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Non-Hadronic Searches for Dark Matter at CMS

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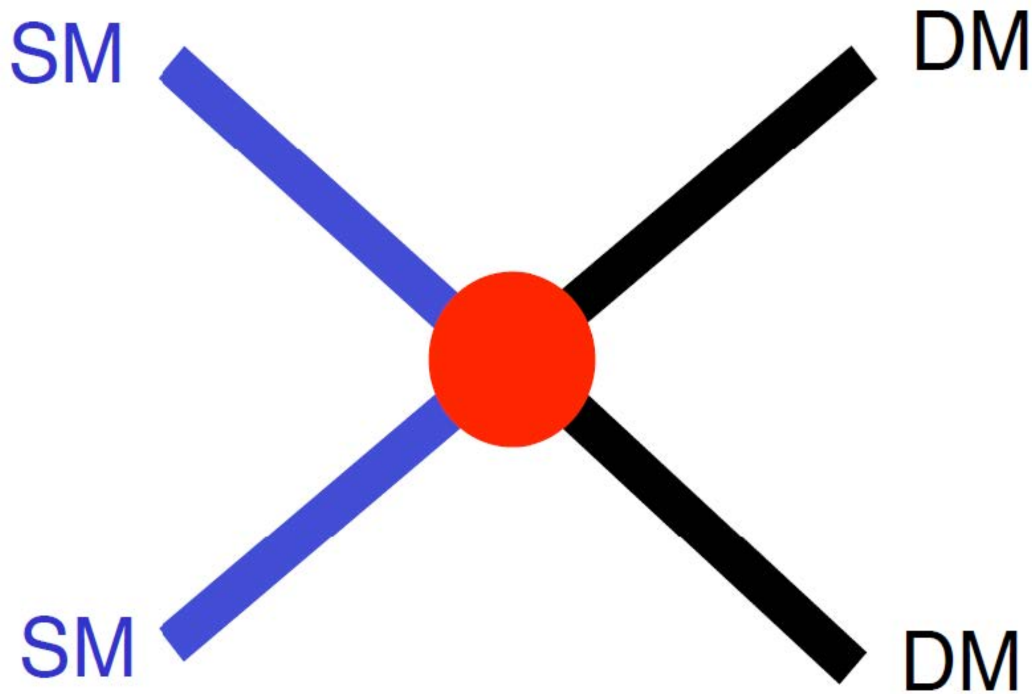
Outline

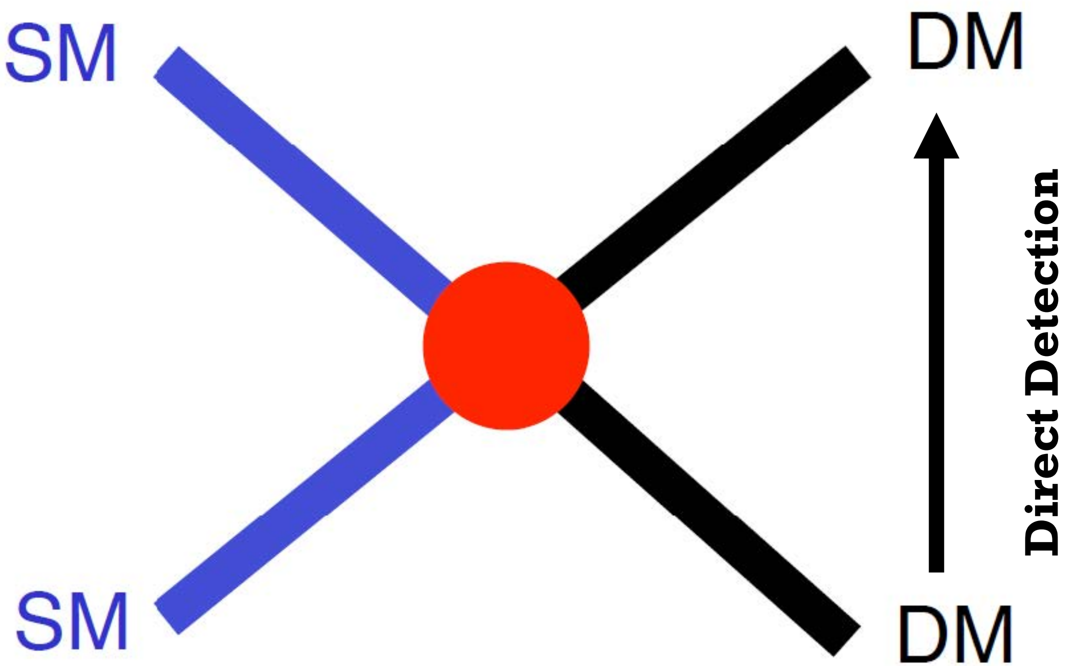
- Signatures of Dark Matter at the CMS
- Detection in CMS
- Different Channels
  - Monophoton : 2015 (2.3 fb^{-1})
  - Mono-boson (W) : 2012 (19.7 fb^{-1})
  - Mono-boson (Z) : 2012 (19.7 fb^{-1})
    - ZH : 2015 (2.3 fb^{-1})

Detection Techniques

- Three major categories of investigations.
- Important to maintain the theoretical connection between these approaches



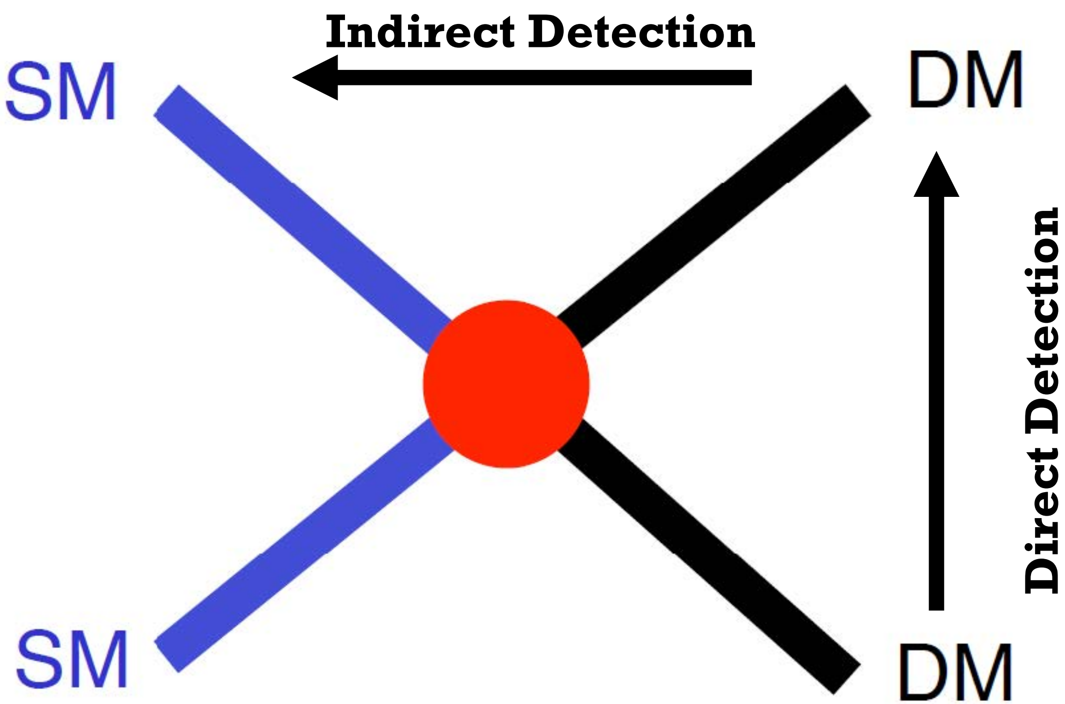
Detection Techniques



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

Detection Techniques

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



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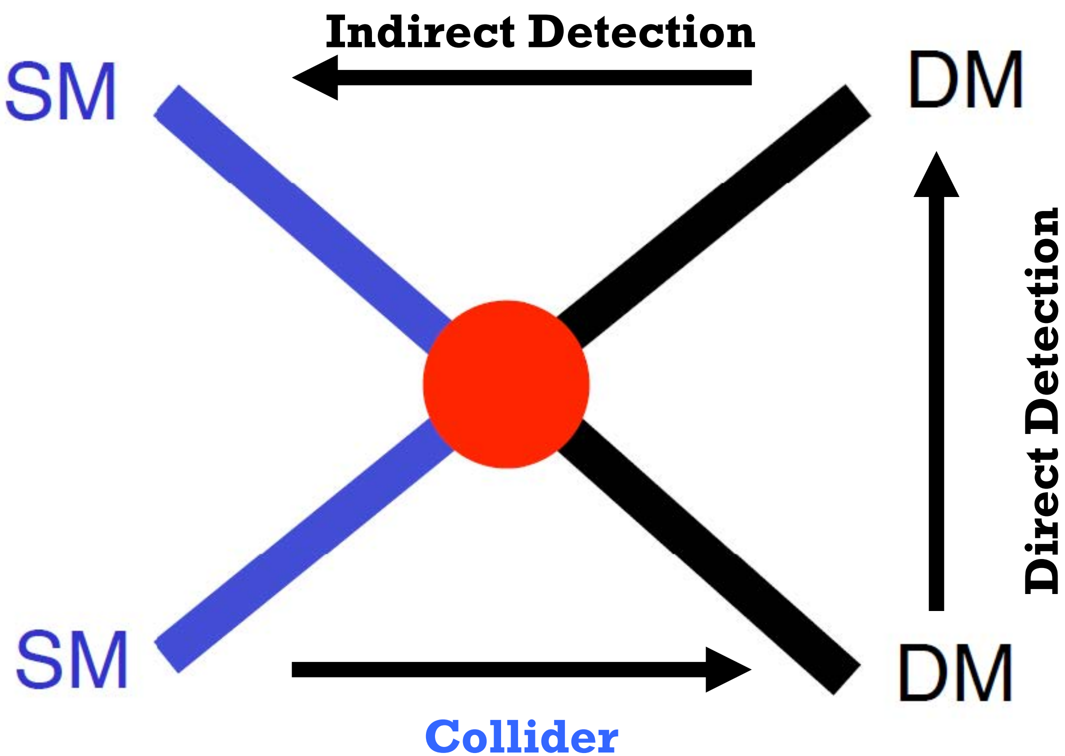


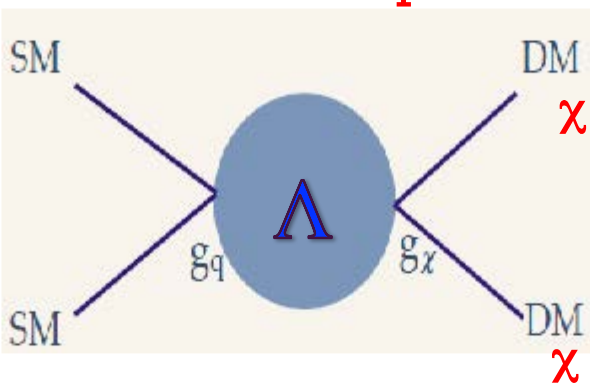
Scattering of DM particles on nuclei of detector material ; detect recoil. For a given cross section sensitivity scales with detector size.

DM may be pair produced in pp collisions at the LHC, with masses <1/2 parton-parton c.o.m. Yields experimental signature of MET

Dark Matter at the LHC (Run-1)

pp collisions

Pair of DM particles



Scale of Interaction Λ

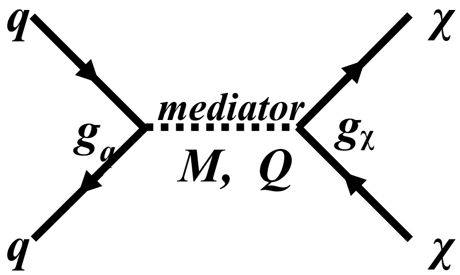
New physics expressed with a contact interaction between DM and SM particles.

Use effective field theory (EFT) to describe interactions in a model independent way.

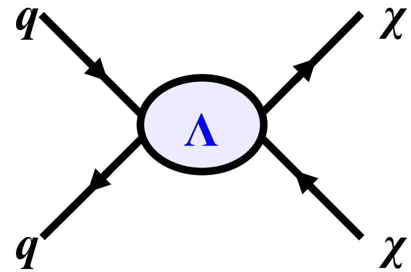
➡ **Signature oriented search**

EFT and Simplified Models

- EFT depend only on **two parameters**:
  - DM mass m_χ and interaction scale $\Lambda \approx M / \sqrt{g_\chi g_q}$



Simplified Model, Run2



EFT, Run1

- EFT are reliable only if $M^2 \gg \langle Q^2 \rangle$ — *not always true at LHC energies!*
  - **Truncation**: remove signal events where $Q^2 > M^2 \sim g_\chi g_q \Lambda^2$

spin independent: D1

spin dependent: D5, D8, D9

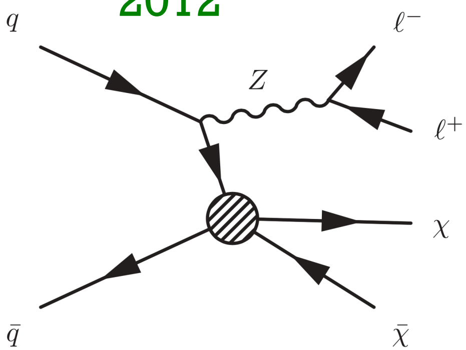
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$

χ *is a Dirac fermion*

How to make DM visible at the LHC?

