Introduction to meeting

(some personal thoughts)

Uli Haisch
University of Oxford

2nd LHC Dark Matter WG public meeting,
19-20 September 2016, CERN

Outcome of 1st meeting

[Boveia et al., 1603.04156]

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

Document summarises proposal of LHC DM WG on how-to present LHC results on s-channel simplified DM models & to compare them to direct (indirect) detection experiments

Scope of 2^{nd} meeting

Main focus of meeting on experimental & theoretical questions dealing with DM searches at LHC:

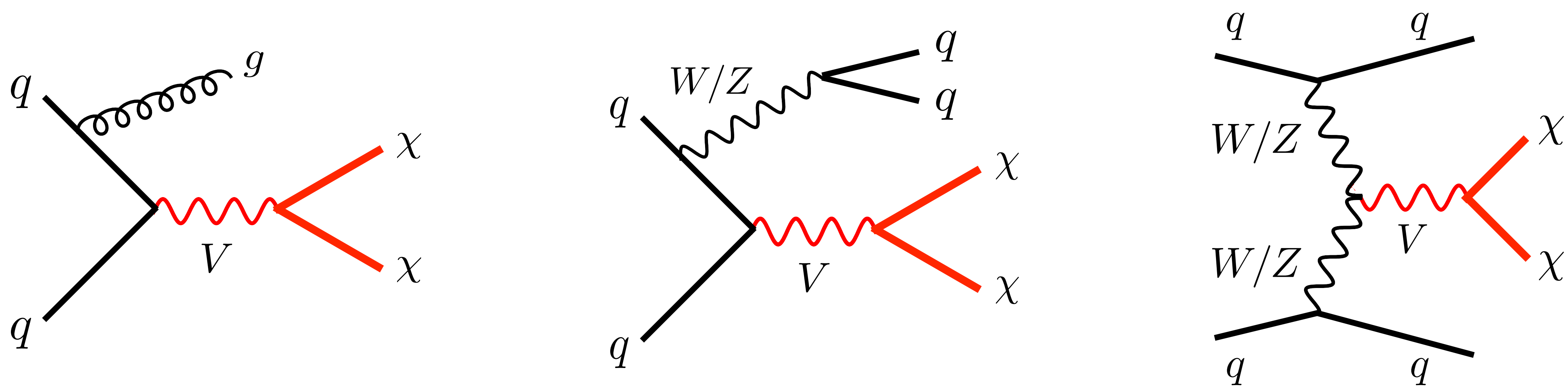
(i) complementarity & interplay of mediator searches leading to $E_{T,\,miss}$ & non-$E_{T,\,miss}$ signatures

(ii) limitations of existing s-channel simplified DM models & possible improvements

(iii) review of progress in t-channel, spin-2 DM & gluphilic models

(iv) discussion about experimental & theoretical issues concerning SM backgrounds relevant for $E_{T,\,miss}$ searches

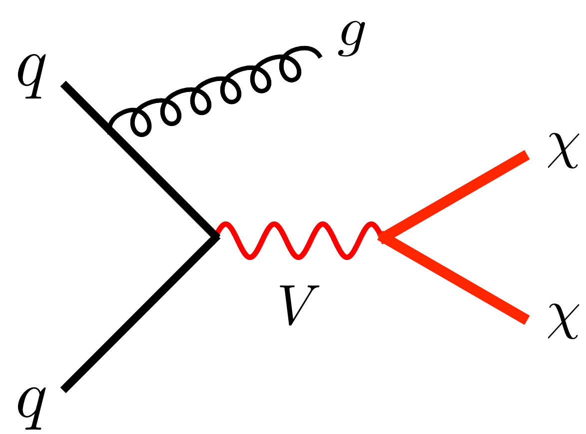
Mono-jet searches at 13 TeV

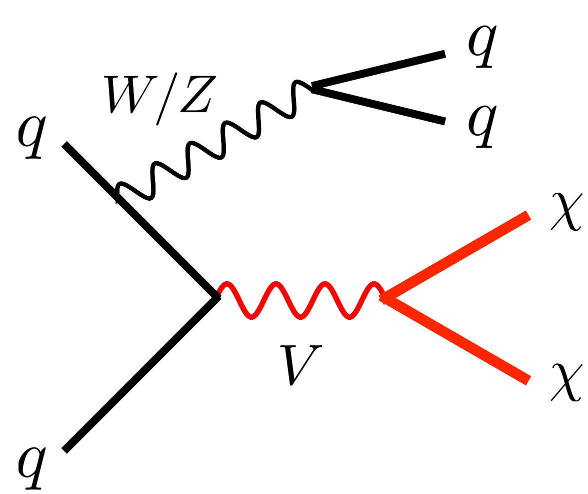


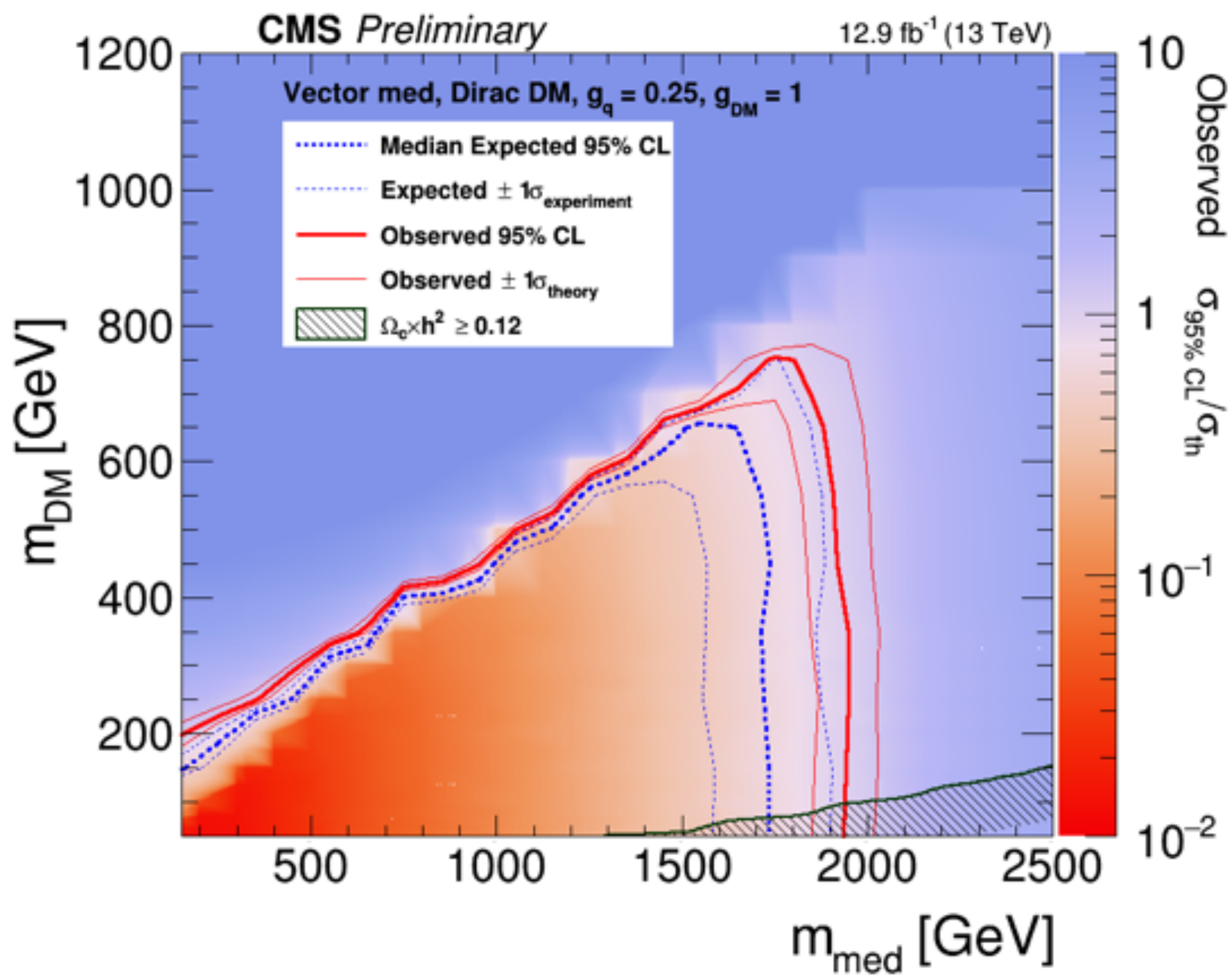
Latest mono-jet searches are more complex than simple cut & count analyses of Run I. A jet veto is not imposed anymore & hence searches sensitive to both initial state radiation (ISR) as well as gauge boson induced scatterings. Signal models need to correctly describe all possible $E_{T,\,miss}$+jets production topologies

Spin-1 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]





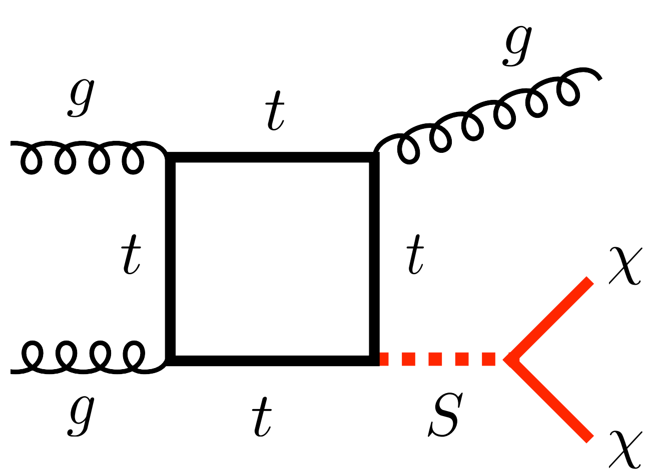


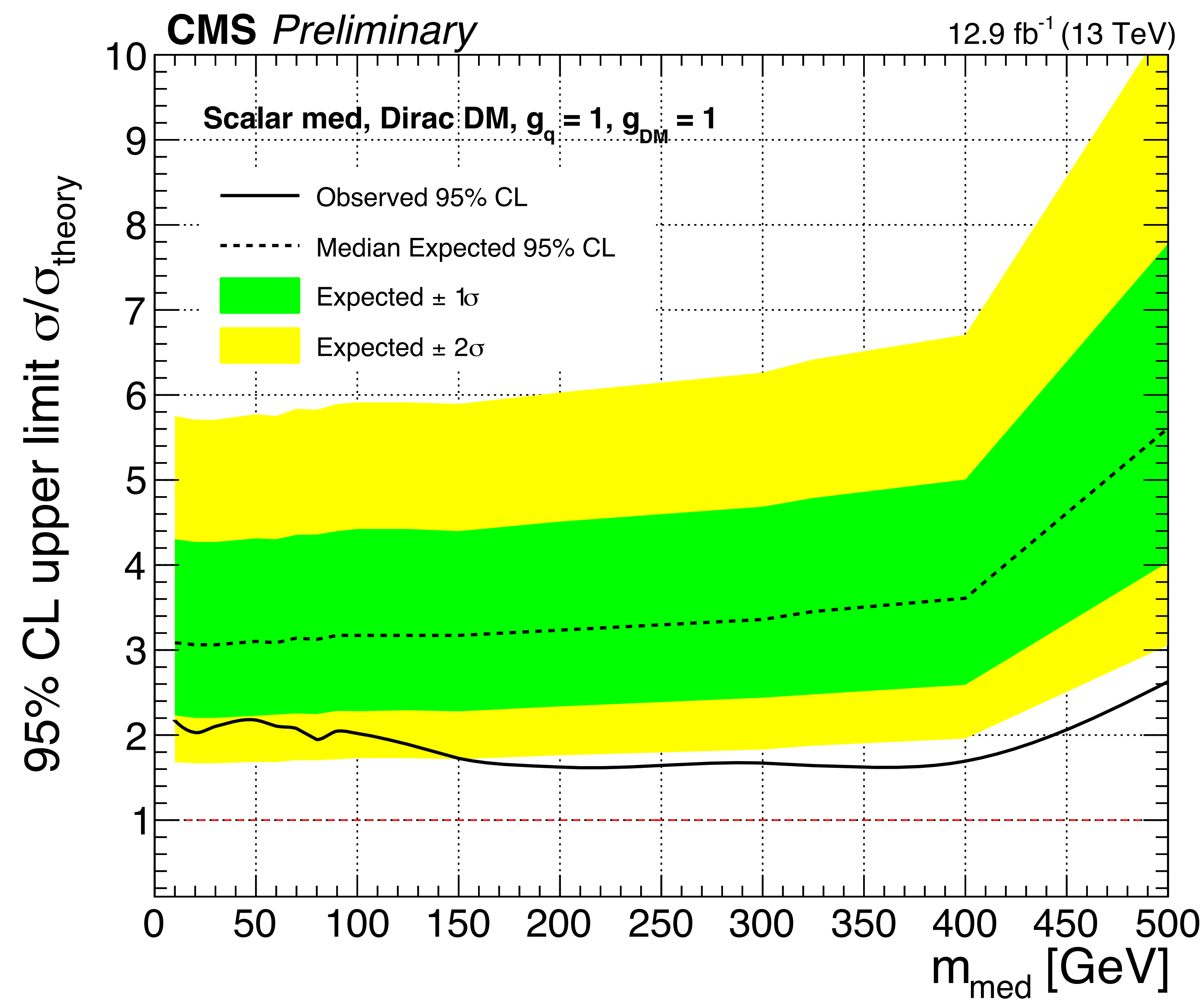
Latest $E_{T,\,\text{miss}}$+jets searches exclude mediator masses up to close to 2 TeV for both vector & axialvector exchange if $g_q = 0.25$, $g_\chi = 1$

[details in talks by Caterina, Zeynep, Antonio & Tristan]

Spin-0 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]



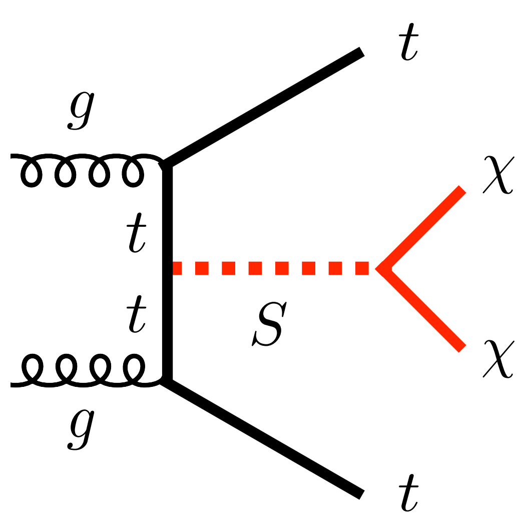


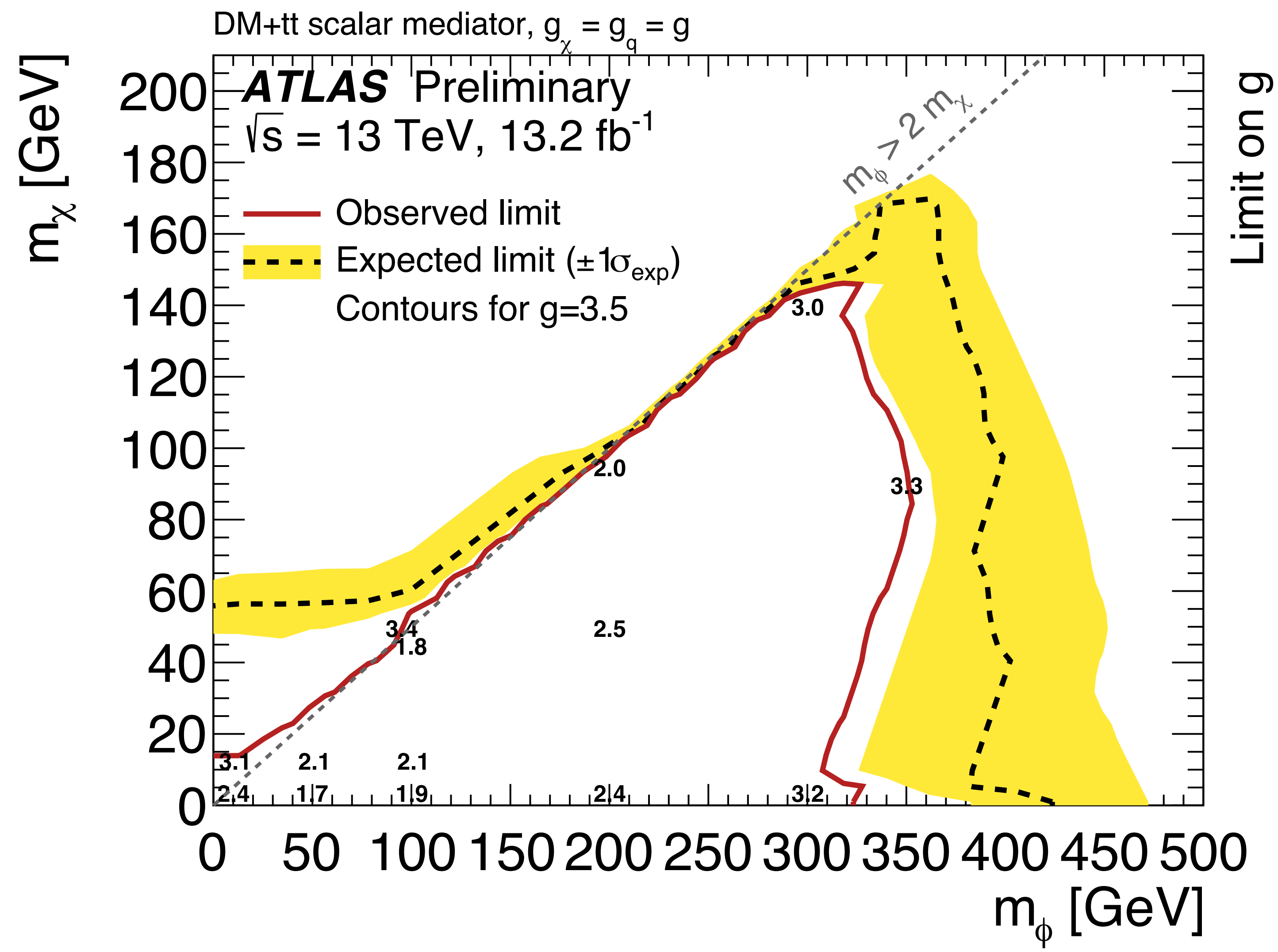
Mono-jet searches not yet sensitive to scalar models with weak couplings

