VBF DM models

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Introduction

- Long standing interest in Spin 0 DM searches, in the past worked on DM+tt and DM+H
- Aim to extend towards new production mechanisms
- Studied comprehensive set of early VBF models: `http://arxiv.org/abs/1603.07739`
- Study sensitivities, signatures, etc (big picture)
- Two classes of models: EFT and simplified models with several subclasses

Models

- Simplified Models
  - Higgs-Portal: Higgs-like scalar with on/off-shell DM production
  - 2 Higgs Doublet Model: General pseudo scalar (A) and scalar mediatorsInteractions via W/Z boson
- EFT Models
  - Use higher dim operators to describe those
  - Coupling-strength set by operator scale, m_{DM} free parameter

The fine print

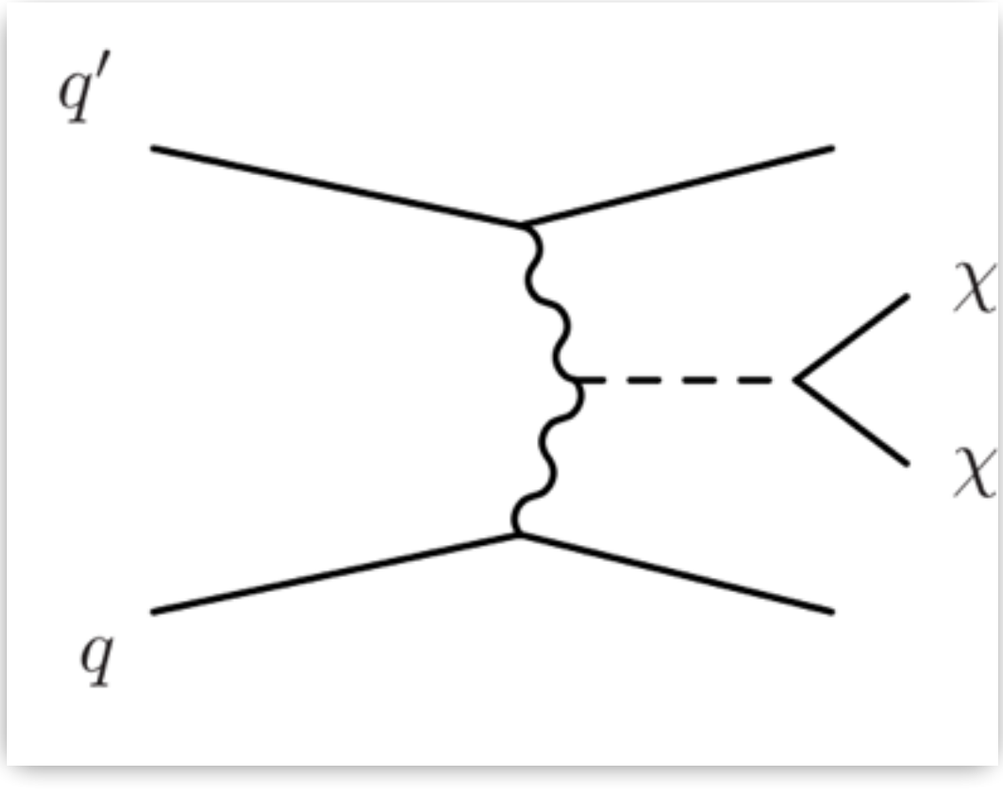
- Paper aimed to develop experimental realistic approach
- Studied systematic and pileup effects but these are notoriously difficult to model
- No mixing effects considered, different couplings to heavy quarks etc

