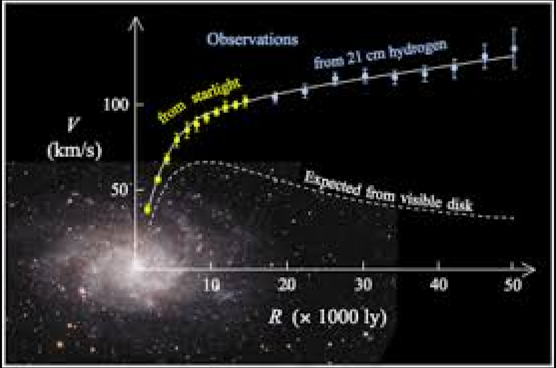
Search for Dark Matter in non-hadronic final states in CMS

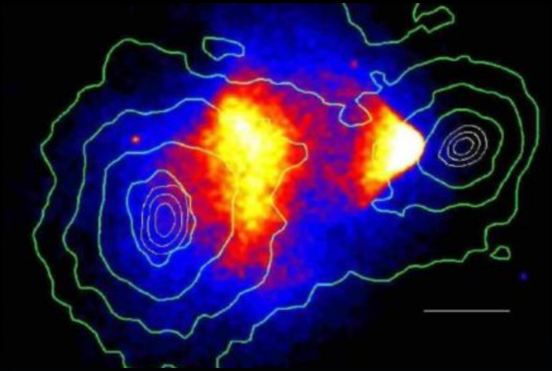
Shamik Ghosh

- On behalf of CMS collaboration

- Astrophysical observations point to the existence of Dark Matter (DM)



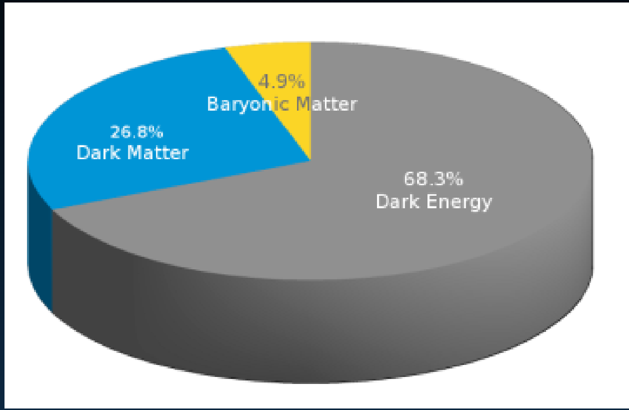
Rotation curves



Bullet Cluster

- Nature of DM remains unknown
- Our knowledge about dark matter comes from non-interactions and gravity
- Electrically neutral, non-baryonic, long-lived, non-relativistic, interaction cross-section ~ weak interaction

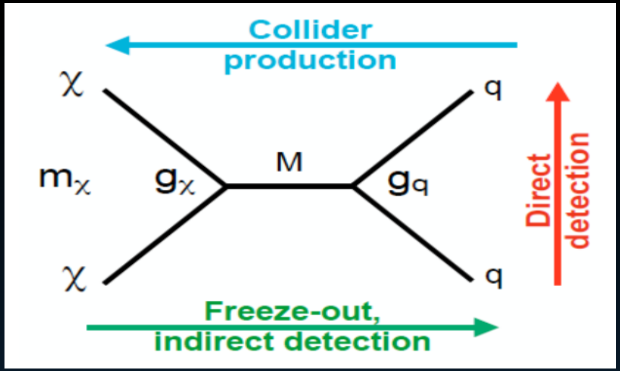
- **WIMP:** Motivation to consider collider searches for DM

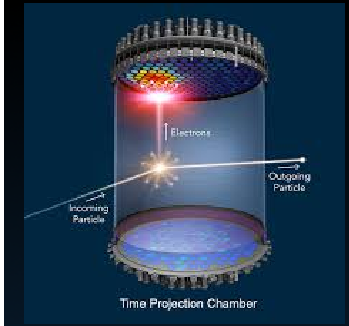


DM Production and Detection

DM may be pair produced in pp collisions at the LHC, Yields experimental signature of MET

LHC





Scattering of DM particles on nuclei of detector material ; detect recoil. For a given cross section sensitivity scales with detector size.

LUX, PANDAX

Assume annihilation of DM particles, eg. In the sun. Detect annihilation products.

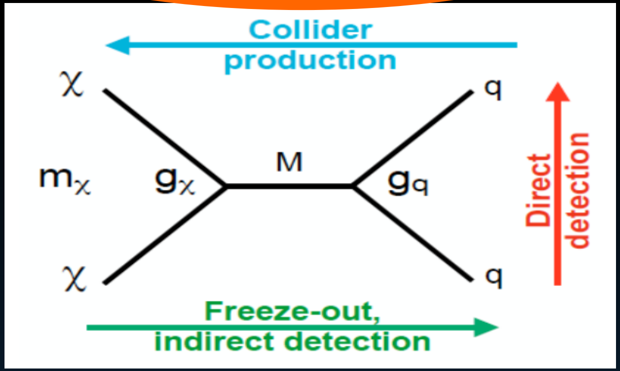
PAMELA, AMS

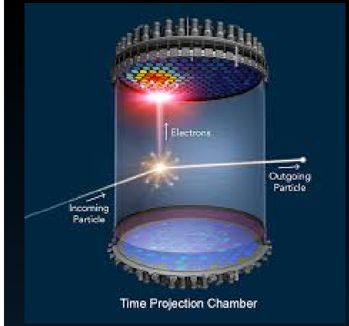
DM Production and Detection

DM may be pair produced in pp collisions at the LHC, Yields experimental signature of MET

LHC

Focus of the Talk





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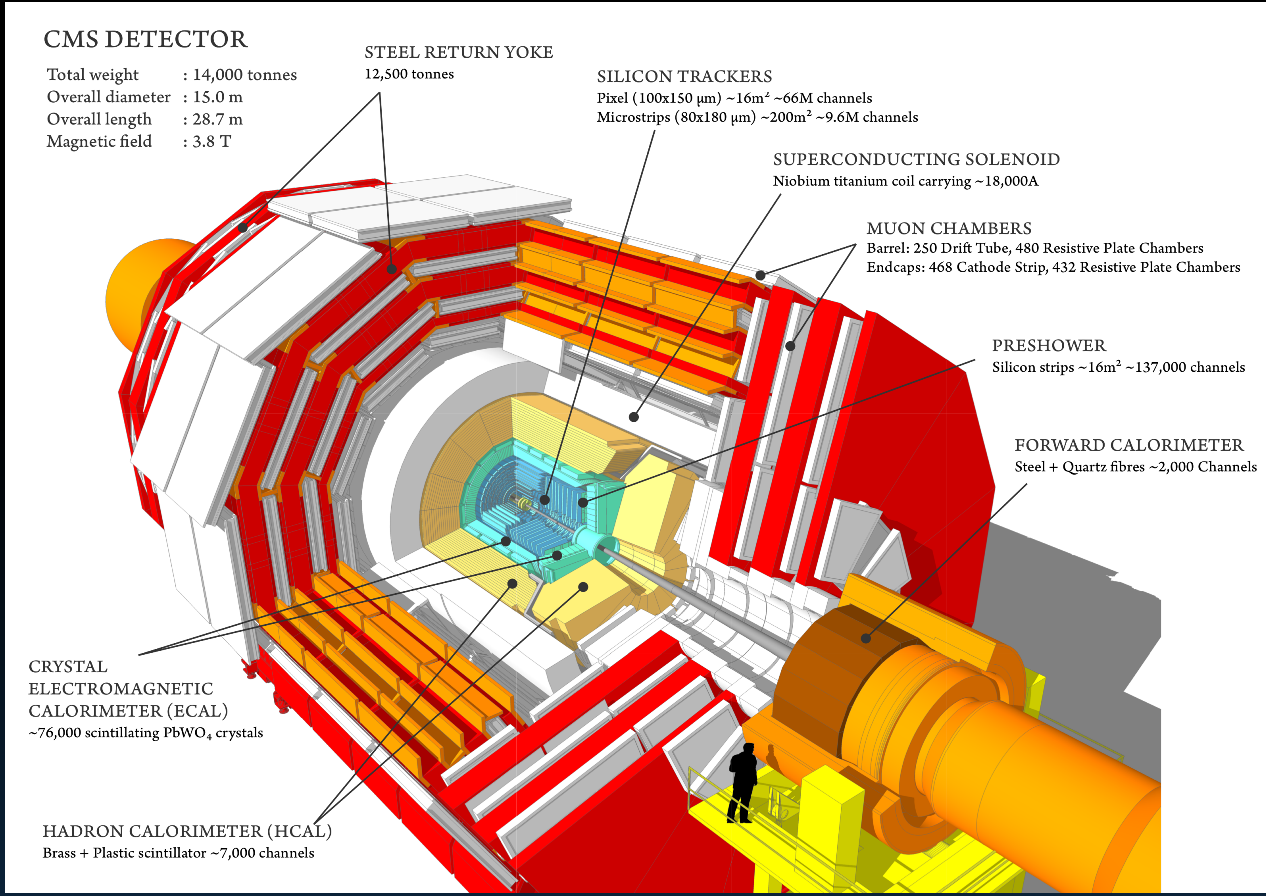
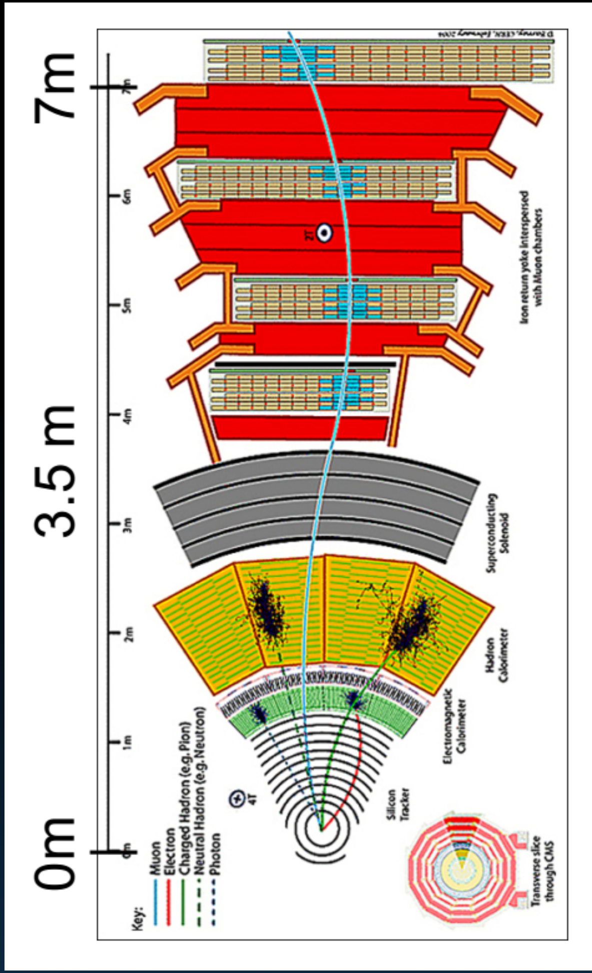
PAMELA, AMS

