Dark matter at the LHC: Effective field theories, simplified models & beyond

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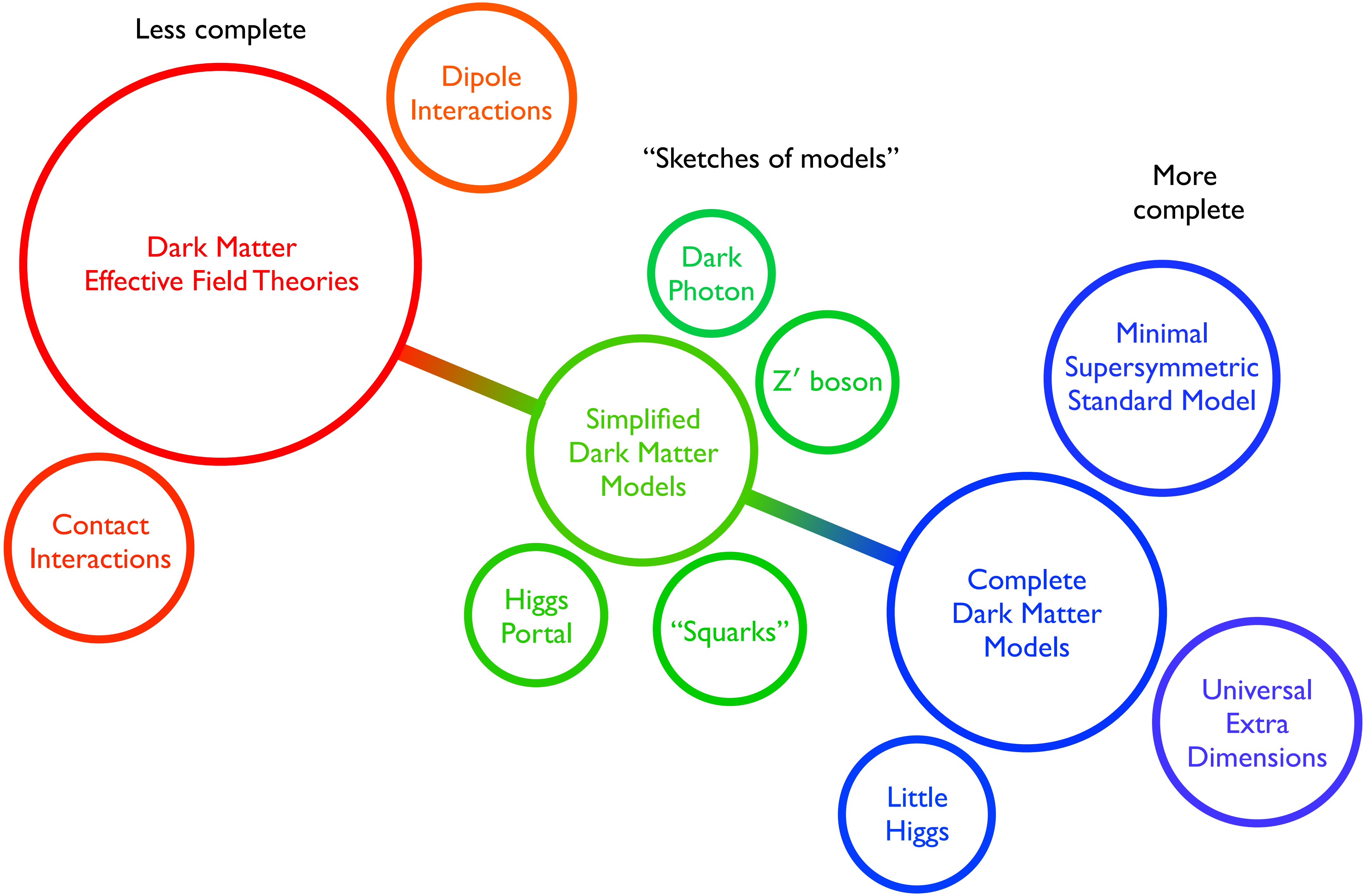
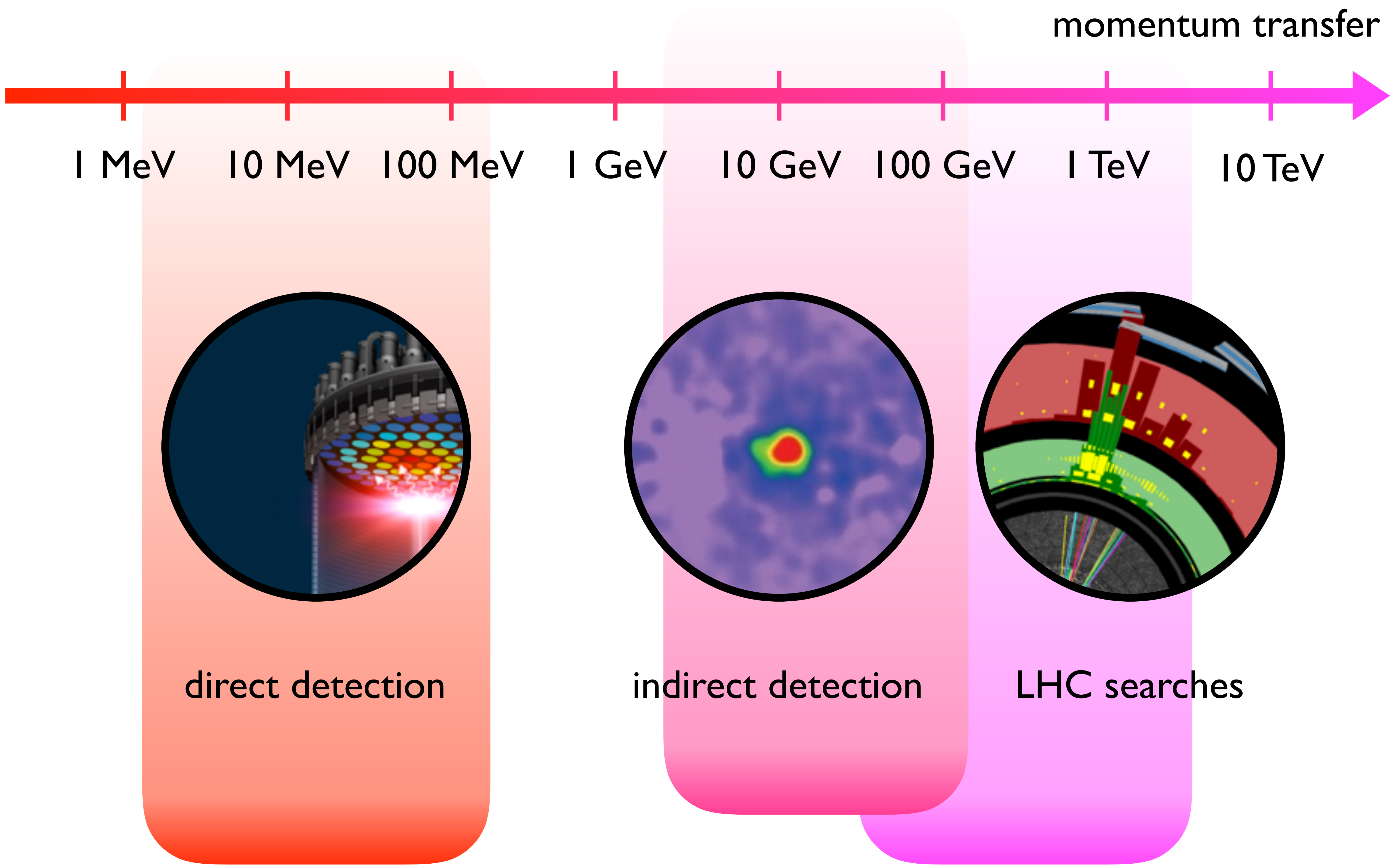
Dark matter (DM) theory space



[Worm et al., 1506.03116 based on artwork by Tait]

Scales in DM searches



momentum transfer

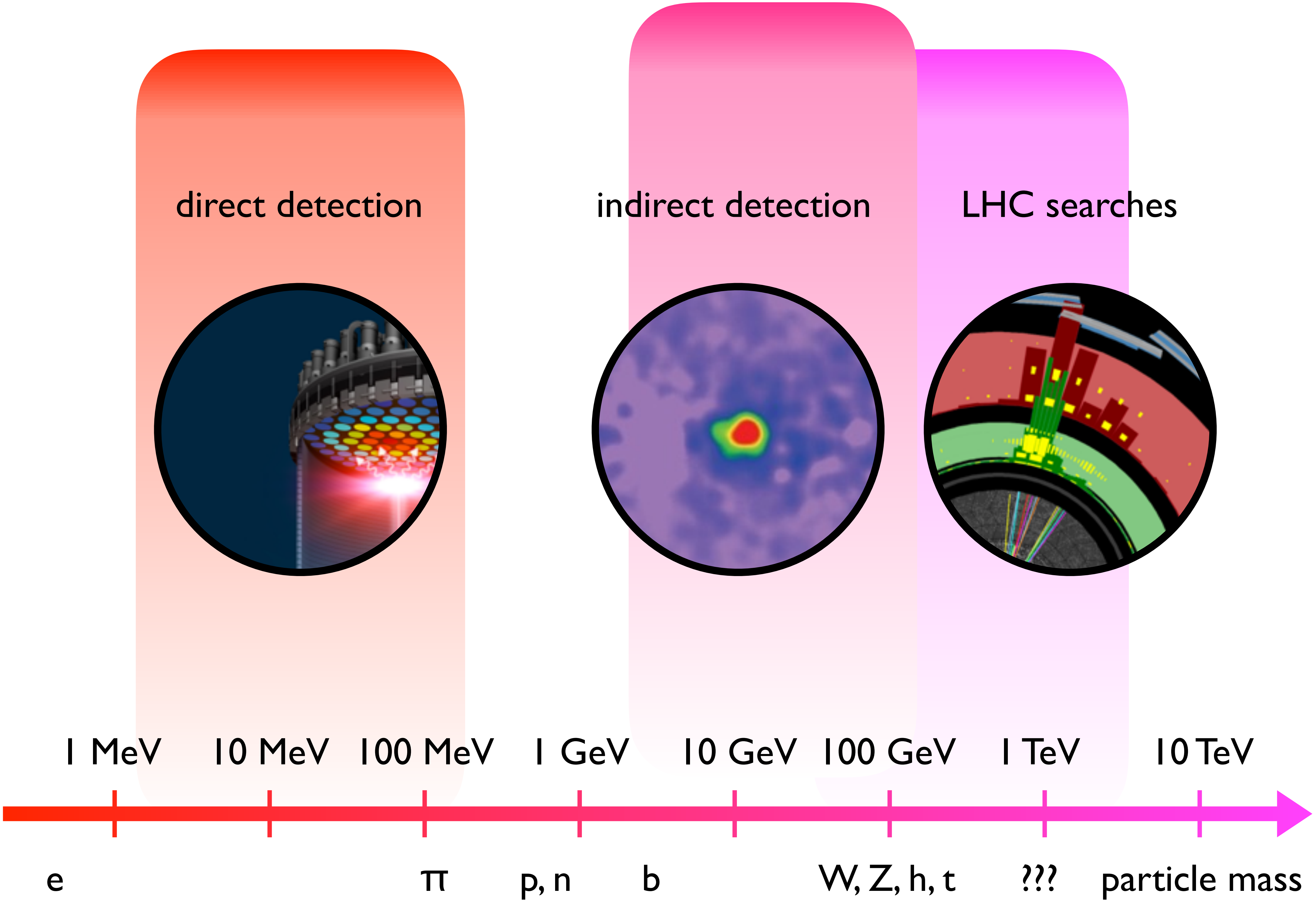
1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV 10 TeV

direct detection

indirect detection

LHC searches

Scales in DM searches



direct detection

indirect detection

LHC searches

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV 10 TeV

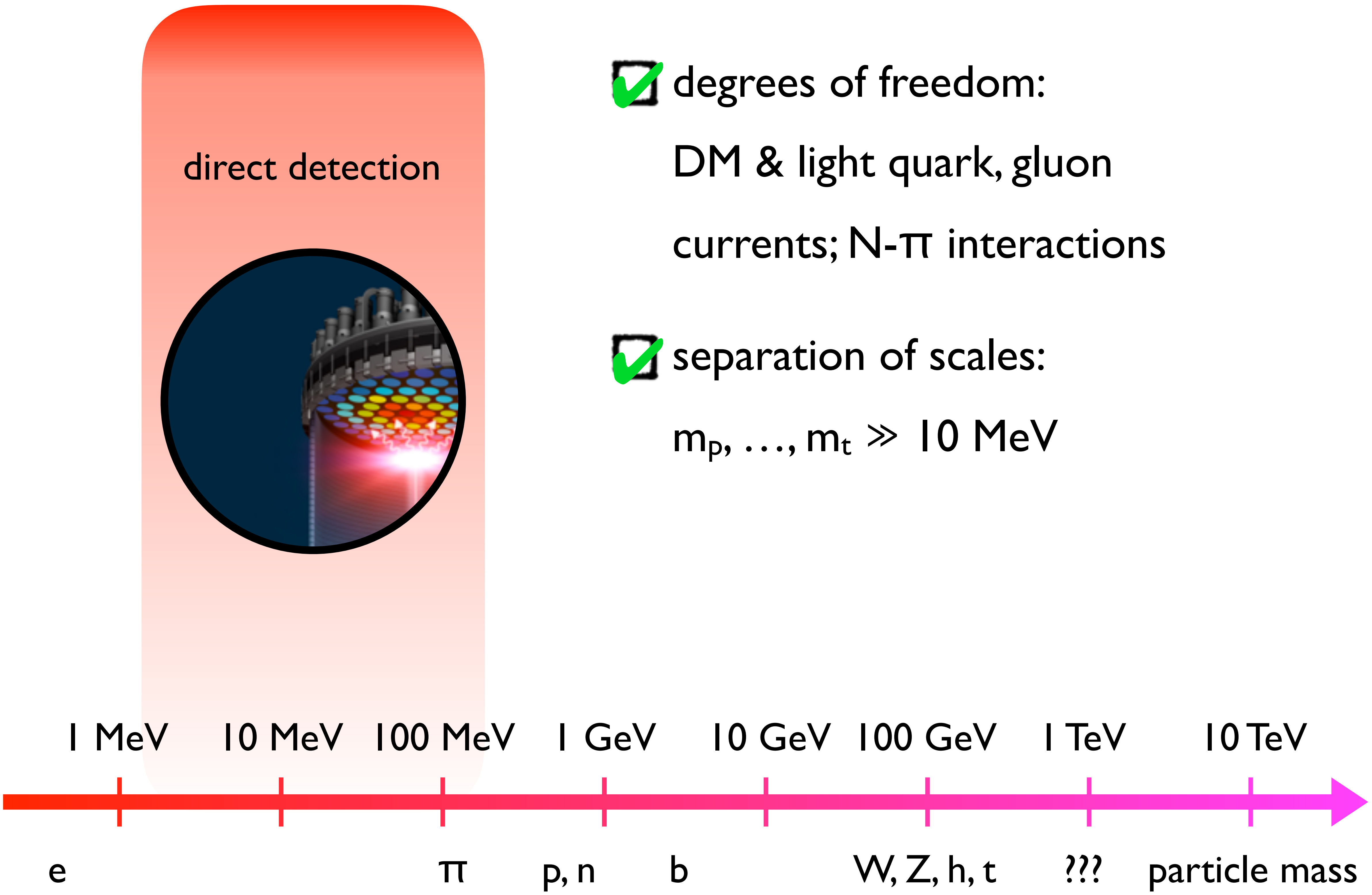
e π p, n b W, Z, h, t ??? particle mass

What is an effective field theory (EFT)?

[…] An effective field theory includes the appropriate degrees of freedom to describe physical phenomena occurring at a chosen length scale or energy scale, while ignoring substructure and degrees of freedom at shorter distances (or, equivalently, at higher energies) […] Effective field theories typically work best when there is a large separation between length scale of interest and the length scale of the underlying dynamics […]

[from Wikipedia, the free encyclopedia, https://en.wikipedia.org/wiki/Effective_field_theory]

EFT for direct detection



direct detection

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV 10 TeV

e π p, n b W, Z, h, t ??? particle mass

☑ degrees of freedom:

DM & light quark, gluon currents; N-π interactions

☑ separation of scales:

$m_p, \ldots, m_t \gg 10$ MeV

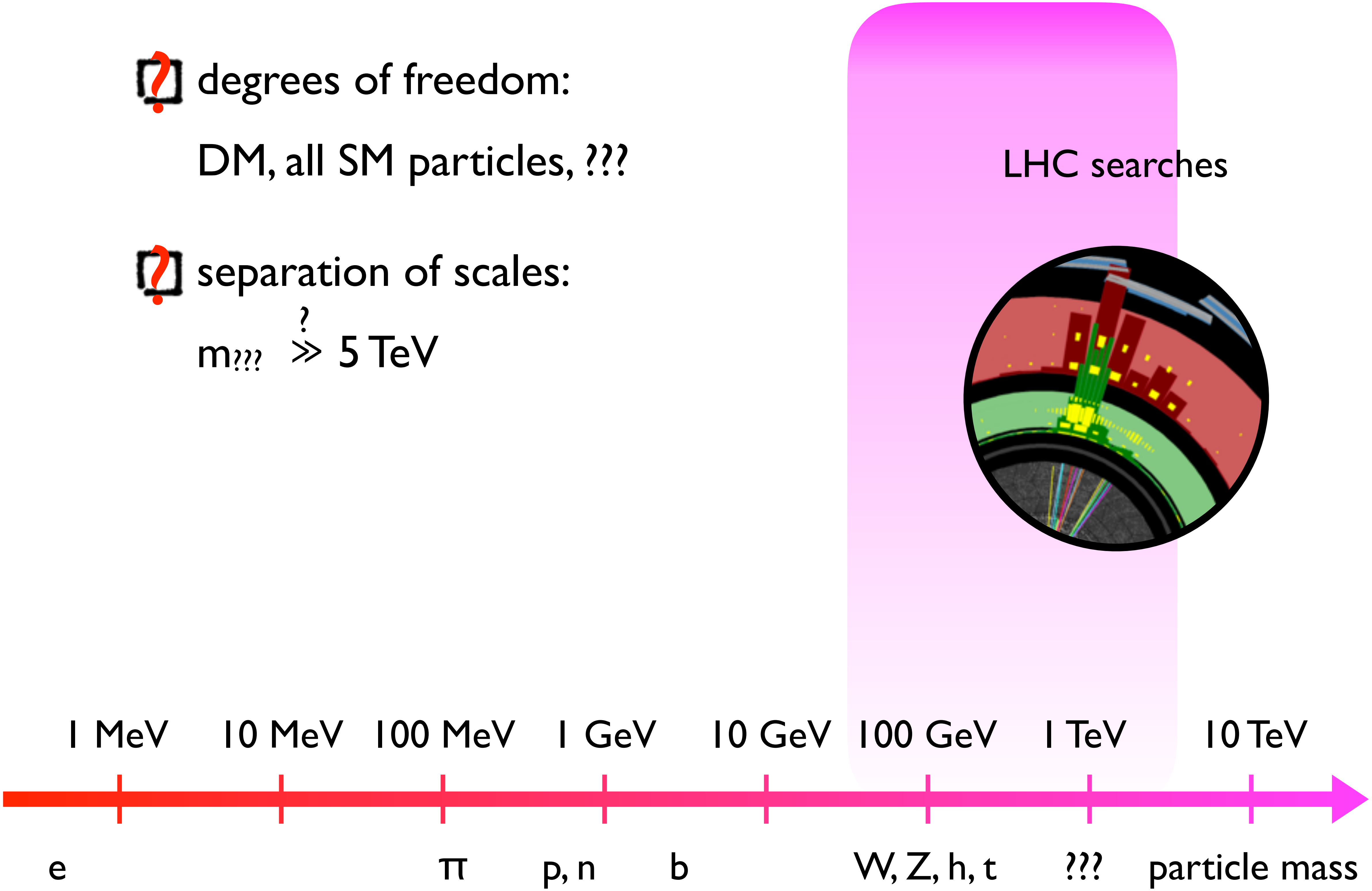
EFT for LHC DM searches

- degrees of freedom:

  DM, all SM particles, ???

- separation of scales:

  $m_{???} \overset{?}{\gg} 5\ \text{TeV}$



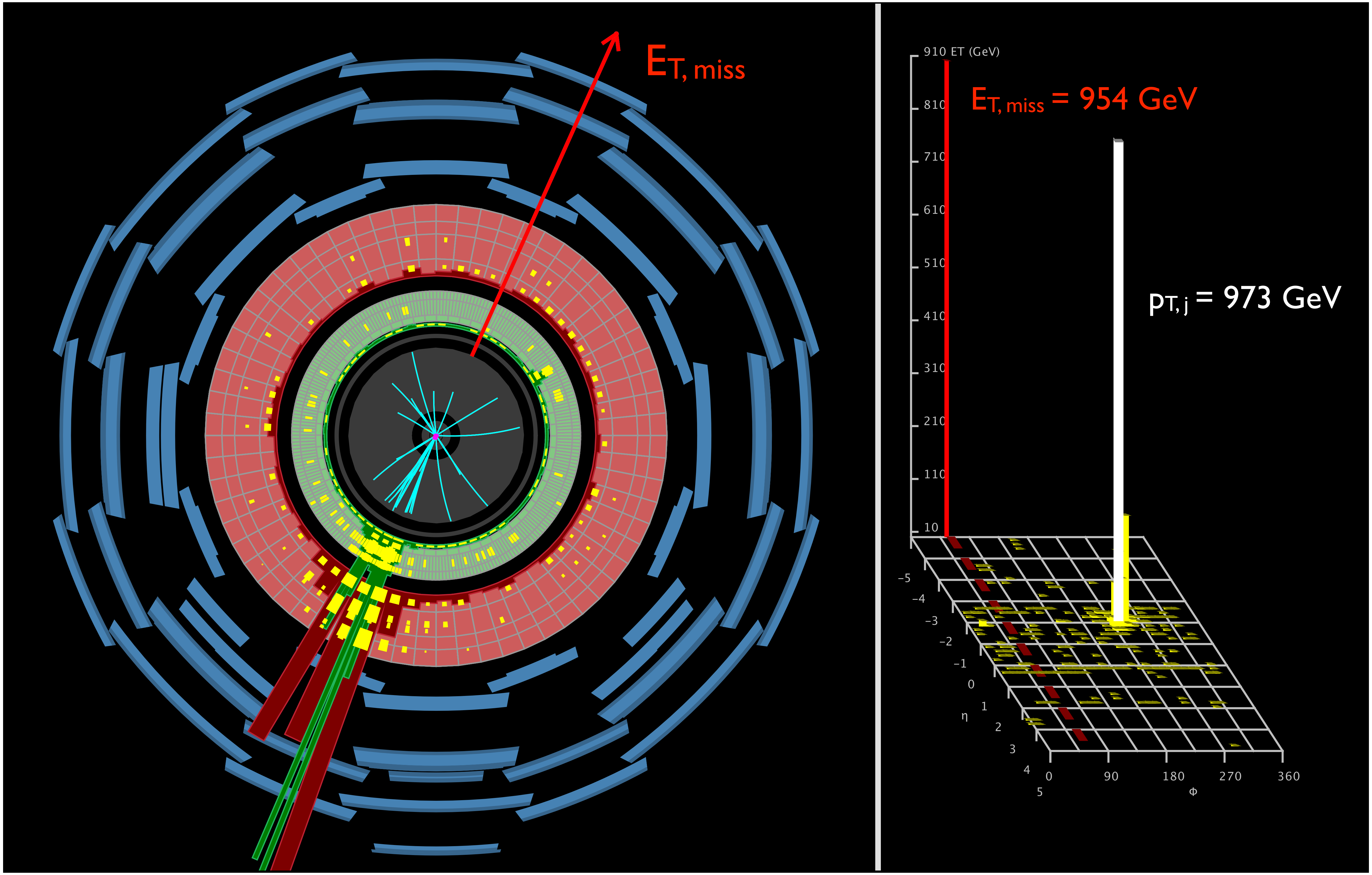
LHC searches

1 MeV 10 MeV 100 MeV 1 GeV 10 GeV 100 GeV 1 TeV 10 TeV

e π p, n b W, Z, h, t ??? particle mass

Mono-jet searches

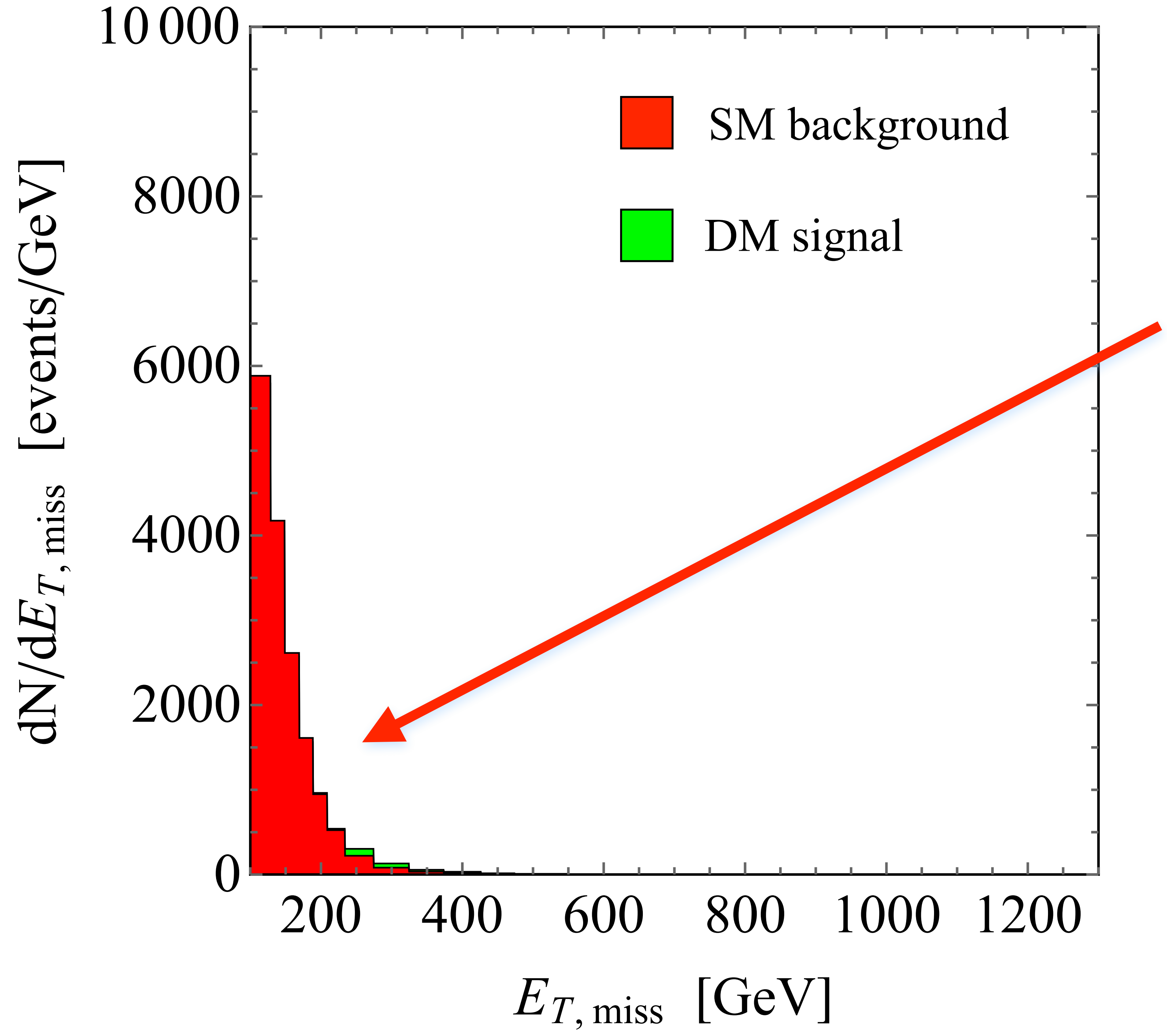
[2015 ATLAS data (event 606734214, run 279284)]



$E_{T,\,\text{miss}}$ = 954 GeV

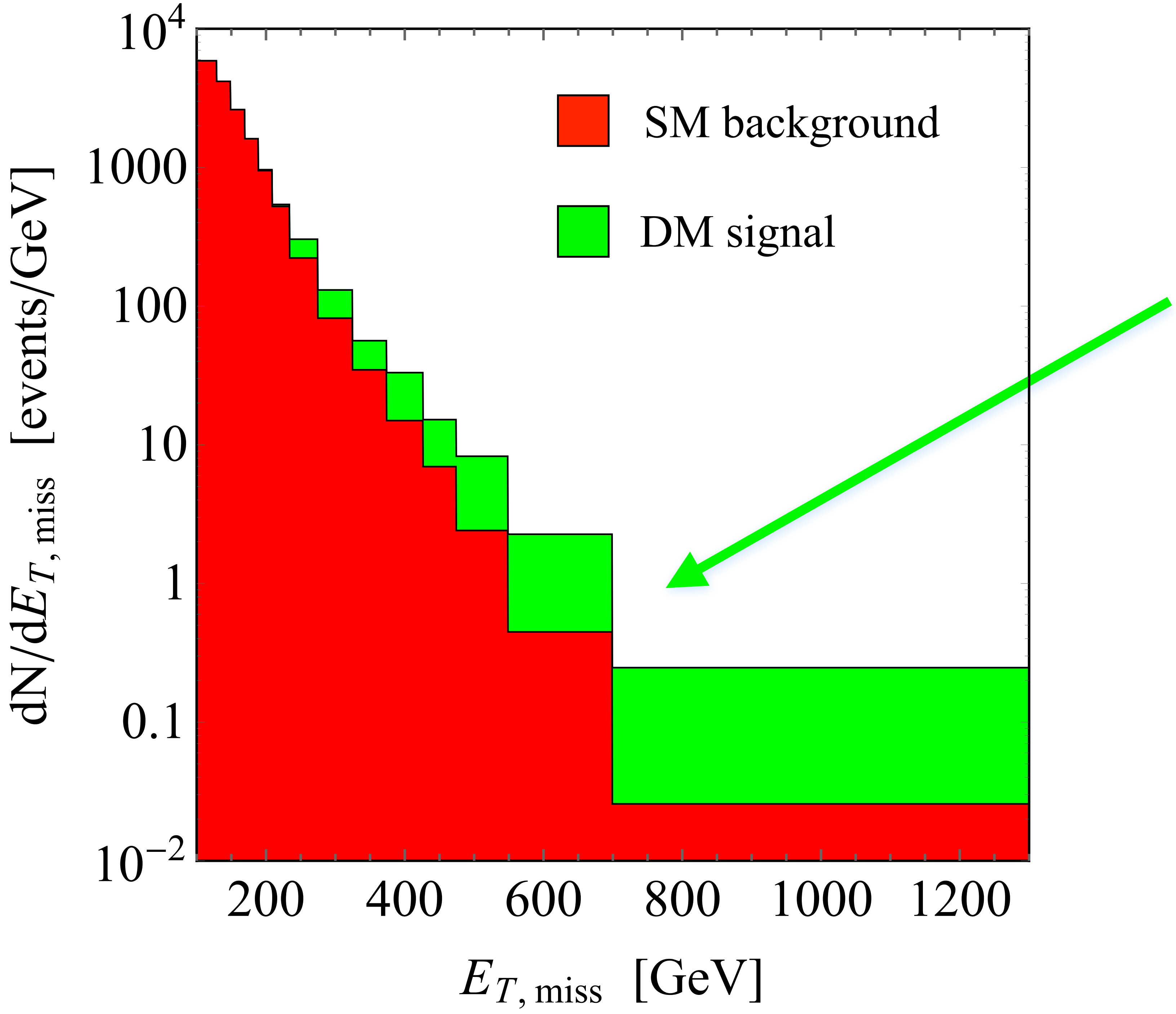
$p_{T,\,j}$ = 973 GeV

Signal vs. background



Huge SM background, that arises in case of mono-jet searches from Z + jet production with Z boson decaying to neutrinos

Signal vs. background



Presence of DM manifests itself in small enhancement in tail of missing energy $E_{T,\mathrm{miss}}$ distribution

Does DM EFT work at LHC?

