GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

CMS

Search for Dark Matter at CMS

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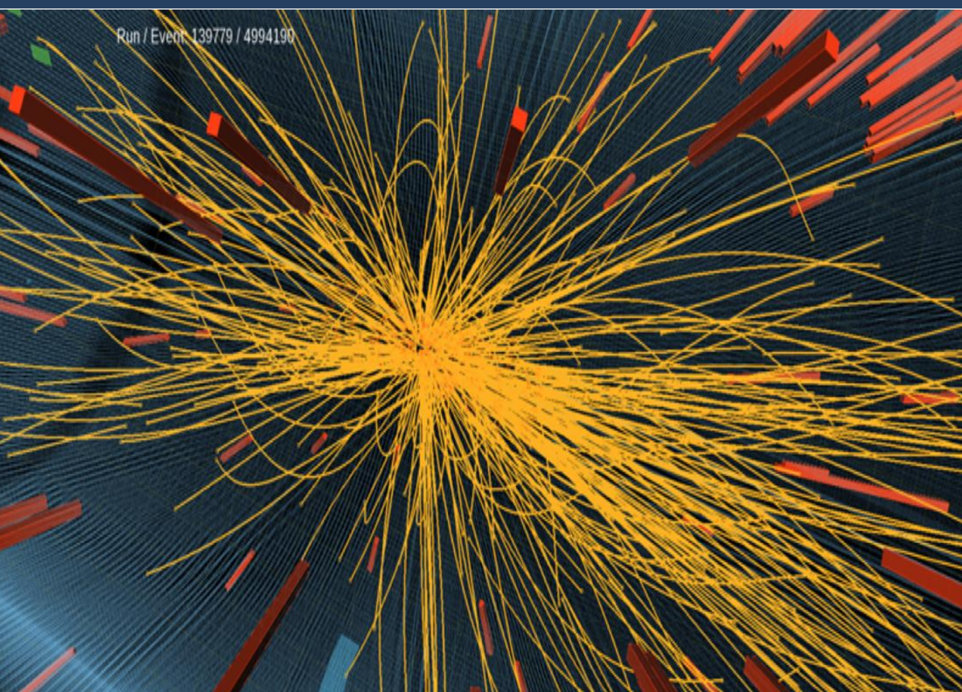
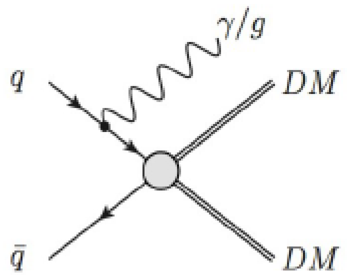
On behalf of the CMS collaboration

PANIC Conference 2014, Hamburg, Germany



Introduction

- Dark matter (DM) is part of cosmological SM, little is known about its properties
- DM (denoted χ) might be produced in pairs in pp collisions at the LHC
- Searches are complementary to (in)direct experiments



Modelling DM production with effective field theories (EFT):

- Collapse SM-DM interaction in effective 4-points operator
- Few parameters: mass $\mathbf{m_\chi}$, cut-off scale $\mathbf{\Lambda = M / \sqrt{g_\chi\, g_q}}$
- Easy to translate to DM-nucleon cross section $\sigma(\chi N \to \chi N) \sim \frac{g_q^2 g_\chi^2}{M^4} \mu_{\chi N}^2$

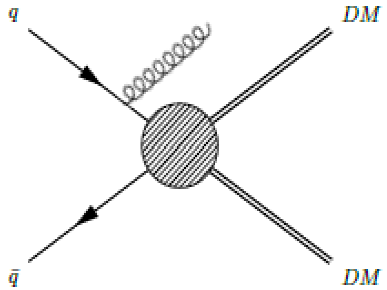
- Requires M > collision energy scale
- Probes one interaction at the time
- **Different operators** depending on mediator's coupling

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)]

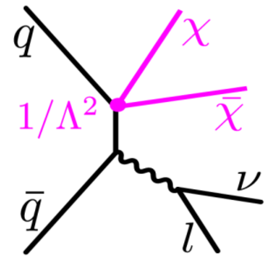
How to make DM visible at the LHC?

Signatures – simple and striking



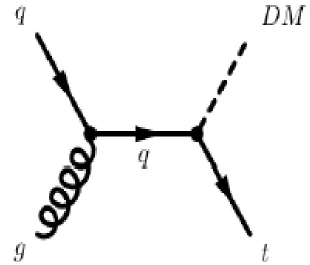
ISR of a jet / photon

arXiv:1408.3583
CMS-PAS-EXO-12-047



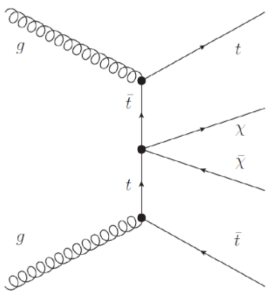
Recoil of a W-boson
W→lν with l=e,μ

arXiv:1408.2745



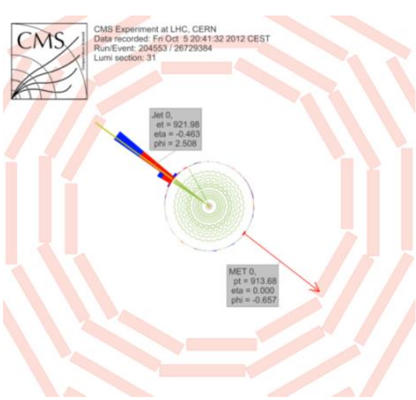
Single top
s- and t-channel

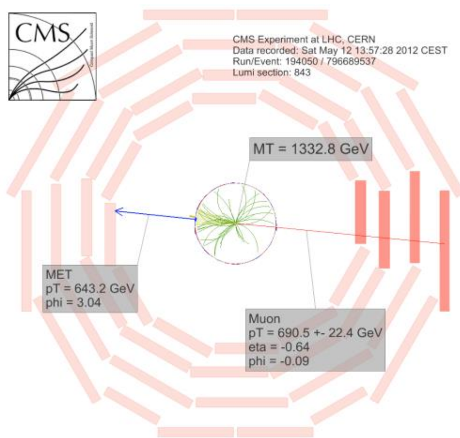
CMS-PAS-B2G-12-022

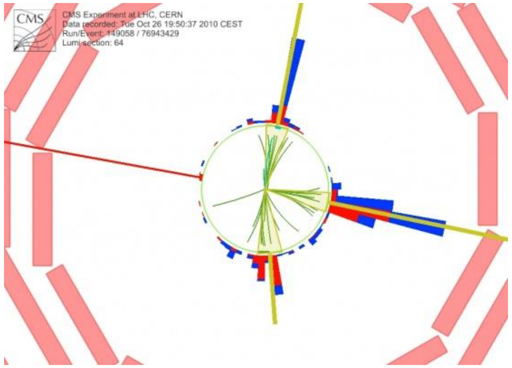


Production in
association with ttbar

CMS-PAS-B2G-13-004
CMS-PAS-B2G-14-004



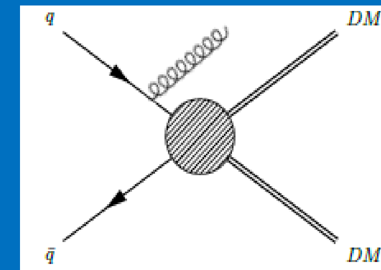


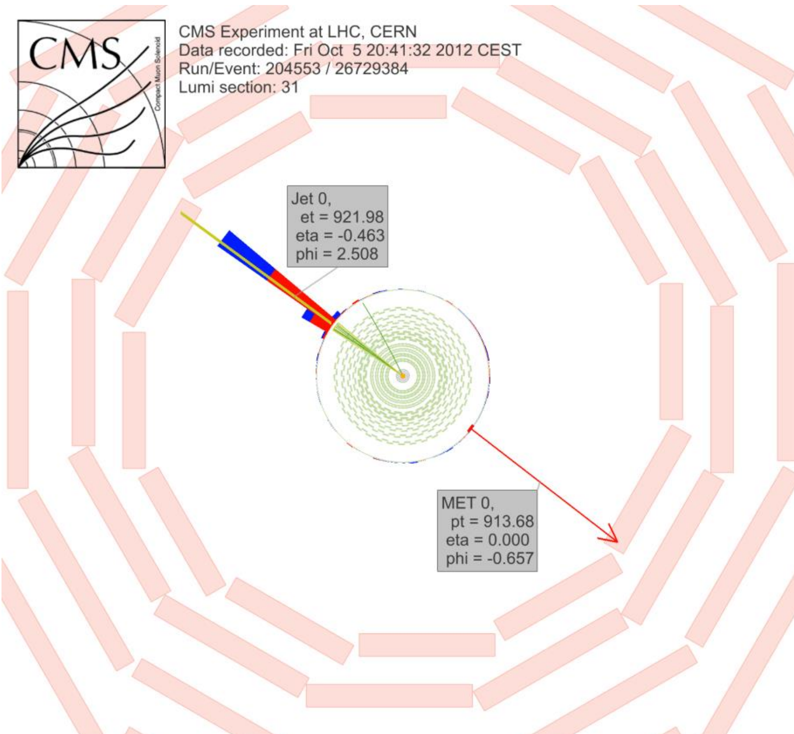


Example, not this analysis

All analyses with full 2012 data-set of 20/fb

Pair Produced Dark Matter in Monojet Channel





Signature:

high p_T jet (p_T > 110 GeV)

