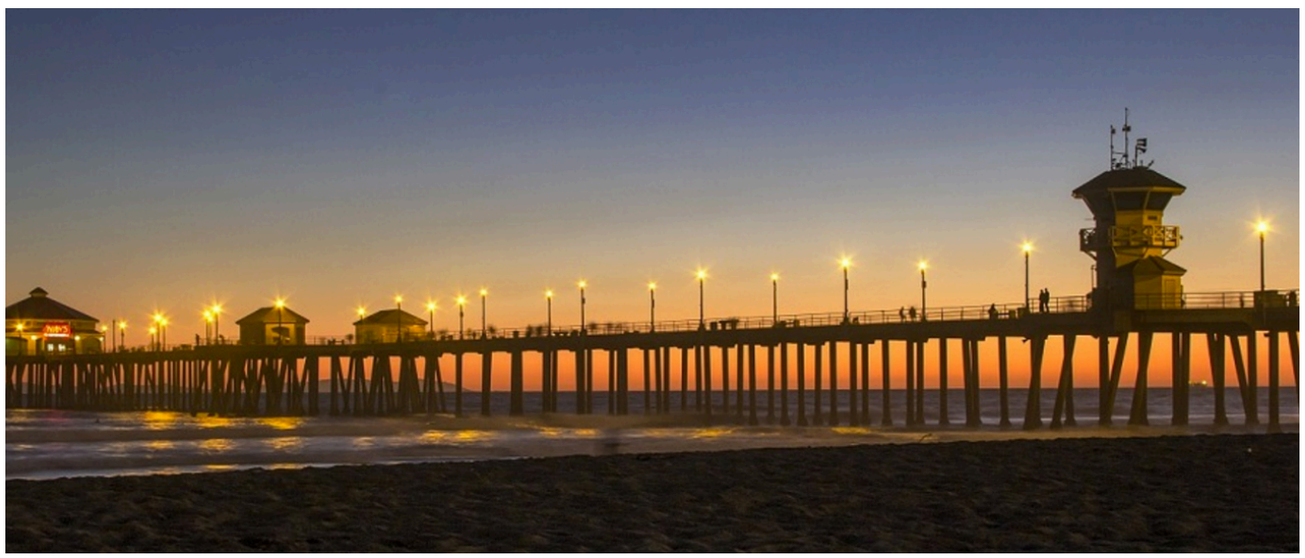
Loop-induced DM production via ZH

DM@LHC 2017

Irvine - 04.04.2017

Dorival Gonçalves

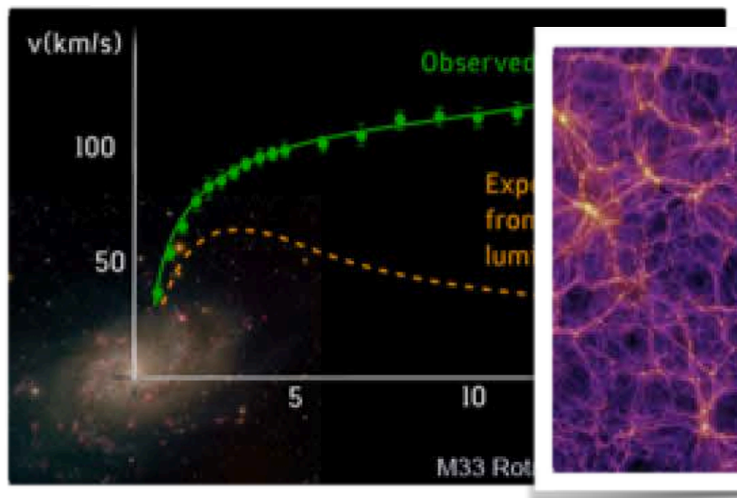


Motivation

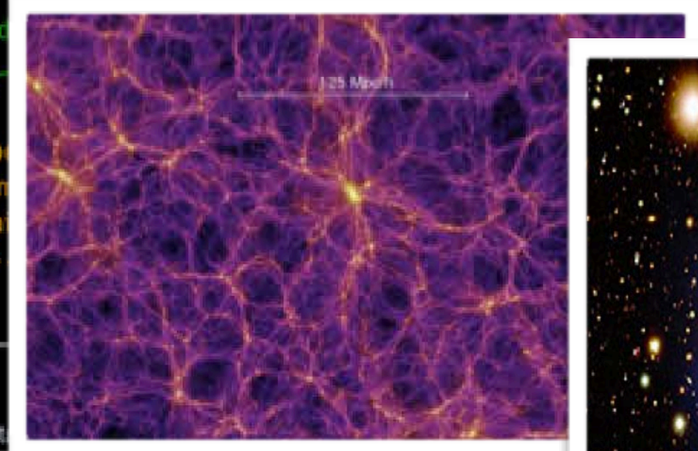
- After the Higgs discovery at the LHC
  Dark Matter is the next most important physics problem to tackle at the LHC
  DM@LHC?!
- The evidence just keeps pilling up

Galaxy clusters

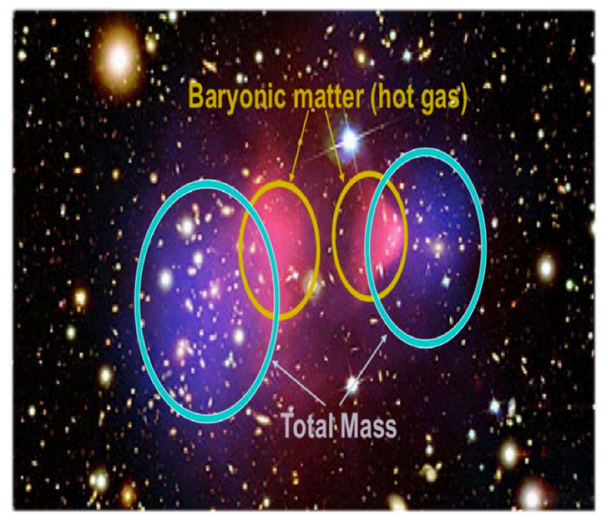
Galactic Rotation Curves



CMB



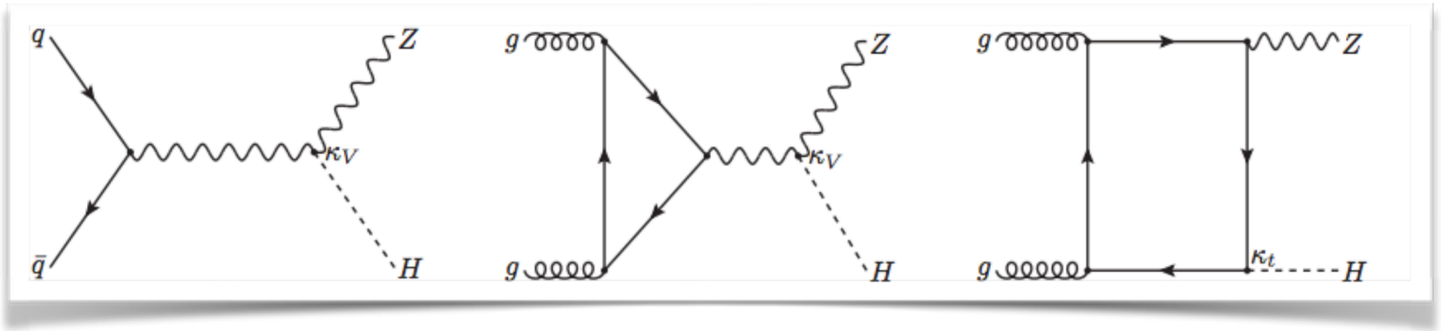
Bullet cluster



- New paths to address this problem at the LHC are very welcome
  We will focus on ZH channel and show that loop-induced open new possibilities
  - Invisible Higgs searches
  - Simplified Models for Dark Matter
  - Simple Models for Dark Matter: Pseudoscalar Portal

ZH Production

- ZH signal components:



@LO~O(α_{EW}^2)

@LO~O($\alpha_s^2\alpha_{EW}^2$)

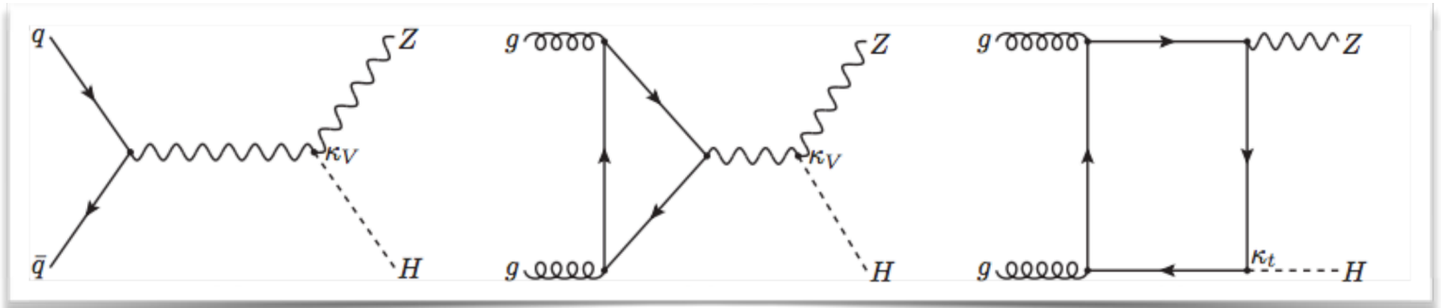
Altenkamp, Dittmaier, Harlander, Rzehak, Zirke (2013)
Englert, McCullough, Spannowsky (2013)
Hespel, Maltoni, Vryonidou (2015)
Campbell, Ellis, Williams (2016)

- There are four major factors that guarantee GF larger than the anticipated naive $\alpha_s^2 \approx 1\%$:
  - Larger gluon PDF
  - Larger initial state colour factor
  - Top Yukawa coupling appears in the place α_{EW} factors: $y_t \sim O(1)$
  - Threshold enhancement at $m_{ZH} \sim 2m_t$, which gives rise to relevant rates at the boosted regime $p_{TH} \sim m_t$

DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

ZH Production

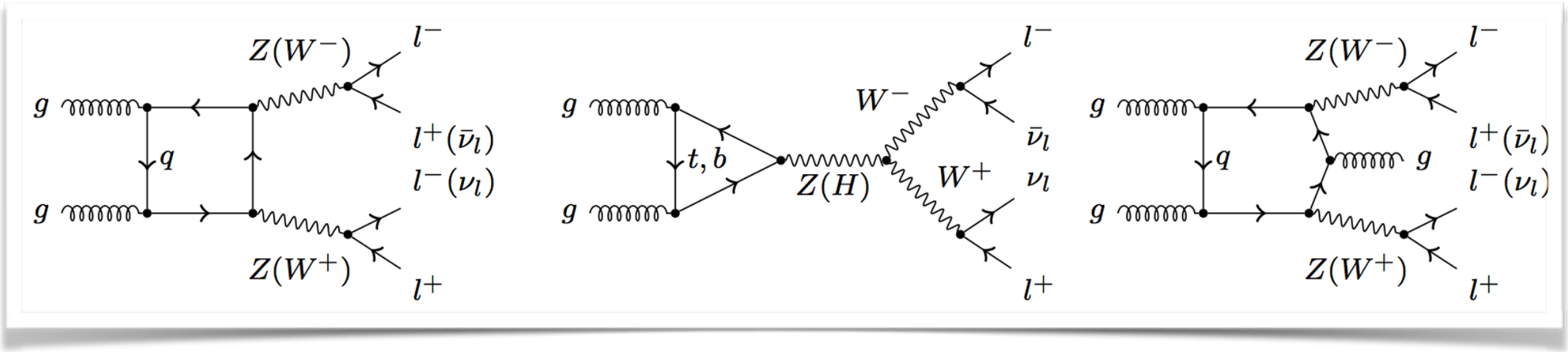
- ZH signal components:



@LO~O(α_{EW}^2) @LO~O($\alpha_s^2\alpha_{EW}^2$)

- By the same arguments, we should also consider the loop-induced background contributions

  E.g., the major backgrounds for Invisible searches VV' also present relevant loop-induced components



DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

- The studies presented here were performed with Sherpa+OpenLoops

  See Stefano's talk for details on OpenLoops

ZH Production

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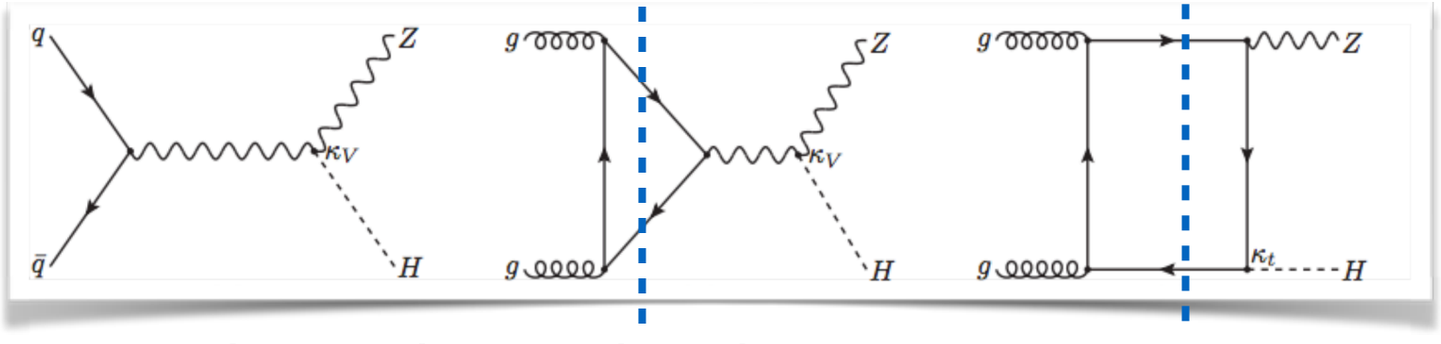
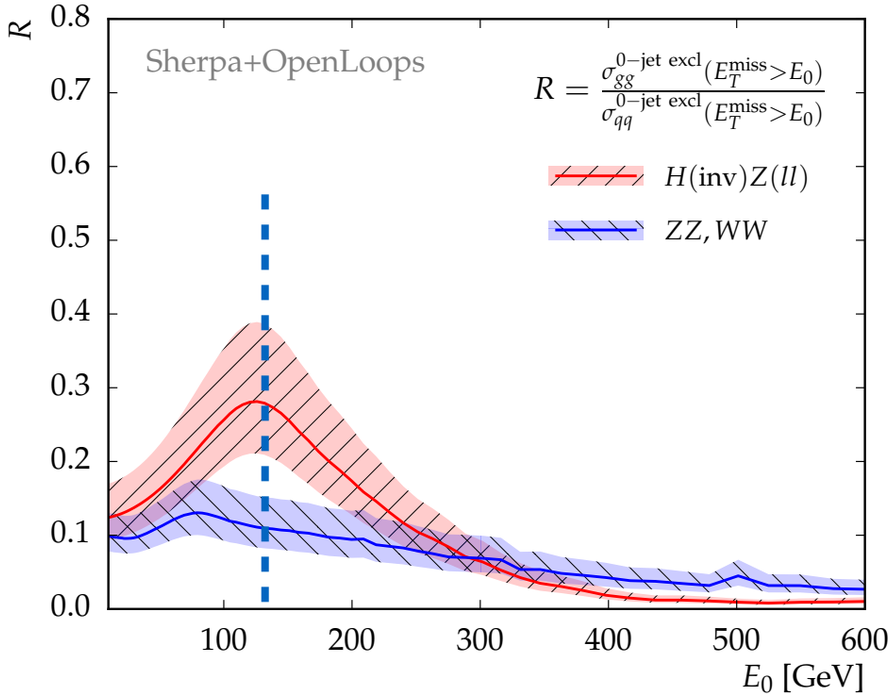
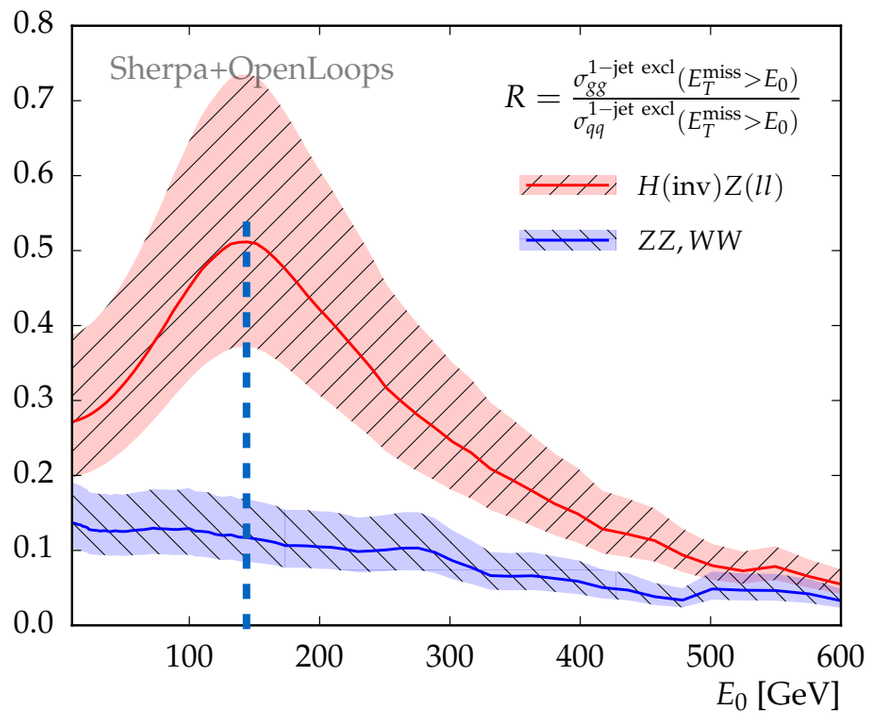


- Boosted kinematics enhances loop-induced component



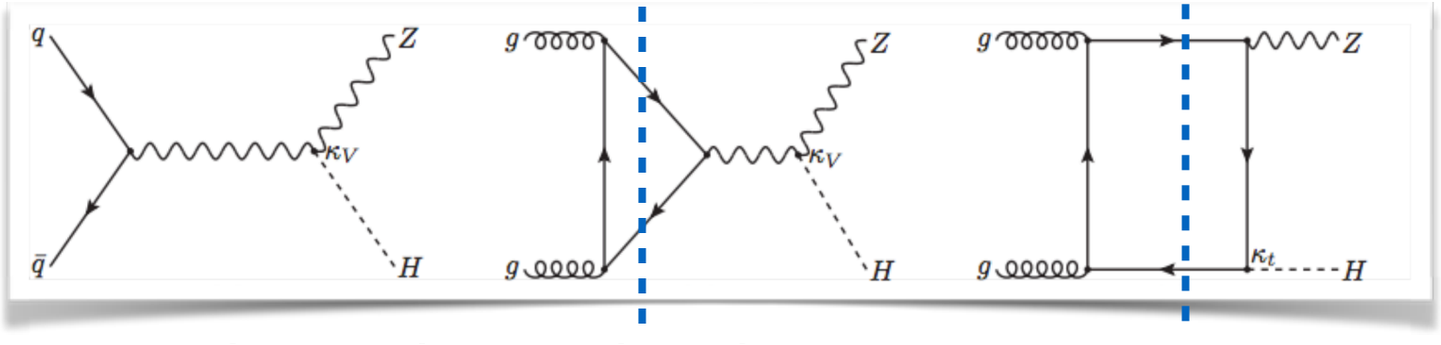


- DY signal/back via MEPS@NLO (0 and 1-jet at NLO): it works as towers of MC@NLO
- Loop-induced signal/back via MEPS@Loop^2 (0 and 1-jet loop^2): CKKW merging

DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

ZH Production

- ZH signal components:



