Recent Dark Matter Limits from CDF and CMS

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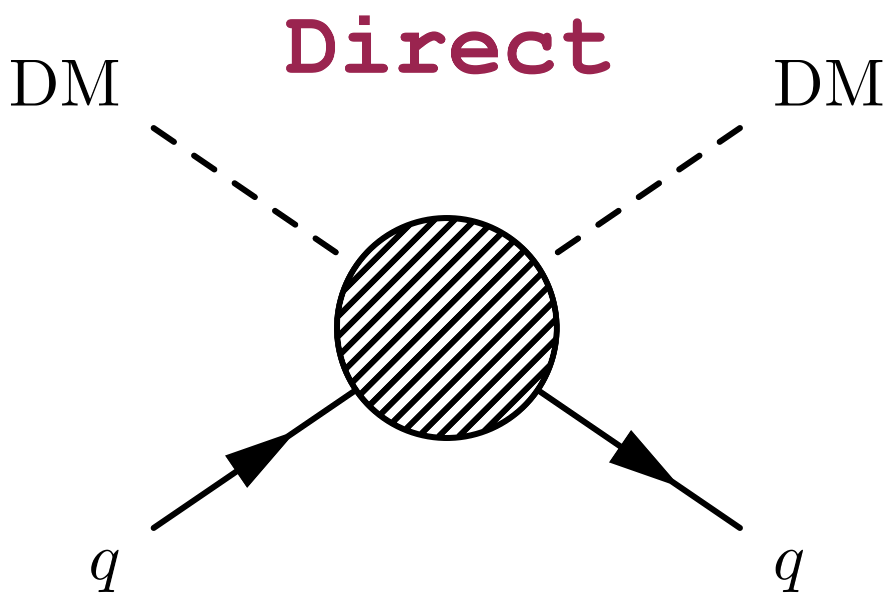
Dark Matter in Collision Workshop
University of California, Davis
Thursday, April 12th, 2012

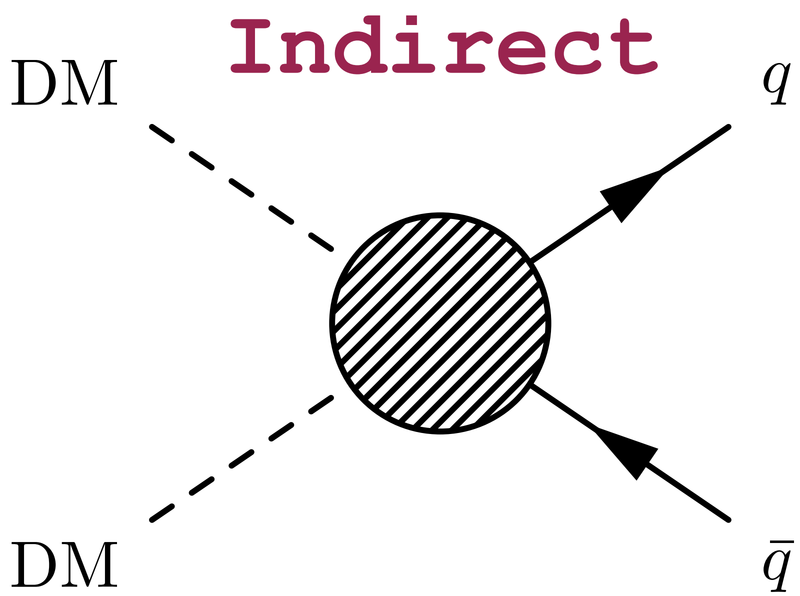
Outline

- Brief theoretical introduction
- CMS results
  - Monophoton
  - Monojet
- CDF results
  - Monojet
  - Monotop
- Conclusions and talking points

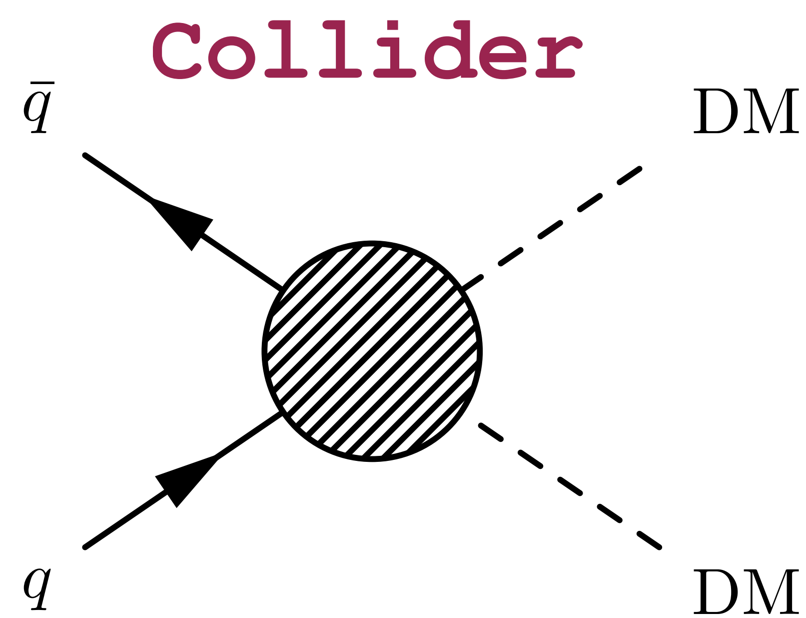
Introduction

- Focus of this talk is on collider DM searches (not necessarily within the framework of CMSSM)
- Key to collider searches: rotate Feynman diagrams assumed in direct-detection experiments (use s-channel, instead of t-channel mode)

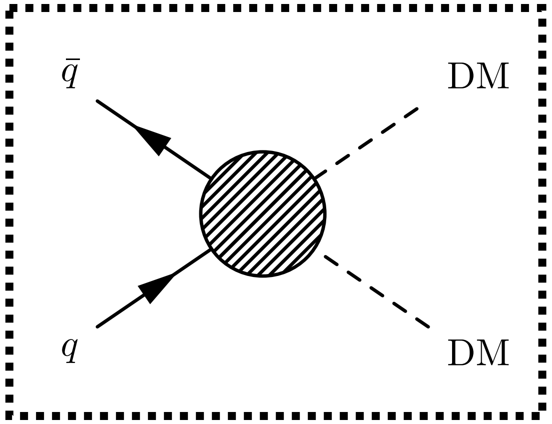




Time $\Longrightarrow$

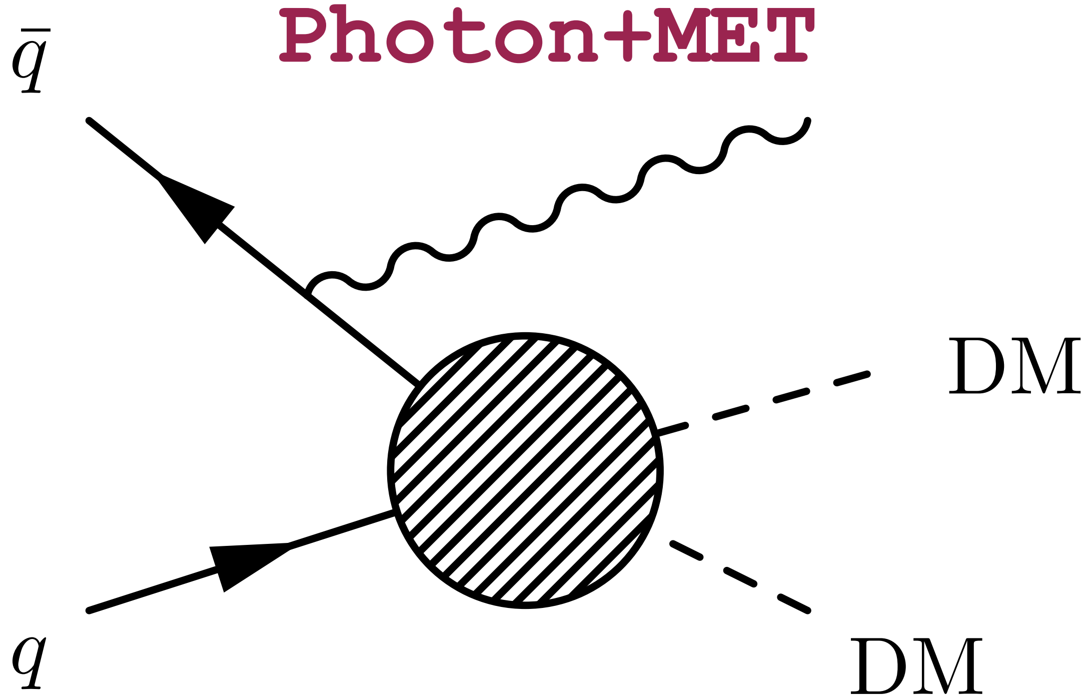


Signature

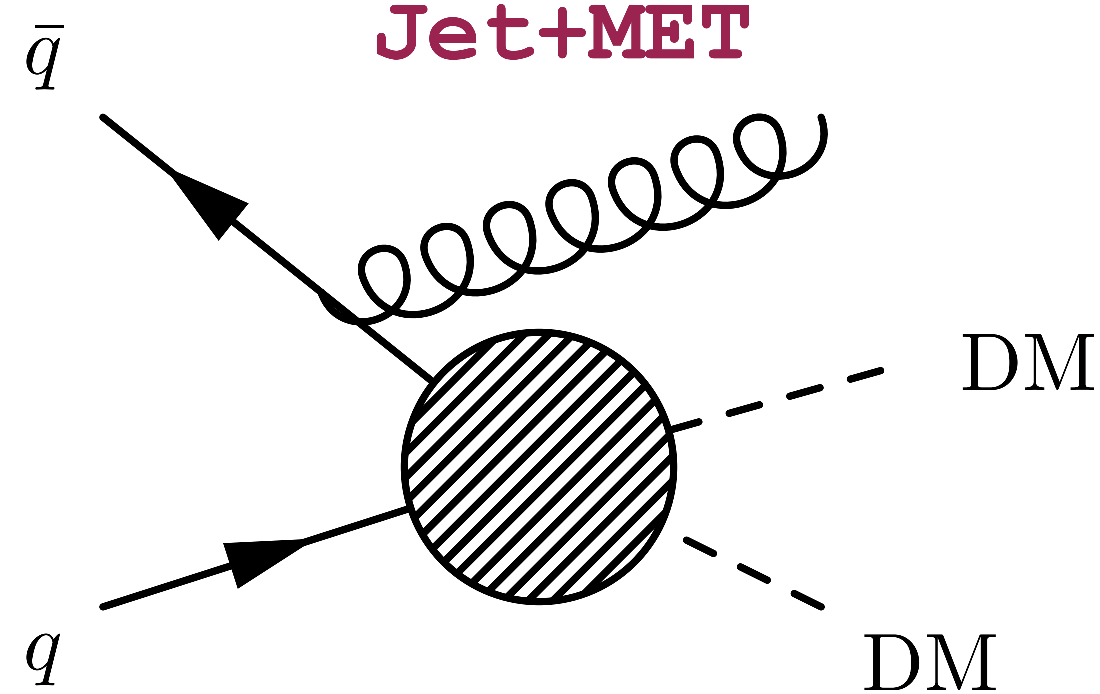
- Of course  is unobservable at a hadron collider

- Use QED/QCD initial state radiation (ISR) to “tag” DM events
  - results in a “monophoton” or “monojet” signature with missing transverse energy (MET) balancing the photon or jet

Photon+MET

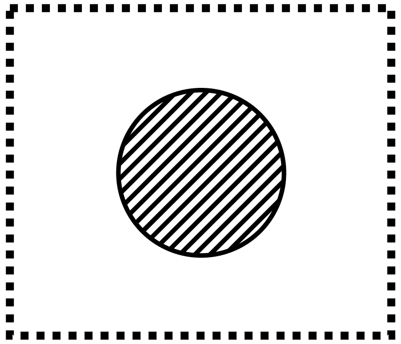


Jet+MET



Phenomenology

couplings to χ and q

- Treat  as a contact interaction term

$$\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M_M^2}$$

- treat as an effective theory where we integrate out a **massive** mediator

$$\mathcal{O}_{\rm V} = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$ s-channel vector ⟺ spin independent (SI)

$$\mathcal{O}_{\rm A} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$ s-channel axial-vector ⟺ spin dependent (SD)

$$\mathcal{O}_{\rm t} = \frac{(\bar{\chi}P_{\rm R}q)(\bar{q}P_{\rm L}\chi)}{\Lambda^2} + ({\rm L} \leftrightarrow {\rm R})$$ t-channel ⟺ (mostly) SI

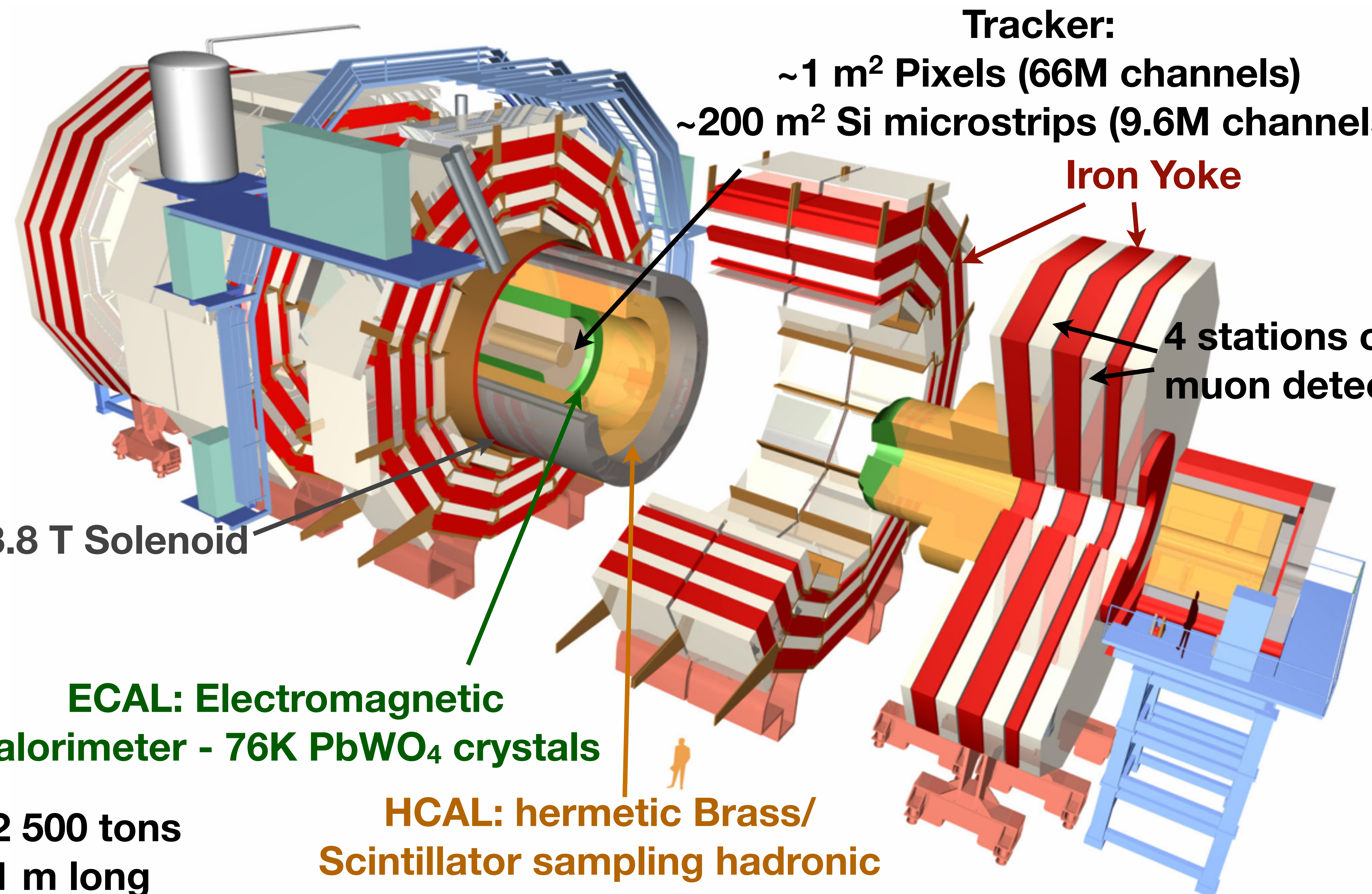
SI and SD χ-nucleon σ:

$$\sigma_{\rm SI} = \frac{9}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2 \qquad \sigma_{\rm SD} = \frac{0.33}{\pi}\left(\frac{\mu}{\Lambda^2}\right)^2$$

(μ is the reduced mass of the χ and proton)

