Beyond
the DM effective theory
&
a Simplified Model

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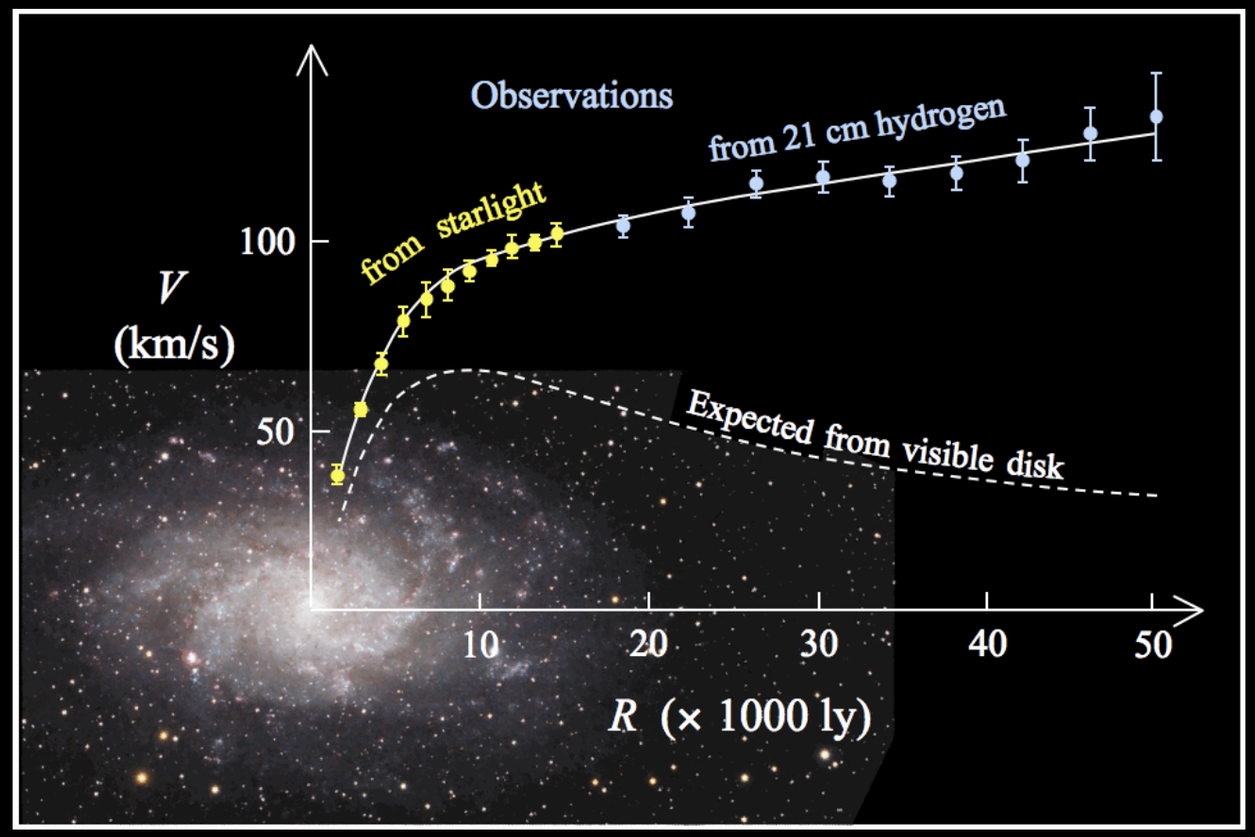
arXiv:1506.06556

COSPA 2015

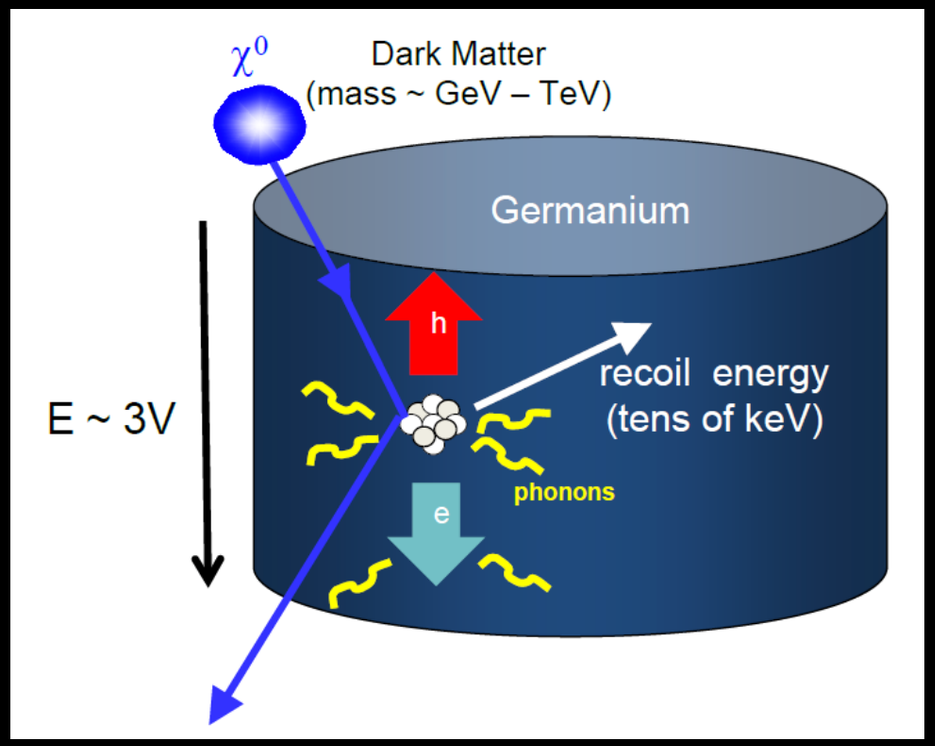


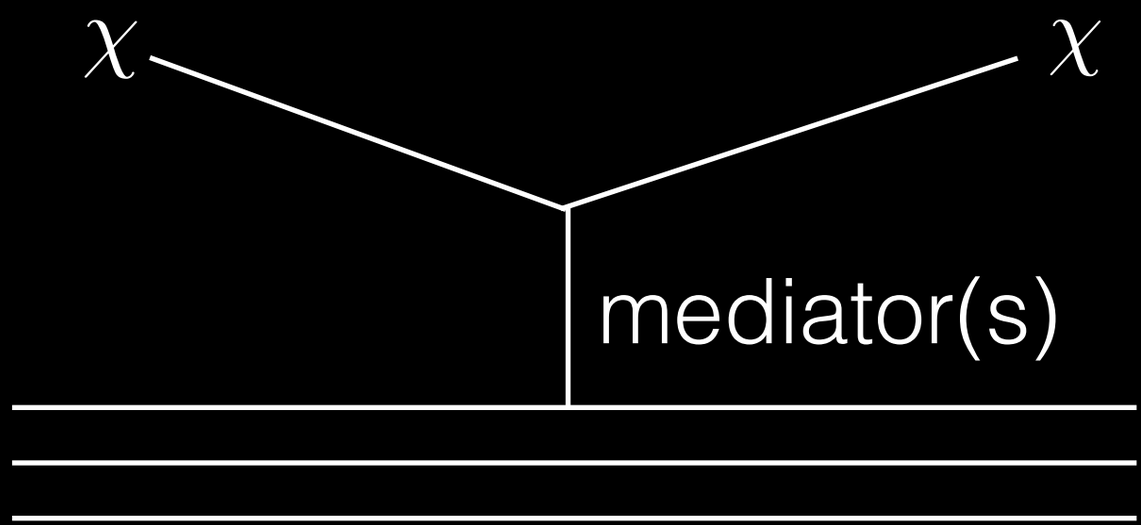
- We don’t know how many dark matters exist
- We don’t know the type of dark matter(s)
- We don’t know the interaction among dark sectors and Standard Model sectors.

ONLY

- We know the existence of a dark sector.