[details in talks by Caterina, Zeynep, Antonio & Tristan]

Spin-0 simplified models: 13 TeV limits

[ATLAS-CONF-2016-050]



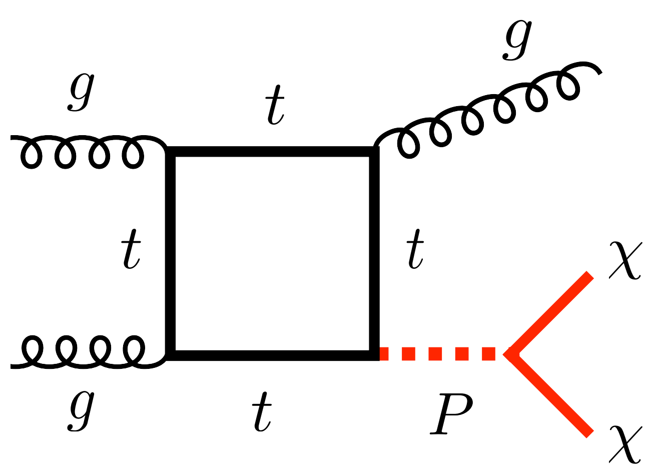


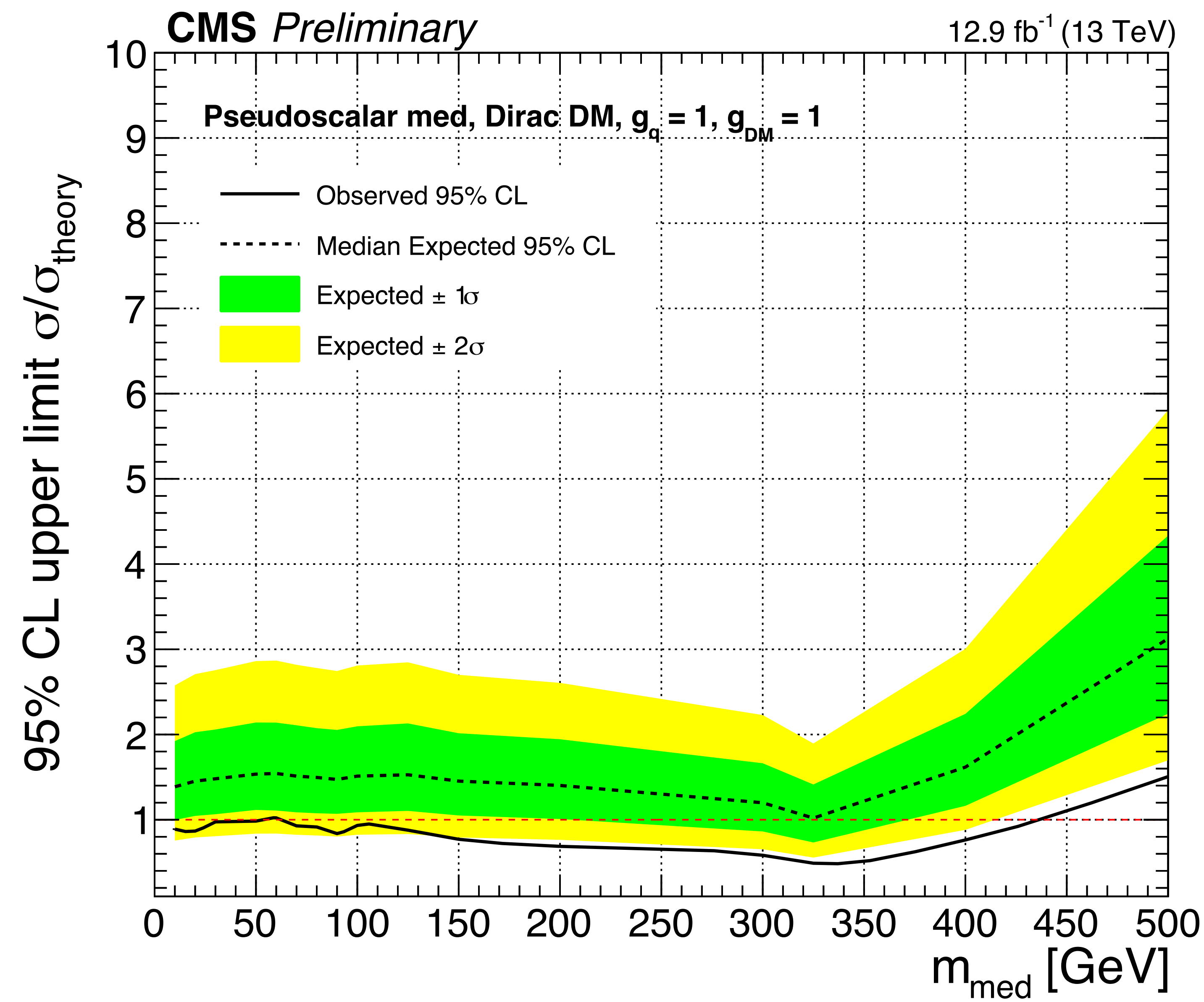
Strongly-coupled scalar models with mediator masses of 300 GeV can be tested via $E_{T,\mathrm{miss}}+t\bar{t}$. Mediator broad in large parts of parameter space

[details in talks by Johanna, Eitan & Kevin]

Spin-0 simplified models: 13 TeV limits

[CMS PAS EXO-16-037]



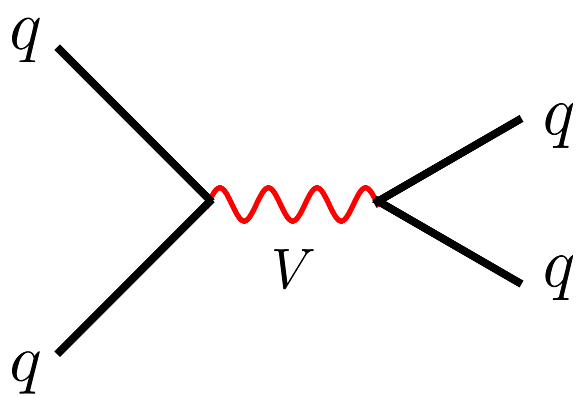


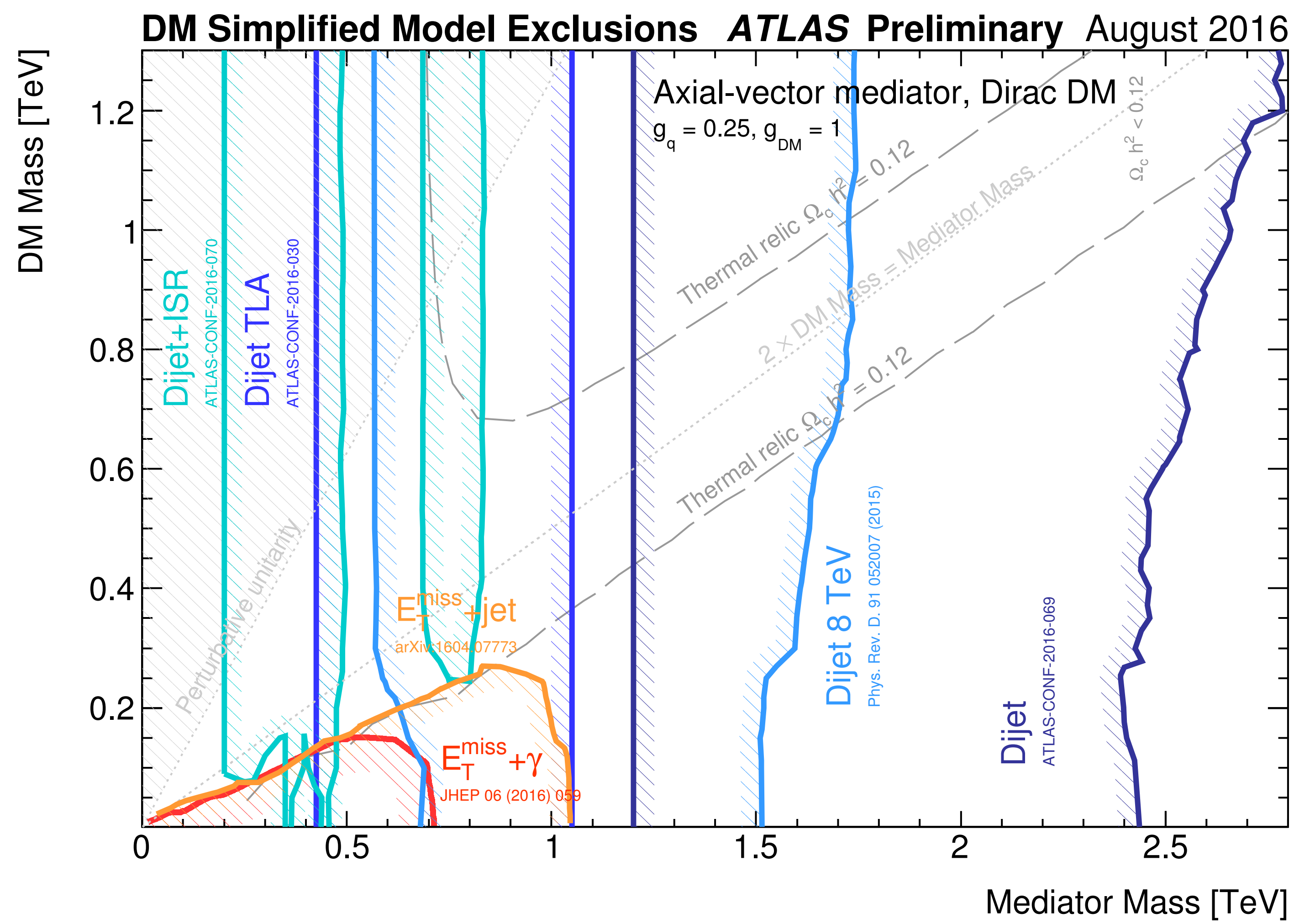
Since pseudoscalar production enhanced by a factor of more than 2, mediator masses close to 450 GeV are excluded for $g_q = g_\chi = 1$

[details in talks by Caterina, Zeynep, Antonio & Tristan]

Spin-1 simplified models: di-jet limits

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



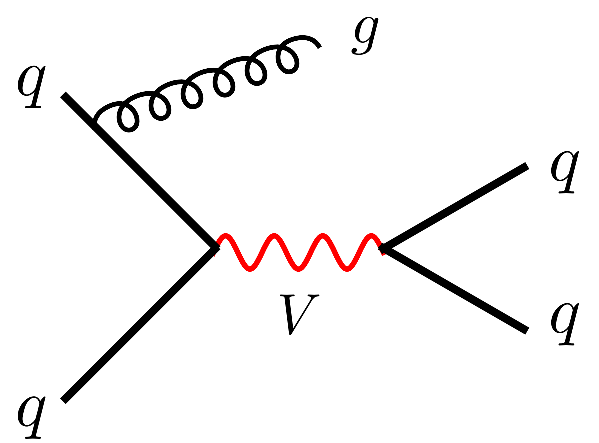


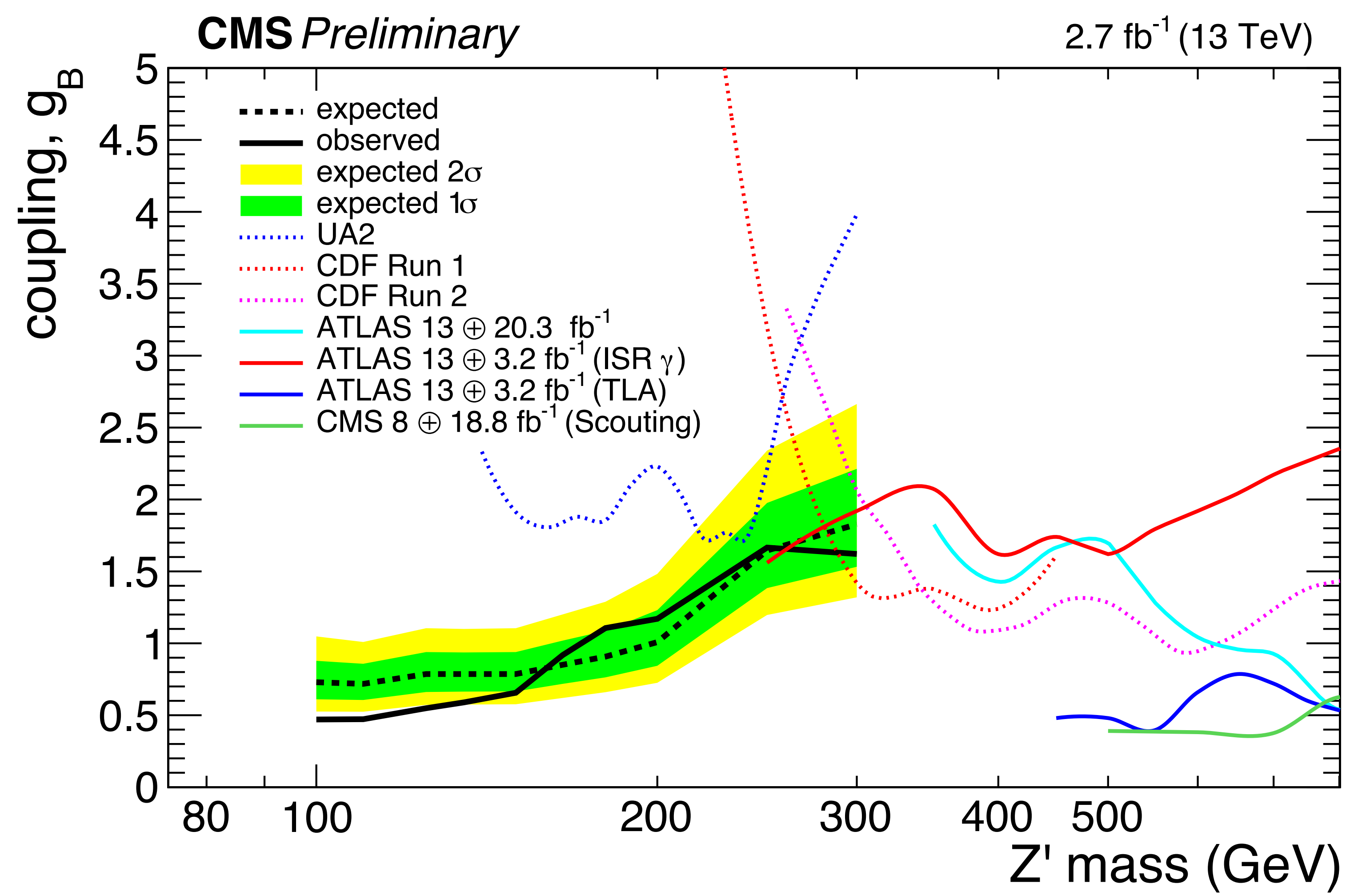
For coupling choice $g_q = 0.25$, $g_X = 1$ di-jet searches provide complementary constraints & exclude mediator masses from 200 GeV to 2.8 TeV

[details in talks by Caterina, Zeynep, Antonio & Tristan]

Spin-1 simplified models: tri-jet limits

[CMS PAS EXO-16-030]

