Search for Dark Matter and Large Extra Dimensions in 7 TeV pp collisions at CMS

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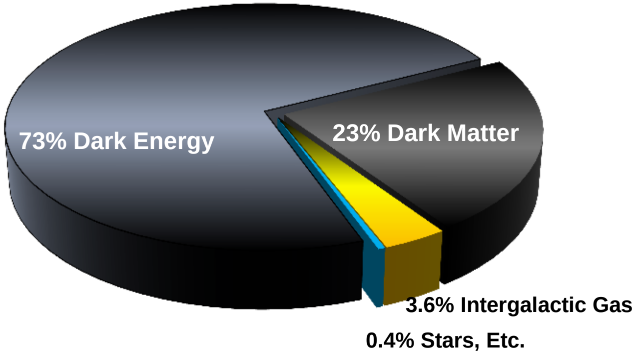
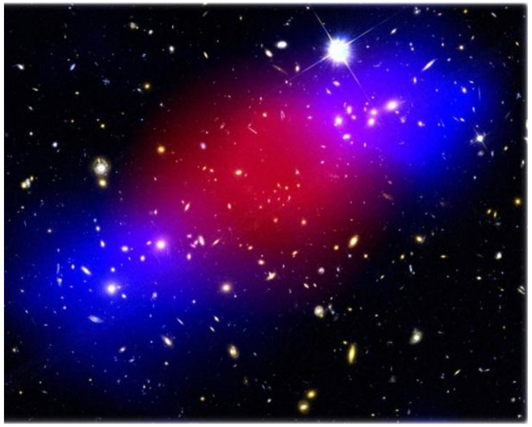
Outline

- New physics with MonoJet & Missing Transverse Energy at LHC
  - Dark Matter
  - Large Extra Dimension Model ADD (Arkani, Dimopoulos, Dvali)
- Event selection
- Background estimation
- Results

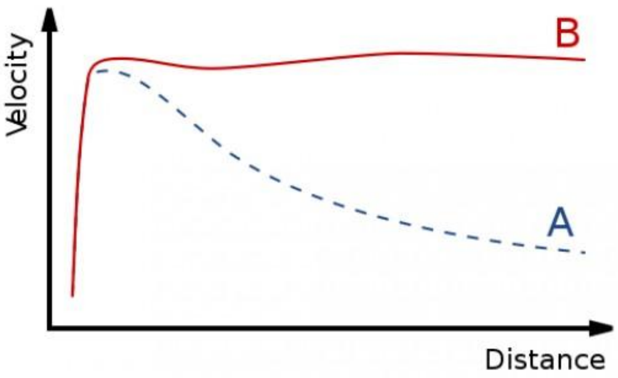
Astrophysical Evidence of Dark Matter

- There is strong astrophysical evidence for the existence of dark matter
- Evidence from motion of the galaxies, rotational speeds of galaxies, gravitational lensing, cosmic microwave background, nucleosynthesis models, evolution of large cosmic structures.
- It is 6 times more abundant than baryons.

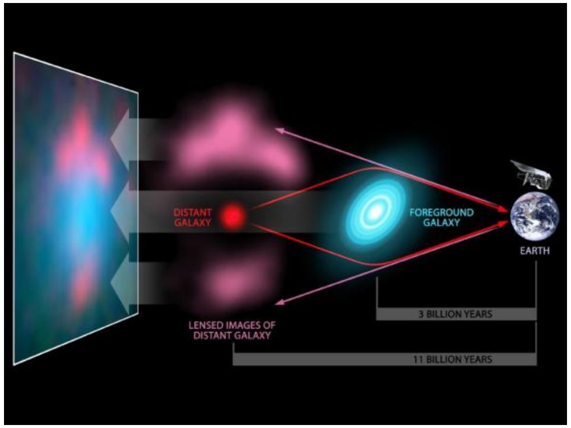




Bullet Cluster



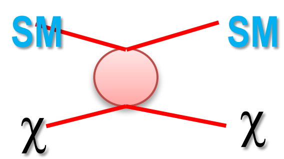
Rotation Curves of Galaxies



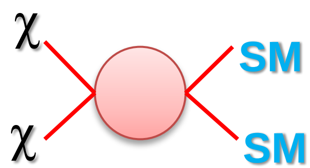
Gravitational Lensing

Non Astrophysical Experiments

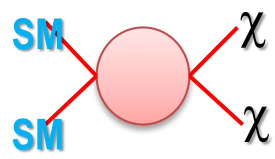
- **1- Direct Detection Experiments**
  - Aim to observe recoil of DarkMatter off nucleus.
  - Low mass region (χ_{mass} <3.5 GeV) not accessible.
  - Less sensitive to spin-dependent couplings.
  - XENON-100, CDMS, CoGeNT

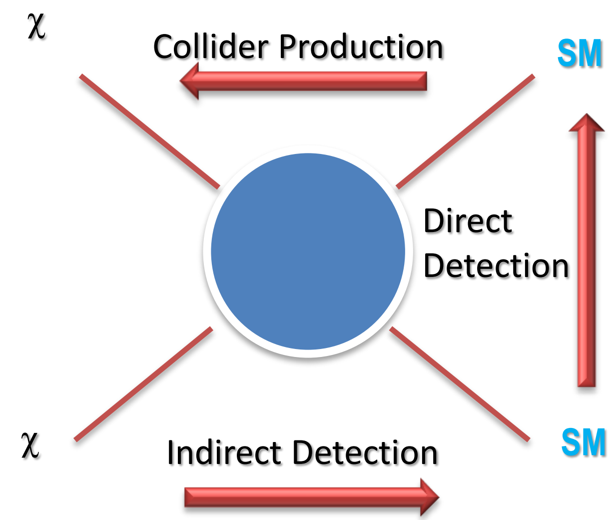


- **2- Indirect Detection Experiments**
  - Aim to observe annihilation products of the DarkMatter particles.
  - Low mass region not accessible
  - Super-Kamiokande, IceCube