+ MET > 250 GeV

arXiv:1408.3583

CMS-PAS-EXO-12-048

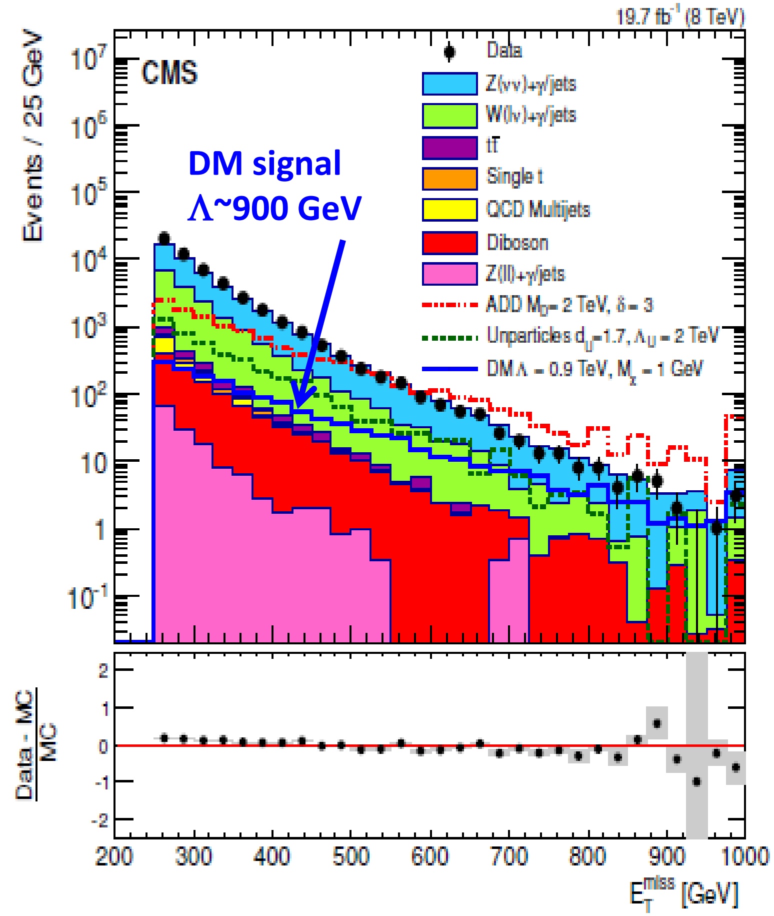
20/fb of 2012 pp data at √s = 8 TeV

Monojet Event Selection

CMS-PAS-EXO-12-048 arXiv:1408.3583

Event selection:

- MET trigger defines lower analysis boundary MET>250 GeV
- One central jet p_T>110 GeV. Second softer jet if close to first
- Jet quality: >20% carried by charged hadrons, <70% carried by neutral hadron or photon
- No isolated lepton (e,mu,tau)



Backgrounds:

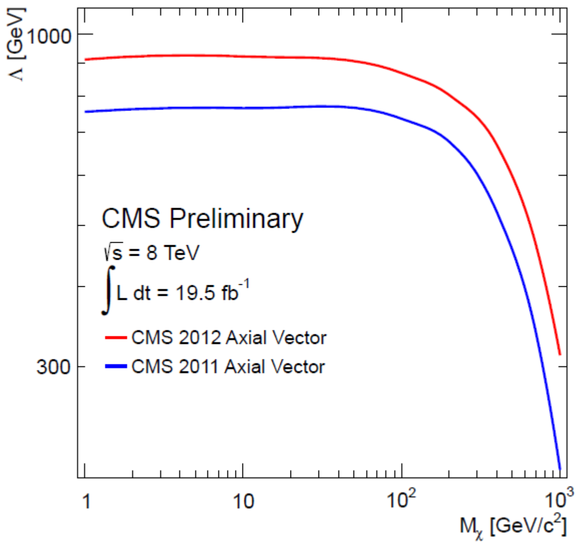
- Dominant background (~70%) is Z→νν + j
  → Data driven estimate from Z→μμ + j
- W+jets (~30%) also from data driven
- QCD : rejected by $\Delta\phi$ (j1, j2) cut

95% C.L. limits on σ × A × ε

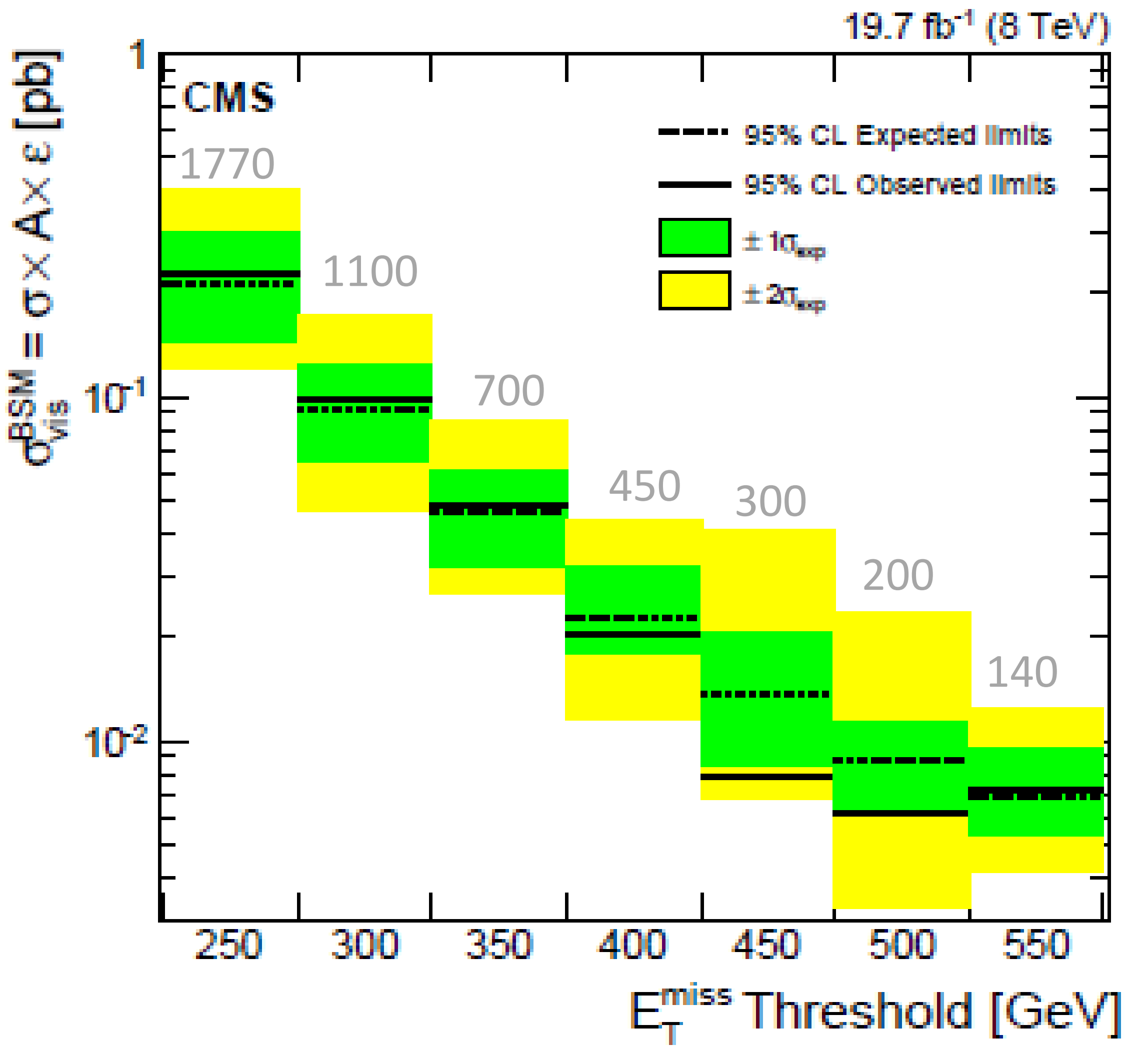
CMS-PAS-EXO-12-048 arXiv:1408.3583

Search performed in 7 bins of MET

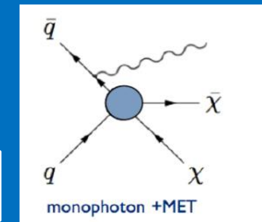
Lambda limit
~900 GeV
AV & V for Mχ < 100 GeV

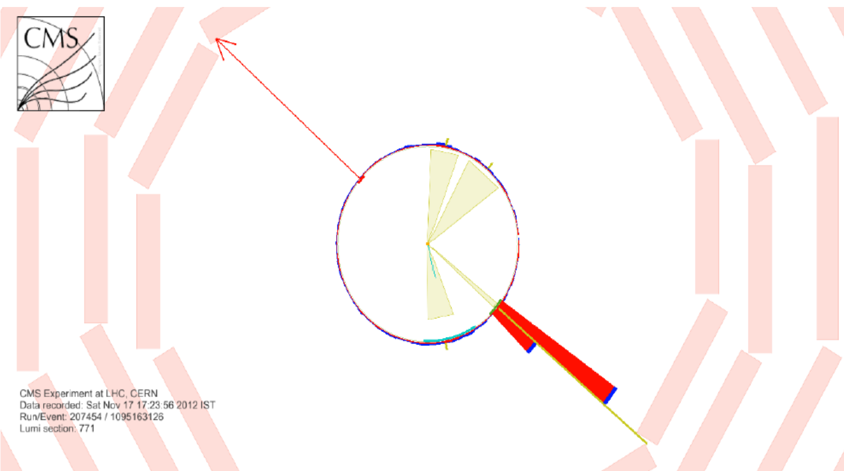


Expected # signal events for Λ=850 GeV, Mχ=1 GeV



Search for Pair Produced Dark Matter in Monophoton Channel





Highest photon p_T candidate event.
Photon p_T = 653 GeV, MET = 716 GeV

Signature:

high p_T Photon (E_T > 145 GeV)