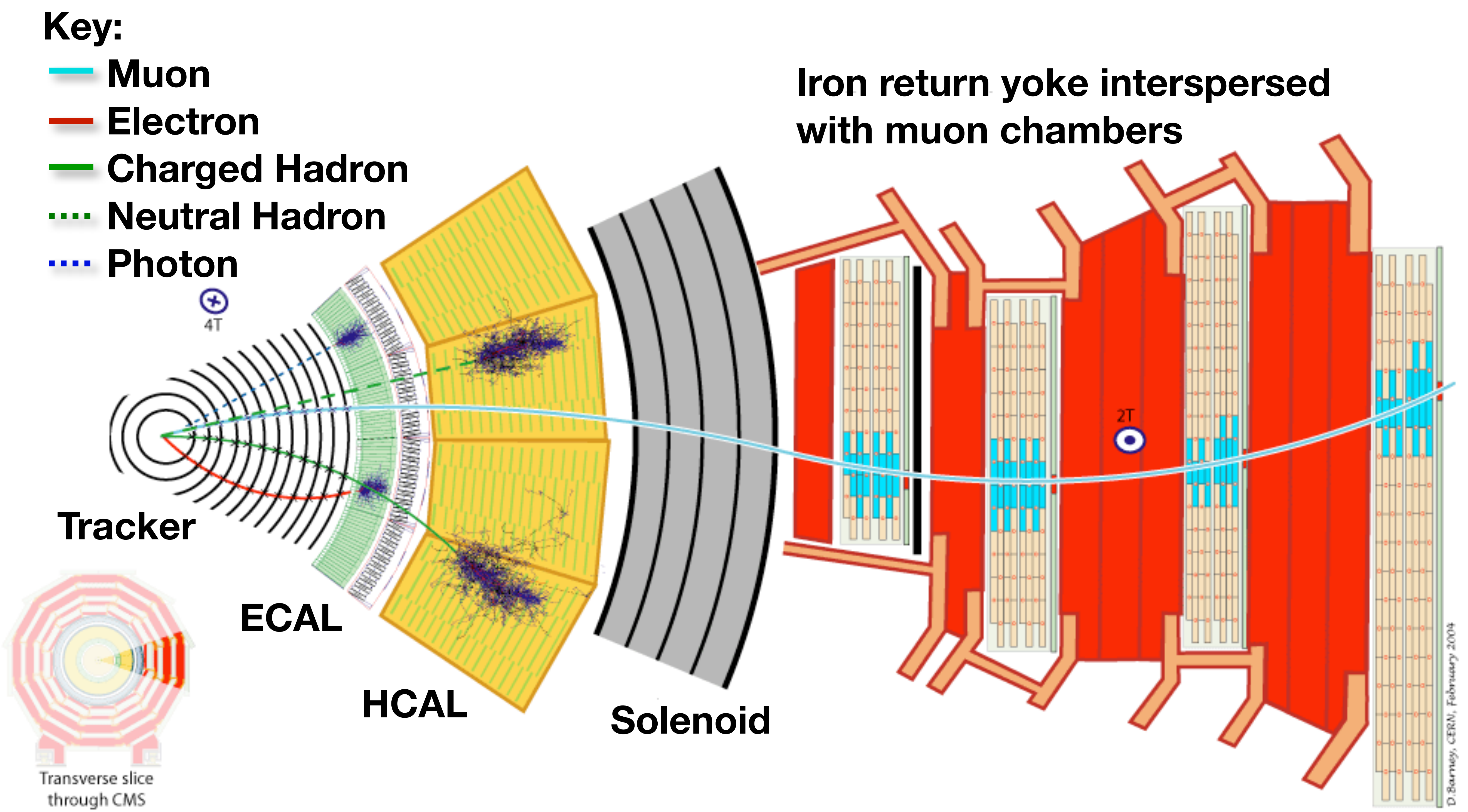
Bai, Fox, and Harnik, JHEP **12** (2010) 048

CMS Detector

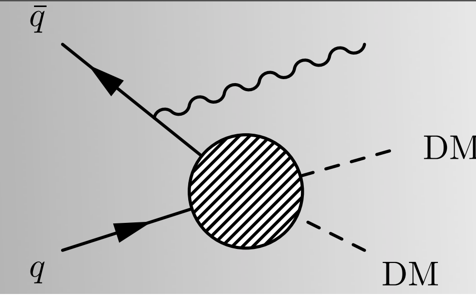


12 500 tons
21 m long
15 m diameter

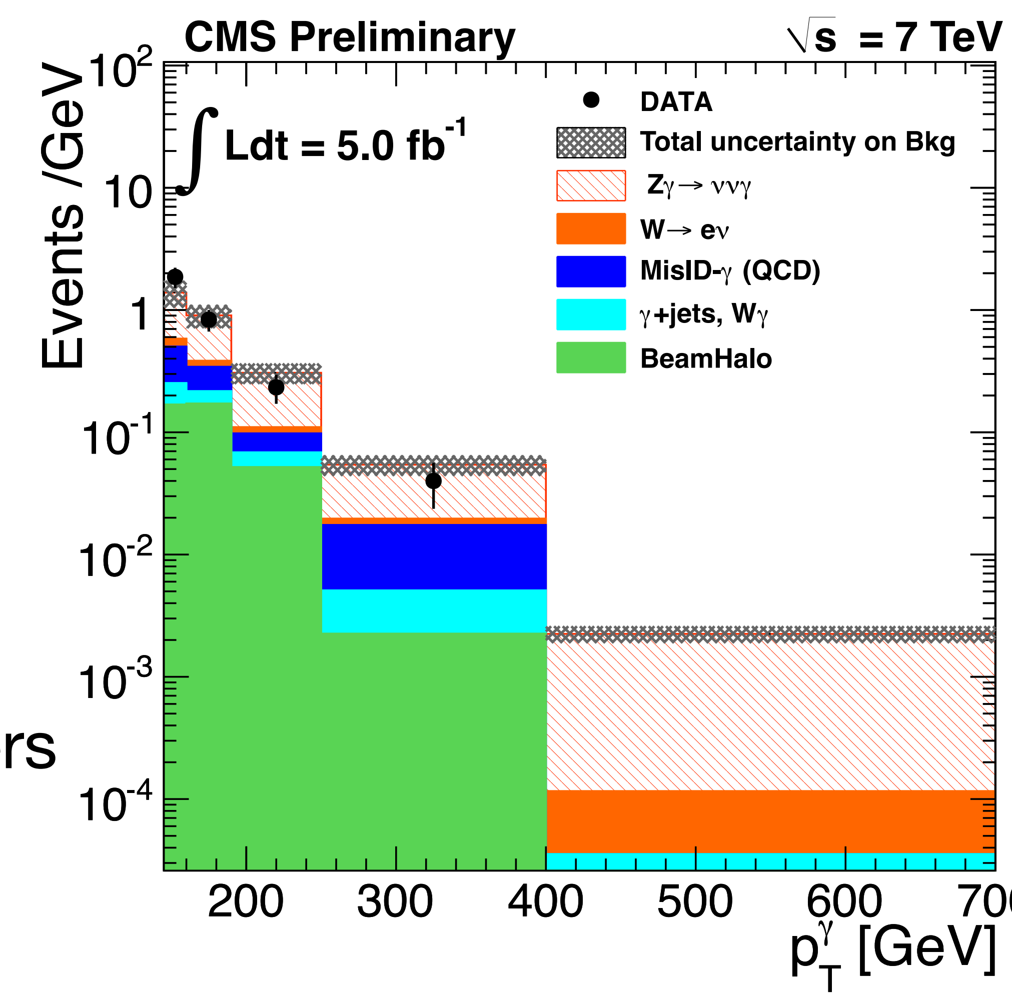
Particle ID at CMS



CMS Monophoton: Selection

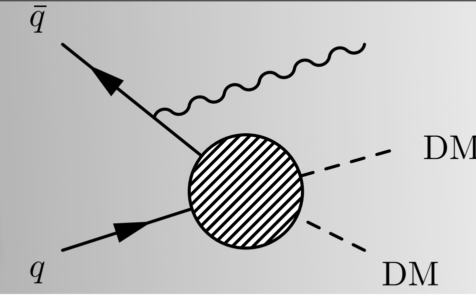


- Require a single photon in an event with...
  - High transverse momentum: p_T>145 GeV
  - Central (best reconstruction purity): |η|<1.44
  - Shower shape and timing consistent with a photon
  - “particle flow” MET > 130 GeV
  - photon must be isolated separately in the tracker, hadronic & electromagnetic calorimeters
- Suppress electroweak backgrounds with lepton (track) veto
  - No track away from γ (ΔR>0.04) with p_T>20 GeV
- Suppress QCD background with jet veto
  - No high p_T jet away from γ (ΔR>0.5) with p_T>40 GeV and |η|<3.0



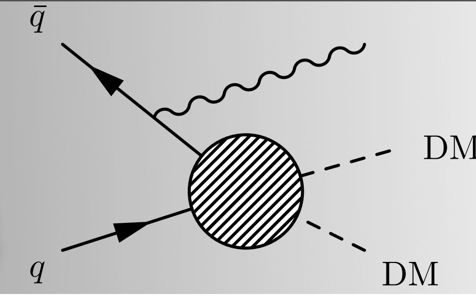
73 events pass selection (and do not fail either veto)

CMS Monophoton: Monte Carlo Backgrounds



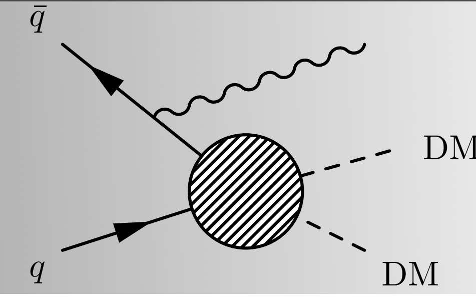
- Z(νν)+γ (45.3 ± 6.8 events)
  - Irreducible background
  - Generated by Pythia; scaled to theoretical NLO cross section from Bauer
- W+γ
  - lepton escapes isolated-track veto
  - Generated by Madgraph; scaled by NLO K factor from MCFM
- γ+jet
  - jet veto not flagged
  - due to jet/MET mis-measurement
- γγ
  - due to MET mis-measurement
- Contribution from W+γ, γ+jet, and γγ: 4.1 ± 1.0 events

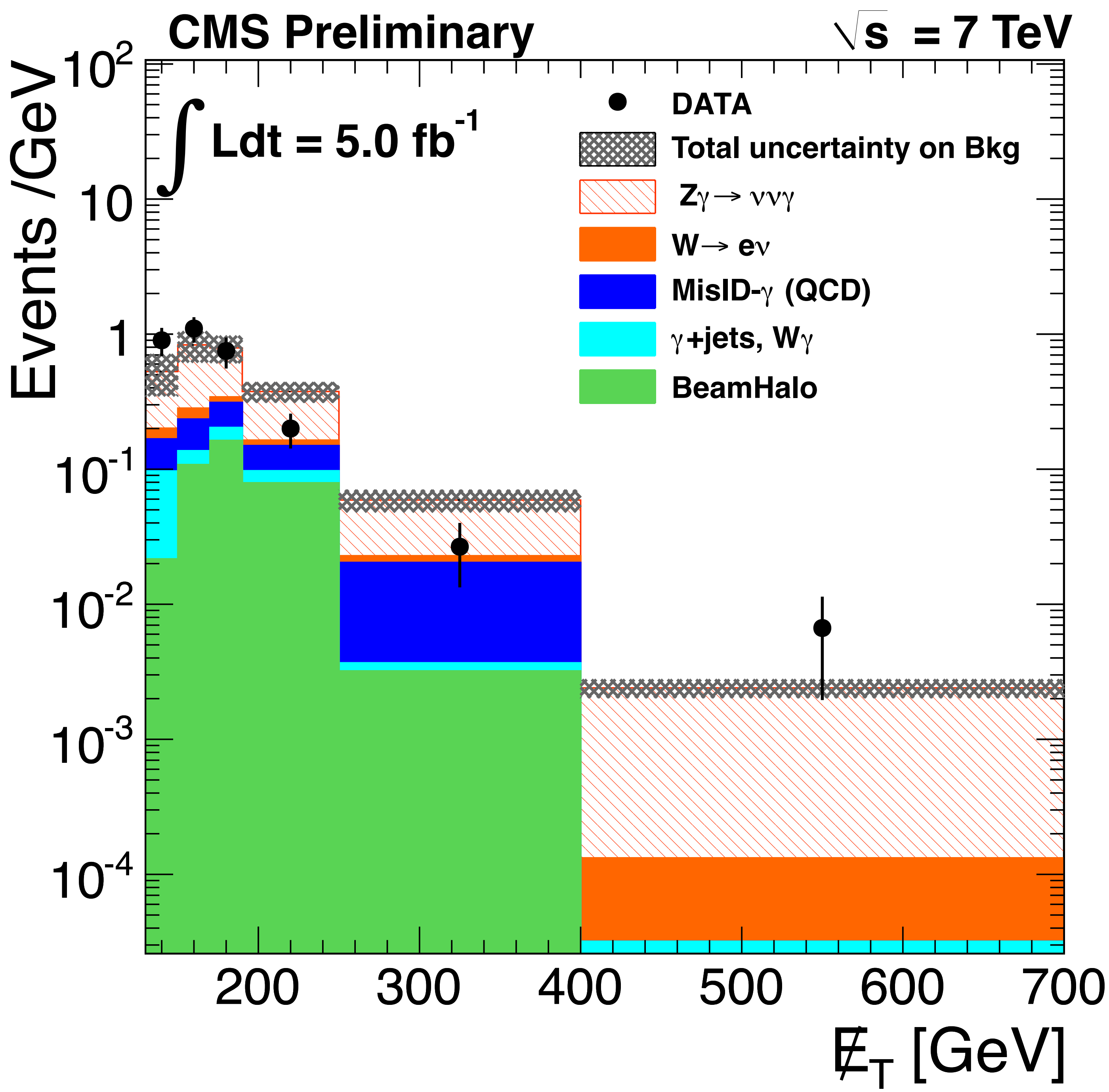
CMS Monophoton: Instrumental Backgrounds



- Jets mimicking photons (11.2 ± 2.8 events)
  - dominated by jets fluctuation to a hard π^0
  - Use EM-enriched multijet sample to measure ratio of isolated photons to non-isolated, “photons” objects
  - Statistically subtract out direct photon contribution to multijet sample by fitting shower shape templates
  - apply ratio to non-isolated “photons” in the signal sample to estimate the total contribution
- Out-of-time backgrounds (11.1 ± 5.6 events)
  - dominated by beam-halo events (also tiny contribution from cosmic rays and anomalous noise)
  - Fit shower-shape templates to the signal sample but **without any timing requirements**
  - Extrapolate contributions to in-time photons
- Electrons mimicking photons (3.5 ± 1.5 events)
  - Principally from $W \rightarrow e\nu$
  - Electrons and photons are distinguished by hits in the pixel tracker. The inefficiency is small (<0.5%) and well-predicted in simulation
  - Background determined by extrapolation from control sample of electrons

CMS Monophoton: Background Summary





Z(νν)+γ: 45.3 ± 6.8

Jets faking photons: 11.2 ± 2.8

Out-of-time backgrounds: 11.1 ± 5.6

W+γ, γ+jet, γγ: 4.1 ± 1.0

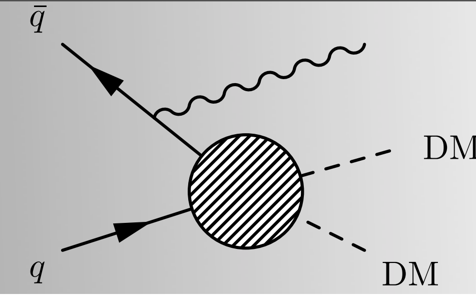
Electrons faking photons: 3.5 ± 1.5

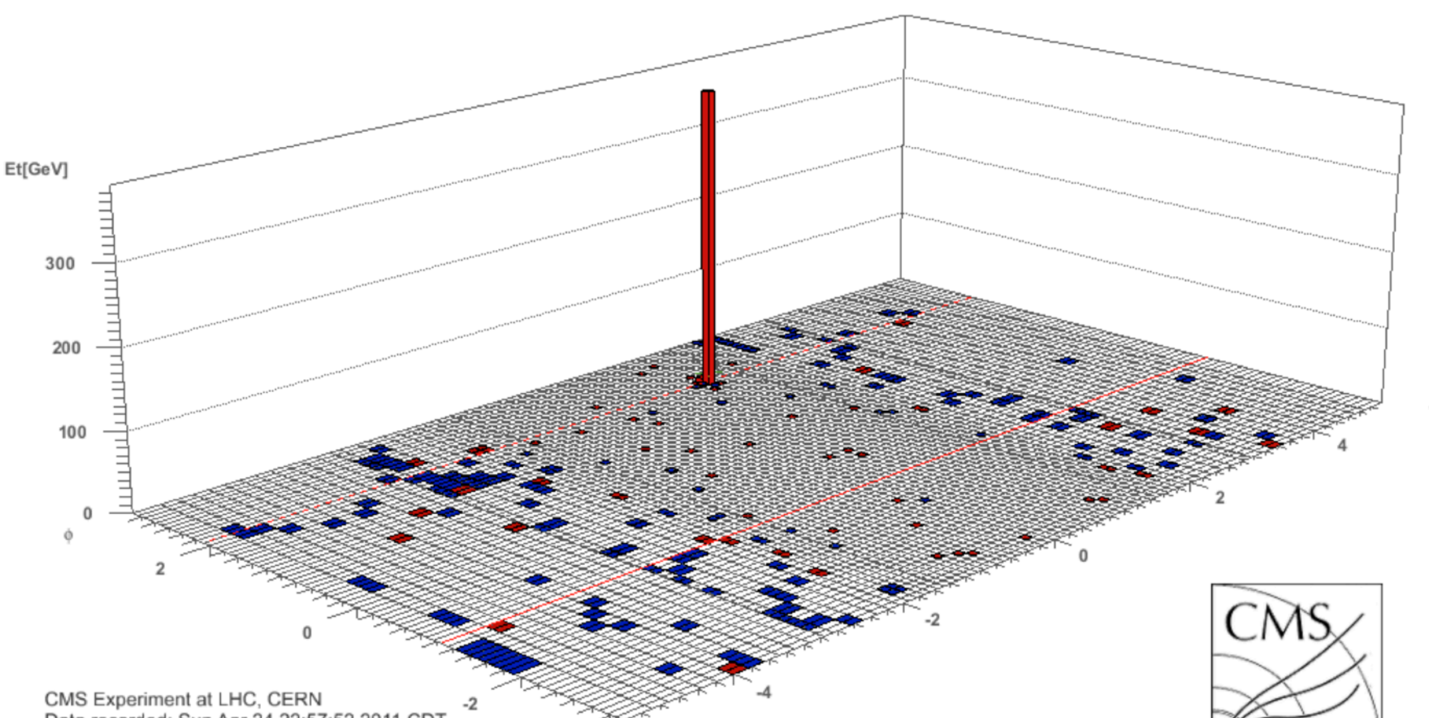
Total expected events: 75.1 ± 9.4

Total observed events: 73

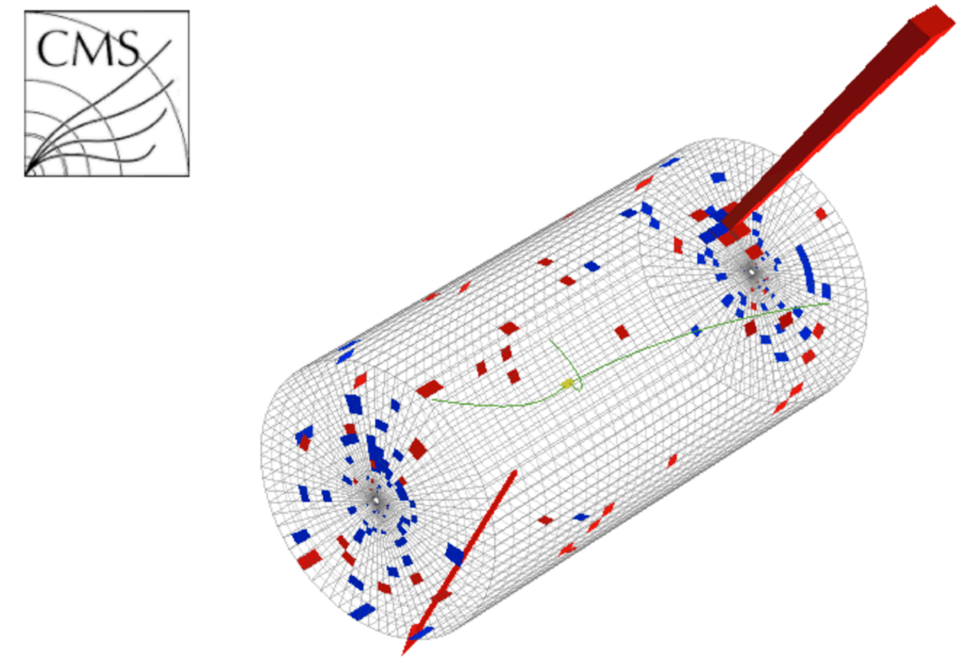
Data show generally good agreement with standard model predictions (both rate and shape)