Dark matter Direct Search (DD)





- Energy transfer is very small compared to mediator(s)

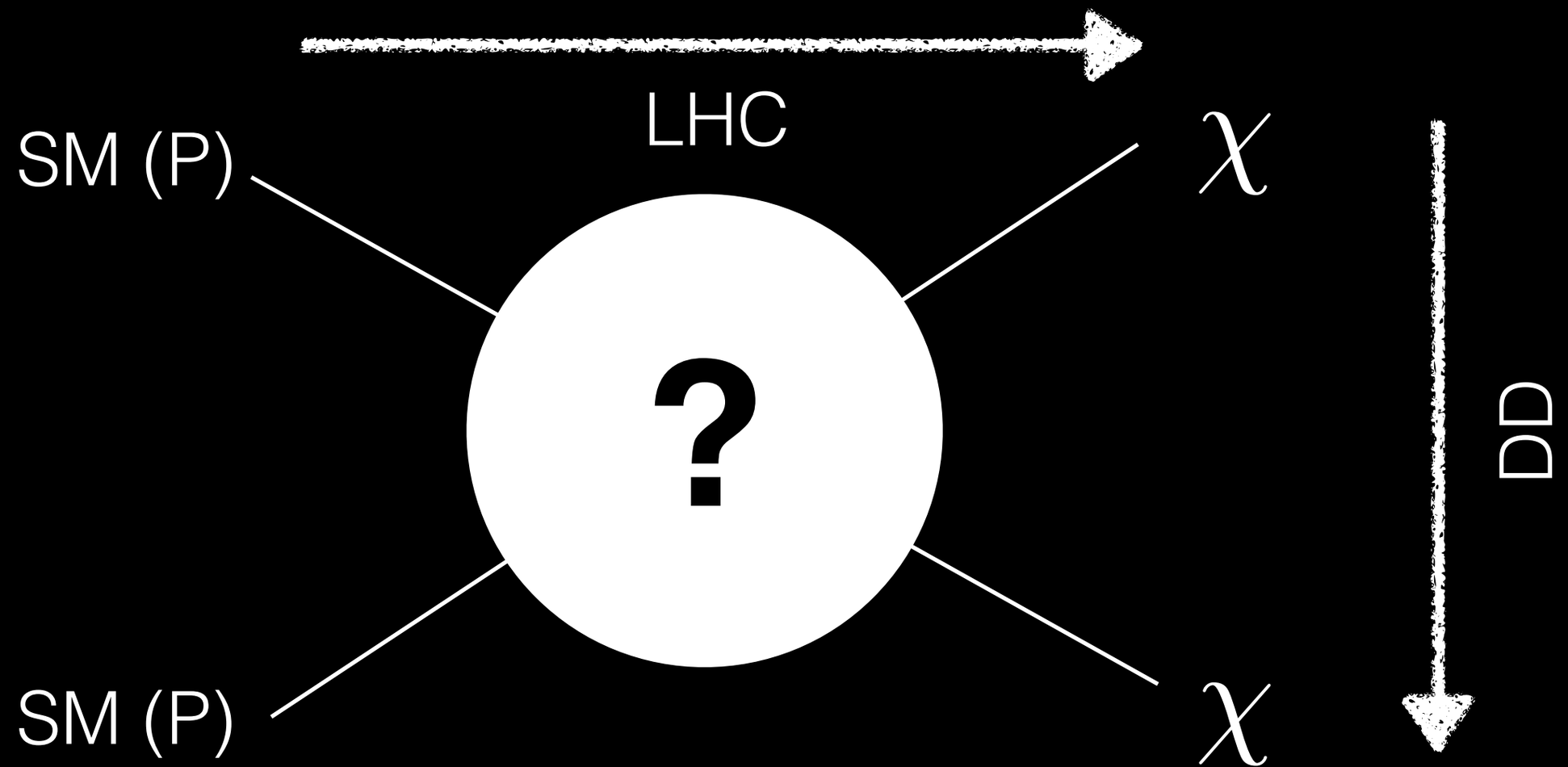
- Interpreted with finite effective operators.
- Insensitive to mediator(s)'s properties.

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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

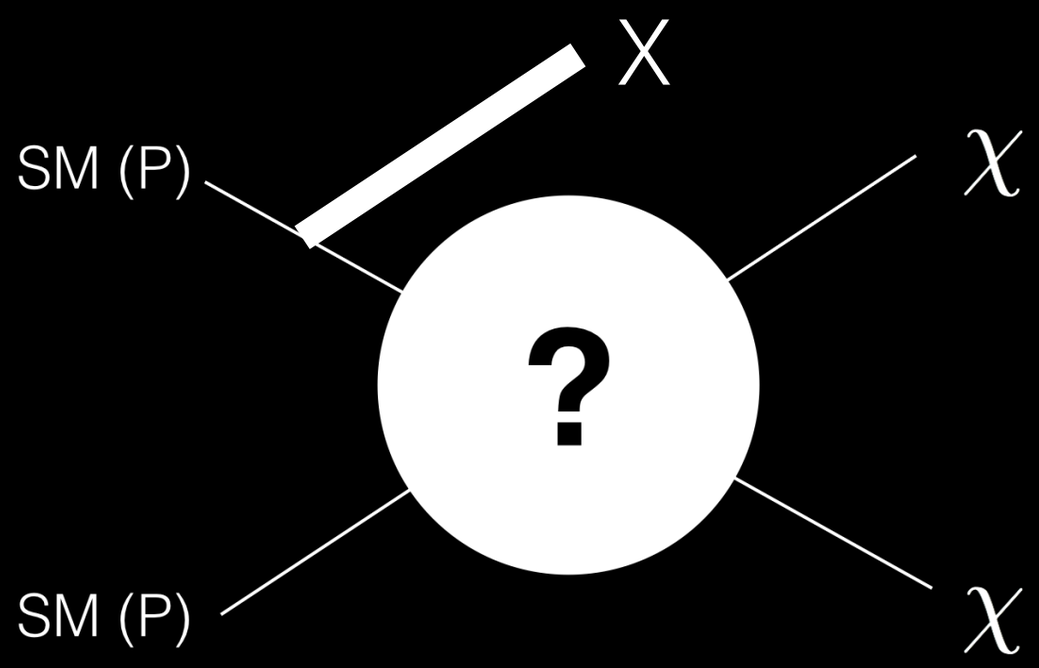
Tim Tait. et.al.
Phys.Rev. D82 (2010) 116010

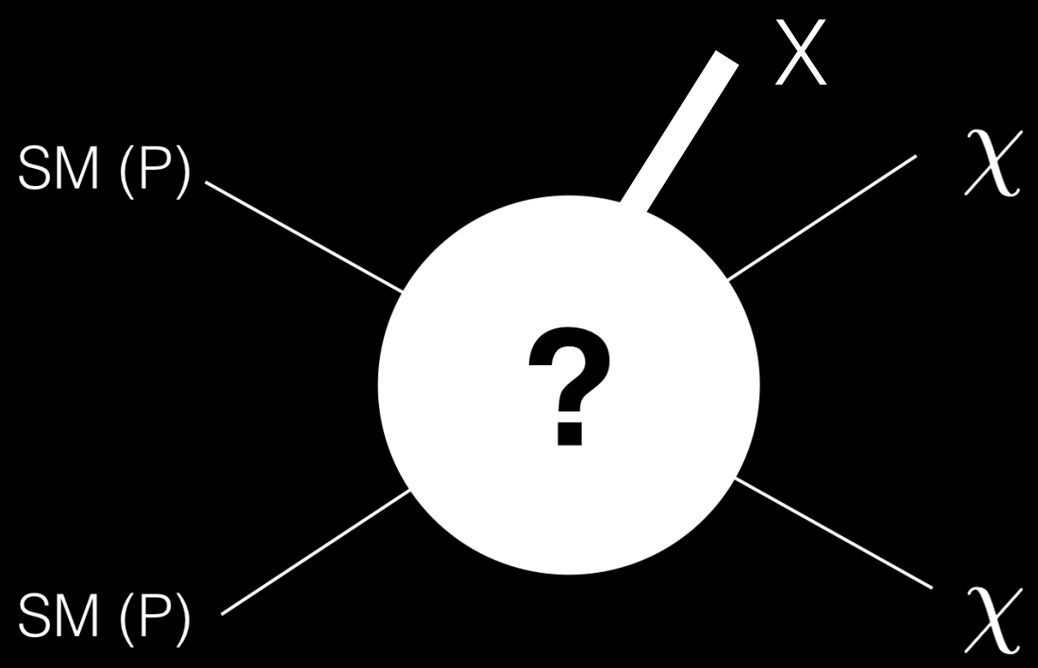
Orthogonal search@LHC



Q: What will be the **MINIMAL** search channel ?
(A channel that needs minimum **assumptions**)

