Scalar Simplified Models for Dark Matter

arXiv: 1410.6497 M. Buckley, D. Feld, DG

CMS-IPPP workshop: DM at colliders
December 9th 2014 Bristol

Dorival Gonçalves

Outline

- Scalar Simplified Models for Dark Matter
    - EFT ⟶ Full Theory ⟶ Full Theory with heavy quark mass effects
- Combining different jet bins with their heavy quark mass dependence
    - Scalar/pseudoscalar + jets MEPS merging @LO & @NLO$_{approx}$
- Collider bounds: Monojets, tops(bottoms)+MET

Beyond Effective Operators

- Bottom-up approach: Model independent searches for New Physics

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i^{Dim6} + \ldots$$

- Despite its simplicity, the DM EFT @LHC rules out rather "baroque theories" of DM
  - Validity $\Lambda > 1$TeV → $c_i >> 1$ unnatural
  - General problem for the EFT collider constrains:

    Λ^{-2} terms need to be smaller than Λ^{-4} terms…

Buchmueller, Dolan, McCabeb (2013)
Busoni, Simone, Morgante, Riotto (2013)
Haisch, Hibbs, Re (2013)
…

- Bottom up beyond EFT: t-channel mediator (must be coloured)

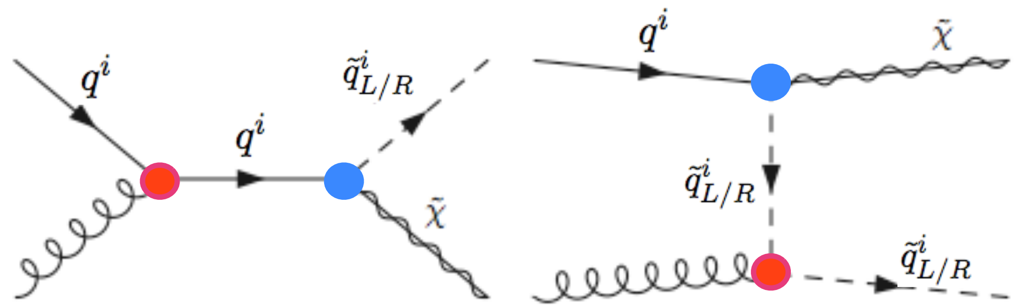
  s-channel mediator (colour neutral)

Beyond Effective Operators

- **t-channel -** Similar to SUSY $pp \to \tilde{q}\tilde{\chi}$:

DiFranzo, Nagao, Rajaraman, Tait (2013)
Papucci, Vichi, Zurek (2014)

Flavor-locked & semi-weak process sensitive to $q\tilde{q}\tilde{\chi}_1$ coupling: $\sigma^{LO} \sim \mathcal{O}\left(\alpha_{EW}\alpha_s\right)$

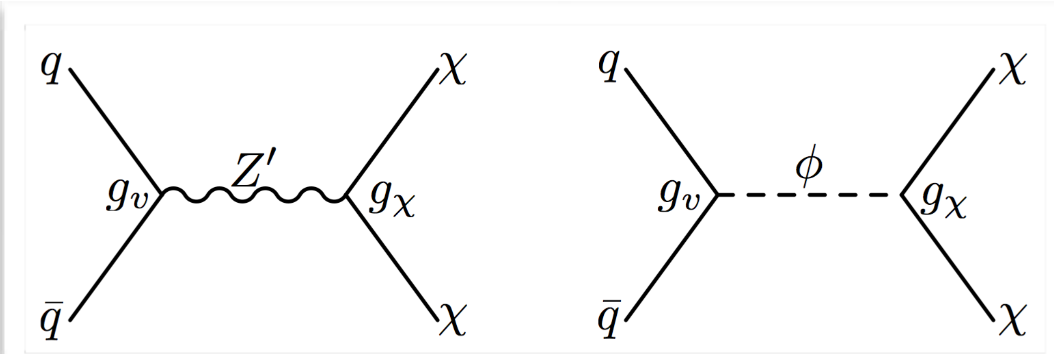


- In SUSY couplings size correlated with SUSY breaking

  Possible to identify Bino, Wino or Higgisino-like neutralino

Binoth, D. Goncalves, Lopez-Val, Mawatari, Plehn, Wigmore (2011)
Allanach, Grab, Haber (2010)

- **s-channel -** New resonance with couplings to dark matter and SM particles



Goodman, Shepard (2011)
Frandsen, Kahlhoefer, Preston,Sarkar,Hobergt (2012)
Haisch, Hibbs, Re (2013)
Buchmueller, Dolan, McCabeb (2013)
Buckley, Feld, DG (2014)
Harris, Khoze, Spannowsky, Williams (2014)
...

Scalar Simplified Models for DM

- Dark matter communicating to Standard Model through scalar/pseudoscalar mediators

  "Easy" to accommodate in extended Higgs sectors (2HDM, NMSSM, …)

$$\mathcal{L}_S = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - g_\chi\phi\bar{\chi}\chi - \sum_{\rm fermions} g_v y_f \phi \bar{f} f \,,$$
$$\mathcal{L}_A = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu A)^2 - \frac{1}{2}m_A^2 A^2 + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi - ig_\chi A\bar{\chi}\gamma^5\chi - \sum_{\rm fermions} ig_v y_f A\bar{f}\gamma^5 f.$$

- Fermionic couplings proportional to the SM Yukawas (y_f) - MFV avoids Flavor constrains

- Minimal model 5D: $\boxed{m_{\phi(A)},\ m_\chi,\ g_v,\ g_\chi,\ \Gamma_{\phi(A)}}$

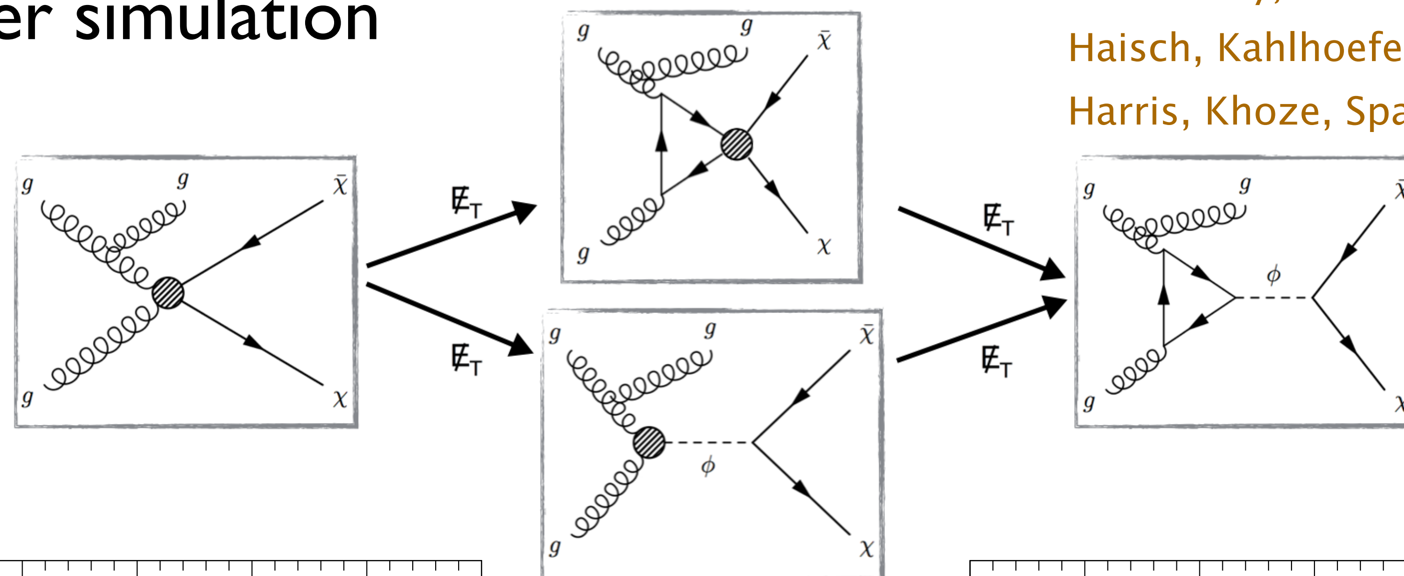
  We keep Γ free to allow possible extra decay modes

