LHC Dark Matter Searches

Overview of recent developments*

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**Including work in collaboration with:*
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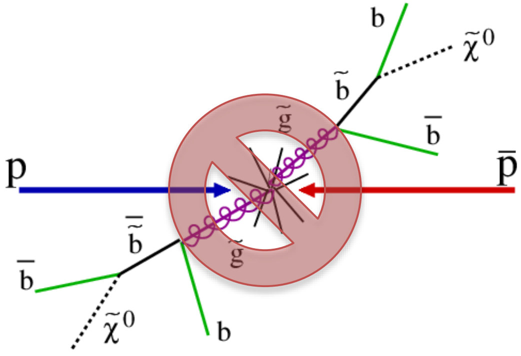
JHEP 1207 (2012) 123, JHEP 1307 (2013) 125, JCAP 1304 (2013) 050 and JHEP 1312 (2013) 007

Disclaimer

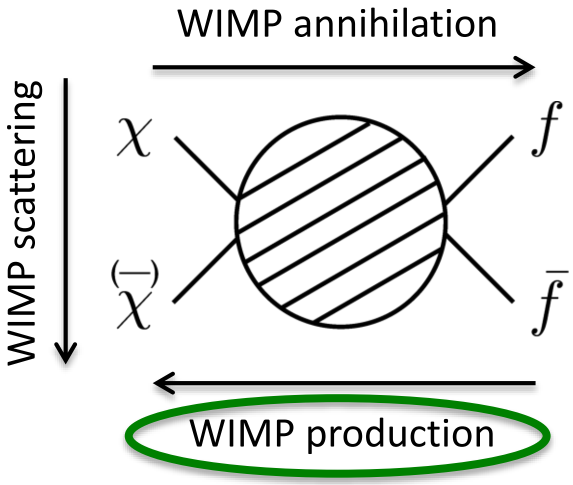
- What this talk is NOT:

  A discussion of SUSY searches involving missing transverse energy and SM states from the decay of new heavy states.

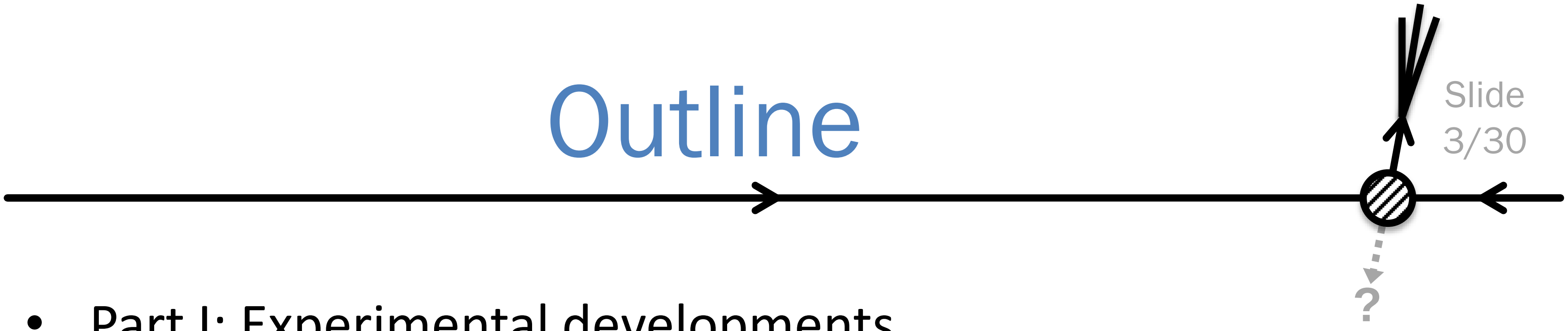


- What this talk IS:

  A discussion of the LHC as a probe of the direct couplings between WIMPs and SM particles.



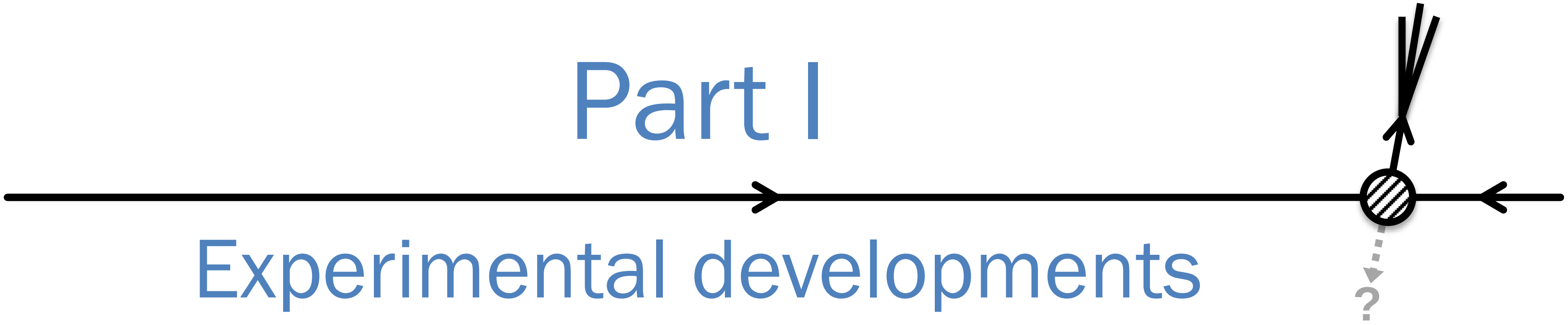
Outline



- Part I: Experimental developments
  - Monojet searches
  - Mono-X searches
  - Invisible Higgs decays

- Part II: Theoretical developments
  - Effective field theories
  - Beyond EFTs
  - Loop corrections

- Part III: Outlook

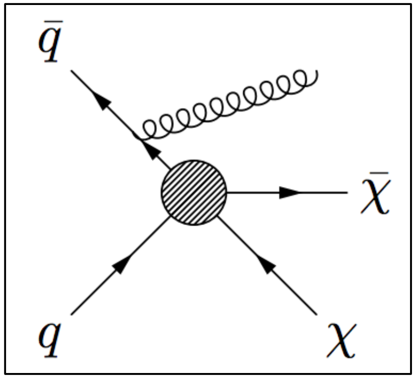


Part I

Experimental developments

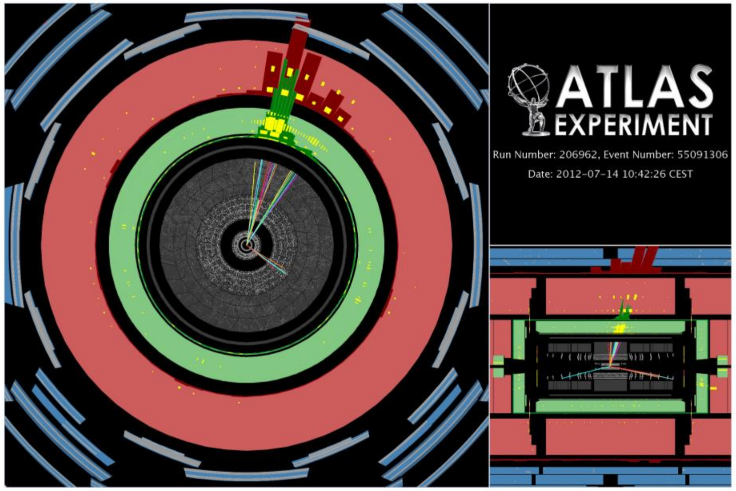
- Any WIMPs produced at colliders will escape from the detector unnoticed. But if other particles (such as jets) are produced in association with a pair of WIMPs, we may observe large amounts of missing transverse energy (MET).

Monojet searches



Theory

Reality*



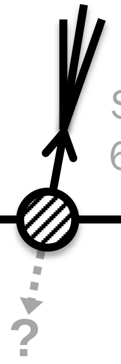
- Typical event selection (CMS):
  - MET > 200 GeV, # of Jets = 1 or 2
  - Leading Jet: pT > 110 GeV, |η| < 2.4
  - Second Jet: pT > 30 GeV
  - Δφ(jet1,jet2) < 2.5

⇒QCD background rejected

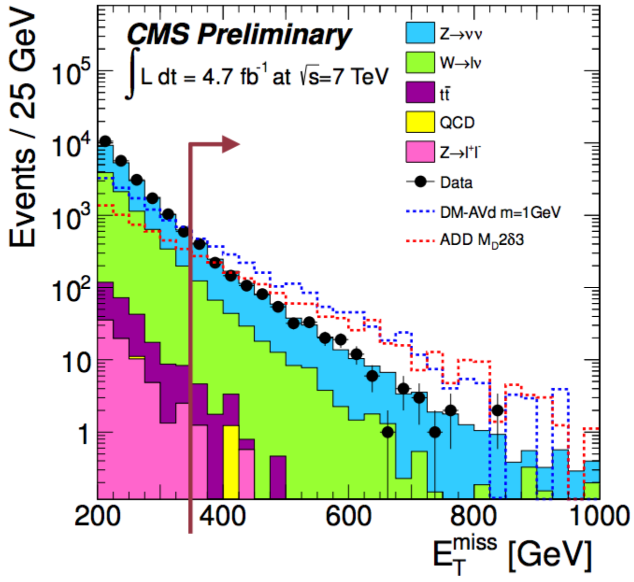
- Typical backgrounds:
  - Z+jet(s) → νν+jet(s)
  - W+jet(s) → lν+jet(s) with lost lepton

*May not be dark matter

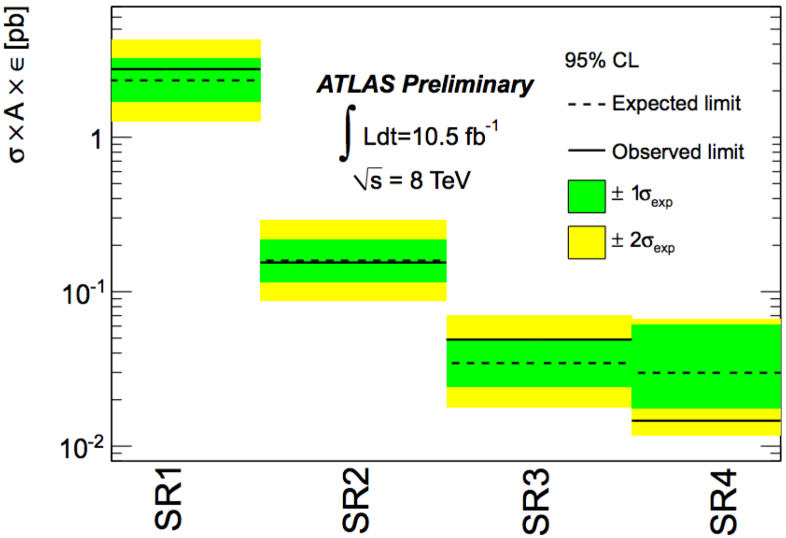
Monojet searches



- Only observable: Missing transverse energy
- The spectrum of the signal, however, is essentially featureless (although slightly harder than the background).



