Dark matter samples and theory calculations for Run 3: s-channel and Higgs to invisible

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LHC DM WG meeting
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Goal

Converge to a common prescription to be used in Run 3 ATLAS and CMS papers for

- presentation of DM results and comparison with DM experiments
- generation (and normalisation) of MC samples used in DM searches
- harmonisation with other searches (e.g. hidden sector scalars)

Disclaimers

#1 This talk will present some ***first suggestions to be discussed with the collaborations***

#2 We only address *Higgs to invisible* and *s-channel interpretations* in this talk

refer to *Abe et al, 1810.09420* for 2HDMa

t-channel: *Arina et al, 2001.05024*

Higgs to invisible

EFT limits on $\sigma_{nucl\text{-}DM}$ vs m_{DM}

1. Scalar DM - nucleon cross-section

$$\sigma_{SN} = 8\frac{\mathrm{BR}}{1-\mathrm{BR}}\frac{\Gamma_h}{v^2}\frac{m_N^4 f_N^2}{m_h^3(m_s+m_N)^2}\left(1-4\frac{m_s^2}{m_h^2}\right)^{-1/2}$$

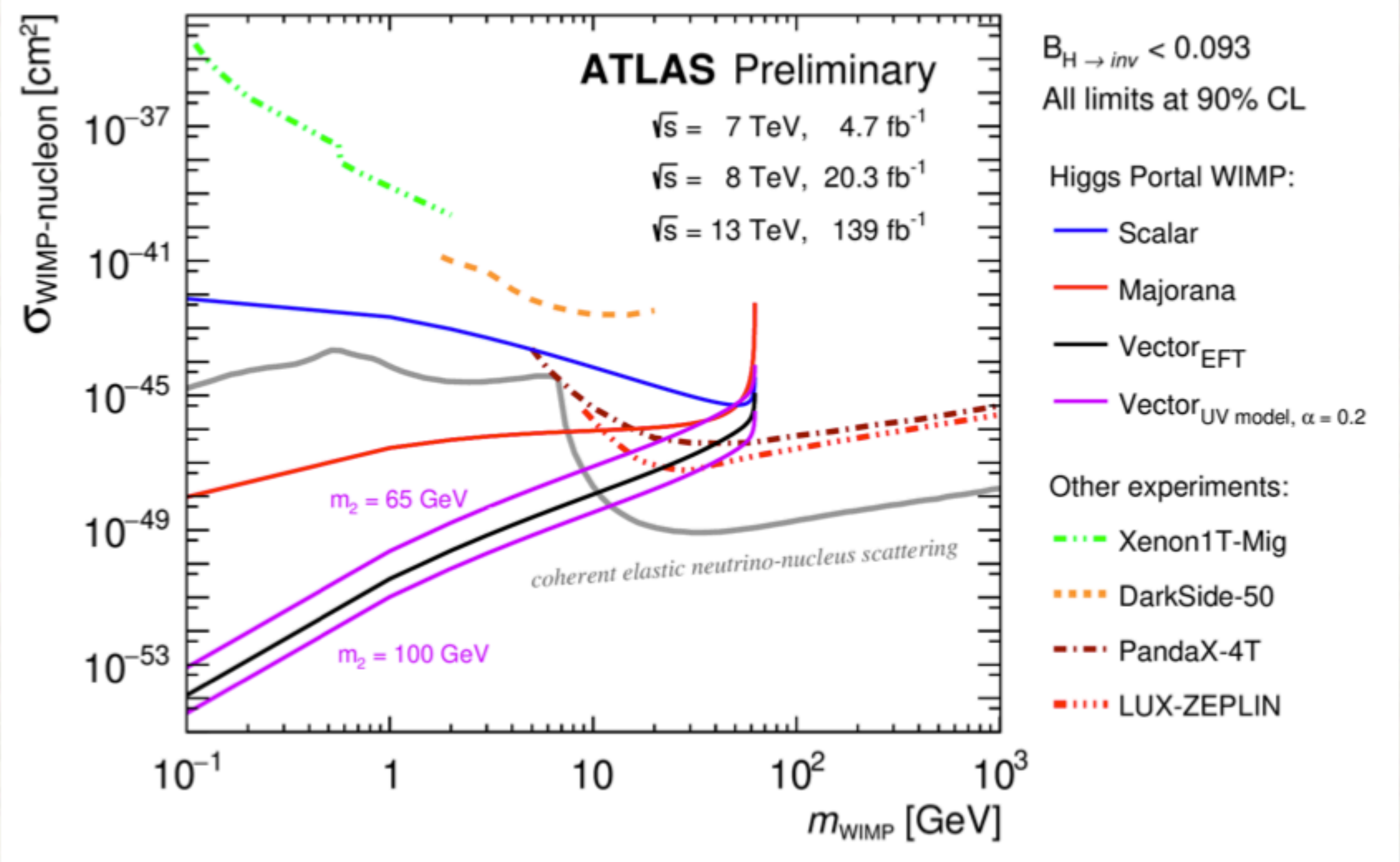
2. Majorana DM - nucleon cross-section

$$\sigma_{fN} = 16\frac{\mathrm{BR}}{1-\mathrm{BR}}\frac{\Gamma_h}{v^2}\frac{m_N^4 m_f^2 f_N^2}{m_h^5(m_f+m_N)^2}\left(1-4\frac{m_f^2}{m_h^2}\right)^{-3/2}$$

3. Vector DM - nucleon cross-section

$$\sigma_{VN} = 32\frac{\mathrm{BR}}{1-\mathrm{BR}}\frac{m_N^4 m_V^4 f_N^2}{v^2 m_h^7(m_V+m_N)^2}\frac{\Gamma_h}{\sqrt{1-4\frac{m_V^2}{m_h^2}}\left(1-4\frac{m_V^2}{m_h^2}+12\frac{m_V^4}{m_h^4}\right)}$$

Formulae from Djouadi et al, 1112.3299 with v=246 GeV



with:

