Dark Matter Mono-X Search

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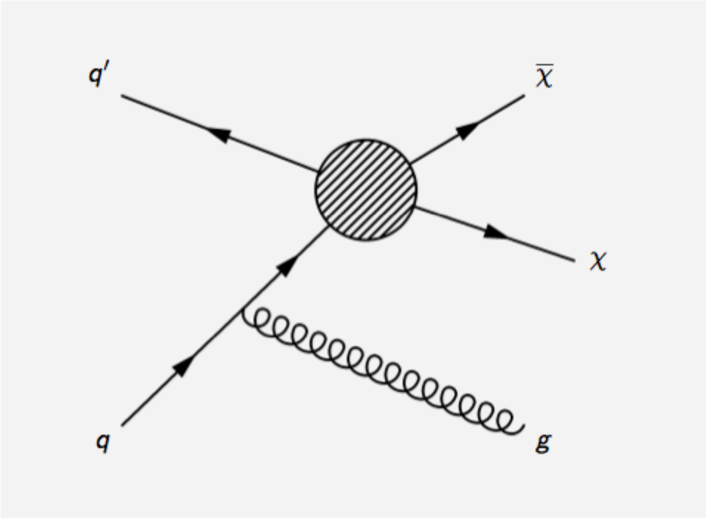
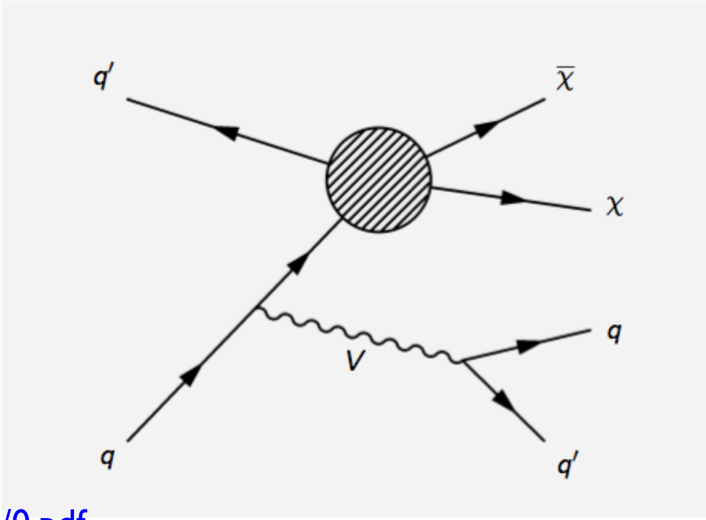
DM Production @ LHC

Target signatures of MET + Hadronic recoil (X):

- Build on existing CMS mono-jet analysis (EXO-12-048)
- Take advantage of Improvements in V-tagging (JME-14-002) to categorize and add sensitivity
- Signal extracted with shape analysis.

Monojet	: AN-14-183
+V-tags	: EXO-12-055





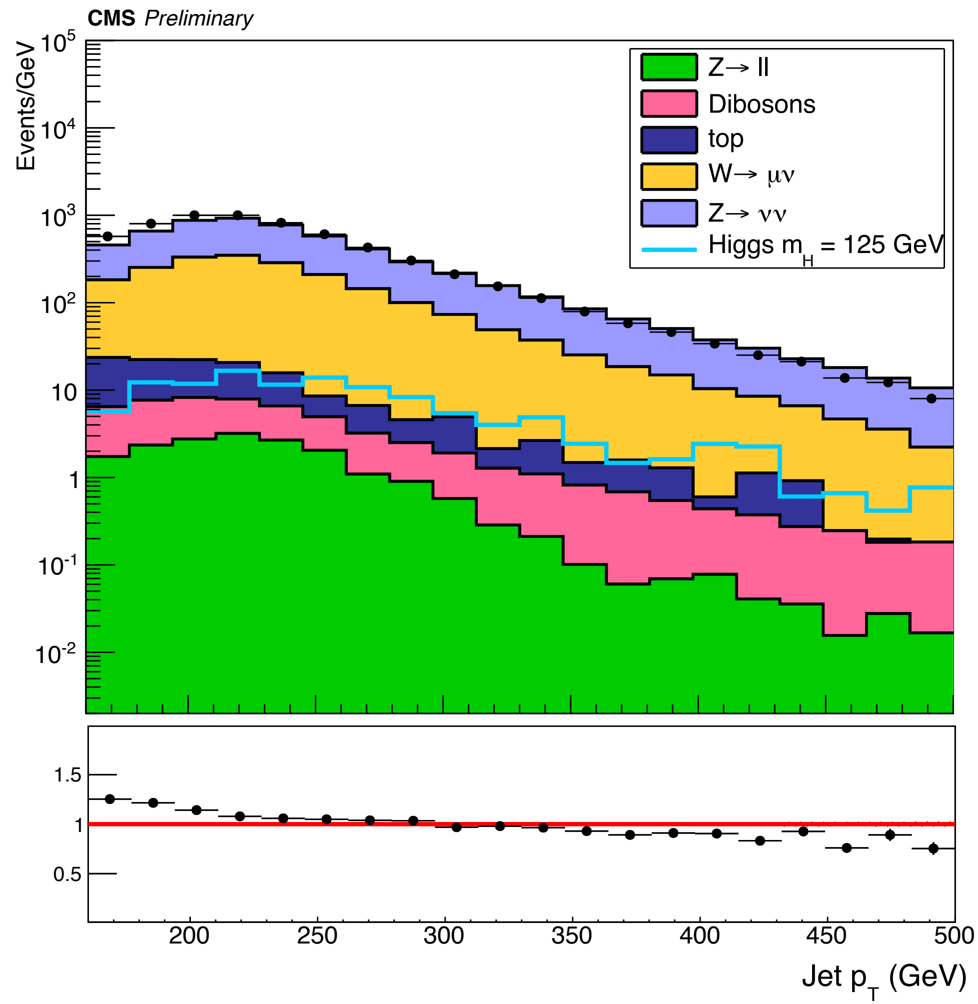
Interpretations under:

- EFT
- Simplified Models*
- Higgs-DM

*Working closely with EXO MC&interpretations group..
See https://indico.cern.ch/event/351904/contribution/2/material/slides/0.pdf

Jet+MET triggers:
- Jet80+MET95/105
- MET120

Selection:
- Require a (ak5) Jet, pT > 150,
- $|\eta| < 2.0$
- Veto events with >1 jets if
- $\Delta\varphi(j1,j2) > 2.0$
- Require MVA MET > 200 GeV*
- $\Delta\varphi(j1,MET) > 2.0$
- Veto events with leptons, taus and photons.



Shape analysis to extract signal. Largest backgrounds corrected to remove "trend" observed in Data/MC

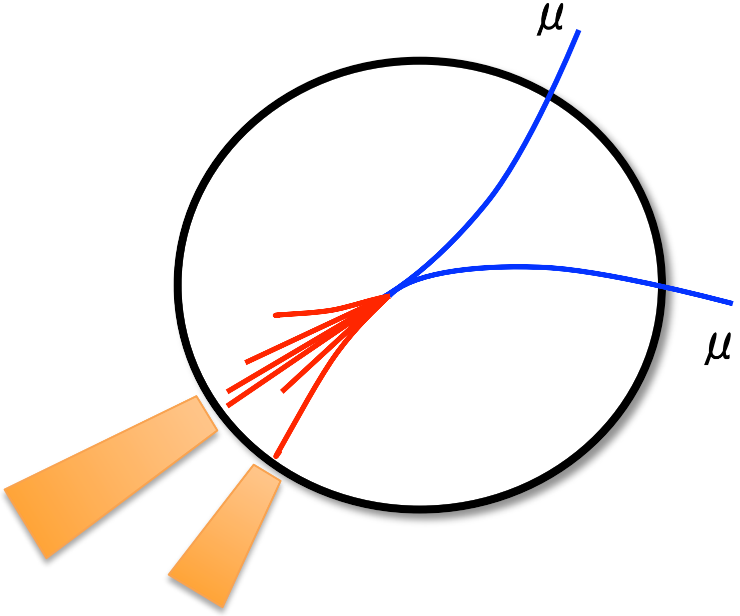
**MET filters applied*

V+Jets are the dominant backgrounds.
We can determine their contributions in the signal region using control regions in data

The idea is to use events with precisely measured objects recoiling from a jet and calculate "fake" MET. Control samples are defined using signal selection + …

- **Di-muon (for Z(vv)+jets)**
  - Two isolated muons $60 < m_{\mu\mu} < 120$

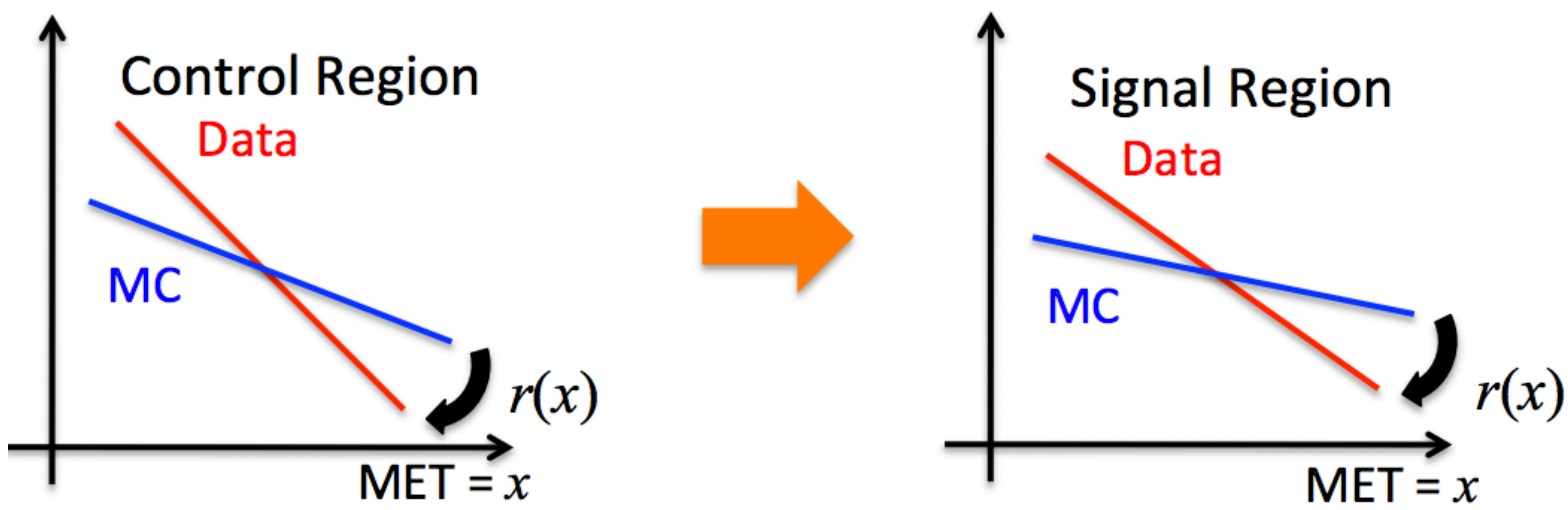
- **Single-muon (for W(lv)+jets)**
  - Exactly one muon pT>20, $|\eta| < 2.4$
  - 50 < mT < 100



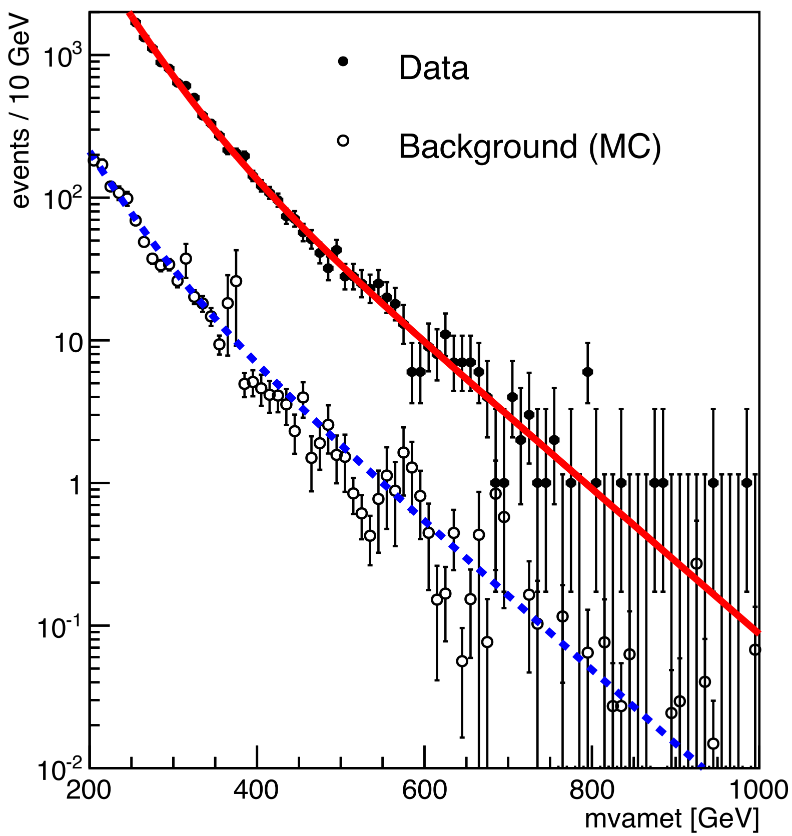
Systematic uncertainties are only due to MC description of muon acceptance and efficiency.