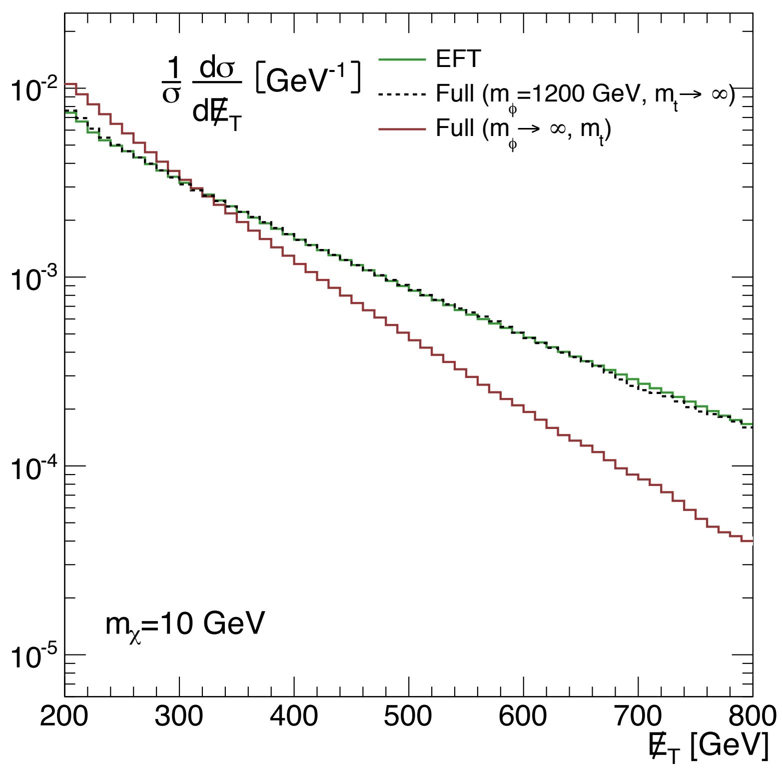
- **Collider bounds** - I will show bounds from existing searches:
  - **"Monojets":** $pp \to \not\!\!E_T + j(j)$
  - **Tops+MET:** $pp \to \not\!\!E_T + t\bar{t}$
  - **Bottoms+MET:** $pp \to \not\!\!E_T + b\bar{b}$