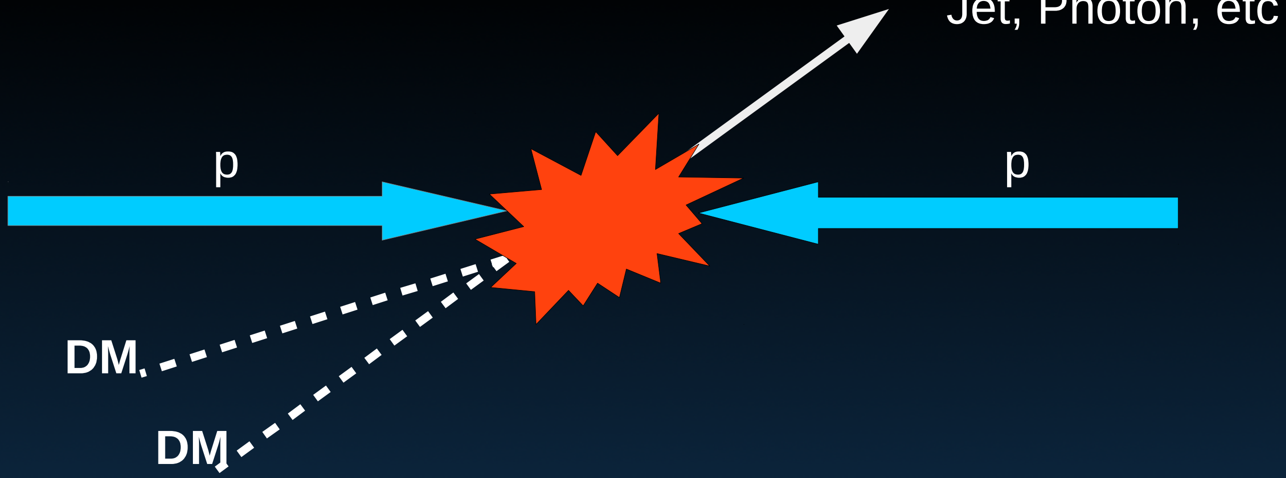
Compact Muon Solenoid



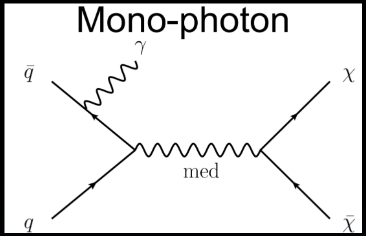


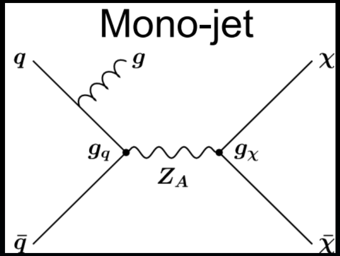
Dark Matter signatures at LHC

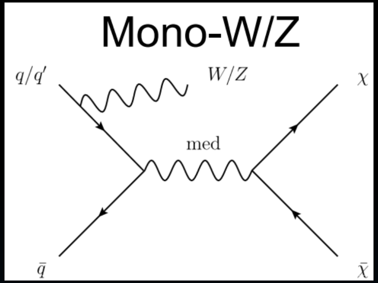
- Dark Matter particles will pass undetected through the detector
- They may recoil against visible high pT object **X** (= jet, photon, Z, etc)
- Large transverse momentum imbalance created as a result
  $\mathbf{E_T^{miss}}$ **+ X** systems created



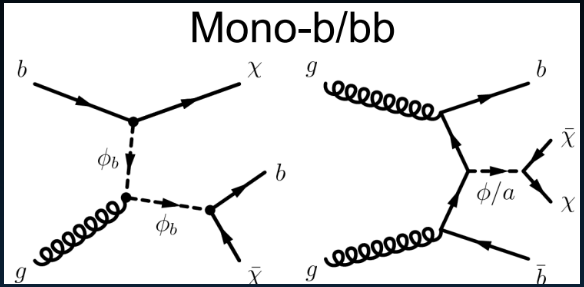
A wide range of final states can be investigated with CMS

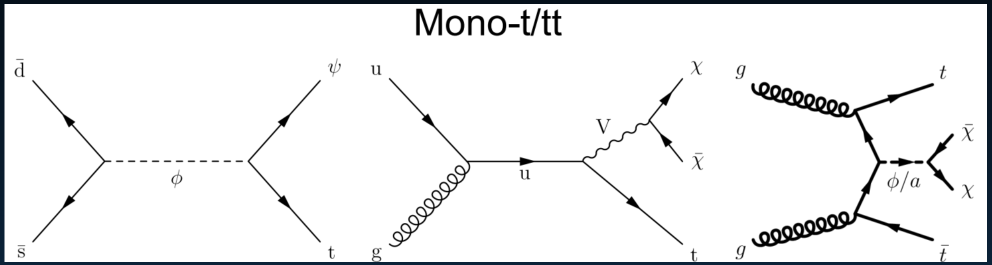




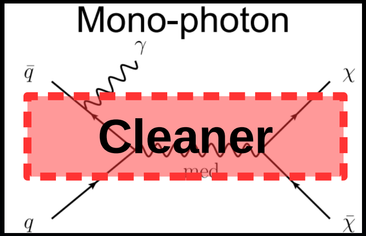


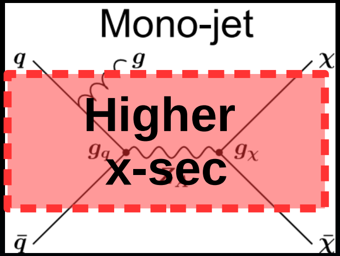
Mono-X Signatures – simple and striking

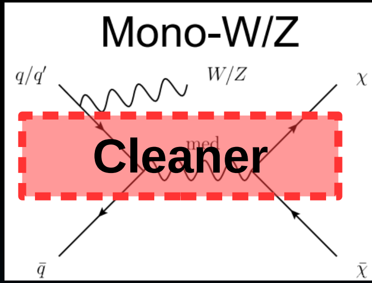




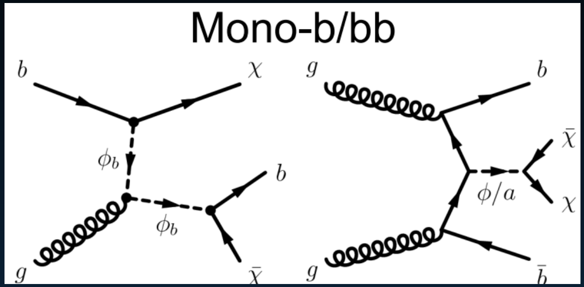
A wide range of final states can be investigated with CMS

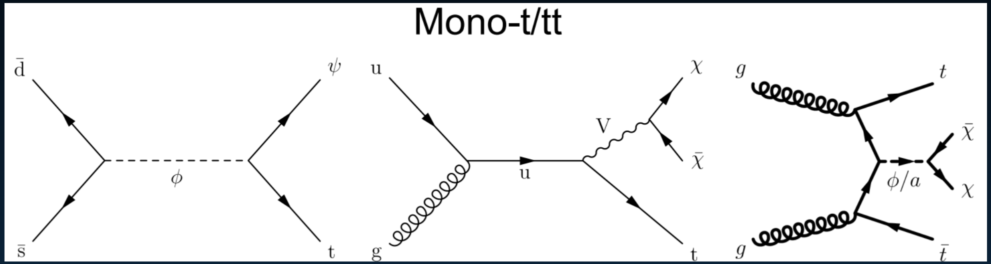






Mono-X Signatures – simple and striking





Dark Matter Simplified Models

- Searches interpreted using generic 'simplified models'

  Fermionic DM pair and a massive boson that mediates the interaction between DM and SM quarks

- Model Parameters :

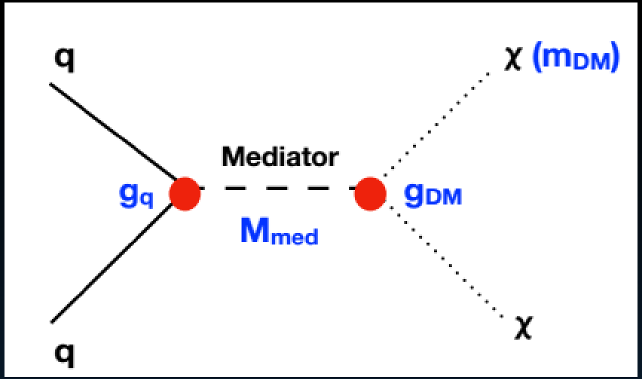
➢ Spin/parity of the mediator

➢ Mediator mass (M_{med})

➢ DM mass (m_{DM})

➢ Mediator coupling to quarks (g_q)

➢ Mediator coupling to DM (g_{DM})

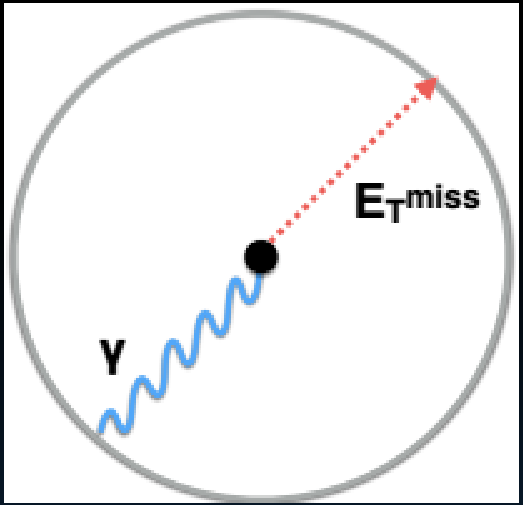


ArXiv:1507.00966

Monophoton: Event Selection

Searching for single photon recoiling against E_T^{miss}

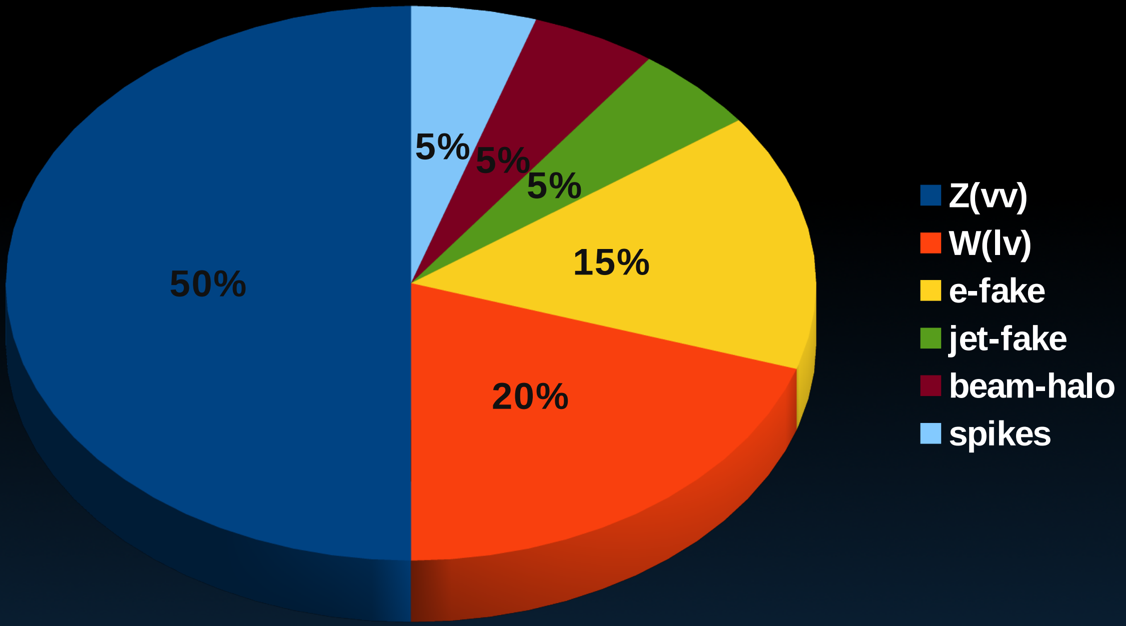
- High energetic photon with p_T > 175 GeV : $|\eta| < 1.4442$
- Missing Transverse Energy E_T^{miss} > 170 GeV
- $\Delta\phi(\gamma, E_T^{miss}) > 0.5$: to reject W+jets and fake E_T^{miss} from γ
- $\Delta\phi(j, E_T^{miss}) > 0.5$: to reject fake E_T^{miss} from jets
- $E_T^{\gamma} / E_T^{miss} < 1.4$: γ + jets reduction
- Veto electrons and leptons with p_T > 10GeV



