GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Hunting the Invisible -- Searches for Dark Matter at the LHC

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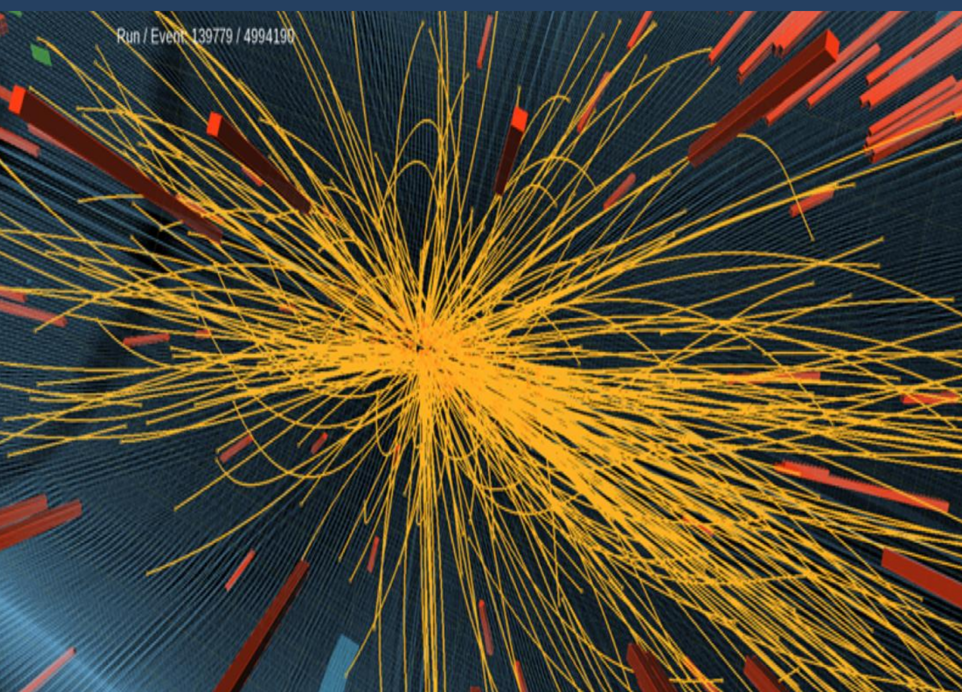
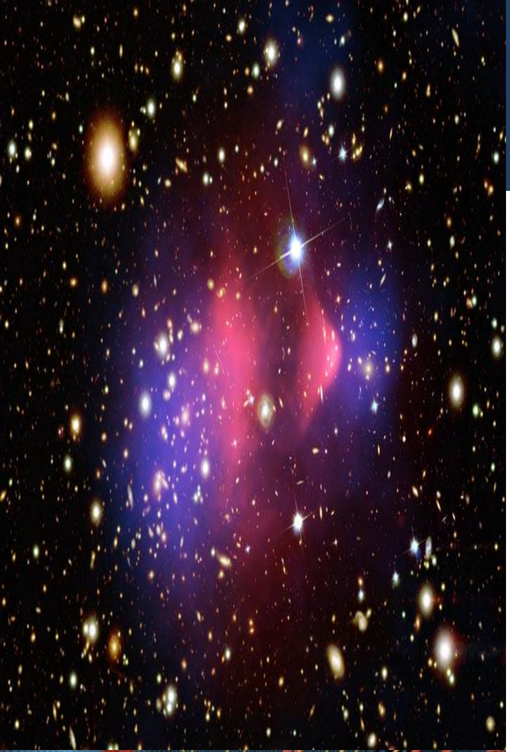
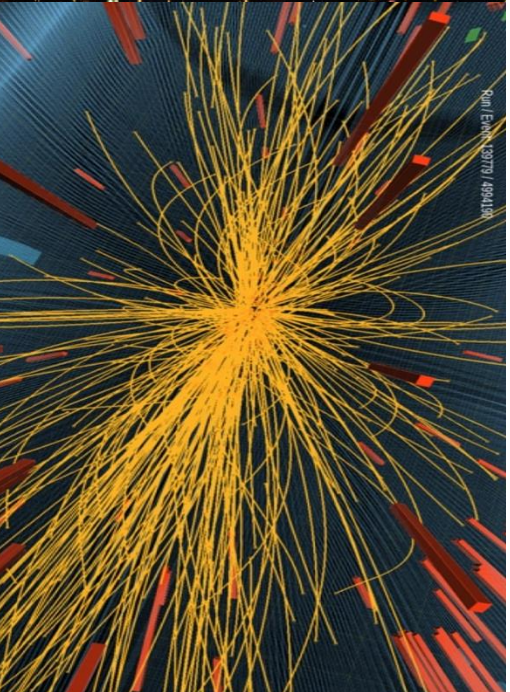
DESY Seminar February 11th 2014





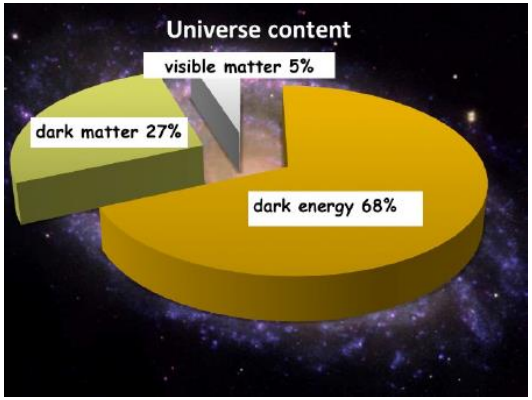


Outline

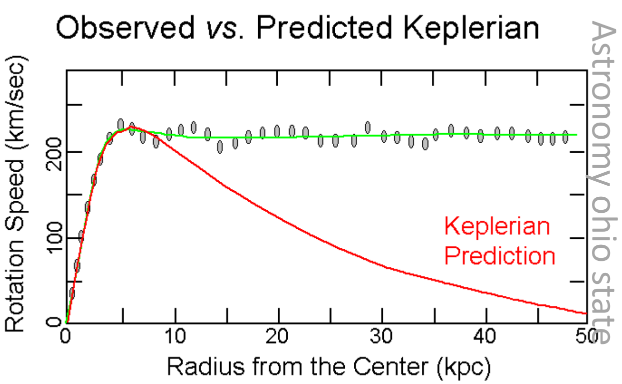
1. Signatures of Dark Matter at the LHC
2. Detection in CMS and ATLAS
3. Monojet (historically leading channel)
4. Monophoton
5. Mono-boson
   - Leptons (access to u/d-type couplings)
   - Hadronically decaying W/Z (max. sensitivity)
6. The big picture

Indications for Dark Matter

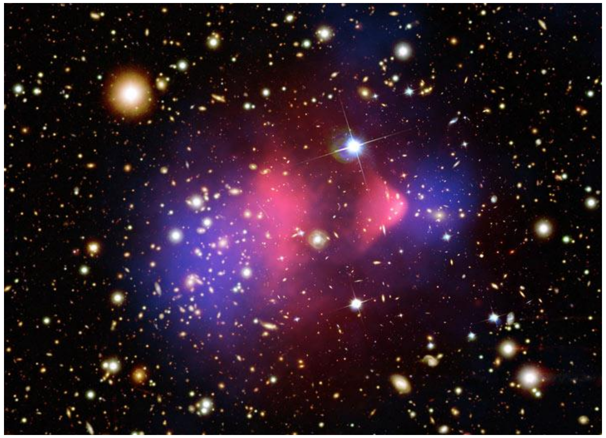
- Astrophysical measurements point to existence of **non-baryonic form of matter** (DM)
  → one compelling evidence for physics beyond Standard model (SM)

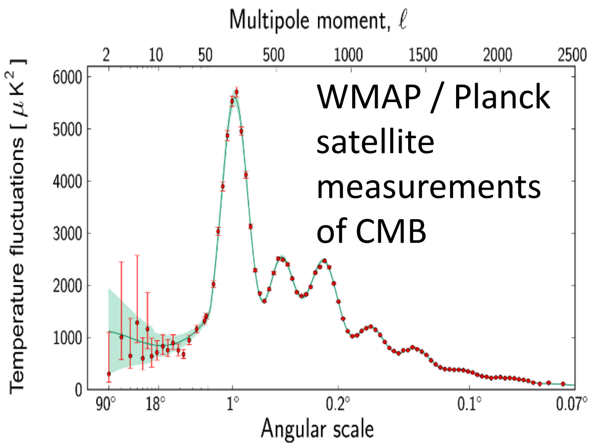


Rotation curves of galaxies



Gravitational lensing





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

DM Properties

No direct observation of DM yet

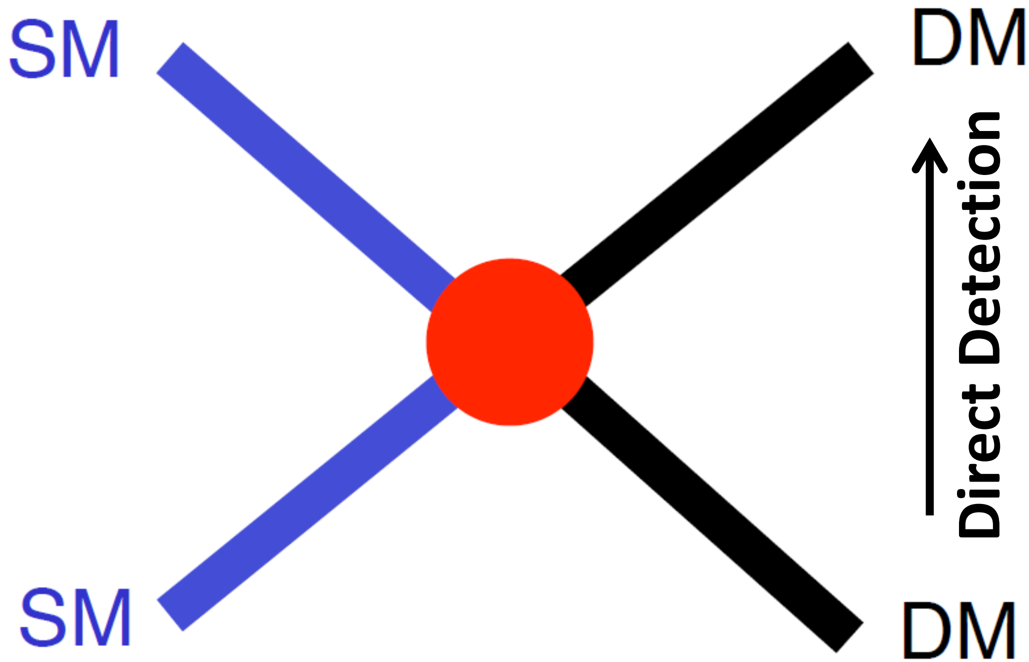
Most popular class of candidates to explain observations suggests **properties**:

- Fermionic matter
- Interacts only weakly
- Massive particles (GeV→TeV)
- Expected to be neutral
- Cold: non-relativistic

Dark matter = part of cosmological SM

Requires beyond SM physics

Detecting Dark Matter

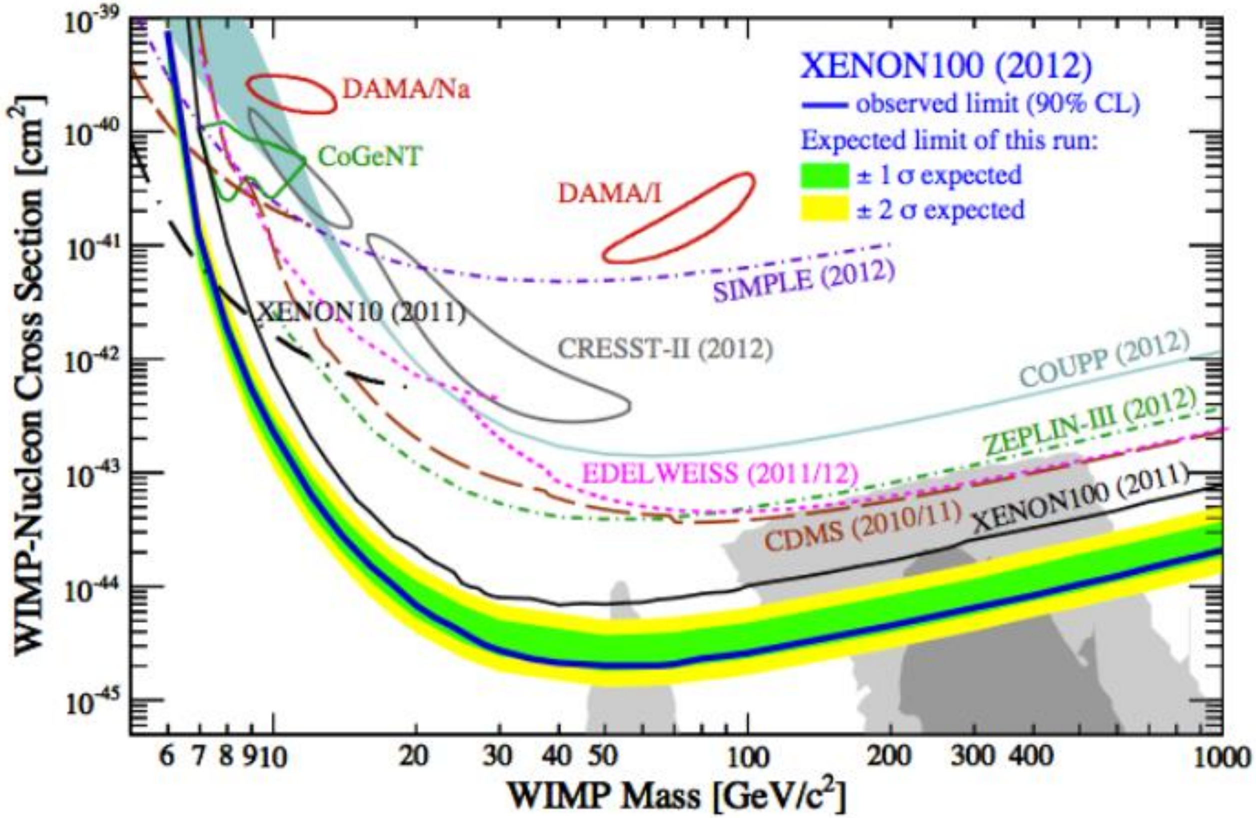


Scattering of DM particles on nuclei of detector material; detect recoil.
For a given cross section sensitivity scales with detector size.

Result is Not Conclusive...

Wealth of direct detection experiments.

WIMP search status < October 2013

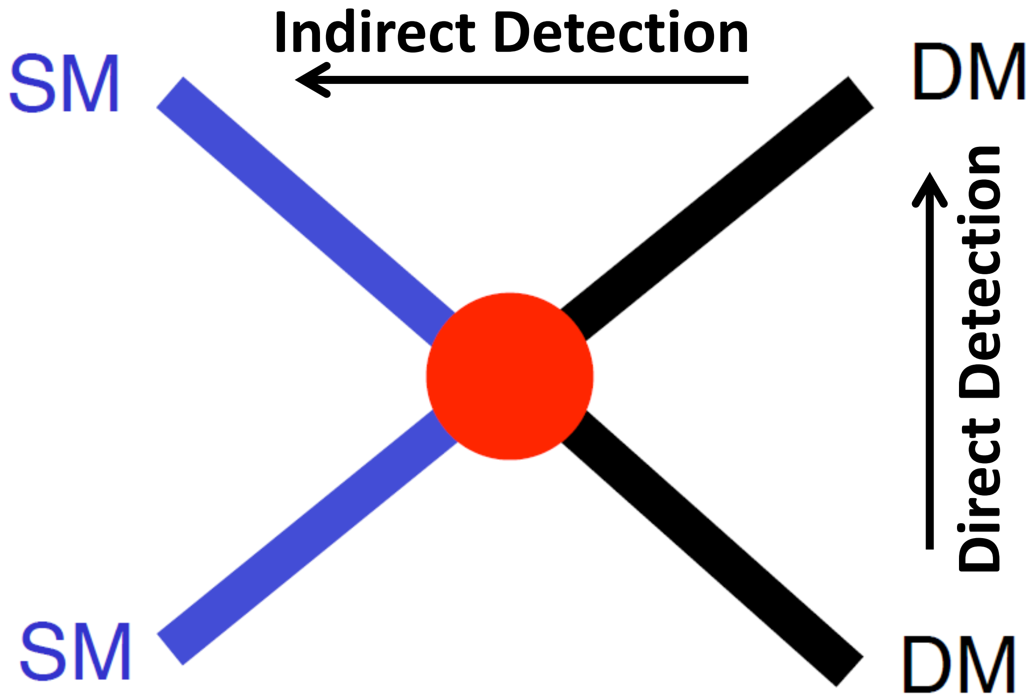


90% CL

[Xenon coll.: arXiv:1207.5988](https://arxiv.org/abs/1207.5988) [astro-ph.CO]

Detecting Dark Matter

Assume annihilation of DM particles, e.g. in the sun. Detect annihilation products.



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Detecting Dark Matter

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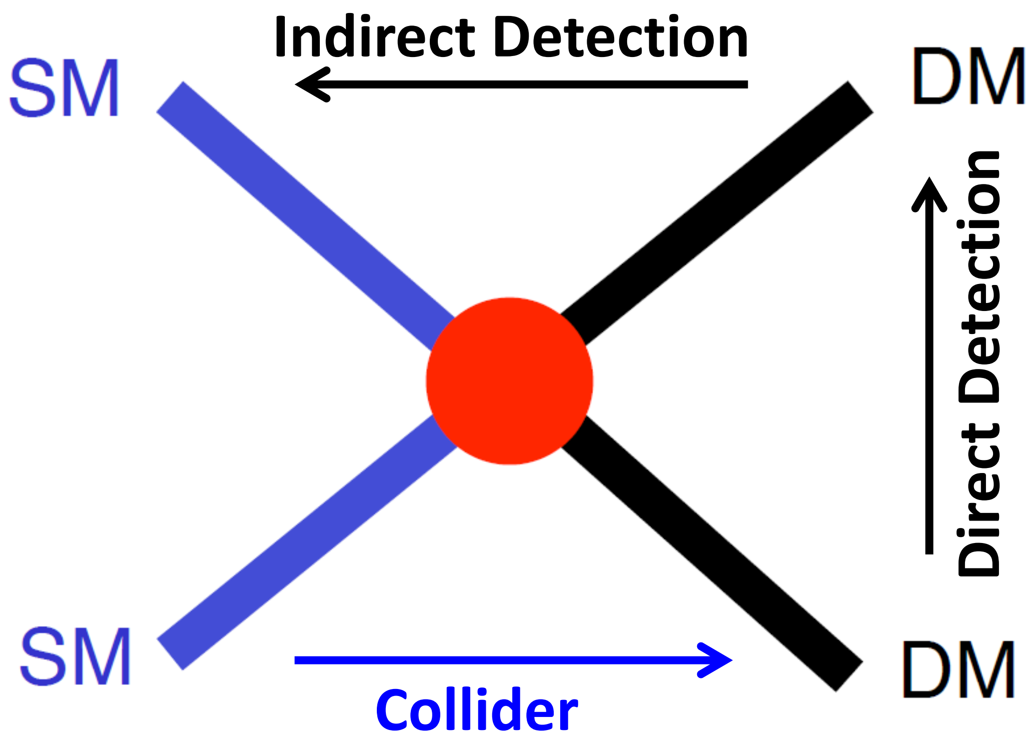


Scattering of DM particles on nuclei of detector material; detect recoil.
For a given cross section sensitivity scales with detector size.

DM may be pair produced in pp collisions at the LHC, with masses < ½ parton-parton c.o.m. Yields experimental signature of MET.