- **3- Collider Experiments**
  - Aim to observe cross section of DarkMatter + Jet(s) final state.
  - Sensitive to low mass region.
  - Sensitive to spin-dependent couplings.
  - Tevatron, LHC…



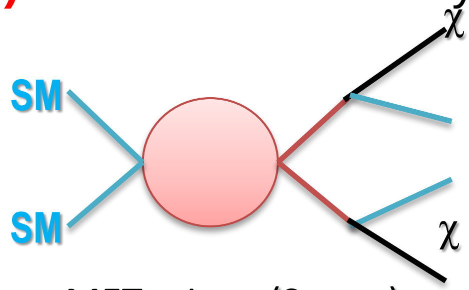


Dark Matter Search

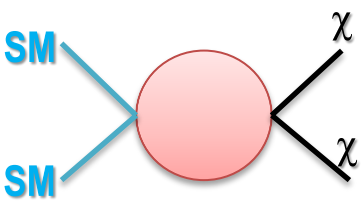
There are 2 scenarios for dark matter production at colliders

1) Colliders can produce heavier particles beyond the SM that decay to dark matter pairs and SM particles

2) Colliders can directly produce dark matter pairs

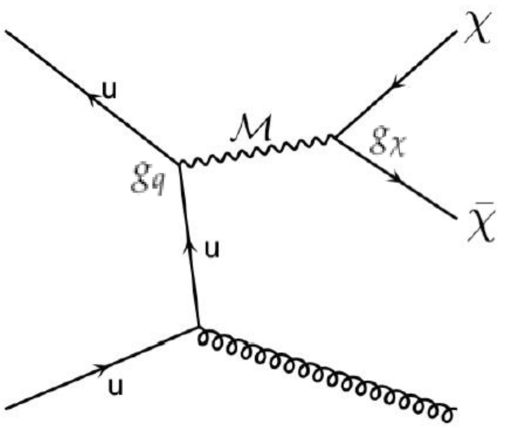


MET + Jets (Susy…)



MET + MonoJet or MonoPhoton

- We consider very heavy mediator. (Contact Point)
- Dark Matter Mass from 1 GeV to 1000 GeV.
- The operator has axial-vector and vector contributions and we translate both operator results to spin dependent and spin independent limit of dark matter nucleon cross section



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

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

M: Mediator

g_χ and g_q :coupling to dark matter and SM quark

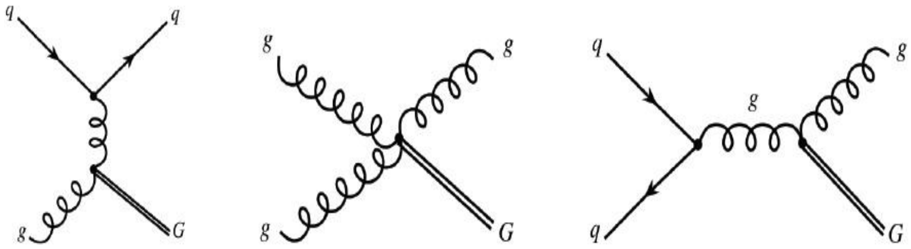
arXiV: 1109.4398 Fox, Harnik et. al.

Large Extra Dimension Models (LED)

- Several models proposed to solve the **hierarchy problem** between the electroweak and Planck scales.
- One of the popular model is LED.
  - δ extra dimensions compactified over a torus with radius R
  - The SM is confined to a 4D manifold called a 3-brane
  - Only gravity propagates in the extra dimensions. .

- **The ADD (Arkani, Dimopoulos, Dvali) model**
- $4D \rightarrow (4+\delta)D$
- $M_{Pl} \rightarrow M_D \sim M_{EW}$
- $$F(r) \sim \begin{cases} \frac{1}{M_{Pl}^2} \frac{m_1 m_2}{r^2} & r \gg R \\ \frac{1}{M_D^{\delta+2}} \frac{m_1 m_2}{r^{\delta+2}} & r \ll R \end{cases}$$
- $\boldsymbol{M_{Pl}^2 = M_D^{\delta+2} R^{\delta}}$

Once graviton pass the extra dimension leave behinds a **Jet** and Large Missing Transeverse Energy (**MET**)



$M_D = 2\text{TeV}, \delta = 2$

qg→qG **43%**   gg→gG **52%**   qq→gG **5%**

(ADD: Phys. Lett. B429 (1998) 263)

Event Selection

Trigger

- High Level Trigger
  - MET>80 or 95 GeV , Leading Jet pT> 80 GeV and **| η |**<2.6