CMS PAS EXO-16-053

Monophoton: Main Backgrounds

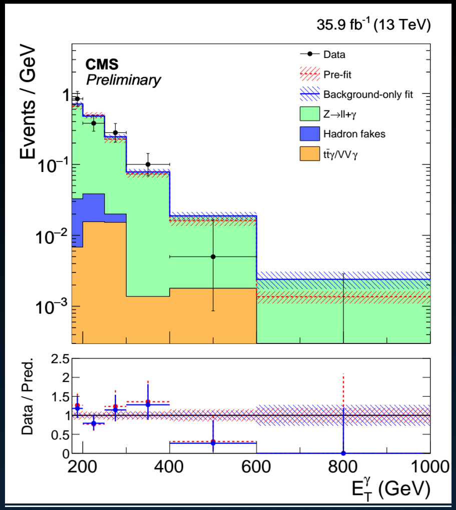
Irreducible	Z (νν) + γ	W (ɫν) + γ
Fakes	Electrons	Hadrons
Anomalous	Beam Halo	Spike



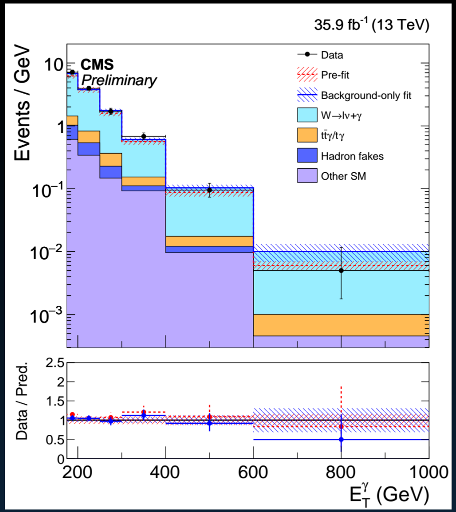
Monophoton: Main Backgrounds

Irreducible	Z (νν) + γ	W (łν) + γ
Fakes	Electrons	Hadrons
Anomalous	Beam Halo	Spike

Simultaneous fits between signal and control region (single and di-lepton)



Zγ->(ee)γ



Wγ->(μν)γ

Monophoton: Main Backgrounds

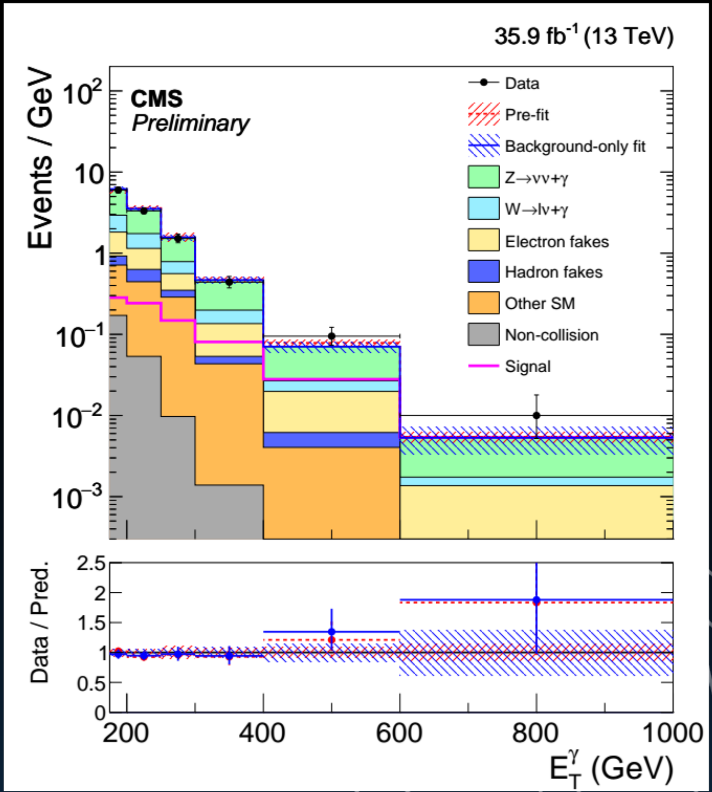
Irreducible	$Z(\nu\nu) + \gamma$	$W(\ell\nu) + \gamma$
Fakes	Electrons	Hadrons
Anomalous	Beam Halo	Spike

To constrain beam halo normalisation, signal region is split into high and low phi regions

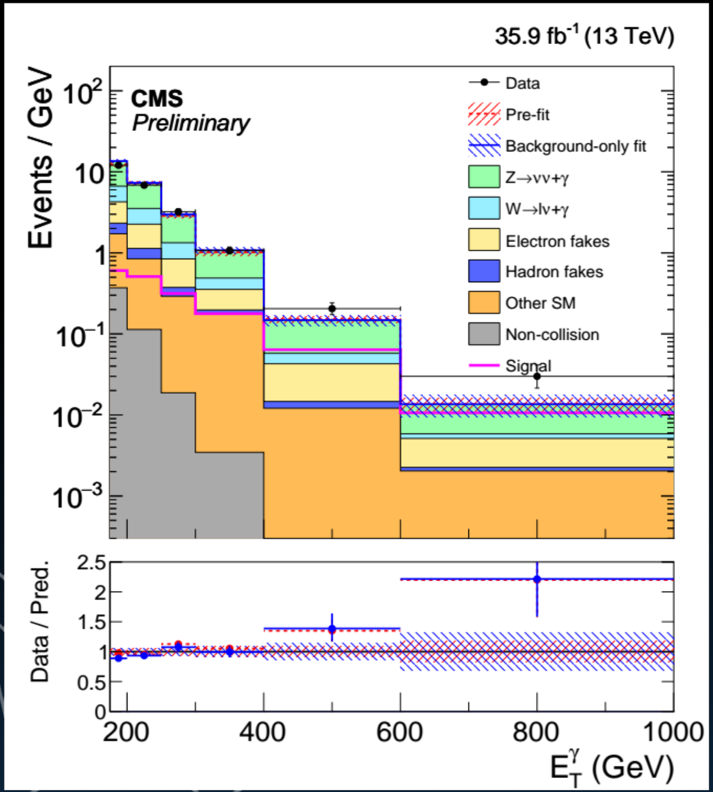
Data driven estimations

Monophoton:Results

Low phi |Φ| < 0.5



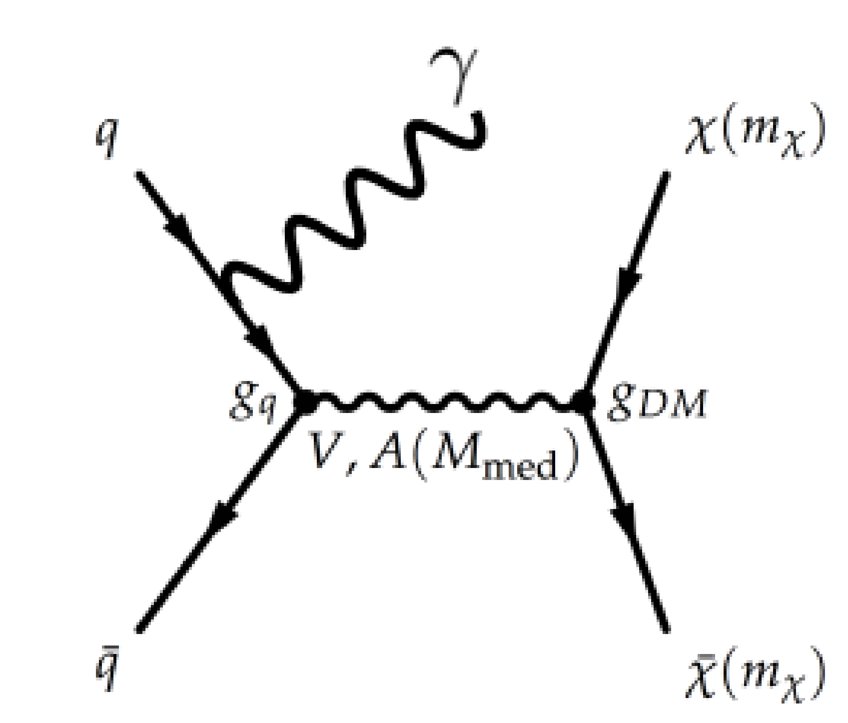
High phi |Φ| > 0.5



- Better resolution and control over uncertainities than ETmiss spectrum.
- No excess observed from expected

