Beyond the Dark matter effective field theory and a simplified model approach at colliders

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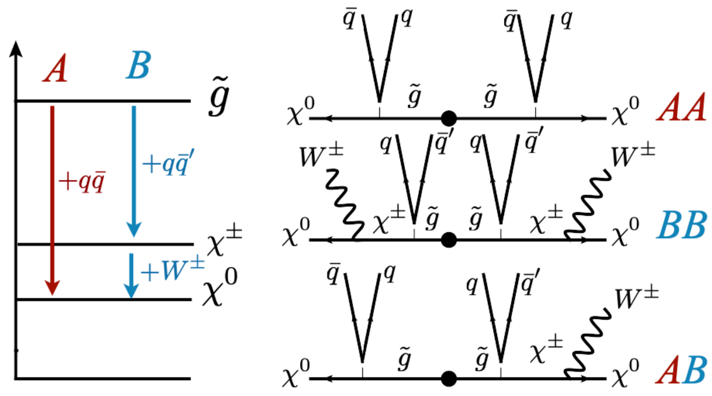
Based on
Seungwon Baek, P. Ko, Myeonghun Park, Wan-Il Park, Chaehyun Yu (Physics Letters B 756 (2016) 289)

Roadmap of Dark Matter models for Run 3

Simplified model since 2011

- Simplified Models for LHC New Physics Searches (arXiv:1005.2838)
  - **<u>Signature based approach (to be model independent)</u>**



= can be recasted to various models (DM production processes)

- Simplified Models for Dark Matter Searches at the LHC (arXiv:1506.03116)
  1) **Type of Dark Matter** : **Spin,** (Gauge charge under the SM)
  2) **Type of Mediators** : **Spin**, The Standard Model particles to interact with. (Gauge charge under the SM)

  - **Criteria for Simplified Models** ∋ <u>Lagrangian should contain (in principle) all terms</u> that are **renormalizable** and consistent with **Lorentz invariance**, **the SM gauge symmetries**, and **DM stability**.

Simplified model in action

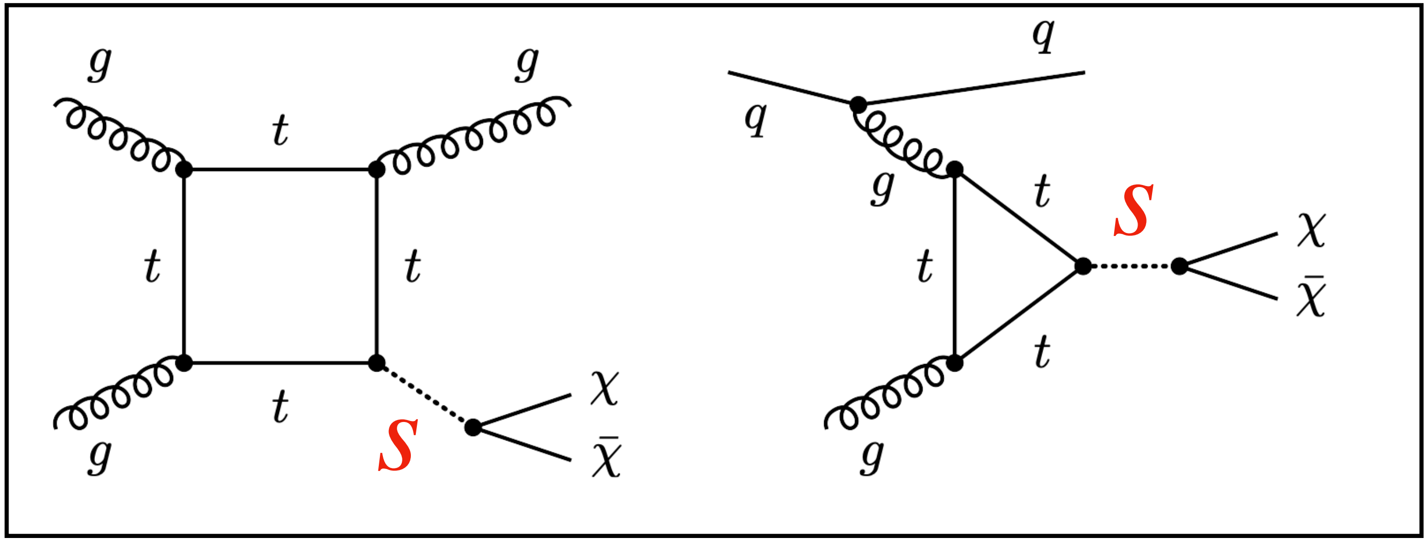
- "The additional interactions should not violate the exact and approximate accidental global symmetries of the SM...", for example flavor : **Minimal Flavor Violation (MFV)**

  - For "MFV Spin-0 s-channel model", interactions with the Spin-0 mediator with quark sector should be of **Yukawa type.**

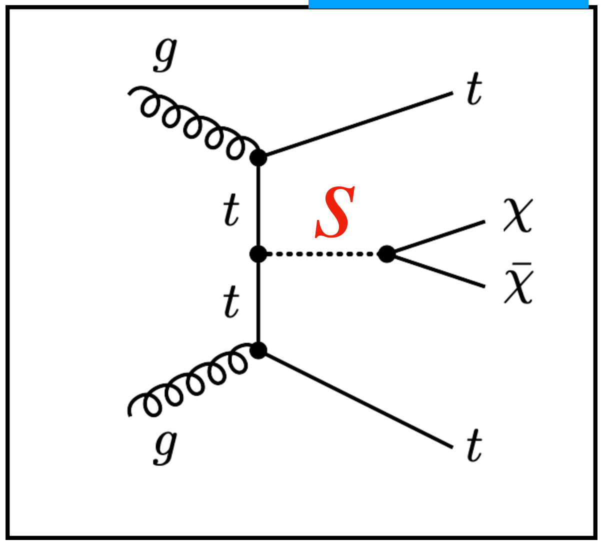
$$\mathcal{L} \supset -\sum_{i,j}\left((Y^u)_{ij}\bar{q}_i H u_j + (Y^d)_{ij}\bar{q}_i \tilde{H} d_j + \mathrm{h.c.}\right) \quad \Rightarrow \quad \mathcal{L} \supset -\frac{h}{\sqrt{2}}\sum_i \left(y_i^u \bar{u}_L^{(i)} \bar{u}_R^{(i)} + y_i^d \bar{d}_L^{(i)} d_R^{(i)}\right)$$

S : "Dark higgs"

