Dark-matter at colliders, and QCD

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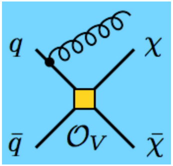
Effective Theories and Dark Matter

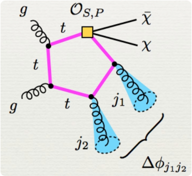
Mainz, 25 March 2014

Outline

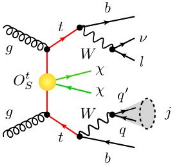
1. QCD effects in monojet searches
   [Haisch,Kahlhoefer,ER '13]



2. the $jj + \not{E}_T$ signature [Haisch,Hibbs,ER '13]

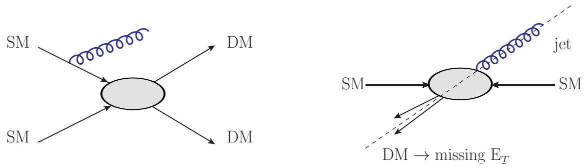


3. Dark-Matter heavy-flavour at the LHC
   [Haisch,ER '15]

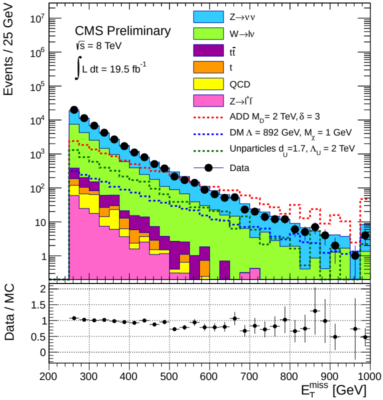


1. monojets and QCD corrections

Why NLO ?



- NLO predictions for signal & backgrounds will reduce theoretical uncertainties:
  - no excess: with NLO, more precise bounds
  - potential excess: knowledge of background relevant to draw a solid conclusion
    [TH input might be needed]
  - established excess: accurate predictions for signal and background helpful to “read out” parameters
- NLO corrections (“K-factor”) can be sizeable



Dark Matter / SM interaction

- all I discuss here is limited to spin-0 and spin-1 “s-channel mediated” processes
- useful to classify interactions using effective operators

$$\mathcal{O}_V = \frac{1}{\Lambda^2}\left(\bar{q}\gamma_\mu q\right)\left(\bar{\chi}\gamma^\mu\chi\right) \quad , \quad \mathcal{O}_A = \frac{1}{\Lambda^2}\left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$

$$\mathcal{O}_S = \frac{m_q}{\Lambda^3}\left(\bar{q}q\right)\left(\bar{\chi}\chi\right) \quad , \quad \mathcal{O}_P = \frac{m_q}{\Lambda^3}\left(\bar{q}\gamma_5 q\right)\left(\bar{\chi}\gamma_5\chi\right)$$

$$\mathcal{O}_G = \frac{\alpha_s}{\Lambda^3} G^a_{\mu\nu}G^{a,\mu\nu}\left(\bar{\chi}\chi\right) \quad , \quad \mathcal{O}_{\tilde{G}} = \frac{\alpha_s}{\Lambda^3} \tilde{G}^a_{\mu\nu}G^{a,\mu\nu}\left(\bar{\chi}\gamma_5\chi\right)$$

- these interactions arise from “integrating out” heavy mediators
- the EFT approach has several limitations

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

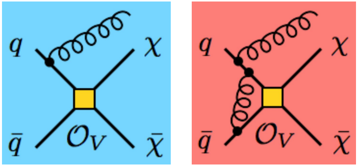
[Buchmueller,Dolan,McCabe, 1308.6799]

...

- in 1310.4491, we focussed on EFT; comprehensive study possible also for “simplified models”
  - for instance, for V/A mediators, public code was used in [Buchmueller,Dolan,Malik,McCabe, 1407.8257]

NLO & NLO+PS results

- main background $Z(\to \nu\bar{\nu}) + j$ known at NLO for a long time [Giele,Glover, '92]
  (and will be know at NNLO in the not-too-distant future)
- monojet cross-sections first computed at NLO (parton-level only) more recently [Fox,Williams, 1211.6390]



- if interested in full event simulation while keeping NLO accuracy, need to match to parton-showers

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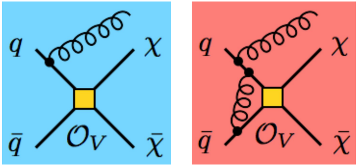

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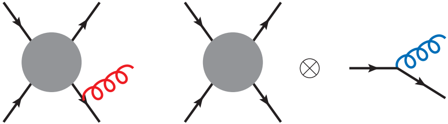
☞ problem are overlapping regions!