Name	Operator	Coefficient
D1	$\bar\chi\chi\bar q q$	m_q/M_*^3
D2	$\bar\chi\gamma^5\chi\bar q q$	im_q/M_*^3
D3	$\bar\chi\chi\bar q\gamma^5 q$	im_q/M_*^3
D4	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	m_q/M_*^3
D5	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	$1/M_*^2$
D6	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	$1/M_*^2$
D7	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar\chi\sigma_{\mu\nu}\gamma^5\chi\bar q\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar\chi\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar\chi\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar\chi\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar\chi\gamma^5\chi G_{\mu\nu}\tilde G^{\mu\nu}$	$\alpha_s/4M_*^3$

One way to check:

(i) Pick one operator

(ii) Construct simplified model that leads to operator in heavy mediator limit

(iii) Calculate $E_{T,\text{miss}}$ & other distributions in both EFT & simplified model

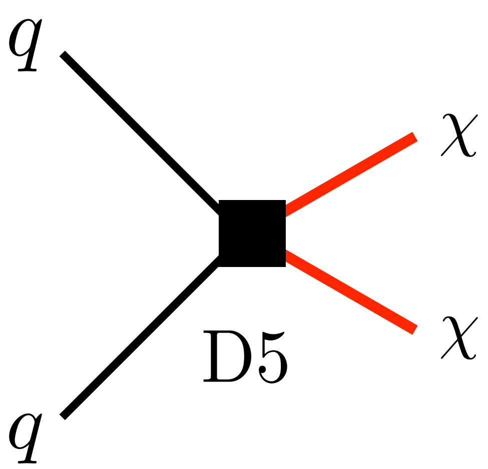
(iv) If shapes of distributions are similar, can use EFT as proxy for simplified model, otherwise not

[Zhang et al., 0912.4511; Beltran et al., 1002.4137;
Goodman et al., 1005.1286, 1008.1783, 1009.0008;
Bai et al., 1005.3797; Rajaraman et al., 1108.1196;
Fox et al., 1109.4398; …]

Tree-level example

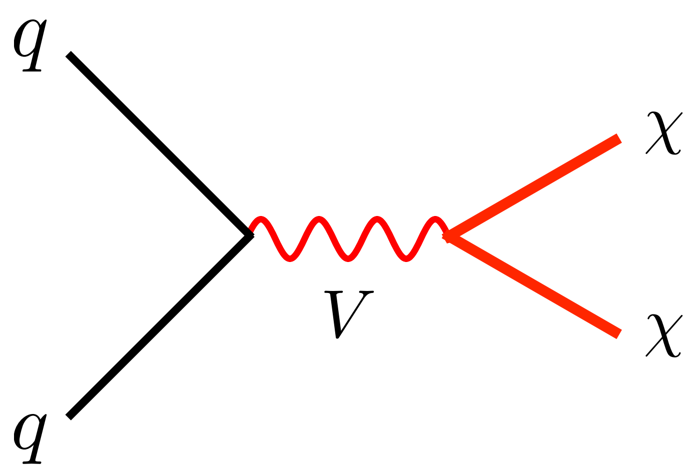
Vector operator:

$$\mathrm{D5} = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$



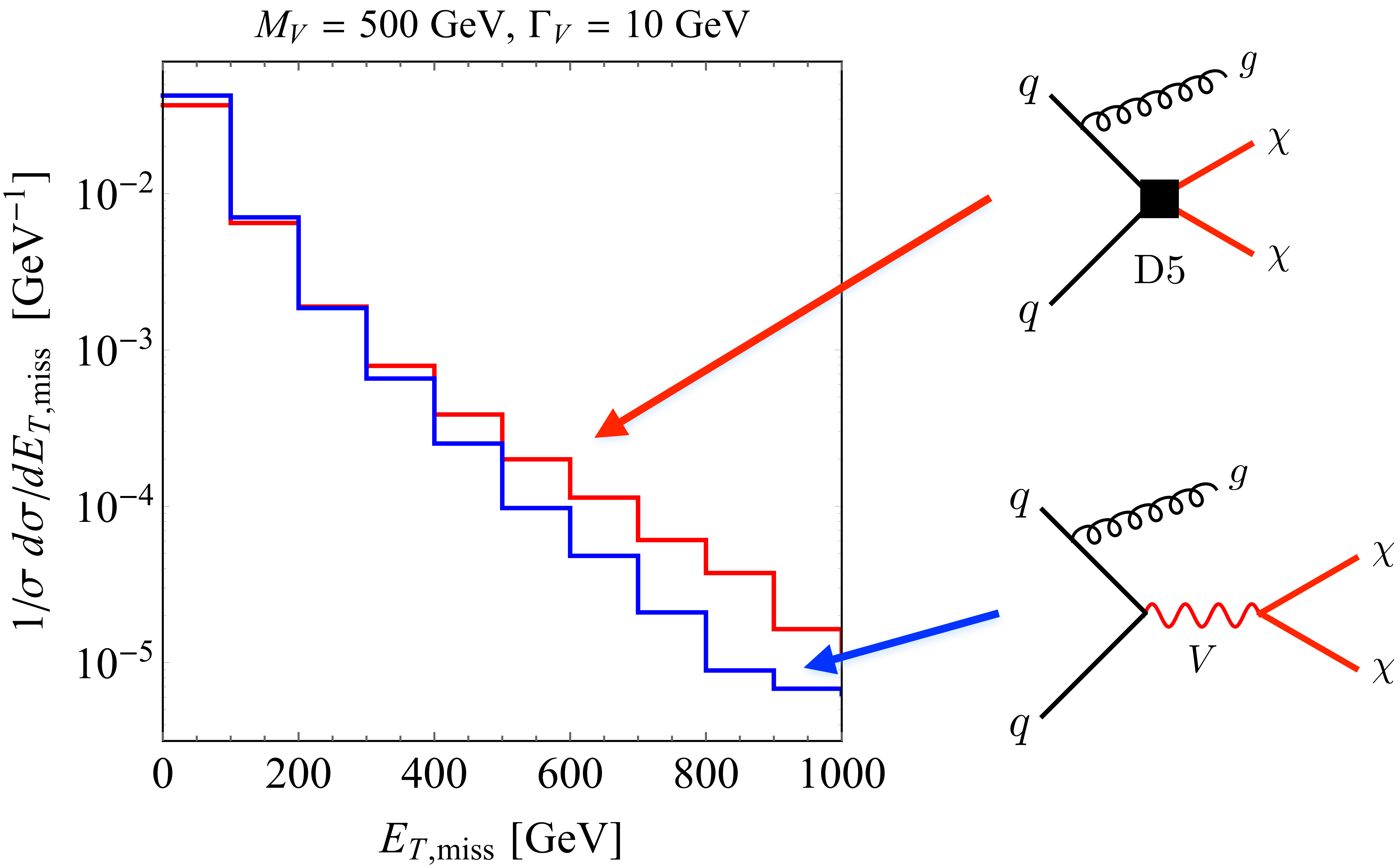
Spin-1 simplified model:

$$\mathcal{L}_V \supset g_\chi \bar{\chi}\gamma^\mu\chi V_\mu + \sum_q g_q \bar{q}\gamma^\mu q V_\mu$$



[Dudas et al., 0904.1745; Fox et al., 1104.4127; Frandsen et al., 1204.3839; …]

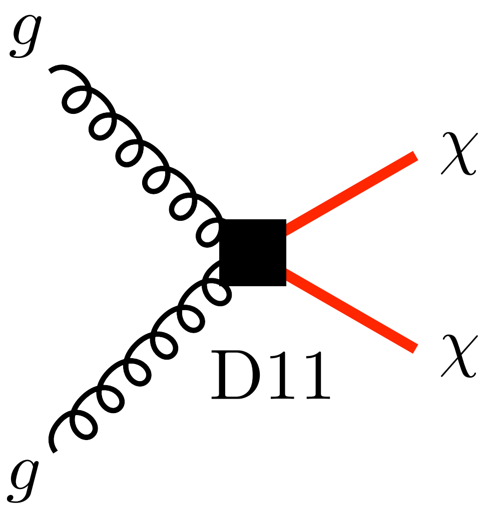
D5: EFT vs. simplified model



Loop-level example

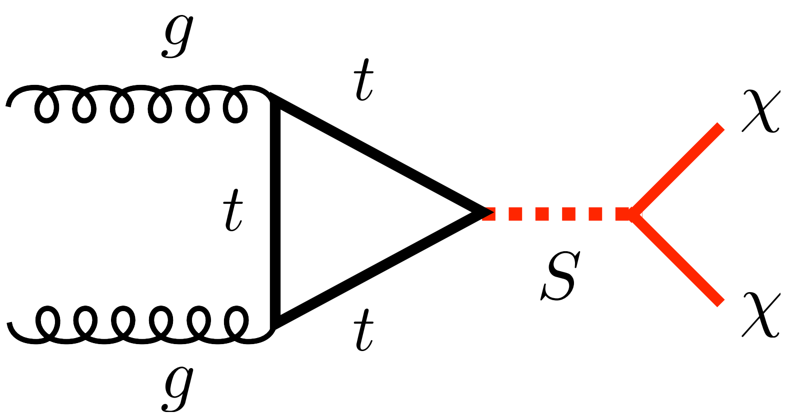
Gluonic operator:

$$\mathrm{D11} = \bar{\chi}\chi G_{\mu\nu} G^{\mu\nu}$$



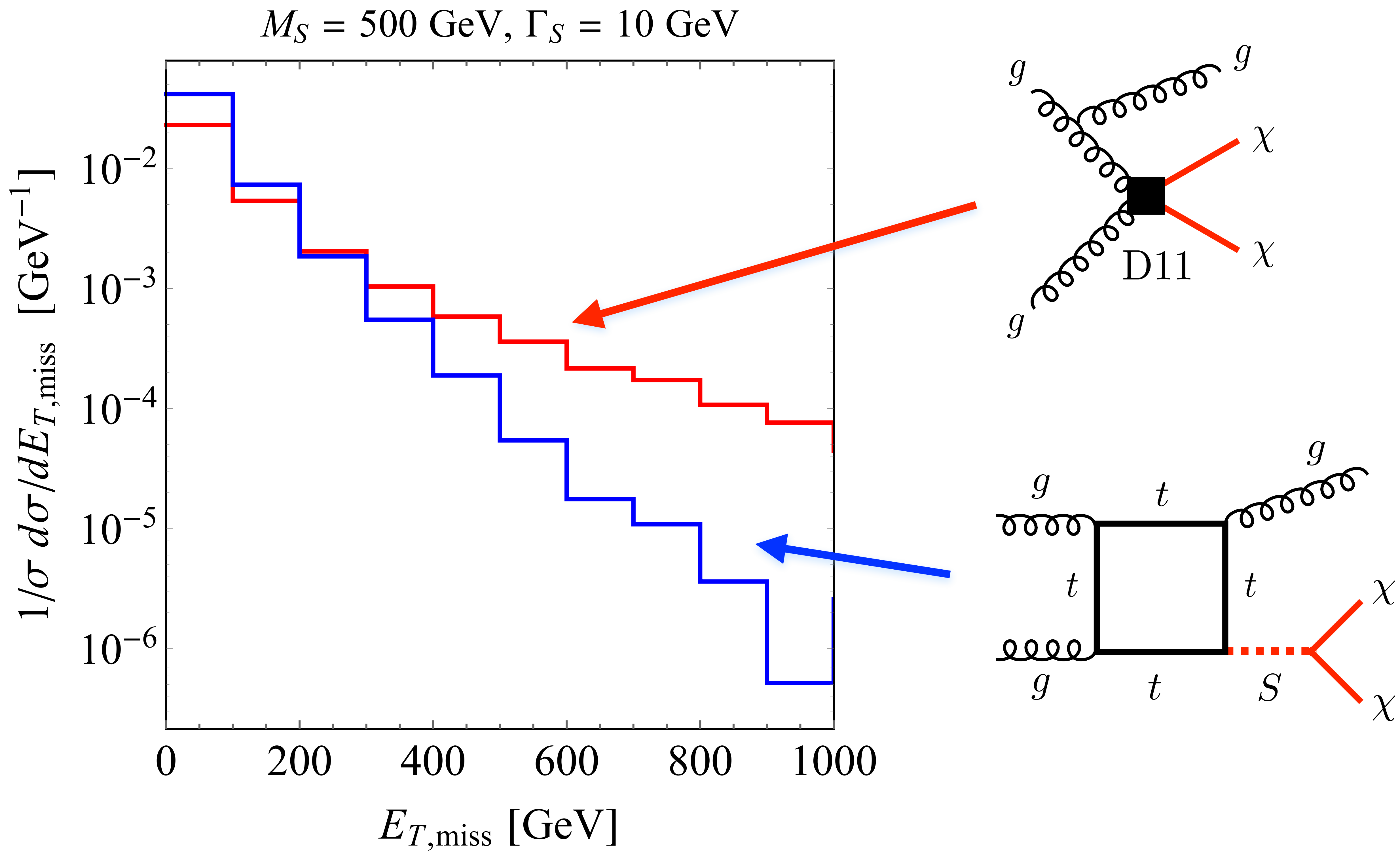
Spin-0 simplified model:

$$\mathcal{L}_S \supset g_\chi \bar{\chi}\chi S + \sum_q \frac{g_q y_q}{\sqrt{2}} \bar{q}qS$$



[UH et al., 1208.4605, 1311.713, 1503.00691; Buckley et al.,1410.6497; Harris et al., 1411.0535; …]

D11: EFT vs. simplified model



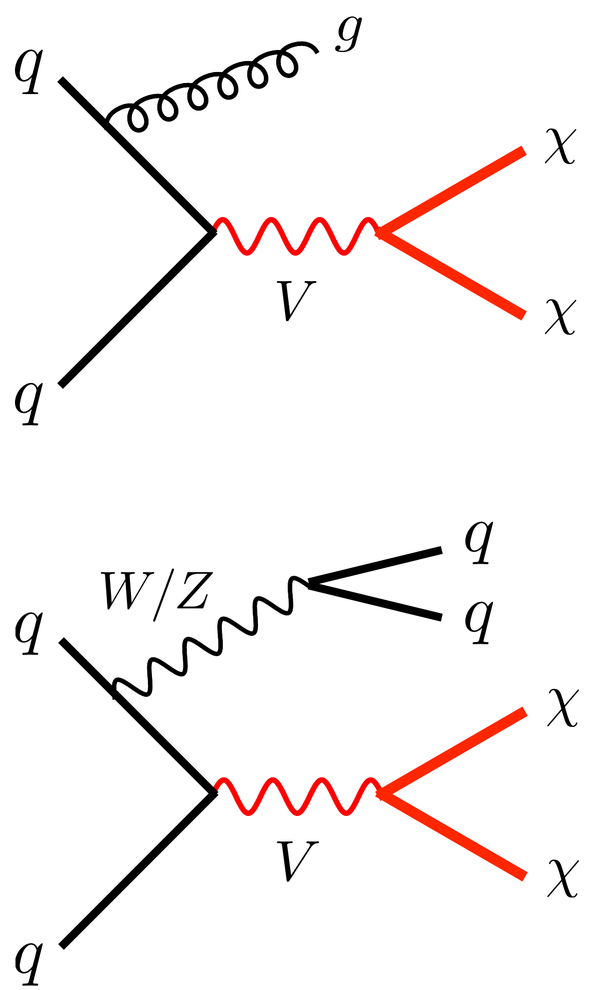
EFT vs. simplified models: verdict

EFT often fails to correctly describe kinematical distributions of weakly-coupled simplified models with weak- or TeV-scale mediators. This flaw prompted ATLAS & CMS to move from EFT to simplified models when interpret $E_{T,\text{miss}}$ searches in LHC Run II

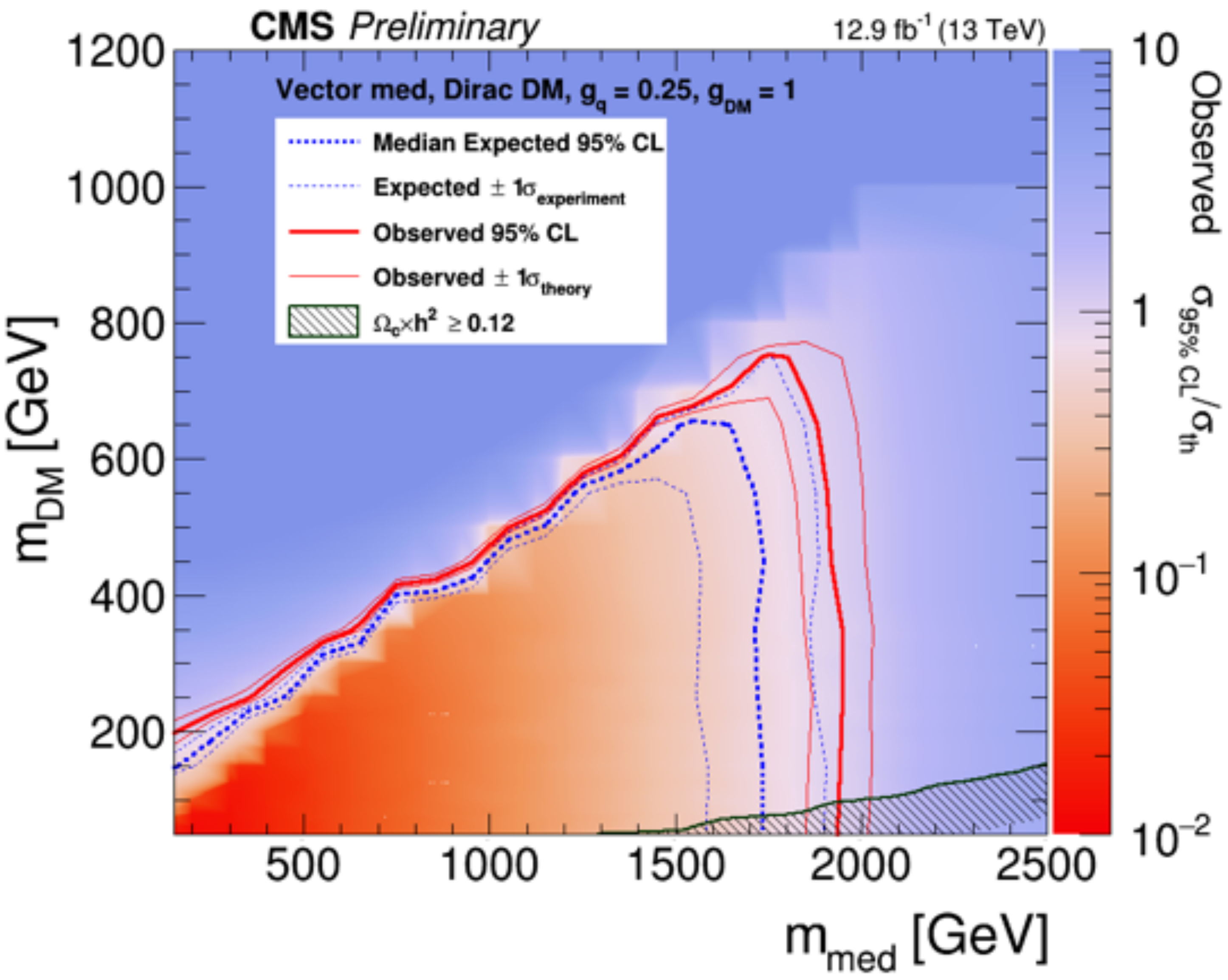
But in case of strongly-coupled DM candidates — composite fermions, pseudo-Nambu-Goldstone bosons, Goldstini, … — EFT appropriate & sometimes even necessary to describe most important interactions at LHC

[parallel talks by Jacques on Thursday & by Bruggisser on Friday]

Spin-1 simplified models: 13 TeV limits



[CMS PAS EXO-16-037]

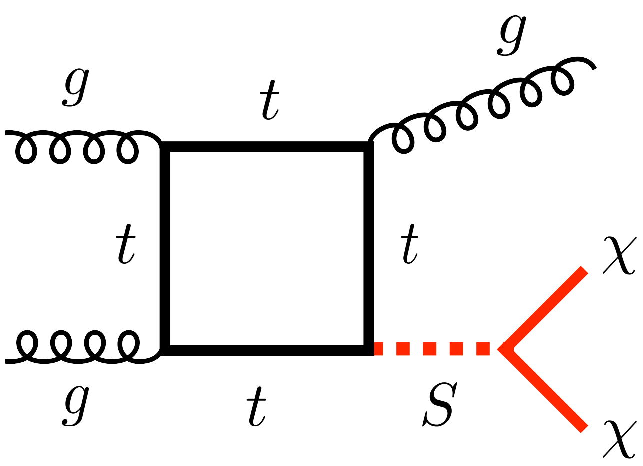


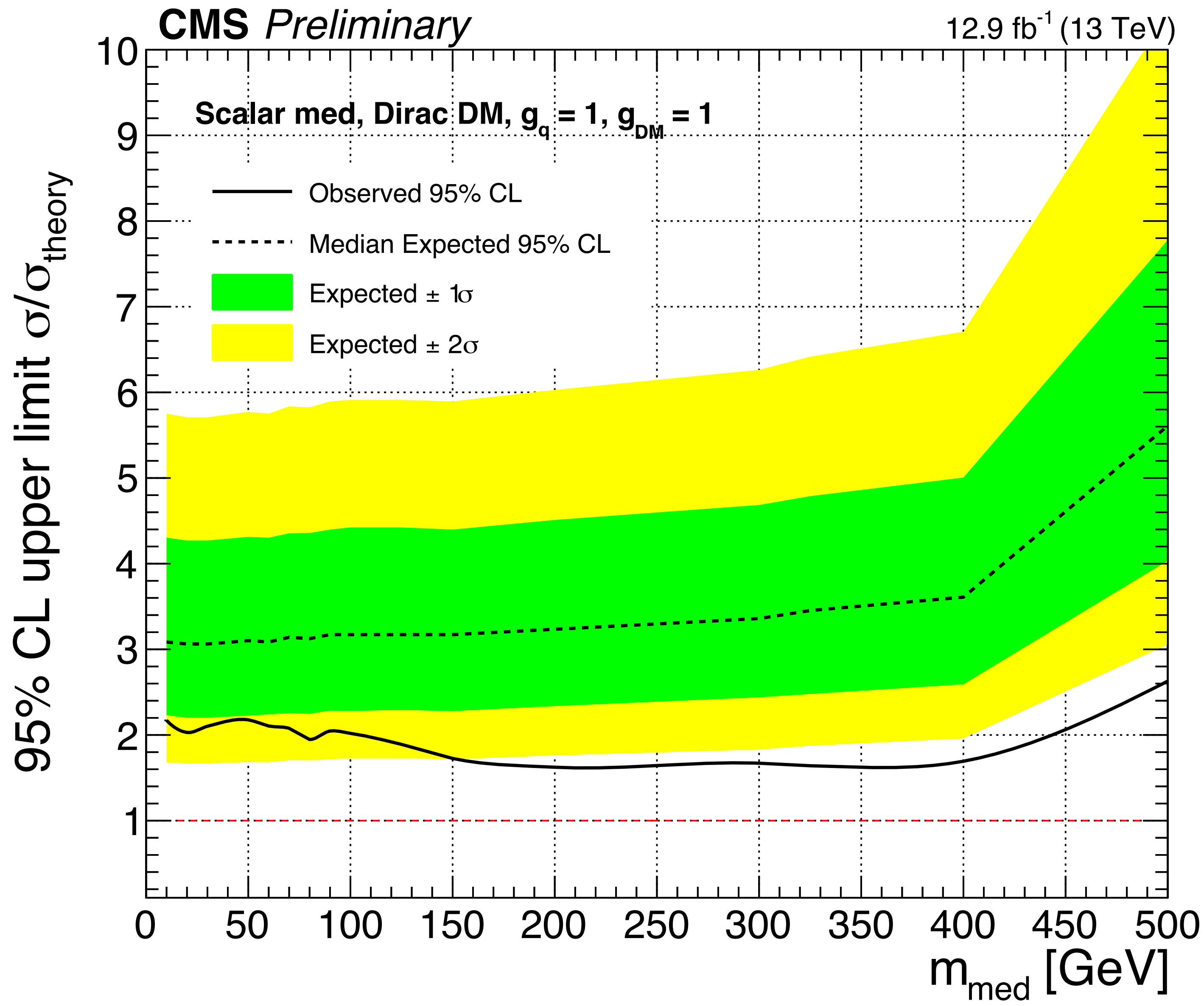
Latest $E_{T,\,miss}$+jets searches exclude mediator masses up to close to 2 TeV for both vector & axialvector exchange if $g_q = 0.25$, $g_\chi = 1$

[parallel talk by Moon on Monday]

Spin-0 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]



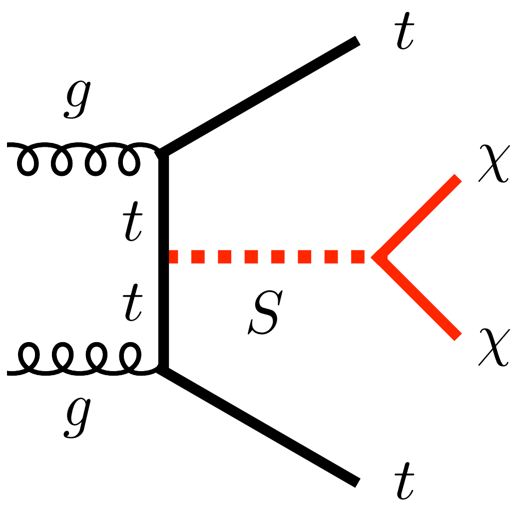


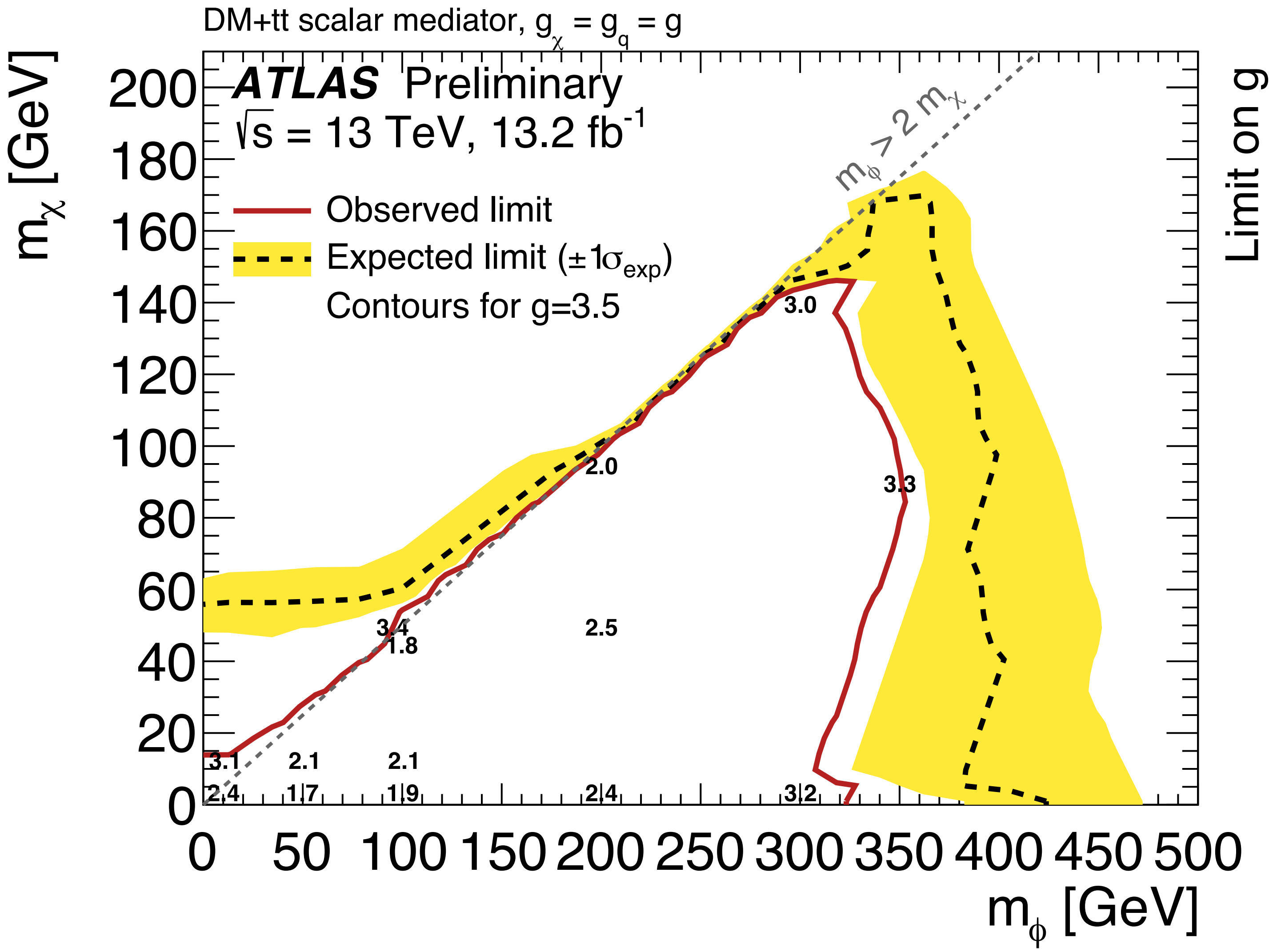
Mono-jet searches not yet sensitive to scalar models with weak couplings

[parallel talk by Moon on Monday]

Spin-0 simplified models: 13 TeV limits

[ATLAS-CONF-2016-050]



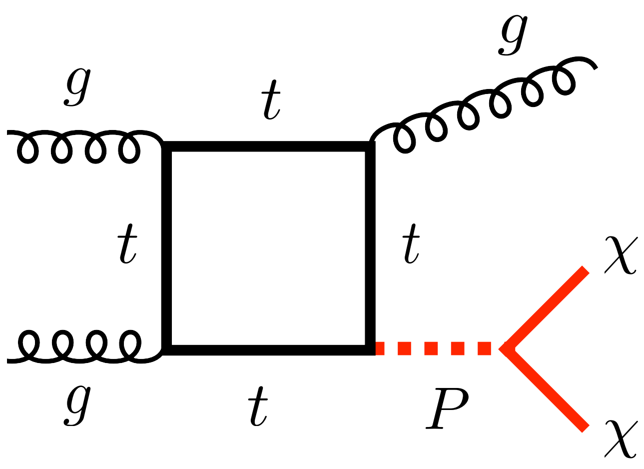


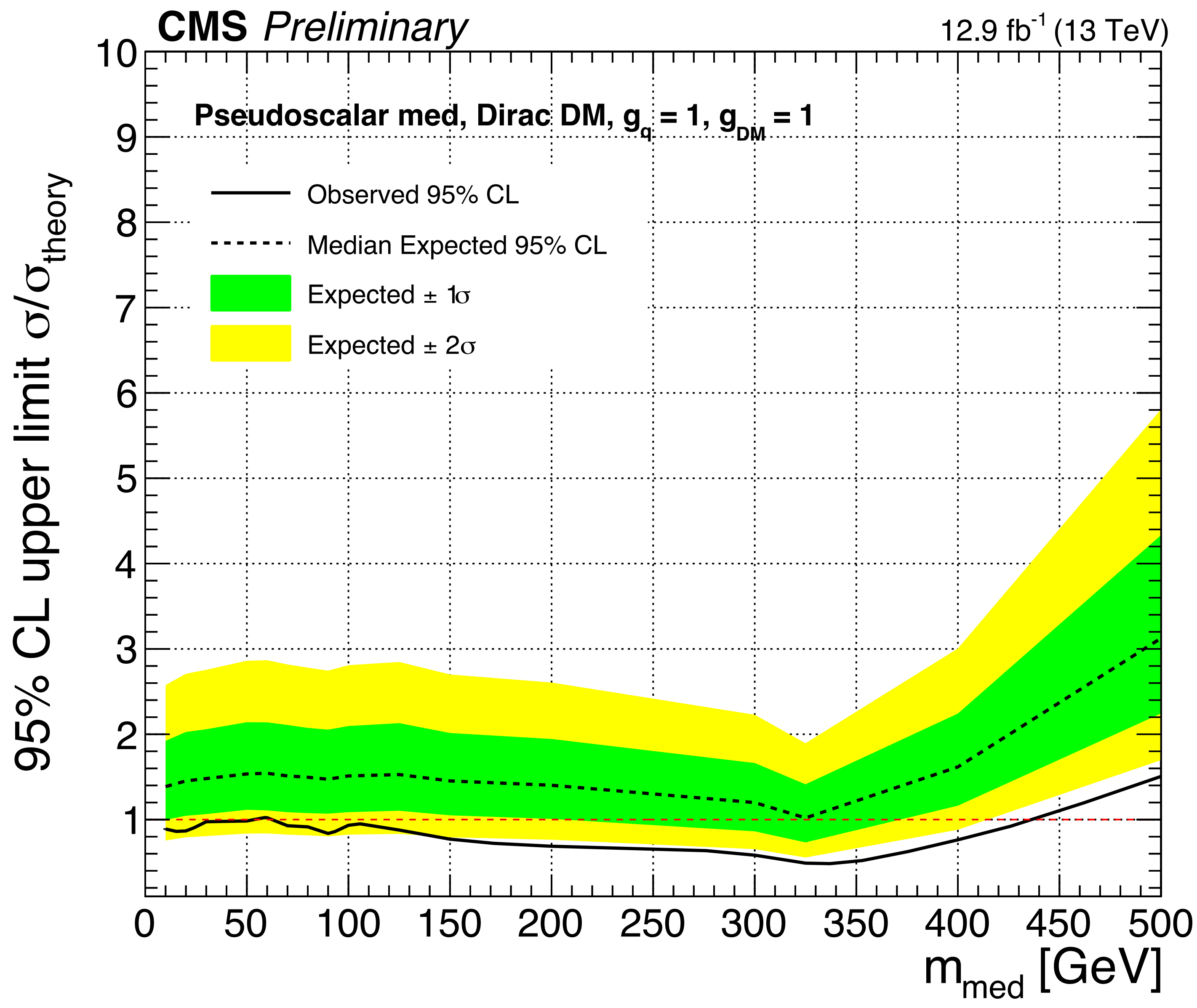
Strongly-coupled scalar models with mediator masses of 300 GeV can be tested via $E_{T,\mathrm{miss}}+t\bar{t}$. Mediator broad in large parts of parameter space

[see backup slides for details]

Spin-0 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]



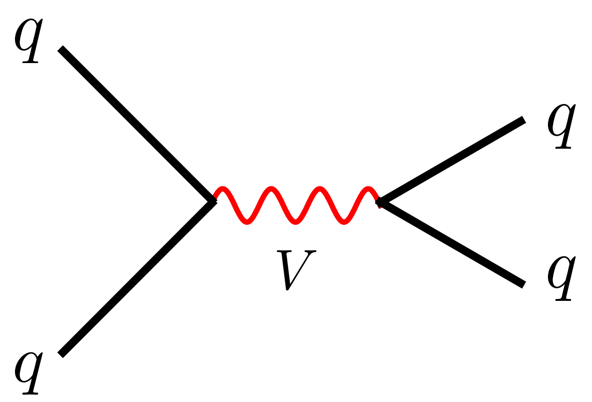


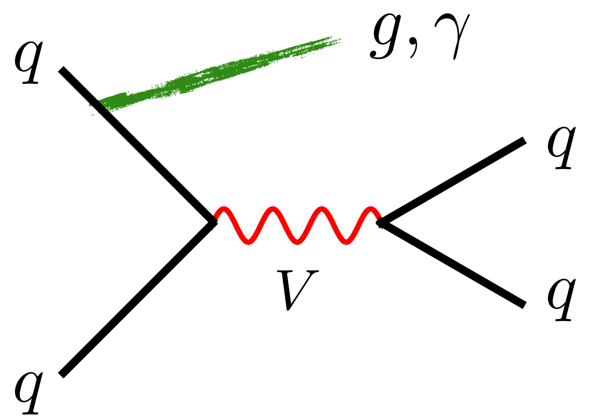
Since pseudoscalar production enhanced by a factor of more than 2, mediator masses close to 450 GeV are excluded for $g_q = g_\chi = 1$