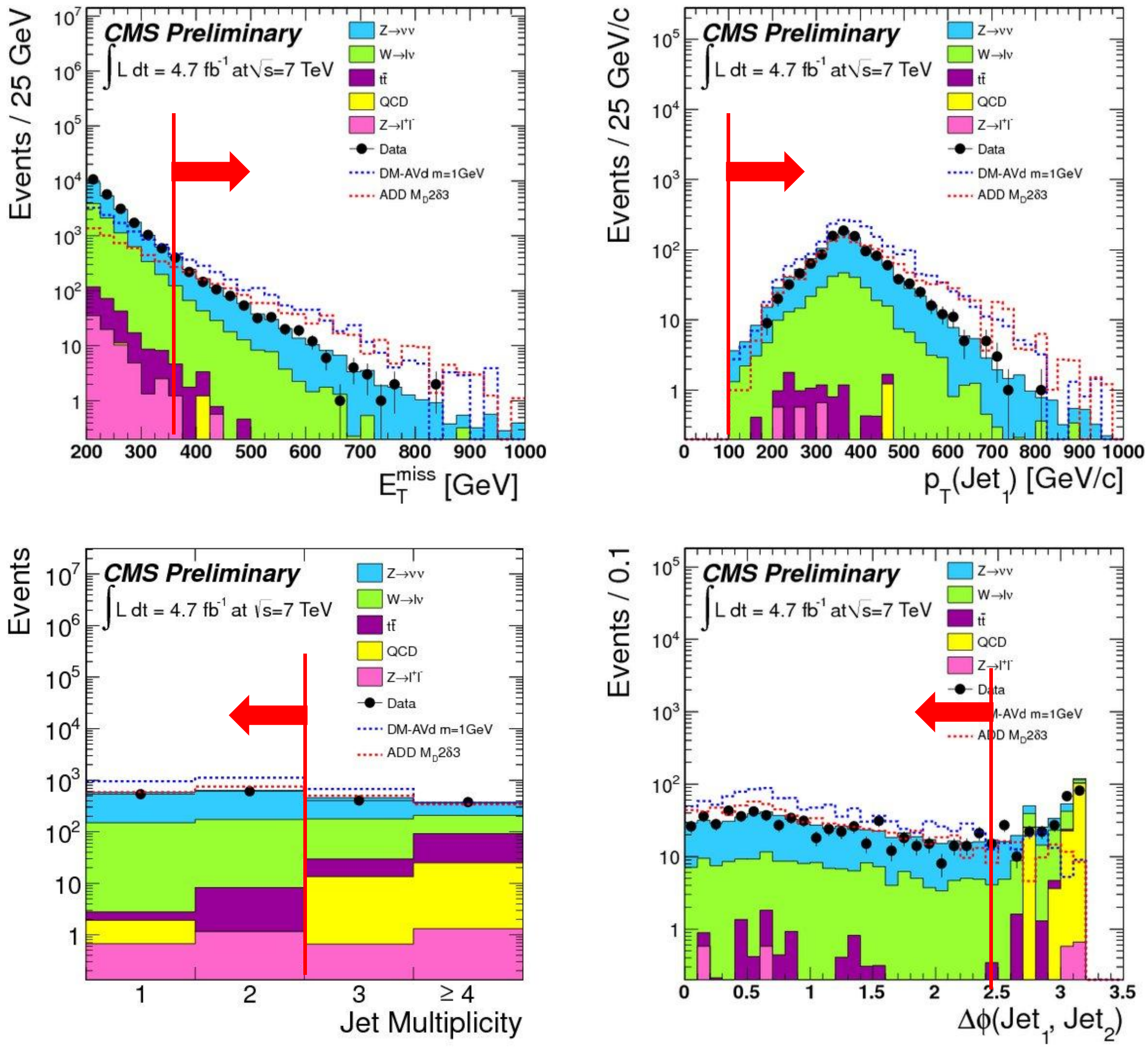
General Selection and Event Cleaning

- Reject detector noise, beamhalo, cosmic via vertex requirement and particle flow jet neutral and charged energy fractions.

MonoJet Event Selection

- 1- MET > **200 GeV**
- 2- All jets **pT>30 GeV and |η|<4.5** (Count jets again)
- 3- Leading jet **pT>110 GeV and |η|<2.4**
- 4- **JetMultiplicity < 3** to reject QCD and top events
- 5- Δ**ϕ(Jet1, Jet2) < 2.5** to reject remaining QCD events
- 6- Veto events with isolated electron, muon and tracks
  - Events with well Isolated muon or electron **pT >10** GeV
  - Events with well Isolated Tracks **pT >10** GeV

Kinematic Distribution of MonoJet Events



Optimisation study on ADD and DM signals shows best expected limit for **MET > 350**

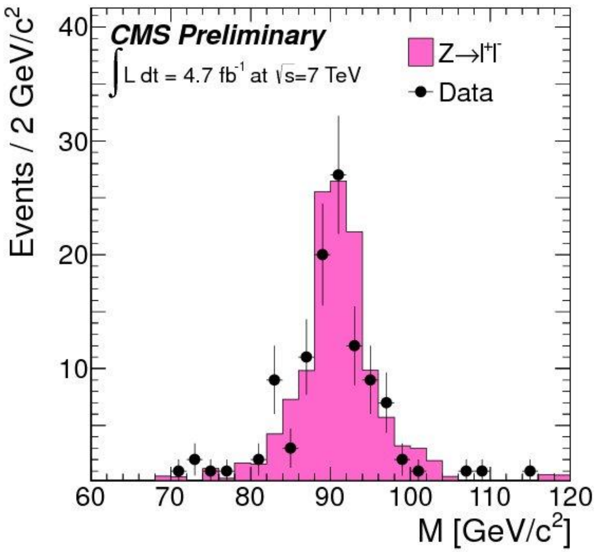
# of Observed MonoJet events: **1142**

Background Estimation

Estimation of Z→νν

- Control sample **Z→μμ**
- Select 2 opposite sign muons same as signal
- Well isolated muons pT>20 GeV , |η| < 2.1
- Invariant mass between 60-120 GeV
- Uncertainty in method is 10.4% mainly from stats 9.5%

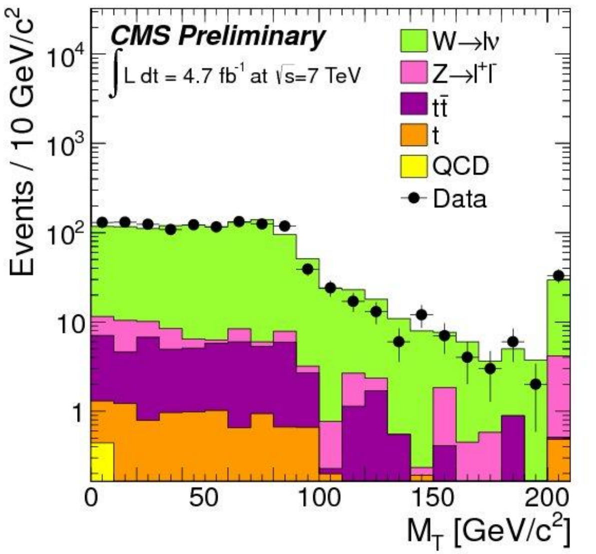
Z→νν : 900 ± 94



Estimation of Wjet where lepton is lost

- Control sample **W→μν**
- Select single muon same as signal
- Well isolated muon pT >20 GeV , |η| < 2.1
- Transverse mass between 50-100 GeV
- Uncertainty in method is 11.3% mainly from acceptance (7.7%) and selection efficiency (6.8%)