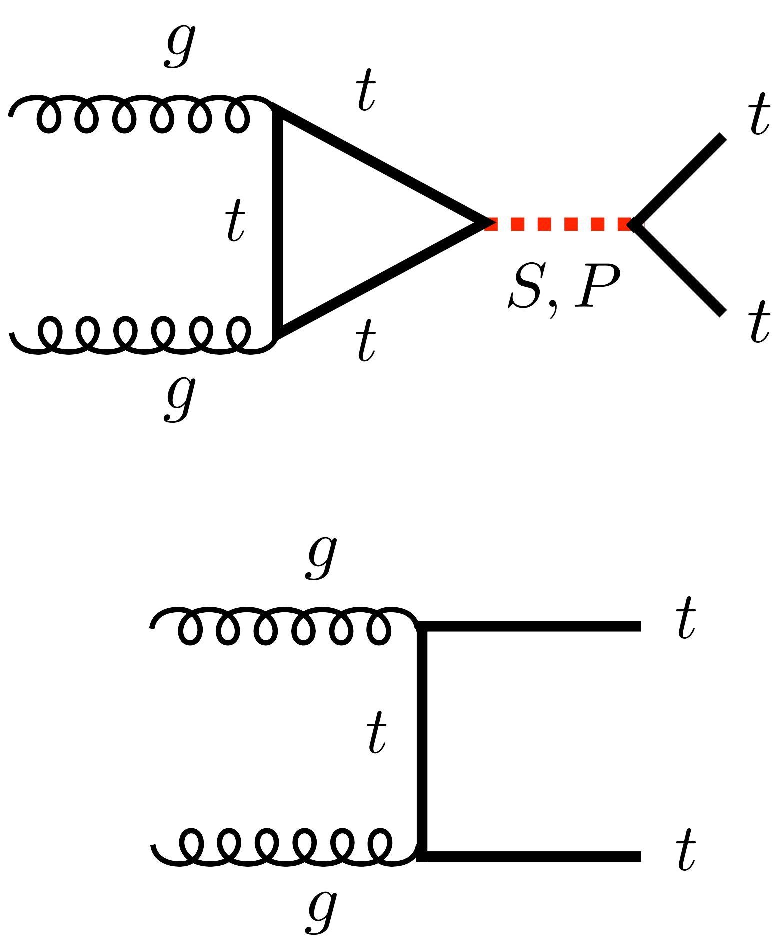




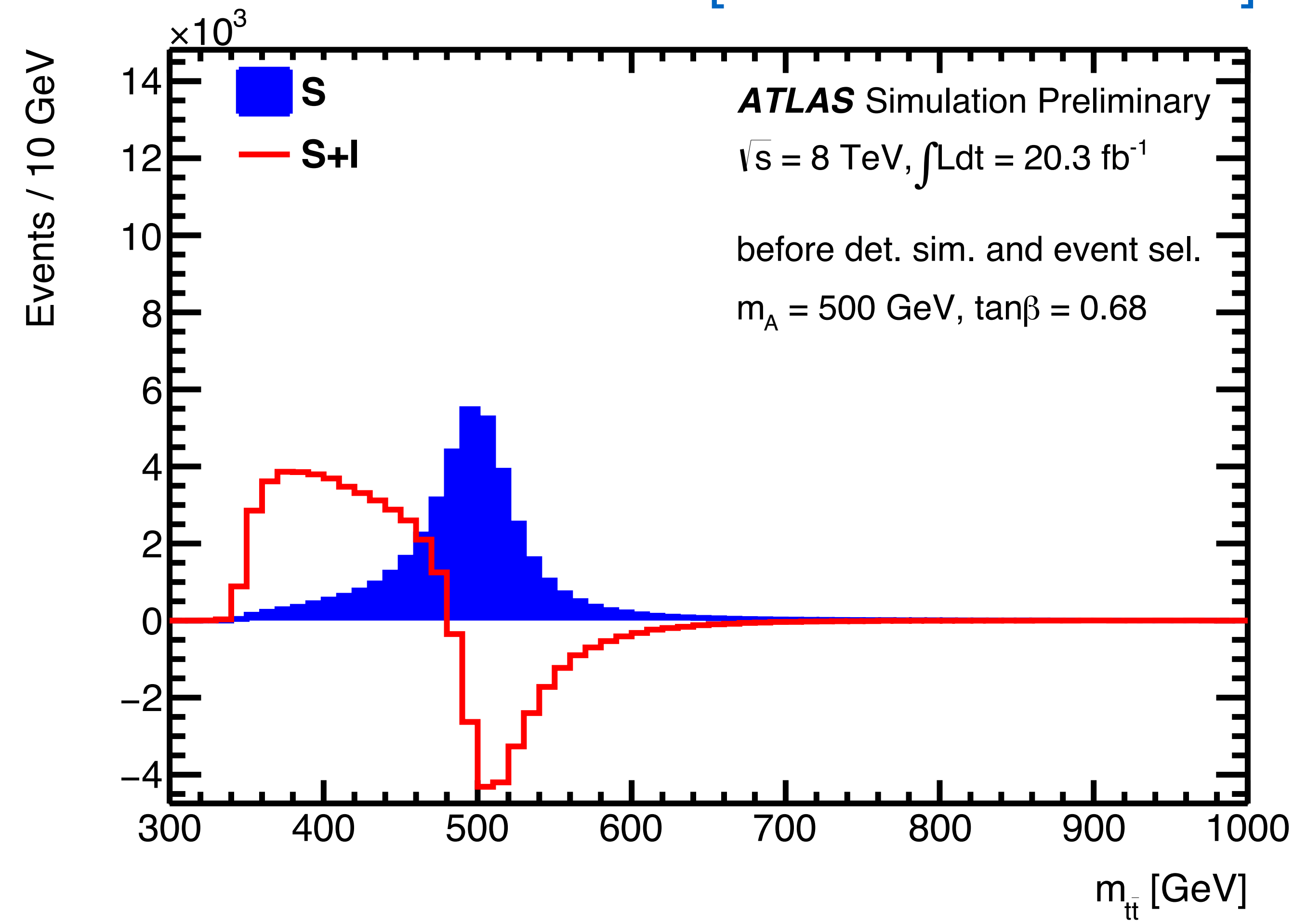
Mediators with mass down to 100 GeV can be tested by considering tri-jet events where one jet is hard & comes from ISR

[di-lepton limits on spin-1 models discussed by Bryan, Felix & Stefan]

Spin-0 simplified models: di-top limits



[ATLAS-CONF-2016-073]

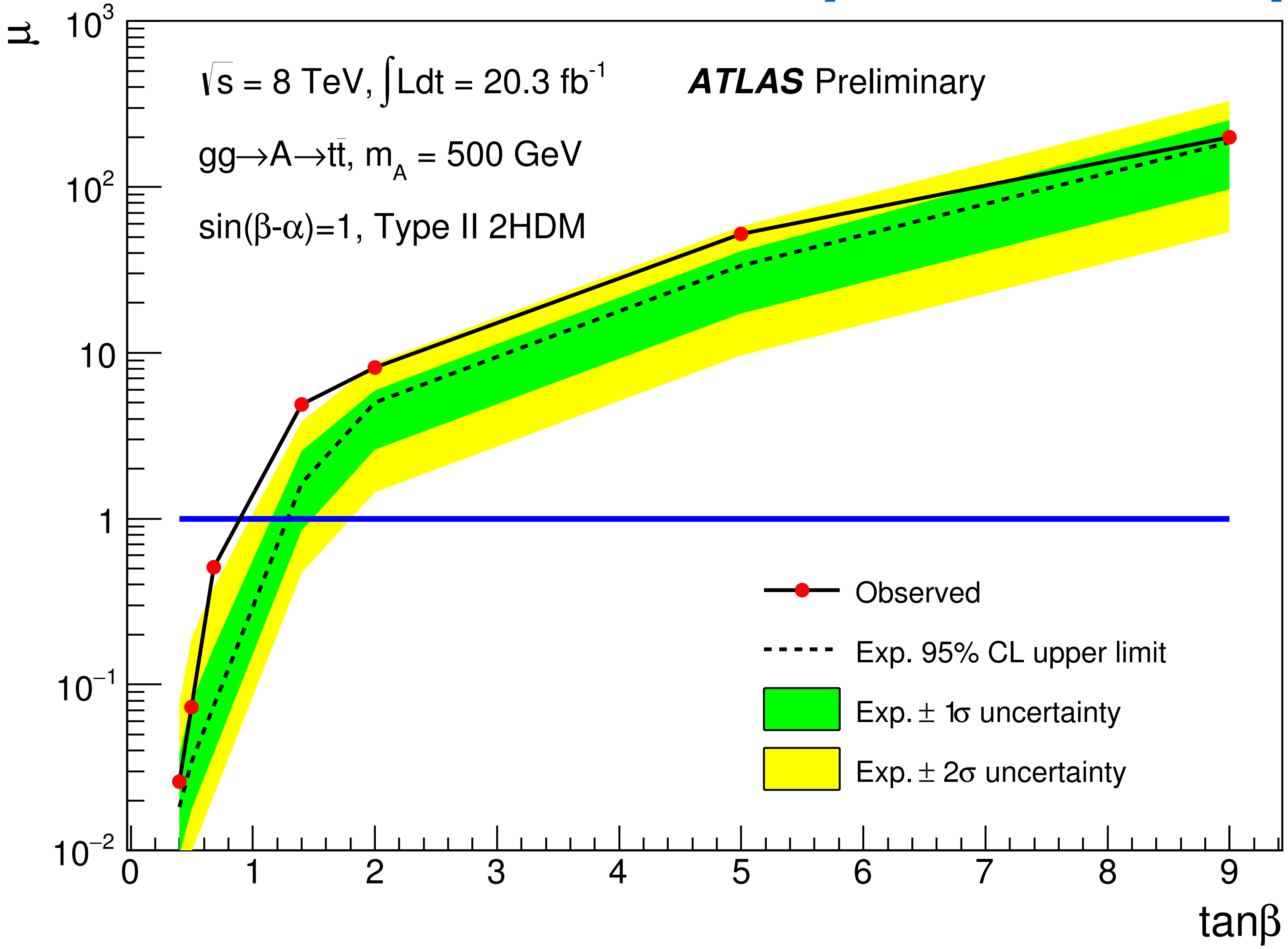


Spin-0 di-top resonances interfere maximal with SM background, which leads to a peak-dip structure in $m_{t\bar{t}}$ invariant mass spectrum

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

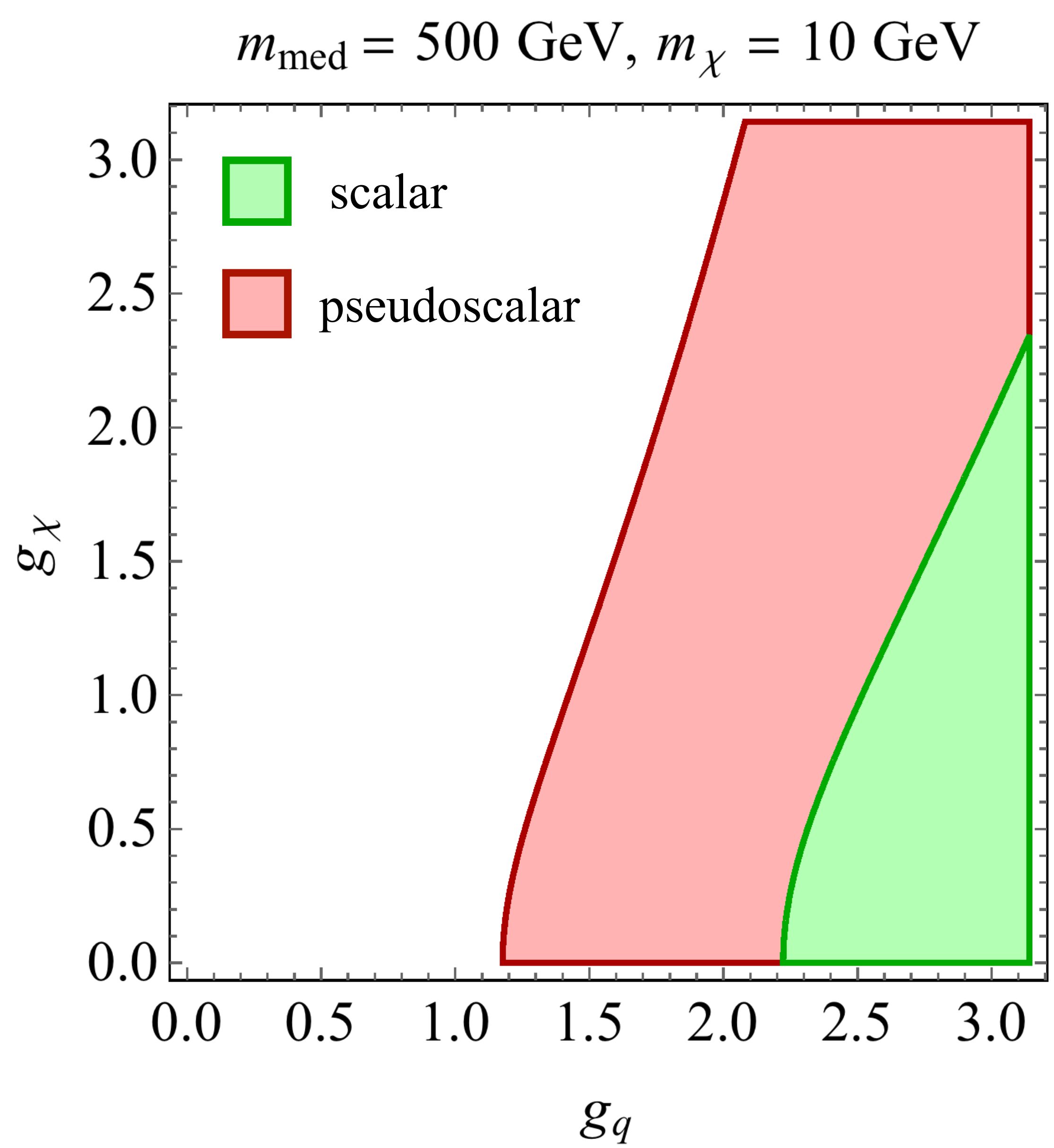
Spin-0 simplified models: di-top limits

[ATLAS-CONF-2016-073]



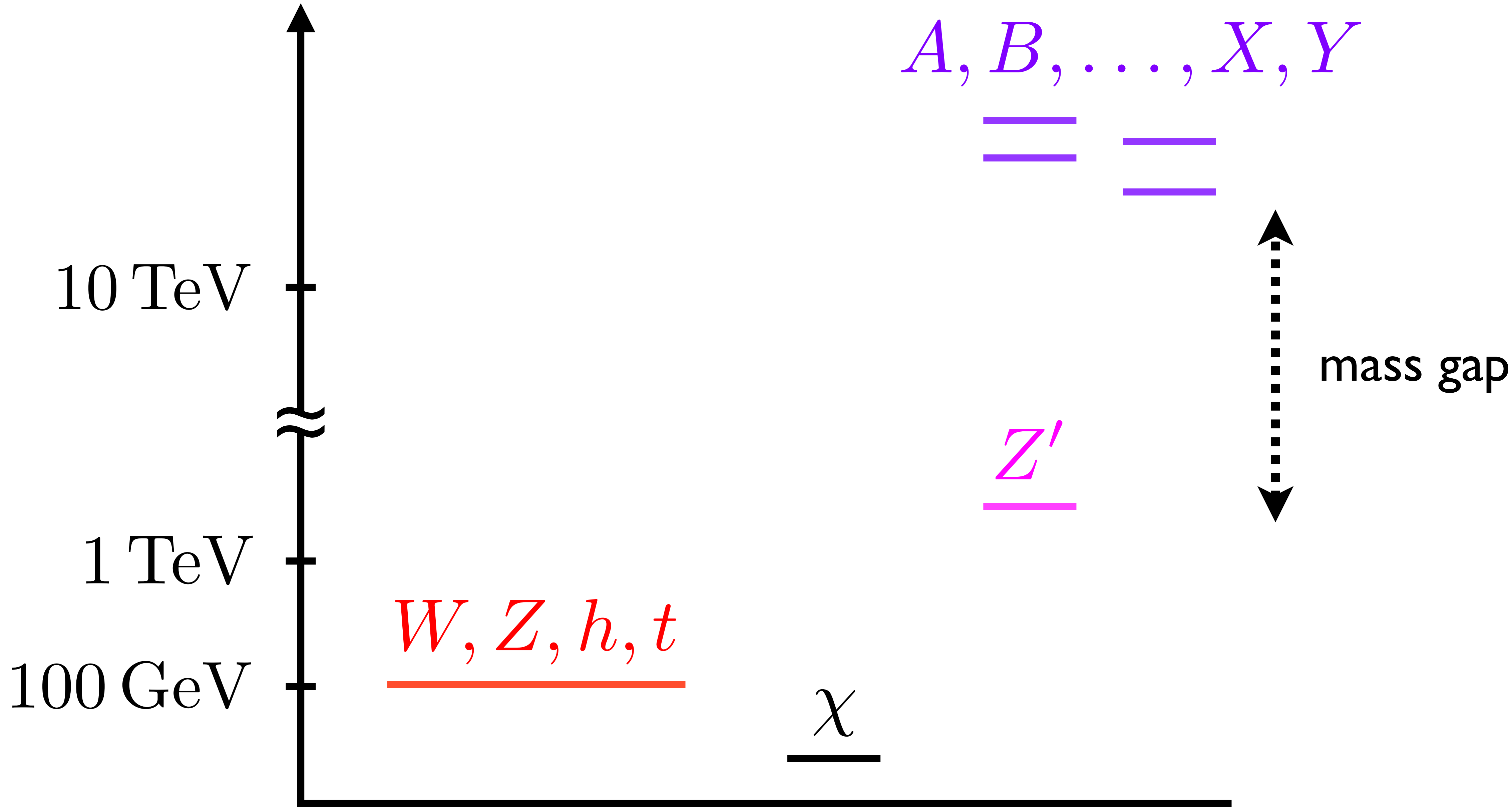
For a pseudoscalar (scalar) of 500 GeV, values of tanβ < 0.85 (tanβ < 0.45) are excluded at 95% CL in type II 2-Higgs doublet model (2HDM-II)

Spin-0 simplified models: 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

Cartoon of simplified model



Are DM simplified models perfect?