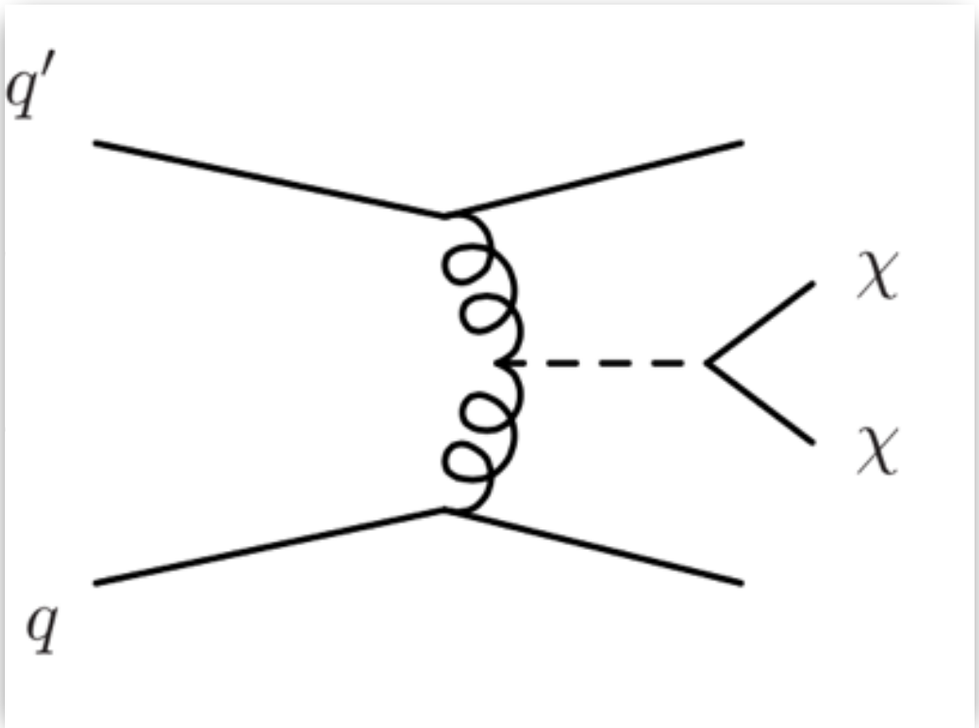
Spin 0 Mediators

- Add SM Higgs-DM interaction to Lagrangian

$$\mathcal{L}_{h\chi\chi} \supseteq -g_\chi(\bar{\chi}\chi)H_{125}$$

- Allows dark matter production via all Higgs production modes:
  - Gluon fusion
  - VBF
  - Associated production
  - ttH
- VBF second largest production mode most sensitive because of bkgds
- For m_{DM}< 125/2 GeV non-SM decay into H→inv. will occur