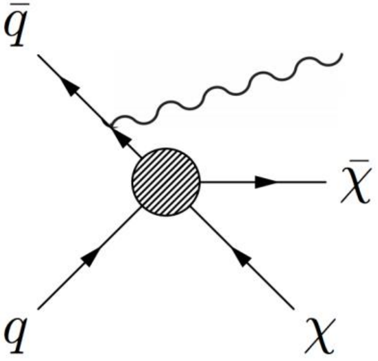
CMS: arXiv:1206.5663

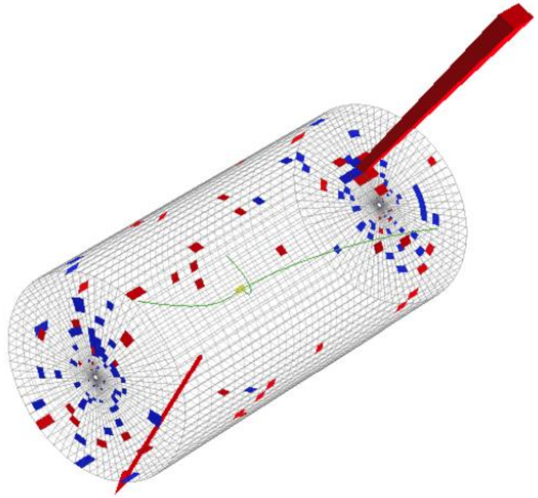


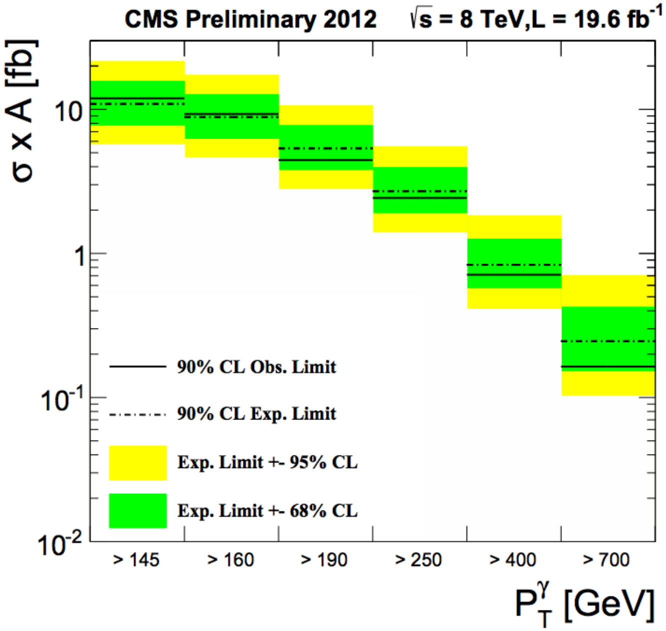
ATLAS-CONF-2012-147

Mono-X searches

- Monojet searches typically give the strongest constraints.
- For a discovery one would hope to see DM also in other channels:
  - Monophoton searches*







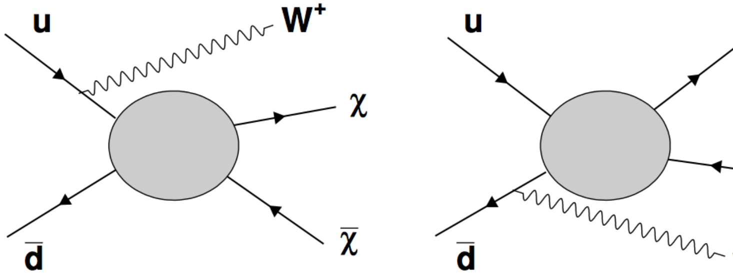
CMS PAS EXO-12-047

* Also interesting for low-energy e^+e^- colliders

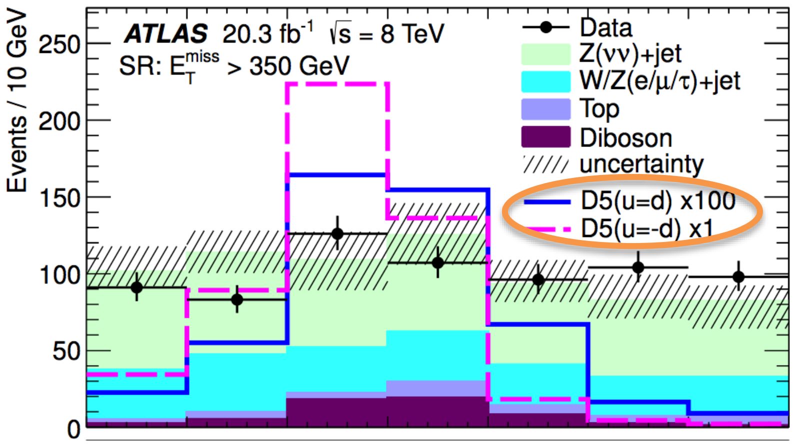
Essig, Mardon, Papucci, Volansky, Zhong: arXiv:1309.5084

Mono-X searches

- Monojet searches typically give the strongest constraints.
- For a discovery one would hope to see DM also in other channels:
  - Monophoton searches
  - Mono-W searches



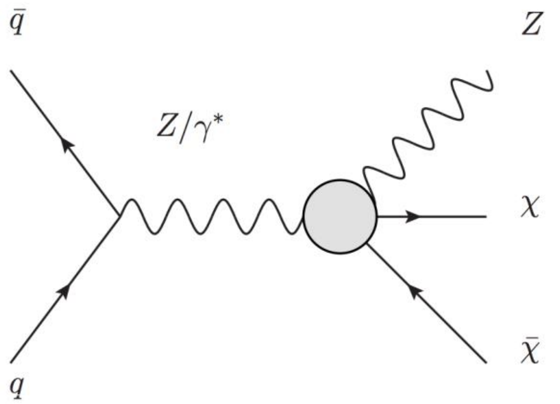
Very sensitive to the relative sign between up-quark and down-quark couplings!



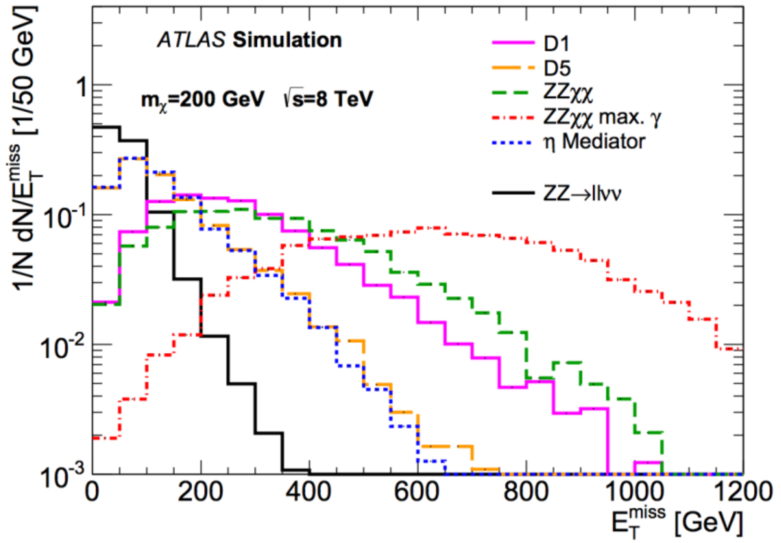
ATLAS: arXiv:1309.4017

Mono-X searches

- Monojet searches typically give the strongest constraints.
- For a discovery one would hope to see DM also in other channels:
  - Monophoton searches
  - Mono-W searches
  - Mono-Z searches



Probing the couplings of WIMP to SM gauge bosons

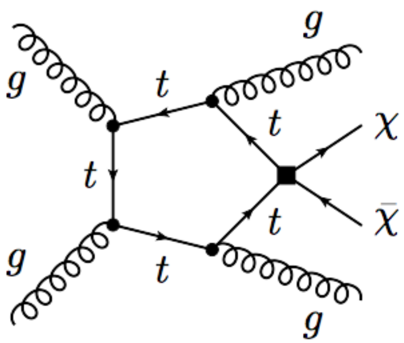


ATLAS: arXiv:1404.0051

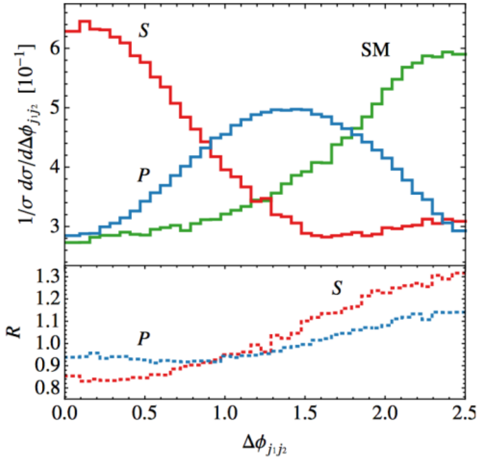
Multi-X searches

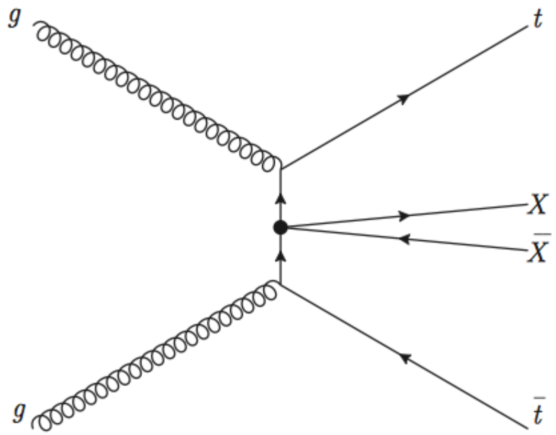
- Monojet searches typically give the strongest constraints.
- For a discovery one would hope to see DM also in other channels:
  - Monophoton searches
  - Mono-W searches
  - Mono-Z searches
  - Dijet+MET searches

