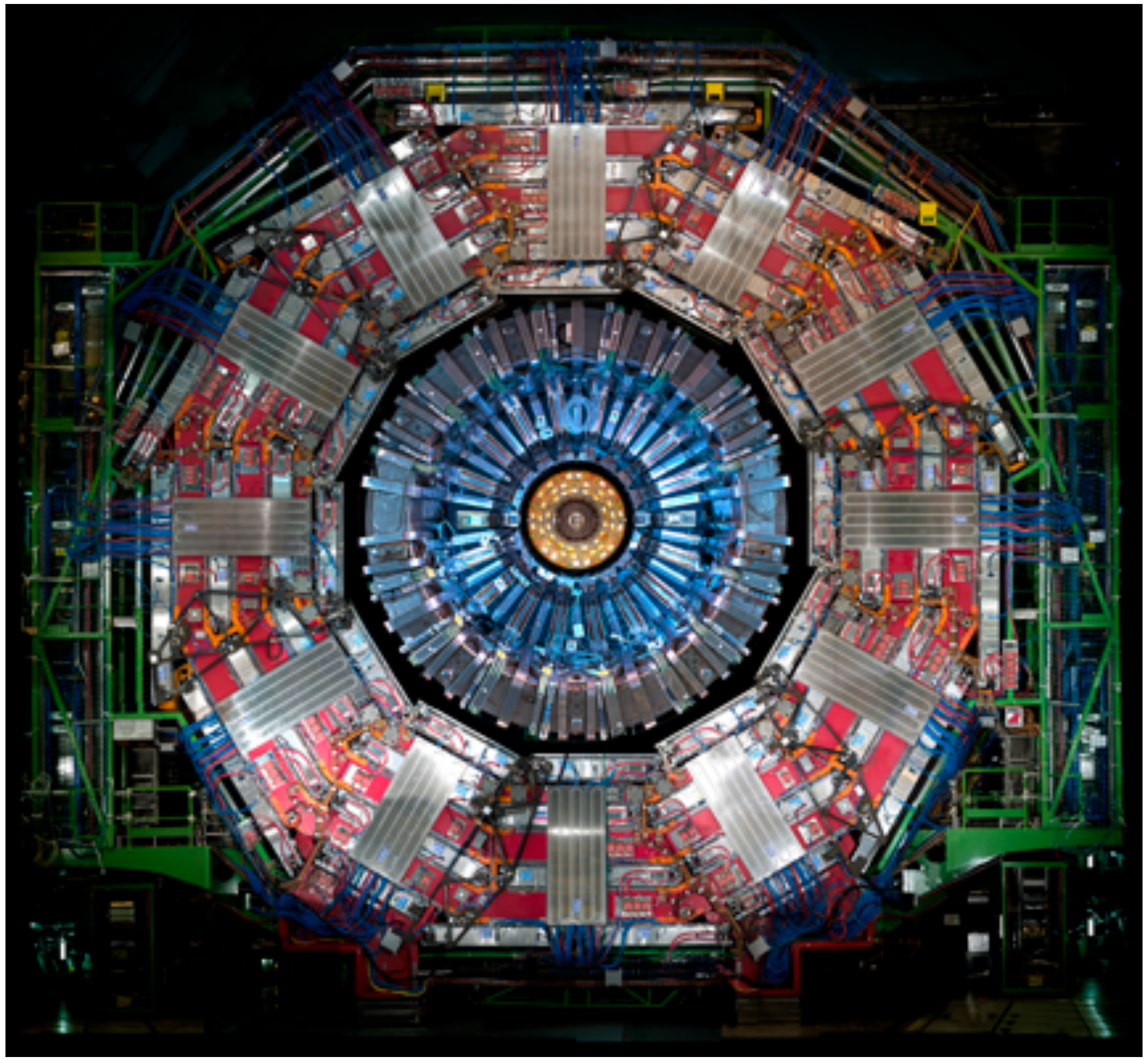
Dark Matter Searches at CMS

Sandhya Jain

Saha Institute of Nuclear Physics, Kolkata

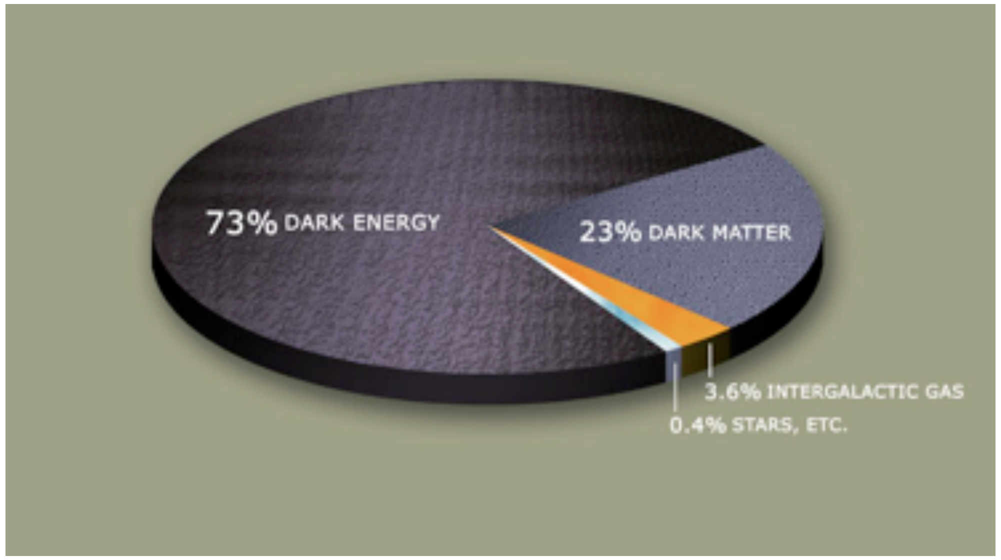
on behalf of CMS collaboration



Particle Physics and Cosmology, 2012

Dark Matter

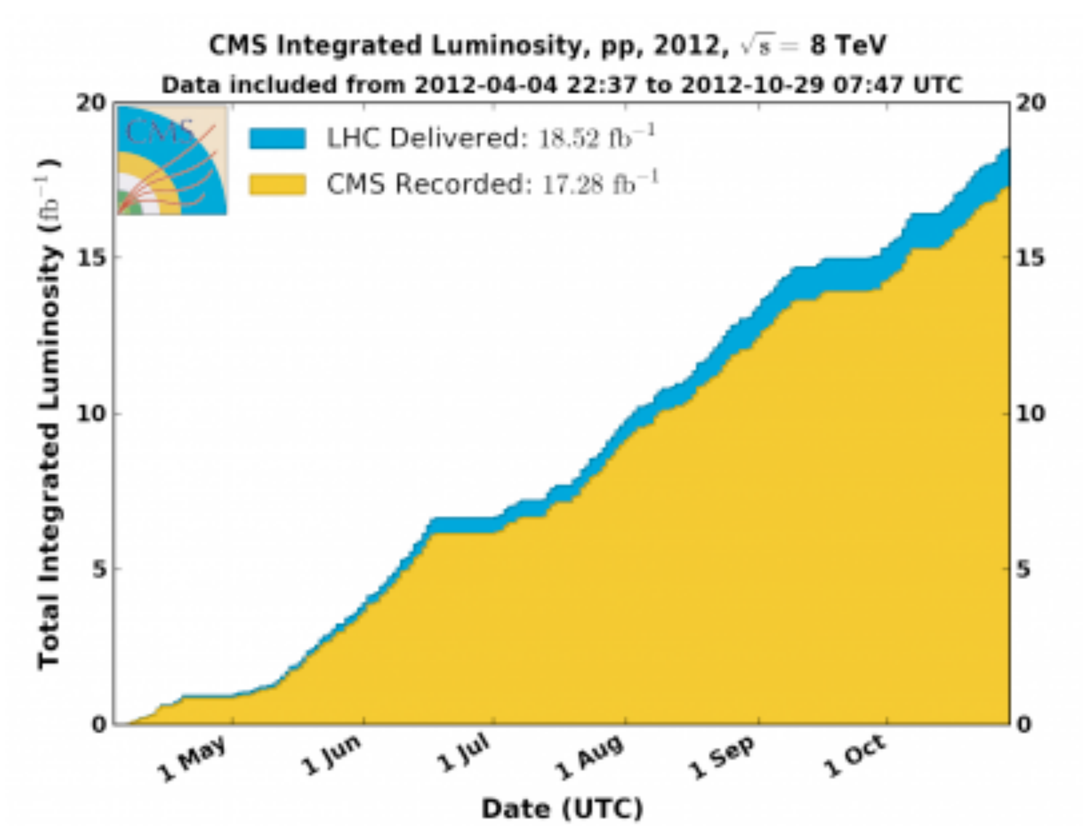
- Strong astrophysical evidence for existence of Dark Matter(DM)
- Direct detection experiments
  - Aim to observe recoil of DM off the nucleus
  - Excesses observed by several experiments, not observed by others
- Need for independent verification from non-astrophysical experiments
- Colliders provide a complementary way to search for dark matter

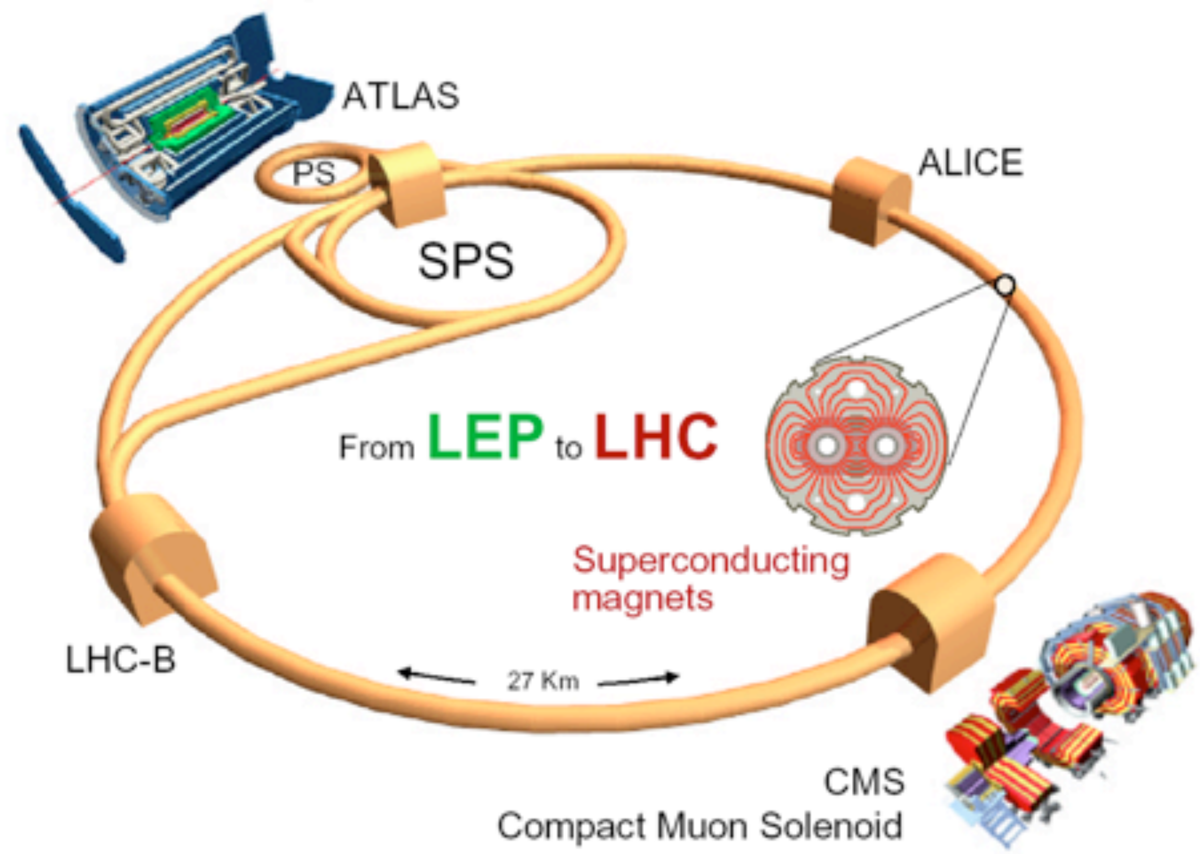


Plan of the talk

- Exotic searches with production of Dark Matter particle in monophoton and monojet final states
- SUSY based searches looking for Lightest Supersymmetric Particle (LSP) in EWK production

Large Hadron Collider (LHC)