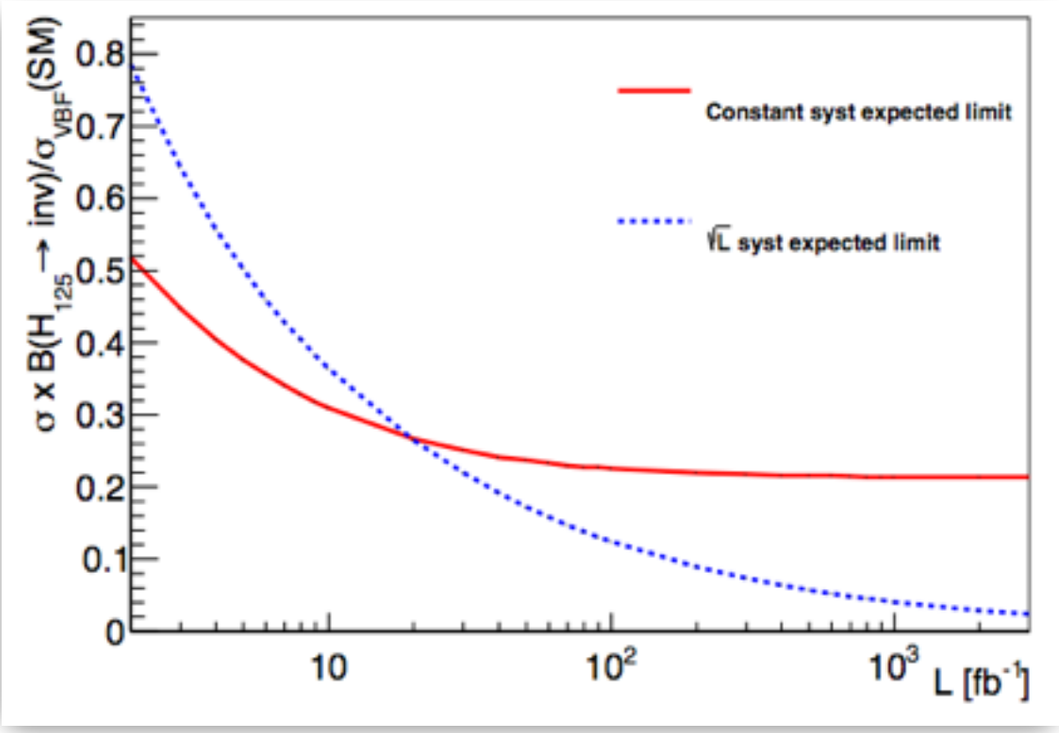


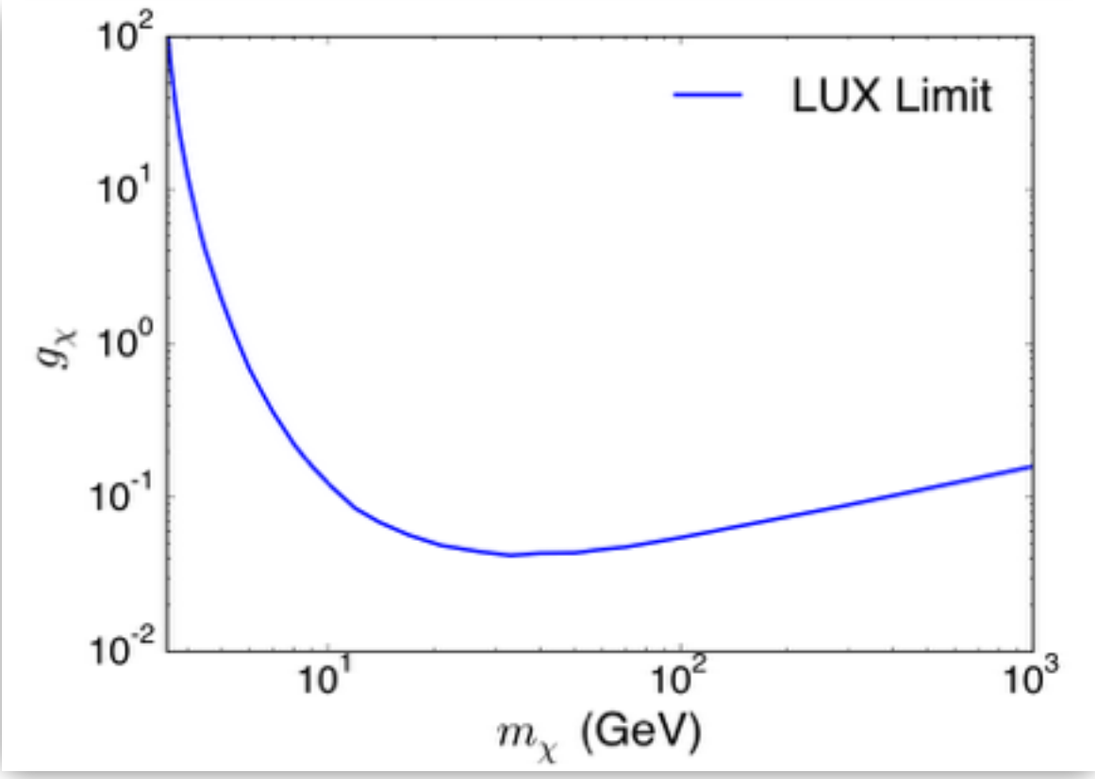
Higgs→inv.

- H → inv. BR decay is defined by coupling strength and m_{DM}

$$\Gamma(h \to \chi\bar{\chi}) = \frac{g_\chi^2 m_{H_{125}}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{H_{125}}^2}\right)^{3/2}$$

- Current constraints <0.25
- Higgs scalar → spin-independent direct detection
  - Stringent constraints form direct searches





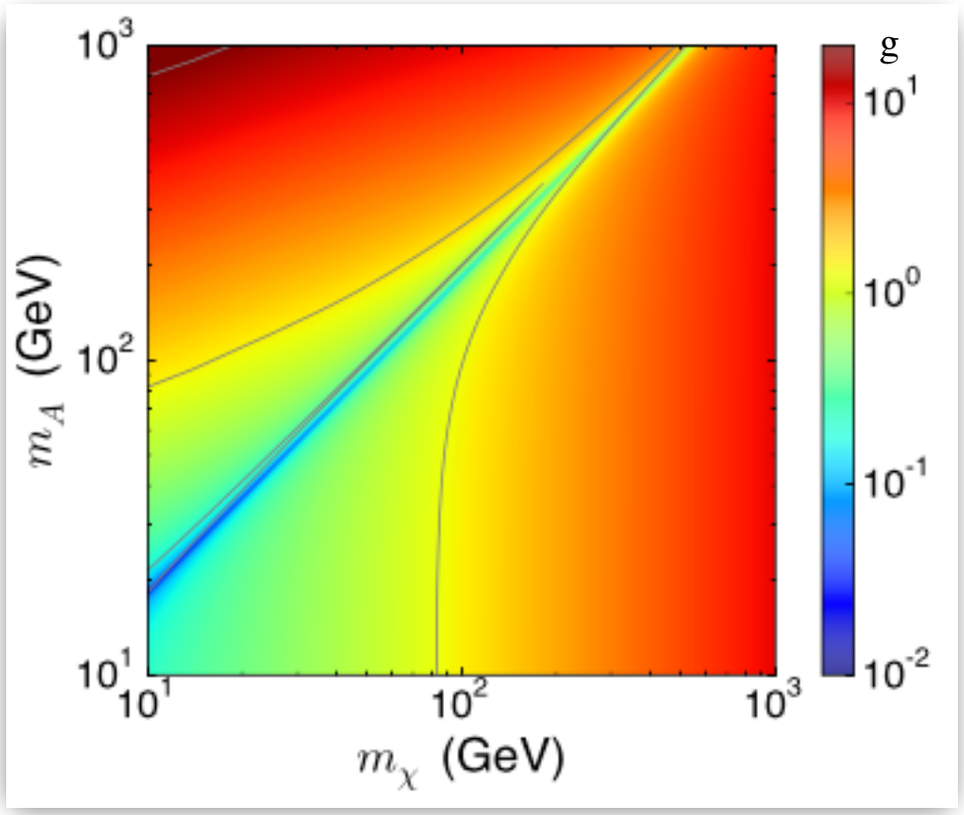
General (Pseudo)-Scalars

- Generalize to new scalar *H* and pseudo-scalar *A* mediators
- Four dim. phase space (m_{DM}, $m_{H/A}$, g_x, g_v).

