Dark Matter Searches at the CMS

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On behalf of the CMS collaboration

CosPA2015, Oct 12-16 2015

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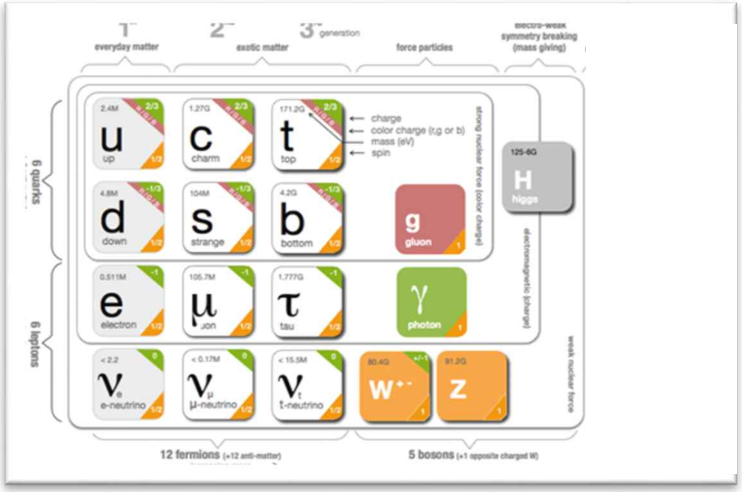
** SUSY searches are not included in this talk due to the time limit.

Introduction

- The discovery of the Higgs particle implies the Standard Model(SM) describes nature very well.

- However, the incompleteness of the SM may hint the bigger quantum symmetrized universe.

- The Higgs discovery naturally leads to attempt to understand whether new phenomena beyond the SM exist or not.
  - The beyond SM like SUSY, Extra Dimensions and many extended SMs.



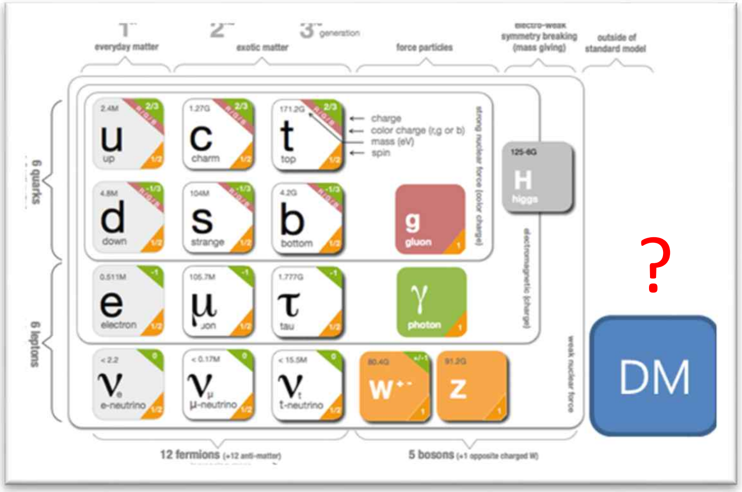
- Moreover, the dark matter(DM) is one of the biggest mysteries in understanding of universe after the discovery of Higgs.

- The discovery of a dark matter is very important since the existence of dark matter has been certified by astronomic observations.

- The LHC at CERN with new energy has a great chance to discover a dark matter or probe unknown nature.

- Searches of a dark matter (and unknown phenomena) at the LHC would be one of the most exciting moments enhancing mankind knowledge in the Universe !

Introduction



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- However, the incompleteness of the SM may hint the bigger quantum symmetrized universe.
- The Higgs discovery naturally leads to attempt to understand whether new phenomena beyond the SM exist or not.
  - The beyond SM like SUSY, Extra Dimensions and many extended SMs.
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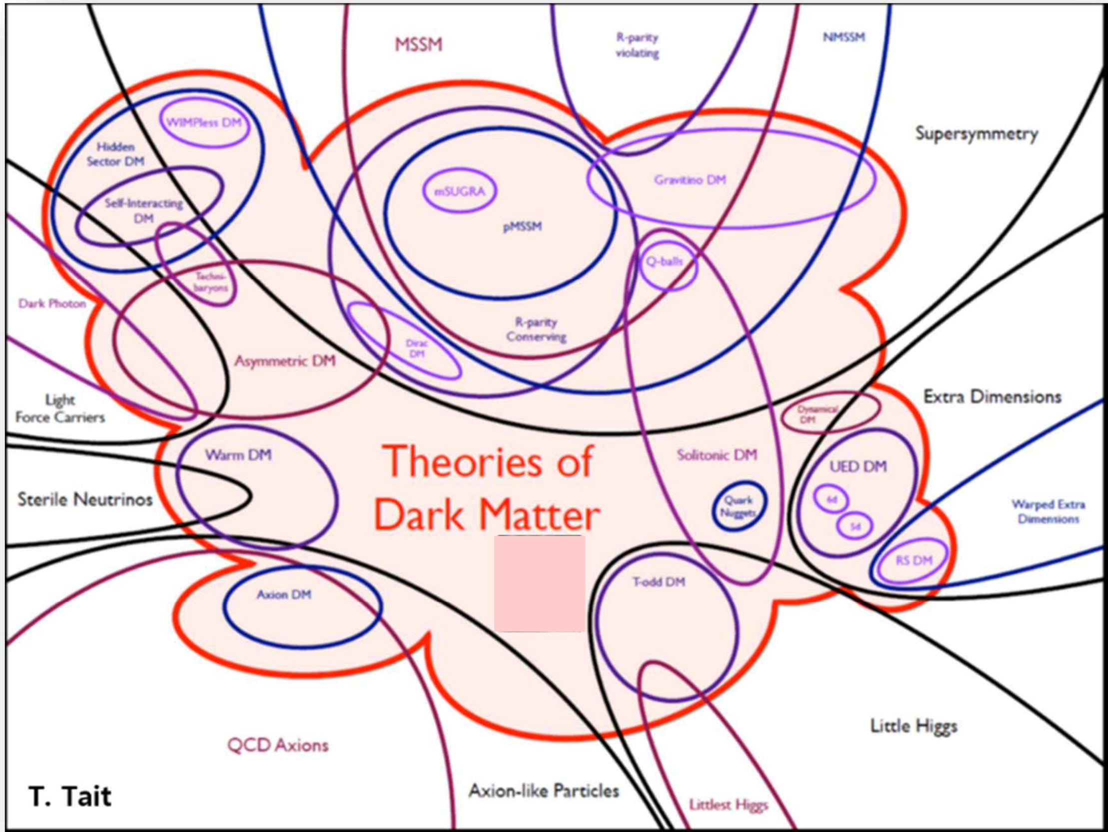
- The discovery of a dark matter is very important since the existence of dark matter has been certified by astronomic observations.
- The LHC at CERN with new energy has a great chance to discover a dark matter or probe unknown nature.
- Searches of a dark matter (and unknown phenomena) at the LHC would be one of the most exciting moments enhancing mankind knowledge in the Universe !

Dark matter ?

- WIMPs: Weakly Interacting Massive Particles ?
- Super-WIMPs ?
- Axions ?
- Sterile neutrinos ?
- FIMPs : Feebly IMPs ?



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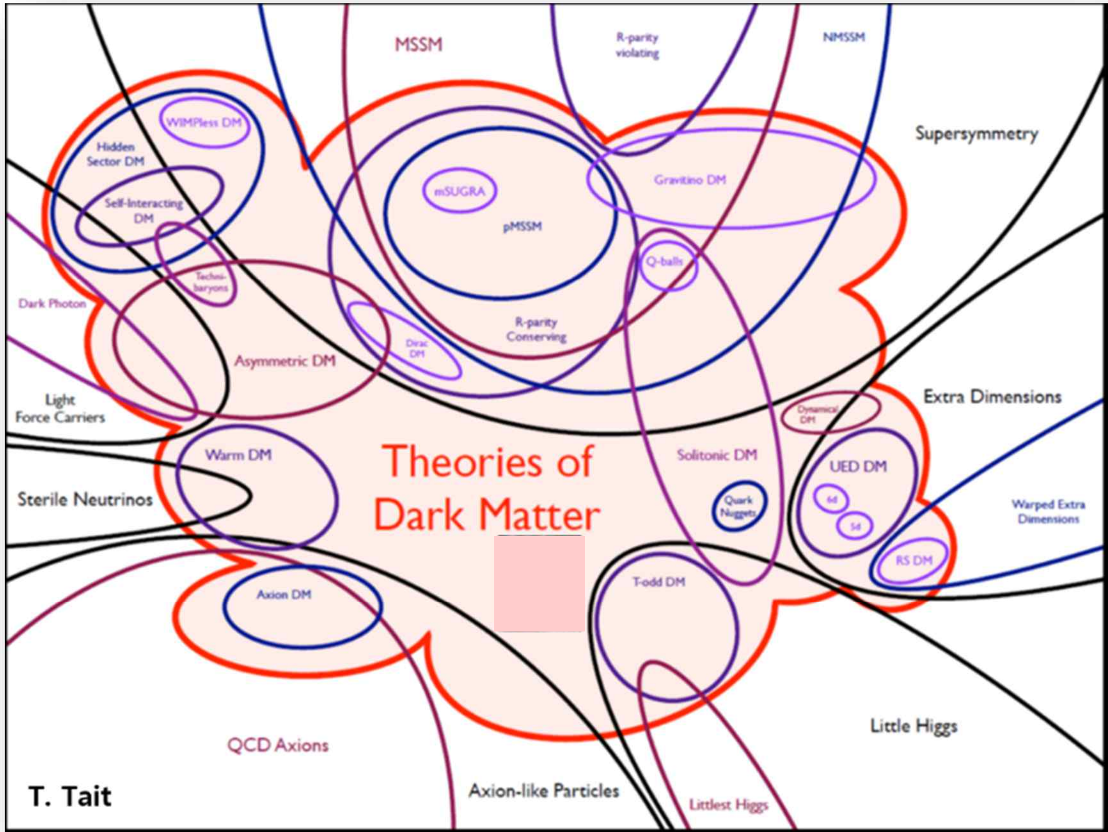
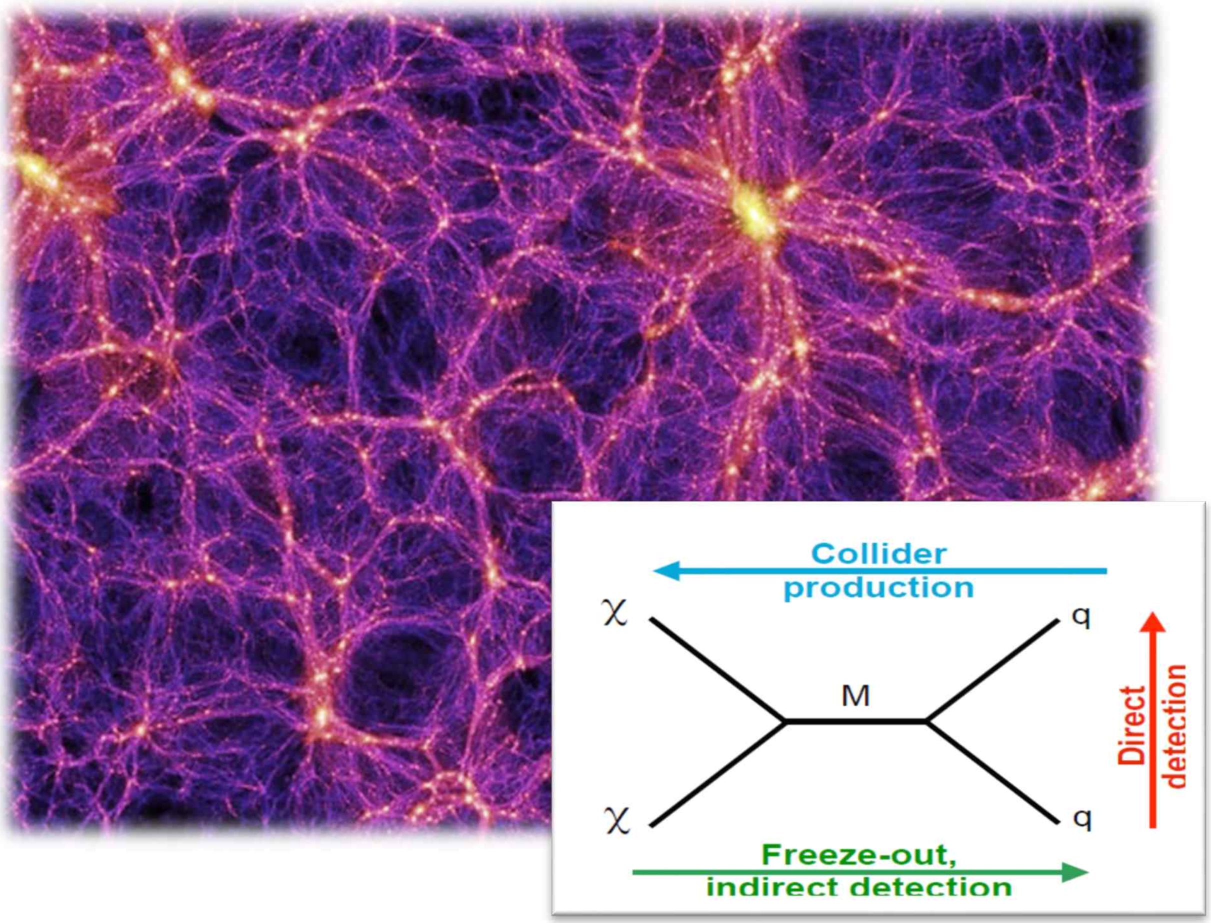
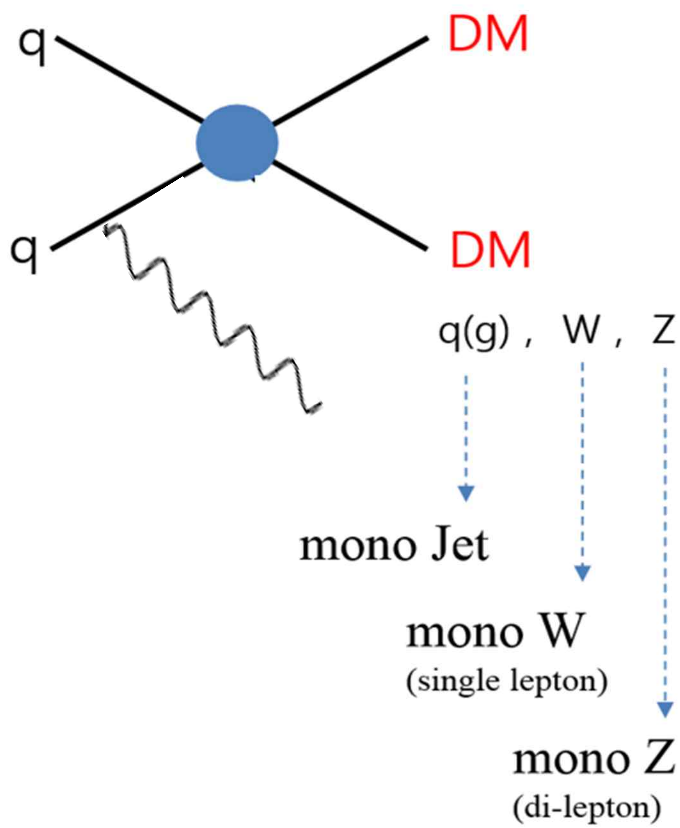


→ **Something invisible !!**

Dark Matter Production at colliders

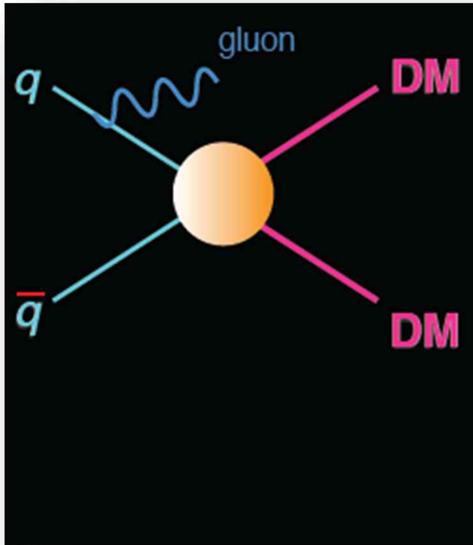
- There are many models from the theoretical point of view.
- However the final states are simple from the experimental point of view.
  - Events characterized by ISR recoil of X
  - mono X + missing energy in collider experiments





Effective Field Theory for dark matter

- Effective Field Theory(EFT) interaction between DM and SM particles is a contact interaction.
- Consider operator at the new physics scale Λ.



eff. operator $\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$

parton-level differential cross section:

$$\frac{d^2\hat{\sigma}_{\rm eff}}{dp_T d\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_T}\frac{1}{\Lambda^4} \cdot \frac{\left[Q_{\rm tr}^2 - 4m_{\rm DM}^2\right]^{3/2}\left[1 + \frac{Q_{\rm tr}^4}{(x_1 x_2 s)^2}\right]}{Q_{\rm tr}}$$

matching: $\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M^2}$

The Results applied to Run 1 analysis at the LHC

Advantage : Limited number of degrees of freedom scale of interaction

Disadvantage : Only applicable at low momentum transfer

DM Production in EFT

General Interaction Lagrangian for DM in EFT frame can be

$$\mathcal{L} = \sum_q \left\{ \frac{m_q}{\Lambda^3_{D1}} \bar{q}q\,\bar{\chi}\chi + \frac{1}{\Lambda^2_{D8}} \bar{q}\gamma^\mu\gamma_5 q\,\bar{\chi}\gamma_\mu\gamma_5) + \frac{1}{\Lambda^2_{D5}} \bar{q}\gamma^\mu q\,\bar{\chi}\gamma_\mu\chi + \frac{1}{\Lambda^2_{D9}} \bar{q}\sigma^{\mu\nu} q\,\bar{\chi}\sigma_{\mu\nu}\chi \right\}$$

D1 : Scalar, D8 : Axial-Vector, D5 : Vector and D9 : Tensor
χ : Dirac Fermion Dark Matter
Λ : interaction scale(or suppression scale)

