Simplest mode of DM production *unobservable* @ LHC

Dark Matter is **DARK**
- Leaves no activity in the detector
- Nothing to trigger on / reconstruct above

“Mono-X” (or “MET+X”) includes “X” for viable detection
- X: quarks/gluons, photons, W/Z …

DM must instead recoil against *something* to become “visible”
Non-interacting particles escape the detector

- Their presence inferred from energy/momentum imbalance
  \[ E_T^{\text{miss}} = - \sum_i E_T^i \hat{n}_i = - \sum_i E_T^i \]

- \( E_T^{\text{miss}} \) = Negative vector sum of all visible pT

- A closely related observable: hadronic recoil
  - Subtract off visible final state particles, eg: in \( Z(\ell\ell) \) events, to obtain system pT (U)

Well understood collider observables

- Wide use in SM measurements
BGs from processes producing significant $E_T^{\text{misss}}$

- Generally, those containing neutrinos
  - Eg: Z ($\nu\nu$) + jets, W ($\tau[qq']\nu$) + jets
- Sometimes also with non-fiducial and/or misreconstructed particles
  - Eg: W (e$\nu$) + jets, W ($\mu\nu$) + jets, ttbar ...

The connection to QCD ....

- DM searches probe the $E_T^{\text{misss}}$ tails of these SM processes
- Sensitivity achieved through a precise understanding of these processes at high-pT and high-multiplicity
DM searches in many final states ...
DM Searches

DM searches in many final states ...

Will focus on monojet (+mono-V) ...

- Provides largest collider reach in many several DM (eg: spin-1 mediators)
- Analysis strategy generally the most mature
Monojet / Mono-V : general strategy

Looking for high-pT DM recoils against hadronic activity

- Monojet actually targets multijets + $E_T^{\text{miss}}$
- Hadronic decays of EW bosons can also produce a high-pT jet + $E_T^{\text{miss}}$ signature ...
  - Decay products **boosted** if DM recoil is significant
  - Reconstruction algorithms can merge these into a ~small radius jet
  - But can use jet grooming / substructure techniques to identify the underlying 2-prong nature

At least one central ($|\eta| < 2.4$), good-quality, high-pT (eg >250 GeV) jet

Require minimum $\Delta\phi$ separation between jets and $E_T^{\text{miss}}$ to suppress misreconstruction BGs

Significant $E_T^{\text{miss}}$ (eg >200 GeV)

Veto additional objects: electrons, muons, tau leptons, photons, bjets ...
Select boosted mono-V and monojet signal regions

Extract signal from combined profile likelihood fit to $E_T^{\text{miss}}$ distributions

- Searches pushing into the $E_T^{\text{miss}}$ tails > 1TeV!
- How can we control backgrounds in these regions?

NB: high-$E_T^{\text{miss}}$ uncertainties are just ~15%!
Use SM control regions to constrain high-$E_T^{\text{miss}}$ BGs

- Use observable analogues of the invisible SM processes
- Subtract visible signatures $\rightarrow$ hadronic recoil, a proxy for $E_T^{\text{miss}}$
- Use theory to translate from CRs to visible bkgs predictions in SR!

\[
L_k(\mu^{Z(\nu\bar{\nu})}, \mu, \theta) = \prod_i \text{Poisson}\left( d_i^\gamma | B_i^\gamma (\theta) + \frac{Z(\nu\bar{\nu})}{R_i^\gamma (\theta)} \right) \\
\times \prod_i \text{Poisson}\left( d_i^{\mu| \mu} | B_i^{\mu| \mu} (\theta) + \frac{\mu Z(\nu\bar{\nu})}{R_i^{\mu| \mu} (\theta)} \right) \\
\times \prod_i \text{Poisson}\left( d_i^{ee} | B_i^{ee} (\theta) + \frac{Z(\nu\bar{\nu})}{R_i^{ee} (\theta)} \right) \\
\times \prod_i \text{Poisson}\left( d_i^{\mu|} | B_i^{\mu|} (\theta) + \frac{f_i(\theta)\mu Z(\nu\bar{\nu})}{R_i^{\mu|} (\theta)} \right) \\
\times \prod_i \text{Poisson}\left( d_i^{e|} | B_i^{e|} (\theta) + \frac{f_i(\theta)\mu Z(\nu\bar{\nu})}{R_i^{e|} (\theta)} \right) \\
\times \prod_i \text{Poisson}\left( d_i | B_i (\theta) + (1 + f_i(\theta))\mu Z(\nu\bar{\nu}) + \mu S_i (\theta) \right)
\]

