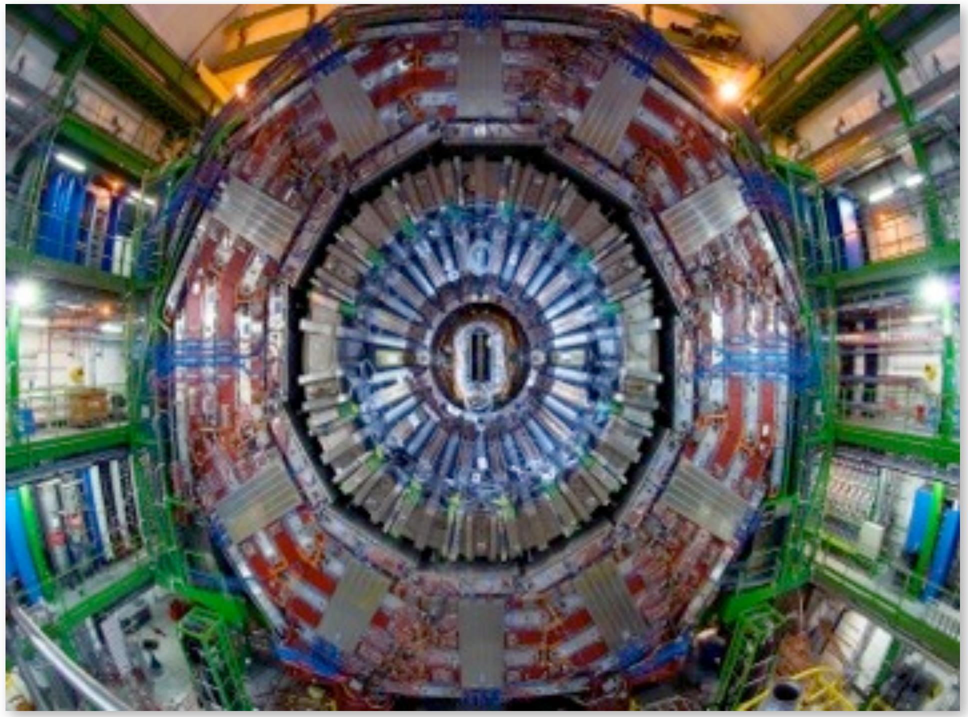
SEARCHES FOR *DARK MATTER* IN MONOJETS AND MONOPHOTON EVENTS AT CMS

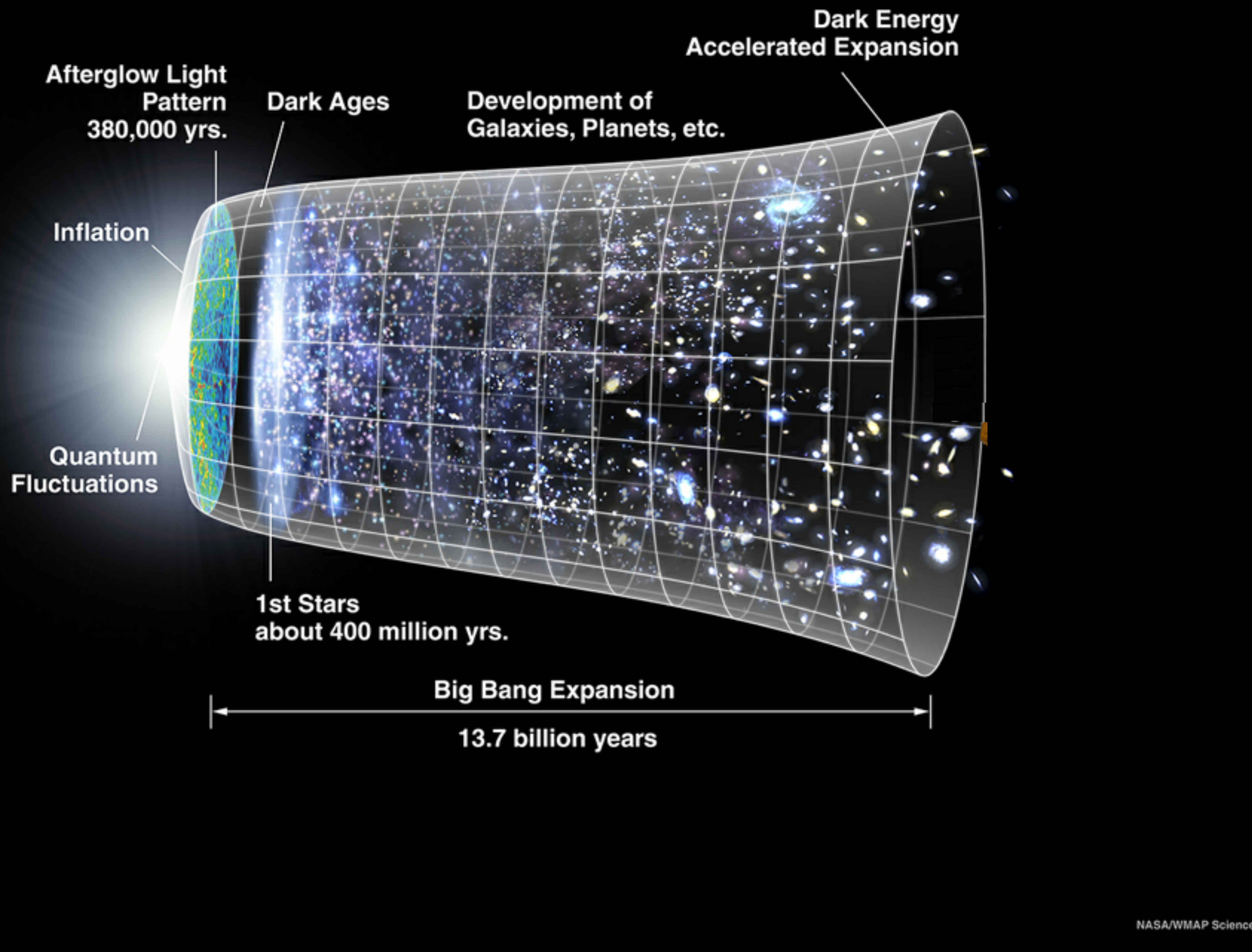


Steve Worm

Saclay, 18 June 2012