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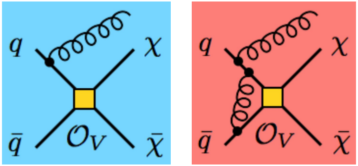

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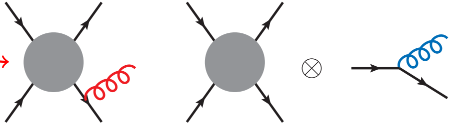
NLO:



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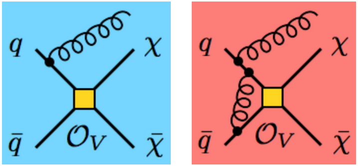

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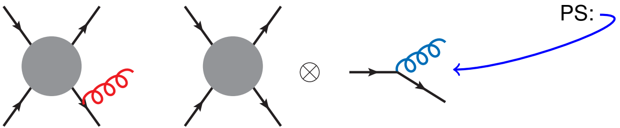

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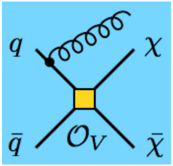
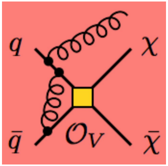




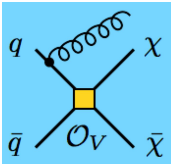
- if interested in full event simulation while keeping NLO accuracy, need to match to parton-showers
- there are well-established methods to consistently match these approximations [POWHEG,MC@NLO]
- will show example where important effects would be missed if using pure parton-level NLO

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^{-1}
$\lvert\eta_j\rvert < 4.5,\ p_{T,j} > 30\,\mathrm{GeV},\ N_j \leq 2$
$\Delta\phi_{j_1,j_2} < 2.5$
$\lvert\eta_{j_1}\rvert < 2.4,\ p_{T,j_1} > 110\,\mathrm{GeV},\ E_{T,\mathrm{miss}} > 350\,\mathrm{GeV}$

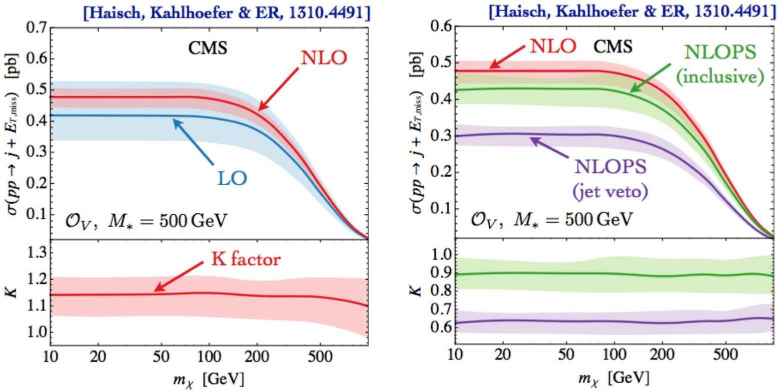


- from QCD point of view, monojet production is a process with more than one typical scale $(E_{T,\mathrm{miss}}, p_{T,j}, m_\chi, m_{\chi\bar{\chi}})$
- dynamic choice for factorization and renormalization scale:

$$\mu = \xi \frac{H_T}{2} \qquad\qquad H_T = \sqrt{m^2_{\chi\bar{\chi}} + p^2_{T,j}} + p_{T,j}$$