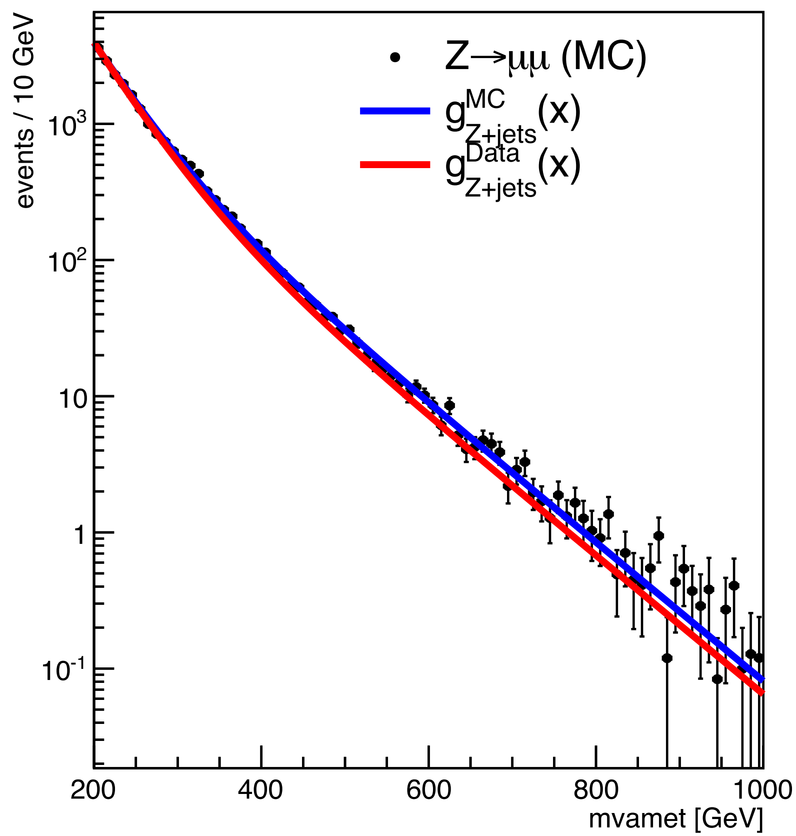
MET Spectrum of Z+Jet and W+Jet MC corrected using di-muon and single muon control regions respectively:

- Compare MET spectrum between data and MC in control region using parametric fit (double exponential) to both.
- Correction function defined as ratio of fits, r(x)
- Correction applied as re-weight per event to MC In signal region

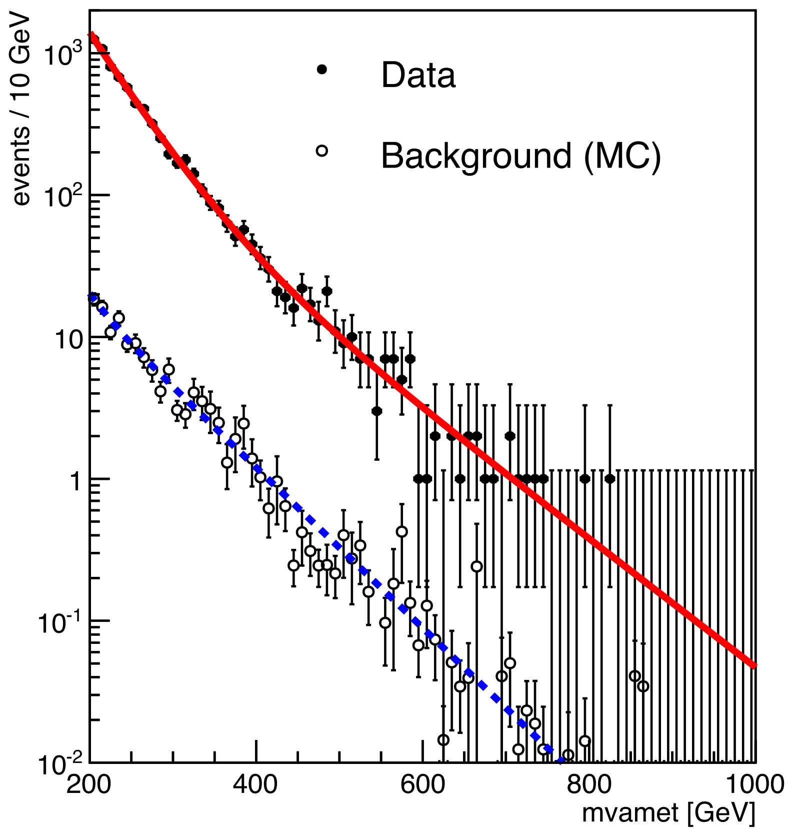


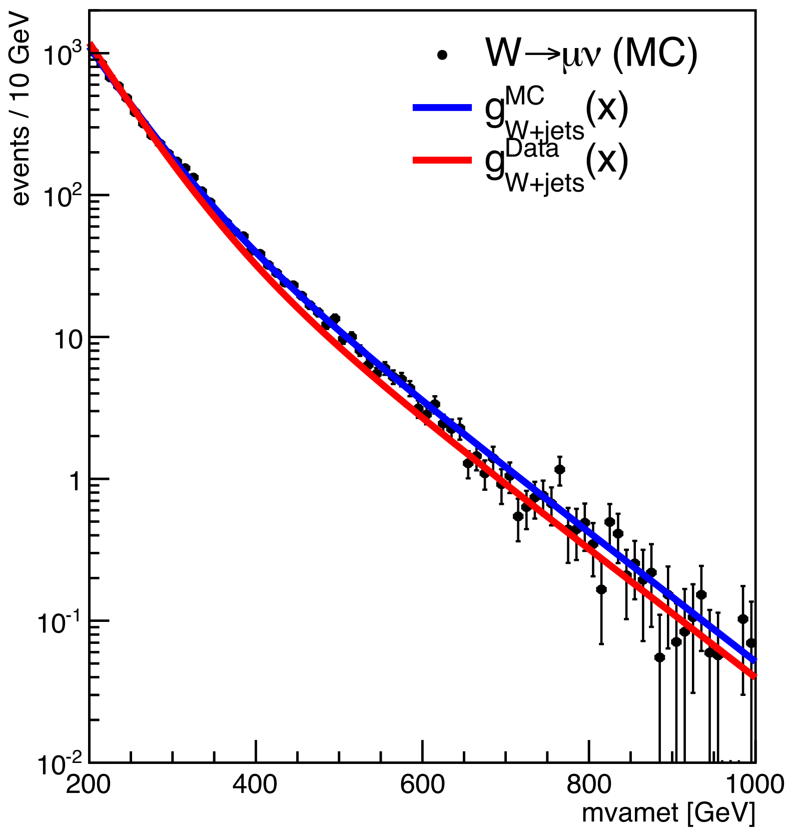
Fit of double exponential to Z(mm) Data and MC in Di-muon control region



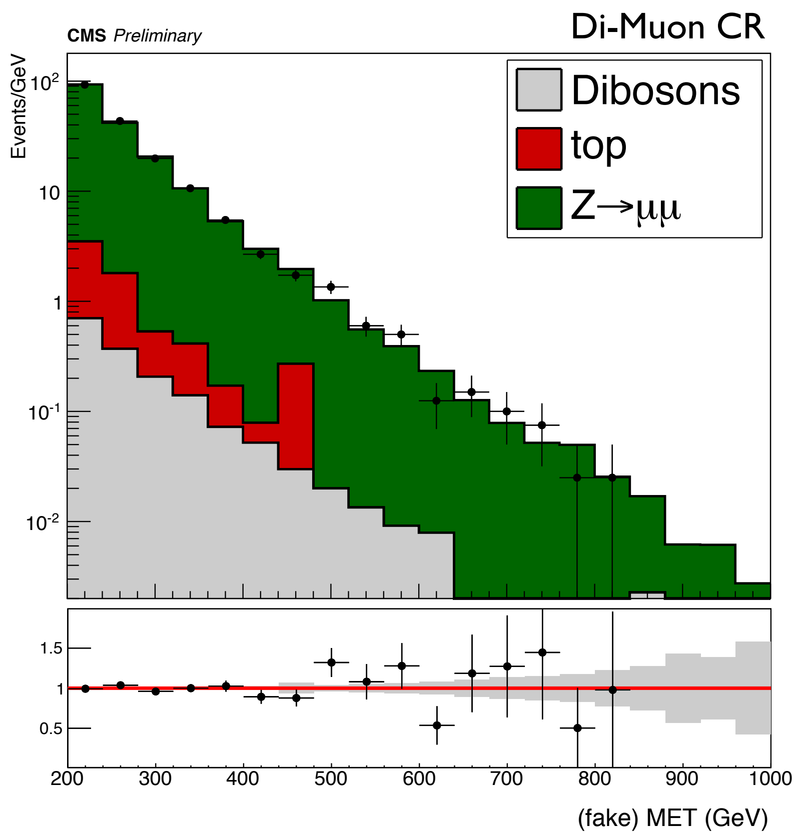


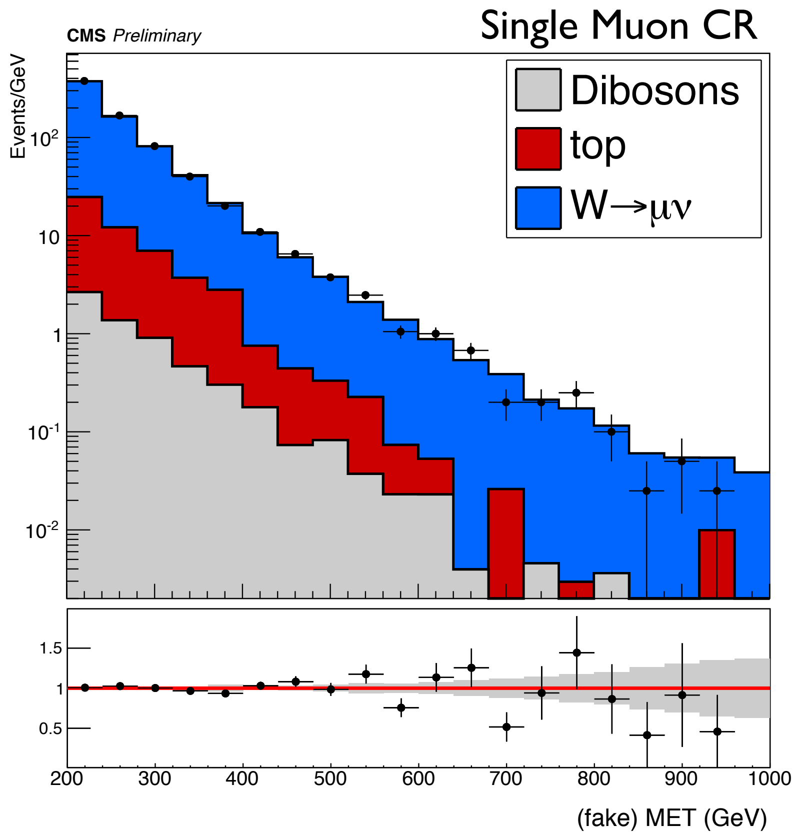
Fit of double exponential to W(lv) Data and MC in single muon control region





After applying corrections, yields in both control regions agree very well (as expected).





Several sources of systematic from background modeling considered

Parametric fit uncertainties:

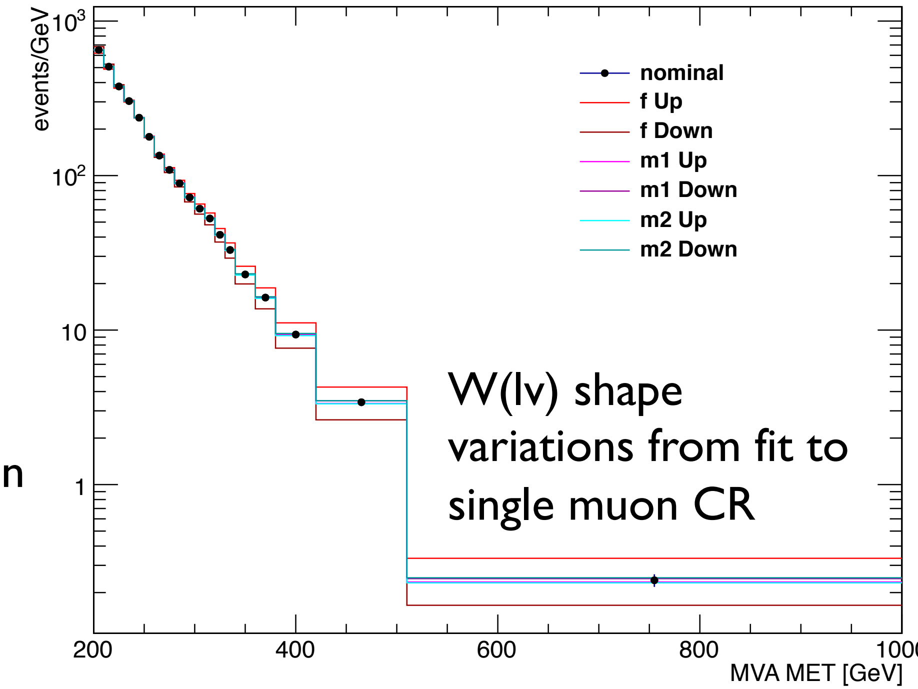
- Diagonalize covariance matrix to produce uncorrelated set of shape variations from limited data in CRs.
- Normalization effects modeled with gamma nuisance.

