Missing energy signals ($E_{T,\,miss}$)

~~Dark matter (DM)~~
at the LHC

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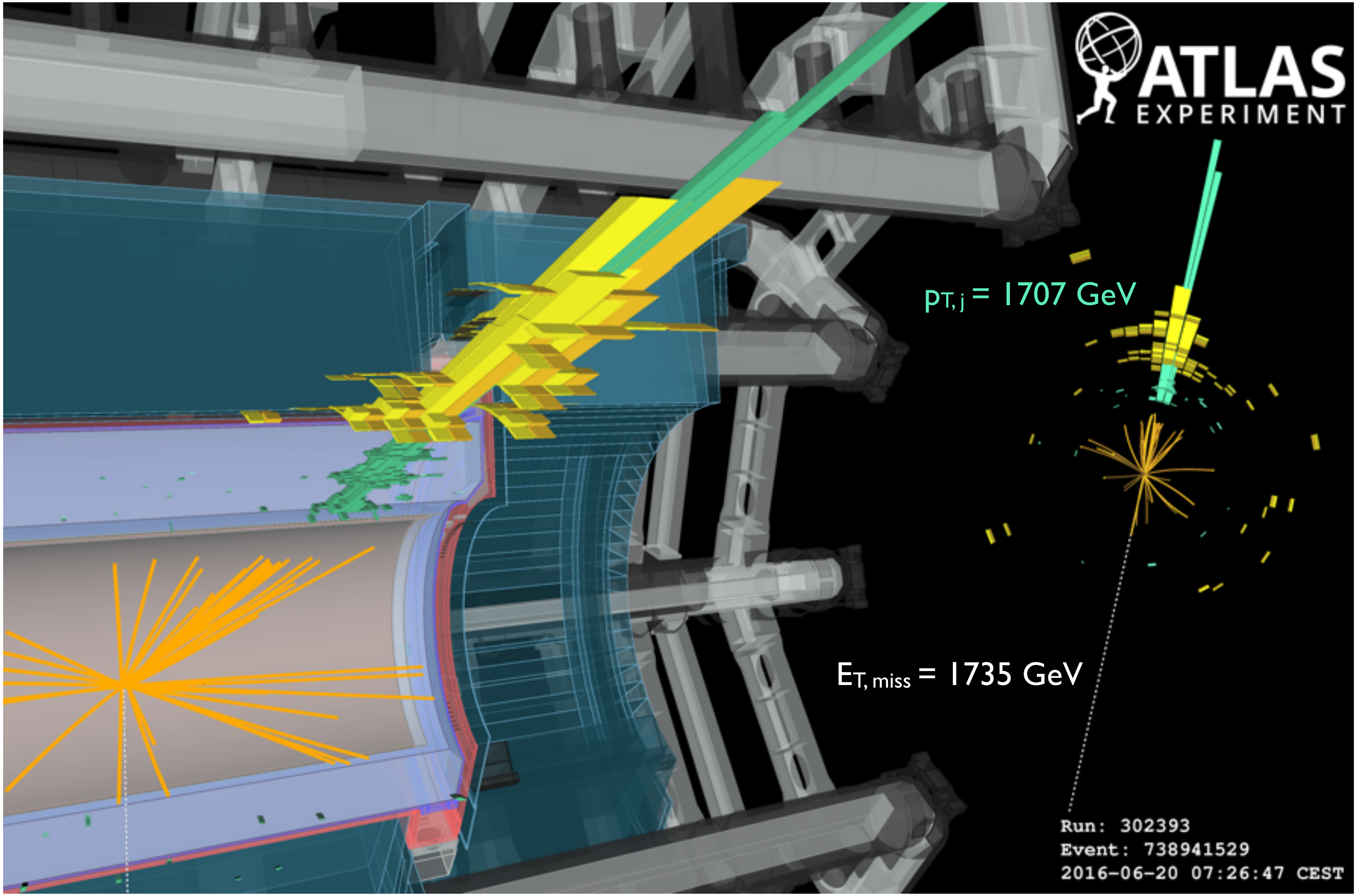
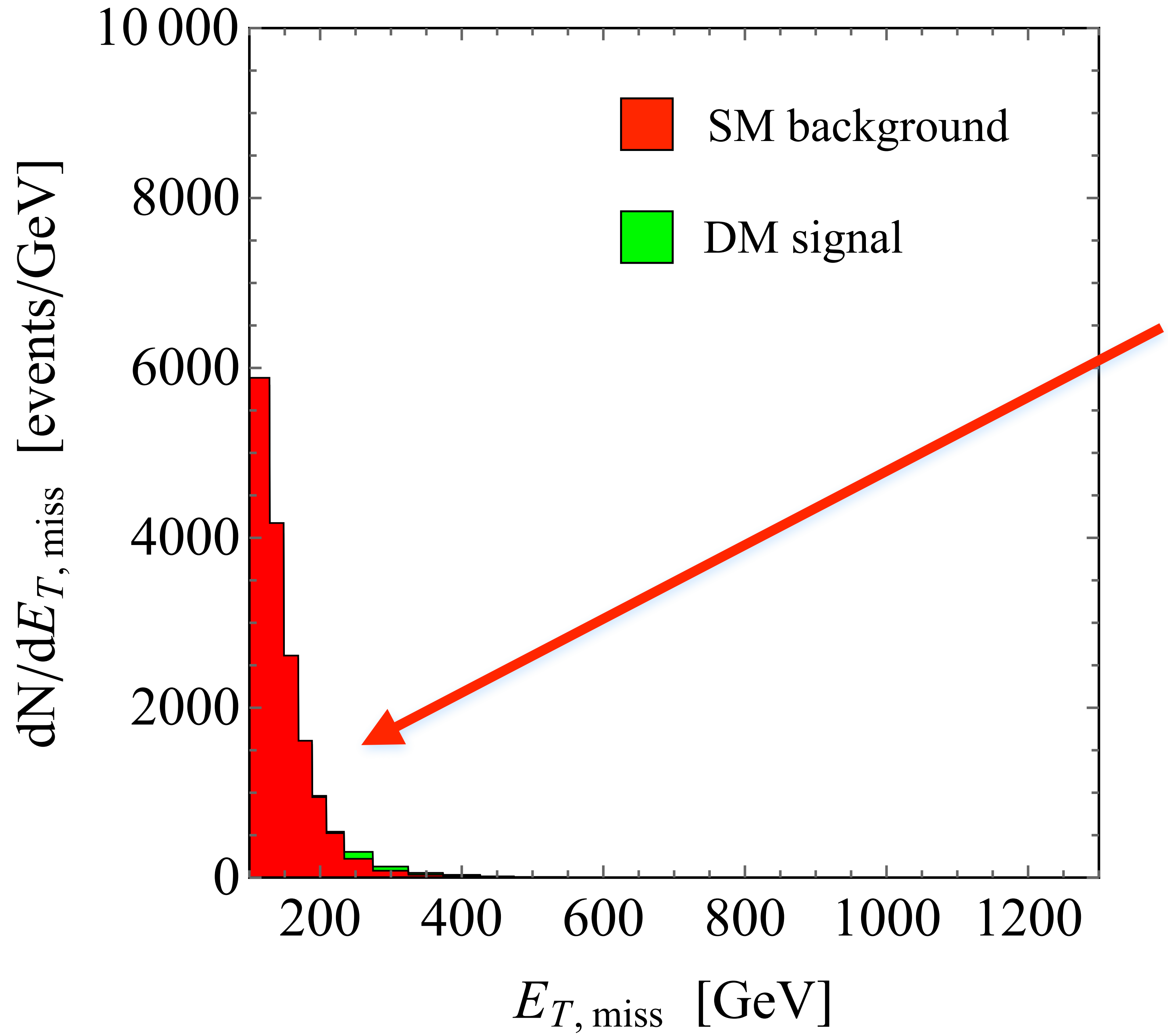
Workshop on the physics of HL-LHC, and perspective at HE-LHC, 1 November 2017, CERN

Mono-jet searches

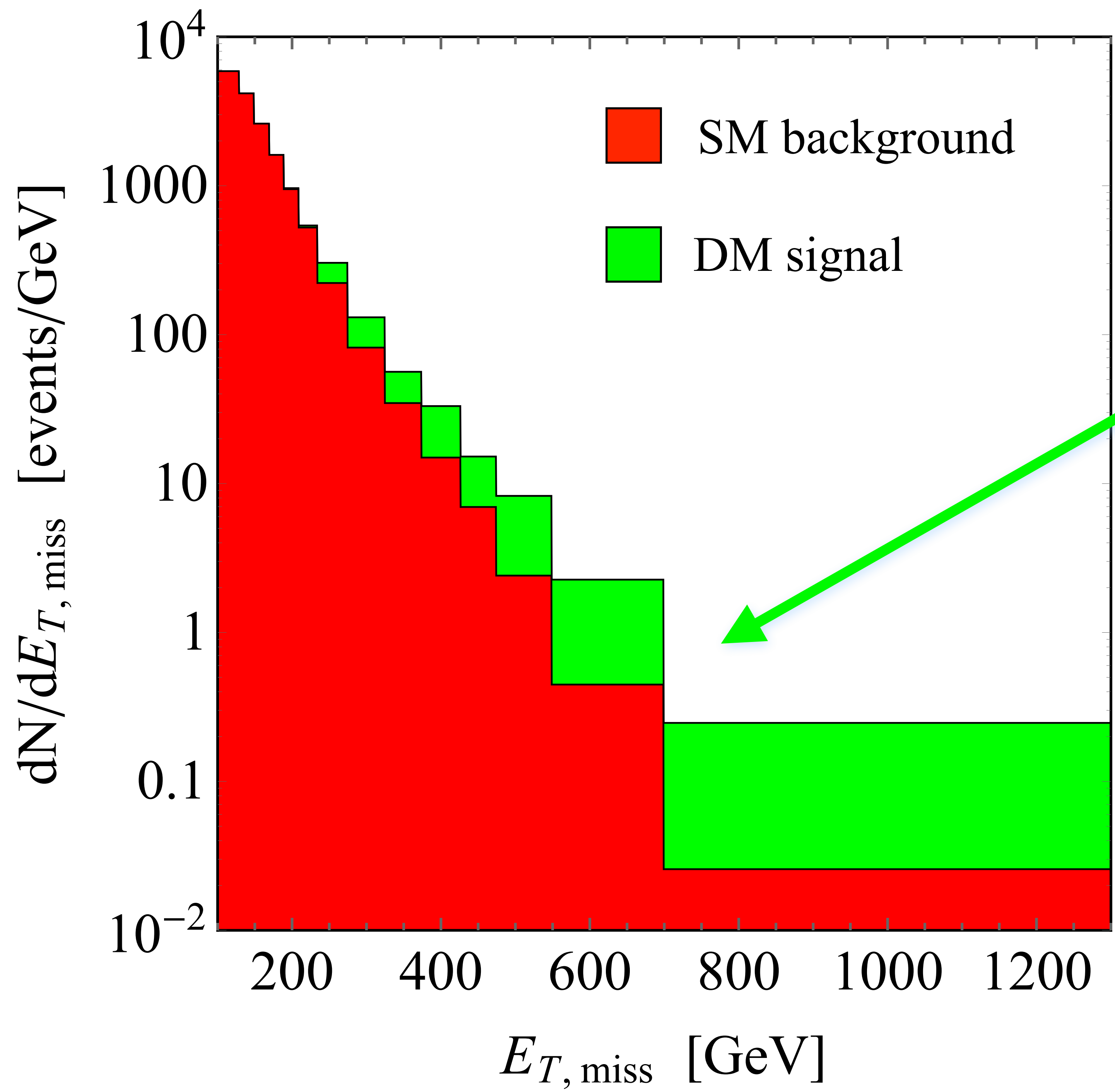


Mono-jet: signal vs. background



huge SM background from Z+jet production with Z decaying to neutrinos

Mono-jet: signal vs. background



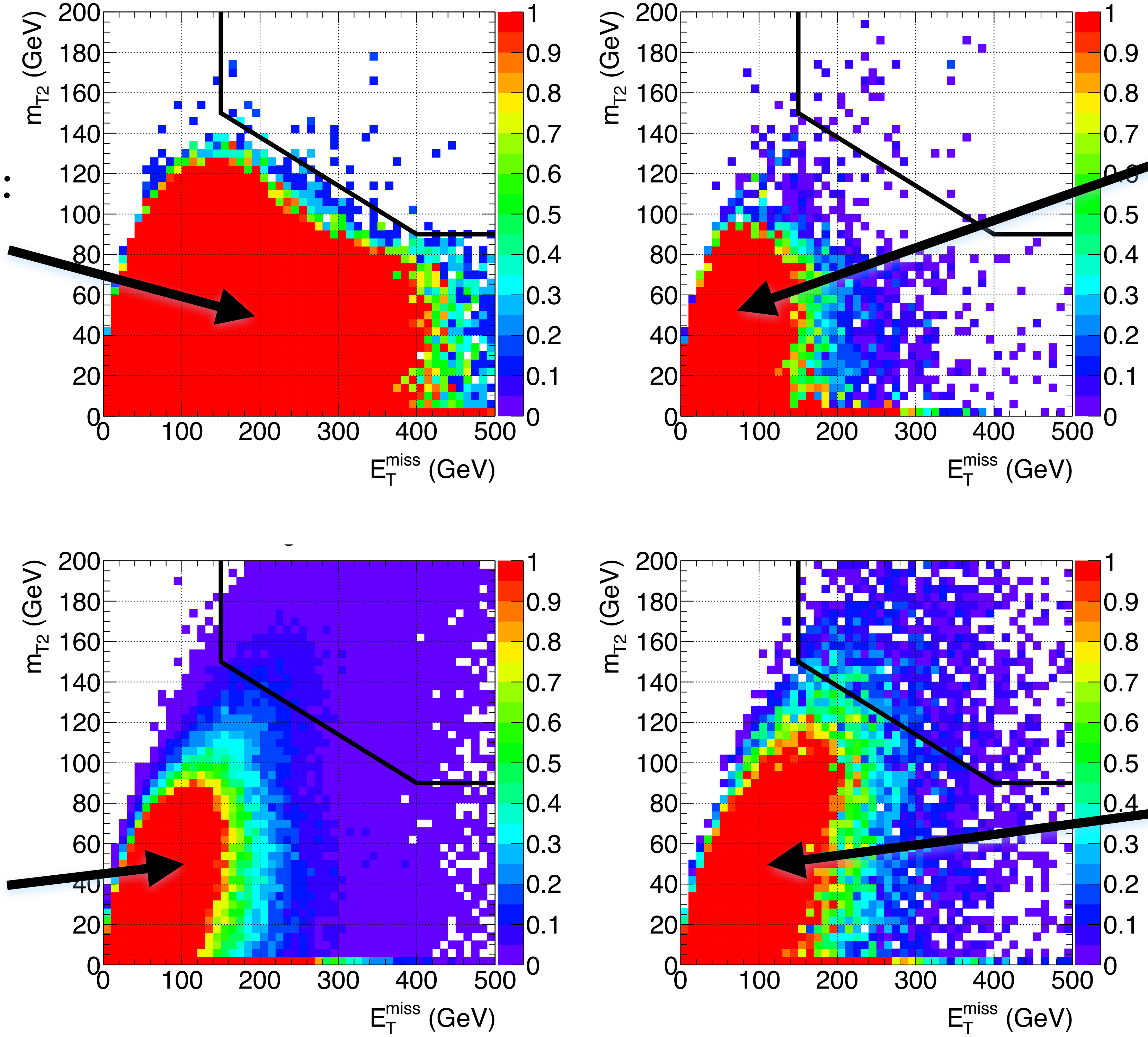
presence of DM manifests itself in small enhancement in tail of $E_{T,\,\mathrm{miss}}$ distribution

$E_{T,miss}$+$t\bar{t}$: signal vs. background

[UH, Pani & Polesello , 1611.09841]

top background: $t\bar{t}$ & tW

reducible background: WW, WZ, ZZ & Z+jets



irreducible background: $t\bar{t}Z$ & $t\bar{t}W$

DM signal

$E_{T,miss}$ signals: challenges

Exploiting full physics potential of DM searches at HL-LHC requires precise control of backgrounds in signal region. In case of mono-jet searches for example, following problems have to be tackled:

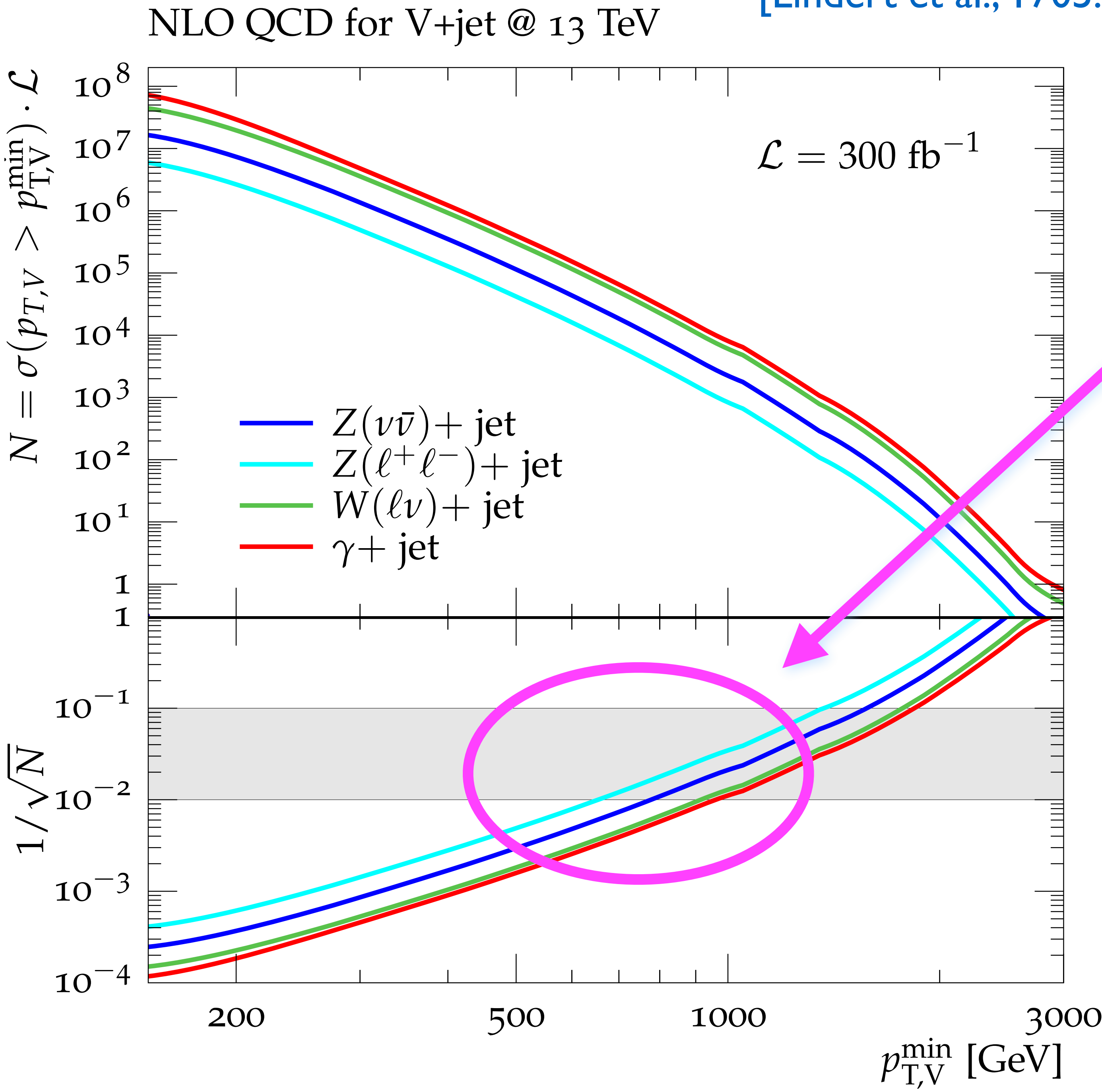
(i) Take accurate data in control regions dominated by $Z(l^+l^-)$+jet, $W(l\nu)$+jet & γ+jet production & extrapolate to $Z(\nu\bar{\nu})$+jet background by means of precise theoretical predictions

(ii) Understand $E_{T,\,miss}$ measurement performance accurately in very high pile-up environment of HL-LHC

Similar issues arise in many other $E_{T,miss}$ channels

Mono-jet: statistical precision

[Lindert et al., 1705.04664]

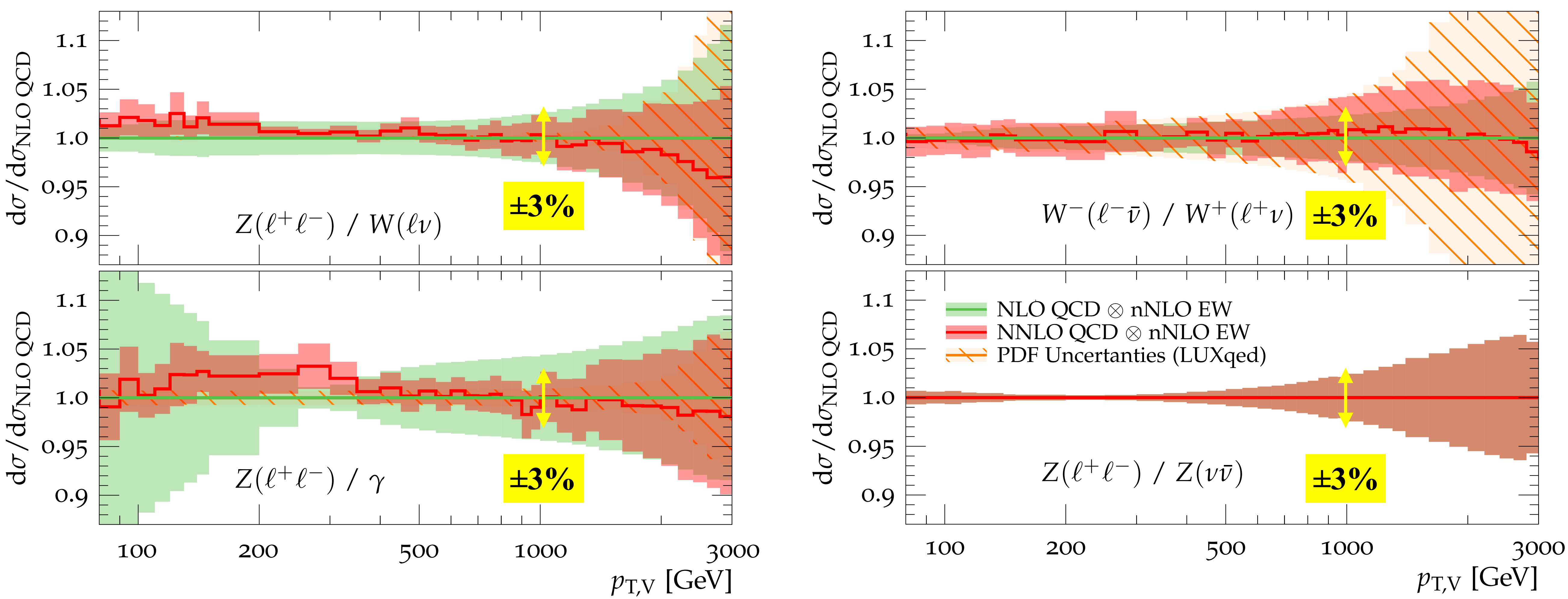


for $p_{T,V} \in [0.5, 1]$ TeV statistical uncertainty on background will be at 1% level already with 300 fb^{-1}

Is a precision of a few % possible theoretically?

Mono-jet: recent theory progress

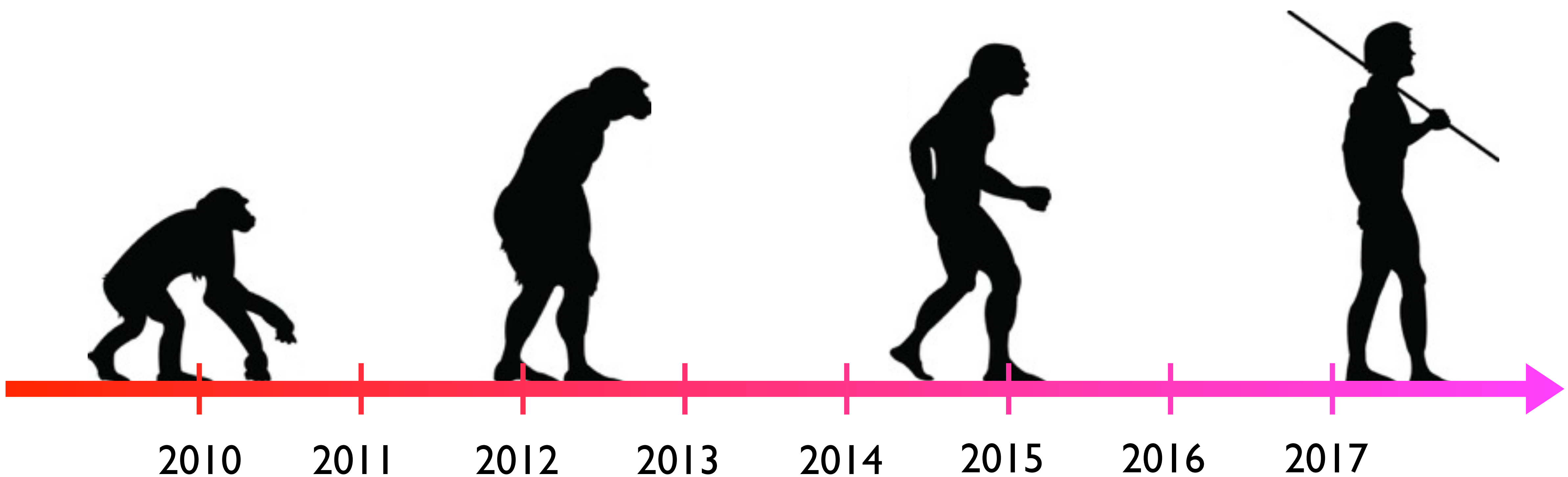
[Lindert et al., 1705.04664]



Combined uncertainties of (1-5)% on V+jet ratios at NNLO QCD & NNLO QED for $p_{T,V}$ < 1 TeV. Results already used in latest ATLAS & CMS analyses & will in future allow to set unprecedented limits on mono-jet DM production

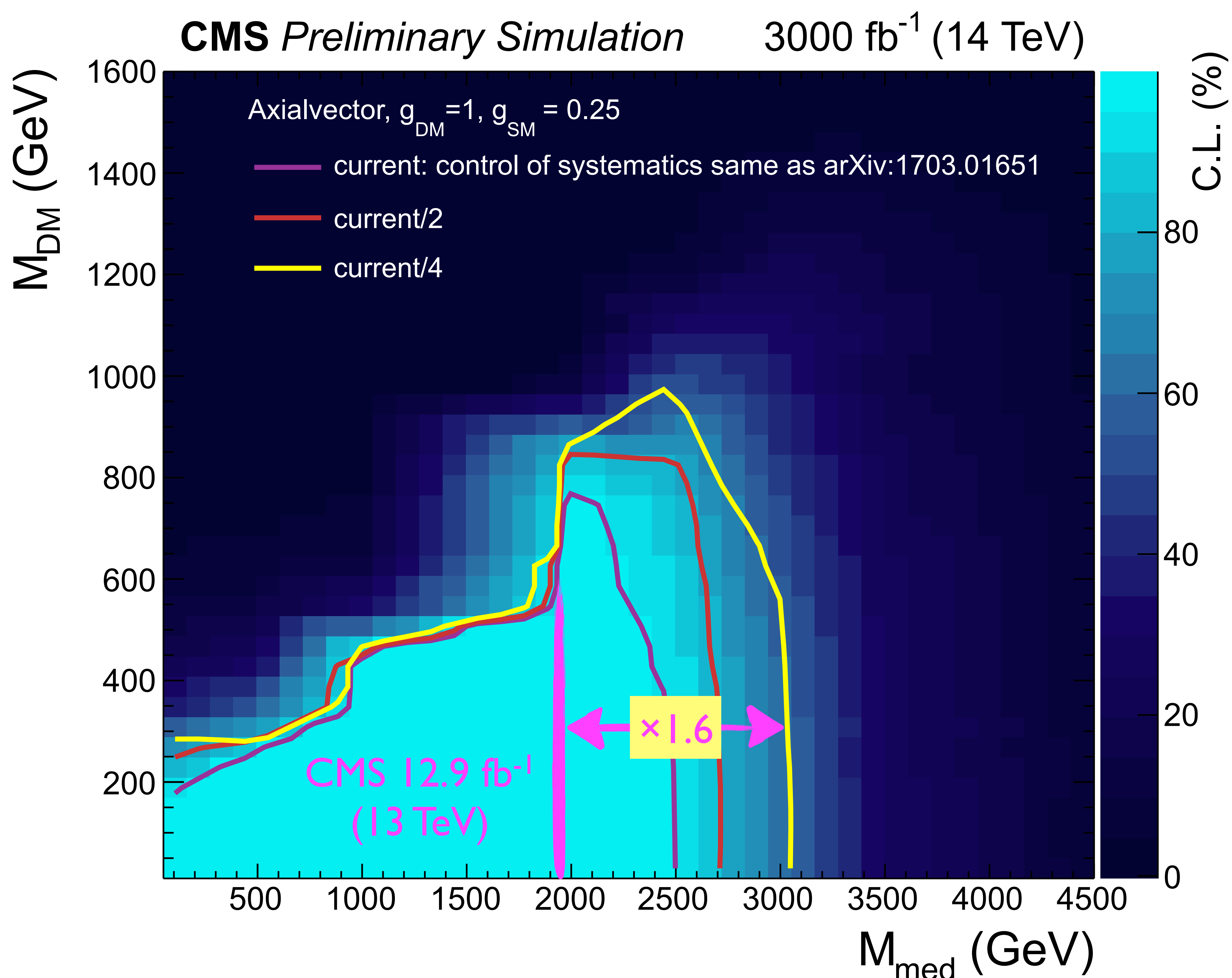
Evolution of LHC DM models

Effective field theory (EFT)	Simplified models	Consistent simplified models
$\frac{m_q}{\Lambda^3}\,\bar{\chi}\chi\bar{q}q$	$g_\chi \bar{\chi}\chi S + \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$	$g_\chi \bar{\chi}\chi s + Y_q \bar{q}Hq + \mu s\|H\|^2$



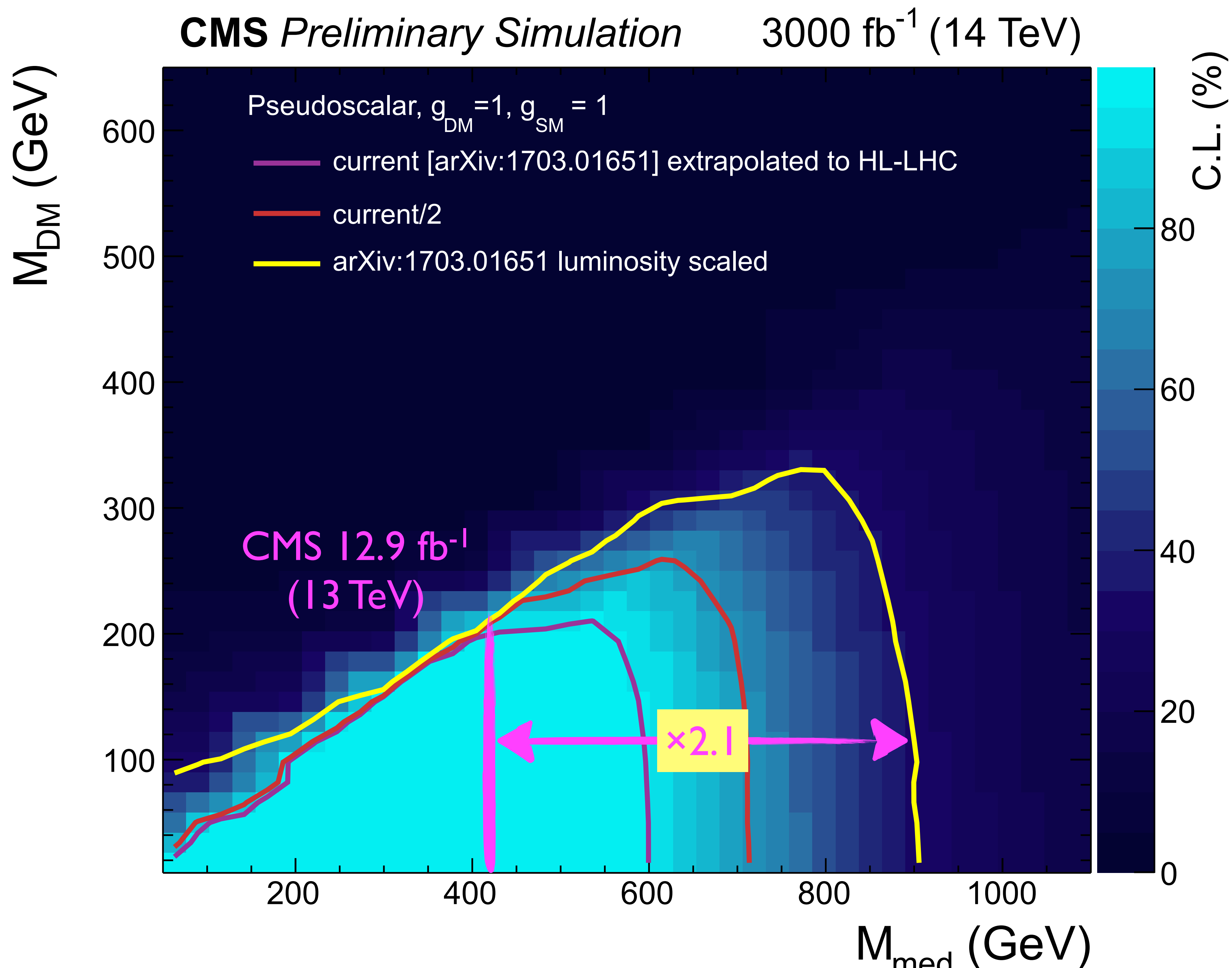
[idea & artwork adopted from Bauer]

Simplified models: HL-LHC prospects



[CMS-PAS-FTR-16-005]

Simplified models: HL-LHC prospects



[CMS-PAS-FTR-16-005]

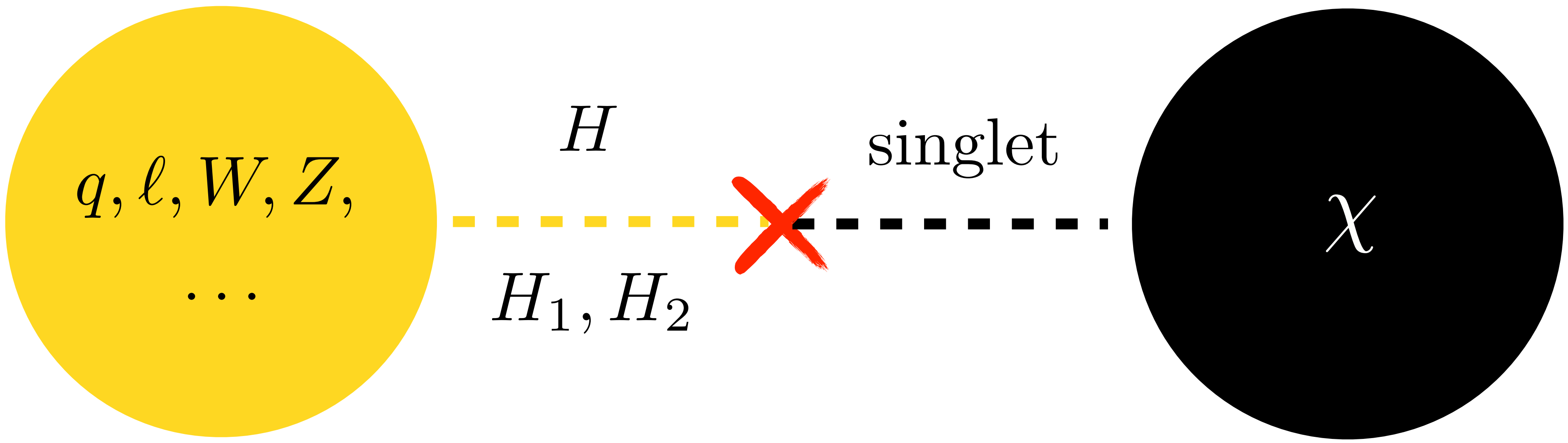
Are simplified models perfect?

Simplified models are minimal extensions of EFT that besides DM typically contain a single mediator. Standard model (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

Consistent spin-0 simplified models



Spin-0 models with fermionic DM can be made $SU(2)_L \times U(1)_Y$ invariant by introducing a new dark Higgs that couples to visible scalar sector. If scalar sector minimal, SM Higgs is mediator & Higgs constraints are severe. But Higgs constraints avoided in decoupling or alignment limit of two-Higgs-doublet model (THDM) extensions

[Kim et al., 0803.2932; Baek et al., 1112.1847; Lopez-Honorez et al., 1203.2064; Fairbairn & Hogan, 1305.3452; Carpenter, 1312.2592; Berlin et al., 1402.7074, 1502.06000; … ; Ko & Li, 1610.03997; Bell et al., 1612.04593; …]

THDM plus pseudoscalar model

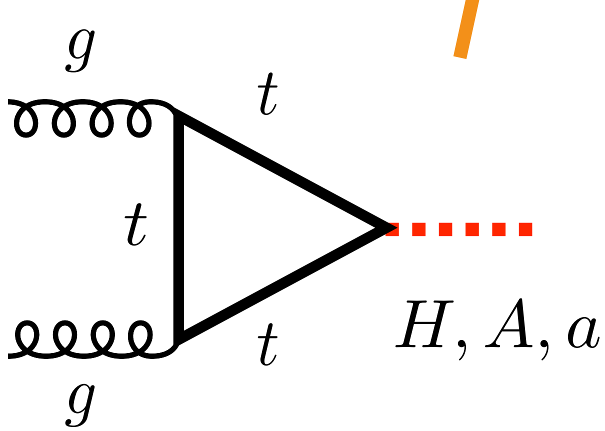
$$\mathcal{L} \supset -\bar{Q} Y_u \tilde{H}_2 d_R + \bar{Q} Y_d H_1 u_R - i b_P P H_1^\dagger H_2 - i y_\chi P \bar{\chi} \gamma_5 \chi + \text{h.c.}$$

$$\text{States}: h, H, A, H^\pm, a$$

h is SM-like for $\cos(\beta-\alpha) \simeq 0$

mostly P for small θ

$$\text{Angles}: \alpha, \beta, \theta$$

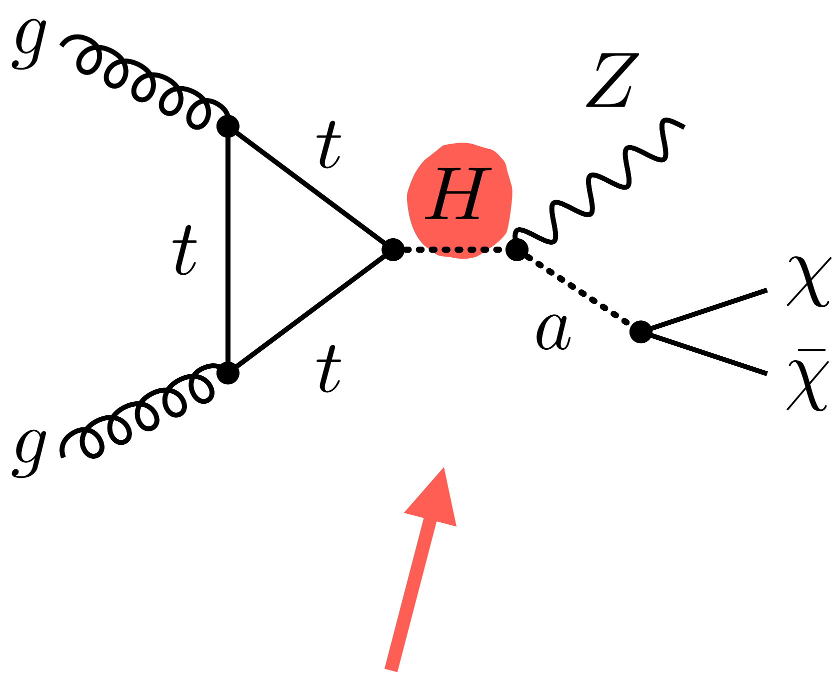


$$\propto \frac{1}{\tan\beta}$$

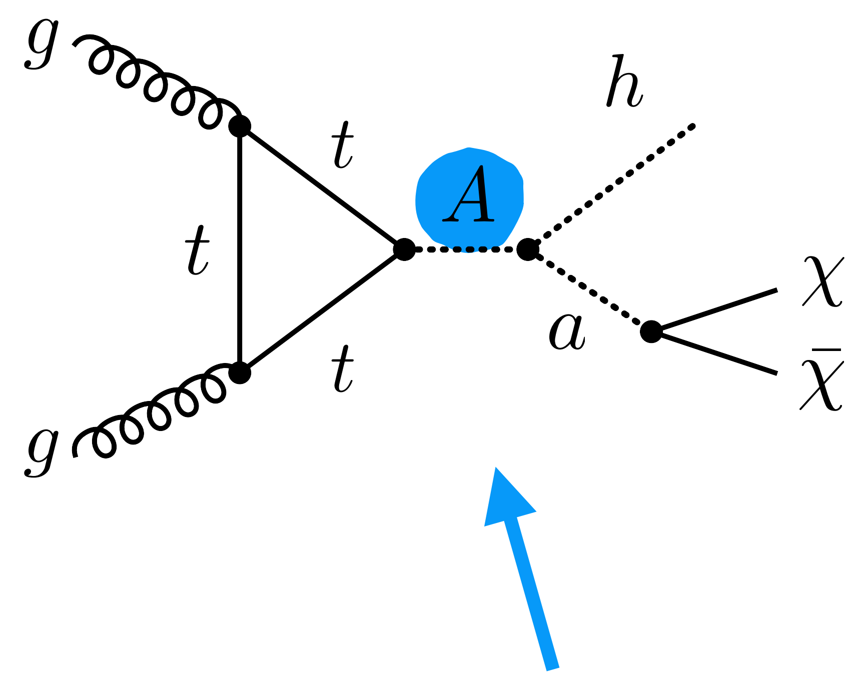
[Ipek et al. 1404.3716; No, 1509.01110; Goncalves et al., 1611.04593; Bauer et al., 1701.07427]

Resonant mono-X signatures

Mono-Z & mono-Higgs signals are subleading in minimal spin-0 simplified models. In THDM plus pseudoscalar (THDMP) model, presence of H & A allows for resonant mono-Z & mono-Higgs production:



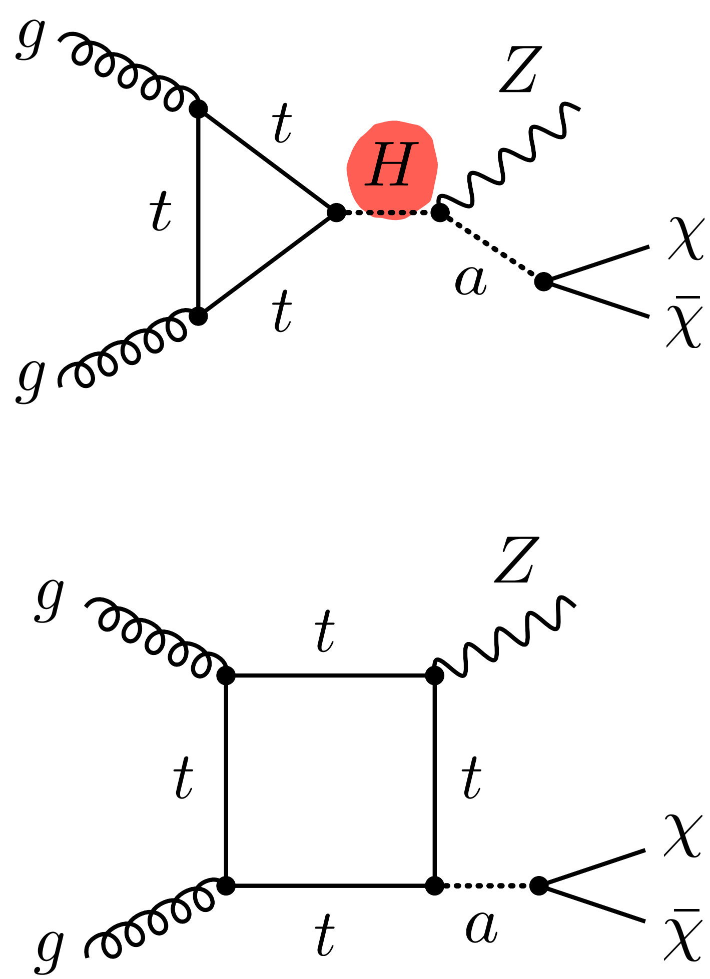
dominant for M_H, M_a < $M_A \simeq M_{H^\pm}$

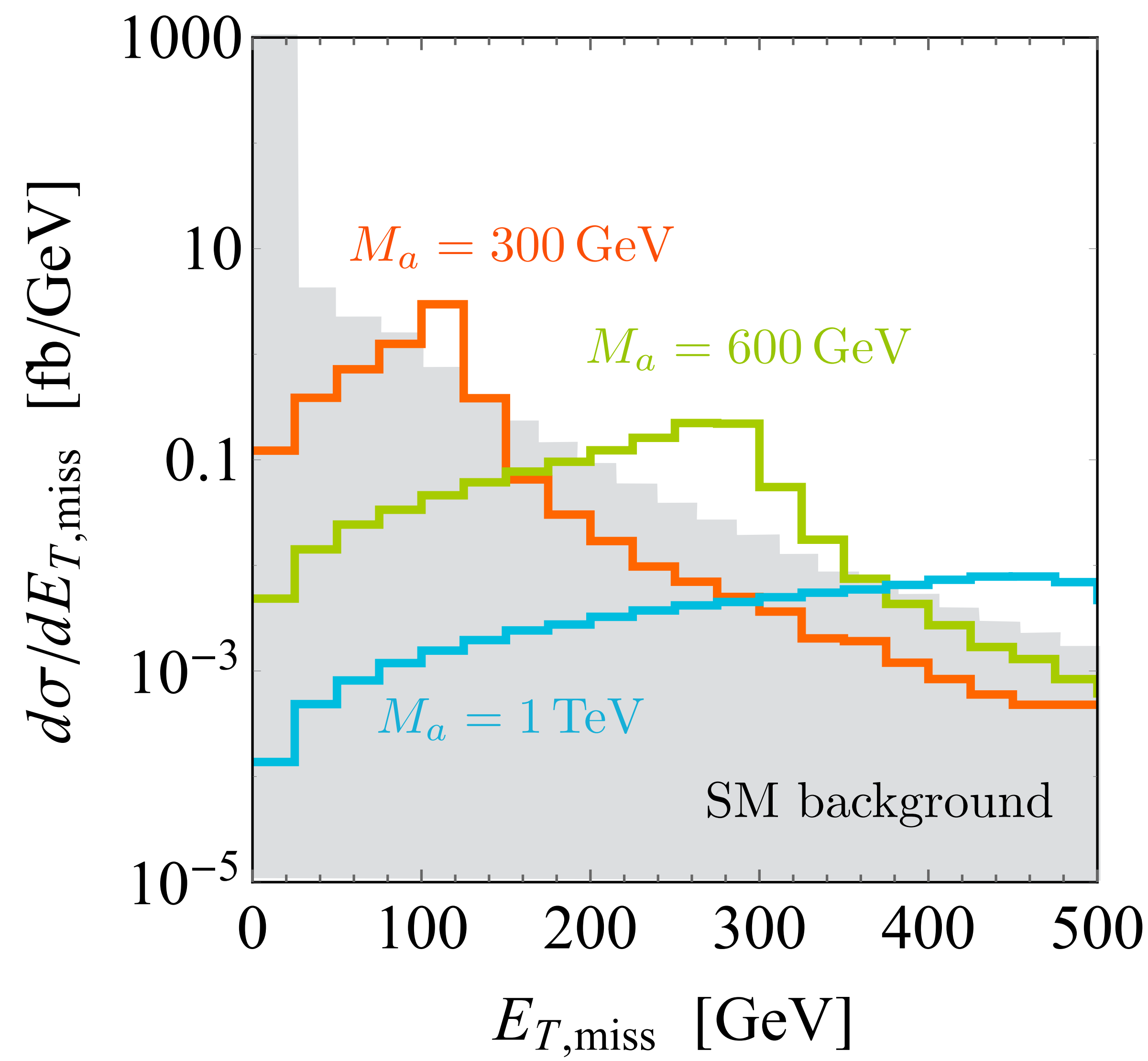


dominant for M_A, M_a < $M_H \simeq M_{H^\pm}$

[No, 1509.01110; Goncalves et al., 1611.04593; Bauer et al., 1701.07427]

Resonant mono-X signatures

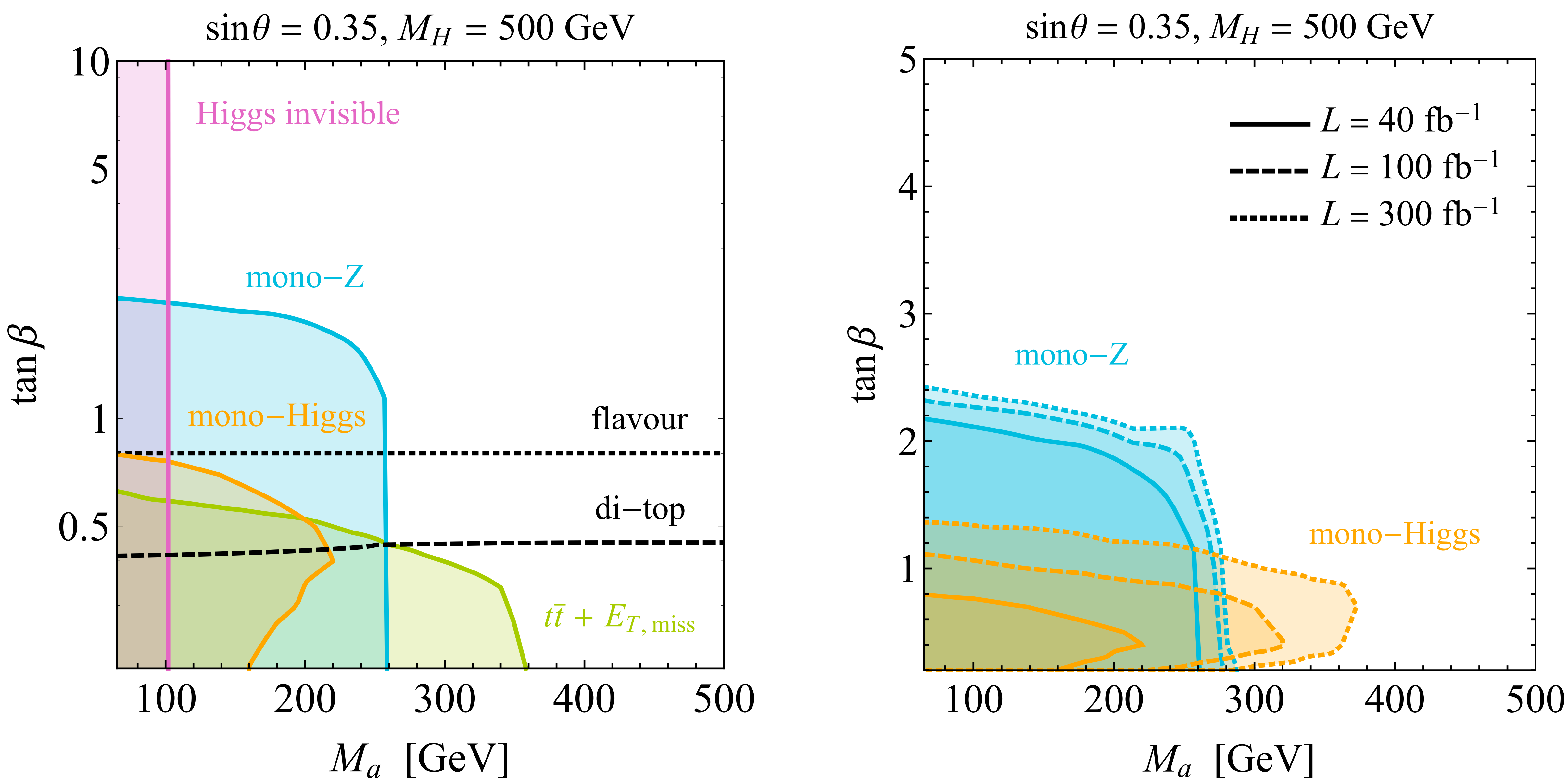




$E_{T,\mathrm{miss}}$ distribution of mono-Z signal has Jacobian peak. Same feature appears in mono-Higgs signature in THDMP model