Mono-X Signatures – simple and striking

2012

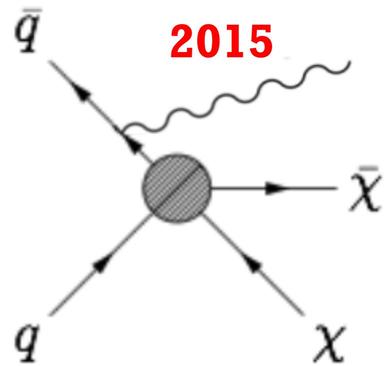


MonoZ+MET

CMS-PAS-EXO-12-060

Full 2012 dataset 20/fb

2015

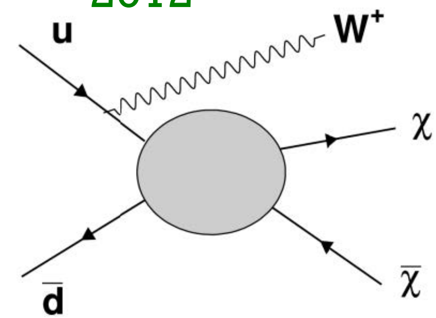


Monophoton+ MET

CMS-PAS-EXO-15-014

Full 2015 dataset 2.3/fb

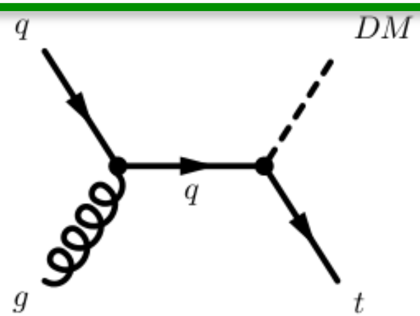
2012

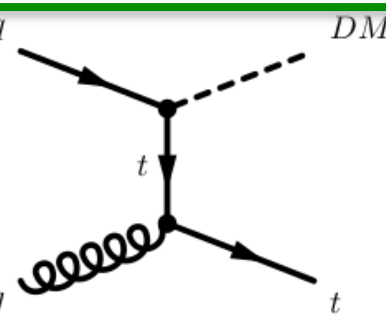


MonoW+ MET

CMS-PAS-EXO-13-004

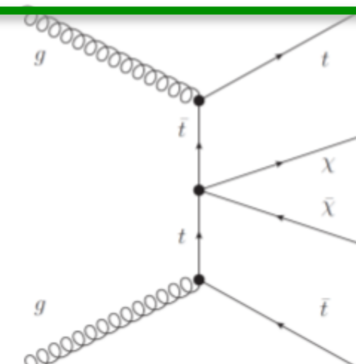
Full 2012 dataset 20/fb





Monotop+MET

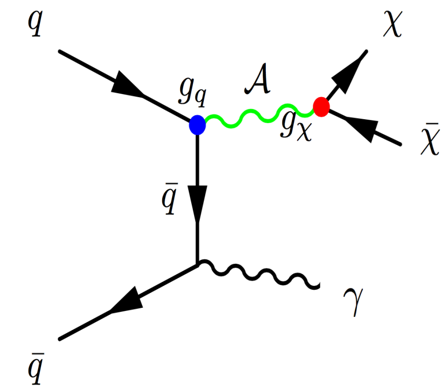
See talk of
Douglas Ryan Berry

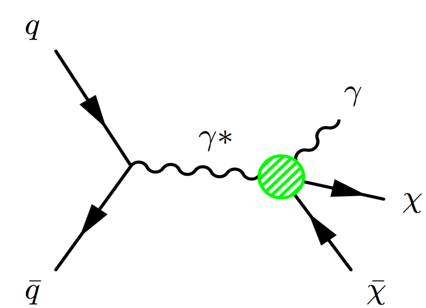


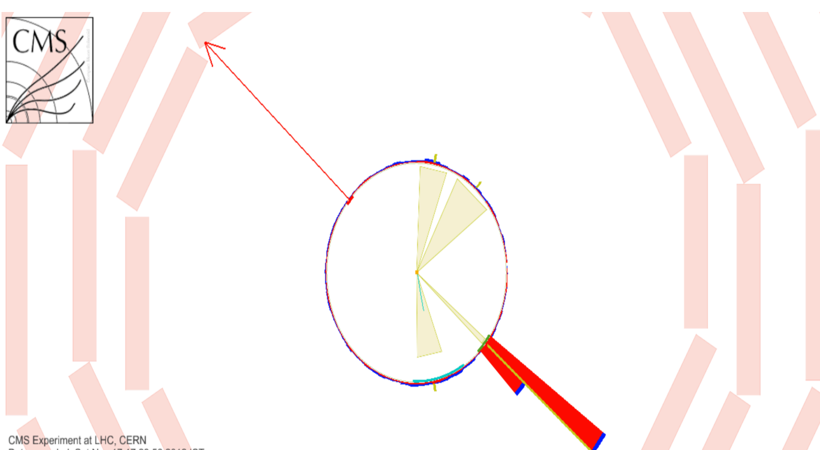
Bbbar/TTBar

Search for Pair Produced Dark Matter in **Mono-photon** Channel

- Characterized by a high-energy photon and large E_T^{miss}
  - Photon from initial-state EM radiation
    - **8 TeV:** EFT with contact interaction, $qq\chi\chi$
    - **13 TeV:** Simplified model with intermediate boson in s-channel, $qq \rightarrow \mathrm{V} \rightarrow \chi\chi$
  - Electroweak model with direct photon-DM interaction
    - **13 TeV only:** EFT with dimension-7 operator, $\gamma\gamma\chi\chi$







Photon + E_T^{miss} event at 8 TeV

Phys. Lett. B 755 (2016) 102

CMS-PAS-EXO-16-014

New 2015 results

Mono-photon : Event Selection

Search for single photon recoiling against MET

- One energetic photon p_T >175 GeV, $|\eta|$< 1.44
- Missing Transverse Energy : MET > 170 GeV
- Azimuthal separation between photon and MET $\Delta\Phi$ (photon, MET) > 2
- Reject backgrounds
  - Backgrounds with leptons $(W \to \ell\nu, Z \to \ell\ell)$
    - Lepton veto: reject e or μ with $p_T > 10$ GeV
  - Noncollision backgrounds (electronic noise, beam-halo & cosmic-ray muons):
    - Timing: EM showers within ± 3 ns of the time expected for collision product
  - Backgrounds with jets (γ+jets)
    - Azimuthal separation between closest jet and MET $\Delta\Phi$ (jet, MET) > 0.5

Mono-Photon : Main Backgrounds

Same Final Sta

$Z\gamma \to \nu\nu\gamma$, $W\gamma \to (\ell)\nu\gamma$ (ℓ not reconstructed) ~ 80% of total background

- estimated from **simulations** with **NNLO QCD** & **NLO EW** corrections
- validated using **data control samples**: $Z\gamma \to \ell^+\ell^-\gamma$, $W\gamma \to \ell\nu\gamma$

Fake photons

$W \to e\nu$ with e misidentified as a **photon**

- measured in $W \to e\nu$ data, with data-driven $e \to \gamma$ **mis-ID rate**

QCD multijet events with a **jet** misidentified as a **photon**

- measured in **jet-enriched** data, with data-driven **jet** $\to \gamma$ **mis-ID rate**

Noncollision

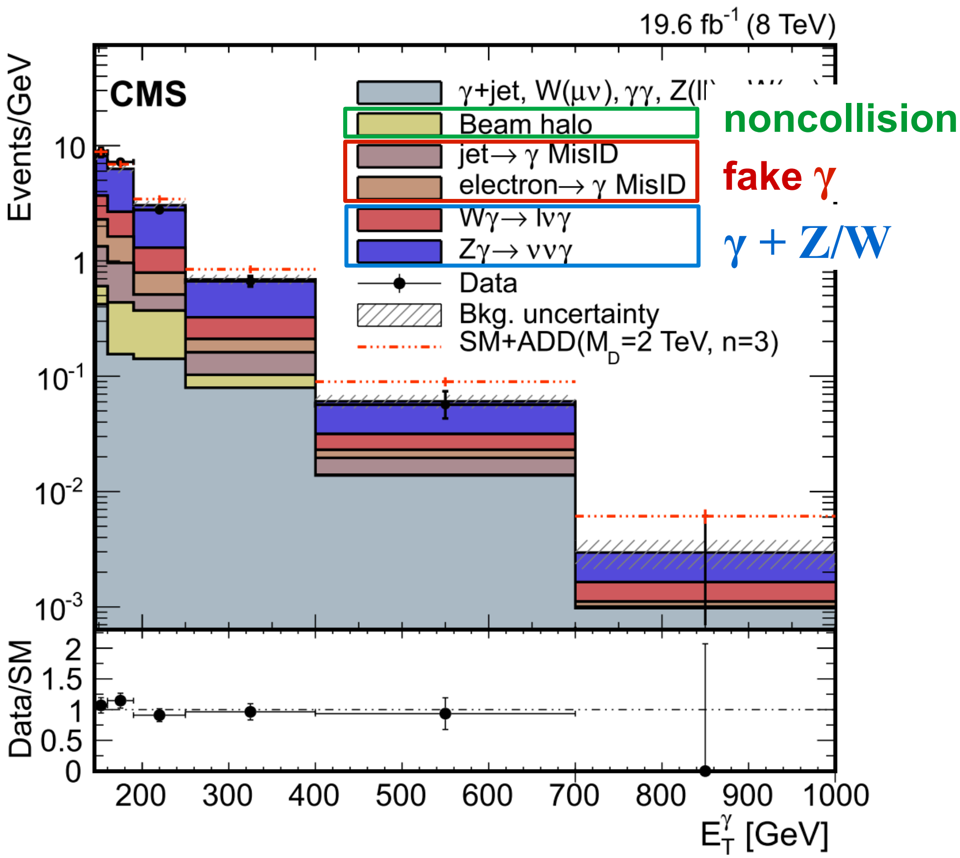
Noncollision background (mostly **beam halo**)

Measured in data from a **template fit** to calorimeter **timing profiles**

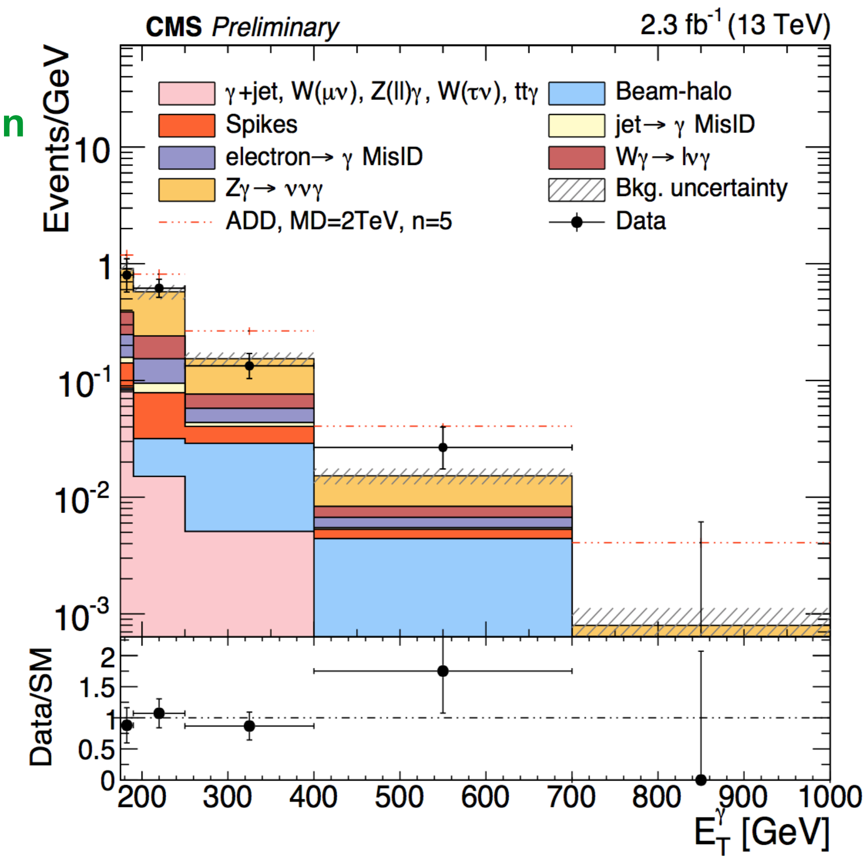
Mono-photon

Results: Photon E_T Spectra

$\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1}



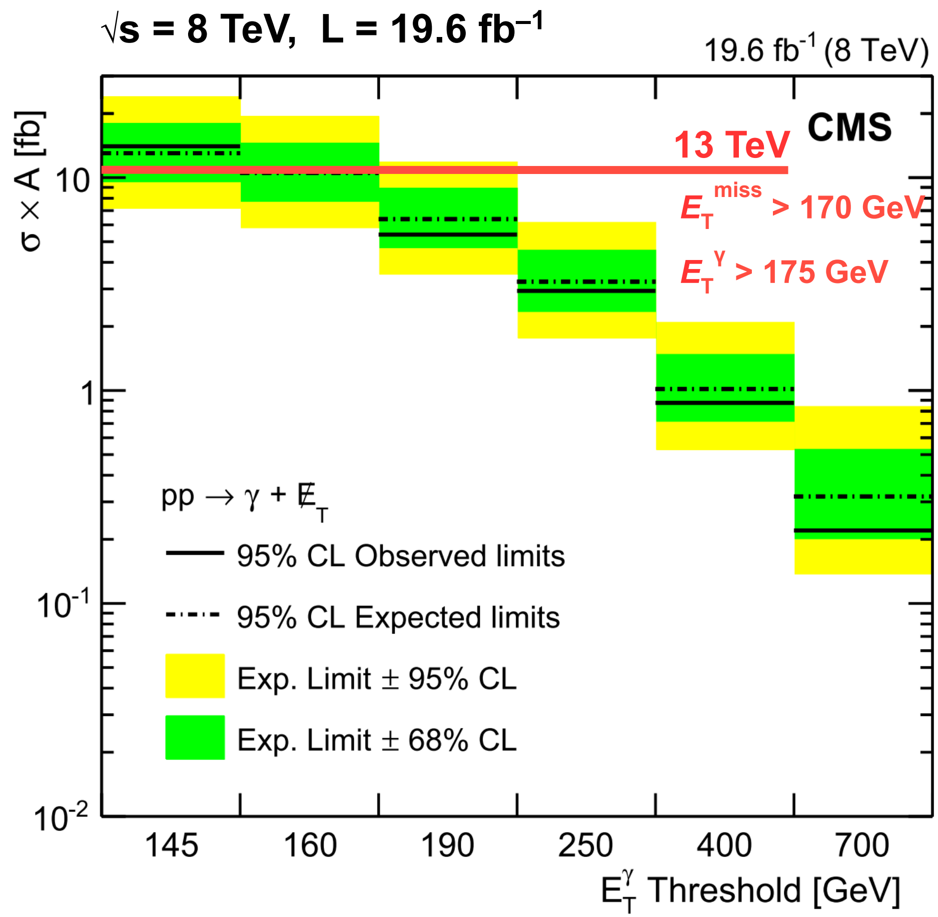
$\sqrt{s}$ = 13 TeV, L = 2.3 fb^{-1}



Mono-photon

Results: Limits on Visible Cross Section

- Using the CL_S construct and a profile-likelihood test statistic, 95% CL limits are set on the cross section × acceptance at 8 TeV, in a region defined by $E_T^{miss} > 140$ GeV and different photon E_T^{γ} minimum cuts