PDF (CT10) sets:

- Reweight CR MC with PDF weights to obtain alternate correction functions. Minor impact from small variations in muon acceptance.

Muon Efficiency Scale factors

- systematic studies for T+P Data/MC scale factor measurements ongoing.

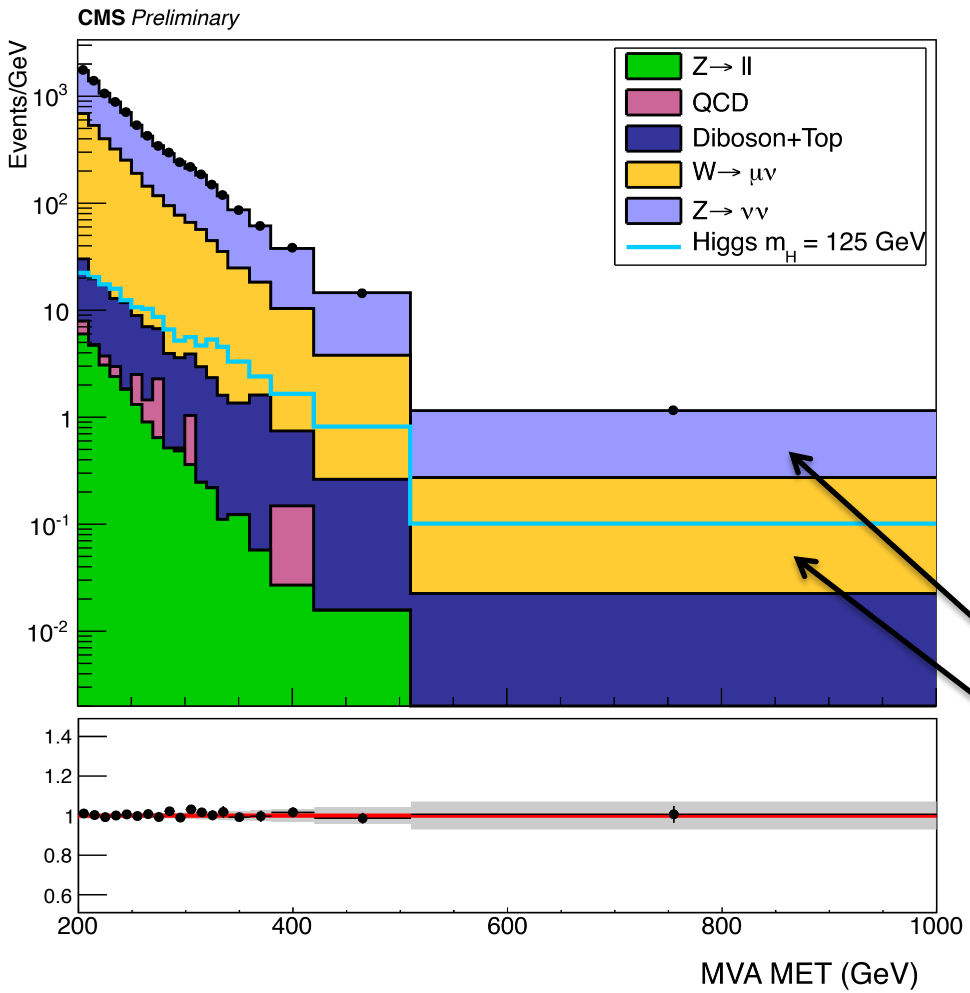


W(lv) shape variations from fit to single muon CR

Additionally checked different parameterizations for fit model. Closure tests show that no additional systematic needed.

Signal region

Excellent Data/MC agreement in signal region after applying corrections



Data	89618
Z(vv)	57298.8
W(lv)	30519.0
Di-bosons + Top	1136.0
Zll	234.1
QCD	78.1
Higgs mH = 125 GeV	1804.6
Total MC	89266.1

Z(vv) from di-muon CR

W(mv) from single muon CR

"Post-fit" uncertainties include all systematics (constrained also from data in signal region)

Systematics included:

Systematics	%	Notes
Z(vv)	~1.17	gmN
W(lv)	~0.61	gmN
W(lv)/Z(vv) MET spectrum	-	Shapes
Luminosity	2.6	All processes except Z(vv) or W(lv)
QCD	50	Normalisation
Diboson/Top	20	Normalisation
PDF	-	W(lv)/Z(vv) shape variation
ggH pT	-	Scale variations alter pT spectrum of g-fusion Higgs

Expected Limit (from Higgs PAG tool) on Higgs Invisible Branching Ratio:

BR < 0.86 (0.71) @ 95 (90)% CL

Simplified Models

Simplified models provide description of Generic Mediator coupling to DM

For MET searches, relevant parameters (causing largest shape variations) are:

- Mediator Type (Vector/Axial, Scalar/Pseudo-scalar)
- Mediator Mass

Generate events using MCFM, shower with Pythia8.

Events smeared with parameteric model tuned to CMS simulation

Scan over mDM, mMed, gDM. Reweight Higgs signal as function of reco-pt to produce "reco-level" MET templates at each point.

Vector	Axial
$g_{\mathrm{DM}} Z'_{\mu} \bar{\chi} \gamma^{\mu} \chi$	$g_{\mathrm{DM}} Z''_{\mu} \bar{\chi} \gamma^{\mu} \gamma^{5} \chi$
EWK style coupling (equal to all leptons)	EWK style coupling (equal to all leptons)
Sensitive w/Direct Detection	Less Sensitive w/DD
Scalar	**Pseudoscalar**
$g_{\mathrm{DM}} S \bar{\chi} \chi$	$g_{\mathrm{DM}} P \bar{\chi} \gamma^{5} \chi$
Yukawa style coupling (Mass based coupling)	Yukawa style coupling (Mass based coupling)
Less Sensitive w/DD	No bounds from DD Only Cosmic bounds exist

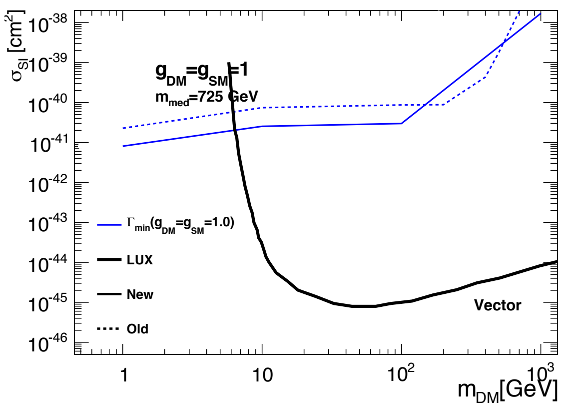
See http://arxiv.org/pdf/1411.0535v1.pdf

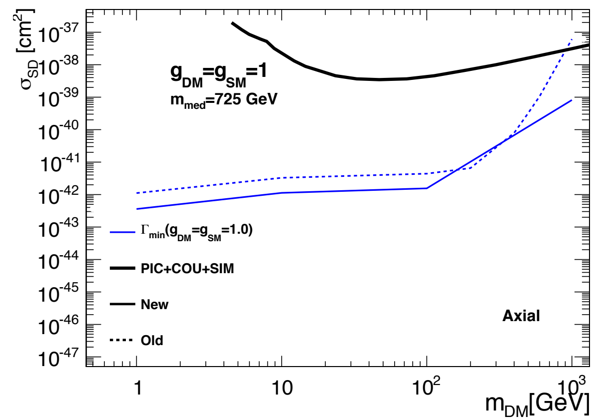
Compare monojet shape analysis with existing CMS monojet (labelled old) analysis (datacard reproduced) and direct detection experiments.

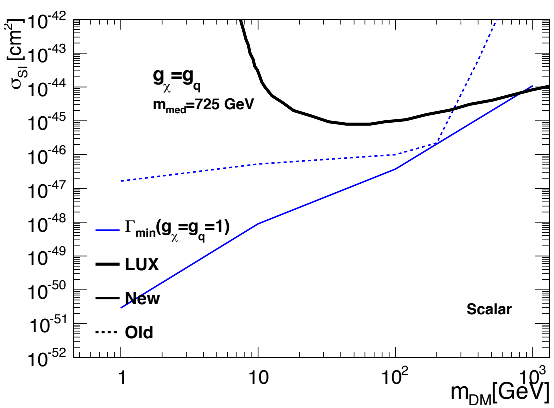
Compare upper limits on SI/SD cross-sections as a function of DM mass.

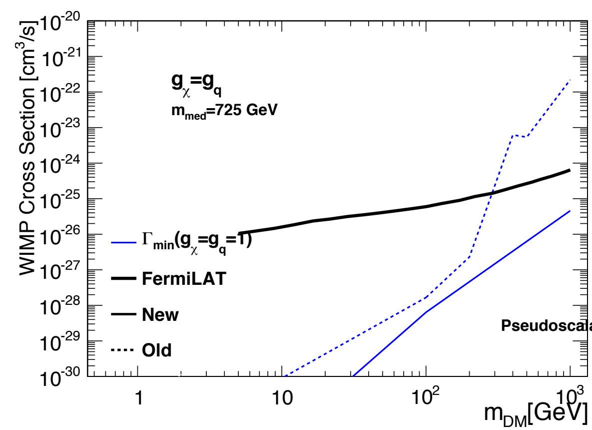
Final set of points to run at in discussion with MC&InterpsGrpup. Request for full simulation in preparation.

Initial look at SM interpretation shows improvements wrt public CMS analysis



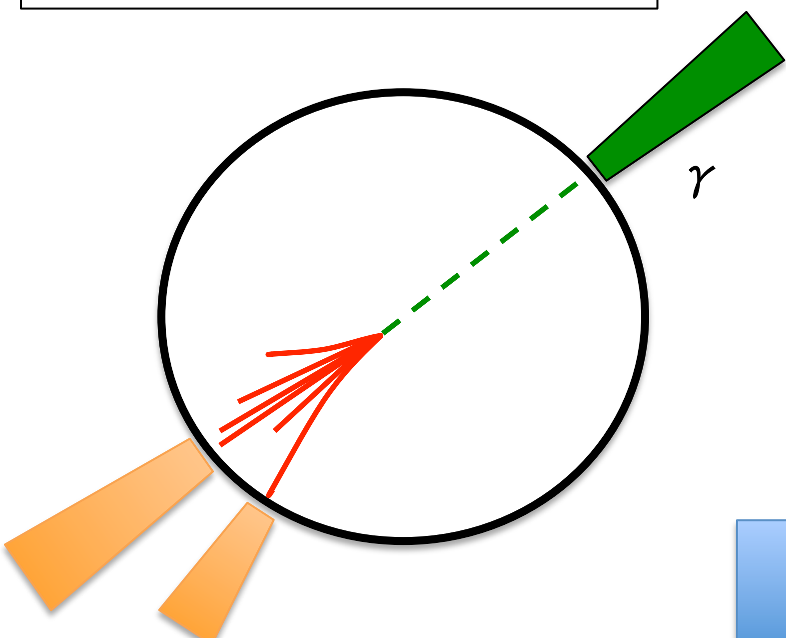


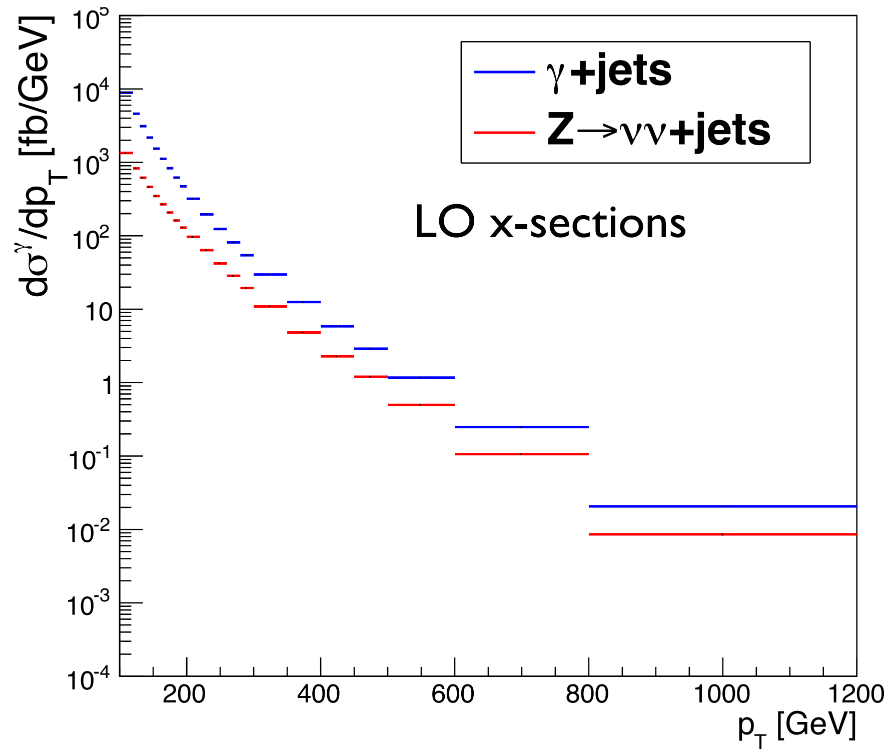




Constraint on Z(νν) from di-muon control region is statistically limited (~8x fewer events in CR).