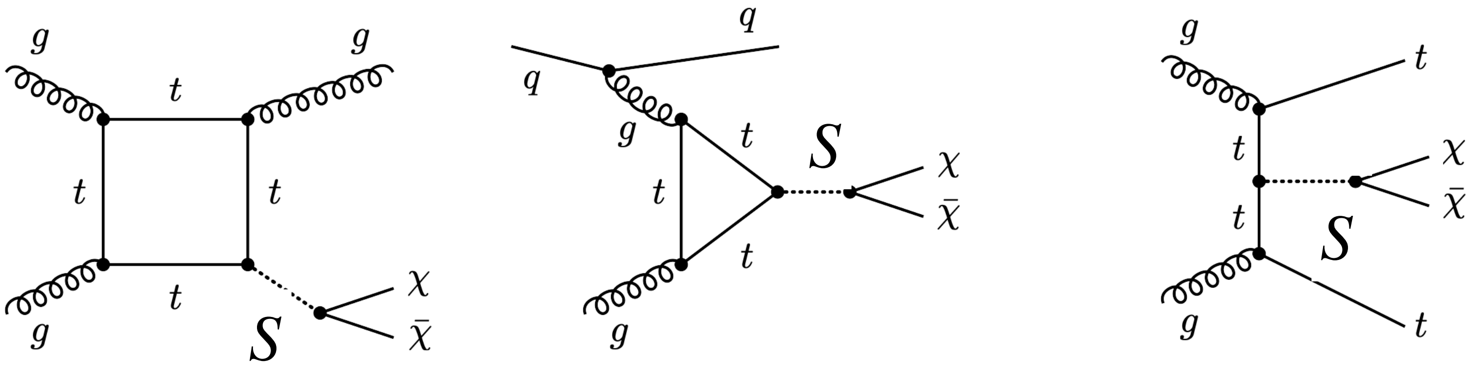
Mono-X + MET



$t\bar{t}$ + MET



Unitarity violation from disregarding gauge symmetry



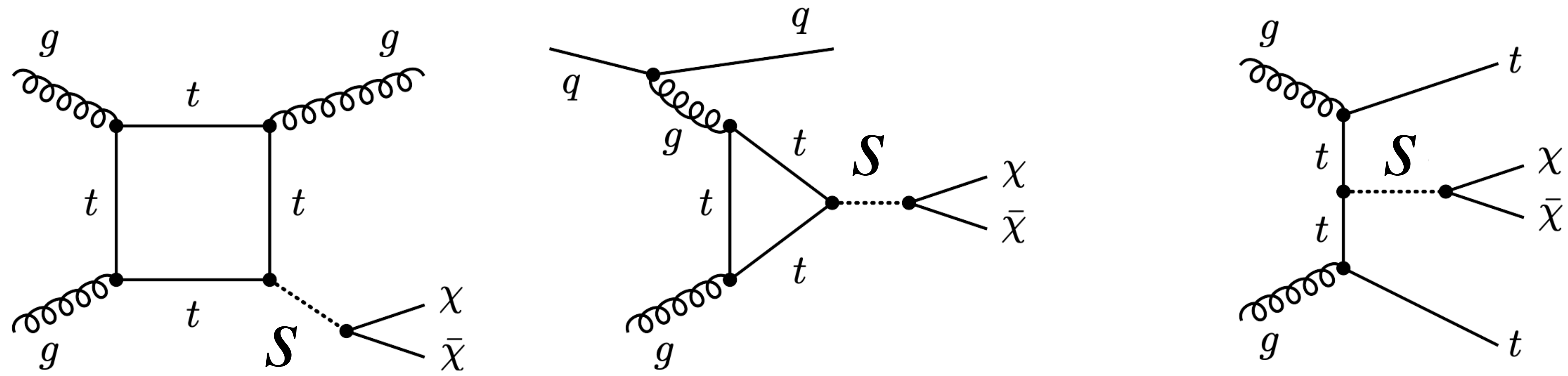
- If you use only one operator, say $S\,\bar{t}t$, it breaks $SU(2)$ gauge symmetry explicitly, it may come from ...

$$\mathcal{L}_{\text{Yuk}} \supset -g_{Htt}\ \bar{t}tH \quad \text{or} \quad ig_{Att}\ \bar{t}\gamma_5 tA\,,$$

which can be generated via a dimension-5 or higher operator for instance

Physics Reports 842 (2020) 1–180
(Giorgio Arcadi, Abdelhak Djouadi, Martti Raidal)

- Thus, this operator is an effective operator, **it should have a cut-off** Otherwise, you will have the **side-effect of unitarity violation**, usually **over-sampled high-p_T events** in our Monte Carlo samples that will overestimate analysis result (= limit)



- But **singlet scalar** ("Dark Higgs") can't have renormalizable interaction with SM fermion f as $S\bar{f}f$ breaks $SU(2)$ gauge symmetry.

- Also, **SM Higgs** doesn't have a dim-4 operator with **SM singlet DM field**.

  - It has a dim-5 operator $H^\dagger H\bar{\chi}\chi$ for Fermionic DM
    or dim-6 $H^\dagger H F_D F_D$ for Vector DM

- Thus, (as we know) we need to have **both "SM Higgs" and "Dark Higgs"** to keep SM gauge invariance within dim-4, renormalizable interaction terms.

- Thus, we need to have **both "SM Higgs" and "Dark Higgs"** to keep SM gauge invariance within dim-4, renormalizable interaction terms.

Simplified model in action with respecting the SM Gauge symmetry → more structures

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

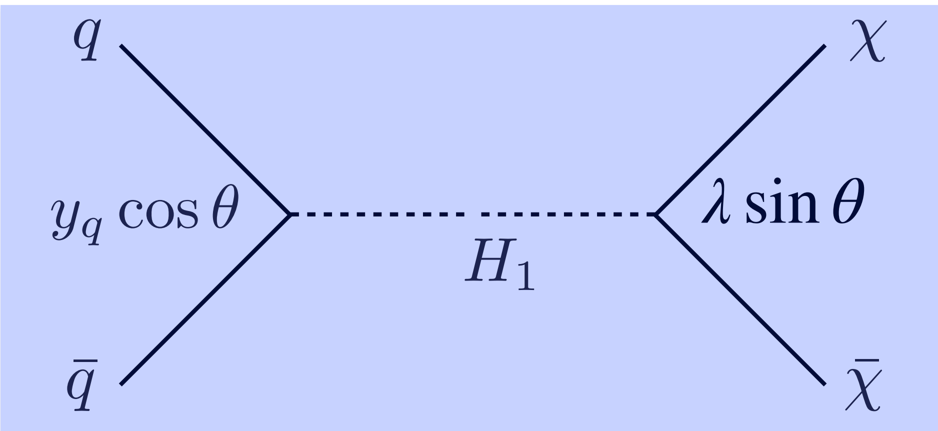
- to the Mass eigenstate

$$\begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

$$H_1 = h\cos\theta - s\sin\theta\,,$$ (SM Higgs like)

$$H_2 = h\sin\theta + s\cos\theta\,.$$

P. Ko et al (2011)



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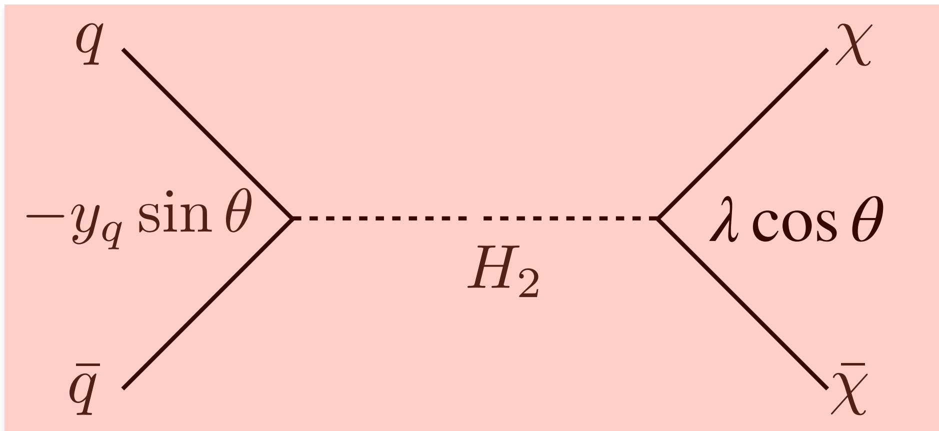
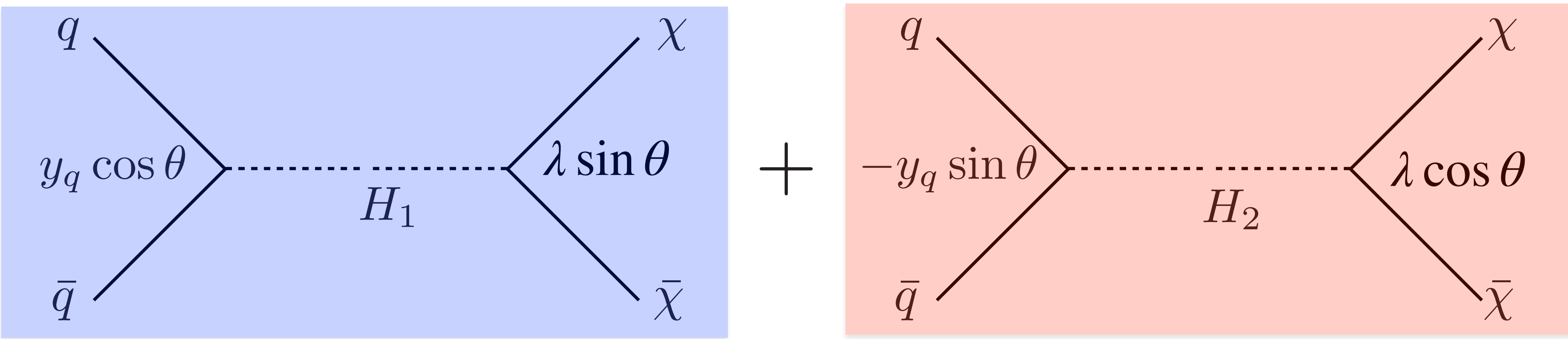




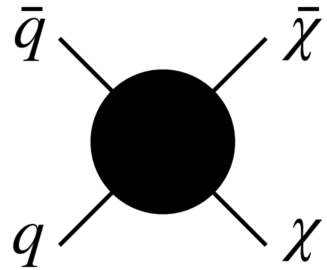
$M_{\mathrm{H_{SM}}}$ $\quad\quad$ M_S

$$M = \frac{m_q}{\bar{\Lambda}^3_{dd}} \left(\frac{1}{\hat{s} - m^2_{H_1} + i m_{H_1} \Gamma_{H_1}} - \frac{m_{H_1}}{\hat{s} - m^2_{H_2} + i m_{H_2} \Gamma_{H_2}} \right)$$

$$\equiv M_{\mathrm{H_{SM}}} + M_{\mathrm{S}} \quad \left(\bar{\Lambda}^3_{dd} = \frac{2 m^2_{H_1} v_H}{\lambda \sin 2\theta} \right)$$

- Dark matter productions are **with two diagrams**
  - There should be a richer phenomena with a Quantum Interference
  (can have a destructive interference in some regions)