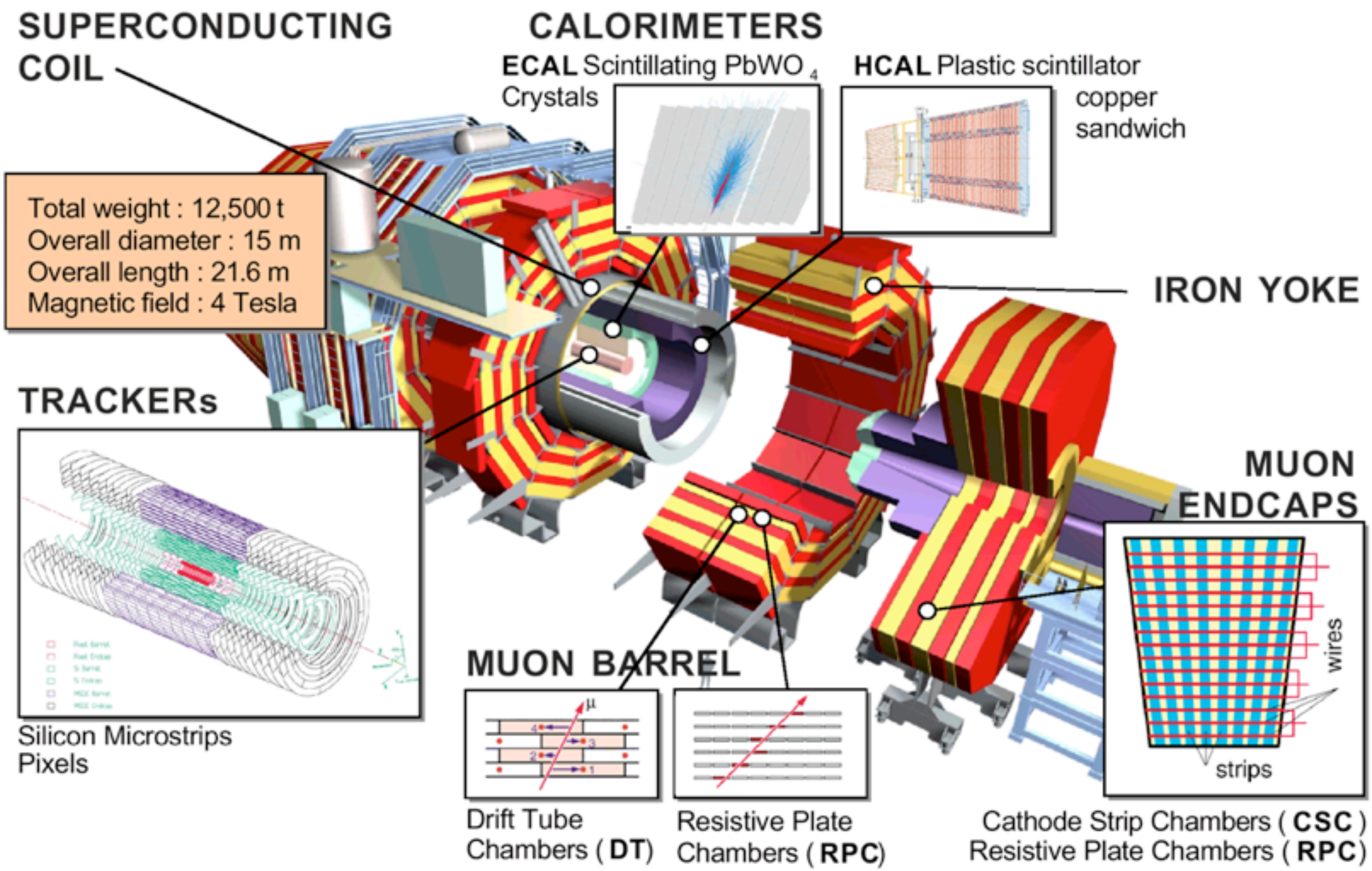
Machine is running good and delivering data fast for experimentalists to work on.

LHC already delivered > 18 fb^{-1} @8TeV Run

Excellent performance by CMS

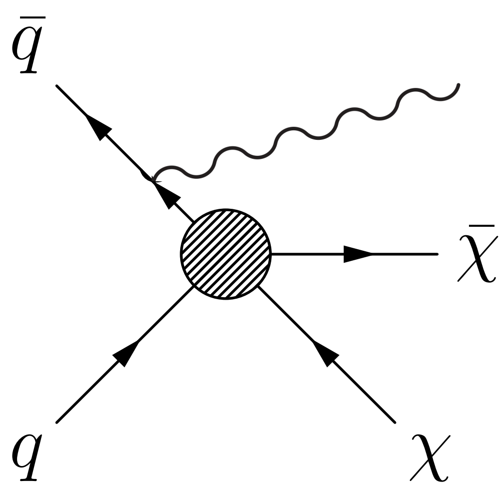
Results shown here are based on 5fb^{-1} @7TeV

CMS Detector

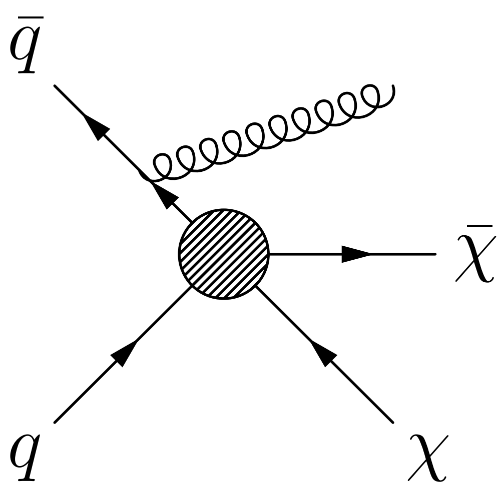


Production of Dark Matter at CMS

- Search for evidence of Dark Matter particle (χ) production at colliders
  - Dark Matter particle production gives Missing transverse energy (MET) in an event
  - Photons/gluons radiated off the quarks makes it visible in the detector and gives experimentalists a chance to look at its production in the detector.



Monophoton +MET



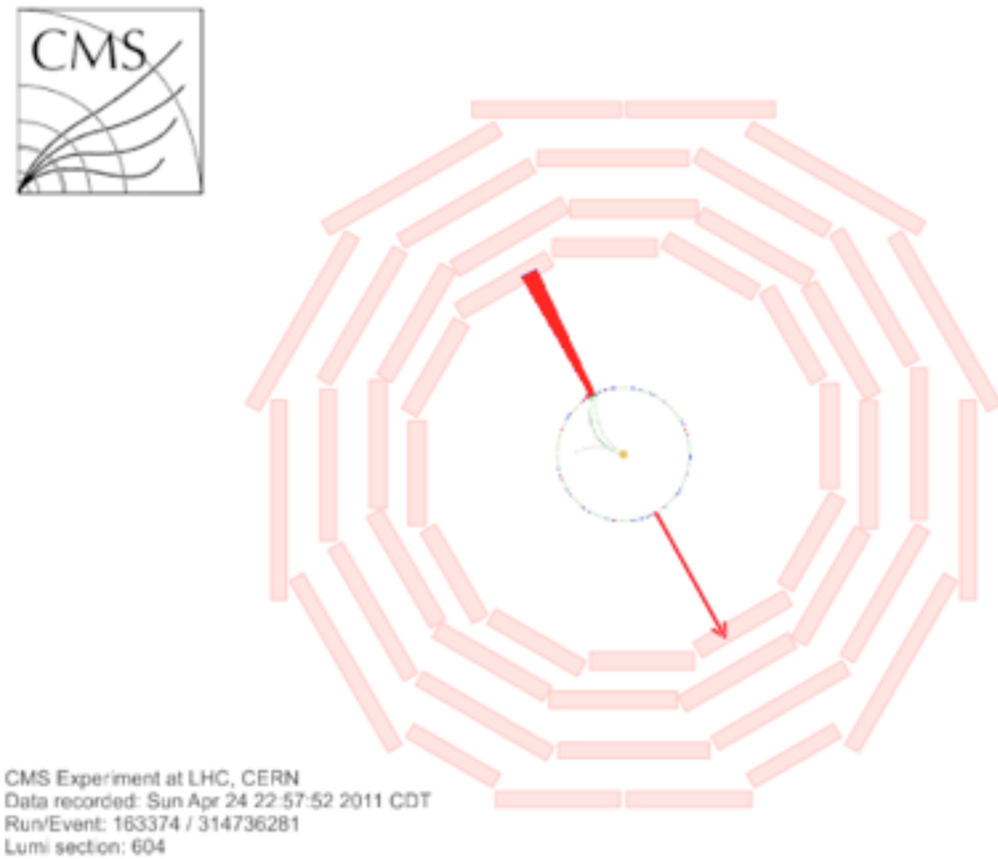
Monojet+MET

Methodology for collider based search

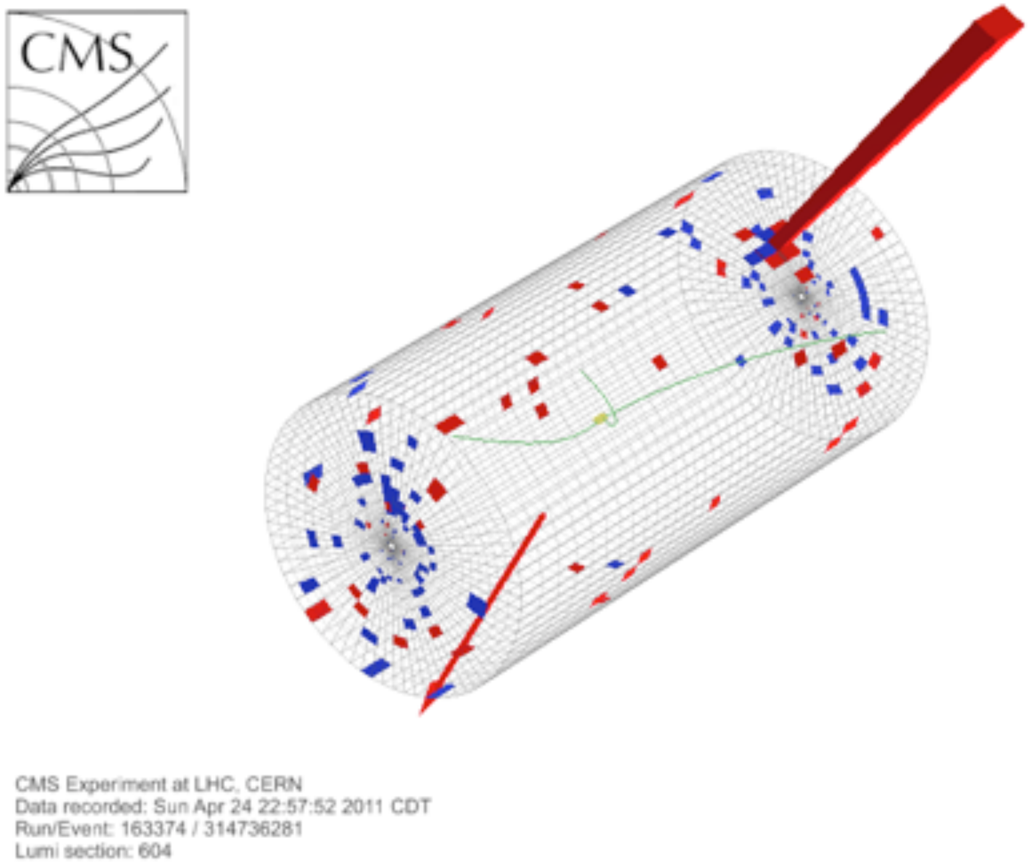
- Make an event selection on data and count the number of events in signal region (Cut and Count experiment)
- Look for excess of events observed above the Standard Model expectation.
- Understanding the backgrounds is very crucial.
- Estimate the backgrounds using MC and data itself, mostly called as Data-driven techniques.
- Systematic uncertainties are to be studied.
- If no excess is seen, limits are put on the cross section and an exclusion is made in the parameter space of the model.

Monophoton Event Topology

X-Y View



3D View



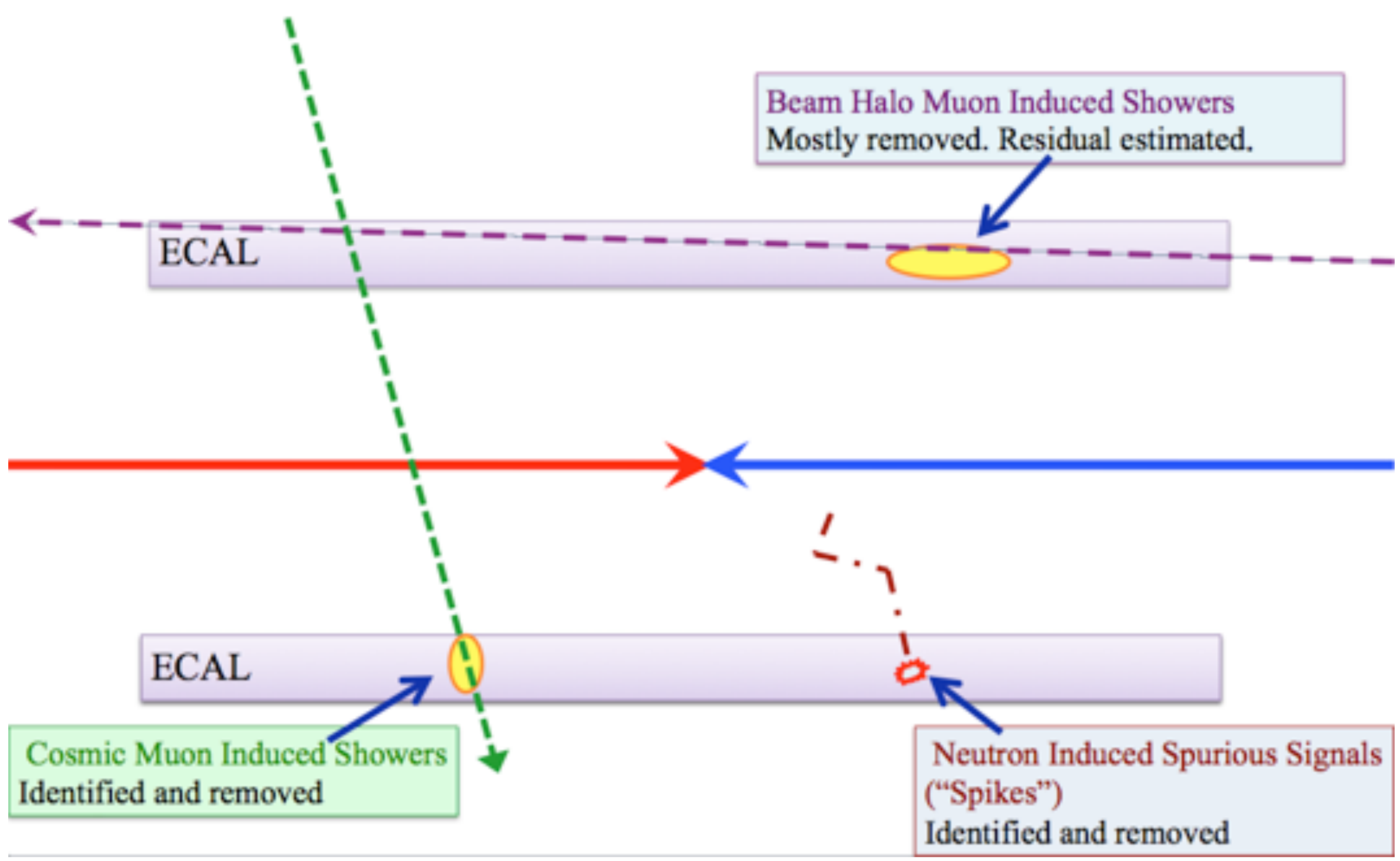
Highest P_T monophoton event,
P_T^{γ} = 384 GeV, MET = 407 GeV

