Searches for Dark Matter at the CMS

SLAC Seminar, May 26th 2015

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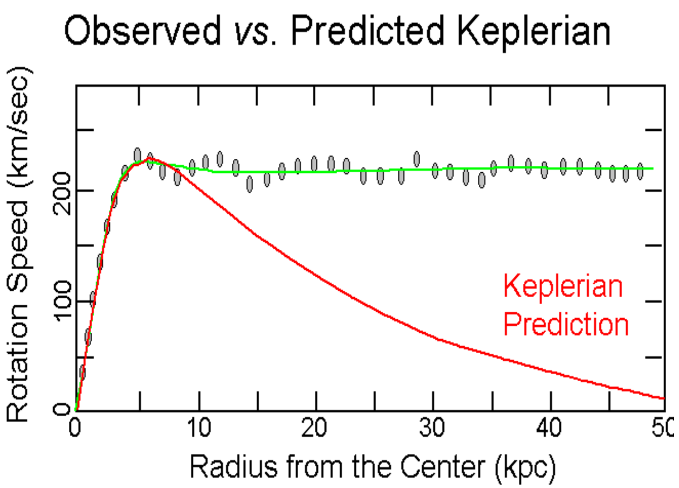
Outline

- Signatures of Dark Matter at the CMS
- Detection in CMS
- Different Channels
  - Monojet
  - Monophoton
  - Mono-boson
    - Leptons
  - Next Run – 13 TeV

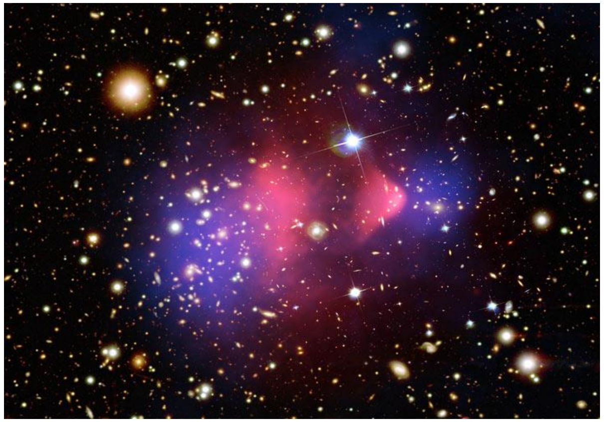
Evidence for dark matter

- Strong astrophysical evidence for the existence of dark matter
  - From rotational curves, gravitational lensing/bullet cluster, CMB power spectrum

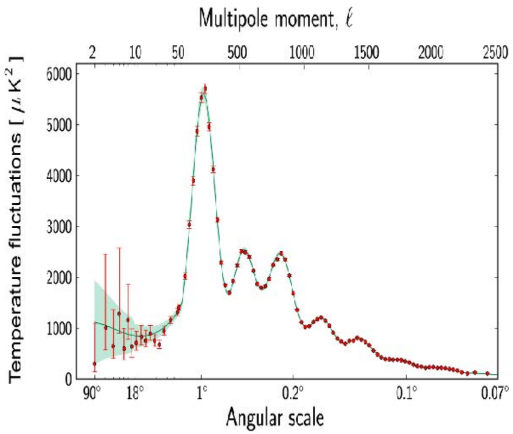
Rotation curve of galaxies



Gravitational lensing

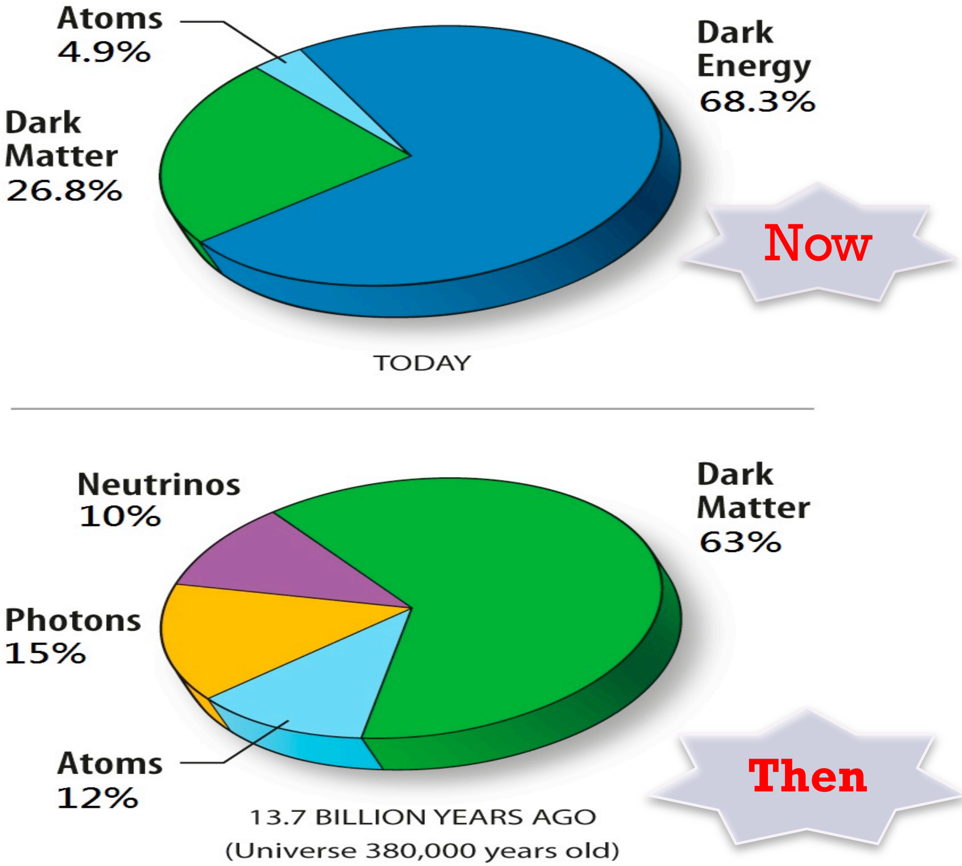


Planck 2013 : CMB



- Increasing number of observations consistent with DM existence
  - No direct observation yet

The Evolution of the Universe

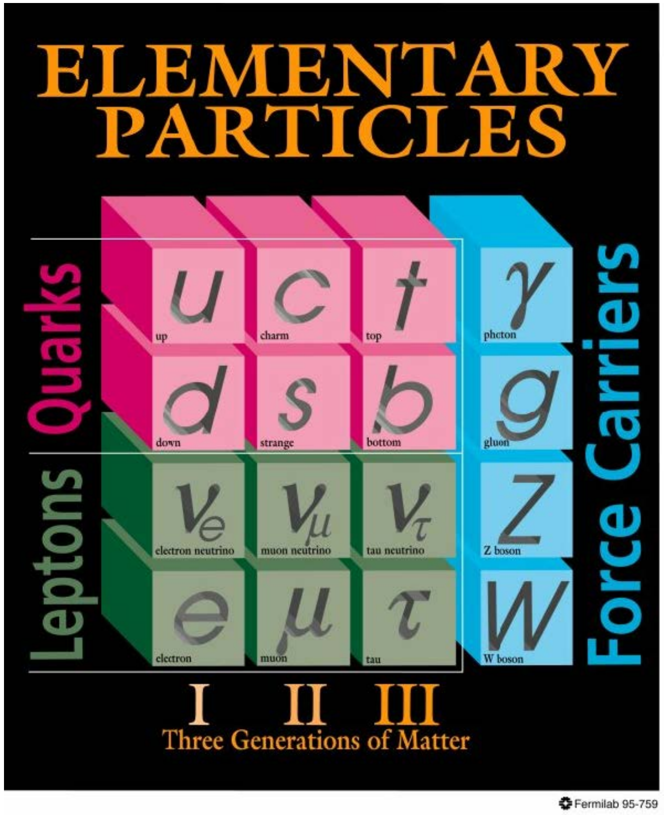


DM is six times more abuntant than baryons.

Contribute ~1/4 of the total energy budget!

Particle description of DM en vogue…testable at the LHC?

Composition of Matter

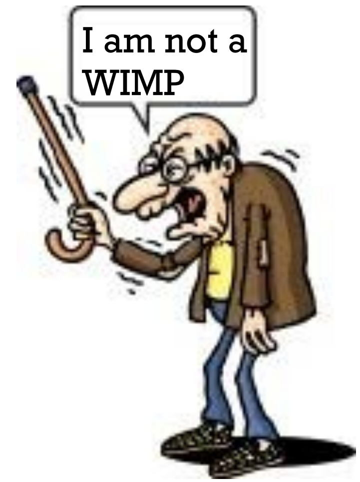


85% of matter

the rest

DM Properties

- No direct observation of DM yet
- Most popular class of candidates to explain observation suggest **properties** :
  - **Fermionic** matter
  - Interacts only **weakly**
  - **Massive** particle (GeV -> TeV)
  - Expected to be **neutral**
  - **Cold**; non-relativistic

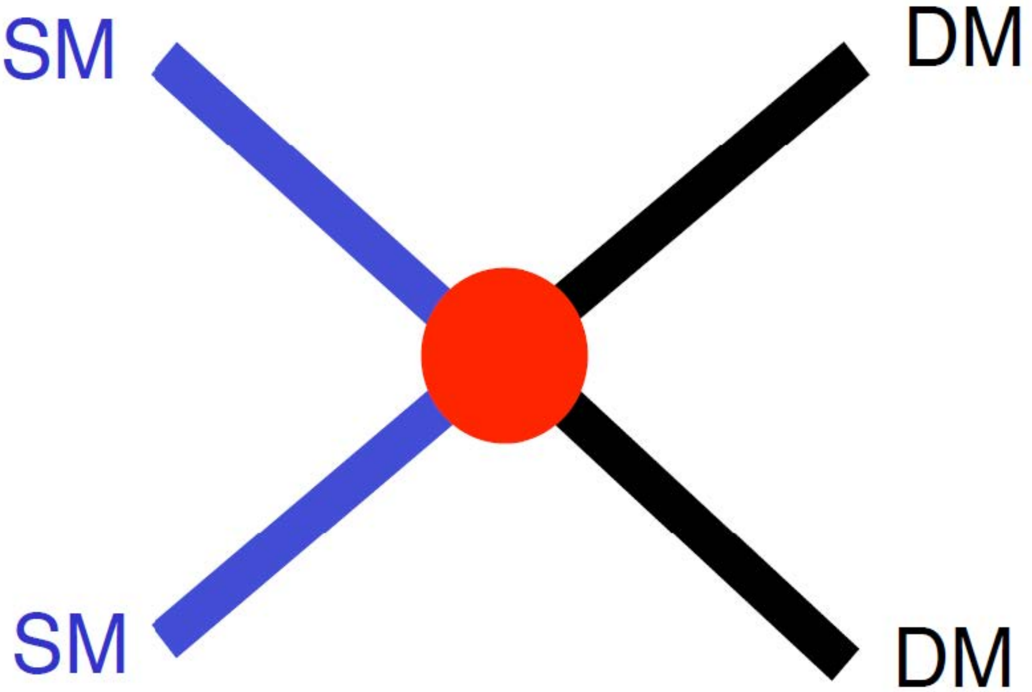


Dark matter = part of cosmological SM

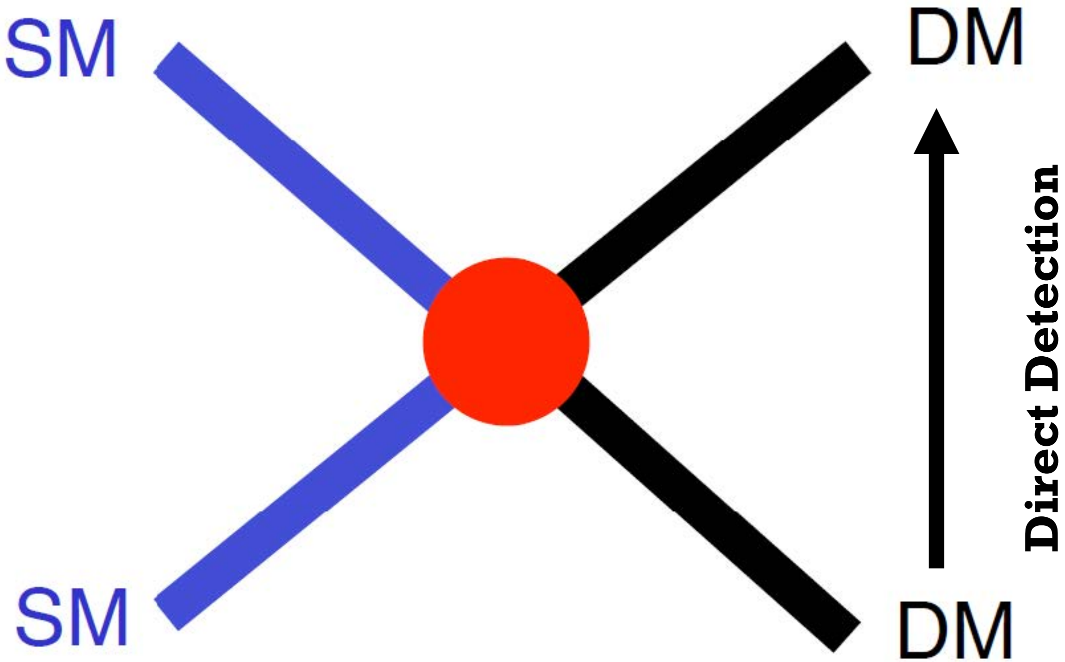
Requires beyond SM physics

Detection Techniques

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



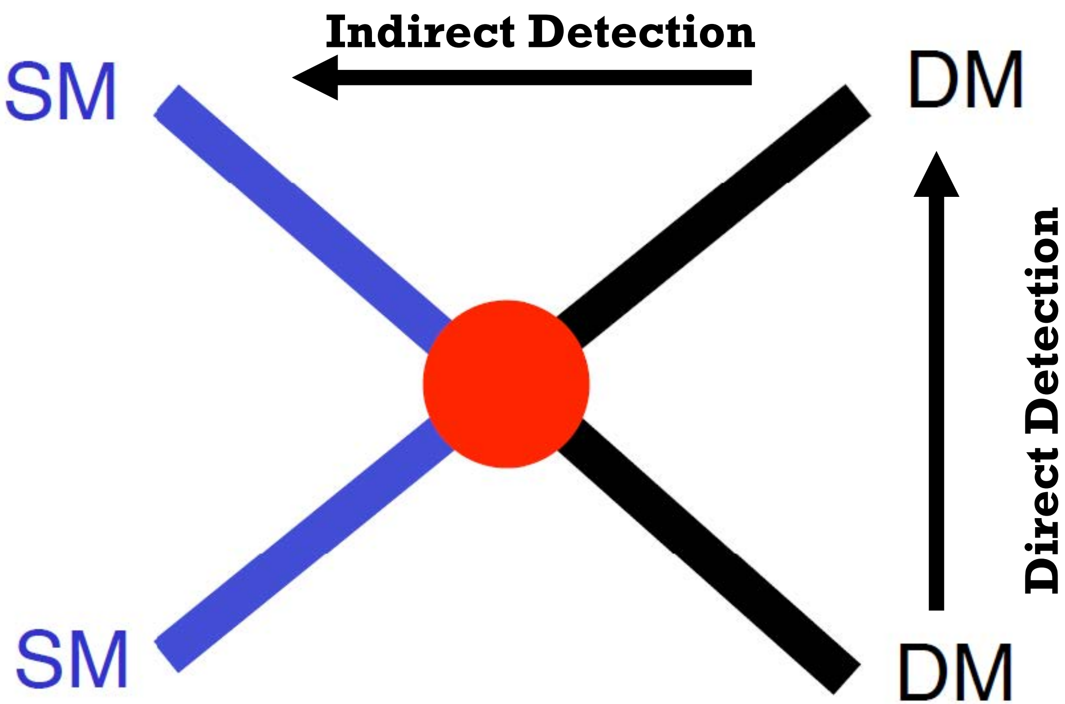
Detection Techniques



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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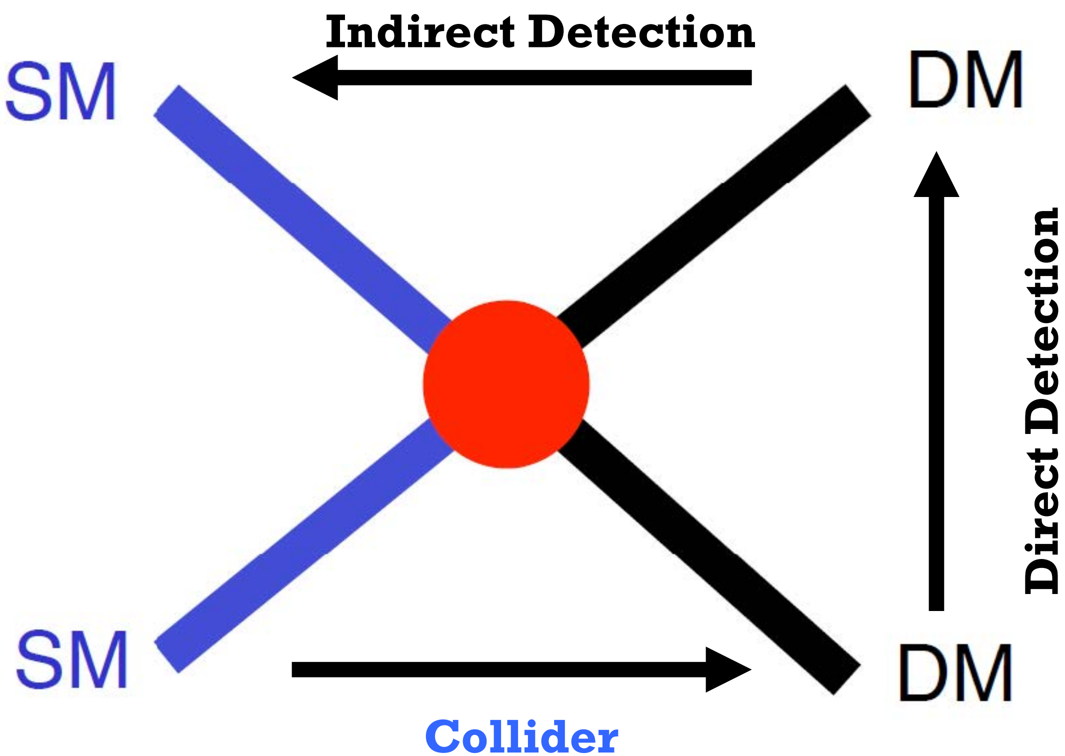


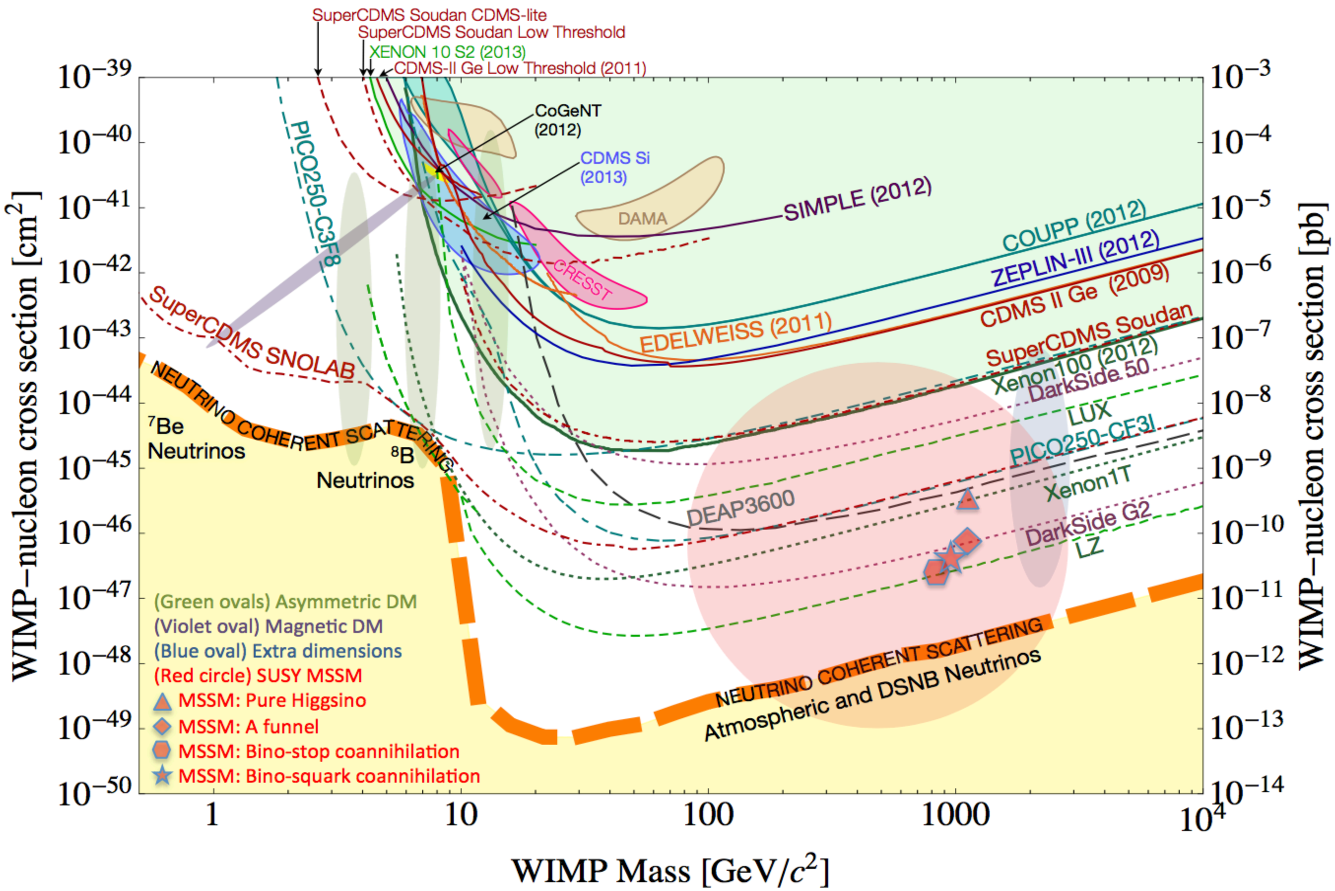
Scattering of DM particles on nuclei of detector material ; detect recoil. For a given cross section sensitivity scales with detector size.