By construction DM & mediator only relevant degrees of freedom at LHC energies. SM- & DM-mediator couplings are treated as free parameters & mechanism that provides mass to DM & mediator 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 effects of new particles decouple or in fact change LHC phenomenology

How-to spot potential problems?

There are at least two ways to figure out if use of simplified model is viable at LHC:

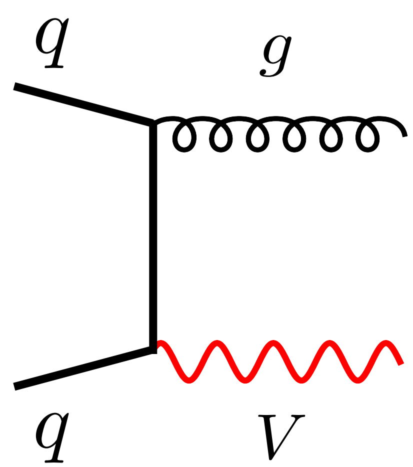
(i) take simplified model as is & see if scattering amplitudes relevant to DM searches violate perturbative unitarity at LHC energies

[see for instance Englert et al., 1604.07975]

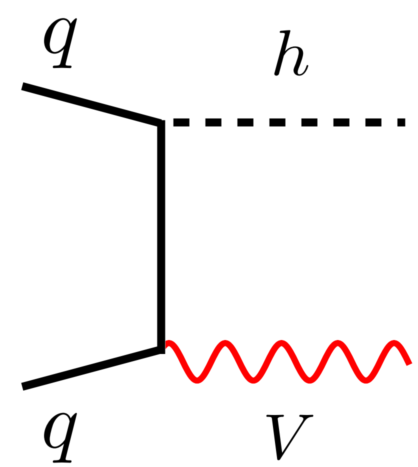
(ii) extend simplified model by a dark Higgs sector, new fermion sector, etc. & study if additional particle content modifies existing signals or leads to new signatures

[see for instance Kahlhoefer et al., 1510.02110; Duerr et al.,1606.07609]

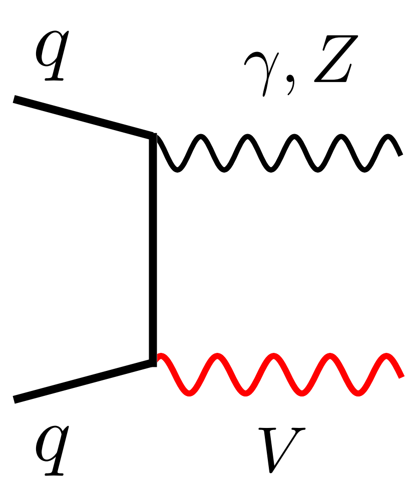
Spin-1 mono-X amplitudes



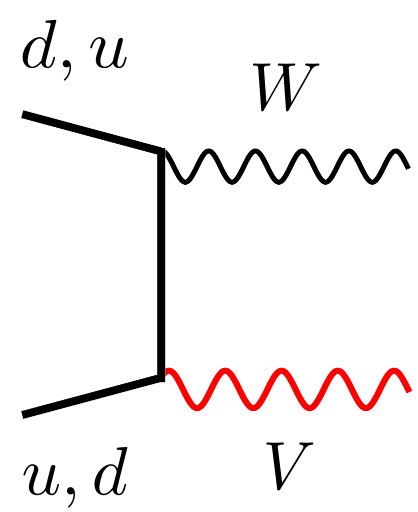
$$\sim s^0$$



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



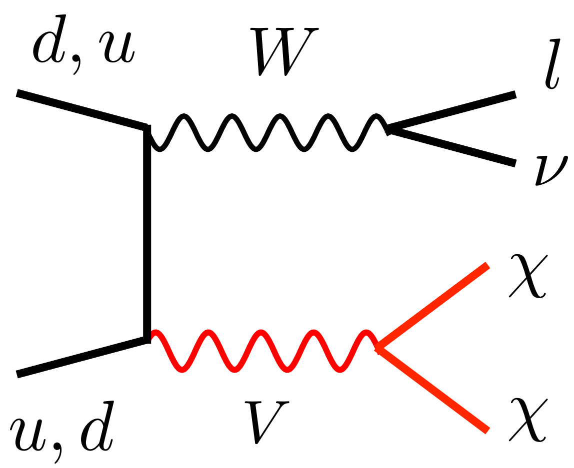
$$\sim s^0, \;\; y_q \, g_q^A \, \frac{s^{1/2}}{M_V}$$

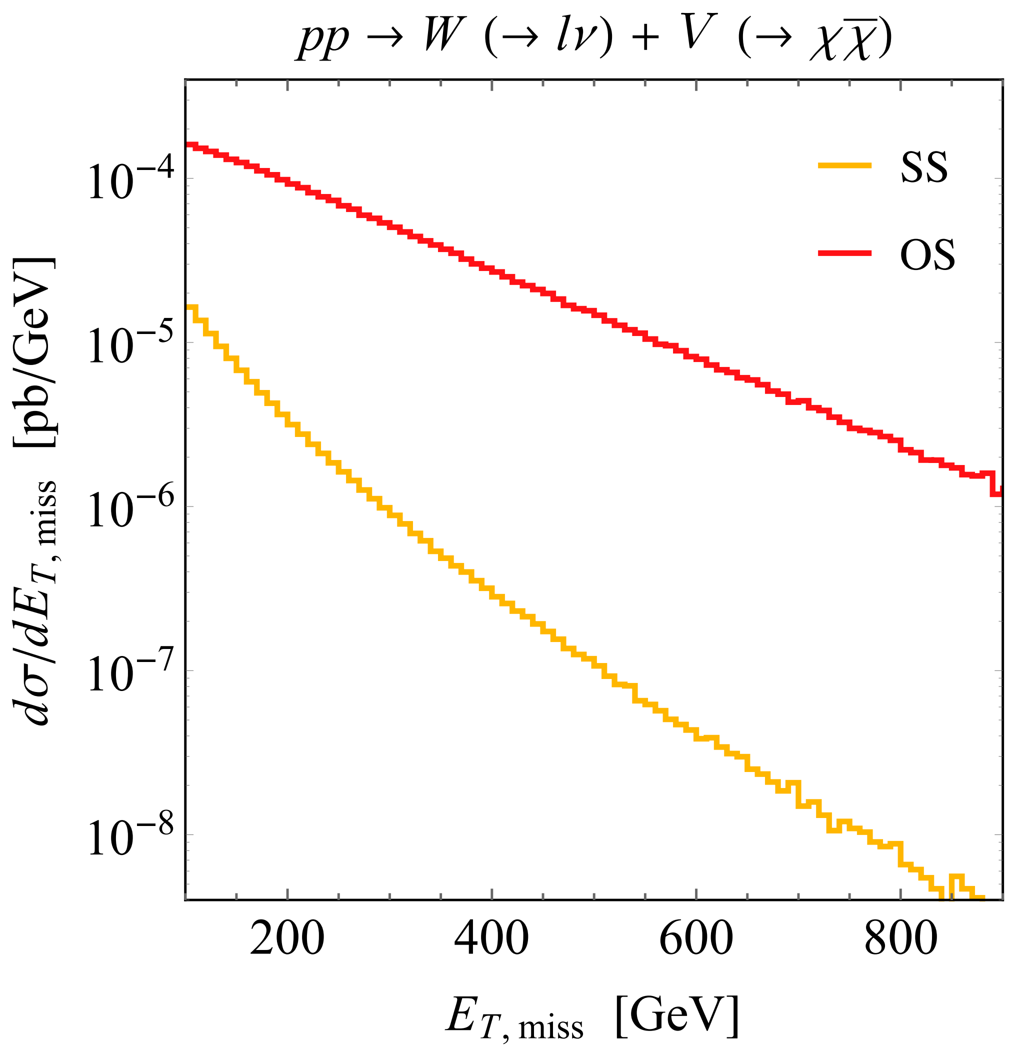


$$\sim \left(g_u^L - g_d^L\right) \frac{s}{M_W M_V}$$

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

[UH, Kahlhoefer & Tait, 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]

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

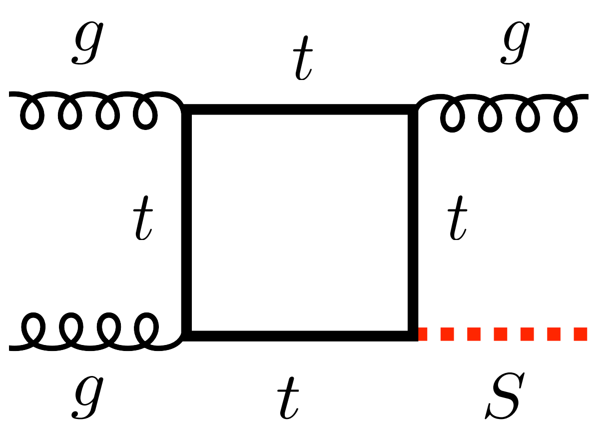
(ii) add a WWV vertex to spin-1 simplified model

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

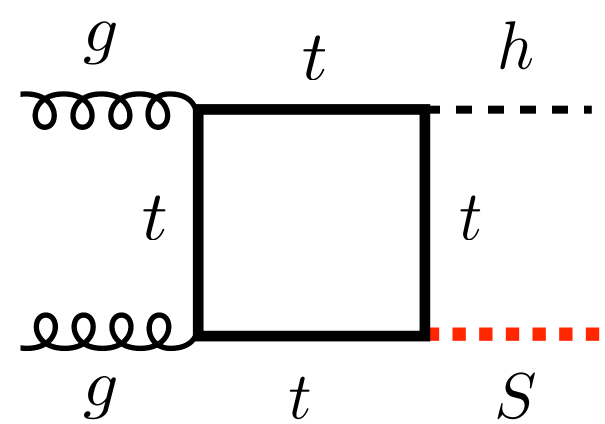
Irrespectively of how issue is resolved, sensitivity of mono-jet searches will always exceed that of mono-W channel in modified theory. Same verdict has been reached in EFT case & t-channel simplified DM models with coloured scalar exchange

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

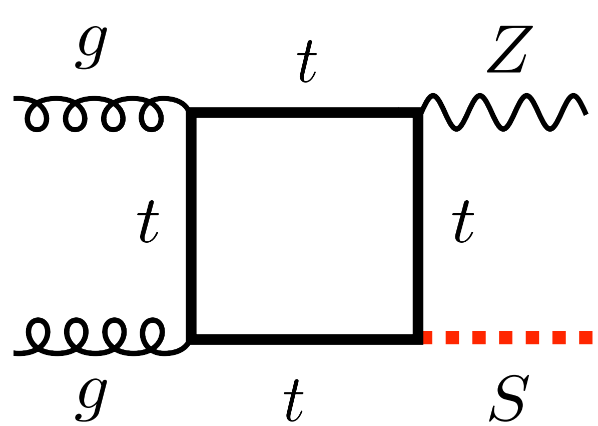
Spin-0 mono-X amplitudes



$\sim s^0$



$\sim s^0$



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

1-loop $gg \to Z+S$ 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

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?

Extensions of spin-0 simplified model

$\mathcal{L} \supset \mu s H^\dagger H$ → Two physical spin-0 states h, S & single mixing angle θ

↓

Model predicts universal suppression of Higgs couplings as modifications of gauge-scalar & fermion-scalar couplings fully correlated. If kinematically allowed new Higgs decays $h \to \chi\bar{\chi}$ & $h \to SS$ present. All $E_{T,miss}$ cross sections are changed. In particular, $V+E_{T,miss}$ as well as VBF+$E_{T,miss}$ contributions arise

[details in talks by Felix, Giorgio & Kristian]

Extensions of spin-0 simplified model

$$\mathcal{L} \supset i\mu a H_u^\dagger H_d + \text{h.c.}$$

Six physical spin-0 states h, H, A, $H^\pm$, P & three mixing angle α, β, θ

Can decouple gauge-scalar & fermion-scalar couplings which allows to avoid Higgs constraints. Besides invisible & exotic Higgs decays, also neutral & charged Higgs searches & flavour physics constrain parameter space. In alignment/decoupling limit, $E_{T,miss}$ signatures driven by fermionic contributions while V+$E_{T,miss}$ & VBF+$E_{T,miss}$ channels necessarily small

Mono-jet backgrounds at 8 TeV

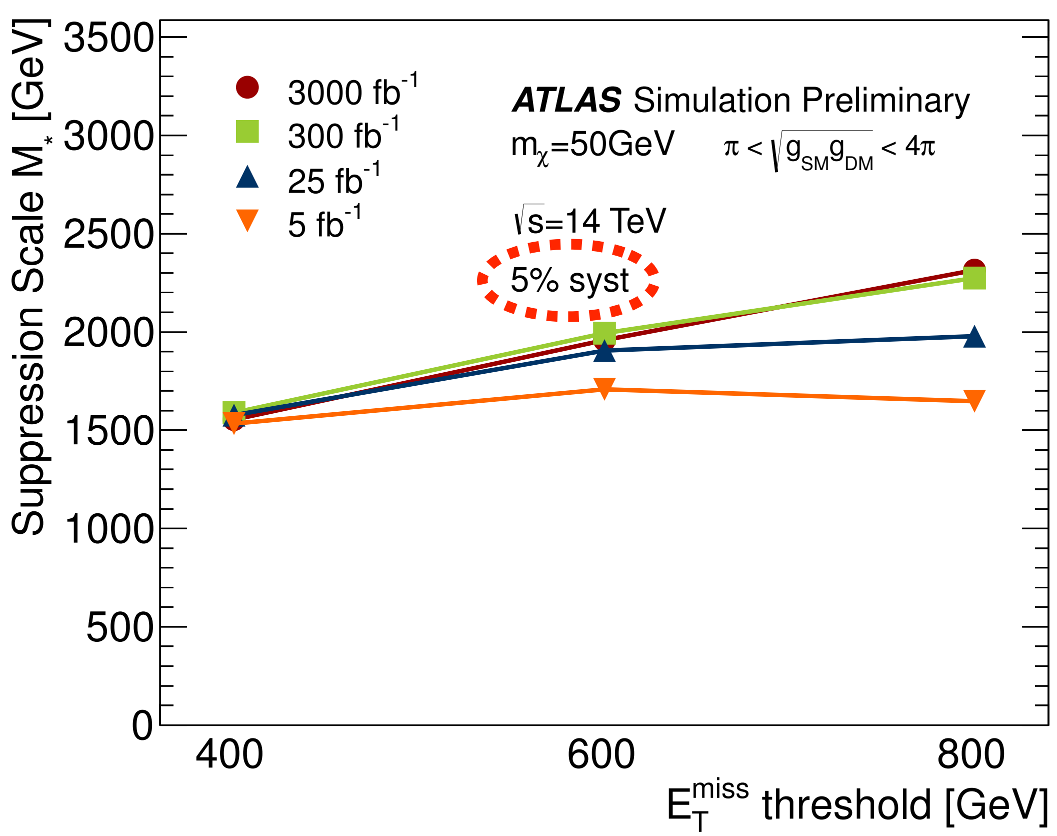
[CMS, 1408.3583]