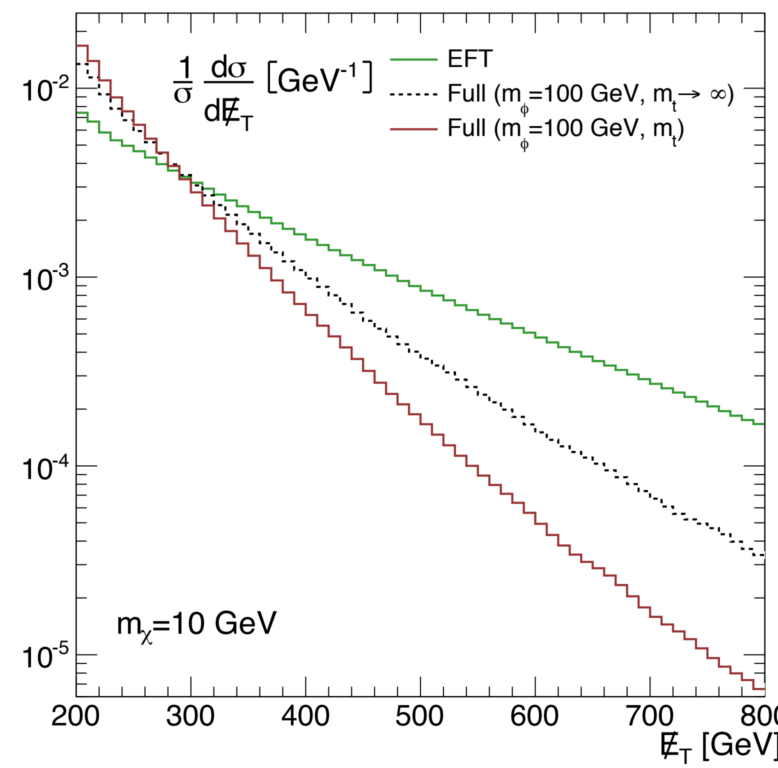
Scalar Simplified Models for DM

- Monojets: Collider simulation

M. Buckley, D. Feld, D. Goncalves (2014)
Haisch, Kahlhoefera, Unwin (2013)
Harris, Khoze, Spannowsky, Williams (2014)

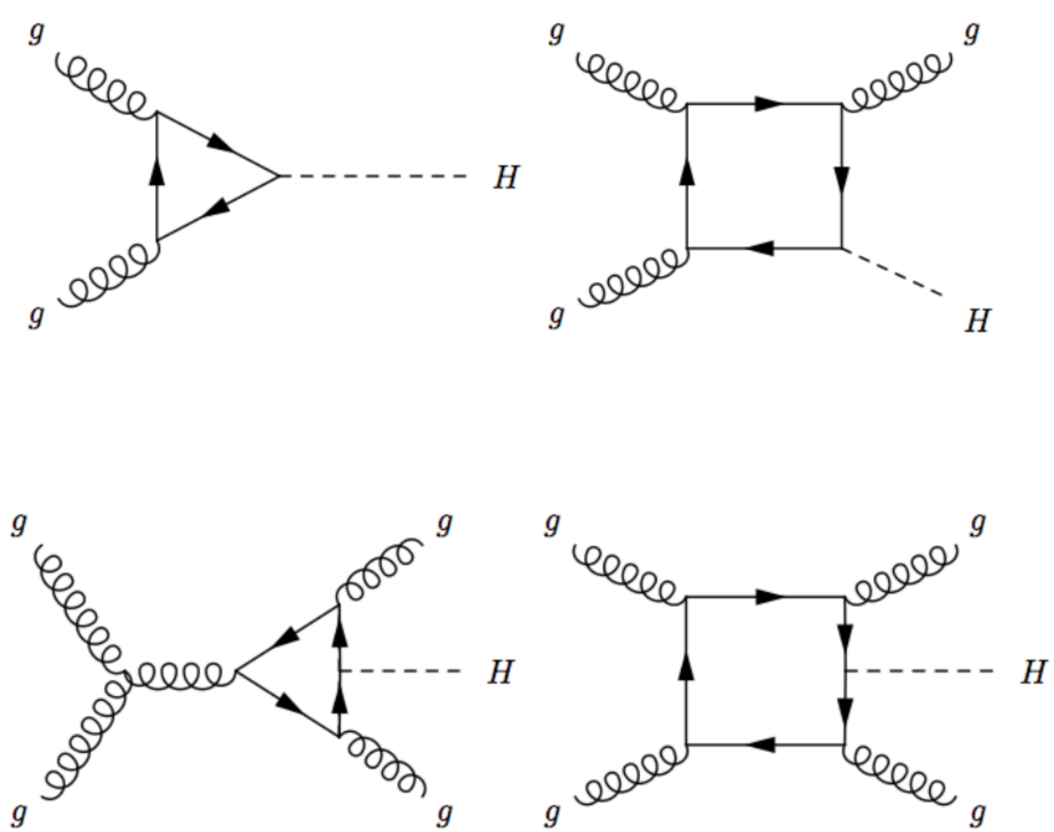


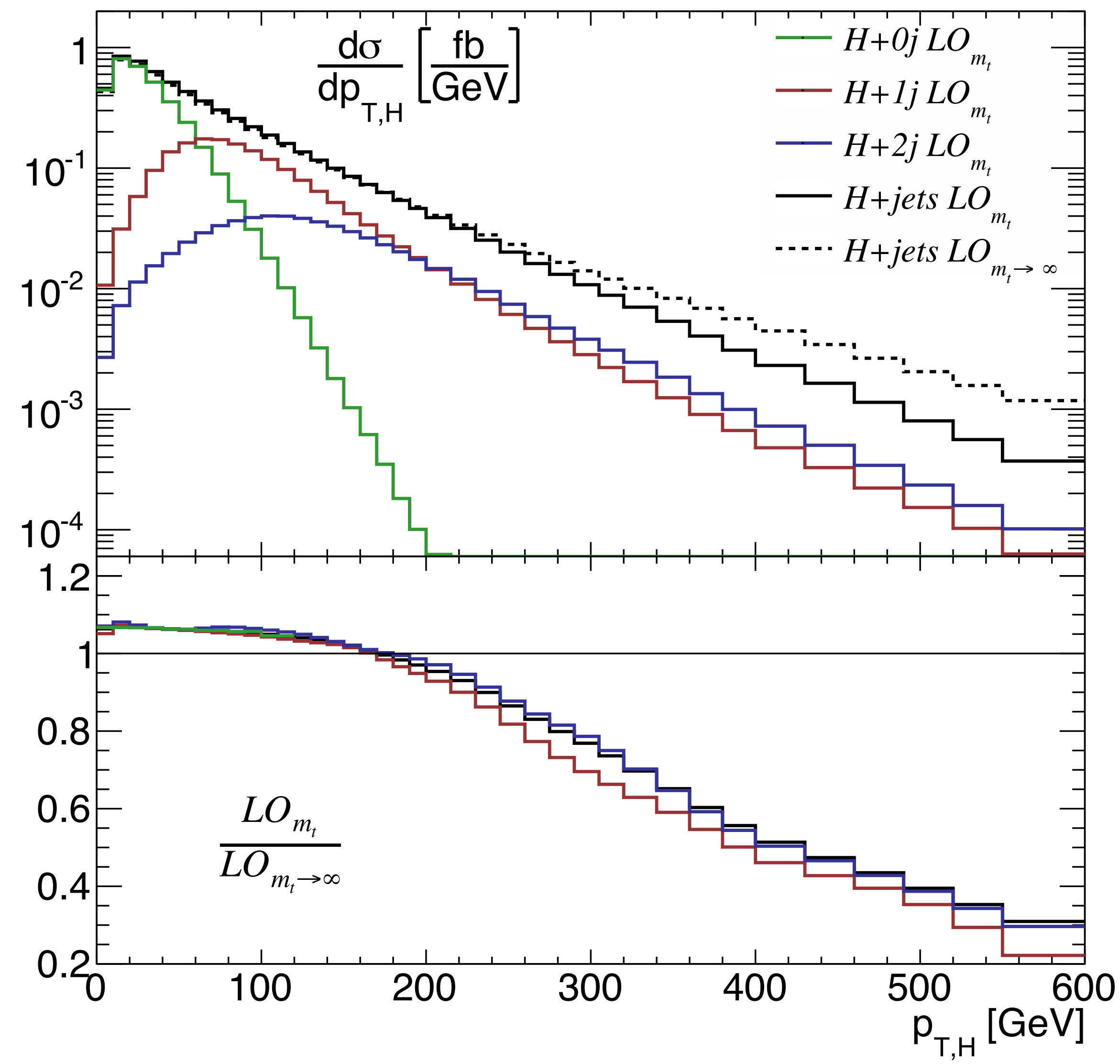




- Top mass effects need to be included for the CMS analysis. Most sensitive bins $\not{E}_T$ >350GeV
- Extended MCFM to off-shell mediators and to produce lhe events for shower in Pythia8

Top mass effects: H+jets CKKW merging

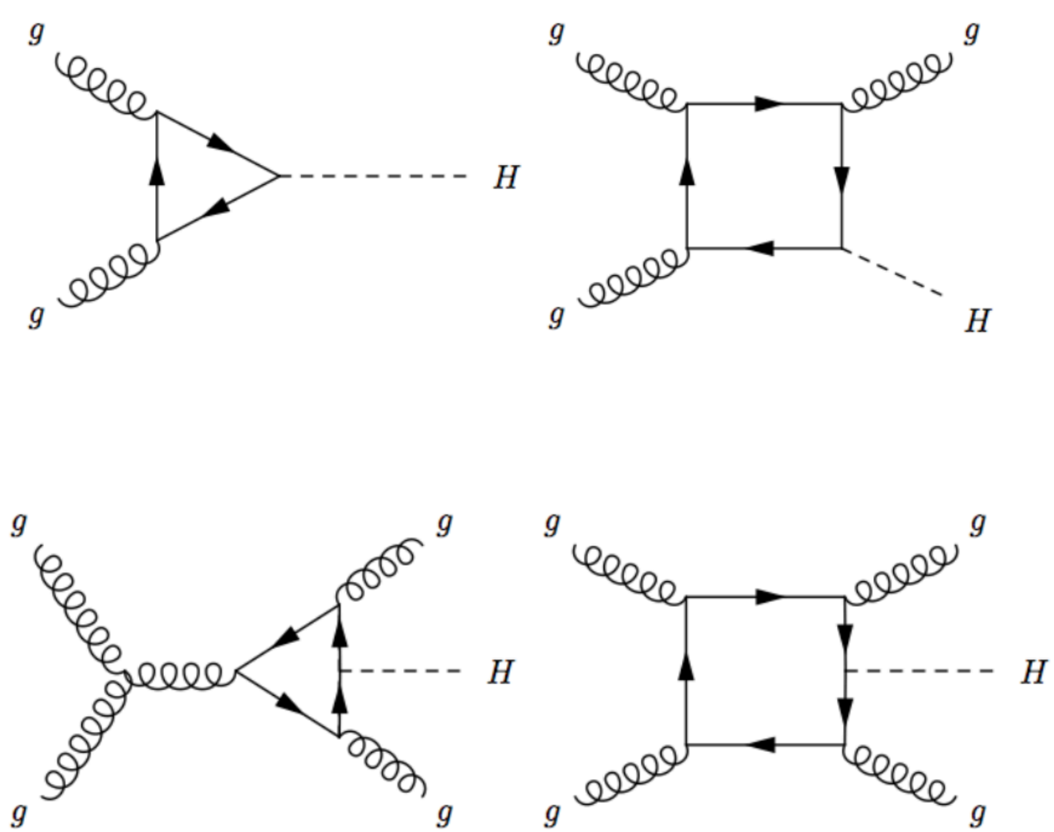


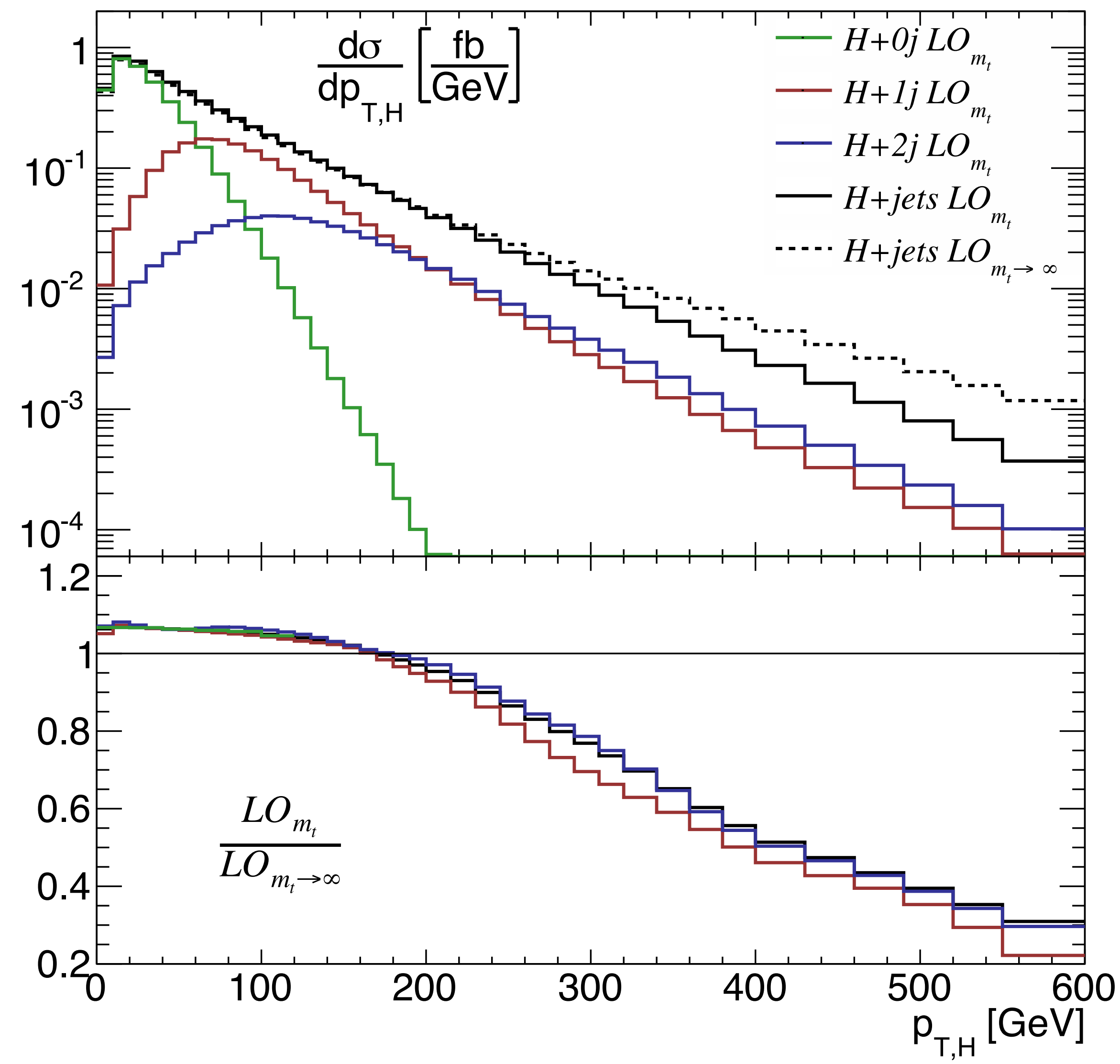


M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn (2014)