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

Result :

Wealth of direct detection experiments

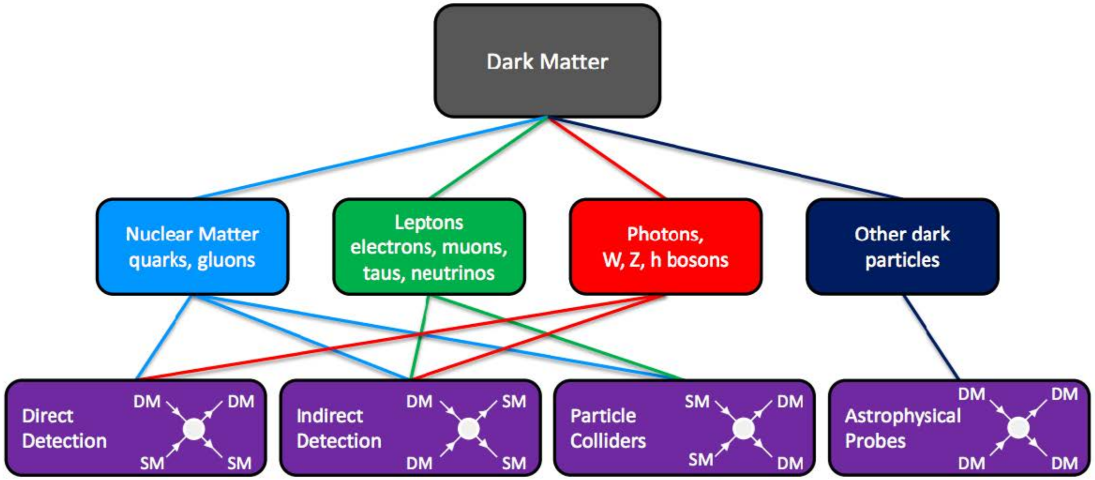
WIMP Search status – Snowmass 2014



Snowmass "Complimentarity" Report

- Snowmass: US-based decadal prioritization exercise for High Energy Physics
- Collider-based searches for DM flagged as one of the four pillar of the field.

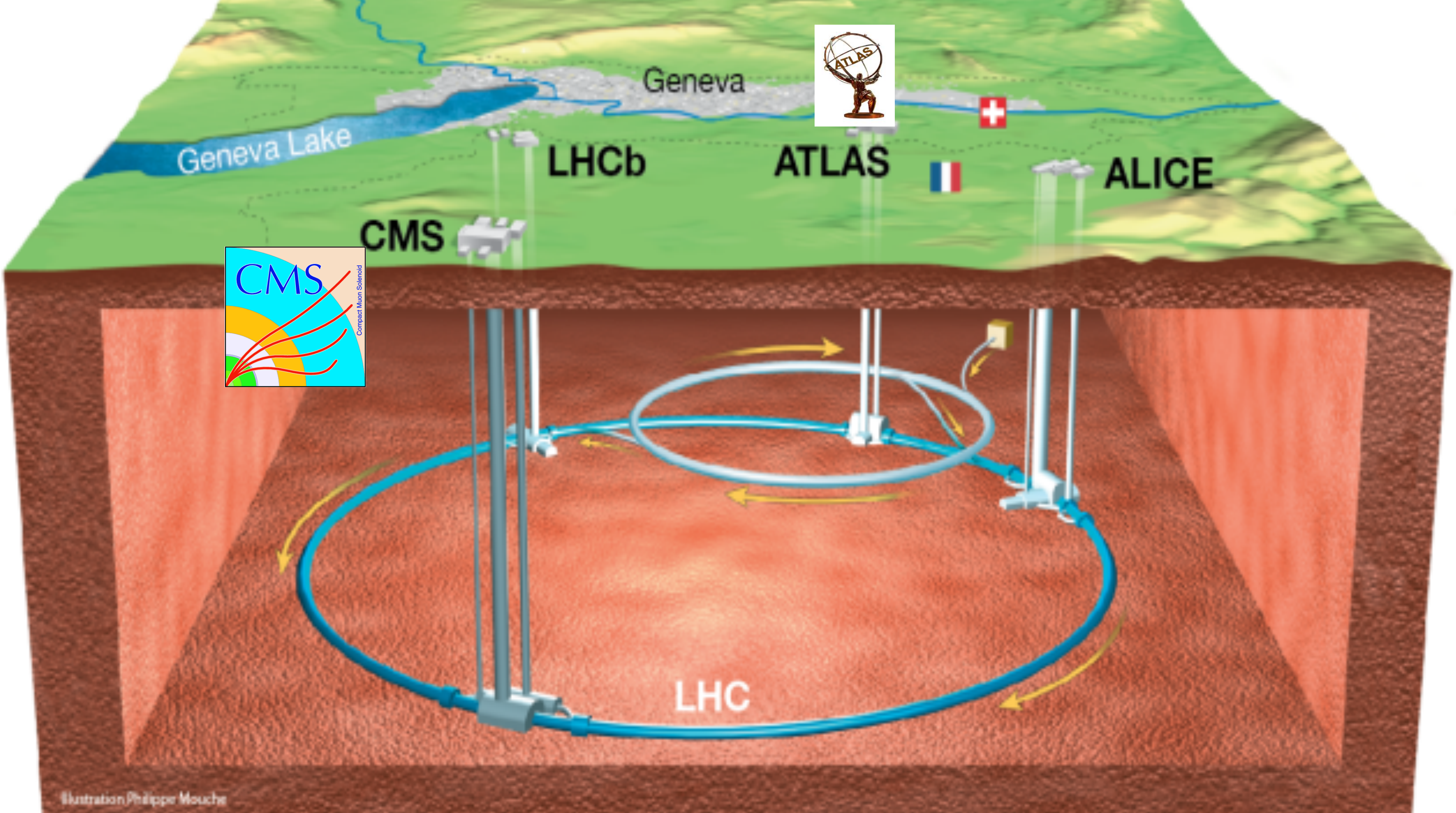
….after only two years, an equal footing with direct and indirect searches!



The Large Hadron Collider (LHC)

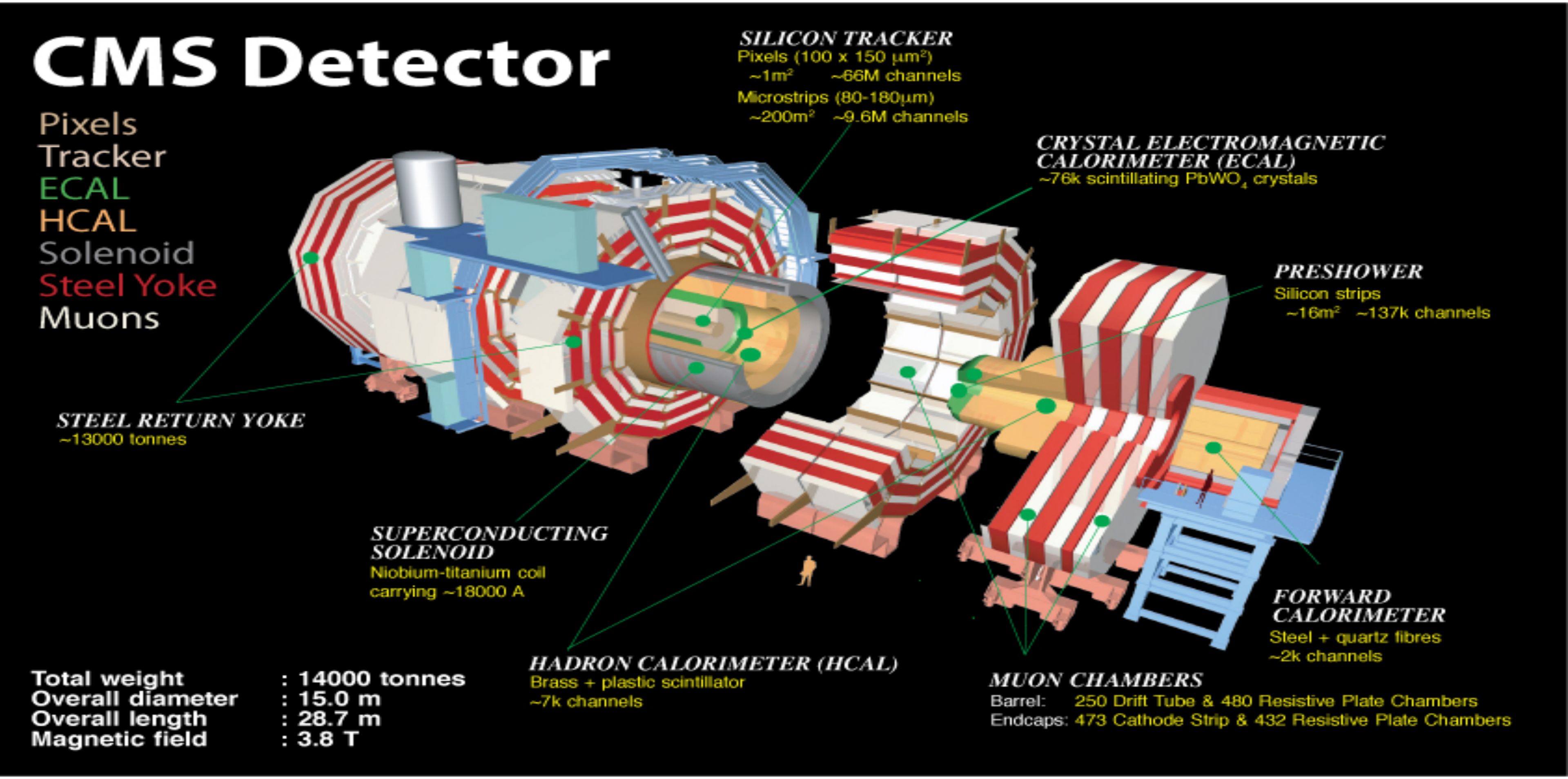
Two General Purpose Experiments:

CMS & ATLAS



Compact Muon Solenoid (CMS)

Emphasis on electron and photon energy measurement, full silicon tracker providing high momentum resolution

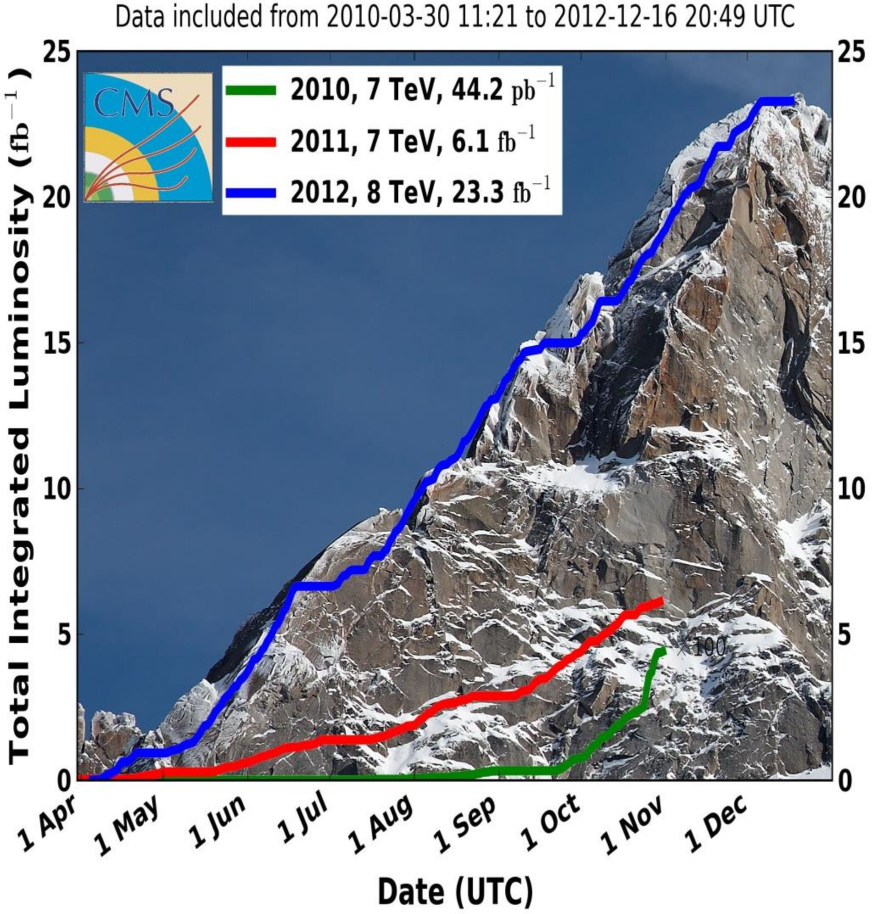


LHC Data Taking

Recorded luminosity of high quality data ~25 fb^{-1}

Data taking efficiency >90% for CMS

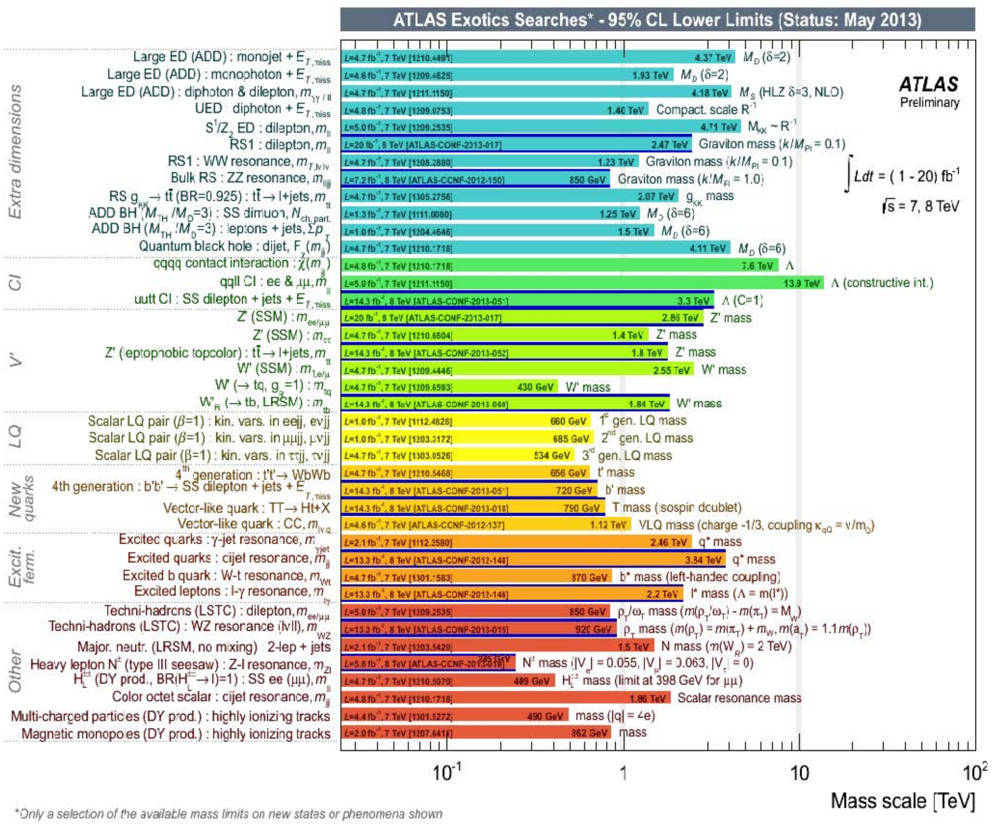
Results presented in this talk are from a mix of data from 2011 and 2012 runs with p-p collisions @7 TeV (~5 fb^{-1}) and @ 8 TeV (~20 fb^{-1}) respectively

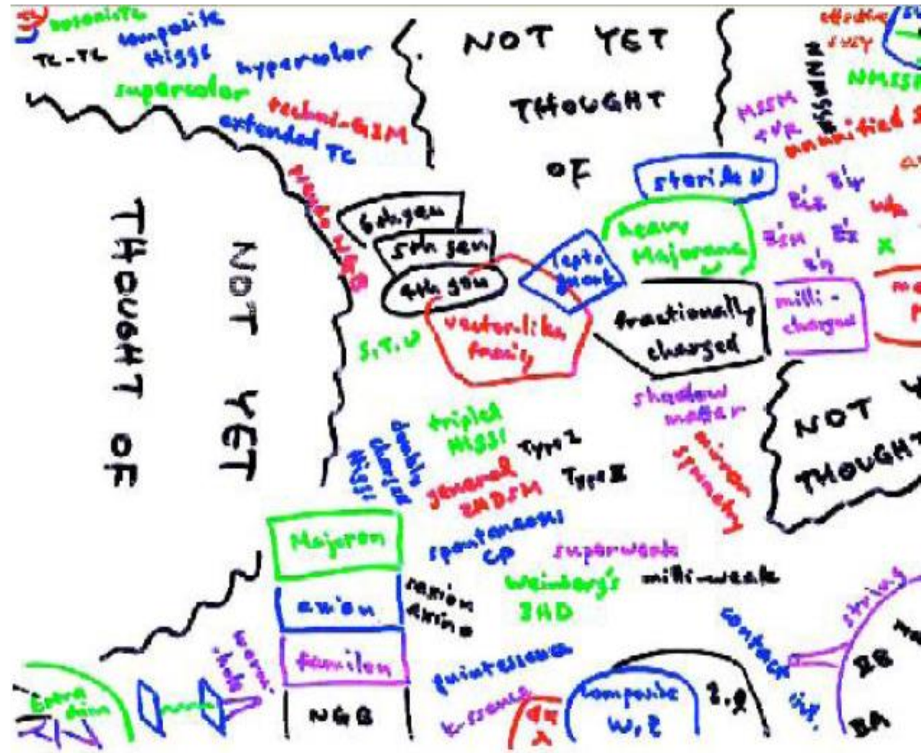


Many Searches Performed at the LHC to address open questions of SM

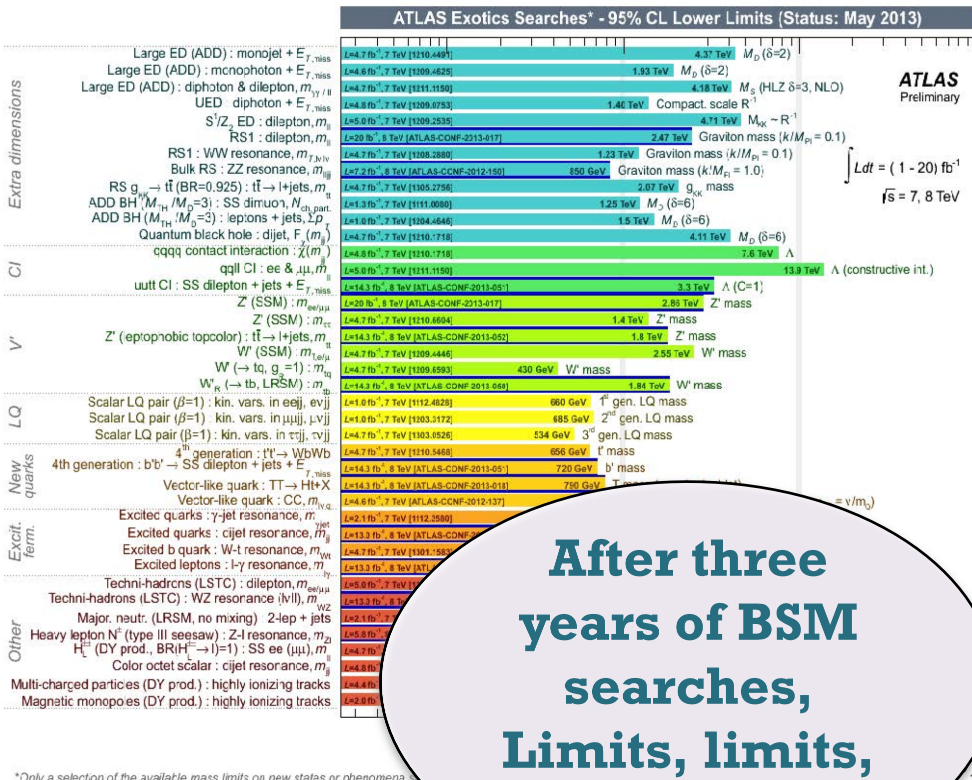
Final States allow different interpretations
Be ready for the unexpected

Searches guided by specific models trying to address open questions ⟹ beyond Higgs-boson no further new particles or phenomena yet





+ Searches guided by specific models trying to address open questions ⟹ beyond Higgs-boson no further new particles or phenomena yet



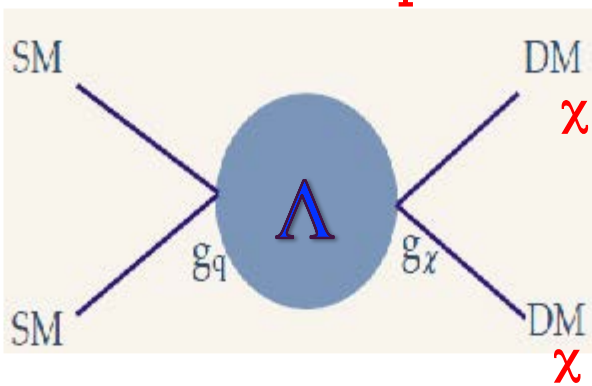
After three years of BSM searches, Limits, limits, limits....