+ MET > 140 GeV

CMS-PAS-EXO-12-047

20/fb of 2012 pp data at √s = 8 TeV

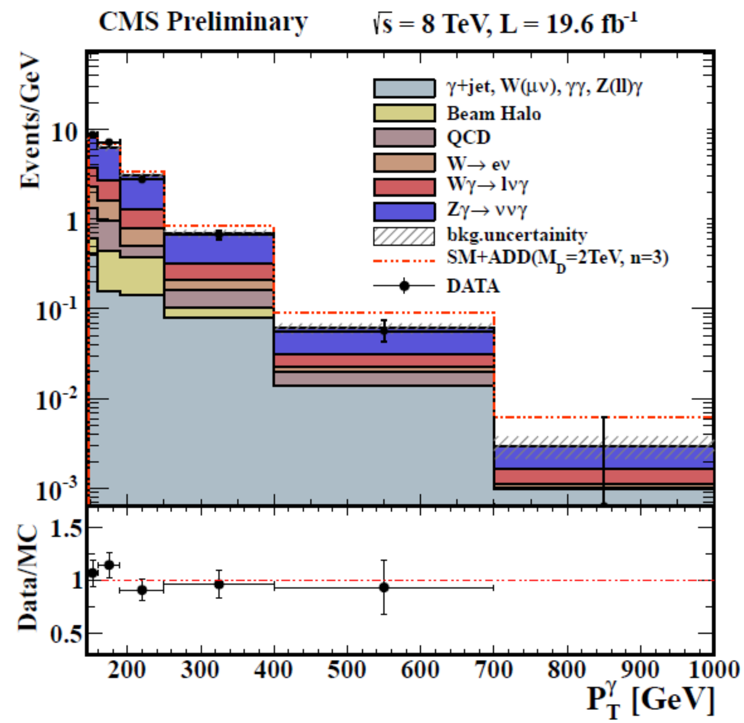
Monophoton Event Selection

CMS-PAS-EXO-12-047

Event selection:

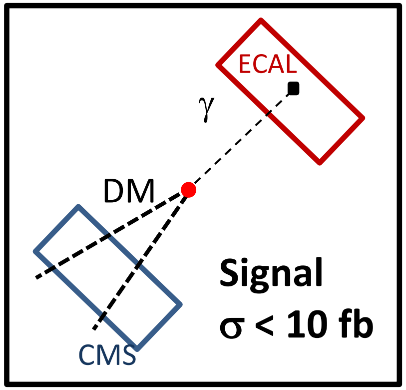
Photon and photon+MET trigger defines lower analysis boundary

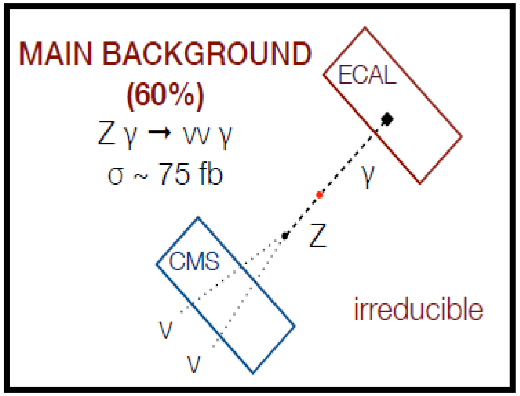
- MET > 140 GeV and p_T^γ > 145 GeV with $\Delta\phi$(MET, p_T^γ) > 2
- Photon ID cuts to reject fakes
- Veto on electron/muon and hadronic activity
- Search performed in 6 bins of p_T^γ



Backgrounds:

- Irreducible Z(→νν) + γ background dominant after selection
- Other bkgr with genuine photon: W(→lν) + γ
- Fake photon backgroundss: W→eν, QCD, beam halo

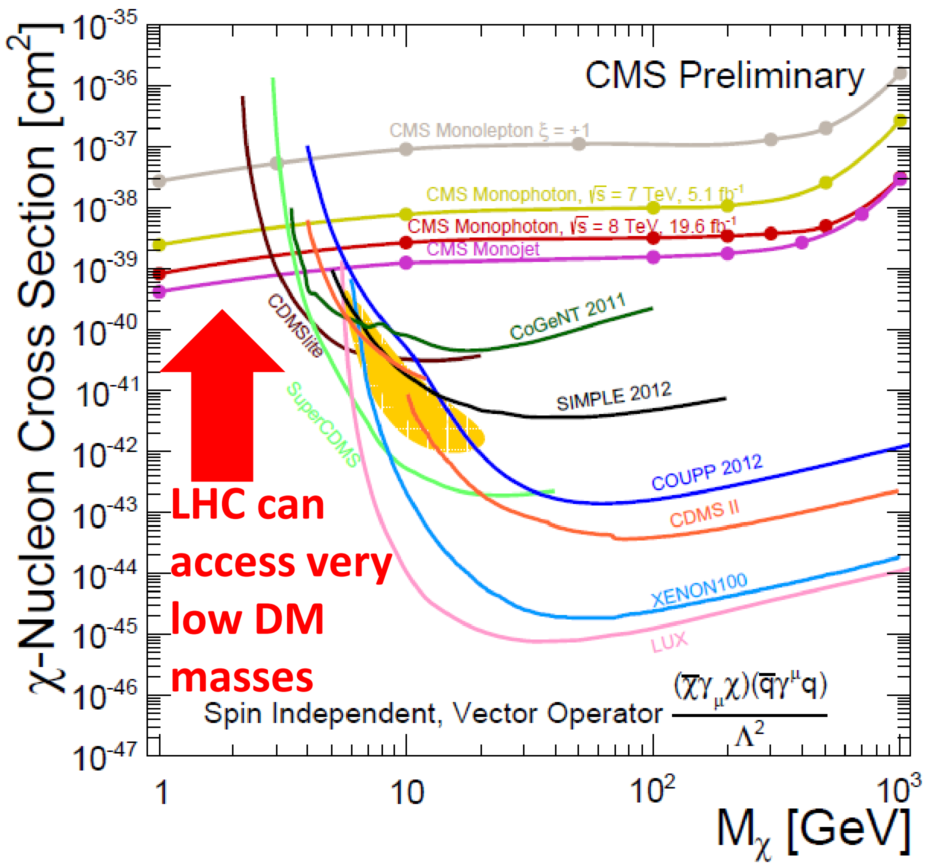


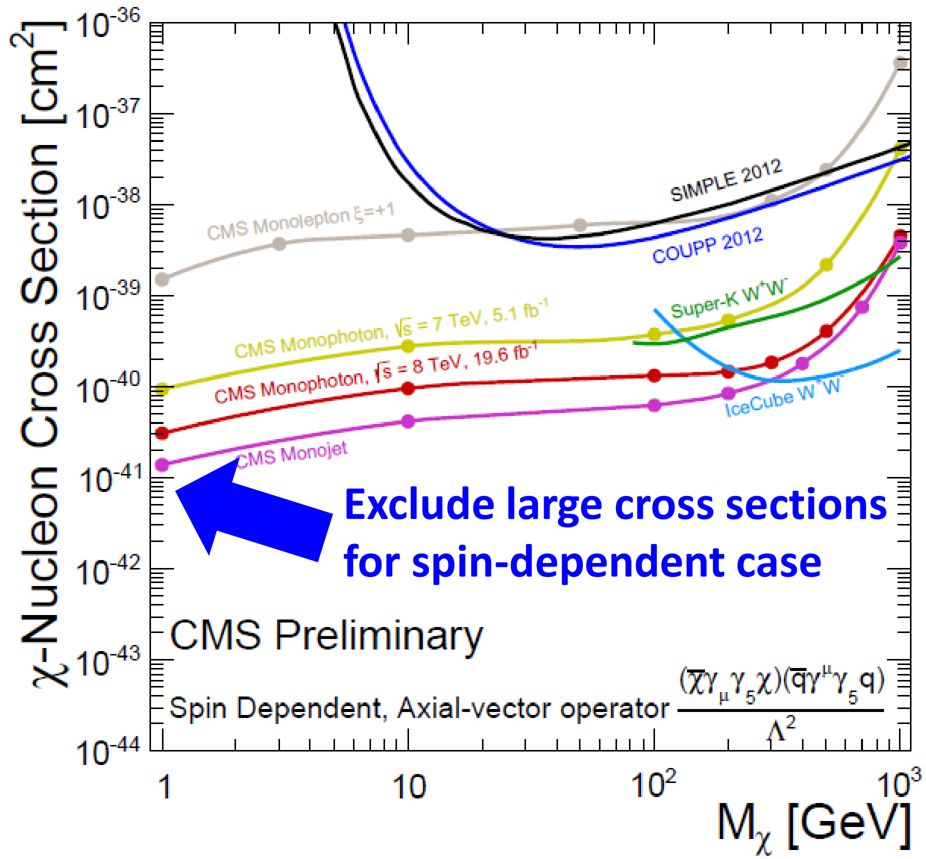


DM-Nucleon Cross-section Limits
Mono-Photon/Jet

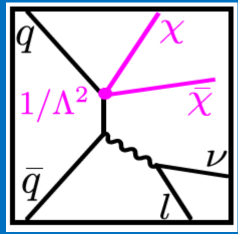
CMS-PAS-EXO-12-047

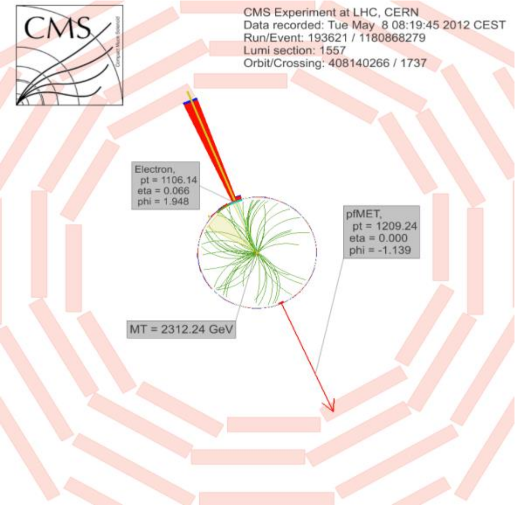
- Data compatible with SM expectation
- 90% C.L. limits set on EFT scale Λ using effective operators in EFT approach
- Translate to elastic DM-nucleon cross-section vs. DM mass $M\chi$