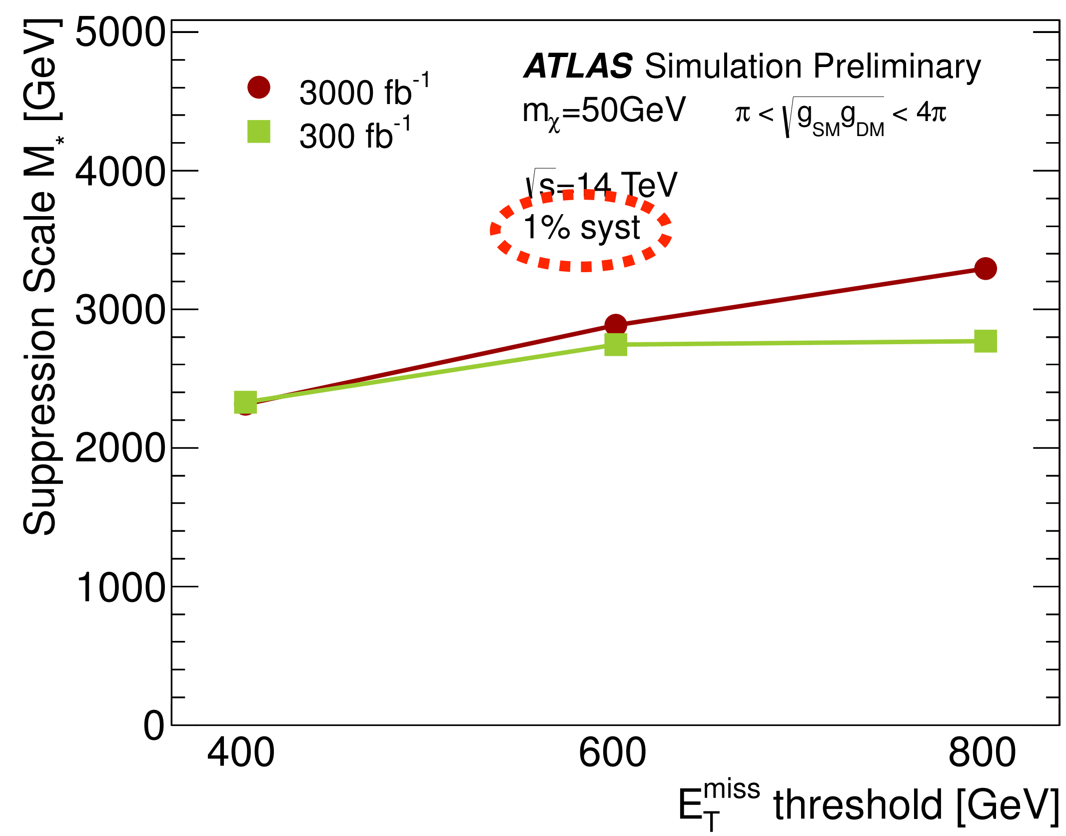
E_T^{miss} (GeV)	>250	…	>550	relative uncertainty
$Z(\nu\nu)$+jets	32100 ± 1600		362 ± 64	13%
W+jets	17600 ± 900		123 ± 13	3%
$t\bar{t}$	446 ± 220		2.8 ± 1.4	
$Z(\ell\ell)$+jets	139 ± 70		1.0 ± 0.5	
Single t	155 ± 77	…	—	
QCD multijets	443 ± 270		0.5 ± 0.3	
Diboson	980 ± 490		20 ± 10	2%
Total SM	51800 ± 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 these uncertainties down? 1% seems like a big challenge for both experiment & theory

I am looking forward …

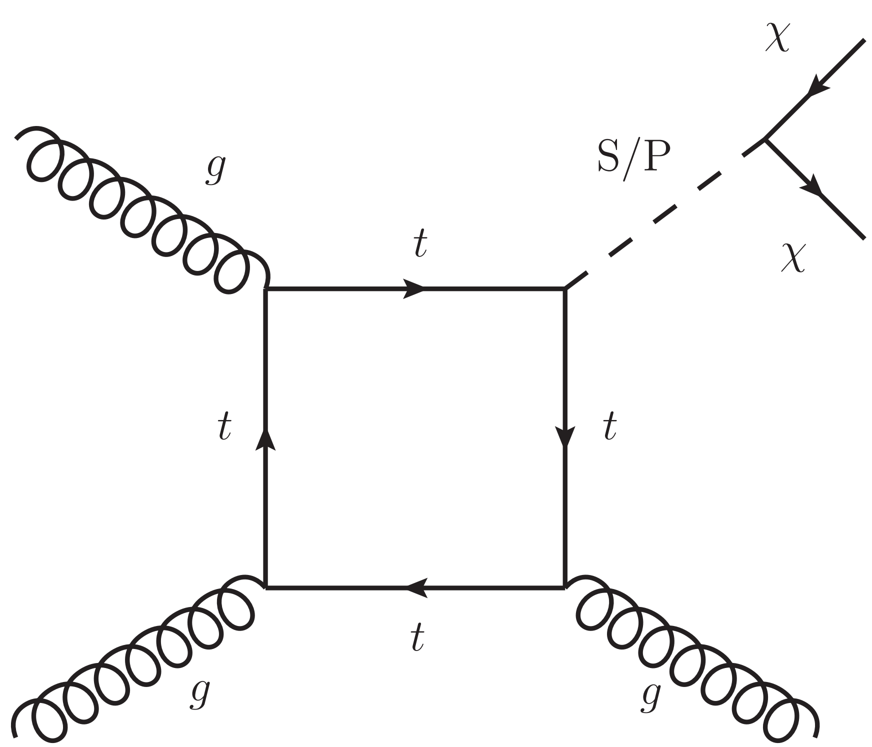
to 19 presentations & two days of lively discussions about the future of DM searches at the LHC

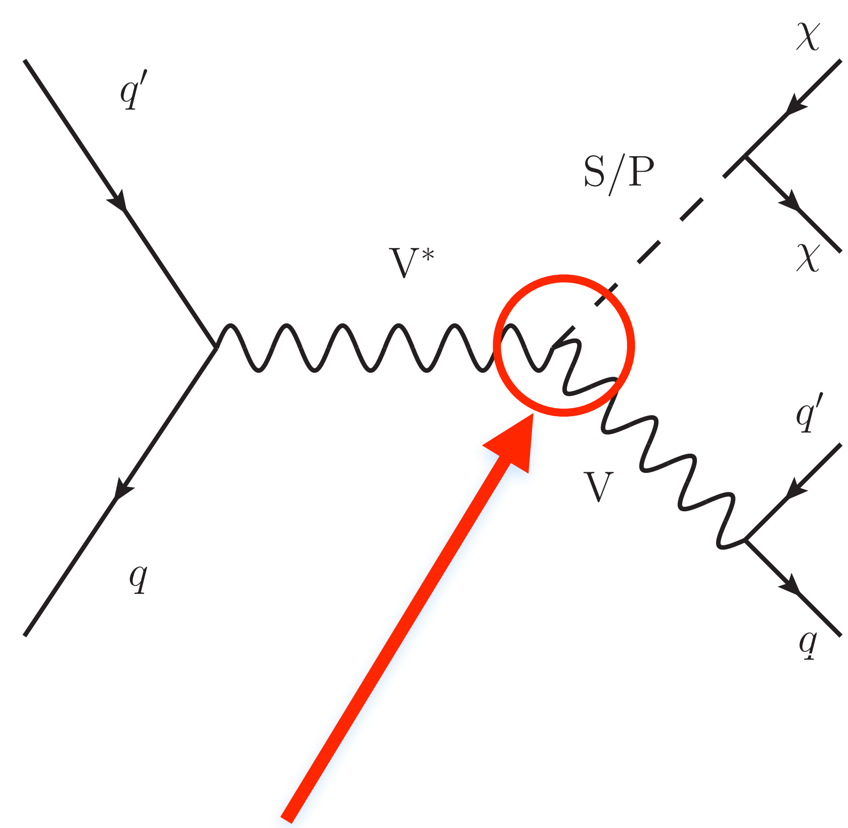
Backup

CMS, 1607.05764

$$\mathcal{L}_{\mathrm{scalar}} \supset -\frac{1}{2} m_{\mathrm{MED}}^2 \mathrm{S}^2 - g_{\mathrm{DM}} \mathrm{S} \overline{\chi} \chi - g_{\mathrm{q}} \sum_{\mathrm{q=b,t}} \frac{m_{\mathrm{q}}}{v} \mathrm{S} \overline{\mathrm{q}} \mathrm{q} - m_{\mathrm{DM}} \overline{\chi} \chi,$$

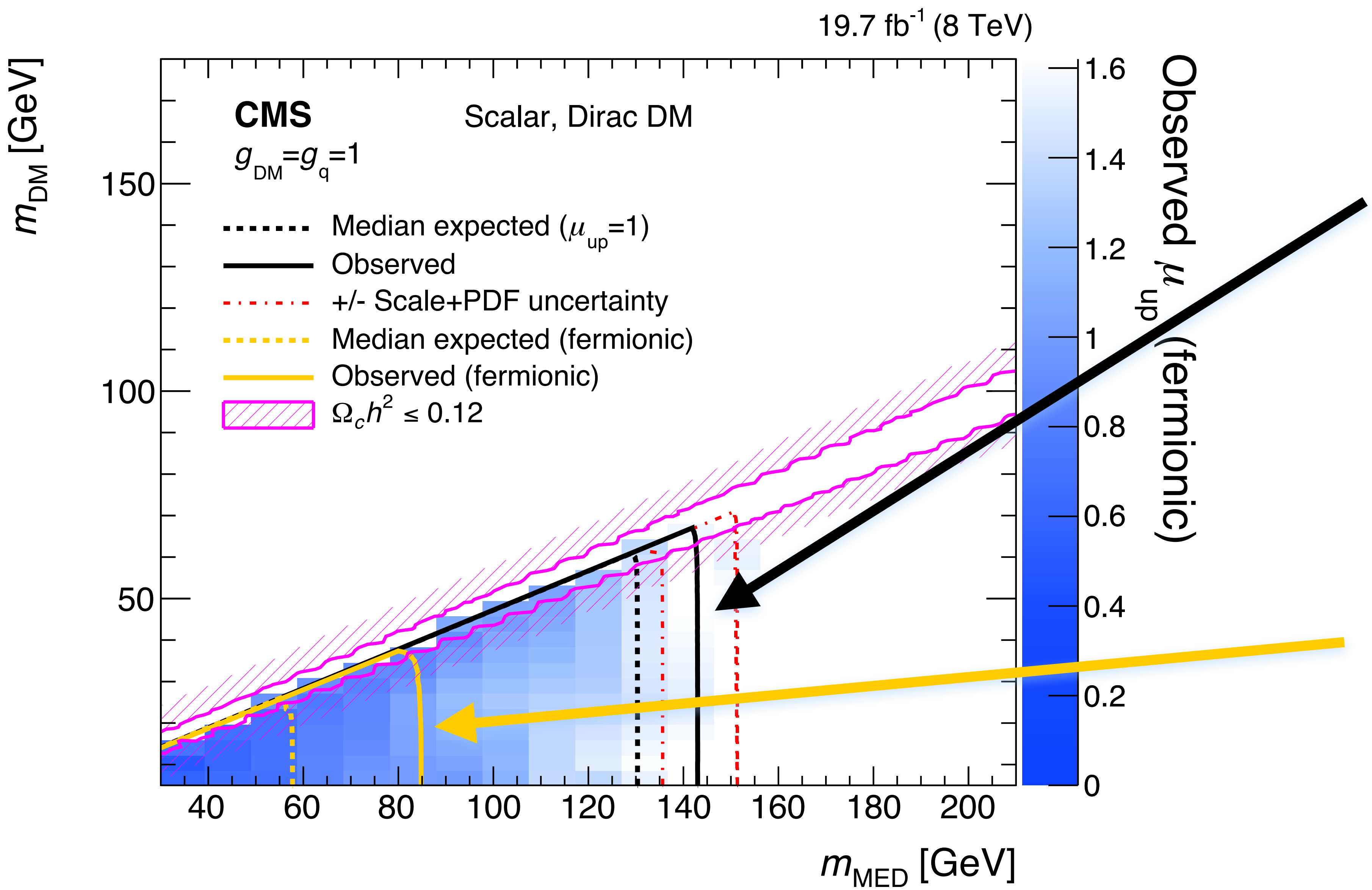
$$\mathcal{L}_{\mathrm{pseudoscalar}} \supset -\frac{1}{2} m_{\mathrm{MED}}^2 \mathrm{P}^2 - i g_{\mathrm{DM}} \mathrm{P} \overline{\chi} \gamma^5 \chi - i g_{\mathrm{q}} \sum_{\mathrm{q=b,t}} \frac{m_{\mathrm{q}}}{v} \mathrm{P} \overline{\mathrm{q}} \gamma^5 \mathrm{q} - m_{\mathrm{DM}} \overline{\chi} \chi,$$

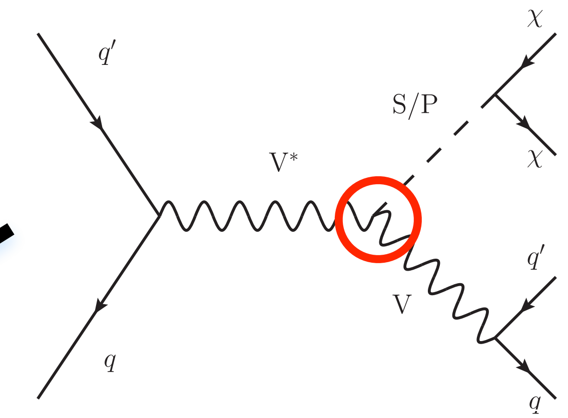


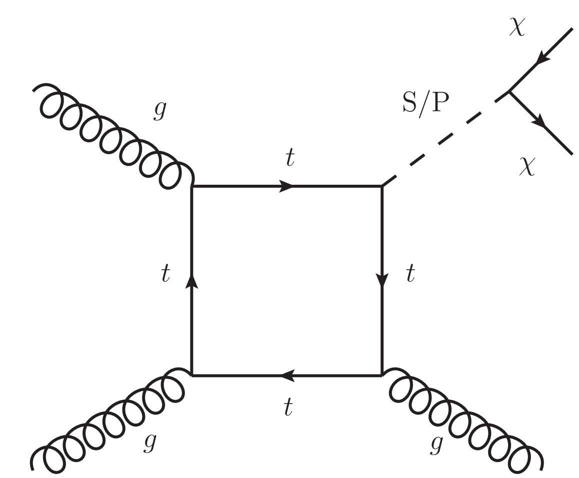


where does this vertex come from?