Photon+Jet kinematics *similar* to Z at large boson pT; Many more events available.

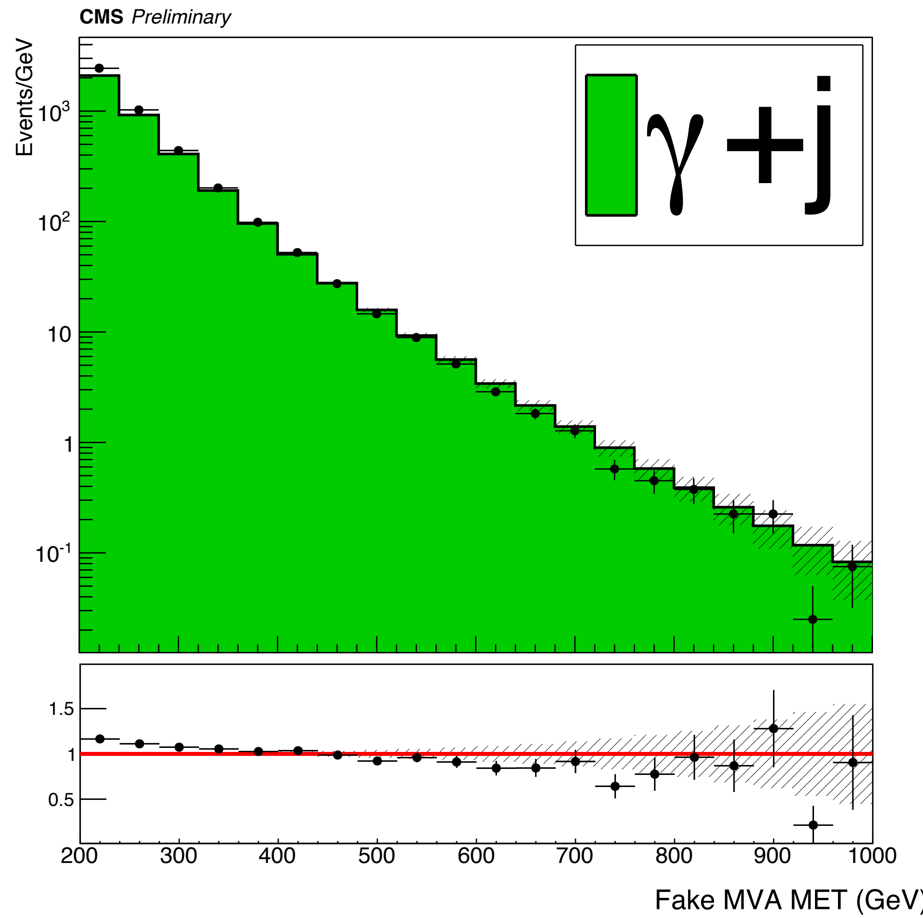




Use both photon + jet control region and the di-muon control region to constrain Z(νν)

Photon Selection

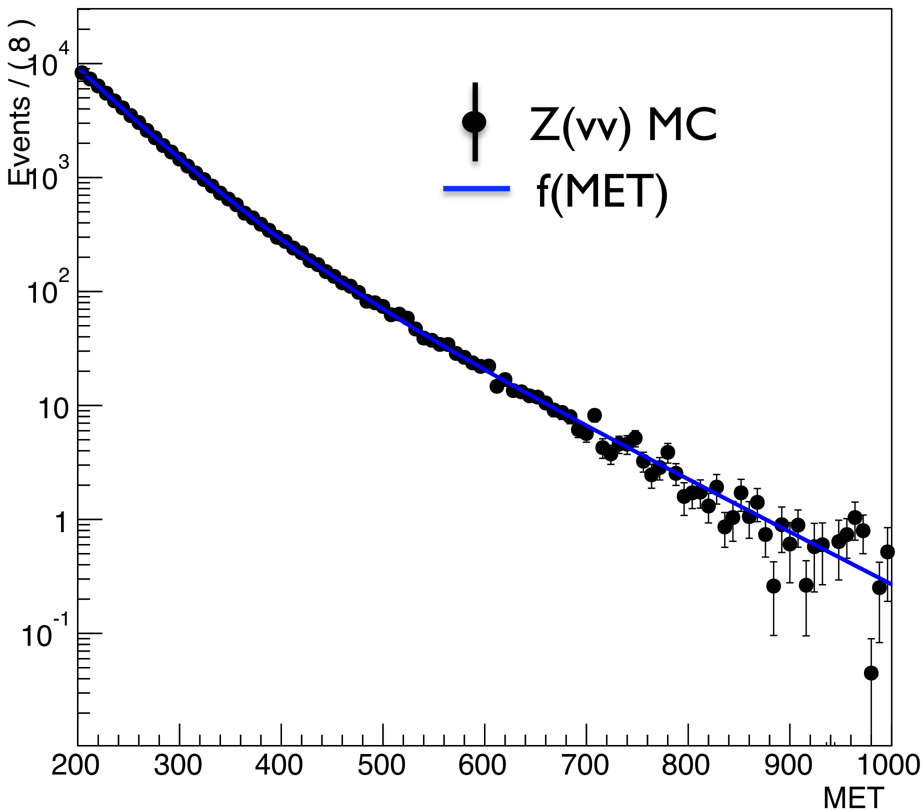
- Exactly one photon passing EG medium ID
- pT > 160, | η | < 2.5 (!transition)



- Photon Selection Efficiencies taken from MC Data/MC scale-factors from EGamma POG [1]
- For backgrounds, use data-driven photon purity measurements (EGM-14-001) in CR (~97 % for pT>150 GeV)

[1] https://twiki.cern.ch/twiki/bin/viewauth/CMS/CutBasedPhotonID2012

Assume that MET spectrum follows a double exponential



Fit Z(νν) MC in signal region with double exponential

Define the number of expected Z(νν) events as …

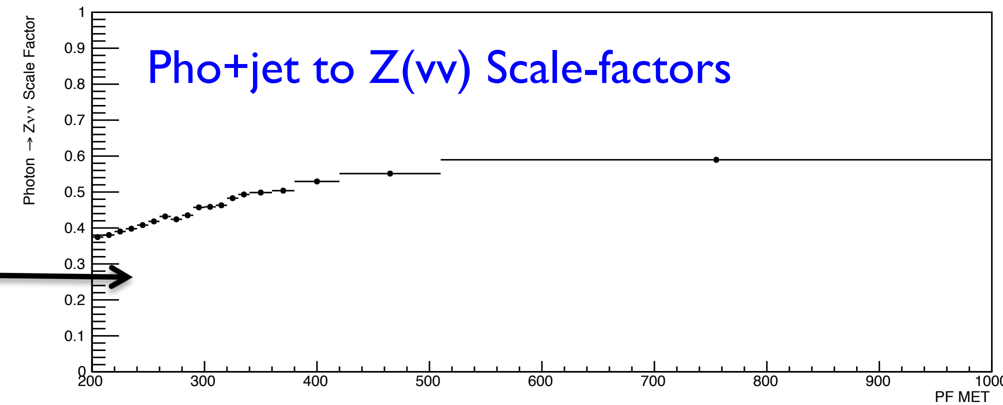
$$n_i^{Z\nu\nu}(\boldsymbol{a}) = \int_i f(MET, \boldsymbol{a})$$

Parameters (**a**) are the double exponential parameters. No constrain on these parameters is taken from the fit, this is just to initialize their values.

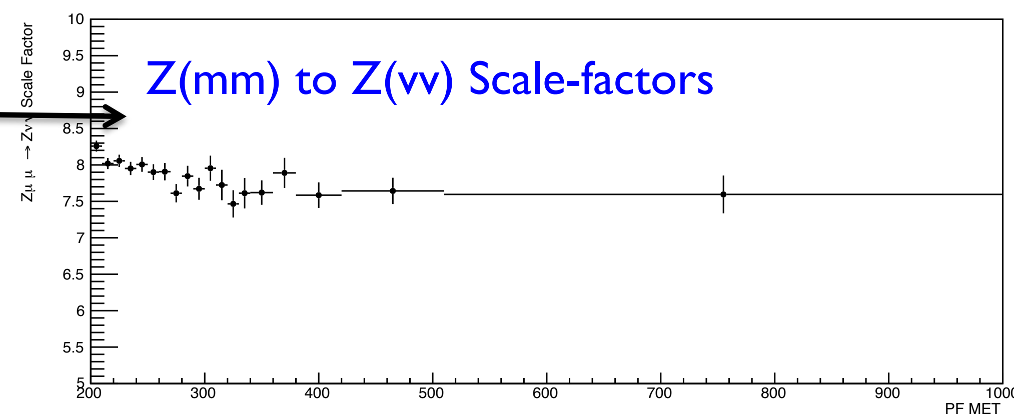
Expected yields in two control regions expressed via scale factors (R)

$$n_i^{Z\mu\mu/\gamma+j}(\boldsymbol{a},\theta) = \prod_j (1+\theta_j)\, R_i^{Z\mu\mu/\gamma+j}\, n_i^{Z\nu\nu}(\boldsymbol{a})$$

- Photon scale factors account for differential cross-sections and photon acceptance x efficiency



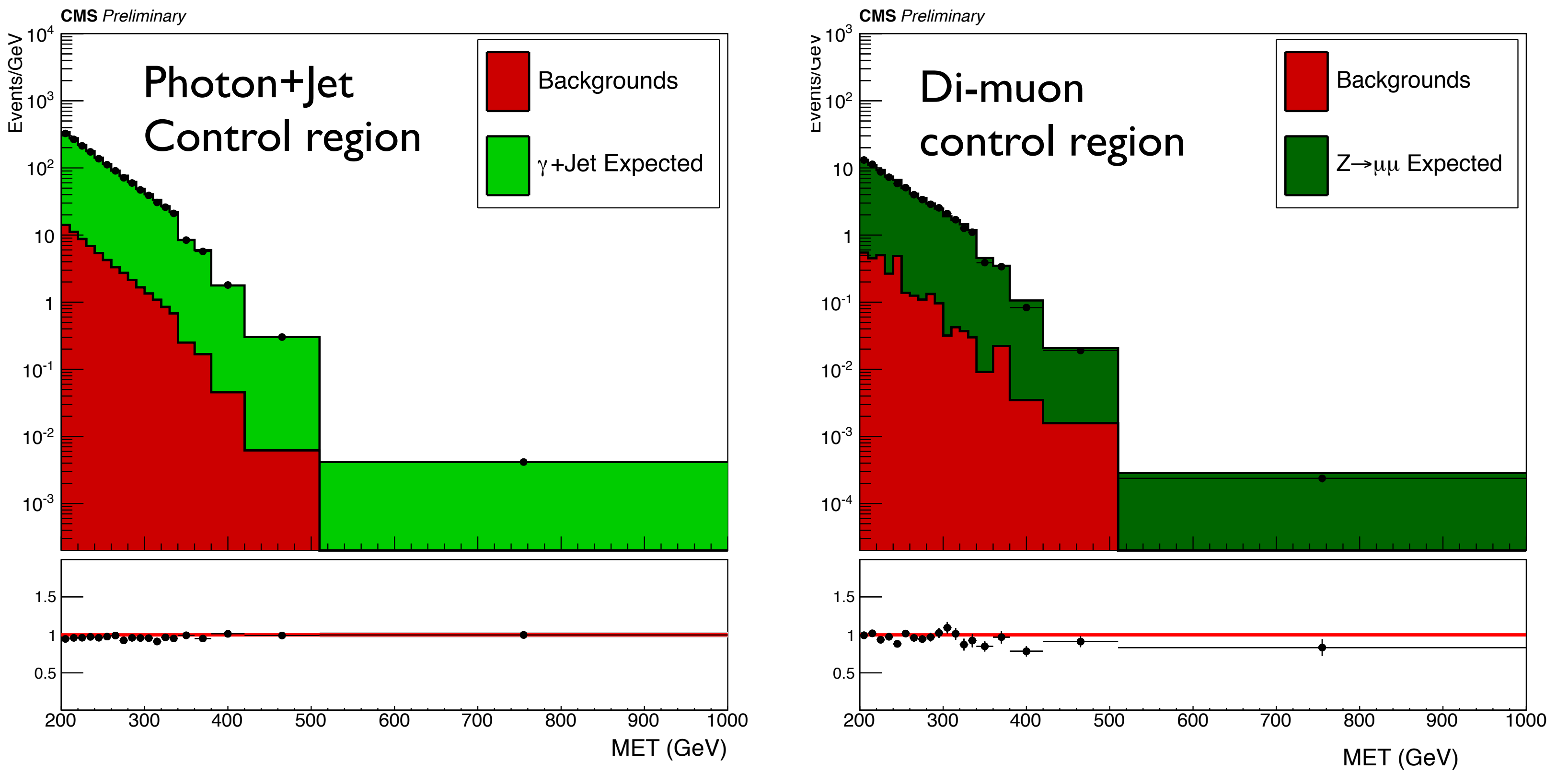
- Z(mm) scale factors account for muon acceptance x eff and BR(Zvv)/BR(Zmm)