Monophoton Search

Backgrounds coming from pp-collsions

$pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$	irreducible background	(MC)
$pp \rightarrow W \rightarrow e\nu$	electron mis-identified as photon	(Data-Driven)
$pp \rightarrow \text{jets} \rightarrow$ "γ" + MET	one jet mimics photon, MET from jet mis-measurement	(Data-Driven)
$pp \rightarrow \gamma + \text{jet}$	MET from jet mis-measurement	(MC)
$pp \rightarrow W\gamma \rightarrow l\nu\gamma$	charged lepton escapes detection	(MC)
$pp \rightarrow \gamma\gamma$	one photon mis-measured to give MET	(MC)

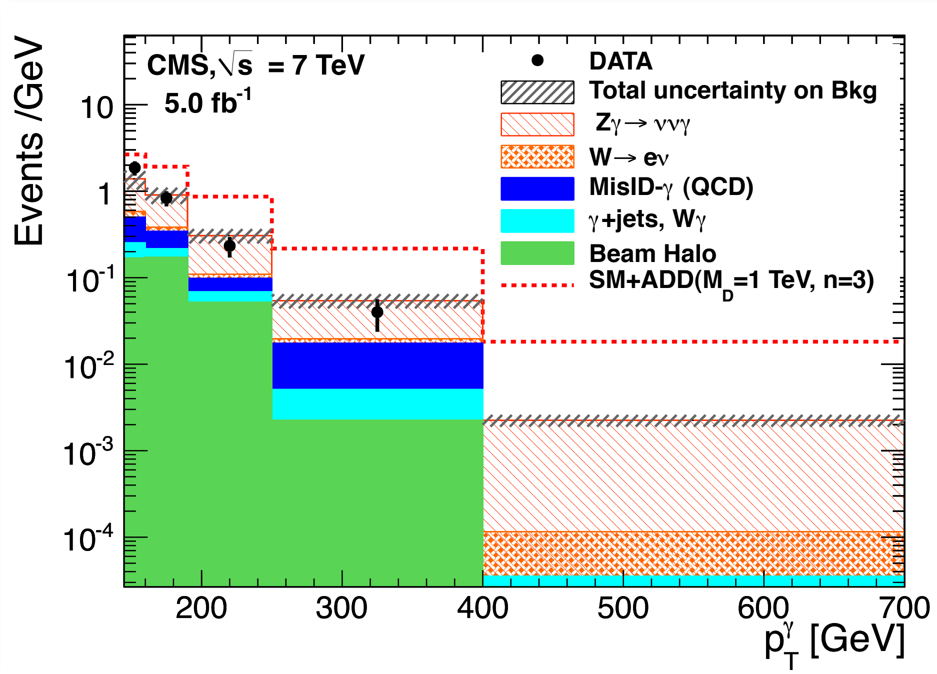
Instrumental Backgrounds like beam halo etc..

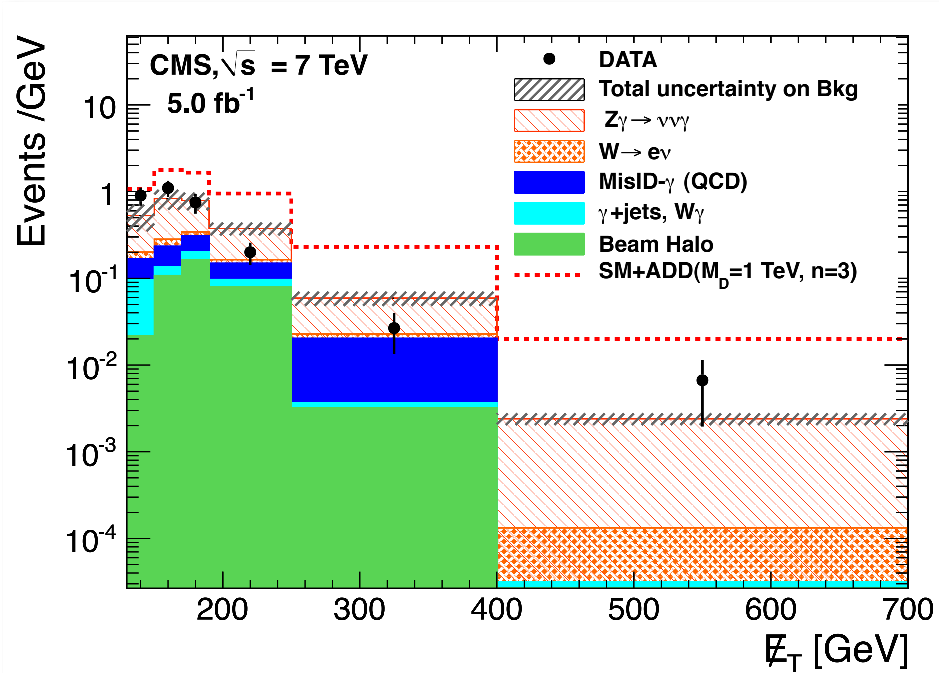


Monophoton Selection

- **Require atleast a photon in an event with**
  - High energy : $P_T^{\gamma} > 145$GeV
  - Central part of the detector: $|\eta| < 1.4442$
  - Shower Shape consistent with the photon coming from collision : $\sigma_{i\eta i\eta} < 0.13$
- **Require MET > 130 GeV**
- **Remove events with**
  - Central jet: $P_{T(jet)} > 40$GeV and $|\eta| < 3.0$
  - Tracks near the photon with $\triangle R > 0.04$ above $P_T > 20$GeV
  - Veto events with significant electromagnetic calorimeter activity ($\triangle R < 0.4$)
  - Veto events with significant hadronic activity($\triangle R < 0.4$, $E_{Hcal}/E_{Ecal} < 0.05$)

Monophoton Results





Source	Estimate
Jet Mimics Photon	11.2 ± 2.8
Beam Halo	11.1 ± 5.6
Electron Mimics Photon	3.5 ± 1.5
$W\gamma$	3.0 ± 1.0
γ+jet	0.5 ± 0.2
$\gamma\gamma$	0.6 ± 0.3
$Z(\nu\bar{\nu})\gamma$	45.3 ± 6.9
Total Background	75.1 ± 9.5
Total Observed Candidates	73

No excess observed between data and background expectation

Monophoton Results

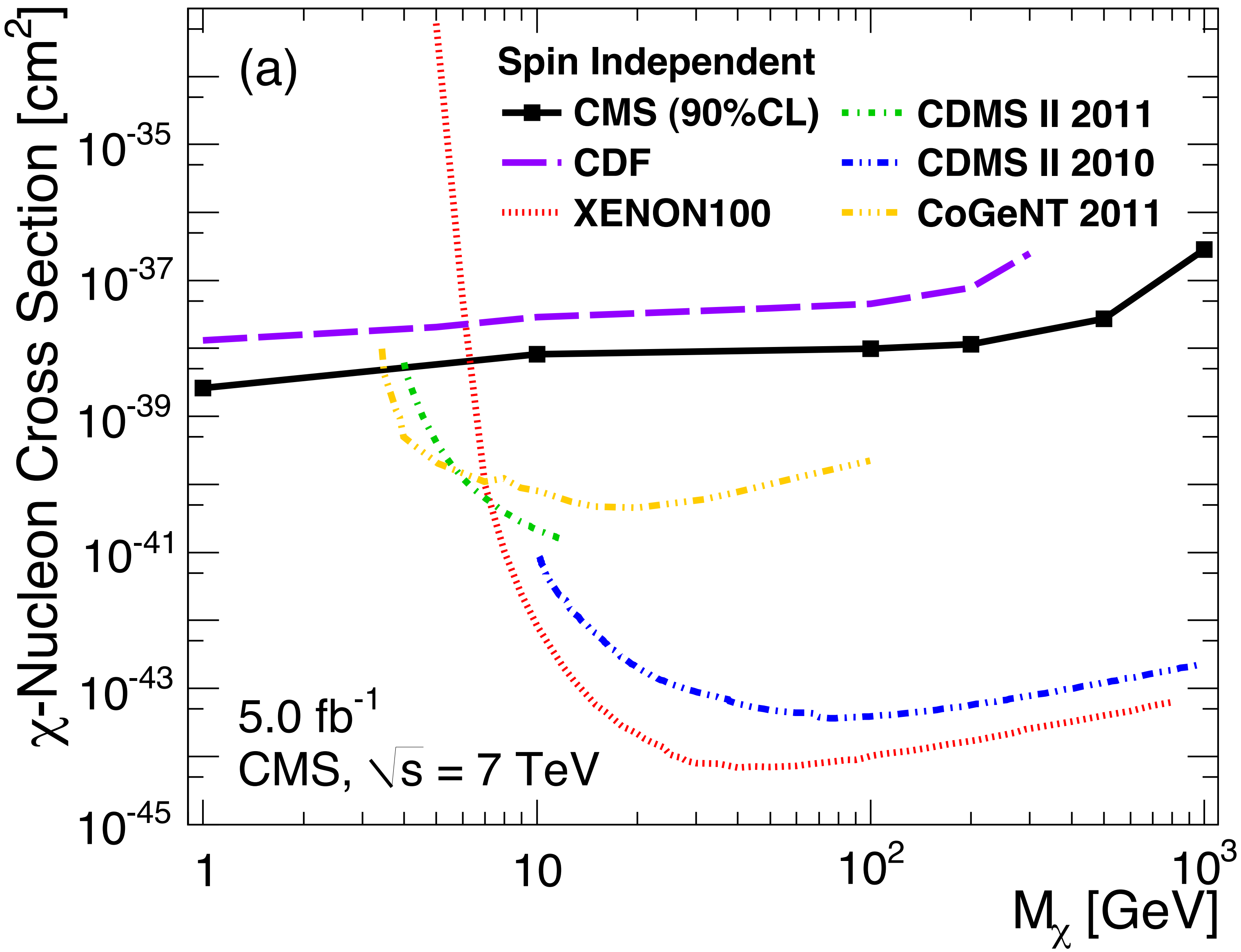
- Signal Generation with Madgraph4 + Pythia6 with 10 TeV mediator mass
- Acceptance times efficiency for Dark Matter signal
  - A X $\epsilon_{MC} \approx$ 0.3, for both vector and axial-vector operator
  - Since kinematics comes from ISR photon, A X ϵ_{MC} is fairly constant in the range M_χ = 1-1000GeV.
- Systematic uncertainties - +4.8% -4.9%
  - Energy scale and resolution effects for photon, MET and jet measurement
  - Pile up modeling
  - Photon vertex assignment
  - Parton Distribution Function
- 90% CL limits are shown below compared with expected in parenthesis

$$\Lambda = \Lambda_{th.} \left(\frac{\sigma_{th.}^{\chi\bar{\chi}}}{\sigma_{meas.}^{\chi\bar{\chi}}} \right)^{1/4}$$

M_χ [GeV]	Vector		Axial-Vector	
	σ [fb]	Λ [GeV]	σ [fb]	Λ [GeV]
1	14.3 (14.7)	572 (568)	14.9 (15.4)	565 (561)
10	14.3 (14.7)	571 (567)	14.1 (14.5)	573 (569)
100	15.4 (15.3)	558 (558)	13.9 (14.3)	554 (550)
200	14.3 (14.7)	549 (545)	14.0 (14.5)	508 (504)
500	13.6 (14.0)	442 (439)	13.7 (14.1)	358 (356)
1000	14.1 (14.5)	246 (244)	13.9 (14.3)	172 (171)

Monophoton - χ-nucleon cross-section

Spin Independent (SI) Limits



- lower limits on Λ are then used to compute χ-nucleon cross-section versus M_χ using:

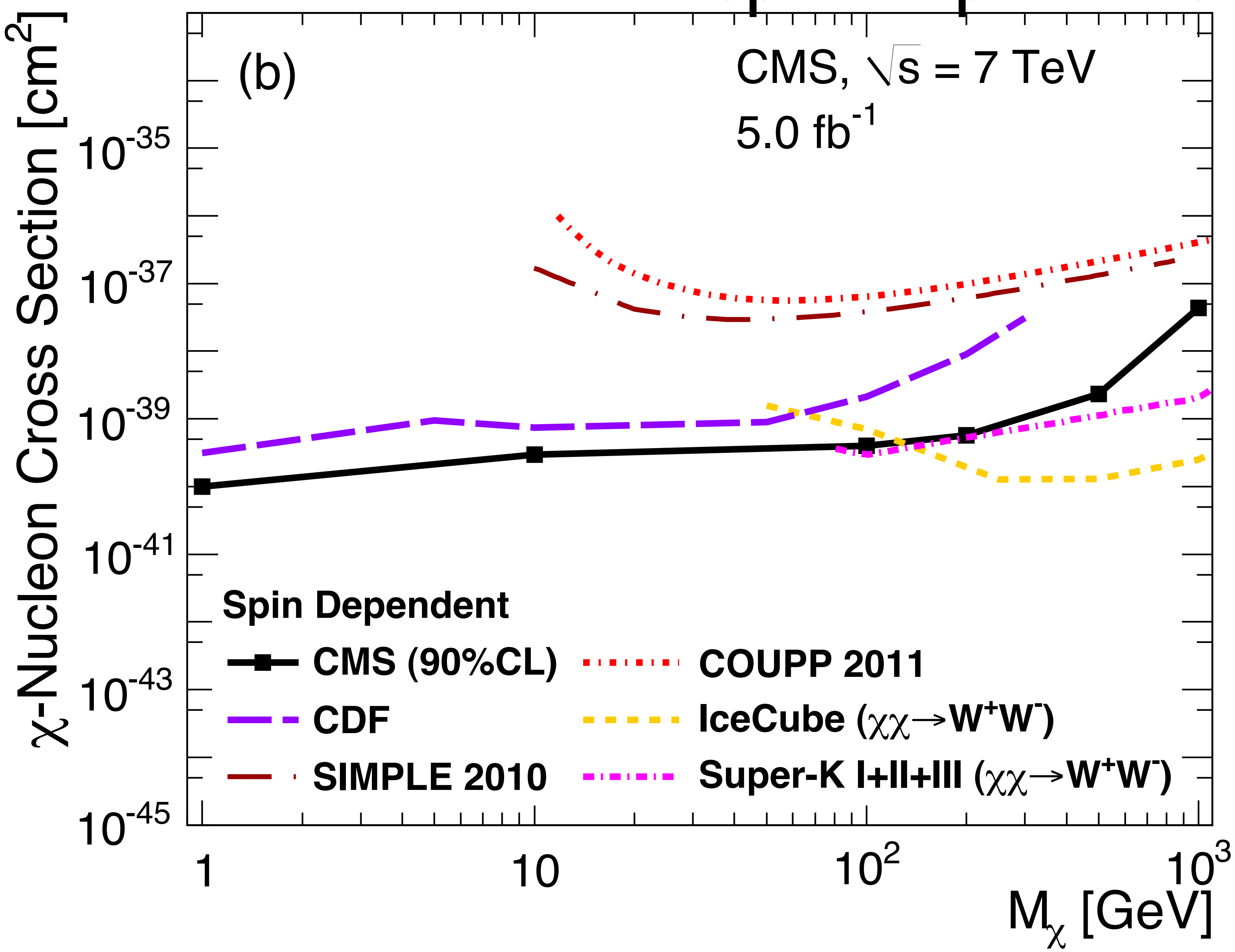
$$\sigma_{SI}^{\chi\text{-N}} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