Monophoton: DM Interpretation

Spin 1 mediator limits



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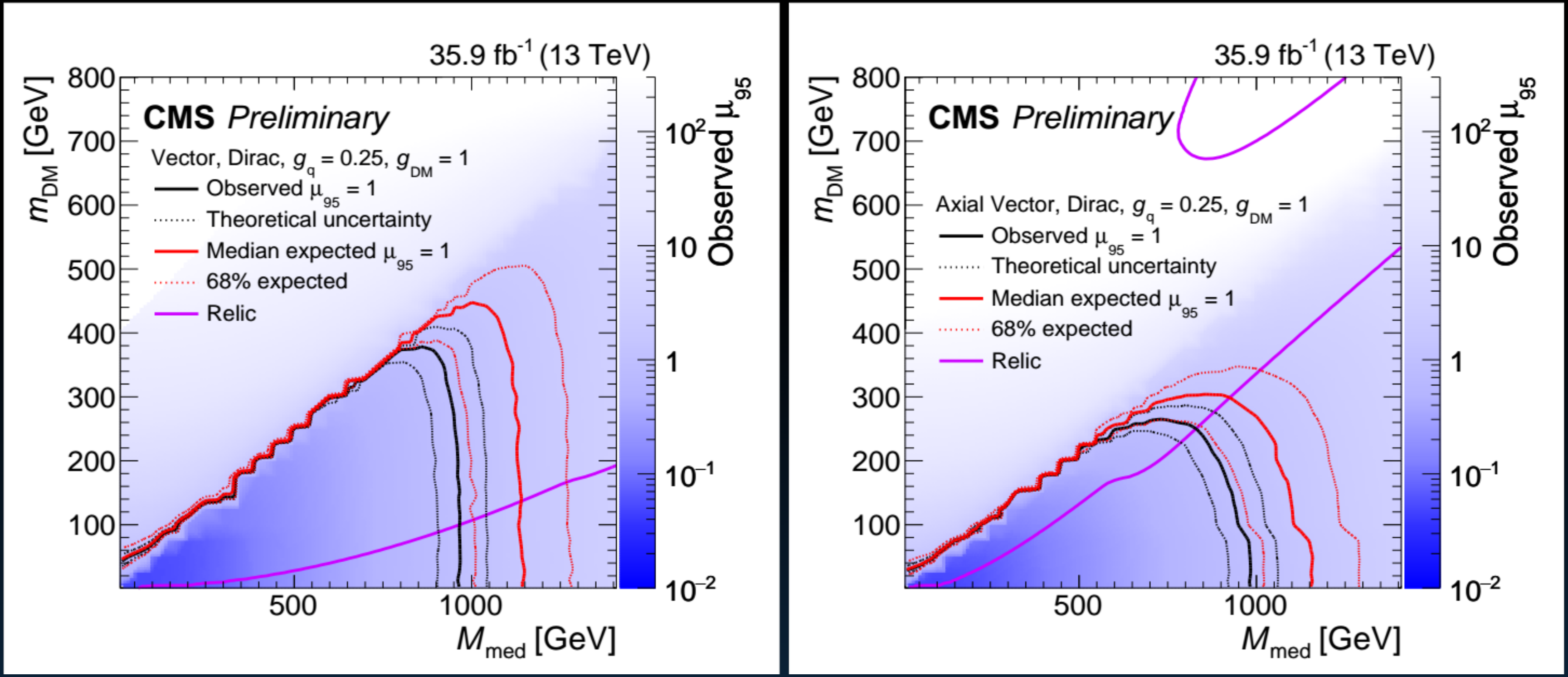
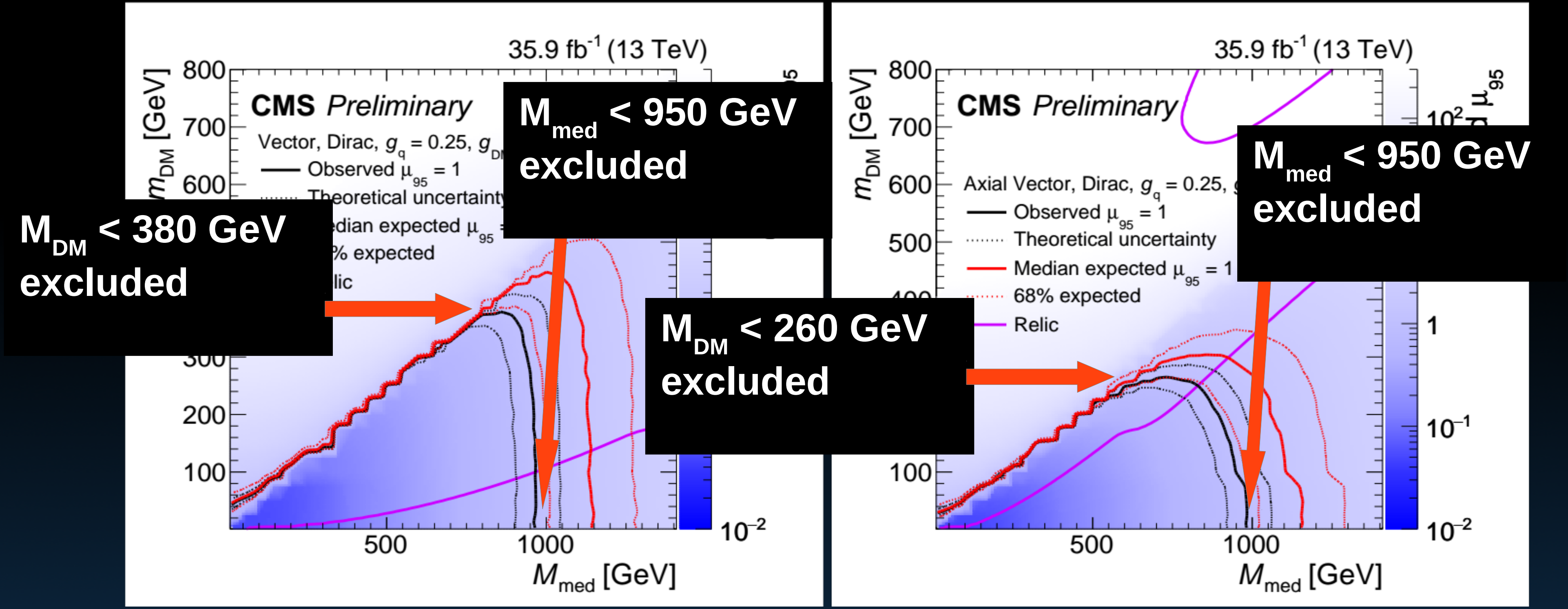


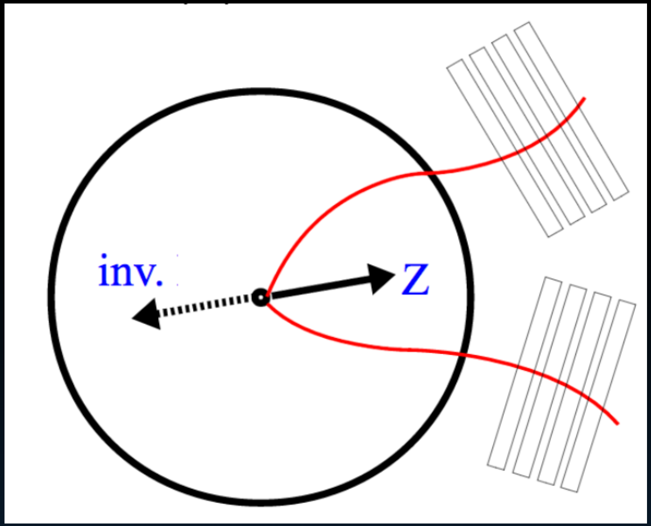
Monophoton: DM Interpretation



Mono – Z(ll): Event Selection

Searching for single Z recoiling against E_T^{miss}

- Dilepton $p_T > 60$ GeV
- Z boson requirement $|m_{ll} - m_Z| < 15$ GeV
- $\Delta\phi(p_T^{ll}, E_T^{miss}) > 2.6$
- $\Delta\phi(p_T^{jet}, E_T^{miss}) > 0.5$
- $\Delta R(ll) < 1.8$
- At most one jet , Veto b-tagged jets
- Veto additional electrons or muons
- Veto hadronically decaying tau



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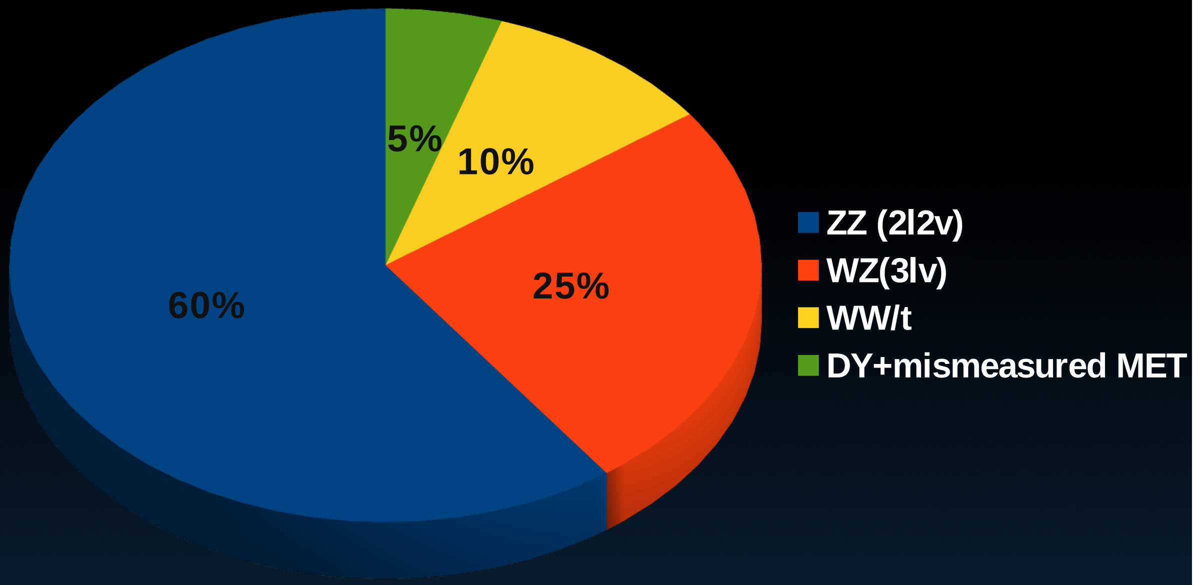
Mono – Z(ll): Main Backgrounds

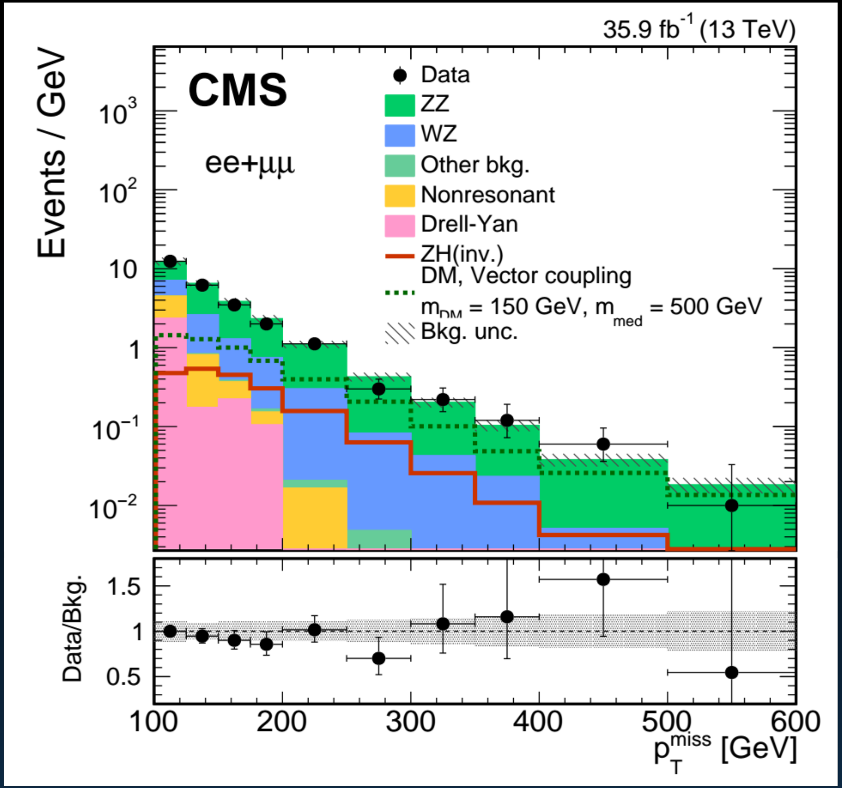
- Main backgrounds are ZZ(2l2v) WZ (3lv) estimated using simultaneous fits to control and signal region like monophoton

- Non resonant and Drell-Yan backgrounds by data driven techniques



Mono – Z(ll): Results

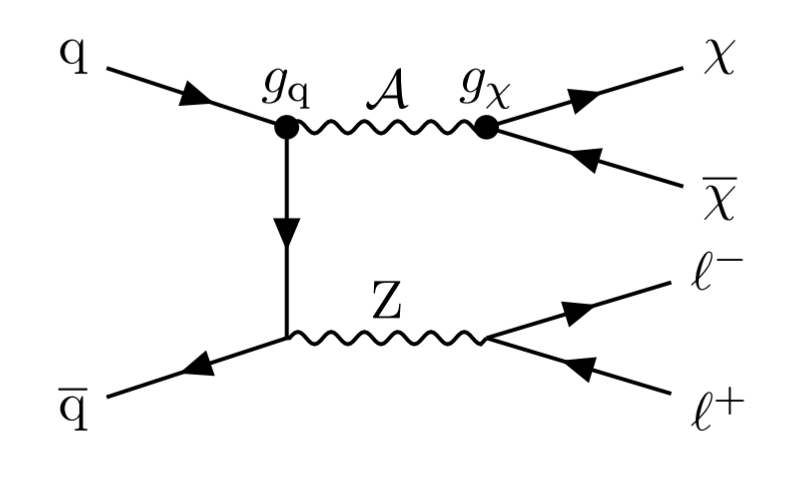
Observed and expected yeilds



- Distribution of p_T^{miss} from ee + μμ combined
- No excess observed from expected

