Searches for Dark Matter in CMS

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on behalf of the CMS Collaboration

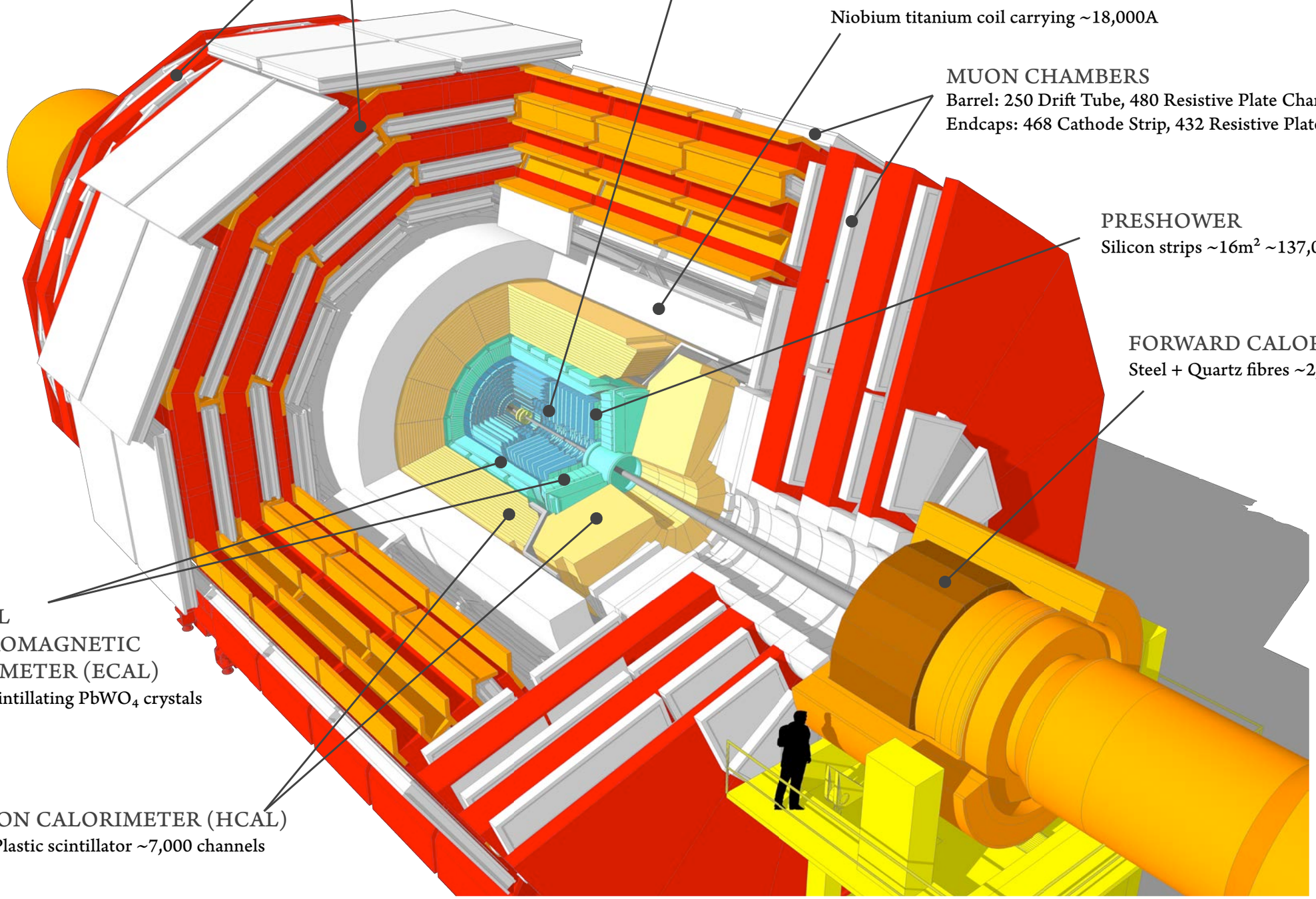
Latest Results in Dark Matter Searches,
12 - 14 May 2014
Nordic Institute for Theoretical Physics, Sweden

Compact Muon Solenoid (CMS)

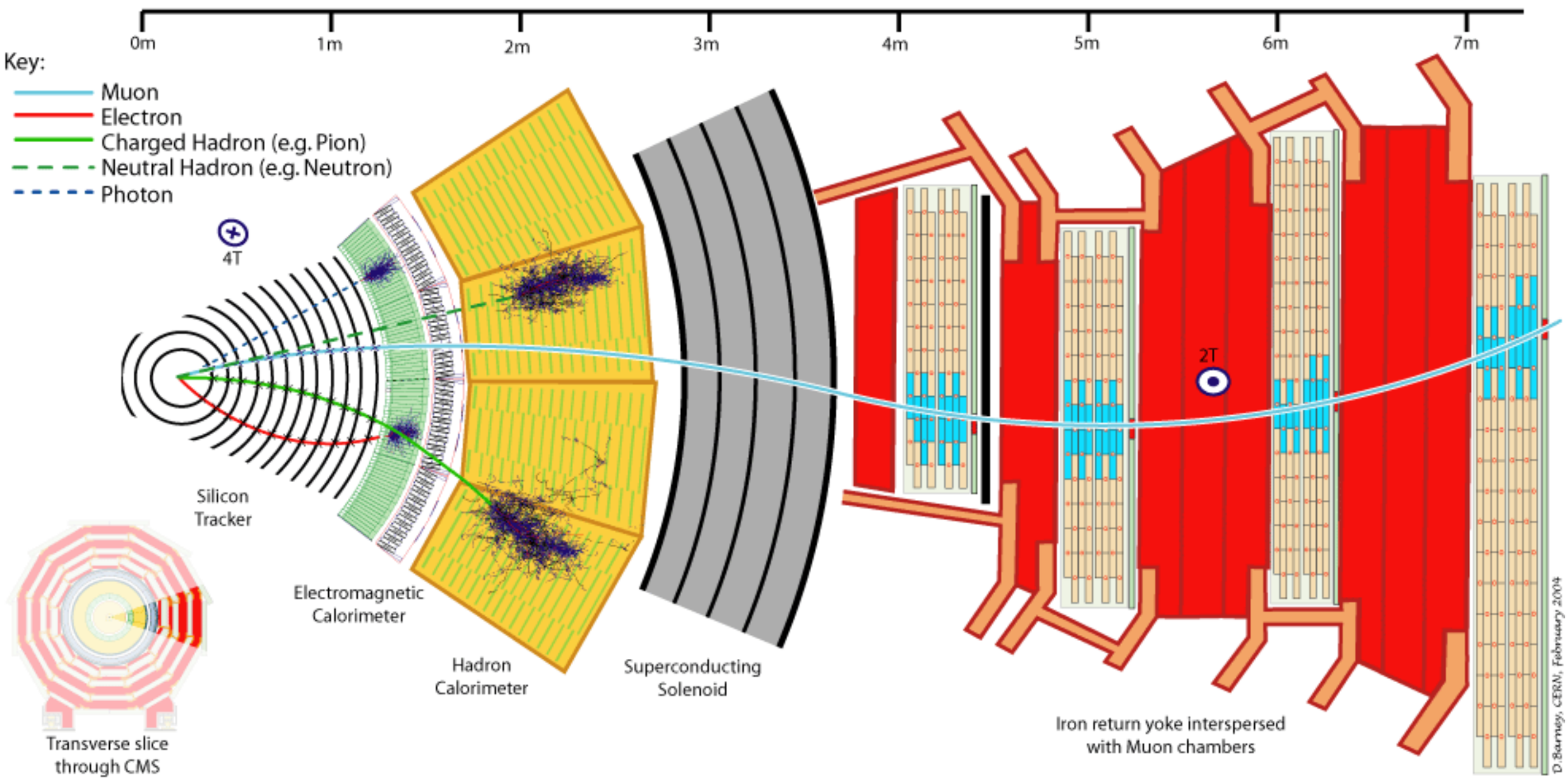
CMS DETECTOR

Total weight	: 14,000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T

Schematic view of the CMS Detector showing its main components.



Compact Muon Solenoid (CMS)



Dark Matter models

Dirac fermion, 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	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	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	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
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, 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	$G\tilde{G}$	$\alpha_s/8M_*^3$
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$

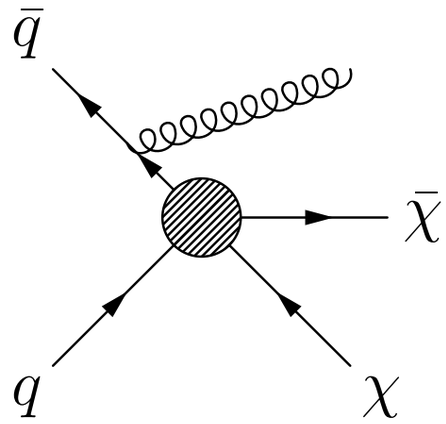
Real scalar, 1008.1783

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

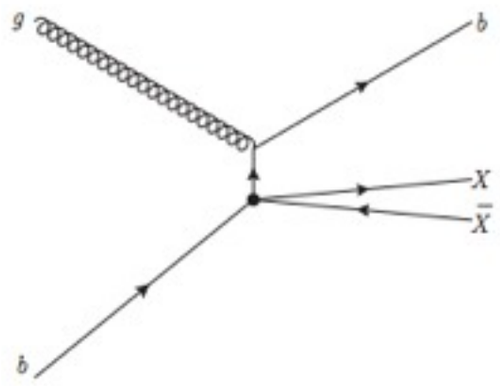
Complex scalar, 1008.1783

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

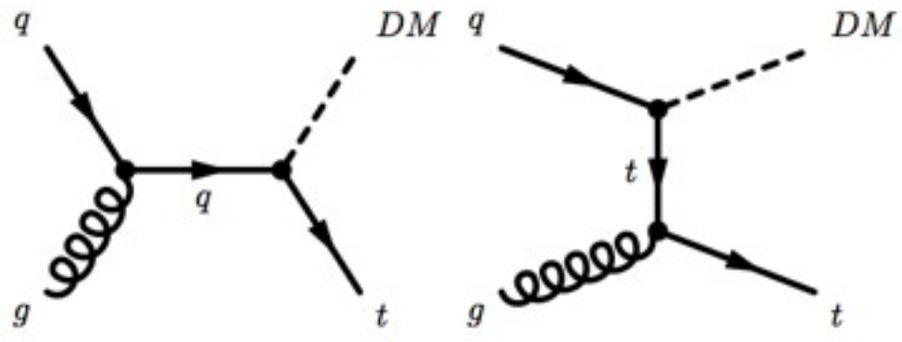
X + Missing Transverse Energy



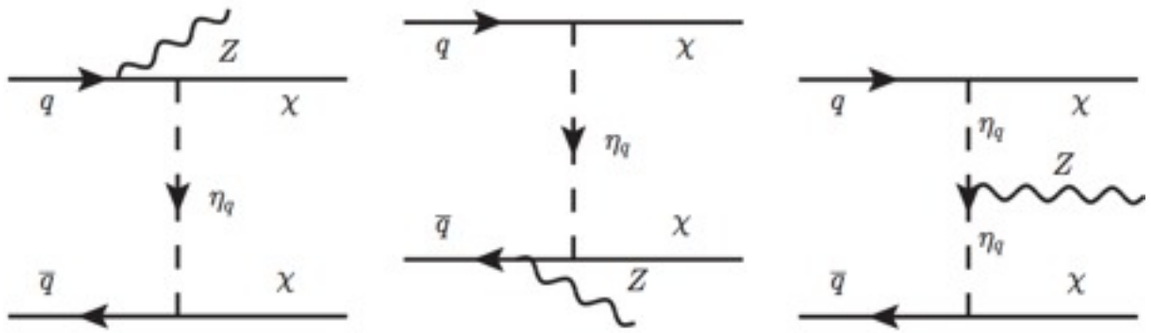
Monojet



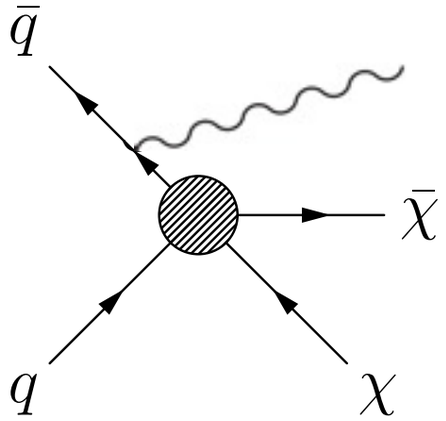
MonoB



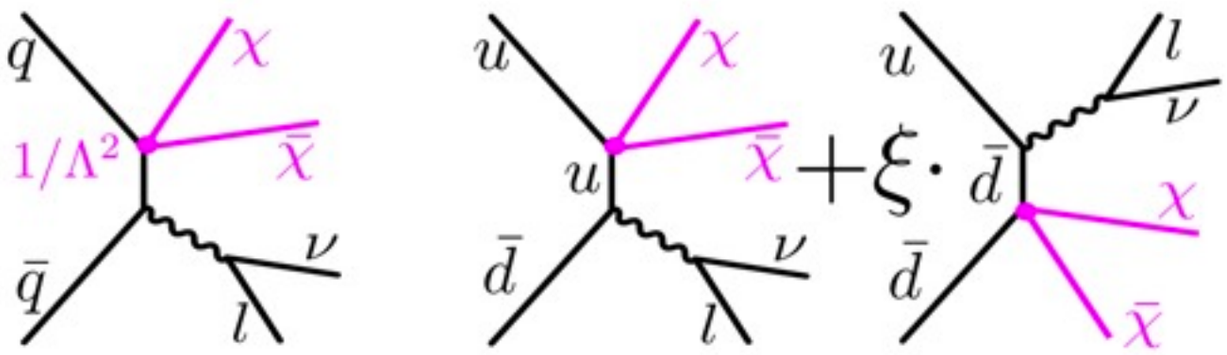
MonoTop



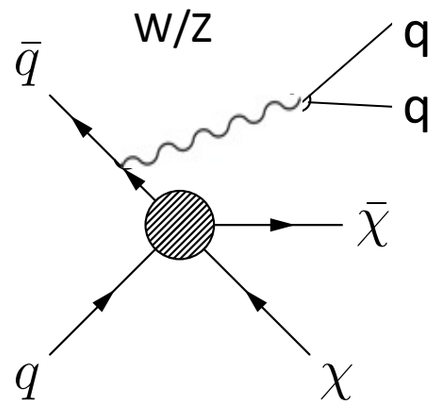
MonoZ



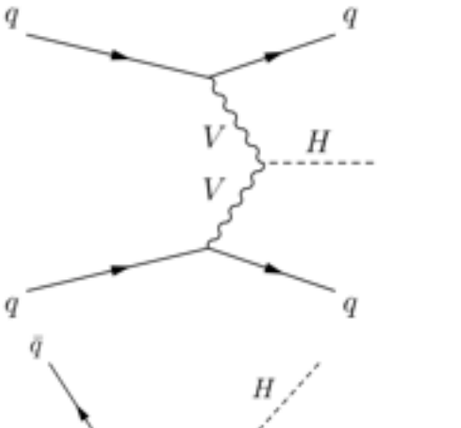
MonoPhoton

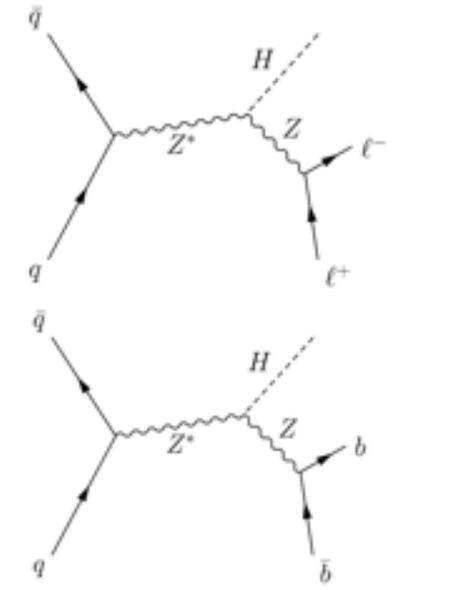


MonoW (monoLepton)

