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

Kerstin Hoepfner, RWTH Aachen, III. Phys. Inst. A

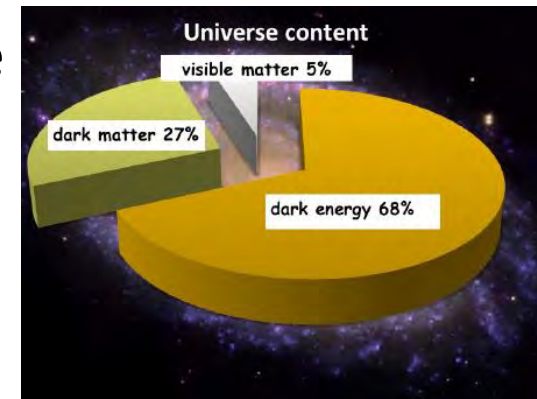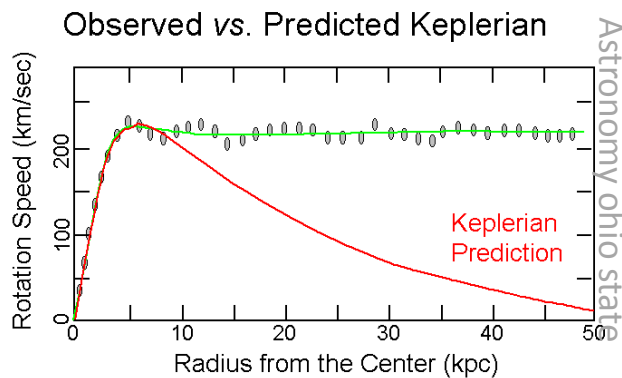**DESY Seminar February 11th 2014**
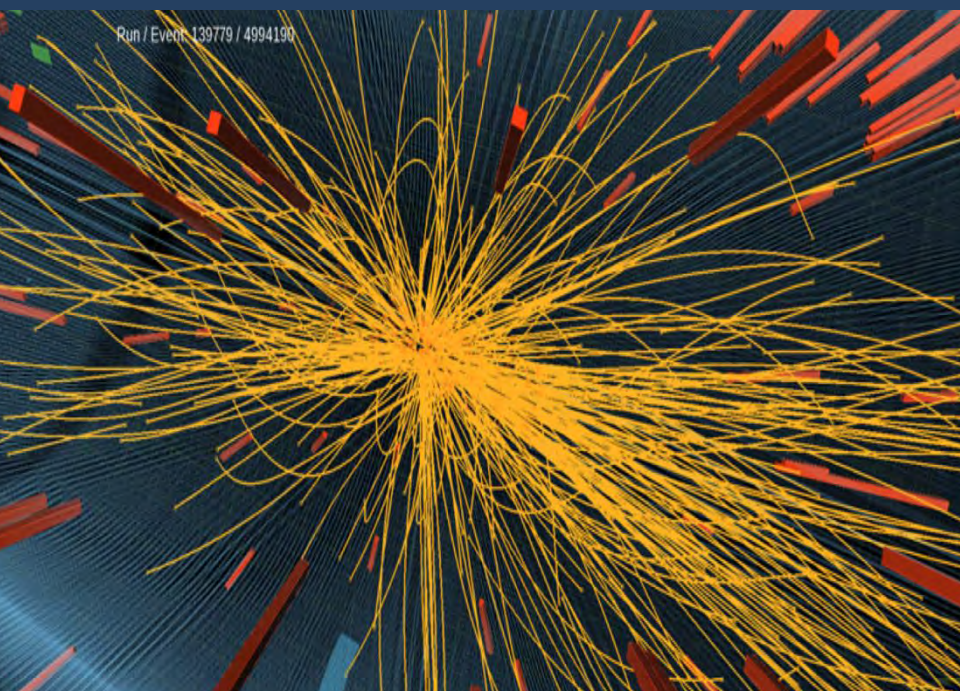
Outline

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**
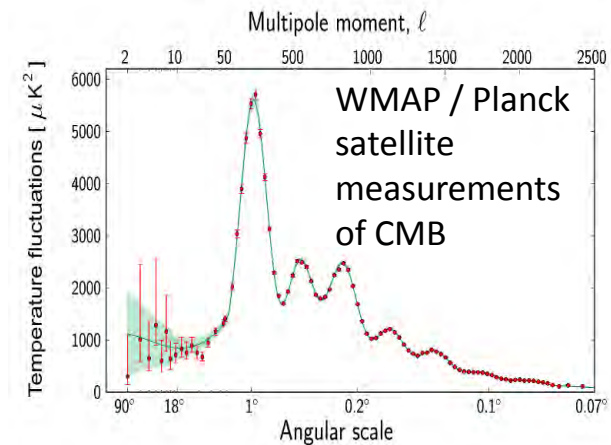
Indications for Dark Matter

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

Universe content
- visible matter 5%
- dark matter 27%
- dark energy 68%

Rotation curves of galaxies

Observed *vs*. Predicted Keplerian

Keplerian Prediction

Astronomy ohio state

Gravitational lensing

WMAP / Planck satellite measurements of CMB

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

DM Properties

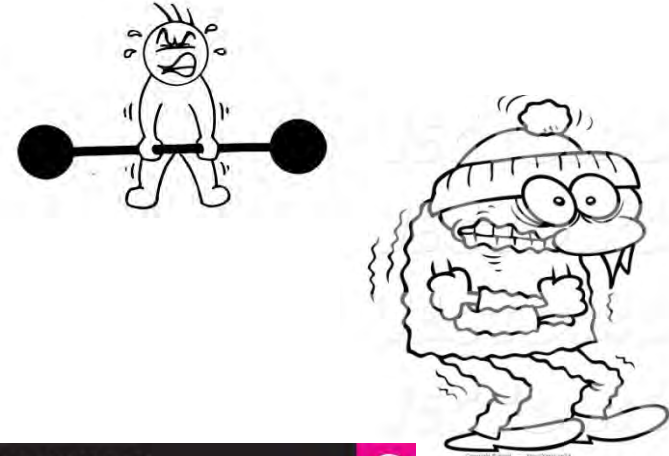No direct observation of DM yet

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

SM

SM

DM

DM

Direct Detection

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 [astro-ph.CO]

Detecting Dark Matter

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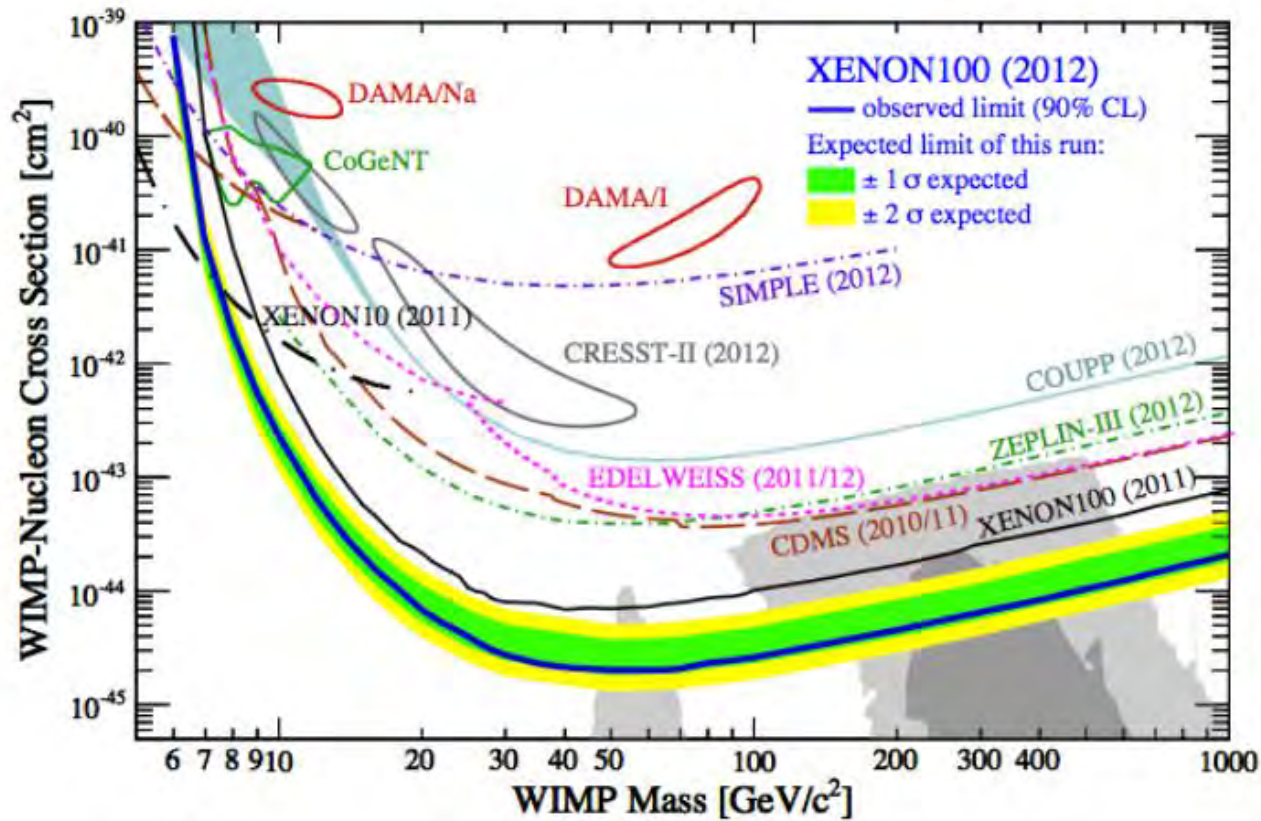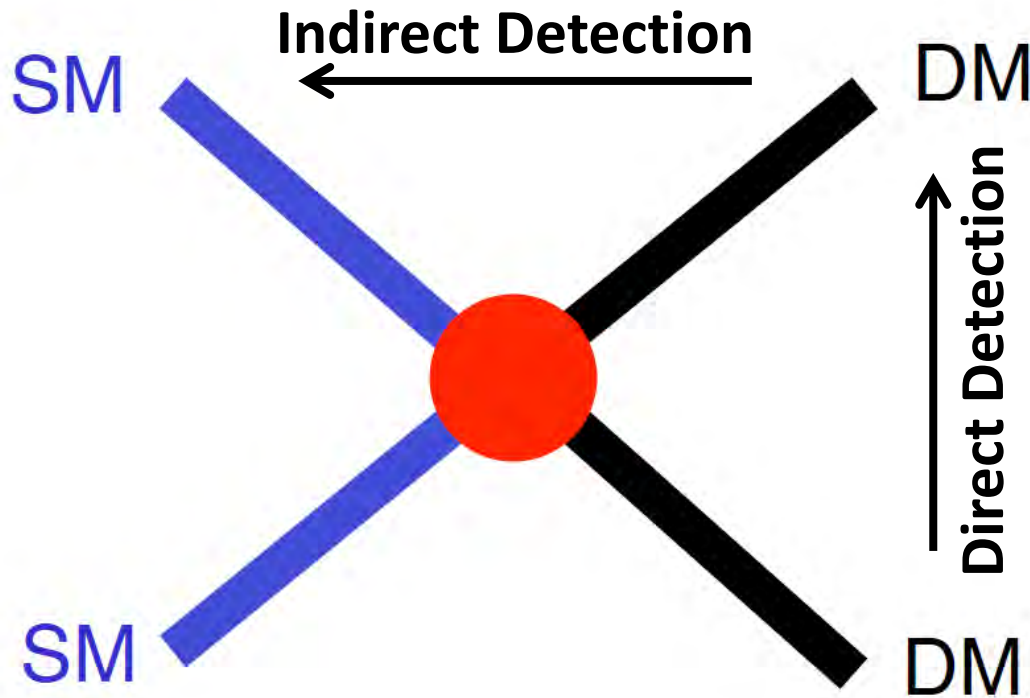
Indirect Detection

SM DM

SM DM

Direct Detection

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

Detecting Dark Matter

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

Indirect Detection

SM ← DM

SM → DM

Collider

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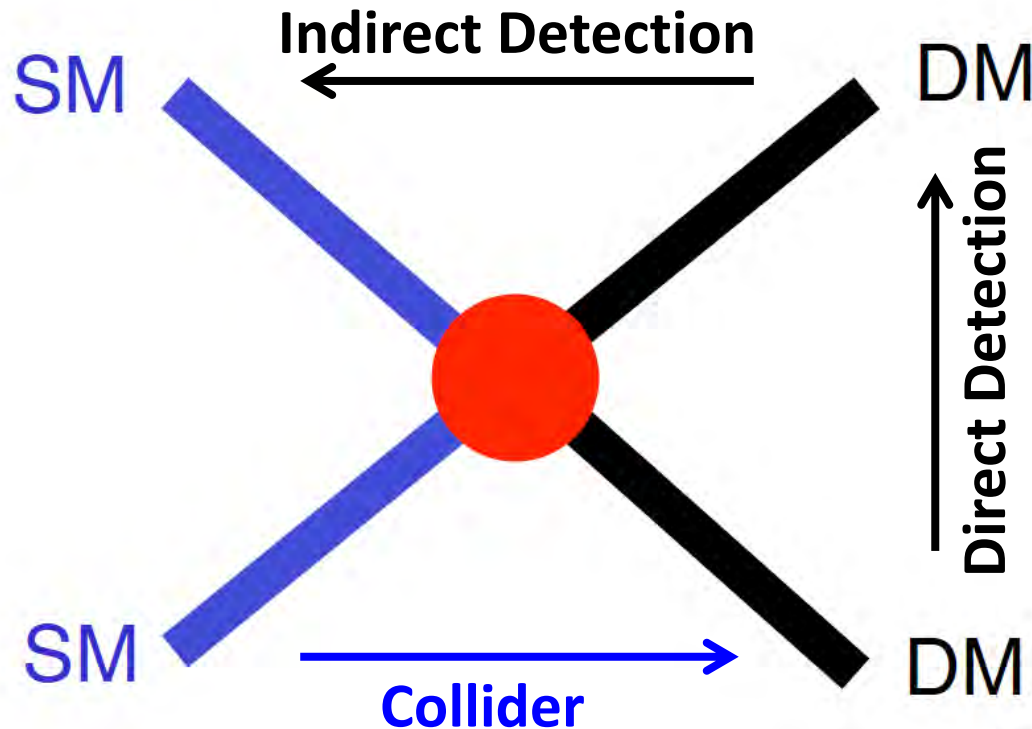
Scattering of DM particles on nuclei of detector material; detect recoil.
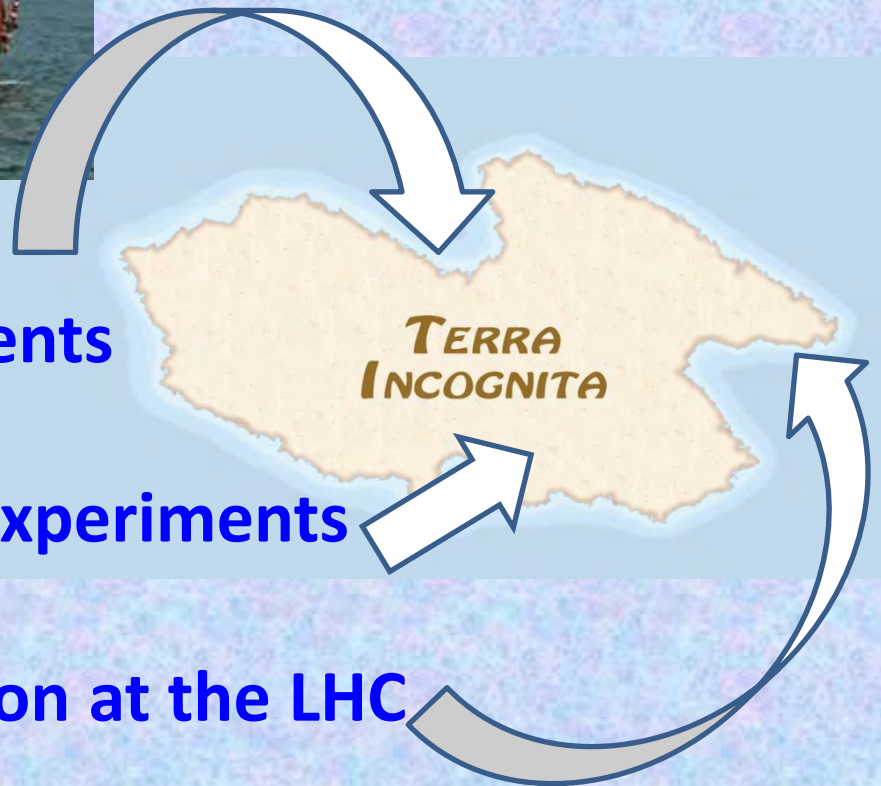For a given cross section sensitivity scales with detector size.

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

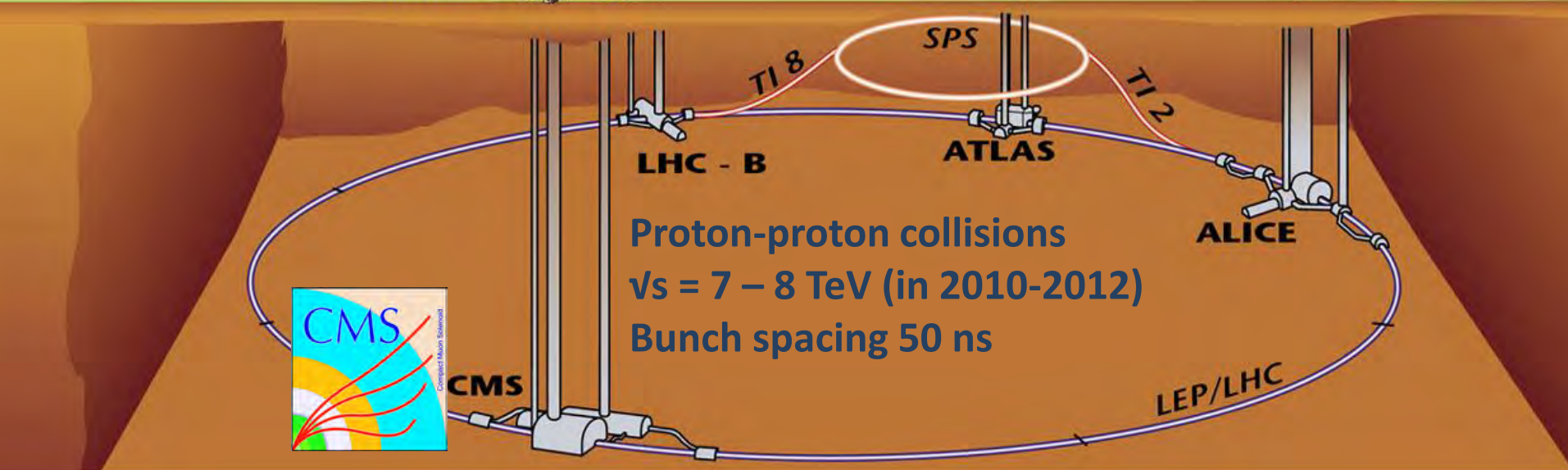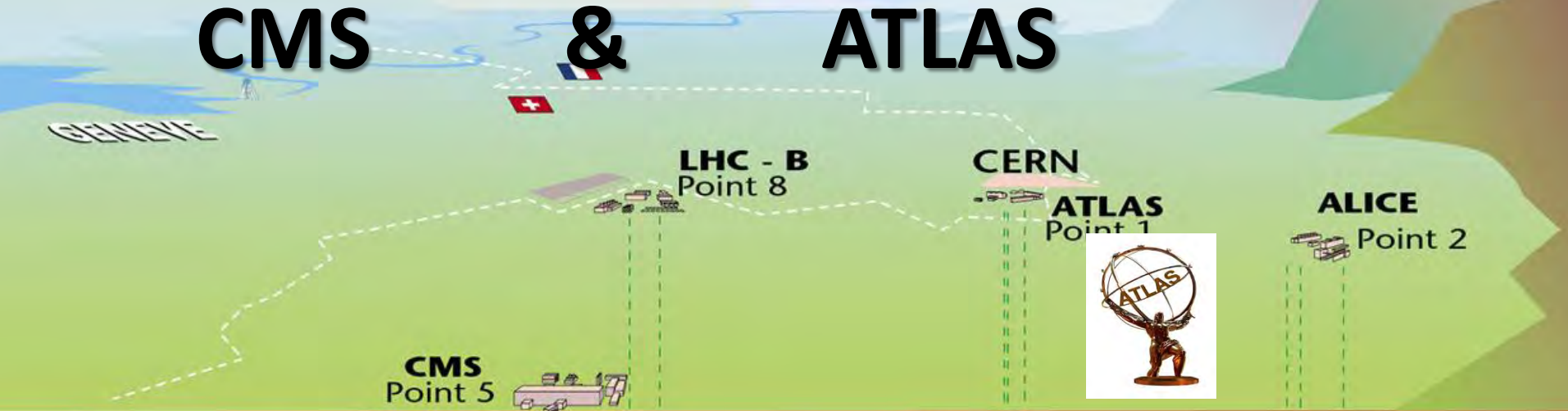**Direct scattering experiments**

