

Characterisation of the NLO cross sections for the associated production of dark matter with heavy quarks

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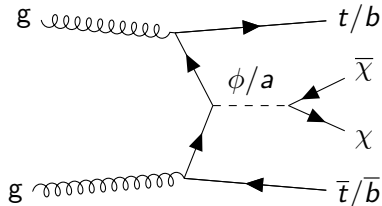
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- Focusing on the specific case of spin-0 mediator models produced in association with heavy quarks (Yukawa-like couplings).
- Using MadGraph5_aMC@NLO for cross section calculations ([1405.0301](#)).
- Motivation:
 - Use more accurate description of the signal cross section (LO \rightarrow NLO).
 - Reduce the signal theoretical uncertainties.
 - Propose a final recommendation for the cross section calculations for both ATLAS and CMS collaborations.
- Scope:
 - Study the dependence of the NLO cross sections on the PDF and scale choices.
 - Address for the first time the NLO corrections for the dark matter production with bottom quarks.

- Weakly Interacting Massive Particle: Mediator (spin-0) between SM particles and DM particles (spin-1/2):
 - Scalar mediator: $\mathcal{L}_\phi^{int} = -g_\chi \phi \bar{\chi} \chi - \sum_{fermions} g_\nu \frac{y_f}{\sqrt{2}} \phi \bar{f} f$
 - Pseudo-scalar mediator: $\mathcal{L}_a^{int} = -ig_\chi a \bar{\chi} \gamma^5 \chi - \sum_{fermions} ig_\nu \frac{y_f}{\sqrt{2}} a \bar{f} \gamma^5 f$
- Motivation to look at processes with heavy flavour quarks.
- Free Parameters: $m_{\phi/a}$, m_χ , g_χ , g_ν .
- Fixing $m_\chi = 1\text{GeV}$, $g_\chi = g_\nu = 1$.



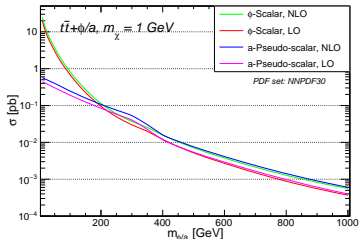
1 Final States with $DM+t\bar{t}$

2 Final States with $DM+b\bar{b}$

DM+ $t\bar{t}$: Signal Production

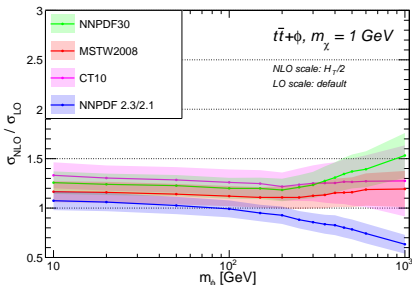
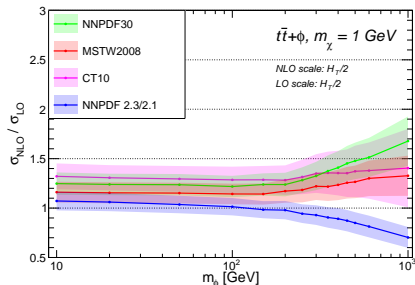
- Using DMSimp ([1508.05327](#)) for signal production, contains five massless flavours (**5FS**).
- Investigating two different scales:
 - $H_T/2$ scale: H_T is the sum of transverse masses of the final state particles.
 $p p \rightarrow t \bar{t} \chi d \chi \bar{d}$ [QCD]
 - **default scale**: transverse mass of the $2 \rightarrow 2$ partonic system resulting from a k_T -clustering of the final state particles.
 $p p \rightarrow t \bar{t} \chi d \chi \bar{d}$

- NLO: $H_T/2$ scale.
- LO: **default scale**.
- For high mediator masses cross sections are similar for ϕ/a .



DM+ $t\bar{t}$: PDF Sets

- Comparing different PDF sets:
 - Blue: 1508.05327 (DMSimp)
 - Green: 1710.11412 (ATLAS)
- NLO scale: $H_T/2$. LO scale: $H_T/2$ (left), **default scale** (right).
- Independence from the scale choice for the k-factors.
- Values for k-factors increase when a decay to a top-pair is allowed.