CERN

Science & Technology Facilities Council
Rutherford Appleton Laboratory



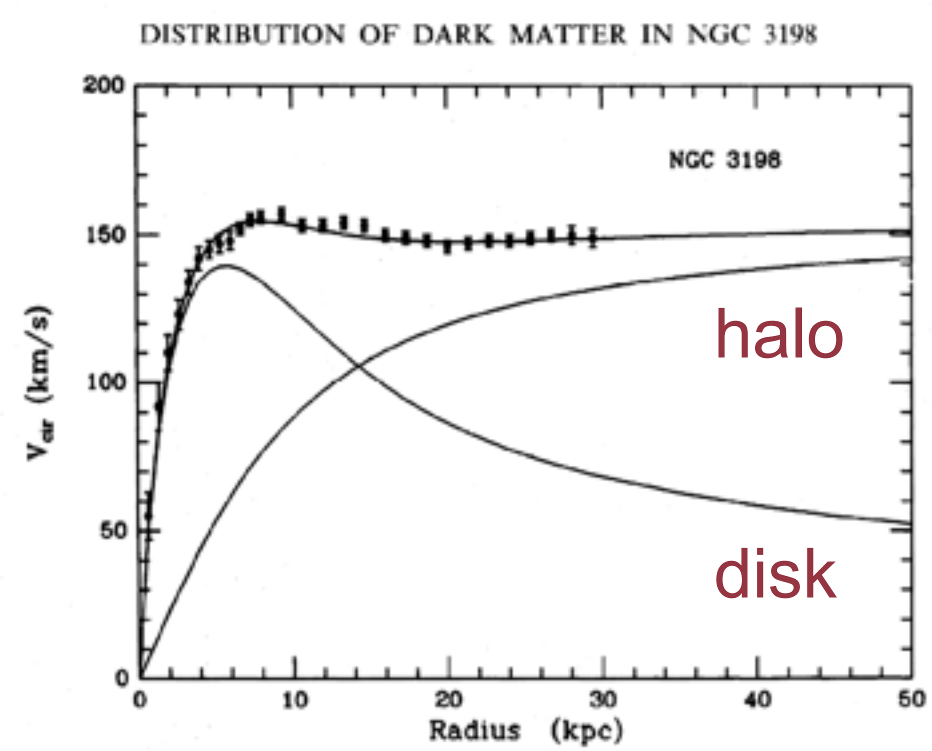
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science