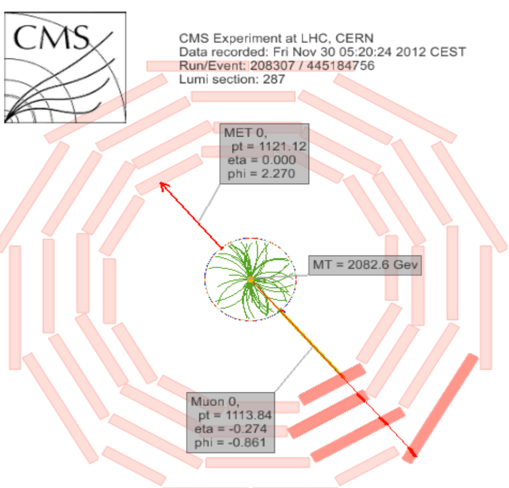




Pair Produced Dark Matter in Monolepton Channel







Events with max M_T in either channel

Signature W + MET:

high p_T electron (E_T>85 GeV) + MET

High p_T muon (p_T>40 GeV)+ MET

All results combine electron + muon channels

arXiv:1408.2745

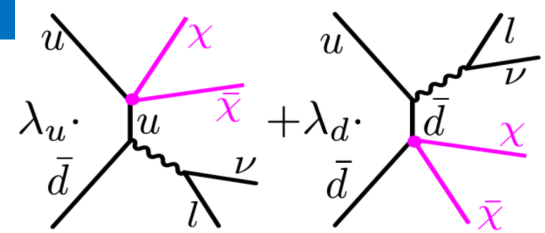
CMS –PAS-EXO-13-004

20/fb of 2012 pp data at √s = 8 TeV

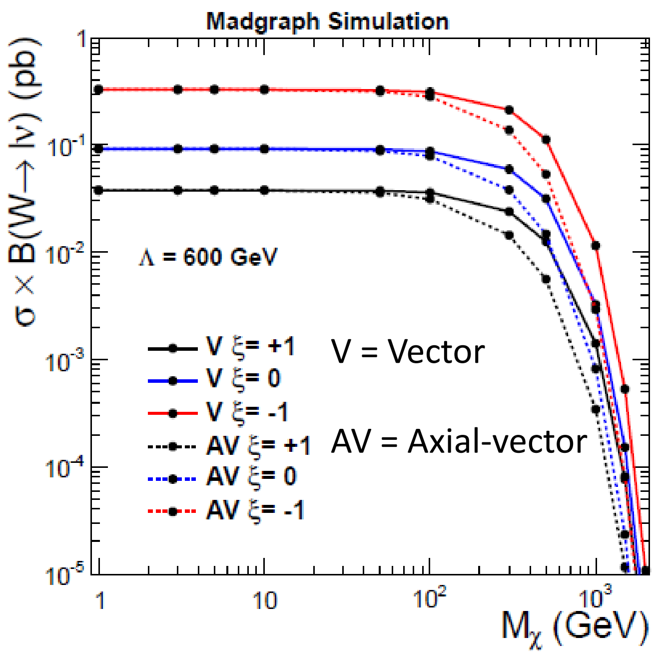
Search strategy following arXiv:1208.4861v2

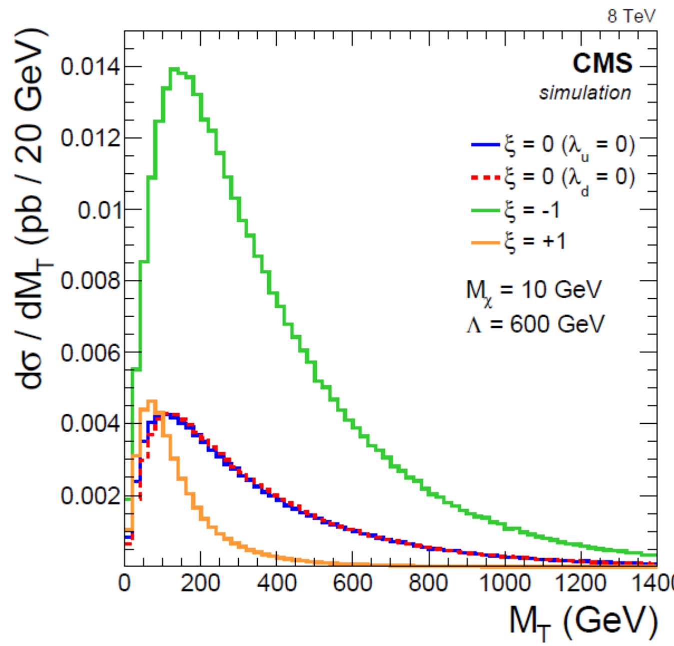
Monolepton is Special

Monolepton channel sensitive to possibly different coupling to u- and d-type quarks



Parametrized by $\xi = -1,\ 0,\ +1$ $\xi = \lambda_u \cdot \lambda_d$ $with\ |\lambda_i| = 0\ or\ 1$
(interference)





Largest cross section for χ = -1
For Mχ <~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

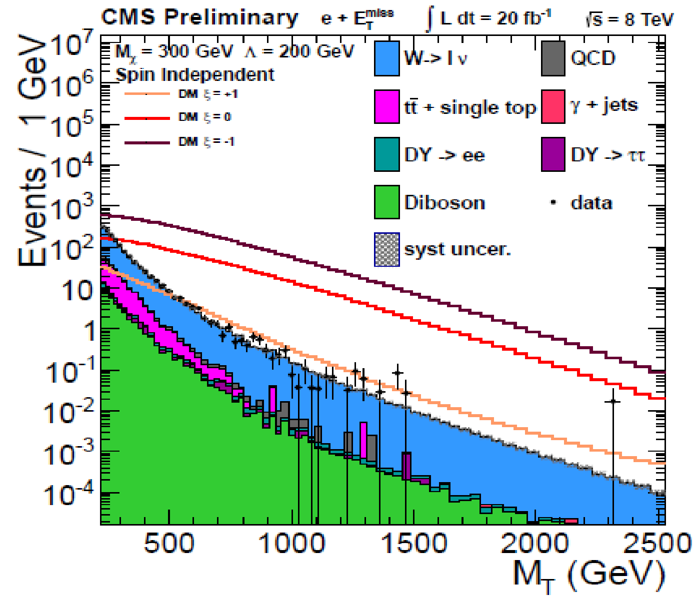
arXiv:1408.2745

Event selection

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

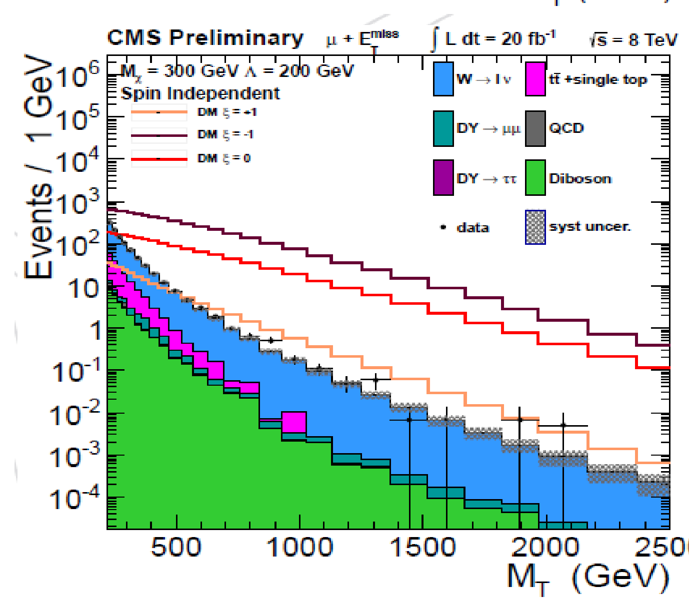
  $0.4 < p_T\ /\ \mathrm{MET} < 2$

  $\Delta\phi < 0.8$



Transverse mass distribution

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

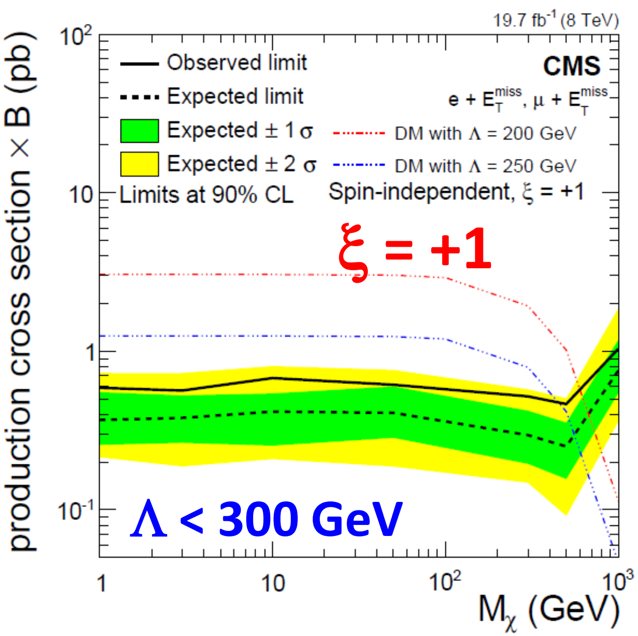


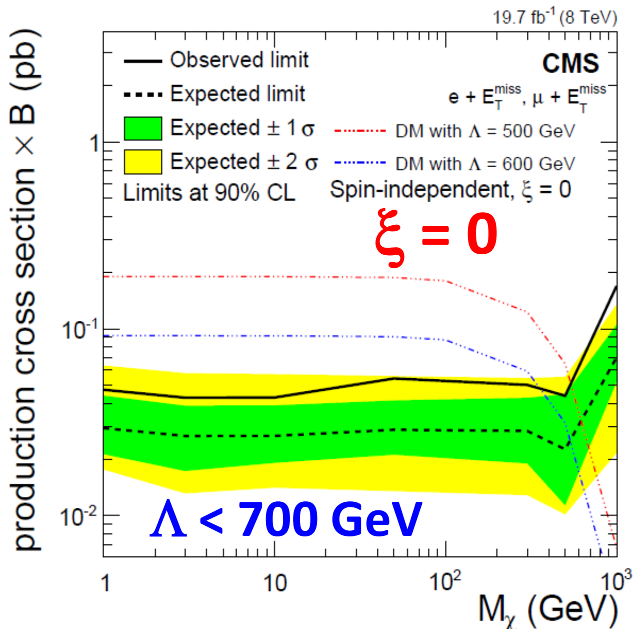
Background

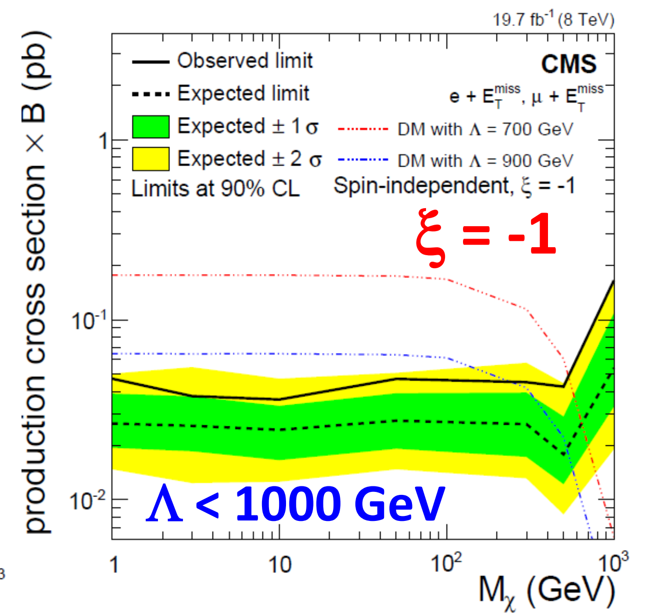
- Derived from simulation
- Main bkgr: W→lν with MT binned k-factor
- NLO xsec's