$$\mathcal{L}_H \supseteq -g_\chi H \bar{\chi}\chi - \sum_f \frac{g_v y_f}{\sqrt{2}} H \bar{f} f,$$

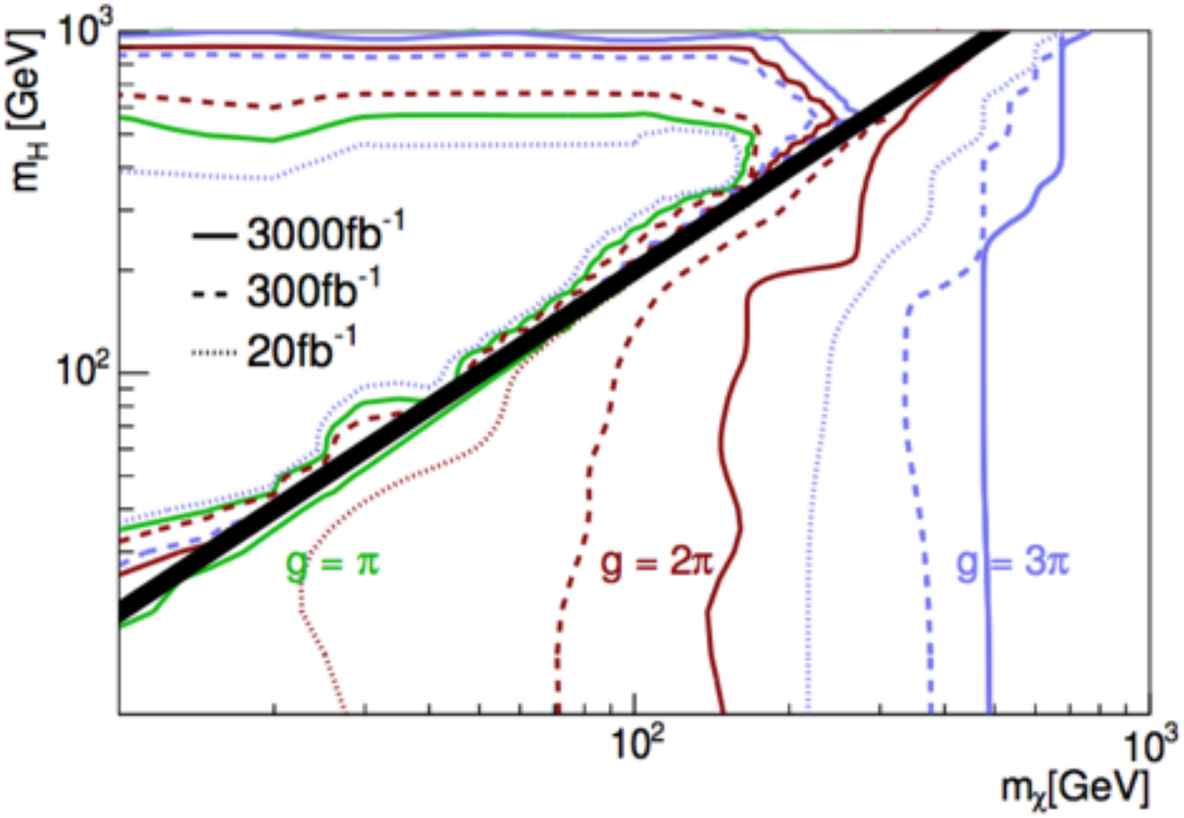
$$\mathcal{L}_A \supseteq -i g_\chi A \bar{\chi}\gamma^5\chi - \sum_f \frac{i g_v y_f}{\sqrt{2}} A \bar{f}\gamma^5 f$$

