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 piling up

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 signal components:

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 $\alpha_{EW}$ factors: $y_t \sim O(1)$
- Threshold enhancement at $m_{ZH} \sim 2m_t$, which gives rise to relevant rates at the boosted regime $p_{TH} \sim m_t$

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

DG, Krauss, Kuttimalai, Maierhoefer (2015, 2016)
ZH signal components:

\[ @\text{LO} \sim O(\alpha_{\text{EW}}^2) \]

\[ @\text{LO} \sim O(\alpha_s^2 \alpha_{\text{EW}}^2) \]

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.

The studies presented here were performed with Sherpa+OpenLoops.

See Stefano's talk for details on OpenLoops.
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
ZHi Production

ZH signal components:

Boosted kinematics enhances loop-induced component

Despite looking at 0 and 1-jet bins, CMS Run I analyses neglect this component. This impacts on:

- Invisible bounds from Z(\text{ll})H(\text{inv})
- And $\gamma_b$ from Z(\text{ll})H(bb)

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

Dorival Gonçalves
ZH Production

ZH signal components:

Boosted kinematics enhances loop-induced component

Loop-induced ZH makes the BR$_{inv}$ bound stronger by more than 30%

DG, Krauss, Kuttimalai, Maierhoefer (2015,2016)
As the GF becomes a significant player at boosted regimes, a proper modelling is of vital importance.

Effects induced by higher jet multiplicity ME beyond the scope of conventional PS alone.

Multi-jet merging correctly fill these phase space regions.

DG, Krauss, Kuttimalai, Maierhoefer (2015, 2016)
Let’s focus on Dirac fermion DM with scalar/pseudoscalar mediator.
Fermionic couplings proportional to the SM Yukawas ($y_f$) - MFV avoids Flavor constrains

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

Three well studied signatures at Run-I LHC:

Loop-induced ZH produce a relevant new signature:
Let's focus on Dirac fermion DM with scalar/pseudoscalar mediator. Fermionic couplings proportional to the SM Yukawas ($y_f$) - MFV avoids Flavor constrains.

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

\[ \sim g^\phi / A \ln \left( \frac{s}{m^2} \right) \]

DG, Krauss, Kuttimalai, Maierhoefer (2016)
Can we improve these searches and/or find another sensitive channel(s)?

Which kind of UV completions are we mapping? Simplified Models

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

\[ \mathcal{L}_s = \bar{\chi} i \partial \phi - m_\chi \chi + \frac{1}{2} (\partial \mu a)^2 - \frac{m^2}{2} a^2 - g_\chi a \bar{\chi} i \gamma^5 \chi - g_{SM} a \sum_f \frac{y_f}{\sqrt{2}} \bar{f} i \gamma^5 f \]

if \( \chi \) 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

\[ \mathcal{L} \supset -y_f \bar{f} H f - \mu_\phi \phi |H|^2 - y_\chi \phi \bar{\chi} \chi \]


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

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

\[ \mathcal{L} \supset -V_{2\text{HDM}} - \frac{m_{a_0}^2}{2} a_0 - ig_\chi a_0 \bar{\chi} \gamma_5 \chi + \left( i \kappa a_0 H_1^\dagger H_2 + \text{h.c.} \right) \]

with \( y_\chi, \kappa \in \mathbb{R} \text{eal} \) & no CP-violation in 2HDM

\[ V_{\text{dark}} \supset g_\chi (c_\theta a + s_\theta A) \bar{\chi} i \gamma^5 \chi \]

mixing

\[ A = c_\theta A_0 + s_\theta a_0 \]
\[ a = c_\theta a_0 - s_\theta A_0 \]

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

2HDM Yukawas:

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

DG, Machado, No (2016)
Bauer, Haisch, Kahlhoefer (2017)
SM + DM + "a" mediator + new states

1) \( m_{A,H^\pm,H_0} \sim m_a \)

2) \( m_{A,H^\pm,H_0} \gg m_a \)

A: new (heavier) mediator

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

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

Closer to Simplified Model

DG, Machado, No (2016)
SM + DM + “a” mediator + new states

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

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

$$E_T^{\max} \sim \frac{1}{2m_H} \sqrt{(m_H^2 - m_a^2 - m_Z^2)^2 - 4m_Z^2m_a^2}$$

$A$: new (heavier) mediator

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

DG, Machado, No (2016)
**Pseudoscalar Portal**

**Impact on usual monojets search:**

![Graph showing the impact on usual monojets search](image)

**Precision is fundamental:** Top mass effects correction of $O(4)$ at $p_{T,H} \approx 600$ GeV

![Graph showing precision effects](image)

**DM searches commonly require $m_\chi \gg m_\chi$**

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

DG, Machado, No (2016)

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

---

Dorival Gonçalves

Irvine - 04.04.2017
Top mass effects show up in other frameworks too. Take EFT as an example:

Precision is fundamental: Top mass effects correction of $O(4)$ at $p_{T,H}(A) \sim 600$ GeV

Buckley, Feld, DG (2014)
Haisch, Kahlhoefer, Unwin (2013)

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

DM searches commonly require $E_T \gg m_t$
Monojets searches will soon face systematic uncertainty wall at Run-II

New channels are welcome. Mostly ones with better control on backgrounds

$Z(\gamma)A(\gamma\gamma)$ provides competitive bounds to monojets in the pseudoscalar portal scenario
Loop-induced $ZH(\text{inv})$ 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 $Z\alpha(\chi\chi)$ 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 Models for DM

Pseudoscalar Portal matches well with the Higgs(es) search program.
Thank you for your attention!