What have we learned about dark matter?

Dark Matter at the LHC

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**

Possible Couplings

Pair production of χ can be characterized by a contact interaction with most prominent couplings

Two important couplings used by CMS are :

Vector coupling (V)

- Spin-independent (SI)

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Axial-Vector coupling (AV)

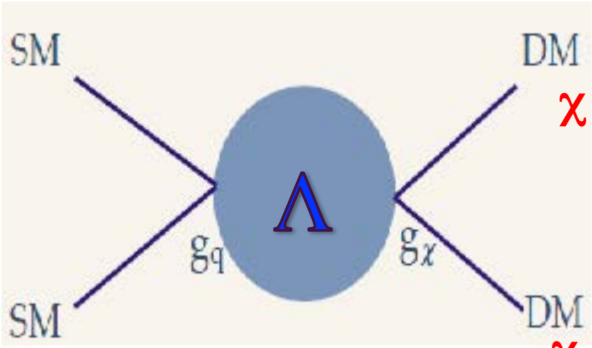
- Spin-dependent (SD)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Dark Matter at the LHC

pp collisions

Pair of DM particles



χ

χ

Mediator of mass M

Cross section depends on the mass (**mχ**) and scale Λ (for couplings gχ, gq)

Spin-Independent (SI) and Spin-dependent (SD) cross sections

Charaterizing parameters:

a) Scale of effective interaction

$$\Lambda = M/\sqrt{g_\chi g_q}$$

b) Mass mχ

[Bai, Fox and Harnik, JHEP 1012.048 (2010)]

[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010(2010)]

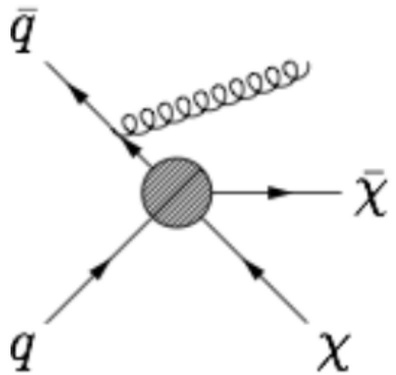
$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4}$$

$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

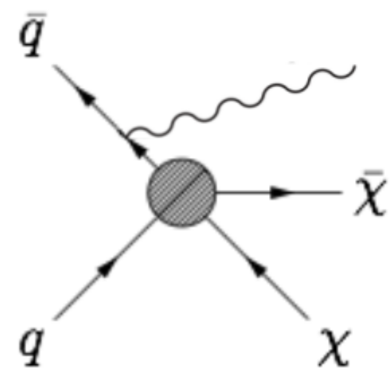
$$\mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

How to make DM visible at the LHC?

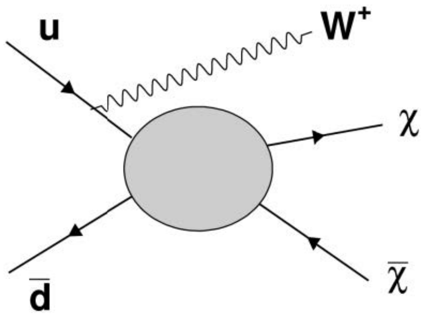
Mono-X Signatures – simple and striking



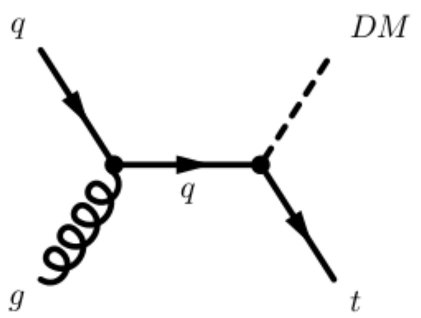
Monojet+MET
CMS-PAS-EXO-12-048
Full 2012 dataset 20/fb

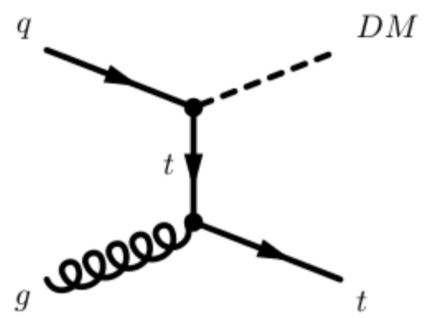


Monophoton+ MET
CMS-PAS-EXO-12-047
Full 2012 dataset 20/fb

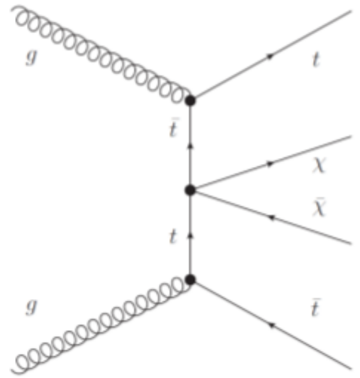


MonoW+ MET
CMS-PAS-EXO-13-004
Full 2012 dataset 20/fb



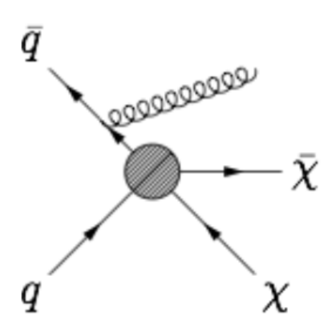


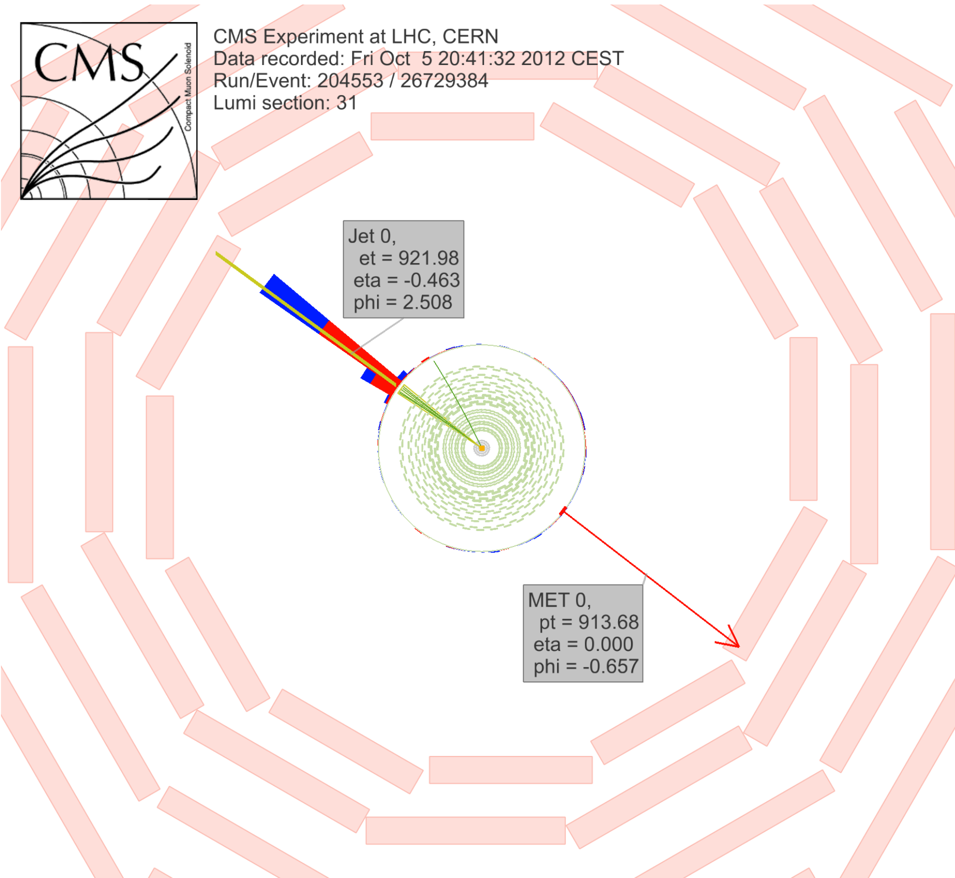
Monotop+MET
CMS-PAS-B2G-12-022



Bbbar/TTBar
CMS-PAS-B2G-13-004

Search for Pair Produced Dark Matter in **Monojet** Channel





Signature: high p_T jet + MET

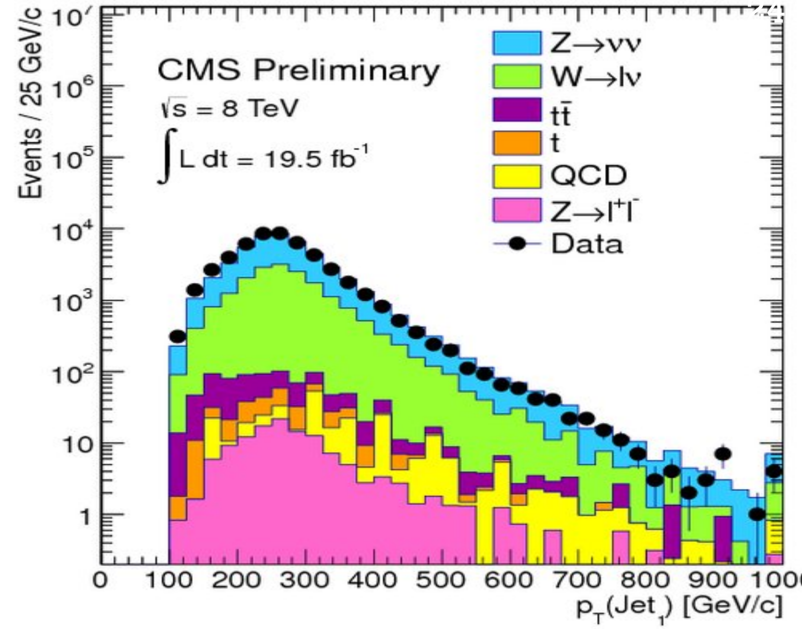
CMS-PAS-EXO-12-048 (20/fb)

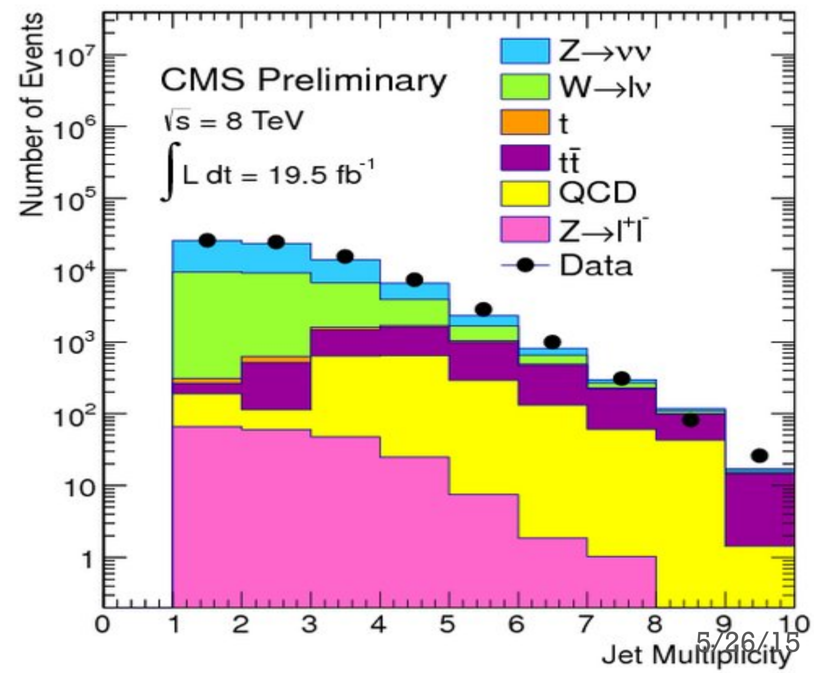
Channel to start DM searches at colliders
2012 results

Event Selection

Search for single jet recoiling against MET

- Good primary vertex
- Large missing E_T > 250 GeV
- Anti-kT jet with R=0.4 within $|\eta|$< 2.4
  - p_T >110 GeV
- Allow for second jet with p_T > 30 GeV if
  - $\Delta\Phi$ (j1,j2) < 2.5
- Jet quality
- Lepton Veto
  - Isolated electrons, muons or hadronic taus with p_T >10 GeV (20 GeV) for tau

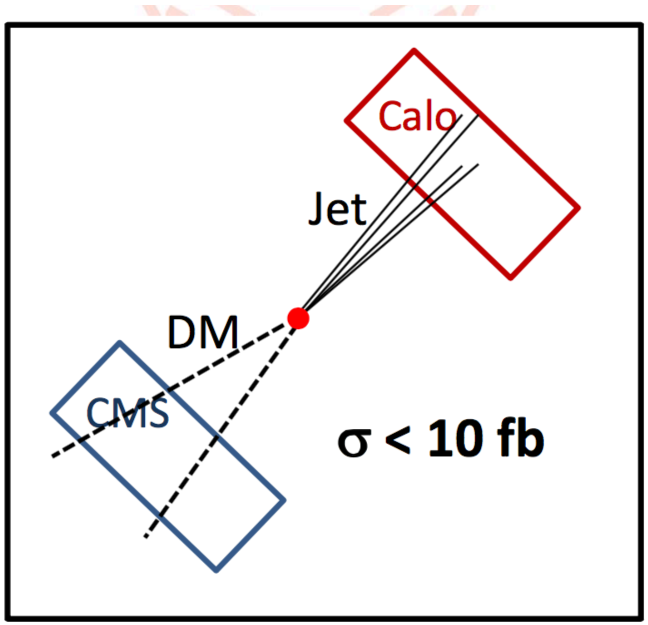




Signal

Search for single jet recoiling against MET

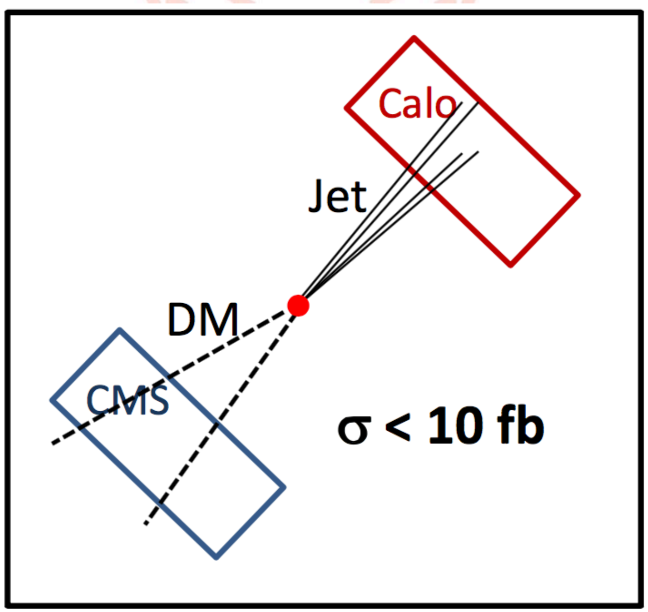
- DM is undetectable → MET
- Jet to balance p in transverse plane
  - High p_T object

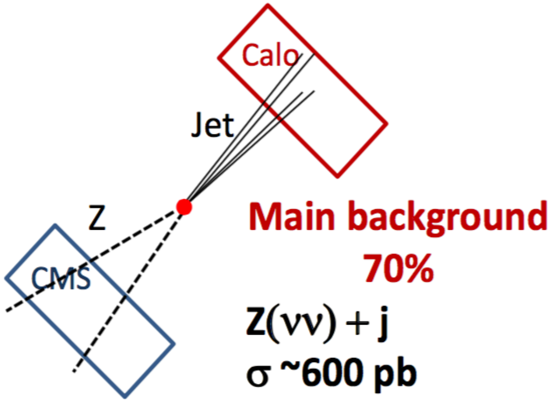


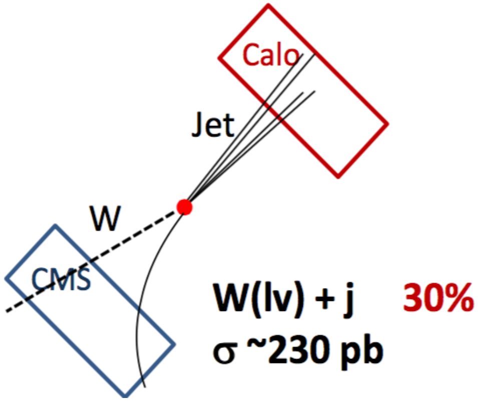
Signal and Background

Search for single jet recoiling against MET

- DM is undetectable → MET
- Jet to balance p in transverse plane
  - High p_T object







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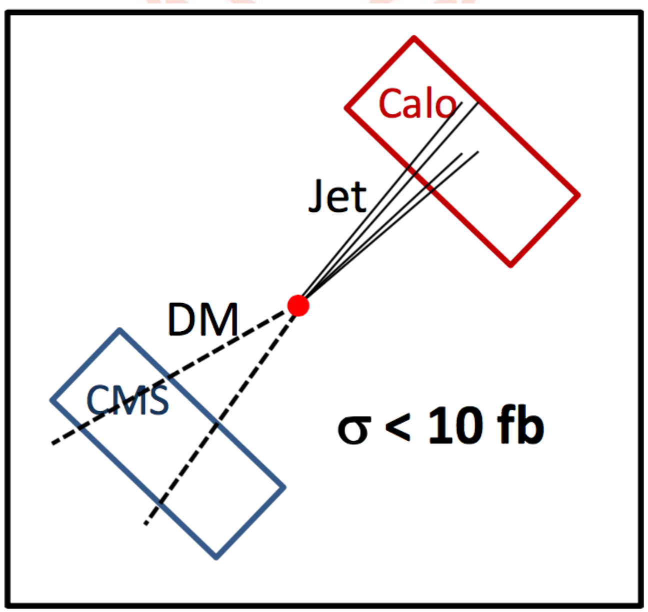
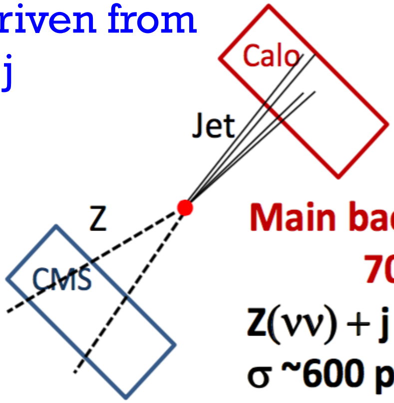


