Dark Matter @ CMS

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On behalf of the CMS Collaboration

From Higgs to Dark Matter: Second Topical Meeting,

Dr Holms Hotel, 14-17 Dec 2014, Geilo (Norway)

OUTLINE

- ✧ **DM Models & Signatures in CMS searches**
- ✧ **Analyzing CMS data**
- ✧ **MonoJet, MonoLepton, MonoPhoton, MonoTop, Top pairs**
- ✧ **SUSY Searches**
- ✧ **Perspectives for LHC Run 2**

Some material borrowed from Phil Harris, Nadir Daci, Steven Lowette, Fedor Ratnikov

Introduction

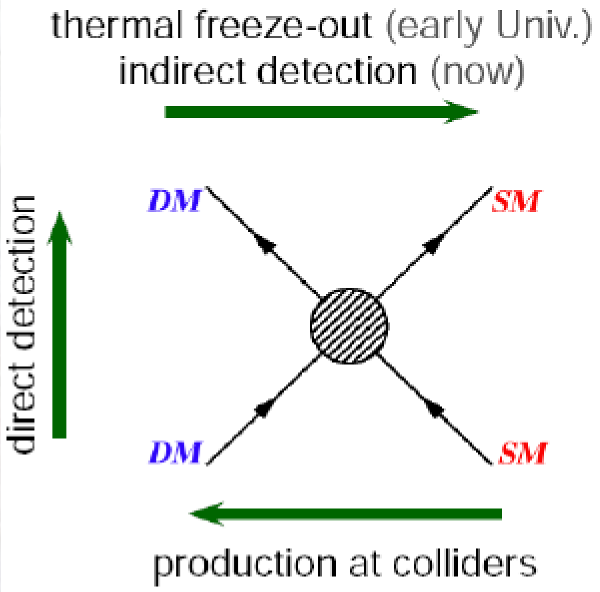
First was unveiled to us through gravitational effects few decades ago, but still we know very little about it:

Particle(?), electrically neutral, not short-lived, not baryonic, not hot

as a result, the theoretical landscape is huge

three complementary search strategies

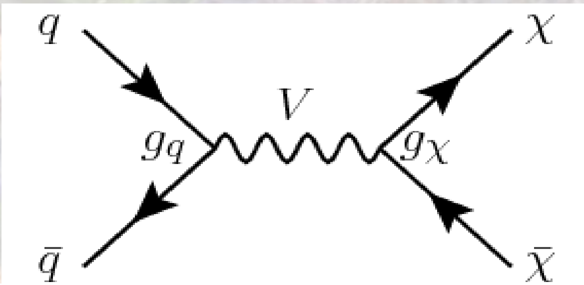
- direct detection
- indirect detection
- production at colliders

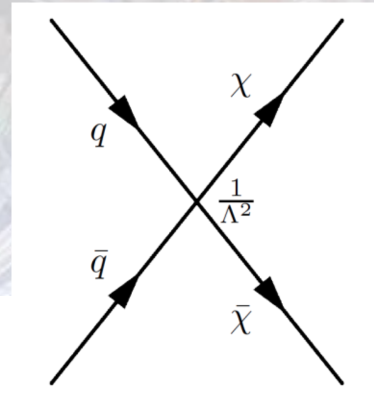


DM models in CMS searches

✧ Most of the CMS DM searches use **Effective Field Theories** :

⇒ ***MonoJet, MonoLepton, MonoPhoton, Top pair***





$$L = \frac{M_V}{\sqrt{g_c g_q}}$$

VECTOR	AXIAL-VECTOR
$g_{\rm DM} Z'_\mu \bar{\chi}\gamma^\mu\chi$	$g_{\rm DM} Z''_\mu \bar{\chi}\gamma^\mu\gamma^5\chi$
EWK style coupling (equal to all leptons)	EWK style coupling (equal to all leptons)
Sensitive w/Direct Detection	Less Sensitive w/DD
SCALAR	**PSEUDOSCALAR**
$g_{\rm DM} S \bar{\chi}\chi$	$g_{\rm DM} P \bar{\chi}\gamma^5\chi$
Yukawa style coupling (Mass based coupling)	Yukawa style coupling (Mass based coupling)
Less Sensitive w/DD	No bounds from DD Only Cosmic bounds exist

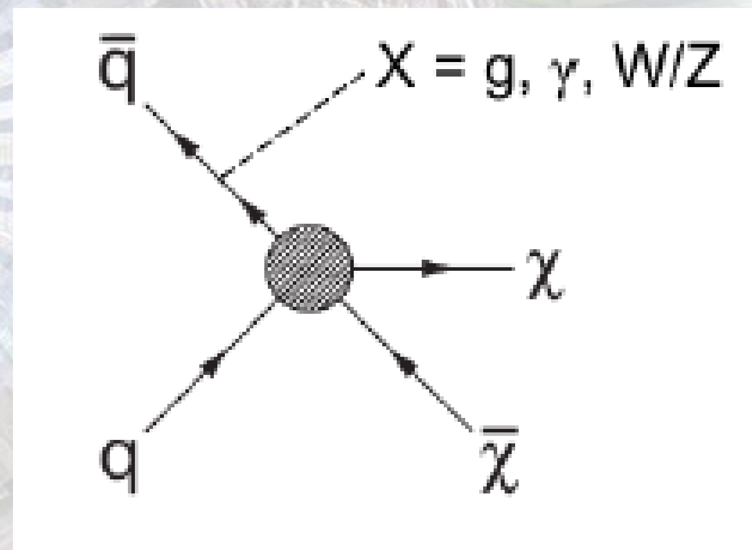
➢ **Validity**:
$M_V >> \sqrt{s} = O(10\ \text{TeV})$

➢ **Search parameters** :
cut-off scale Λ ; DM mass m_χ

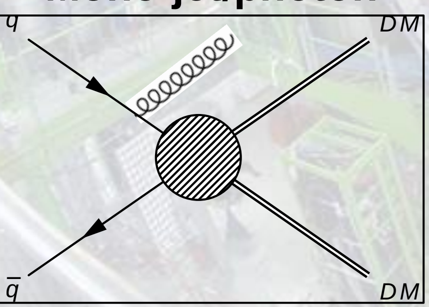
➢ **Operators** :
probe spin-(in)dependent interactions

DM Production in Colliders

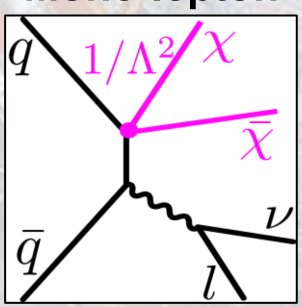
- Production in the cascade
  - SUSY, LSP in R-Parity conserving models
  - Higgs portal, Invisible higgs decay width (limited by the higgs mass)
- Pair production
  - Featured in most scenarios,
  - back-to-back pair are invisible!
  - Recoil of an SM particle against the DM pair



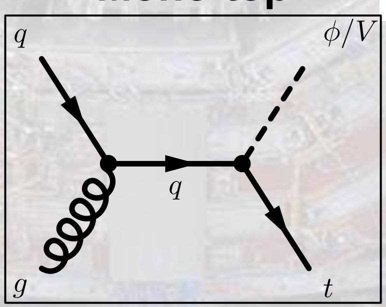
ISR jet/photon
Mono-jet/photon



Recoiling W
Mono-lepton



Single top
Mono-top

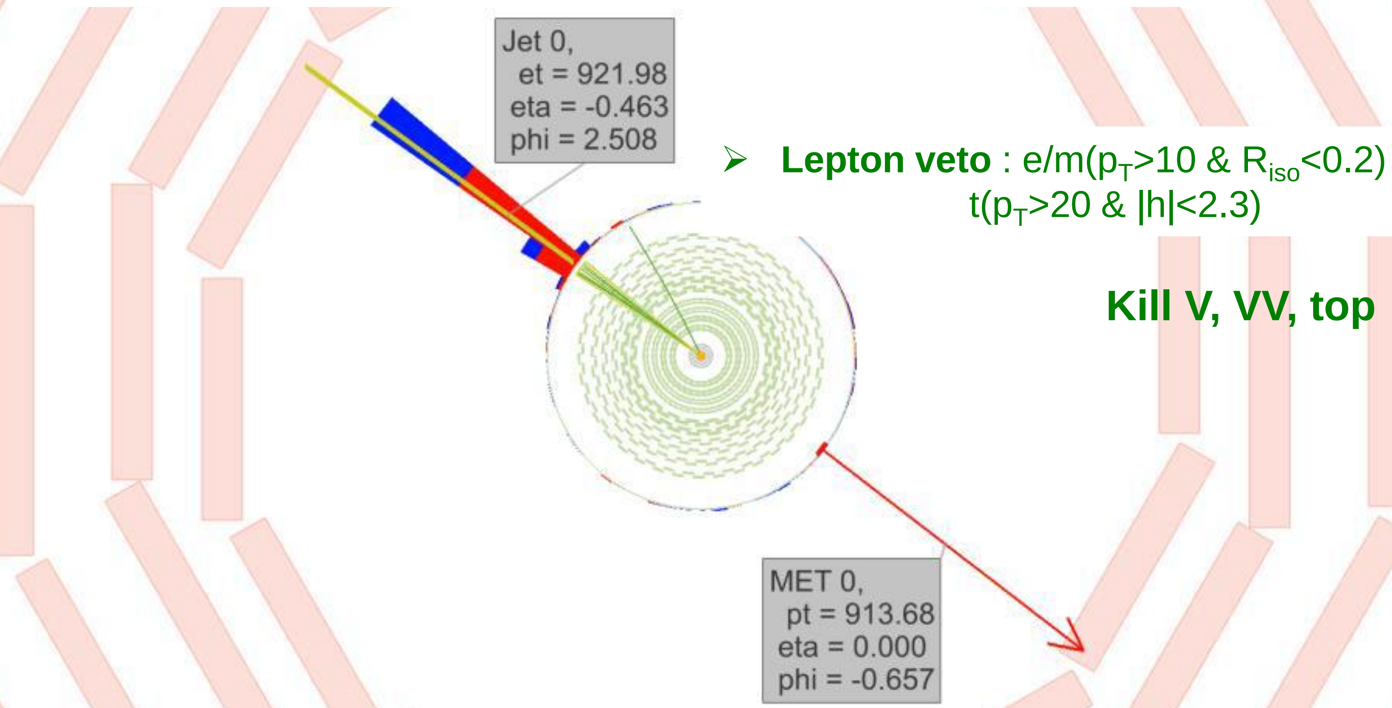


MonoJet : event selection

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

- **Jet** p_T>110 & $|\eta|$<2.4
- p_T fractions : ch. had. ≥ 20% & neutr. had. ≤ 70% & photons ≤ 70%
- Accept 2nd jet (p_T>30 & $|\eta|$<4.5 & $D\phi_{J1J2}$ <2.5) ; Veto 3rd jet (p_T, η)