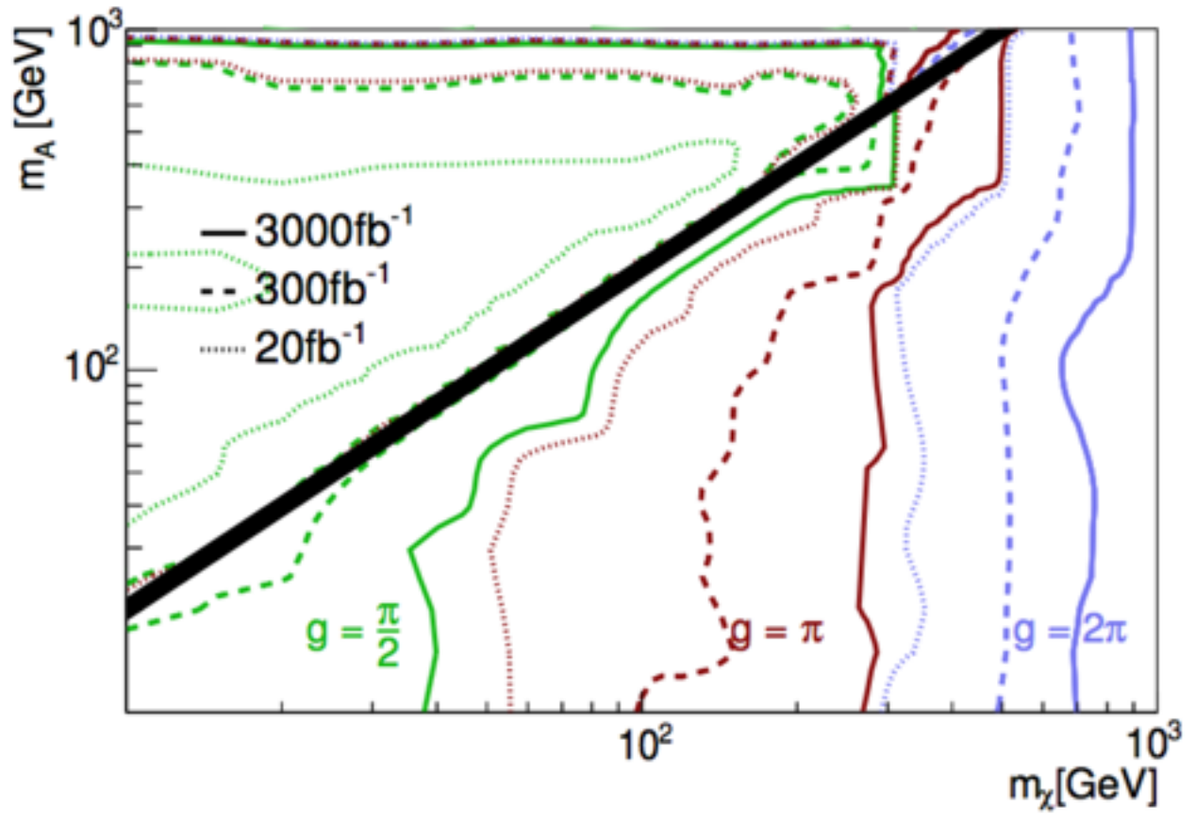
- Production dominated by gluon fusion and top quark loops*
- On-shell $\sigma \sim g^2$, off-shell $\sigma \sim g^4$
- Also derive limits from Fermi-LAT data



* can be easily avoided, e.g. tan β enhancements on b-quarks

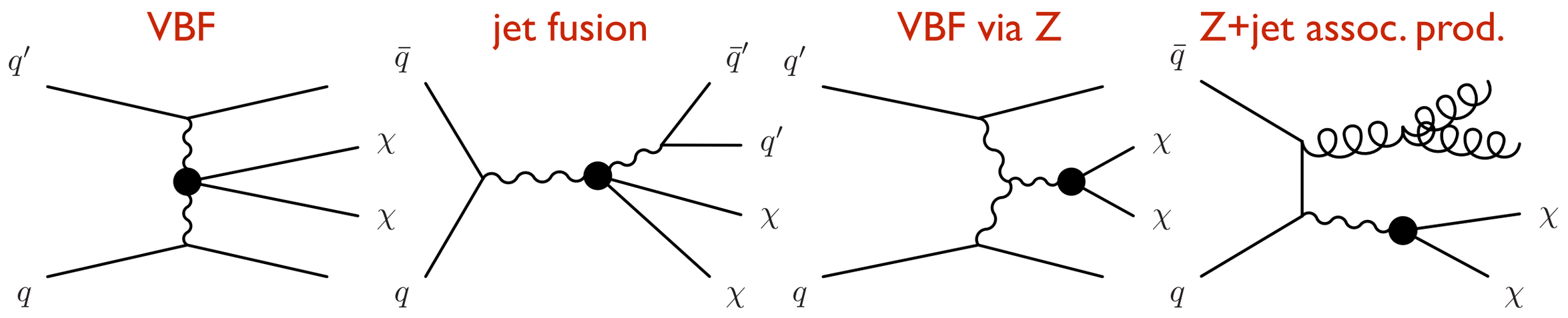
Projections Simplifed





- Projections for several luminosity assumptions
- Only produce g=1, rescaling possible
- Able to probe full on-shell region and part of off-shell regions