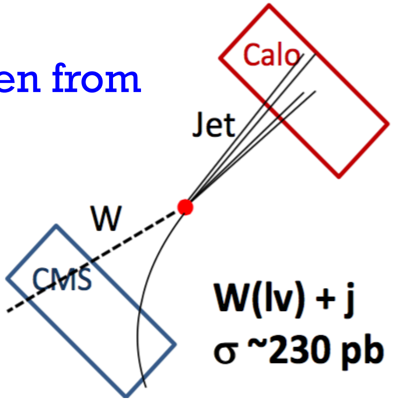
Data driven from $Z(\mu\mu)$+j



Main background 70%

$Z(\nu\nu) + j$
σ ~600 pb
irreducible

Data driven from $W(\mu\upsilon)$+j



$W(l\nu) + j$ 30%
σ ~230 pb

Signal and Background

Search for single jet recoiling against MET

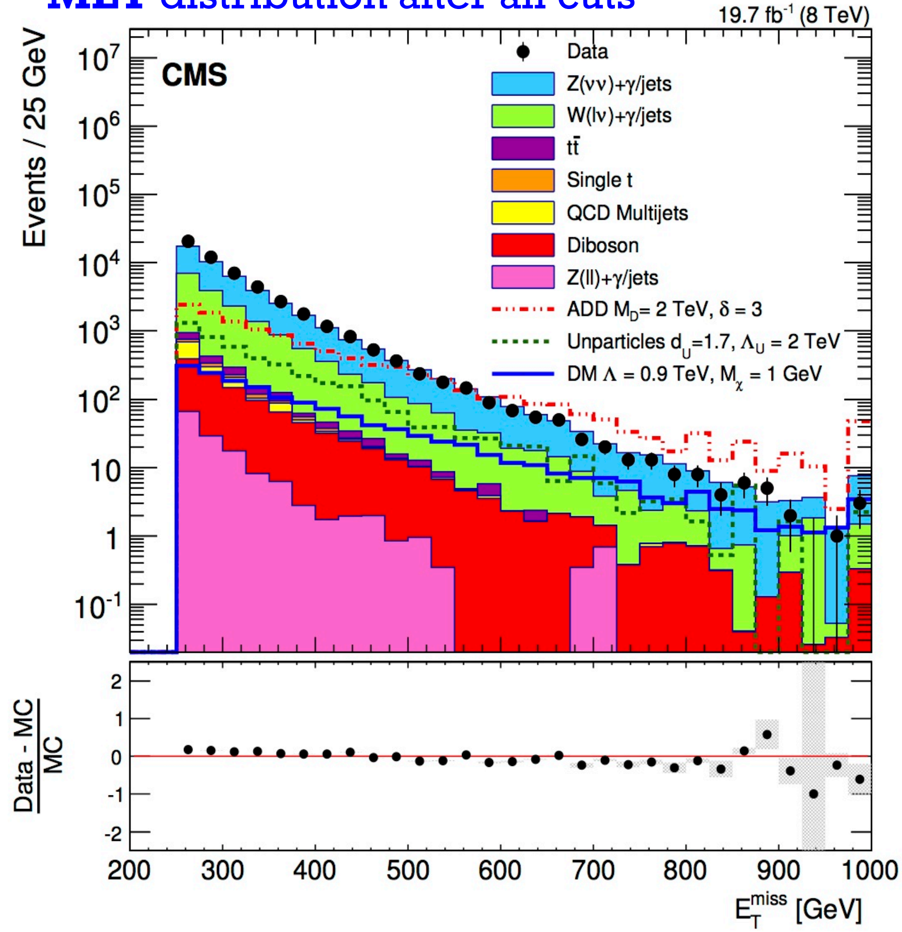
- Dominant background Z(νν)+j
  - Data driven from Z(μμ)+j

$$N(Z(\nu\nu)) = \frac{N^{obs} - N^{bgd}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$$

E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
N_{obs}	3695	1538	685	348	183	96	47
N_{bgd}	129	60	34	17	9.3	5.8	3.4
Acceptance	0.790	0.829	0.862	0.881	0.883	0.890	0.903
Efficiency	0.855	0.851	0.843	0.836	0.818	0.825	0.812
g^* corr. fac.	1.023	1.023	1.023	1.023	1.023	1.023	1.023
$N(Z(\nu\nu))$	32097±1649	12734±719	5452±359	2735±216	1463±144	747±96	362±64

- Systematic uncertainty 5 ->15%
  - Dominated by statistics and sele efficiency

Possible signal and background in **MET** distribution after all cuts



Signal and Background

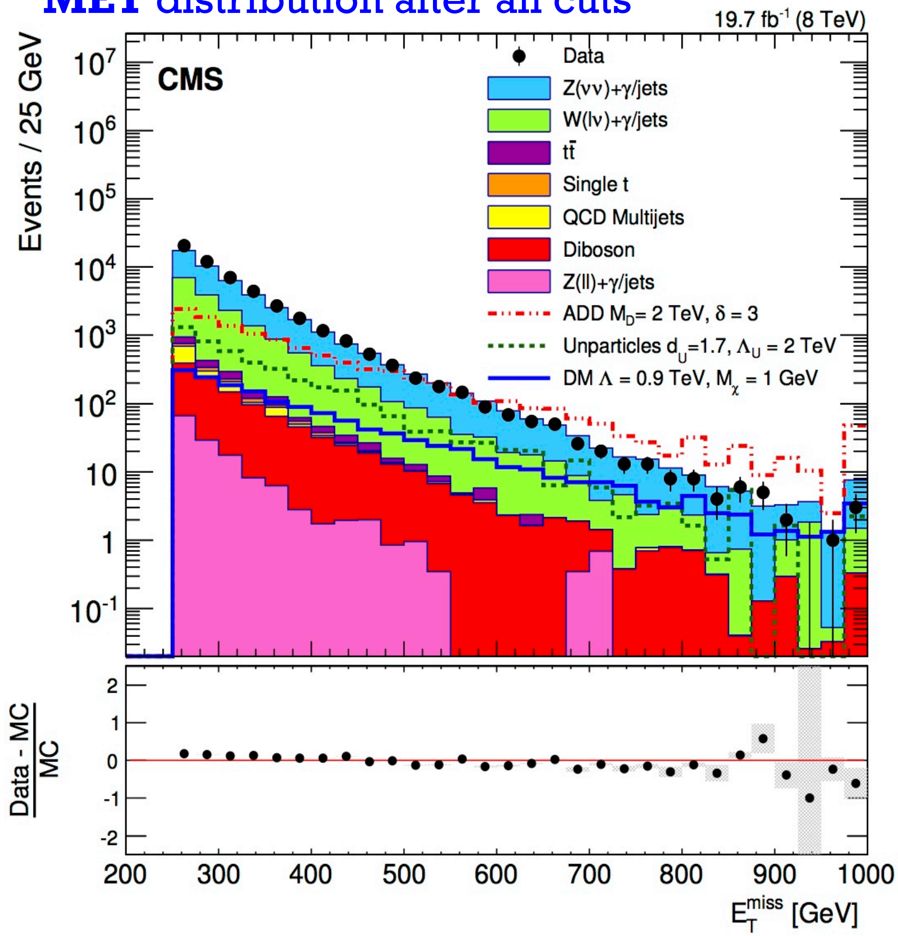
Search for single jet recoiling against MET

- Dominant background Z(νν)+j
  - Data driven from Z(μμ)+j

$$N(Z(\nu\nu)) = \frac{N^{\text{obs}} - N^{\text{bgd}}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$$

- W+jets (~30%) data driven
- QCD : rejected by ΔΦ cut
- EWK : veto events with isolated tracks and isolated leptons
- Other backgrounds are negligible (~1%), taken from MC

Possible signal and background in **MET** distribution after all cuts



Experimental Results

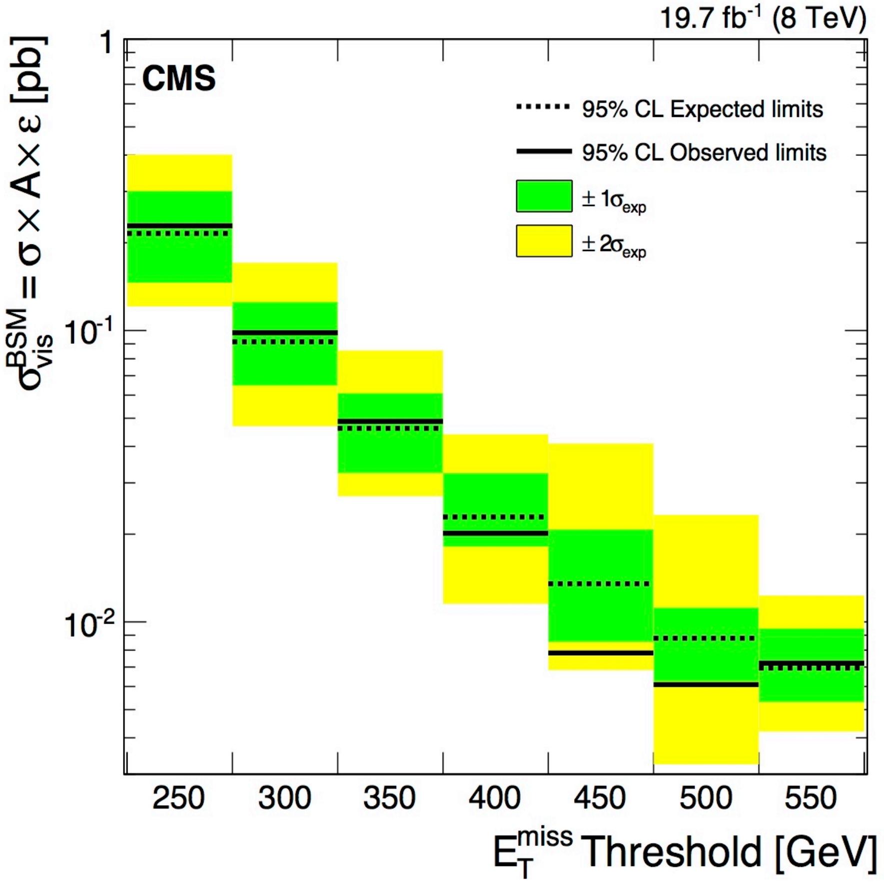
- Main experimental results : table of expected and observed
  - Simple cut and count based approach use
  - Compare expected and observed to get limits on new physics (alas, no evidence)
  - Limits on new physics (cross section) proportional to the (systematic) error on background.

- "Generic" results very useful (next slide)

E_T^{miss} (GeV) $\rightarrow$	>250	>300	>350	>400	>450	>500	>550
$Z(\nu\nu)$+jets	32100 ± 1600	12700 ± 720	5450 ± 360	2740 ± 220	1460 ± 140	747 ± 96	362 ± 64
W+jets	17600 ± 900	6060 ± 320	2380 ± 130	1030 ± 65	501 ± 36	249 ± 22	123 ± 13
$t\bar{t}$	446 ± 220	167 ± 84	69 ± 35	31 ± 16	15 ± 7.7	6.6 ± 3.3	2.8 ± 1.4
$Z(\ell\ell)$+jets	139 ± 70	44 ± 22	18 ± 9.0	8.9 ± 4.4	5.2 ± 2.6	2.3 ± 1.2	1.0 ± 0.5
Single t	155 ± 77	53 ± 26	18 ± 9.1	6.1 ± 3.1	0.9 ± 0.4	—	—
QCD multijets	443 ± 270	94 ± 57	29 ± 18	4.9 ± 3.0	2.0 ± 1.2	1.0 ± 0.6	0.5 ± 0.3
Diboson	980 ± 490	440 ± 220	220 ± 110	118 ± 59	65 ± 33	36 ± 18	20 ± 10
Total SM	51800 ± 2000	19600 ± 830	8190 ± 400	3930 ± 230	2050 ± 150	1040 ± 100	509 ± 66
Data	52200	19800	8320	3830	1830	934	519
Exp. upper limit $+1\sigma$	5940	2470	1200	639	410	221	187
Exp. upper limit -1σ	2870	1270	638	357	168	123	104
Exp. upper limit	4250	1800	910	452	266	173	137
Obs. upper limit	4510	1940	961	397	154	120	142

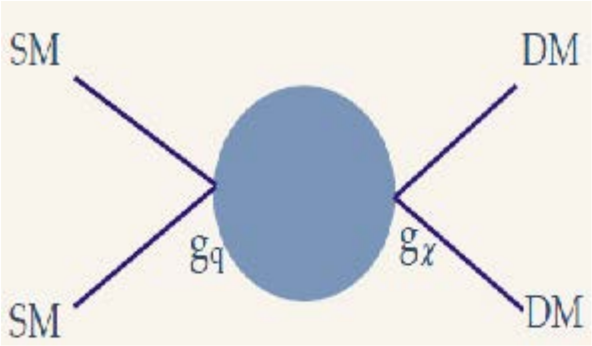
Monojet Model Independent Limits

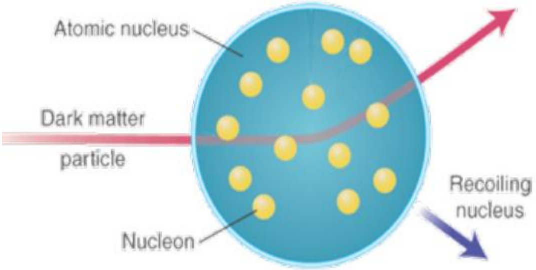
- Search performed in bins of MET
- CMS quote model-independent limits for generic applicability to SUSY compressed spectra, invisible Higgs or any other "monojet" signature



Translate production cross-section limit into DM-nucleon limit

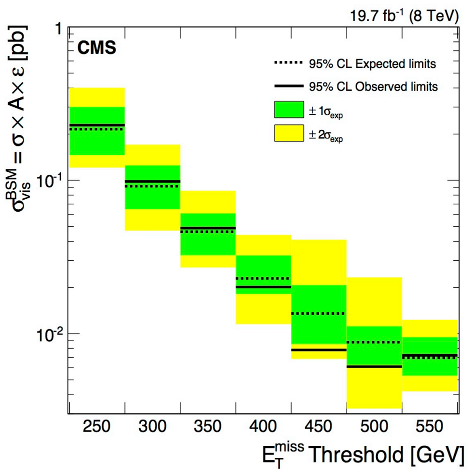
- Purpose : to compare to direct detection limits





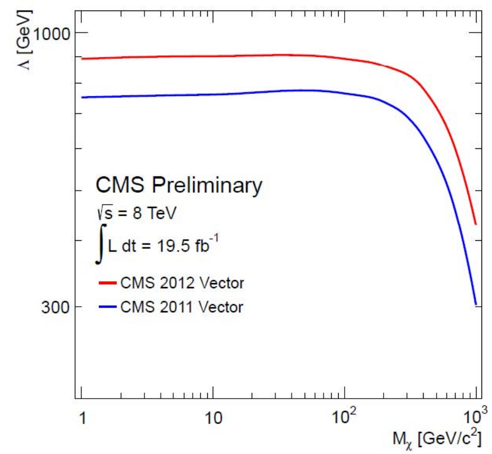
EFT to translate limits to same plane as direct detection limits

Experimental results

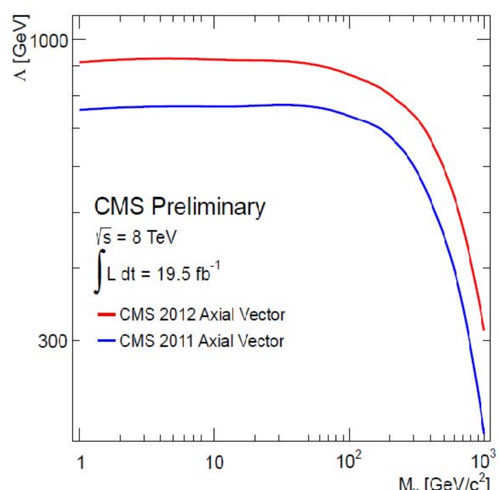


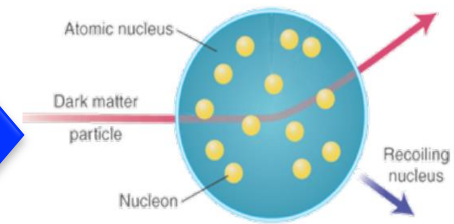
Convert pp xsec limit into Λ

Vector



Axial-Vector



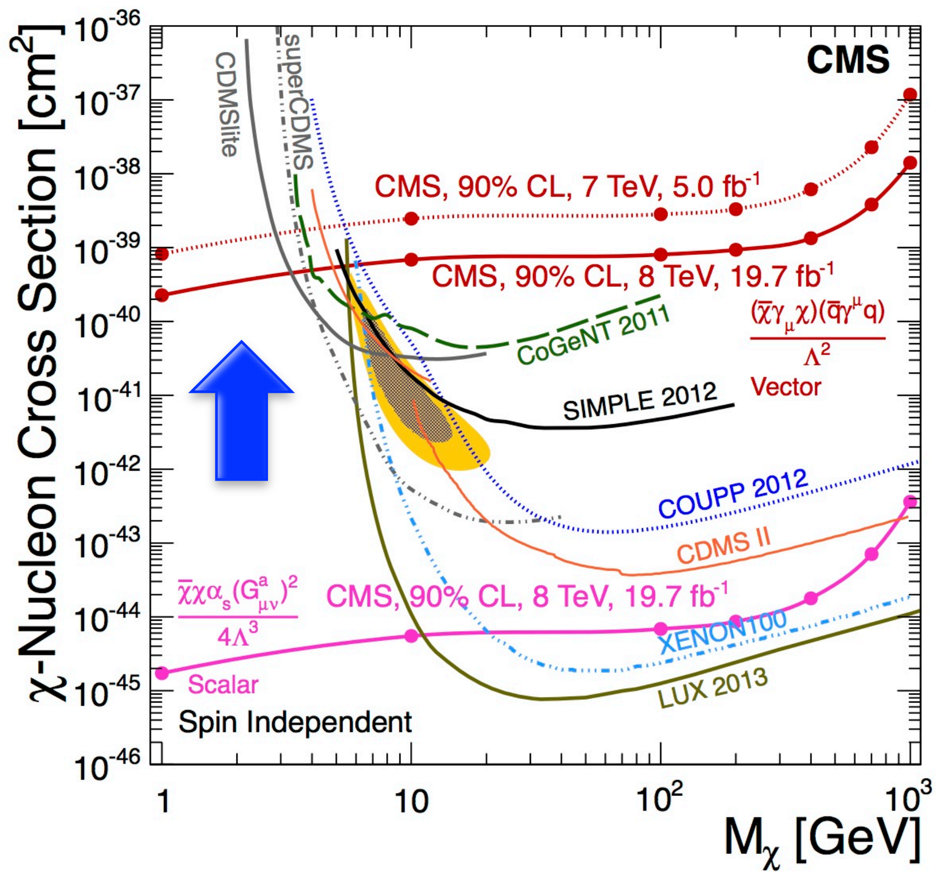


$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4}$$

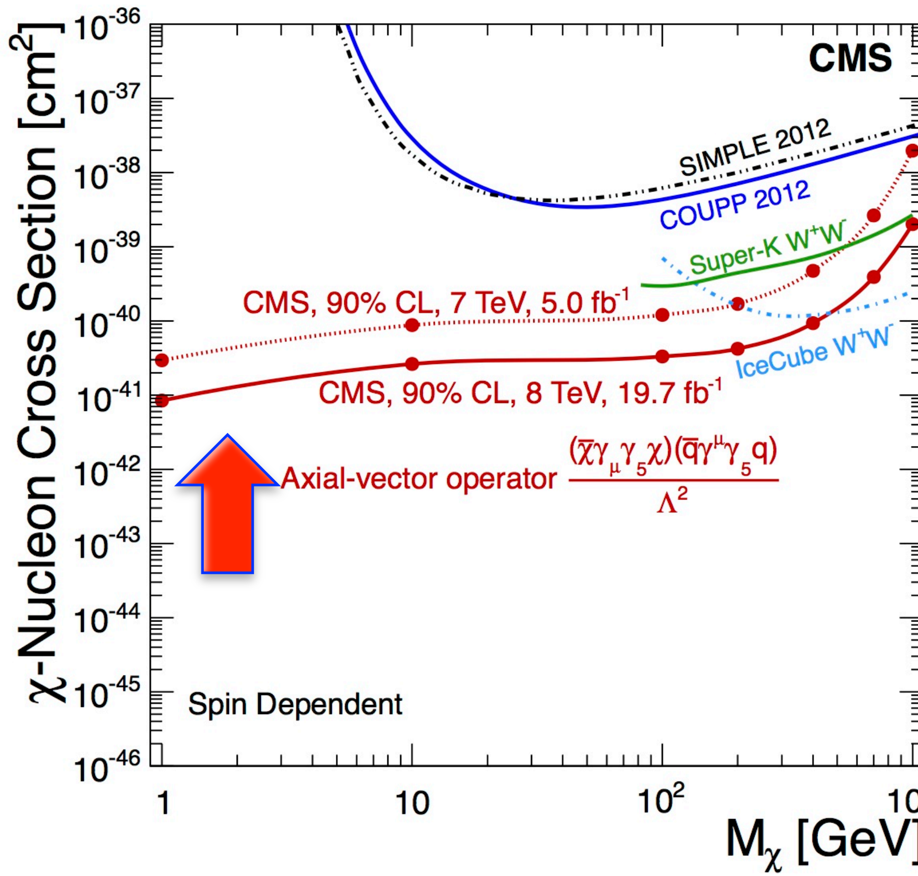
$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