Indirect detection experiments

Pair-production at the LHC

TERRA INCOGNITA

The **L**arge **H**adron **C**ollider (LHC)
Two General-Purpose Experiments:
CMS & ATLAS

LHC - B
Point 8

CERN

ATLAS
Point 1

ALICE
Point 2

CMS
Point 5

SPS

TI 8

TI 2

LHC - B

ATLAS

ALICE

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

CMS

LEP/LHC

ATLAS

Excellent stand-alone muon measurement. Emphasis on jet and missing-E_T (MET) resolution, particle identification
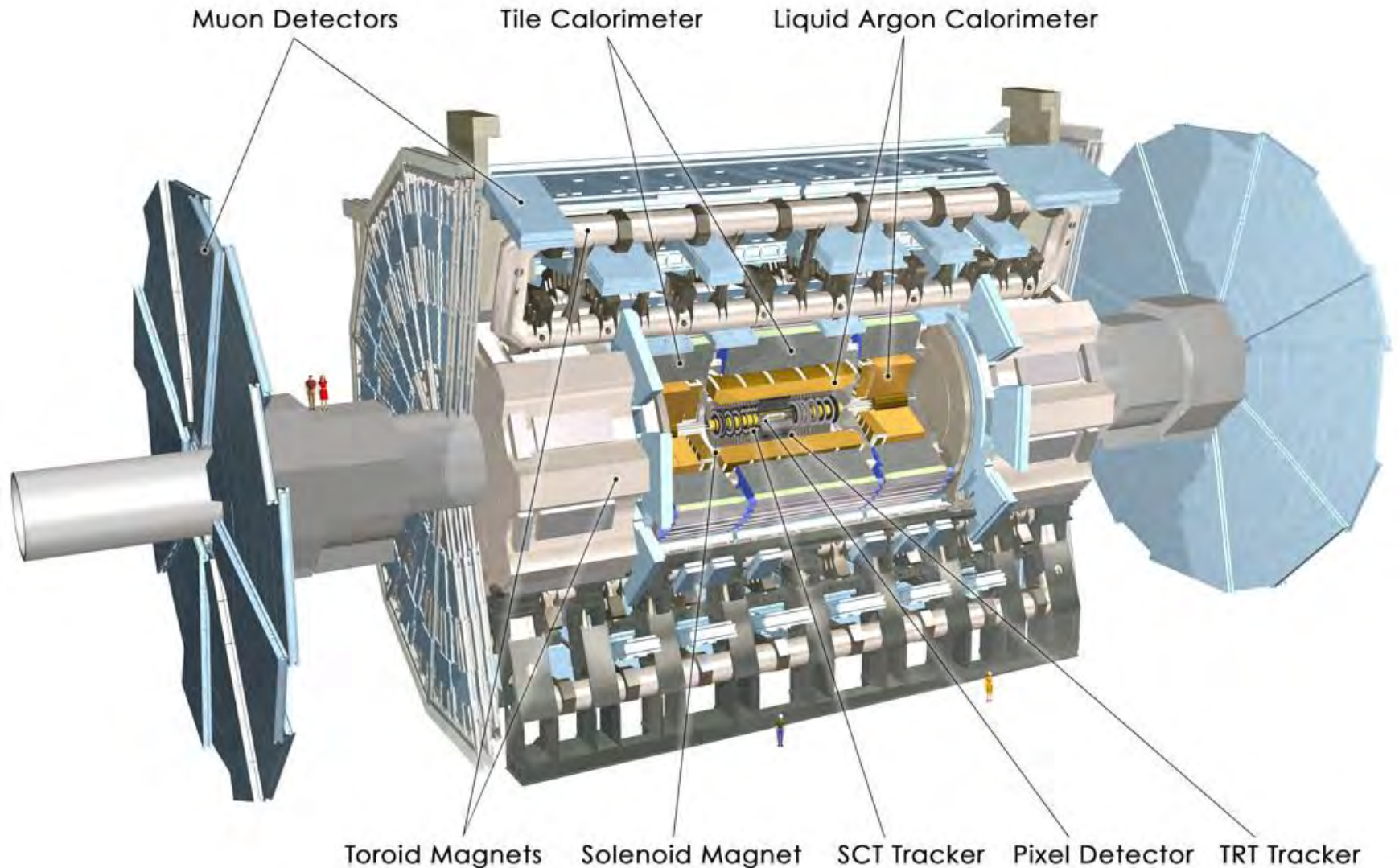
Compact Muon Solenoid (CMS)
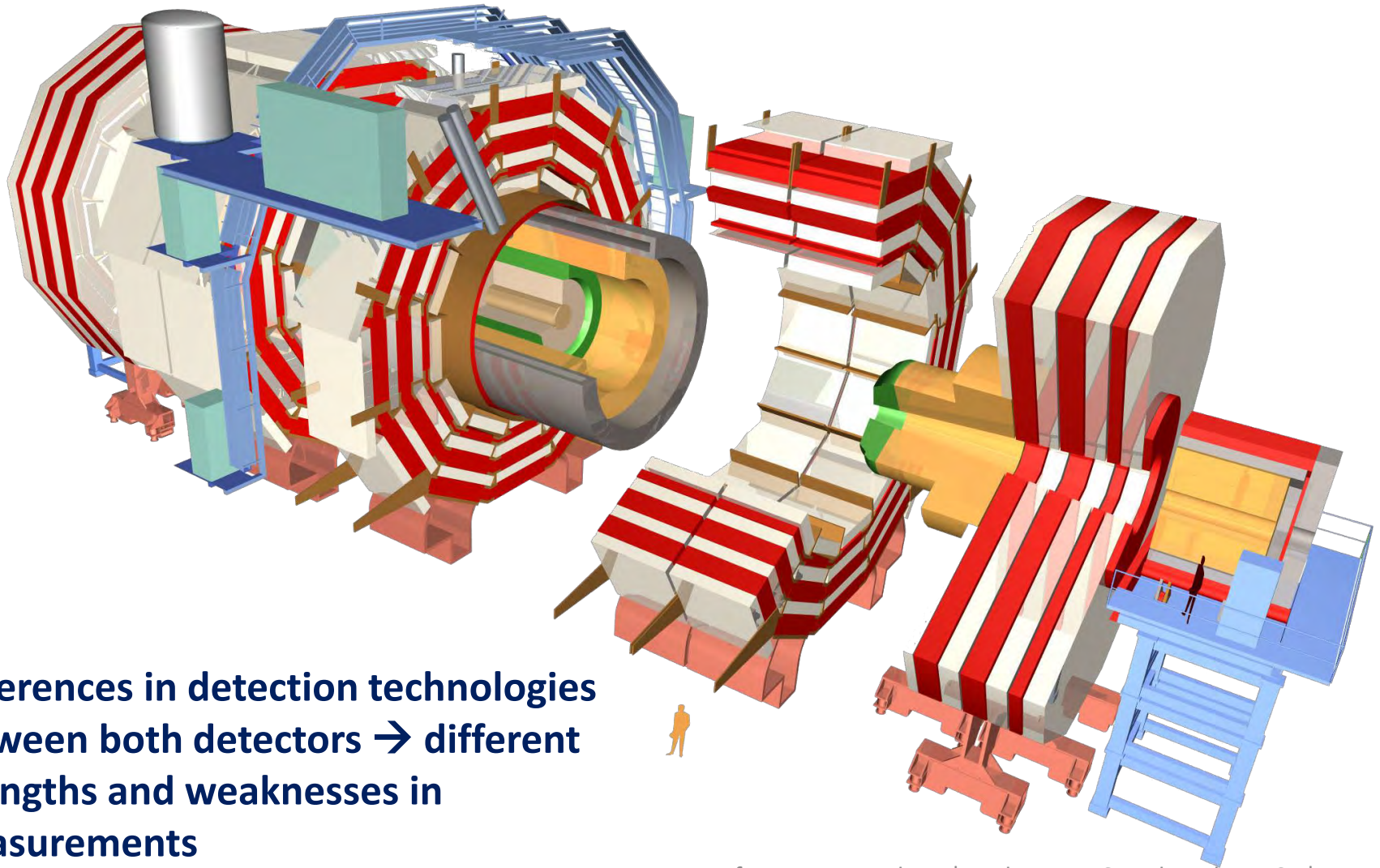
Emphasis on electron and photon energy measurement, full silicon tracker providing high momentum resolution

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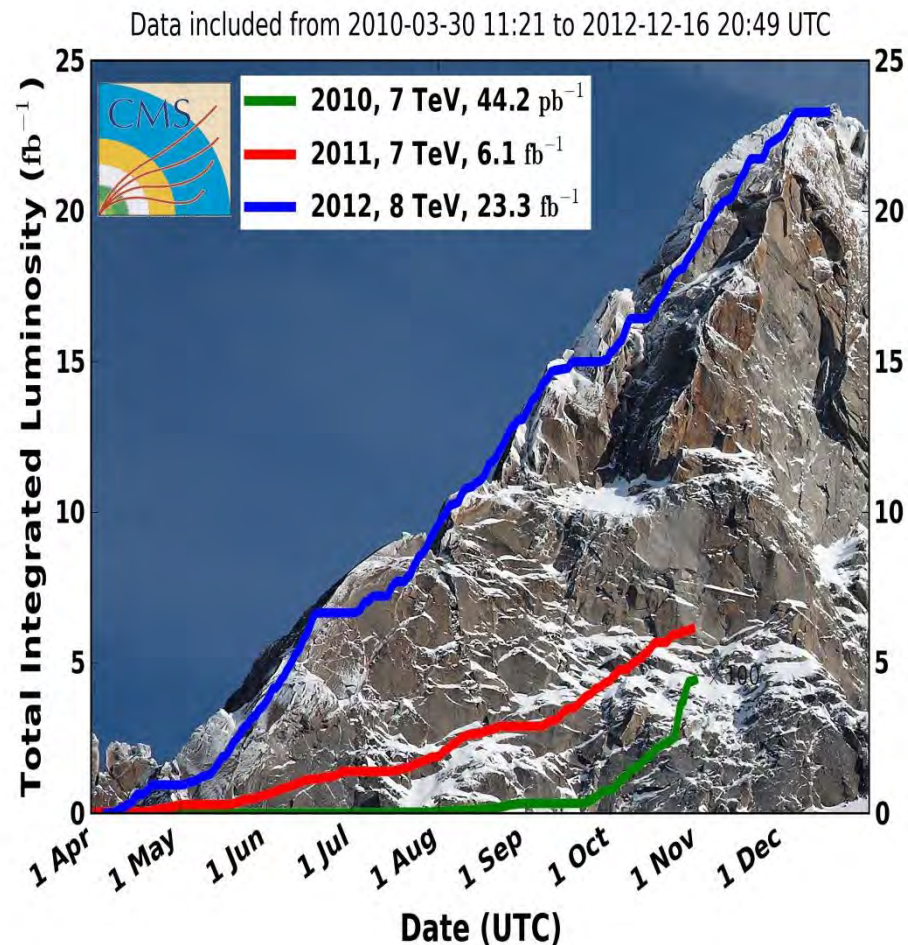
LHC Data Taking

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

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC

2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}

Total Integrated Luminosity (fb^{-1})

Date (UTC)

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
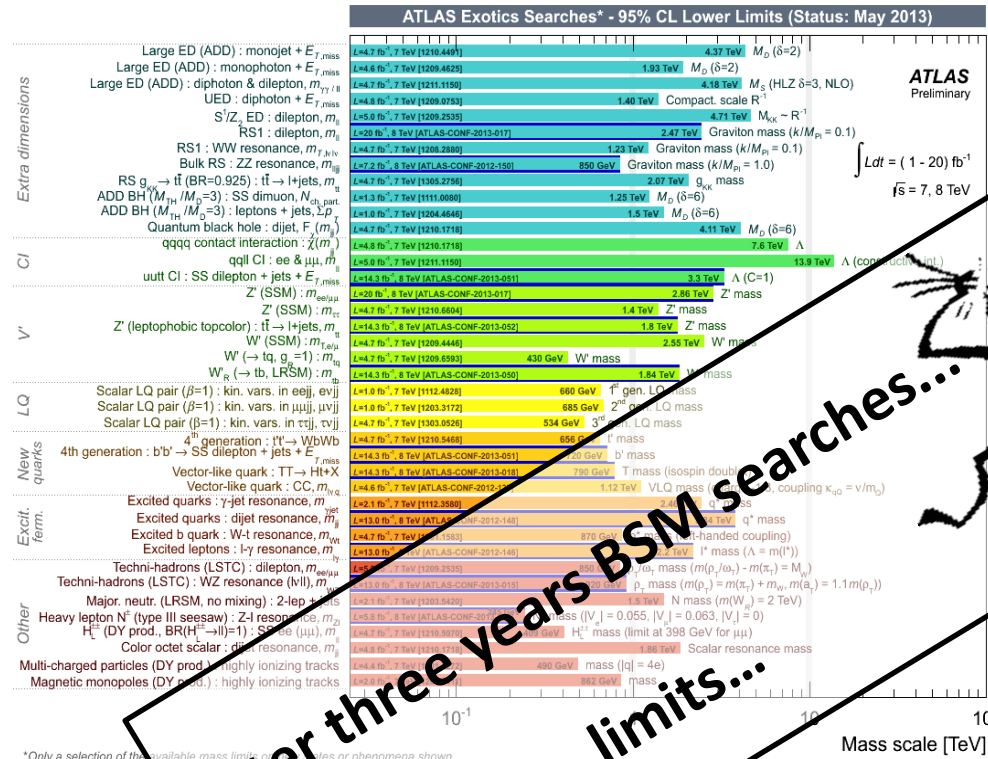

Hitoshi Murayama

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

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)

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
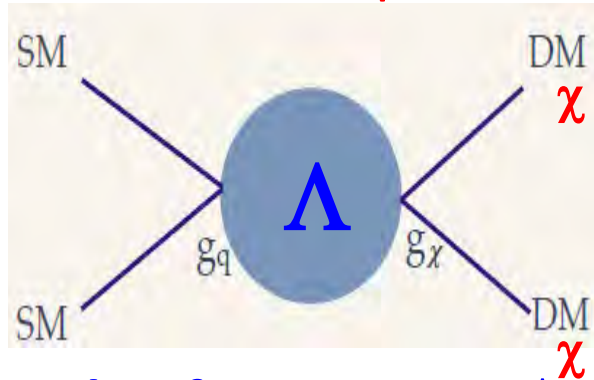
Scale of interaction Λ

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
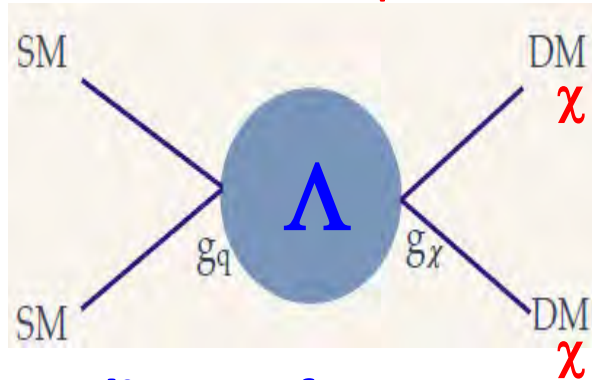
Mediator of mass M

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

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)]

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

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

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

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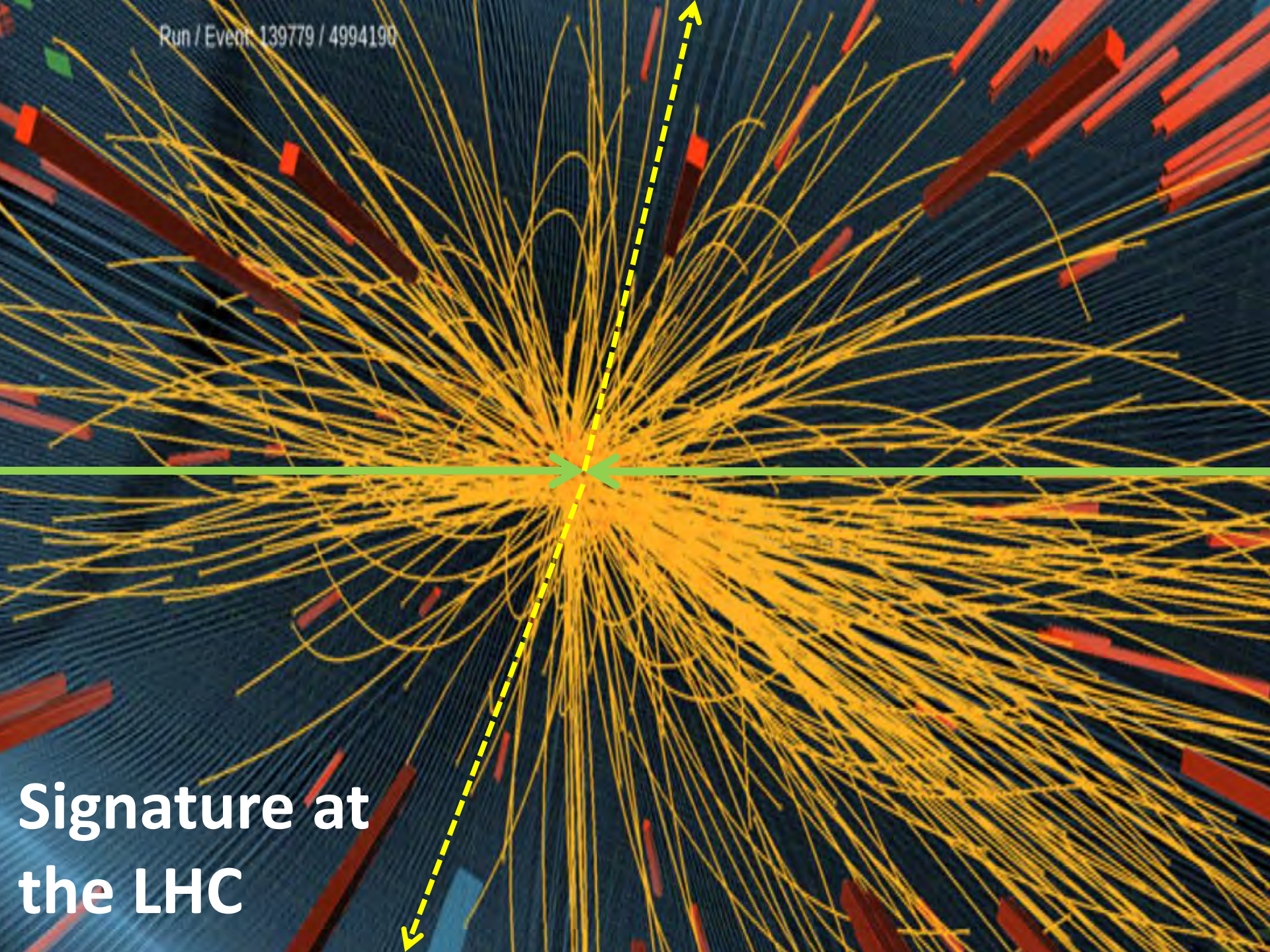
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu \gamma_5 \chi)(\bar{q}\gamma^\mu \gamma_5 q)}{\Lambda^2}$$