\[d_i\] : observed #events

\[B_i(\theta)\] : predicted yields from sub-dominant backgrounds

\[f_i(\theta)\] : $W(l\nu) \leftrightarrow Z(\nu\nu)$ constraint

\[R_i(\theta)\] : visible processes in CR $\rightarrow$ invisible $Z(\nu\nu)$ bkg in SR transfer
Use SM control regions to constrain high-$E_T^{\text{miss}}$ BGs

- Use observable analogues of the invisible SM processes
- Subtract visible signatures → hadronic recoil, a proxy for $E_T^{\text{miss}}$
- Use theory to translate from CRs to visible bkgs predictions in SR!

\[
\times \prod_i \text{Poisson} \left( d_i^{\mu\mu} | B_i^{\mu\mu}(\theta) + \frac{\mu_i^{Z(\nu\nu)}}{R_i^{\mu\mu}(\theta)} \right)
\times \prod_i \text{Poisson} \left( d_i^{ee} | B_i^{ee}(\theta) + \frac{\mu_i^{Z(\nu\nu)}}{R_i^{ee}(\theta)} \right)
\]

Good: $Z(\mu\mu)$ + jets, $Z(ee)$ + jets
- Same kinematics as dominant $Z(\nu\nu)$ + jets background
- But smaller yields than target background in signal region

35.9 fb$^{-1}$ : CMS-PAS-EXO-16-048

- $Z(\mu\mu)$ + jets
- $Z(ee)$ + jets
- Same kinematics as dominant $Z(\nu\nu)$ + jets background
- But smaller yields than target background in signal region
Use SM control regions to constrain high-$E_T^{miss}$ BGs

- Use observable analogues of the invisible SM processes
- Subtract visible signatures → hadronic recoil, a proxy for $E_T^{miss}$
- Use theory to translate from CRs to visible bkgs predictions in SR!

Better : $W(\mu\nu) + \text{jets}, W(e\nu) + \text{jets}$

- Improved yields
- Can also estimate $W(l\nu) + \text{jets}$ background in signal region

\[ \times \prod_i \text{Poisson} \left( d_i^H | B_i^H (\theta) + \frac{f_i(\theta) \mu_i^{Z(\nu\bar{\nu})}}{R_i^H (\theta)} \right) \]

\[ \times \prod_i \text{Poisson} \left( d_i^C | B_i^C (\theta) + \frac{f_i(\theta) \mu_i^{Z(\nu\bar{\nu})}}{R_i^C (\theta)} \right) \]
Use SM control regions to constrain high-$E_T^{miss}$ BGs

- Use observable analogues of the invisible SM processes
- Subtract visible signatures → hadronic recoil, a proxy for $E_T^{miss}$
- Use theory to translate from CRs to visible bkgds predictions in SR!

$$\prod_i \text{Poisson} \left( d_i^\gamma | B_i^\gamma (\theta) + \frac{\mu_i}{R_i^\gamma (\theta)} \right)$$

Best : $\gamma$ + jets
- High yield control region with similar kinematics as W/Z + jets at high $E_T^{miss}$ (*)

* for caveats, see 1705.04664
Uncertainties & Correlations

Transfer factors uncertainties → nuisance parameters in the fit

- Consider both QCD & EWK uncertainties on the \( R_X = \frac{d\sigma^X}{dp_T} / \frac{d\sigma^{Z(\nu\nu)}}{dp_T} \)
- Account for correlations between processes & bins

Recent past (eg: CMS-EXO-16-037)

- No comprehensive theory guidance, so take a conservative approach
  - QCD uncertainties (\( \mu_R, \mu_F \)) : fully correlated
Uncertainties & Correlations