CMS Monophoton: Event Display



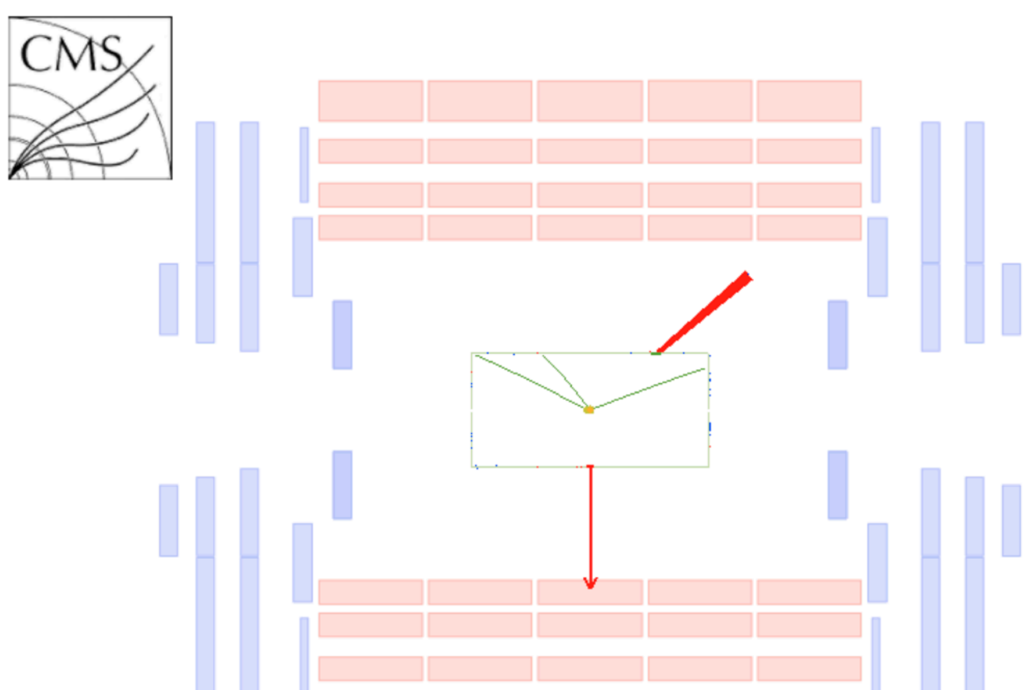


CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604



CMS Experiment at LHC, CERN
Data recorded: Sun Apr 24 22:57:52 2011 CDT
Run/Event: 163374 / 314736281
Lumi section: 604

photon p_T=384 GeV
MET=407 GeV



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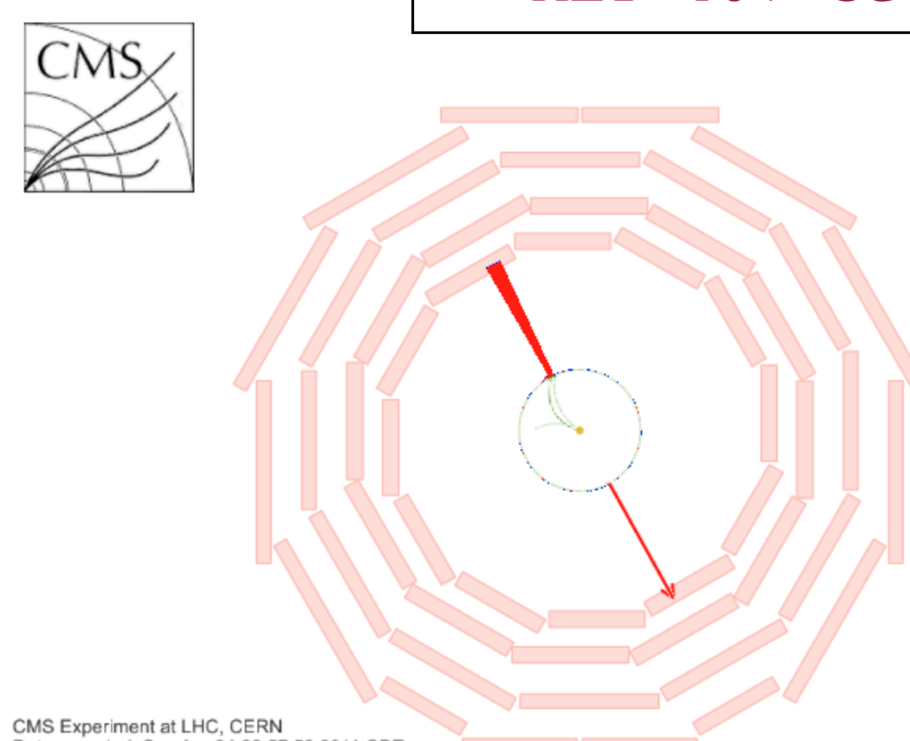

CMS Experiment at LHC, CERN
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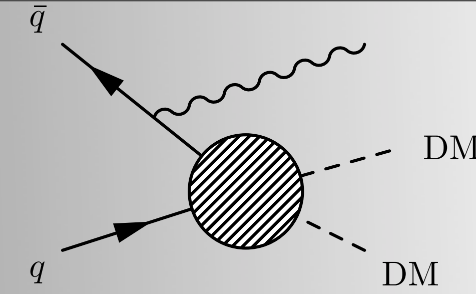
Lumi section: 604

CMS Monophoton: Limit Setting

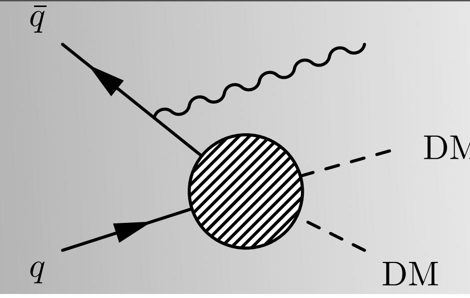


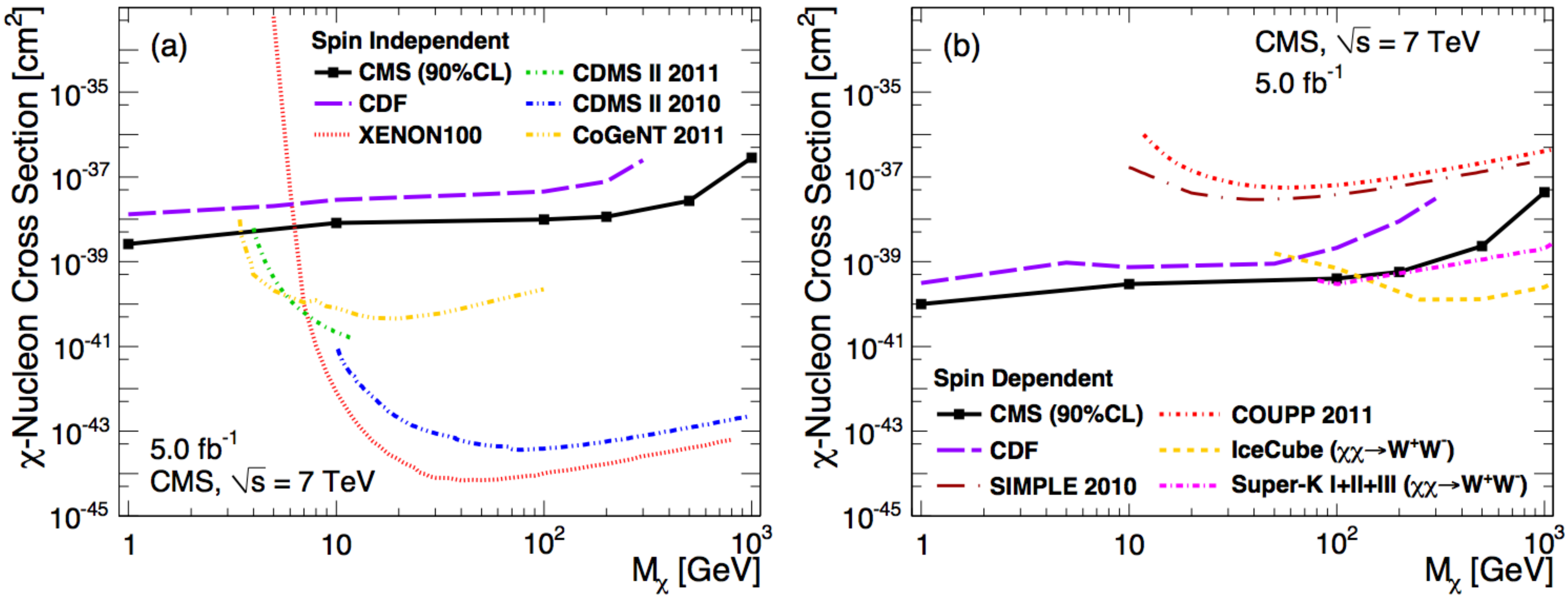
- Model signal with Madgraph4 (matrix element) + Pythia6 (showering)
  - Λ=M=10 TeV (mediator couplings set to unity)
  - small systematic uncertainties from photon energy scale (2.3%), pile-up modeling (2.4%), jet-energy scale (1.2%), etc.
- Use modified frequentist CL_S prescription to set 90% CL limits on production cross section for additional signal contribution
  - translate to limits on Λ and subsequently to the WIMP-nucleon cross section

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)

90% CL limits for V and AV couplings (expected limits shown in parentheses)

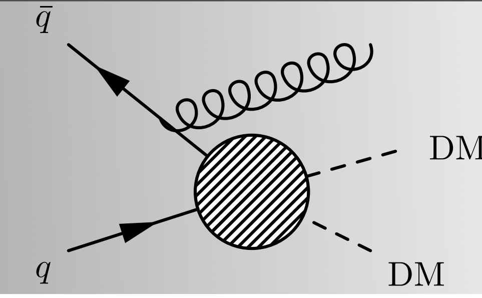
CMS Monophoton: Cross Section Limits



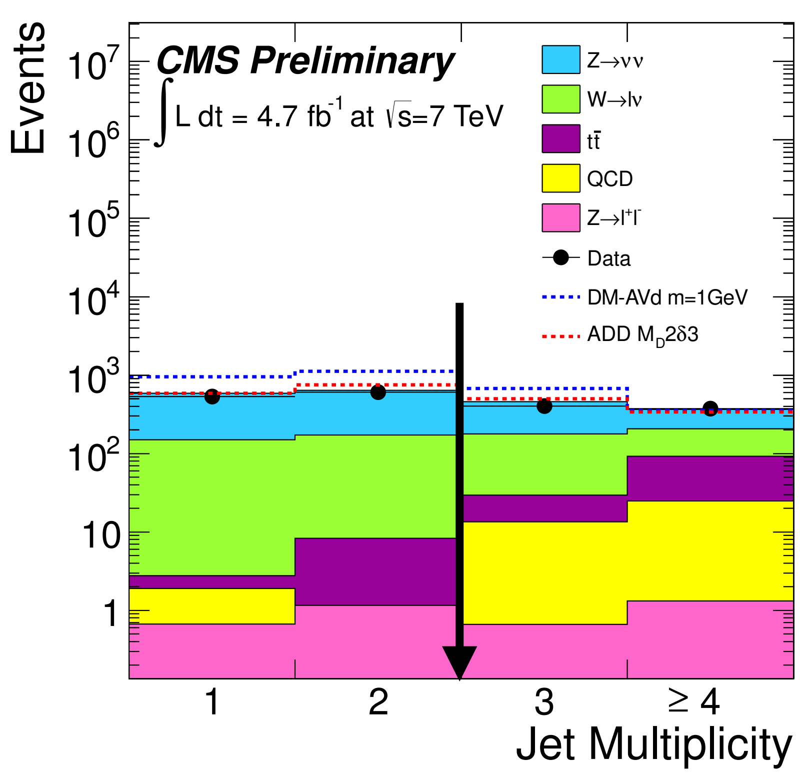


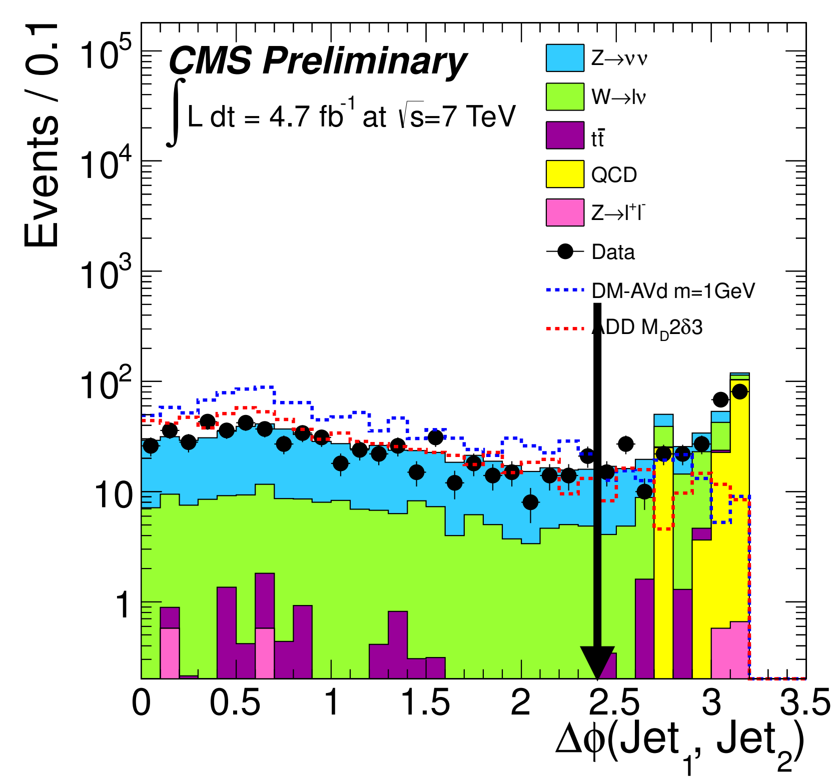
XENON100: PRL **107** (2011) 131302	SIMPLE: PRL **105** (2010) 211301
CDMS 2010: Science **327** (2010) 1619	COUPP: PRL **106** (2011) 021303
CDMS 2011: PRL **106** (2011) 131302	IceCube: PRD **85** (2012) 042002
CoGeNT: PRL **106** (2011) 131301	Super-K: ApJ **742** (2011) 78
	CDF: arXiv:1203.0742 (submitted to PRL)

CMS Monojet: Jet Selection

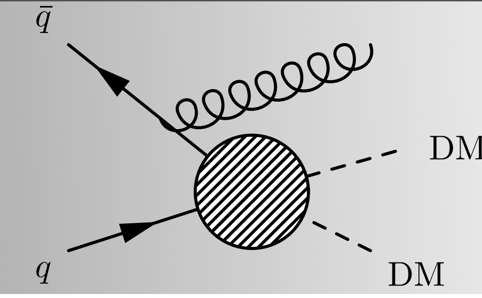


- Require **1 or 2** jets ordered in p_T where...
  - Leading jet has p_T>110 GeV and $|\eta|$<2.4; second jet may have p_T>30 GeV
  - $\Delta\phi(jet_1, jet_2) < 2.5$
  - Jets reconstructed with particle flow; anti-k_T algorithm with R=0.5
  - suppress cosmic muons, instrumental noise, and beam-related backgrounds
    - charged hadron fraction of leading jet >20%
    - neutral hadron or neutral electromagnetic fraction of leading jet <70%
    - neutral hadron fraction of subleading jet <70%