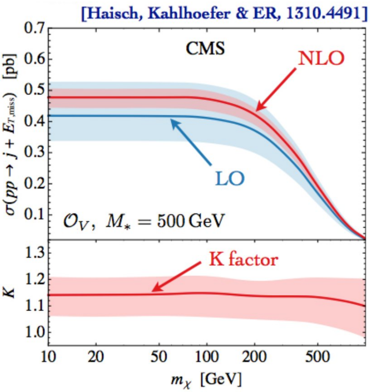
and as usual ξ varied in $[1/2, 2]$

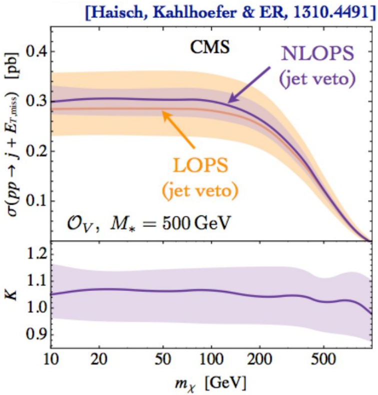
fixed order → full simulation



- 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)

NLO+PS vs LO+PS: V case





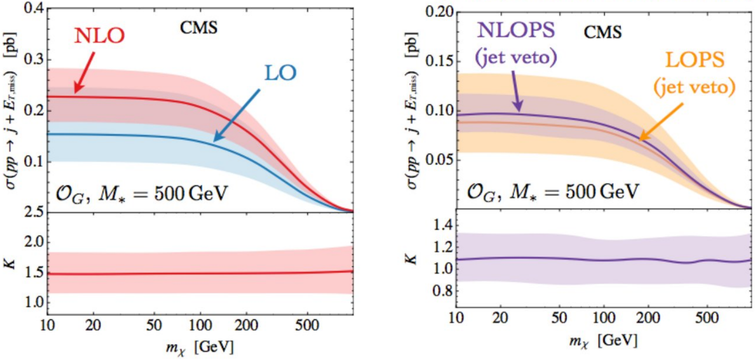
$$(\bar{q}\gamma_\mu q)\,(\bar{\chi}\gamma^\mu \chi)$$

✗ 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.
- more reliable extraction of exclusion bounds

NLO+PS vs LO+PS: G case

[Haisch, Kahlhoefer & ER, 1310.4491]

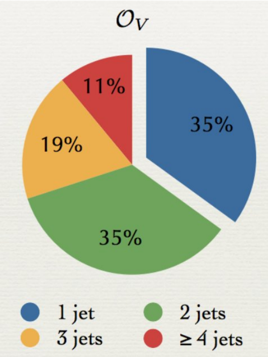


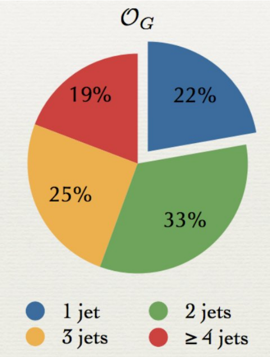
$$\alpha_s G^a_{\mu\nu} G^{a,\mu\nu} \, (\bar{\chi}\chi)$$

- ✗ 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.
  - more reliable extraction of exclusion bounds

2. the $jj + \not{E}_T$ signature

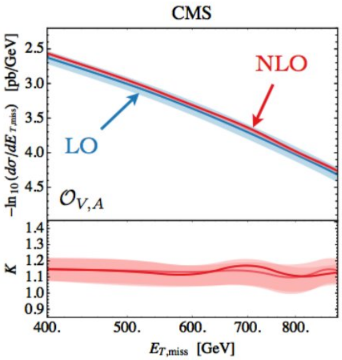
a closer look to "mono"-jet events





- large centre-of-mass energy: soft QCD radiation can easily generate additional jets with $p_{T,j} > 30$ GeV
- large fraction of 2-jet events: reduces impact of genuine fixed-order NLO corrections
- similarly, 3 (or more) jet events are not that rare, hence jet-veto has large impact; more so for gluon-induced processes

structure of the interaction



- different interactions will give different total x-sections
- however, p_T spectrum of signal is featureless
  - same masses (and widths)

    $\Downarrow$

    same shape for different s-channel interactions

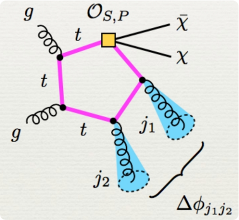
- it seems impossible* to distinguish between $\mathcal{O}_V, \mathcal{O}_A, \mathcal{O}_S, \mathcal{O}_G, \ldots$ just by using monojets
- what about looking into 2-jets events?