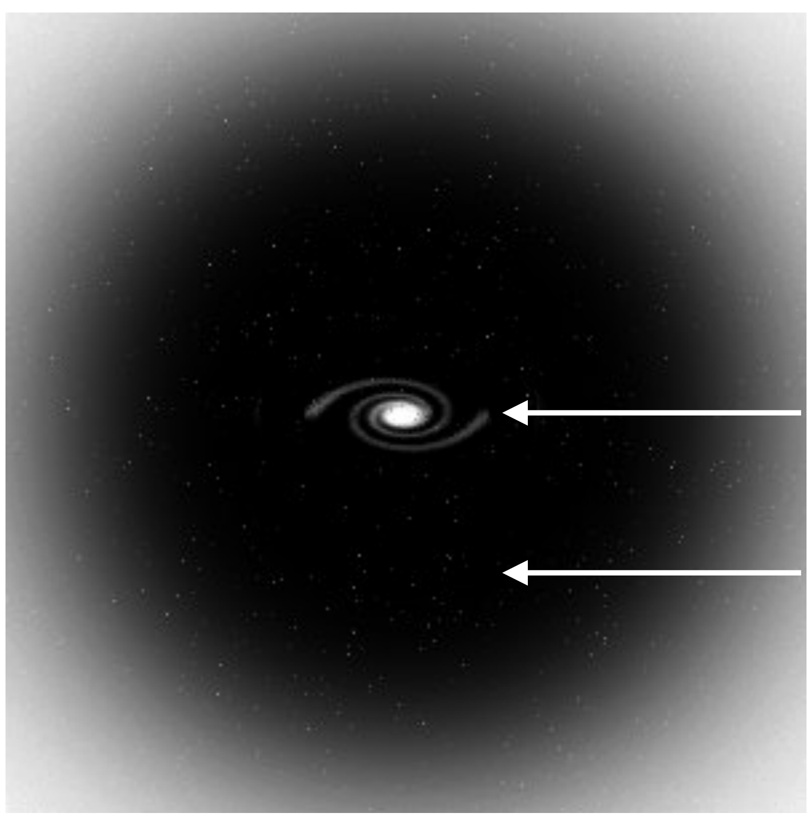
In 1933, Fritz Zwicky calculated the mass of the Coma cluster using galaxies on the outer edge, and came up with a number 400 times *larger* than expected.

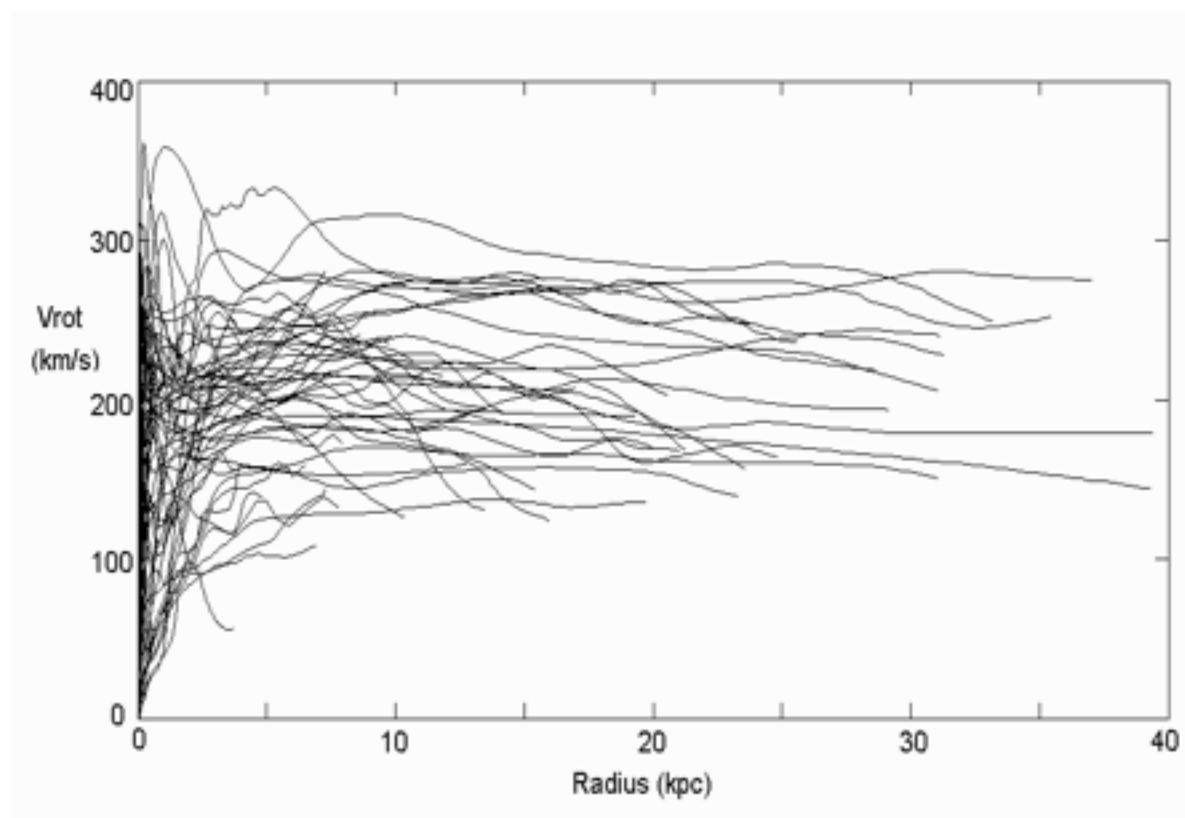
GALACTIC ROTATION

- Starting in the 1970's, Vera Rubin and (many) others measured the velocity curve of edge-on spiral galaxies
- They found them to be flat, consistent with ~10x as much "dark" mass...