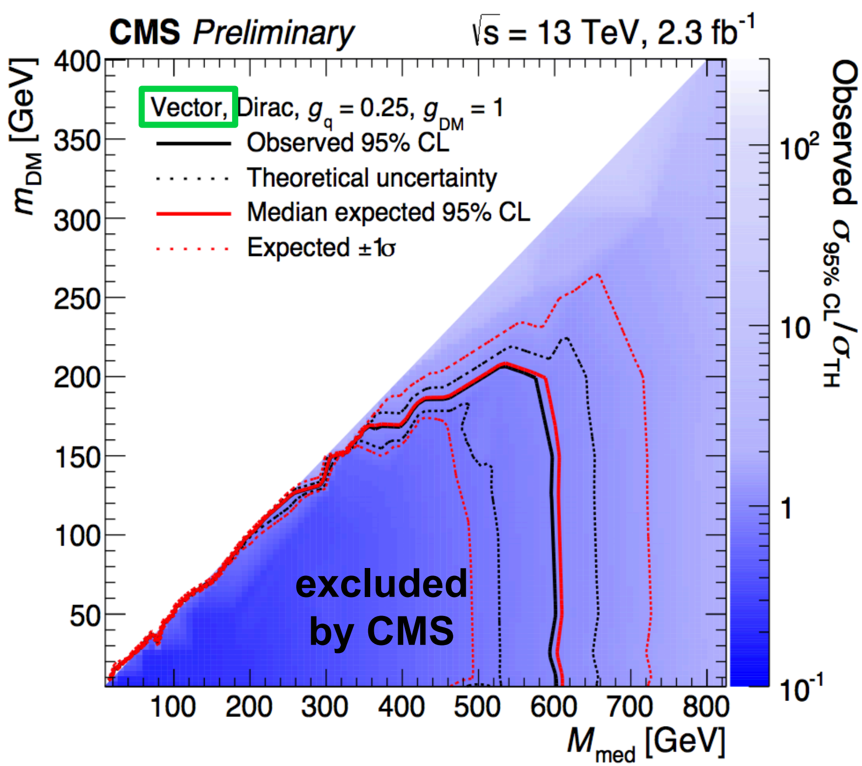
- For comparison, the limit on the 13 TeV cross section is shown for $E_T^{miss} > 170$ GeV, $E_T^{\gamma} > 175$ GeV:

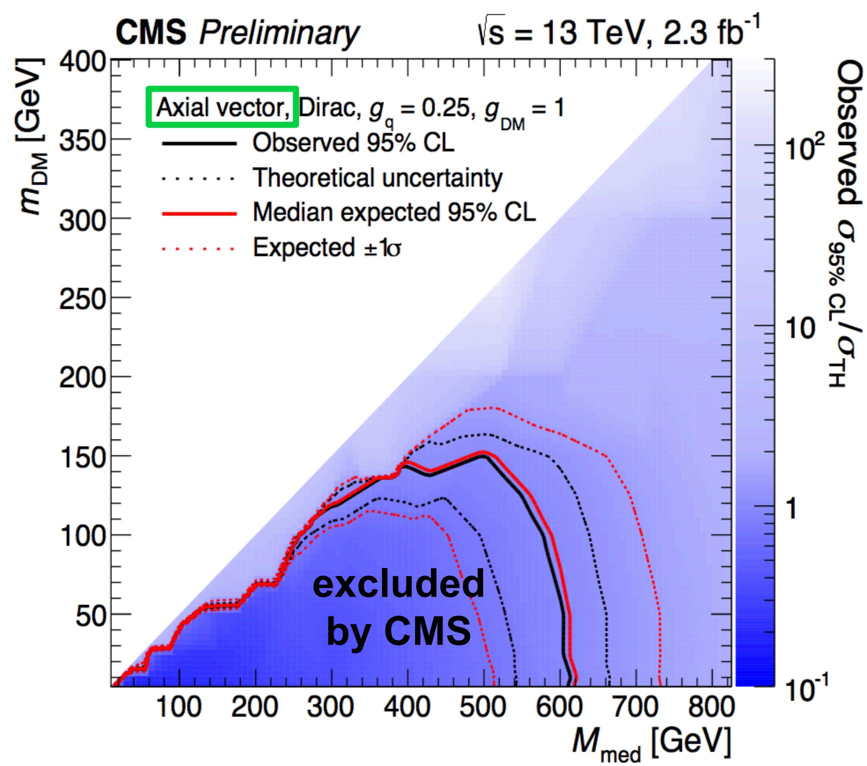
  $\sigma_{13\,TeV} \times A < 10.7$ fb

Mono-photon

Interpretation: Vector and Axial-Vector Mediators

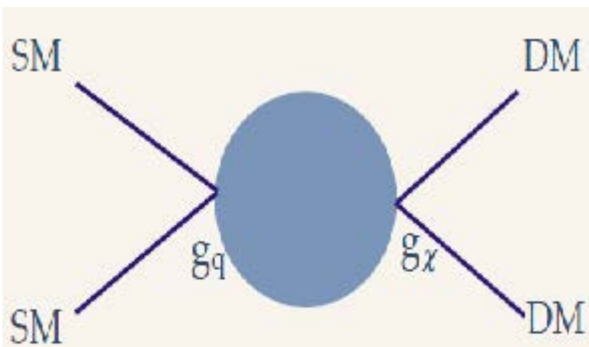
- Comparing the cross section limits with models of DM production via vector
  and axial-vector mediators, constraints on such models are set in the DM mass-mediator mass plane, m_{DM} - M_{med}
  - 13 TeV data, 2.3 fb^{-1}: counting experiment approach, simplified

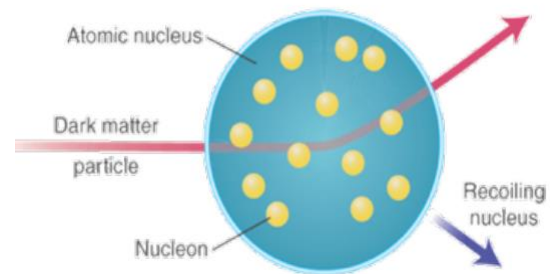




Translate production cross-section limit into DM-nucleon limit

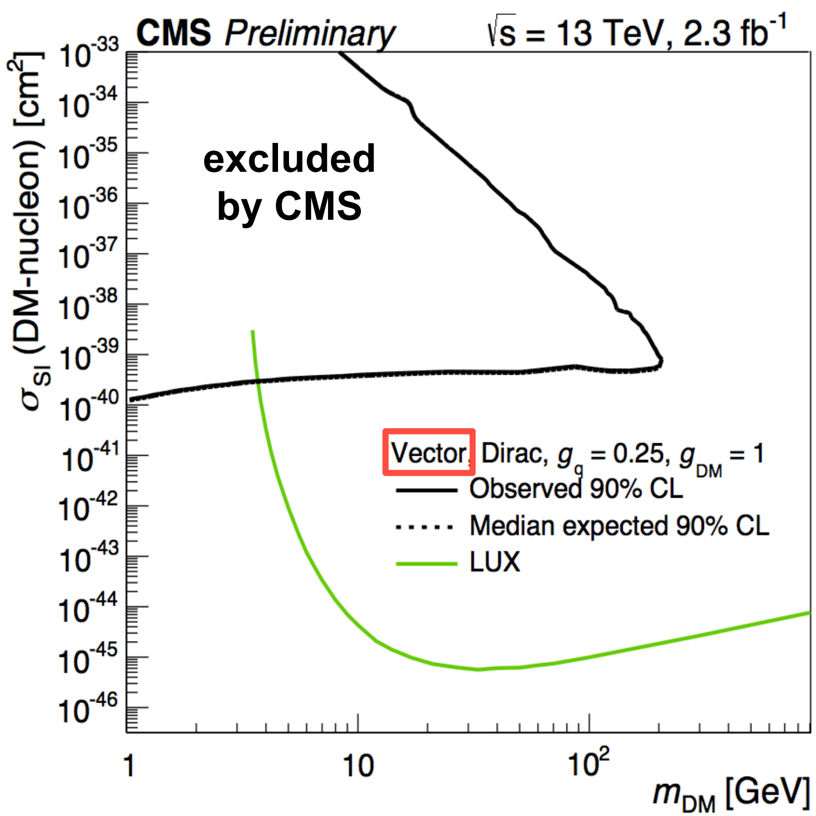
- Purpose : to compare to direct detection limits

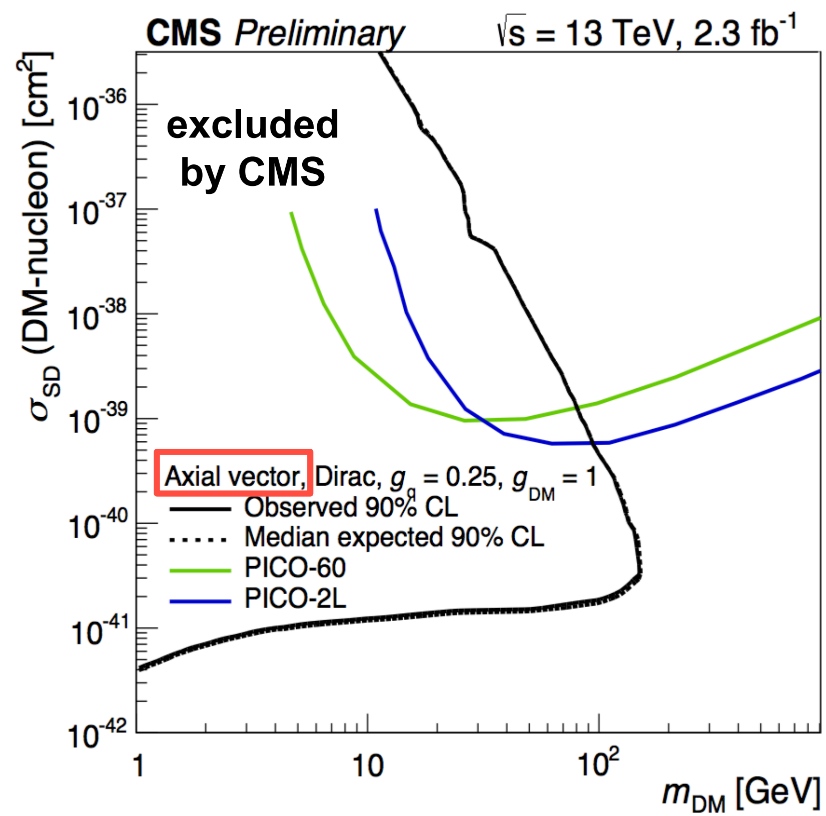




Mono-photon: Limits on DM-Nucleon X-section

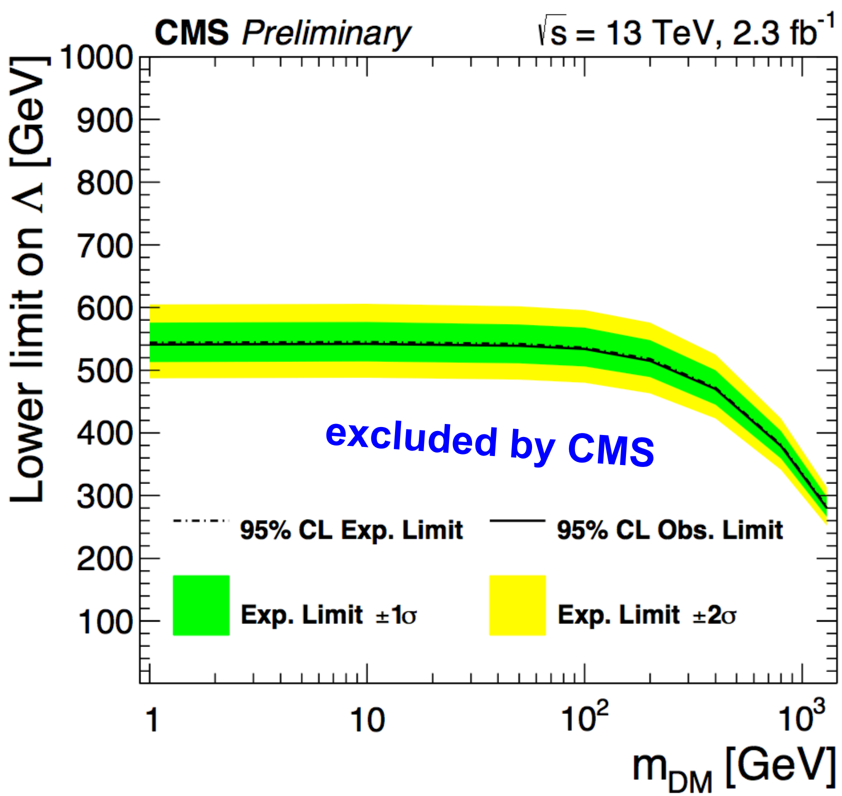
- For each model, limits on the DM-pair production at the LHC ($qq \rightarrow \chi\chi$) Translated into limits on the DM-nucleon elastic scattering ($\chi N \rightarrow \chi N$) and compared with results from direct-detection experiments

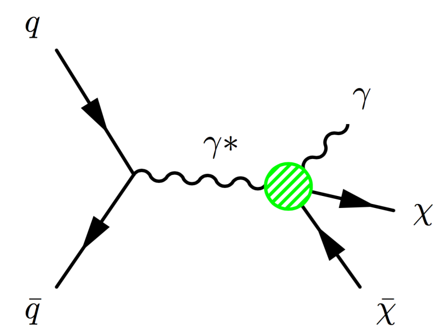




+ Mono-photon : Electroweak Dim-7 Operator

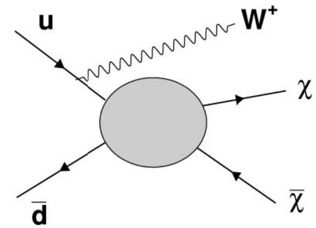
- **EFT** with **contact interaction** of type $\gamma\gamma\chi\chi$ opens channel $qq \rightarrow \gamma^* \rightarrow \gamma\chi\chi$
  - Two main parameters: DM mass m_{DM} and suppression scale Λ
  - Upper limits on the production cross section are translated into lower limits on Λ