Transfer factors uncertainties → nuisance parameters in the fit

- Consider both QCD & EWK uncertainties on the $R_{X_i} = \frac{d\sigma^X}{dp_T} / \frac{d\sigma^{Z(\nu\nu)}}{dp_T}$
- Account for correlations between processes & bins

Recent past (eg: CMS-EXO-16-037)

- No comprehensive theory guidance, so take a conservative approach
  - QCD uncertainties ($\mu_R, \mu_F$): tune to the largest uncertainty in the ratio

![Diagram showing scale uncertainties and correlated uncertainties between processes]
Uncertainties & Correlations

Transfer factors uncertainties → nuisance parameters in the fit

- Consider both QCD & EWK uncertainties on the $R_X^i = \frac{d\sigma^X}{dp_T} / \frac{d\sigma^{Z(\nu\nu)}}{dp_T}$
- Account for correlations between processes & bins

Recent past (eg: CMS-EXO-16-037)

- No comprehensive theory guidance, so take a conservative approach
  - QCD uncertainties ($\mu_R, \mu_F$): tune to the largest uncertainty in the ratio
  - EWK: take full correction as uncertainty, decorrelate across bins
Uncertainties & Correlations

Present-day: a comprehensive treatment of QCD & EWK uncertainties + correlations (see 1705.04664)

- **Pure QCD effects**: scale/normalization, shape dependence, process dependence
- **Pure EWK effects**: missing NNLO, unknown Sudakov logs, NLL Sudakov approximation
- **Combined**: multiplicatively, uncertainty for possible non-factorization

![Graphs showing QCD and EWK effects](image-url)
Uncertainties & Correlations

Present-day: a comprehensive treatment of QCD & EWK uncertainties + correlations (see 1705.04664)

- Significant reduction in theory uncertainties
- Proper treatment of process and $p_T$ correlations
Improvements led to the most stringent monojet limit to date …
DM Searches

DM searches in many final states ...

- **Mono-jet**
- **Mono-Z(lepotic)**
- **Mono-W/Z(hadronic)**
- **Mono-photon**
- **Mono-h (bb, γγ)**
- **Mono-tt(bb)**
- **Mono-top**

A few comments on heavy flavor + $E_T^{\text{miss}}$

- Complementary to monojet in some scenarios (eg: spin-0 mediators)
- Backgrounds beyond the usual V+jets ...
**Combined** search using all $tt+E_{T}^{miss}$ and $bb+E_{T}^{miss}$ channels

Similar strategy as monojet/mono-$V$

- Simultaneous $E_{T}^{miss}$ fit using 8 SRs + 19 CRs

Employs *resolved* top quark tagger to reconstruct moderate $p_T$ hadronic decays

- Top $p_T$ is soft in for mediator masses for which there is LHC sensitivity
- Categorize signal and bkg according to number of top tags
- Main backgrounds in $tt$ SR from SM $tt$ with one less (and lost) lepton

Search uses just 2.2 fb-1 from Run2

- Analysis of full 35.9 fb-1 in progress
CMS tt/bb + DM

2.2 fb⁻¹ (13 TeV)

- {\text{Events / bin}}
- $p_T^{\text{miss}}$ [GeV]

**bb signal region**

- CMS
- $t\bar{b}$ tag $b\bar{b} + p_T^{\text{miss}}$
- Data
- tt
- W($\ell$)+jets
- Z($\ell\nu$)+jets
- Single t
- Diboson
- Multijets
- Bkg. unc.
- Prefit
- $m_\chi = 300$ GeV, $m_{A,\chi} = 1$ GeV

**dileptonic $\ell\ell$ signal region**

- CMS
e\mu dileptonic $t\bar{t} + p_T^{\text{miss}}$
- Data
- tt
- Z($\ell\nu$)+jets
- Single t
- Diboson
- Lepton fakes
- Bkg. unc.
- Prefit
- $m_\chi = 300$ GeV, $m_{A,\chi} = 1$ GeV

**semileptonic signal region**

- CMS
- $1+\ell$ jets $t\bar{t} + p_T^{\text{miss}}$
- Data
- tt
- W($\ell$)+jets
- Z($\ell\nu$)+jets
- Single t
- Diboson
- Bkg. unc.
- Prefit
- $m_\chi = 300$ GeV, $m_{A,\chi} = 1$ GeV

