

# *QCD effects in mono-jet searches for dark matter*

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- ▶ why NLO ?
  - ▶ POWHEG implementation and results
  - ▶ what have we learned ?
  - ▶ DM + 2 jets ?

Haisch, Kahlhoefer, ER [1310.4491]

Haisch, Hibbs, ER [1311.7131]

- ▶ it is useful to classify interactions between DM and SM in terms of effective operators

$$\begin{aligned}\mathcal{O}_V &= \frac{1}{\Lambda^2} (\bar{q}\gamma_\mu q) (\bar{\chi}\gamma^\mu \chi) \quad , \quad \mathcal{O}_A = \frac{1}{\Lambda^2} (\bar{q}\gamma_\mu \gamma_5 q) (\bar{\chi}\gamma^\mu \gamma_5 \chi) \\ \mathcal{O}_S &= \frac{m_q}{\Lambda^3} (\bar{q}q) (\bar{\chi}\chi) \quad , \quad \mathcal{O}_P = \frac{m_q}{\Lambda^3} (\bar{q}\gamma_5 q) (\bar{\chi}\gamma_5 \chi) \\ \mathcal{O}_G &= \frac{\alpha_s}{\Lambda^3} G_{\mu\nu}^a G^{a,\mu\nu} (\bar{\chi}\chi) \quad , \quad \mathcal{O}_{\tilde{G}} = \frac{\alpha_s}{\Lambda^3} \tilde{G}_{\mu\nu}^a G^{a,\mu\nu} (\bar{\chi}\gamma_5 \chi)\end{aligned}$$

- ▶ these interactions arise from “**integrating out**” heavy mediators
- ▶ the EFT approach has several limitations
- ▶ however **useful as a starting point**

[Busoni et al., 1307.2253,...]

[Buchmueller,Dolan,McCabe, 1308.6799]

- 
- ▶ discussion here will be limited to “s-channel mediated” processes
  - ▶ will present mainly results obtained with EFT approach, but public code available since October: can include full propagator (including widths) for heavy/light mediators

# Why NLO?

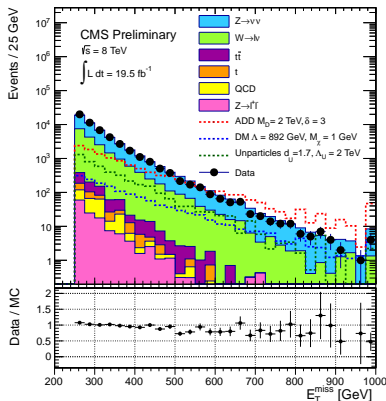
- ▶ **backgrounds** in  $E_{T,\text{miss}} + \text{jet(s)}$  are typically **large** and  $p_T$  spectrum of signal is **featureless**

(and shape is essentially the same for different  $s$ -channel mediated interactions, if all is computed within the same approximation)

- ▶ NLO predictions for signal & backgrounds will **reduce theoretical uncertainties**:

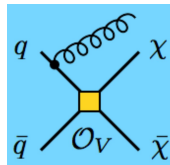
→ should a small excess be found, this could be important to draw a solid conclusion

→ if large excess found, NLO less important (although having accurate QCD predictions is helpful to “read out” parameters from such an excess)



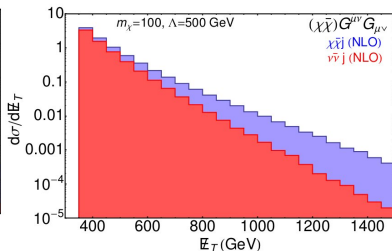
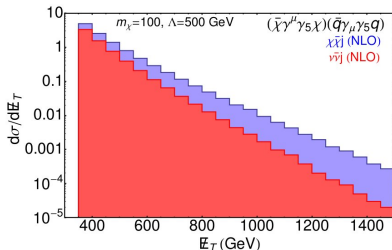
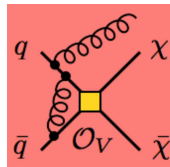
# NLO results

- main background  $Z(\rightarrow \nu\bar{\nu}) + j$  known at NLO for a long time  
[Giele,Glover, '92]



- NLO corrections to signal will **reduce scale ambiguities**, and **potentially give non-negligible K-factors**

- monojet cross-sections first computed at NLO (parton-level only) by Fox & Williams. Available in MCFM  
[Fox,Williams, 1211.6390]