Kill QCD, ttbar

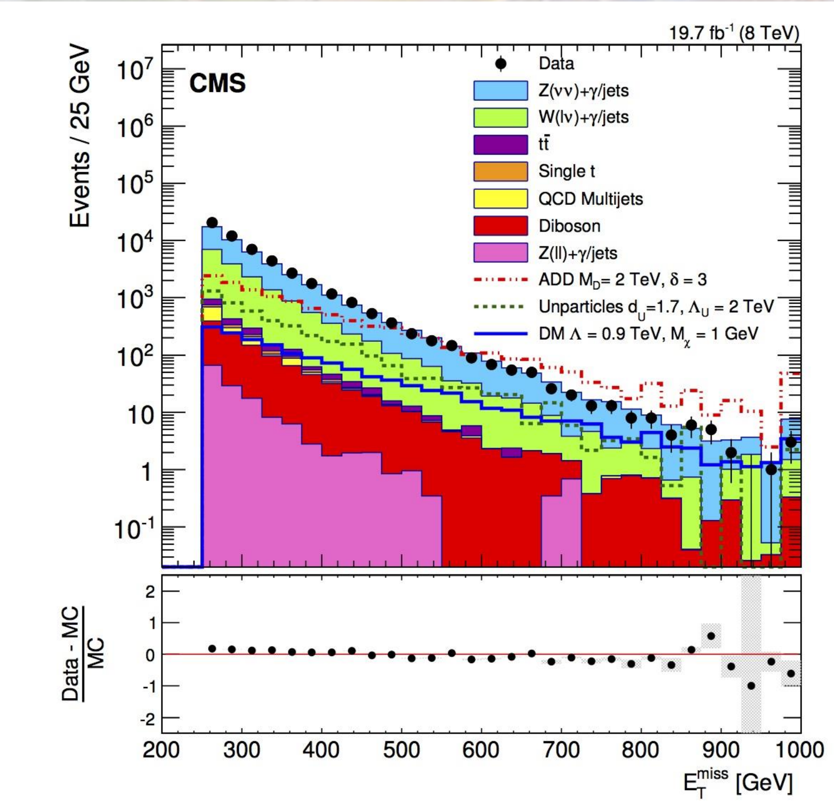


- **Lepton veto** : e/m(p_T>10 & R_{iso}<0.2)
  t(p_T>20 & |h|<2.3)

Kill V, VV, top

- **MET ≡** Missing Transverse Energy = Vectorial sum of the visible objects
- **7 MET Regions** : MET > {250, 300, 350, 400, 450, 500, 550} GeV

MonoJet : signal extraction



⟹ Single-bin counting experiment after optimal MET cut

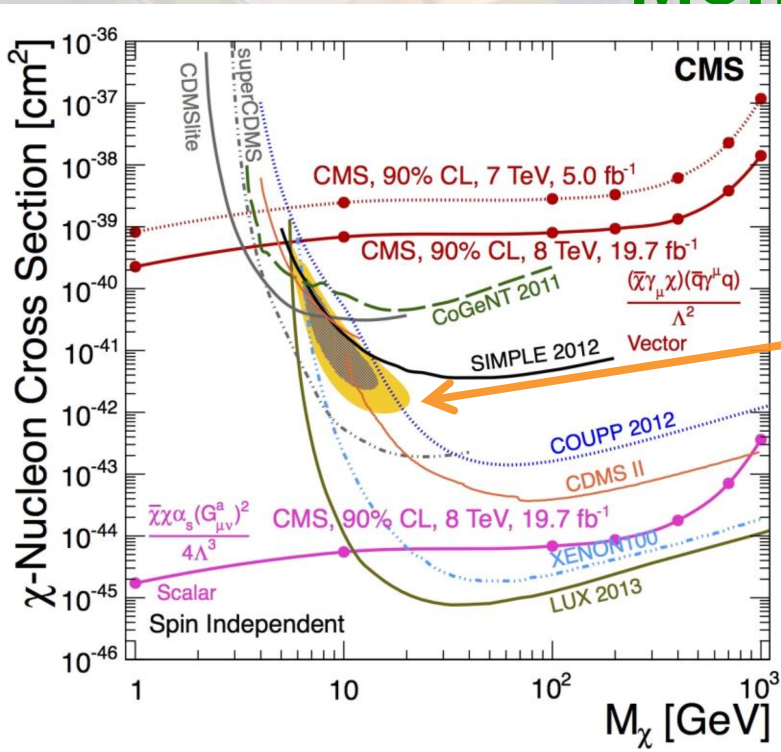
Z→νν & Wjets are estimated using μ+jets and cross checked with Z->μμ.

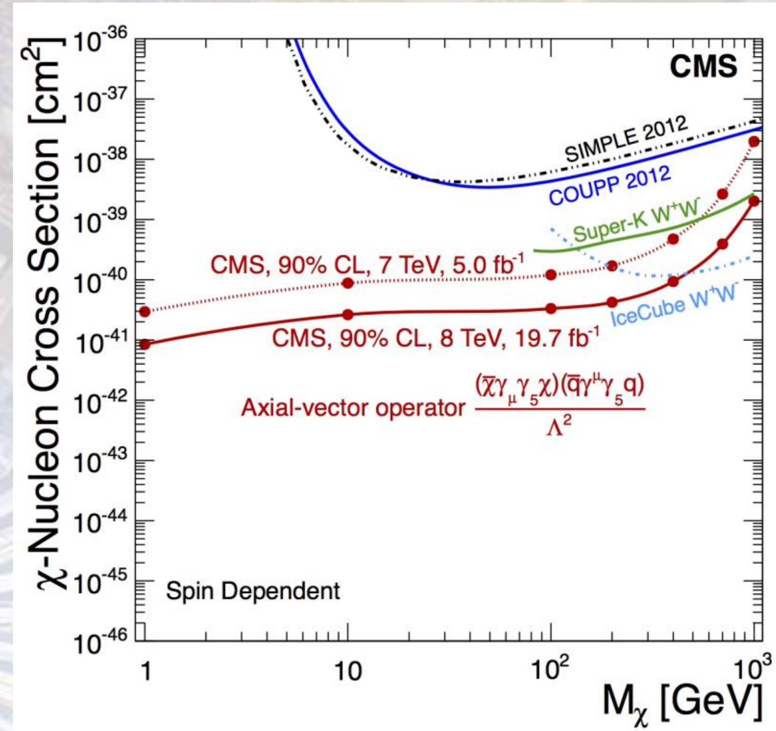
$$QCD = QCD^{Sgn}_{MC} \times \frac{QCD^{Ctrl}_{\text{Data}}}{QCD^{Ctrl}_{MC}}, \text{Ctrl} = \{\text{relax N}; \Delta\varphi_{J1J2} < 0.3\}$$

E_T^{miss} (GeV) →	> 250	> 300	> 350	> 400	> 450	> 500	> 550
$Z(\nu\nu)$+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
$Z(\ell\ell)$+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ±88.5	76 ±38.0	23 ±11.5	3 ±1.5	2 ±1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131

MonoJet : results

CMS PAS EXO-12-048





Vector coupling

Spin-independent interaction

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

Axial-Vector coupling

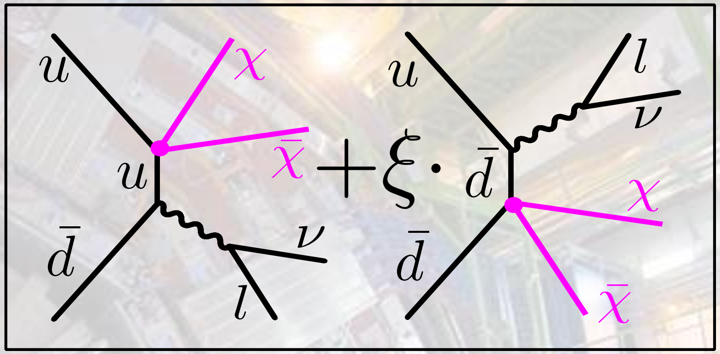
Spin-dependent interaction

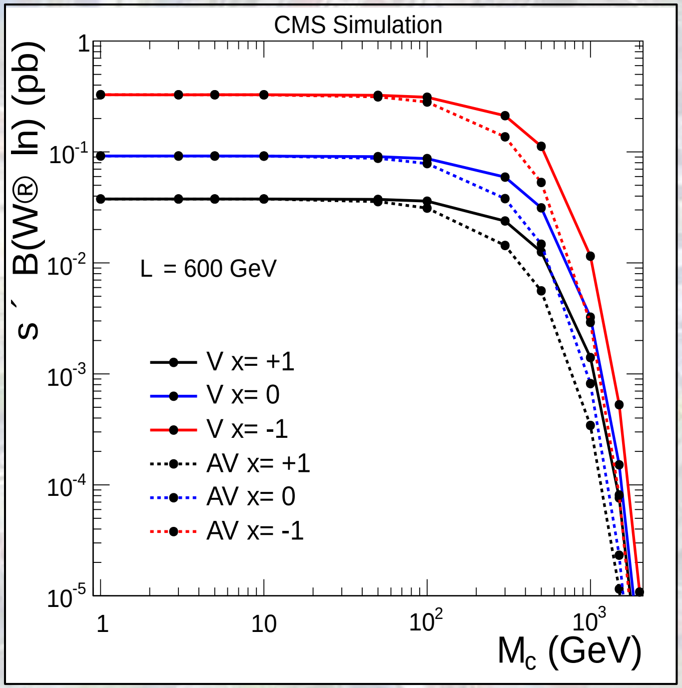
$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

MonoLepton

✧ **Advantages** : clean leptonic signature
⟹ less background @ LHC
⟹ easier to trigger than monojet/monophoton

✧ **Interferences** ⟹ sensitive to different couplings for Up- and Down- type quarks

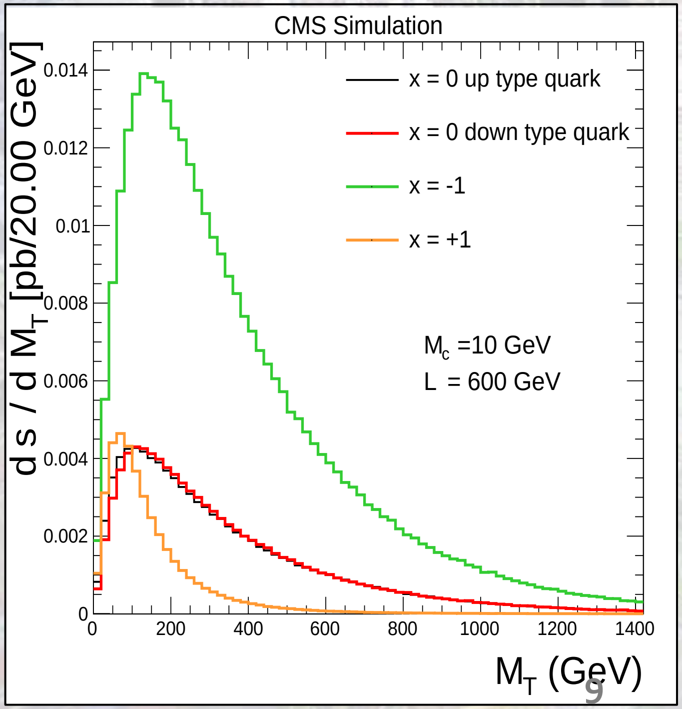




- Largest σ for ξ=-1
- Mχ > 100 GeV ⟹ steep drop (limited ϕ-space)
- "edge" depends on ξ.