Mono - Z(ll): DM Interpretation

Spin 1 mediator limits



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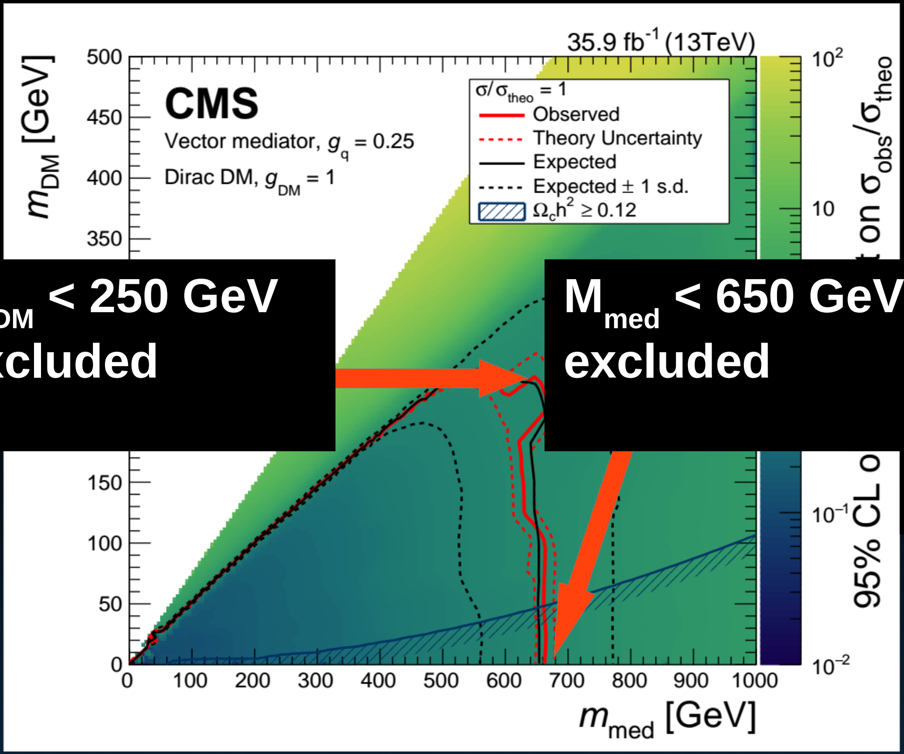
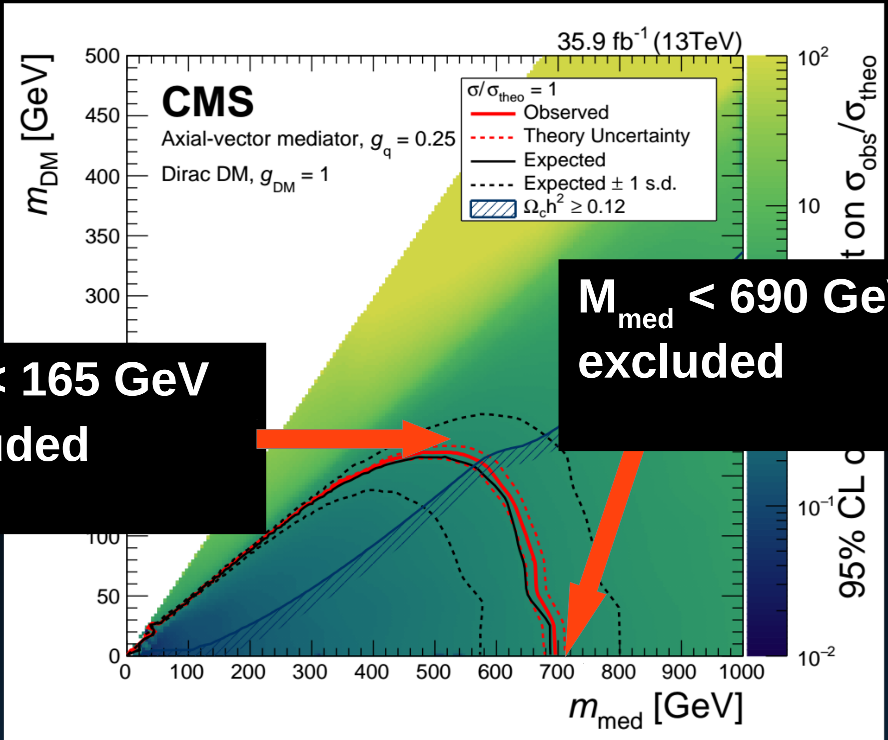


M_{DM} < 250 GeV excluded

M_{med} < 650 GeV excluded



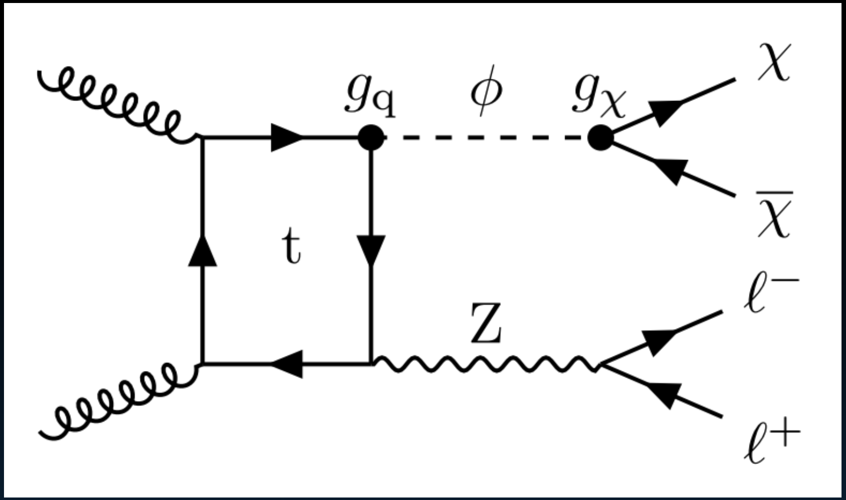
M_{DM} < 165 GeV excluded

M_{med} < 690 GeV excluded

Mono – Z(ll): DM Interpretation

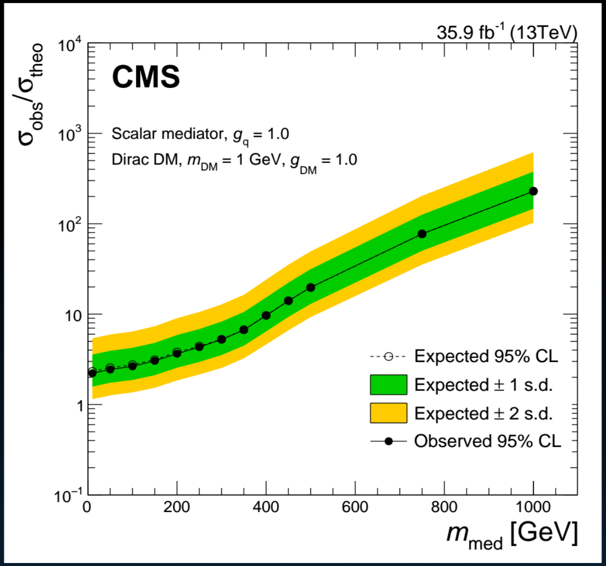
Spin 0 mediator limits

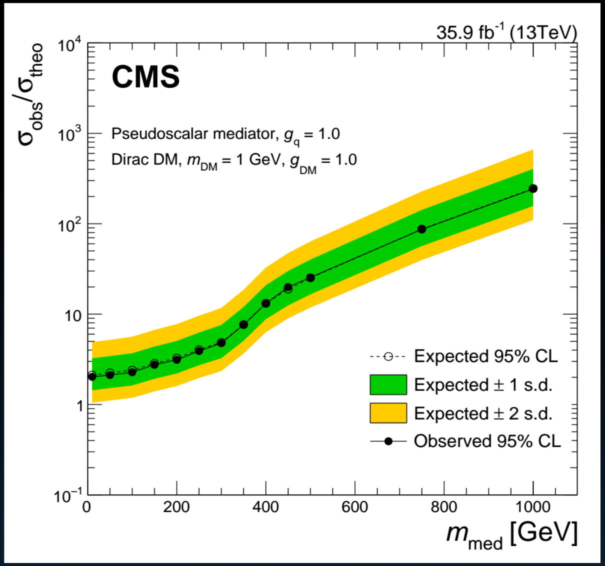
- Spin-0 scalar and pseudoscalar
- Minimal Flavor Violation : mediator and quark interaction have Yukawa structure
- Quark couplings proportional to quark mass