# Why NLO+PS (POWHEG)?

## NLO

- ✓ precision
- ✓ nowadays this is the standard
- ✗ limited multiplicity
- ✗ (fail when resummation needed)

## parton showers

- ✓ realistic + flexible tools
- ✓ widely used by experimental coll's
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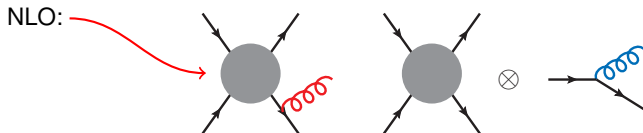
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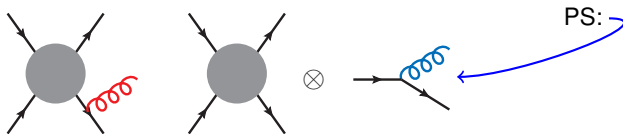
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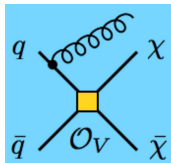
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- ▶ POWHEG is a method that allows to consistently match these approximations
- ▶ DM+monojet production included in the POWHEG-BOX package: this allows NLO+PS simulation of monojet events  
(pure parton-level NLO is a byproduct)
- ▶ will show example where important effects would be missed if using pure parton-level NLO

## Results: cuts and scale choice (CMS)

- ▶ we studied both ATLAS and CMS cuts. For CMS setup:

[CMS-PAS-EXO-12-048]

CMS, 8 TeV, 19.5 fb <sup>-1</sup>
$ \eta_j  < 4.5, p_{T,j} > 30 \text{ GeV}, N_j \leq 2$ $\Delta\phi_{j_1,j_2} < 2.5$
$ \eta_{j_1}  < 2.4, p_{T,j_1} > 110 \text{ GeV}, E_{T,\text{miss}} > 350 \text{ GeV}$

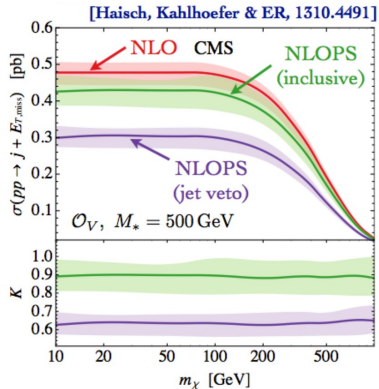
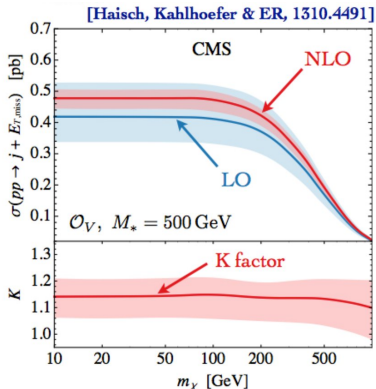


- ▶ from QCD point of view, monojet production is a process with more than one typical scale ( $E_{T,\text{miss}}, p_{T,j}, m_\chi, m_{\chi\bar{\chi}}$ )
- ▶ dynamic choice for factorization and renormalization scale:

$$\mu = \xi \frac{H_T}{2}$$

$$H_T = \sqrt{m_{\chi\bar{\chi}}^2 + p_{T,j}^2} + p_{T,j}$$

and as usual  $\xi$  varied in  $[1/2, 2]$



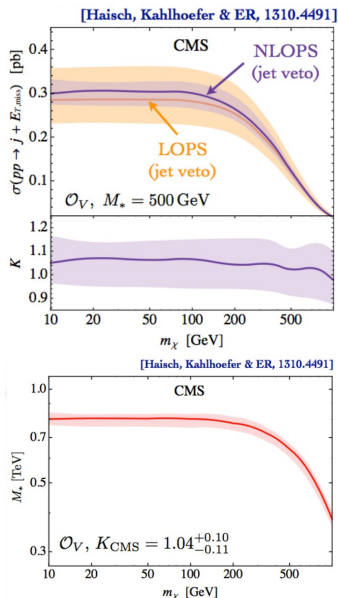
- ▶ **uncertainties reduced by a factor of 2**. Constant K-factor of 1.1 for our scale choice
- ▶ for “inclusive cuts”, PS & hadronization effects visible but small ( $R=0.4$ )
- ▶ for **realistic cuts** (i.e. with jet veto on 3rd jet), **NLOPS cross section reduced by about 40 %**
- ▶ notice that with fixed-order result you don't see this effect at all (no 3rd jet)

- ▶ comparing LO+PS to NLO+PS gives an estimate of size of effects that **could be missing from current experimental analysis**

✗ LOPS vs NLOPS shows that NLO/LO K-factor is **partially washed away** from PS effects.