- Mediate DM + q/g interaction under $M > M_\chi$
  - M_χ : Dark Matter mass, M : Mediator mass
- Suppression scale by Λ (or M_*) ~ $M/(g_\chi g_q)^{1/2}$
- $M_\chi < M/2$ required for four-m/m conservation
- $g_\chi g_q < (4\pi)^2$ required for perturbation
  → $\Lambda > M_\chi / 2\pi$

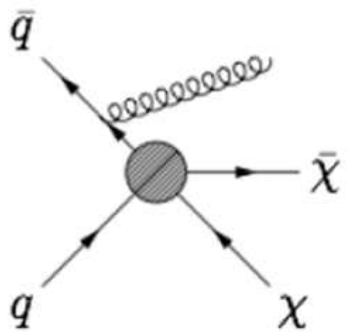
Dirac Fermions

Name	Operator	Coefficient
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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

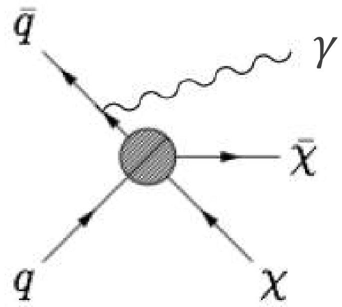
scalar (D1), vector (D5), scalar (D11) → Spin-independent
axial -vector (D8), tensor (D9) → Spin dependent

J. Goodman et. al, Phys. Rev. D 82, 116010 (2010)

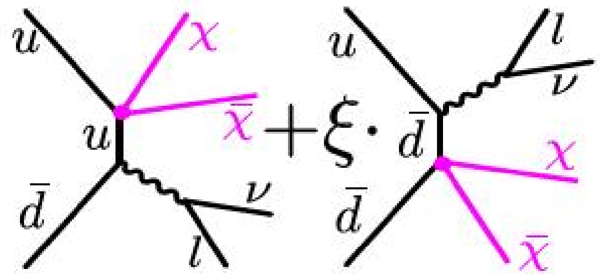
Channels for Dark matter at the LHC



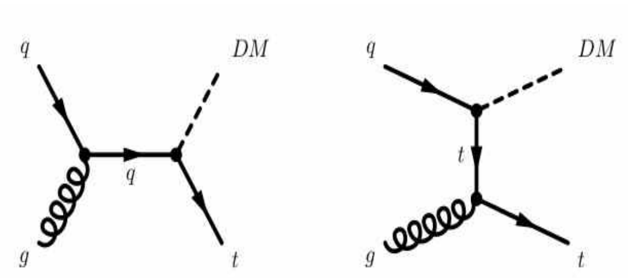
Mono-jet



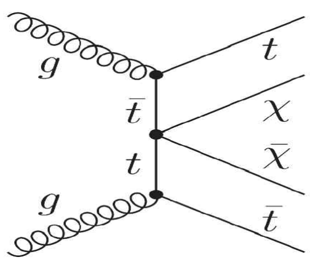
Mono-photon



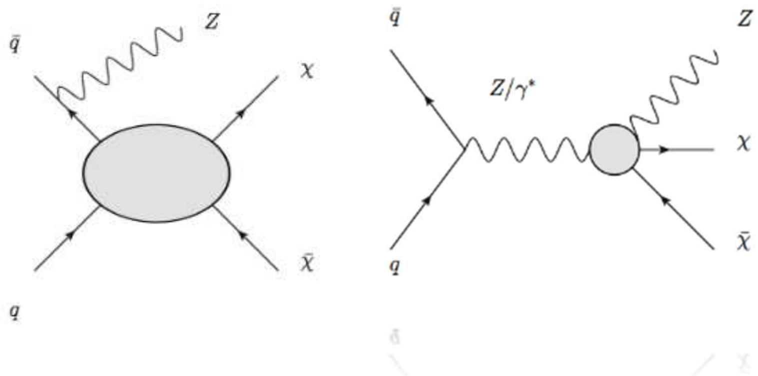
Mono-W



Mono-top



Top pair



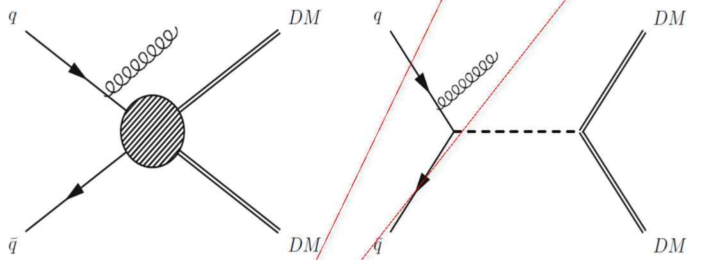
Mono-Z

Mono-jet

CMS-EXO-12-048

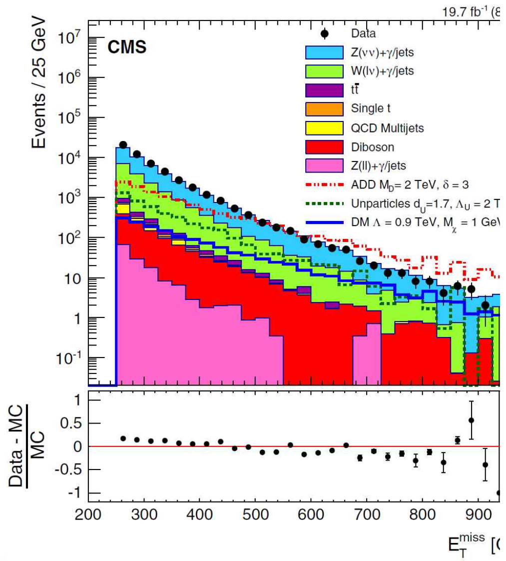
Eur. Phys. J. C (2015) 75:235

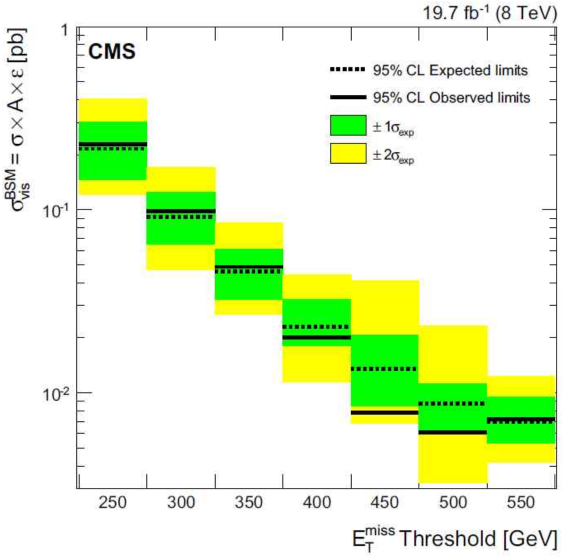
- A Jet from ISR
- one energetic jet and large missing energy (MET)
  - Z(→νν) +jet, irreducible background and W+jets(lost lepton) : main backgrounds(62 and 36%)
  - QCD jet misidentified, $t\bar{t}$ etc.
- Selection → very large MET !
  - $p_T > 110$ GeV, $|\eta| < 2.4$
  - second jet are allowed , if Δφ(jet1, jet2) < 2.5
  - MET > 250, 300, 350, 400, 450, 500, 550 GeV
  - Veto events with isolated leptons.



- Estimates of Standard Model contributions
  - Data-driven : Z(νν) + jets (from Z → $\mu\mu$)
  - Data-driven : W + jets (from W → $\mu\nu$)
  - single-top, multi-jets (QCD), $t\bar{t}$, $Z(\ell\ell)$

E_T^{miss} (GeV) →	>250	>300	>350	>400	>450	>500	>550
Z(νν) + jets	32100 ± 1600	12700 ± 720	5450 ± 360	2740 ± 220	1460 ± 140	747 ± 96	362 ± 64
W + jets	17600 ± 900	6060 ± 320	2380 ± 130	1030 ± 65	501 ± 36	249 ± 22	123 ± 13
$(t\bar{t})$	446 ± 220	167 ± 84	69 ± 35	31 ± 16	15 ± 7.7	6.6 ± 3.3	2.8 ± 1.4
$Z(\ell\ell)$ + jets	139 ± 70	44 ± 22	18 ± 9.0	8.9 ± 4.4	5.2 ± 2.6	2.3 ± 1.2	1.0 ± 0.5
Single t	155 ± 77	53 ± 26	18 ± 9.1	6.1 ± 3.1	0.9 ± 0.4	–	–
QCD multijets	443 ± 270	94 ± 57	29 ± 18	4.9 ± 3.0	2.0 ± 1.2	1.0 ± 0.6	0.5 ± 0.3
Diboson	980 ± 490	440 ± 220	220 ± 110	118 ± 59	65 ± 33	36 ± 18	20 ± 10
Total SM	51800 ± 2000	19600 ± 830	8190 ± 400	3930 ± 230	2050 ± 150	1040 ± 100	509 ± 66
Data	52200	19800	8320	3830	1830	934	519
Exp. upper limit +1σ	5940	2470	1200	639	410	221	187
Exp. upper limit −1σ	2870	1270	638	357	168	123	104
Exp. upper limit	4250	1800	910	452	266	173	137
Obs. upper limit	4510	1940	961	397	154	120	142

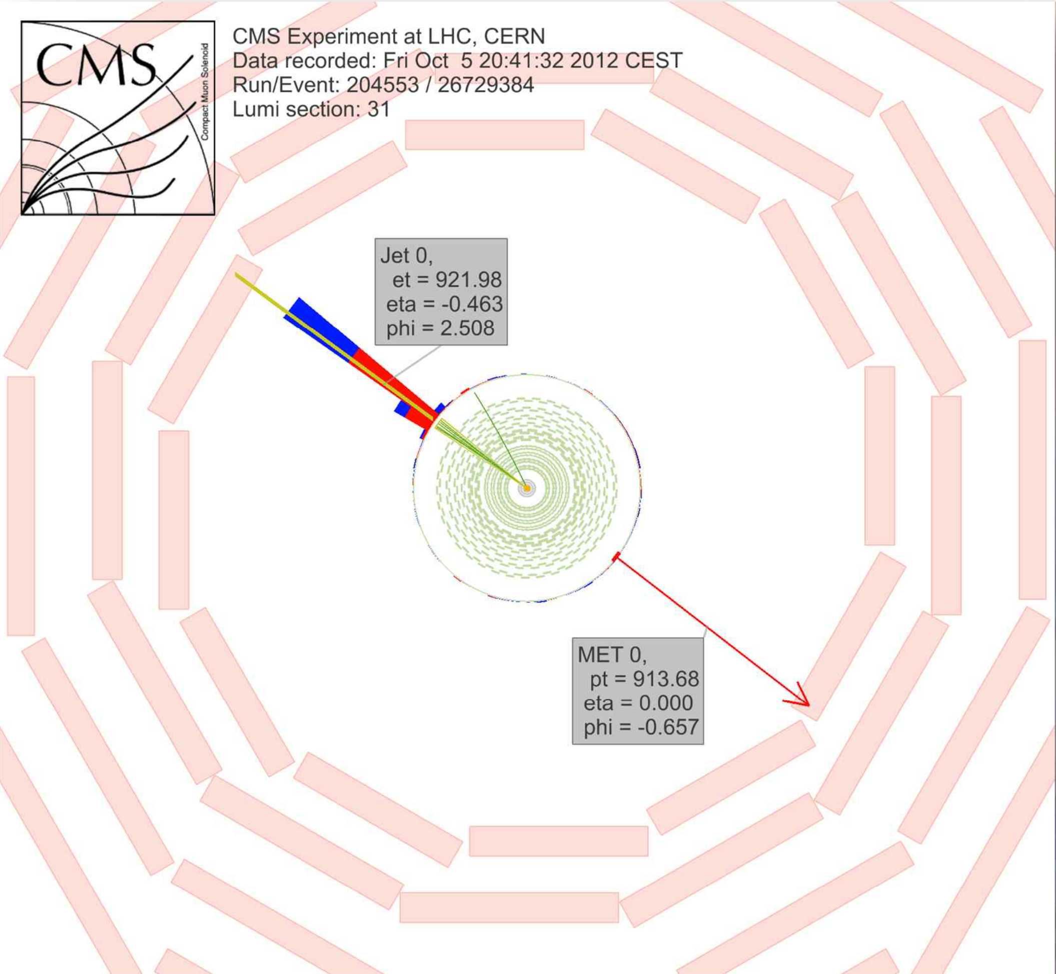


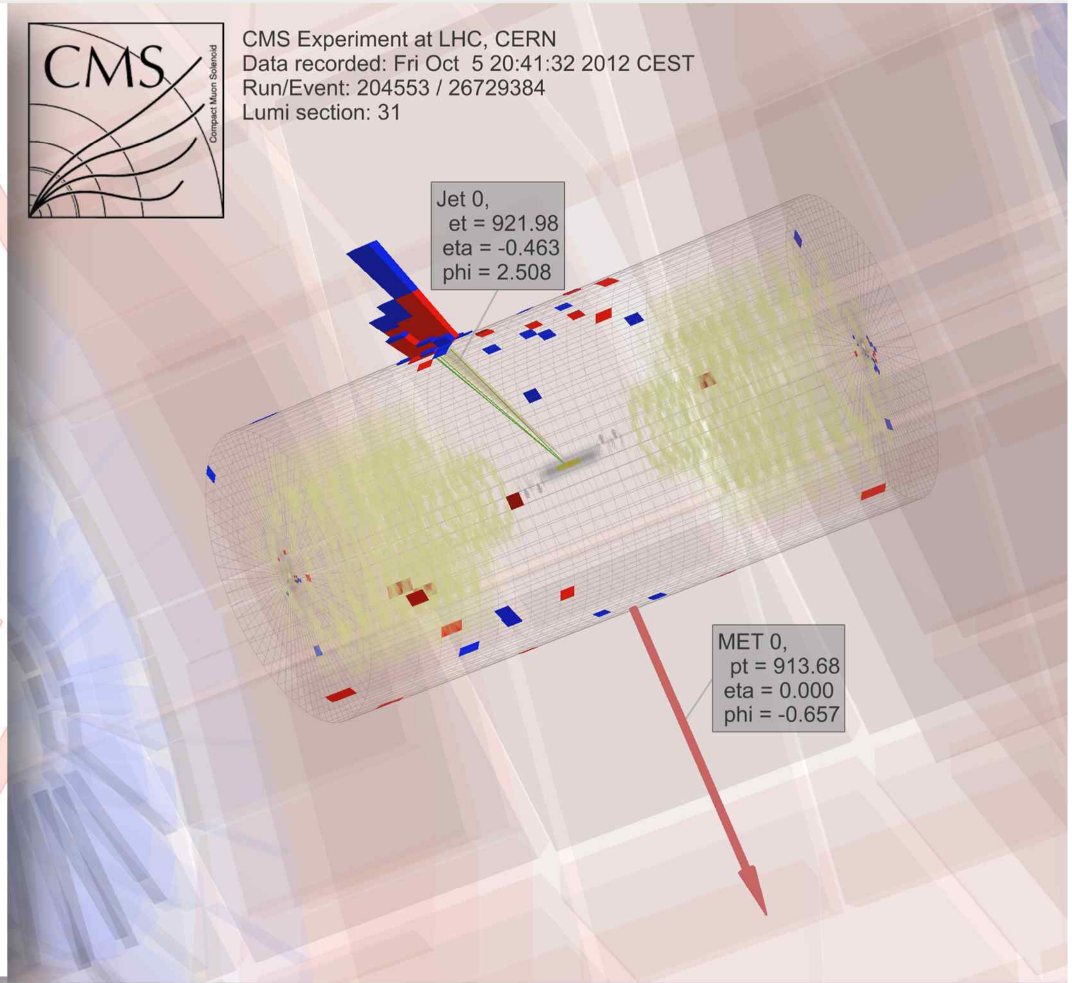


- Consistent with the SM backgrounds
- Set the model-independent observed 95% CL upper limits on the visible x-section for non-SM production according to MET cuts

Compact Muon Solenoid experiment at CERN's LHC

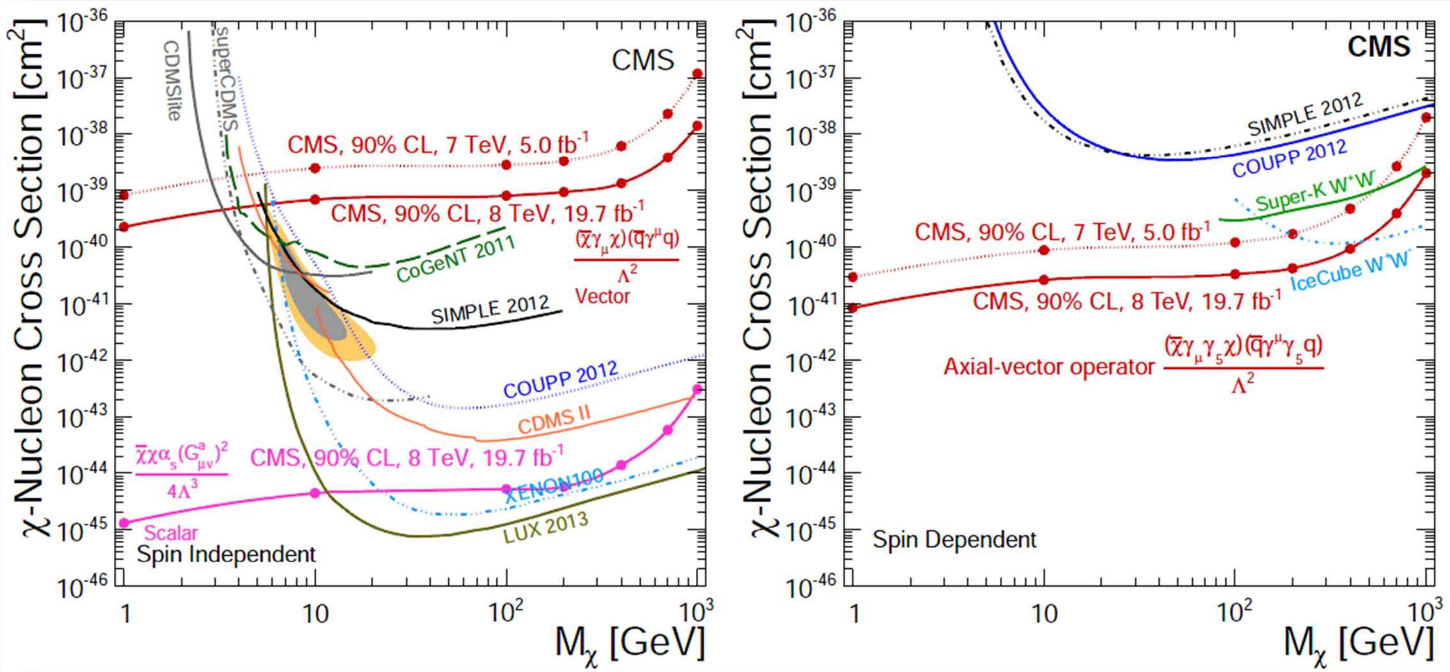
Typical Mono-jet Event





Compact Muon Solenoid experiment at CERN's LHC

Mono-jet (DM mass vs x-section)

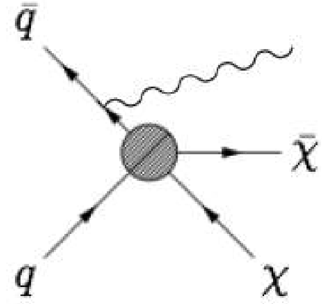


- The observed limit on the x-section depends on Mχ and nature of its interaction with SM particles.
- The limits on the effective contact interaction scale as a function of Mχ translated into a limit on the dark matter-nucleon scattering cross section in the framework of EFT.
- Shown for the vector & scalar case(SI) and axial vector(SD).
- Better results shown in Spin Dependent than direct detection experiments → ~ 1000 times better
- Sensitive to low Mχ for Spin Independent case.