Mono-X
(+Missing Energy)



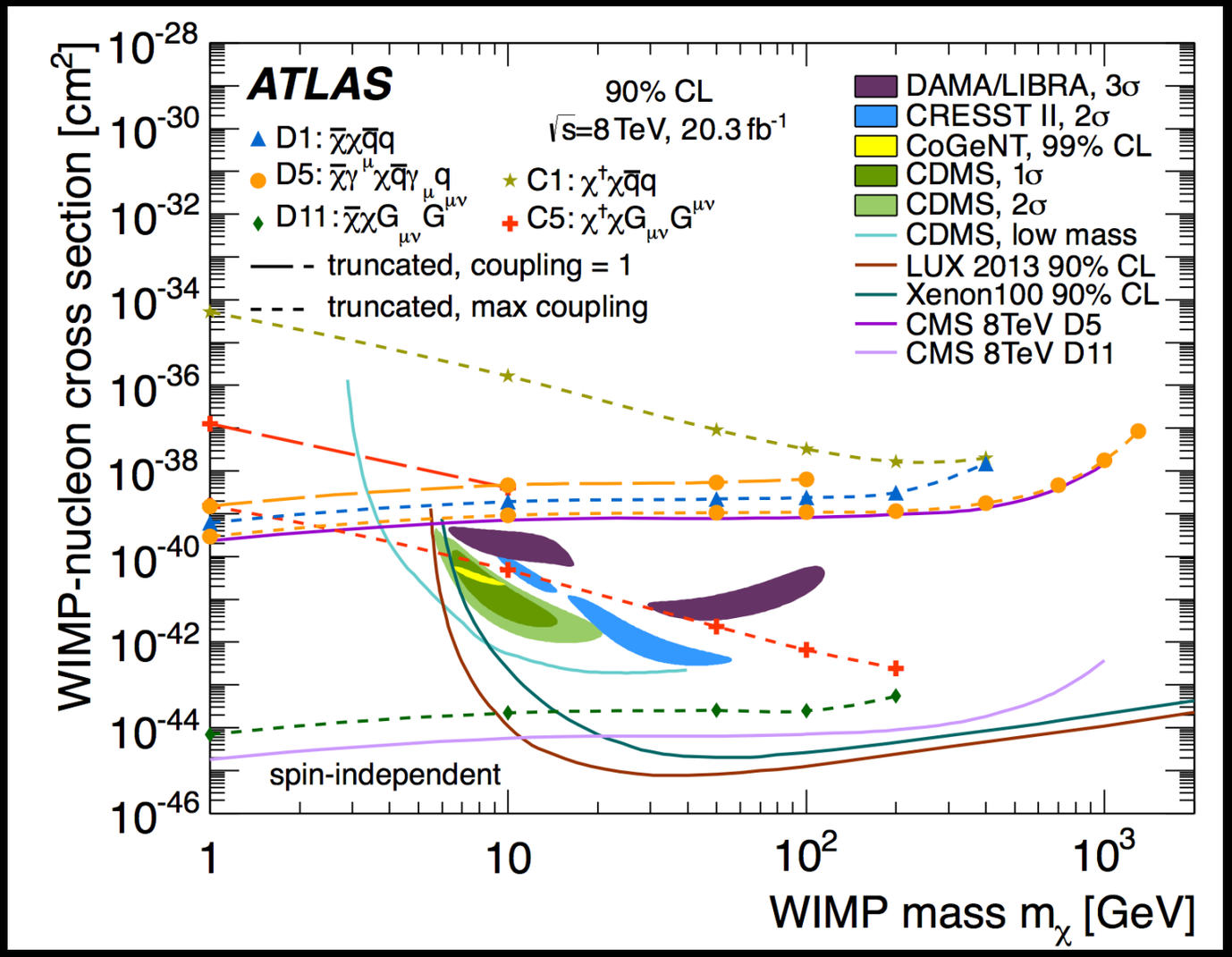


X can be:

- QCD jet (from Initial state radiations or Heavy quarks)
- Electro-weak Gauge bosons or the Higgs particle

LHC and DD

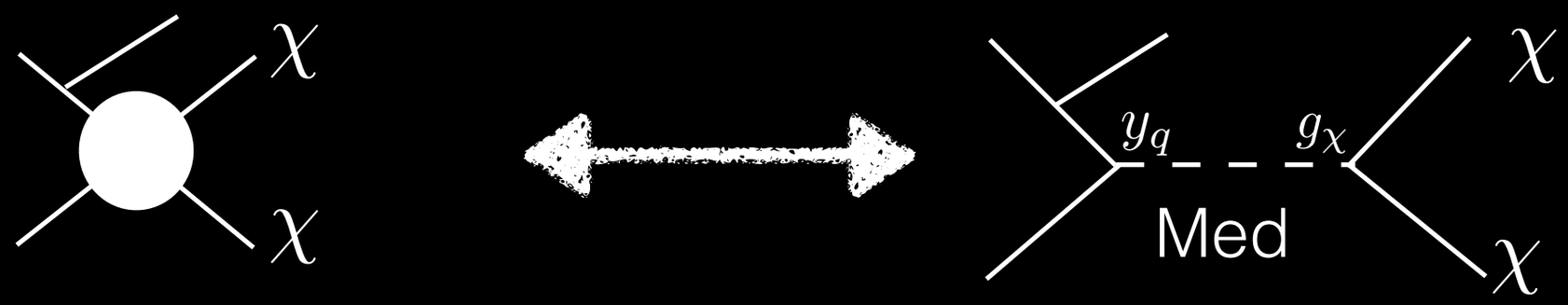
- Can we compare results from DD and from LHC ?



Comparison
the LHC null results
with DD using
effective operators

Limits of effective operator approaches @ LHC

- The LHC is high energy machine that has the POWER to be beyond the effective couplings.



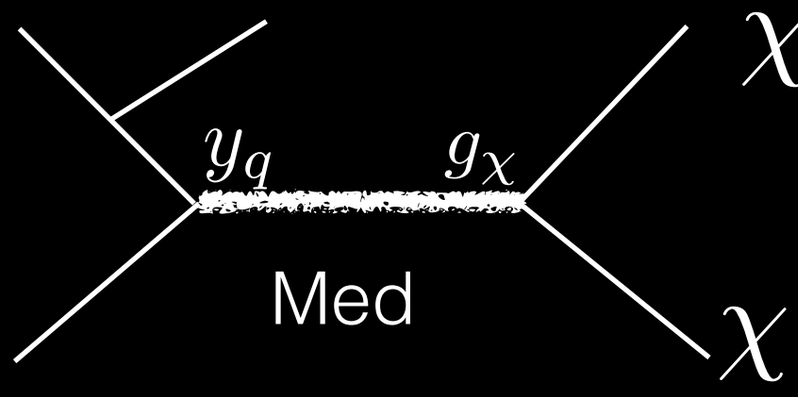
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ $\frac{g_\chi y_q}{M_{med}^2}\bar{\chi}\chi\bar{q}q$

Energy Transfer $Q_{tr} < M_{med} \longrightarrow \Lambda > \frac{Q_{tr}}{\sqrt{g_\chi y_q}} > \frac{Q_{tr}}{4\pi} > \frac{m_\chi}{2\pi}$