Mono – Z(ll): DM Interpretation

Limits are evaluated for scalar and pseudo-scalar mediators





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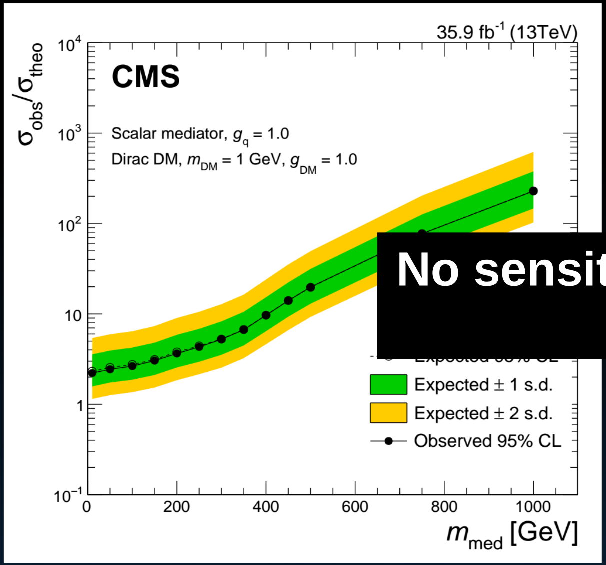
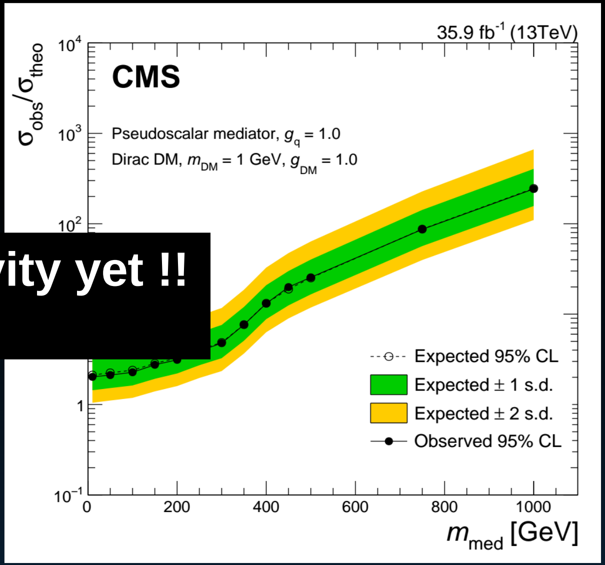
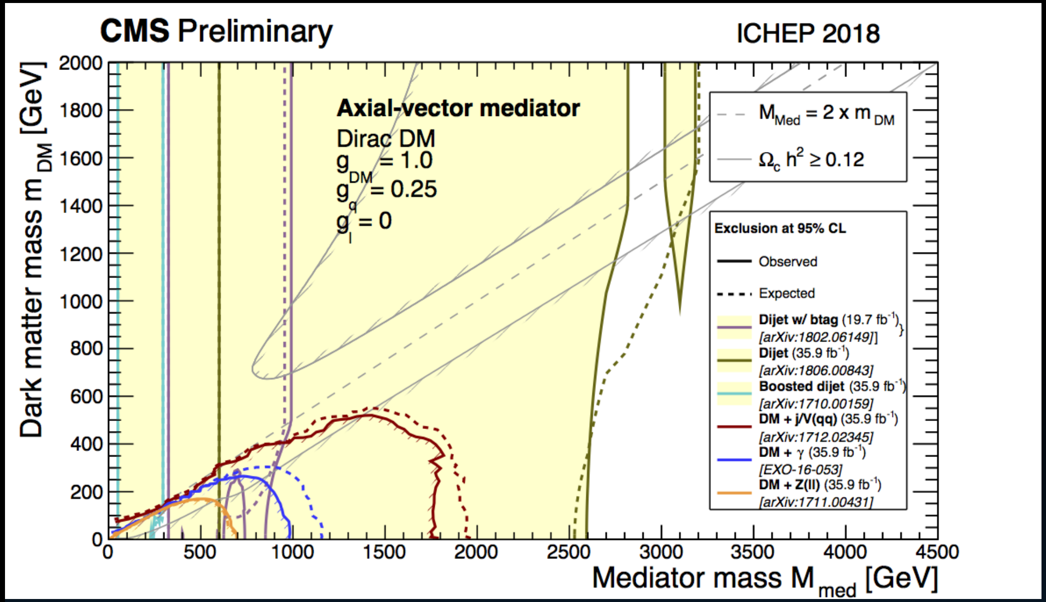
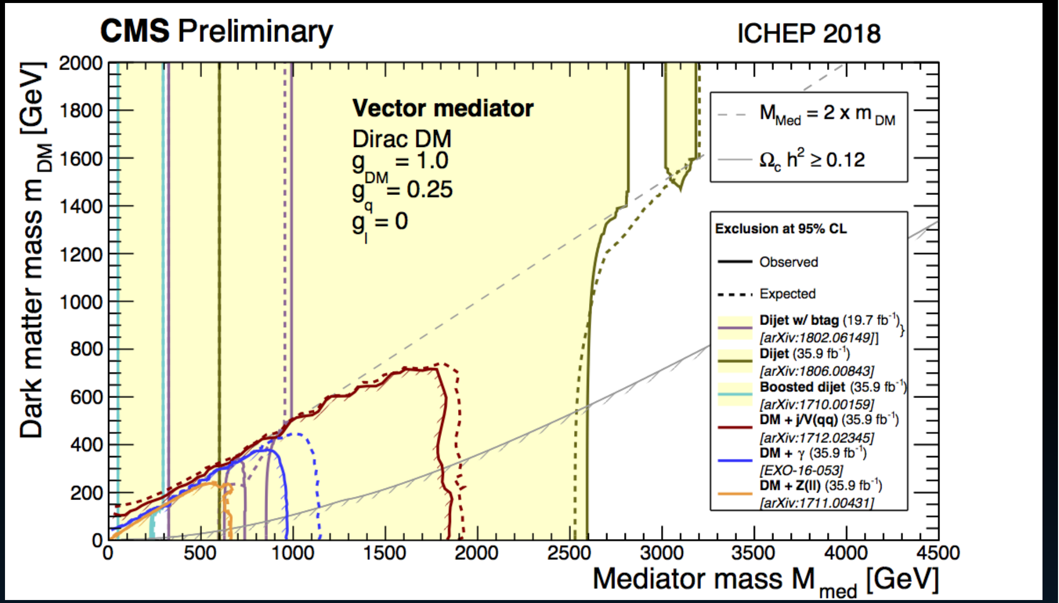




No sensitivity yet !!

Summary : Spin 1 mediators





Mono-X searches sensitive to on-shell region
$M_{med} > 2 \times M_{DM}$

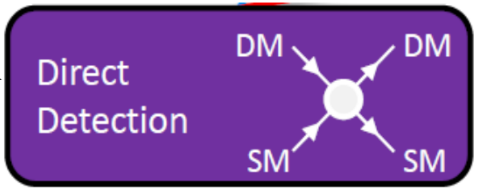
Dijets provide sensitivity to off-shell region
Complementarity to Mono-X searches

Collider to Direct Detection Limits

Limits from collider experiments can be recast to compare with direct detection experiments

$$\sigma_{\mathrm{SI}}^{\mathrm{vector}} \simeq 6.9\times10^{-41}\,\mathrm{cm}^2 \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

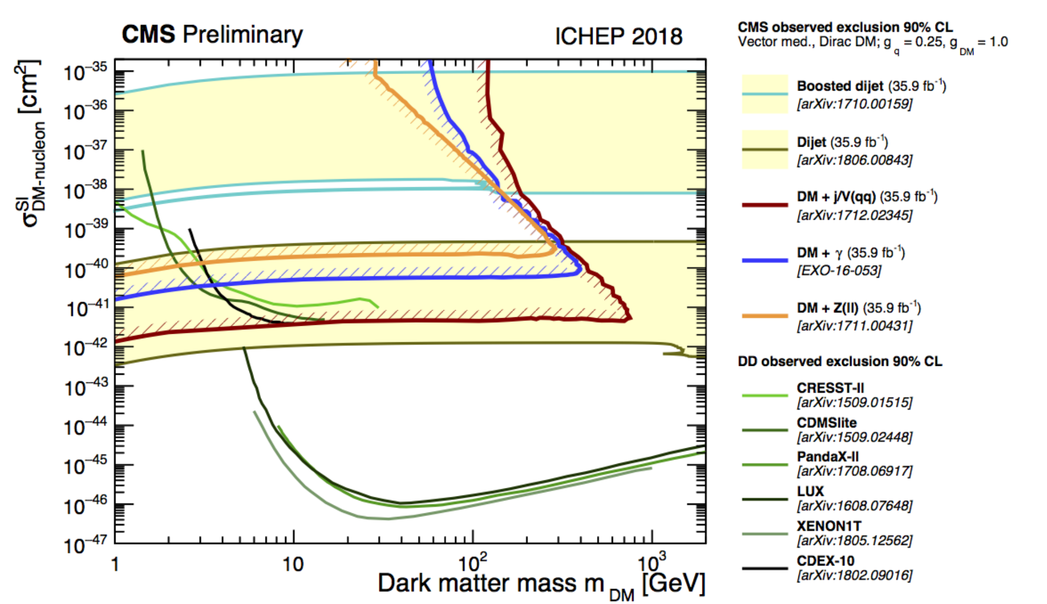
$$\sigma_{\mathrm{SD}}^{\mathrm{axial}} \simeq 2.4\times10^{-42}\,\mathrm{cm}^2 \left(\frac{g_q g_{\mathrm{DM}}}{0.25}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{med}}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ \mathrm{GeV}}\right)^2$$

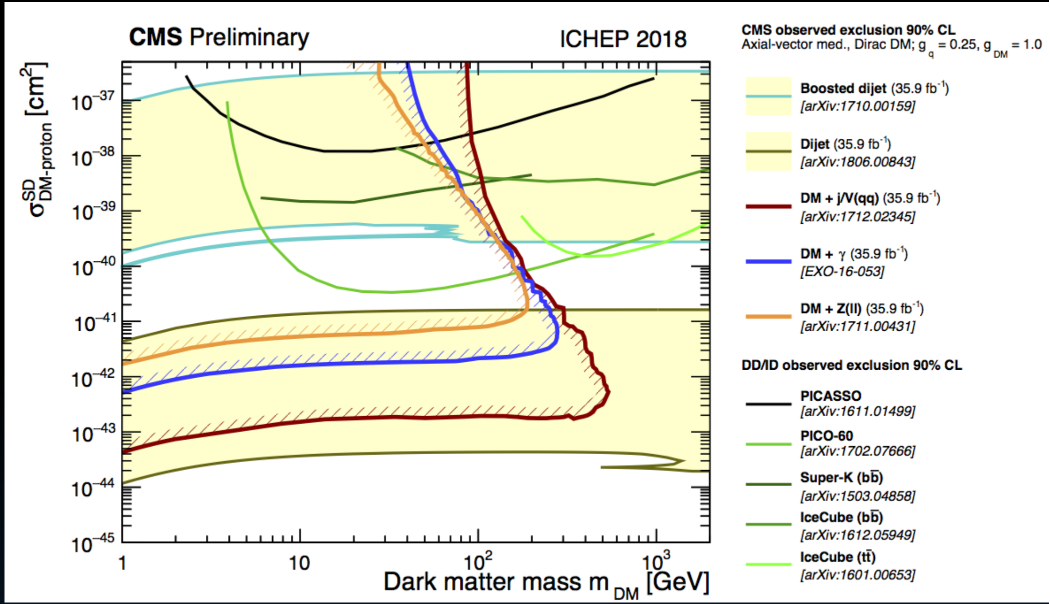


$\mu_{n\chi} = m_n m_{DM}/(m_n + m_{DM})$ is the DM-nucleon reduced mass

ArXiv:1603.04156

Summary : Direct Detection Limits





- Collider results sensitive to low DM masses
- More sensitive than Direct detection experiments for spin dependant mediators

A detour from things non-hadronic

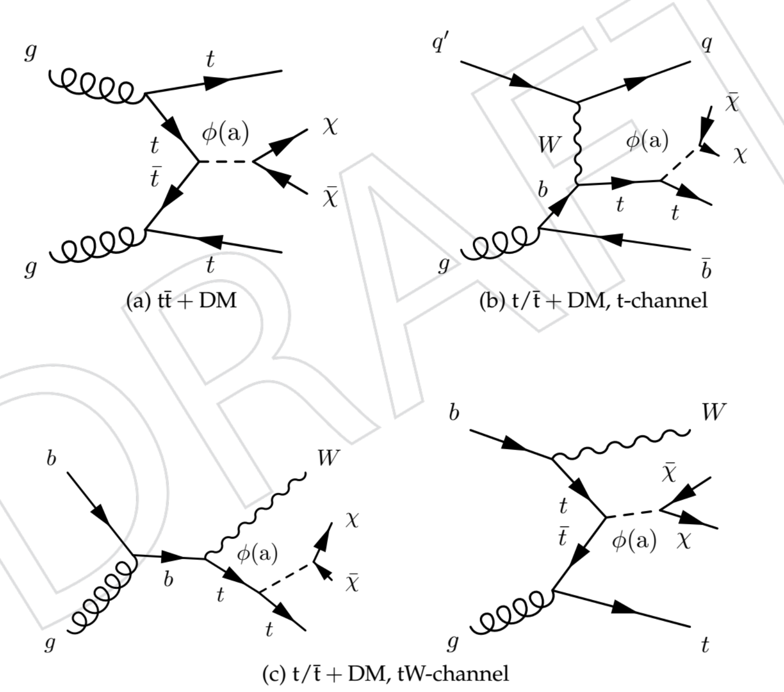
A new and exciting result from CMS !!