Direct scattering experiments

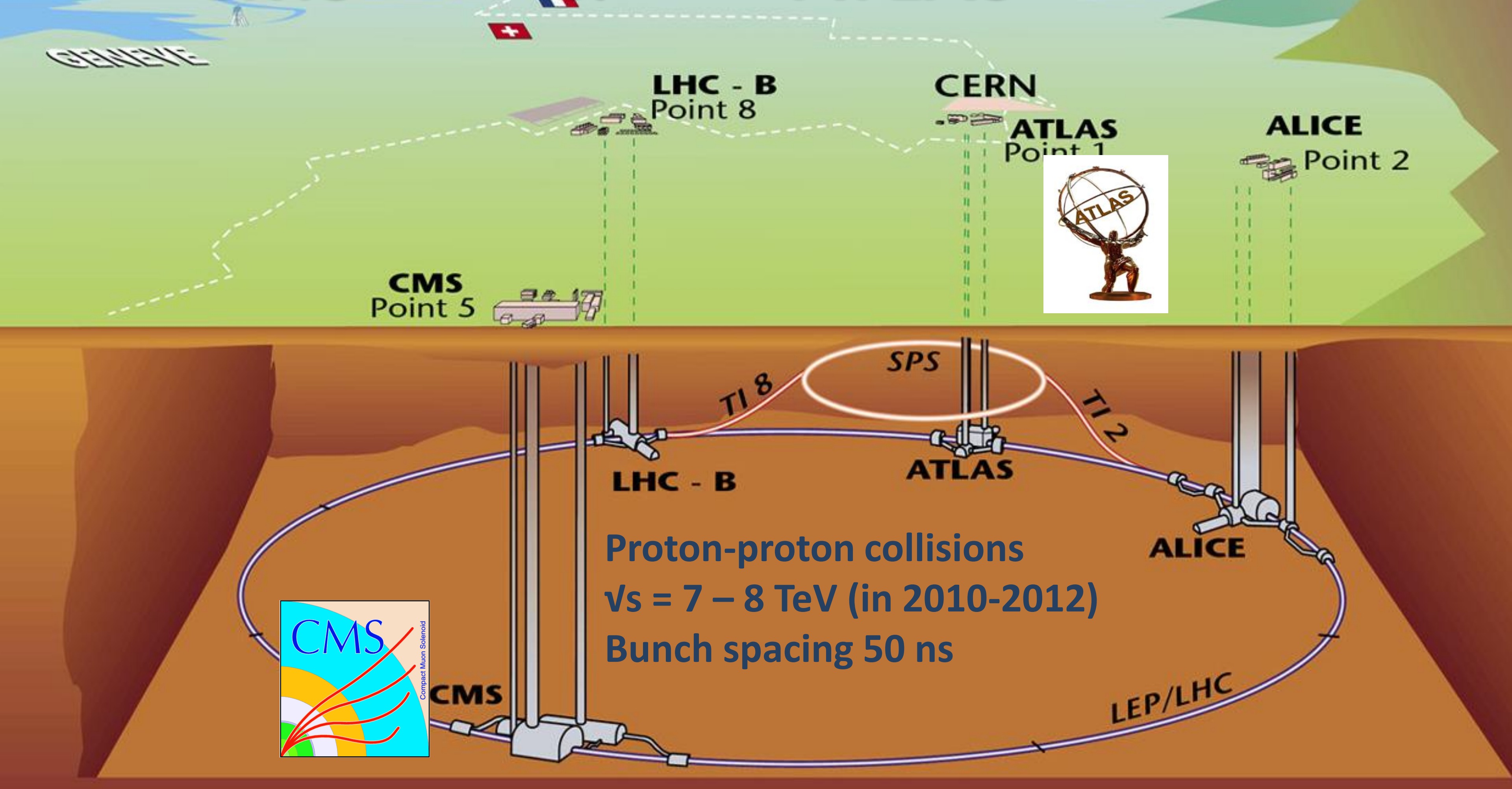
Indirect detection experiments

Pair-production at the LHC

The Large Hadron Collider (LHC)

Two General-Purpose Experiments:

CMS & ATLAS

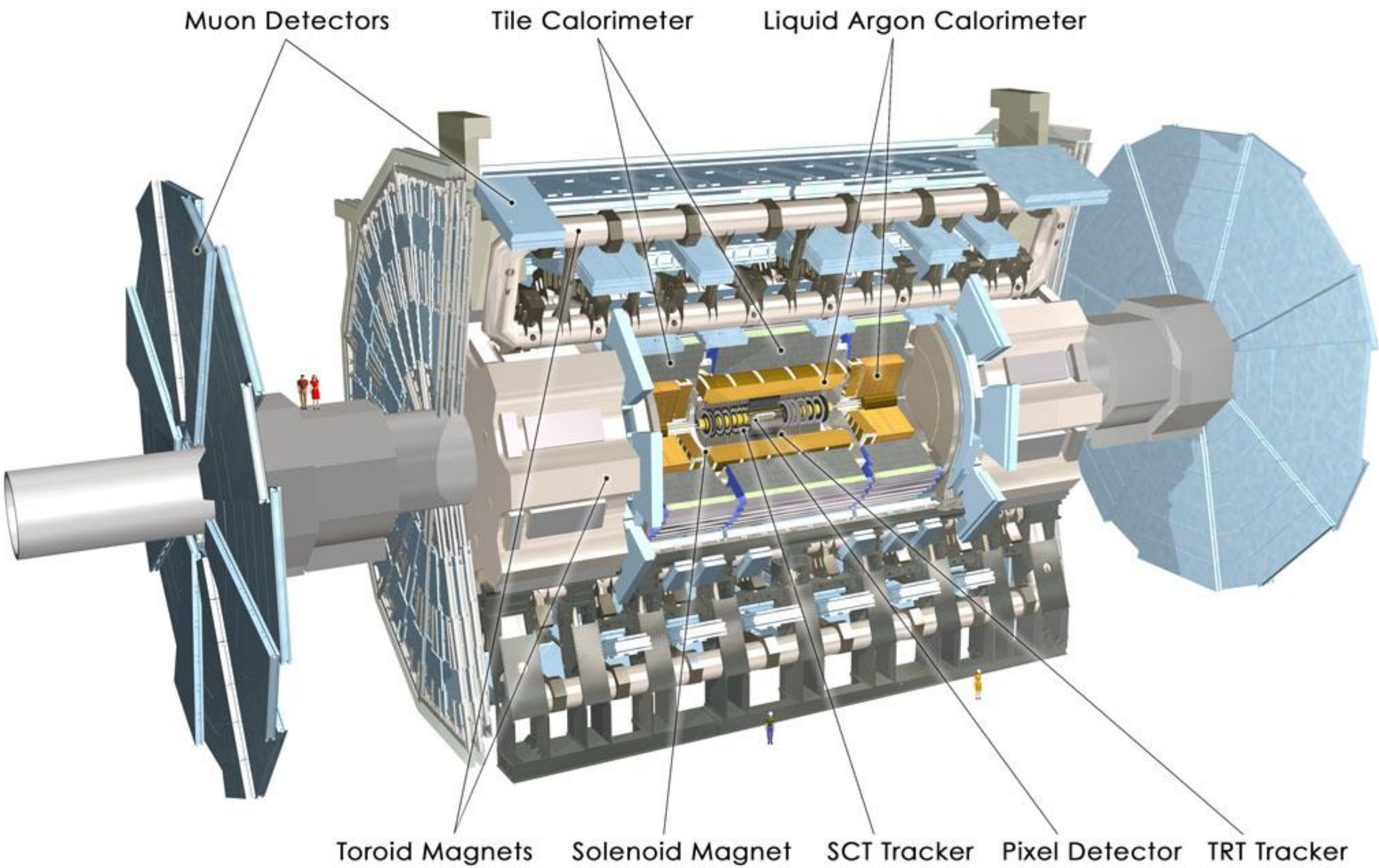


Proton-proton collisions
√s = 7 – 8 TeV (in 2010-2012)
Bunch spacing 50 ns

ATLAS

[ATLAS coll.: JINST 3, S08003 (2008)]

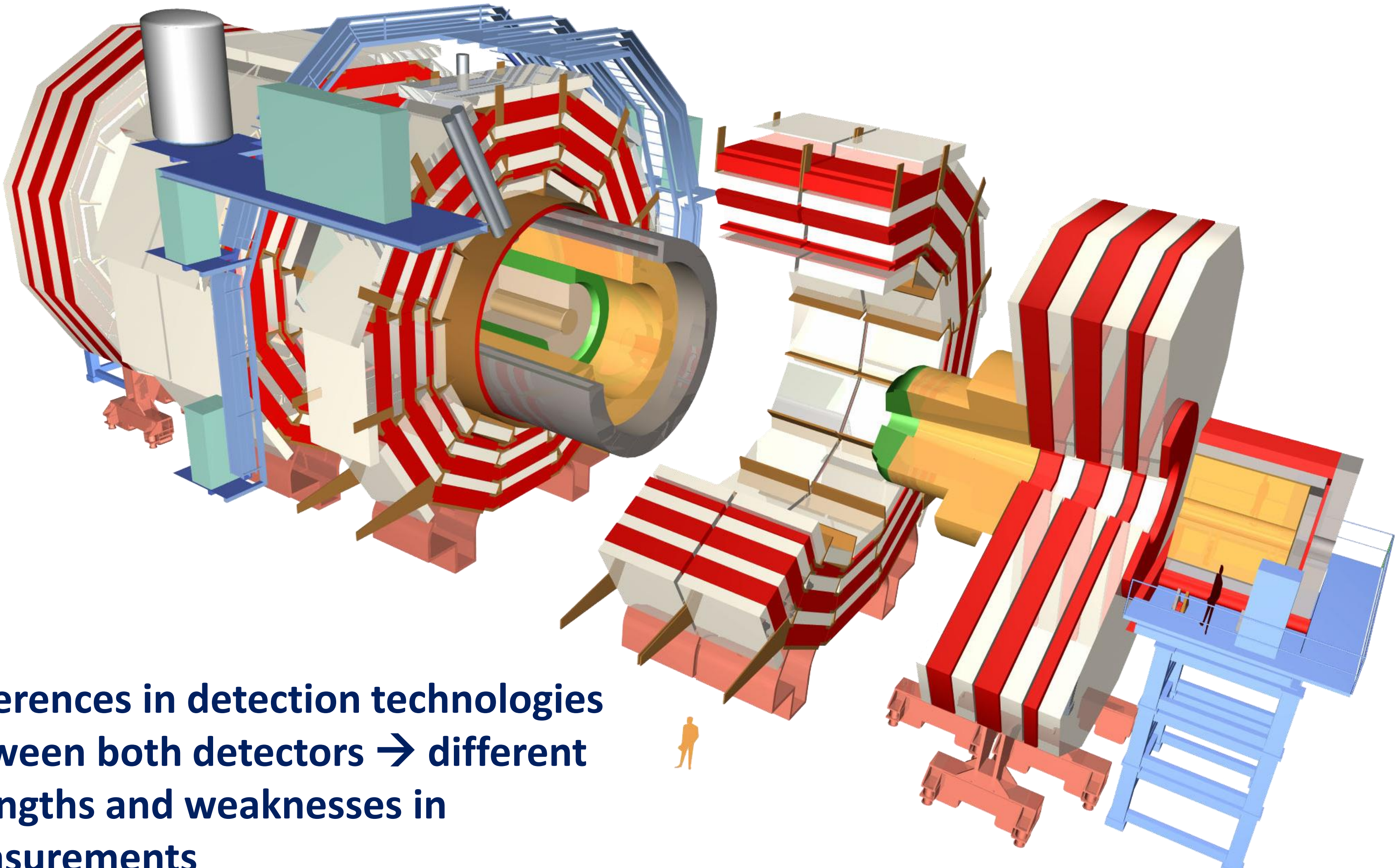
Excellent stand-alone muon measurement. Emphasis on jet and missing-E_T (MET) resolution, particle identification



Compact Muon Solenoid (CMS)

[CMS coll.: JINST **3** (2008), no. S08004]

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



Differences in detection technologies between both detectors → different strengths and weaknesses in measurements

LHC Data Taking

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

√s (LHC) = 4 x √s (Tevatron)

Data taking efficiency >90% for ATLAS and CMS

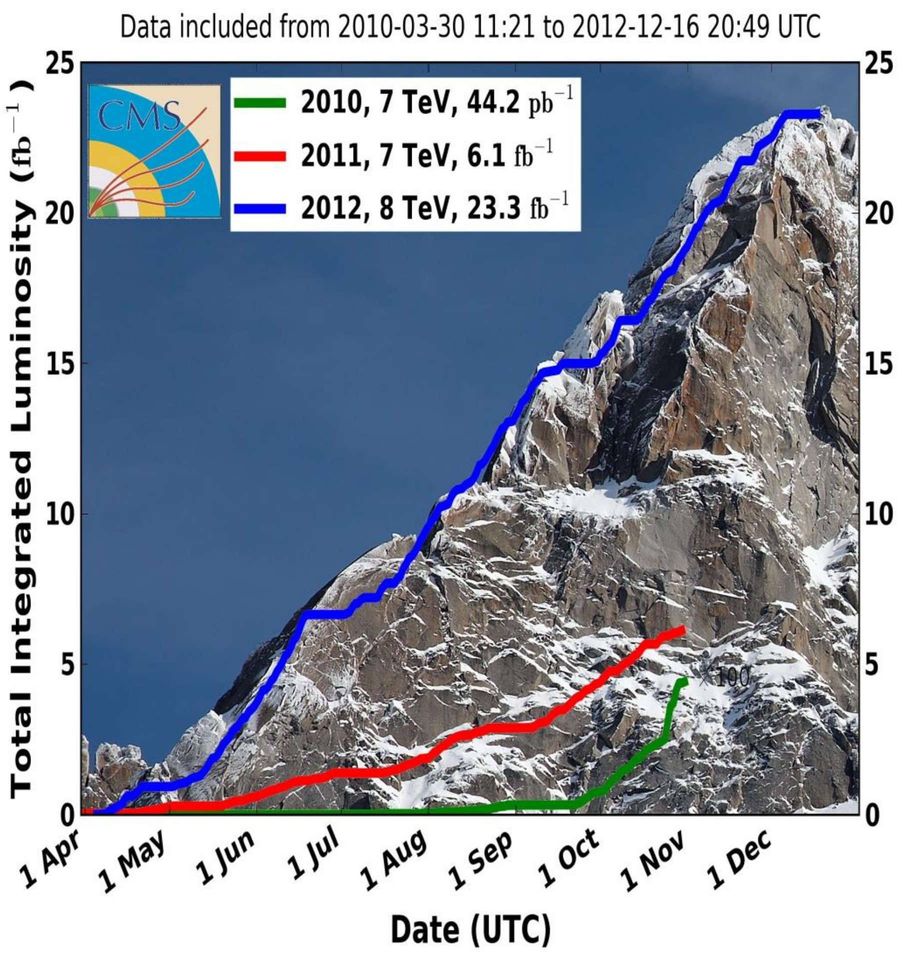
$$\mathcal{L} = f \cdot k^2 \cdot \frac{n^2}{A}$$

f=frequency

k=number of bunches

n=particles/bunch

A=beam cross section

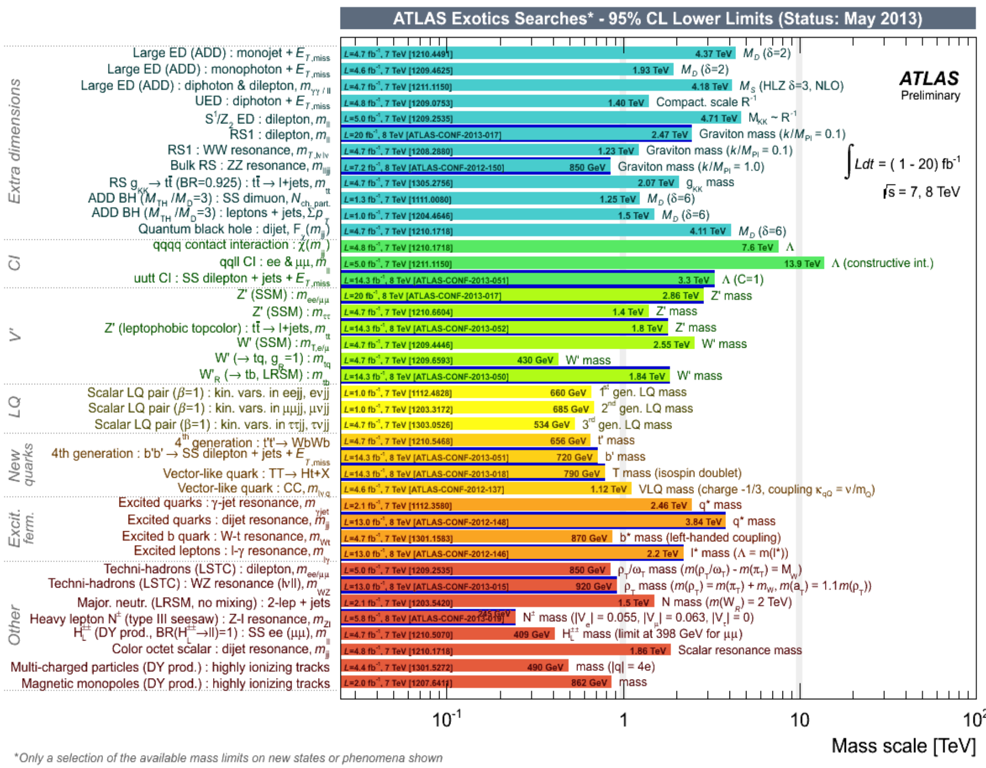


Many Searches Performed at the LHC to address open questions of SM

Hitoshi Murayama

Final states allow different interpretations
Be ready also for the unexpected

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



Hitoshi Murayama

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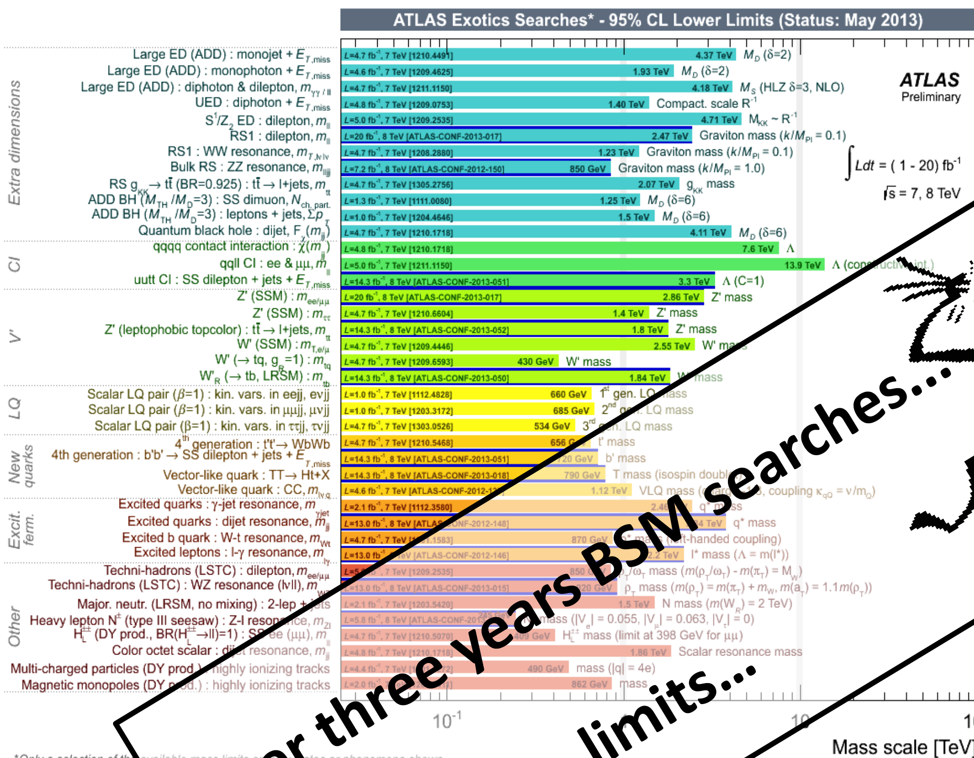


After three years BSM searches...

Limits, limits, limits...

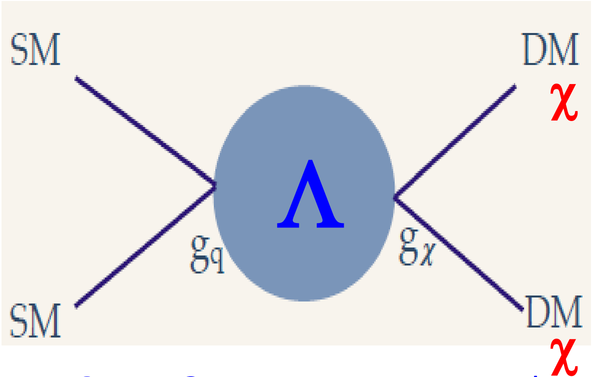
Hitoshi Murayama

Can we learn something 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.

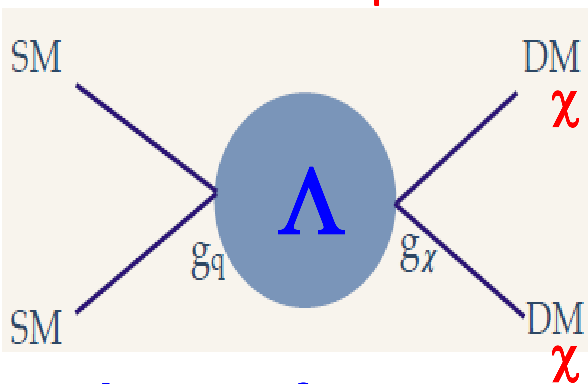
Use effective field theory (EFT) to describe interactions in a model independent way.