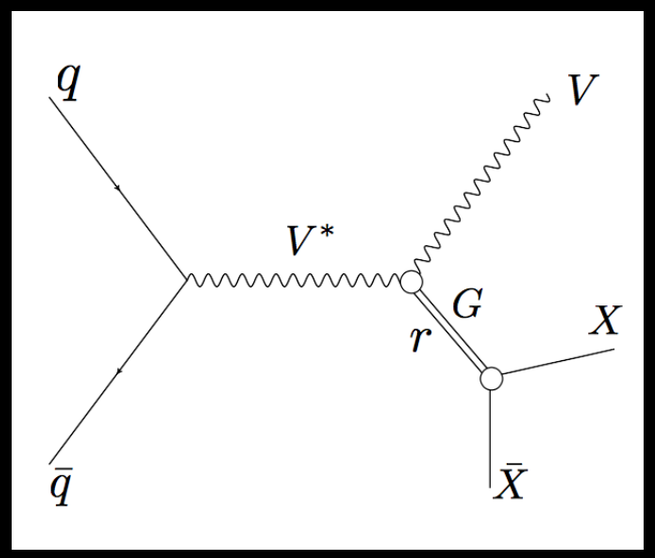
Busoni et.al. arxiv:1402.1275

Beyond the effective operators

- Next step: Representative model (Simplified model)



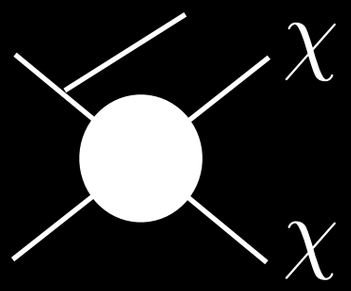
Unzip the effective operators using the type of the Mediator, Spin = 0, 1, 2



Spin = 2, Hyun Min Lee, Veronica Sanz, MP arxiv:1306.4107

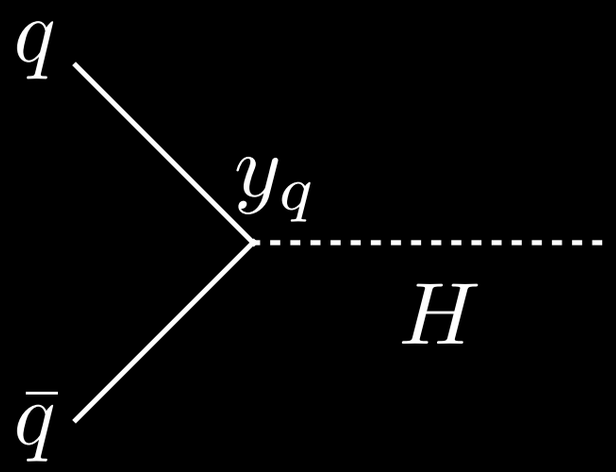
Can Simplified Models represent **all** good BSM models?

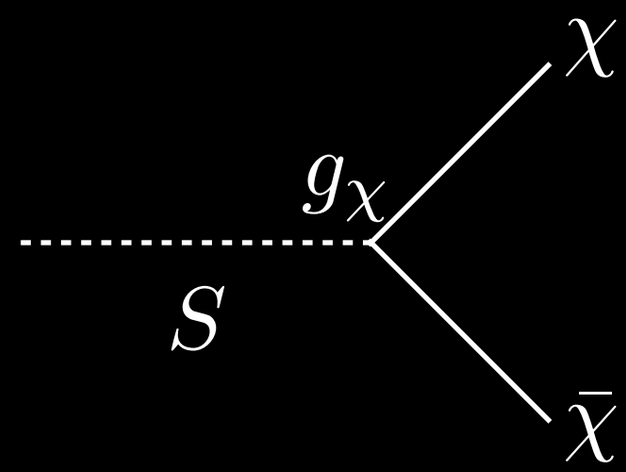
Scalar operator



$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$

- A scalar field interacts with SM fermions, and the other scalar field for the Dark matter



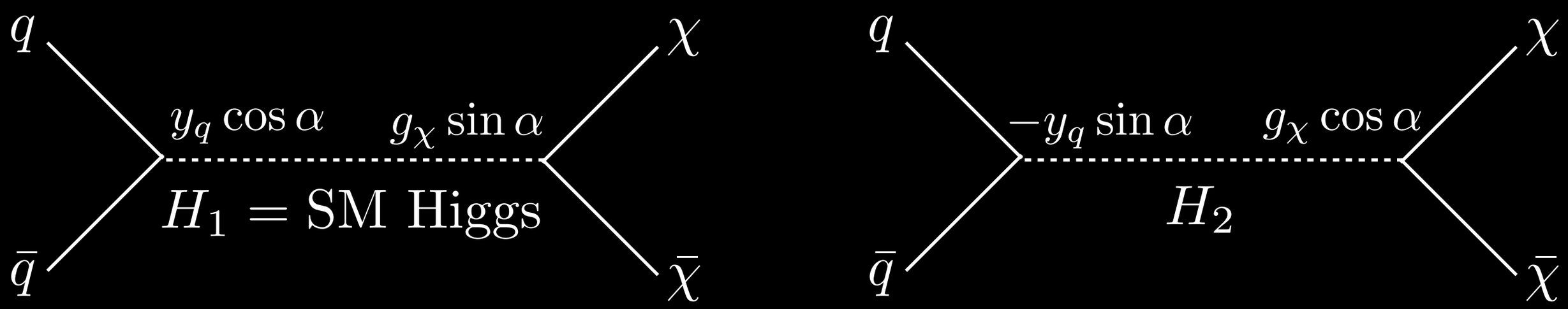


$$\mathcal{L} \ni -\lambda_{HS} H^\dagger H S^2 - \mu_{HS} S H^\dagger H - \mu_0^3 S - \frac{\mu_s}{3!} S^3 - \frac{\lambda_S}{4!} S^4$$

allowing mixing beween H and S

Beyond the Simplified Model

- We have two diagrams for the DM productions @ LHC.



- Two diagrams have the relative opposite sign in the coupling.

- Two propagators have different “resonance” masses.

LHC analysis

- LHC analyses are divided into two major parts:

1. Theoretical Cross section σ
   - Relative “-” gives effects on the cross section

2. Effective Cross section $\sigma \times \epsilon$
   - Different masses of internal lines will give effects on the efficiencies ϵ of “analysis cuts”

Effects on the ϵ

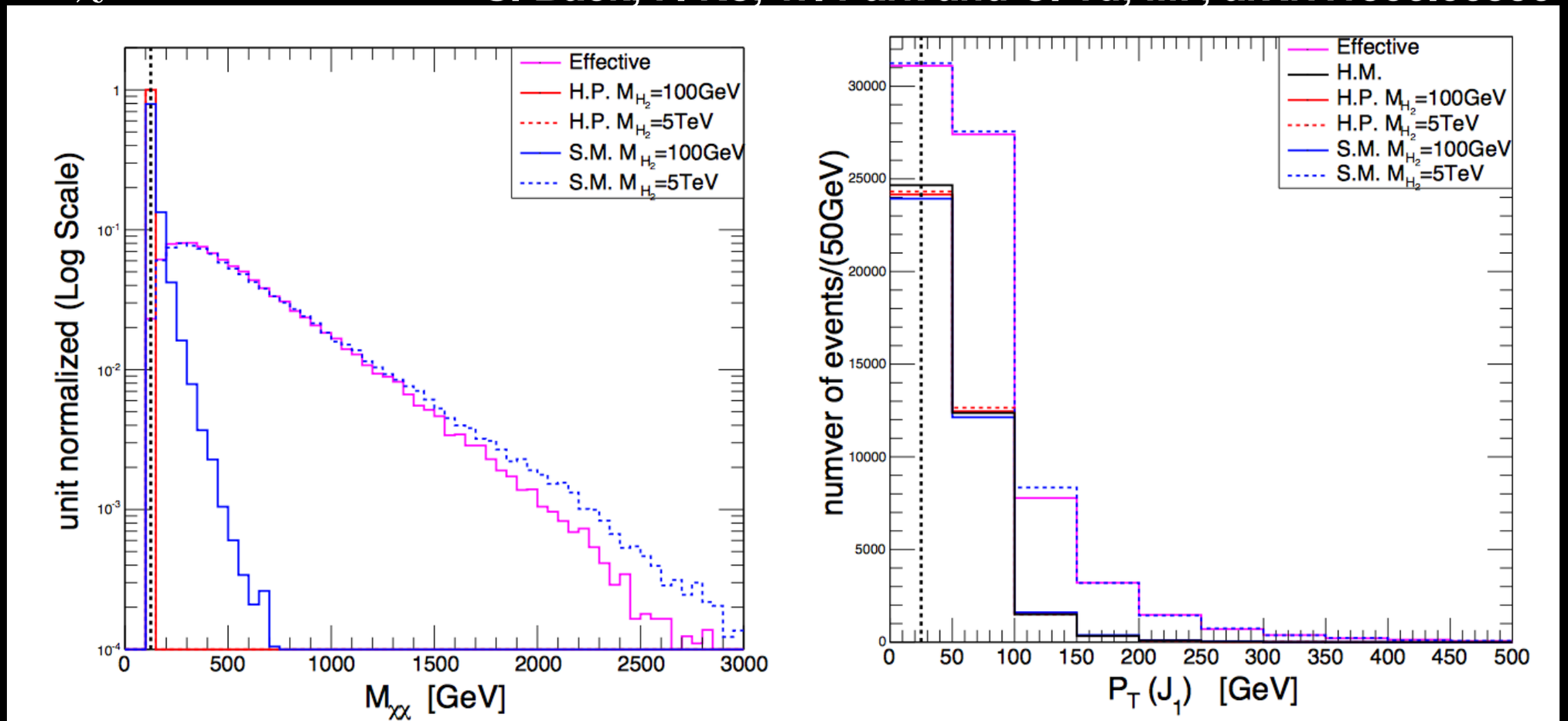
- If the mass of S-channel resonance is within the LHC energy range, the $\mathbf{Q_{tr}}$ can be localized near that resonance mass spectrum.