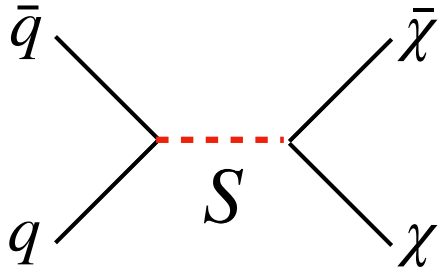
Other "simple" scenarios



- EFT: $L_{\rm int} = \frac{m_q}{M_*^3}\bar{q}q\bar{\chi}\chi$

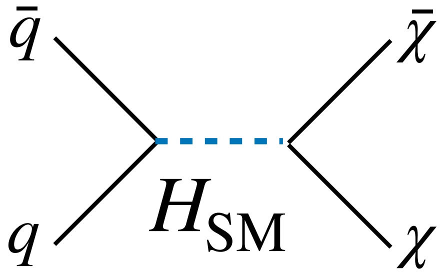
  - from $L \ni \frac{y_u\, y_\chi}{\Lambda^3}\bar{Q}_L\tilde{H}u_R\bar{\chi}\chi + \frac{y_d\, y'_\chi}{\Lambda^3}\bar{Q}_L H d_R\bar{\chi}\chi$

    if we write down in the SM gauge invariant way



- S.M. (Scalar mediator, "**dark Higgs**" model):

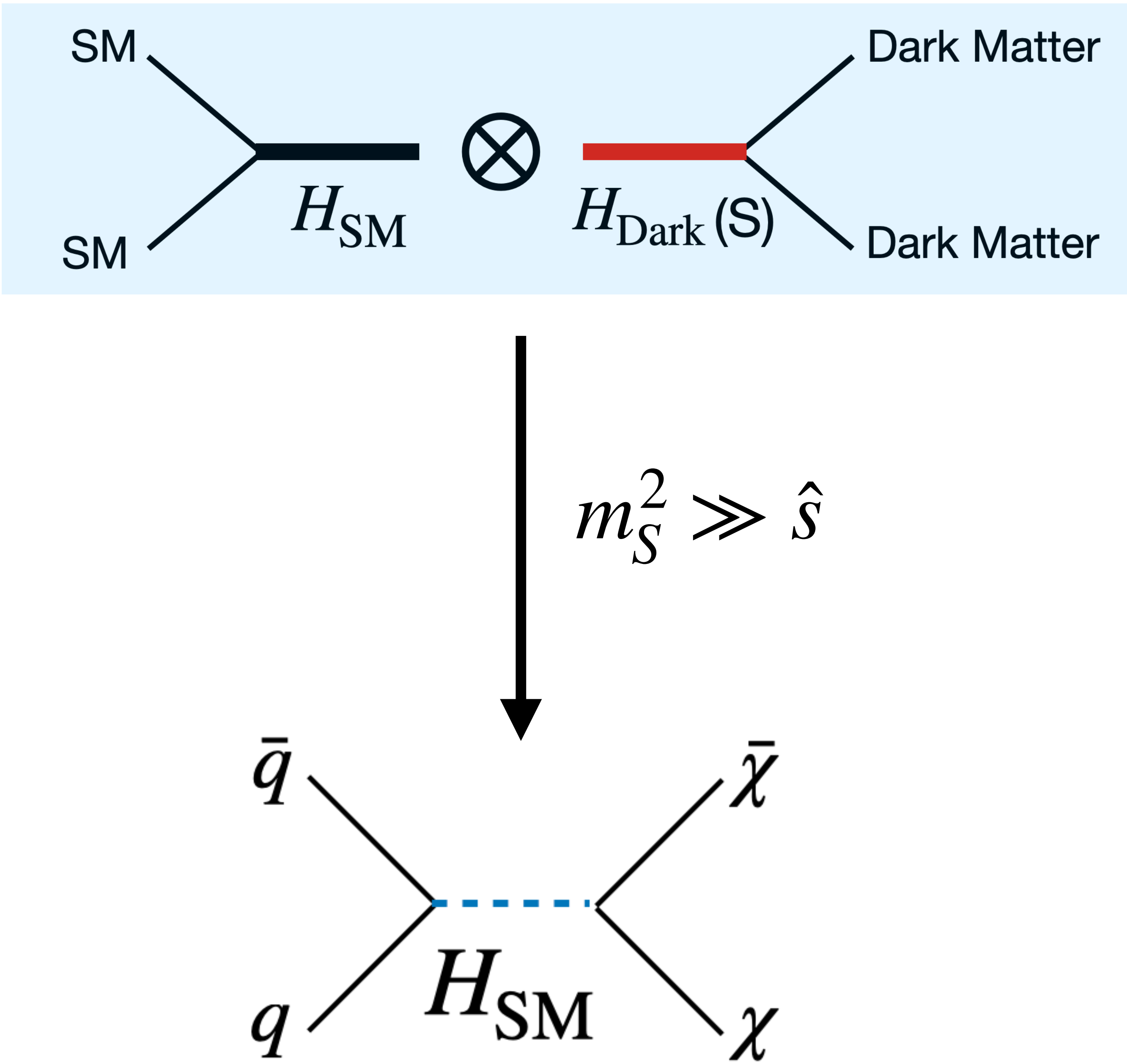
$$L_{\rm int} = \left(\frac{m_q}{v_H}\sin\theta\right) S\bar{q}q + (\lambda\cos\theta)\, S\bar{\chi}\chi$$



- H.M. (SM **Higgs mediator**):

$$L_{\rm int} = \left(\frac{m_q}{v_H}\cos\theta\right) H_{\rm SM}\bar{q}q + \left(\lambda\sin\theta\right) H_{\rm SM}\bar{\chi}\chi$$

(1) Naive expectation @ LHC



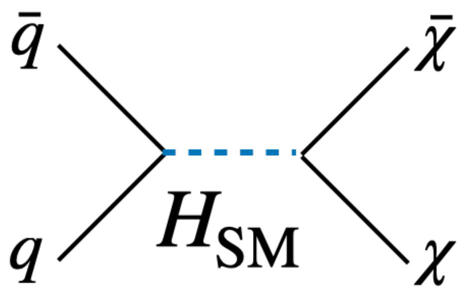
(1) Naive expectation @ LHC

$$|M|^2 = |M_{H_{\mathrm{SM}}}|^2 + 2\mathrm{Re}\left(M_{H_{\mathrm{SM}}}\right)\left(M^*_{H_{\mathrm{Dark}}}\right) + |M_{H_{\mathrm{Dark}}}|^2$$

$$m_S^2 \gg \hat{s}$$

$$\sim \frac{1}{\hat{s}^2}\left(1 + \mathcal{O}\left(\frac{\hat{s}}{m_S^2}\right) + \mathcal{O}\left(\frac{\hat{s}^2}{m_S^4}\right)\right)$$

$$m_S^2 \ggg \hat{s}$$

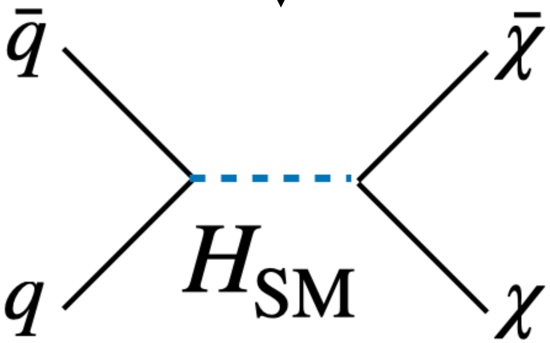


- Due to Quantum interference, **the convergence to H_{SM} (Higgs mediator) would be slower than expected.**