→ **Signature oriented search**

Dark matter at the LHC

pp collisions

Pair of DM particles



Mediator of mass M

Characterizing parameters:

- scale of effective interaction

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

- mass m_χ

[Bai, Fox and Harnik, JHEP 1012:048 (2010)]

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

Cross section depends on the mass (m_χ) and scale Λ (for couplings g_χ, g_q)

Spin-independent (SI) and spin-dependent (SD) cross sections

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

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

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

Possible Couplings

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

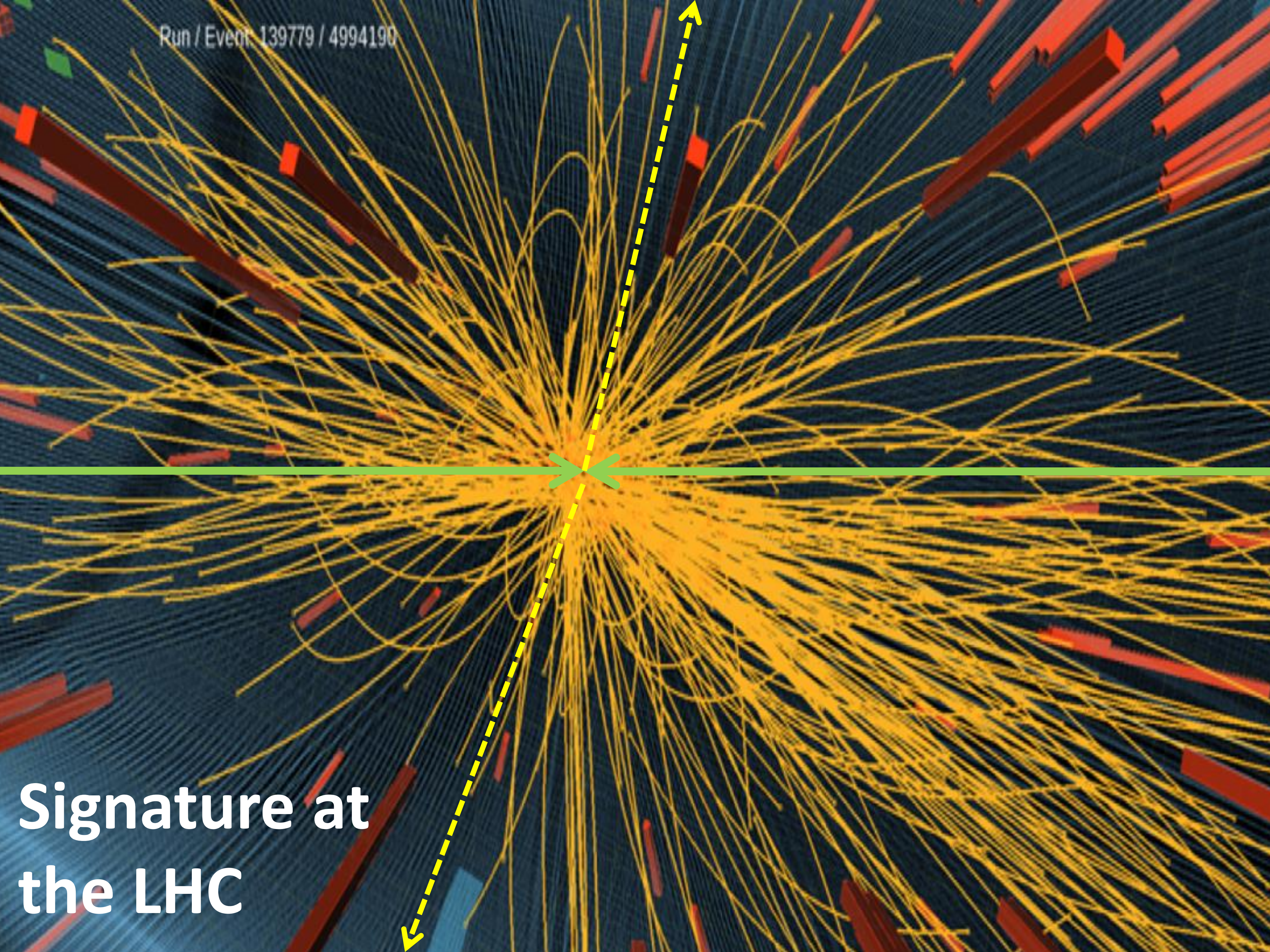
Vector coupling (V) D5
→ Spin-independent (SI)

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

Axial-vector coupling (AV) D8
→ Spin-dependent (SD)

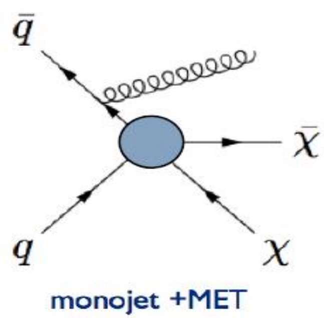
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

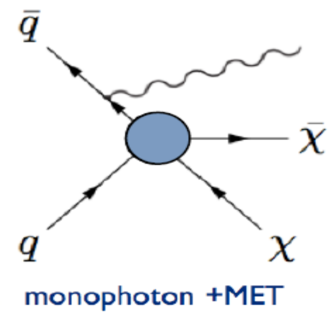
Also studied:
scalar D1, D11 (ATLAS mono- jet/photon) → SI
tensor D9 (ATLAS mono-photon) → SD


Run / Event: 139779 / 4994190
Signature at
the LHC

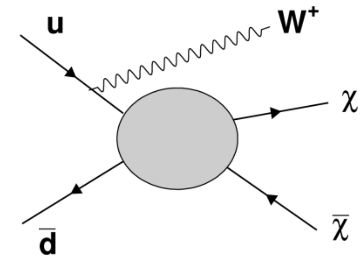
How to make DM visible at the LHC?

Mono-X Signatures – simple and striking





Radiation of a jet / photon from initial state



Radiation of W/Z-boson

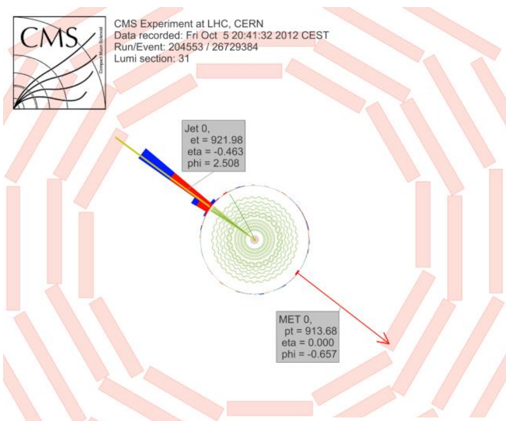
Different W/Z decay channels

CMS-PAS-EXO-12-048

Full 2012 dataset 20/fb

ATLAS-CONF-12-147 (JHEP 04 (2013) 075)

Full 2011 dataset 5/fb

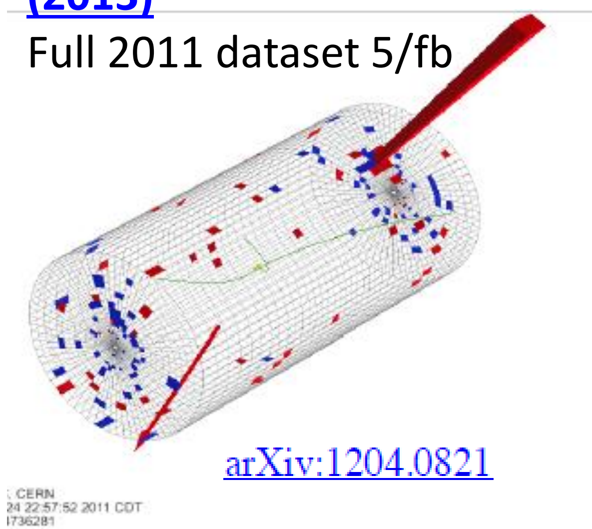


arXiv:1206.5663

CMS-PAS-EXO-11-096 (PRL 108, 261803 (2013))

ATLAS PRL 110, 011802 (2013)

Full 2011 dataset 5/fb

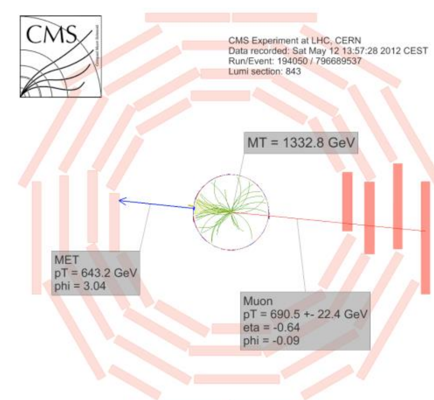


arXiv:1204.0821

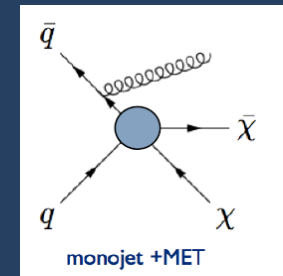
CMS-PAS-EXO-13-004

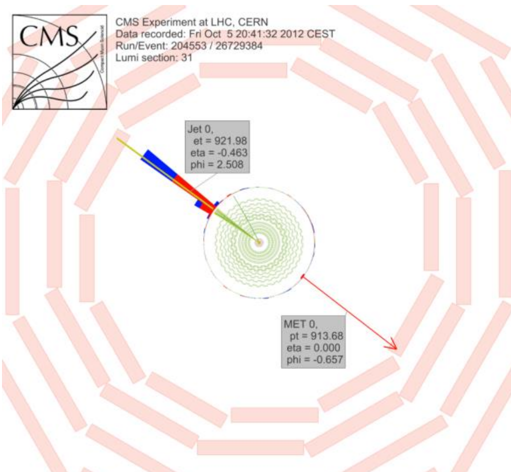
ATLAS-CONF-13-073 (PRL 112 (041802))

Full 2012 dataset 20/fb



Search for Pair Produced Dark Matter in Monojet Channel



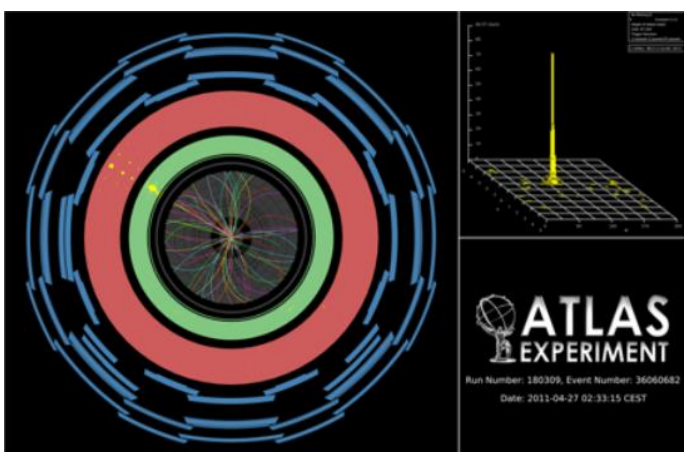


Signature: high p_T jet + MET

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

ATLAS-CONF-12-147 (10.5/fb)

2012 pp data at √s = 8 TeV



Channel to start DM searches at colliders

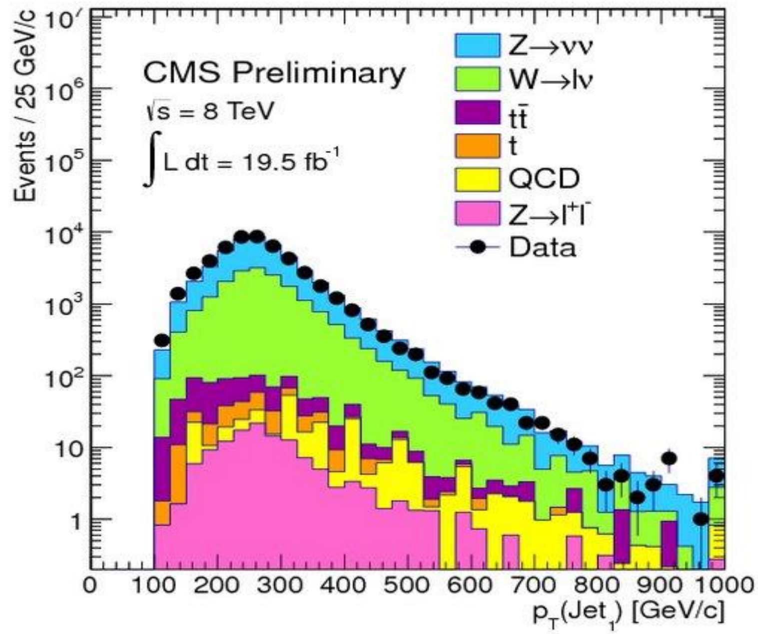
2012 results

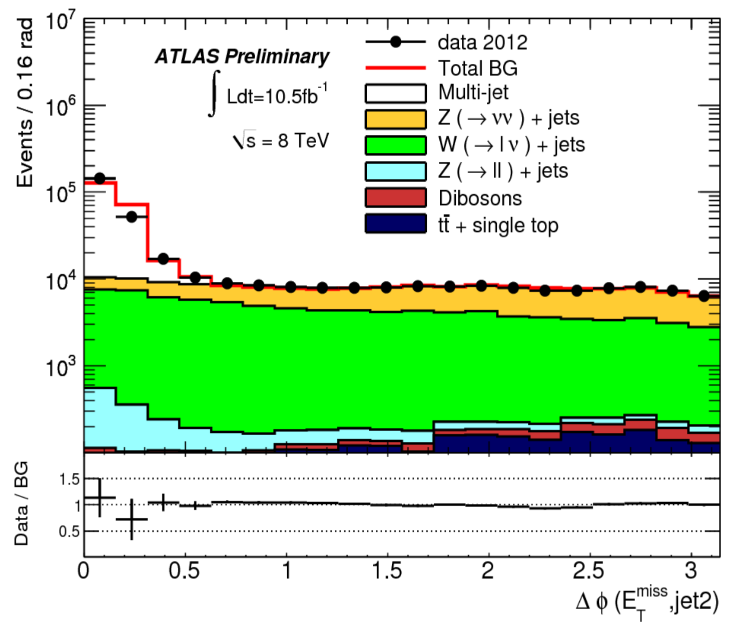
Event Selection

CMS-PAS-EXO-12-048 (20/fb) ATLAS-CONF-2012-147 (10.5/fb)

Search for single jet recoiling against MET

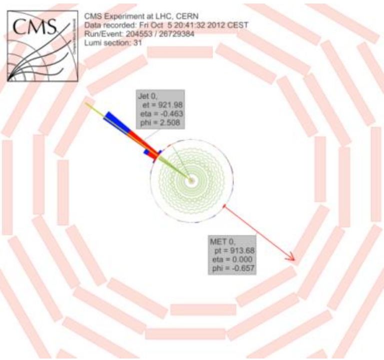
- Good primary vertex
- Large missing E_T
  - MET(CMS)>250 GeV
  - MET(ATLAS)>120 GeV
- Anti-kT jet with R=0.4 within $|\eta|<2.0$
  - p_T (CMS)>110 GeV
  - p_T(ATLAS)>120 GeV
- Allow for second jet with p_T>30 GeV if $\Delta\phi$ (j1, j2) <2.5 or $\Delta\phi$ (MET, j2)>0.5
- Jet quality
- Lepton veto

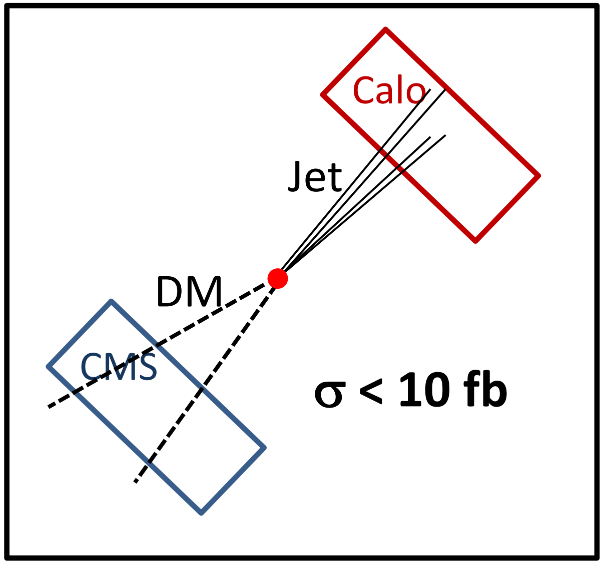




Signal

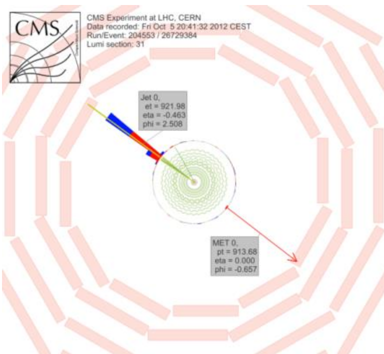
DM is undetectable → MET
Jet to balance p in transverse plane
→ high pT object

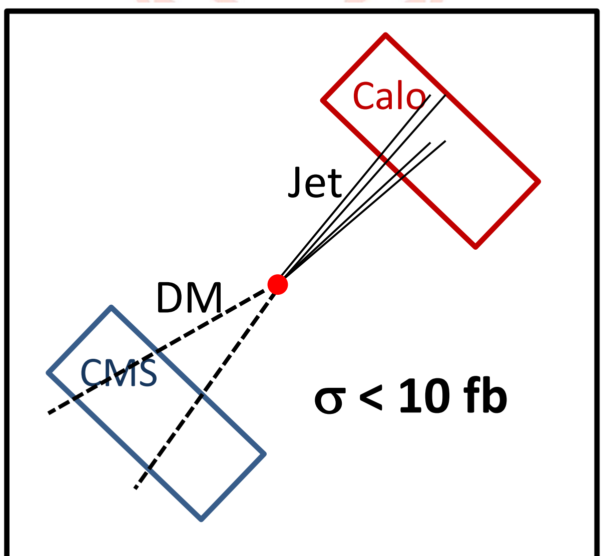


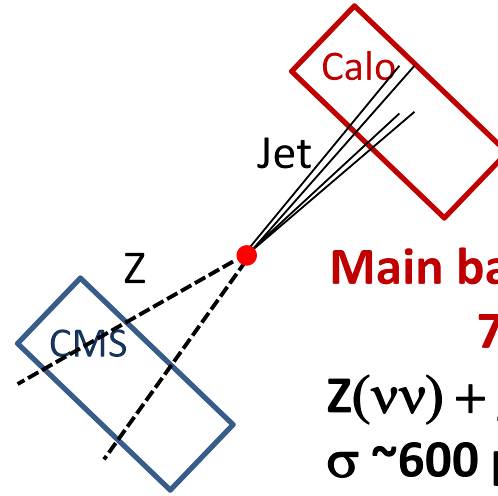


Signal and Background

DM is undetectable → MET
Jet to balance p in transverse plane
→ high pT object

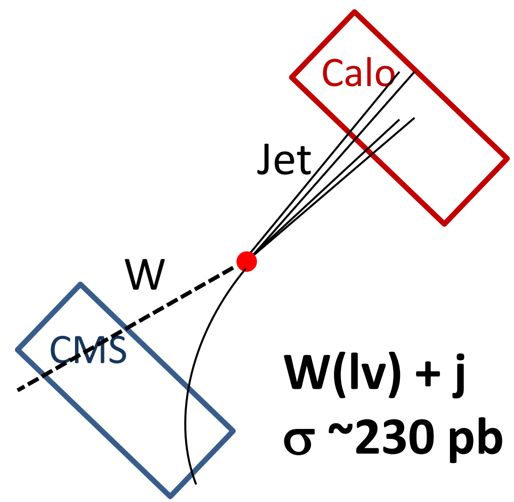






Main background
70%

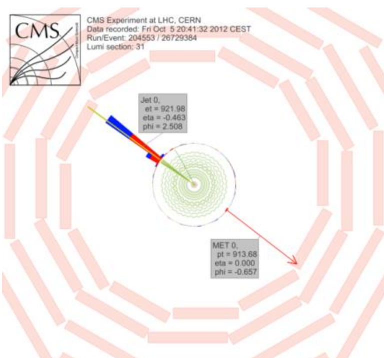
Z(νν) + j
σ ~600 pb
irreducible

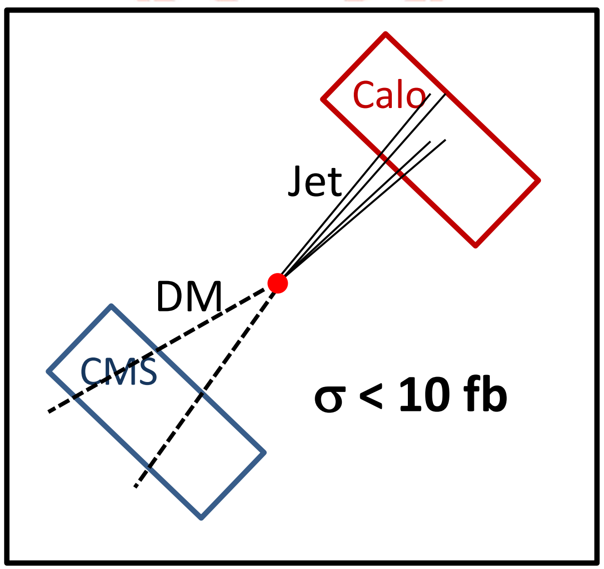


W(lν) + j **30%**
σ ~230 pb

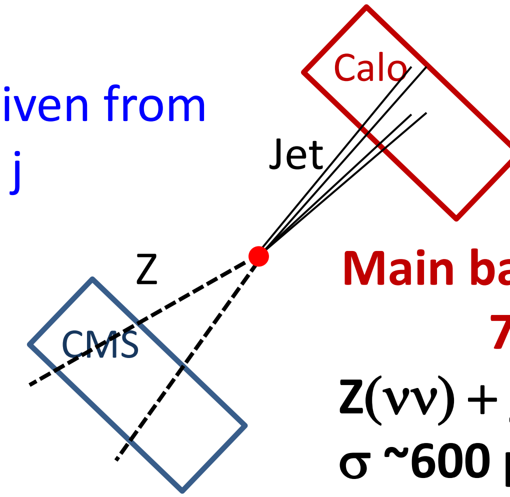
Signal and Background

DM is undetectable → MET
Jet to balance p in transverse plane
→ high pT object





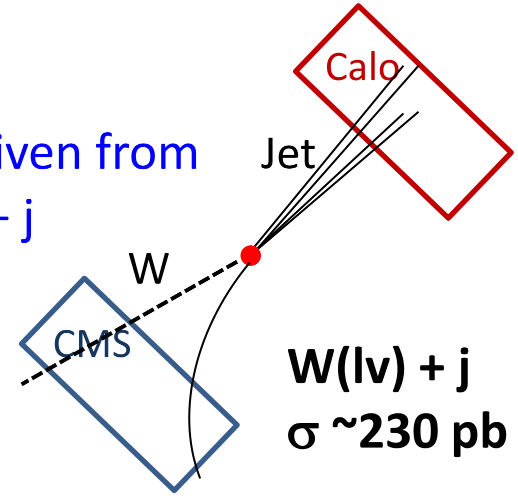
Data driven from
$Z(\mu\mu) + j$



Main background 70%

$Z(\nu\nu) + j$
σ ~600 pb
irreducible

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



$W(l\nu) + j$ 30%
σ ~230 pb

Signal and Background

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

Dominant background $Z\rightarrow\nu\nu + j$
data driven from $Z\rightarrow\mu\mu + j$

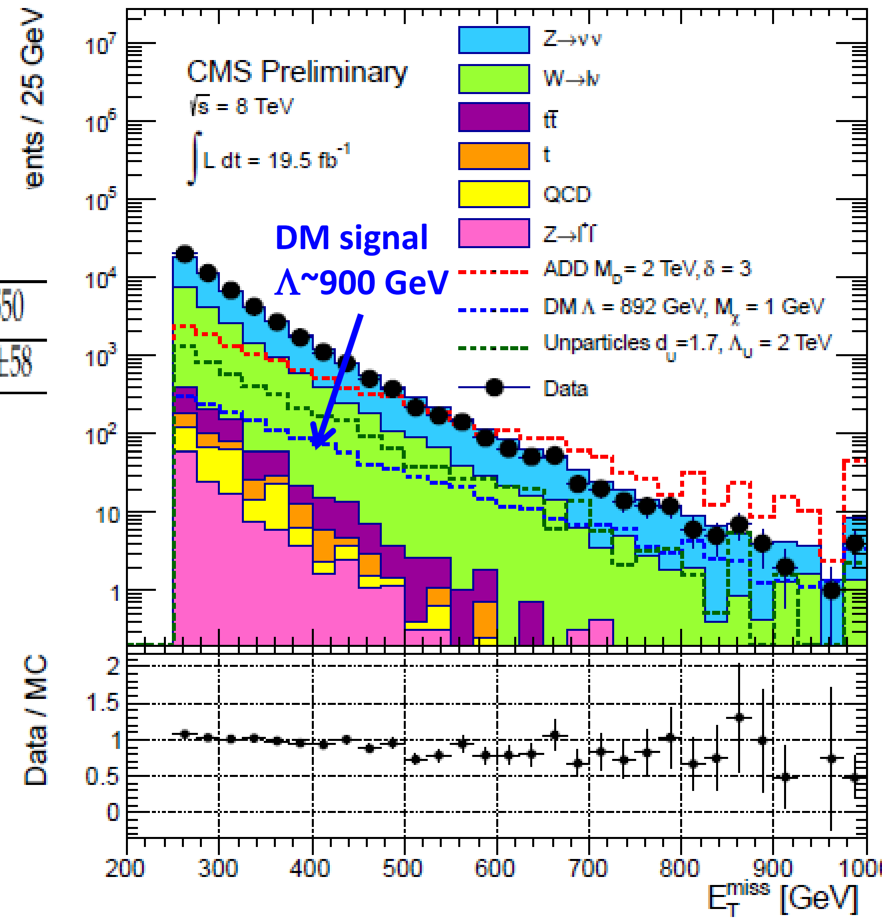
$$N(Z(\nu\nu)) = \frac{N^{\mathrm{obs}} - N^{\mathrm{bgd}}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\nu)}{Z(\mu\mu)}\right)$$

Table 3: Data-driven prediction of $Z(\nu\nu)$ events for different E_T^{miss} regions.