$\Gamma_h \equiv \Gamma_h^{\mathrm{SM}} = 4.07\ \mathrm{MeV}$

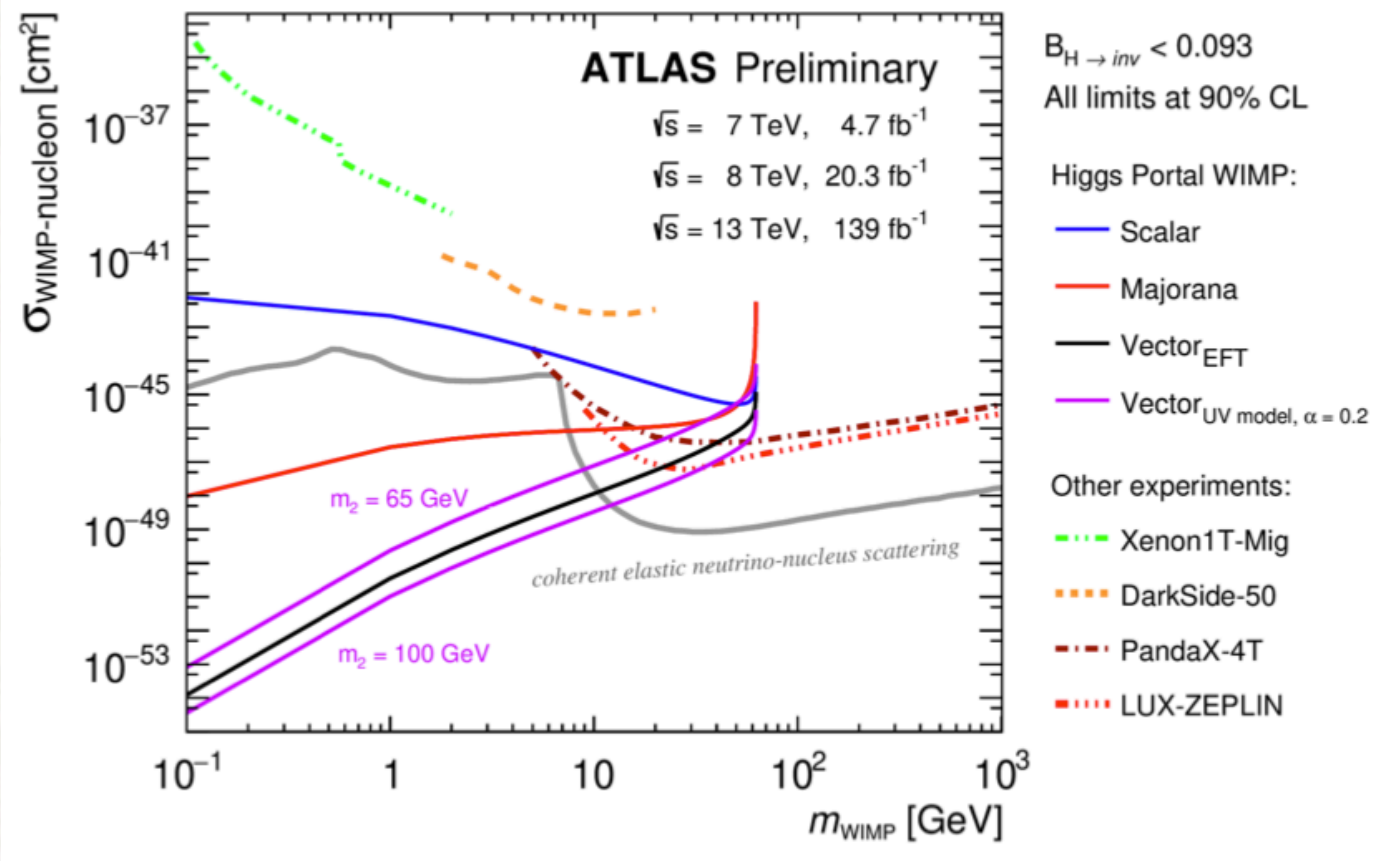
$v = 246\ \mathrm{GeV}$ [NB: in 1112.3299 v/√2 is used]

$m_N = 939\ \mathrm{MeV}$

$f_N = 0.308$ [1708.02245]

UV complete models

- Vector DM charged under U(1)′
- Dark Higgs field h_2 breaks U(1)′ generating DM mass
- mixing between dark and SM Higgs ~ cos**θ**



Suggestion

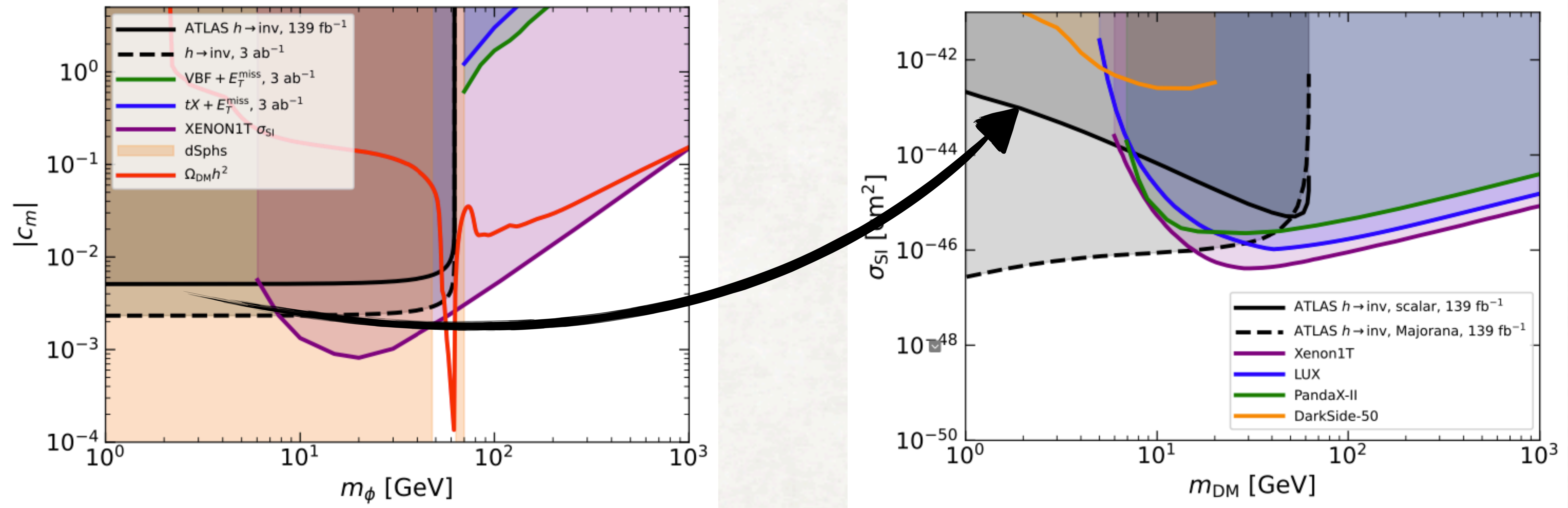
➡ ***show UV model from Arcadi et al, 2001.10750*** *(also described in Zaazoua et al, 2107.01252)* ***using m_2=65,100 GeV***

➡ ***reference also radiative UV-complete model DiFranzo et al, 1512.06853 mentioning that it reproduces the vector EFT curve***

$$\sigma_{UV} = 32\cos^4\theta \frac{\mathrm{BR}}{1-\mathrm{BR}} \frac{\Gamma_h}{v^2} \frac{m_V^4 m_N^4 f_N^2}{m_h^3 (m_V^2 + m_N^2)} \frac{1}{\sqrt{1-4\frac{m_V^2}{m_h^2}}\left(1-4\frac{m_V^2}{m_h^2}+12\frac{m_V^4}{m_h^4}\right)} \left(\frac{1}{m_2^2}-\frac{1}{m_h^2}\right)^2$$

Presentation of EFT limits - an apparent paradox

Limits on Wilson coefficient | **Limits on WIMP-nucleon cross-section**



- for small m_{DM}:
  - limit on Wilson coefficient is constant since **Γ**(h→DM DM) independent of m_{DM} as $m_{DM}\to 0$
  - *but* limit on cross-section improves/deteriorates for fermion/scalar DM
- this is because of the dependence of **σ** on m_{DM}: $\sigma_{SN} \propto 1/m_S^2\ ,\ \sigma_{fN} \propto m_f^2/(m_f+m_N)^2$
  - see discussion in 2109.13597