(2) Limiting case

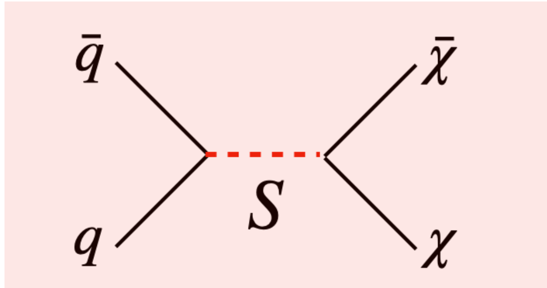
Higgs Portal

$$m_S^2 \ggg \hat{s}$$



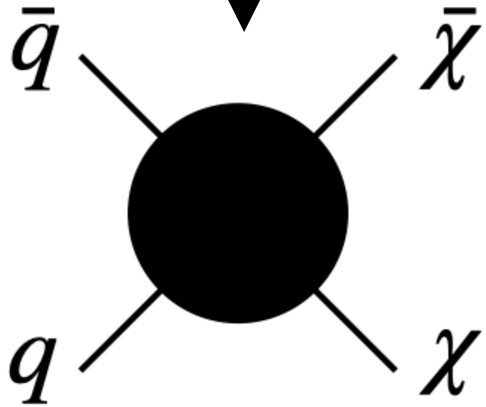
$\neq$

(simple) **Dark Higgs**



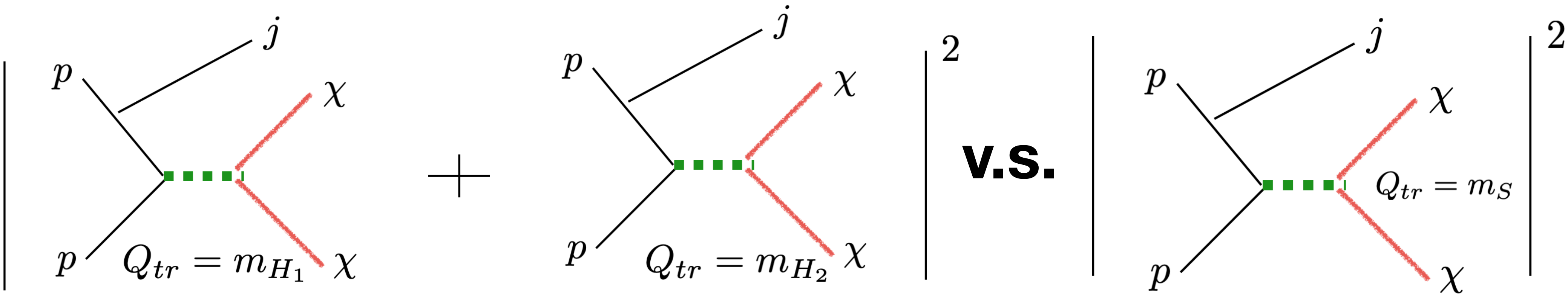
- **it should have a cut-off**
  = We can't rely on High PT analysis with this model

$$m_S^2 \gg \hat{s}$$



Mono-X +MET

- P_t (or Energy) of j (ISR or mono-X) is proportional to the energy transfer Q_{tr}.
- If $\hat{s} > m^2_{\text{mediator}}$, the energy transfer would be localized to the pole of the propagators.



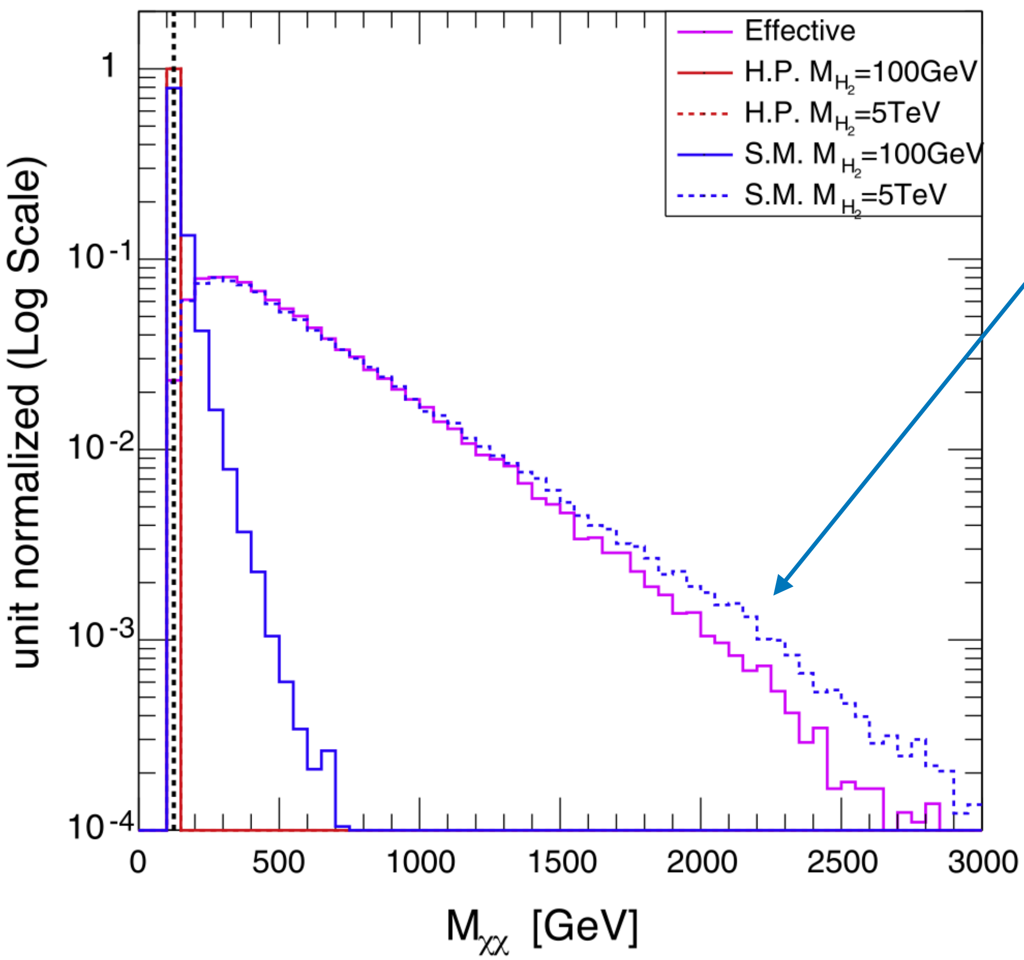
Higgs Portal

(simple) Dark Higgs

Richer kinematics results at the LHC (Run 1)

Mono-X + MET

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

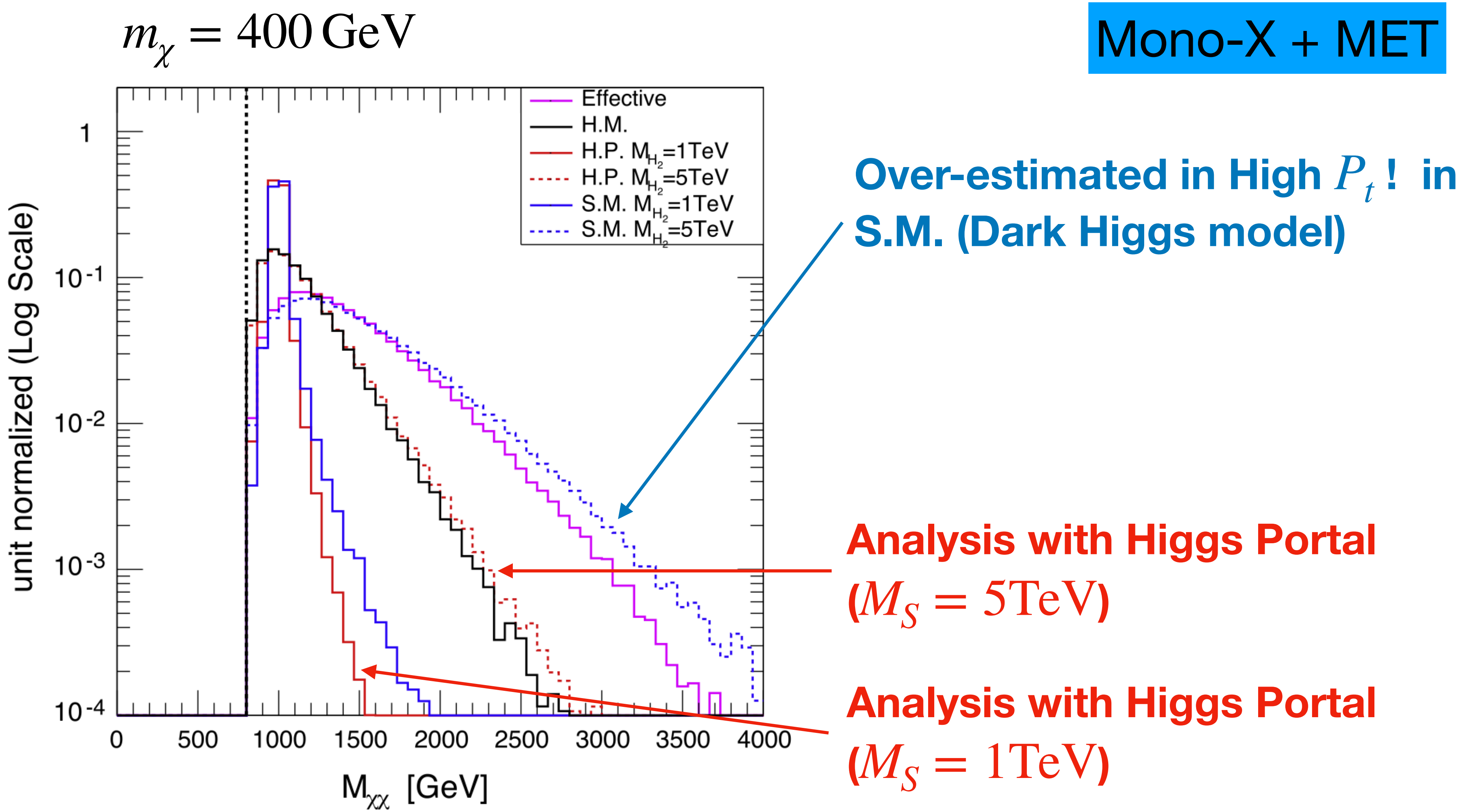


Over-estimated in High P_t ! in S.M. (Dark Higgs model)

- $2m_\chi < m_{H_{SM}}$, energy transfer is localized around Higgs mass (pole of the propagator).