Study heavy-quark couplings and angular correlations



Haisch, Hibbs, Re: arXiv:1311.7131



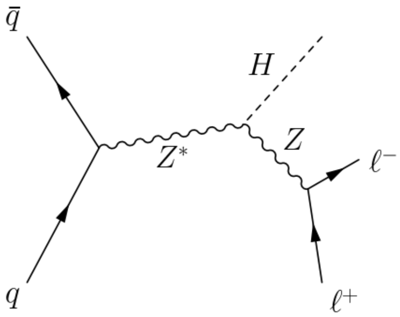


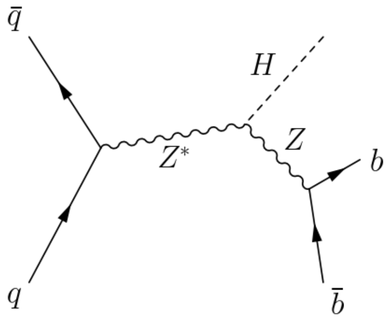
Lin, Kolb, Wang: arXiv:1303.6638

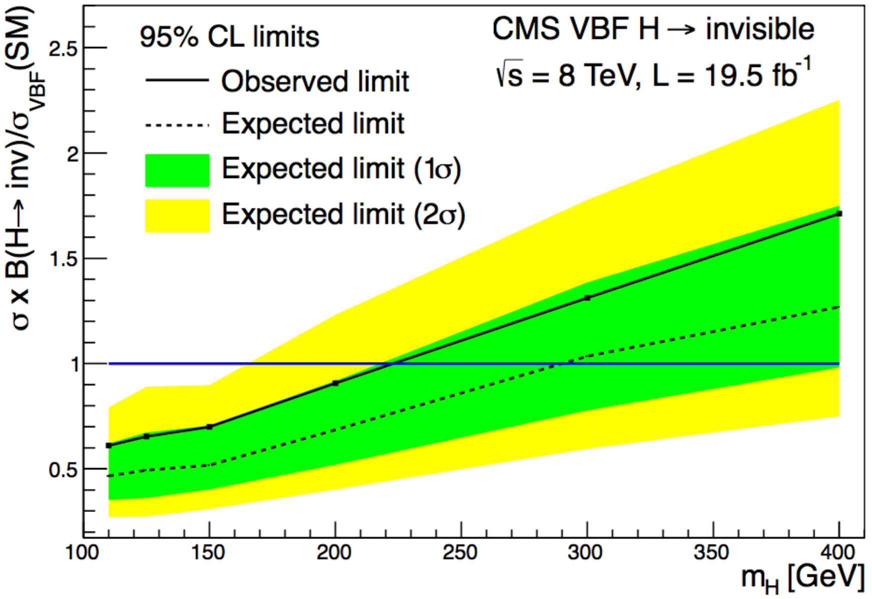
Invisible Higgs decays

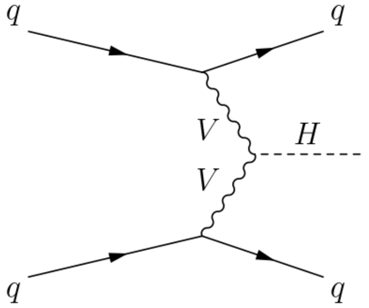
- A related idea: Search for invisibly decaying Higgs particles produced in association with other SM states (e.g. a Z boson or two forward jets).

(see also talk by Theodota Lagouri)









VBF is typically the most constraining search channel

CMS: arXiv:1404.1344

BF(H_{125}→invisible) < 0.58 (0.44 exp) @ 95% CL

(assuming SM production x-section & kinematics)

Invisible Higgs decays

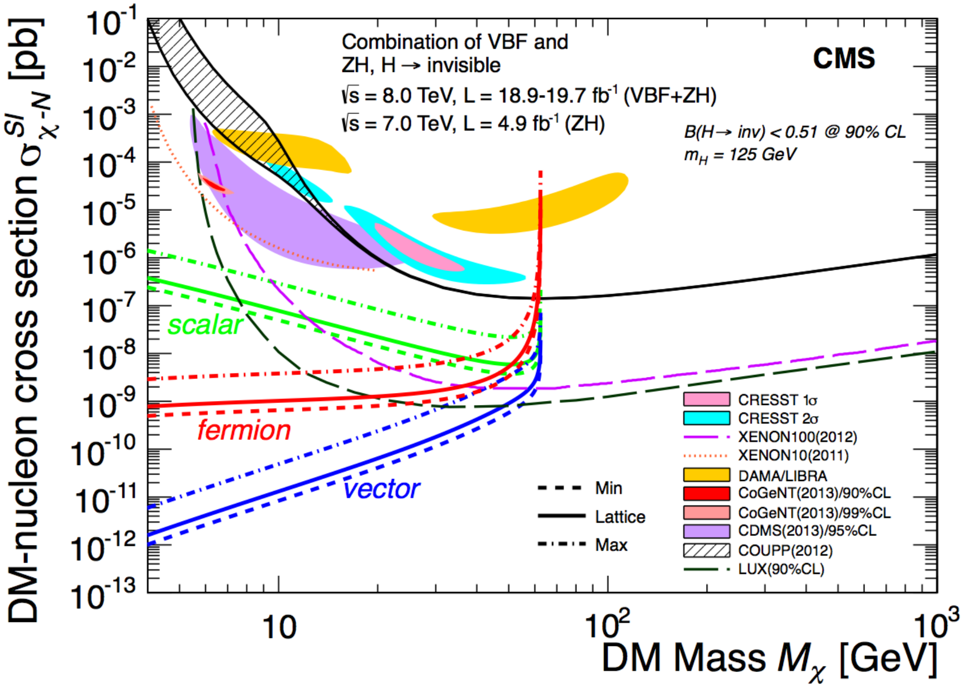
- Using the frame-work of Higgs portal dark matter, bounds from invisible Higgs decays can be translated into bounds on the WIMP scattering cross section.
- Resulting bounds apply only for $m_\chi < m_h/2$ and depend on whether the WIMP is a scalar, fermion or vector.

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS}H^\dagger H S^2\,,$$

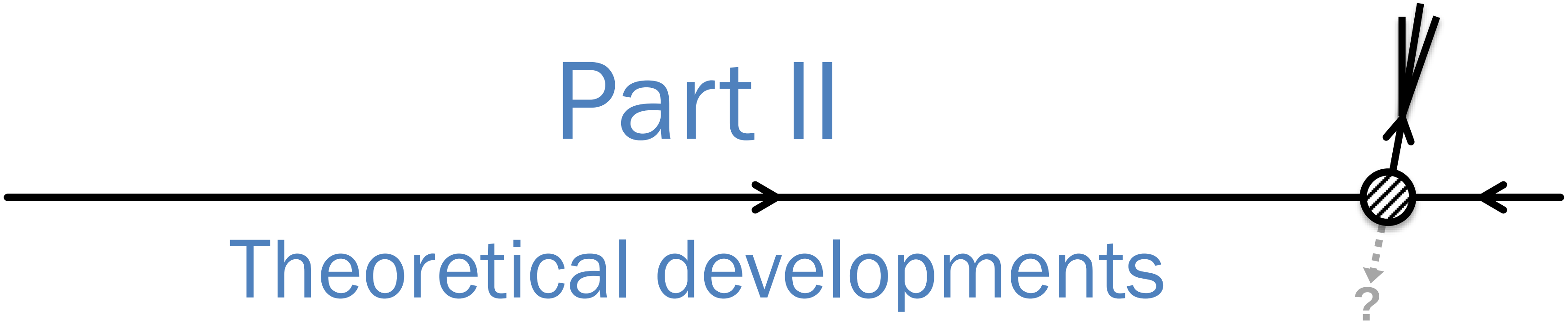
$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV}H^\dagger H V_\mu V^\mu,$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda}H^\dagger H \bar{\chi}\chi$$