✓ Theoretical uncertainty is still much smaller when NLO included.

👉 K-factor including PS & hadronization can be used to **promote experimental LOPS bounds to NLOPS**

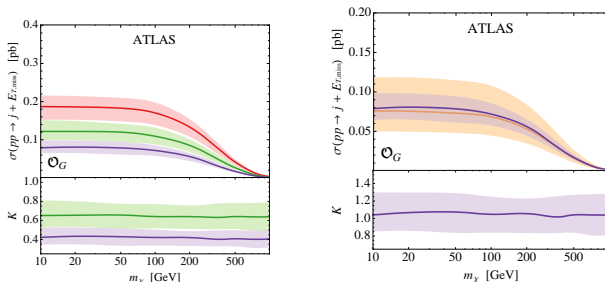


- ATLAS setup:

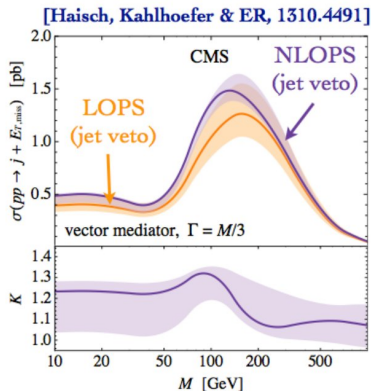
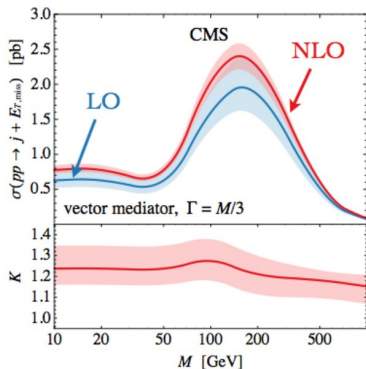
[ATLAS-CONF-2012-147]

$\text{ATLAS, 8 TeV, } 10.5 \text{ fb}^{-1}$ $ \eta_j  < 4.5, p_{T,j} > 30 \text{ GeV}, N_j \leq 2$ $\Delta\phi_{j2, E_{T,\text{miss}}} > 0.5$ $ \eta_{j1}  < 2, p_{T,j1}, E_{T,\text{miss}} > 350 \text{ GeV}$
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- main difference with CMS is that symmetric cuts used (on  $p_{T,j1}$  and  $E_{T,\text{miss}}$ )



- for gluonic operators, K-factors larger than vectorial operators

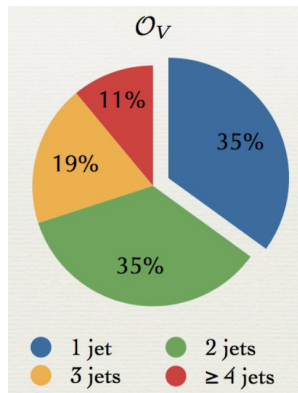


- ▶  $m_\chi = 50$  GeV in these plots
- ▶ in 1310.4491 we haven't performed a thorough study of differences between EFT and explicit mediator
- ▶ however the code is quite general, and can simulate events with intermediate spin-0 or spin-1 s-channel mediator