Single top/top pair + DM

A new and important analysis at CMS

Spin-0 mediator : coupling proportional to quark mass → preferential coupling to top quark

Top pair + DM processes are investigated together with a single top quark + DM (studied for the first time)



(a) $t\bar{t}+\mathrm{DM}$ (b) $t/\bar{t}+\mathrm{DM}$, t-channel (c) $t/\bar{t}+\mathrm{DM}$, tW-channel

CMS PAS EXO-18-010

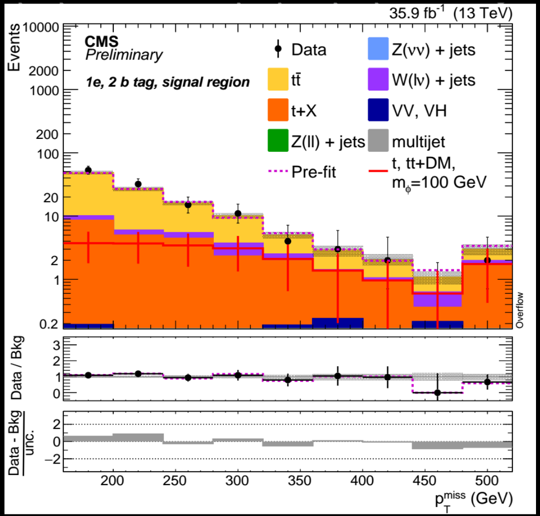
Search focused on t + DM production

Dedicated signal regions (SR) with all hadronic (AH) and single lepton (SL) selection to increase sensitivity further categorized into:

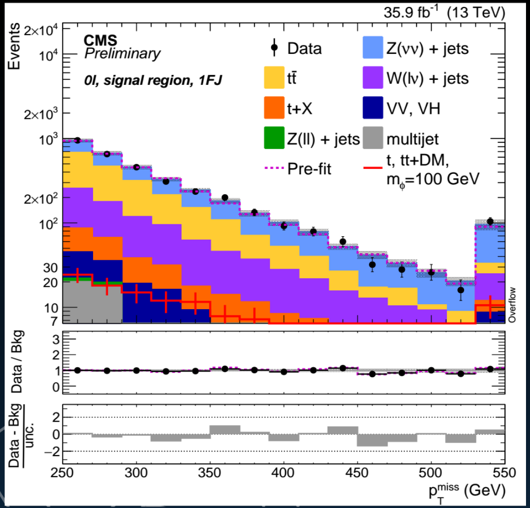
- Orthogonal #b jets (one or ≥ 2 b tagged jets) categories
- Also categorized into number of forward jets

Major SM backgrounds determined in simultaneous fit to data in orthogonal control regions (CR)

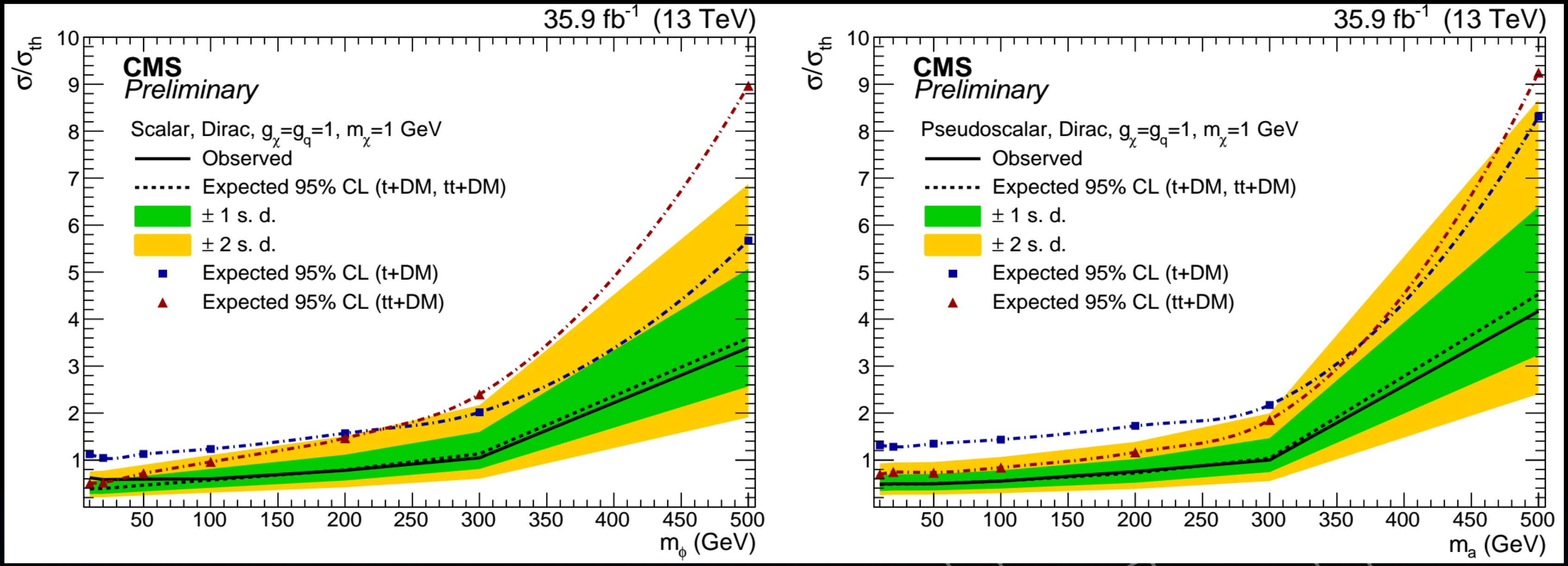
No excess from SM expectations



Single Lepton SR:
1 electron
2 b jets



All Hadronic SR:
0 lepton
1 forward jet



Scalar and pseudoscalar mediator masses below 290 and 300 GeV are excluded
The most stringent limits at the LHC for spin-0 mediator particles.

A factor of two improvement at high mediator masses on the limits when compared to previous results : 'Search for dark matter particles produced in association with a top quark pair at sqrt(s) = 13 TeV', (2018). arXiv:1807.06522
For details check out the linked PAS

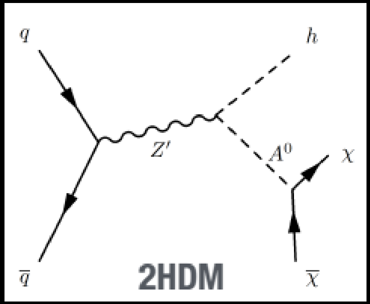
Non -minimal scenario: mono-Higgs (γγ) +DM

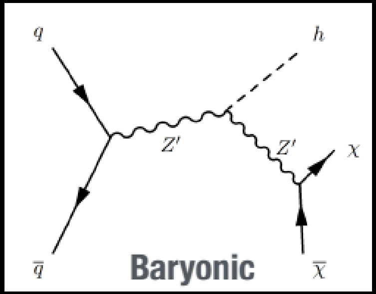
Diphoton mass and MET are the key variables

Split events into low(50-130 GeV) and high (> 130 GeV) p_T^{miss} categories

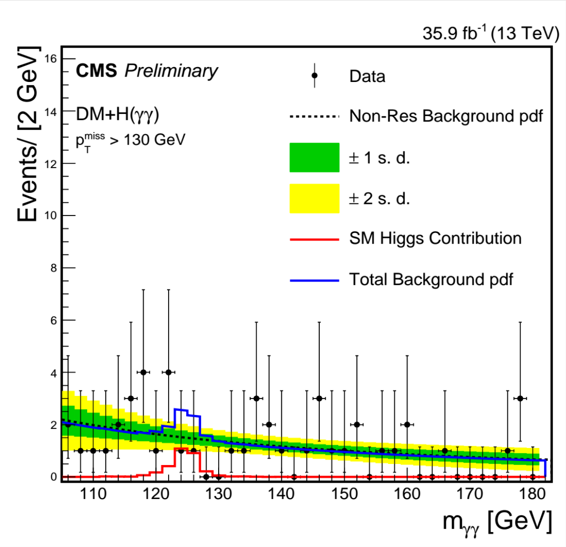
Fit the diphoton $m_{\gamma\gamma}$ distribution of the data in both categories
- Estimate continuum background from an analytic function
- Estimate resonant Higgs contribution to the fit from MC

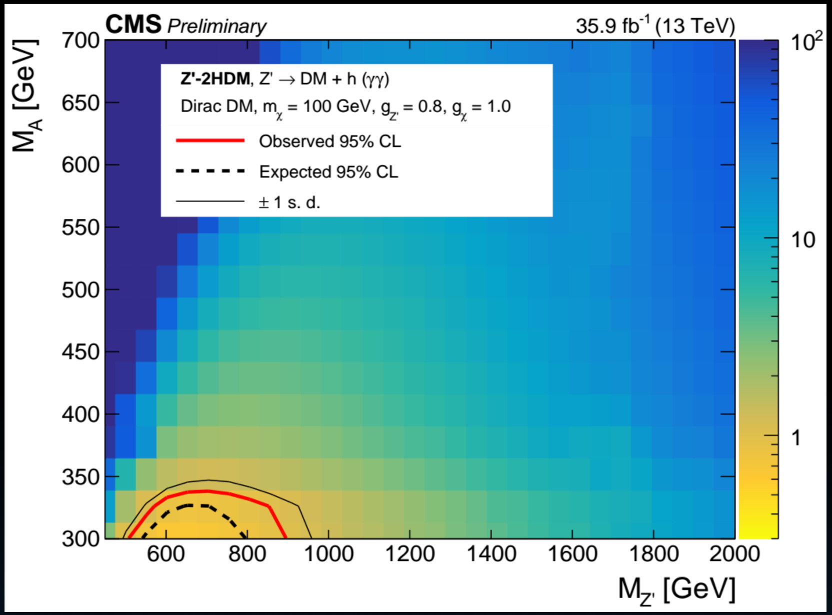
Results interpreted in term of two simplified models:
- Type 2 2HDM model
- Z' baryonic model