WJet: 312 ± 35



Total Background Prediction

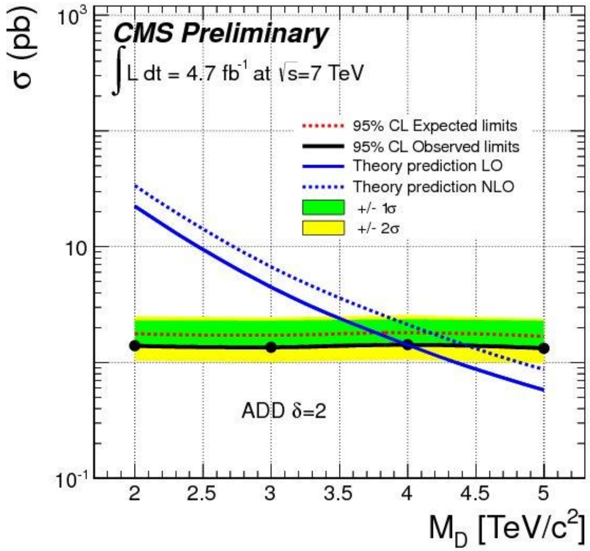
Background process	Events
$Z \rightarrow \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

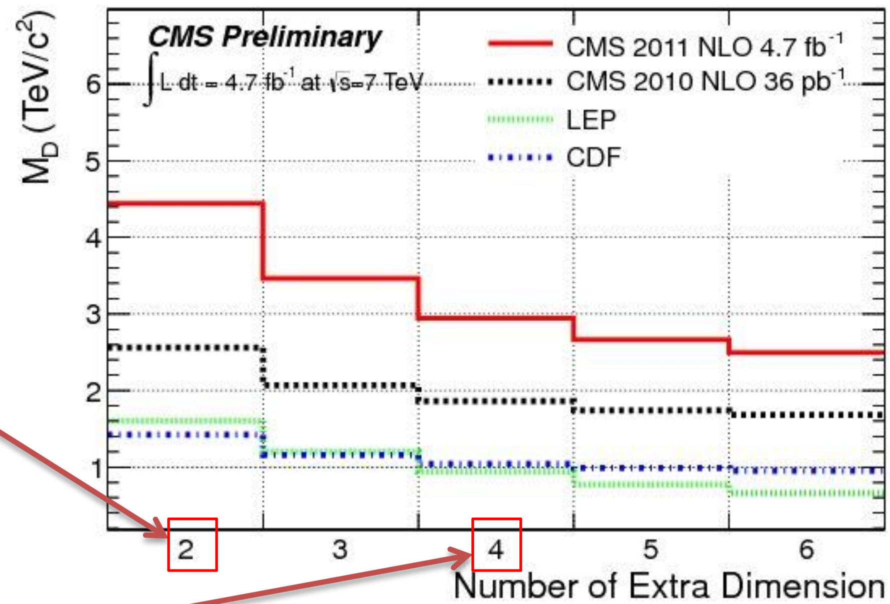
Signal Uncertainties	
Jet Energy Scale	10%
Initial / Final State Radiation	2%
PDF (using PDF4LHC)	2-5%
Pile-Up	3%
Total	15%

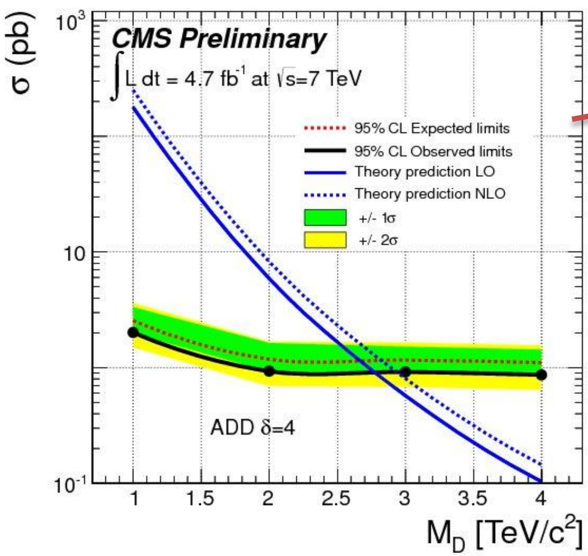
- Luminosity = 4.7 fb^{-1} ± 4.5%

Data are consistent with the SM expectations. We used this to set limits on DM and ADD models.