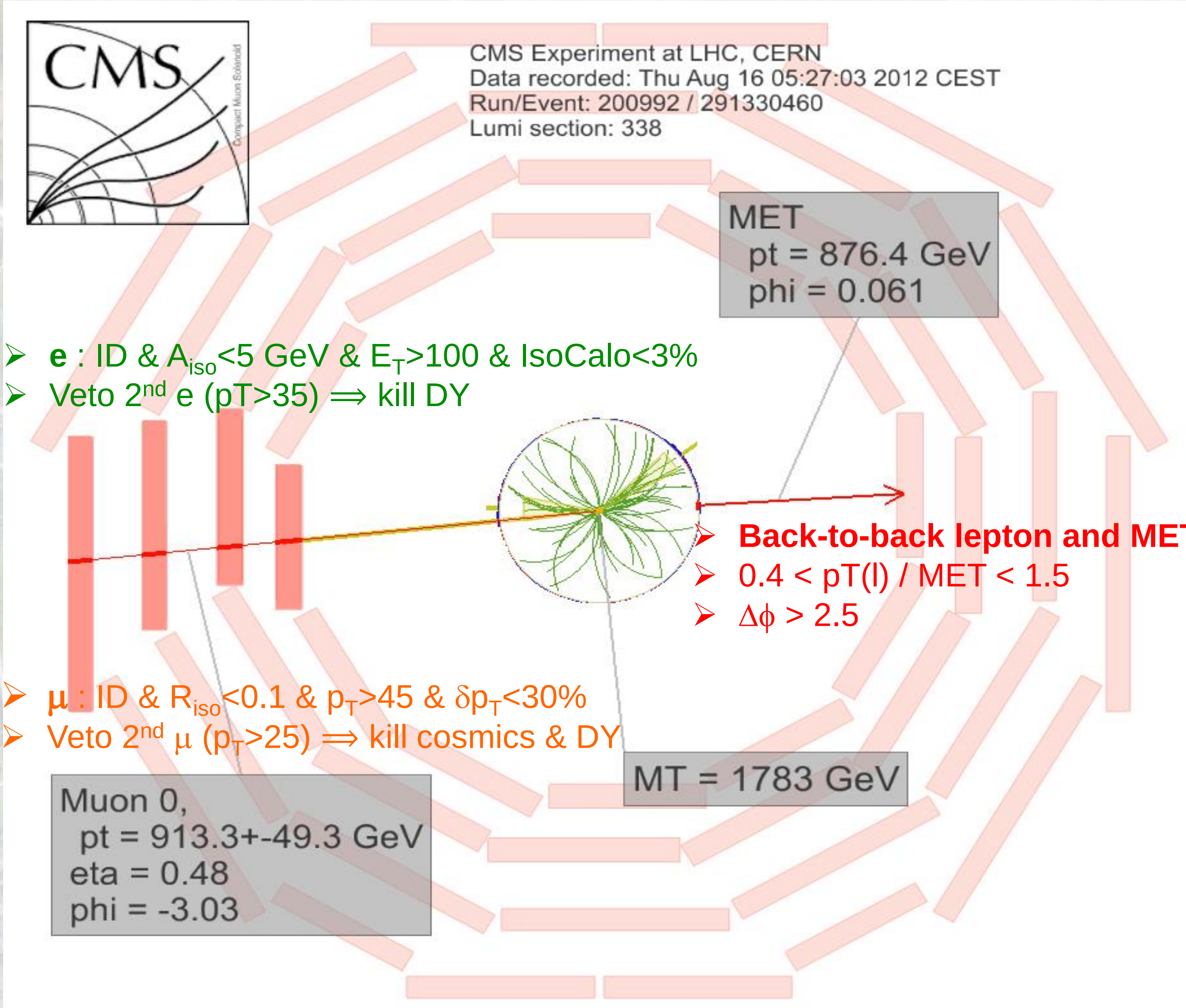
Master variable → transverse mass m_T

$$M_T = \sqrt{2 \cdot p_T(\ell) \cdot \not{E}_T \cdot (1 - \cos\Delta\phi(\ell,\nu))}$$



- Shape m_T depends on ξ !

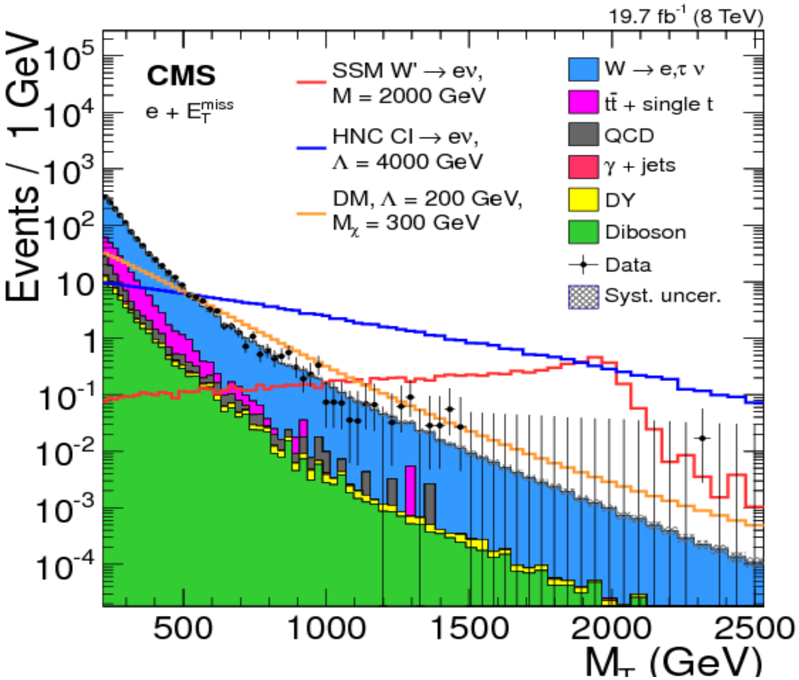
MonoLepton : event selection

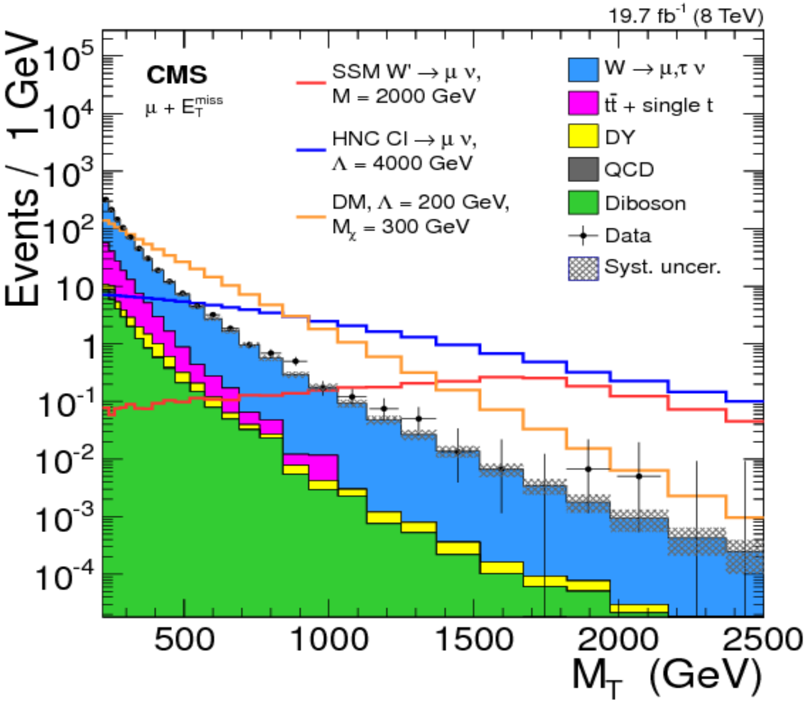


- **e** : ID & A_{iso}<5 GeV & E_T>100 & IsoCalo<3%
- Veto 2nd e (pT>35) ⟹ kill DY

- **Back-to-back lepton and MET**
- 0.4 < pT(l) / MET < 1.5
- $\Delta\phi > 2.5$

- **μ** : ID & R_{iso}<0.1 & p_T>45 & δp_T<30%
- Veto 2nd μ (p_T>25) ⟹ kill cosmics & DY





MonoLepton : signal extraction

⟹ m_T shape analysis : multi-bin counting

Major backgrounds = MC x SF from data

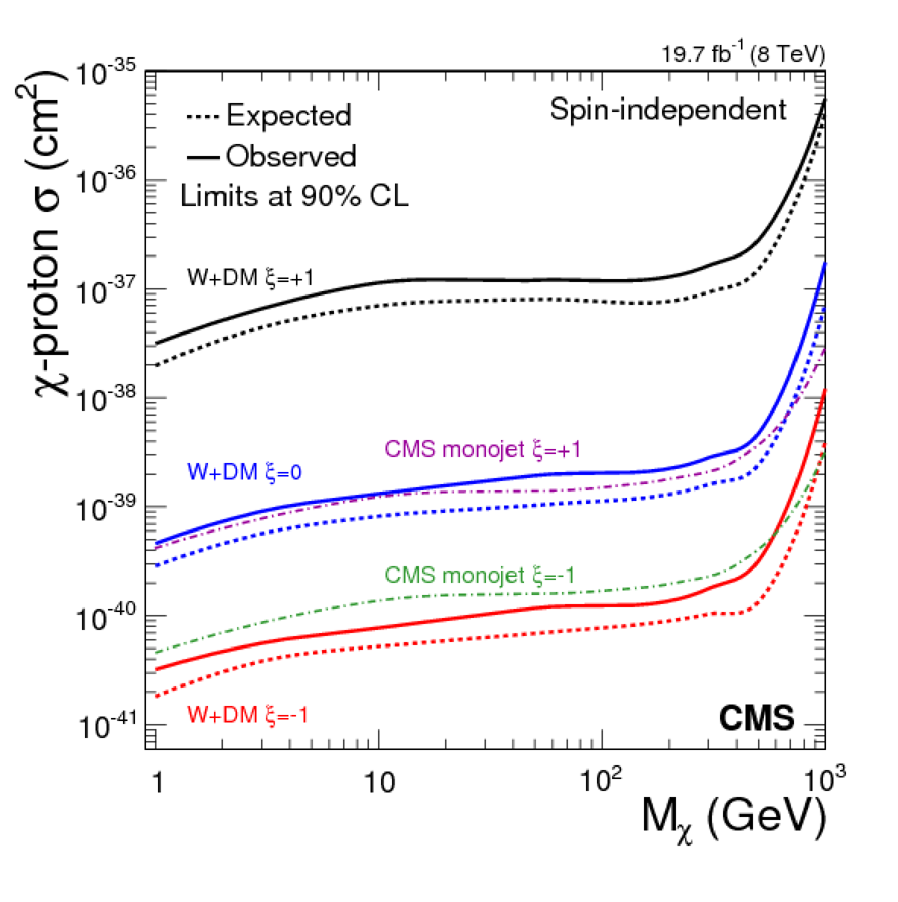
$$QCD = Data^{Sgn}_{\text{e fails iso}} \times \frac{r_{ttl}}{1 - r_{ttl}}, \; r_{ttl}(E_T^e, \eta^e) = \frac{Data^{Ctrl}_{\text{e pass iso}}}{Data^{Ctrl}}$$