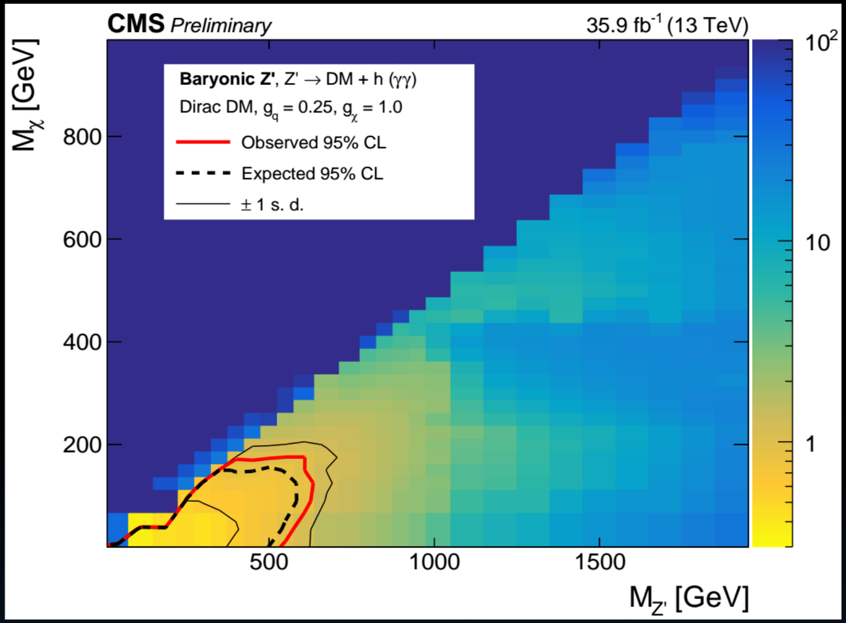




arXiv:1806.04771







Exclude $M_{Z'}$ till ~ 900 GeV and M_A till ~ 330 GeV

Exclude $M_{Z'}$ till ~ 600 GeV and M_{DM} till ~ 150 GeV

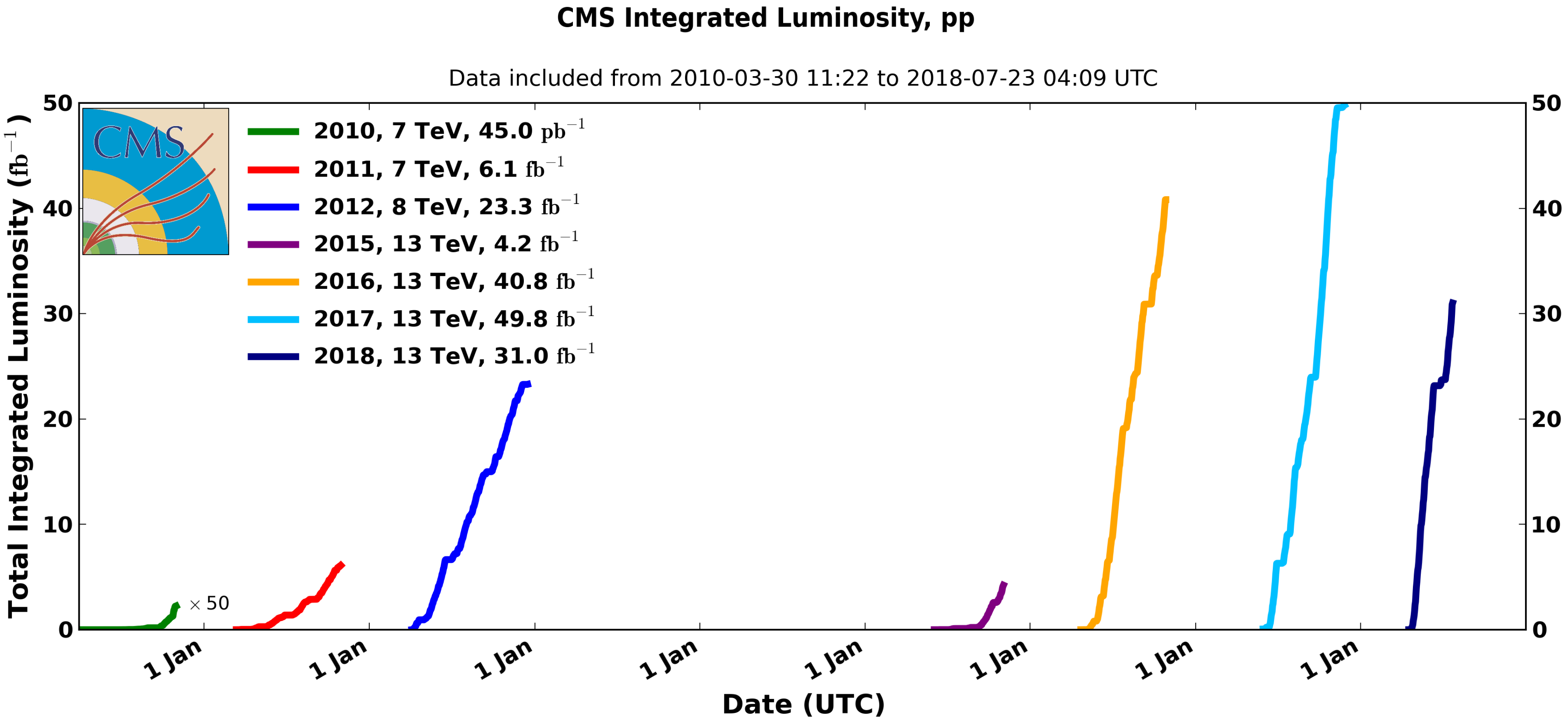
Combination with tau tau channel gives improved limits. For details See **arXiv:1806.04771**

Summary

- Extensive dark matter searches going on at LHC (in CMS)
- No DM observed yet, limits are more stringent
- LHC searches provide complementarity to direct detection searches
- Much more LHC data to be analyzed
- Stay tuned !!

Thanks for your attention!!

BACKUPS


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:22 to 2018-07-23 04:09 UTC
Total Integrated Luminosity (fb^{-1})
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.2 fb^{-1}
2016, 13 TeV, 40.8 fb^{-1}
2017, 13 TeV, 49.8 fb^{-1}
2018, 13 TeV, 31.0 fb^{-1}
× 50
0
10
20
30
40
50
1 Jan
Date (UTC)

monophoton

Signal region yield:
$W\gamma + Z\gamma = (1 + f)\, Z\gamma$

$$\mathcal{L} = \prod_i \Bigg[\prod_{K=\text{horiz.,vert.}} \mathcal{P}\left(d_{K,i} \,\Big|\, \left(1 + f^{W\gamma}_{Z\gamma,i}(\theta)\right) C_K N_i^{Z\gamma} + h n^{\text{halo}}_{K,i}(\theta) + b_{K,i}(\theta) \right)$$

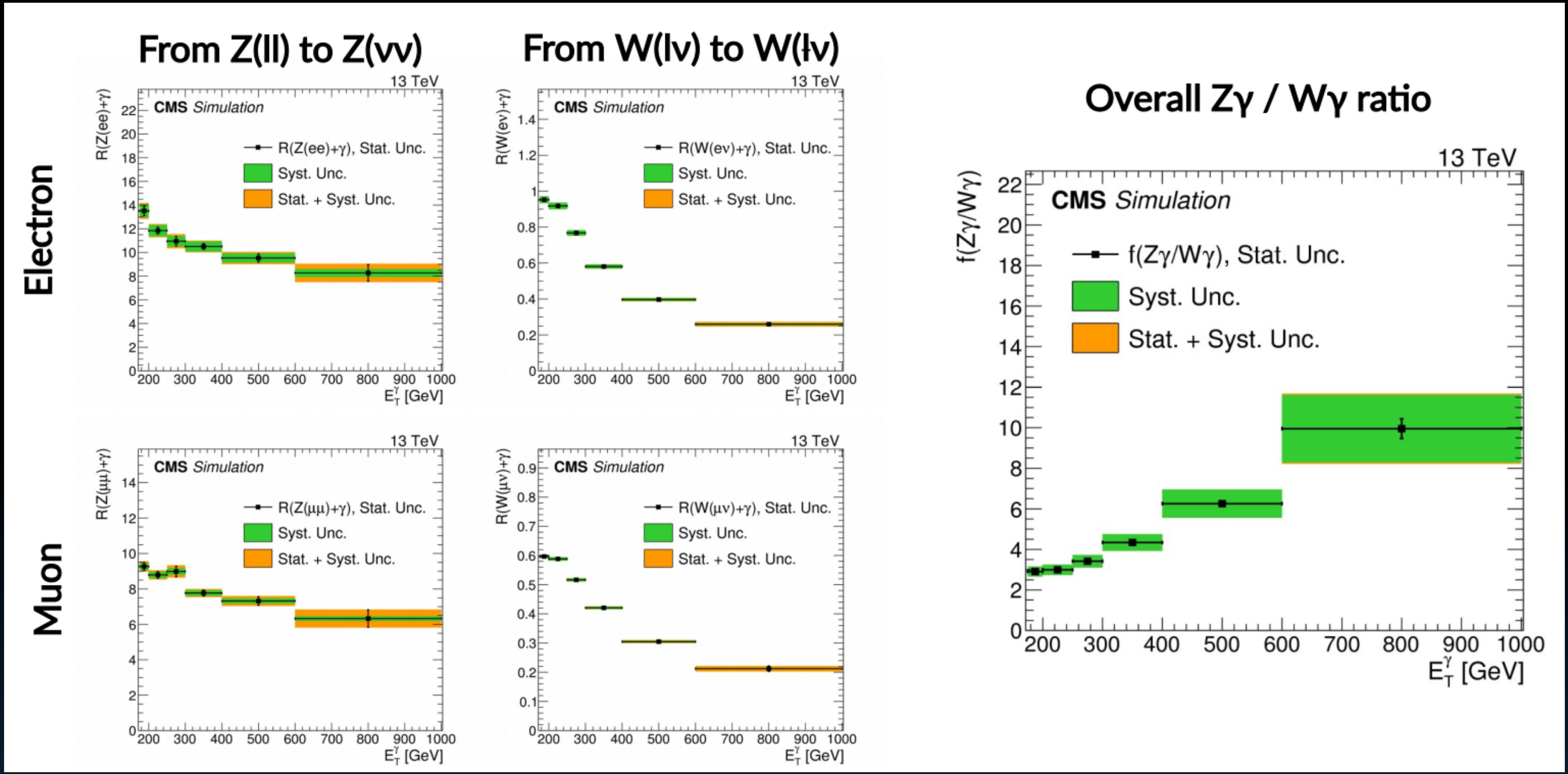
$$\cdot \prod_{K=e\gamma,\mu\gamma} \mathcal{P}\left(d_{K,i} \,\Big|\, R^{W\gamma}_{K,i}(\theta)\, f^{W\gamma}_{Z\gamma,i}(\theta) N_i^{Z\gamma} + b_{K,i}(\theta) \right)$$

$$\cdot \prod_{K=ee\gamma,\mu\mu\gamma} \mathcal{P}\left(d_{K,i} \,\Big|\, R^{Z\gamma}_{K,i}(\theta) N_i^{Z\gamma} + b_{K,i}(\theta) \right) \Bigg]$$

$$\cdot \prod_j \mathcal{N}(\theta_j),$$

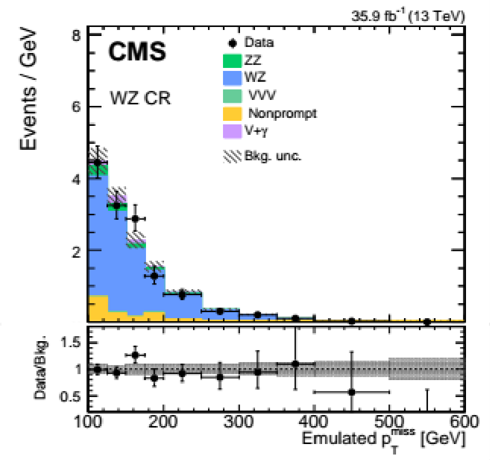
Transfer factors from control to signal regions

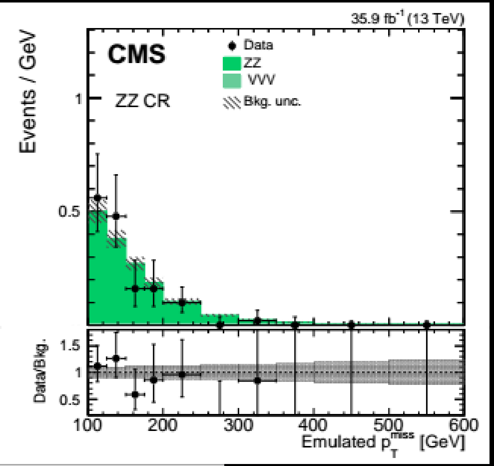
Likelihood : From A.Albert ICHEP2018

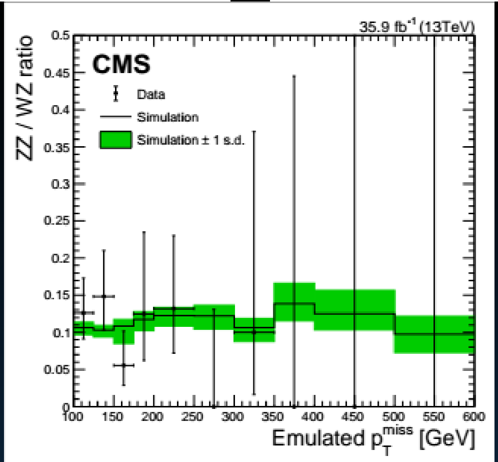


Ratios : A.Albert ICHEP2018

Mono-Z


CMS
35.9 fb^-1 (13 TeV)
WZ CR
Data
ZZ
WZ
VVV
Nonprompt
V+γ
Bkg. unc.
Events / GeV
Data/Bkg.
Emulated p_T^miss [GeV]


CMS
35.9 fb^-1 (13 TeV)
ZZ CR
Data
ZZ
VVV
Bkg. unc.
Events / GeV
Data/Bkg.
Emulated p_T^miss [GeV]


CMS
35.9 fb^-1 (13TeV)
Data
Simulation
Simulation ± 1 s.d.
ZZ / WZ ratio
Emulated p_T^miss [GeV]

Single t/tt +DM