[No, 1509.01110; Goncalves et al., 1611.04593; Bauer et al., 1701.07427]

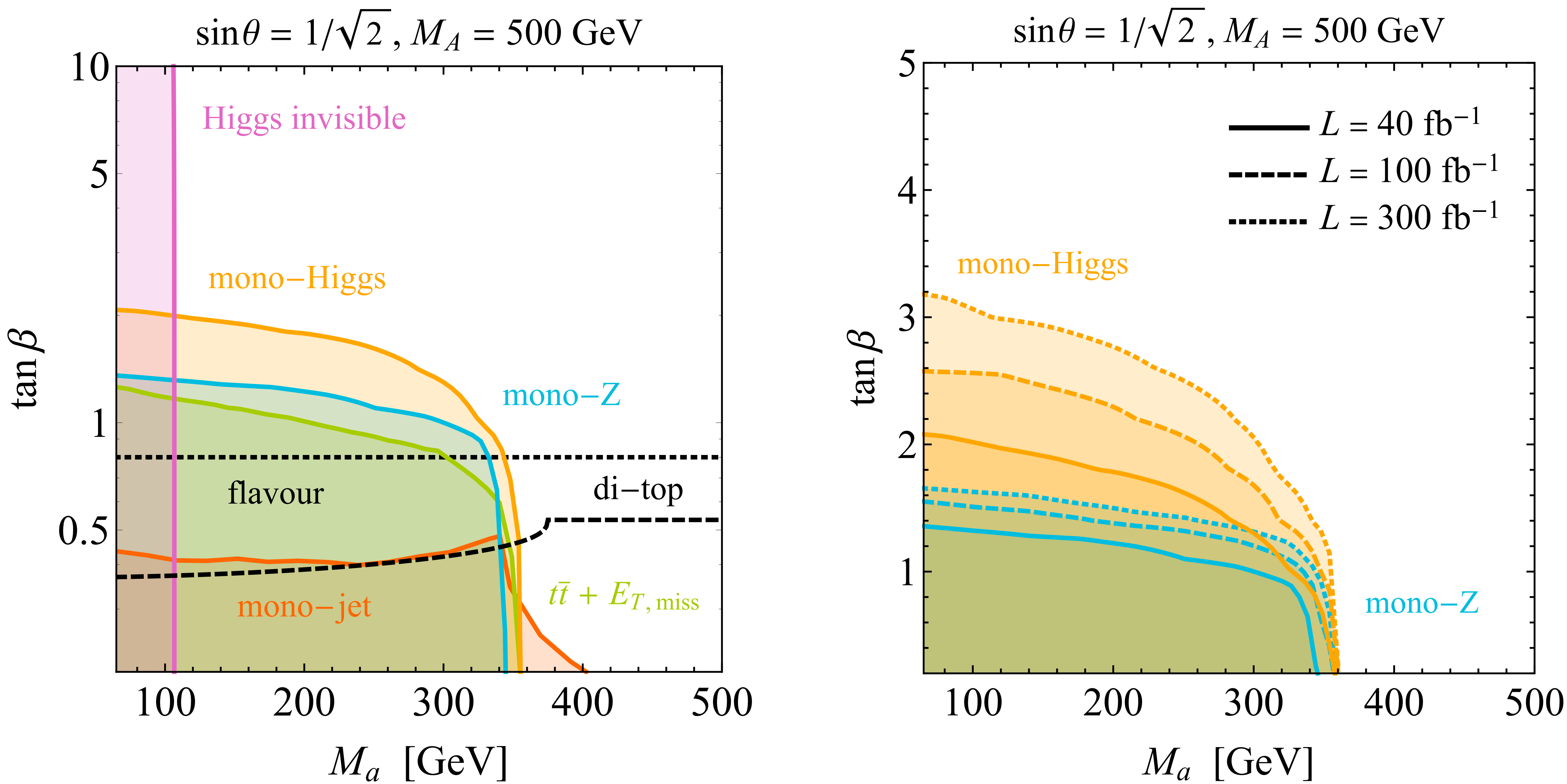
THDMP benchmark: M_H, M_a < M_A



Depending on Higgs-mass spectrum either $E_{T,\text{miss}}$+Z or $E_{T,\text{miss}}$+h provides leading constraint in large parts of parameter space

[Bauer et al., 1701.07427]

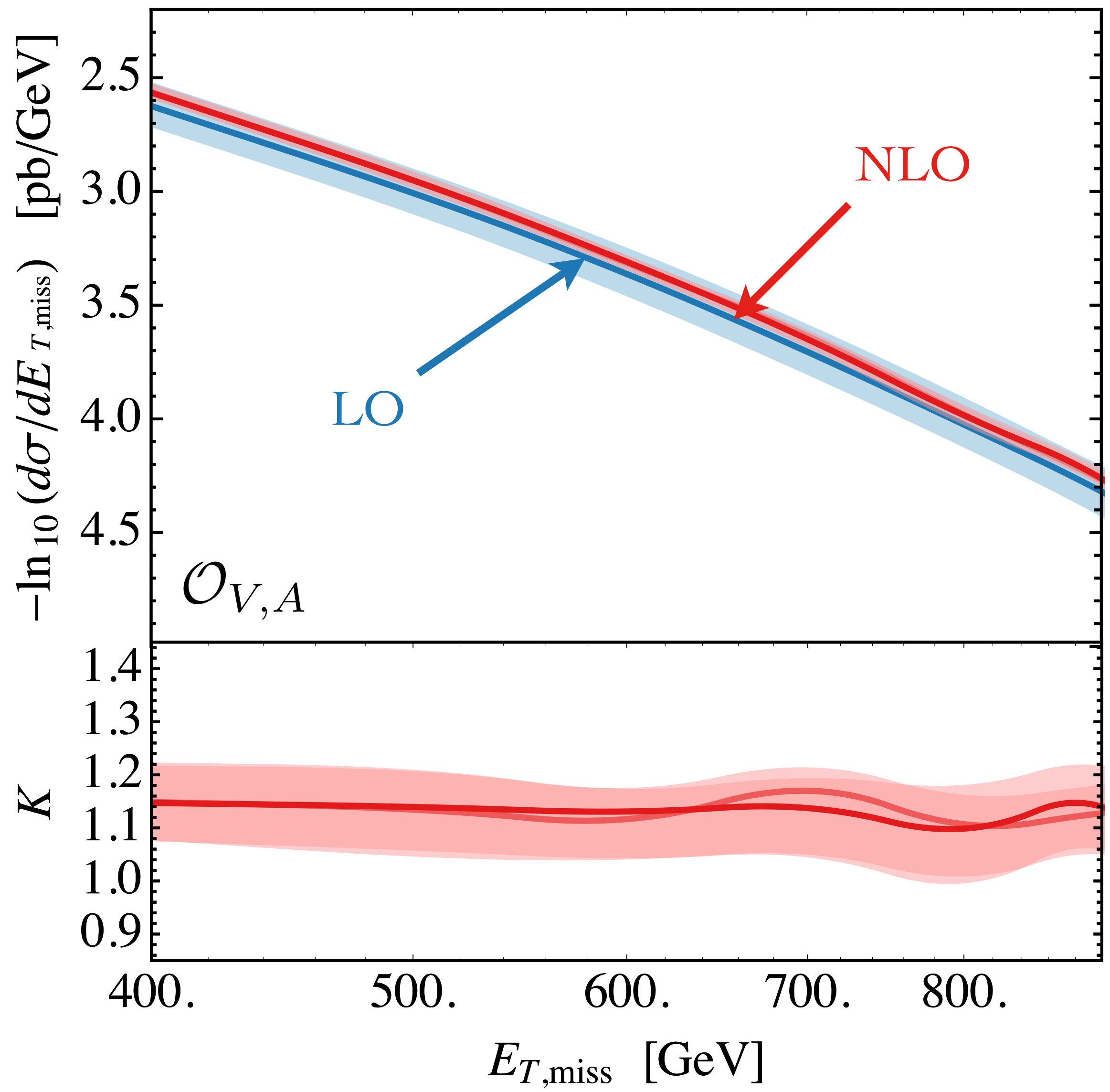
THDMP benchmark: M_A, $M_a < M_H$



Depending on Higgs-mass spectrum either $E_{T,\,\mathrm{miss}}$+Z or $E_{T,\,\mathrm{miss}}$+h provides leading constraint in large parts of parameter space

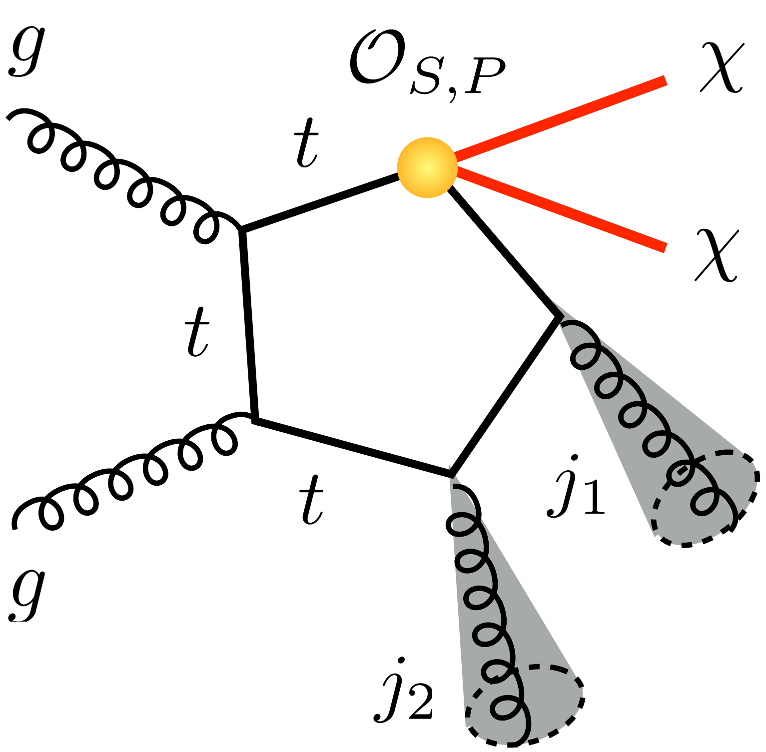
[Bauer et al., 1701.07427]

Discovery! What next?

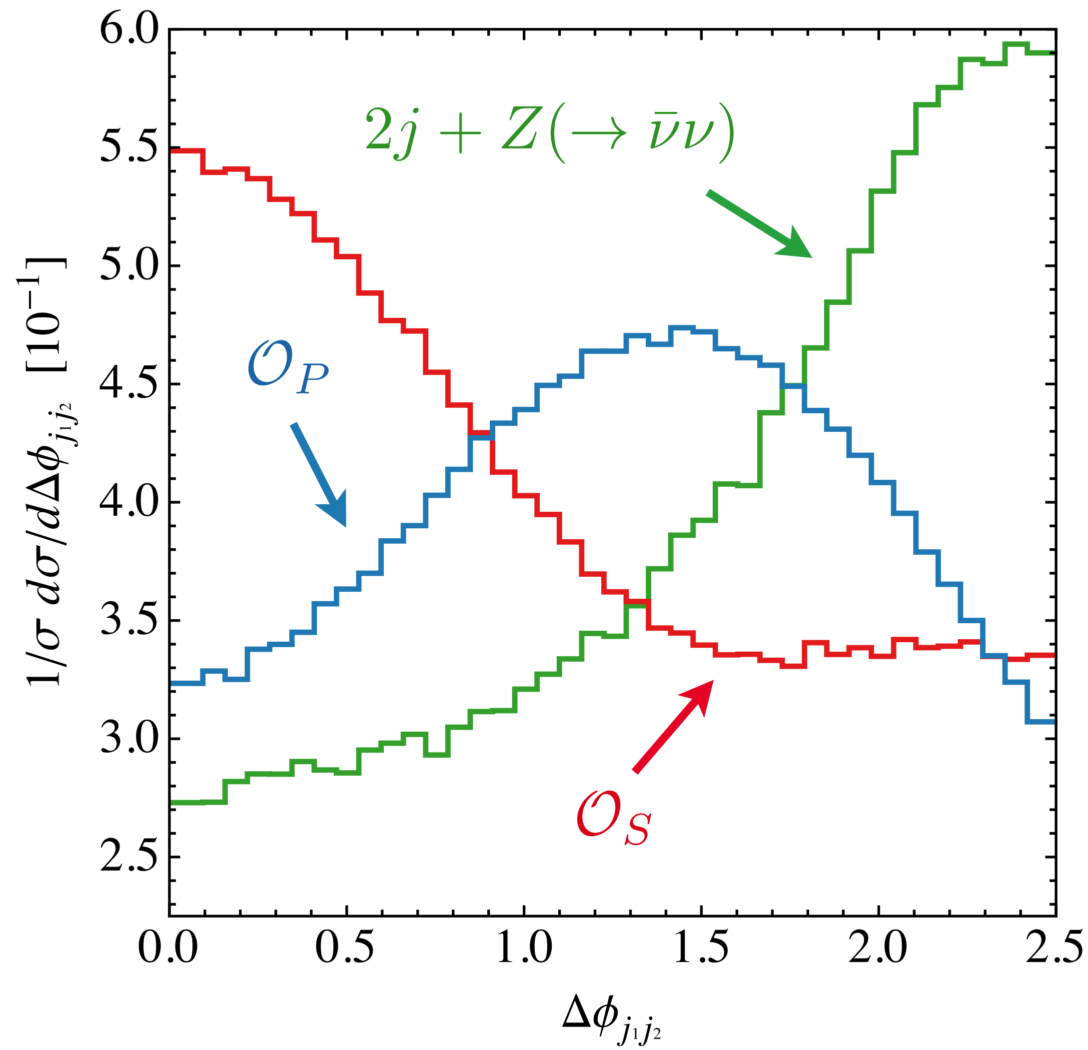


Unfortunately, mono-jet searches not sensitive to chirality of spin-1 SM-DM interactions. What about spin-0 case?

DM-pair production & 2 jets



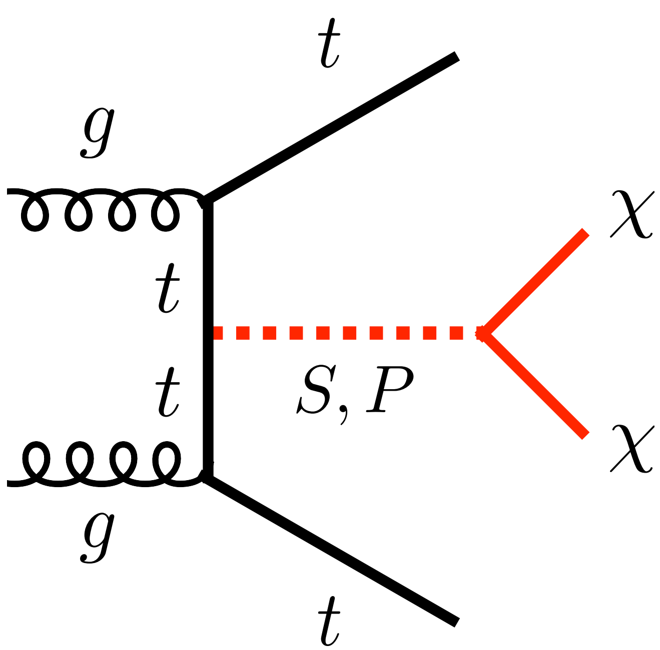
[UH et al., 1311.7131]



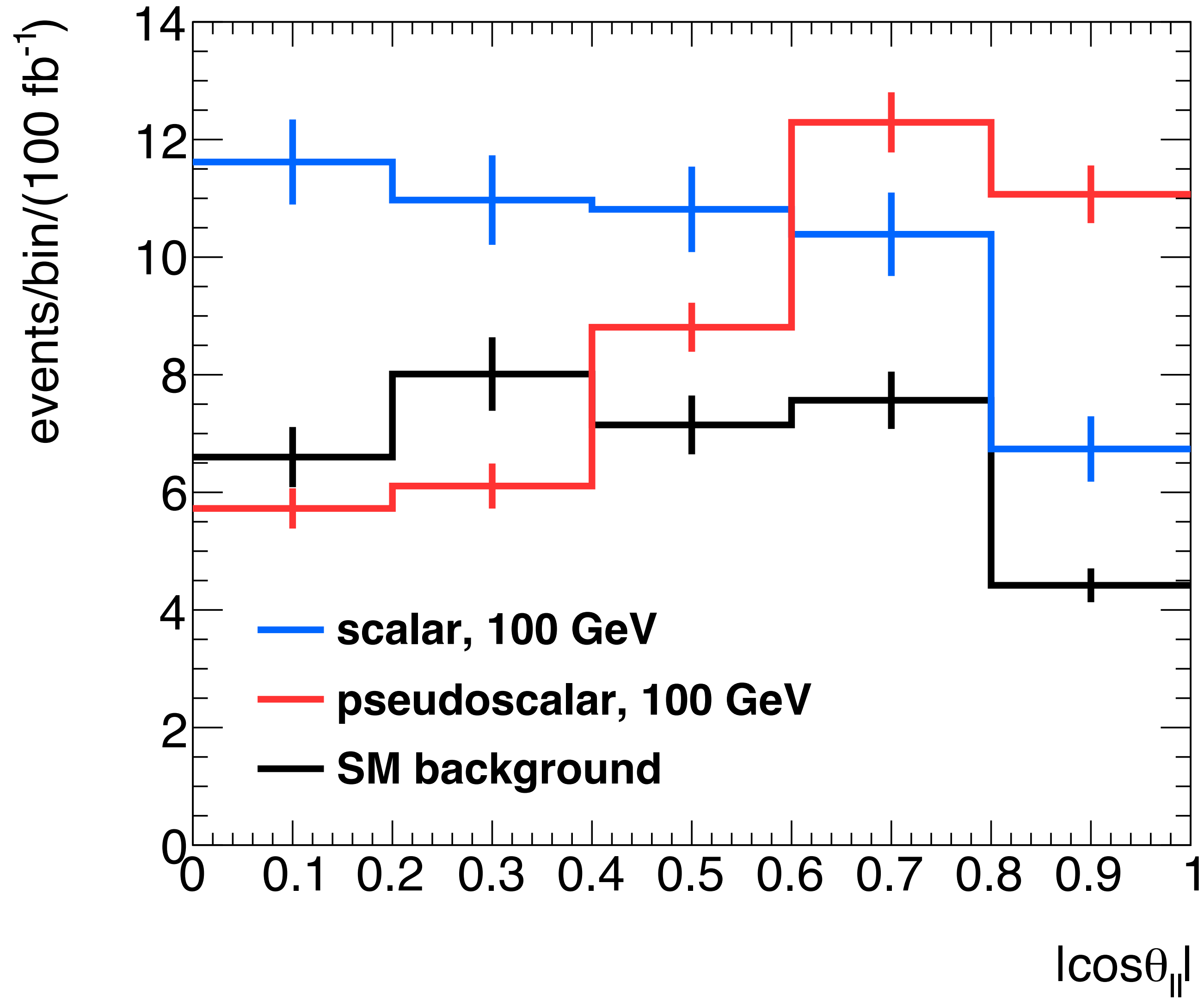
Azimuthal angle difference $\Delta\phi_{j1j2}$ in $E_{T,miss}$+2j events gold-plated observable to probe structure of DM-SM spin-0 interactions

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

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



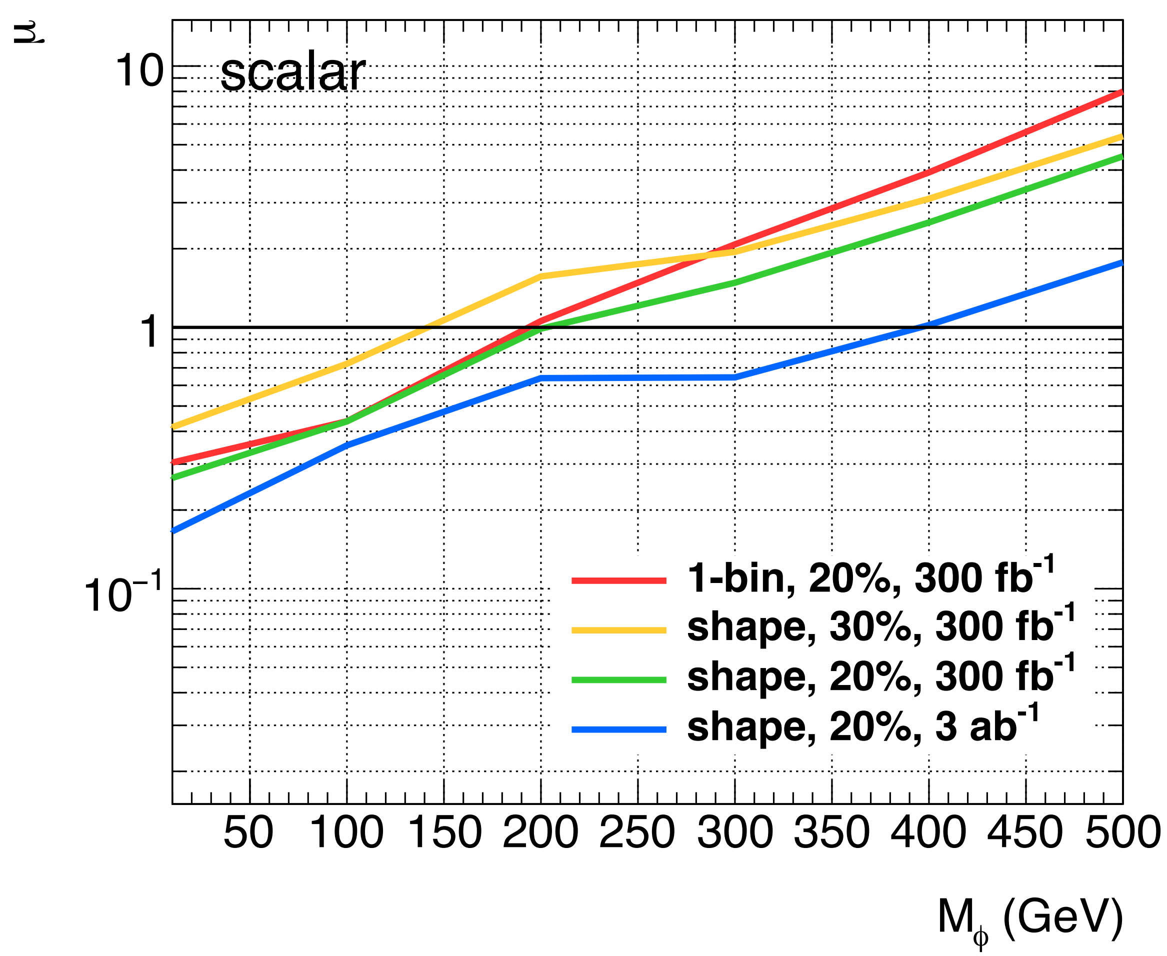
[UH, Pani & Polesello , 1611.09841]

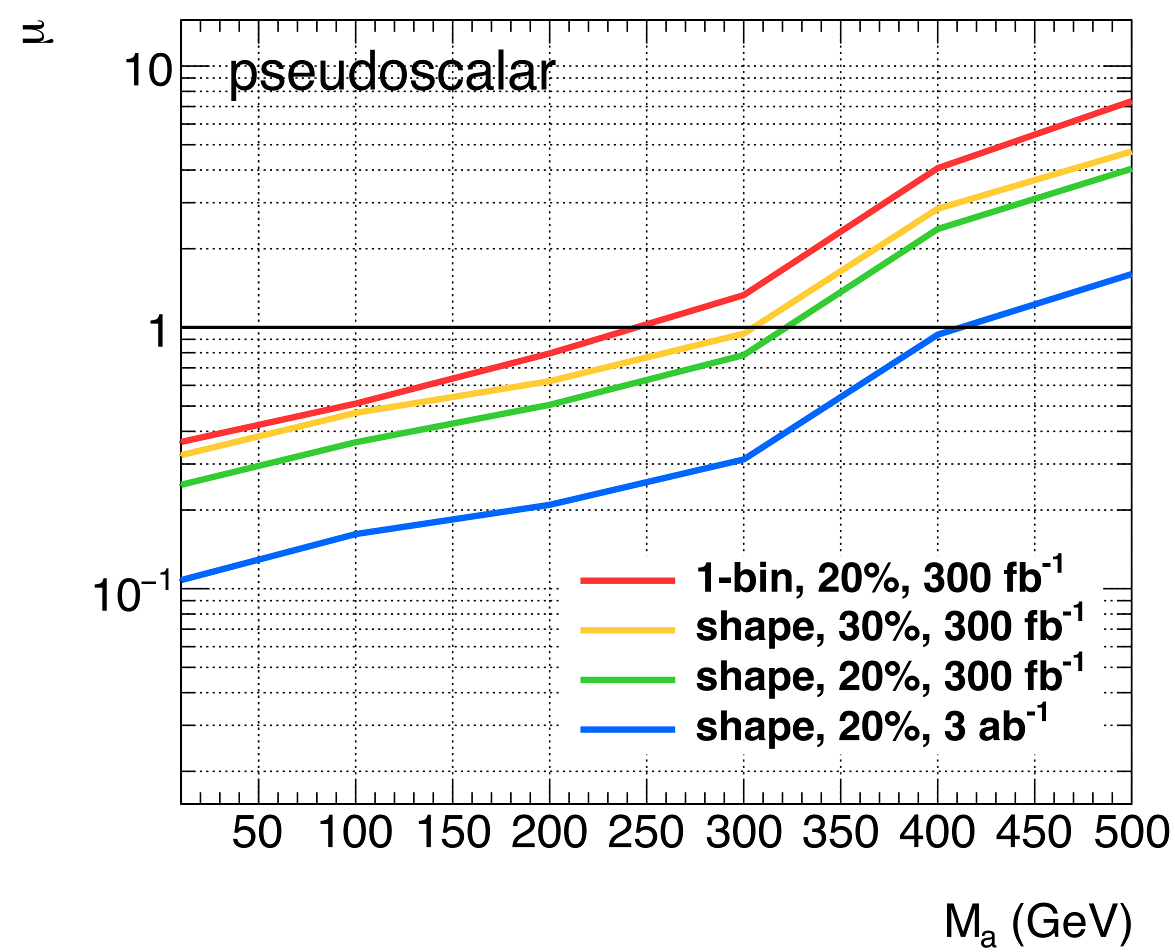


Pseudorapidity difference of two leptons $\cos(\theta_{ll}) = \tanh(\Delta\eta_{ll}/2)$ in di-leptonic top decays powerful probe CP-property of spin-0 mediators

$E_{T,miss}$+$t\bar{t}$ searches: projections

[UH, Pani & Polesello , 1611.09841]

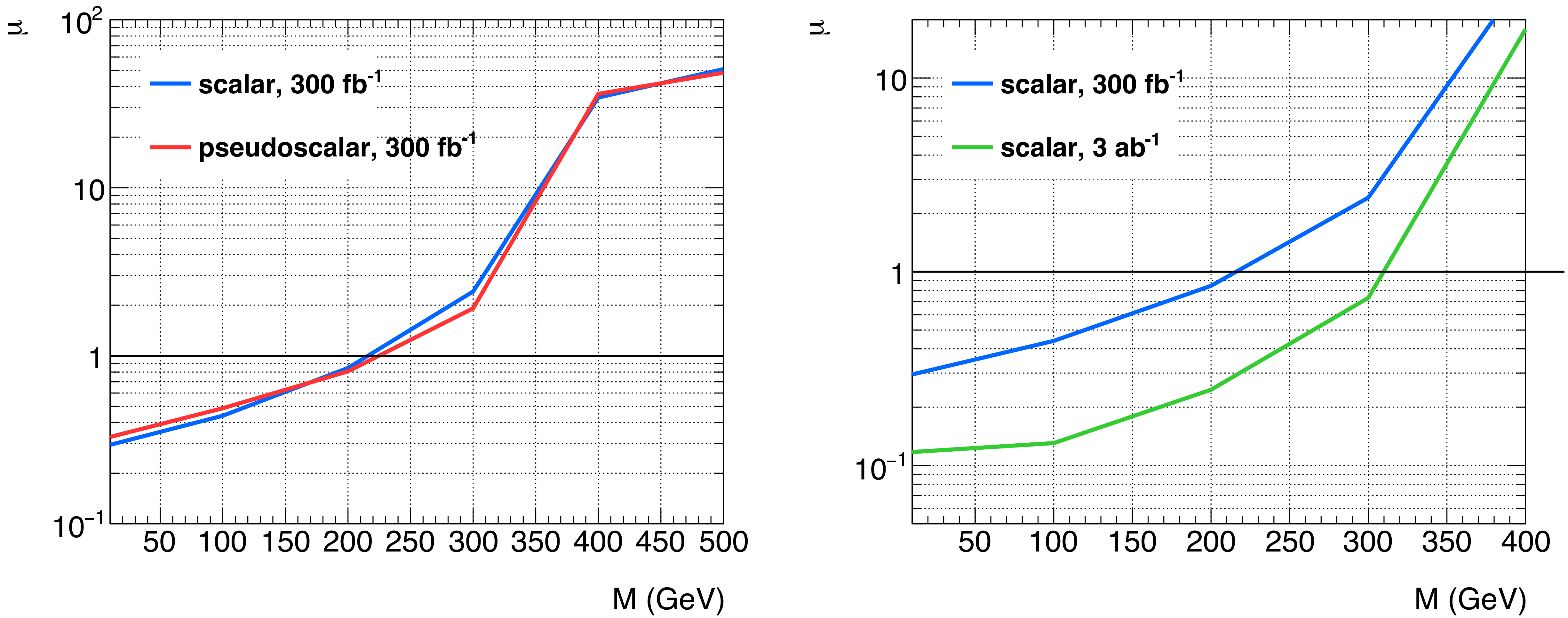




Likelihood shape fit provides a significant improvement over the counting experiment for high-mass mediators irrespectively of their CP nature

$E_{T,miss}$+$t\bar{t}$ searches: projections

[UH, Pani & Polesello , 1611.09841]



Scalar hypothesis can be excluded at 95% CL in favour of pseudoscalar one & vice versa for masses up to around 200 GeV (300 GeV) with 300 fb^{-1} (3 ab^{-1})

Conclusions

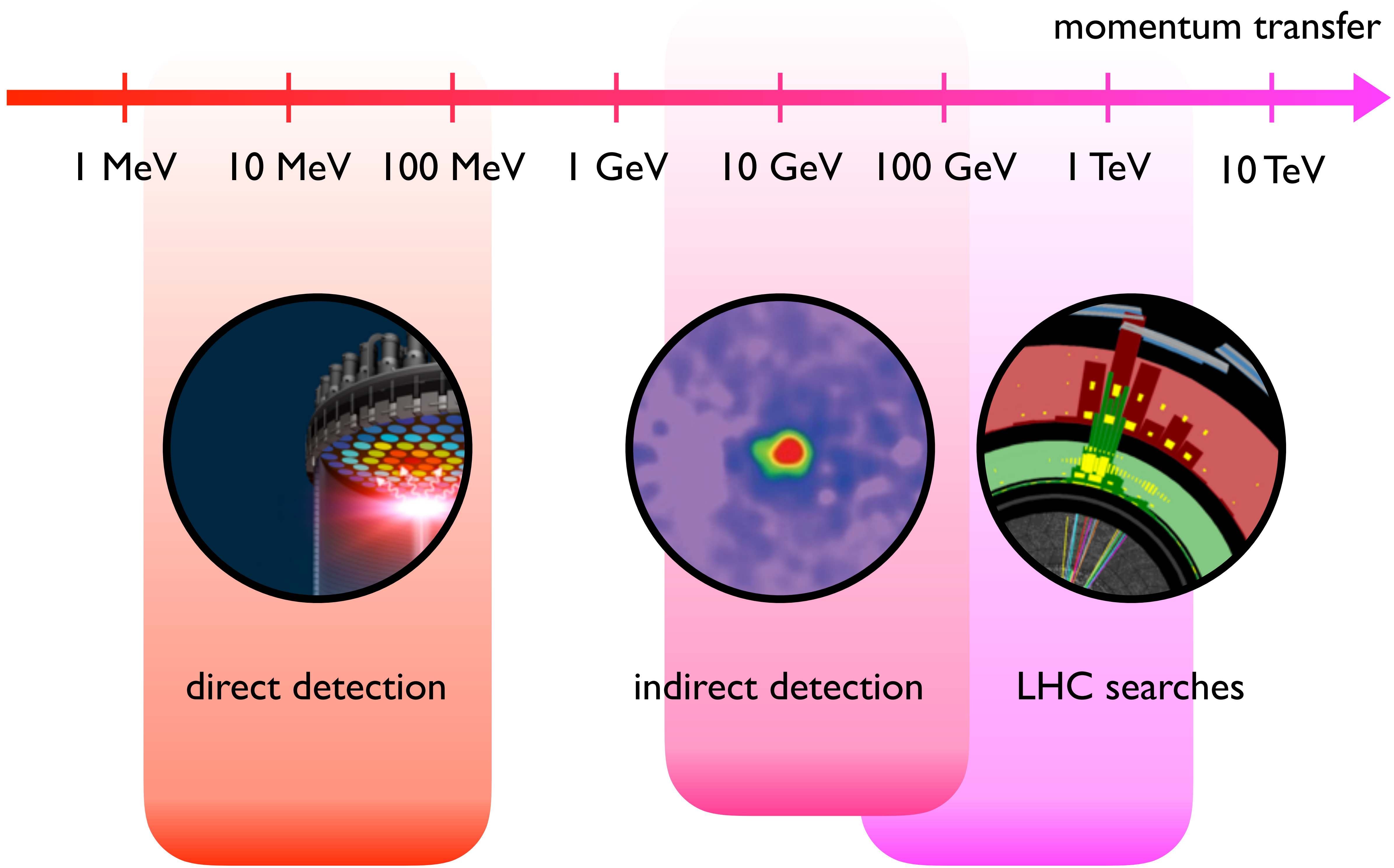
- ATLAS & CMS searches for DM in $E_{T,\,miss}$+X with X = j, γ, W, Z, h, t, $t\bar{t}$, $b\bar{b}$, … & their interpretations in context of simplified models & sometimes EFTs well-established

- Channels such as mono-Z & mono-Higgs (& maybe others) that typically provide only weak constraints can furnish leading bounds in consistent spin-0 simplified models with an extended Higgs sector

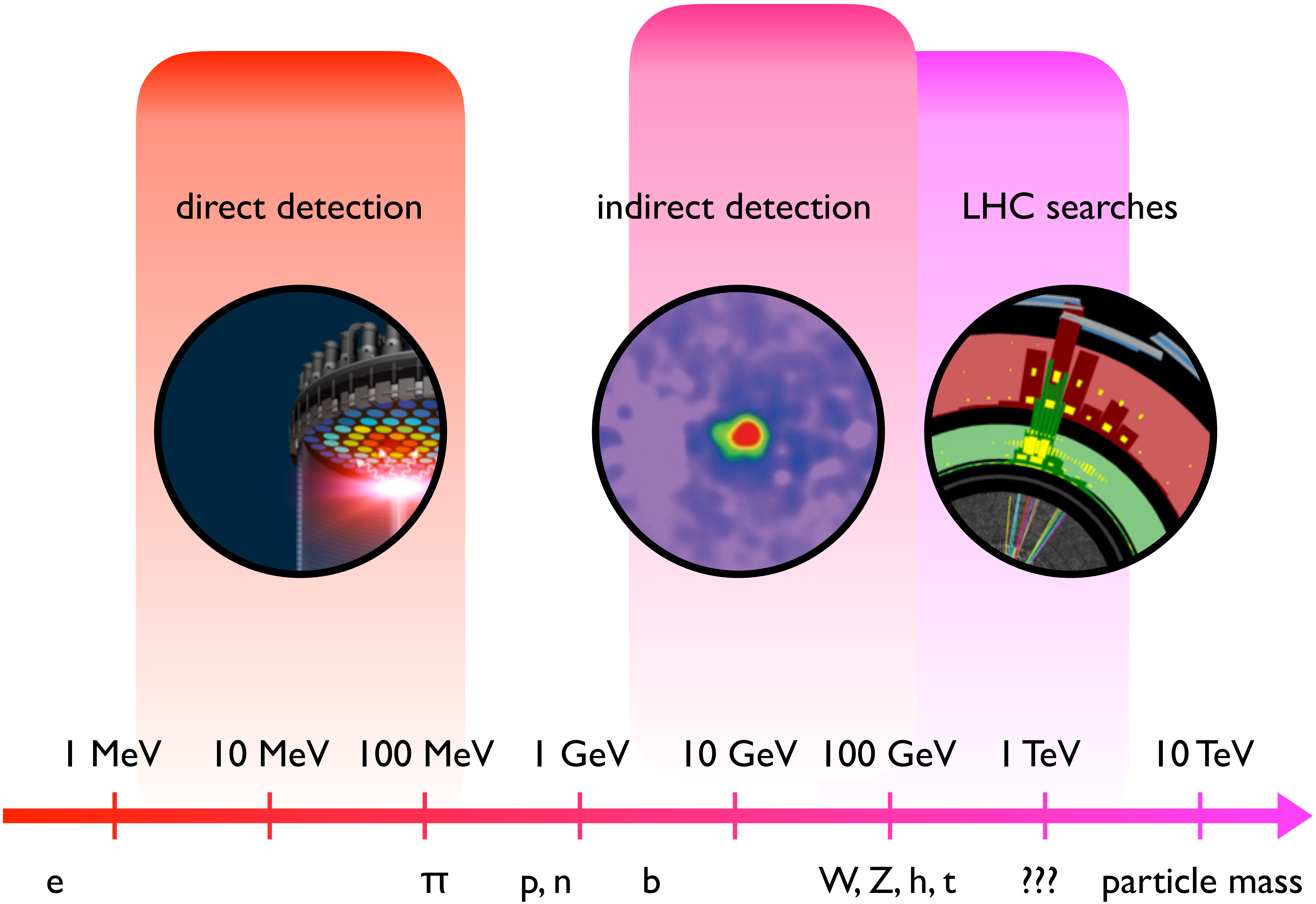
- At HL-LHC possible to search for $E_{T,\,miss}$+X more differential. In particular, angular correlations can be used to characterise portal interactions. More studies in this direction would be very welcome

Backup

Scales in DM searches



Scales in DM searches



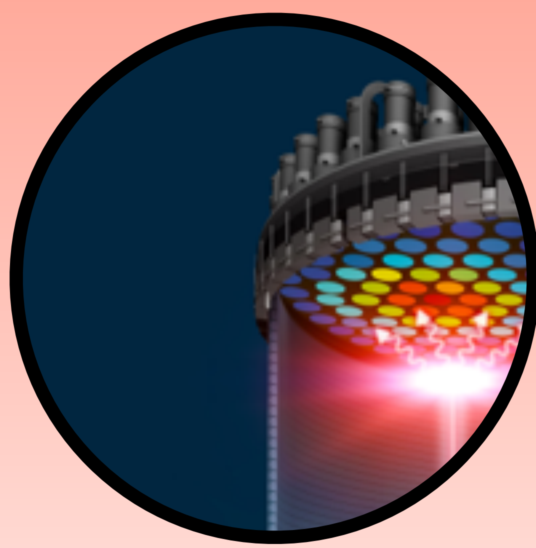
What is an effective field theory (EFT)?

[…] 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



- degrees of freedom:
  DM & light quark, gluon currents; N-π interactions
- separation of scales:
  $m_p, \ldots, m_t \gg 50$ MeV

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

EFT for LHC DM searches

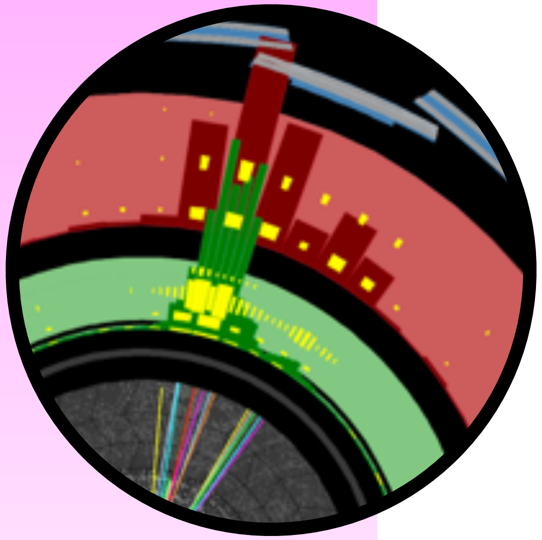
- degrees of freedom:

  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

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 $E_{T,\,\mathrm{miss}}$ & other distributions in both EFT & simplified model

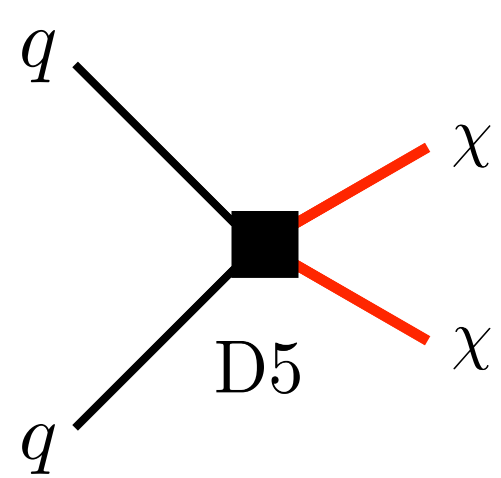
(iv) If shapes of distributions are similar, can use EFT as proxy for simplified model, otherwise not

[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

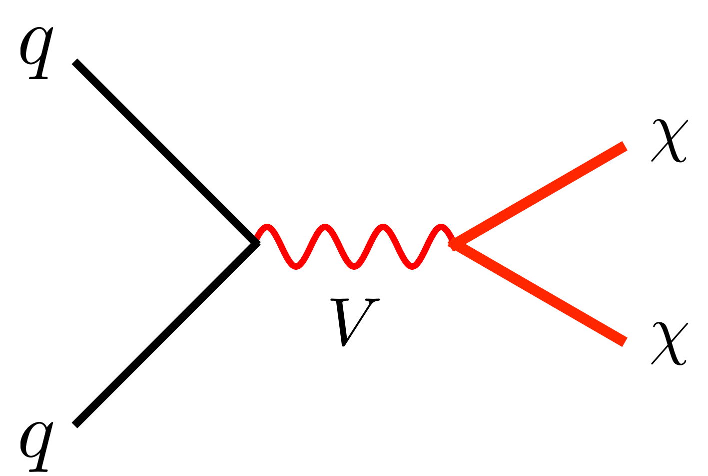
Vector operator:

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



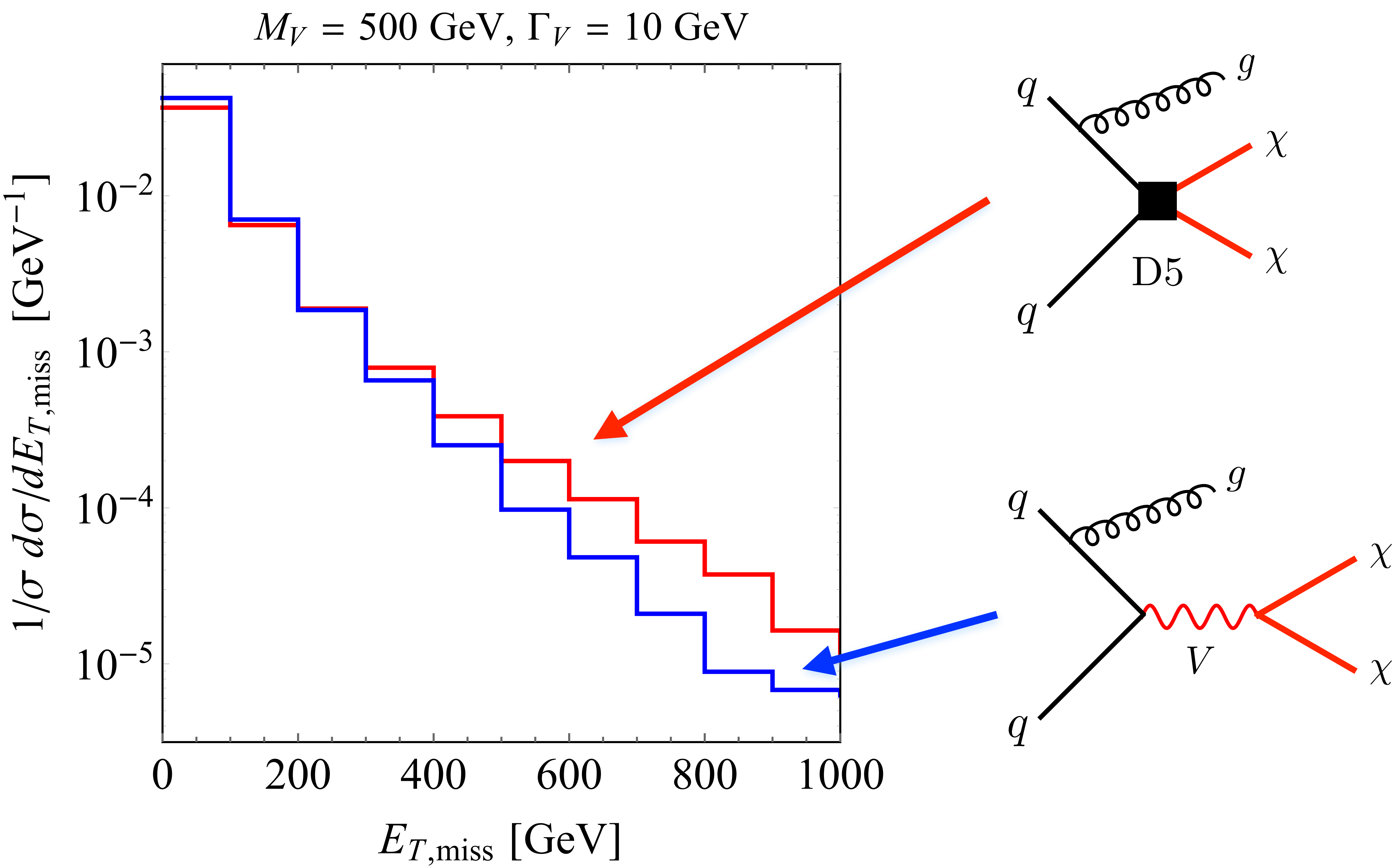
Spin-1 simplified model:

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



[Dudas et al., 0904.1745; Fox et al., 1104.4127; Frandsen et al., 1204.3839; …; see also talk by Park]

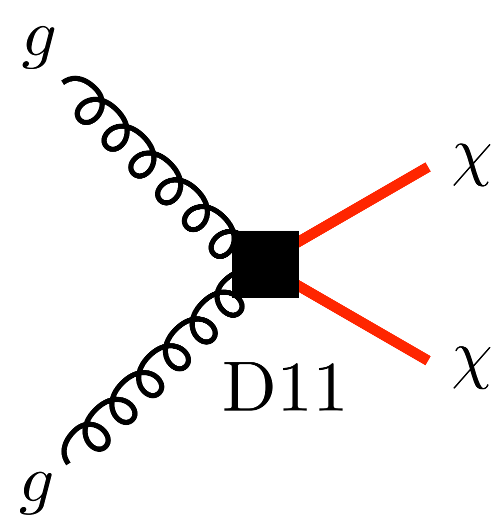
D5: EFT vs. simplified model



Loop-level example

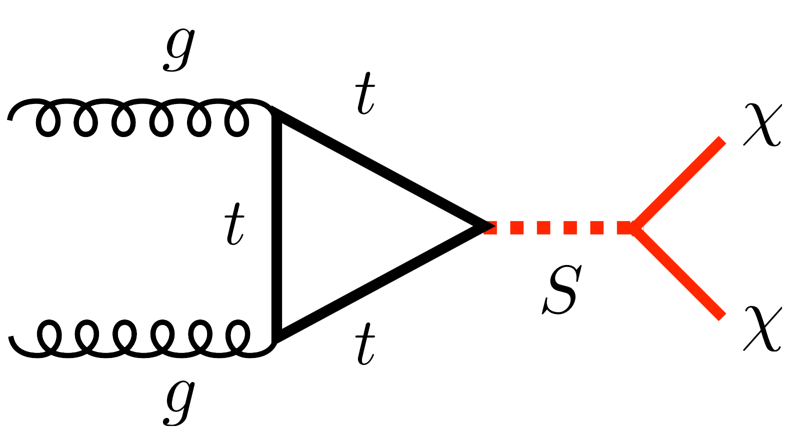
Gluonic operator:

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



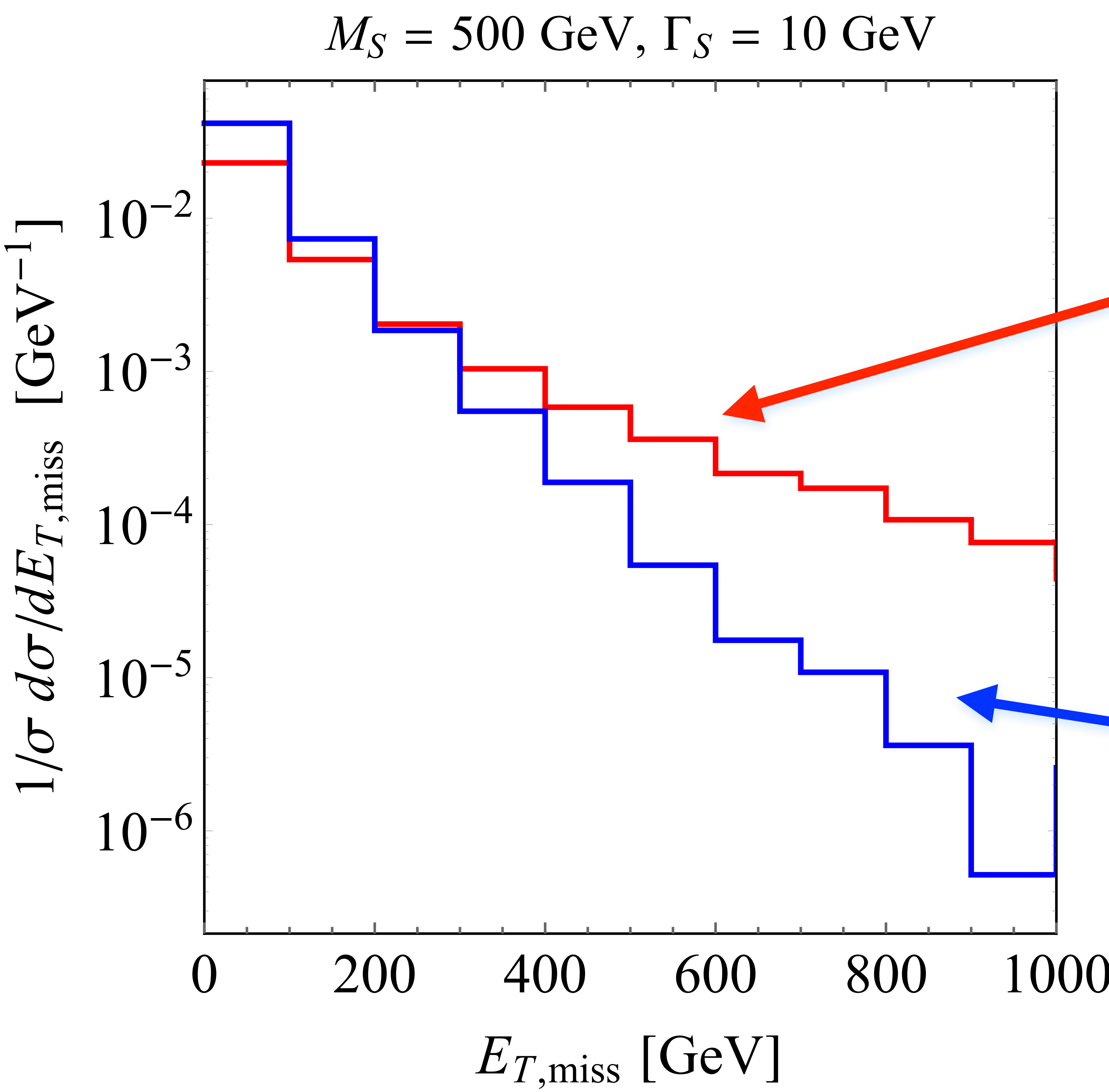
Spin-0 simplified model:

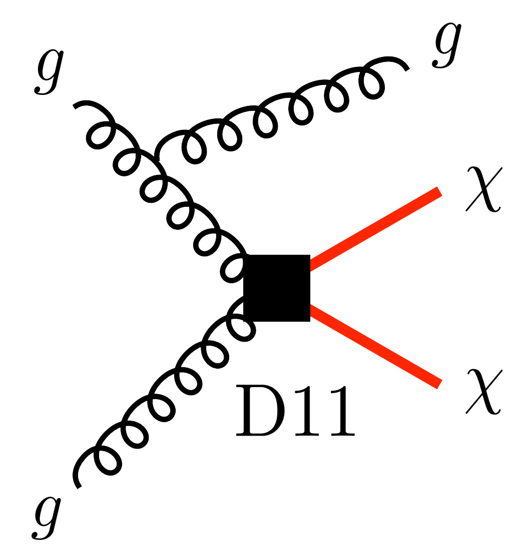
$$\mathcal{L}_S \supset g_\chi \bar{\chi}\chi S + \sum_q \frac{g_q y_q}{\sqrt{2}}\,\bar{q}qS$$

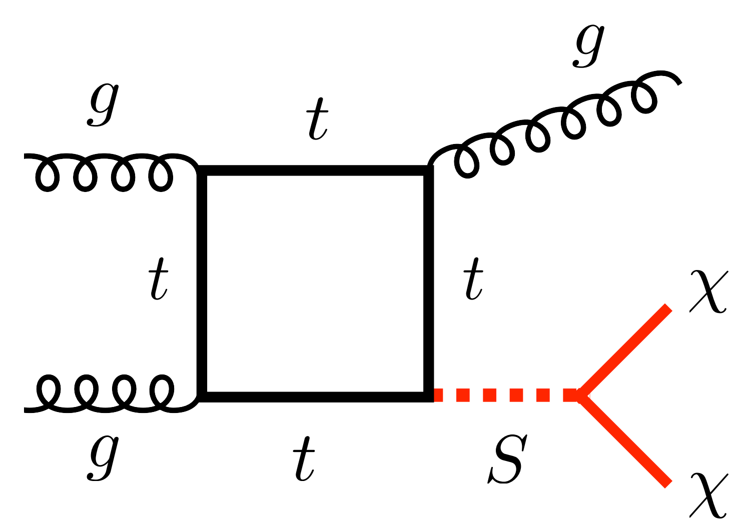


[UH et al., 1208.4605, 1311.713, 1503.00691; Buckley et al.,1410.6497; Harris et al., 1411.0535; …]

D11: EFT vs. simplified model







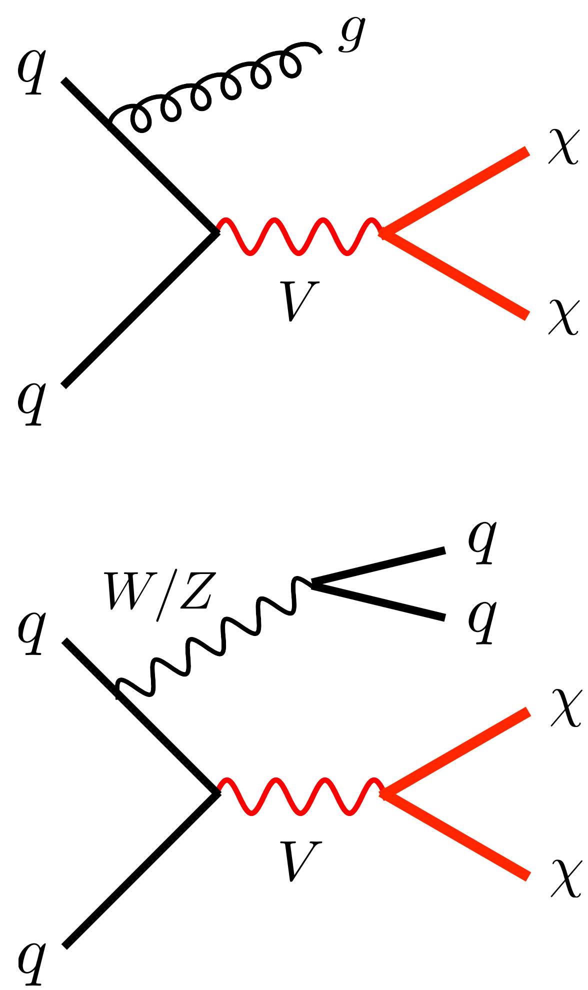
EFT vs. simplified models: verdict

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 $E_{T,\,miss}$ searches in LHC Run II

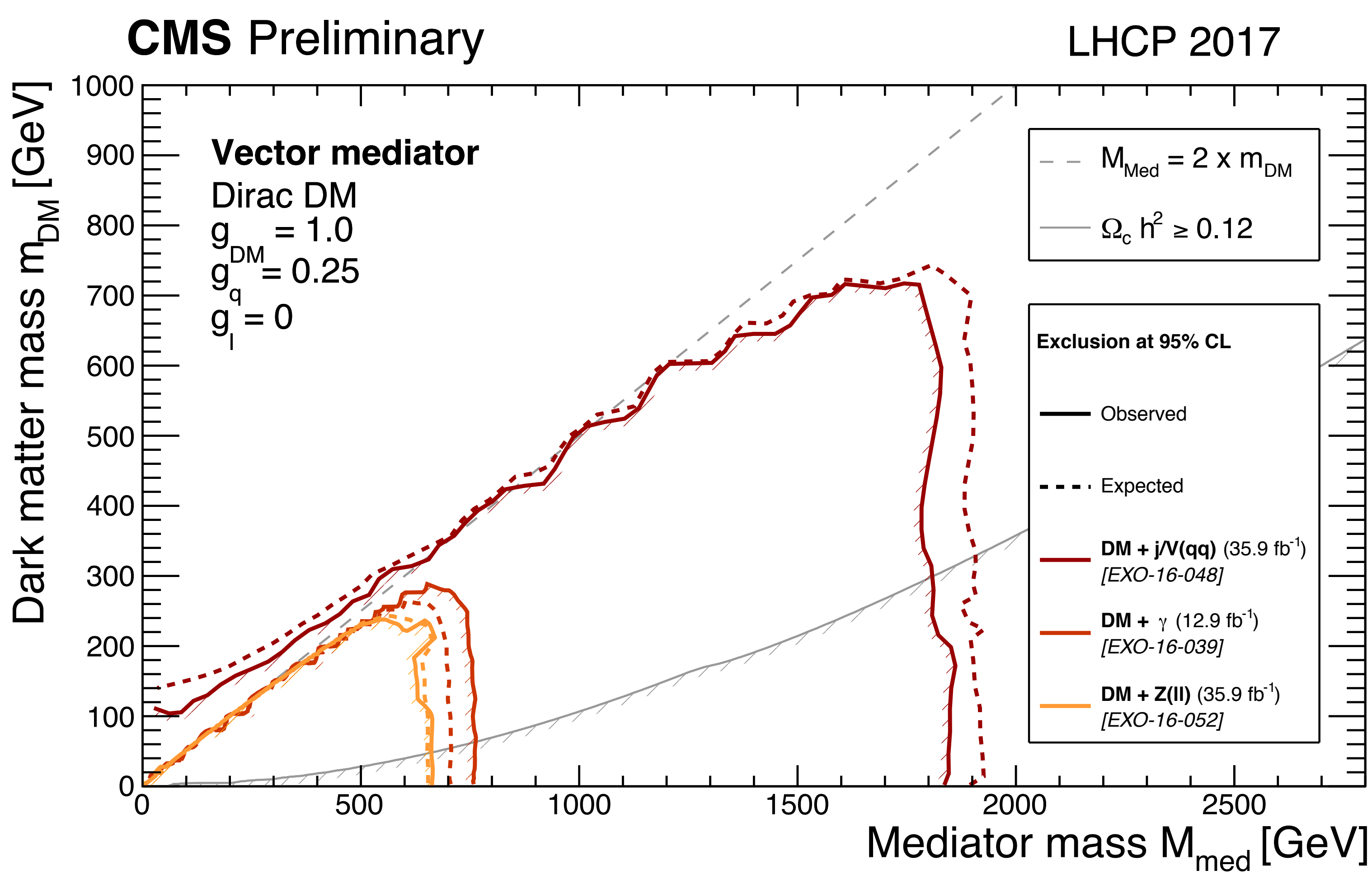
But in case of strongly-coupled DM candidates — composite fermions, pseudo-Nambu-Goldstone bosons, Goldstini, … — EFT appropriate & sometimes even necessary to describe most important interactions at LHC

[see e.g. Bruggisser, Riva & Urbano, 1607.02474 & 1607.02475 for EFT discussion of strongly-coupled DM]

Spin-1 simplified models: 13 TeV limits



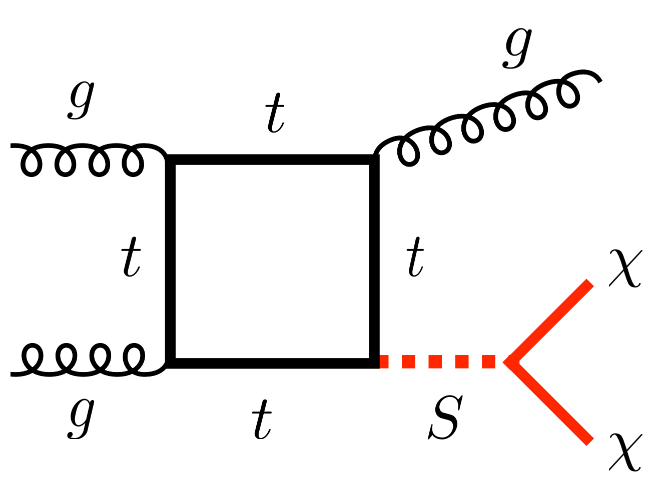
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO]

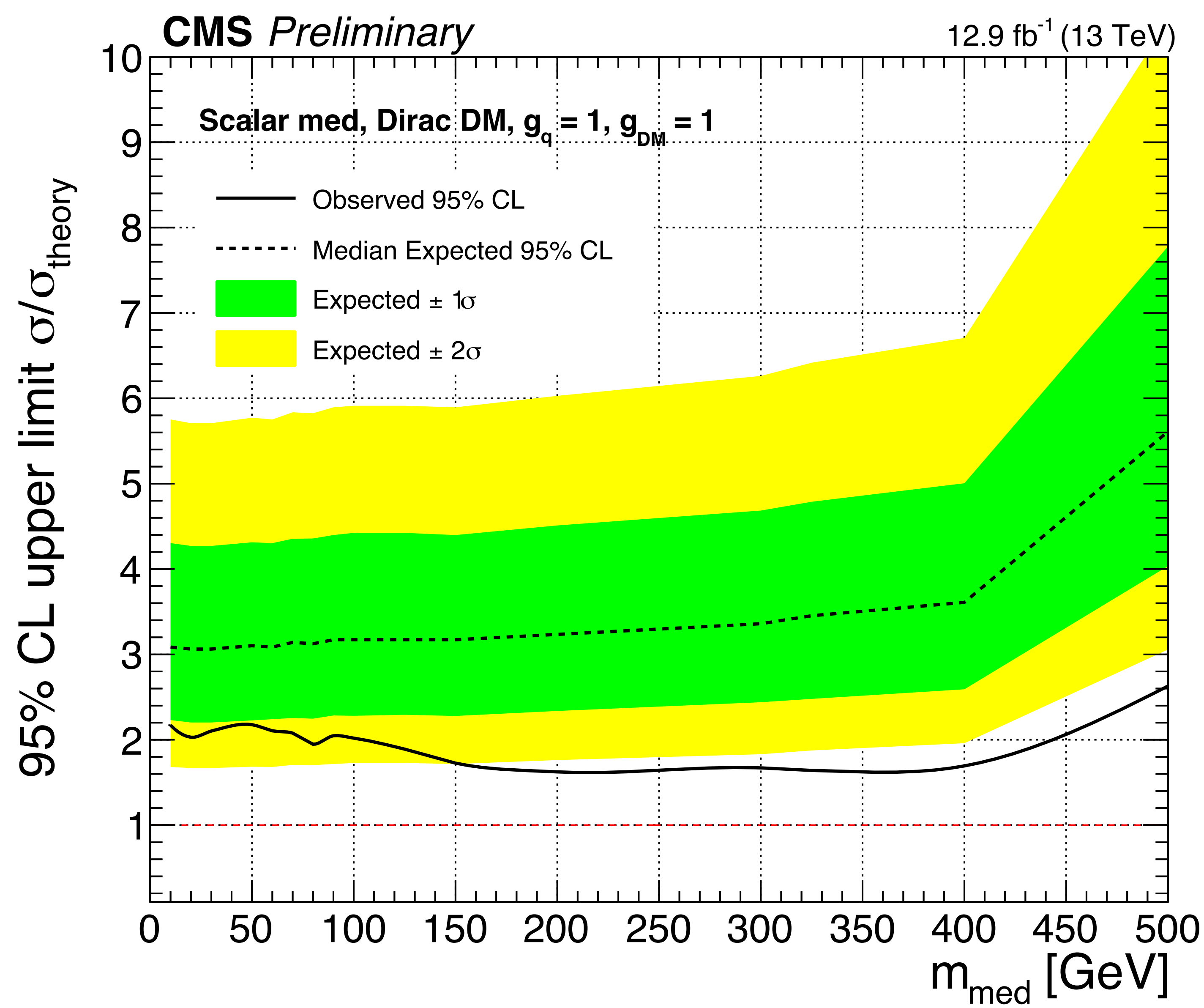


Latest $E_{T,\,miss}$+jets searches exclude mediator masses up to around 1.8 TeV for both vector & axialvector exchange if $g_q = 0.25$, $g_{DM} = 1$

Spin-0 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]

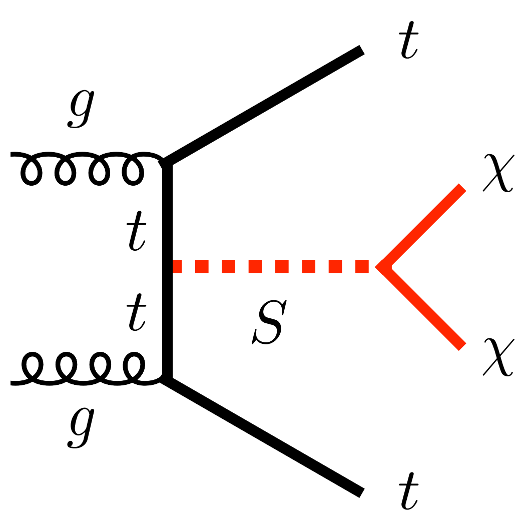


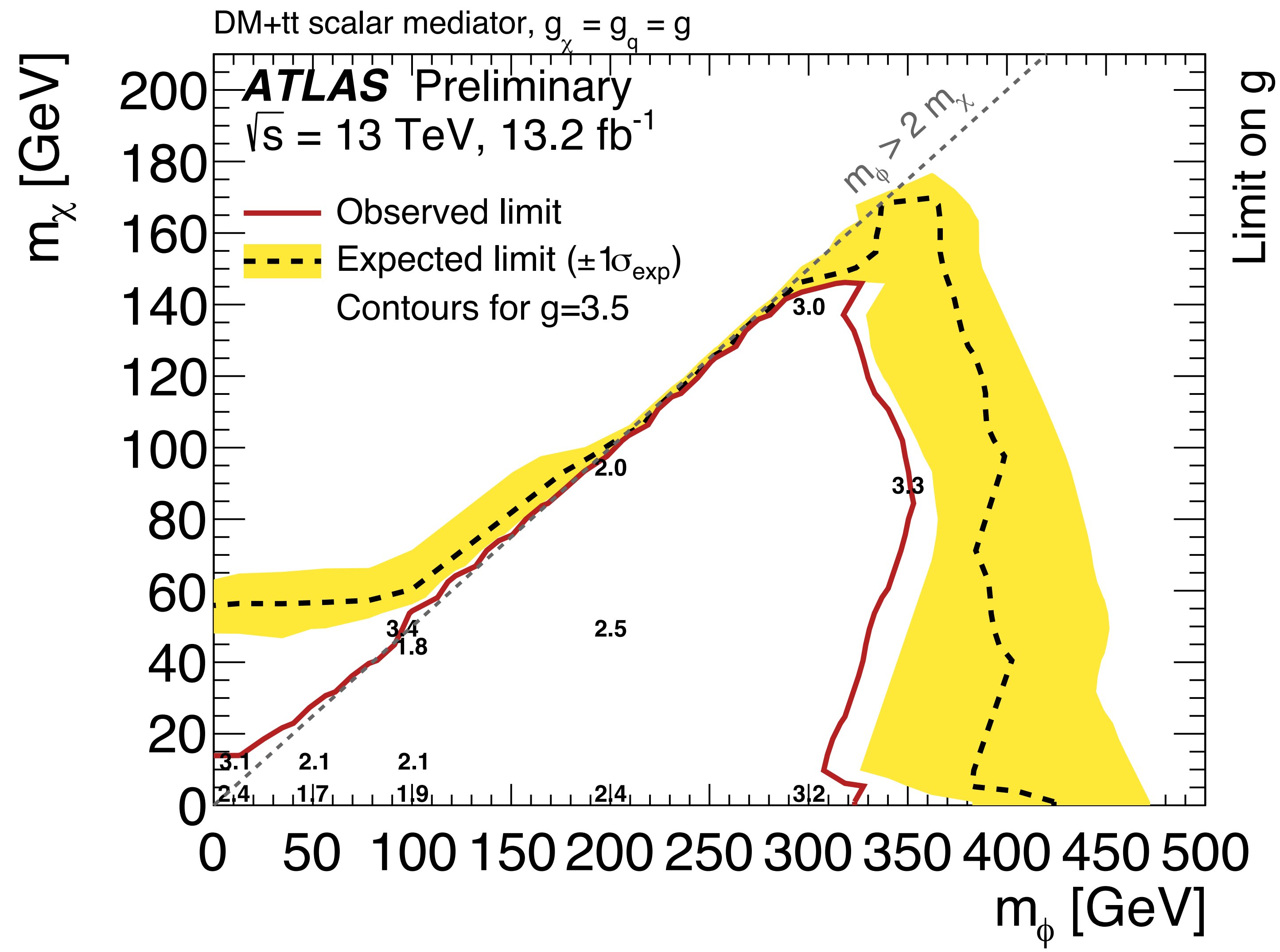


Mono-jet searches not yet sensitive to scalar models with weak couplings

Spin-0 simplified models: 13 TeV limits

[ATLAS-CONF-2016-050]

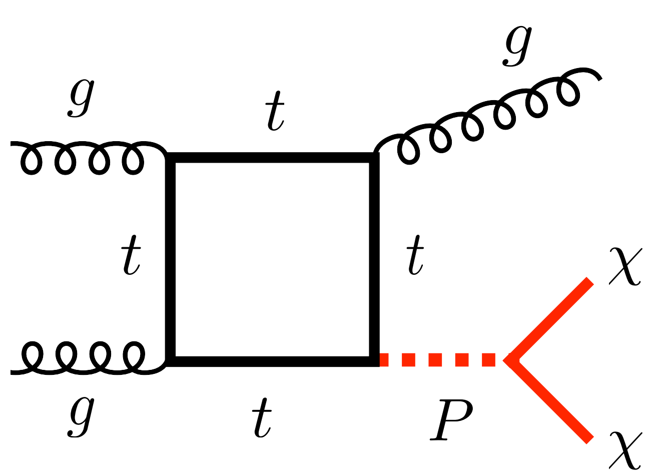


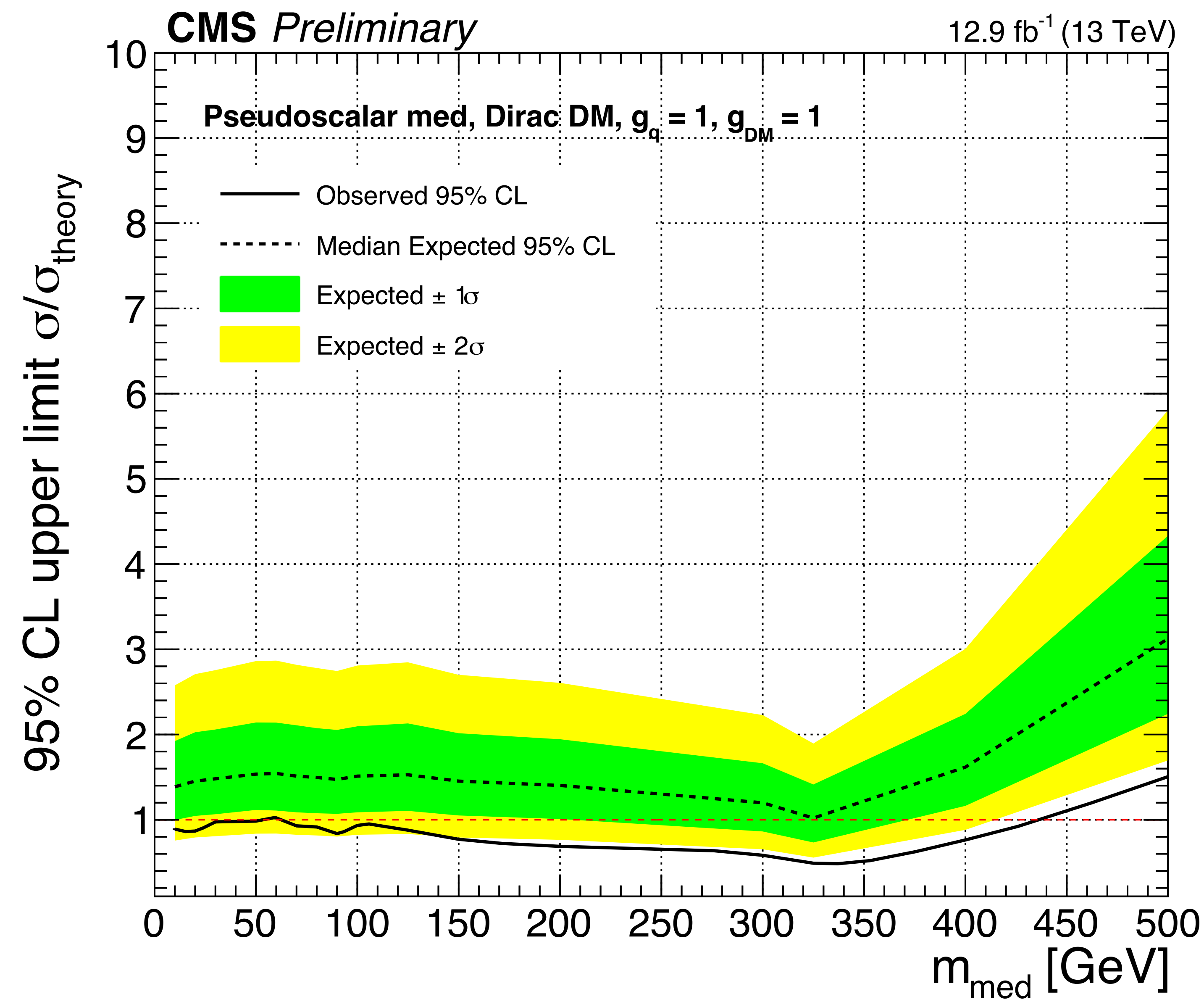


Strongly-coupled scalar models with mediator masses of 300 GeV can be tested via $E_{T,\text{miss}}+t\bar{t}$. Mediator broad in large parts of parameter space

Spin-0 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]

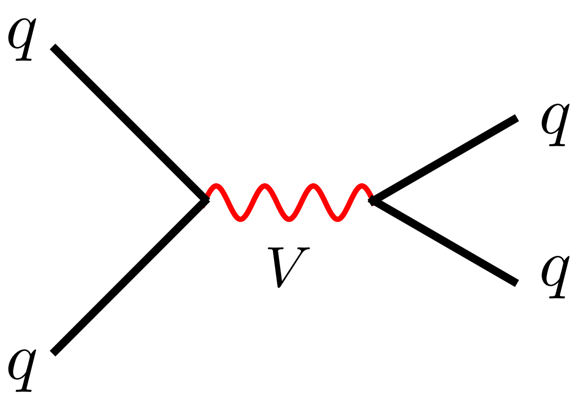


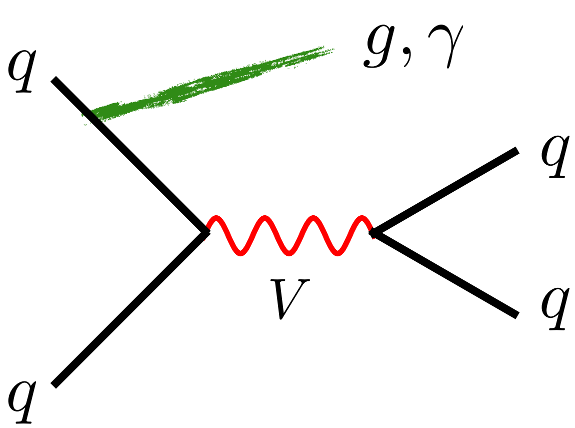


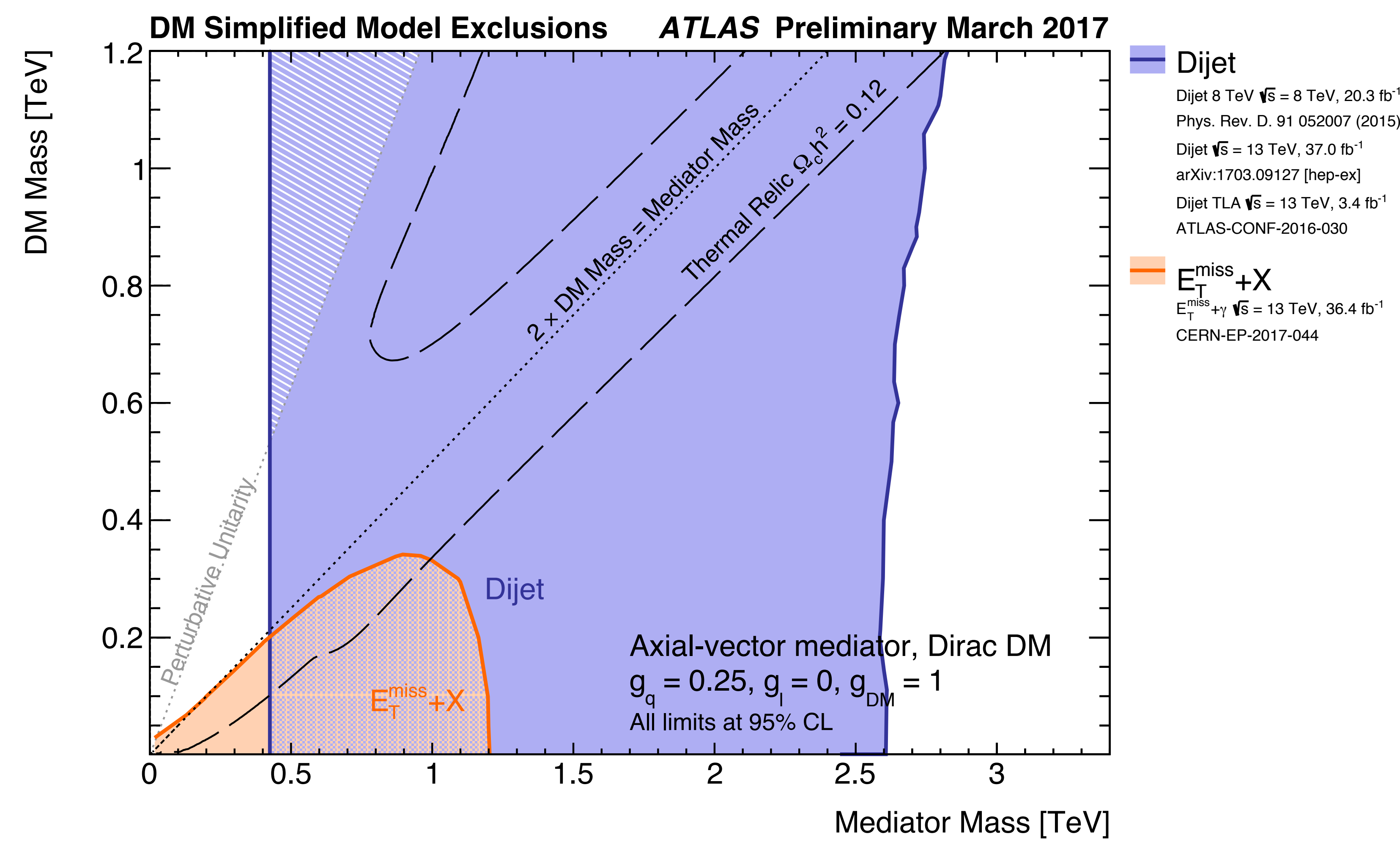
Since pseudoscalar production enhanced by a factor of more than 2, mediator masses close to 450 GeV are excluded for $g_q = g_{DM} = 1$

Spin-1 simplified models: di-jet limits

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



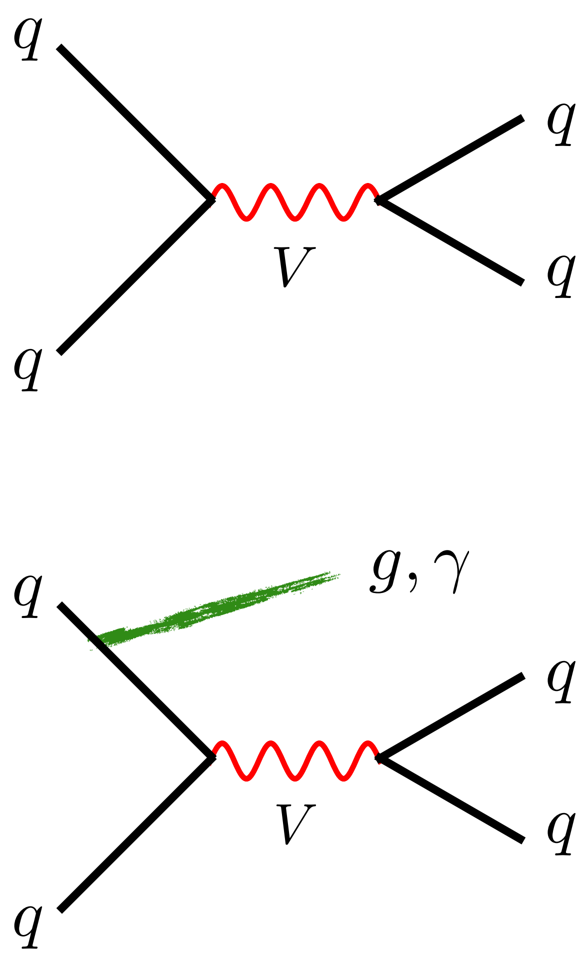


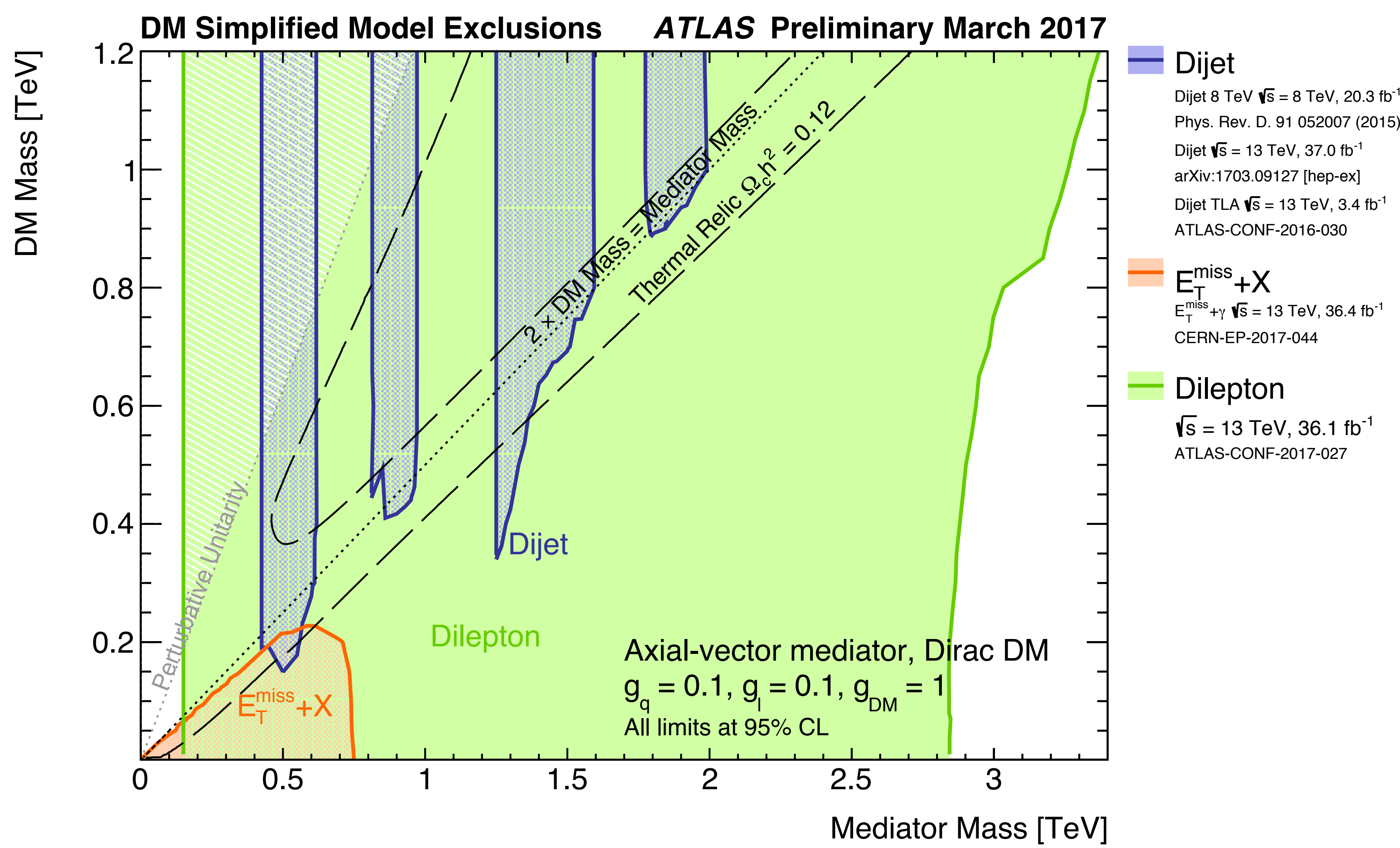


For coupling choice $g_q = 0.25$, $g_{DM} = 1$ di-jet searches provide complementary constraints & exclude mediator masses from around 400 GeV to 2.8 TeV

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_{DM} kept perturbative mono-jet bounds also mitigated in such a case

Other LHC non-$E_{T,\,\mathrm{miss}}$ 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 $g_l \neq 0$

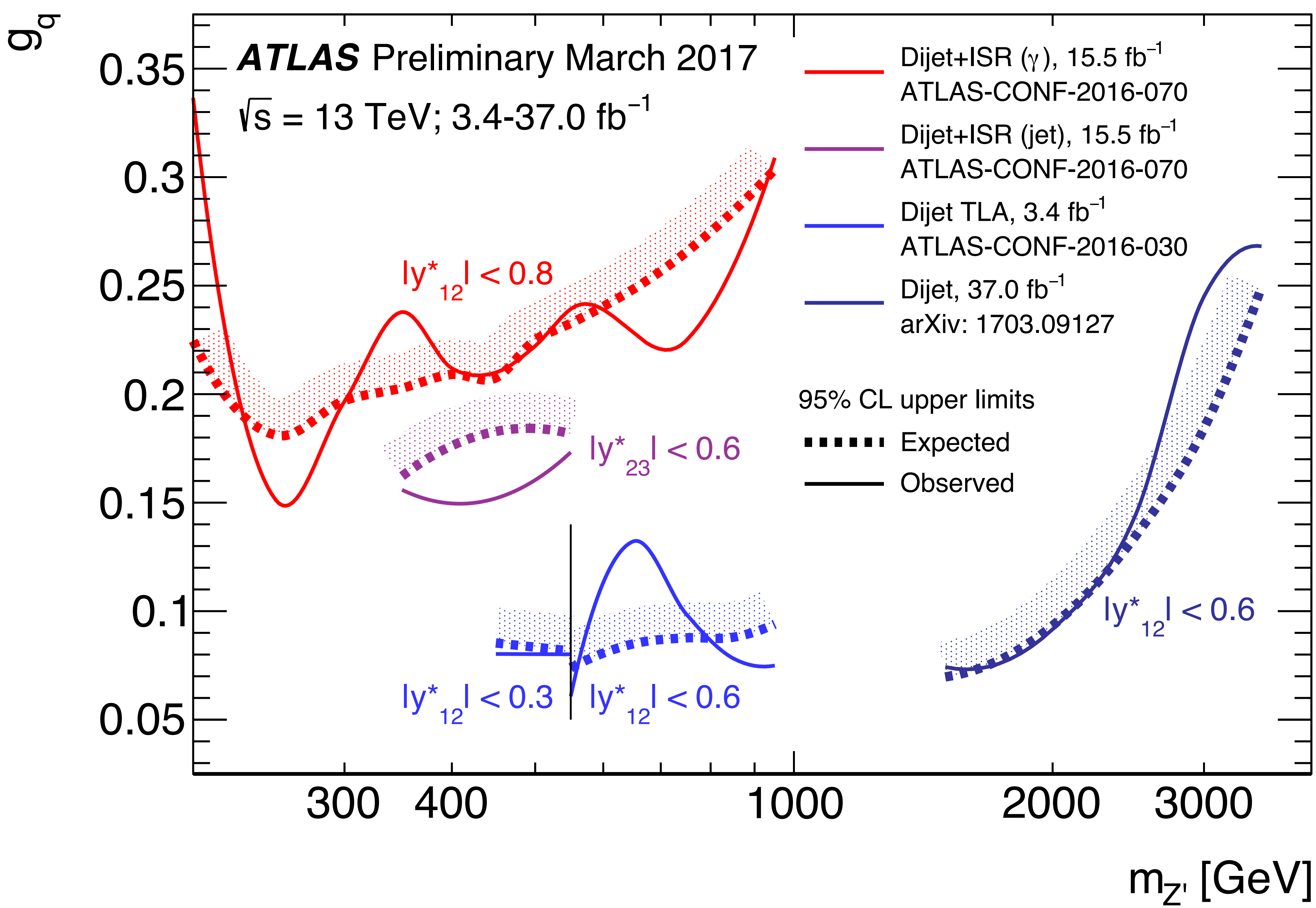
[see Kahlhoefer et al., 1510.02110]

(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

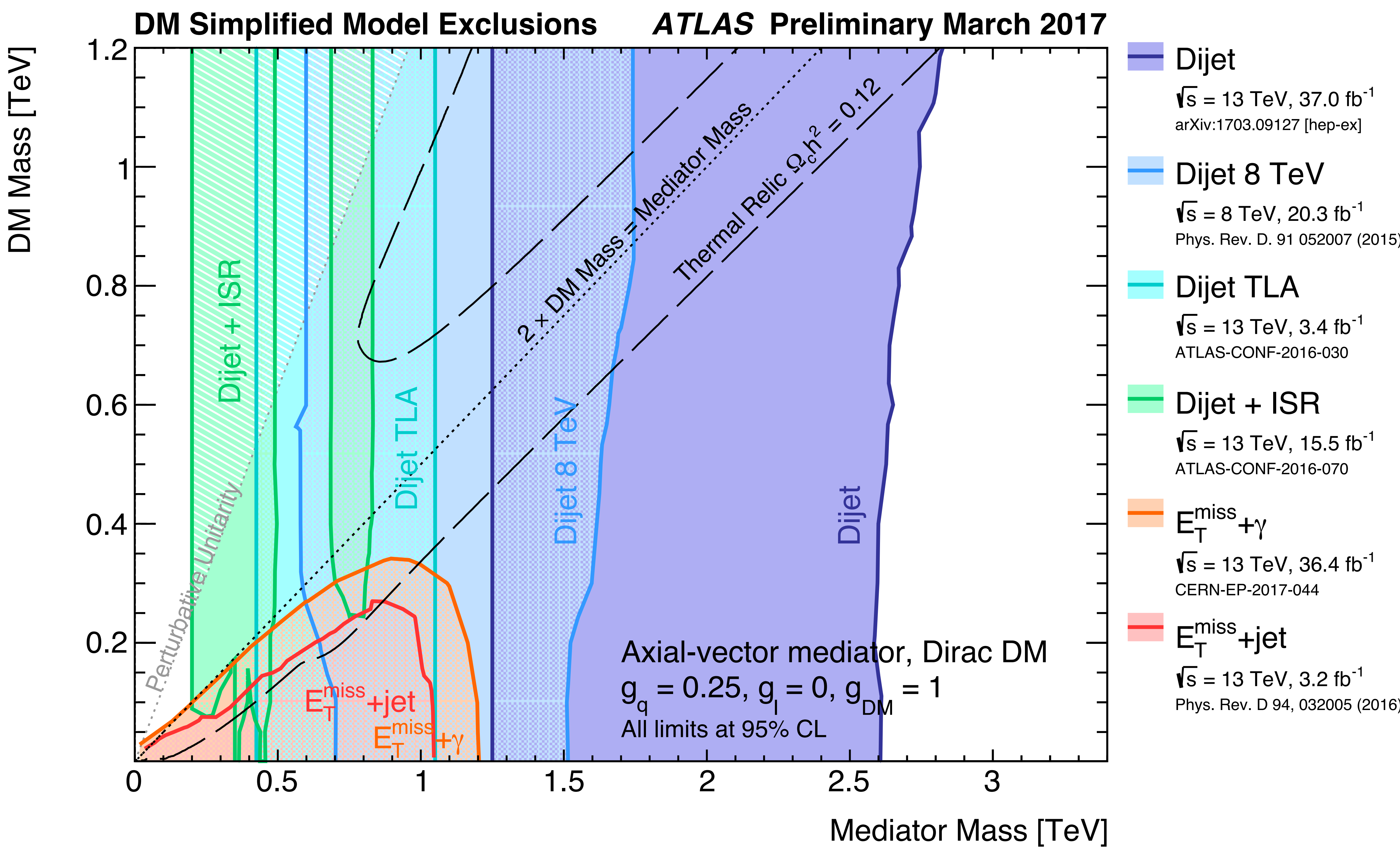
[see Chala et al., 1503.05916]

Di-jet limits

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



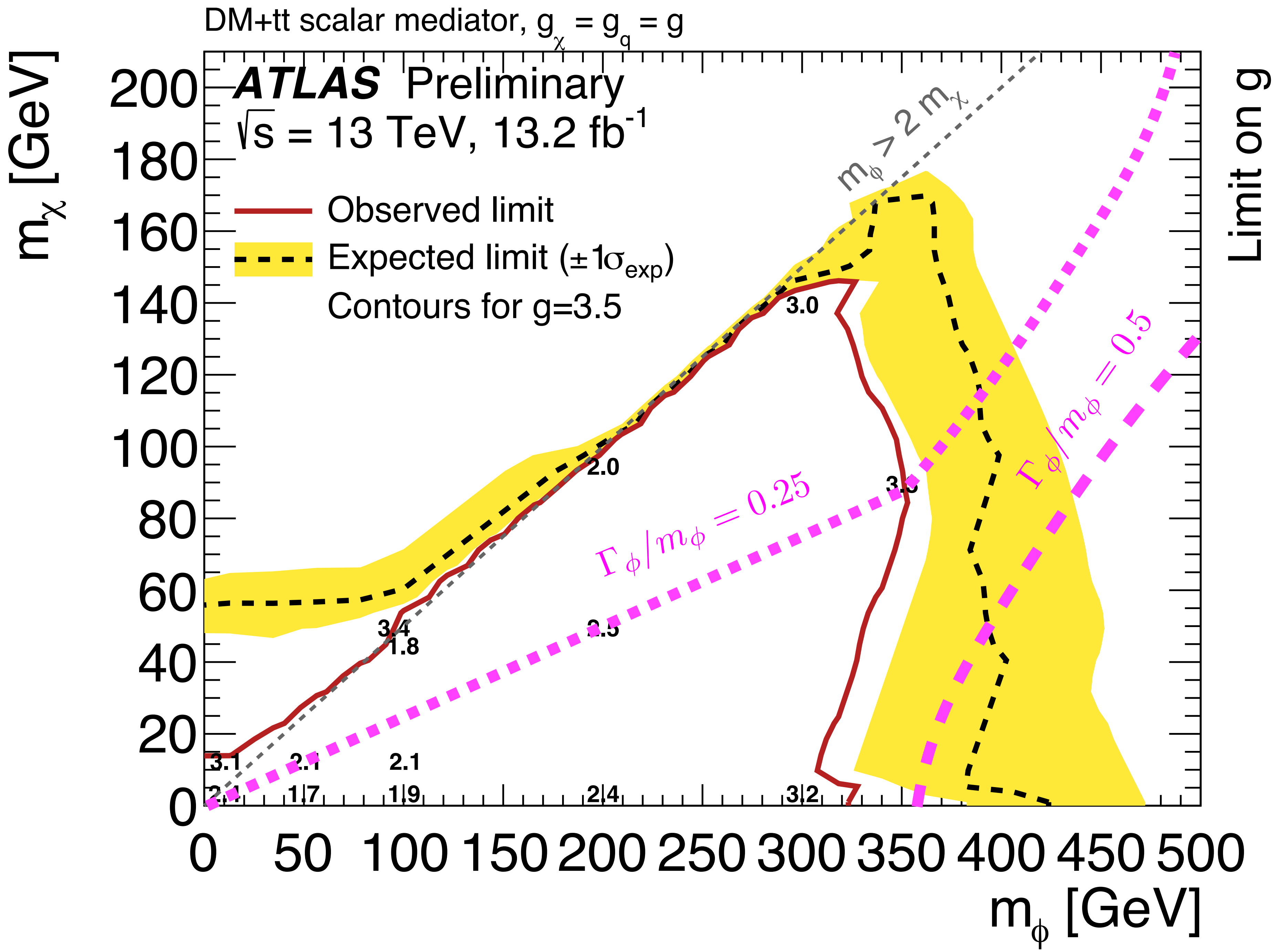
Di-jet limits



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

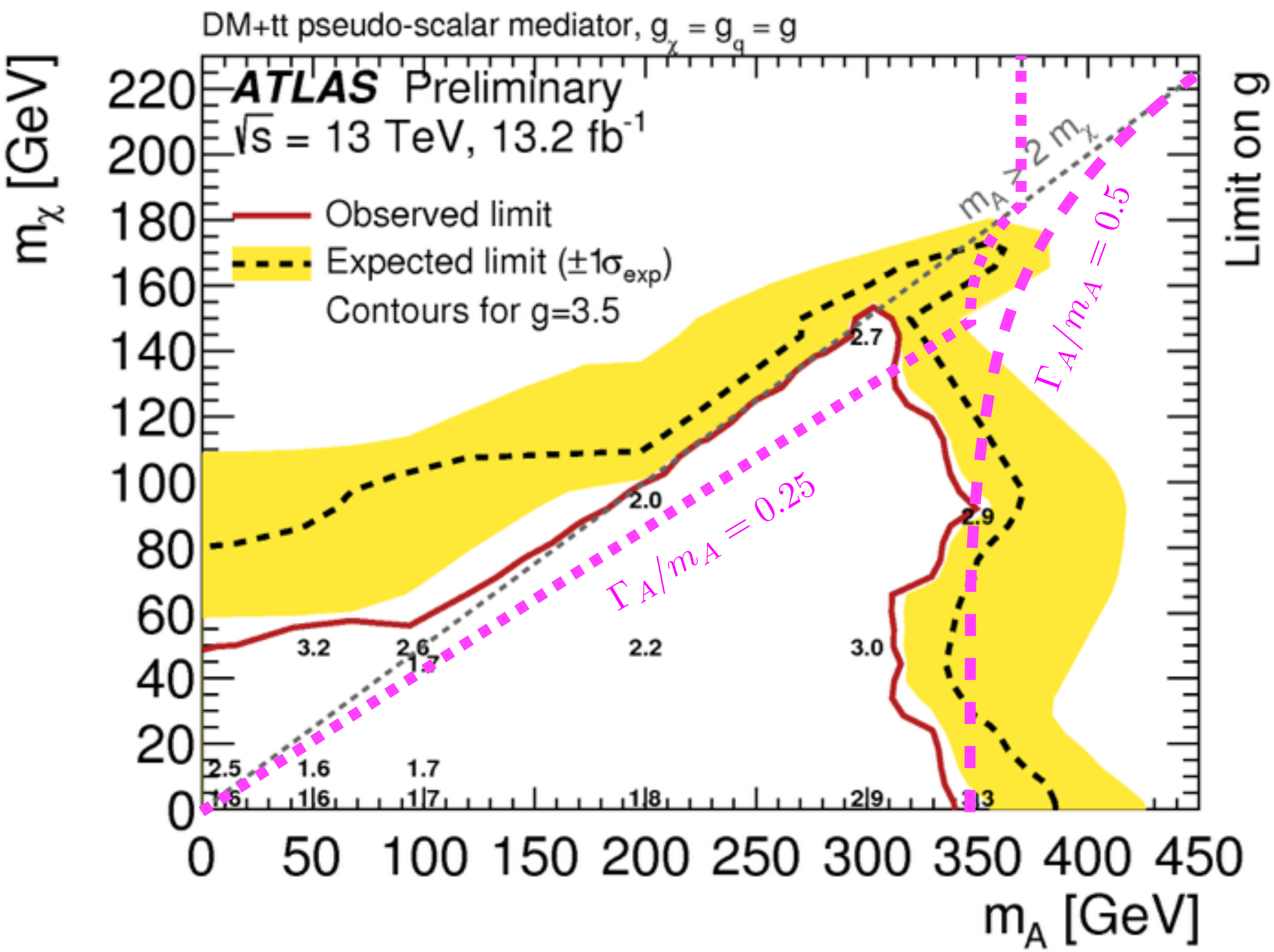
13 TeV limits on $E_{T,\,miss}$+$t\bar{t}$