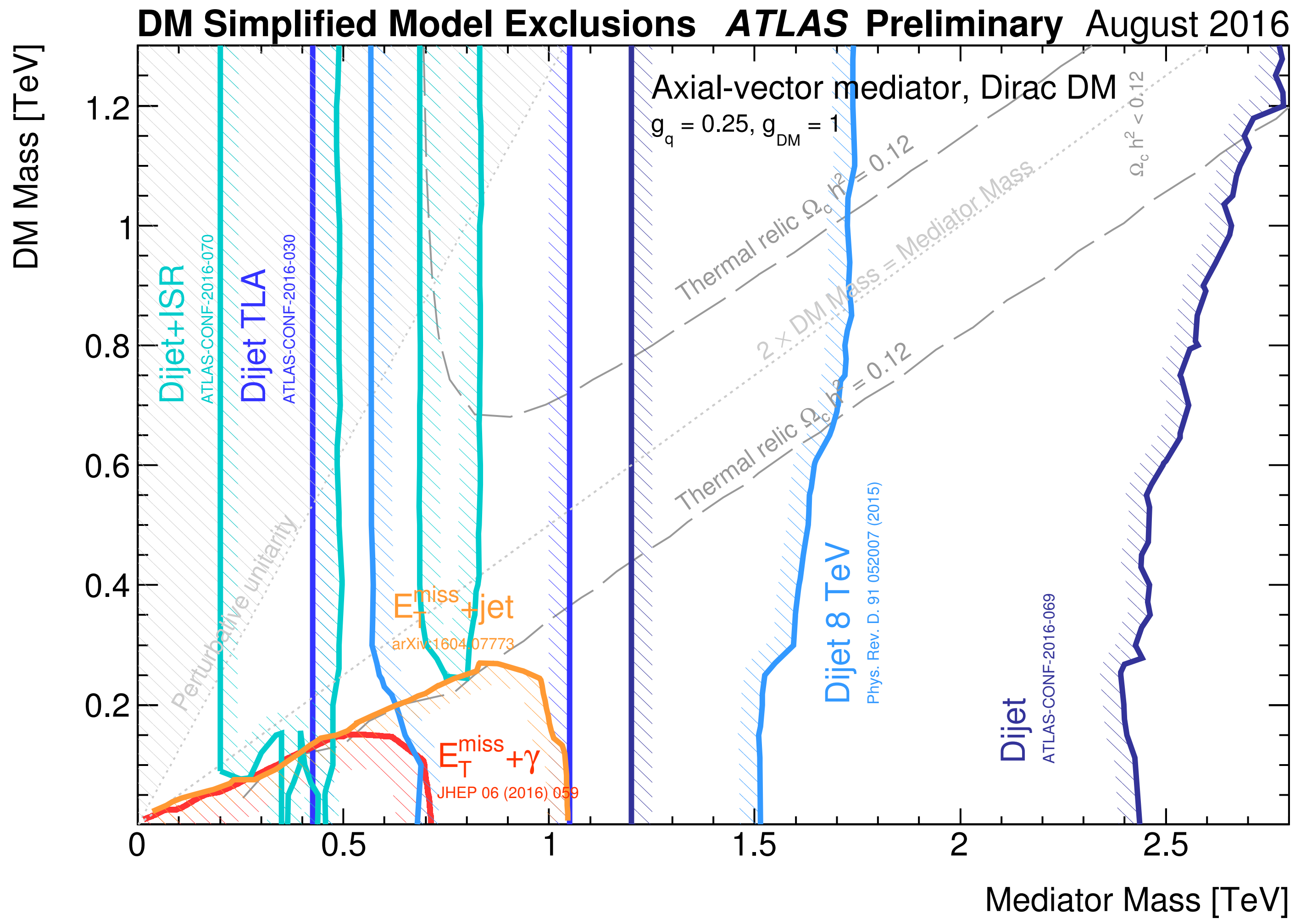
[parallel talk by Moon on Monday]

Spin-1 simplified models: di-jet limits

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]





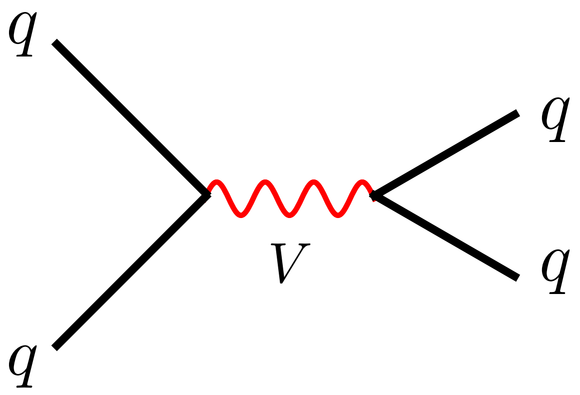


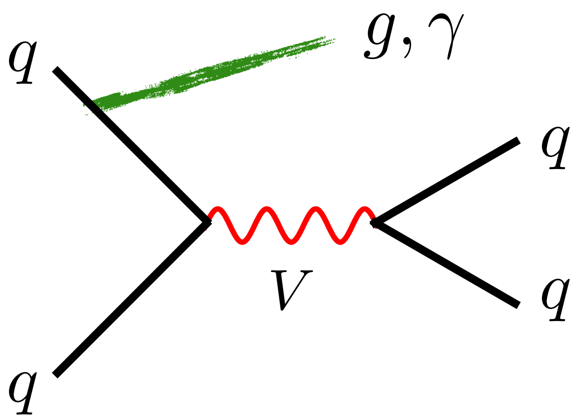
For coupling choice $g_q = 0.25$, $g_\chi = 1$ di-jet searches provide complementary constraints & exclude mediator masses from 200 GeV to 2.8 TeV

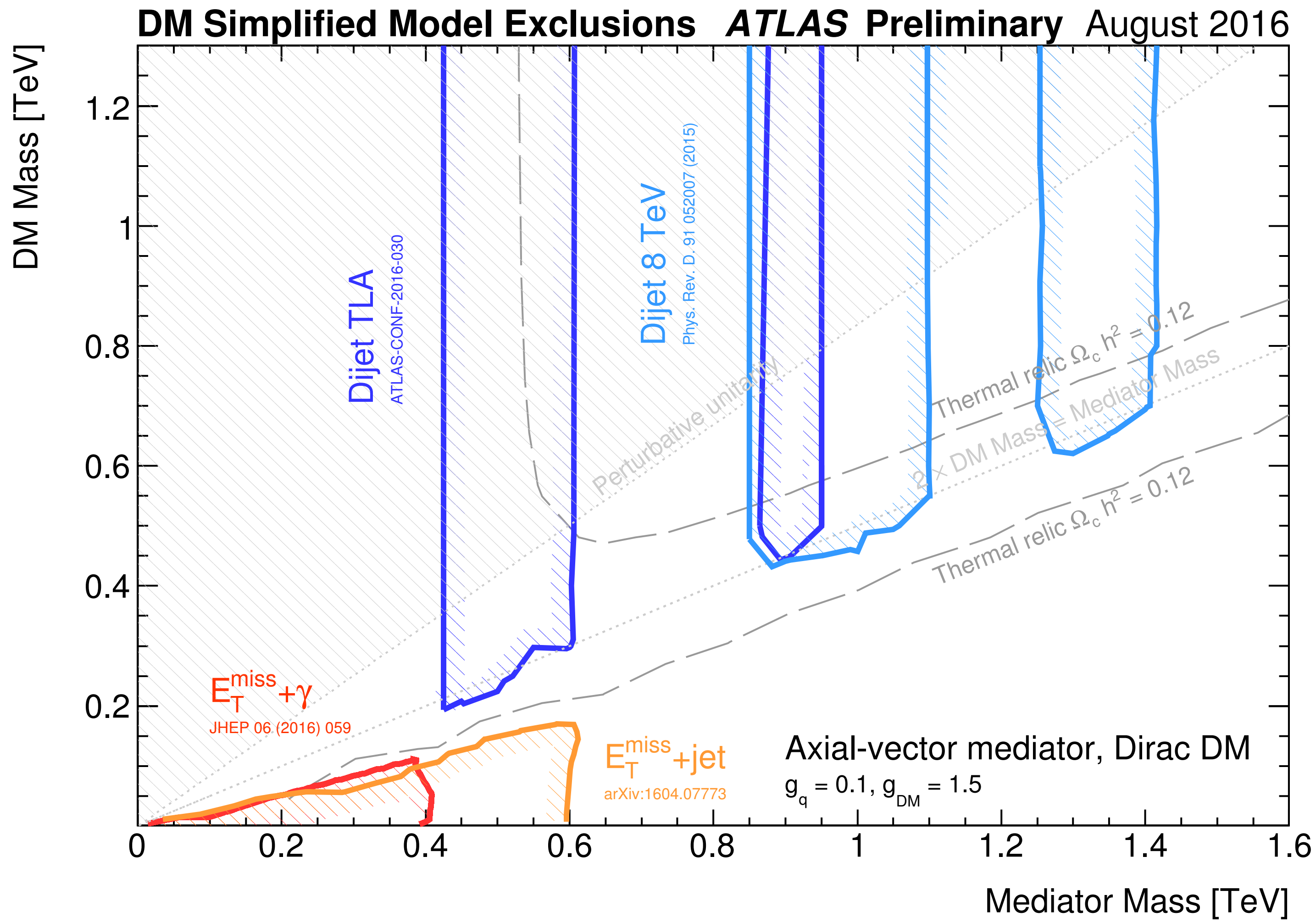
[parallel talks by Rosten on Monday & by Kahlhoefer on Thursday]

Spin-1 simplified models: di-jet limits

[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]







Di-jet limits can be weakened by reducing mediator-quark couplings g_q.

If g_χ kept perturbative mono-jet bounds also mitigated in such a case

[parallel talks by Rosten on Monday & by Kahlhoefer on Thursday]

Other LHC non-$E_{T, \text{miss}}$ constraints

DM simplified models are also subject to

(i) di-lepton bounds: only relevant in spin-1 case & simply avoided by setting $g_l = 0$ — unproblematic in vector case, but in simplest extension of axialvector model gauge invariance requires $g_l \neq 0$

[see Kahlhoefer et al., 1510.02110 & parallel talk by Vogel]

(ii) di-top bounds: in spin-1 case not as stringent as di-jet limits, while in spin-0 models simple resonance searches not directly applicable due to interference of SM background with signal

[see Chala et al., 1503.05916 & backup slides]

t-channel flavoured mediators

DM fermion singlet

scalar flavour triplet

$$\mathcal{L}_{\text{fermion},\tilde{u}} \supset \sum_{i=1,2,3} g\phi_i^* \bar{\chi} P_R u_i + \text{h.c.} \qquad \phi_i = \{\tilde{u}, \tilde{c}, \tilde{t}\}$$

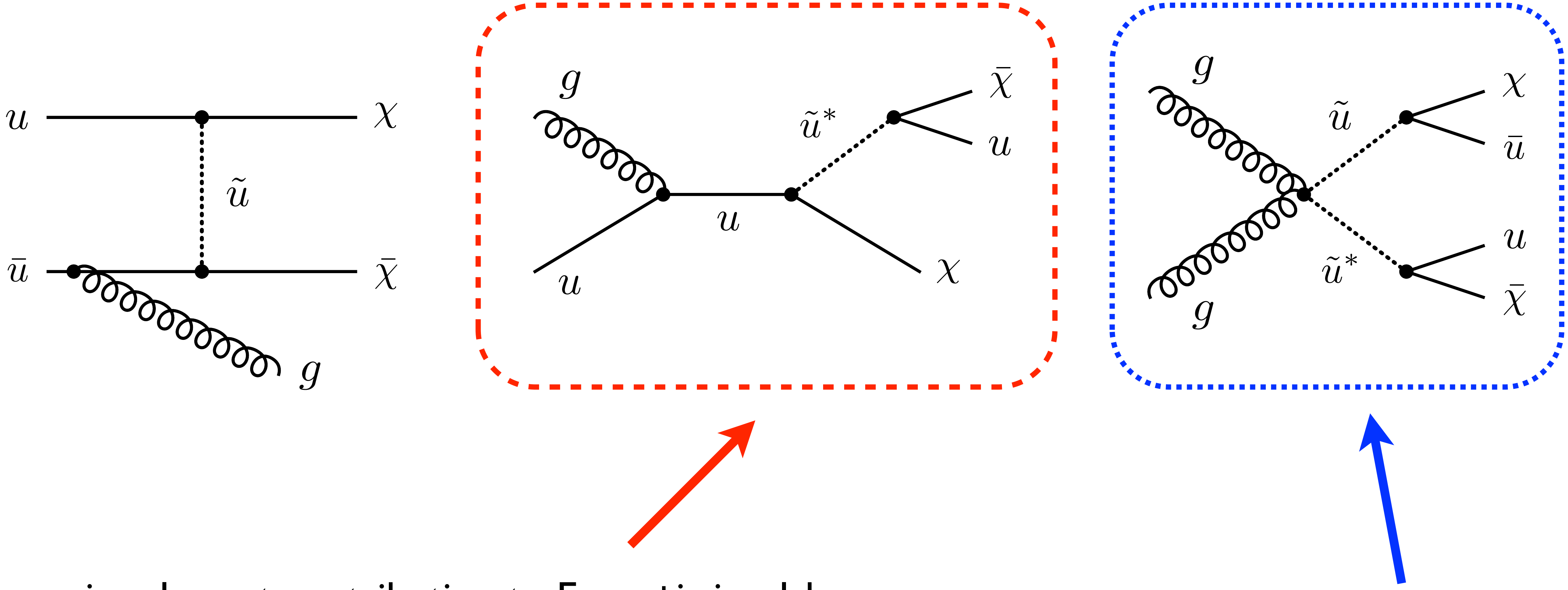
universal couplings to have minimal flavour violation (MFV),
which is needed to avoid flavour constraints

$$\{m_\chi,\ M_{1,2},\ M_3,\ g_{1,2},\ g_3\}$$

universality broken by $Y_u^\dagger Y_u$ flavour spurion (fine with MFV)

[Bell et al., 1209.0231; Chang et al., 1307.8120; An et al., 1308.0592;
Bai & Berger, 1308.0612; DiFranzo et al., 1308.2679; Papucci et al., 1402.2285; …]

t-channel flavoured mediators

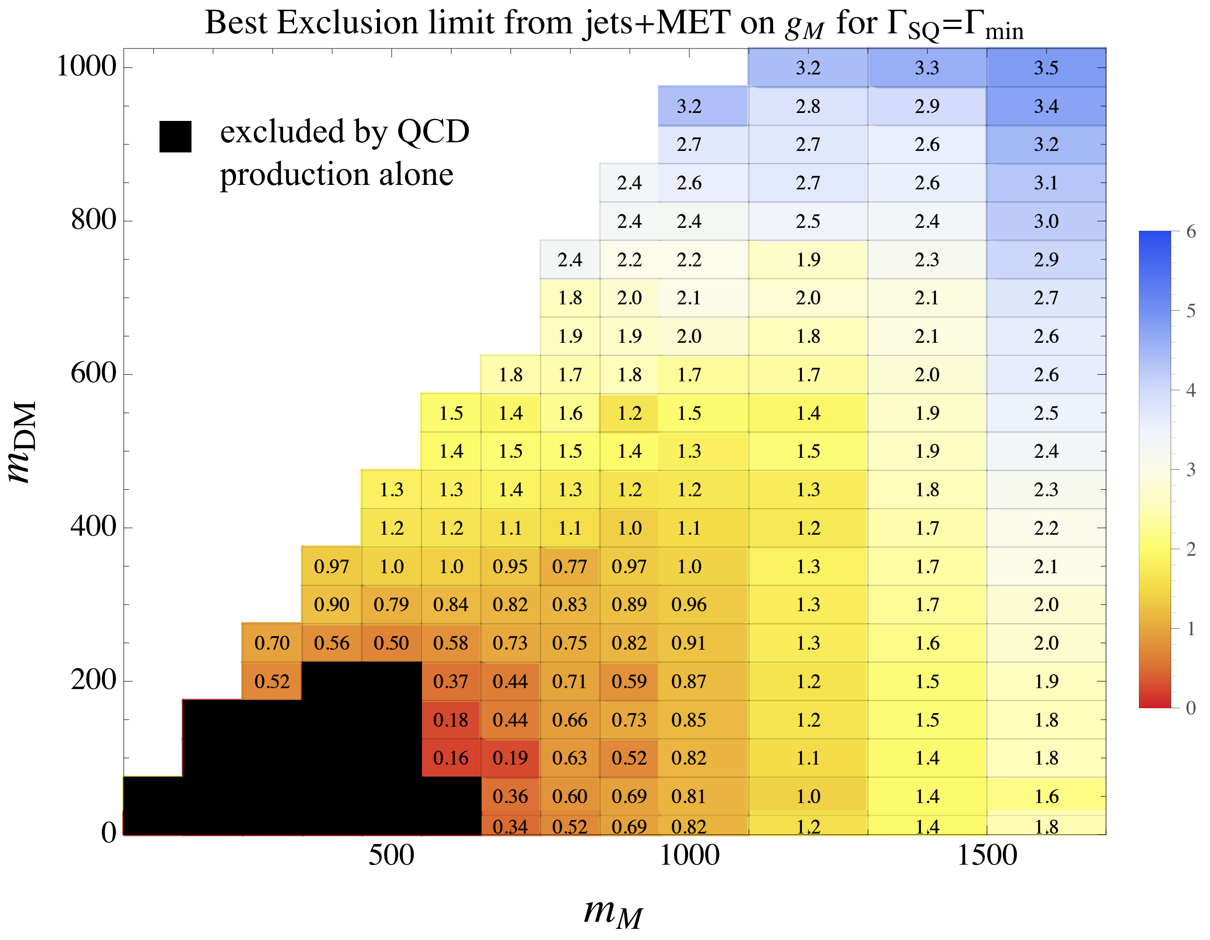


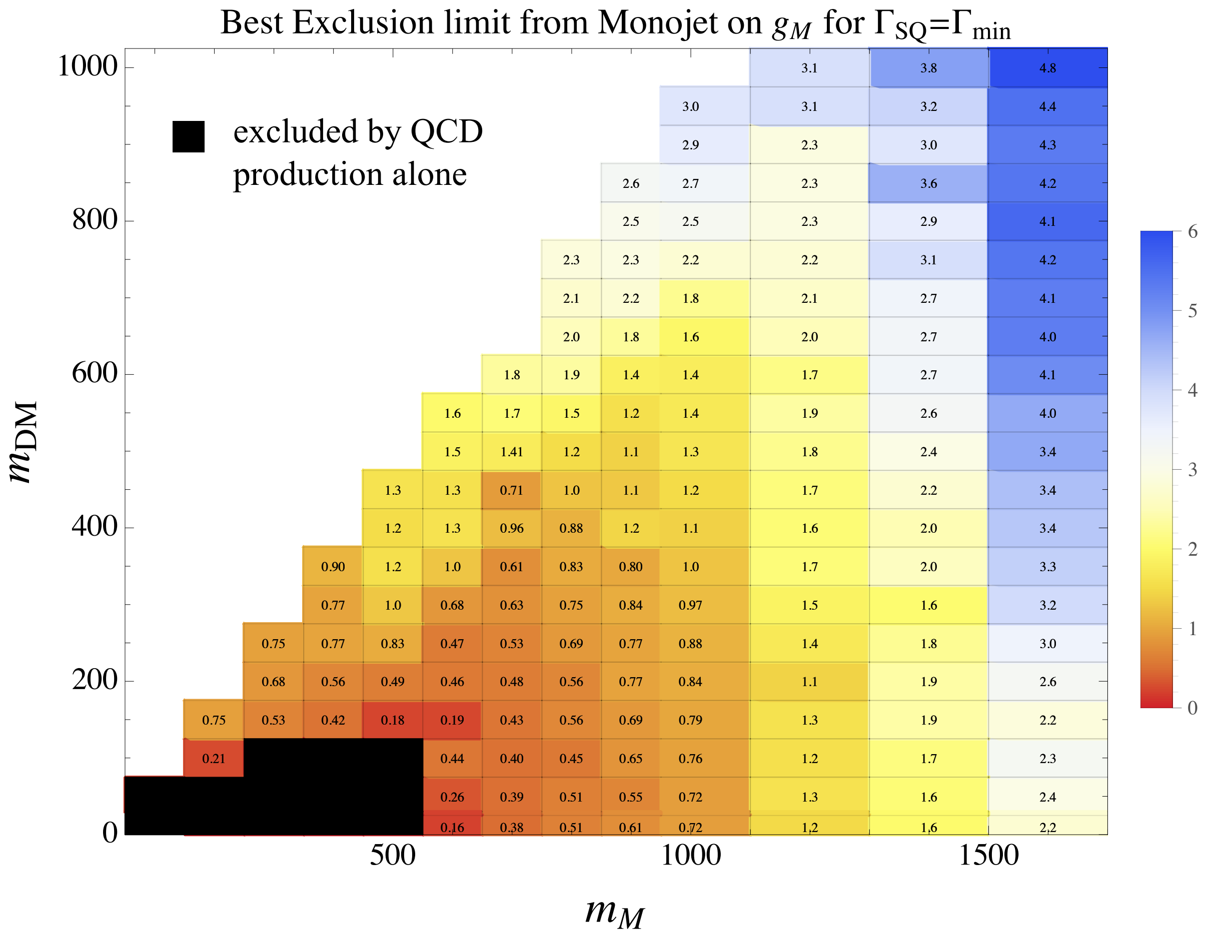
gives largest contribution to $E_{T,\text{miss}}$+j signal, because compared to initial state radiation (ISR) diagram phase-space enhanced, profits from gluon luminosity & jet typically harder than in ISR; dominance of associated production channel is a distinct feature of t-channel models

$E_{T,\text{miss}}$+2j channel can dominate over $E_{T,\text{miss}}$+j signal if $g_l >> g_s$

t-channel flavoured mediators

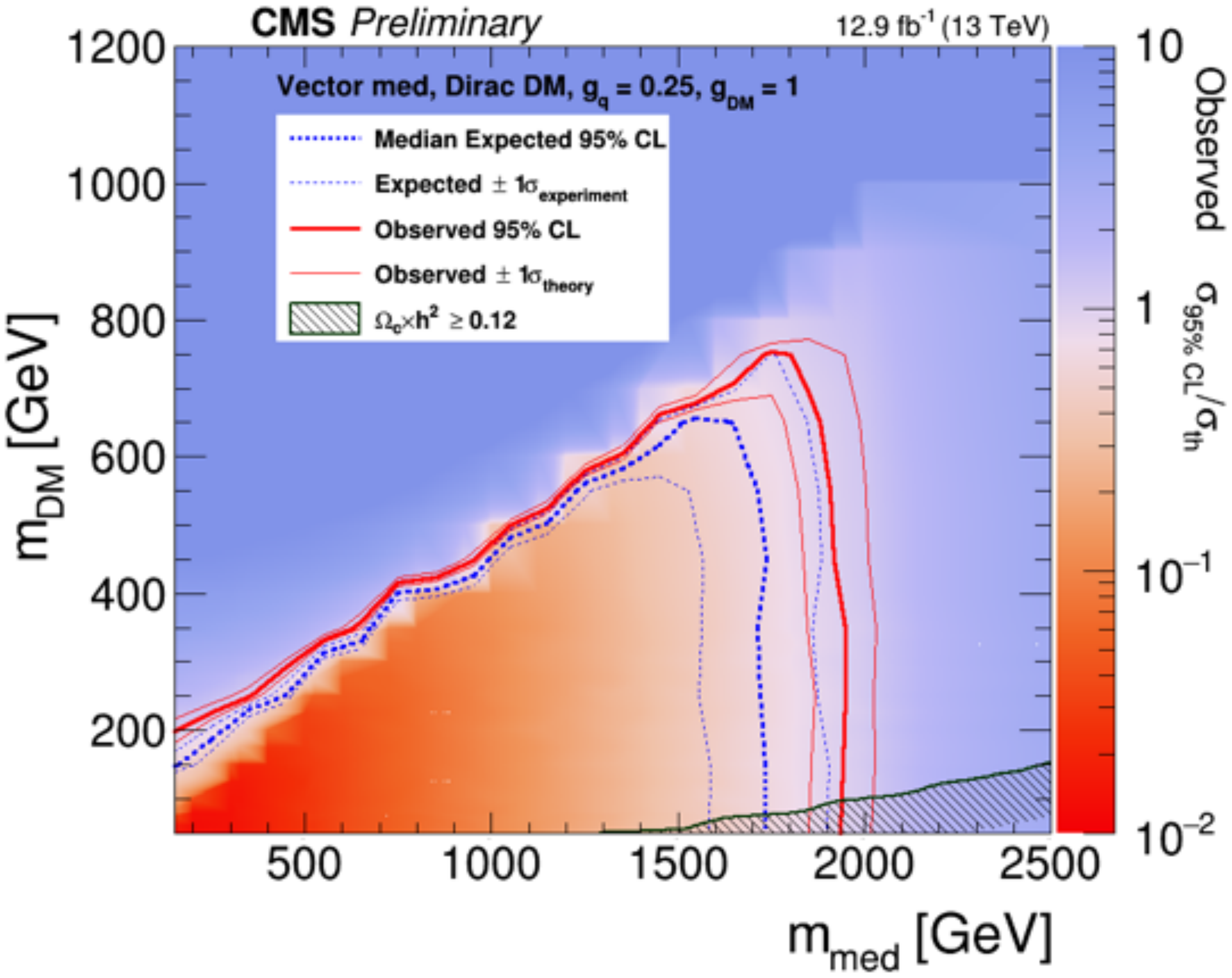
[Papucci et al., 1402.2285]





Mono-jet & supersymmetric (SUSY) searches provide comparable bounds in most of parameter space. SUSY searches often slightly better, except if mass of DM particle & mediator is degenerate

From LHC bounds …



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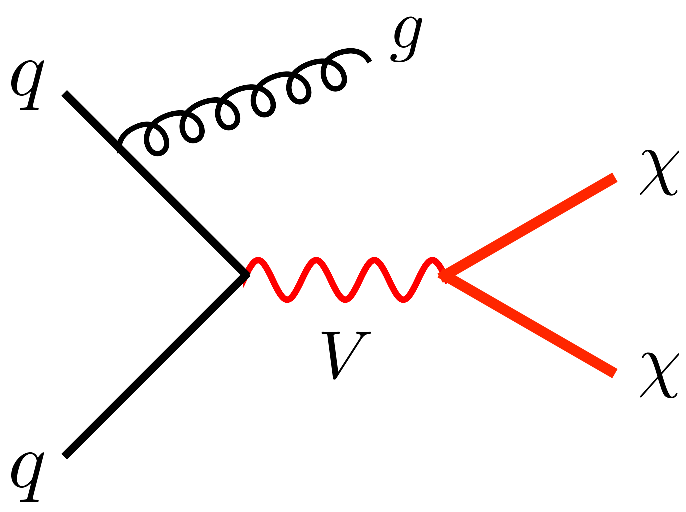


… using an EFT …

Most general EFT needed to describe χ-N interactions contains up to 14 different operators that induce 6 types of nuclear response functions:

$$\boxed{\mathcal{O}_1 = 1_\chi 1_N}$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\boxed{\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N}$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

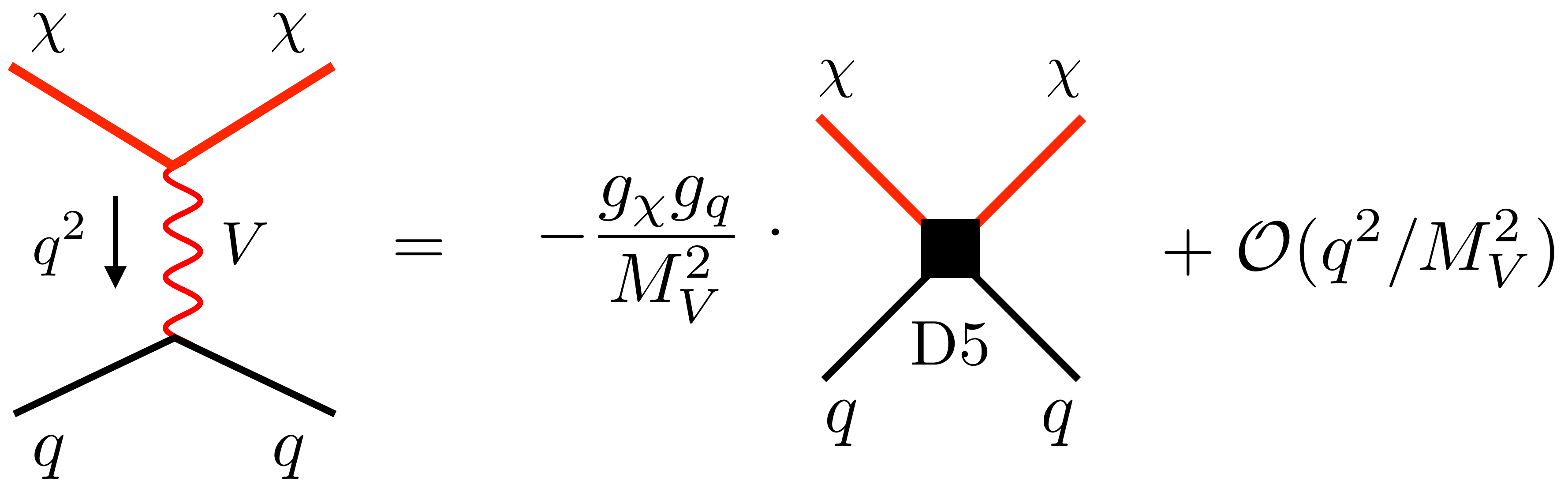
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

🟥 spin-independent (SI)

🟩 spin-dependent (SD)

[Fitzpatrick et al., 1203.3542, 1211.2818; Anand et al., 1308.2288, 1405.6690; …]

… to DD limits …

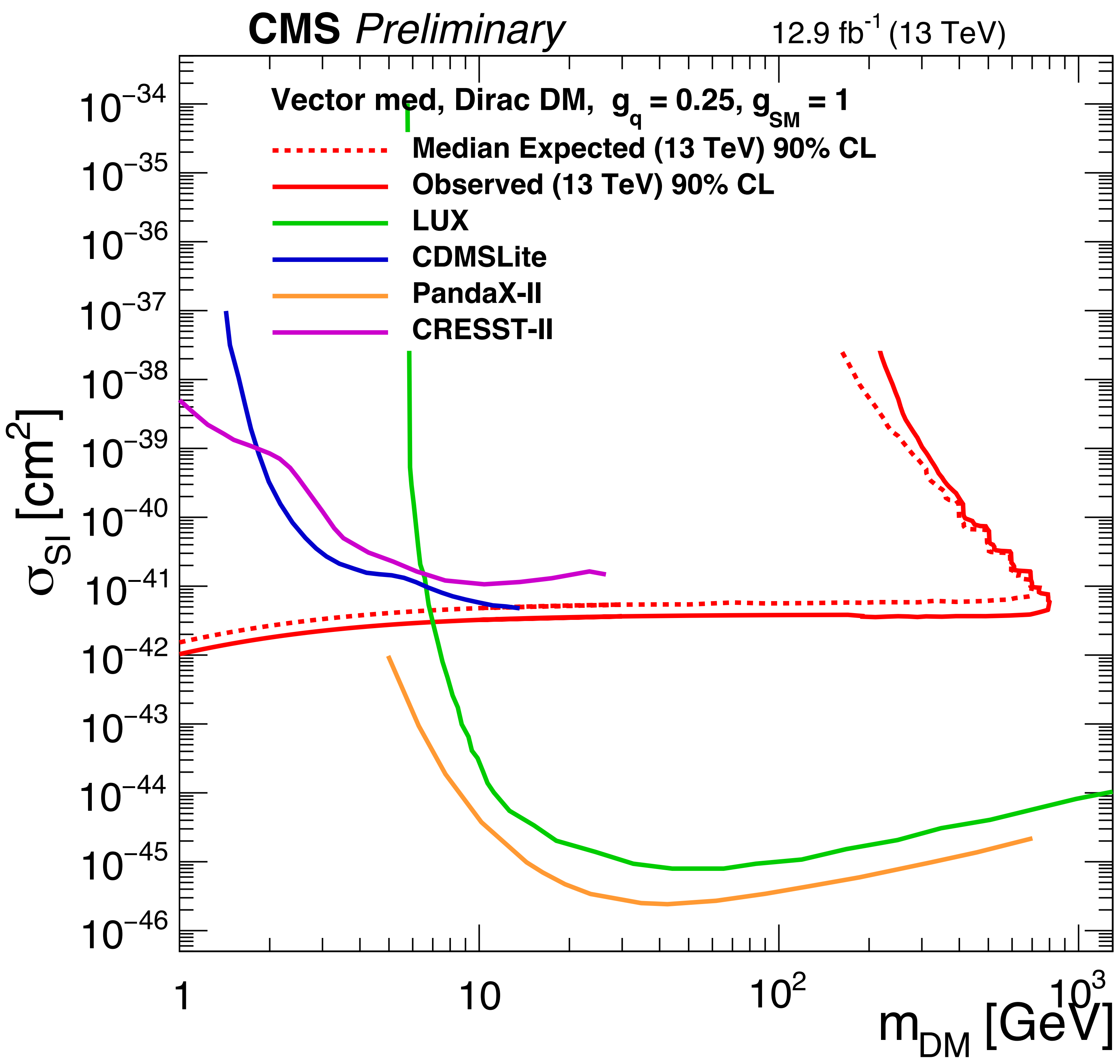


$$\text{D5} = \bar{\chi}\gamma^\mu \chi \bar{q}\gamma_\mu q \quad \longrightarrow \quad \mathcal{O}_1 = 1_\chi\, 1_N$$

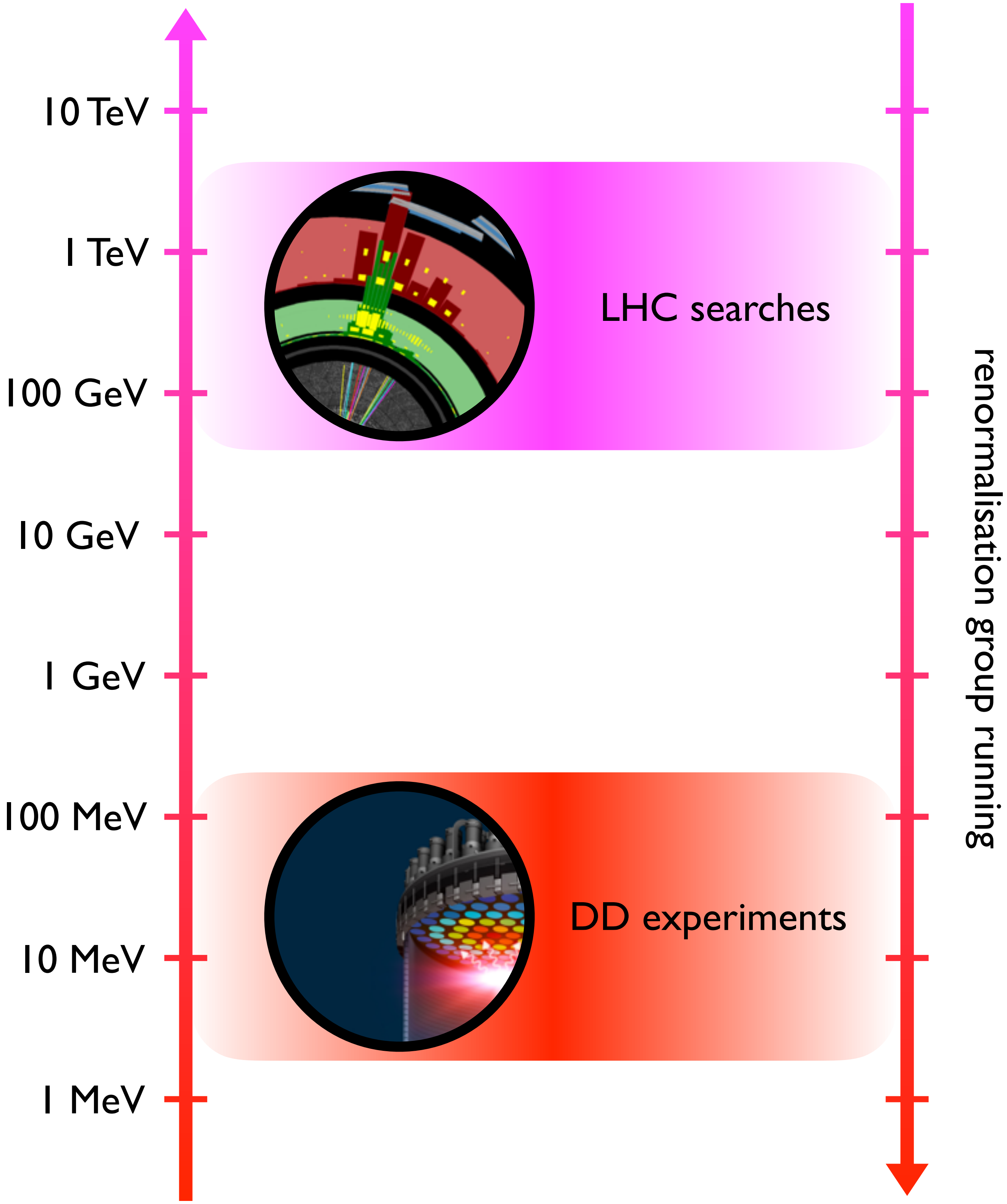
$$\sigma_{\text{SI}} \simeq 6.9 \cdot 10^{-41}\,\text{cm}^2 \left(\frac{g_\chi g_q}{0.25}\right)^2 \left(\frac{1\,\text{TeV}}{M_V}\right)^4 \left(\frac{\mu_{n\chi}}{1\,\text{GeV}}\right)^2$$

