

Searches for Dark Matter with Mono-objects and MET @ CMS

Bhawna Gomber

Saha Institute of Nuclear Physics, India
On behalf of the CMS Collaboration

1.5



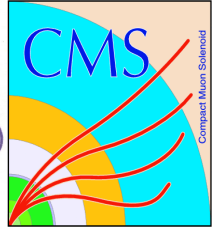
SUSY2014 : 21st – 26th August

MANCHESTER
1824

The University of Manchester

CMS Detector

Schematic view



CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

SILICON TRACKER
Pixels (100 x 150 μm^2)
~1m² ~66M channels
Microstrips (80-180 μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO₄ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A

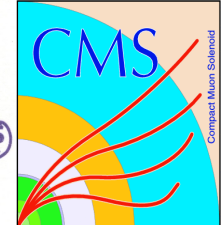
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

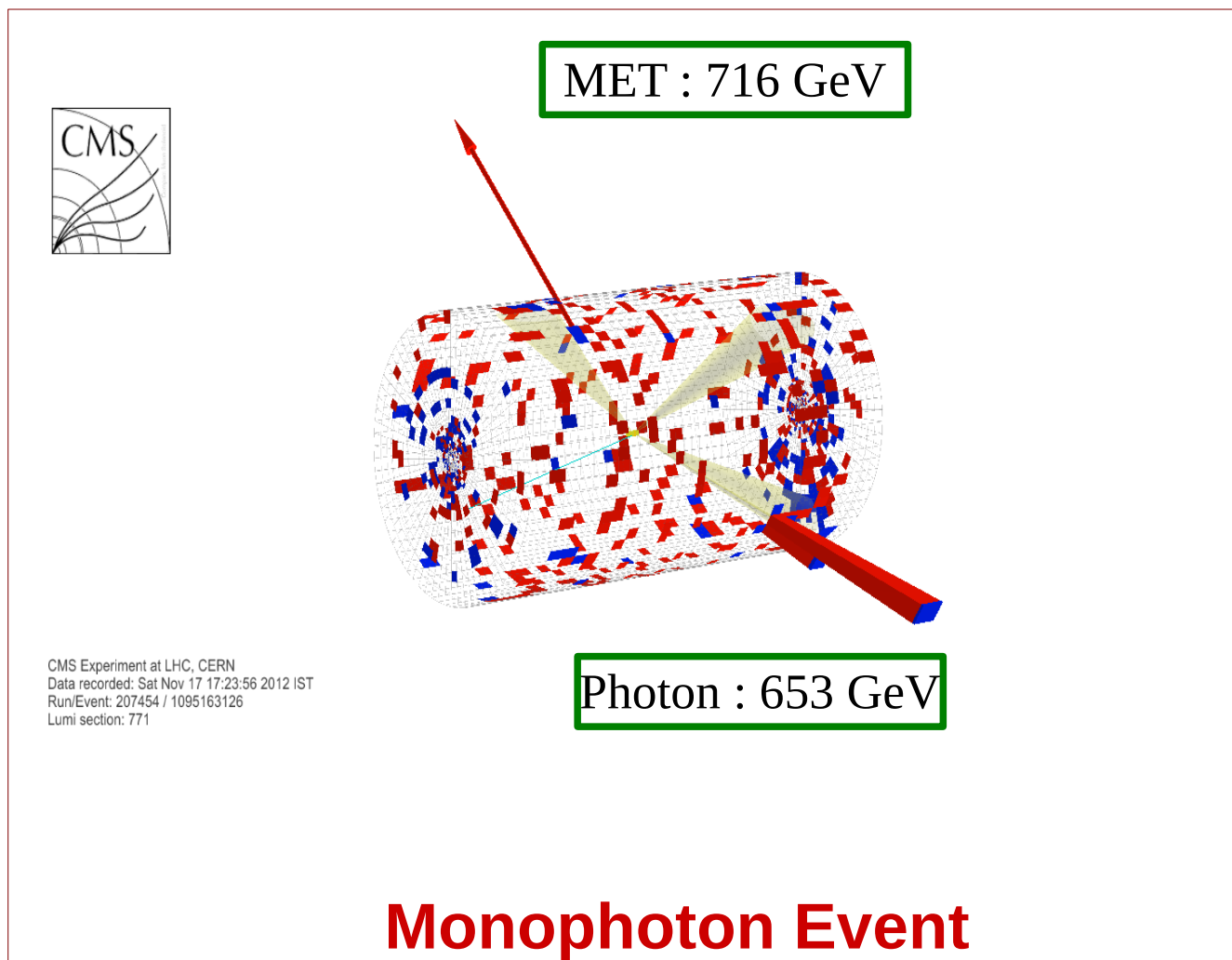
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Missing Transverse Energy

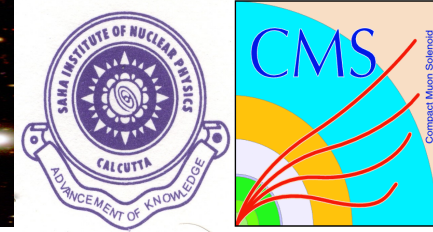


The hallmark signature for dark matter (“DM”) is a momentum imbalance or missing transverse energy (“MET”)

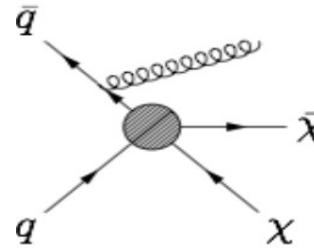
- ▣ DM particles escapes the detector without interaction
- ▣ Nature still conserves momentum (always!)
- ▣ Infer presence of DM by imbalance in momentum



DM Effective Field Theory



Exhaustive List of ...



Effective Field Theory (EFT) :
Interaction between DM and SM particles is contact interaction

Dirac fermion, arxiv:1008.1783

D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Majorana fermion, arxiv:1005.1286

M1	qq	$m_q/2M_*^3$
M2	qq	$im_q/2M_*^3$
M3	qq	$im_q/2M_*^3$
M4	qq	$m_q/2M_*^3$
M5	qq	$1/2M_*^2$
M6	qq	$1/2M_*^2$
M7	GG	$\alpha_s/8M_*^3$
M8	GG	$i\alpha_s/8M_*^3$
M9	$G\bar{G}$	$\alpha_s/8M_*^3$
M10	$G\bar{G}$	$i\alpha_s/8M_*^3$

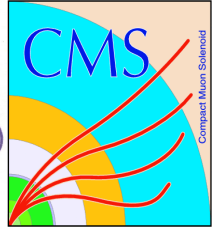
Real scalar, arxiv:1008.1783

R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5q$	$im_q/2M_*^2$
R3	$\chi^2G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

Complex scalar, arxiv:1008.1783

C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

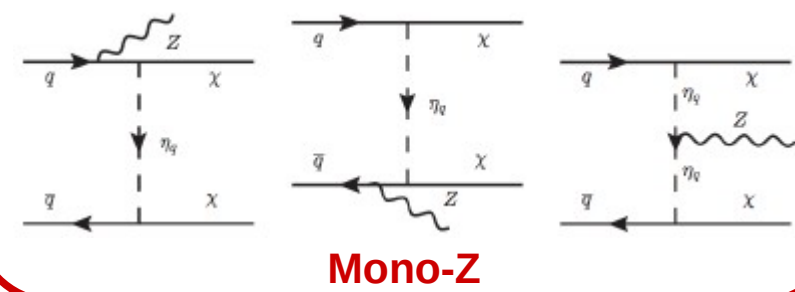
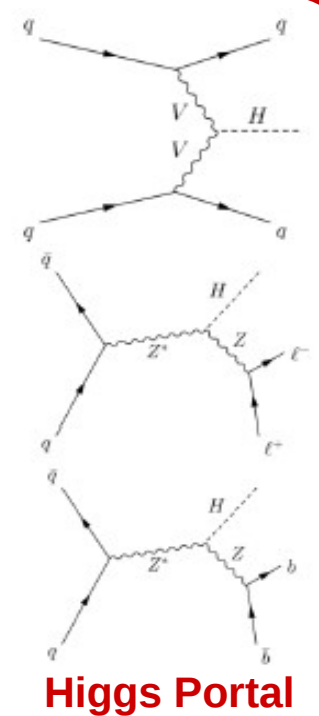
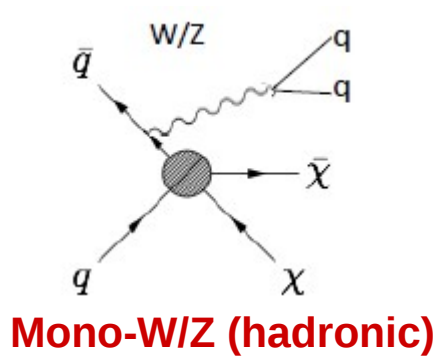
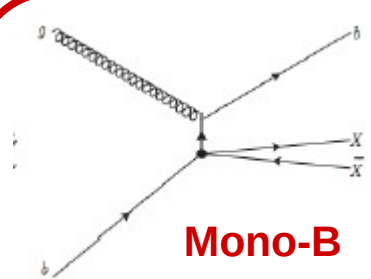
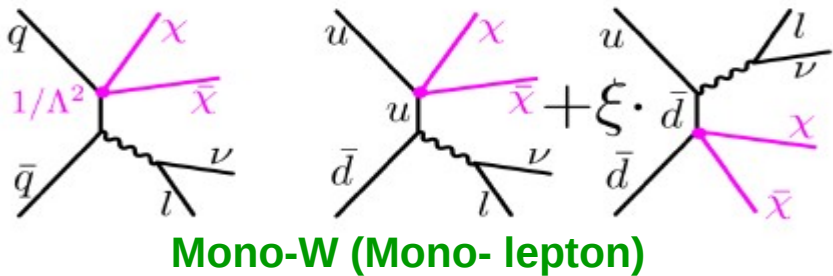
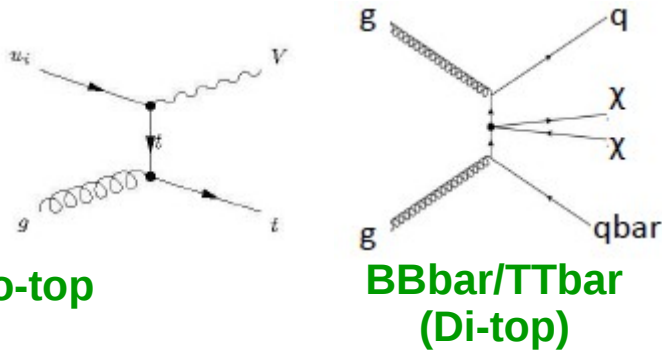
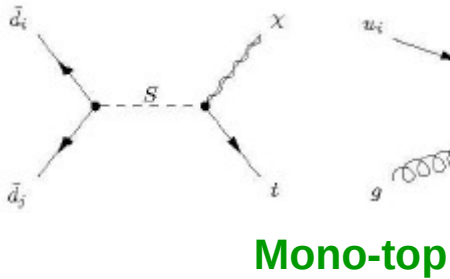
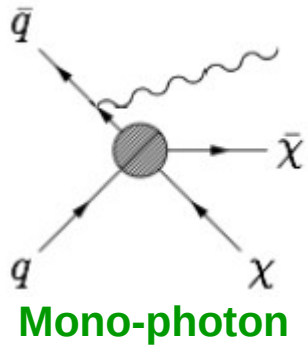
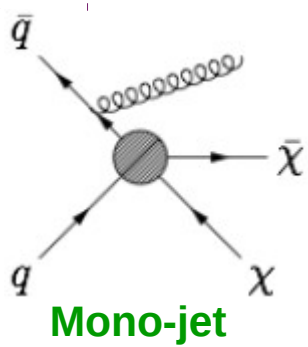
MET + X Searches