[ATLAS-CONF-2016-050]



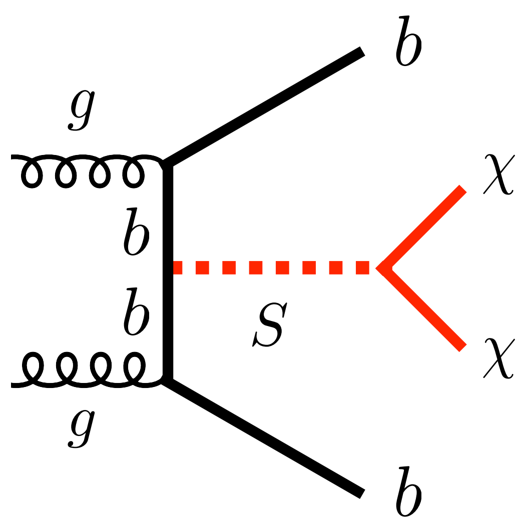
13 TeV limits on $E_{T,\,miss}$+$t\bar{t}$

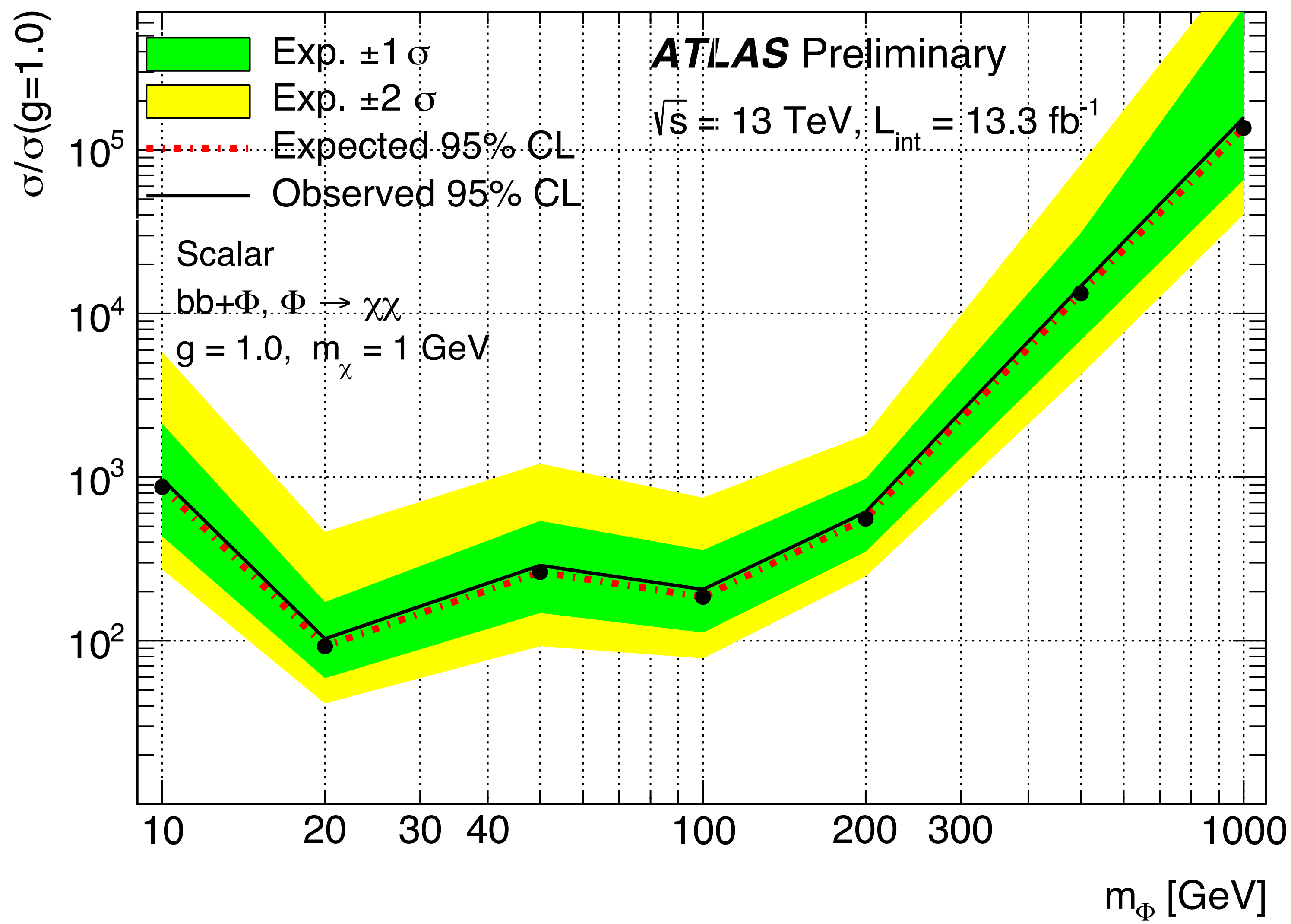
[ATLAS-CONF-2016-050]



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

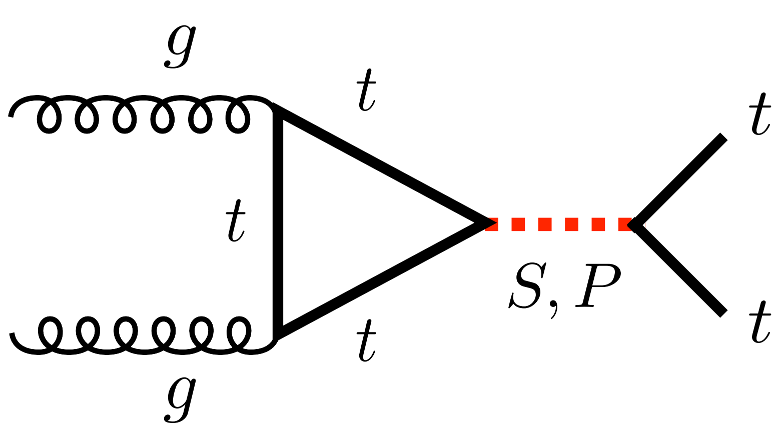
[ATLAS-CONF-2016-086]

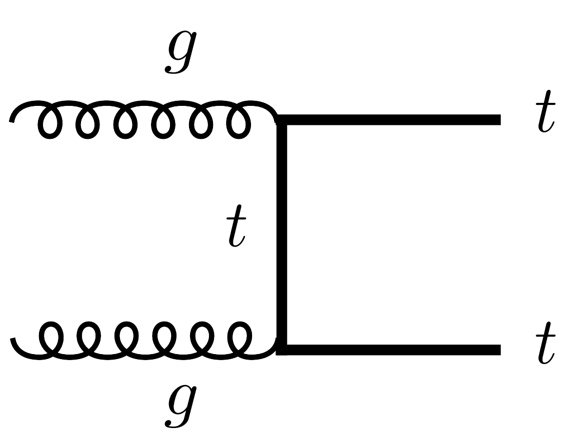




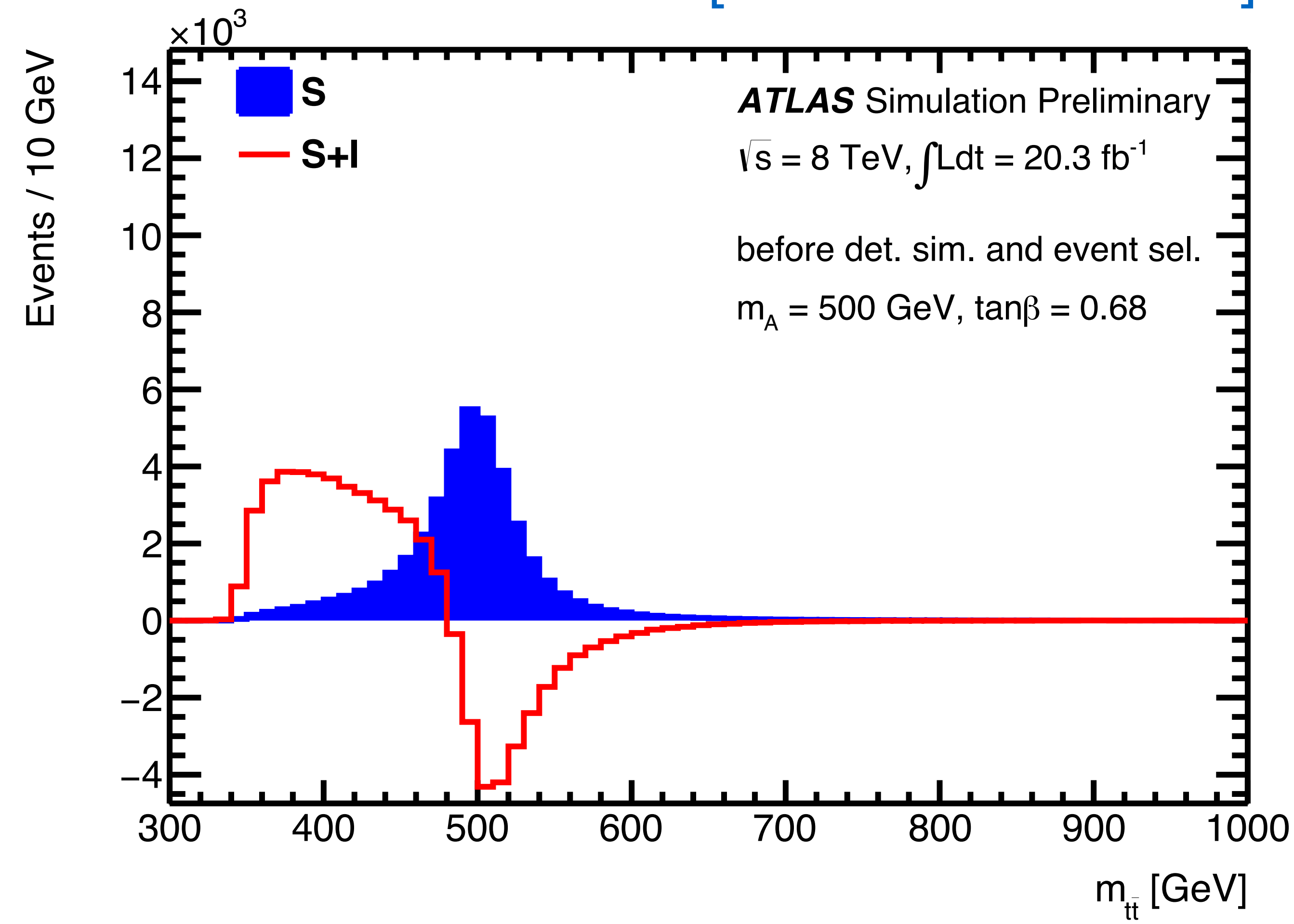
$E_{T,\,miss}$+$b\bar{b}$ searches not yet sensitive to spin-0 models with weak couplings

Di-top limits





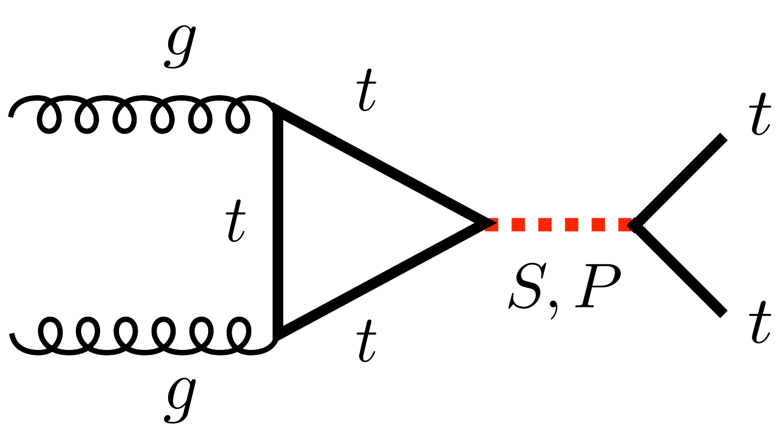
[ATLAS-CONF-2016-073]

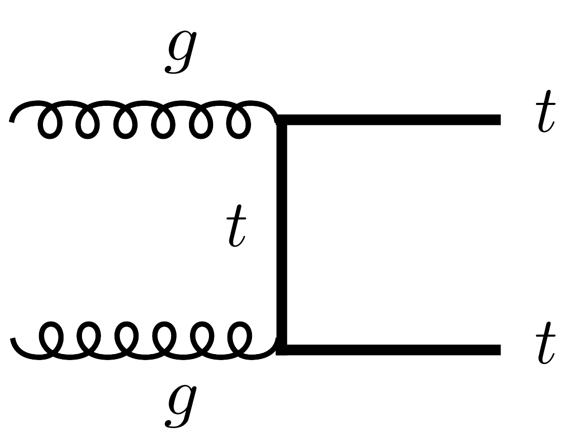


Spin-0 di-top resonances interfere maximal with SM background, which leads to a peak-dip structure in $m_{t\bar{t}}$ invariant mass spectrum

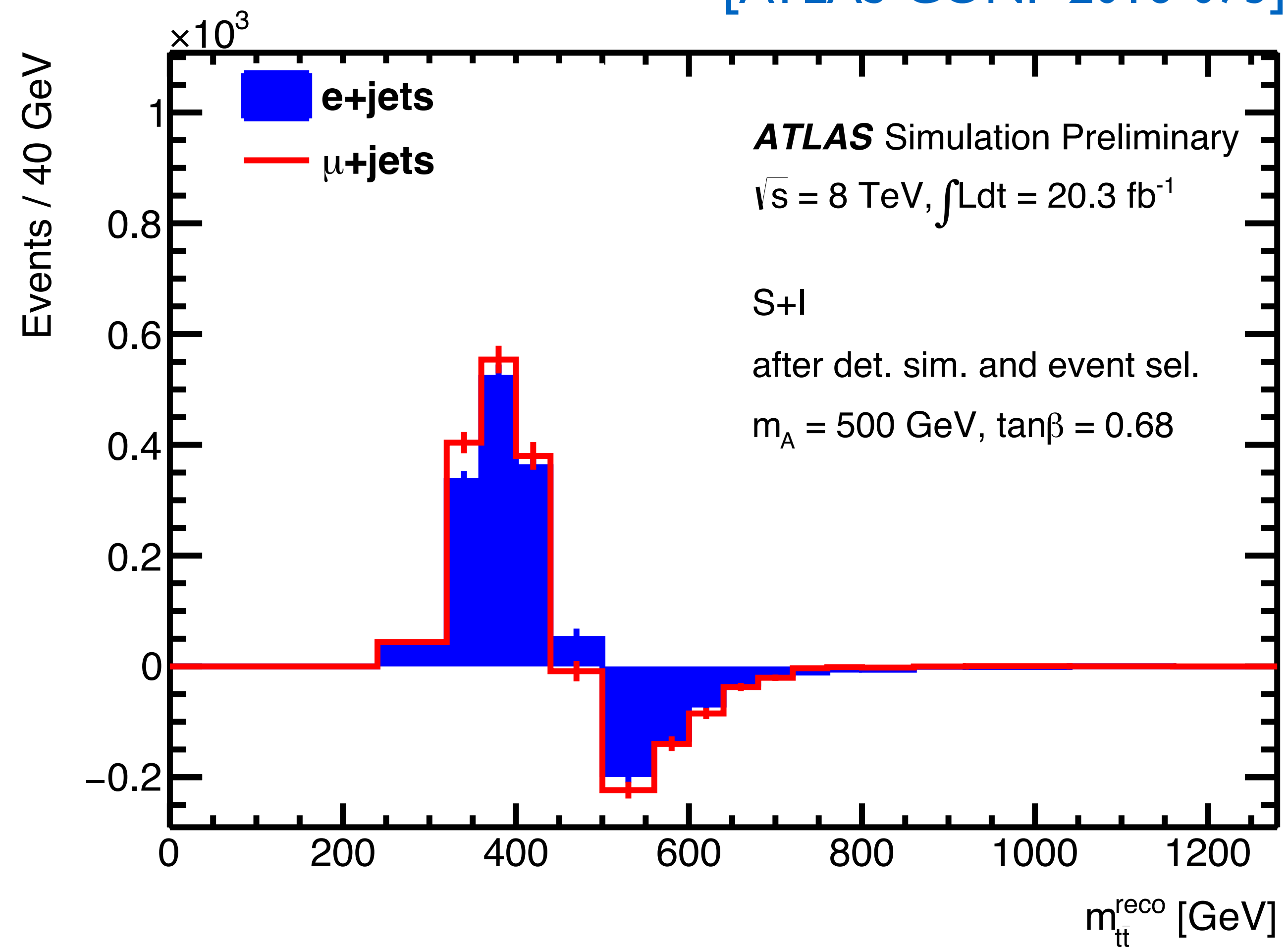
[Dicus et al., 9404359; Frederix & Maltoni, 0712.2355; Craig et al., 1504.04630; Bernreuther et al., 1511.05584; …]

Di-top limits





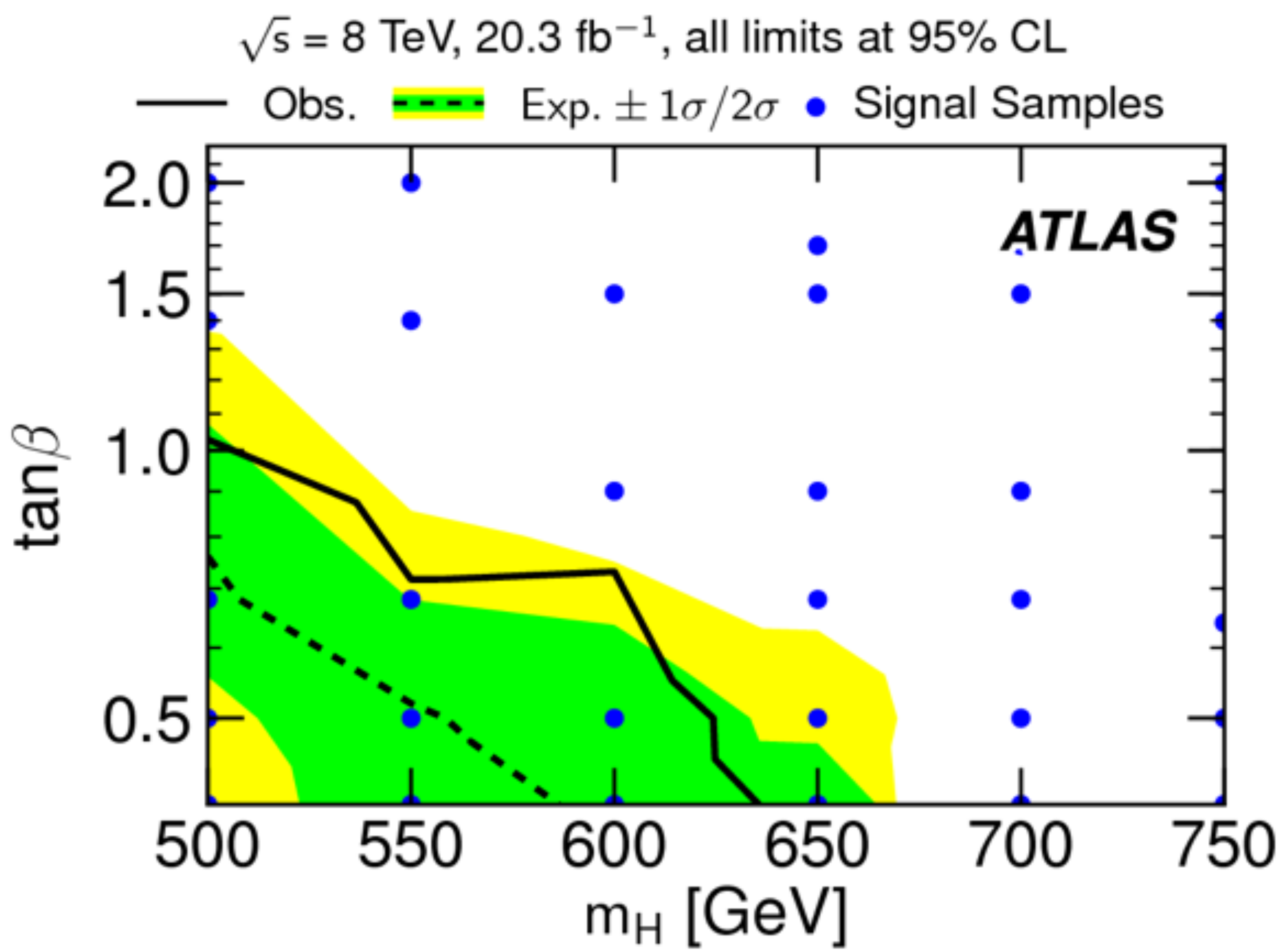
[ATLAS-CONF-2016-073]



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

Di-top limits

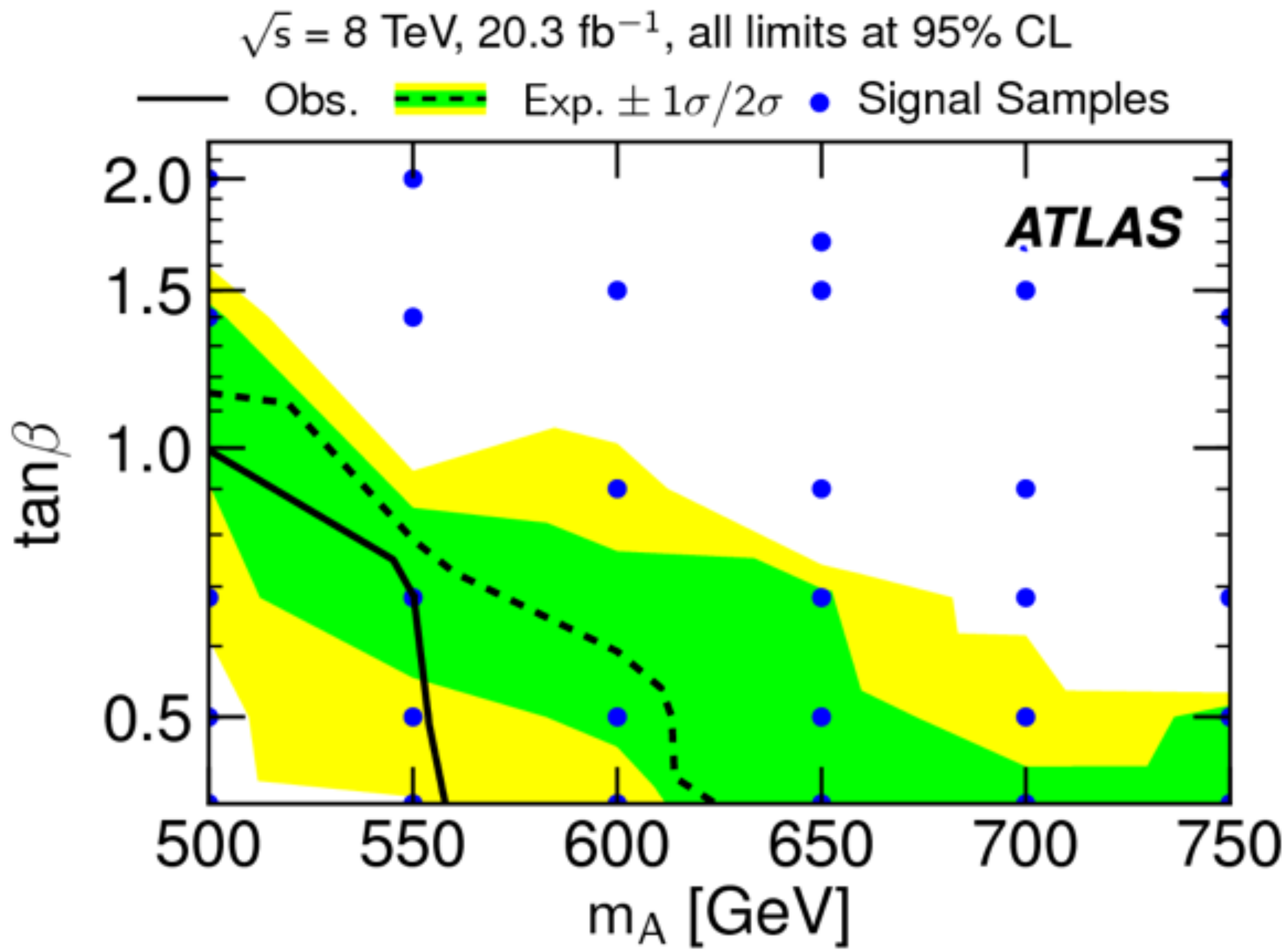
[ATLAS, 1707.06025]



For a scalar of 500 GeV (600 GeV) values of tanβ < 1.0 (tanβ < 0.73) are excluded at 95% CL in THDM of type II

Di-top limits

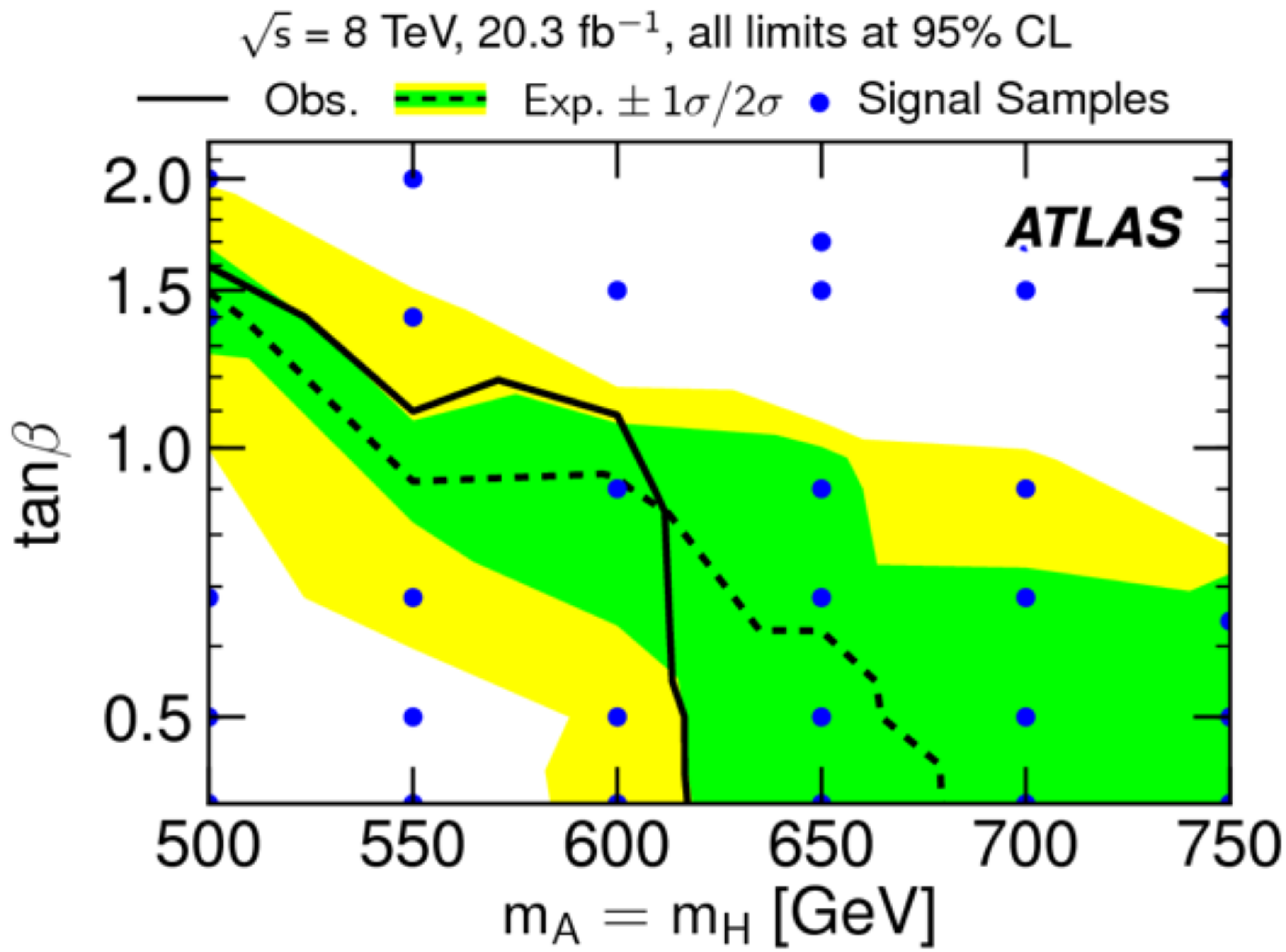
[ATLAS, 1707.06025]



For a pseudoscalar of 500 GeV (550 GeV) values of tanβ < 1.0 (tanβ < 0.69) are excluded at 95% CL in THDM of type II

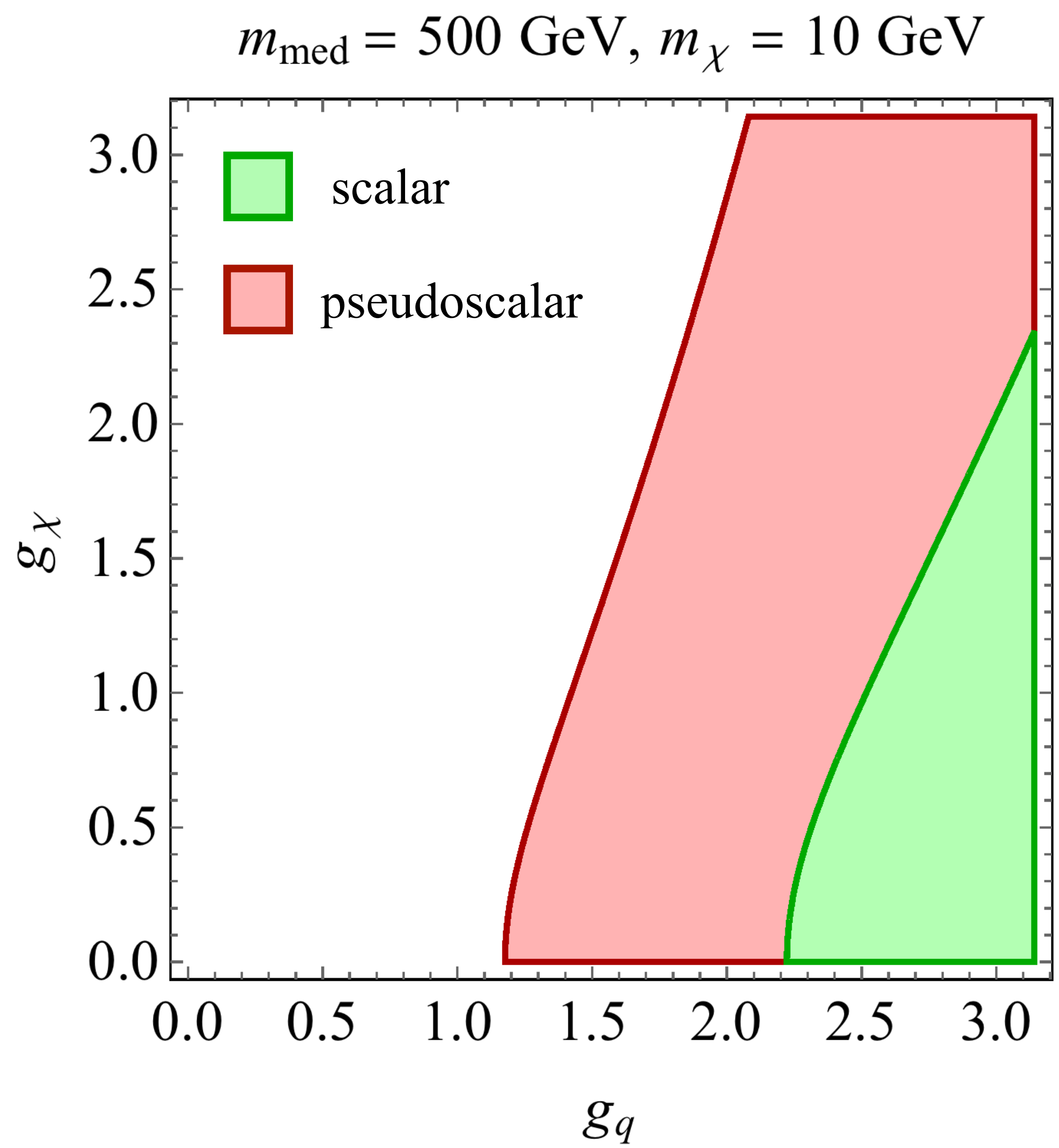
Di-top limits

[ATLAS, 1707.06025]



In mass degenerate case, scenarios with 500 GeV (600 GeV) & values of tanβ < 1.55 (tanβ < 1.09) are excluded at 95% CL in THDM of type 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

t-channel flavoured mediators

DM fermion singlet

scalar flavour triplet

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

universal couplings to have minimal flavour violation (MFV),

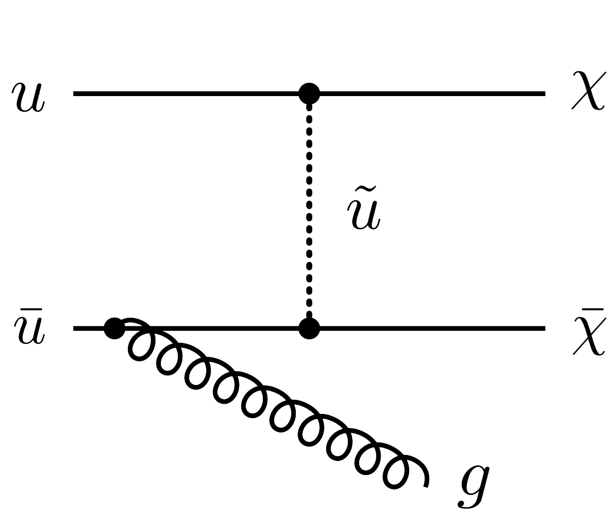
which is needed to avoid flavour constraints

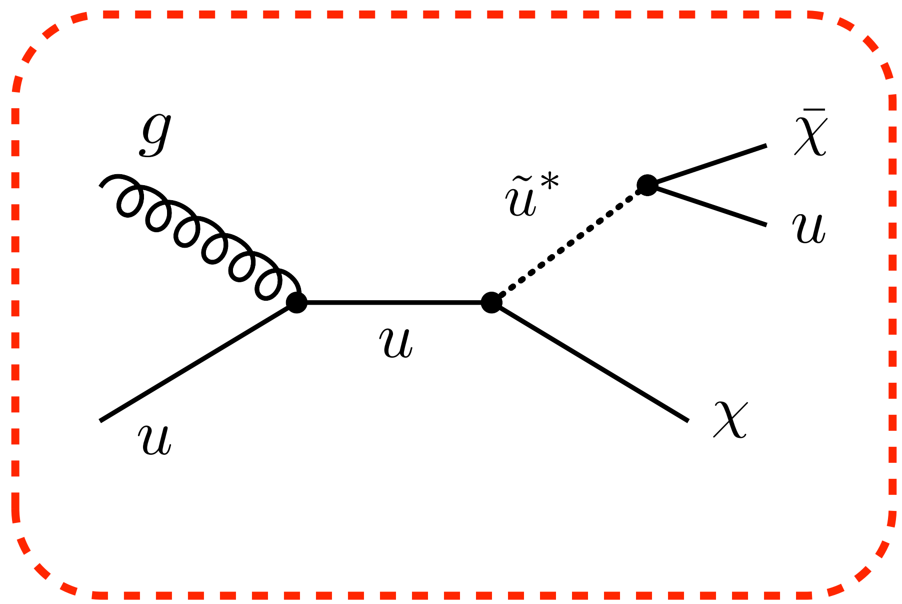
$$\{m_\chi,\ M_{1,2},\ \boxed{M_3},\ g_{1,2},\ \boxed{g_3}\}$$

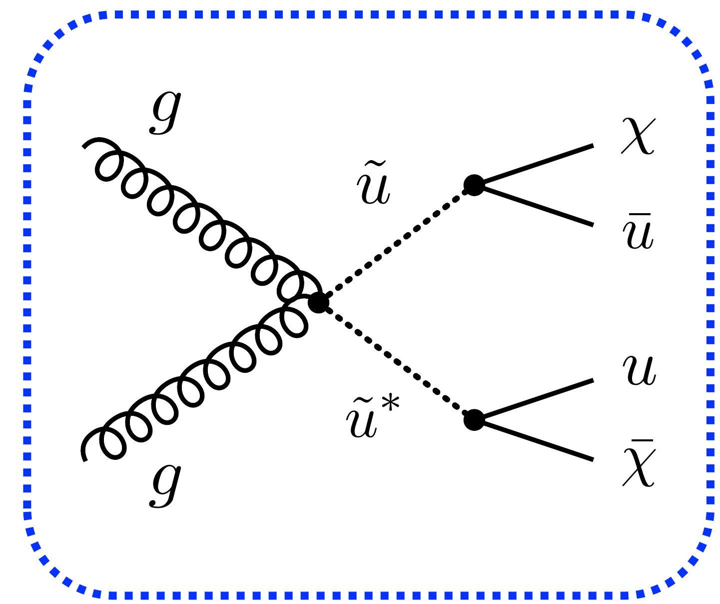
universality broken by $Y_u^\dagger Y_u$ flavour spurion (fine with MFV)

[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





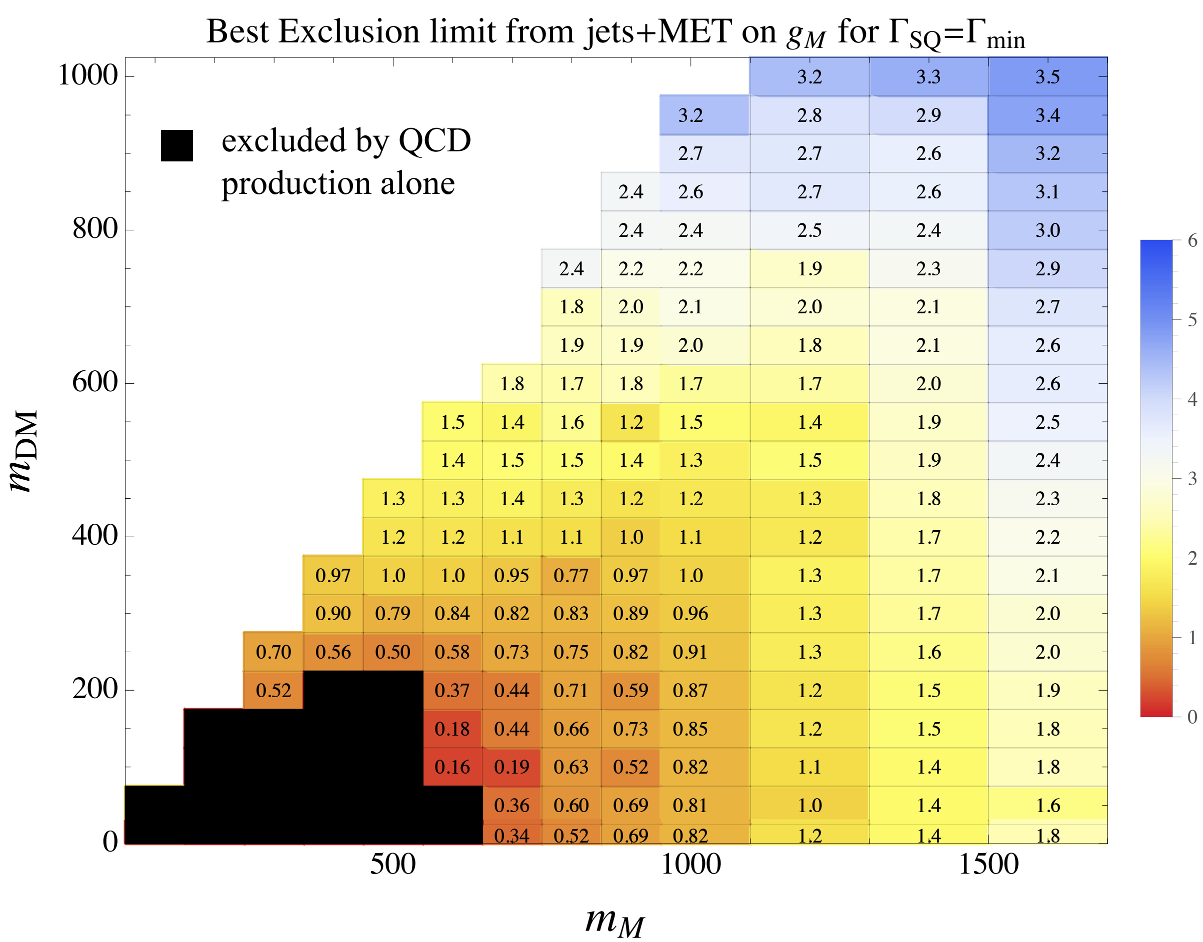


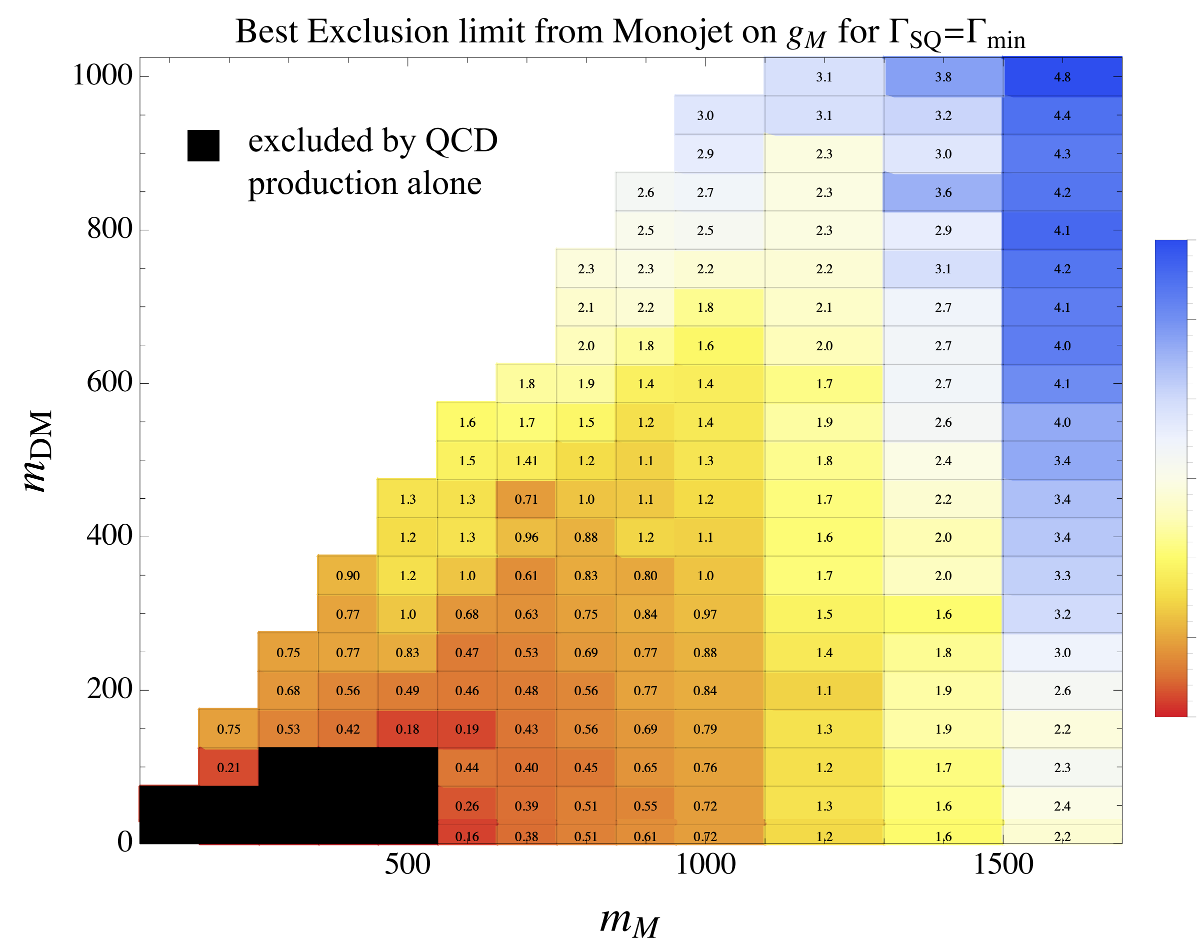
gives largest contribution to $E_{T,\,miss}$+j signal, because compared to initial state radiation (ISR) diagram phase-space enhanced, profits from gluon luminosity & jet typically harder than in ISR; dominance of associated production channel is a distinct feature of t-channel models

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

t-channel flavoured mediators

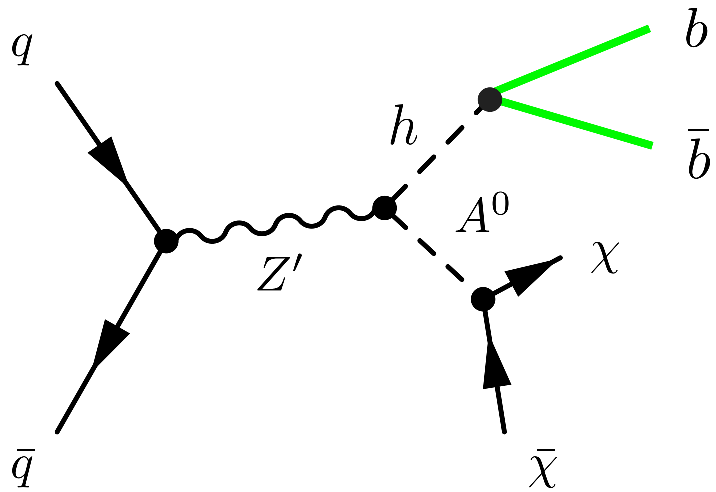
[Papucci et al., 1402.2285]



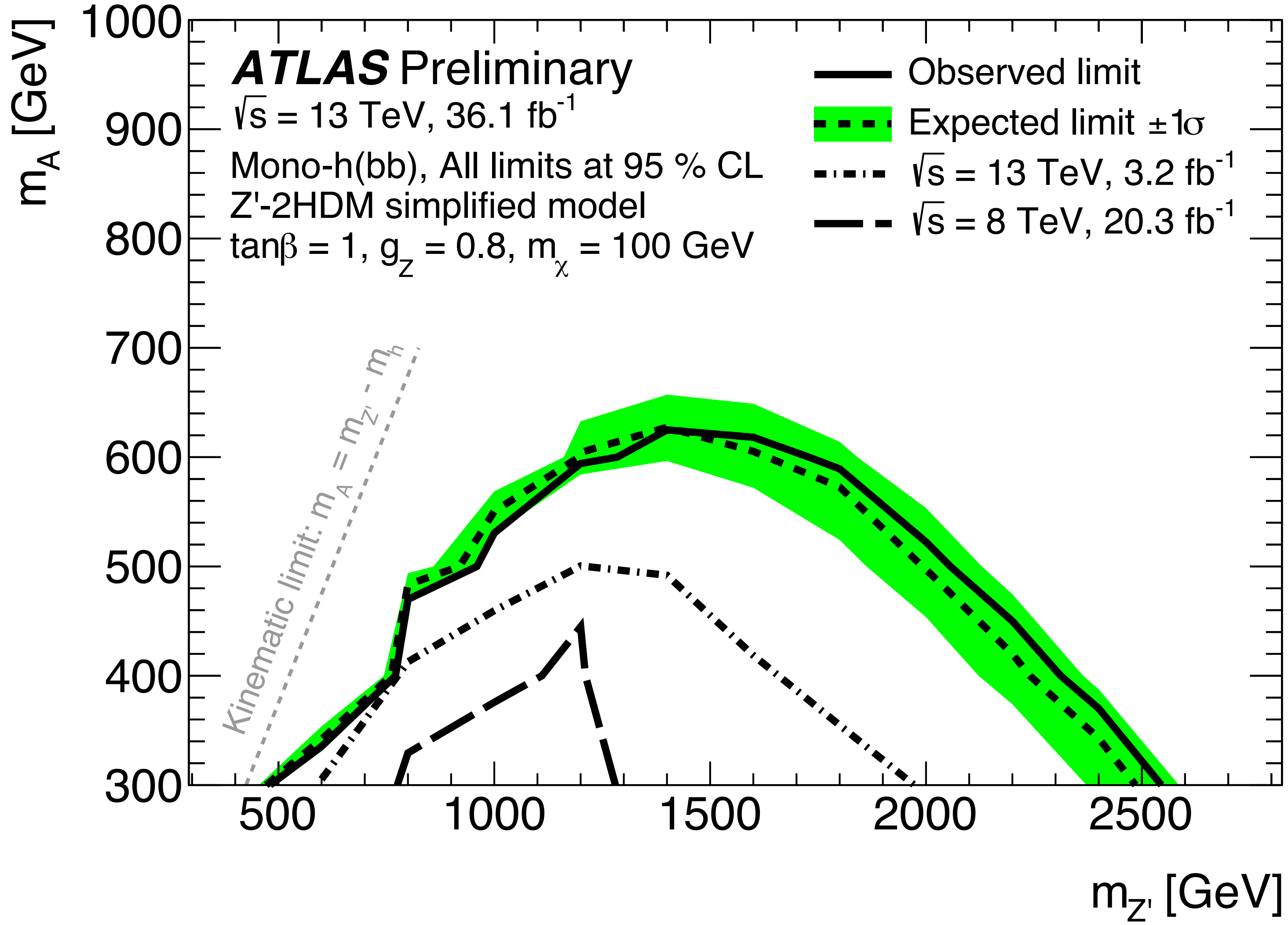


Mono-jet & supersymmetric (SUSY) searches provide comparable bounds in most of parameter space. SUSY searches often slightly better, except if mass of DM particle & mediator is degenerate