➡ ***Suggestion:*** ***in addition to the limits on the σ-m_{DM} plane publish also the limits as a function of the Wilson coefficient vs m_{DM}***

EFT limits on Wilson coeff. vs m_{DM}

1. Scalar DM

$$\lambda^2_{hSS} = 128\pi \frac{\mathrm{BR}}{1-\mathrm{BR}} \frac{\Gamma_h}{v^2} \frac{m_h}{\sqrt{1-m_s^2/m_h^2}}$$

2. Majorana DM

$$\frac{\lambda^2_{hff}}{\Lambda^2} = 64\pi \frac{\mathrm{BR}}{1-\mathrm{BR}} \frac{\Gamma_h}{v^2} \frac{1}{m_h(1-m_s^2/m_h^2)^{3/2}}$$

3. Vector DM

$$\lambda^2_{hVV} = 512\pi \frac{\mathrm{BR}}{1-\mathrm{BR}} \frac{\Gamma_h}{v^2} \frac{m_V^4}{m_h^3\sqrt{1-m_V^2/m_h^2}\left(1-4\frac{m_V^2}{m_h^2}+12\frac{m_V^4}{m_h^4}\right)}$$

with:

$\Gamma_h \equiv \Gamma_h^{\mathrm{SM}} = 4.07\ \mathrm{MeV}$

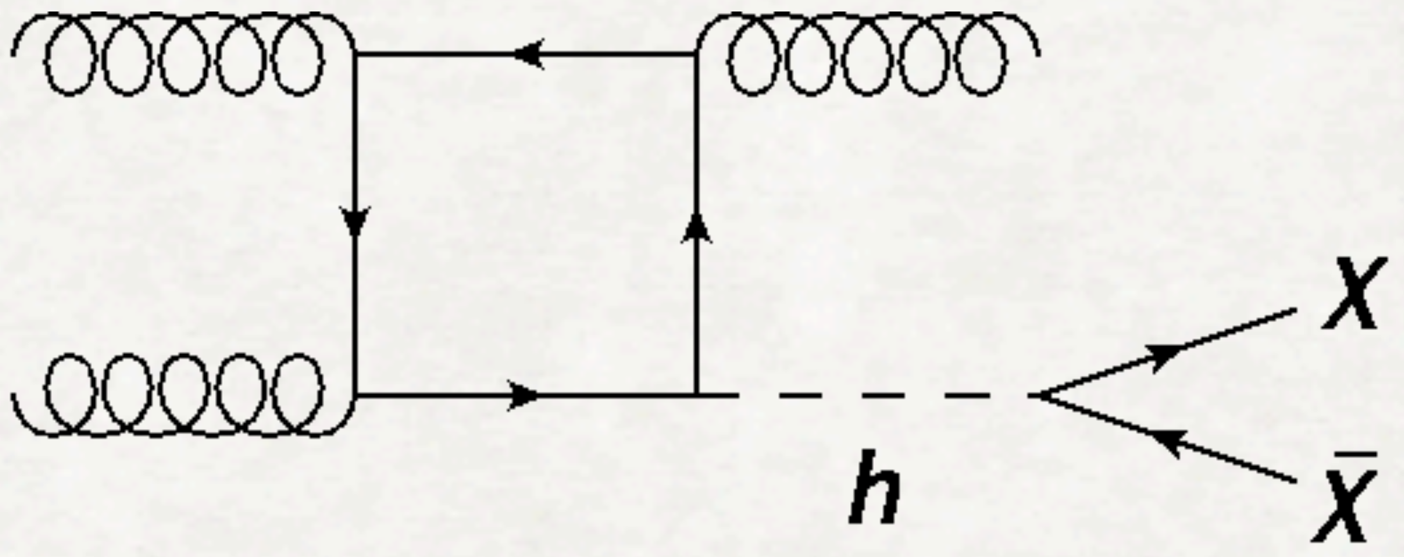
$v = 246\ \mathrm{GeV}$ [NB: in 1112.3299 v/√2 is used]

- ***Formulae from Djouadi et al, 1112.3299***
- DD limits would have to be translated based on formulae in backup

Mono-jet samples

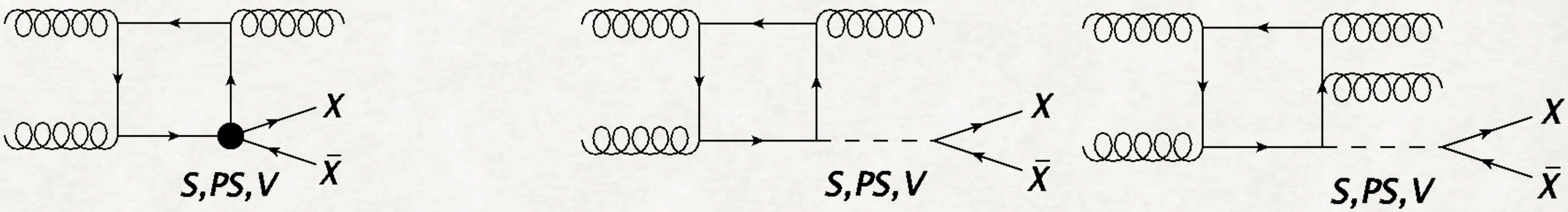
Mono-jet samples for Higgs to invisible

- Mediator is the SM Higgs
- Highest achievable precision wanted
- Recommendations driven by Higgs groups generally following recommendations of LHC Higgs Cross-Section WG published in YR4 1610.07922
- We will not attempt to provide recommendations for SM Higgs samples - for a reference of available calculations see backup