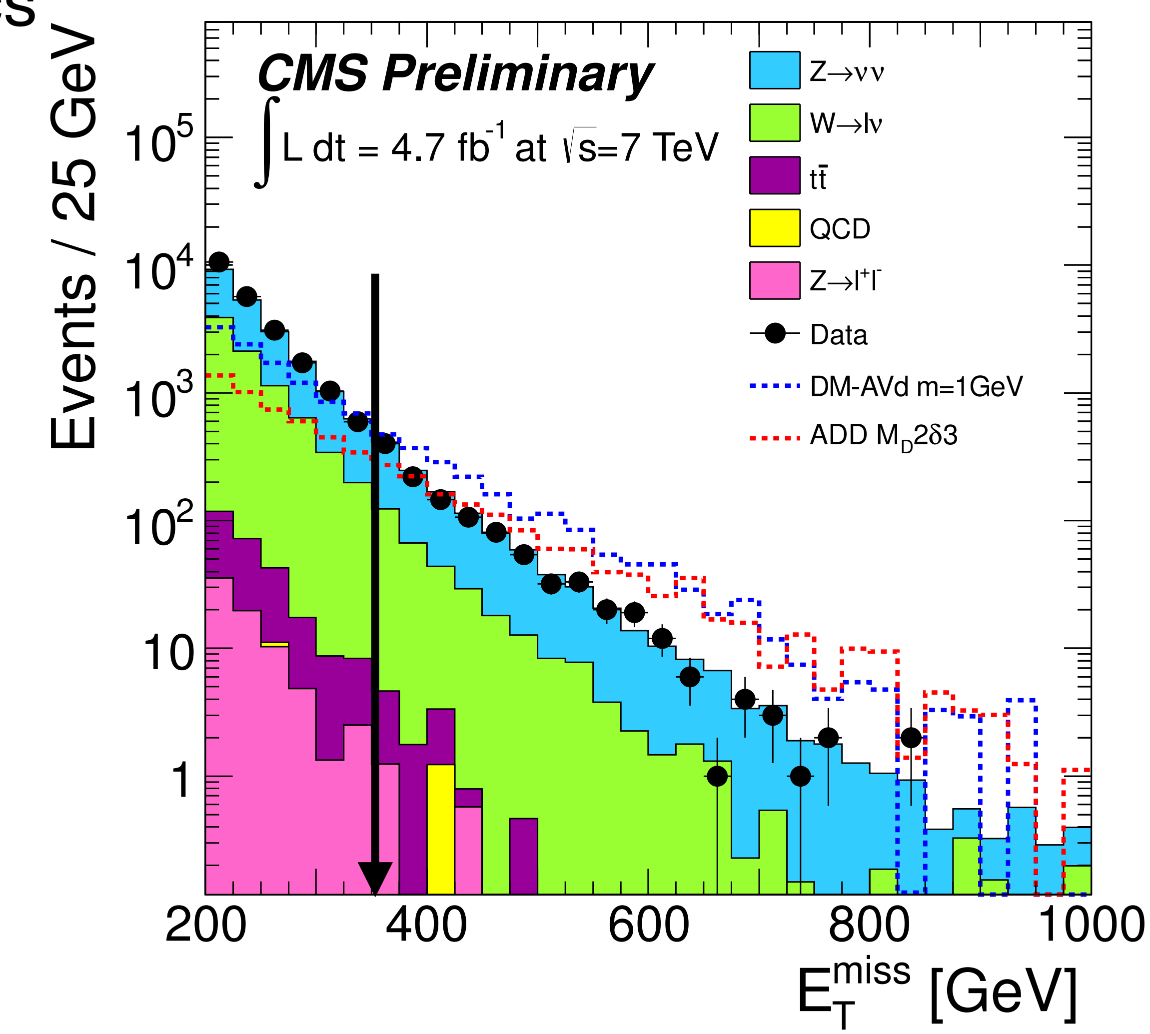


CMS Monojet: Event Selection



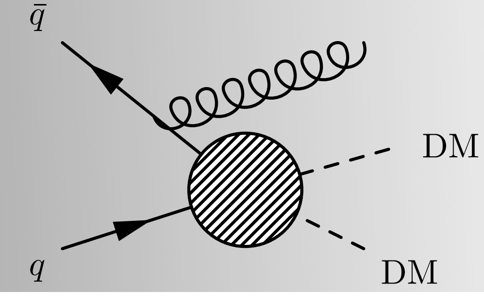
- Trigger on events with jet p_T>80 GeV and MET>95 GeV
- Suppress electroweak contributions
  - reject events with an isolated electron, muon or track with p_T>10 GeV
- Require "particle flow" MET>350 GeV
  - optimized for best sensitivity to new physics

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, $\|\eta(j_1)\| < 2.4$	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



Good agreement between data and SM backgrounds (1224±101 expected versus 1142 observed)

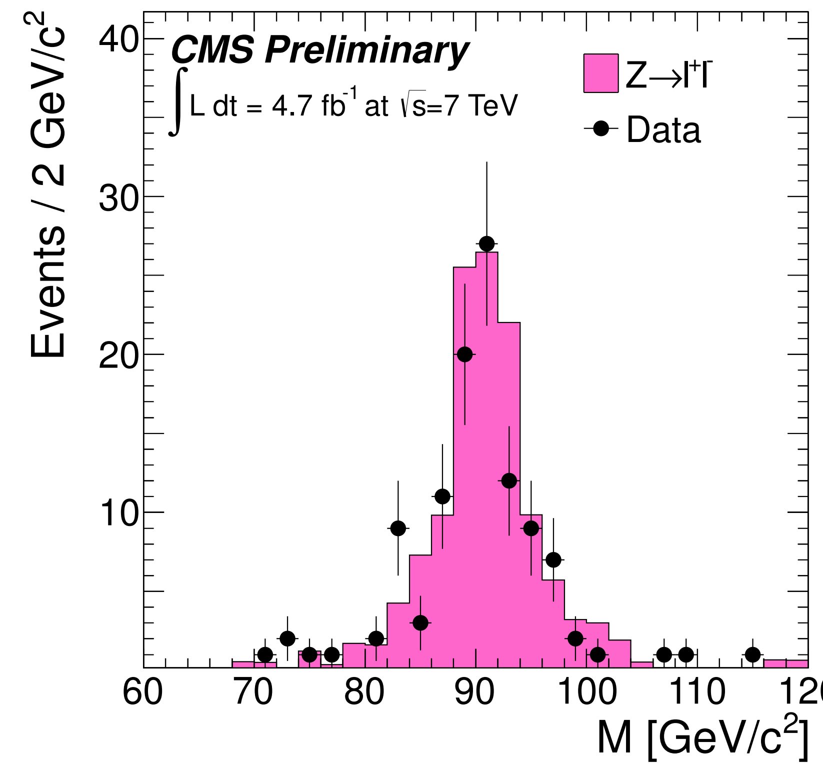
CMS Monojet: Background Estimation

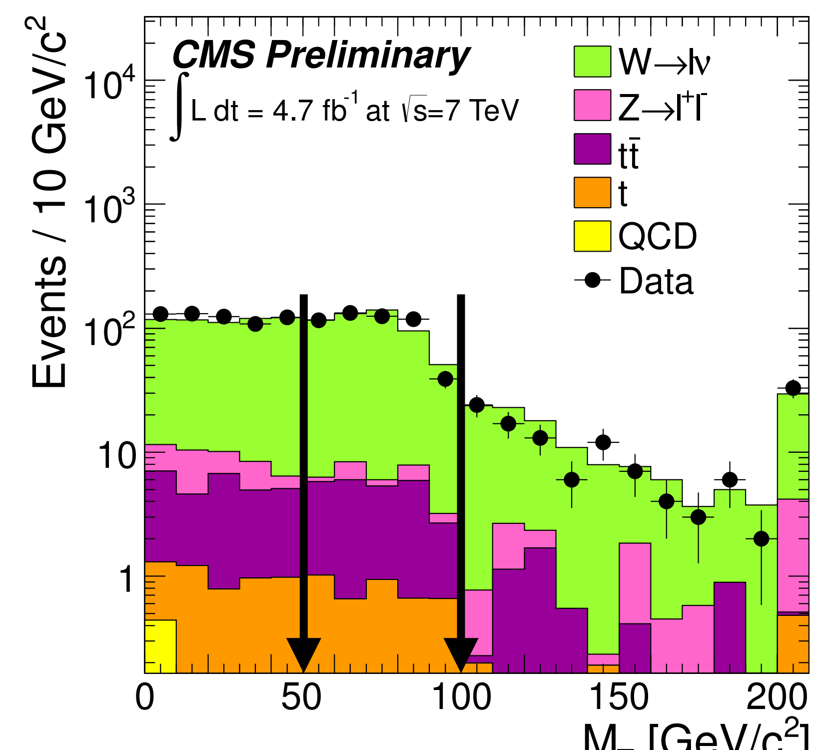


- Data-driven estimation of Z(νν)+jets
  - Release lepton suppression and use Z(μμ)+jets that pass monojet trigger and selection
  - $60<M_{\mu\mu}<120$ GeV (and leptons have opposite charge)
  - Extrapolate from μμ events to νν events:

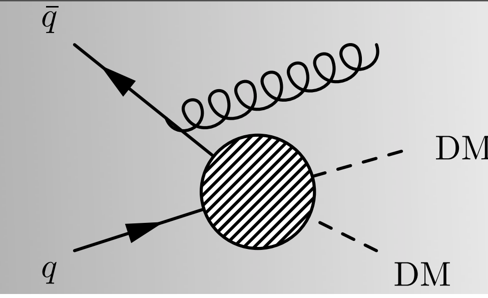
$$N(Z\to\nu\nu) = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\mathcal{A}\times\epsilon}\cdot R\left(\frac{Z\to\nu\nu}{Z\to\ell\ell}\right)$$

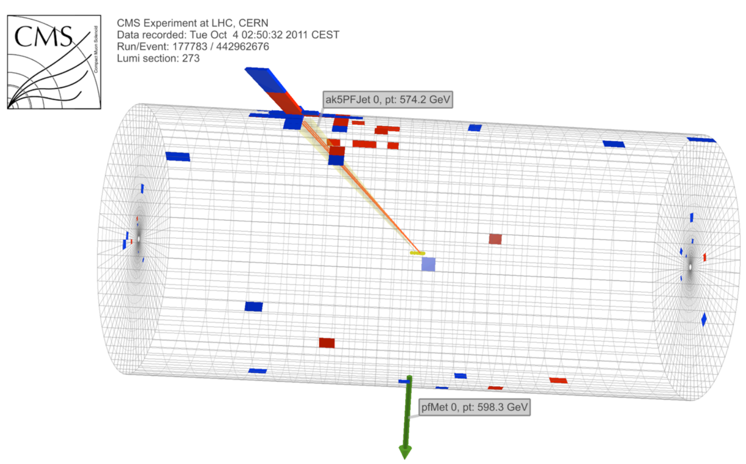
  - 10.4% systematic uncertainty (mainly from statistical uncertainty of Z(μμ)+jets data)
- Similar method used to estimate subdominant W+jets background where a lepton is "lost"
  - use MC to estimate acceptance (7.7% uncertainty) and efficiency (6.8% uncertainty) but normalize to events with one lepton and $50<M_T<100$ GeV