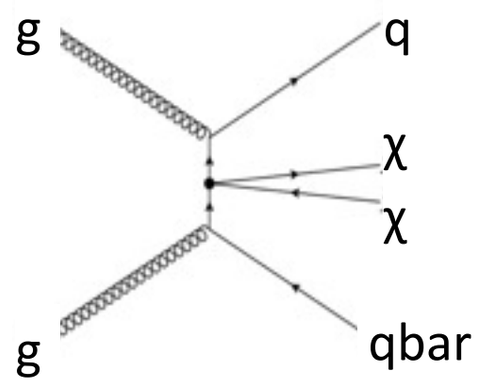


MonoW/Z (Hadronic)





Higgs Portal



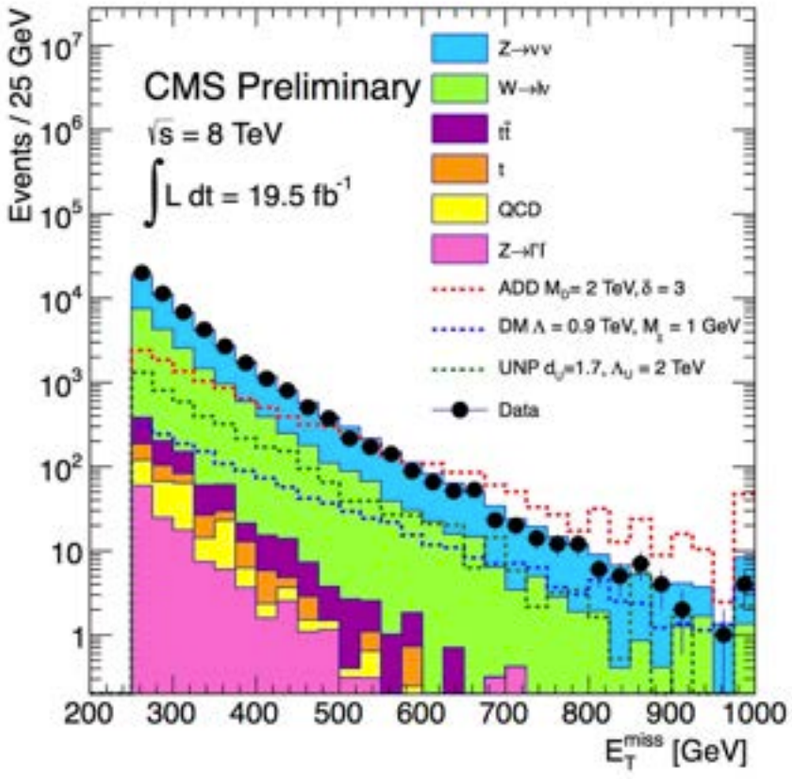
BBbar /TTbar

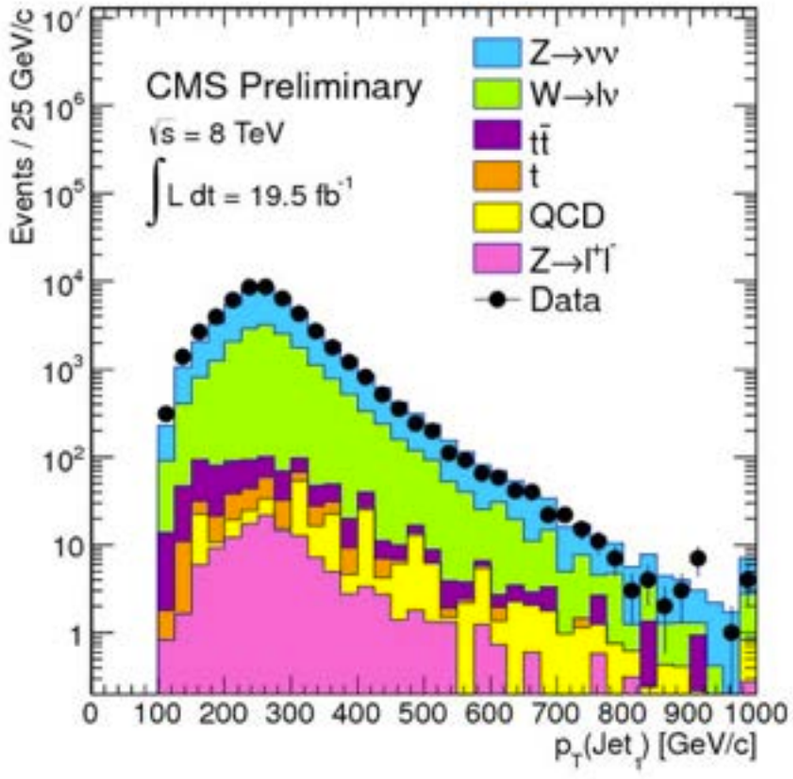
Monojet

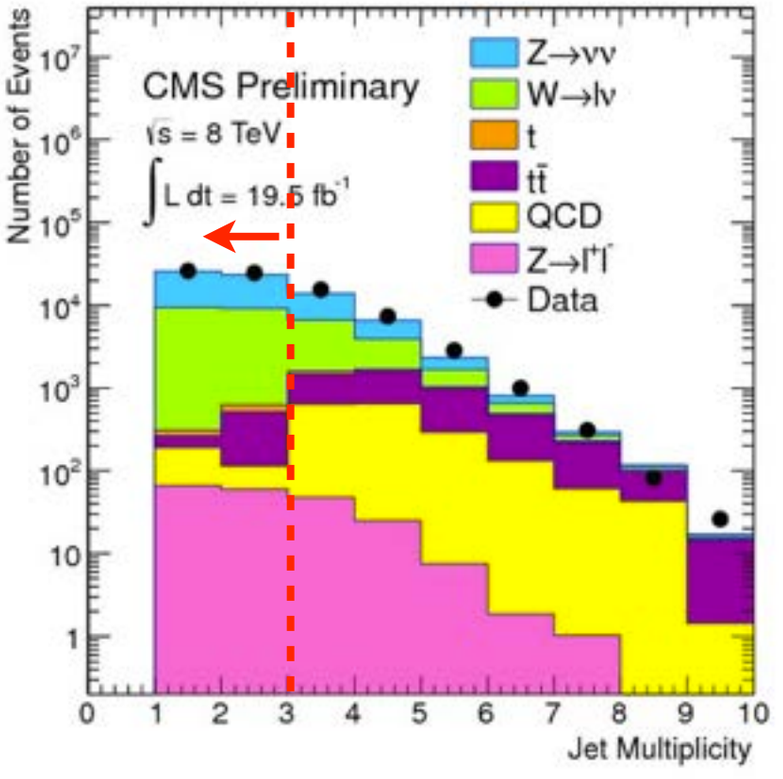
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

Event selection

- MET > 400 GeV
- One energetic jet, p_T > 110 GeV, $|\eta|$ < 2.4, and allow an additional jet (p_T > 30 GeV)
- Veto event if j_3 p_T > 30 GeV
- Veto event if DeltaPhi(j_1,j_2)>2.5
- Veto event if they contain isolated electrons, isolated muons, or hadronic tau with p_T >10 GeV (20 GeV for tau)