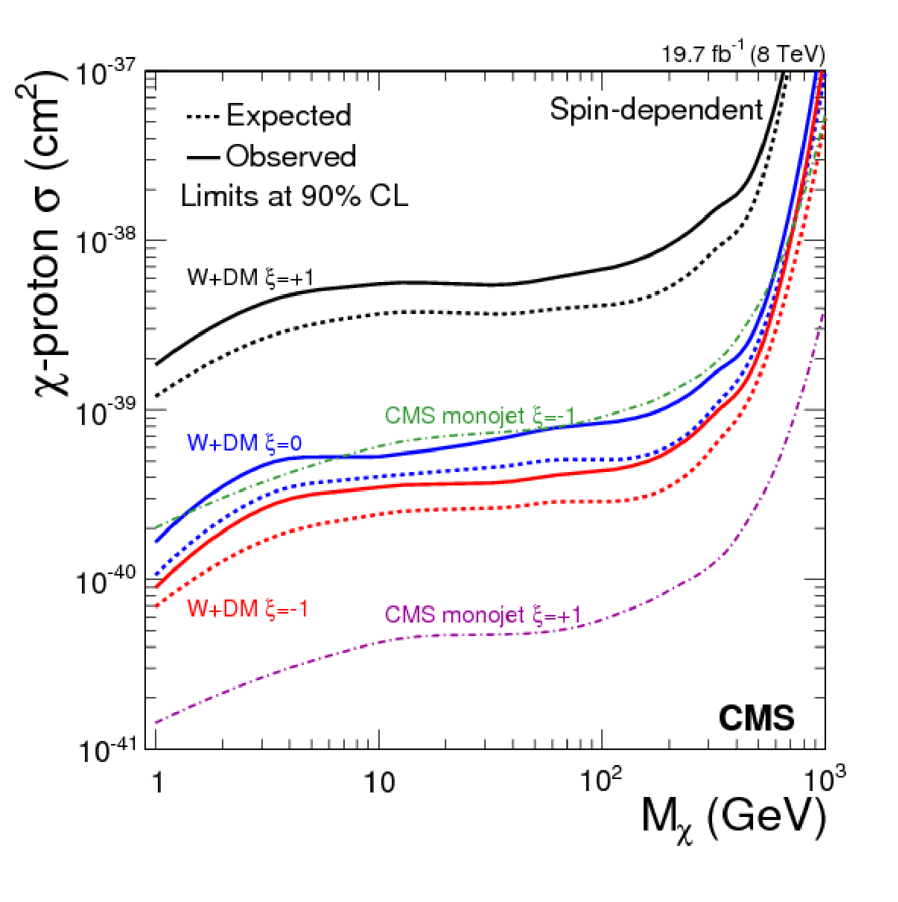
$$\text{Ctrl} = \{1.5 < \frac{E_T^e}{MET} < 10\}$$

High mT tail : fit $f(m_T) = e^{a + bm_T + cm_T^2} \times m_T^d$

MonoLepton : results

CMS PAS EXO-12-060





Vector coupling

Spin-independent
Interaction

Comparable to monojet reach

Axial-Vector coupling

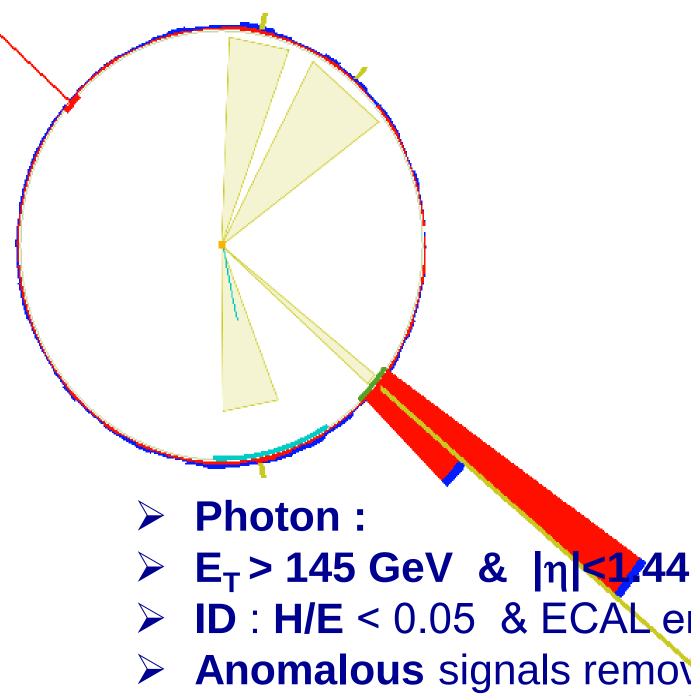
Spin-dependent
interaction

MonoPhoton : event selection

- **MET > 140**
- $\Delta\phi$(MET-γ) > 2.0
- "MET ID" : χ^2 fit using unclustered energy
  $\Rightarrow$ remove fake MET

- **Lepton veto :** $\geq$1 isolated lepton
- R_{iso} < 0.2 (e) / 0.1 (μ)

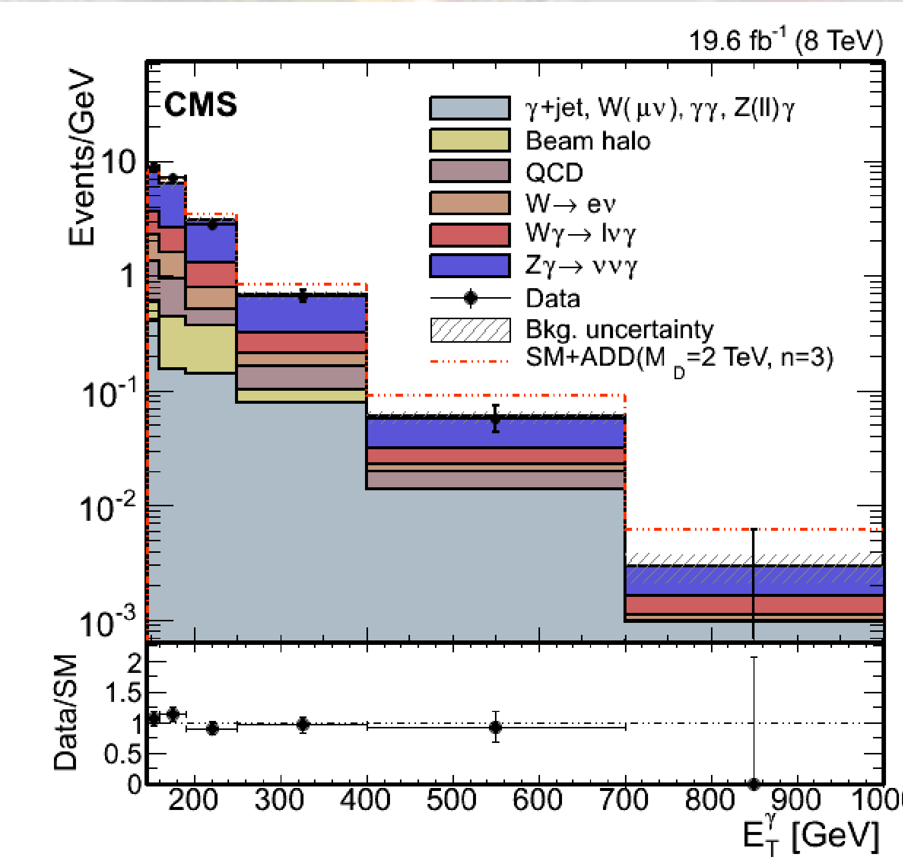
Kill W(lν)+γ



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

- **Photon :**
- **E_T > 145 GeV & $|\eta|$<1.44 (purity)**
- **ID** : **H/E** < 0.05 & ECAL energy deposit's **shape**
- **Anomalous** signals removal, **timing** cut (BX$\pm$3ns)
- **PF isolation** : surrounding $h^{\pm,0}$ and photons
- **Fake** photons from electrons removed

MonoPhoton : signal extraction



⟹ Single-bin counting experiment after $p_T(\gamma)$ cut

Major backgrounds = MC x SF from data

$$W(e\nu) = Data(\text{Sgn, PIX matching}) \times \frac{1 - \varepsilon^{\text{Match PIX}}_{\text{Data}}}{\varepsilon^{\text{Match PIX}}_{\text{Data}}}$$

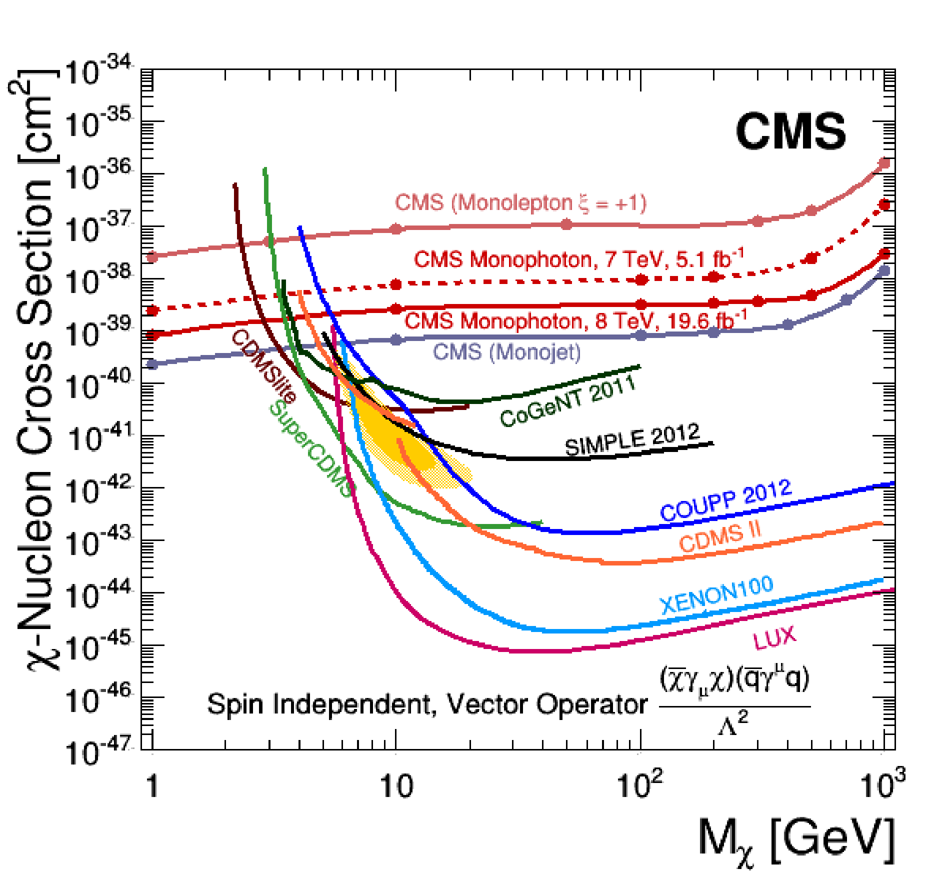
$$QCD = Data^{Sgn,\gamma\ \text{fails iso}} \times \frac{QCD^{jet\ \text{pass}\ \gamma\ \text{ID}}_{Data} - QCD^{\text{real}\ \gamma}_{MC}}{QCD^{jet\ \text{fail} \geq 1\ \text{iso cut}}_{Data}}$$