Limits on production cross section + λ

arXiv:1408.2745

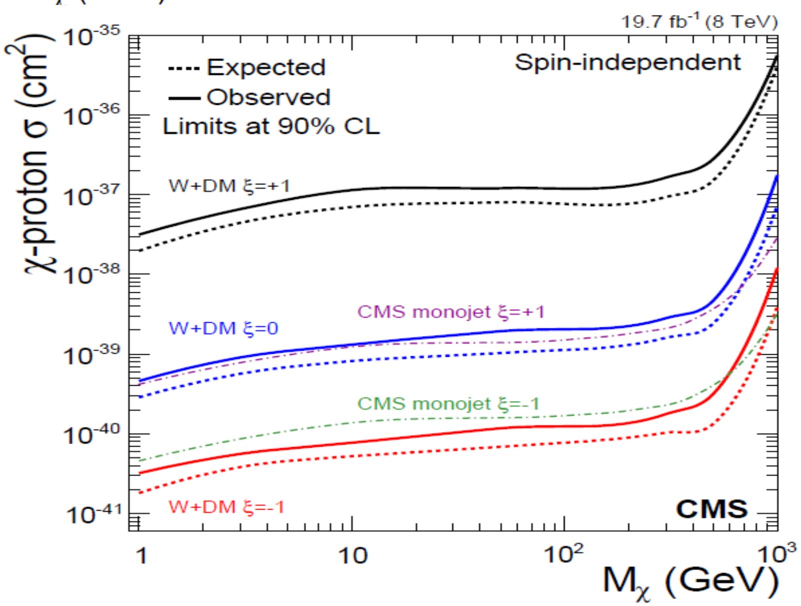






Cross section limits nearly independent on coupling (vector vs axial vector) due to cross section → Similar Λ-limits

Translation to DM-nucleon (SI case) ⟶



Test Scalar Coupling with heavy Top Quark(s)

New

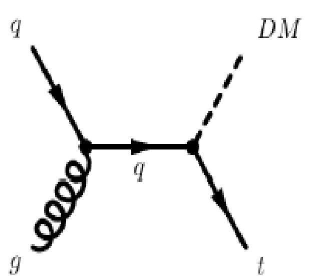
Couplings discussed so far proportional to **$1/\Lambda^2$**

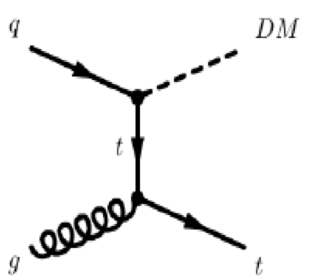
Scalar couplings (D1) $C = \frac{m_q}{\Lambda^3}$

(C1) $C = \frac{m_q}{\Lambda^2}$

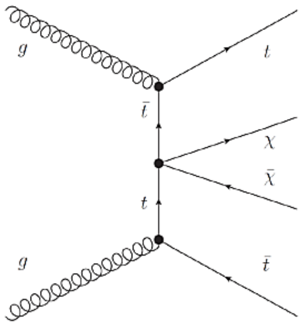
Quark mass. Best with heavy quarks → top

Single Top



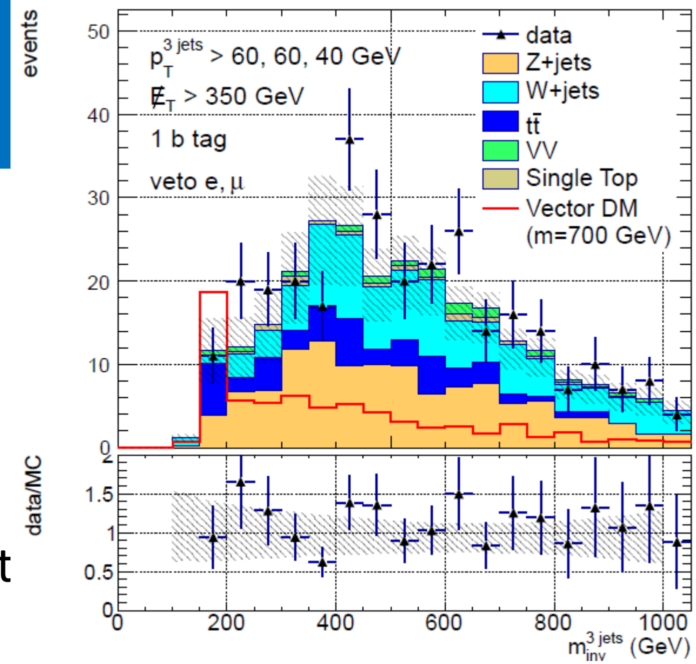


Association with top-pairs



Mono-Top Search

CMS-PAS-B2G-12-022



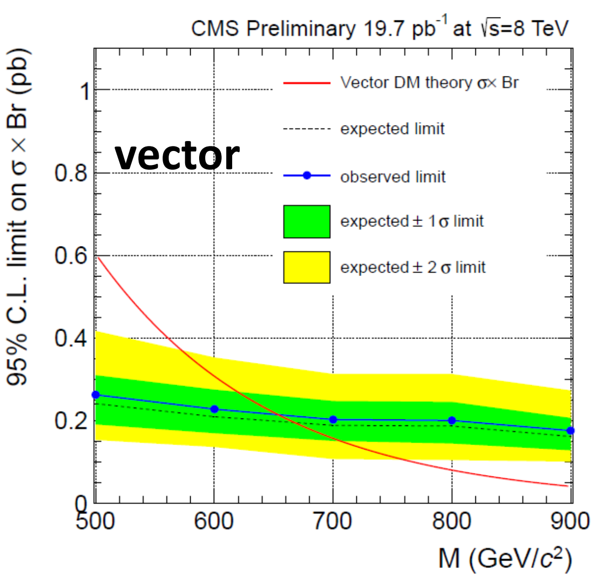
Event selection:

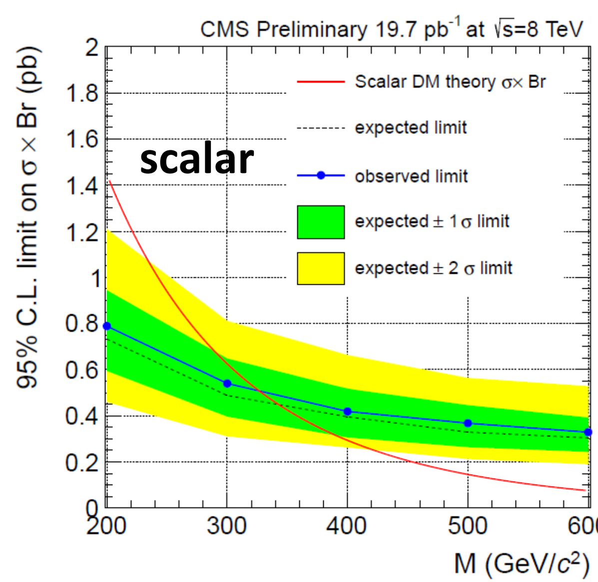
- MET > 350 GeV
- 3 jets, of which 1 b-tagged (removes 4/5 of bkgr)
- No isolated electron/muon

Main backgrounds are ttbar (with MET from W leptonic), V+jet

QCD, VV and V+jets suppressed by b-tag.

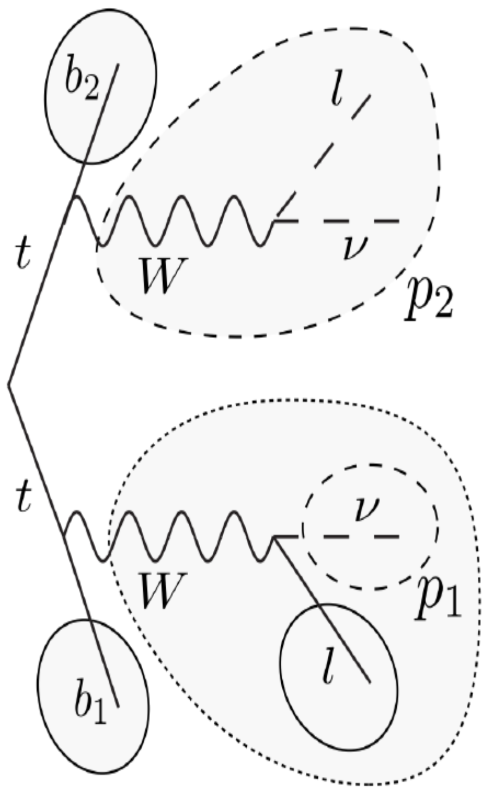
DM excluded vector (Mχ<655 GeV) and scalar (Mχ<327 GeV) couplings @95% C.L.