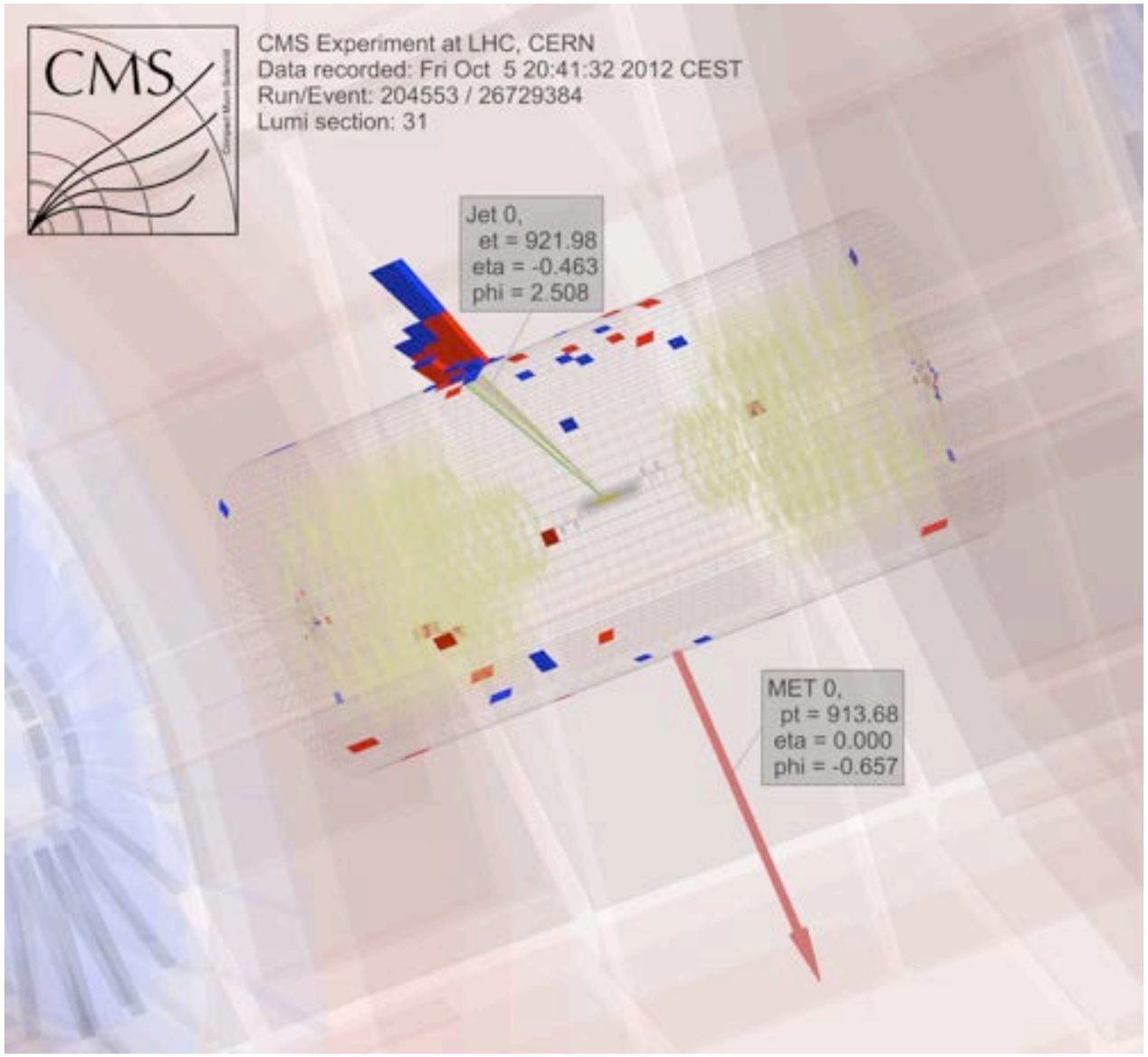


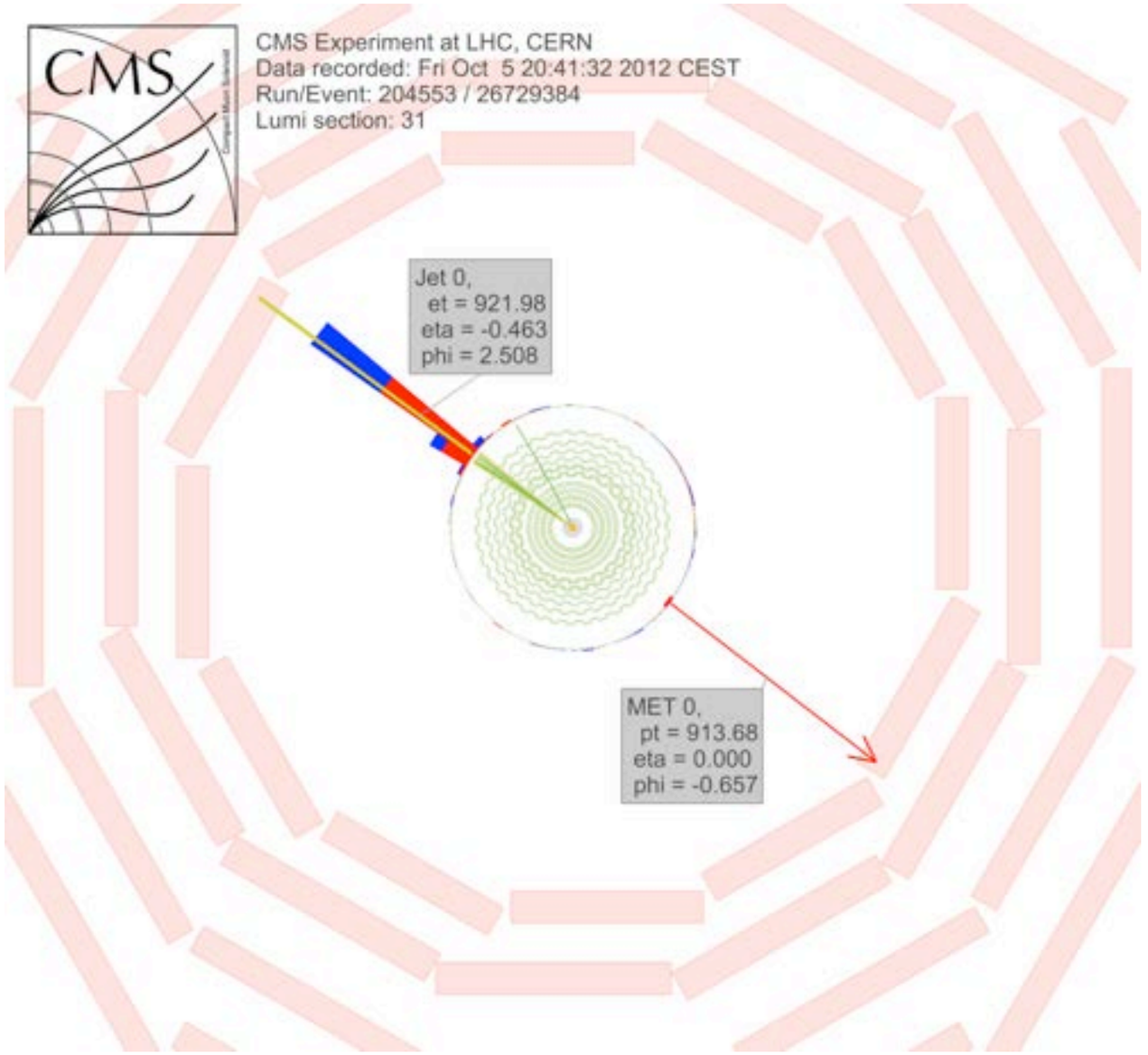


Monojet

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

Event display

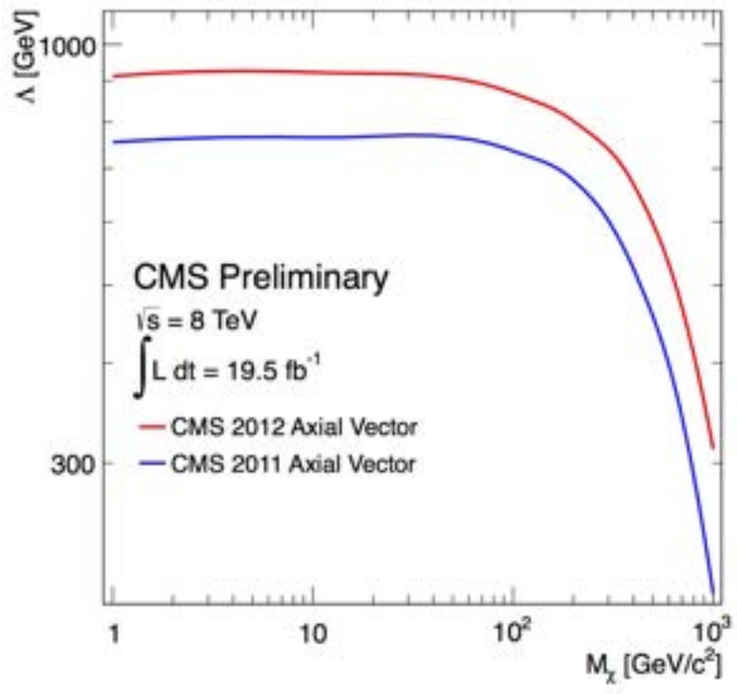


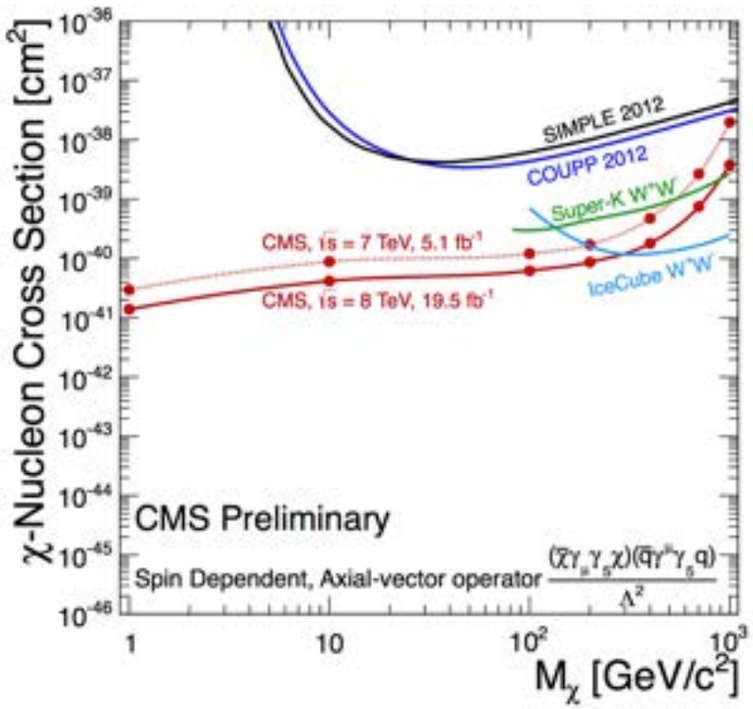


Monojet

Results

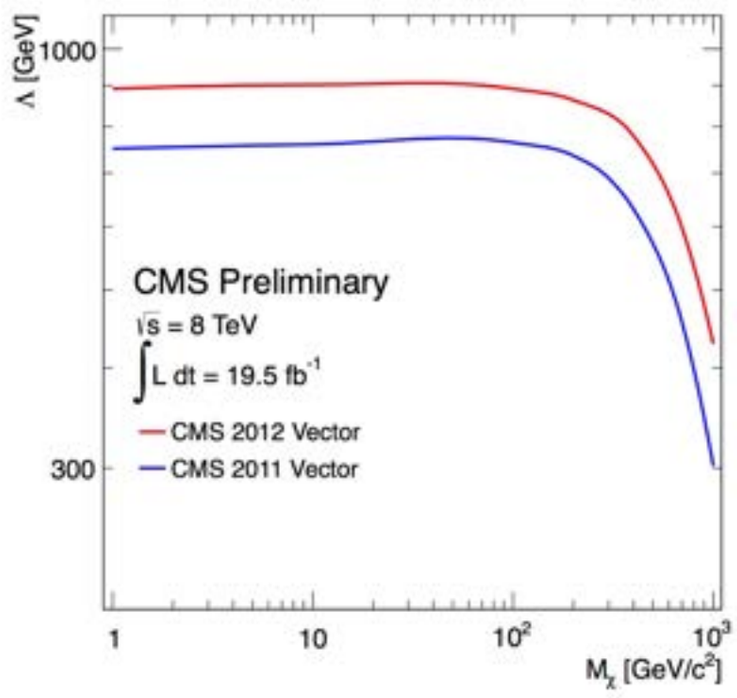
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048

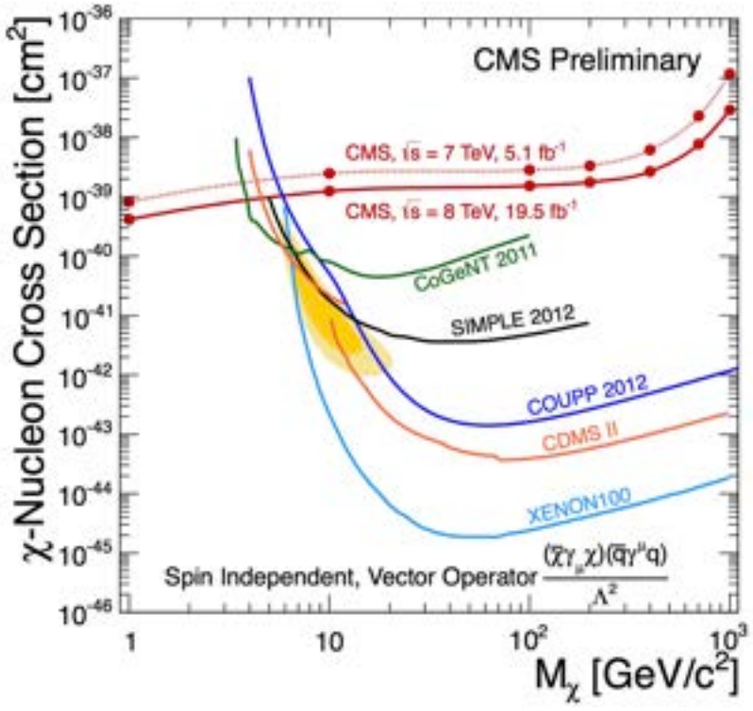




Axial-vector operator
spin-dependent (SD)

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





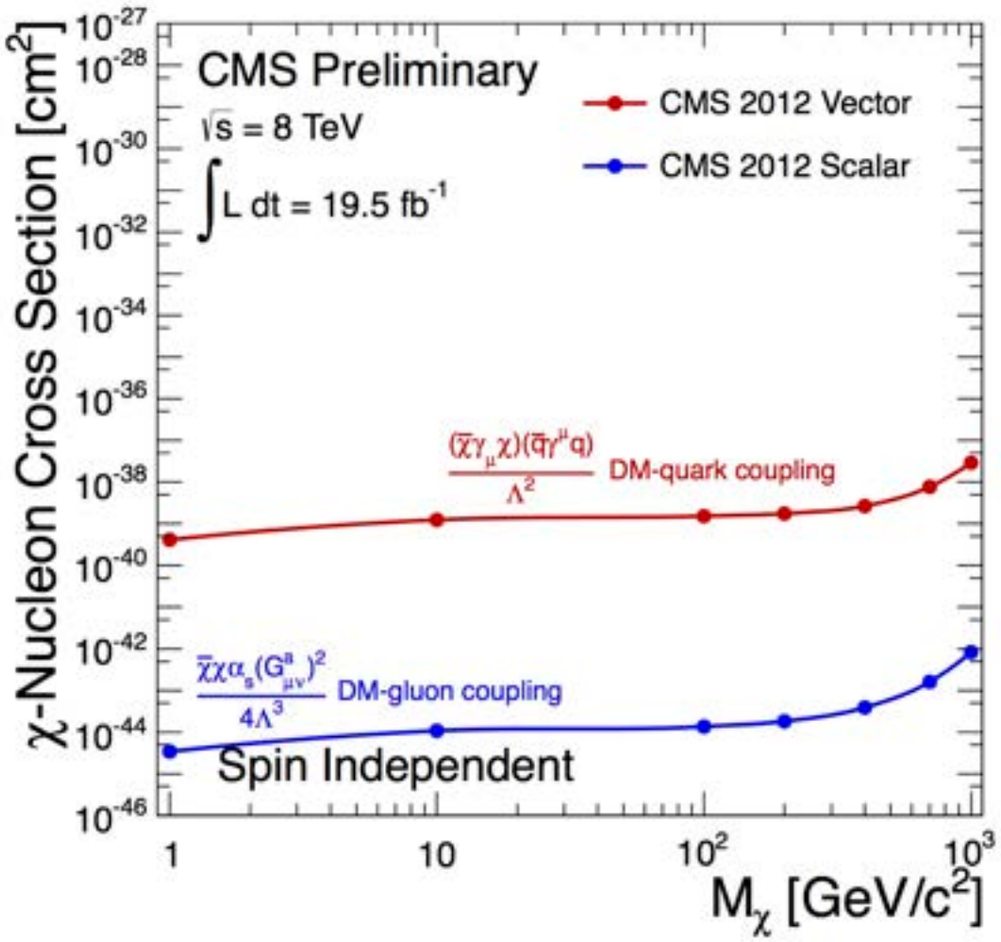
Vector operator
spin independent (SI)

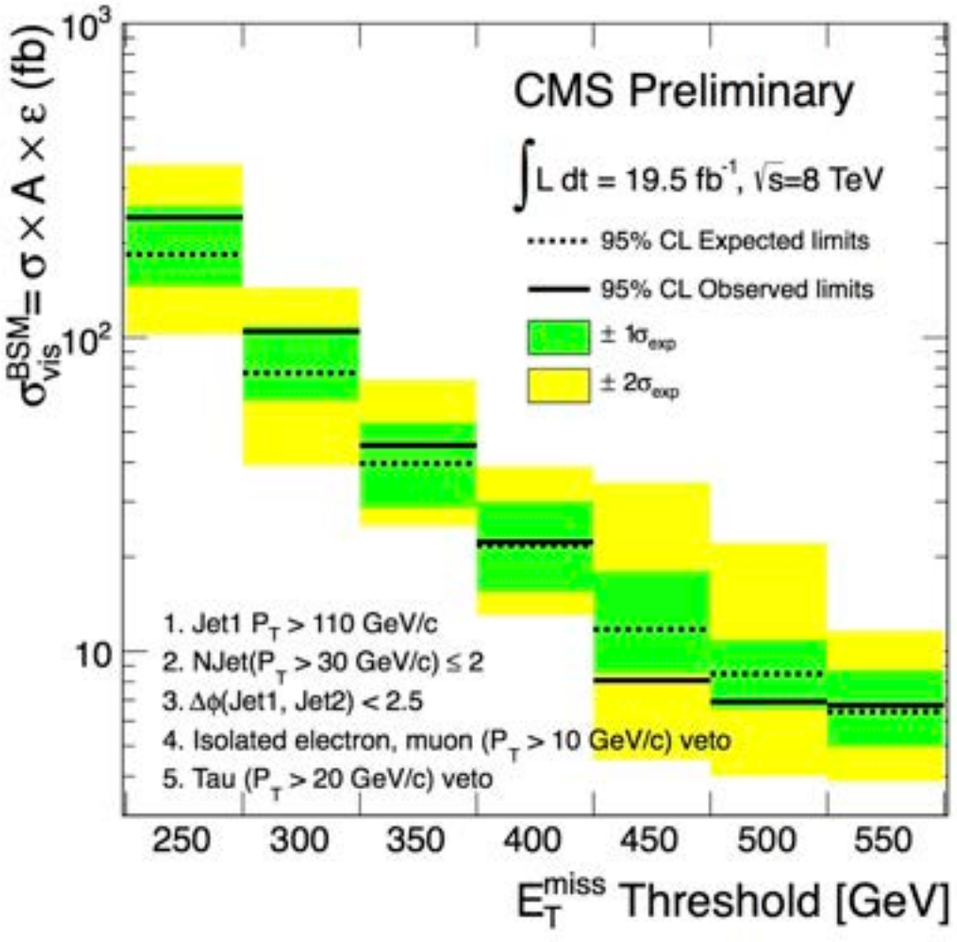
$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