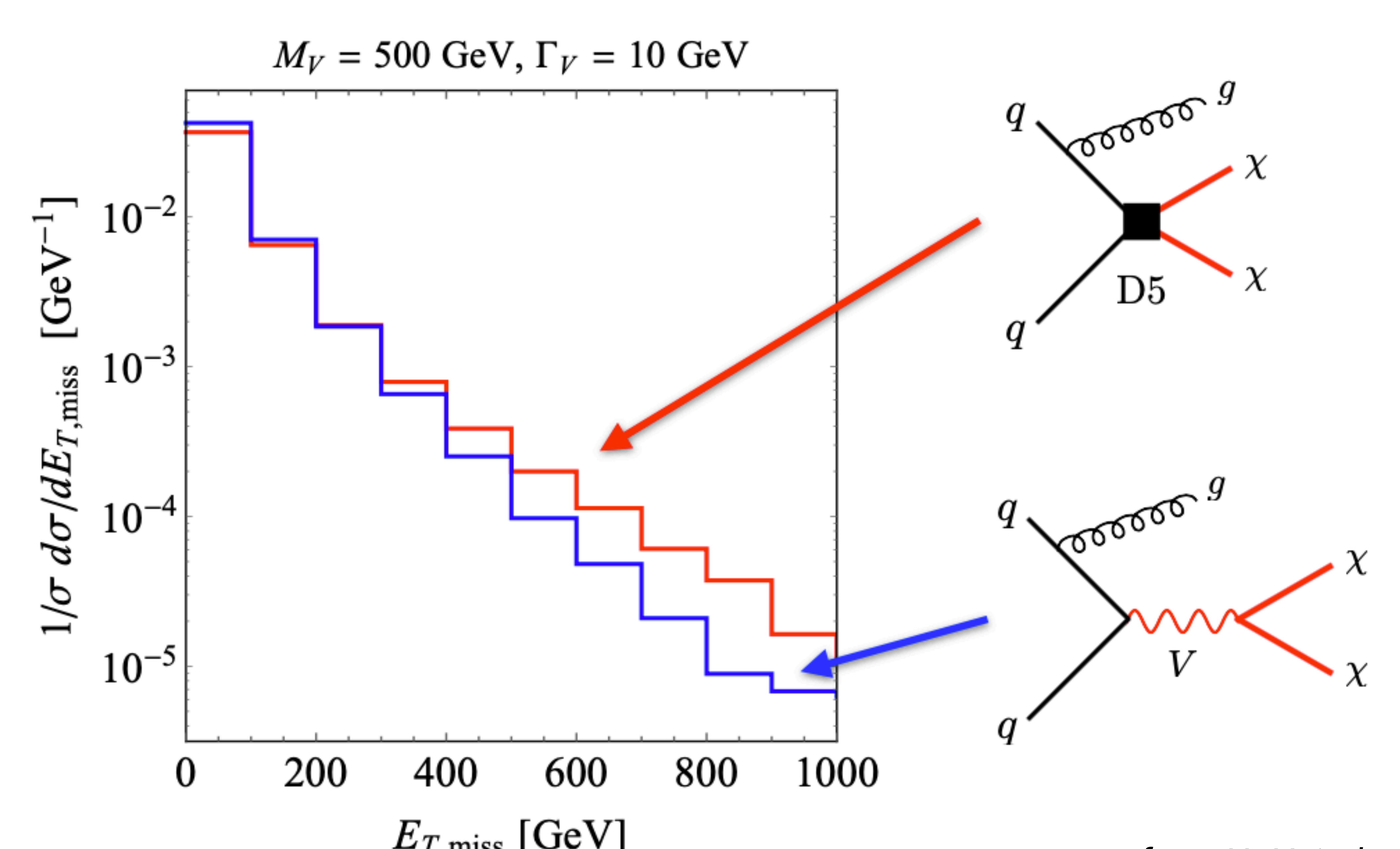


Mono-jet samples for s-channel interpretations

Powheg DMsimp



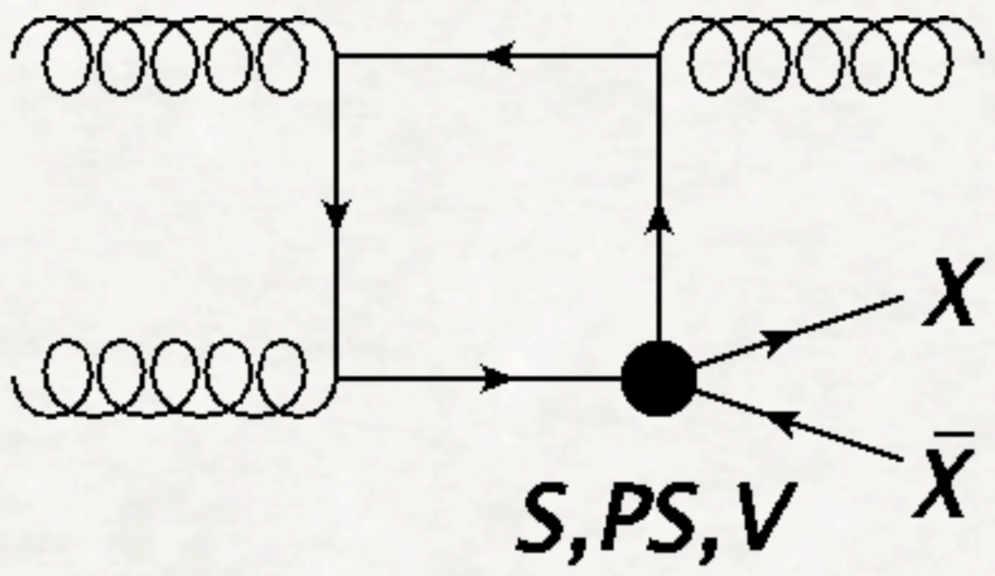
- Important to include finite m_{top} effects
  - infinite m_{top} leads to very hard pT spectrum with differences of O(100%) Haisch, Re, 1503.00691
- 2 calculations with finite m_{top}
  - Powheg (DMV Haisch et al, 1310.4491 , DMS_tloop Haisch et al, 1503.00691) - DM propagator integrated out
  - MG5aMC + DMsimp UFO Backovic et al, 1508.05327 DM propagator kept
- Problems with Powheg implementations:
  - poor description of high p_T region with EFT
  - Powheg can do only 1 jet in the ME