Uncertainties from acc x eff and theory modify scale factors. Include them as nuisance parameters θ

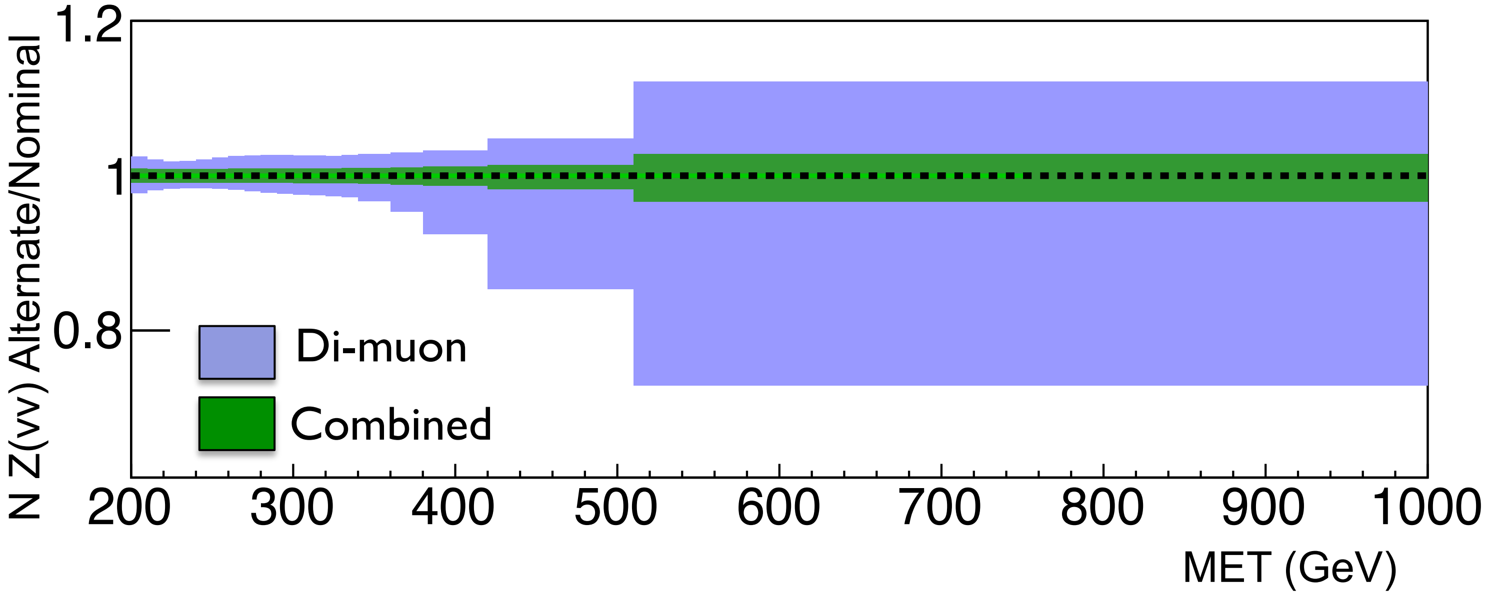
Photon +Jet and di-muon Combined

Simultaneous fit (combination of counting experiments) across MET bins between two control regions provides strongest constraint on Z(νν) background.



Photon +Jet and di-muon Combined

Comparison of Z(vv) template uncertainties from using di-muon control region only vs combining di-muon with photon+jet control regions.



Using combined control regions yields ~30% improvement in expected limit on Invisible Higgs BR*

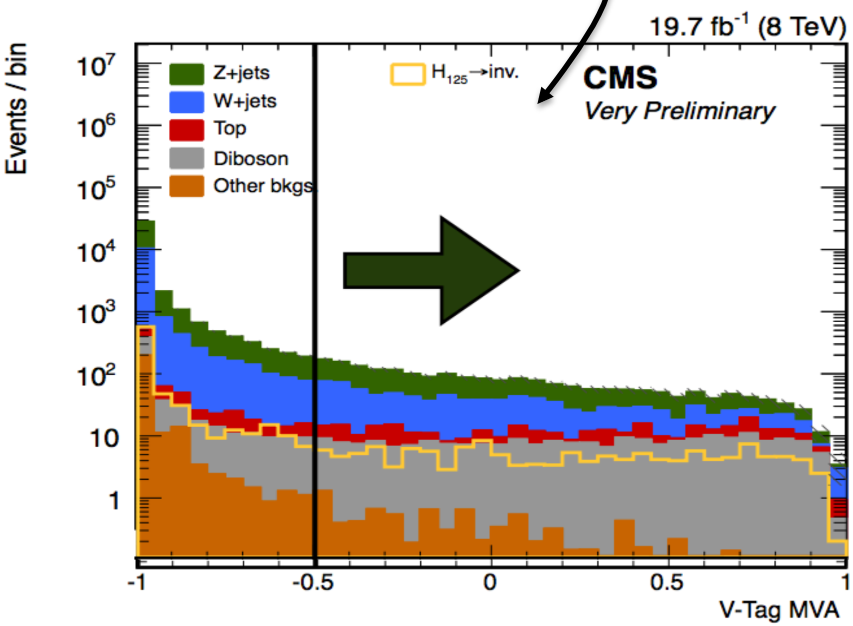
*Studies using aMC@NLO to calculate differential cross-sections for scale-factors ongoing. (see backup)

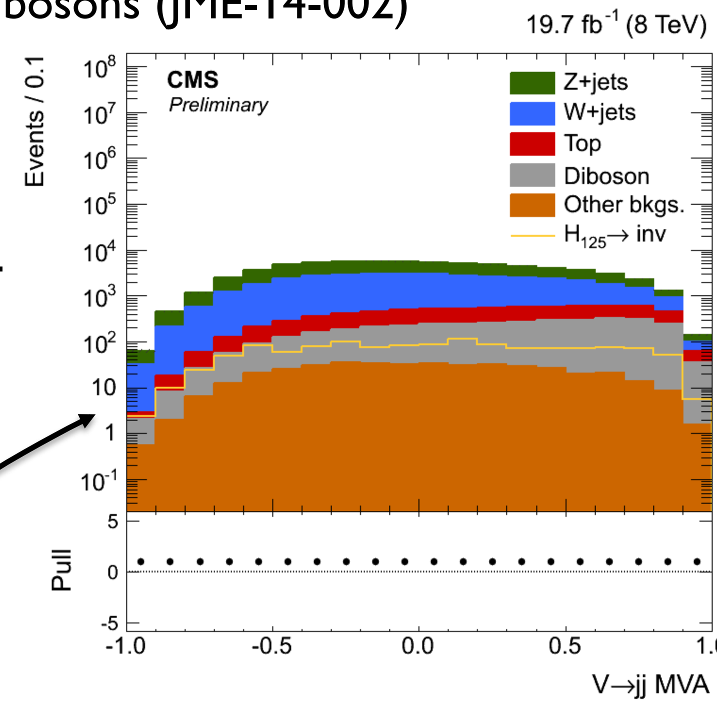
V-Tagging

Can identify events with hadronically decaying W/Z bosons (JME-14-002)

If the V is sufficiently boosted, daughter jets merge into a single "Fat" jet:

- Jet grooming algorithms provide jet-mass
- Jet Sub-structure information combined with jet-mass in BDT.





For medium V-pT, the jets can be resolved.

- Directly apply cut on invariant dijet mass.
- Combine QGL, modified mass drop, dijet(pT/m) and Jet Pull angle into BDT to reject combinatorial bkgs.

Analysis Flow

Separate V-tagged events and split into two categories

1. **Boosted Mono-V category (Vj) :**
   - MET > 250
   - Fat Jet (ak8) with pT > 250 GeV
   - Boosted V-tag variables combined into BDT discriminator (> -0.5[1])

2. **Resolved Mono-V category (Vjj):**
   - MET > 250
   - Two small-cone jets (pT>30)
   - Dijet Mass cut (60 < mjj < 110)
   - BDT Selection (>0.6[2])

3. **Untagged Category:**
   - Events failing above tags are left in “monojet-like” category.

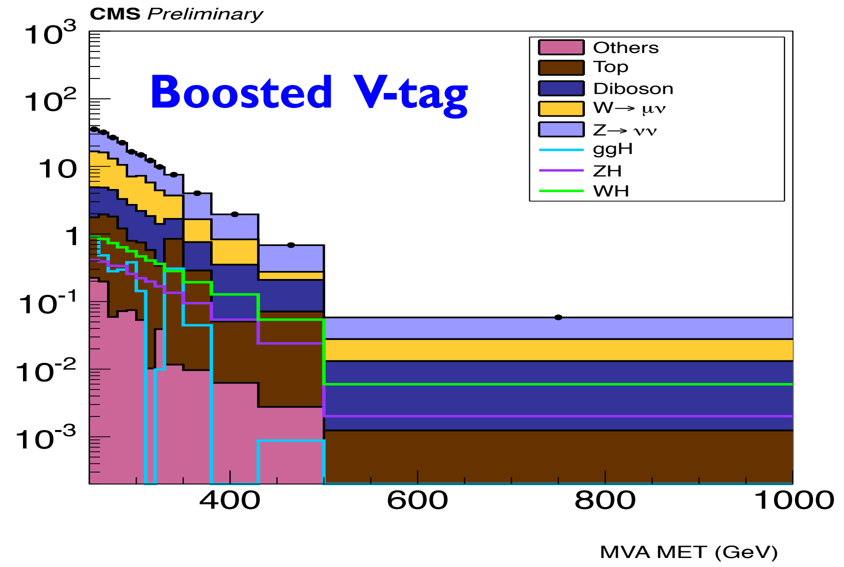
All categories use a shape anlaysis with MVA MET as the observable

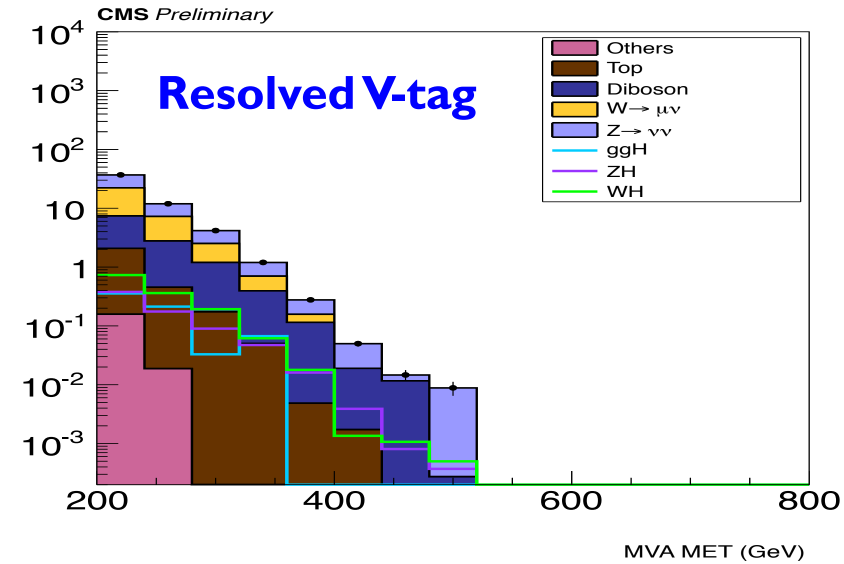
[1,2]optimized for Higgs

Signal Regions

Data in signal region blinded (points are set to expected background)

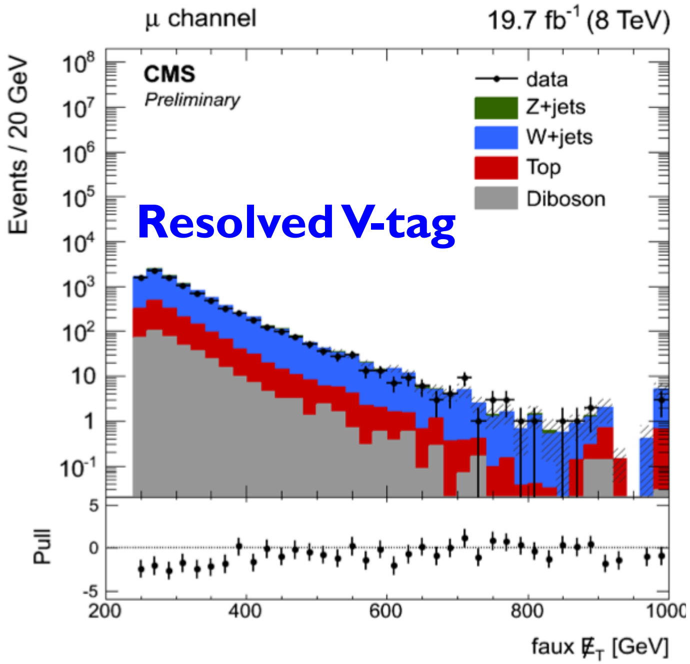
	Resolved	Boosted
Data	XXX	XXX
Z(vv)	863.5	1134.0
W(lv)	839.1	653.7
Di-bosons	366.0	225.7
Top	103.6	116.9
Others	7.1	8.3
Higgs mH=125	109.9	140.2
Total BKG MC	2179.3	2138.6