Monojet

Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12048



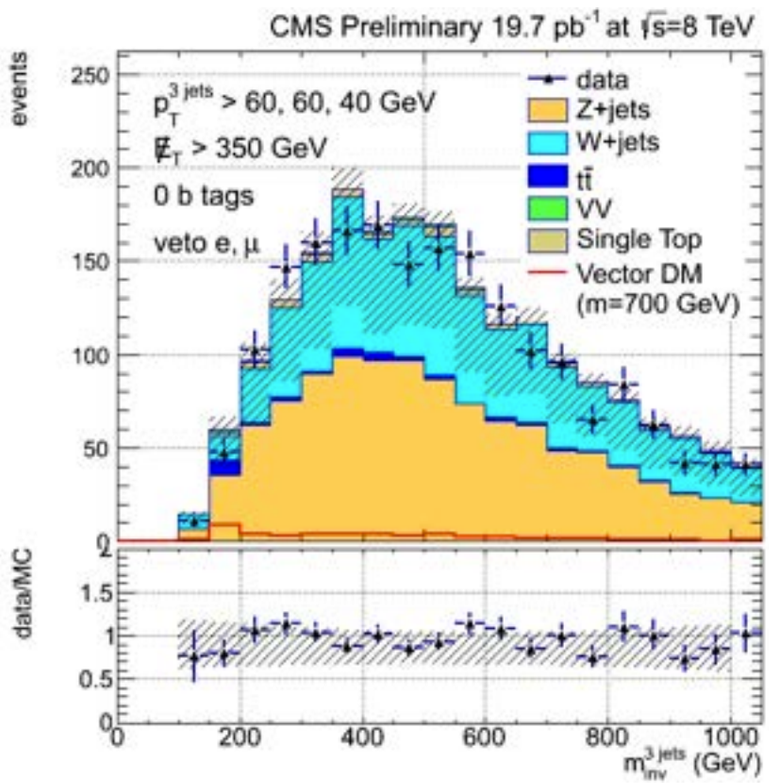


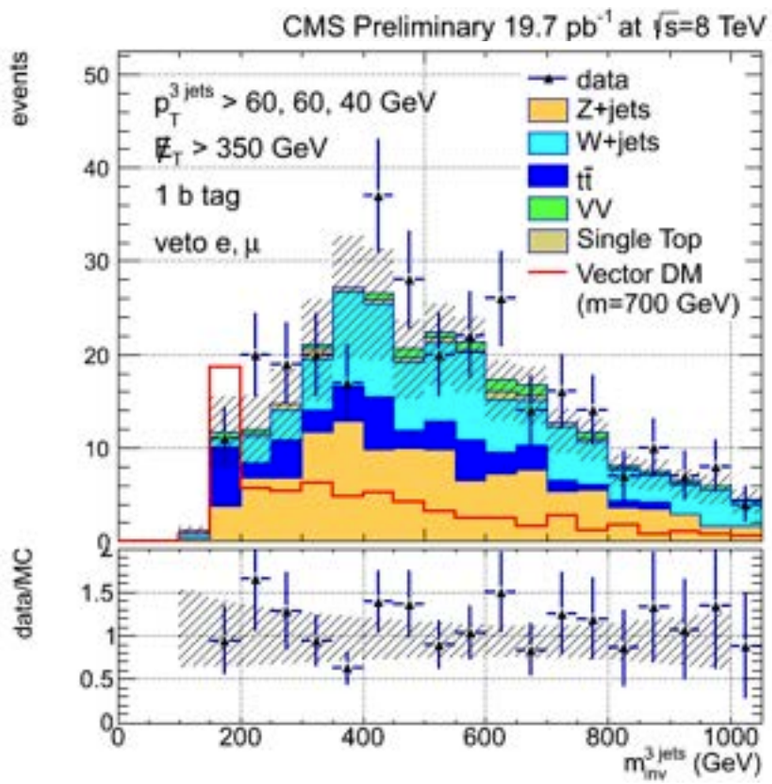
Monotop (top decays hadronically)

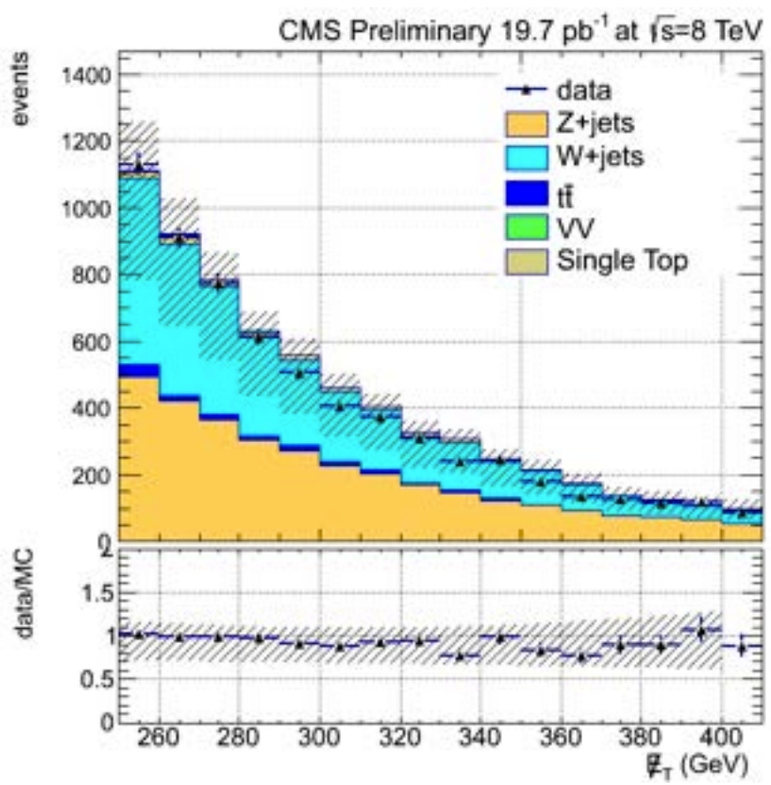
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12022

Event selection

- 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
- Veto events with j_4 p_T > 35 GeV or isolated e(μ) p_T > 20(10) GeV
- M($j_1 j_2 j_3$) < 250 GeV
- MET> 350 GeV







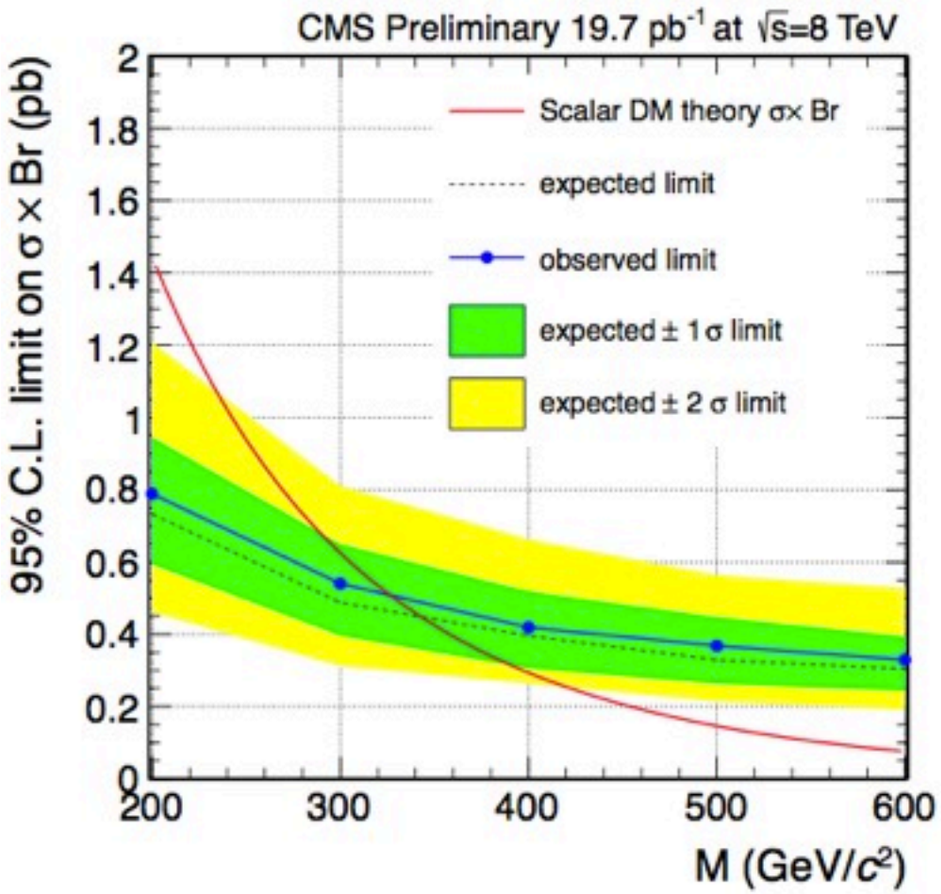
Monotop (top decays hadronically)

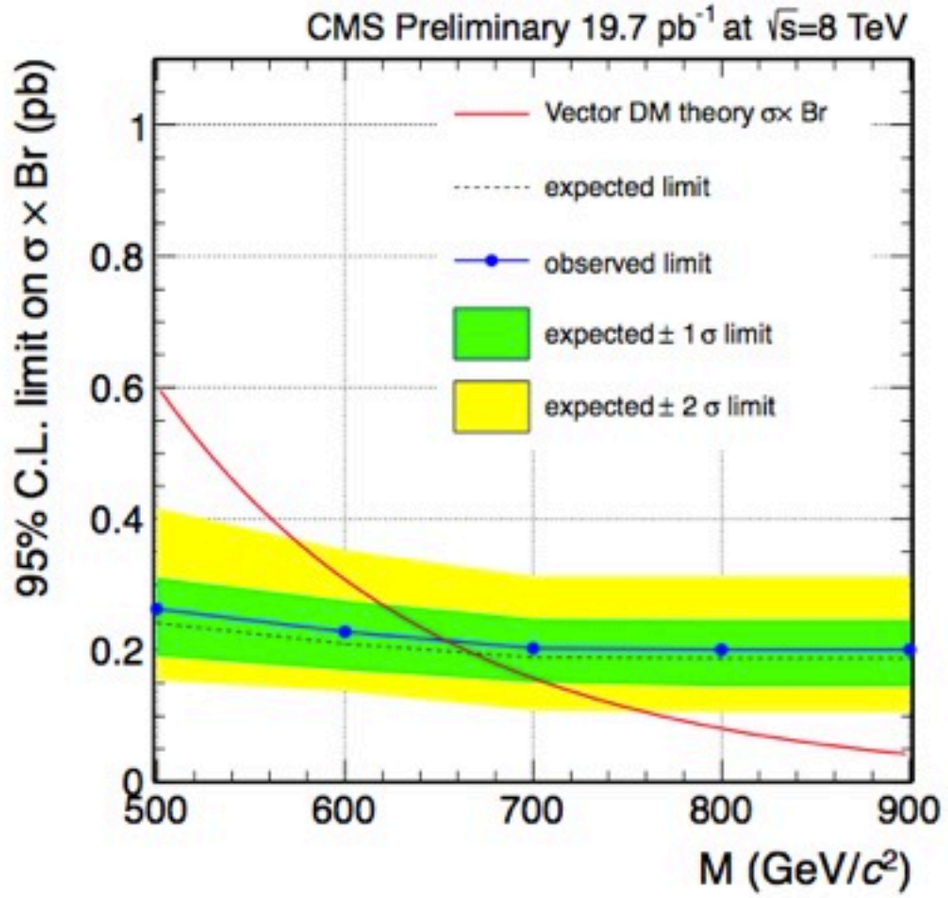
Results

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G12022

- Excellent agreement with data
- DM coupling set to 0.1 for q=u/d [arXiv:1106.199]
- Exclude scalar (vector) DM masses below 327 (655) GeV

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





Monolepton

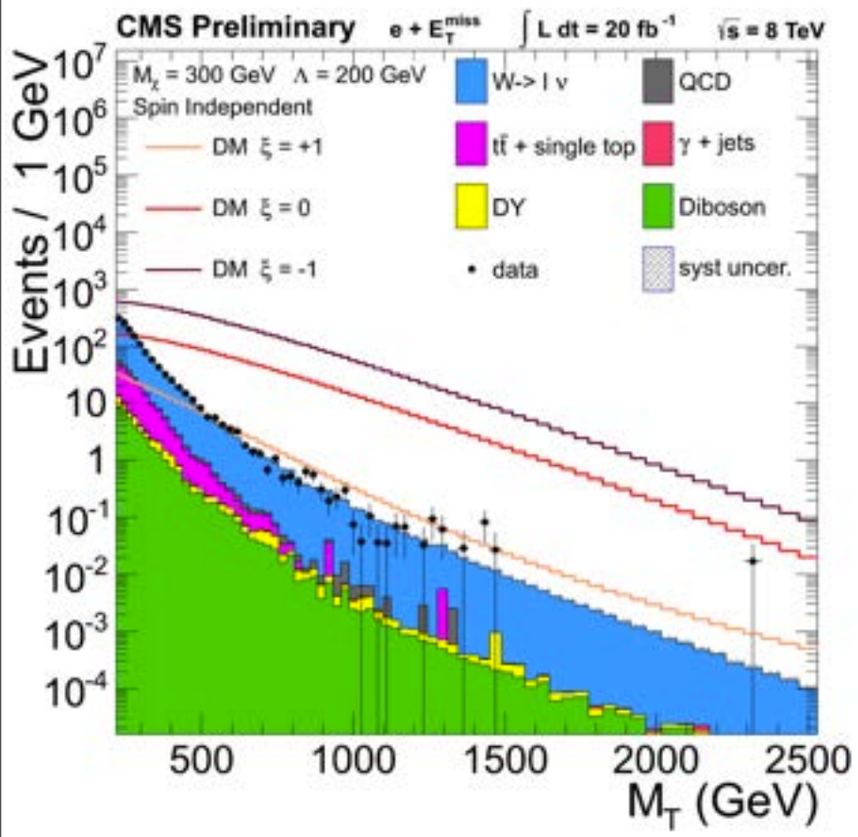
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO13004