Links

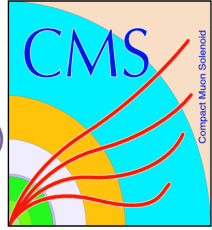
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

This Talk

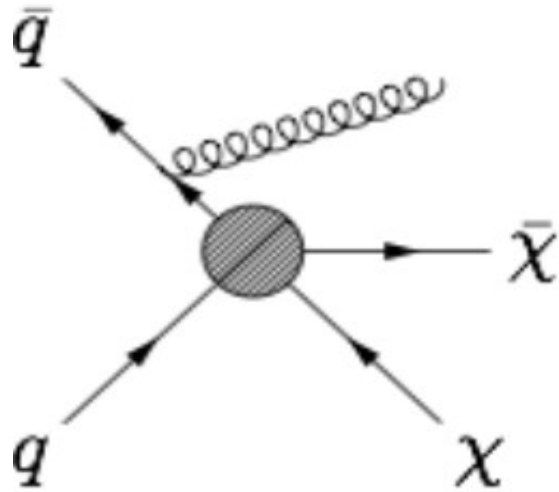


Mono-jet

Event Selection

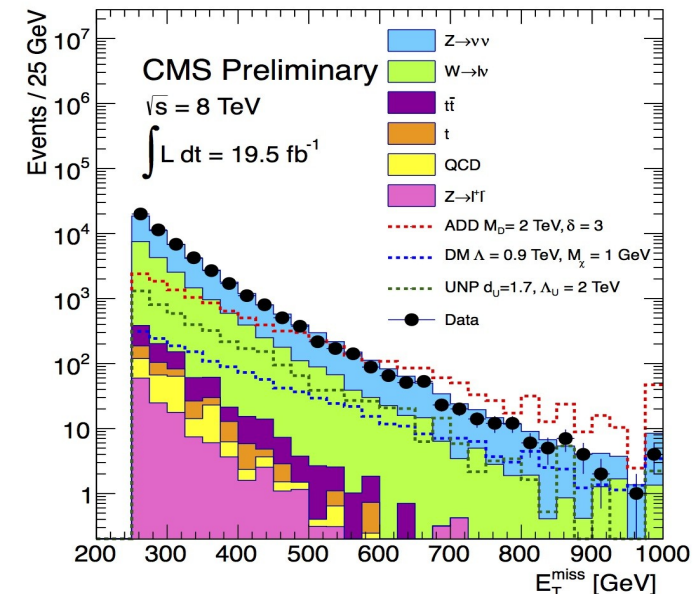
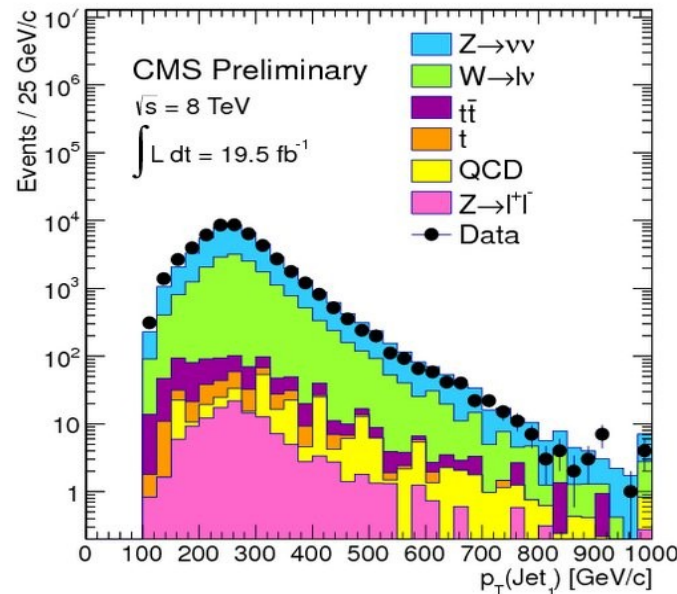
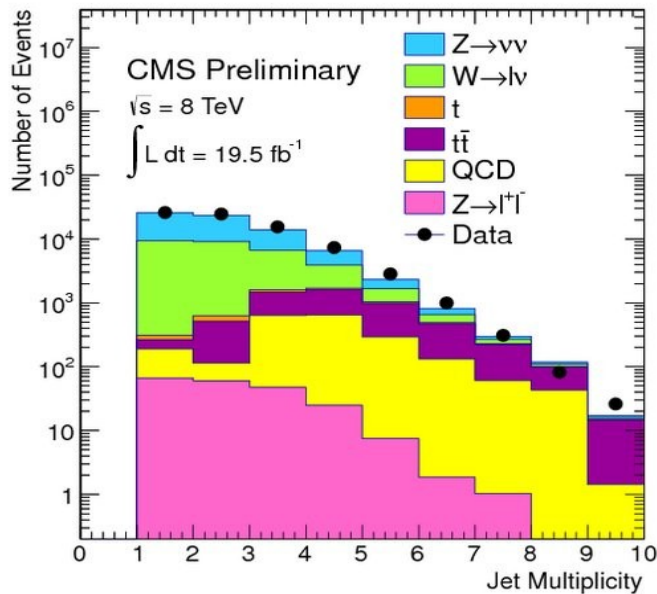


CMS PAS EXO-12-048



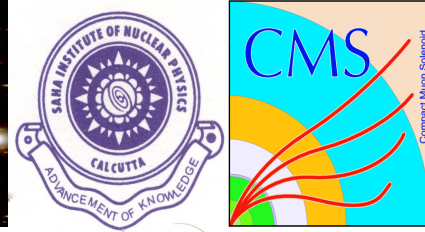
- ▣ One energetic jet, $p_T > 110$ GeV, $|\eta| < 2.4$, allow an additional jet, $p_T > 30$ GeV
- ▣ MET > 400 GeV
- ▣ Veto event

- ✗ If $j_3 p_T > 30$ GeV
- ✗ $\Delta\phi(j_1, j_2) > 2.5$
- ✗ If isolated electrons, isolated muons or hadronic taus with $p_T > 10$ GeV (20 GeV for tau)

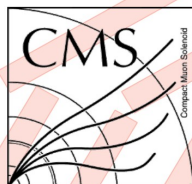
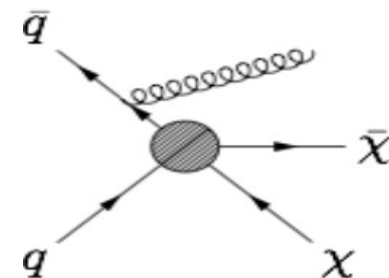


Mono-jet

Event Display



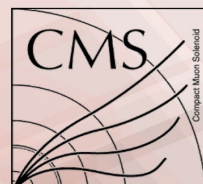
CMS PAS EXO-12-048



CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31

Jet 0,
et = 921.98
eta = -0.463
phi = 2.508

MET 0,
pt = 913.68
eta = 0.000
phi = -0.657



CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 20:41:32 2012 CEST
Run/Event: 204553 / 26729384
Lumi section: 31

Jet 0,
et = 921.98
eta = -0.463
phi = 2.508

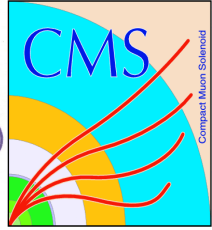
MET 0,
pt = 913.68
eta = 0.000
phi = -0.657