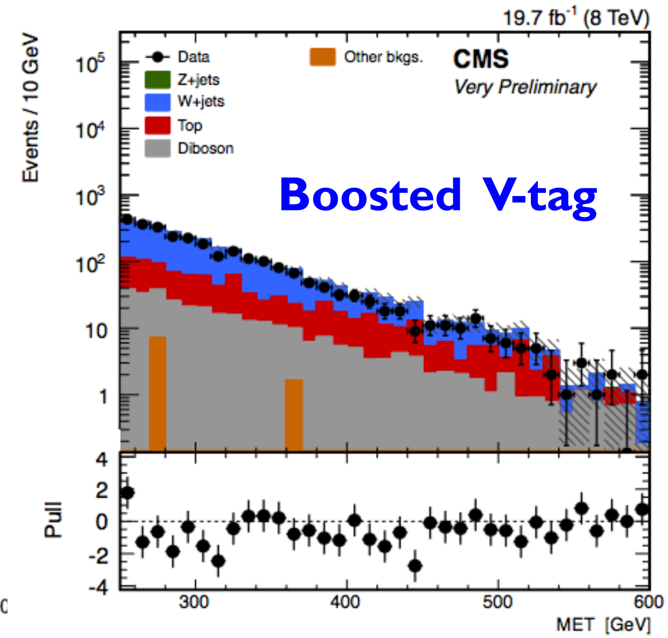




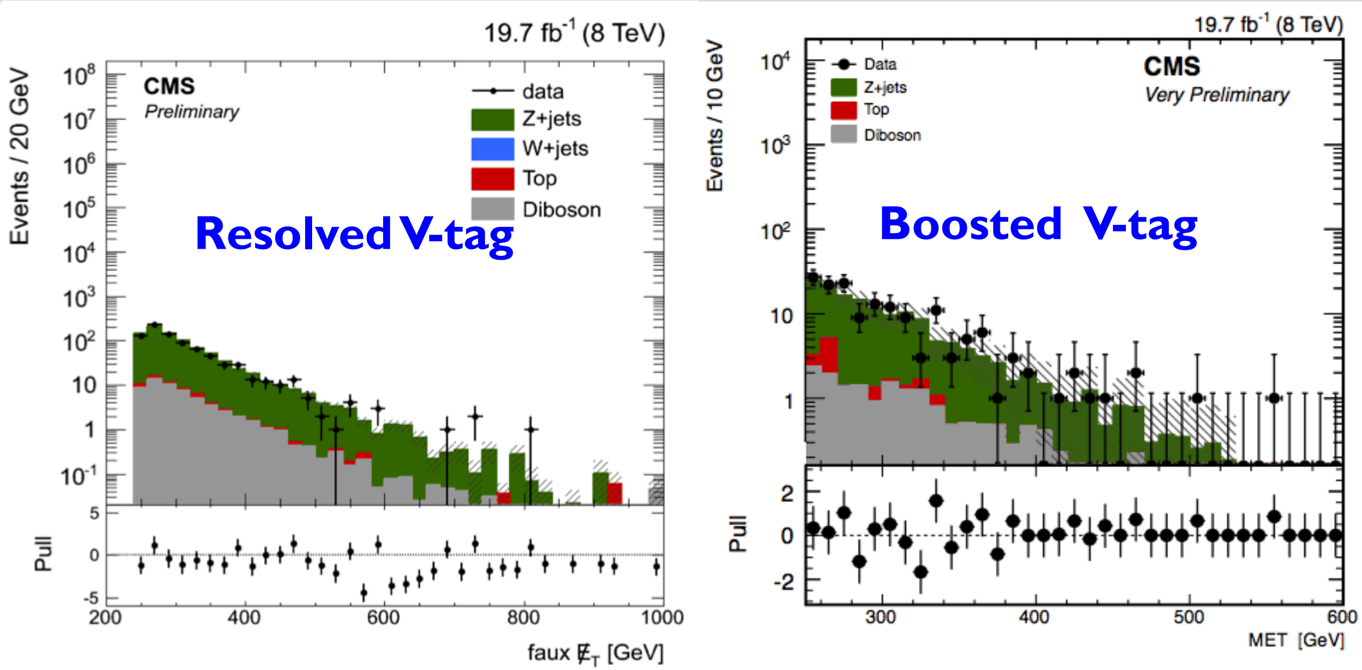
Overlap between categories not yet accounted for. Should be completed soon.

Single-muon control regions





	Resolved	Boosted
Data	8856	2698
W(mv)	7628	1981.0
Di-bosons	406.8	302.9
Top	1358.8	583.5
Total MC	9566.3	2904.0



	Resolved	Boosted
Data	823	158
Z(mm)	784.5	125.6
Di-bosons	60.2	17.8
Top	7.5	5.4
Total MC	852.2	148.8

Conclusions

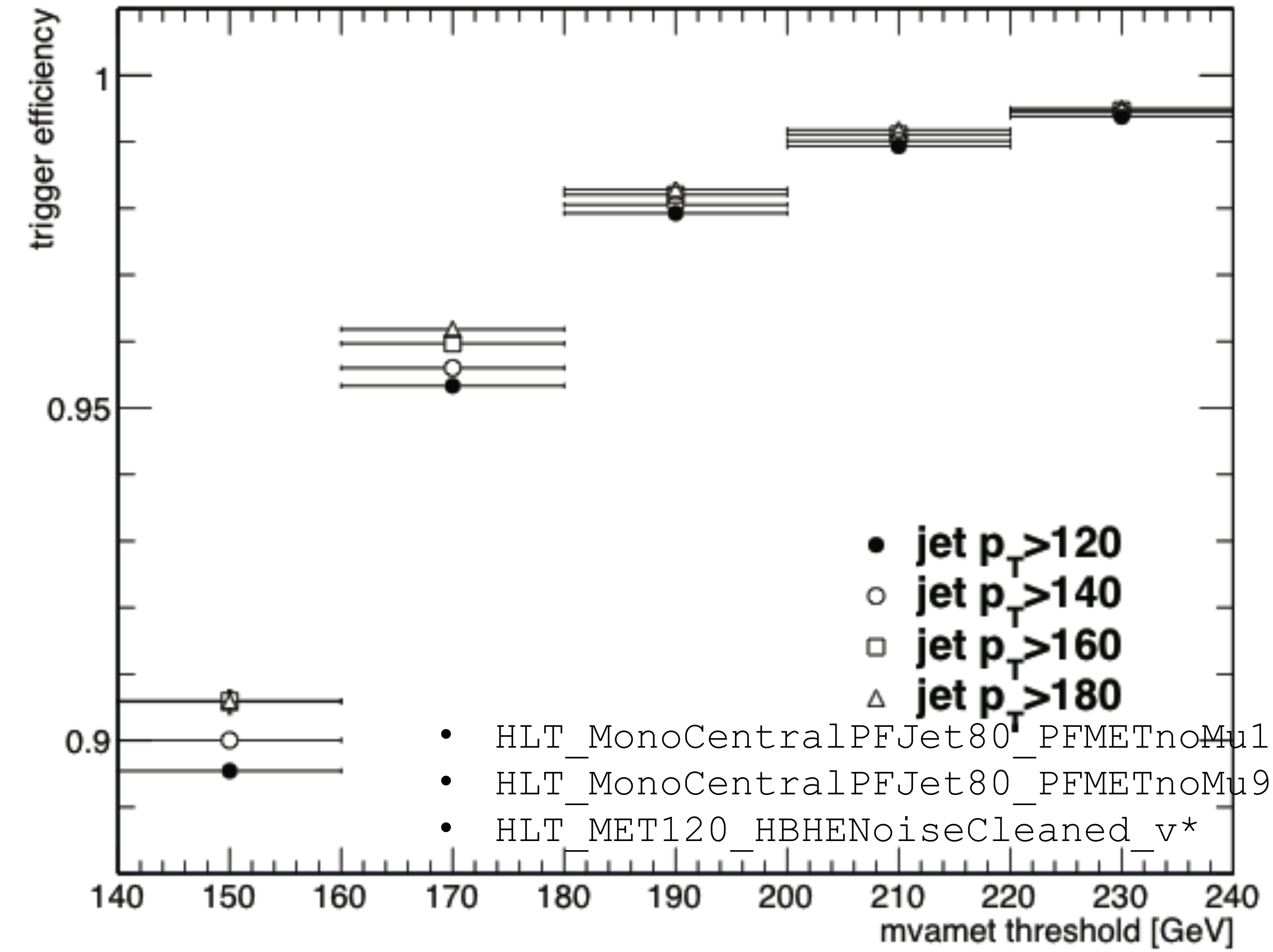
Monojet Analysis:

- Started from existing CMS monojet analysis selections/cuts
- Added shape analysis using MVA MET as observable
- 3 data control regions presented for constraining V+Jet backgrounds.
- Method shown for background modeling with CRs
- Working on combinations of CRs to improve Z(vv) constraint. Ongoing work to reduce theoretical uncertainty for photon/Z(vv) + jet x-sections.
- Expected limit calculated for Higgs BR in monojet analysis.
- First look at interpretation of the shape analysis within SM framework. Results are already promising.

V-Tagged Analysis:

- Exploits improvements from jet-pruning and substructure algorithms.
- Boosted and Resolved (new) categorization outlined. Monojet analysis "demoted" to untagged category.
- Single/di-muon control regions having applied V-tagging look good. Working on implementing background modeling for those categories. Should be ready to combine with untagged category soon…

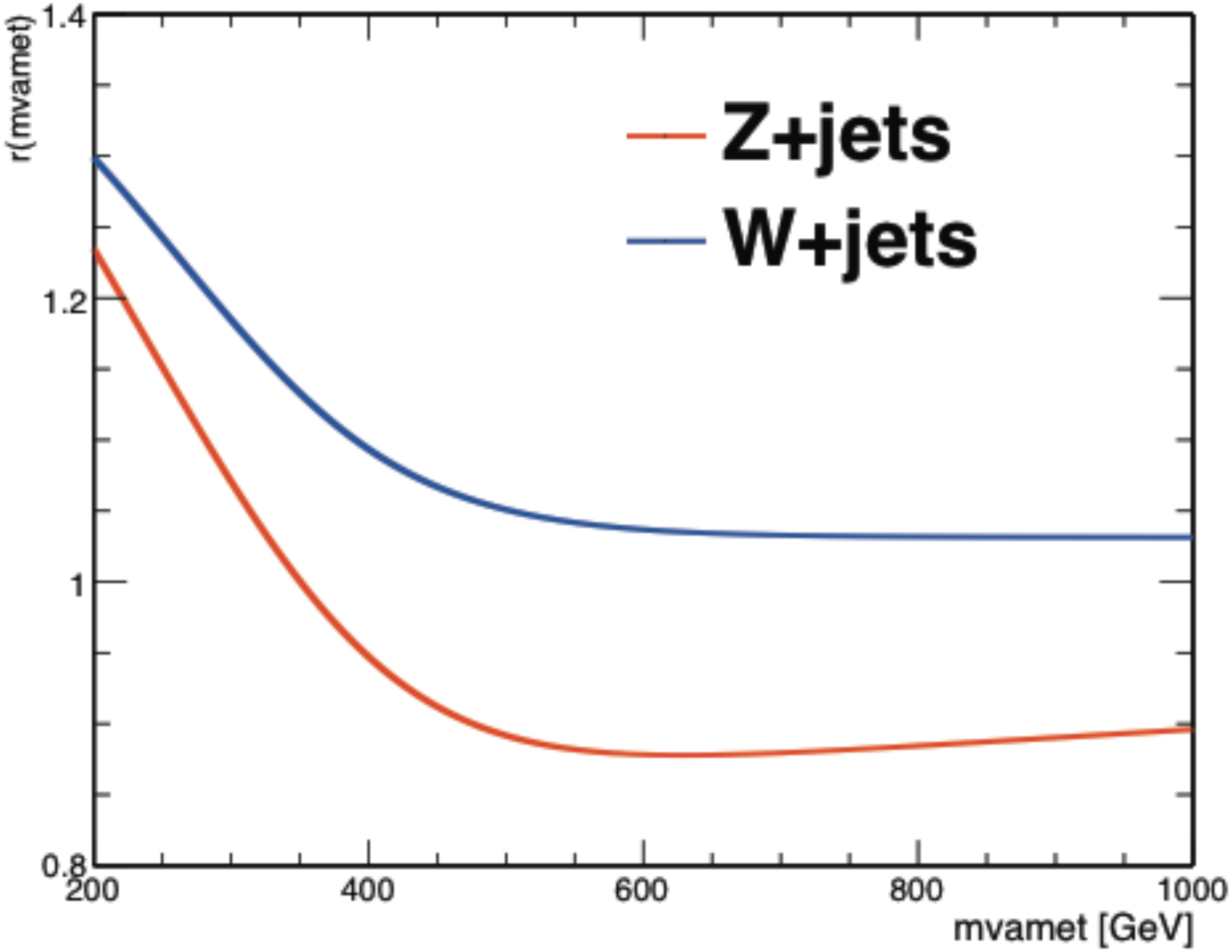
BACKUP SLIDES



- HLT_MonoCentralPFJet80_PFMETnoMu105_NHEF0p95_v*
- HLT_MonoCentralPFJet80_PFMETnoMu95_NHEF0p95_v*
- HLT_MET120_HBHENoiseCleaned_v*