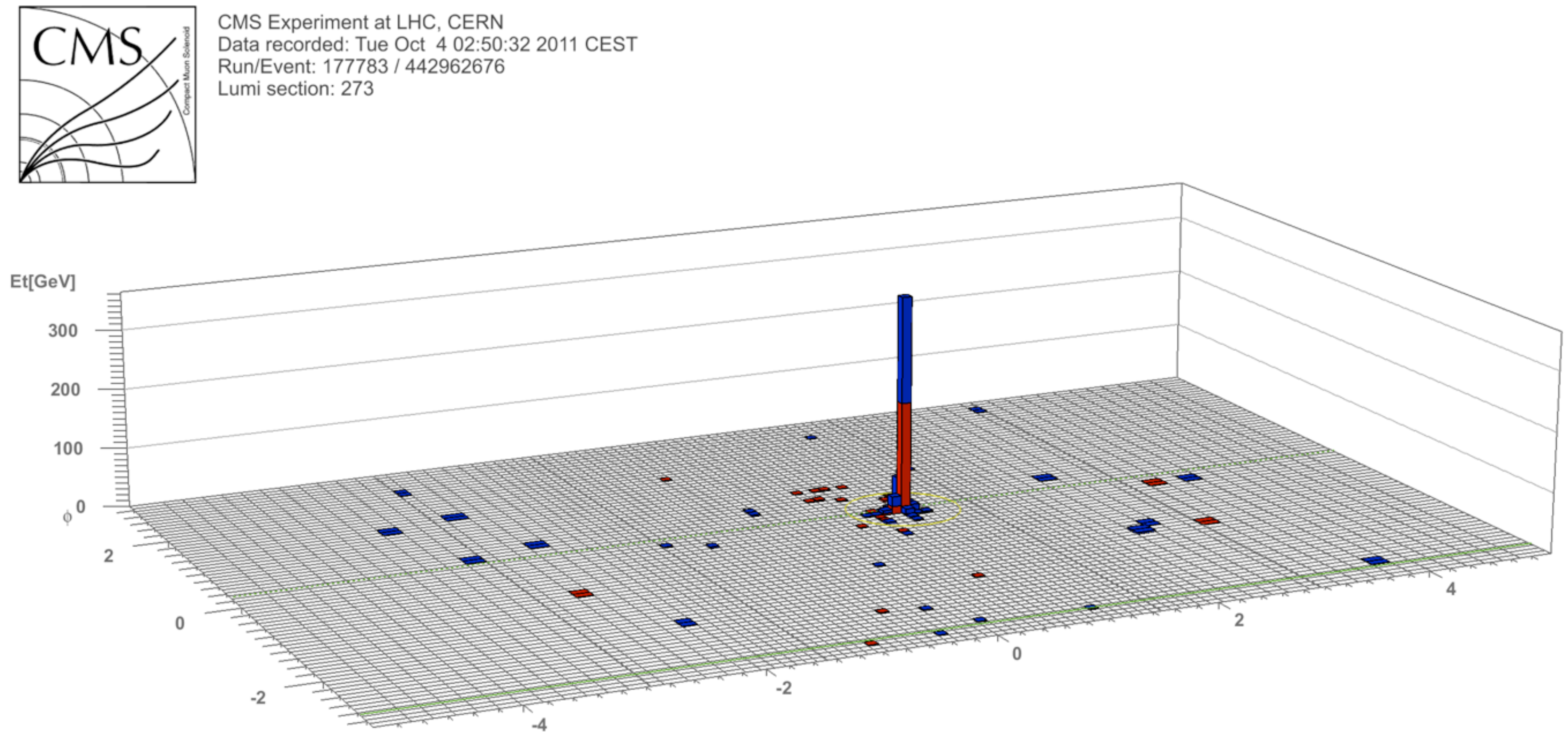


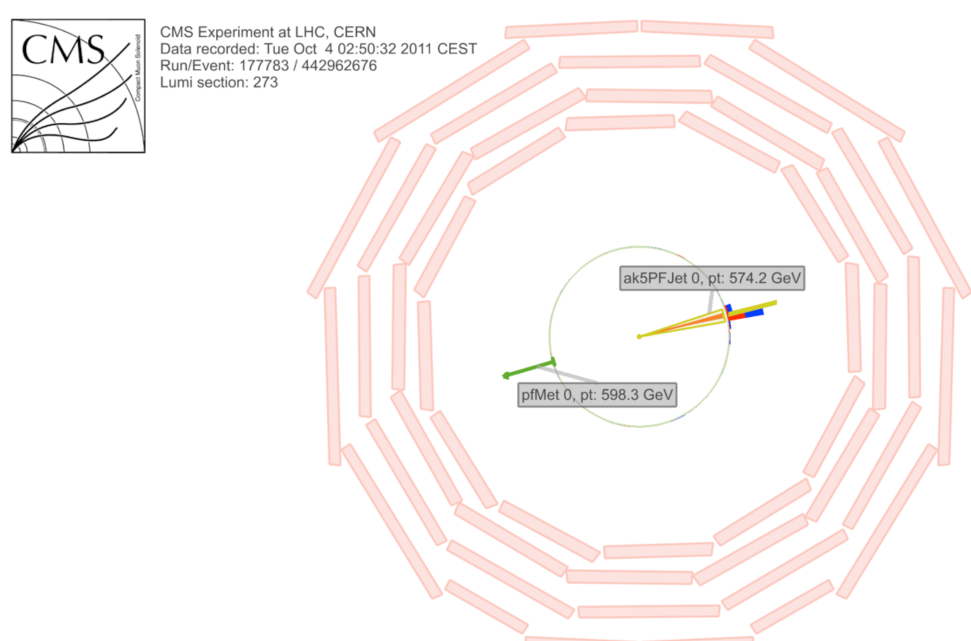


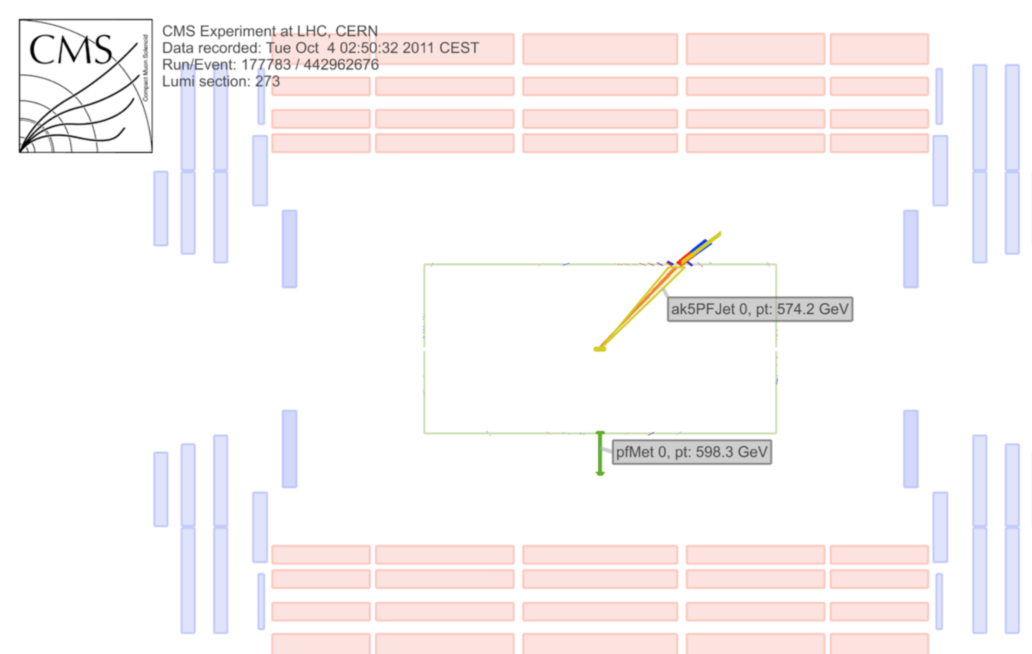
CMS Monojet: Event Display



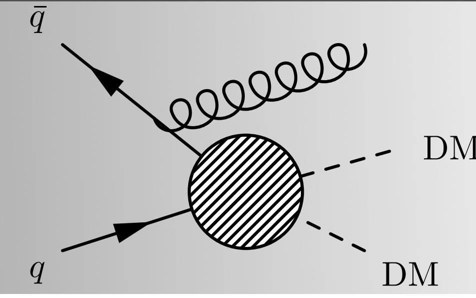








CMS Monojet: Limit Setting

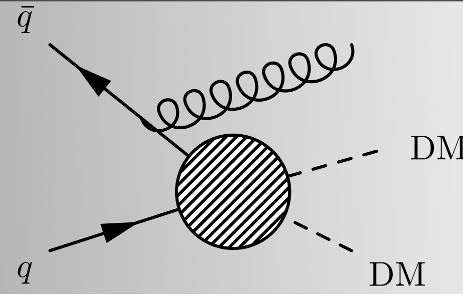


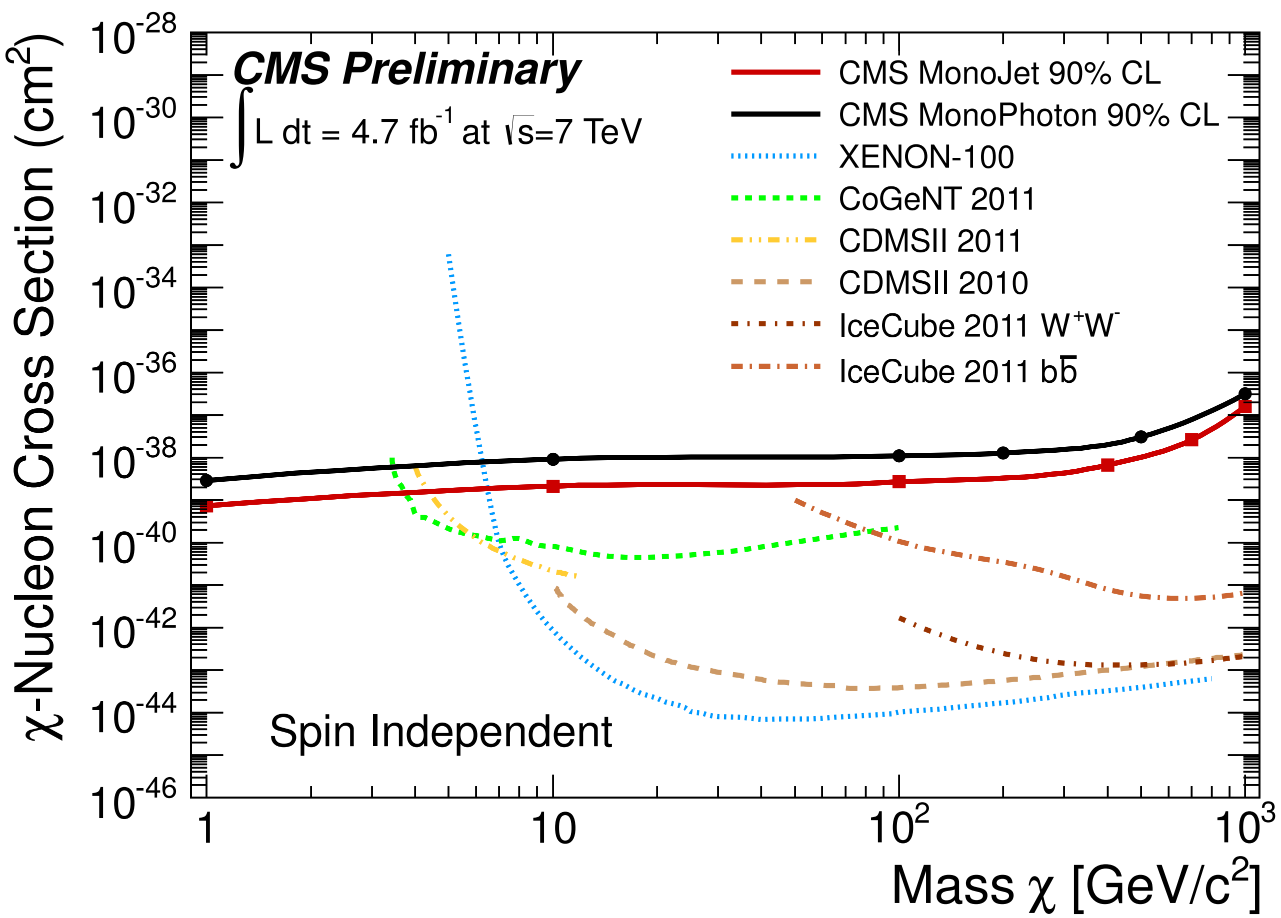
- Model signal with Madgraph5 (matrix element) + Pythia6 (showering)
  - Λ=M=40 TeV (mediator couplings set to unity)
- Larger systematic uncertainties than monophoton search coming from
  - Jet energy scale ~10%
  - luminosity 4.5%
  - PDF acceptance uncertainties 2-4%
  - Jet energy resolution 2%
- Use CLs as before to set 90% CL limits on the mediator mass and subsequently the WIMP-nucleon cross section

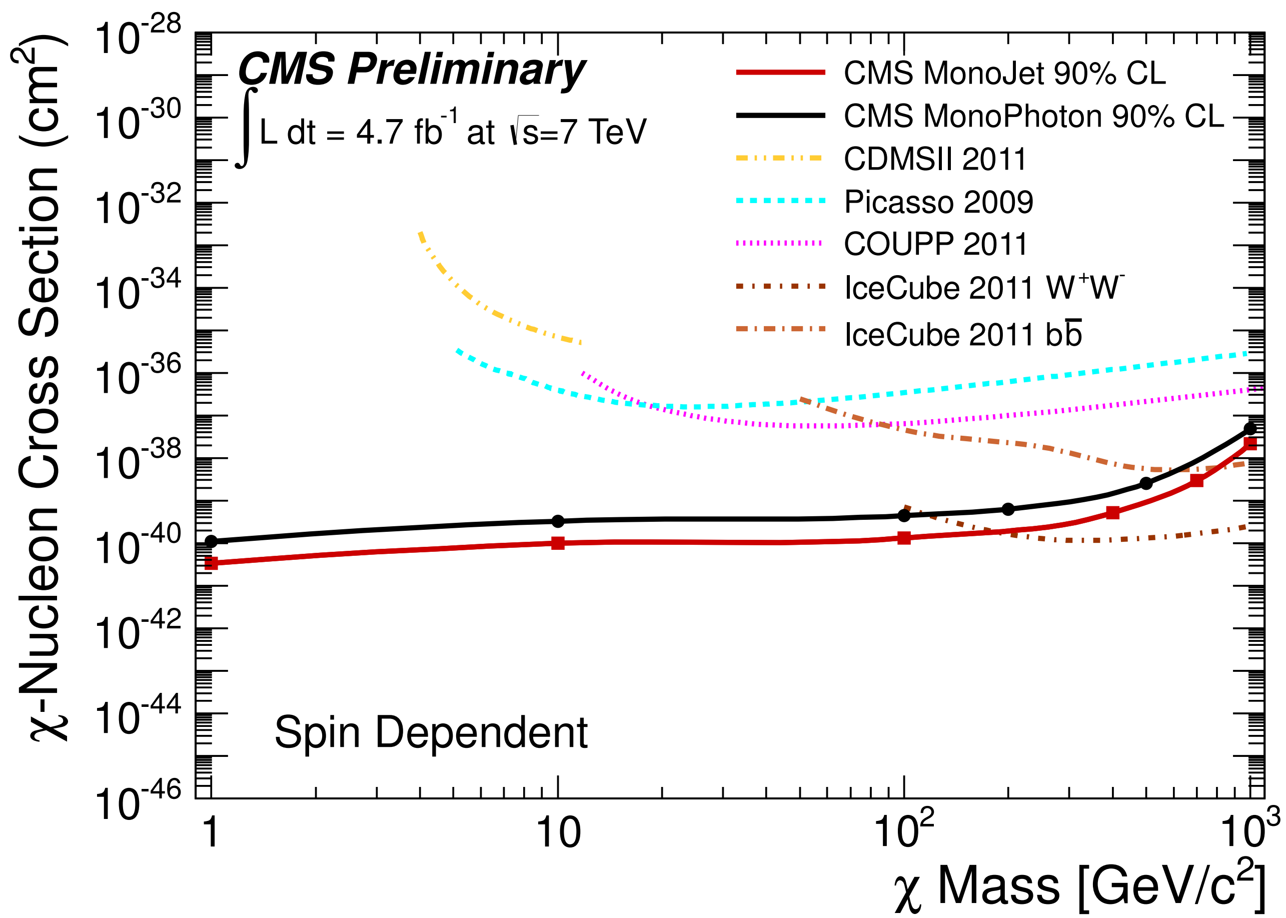
Background process	Events
$Z \to \nu\bar{\nu}$	900 ± 94
W+jets	312 ± 35
$t\bar{t}$	8 ± 8
$Z(\ell\ell)$+jets	2 ± 2
QCD multijet	1 ± 1
Single t	1 ± 1
Total background	1224 ± 101
Observed in data	1142

	Spin-dependent		Spin-independent	
M_χ (GeV/c^2)	σ(cm^2)	Λ(GeV)	σ(cm^2)	Λ(GeV)
1	3.37×10^{-41}	730	7.20×10^{-40}	776
10	9.83×10^{-41}	744	2.12×10^{-39}	789
100	1.33×10^{-40}	718	2.65×10^{-39}	776
400	5.14×10^{-40}	514	6.66×10^{-39}	619
700	2.95×10^{-39}	332	2.62×10^{-38}	440
1000	2.15×10^{-38}	202	1.57×10^{-37}	281

CMS Monojet: Cross Section Limits

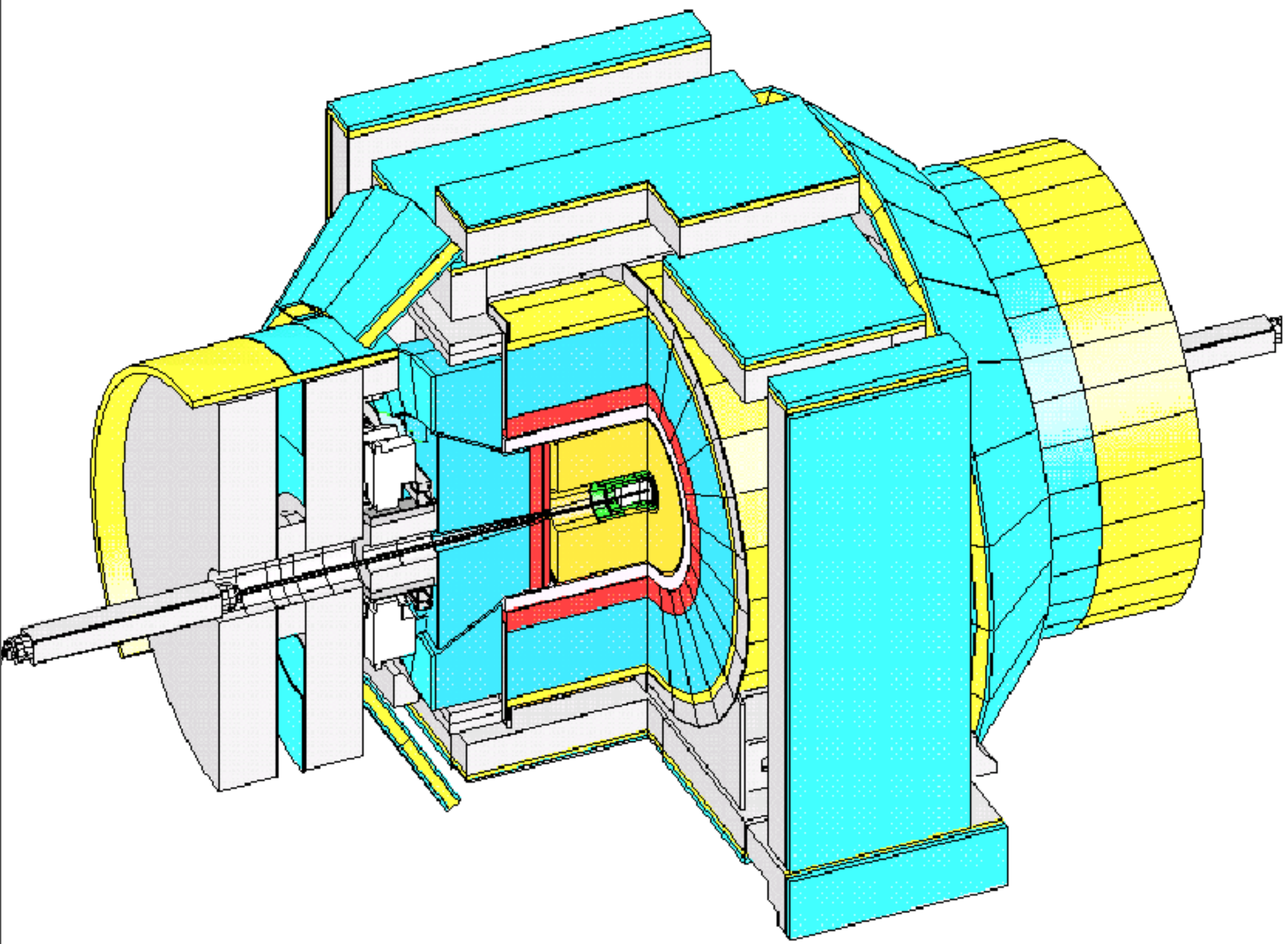


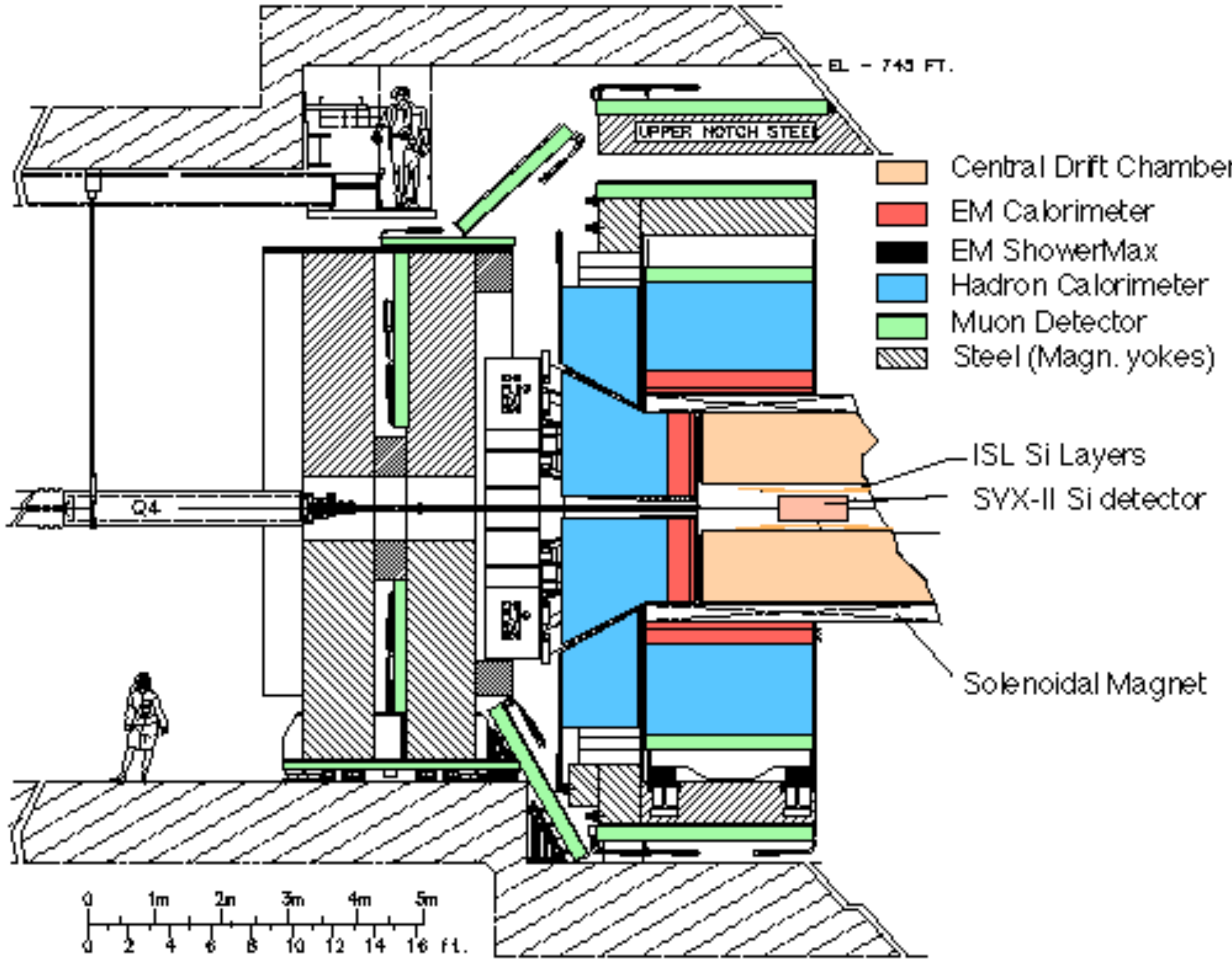




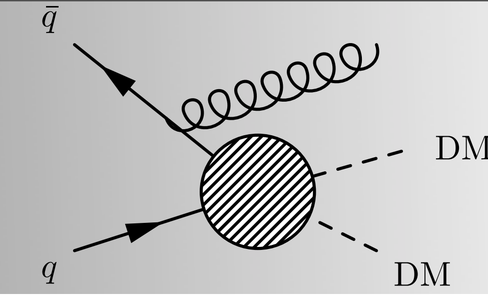
Presents best limits for low mass (<6 GeV) in the SI mode and up to ~200 GeV in the SD mode