Jet

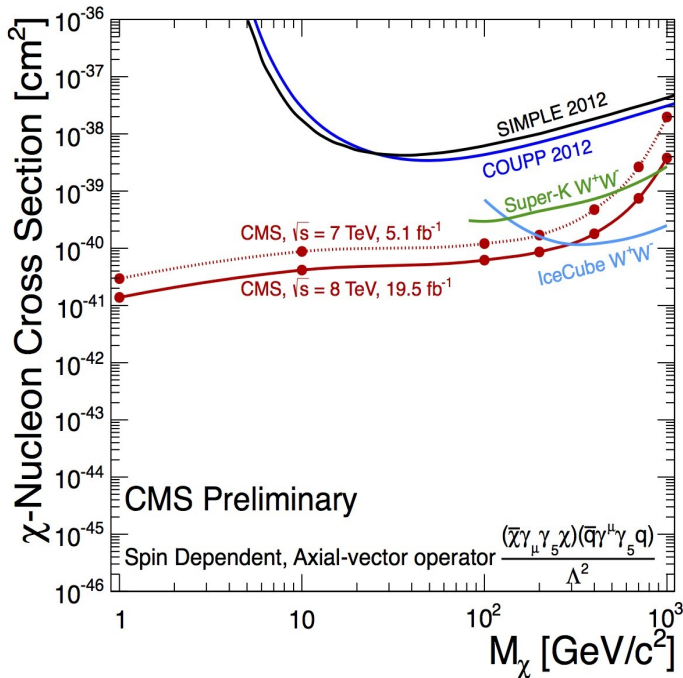
MET

Mono-jet

Results

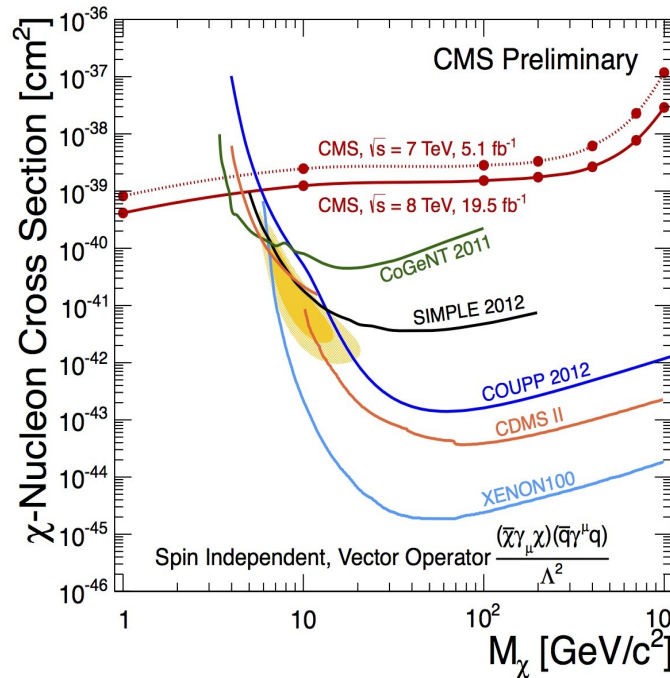


CMS PAS EXO-12-048



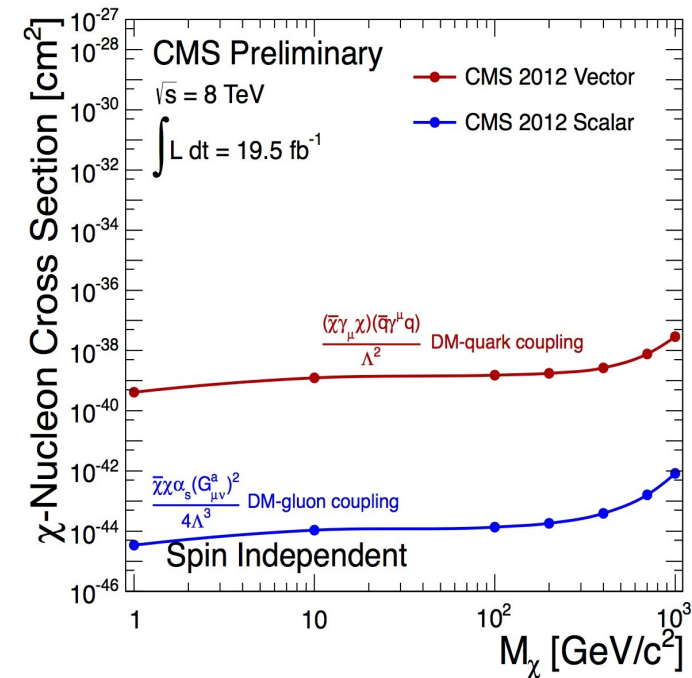
Axial-vector operator spin-dependent (SD)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_{\mu}\gamma_5\chi)(\bar{q}\gamma^{\mu}\gamma_5q)}{\Lambda^2}$$

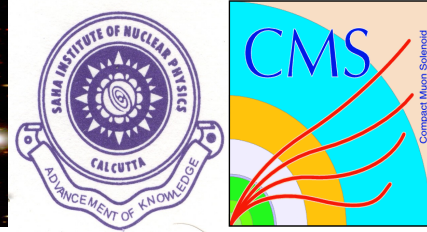


Vector operator spin-independent (SI)

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



Λ : Interaction scale



Limitation of EFT \longrightarrow Simplified Model with M_*

⊙ EFT is valid when mediator mass (M_*) $>$ a few TeV

⊙ The couplings required are large. Comparing this with known couplings :

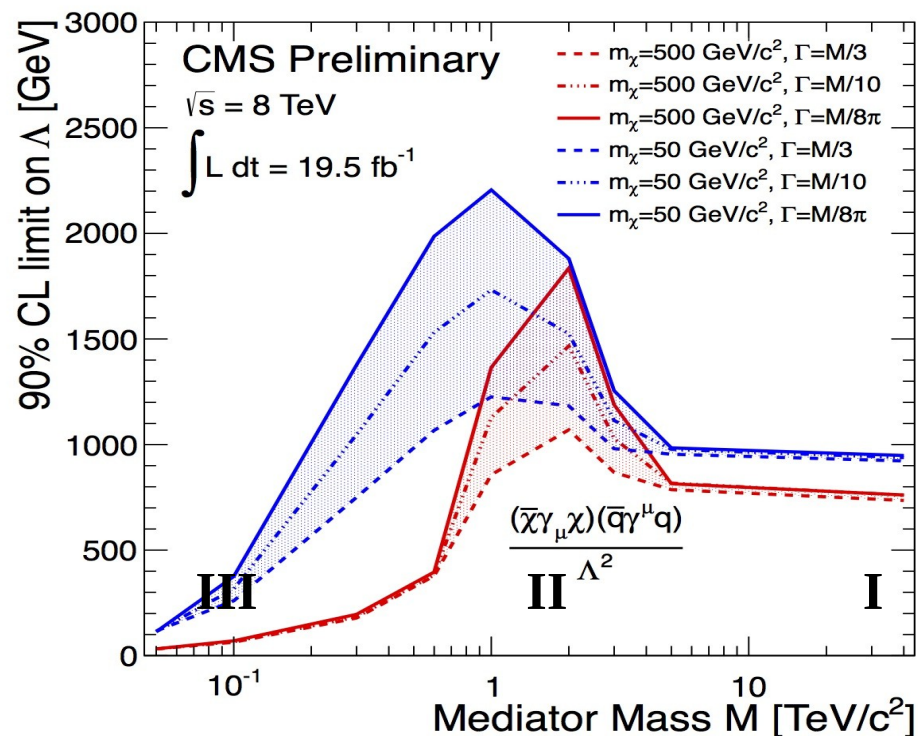
- ✗ strong interaction ~ 1.2
- ✗ weak interaction ~ 0.6

⊙ Theory is non-perturbative if

$$\sqrt{(g_q g_{DM})} > 4\pi$$

⊙ Width larger than mass, so unlikely mediator will be identified as a particle.

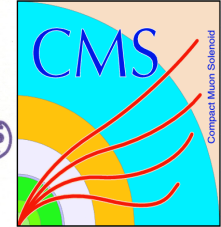
- ✓ Region I : EFT limit is good!
- ✓ Region II : EFT limit is too weak!
- ✓ Region III : EFT limit is too strong!



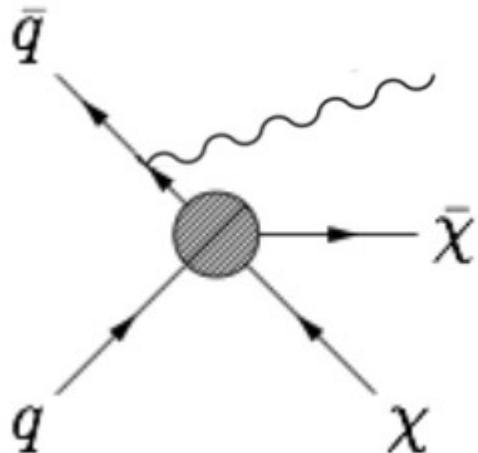
See for example, [arXiv:1308.6799](https://arxiv.org/abs/1308.6799) for further reading