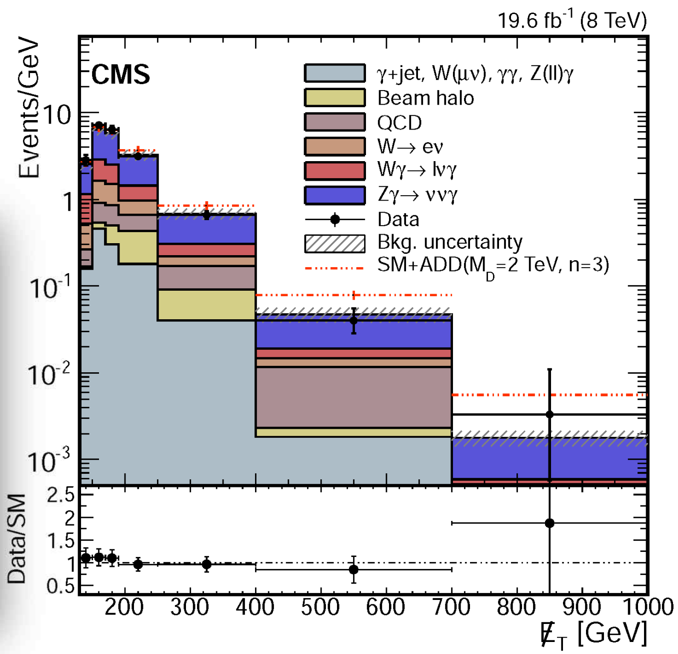
Mono-photon

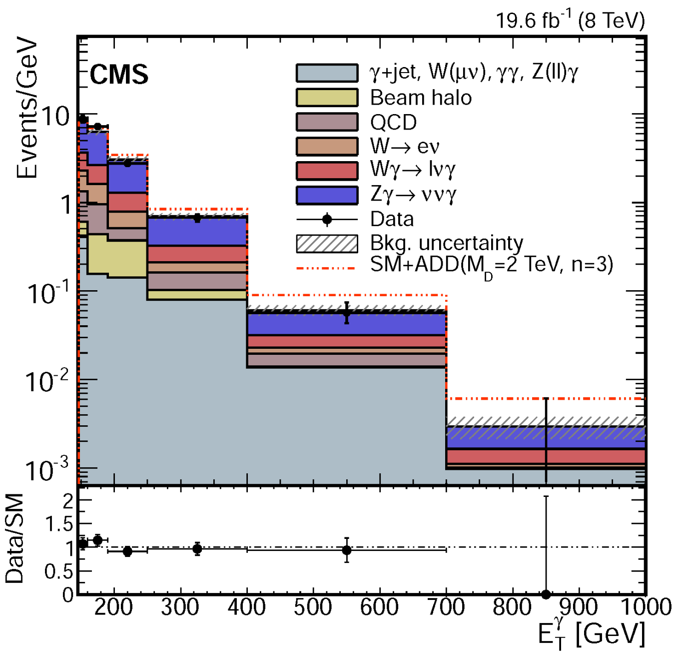
CMS-EXO-12-047

- Dark matter particle can be produced in process of photon radiated by one of incoming quarks.
- Signature : 1 photon + 2 dark matters
  - One isolated photon
  - Very large MET (> 140 GeV) and photon pT(> 145 GeV)
  - Zγ → ννγ as irreducible background, Wγ, W, γ+jets, QCD multijet, diphotons etc..



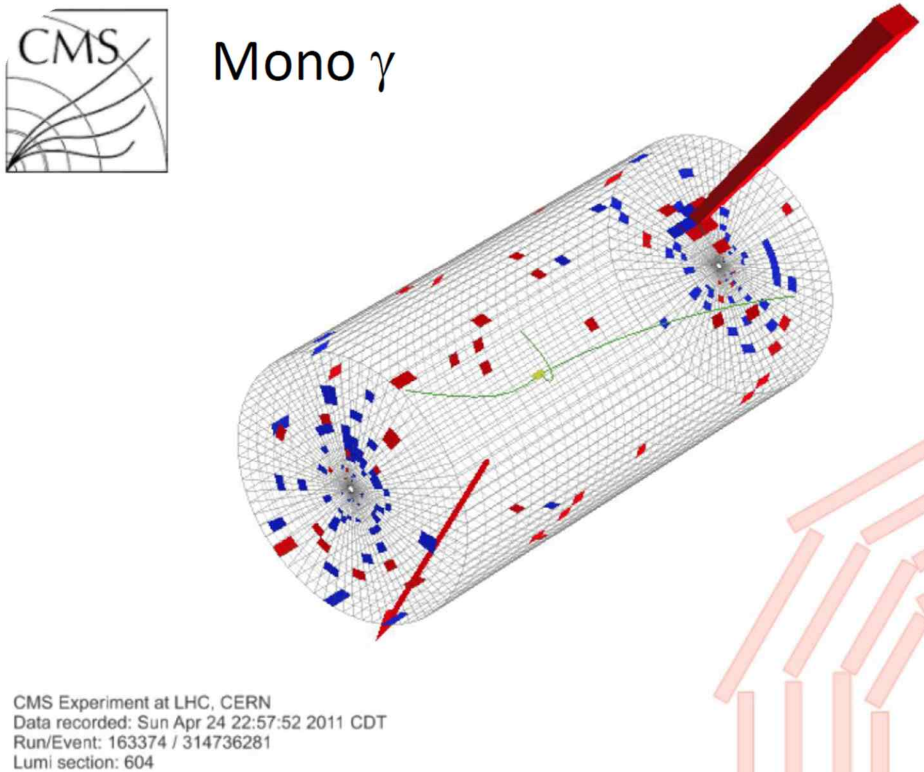
Process	Estimate
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	345 ± 43
$W(\rightarrow \ell\nu) + \gamma$	103 ± 21
$W \rightarrow e\nu$	60 ± 6
jet $\rightarrow \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	614 ± 63
Data	630

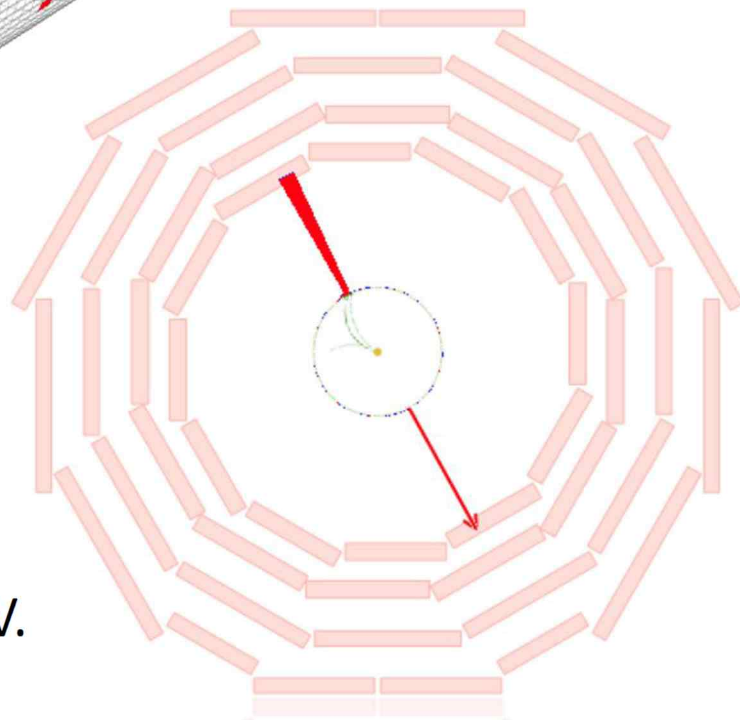




A good agreement with expectations from SM background.

Mono-photon event



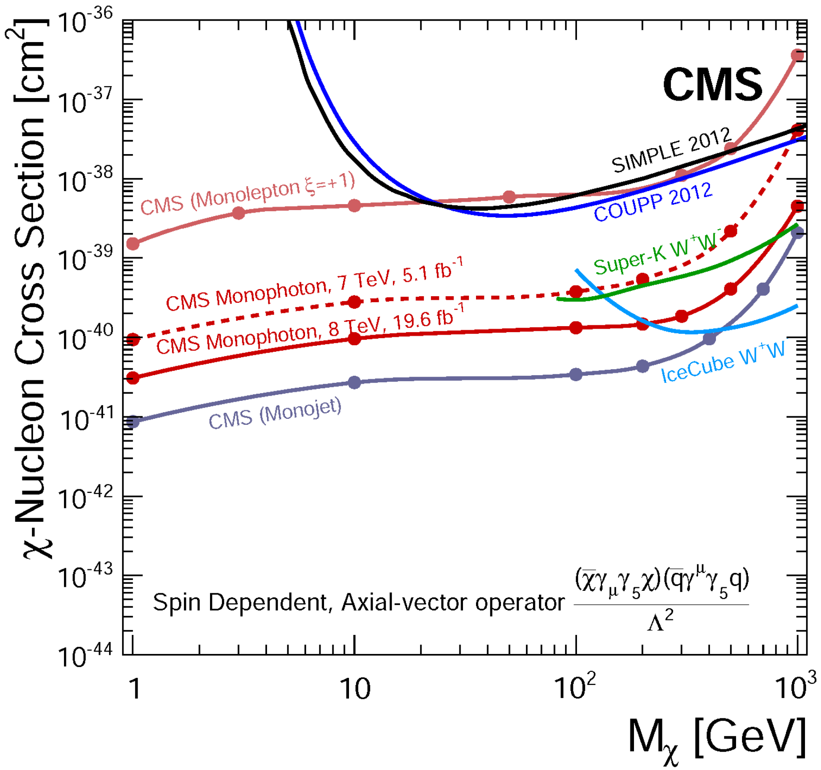


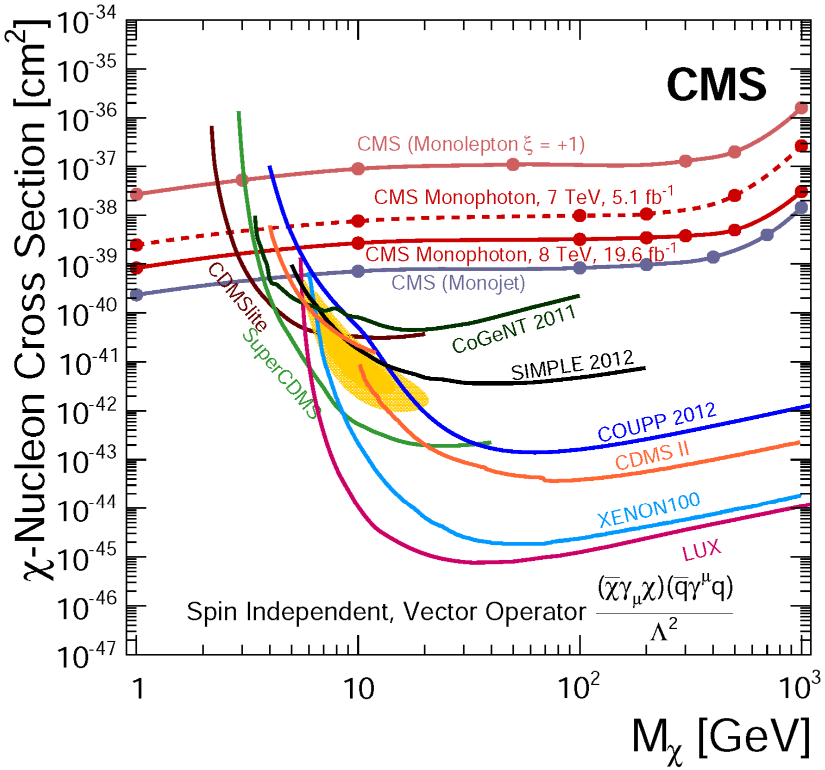
p_T^{γ}=384 GeV, MET=407 GeV.

p_T^{γ}=384 GeV, MET=407 GeV.

Mono-photon results

- The 90% CL upper limits on the χ-nucleon cross section as a function of the DM mass (Mχ)
- Results also shown for CMS mono-jet and mono-lepton signatures
  - ζ is the interference parameter
- Also shown several direct detection experiments for comparison
  - The yellow contours show the 68% and 95% CL contours respectively for a possible signal from CDMS





Mono-W(to lepton)

CMS-EXO-12-060

PHYSICAL REVIEW D **91,** 092005 (2015)

- Experimental point of view :
  - Easier to trigger (mono-lepton)
  - Clean, well simulated background
  - Low systematic uncertainties from the detector

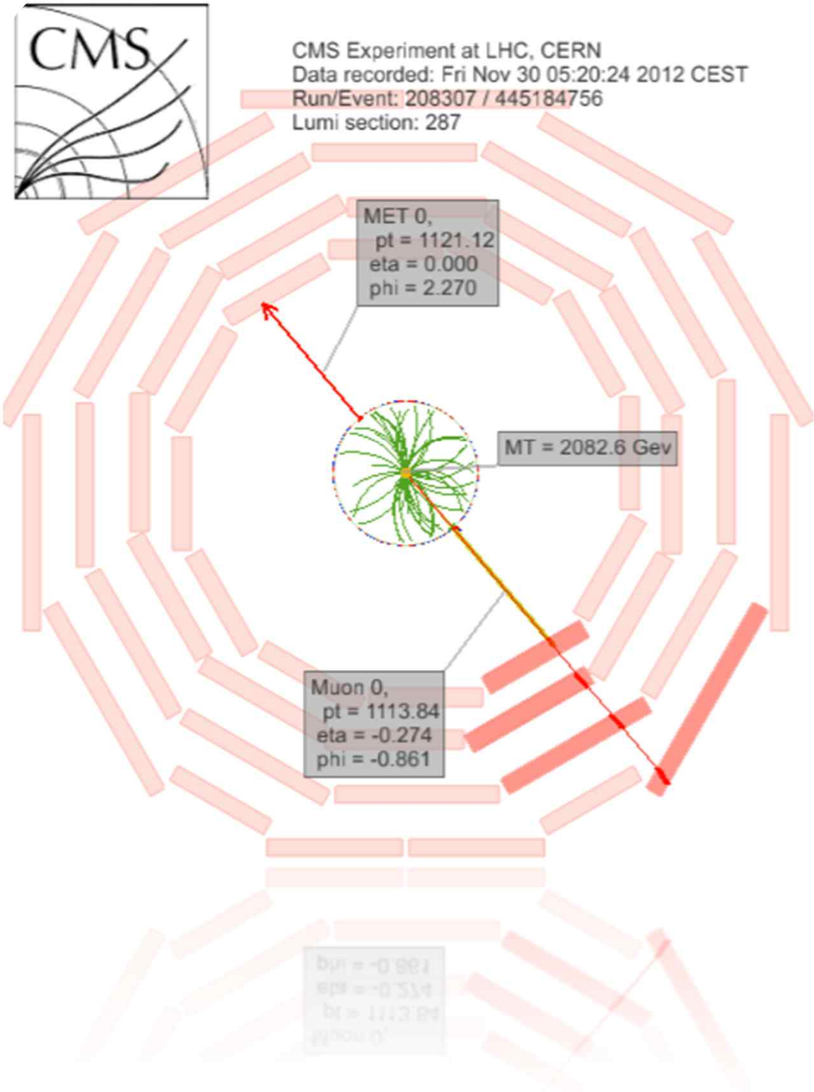
- Theoretical point of view :
  - Higher production cross section than mono-Z
  - Well simulated, Quark-sensitive interference effects

- Plenty reinterpretations to the model

• Sequential Standard Model W'
  - Interference W-W'
  - Mass Limit M(W') > 3.35 TeV

• Split-UED model
  - 2-dim. limits are set in (1/R, μ) space

• Helicity-Non-Conserving Contact Interaction (HNC-CI)
  - Limits are set on Λ (binding energy)



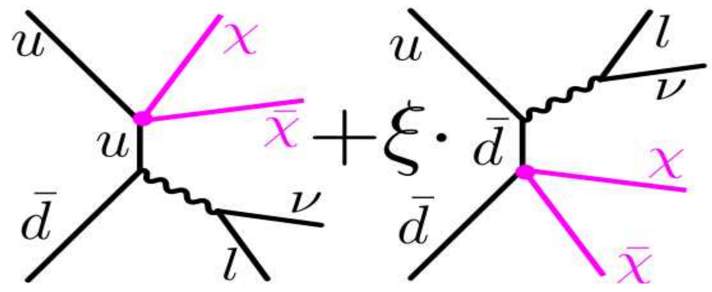
Compact Muon Solenoid experiment at CERN's LHC

Huge Interference effects

- The DM particles either couple to the up- or the down-type quark with their relative coupling strength parameterized by the factor ξ.