*distinguish between coupling to gluons or vectors trying to identify the jet flavour has been explored [Agrawal,Rentala,1312.5325]

DM + 2 jets (EFT)

- we looked at the case where DM-SM interactions take place via

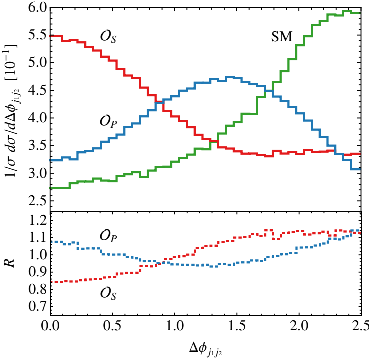
$$\mathcal{O}_S = \frac{m_t}{\Lambda^3}(\bar{t}t)(\bar{\chi}\chi) \quad \text{or} \quad \mathcal{O}_P = \frac{m_t}{\Lambda^3}(\bar{t}\gamma_5 t)(\bar{\chi}\gamma_5\chi)$$



- bounds from $j + E_{T,\text{miss}}$ and $t\bar{t} + E_{T,\text{miss}}$:
  $\Lambda \gtrsim 150 - 170$ GeV [m_χ = 50 GeV]

- (normalized) azimuthal correlation $\Delta\Phi_{jj}$:
  - ☞ distinguish between background and signal hypothesis
  - ☞ distinguish between $\mathcal{O}_S$ and $\mathcal{O}_P$ (and $\mathcal{O}_{V/A}$)

- LHC 14 TeV w/ CMS cuts + $m_{jj} > 600$ GeV:
  $\sigma(E_{T,\text{miss}} + jj) \simeq 0.3\sigma(E_{T,\text{miss}} + j)$, $\sigma_S \simeq \sigma_B$



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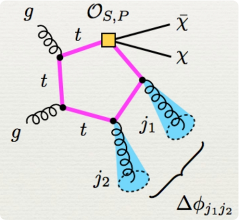

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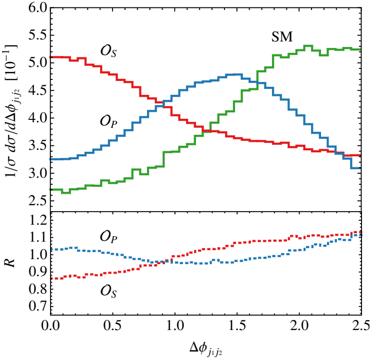

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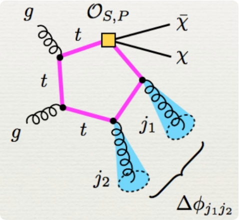

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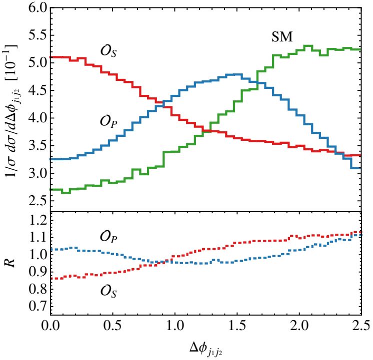

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  $\sigma(E_{T,\text{miss}} + jj) \simeq 0.3\sigma(E_{T,\text{miss}} + j)$, $\sigma_S \simeq \sigma_B$

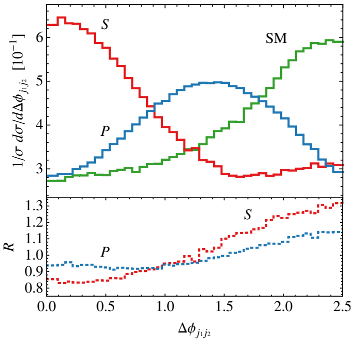
- pattern visible also in heavy-top limit $[G_{\mu\nu}G^{\mu\nu}\bar{\chi}\chi]$
  (although x-section overestimated (factor 10))

DM + 2 jets (full theory)