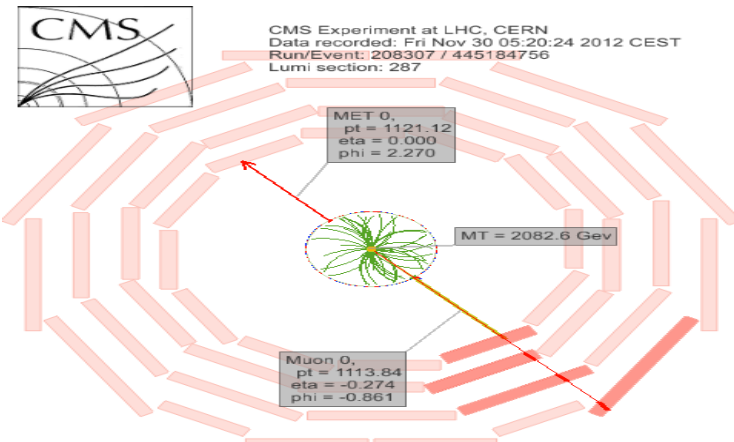


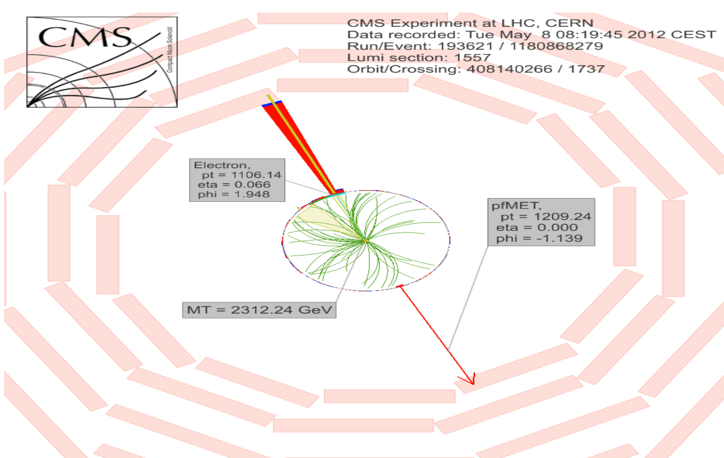


For low DM mass, values of Λ up to ~ 540 GeV are excluded at 95% CL

Search for Pair Produced Dark Matter in **Mono-W(ℓν)** Channel







Signature: W+MET
high pT electron +MET
high pT muon+MET

CMS-PAS-EXO-13-004
20/fb of 2012 pp data at 8 TeV

Phys. Rev. D 91, 092005

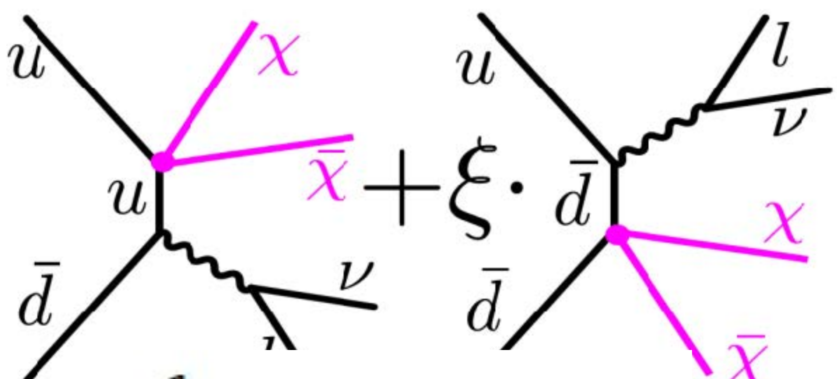
2012 results

+ Mono-W($\ell\nu$) : Interference

- Lower rate than mono-jet and mono-photon, but cleaner signature
  - Lower background, lower trigger thresholds
- Mono-jet/photon channel insensitive to quark type
- For W possibly different coupling to u- and d-type quarks

If [C(u) = C(d)] destructive interference

If [C(u) = -C(d)] constructive interference → mono-boson more sensitive than mono-jet



$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi \qquad \xi_i\bar{q}_i\gamma_{\mu}q_i$$

Neutrino+DM contribute to MET

+ Mono-W($\ell\nu$) Selection

Event Selection

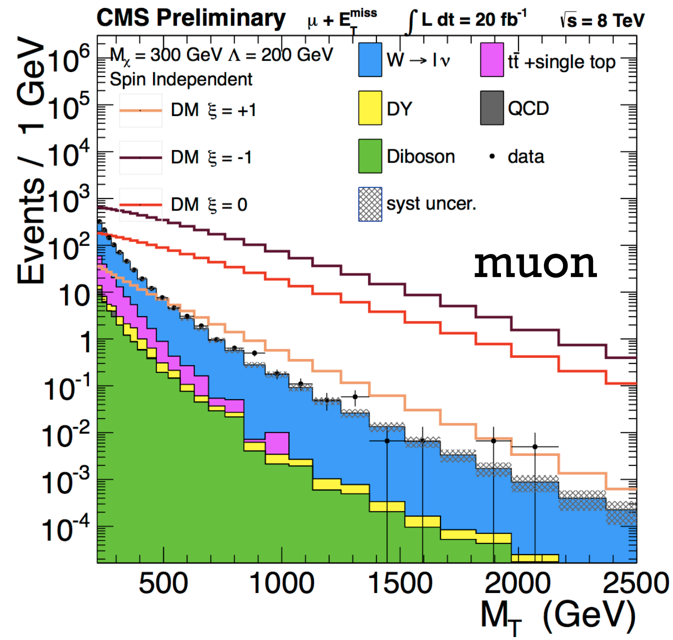
- Single electron (muon) trigger with p_T>85(40) GeV
- Kinematics selection:
  - $0.4 < p_T$ / MET < 2
  - $\Delta\Phi > 2.5$

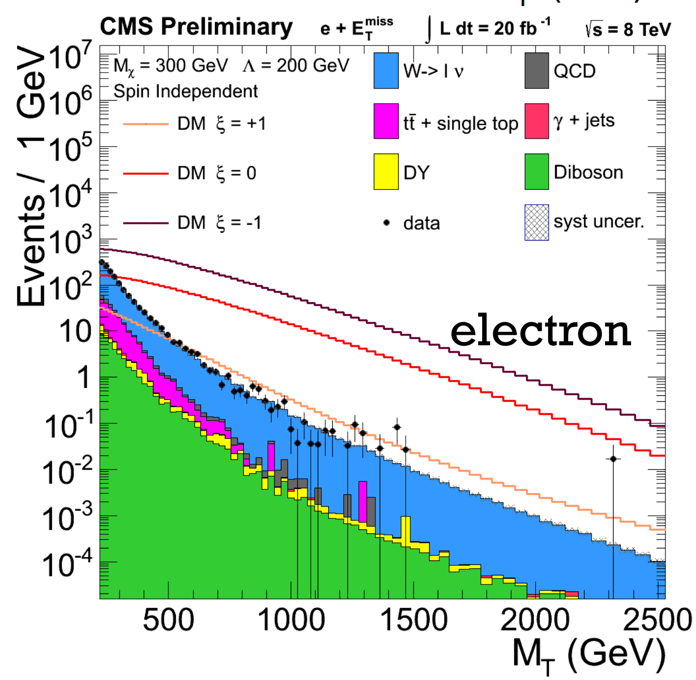
Transverse Mass distribution

$$M_T = \sqrt{2 \cdot p_T^{\ell} \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

Background

- Derived from simulation
- Challenge High MT tail
- Main bkg : W->lν with M_T binned K-factor
- NLO xsec

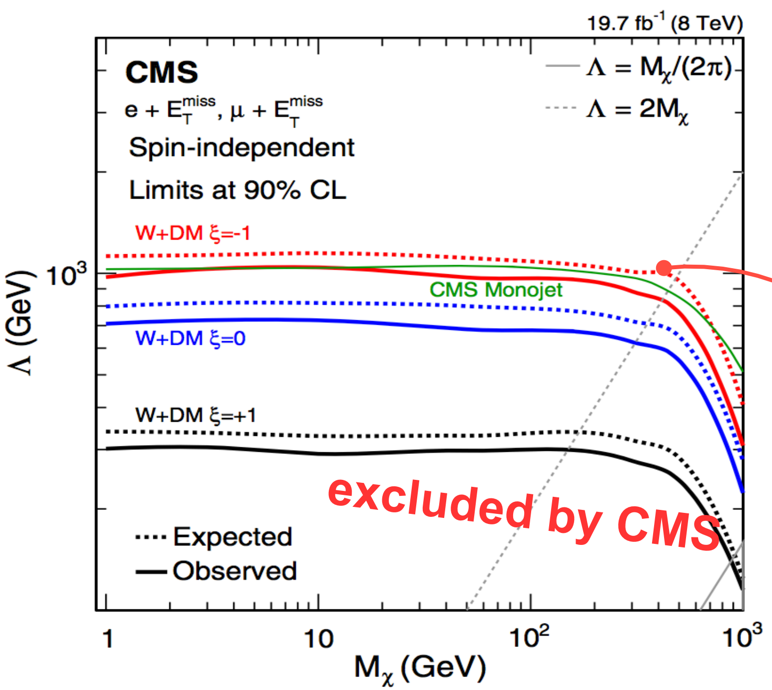




+ # Mono-W(ℓν): Results and Interpretation

- Analysis performed on **19.7 fb^{-1}** of data at **8 TeV**
- Interpretation in terms of **DM EFT** with contact interaction $qq\chi\chi$
  - Limits on the $pp \to W(\ell\nu)\,\chi\chi$ **production** from binned-likelihood fit to M_T spectrum
  - Converted to limits on the effective scale Λ

Lower limit on Λ



Spin-independent vector operator D5

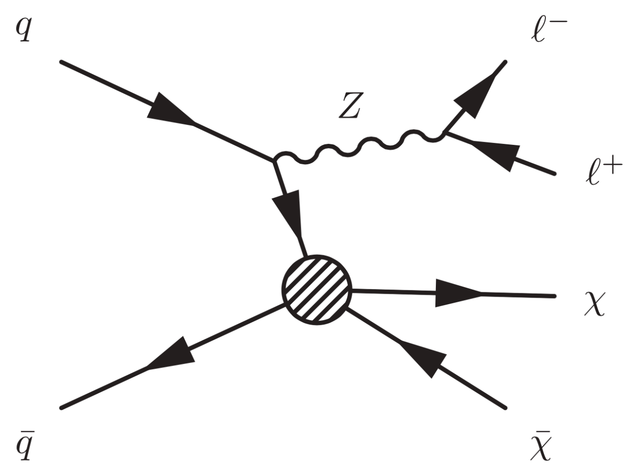
(similar limits for axial-vector operator D8)

$\Lambda > 0.3$ - 1 TeV, depending on the model parameter

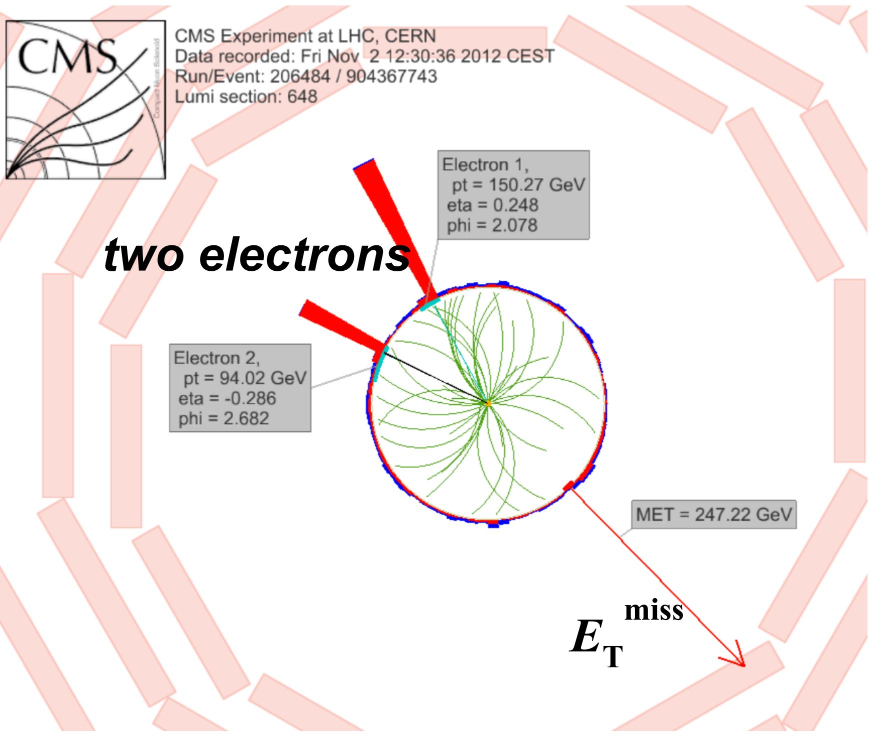
For constructive interference ($\xi = -1$) exclusion limits comparable with those from monojet

Search for Pair Produced Dark Matter in **Mono-Z(ℓℓ)** Channel

- Characterized by a pair of leptons from a Z boson + large E_T^{miss}
  - Very clear signature, relatively low background, simple leptonic triggers