Mono-photon

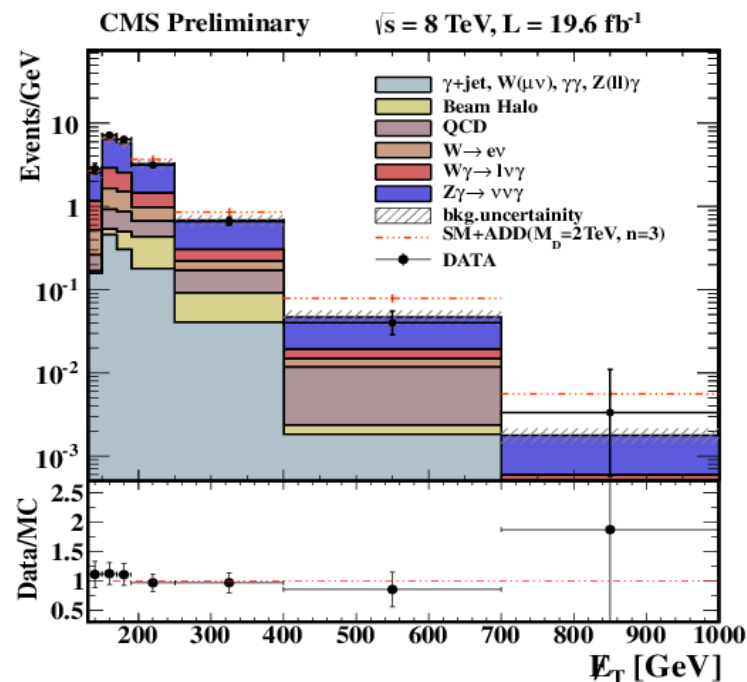
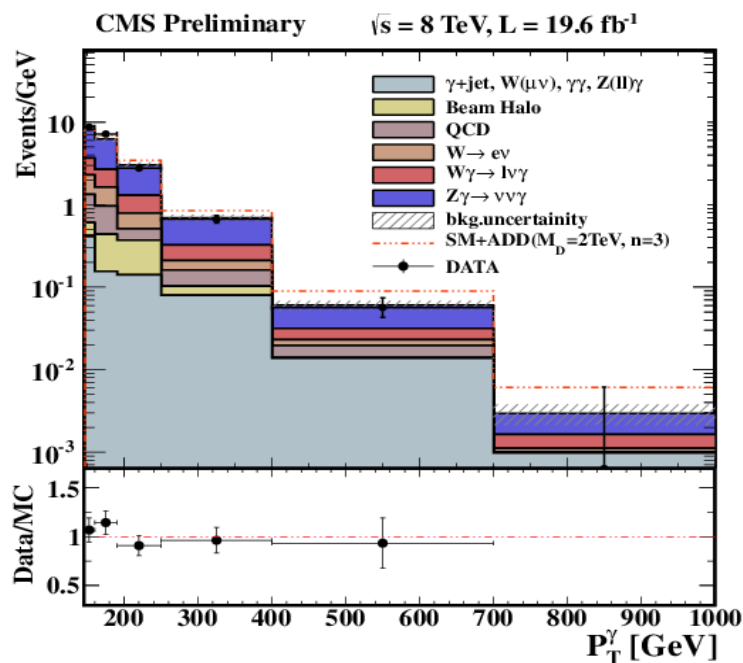
Event Selection



CMS PAS EXO-12-047

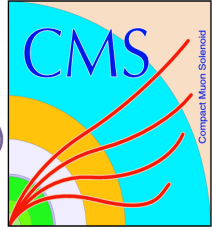


- One energetic photon, $p_T > 145$ GeV, $|\eta| < 1.44$
- MET > 140 GeV
- Veto events if $j_2 p_T > 30$ GeV
- Veto on leptons and pixel seed (hit pattern in the pixel detector)
- $\Delta\phi(\text{photon, MET}) > 2$
- MinMET > 120 GeV, Prob(χ^2) (Reduce fake MET events)

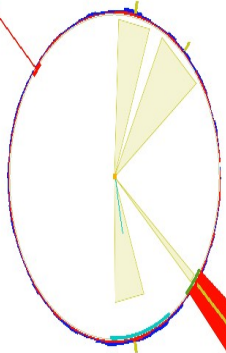
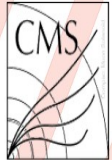


Mono-photon

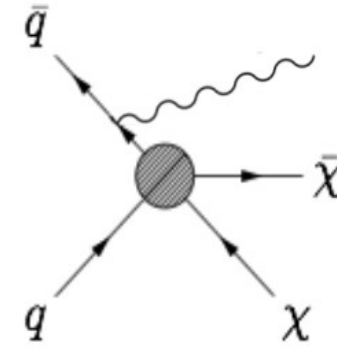
Event Display



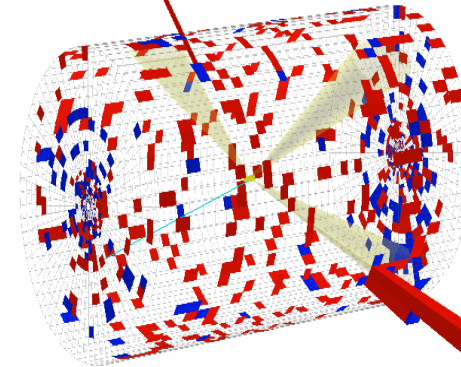
CMS PAS EXO-12-047



CMS Experiment at LHC, CERN
Data recorded: Sat Nov 17 17:23:56 2012 IST
Run/Event: 207454 / 1095163126
Lumi section: 771



MET

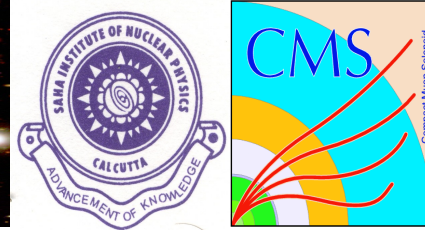


Photon

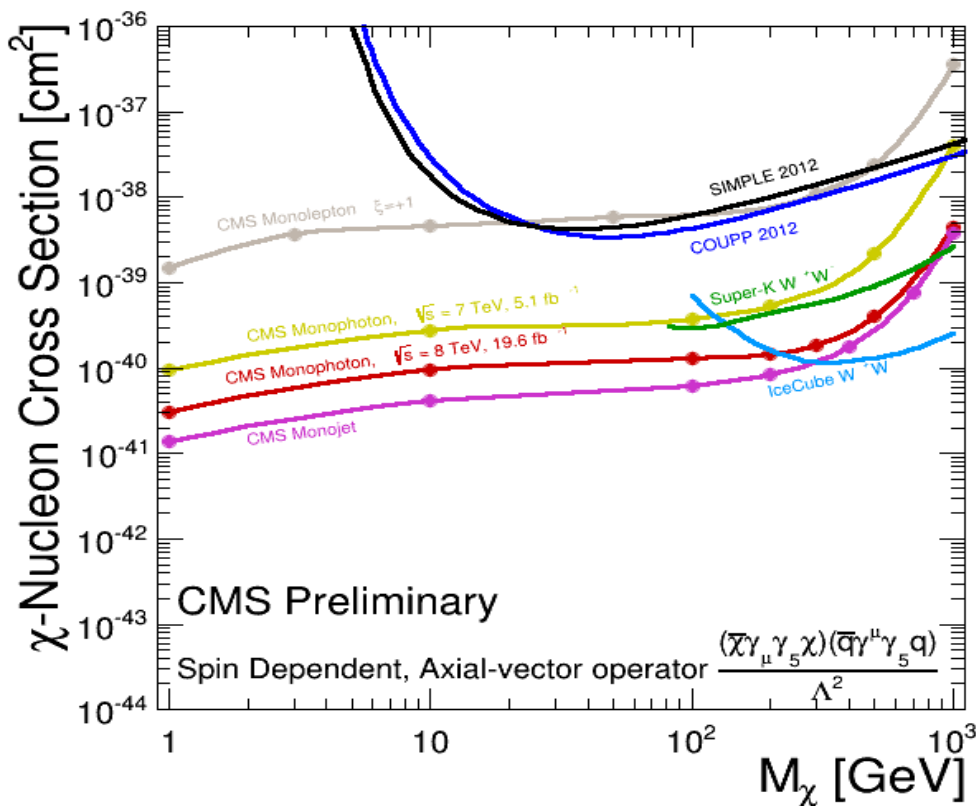
CMS Experiment at LHC, CERN
Data recorded: Sat Nov 17 17:23:56 2012 IST
Run/Event: 207454 / 1095163126
Lumi section: 771

Mono-photon

Results

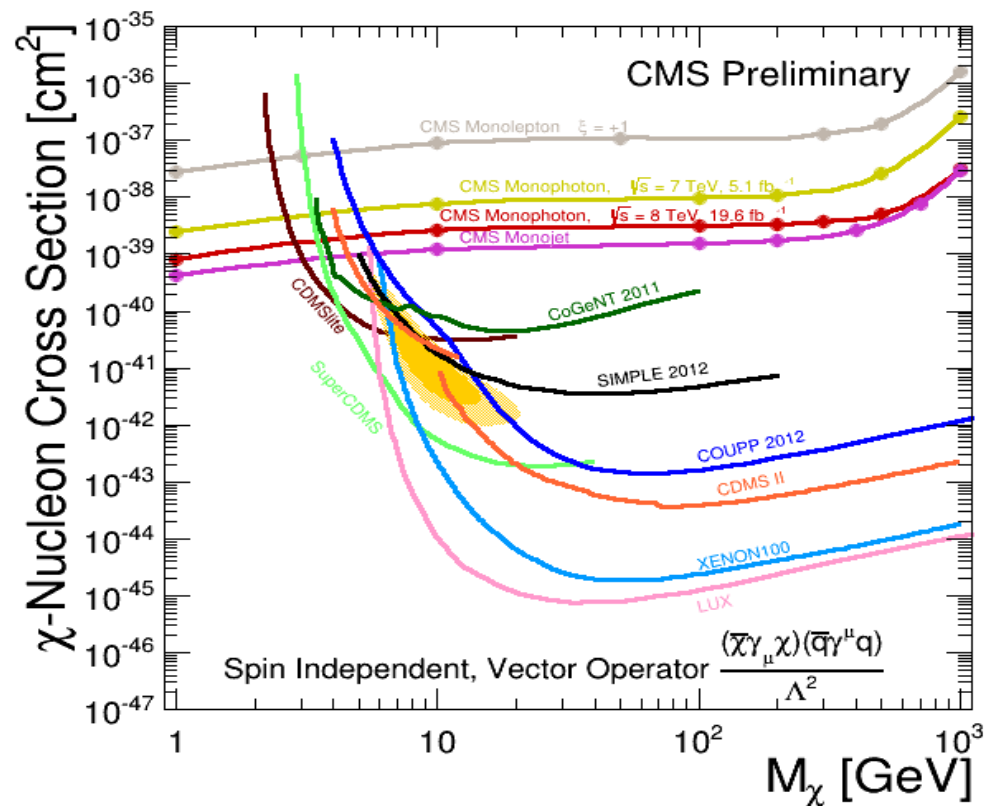


CMS PAS EXO-12-047



**Axial-vector operator
spin-dependent (SD)**

$$O_{AV} = \frac{(\bar{\chi}\gamma_{\mu}\gamma_5\chi)(\bar{q}\gamma^{\mu}\gamma_5q)}{\Lambda^2}$$



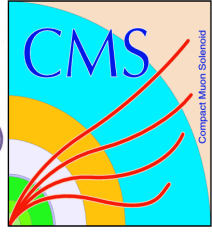
**Vector operator
spin-independent (SI)**