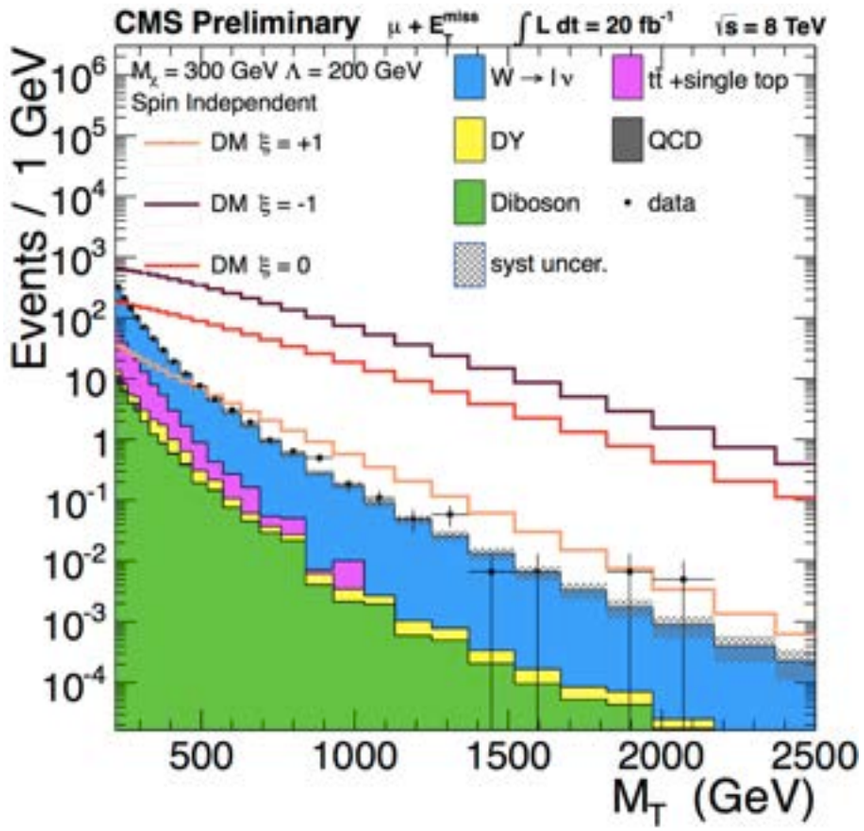
Dark Matter production with a W

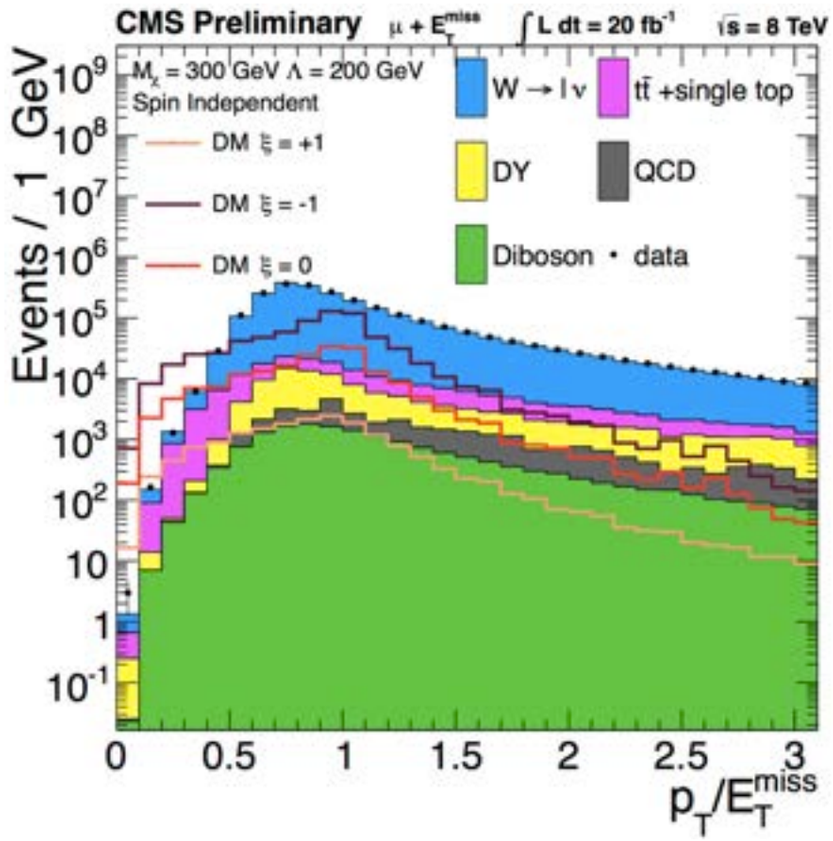
- W recoiling against pair-produced DM
- Vector- and axial-vector couplings considered
- Interference effects parameterized by ξ (W+)

Event selection

- Muon (Electron) P_T > 45 (100) GeV
- 0.4 < P_T/MET < 1.5
- DeltaPhi(lepton,MET) > 0.8*Pi





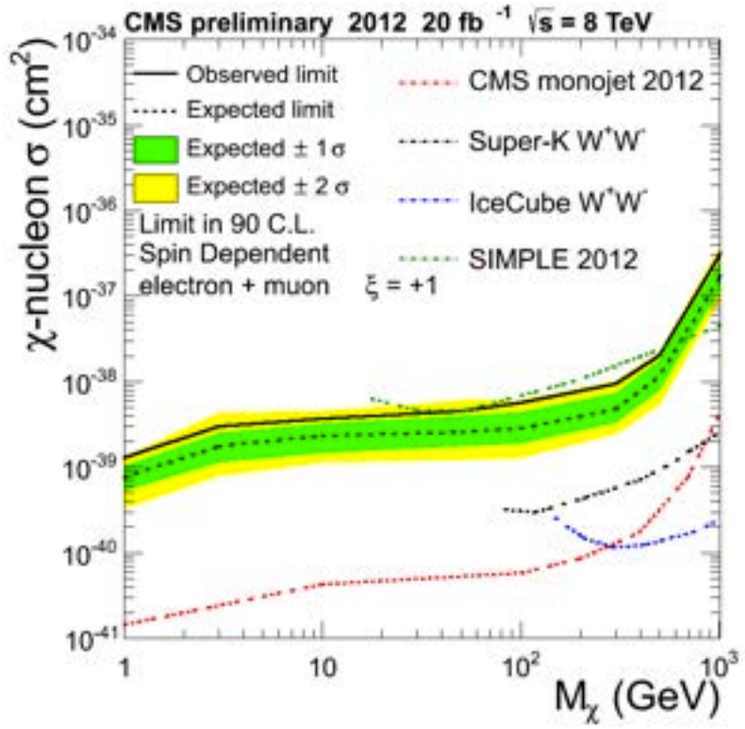


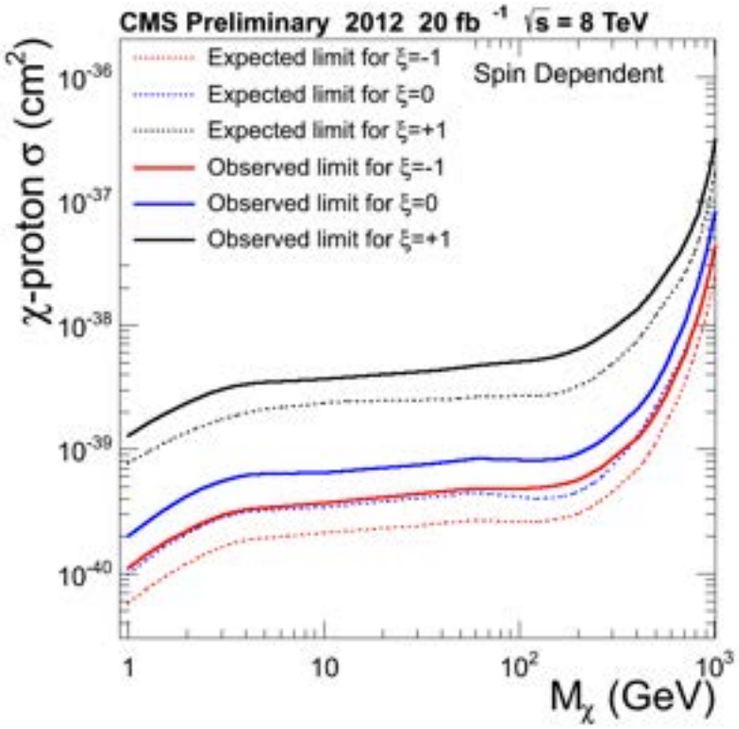
$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

Monolepton

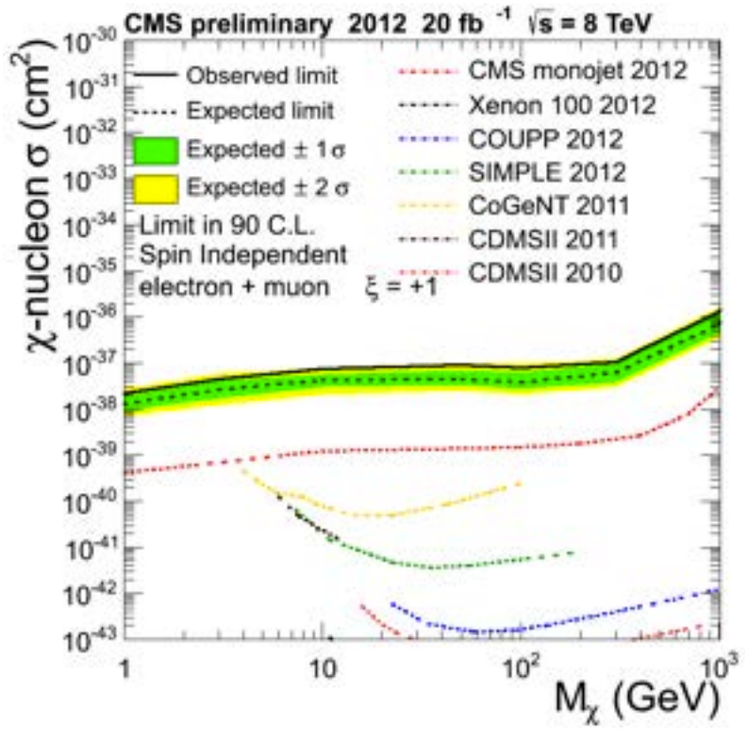
Results

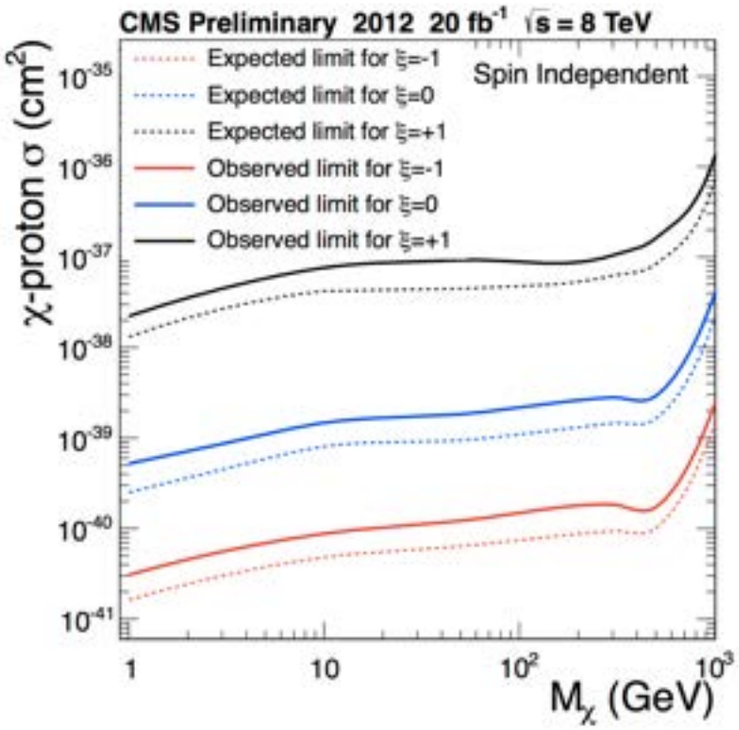
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO13004





Axial-vector operator spin-dependent (SD)





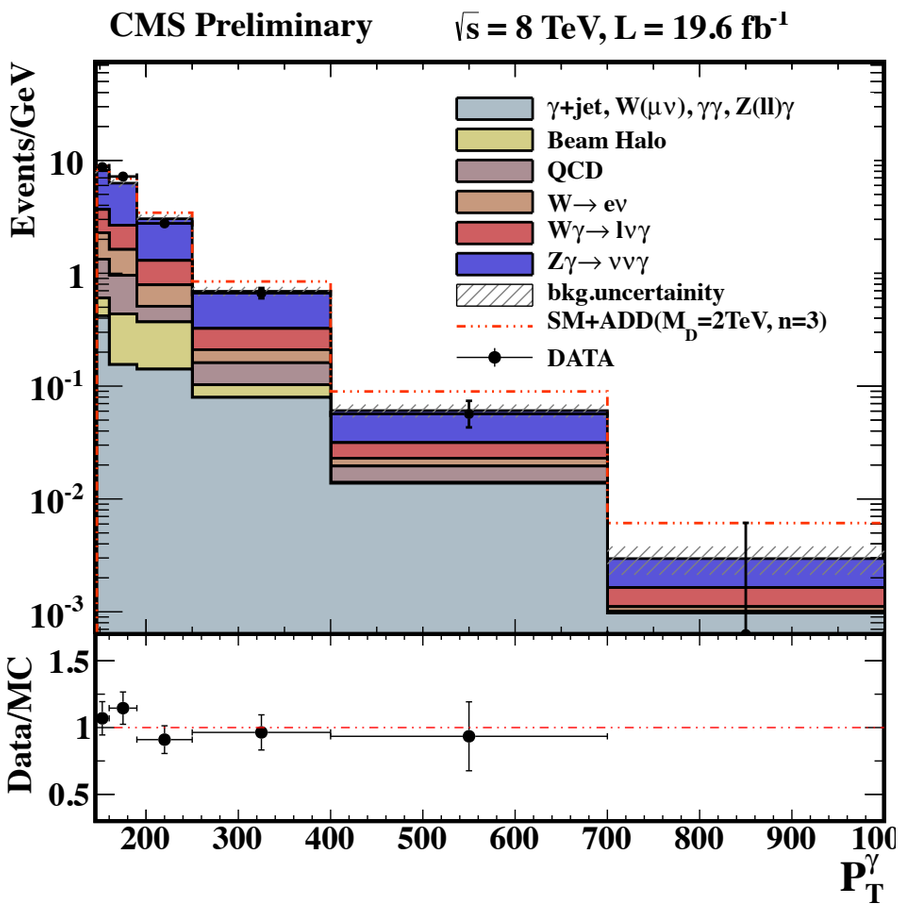
Vector operator spin independent (SI)