Djouadi, Lebedev, Mambrini, Quevillon: arXiv:1112.3299



CMS: arXiv:1404.1344



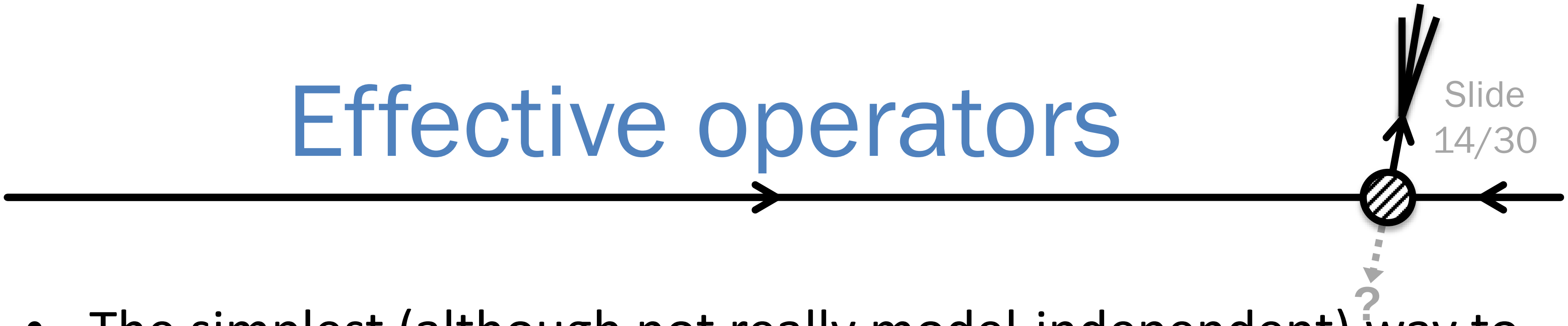
Part II

Theoretical developments

1. How do we make predictions (such as signal distributions) in order to optimize experimental cuts?

2. How do we interpret LHC searches in order to compare them with other experiments (such as direct detection)?

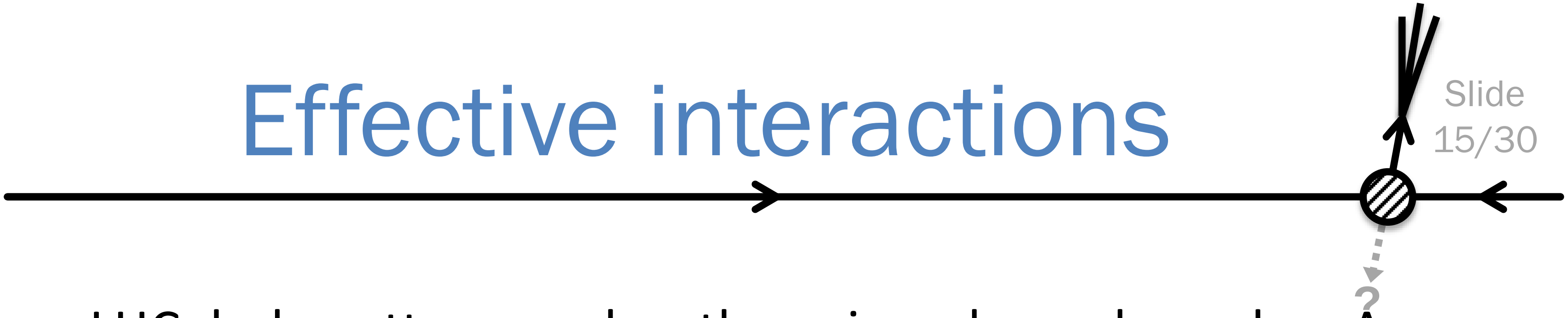
Effective operators



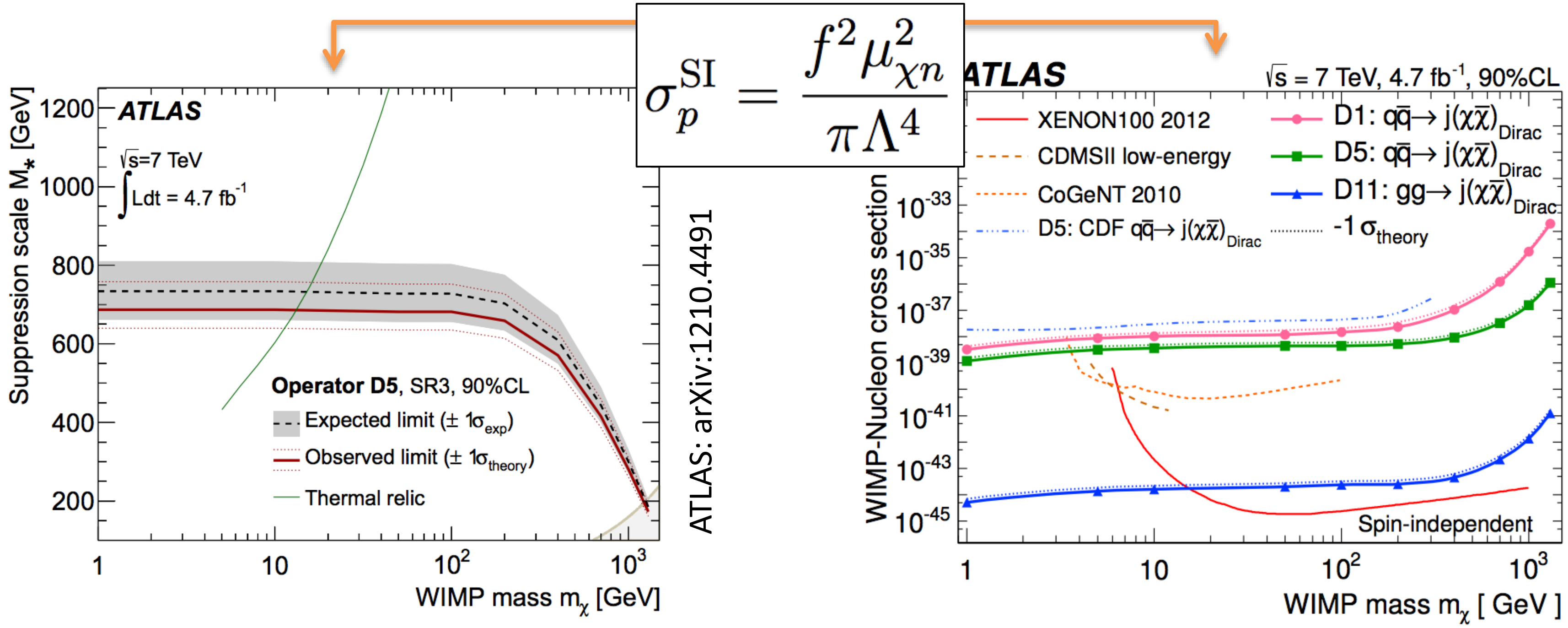
- The simplest (although not really model-independent) way to describe interactions between WIMPs and quarks is to use effective operators, for example $\mathcal{L}_\chi^{\text{eff}} = \frac{1}{\Lambda^2} \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$.
- This effective operator could arise from integrating out a vector mediator with mass m_R and vector couplings g_q to quarks and g_χ to the WIMP: $\Lambda = m_R/\sqrt{g_q g_\chi}$.
- We can use these effective operators to calculate signal distributions. The total predicted cross section will be proportional to Λ^{-4}.

Beltran, Hooper, Kolb, Krusberg, Tait: arXiv:1002.4137
Bai, Fox, Harnik: arXiv:1005.3797

Effective interactions



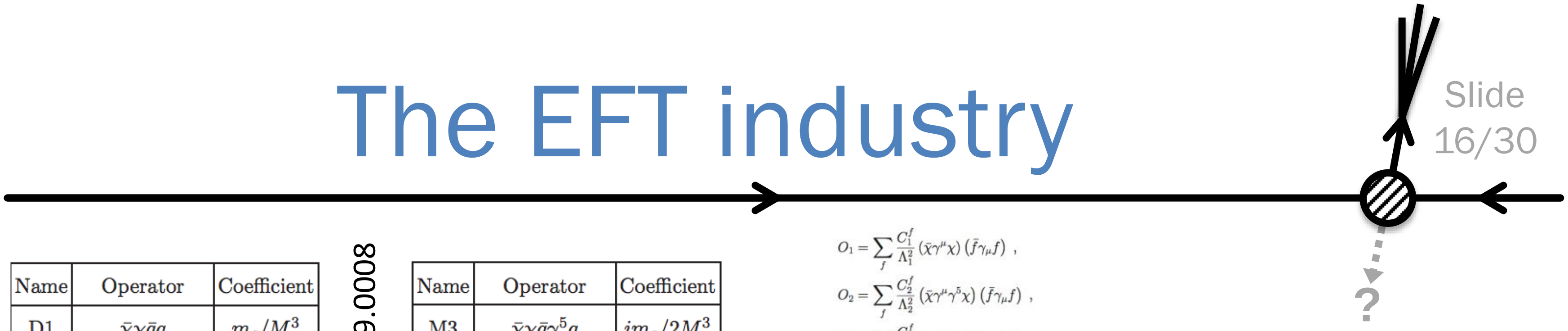
- LHC dark matter searches then give a lower bound on Λ.
- In the EFT framework, the same scale also enters in other processes (e.g. WIMP annihilation and WIMP scattering).



$$\sigma_p^{\mathrm{SI}} = \frac{f^2 \mu_{\chi n}^2}{\pi \Lambda^4}$$

ATLAS: arXiv:1210.4491

The EFT industry



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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D
M1	$\bar{\chi}\chi\bar{q}q$	$m_q/2M_*^3$
M2	$\bar{\chi}\gamma^5\chi\bar{q}q$	$im_q/2M_*^3$
M3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	$im_q/2M_*^3$
M4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$m_q/2M_*^3$
M5	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/2M_*^2$
M6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/2M_*^2$
M7	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^3$
M8	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/8M_*^3$
M9	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^3$
M10	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/8M_*^3$
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu: arXiv:1009.0008

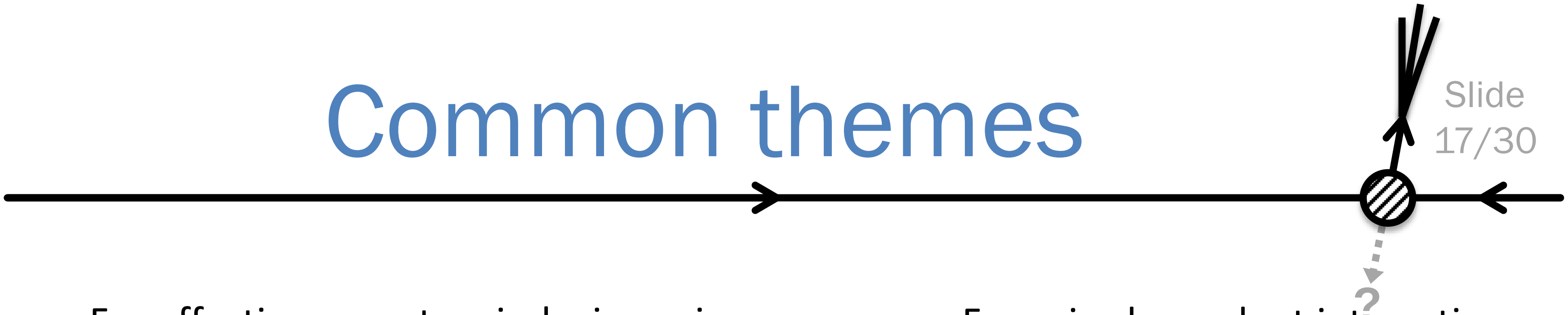
$$O_1 = \sum_f \frac{C_1^f}{\Lambda_1^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f) ,$$
$$O_2 = \sum_f \frac{C_2^f}{\Lambda_2^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma_\mu f) ,$$
$$O_3 = \sum_f \frac{C_3^f}{\Lambda_3^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu\gamma^5 f) ,$$
$$O_4 = \sum_f \frac{C_4^f}{\Lambda_4^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma_\mu\gamma^5 f) ,$$
$$O_5 = \sum_f \frac{C_5^f}{\Lambda_5^2}(\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{f}\sigma_{\mu\nu} f) ,$$
$$O_6 = \sum_f \frac{C_6^f}{\Lambda_6^2}(\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi)(\bar{f}\sigma_{\mu\nu} f) ,$$
$$O_7 = \sum_f \frac{C_7^f m_f}{\Lambda_7^3}(\bar{\chi}\chi)(\bar{f}f) ,$$
$$O_8 = \sum_f \frac{iC_8^f m_f}{\Lambda_8^3}(\bar{\chi}\gamma^5\chi)(\bar{f}f) ,$$
$$O_9 = \sum_f \frac{iC_9^f m_f}{\Lambda_9^3}(\bar{\chi}\chi)(\bar{f}\gamma^5 f) ,$$
$$O_{10} = \sum_f \frac{C_{10}^f m_f}{\Lambda_{10}^3}(\bar{\chi}\gamma^5\chi)(\bar{f}\gamma^5 f) .$$
$$O_{11} = \frac{C_{11}}{\Lambda_{11}^3}(\bar{\chi}\chi)\left(-\frac{\alpha_s}{12\pi}G^{\mu\nu}G_{\mu\nu}\right) ,$$
$$O_{12} = \frac{iC_{12}}{\Lambda_{12}^3}(\bar{\chi}\gamma^5\chi)\left(-\frac{\alpha_s}{12\pi}G^{\mu\nu}G_{\mu\nu}\right) ,$$
$$O_{13} = \frac{C_{13}}{\Lambda_{13}^3}(\bar{\chi}\chi)\left(\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}\right) ,$$
$$O_{14} = \frac{iC_{14}}{\Lambda_{14}^3}(\bar{\chi}\gamma^5\chi)\left(\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}\right) .$$
$$O_{15} = \sum_f \frac{iC_{15}^f}{\Lambda_{15}^2}\left(\chi^\dagger\overleftrightarrow{\partial_\mu}\chi\right)(\bar{f}\gamma^\mu f) ,$$
$$O_{16} = \sum_f \frac{iC_{16}^f}{\Lambda_{16}^2}\left(\chi^\dagger\overleftrightarrow{\partial_\mu}\chi\right)(\bar{f}\gamma^\mu\gamma^5 f) ,$$
$$O_{17} = \sum_f \frac{C_{17}^f m_f}{\Lambda_{17}^2}(\chi^\dagger\chi)(\bar{f}f) ,$$
$$O_{18} = \sum_f \frac{iC_{18}^f m_f}{\Lambda_{18}^2}(\chi^\dagger\chi)(\bar{f}\gamma^5 f) ,$$
$$O_{19} = \frac{C_{19}}{\Lambda_{19}^2}(\chi^\dagger\chi)\left(-\frac{\alpha_s}{12\pi}G^{\mu\nu}G_{\mu\nu}\right) ,$$
$$O_{20} = \frac{C_{20}}{\Lambda_{20}^2}(\chi^\dagger\chi)\left(\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}\right) .$$