DM-Nucleon limits

Spin-Independent



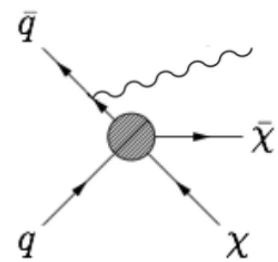
Spin-Dependent

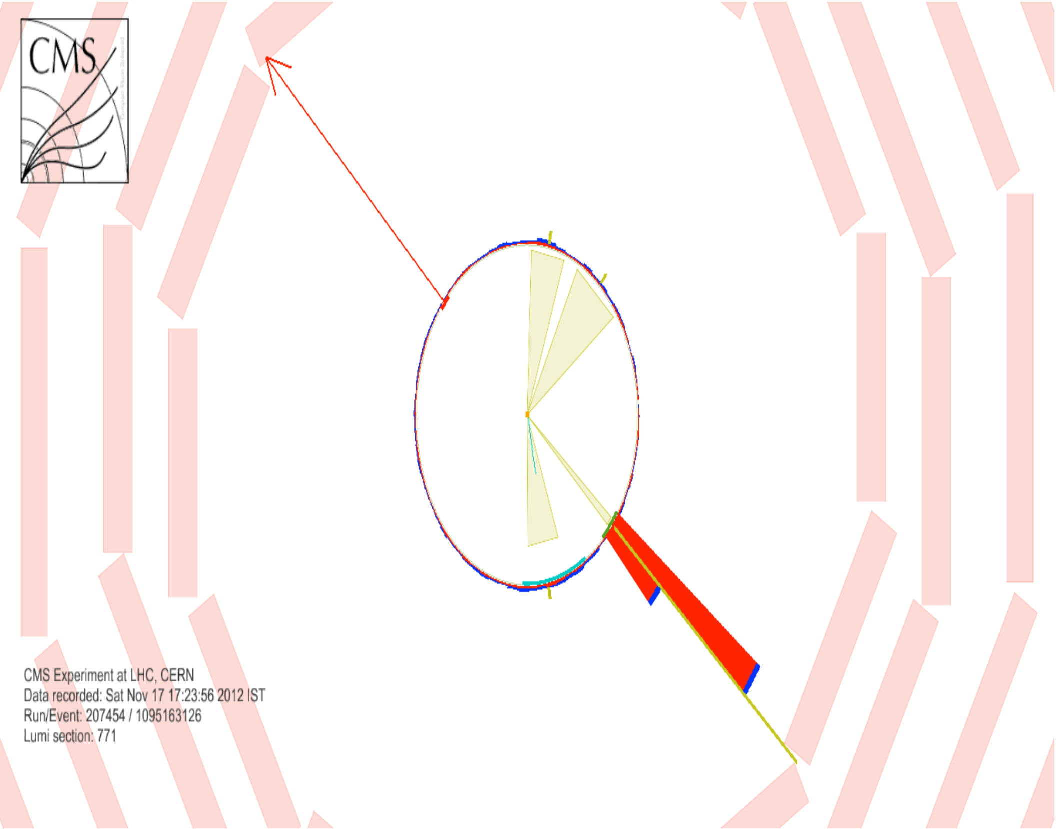


LHC can access very low DM masses

Exclude large cross sections for SD case

Search for Pair Produced Dark Matter in **Monophoton** Channel





Signature: high p_T photon+MET

CMS-PAS-EXO-12-047 (20/fb)

New 2012 results

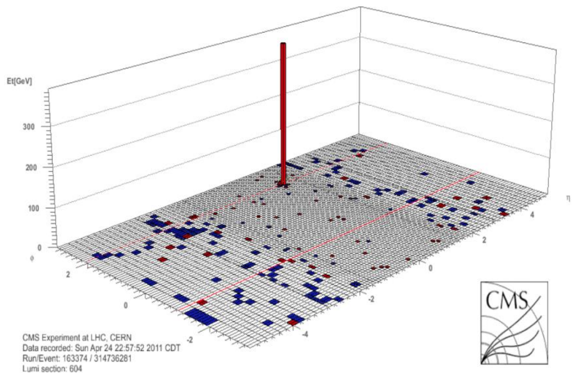
Event Selection

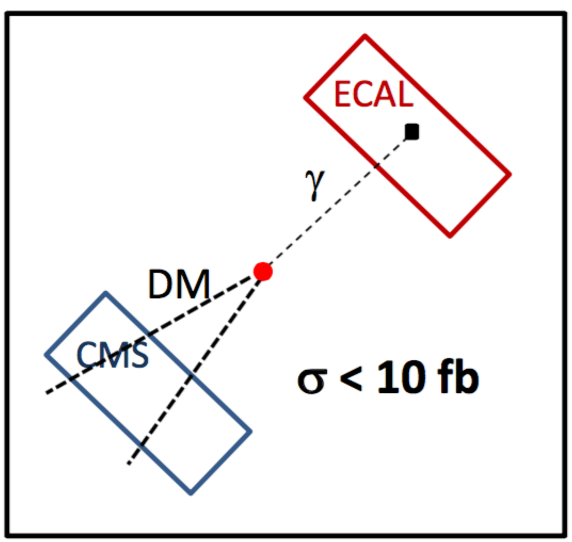
Search for single photon recoiling against MET

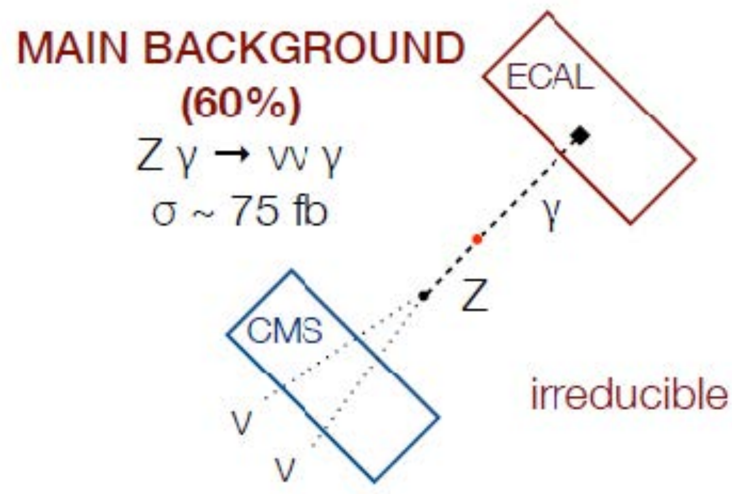
- Good primary vertex
- One energetic photon p_T >145 GeV, $|\eta|$< 1.44
- MET > 140 GeV
- Veto
  - Jet Veto : veto events if second jet p_T > 30 GeV
  - Lepton Veto
    - Isolated electrons, muons with p_T >10 GeV
  - Veto on pixel seed (hit patterns in the pixel detector)
- $\Delta\Phi$ (photon, MET) > 2
- Reduce fake met using minimized MET criteria

Signal and Background

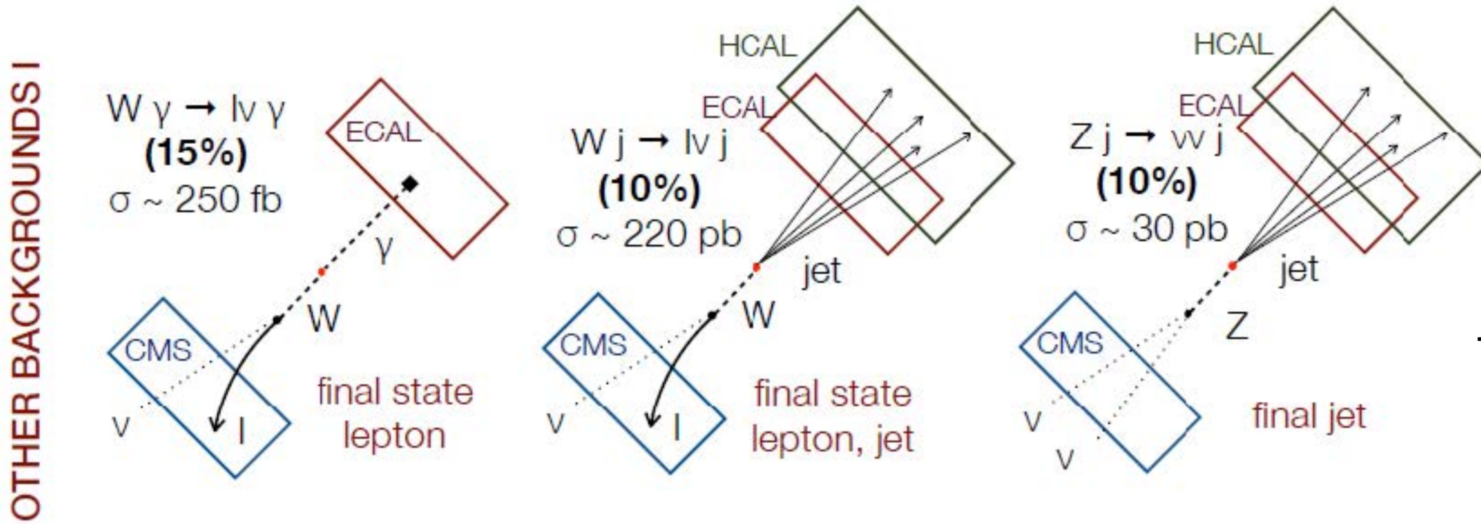
Search for single photon recoiling against MET







Signal and Background



+gj, jj, gg < 5%

Instrumental backgrounds (~30%) from misindentification and beam halo

SM backgrounds (~70%)
Needs good understanding of cross sections for Zγ, Wγ

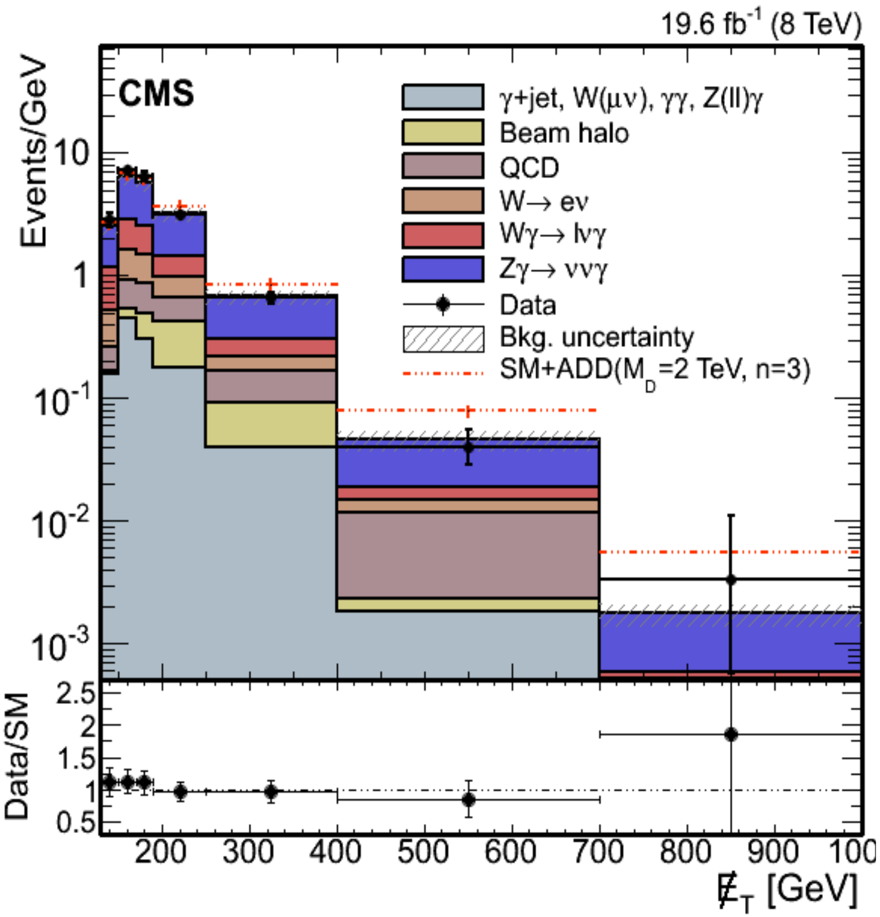
NLO corrections : $p_T(\gamma)$ dependent SF for Zγ (~1.4 global) and Wγ (~1.5 global)

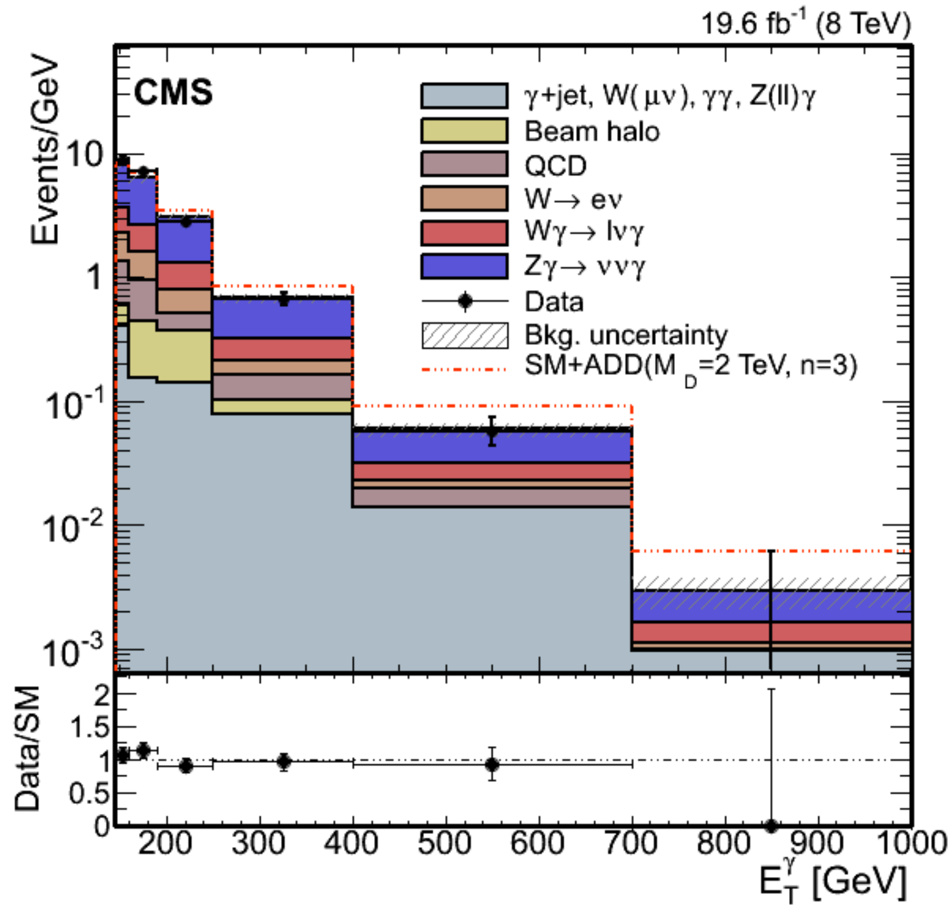
Process	Estimate
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	345 ± 43
$W(\rightarrow \ell\nu) + \gamma$	103 ± 21
$W \rightarrow e\nu$	60 ± 6
jet $\rightarrow \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	614 ± 63
Data	630

Monophoton Results

Good agreement with data

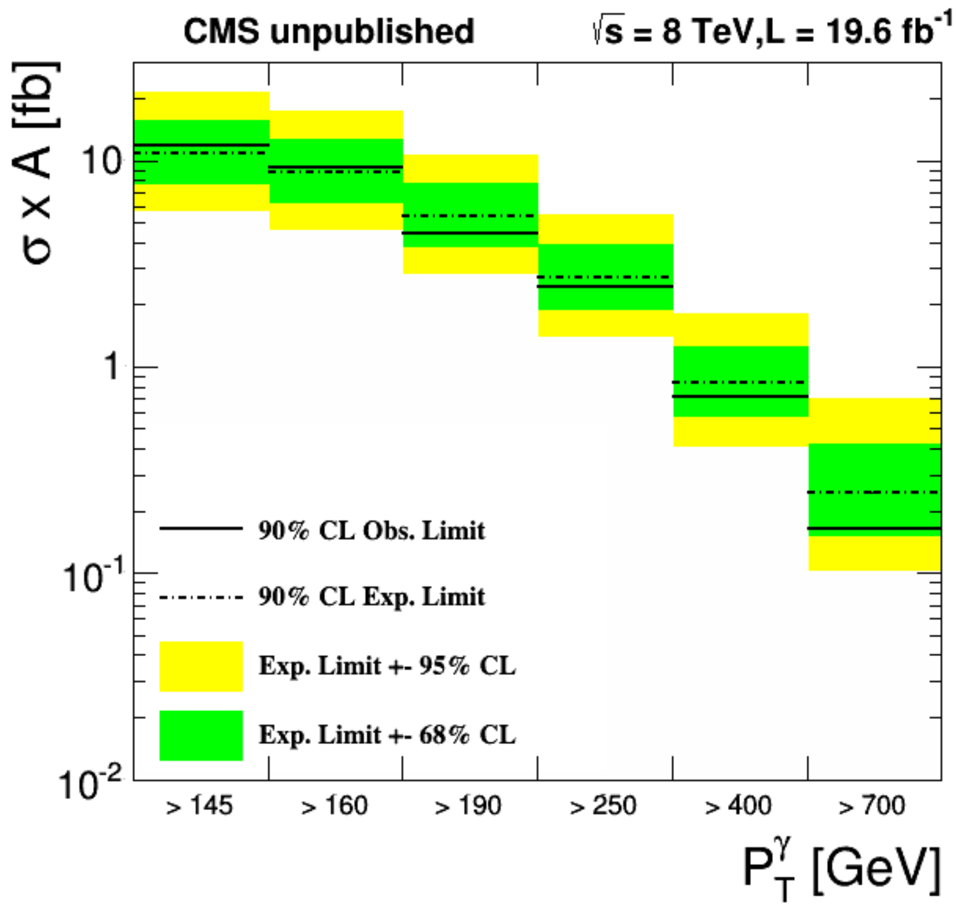
Observed : 630 events, Expected : 614 +/- 63 events





+ Monophoton Model Independent Limits

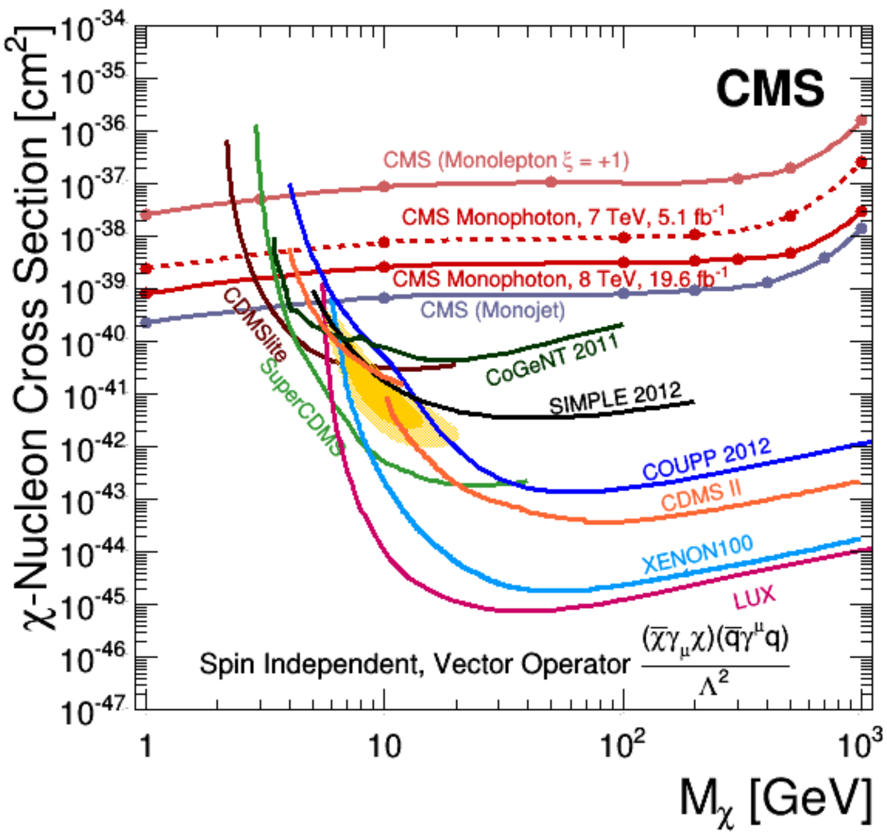
- Set limits on cross section within acceptance (σ x A)
  - Computed as a function of increasing cut of photon p_T
  - Most general result as can be interpreted with any signal given acceptance