Dielectron + E_T^{miss} event at 8 TeV

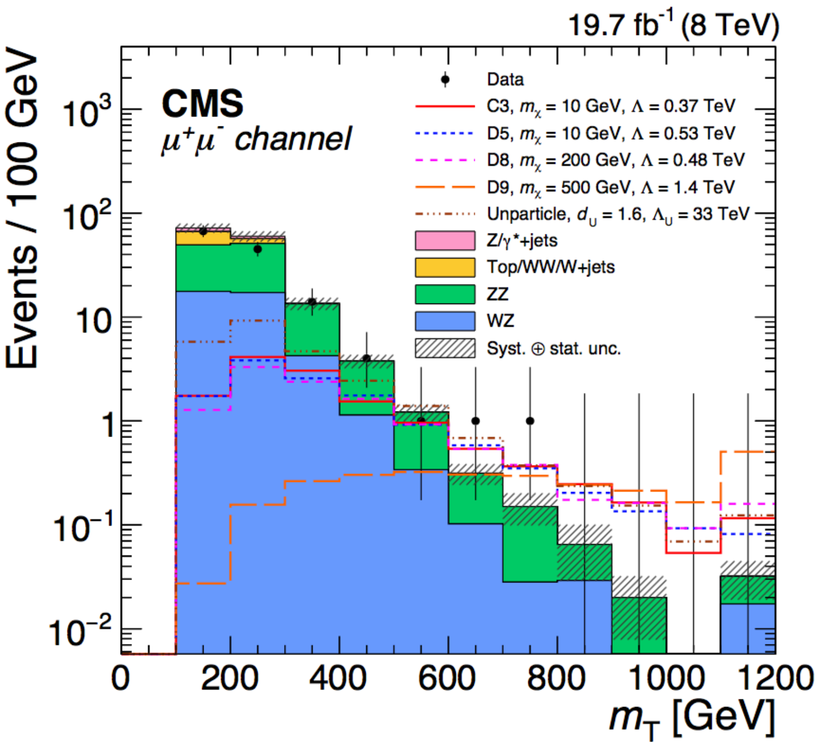


Phys. Rev. D 93, 052011

Mono-Z($\ell\ell$) : Analysis Strategy

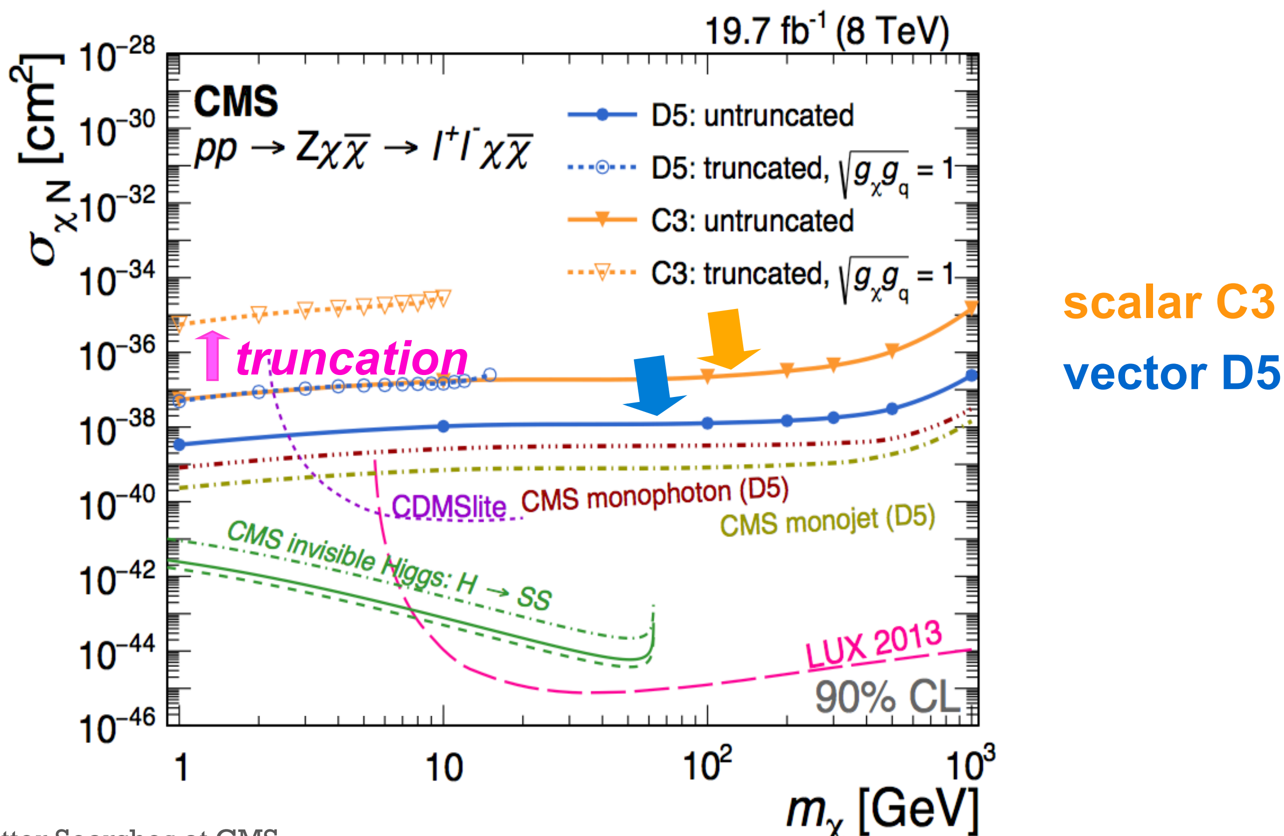
- *Signal selection*
  - Lepton pair e^+e^- or $\mu^+\mu^-$ with mass in $M_Z \pm 10$ GeV and $p_T(\ell\ell) > 45$ GeV
  - Large E_T^{miss} + requirements on $\Delta\varphi(\ell\ell, p_T^{miss})$ angle and $E_T^{miss}/p_T(\ell\ell)$ balance
  - No additional leptons, no b-tagged jets

- *Main backgrounds*
  - $ZZ \rightarrow 2\ell 2\nu$, $WZ \rightarrow 2\ell(\ell)\nu$
    - estimated from simulation (with NLO cross section)
  - WW, tt, tW, $\tau\tau$
    - flavor symmetric, estimated from $e\mu$ data
  - $Z + \text{jets} \rightarrow 2\ell + \text{jets}$
    - estimated from simulation, with data-driven normalization from DY-enriched control sample



Mono-Z($\ell\ell$) : Results and Interpretation

- Analysis performed on 19.7 fb^{-1} of data at 8 TeV in the context of an EFT
  - Limits computed from a profile-likelihood fit to the transverse mass spectrum
  - Limits on the DM-nucleon cross section for different models
  - Truncated limits are also provided



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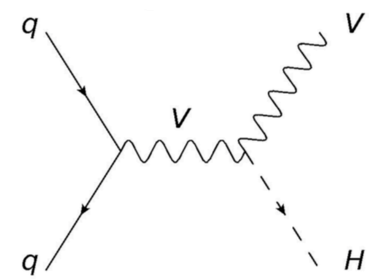
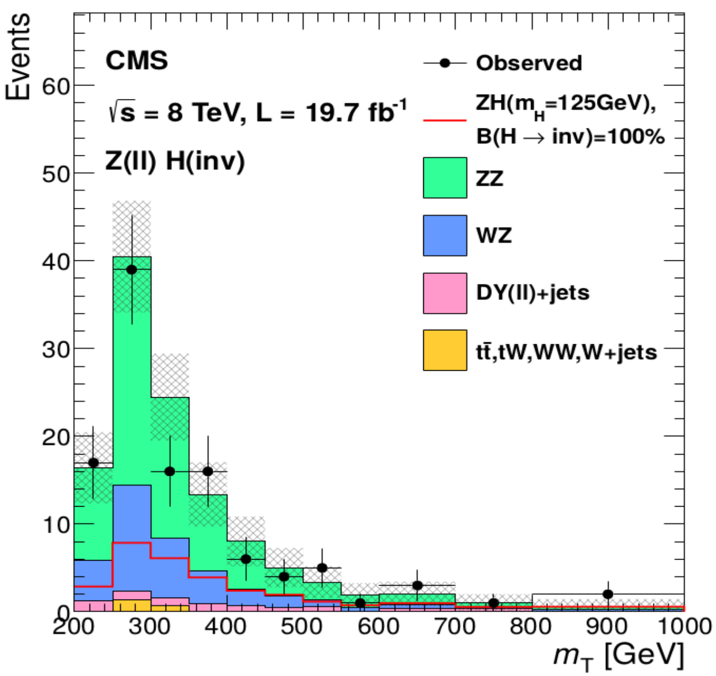
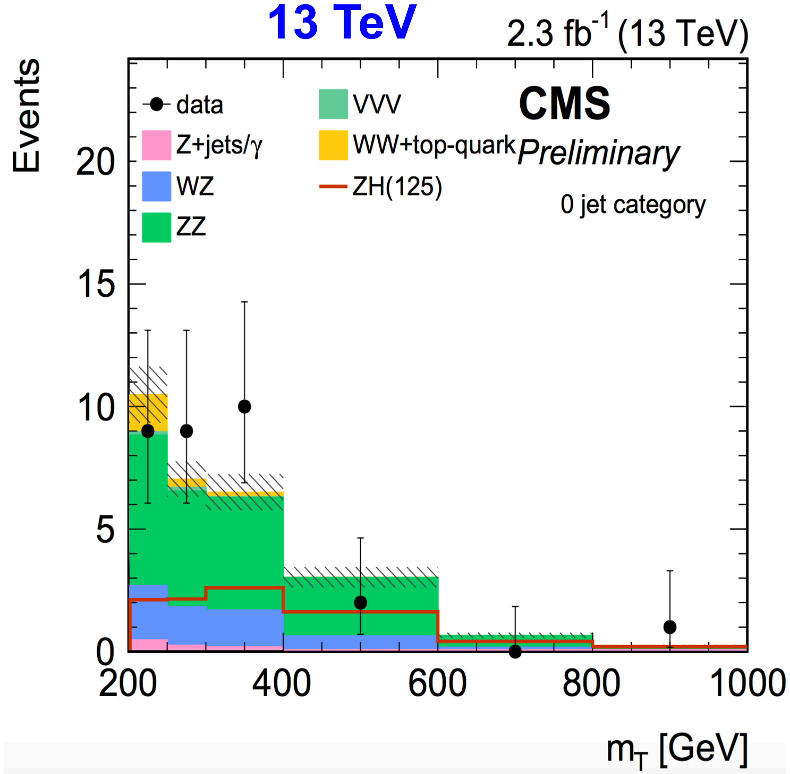


- The same data can be used to search for Higgs bosons with invisible decays
  - ➔ Higgs-portal models: Higgs as only mediator between SM and DM
- Signal: SM-like Higgs (125 GeV), $B(H \rightarrow \text{invisible}) = 100\%$

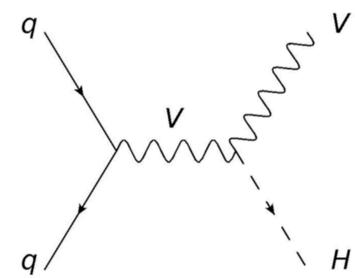
8 TeV Transverse mass



13 TeV



Mono-Z($\ell\ell$) : Results and Interpretation



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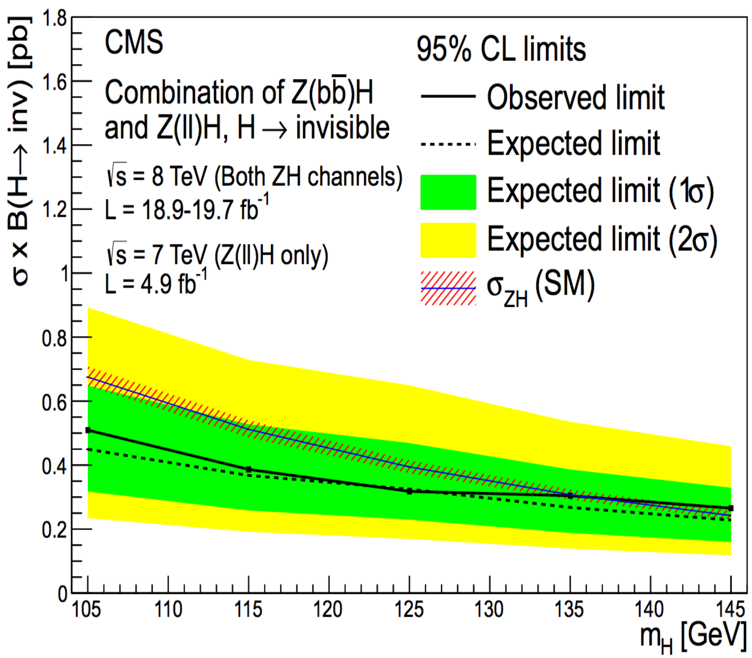
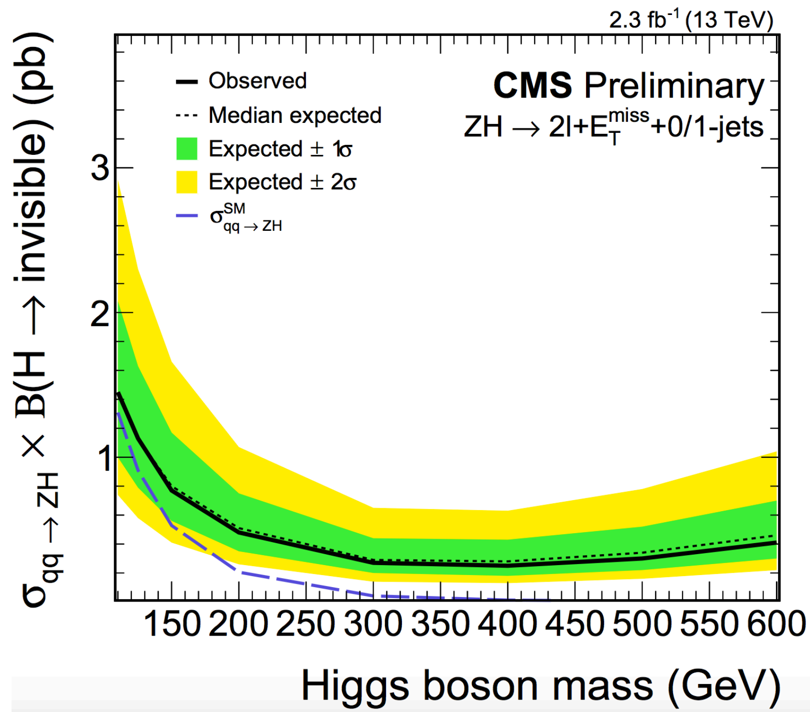
Eur. Phys. J. C 74 (2014) 2980
CMS-PAS-HIG-16-008