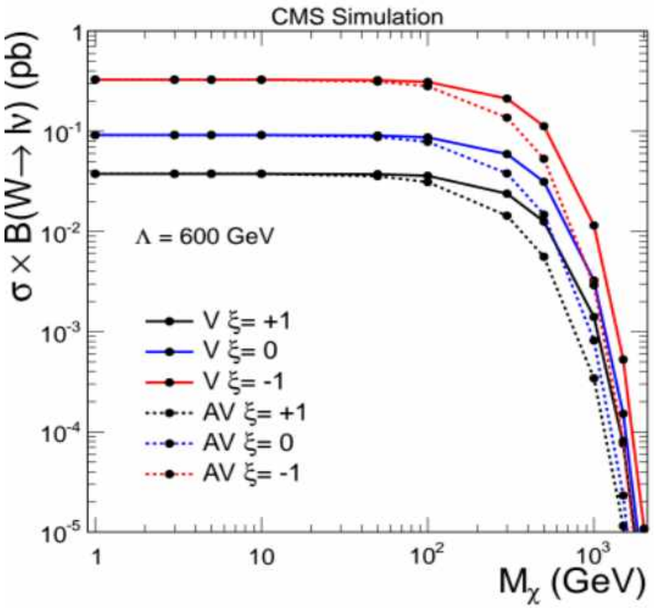
$$\text{V: } \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\chi \quad (\bar{u}\gamma^{\mu}u + \xi\bar{d}\gamma_{\mu}d)$$

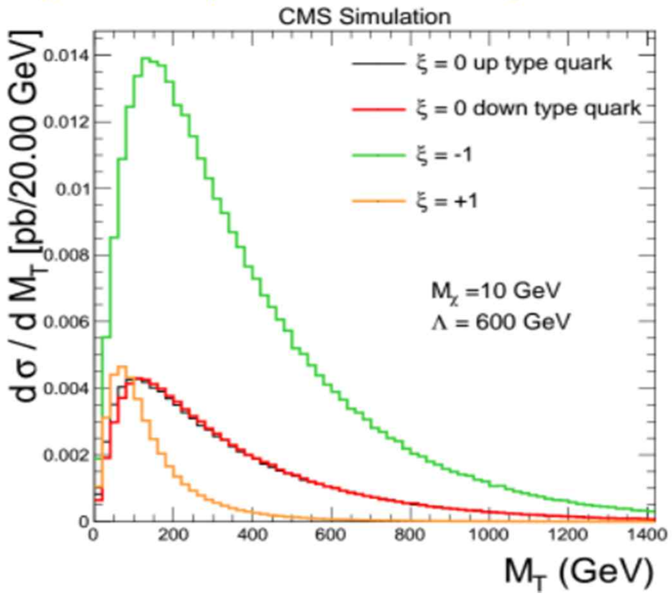
$$\text{AV: } \frac{1}{\Lambda^2}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi \quad (\bar{u}\gamma^{\mu}\gamma_5 u + \xi\bar{d}\gamma^{\mu}\gamma_5 d)$$



The interesting values are $\xi = -1, 0, +1$

signal shape for different ξ





- Strong dependence on ξ

factor ξ =+1(destructive)

0 (u/d no differ-)

-1(constructive)

- The interference changes the total cross-section and steepens the Mt spectrum

One can expect the results have a strong dependence on the interference.

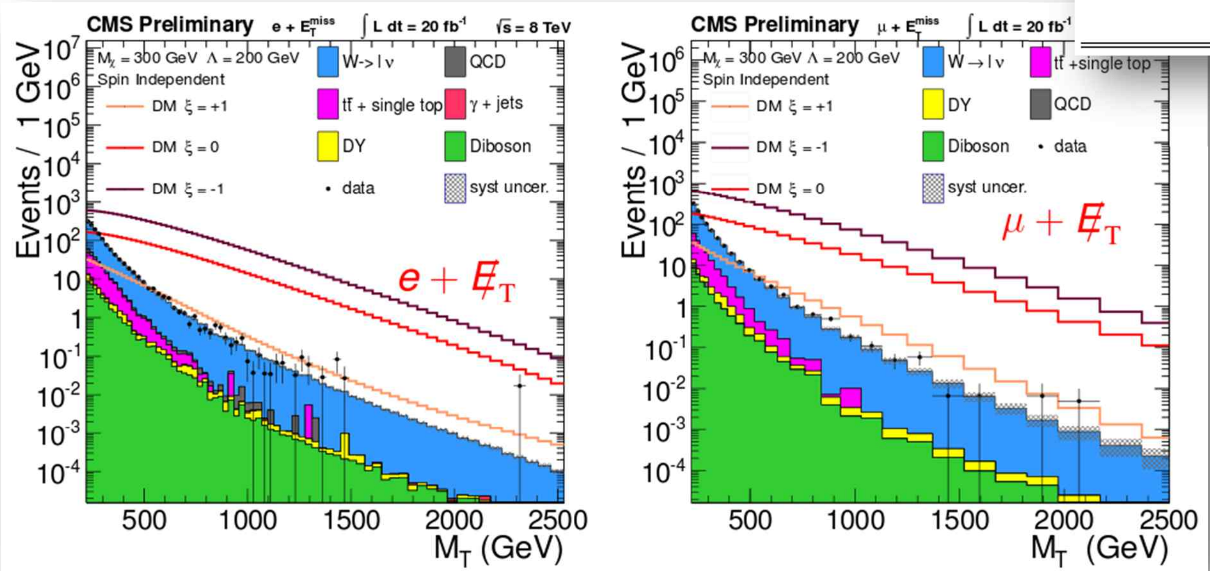
Compact Muon Solenoid experiment at CERN's LHC

M_T distribution with DM expectations

- 1 high-Pt lepton (>45GeV for mu & >100GeV for e)
- Ratio of lepton PT to MET is between 0.4 and 1.5
- Δφ(lep, MET)>0.8 pi
- The main value to identify signal events is MT

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

		$M_T > 1.0$ TeV	$M_T > 1.5$ TeV	$M_T > 2.0$ TeV
Electron channel				
Data		24	1	1
SM Background		$26.0^{+2.5}_{-2.5}$	$2.02^{+0.26}_{-0.25}$	$0.207^{+0.036}_{-0.033}$
W'	$M_{W'} = 2.5$ TeV	$50.5^{+7.5}_{-7.5}$	$38.8^{+6.1}_{-6.1}$	$24.0^{+3.9}_{-3.9}$
	$M_{W'} = 3$ TeV	$10.3^{+2.1}_{-2.1}$	$7.8^{+1.9}_{-1.9}$	$5.8^{+1.5}_{-1.5}$
HNC-CI	$\Lambda = 4$ TeV	1120^{+110}_{-110}	368^{+47}_{-47}	105^{+19}_{-19}
	$\Lambda = 9$ TeV	$43.4^{+4.3}_{-4.3}$	$14.3^{+1.8}_{-1.8}$	$4.08^{+0.75}_{-0.75}$
DM vector coupling, $M_\chi = 50$ GeV, $\Lambda = 300$	$\xi = +1$	$0.402^{+0.050}_{-0.050}$	$0.0346^{+0.0072}_{-0.0070}$	$0.0033^{+0.0010}_{-0.0010}$
	$\xi = 0$	$6.8^{+1.5}_{-1.5}$	$1.25^{+0.42}_{-0.42}$	$0.22^{+0.11}_{-0.11}$
	$\xi = -1$	$27.4^{+5.9}_{-5.9}$	$5.0^{+1.7}_{-1.7}$	$0.89^{+0.44}_{-0.43}$
Muon channel				
Data		35	3	1
SM background		$26.1^{+4.4}_{-4.3}$	$2.35^{+0.70}_{-0.60}$	$0.33^{+0.16}_{-0.12}$
W'	$M_{W'} = 2.5$ TeV	$48.7^{+4.1}_{-4.1}$	$36.1^{+2.8}_{-3.1}$	$20.3^{+3.0}_{-3.4}$
	$M_{W'} = 3$ TeV	$9.88^{+0.99}_{-0.98}$	$7.33^{+0.64}_{-0.65}$	$5.00^{+0.16}_{-0.39}$
HNC-CI	$\Lambda = 9$ TeV	$42.4^{+3.8}_{-3.8}$	$13.8^{+2.0}_{-2.0}$	$4.47^{+0.90}_{-0.94}$
	$\Lambda = 4$ TeV	1091^{+97}_{-98}	356^{+50}_{-52}	115^{+23}_{-24}
DM vector coupling, $M_\chi = 50$ GeV, $\Lambda = 300$	$\xi = +1$	$0.271^{+0.070}_{-0.067}$	$0.0151^{+0.0061}_{-0.0056}$	$0.00088^{+0.00051}_{-0.00043}$
	$\xi = 0$	$6.7^{+1.6}_{-1.6}$	$1.43^{+0.54}_{-0.51}$	$0.31^{+0.17}_{-0.15}$
	$\xi = -1$	$27.1^{+6.6}_{-6.5}$	$5.8^{+2.2}_{-2.1}$	$1.25^{+0.68}_{-0.60}$



A good agreement with expectations from SM background.

Compact Muon Solenoid experiment at CERN's LHC

X-sections w(w/o) interference

- The excluded cross section is flat as a function of Mχ,

  → because the signal kinematics do not change appreciably for different Mχ

- The coupling does not have a large effect on the excluded cross section

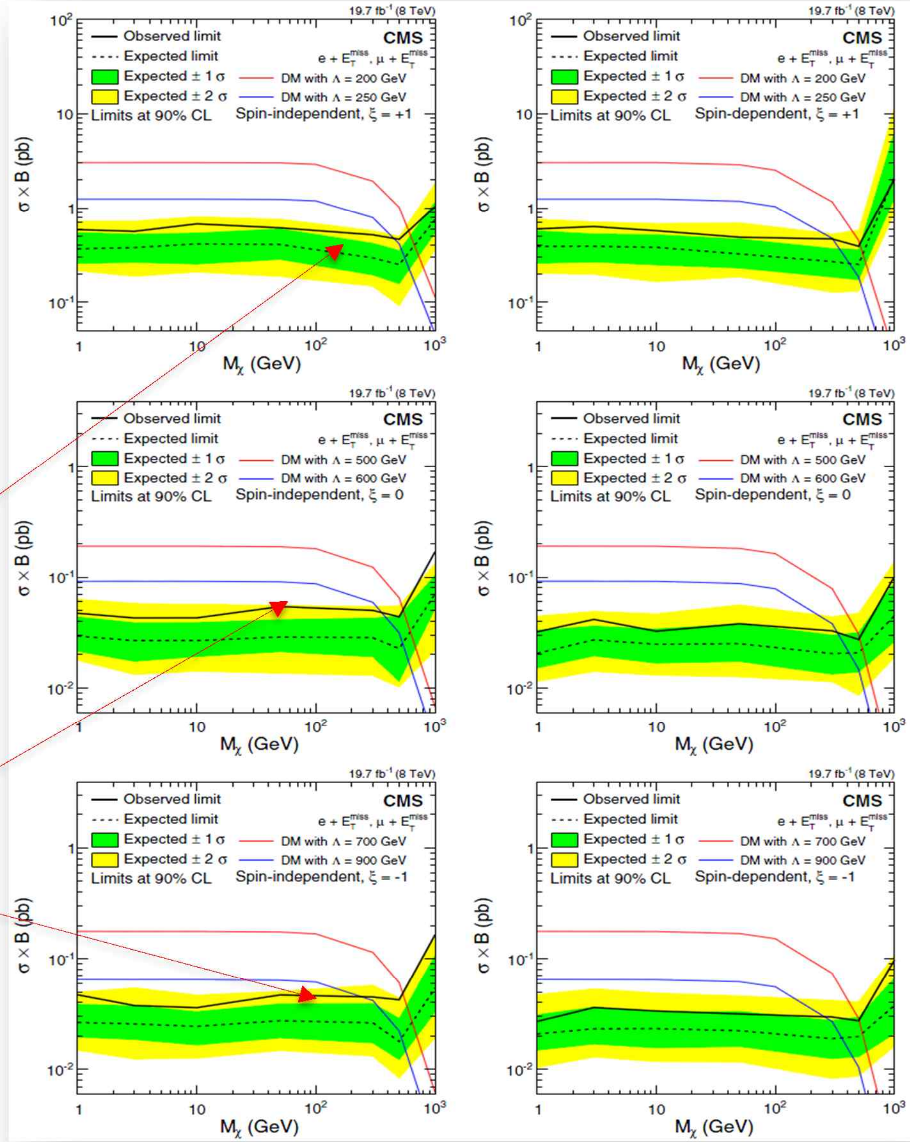
- The different interference scenarios have a visible influence on the limit

  → for ξ = +1, a cross section > 0.6 pb excluded

  → for ξ = 0 and ξ = −1, the x-section limit is 0.05 pb

- For high Mχ the phase space to produce two heavy particles and a W-boson is small

  → the signal cross section is reduced



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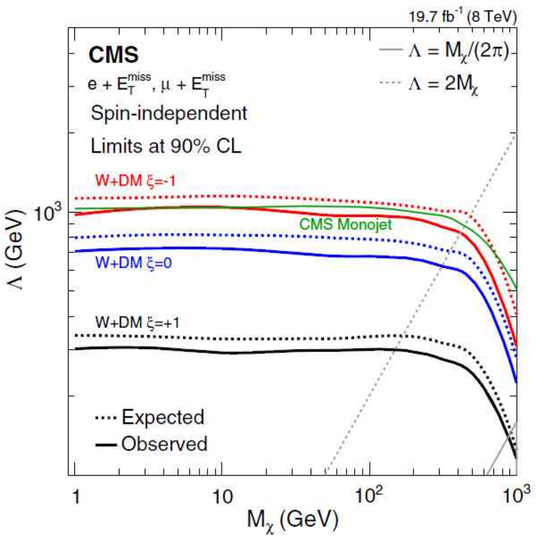
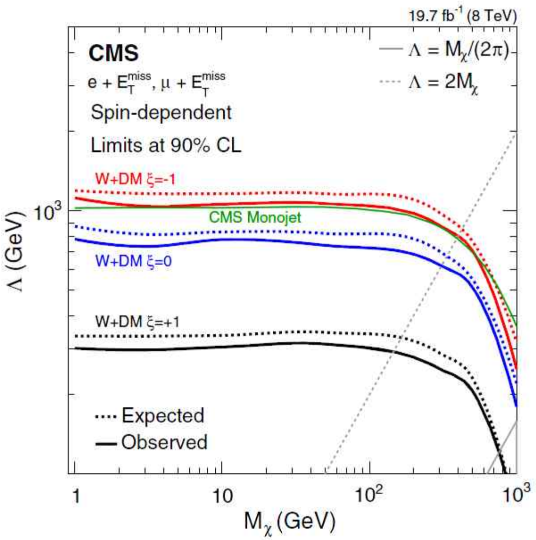
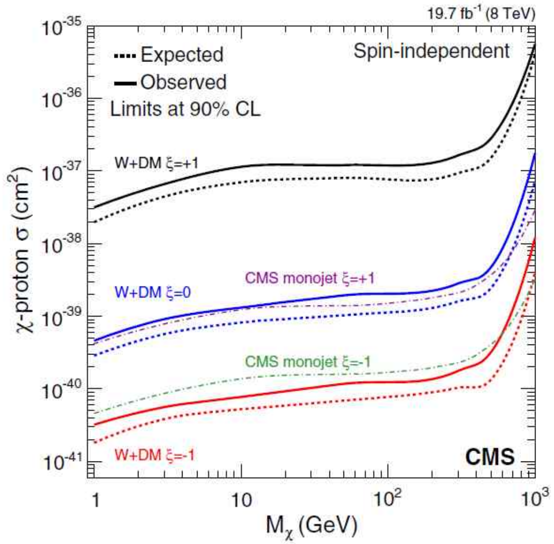
Λ and σ_χ vs M_χ

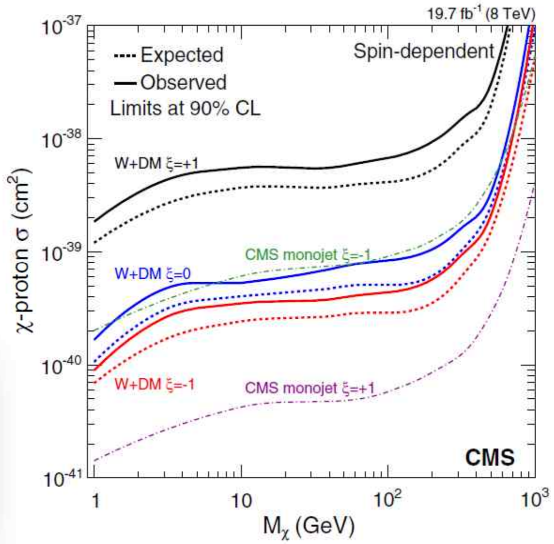




- Cross section upper limits transformed into lower limits on the effective scale parameter Λ as a function of $M\chi$
- For lower masses a constant Λ exclusion obtained for $M\chi \leq 100$ GeV
  - $\Lambda < 300$ GeV for $\xi = 1$, $\Lambda < 700$ GeV for $\xi = 0$, and $\Lambda < 1000$ GeV for $\xi = -1$.
- The difference between vector-like and axial-vector-like couplings is small for low $M\chi$ for all three values of ξ, but a difference is observed in the high-$M\chi$ region, > 100 GeV
- The χ-proton cross section upper limits at 90% for $M\chi = 10$ GeV as an example

ξ	Vector coupling (cm^2)	Axial-vector coupling (cm^2)
−1	4×10^{-41}	1×10^{-40}
0	6×10^{-40}	2×10^{-40}
+1	3×10^{-38}	2×10^{-39}



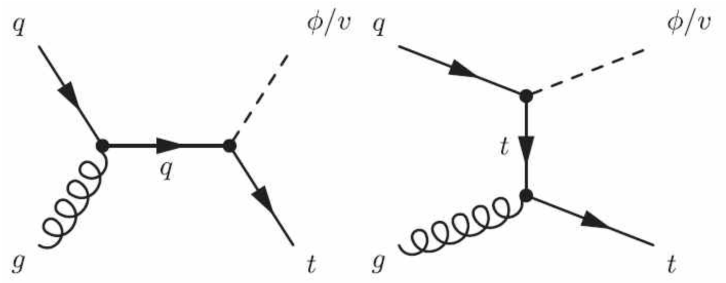


Mono-lepton results are better than mono-jet for the construction case.