E_T^{miss} (GeV)	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$	30600±1493	12119±640	5286±323	2569±188	1394±127	671±81	370±58

Syst. Uncertainties 5→15% (dominated by statistics, selection efficiency)

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



CMS search performed in 7 bins of MET

Signal and Background

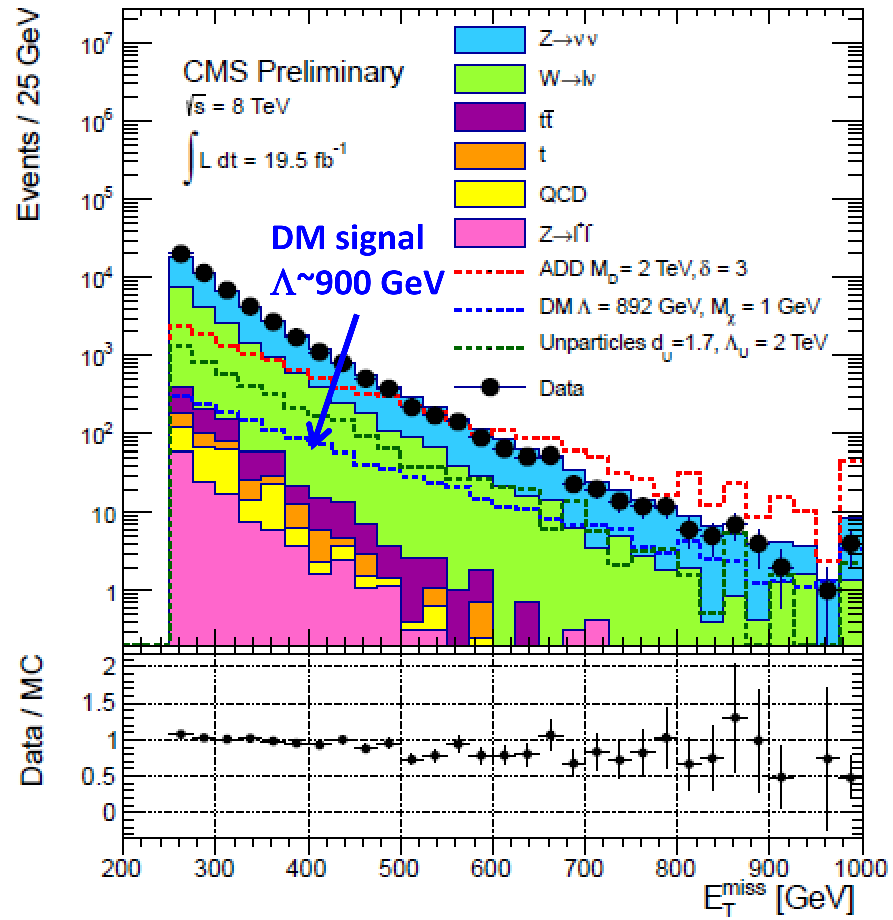
CMS-PAS-EXO-12-048 (20/fb)

Dominant background Z→νν + j
data driven from Z→μμ + j

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

- 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 backgrounds in **MET** distribution after all cuts



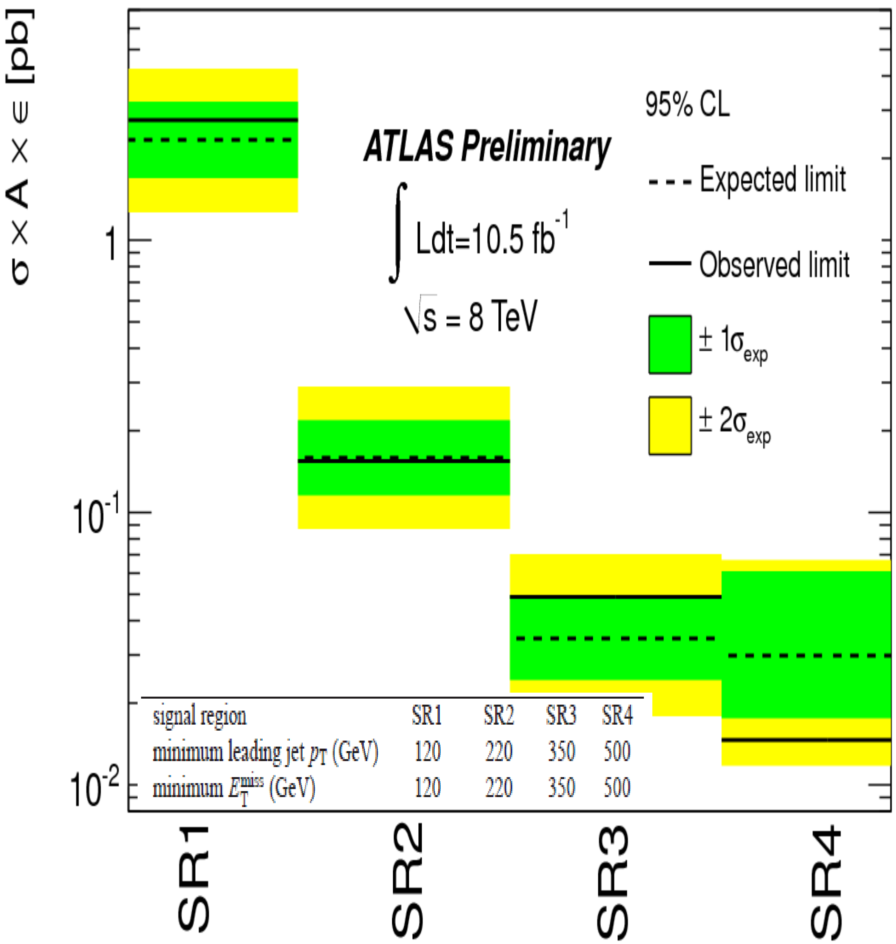
CMS search performed in 7 bins of MET

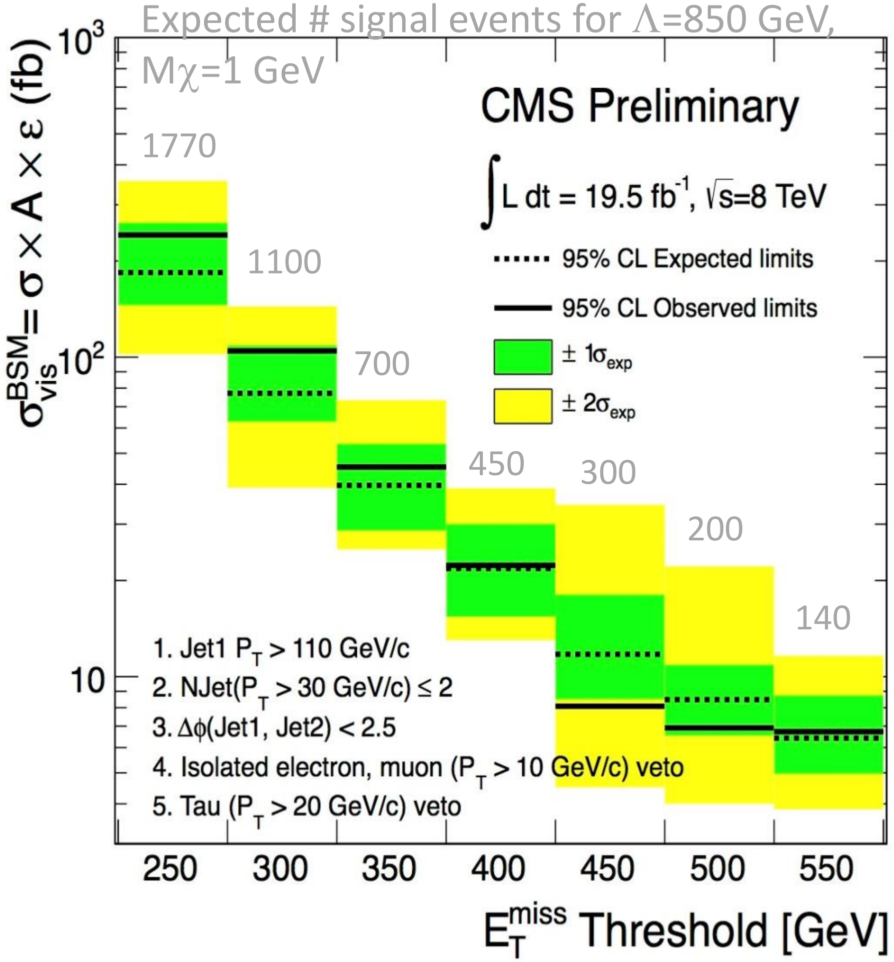
Monojet Model Independent Limits

ATLAS-CONF-2012-147 (10.5/fb)   CMS-PAS-EXO-12-048 (20/fb)

→ Search performed in bins of MET

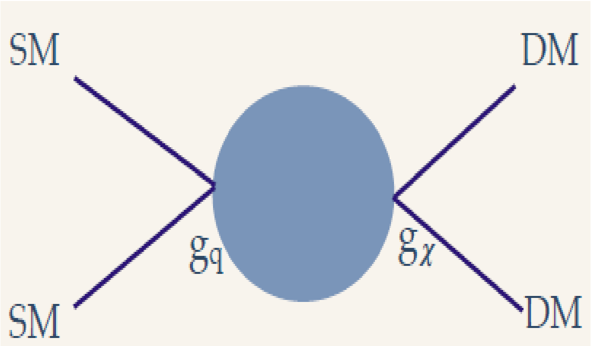
Both experiments quote model-independent limits

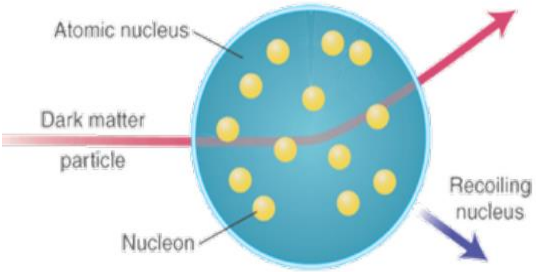




Translate production cross section limit into DM – nucleon limits

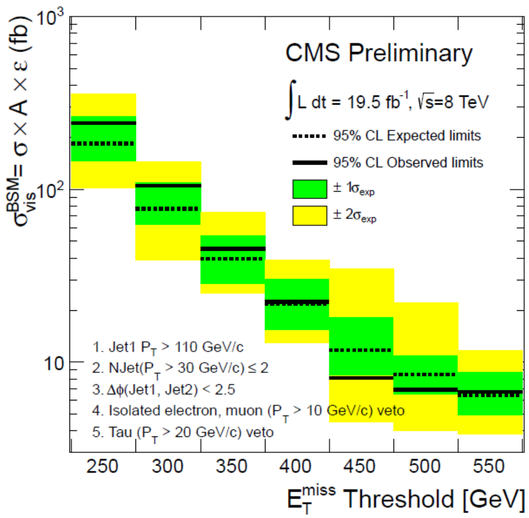
Purpose: to compare to direct detection experiments



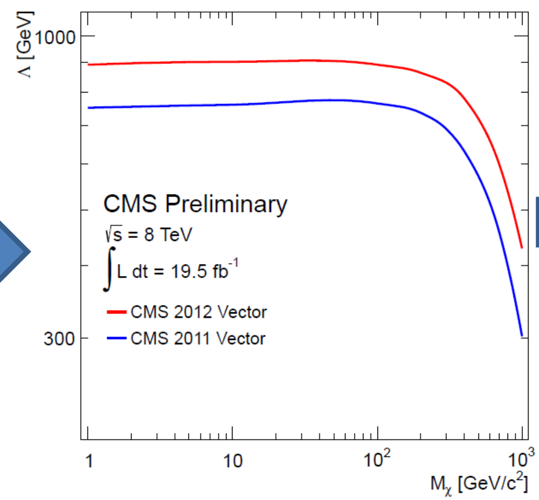


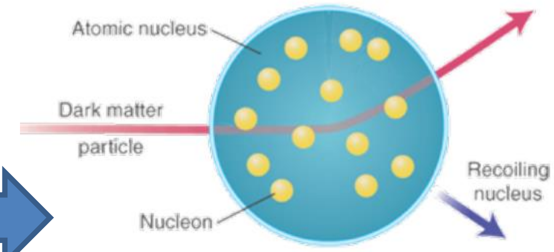
EFT to translate limits to same plane as direct detection experiments

Experimental result



Convert pp xsec limit into Λ





Spin-Independent

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

Coefficient relating nucleon and quark operator

Vector operator

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

μ = reduced mass of the nucleon (p or n) system

$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4}\left(\sum_q f_q^N\right)^2$$

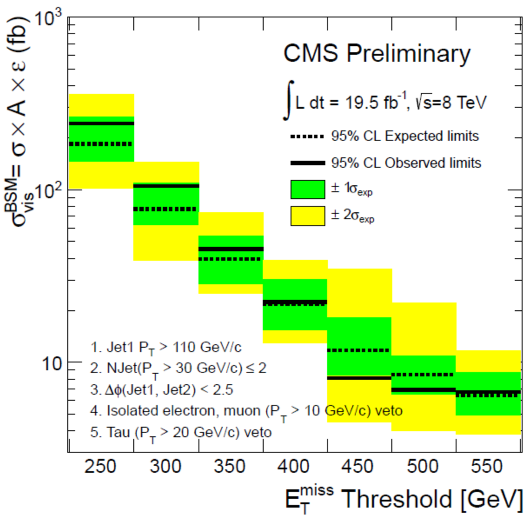
with $f_u^p = f_d^n = 2, f_d^p = f_u^n = 1$

$f = 0$ for other quarks

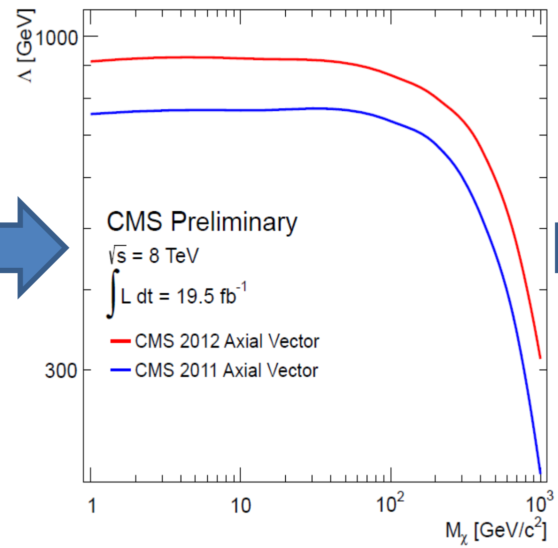
arXiv:0803.2360.

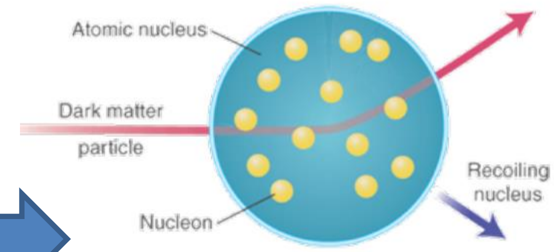
EFT to translate limits to same plane as direct detection experiments

Experimental result



Convert pp xsec limit into Λ





Axial-Vector operator

$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_\mu\gamma^5 q_i$$

Spin-Dependent

$$\mathcal{O}^{Nq} = \Delta_q^N \frac{(\bar{N}\gamma^\mu\gamma_5 N)(\bar{\chi}\gamma_\mu\gamma_5\chi)}{\Lambda^2}$$

Sum of quark helicities

μ = reduced mass of the nucleon (p or n) system

$$\sigma_{SI} = \frac{3\mu^2}{\pi\Lambda^4}\left(\sum_q \Delta_q^N\right)^2$$

$$\Delta_u^p = \Delta_d^n = 0.842 \pm 0.012$$

$$\Delta_d^p = \Delta_u^n = -0.427 \pm 0.013$$

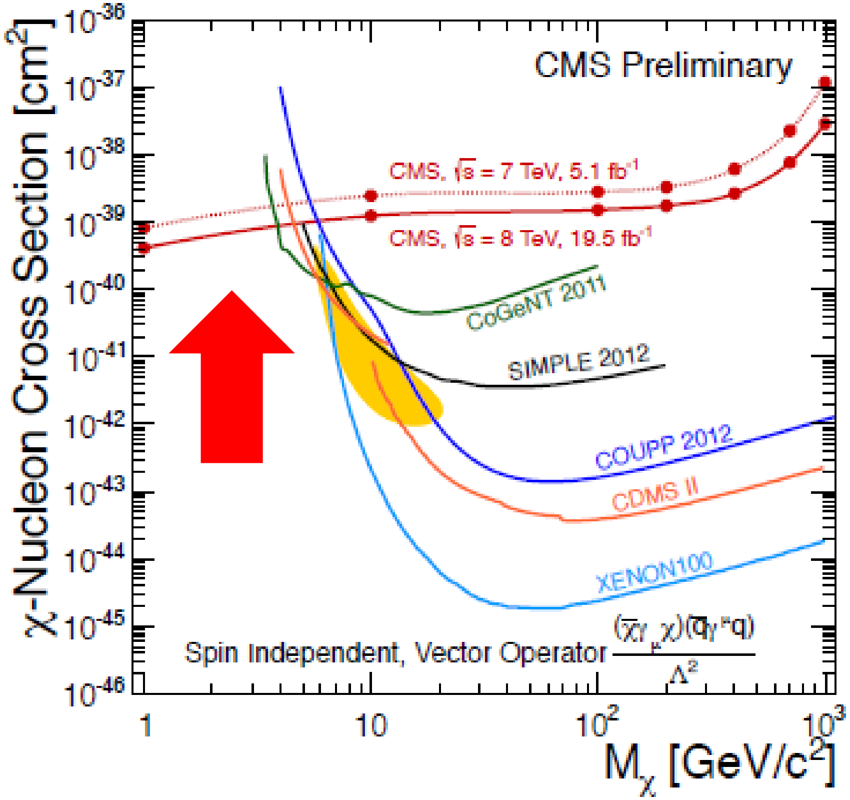
$$\Delta_s^p = \Delta_s^n = -0.085 \pm 0.018$$

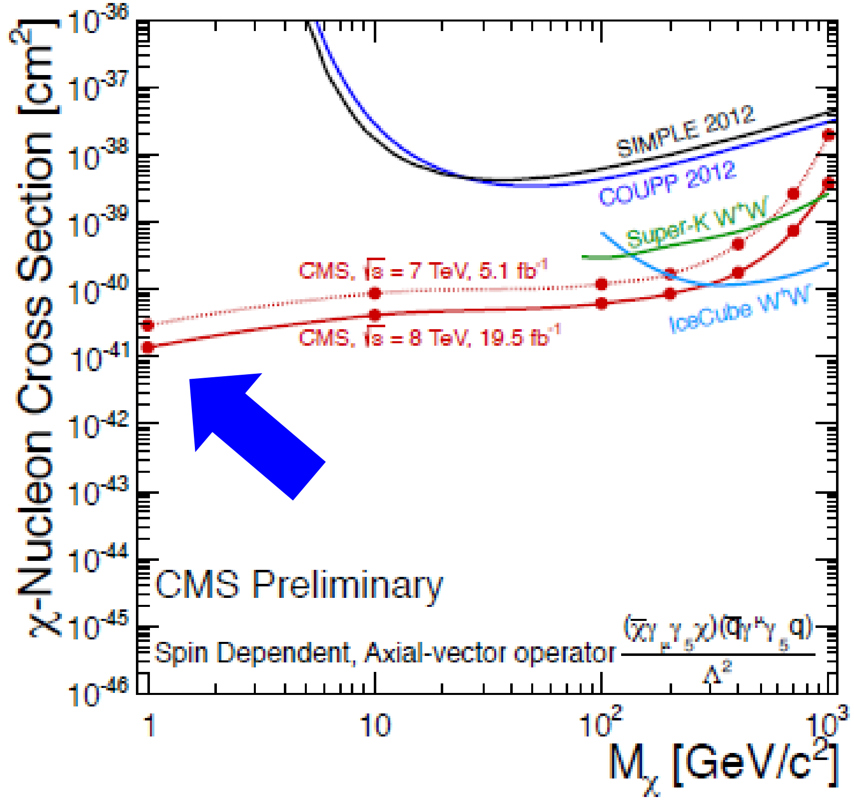
arXiv:0803.2360.