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
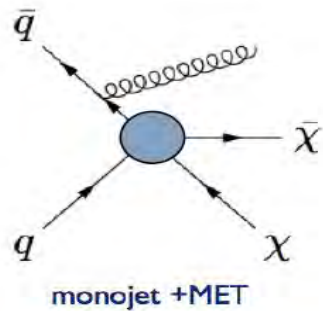
Radiation of a jet / photon from initial state
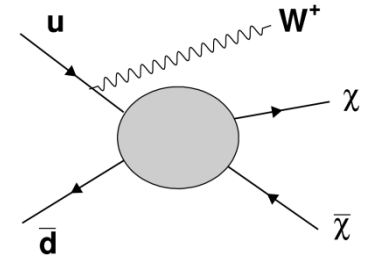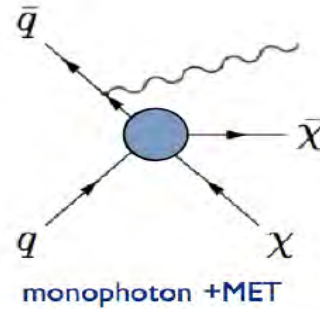
Radiation of W/Z-boson
Different W/Z decay channels

CMS-PAS-EXO-12-048
Full 2012 dataset 20/fb
ATLAS-CONF-12-147 (JHEP 04 (2013) 075)
Full 2011 dataset 5/fb

CMS-PAS-EXO-11-096 (PRL 108, 261803 (2013))
ATLAS PRL 110, 011802 (2013)
Full 2011 dataset 5/fb

CMS-PAS-EXO-13-004
ATLAS-CONF-13-073 (PRL 112 (041802))
Full 2012 dataset 20/fb

arXiv:1206.5663

arXiv:1204.0821
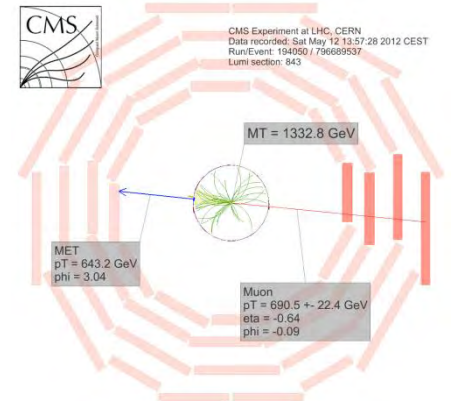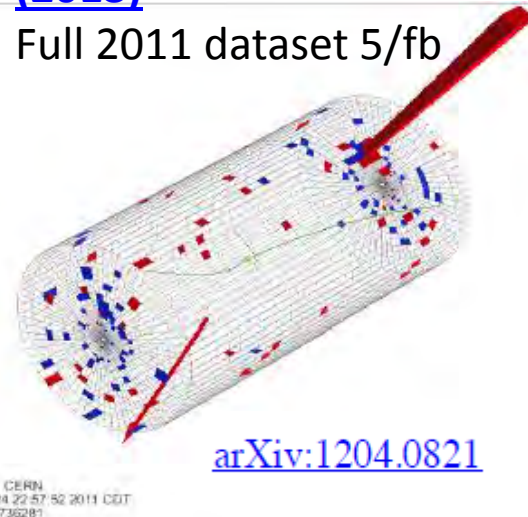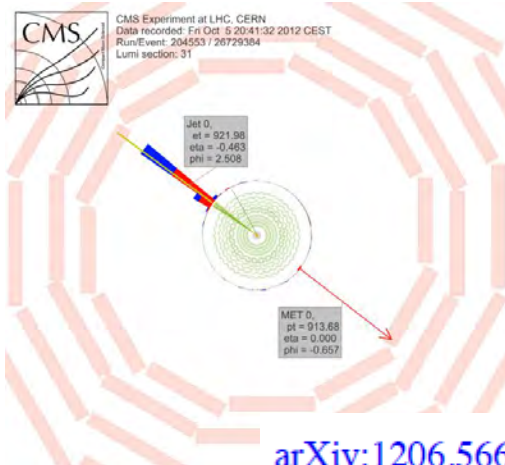
Search for Pair Produced Dark Matter in **Monojet** Channel
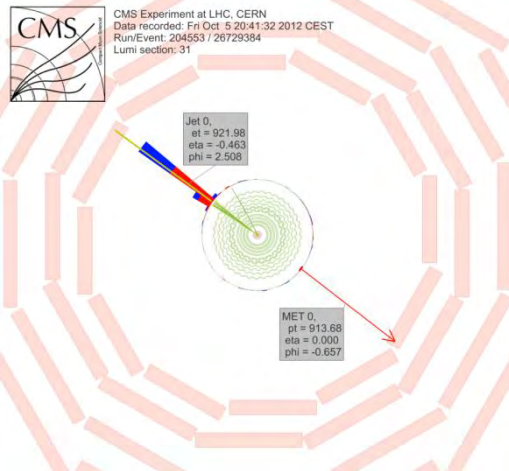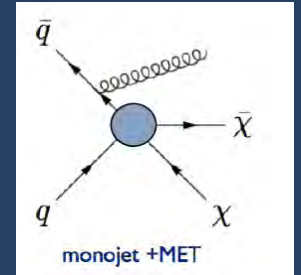
Signature: high p_T jet + MET

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

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

2012 pp data at √s = 8 TeV
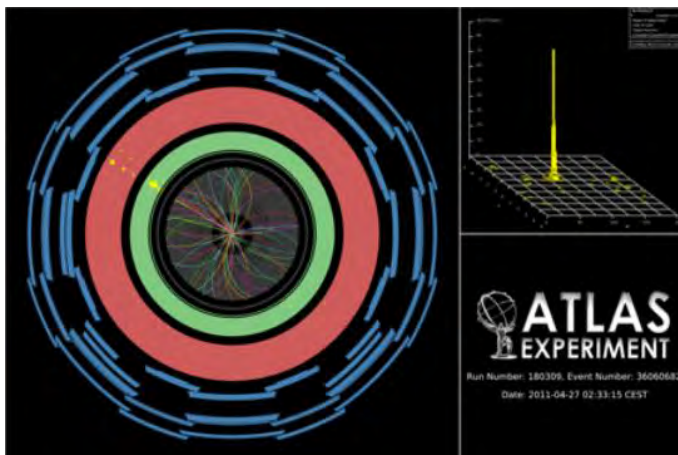
Channel to start DM searches at colliders
2012 results

Event Selection

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
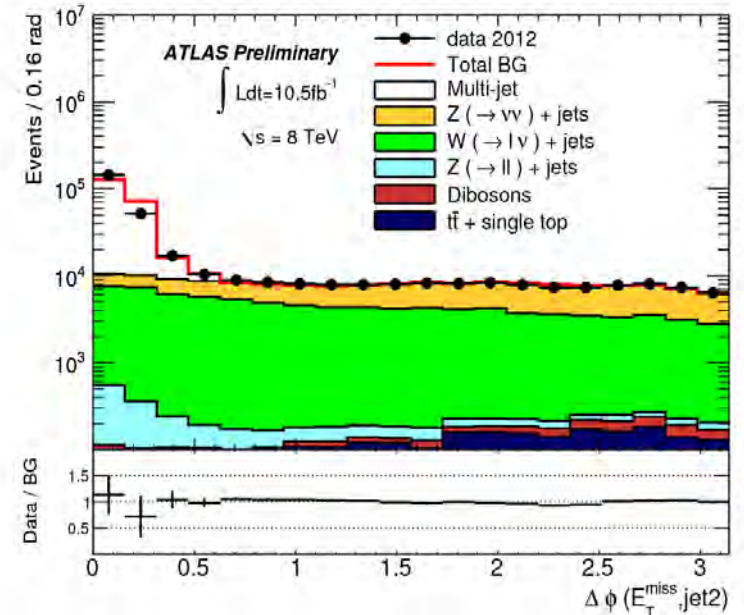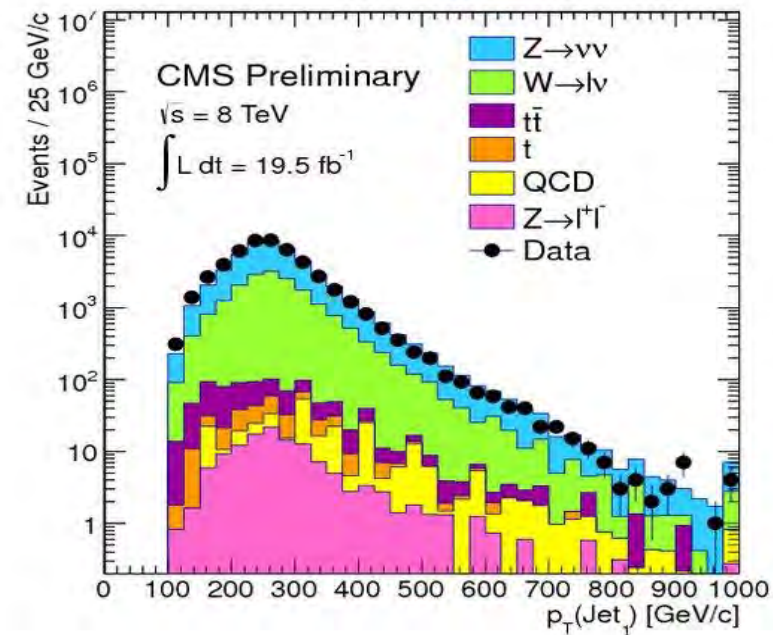
Signal

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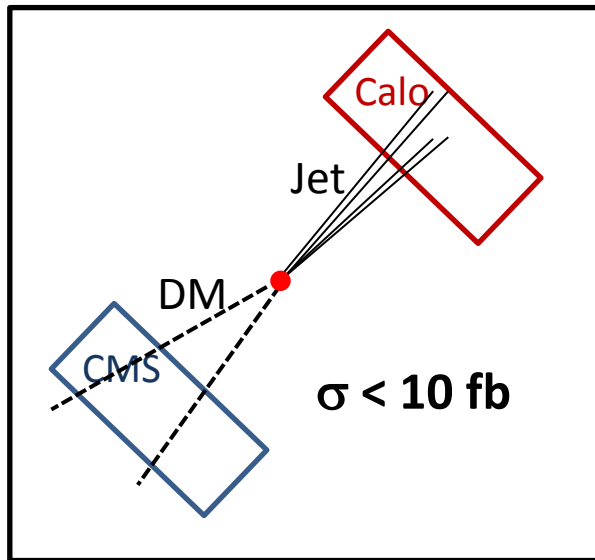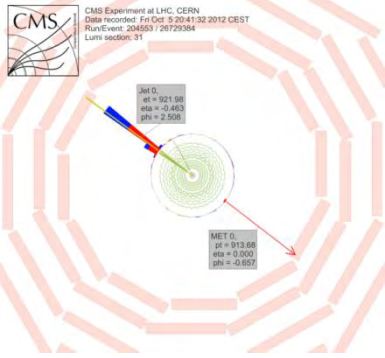
Calo

Jet

DM

CMS

σ < 10 fb

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

σ < 10 fb

W(lν) + j   30%
σ ~230 pb
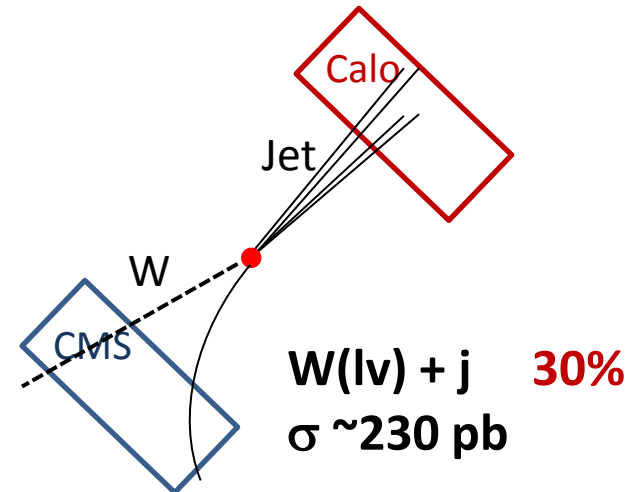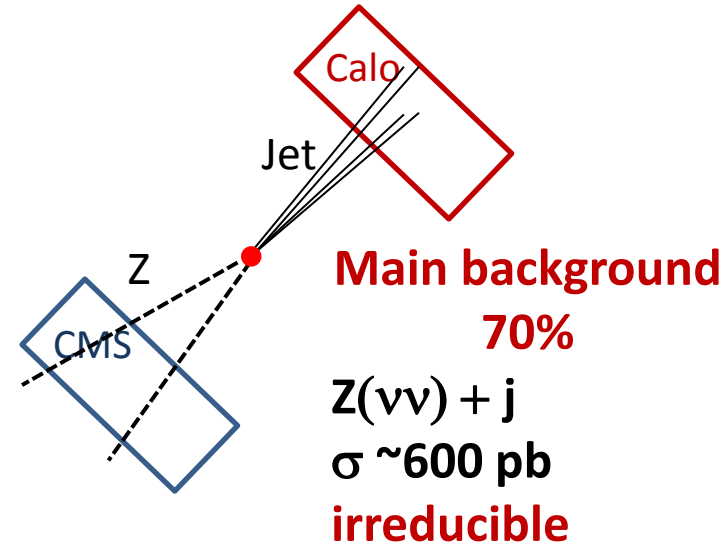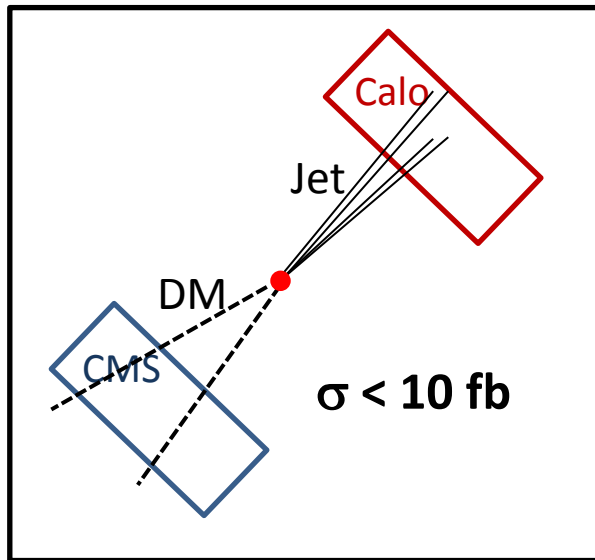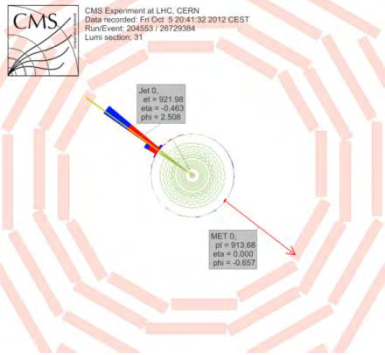
Signal and Background

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

Data driven from
Z(μμ) + j
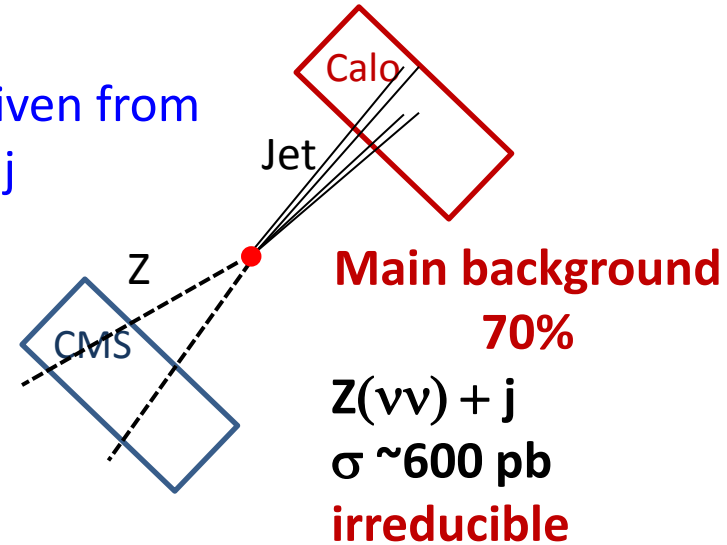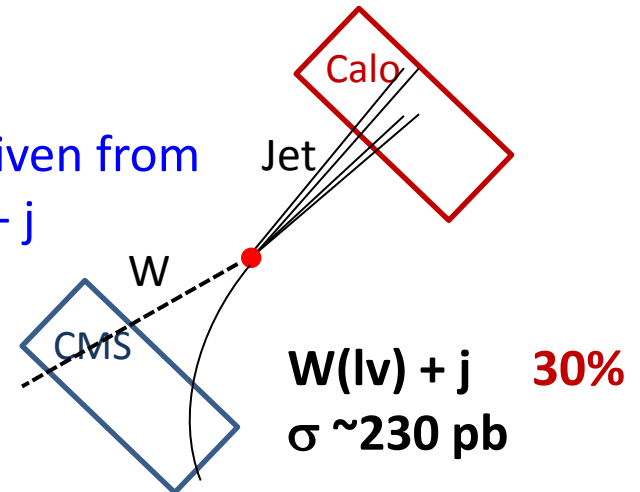
**Main background
70%**

**Z(νν) + j
σ ~600 pb
irreducible**

Data driven from
W(μν) + j

**W(lν) + j   30%
σ ~230 pb**

σ < 10 fb

Signal and Background

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

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

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
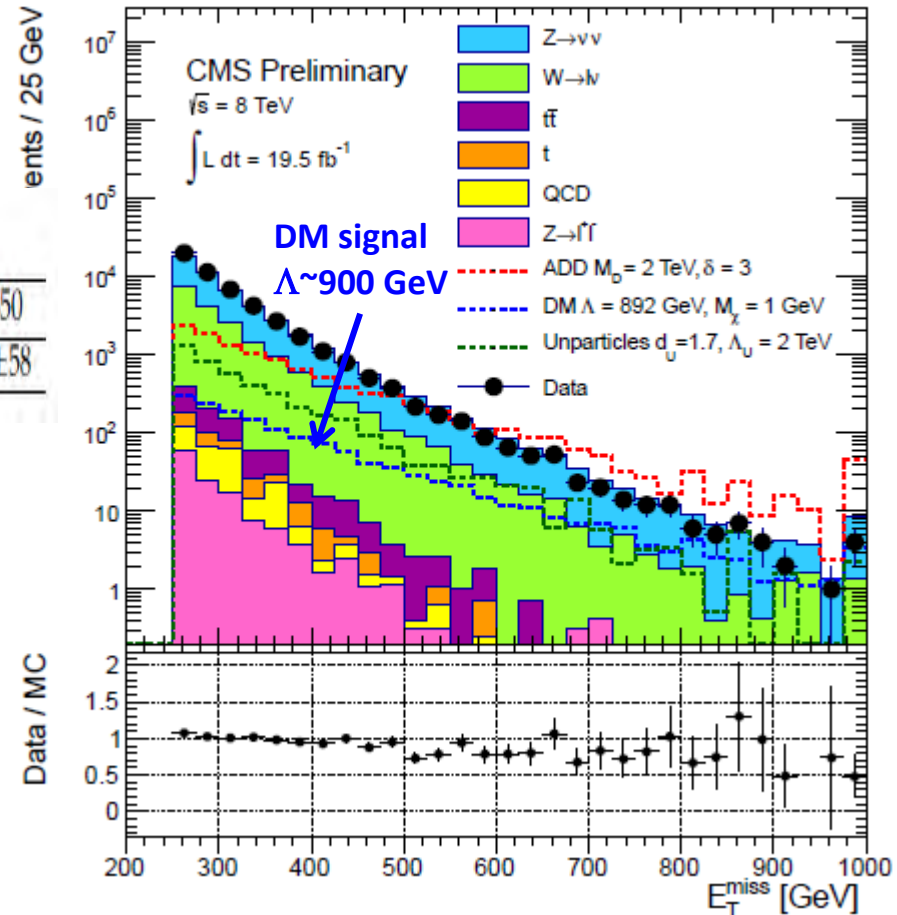
CMS search performed in 7 bins of MET