CDF Detector

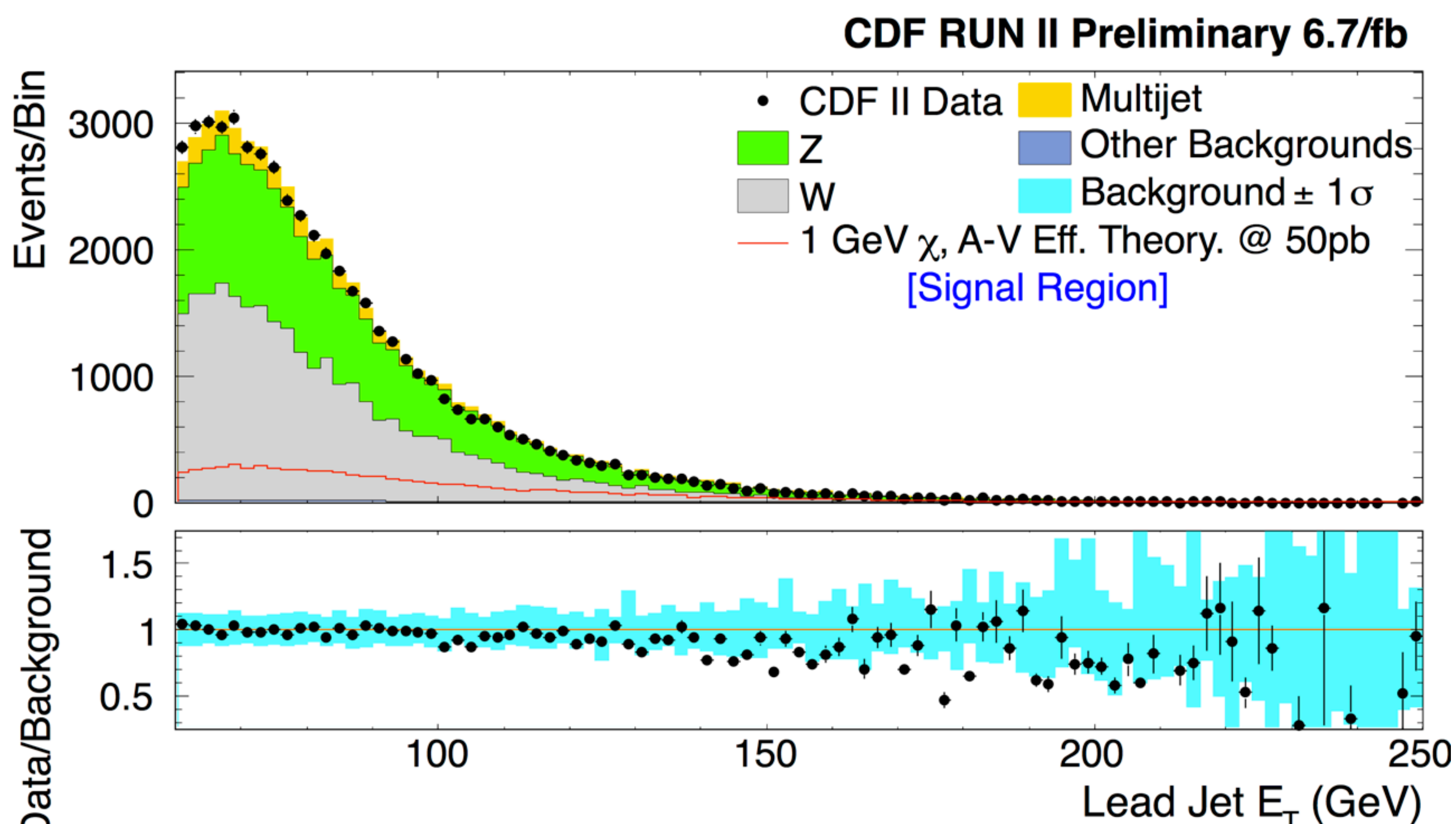




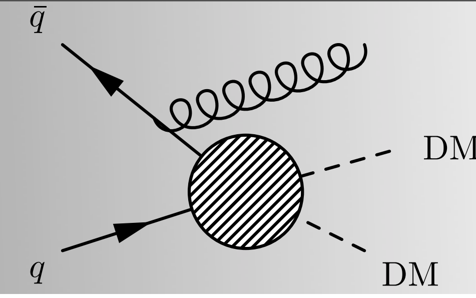
CDF Monojet: Jet Selection



- Require **1 or 2** jets ordered in p_T where...
  - Leading jet has p_T>60 GeV and $|\eta|$<1.0
  - sub-leading jet with 20<p_T<30 GeV
  - no jet has EMF<90%
  - jets do not lie near calorimeter "cracks"
  - contain at least one track with p_T>10 GeV
  - Reconstructed with JetClu algorithm, R=0.4



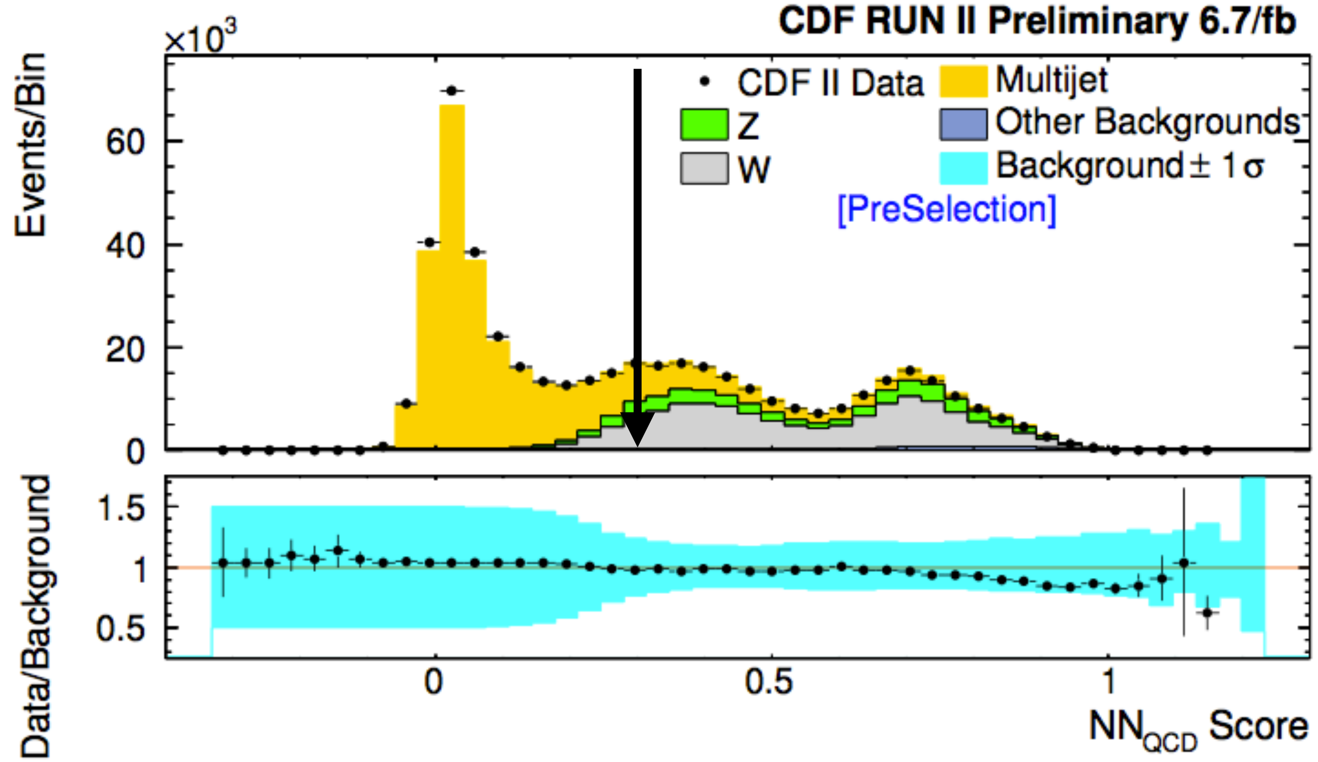
CDF Monojet: Event Selection



- Trigger on events with MET>40 GeV
  - In addition to jet selection, require large MET>60 GeV
- Clean-Up cuts
  - jet-MET must be back-to-back: $\Delta\phi(MET, jet_1) > 2.5$
  - Consistent MET and "$TrkMET_{10}$": $\Delta\phi(TrkMET_{10}, MET) < 0.4$ and $|TrkMET_{10}| < |MET|$
    - ($TrkMET_{10}$ is the "MET" computed with tracks with $p_T > 10$ GeV)
  - Event consistent with hadronic jet: 0.35>event EM fraction>0.85
  - MET significance<15
  - QCD rejected via cut on neural-net output: $NN_{QCD} > 0.3$

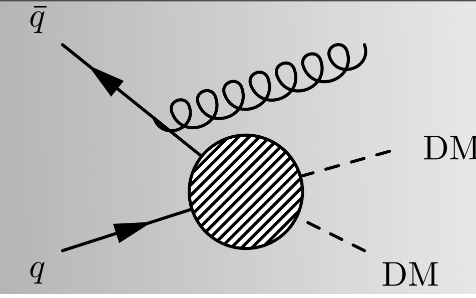
R = (scalar sum of lead and sub-leading jet E_T) / (scalar sum of lead and sub-leading jet E_T and MET).

$NN_{QCD} > 0.3$ selection rejects 83% of QCD, while maintaining ~90% of DM events



NN_{QCD} Inputs
minimum $\Delta\Phi(\vec{\not{E}}_T$,any jet)
R [27]
$\Delta\Phi(\vec{\not{E}}_T$,lead-$E_T$ jet)
$\not{E}_T$
Lead-jet E_T
Number of jets
$\Delta\Phi(\vec{\not{E}}_T, TrkMET_{10})$
Magnitude of the $TrkMET_{10}$
$\Delta\Phi(TrkMET_{10}$, lead-E_T jet)
Event EM fraction
Lead-jet detector η

CDF Monojet: Background Estimation



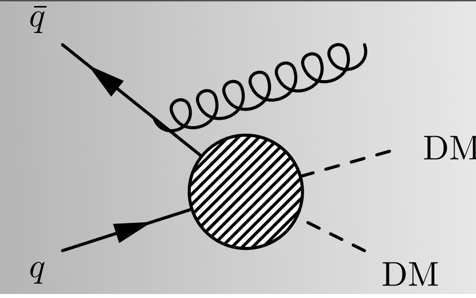
- Z+jets, W+jets, WW, WZ, ZZ, ttbar, and single-top estimated with MC simulation
- Non-collision backgrounds estimated to have (1±1)% **in**efficiency
- QCD Multijet background
  - Shape estimated from "rate matrix" technique
  - Establish fraction of events due to QCD multijets as a function of 6 parameters in a QCD-enriched control region
  - normalize in NN_{QCD} side-band of signal region (50% uncertainty)

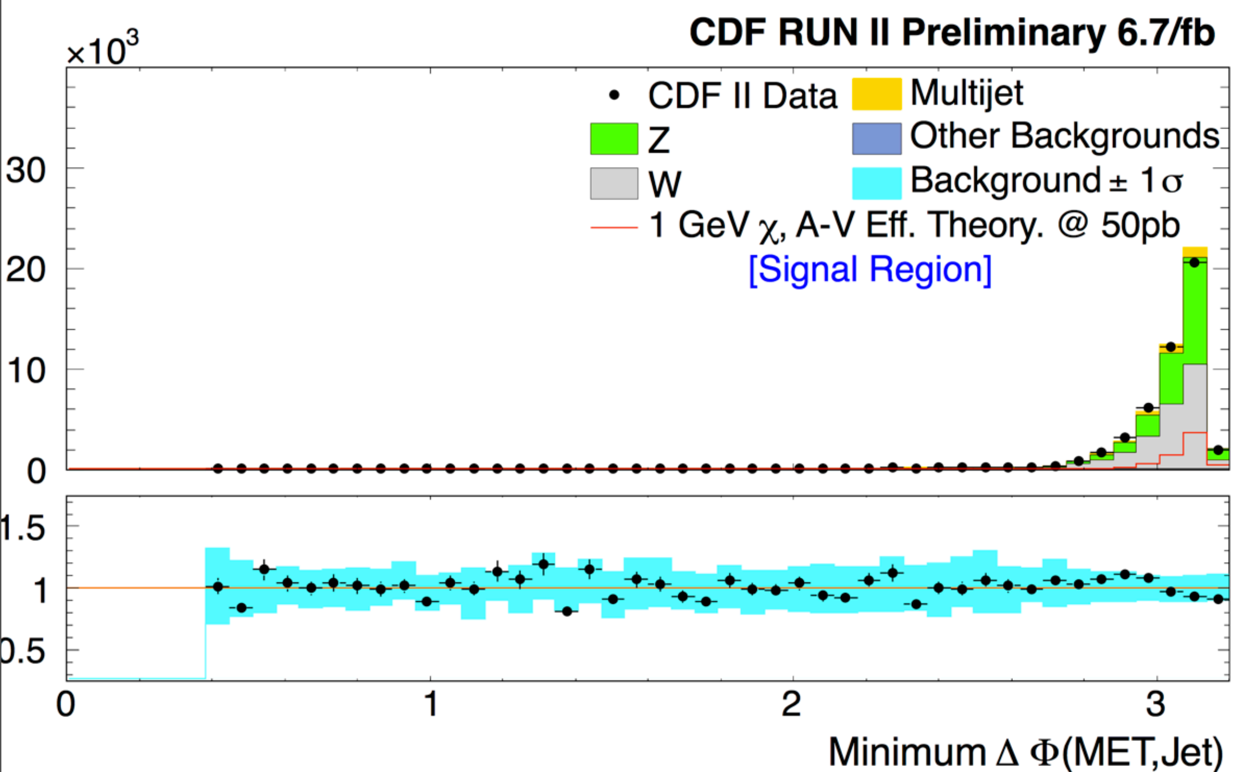
Parameter	binning
Magnitude of $TrkMET_{10}$	$[0,1,10,20,\geq 200]$
Minimum $\Delta\Phi(\vec{\not{E}}_T$,any jet)	$[0,0.5,0.8,2,3,3.1,3.14]$
Number of Jets	$[1,2,\geq 3]$
$\not{E}_T$	$[60,70,\geq 200]$
$\not{E}_T$ significance	$[0,7.5,15.1]$
R	$[0,0.45,0.5,0.55,1]$

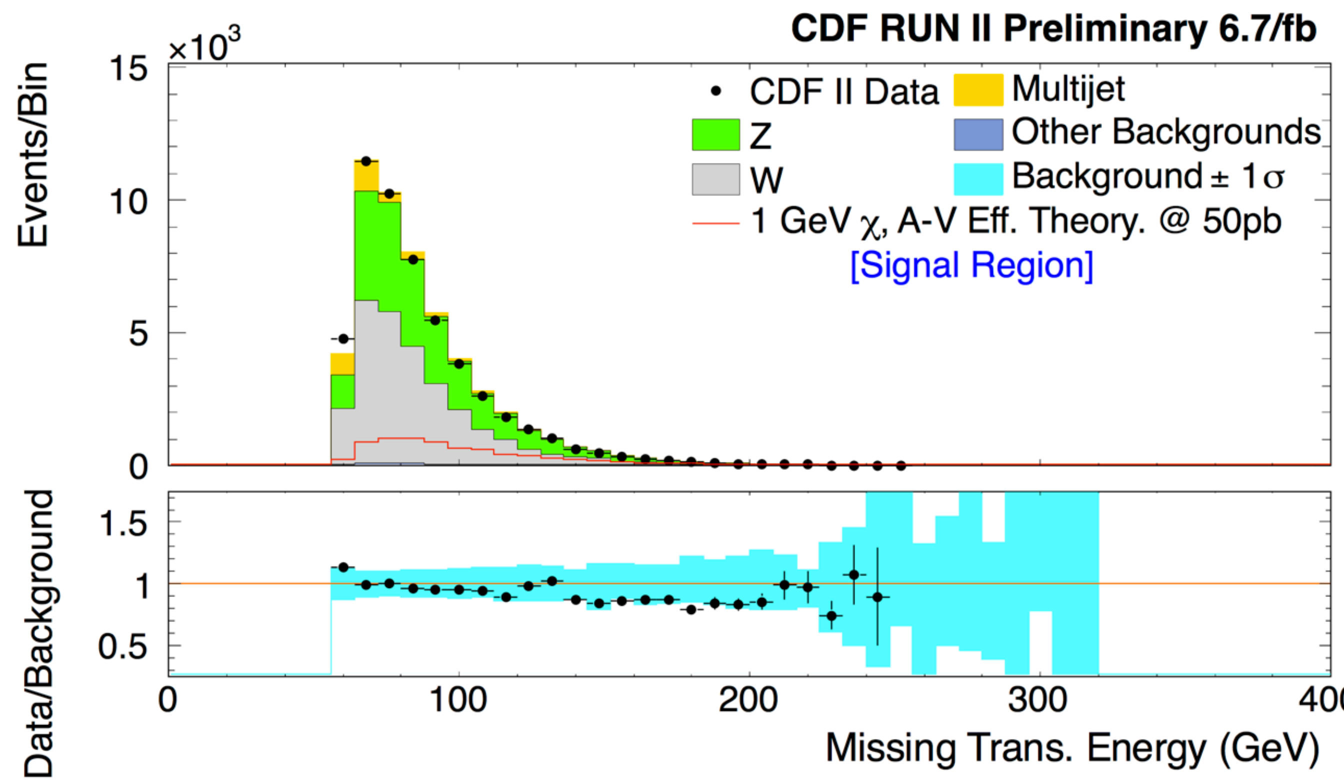
—— CDF Run II Preliminary 6.7 fb^{-1} ——