- with previous settings, EFT validity questionable
- studied specific case with simplified s-channel model:

$$\mathcal{L}_S = g_\chi^S \, (\bar{\chi}\chi) \, S + g_t^S \, \frac{m_t}{v} \, (\bar{t}t) \, S$$

  - (pseudo)-scalar mediator, $M_{P/S} = 500$ GeV, $m_\chi = 200$ GeV, $g = 1$
- all constraints from LHC and cosmology satisified
- width explicitly computed (here turns out $\Gamma/M \simeq 3-6\%$)



☞ modulation pattern survives

see also [Cotta,Hewett,Le,Rizzo, 1210.0525] for similar ideas

3. Dark-Matter heavy-flavour at the LHC

dark-matter top-quark interactions

- study spin-0 mediators and LHC discovery/exclusion potential

see also [Buckley et al., 1410.6497],[Harris et al., 1411.0535]

- if MFV assumed, the more relevant DM-SM interactions are those involving heavy quarks
- we wanted to look how searches in monojets and $t\bar{t} + \not{E}_T$ compare (and how they compare with direct-detection limits)

- simplified model

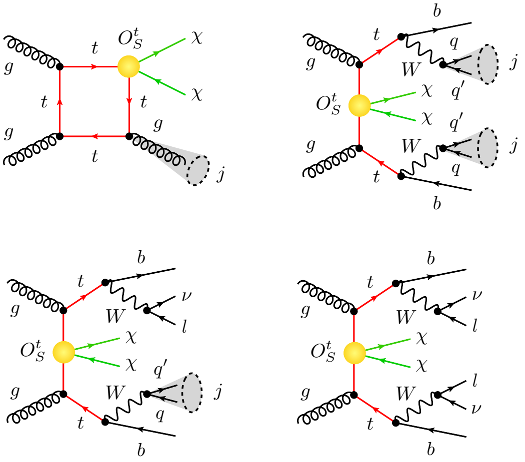
$$\mathcal{L} \supset g^S_{\rm DM}\,(\bar{\chi}\chi)\,S + g^S_{\rm SM}\sum_q \frac{m_q}{v}\,(\bar{q}q)\,S + i g^P_{\rm DM}\,(\bar{\chi}\gamma_5\chi)\,P + i g^P_{\rm SM}\sum_q \frac{m_q}{v}\,(\bar{q}\gamma_5 q)\,P$$

- EFT description

$$O^q_S = \frac{m_q}{\Lambda^3_S}\,\bar{\chi}\chi\,\bar{q}q\,, \qquad O^q_P = \frac{m_q}{\Lambda^3_P}\,\bar{\chi}\gamma_5\chi\,\bar{q}\gamma_5 q \qquad \Lambda = \left(\frac{vM^2}{g_{\rm SM}\,g_{\rm DM}}\right)^{1/3}$$

- unless stated, we always keep full top-mass dependence
- for simplicity, same factors for up-down type families: $g^{P/S}_{\rm SM} \equiv g^{P/S}_{\rm u,SM} = g^{P/S}_{\rm d,SM}$

available searches



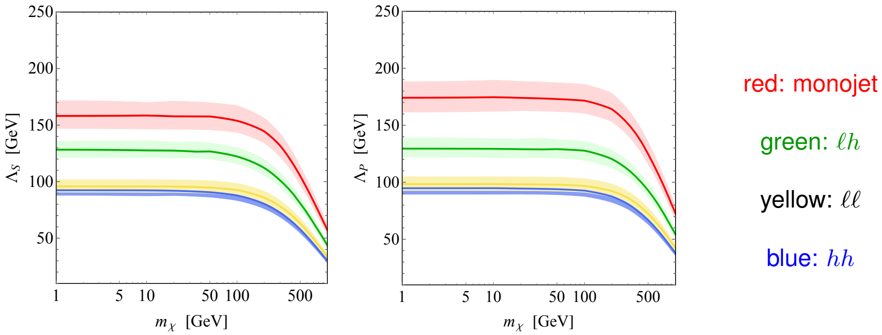
- monojet:
  - 1408.3583 [CMS]

  $t\bar{t}$ dileptonic:
  - B2G-13-004 [CMS]

  $t\bar{t}$ single-lepton:
  - 1410.4013 [ATLAS]