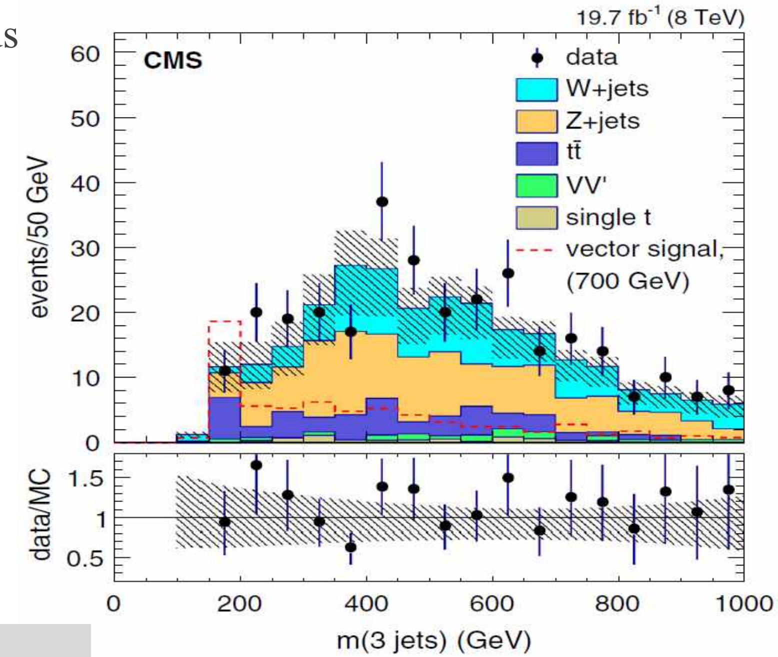
Mono-top

PRL **114**, 101801 (2015)

- DM particle(either scalar or vector) could be produced in association with a top quark.
  - Could be invisible particle produced top quark by quark flavor changing
  - R-parity violating SUSY or FC interaction mediated by invisible state
  - Both with branching fraction to unity assumed
- A single top decays a bottom quark and two light quarks
  - Only jets with pT ≥ 35 GeV and |η| < 2.4
  - The two highest-pT (leading) jets > 60 GeV, third highest pT > 40GeV
  - The inv. mass of the 3 jets < 250 GeV and rejected additional jets with a pT > 35 GeV
  - requiring one of the three jets to be identified as a candidate jet from a b quark
- 3 jets with MET, Z + jets(73%), W + jets(13%) and $t\bar{t}$ as backgrounds



	No b tag	One b tag
$t\bar{t}$	$6 \pm 0 \pm 5$	$12 \pm 0 \pm 12$
$W +$ 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'	$5 \pm 0 \pm 0$	$0 \pm 0 \pm 0$
Multijet	$6(\pm 39)$	$1(\pm 9)$
Total background	140 ± 36	28 ± 16
Signal	2 ± 6	3 ± 11
Data	143	30



No excess is observed above the background expectation

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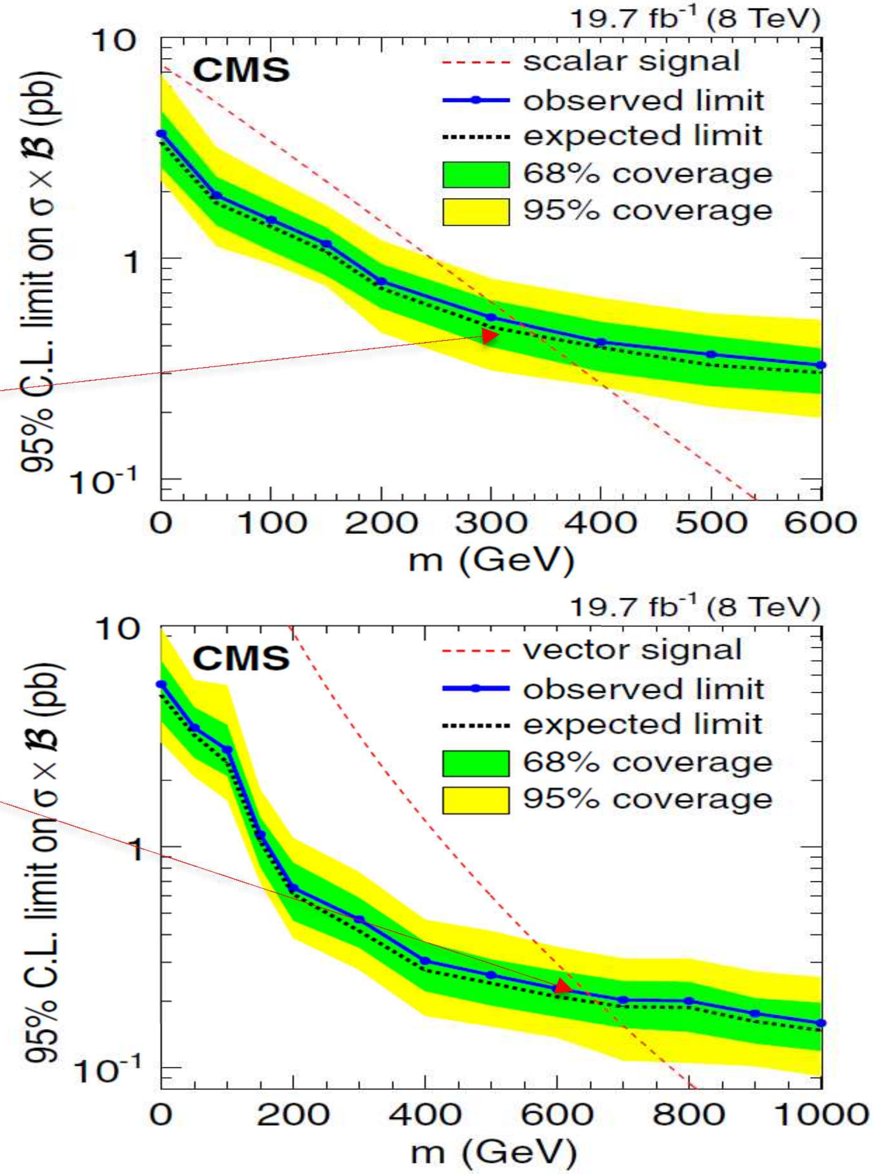
Mono-top Results

- The 95% C.L. expected and observed limits on product of production cross section of mono-top as function of mass of invisible bosonic state. (scalar and vector fields)

- The scalar and vector particles, with masses below 330 and 650 GeV, respectively, are excluded at 95% confidence level.
- The substantial Extension of previous limit on the search from the CDF
- Complementary with the ATLAS results obtained with the leptonic top decay channel.
- This results can be applied to the non-thermal DM model as well.

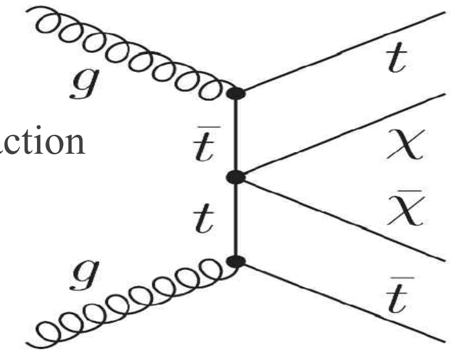


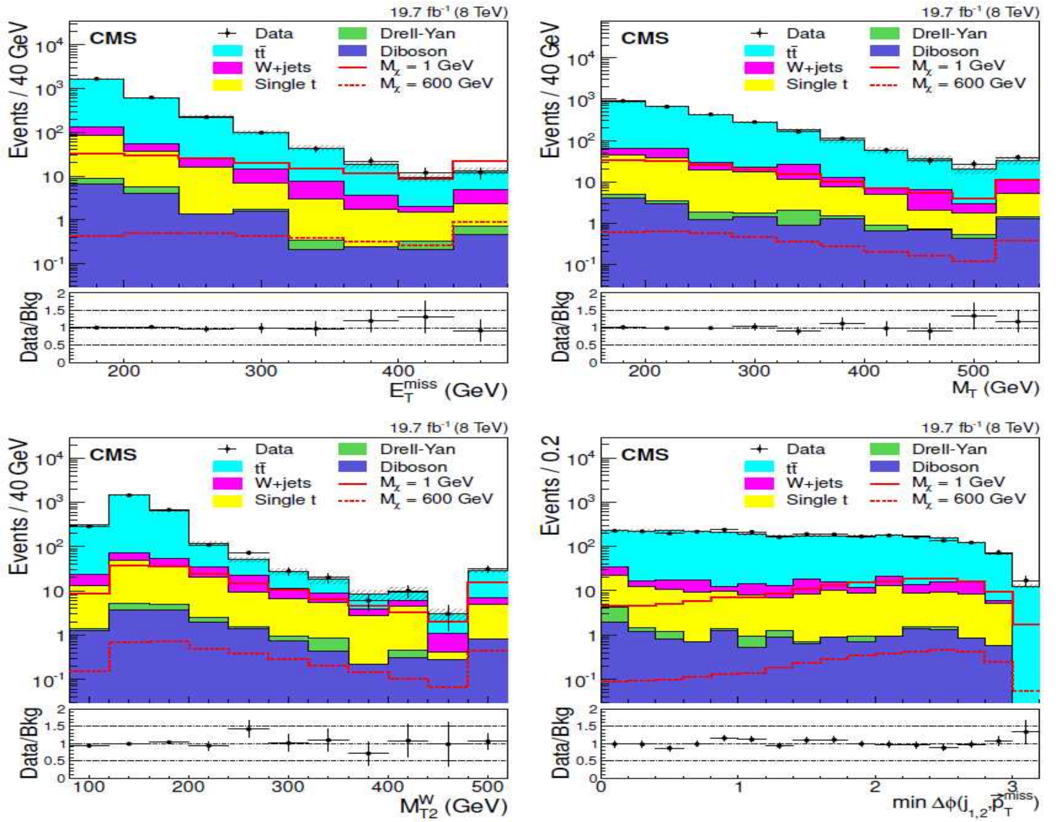
Compact Muon Solenoid experiment at CERN's LHC

Top-quark pairs associated

JHEP06(2015)121

- Assume only one new Dirac fermion related to DM by EFT Lagrangian
  - Assume coupling strength proportional to the mass of quark.
    - → suppressed to light quarks → dominant to 3rd generation quarks
- Consider DM production in association with top quark pair and only scalar interaction
- Requiring the presence of one lepton, multiple jets and large MET
- Backgrounds : $t\bar{t}$ +jets, $t\bar{t}$+γ/W/Z, W+jets, single top, dibosons and DY



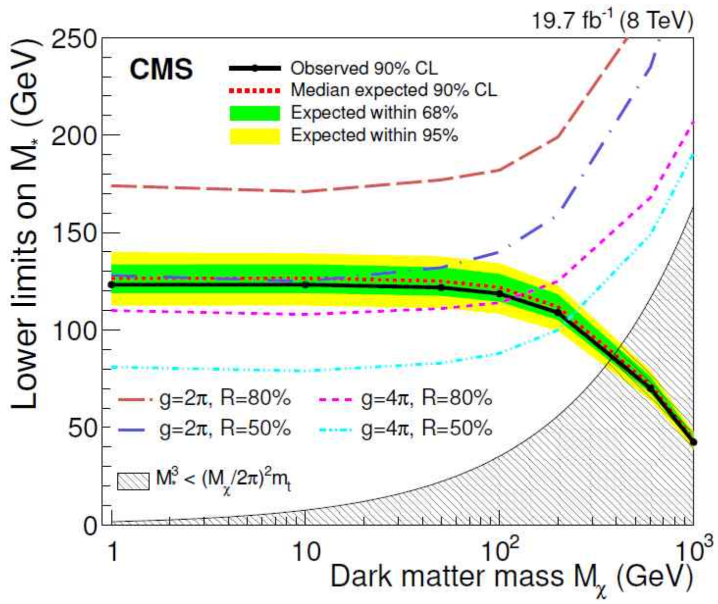


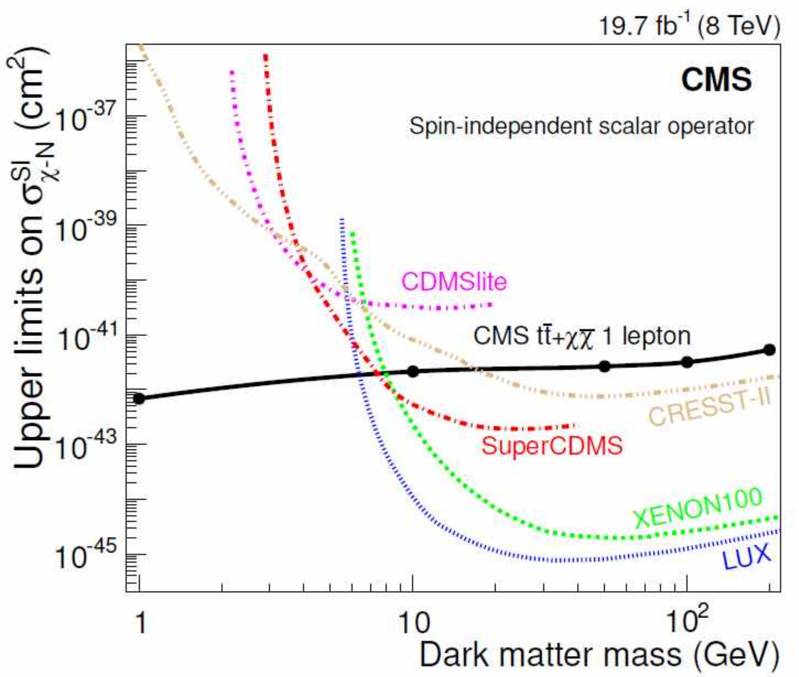
Source	Yield (±stat ±syst)
$t\bar{t}$	$8.2 \pm 0.6 \pm 1.9$
W	$5.2 \pm 1.8 \pm 2.1$
Single top	$2.3 \pm 1.1 \pm 1.1$
Diboson	$0.5 \pm 0.2 \pm 0.2$
Drell-Yan	$0.3 \pm 0.3 \pm 0.1$
Total Bkg	$16.4 \pm 2.2 \pm 2.9$
Data	18

The data are in good agreement with expectations from SM background.

Top quark-pair : Results

- Observed exclusion limits in the plane of ($M\chi$, M_*) at a 90% CL.
- The background-only expectations are represented by dashed line (68% and 95% CL bands).
- A lower bound of the validity of the EFT indicated by the upper edge of the hatched area.
- The four curves corresponding to different g and R values
  - represent the lower bound on M_* for different (g, R) set
  - indicate further restrictions on the applicability of EFT





- The 90% CL upper limits on the DM-nucleon spin-independent scattering cross section as a function of $M\chi$ for the scalar operator.
- Also shown are 90% CL limits from various direct DM search experiments

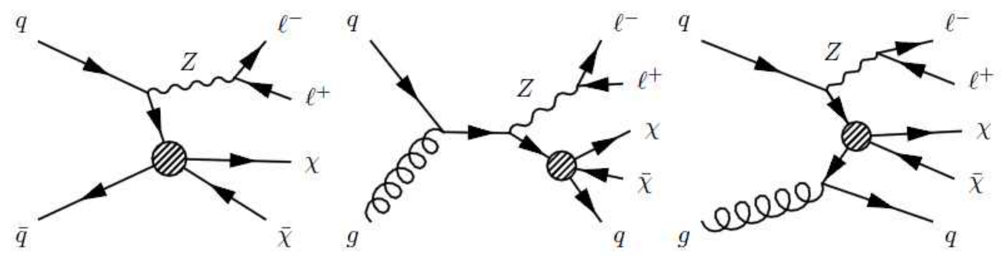
Better result in $M\chi$ < ~ 5 -10 GeV region in comparison with DD experiments

Compact Muon Solenoid experiment at CERN's LHC

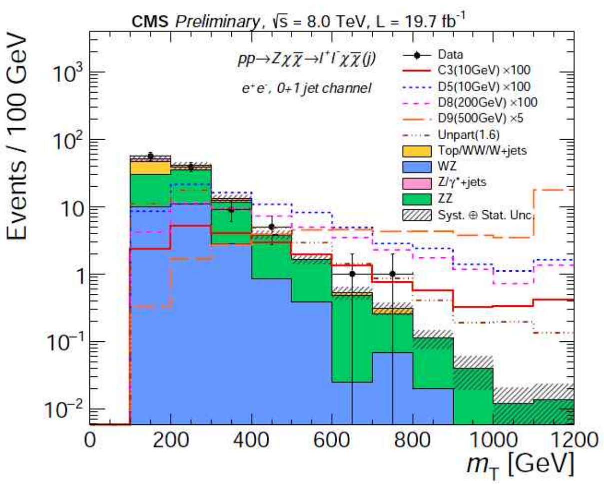
Mono-Z(to Dilepton)

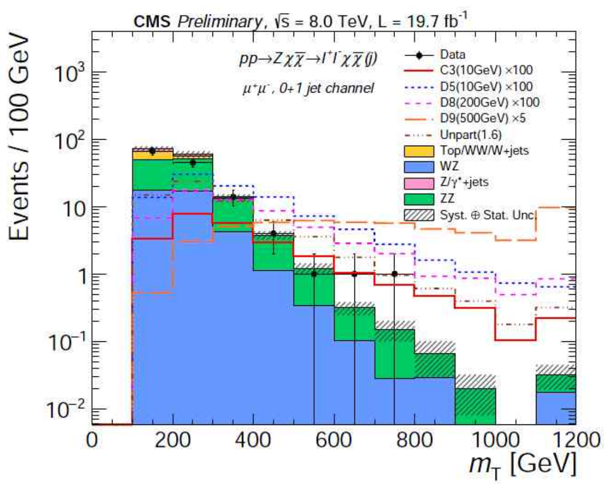
CMS PAS EXO-12-054

- Dark matter production : Z boson is radiated(ISR) or interacts directly with DMs
- Signature : 2 leptons + 2 dark matters
  - 2 isolated leptons (electrons or muons)
  - Mass(ll) in Z boson mass window
  - Large missing transverse energy



- ZZ/WZ main backgrounds, $t\bar{t}$, tW, WW etc. as well.
- Applying to vector (D5), axial-vector (D8) and tensor (D9) coupling to the SM quarks for Dirac fermion DM and vector (C3) coupling for complex scalar DM.