...and not just one galaxy

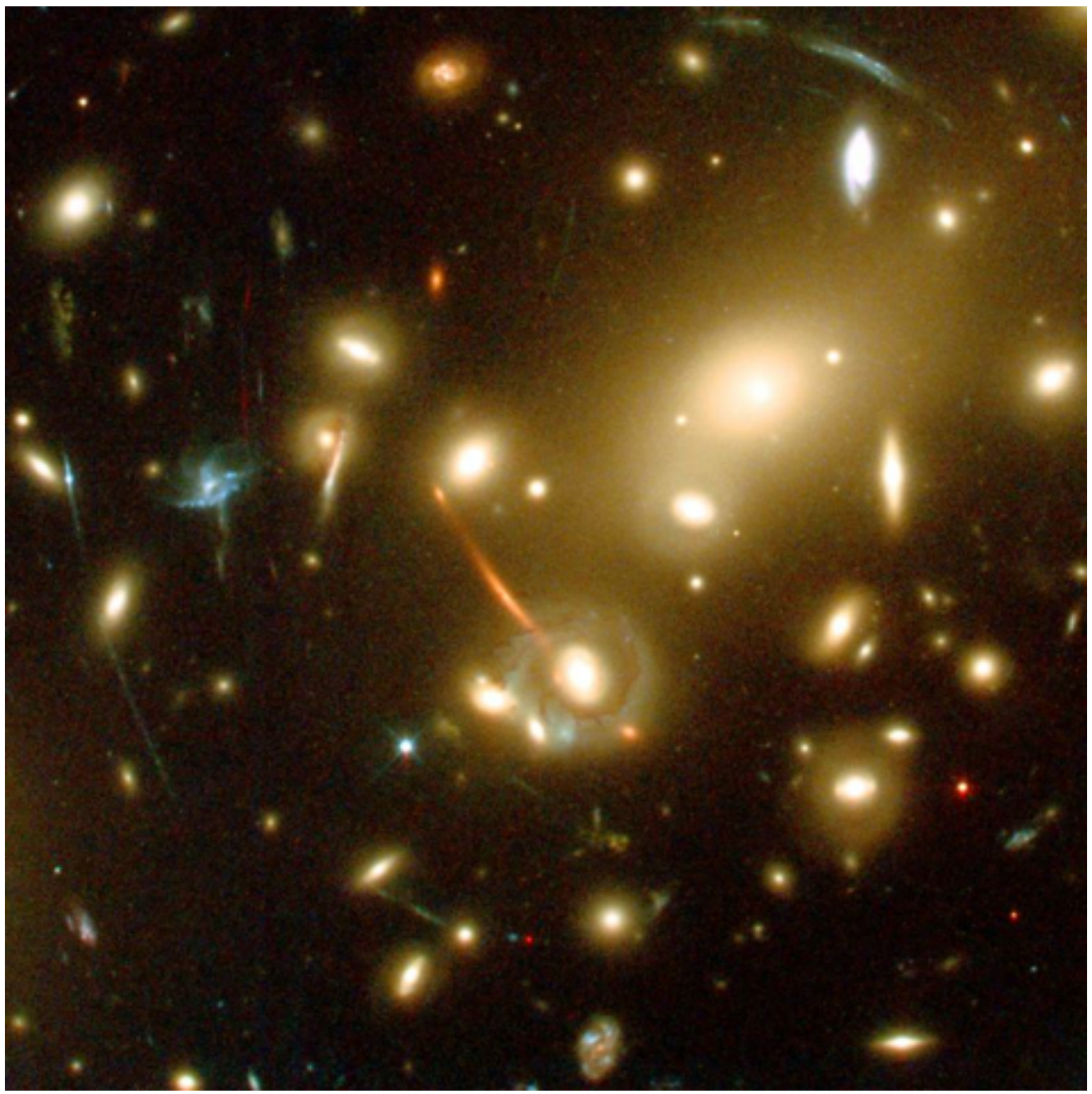


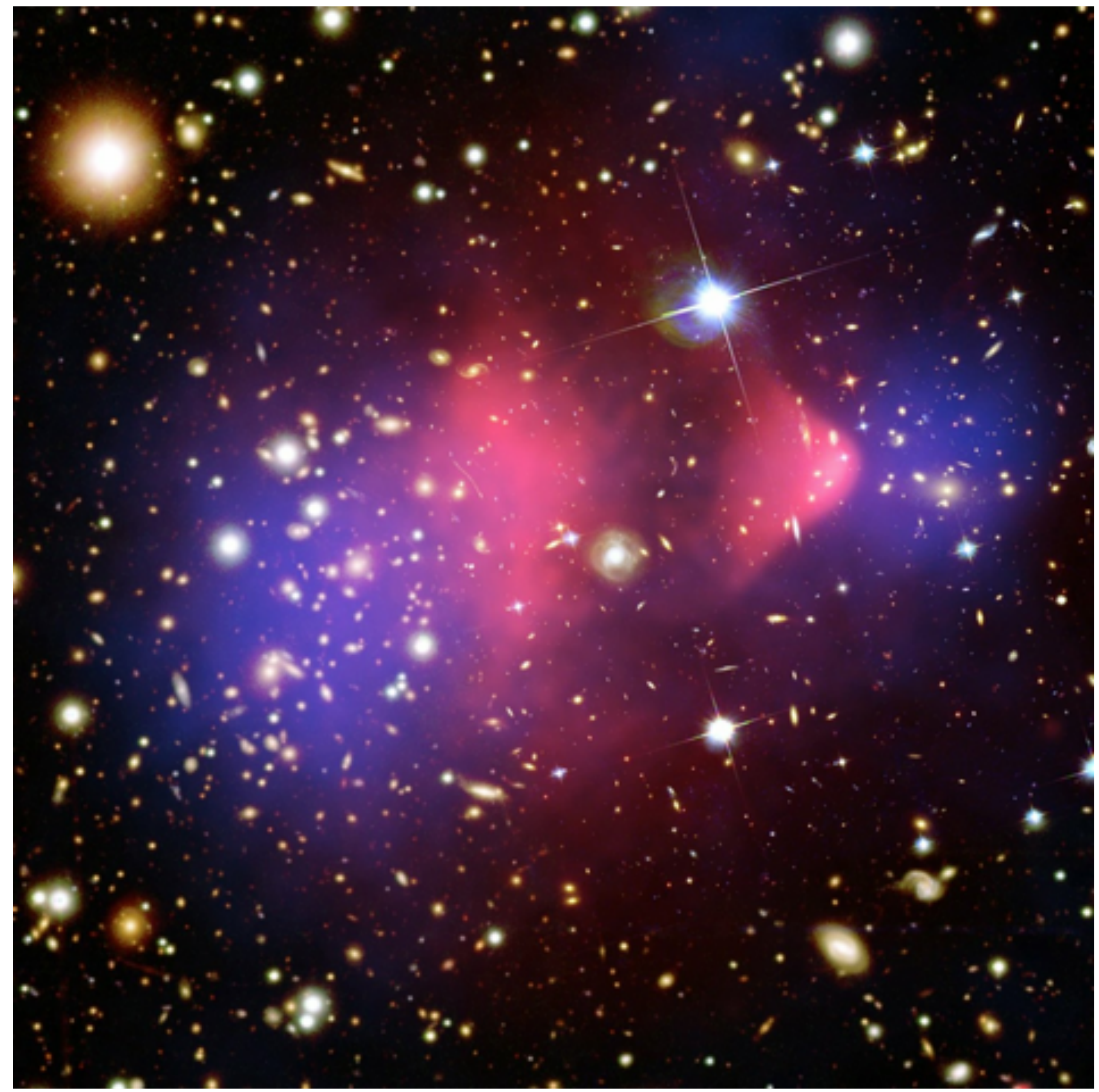




Evidence Piling Up…

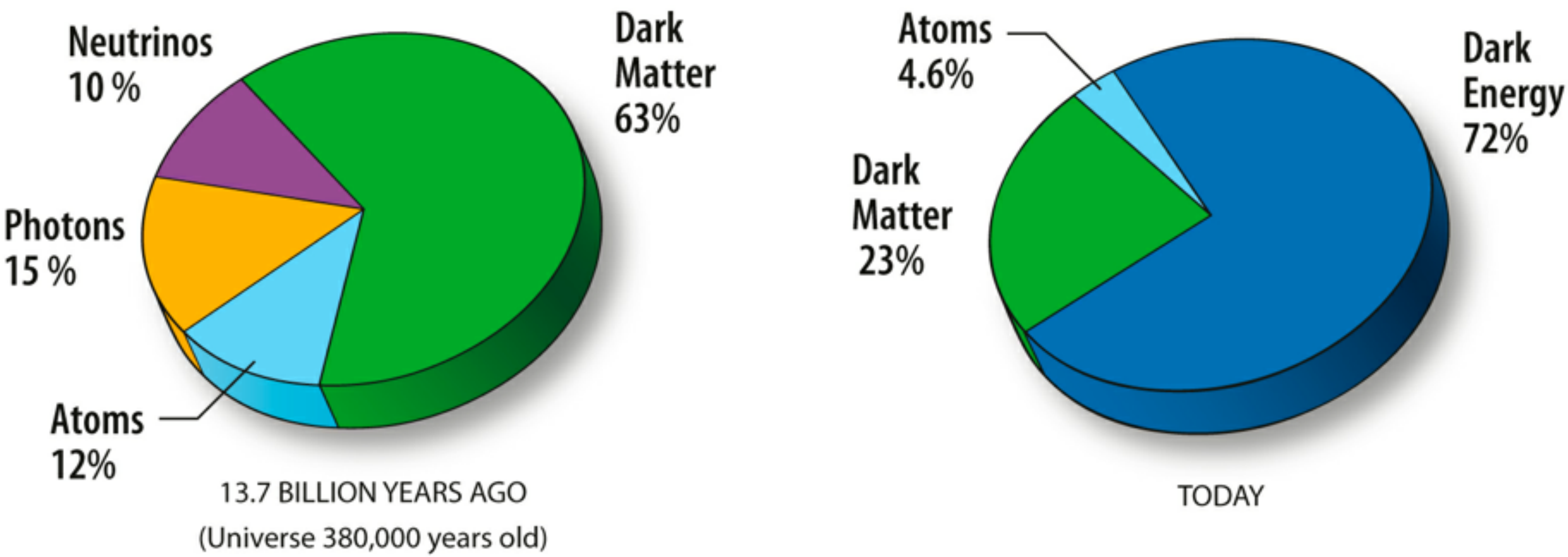
- Gravitational Lensing
  - much more lensing than can be explained by visible mass
- Bullet Cluster; colliding galaxies
  - Composite x-ray, visible image, 10x DM
  - Does not really match modified gravity*





*unless you are here for 17th Rencontres Itzykson - Heart of Darkness!