**all-hadronic $0.1RTT$ signal region**

- CMS
- 0.1RTT all-hadronic $t\bar{t} + p_T^{\text{miss}}$
- Data
- tt
- W($\ell$)+jets
- Z+jets
- Single t
- Diboson
- Multijets
- Bkg. unc.
- Prefit
- $m_\chi = 300$ GeV, $m_{A,\chi} = 1$ GeV
- Selection requirements entail high multiplicity events
- Very large $E_T^{\text{miss}}$ tends to selects large top pT … modeling problems
- EW backgrounds with heavy quarks (eg: $Z(\nu\nu)+bb$)
- Must contend w/ irreducible $t\bar{t}+V$
QCD uncertainties have a large impact on the search.
CMS tt/bb + DM Limits

Per-channel, scalar

Full combination, scalar

Per-channel pseudoscalar

Full combination, pseudoscalar
Precise QCD + EW modeling of V+jets & control of related uncertainties are crucial for LHC DM searches

- To maximize reach w/ 300 fb-1, syst. must remain < 10% up to ~3TeV

Theory advances (1705.04664) have shown this is possible

- Already percent-level uncertainties to 2 TeV
- Framework has been quickly adopted by LHC exps.

Outlook

- Other DM channels (eg: HF) would soon benefit similar treatments
- Continued improvements at high pT?
  - HL-LHC (300 fb-1 / year!) is not far off …
  - “New Unc.” scheme assumes theory (NNLO) uncertainties of 1-2% up to 3 TeV
- Impact on sensitivity with new machines?
  - 28 TeV? 100 TeV?
Impact of the electroweak corrections

We care about the of the two

pp → Z + 1j @ 8 TeV

pp → γ + 1j @ 8 TeV

Δφ(j₁, j₂) < 2.5

νp-ph/1511.08692
νp-ph/0508253

LO
NLO QCD
NLO QCD+EW
NLO QCD×EW

1.1
1
0.9
0.8
0.7
0.6
0.5

250 500 750 1000 1250 1500
p_T,Z [GeV]

1.1
1
0.9
0.8
0.7
0.6
0.5

500 1000 1500
p_T,γ [GeV]
Some of the more heinous diagrams

Adding the EWK corrections brings back agreement

CMS Z/gamma ratio (8 TeV) measurement compared to different generators
Figure 3: Higher-order QCD predictions and uncertainties for $Z(\ell^+\ell^-)+\text{jet}$, $W^\pm(\ell\nu)+\text{jet}$, and $\gamma+\text{jet}$ production at 13 TeV. Absolute predictions at LO, NLO and NNLO QCD are displayed in the main frame. In the ratio plots all results are normalised to NLO QCD, and the bands at LO and NLO correspond to the combination (in quadrature) of the three types of QCD uncertainties, $\delta^{(i)}K_{\text{NLO}}$, i.e. scale uncertainties according to Eq. (15), shape uncertainties according to Eq. (17), and process-correlation uncertainties according to Eq. (20). The band at NNLO corresponds to just scale uncertainties.
Figure 4: Ratios of $p_T$-distributions for various $pp \to V+\text{jet}$ processes at LO, NLO QCD and NNLO QCD. The NLO QCD uncertainties, estimated according to Eq. (15), Eq. (17), and Eq. (20) are correlated amongst all processes and combined in quadrature. At LO and NNLO only nominal predictions are shown.
Figure 5: QCD $K$-factors at NLO (with respect to LO) and NNLO (with respect to NLO) for the various $pp \rightarrow V + \text{jet}$ processes at 13 TeV. The bands in the two upper frames correspond to scale variations, i.e. $\delta^{(1)} K_{\text{NLO}}$ and $\delta^{(1)} K_{\text{NNLO}}$. The lower frames show the individual uncertainties defined in Eq. (15), Eq. (17), and Eq. (20) at NLO. They are displayed as ratios $\delta^{(i)} K_{\text{NLO}} / K_{\text{NLO}}$, which corresponds to the relative impact of uncertainties on $p_T$ distributions at NLO.