Results for ADD Model

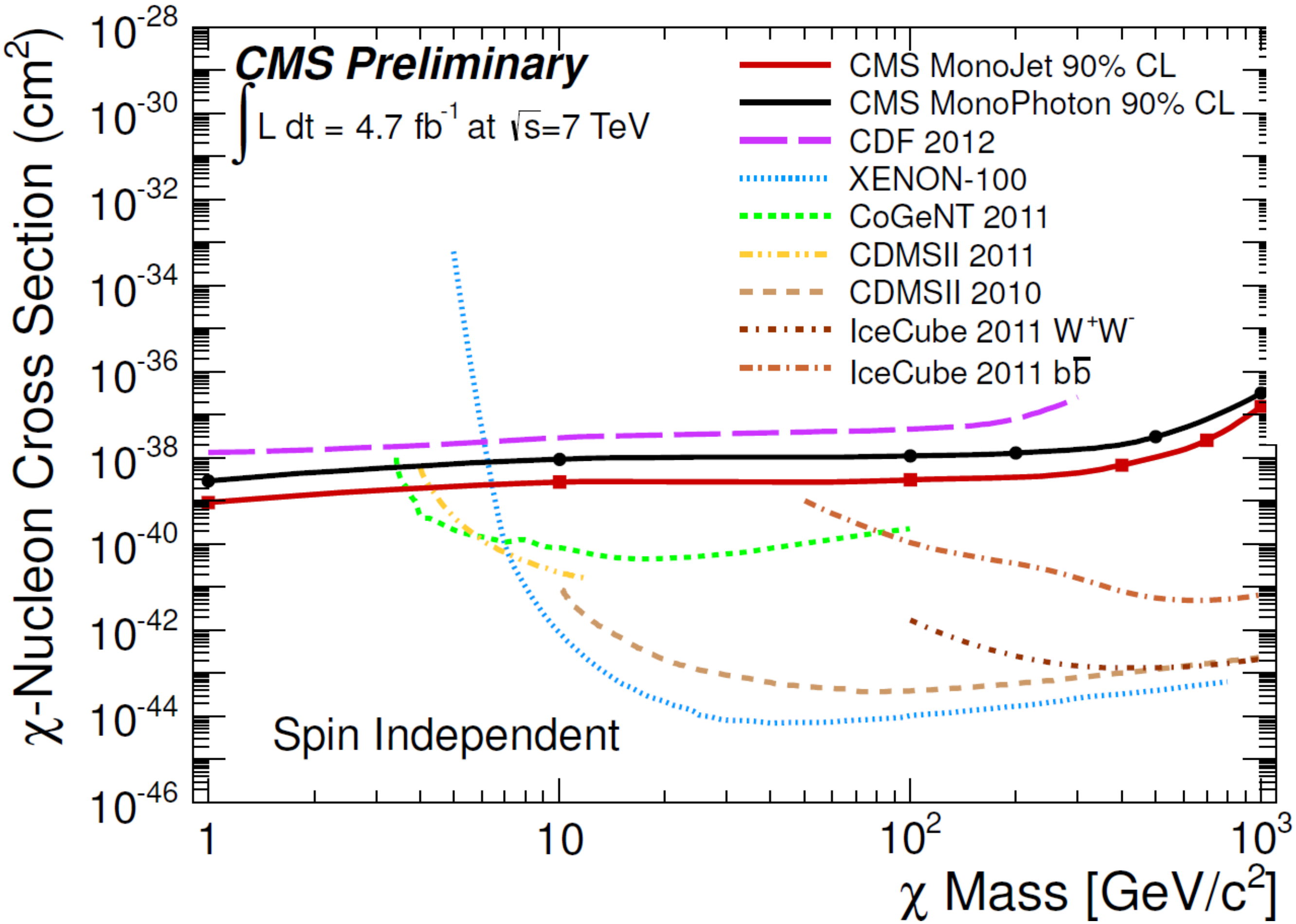






	LO		NLO	
δ	Exp. Limit	Obs. Limit	Exp. Limit	Obs. Limit
2	3.76	4.00	4.16	4.44
3	3.04	3.18	3.29	3.46
4	2.68	2.78	2.83	2.94
5	2.42	2.52	2.56	2.66
6	2.27	2.37	2.39	2.49

Results for Dark Matter



$$\Lambda^4 = \Lambda_d^4 + \Lambda_u^4$$

$$\sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4}$$

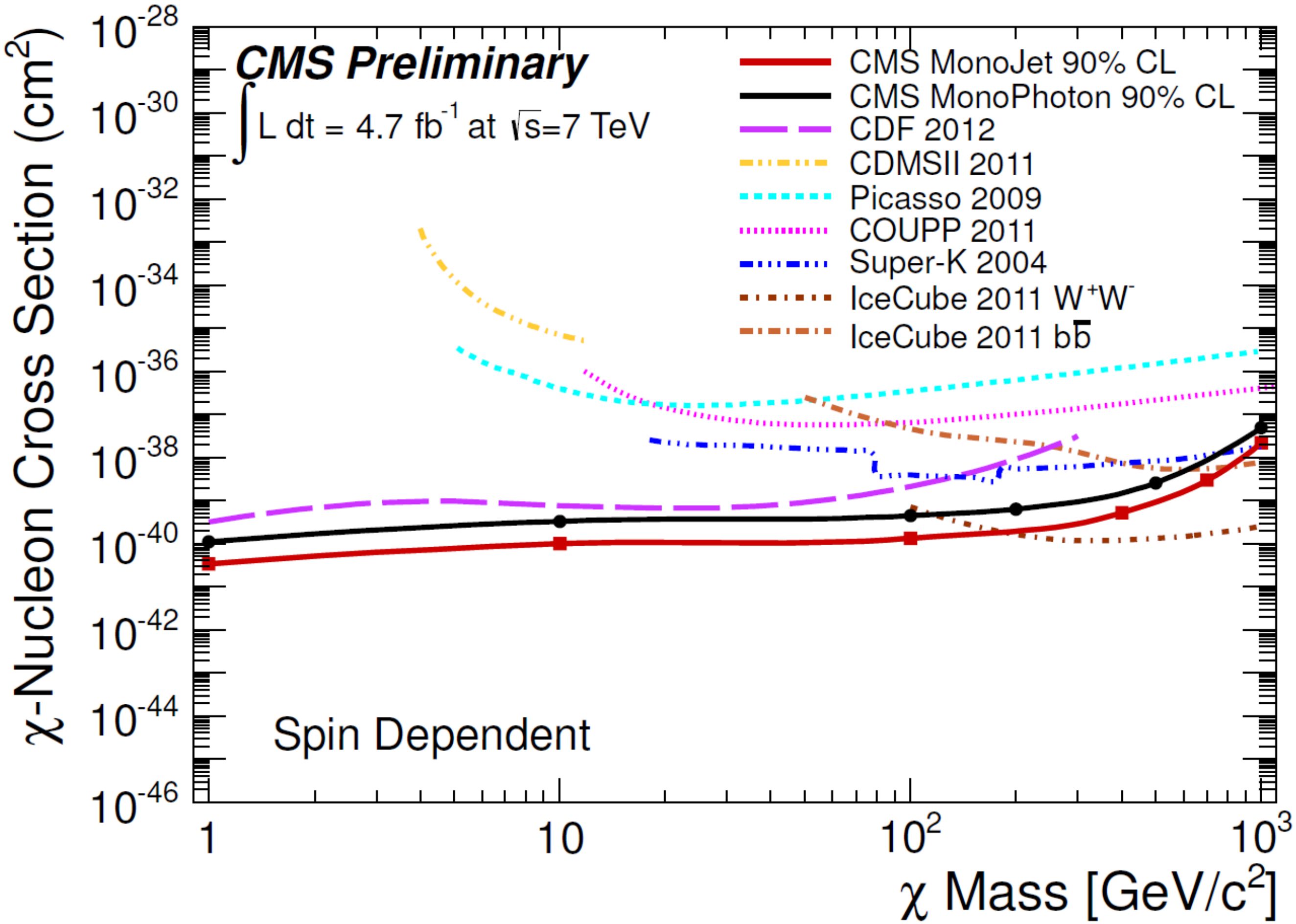
$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

$$\Lambda = M/\sqrt{g_\chi g_q}$$

$$\mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

Best Limit for DarkMatter Mass < 3.5 GeV a region as Unexplored
By Direct Detection Experiments