THDM plus Z′ model: h+$E_{T,\,miss}$ searches



[ATLAS-CONF-2017-028]



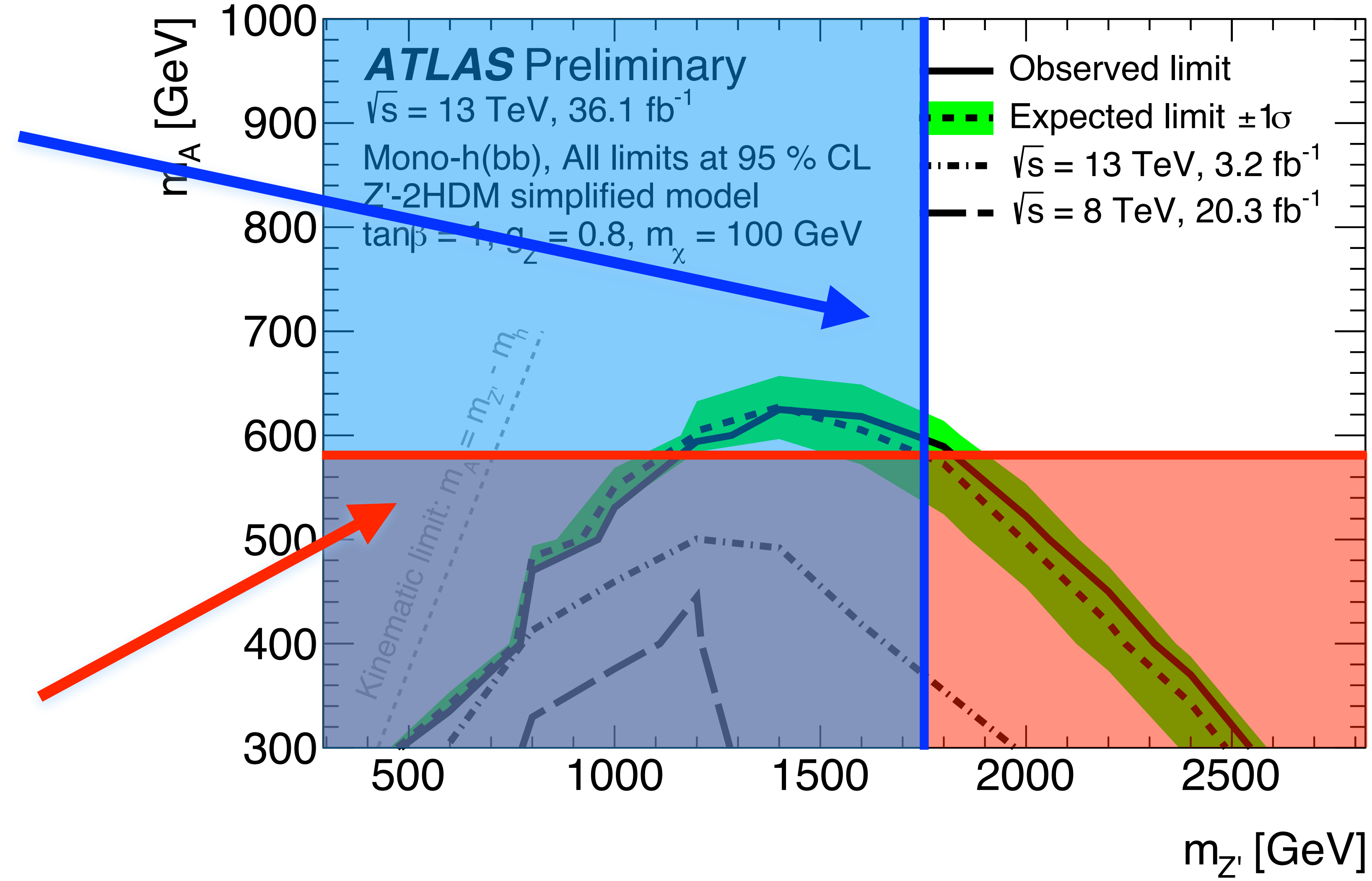
THDM plus Z′ model: h+$E_{T,\,miss}$ searches

disfavoured at 95% CL

by ρ parameter

[Berlin et al., 1402.7074]

[ATLAS-CONF-2017-028]



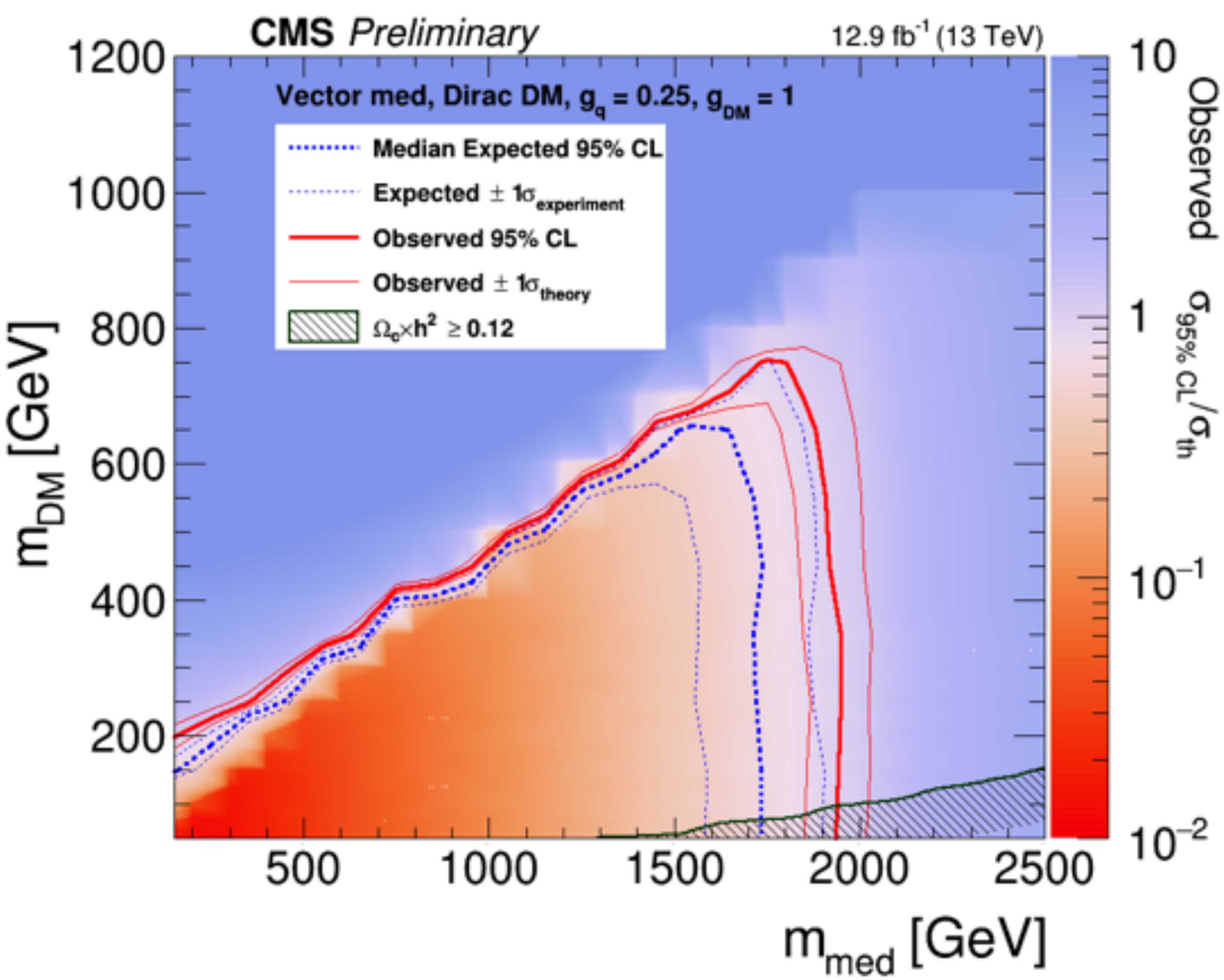
disfavoured at 95% CL

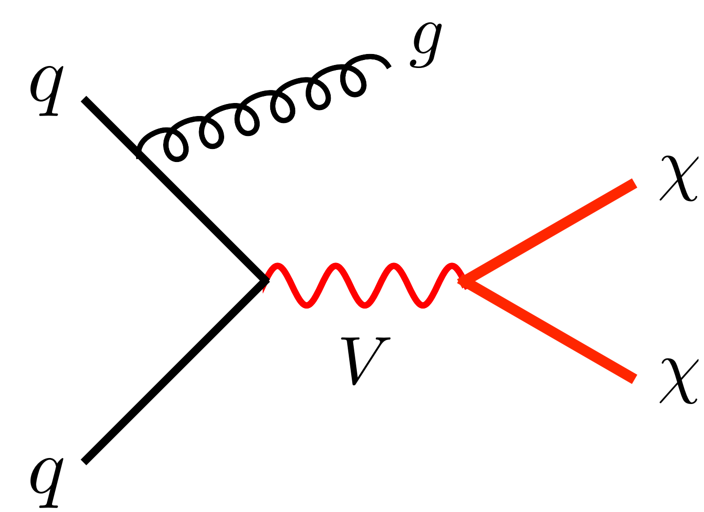
by $B \to X_s \gamma$

[Misiak & Steinhauser, 1702.04571]

From LHC bounds …

[CMS PAS EXO-16-037]





… 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:

$$\boxed{\mathcal{O}_1 = 1_\chi 1_N}$$
$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\boxed{\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N}$$
$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$
$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$
$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$
$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

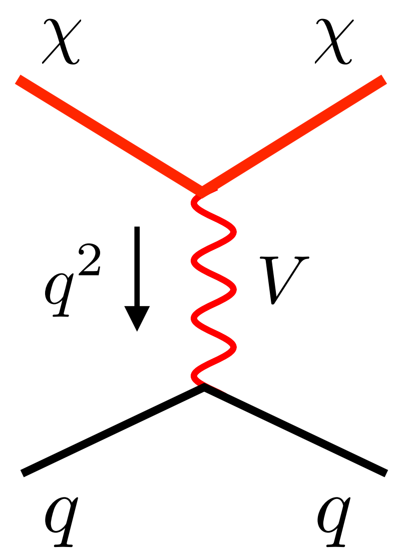
$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$
$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$
$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$
$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$
$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

spin-independent (SI)

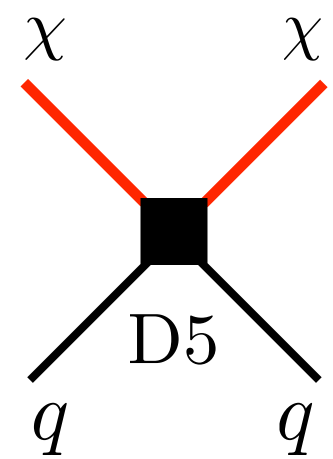
spin-dependent (SD)

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

… to DD limits …



$$= \quad -\frac{g_\chi g_q}{M_V^2} \cdot$$



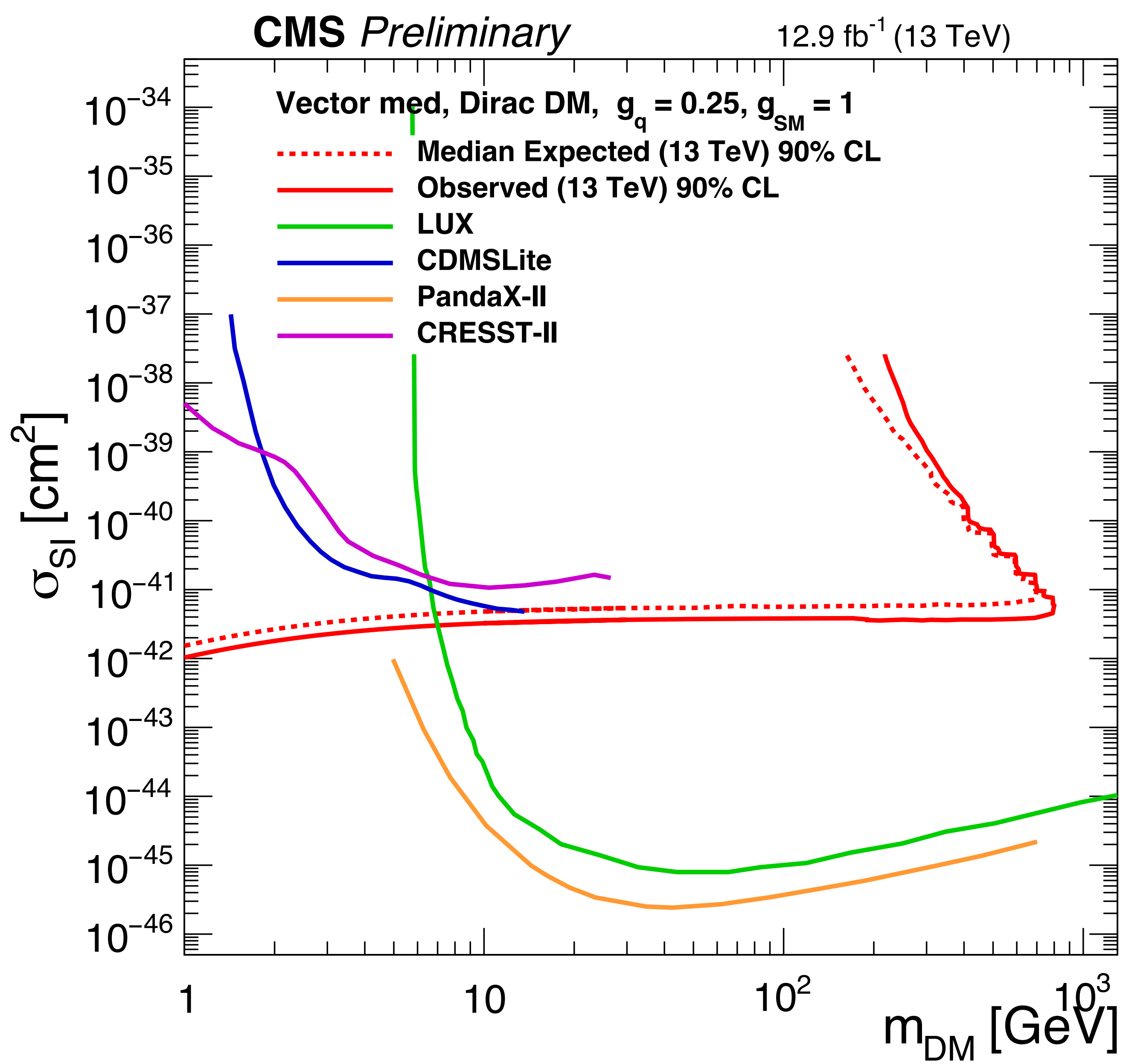
$$+ \mathcal{O}(q^2/M_V^2)$$

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

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

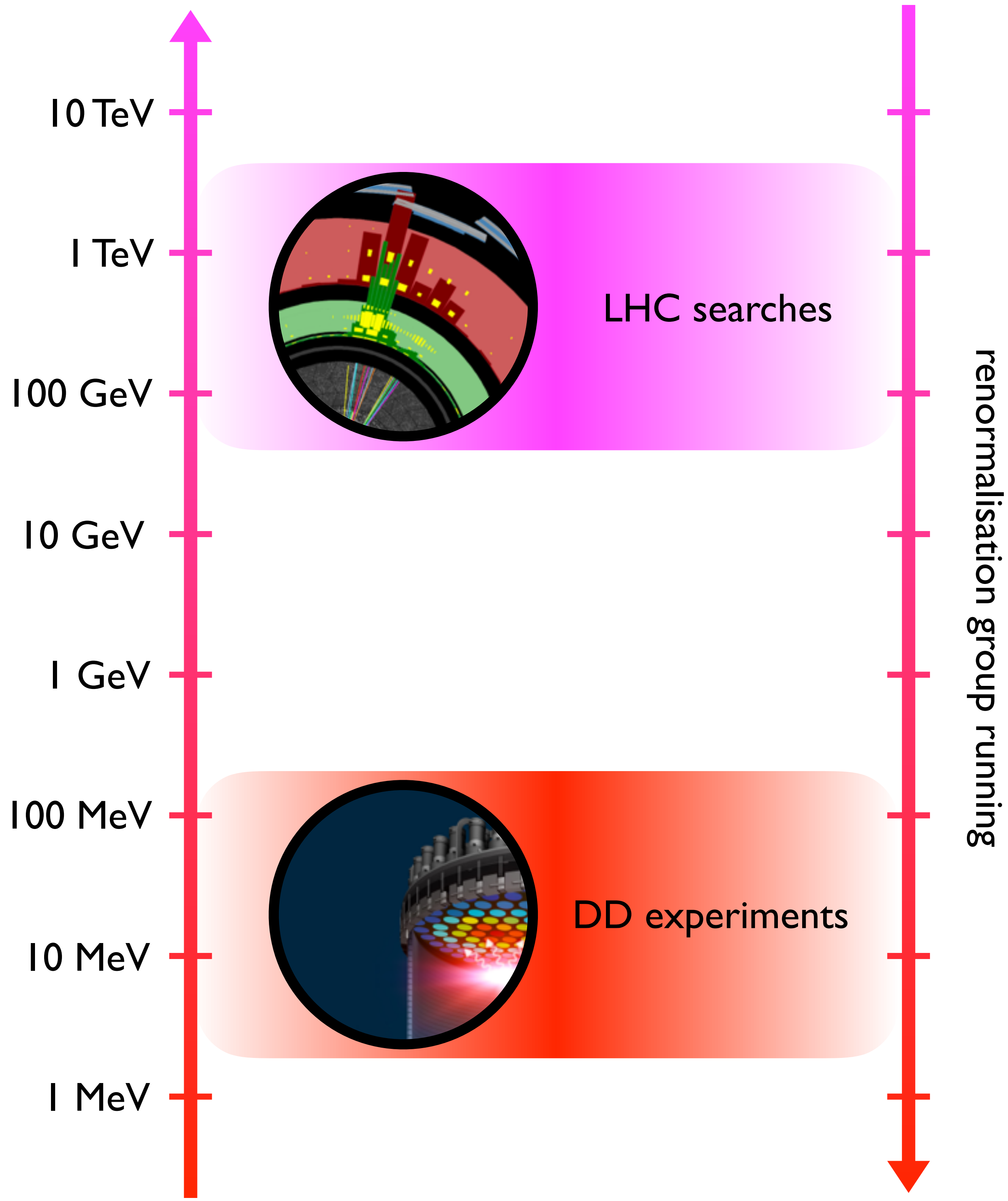
… & finally to a plot

[CMS PAS EXO-16-037]



For SI interactions LHC only competitive for low DM mass, where direct detection is challenging due to small nuclear recoil

Classification of χ-N interactions

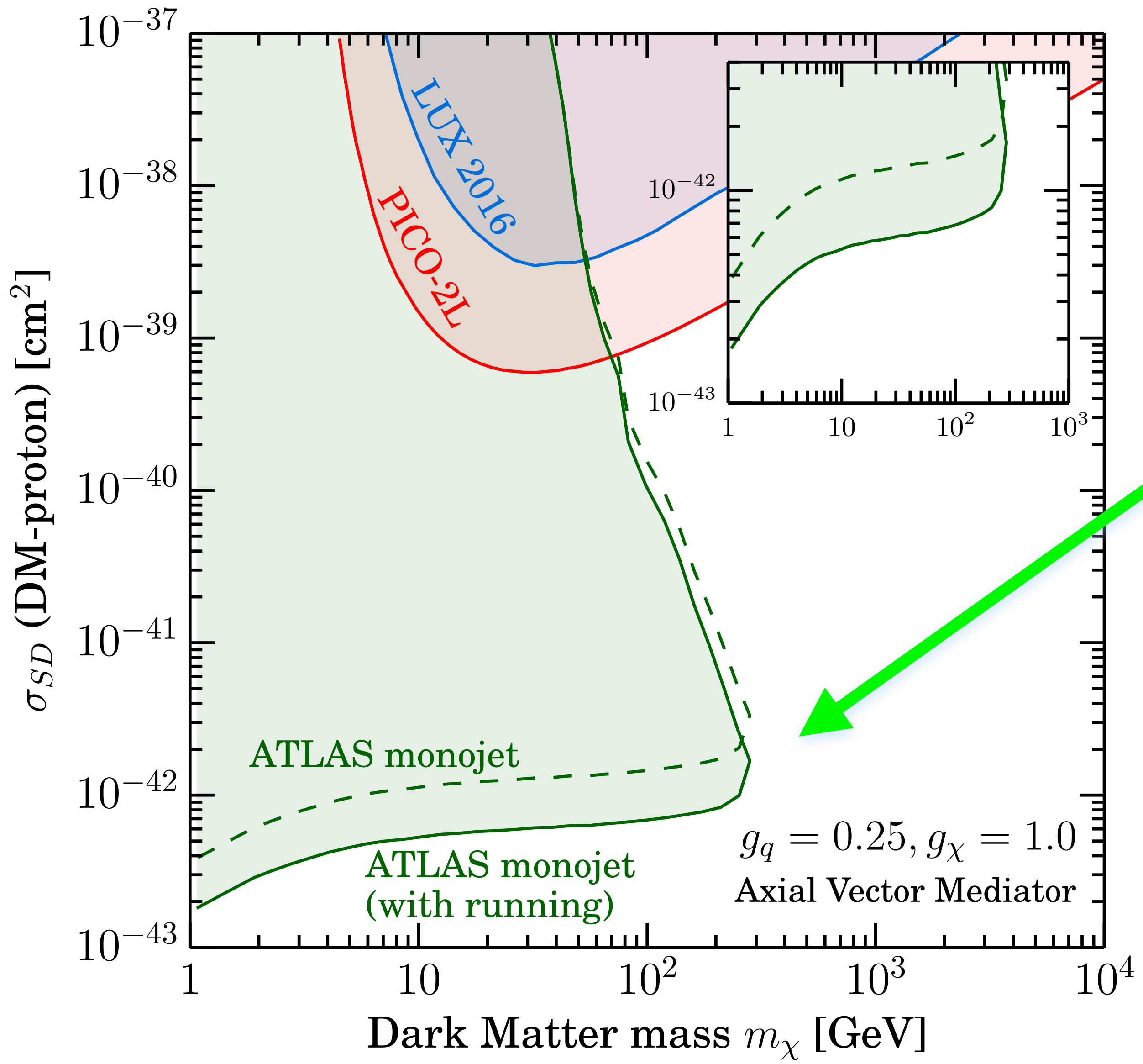


Distinction between SI & SD (or q-suppressed) χ-N couplings not stable under radiative corrections. Effects particular important for mixing of suppressed into unsuppressed operators

[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: SD effects

[D'Eramo et al., 1605.04917]



in axialvector case bounds are strengthened by a factor of around 2 by renormalisation group running

While LHC limit quite similar to SI case, direct detection weakened significantly since DM-nucleon scattering is incoherent in SD case

LHC vs. direct detection

$$\boxed{\mathcal{L}_V} \longrightarrow \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \longrightarrow \boxed{\mathcal{O}_1 = 1_\chi 1_N}$$

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}\,, \qquad \mu_{n\chi} = \frac{m_n m_{\rm DM}}{m_n + m_{\rm DM}}\,, \qquad m_n \simeq 0.939\,{\rm GeV}$$

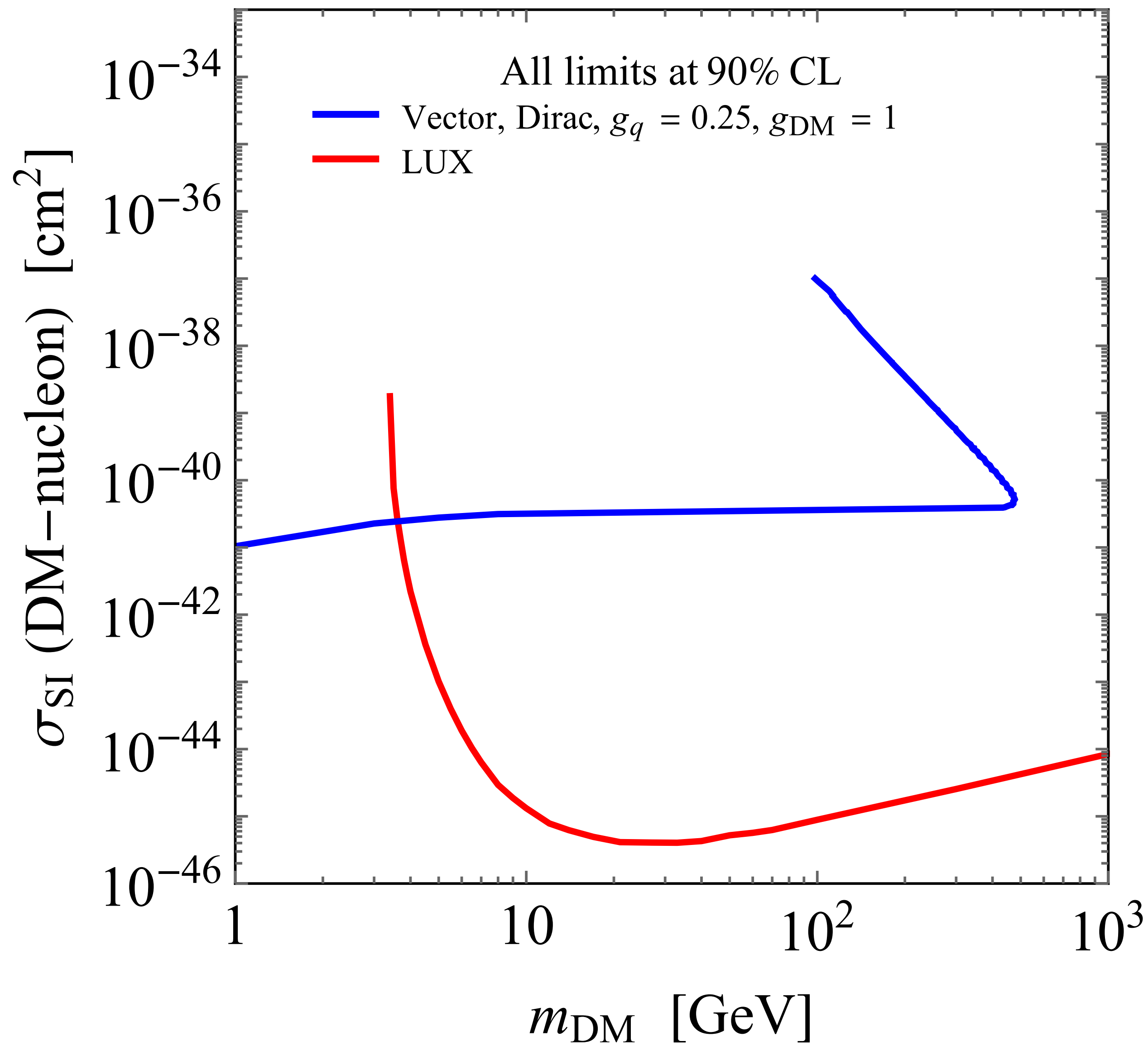
$$f(g_q) = 3 g_q$$

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

†formula for $f(g_q)$ assumes universal couplings to quarks

LHC vs. direct detection

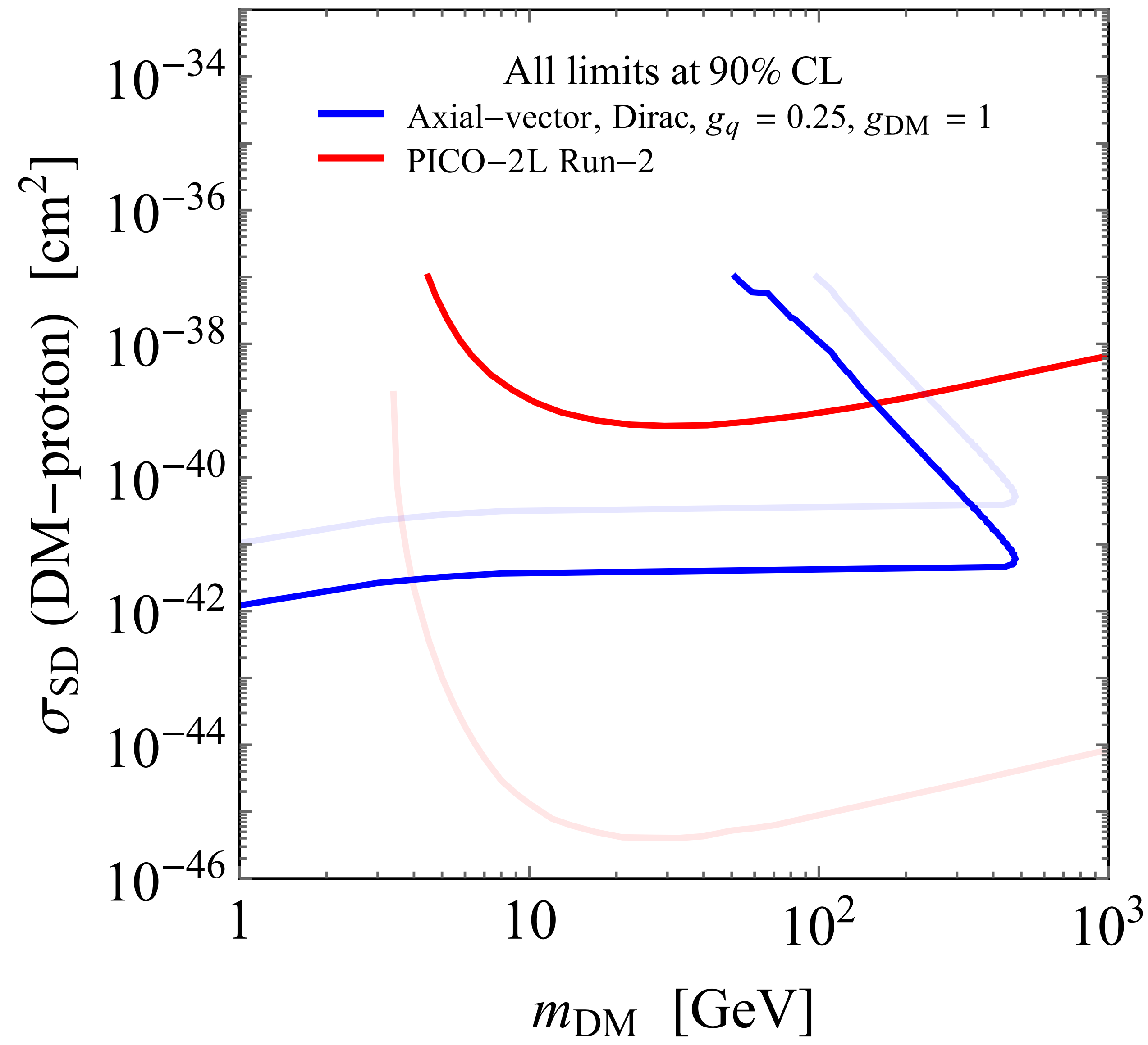
[Boveia et al., 1603.04156]



Like direct detection also mono-jet bound assumes that χ constitutes all of DM in Universe. If this is not case direct detection limit would become weaker, while LHC bound would remain unchanged

LHC vs. direct detection

[Boveia et al., 1603.04156]



$$\boxed{\mathcal{L}_A} \longrightarrow \bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu\gamma_5 q \longrightarrow \boxed{\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N}$$

DM-N scattering for spin-0 mediators

$$\mathcal{L}_S \longrightarrow \bar{\chi}\chi\bar{q}q \longrightarrow \boxed{\mathcal{O}_1 = 1_\chi 1_N}$$

$$\mathcal{L}_P \longrightarrow \bar{\chi}i\gamma_5\chi\bar{q}i\gamma_5 q \longrightarrow \boxed{\mathcal{O}_6 = \frac{1}{m_N^2}\left(\vec{S}_\chi \cdot \vec{q}\right)\left(\vec{S}_N \cdot \vec{q}\right)}$$

SI

SD & momentum suppressed

Due to loss of coherence & since $q = O(0.1\ \text{GeV})$ resulting DM-N cross section $O(10^{-11})$ lower than σ_{SI}. As a result very poor direct detection limits

DM annihilation: pseudo-scalar case

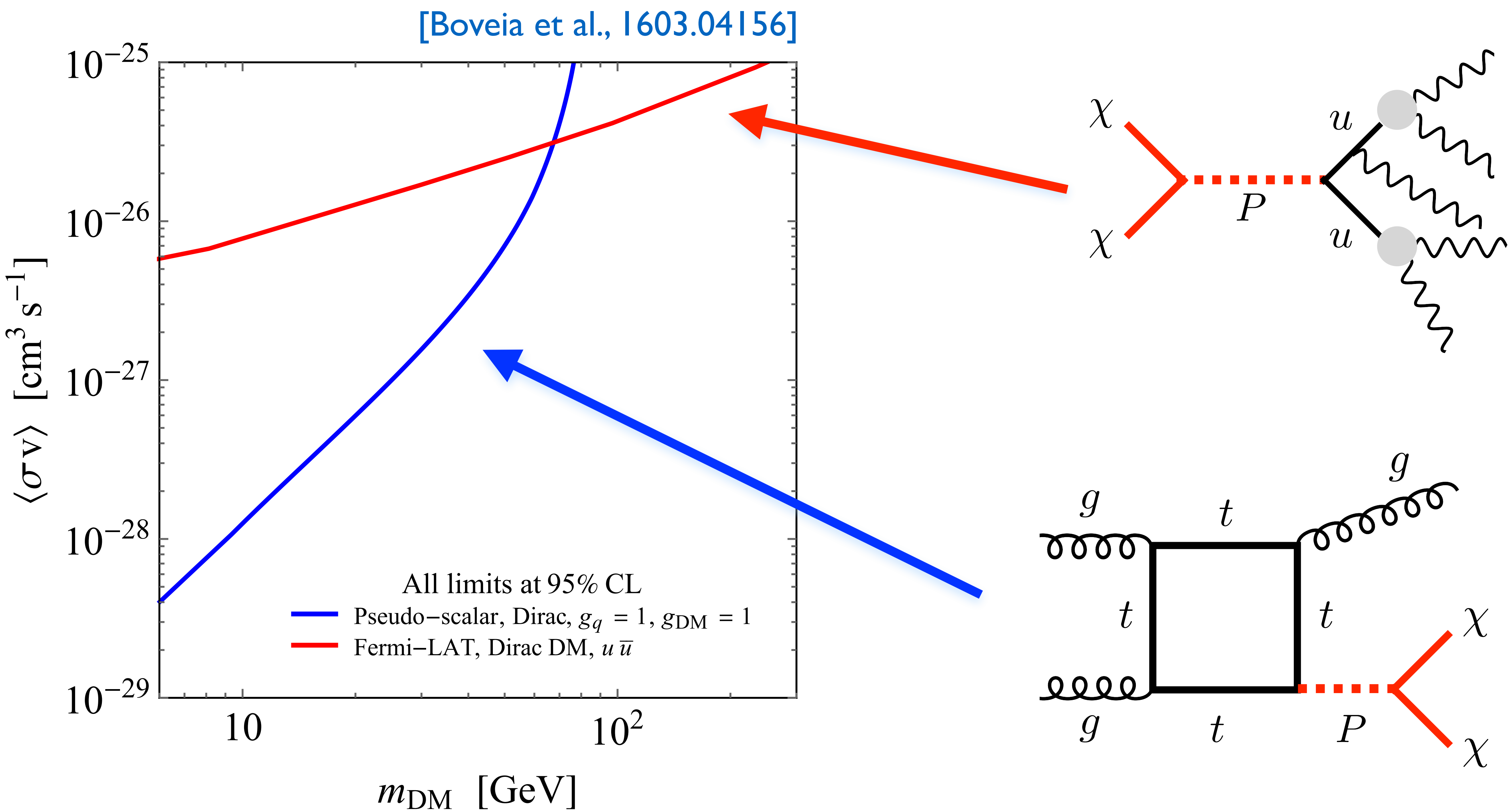
$$\langle \sigma v_{\mathrm{rel}} \rangle_q = \frac{3m_q^2}{2\pi v^2} \frac{g_q^2 g_{\mathrm{DM}}^2 m_{\mathrm{DM}}^2}{(M_{\mathrm{med}}^2 - 4m_{\mathrm{DM}}^2)^2 + M_{\mathrm{med}}^2 \Gamma_{\mathrm{med}}^2} \sqrt{1 - \frac{m_q^2}{m_{\mathrm{DM}}^2}}$$

$$\langle \sigma v_{\mathrm{rel}} \rangle_g = \frac{\alpha_s^2}{2\pi^3 v^2} \frac{g_q^2 g_{\mathrm{DM}}^2}{(M_{\mathrm{med}}^2 - 4m_{\mathrm{DM}}^2)^2 + M_{\mathrm{med}}^2 \Gamma_{\mathrm{med}}^2} \left| \sum_q m_q^2 f_{\text{pseudo-scalar}} \left(\frac{m_q^2}{m_\chi^2} \right) \right|^2$$

$$f_{\text{pseudo-scalar}}(\tau) = \tau \arctan^2 \left(\frac{1}{\sqrt{\tau - 1}} \right)$$

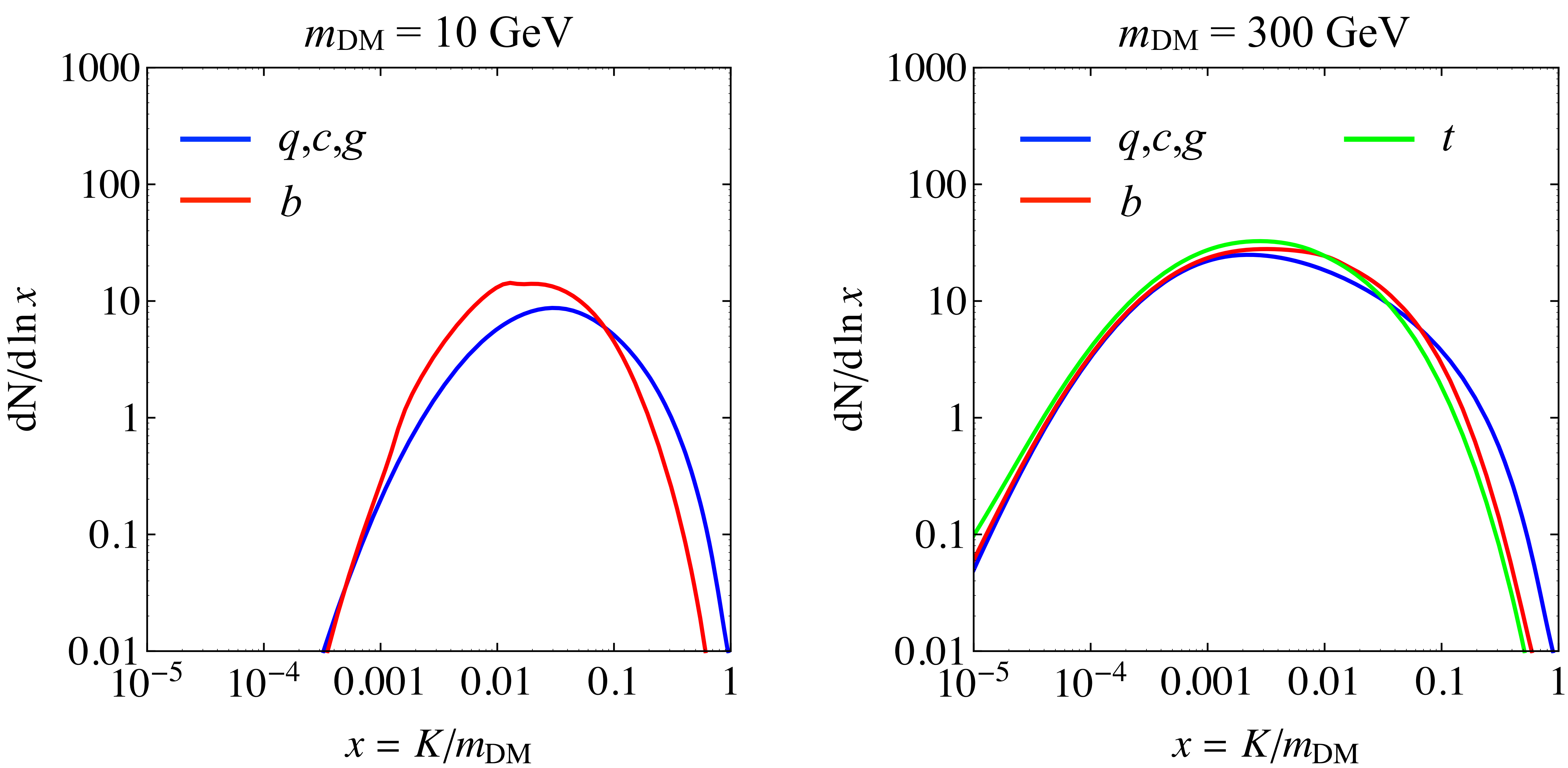
Due to m_q^2 terms annihilation to heaviest kinematically accessible quark dominates total annihilation rate

LHC vs. indirect detection



For pseudo-scalar mediator model nice complementarity between LHC mono-jet bound & indirect detection limit from Fermi-LAT

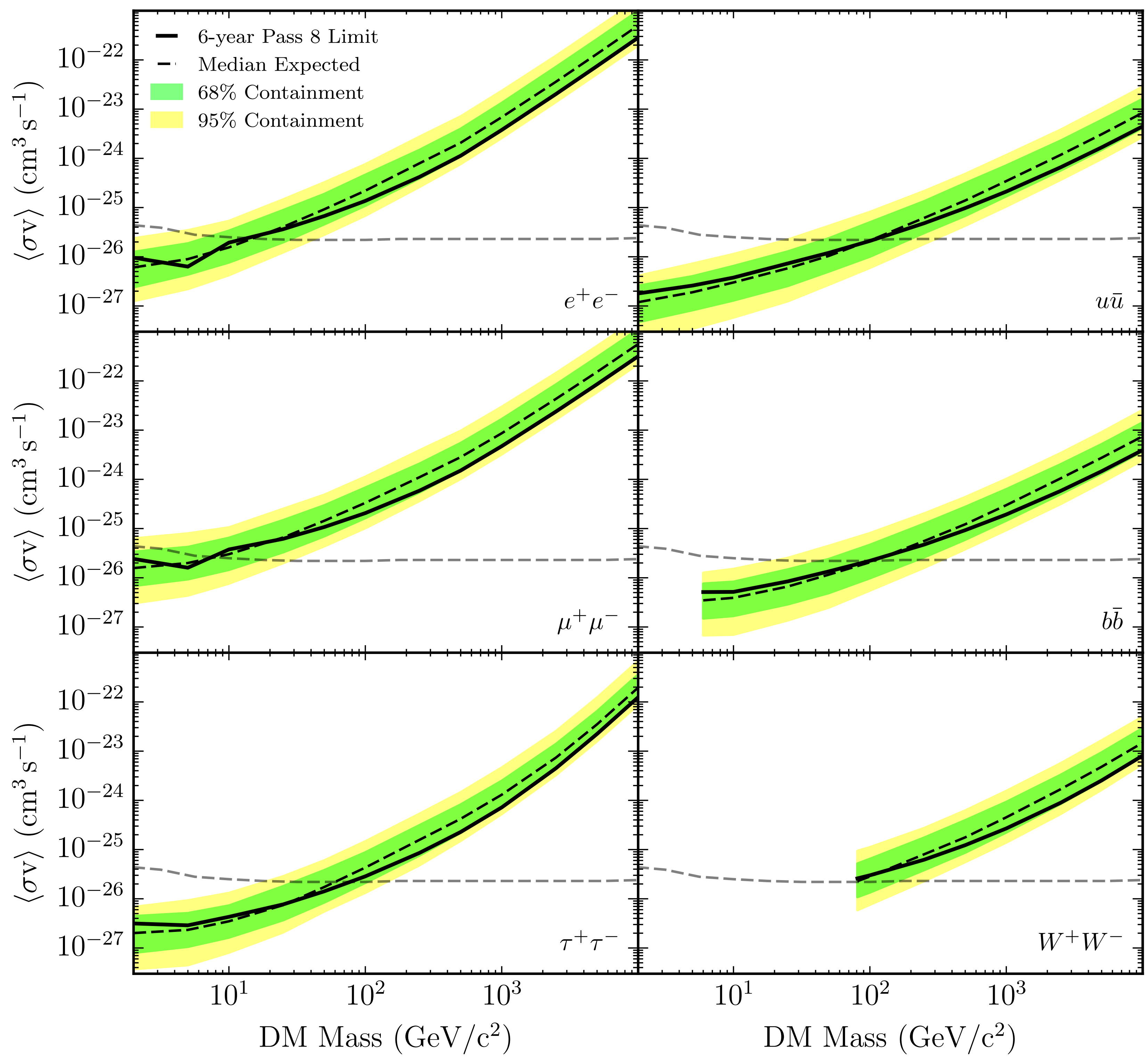
γ-ray spectra from DM annihilation



[Cirelli et al., 1012.4515; http://www.marcocirelli.net/PPPC4DMID.html]

DM annihilation bounds from dwarfs

[Fermi-LAT, 1503.02641]



DM-N cross section: scalar case

$$\sigma_{\rm SI} = \frac{f^2(g_q) g_{\rm DM}^2 \mu_{n\chi}^2}{\pi M_{\rm med}^4}\,, \qquad \mu_{n\chi} = \frac{m_n m_{\rm DM}}{m_n + m_{\rm DM}}\,, \qquad m_n \simeq 0.939\,{\rm GeV}$$

$$f(g_q) = 1.16 \cdot 10^{-3}\, g_q$$

$$\sigma_{\rm SI} \simeq 6.9 \cdot 10^{-43}\ {\rm cm}^2 \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\,{\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\,{\rm GeV}}\right)^2$$

† formula for $f(g_q)$ assumes universal couplings to quarks

DM-N cross section: axial-vector case

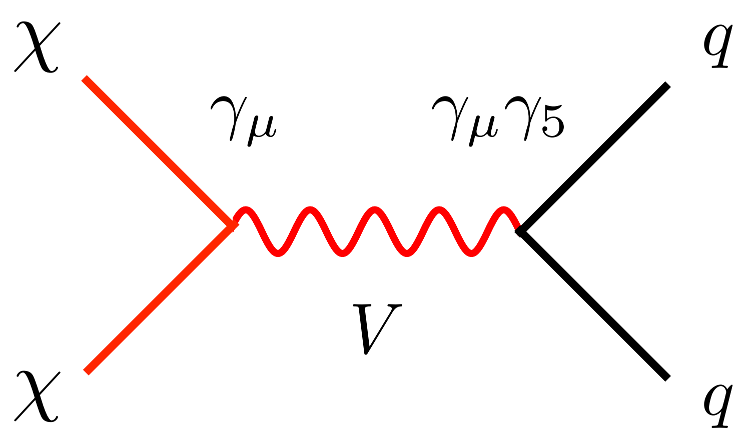
$$\sigma_{\mathrm{SD}} = \frac{3 f^2(g_q) g_{\mathrm{DM}}^2 \mu_{n\chi}^2}{\pi M_{\mathrm{med}}^4}\,, \qquad \mu_{n\chi} = \frac{m_n m_{\mathrm{DM}}}{m_n + m_{\mathrm{DM}}}\,, \qquad m_n \simeq 0.939\,\mathrm{GeV}$$

$$f(g_q) = 0.32\, g_q$$

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

† formula for $f(g_q)$ assumes universal couplings to quarks

From suppressed to unsuppressed DD



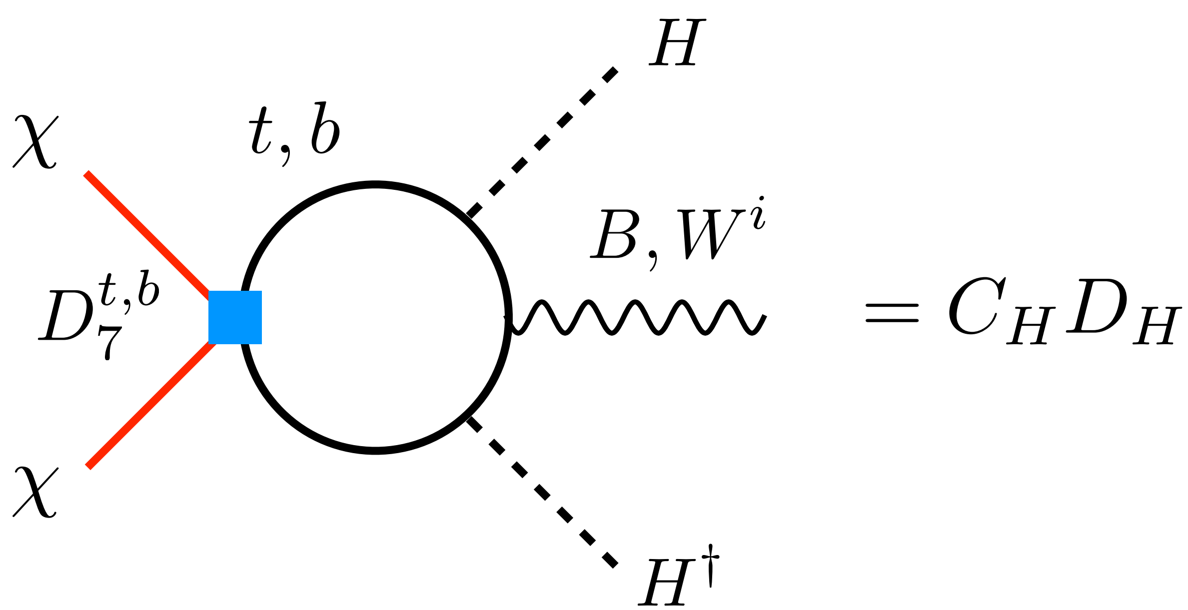
$= C_7^q D_7^q$

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

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

From suppressed to unsuppressed DD

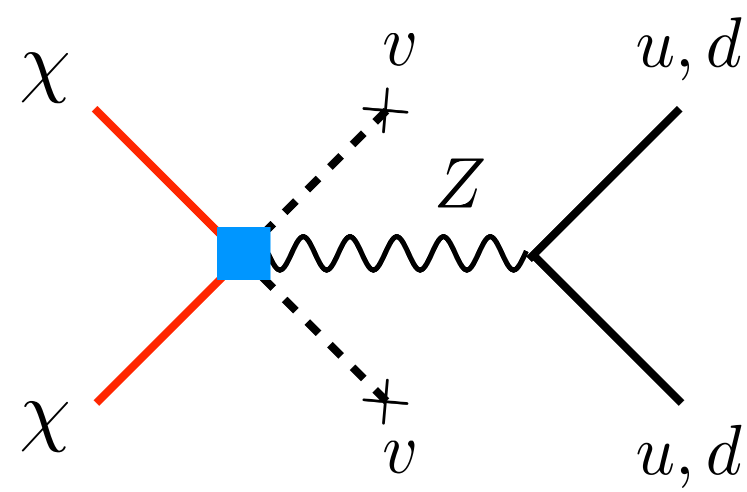
[Crivellin et al. 1402.1173]