- In the Higgs Portal (H.P.) model, at least the SM Higgs is within the energy range of the LHC.

Mono-jet search

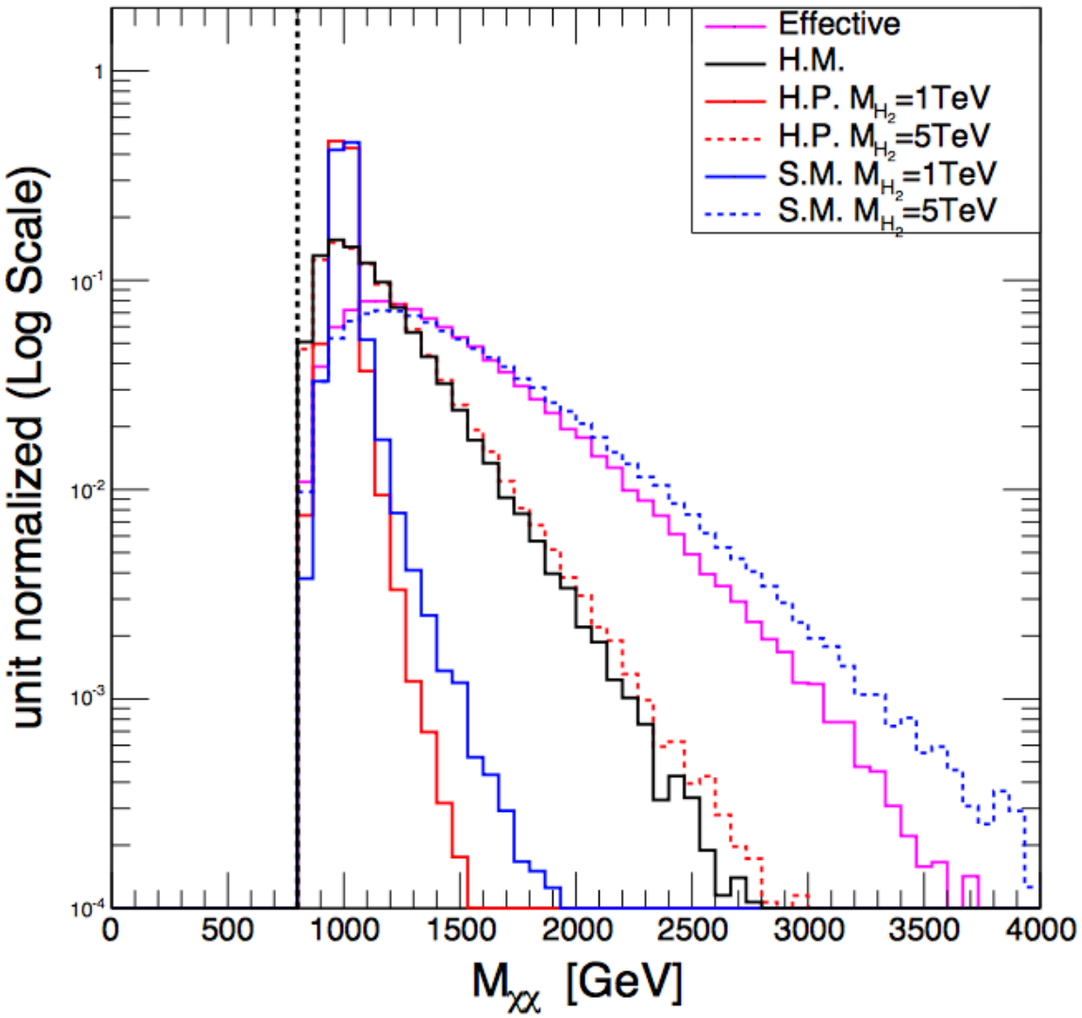
$m_\chi = 50\,\mathrm{GeV}$

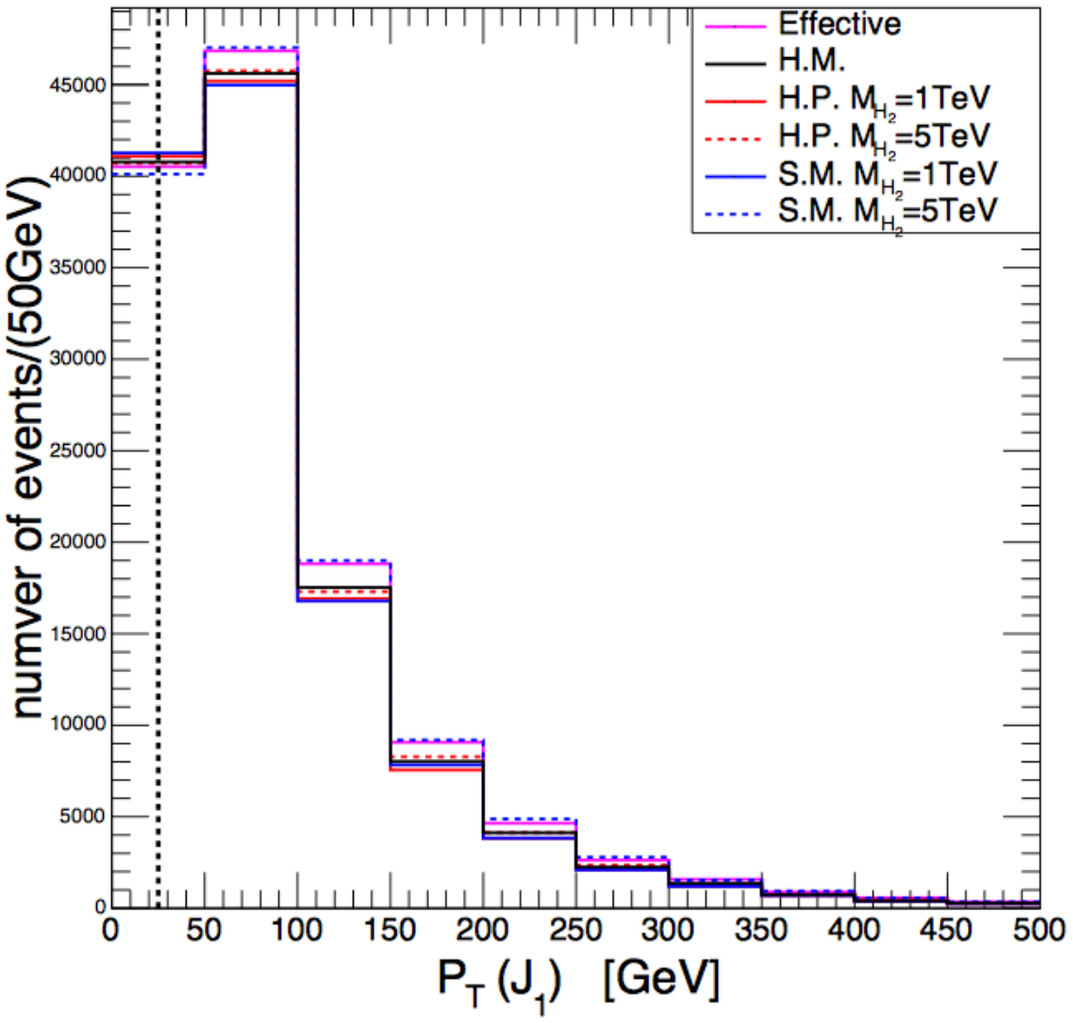
S. Baek, P. Ko, WI Park and C. Yu, MP, arXiv:1506.06556