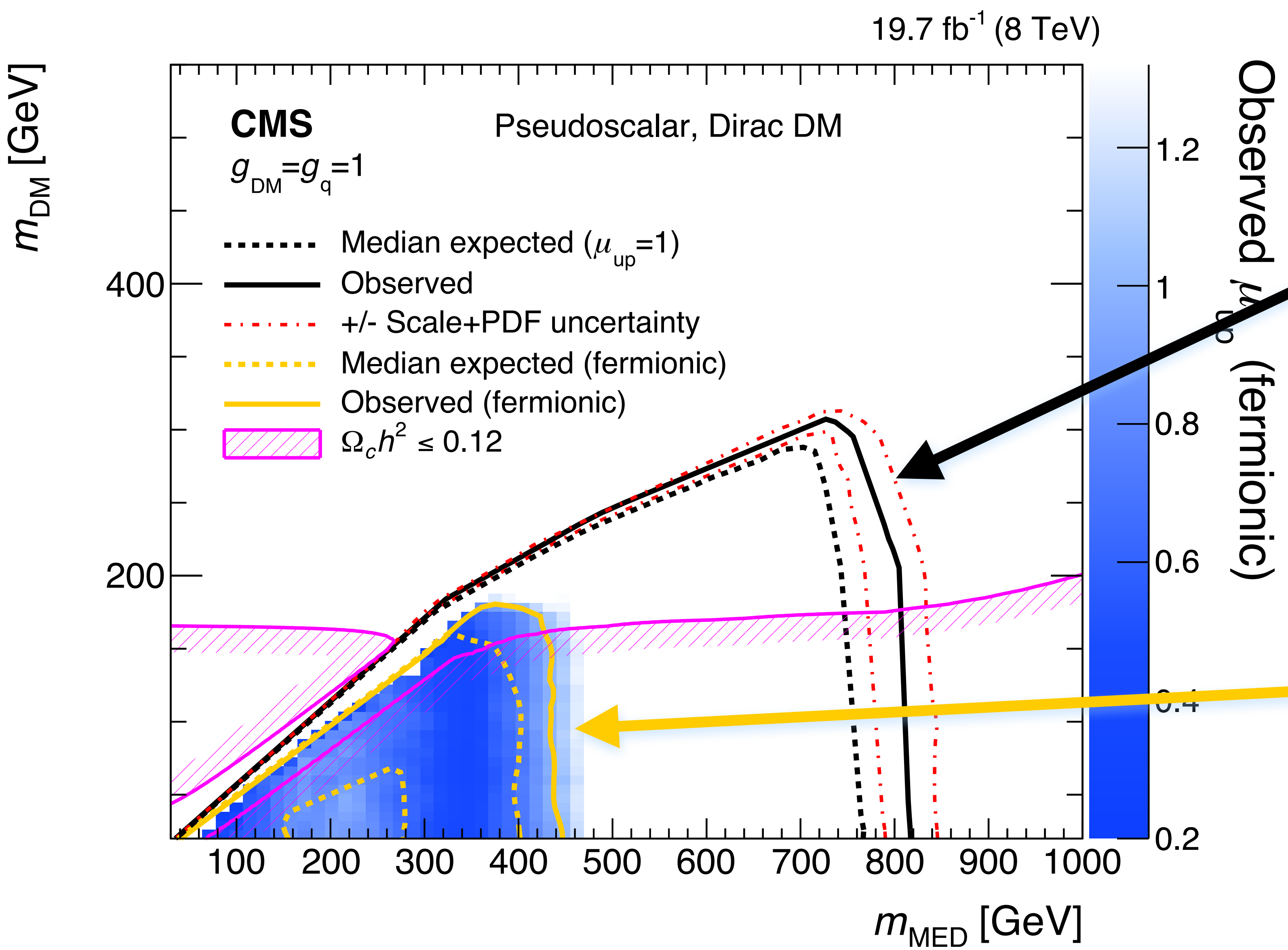
CMS, 1607.05764

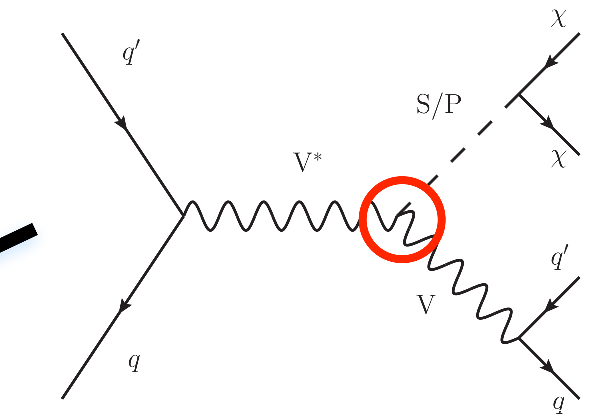


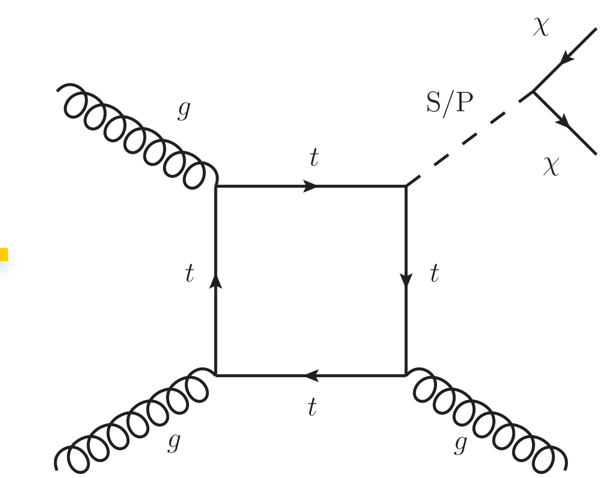




CMS, 1607.05764

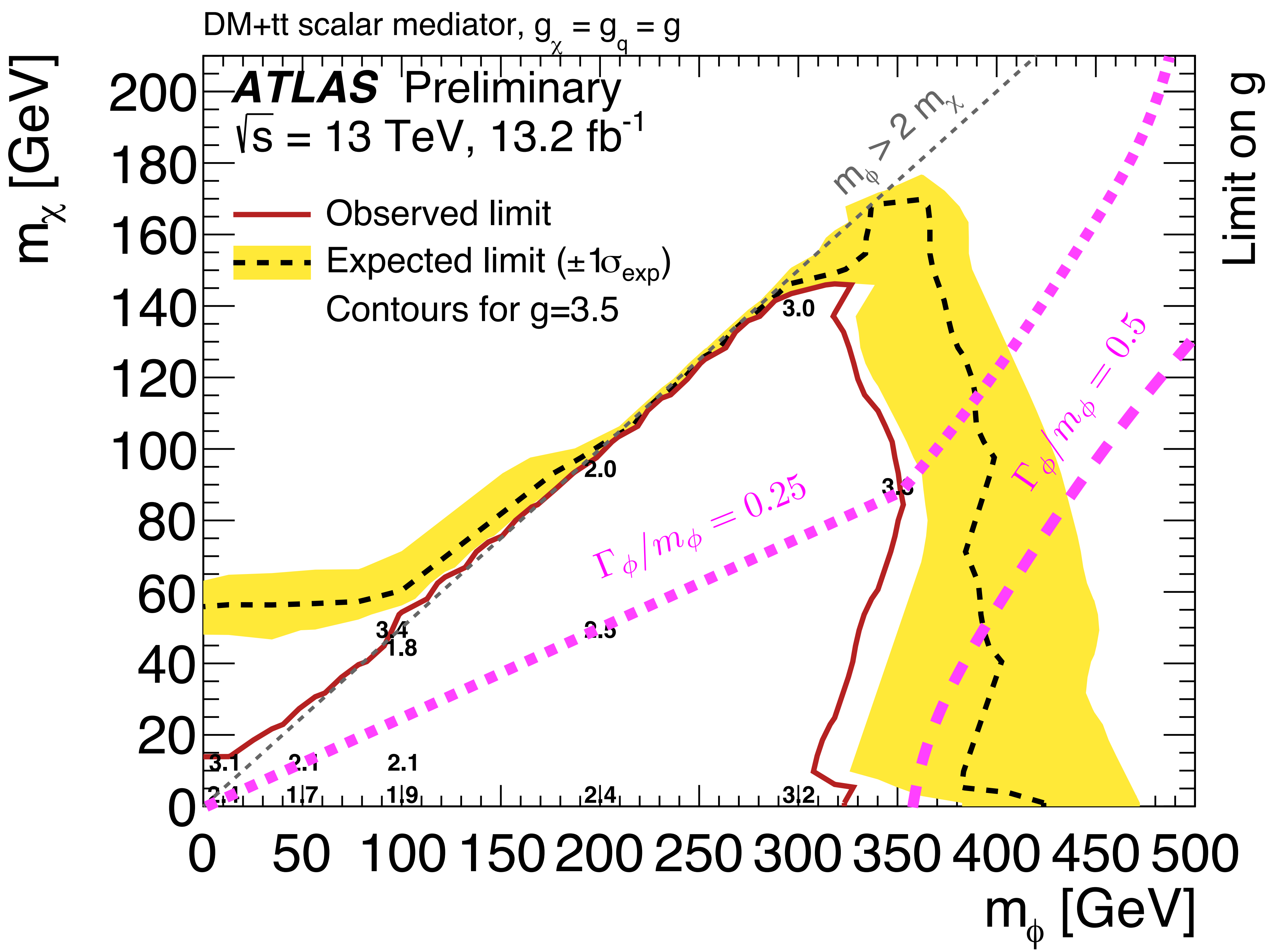






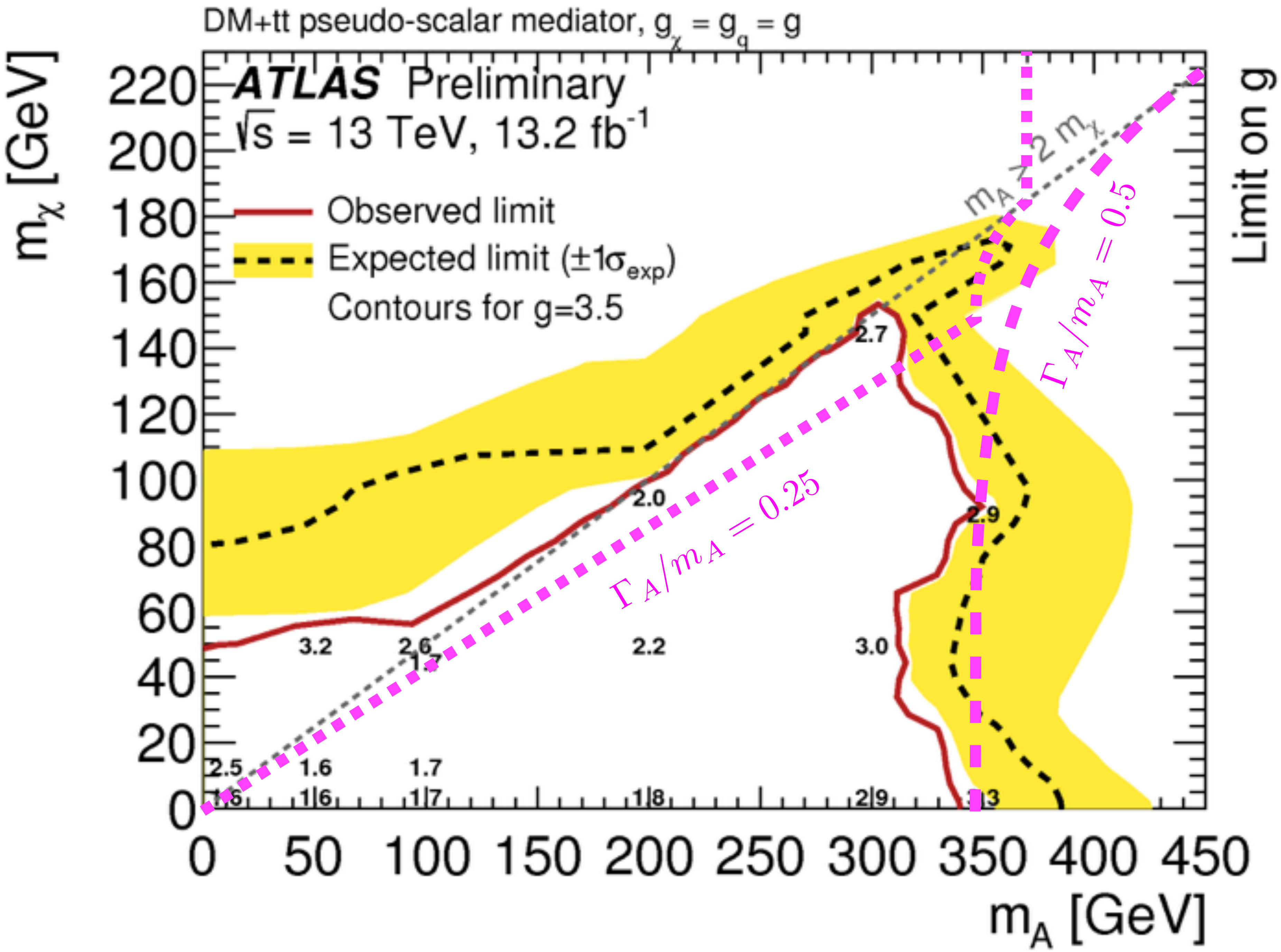
13 TeV limits on $E_{T,\,miss}$+$t\bar{t}$

[ATLAS-CONF-2016-050]



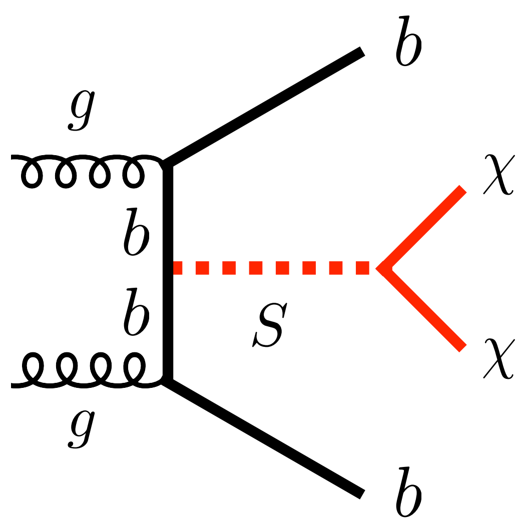
13 TeV limits on $E_{T, miss}$+$t\bar{t}$

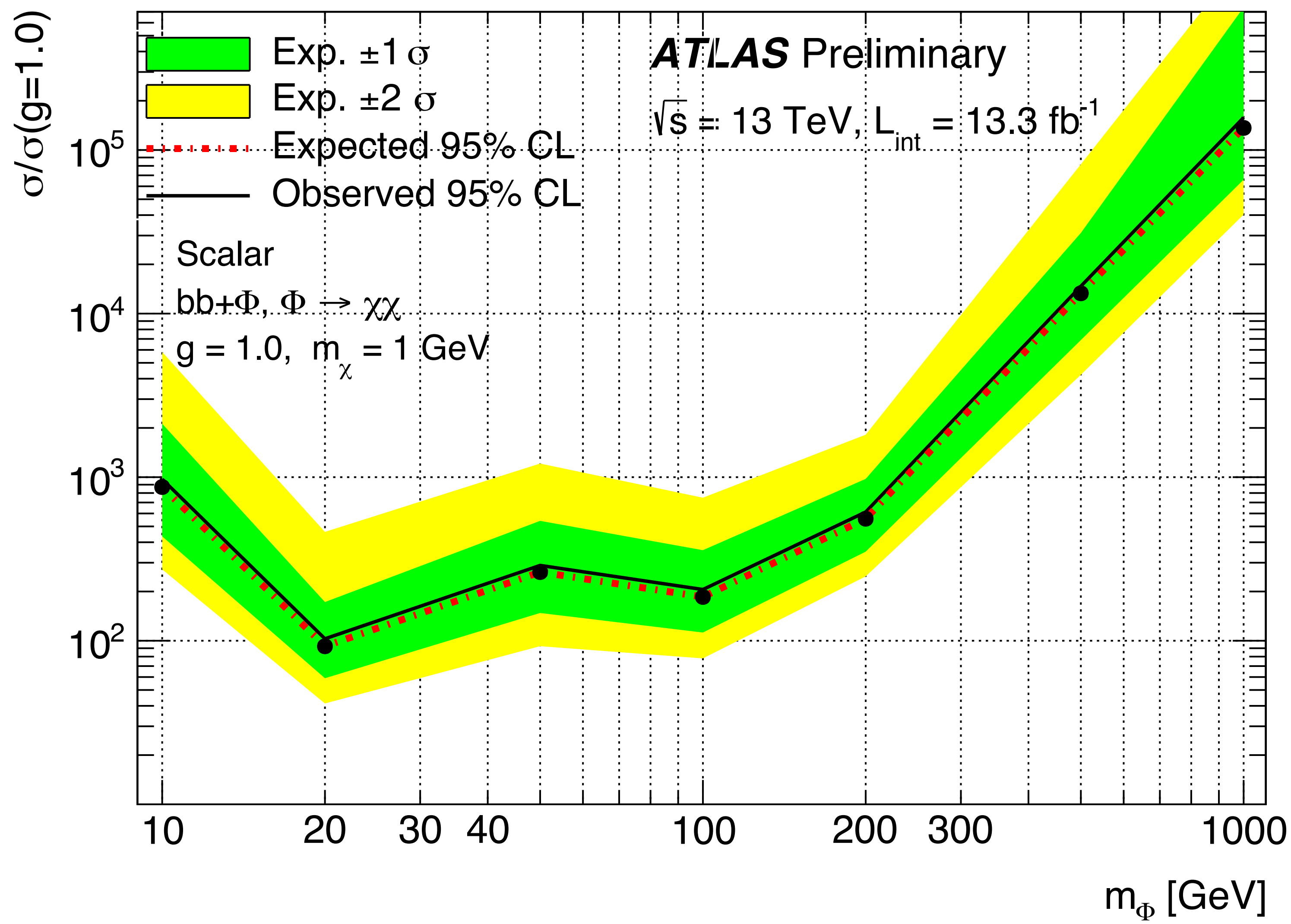
[ATLAS-CONF-2016-050]



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

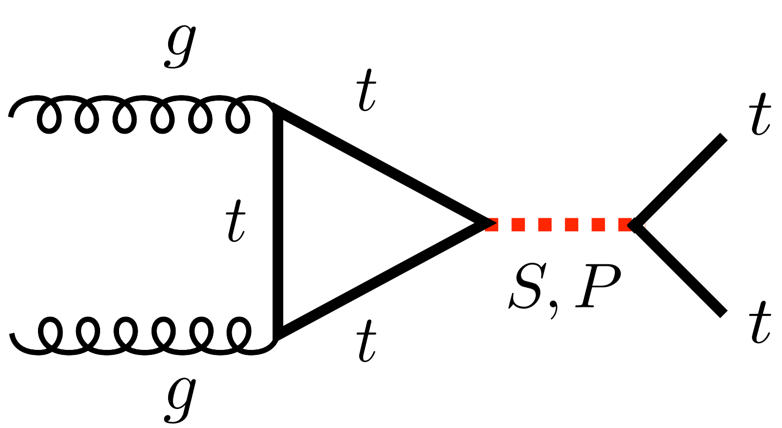
[ATLAS-CONF-2016-086]