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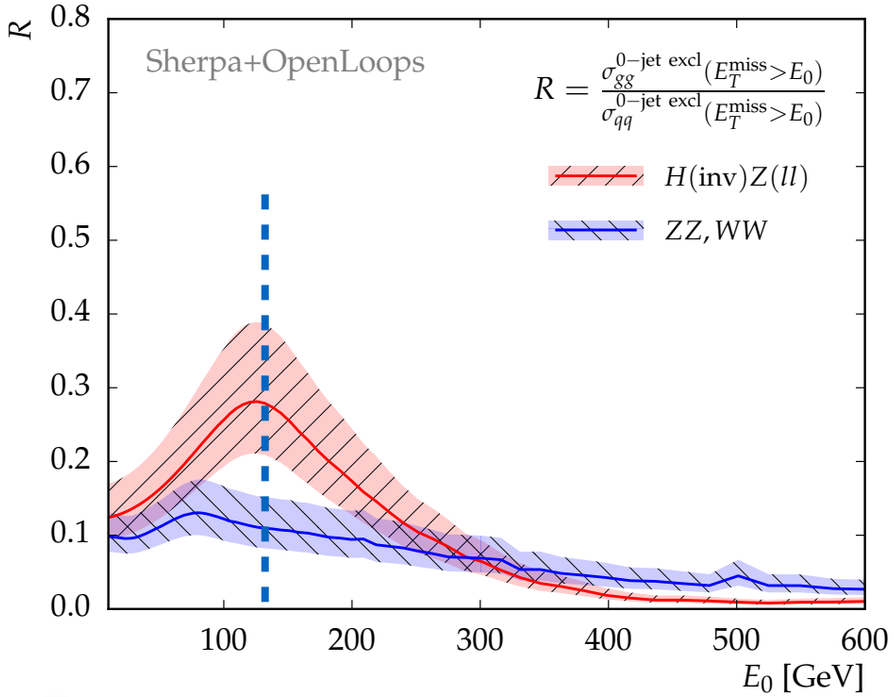

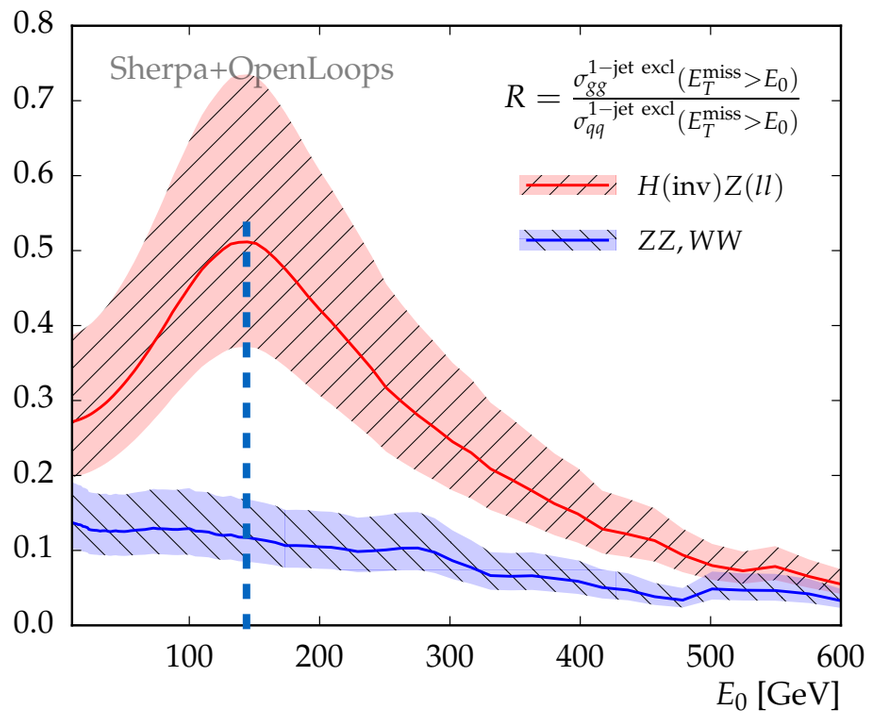

- Despite looking at 0 and 1-jet bins, CMS Run I analyses neglect this component. This impacts on:
  - Invisible bounds from Z(ll)H(inv)
  - And y_b from Z(ll)H(bb)

DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

ZH Production

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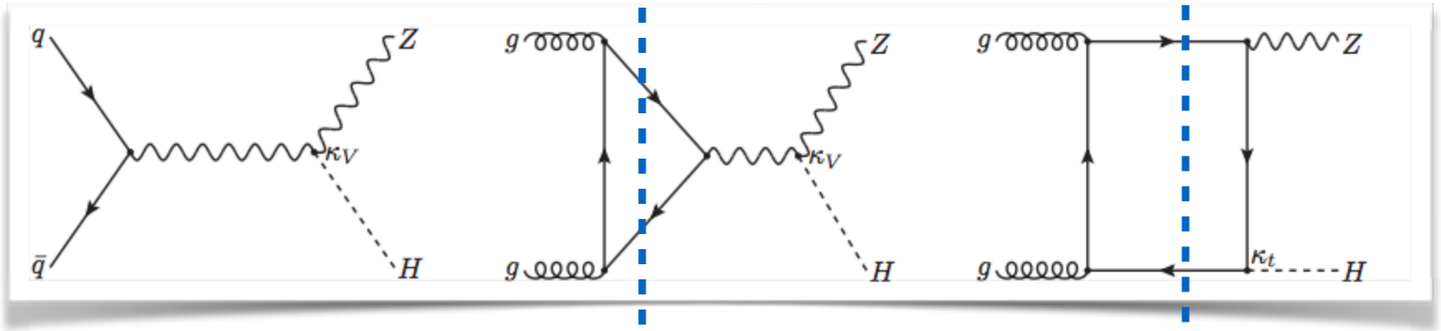

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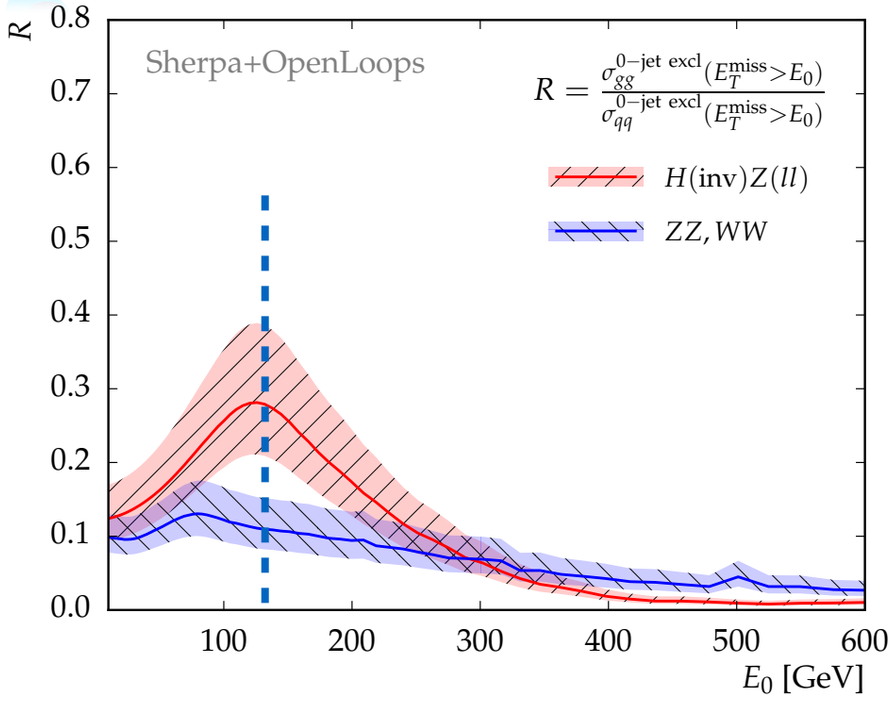
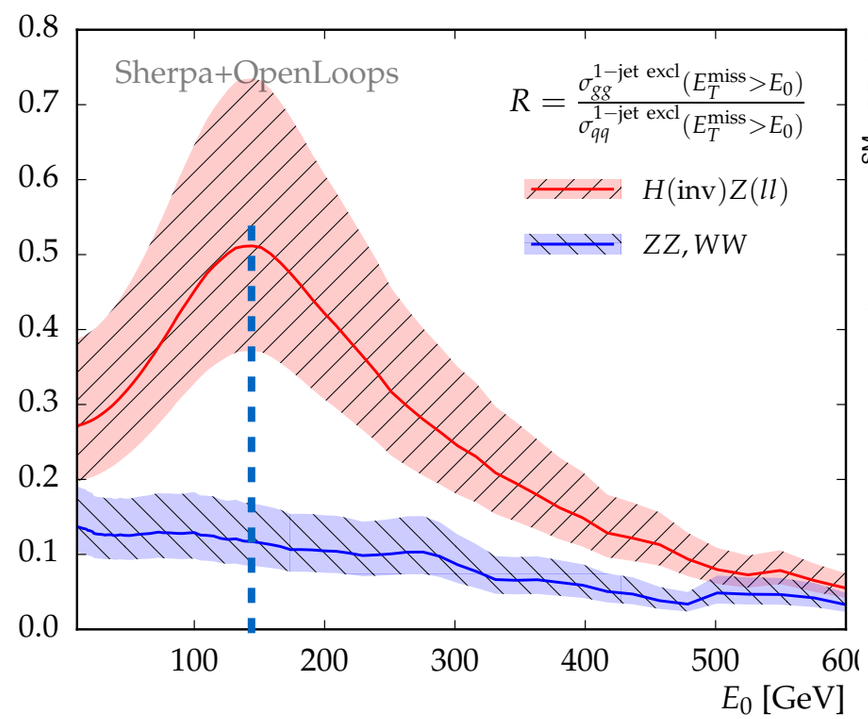
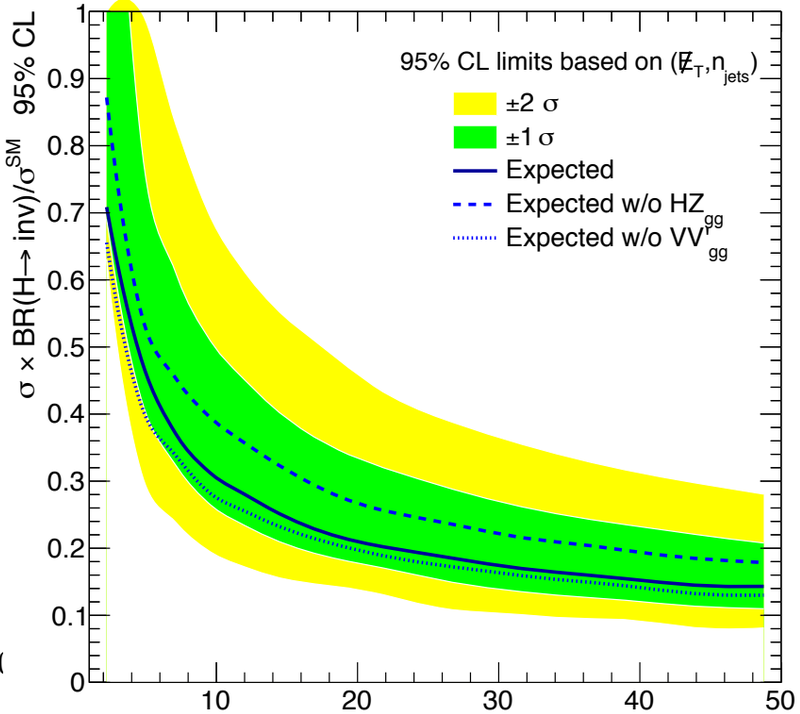