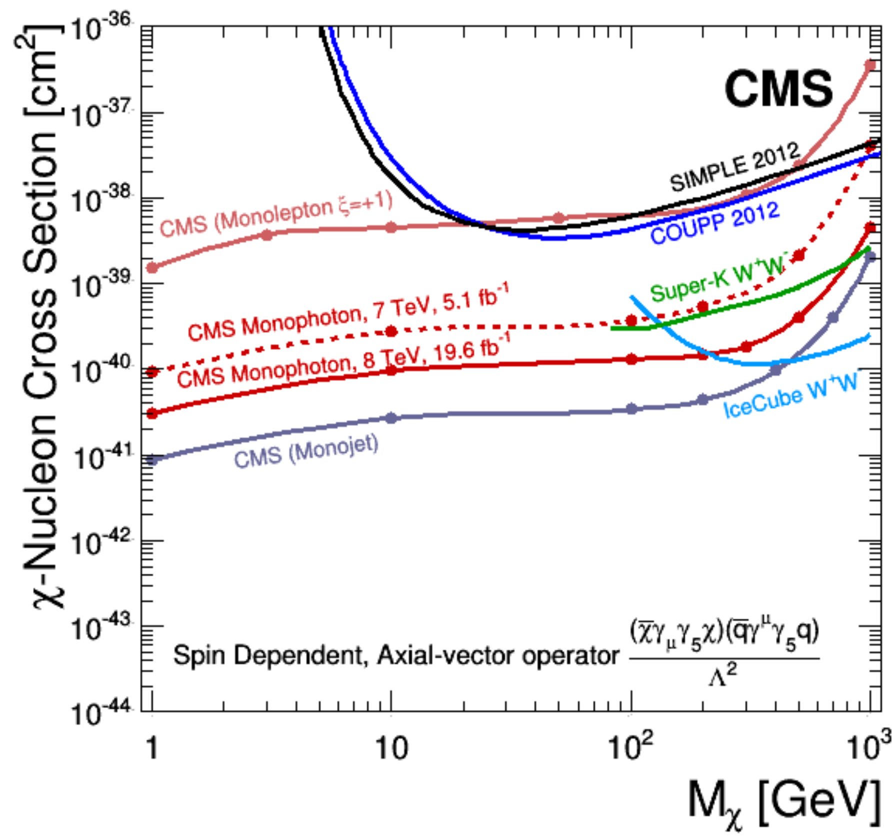


+ DM-Nucleon Cross Section limits

11

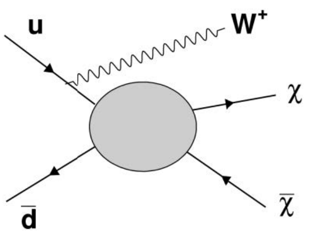
Model-independent 90% CL upper limits on cross section
11 fb (V and AV) for M_χ < 200 GeV → Λ > 700 GeV

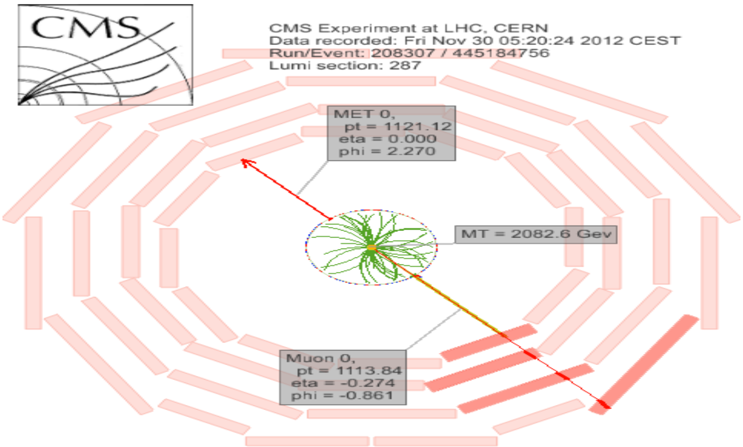


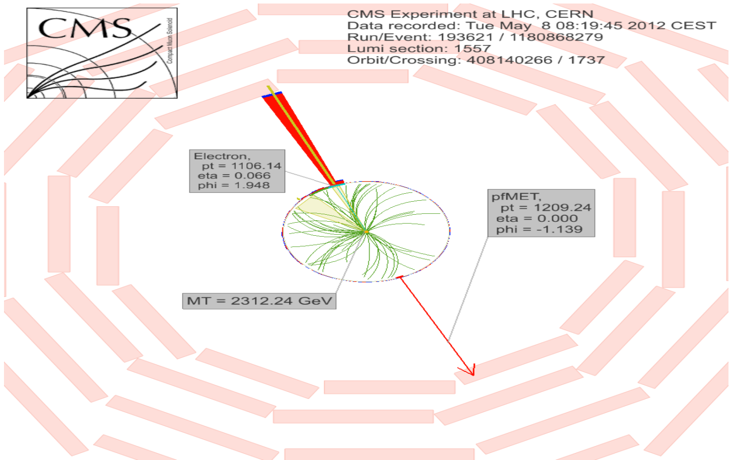


10 x times higher sensitivity with 8 TeV statistics

Search for Pair Produced Dark Matter in **Monolepton** 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

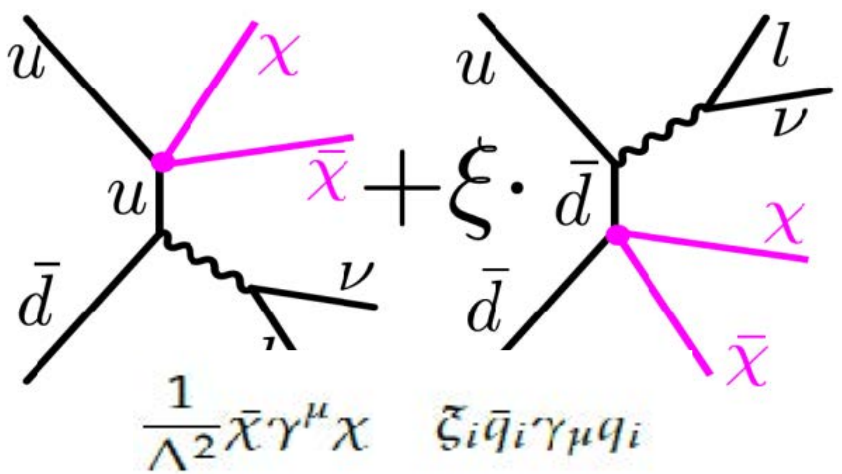
New 2012 results

Interference

- Mono-jet/photon channel insensitive to quark type
- For W possibly different coupling to u- and d-type quarks

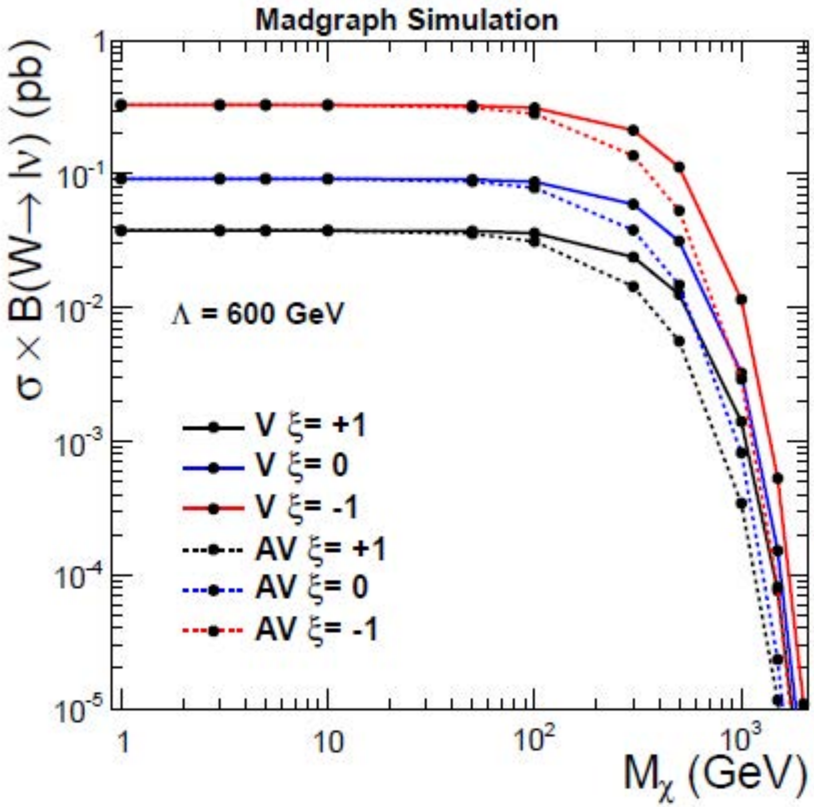
If [C(u) = C(d)] destructive interference

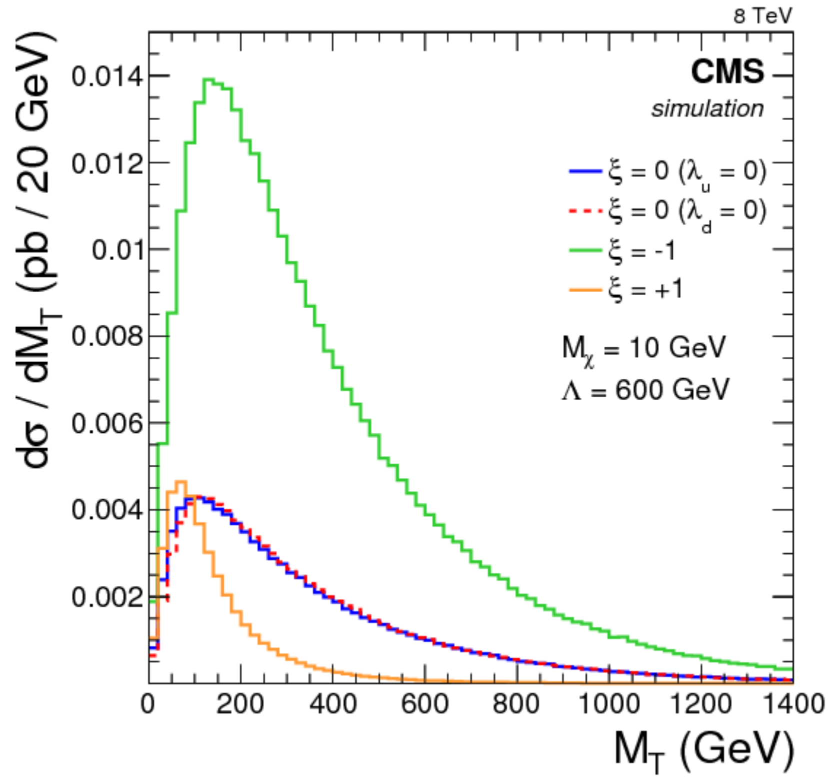
If [C(u) = -C(d)] constructive interference → mono-boson more sensitive than mono-jet



Neutrino+DM contribute to MET

+ 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

+ Monolepton Selection

Event Selection

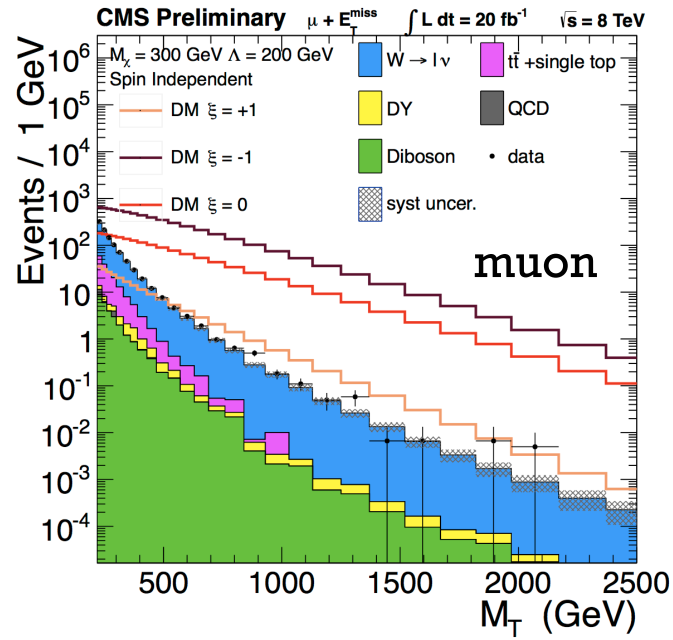
- Single electron (muon) trigger with p_T>85(40) GeV
- Kinematics selection:
  - $0.4 < p_T / MET < 2$
  - $\Delta\Phi > 2.5$

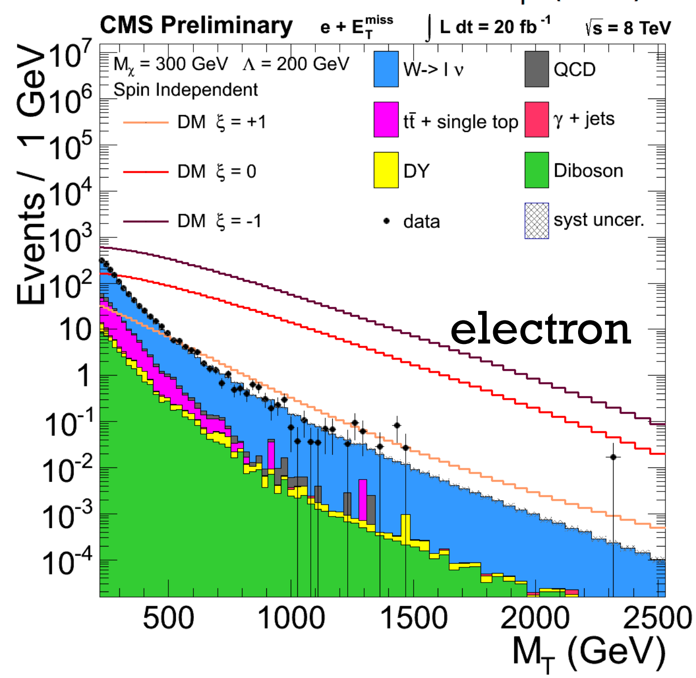
Transverse Mass distribution

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

Background

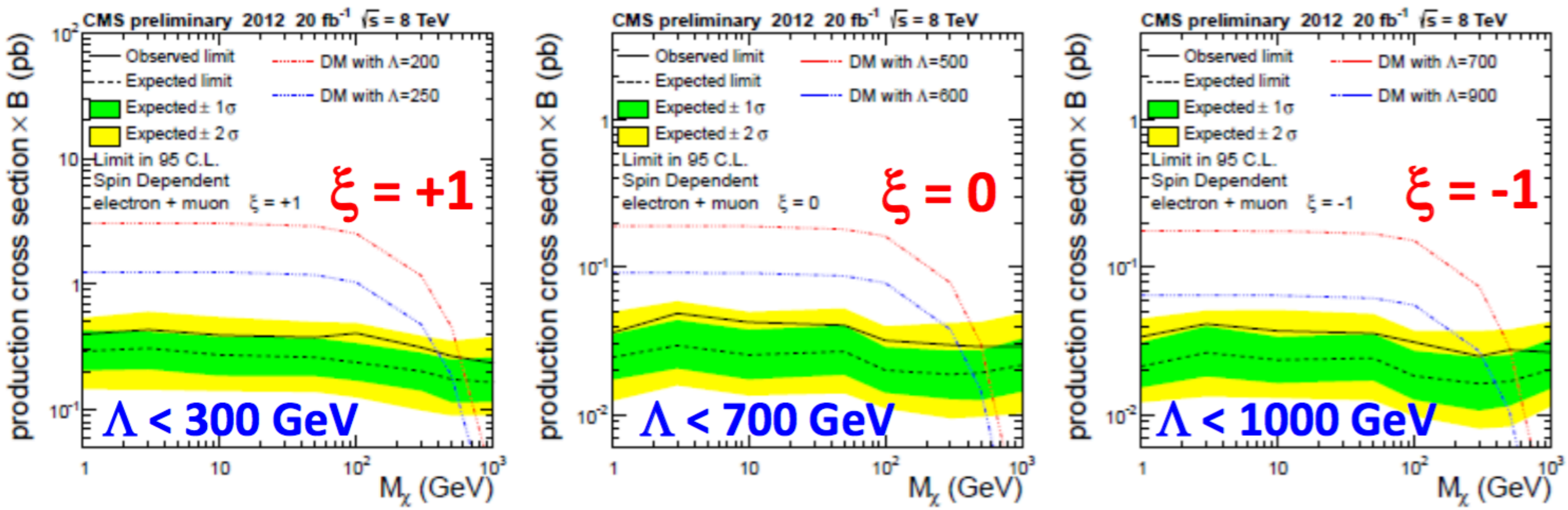
- Derived from simulation
- Challenge High MT tail
- Main bkg : W->ln with MT binned K-factor
- NLO xsec



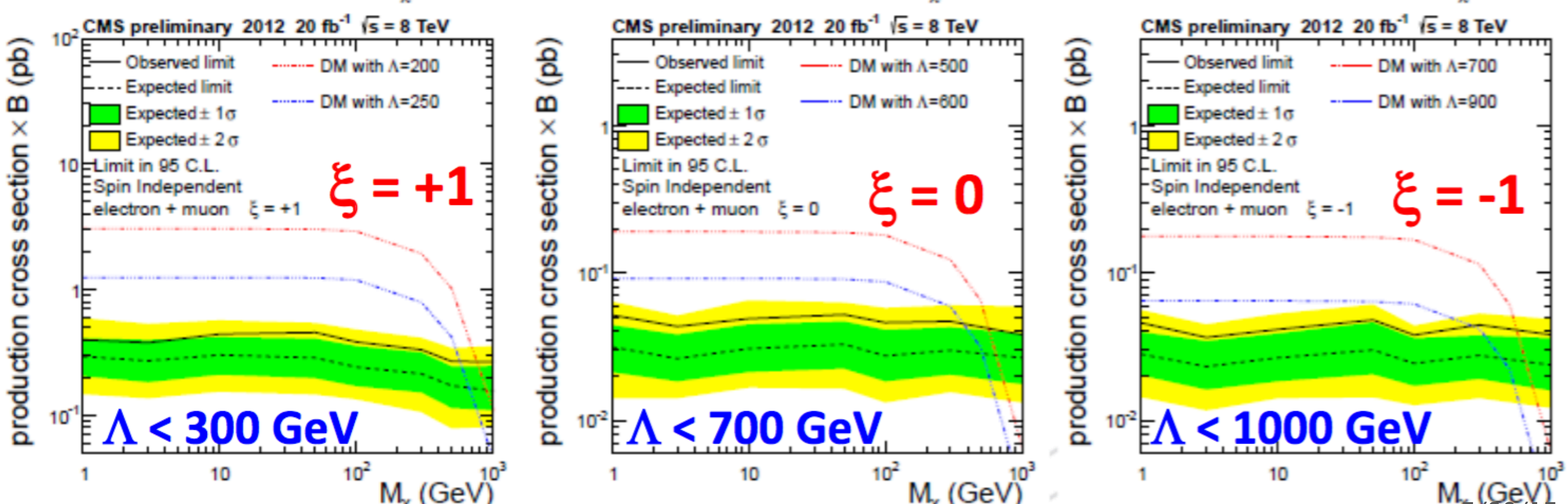


Limits on production cross section

V Spin In-dependent

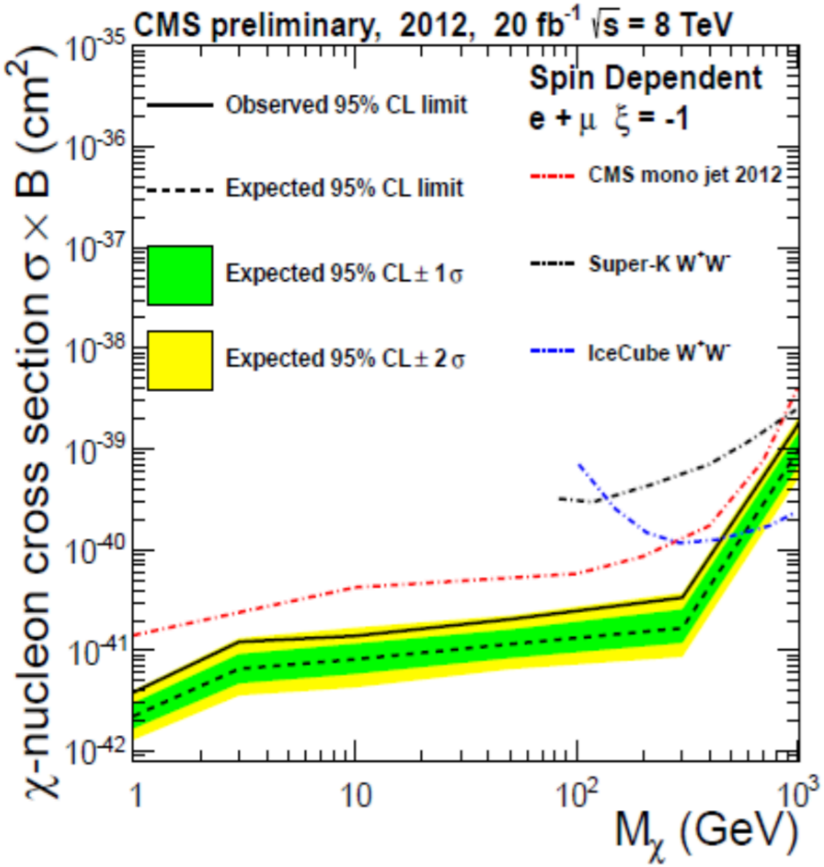


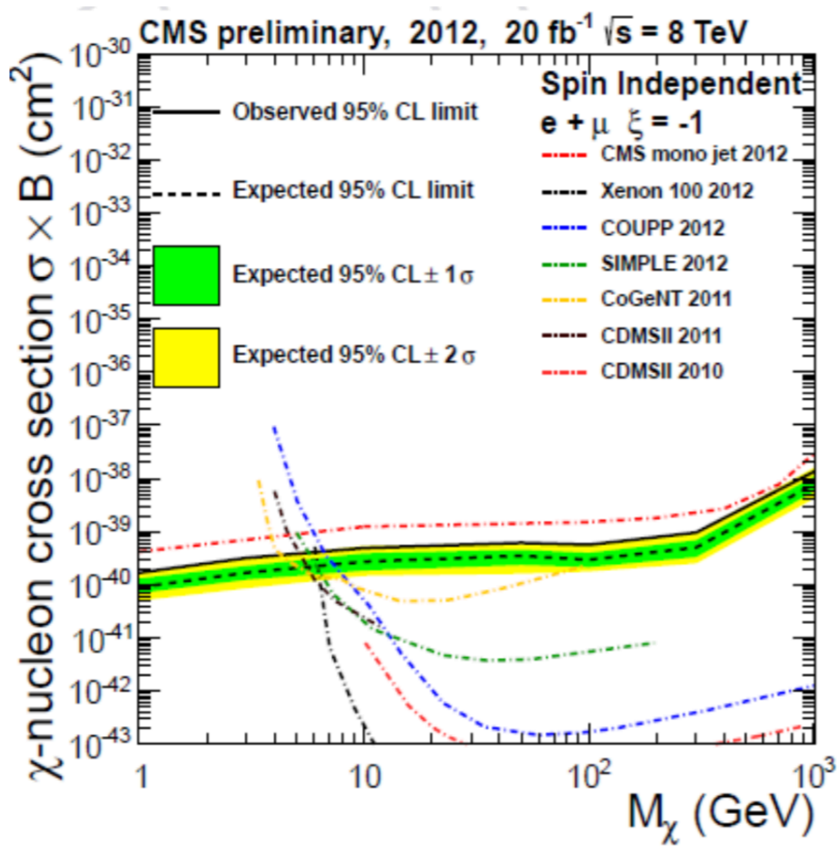
AV Spin depen dent



+ Monolepton ξ= -1 (max. Sensitivity)