  $t\bar{t}$ hadronic:
  - 1410.4013 [ATLAS]

EFT analysis



- bands from scale uncertainties
- monojet search currently provide the (EFT) best constraints
- from $t\bar{t} + \not{E}_T$, single-lepton search seems the more promising

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- difference between P and S at low m_χ: $\Lambda_P \simeq (3/2)^{1/3} \Lambda_S$
- $m_\chi \gtrsim 100$ GeV: S bound falls faster because of scaling property of cross-section (P: β vs S: β^3, where $\beta = \sqrt{1 - 4m_\chi^2/m_{\chi\bar{\chi}}^2}$)

simplified model

$$\mathcal{L} \supset g^S_{\rm DM}\,(\bar\chi\chi)\,S + g^S_{\rm SM}\sum_q \frac{m_q}{v}\,(\bar q q)\,S + i g^P_{\rm DM}\,(\bar\chi\gamma_5\chi)\,P + i g^P_{\rm SM}\sum_q \frac{m_q}{v}\,(\bar q\gamma_5 q)\,P$$

- 4 free parameters: g_{DM}, g_{SM}, m_χ, $M_{S/P}$
- width always computed: include $S \to \chi\bar\chi$, $S \to t\bar t$, $S \to gg$ and $S \to b\bar b$
- this is the minimal width, within the simplified model we are considering

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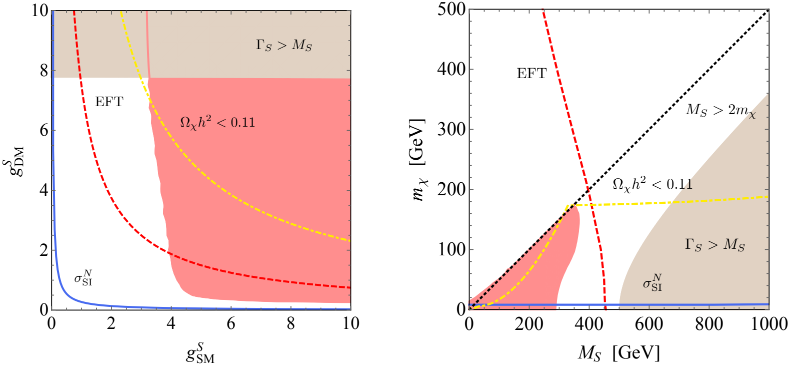
- no approximate NLO/LO K-factor for monojet x-section, since NLO for $H/A + j$ with top-mass dependence is not known (if $m_t \to \infty$, $K \simeq 1.6$)
- PDF: MSTW2008LO
  $\mu = H_T/2$, where $H_T = \sqrt{m^2_{\chi\bar\chi} + p^2_{T,j}} + p_{T,j}$
  `Pythia6`

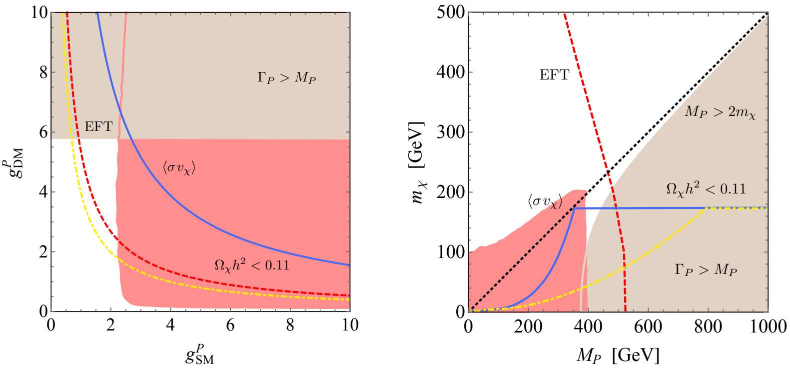
scalar: results



- left: $m_\chi = 100$ GeV, $M_S = 300$ GeV.
- right: $g = 4$ (not very weak)