Richer kinematics results at the LHC (Run 1)

Mono-X + MET

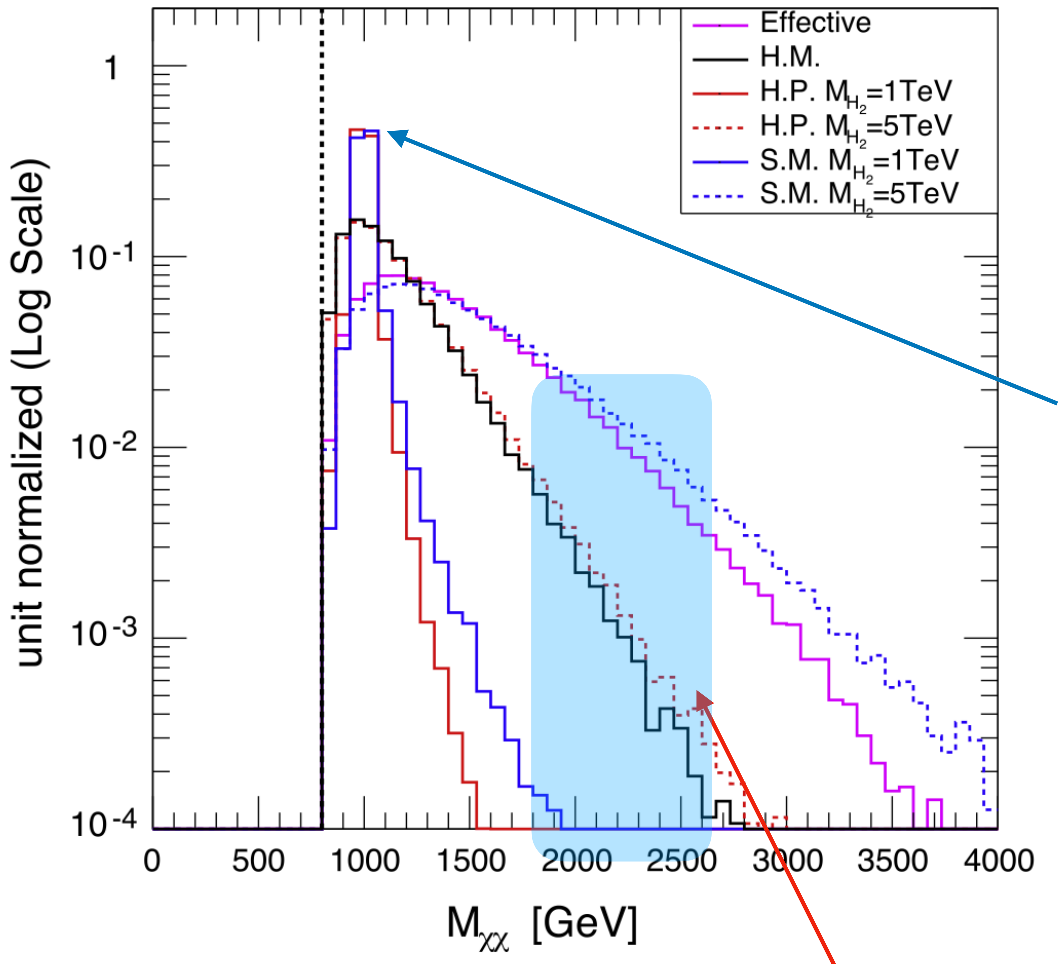


- To produce Dark matters, $\sqrt{\hat{s}} > 2m_\chi > m_{H_{\rm SM}}$ in this case.
  Thus, energy transfer is **not** localized to Higgs mass.
- So, if the LHC can reach the mass scale of dark Higgs,
  the H.P. case would be totally different from H.M. nor S.M.

Richer kinematics results at the LHC (Run 1)

Mono-X + MET

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



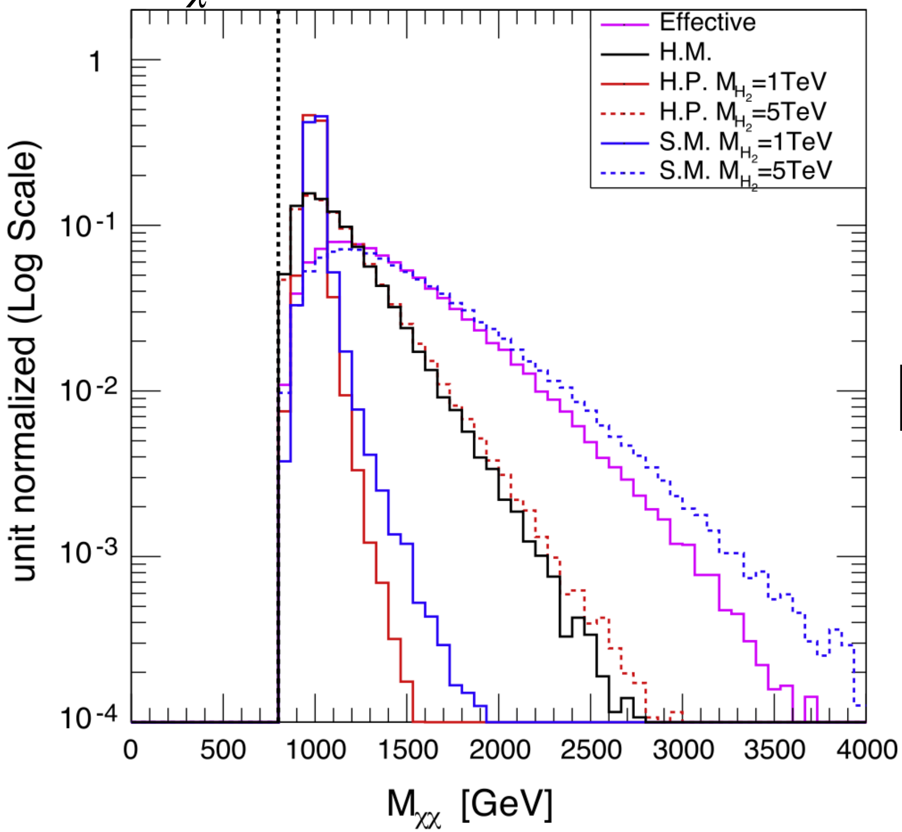
Energy transfer is localized around m_S for S.M. (Dark Higgs model)

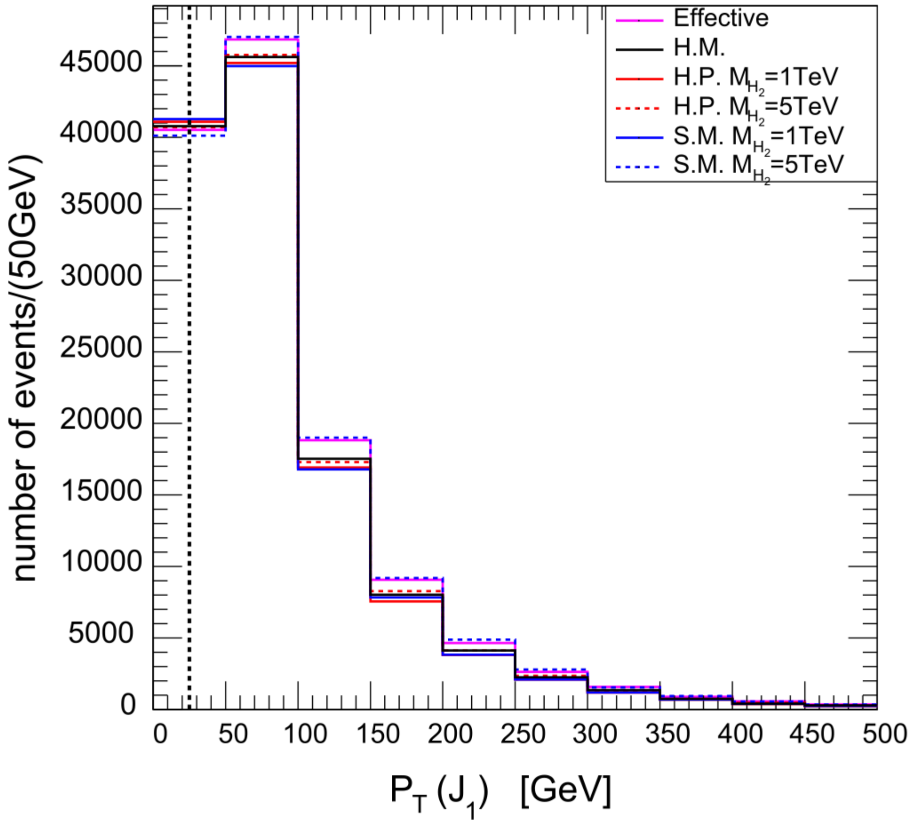
- **H.P. has an constructive interference effect** compared to HM