- Extends the limits for M_χ < 3.5 GeV - which remained unexplored by direct detection experiments for SI case

CMS: Phys.Rev. Lett. 108(2012) 261803.
CDF: Phys. Rev. Lett. 101 (2008) 181602.
CDMS II: Science 327 (2010) 1619. Phys. Rev. Lett. 106 (2011) 131302.
XENON100: Phys. Rev. Lett 107 (2011) 131302
CoGeNT: Phys. Rev. Lett 106 (2011) 131301

Monophoton - χ-nucleon cross-section

Spin Dependent Limits



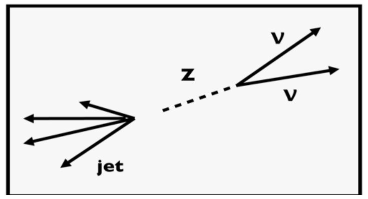
- lower limits on Λ are then used to compute χ-nucleon cross-section versus M_χ using:

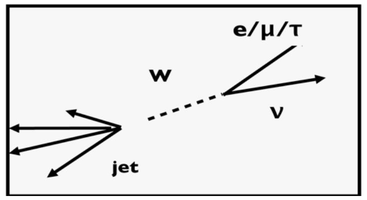
$$\sigma_{SD}^{\chi\text{-N}} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

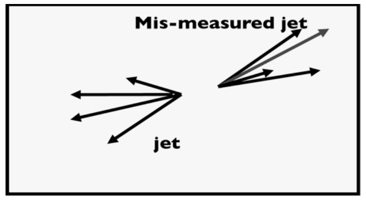
- Extends the limits for $M_\chi < 100$ GeV for Spin dependent case

CMS: Phys.Rev. Lett. 108(2012) 261803.
CDF: Phys. Rev. Lett. 101 (2008) 181602.
SIMPLE: Phys. Rev. Lett. 105 (2010) 211301.
COUPP: Phys. Rev. Lett. 106 (2011) 021303.
IceCube: Phys. Rev. D 85 (2012) 042002.
Super-K: ApJ 742 (2011) 78.

Monojet Search details







Backgrounds coming from SM processes

Z+jets - irreducible

W+jets - if e/u is not detected or tau decays hadronically

QCD - jet is mis-measured giving rise to MET

Baseline selection:

- Select jets with cuts on its constituents - charged/neutral/EM hadronic fractions

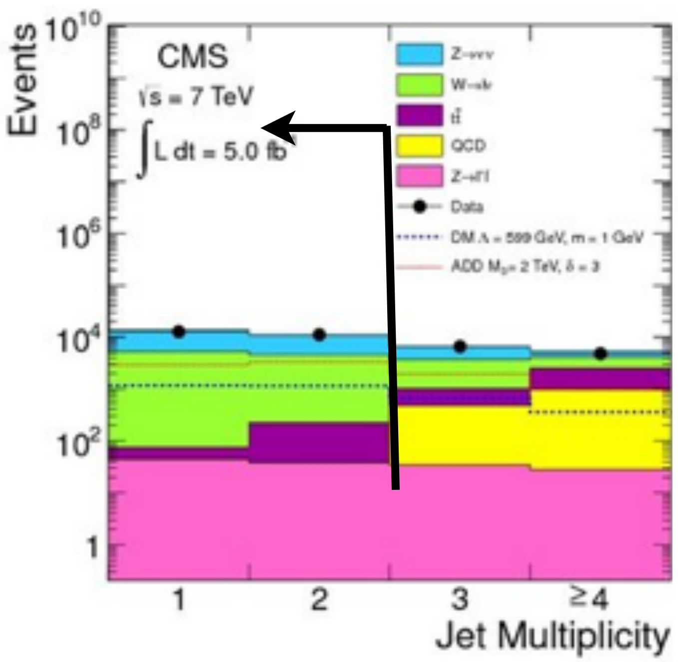
Topological selection:

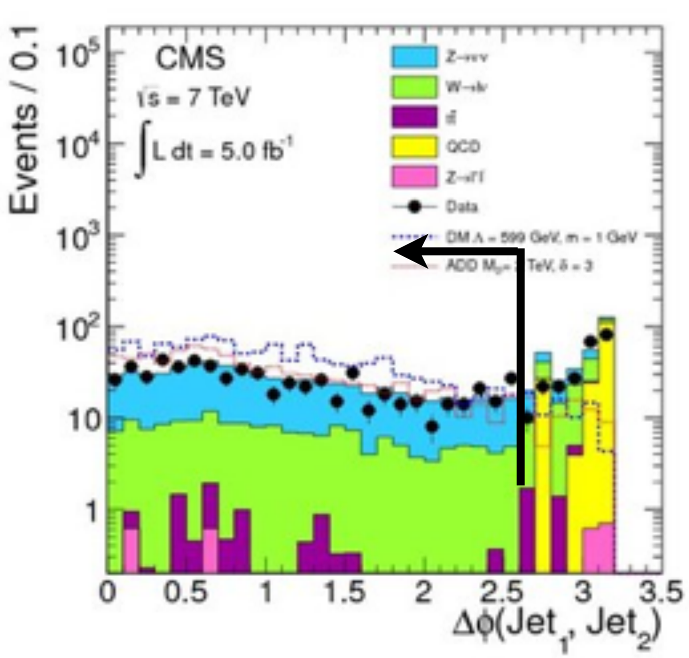
- Number of Jets = 1 or 2
- Leading Jet: P_T(jet) > 110 GeV, $|\eta|$ < 2.4
- Second Jet: P_T(jet) > 30 GeV
- $\Delta\Phi$(jet1, jet2) < 2.5

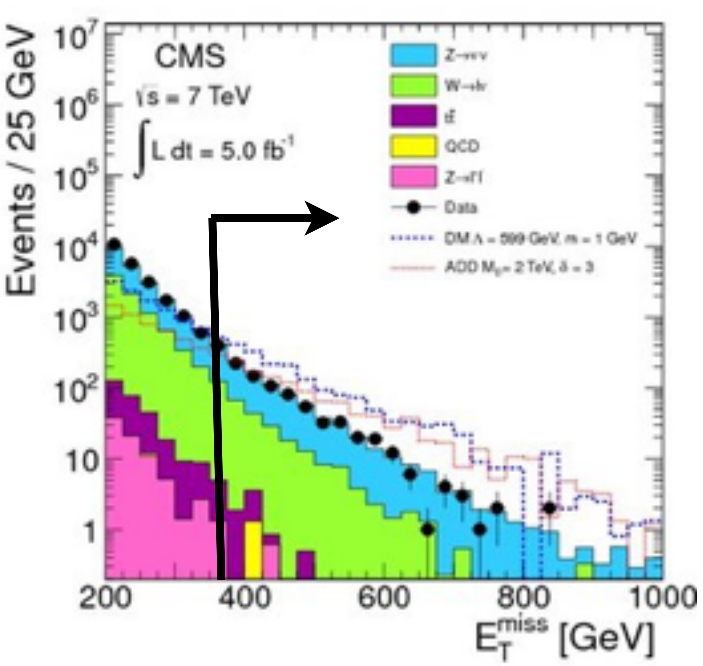
MET > 200 GeV, optimized to 350 GeV for DM search

Remove leptons:

- Reject events having isolated electron/muon in cone of ΔR < 0.3
- Reject events having isolated tracks in a cone of ΔR < 0.3