Effective Field Theory



- Various EFT operators for DM-W/Z interaction
- Labeling reflects dimensionality (dim 5 - 7)
- Normalise such that DM-photon interactions are suppressed (‘dark’ matter)

$$\mathcal{L}_{\mathrm{D5a}} \supseteq \frac{1}{\Lambda}[\bar{\chi}\chi]\left[\frac{Z_\mu Z^\mu}{2} + W_\mu^+ W^{-\mu}\right],$$

$$\mathcal{L}_{\mathrm{D5b}} \supseteq \frac{1}{\Lambda}[\bar{\chi}\gamma^5\chi]\left[\frac{Z_\mu Z^\mu}{2} + W_\mu^+ W^{-\mu}\right],$$

$$\mathcal{L}_{\mathrm{D5c}} \supseteq \frac{g}{\Lambda}[\bar{\chi}\sigma^{\mu\nu}\chi]\left[\frac{\partial_\mu Z_\nu - \partial_\nu Z_\mu}{\cos\theta_W} - ig\left(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-\right)\right],$$

$$\mathcal{L}_{\mathrm{D5d}} \supseteq \frac{g}{\Lambda}[\bar{\chi}\sigma_{\mu\nu}\chi]\,\epsilon^{\mu\nu\sigma\rho}\left[\frac{\partial_\sigma Z_\rho - \partial_\rho Z_\sigma}{\cos\theta_W} - ig\left(W_\sigma^+ W_\rho^- - W_\rho^+ W_\sigma^-\right)\right],$$

$$\mathcal{L}_{\mathrm{D6a}} \supseteq \frac{g}{\Lambda^2}\partial^\nu[\bar{\chi}\gamma^\mu\chi]\left[\frac{\partial_\mu Z_\nu - \partial_\nu Z_\mu}{\cos\theta_W} - ig\left(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-\right)\right],$$

$$\mathcal{L}_{\mathrm{D6b}} \supseteq \frac{g}{\Lambda^2}\partial_\nu[\bar{\chi}\gamma_\mu\chi]\,\epsilon^{\mu\nu\rho\sigma}\left[\frac{\partial_\sigma Z_\rho - \partial_\rho Z_\sigma}{\cos\theta_W} - ig\left(W_\sigma^+ W_\rho^- - W_\rho^+ W_\sigma^-\right)\right],$$

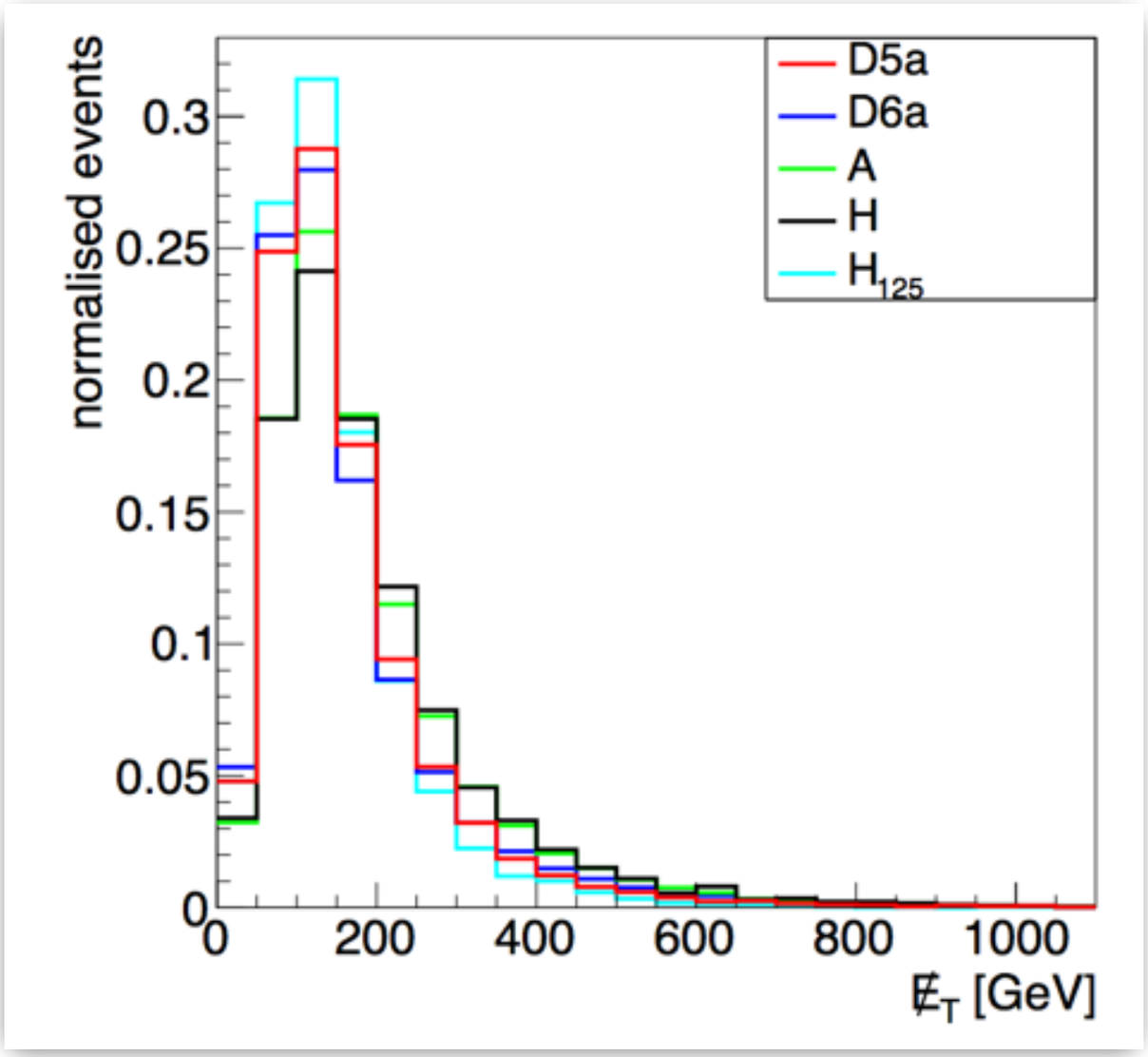
$$\mathcal{L}_{\mathrm{D7a}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\chi]\,W^{i,\mu\nu}W^i_{\mu\nu},$$