Signal and Background

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
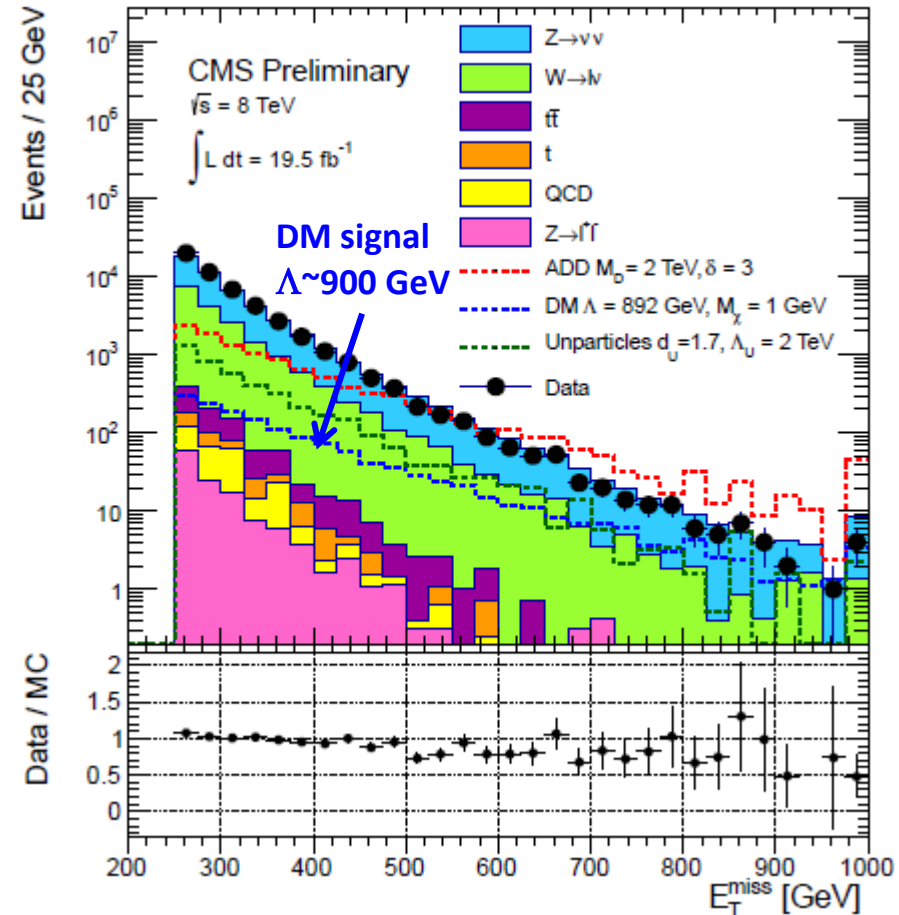
CMS search performed in 7 bins of MET

Monojet Model Independent Limits

→ Search performed in bins of MET

Both experiments quote model-independent limits
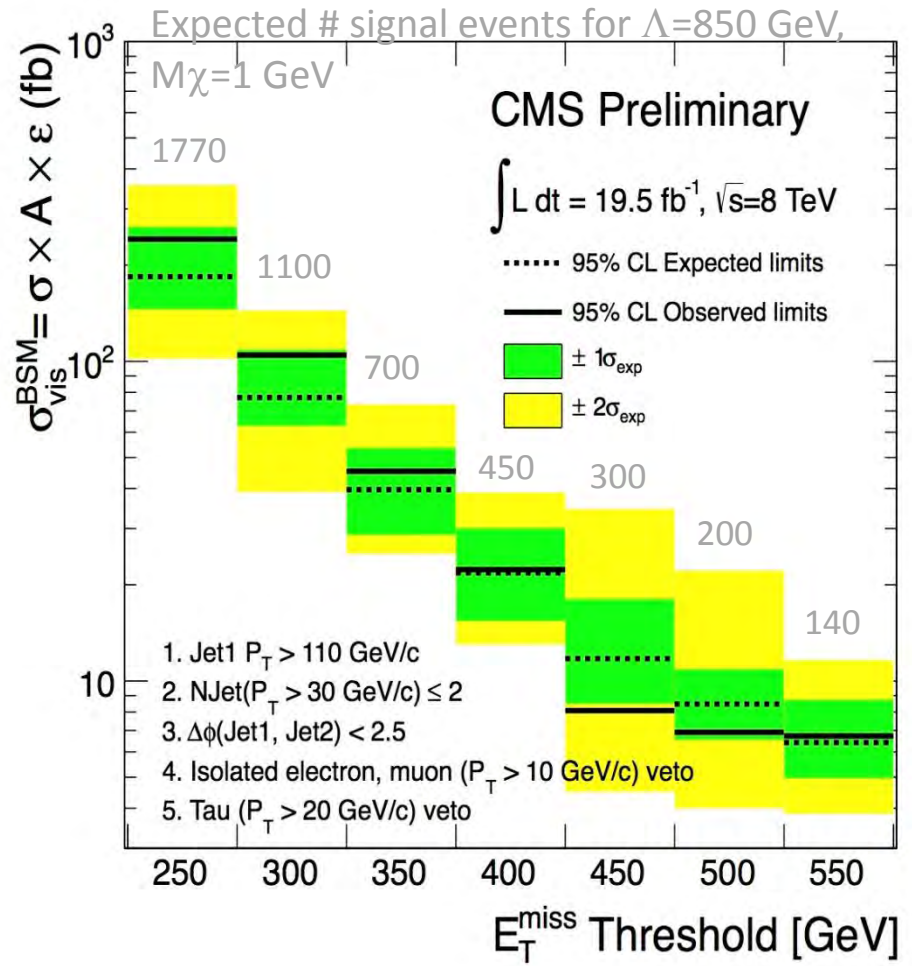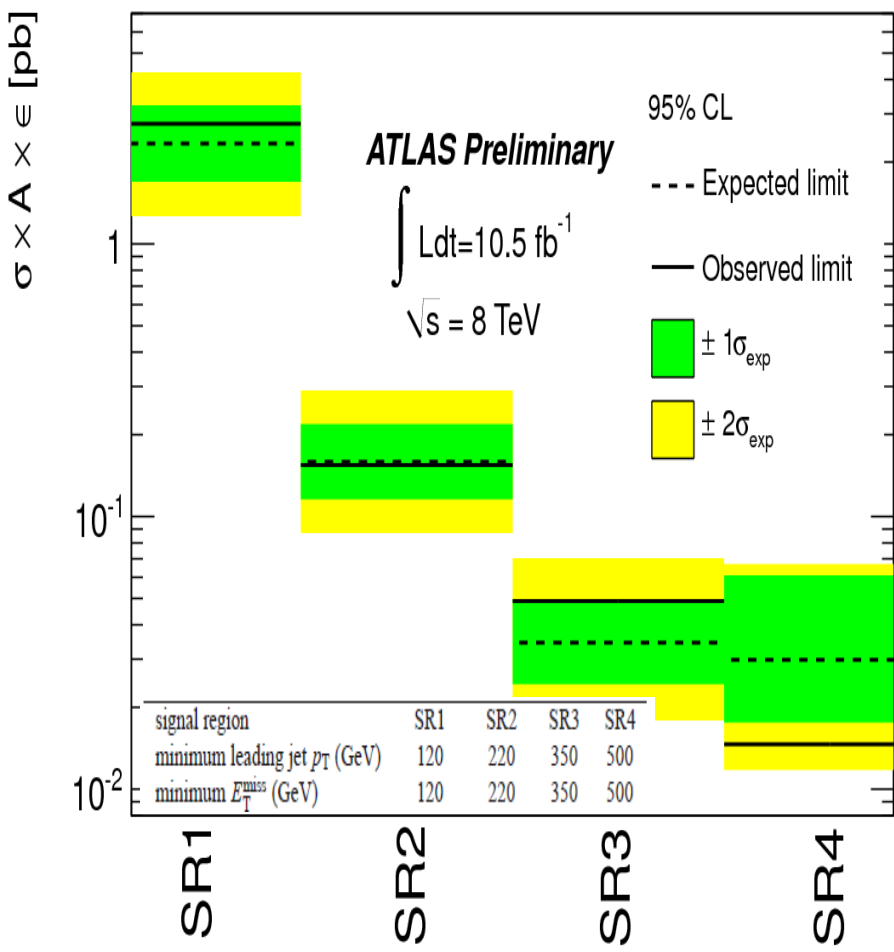
Translate production cross section limit into DM – nucleon limits

Purpose: to compare to direct detection experiments
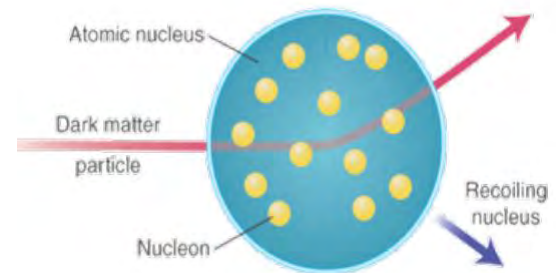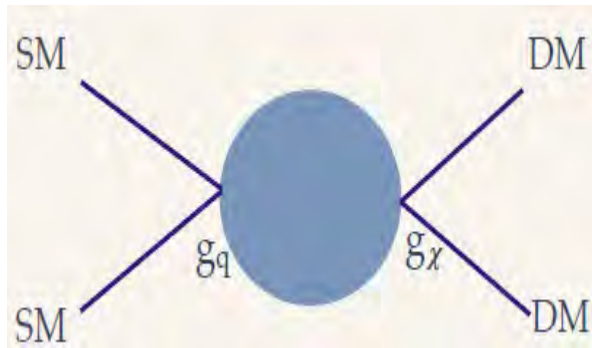
EFT to translate limits to same plane as direct detection experiments

Experimental result
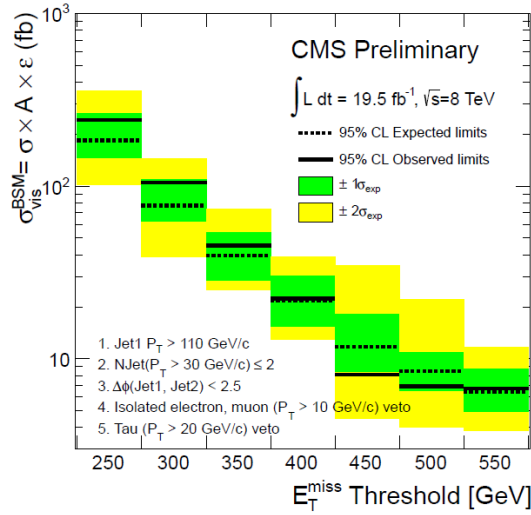
Convert pp xsec limit into Λ
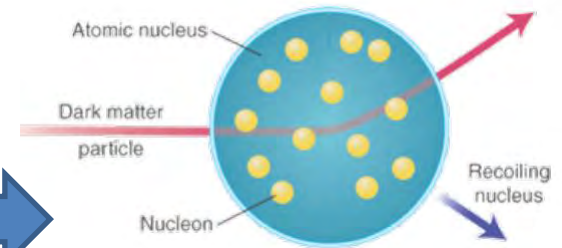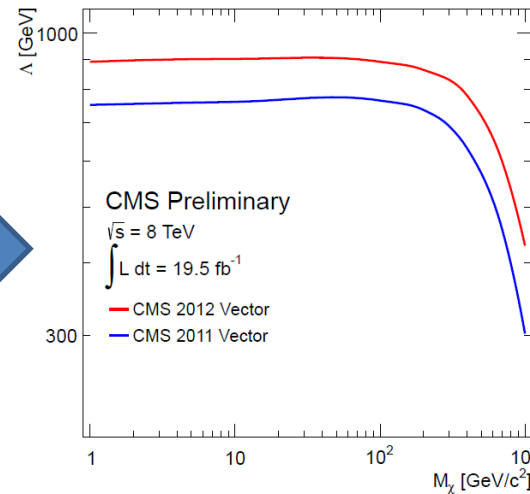
Spin-Independent

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

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

Spin-Dependent

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

Sum of quark helicities

Axial-Vector operator

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

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

$$\Delta_u^p = \Delta_d^n = 0.842 \pm 0.012$$
$$\Delta_d^p = \Delta_u^n = -0.427 \pm 0.013$$
$$\Delta_s^p = \Delta_s^n = -0.085 \pm 0.018$$
arXiv:0803.2360.

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

DM – Nucleon Limits

ATLAS and CMS results similar for 7 TeV data, improved with 8 TeV
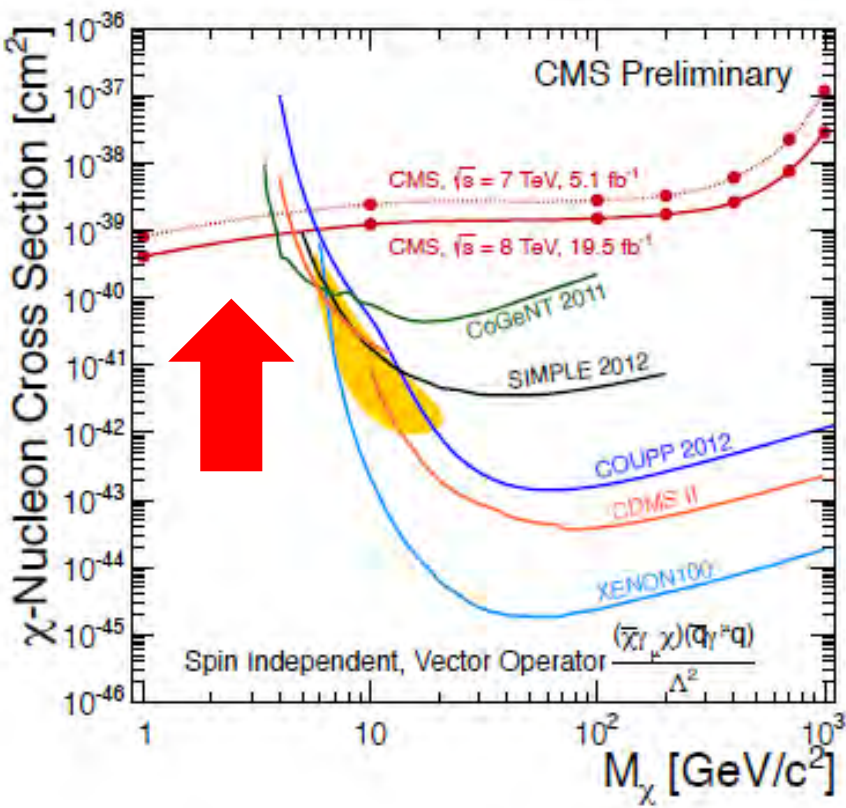
LHC can access very low DM masses
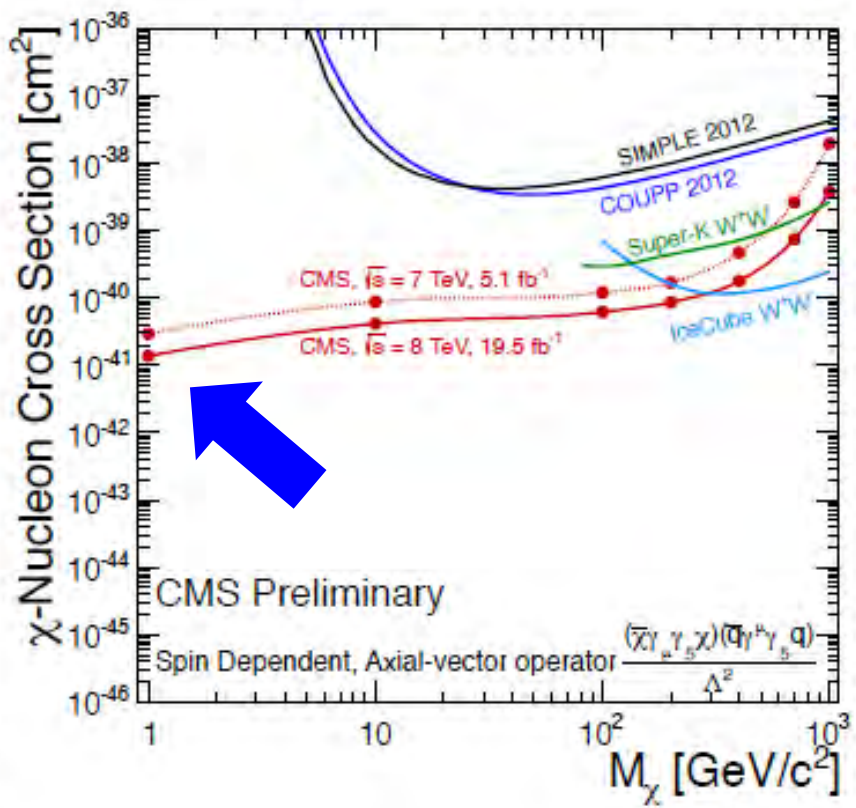
Exclude large cross sections for spin-dependent case

Search for Pair Produced Dark Matter in **Monophoton** Channel
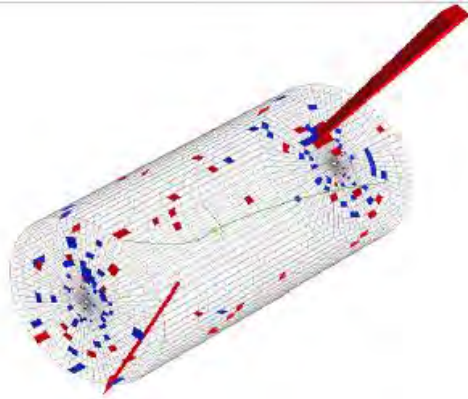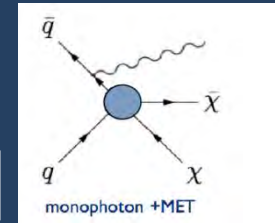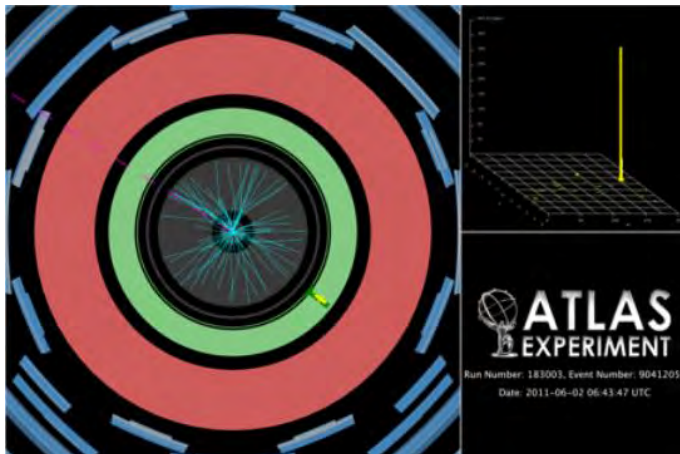
monophoton +MET

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

CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604

MAIN BACKGROUND (60%)