- Hj and Hjj signal have about the same size for boosted Higgs
- HEFT and Full scale on the same way for $p_{T,H} < m_t$
- $p_{T,H} < m_t \rightarrow$ constant scaling factor 1.065 for the Higgs–gluon coupling

Top mass effects: H+jets CKKW merging





M. Buschman, DG, F. Krauss, S. Kuttimalai, M. Schonherr, T. Plehn (2014)

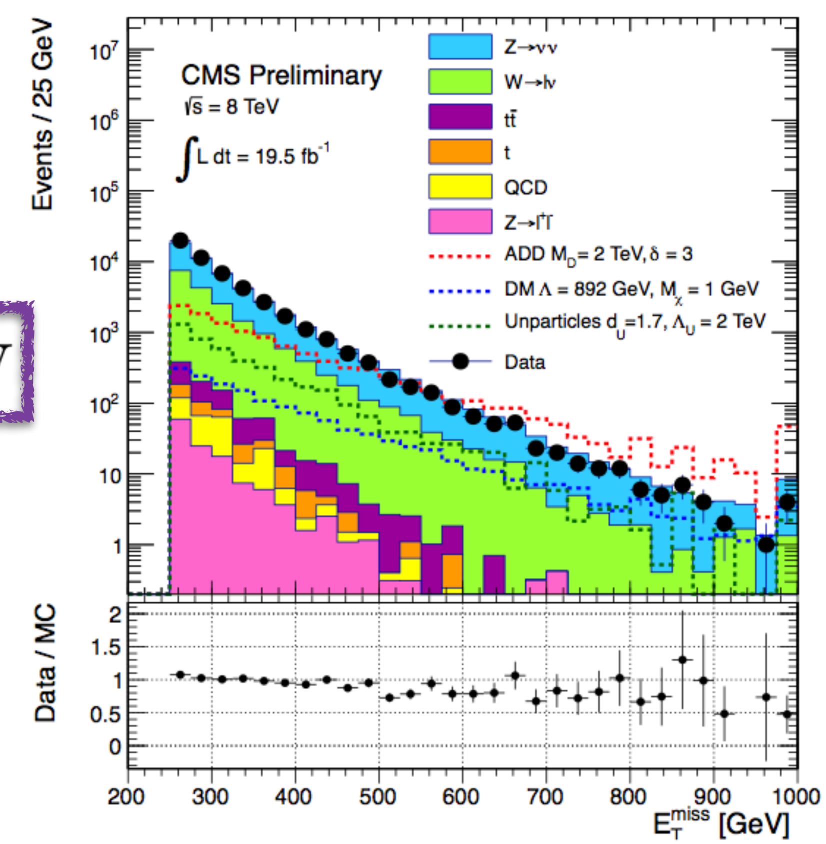
- Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV
- Each jet multiplicity has approximately same top mass correction
- Consequently the same happens for the merged result

Search: Monojets

- "Monojets" searches:
  - Benchmark with CMS 20 fb^{-1} search (1408.3583)
  - Trigger on $\not\!\!E_T > 120$ GeV or $p_{T,j} > 80$ GeV, $\not\!\!E_T > 105$ GeV and then require 1 jet with $p_{T,j} > 110$ GeV
    - 2nd jet allowed, no more than 2 with $p_{T,j} > 30$ GeV
    - 7 signal bins with

$$\not\!\!E_T > 250,\ 300,\ 350,\ 400,\ 450,\ 500,\ 550\ \text{GeV}$$

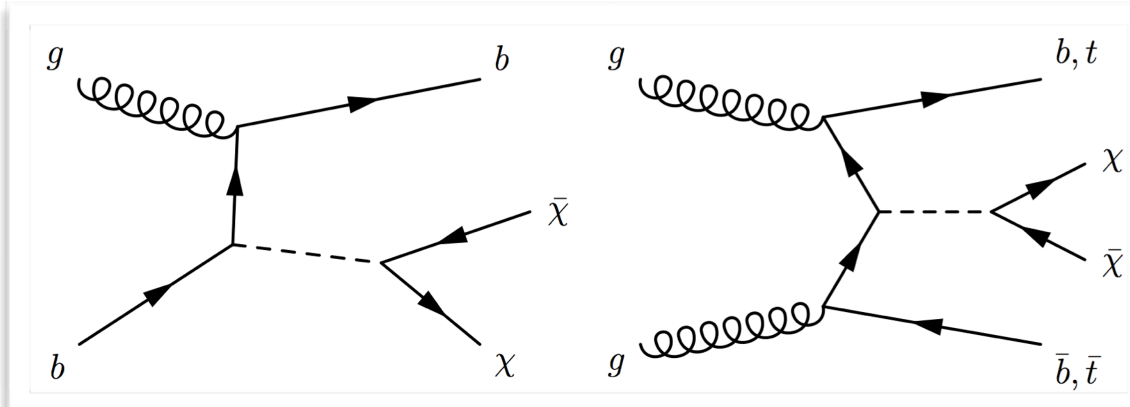
  - CMS very helpfully gives enough information on backgrounds to plot 95% confidence levels for new physics models



CMS EXO-12-048/1408.3583

Search: Heavy flavour + MET

- **Heavy flavor + MET:** Tree level couplings



➡ **Tops + MET:** dilepton+MET channel

Benchmark CMS B2G-13-004 (EFT)

$$\not{E}_T > 320 \text{ GeV}, \ |p_{T,j_1}| + |p_{T,j_2}| < 400 \text{ GeV}, \ |p_{T,\ell_1}| + |p_{T,\ell_2}| > 120 \text{ GeV}$$

➡ **Bottoms + MET:** Recently ATLAS published arXiv:1410.4031

dedicated search for DM produced in associated with b-tagged jets

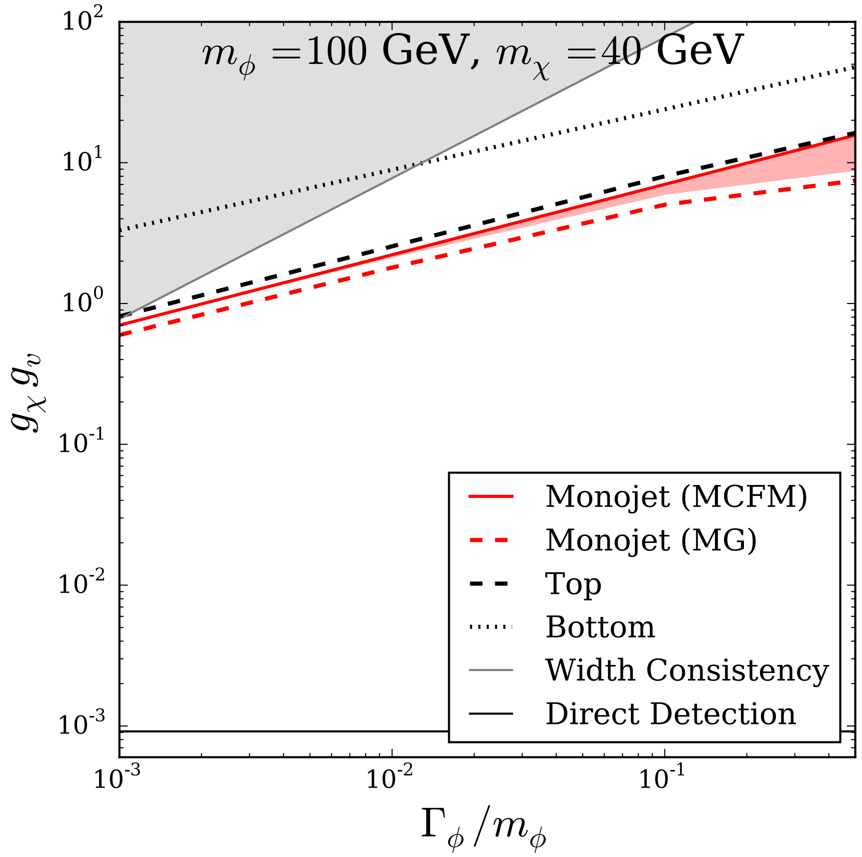
$$\not{E}_T > 300\,GeV, \, \Delta\phi_{j\not{E}_T} > 1, p_{Tj} > 100GeV$$