## a closer look to “mono”-jet events

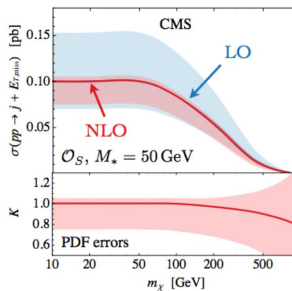
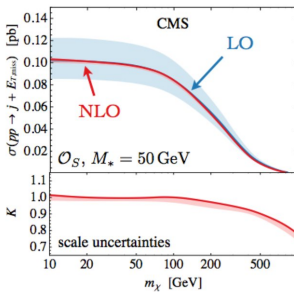
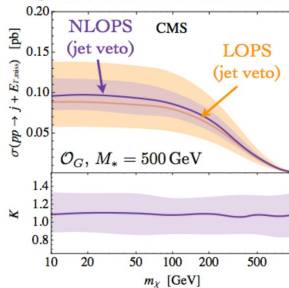
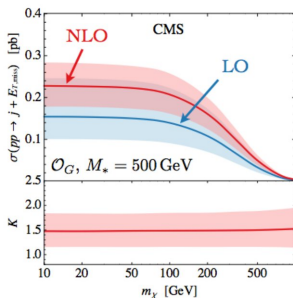
- ▶ given the large centre-of-mass energy, soft QCD radiation (modelled by POWHEG and following PS) can easily generate additional jets with  $|\eta_j| < 4.5$  and  $p_{T,j} > 30$  GeV
- ▶ even after all cuts, large fraction of 2-jet events: this is LO-accurate, and necessarily reduces impact of genuine fixed-order NLO corrections
- ▶ similarly, 3 (or more) jet events are not that rare, hence jet-veto has large impact

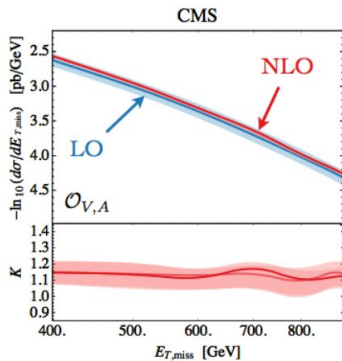
☞ since fraction of 2-jet events quite large, it makes sense to try looking carefully there too...



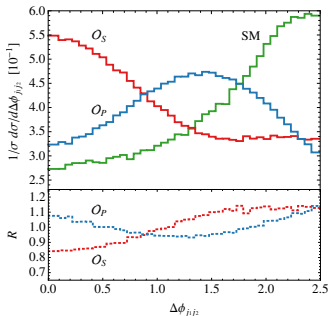
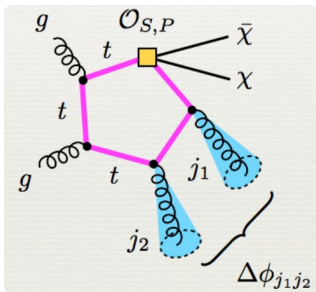
# other interactions included

[Haisch, Kahlhoefer & ER, 1310.4491]





- ▶ shapes of spectra are always extremely similar
- ▶ different operators will give different x-sections, but it seems impossible to distinguish between  $\mathcal{O}_V, \mathcal{O}_A, \mathcal{O}_S, \mathcal{O}_G, \dots$  just by using monojets.
- ▶ what about looking into 2-jets events?



- ▶ in 1311.7131, we studied DM+ $jj$  events: same cuts as CMS +  $m_{jj} > 600$  GeV
- ▶  $\sigma(jj)/\sigma(j) \sim 0.3$ , for  $m_\chi = 50$  GeV,  $\Lambda = 150$  GeV (14 TeV LHC)
- ▶ scalar and pseudoscalar-mediated couplings, using heavy-top limit (bottom panel) or full mass effects (upper panel)
- ▶ by looking at azimuthal correlation between 2 jets, [can distinguish between background hypothesis and loop-mediated DM-SM interactions](#)
- ▶ pattern visible also in heavy-top limit, although x-section overestimated (factor 10)
- ▶ [can also distinguish scalar and pseudoscalar mediator](#)
- ▶ pattern survives also when including explicit mediator

- ▶ for monojet searches, this POWHEG implementation is the **best prediction available**
- ▶ can be used **both** in the EFT approximation **and** with explicit mediators
  - ▶  $\tilde{G}_{\mu\nu,a} G^{\mu\nu,a} (\bar{\chi} \gamma_5 \chi)$  now implemented at NLO (will be publicly available soon)
- ▶ be aware of **veto**s on number of jets. Since  $E_{T,\text{miss}}$  and  $p_{T,j}$  are large, a severe veto will have a very big impact

(QCD tells you also that when you are introducing hierarchies of scales, you should resum the associated logs: notice that here we are exactly in this situation, a MC will model this at LL, an analytic resummation for this case is not available. This affects both signal and Zj background)
- ▶ for monophoton searches, computation is very similar, matching NLO to a PS is doable but not as simple as for monojets...

 **2 jets region: an opportunity worth exploring ?**

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*Thank you for your attention!*