$Z\gamma \rightarrow \nu\nu\gamma$

$\sigma \sim 75$ fb

irreducible

ECAL

γ

Z

CMS

ν

ν

ECAL

γ

DM

CMS

$\sigma < 10$ fb
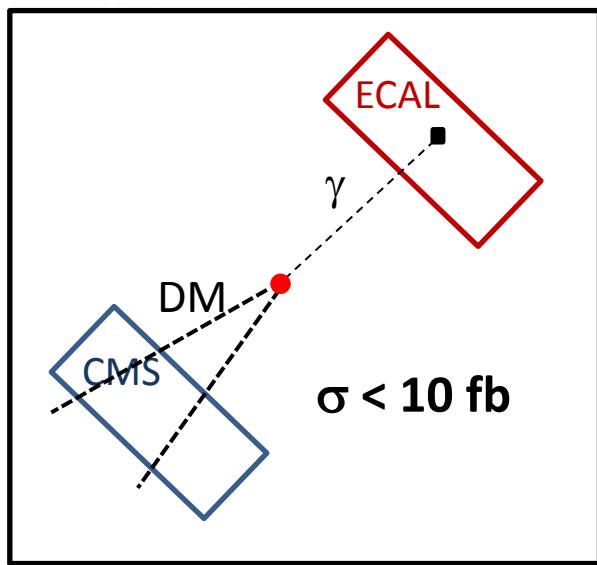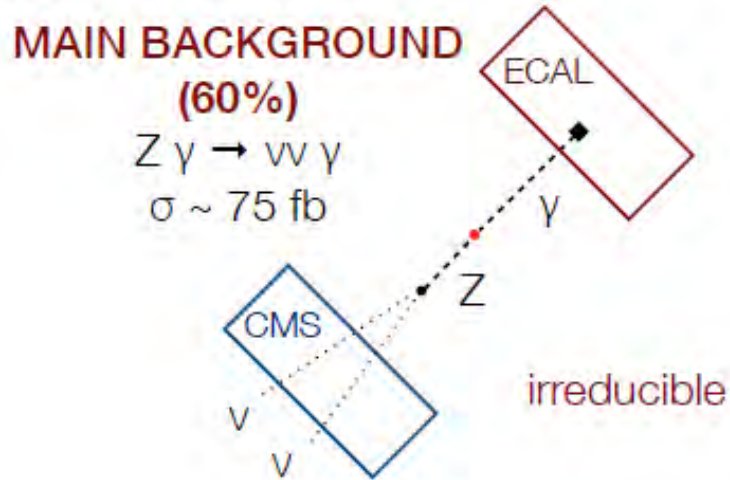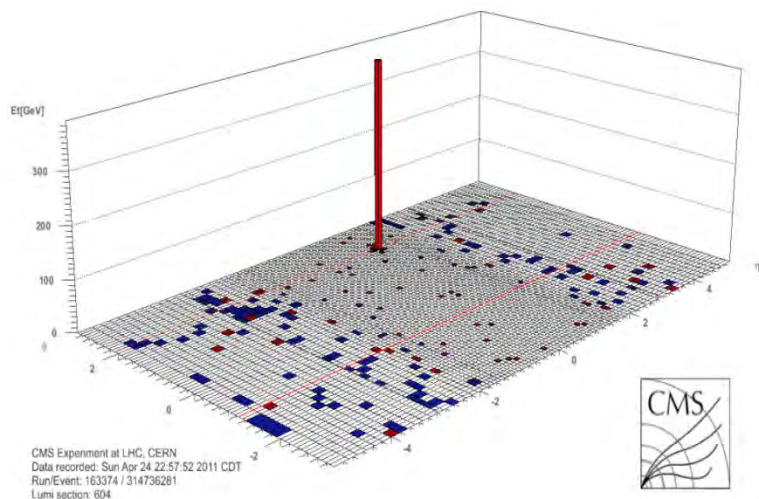
Several Other Backgrounds

OTHER BACKGROUNDS

$W \gamma \to l \nu \gamma$
(15%)
$\sigma \sim 250$ fb

final state lepton

$W j \to l \nu j$
(10%)
$\sigma \sim 220$ pb

final state lepton, jet

$Z j \to \nu \nu j$
(10%)
$\sigma \sim 30$ pb

final jet

+ γj, jj <5% each
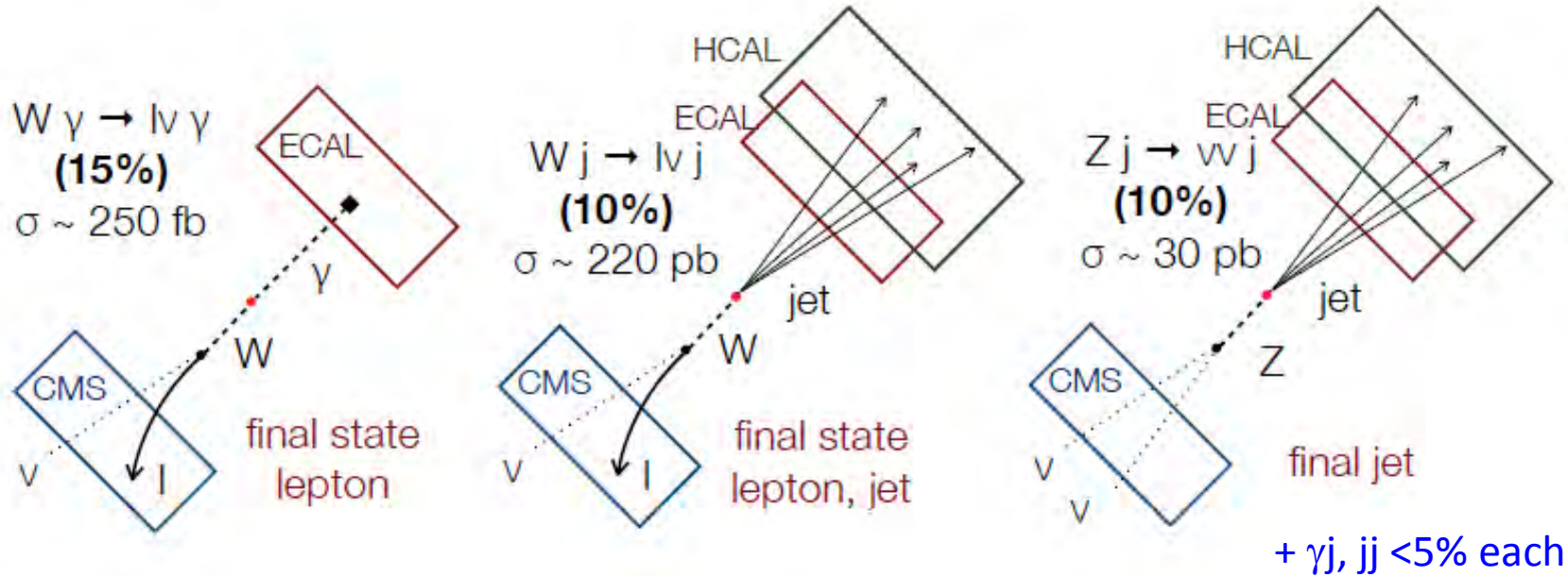
Instrumental backgrounds (~30%) from mis-identification and beam halo

SM backgrounds (~70%):

- Needs good understanding of cross section for $Z\gamma$, $W\gamma$.

- NLO corrections. NLO k-factor (1.3 global SF for $W\gamma$, $p_T(\gamma)$ dependant SF for $Z\gamma$ (~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

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

Model-independent 90% CL upper limits on cross section

14 fb (V and AV) for M_χ < 200 GeV $\rightarrow$ Λ > 570 GeV

2011 data
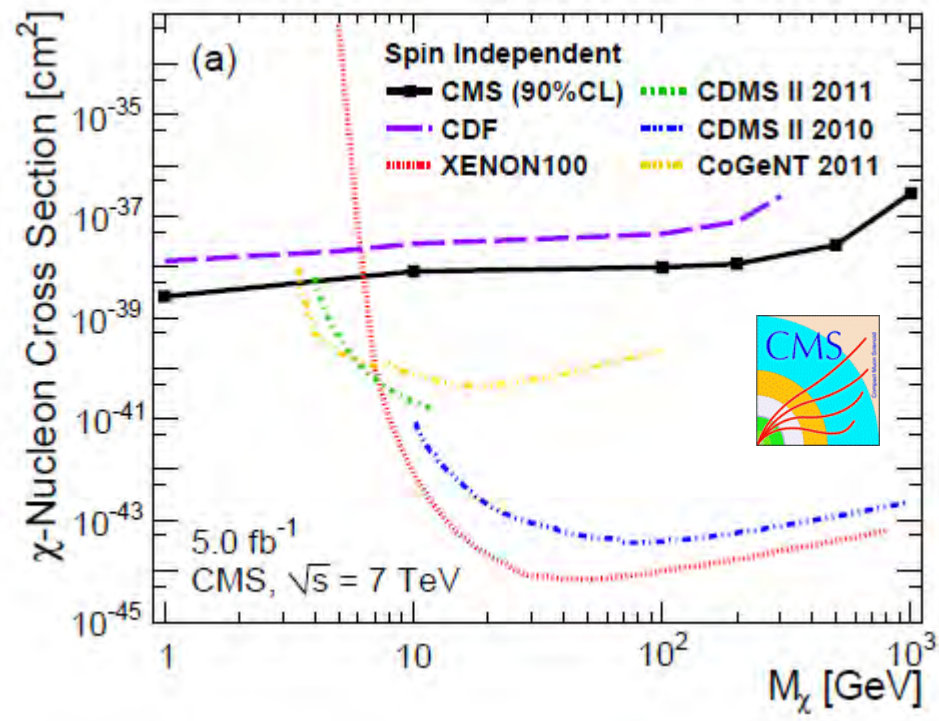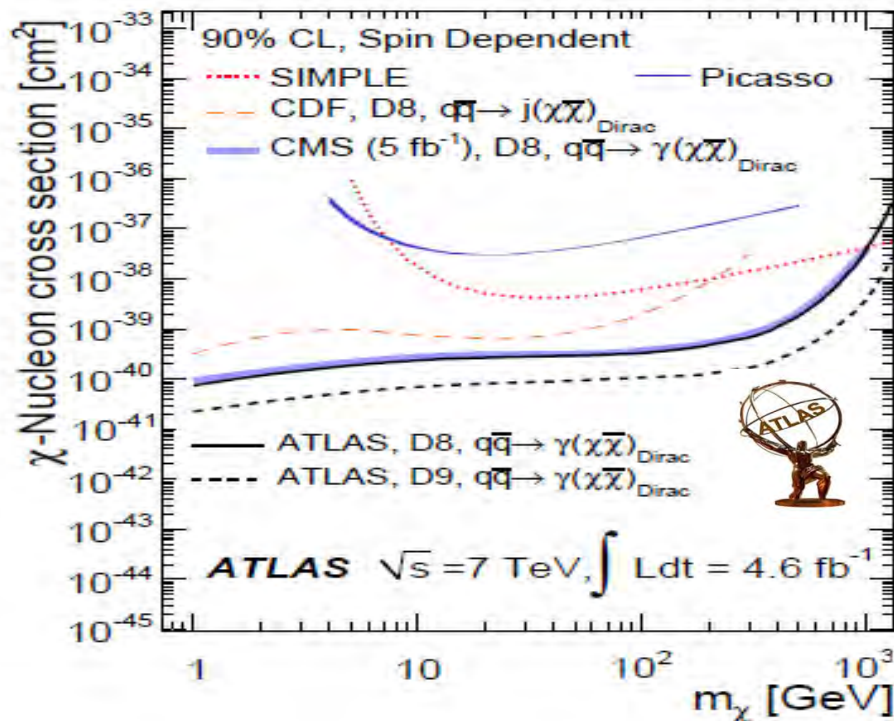
ATLAS and CMS comparable results at 7 TeV.

With 8 TeV statistics expect 10x higher sensitivity.

Search for Pair Produced Dark Matter in **Monolepton** Channel
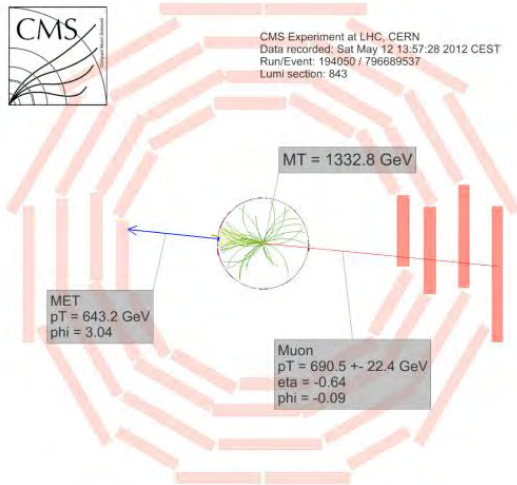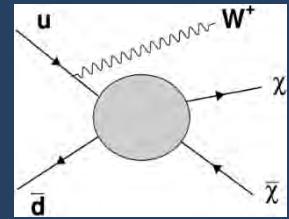
Signature W + MET:

high p_T electron + MET

High p_T muon + MET

New 2012 legacy result
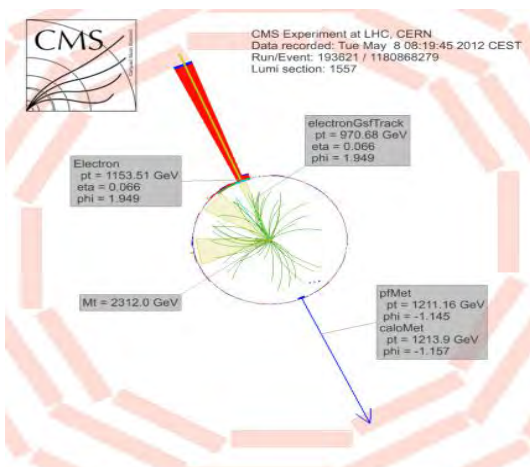
CMS –PAS-EXO-13-004

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
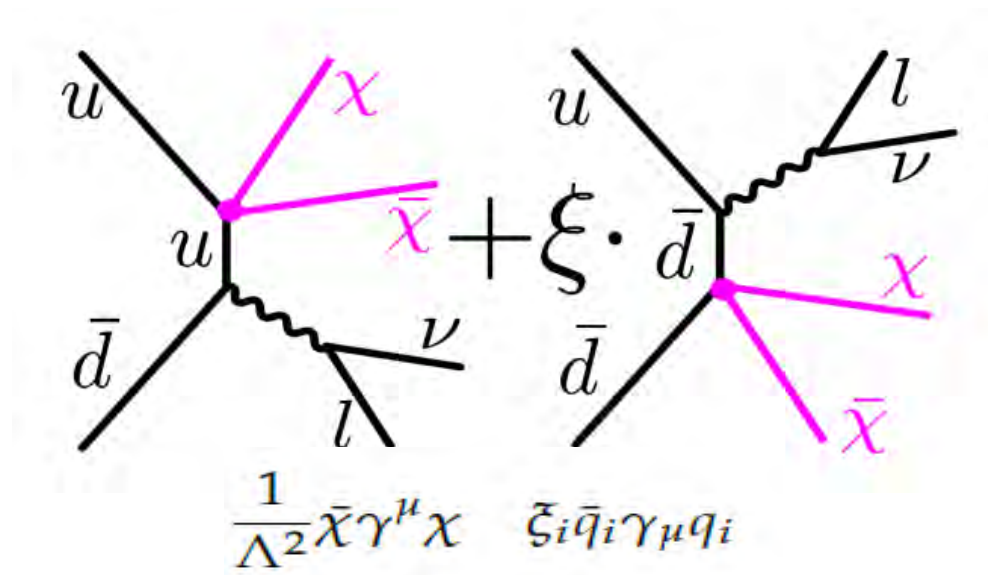
Neutrino + DM contribute to MET

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

Mono-jet $\xi = +1$
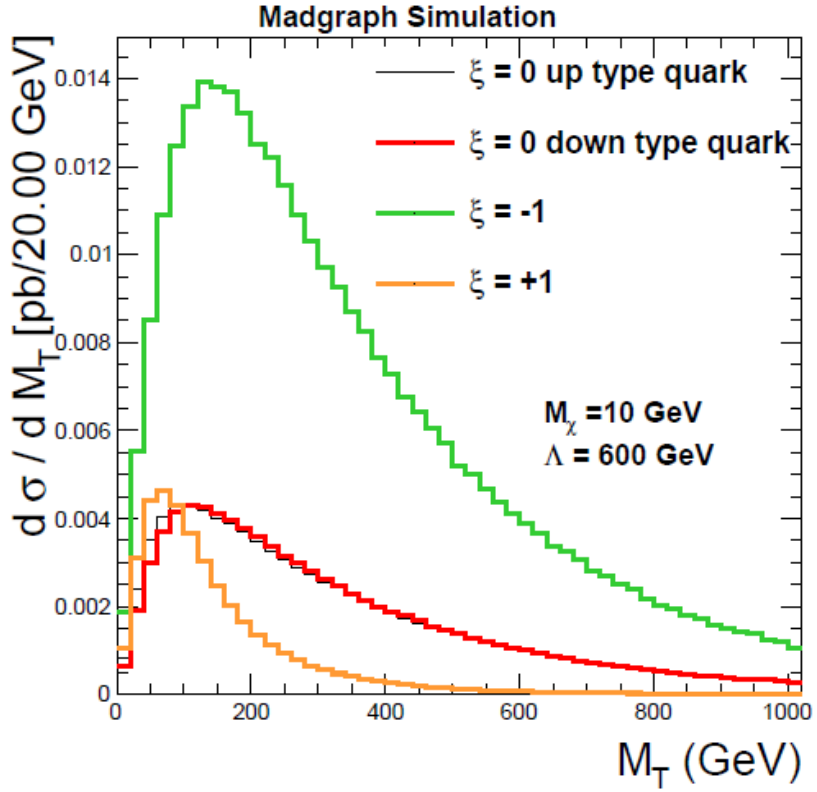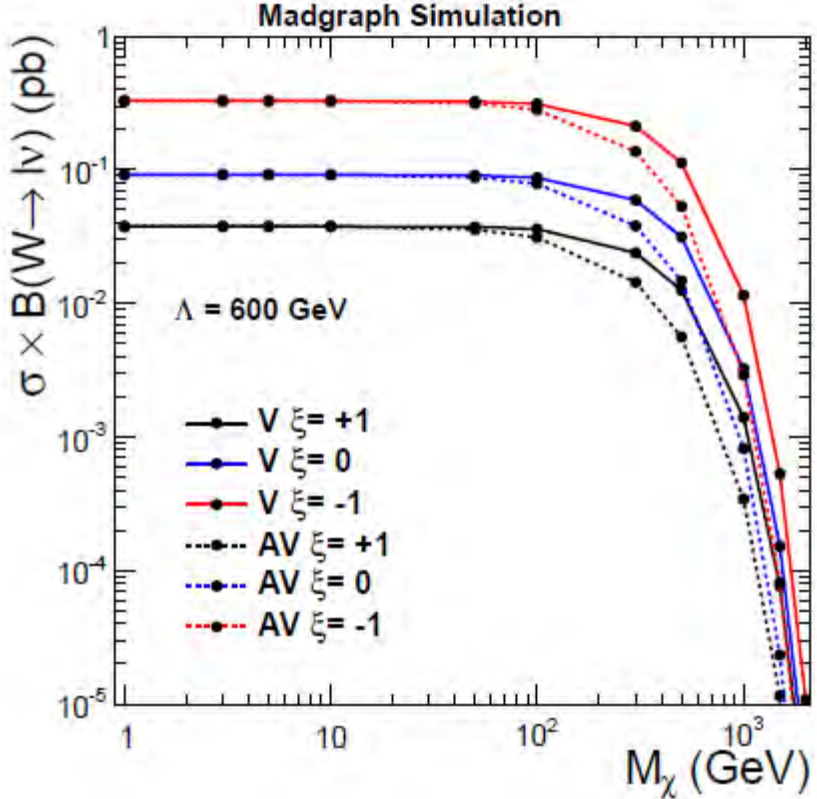
Largest cross section for $\chi = -1$
For $M_\chi < \sim 70$ GeV same cross section for V and AV coupling of fixed ξ