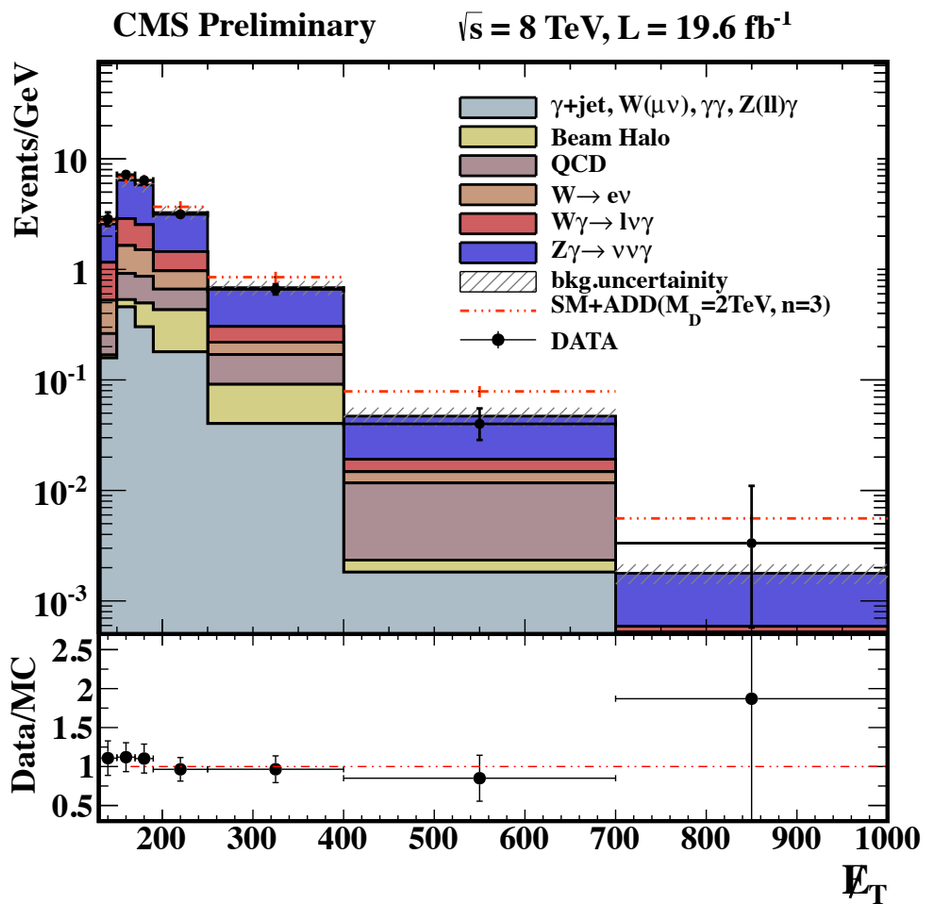
Monophoton

EXO-12-047

Event selection

- MET > 140 GeV
- One energetic photon, p_T > 145 GeV, $|\eta|$ < 1.4442
- Veto on jets, leptons, and pixel seeds (hit pattern in the pixel detector)
- DeltaPhi(photon,MET) > 2
- MinMET > 120 GeV, Prob(χ^2) (Reduce fake MET events)

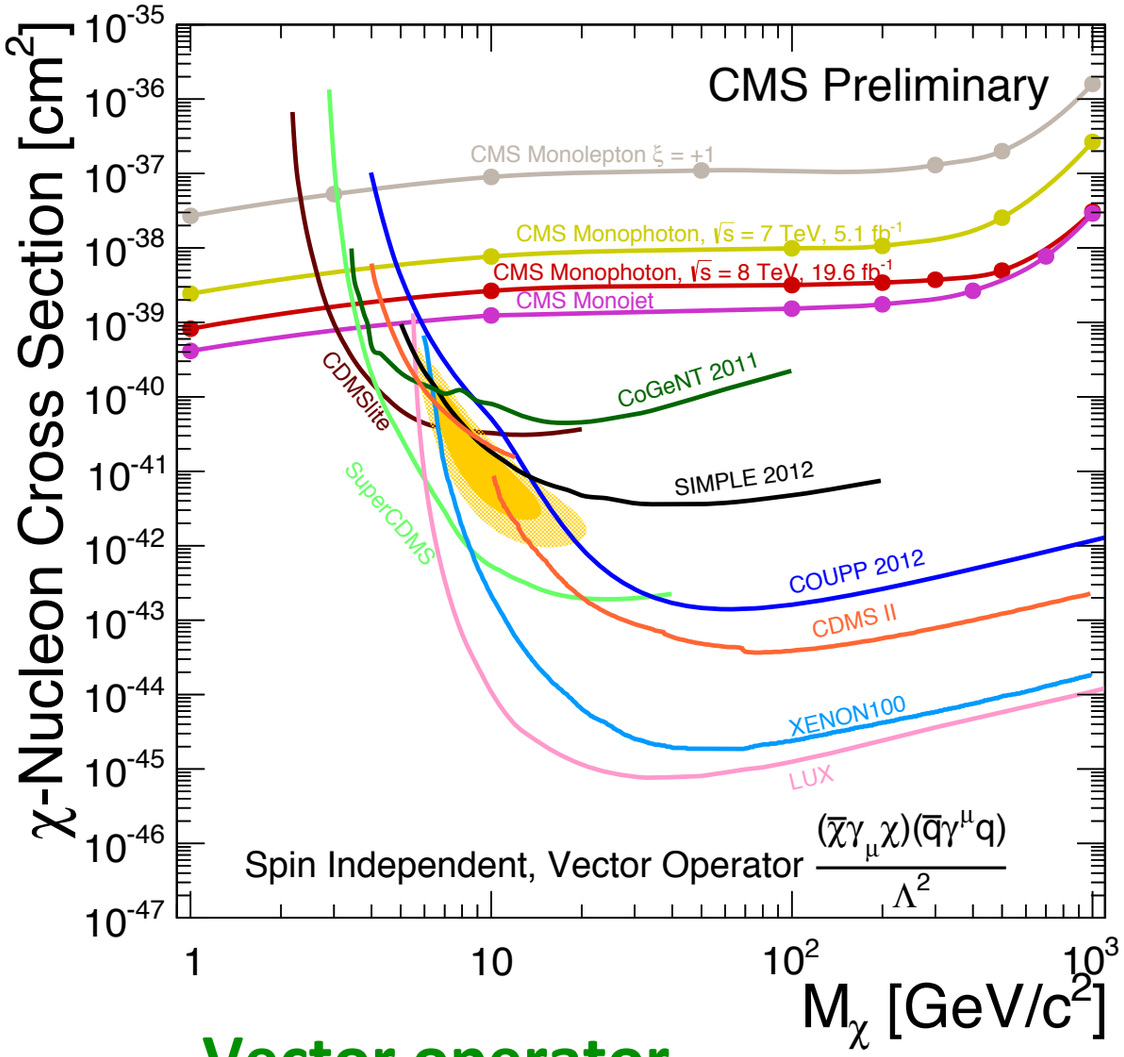




Monophoton

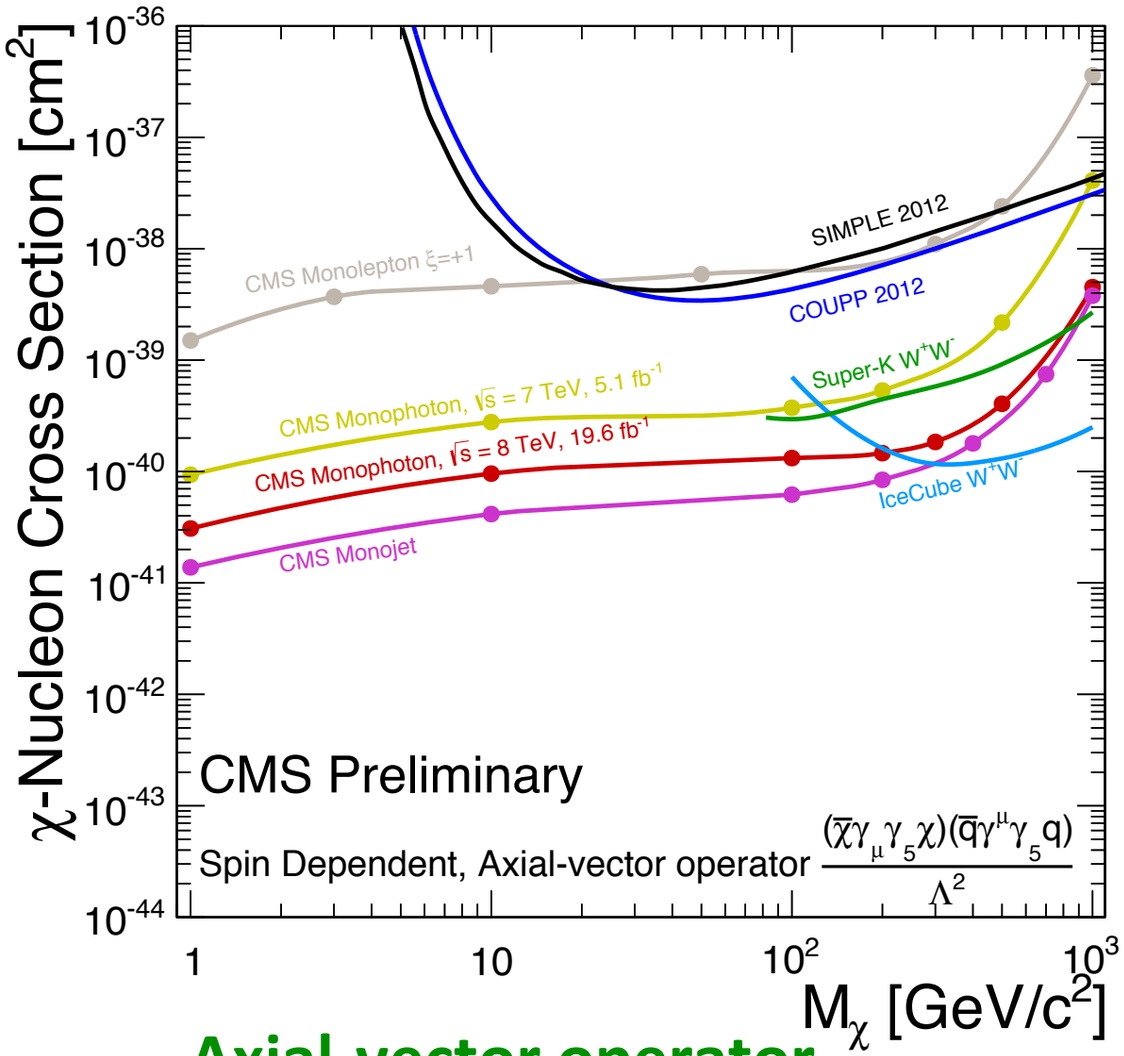
Results

EXO-12-047



Vector operator
spin independent (SI)

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



Axial-vector operator
spin-dependent (SD)

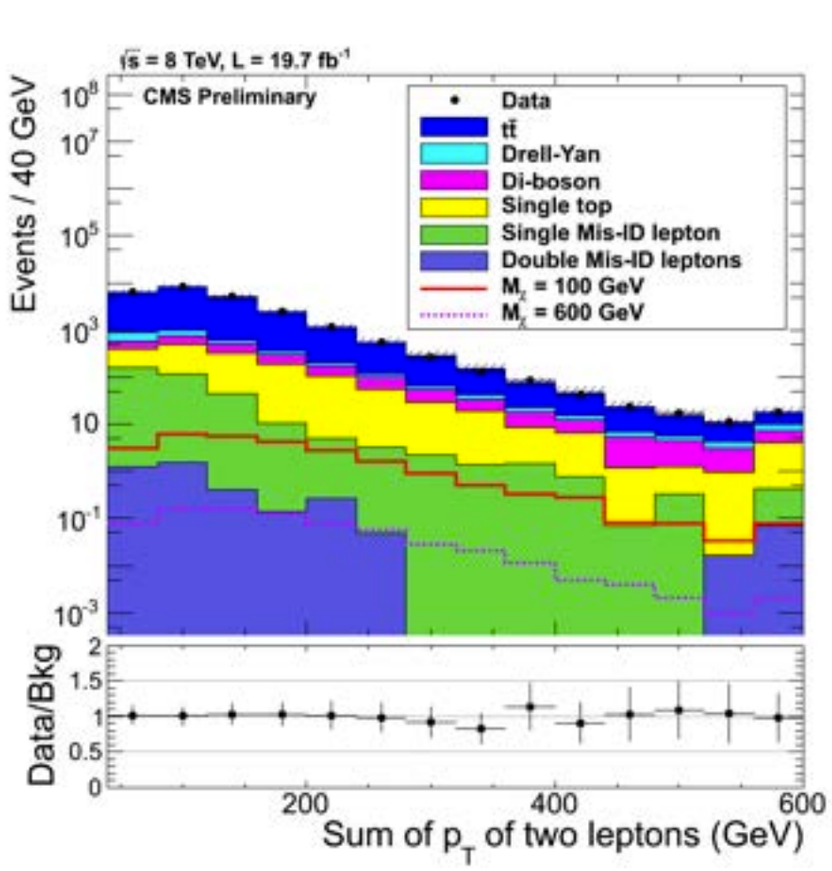
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