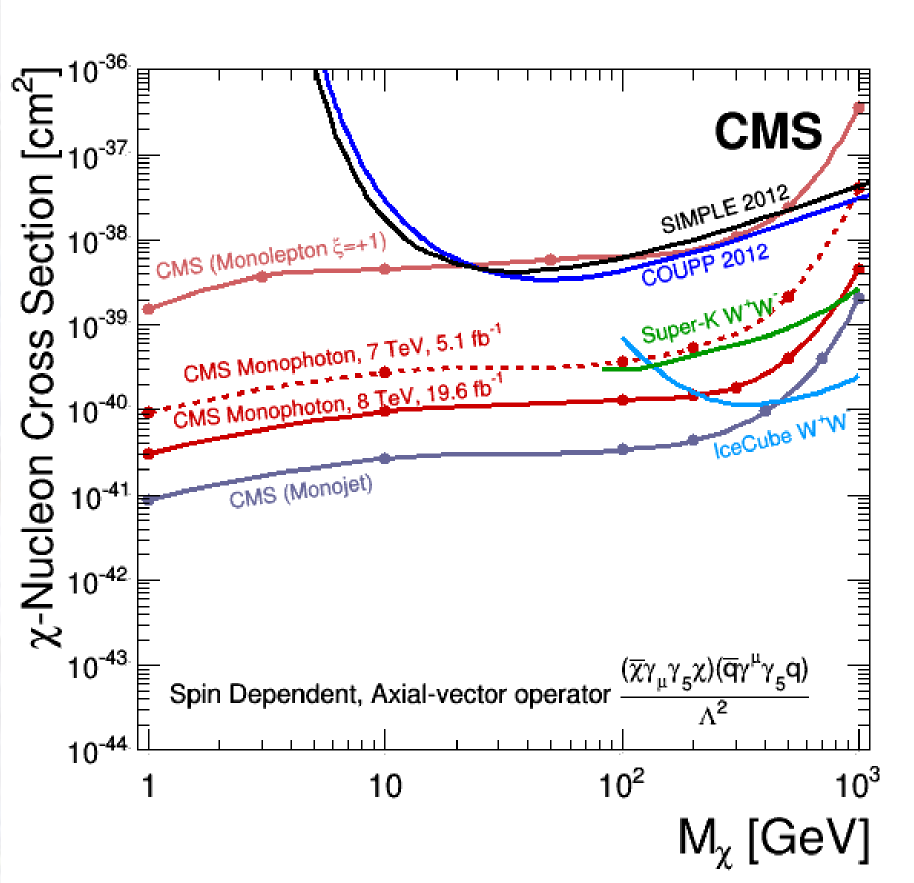
Beam halo ⟹ timing distribution in data

Process	Estimate
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	345 ± 43
$W(\rightarrow \ell\nu) + \gamma$	103 ± 21
$W \rightarrow e\nu$	60 ± 6
jet $\rightarrow \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	614 ± 63
Data	630

MonoPhoton : results

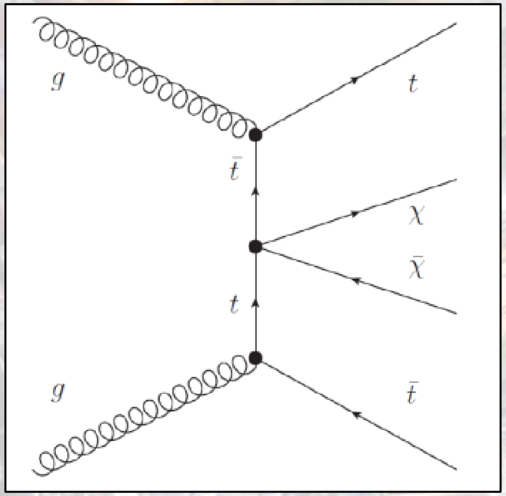
CMS PAS EXO-12-047





Top Pairs & MonoTop

➢ Top pairs



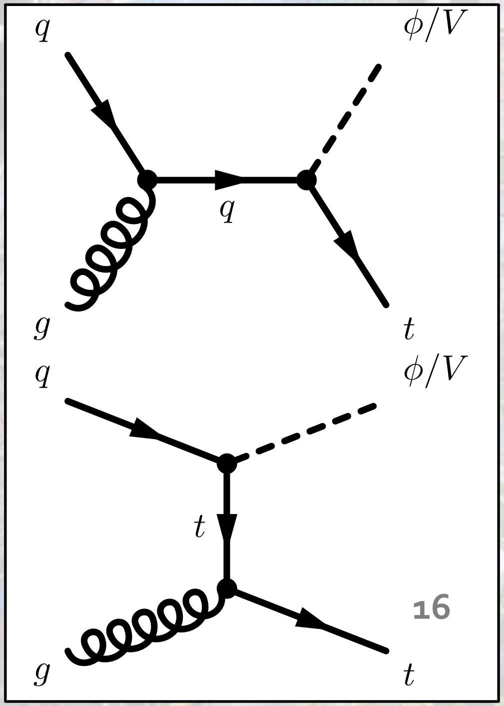
- ✧ Heavy quarks enhance sensitivity to **scalar** interactions

$$L_{\text{int}} = \frac{m_q}{\mathrm{L}^3} q\bar{q}\, c\bar{c}$$

- ✧ Two possible final states : $tt \rightarrow bb + ll / ljj$

- ✧ **Signatures**: 1. Large MET + 2 leptons + ≥2 Jets @low pT
  2. Large MET + 1 lepton

➢ MonoTop



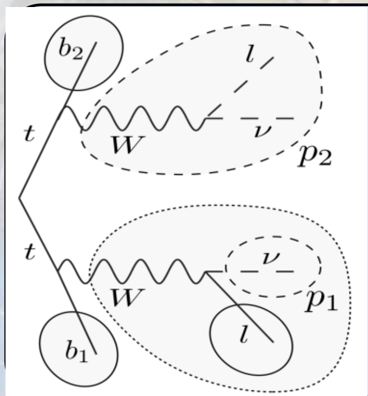
- ✧ Probe couplings that favor heavy quarks

- ✧ **FCNC** diagrams with new particle in the final state

- ✧ Search for scalar & vector DM particle

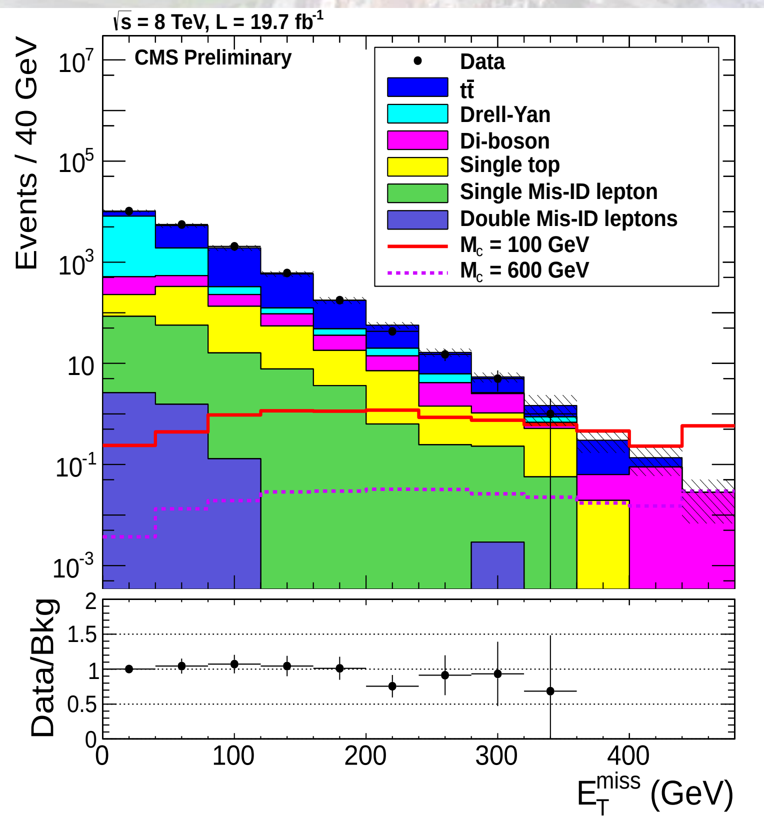
- ✧ **Signature** : t → bW(qq) → 1 b-jet + 2 jets + MET

Top Pairs dileptonic



- Leptons : $R_{iso} < 0.12(\mu)$, 0.1 (e) ; $p_T > 20$; $|\eta| < 2.4$ (μ), 2.5 (e)
- Leptons : m_{L1L2}>20 ; $m_{ll} = m_Z \pm 15$ GeV ; scalar pT sum > 120 ; $\Delta\phi$<2
- Jets : ≥2 Jets pT>30 & |h|<5 & loose ID
- Jets : scalar pT sum < 400
- MET > 320

⟹ Fit (S,B) to data



- Irreducible backgrounds = MC x SF from data
⟹ tt, t, DY, VV

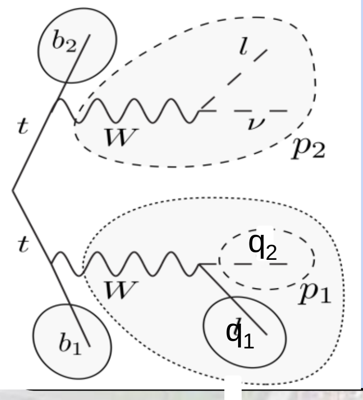
- Fakes : 1 or 2 mis-ID lepton(s)

$$Fake^{NL}_{Data} = Data^{\text{1 Lepton fails Tight but passes Loose}}_{\text{1 Lepton passes Tight ID}} \times \frac{e^{\text{Nloose L passes tight ID}}_{Data}}{1 - e^{\text{Nloose L passes tight ID}}_{Data}}$$