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



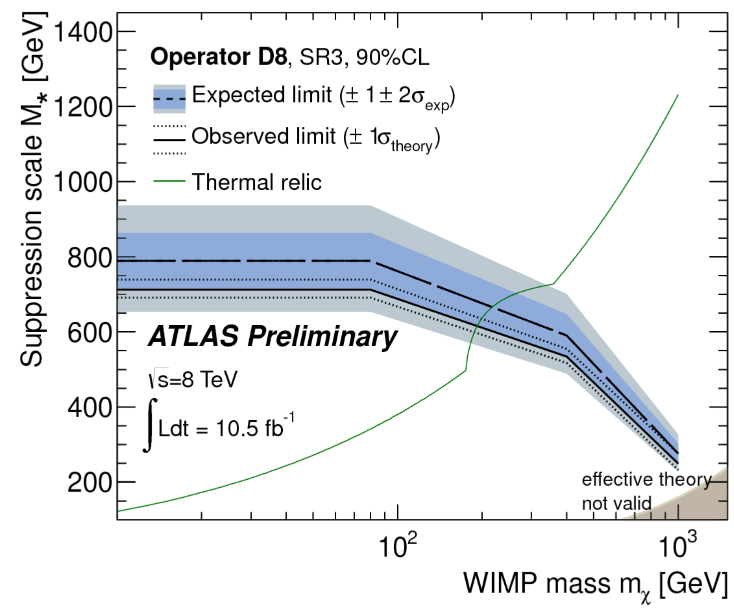


Validity of the EFT

Busoni, De Simone, Morgante, Riotto, arXiv: 1307.2253

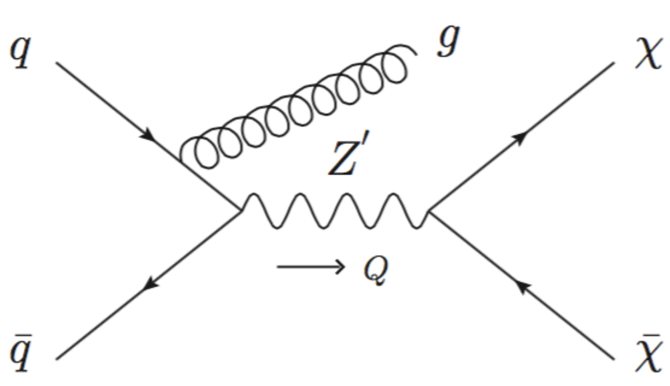
- EFT is strictly valid when $q^2 << M^2$ and $M > m_\chi$
- For the theory to be calculable, one further needs $g_\chi, g_q < 4\pi$, which implies : $\Lambda > m_\chi/4\pi$
- Further, from kinematics of the s-channel exchange, $q^2 > (2m_\chi)^2$
- Now since $2m_\chi < q < M$, implies $\Lambda > m_\chi/2\pi$
- This is important condition to keep in mind
  - This is the ATLAS monojet limit; it applies for $m_\chi <\sim 1$ TeV

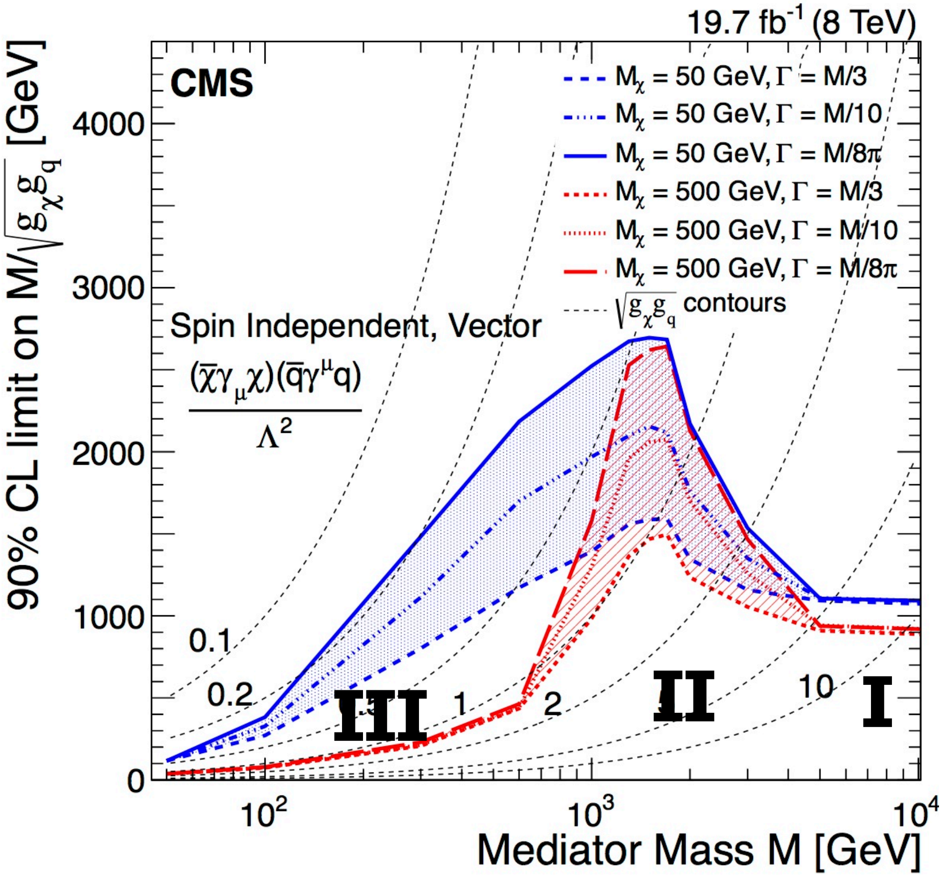
ATLAS , arXiv: 1309.4017



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

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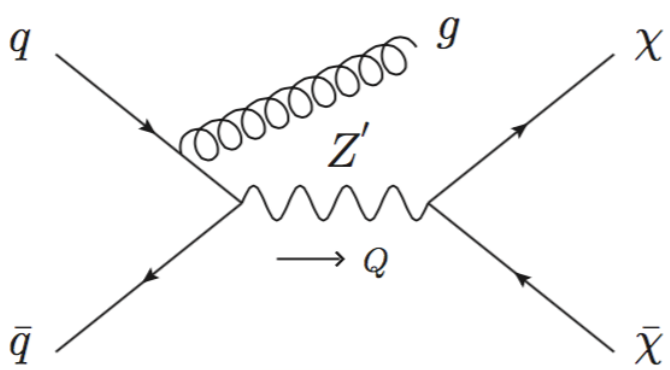

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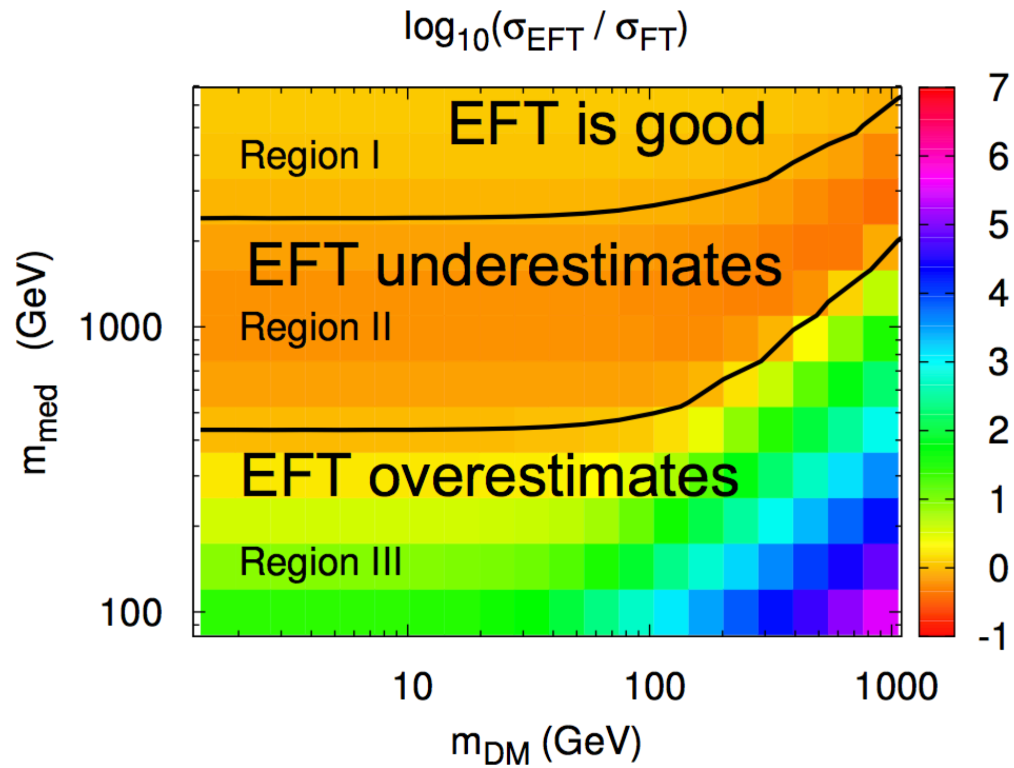


Buchmeller, Dolan, McCabe, arXiv : 1308.6799

What's Next

- Signature oriented searches strongly supported by theory
- Extend simple contact interaction
  - A new ATLAS-CMS DM forum along with theorist formed in January 2015.

    https://twiki.cern.ch/twiki/bin/view/LHCDMF/Mandate

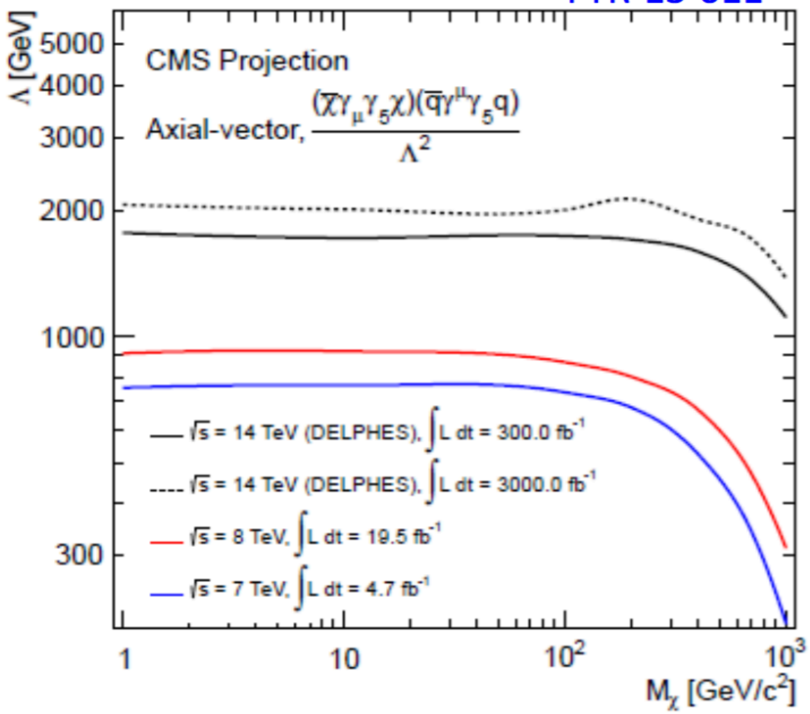
  - Main focus to decide on small set of benchmark simplified models by both collaborations for Run-2 searches
- Simplified Models : Summary from ATLAS-CMS DM forum

m_{DM} (GeV)	m_{med} (GeV)									
1	10	20	50	100	200	300	500	1000	**2000**	5000
10	10	15	50	100						5000
50	10		50	95	200	300				5000
150	10				200	295	500			5000
500	10						500	995	***2000***	5000
1000	*10*							*1000*	***1995***	*5000*

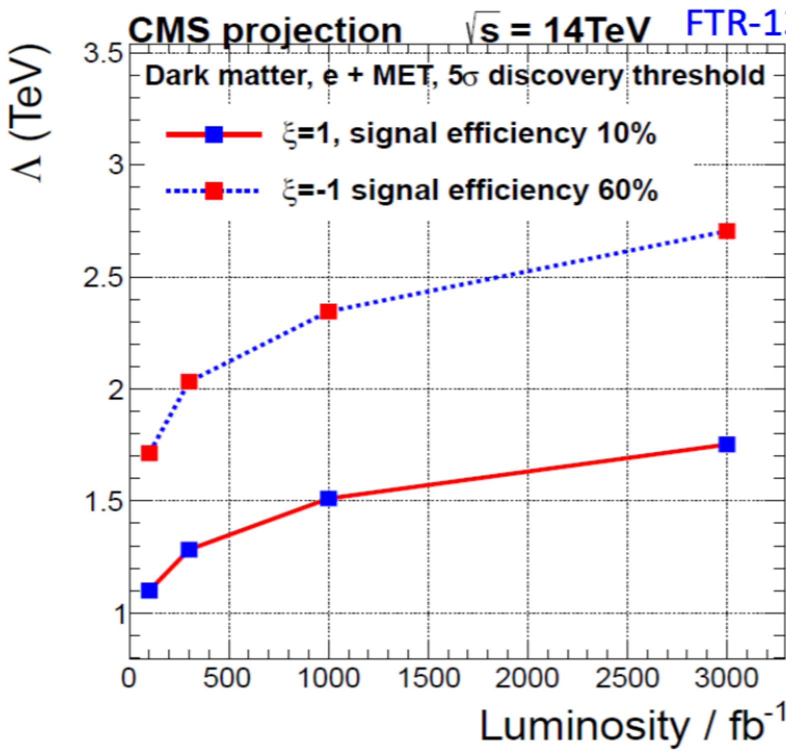
Table 1: Simplified model benchmarks for all s-channel simplified models (spin-1 and spin-0 mediators decaying to Dirac DM fermions taking the minimum width for $g_q = g_{DM} = 1$). Points in **bold** are only generated for the V and A cases, while points in *italics* are generated for the monojet analysis (V,A,S,P cases) but not for the search including heavy quarks.

Reach at 14 TeV?

FTR-13-011



FTR-13-012



Gain sensitivity with increasing sqrt(s).

At 14TeV and 300/fb. Reach in lambda O(x2)

Main challenge MET in high PU.

+ Summary

- LHC dark matter searches are exciting.
  - Major opportunity for new physics!
- Several LHC BSM searches reintepreted in terms of dark matter models.
- Work closely with theorists to develop therotical assumptions and models.
- Complementary to direct detection experiments. Study DM properties in case of discovery
- Improved sensitivity in Run-2 of the LHC

Backup

Cross Section Comparison

- The cross section of DM interaction in DD experiments is given by: $\sigma_{DD} = g_\chi^2 g_q^2 \frac{\mu^2}{M^4}$
  - Here g_χ and g_q are the mediator couplings to DM and quarks, M is the mediator mass, and μ is the reduced mass of DM-nucleon
- In contrast, at colliders one deals mainly with the s-channel exchange, which gives for, e.g. a monojet production:

$$\sigma_{1j} \sim \begin{cases} \alpha_s \, g_\chi^2 \, g_q^2 \, \frac{1}{p_T^2} & M \lesssim p_T \, , \\ \alpha_s \, g_\chi^2 \, g_q^2 \, \frac{p_T^2}{M^4} & M \gtrsim p_T \, , \end{cases}$$

  - Here p_T is the ISR jet p_T
  - Naively, for a light mediator $\sigma_{DD}/\sigma_{1j} \sim 1/M^4$ and direct detection wins over collider constraints
  - However, there is an interesting regime of $2m_\chi < M < s^{1/2}$ where one could have two-body resonant production

Comparing DD & Colliders

- Here is where the problems start to appear
- Let's consider a scalar mediator for simplicity
- Compare the effective four-point interaction with the matrix element given by:

$$\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$$

  with the s-channel exchange expression for heavy mediator, when the propagator is just $-1/M^2$

$$\mathcal{O}_1 \quad = \quad \frac{i\, g_\chi\, g_q}{q^2 - M^2}\,(\bar{q}q)\,(\bar{\chi}\chi)$$

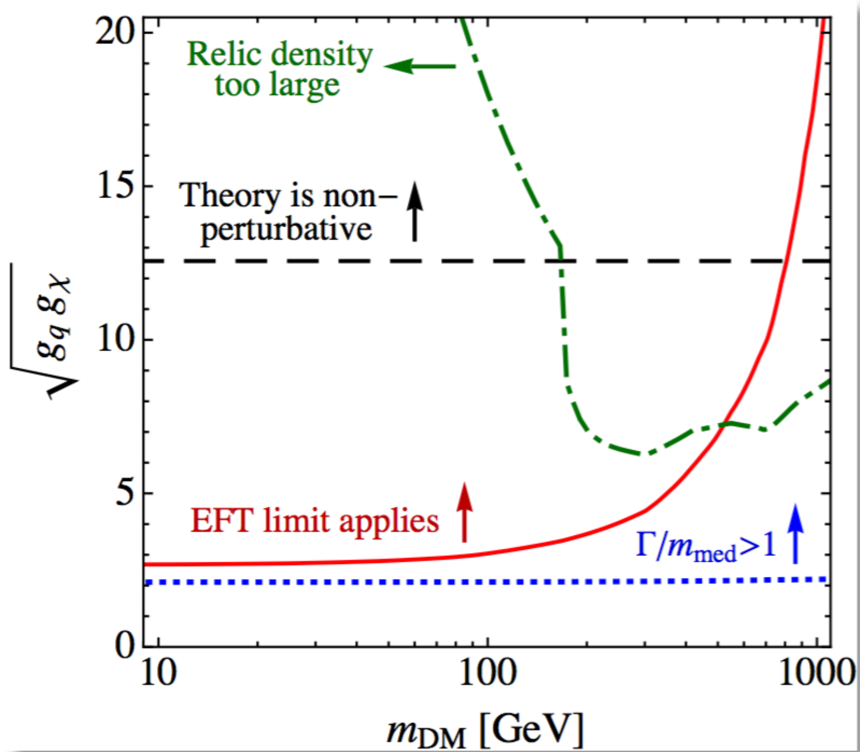
- Equating the two ME squared, for $q^2 \ll M^2$, gives:

$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$$

- This expression is crucial for translating collider limits in the DD limits

Validity of the Limits

- The problem is that we treat fundamentally 3D problem (Λ, m_χ, M) in the plane of just two parameters, which integrates out the third one over the entire range, i.e. over several fundamentally different regimes
- The previous plot allows us to fix the minimum M for which the EFT approach is valid for a given m_χ, but this doesn't correspond to unique value of Λ
- If we now translate the boundary where the EFT limit applies in the value of coupling, we realize that the EFT regime requires the mediator to have the width exceeding its mass, which defeats the very purpose of using single-particle exchange approximation, as such an object can not be a single particle!
- It also makes the EFT approximation applicable only to a very class of models with very large couplings