7+8 TeV



13 TeV



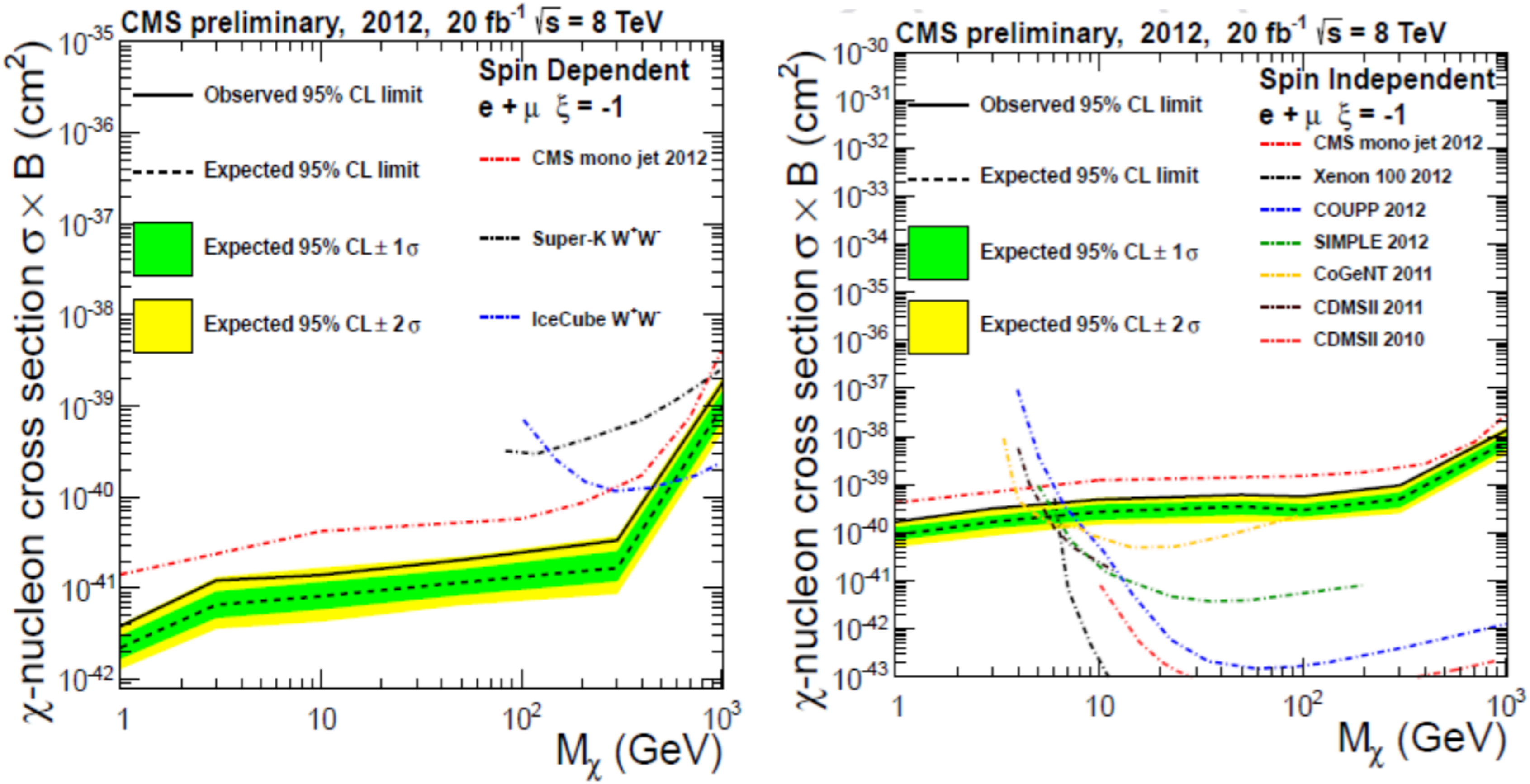
Summary

- LHC dark matter searches are exciting.
  - Major opportunity for new physics!
  - No DM yet ☹
- Several LHC BSM searches reintepreted in terms of dark matter models.
- Work closely with theorists to develop theoretical assumptions and models.
- Complementary to direct detection experiments.
- LHC Run 2 data taking is going pretty well
  - New exciting results will come soon. Stay Tuned ☺

Backup

Monolepton ξ= -1 (max. Sensitivity)

2012 results in comparison to monojet and some direct detection experiments, 90% C.L.



Non Collision Backgrounds

Full Timing

- Non-collision backgrounds are estimated using the ECAL timing information
- First we look at full timing distribution of photons
  - Default supercluster reconstruction algorithm discards hits with |t|> 3 ns cut
  - Full re-reconstruction of 2015 performed removing this constraint

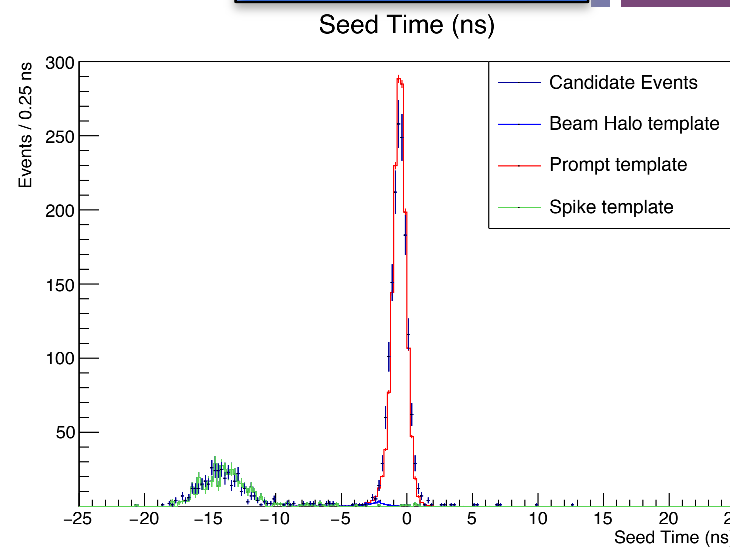
Halo Template : Mip total energy > 4.9 GeV

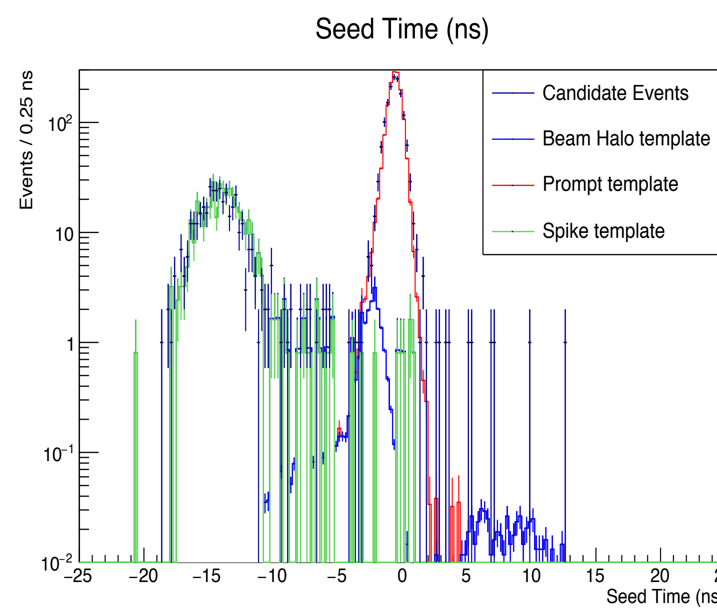
Spike Template : Full candidate selection and reverse the topological shower shape spike cleaning cuts

Prompt Template : W Candidates selection with pixel match and good shower shape

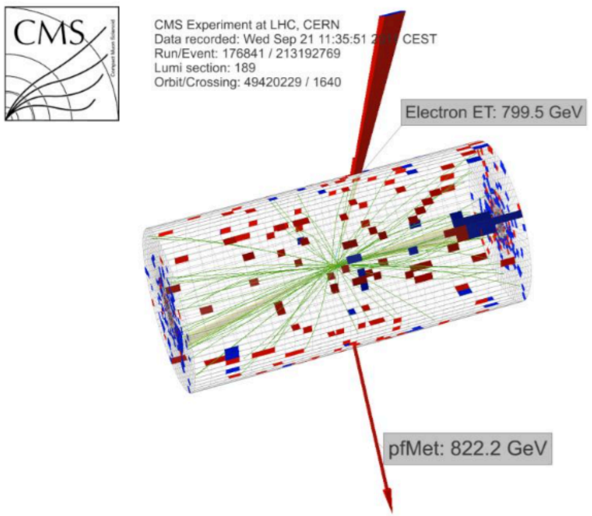
Beam Halo : 13.41 +/- 6.27 events

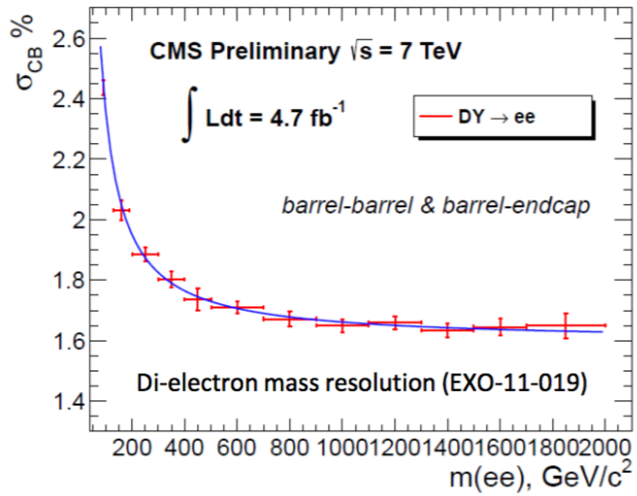
Spike : 5.63 +/- 2.2 events





Electron Selection

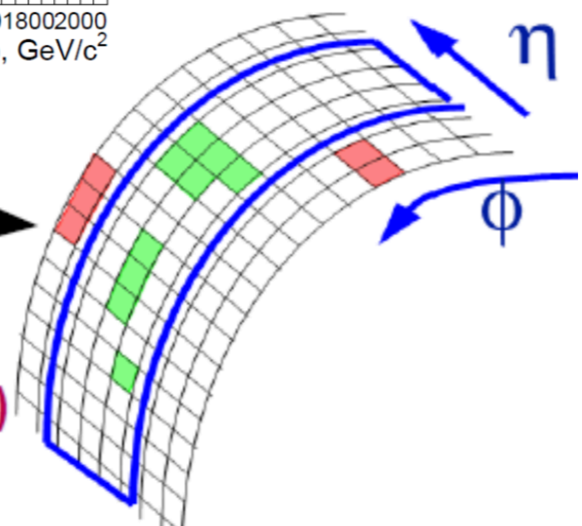




ECAL made of matrix of fully active crystals. Measured energy resolution ~2%

Electrons are reconstructed from energy clusters
In the ECAL and tracks from the silicon tracker
Electron ID optimized for high E_T requires:

- $E_T > 85$ GeV
- $|\eta| < 1.442$ (barrel) or $1.56 < |\eta| < 2.5$ (endcap)
- Good quality of track and cluster
- Matching between the two
- Isolation



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

K.Hoepfner, RWTH Aachen | CMS Heavy Resonances |

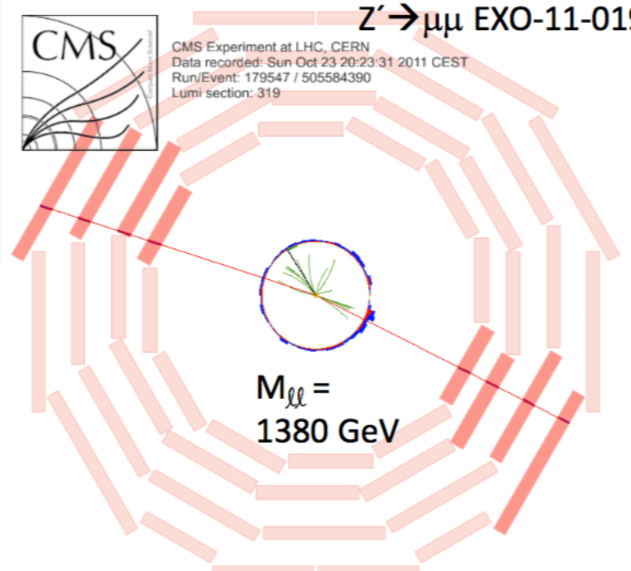
+ Muon Selection

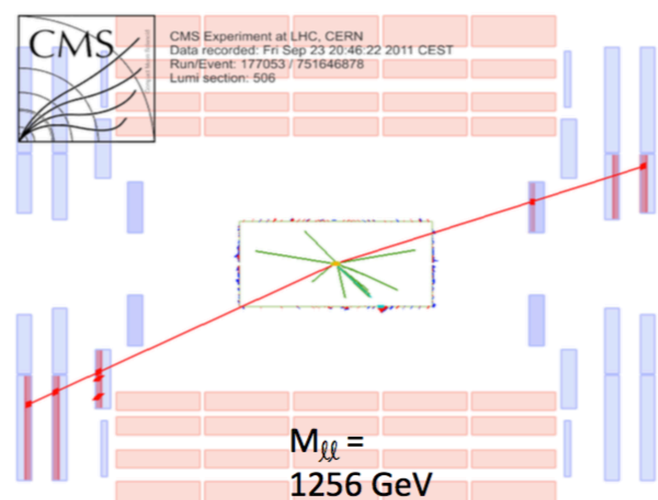
High redundancy of mu system, 4 stations along track
Iron between stations may cause **bremsstrahlung** for O(TeV) muons
p_T<200 GeV tracker in B=3.8T, p_T>200 GeV mu+tracker

Dedicated muon selection:

- Special algorithm to consider showering
- At least 1 pixel hit
- Number of measured tracker layers > 8
- Transverse impact parameter d0 < =0.2cm (Z´), 0.02cm (W´) reject cosmics, value for W´ tighter than other analyses, Z´ rejects in addition back-to-back muons
- >= 2 matched muon segments
- Relative track isolation <0.10 in ΔR < 0.3
- No cut on chi2 cut introduces a 4-6% inefficiency for muons >500 GeV

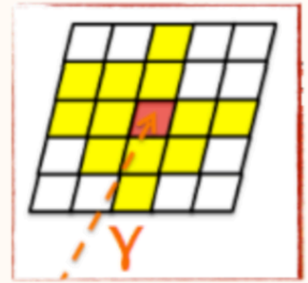
Event displays from $Z' \rightarrow \mu\mu$ EXO-11-019



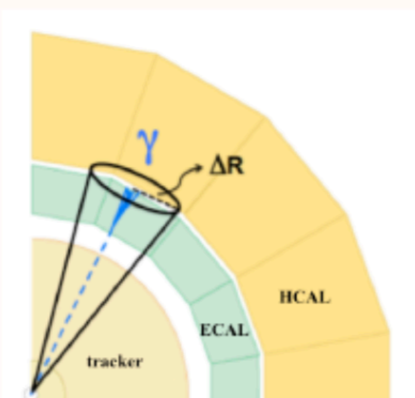


Photon Selection

- Background contamination and invariant mass resolution depends on:
  - pseudorapidity
  - cluster shape, i.e. conversion probability (R9)