DM – Nucleon Limits

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

ATLAS and CMS results similar for 7 TeV data, improved with 8 TeV

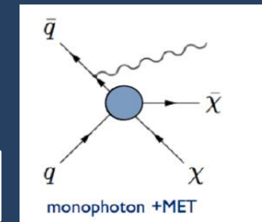


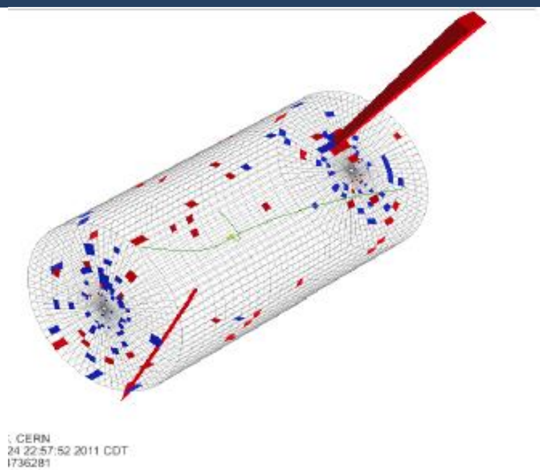


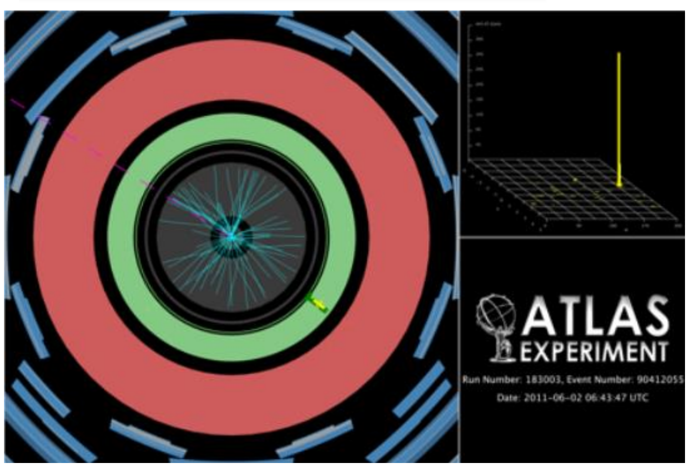
LHC can access very low DM masses

Exclude large cross sections for spin-dependent case

Search for Pair Produced Dark Matter in Monophoton Channel







Signature: high p_T Photon + MET

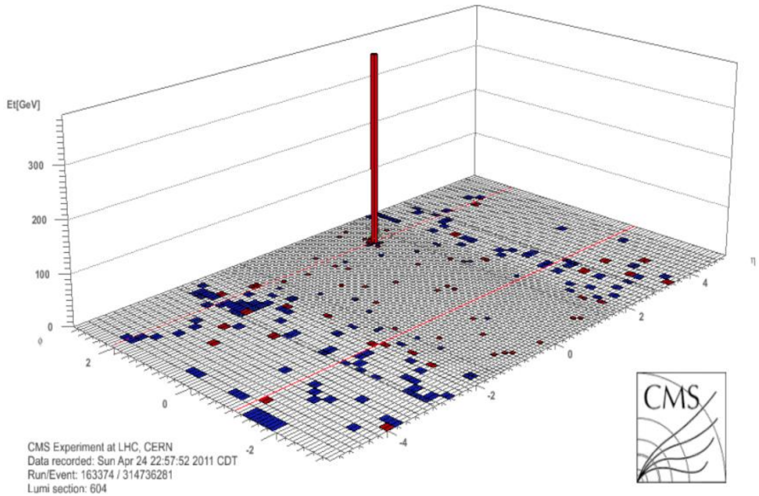
CMS PRL 108, 261803 (2012)

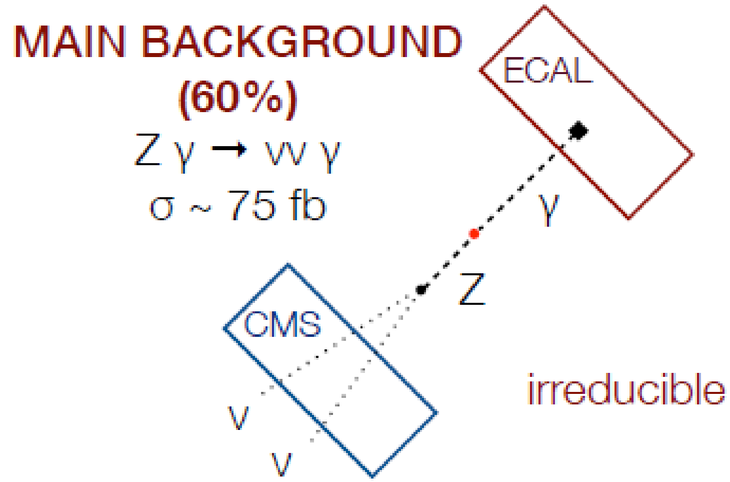
ATLAS PRL 110, 011802 (2013)

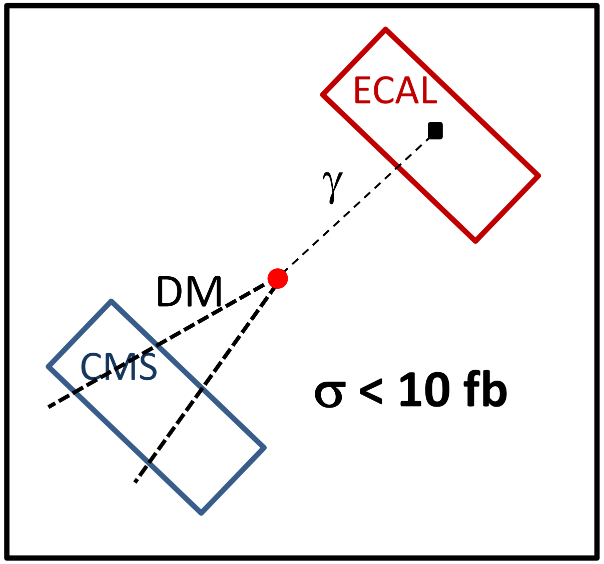
2011 pp data at √s = 7 TeV

2011 result
Stay tuned for 2012 update

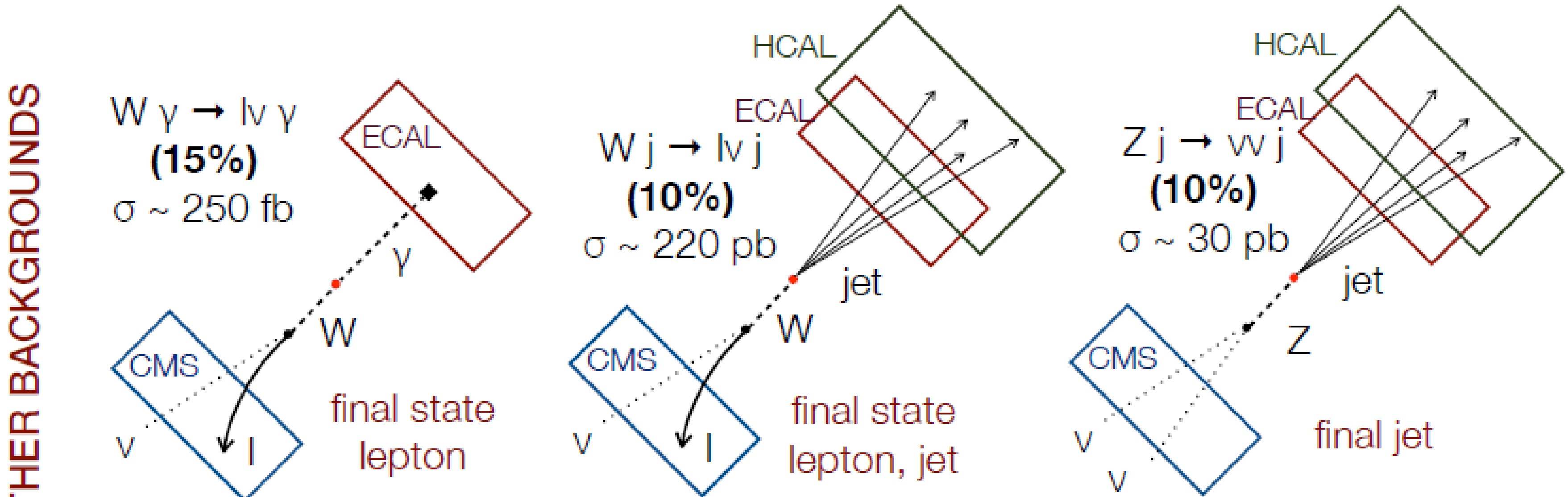
Signal and Background







Several Other Backgrounds



+ γj, jj <5% each

Instrumental backgrounds (~30%) from mis-identification and beam halo

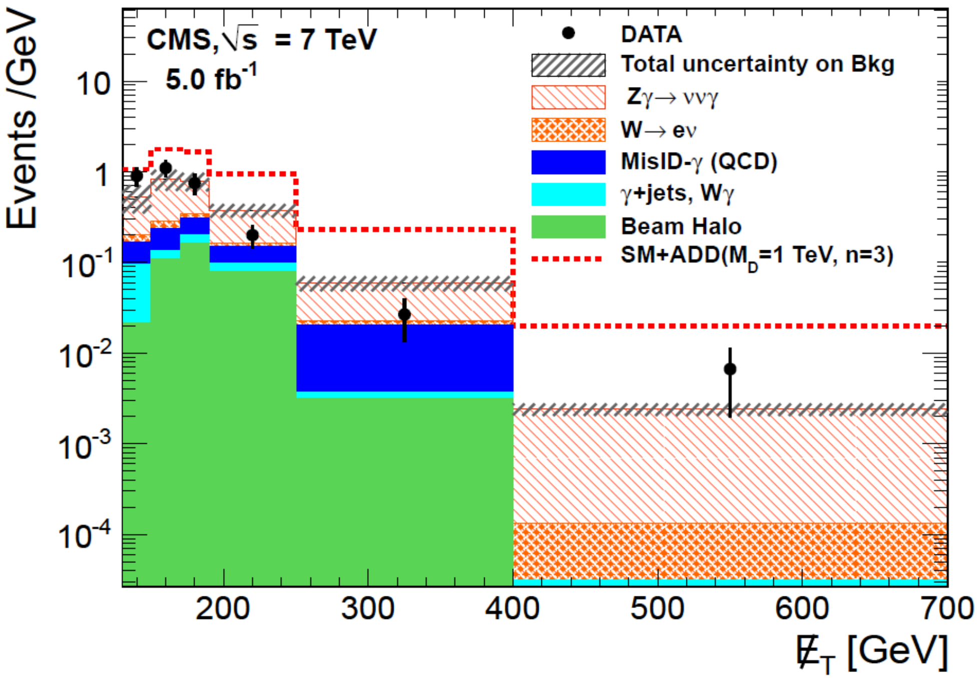
SM backgrounds (~70%):

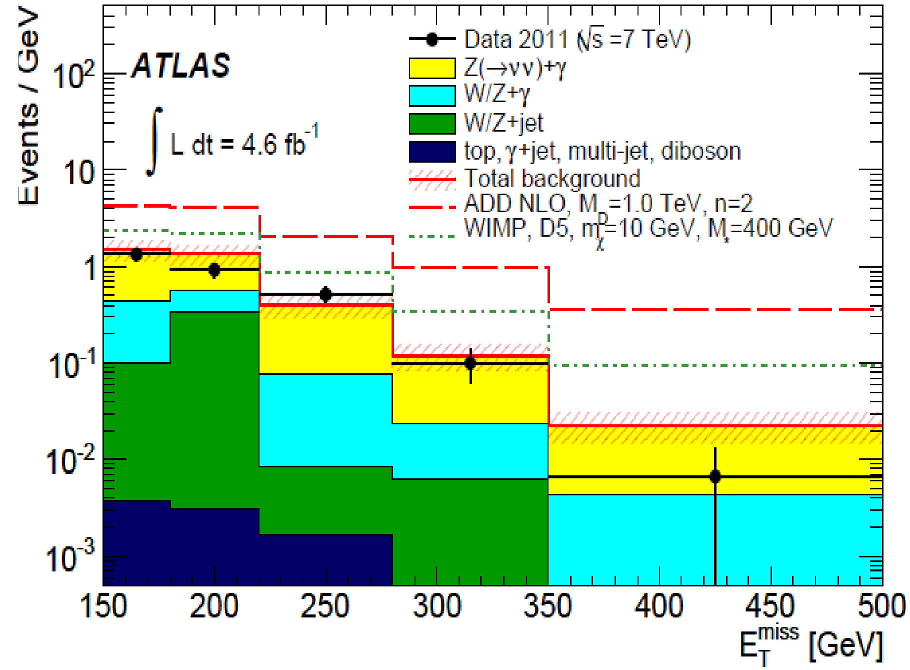
- Needs good understanding of cross section for Zγ, Wγ.
- NLO corrections. NLO k-factor (1.3 global SF for Wγ, $p_T(\gamma)$ dependant SF for Zγ (~1.5 global)

Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu\bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73

Monophoton Result

CMS PRL 108, 261803 (2012)
ATLAS PRL 110, 011802 (2013)





Good agreement with SM in both analyses

- ATLAS Exp. 137± 20 Obs. 116
- CMS Exp. 75.1 ± 9.5 Obs. 73

ATLAS Monojet 2011
Exp. 2180 ± 170
Obs. 2353

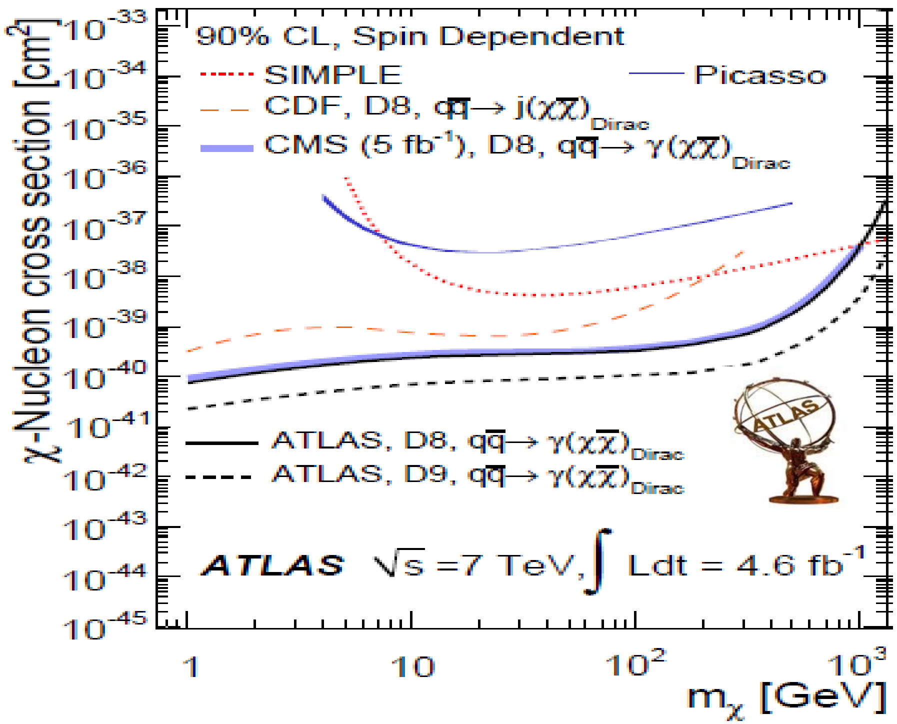
DM-Nucleon Cross Section

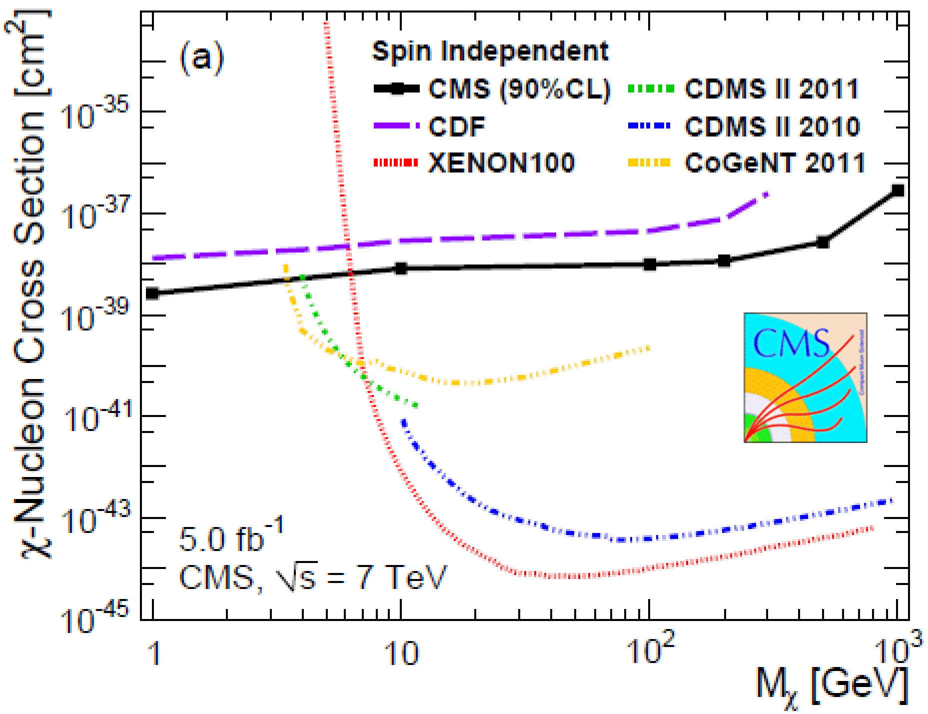
CMS PRL 108, 261803 (2012)
ATLAS PRL 110, 011802 (2013)

Model-independent 90% CL upper limits on cross section

2011 data

14 fb (V and AV) for M_χ < 200 GeV → Λ > 570 GeV

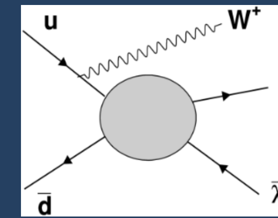


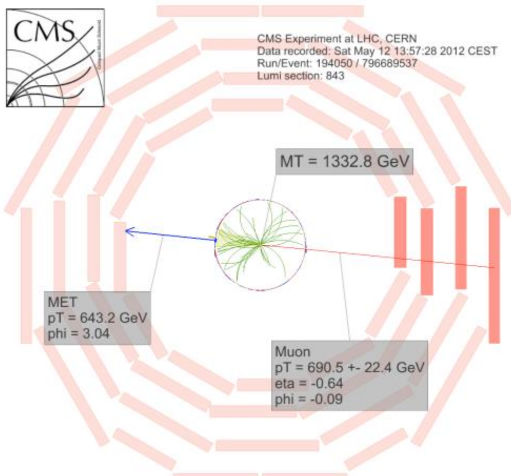


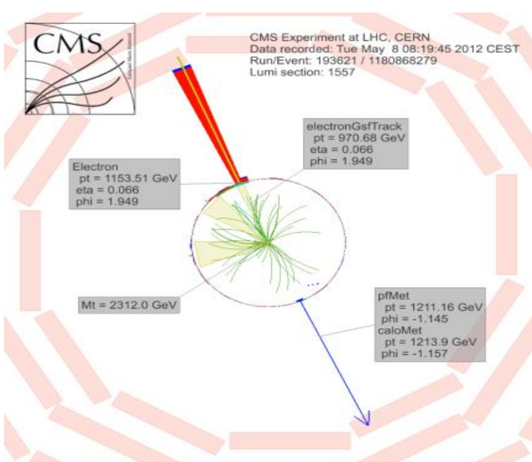
ATLAS and CMS comparable results at 7 TeV.

With 8 TeV statistics expect 10x higher sensitivity.