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

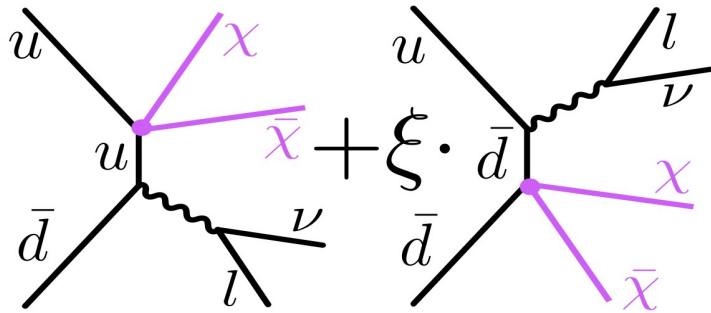
Λ : Interaction scale

Mono-lepton

Event Selection



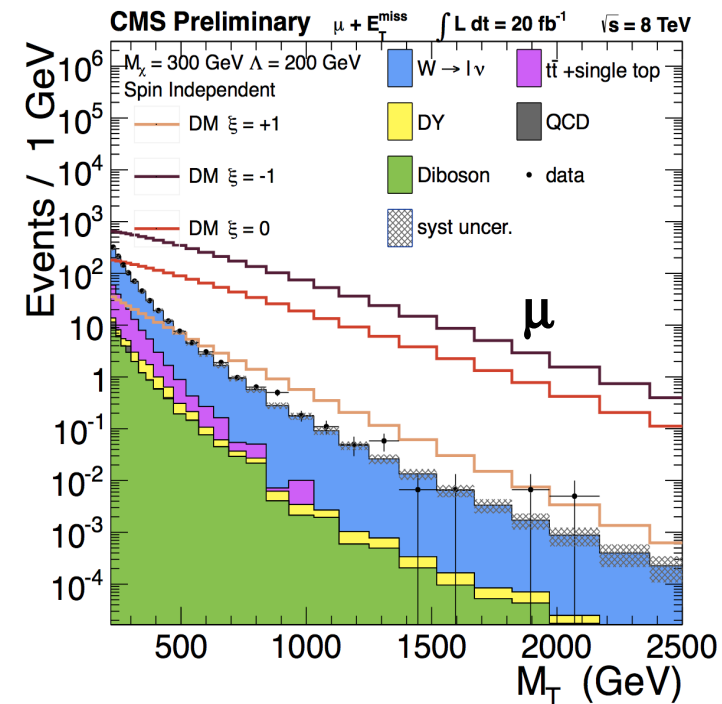
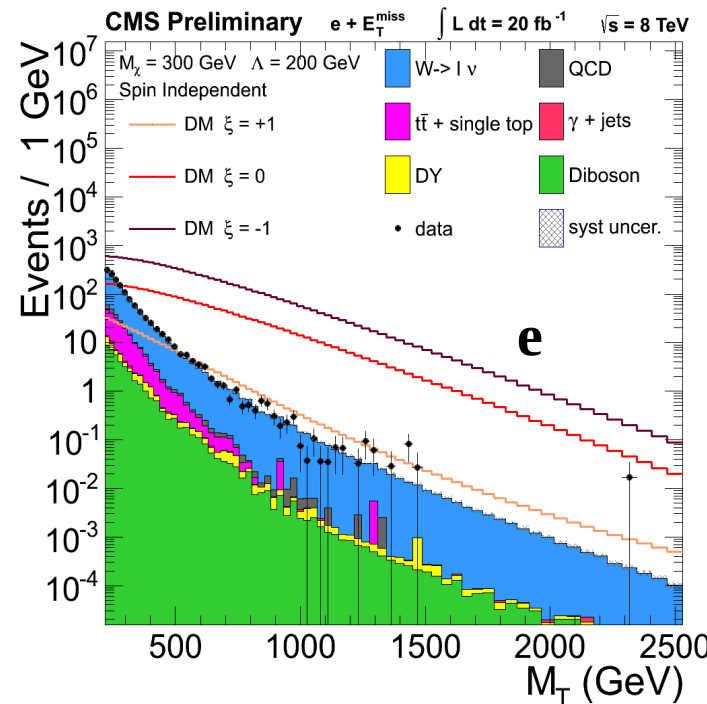
CMS PAS EXO-13-004



- Dark Matter production with a W
- W recoiling against pair-produced DM
- Vector- and axial-vector couplings considered
- Interference effects parameterized by ξ (W+)

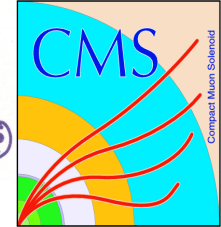
$$M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell, \nu})}$$

- $\mu(e) p_T > 45(100) \text{ GeV}$
- $0.4 < p_T / \text{MET} < 1.5$
- $\Delta\phi (\text{lepton, MET}) > 0.8 \cdot \pi$



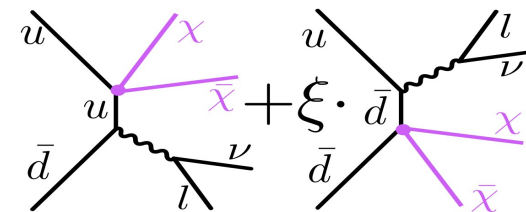
Mono-lepton

Event Display



CMS PAS EXO-13-004

Electron Channel



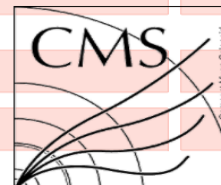
CMS Experiment at LHC, CERN
Data recorded: Tue May 8 08:19:45 2012 CEST
Run/Event: 193621 / 1180868279
Lumi section: 1557

Electron
pt = 1153.51 GeV
eta = 0.066
phi = 1.949

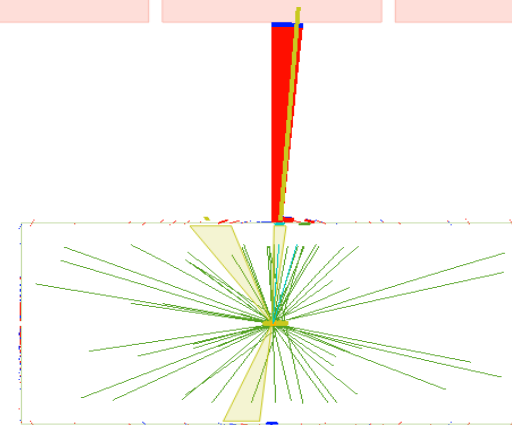
electronGsfTrack
pt = 970.68 GeV
eta = 0.066
phi = 1.949

Mt = 2312.0 GeV

pfMet
pt = 1211.16 GeV
phi = -1.145
caloMet
pt = 1213.9 GeV
phi = -1.157

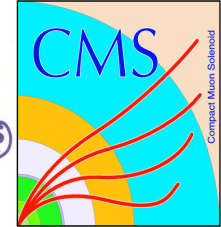


CMS Experiment at LHC, CERN
Data recorded: Tue May 8 08:19:45 2012 CEST
Run/Event: 193621 / 1180868279
Lumi section: 1557
Orbit/Crossing: 408140266 / 1737