Richer kinematics results at the LHC (Run 1)

Mono-X + MET

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

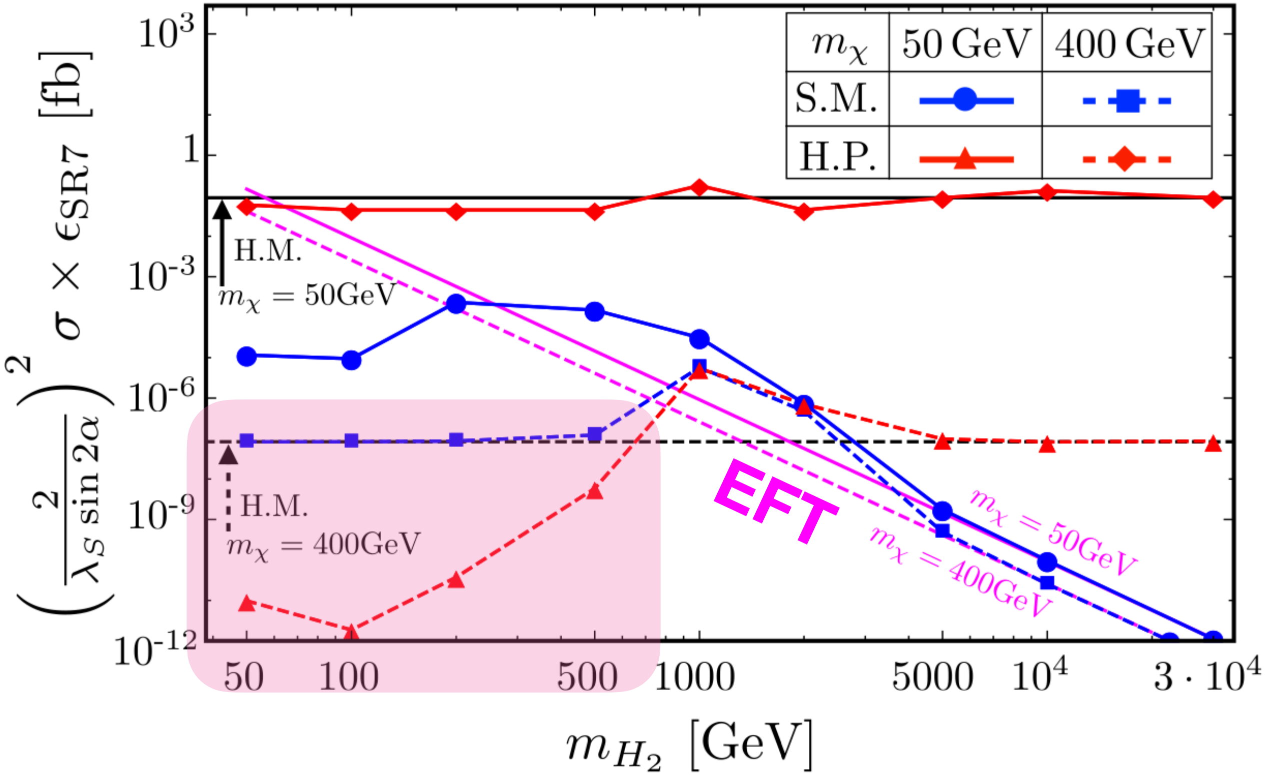




- The energy transfer (or $\sqrt{\hat{s}}$) provides an effect to P_T of Mono-X.

  - @ LHC Run 1 (8TeV) analysis, the effect is milder
  (But, HL-LHC would have non-negligible differences)

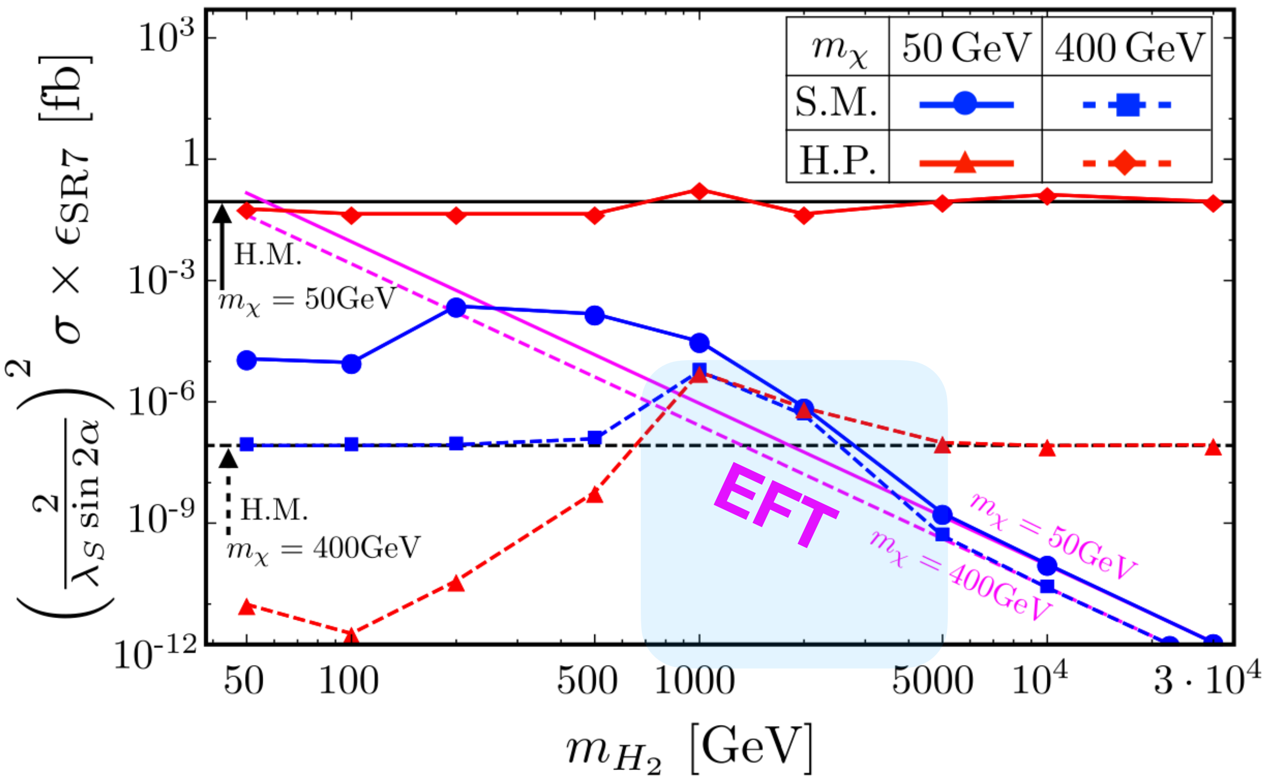
Effect on the analysis (cut-eff)



- In $m_S < 2m_\chi$ region, $\sqrt{\hat{s}} \simeq 2m_\chi$, so that destructive interference as

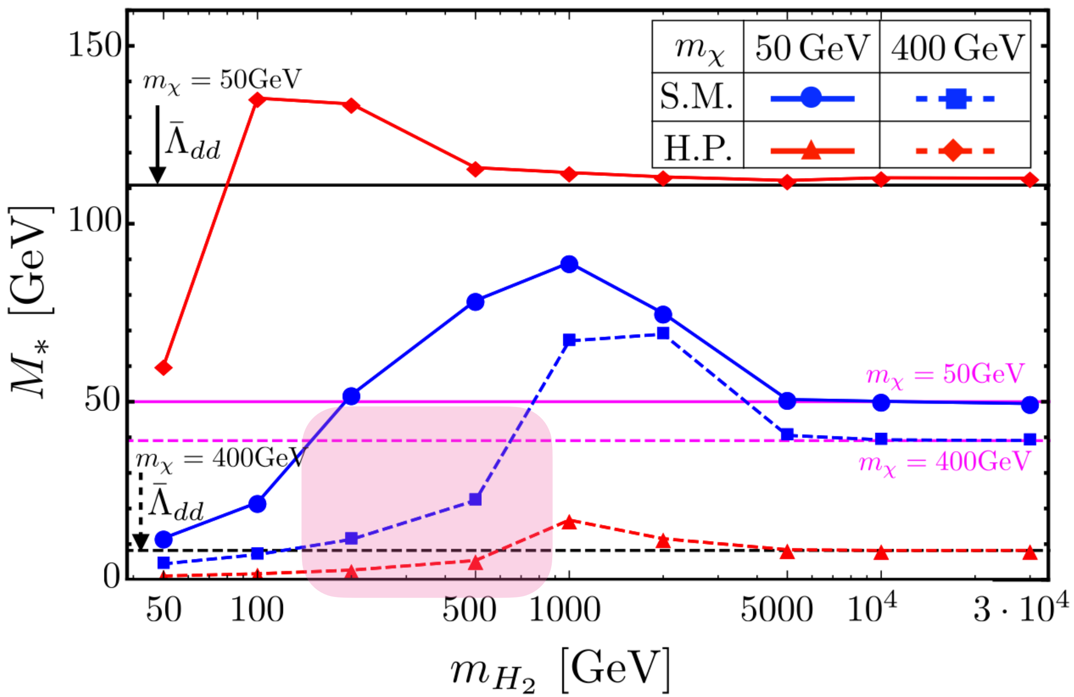
$$\frac{1}{\hat{s} - m_{H_{\rm SM}}} - \frac{1}{\hat{s} - m_S^2} \simeq (+) - (+)$$