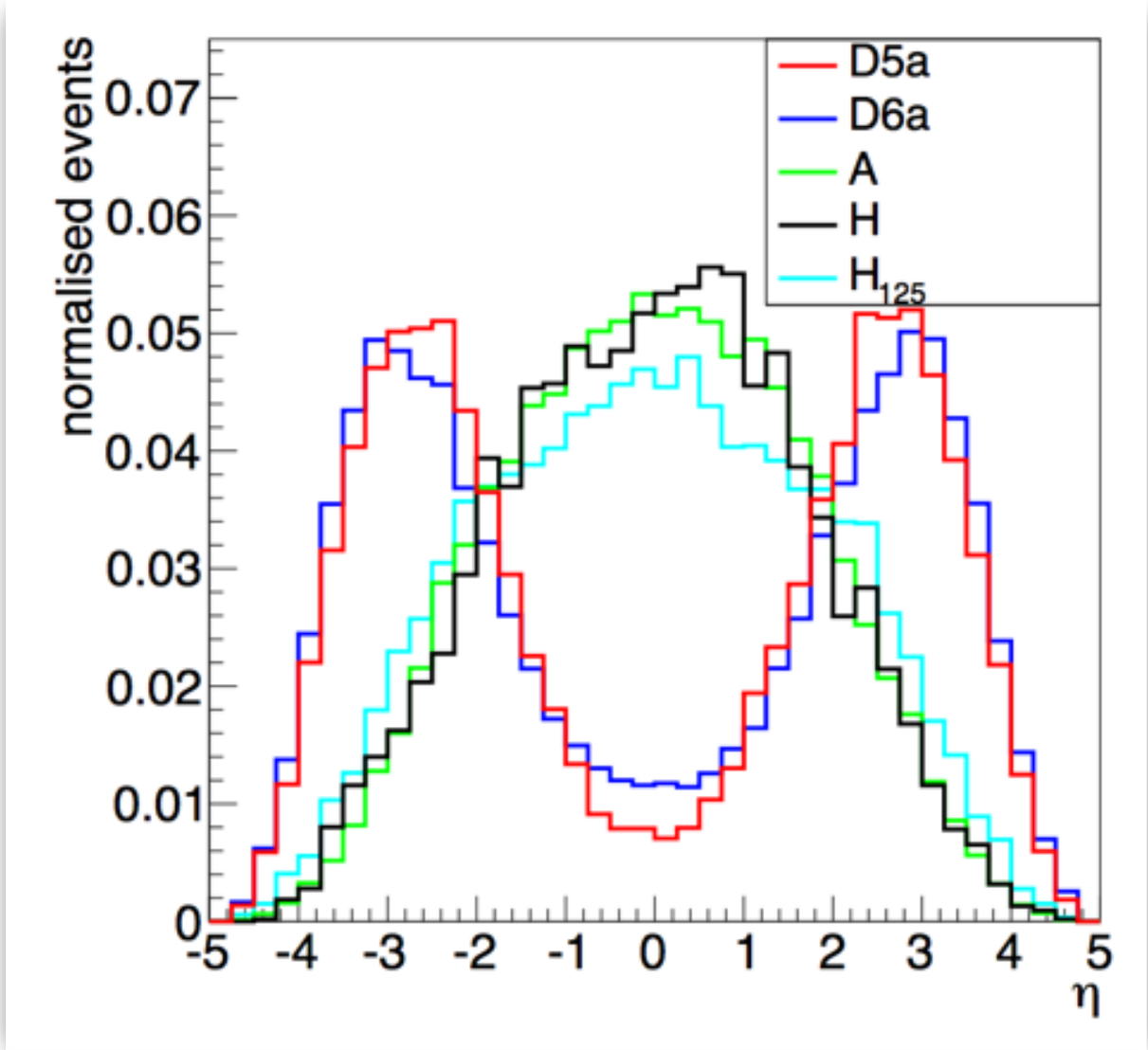
$$\mathcal{L}_{\mathrm{D7b}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\gamma^5\chi]\,W^{i,\mu\nu}W^i_{\mu\nu},$$