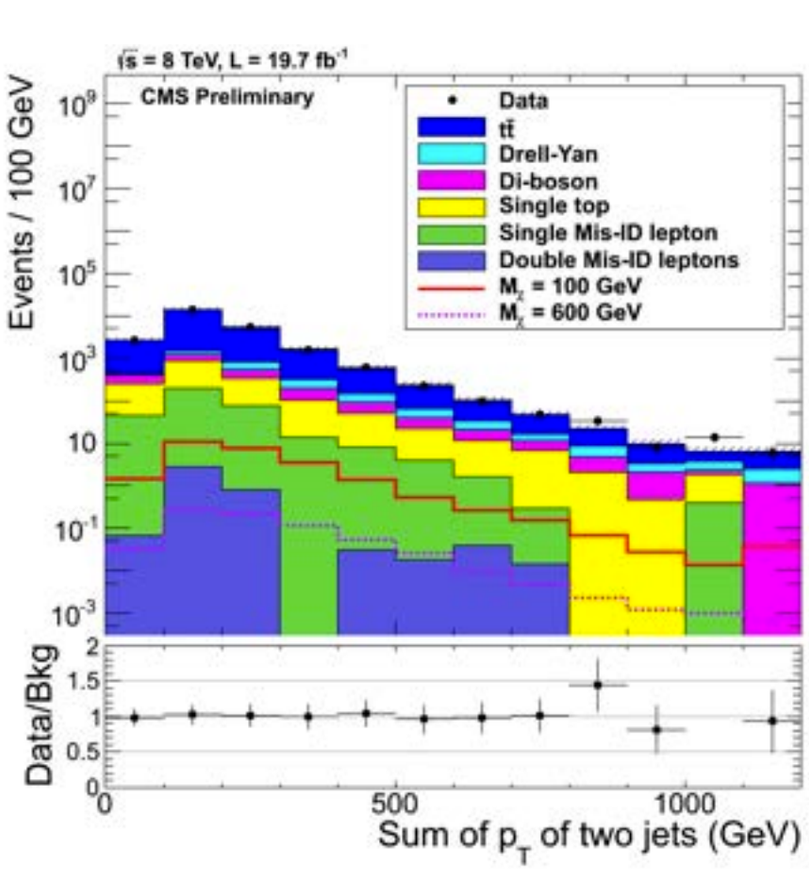
Top quark pair

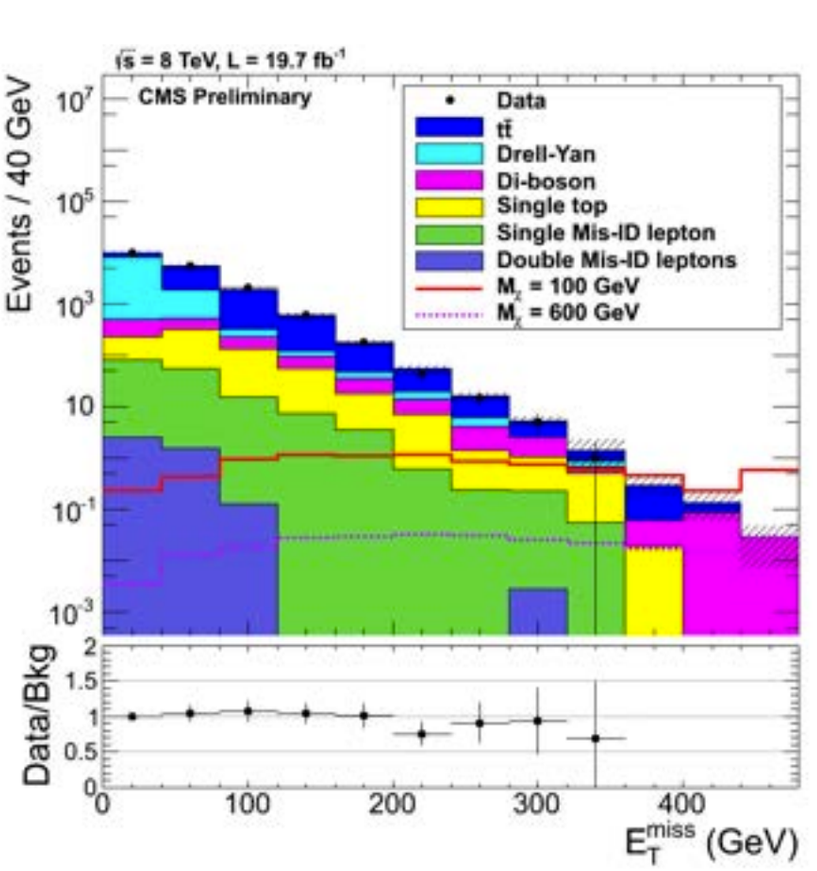
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G13004

Event selection

- Select pairs of top quarks in the di-lepton channels
- Exactly two identified leptons, and at least two jets are selected.
- M(ll) > 20 GeV and |M(ll) − 91 GeV| > 15 GeV
- MET > 320 GeV
- HT(j_1, j_2) < 400 GeV, HT(l_1, l_2) > 120 GeV, DeltaPhi(l_1, l_2) < 2



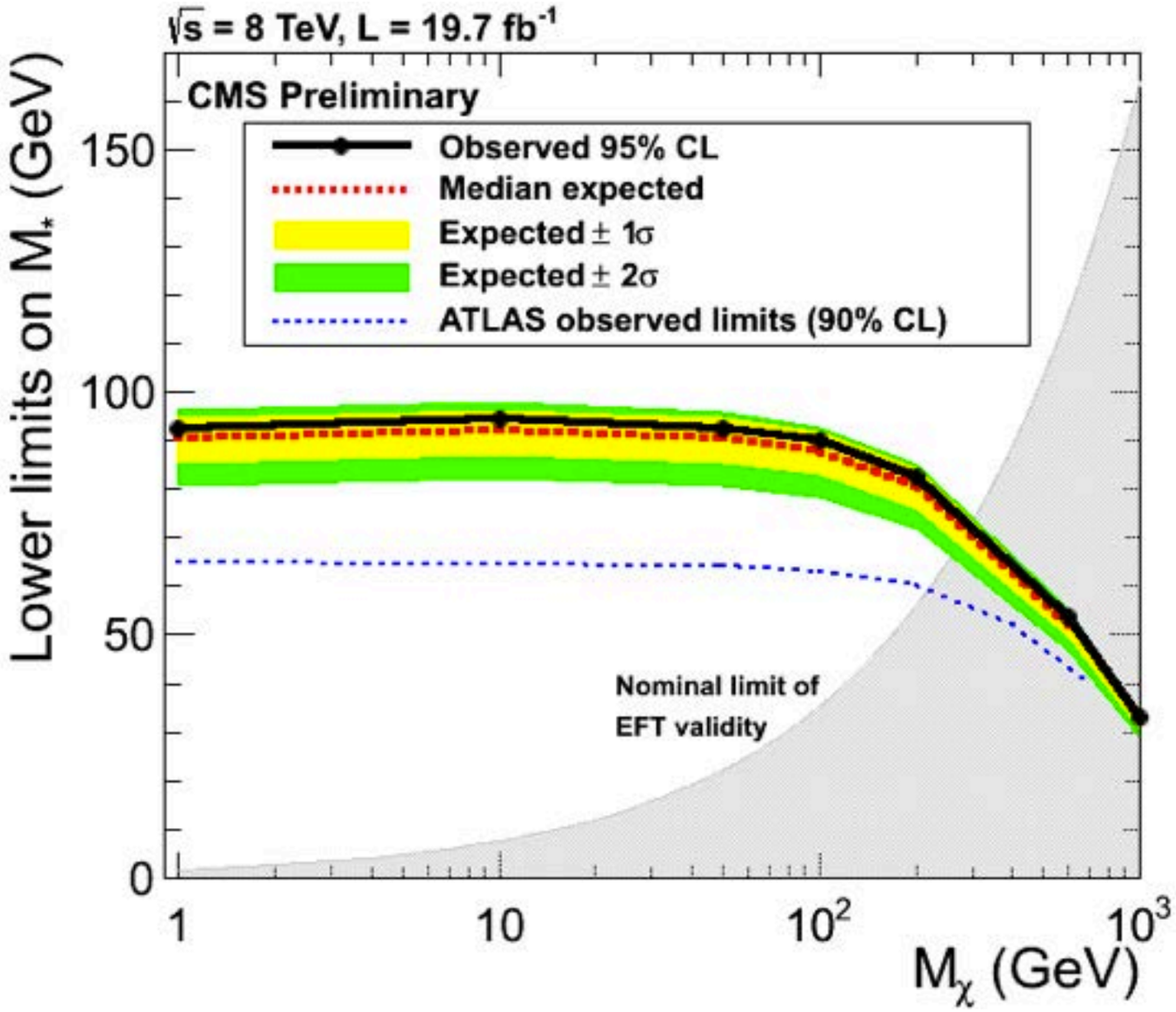




Top quark pair

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G13004

Results



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	$1.88 \pm 0.11 \pm 0.07$

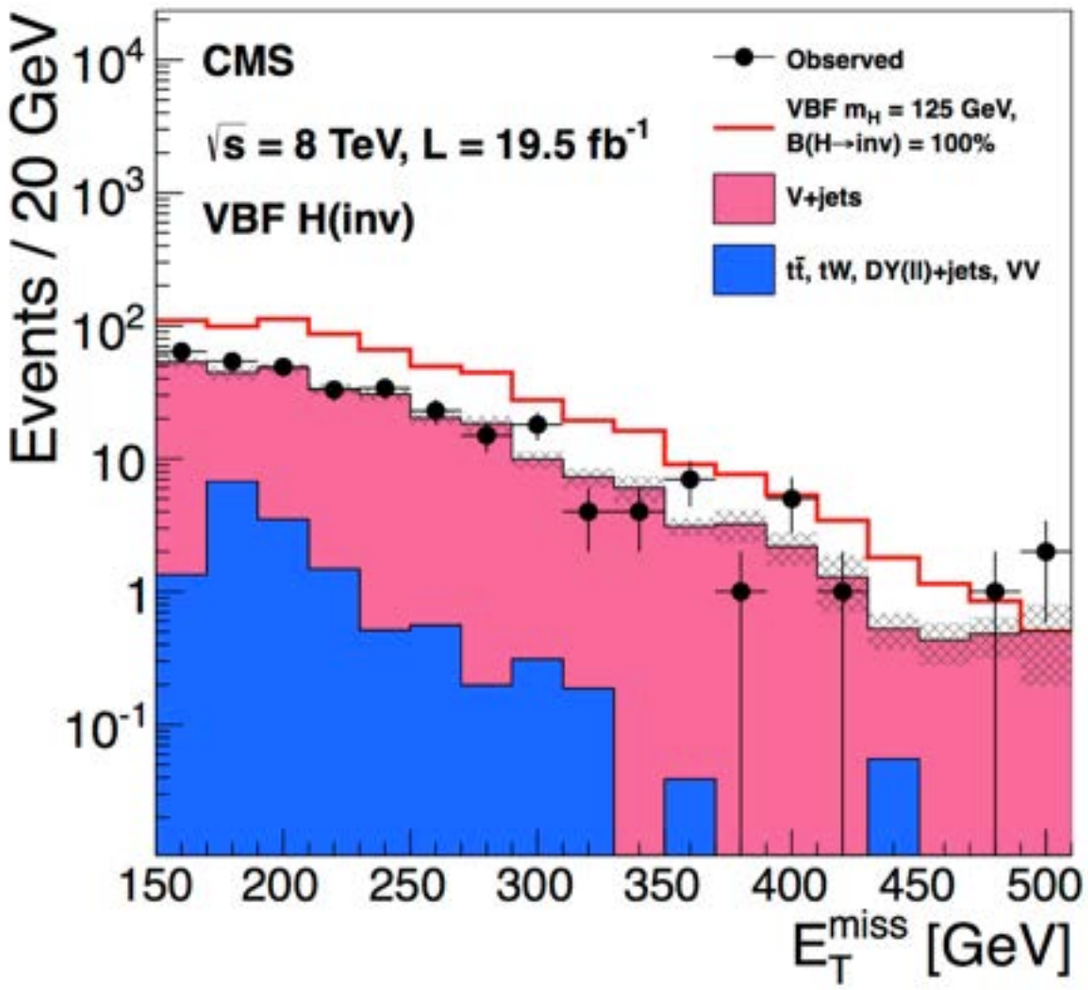
M_χ (GeV)	Signal efficiency (%)	$\sigma^{\text{lim}}_{\text{exp}}$	$\sigma^{\text{lim}}_{\text{obs}}$
1	$1.28 \pm 0.09 \pm 0.04$	0.35	0.31
10	$1.45 \pm 0.10 \pm 0.05$	0.31	0.27
50	$1.65 \pm 0.11 \pm 0.05$	0.27	0.24
100	$1.96 \pm 0.12 \pm 0.06$	0.23	0.20
200	$2.31 \pm 0.12 \pm 0.05$	0.19	0.17
600	$3.45 \pm 0.17 \pm 0.09$	0.13	0.11
1000	$4.35 \pm 0.24 \pm 0.10$	0.10	0.09

Higgs Portal to Dark Matter

arXiv:1404.1344v2

DM particles have the direct couplings to the SM Higgs sector,
$H \rightarrow X\,X$

- Limits on branching fraction of Higgs to "invisible" particles used for limits on DM
- Can be scalar, vector or fermionic couplings
- Limits only up to DM mass $M_X < M_H/2$



Event selection: VBF+H(inv)