Effect on the analysis (cut-eff)



- In $m_S > 2m_\chi$ region, $\sqrt{\hat{s}} < m_S$ for high m_S, so that constructive interference as $\frac{1}{\hat{s} - m_{H_{\mathrm{SM}}}} - \frac{1}{\hat{s} - m_S^2} \simeq \frac{1}{\hat{s}} + \frac{1}{m_S^2 - \hat{s}} \simeq (+) + (+)$

Mono-jet + MET



- Bounds on S.M. and H.P. are translated to M_* (suppression scale)

$$\frac{m_q}{M_*^3} = \frac{m_q \lambda \sin\alpha \cos\alpha}{v_H}\frac{1}{m_S^2} \rightarrow M_*^3 = \left(\frac{2 v_H}{\lambda \sin 2\alpha}\right) m_S^2.$$

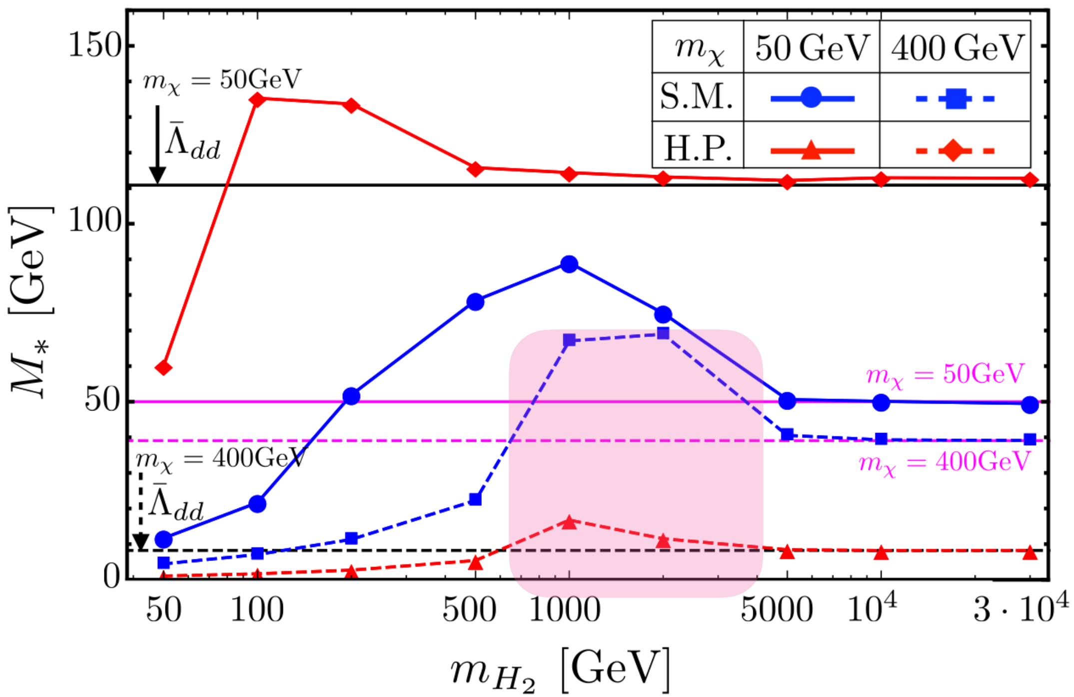
$$\left[\left(\frac{1}{M_*^3}\right)^2 \left(\frac{\lambda \sin 2\alpha}{2 v_H m_S^2}\right)^{-2} \sigma_{(\text{S.M.})}\right] \times \epsilon_{(\text{S.M.})} = \frac{\text{N}_{obs}}{\mathcal{L}}$$

for the case of S.M.,
and similarly for the H.P

- In $m_S < 2m_\chi$ region, due to destructive interference in H.P. case, other scenarios (SM, EFT) have overestimated limit for the Dark physics scale.

- $\bar{\Lambda}_{dd}$ is the energy scale in the limiting case when $m_{H_{\text{Dark}}} \gg m_{H_{\text{SM}}}$ at the DD search of $\chi + q \rightarrow \chi + q$, so "effectively" Higgs mediator case.

Mono-jet + MET



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$$\left[\left(\frac{1}{M_*^3}\right)^2 \left(\frac{\lambda \sin 2\alpha}{2v_H m_S^2}\right)^{-2} \sigma_{(\text{S.M.})}\right] \times \epsilon_{(\text{S.M.})} = \frac{\text{N}_{obs}}{\mathcal{L}}$$

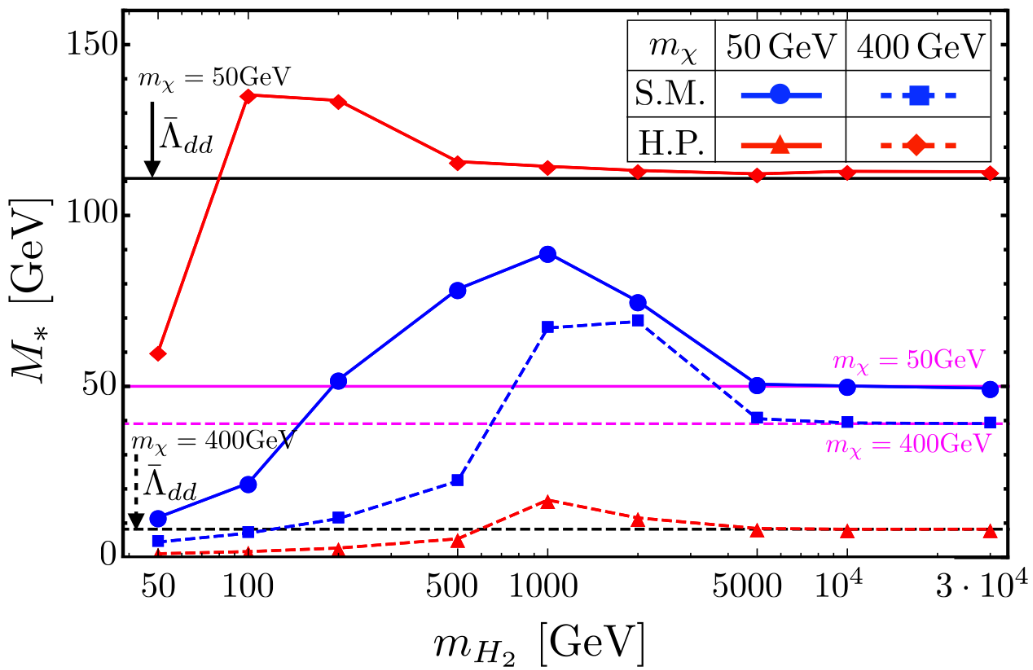
for the case of S.M.,
and similarly for the H.P