- Simulated with MadGraph5_aMC@NLO

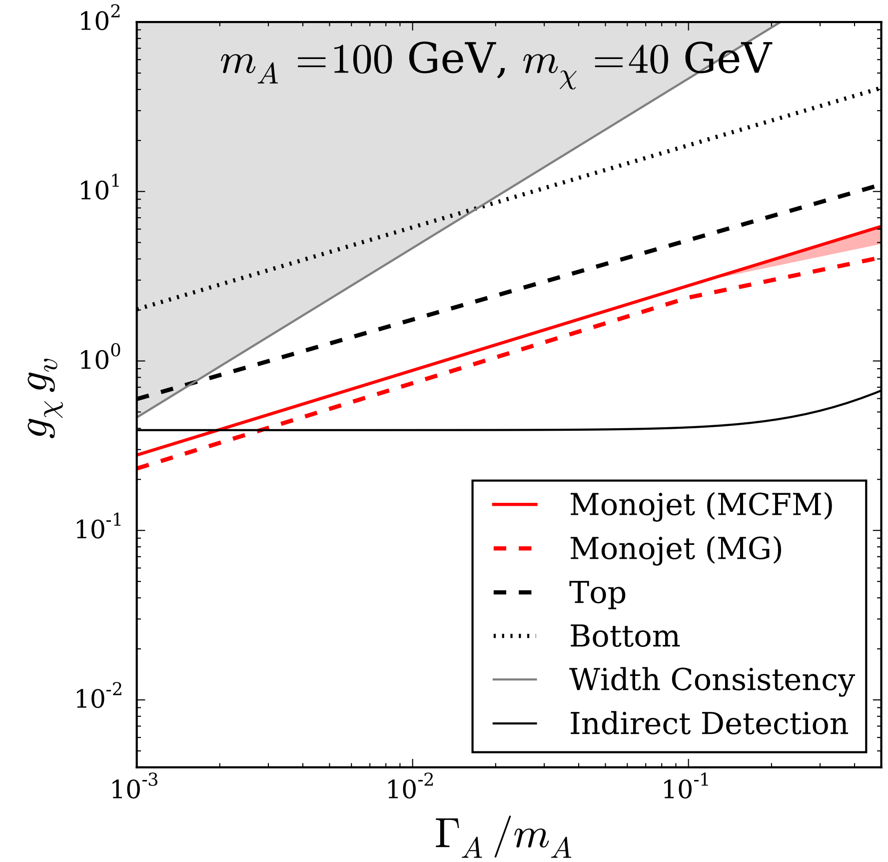
Scalar Bounds

- Full simulation gives a completely different bound in the monojet analysis and it is much weaker

Scalar mediator



Pseudoscalar mediator



- Linear dependence in the monojet curve. Scales like narrow width approximation
- Width consistency - minimum value of the product $g_\chi g_v$ which would allow:

$$\Gamma_{\phi(A)} > \frac{g_\chi^2 m_{\phi(A)}}{8\pi}\left(1-\frac{4m_\chi^2}{m_{\phi(A)}^2}\right)^{n/2} + \sum_f \frac{g_v^2 y_f^2 m_{\phi(A)}}{16\pi}\left(1-\frac{4m_f^2}{m_{\phi(A)}^2}\right)^{n/2}$$

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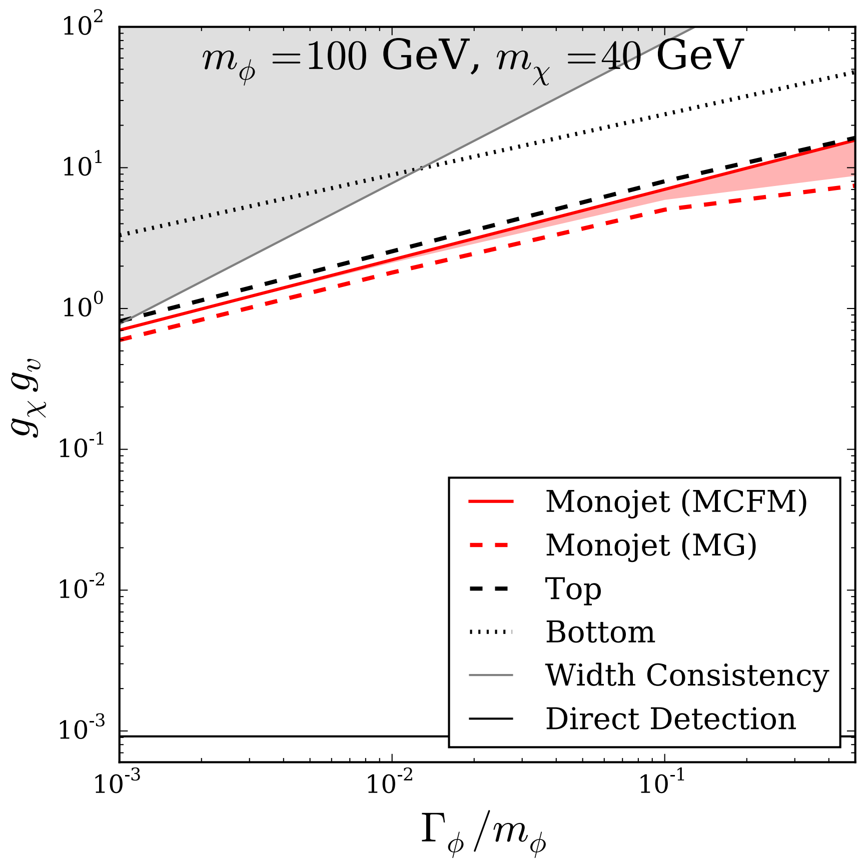
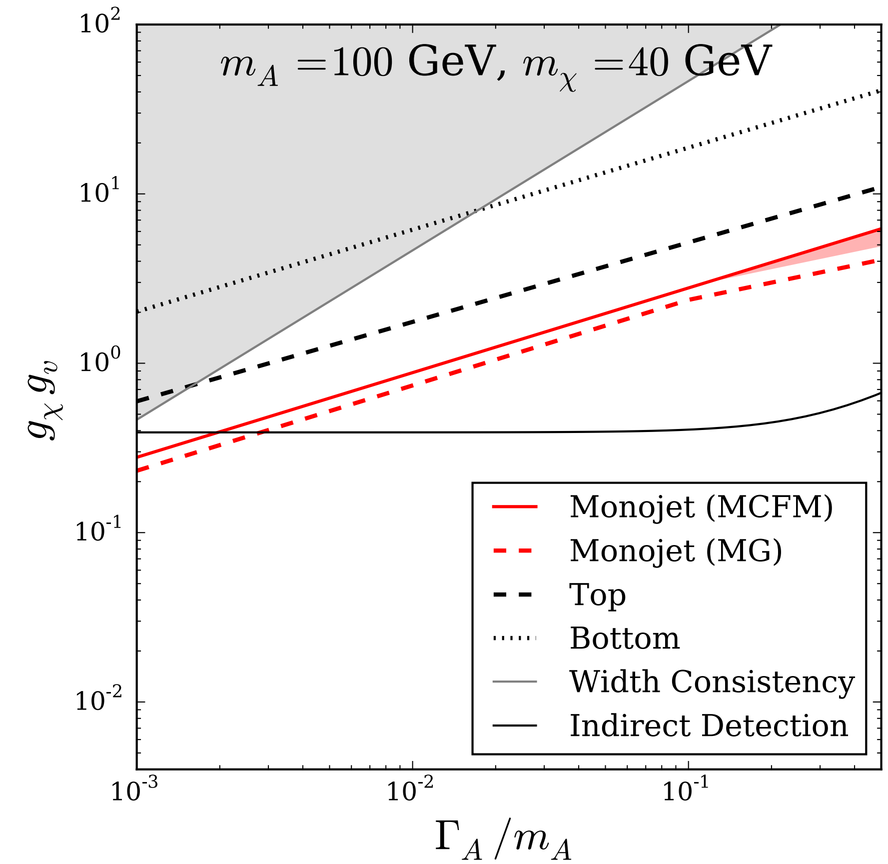
Scalar mediator