Results for Dark Matter



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$$\sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

$$\Lambda = M/\sqrt{g_\chi g_q}$$

$$\mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

Limits represent the most stringent constraints by several orders of magnitude over entire 1-200 GeV mass range

Conclusion

- Good aggrement between data and estimated SM background.
- Data driven background estimation for main bacgrounds **Z→νν** and **Wjets**
- Z and W was measured with muon
- Limit for low mass DarkMatter region for spin-independent and spin-dependent of direct detection experiments.
- Much strong limit for spin-dependent DarkMatter than direct detection experiments.
- ADD limit improved for fundamental mass scale $M_D\ (TeV)$ for dimension from 2 to 6

Backup

Mono-Jet Cut Flow Data & Background

Requirement	W+jets	$Z(\nu\nu)$ +jets	$Z(\ell\ell)$ +jets	$t\bar{t}$	Single t	QCD multijet	Total bgd	Data
$E_T^{miss} > 200\,GeV$	55269	30312	4914	12455	1090	14959	118999	104485
$p_T(j_1) > 110\,GeV/c$, $\lvert\eta(j_1)\rvert < 2.4$	52100	28267	4590	11107	968	14743	111775	100658
$N_{jets} \leq 2$	37112	21245	3229	1484	256	4952	68278	62395
$\Delta\phi(j_1, j_2) < 2$	33123	19748	2936	1256	222	58	57343	53846
Lepton Removal	9561	14663	76	200	33	2	24535	23832
$E_T^{miss} > 250\,GeV$	2632	5106	21	65	10	2	7836	7584
$E_T^{miss} > 300\,GeV$	816	1908	6	21	3	1	2755	2774
$E_T^{miss} > 350\,GeV$	312	900	2	8	1	1	1224	1142
$E_T^{miss} > 400\,GeV$	135	433	1	3	0	1	573	522

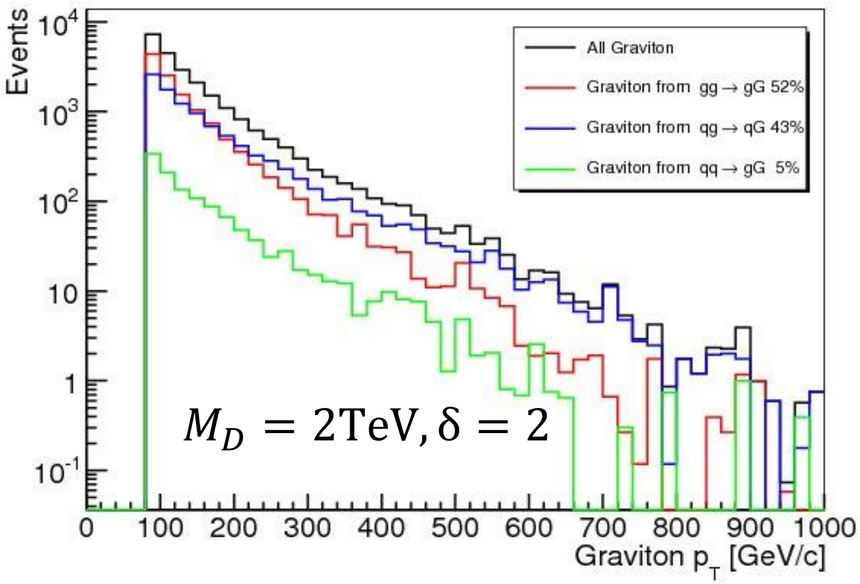
Z(invis)+jets (74%) and W+jets(25%) are the only significant backgrounds
other backgrounds (~1%)