Top-Quark Pairs

CMS-PAS-B2G-13-004 (di-lepton)
CMS-PAS-B2G-14-004 (semi-leptonic)



Depending on W decay mode, final state

- llbb+MET (di-lepton)
- ljjjb+MET (semi-leptonic)

Concentrates on scalar operator where other channels are weak

Search strategy following Phys. Rev. D 88.063510

Event Selection

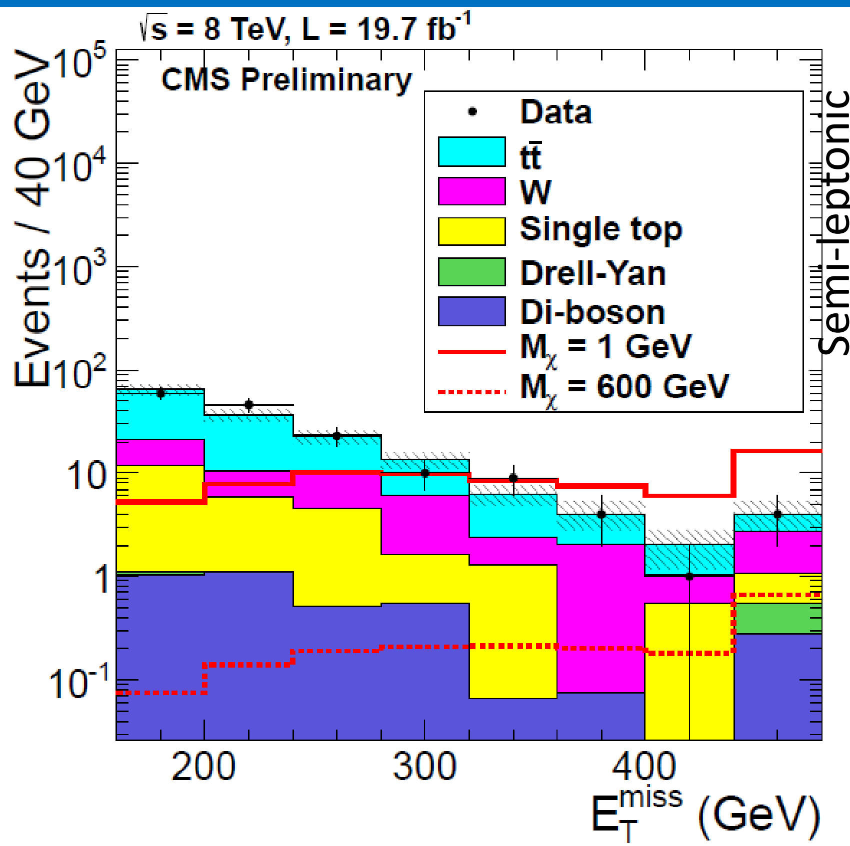
CMS-PAS-B2G-13-004 (di-lepton)
CMS-PAS-B2G-14-004 (semi-leptonic)

Selection **semileptonic** channel:

- 1lepton + ≥3 jets + ≥1 b-jet + MET
- Large MET (due to DM) → MET>320 GeV
- Both W reconstructed via M_T

Selection **dilepton** channel:

- 2 electrons/muons + ≥ 2 jets
- MET > 320 GeV
- Cuts on scalar sum of leptons and jets, and lepton opening angle



Main Background for both analyses is ttbar.
Signal efficiencyies ~1-2% for both channels.

Dilepton nearly bkgr-free but low signal.
Both are higher in semi-leptonic.
Signal efficiency and sensitivity comparable.

dilepton

Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal	$1.88 \pm 0.11 \pm 0.07$

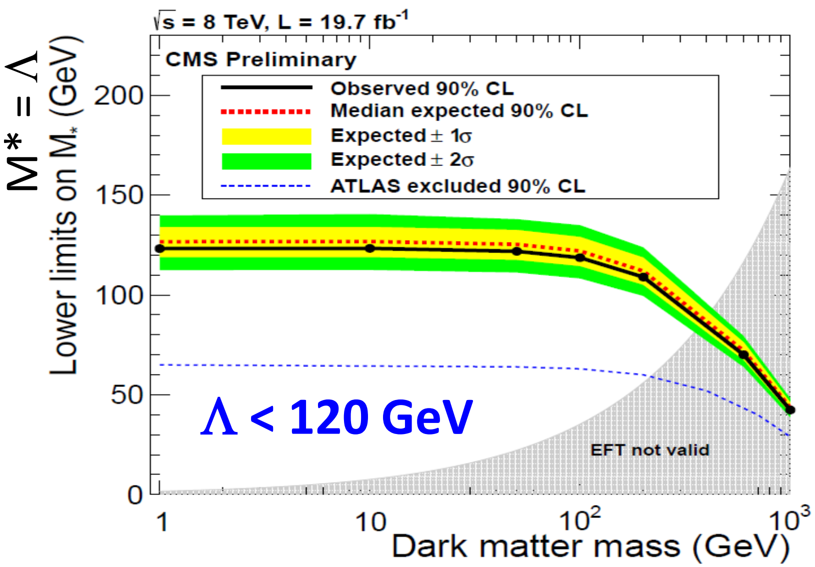
Semi-leptonic

Background Source	Yield
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.7 \pm 0.6$
Single top	$2.3 \pm 1.1 \pm 1.1$
Di-boson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.7$
Data	18
Signal	$38.3 \pm 0.7 \pm 2.1$

Exclusion Limits ttbar

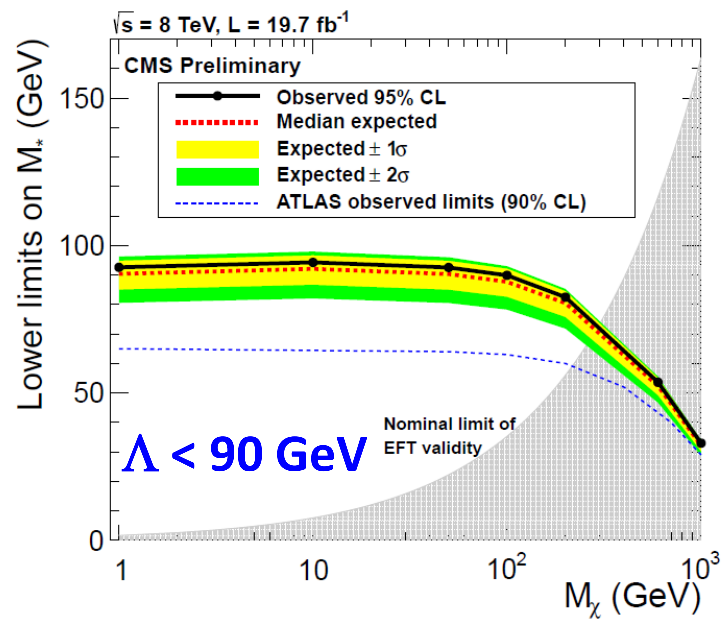
CMS-PAS-B2G-13-004 (di-lepton)
CMS-PAS-B2G-14-004 (semi-leptonic)

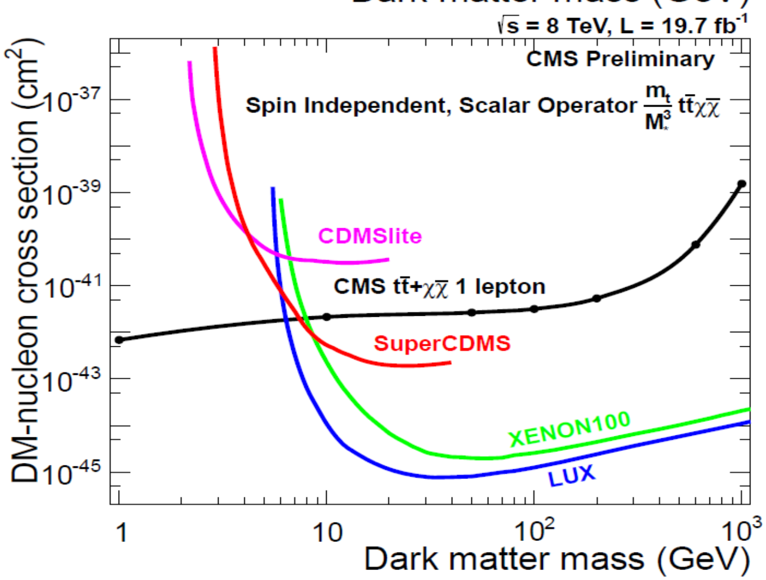
Semileptonic CMS-PAS-B2G-14-004



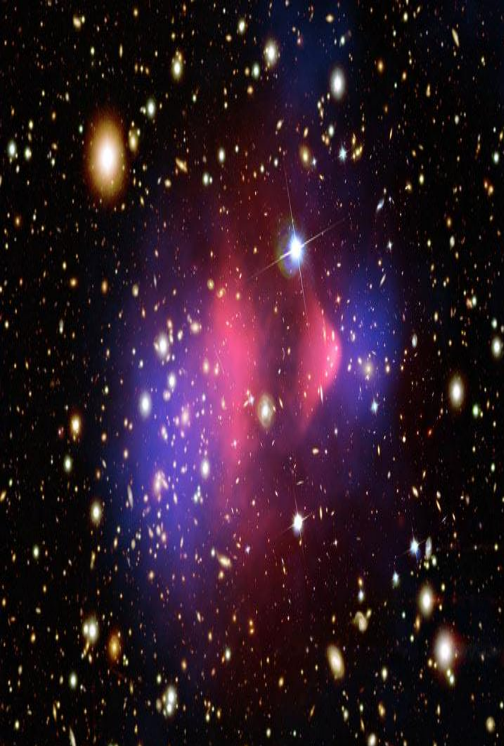
Semileptonic CMS-PAS-B2G-13-004

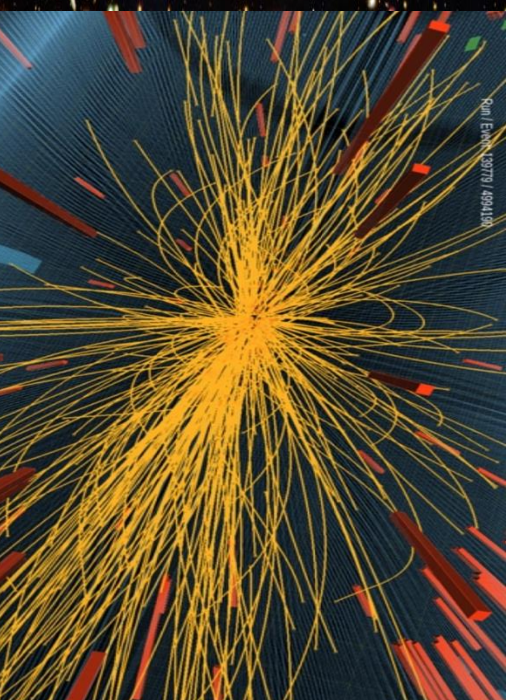
90% CL





Concentrate on scalar interaction, where mono-X does not set limits due to low sensitivity