Cheung, Tseng, Tsai, Yuan: arXiv:1201.3402

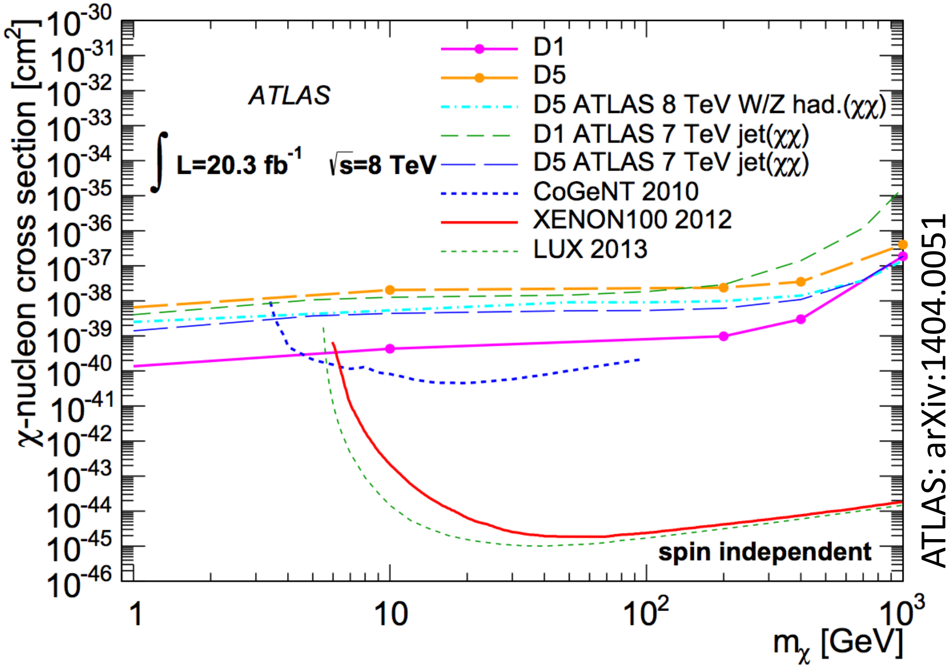
$\Delta\mathscr{L}$		Int.	Suppression
$\mathcal{O}_s^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}f$	SI	1
$\mathcal{O}_v^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_{va}^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2
$\mathcal{O}_p^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_s^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}f$	SI	1
$\mathcal{O}_v^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_a^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	1
$\mathcal{O}_t^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\sigma^{\mu\nu}\psi\bar{f}\sigma_{\mu\nu}f$	SD	1
$\mathcal{O}_p^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4
$\mathcal{O}_{va}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2, q^2
$\mathcal{O}_{pt}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\sigma^{\mu\nu}\gamma^5\psi\bar{f}\sigma_{\mu\nu}f$	SI	q^2
$\mathcal{O}_{ps}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\gamma^5\psi\bar{f}f$	SI	q^2
$\mathcal{O}_{sp}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_{av}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu f$	SI SD	v^2 q^2
$\hat{\mathcal{O}}_s^\phi$:	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_s^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\psi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_p^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4

March-Russell, Unwin, West: arXiv:1203.4854

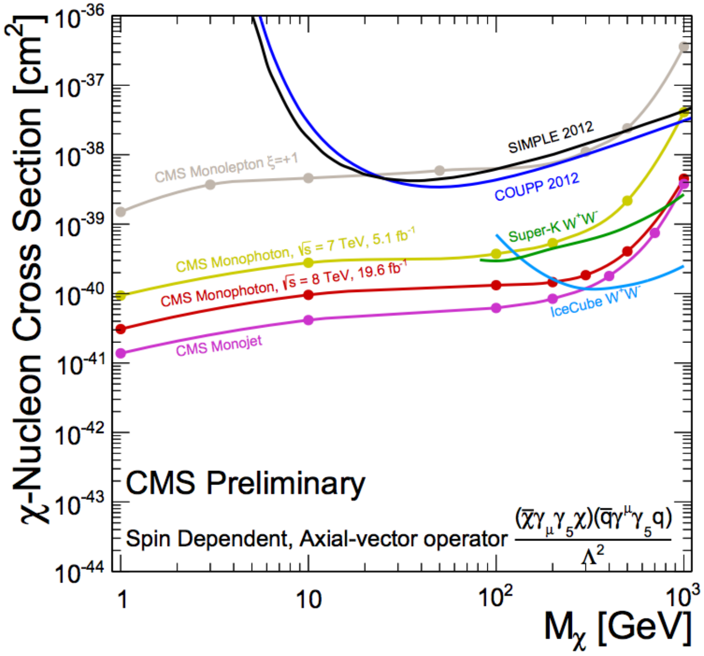
Common themes



- For effective operators inducing spin-independent interactions, LHC searches are typically inferior to direct detection (except for very light masses), since the latter benefit from coherent enhancement.
- For spin-dependent interactions, direct detection cross sections are not enhanced and LHC searches typically give the strongest bounds.

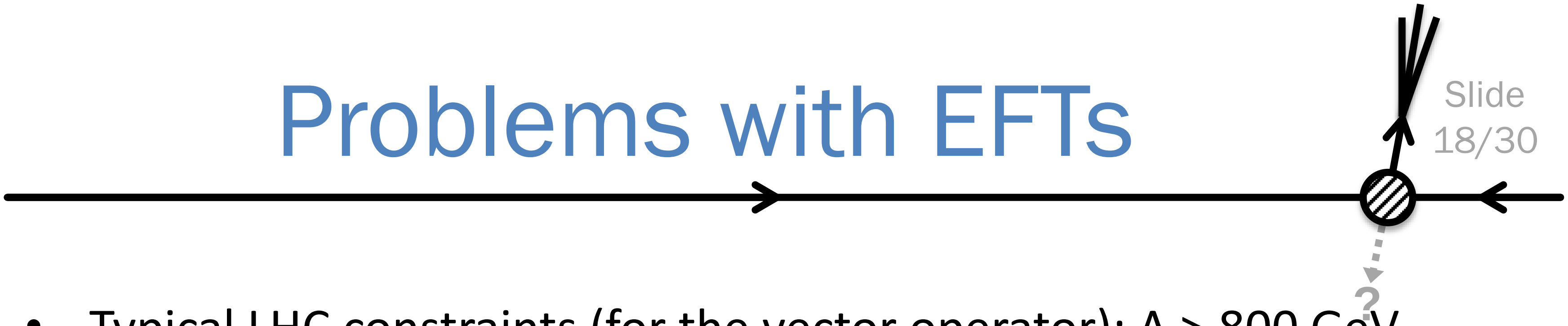


ATLAS: arXiv:1404.0051



CMS: CMS-PAS-EXO-12-047

Problems with EFTs



- Typical LHC constraints (for the vector operator): Λ > 800 GeV

⇒ Problem with perturbativity:

We require g_q, $g_\chi < (4\pi)^{1/2}$, so for $\Lambda = m_R/\sqrt{g_q g_\chi}$ we obtain $m_R < 2.5$ TeV.

Fox, Harnik, Kopp, Tsai: arXiv:1109.4398, arXiv:1103.0240

⇒ Problem with unitarity:

For vector couplings the requirement of partial wave unitarity

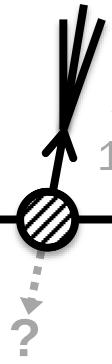
$$|a^J(s)| = \left|\frac{1}{32\pi}\int_{-1}^{1} \mathrm{d}(\cos\theta)\mathrm{P_J}(\cos\theta)\mathcal{M}(\mathrm{s},\cos\theta)\right| < 1 \quad \text{with} \quad \mathcal{M} = 2\sqrt{3}\frac{s}{\Lambda^2}$$

is violated for $\sqrt{s} > 2$ TeV.

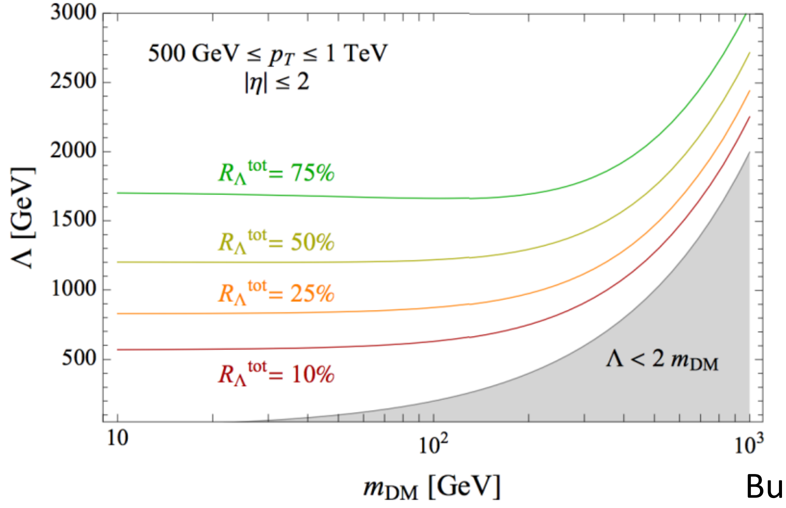
Shoemaker, Vecchi, arXiv:1112.5457
Fox, Harnik, Primulando, Yu, arXiv:1203.1662

- New physics must appear below these scales!

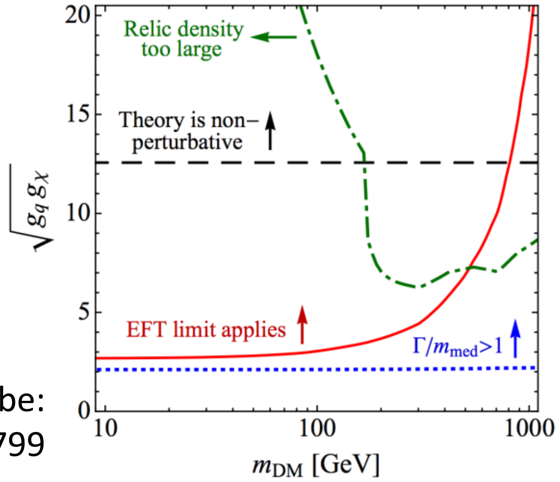
Beyond EFTs



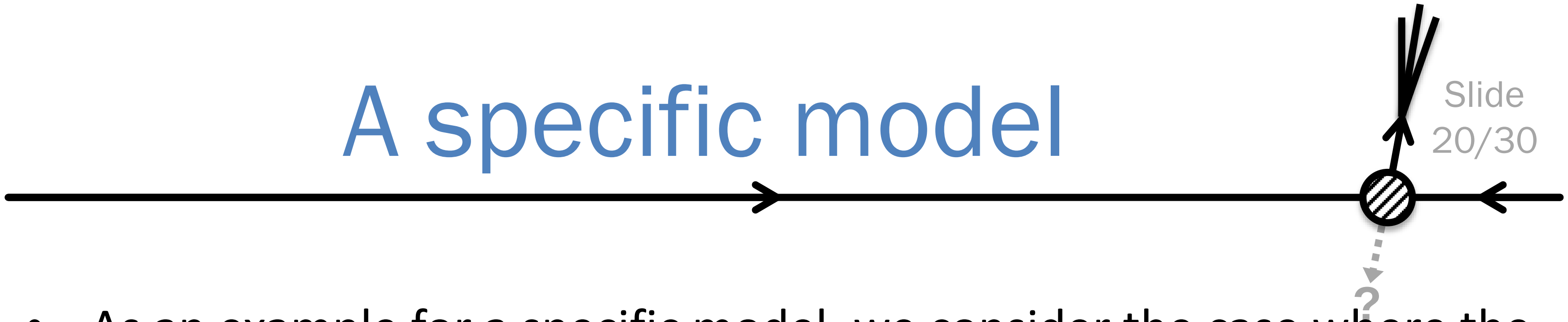
- Effective operators may *not* be valid at the LHC.
- It is quite possible that the mediator mass is comparable to LHC energies (m_R ~ TeV) and that the mediator can be produced *on-shell.*
- In order to move on from an effective field theory, we need to specify the properties of the mediator (couplings, mass, width).