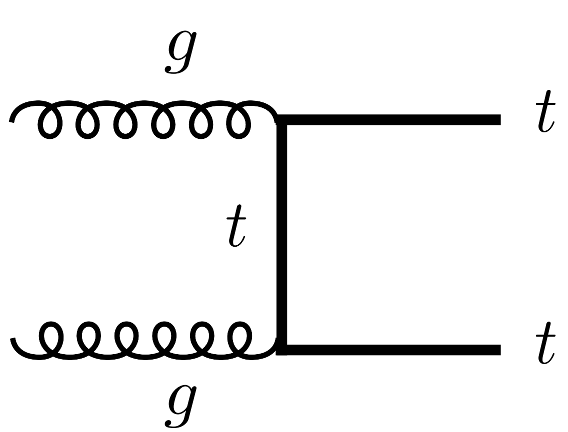




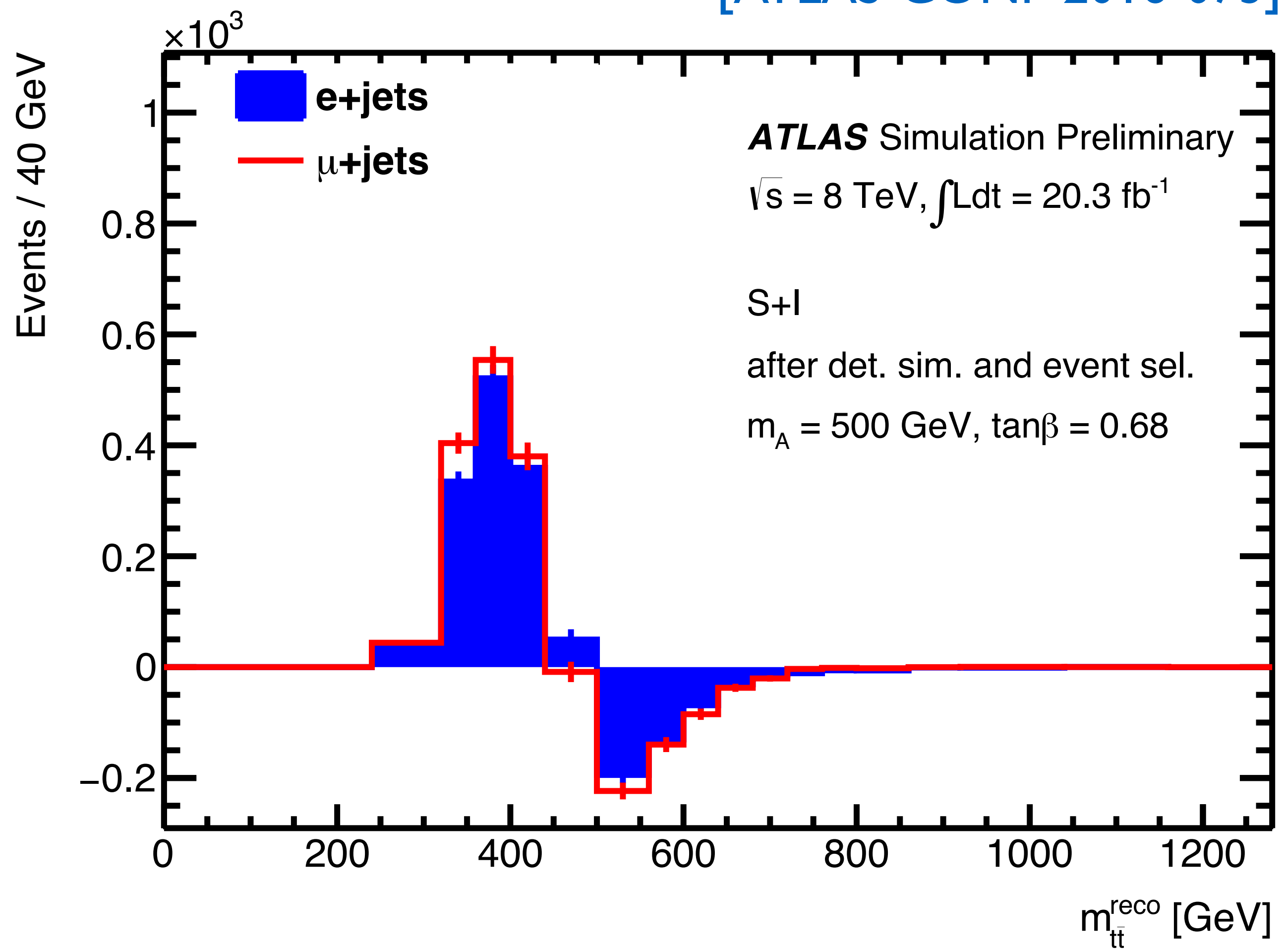
$E_{T,\,miss}$+$b\bar{b}$ searches not yet sensitive to spin-0 models with weak couplings

Di-top limits





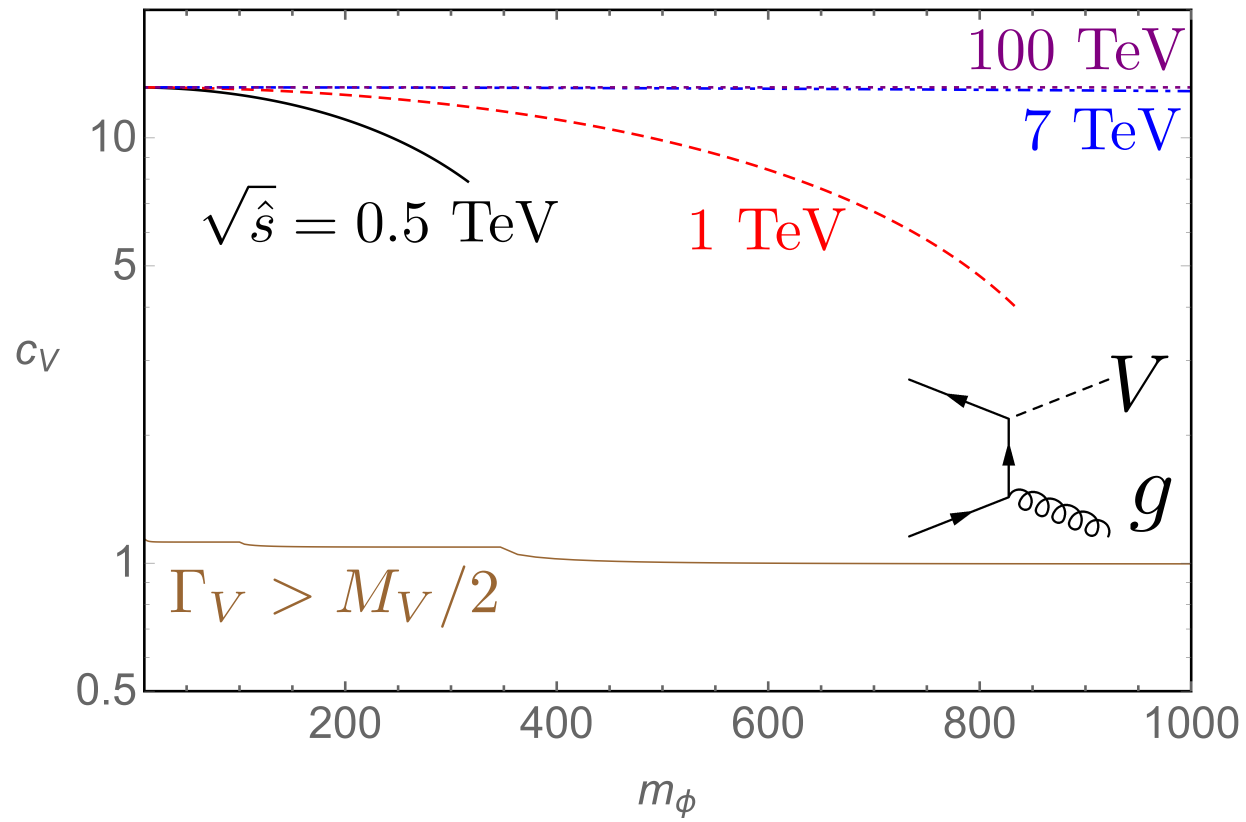
[ATLAS-CONF-2016-073]

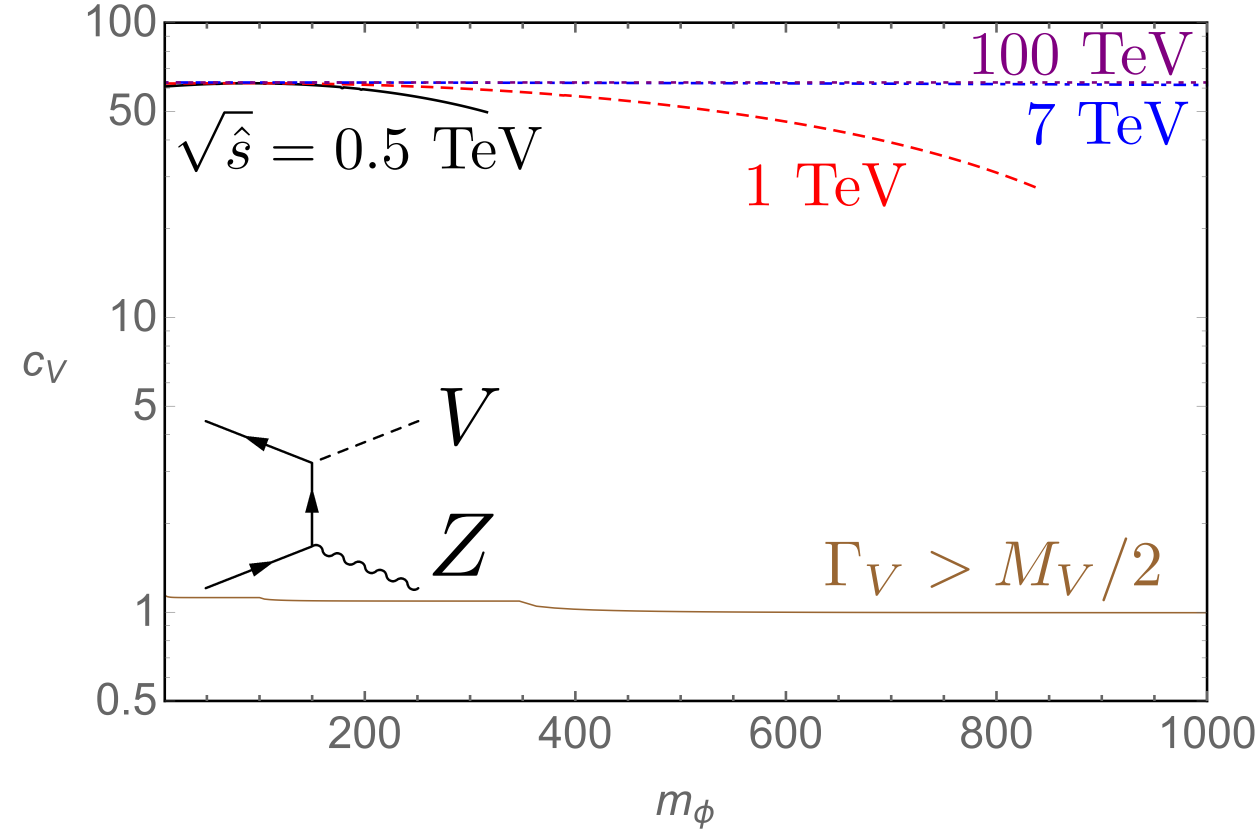


Compared to parton-level spectra, reconstructed distributions with narrower resonances are more strongly distorted due detector resolution

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

[Englert et al., 1604.07975]



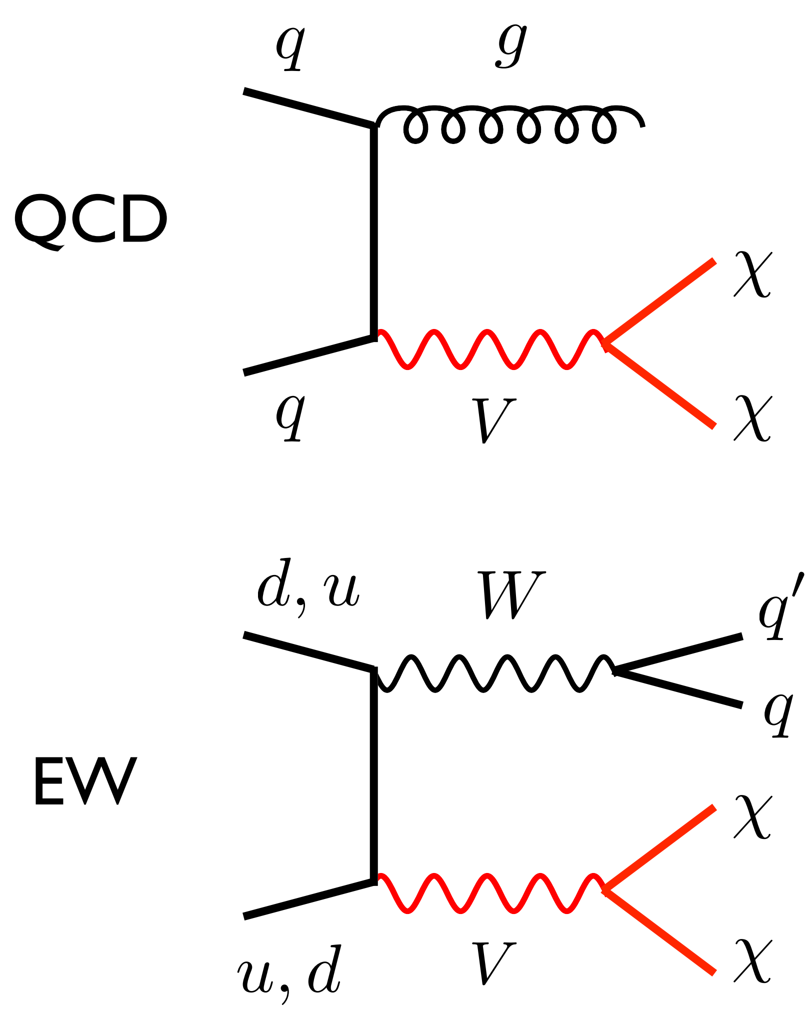


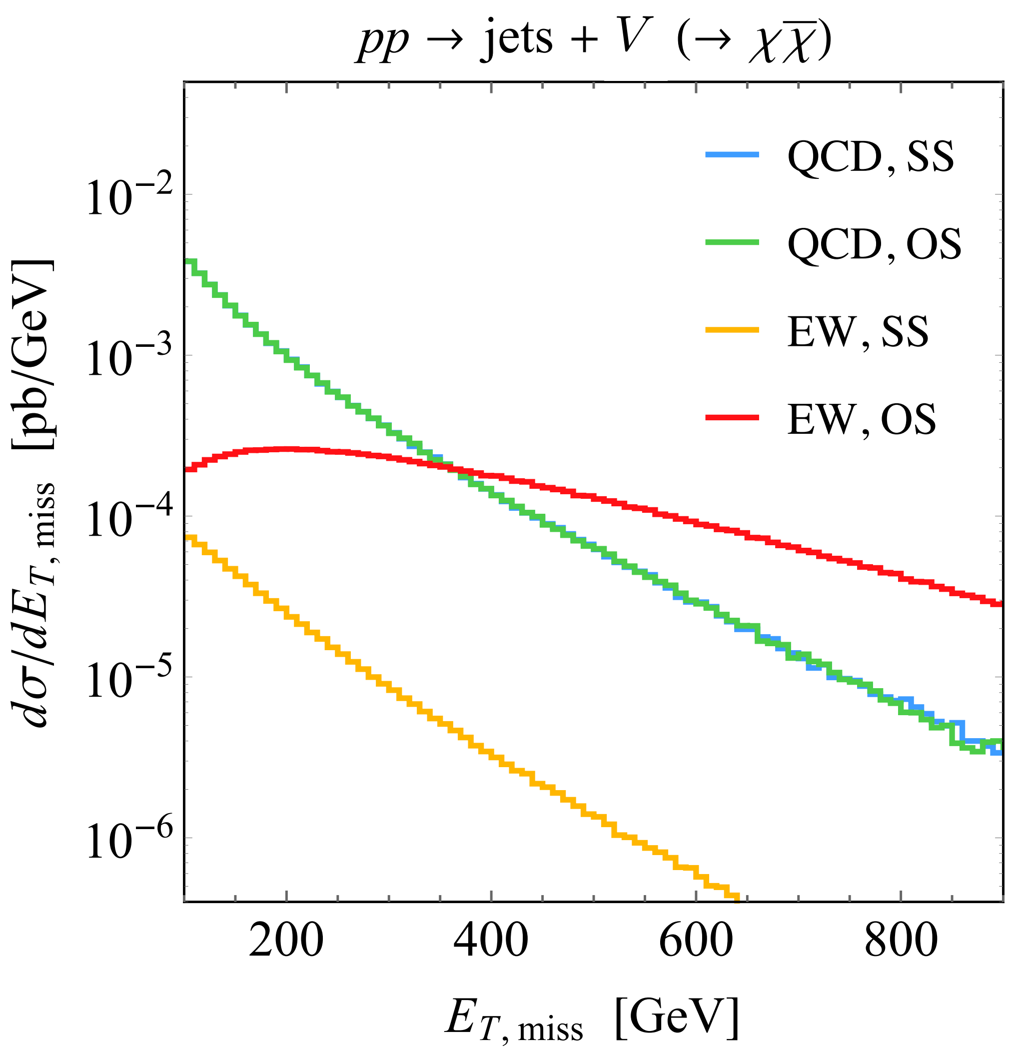
$E_{T,\text{miss}}$+jet, Z, h amplitudes in spin-1 models have no problem with unitarity at LHC energies & beyond unless DM-mediator couplings are non-perturbative†