Object Definitions

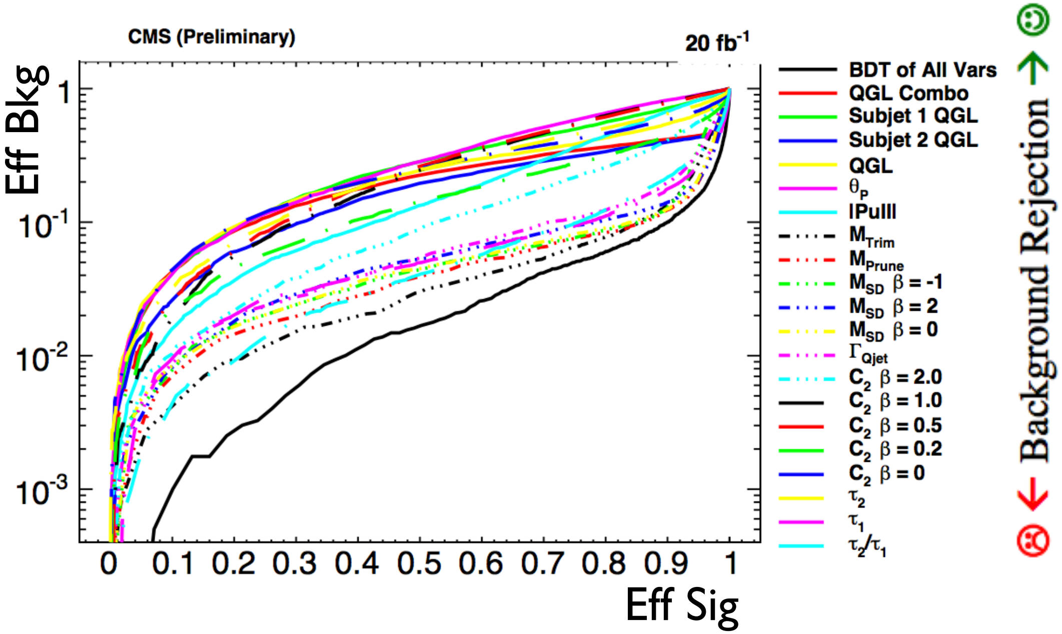
- Muons:
  - PF muons, pT>10, |η|<2.4
  - Tight ID (POG) and Iso (MVA rings>0.4) for W+jets control region only
    - Will move to std PF beta isolation
  - Loose ID and no iso for the muon veto
- Electrons:
  - GSF electrons, pT>10, |η|<2.5
  - VBTFWorkingPoint95 + relative isolation
    - Will move to looser ID
  - Conversion veto applied
- Taus:
  - HPS Loose taus
- Photons:
  - CiC
- Jets:
  - Akt5PF
  - L1+L2+L3(+L2L3Res) corrected
- Jet cleaning:
  - $f_{CH} > 0.2$, $f_{NEM} < 0.7$, $f_{NH} < 0.7$ (as suggested in EXO-12-048)
  - Applied to leading jet only
  - If leading jet doesn't fulfill that => discard the event
- MET:
  - Currently using MVA MET
  - Corrected PF MET available too
    - Type 0, type 1 and shift corrected
- MET filters:
  - Apply filters as recommended by JetMET
  - Remove events from bad event list
  - Muons are removed by hand (vectorial difference) when needed

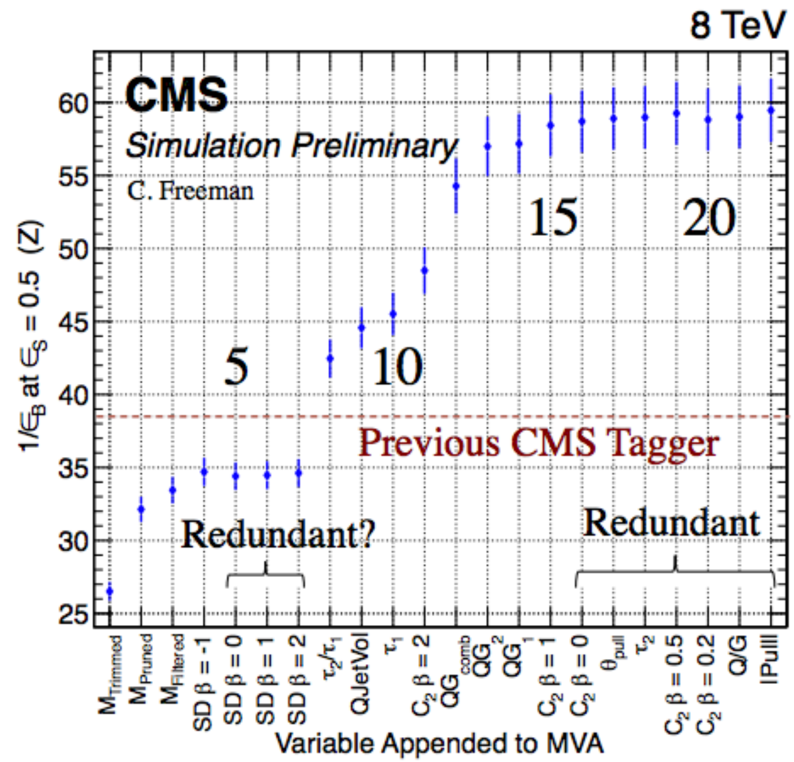


r(mvamet)
1.4
1.2
1
0.8
200
400
600
800
1000
mvamet [GeV]
Z+jets
W+jets

Boosted V-tag Performance

Tag W/Z decaying hadronically using jet-grooming and jet-substructure algorithms (see JME-14-002)

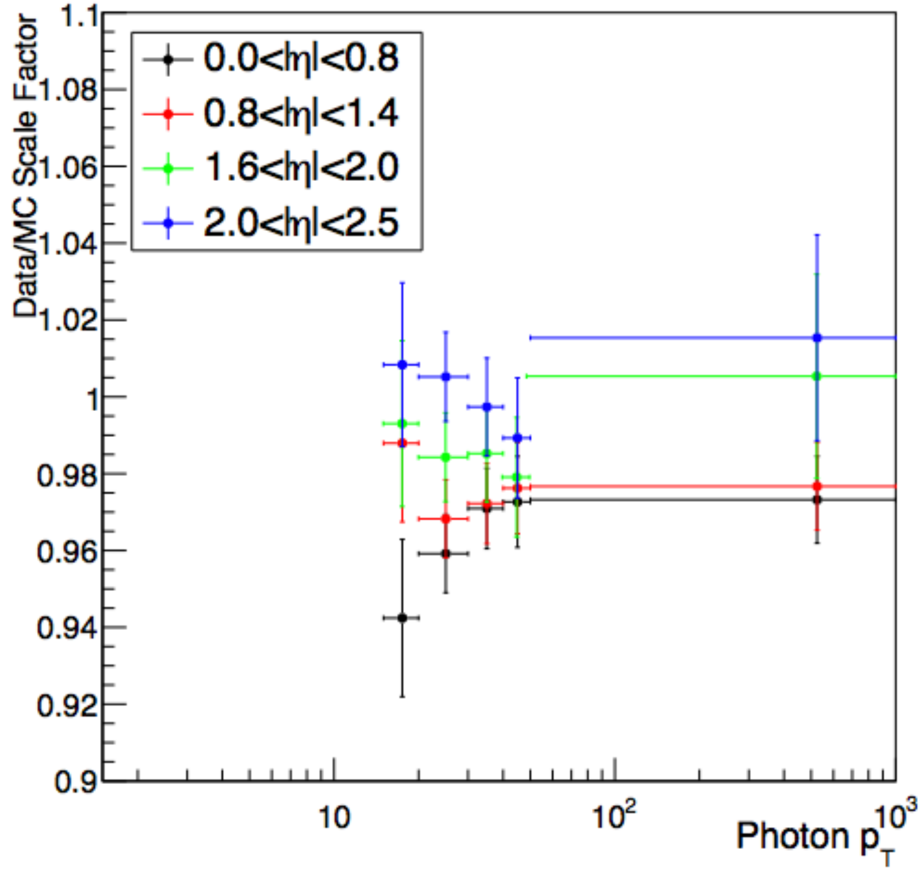




Photon EG Medium Selection

BARREL	Loose (90%)	Medium (80%)
Conversion safe electron veto	Yes	Yes
Single tower H/E	0.05	0.05
$\sigma_{i\eta i\eta}$	0.012	0.011
Rho corrected PF charged hadron isolation	2.6	1.5
Rho corrected PF neutral hadron isolation	3.5 + 0.04*pho_Pt	1.0 + 0.04*pho_Pt
Rho corrected PF photon isolation	1.3 + 0.005*pho_Pt	0.7 + 0.005*pho_Pt

ENDCAPS	Loose (85%)	Medium (75%)
Conversion safe electron veto	Yes	Yes
Single tower H/E	0.05	0.05
$\sigma_{i\eta i\eta}$	0.034	0.033
Rho corrected PF charged hadron isolation	2.3	1.2
Rho corrected PF neutral hadron isolation	2.9 + 0.04*pho_Pt	1.5 + 0.04*pho_Pt
Rho corrected PF photon isolation	-	1.0 + 0.005*pho_Pt



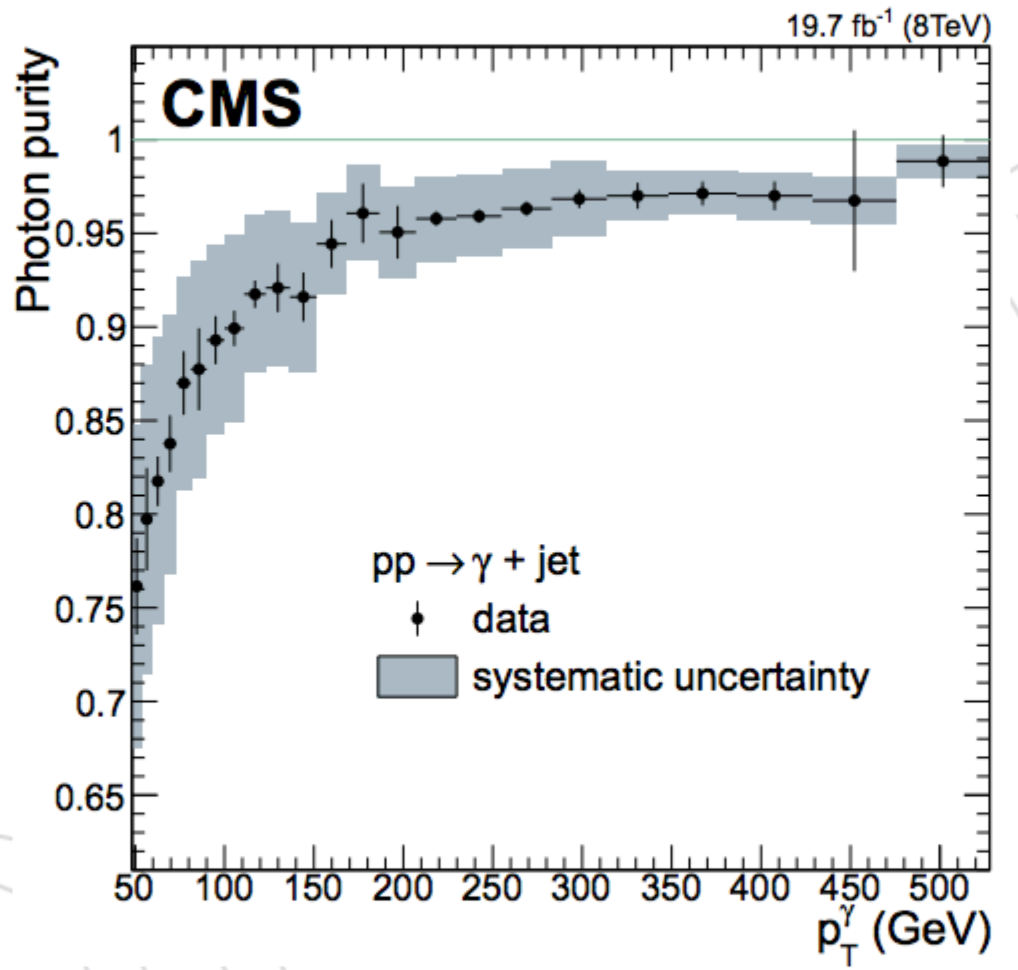
Photon Purity

Photon Purity measurements from EGM-14-001

Assumed a flat purity of 97% for pT > 160 GeV.

Systematic uncertainty 100% correlated across bins
-> Flat uncertainty.

Studies ongoing for sensitivity to Jet definition but early results suggests purity measurement insensitive.