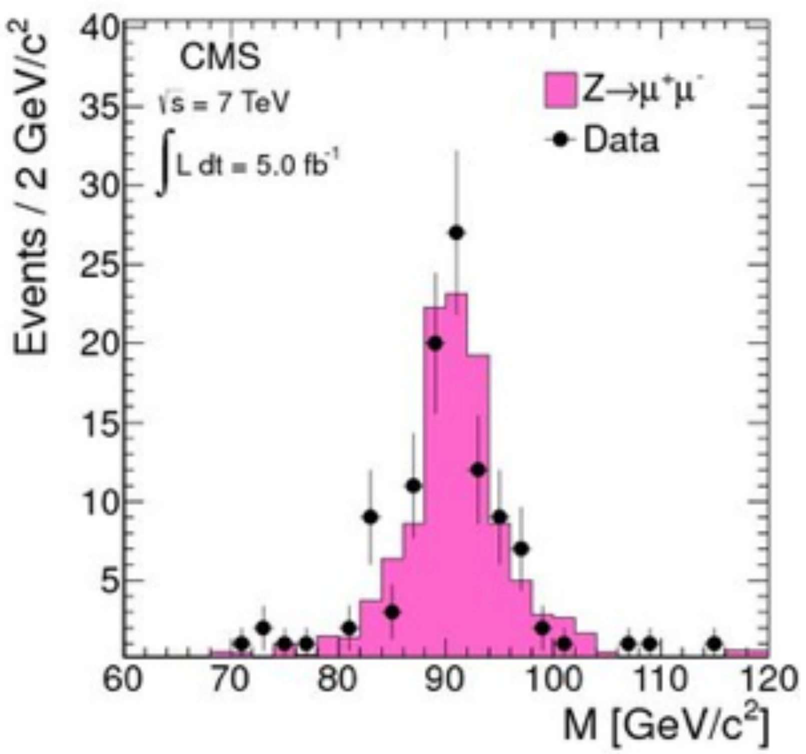


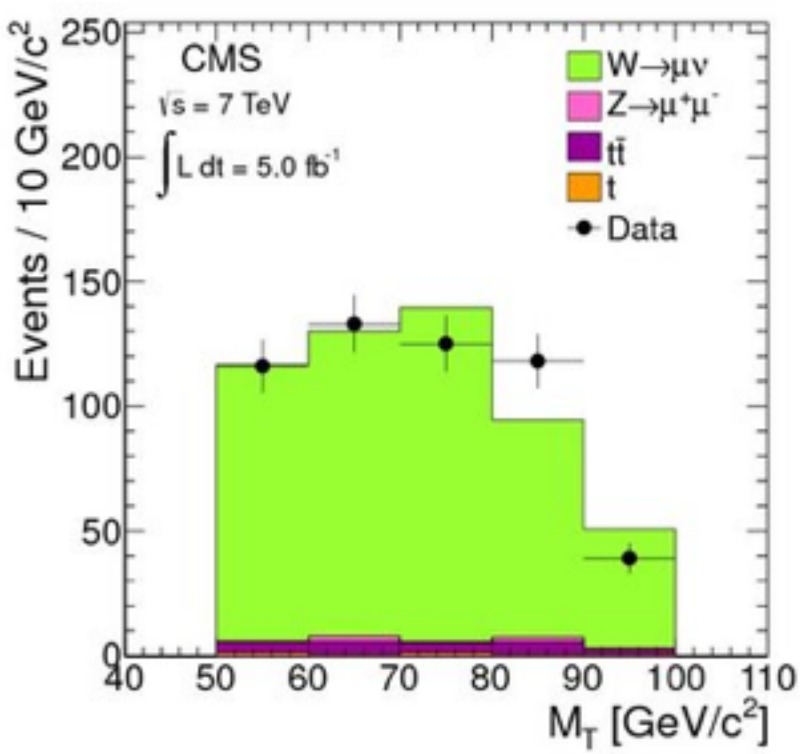




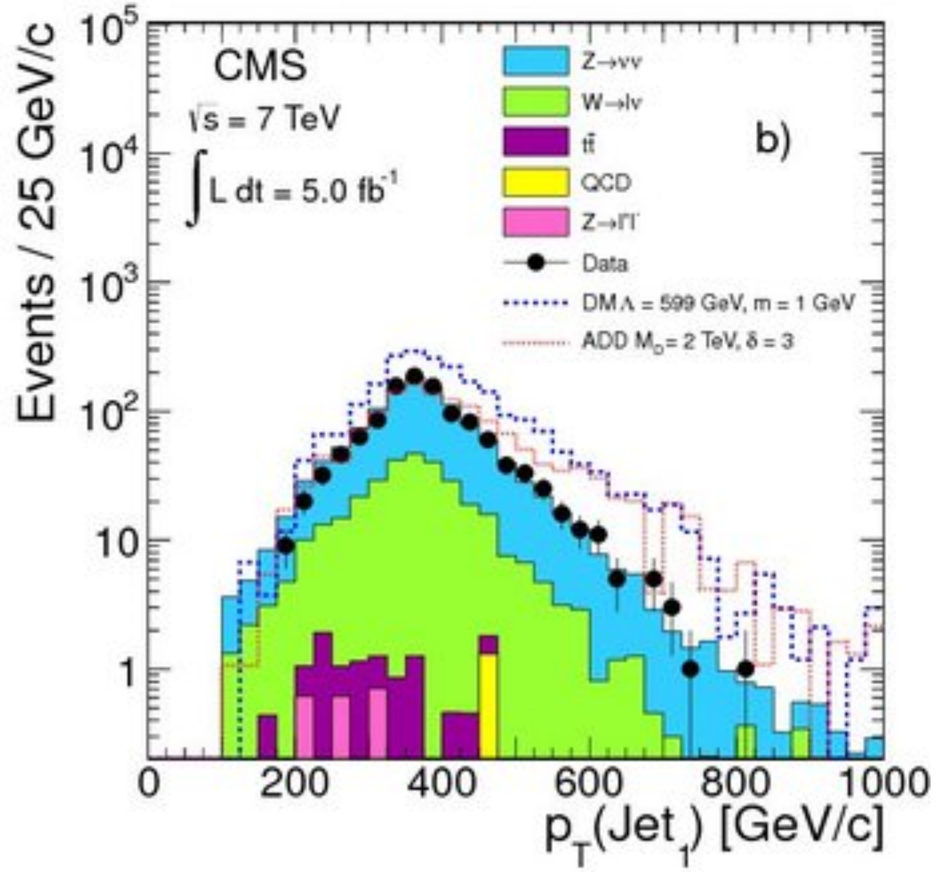
Monojet - Background Estimation

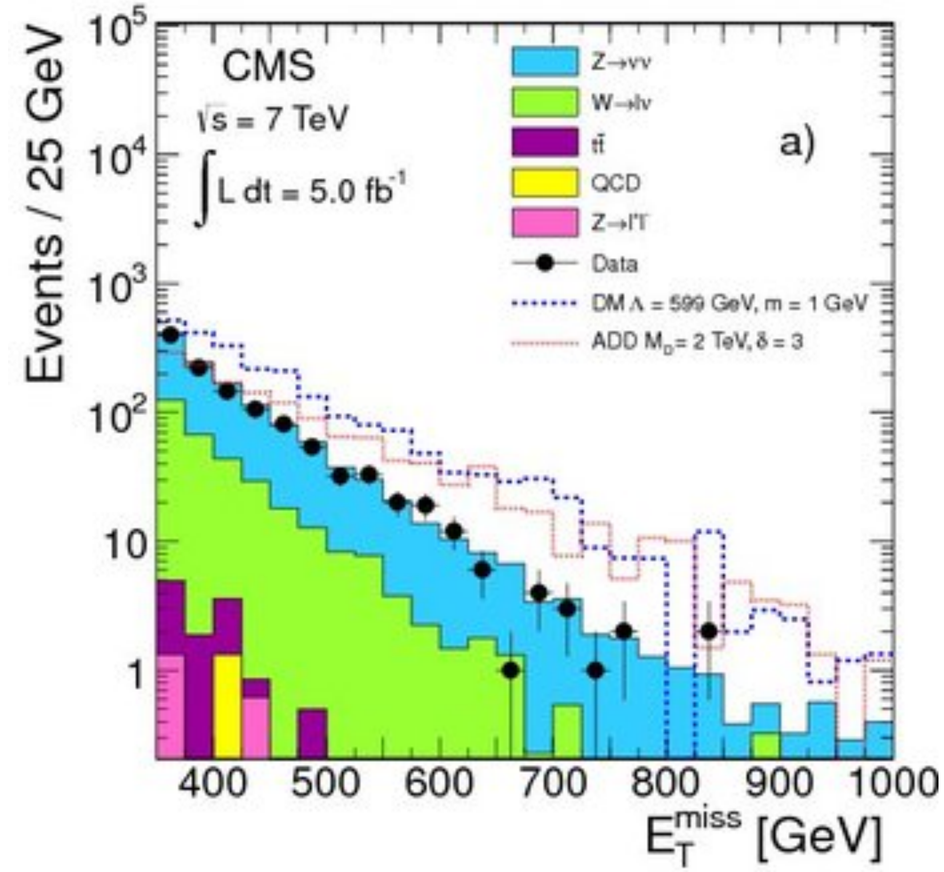
- $Z(\nu\nu)$+jets is estimated from $Z(\mu\mu)$+jet control sample from data
  - Isolated muons with Pt > 20GeV and $|\eta| < 2.1$
  - Opposite Sign muons, invariant mass between 60-120GeV
  - Total Uncertainty is11% mainly due to the size of the control sample(9.5%)
- Wjets is estimated from W($\mu\nu$) control sample from data
  - Isolated muons with Pt > 20GeV and $|\eta| < 2.1$
  - Transverse mass(M_T) between 50-100GeV,
  - Total Uncertainty is 11.8%, primarily from acceptance(7.7%) and selection(6.8%)
- Other small backgrounds from QCD, ttbar, Z+jets and top are taken from MC





Monojet - Results



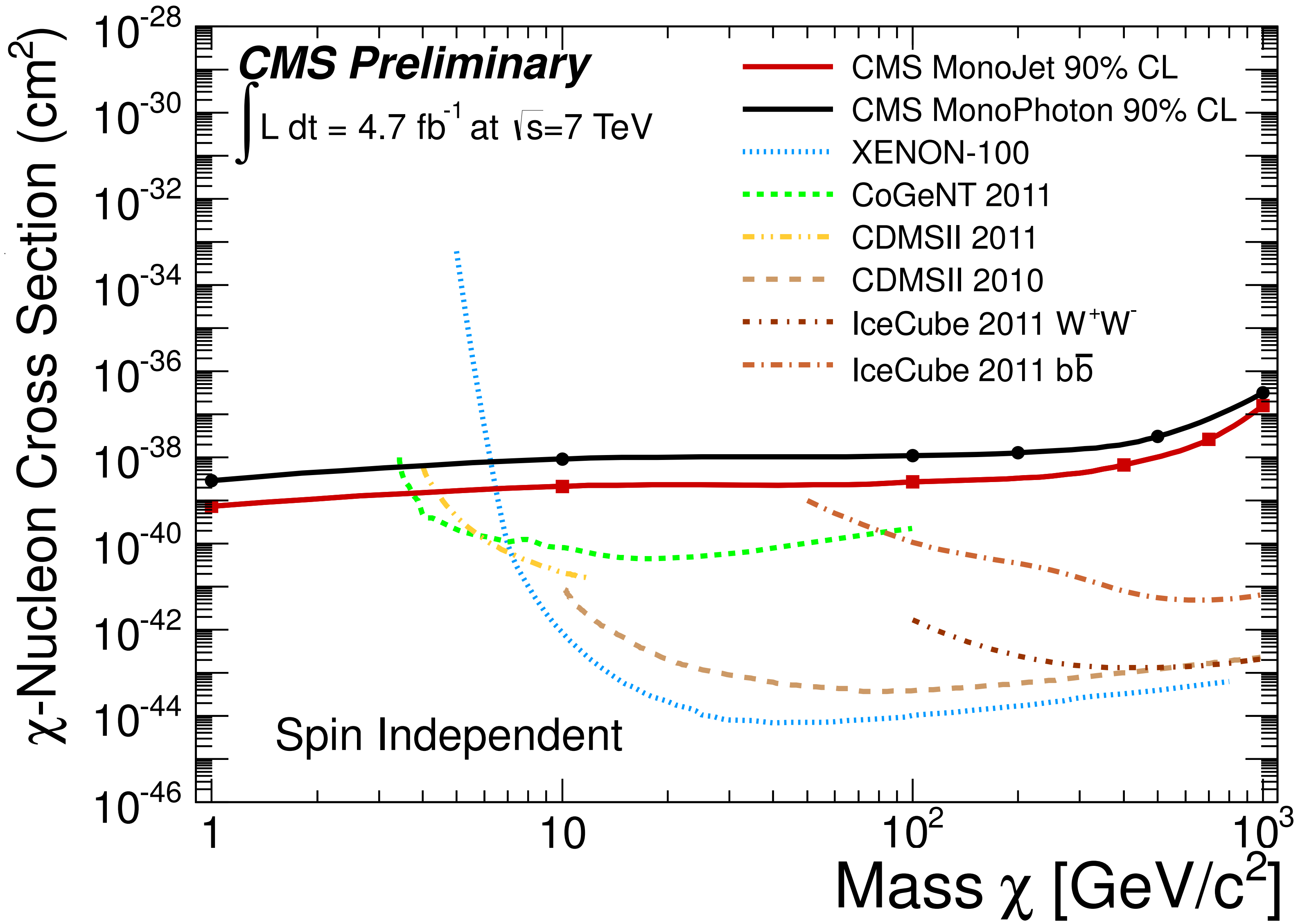


Background process	Events
$Z \rightarrow \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

No excess observed between data and background expectation

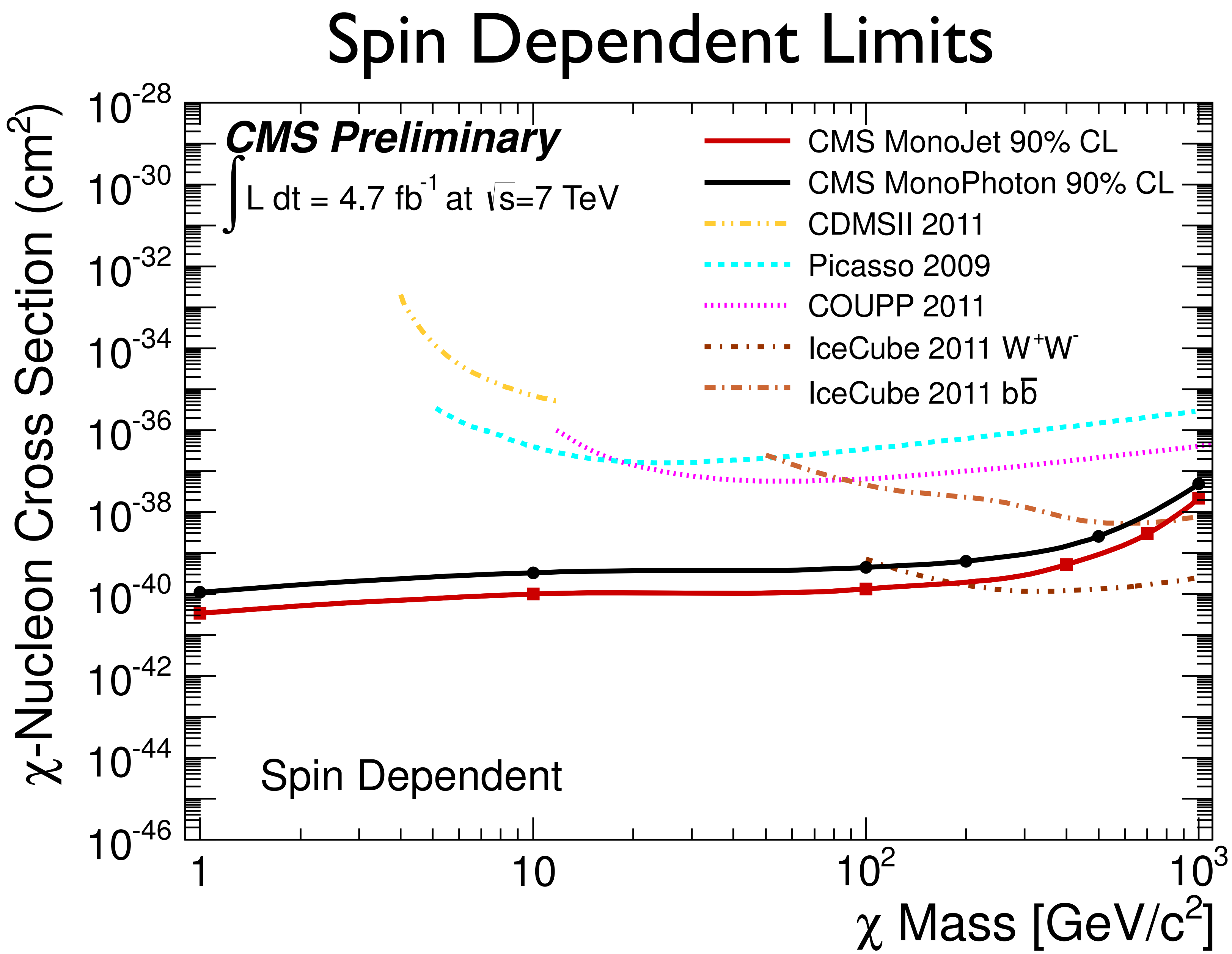
Monojet - χ-nucleon cross-section

Spin Independent Limits



- Extends the limits for M_χ <3.5 GeV - which remained unexplored by direct detection experiments for SI case

Monojet - χ-nucleon cross-section



- Stringent constraints by colliders over whole mass range

SUSY Based Searches

- Since in MSSM, LSP is a candidate for the DM, one can look for its signatures in SUSY.
- Focus on scenarios dominated by direct Electroweak production
  - Clean and probes only in gaugino sector.
  - Characterized with pair-production of charginos and neutralinos.
  - Depending on their mass spectrum, one can have significant branching fraction to leptons or vector bosons
  - In either case, 2 LSP(DM candidates) and neutrino(s) are produced, giving rise to MET

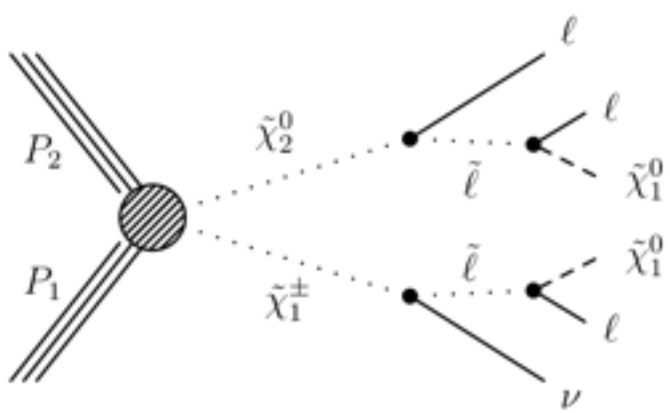
EWK production of Charginos & Neutralinos

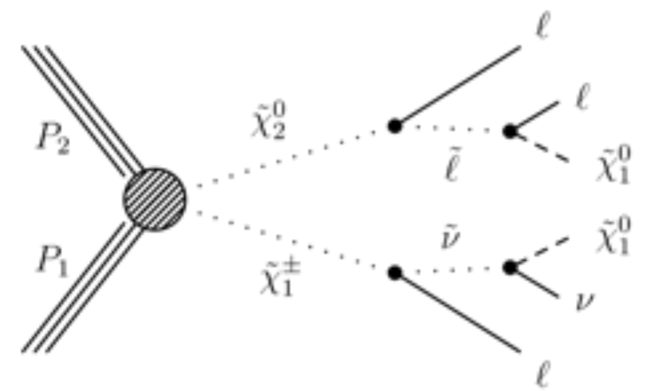
This model lead to tri-lepton signature and motivate the assumption that $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ have similar mass.