1 Final States with $DM+t\bar{t}$

2 Final States with $DM+b\bar{b}$

DM+ $b\bar{b}$: Signal Production

- Scheme choice (b -quark presence inside the proton):
 $m_b \sim Q$: 4FS ; $m_b \ll Q$: 5FS.
- b -quarks+ $\phi/a \rightarrow$ perform the renormalization of y_b in the $\overline{\text{MS}}$ scheme (1409.5301) \rightarrow re-sum logarithms of the form $\log(m_b/m_{\phi/a})$.
- Following 1203.6393, 1605.09411, renormalisation at NLO is set to $H_T/3$.

- Production using 4FS:

```
define p = g u c d s u~ c~ d~ s~  
define j = g u c d s u~ c~ d~ s~  
p p > h1 b b~ [QCD]
```

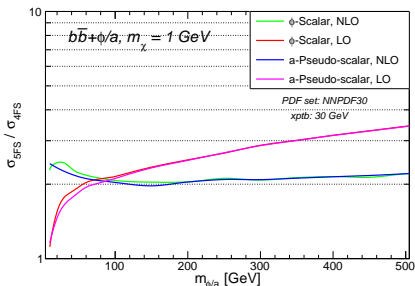
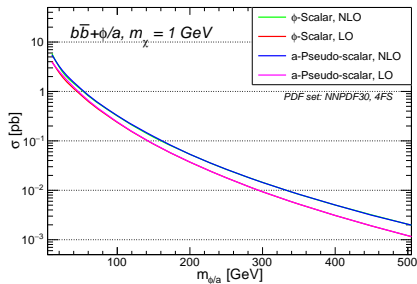
- Production using 5FS:

```
define p = g u c d s u~ c~ d~ s~ b b~  
define j = g u c d s u~ c~ d~ s~ b b~  
p p > h1 j [QCD]
```



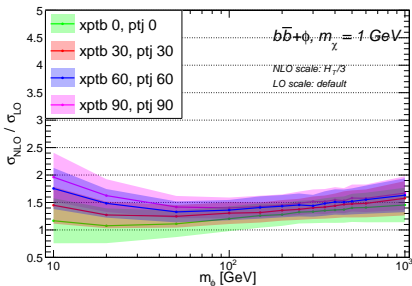
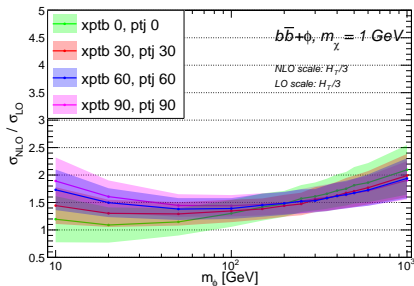
DM+ $b\bar{b}$: Signal Production

- Useful to compare the results in both scheme choices.
- Calculating using **4FS** (left) and the ratio between the **5FS** and **4FS** choices (right).
- NLO: $H_T/3$ scale; LO: **default scale**.
- Different flavour schemes differ by a factor of 2 at NLO accuracy, and has a strong dependence on the mediator mass for LO accuracy.



DM+ $b\bar{b}$: 'xptb' Cut Effect

- 'xptb': at least one b -jet with a minimum p_T requirement.
- This cut creates an effective filter applied on the cross section.
- ATLAS: using NLO 4FS with 'xptb' of 30 GeV. CMS: using LO 5FS with no 'xptb' cut.
- Comparing different 'xptb' cuts using the 4FS.
NLO scale: $H_T/3$. LO scale: $H_T/3$ (left), default scale (right).
- Dependence is mostly relevant for low mediator mass.



- The $DM+t\bar{t}$ NLO cross sections have been investigated:
 - As a function of different PDF sets.
 - For two choices of renormalisation scales.
- The $DM+b\bar{b}$ NLO cross sections have been investigated:
 - Under two different flavour schemes.
 - For two choices of renormalisation scales.
 - Under various transverse momentum requirements on the jets and b -jets in the final state.
- Our recommendations:
 - $DM+t\bar{t}$: apply NLO calculations using DMSimp, using NNPDF30 (already used by ATLAS).
 - $DM+b\bar{b}$: apply NLO calculations using 5FS, dropping 'xptb' requirement.

Thank You

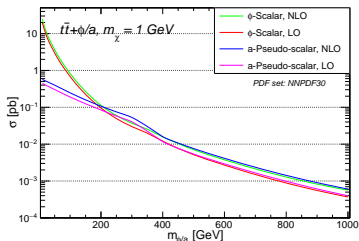
THANK
YOU!