- To compare the effects from mediator(s)
  - Effective : Effective operator
  - S.M.: Simplified Model with one scalar S
  - H.M. : The SM Higgs boson as a mediator
  - H.P. : Higgs portal model with a SM Higgs and S

$m_\chi = 400\,\mathrm{GeV}$

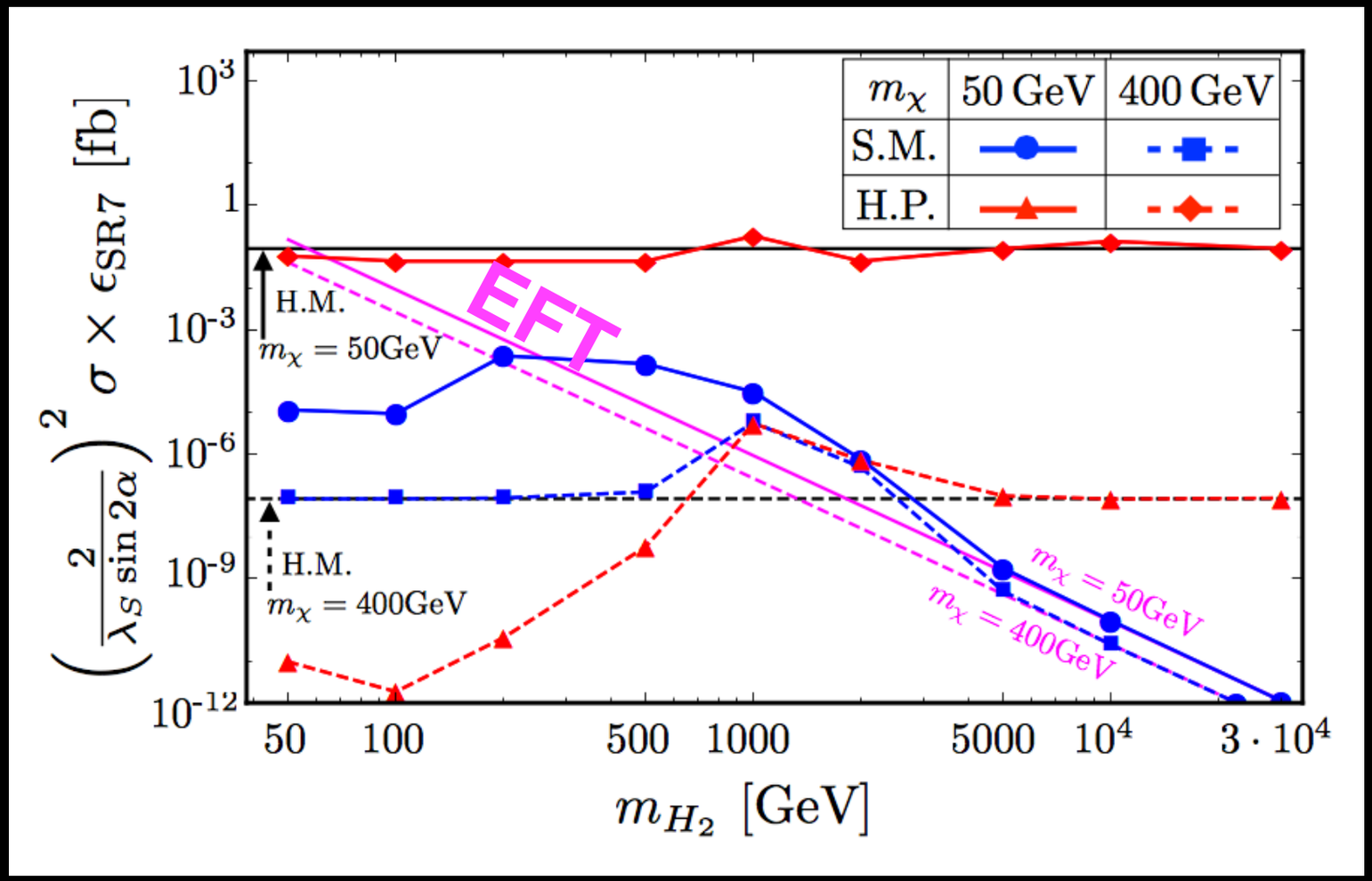




$$\Gamma_S = \frac{m_S}{8\pi}$$

S. Baek, P. Ko, WI Park and C. Yu, MP, arXiv:1506.06556

Effects from Mediators

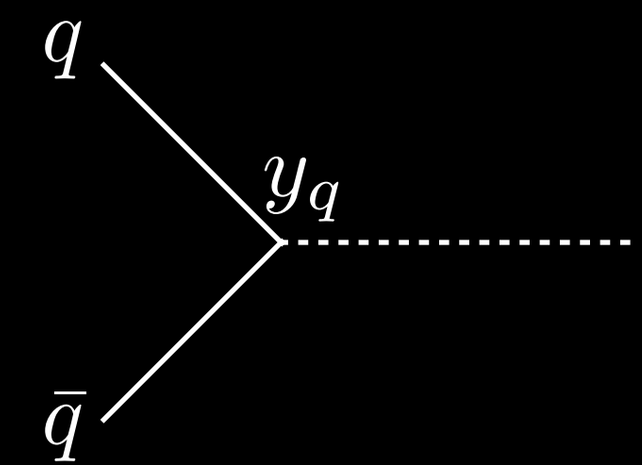


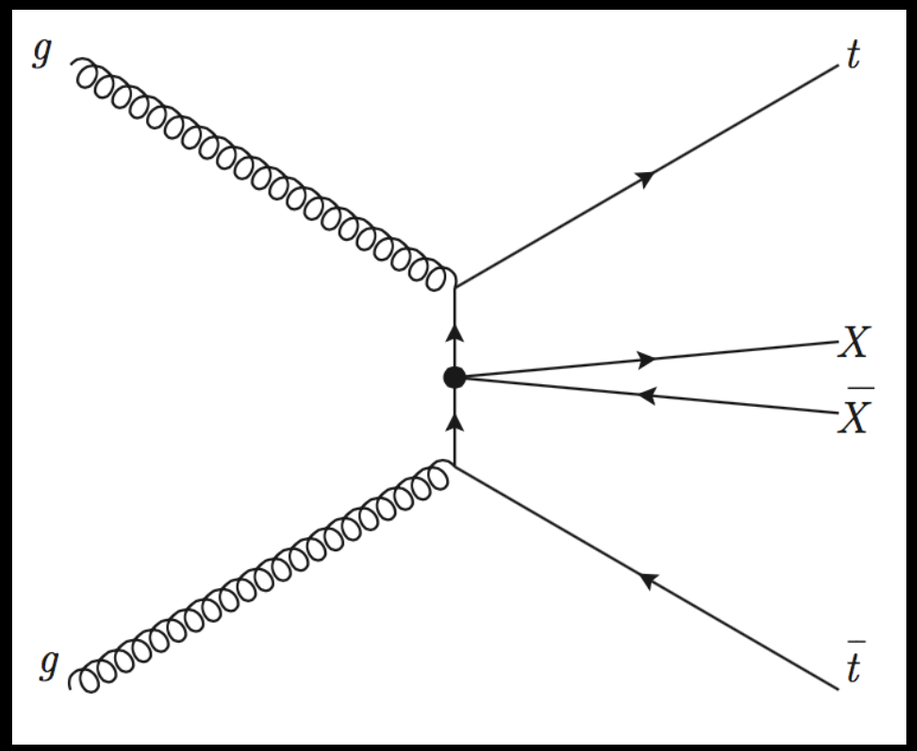
$\epsilon_{SR7}\,(\mathrm{MET} > 500\,\mathrm{GeV})$

Divided by common coupling factor
- Effects from the two propagators
and kinematics from the resonant masses.