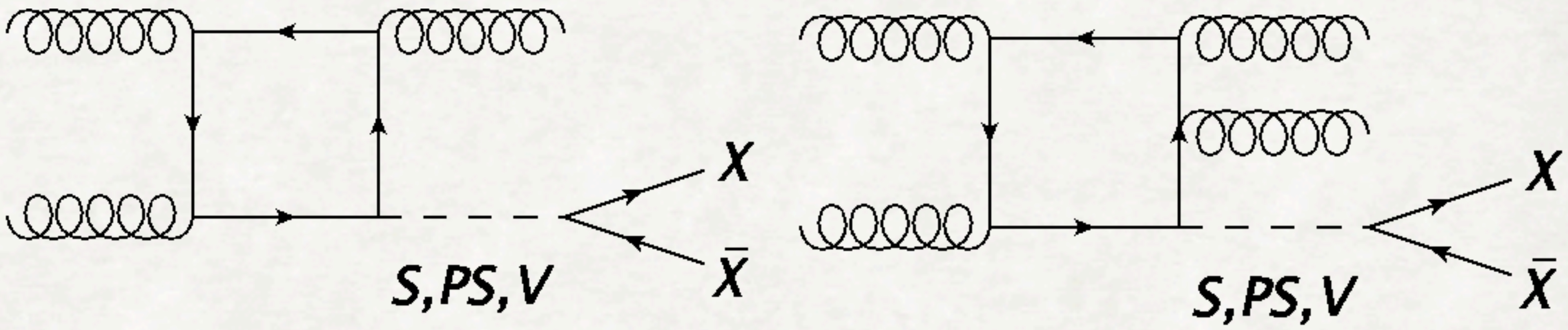
from U. Haisch

Mono-jet samples for s-channel interpretations

Powheg



DMsimp

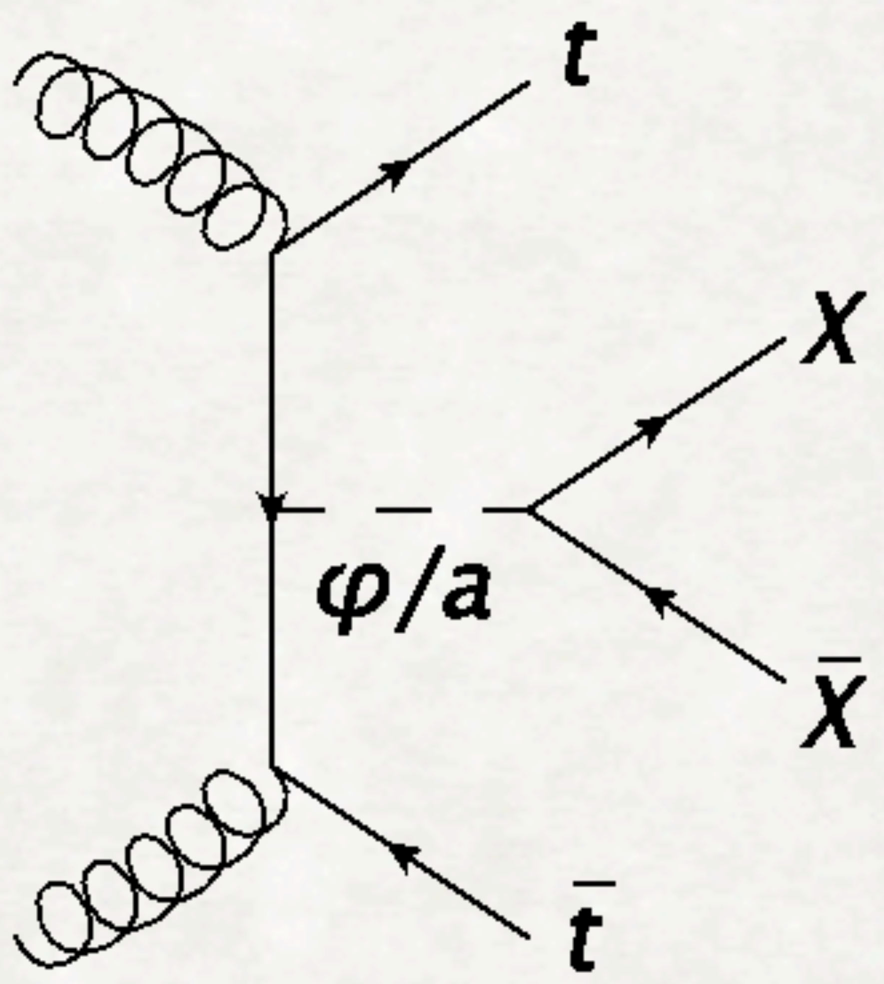


➡ ***Suggestion:*** *switch to DMsimp calculation using multi-jet merging with up to 2 jets @ LO as done in* *Haisch, Polesello, 1812.08129*

- Normalisation can be taken from MG5aMC calculation

Top+E_T^{miss} samples

Top+E_T^{miss} samples for s-channel interpretations

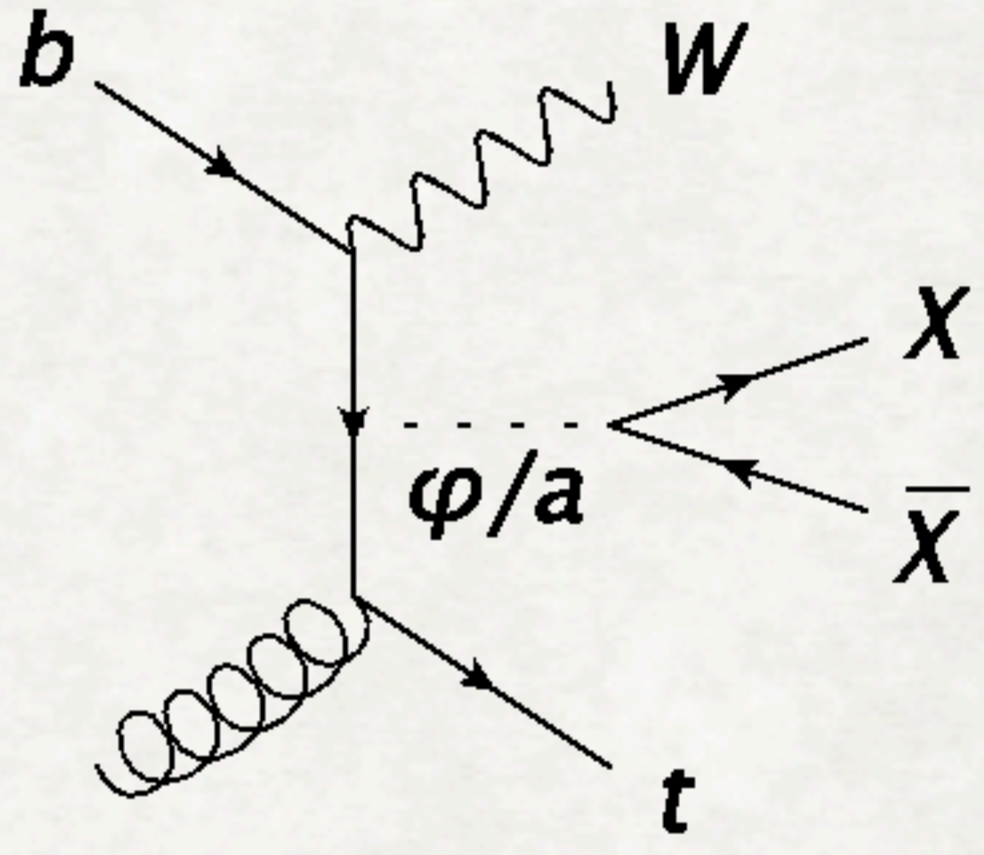


- Current approach:
  - UFO: DMsimp
  - generate tt or tW + χχ with 0+1j @ LO
  - normalisation: calculated from the 0j @ NLO calculation of MG5aMC (α_s^3 for tt+E_T^{miss} and α_s^2 for tW+E_T^{miss})

Suggestions:

➡ **use modified DMsimp UFO and generate 0 + 1j @ NLO** *Haisch, Polesello, 1812.00694*

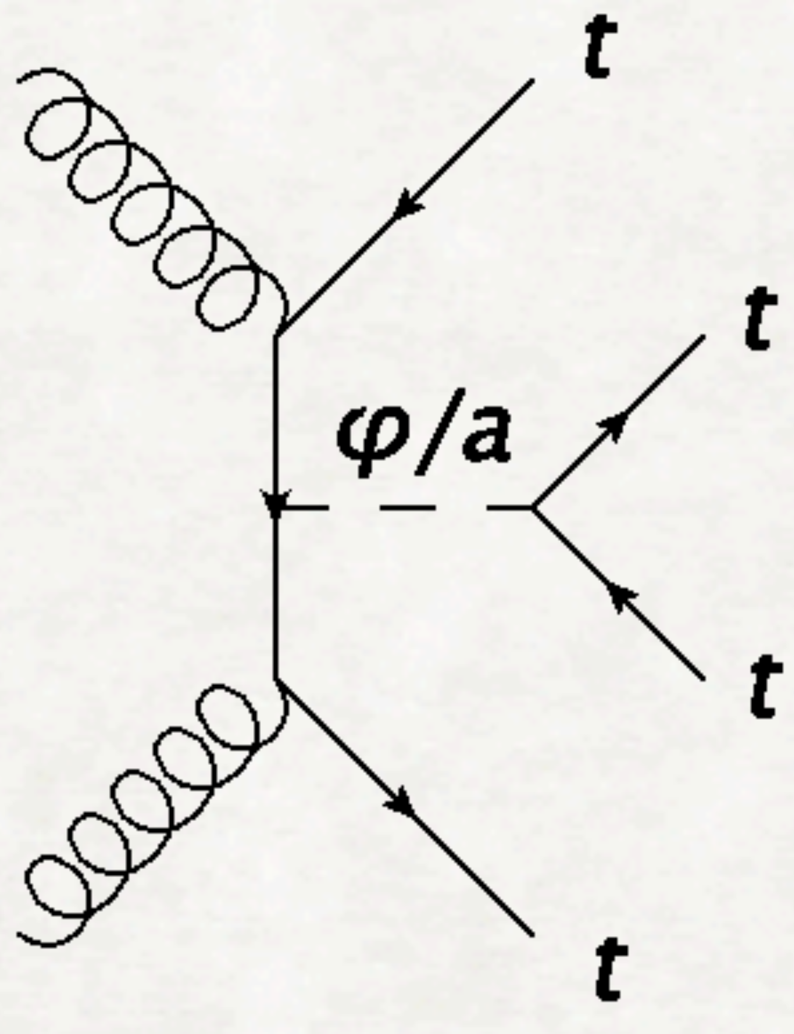
➡ **only include scalar couplings to top** (no ϕbb/ϕWW couplings)