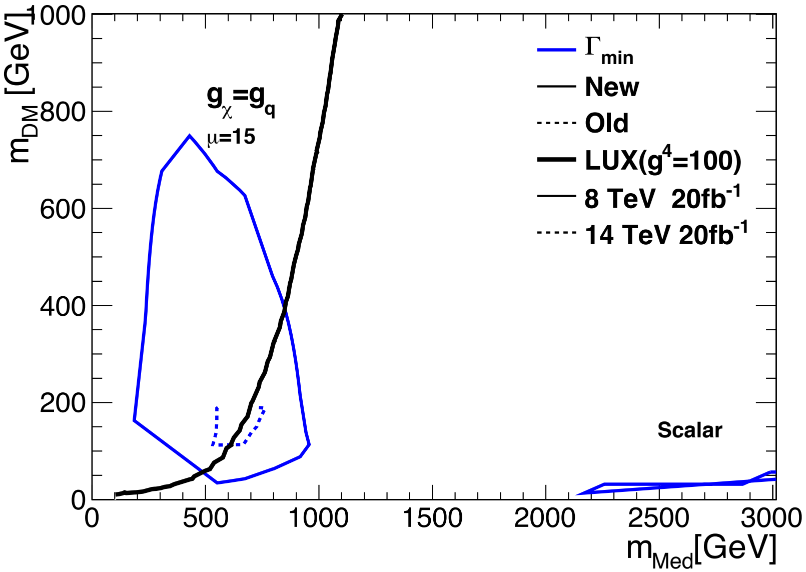
MC Samples

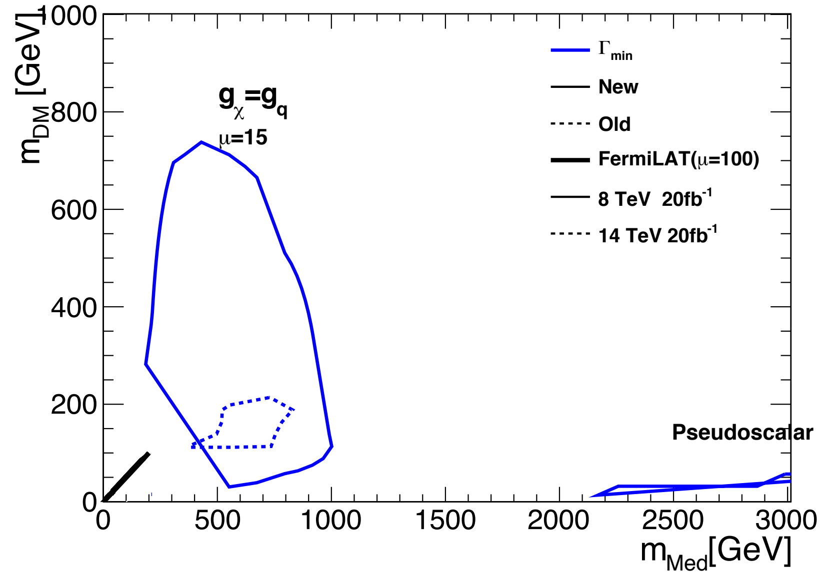
Sample
/GluGlu_HToInvisible_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/VBF_HToInvisible_M-125_8TeV-powheg-pythia6/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/ZJetsToNuNu_PtZ-100_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/ZJetsToNuNu_PtZ-70To100_8TeV/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/ZJetsToNuNu_50_HT_100_TuneZ2Star_8TeV_madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/ZJetsToNuNu_100_HT_200_TuneZ2Star_8TeV_madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/ZJetsToNuNu_200_HT_400_TuneZ2Star_8TeV_madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/ZJetsToNuNu_400_HT_inf_TuneZ2Star_8TeV_madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/WJetsToLNu_PtW-100_TuneZ2star_8TeV_ext-madgraph-tarball/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/WJetsToLNu_PtW-100_8TeV-herwigpp/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/WJets_0p1_1p2_2p10_3p20_4p20_5p20_CT10_8TeV-sherpa/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/W1JetsToLNu_TuneZ2Star_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/W2JetsToLNu_TuneZ2Star_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/W3JetsToLNu_TuneZ2Star_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/W4JetsToLNu_TuneZ2Star_8TeV-madgraph/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/DYJetsToLL_PtZ-100_TuneZ2star_8TeV_ext-madgraph-tarball/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSIM
/DYJetsToLL_PtZ-70To100_TuneZ2star_8TeV_ext-madgraph-tarball/Summer12_DR53X-PU_S10_START53_V7C-v1/AODSI
/DYJetsToLL_M-50_TuneZ2Star_8TeV-madgraph-tarball/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/WW_TuneZ2star_8TeV_pythia6_tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/WZ_TuneZ2star_8TeV_pythia6_tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/ZZ_TuneZ2star_8TeV_pythia6_tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/TT_CT10_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/TT_CT10_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v2/AODSIM
/T_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/Tbar_tW-channel-DR_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/T_s-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/Tbar_s-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/T_t-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v3/AODSIM
/Tbar_t-channel_TuneZ2star_8TeV-powheg-tauola/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/QCD_HT-100To250_TuneZ2star_8TeV-madgraph-pythia/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/QCD_HT-250To500_TuneZ2star_8TeV-madgraph-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/QCD_HT-500To1000_TuneZ2star_8TeV-madgraph-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM
/QCD_HT-1000ToInf_TuneZ2star_8TeV-madgraph-pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM

Photon + Jet to Z(vv) Studies

Sample	x-sec (pb)
/G_Pt-30to50_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	19931.62
/G_Pt-50to80_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	3322.309
/G_Pt-80to120_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	558.2865
/G_Pt-120to170_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	108.0068
/G_Pt-170to300_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	30.12207
/G_Pt-300to470_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	2.138632
/G_Pt-470to800_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	0.2119244
/G_Pt-800to1400_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	0.007077847
/G_Pt-1400to1800_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	0.00004510327
/G_Pt-1800_TuneZ2star_8TeV_pythia6/Summer12_DR53X-PU_S10_START53_V7A-v1/AODSIM	0.000001867141
/ZJetsToNuNu_50_HT_100_TuneZ2Star_8TeV_madgraph_ext/Summer12-START52_V9-v1/AODSIM	381.2
/ZJetsToNuNu_100_HT_200_TuneZ2Star_8TeV_madgraph_ext/Summer12-START52_V9-v1/AODSIM	160.3
/ZJetsToNuNu_200_HT_400_TuneZ2Star_8TeV_madgraph_ext/Summer12-START52_V9-v1/AODSIM	41.49
/ZJetsToNuNu_400_HT_Inf_TuneZ2Star_8TeV_madgraph_ext/Summer12-START52_V9-v1/AODSIM	5.274

Constraints in mDM vs mMed

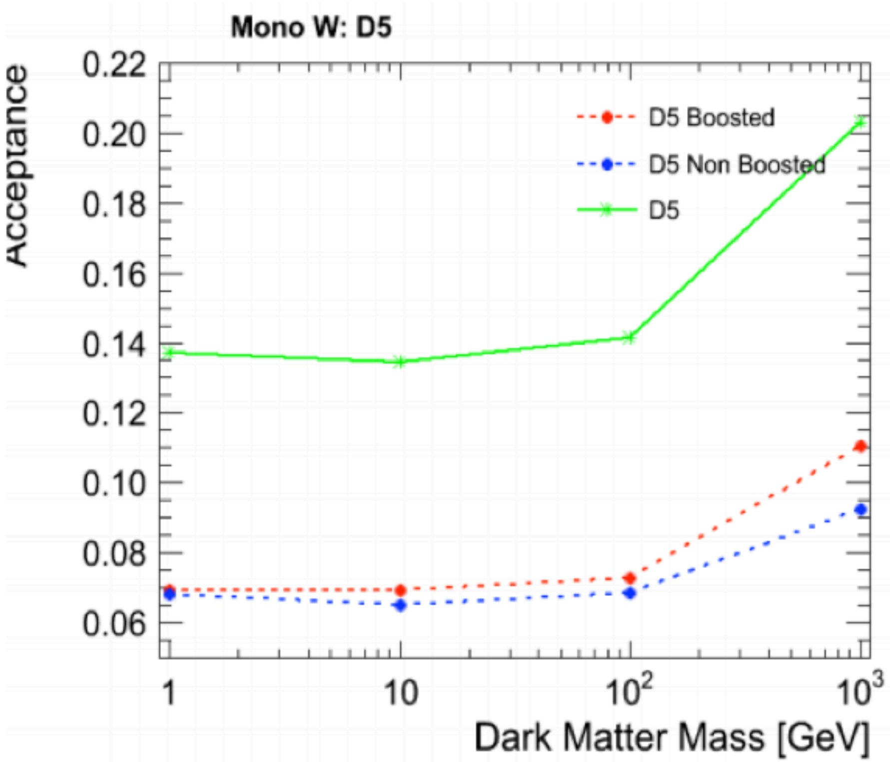


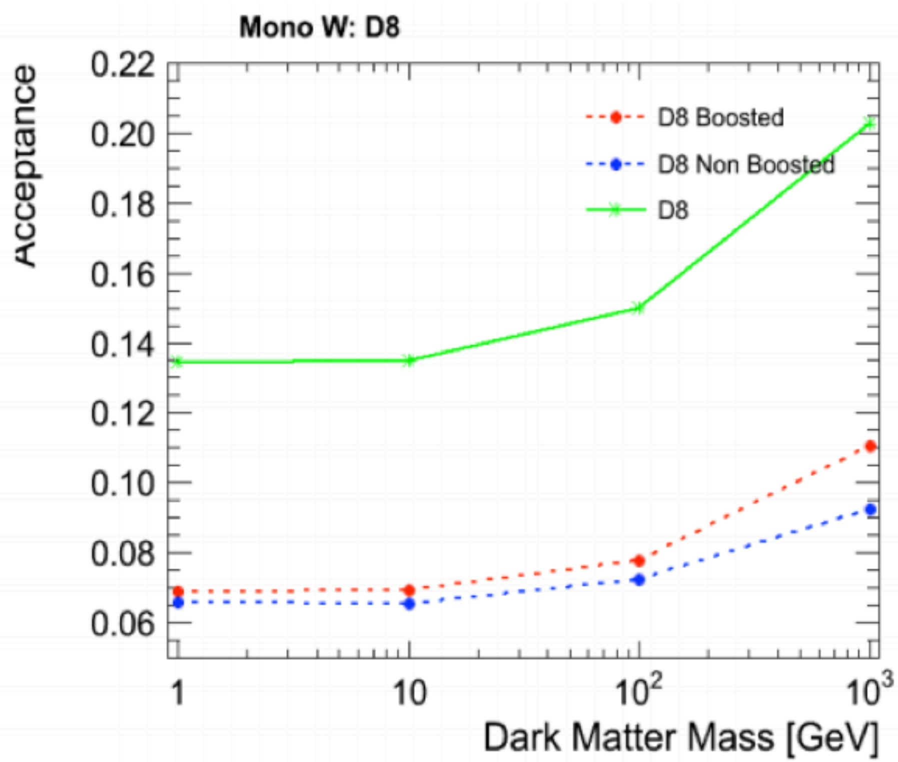


Note, that the contours are derived from relatively few points in the plain so interpolation is not guaranteed accurate. We are running more points to fill in the gaps

V-Tagging

Boosted and Resolved V (hadronic) decays have similar acceptances in specific DM models ➔ Split events into boosted and resolved categories.



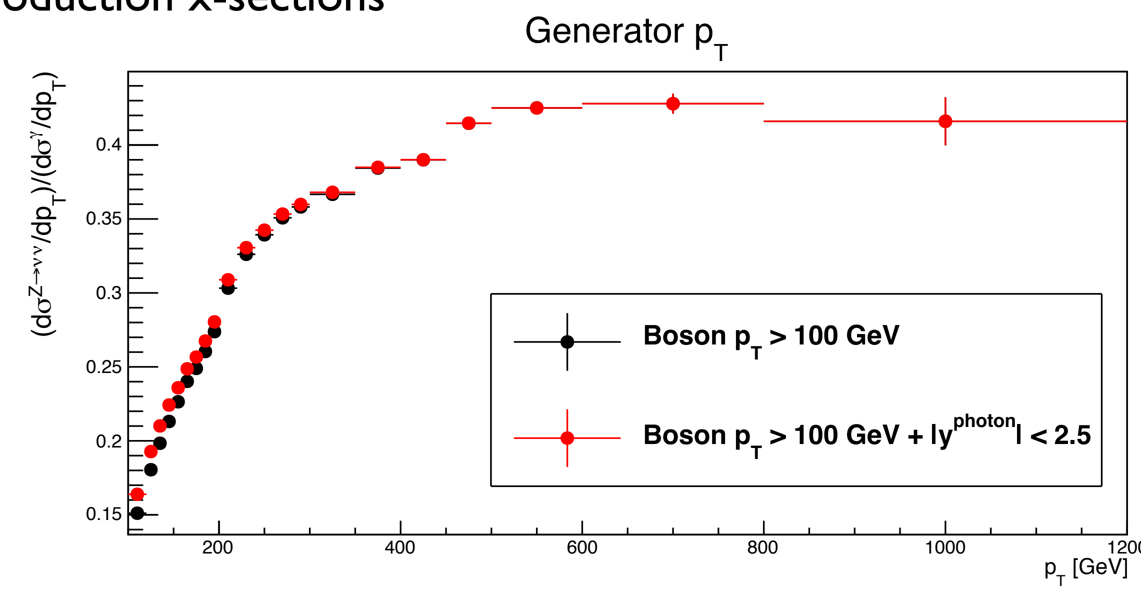


HO Differential Cross-sections

Ratio of photon+jet to Z+jet production x-sections
NB// also include BR(Zvv)

Leading order differential x-section ratio.

~10-20% theoretical uncertainty



aMC@NLO:

Higher order calculation yields ~2-3% uncertainty overall