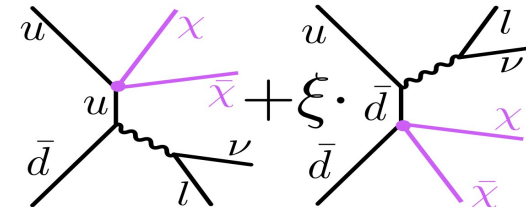
Mono-lepton

Event Display

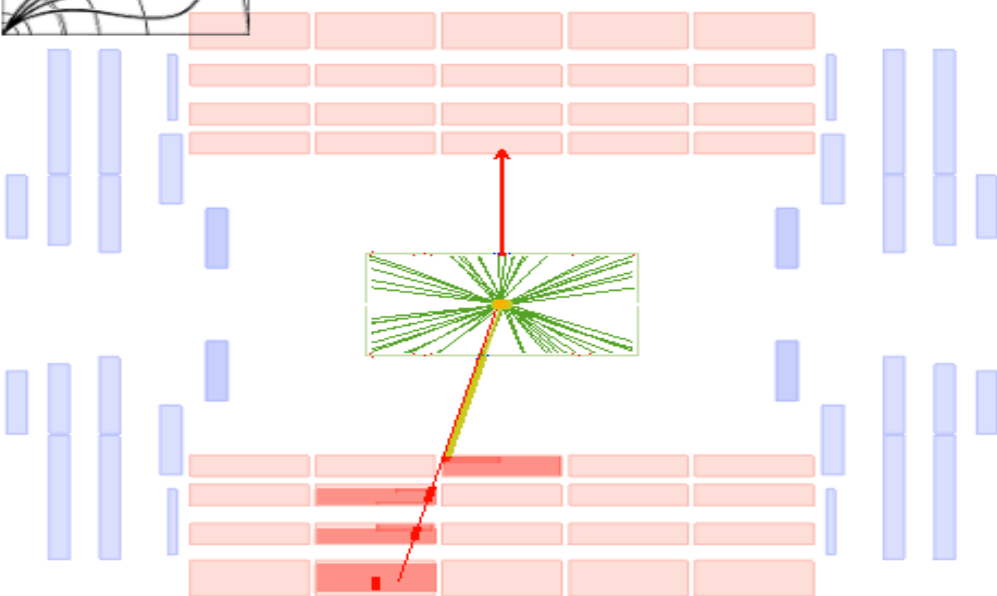


CMS PAS EXO-13-004

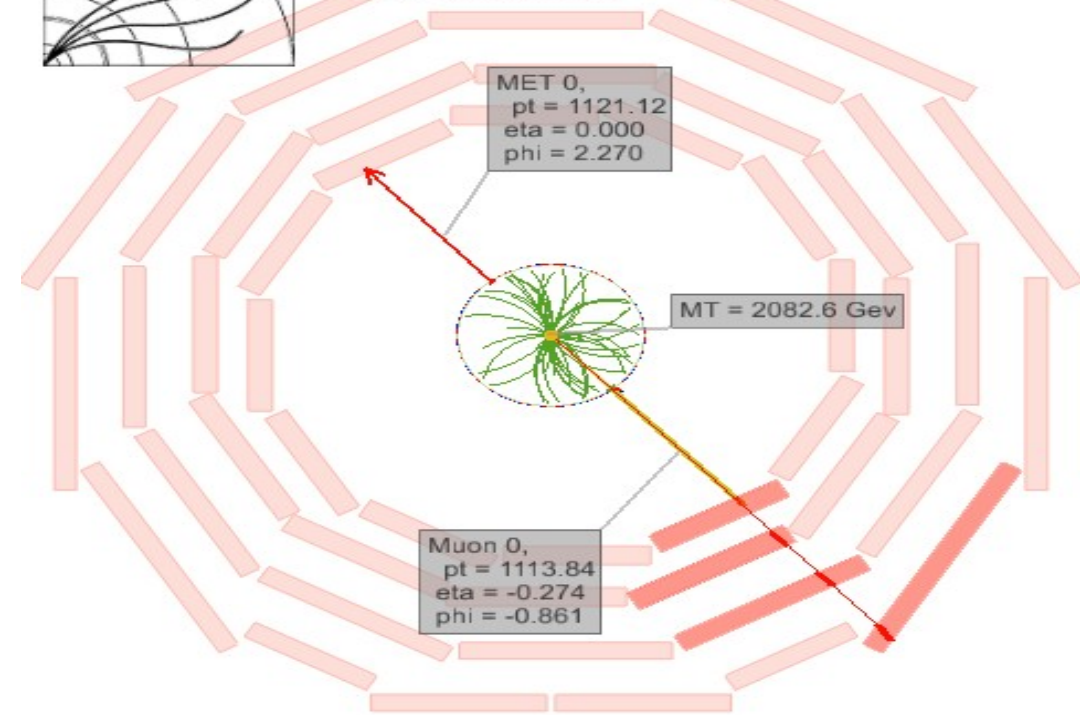
Muon Channel



CMS Experiment at LHC, CERN
Data recorded: Fri Nov 30 05:20:24 2012 CEST
Run/Event: 208307 / 445184756
Lumi section: 287

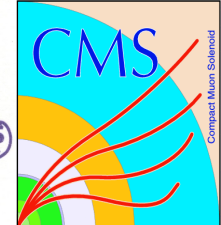


CMS Experiment at LHC, CERN
Data recorded: Fri Nov 30 05:20:24 2012 CEST
Run/Event: 208307 / 445184756
Lumi section: 287

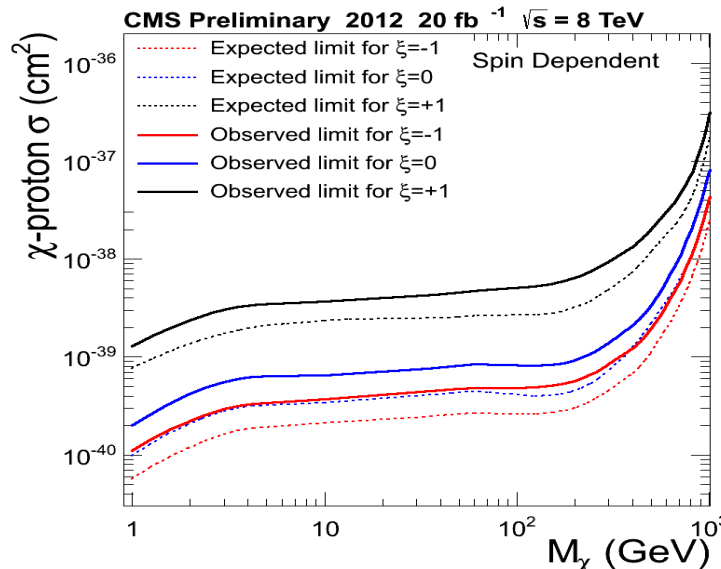
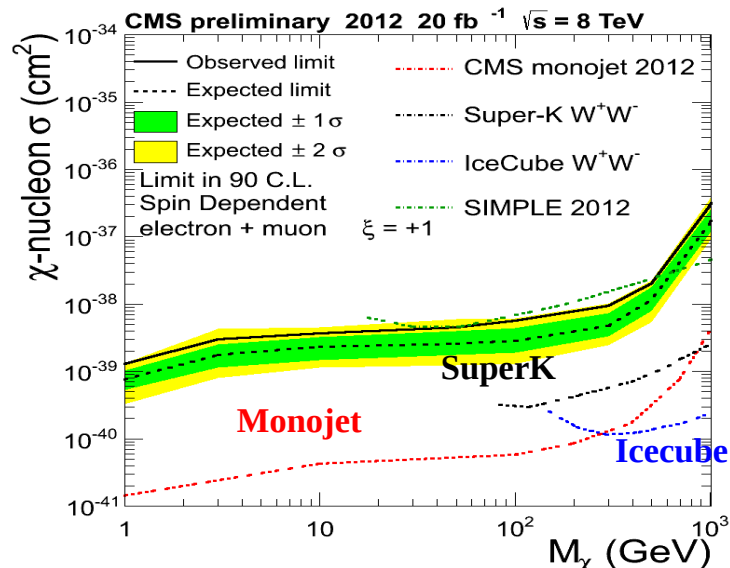


Mono-lepton

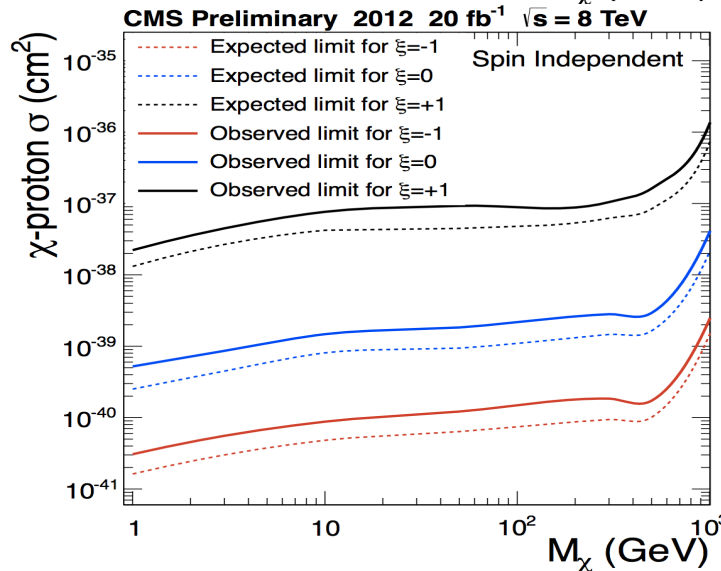
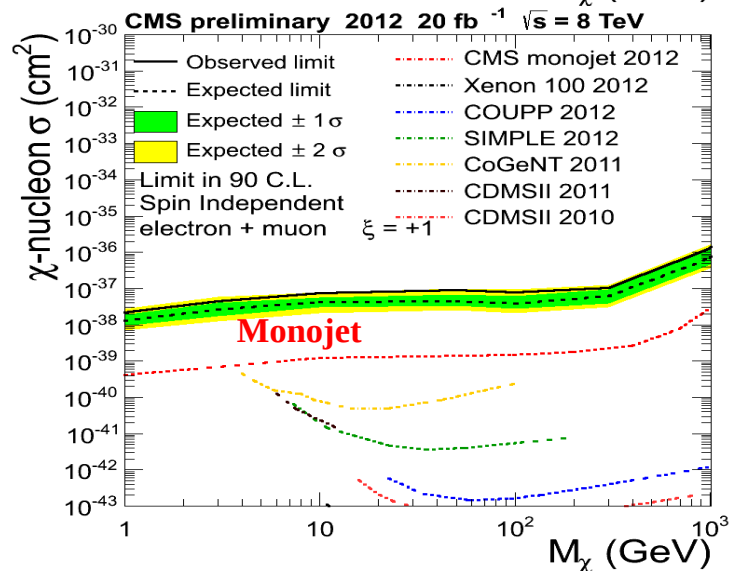
Results



CMS PAS EXO-13-004



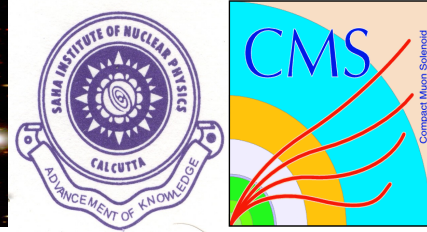
Axial-vector operator spin-dependent (SD)



Vector operator spin-independent (SI)

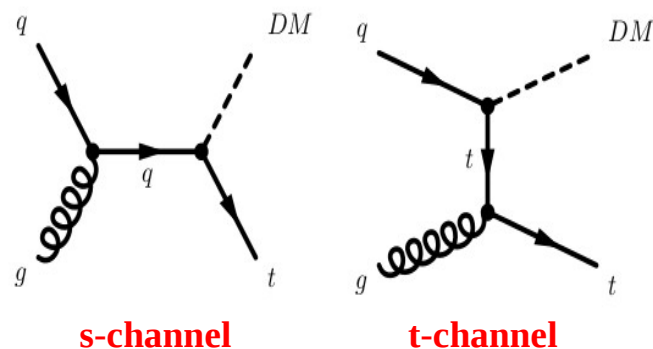
Mono-top ($t \rightarrow jjb$)