Search for Pair Produced Dark Matter in Monolepton Channel







Signature W + MET:

high p_T electron + MET

High p_T muon + MET

New 2012 legacy result

CMS –PAS-EXO-13-004

20/fb of 2012 pp data at √s = 8 TeV

Search strategy following
Bai and Tait: arXiv:1208.4861v2

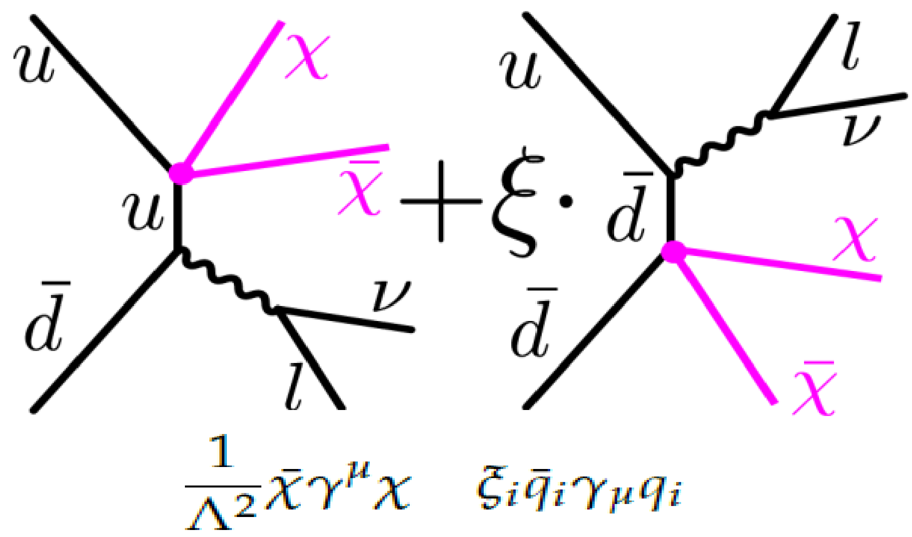
Interference

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

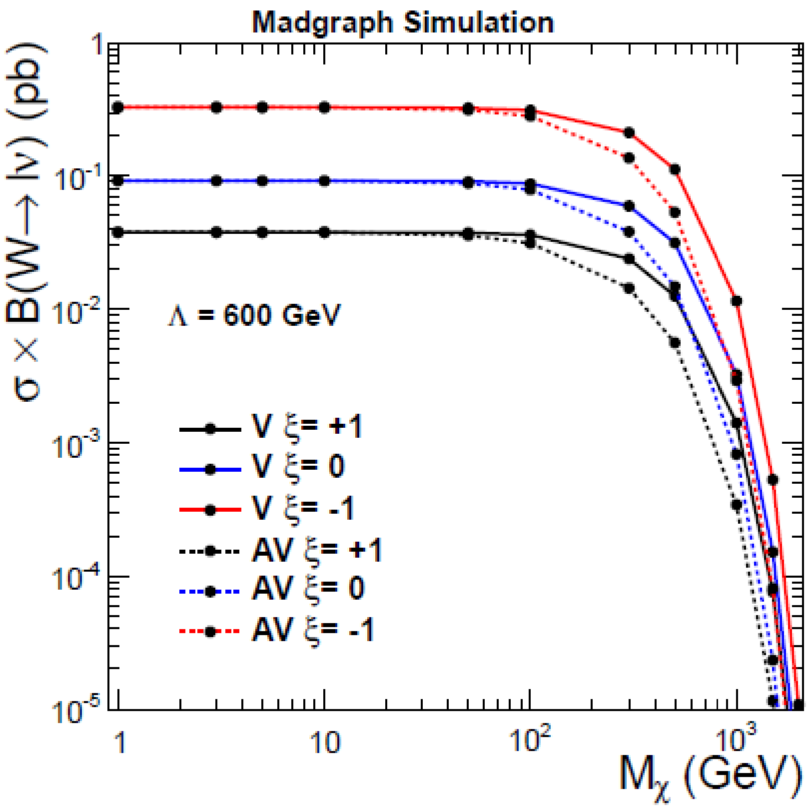
if [C(u) = -C(d)] → constructive interference → mono-boson more sensitive than mono-jet

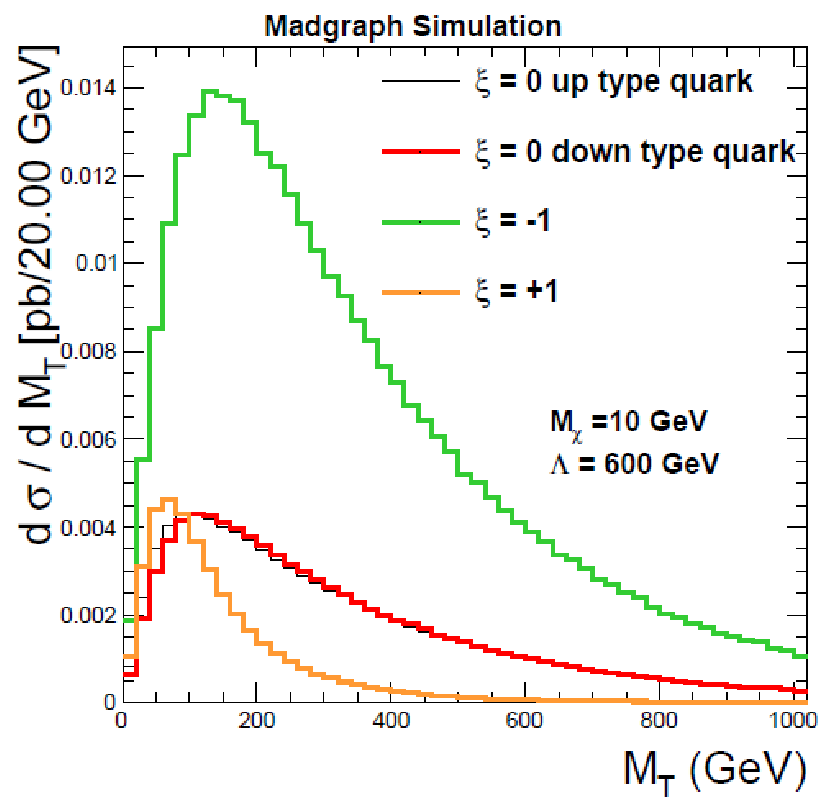


Neutrino + DM contribute to MET

Interference Parametrized by $\xi = -1, 0, +1$

Mono-jet ξ=+1





Largest cross section for χ = -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

Selecting Monolepton Events

CMS-PAS-EXO-13-004

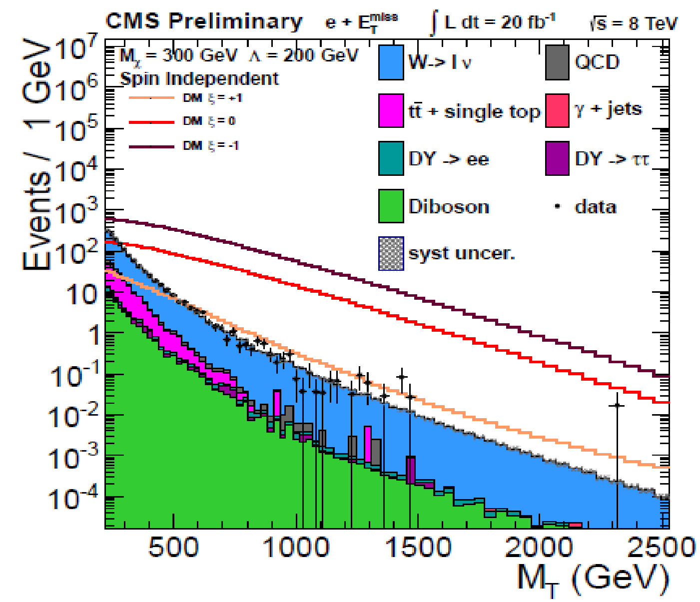
Event selection

- Single electron(muon) trigger with p_T>85(40) GeV
- Lepton ID optimized for high p_T
- Kinematical selections:

  $0.4 < p_T / MET < 2$

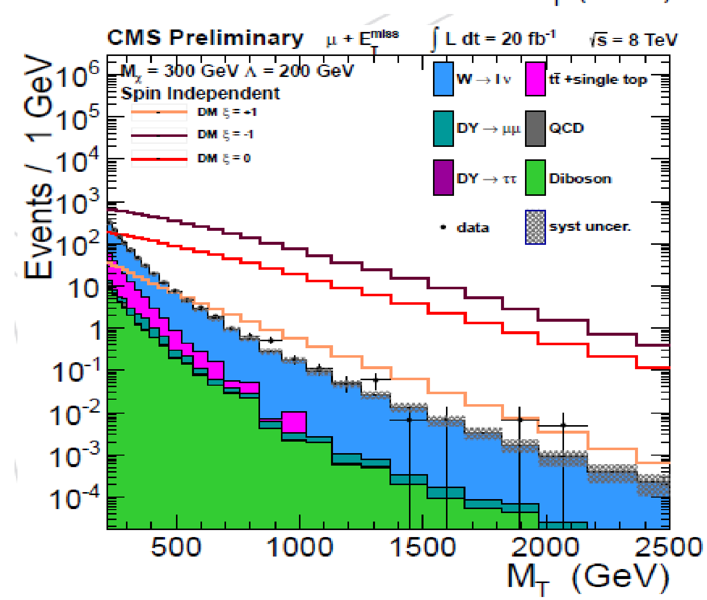
  $\Delta\phi < 0.8$

Search strategy for lepton +MET following Bai & Tait: arXiv:1208.4361



Transverse mass distribution

$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos\Delta\phi_{\ell,\nu})}$$



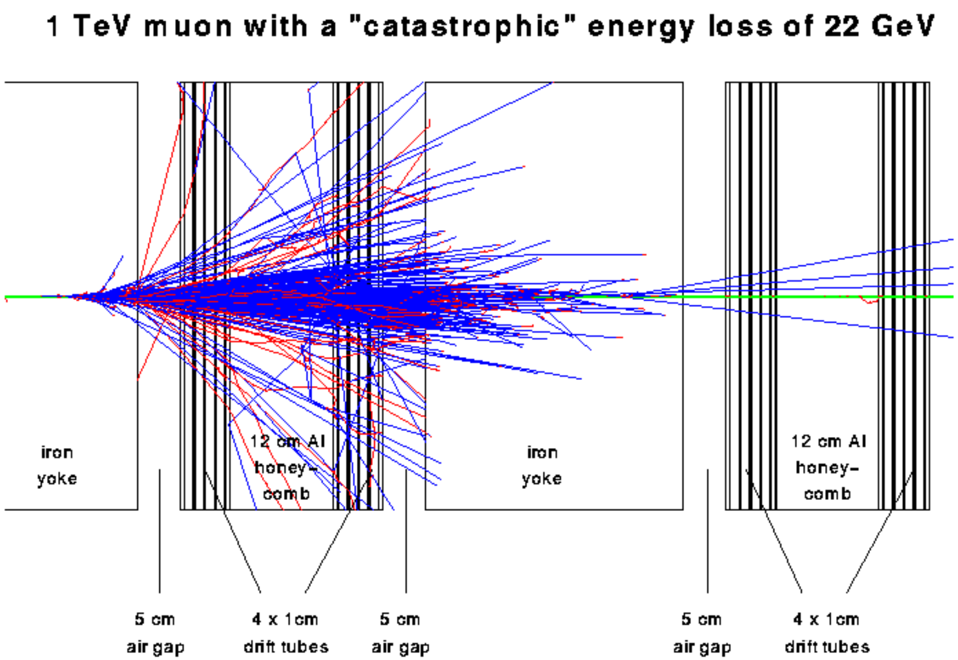
Background

- Derived from simulation
- Challenge high M_T tail
- Main bkgr: W→lν with M_T binned k-factor
- NLO xsec's

Challenge of TeV Leptons

Heavy particles yield final state leptons with high momentum → dedicated reconstruction algorithms (especially for l+MET)

Muons $E_{critical}$ ~900 GeV → Muon shower (in CMS return yoke,~10 X_0)



Limits on production cross section + λ

CMS-PAS-EXO-13-004

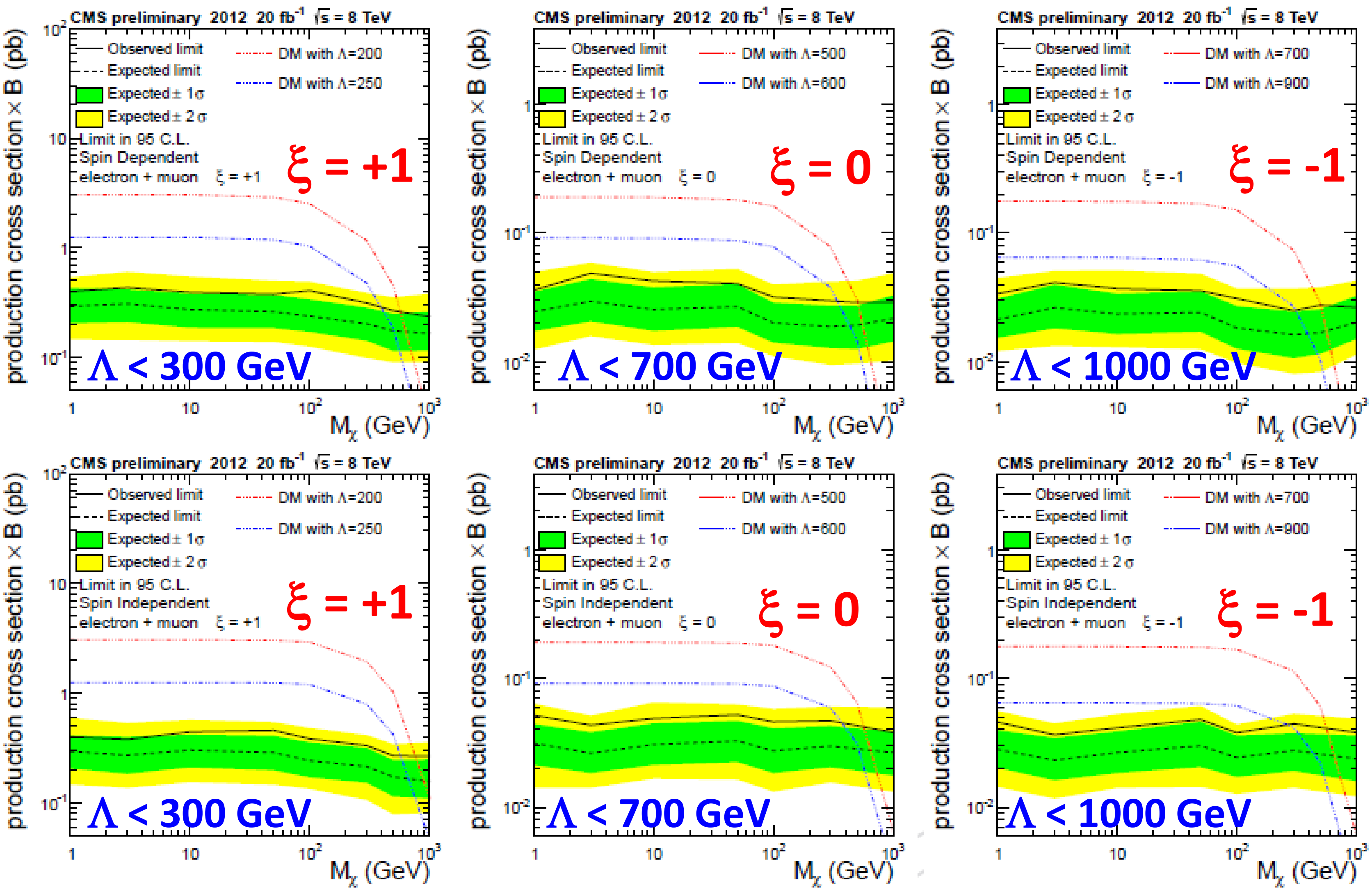
V

Spin

In-
depen
dent

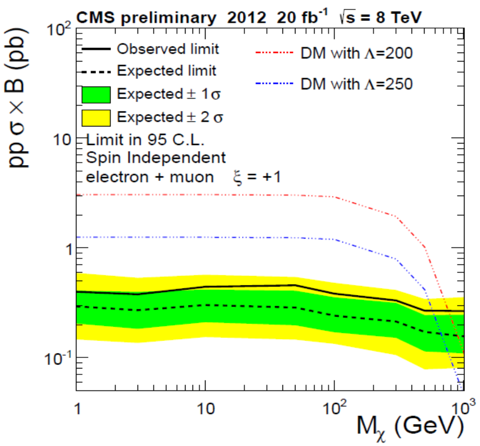
AV

Spin
depen
dent



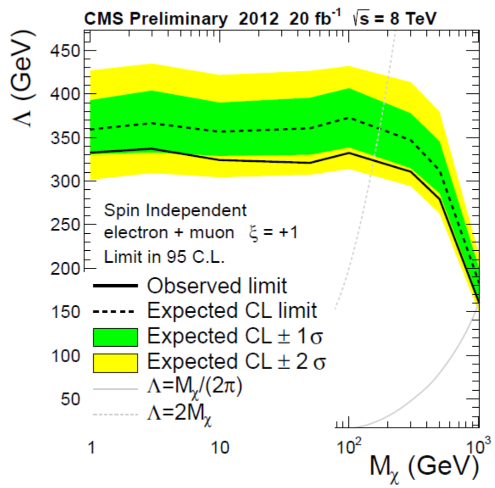
Translation to DM-Nucleon

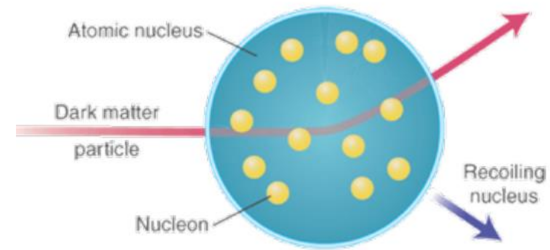
Same procedure as for monojet. Standard assumption is ξ=+1



Vector operator

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





Spin-Independent

$$\mathcal{O}^N = f_q^N \frac{\left(\bar{N}\gamma^{\mu}N\right)\left(\bar{\chi}\gamma_{\mu}\chi\right)}{\Lambda^2}$$

Coefficient relating nucleon and quark operator

$$\sigma_{SI} = \frac{\mu^2}{\pi\,\Lambda^4}\left(\sum_q f_q^N\right)^2$$

Channel	Lambda limit for Mchi < 200 GeV
l+MET ξ = +1	300 GeV
l+MET ξ = 0	700 GeV
l+MET ξ = -1	1000 GeV
Jet + MET	900 GeV

ξ

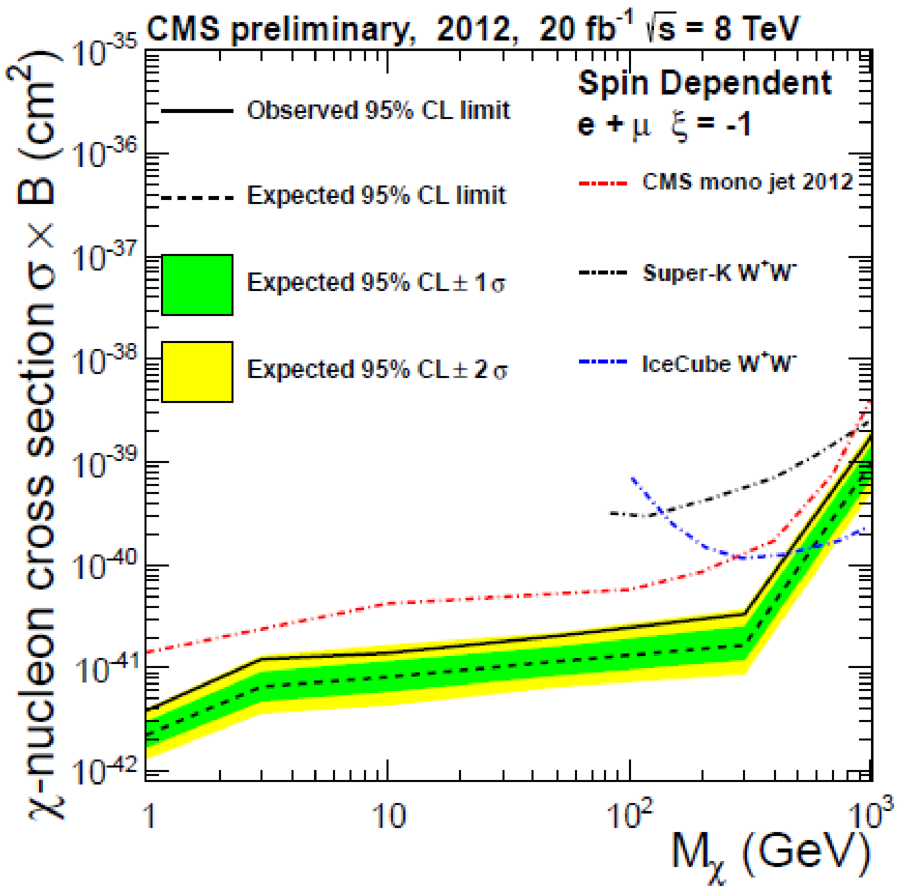
$$\text{with } f_u^p = f_d^n = 2, f_d^p = f_u^n = 1$$
$$f = 0 \text{ for other quarks}$$

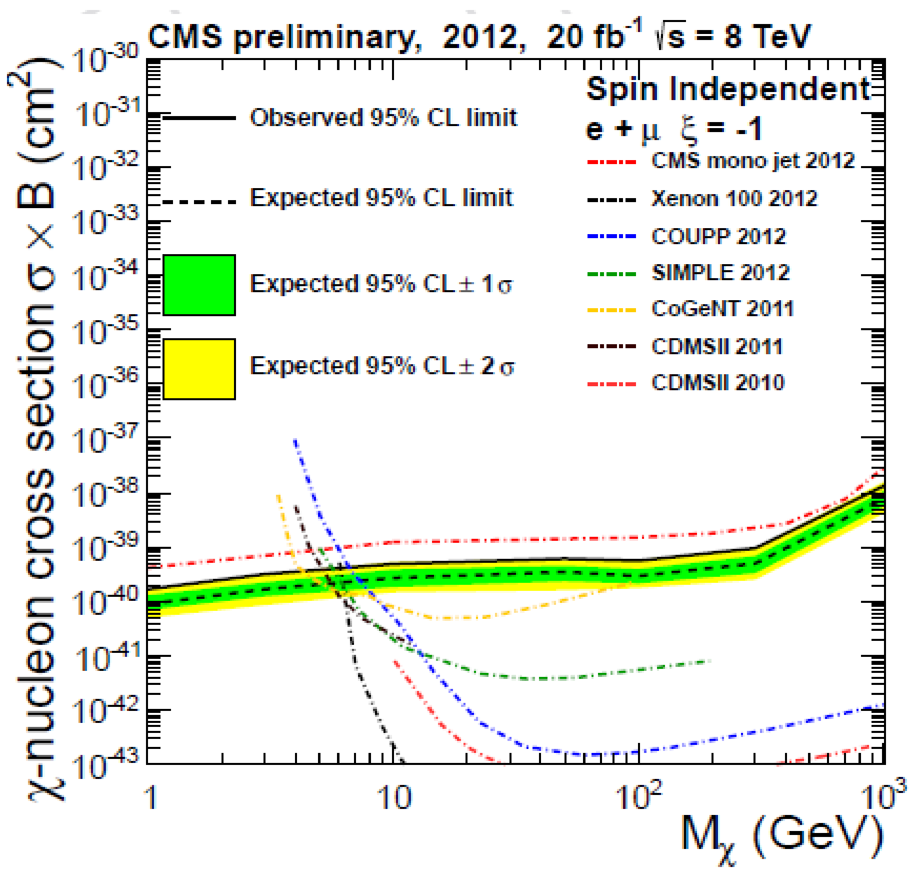
arXiv:0803.2360.