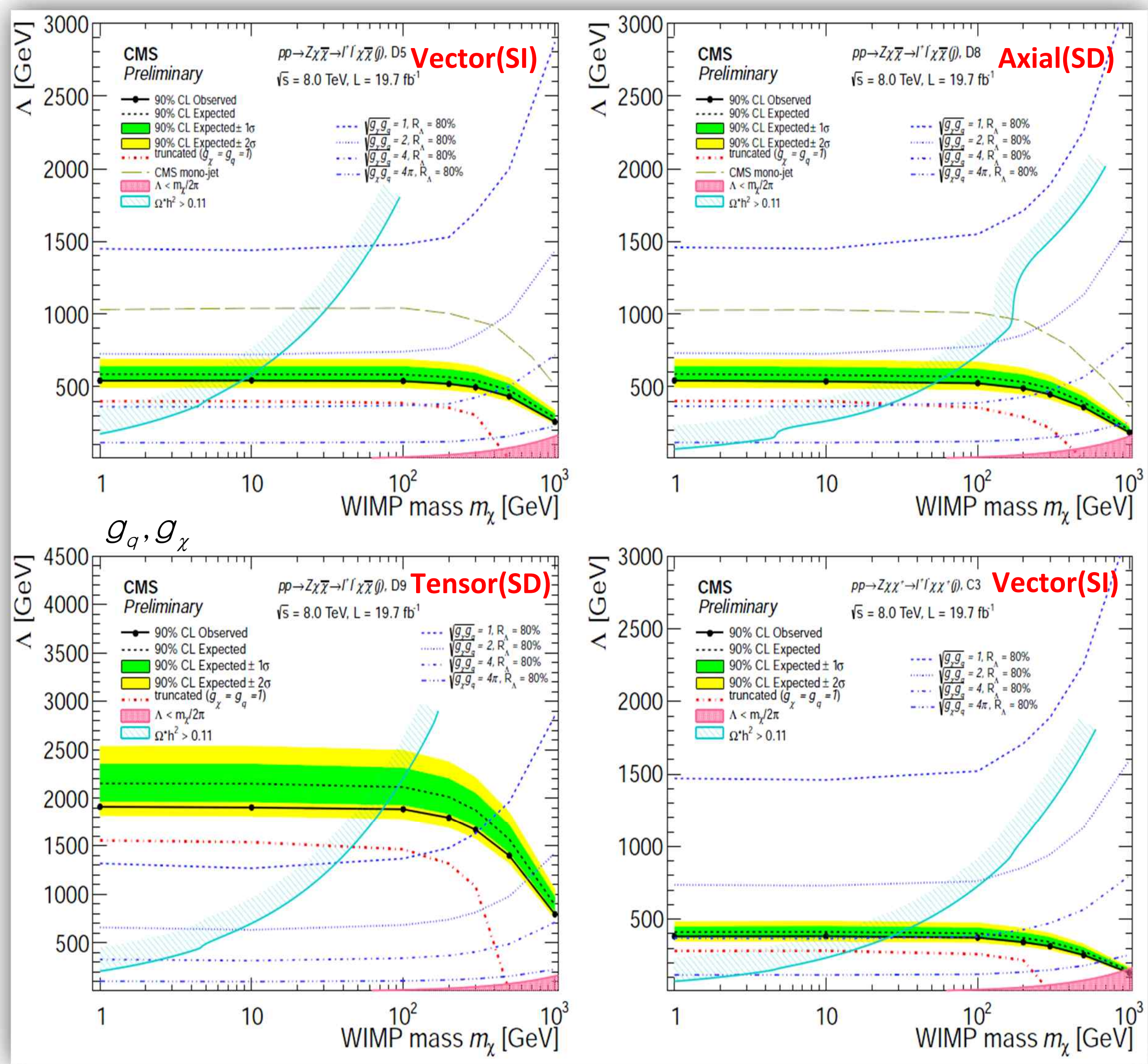


Process	e^+e^-	$\mu^+\mu^-$
C3(10GeV)	$0.20 \pm 0.004 \pm 0.02$	$0.24 \pm 0.005 \pm 0.02$
D5(10GeV)	$0.79 \pm 0.02 \pm 0.09$	$0.97 \pm 0.02 \pm 0.09$
D8(200GeV)	$0.48 \pm 0.01 \pm 0.06$	$0.59 \pm 0.01 \pm 0.05$
D9(500GeV)	$10.24 \pm 0.12 \pm 1.59$	$10.80 \pm 0.13 \pm 0.98$
Unparticle(1.6)	$48.96 \pm 0.88 \pm 3.26$	$65.80 \pm 1.07 \pm 4.38$
$Z/\gamma^* \to \ell^+\ell^-$	$8.18 \pm 1.93 \pm 0.82$	$8.59 \pm 3.01 \pm 1.02$
$WZ \to 3\ell\nu$	$25.08 \pm 0.53 \pm 2.84$	$40.70 \pm 0.69 \pm 4.50$
$ZZ \to 2\ell 2\nu$	$58.81 \pm 0.65 \pm 10.30$	$78.68 \pm 0.79 \pm 13.83$
$Top/WW/Z \to \tau^+\tau^-$	$18.74 \pm 3.39 \pm 3.27$	$22.92 \pm 2.29 \pm 3.44$
$W + $jets	$1.84 \pm 0.64 \pm 0.27$	
Total bkg.	$113 \pm 4 \pm 13$	$151 \pm 4 \pm 18$
Data	111	133

The data agree with SM background prediction and no excess is observed.

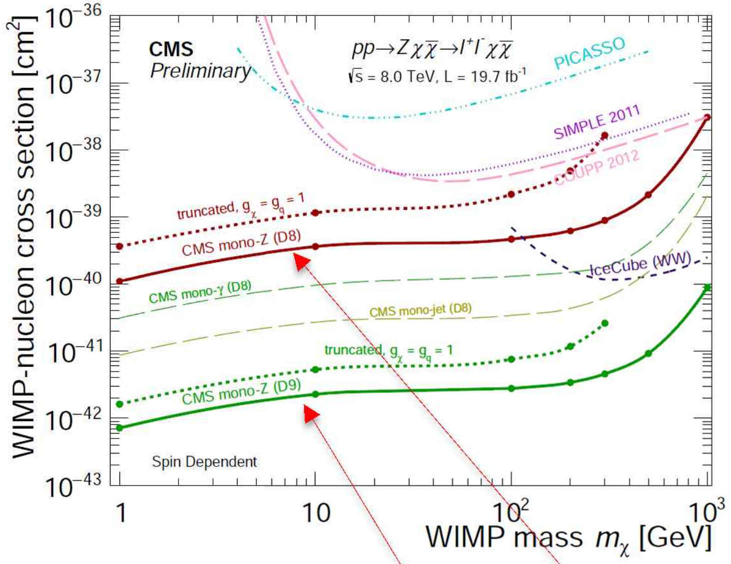
Dilepton - Λ vs Mχ

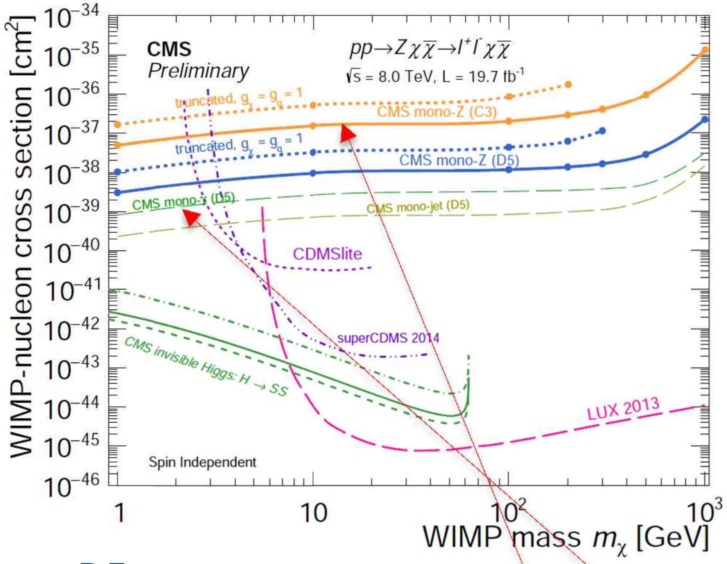
- 90% expected and observed CL Limits set on (Mχ, Λ) plane
- Appropriate choices of couplings and masses made for valid EFT
  - Consider massive mediator(M) couples to DM and quarks.(g_q and g_χ)
  - Can be $\Lambda \sim M/\sqrt{g_q g_\chi}$
- Lower bound set to Λ > Mχ/2π with condition $\sqrt{g_q g_\chi} < 4\pi$
- Realistically RΛ to be 80% with various values as well as truncated limits
  - RΛ more realistic min. constraint Q_{tr} < M applied → fraction of total events w/ the constraint of Q less than cutoff scale
  - Truncated : removed events w/ Q_{tr} > M at gen. level → this limit curve pattern coincides with the observed one in shape
- $\Omega h^2 = 0.11$ measured by WMAP
- In overall, tune very much within EFT
- Poor results than CMS mono-jet for D5 and D8



Dilepton – Nucleon xsection vs Mχ

- The 90% CL upper limits on the DM-nucleon cross section as a function of the DM particle mass
- Spin-dependent(D8 and D9) and Spin-Independent(C3 and D5) limits
- Comparisons with various direct detection experiments
- CMS mono-jet, mono-photon and Higgs portal DM results as well.
- In general, dominant contributions to SD against direct detection experiments
- In the region Mχ < 5 to10 GeV, LHC is better than DD experiments for the case of SI





D8

M_χ	Expected		Expected -1σ		Expected $+1\sigma$		Observed	
(GeV)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)
1	586	8.05×10^{-41}	641	5.63×10^{-41}	535	1.16×10^{-40}	542	1.10×10^{-40}
10	579	2.65×10^{-40}	633	1.85×10^{-40}	528	3.82×10^{-40}	536	3.62×10^{-40}
100	568	3.37×10^{-40}	621	2.36×10^{-40}	518	4.86×10^{-40}	523	4.66×10^{-40}
200	532	4.42×10^{-40}	581	3.09×10^{-40}	485	6.38×10^{-40}	488	6.22×10^{-40}
300	488	6.24×10^{-40}	534	4.37×10^{-40}	445	9.01×10^{-40}	446	8.96×10^{-40}
500	394	1.48×10^{-39}	430	1.04×10^{-39}	359	2.14×10^{-39}	358	2.15×10^{-39}
1000	203	2.10×10^{-38}	222	1.47×10^{-38}	185	3.03×10^{-38}	184	3.07×10^{-38}

D5

M_χ	Expected		Expected -1σ		Expected $+1\sigma$		Observed	
(GeV)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)
1	585	2.23×10^{-39}	640	1.56×10^{-39}	534	3.22×10^{-39}	541	3.05×10^{-39}
10	584	7.08×10^{-39}	638	4.95×10^{-39}	532	1.02×10^{-38}	542	9.49×10^{-39}
100	583	8.34×10^{-39}	638	5.83×10^{-39}	532	1.20×10^{-38}	538	1.15×10^{-38}
200	565	9.55×10^{-39}	618	6.68×10^{-39}	515	1.38×10^{-38}	519	1.34×10^{-38}
300	542	1.13×10^{-38}	593	7.88×10^{-39}	495	1.63×10^{-38}	495	1.62×10^{-38}
500	474	1.94×10^{-38}	519	1.35×10^{-38}	433	2.79×10^{-38}	432	2.81×10^{-38}
1000	286	1.46×10^{-37}	313	1.02×10^{-37}	261	2.11×10^{-37}	258	2.21×10^{-37}

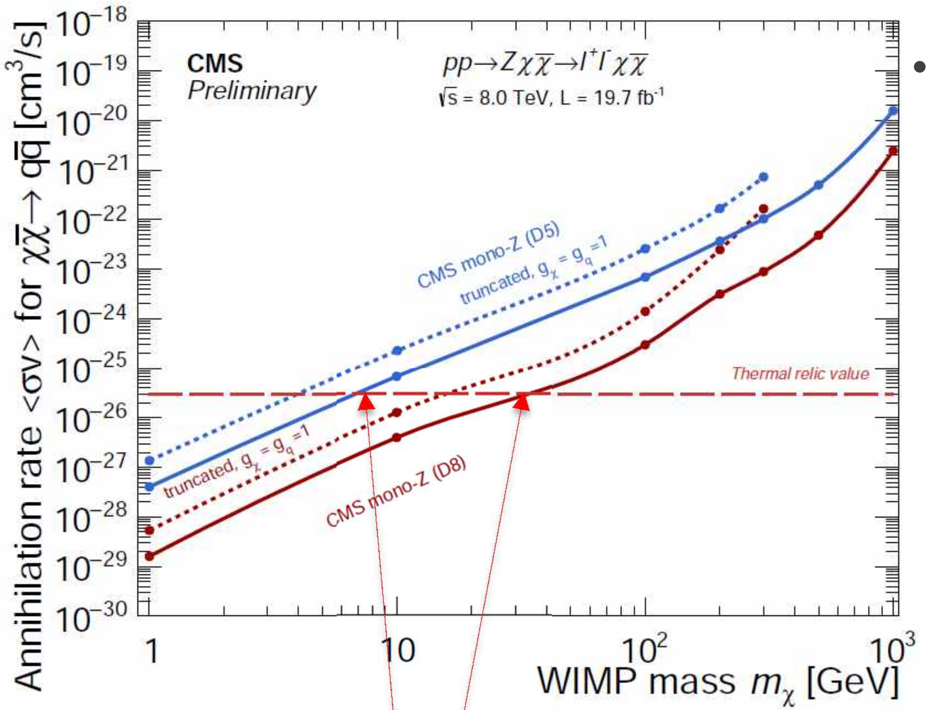
D9

M_χ	Expected		Expected -1σ		Expected $+1\sigma$		Observed	
(GeV)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)
1	2151	4.44×10^{-43}	2352	3.10×10^{-43}	1962	6.40×10^{-43}	1909	7.14×10^{-43}
10	2148	1.40×10^{-42}	2350	9.78×10^{-43}	1960	2.02×10^{-42}	1902	2.28×10^{-42}
100	2113	1.75×10^{-42}	2311	1.23×10^{-42}	1928	2.53×10^{-42}	1884	2.78×10^{-42}
200	2011	2.16×10^{-42}	2199	1.51×10^{-42}	1835	3.12×10^{-42}	1795	3.40×10^{-42}
300	1873	2.88×10^{-42}	2048	2.01×10^{-42}	1709	4.16×10^{-42}	1668	4.58×10^{-42}
500	1570	5.84×10^{-42}	1717	4.09×10^{-42}	1433	8.43×10^{-42}	1401	9.23×10^{-42}
1000	892	5.63×10^{-41}	975	3.94×10^{-41}	813	8.13×10^{-41}	795	8.90×10^{-41}

C3

M_χ	Expected		Expected -1σ		Expected $+1\sigma$		Observed	
(GeV)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi-N}$ (cm^2)
1	411	3.66×10^{-38}	450	2.56×10^{-38}	375	5.28×10^{-38}	382	4.93×10^{-38}
10	412	1.14×10^{-37}	451	7.96×10^{-38}	376	1.64×10^{-37}	382	1.54×10^{-37}
100	403	1.47×10^{-37}	440	1.02×10^{-37}	367	2.11×10^{-37}	373	1.99×10^{-37}
200	371	2.05×10^{-37}	406	1.43×10^{-37}	339	2.95×10^{-37}	341	2.87×10^{-37}
300	342	2.84×10^{-37}	374	1.99×10^{-37}	312	4.10×10^{-37}	314	4.03×10^{-37}
500	278	6.53×10^{-37}	304	4.56×10^{-37}	254	9.42×10^{-37}	253	9.62×10^{-37}
1000	145	8.85×10^{-36}	159	6.18×10^{-36}	132	1.28×10^{-35}	131	1.34×10^{-35}

DM Annihilation Rate limit



- The limits from D5(vector) and D8(axial-vector) translated into upper limits on the dark matter annihilation rate.
  - A 100% branching fraction of DM annihilating to quarks is assumed.
  - The corresponding truncated limits for D5 and D8 with sqrt(gqgχ) = 1 are also presented.
  - The value required for DM to make up the relic abundance labeled "Thermal relic value" is shown as a red dashed line.

- The annihilation rate of Dirac fermion DM ruled out at 90% CL.
  - $m\chi < 7$ GeV for vector coupling
  - $m\chi < 32$ GeV in case of axial-vector coupling.
- Indicate same conclusions in comparison with FNAL-LAT experiment.

Compact Muon Solenoid experiment at CERN's LHC

Run 1 Summary

- Searches for DM at collider have evolved since the Higgs discovery.
  - The most recent one : Mono-Z(to Dilepton) analysis contains the most tuned EFT
  - Indicate no-longer valid EFT → Requiring new DM model rather than EFT at new energy
- Qualitative picture on DM searches by the LHC is complementary with Direct Detection experiments regardless of decay channels by the LHC.
  - Dominant contribution in Spin-dependent by the LHC
  - Dominant in spin-independent by the Direct Detection experiments but the LHC is better in the region of DM mass less than ~ 5 - 10 GeV region.
- Need more reliable model rather than EFT at the new energy LHC era since momentum transfer is very high.

EFT applicable to Run 2 ?