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

From suppressed to unsuppressed DD

[Crivellin et al. 1402.1173]



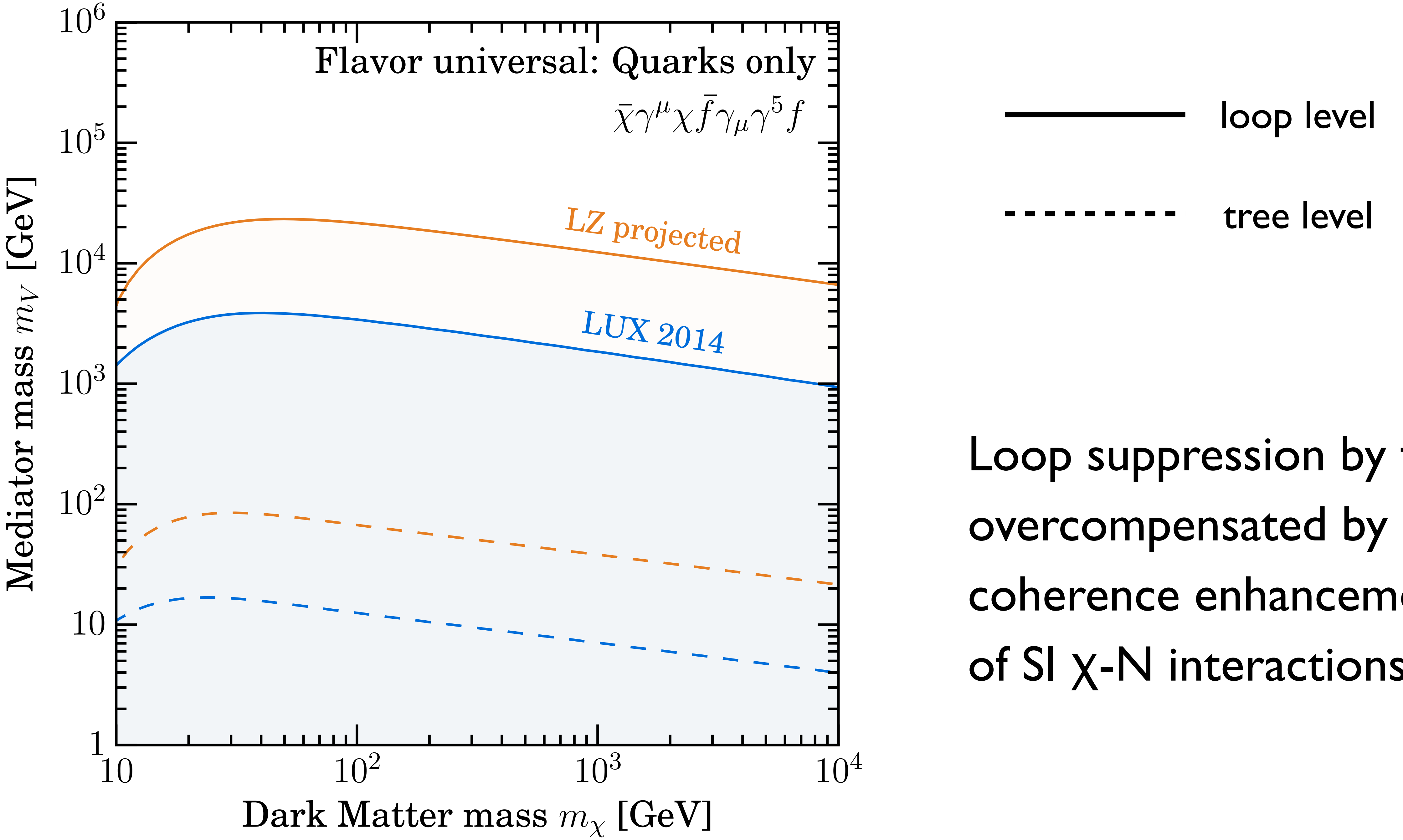
$$= C_5^{u,d} D_5^{u,d}$$

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

operator leads to SI χ-N interactions

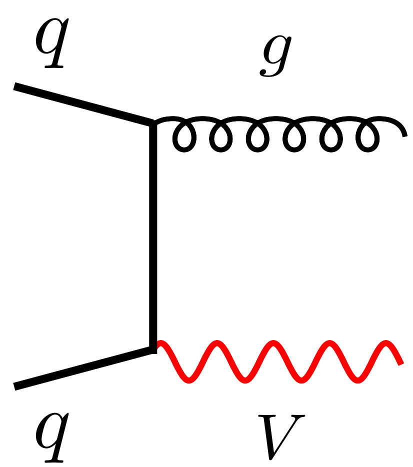
From suppressed to unsuppressed DD

[D'Eramo et al., 1605.04917]

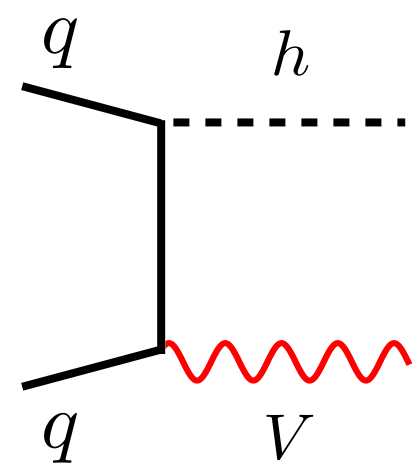


Loop suppression by far overcompensated by coherence enhancement of SI χ-N interactions

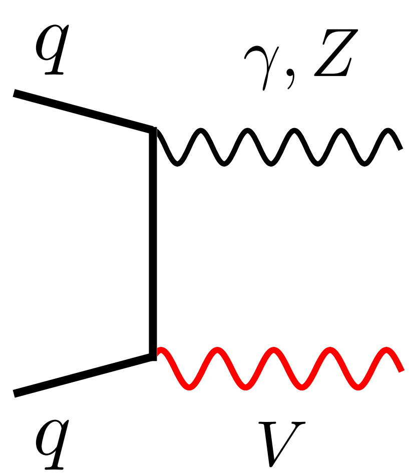
Spin-1 mono-X amplitudes



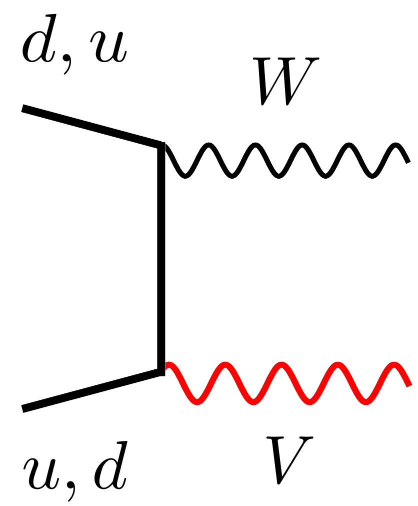
$$\sim s^0$$



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

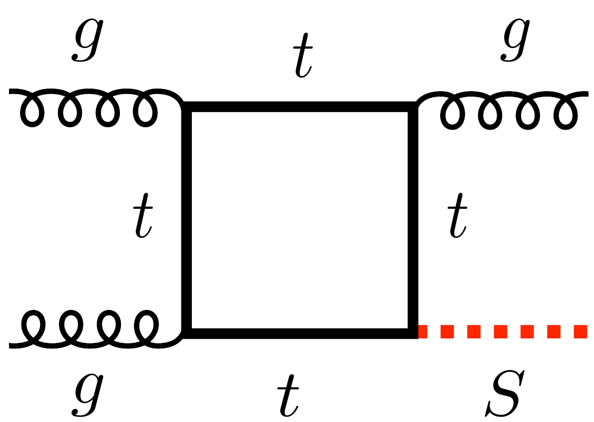


$$\sim s^0, \;\; y_q \, g_q^A \, \frac{s^{1/2}}{M_V}$$

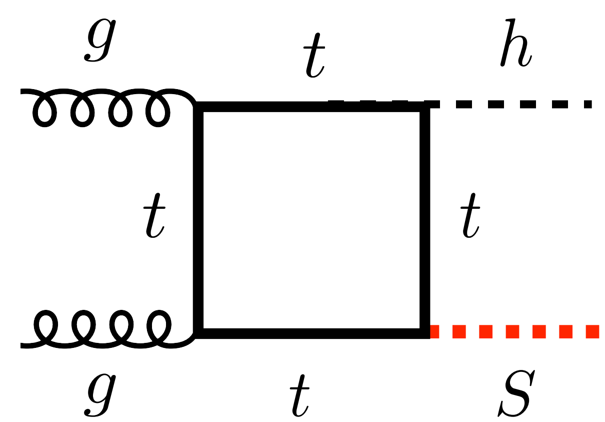


$$\sim \left(g_u^L - g_d^L\right) \frac{s}{M_W M_V}$$

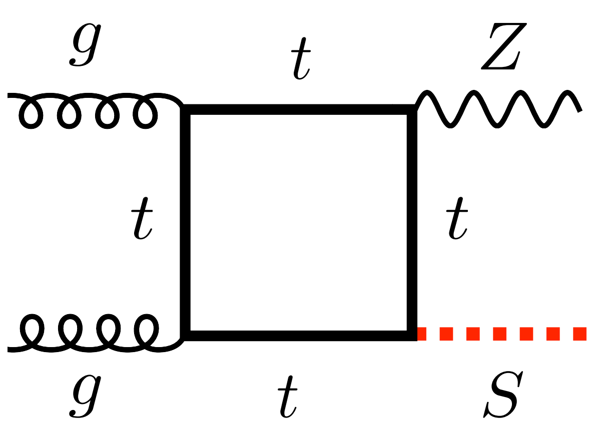
Spin-0 mono-X amplitudes



$$\sim s^0$$



$$\sim s^0$$

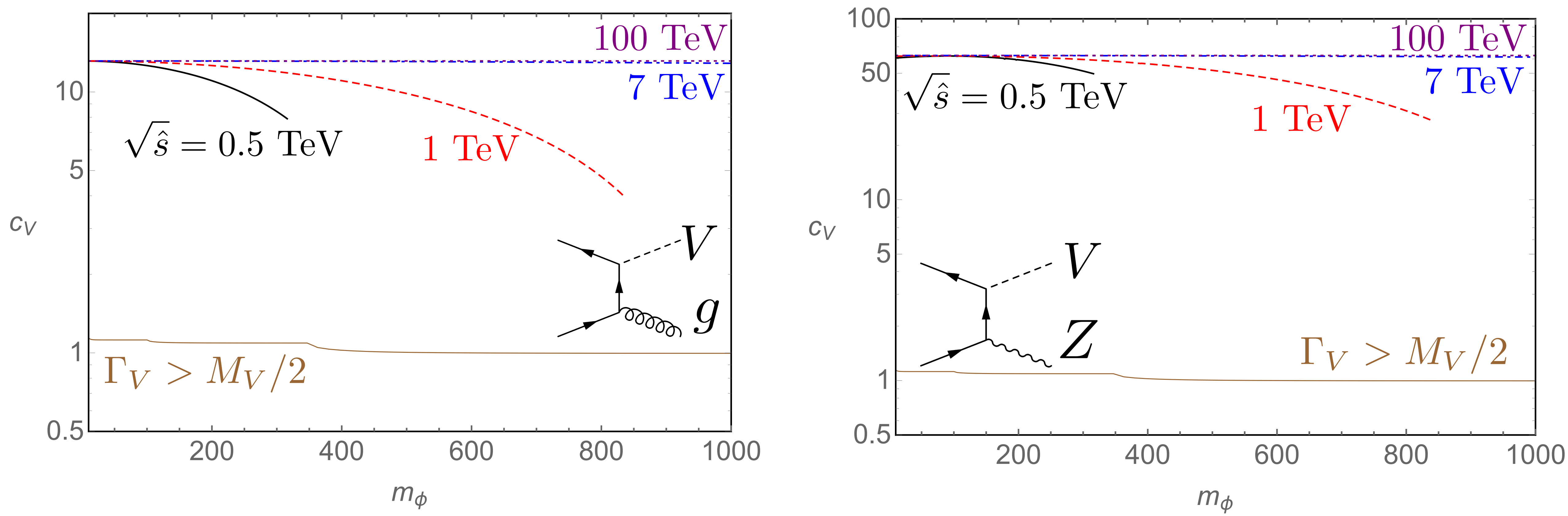


$$\sim \frac{\alpha_s}{4\pi}\, y_t^2\, g_t^S \, \ln^2\left(\frac{s}{m_t^2}\right)$$

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

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

[Englert et al., 1604.07975]

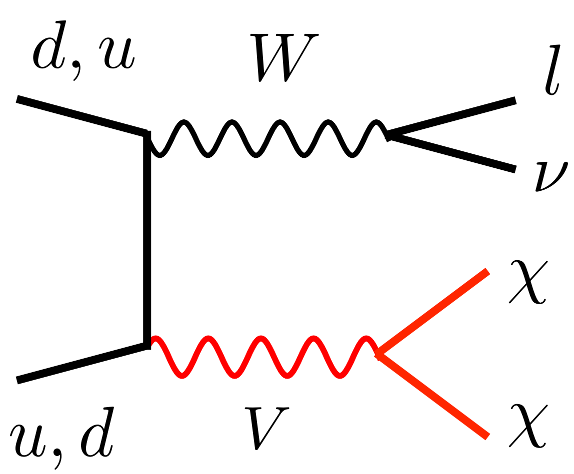


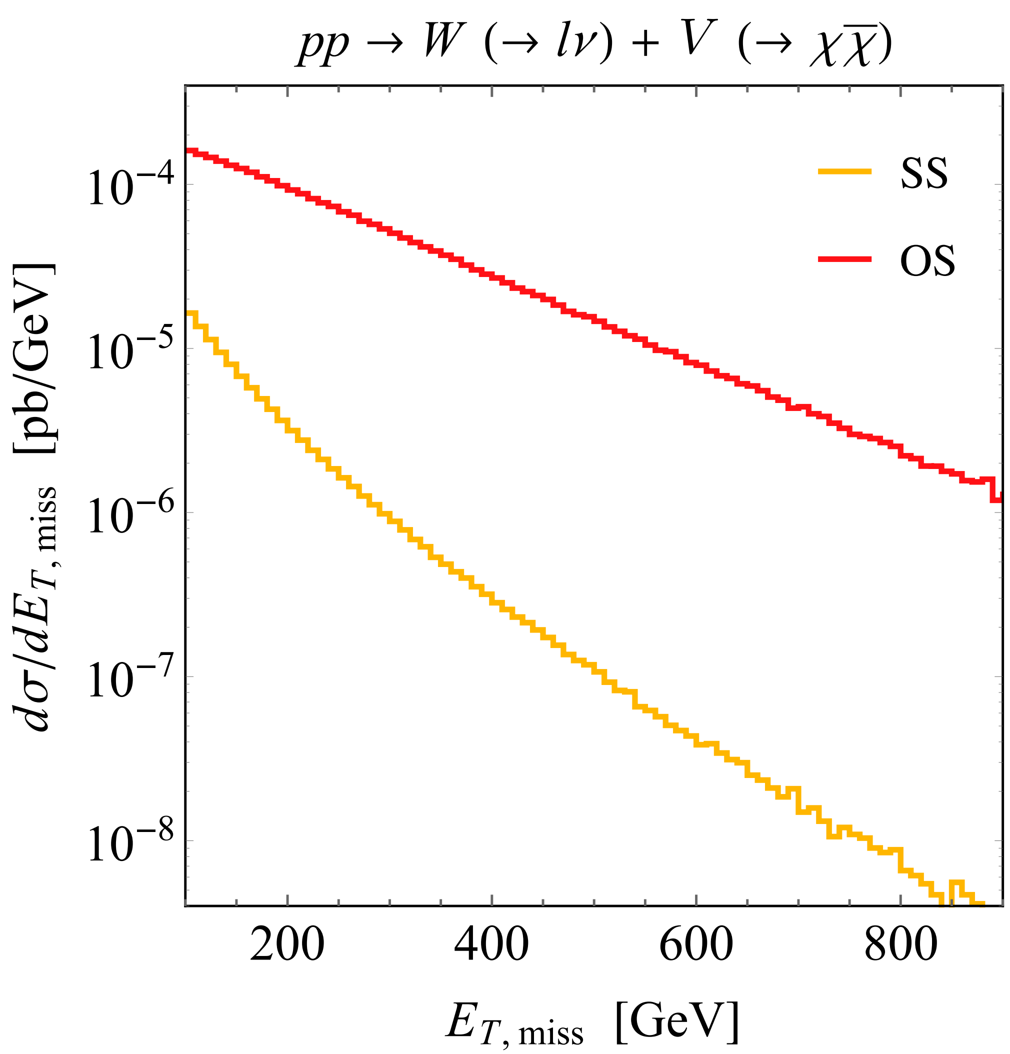
$E_{T,\text{miss}}$+jet, Z, h amplitudes in spin-1 models have no problem with unitarity at LHC energies & beyond unless DM-mediator couplings are non-perturbative†

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

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

[UH et al., 1603.01267]





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

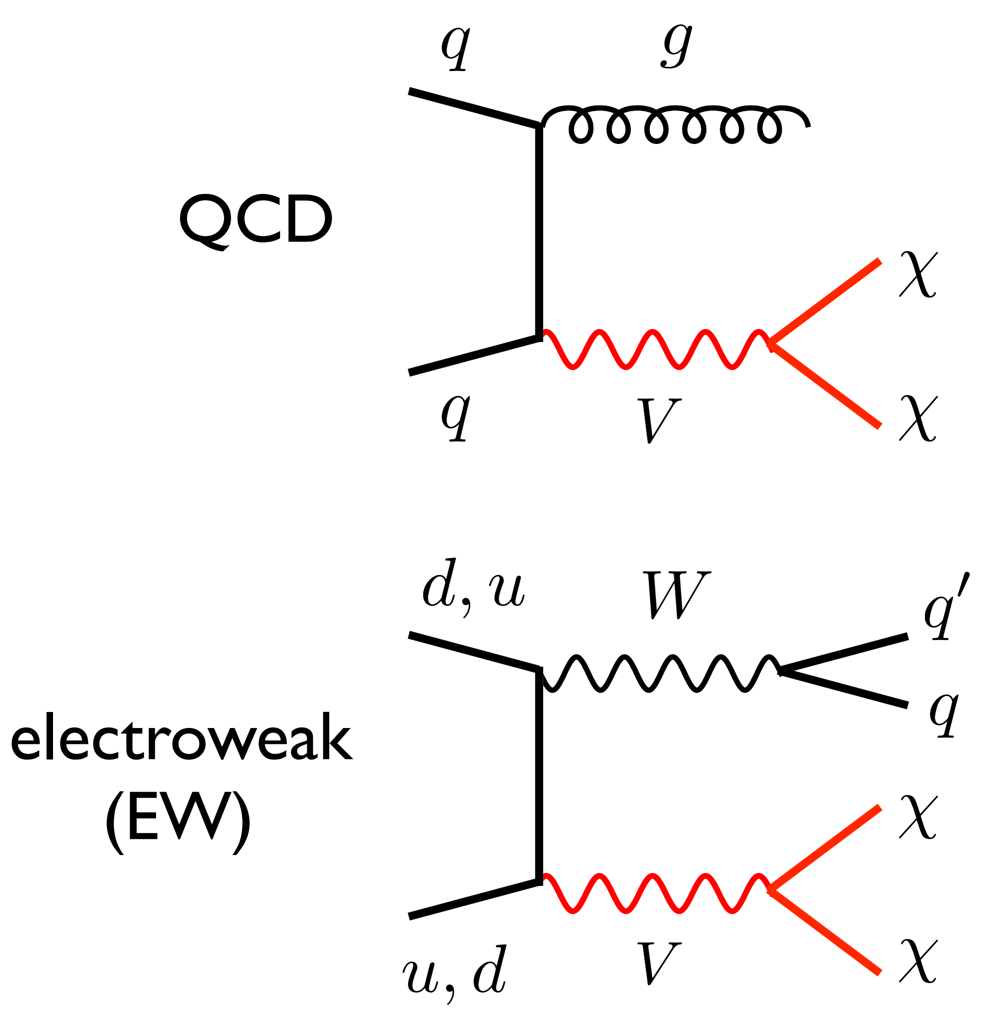
opposite-sign (OS): $g_u = -g_d$

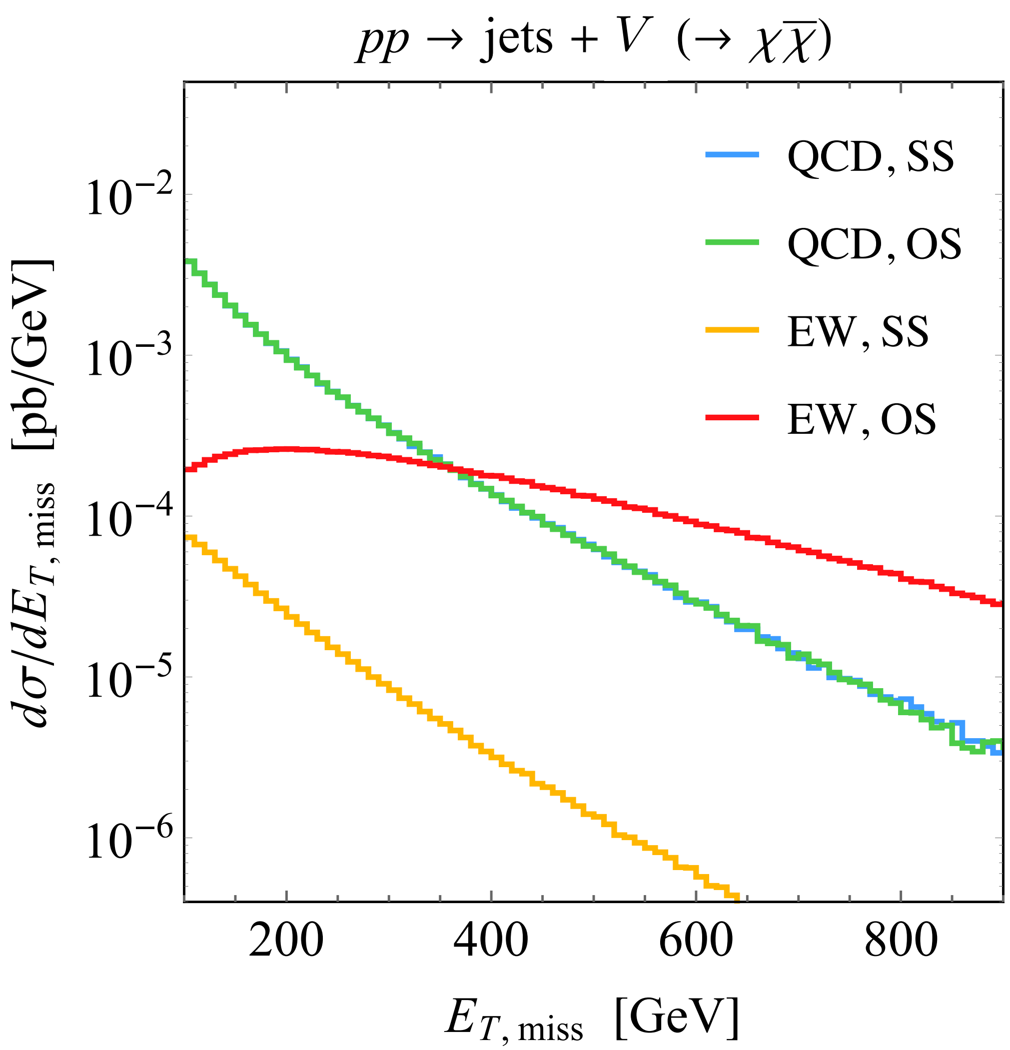
For OS couplings $E_{T,miss}$ spectrum significantly harder than in SS case. This is an artefact of unitarity violation & thus unphysical

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

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

[UH et al., 1603.01267]

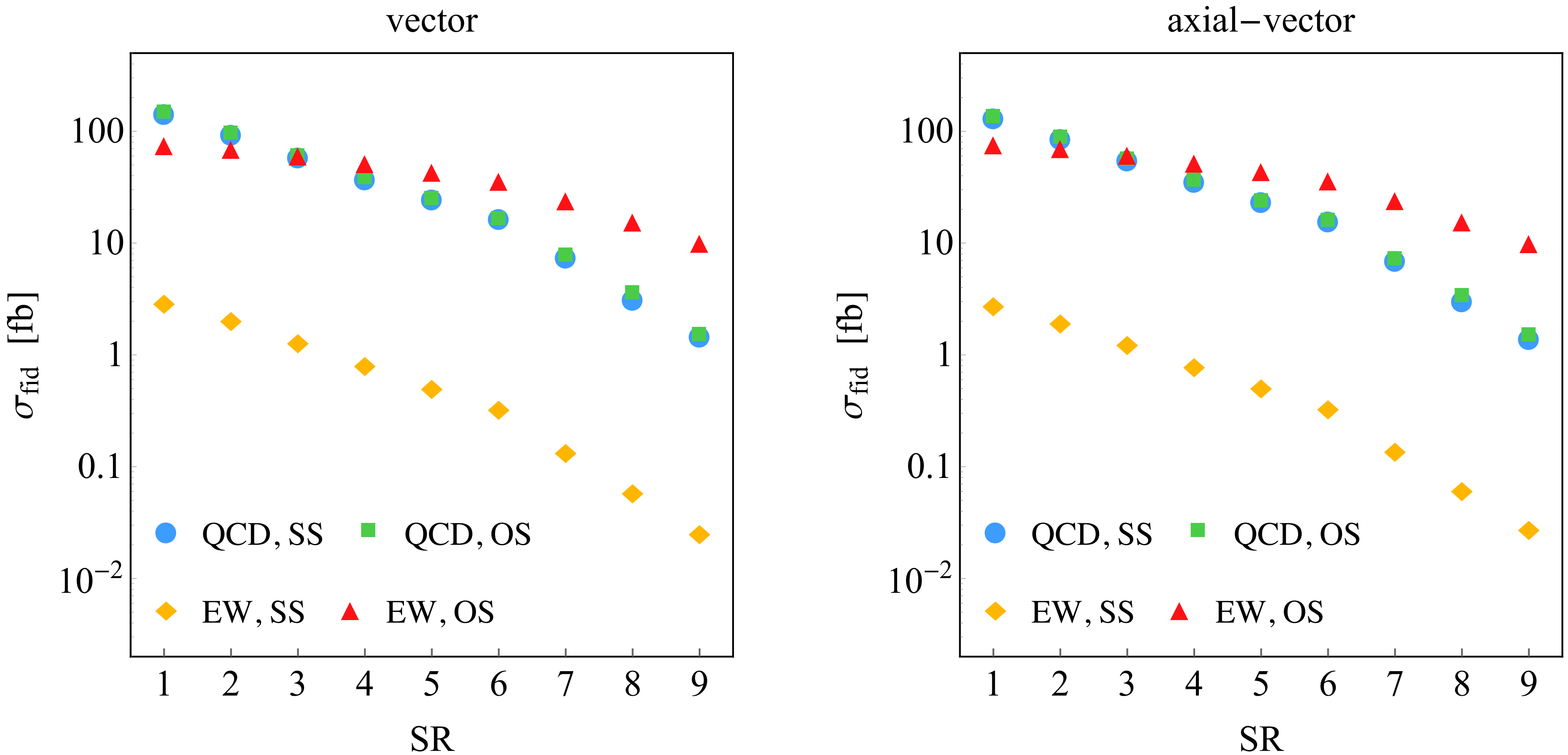




In fact, EW channel $pp \to W(\to q\bar{q}') + V(\to \chi\bar{\chi})$ even produces harder mono-jet events than QCD process $pp \to \text{jets} + V(\to \chi\bar{\chi})$

Mono-W problem in mono-jets

[UH et al., 1603.01267]



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

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

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

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

Unitarity problem persists after parton shower, hadronisation corrections & detector effects. As a result, EW contribution gives rise to majority of events in high-$E_{T,\mathrm{miss}}$ 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:

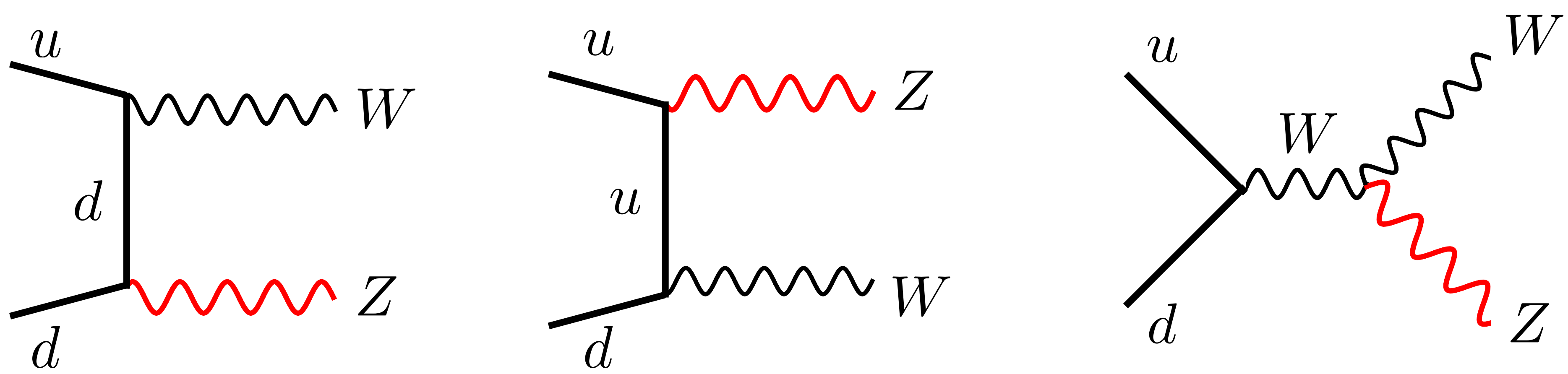
$$\mathcal{L}_{Vq\bar{q}} = -\sum_{u,d} V_\mu \left(g_Q \bar{Q}_L \gamma^\mu Q_L + g_u \bar{u}_R \gamma^\mu u_R + g_d \bar{d}_R \gamma^\mu d_R \right)$$

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

[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:

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

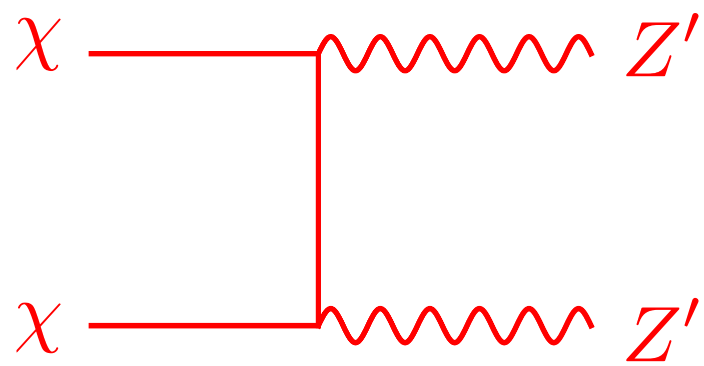
In such a case $SU(2)_L$ breaking is however not O(1), but given by†

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

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

$$\mathcal{L}_{\mathrm{DM}} = \frac{i}{2}\bar{\psi}\not{\partial}\psi - \frac{1}{2}g^{A}_{\mathrm{DM}}Z'^{\mu}\bar{\psi}\gamma_\mu\gamma_5\psi - \frac{1}{2}y_{\mathrm{DM}}\bar{\psi}\left(P_L S + P_R S^*\right)\psi$$

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

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

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

[Kahlhoefer et al.,1510.02110]

Z′ interactions

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

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

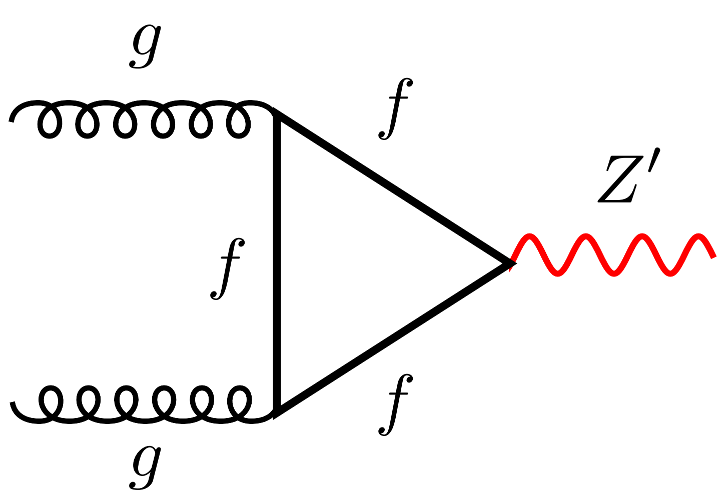
$$- \sum_{f=q,\ell,\nu} g' Z'^\mu \left(\bar{q}_{f_L} \bar{f}_L \gamma_\mu f_L + \bar{q}_{f_R} \bar{f}_R \gamma_\mu f_R\right)$$

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



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

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:

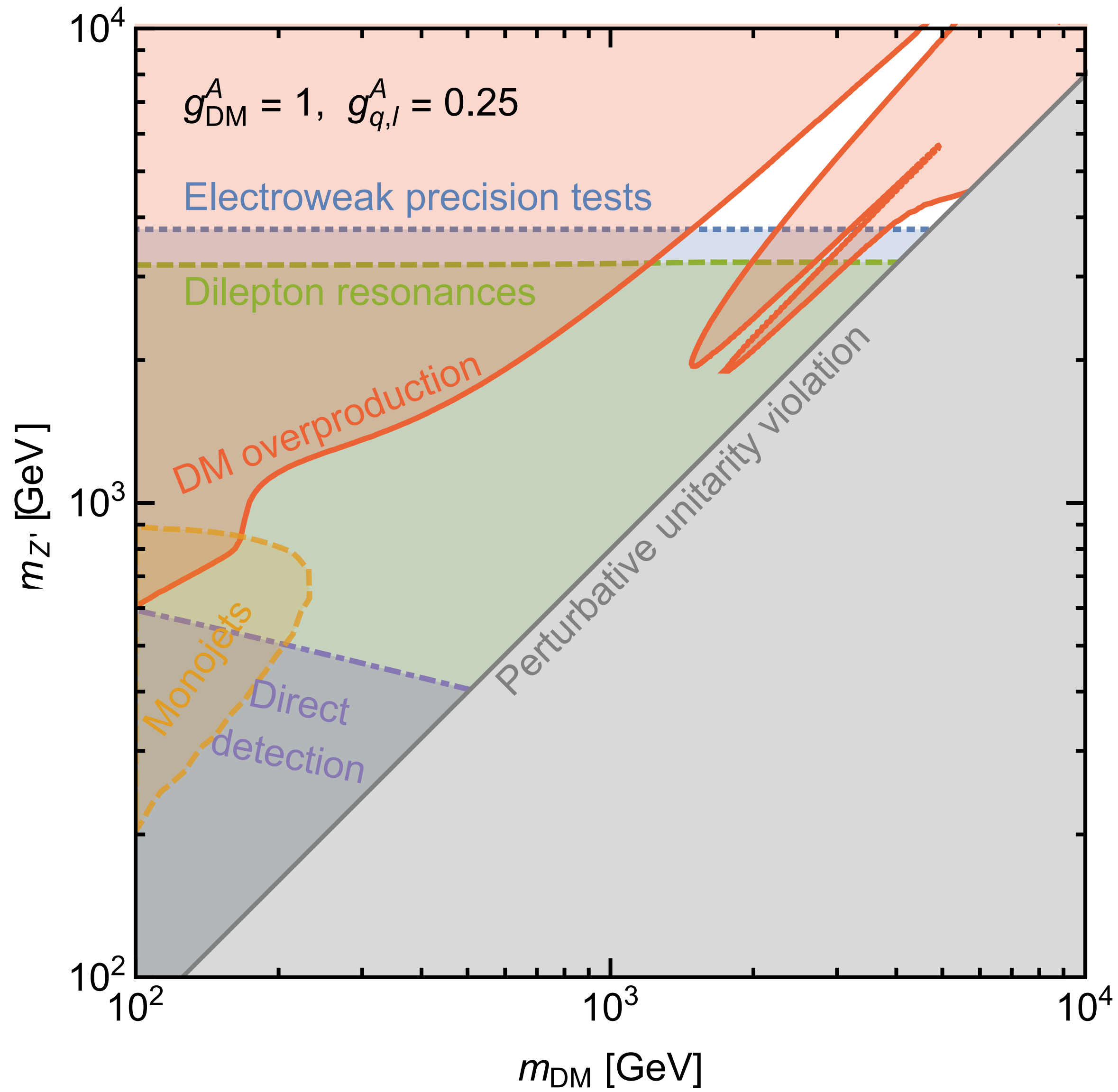
- Z' must couple with same strength to quarks & leptons (assuming one Higgs doublet), resulting in stringent constraints from di-lepton resonance searches

- 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

Structure of spin-0 simplified model

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

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

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

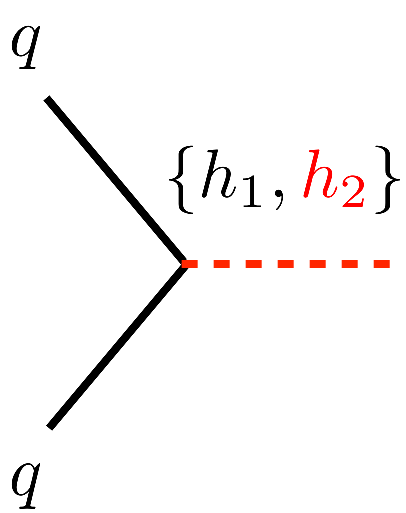
As a result of portal coupling μ, SM Higgs h & singlet s mix, giving rise to mass eigenstates $h_{1,2}$:

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

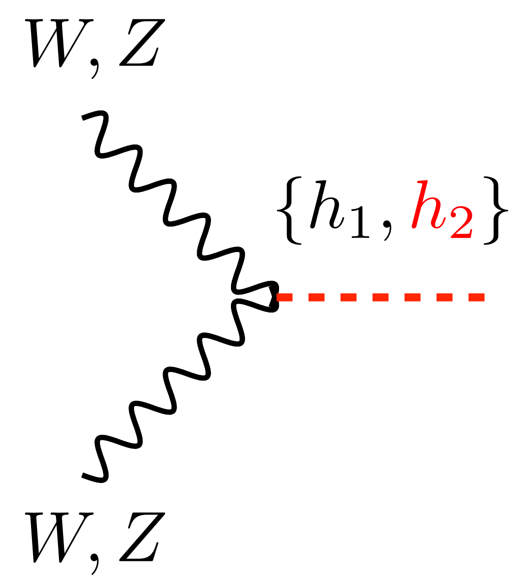
For small $\theta \ll 1$, h_1 (h_2) SM Higgs-like (singlet-like)

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

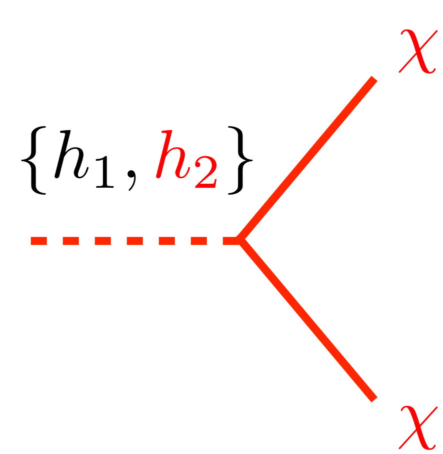
Fermion singlet DM: vertices



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



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



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

Fermion singlet DM: signatures

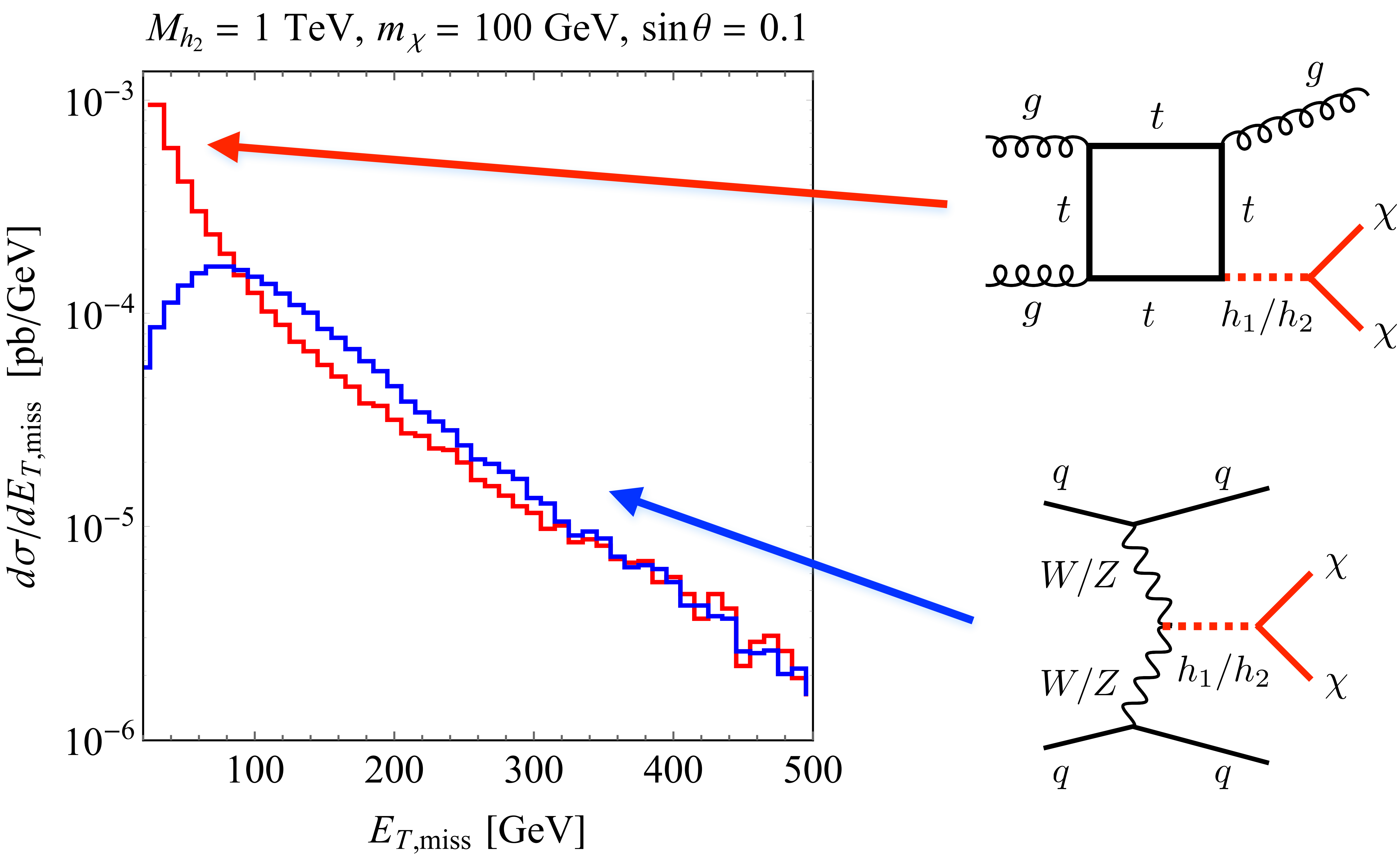
Compared to spin-0 simplified model LHC phenomenology is richer in fermion singlet DM scenario:

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

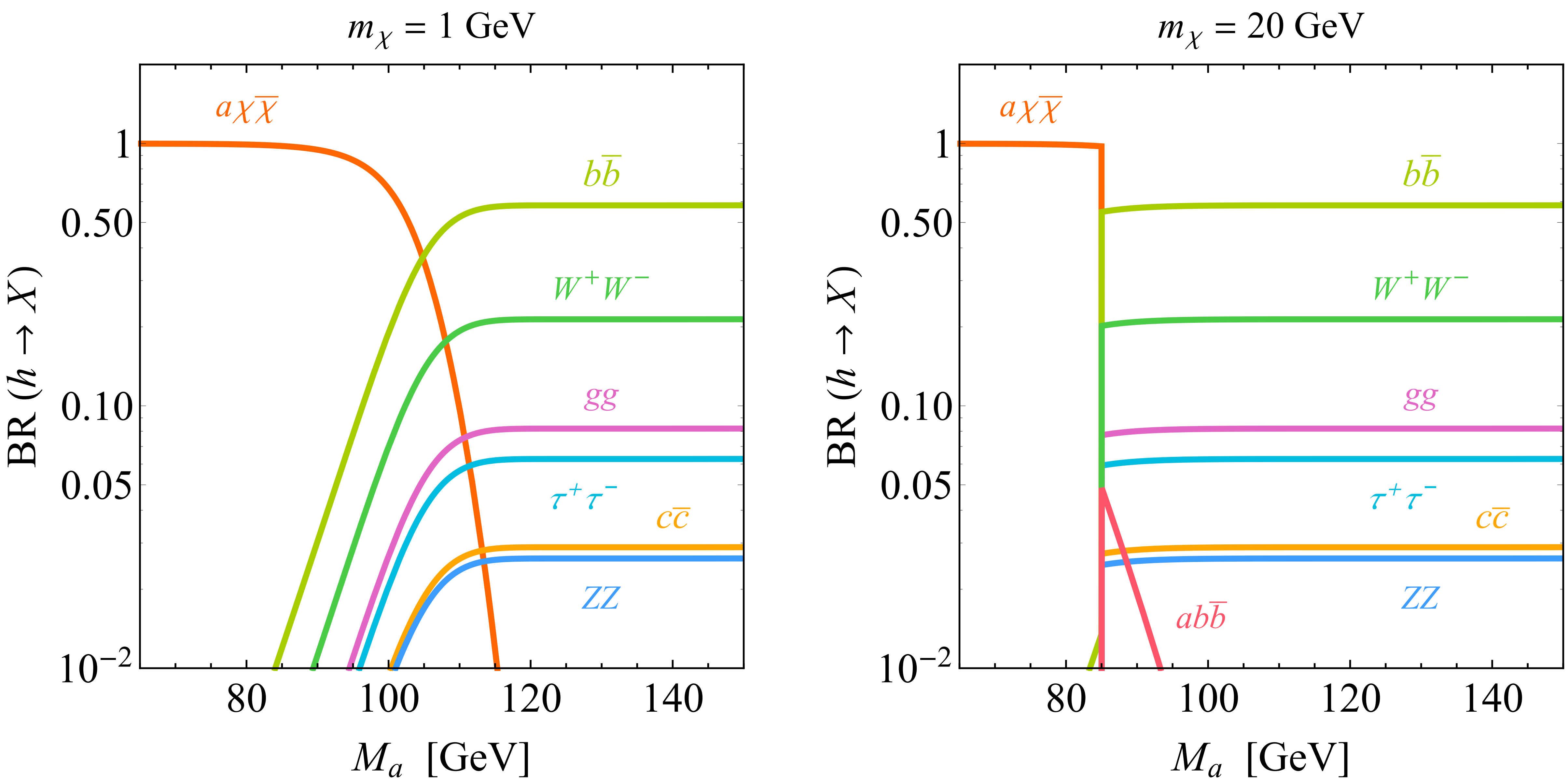
(ii) new SM Higgs decay modes $h_1 \to \chi\bar{\chi}$ & $h_1 \to h_2 h_2$ if kinematically allowed