Monolepton ξ = -1 (max. sensitivity)

CMS-PAS-EXO-13-004

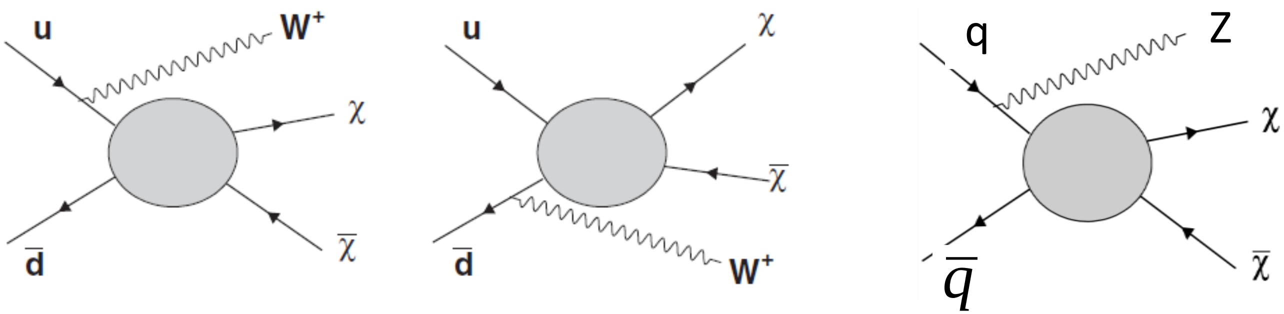
2012 results in comparison to monojet and some direct detection experiments, 90% C.L.





Hadronically Decaying W/Z

New 2012 legacy result



Signature W or Z + MET: two merged jets + MET

Use hadronic decays with large BR (~70%). Resulting final states (W/Z) cannot be distinguished.

W is sensitive to interference = different u/d couplings.

[also a search for WH, ZH with H→$\chi\chi$]

ATLAS-CONF-13-073 (PRL 112 (041802))

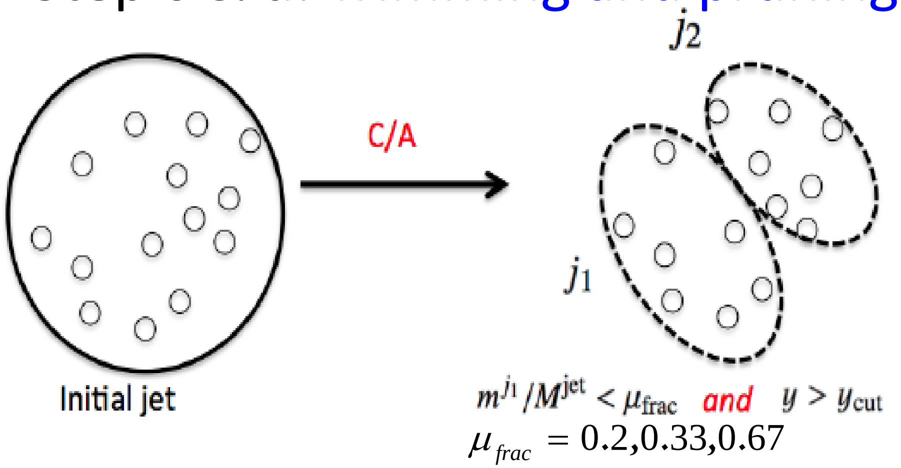
20/fb of 2012 pp data at √s = 8 TeV

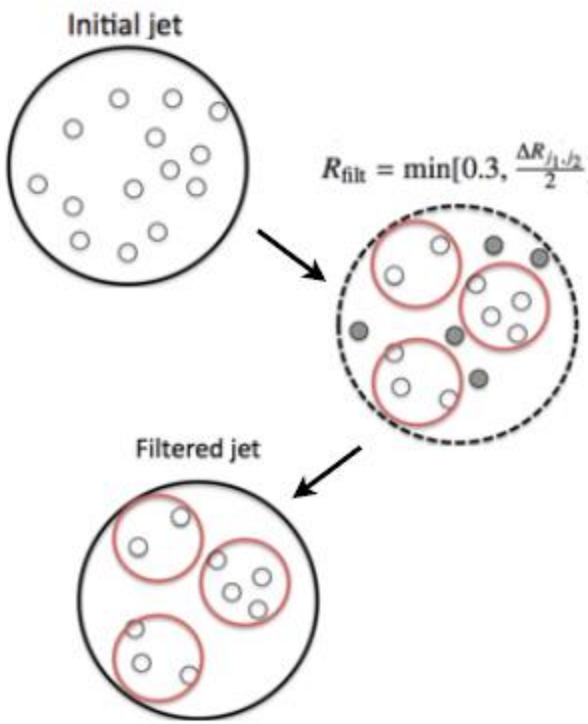
Hadronically Decaying W/Z

ATLAS paper on jet sub-structure arXiv:1306.4945

Increasing rate of overlapping jets → Reconstructed as one „large-radius" jet with Cambridge-Aachen algorithms:

- Step a: Splitting in two subjets (mass-drop filtering procedure)
- Step b: Filtering, reclustering 3 jets with C/A
- Step c & d: Trimming and pruning





Split in 2 sub-jets j_1, j_2 with $m^{j1} < m^{j2}$
Splitting approx. symmetric in energy sharing and opening angle.

Search Performed in MET Distribution

Main Background Z(νν)+jets 60%, W(lν)+jets 30%

Data agree with SM expectation

Control regions Z→μμ, W→μν

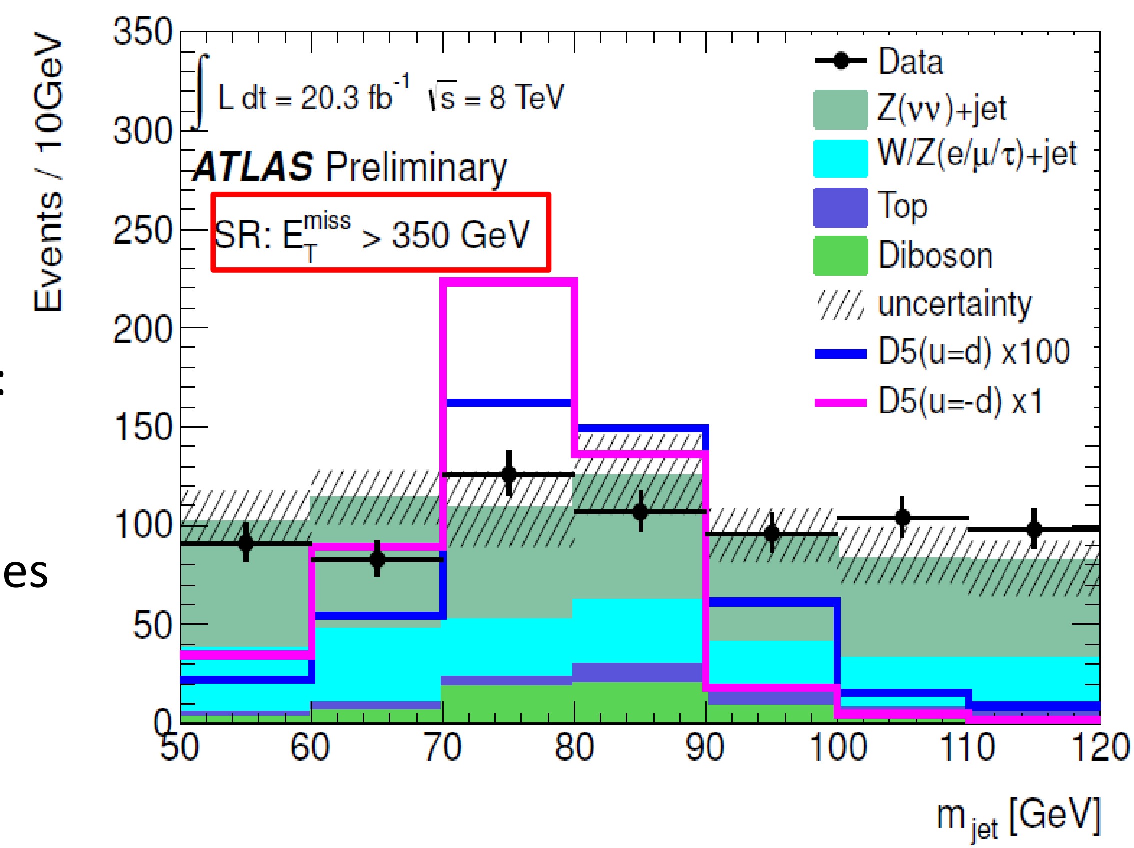
Two signal regions:

MET > 350 GeV

MET > 500 GeV

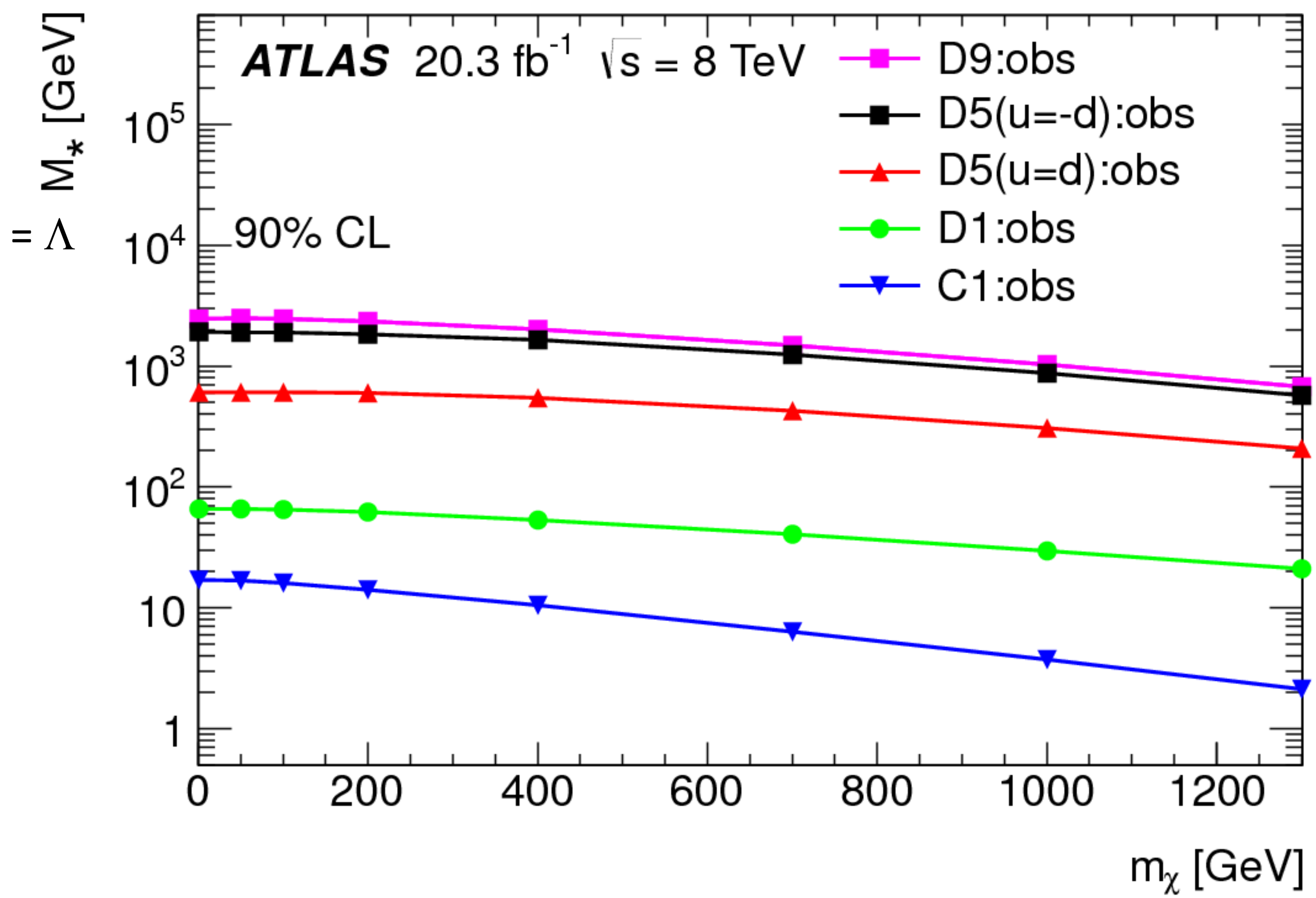
Dominating syst. uncertainties:

- limited statistics in control samples,
- theo.uncertainties in samples used for extrapolations,
- jet and MET reconstruction



Mono-W/Z Limits

Using predicted **shape** of M_{jet} distribution in each signal region
CLs method



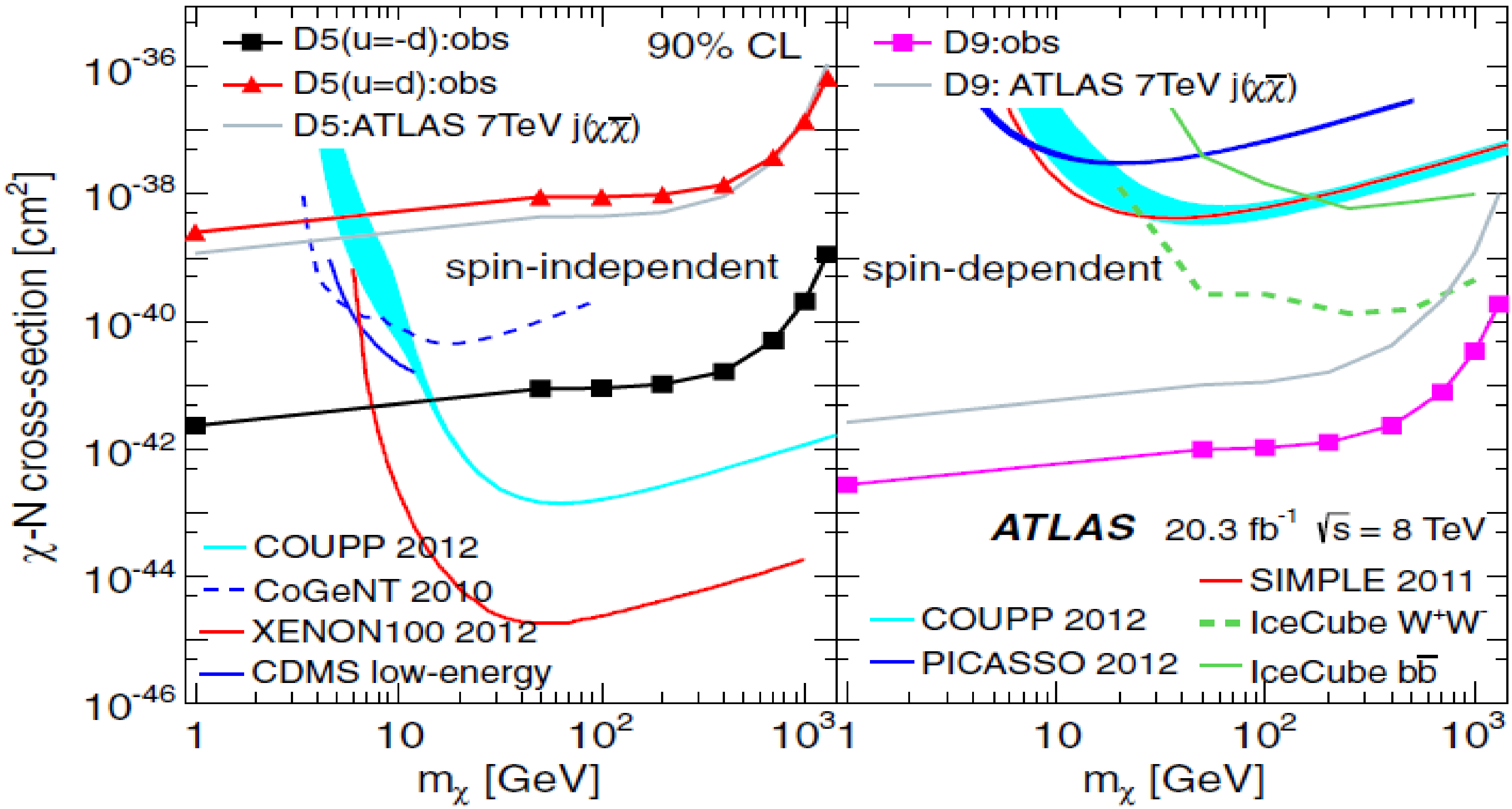
Different vector couplings to u/d for W
Constructive u=-d (larger xsec)
destructive u=d

Operators:
D9 = tensor (SD)
D5 = vector (SI)
D1, C1 = scalar (SI)
D8 = axial-vector

Mono-W/Z in the χ-N plane

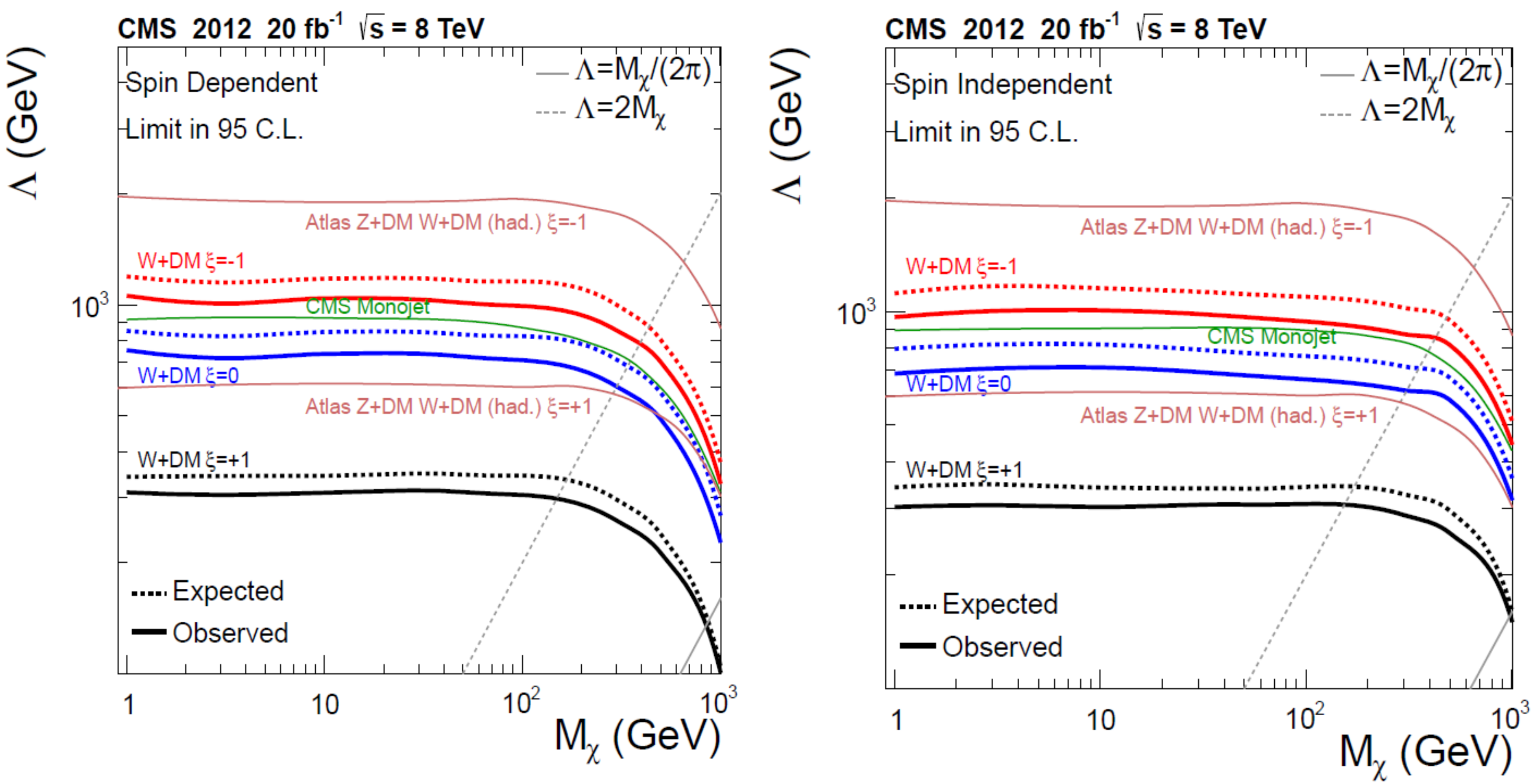
Spin-independent limits very strong **10^{-42} cm²** for vector coupling when u & d have opposite sign

Set strong spin-dependent limits **10^{-43} cm²** for tensor operator



The Big (LHC) Picture…

All 2012 Mono-X Together



Effective theory valid up to $\Lambda < 2 M\chi$

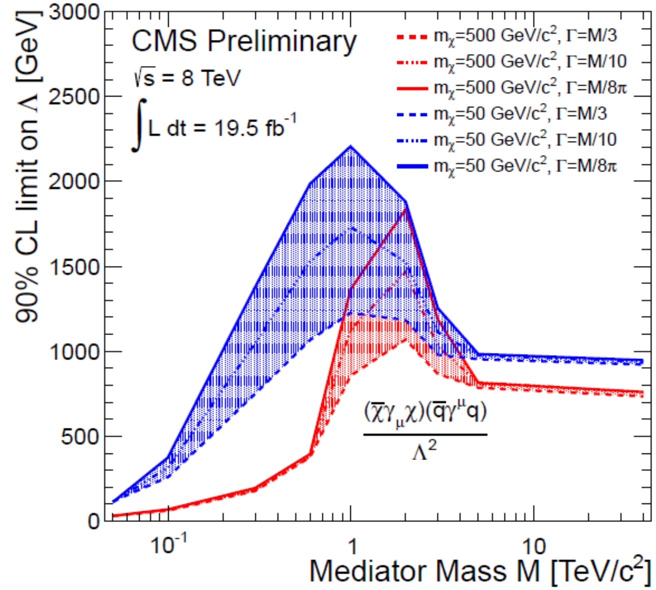
What's Next?