Event Selection



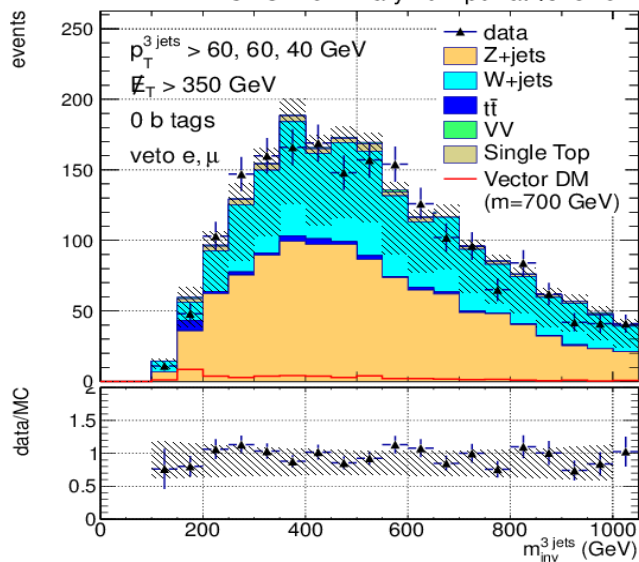
CMS PAS B2G-12-022

- Three jets, with j_1 and j_2 $p_T > 60$ GeV and j_3 $p_T > 40$ GeV
- One jet is tagged b-jet
- MET > 350 GeV
- Veto event with j_4 $p_T > 35$ GeV or isolated $e(\mu)$ $p_T > 20$ (10) GeV
- $M(j_1 j_2 j_3) < 250$ GeV

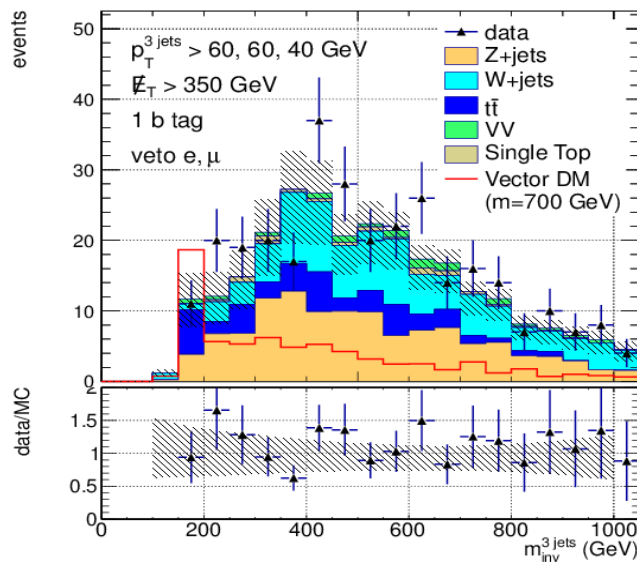


$M(3j)^{0b}$

CMS Preliminary 19.7 pb^{-1} at $\sqrt{s}=8 \text{ TeV}$

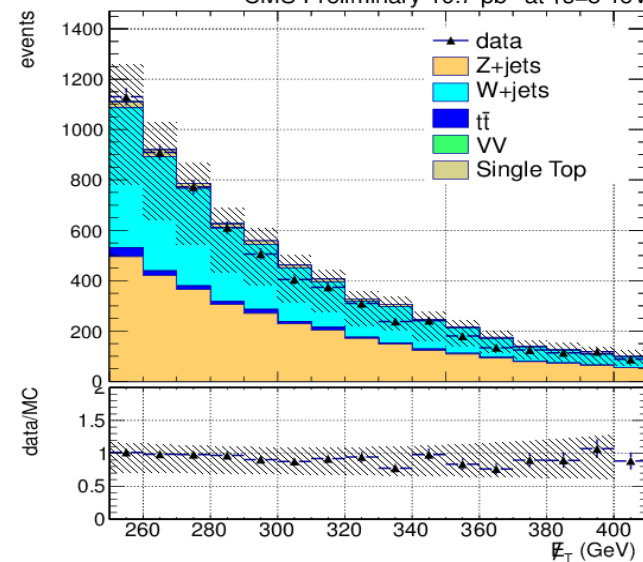


$M(3j)^{1b}$



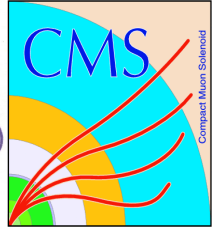
MET

CMS Preliminary 19.7 pb^{-1} at $\sqrt{s}=8 \text{ TeV}$



Mono-top

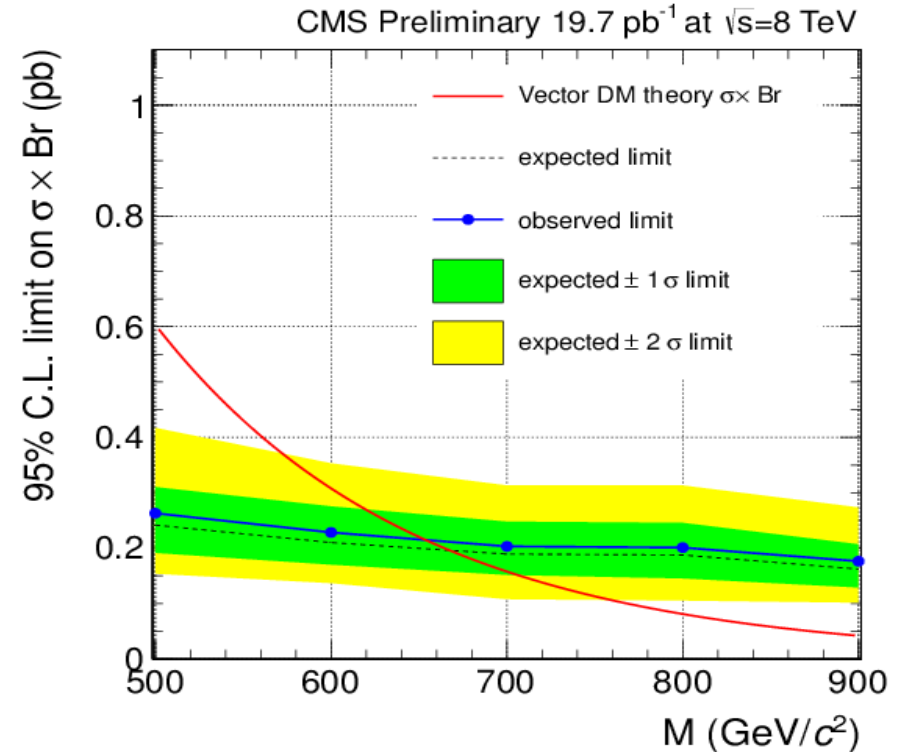
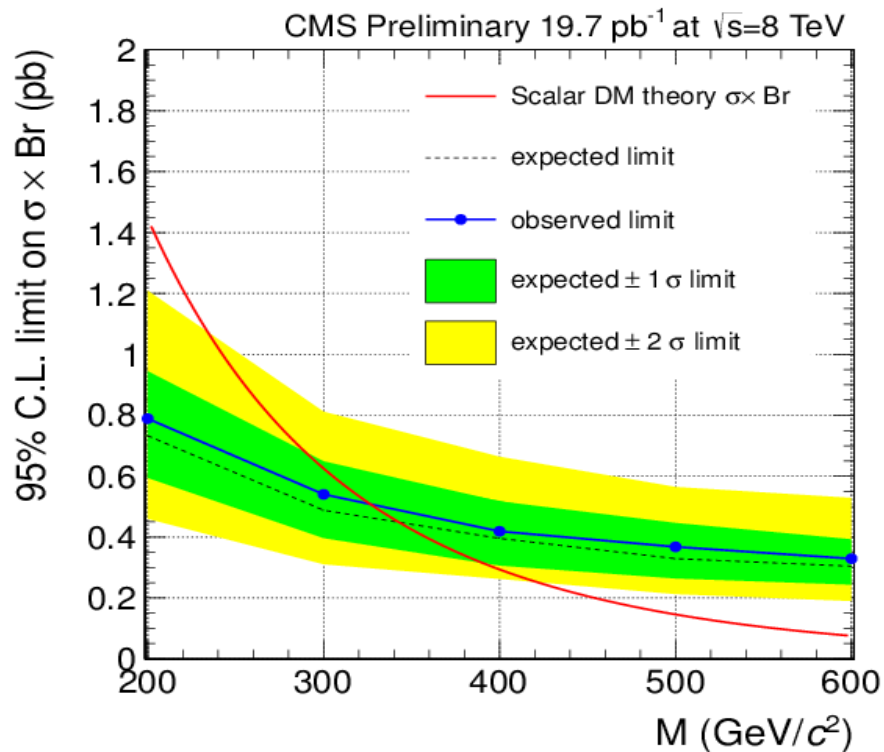
Results



CMS PAS B2G-12-022

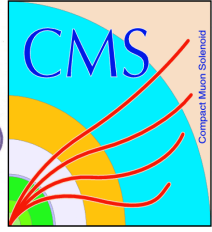
- Excellent agreement with data
- DM coupling set to 0.1 for $q = u/d$
[arXiv:1106.6199]
- Exclude scalar (vector) DM masses below 327 (655) GeV

# of b tags	Zero CSVm b tag	One CSVm b tag
tt	$6 \pm 0 \pm 5$	$12 \pm 0 \pm 12$
W+jets	$18 \pm 9 \pm 7$	$3 \pm 1 \pm 2$
Z+jets	$103 \pm 33 \pm 9$	$11 \pm 10 \pm 1$
Single top	$2 \pm 1 \pm 1$	$1 \pm 1 \pm 1$
VV	$5 \pm 0 \pm 0$	$0 \pm 0 \pm 0$
QCD	6	1
sum	140 ± 36	28 ± 16
Data	143	30