- In $m_S > 2m_\chi$ region, due to constructive interference in H.P. case,

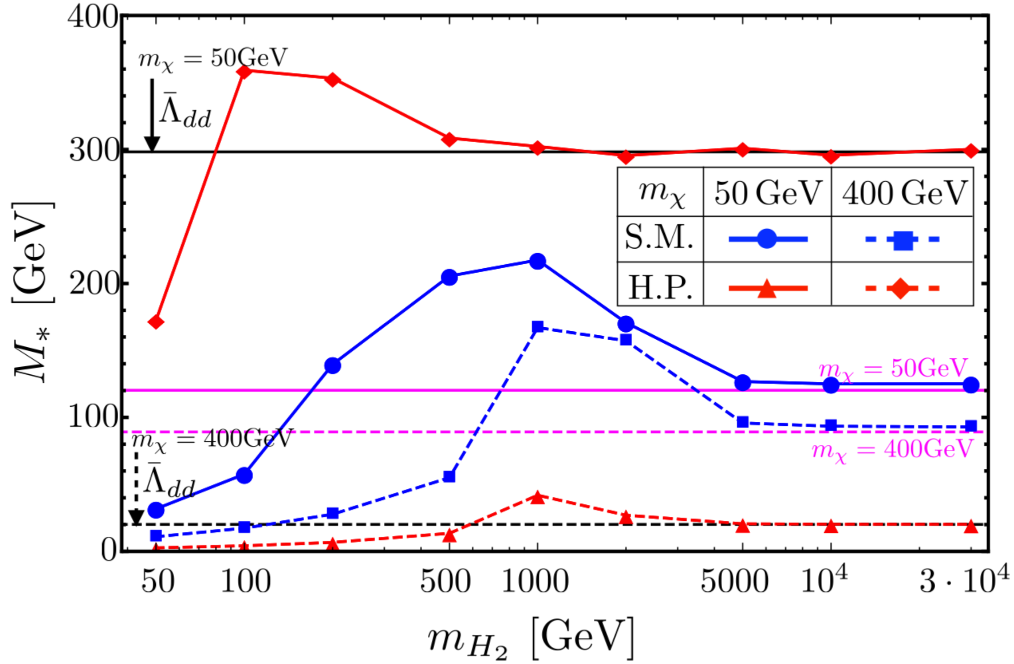
1) HM has an underestimated limit for Dark physics scale

2) SM and EFT have still overestimated limit for Dark physics scale

Mono-jet + MET



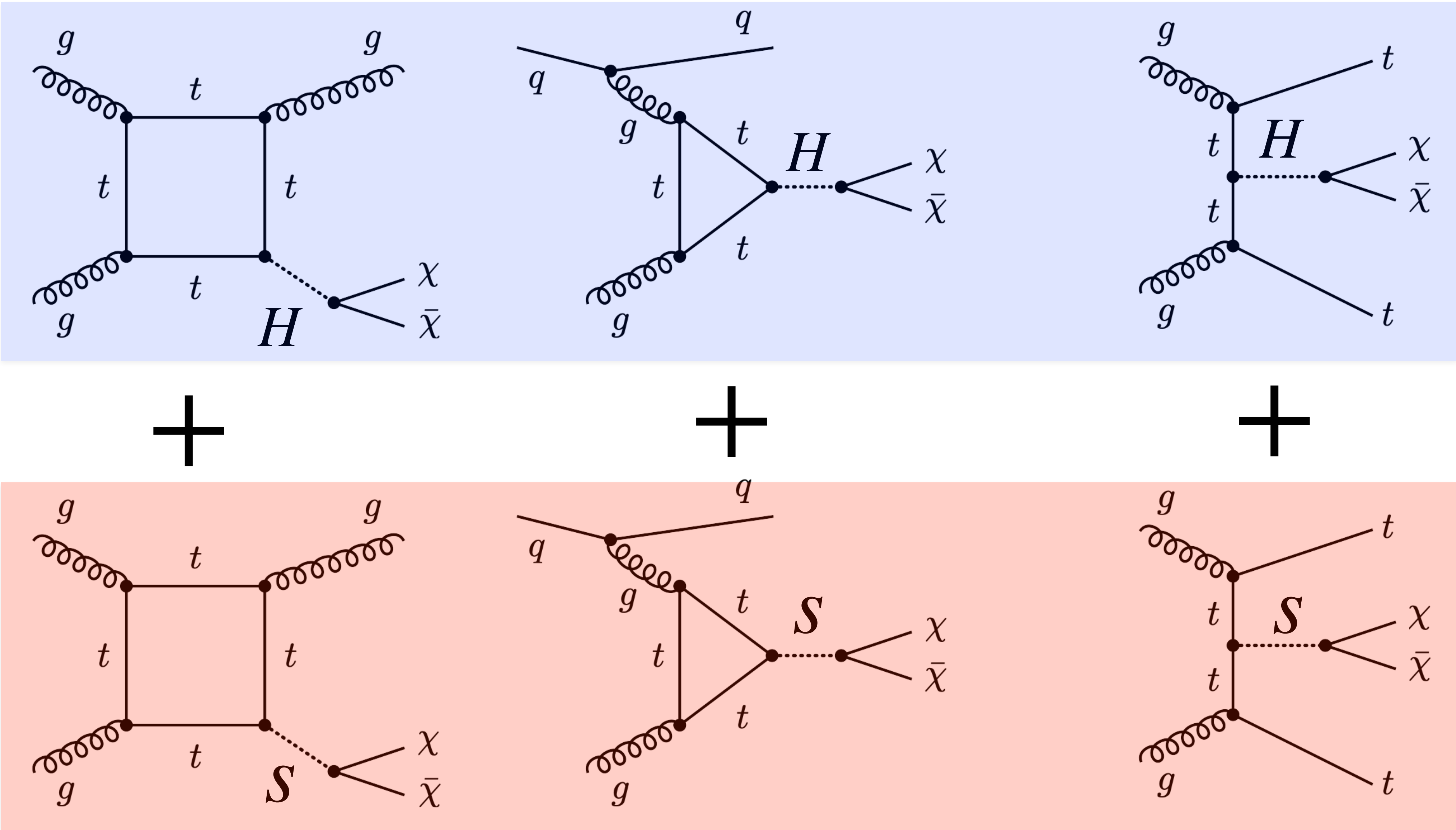
$t\bar{t}$+ MET



- Similar to Mono-jet + MET analysis, $t\bar{t}$ + MET analysis has a same tendency

  - Energy scale of DM production is related to the P_t of decaying products from top-quark.

In short, DM model with respecting the SM Gauge symmetry → more structures



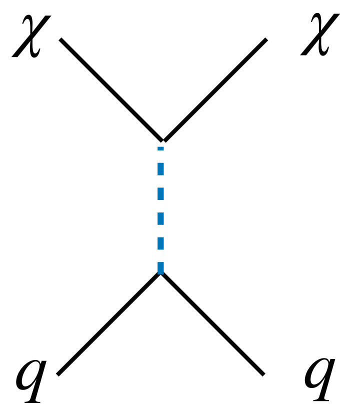
Recap

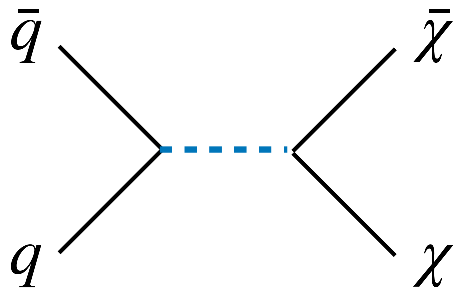
- If we want to capture Dark sector in a simplified model approach,
  - We need to be careful not to destroy the beauty of the SM !
- Higgs portal dark matter scenario provides very interesting interference effects on the LHC analysis and it will be more interesting as LHC go to the HL region.
- In this short talk, I focused on s-channel mediator case.
  For t-channel, please check
  - P. Ko, Alexander Natale, Myeonghun Park and Hiroshi Yokoya (JHEP 01(2017) 086)

Back-up for $\bar{\Lambda}_{dd}$

Dark matter Direct search

LHC





Crossing symmetry

$\Longleftrightarrow$

$$\mathcal{M} = -\overline{u(p')}u(p)\overline{u(k')}u(k)\,\frac{m_q}{v_H}\lambda\sin\alpha\cos\alpha \times \left[\frac{1}{t-m_{H_1}^2+im_{H_1}\Gamma_{H_1}} - \frac{1}{t-m_{H_2}^2+im_{H_2}\Gamma_{H_2}}\right]$$

$$\to \overline{u(p')}u(p)\overline{u(k')}u(k)\,\frac{m_q}{2v_H}\lambda\sin 2\alpha\left[\frac{1}{m_{H_1}^2}-\frac{1}{m_{H_2}^2}\right]$$

$$\equiv \frac{m_q}{\Lambda_{dd}^3}\overline{u(p')}u(p)\overline{u(k')}u(k),$$ (in $t \to 0$ limit)

$$\frac{1}{\Lambda_{dd}^3} \to \frac{1}{\bar{\Lambda}_{dd}^3}\left[\frac{m_{H_1}^2}{\hat{s}-m_{H_1}^2+im_{H_1}\Gamma_{H_1}} - \frac{m_{H_1}^2}{\hat{s}-m_{H_2}^2+im_{H_2}\Gamma_{H_2}}\right] \equiv \frac{1}{\Lambda_{col}^3(\hat{s})},$$

$$\Lambda_{dd}^3 \equiv \frac{2m_{H_1}^2 v_H}{\lambda\sin 2\alpha}\left(1-\frac{m_{H_1}^2}{m_{H_2}^2}\right)^{-1}$$

$$\bar{\Lambda}_{dd}^3 \equiv \frac{2m_{H_1}^2 v_H}{\lambda\sin 2\alpha},$$ (in $m_{H_2} \gg m_{H_1}$ limit)