Heavy flavor channel

- Since the scalar operator is proportional to the mass of SM quarks, ttbar+ MET becomes important channel too.





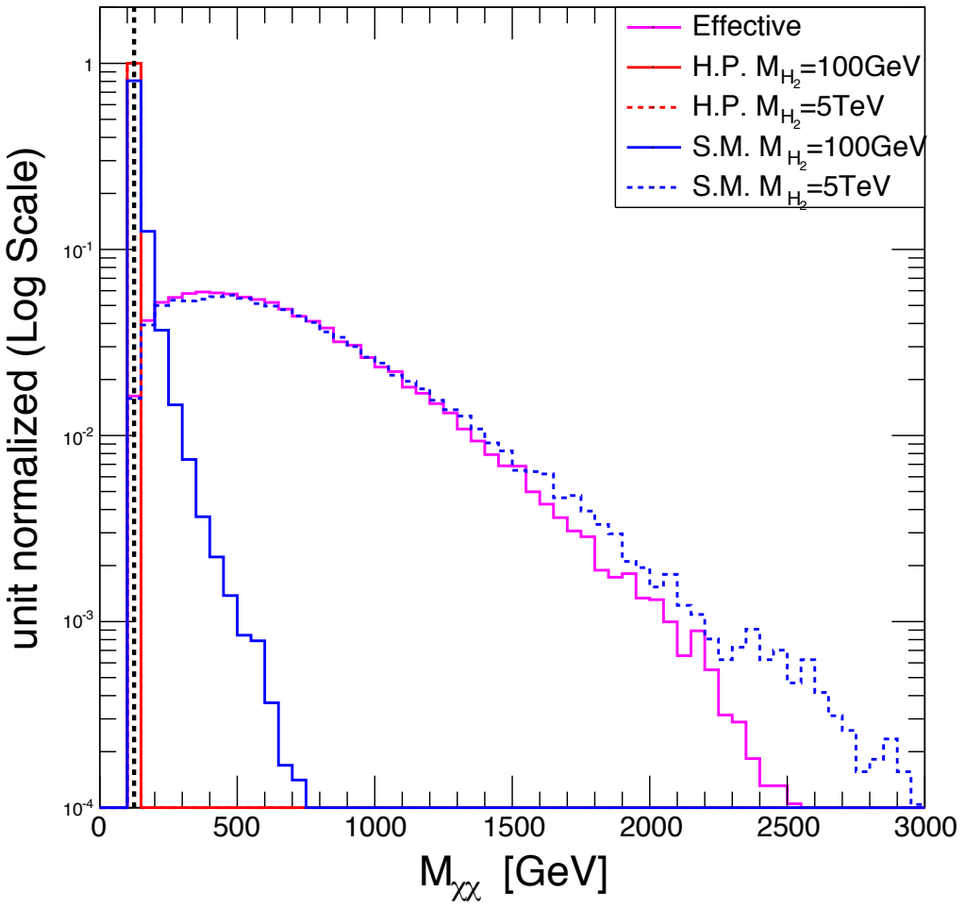
Lin et.al, arxiv:1303.6638

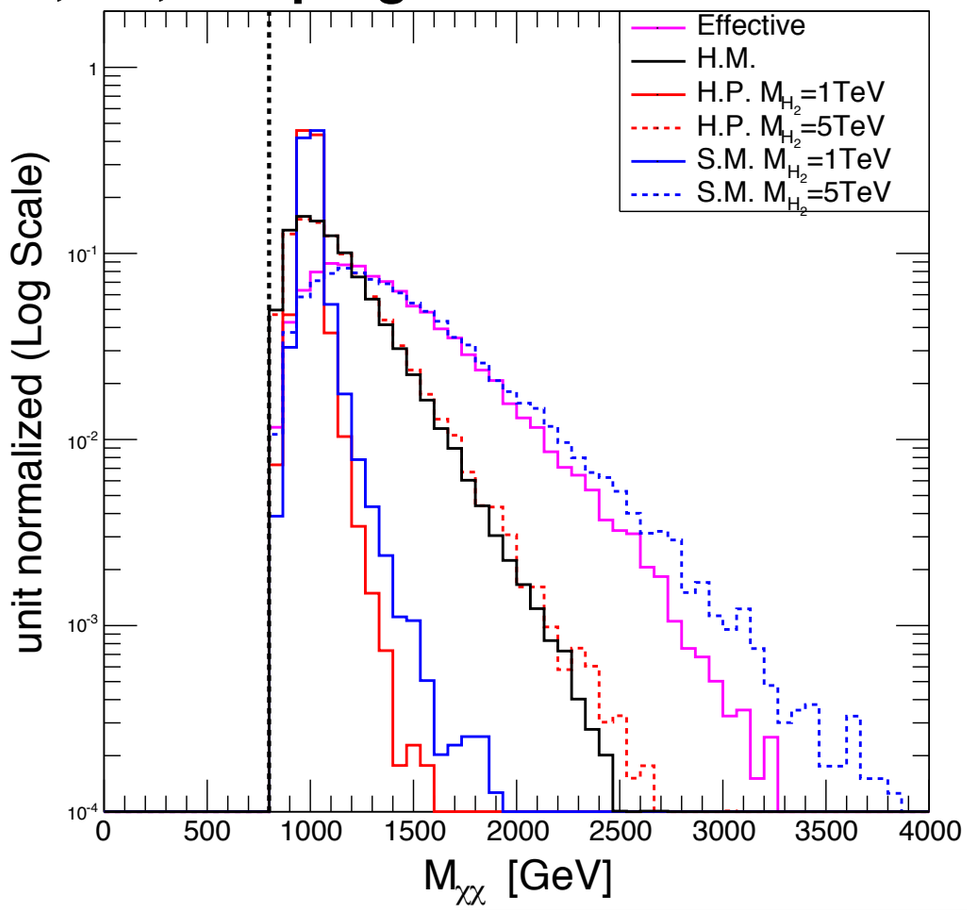
The **Kinematics** depends on Mxx

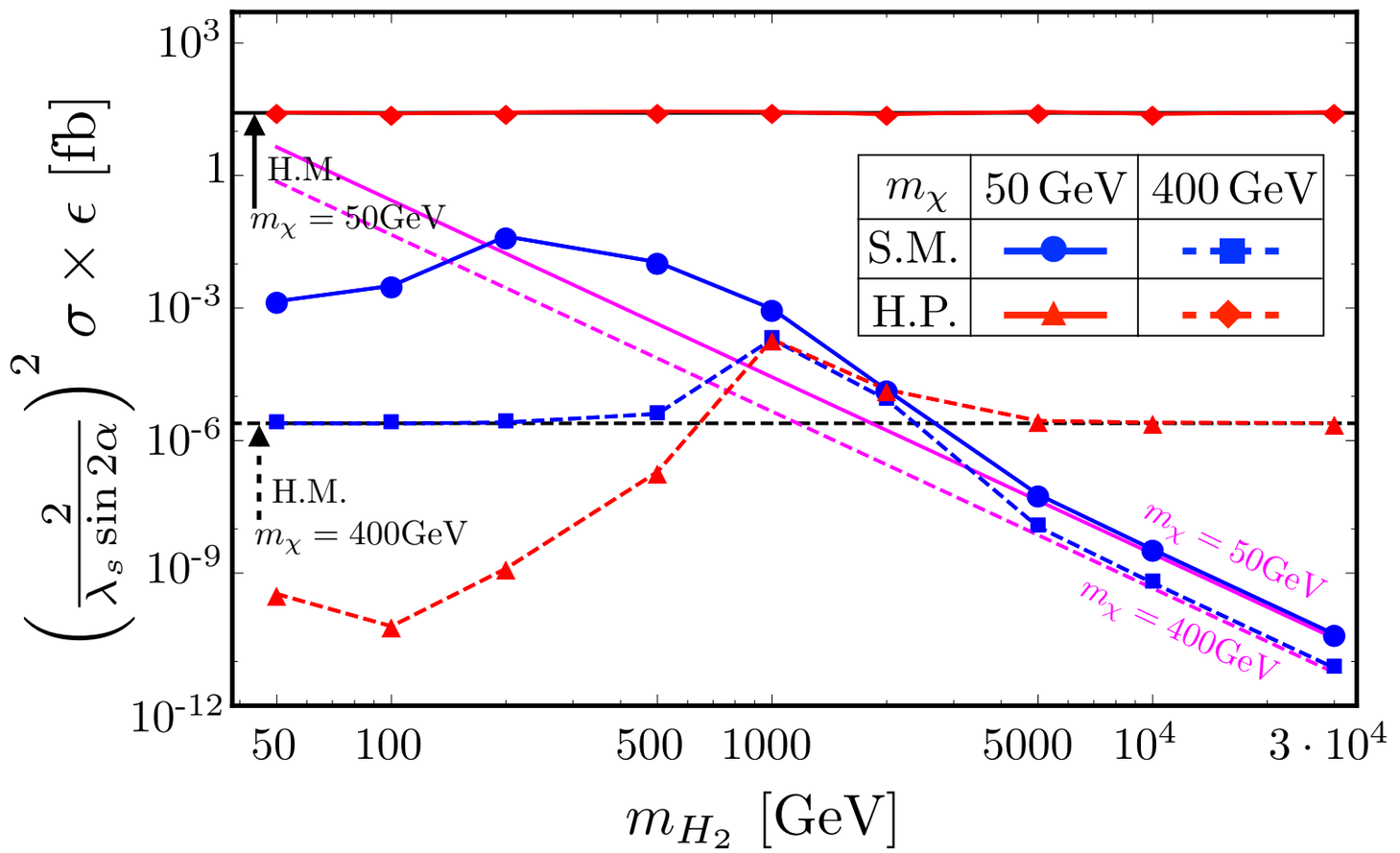
efficiencies of analysis cuts,

no matter what complicated analysis ATLAS/CMS use (MTW)

S. Baek, P. Ko, WI Park and C. Yu, MP, in a progress…