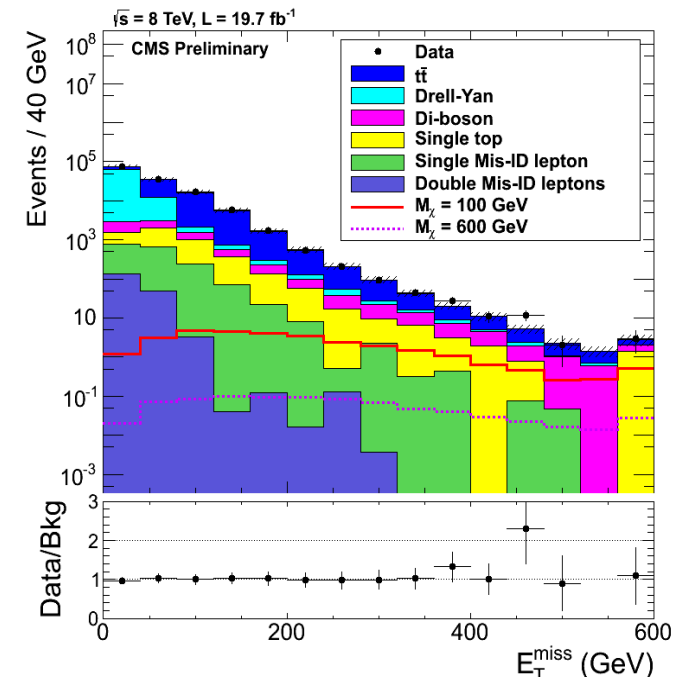
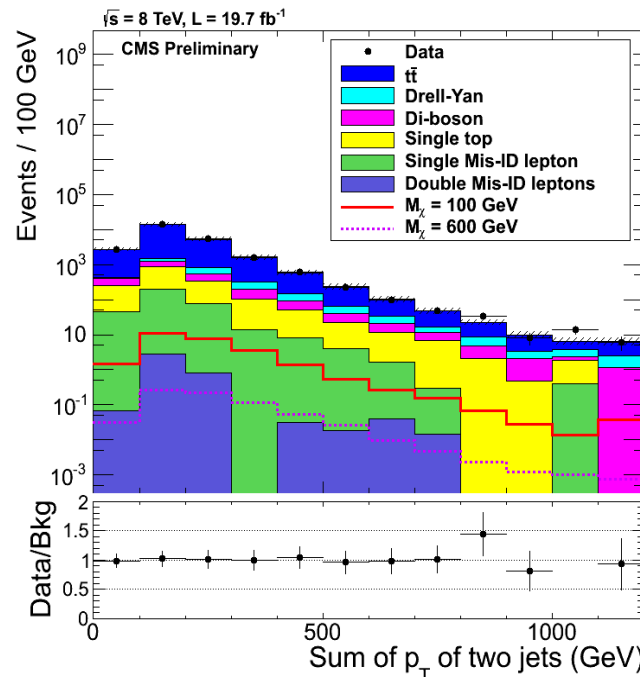
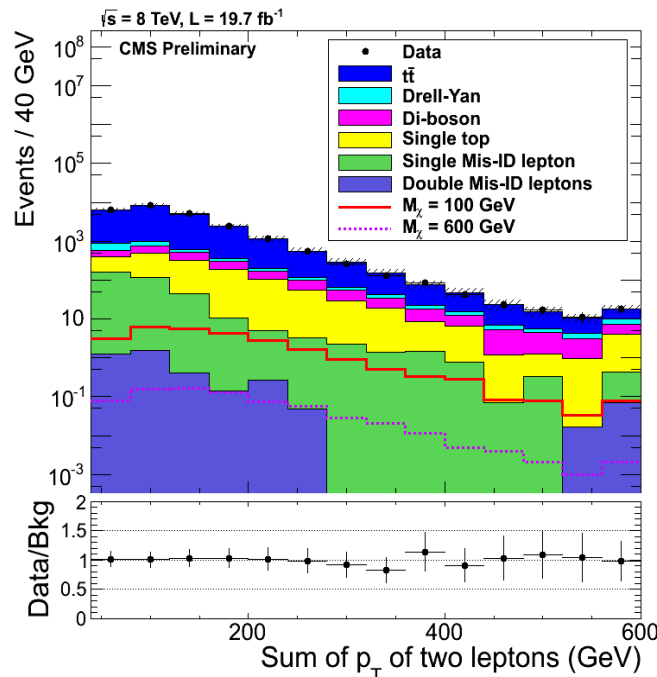
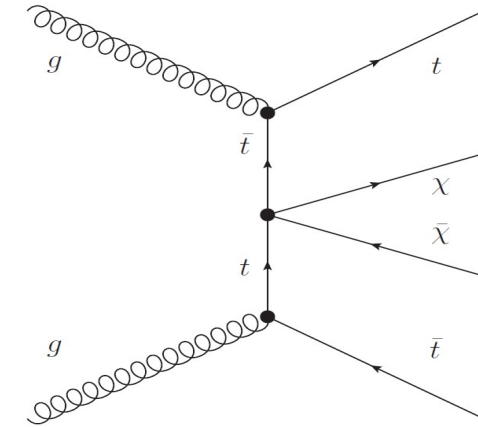
Di-top

Event Selection

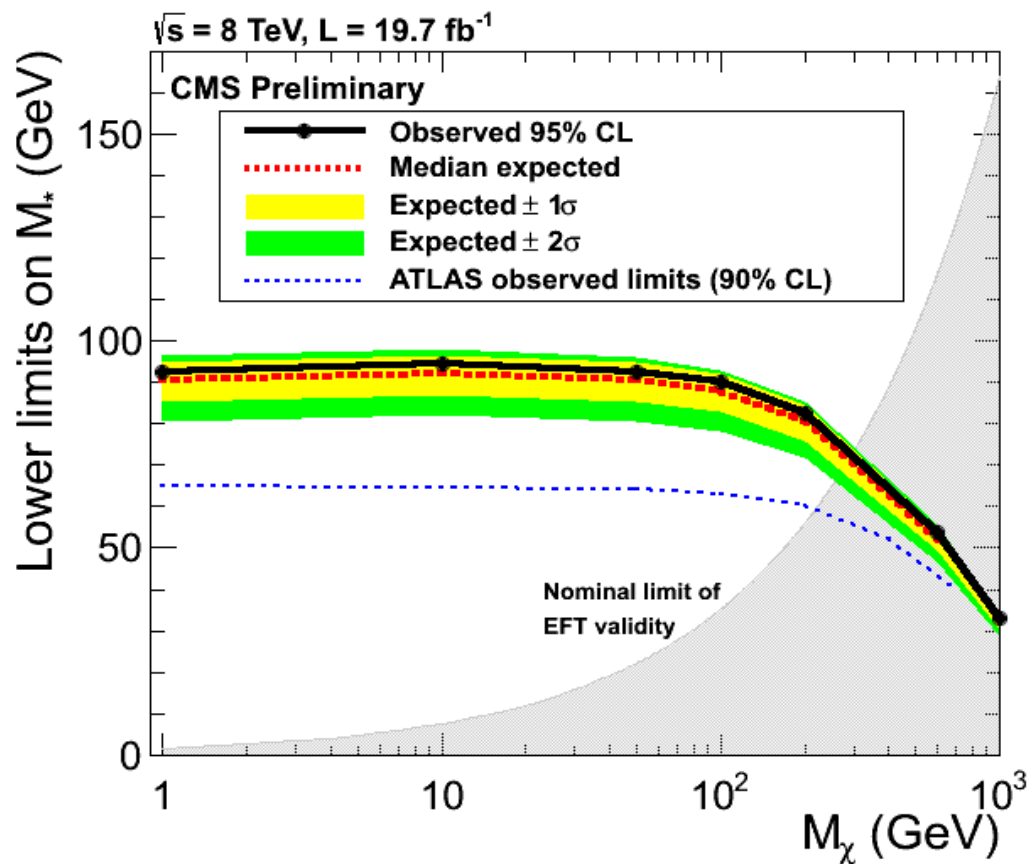


CMS PAS B2G-13-004

- Select pair of top quarks in the di-lepton channel
- Exactly two identified leptons, and at least two jets are selected
- $M(\text{ll}) > 20 \text{ GeV}$ and $|M(\text{ll}) - 91 \text{ GeV}| > 15 \text{ GeV}$
- $\text{MET} > 320 \text{ GeV}$
- $\text{HT}(j_1, j_2) < 400 \text{ GeV}$, $\text{HT}(l_1, l_2) > 120 \text{ GeV}$, $\Delta\phi(l_1, l_2) < 2$



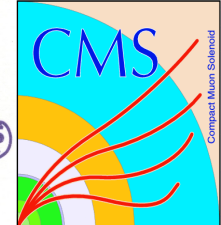
CMS PAS B2G-13-004



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	$1.88 \pm 0.11 \pm 0.07$

■ For dark particle mass 100 GeV, the interaction scale is excluded at 95% CL below 90 GeV

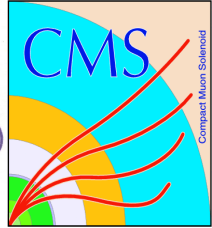
Summary



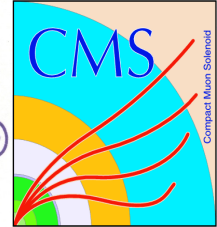
- ◆ Presented results of dark matter search in CMS with the 8 TeV data, with a number of signatures
 - ◆ Mono jet/photon/lepton
 - ◆ Mono top (pair)
- ◆ Data is consistent with standard model prediction
 - ◆ No sign of dark matter signal
- ◆ Looking forward to the 13 TeV data

Thank You

BACKUP



MHT Minimization



A way to identify and reduce the fake met contribution, where you minimize the unclustered energy in the event by trying to re-distribute the energy back into the visible objects.

$$\chi^2 = \sum_{i=\text{objects}} \left(\frac{(p_T^{\text{reco}})_i - (\hat{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left(\frac{\hat{E}_T}{\sigma_{\hat{E}_T}} \right)^2$$

$$\hat{E}_{x,y} = E_{x,y}^{\text{reco}} + \sum_{i=\text{objects}} (p_{x,y}^{\text{reco}})_i - (\hat{p}_{x,y})_i$$

$$E_T^2 = E_x^2 + E_y^2$$

- If the MET is intrinsic, balancing the object momenta wouldn't be easy and will result in higher χ^2 .
- The variables that give good discrimination are the recalculate minimized MET and $\text{Prob}(\chi^2)$