Summary

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

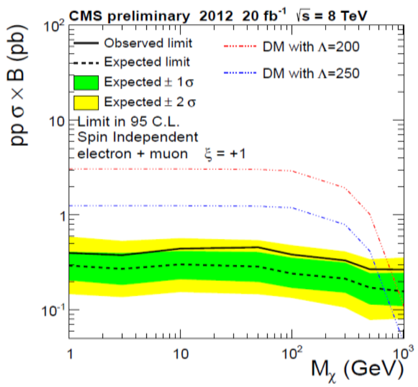
Search for pair produced dark matter candidates with CMS

- Results **with full 2012** dataset at sqrt(s)=8 TeV
- Channels:
  - jet + MET (vector and axial-vector coupling)
  - lepton + MET (vector and axial-vector)
  - Monophoton + MET (vector and axial-vector)
  - Single top + MET (scalar and vector)
  - Ttbar + MET (scalar coupling)

- No indication of a signal observed
- Exclude production cross section of 10^{-1}…10^{-2} pb
- For Mχ < 10 GeV only collider limits
- Exclude χ-nucleon cross sections from 10^{-38}…10^{-42}cm^2

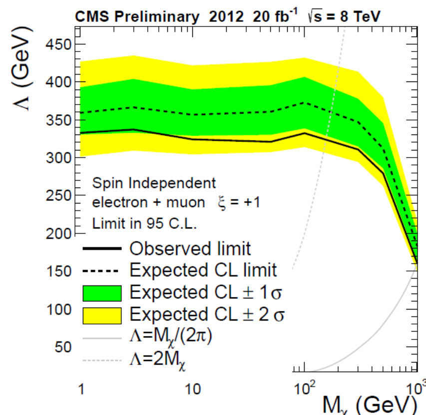
Additional Material

Translate limits to same plane as direct detection experiments

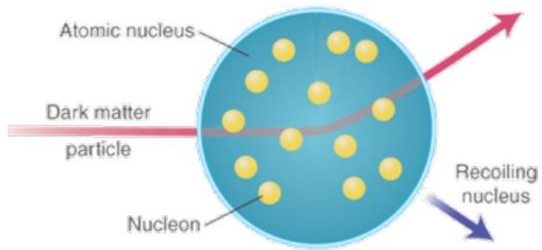


Vector operator

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



Convert pp xsec limit into Λ–limit



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

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

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

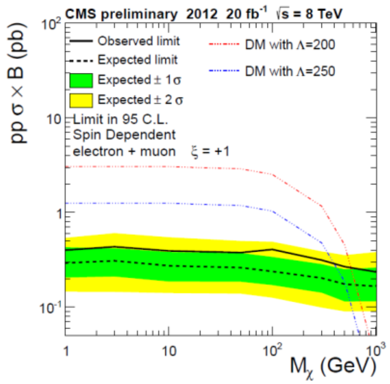
$$\sigma_{SI} = \frac{\mu^2}{\pi\Lambda^4}\left(\sum_q f_q^N\right)^2$$

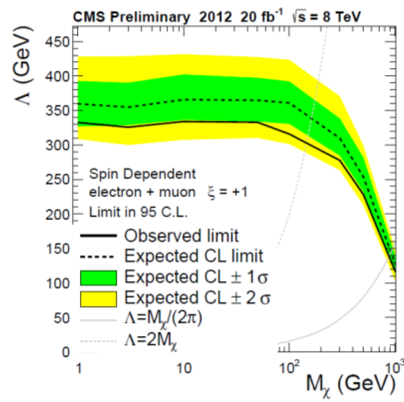
with $f_u^p = f_d^n = 2, f_d^p = f_u^n = 1$

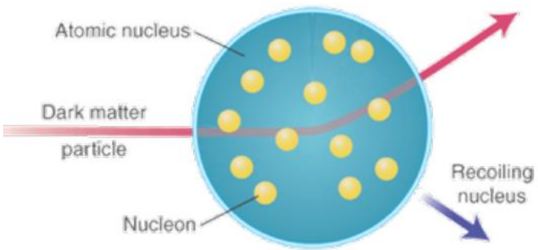
$f = 0$ for other quarks

arXiv:0803.2360.

Translate limits to same plane as direct detection experiments







Axial-Vector operator

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

Convert pp xsec limit into Λ–limit

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

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

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

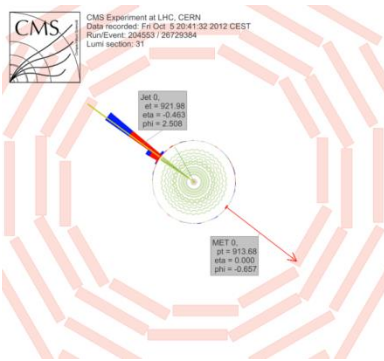
$$\Delta_u^p = \Delta_d^n = 0.842 \pm 0.012$$
$$\Delta_d^p = \Delta_u^n = -0.427 \pm 0.013$$
$$\Delta_s^p = \Delta_s^n = -0.085 \pm 0.018$$

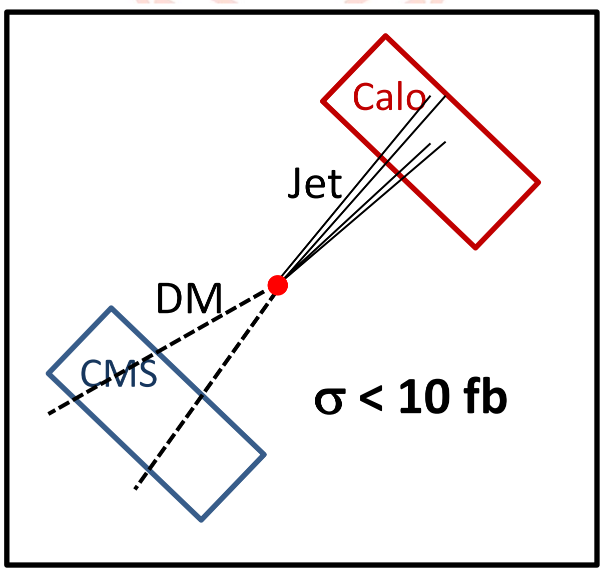
arXiv:0803.2360.

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

Monojet Signal

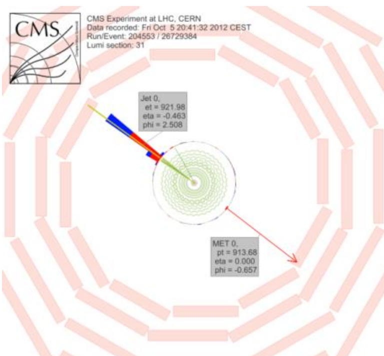
DM is undetectable → MET
Jet to balance p in transverse plane
→ high pT object