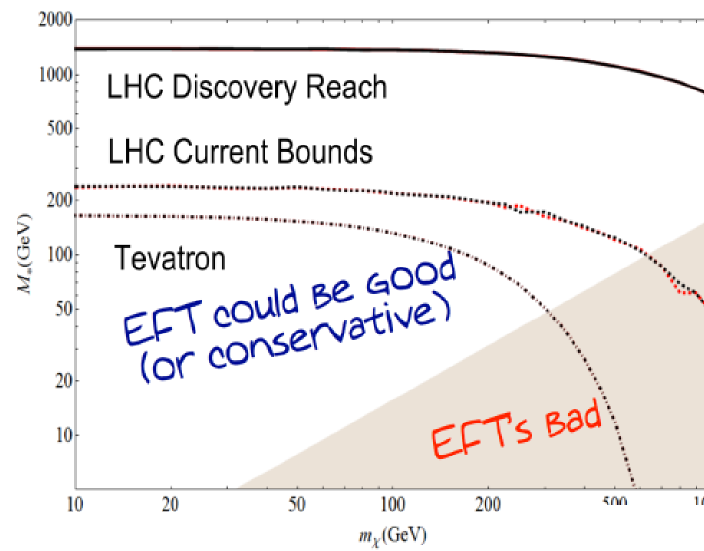
- Signature oriented searches strongly supported by theory
- **Extend** simple contact interaction, more operators, …. Discussions with theorists, [http://kicp-workshops.uchicago.edu/DM-LHC2013/index.php]

- **Scan over mediator mass** (CMS monojet analysis)

- Consider **limitations of EFT**. Good/conservative results above a few hundred GeV.

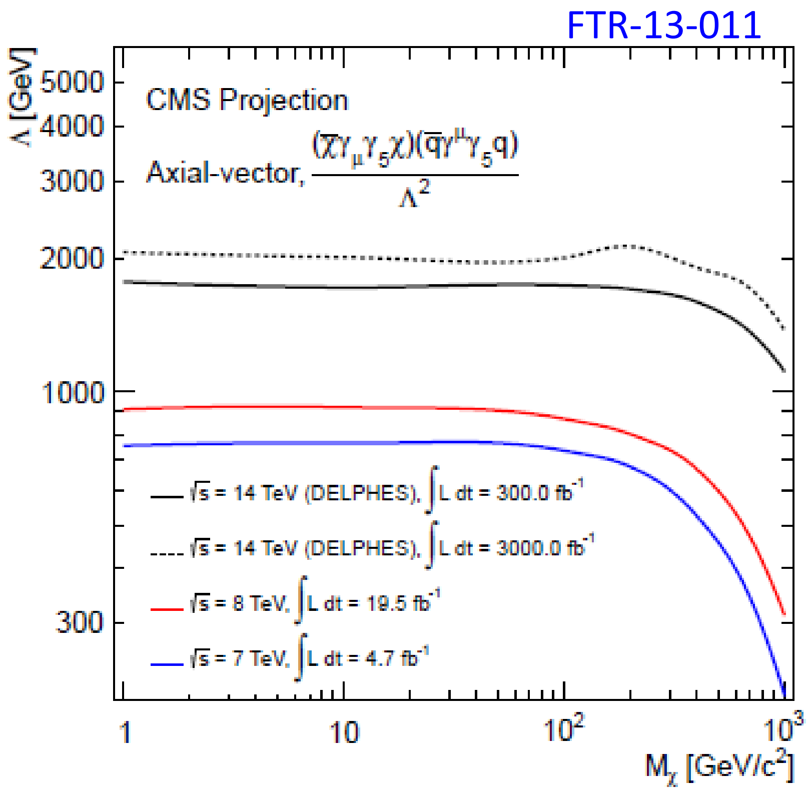
CMS-PAS-EXO-12-048 (20/fb)

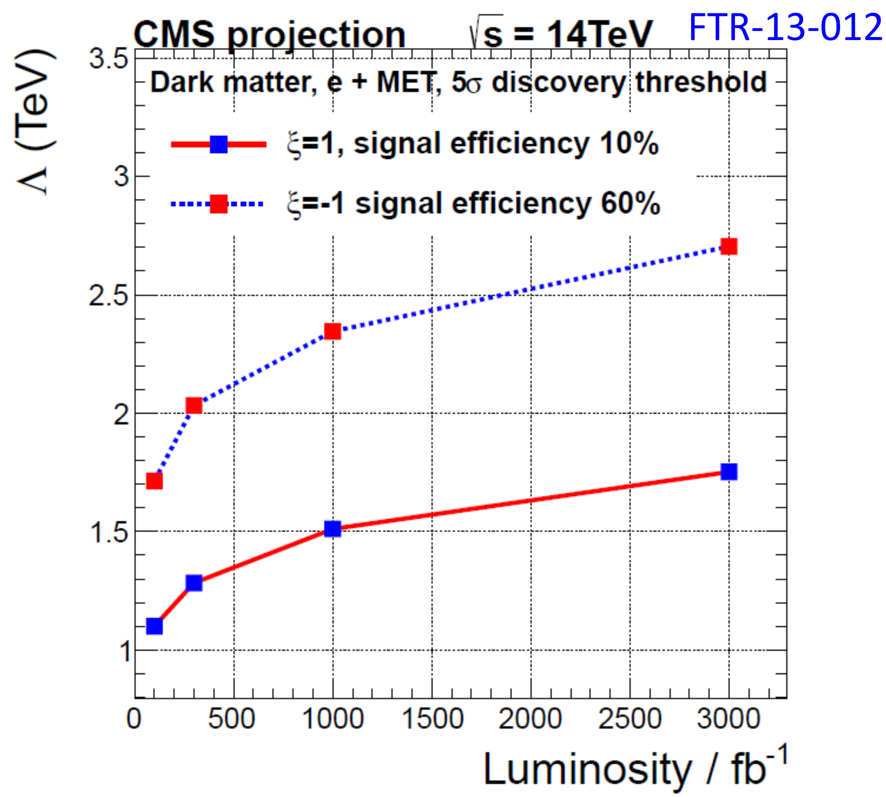




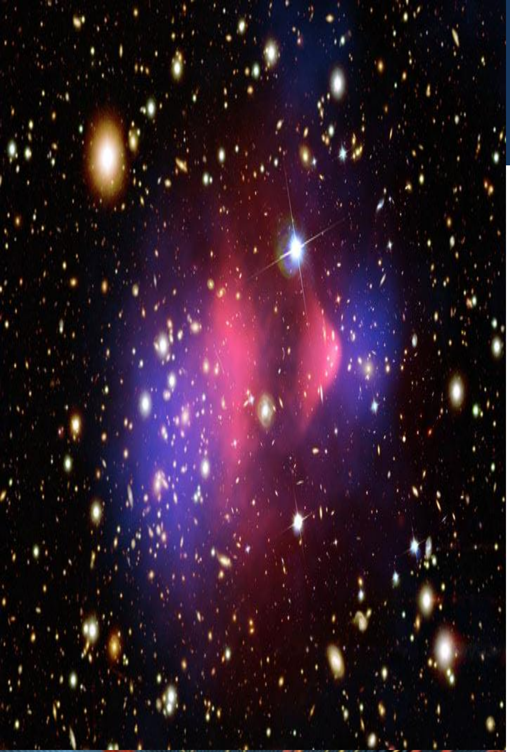
[from R. Harnik, Dark Matter in Collision, UC Davis, 2012]

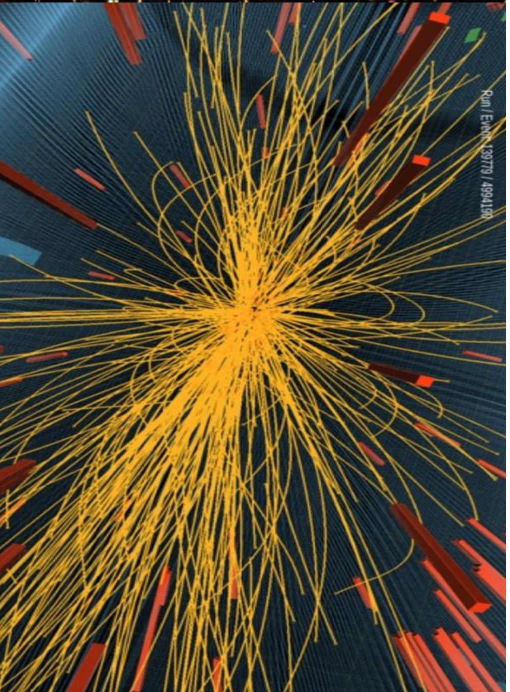
What Can We Reach at 14 TeV?





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





Summary

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Exciting new field. **Major opportunity for new physics!**

Several LHC BSM searches reinterpreted in terms of dark matter models.

Work closely with theorists to develop theoretical assumptions and models.

Complementary to direct detection experiments. Study DM **properties** in case of discovery.

Improved sensitivity in Run-2 of the LHC.

Additional Material

Possible 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) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_\mu\gamma^5 q_i$

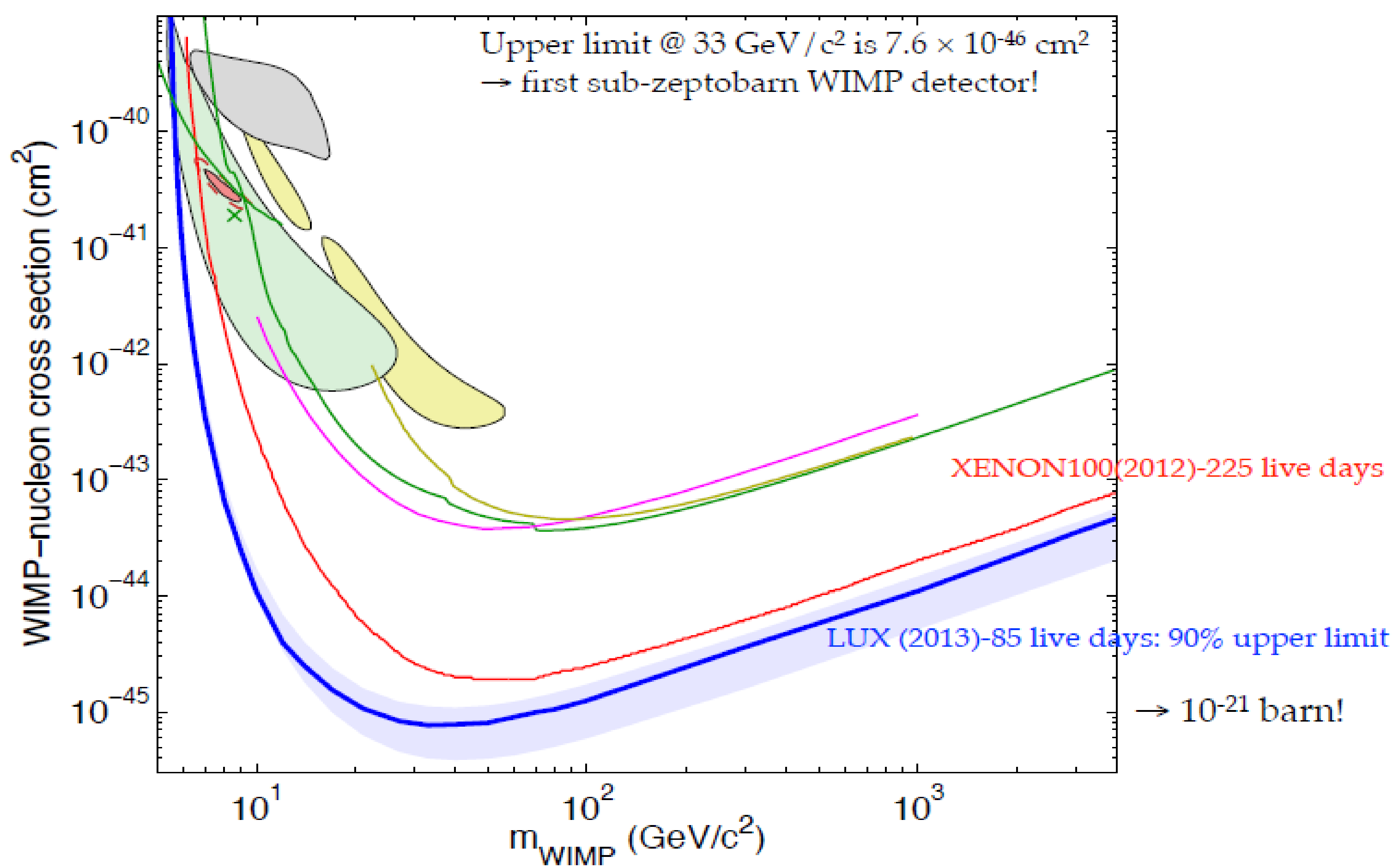
Name	Type	Operator	Coefficient
D1	scalar (qq)	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D5	vector	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D8	axial-vector	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	tensor	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$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

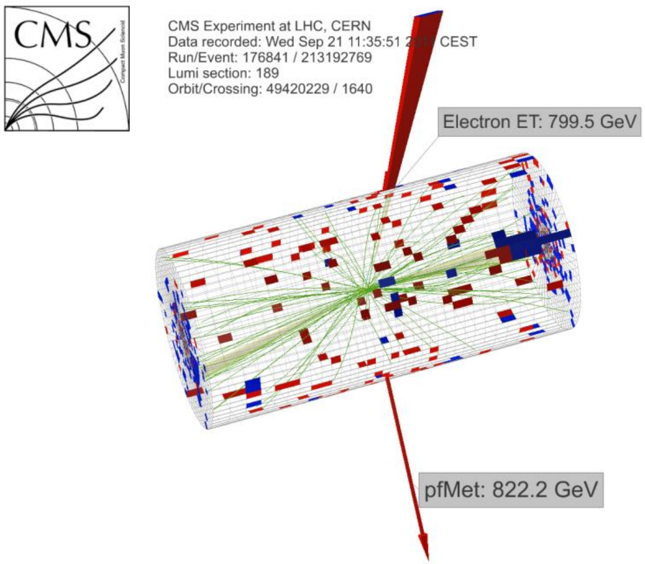
Lux Result

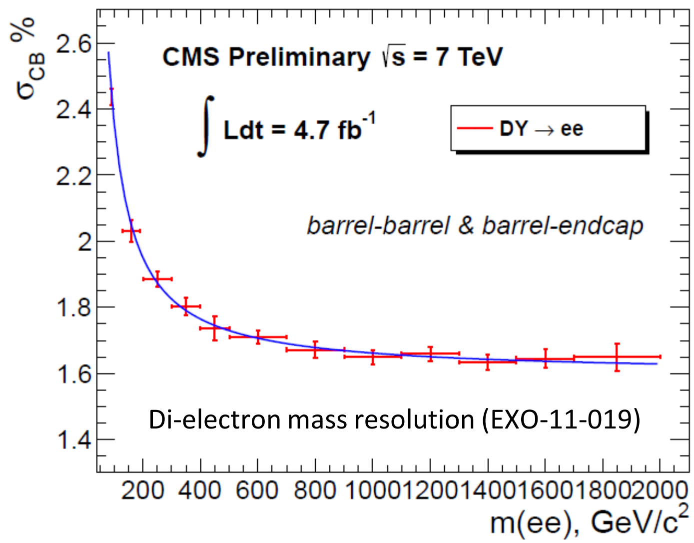
Spin-independent sensitivity



C. Ghag — University College London — 19 Nov. 2013 Slide 50

High Energy Electron Selection



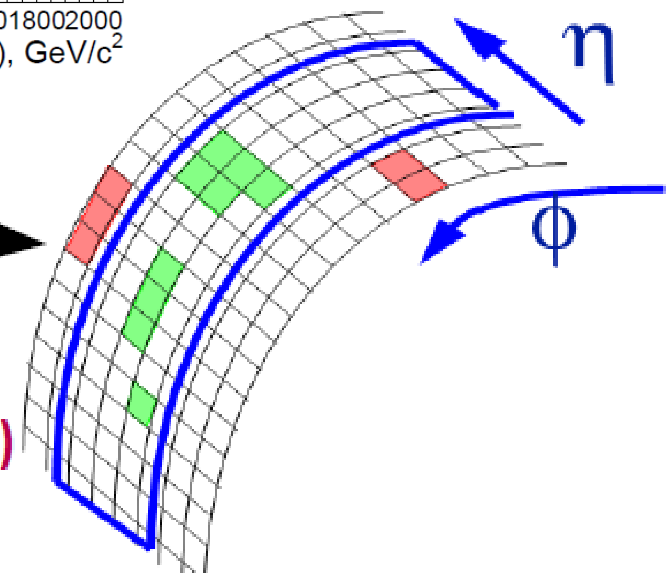


ECAL made of matrix of fully active crystals. Measured energy resolution ~2%

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

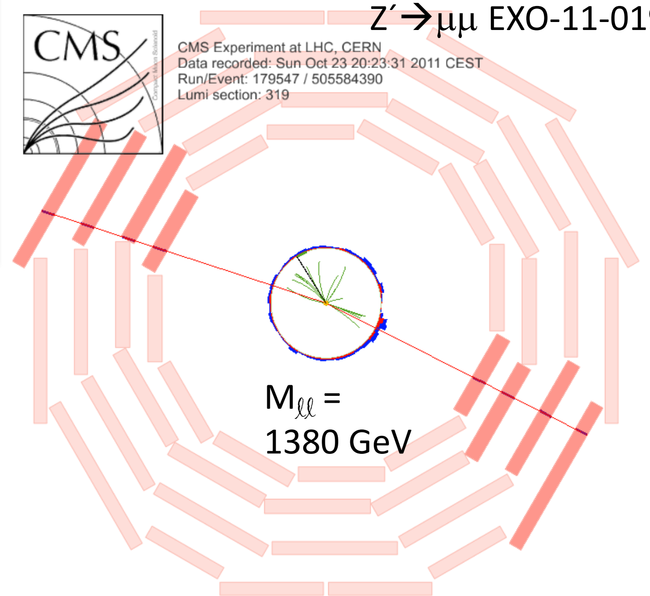


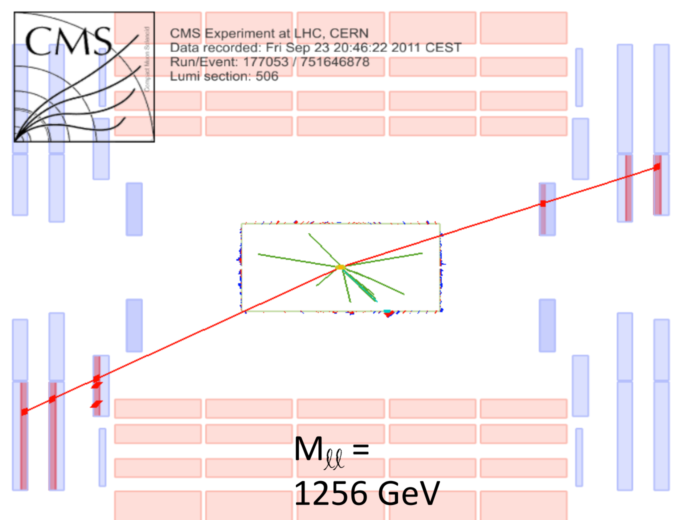
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

High p_T 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





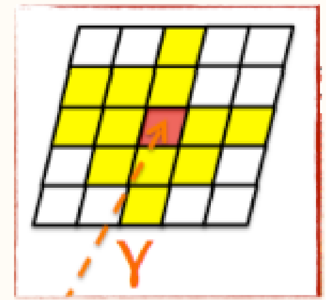
Dedicated muon selection:

- 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 identification

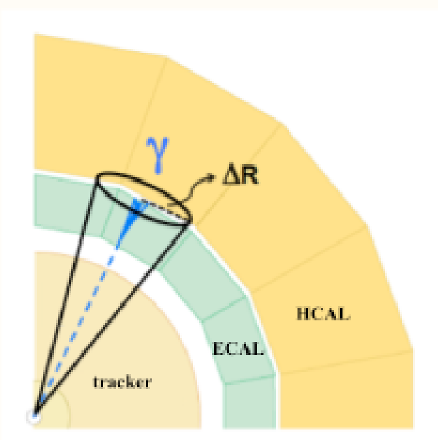
✓ Background contamination and invariant mass resolution depends on:

- 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