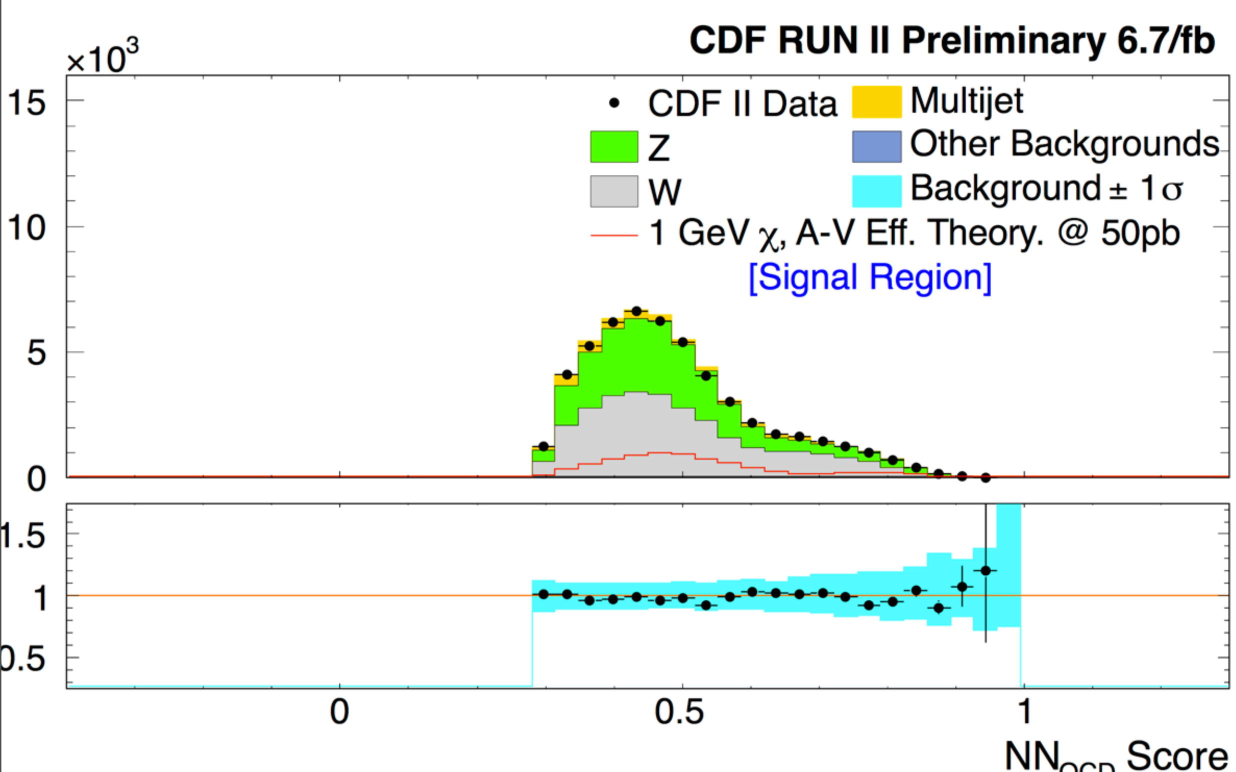
Contribution	PreSelection	QCD Control	EWK Control	Signal Region
non-collision	337 ± 337	49 ± 48	1 ± 1	6 ± 6
Z	44636 ± 5393	6949 ± 840	1280 ± 155	22191 ± 2681
W	131070 ± 17552	14986 ± 2007	5582 ± 747	27892 ± 3735
diboson	2843 ± 248	626 ± 55	101 ± 9	412 ± 36
$t\bar{t}$	3887 ± 743	1122 ± 215	20 ± 4	23 ± 4
single-top	2229 ± 303	397 ± 54	27 ± 4	104 ± 14
multijet	280143 ± 140072	165479 ± 82740	1066 ± 533	3278 ± 1639
total background	465145 ± 141799	189608 ± 82787	8076 ± 1011	53904 ± 6022
A-V[$\mathcal{M}_{10\,TeV}, \chi_{1\,GeV}$]@ 50 pb	261 ± 19	52 ± 4	10 ± 1	151 ± 11
data	465084	188361	7942	52633

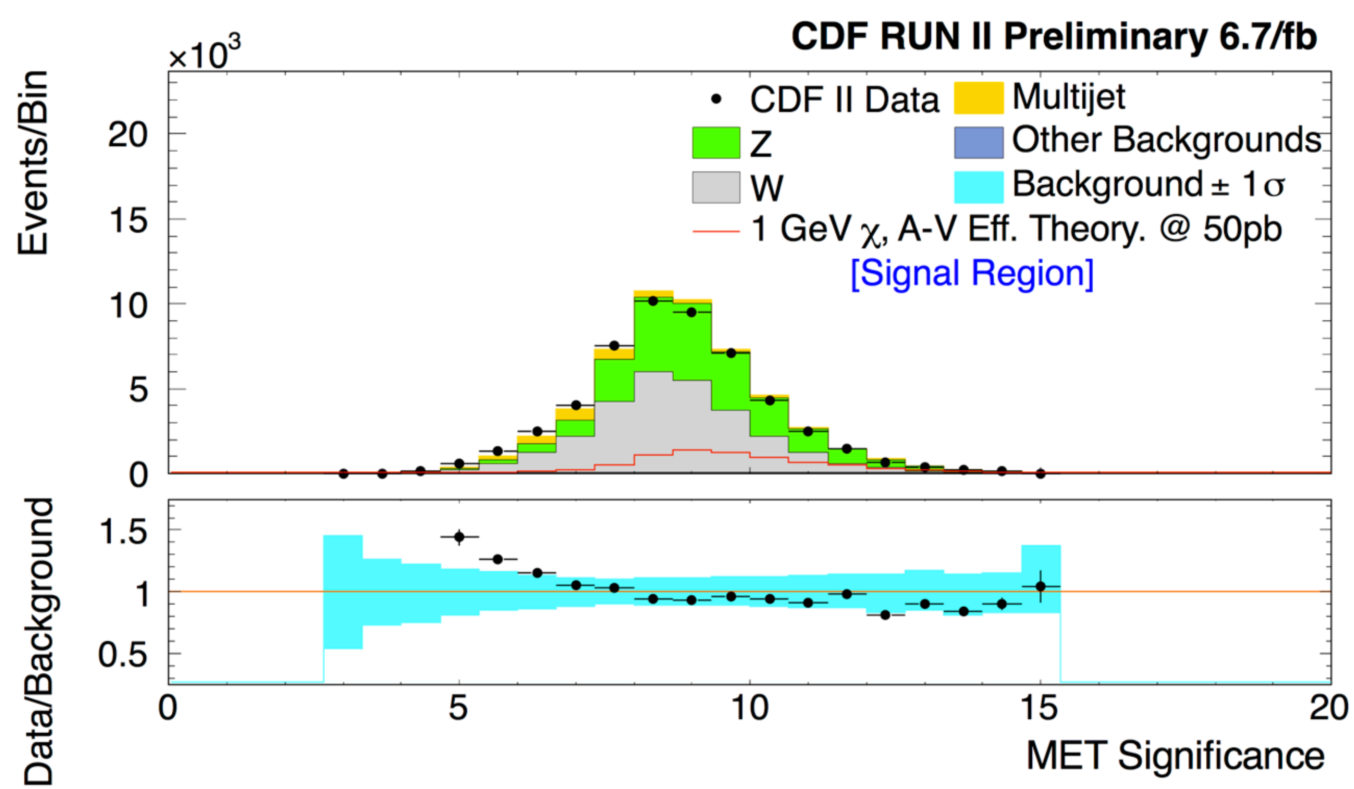
CDF Monojet: Kinematic Distributions



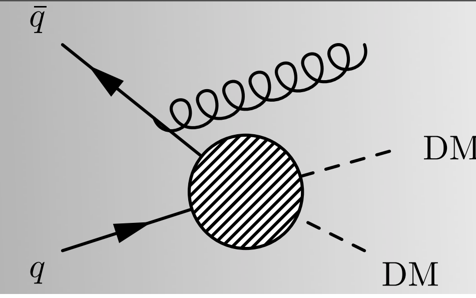






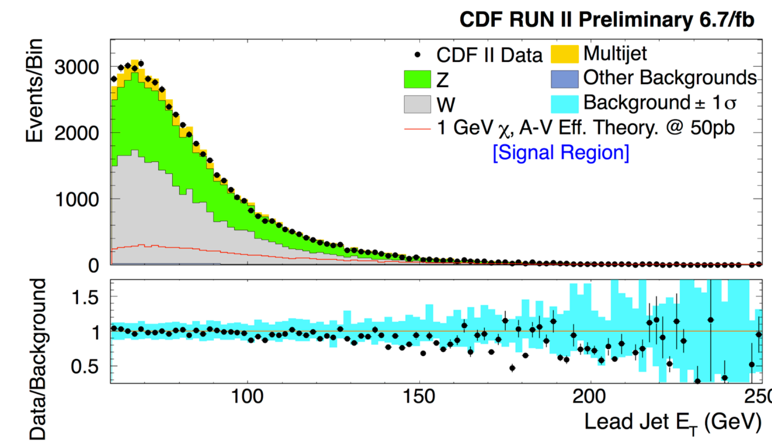


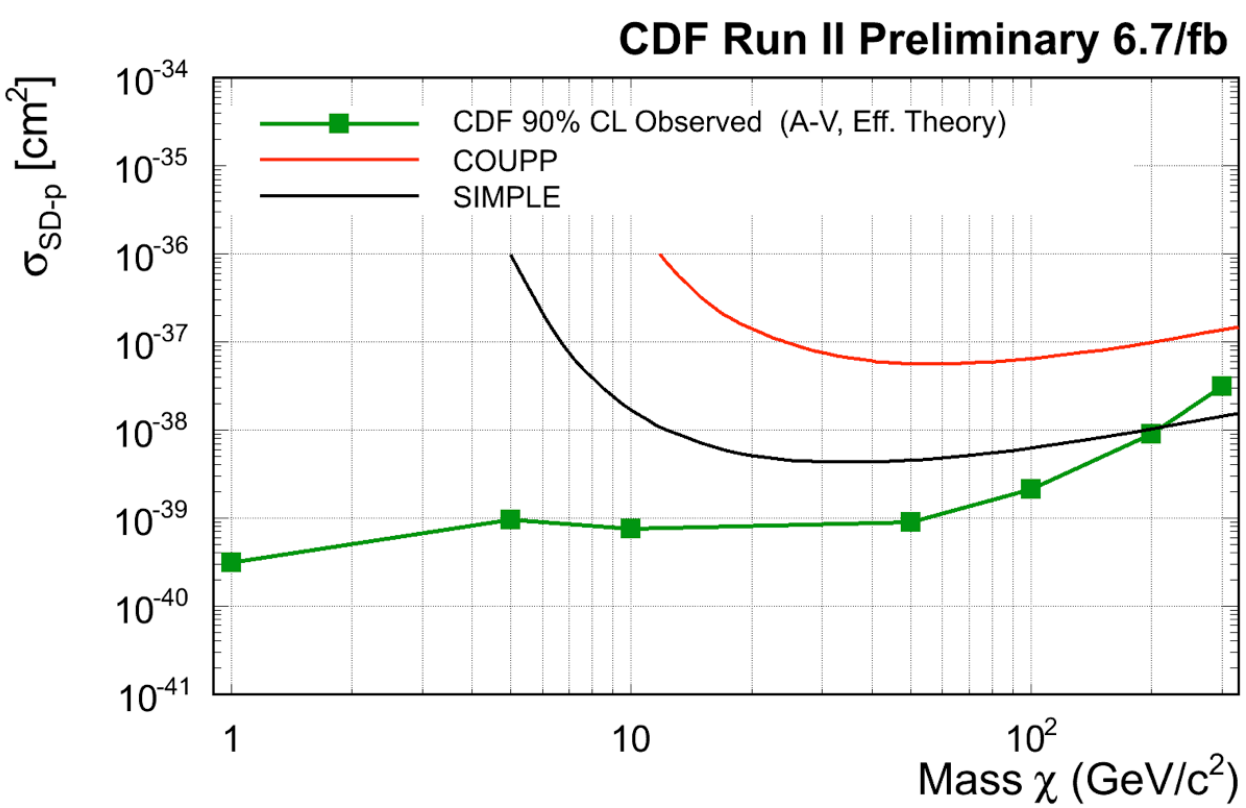
CDF Monojet: Limit Setting

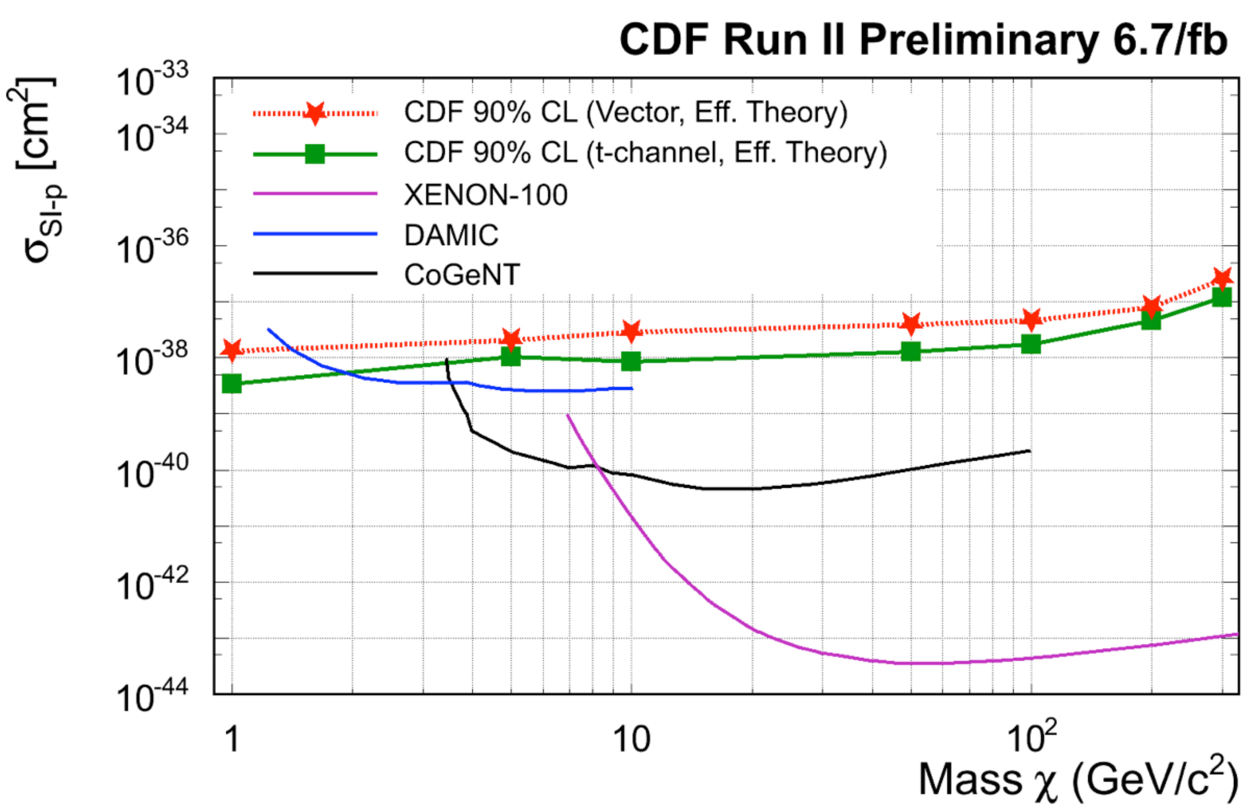


- Use Bayesian approach to compute 90% CL upper limits on DM production using a binned likelihood in lead jet p_T

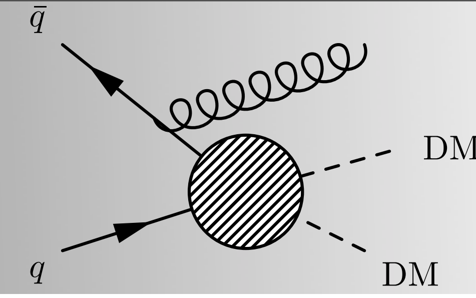
exclude upper limits on production cross section for DM particles between 0.96 and 42.8 pb