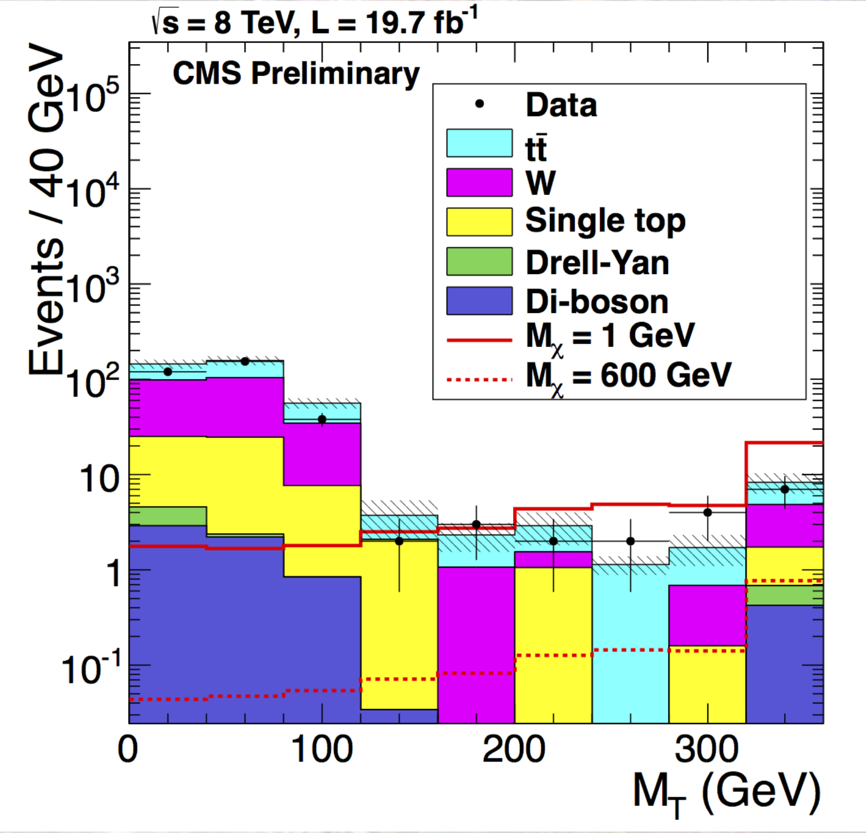
Background Source	Yield
$t\bar{t}$	$0.87 \pm 0.18 \pm 0.27$
Single top	$0.48 \pm 0.46 \pm 0.09$
Di-boson	$0.32 \pm 0.09 \pm 0.05$
Drell-Yan	$0.19 \pm 0.14 \pm 0.03$
One Mis-ID lepton	$0.02 \pm 0.07 \pm 0.02$
Double Mis-ID leptons	$0.00 \pm 0.00 \pm 0.00$
Total Bkg	$1.89 \pm 0.53 \pm 0.39$
Data	1
Signal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

Top Pairs semileptonic

CMS PAS B2G-14-004



- 1 Lepton : $R_{iso} < 0.12(\mu)$, 0.1 (e) ; $p_T > 30$; $|\eta| < 2.1$ (μ), 2.5 (e)
- Jets : ≥3 Jets pT>30 & $|\eta|<4$ & loose ID & ≥1 b-jet
- Jets/MET : $\Delta\phi$(Jet1+Jet2 , MET) > 1.2
- MET>320 GeV & m_T>160 GeV & m_{T2}^W (W decay kinematics)>200 GeV

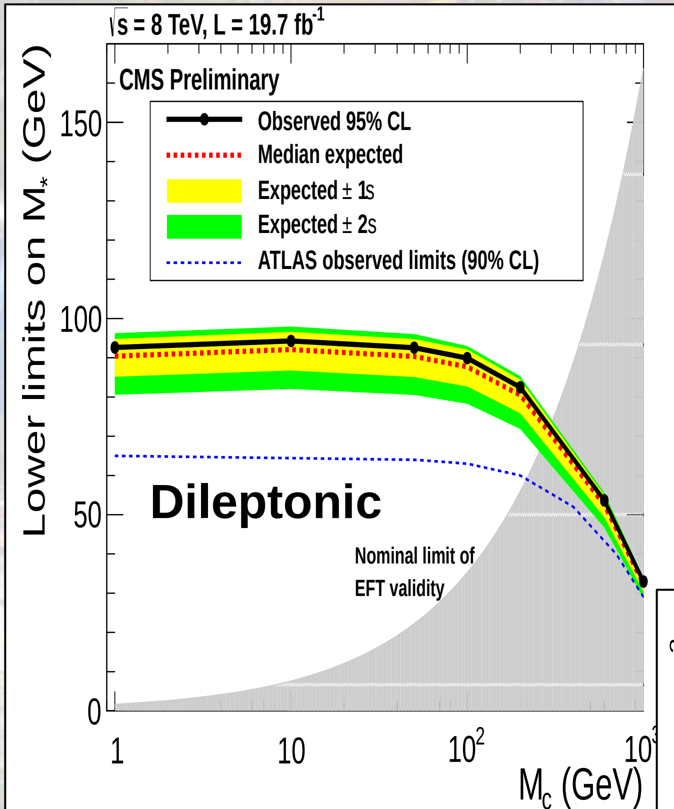


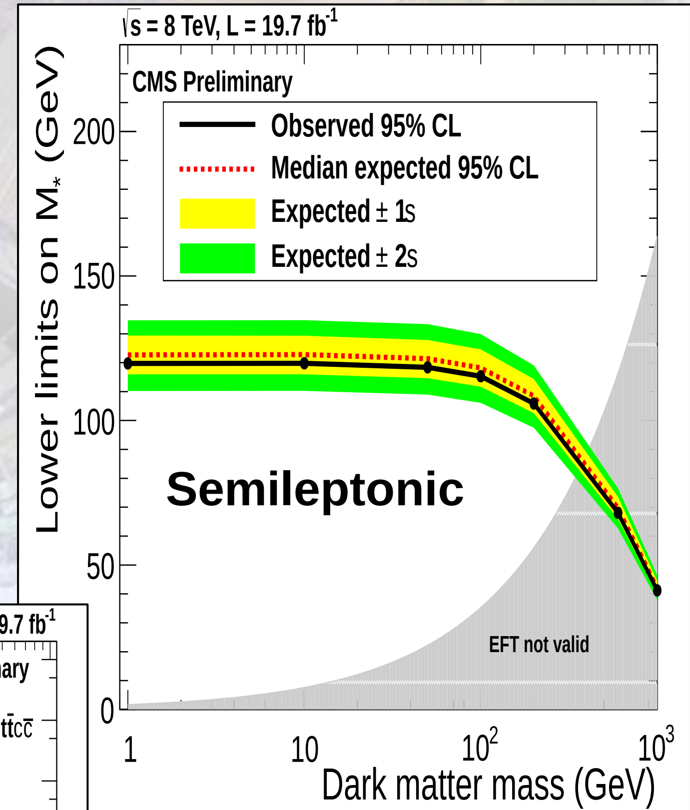
⟹ **Fit (S,B) to data**

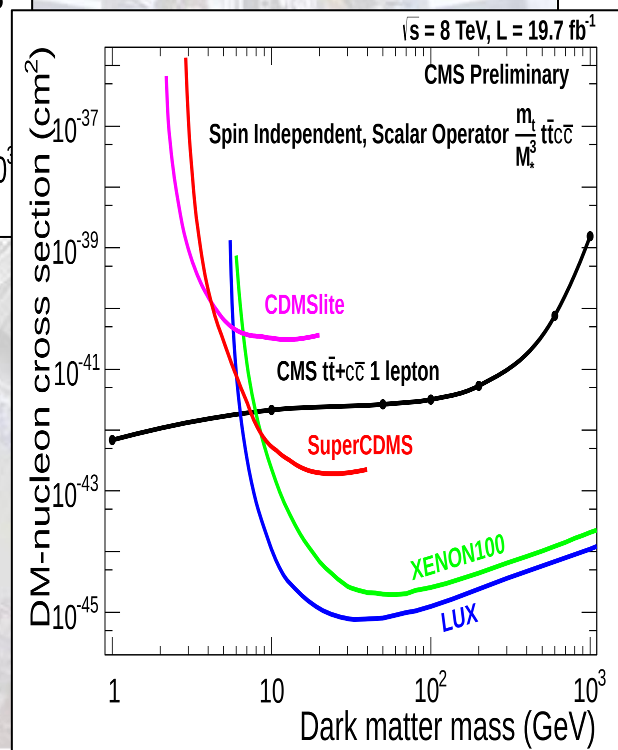
- All backgrounds = MC x SF from data

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	$38.3 \pm 0.7 \pm 2.1$

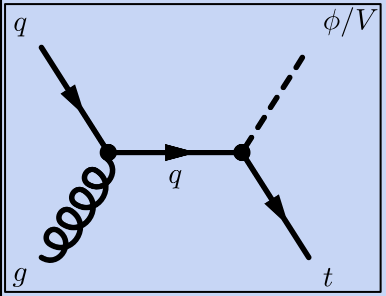
Top Pairs : results



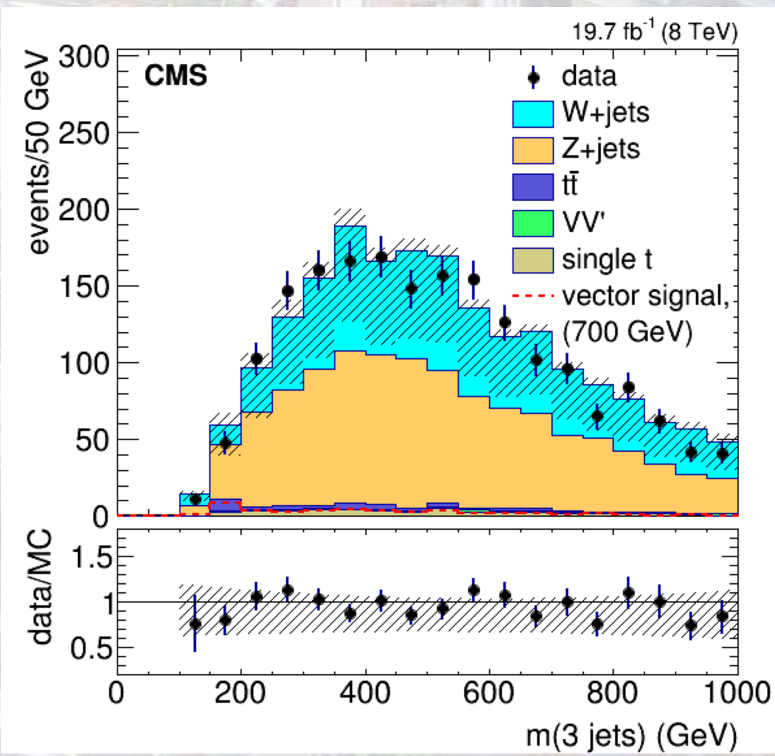




MonoTop : event selection



- 2 jets pT>60, 3rd jet pT>40 ; m3j<250 ; 1 b-jet ; all jets : |eta|<2.4
- 4th jet veto : pT > 35
- Lepton veto : pT>10(20) m(e) ; |h|<2.4(2.5) m(e) ; Riso ≤ 2
- MET > 350