Here, $m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ and the slepton mass is parameterized as

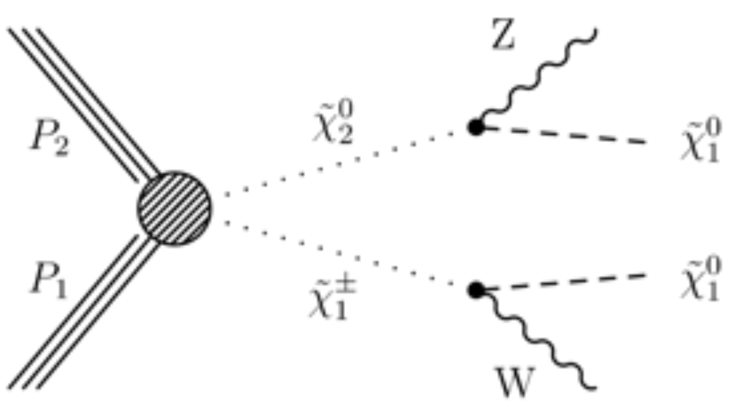
$$m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + x_{\tilde{\ell}} \left(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} \right) \qquad \text{with, } 0 < x_{\tilde{\ell}} < 1$$

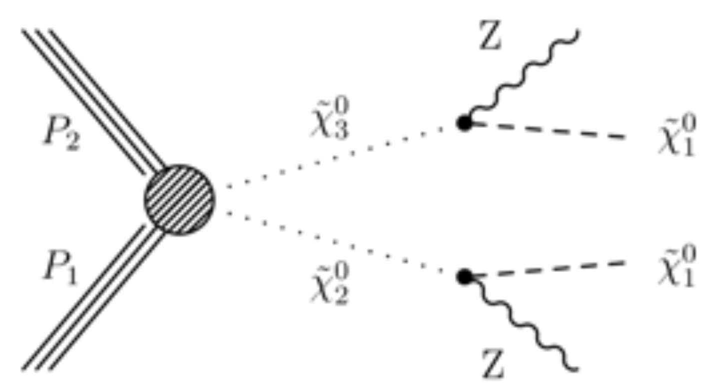
Present results with $x_{\tilde{\ell}} = 0.5$





sleptons are light and mediate the decays to LSP





sleptons are heavy and and whole BF to vector bosons and LSP

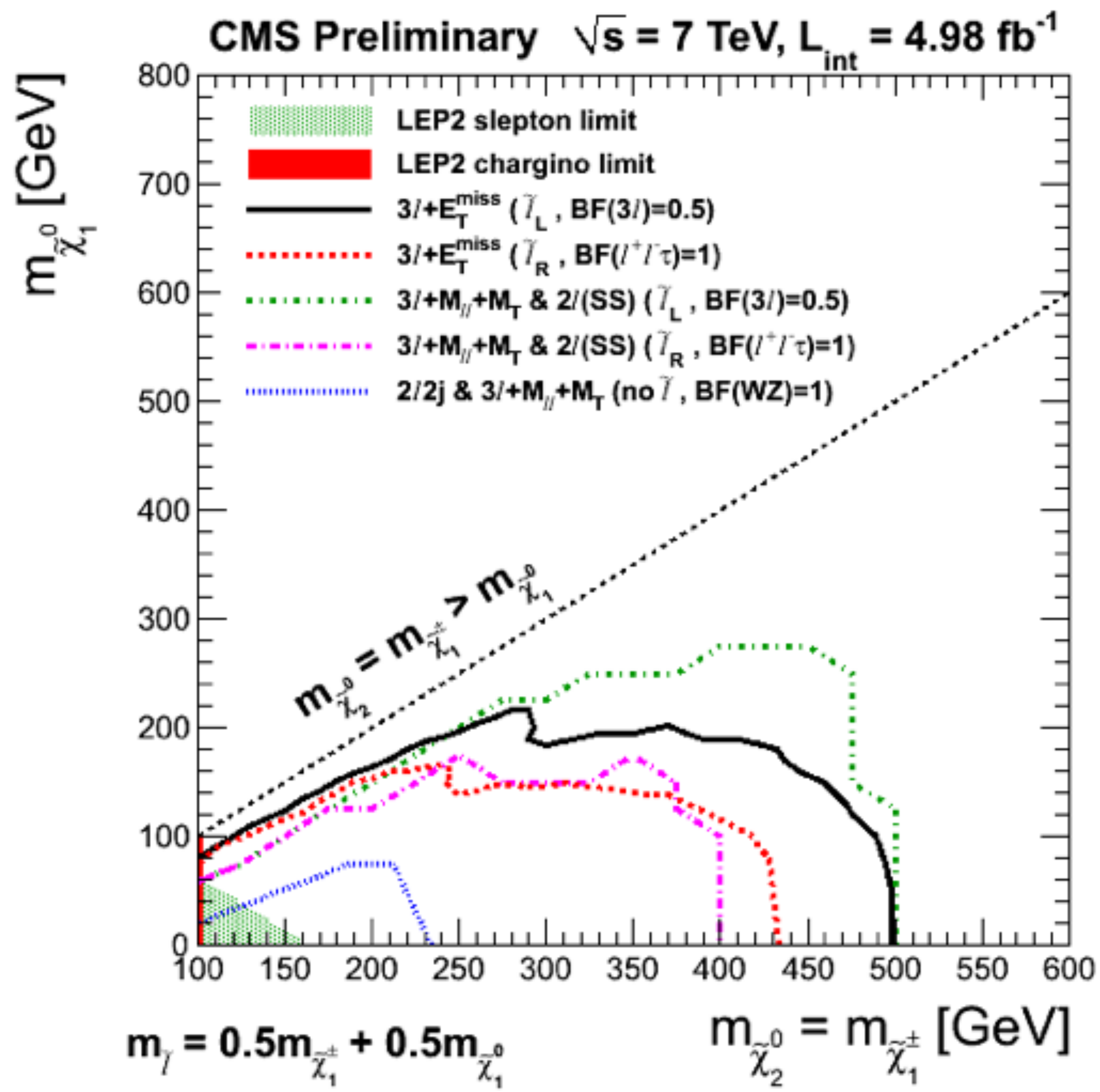
Signatures explored @7TeV

- 3(4) leptons + MET
  - MET as the observable to distinguish between signal and background, better sensitivity when mass splitting is large
  - M(ll) and M_T as the observables, better sensitivity when LSP mass approaches the mass of chargino/netralino.
- Same Sign dilepton + MET
- Opposite Sign dilepton + dijet + MET

No evidence of the signal and hence limits are placed on cross section for the pair production times the BF for these scenarios

arXiv:1209.6620v1
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS12006

Limits - EWK production



◉ Probe M(χ±, χ0) up to ~ 200-500 GeV, depending on the search mode

Conclusions

- CMS Searches for Dark Matter are presented with the integrated luminosity of $5fb^{-1}$ @7 TeV center of mass energy.
- No excess has been observed yet. Limits are being set on Dark Matter production resulting in extension of results in the parameter space.
- MSSM searches in the EWK production shows no excess above the SM expectation.
- Searches are continued at 8 TeV - stay tuned!

Thanks!!

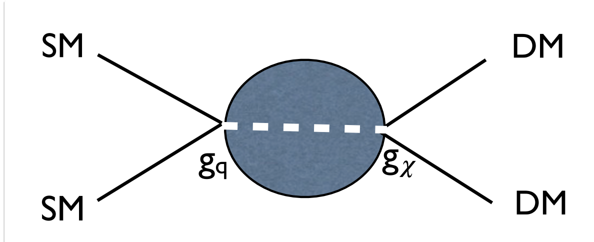
Find all the results here:

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

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

Phenomenology of χ production

- In the effective theory, pair production of χ is characterized by contact interaction



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

where,
M : mediator mass,
g_χ : coupling with DM particle
g_q: coupling with SM quark

- Nature of the mediator tells the form of interactions

➡ Vector mediator (Spin Independent)

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \qquad \sigma_{SI} = 9\frac{\mu^2}{\pi\Lambda^4}$$

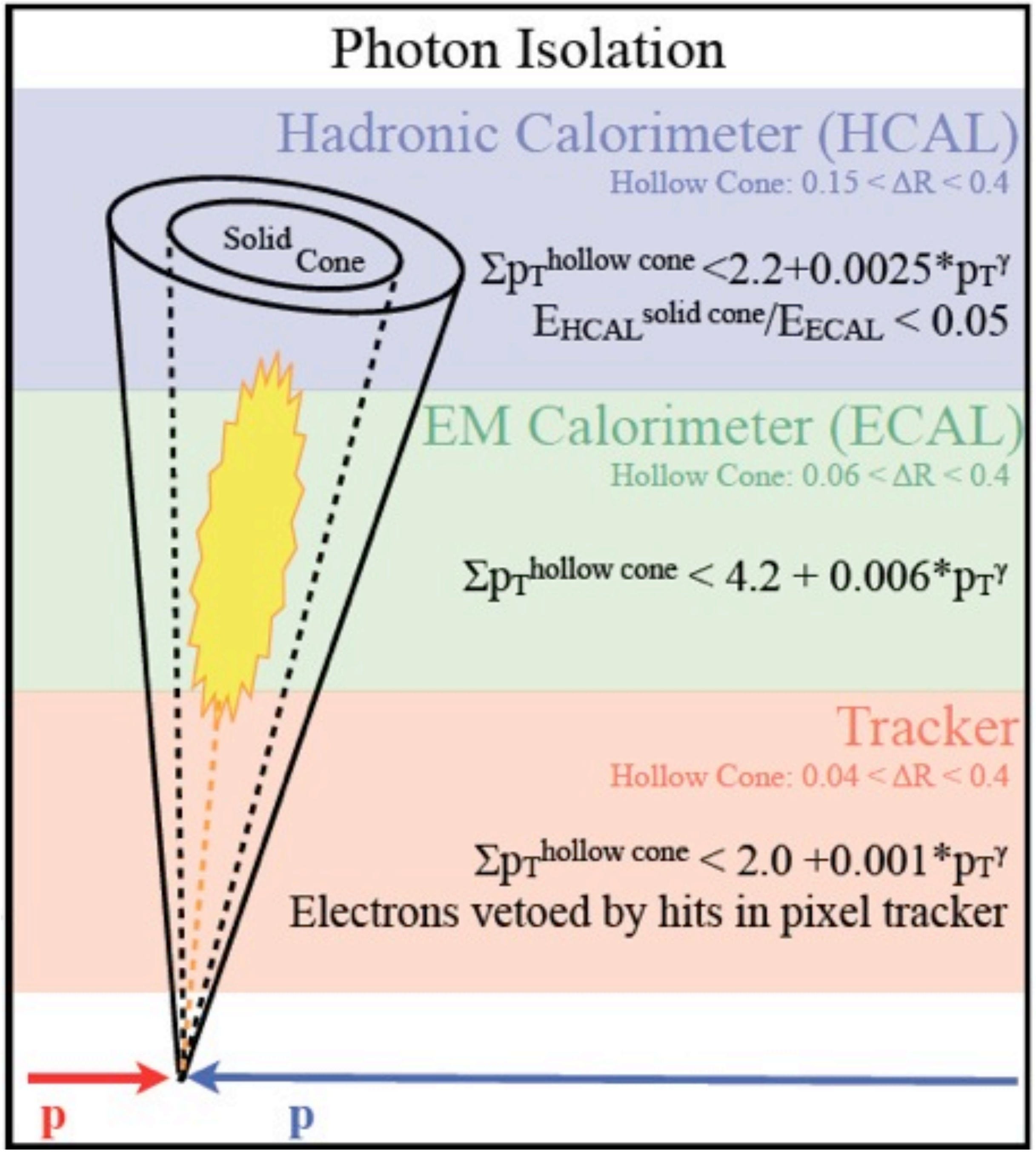
➡ Axial-vector Mediator (Spin Dependent)

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2} \quad \sigma_{SD} = 0.33\frac{\mu^2}{\pi\Lambda^4}$$

Where μ is the reduced mass, $\mu = \dfrac{m_\chi m_p}{m_\chi + m_p}$

Bai,Fox and Harnik [JHEP 1012:048(2010)]

Isolation variables



Sub detector resolutions

ηl < 2.5 : Tracker $\sigma/p_T \approx 10^{-4}\, p_T \oplus 0.005$ (TeV)
lηl < 4.9 : Electromagnetic Calorimeter $\sigma/E \approx 0.03/\sqrt{E} \oplus 0.003$ (GeV)
lηl < 4.9 : Hadronic Calorimeter $\sigma/E \approx 1.00/\sqrt{E} \oplus 0.050$ (GeV)
lηl < 2.6 : Muon Spectrometer $\sigma/p_T \approx 0.10$ (GeV) (1 TeV

Monojet - Backgrounds

- Z(νν)+jets is estimated from Z(μμ)+jet control sample from data
  - Isolated muons with Pt > 20GeV and |η| < 2.1
  - Opposite Sign muons, invariant mass between 60-120GeV
  - Total Uncertainty is11% mainly due to the size of the control sample(9.5%)

Estimated using:

$$N(Z(\nu\bar{\nu})) = \frac{N^{\mathrm{obs}} - N^{\mathrm{bgd}}}{A \times \epsilon} \cdot R\left(\frac{Z(\nu\bar{\nu})}{Z(\mu\mu)}\right)$$