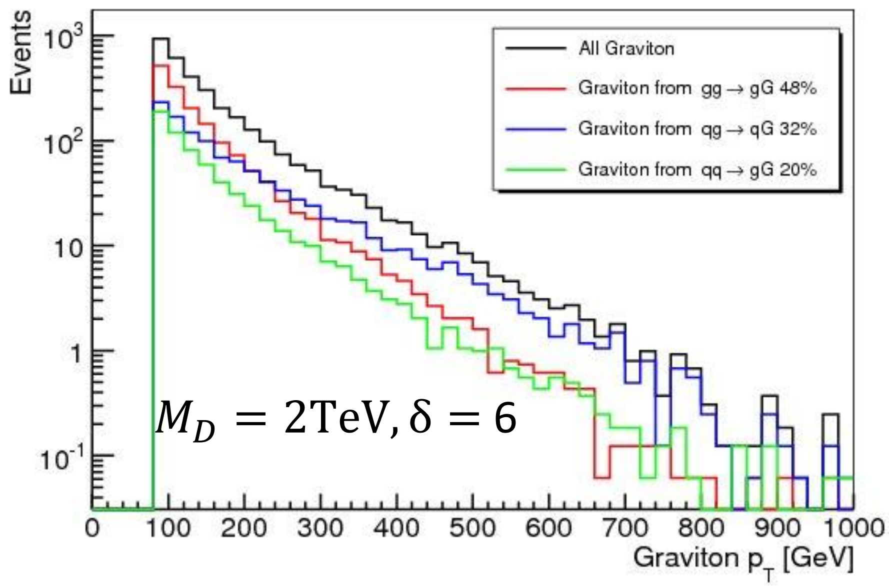
Data Driven Normalization applied

Production Process for different M_D, δ

	ADD Signal	gg→gG %	qg→qG %	qq→gG %	Total σ (pb^{-1})	Acceptance MET>200 GeV %	Acceptance MET>350 GeV %
δ=2	MD1 d2	54	42	4	304	9.80	1.2
	MD2 d2	52	43	5	22.23	12.5	2.5
	MD3 d2	52	43	5	4.44	12.5	2.4
	MD4 d2	52	43	5	1.41	12.3	2.4
δ=3	MD1 d3	54	40	6	211	11.8	1.8
	MD2 d3	52	40	8	9.8	13.8	3.1
	MD3 d3	50	40	10	1.37	14.2	3.3
	MD4 d3	50	40	10	0.324	14.2	3.3
δ=4	MD1 d4	55	36	9	178	11.6	1.6
	MD2 d4	50	36	14	5.93	14.6	3.4
	MD3 d4	48	38	14	0.573	15.2	3.8
	MD4 d4	48	38	14	0.1023	15.1	3.8
δ=5	MD1 d5	56	32	12	166	11.5	1.7
	MD2 d5	50	33	17	4.08	14.4	3.3
	MD3 d5	46	35	19	0.295	15.5	3.9
	MD4 d5	46	35	19	0.0394	15.9	4.2
δ=6	MD1 d6	55	31	14	183	10.8	1.6
	MD2 d6	48	32	20	3.08	14.5	3.2
	MD3 d6	45	32	23	0.167	15.5	3.8
	MD4 d6	44	33	23	0.0177	15.9	4.0