$$Z(nn) = \frac{Z(mm+3Jets)^{Sgn}_{\mathrm{Data}} - Bkg^{Sgn}_{MC}}{A_{\mathrm{MC}} \times e_{\mathrm{MC}} \times \mathrm{SF}^{\mathrm{Data}}_{\mathrm{MC}}} \times \frac{BR(Z \rightarrow nn)}{BR(Z \rightarrow mm)}$$

$$W(ln) = \frac{W(ln+3J)^{\mathrm{Sgn}}_{\mathrm{Data}} - Bkg^{\mathrm{Sgn}}_{MC}}{A^{m}_{\mathrm{MC}} ´ e^{m}_{\mathrm{MC}} ´ \mathrm{SF}(m)} ´ \quad å_{l=e,m,t_h} \; p(\text{lost l}) ´ \; p_{MC}(b - tag)$$

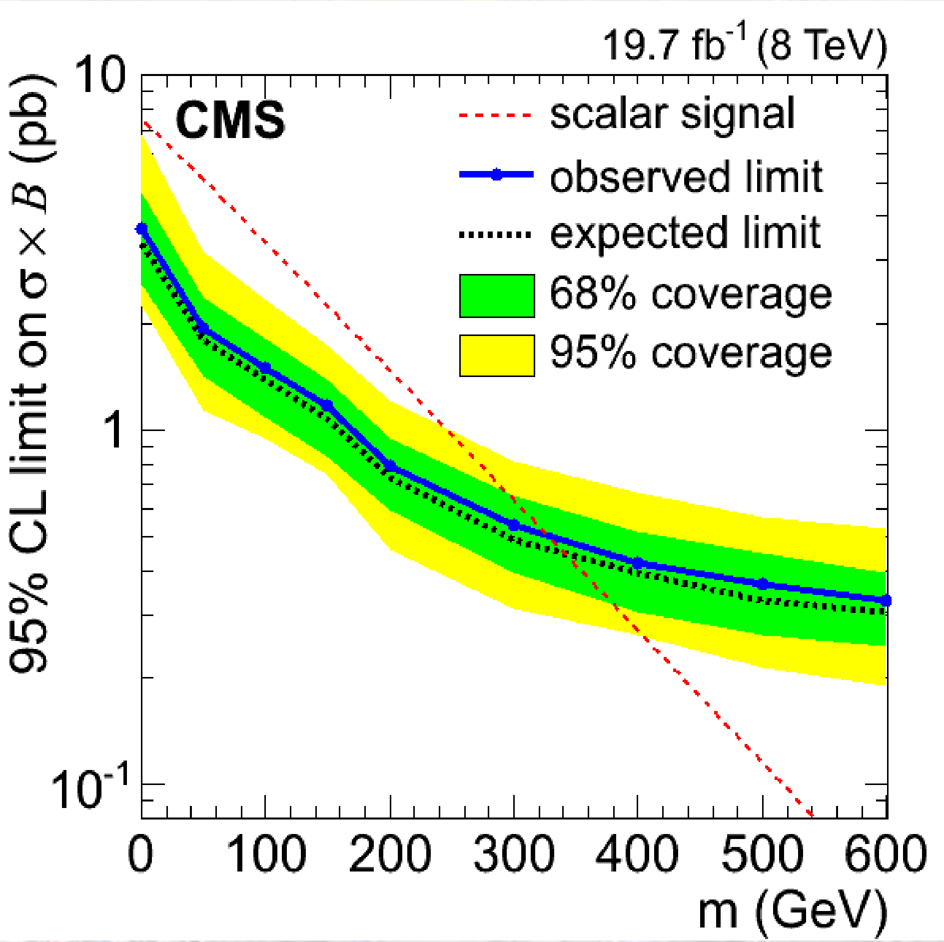
$$\begin{cases} N^{0b} = p^{0b}_{sig} \cdot N_{sig} + p^{0b}_{QCD} \cdot N_{QCD} + N^{0b}_{other\ bg} \\ N^{1b} = p^{1b}_{sig} \cdot N_{sig} + p^{1b}_{QCD} \cdot N_{QCD} + N^{1b}_{other\ bg} \end{cases}$$

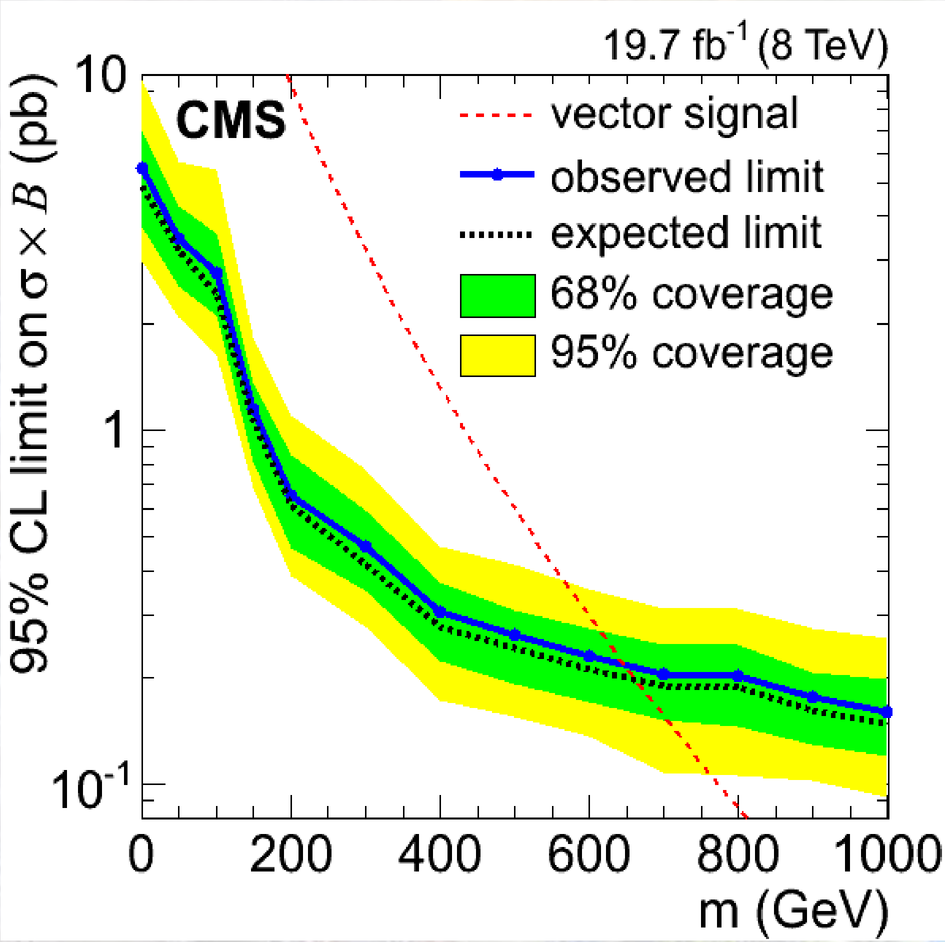
$$\mathcal{L}_{S+B}(\sigma_{sig}, \nu) = Poisson\left(N^{0b}_{observed} | N^{0b}\right) \times Poisson\left(N^{1b}_{observed} | N^{1b}\right)$$

CMS PAS B2G-12-022, arXiv:1410.1149, submitted to PRL

MonoTop : results

CMS PAS B2G-12-022





SUSY Searches

CMS PAS SUS-13-020

- To search for an R-Parity Conserving SUSY model reconstruct different relevant variables:
  - High Pt jets, leptons, photons
  - Tag the bjets
  - Total Pt of the event
  - Missing Pt of the event
  - Combined Kinematical Variables: α_T, M_T, M_{CT}, M_{T2}
- Almost all of such SUSY searches can constrain the LSP mass, but they are usually interpreted within the simplified models which do not mean a constraint on the neutralino WIMP mass.
- Complete physics models like phenomenological MSSM which captures most of the phenomenological features of the RPC MSSM are used to constrain the neutralino WIMP mass.

pMSSM Interpretations

Flat pMSSM Parameters 19-D Priors
$-3\,\text{TeV} \le M_1, M_2 \le 3\,\text{TeV}$
$0 \le M_3 \le 3\,\text{TeV}$
$-3\,\text{TeV} \le \mu \le 3\,\text{TeV}$
$0 \le m_A \le 3\,\text{TeV}$
$2 \le \tan\beta \le 60$
$0 \le \tilde{Q}_{1,2}, \tilde{U}_{1,2}, \tilde{D}_{1,2}, \tilde{L}_{1,2}, \tilde{E}_{1,2}, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_3, \tilde{E}_3 \le 3\,\text{TeV}$
$-7\,\text{TeV} \le A_t, A_b, A_\tau \le 7\,\text{TeV},$