… & finally to a plot

[CMS PAS EXO-16-037]



Classification of χ-N interactions

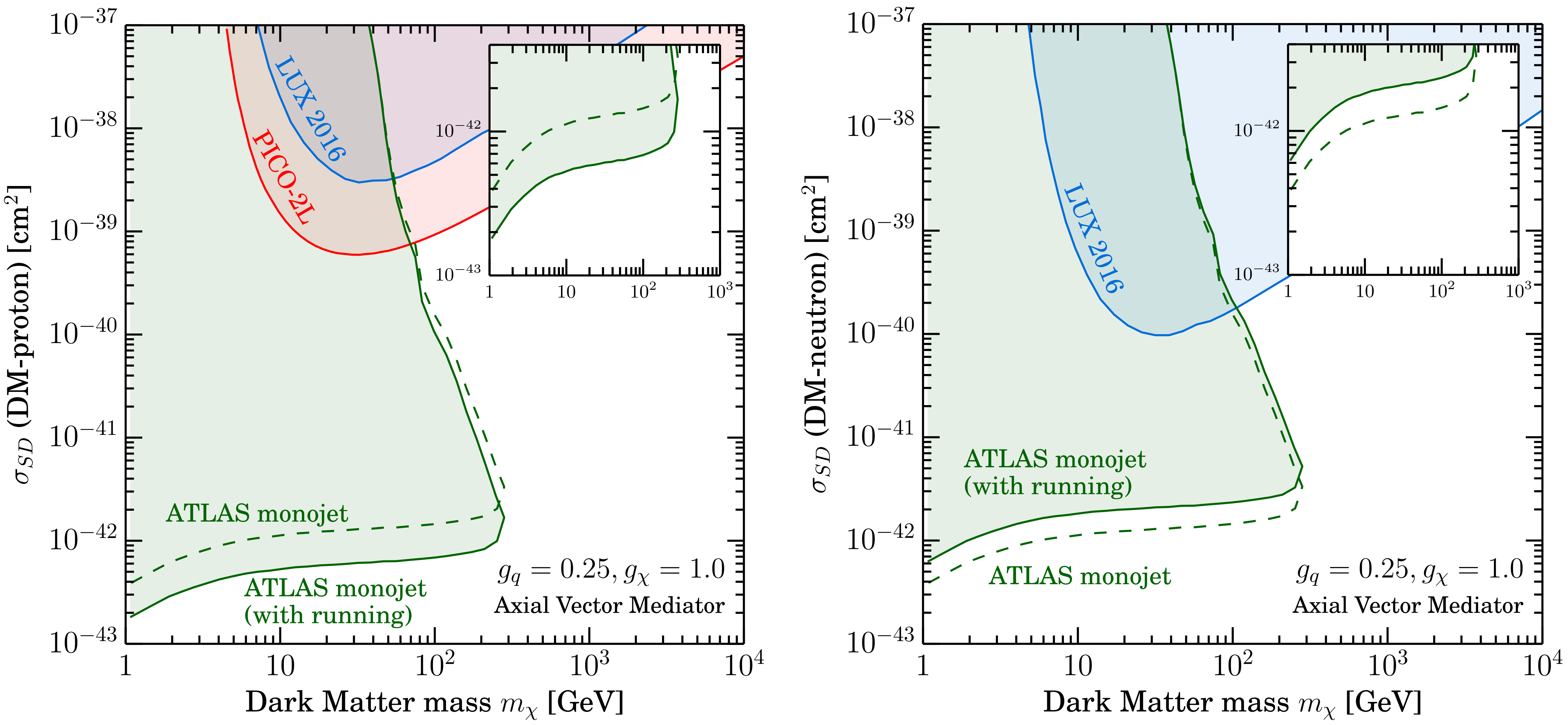


Distinction between SI & SD (or q-suppressed) χ-N couplings not stable under radiative corrections. Effects particular important for mixing of suppressed into unsuppressed operators

[Kopp et al., 0907.3159; Freytsis & Ligeti, 1012.5317; Hill & Solon, 1111.0016; UH & Kahlhoefer 1302.4454; Crivellin et al. 1402.1173, 1408.5046; D'Eramo et al. 1409.2893; …]

Spin-1 simplified models: running effects

[D'Eramo et al., 1605.04917]



In vector mediator model running effects are negligible, while in axialvector case cross-section bounds are changed by a factor of 2

Are simplified models perfect?

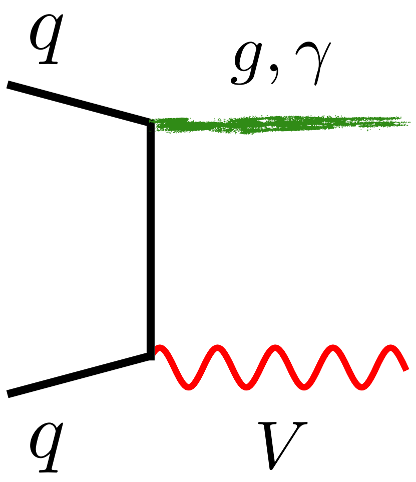
Simplified models are minimal extensions of EFT that besides DM typically contain a single mediator. SM- & DM-mediator couplings are treated as free parameters & mechanism that provides mass to mediator & DM is unspecified

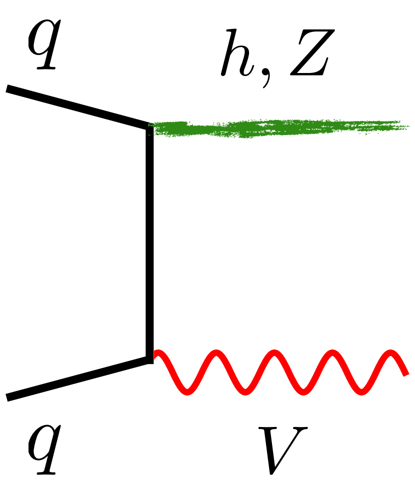
In ultraviolet (UV) complete model such as SM, couplings are usually not random but fixed by for example gauge invariance & anomalies. Higgs mechanism also an important ingredient in SM

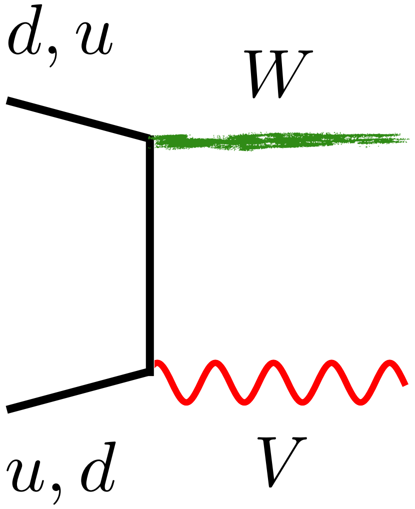
To UV complete simplified models have to add more structure to them & question is whether this will change phenomenology

Spin-1 2 → 2 tree-level amplitudes

$$\mathcal{L}_V \supset g_\chi \bar{\chi}\gamma^\mu \chi V_\mu + \sum_q g_q \bar{q}\gamma^\mu q V_\mu$$





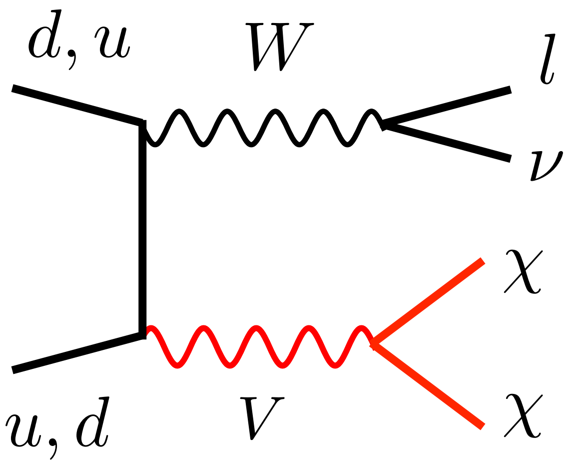


$\sim s^0$ $\qquad$ ~ 0 $\qquad$ $\sim (g_u - g_d)\dfrac{s}{M_W M_V}$

For $g_u \neq g_d$, ud→WV tree-level amplitude diverges in high-energy limit $s\to\infty$ & perturbative unitarity will be violated at some point

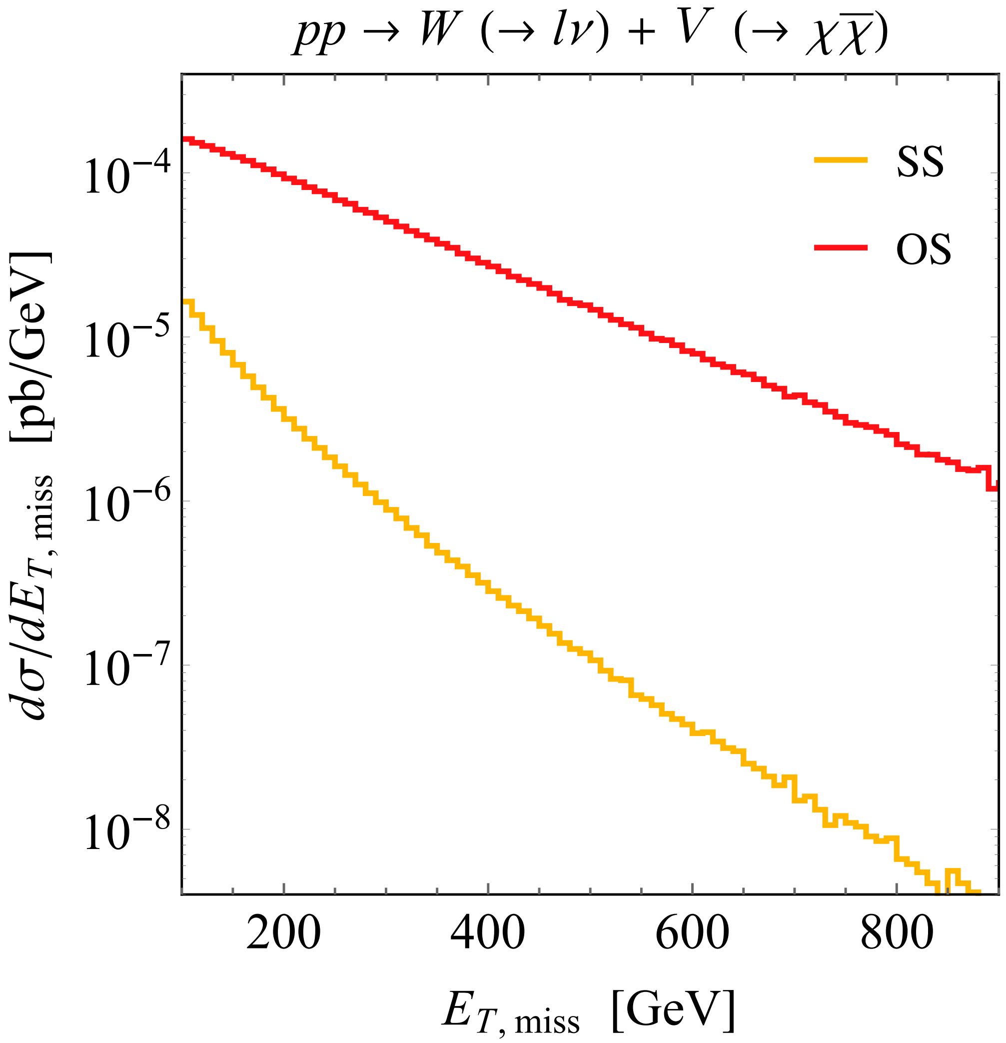
$E_{T,\text{miss}}$ spectra in mono-W sample

[UH et al., 1603.01267]



same-sign (SS): $g_u = g_d$

opposite-sign (OS): $g_u = -g_d$



For OS couplings $E_{T,\text{miss}}$ spectrum significantly harder than in SS case. This is an artefact of unitarity violation & thus unphysical

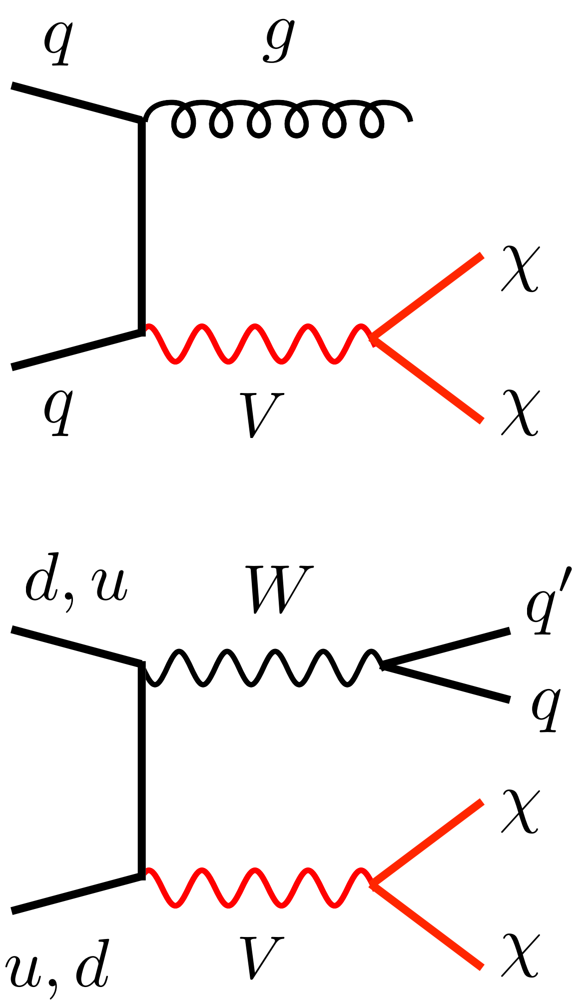
[see also Bell et al., 1503.07874, 1512.00476]

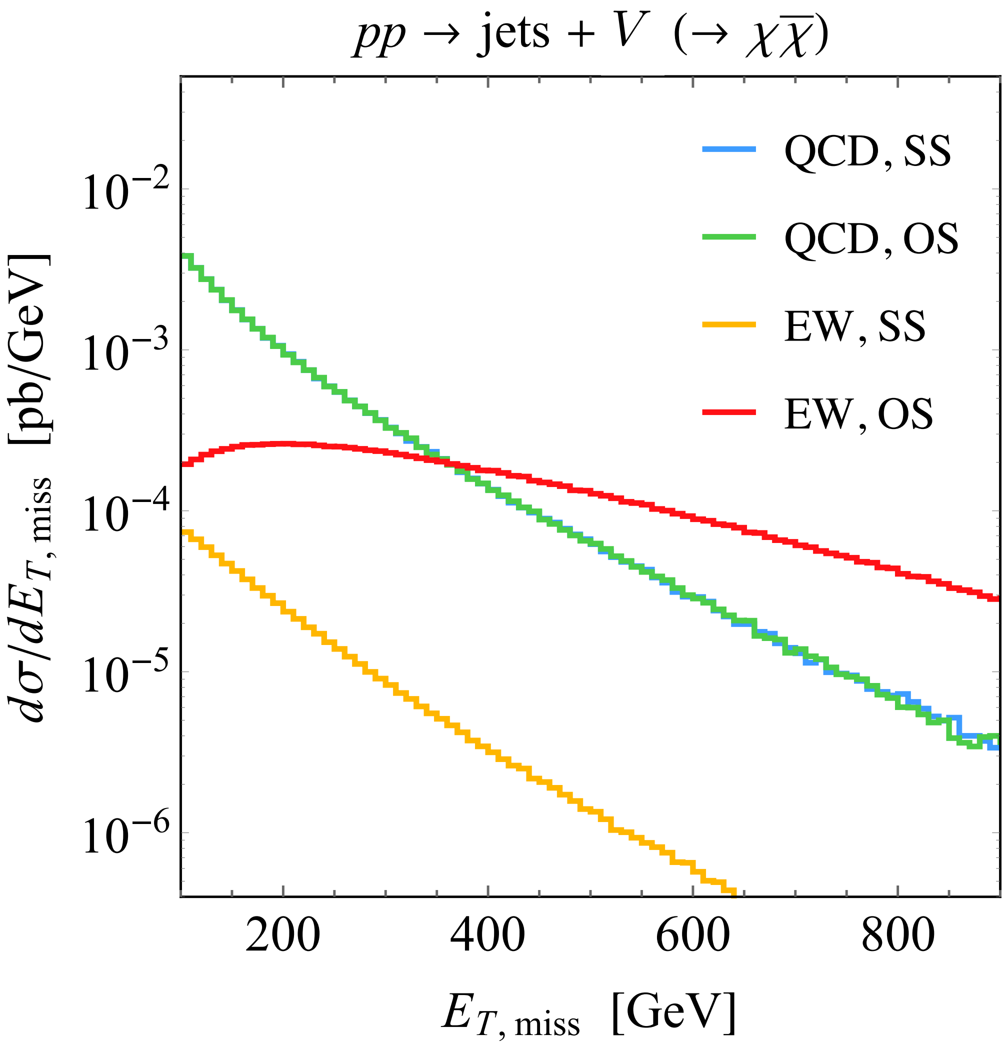
$E_{T,\text{miss}}$ spectra in mono-jet sample

[UH et al., 1603.01267]

QCD

electroweak (EW)





In fact, EW channel $pp \to W(\to q\bar{q}') + V(\to \chi\bar{\chi})$ even produces harder mono-jet events than QCD process $pp \to \text{jets} + V(\to \chi\bar{\chi})$

Cures & consequences

There a several ways to tame unitarity problem in pp→$E_{T,miss}$+W:

(i) formulate couplings between u, d & V in gauge-invariant way

(ii) add a WWV vertex to spin-1 simplified model

(iii) implement interactions of quarks & V via dimension-6 operators

Irrespectively of how issue is resolved, sensitivity of mono-jet searches will always exceed that of mono-W channel in modified theory. Same verdict has been reached in EFT case & t-channel simplified DM models with coloured scalar exchange

[see backup slides for details & Bell et al.,1503.07874, 1512.00476 for EFT & t-channel discussions]

Structure of spin-0 simplified model

Since left- & right-handed SM fermions have different quantum numbers, interaction of form

$$\mathcal{L}_S \supset \sum \frac{g_q y_q}{\sqrt{2}}\, \bar{q} q S = \sum \frac{g_q y_q}{\sqrt{2}} \left(\bar{q}_L q_R + \bar{q}_R q_L \right) S$$

not $SU(2)_L \times U(1)_Y$ gauge invariant

Given that S is a SM singlet, terms like

$$S|H|^2, S^2|H|^2, S^3, S^4$$

not forbidden by EW symmetry. Why are such couplings not included?

Fermion singlet DM

In fact, by adding

$$\mathcal{L}_s \supset y_\chi \bar{\chi}\chi s + \mu s |H|^2$$

to SM Lagrangian both issues can be addressed

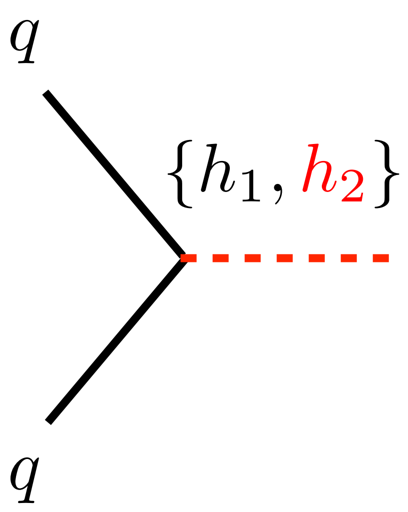
As a result of portal coupling μ, SM Higgs h & singlet s mix, giving rise to mass eigenstates $h_{1,2}$:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} , \qquad \tan(2\theta) = \frac{2v\mu}{M_s^2 - M_h^2}$$

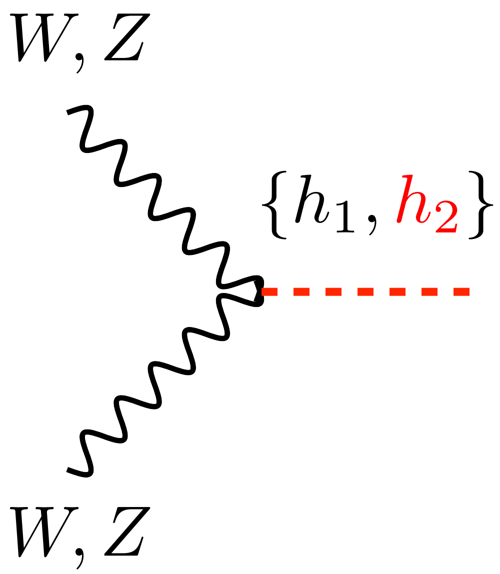
For small $\theta \ll 1$, h_1 (h_2) SM Higgs-like (singlet-like)

[Kim et al., 0803.2932; Baek et al., 1112.1847; Lopez-Honorez et al., 1203.2064; Fairbairn & Hogan, 1305.3452; …]

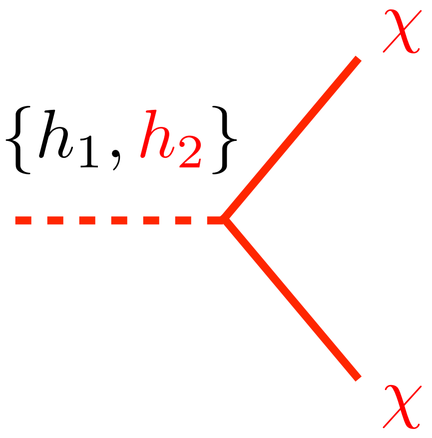
Fermion singlet DM: vertices



$$= \frac{y_q}{\sqrt{2}} \{\cos\theta, -\sin\theta\}$$



$$= M_{W,Z} \{\cos\theta, -\sin\theta\}$$



$$= y_\chi \{\sin\theta, \cos\theta\}$$

Fermion singlet DM: signatures

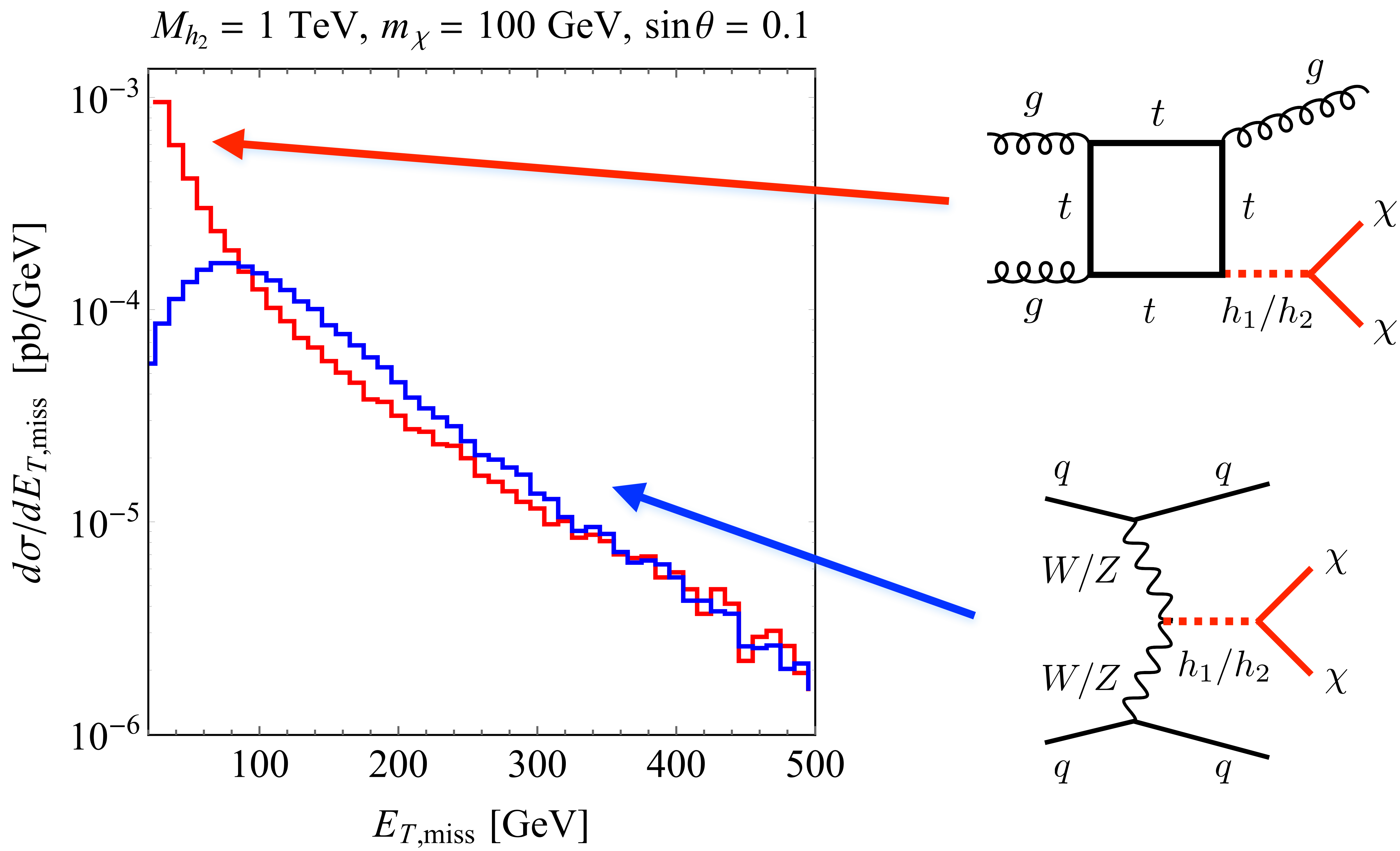
Compared to spin-0 simplified model LHC phenomenology is richer in fermion singlet DM scenario:

(i) universal suppression of SM Higgs couplings by $\cos\Theta$ — LHC Run I data requires already $\sin\Theta \lesssim 0.4$

(ii) new SM Higgs decay modes $h_1 \to \chi\bar{\chi}$ & $h_1 \to h_2 h_2$ if kinematically allowed

(iii) $E_{T,\mathrm{miss}}$ cross sections are changed & new signatures like W/Z+$E_{T,\mathrm{miss}}$ & VBF+$E_{T,\mathrm{miss}}$ arise — $E_{T,\mathrm{miss}}$ processes involving EW bosons cannot be described consistently in spin-0 simplified model

Mono-jet vs. W/Z, VBF+$E_{T,\mathrm{miss}}$ signal



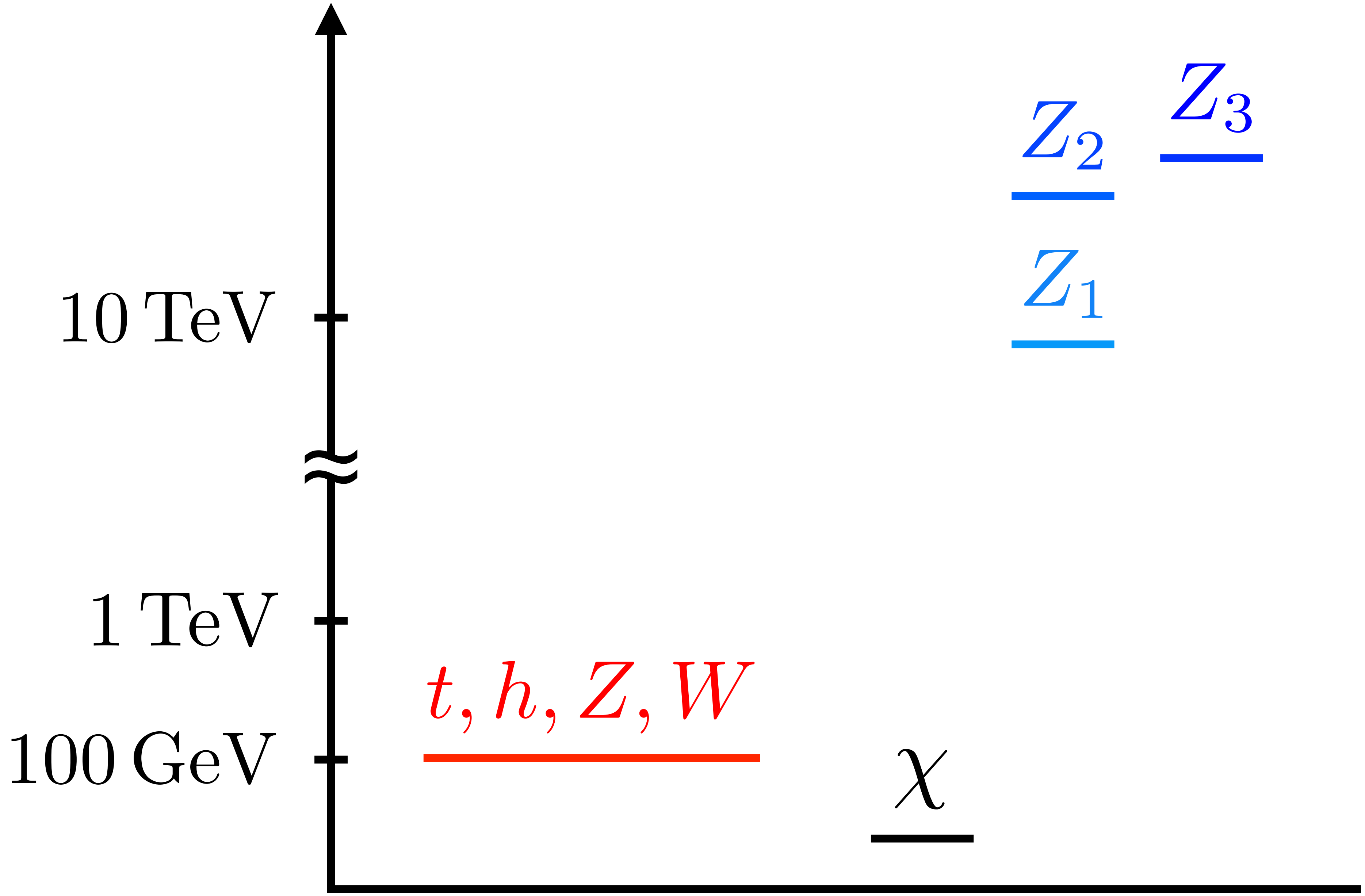
$M_{h_2} = 1$ TeV, $m_\chi = 100$ GeV, $\sin\theta = 0.1$

Conclusions

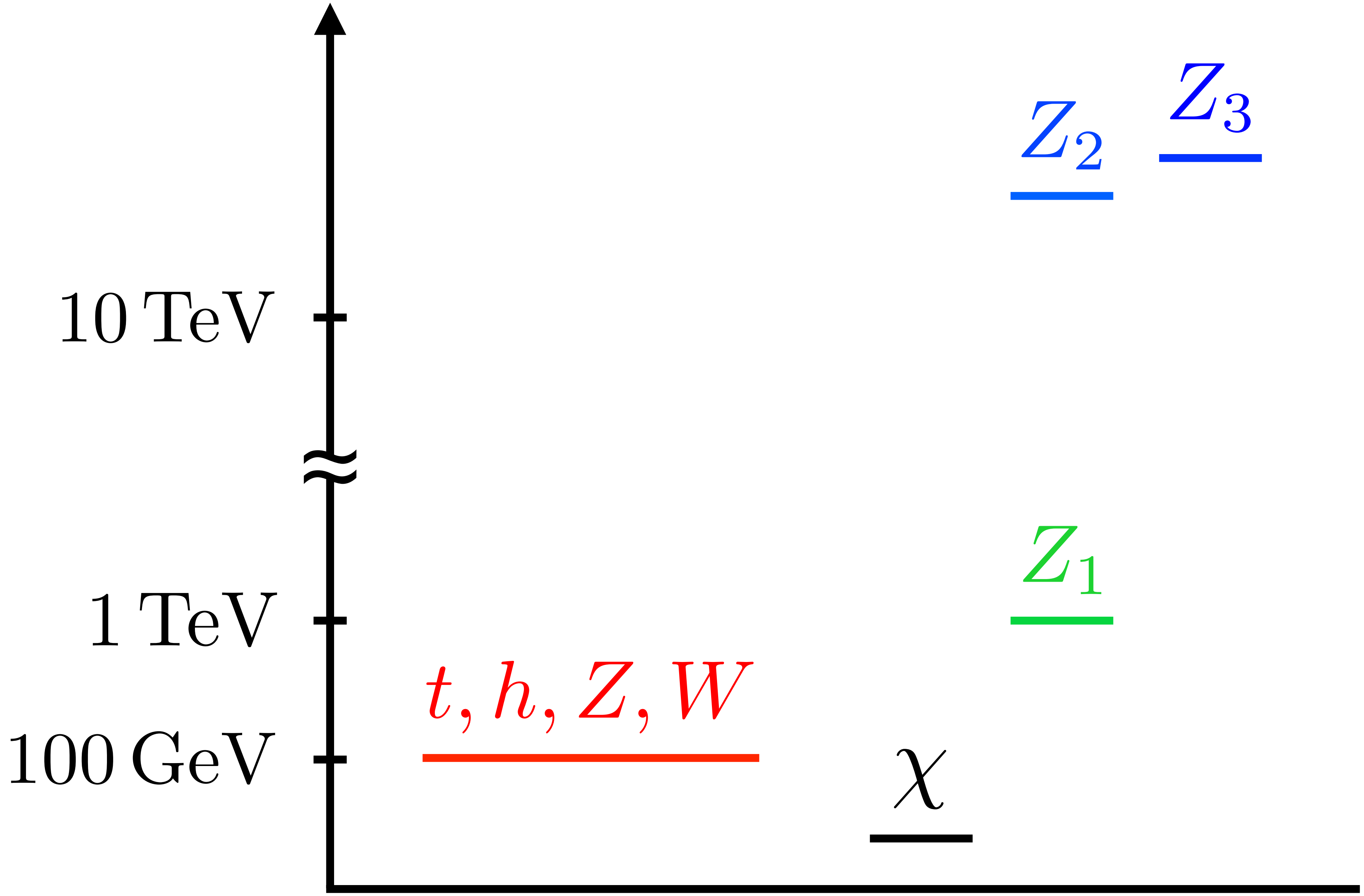
- Very nice first 13 TeV ATLAS & CMS results for a broad range of searches for DM in $E_{T,\,miss}$+X with X = j, γ, W, Z, h, t, $t\bar{t}$, $b\bar{b}$, … & more to come soon
- Interpretations of LHC searches in context of simplified models & sometimes EFTs provide information complementary to other DM searches
- How minimal should DM searches & their interpretations be? Often no sharp boundary both experimentally & theoretically. Is any crucial territory being missed in current approach?