Backup

DM+ $t\bar{t}$: Signal Production

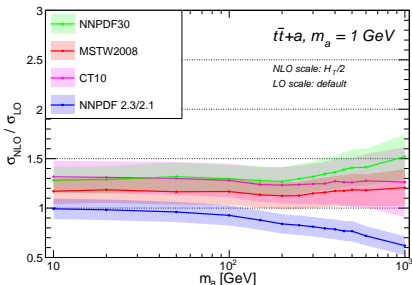
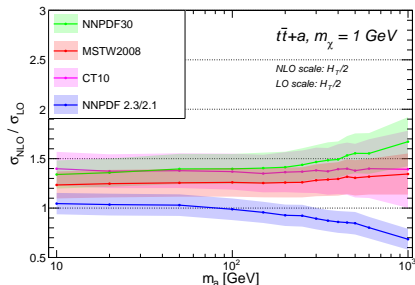
- In case of $m_\chi < m_{\phi/a} \ll m_t$, the production cross section is dominated by $t \rightarrow t + \phi/a$ fragmentation [1508.05327](#).
- For scalar mediator, fragmentation function $\sim (1-x)/x$, where x is the momentum fraction carried by the mediator.
- Scalar: cross section enhancement.
Pseudo-scalar: enhancement term do not exist.

- NLO: $H_T/2$ scale.
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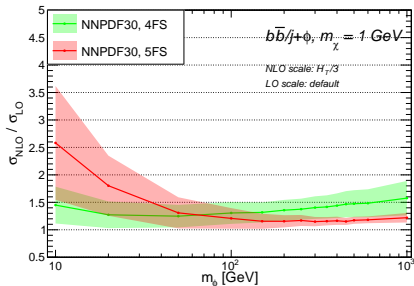
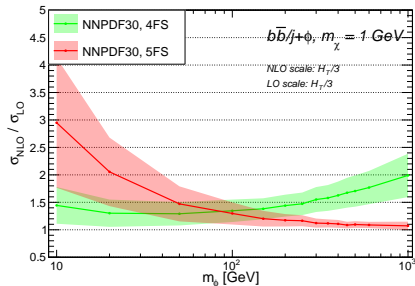


- Comparing different PDF sets:
 - **NNPDF3.0** (LO: 263000 ; NLO: 260000) **1710.11412** (ATLAS).
 - **MSTW2008(68cl)** (LO: 21000 ; NLO: 21100).
 - **CT10** (LO: 10800 ; NLO: 11000).
 - **NNPDF2.1** (LO: 200400) compared to **NNPDF2.3** (NLO: 244600) **1508.05327** (DMSimp).

- Studies for processes with bottom quarks and a heavy particle:
[1203.6393](#), [1605.09411](#).
- The studies have shown that the scale that enters the logarithms is quite reduced compared to the usual hard scale of the process ($m_{\phi/a}$).
- The reduction factor is between 3 and 4 for the mass range that we explore.
- This is why a scale like $H_T/3$ is used.
- In this case differences between the $5FS$ and $4FS$ are also reduced.

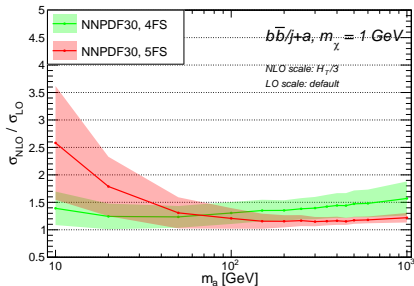
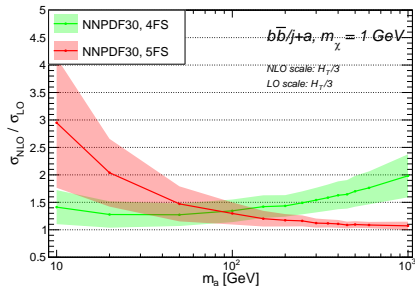
DM+ $b\bar{b}$: Choice of Flavour Scheme

- Comparing two different flavour schemes:
 - Green: 4FS.
 - Red: 5FS.
- NLO scale: $H_T/3$. LO scale: $H_T/3$ (left), **default scale** (right).
- The 4FS k-factor shows a smaller spread as a function of the mediator mass.



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