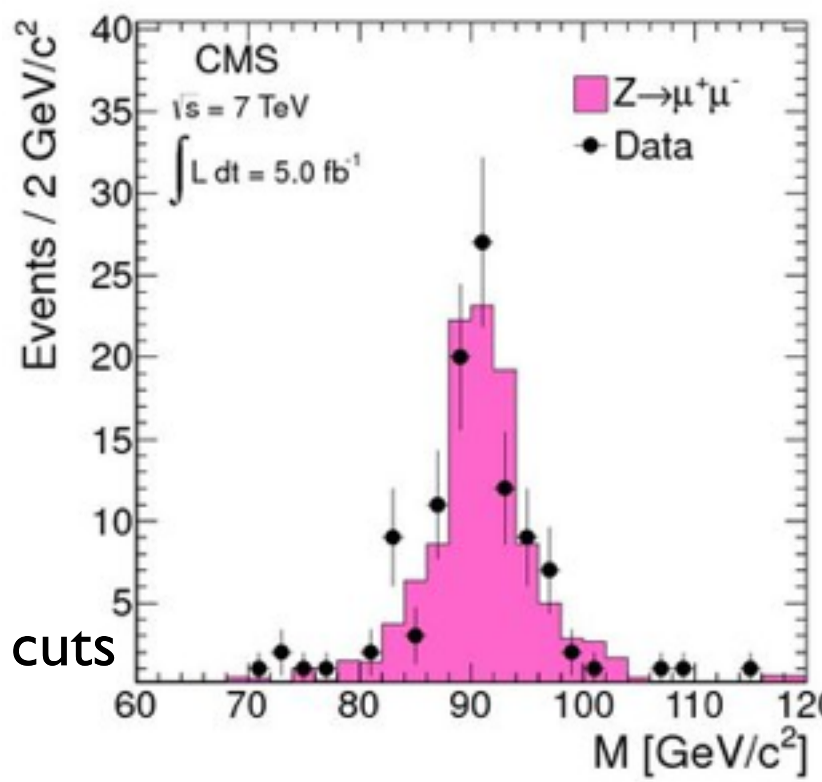
where,

N_{obs} : Observed events in Data

N_{bkd} : Estimated events from Background

R : Ratio of Branching Fraction(BF)

A x ϵ : Detector Acceptance times efficiency for the cuts



Monojet - Backgrounds

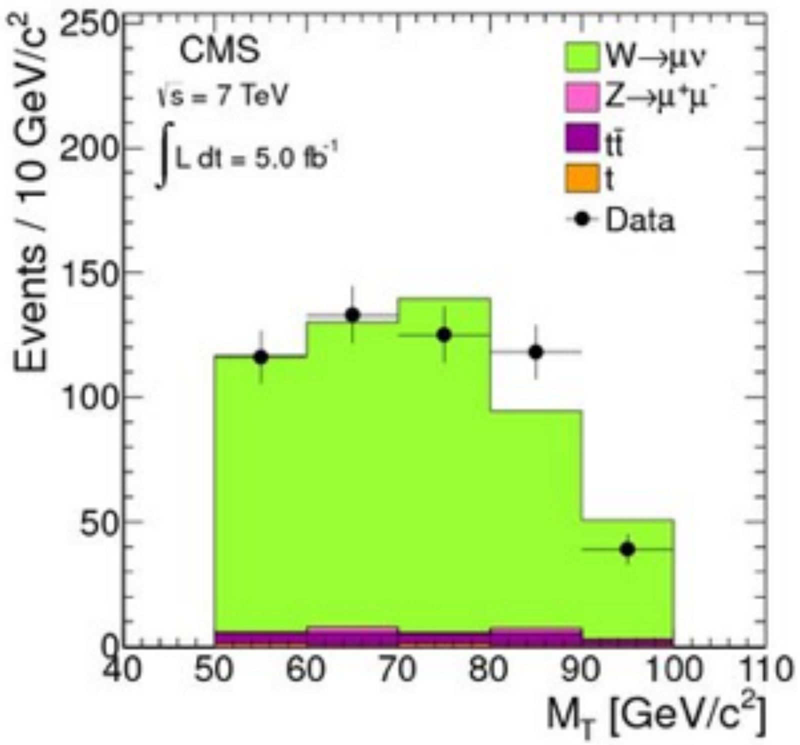
- Wjets is estimated from W(μν) control sample from data
  - Isolated muons with Pt > 20GeV and |η| < 2.1
  - Transverse mass(M_T) between 50-100GeV, $M_T = \sqrt{2 p_T^{\mu} E_T^{miss} (1 - \cos(\Delta\phi))}$
  - Uncertainty is 11.8%, primarily from acceptance(7.7%) and selection(6.8%)

Estimated using:

$$N_{tot} = \frac{N^{obs} - N^{bgd}}{A \times \epsilon}$$

Weighted by inefficiency of lepton veto :

$$N_{\bar{A}} = N_{tot} \times (1 - A)$$
$$N_{\bar{\epsilon}} = N_{tot} \times A \times (1 - \epsilon)$$
$$N_{lost\,\mu} = N_{\bar{A}} + N_{\bar{\epsilon}}.$$



- Other backgrounds from QCD, ttbar, Z+jets and top are taken from MC

Monojet - Dark Matter Signal

- Signal Generation with Madgraph5 + Pythia6 with 40 TeV mediator mass
- Uncertainties here totals to 20%, mainly coming from:
  - Contribution from Jet energy Scale and resolution
  - PDF (PDF4LHC)
- Final numbers for MET>350 GeV: Background - 1224±101, Data - 1142

Limit setting is done as before

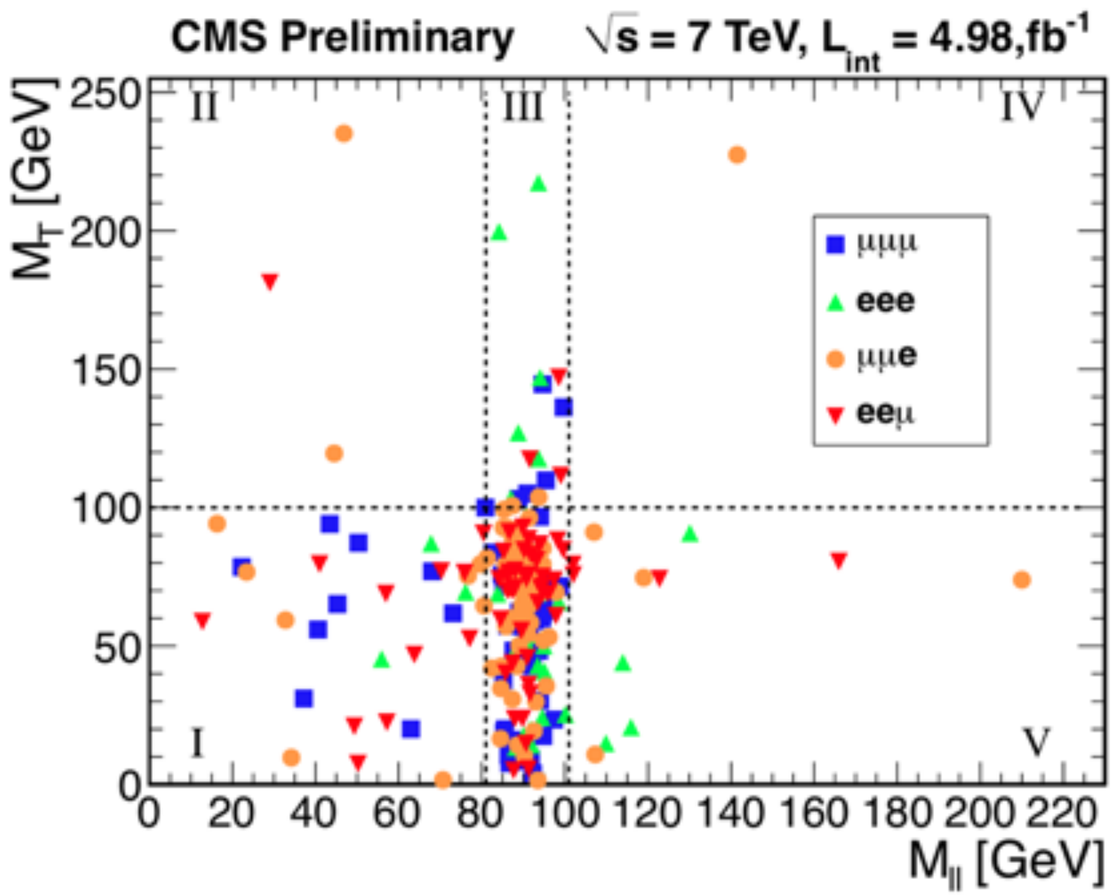
M_χ (GeV/c^2)	Spin-dependent Λ (GeV)	Spin-dependent $\sigma_{\chi N}$ (cm^2)	Spin-independent Λ (GeV)	Spin-independent $\sigma_{\chi N}$ (cm^2)
0.1	754	1.03×10^{-42}	749	2.90×10^{-41}
1	755	2.94×10^{-41}	751	8.21×10^{-40}
10	765	8.79×10^{-41}	760	2.47×10^{-39}
100	736	1.21×10^{-40}	764	2.83×10^{-39}
200	677	1.70×10^{-40}	736	3.31×10^{-39}
300	602	2.73×10^{-40}	690	4.30×10^{-39}
400	524	4.74×10^{-40}	631	6.15×10^{-39}
700	341	2.65×10^{-39}	455	2.28×10^{-38}
1000	206	1.98×10^{-38}	302	1.18×10^{-37}

Systematics in detail

– Stats. uncertainty	1.7%
– Photon PT uncertainty	2.3%
– Jet Energy Scale	1.2%
– MET modelling	0.5%
– Pile-up modelling	2.4%

3 leptons + MET

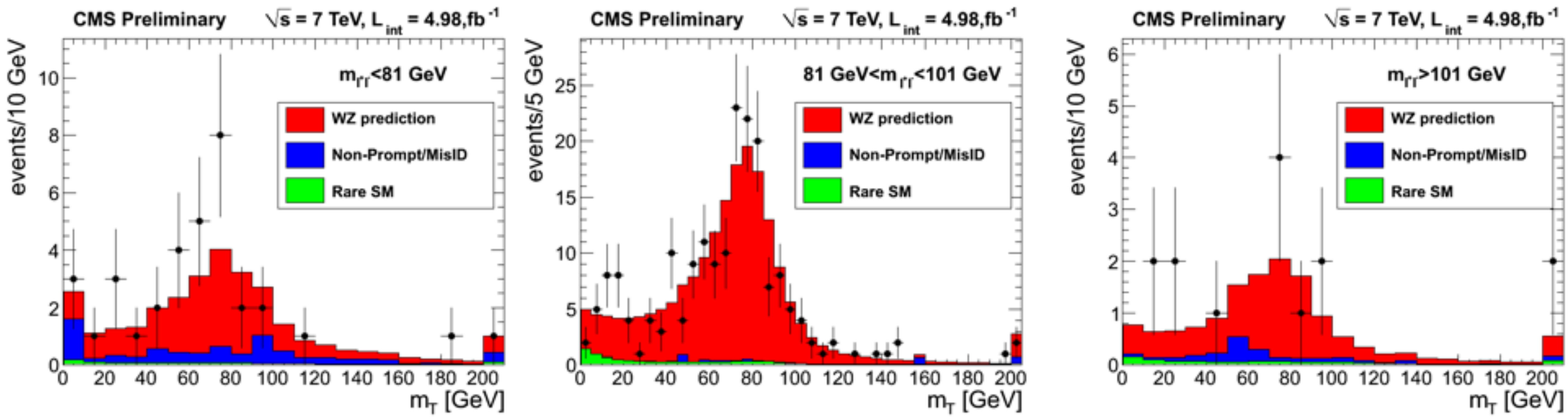
WZ is the main background



This search is done in 6 regions defined in Mll and MT:

- Various regions defined here give best signal to background separation
- Depending on the mass splitting between $\tilde{\chi}_2^0 - \tilde{\chi}_1^0$, signal can appear anywhere