Interference type influences M_T shape $\rightarrow$ impact on sensitivity

Selecting Monolepton Events

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

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

Background

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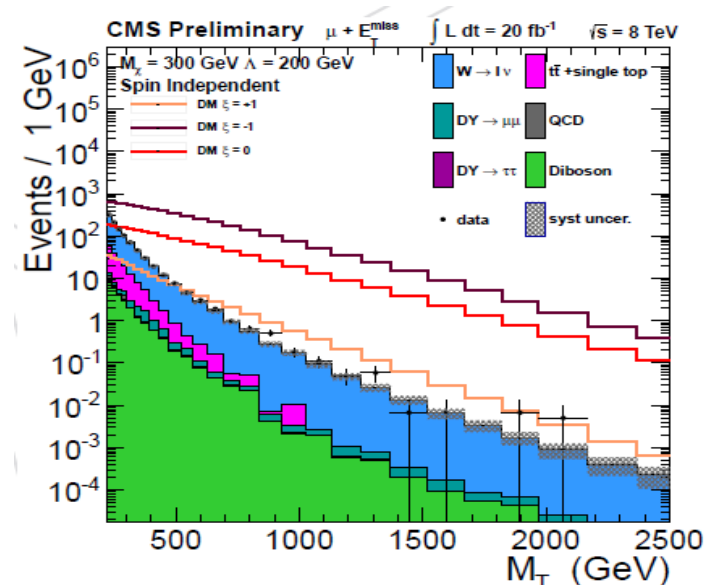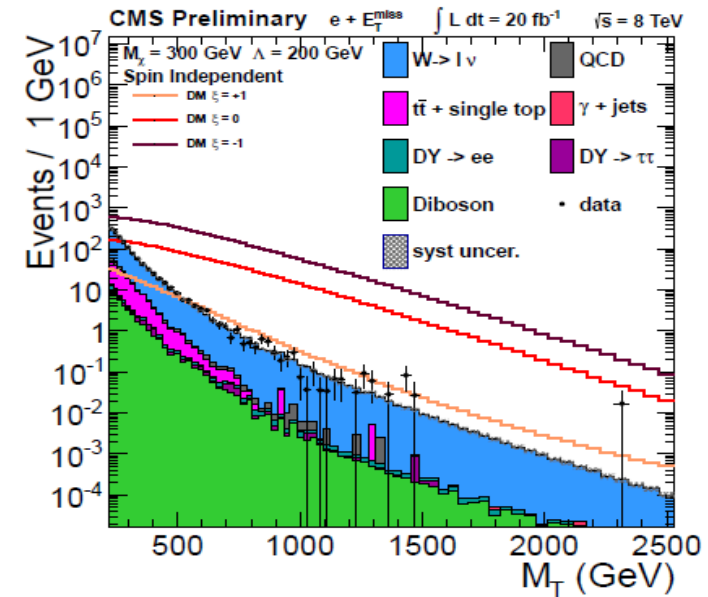
Challenge of TeV Leptons

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)

1 TeV muon with a "catastrophic" energy loss of 22 GeV
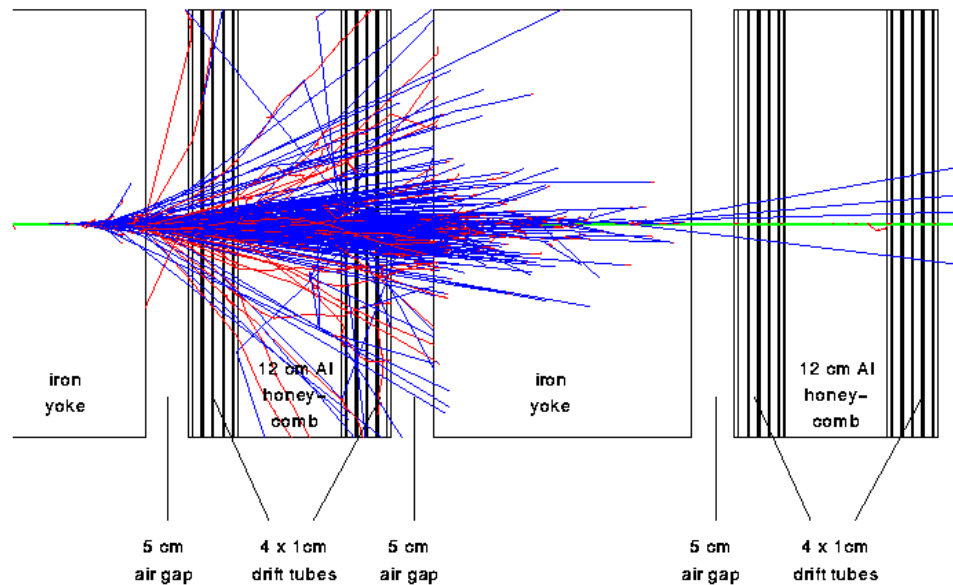
V

Spin

In-
depen
dent
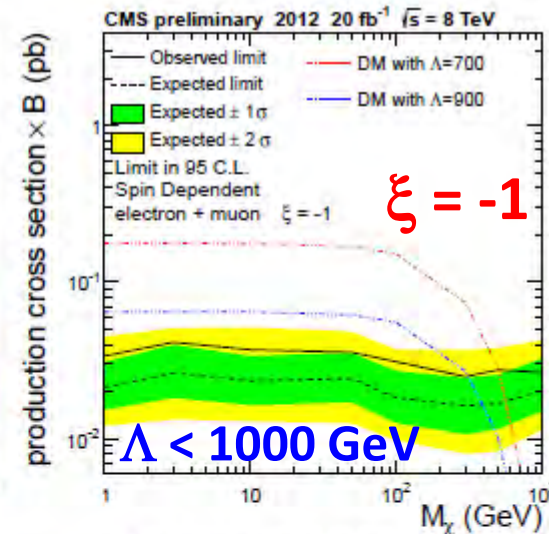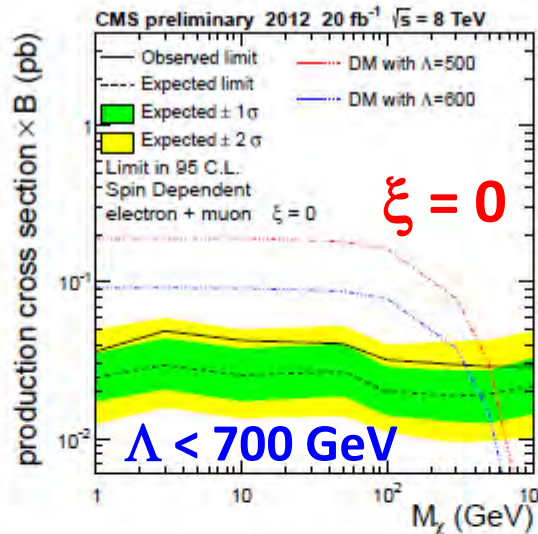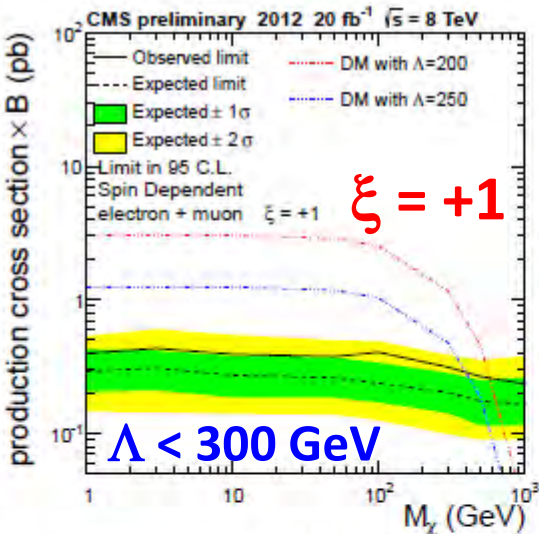
AV

Spin
depen
dent
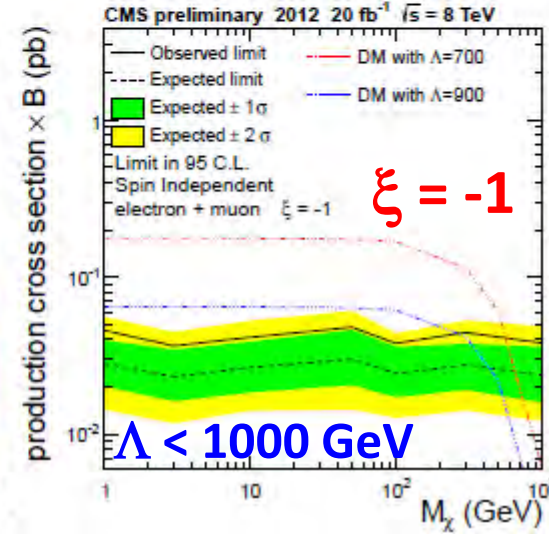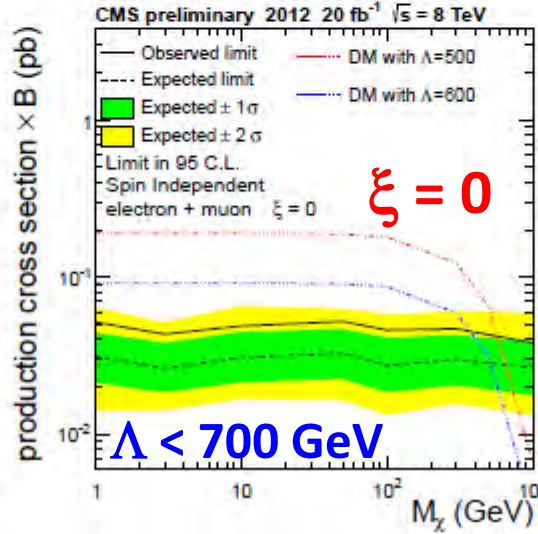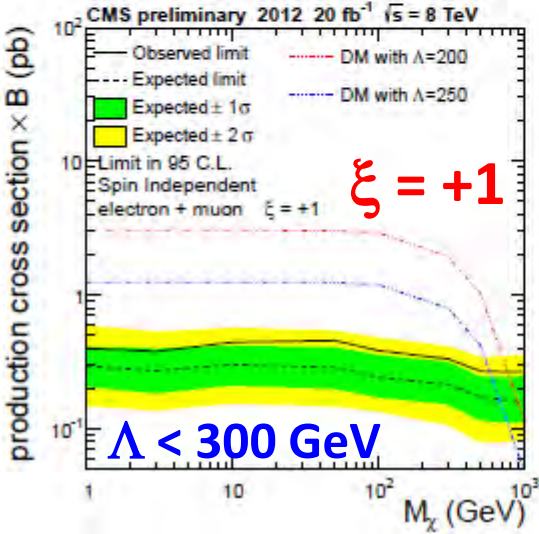
Translation to DM-Nucleon

Same procedure as for monojet. Standard assumption is $\xi = +1$
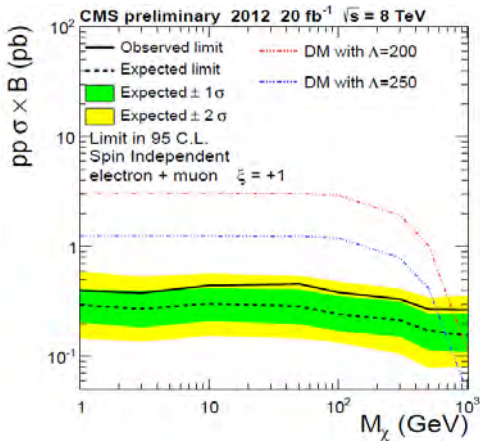
Vector operator

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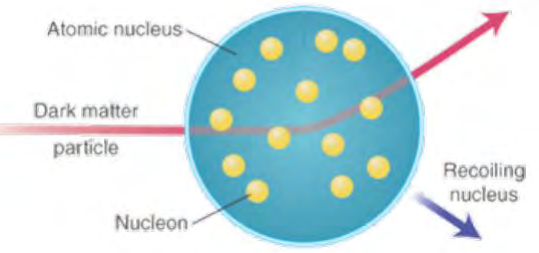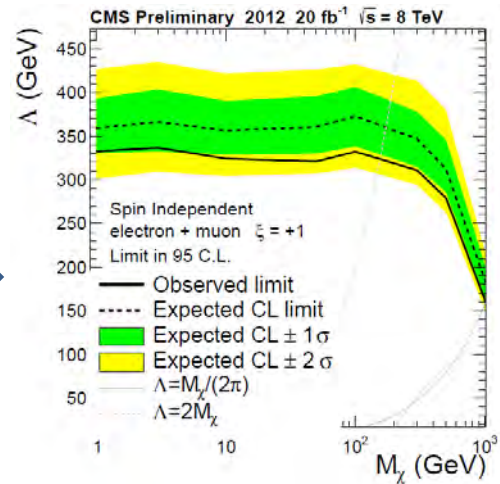
Spin-Independent

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

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 $\xi = +1$	300 GeV
l+MET $\xi = 0$	700 GeV
l+MET $\xi = -1$	1000 GeV
Jet + MET	900 GeV

ξ

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

$f = 0$ for other quarks

arXiv:0803.2360.

Monolepton $\xi = -1$ (max. sensitivity)

2012 results in comparison to monojet and some direct detection experiments, 90% C.L.
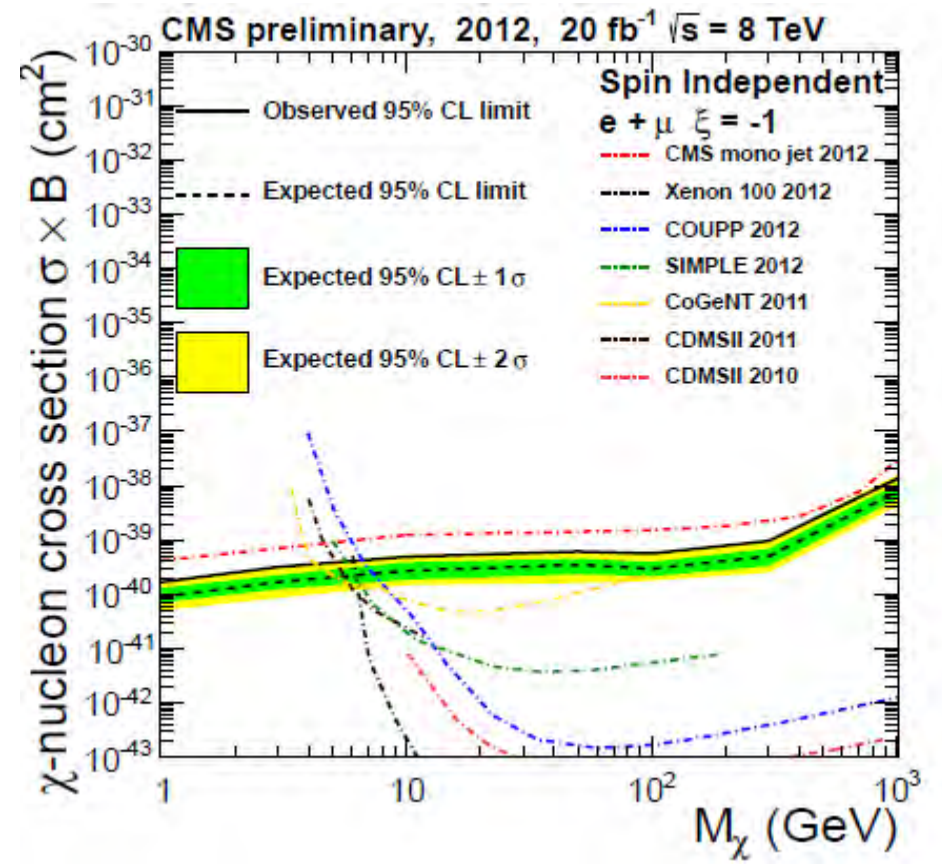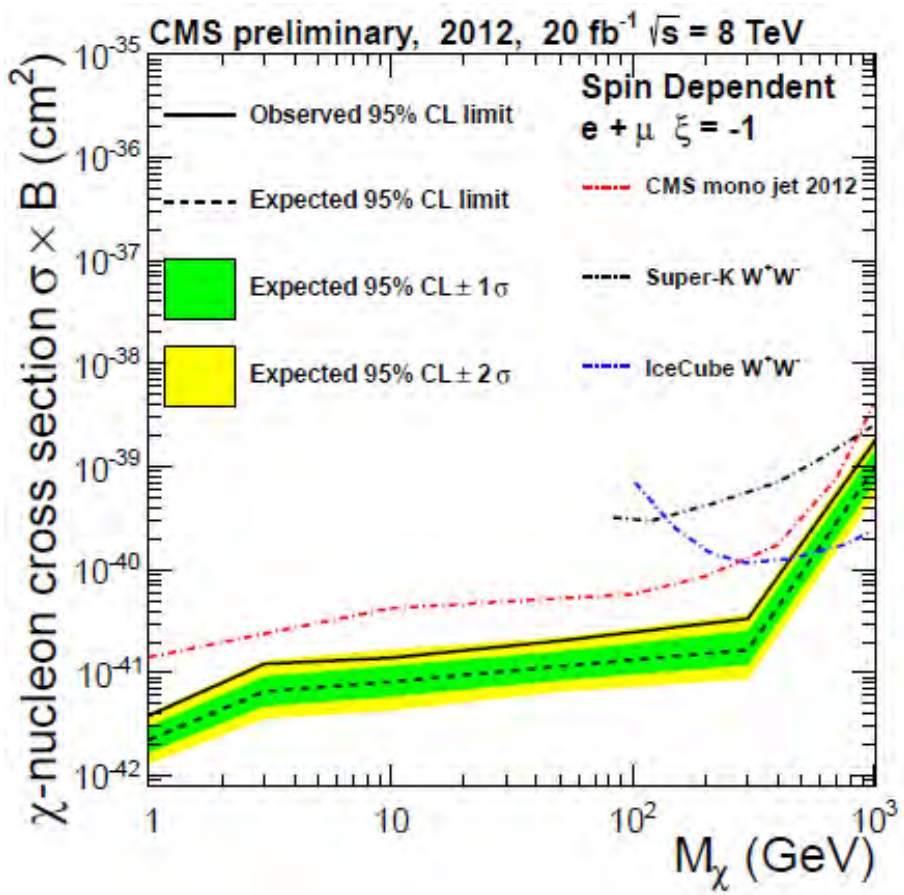
Hadronically Decaying W/Z
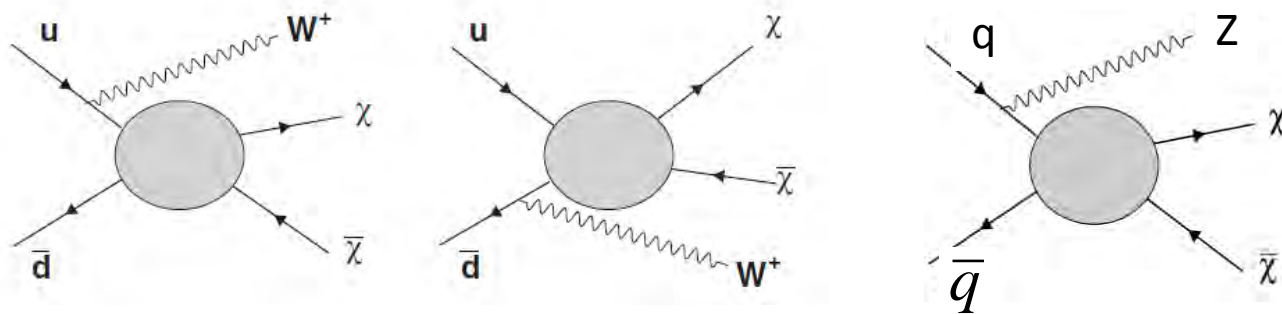
Signature W or Z + MET: two merged jets + MET

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$\rightarrow\chi\chi$]