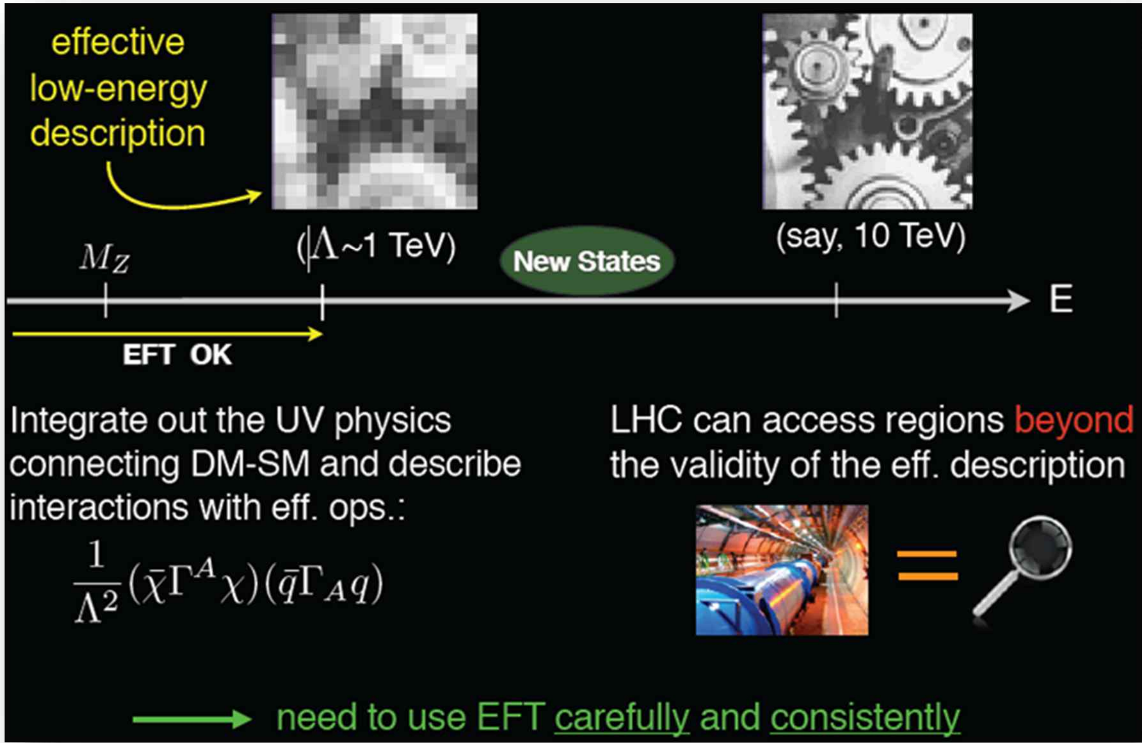
- Since the start-up of the LHC, generic searches for DM production at colliders, and their comparison with direct-detection experiments such as LUX, have become a focal point for both the experimental and theoretical particle and astro-particle communities.

- A comparison of DM searches at collider and DD experiments using the EFT approach does not provide an accurate description of the complementarity of the two search strategies .

- How to go beyond the problematic comparison of DM searches in the EFT framework ??

- An alternative to the EFT interpretation is the Simplified Models.

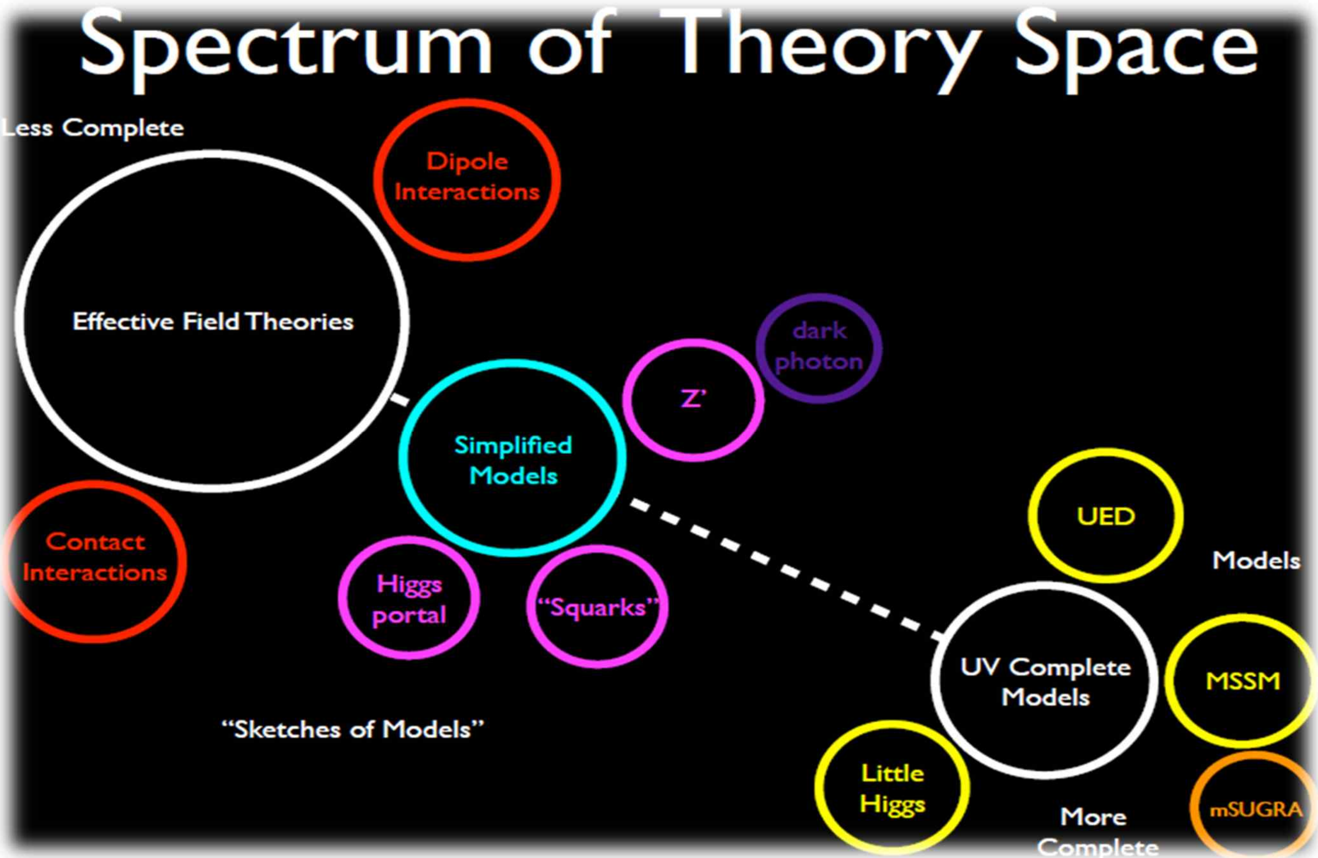
- Simplified models are able to capture properly the relevant kinematic properties of collider searches with only a few free parameters.



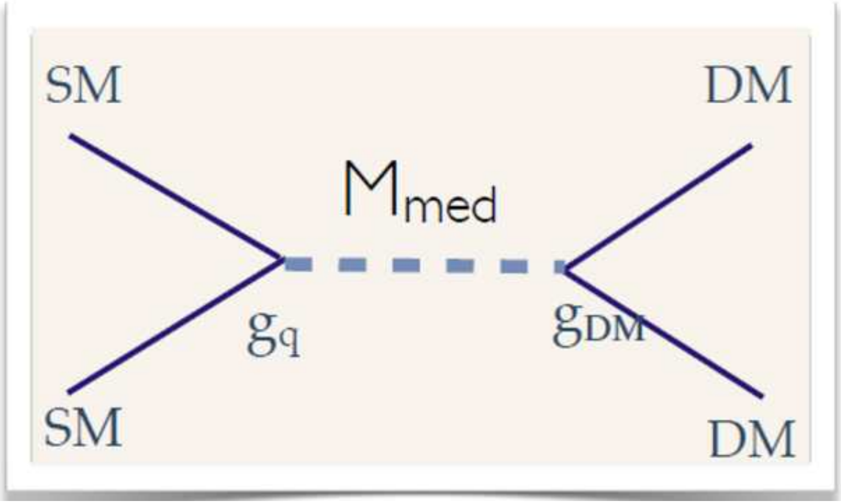
Compact Muon Solenoid experiment at CERN's LHC

Minimal Simplified DM Model

- The model where only the particles and parameters most relevant to the search are included.
- The Minimal Simplified DM(MSDM) model can be understood as a phenomenological sketch of a complete mode.



MSDM Model



Define simplified model with (minimum) 4 parameters	
Mediator mass (M_{med})	DM mass (M_{DM})
g_q	g_{DM}

DM	
Dirac fermion	Scalar - real
Majorana fermion	Scalar - complex

Consider comprehensive set of diagrams for mediator	
Vector	Axial-vector
Scalar	Pseudoscalar

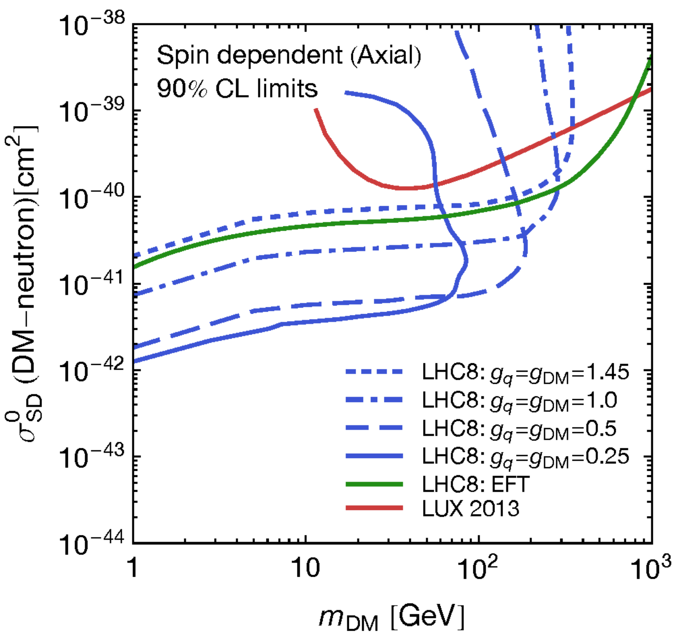
$g_q = g_{DM} = [0.25, 0.5, 1.0, 1.45]$ M_{DM} vs M_{med} assuming $g_q = g_{DM}$

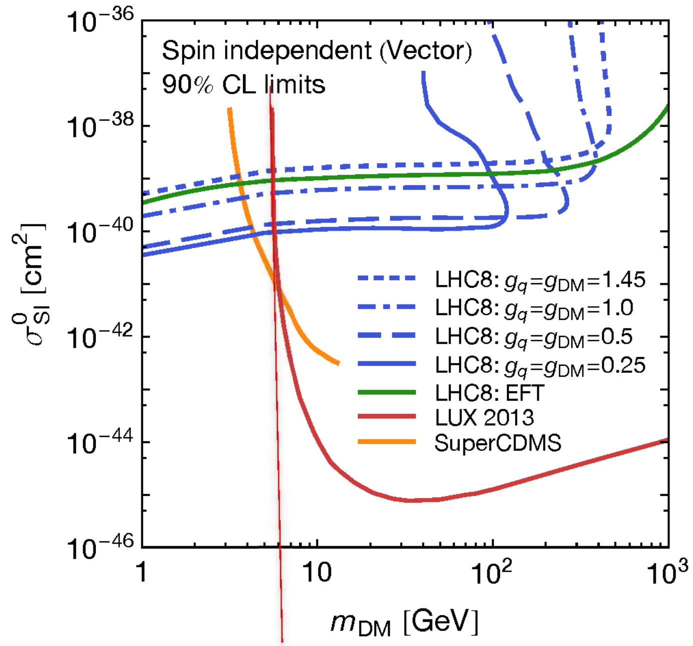
S. Malik et. al, arXiv:1409.4075 (2014) : White Report

Compact Muon Solenoid experiment at CERN's LHC

Dark Matter Searches Results(Run 1)

- The most recent comparison of the LHC and underground experiments
  - LUX : Current world best limit among underground experiments(350 kg Xe)
  - CMS : Mono-jet channel at 8 TeV
  - The LHC results are much better in the case of Spin dependent(Axial)
  - But the LHC is only sensitive in low DM mass(<5 GeV) region in the case of Spin-independent

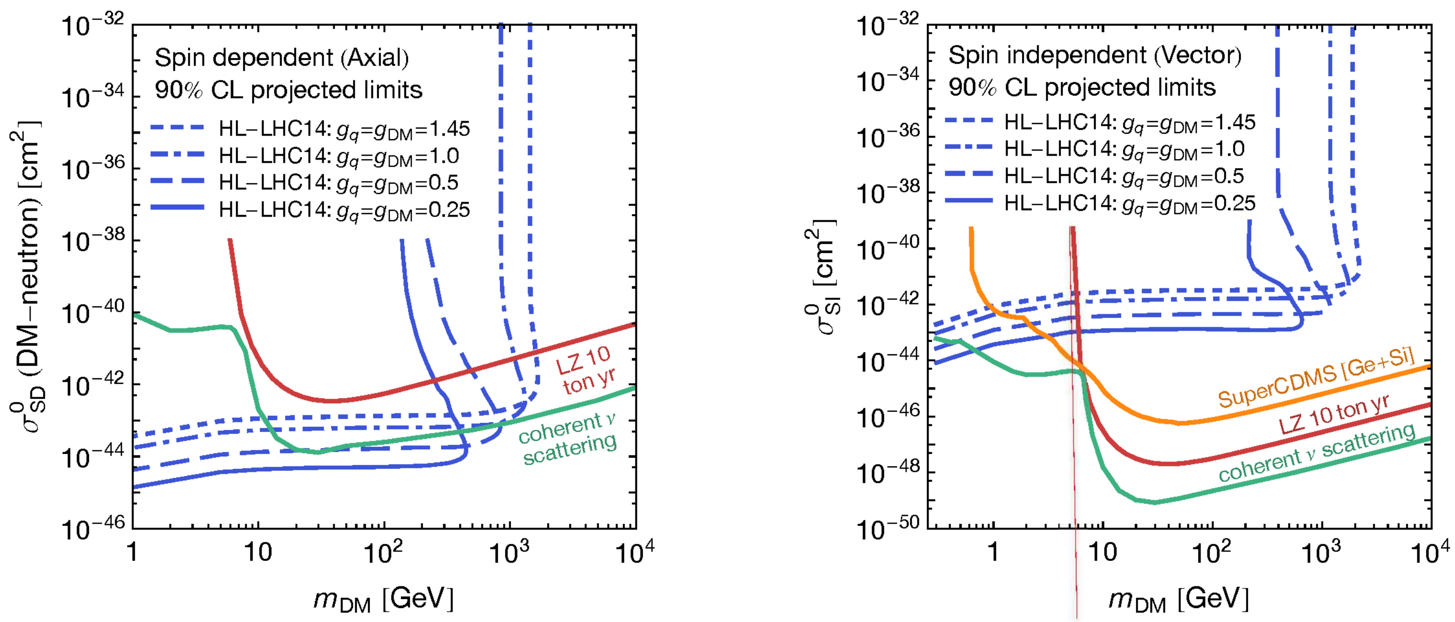




Compact Muon Solenoid experiment at CERN's LHC

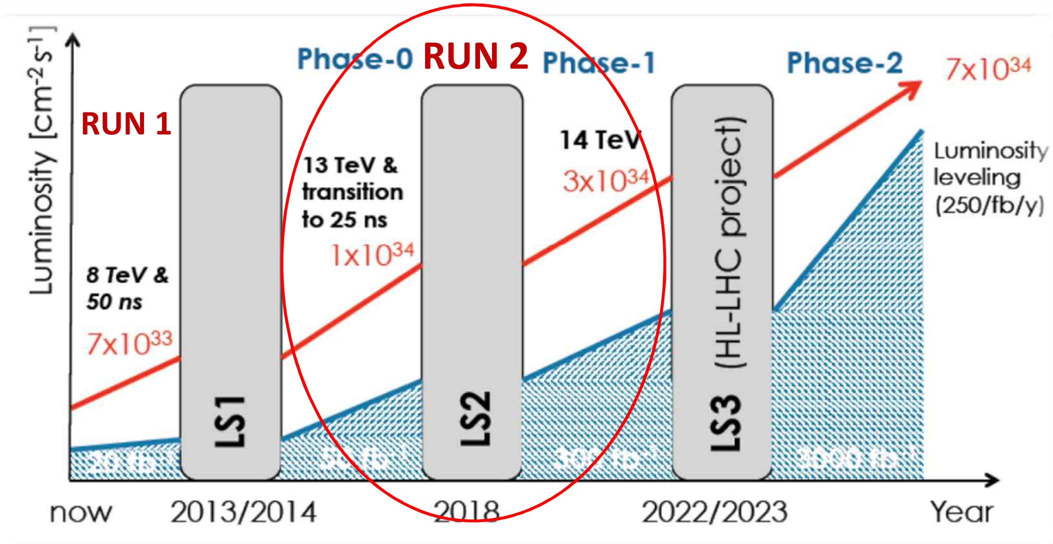
Prospect of Run 2

- Expectations with 14 TeV LHC
  - Comparison with future underground experiments
    - LZ(LUX-ZEPLIN : 7 ton planned) and SuperCDMS
  - Show much better results(10 -100 times more in x-section) with the LHC for spin-dependent case
  - LHC results sensitive in very low dark mass region for spin-independent case



Collider Dark Matter Search is complementary with underground experiments

The LHC Run 2 Original Plan

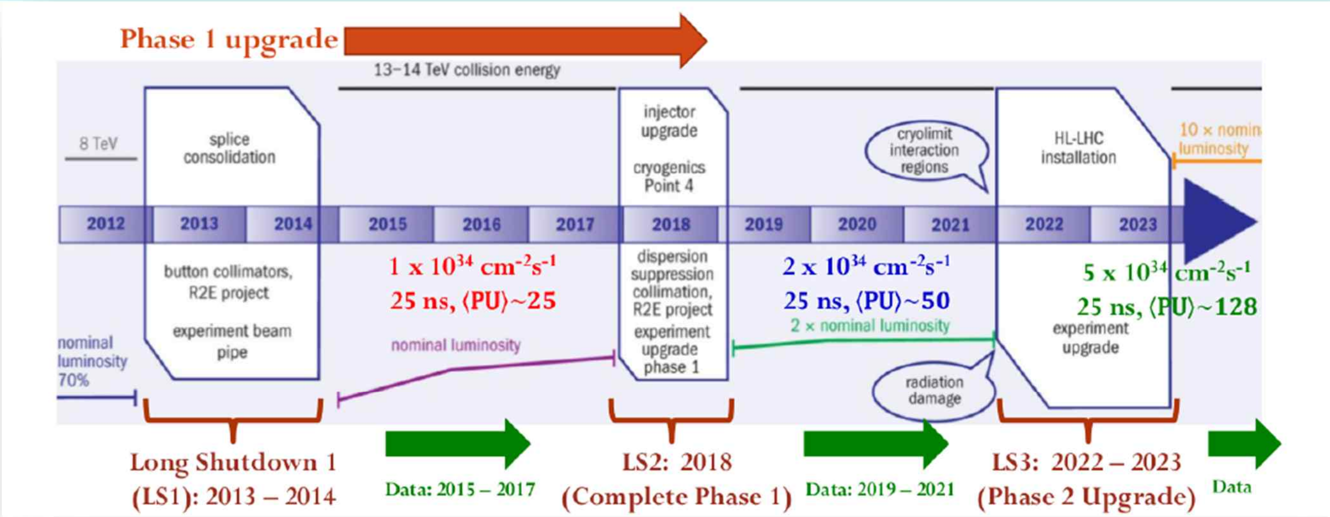


Period	Activity	Label	Peak $\mathscr{L}$	Int $\mathscr{L}$ (fb^{-1})	√s (TeV)	Bunch (ns)
2013-2014	Install Phase 0	LS1				
2015-2017	Running		10^{34}	~100	~14	25
2018	Install Phase I	LS2				
2019-2021	Running		~2×10^{34}	~300	~14	25
2022-2023	Install Phase II	LS3				
2024-2036	Running		~5×10^{34}	~3000	~14	25

The most important period in Particle Physics Field (2013-2014 to 2019-2021)

The Run 2 is main while Run 1 was like introductory even Higgs had been found.