Backup

Spectrum of DM EFT

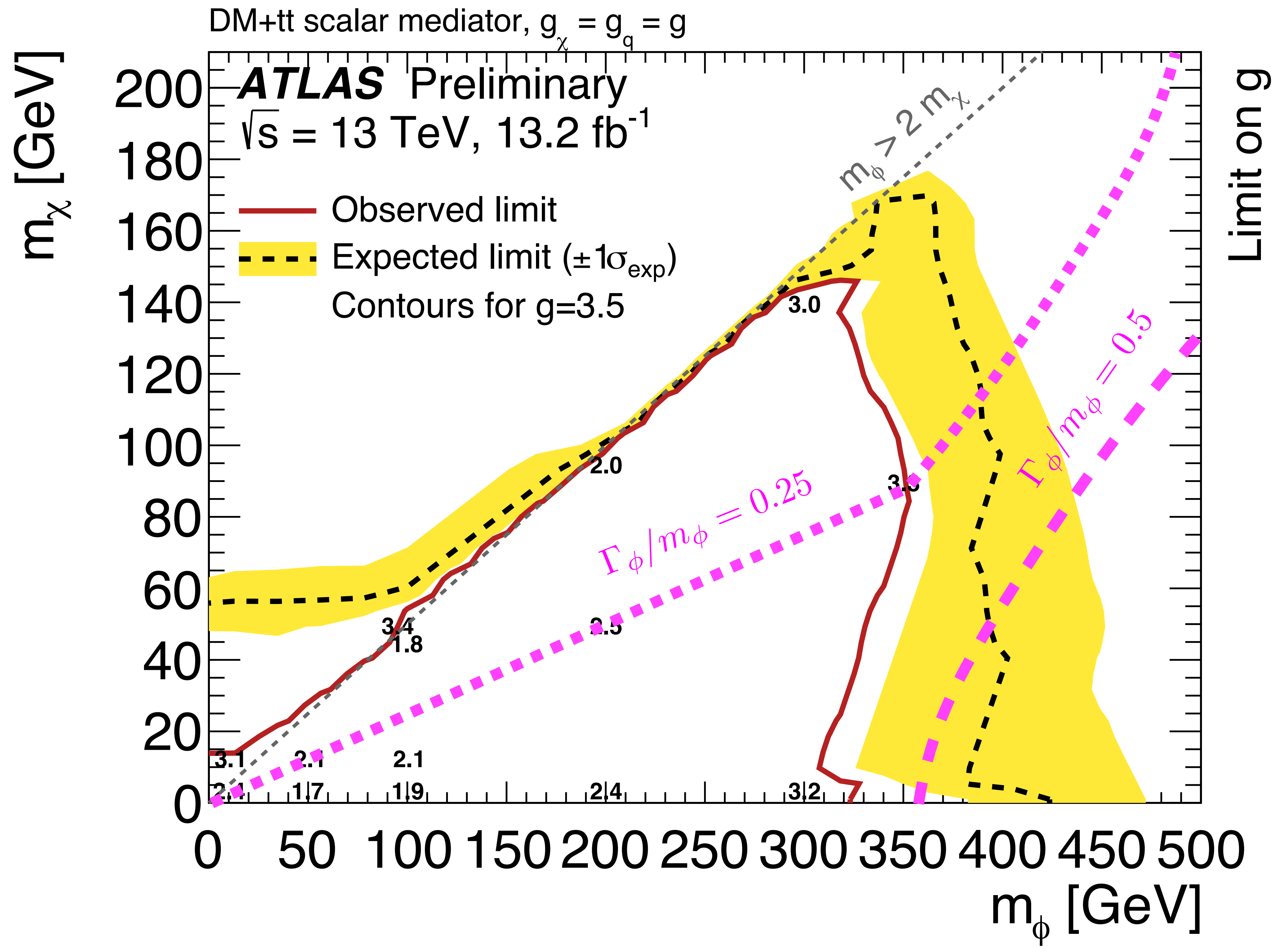


Spectrum of DM simplified model

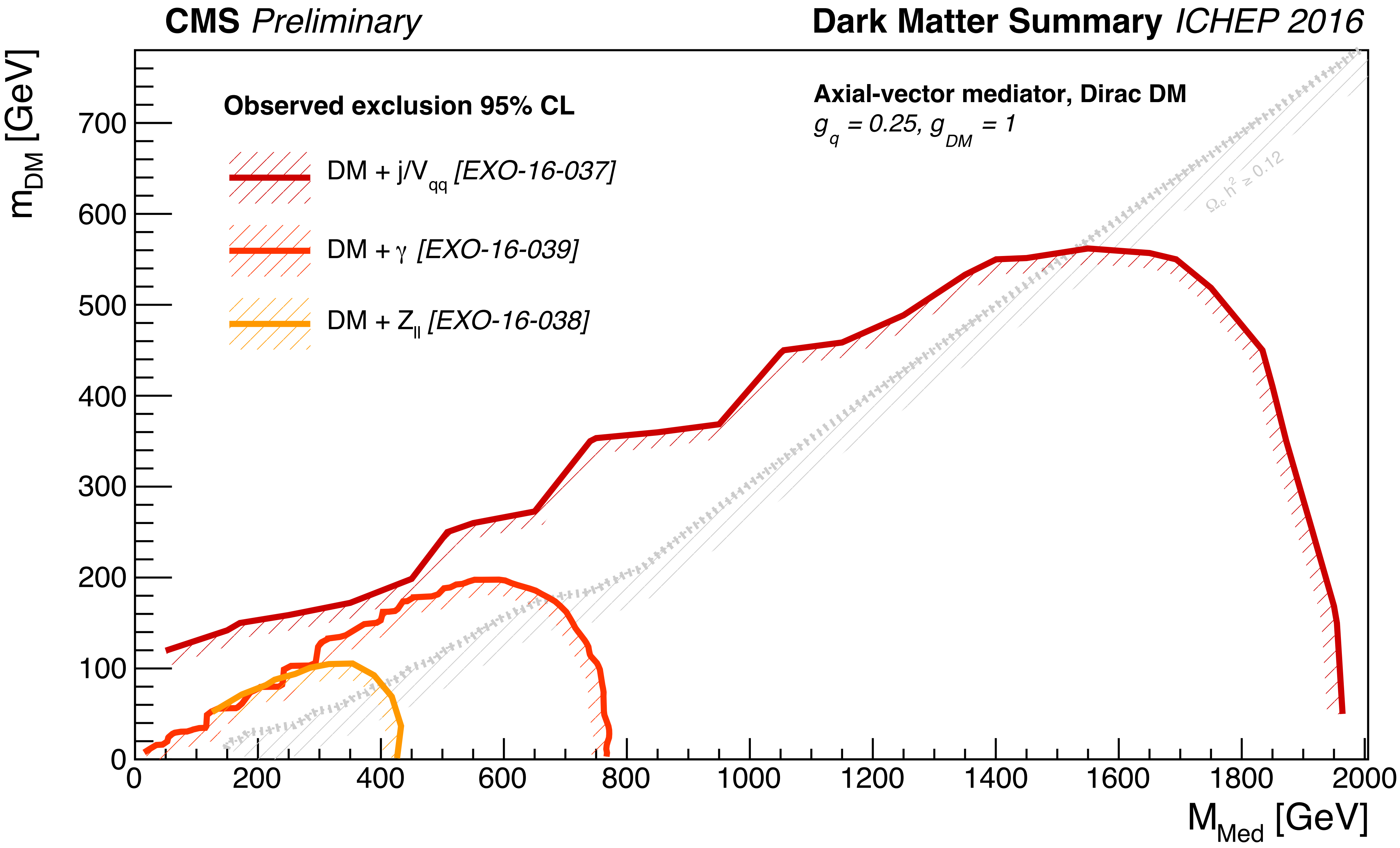


13 TeV limits on $E_{T,\text{miss}}$+$t\bar{t}$

[ATLAS-CONF-2016-050]



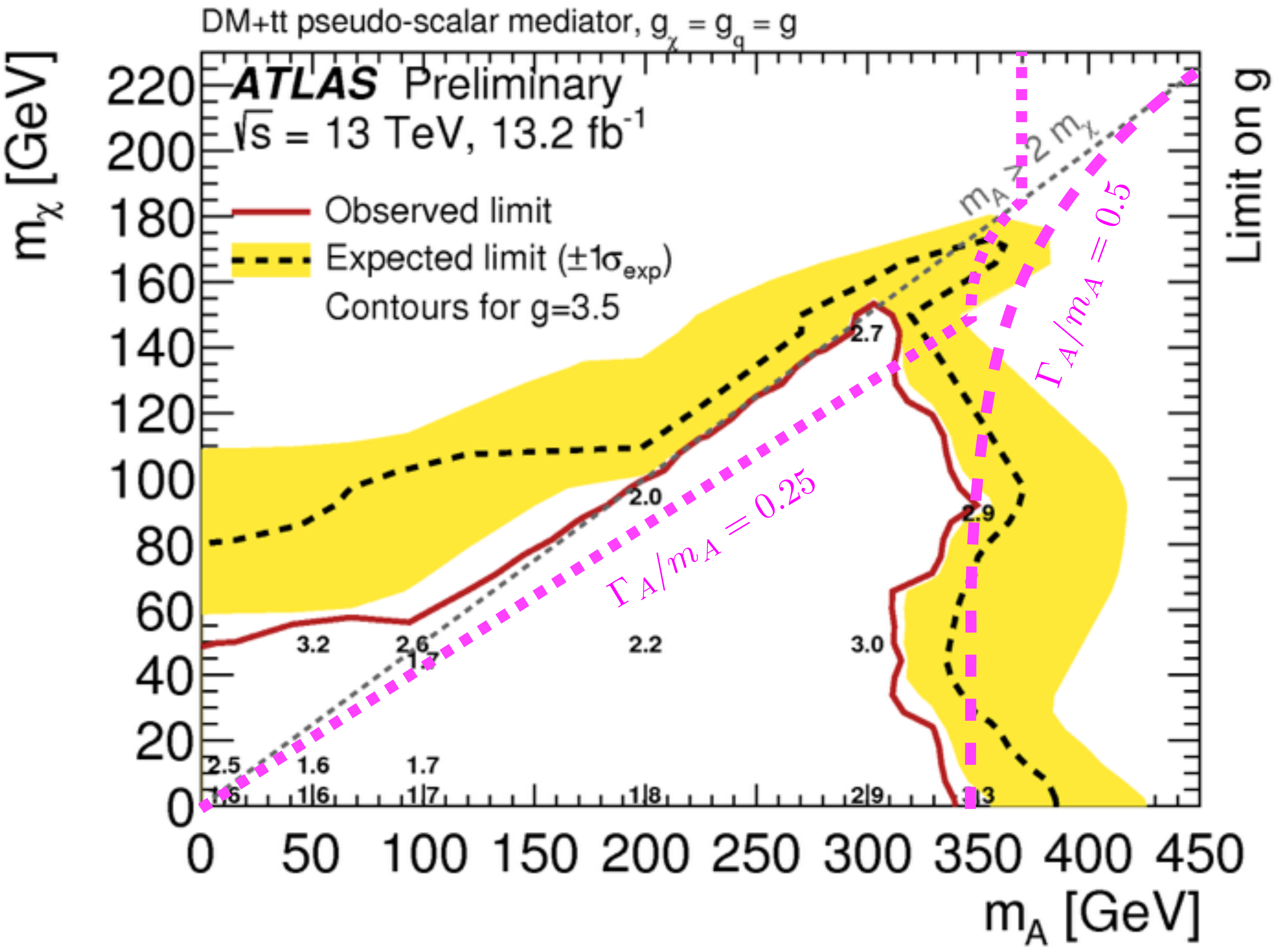
Mono-jet vs. mono-photon/Z



[https://cds.cern.ch/record/2208044/files/DP2016_057.pdf]

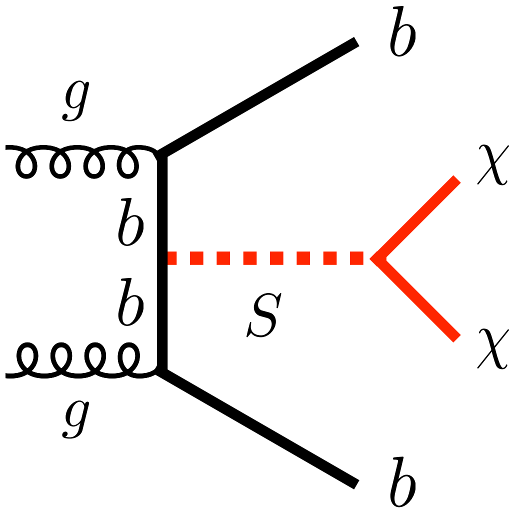
13 TeV limits on $E_{T,\text{miss}}+t\bar{t}$

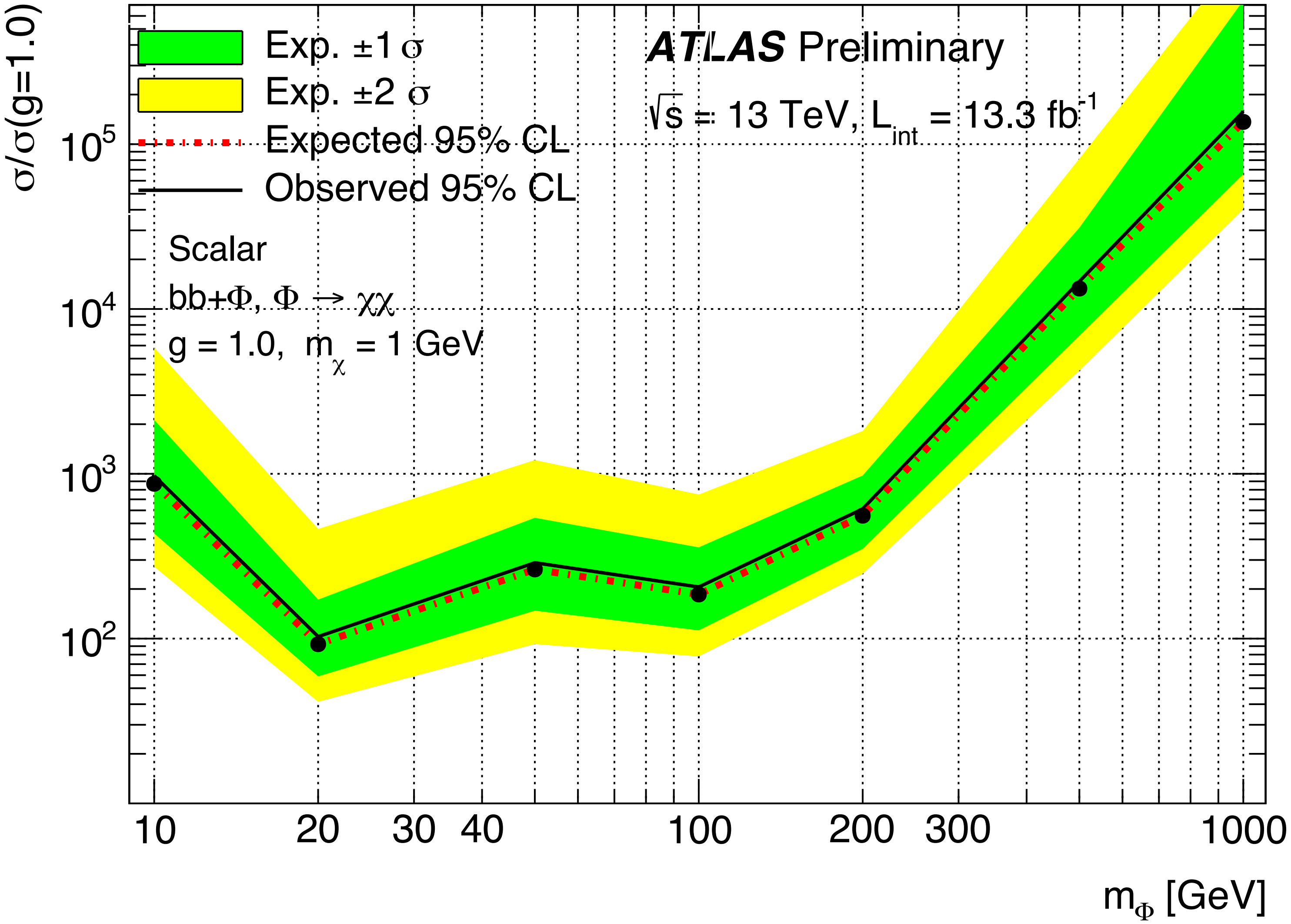
[ATLAS-CONF-2016-050]



13 TeV limits on $E_{T,\,miss}$+$b\bar{b}$

[ATLAS-CONF-2016-086]

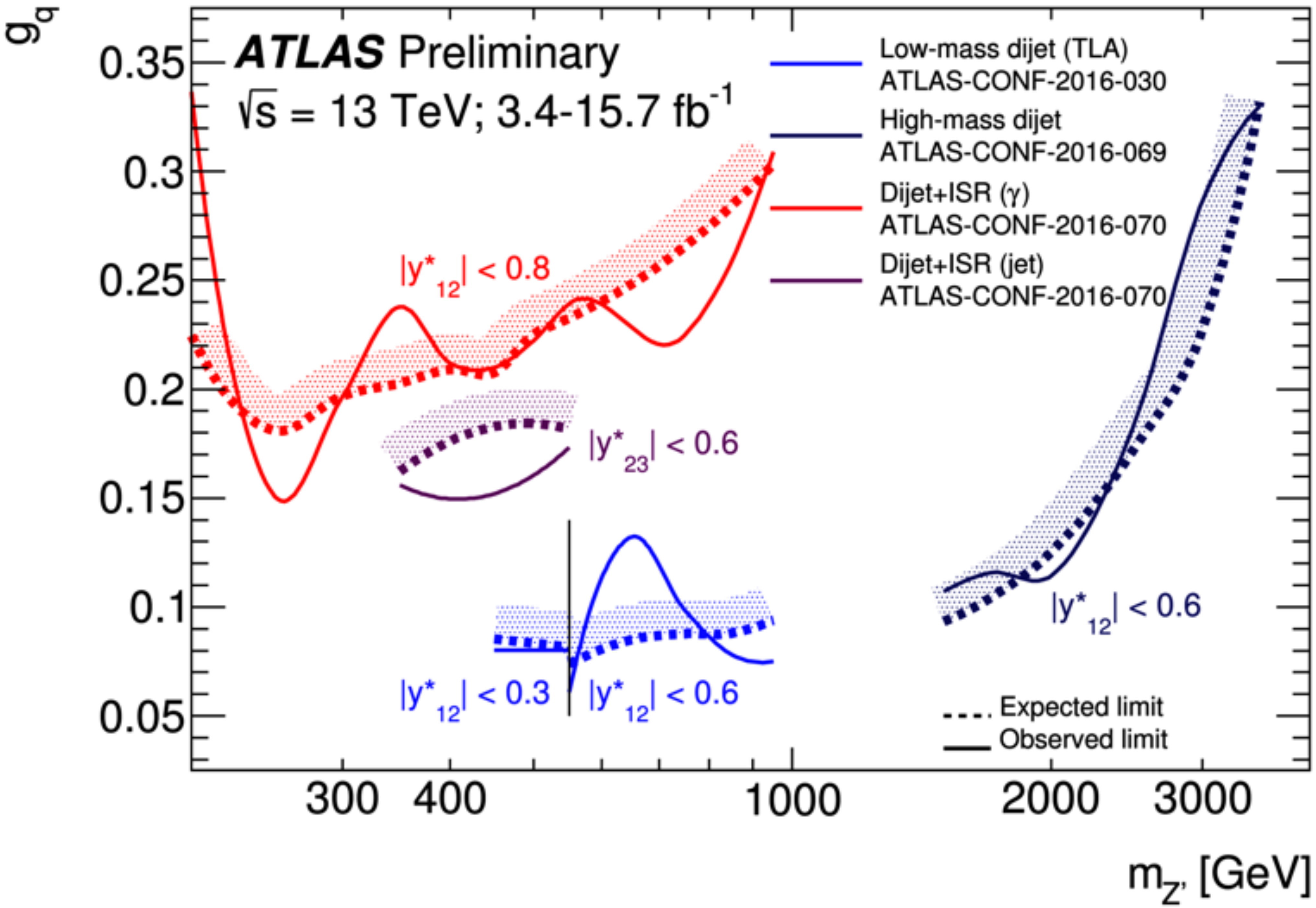




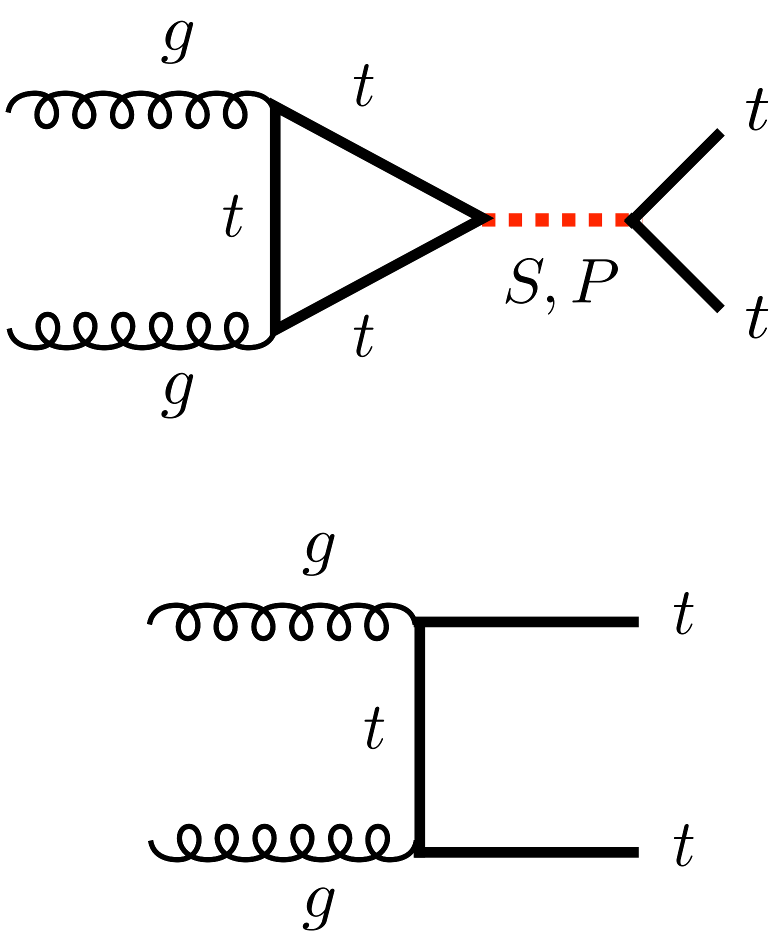
$E_{T,\,miss}$+$b\bar{b}$ searches not yet sensitive to spin-0 models with weak couplings

Di-jet limits

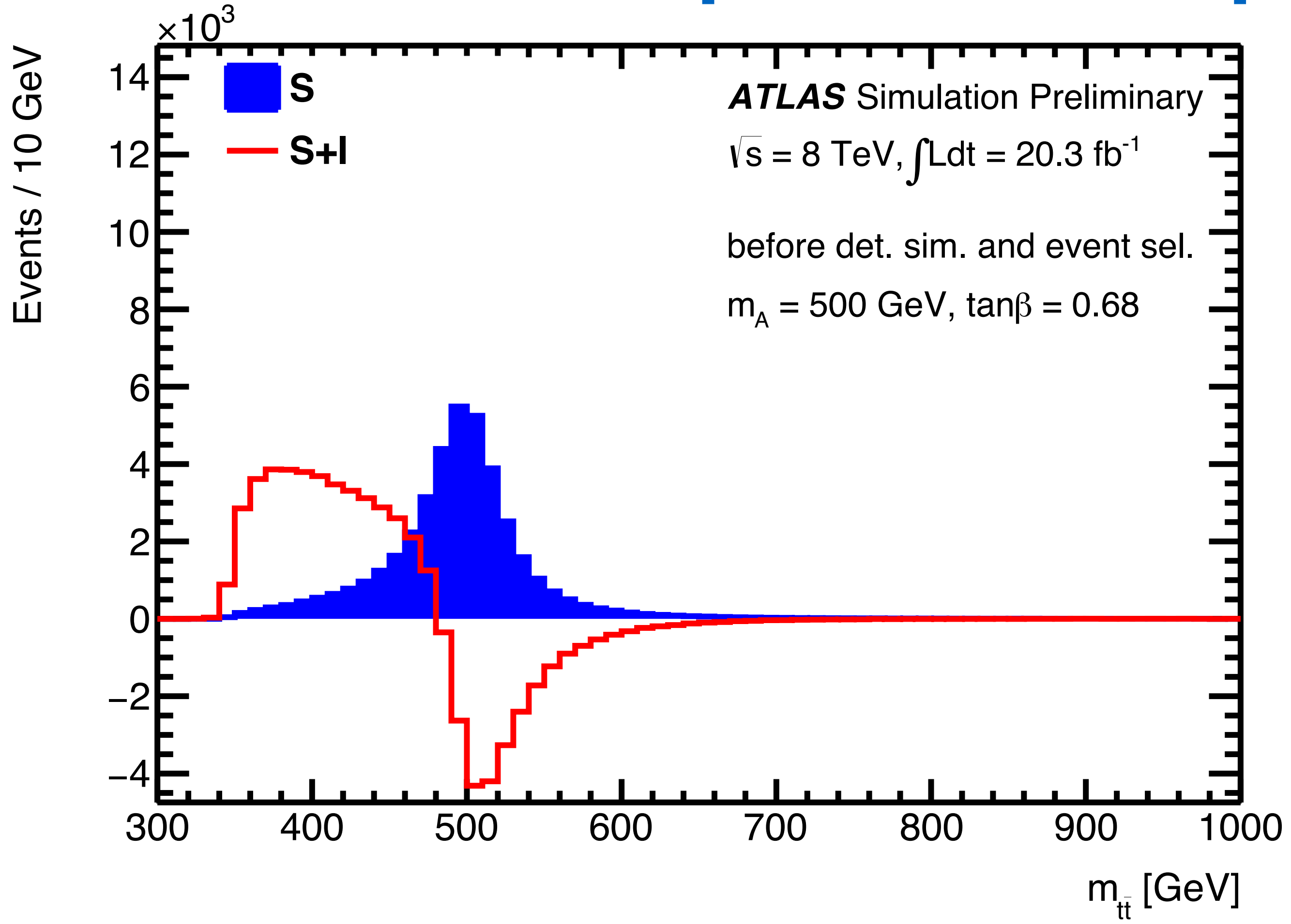
[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults]



Di-top limits



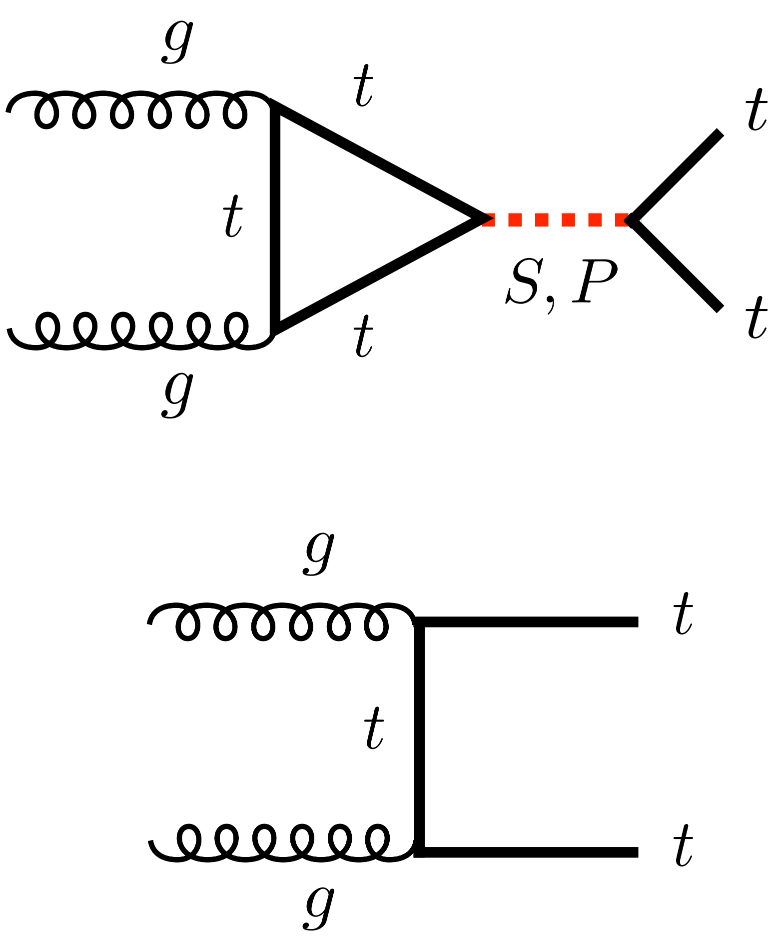
[ATLAS-CONF-2016-073]

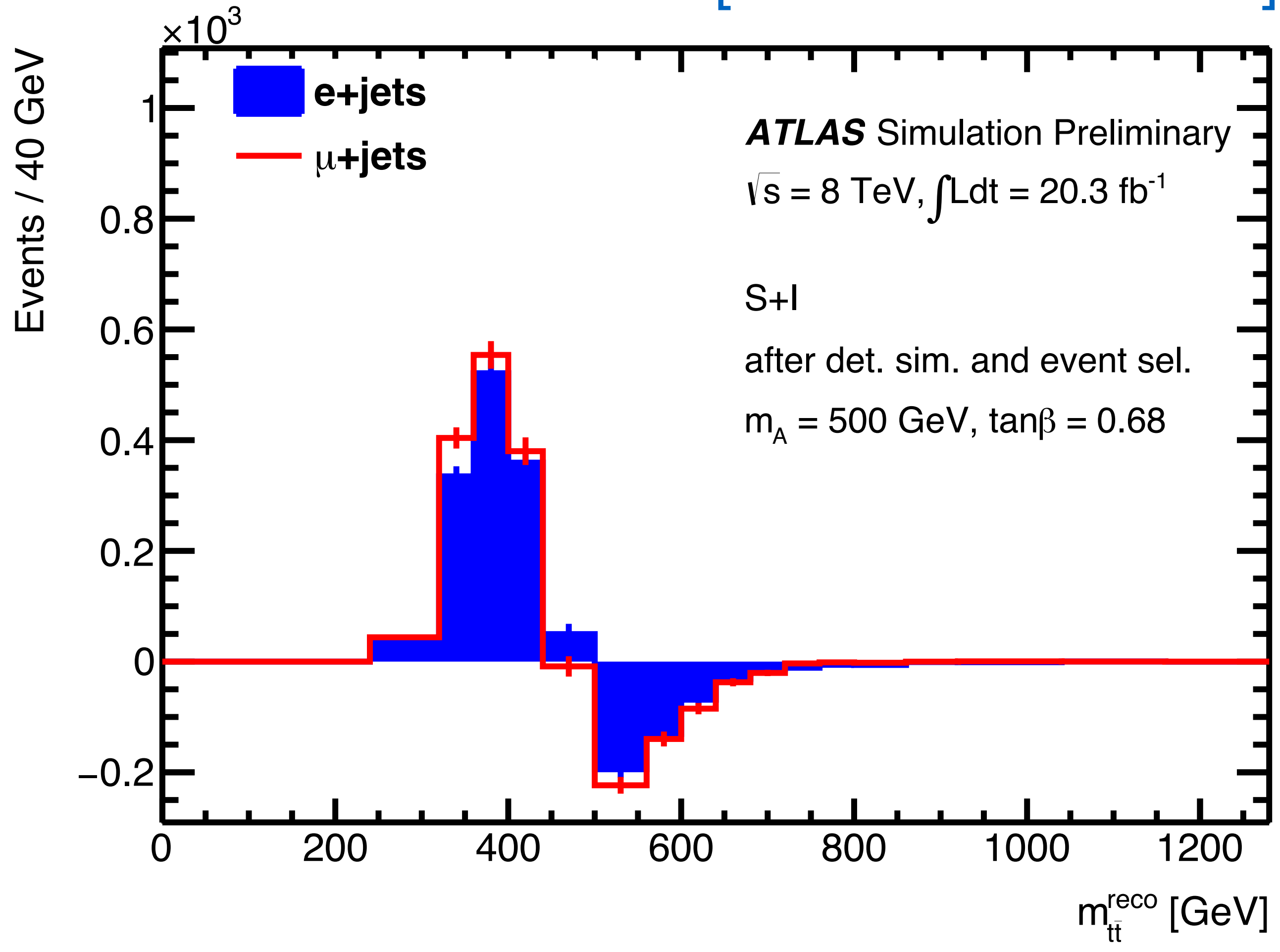


Spin-0 di-top resonances interfere maximal with SM background, which leads to a peak-dip structure in $m_{t\bar{t}}$ invariant mass spectrum

[Dicus et al., 9404359; Frederix & Maltoni, 0712.2355; Craig et al., 1504.04630; Bernreuther et al., 1511.05584; …]