- LHC8 can exclude $g^S_{\rm SM} \gtrsim 3$ and $g^S_{\rm DM} \gtrsim 0.2$
- weakly-coupled scalar mediators seem hard to probe
- direct-detection (LUX) much more constraining

pseudoscalar: results

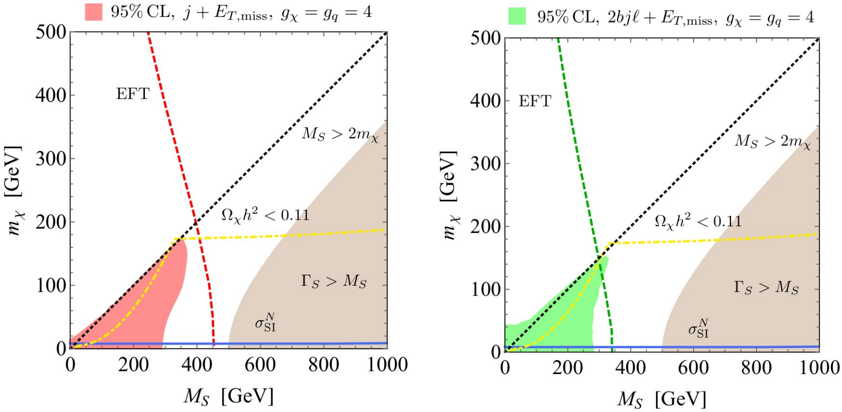


- left: $m_\chi = 100$ GeV, $M_P = 300$ GeV.
- right: $g = 4$ (not very weak)
- can probe off-shell region ($M < 2m_\chi$):

$$|\mathcal{M}(P \to \chi\bar{\chi})|^2 \sim Q^2 \quad \text{vs.} \quad |\mathcal{M}(S \to \chi\bar{\chi})|^2 \sim (Q^2 - 4m_\chi^2)$$

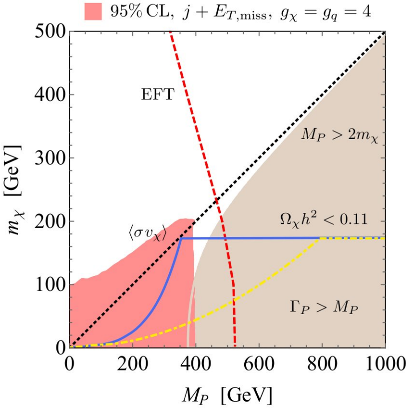
- no direct-detection (spin-dependent DM-nucleon x-section is momentum suppressed)

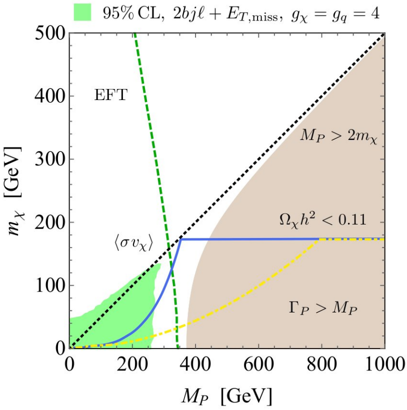
scalar: $\not{E}_T + j$ vs $t\bar{t} + \not{E}_T$



- depending on specific parameters, the 2 searches can have similar reaches and/or become complementary
- $t\bar{t} + \not{E}_T$ not tailored to DM searches

pseudoscalar: $\not{E}_T + j$ vs $t\bar{t} + \not{E}_T$

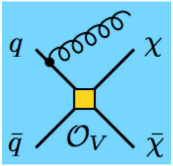




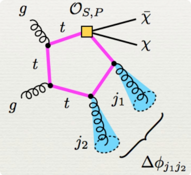
- depending on specific parameters, the 2 searches can have similar reaches and/or become complementary
- $t\bar{t} + \not{E}_T$ not tailored to DM searches

Conclusions

- QCD corrections are/will be relevant for background, and might be also important for the signal
- a full NLO+PS simulation is useful to describe important features (2-jets region, jet-veto,...)



- mono-jet searches good for discovery or to set bounds, not to characterise a signal
- if a signal found, angular correlations can tell a lot more than just monojets



- scalar/pseudoscalar mediators: probe only relatively large couplings. Possible to improve at 14 TeV ?
- simplified models more reliable
- complementarity between different LHC searches (although monojet searches seem so far the more competitive)