Busoni, De Simone, Gramling, Jacques, Morgante, Riotto:
arXiv:1307.2253
arXiv:1402.1275
arXiv:1405.3101
(see also talk by Thomas Jacques)



Buchmueller, Dolan, McCabe:
arXiv:1308.6799



A specific model

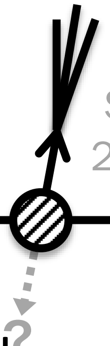
- As an example for a specific model, we consider the case where the mediator is the gauge boson of a new $U(1)$ under which only the WIMP is charged (often called dark Z’ or invisible Z’):

$$\mathcal{L} = -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu - \frac{1}{2} \sin\epsilon \, B_{\mu\nu} Z'^{\mu\nu} + \delta m^2 \, Z_\mu Z'^\mu$$

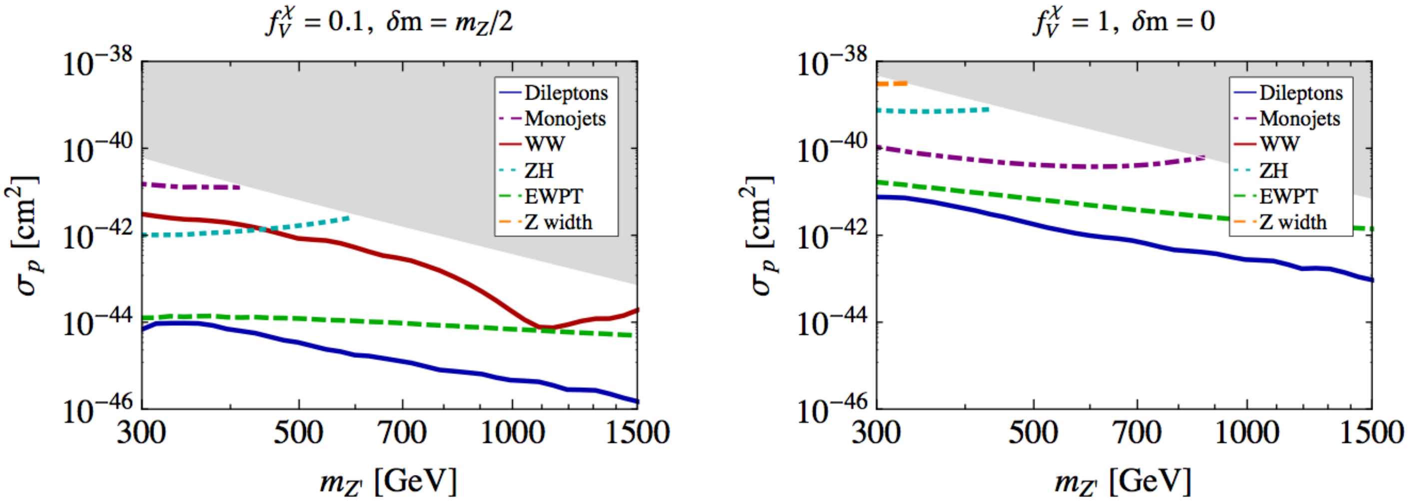
- There are 5 free parameters in this model:
  - The mixing parameters sin ε and δm^2.
  - The direct coupling f_χ between the Z' and the WIMP.
  - The Z' mass $m_{Z'}$ and the WIMP mass m_χ.
- One of these couplings (e.g. sin ε) can be eliminated in favour of the WIMP-proton scattering cross section σ_p.

Fox, Liu, Tucker-Smith, Weiner: arXiv:1104.4127
Frandsen, FK, Sarkar, Schmidt-Hoberg: arXiv:1107.2118

The dark Z’: Constraints



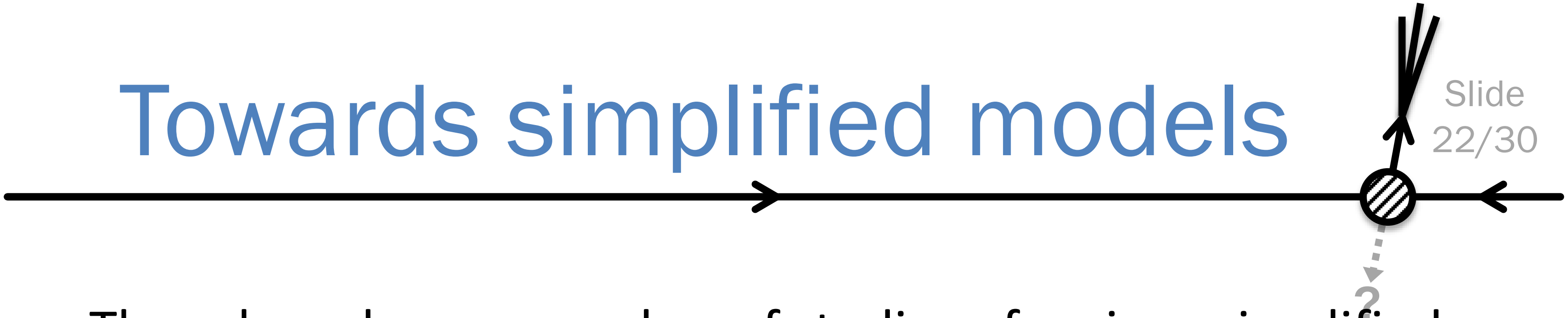
- Constraints on the couplings can then be interpreted directly as constraints on σ_p.



- Since the dark *Z’* has comparable couplings to quarks and leptons, dilepton searches are more constraining than monojet searches, even if we allow for large direct couplings of the Z’ to WIMP.

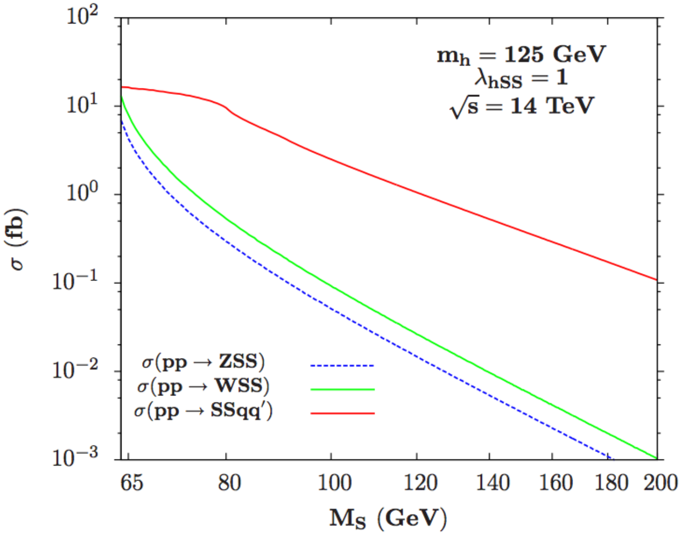
Frandsen, FK, Preston, Sarkar, Schmidt-Hoberg:arXiv:1204.3839

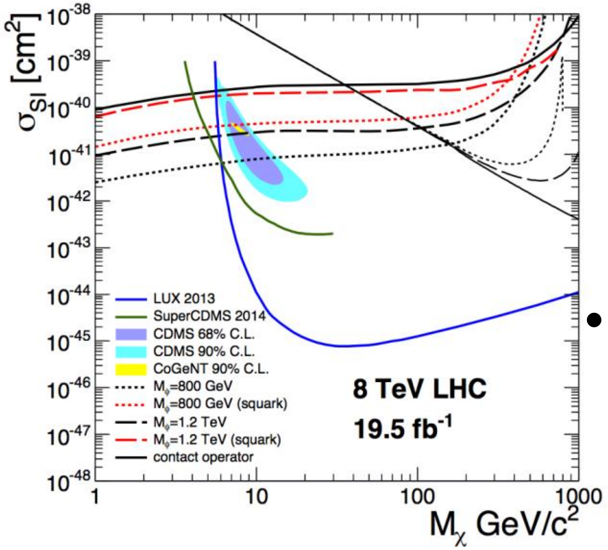
Towards simplified models



- There have been a number of studies of various simplified models involving a new (s-channel or t-channel) mediator that couples to quarks and WIMPs:
  - Higgs-portal models

Djouadi, Lebedev, Mambrini, Quevillon: arXiv:1112.3299
Lopez-Honorez, Schwetz, Zupan: arXiv:1203.2064

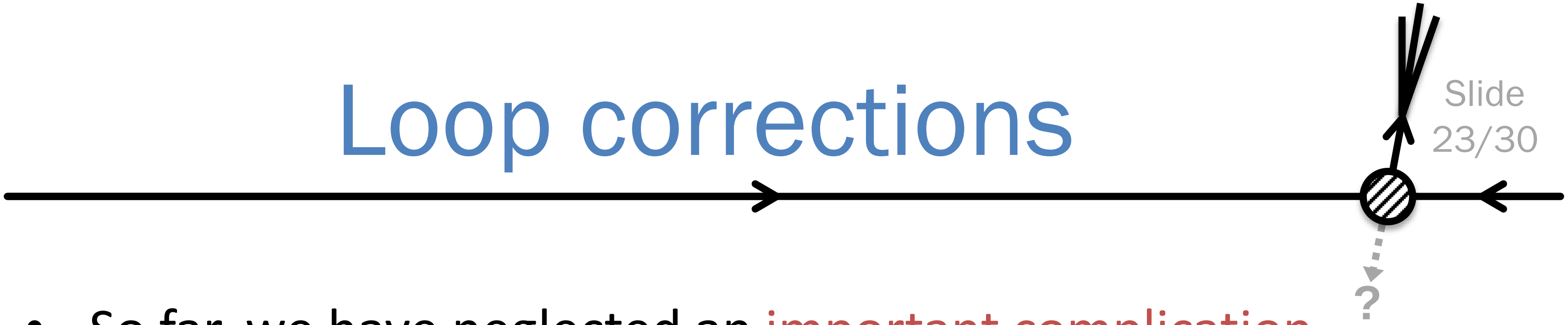




- Squark-like t-channel mediators

An, Wang, Zhang: arXiv:1308.0592
DiFranzo, Nagao, Rajaraman, Tait: arXiv:1308.2679
Papucci, Vichi, Zurek: arXiv:1402.2285

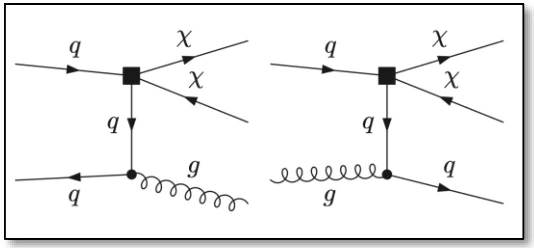
Loop corrections

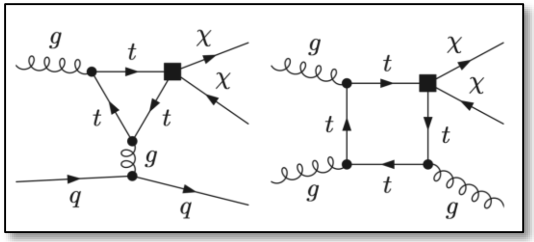


- So far, we have neglected an important complication (important for effective operators AND simplified models): While the LHC probes the TeV scale, dark matter direct detection probes the non-relativistic limit ($v_{\text{WIMP}} \approx 10^{-3}$).
- To calculate direct detection cross sections, we must therefore evolve all (effective) operators from the TeV scale down to the hadronic scale.
- In the process, new interactions may be induced at loop-level, leading to additional operators, which are absent (or small) at the TEV scale.