$$\mathcal{L}_{\mathrm{D7c}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\chi]\,\epsilon^{\mu\nu\rho\sigma}W^i_{\mu\nu}W^i_{\rho\sigma},$$

$$\mathcal{L}_{\mathrm{D7d}} \supseteq \frac{1}{\Lambda^3}[\bar{\chi}\gamma^5\chi]\,\epsilon^{\mu\nu\rho\sigma}W^i_{\mu\nu}W^i_{\rho\sigma}.$$

Kinematic Distributions





- E_T^{miss} << 1 TeV (e.g. EFT valid, admittedly no detailed studies)
- Inclusive distributions for all production modes

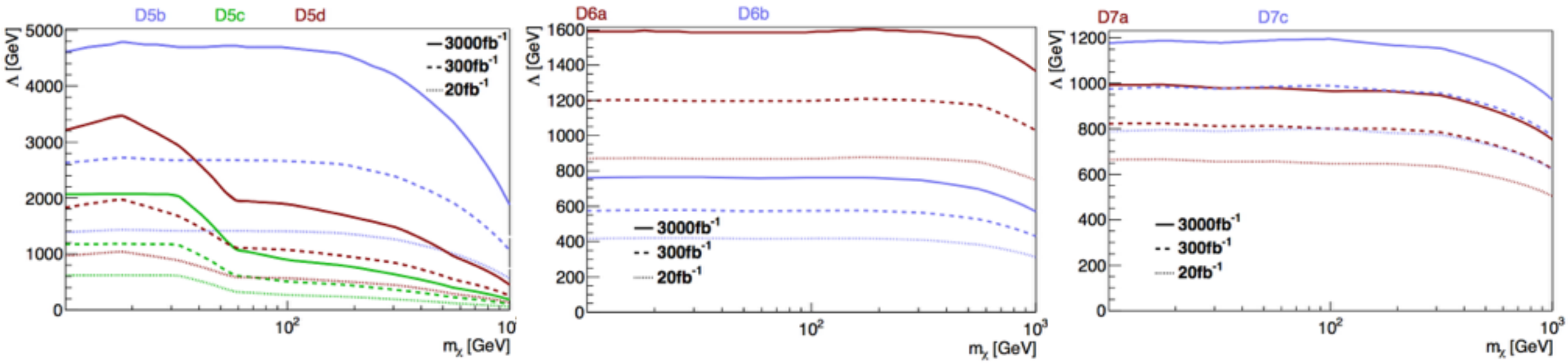
EFT constraints

Operator	Processes (see Fig. 5)	Z decay	Indirect Detection
$\mathcal{L}_{\mathrm{D5a}}$	a, b	no	no
$\mathcal{L}_{\mathrm{D5b}}$	a, b	no	WW, ZZ
$\mathcal{L}_{\mathrm{D5c}}$	a, b, c, d	yes	WW, $f\bar{f}$
$\mathcal{L}_{\mathrm{D5d}}$	a, b, c, d	yes	WW
$\mathcal{L}_{\mathrm{D6a}}$	a, b, c, d	yes	WW, $f\bar{f}$
$\mathcal{L}_{\mathrm{D6b}}$	a, b, c, d	yes	WW
$\mathcal{L}_{\mathrm{D7a}}$	a, b	no	no
$\mathcal{L}_{\mathrm{D7b}}$	a, b	no	WW, ZZ, $\gamma\gamma$, γZ
$\mathcal{L}_{\mathrm{D7c}}$	a, b	no	no
$\mathcal{L}_{\mathrm{D7d}}$	a, b	no	WW, ZZ, $\gamma\gamma$, γZ

- Processes and non-collider constraints application to EFT operators
- Non SM constraints typically m_{DM} ~O(10 GeV) and Λ~O(1T)

permis non-SM Z decay $\langle\sigma v\rangle$ annihilation

- LHC projections: Broadly similar energy scales but higher masses



Summary

- Scalar DM offers unique opportunities:
  - Theoretical very interesting set of models
  - Interesting connections between measurements, DD and ID
- Focused on VBF final states in various classes of models
- Results:
  - SM Higgs: H→inv might be constrained to up to ~5%
  - Generic scalars: probe full on-shell region, parts of off-shell regions
  - EFT: Can probe energy scales of O(1TeV) are higher DM masses than complementary methods.
- Non-exhaustive list of easy extensions: Mixing of mediators, different couplings to heavy quarks, validity studies, adding Mono-X
- Many opportunities in Spin 0 mediators: Access Yukawa coupling, heavy quarks, probe CP structure and properties, additional production modes etc