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

20/fb of 2012 pp data at √s = 8 TeV

Hadronically Decaying W/Z

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

- Step a: Splitting in two subjects (mass-drop filtering procedure)

- Step b: Filtering, reclustering 3 jets with C/A

- Step c & d: Trimming and pruning

$$m^{j_1}/M^{jet} < \mu_{frac} \quad \textbf{and} \quad y > y_{cut}$$
$$\mu_{frac} = 0.2, 0.33, 0.67$$

$$R_{filt} = \min[0.3, \frac{\Delta R_{j_1, j_2}}{2}]$$

Initial jet

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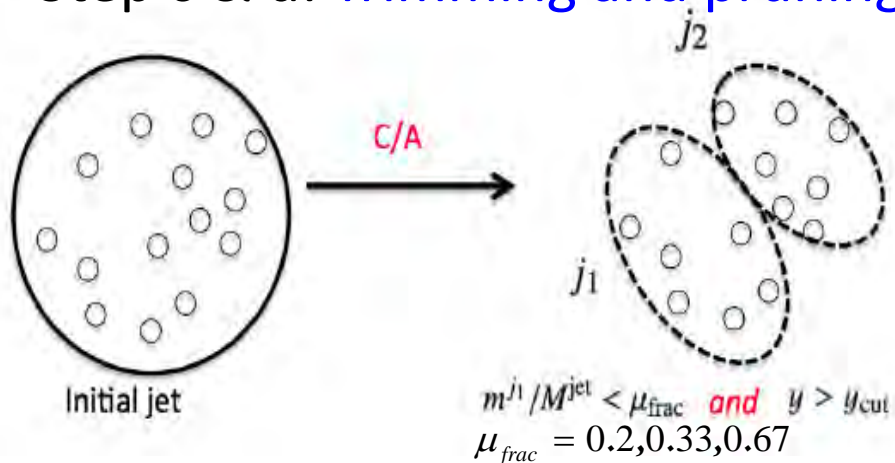
Split in 2 sub-jets j_1, j_2 with $m^{j1} < m^{j2}$
Splitting approx. symmetric in energy sharing and opening angle.
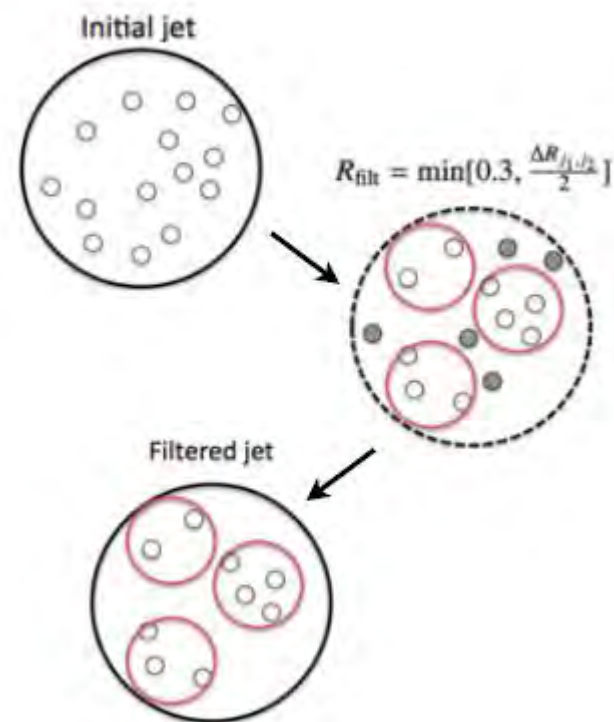
Search Performed in MET Distribution

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
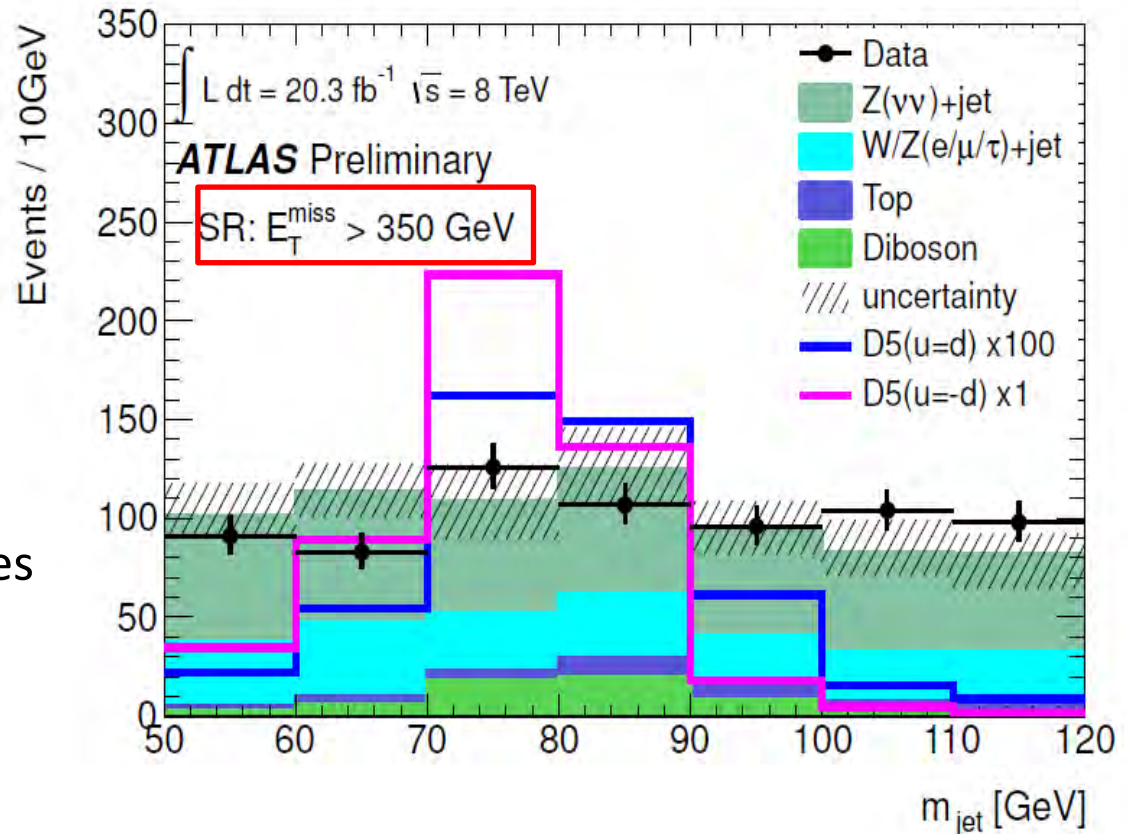
Mono-W/Z Limits

Using predicted **shape** of M_{jet} distribution in each signal region
CLs method
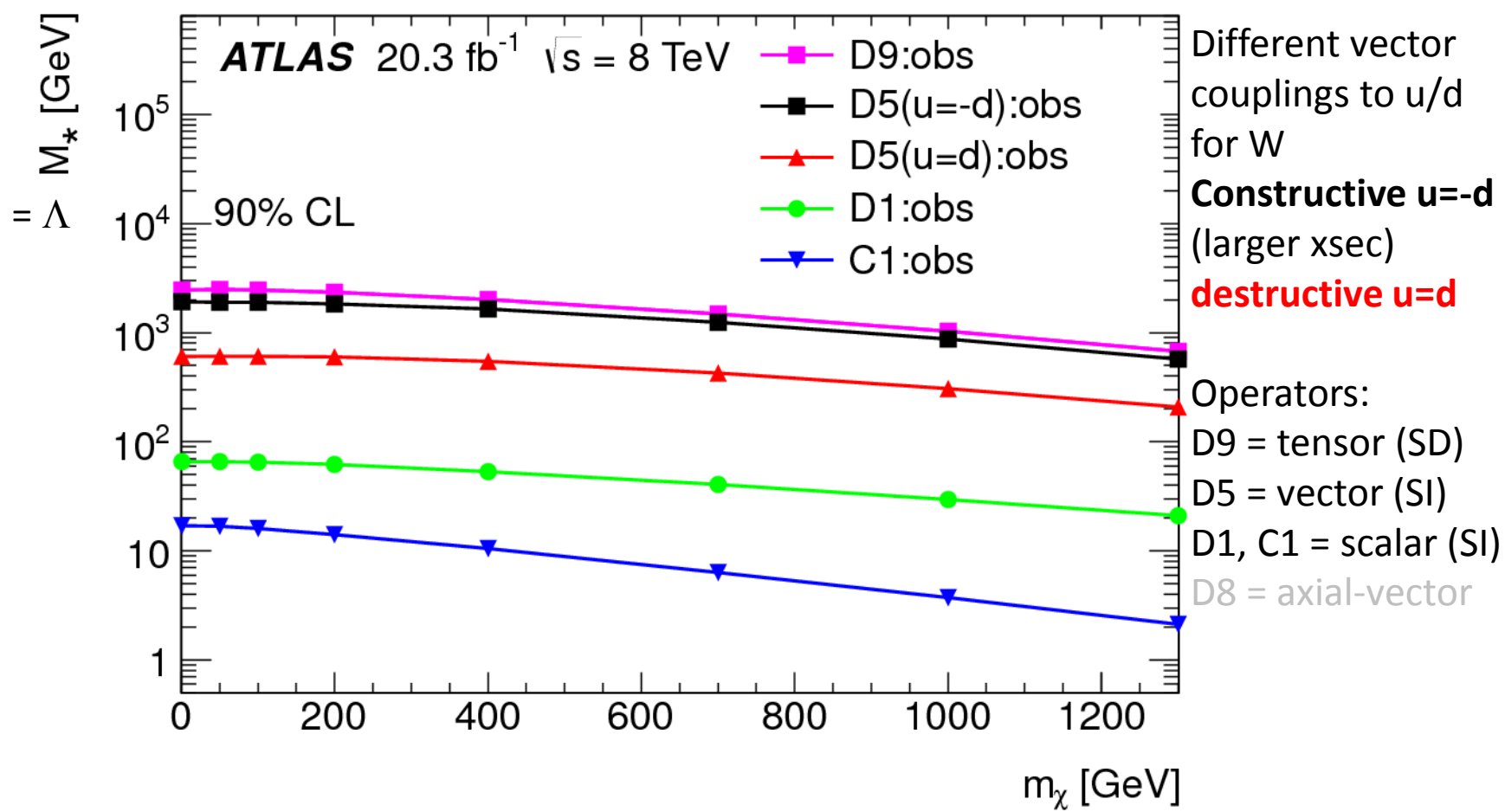
Mono-W/Z in the χ-N plane

Spin-independent limits very strong **10^{-42} cm^2** for vector coupling when u & d have opposite sign

Set strong spin-dependent limits **10^{-43} cm^2** for tensor operator
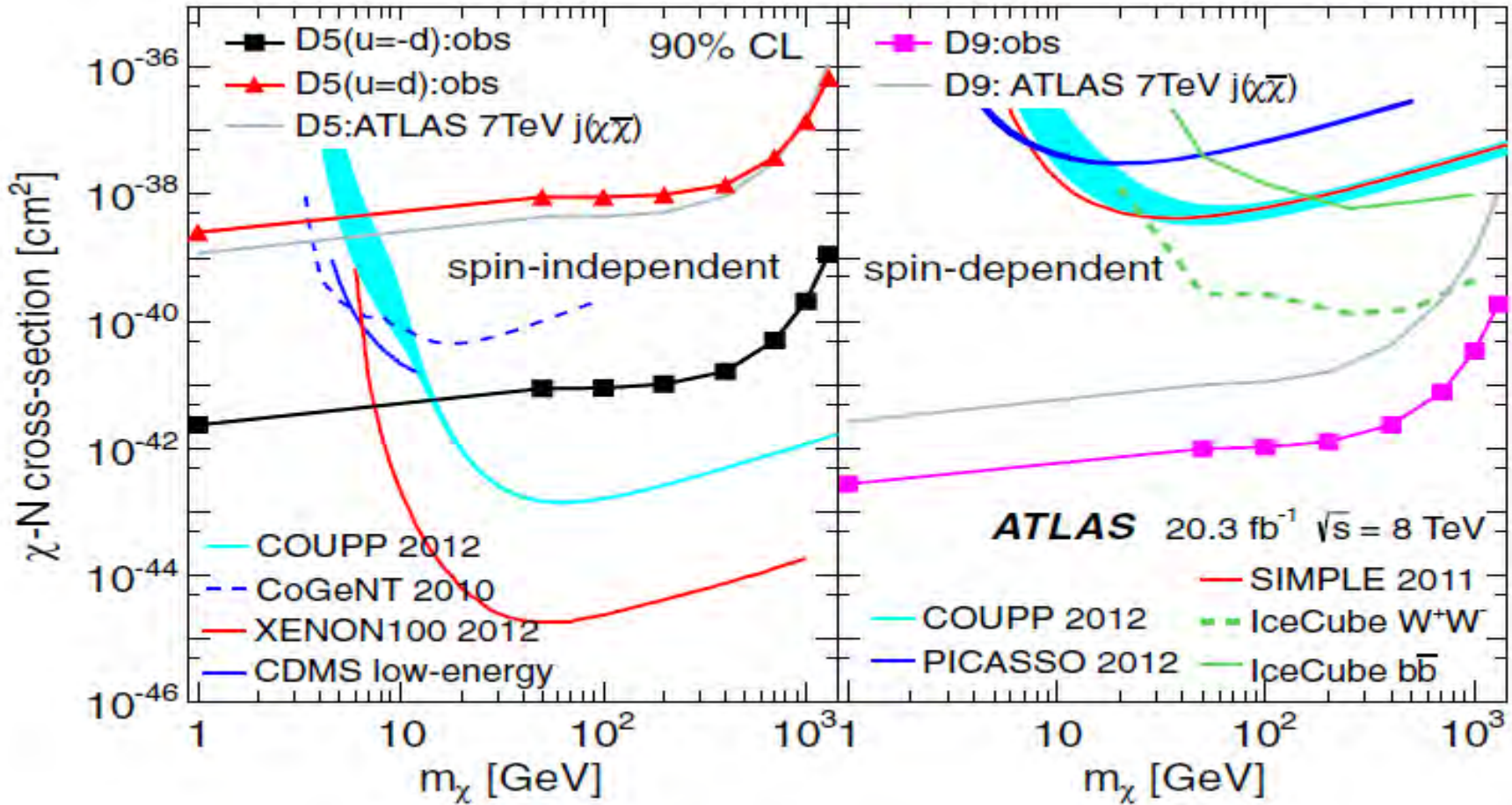
The Big (LHC) Picture…

All 2012 Mono-X Together
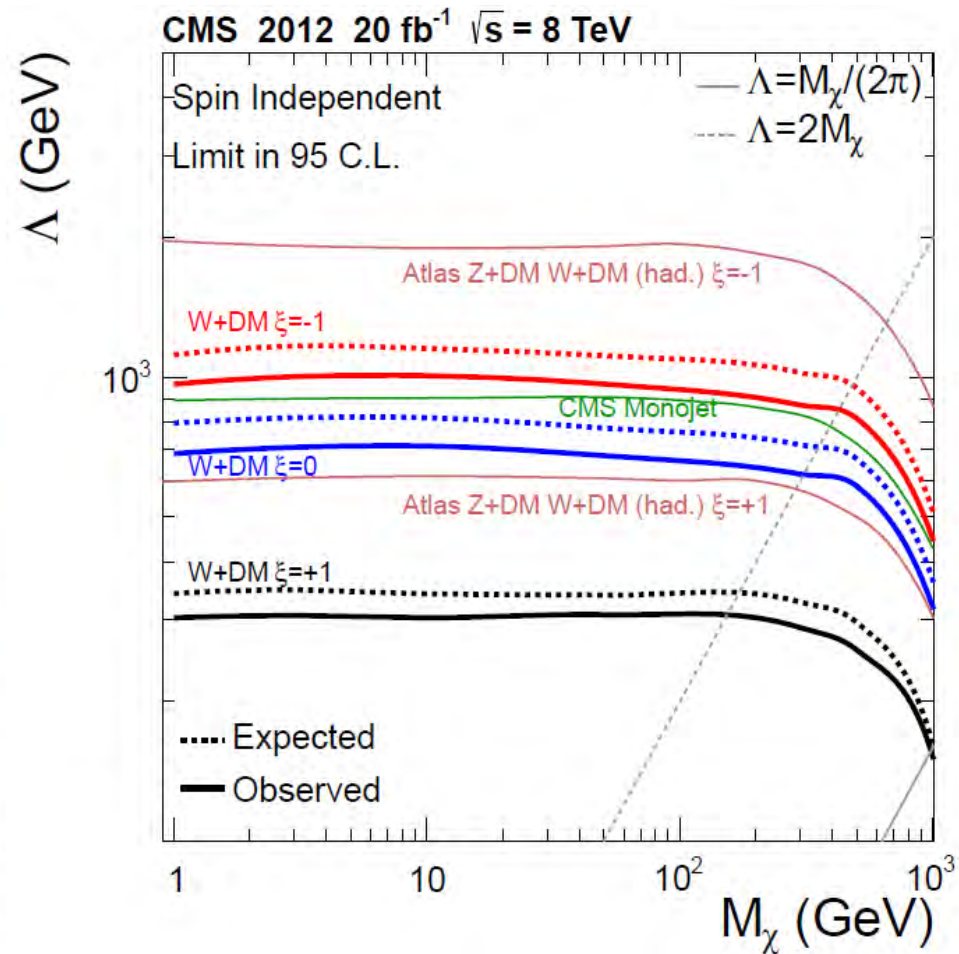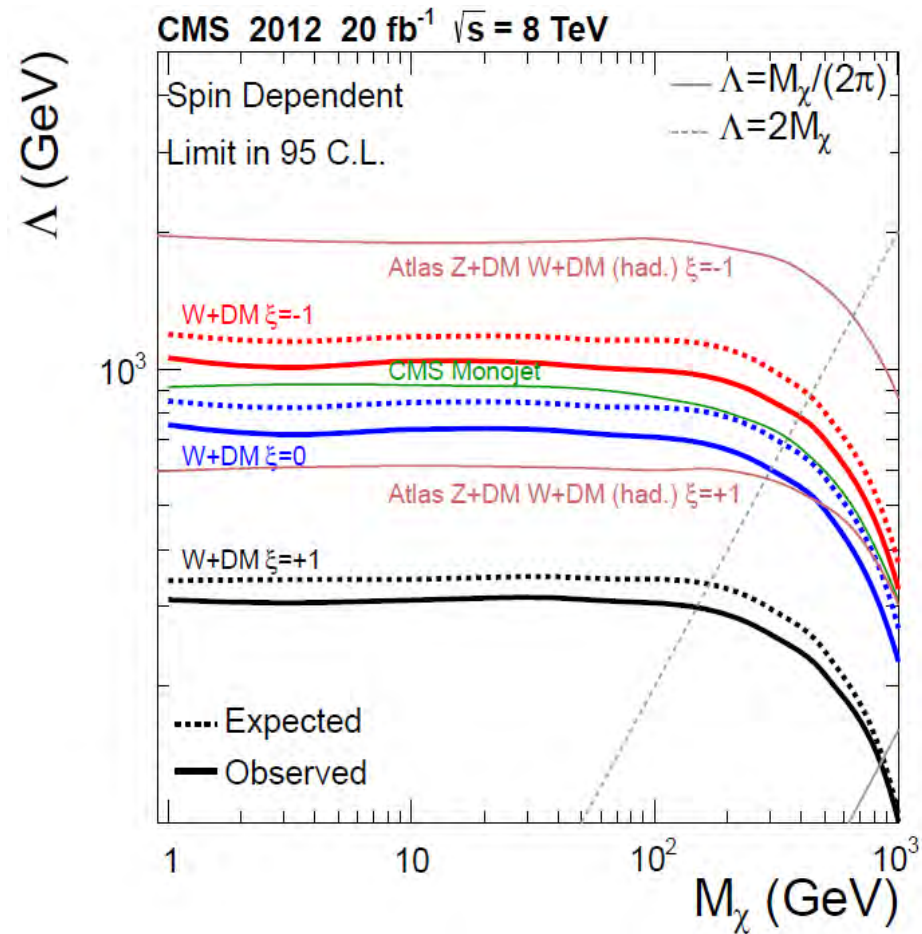
Effective theory valid up to $\Lambda < 2 M_\chi$

What's Next?