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

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

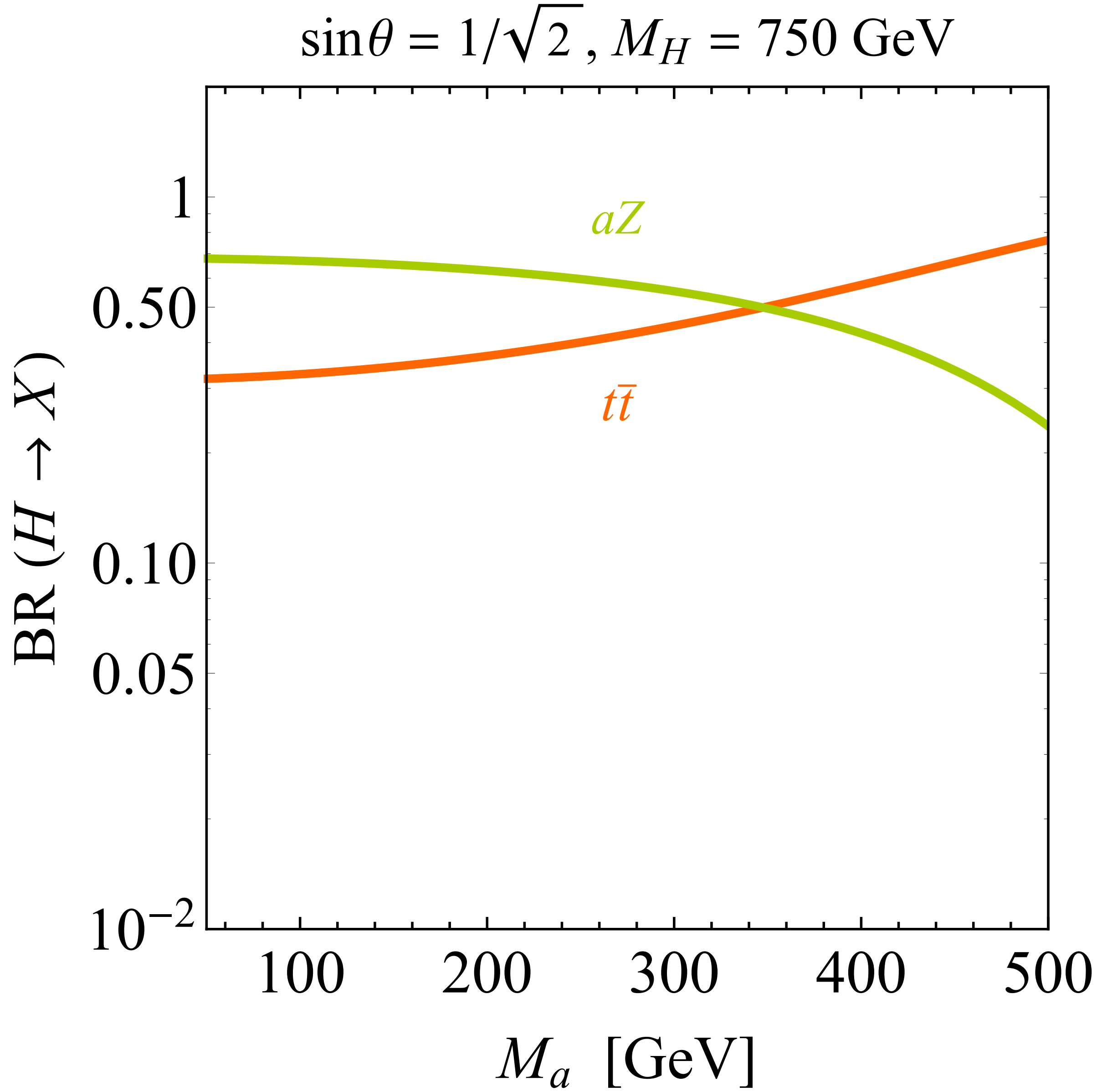


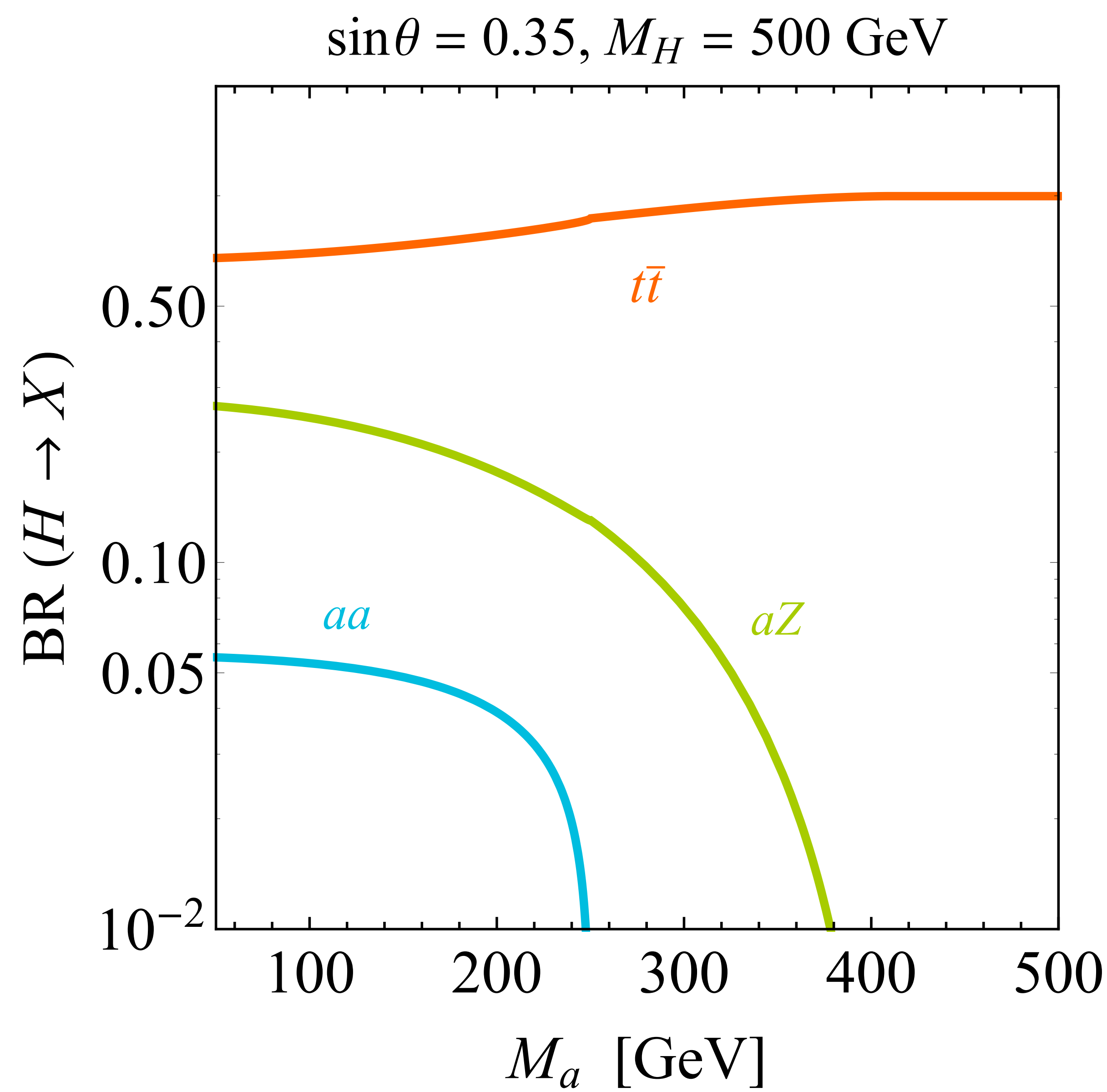
THDMP: h→X branching ratios



[Bauer et al., 1701.07427]

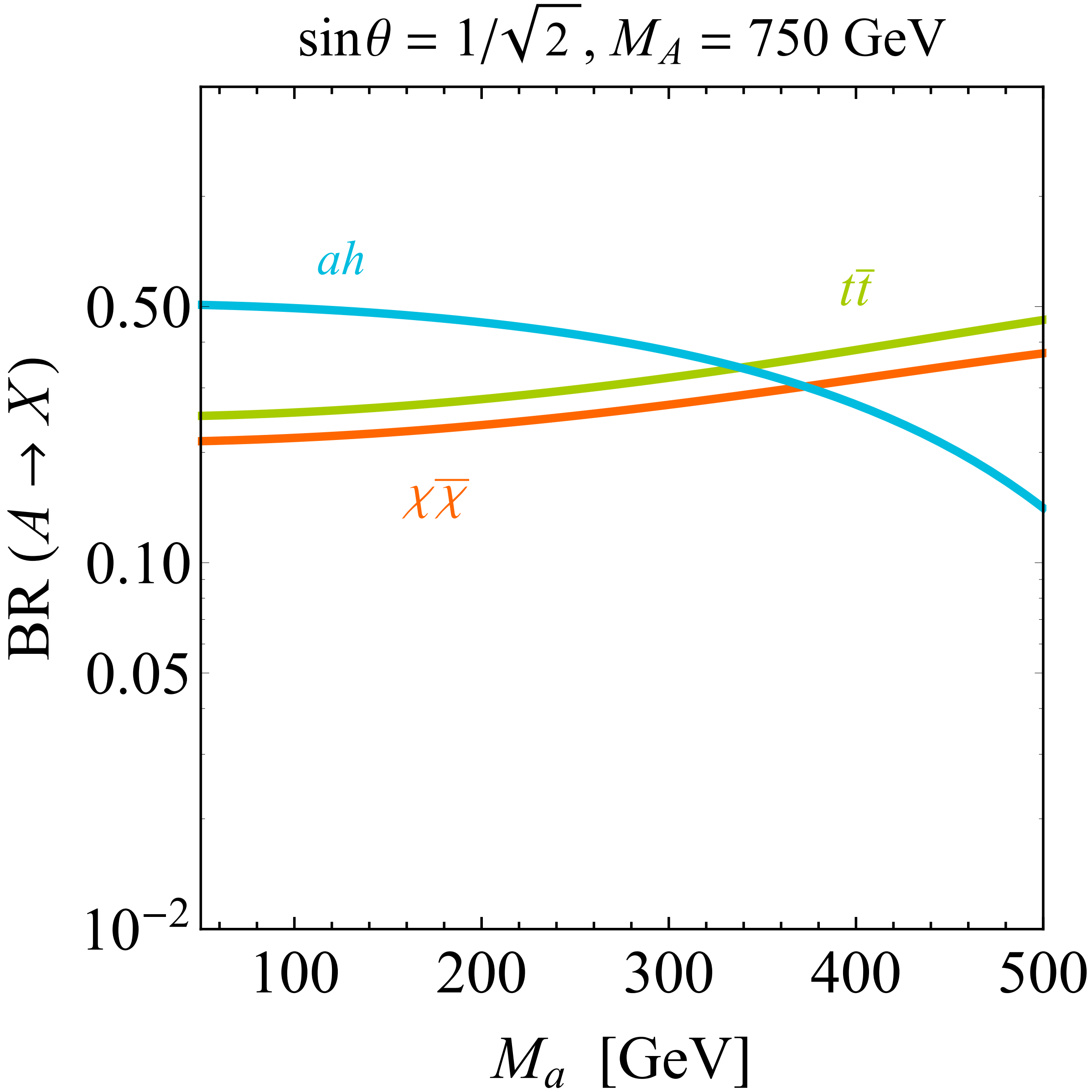
THDMP: H→X branching ratios

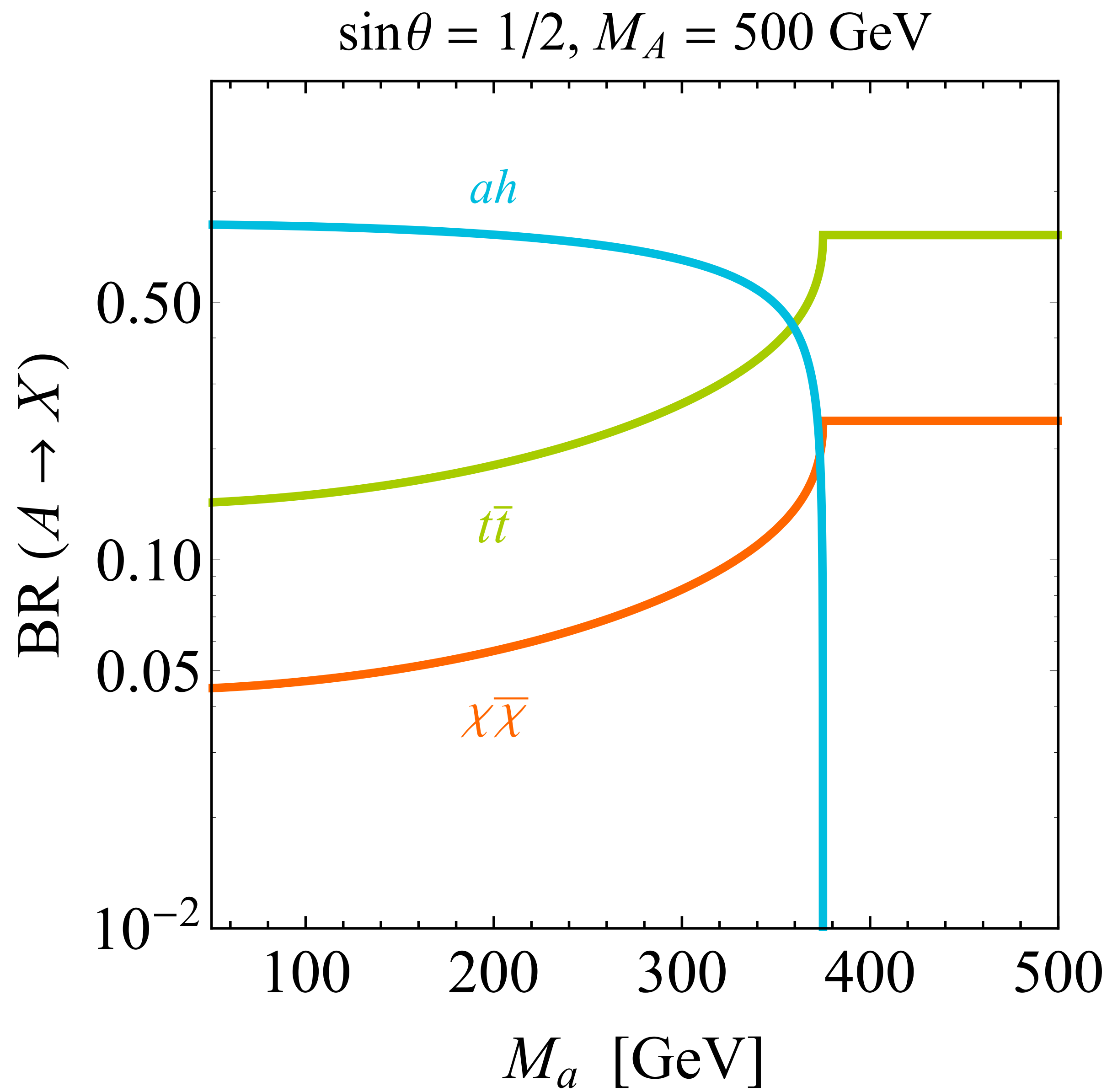




[Bauer et al., 1701.07427]

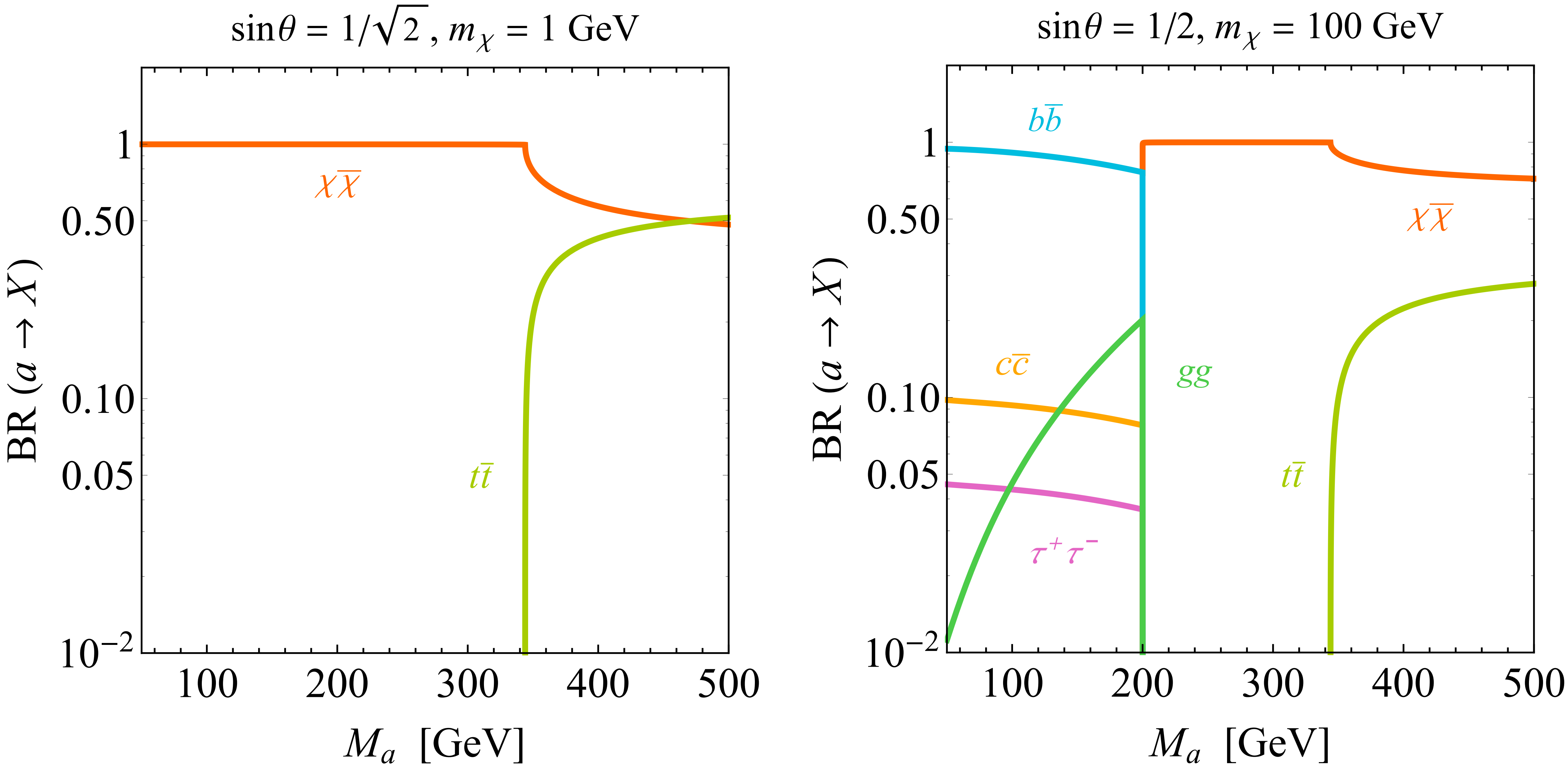
THDMP: A → X branching ratios





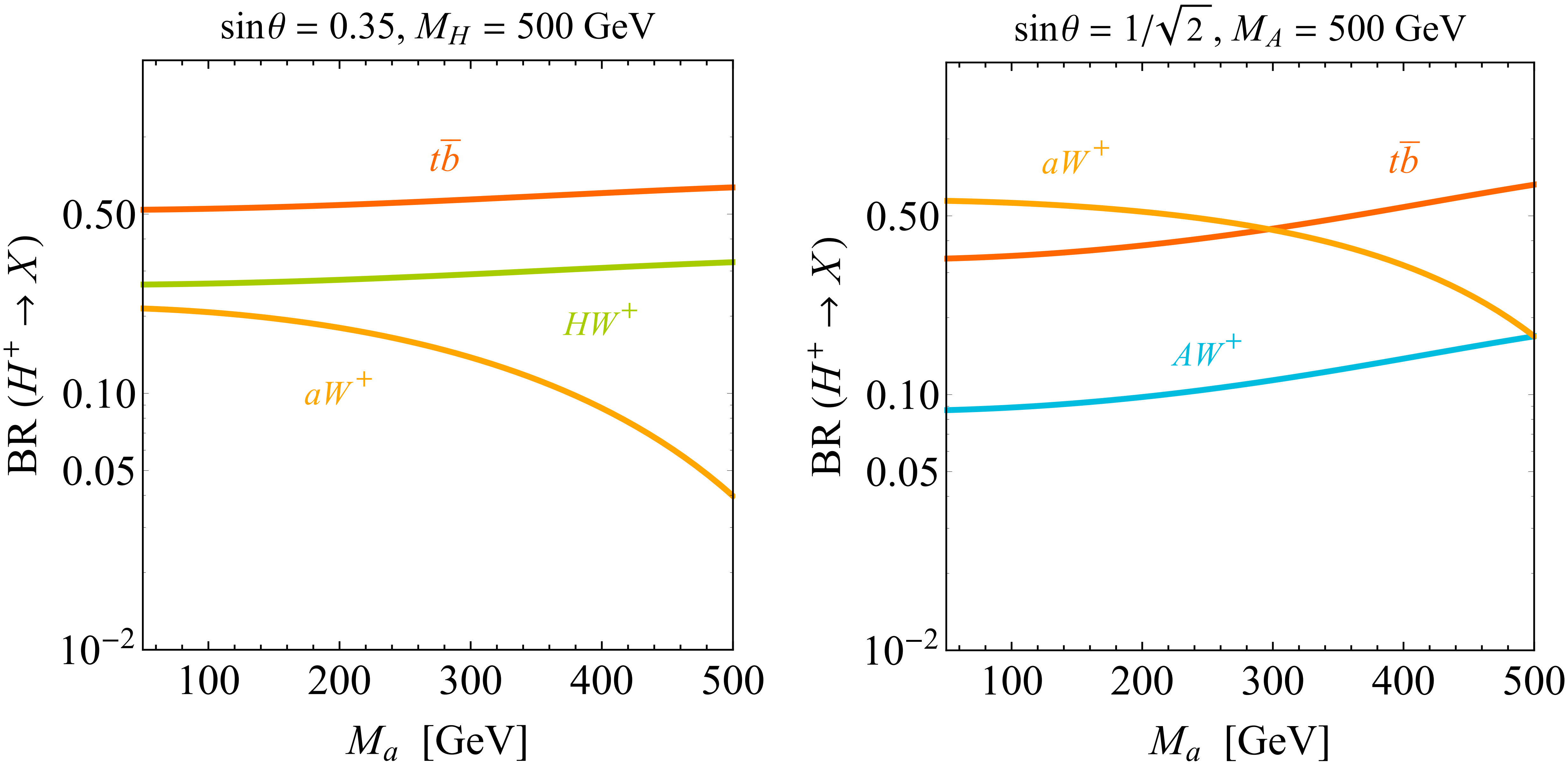
[Bauer et al., 1701.07427]

THDMP: a→X branching ratios



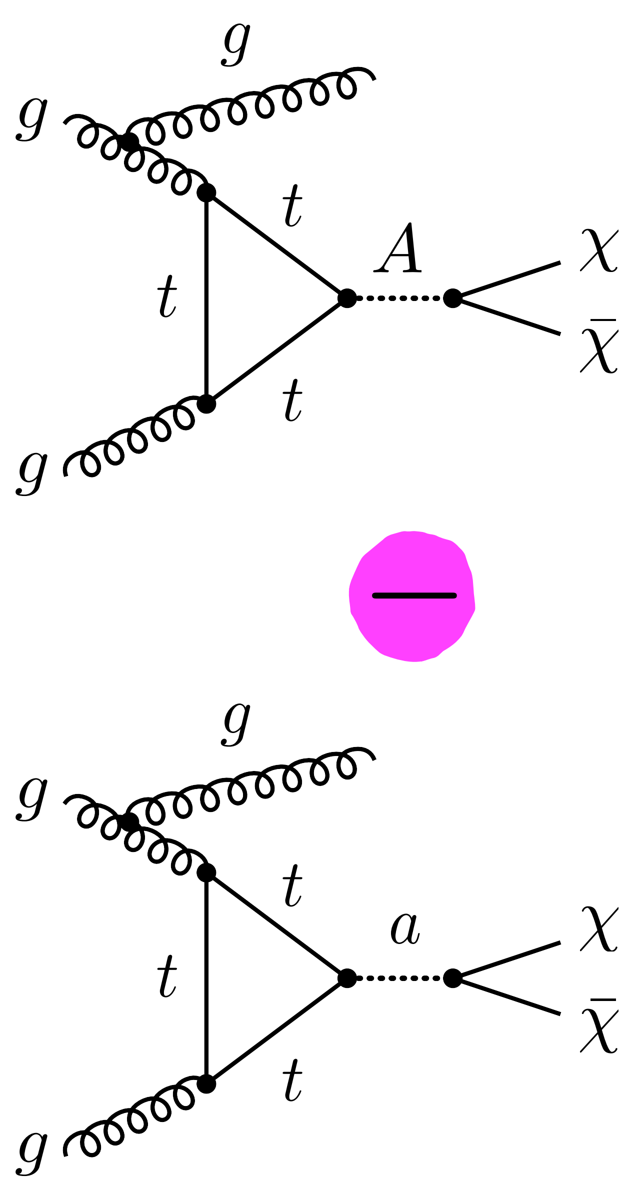
[Bauer et al., 1701.07427]

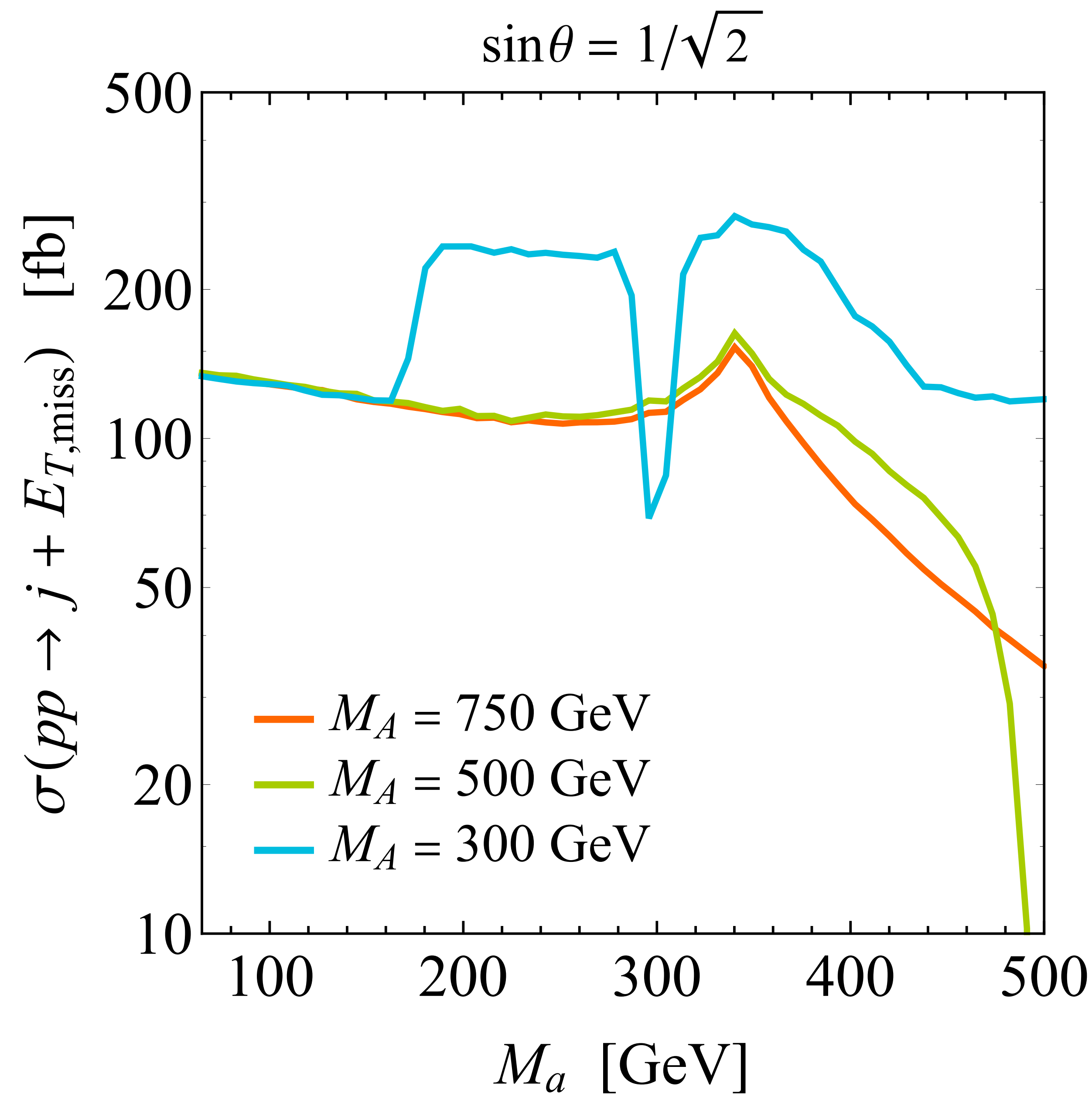
THDMP: $H^+ \to X$ branching ratios



[Bauer et al., 1701.07427]

THDMP: interference effects

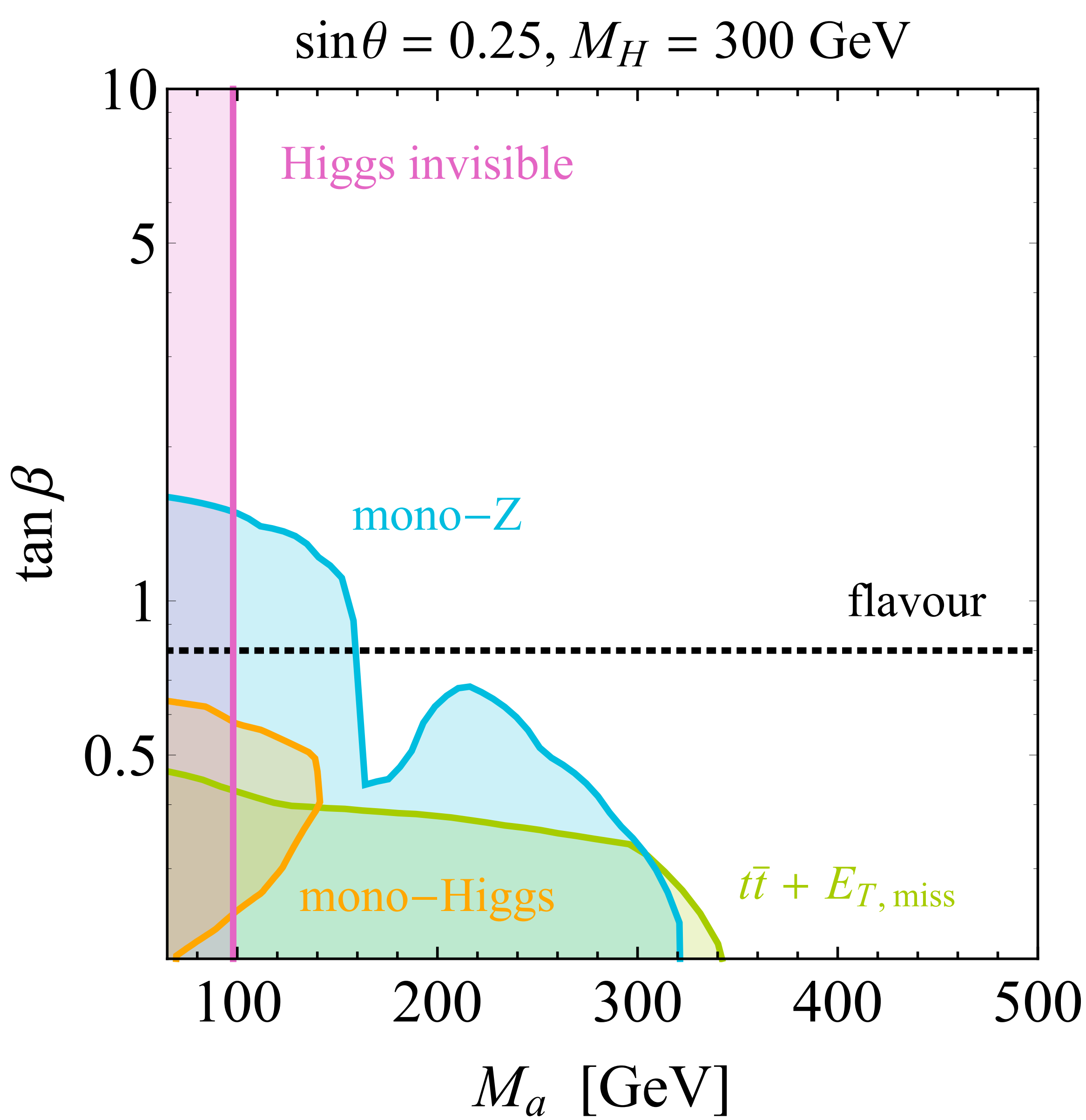


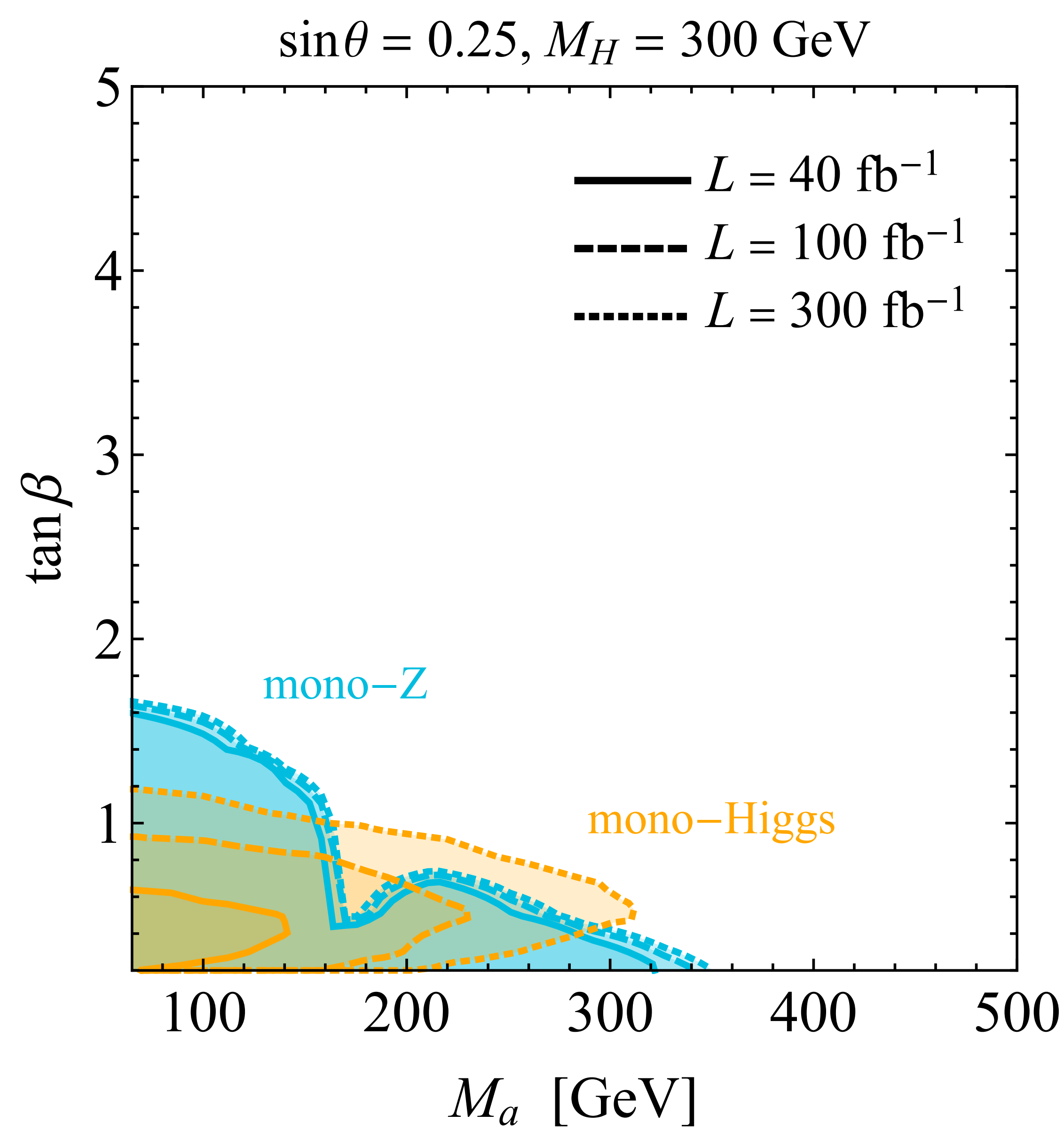


Contributions of A & a to mono-jet, $E_{T,\mathrm{miss}}$+$t\bar{t}$, etc. interfere destructively

[Bauer et al., 1701.07427]

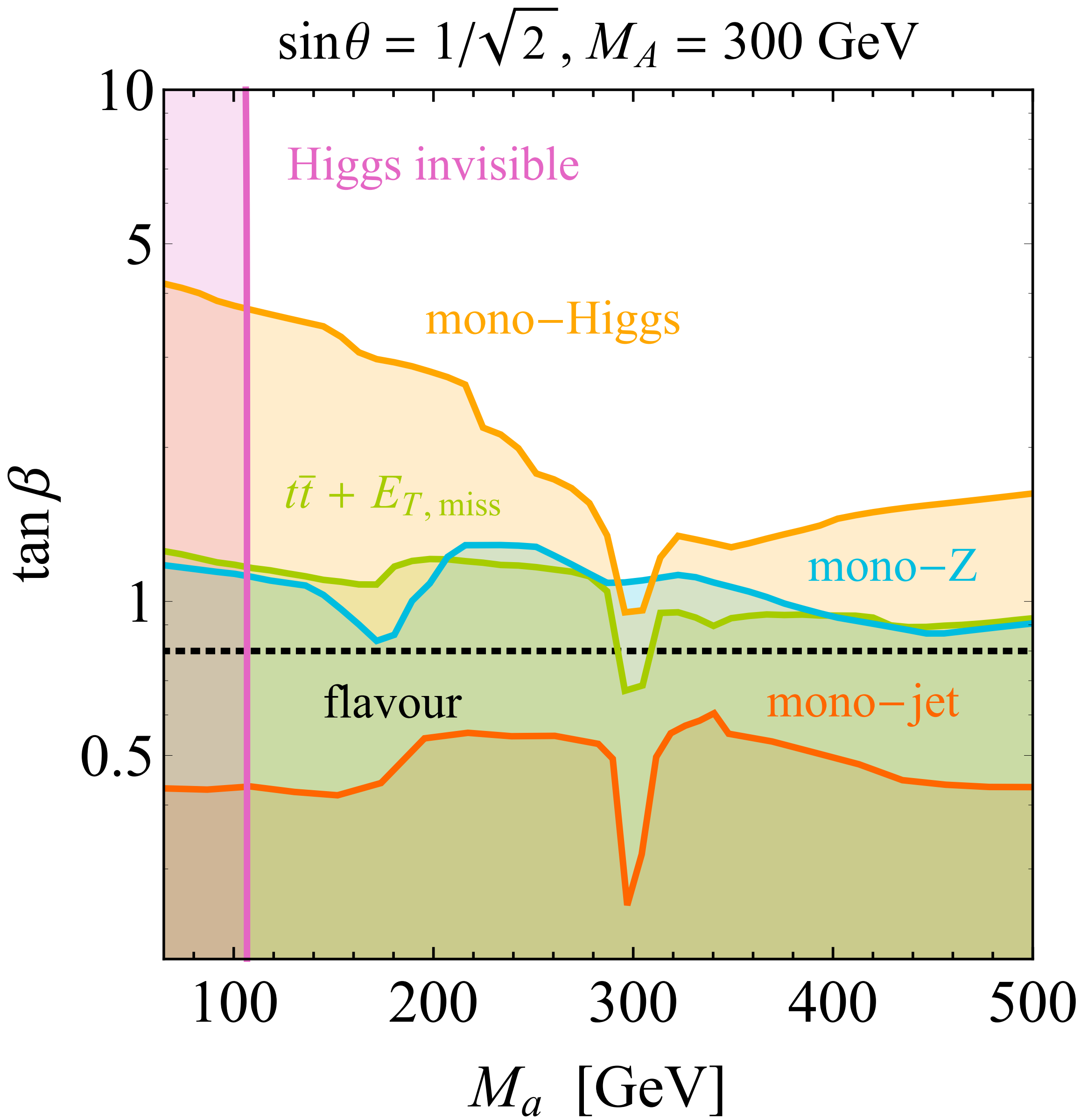
THDMP benchmark: M_H, M_a < M_A

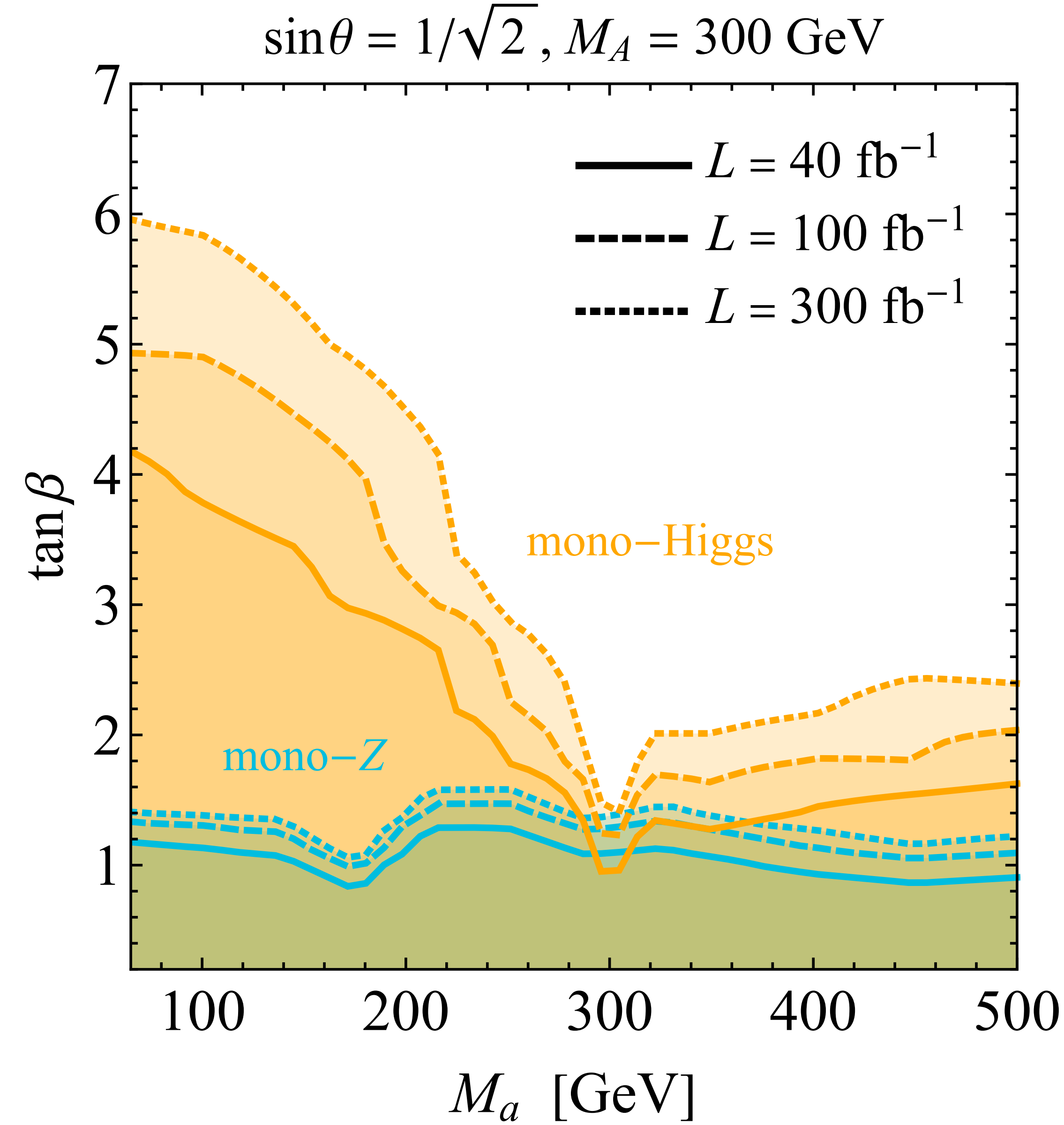




[Bauer et al., 1701.07427]

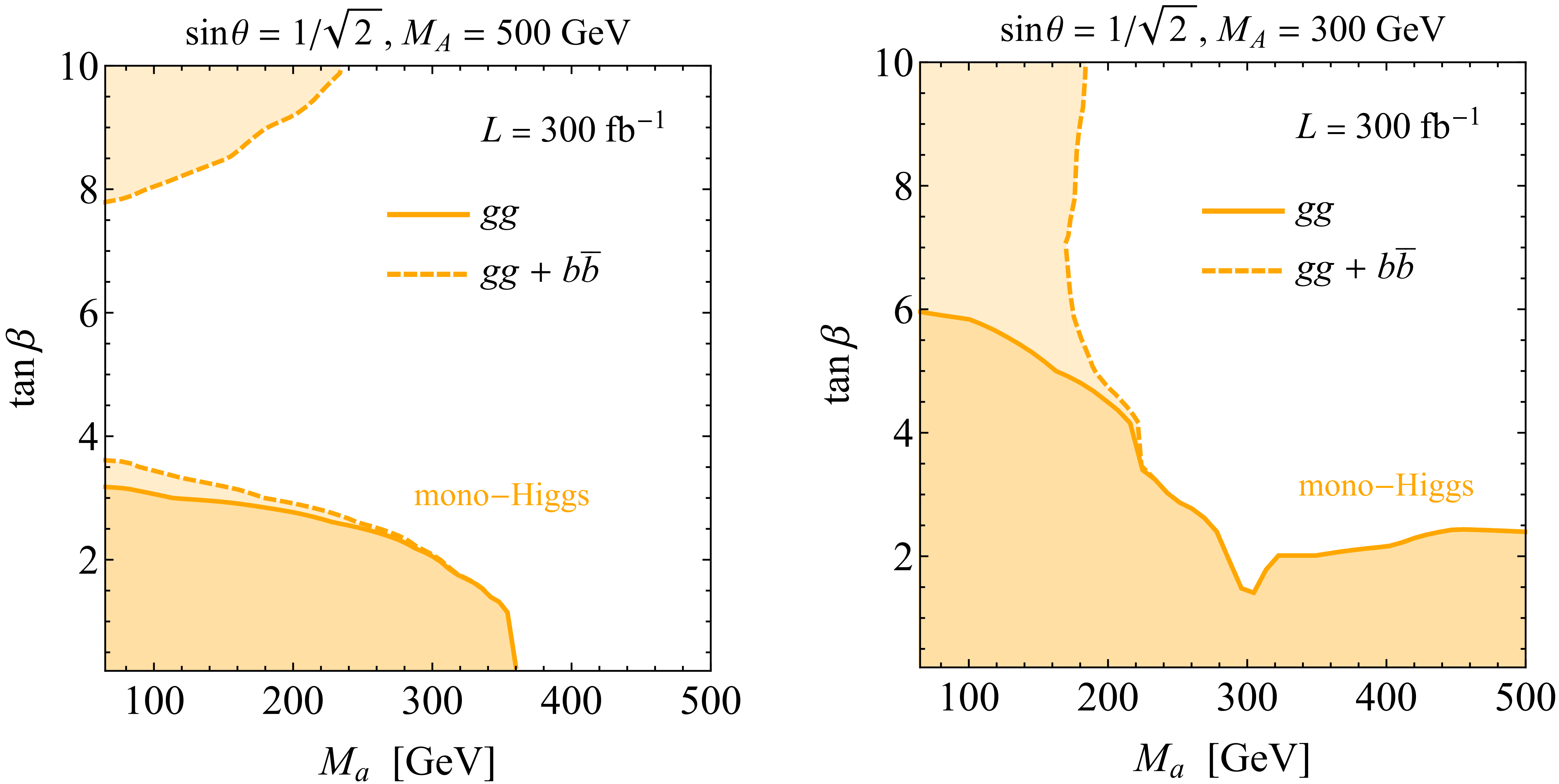
THDMP benchmark: M_A, M_a < M_H





[Bauer et al., 1701.07427]

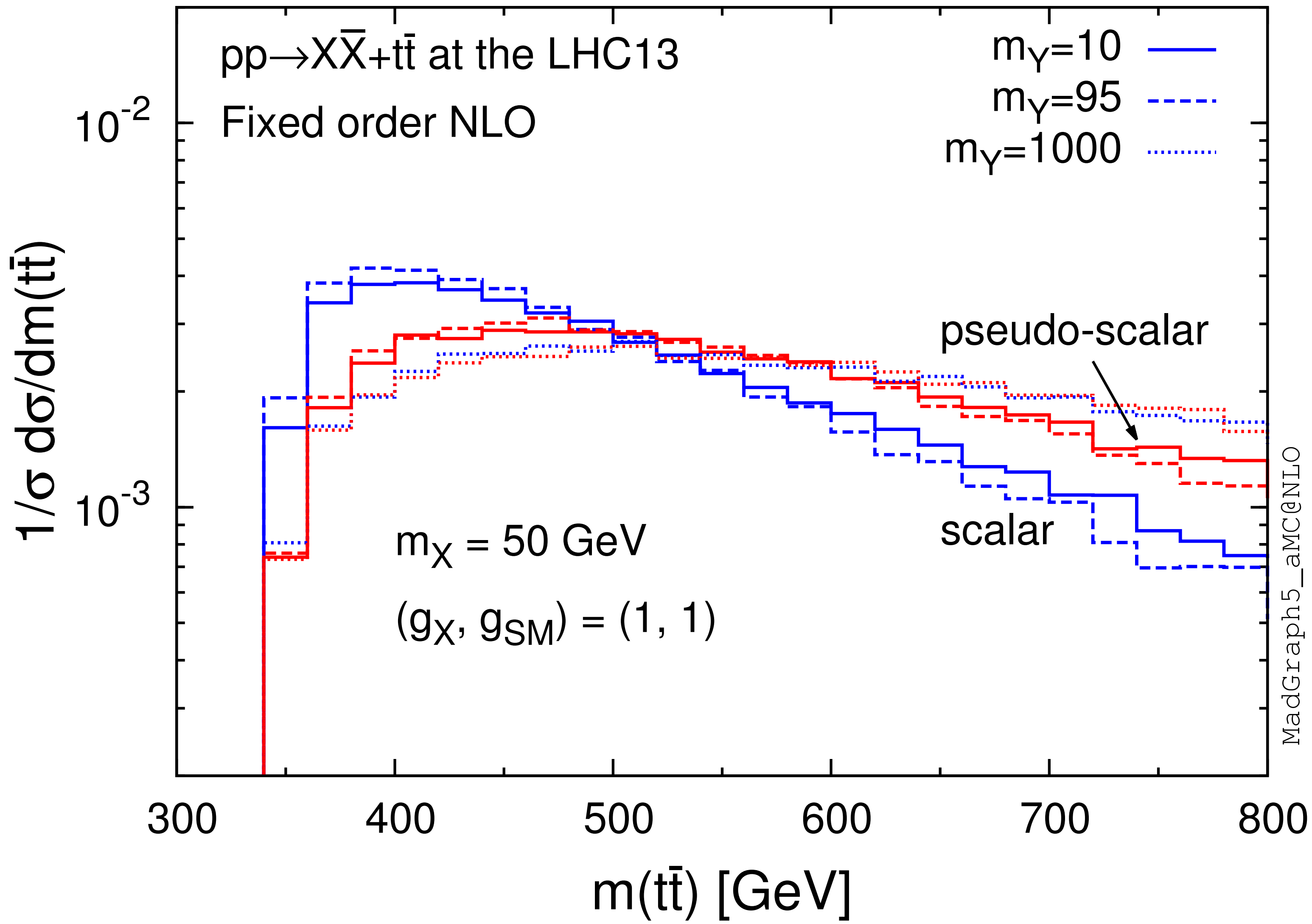
THDMP: $b\bar{b}$ contributions to $h+E_{T,\text{miss}}$



[Bauer et al., 1701.07427]

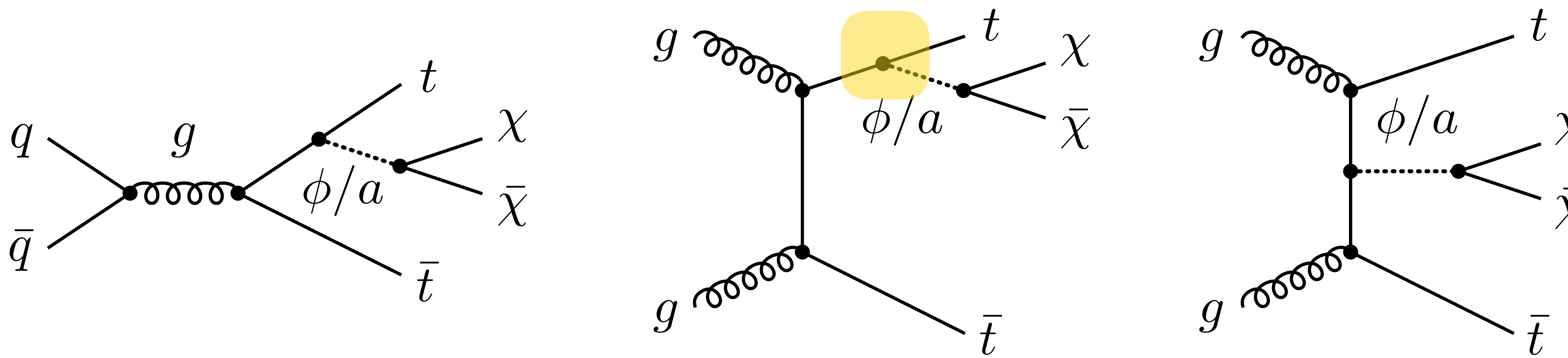
Distribution of $E_{T,miss}$+$t\bar{t}$ events