4top samples

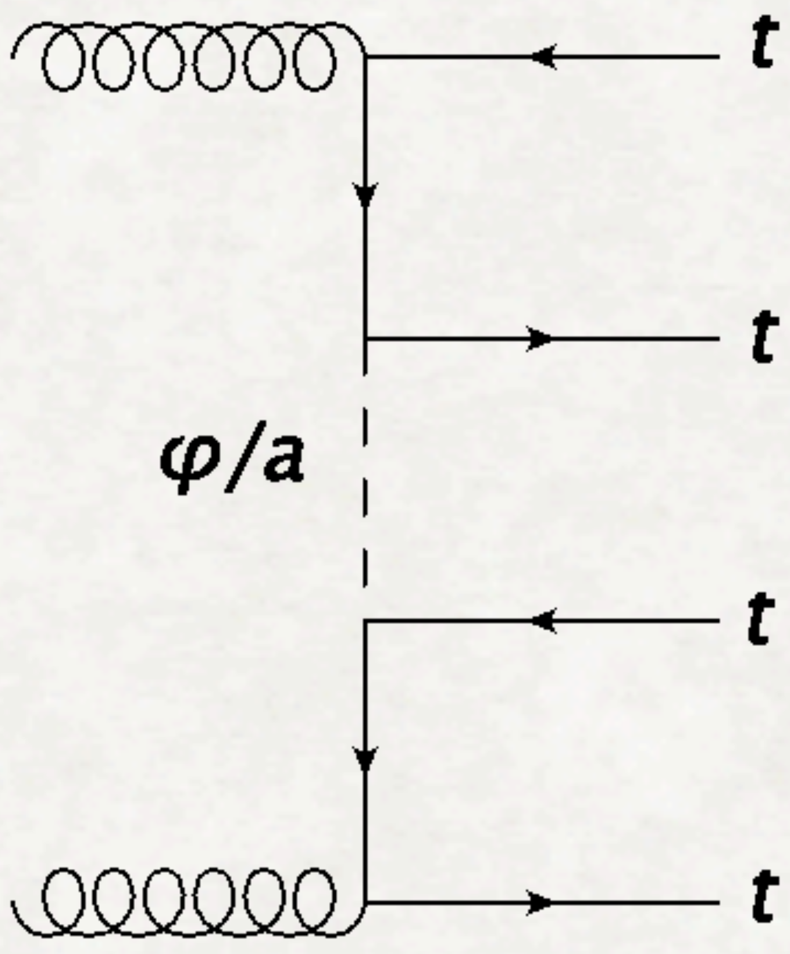
4top sample for s-channel interpretation

- Current prescription:
  - UFO: DMsimp_s_spin0 (1508.05327)
  - use 5 flavour scheme
  - ttϕ+ttϕj generated at LO with subsequent decay of mediator in MadSpin
    - generate p p > t t~ y0 / a z w+ w-
    - add process p p > t t~ y0 j / a z w+ w-
    - decay y0 > t t~
  - normalisation: use normalisation from NLO calculation in MG
    - generate p p > t t~ y0 / a z w+ w- [QCD]



- This misses t-channel contributions

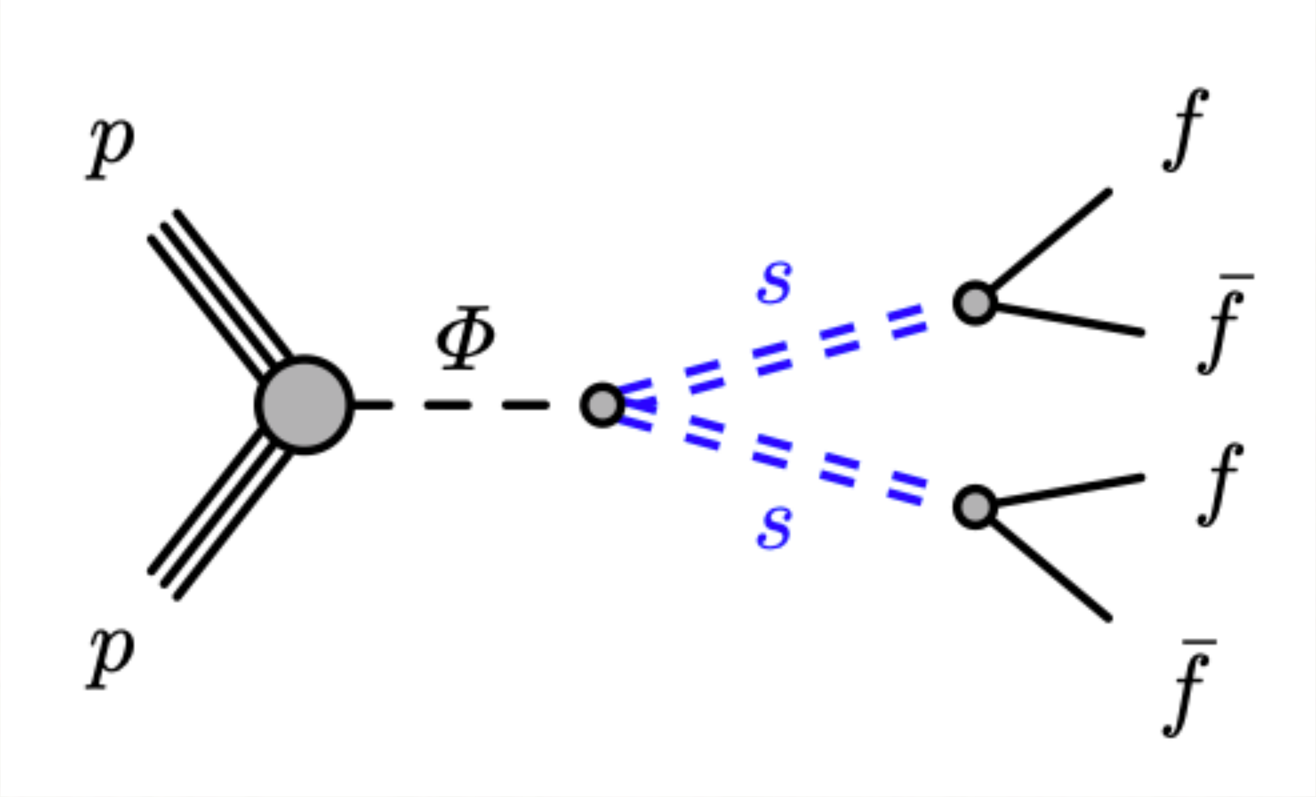
➡ ***Suggestion:*** generate directly 4 top final state
  - generate p p > t t~ t t~ DMS^2==4 QCD^2==4