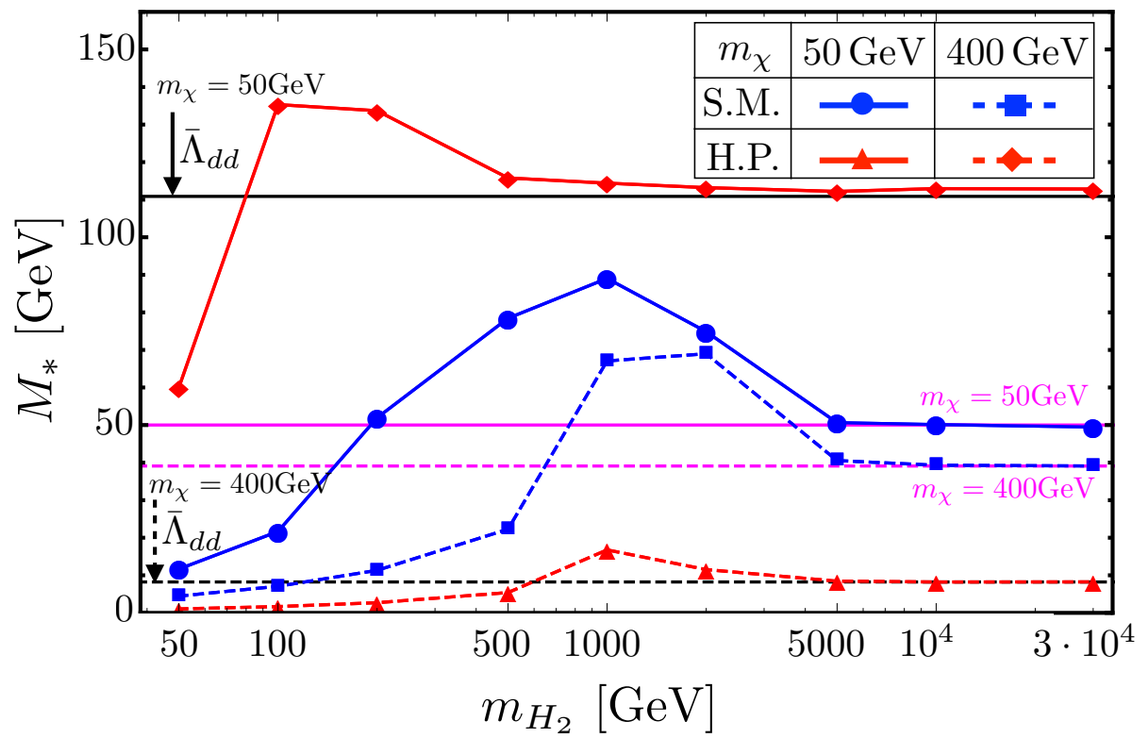


Same behavior with a case of mono-jet channel

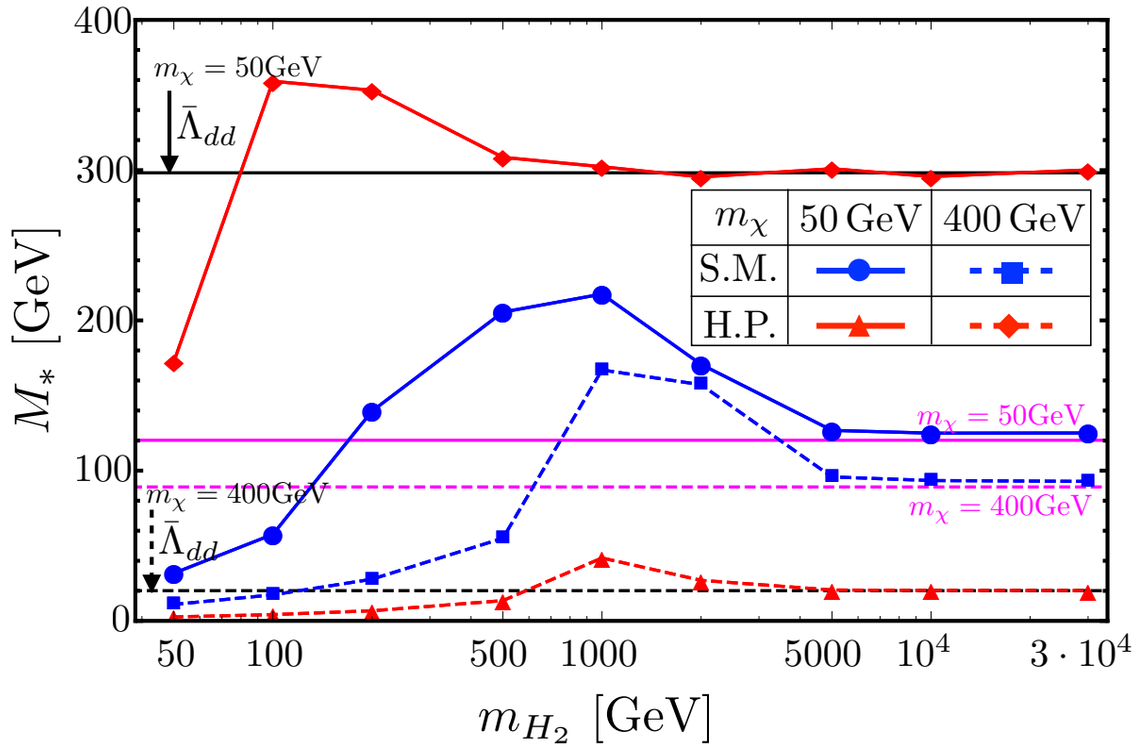
Summary

- The LHC can be an orthogonal tool (and be in a model independent way) to search Dark Matter(s)
- So far, Simplified models and Effective operator approaches have been major interpretations.
- But the model-specific interpretation need to be considered since

Mono-jet channel



ttbar+ MET channel



M_* : effective mass scale of the operator