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

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

[UH, Kahlhoefer & Tait, 1603.01267]

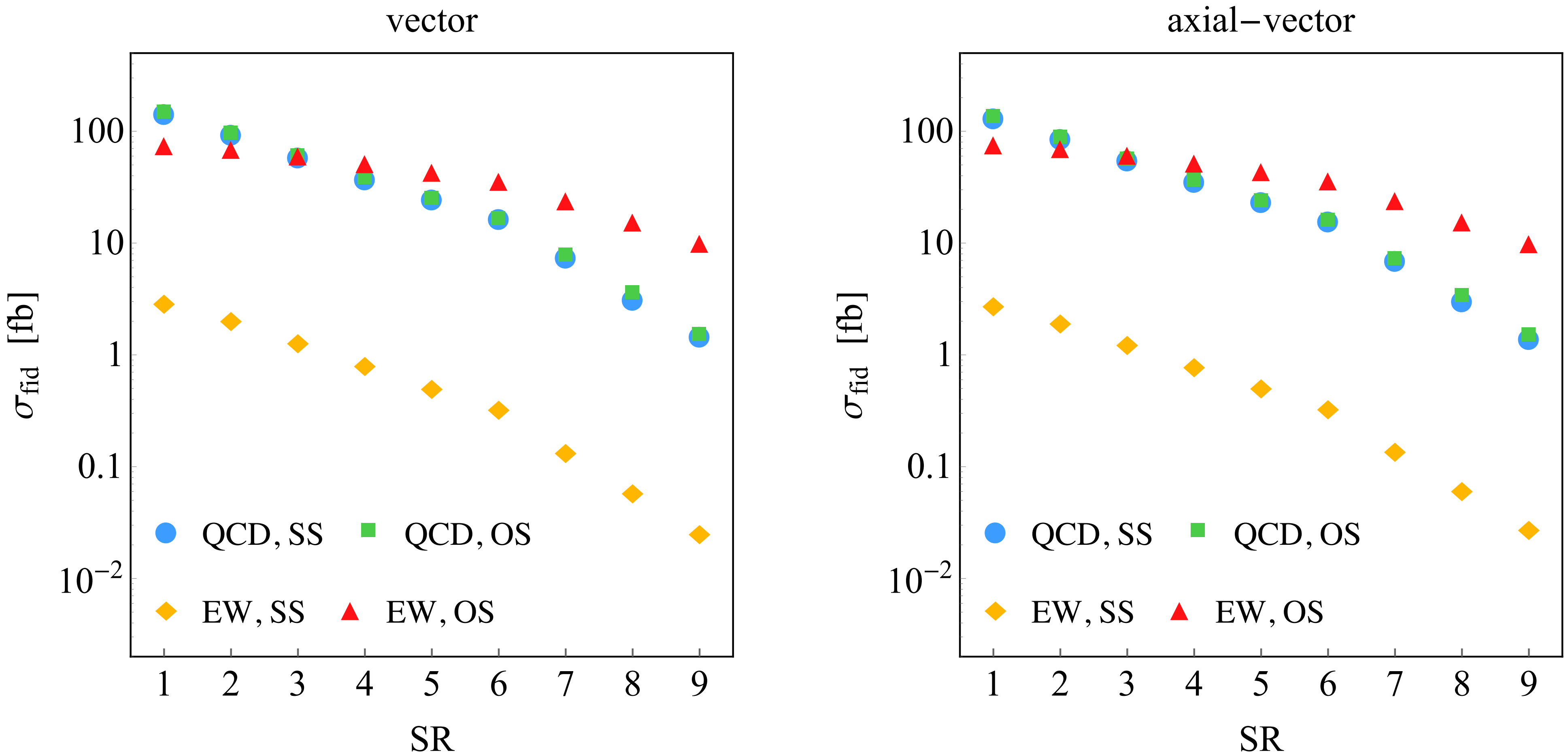




In fact, EW channel $pp \to W(\to q\bar{q}') + V(\to \chi\bar{\chi})$ even produces harder mono-jet events than QCD process $pp \to jets + V(\to \chi\bar{\chi})$

Mono-W problem in mono-jets

[UH, Kahlhoefer & Tait, 1603.01267]



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

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

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

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

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:

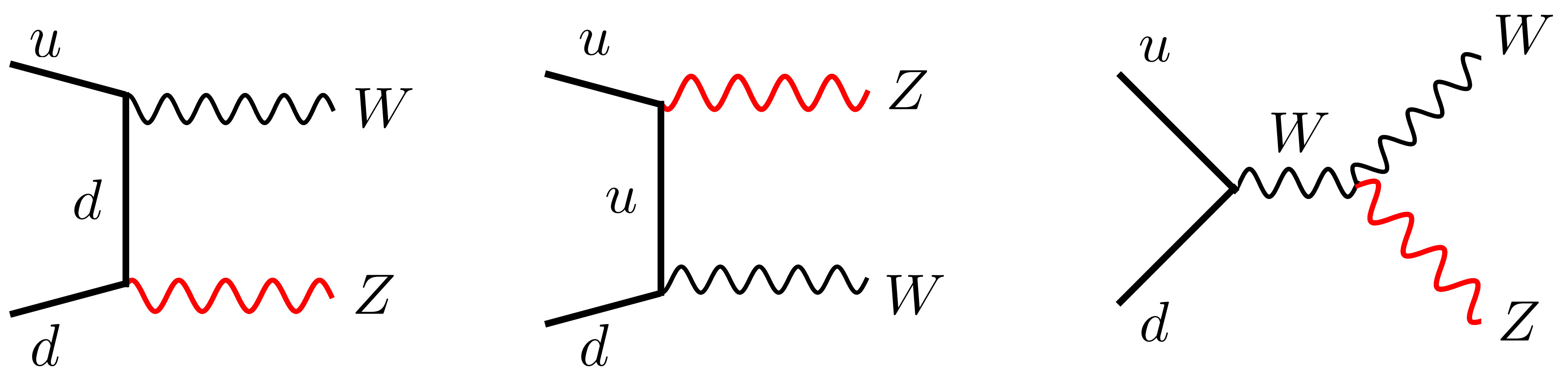
$$\mathcal{L}_{Vq\bar{q}} = -\sum_{u,d} V_\mu \left(g_Q \bar{Q}_L \gamma^\mu Q_L + g_u \bar{u}_R \gamma^\mu u_R + g_d \bar{d}_R \gamma^\mu d_R \right)$$

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

[UH, Kahlhoefer & Tait, 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, Kahlhoefer & Tait, 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, Kahlhoefer & Tait, 1603.01267]

Mono-W problem: solution 3

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

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

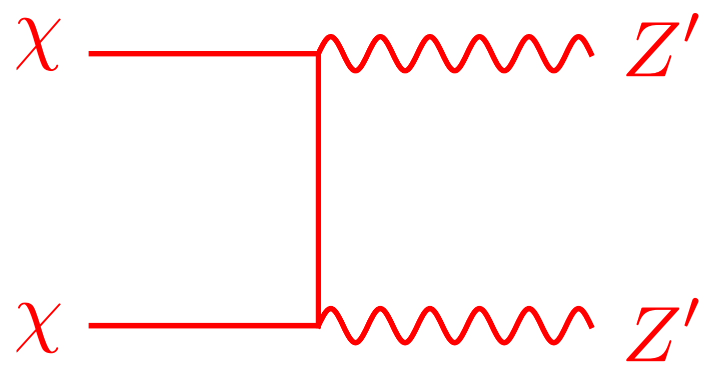
In such a case $SU(2)_L$ breaking is however not O(1), but given by†

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

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, Kahlhoefer & Tait, 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

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g^A_{\rm DM}Z'^{\mu}\bar{\psi}\gamma_\mu\gamma_5\psi - \frac{1}{2}y_{\rm DM}\bar{\psi}\left(P_L S + P_R S^*\right)\psi$$

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

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

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

[Kahlhoefer et al.,1510.02110]

Z′ interactions

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

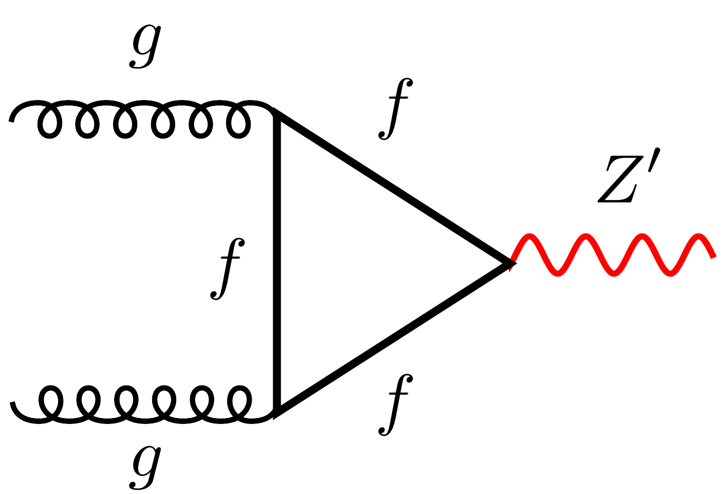
$$\mathcal{L}'_{\rm SM} = \left\{ (D^\mu H)^\dagger (-i g' q_H Z'_\mu H) + \text{h.c.} \right\} + g'^2 q_H^2 Z'^\mu Z'_\mu H^\dagger H$$
$$- \sum_{f=q,\ell,\nu} g' Z'^\mu \left(\bar{q}_{f_L} \bar{f}_L \gamma_\mu f_L + \bar{q}_{f_R} \bar{f}_R \gamma_\mu f_R \right)$$

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:

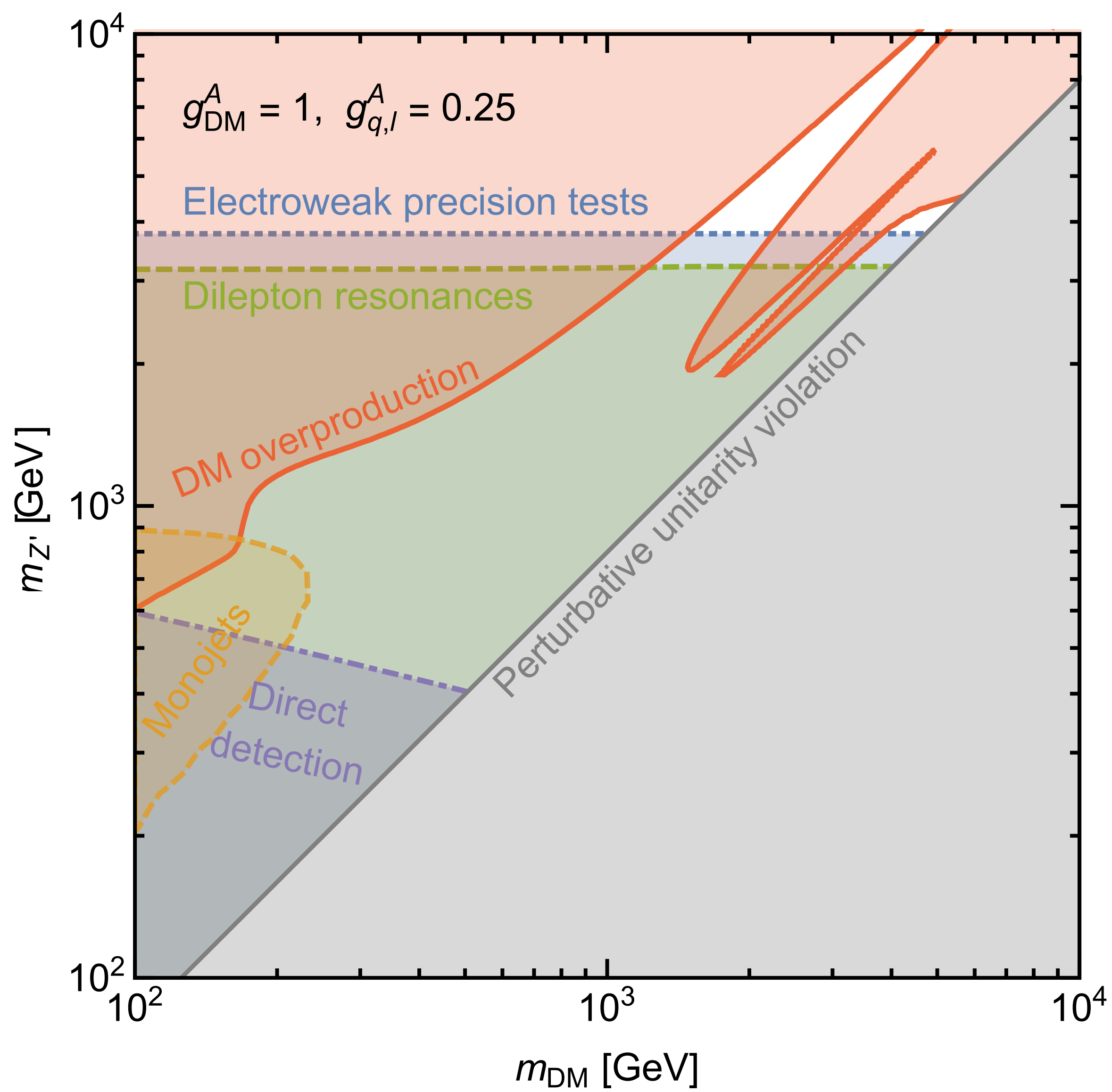
- Z' must couple with same strength to quarks & leptons (assuming one Higgs doublet), resulting in stringent constraints from di-lepton resonance searches

- 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

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

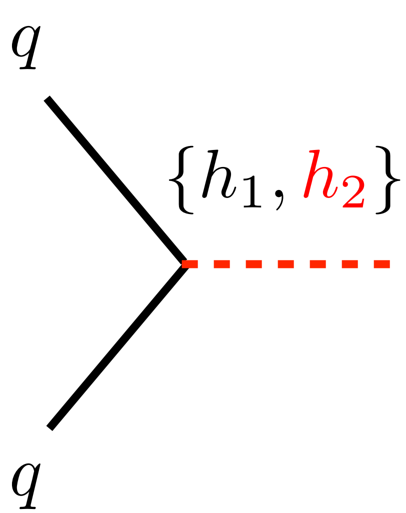
As a result of portal coupling μ, SM Higgs h & singlet s mix, giving rise to mass eigenstates $h_{1,2}$:

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

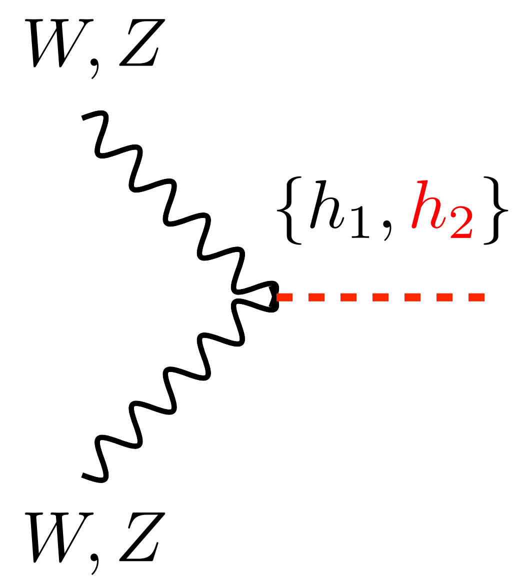
For small $\theta \ll 1$, h_1 (h_2) SM Higgs-like (singlet-like)

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

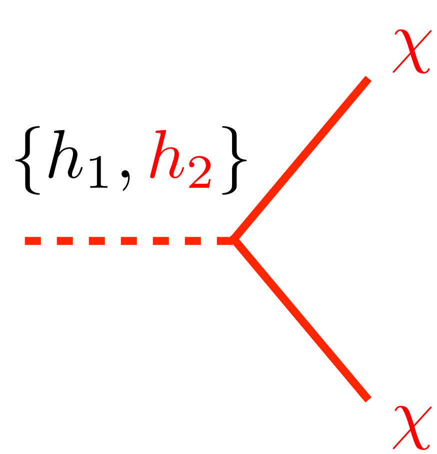
Fermion singlet DM: vertices



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



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



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

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