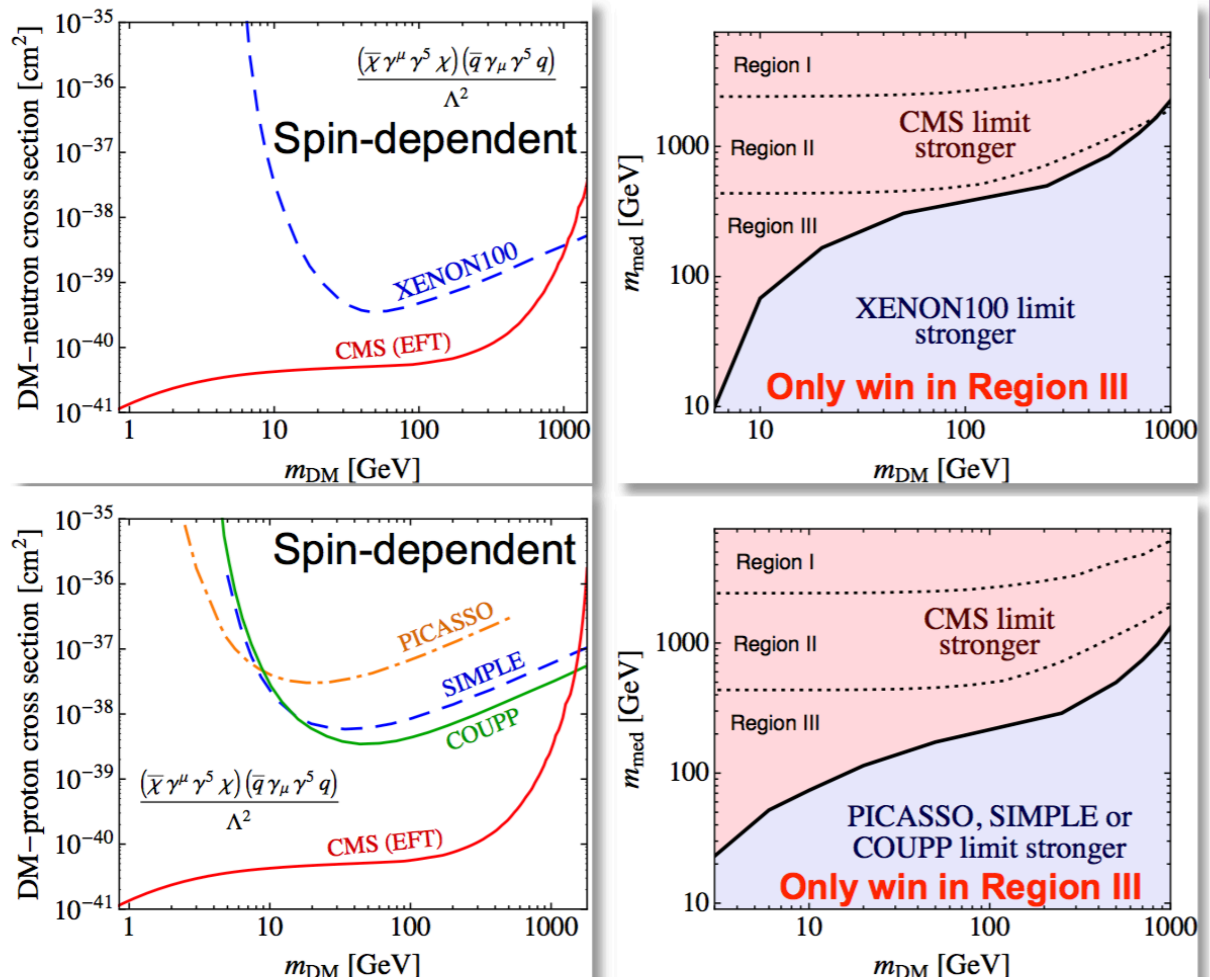
Buchmuller, Dolan, McCabe, arXiv:1308.6799

Comparison w/ DD Limits

- One can now compare the CMS EFT limits with the DD ones:

N.B. CMS limits always win over DD limit for low m_χ, even in the regime where EFT does not apply!

Buchmuller, Dolan, McCabe, arXiv:1308.6799



+ Couplings

Most prominent couplings

Spin-independent vector coupling (V) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \xi_i\bar{q}_i\gamma_\mu q_i$

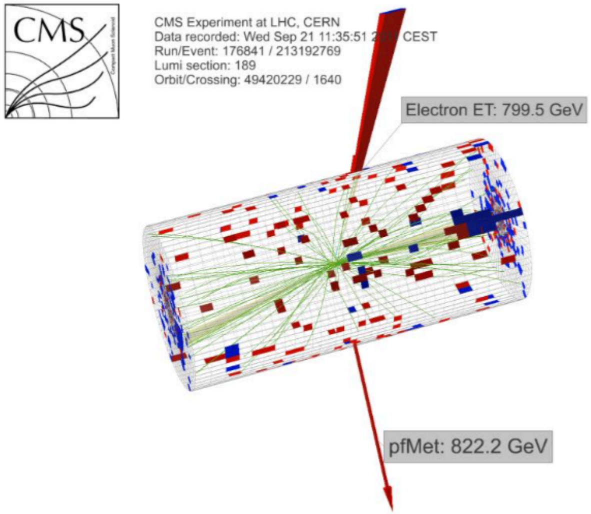
Spin-dependent axial-vector coupling (AV) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_\mu\gamma^5 q_i$

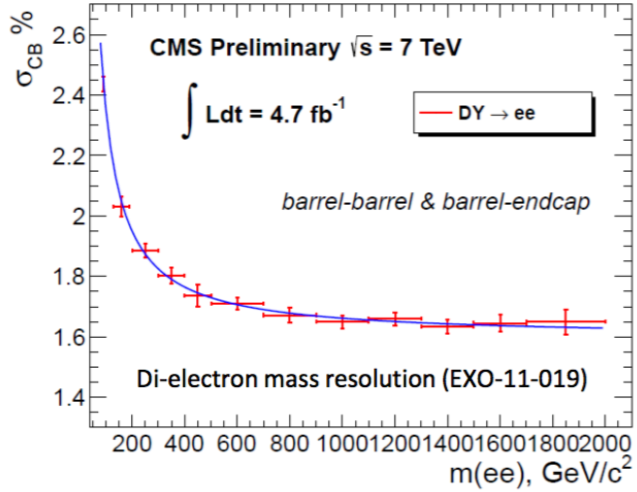
Name	Type	Operator	Coefficient
D1	scalar (qq)	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D5	vector	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D8	axial-vector	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	tensor	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D11	scalar (gg)	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
C1	scalar	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2

According to [J. Goodman et al., Phys. Rev D 82, 116010 (2010)]

The masses of strange and charm quarks are relevant for the cross sections of the D1 operator and they are set to 0.1 GeV and 1.42 GeV, respectively.

Electron Selection



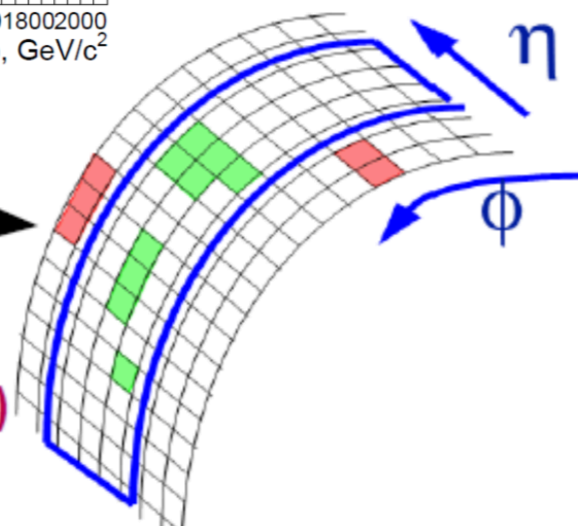


ECAL made of matrix of fully active crystals. Measured energy resolution ~2%

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



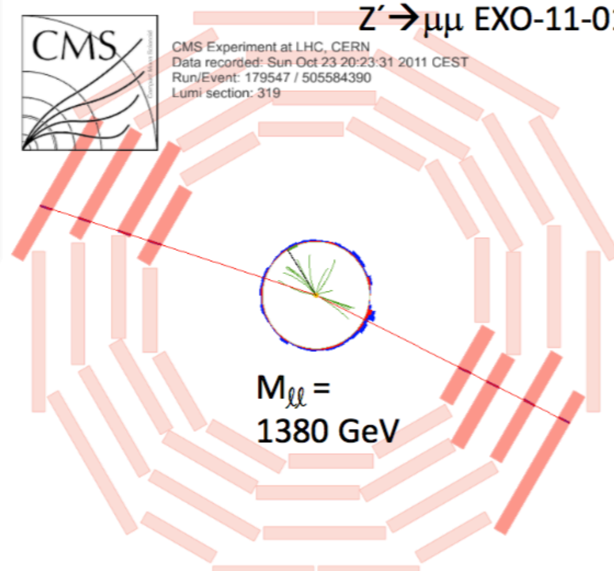
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

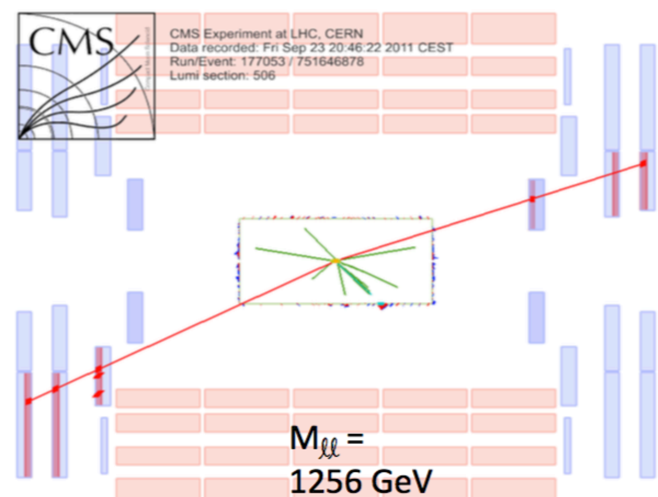
K.Hoepfner, RWTH Aachen | CMS Heavy Resonances |

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

Event displays from Z′→μμ EXO-11-019



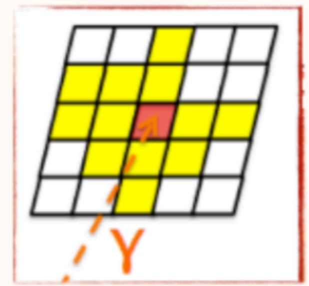


Dedicated muon selection:

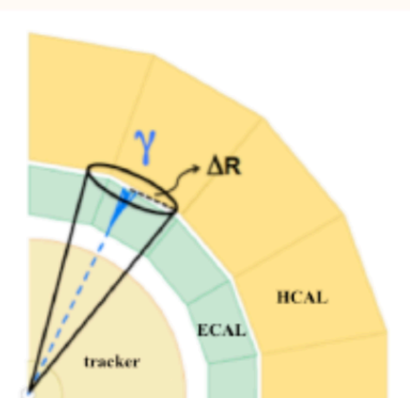
- Special algorithm to consider showering
- At least 1 pixel hit
- Number of measured tracker layers > 8
- Transverse impact parameter d0 < =0.2cm (Z′), 0.02cm (W′) reject cosmics, value for W′ tighter than other analyses, Z′ rejects in addition back-to-back muons
- >= 2 matched muon segments
- Relative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

Photon Selection

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



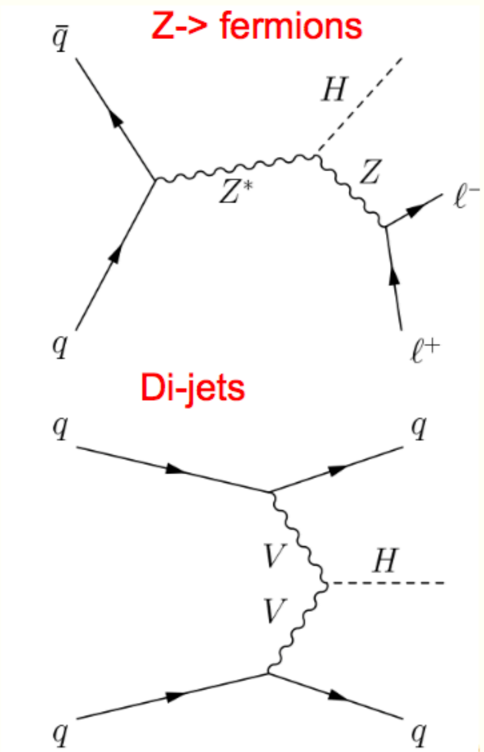
- Same approach like H->γγ standard cut-based photon-ID
  - ECAL fiducial region (|η| < 2.4 excluding EB-EE gap)
  - Isolation and identification requirements:

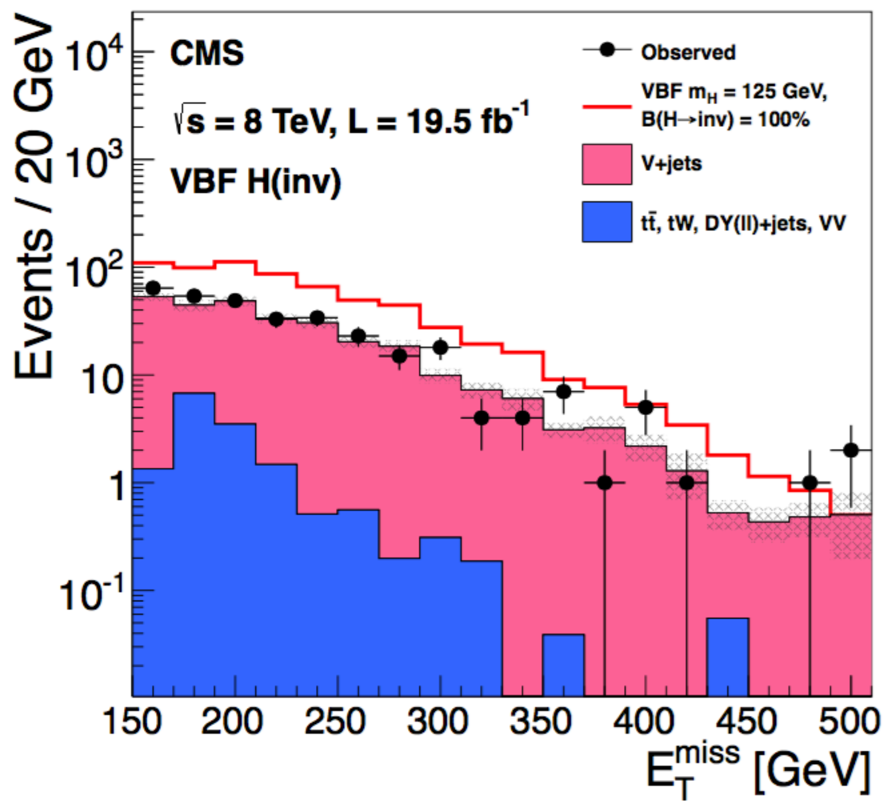


	barrel		endcap	
	$R_9 > 0.94$	$R_9 < 0.94$	$R_9 > 0.94$	$R_9 < 0.94$
PF isolation sum, chosen vertex	6	4.7	5.6	3.6
PF isolation sum worst vertex	10	6.5	5.6	4.4
Charged PF isolation sum	3.8	2.5	3.1	2.2
$\sigma_{i\eta i\eta}$	0.0108	0.0102	0.028	0.028
H/E	0.124	0.092	0.142	0.063
R_9	0.94	0.298	0.94	0.24

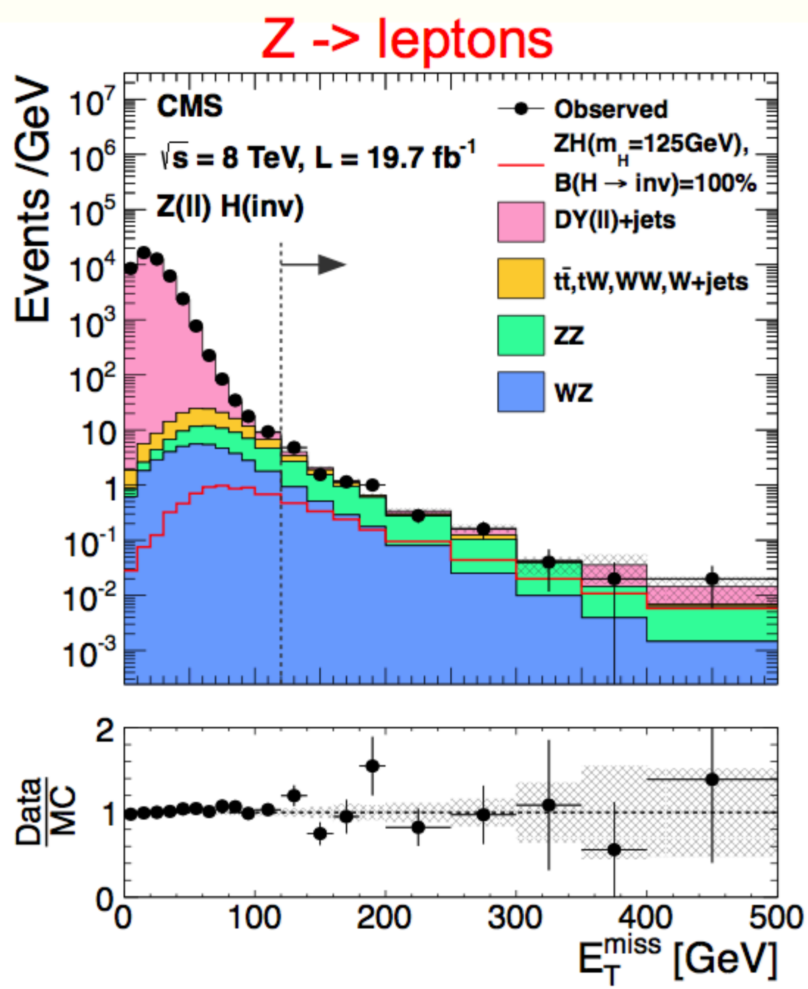
Higgs Modes : CMS VBF

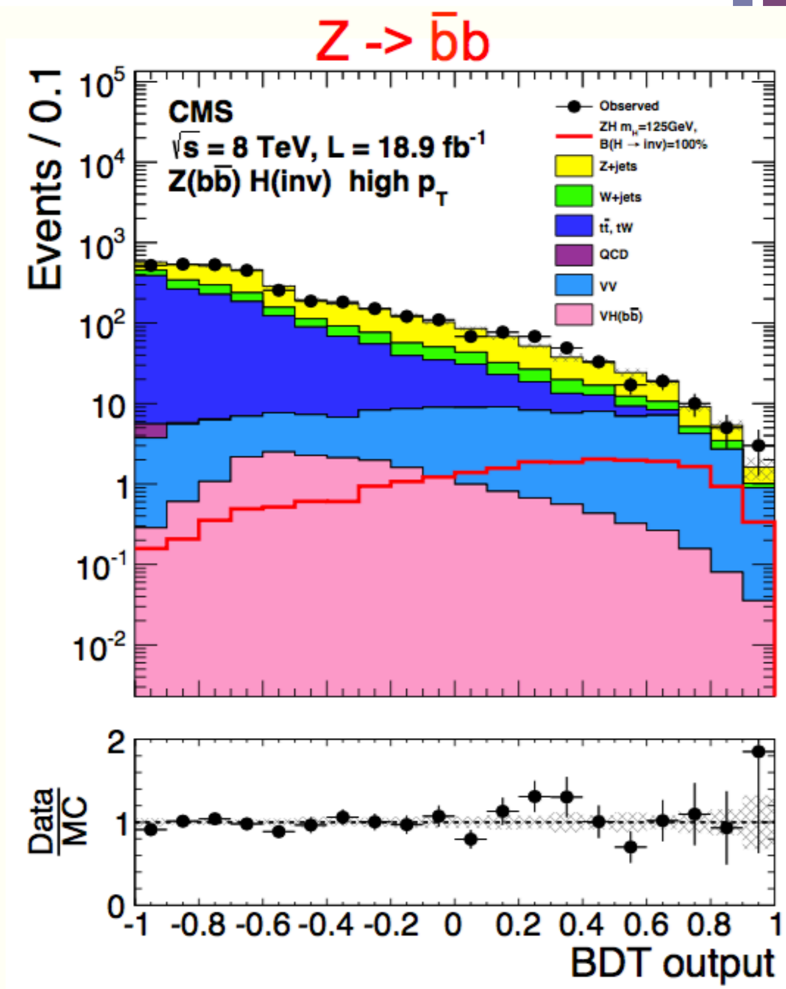
Depending on its nature, DM will couple to theHiggs in various ways. Assuming a Higgs -> Invisible branching, one can search in several channels.





Higgs Modes : CMS ZH





CMS VBF + ZH limits