Pseudoscalar mediator



- We keep the total width a free parameter. Bounds on $g_v * g_\chi$ vs $\Gamma_{\phi(A)}/m_{\phi(A)}$

→ **Primary effect:** decrease/increase in signal rate $\propto BR(\phi \to \chi\chi)$

→ **2nd order effect:** for very large widths, change in experimental acceptance

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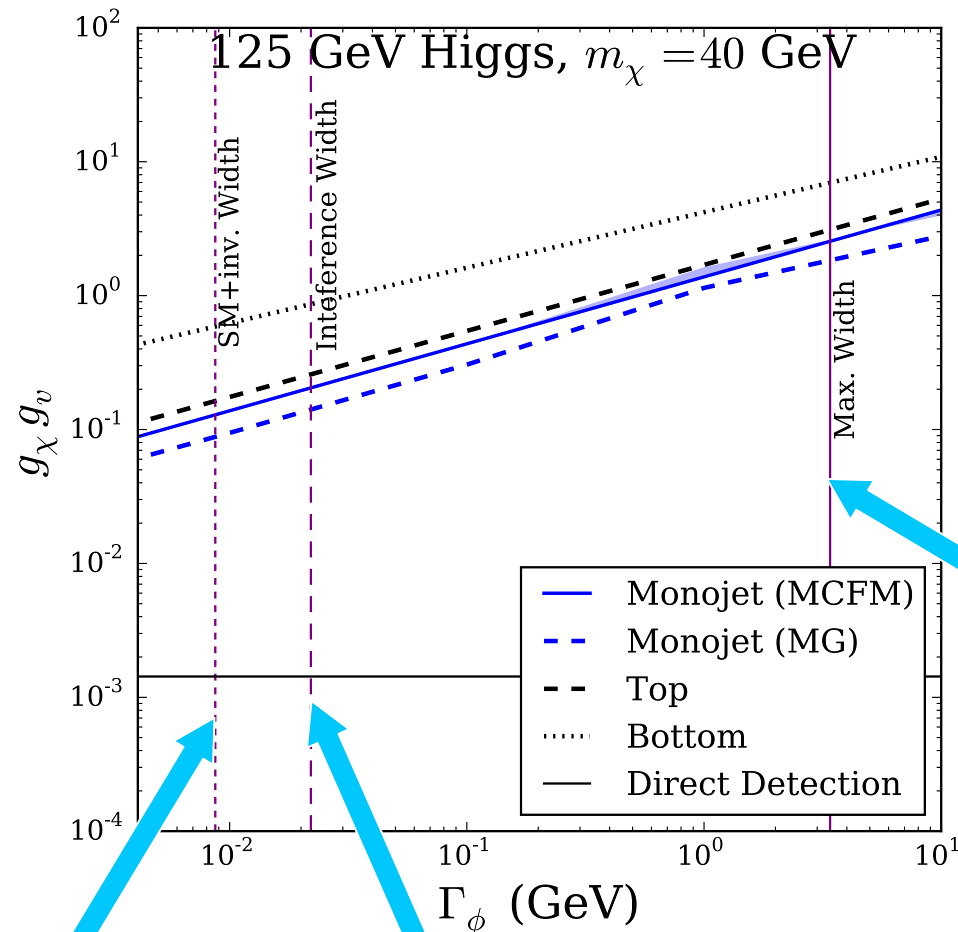
Higgs mediator

- We can play the same game with the Higgs: "Higgs to invisible"

  But here we know a "bit" more about the mediator



direct measurement $h \to ZZ^* \to 4l$

$\Gamma_h < 3.4$ GeV [CMS]

invisible branching ratio must be less than 0.54 at 95% CL [CMS]

Off shell width measurement in the ZZ>4l

$\Gamma_h < 17.4$ MeV (Not completely model independent)

Caola, Melnikov (2013)

Kauer, Passarino (2012)

Campbell, Ellis, Williams (2014)

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Summary

- Simplified models: model independent while still accessing information in multiple channels
- Scalar/pseudoscalars mediators are one of the most interesting and well motivated scenarios
- Mediator width: primary effect $\Longrightarrow$ simple change in the signal rate
- Heavy quark mass effects need to be accounted by EFT & Full Theory at the boosted regime
- Heavy quark mass effects can be described via CKKW merging up to 2-jets in Sherpa+Openloops

Scalar Bounds

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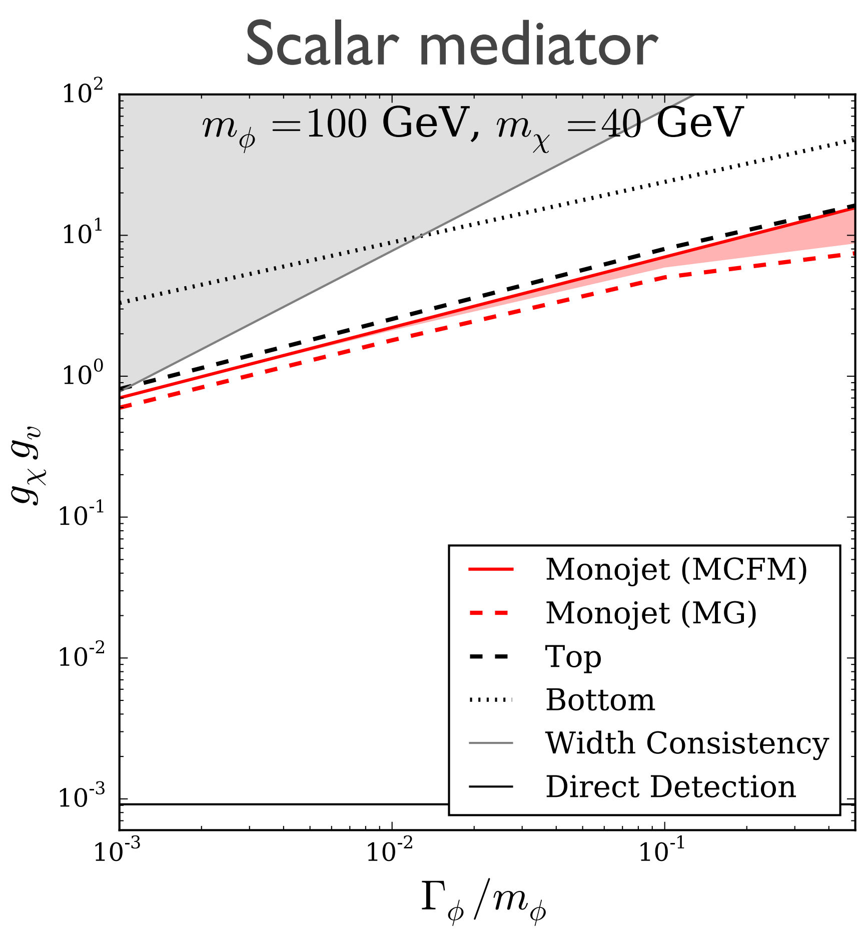