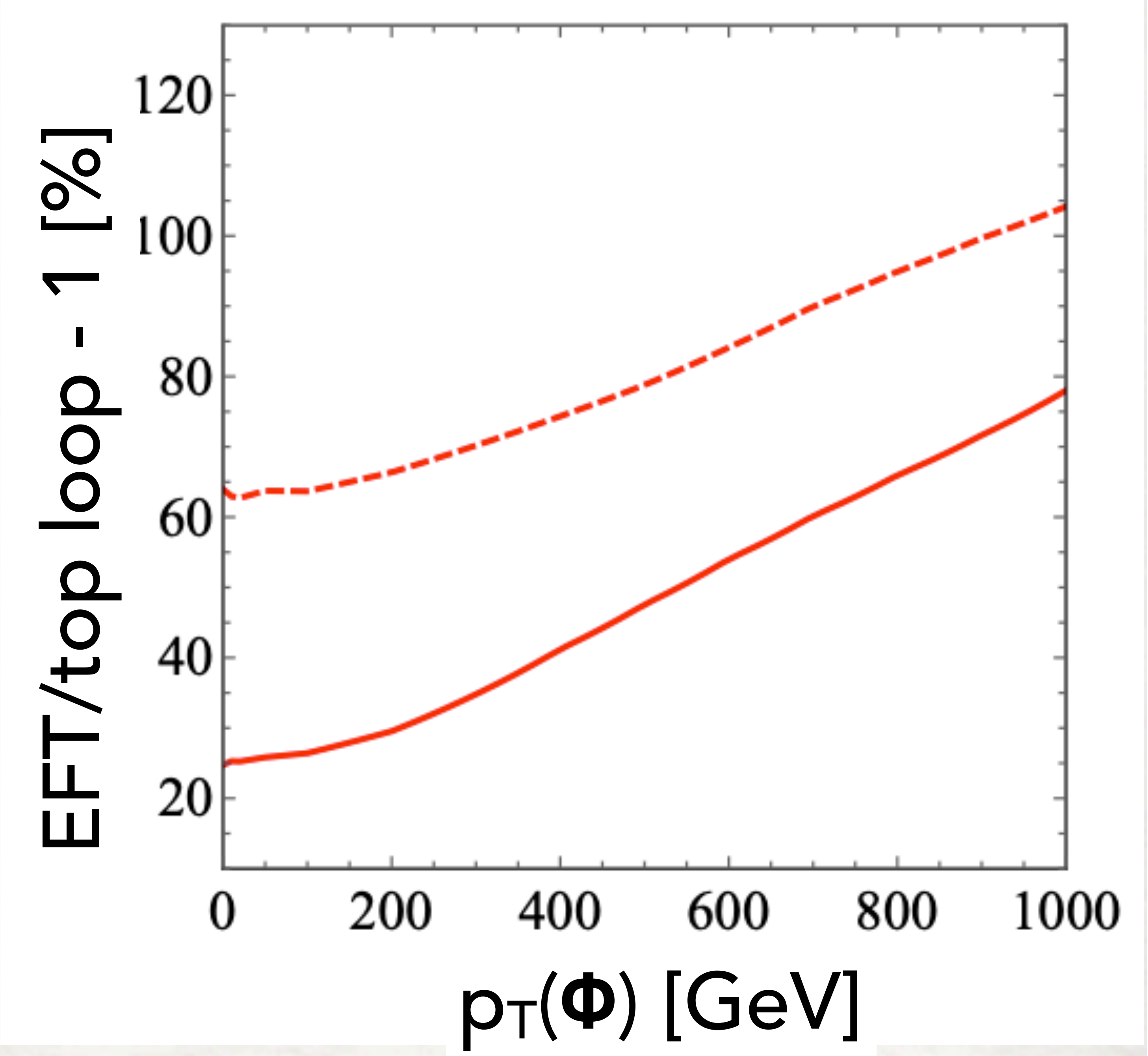


Hidden sector scalars

Long-lived scalars in hidden sector models

- Search for long-lived scalars decaying into fermions using Hidden Abelian Higgs Model [Wells, 0803.1243]
- Hidden $U(1)_X$ spontaneously broken by vev of a new Higgs **Φ** (which is an electroweak singlet) → two real scalars that mix
- Current ggF signal generation [ATLAS, 2203.01009]
  - accuracy: with 0j @ LO
  - infinite m_{top}
  - $p_T(\Phi)$ reweighted to match $p_T(h_{125})$ taken from MG5aMC sample with 0+1+2j @ NLO (FxFx) calculated using HC_NLO_X0_UFO-heft UFO - NB: this again uses infinite m_{top}
- Problems:
  - ◉ infinite m_{top} severely overestimates high $p_T(\Phi)$ yield
  - ◉ ggF-only generation misses important gq channel with different p_T spectrum





[Haisch et al, 1503.00691]

➡ ***Suggestion:*** ***use DMsimp with multi-jet merging***

- generate p p > xr xr [QCD]
- add process p p > xr xr j [QCD]
- add process p p > xr xr j j [QCD]

How to move forward

- We would suggest that both collaborations discuss the suggestions in their respective working groups and provide feedback to us lhc-dmwg-admin@cern.ch

    ➡ volunteers to test feasibility of these suggestions highly welcome!

- Would be good to collect all MG generation commands & UFOs used

- Final recommendations to be fixed soon - will be delivered e.g. via a twiki

Backup

EFT limits on Wilson coeff. vs m_{DM} - DD results

Translate limit on cross-section to limit on Wilson coefficient using:

$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2}$$

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2}$$

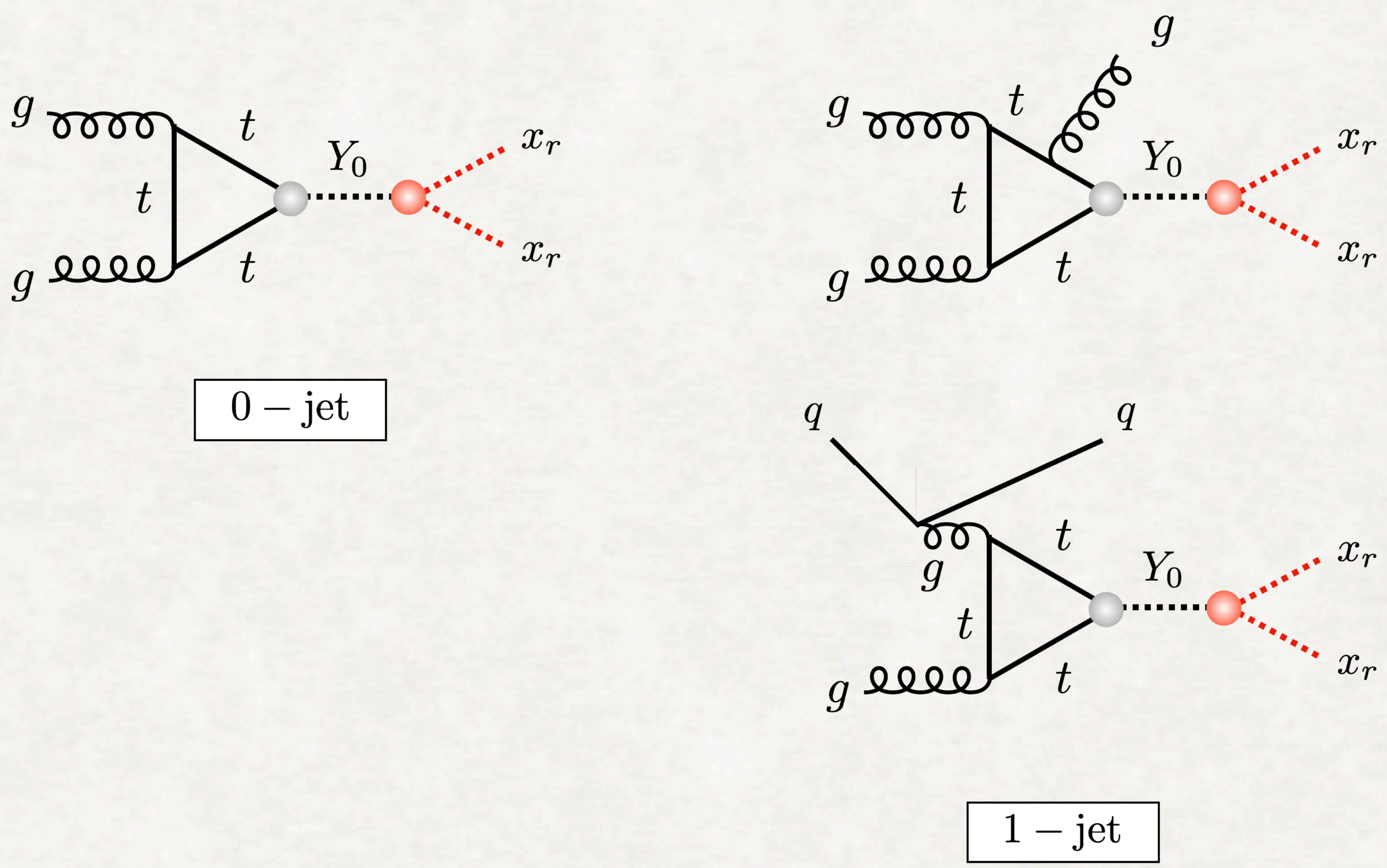
$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2}$$

Formulae from Djouadi et al, 1112.3299

qg contributions for hidden sector LLP samples

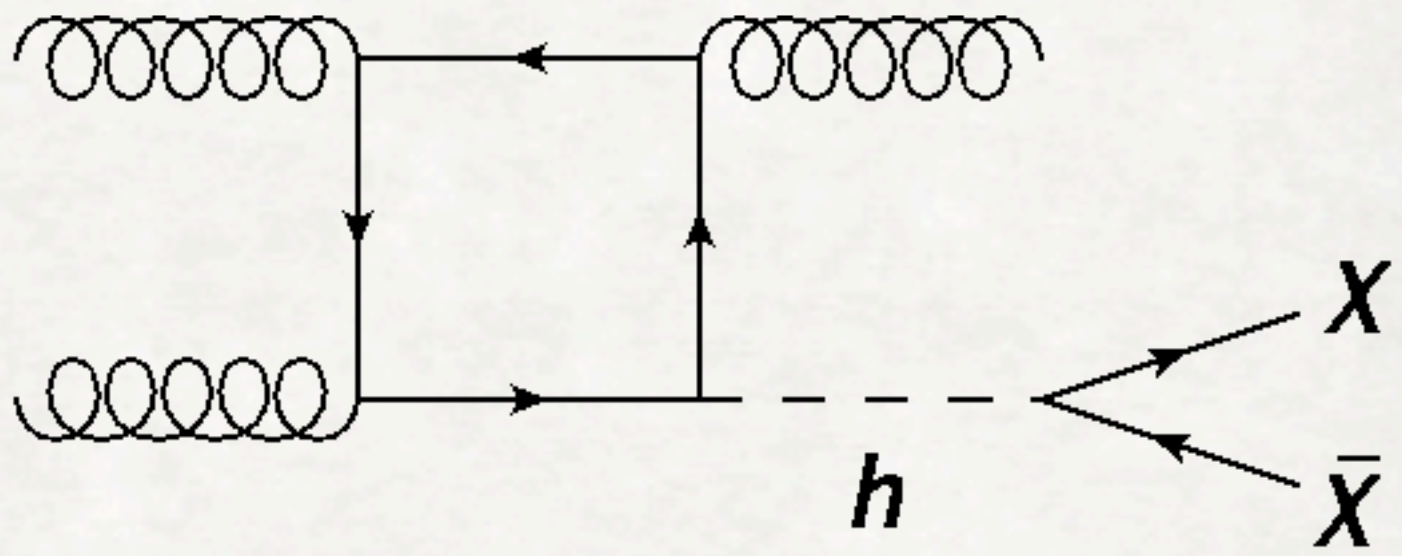
- generate g g > xr xr (j) [QCD] would only give the first row of diagrams

- qg diagrams (2nd row) are not Yukawa suppressed (30% of total cross-section) and has a different p_T spectrum



Mono-jet samples for Higgs to invisible

- Mediator is the SM Higgs - we want highest achievable precision - see recommendations in YR4 1610.07922



- ggF: NNLOPS Hamilton et al, 1309.0017
  - accuracy: 0j @ NNLO + 1j @ NLO + 2j @ LO (α_s^4)
  - quark masses: infinite (current samples) - finite quark mass effects included in Hamilton et al, 1501.04637
  - normalisation: N^3LO+N^3LL QCD + NLO EW Dulat et al, 1802.00827
- VH:
  - NNLOPS only available for WH 1603.01620
  - qq→VH:
    - accuracy: MINLO 0+1j @ NLO (α_s^2) Luisoni et al, 1306.2542
    - normalisation: NNLO QCD + NLO EW 1610.07922
  - gg→ZH:
    - accuracy: Powheg 0j @ LO (α_s^2)
    - quark masses: finite for bottom and top quark
    - normalisation: NLO+NLL QCD Harlander et al, 1410.0217
- ttH:
  - accuracy: Powheg 0j @ NLO (α_s^3) Hartanto et al, https://arxiv.org/pdf/1501.04498.pdf
  - normalisation: NLO QCD+EW 1610.07922
- VBF:
  - accuracy: VBF + 0j @ NLO 0911.5299
    - NLO EW corrections calculated with MG5aMC
    - NB: higher accuracy samples simulations exist: VBF + 1j @ NLO (α_s^3) Jager et al, 1405.6950
  - normalisation: NNLO QCD + NLO EW 1610.07922