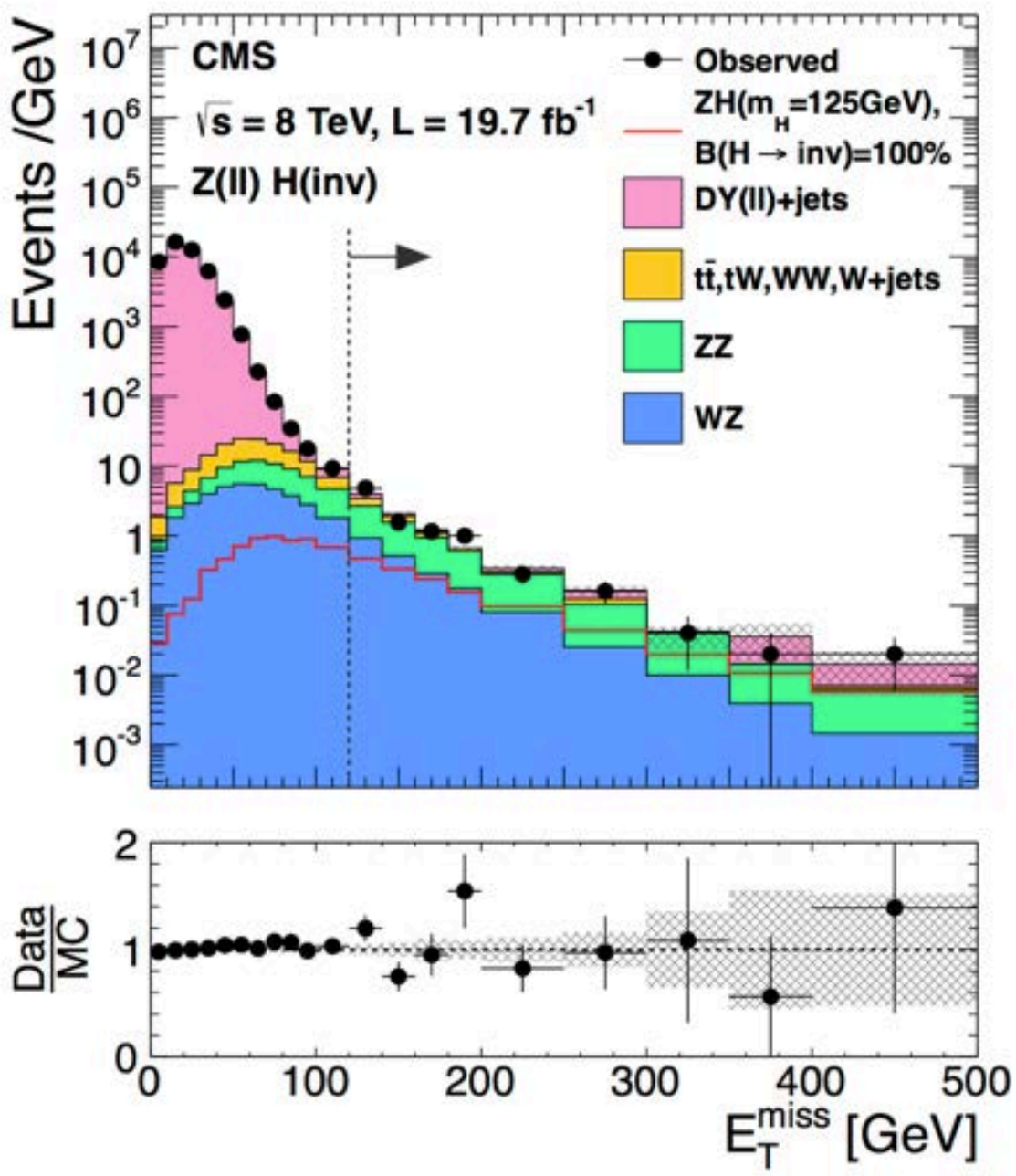
- Veto events with an identified electron, or muon with p_T > 10 GeV.
- VBF tag jet pair, $p_{T,j1}$, $p_{T,j2}$ > 50 GeV, $|\eta| < 4.7$, $\eta_{j1}, \eta_{j2} < 0$, $\Delta\eta_{jj} > 4.2$, and M_{jj} > 1100 GeV
- MET > 130 GeV
- DeltaPhi(j_1,j_2)< 1.0
- Central jet veto (event that has an additional jet with p_T > 30 GeV and pseudorapidity between those of the two tag jets)

Higgs Portal to Dark Matter

arXiv:1404.1344v2

Event selection: Z(ll)+H(inv)

- Two well-identified, isolated leptons of the same flavor and opposite sign with P_T > 20 GeV, M(ll) is within +/- 15 GeV of Z mass
- Veto event if there are two or more jets with P_T > 30 GeV
- Veto event containing a bottom-quark decay identified by either the presence of a soft-muon or by the CSV b-tagging algorithm
- MET > 120 GeV
- $\Delta\phi(\ell\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.7$
- $|E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{\ell\ell}| / p_{\mathrm{T}}^{\ell\ell} < 0.25$

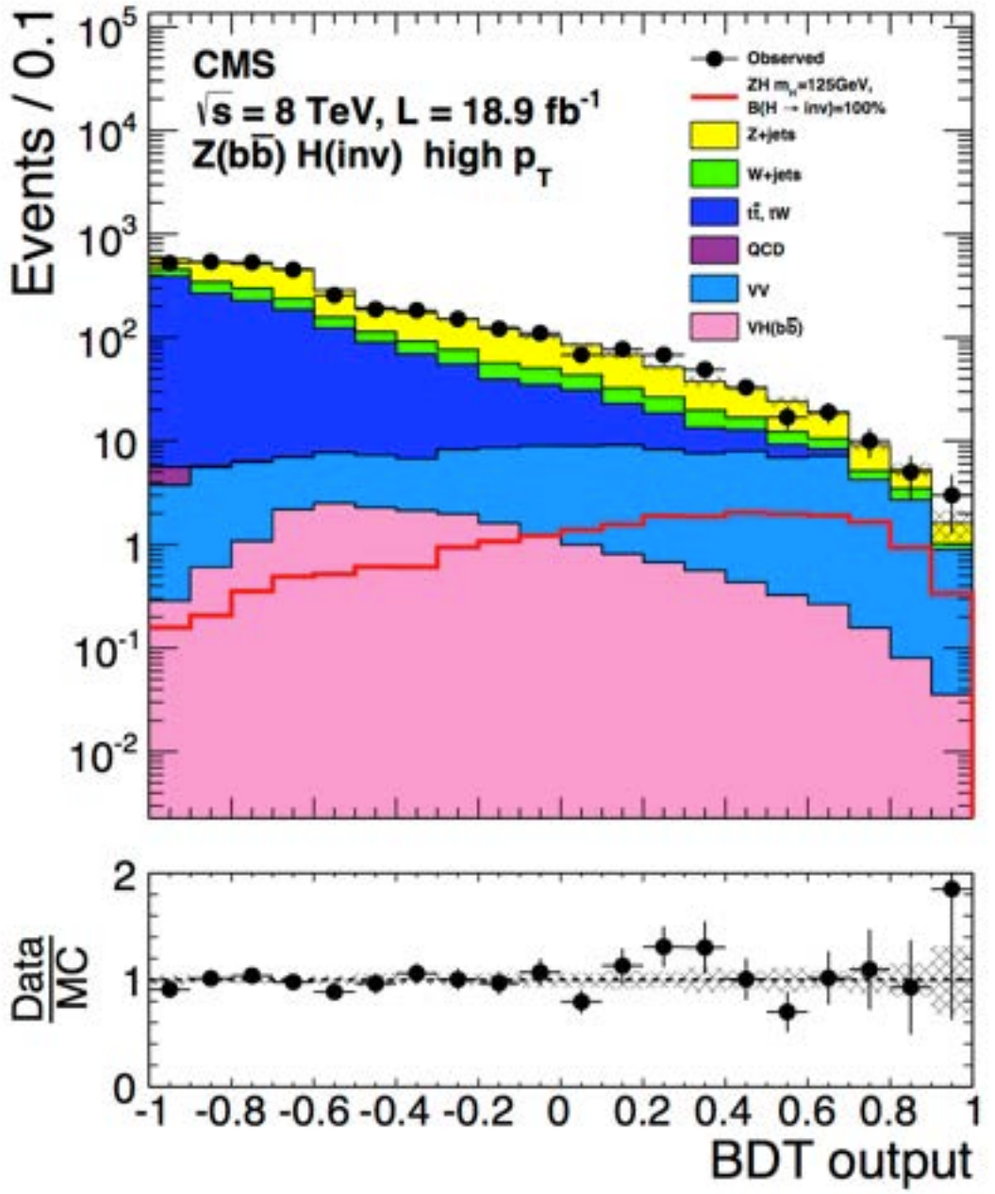


Higgs Portal to Dark Matter

Event selection: Z(bb)+H(inv)

arXiv:1404.1344v2

Variable	Selection		
	Low p_T	Intermediate p_T	High p_T
E_T^{miss}	100–130 GeV	130–170 GeV	>170 GeV
p_T^{j1}	>60 GeV	>60 GeV	>60 GeV
p_T^{j2}	>30 GeV	>30 GeV	>30 GeV
p_T^{jj}	>100 GeV	>130 GeV	>130 GeV
M_{jj}	<250 GeV	<250 GeV	<250 GeV
CSV_{max}	>0.679	>0.679	>0.679
CSV_{min}	>0.244	>0.244	>0.244
N additional jets	<2	—	—
N leptons	=0	=0	=0
$\Delta\phi(Z,H)$	>2.0 radians	>2.0 radians	>2.0 radians
$\Delta\phi(E_T^{miss},j)$	>0.7 radians	>0.7 radians	>0.5 radians
$\Delta\phi(E_T^{miss},E_T^{miss}{}_{trk})$	<0.5 radians	<0.5 radians	<0.5 radians
E_T^{miss} significance	>3	not used	not used



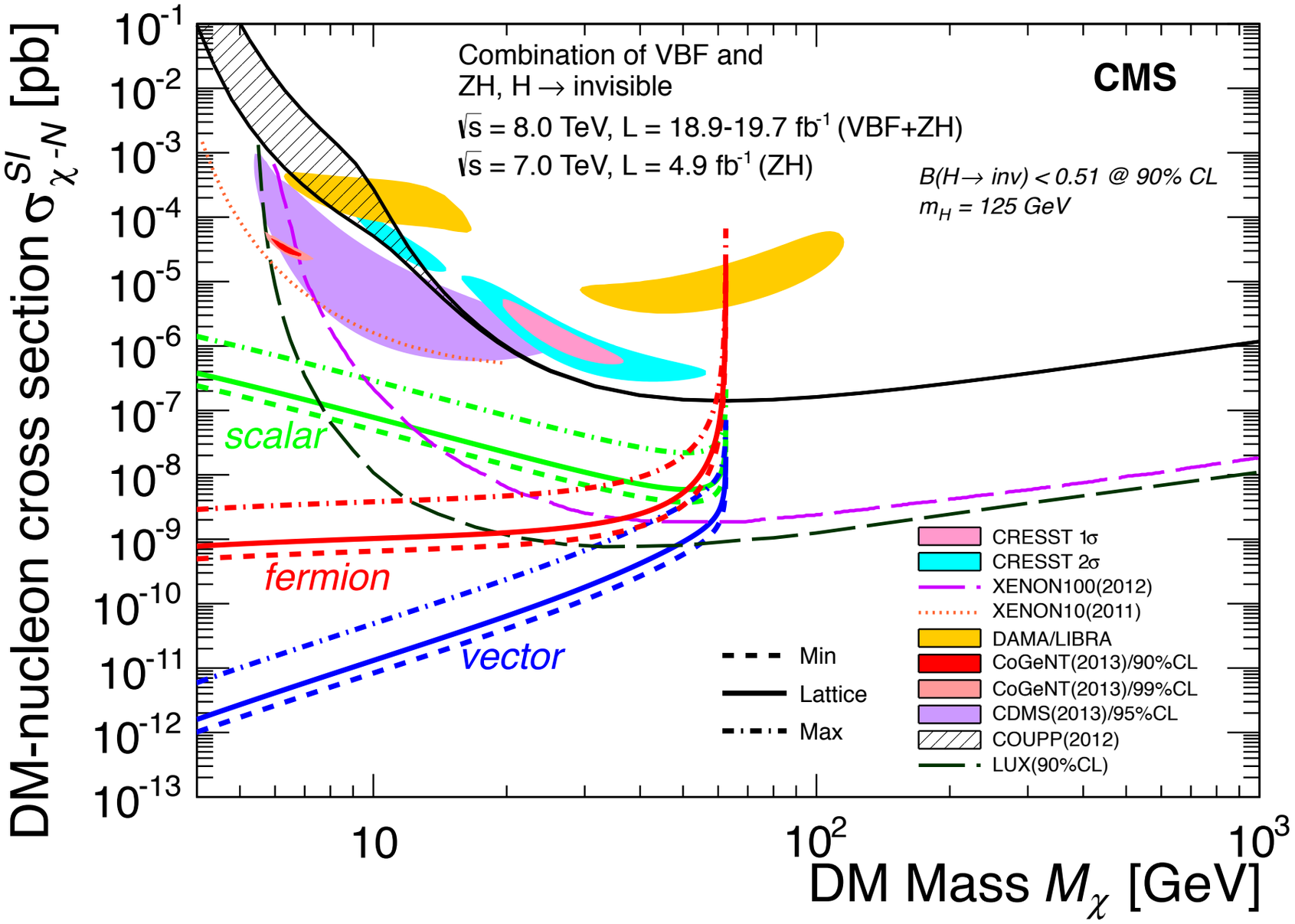
Results (Combine)

- Assuming the SM production cross section and acceptance. mH = 125 GeV
- 95% CL observed upper (expected) limit = 0.58 (0.44)
- 90% CL observed upper (expected) limit = 0.51 (0.38)

Higgs Portal to Dark Matter

Results

arXiv:1404.1344v2



Upper limits on the spin-independent DM-nucleon cross section in Higgs-portal models, derived for mH=125GeV, and B(H→inv) < 0.51 at 90% CL, as a function of the DM mass.

Conclusion

- Presented the collider based search results for Dark Matter at the CMS
- We are trying to cover additional analysis channels, signatures, or models as possibles
- Preparing for LHC Run2 at 13 TeV
  - Triggers
  - Background estimations, and uncertainties
  - Physics models

Backup: minMET (monophoton)

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.

$$\hat{\not{E}}_{x,y} = \not{E}^{reco}_{x,y} + \sum_{i=objects} (p^{reco}_{x,y})_i - (\hat{p_{x,y}})_i$$

$$\hat{\not{E}}_T{}^2 = \hat{\not{E}}_x^2 + \hat{\not{E}}_y^2$$

$$\chi^2 = \sum_{i=objects} \left(\frac{(p_T^{reco})_i - (\hat{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left(\frac{\hat{\not{E}}_x}{\sigma_{\hat{\not{E}}_x}} \right)^2 + \left(\frac{\hat{\not{E}}_y}{\sigma_{\hat{\not{E}}_y}} \right)^2 .$$

If the Met is intrinsic, balancing the object momenta wouldn't be easy and will result in high χ^2 .

The variables that give good discrimination are the Prob(χ^2) and the recalculated minimized Met.

Backup: BDT parameters, Z(bb)+H(inv)

Table 6: Input variables to the $Z(b\bar{b})H(inv)$ BDT.

Variable	
p_T^{j1}, p_T^{j2}	Transverse momentum of each Z boson daughter
M_{jj}	Dijet invariant mass
p_T^{jj}	Dijet transverse momentum
E_T^{miss}	Missing transverse energy
N_{aj}	Number of additional jets ($p_T > 25\,GeV$ and $\|\eta\| < 4.5$)
CSV_{max}	Value of CSV for the Z boson daughter with largest CSV value
CSV_{min}	Value of CSV for the Z boson daughter with second largest CSV value
$\Delta\phi(Z,H)$	Azimuthal angle between E_T^{miss} and dijet
$\Delta\eta_{jj}$	Difference in η between Z daughters
ΔR_{jj}	Distance in η-ϕ between Z daughters
$\Delta\theta_{pull}$	Color pull angle [62]
$\Delta\phi(E_T^{miss}, j)$	Azimuthal angle between E_T^{miss} and the closest jet
CSV_{aj}	Maximum CSV of the additional jets in an event
$\Delta R(H, aj)$	Minimum distance between an additional jet and the Z boson candidate
m_T	Transverse mass of the ZH system