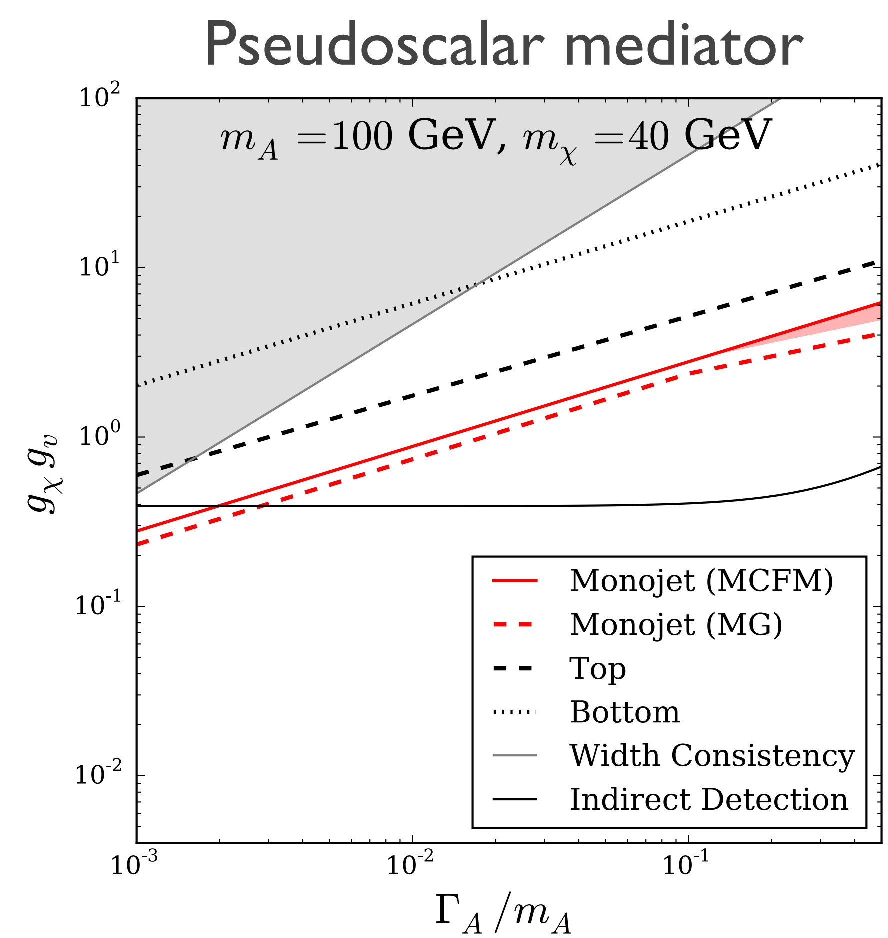

- The pseudoscalar model has no velocity or momentum independent scattering cross section with protons and neutrons

-> no significant limits from **direct detection**. Strong bounds come from LUX (m<6GeV) and CDMS-lite (m>6GeV)

$$\sigma_{\chi-p,n} = \frac{\mu^2}{\pi} f_{p,n}^2,$$

$$f_{p,n} = \sum_{q=u,d,s} f_q^{p,n} \frac{m_{p,n}}{m_q} \left(\frac{g_\chi g_v y_q}{\sqrt{2} m_\phi^2} \right) + \frac{2}{27} f_{TG}^{p,n} \sum_{q=c,b,t} \frac{m_{p,n}}{m_q} \left(\frac{g_\chi g_v y_q}{\sqrt{2} m_\phi^2} \right)$$

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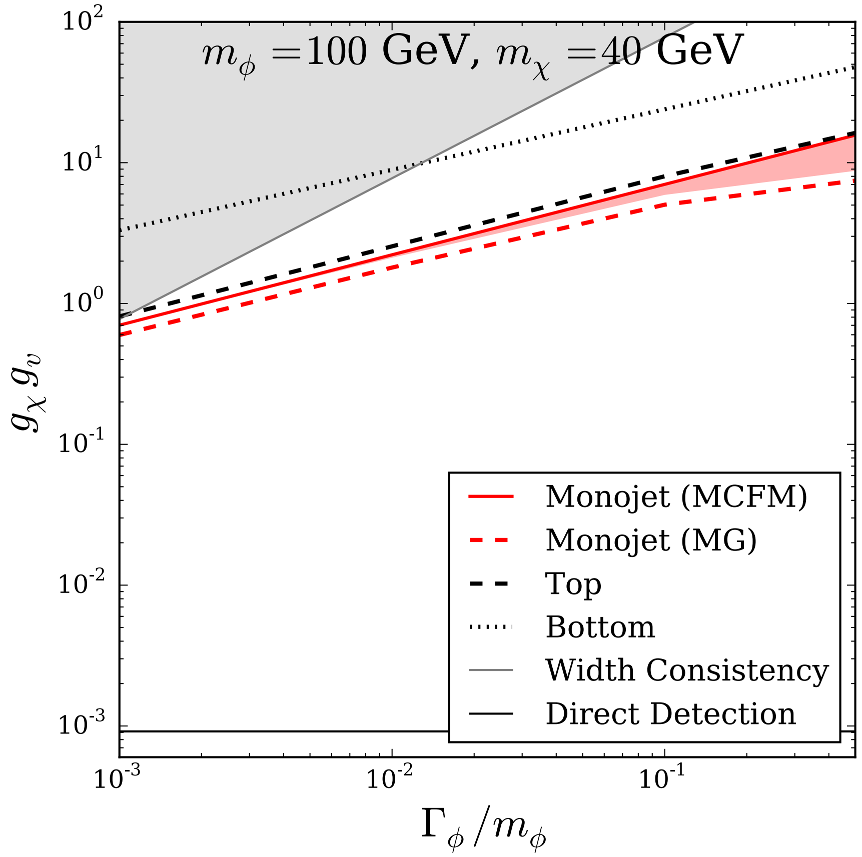
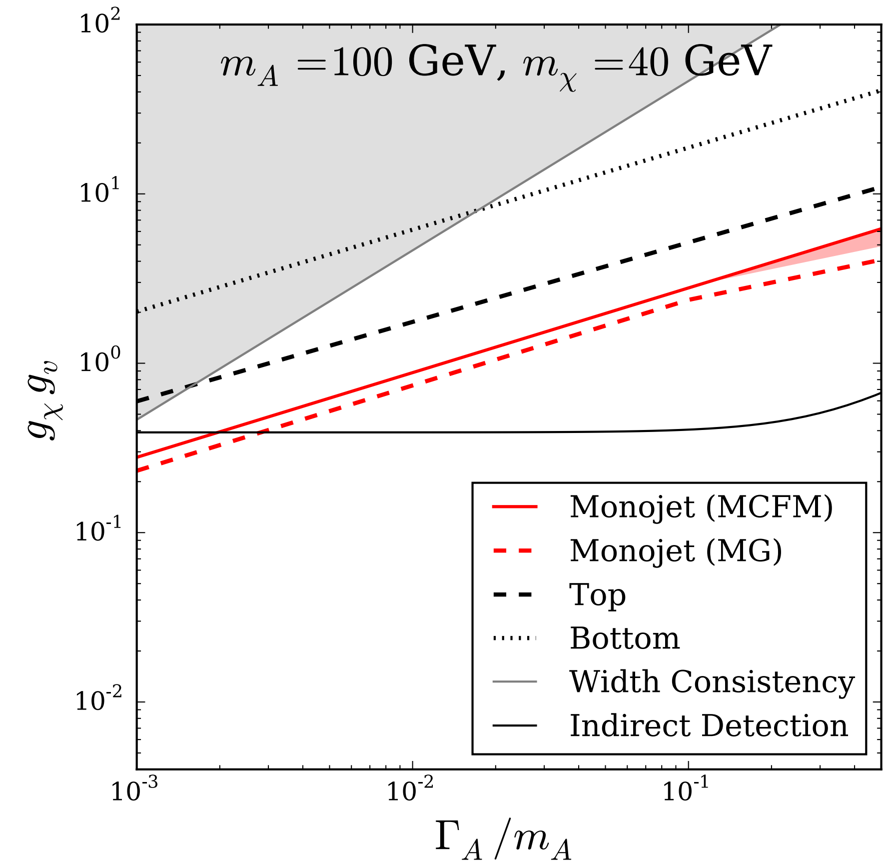
Scalar mediator



Pseudoscalar mediator



- Velocity v of dark matter today is very small v< 10^{-2}c, and so scalar mediators do not result in significant signals in **indirect searhes**