Di-top limits



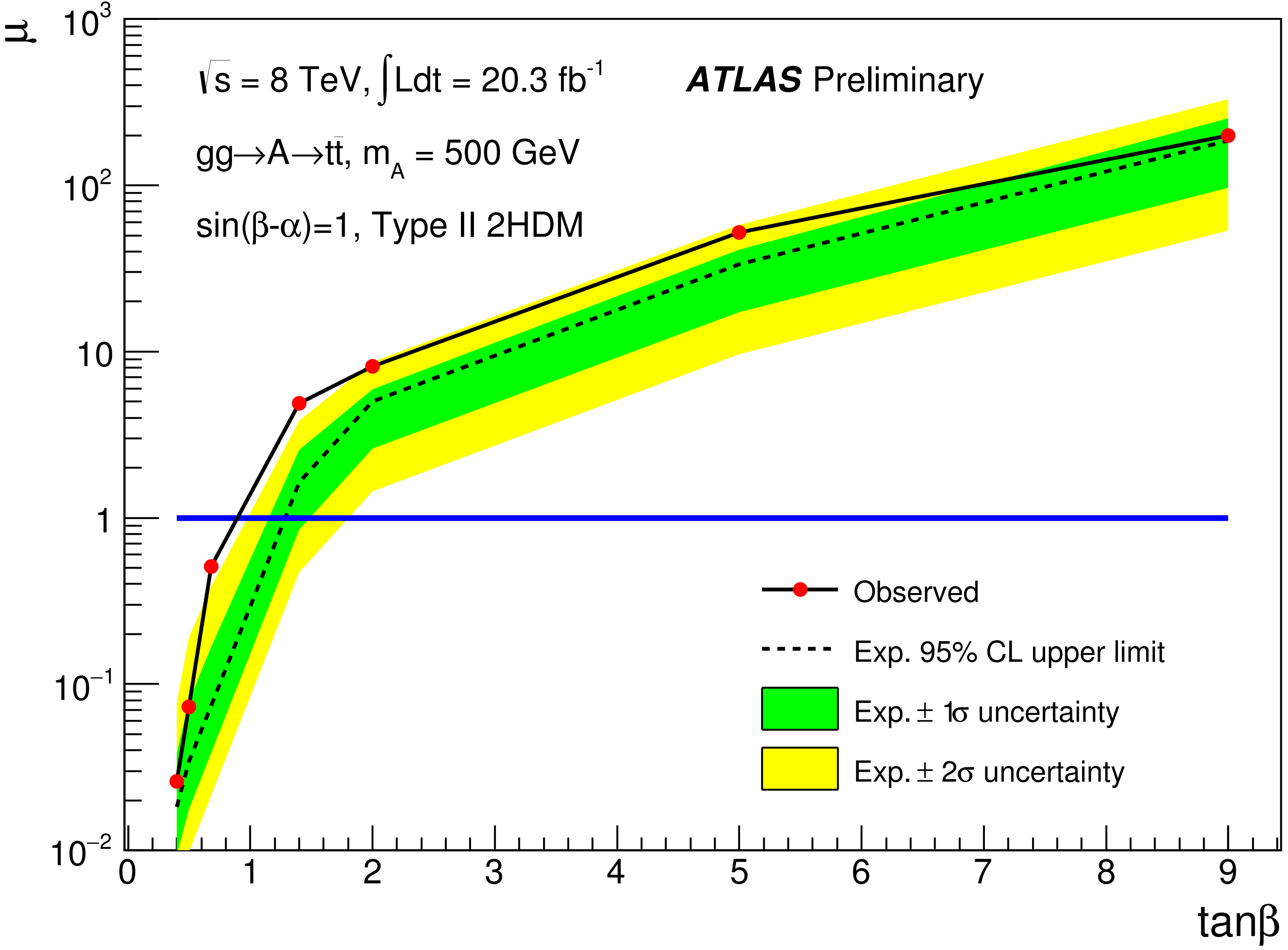


[ATLAS-CONF-2016-073]

Compared to parton-level spectra, reconstructed distributions with narrower resonances are more strongly distorted due detector resolution

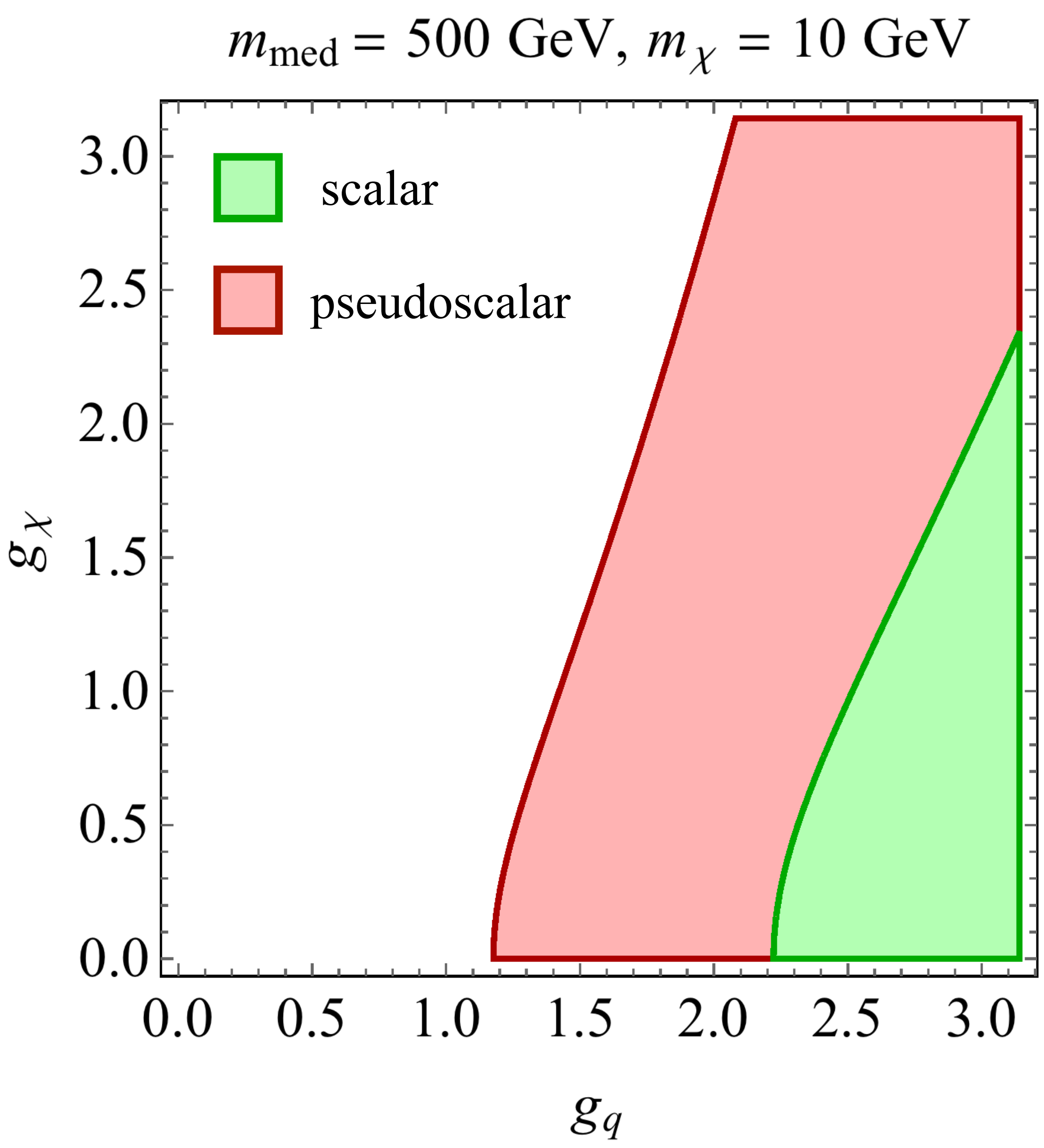
Di-top limits

[ATLAS-CONF-2016-073]



For a pseudoscalar (scalar) of 500 GeV, values of tanβ < 0.85 (tanβ < 0.45) are excluded at 95% CL in type II 2-Higgs doublet model (2HDM-II)

Di-top limits



Easy to recast ATLAS limits to spin-0 simplified model parameter space. For light DM & mediator masses close to $t\bar{t}$ threshold get sensitivity to couplings close to 2 (1) in scalar (pseudoscalar) case

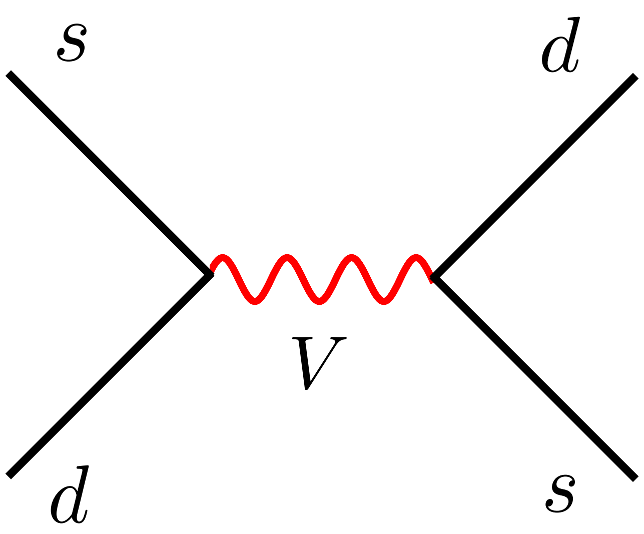
Flavour constraints

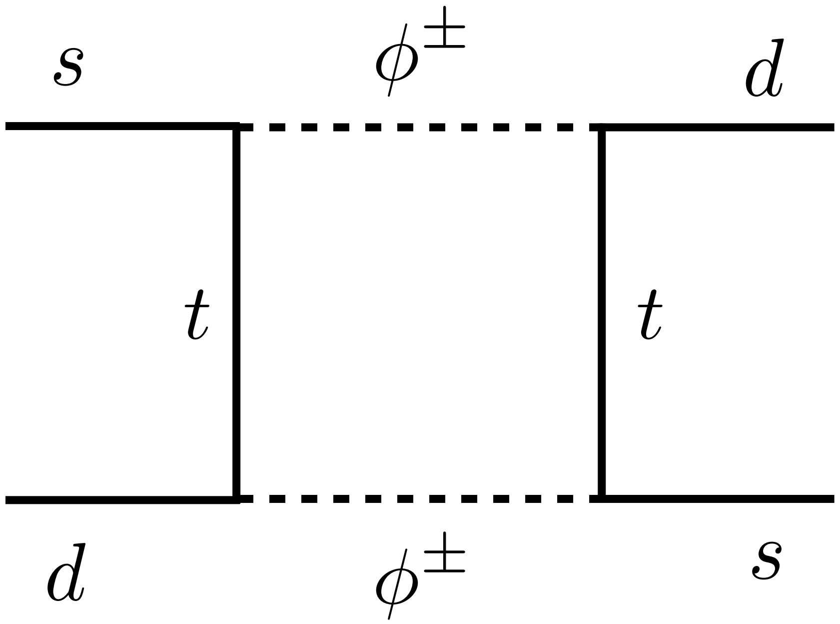
$$\mathcal{L} \supset V_\mu \sum_i \left(g_V + \Delta_V \delta_{i1}\right) \bar{d}_i \gamma^\mu d_i$$

going from weak to mass eigenstates,
assuming that quark mixing matrix V
arises from down-quark rotations alone

$$\mathcal{L} \supset V_\mu \Delta_V \sum_{i,j} L_{ij} \bar{d}_i \gamma^\mu P_L d_j \,, \qquad L = \begin{pmatrix} |V_{ud}|^2 & V_{ud}^* V_{us} & V_{ud}^* V_{ub} \\ V_{us}^* V_{ud} & |V_{us}|^2 & V_{us}^* V_{ub} \\ V_{ub}^* V_{ud} & V_{ub}^* V_{us} & |V_{ub}|^2 \end{pmatrix}$$

Flavour constraints





$$\mathcal{A}(s\bar{d} \to \{V, \mathrm{SM\ box}\} \to \bar{s}d) \sim \left\{ \frac{(V_{us}^* V_{us})^2 \Delta_V^2}{M_V^2}, \frac{\alpha_w^2 (V_{td}^* V_{ts})^2 y_t^2}{256 M_W^2} \right\}$$

Flavour constraints

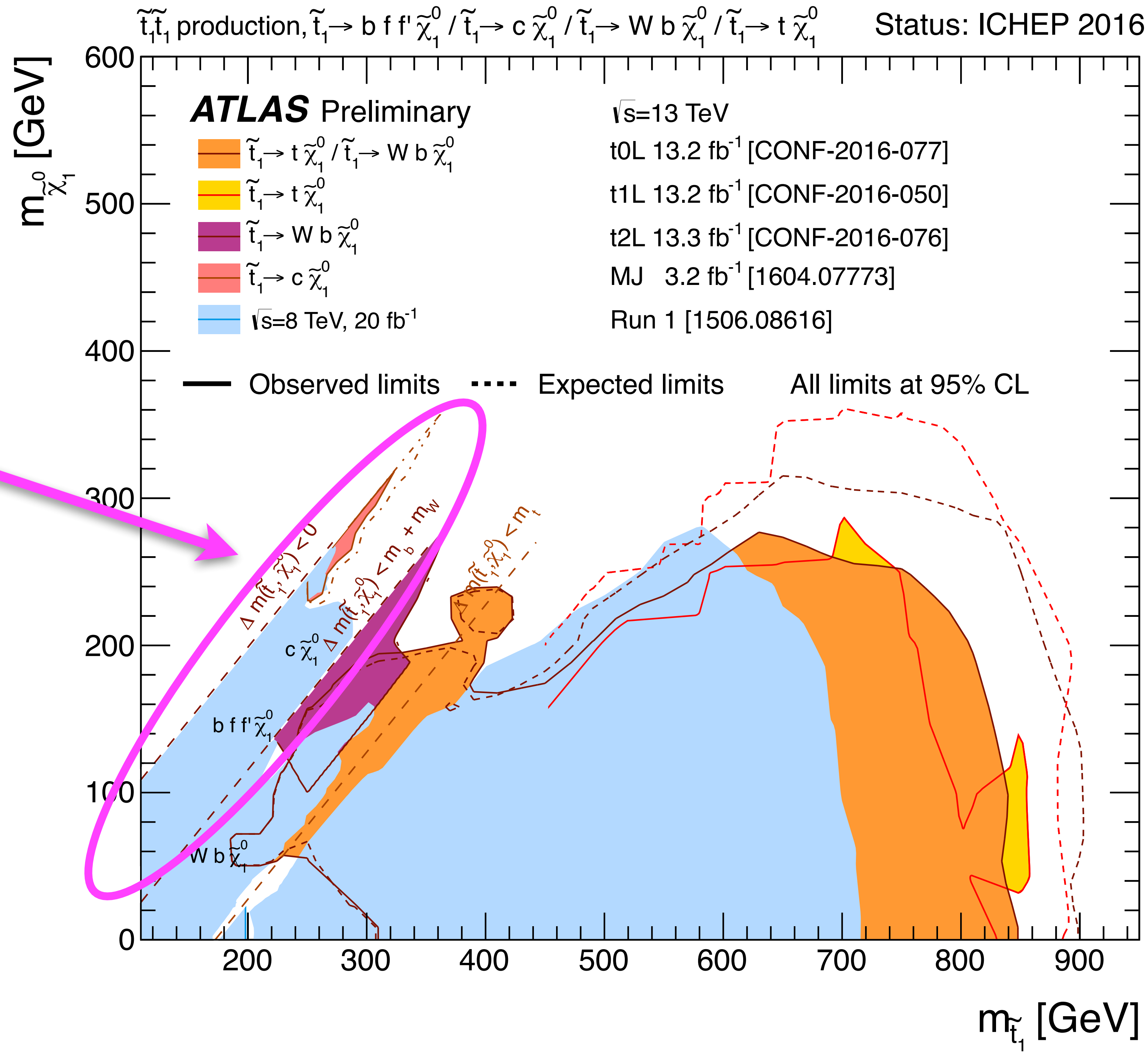
Requiring that new-physics contribution to kaon mixing is not larger than SM amplitude implies that

$$\left|\frac{\Delta_V M_W}{M_V}\right| \lesssim 3 \cdot 10^{-6} \quad \xrightarrow[\Delta_V = 1]{} \quad M_V \gtrsim 3 \cdot 10^{4}\,\mathrm{TeV}$$

To avoid flavour constraints, simplified DM models should be minimal flavour violating (MFV). In spin-1 case, this is achieved by taking $\Delta_V = 0$. In spin-0 case, simplest version of MFV is obtained, if SM couplings are universal & of Yukawa type — but also couplings a la 2HDM-II possible

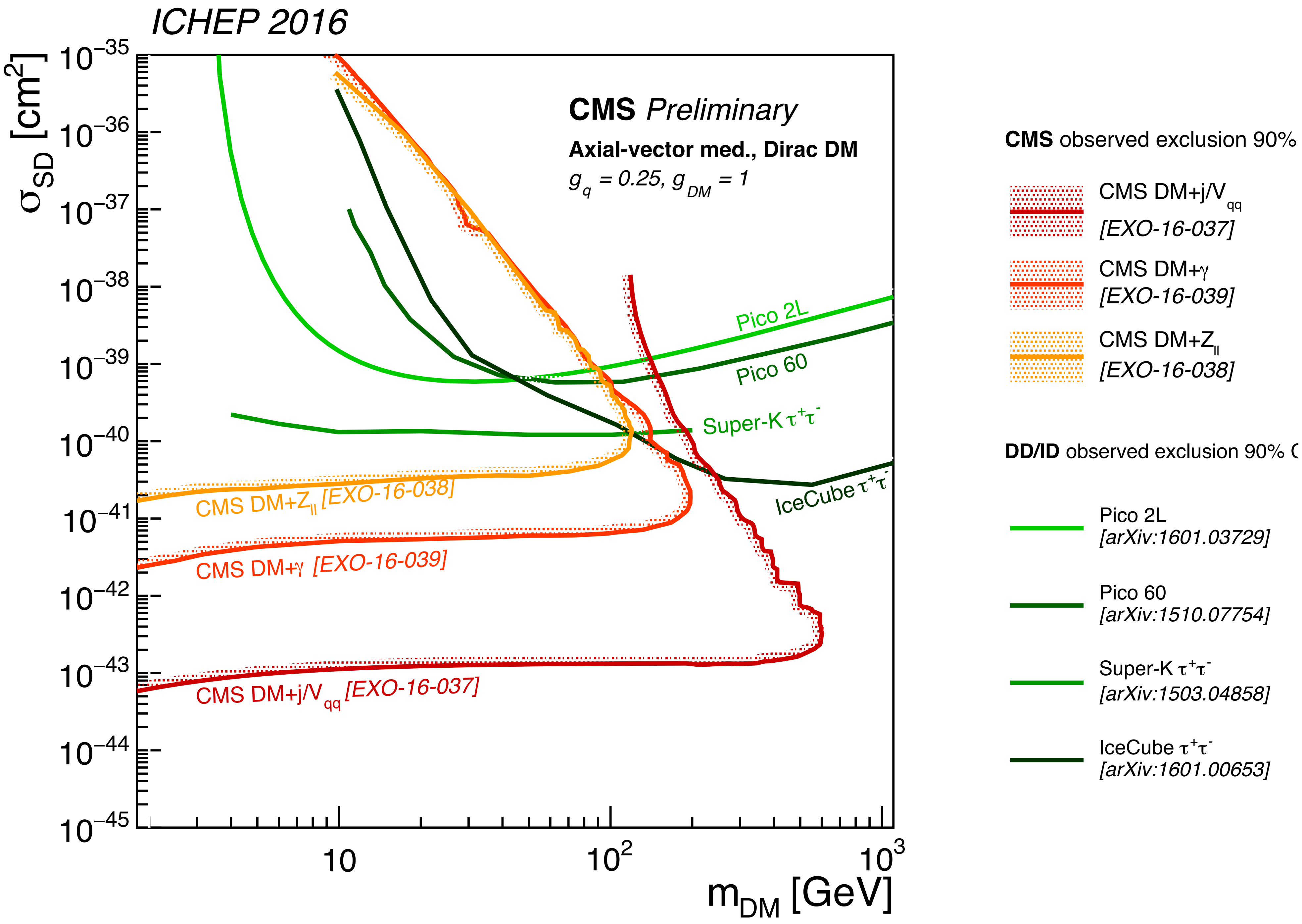
Stop searches

parameter region
constrained by
$E_{T,\text{miss}}$+j searches



[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults]

LHC bounds on SD χ-N interactions



[https://cds.cern.ch/record/2208044/files/DP2016_057.pdf]

From DM EFT to DD EFT

$$\bar{\chi}\chi\bar{q}q \;\rightarrow\; \boxed{\mathcal{O}_1}$$

$$\bar{\chi}\gamma_5\chi\bar{q}\gamma_5 q \;\rightarrow\; \mathcal{O}_6$$

$$\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \;\rightarrow\; \boxed{\mathcal{O}_1}$$

$$\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \;\rightarrow\; \boxed{\mathcal{O}_4}$$

$$\bar{\chi}\chi\bar{q}\gamma_5 q \;\rightarrow\; \mathcal{O}_{10}$$

$$\bar{\chi}\gamma_5\chi\bar{q}q \;\rightarrow\; \mathcal{O}_{11}$$

$$\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu\gamma_5 q \;\rightarrow\; -\mathcal{O}_7 + \frac{m_N}{m_\chi}\mathcal{O}_9$$

$$\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu q \;\rightarrow\; \mathcal{O}_8 + \mathcal{O}_9$$

🟥 spin-independent (SI)

🟩 spin-dependent (SD)

[Fitzpatrick et al., 1203.3542, 1211.2818; Anand et al., 1308.2288, 1405.6690; …]

From DM EFT to DD EFT

$$\begin{tikzcd}
\bar{\chi}\chi\bar{q}q \arrow[r] & \boxed{\mathcal{O}_1} \arrow[r] & M \\
\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \arrow[r] & \boxed{\mathcal{O}_1} \arrow[ur] &
\end{tikzcd}$$

SI nuclear response function

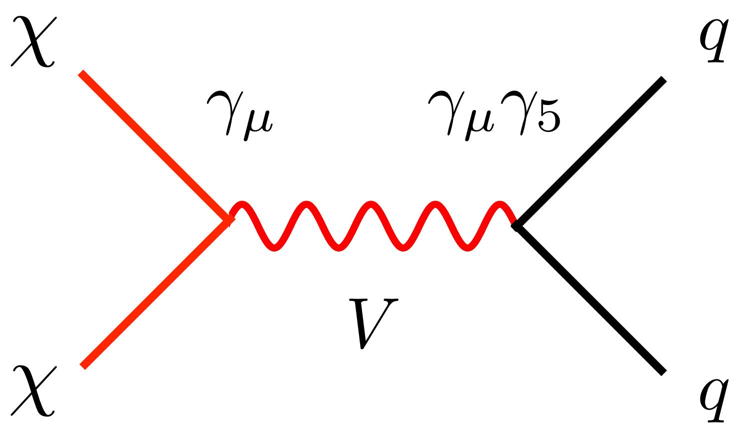
$$\begin{tikzcd}
\bar{\chi}\gamma_5\chi\bar{q}\gamma_5 q \arrow[r] & \mathcal{O}_6 \arrow[r] & \Sigma'' \\
\bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \arrow[r] & \boxed{\mathcal{O}_4} \arrow[ur] \arrow[r] & \Sigma'
\end{tikzcd}$$

SD longitudinal nuclear response function

SD transversal nuclear response function

[Fitzpatrick et al., 1203.3542, 1211.2818; Anand et al., 1308.2288, 1405.6690; …]

From suppressed to unsuppressed DD



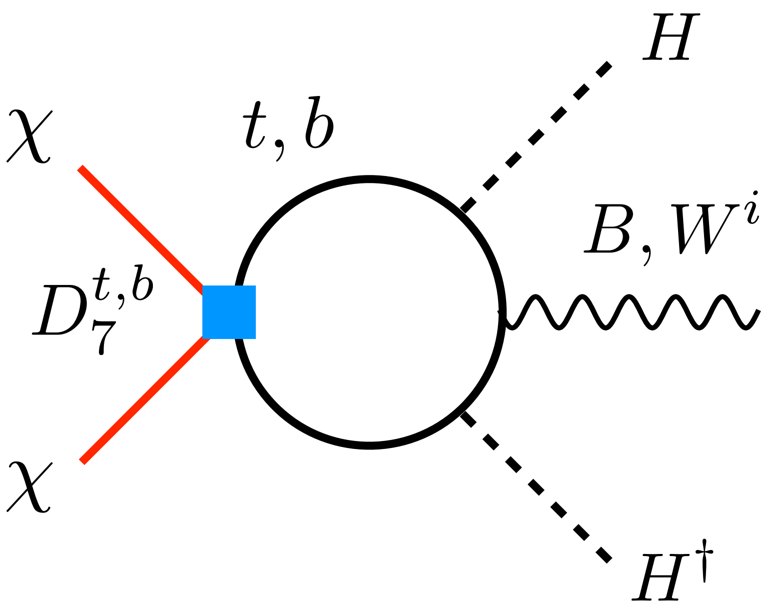
$$= C_7^q D_7^q$$

$$C_7^q = -\frac{g_\chi g_q}{M_V^2}\,, \qquad D_7^q = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma_5 q$$

operator leads to SD χ-N interactions
that are both v^2 & q^2 suppressed

From suppressed to unsuppressed DD

[Crivellin et al. 1402.1173]

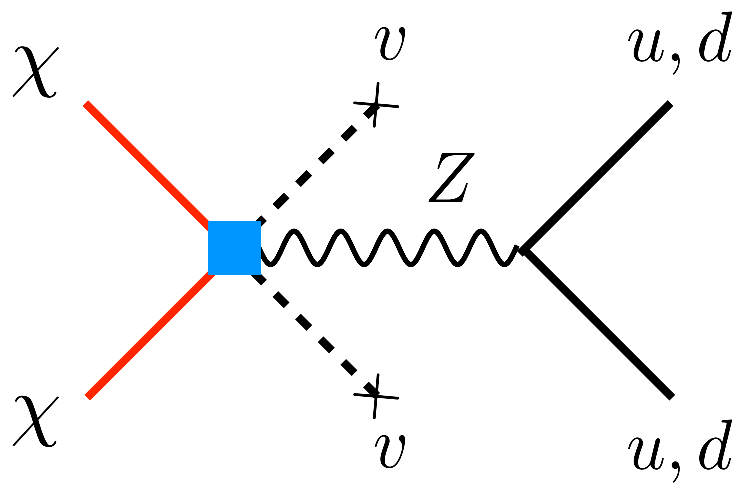


$= C_H D_H$

$$C_H = - \sum_{q=t,b} \frac{3 y_q^2 T_3^q C_7^q}{2\pi^2} \ln\left(\frac{v}{M_V}\right) , \qquad D_H = \bar{\chi} \gamma^\mu \chi \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)$$

From suppressed to unsuppressed DD

[Crivellin et al. 1402.1173]



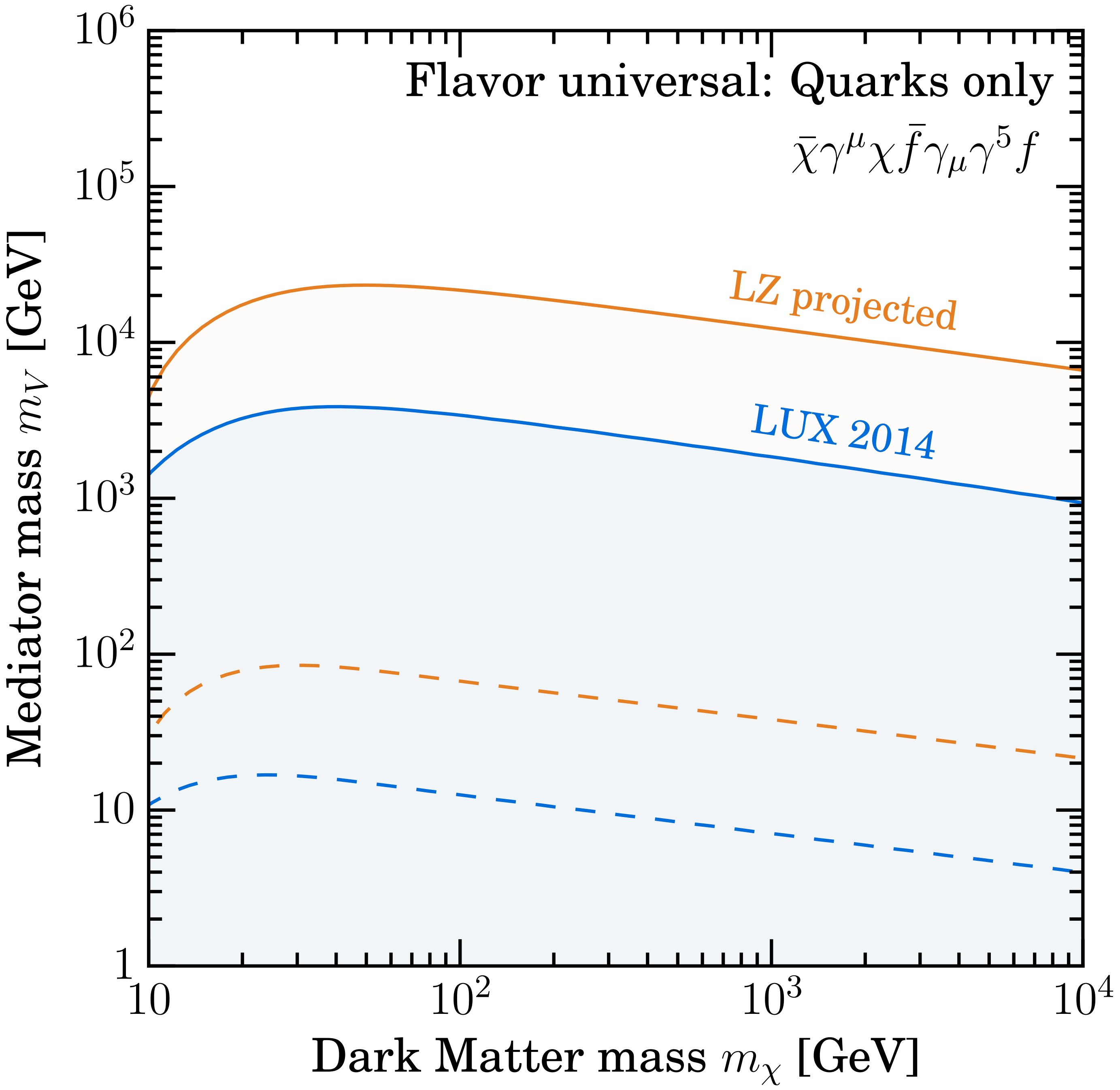
$$= C_5^{u,d} D_5^{u,d}$$

$$C_5^q = \frac{g_\chi}{M_V^2} \left(T_3^q - 2Q_q s_w^2\right) \sum_{p=t,b} \frac{3y_p^2 g_p T_3^p}{2\pi^2} \ln\left(\frac{v}{M_V}\right) , \qquad D_5^q = \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

operator leads to SI χ-N interactions

From suppressed to unsuppressed DD

[D'Eramo et al., 1605.04917]

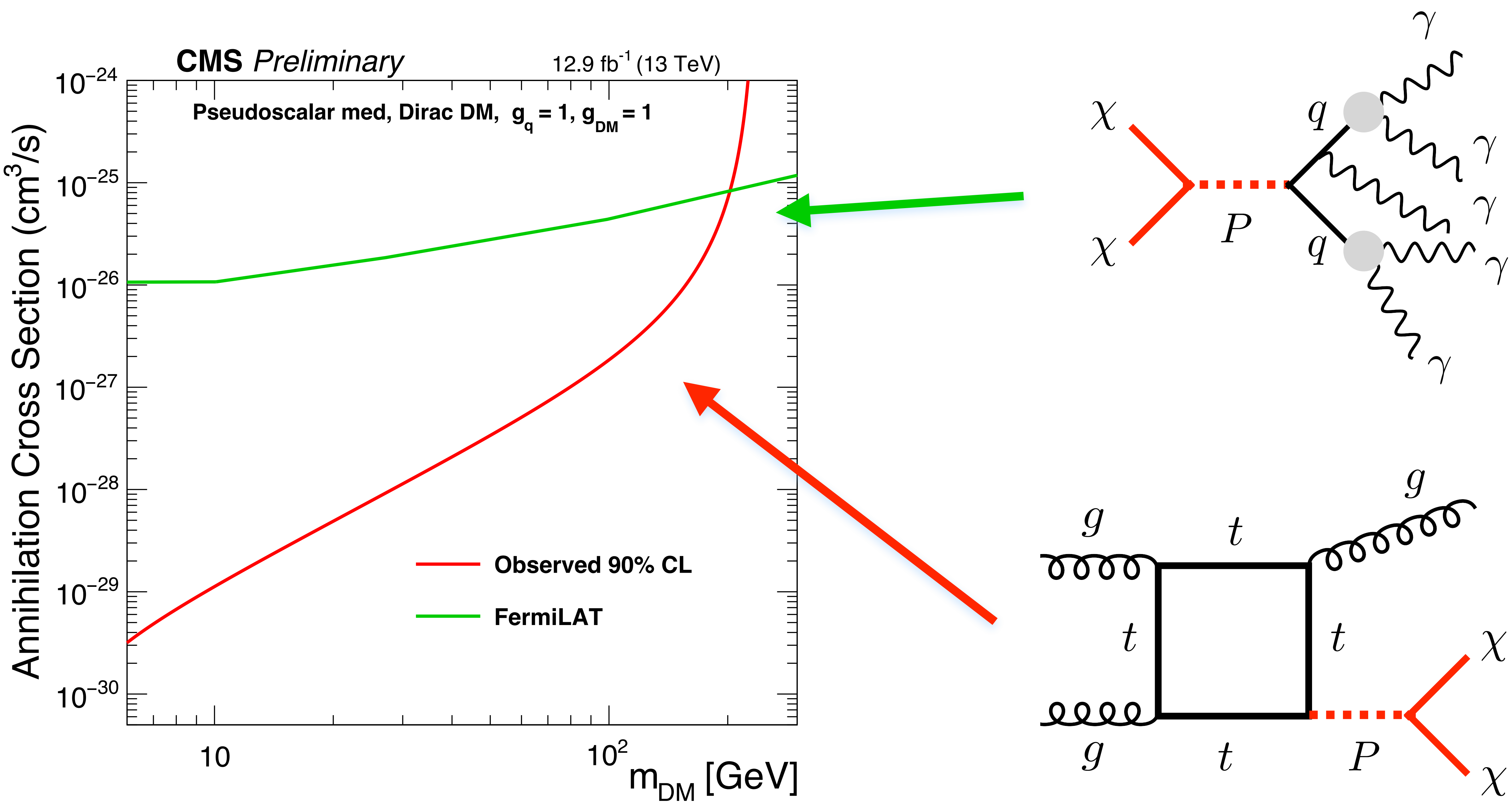


— loop level

- - - tree level

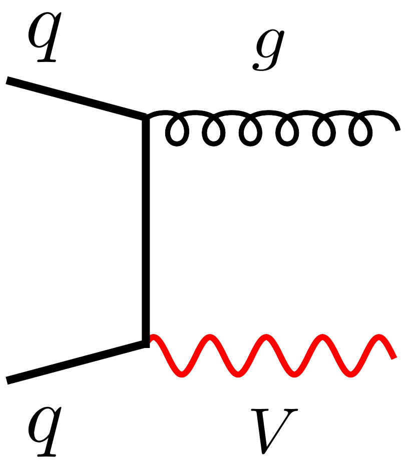
Loop suppression by far overcompensated by coherence enhancement of SI χ-N interactions