THE UNIVERSE, THEN AND NOW

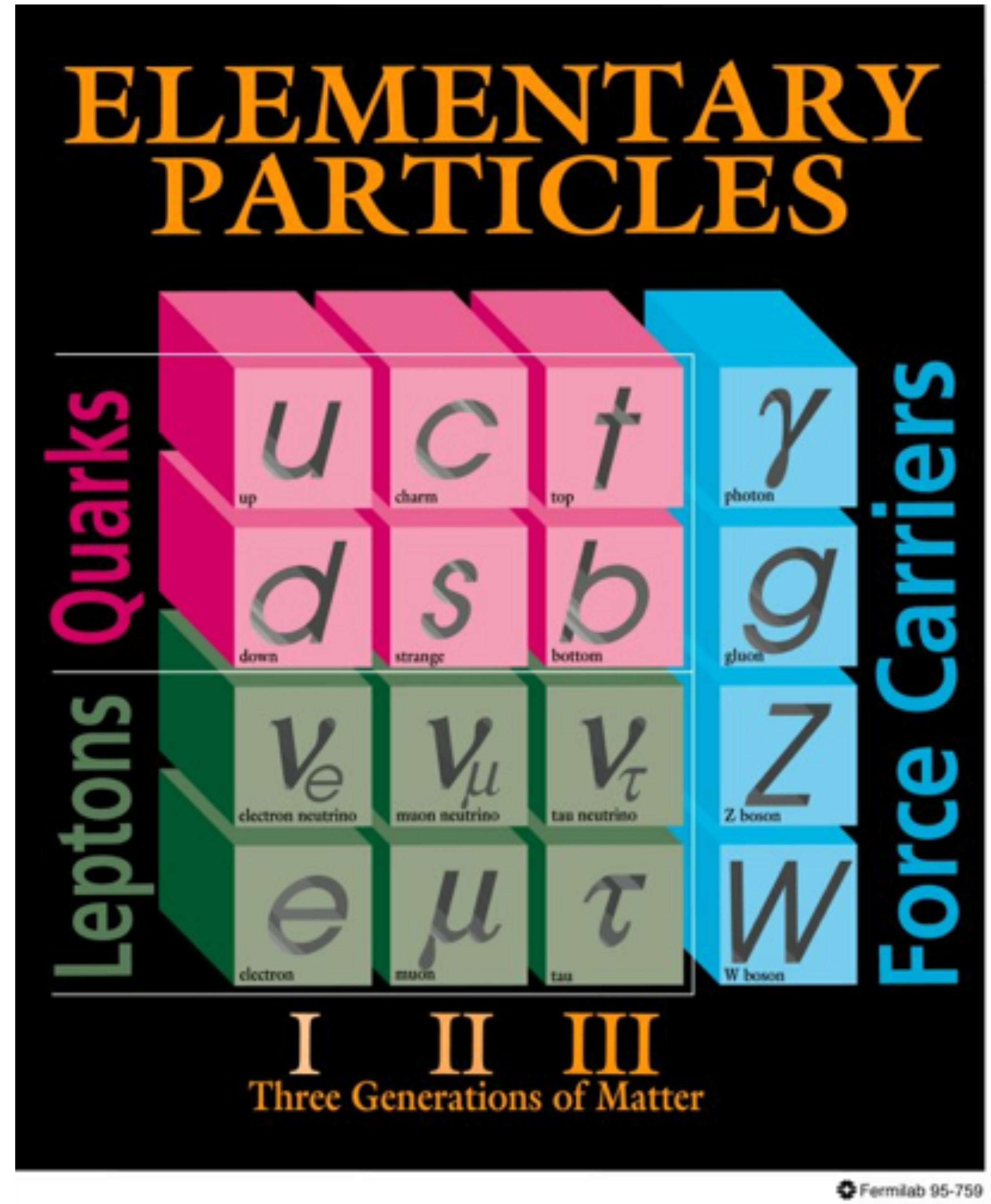


- Strong astrophysical evidence for the existence of dark matter
  - Evidence from bullet cluster, gravitational lensing, rotation curves
  - DM is six times more abundant than baryons
  - Contributes ~1/4 of the total energy budget!