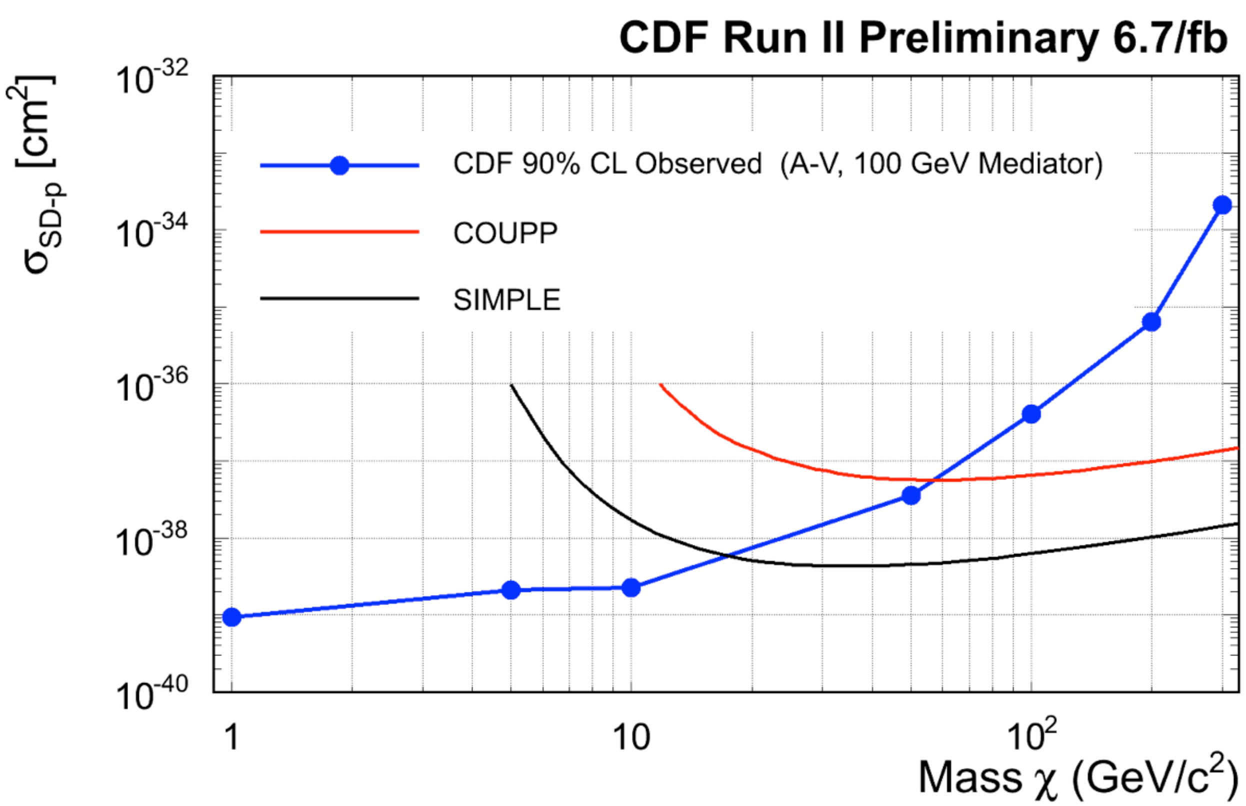


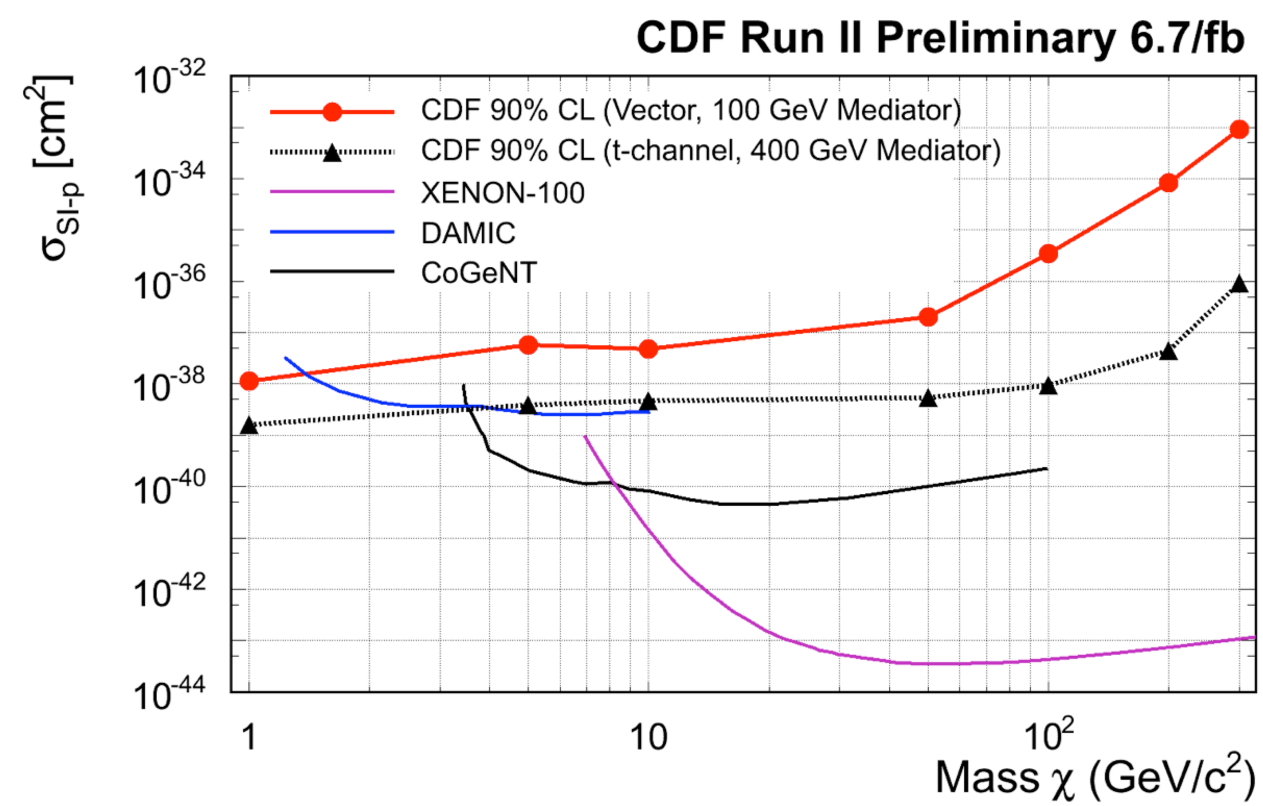


CDF Monojet: Light Mediators



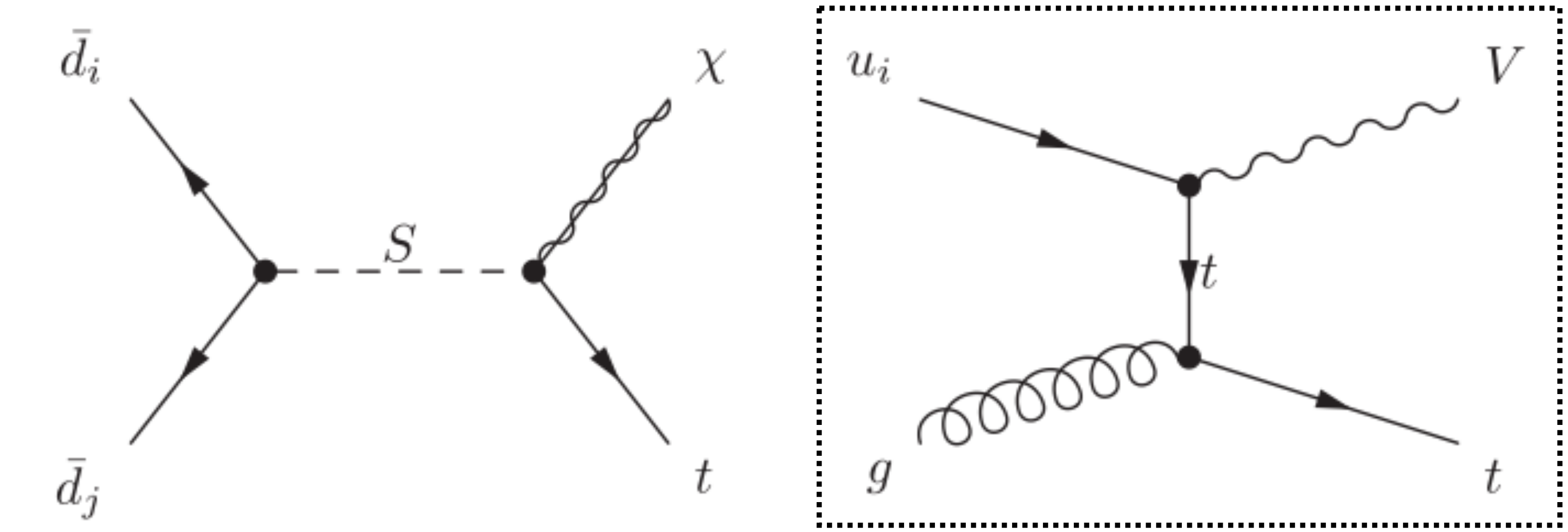
- Light mediators also considered by CDF analysis
  - 100 GeV mediator with 10 GeV width for V and A-V couplings
  - 400 GeV mediator with 8 GeV width for t-channel coupling





CDF Monotop: Introduction

- Search for “monotop” signature
  - allowing either baryon-number violating (left) or flavor-changing (right) interactions to produce a single top recoiling against an invisible DM particle



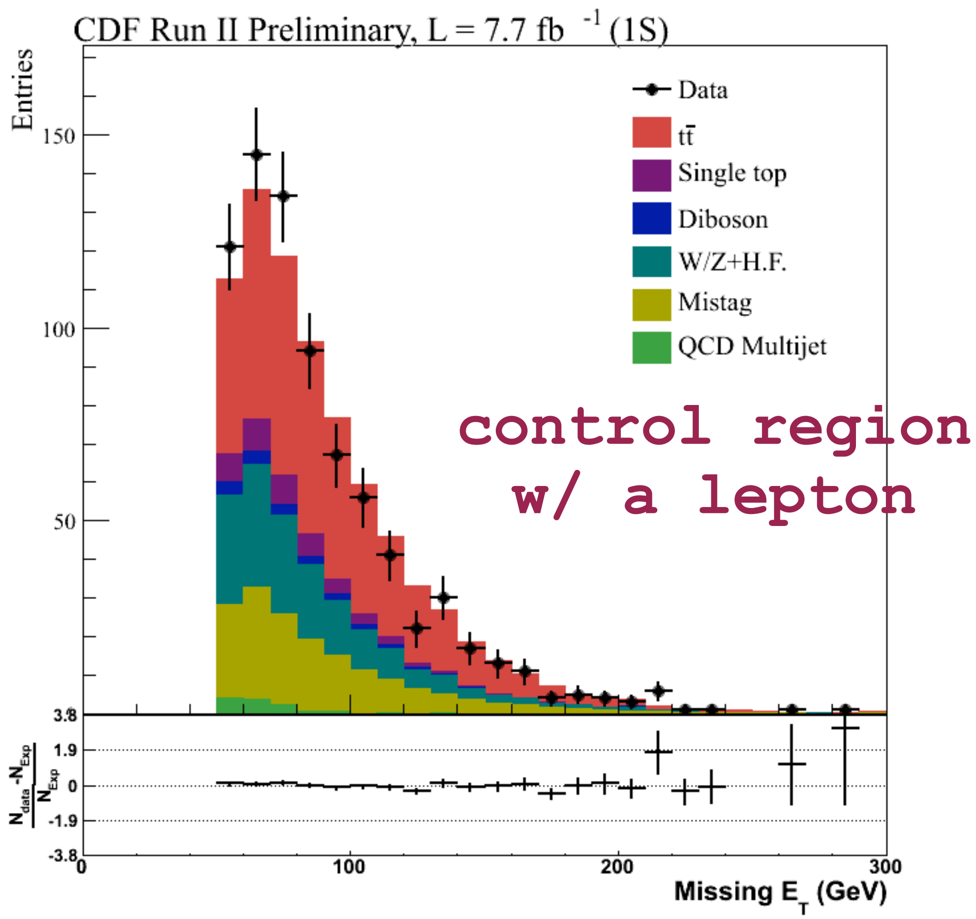
- The signature i
  - Trigger on MET>30 GeV; require 50 GeV offline
  - Require three jets with p_{T1}>35 GeV and 1 b-tagged jet
  - veto events with a muon or electron
  - Suppress mis-measured MET: Δϕ(MET,jet2)>0.7
  - Require kinematics consistent with a top quark: $110 < m_{jjj} < 200$ GeV
  - MET significance>3.5

CDF Monotop: Backgrounds

- Top, diboson, W/Z+Heavy flavor are simulated
- Multijet background uses a “tag rate” matrix technique
  - probability for a QCD multijet event to have a b-tag measured in a control sample and applied to the untagged data
- Mis-tagging of light flavor estimated by applying mistag rate measured in data to simulation

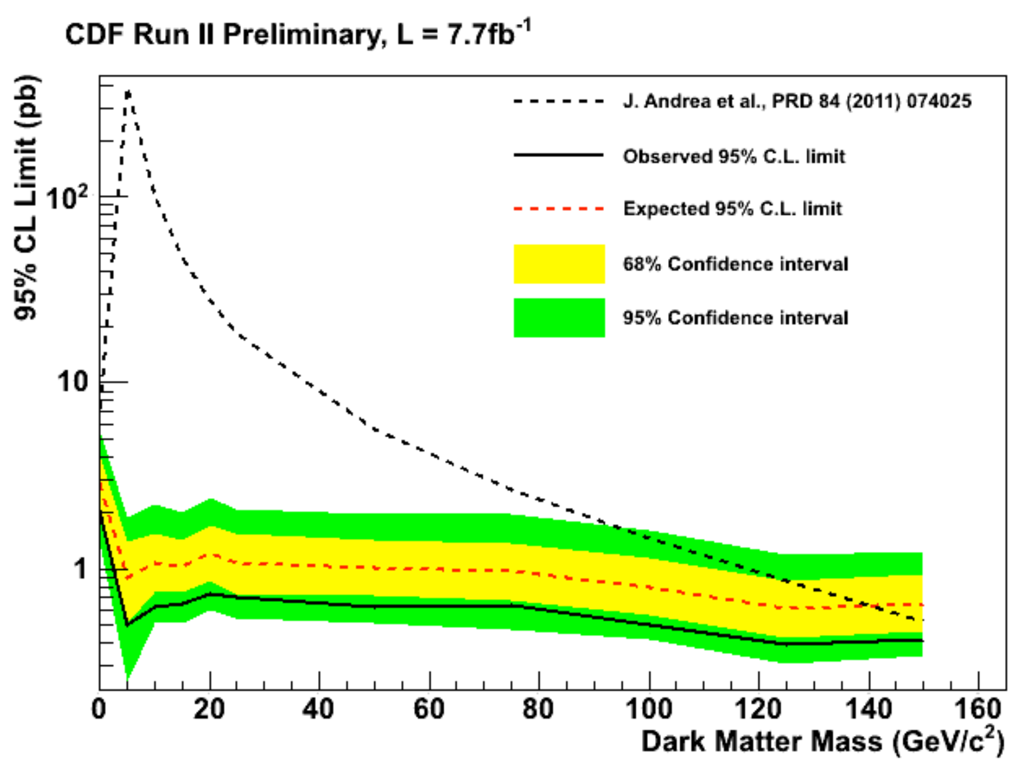
CDF Run II Preliminary, $L = 7.7 fb^{-1}$	
Process	Yields
$t\bar{t}$	182.8 ± 20.2
Single top	24.3 ± 4.5
Diboson	15.7 ± 2.7
W/Z+H.F.	130.5 ± 33.8
Mistag	96.9 ± 39.4
Multijet	210.2 ± 54.5
Expected	660.2 ± 78.1
Data	592

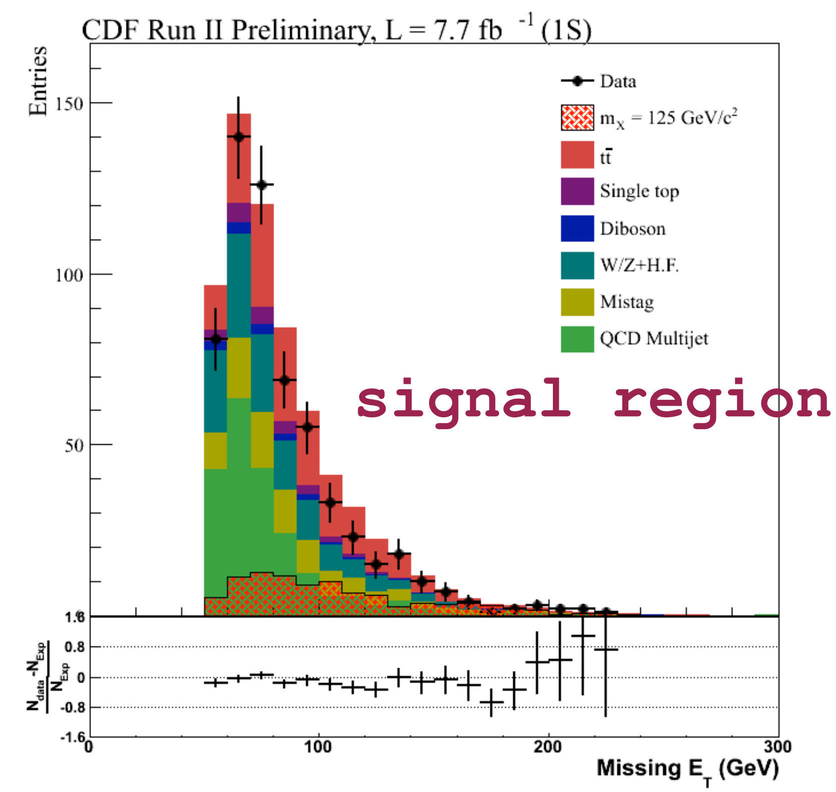
Table: Event yields in the signal region



CDF Monotop: Exclusion Limits

- Use binned-likelihood in MET distribution to measure 95% CL upper limits on monotop production with a Bayesian construction
- Systematic uncertainties dominated by the mistag rate (16.6%) and the background cross sections (6.5%–30%)
  - Also consider PDFs, luminosity, b-tagging efficiency, trigger efficiency, ISR/FSR





signal region

Exclude DM particle in the model below 140 GeV

Conclusions

- Limits demonstrate that hadron-collider experiments can offer an important piece to the dark-matter puzzle
  - Of course, any observation of a monophoton/monojet excess must be interpreted in the context of other searches for DM
    - too many other theories produce the same signatures; it's unlikely that they could be conclusively disentangled
  - But, collider searches do have distinct advantages
    - Sensitivity to very low mass DM
    - Does not pay a large penalty for spin-dependent interactions
    - DM is produced directly; not sensitive to systematic uncertainties related to galactic density, velocity dispersion, etc.