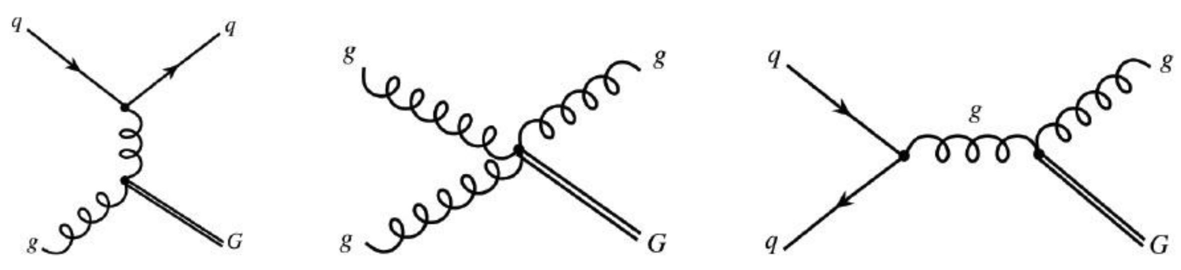
Production Process for ADD points





gg→gG	qg→qG	qq→gG
52%	**43%**	**5%**

gg→gG	qg→qG	qq→gG
48%	**32%**	**20%**

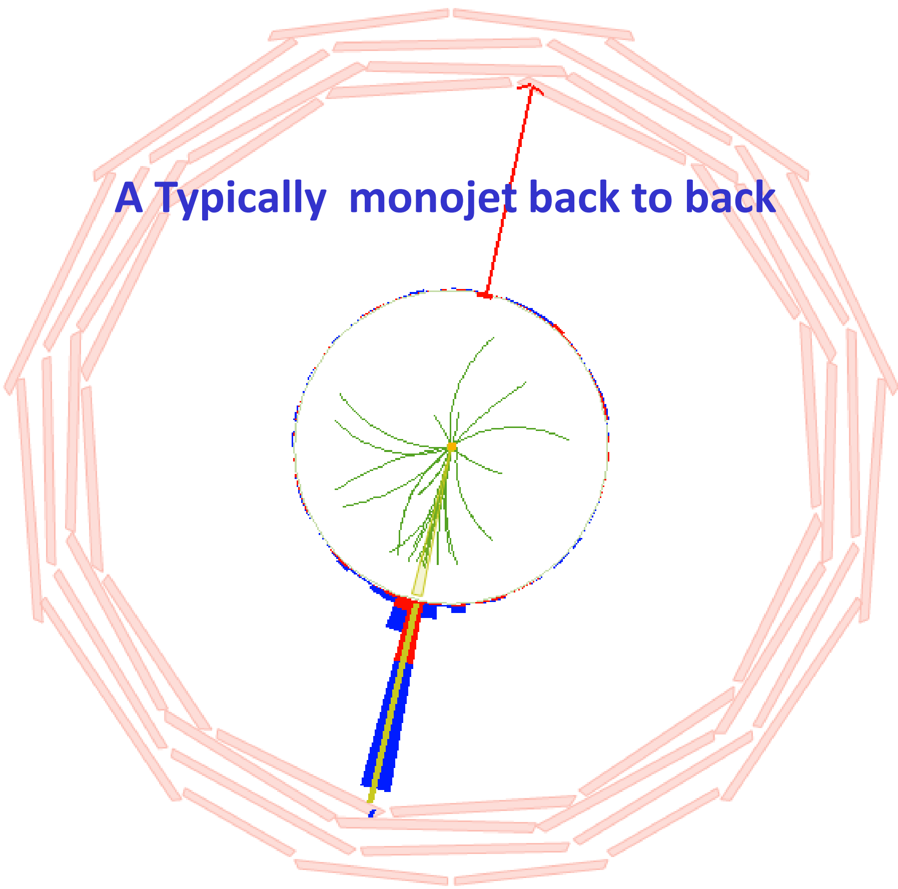


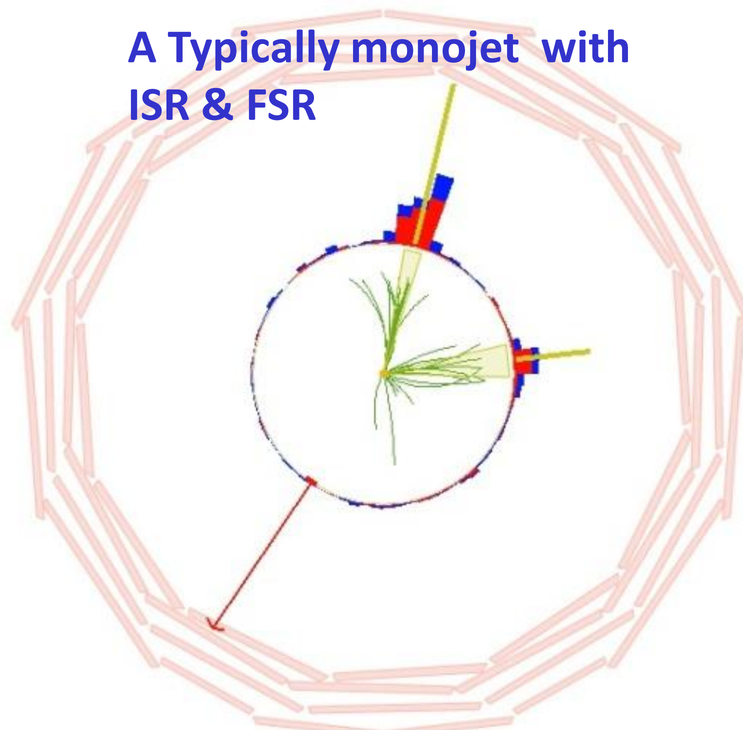
ADD Existing Limits on M_D (TeV)

			2010	2010		2011
δ	**LEP (ϒ +MET)**	**CDF combined**	**ATLAS 33 pb^{-1} Jet+MET [LO]**	**CMS 36 pb^{-1} Jet+MET [LO]**	**[NLO]**	**ATLAS 1 fb^{-1} Jet+MET [LO]**
2	1.60	1.42	2.3	2.29	2.56	3.39
3	1.20	1.16	2.0	1.92	2.07	2.55
4	0.94	1.04	1.8	1.74	1.86	2.26
5	0.77	0.99		1.65	1.74	1.90
6	0.66	0.95		1.59	1.68	1.58

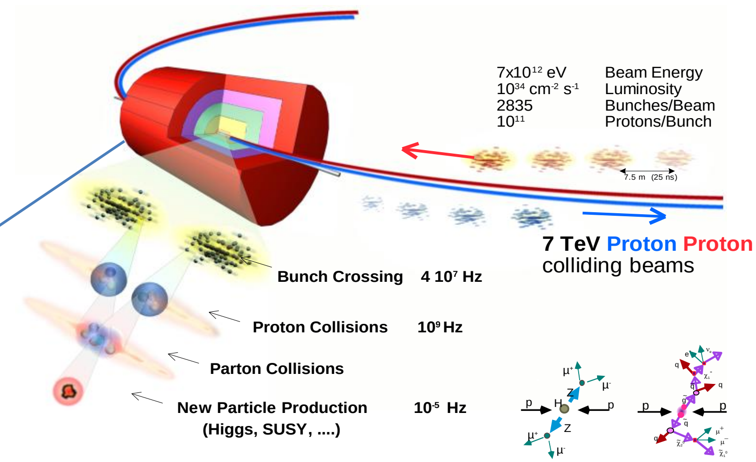
MonoJet signal in Detector

Because of ISR & FSR We can see more than **1 jet** in some events.

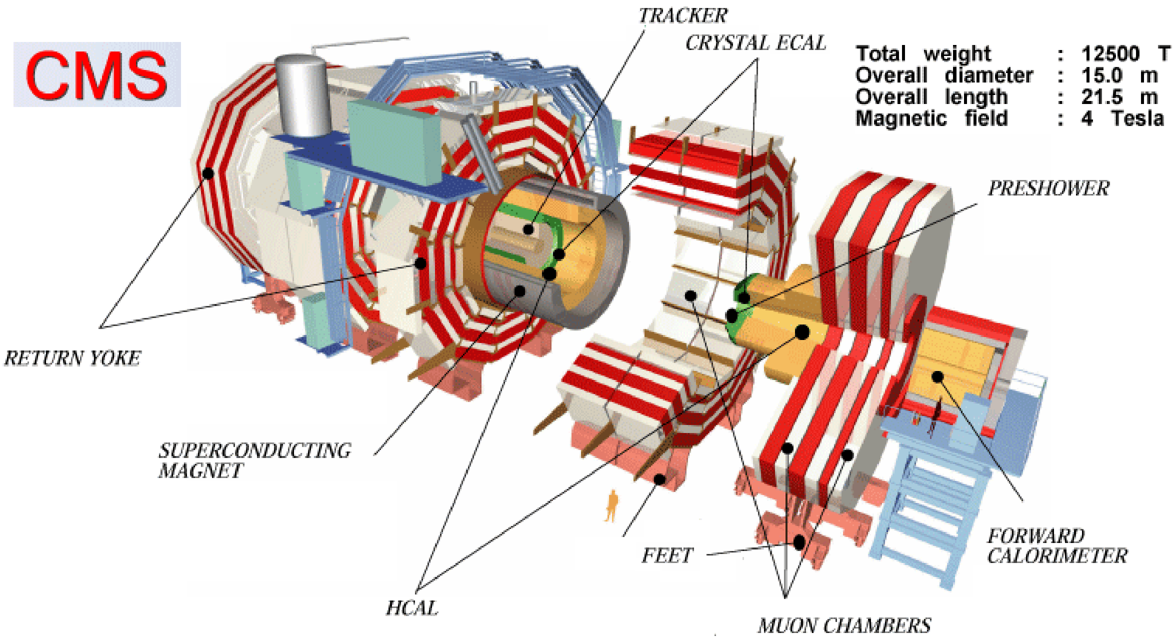




Compact Muon Selenoid (CMS) at LHC



Selection of 1 event in 10,000,000,000,000



Total weight	:	12500 T
Overall diameter	:	15.0 m
Overall length	:	21.5 m
Magnetic field	:	4 Tesla