Heavy-quark loops

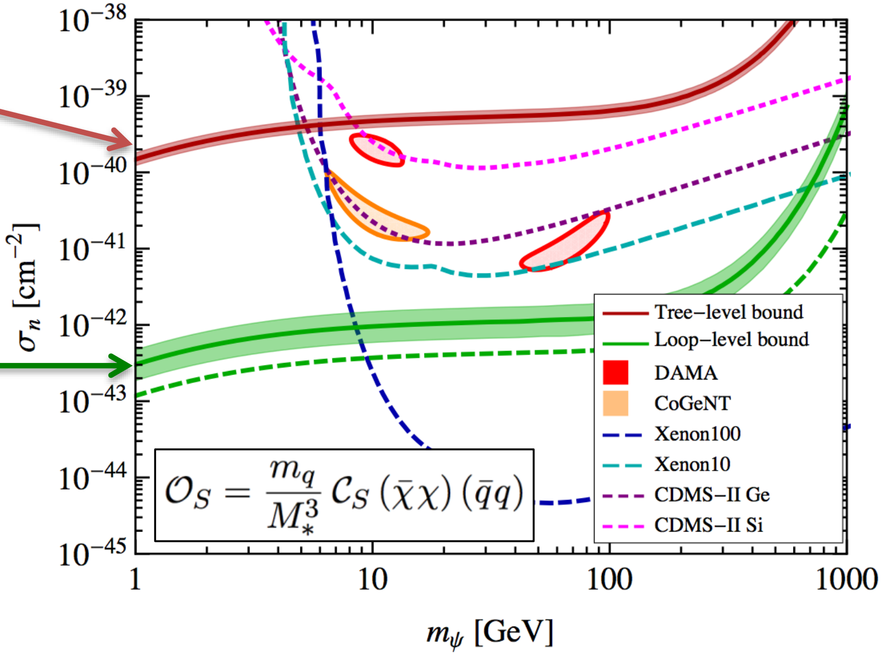
- In some cases, including loops processes can lead to a significant enhancement of the predicted monojet cross section and therefore boosts the bounds from LHC searches.
- Example: WIMP-quark interactions with Yukawa-like couplings





Tree-level bound

Loop-level bound

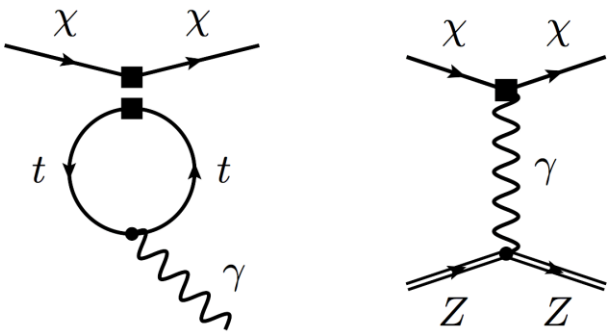


$$\mathcal{O}_S = \frac{m_q}{M_*^3}\,\mathcal{C}_S\,(\bar{\chi}\chi)\,(\bar{q}q)$$

Haisch, FK, Unwin: arXiv:1208.4605

Loop-induced dipole moments

- In other cases, heavy-quark loops can induce WIMP dipole moments, leading to a strong enhancement of direct detection bounds.



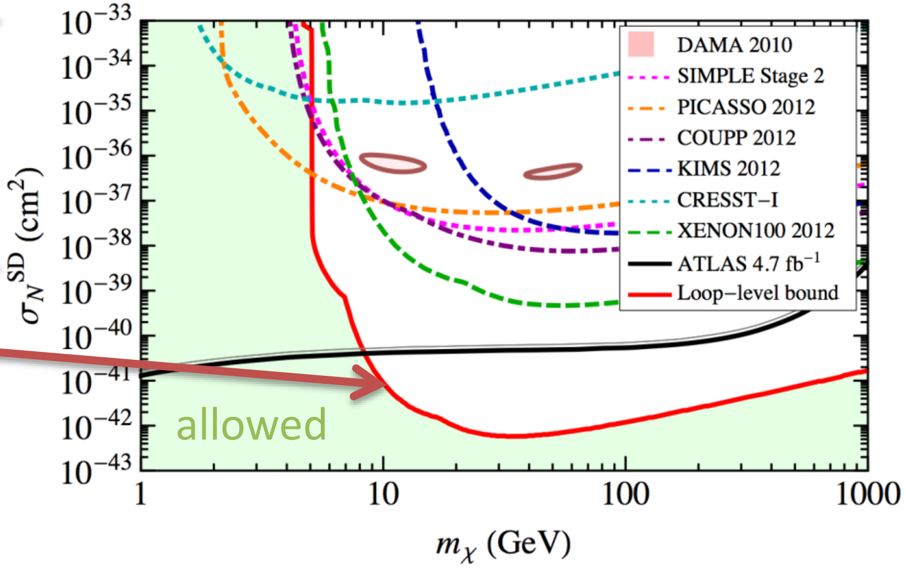
- Example:

$$\mathcal{O}_T = \frac{1}{M_*^2}\left(\bar{\chi}\sigma_{\mu\nu}\chi\right)\left(\bar{q}\sigma^{\mu\nu}q\right)$$

(tree-level bounds)

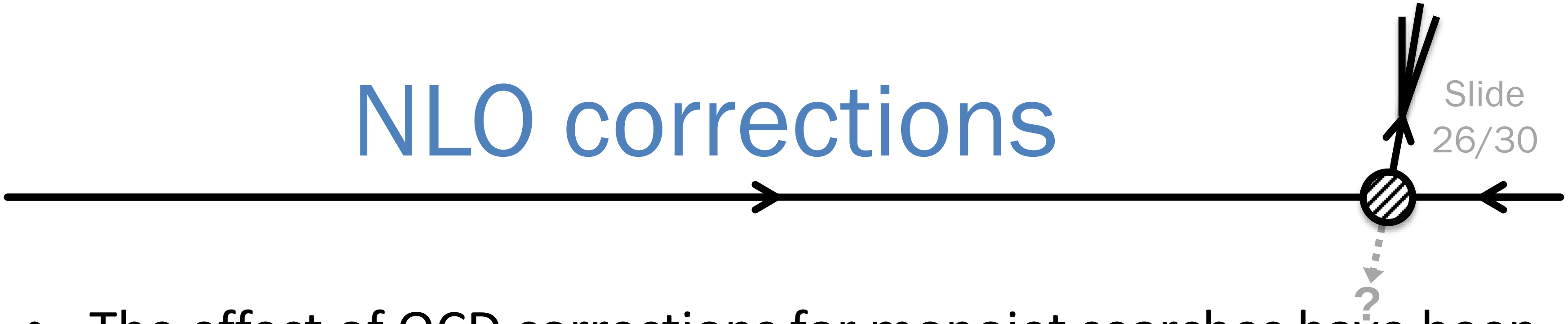
$$\mathcal{O}_M = \frac{1}{M_*^2}\,\mathcal{C}_M\left(\bar{\chi}\sigma_{\mu\nu}\chi\right)F^{\mu\nu}$$

(loop-level bound)

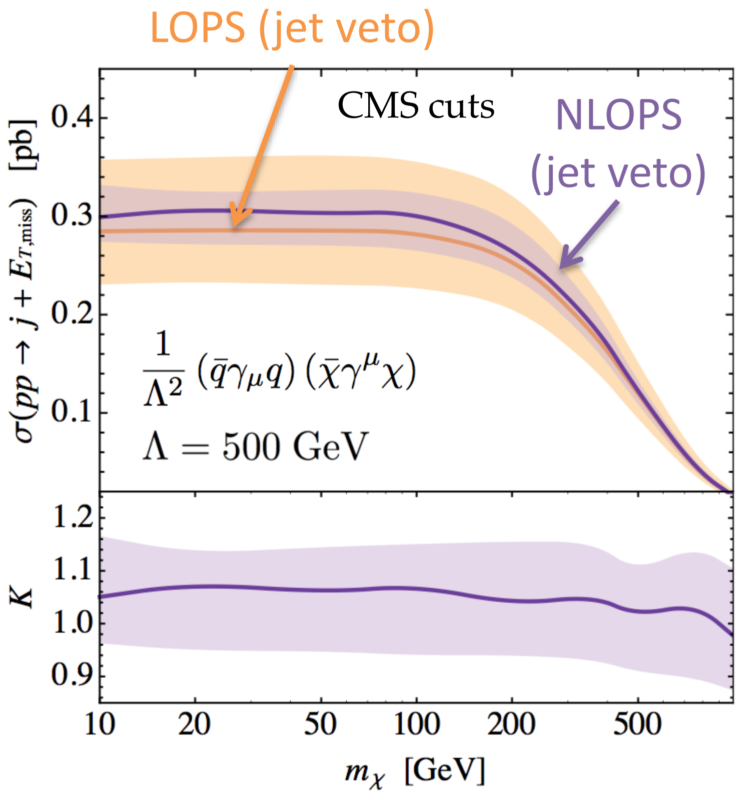


Haisch, FK: arXiv:1302.4454

NLO corrections



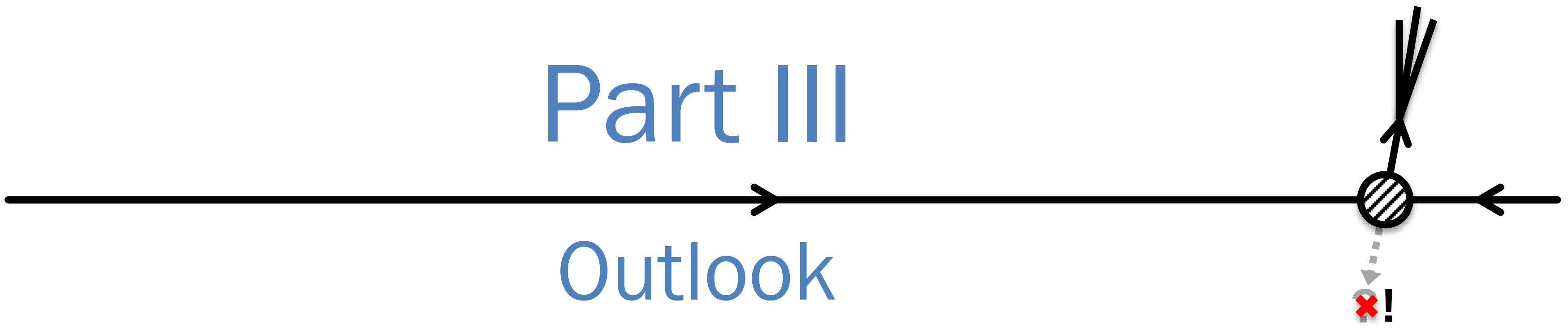
- The effect of QCD corrections for monojet searches have been systematically investigated using MCFM and POWHEG.
- For most operators, NLO corrections are small once parton showering is included.
- These corrections are still important, because they reduce scale dependencies and hence the theoretical uncertainty of the signal prediction.