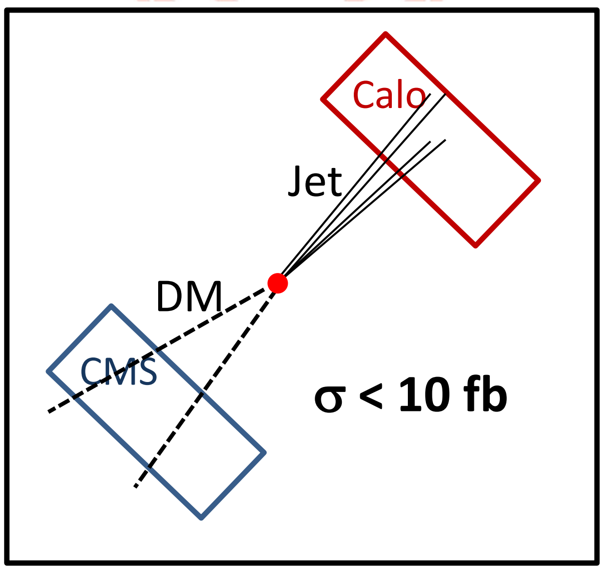




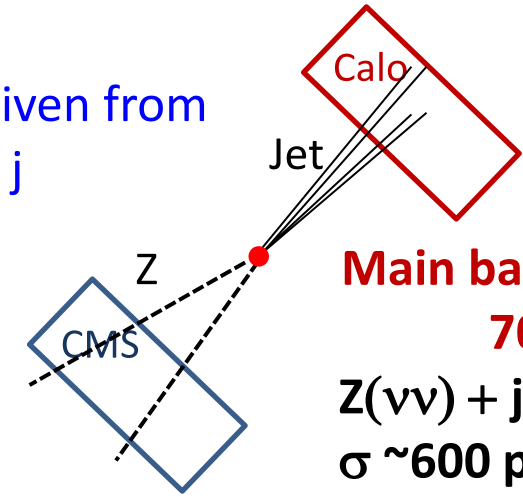
Monojet Signal and Background

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





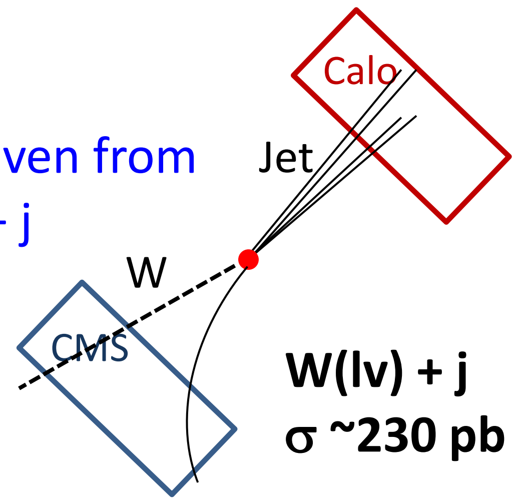
Data driven from
Z(μμ) + j



Main background
70%

Z(νν) + j
σ ~600 pb
irreducible

Data driven from
W(μν) + j



W(lν) + j **30%**
σ ~230 pb

Limits on production cross section + λ

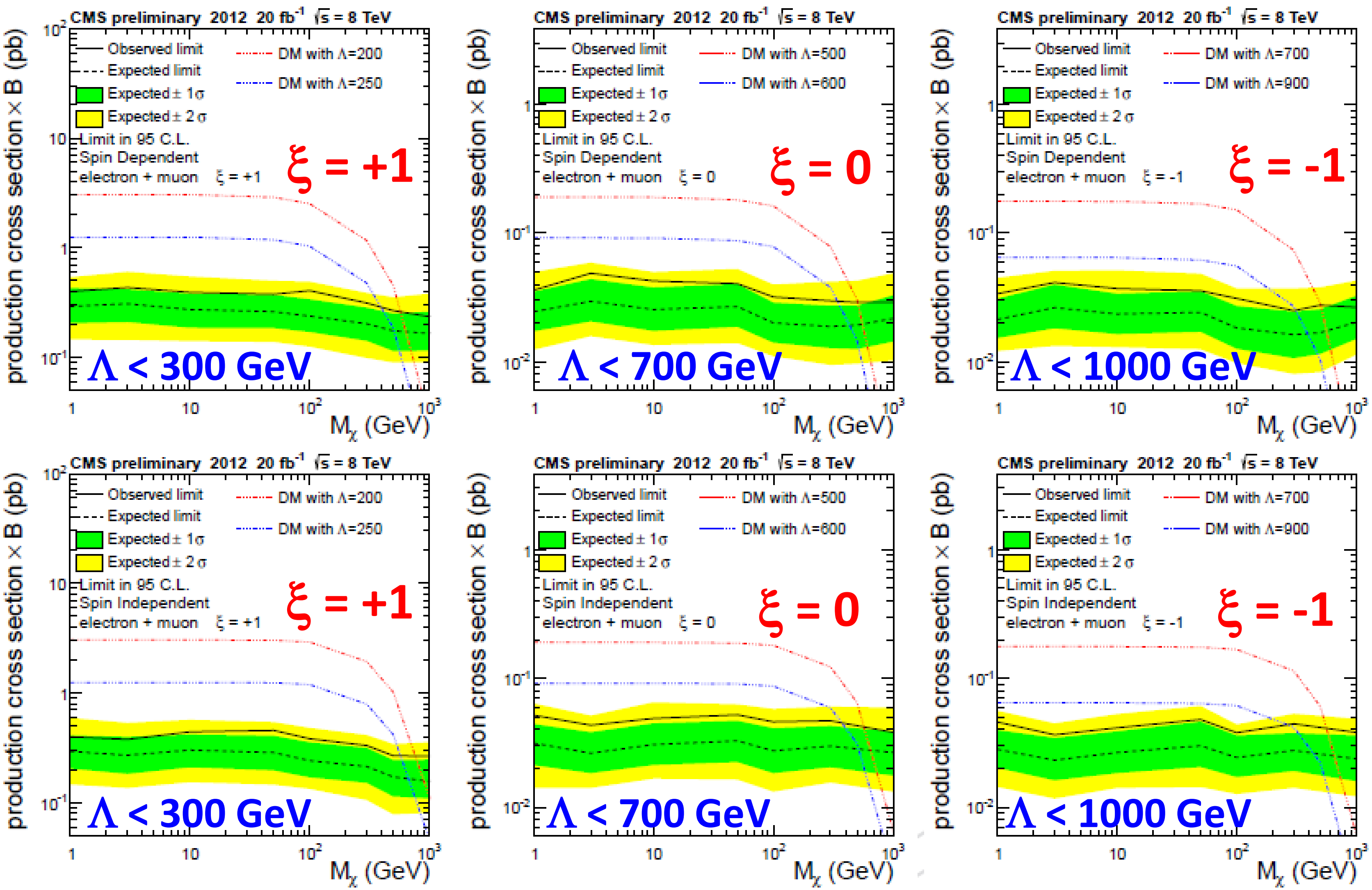
CMS-PAS-EXO-13-004

V

Spin In-dependent

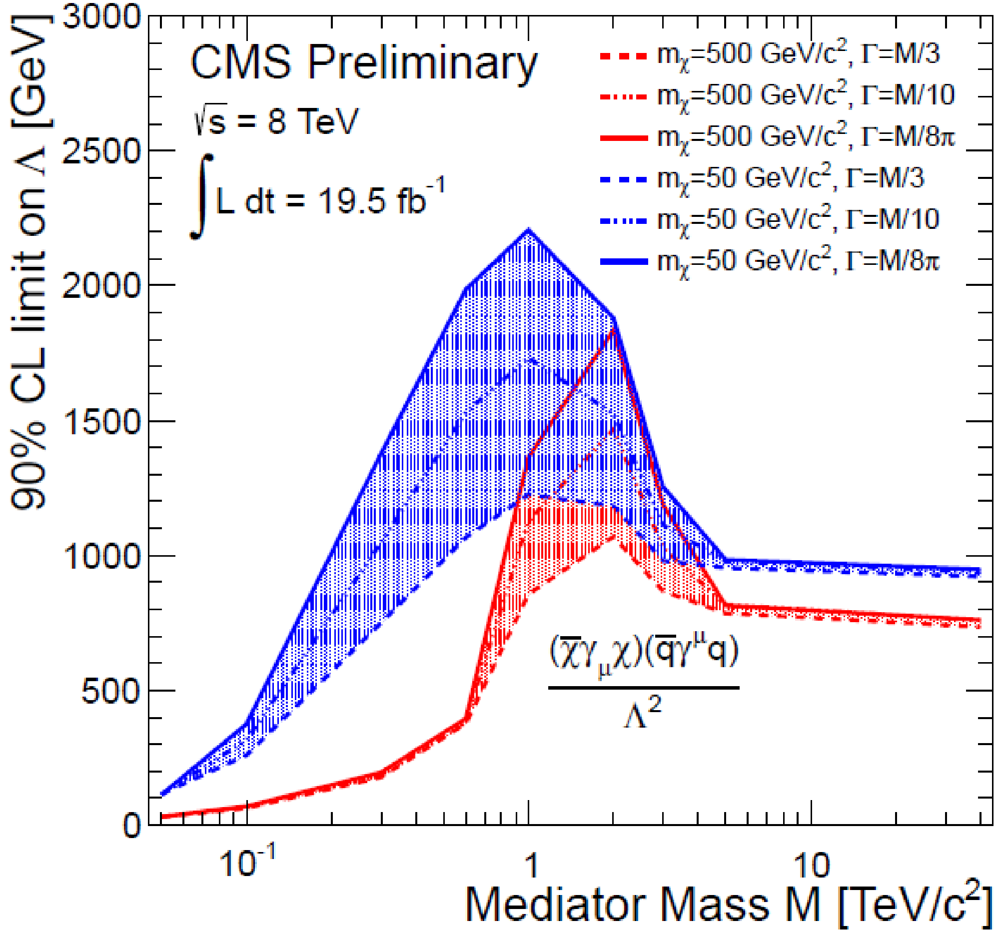
AV

Spin dependent

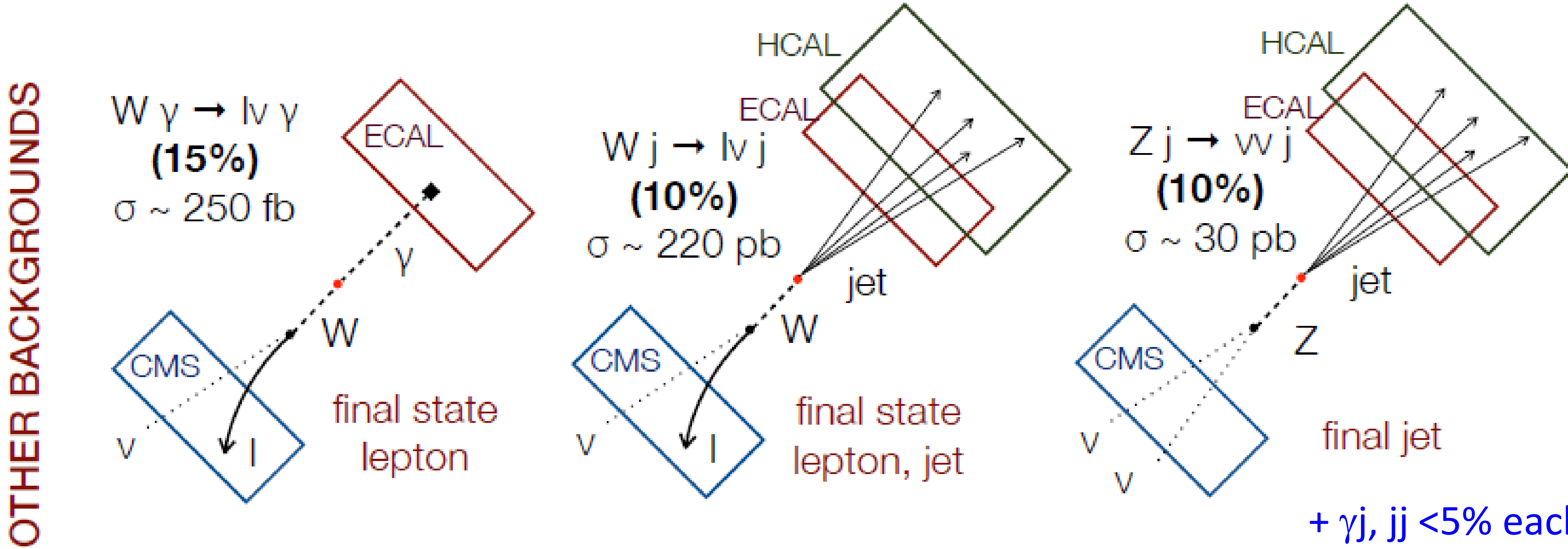


Monojet Λ as fct of mediator mass

Observed limits on Λ as a function of the mass of the mediator (M), assuming vector interactions and a dark matter mass of 50 GeV (blue) and 500 GeV (red). The width of the mediator was varied between M/3, M/10 and M/8Pi.



Monophoton 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