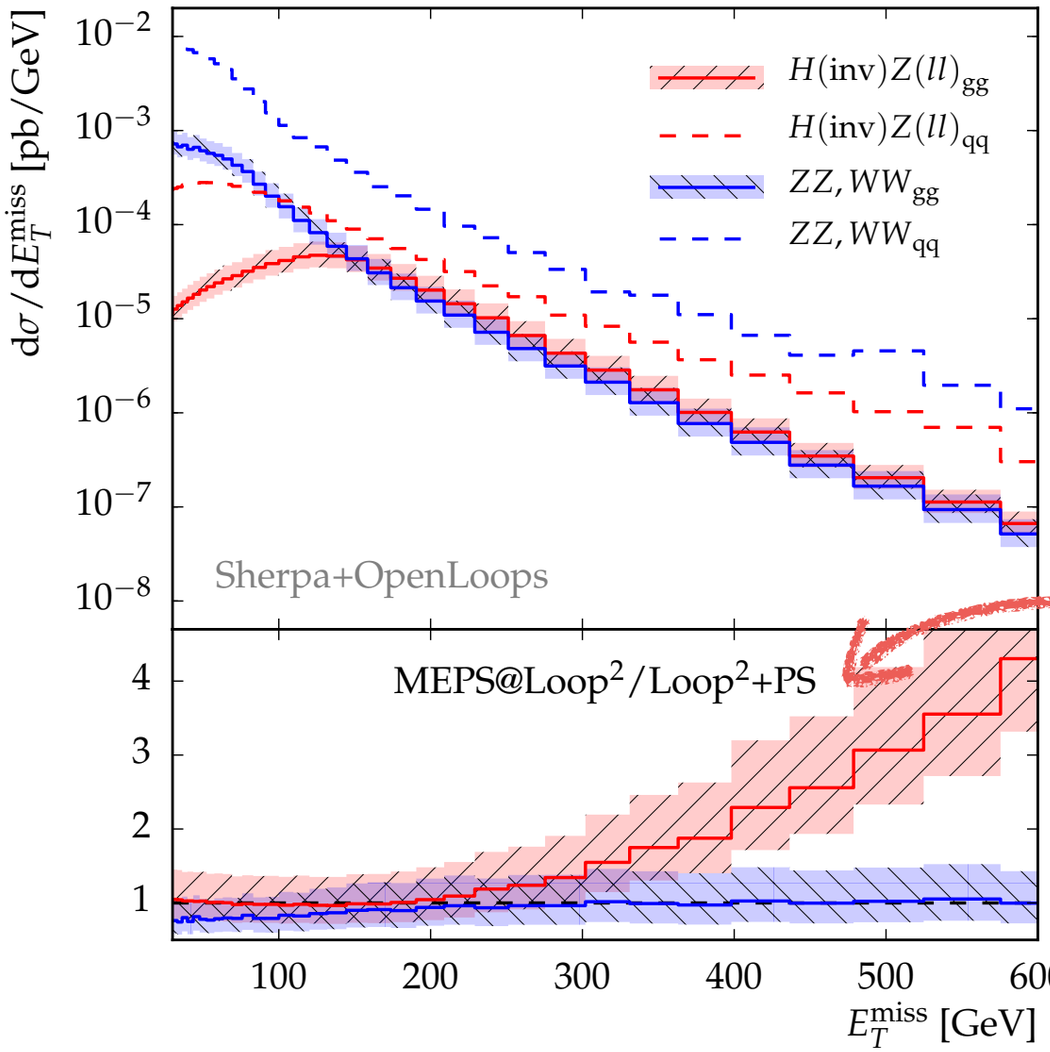


➡ Loop-induced ZH makes the BR_{inv} bound stronger by more than 30%

DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)

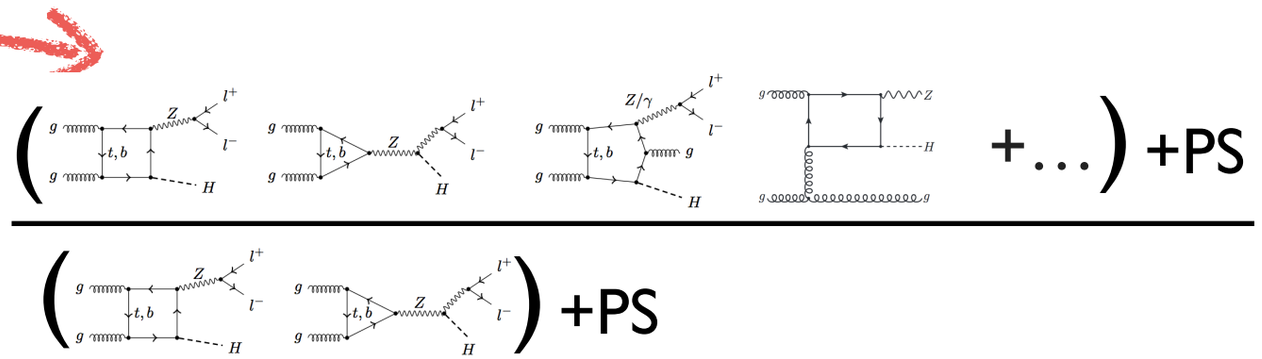
Multi-jet Merging effects

- As the GF becomes a significant player at boosted regimes, a proper modelling is of vital importance



DG, Krauss, Kuttimalai, Maierhoefer (2015, 2016)

- Effects induced by higher jet multiplicity ME beyond the scope of conventional PS alone
- Multi-jet merging correctly fill these phase space regions



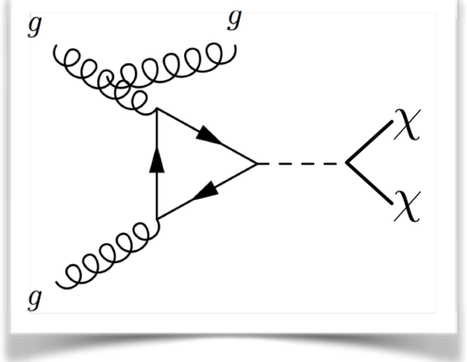
Scalar Simplified Models for DM

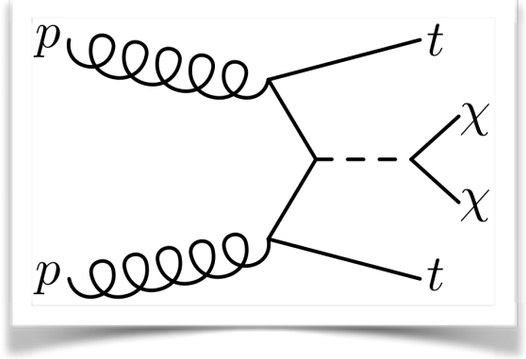
- Let's focus on Dirac fermion DM with scalar/pseudoscalar mediator

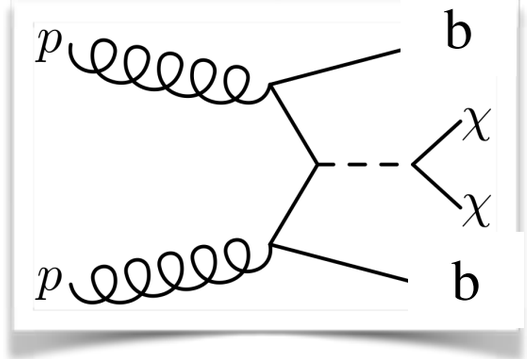
  Fermionic couplings proportional to the SM Yukawas (y_f) - MFV avoids Flavor constrains

$$\mathcal{L} \supset -\sum_f \frac{y_f}{\sqrt{2}} \left(g_v^\phi \phi \bar{f} f + i g_v^A A \bar{f} \gamma_5 f \right) - g_\chi^\phi \phi \bar{\chi} \chi - i g_\chi^A A \bar{\chi} \gamma_5 \chi$$

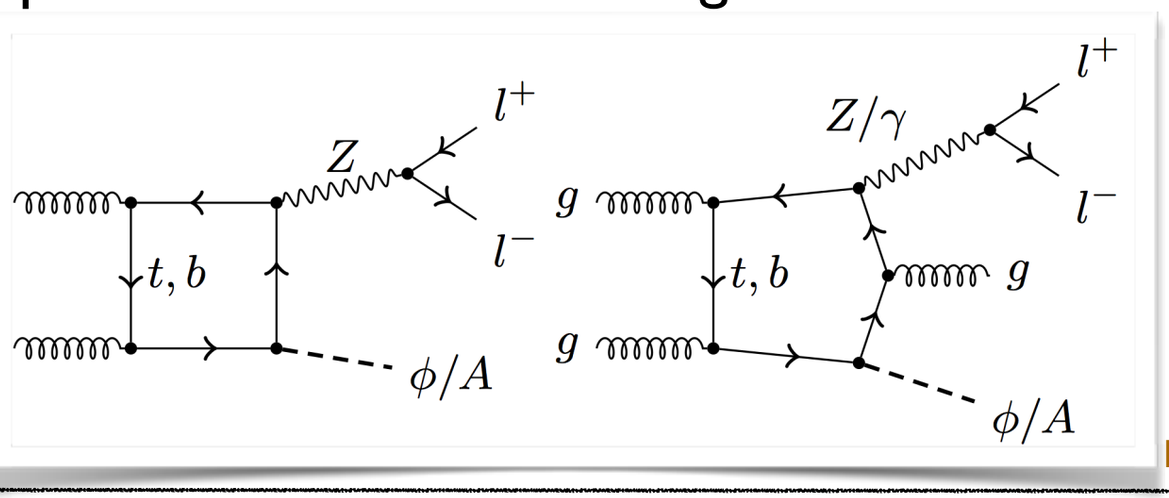
- Three well studied signatures at Run-I LHC:







- Loop-induced ZH produce a relevant new signature:



DG, Krauss, Kuttimalai, Maierhoefer (2016)

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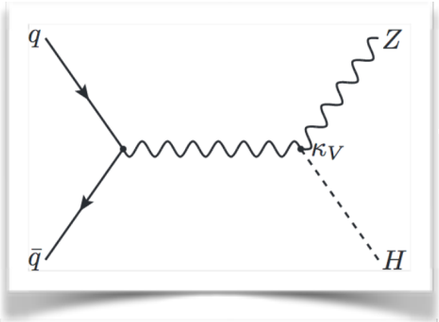
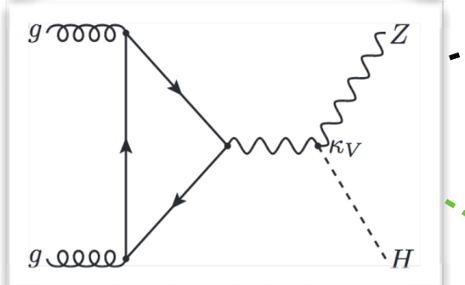
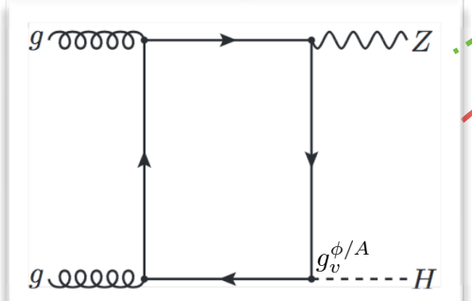
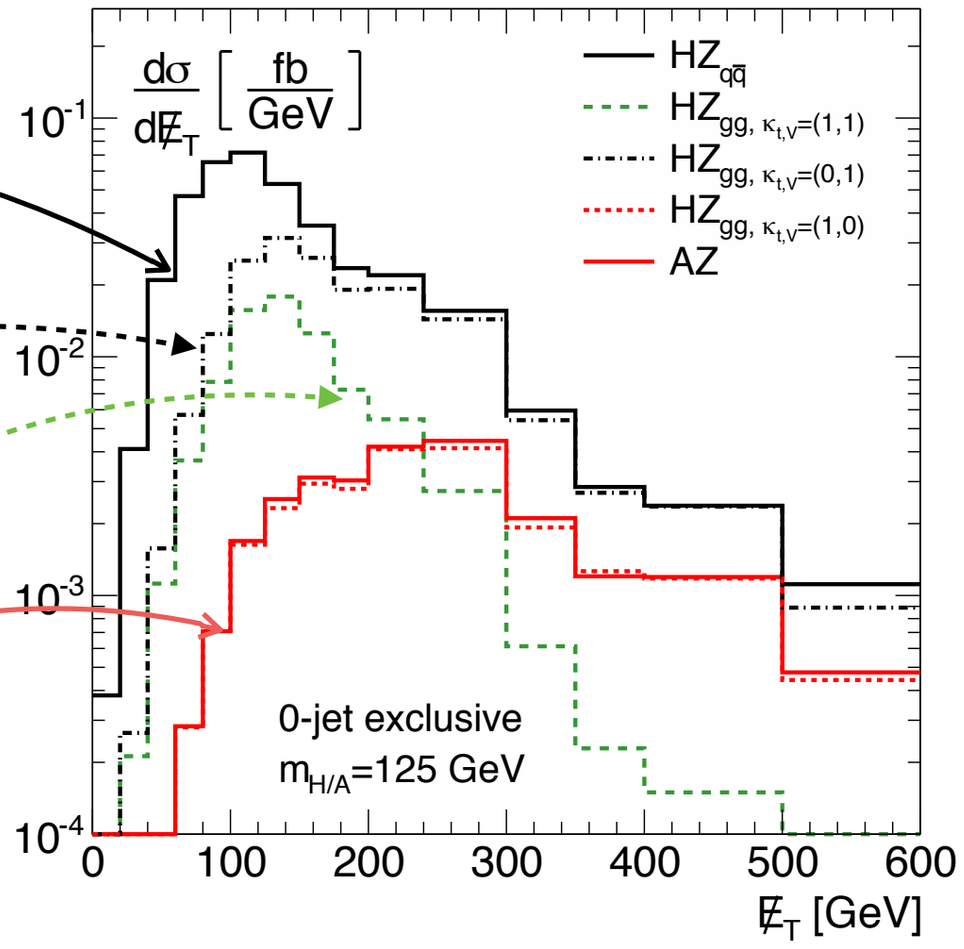






$$\sim g_v^{\phi/A} \ln^2\left(\frac{s}{m_t^2}\right)$$



DG, Krauss, Kuttimalai, Maierhoefer (2016)

UV completions

- Can we improve these searches and/or find another sensitive channel(s)?
- Which kind of UV completions are we mapping? ~~Simplified~~ Simple Models

- Since Scalar case is mostly bound by DD, let's focus on Pseudoscalar scenario where DD is suppressed & LHC is more sensitive

$$\mathcal{L}_s = \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - g_\chi\, a\, \bar{\chi} i\gamma^5 \chi - g_{\rm SM}\, a \sum_f \frac{y_f}{\sqrt{2}}\, \bar{f} i\gamma^5 f$$

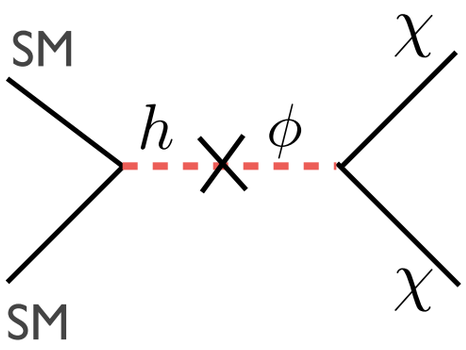
if χ is SM gauge singlet $\mathcal{L}$ is not gauge invariant

"a" needs $SU(2)_L \times U(1)_Y$ charge to couple to SM fermions

Needs mixing between "a" & scalar EW multiplet (new states)

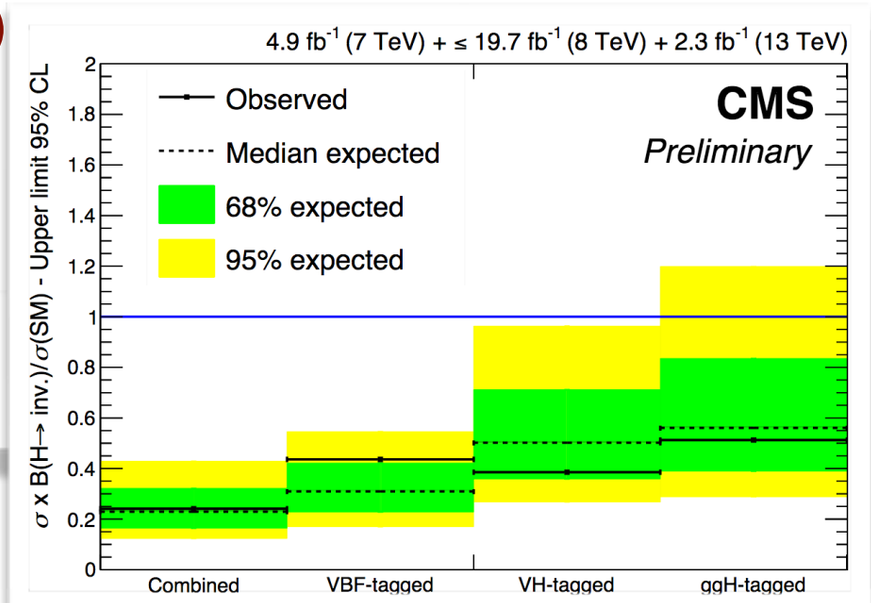
- Ex: Higgs mixing $\mathcal{L} \supset -y_f \bar{f} H f - \mu_\phi \phi |H|^2 - y_\chi \phi \bar{\chi}\chi$

O'Connell, Ramsey-Musolf, Wise (2006)



$$\mathcal{L} \supset \sin\theta\phi \left(\frac{m_f}{v} \bar{f} f + \frac{m_l}{v} \bar{l} l + \frac{2m_W^2}{v} W^2 + \frac{m_Z^2}{v} Z^2 \right)$$

Craig, Lou, McCullough, Thalapillil (2014)



Pseudoscalar Portal

Pseudoscalar Portal: simple renormalizable completion with EW singlet DM

Ipek, McKeen, Nelson (2014)

It works as a generalization of the Higgs Mixing framework to 2HDM

visible sector — dark sector — portal

$$\mathcal{L} \supset -V_{\rm 2HDM} - \frac{m_{a_0}^2}{2} a_0 - i g_\chi a_0 \bar{\chi}\gamma_5\chi + (i\kappa a_0 H_1^\dagger H_2 + h.c.)$$

with $y_\chi, \kappa \in \mathcal{R}eal$ & no CP-violation in 2HDM

$$V_{\rm dark} \supset g_\chi \, (c_\theta \, a + s_\theta \, A) \, \bar{\chi} i\gamma^5 \chi$$

mixing

$$A = c_\theta \, A_0 + s_\theta \, a_0$$
$$a = c_\theta \, a_0 - s_\theta \, A_0$$

$$V_{\rm portal} = \frac{(m_A^2 - m_a^2)\, s_{2\theta}}{2\, v} \, (c_{\beta-\alpha} \, H - s_{\beta-\alpha} \, h) \times \left[aA \, (s_\theta^2 - c_\theta^2) + (a^2 - A^2) \, s_\theta c_\theta \right] .$$

2HDM Yukawas:

DG, Machado, No (2016)

Bauer, Haisch, Kahlhoefer (2017)

Type-I

$$i(c_\theta A - s_\theta a) t_\beta^{-1} \sum_q \frac{y_q}{\sqrt{2}} \bar{q}\gamma^5 q$$

Type-II

$$i(c_\theta A - s_\theta a) \left(t_\beta^{-1} \sum_u \frac{y_q}{\sqrt{2}} \bar{q}\gamma^5 q + t_\beta \sum_d \frac{y_q}{\sqrt{2}} \bar{q}\gamma^5 q \right)$$