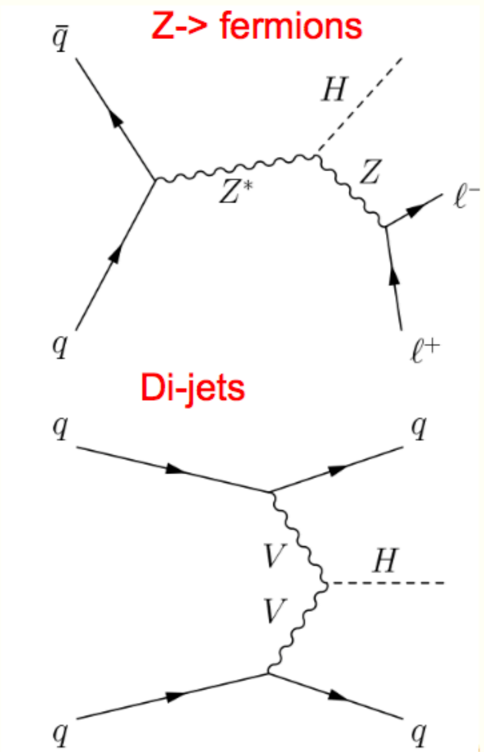
- Same approach like H->γγ standard cut-based photon-ID
  - ECAL fiducial region (|η| < 2.4 excluding EB-EE gap)
  - Isolation and identification requirements:

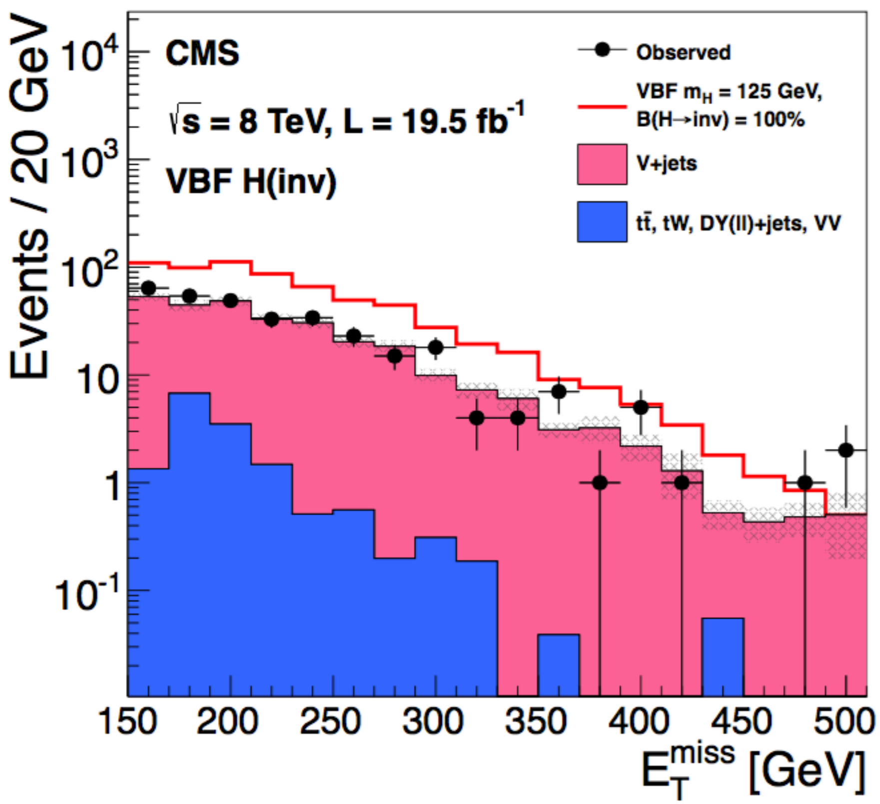


	barrel		endcap	
	$R_9 > 0.94$	$R_9 < 0.94$	$R_9 > 0.94$	$R_9 < 0.94$
PF isolation sum, chosen vertex	6	4.7	5.6	3.6
PF isolation sum worst vertex	10	6.5	5.6	4.4
Charged PF isolation sum	3.8	2.5	3.1	2.2
$\sigma_{i\eta i\eta}$	0.0108	0.0102	0.028	0.028
H/E	0.124	0.092	0.142	0.063
R_9	0.94	0.298	0.94	0.24

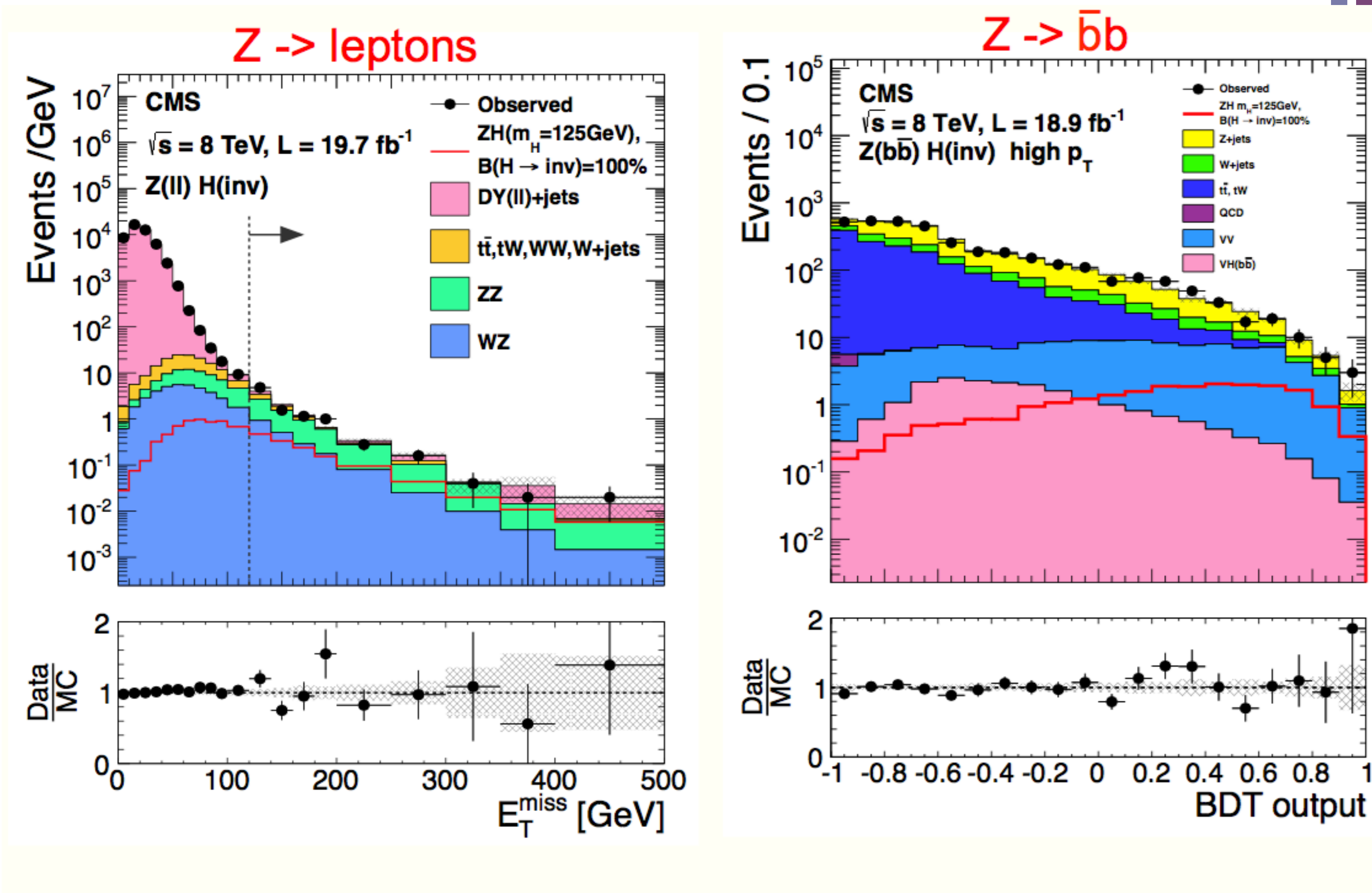
+ Higgs Modes : CMS VBF

Depending on its nature, DM will couple to theHiggs in various ways. Assuming a Higgs -> Invisible branching, one can search in several channels.