[Backović et al., 1508.05327]



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

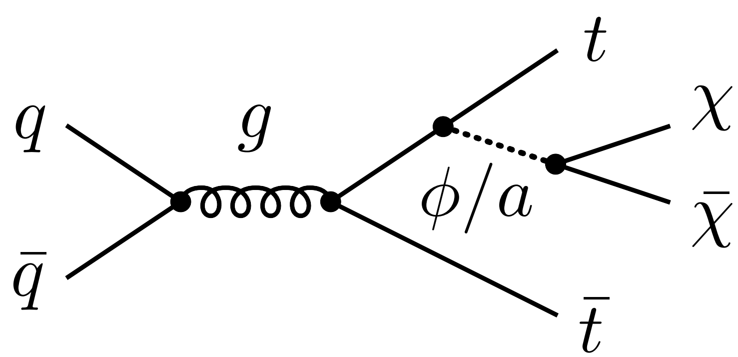
$E_{T,miss}$+$t\bar{t}$ production

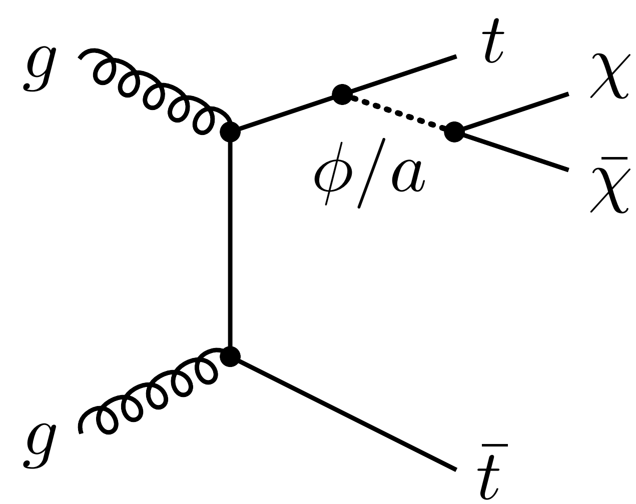


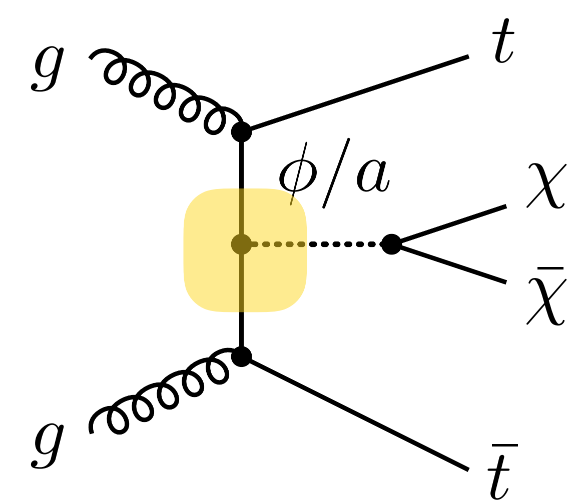
$$f_{t\to\phi}(x) = \frac{g_t^2}{(4\pi)^2}\left[\frac{4\,(1-x)}{x} + x\ln\left(\frac{s}{m_t^2}\right)\right] \qquad f_{t\to a}(x) = \frac{g_t^2}{(4\pi)^2}\left[x\ln\left(\frac{s}{m_t^2}\right)\right]$$

soft singularity enhances
production cross section for light
scalar compared to pseudoscalar

$E_{T,\text{miss}}$+$t\bar{t}$ production





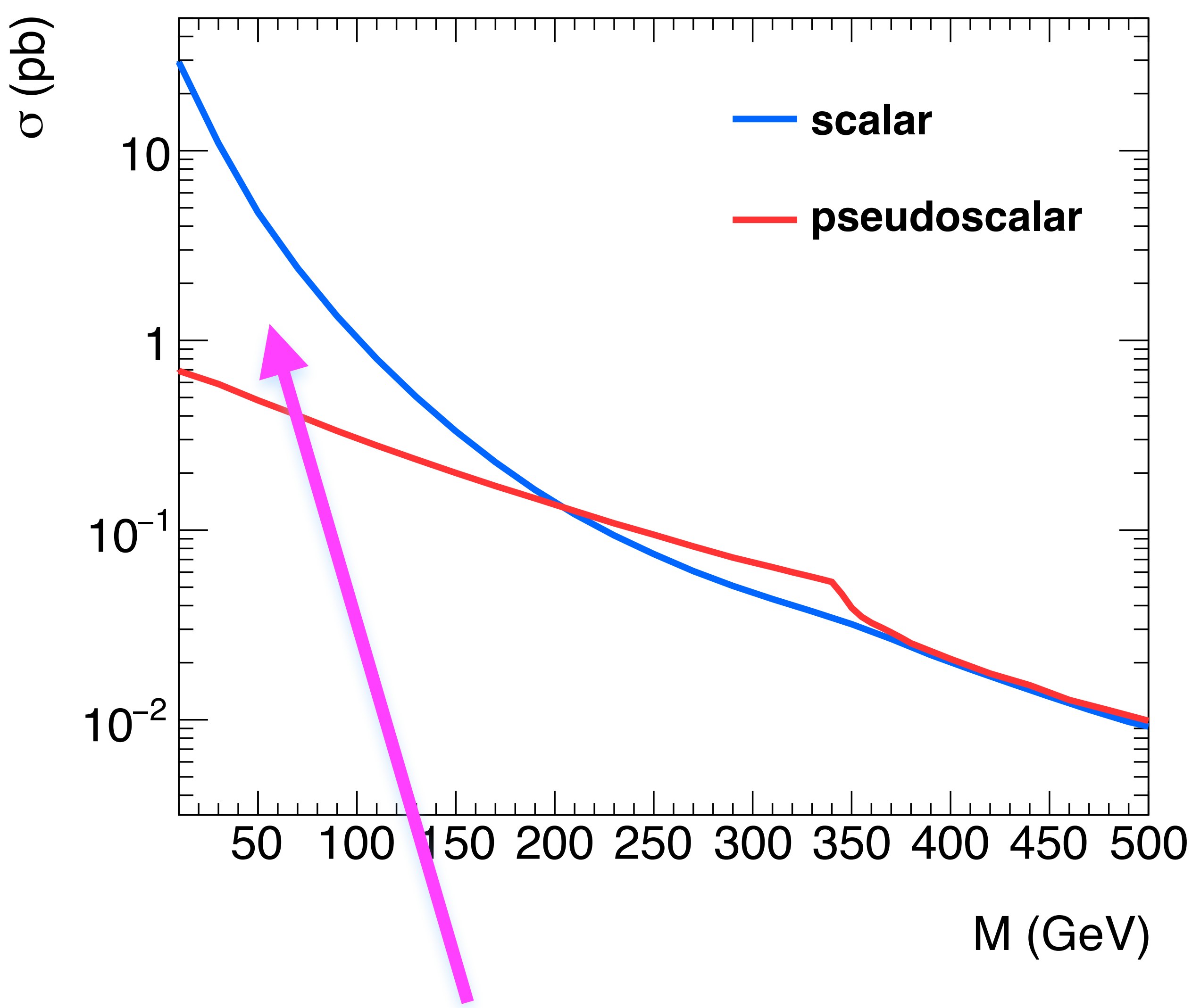


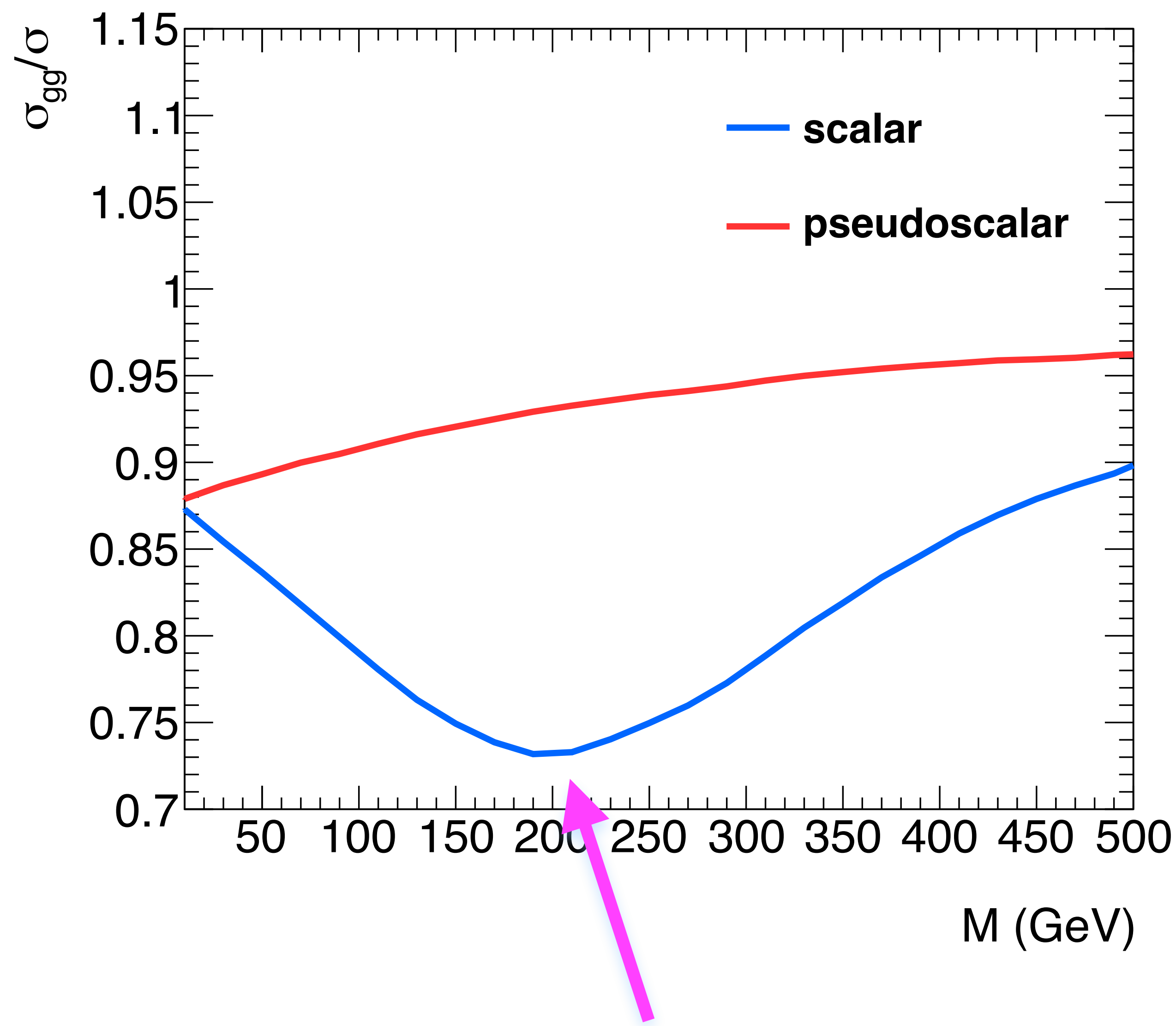
$$\overline{\sum} \left|\mathcal{M}(t\bar{t} \to \phi)\right|^2 = \frac{g_t^2 s}{12} \beta^2 \qquad \overline{\sum} \left|\mathcal{M}(t\bar{t} \to a)\right|^2 = \frac{g_t^2 s}{12}$$

scalar production in top-fusion velocity-suppressed at threshold compared to pseudoscalar production

$E_{T,miss}+t\bar{t}$ production

[UH, Pani & Polesello , 1611.09841]



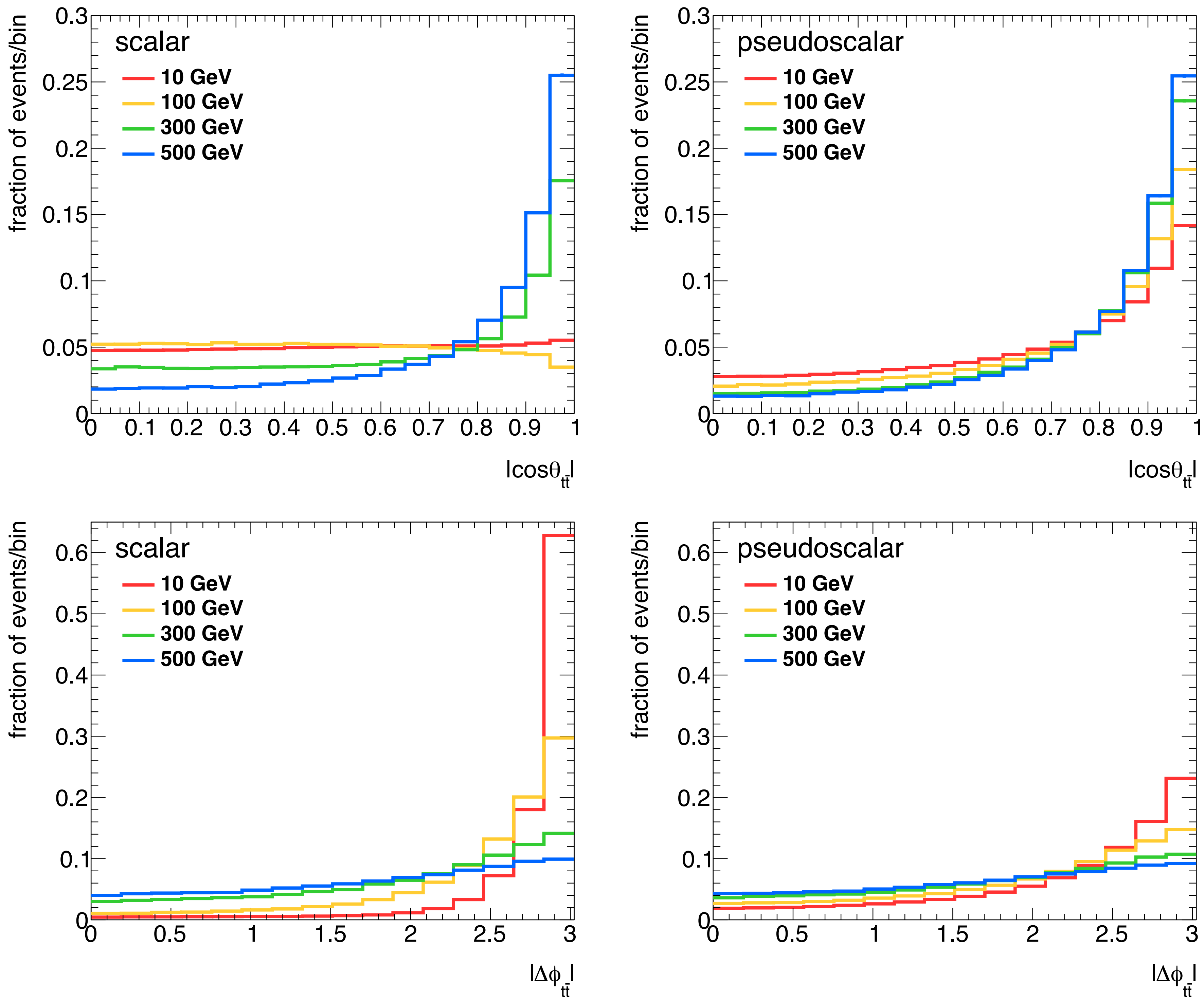


soft enhancement of scalar production in fragmentation/radiation

threshold suppression of scalar production in top-fusion

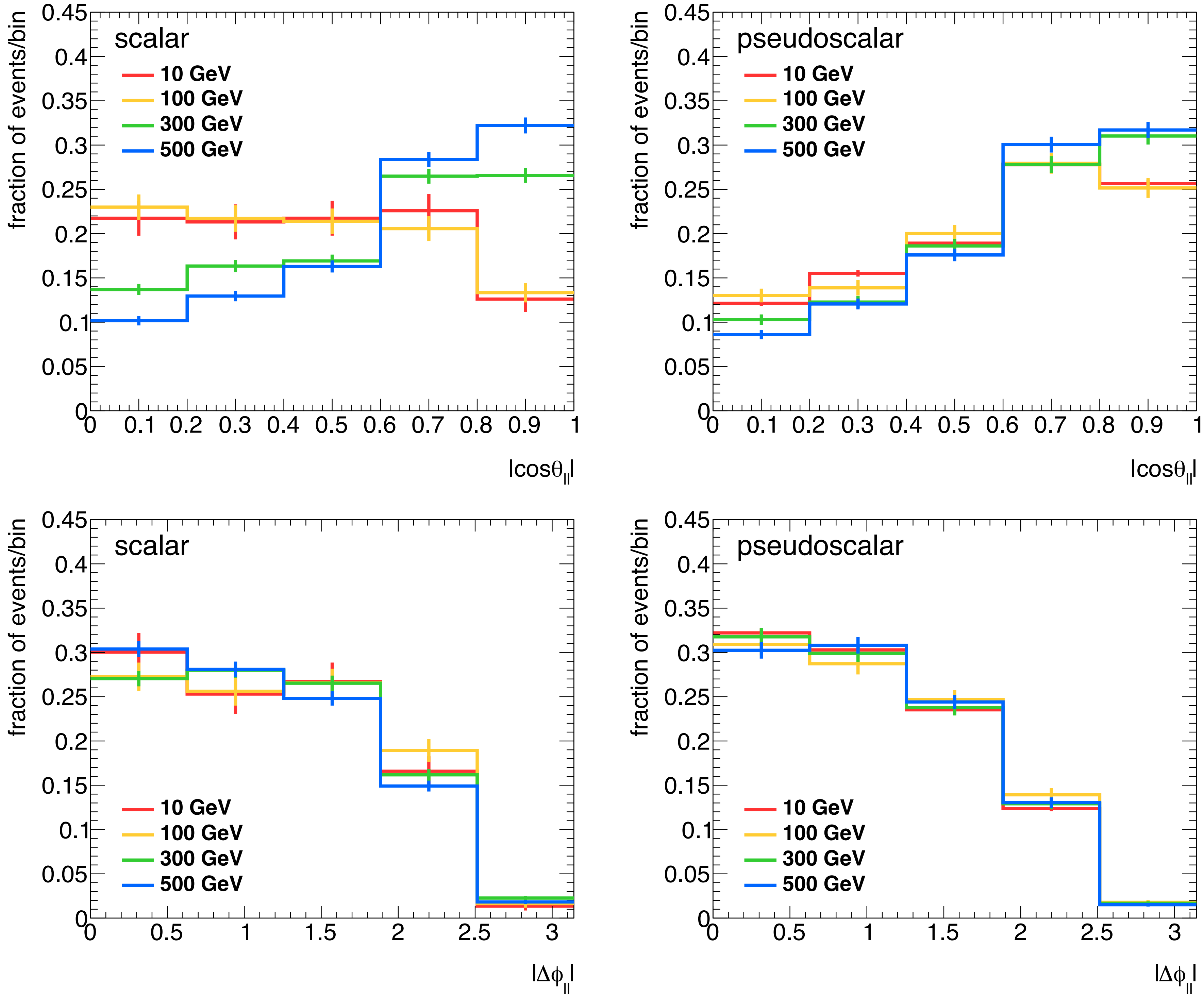
$E_{T,miss}$+$t\bar{t}$ events: tops no cuts

[UH, Pani & Polesello , 1611.09841]



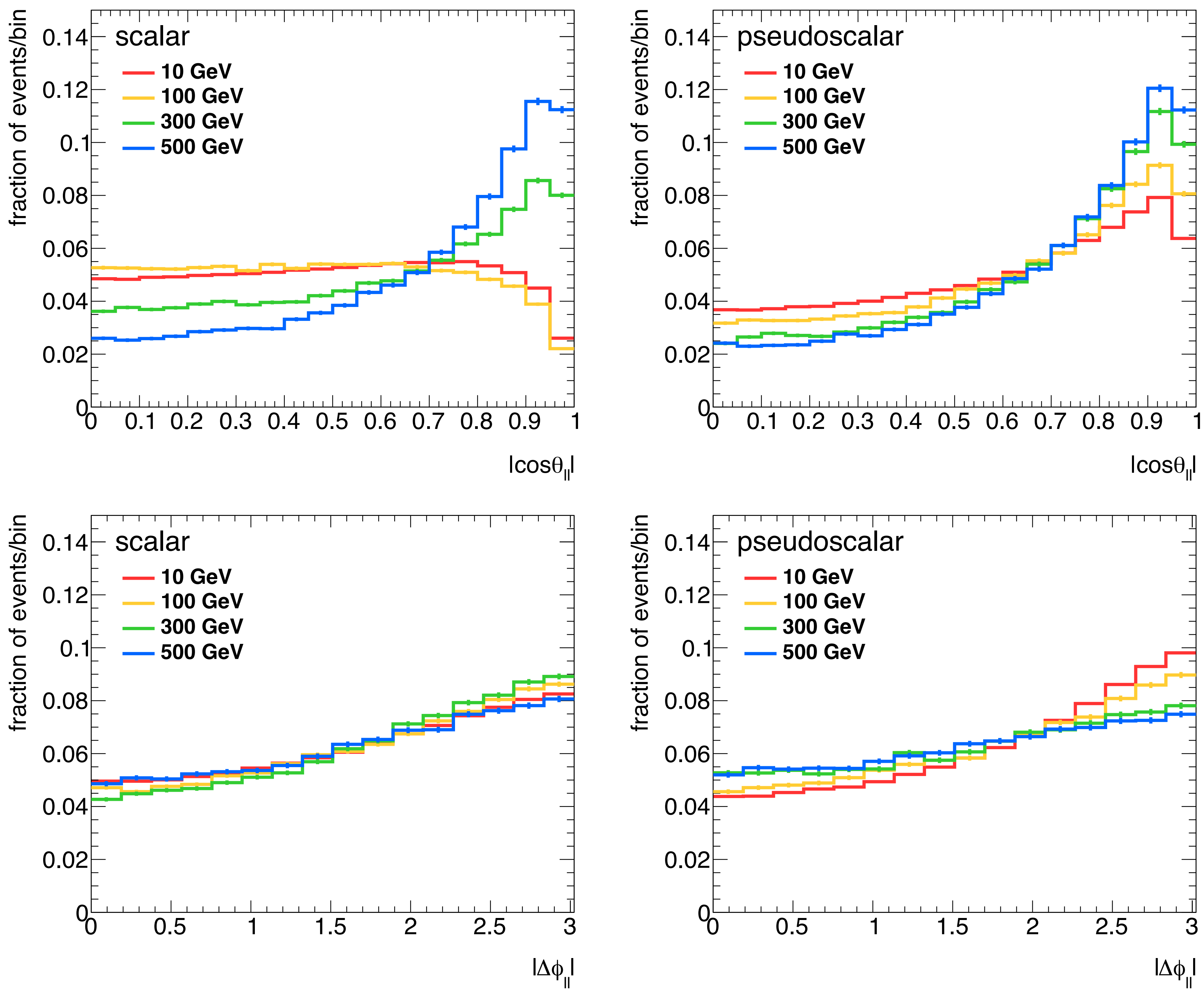
$E_{T,miss}+t\bar{t}$ events: leptons no cuts

[UH, Pani & Polesello , 1611.09841]



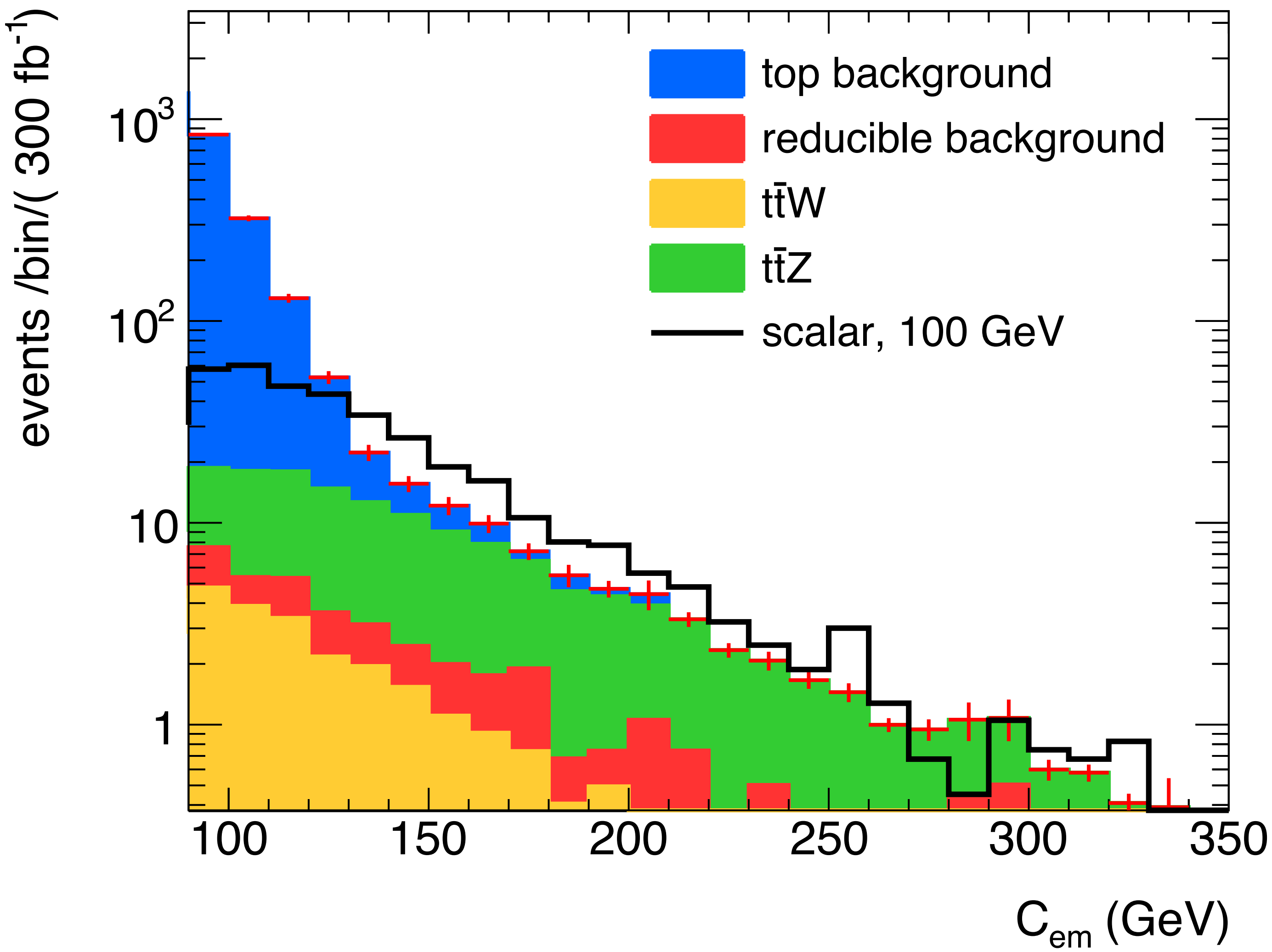
$E_{T,miss}$+$t\bar{t}$ events: leptons with cuts

[UH, Pani & Polesello , 1611.09841]



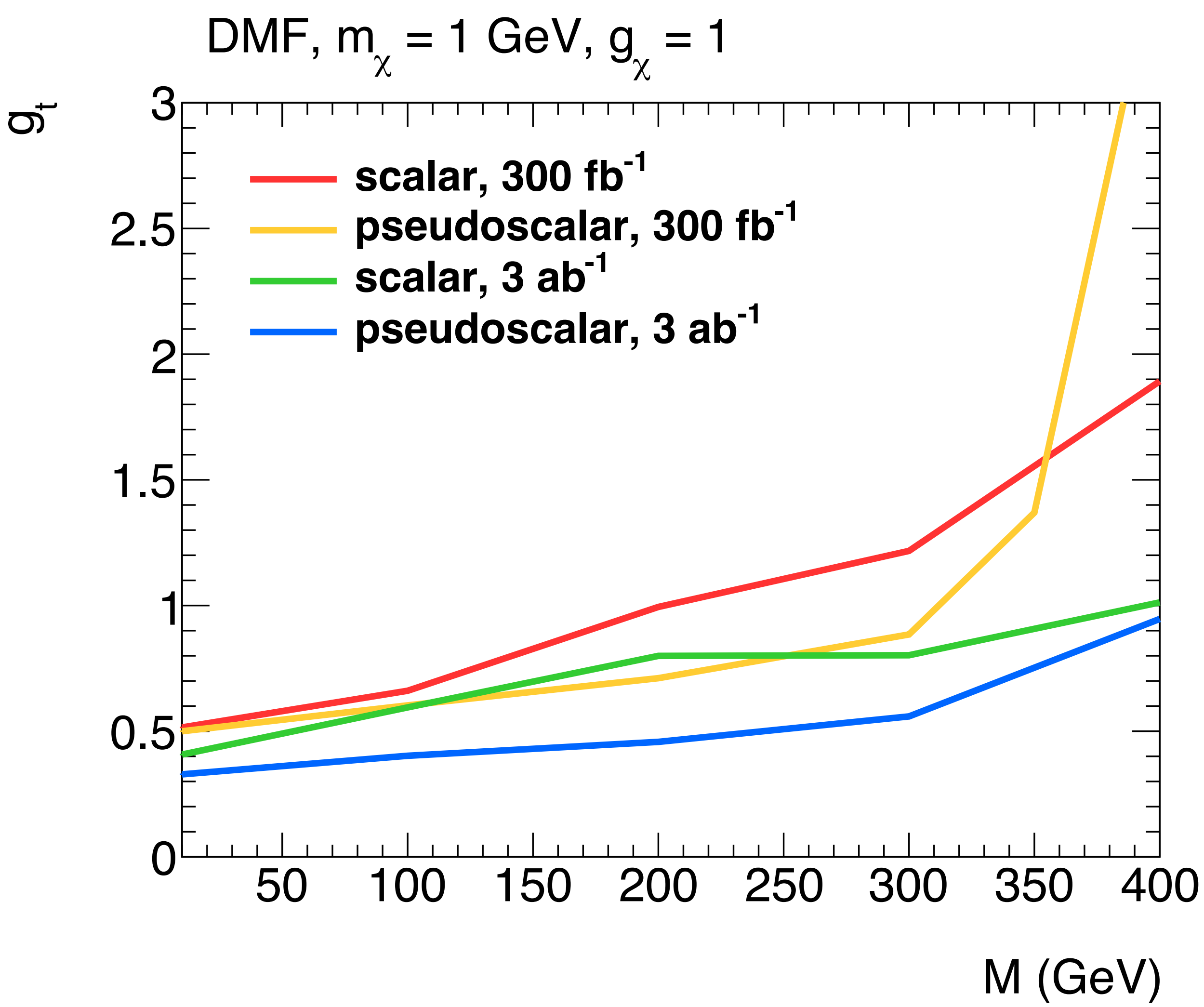
$E_{T,miss}$+$t\bar{t}$: background suppression

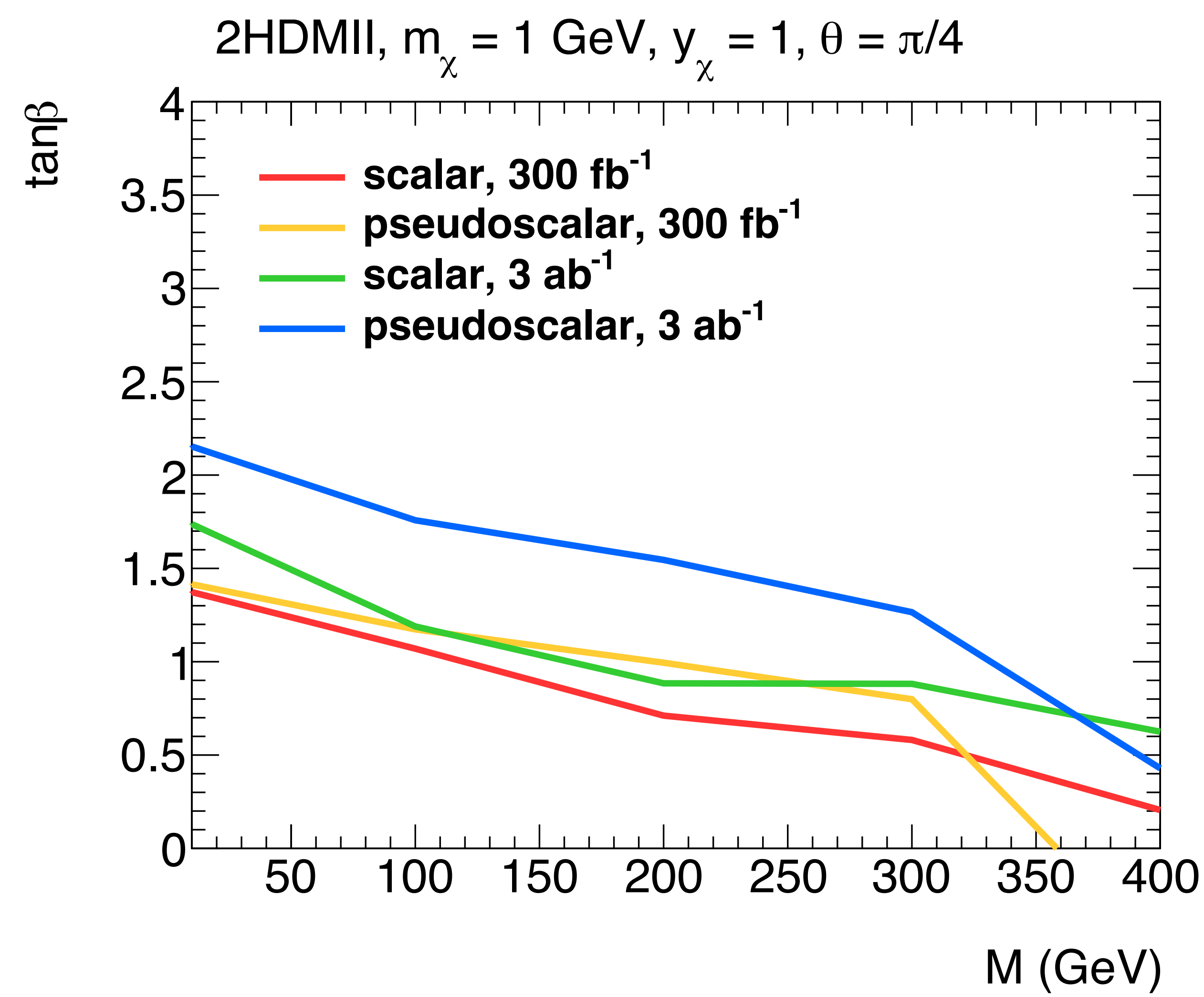
[UH, Pani & Polesello , 1611.09841]



$$C_{\rm em} \equiv m_{\rm T2} + 0.2 \cdot (200\,{\rm GeV} - E_{\rm T}^{\rm miss})$$

$E_{T,miss}+t\bar{t}$ searches: projections



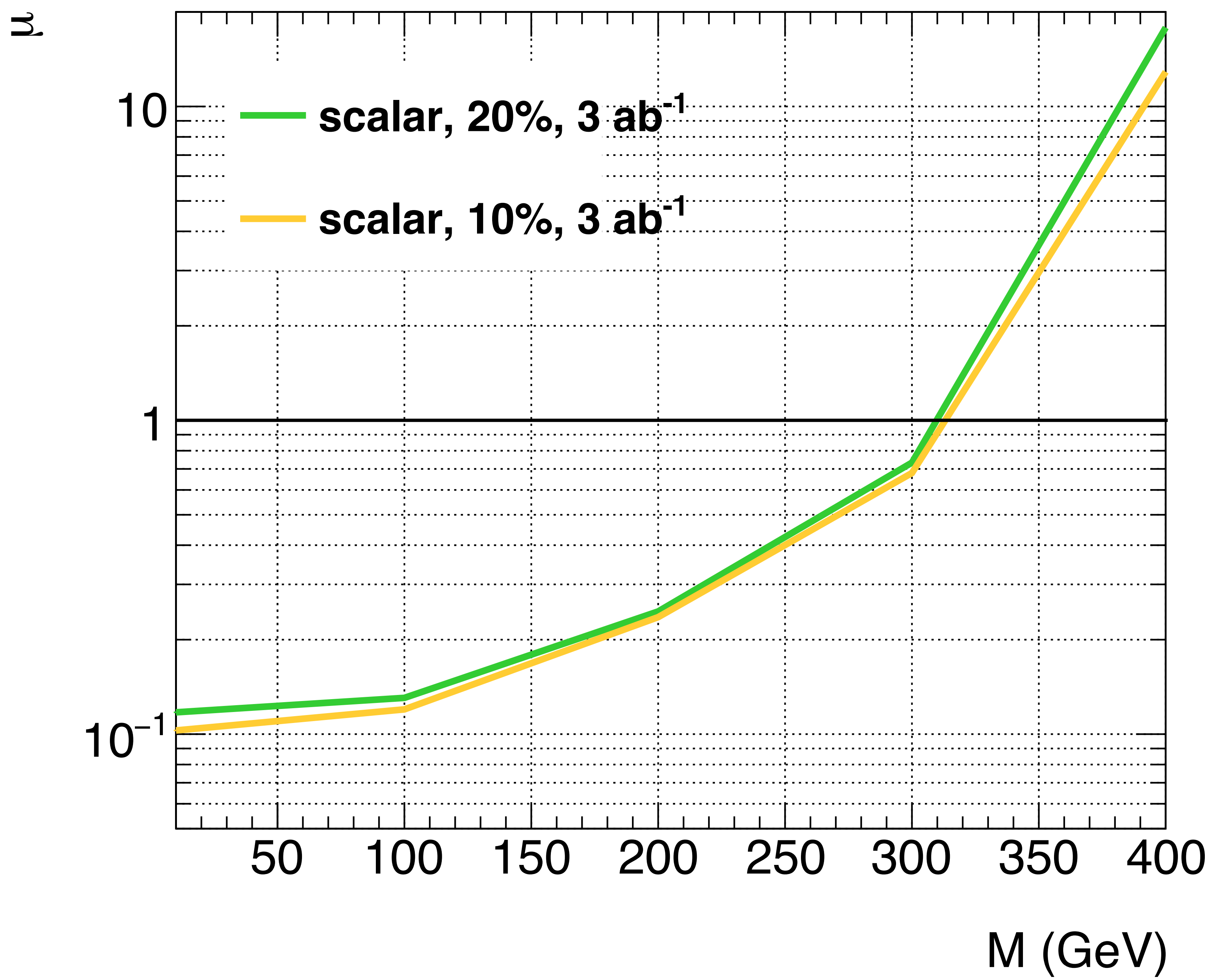


Spin-0 mediators with an effective coupling strength of O(1) to tops can be tested for masses up to 350 GeV (or even above) at future LHC runs

[UH, Pani & Polesello, 1611.09841]

$E_{T,miss}+t\bar{t}$ searches: projections

[UH, Pani & Polesello, 1611.09841]



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

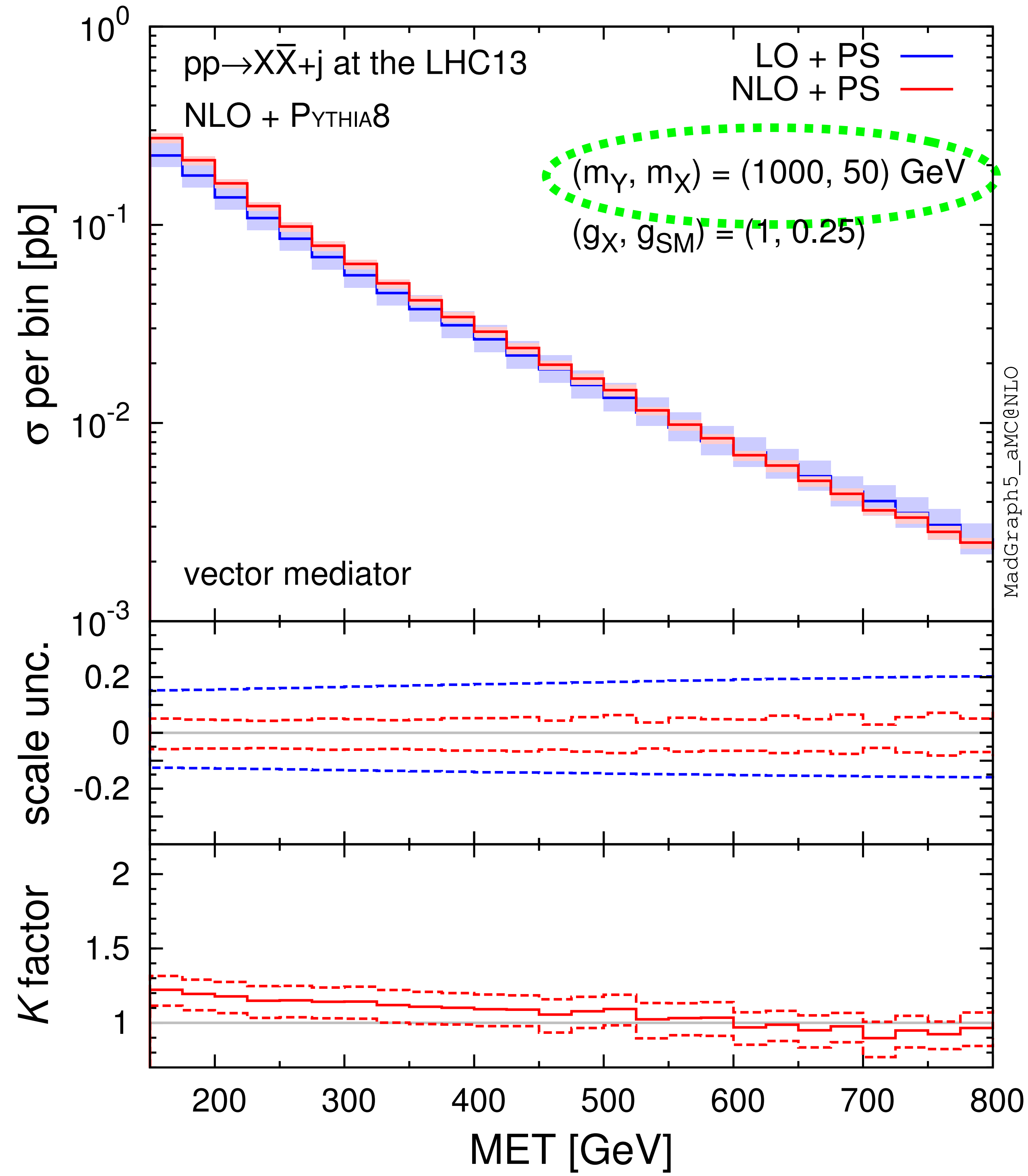
[Fox & Williams, 1211.6390]

NLOPS: spin-1 mediators

[Backović et al., 1508.05327]

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

[UH et al., 1310.4491]

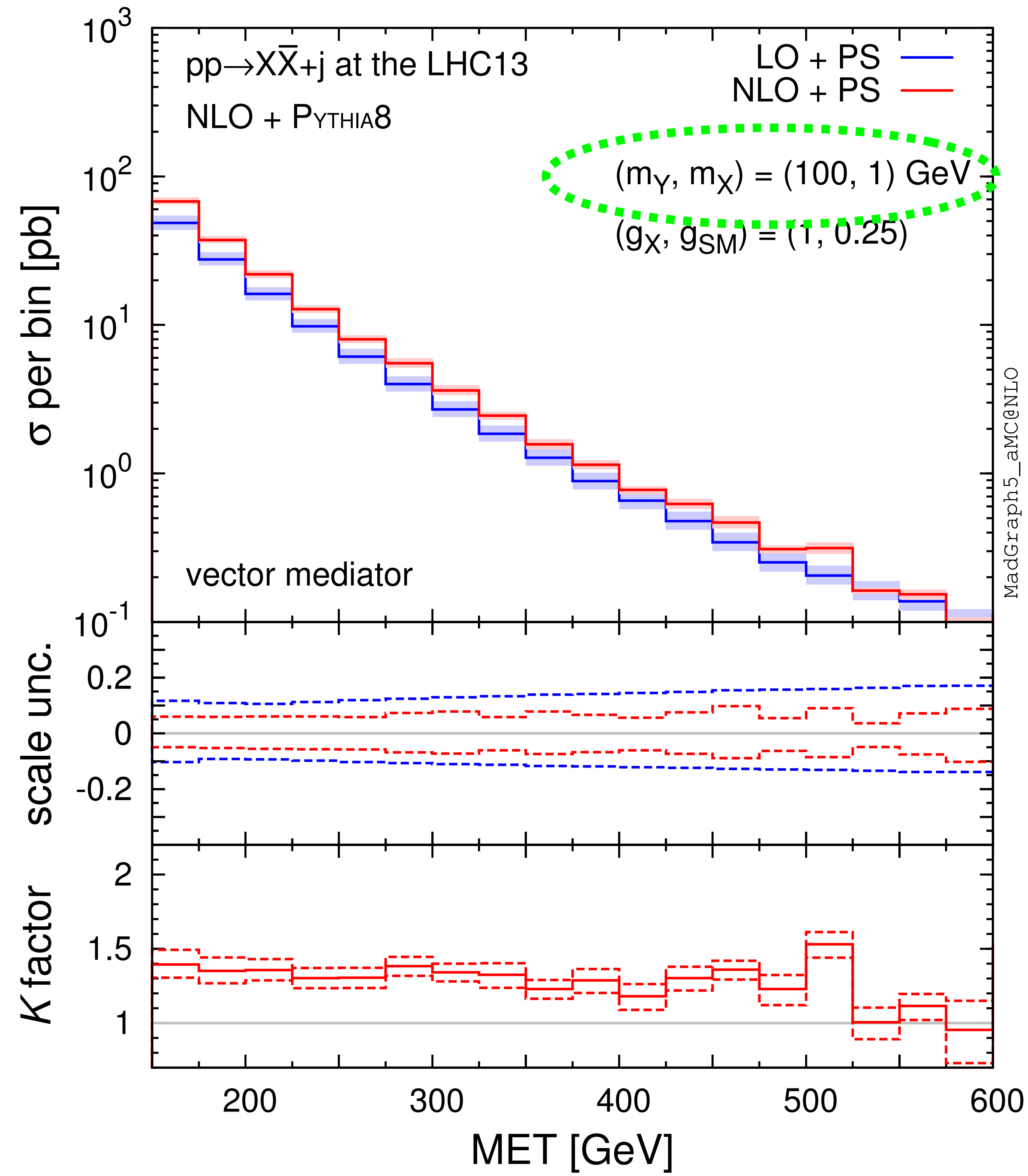


NLOPS: spin-1 mediators

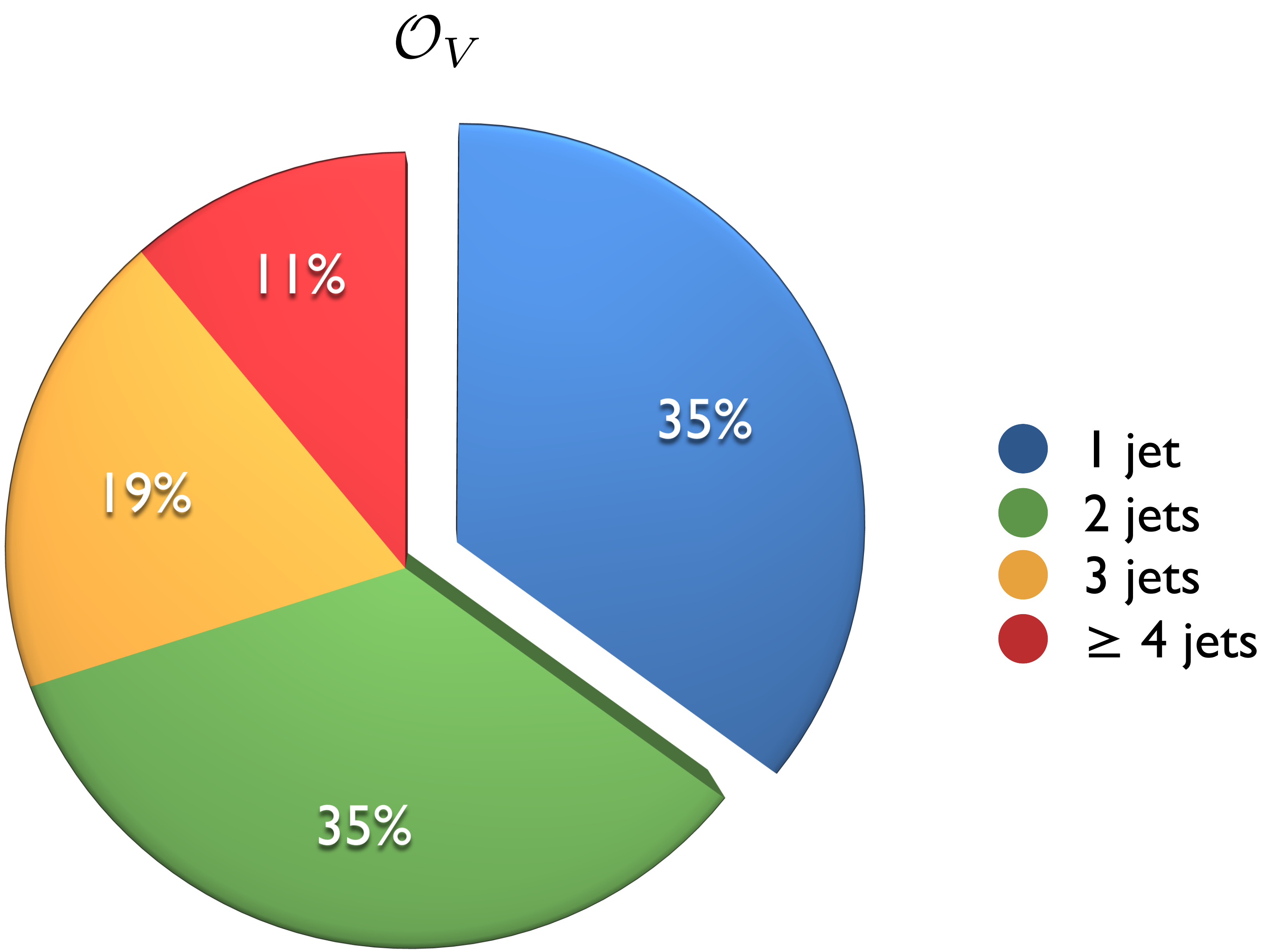
[Backović et al., 1508.05327]

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

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



Mono-jet ≠ $E_{T,\mathrm{miss}}$+j



[UH et al., 1310.4491]