-> Bounds from FGST dwarf analysis

$$\langle \sigma v\rangle(\chi\bar{\chi}\to\phi^*\to f\bar{f}) = \sum_f N_f \frac{3g_\chi^2 g_v^2 y_f^2 (m_\chi^2 - m_f^2)^{3/2}}{8\pi m_\chi^2\left[(m_\phi^2-4m_\chi^2)^2+m_\phi^2\Gamma_\phi^2\right]}T$$

$$\langle \sigma v\rangle(\chi\bar{\chi}\to A^*\to f\bar{f}) = \sum_f N_f \frac{g_\chi^2 g_v^2 y_f^2}{4\pi\left[(m_A^2-4m_\chi^2)^2+m_A^2\Gamma_A^2\right]}\left[m_\chi^2\sqrt{1-\frac{m_f^2}{m_\chi^2}}+\frac{3m_f^2}{4m_\chi\sqrt{1-\frac{m_f^2}{m_\chi^2}}}T\right]$$

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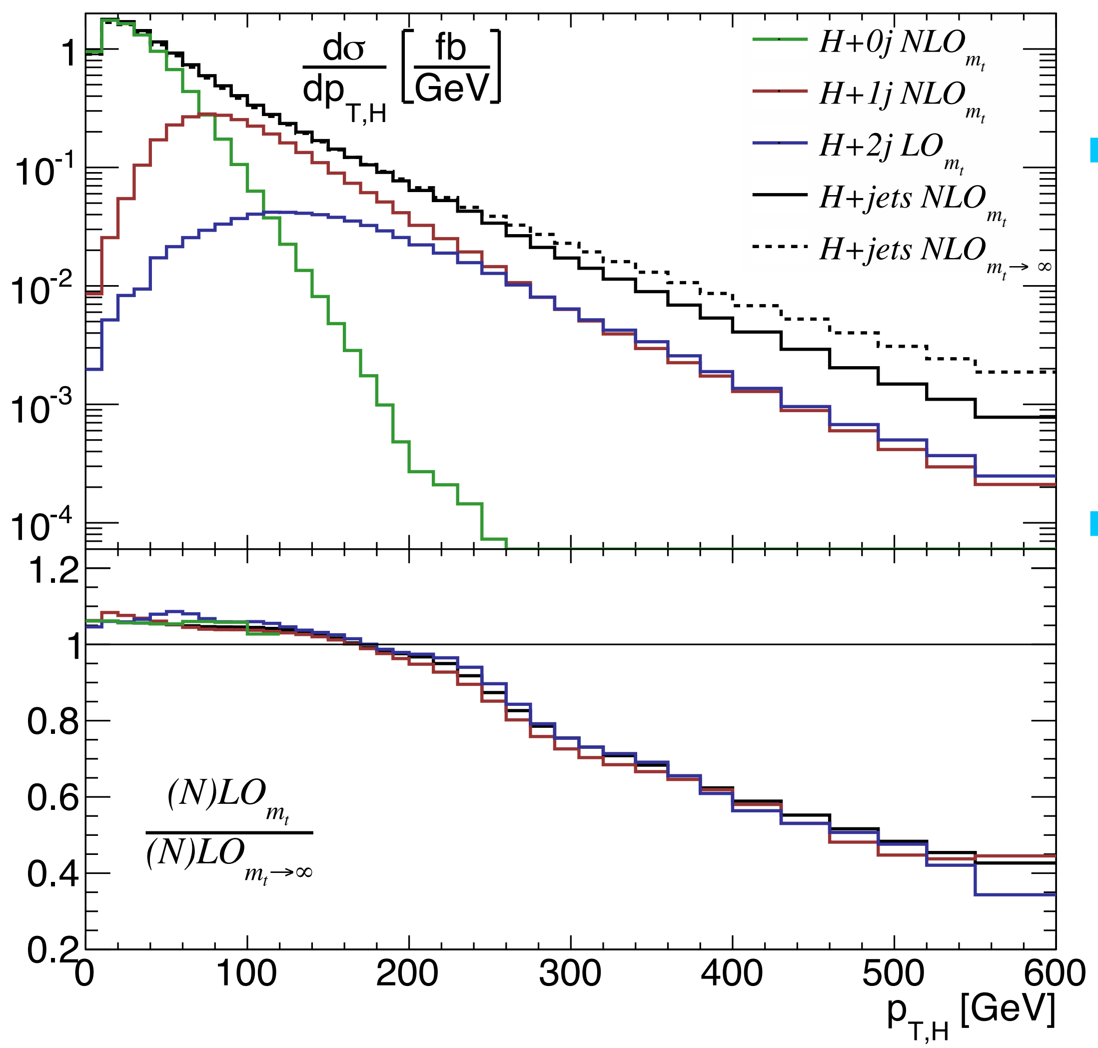
Top mass effects: H+jets MEPS@NLO merging

- Reweighting HEFT amplitudes with Openloops ME: $r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \to \infty)|^2}$

$$d\sigma^{\text{S-MC@NLO}} = d\Phi_n\, r_t^{(n)} \left[\mathcal{B} + \mathcal{V} + \int d\Phi_1\, \mathcal{D}\right] \left(\Delta(t_0) + \int d\Phi_1 \frac{\mathcal{D}}{\mathcal{B}} \Delta(t)\right) + d\Phi_{n+1} \left[r_t^{(n+1)} \mathcal{R} - r_t^{(n)} \mathcal{D}\right]$$



➡ MEPS@NLO need to take into account the heavy quark mass effects at the boosted regime

➡ Similarly to LO merging the top mass effects factorise at NLO merging for each jet bin

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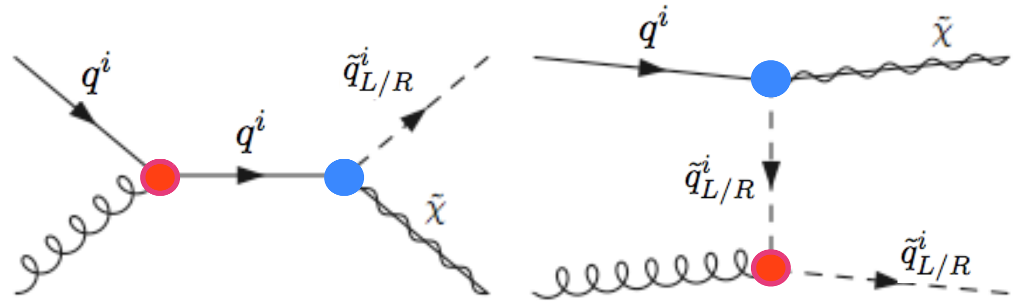
t-channel mediators

- Similar to SUSY $pp \to \tilde{q}\tilde{\chi}$:

  Flavor-locked & semi-weak process sensitive to $q\tilde{q}\tilde{\chi}_1$ coupling: $\sigma^{LO} \sim \mathcal{O}\left(\alpha_{EW}\alpha_s\right)$



- Couplings size correlated with SUSY breaking:

$$\mathcal{L}_{\tilde{N}_{mass}} = -\frac{1}{2}\left(\psi^0\right)^T \mathbf{M}_{\tilde{N}}\psi^0 + c.c.$$

$$\psi^0 = (\tilde{B}, \widetilde{W}^0, \tilde{H}^0_d, \tilde{H}^0_u)$$

$$\mathbf{N}^*\mathbf{M}_{\tilde{\mathbf{N}}}\mathbf{N}^{-1} = \mathrm{diag}\left(m_{\tilde{\chi}^0_1},\, m_{\tilde{\chi}^0_2},\, m_{\tilde{\chi}^0_3},\, m_{\tilde{\chi}^0_4}\right)$$

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

- Msugra models (SPS1-6): typically give $m_Z \lesssim |M_1| \simeq \frac{1}{2}|M_2| \ll |\mu|$

  $\tilde{\chi}^0_1 \simeq \tilde{B}$ (Bino like) e.g. SPS1a $\sigma^{LO}\left(\tilde{u}_R\tilde{\chi}^0_1\right) \gg \sigma^{LO}\left(\tilde{u}_L\tilde{\chi}^0_1\right)$, $\frac{g_{u\tilde{u}_L\tilde{\chi}^0_1}}{g_{u\tilde{u}_R\tilde{\chi}^0_1}} \approx \frac{1}{6}$

- Anomaly mediation (SPS9): $M_1 = \frac{F_\phi}{16\pi^2}\frac{33}{5}g_1^2$; $M_2 = \frac{F_\phi}{16\pi^2}g_2^2 \Rightarrow |M_2| \ll |M_1|$

  $\tilde{\chi}^0_1 \simeq \widetilde{W}$ (Wino like)