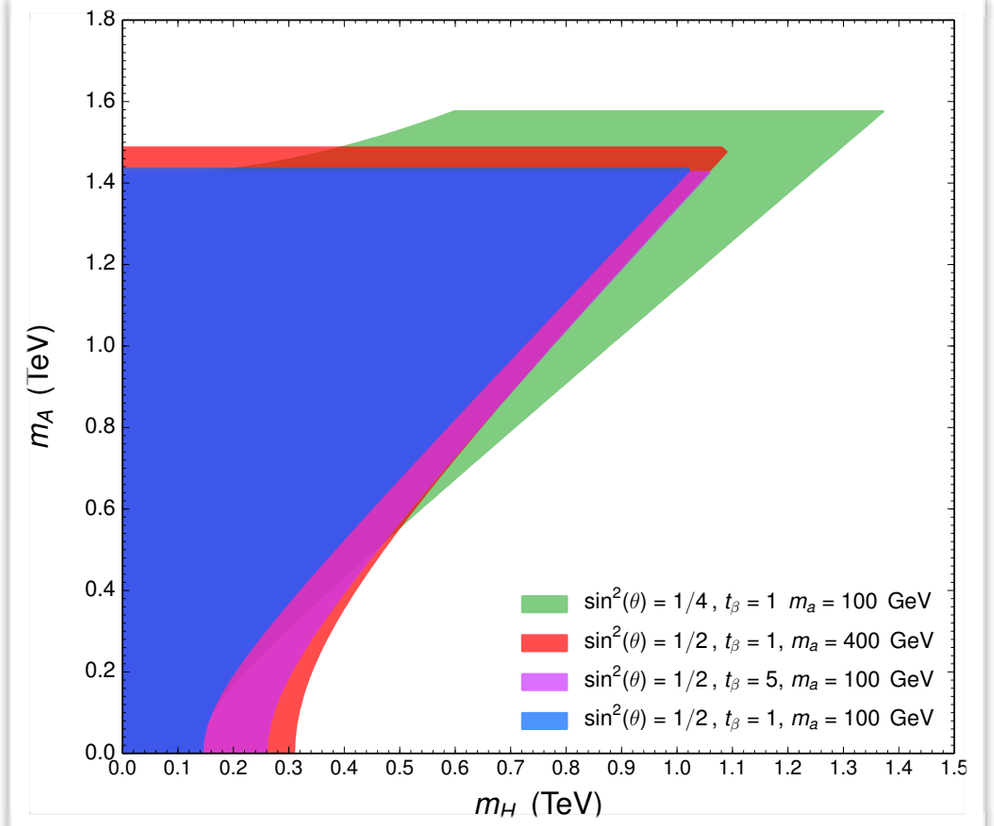
Pseudoscalar Portal

SM + DM + "a" mediator + new states

- A: new (heavier) mediator
- $H^{\pm}, H_0$: New states (mediator gauge partners)

1) $m_{A,H^{\pm},H_0} \sim m_a$ — 2 mediator scenario + $H^{\pm}, H_0$ pheno as in usual 2HDM

2) $m_{A,H^{\pm},H_0} \gg m_a$ — Closer to Simplified Model



DG, Machado, No (2016)

If $\sin\theta$ is fixed new states do not fully decouple

Mass Splittings among A $H^{\pm}$ H_0 bounded by 2HDM Unitarity

Ginzburg, Ivanov, Phys. Rev ***D72*** *(2005) 115010*

$$m_i - m_j \leq \mathcal{O}(\text{few}) \times v$$

Assume $[\, c_{\beta-\alpha} = 0 \qquad m_{H^{\pm}} = m_{H_0} \,]$

Perturbativity unitarity

Pseudoscalar Portal

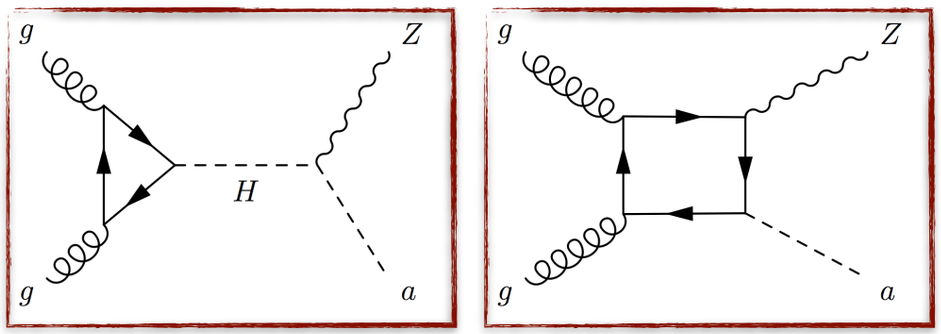
SM + DM + "a" mediator + new states

A: new (heavier) mediator

$H^{\pm}, H_0$: New states (mediator gauge partners)

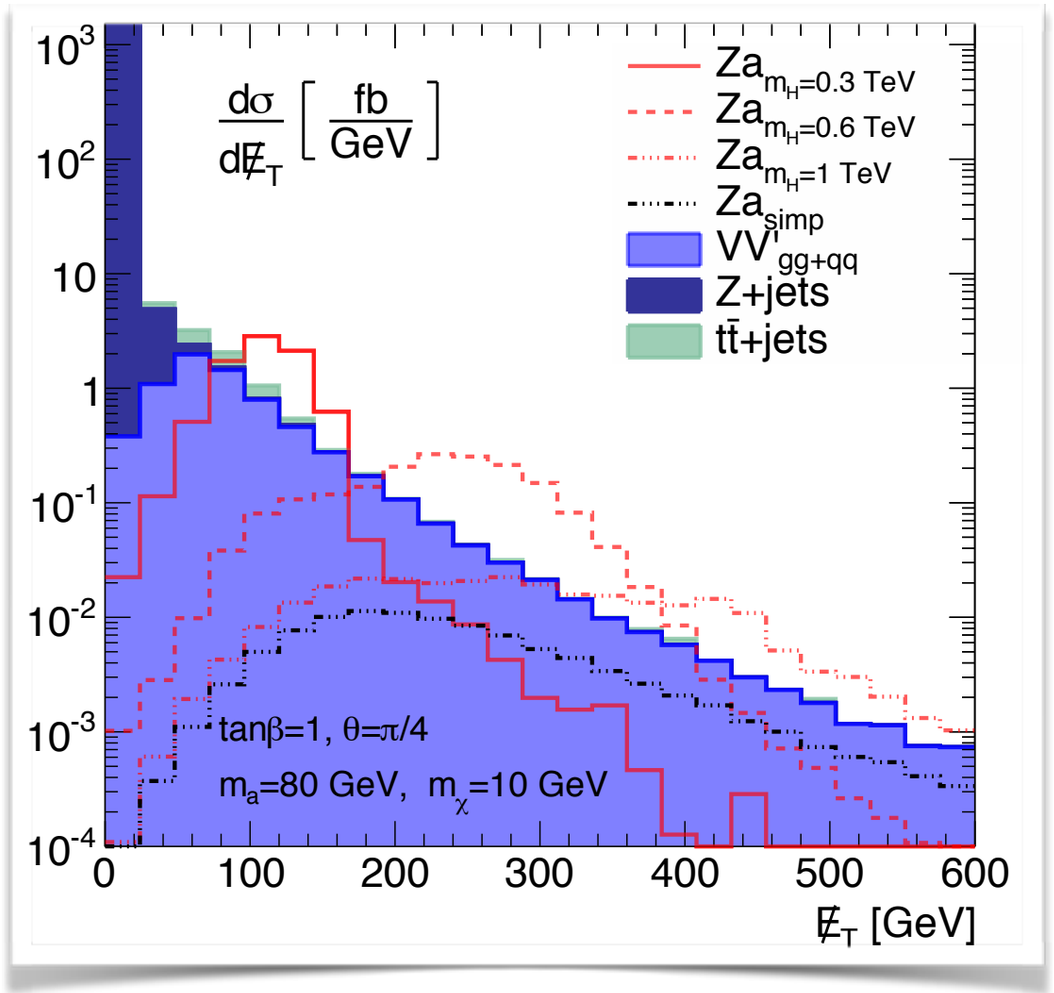
In the presence of mixing new states
do not (fully) decouple

present in Simplified Model



Resonante mono-Z for $m_H > m_a + m_Z$

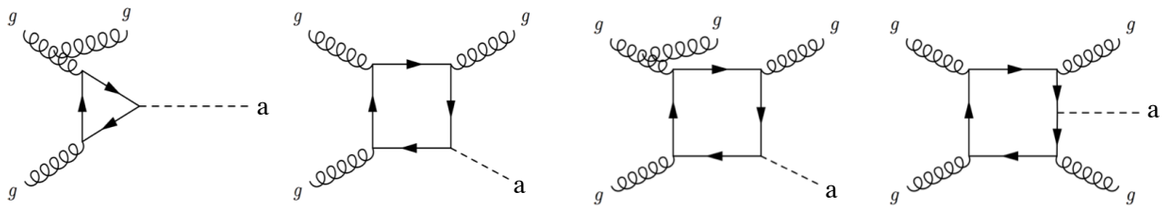
$$\not{E}_T^{\max} \sim \frac{1}{2\,m_H}\sqrt{(m_H^2 - m_a^2 - m_Z^2)^2 - 4m_Z^2 m_a^2}$$