▸ *Particle description of Dark Matter the current favourite...*

COMPOSITION OF MATTER

?



84% of matter

the rest...

Particle Dark Matter

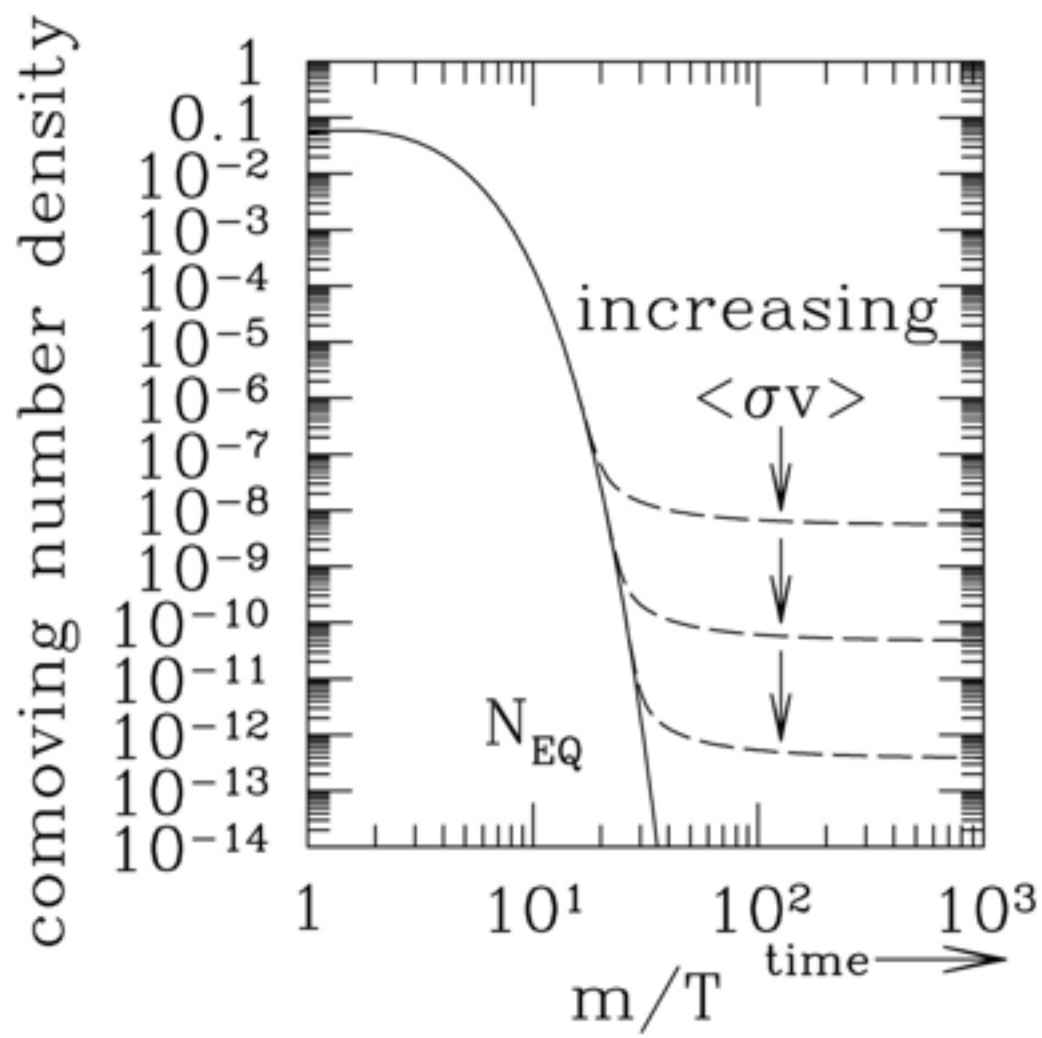
- Properties of Dark Matter
  - old (long lived)
  - slow (non-relativistic)
  - not charged (electric or colour)
  - interacts very weakly with SM
  - feels the effects of gravity

