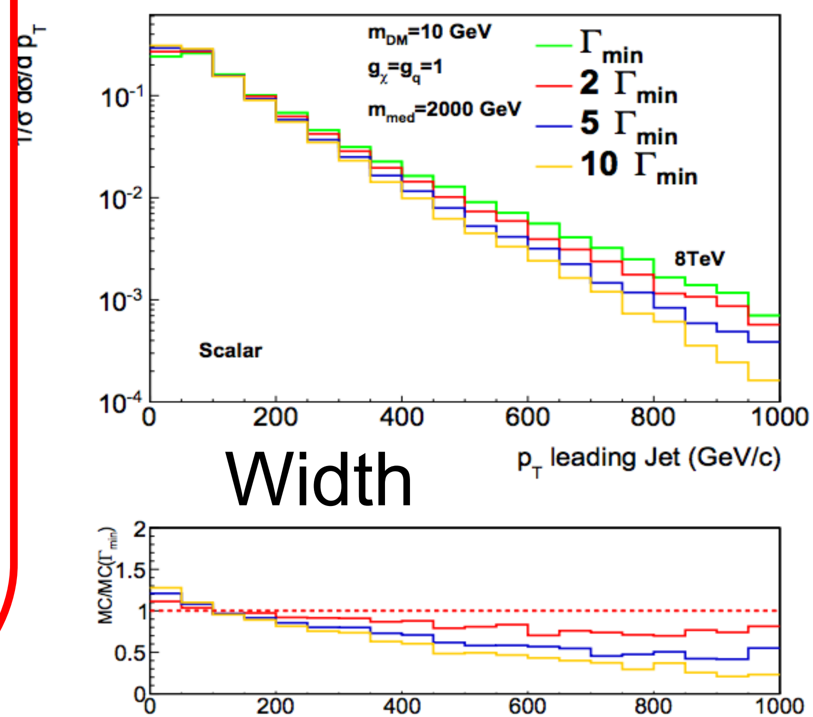
Mediator Mass



Dark Matter Mass



Mediator Model



Width