Results

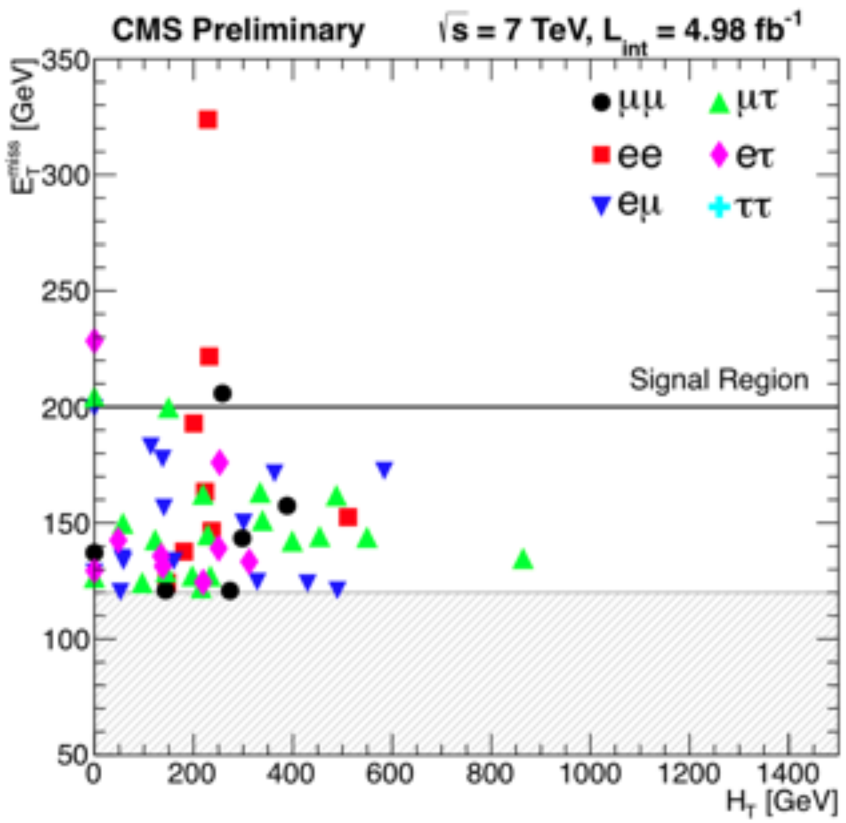


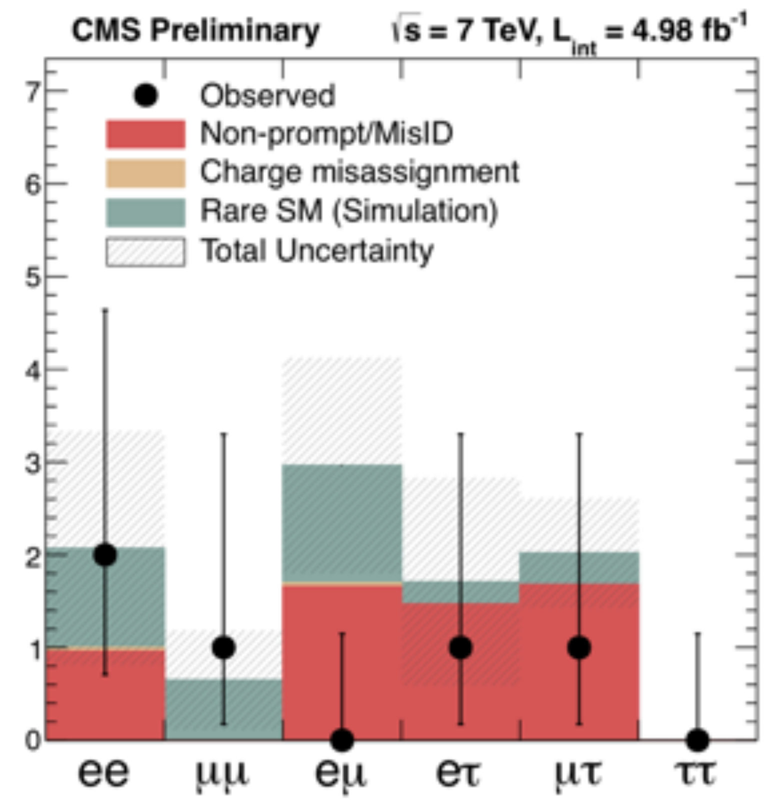
Region	WZ	Non-prompt	Rare SM	Total background	Data
I	16.2 ± 2.9	4.7 ± 2.4	2.1 ± 1.5	23.0 ± 5.1	31
II	3.6 ± 0.8	1.94 ± 1.02	0.4 ± 0.2	6.0 ± 1.3	3
III	15.6 ± 5.7	0.2 ± 0.1	0.8 ± 0.4	16.6 ± 5.7	17
IV	1.6 ± 0.4	0.2 ± 0.1	0.4 ± 0.2	2.2 ± 0.5	2
V	8.7 ± 1.7	1.4 ± 0.8	0.9 ± 0.4	11.0 ± 1.9	12
VI	150.6 ± 25.7	2.6 ± 1.4	11.7 ± 5.8	164.9 ± 26.4	173

No Evidence of the signal

Same Sign two lepton final state

- To increase the sensitivity of the analysis for 3 leptons search, one considers this final state.
- If the mass splitting is such that 3rd lepton is soft, then it can be lost/mis-identified.

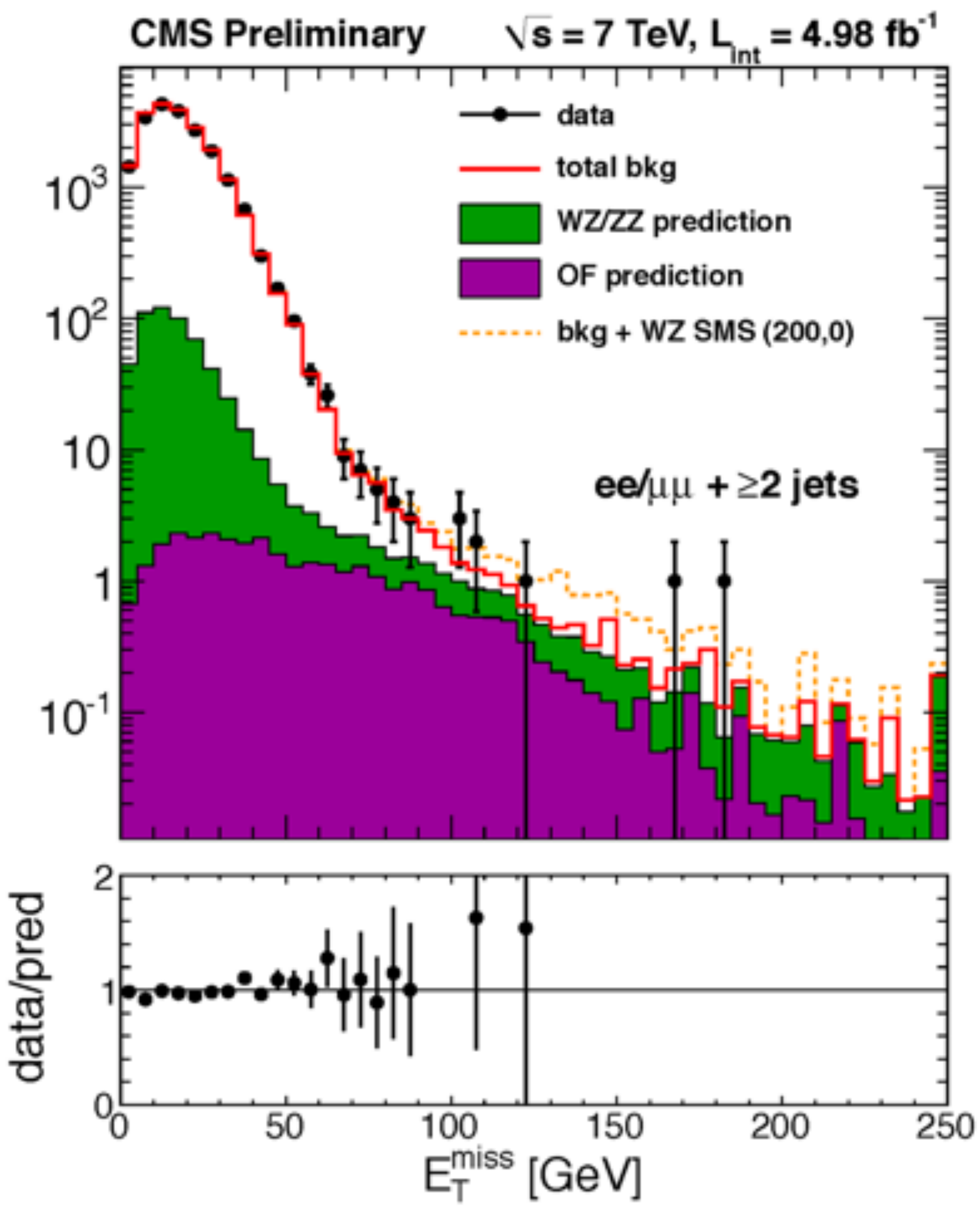




Source	ee	$\mu\mu$	$e\mu$	$e\tau$	$\mu\tau$	$\tau\tau$	Sum
Non-pr/misID	1.0 ± 0.8	0.0 ± 0.2	1.7 ± 1.0	1.5 ± 1.1	1.7 ± 0.6	0.00 ± 0.00	5.8 ± 1.9
Charge mis-as	0.0 ± 0.0	–	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.1	0.00 ± 0.01	0.1 ± 0.1
Rare SM	1.0 ± 0.7	0.7 ± 0.5	1.3 ± 0.7	0.3 ± 0.1	0.4 ± 0.2	0.00 ± 0.00	3.7 ± 1.5
Total background	2.1 ± 1.0	0.7 ± 0.5	3.1 ± 1.2	1.7 ± 1.1	2.0 ± 0.6	0.00 ± 0.01	9.5 ± 2.4
Observed	2	1	0	1	1	0	5

WZ/ZZ + MET with final state of 2 OS leptons + 2 jets + MET

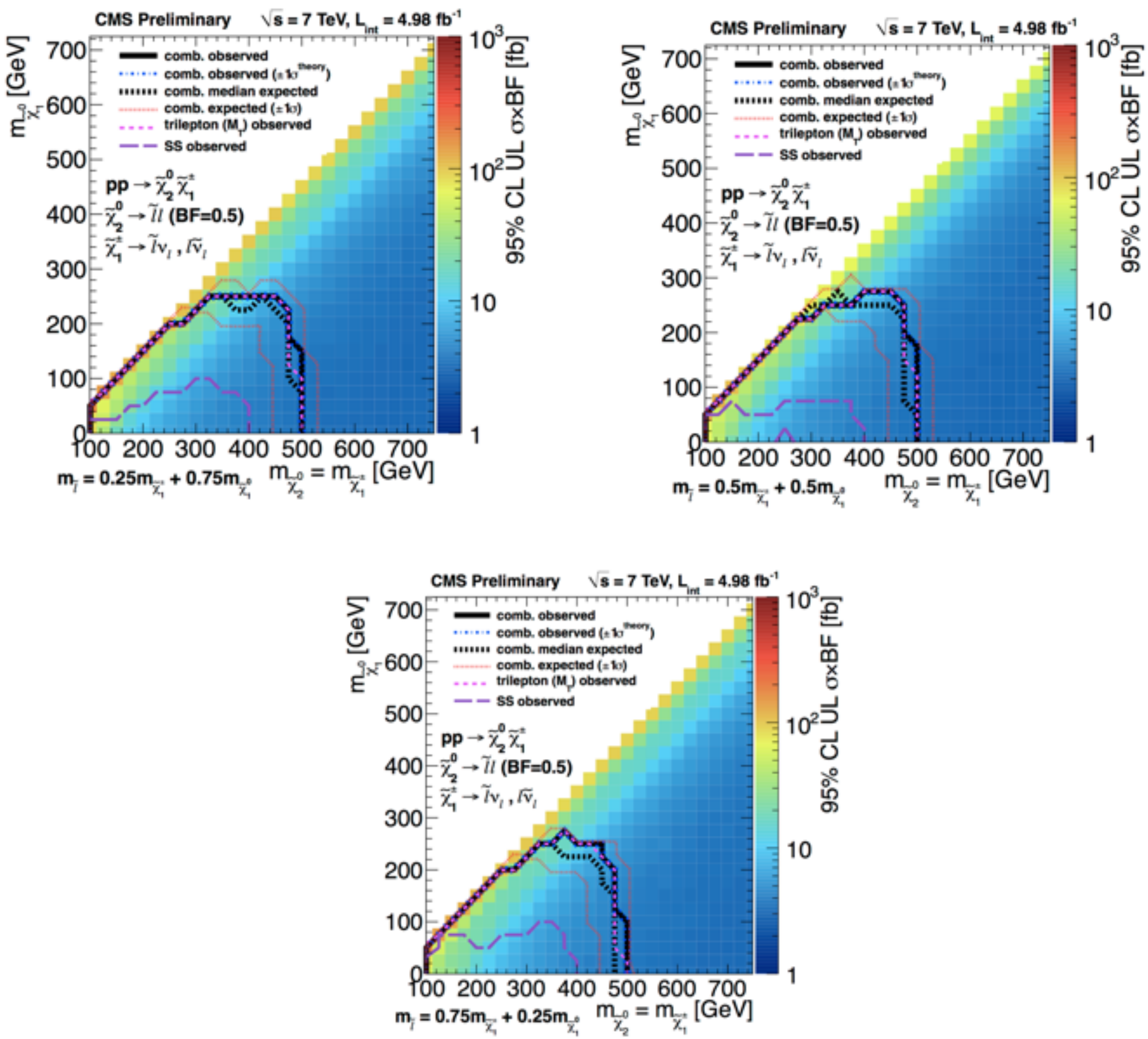
- Increase the sensitivity of the analysis when Z decays to ee/mumu while other Z/W decays to 2 jets



Source	$30 < E_T^{miss} < 60$ GeV	$60 < E_T^{miss} < 80$ GeV	$80 < E_T^{miss} < 100$ GeV
Z + jets background	2298 ± 737	32.9 ± 11.1	5.2 ± 1.8
OF background	11 ± 2	6.6 ± 1.6	4.6 ± 1.2
WZ/ZZ background	50 ± 25	3.9 ± 2.0	2.2 ± 1.1
Total background	2359 ± 737	43.4 ± 11.4	12.0 ± 2.4
Data	2416	47	7

Source	$100 < E_T^{miss} < 150$ GeV	$150 < E_T^{miss} < 200$ GeV	$E_T^{miss} > 200$ GeV
Z + jets background	1.7 ± 0.6	0.4 ± 0.2	0.2 ± 0.09
OF background	4.6 ± 1.2	0.8 ± 0.3	0.06 ± 0.07
WZ/ZZ background	2.5 ± 1.3	0.7 ± 0.4	0.4 ± 0.2
Total background	8.8 ± 1.8	1.9 ± 0.5	0.7 ± 0.3
Data	6	2	0

Limits


CMS Preliminary
$\sqrt{s}$ = 7 TeV, L_{int} = 4.98 fb^{-1}
comb. observed
comb. observed ($\pm 1\sigma^{theory}$)
comb. median expected
comb. expected ($\pm 1\sigma$)
trilepton (M_T) observed
SS observed
$pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
$\tilde{\chi}_2^0 \to \tilde{l}l$ (BF=0.5)
$\tilde{\chi}_1^\pm \to \tilde{l}\nu_l, l\tilde{\nu}_l$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ [GeV]
95% CL UL $\sigma \times$BF [fb]
$m_{\tilde{l}} = 0.25m_{\tilde{\chi}_1^\pm} + 0.75m_{\tilde{\chi}_1^0}$
$m_{\tilde{l}} = 0.5m_{\tilde{\chi}_1^\pm} + 0.5m_{\tilde{\chi}_1^0}$
$m_{\tilde{l}} = 0.75m_{\tilde{\chi}_1^\pm} + 0.25m_{\tilde{\chi}_1^0}$