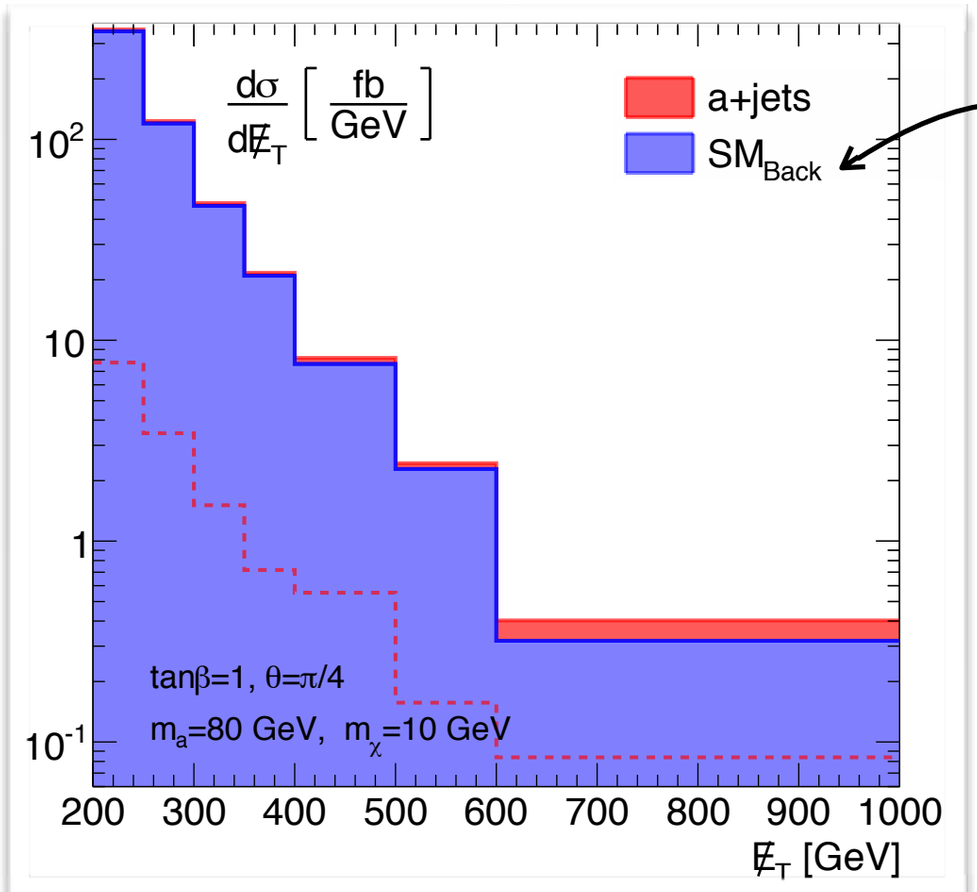


DG, Machado, No (2016)

Pseudoscalar Portal

- Impact on usual monojets search:

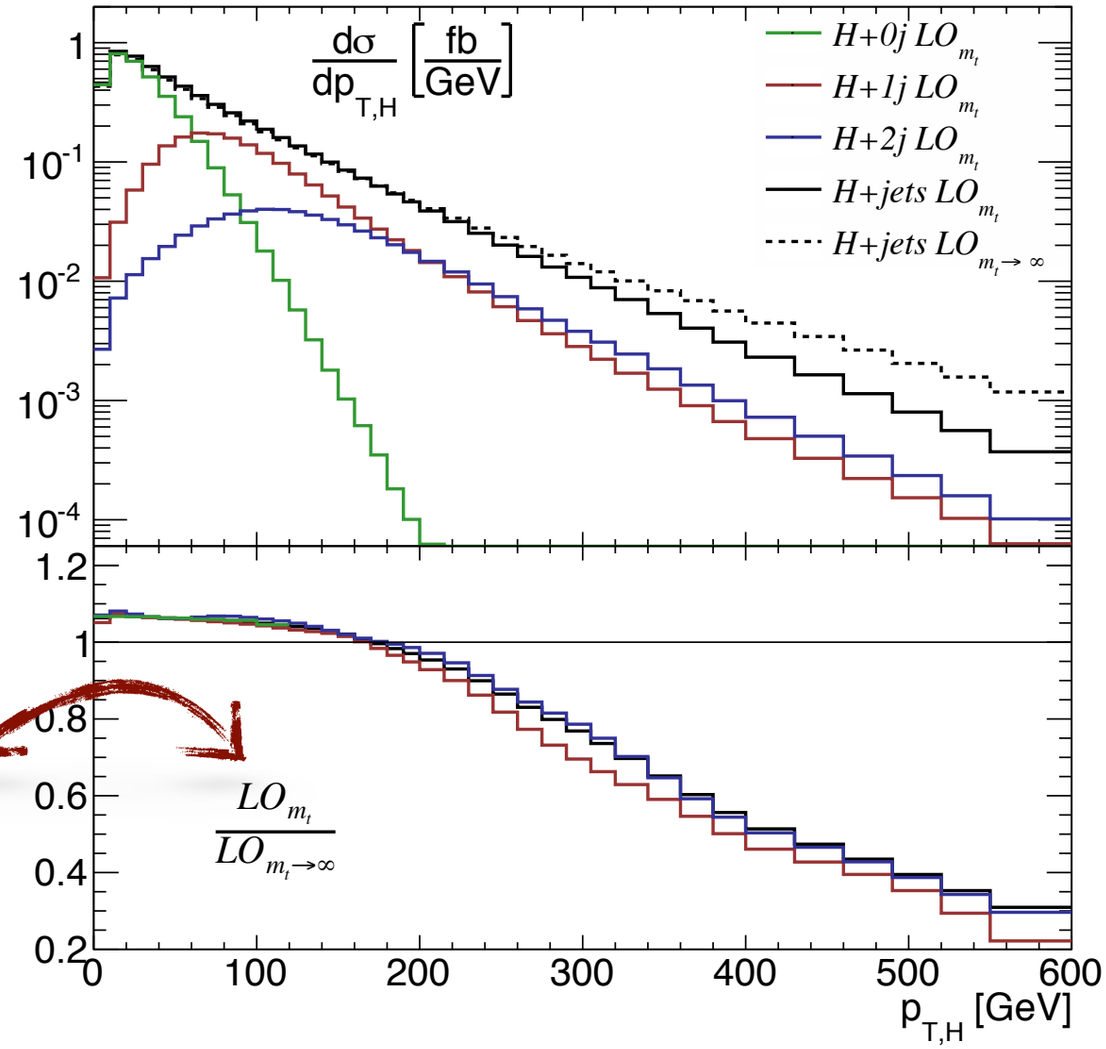


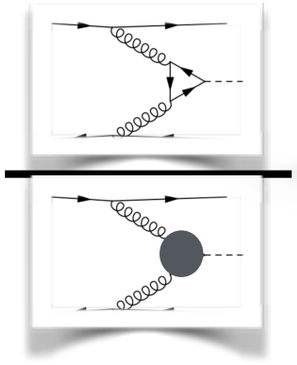


CMS PAS EXO-15-003

DG, Machado, No (2016)

- Precision is fundamental: Top mass effects correction of O(4) at $p_{TH(A)}$~600 GeV





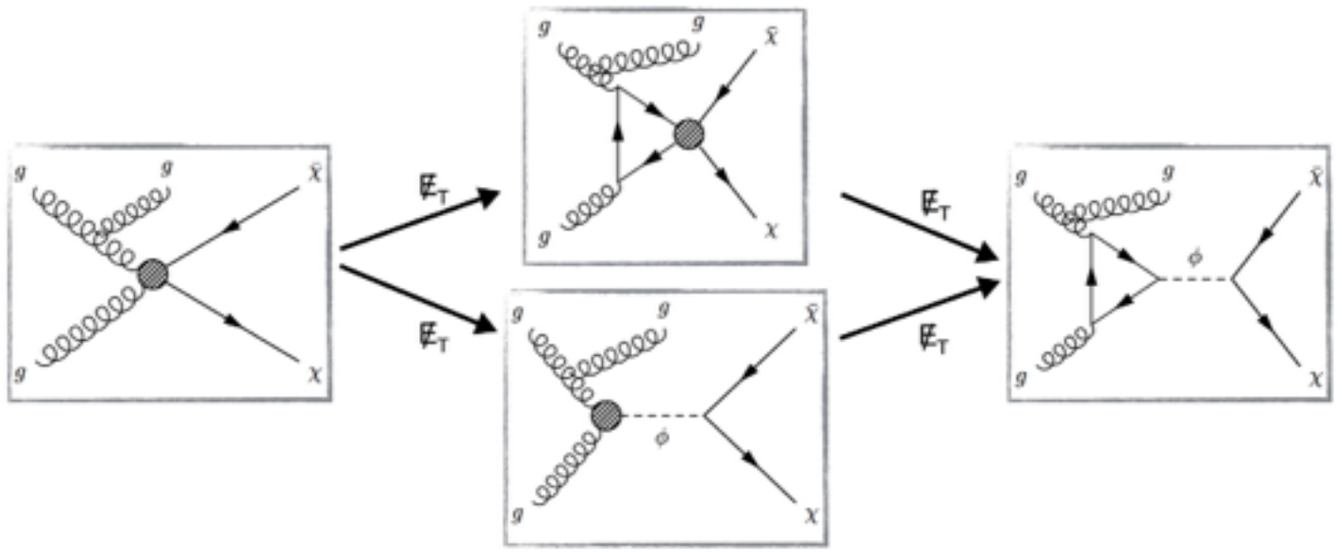
Buschman, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

→ Monojet searches will soon face systematic uncertainty wall at Run-II

→ DM searches commonly require $\not{E}_T$ >> m_t

Pseudoscalar Portal

- Top mass effects show up in other frameworks too. Take EFT as an example:



Buckley, Feld, DG (2014)

Haisch, Kahlhoefer, Unwin (2013)