Non-CMS Data Used

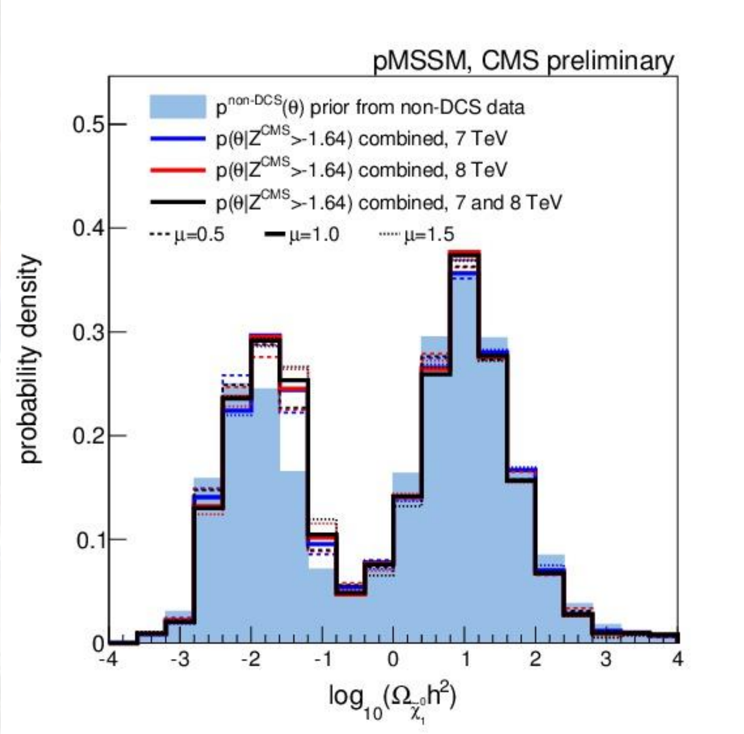
i	Observable $\mu_j(\theta)$	Constraint $D_j^{\text{non-DCS}}$	Likelihood function $L(D_j^{\text{non-DCS}} \vert \mu_j(\theta))$	MCMC / post-MCMC
1a	$BR(b \to s\gamma)$	$(3.55 \pm 0.23^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.09^{\text{sys}}) \times 10^{-4}$	Gaussian	MCMC
1b	$BR(b \to s\gamma)$	$(3.43 \pm 0.21^{\text{stat}} \pm 0.24^{\text{th}} \pm 0.07^{\text{sys}}) \times 10^{-4}$	Gaussian	reweight
2a	$BR(B_s \to \mu\mu)$	observed CLs curve from	$d(1 - CLs)/d(BR(B_s \to \mu\mu))$	MCMC
2b	$BR(B_s \to \mu\mu)$	$(2.9 \pm 0.7 \pm 0.29^{th}) \times 10^{-9}$	Gaussian	reweight
3a	$R(B_u \to \tau\nu)$	1.63 ± 0.54	Gaussian	MCMC
3b	$R(B_u \to \tau\nu)$	1.04 ± 0.34	Gaussian	reweight
4	Δa_μ	$(26.1 \pm 6.3^{\text{exp}} \pm 4.9^{\text{SM}} \pm 10.0^{\text{SUSY}}) \times 10^{-10}$	Gaussian	MCMC
5a	m_t	$173.3 \pm 0.5^{\text{stat}} \pm 1.3^{\text{sys}}$ GeV	Gaussian	MCMC
5b	m_t	$173.20 \pm 0.87^{\text{stat}} \pm 1.3^{\text{sys}}$ GeV	Gaussian	reweight
6	$m_b(m_b)$	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian	MCMC
7	$\alpha_s(M_Z)$	0.1184 ± 0.0007	Gaussian	MCMC
8a	m_h	pre-LHC: $m_h^{low} = 112$	1 if $m_h \ge m_h^{low}$ 0 if $m_h < m_h^{low}$	MCMC
8b	m_h	LHC: $m_h^{low} = 120$, $m_h^{up} = 130$	1 if $m_h^{low} \le m_h \le m_h^{up}$ 0 if $m_h < m_h^{low}$ or $m_h > m_h^{up}$	reweight
9	sparticle masses	LEP (via micrOMEGAs)	1 if allowed 0 if excluded	MCMC

CMS Data Used

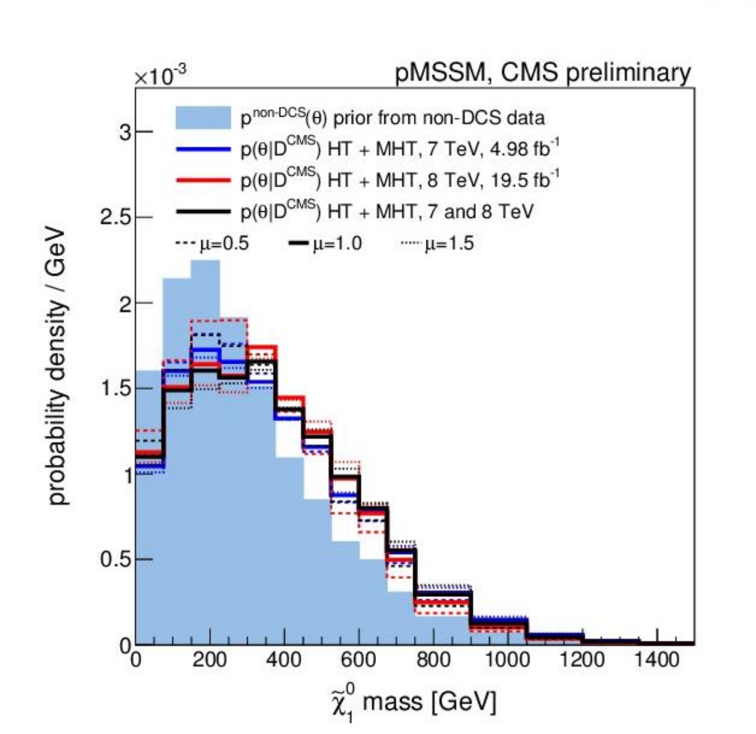
Analysis	$\sqrt{s}$	L	Likelihood	Ref.
Hadronic HT + MHT search	7 TeV	4.98 fb^{-1}	method 1	CMS-SUS-12-011
Hadronic HT + MET + b-jets search	7 TeV	4.98 fb^{-1}	method 1	CMS-SUS-12-003
Leptonic search for EW prod. of $\tilde{\chi}^0$, $\tilde{\chi}^\pm$, $\tilde{l}$	7 TeV	4.98 fb^{-1}	method 1	CMS-SUS-12-006
Hadronic HT + MHT search	8 TeV	19.5 fb^{-1}	method 1	CMS-SUS-13-012
Hadronic HT + MET + b-jets search	8 TeV	19.4 fb^{-1}	method 2	CMS-SUS-12-024
Leptonic search for EW prod. of $\tilde{\chi}^0$, $\tilde{\chi}^\pm$, $\tilde{l}$ (ss, 3l and 4l channels)	8 TeV	19.5 fb^{-1}	method 1	CMS-SUS-12-006

- DCS stands for Direct CMS Search
- No astrophysical data included
- NB, absolute distributions strongly depend on the choice of priors

Relic density and WIMP mass



Relic density



Neutralino mass

μ = Xsec coefficient

Z = signed Bayesian analog of the frequentist "n-sigma"

Z > 5 means discovery

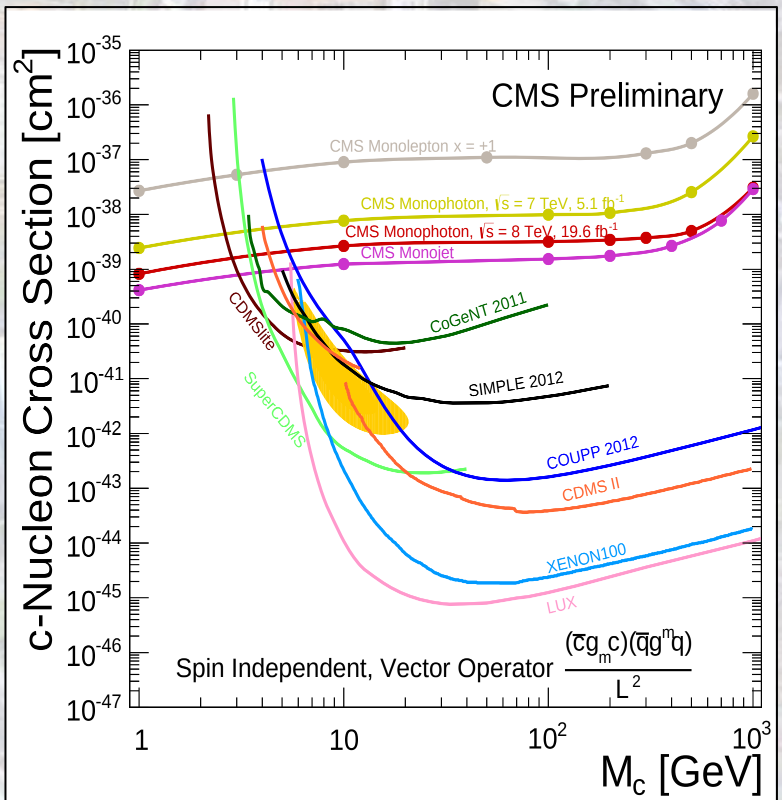
Z < -1.64 means exclusion at 95% CL

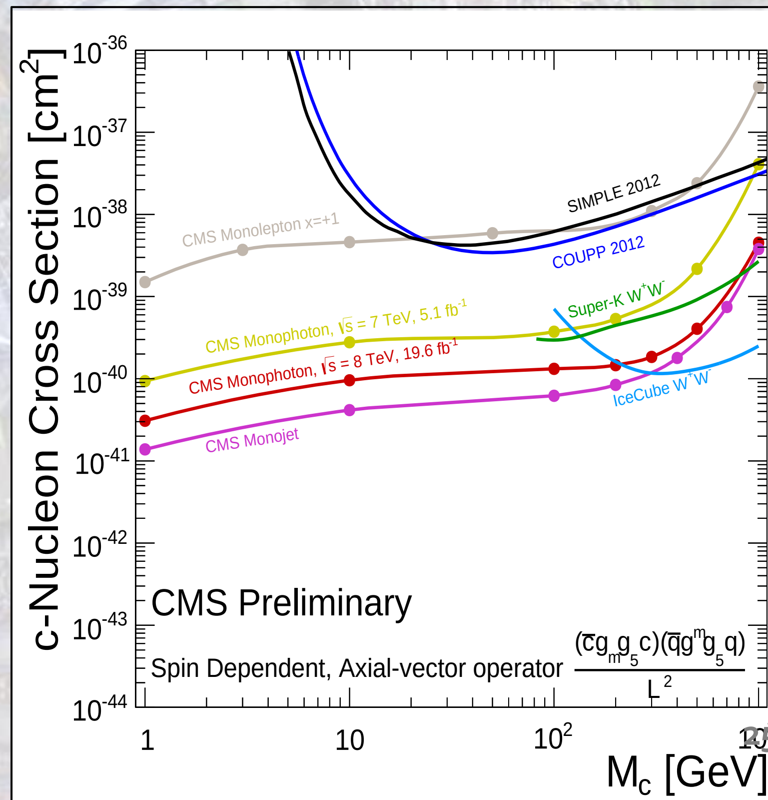
CMS data slightly prefer lower densities and heavier WIMP.

Summary

- ✧ CMS covers already a broad panel of final states, with sensitivities to various scenarios

- ✧ So far, no new signal observed ☹
- ➢ Upper limits on the production cross sections between 10^{-1} and 10^{-2} pb
- ➢ Upper limits on χ-nucleon interaction cross sections between 10^{-38} and 10^{-42} cm^2
- ➢ Collider results ⟹ mainly limits below $M\chi$ < 10 GeV





Perspectives for LHC Run 2

✧ Running conditions : 13 TeV, 25 ns, <PU> = 40 ⟹ expect factor 4 in rate

✧ Need to optimise X+MET triggers to cope with such conditions

✧ Refine background estimations and reduce associated uncertainties

✧ Physics models : EFT validity is an important limitation to current searches
⟹ switch to simplified models with extra search parameters wrt EFT searches