LHC bounds DM annihilation

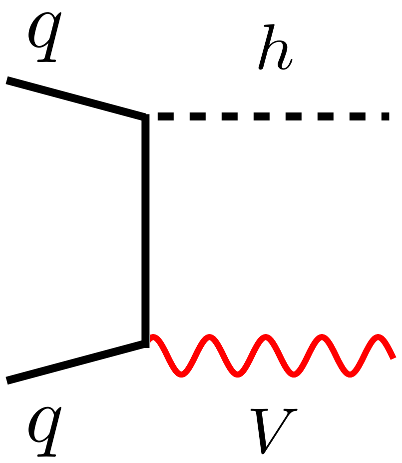


[CMS-PAS-EXO-16-037]

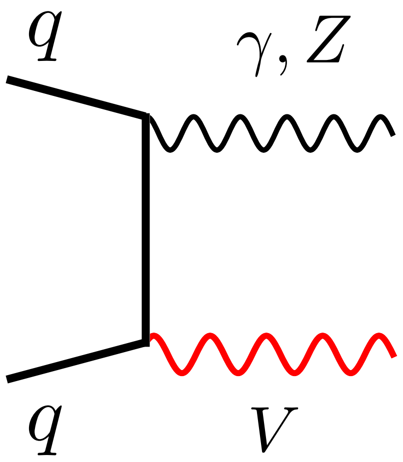
Spin-1 mono-X amplitudes



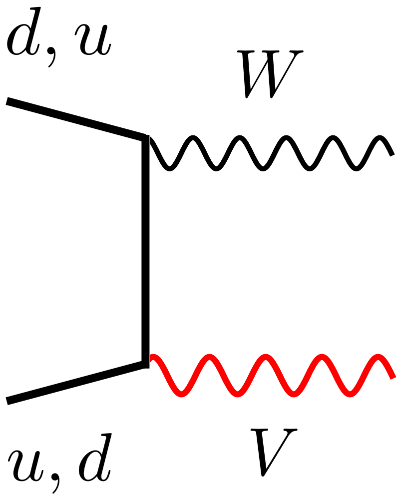
$$\sim s^0$$



$$\sim y_q\, g_q^A\, \frac{s^{1/2}}{M_V}$$

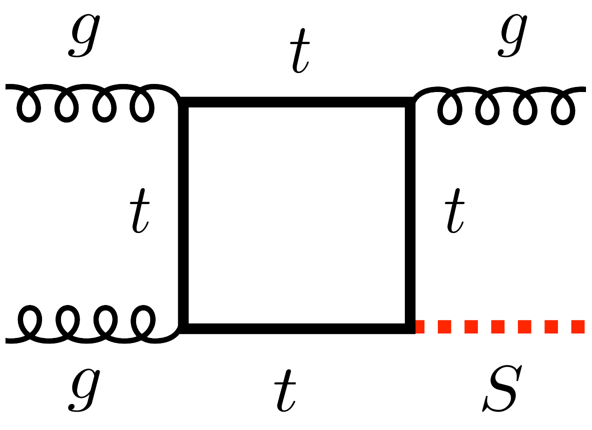


$$\sim s^0,\ \ y_q\, g_q^A\, \frac{s^{1/2}}{M_V}$$

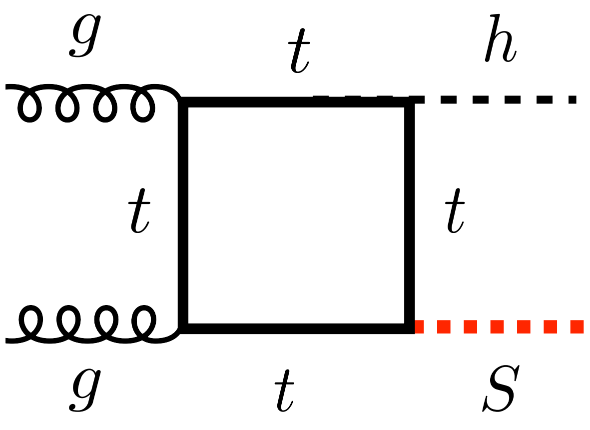


$$\sim \left(g_u^L - g_d^L\right)\, \frac{s}{M_W M_V}$$

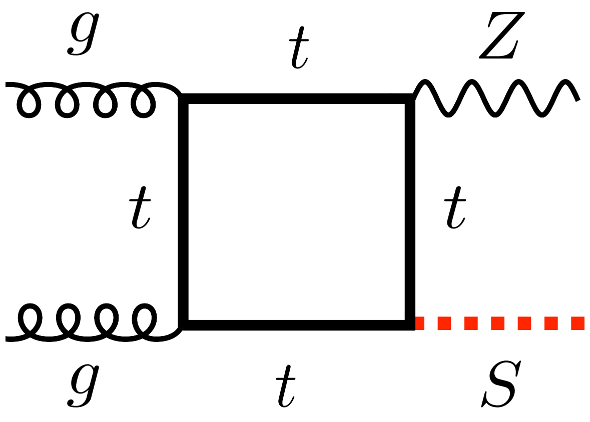
Spin-0 mono-X amplitudes



$\sim s^0$



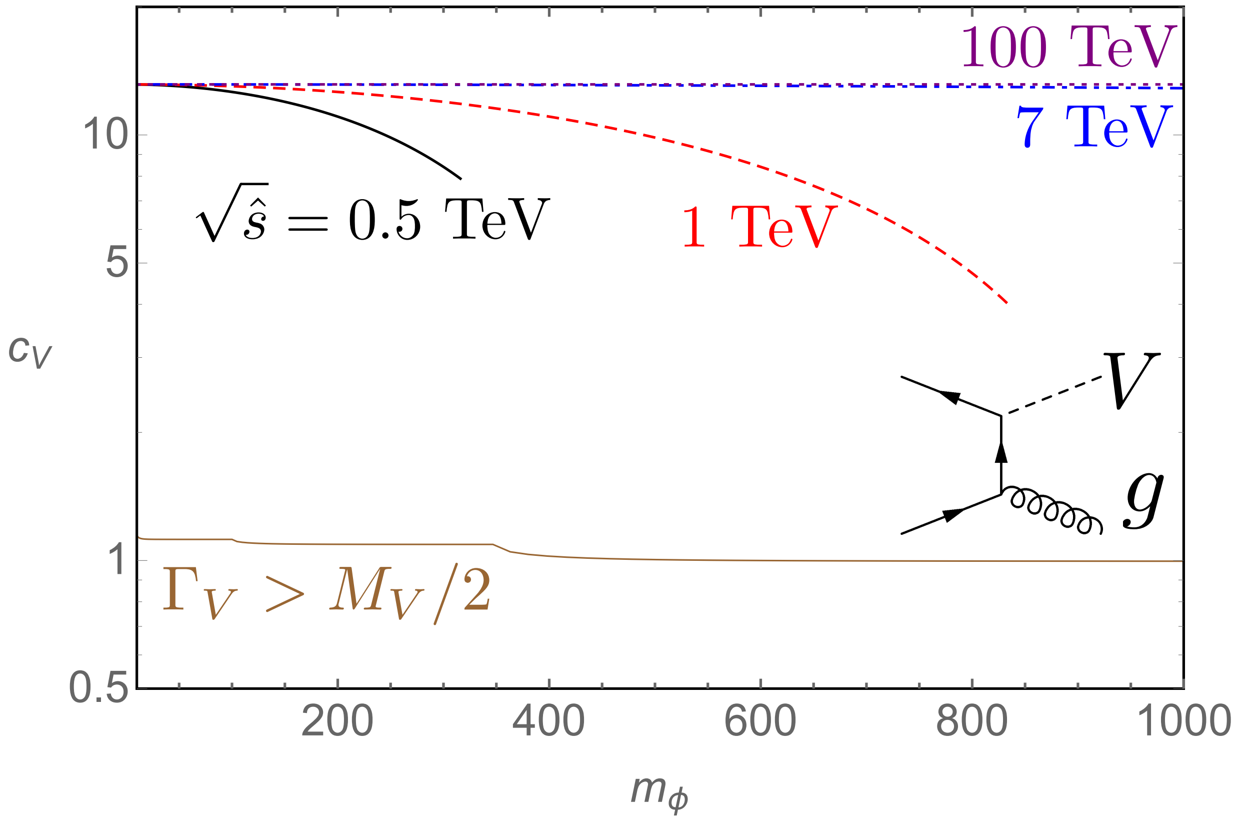
$\sim s^0$



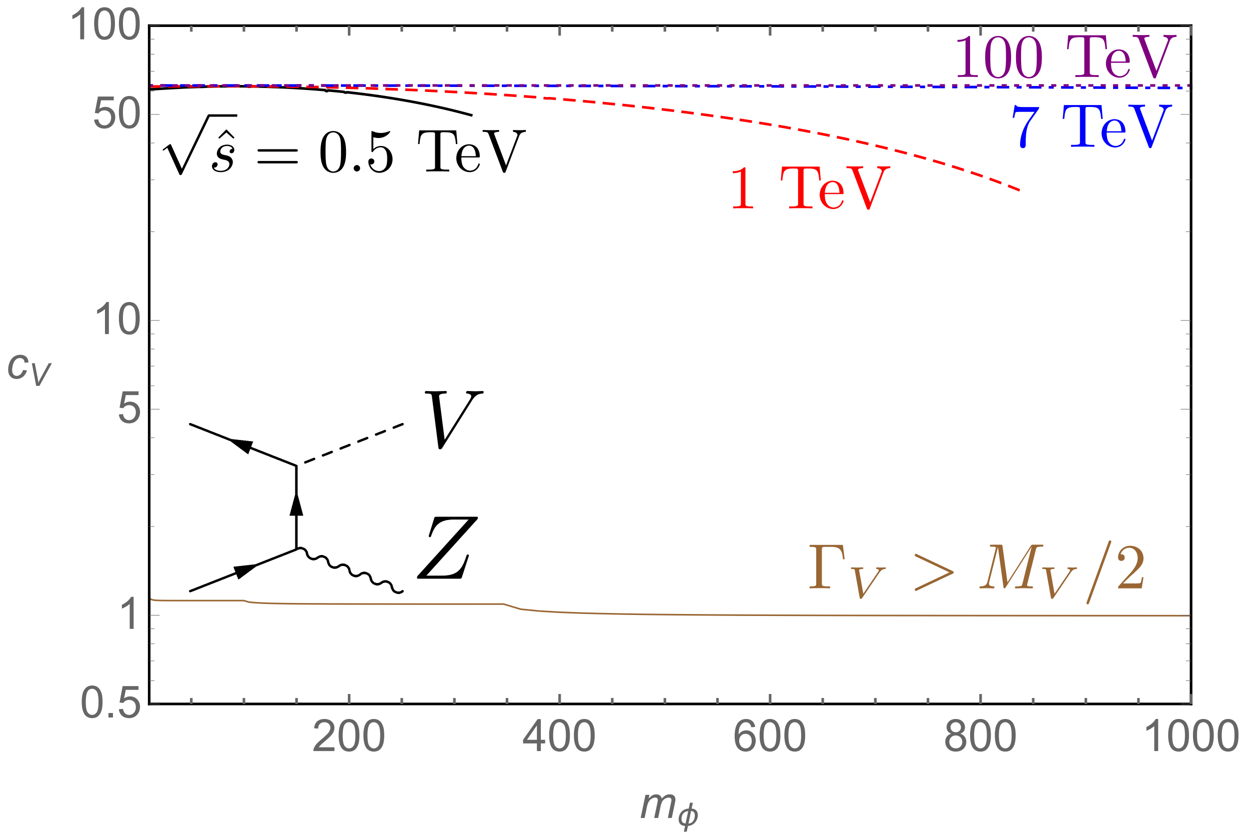
$$\sim \frac{\alpha_s}{4\pi}\, y_t^2\, g_t^S\, \ln^2\left(\frac{s}{m_t^2}\right)$$

1-loop gg→Z+S amplitude diverges for $s \to \infty$. Naively, numerical effect small unless coupling g_t^S large & centre-of-mass energy $s^{1/2} \gg 13$ TeV

Unitarity: $E_{T,\mathrm{miss}}$+jet, Z, h searches



[Englert et al., 1604.07975]

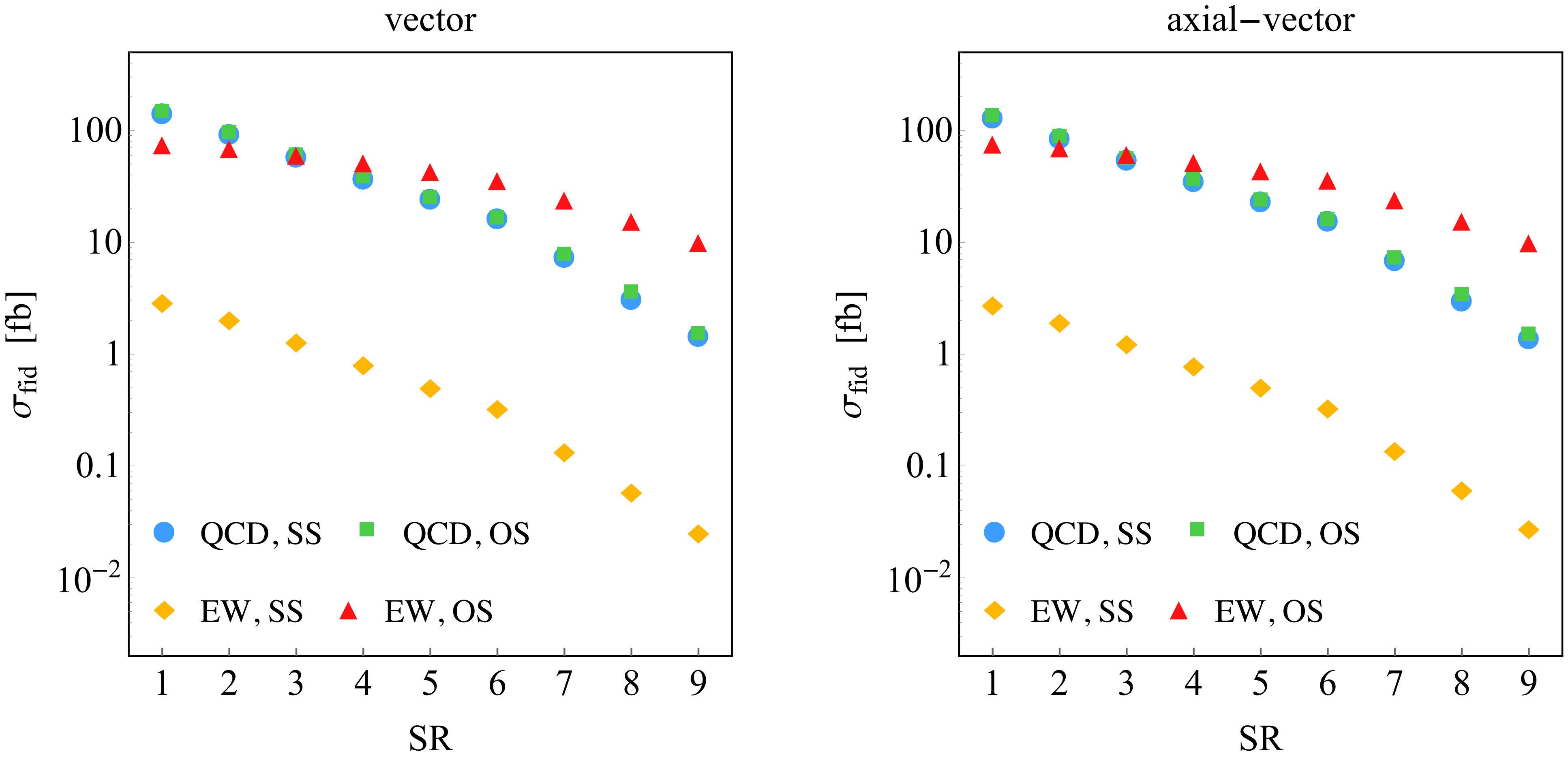


$E_{T,\mathrm{miss}}$+jet, Z, h amplitudes in spin-1 models have no problem with unitarity at LHC energies & beyond unless DM-mediator couplings are non-perturbative†

†For such couplings, one always has $\Gamma_V > M_V$ & simple particle description breaks down

Mono-W problem in mono-jets

[UH et al., 1603.01267]



$M_{Z'} = 1\,\text{TeV}$

$m_\chi = 10\,\text{GeV}$

$g_{\rm DM}^{V,A} = 1$

$|g_{\rm u,d}^{V,A}| = 0.25$

Unitarity problem persists after parton shower, hadronisation corrections & detector effects. As a result, EW contribution gives rise to majority of events in high-$E_{T,\text{miss}}$ signal regions (SRs) of mono-jet searches† in OS case

†Plots show SRs as defined in ATLAS, 1502.01518

Mono-W problem: solution I

Since s-behaviour of ud→W+V amplitude proportional to $g_u^L - g_d^L$ tree-level unitarity recovered for $g_Q = g_d^L = g_u^L$. Latter requirement automatically fulfilled, if quark couplings to V are written in a way that preserves EW symmetry:

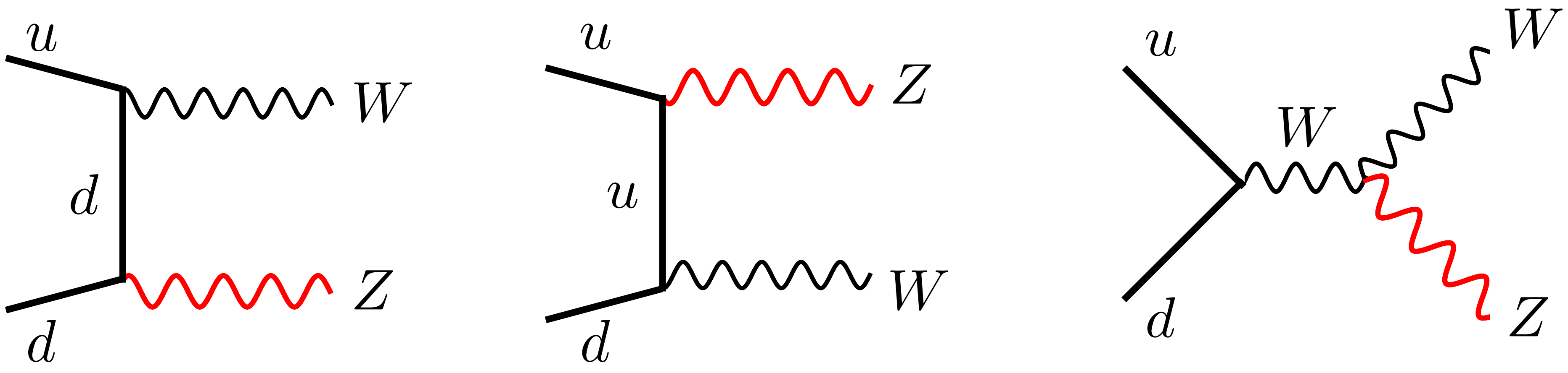
$$\mathcal{L}_{Vq\bar{q}} = -\sum_{u,d} V_\mu \left(g_Q \bar{Q}_L \gamma^\mu Q_L + g_u \bar{u}_R \gamma^\mu u_R + g_d \bar{d}_R \gamma^\mu d_R \right)$$

$$Q_L = (u_L, d_L)^T$$

[UH et al., 1603.01267]

Mono-W problem: solution 2

Second solution obtained by thinking about how unitarity of ud→W+Z amplitude is realised within SM:



$$|\mathcal{M}|^2 = \frac{3g^4 c_w^2 |V_{ud}|^2}{32 M_W^2} \left(d_1 + d_2 - 2d_3\right) s^2 \sin^2\theta$$

Diagram with WWZ coupling cancels divergent s-behaviour of graphs with t-channel quark exchange. This is a result of gauge invariance

Mono-W problem: solution 2

SM result implies that even if

$$\Delta g = g_u^L - g_d^L \neq 0$$

unitarity violation avoided by adding following gauge-boson couplings to Lagrangian:

$$\Delta\mathcal{L} = i\Delta g \Big\{ \left(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+\right) W^{\mu -} V^\nu - \left(\partial_\mu W_\nu^- - \partial_\nu W_\mu^-\right) W^{\mu +} V^\nu$$

$$+ \frac{1}{2} \left(\partial_\mu V_\nu - \partial_\nu V_\mu\right) \left(W^{\mu +} W^{\nu -} - W^{\mu -} W^{\nu +}\right) \Big\}$$

[UH et al., 1603.01267]

Mono-W problem: solution 2

In fact, if V arises through mixing with a new vector field X, that is

$$X_\mu = N_{31}\, A_\mu + N_{32}\, Z_\mu + N_{33}\, V_\mu$$

& X has quark couplings of form

$$\mathcal{L}_{Xq\bar{X}} = -\sum_q X_\mu \bar{q} \left(f_q^V \gamma^\mu + f_q^A \gamma^\mu \gamma_5 \right) q \,, \qquad f_u^L - f_d^L = 0$$

then relevant V couplings automatically obey

$$\Delta g = g_u^L - g_d^L = g N_{23} \,, \qquad g_{WWV} = g N_{23}$$

& modified theory unitary

[UH et al., 1603.01267]

Mono-W problem: solution 3

Quark-couplings of V can also be realised via dimension-6 operators:

$$\mathcal{L}_{VQH} = -\sum_{u,d} V_\mu \left\{ \frac{1}{\Lambda_u^2} (\bar{Q}_L \tilde{H}) \gamma^\mu (\tilde{H}^\dagger Q_L) + \frac{1}{\Lambda_d^2} (\bar{Q}_L H) \gamma^\mu (H^\dagger Q_L) \right\}$$

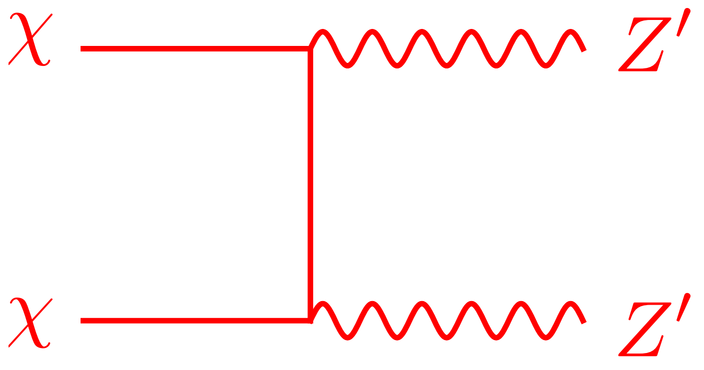
In such a case $SU(2)_L$ breaking is however not O(1), but given by†

$$\Delta g = g_u^L - g_d^L = \frac{v^2}{\Lambda^2}$$

In this model unitary at 13 TeV LHC requires either $|g_u^{V,A}| = |g_d^{V,A}| < 0.05$ or if $|g_u^{V,A}| = |g_d^{V,A}| = 0.25$ & $M_V = 1$ TeV is chosen, one has to employ truncation with $s^{1/2} \lesssim 6$ TeV. Both options reduce mono-W sensitivity

[UH et al., 1603.01267]

Unitarity violation: $\chi\bar{\chi} \to Z'Z'$



$$\sim g_\chi^A \frac{m_\chi}{M_{Z'}^2} s^{1/2}$$

$$s^{1/2} < \frac{\pi M_{Z'}^2}{(g_\chi^A)^2 m_\chi} \simeq \begin{cases} 5\,\mathrm{TeV}\,, & g_\chi^A = 0.25, M_{Z'} = 1\,\mathrm{TeV}\,, m_\chi = 10\,\mathrm{GeV} \\ 0.5\,\mathrm{TeV}\,, & g_\chi^A = 0.25, M_{Z'} = 1\,\mathrm{TeV}\,, m_\chi = 100\,\mathrm{GeV} \end{cases}$$

For m_χ = 10 (100) GeV, new physics must appear before 5 (0.5) TeV to restore unitarity in DM annihilation to Z′ pairs

[Kahlhoefer et al.,1510.02110]

Dark Higgs sector

Simplest way to restore unitarity is to generate mediator mass by Higgsing U(1)′ symmetry. Assuming that DM is Majorana particle (to avoid strong DD constraints due to vector coupling), one can write

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\,\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}\,g^{A}_{\rm DM}\,Z'^{\mu}\,\bar{\psi}\gamma_{\mu}\gamma_{5}\psi - \frac{1}{2}\,y_{\rm DM}\,\bar{\psi}\left(P_L S + P_R S^{*}\right)\psi$$

$$\mathcal{L}_S = \{(\partial^{\mu} + i g_S Z'^{\mu})S\}^{\dagger}\,\{(\partial_{\mu} + i g_S Z_{'\mu})S\} + \mu_s^2 S^{\dagger}S - \lambda_s\left(S^{\dagger}S\right)^2$$

Once S acquires vacuum expectation value (VEV) w, ψ & Z′ get massive

$$m_{\rm DM} = \frac{y_{\rm DM}\,w}{\sqrt{2}}\,, \qquad M_{Z'} \simeq 2 g^{A}_{\rm DM}\,w$$

[Kahlhoefer et al.,1510.02110]

Z′ interactions

Interactions between SM states & Z′ gauge boson can be written as

$$\mathcal{L}'_{\mathrm{SM}} = \left\{ (D^\mu H)^\dagger (-i g' q_H Z'_\mu H) + \mathrm{h.c.} \right\} + g'^2 q_H^2 Z'^\mu Z'_\mu H^\dagger H$$

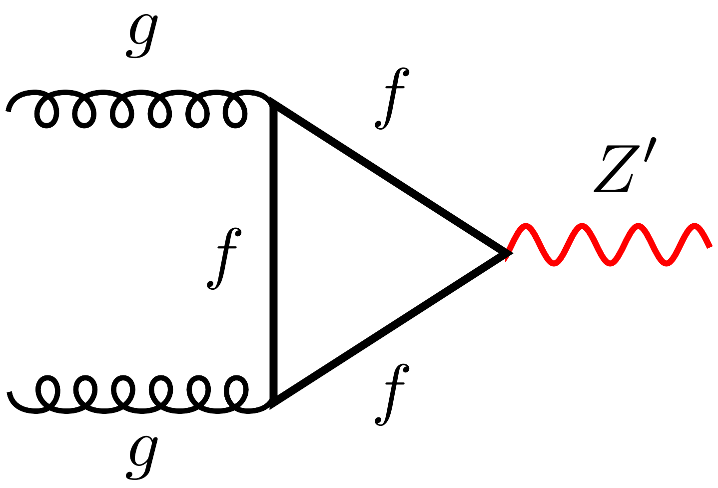
$$- \sum_{f=q,\ell,\nu} g' \, Z'^\mu \left(\bar{q}_{f_L} \bar{f}_L \gamma_\mu f_L + \bar{q}_{f_R} \bar{f}_R \gamma_\mu f_R \right)$$

Gauge invariance of SM Yukawa couplings requires that charges q are generation universal & must satisfy consistency conditions (CCs):

$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

[Kahlhoefer et al., 1510.02110]

Implications of CCs



$$\sim 3\left(2q_{q_L} - q_{u_R} - q_{d_R}\right)$$

For arbitrary charge assignments consistent with CCs, theory will have anomalies, but new fermions F do not need to be coloured since ggZ′ anomaly vanishes automatically. This is a nice feature because masses of new fermions bounded by unitarity:

$$m_F < \sqrt{\frac{\pi}{2}} \frac{M_{Z'}}{g_F^A}$$

[Kahlhoefer et al., 1510.02110]

Implications of CCs

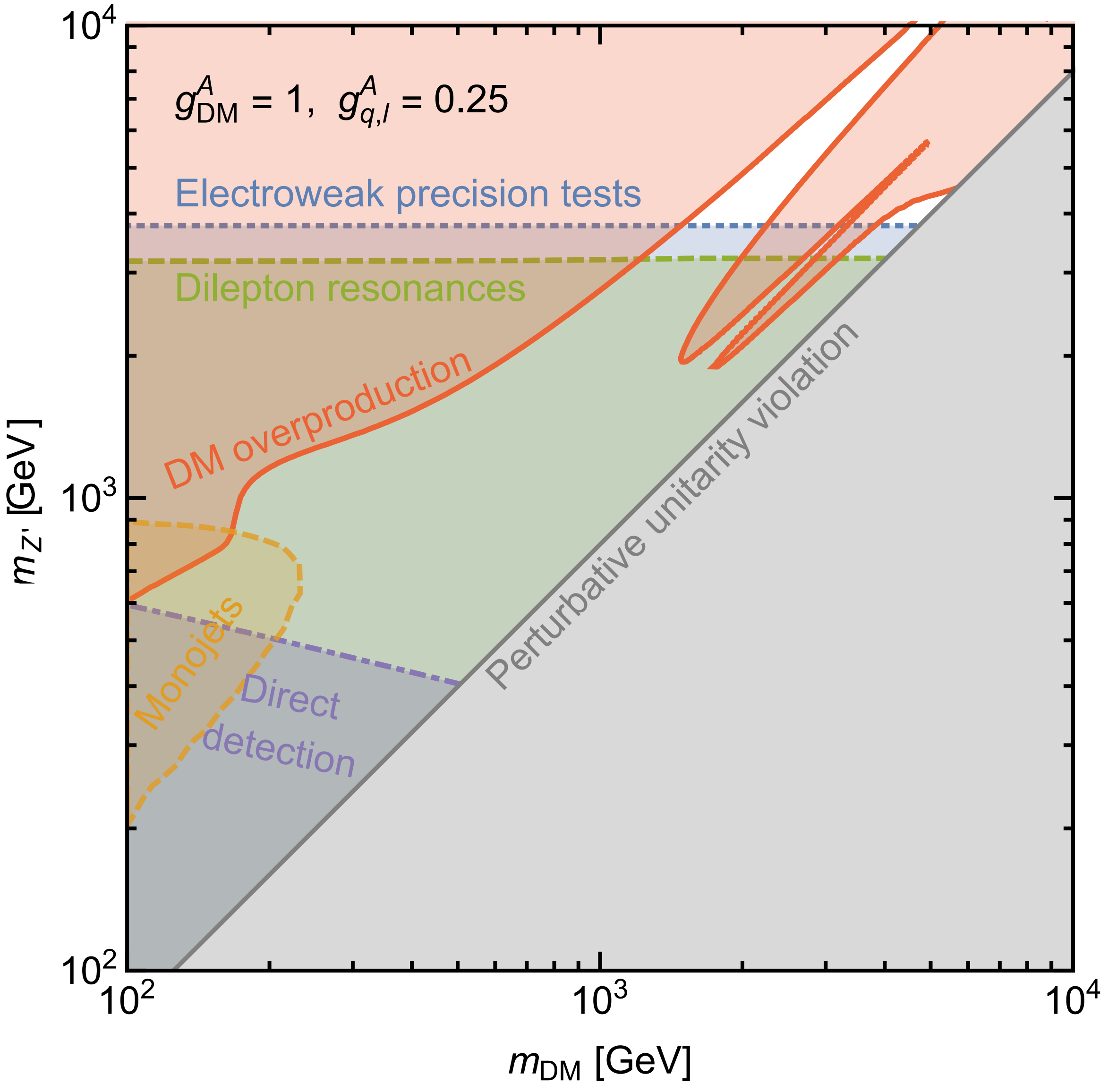
CCs also imply that for non-zero axialvector couplings to SM fermions, SM Higgs must carry U(1)′ charge. This has two important consequences:

- Z′ must couple with same strength to quarks & leptons (assuming one Higgs doublet), resulting in stringent constraints from di-lepton resonance searches
- VEV of SM Higgs leads to Z−Z′ mixing, which is severely constrained by EW precision observables (EWPOs)

[Kahlhoefer et al., 1510.02110]

Axialvector Z′: constraints

[Kahlhoefer et al., 1510.02110]



In simplest UV completion of axialvector model, constraints from mono-jet & di-jet searches & DD not competitive with di-lepton searches & EWPOs

Mono-jet backgrounds at 8 TeV

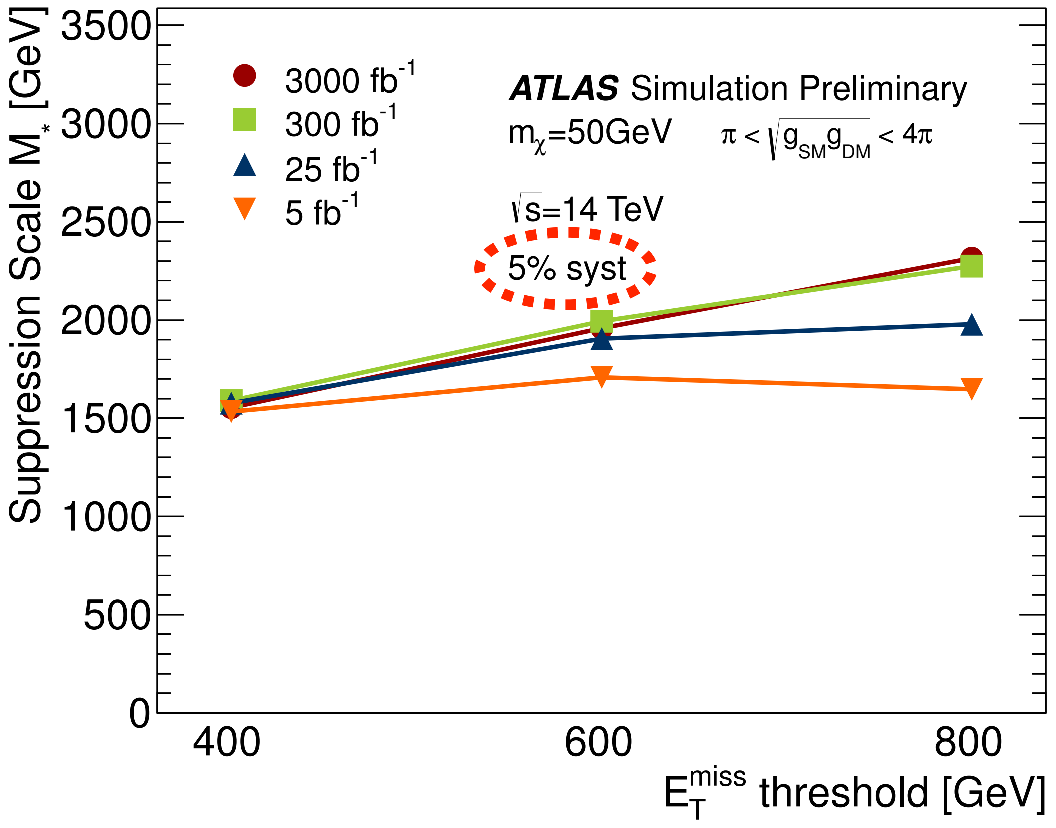
[CMS, 1408.3583]