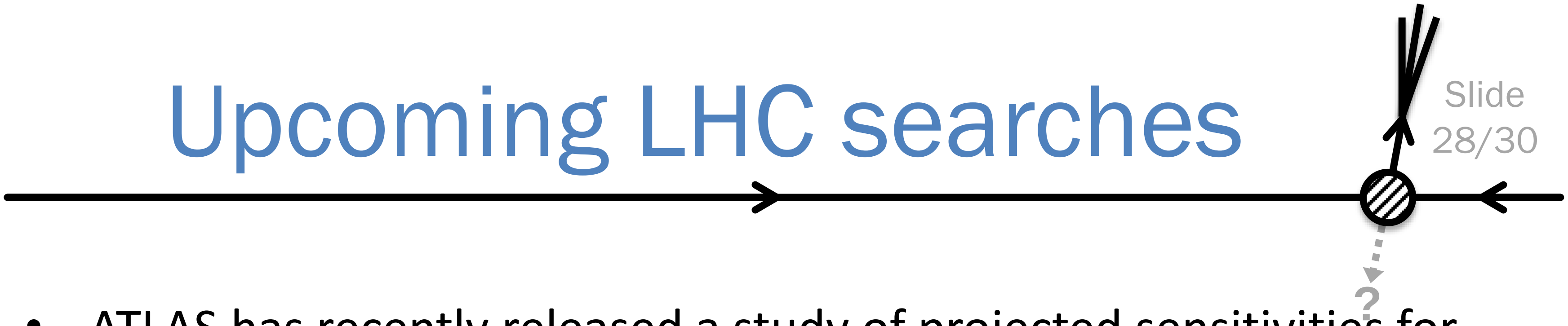
Fox, Williams: arXiv:1211.6390
Haisch, FK, Re: arXiv:1310.4491

Part III

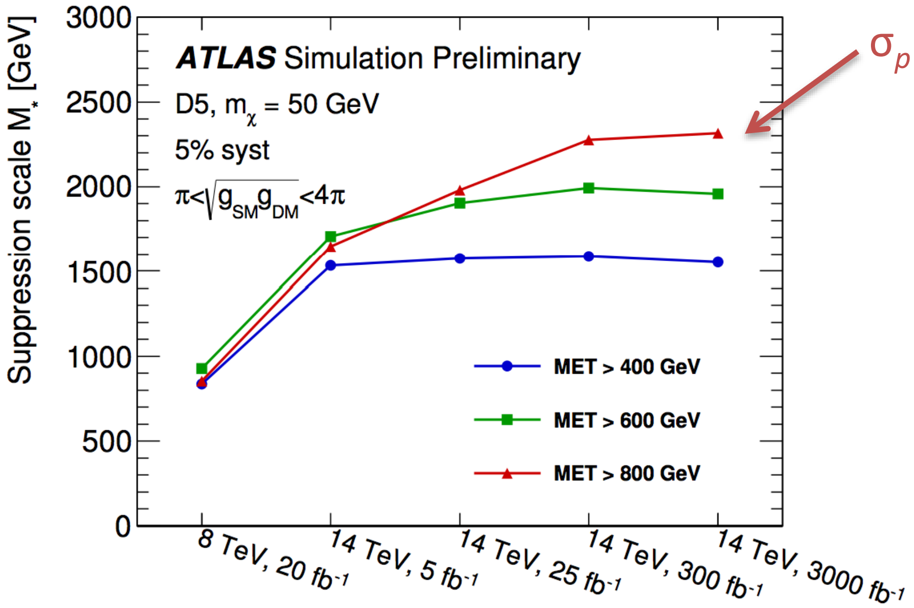
Outlook



Upcoming LHC searches



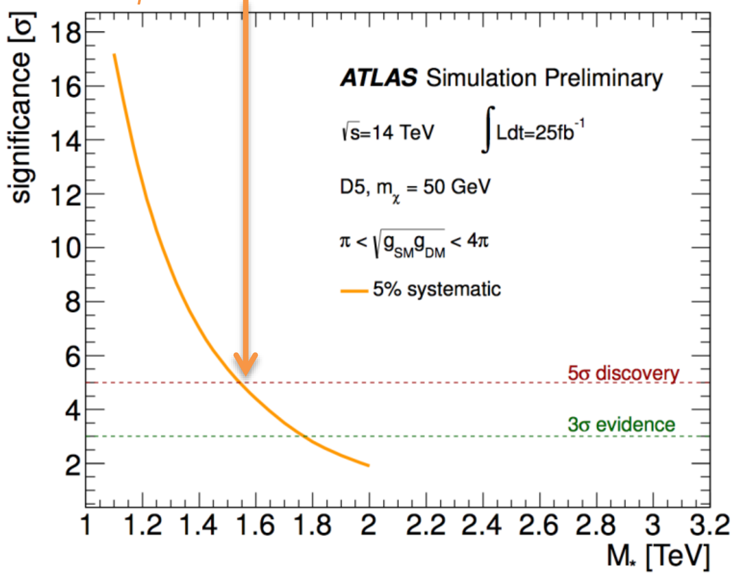
- ATLAS has recently released a study of projected sensitivities for monojet searches at the 14 TeV LHC.
- Conclusion: Higher com energy helps a lot, luminosity not so much.



$\sigma_p = 3 \times 10^{-41}\ \text{cm}^2$

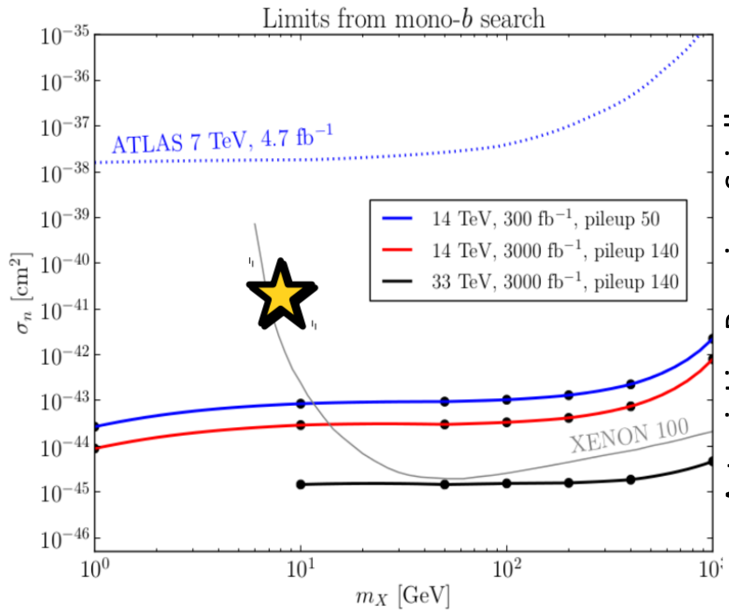
$\sigma_p = 2 \times 10^{-40}\ \text{cm}^2$

ATLAS: ATL-PHYS-PUB-2014-007

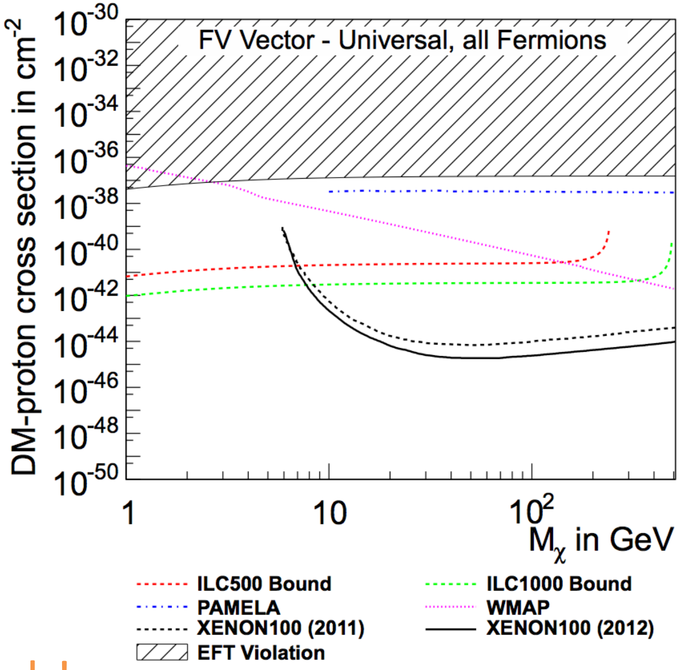


Beyond LHC monojet searches

- It is conceivable that other search channels benefit even more from higher energy and more luminosity.
- Another key issue is to study the reach of dark matter searches at the ILC or 100 TeV proton colliders.



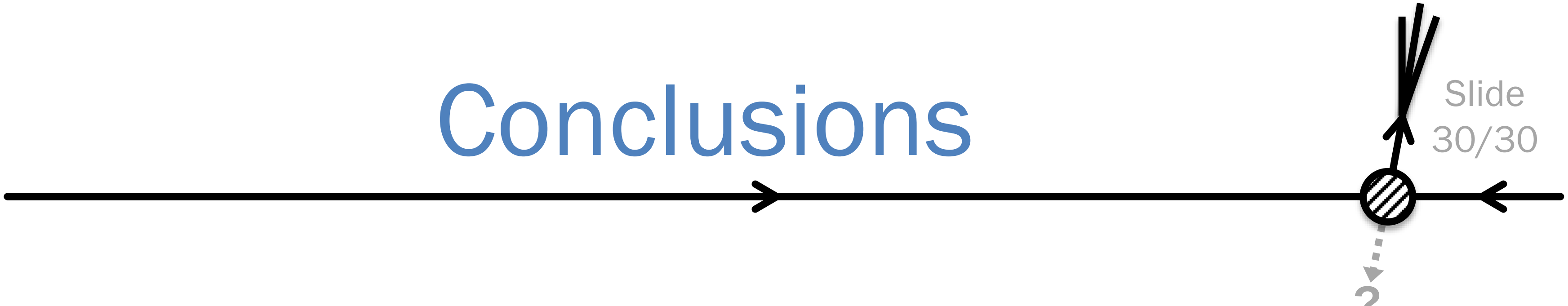
Artoni, Lin, Penning, Sciolla, Venturini: arXiv:1307.7834



Dreiner, Huck, Kraemer, Schmeier, Tattersall: arXiv:1211.2254

Plenty of opportunities for further research!

Conclusions



- The LHC is very well suited to constrain the WIMP production cross section and therefore constrain the same interactions as direct and indirect detection experiments.
- There is a wide range of possible search channels: Monojet, monophoton, mono-Z/W and invisible Higgs searches.
- Effective operator provide a convenient framework to interpret these searches, but the description becomes inaccurate whenever the intermediate particles can be on-shell.
- The first step beyond EFTs is to analyse LHC searches using simplified models (for example a Z’ vector mediator).
- Heavy-quark loops and NLO corrections can lead to important effects and should therefore be included in future analyses.