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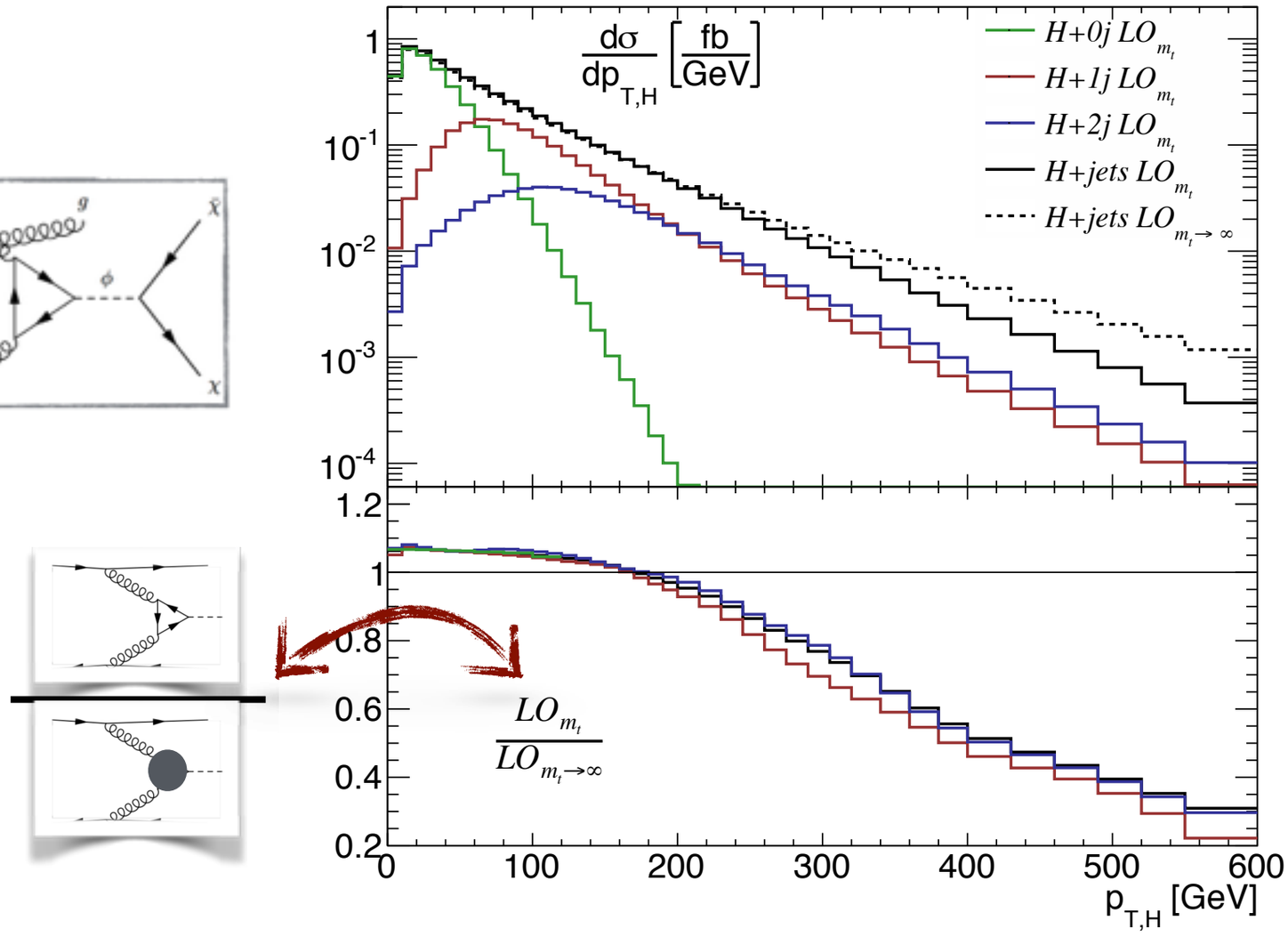
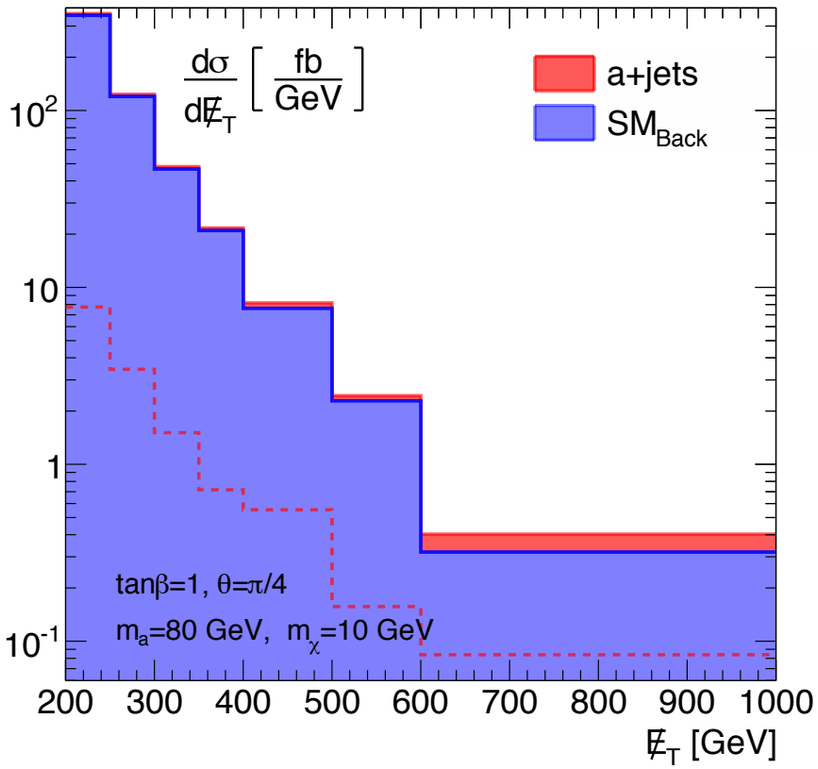


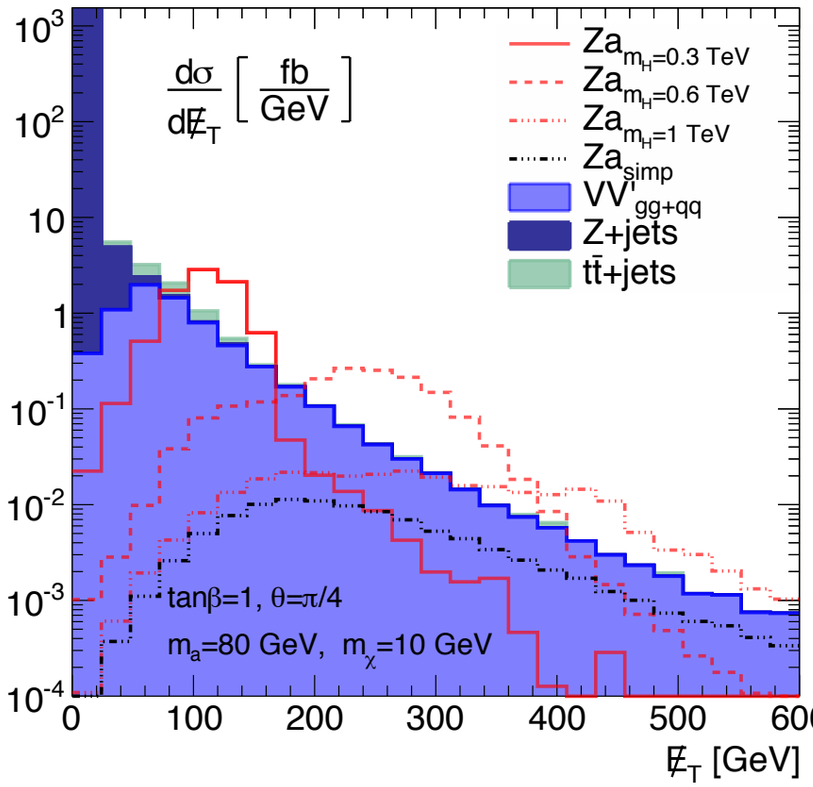
Buschman, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

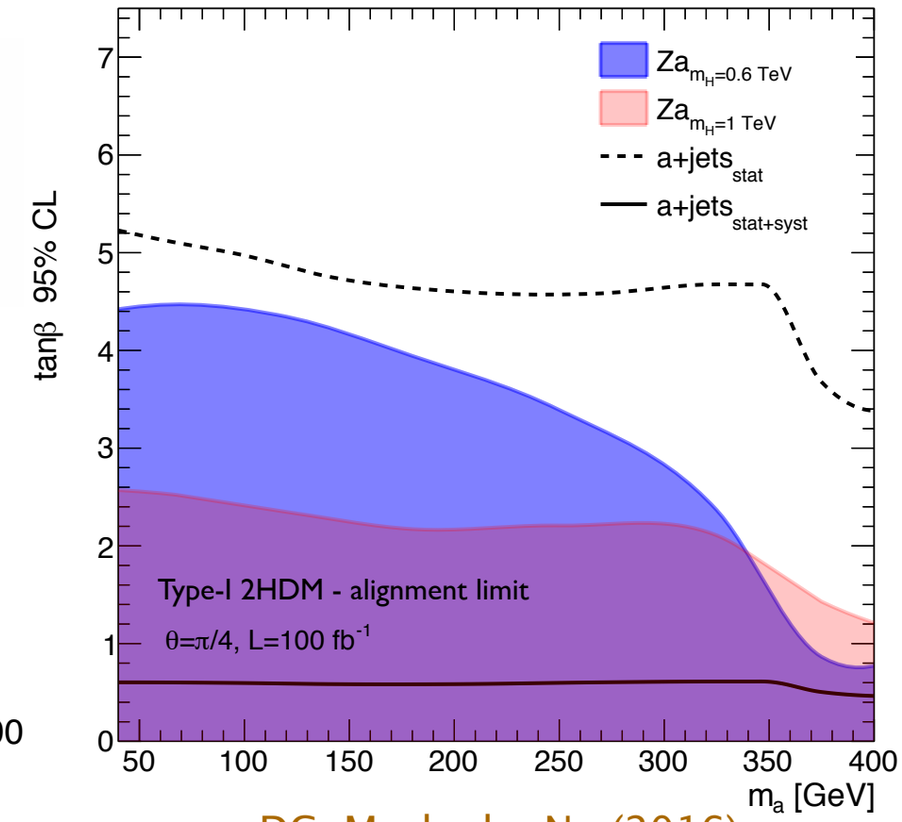
→ DM searches commonly require $\not{E}_T$ >> m_t

Pseudoscalar Portal

Sensitivity comparison:







DG, Machado, No (2016)

- Monojets searches will soon face systematic uncertainty wall at Run-II
- New channels are welcome. Mostly ones with better control on backgrounds
- Z(ll)A(xx) provides competitive bounds to monojets in the pseudoscalar portal scenario

Summary

- Loop-induced ZH(inv) provide relevant contributions: bound stronger by ~30%

- Currently studied Simplified Models channels will severely suffer with systematic uncertainties at Run-II LHC. Alternative channels are welcome

- We showed that $Za(\chi\chi)$ channel provides competitive bounds in the
  - Simplified Model framework (via loop-induced production)
  - Pseudoscalar Portal (via resonant heavy Higgs interfering with loop-induced)

- Extra channels can be motivated with ~~Simplified~~ Simple Models for DM

  Pseudoscalar Portal matches well with the Higgs(es) search program

Thank you for your attention!