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

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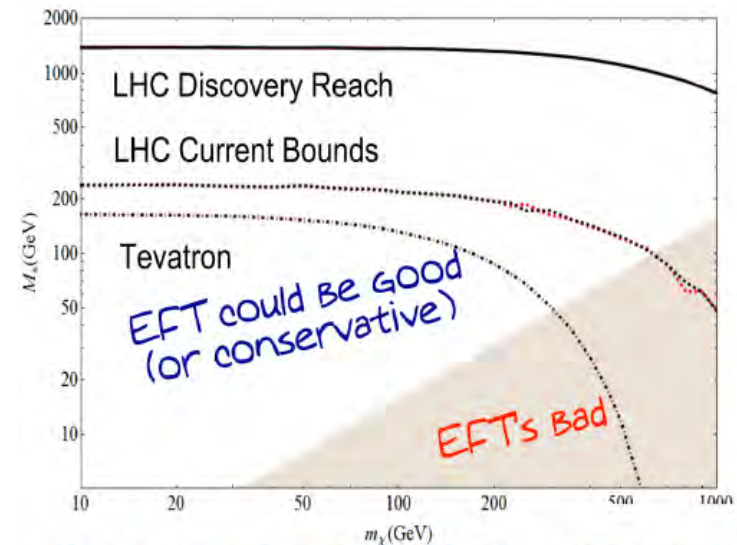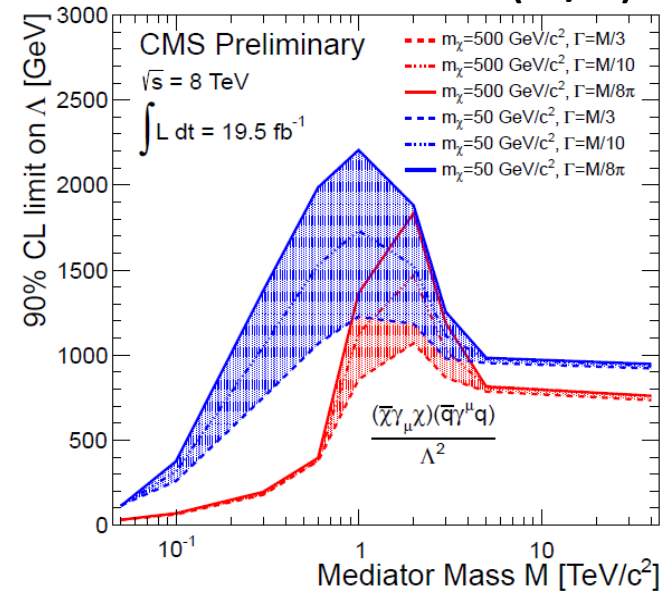
[from R. Harnik, Dark Matter in Collision, UC Davis, 2012]

What Can We Reach at 14 TeV?

FTR-13-011

FTR-13-012
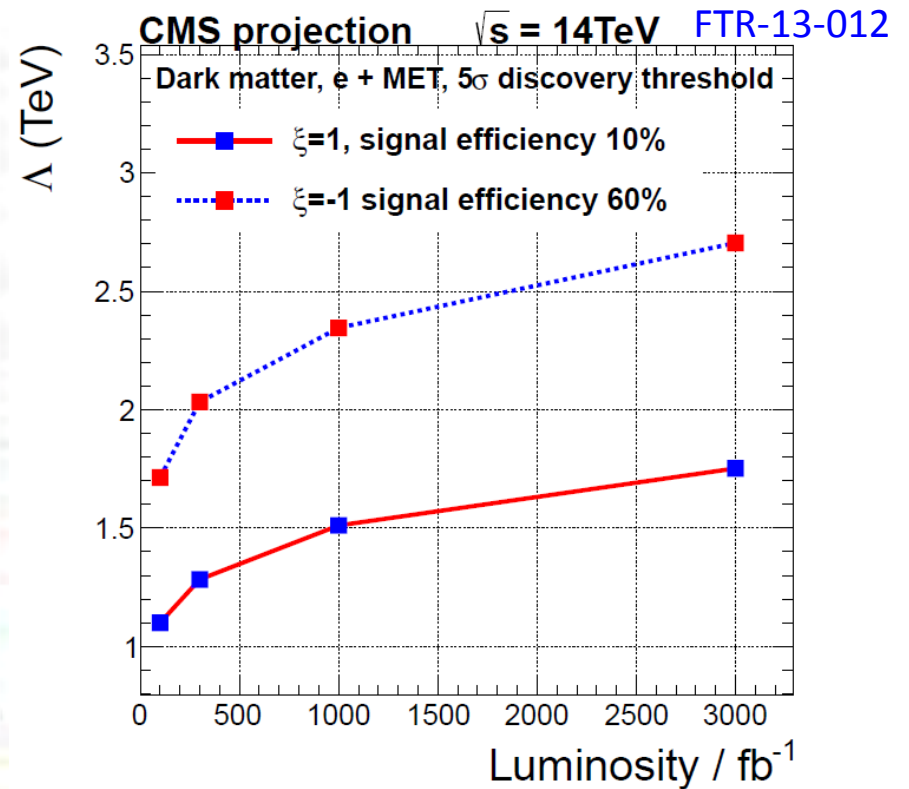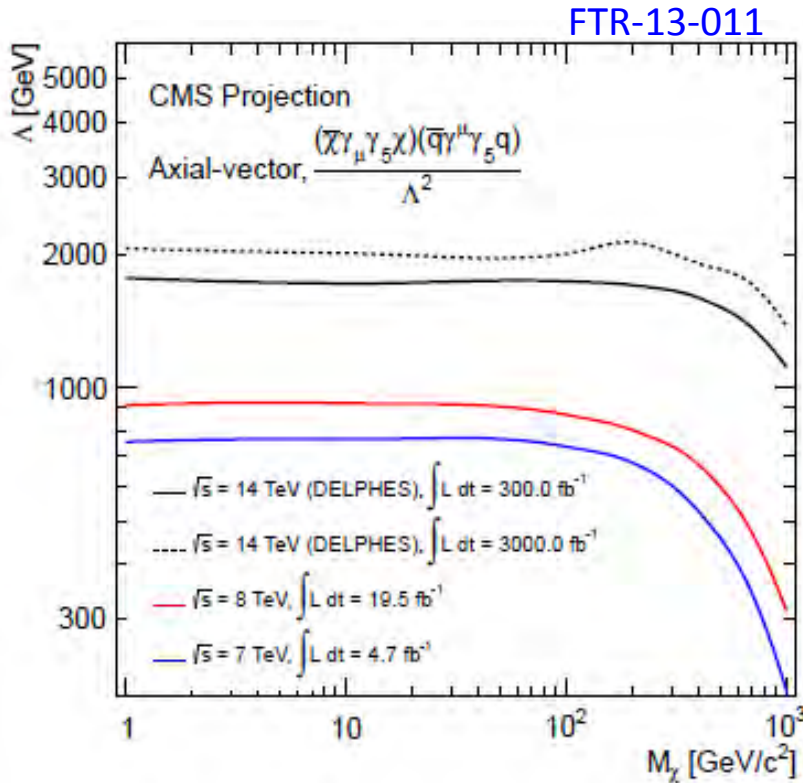
Gain sensitivity with increasing sqrt(s).
At 14TeV and 300/fb. Reach in lambda O(x2)
Main challenge MET in high PU.

Summary

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)

Spin-dependent axial-vector coupling (AV)

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

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

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

Upper limit @ 33 GeV/c^2 is 7.6×10^{-46} cm^2
→ first sub-zeptobarn WIMP detector!

XENON100 (2012)-225 live days

LUX (2013)-85 live days: 90% upper limit

→ 10^{-21} barn!

WIMP–nucleon cross section (cm^2)

m_{WIMP} (GeV/c^2)
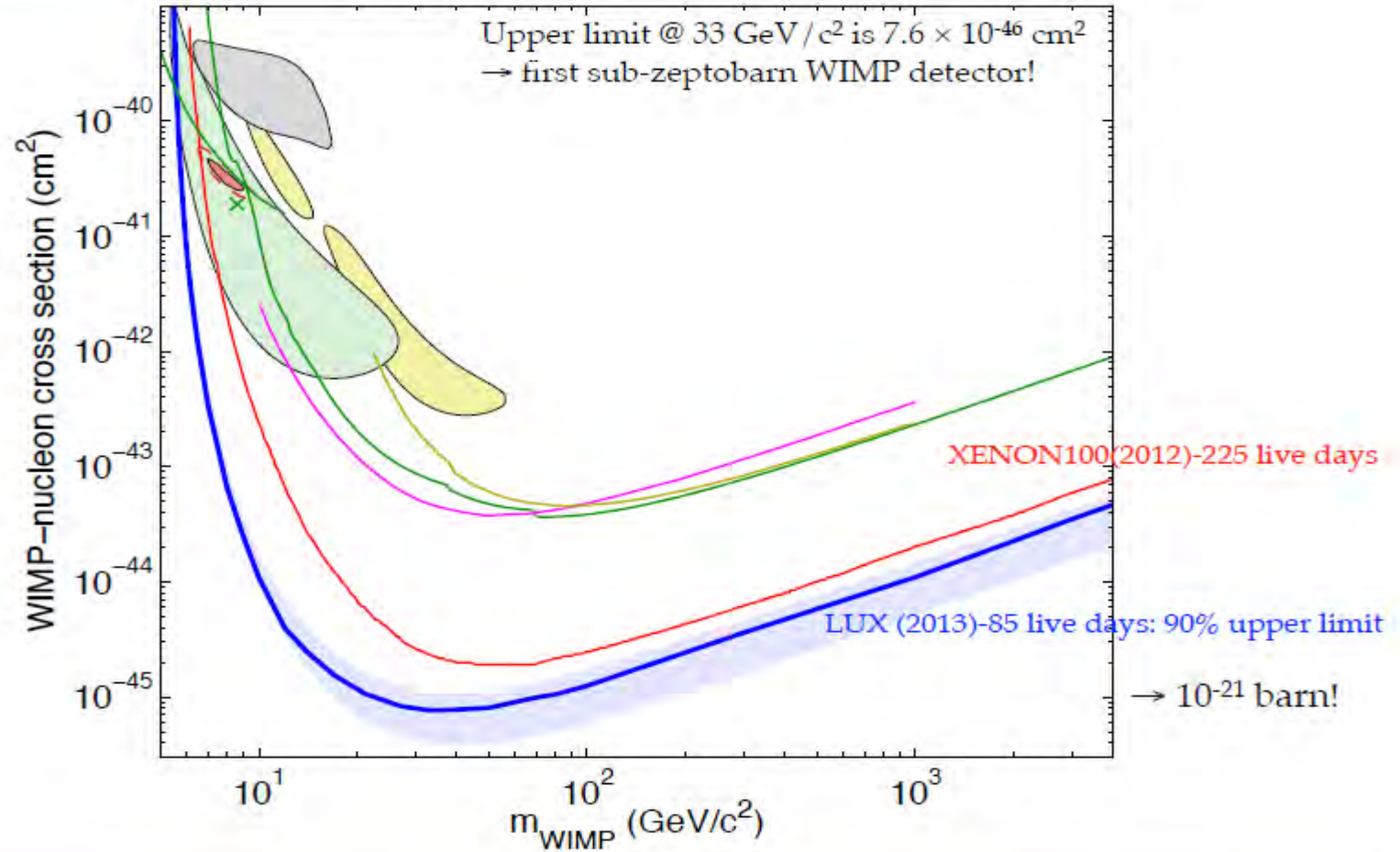
High Energy Electron Selection

CMS Experiment at LHC, CERN
Data recorded: Wed Sep 21 11:35:51 2011 CEST
Run/Event: 176841 / 213192769
Lumi section: 189
Orbit/Crossing: 49420229 / 1640

Electron ET: 799.5 GeV

pfMet: 822.2 GeV

CMS Preliminary $\sqrt{s}$ = 7 TeV

$\int$ Ldt = 4.7 fb^{-1}

DY → ee

barrel-barrel & barrel-endcap

Di-electron mass resolution (EXO-11-019)

σ_{CB} %

m(ee), GeV/c^2
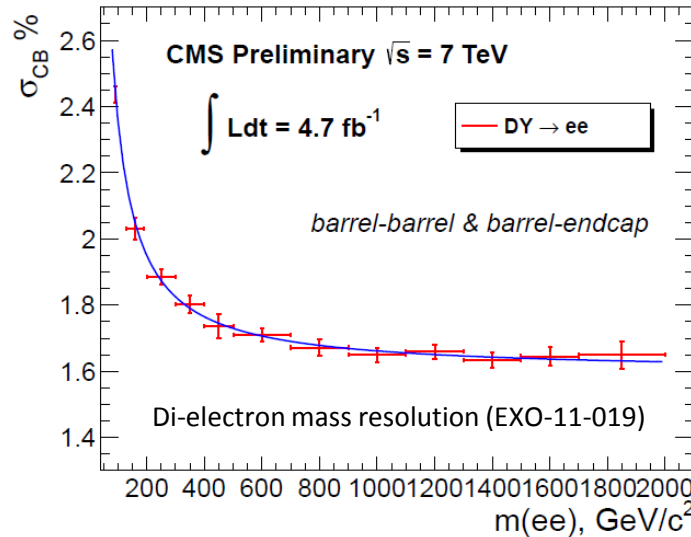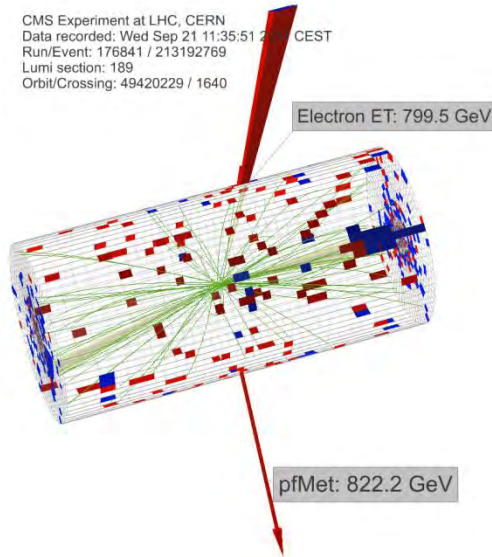
ECAL made of matrix of fully active crystals. Measured energy resolution ~2%

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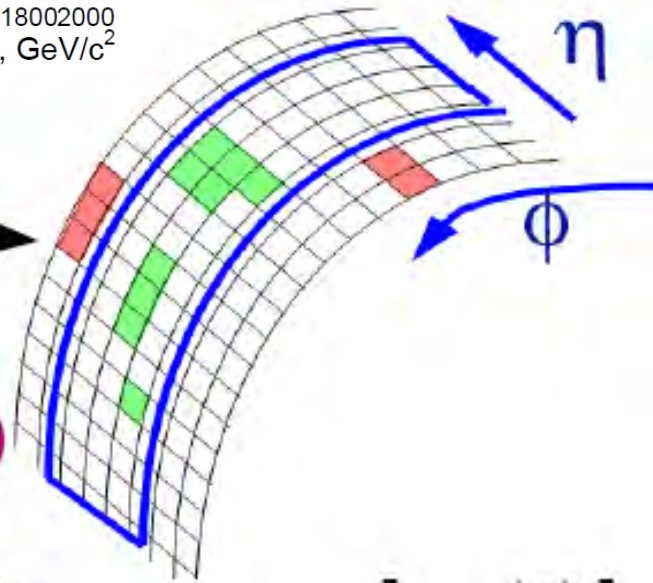
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

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

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Oct 23 20:23:31 2011 CEST
Run/Event: 179547 / 505584390
Lumi section: 319

M$_{\ell\ell}$ = 1380 GeV

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

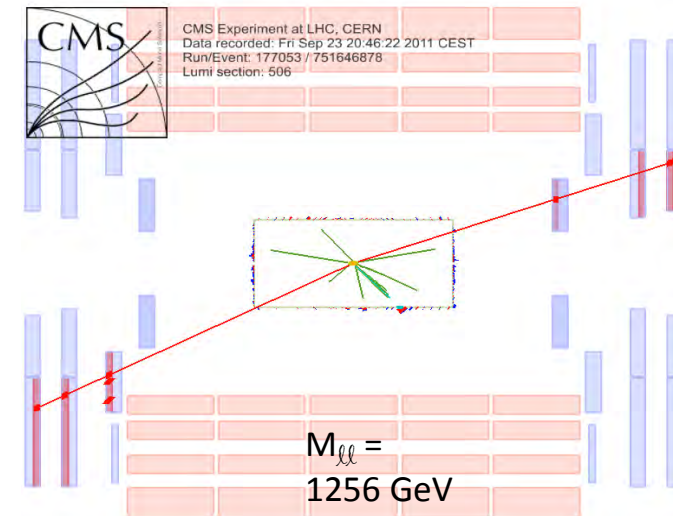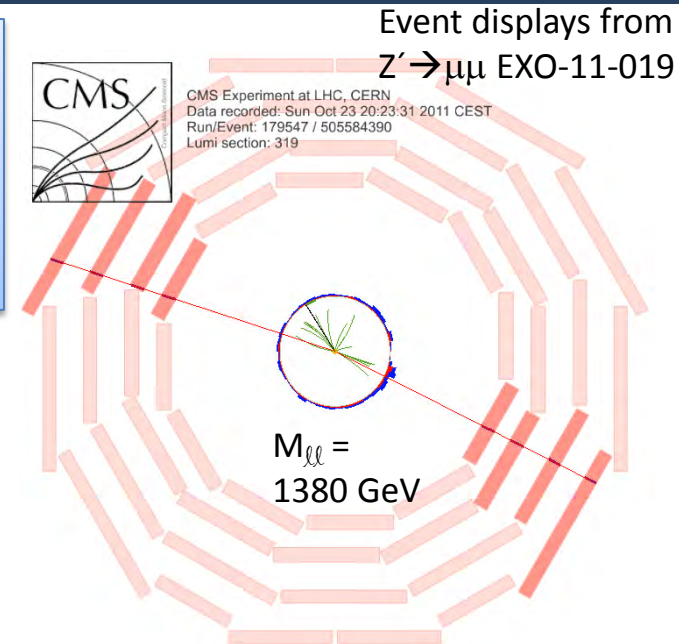- Relative track isolation <0.10 in ΔR < 0.3

- No cut on chi2   cut introduces a 4-6% inefficiency for muons >500 GeV

CMS
CMS Experiment at LHC, CERN
Data recorded: Fri Sep 23 20:46:22 2011 CEST
Run/Event: 177053 / 751646878
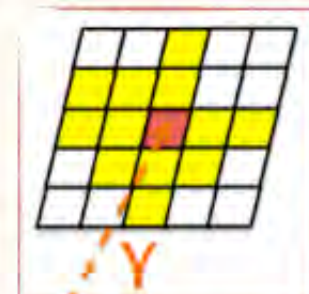Lumi section: 506
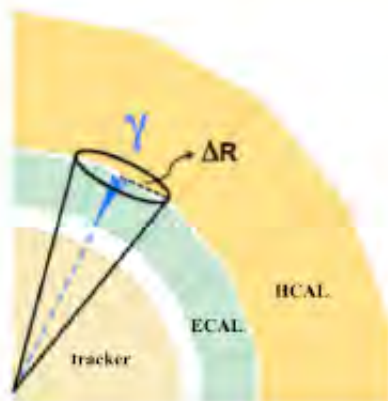
M$_{\ell\ell}$ = 1256 GeV

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