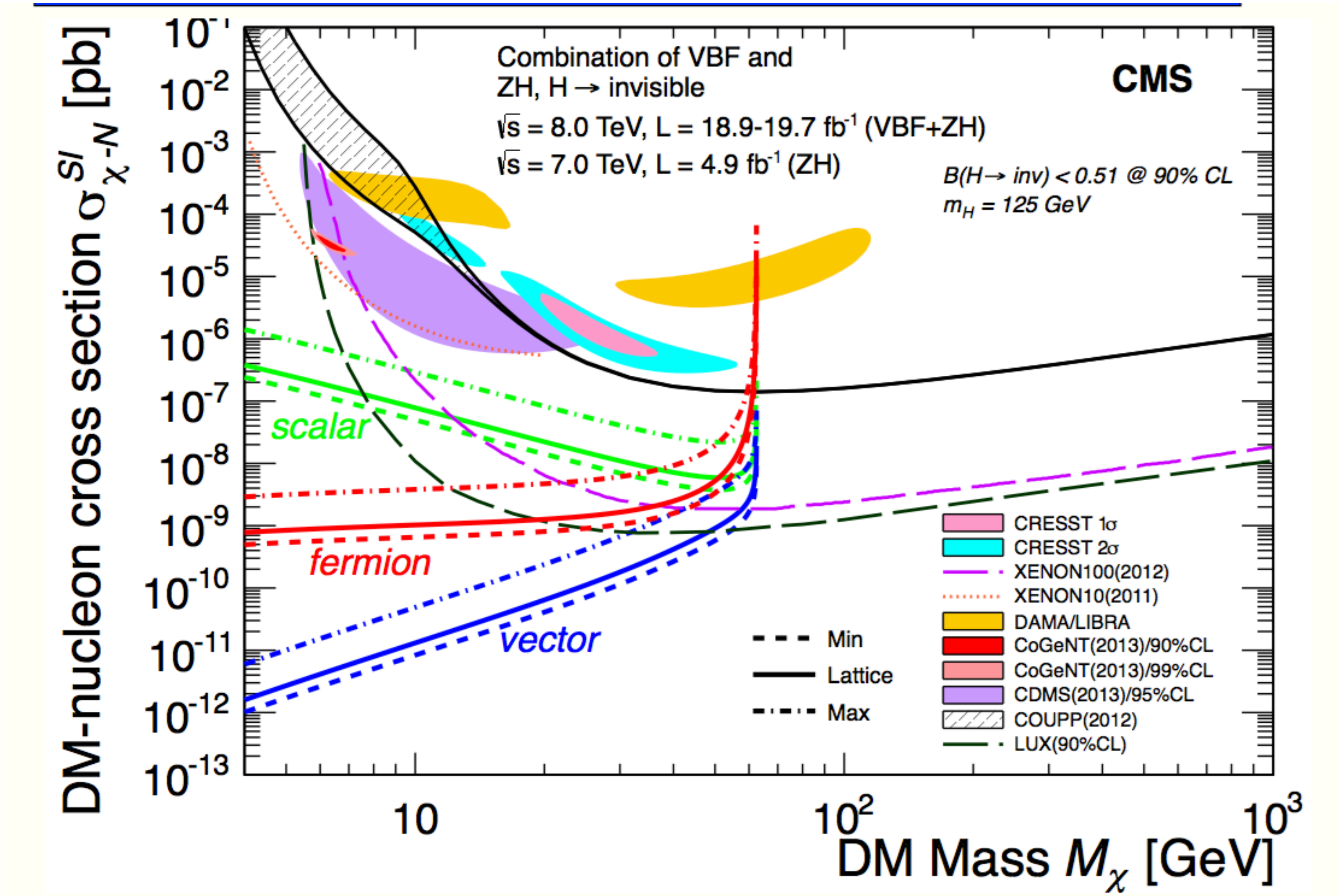




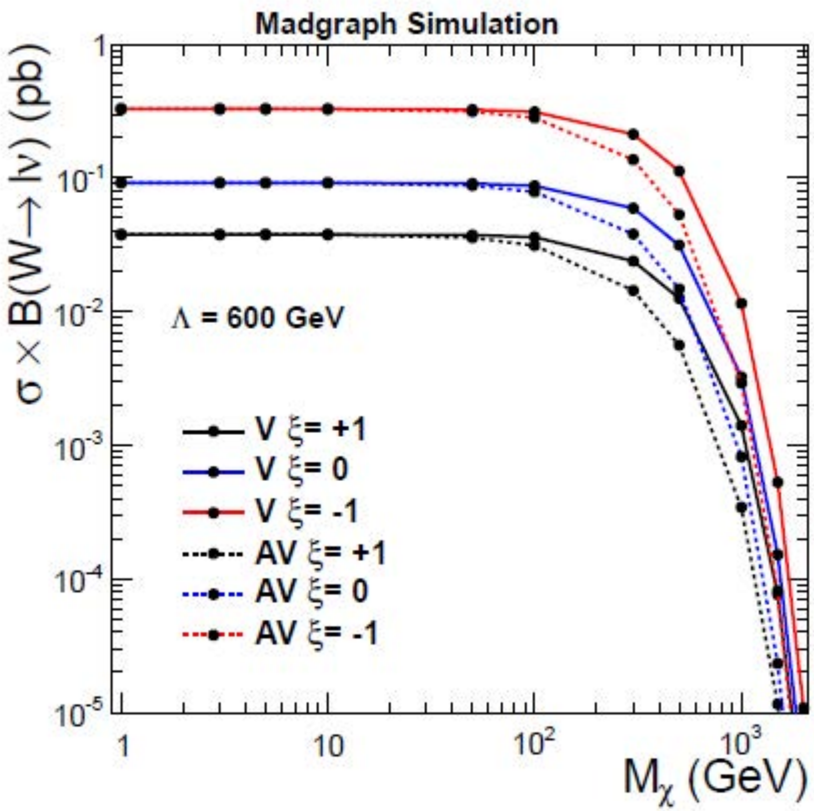
Higgs Modes : CMS ZH

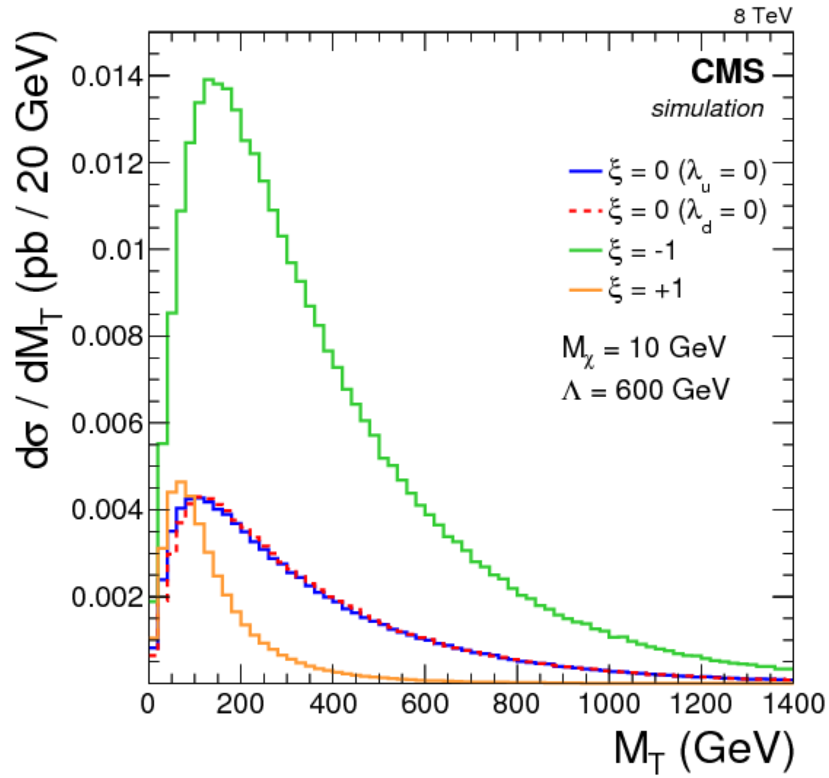


CMS VBF + ZH limits



Interference Parameterized by ξ= -1,0,+1





Largest cross section for $\xi = -1$
For M_χ <~70 GeV same cross section for V and AV coupling of fixed ξ

Interference type influences M_T shape ⟶ impact on sensitivity

Limits on production cross section

V

Spin

In-

depen

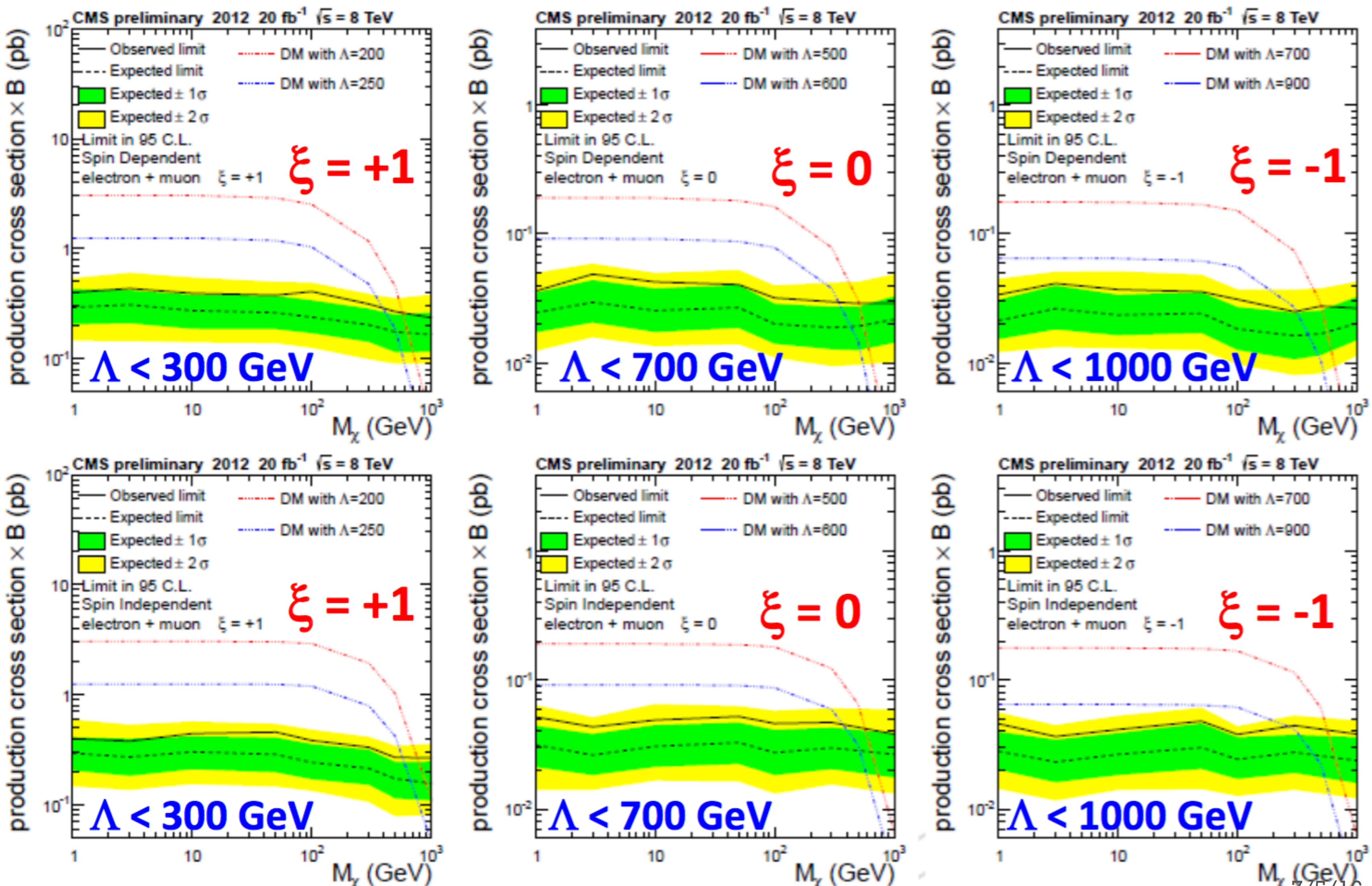
dent

AV

Spin

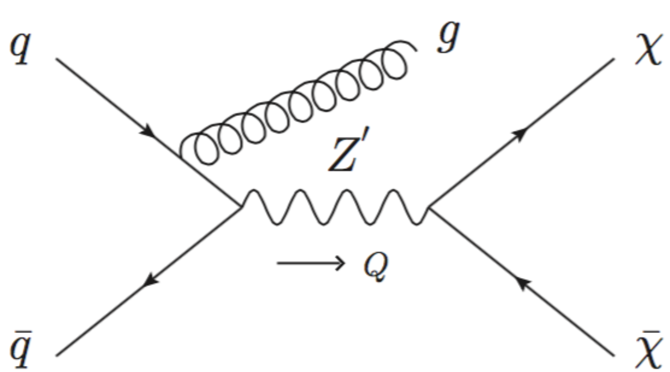
depen

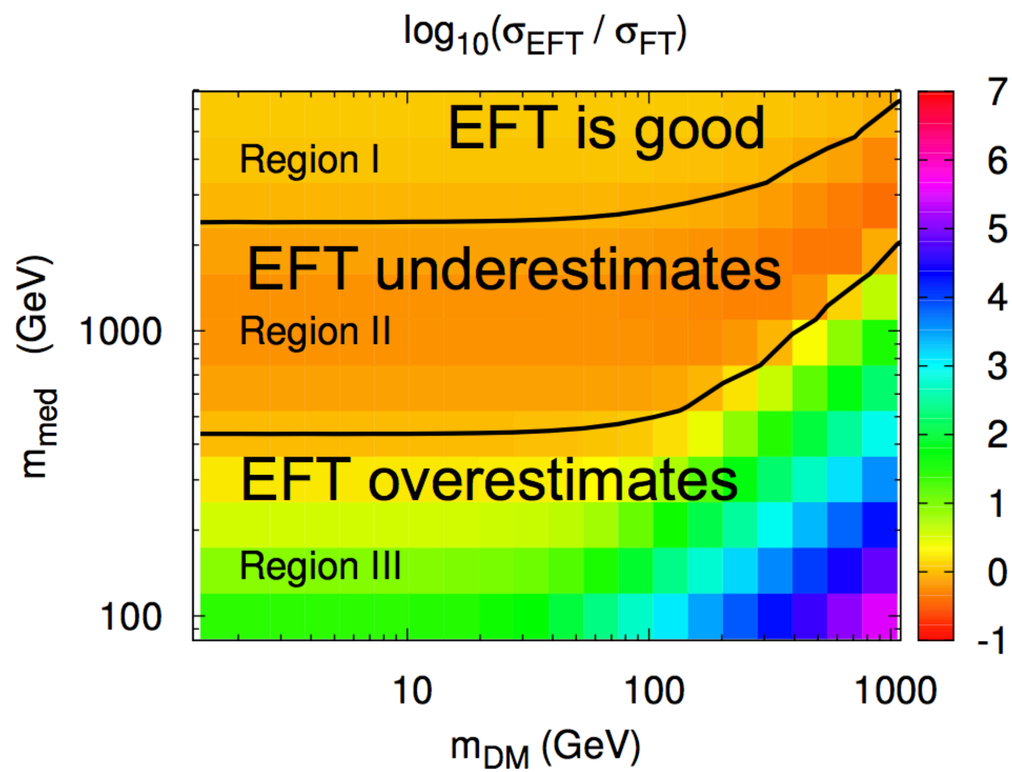
dent



Light Mediator Case

- The most tricky case is that of light mediator
- First step : put in a mediating particle (e.g s-channel Z') and look at limits vs m_z

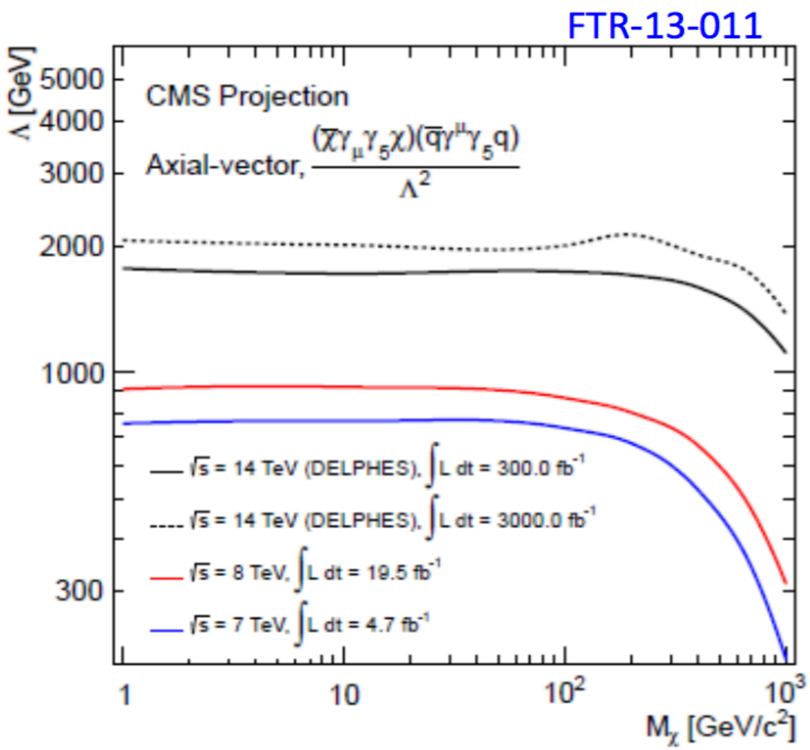


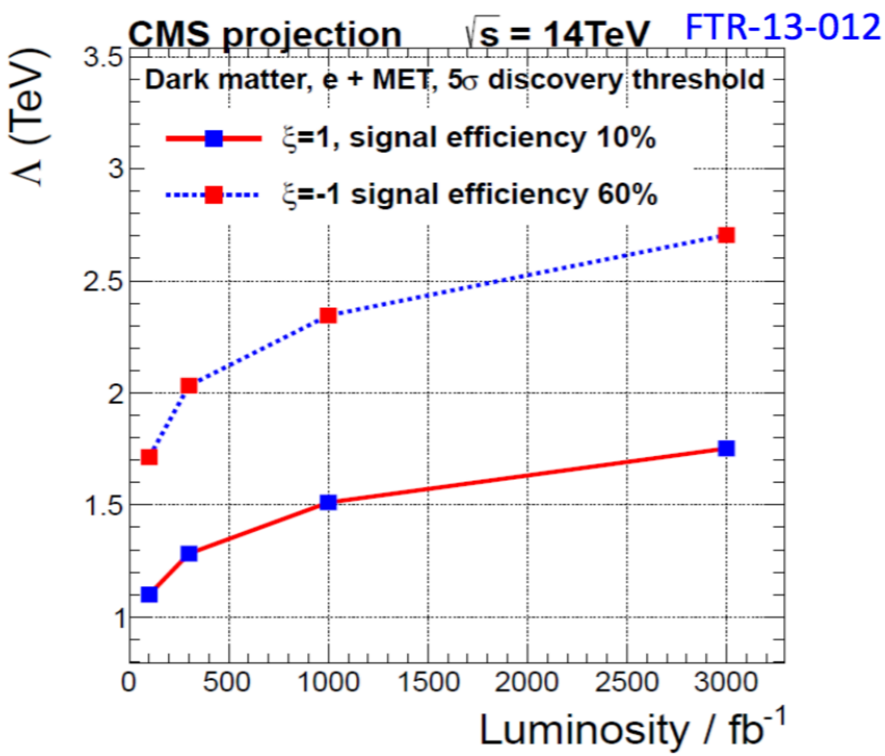


- EFT gives good/conservative results above a few hundred GeV (high M)
  - Region I – EFT is good
  - Region II – EFT underestimate
  - Region III – EFT overestimate

Buchmeller, Dolan, McCabe, arXiv : 1308.6799

Reach at 14 TeV?





Gain sensitivity with increasing sqrt(s).
At 14TeV and 300/fb. Reach in lambda O(x2)
Main challenge MET in high PU.