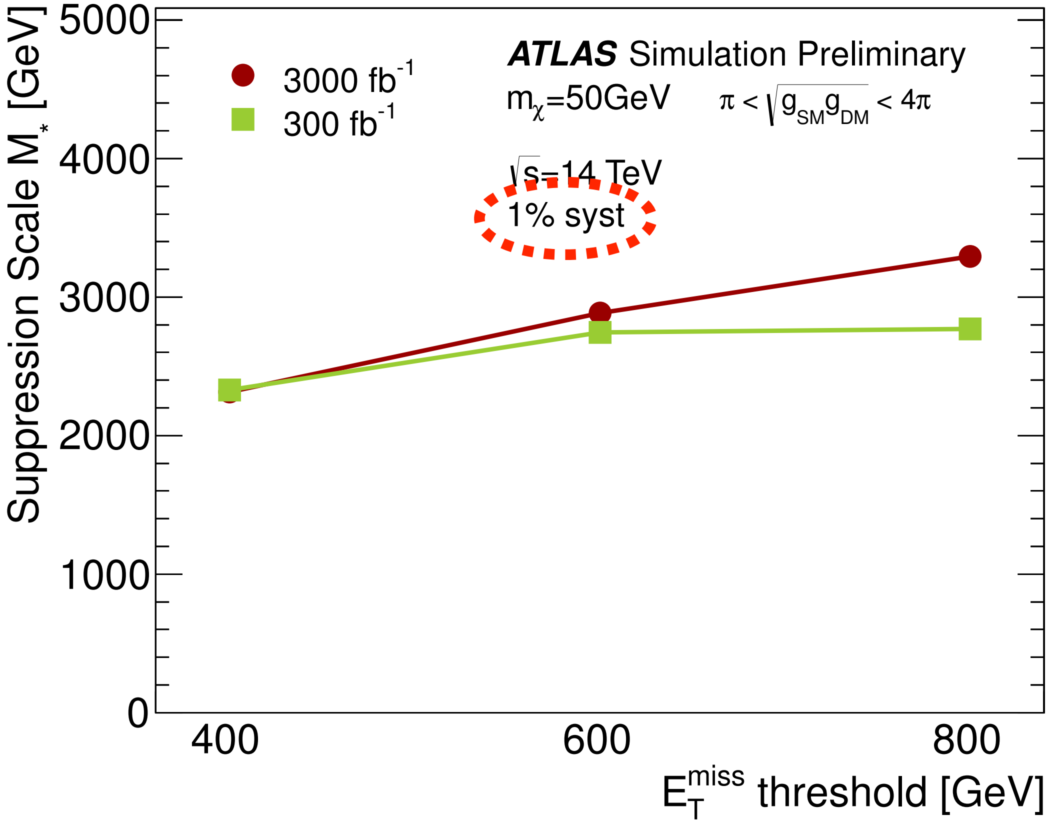
E_T^{miss} (GeV)	>250	…	>550	relative uncertainty
Z($\nu\nu$)+jets	32100 ± 1600		362 ± 64	13%
W+jets	17600 ± 900		123 ± 13	3%
$t\bar{t}$	446 ± 220		2.8 ± 1.4	
Z($\ell\ell$)+jets	139 ± 70		1.0 ± 0.5	
Single t	155 ± 77	…	—	
QCD multijets	443 ± 270		0.5 ± 0.3	
Diboson	980 ± 490		20 ± 10	2%
Total SM	51800 ± 2000		509 ± 66	
Data	52200	…	519	

At 8 TeV SM background to mono-jet searches has an error of O(10%)

Mono-jet prospects at 14 TeV

[ATL-COM-PHYS-2014-549]





At high-luminosity LHC, systematic uncertainties will limit reach of mono-jet searches. How far can one push this uncertainties down? 1% seems like a big challenge for both experiment & theory

Monte Carlo implementations

Both POWHEG BOX & MadGraph5_aMC@NLO able to simulate $E_{T,miss}$+j signals in s-channel simplified DM models at 1-loop level including consistently parton shower (PS) effects

[UH et al., 1310.449; Backović et al., 1508.05327]

Predictions without PS can also be obtained with official MCFM release — there is also a Sherpa+OpenLoops/GoSam package which is however not public

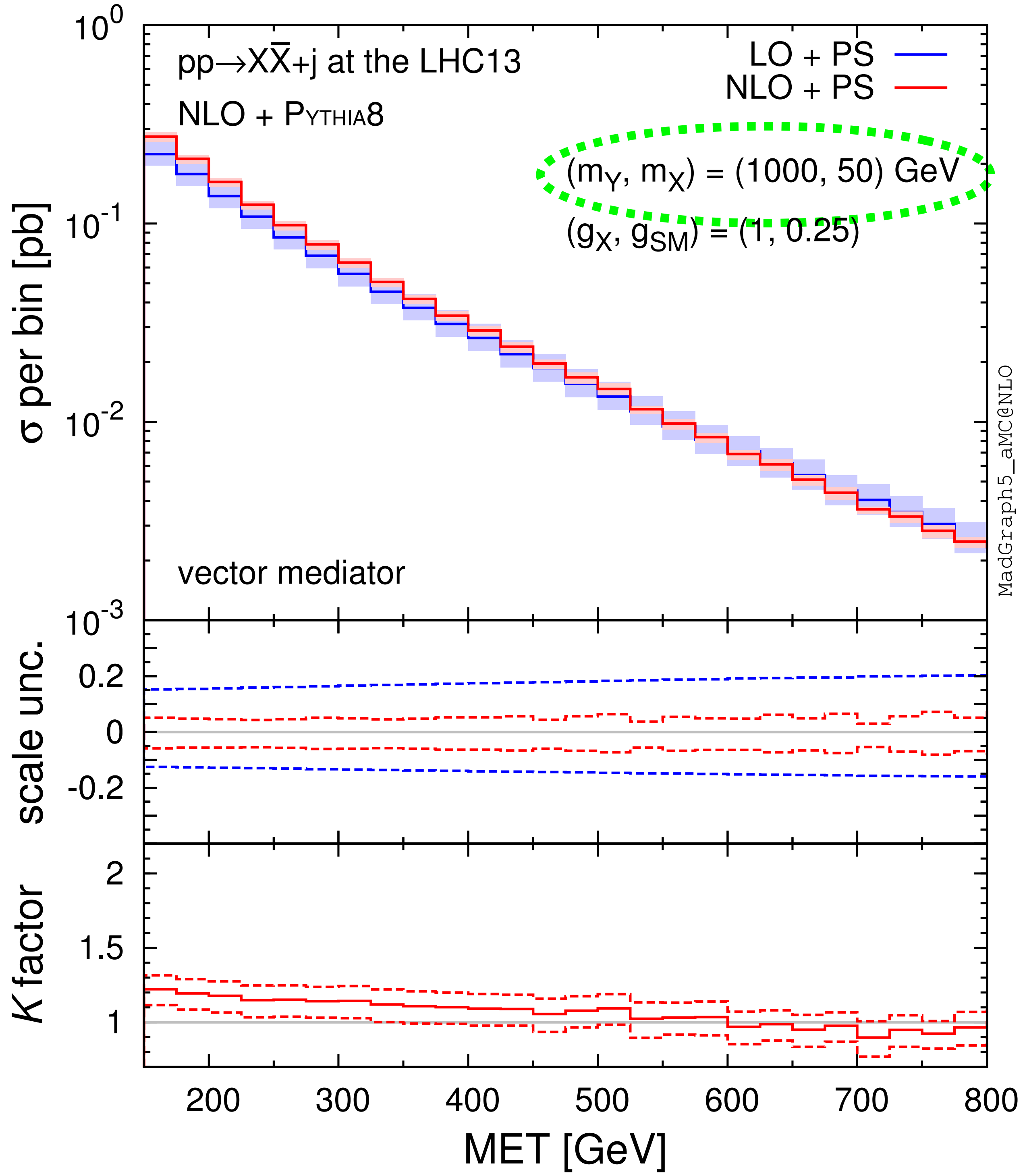
[Fox & Williams, 1211.6390]

NLOPS: spin-1 mediators

- For heavy mediators & hard $E_{T,\mathrm{miss}}$ cuts, impact of QCD corrections small, which results in K-factors close to 1

[UH et al., 1310.4491]

[Backović et al., 1508.05327]

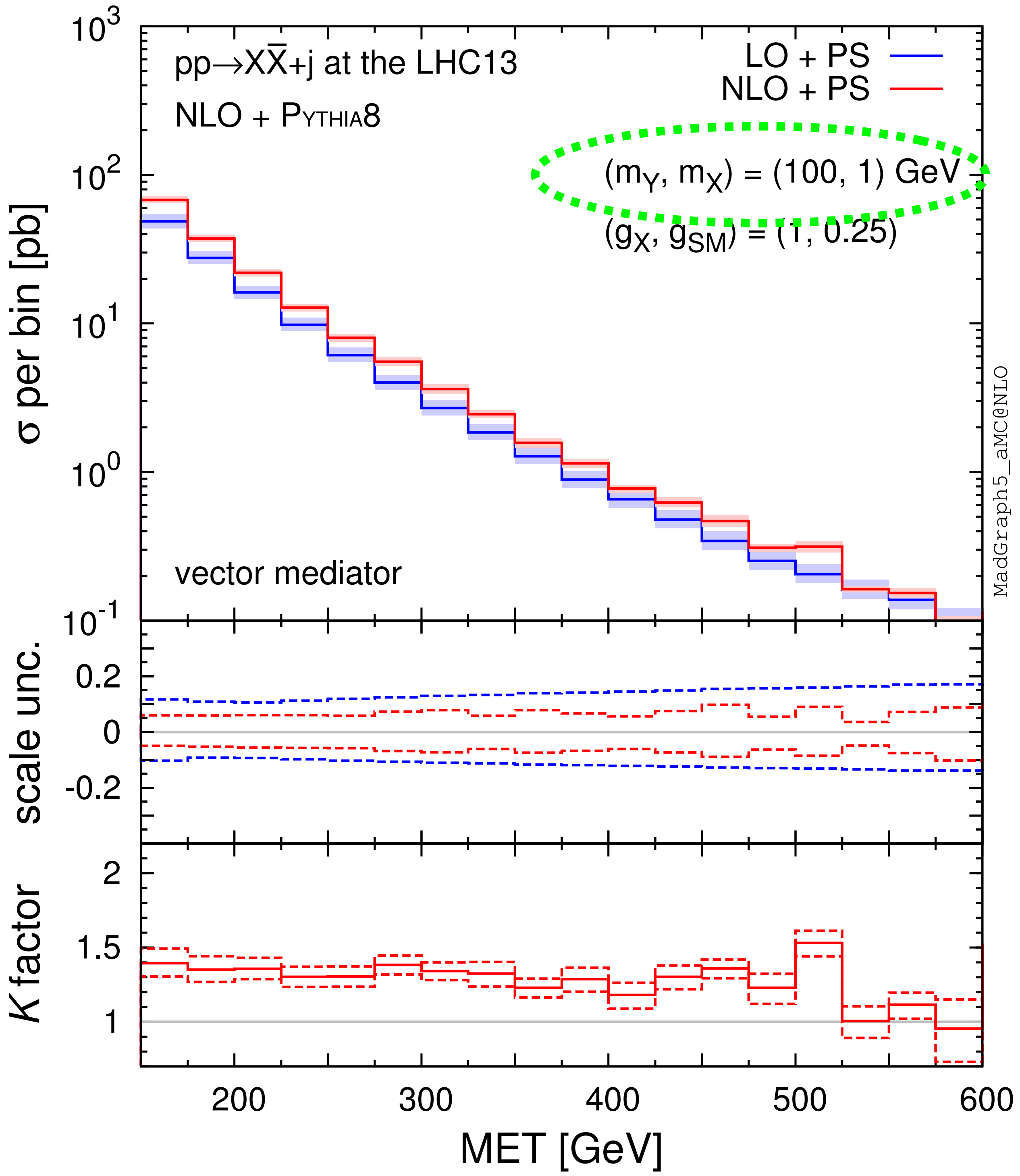


NLOPS: spin-1 mediators

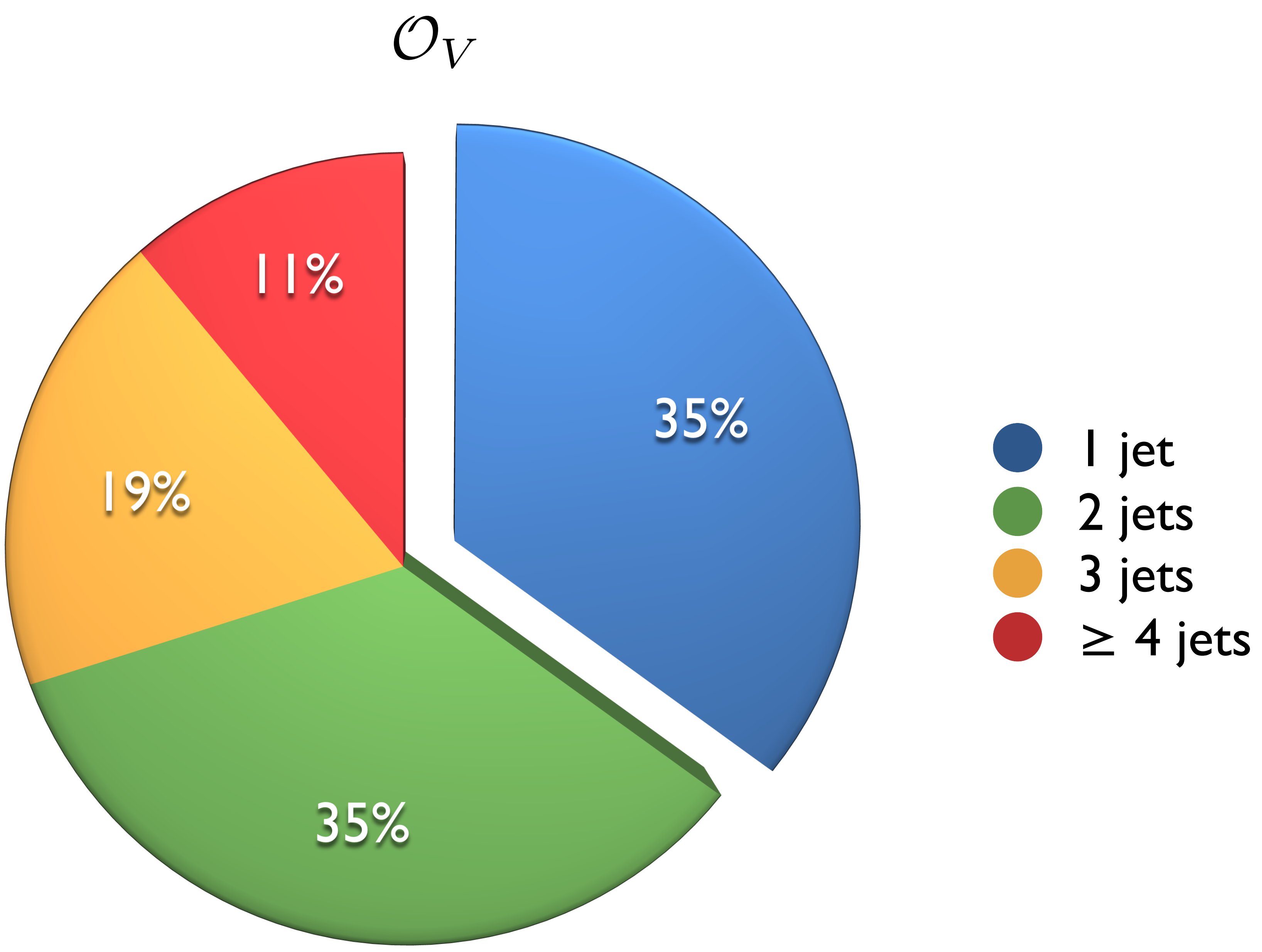
- For heavy mediators & hard $E_{T,\text{miss}}$ cuts, impact of QCD corrections small, which results in K-factors close to 1

- In case of very light mediators & weak $E_{T,\text{miss}}$ cuts, NLO effects are more important, leading to K-factors of O(1.5)

[Backović et al., 1508.05327]

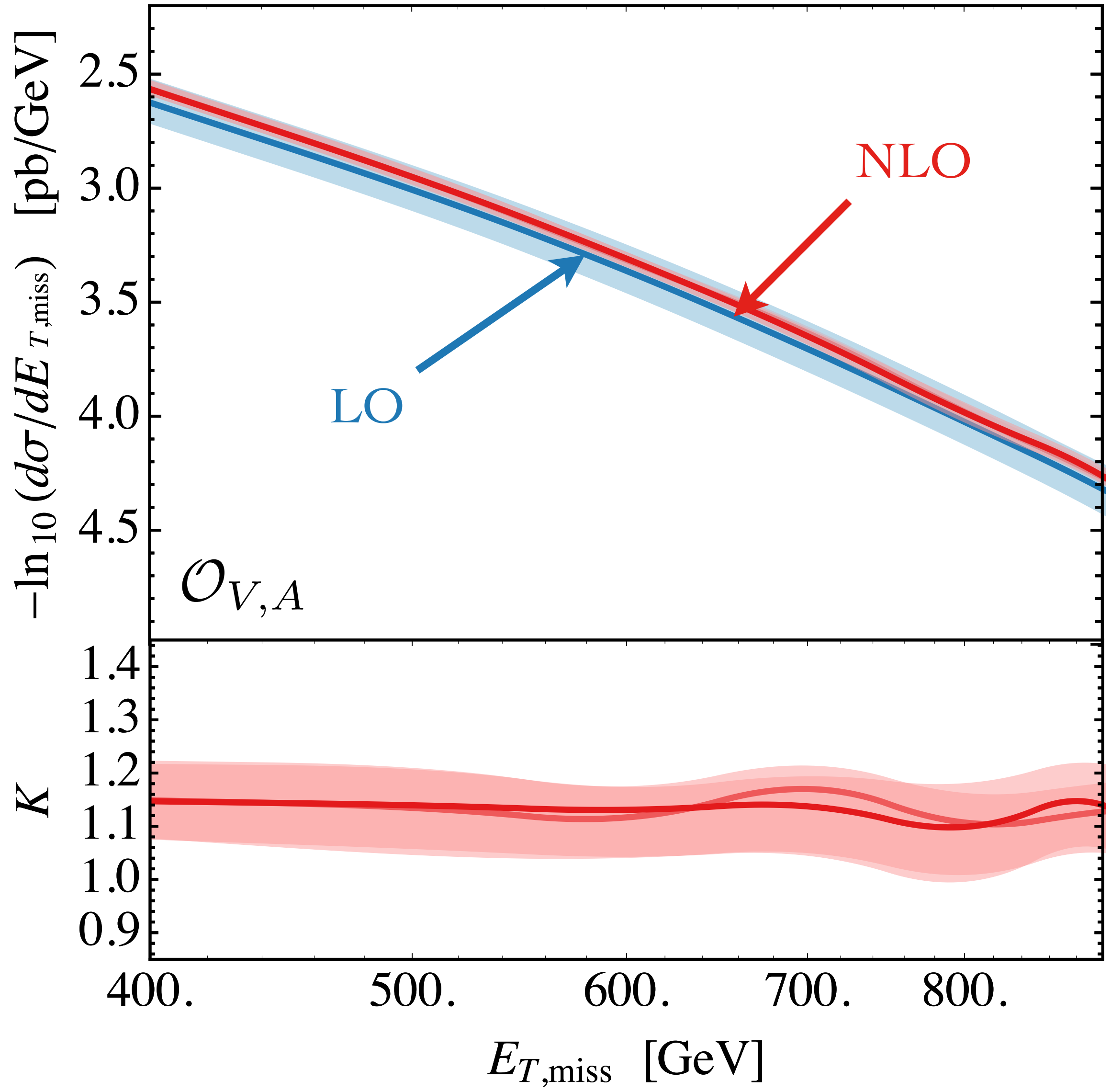


Mono-jet ≠ $E_{T,\text{miss}}$+j



[UH et al., 1310.4491]

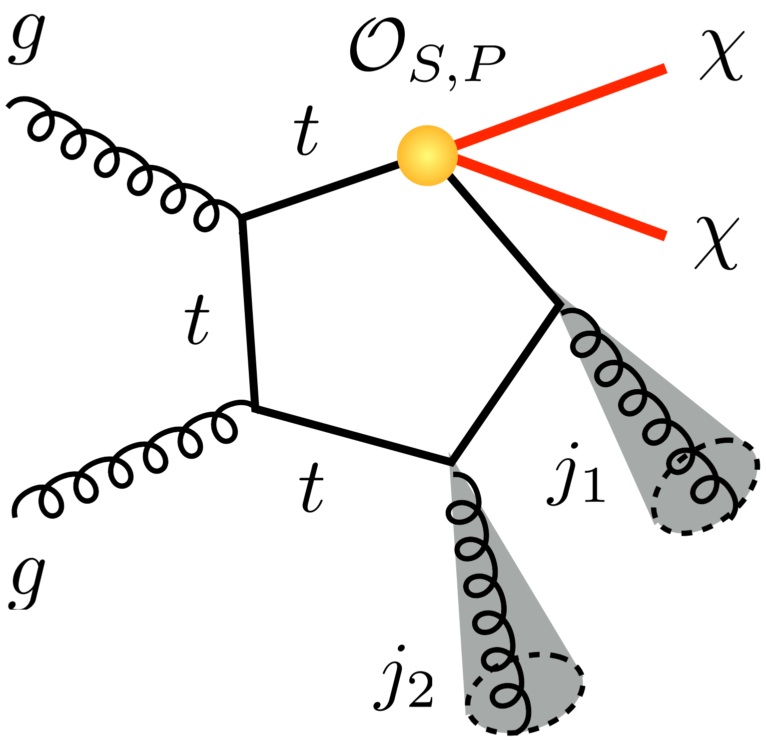
Properties beyond mass scale?



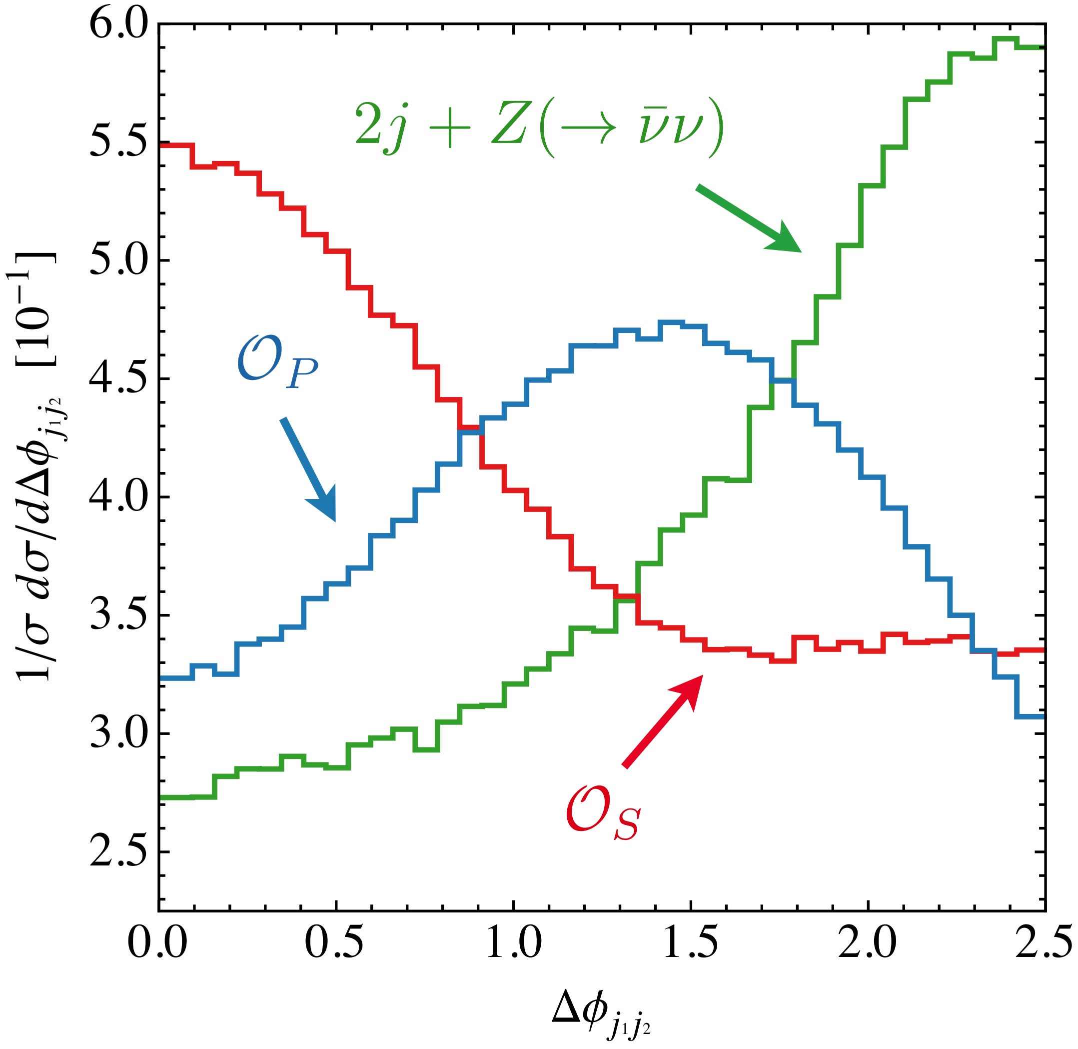
$E_{T,\mathrm{miss}}$ & $p_{T,j1}$ spectra for vector & axialvector operators identical.

Mono-jet searches not sensitive to chirality of interactions

DM-pair production & 2 jets



[UH et al., 1311.7131]

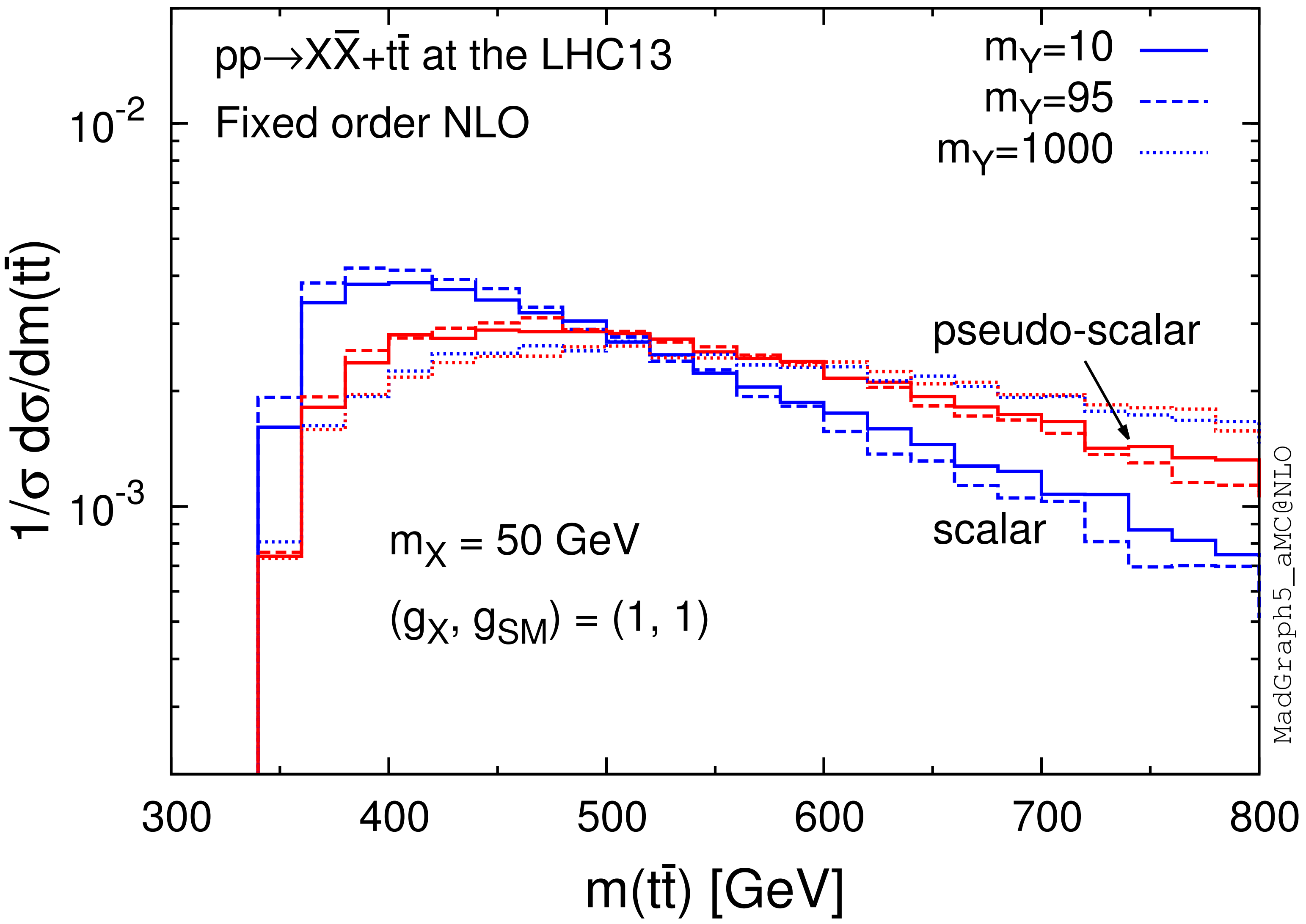


Azimuthal angle difference $\Delta\phi_{j1j2}$ in $E_{T,\mathrm{miss}}$+2j events gold-plated observable to probe structure of DM-SM interactions

[see also Cotta et al.,1210.0525; Crivellin et al. 1501.00907 for related ideas]

Distribution of $E_{T,\mathrm{miss}}$+$t\bar{t}$ events

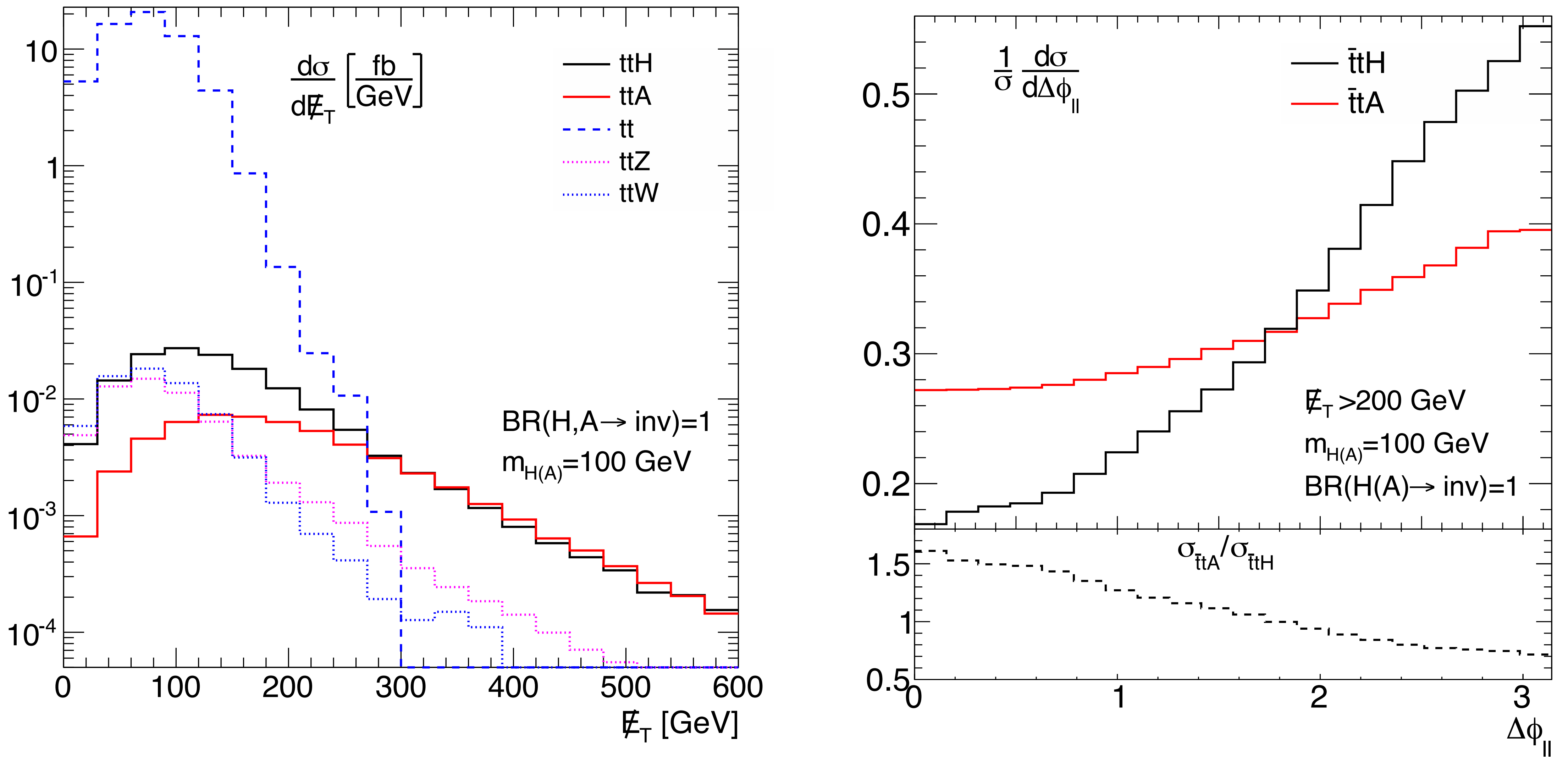
[Backović et al., 1508.05327]



If mediator is light, scalar DM-top interactions can also be distinguished from pseudoscalar couplings by studying invariant $t\bar{t}$ mass distribution

Distribution of $E_{T,\mathrm{miss}}+t\bar{t}$ events

[Buckley & Goncalves, 1511.06451]



Azimuthal angle difference between two leptons $\Delta\phi_{ll}$ in di-leptonic top-quark decays also probes CP-property of spin-0 mediators