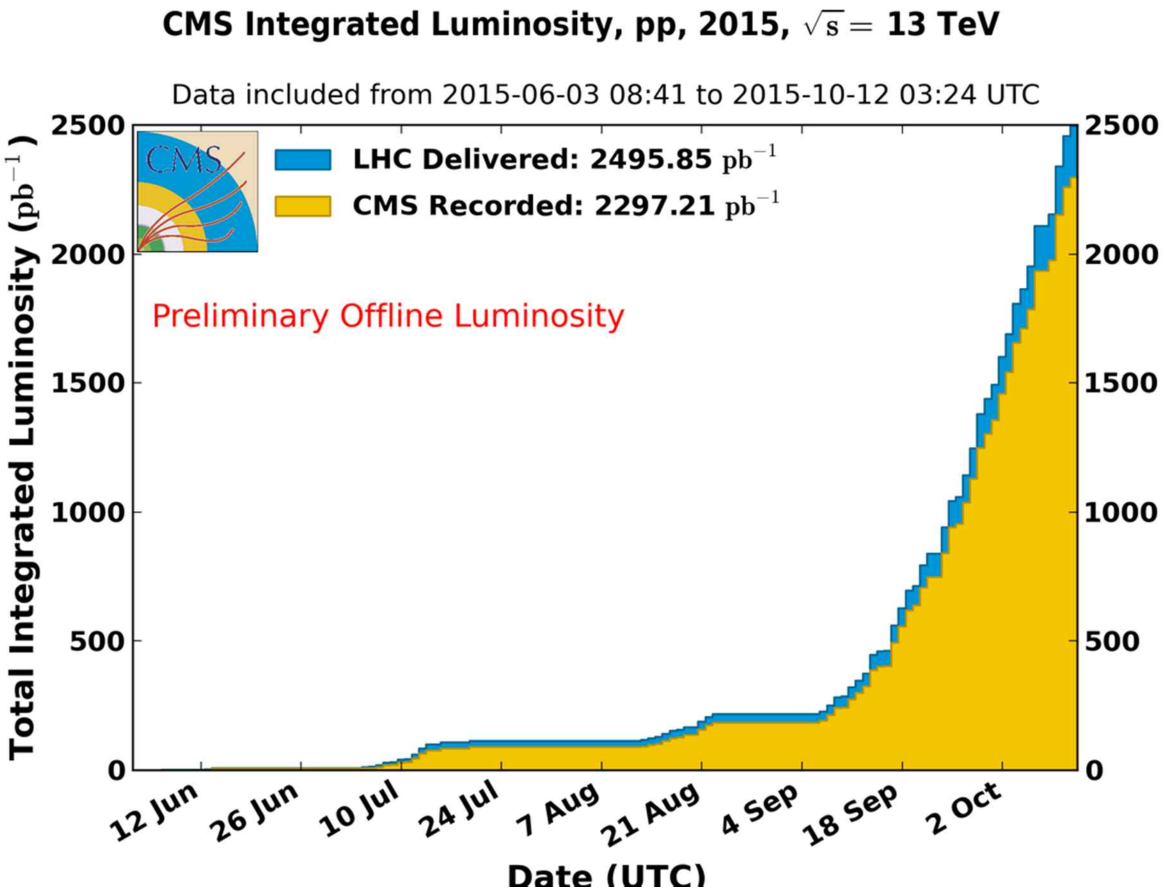
Physics Milestone(Run 2 & 3)



- Run 2 (Phase 1: 2015-2021) : 13 and 14 TeV, ~2 X 10^{34} $cm^{-2}s^{-1}$, 300 fb^{-1}
  - Doubling of new particle mass reach : SUSY and(/or) other unknown phenomena
  - Potential searches of dark matters
  - Higgs Properties : mass, width, couplings and even self-coupling
  - Looking for anomalies through vector-vector scattering
  - Measurements of rare SM processes
- Run 3(Phase 2: 2024-2036) : 14 TeV, ~5 X 10^{34} $cm^{-2}s^{-1}$, 3000 fb^{-1}
  - Characterization of new particle discovered at run 2, or
  - Extension of new particle mass reach : SUSY and(/or) Exotic discovery
  - Precision measurements of Higgs properties : couplings (< 5%), self-coupling (~20%) etc.
  - Precision Measurements of rare SM process

Current Status

- As of Oct 12, 2015, ~ 2.3 fb^{-1} recorded.
- Some fraction of data with no magnetic field on (~20%)
- Data delivered exponentially (similar situation with year 2011 run)



- First results were presented at EPS-HEP conference in July 2015.
- First paper already submitted to PLB for charged Hadron Production.
- All the important physics topics are underway of analysis mode.

Summary

- The LHC experiments are compatible and complementary with the underground experiments.
- The LHC is very strong with spin-dependent DM case and low mass(~< 5 to 10 GeV) DM region in spin-dependent case.
- There had been a development of Minimal Simplified DM model in order to compare with direct detection experiments in parallel.
- We have many interesting results on DM searches at the LHC from Run 1, but have not yet found a signal.
- Dark Matter searches at the LHC are hot topics at the LHC Run 2.
- Hopefully the DM will be unveiled at the LHC Run 2 period.

Summary

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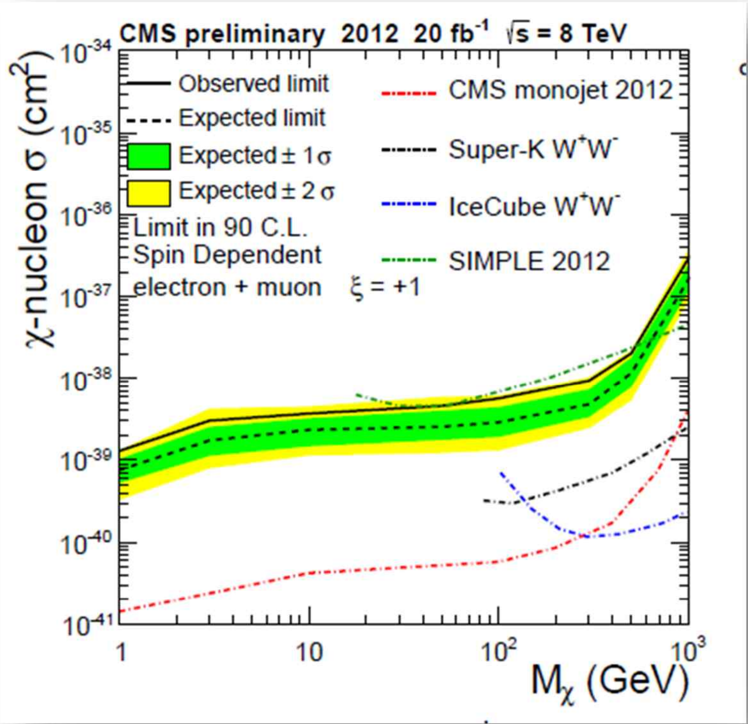
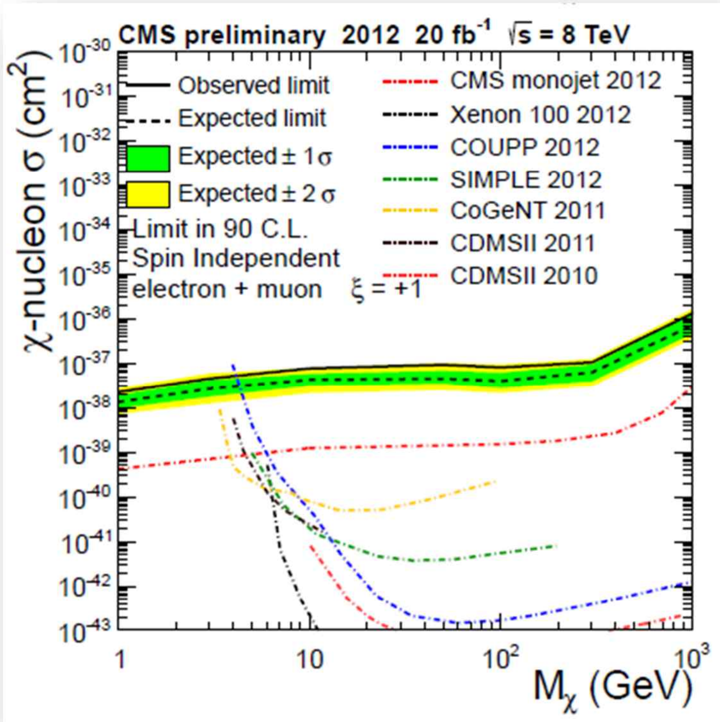
> ‘ The truth is only an agreement between a cognitive spirit and Things.
> Well, Nature never surrenders against any traditions by human being.’

BACKUP

Comparisons with the Direct Detection Expts

- Direct detection much more sensitive on SI(V) coupling for $M\chi > 5$GeV
- Strong in SD(axial) mode :
- very similar with mono-jet case but better for the case constructive interference

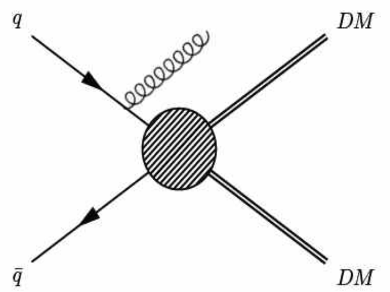


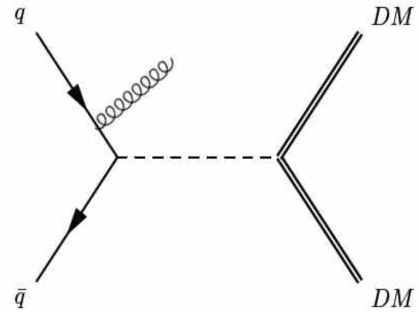


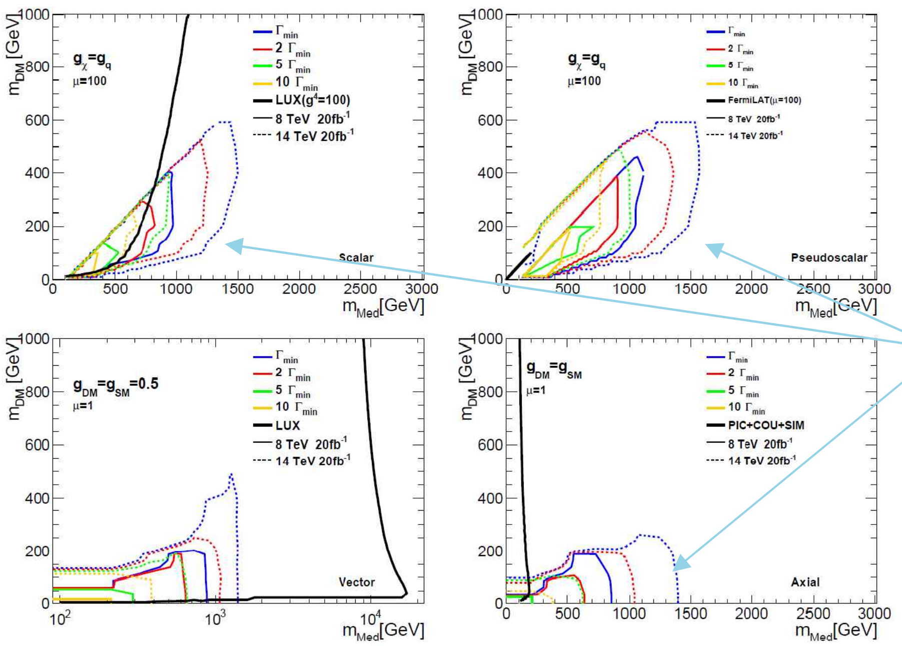
Compact Muon Solenoid experiment at CERN's LHC

Mono-jet + missing energy

- Signature
  - One light jet(gluon initiated) with large missing energy from undetected particle
- Dark matter production scenarios
  - Contact interaction
    - Mediator is heavier than the typical energy transfer at the LHC
    - The framework of effective field theory is used
    - mediator can be scalar, pseudo-scalar, vector or axial vector field.
  - Exchange of mediator
    - Mediator is light enough to be produced at the LHC





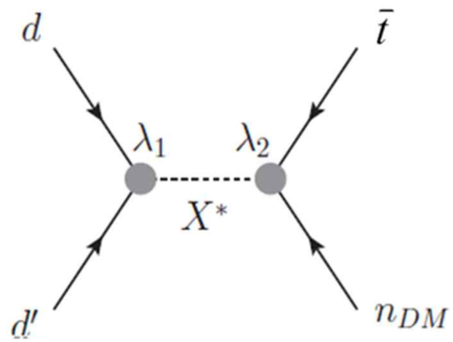


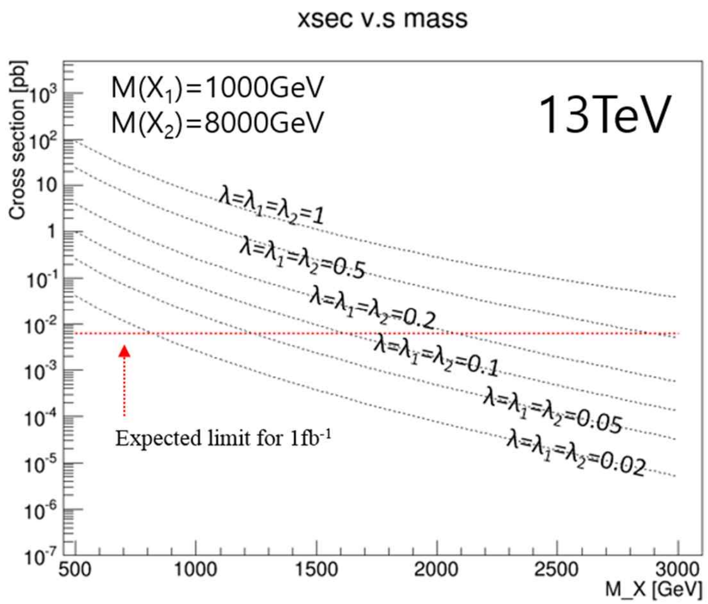
- LHC 14TeV Run can probe much wider region than any other dark matter experiments !

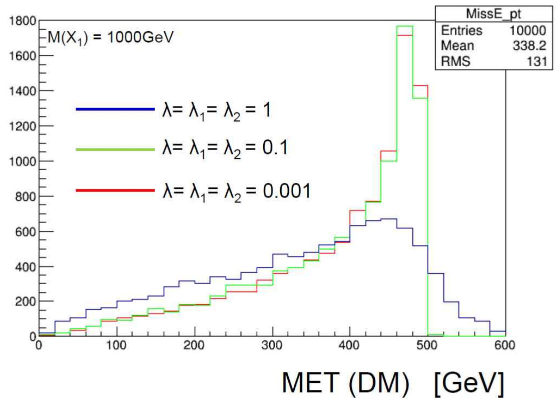
Compact Muon Solenoid experiment at CERN's LHC

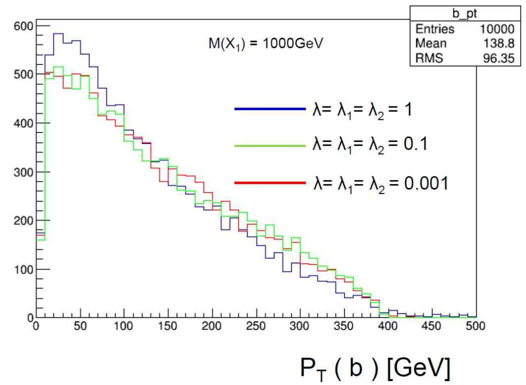
Mono-top Studies at new energy

- Mono-top + missing energy channel
  - Top quark + dark matter production via resonance of scalar particle is considered.
  - Production cross section of pp collision at 13 TeV are calculated.
  - Kinematical properties are studied to setup the trigger and selection scheme for data analysis.









- Confirmed the mono-top channel can be probed for the dark matter
- To be analyzed with the CMS new energy data