- Many candidates for Dark Matter
  - *Warm:* sterile neutrinos, gravitinos
  - *Cold:* Lightest SUSY particle (neutralino, gravitino), Lightest Kaluza-Klein particle
  - *Nonthermal relics:* B.E.C.s, axions, axion clusters, solitons, supermassive wimpzillas

WIMPs

- Perhaps Dark Matter is a (new) elementary particle with weak-scale masses?
  - *Weakly Interacting Massive Particles (WIMPs)*
  - Produced in the Big Bang and interact via $\chi + \chi \rightarrow q + q$ (Standard Model particles)

- As the universe expands and the temperature drops...
  - WIMPs become diluted, interact less often and 'freeze out'.
  - Relic density is measured by their interaction strength, inversely proportional to the annihilation cross-section ($\langle\sigma v\rangle$)



Weakly interacting particles with weak-scale masses naturally provide the right relic abundance - "WIMP miracle"

DM INTERACTIONS WITH ORDINARY MATTER

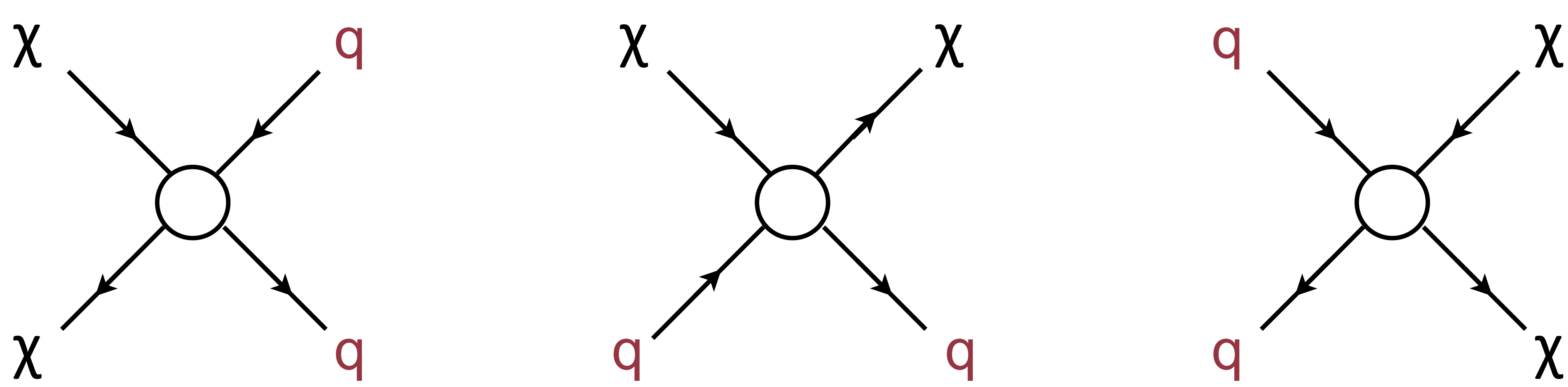
- Dark Matter interactions; important to get the right relic abundance

$$\chi + \chi \rightarrow q + q$$

- Then why not

$\chi + q \rightarrow \chi + q$ and $q + q \rightarrow \chi + \chi$?

- Dark Matter as a particle hints at many interactions with ordinary matter

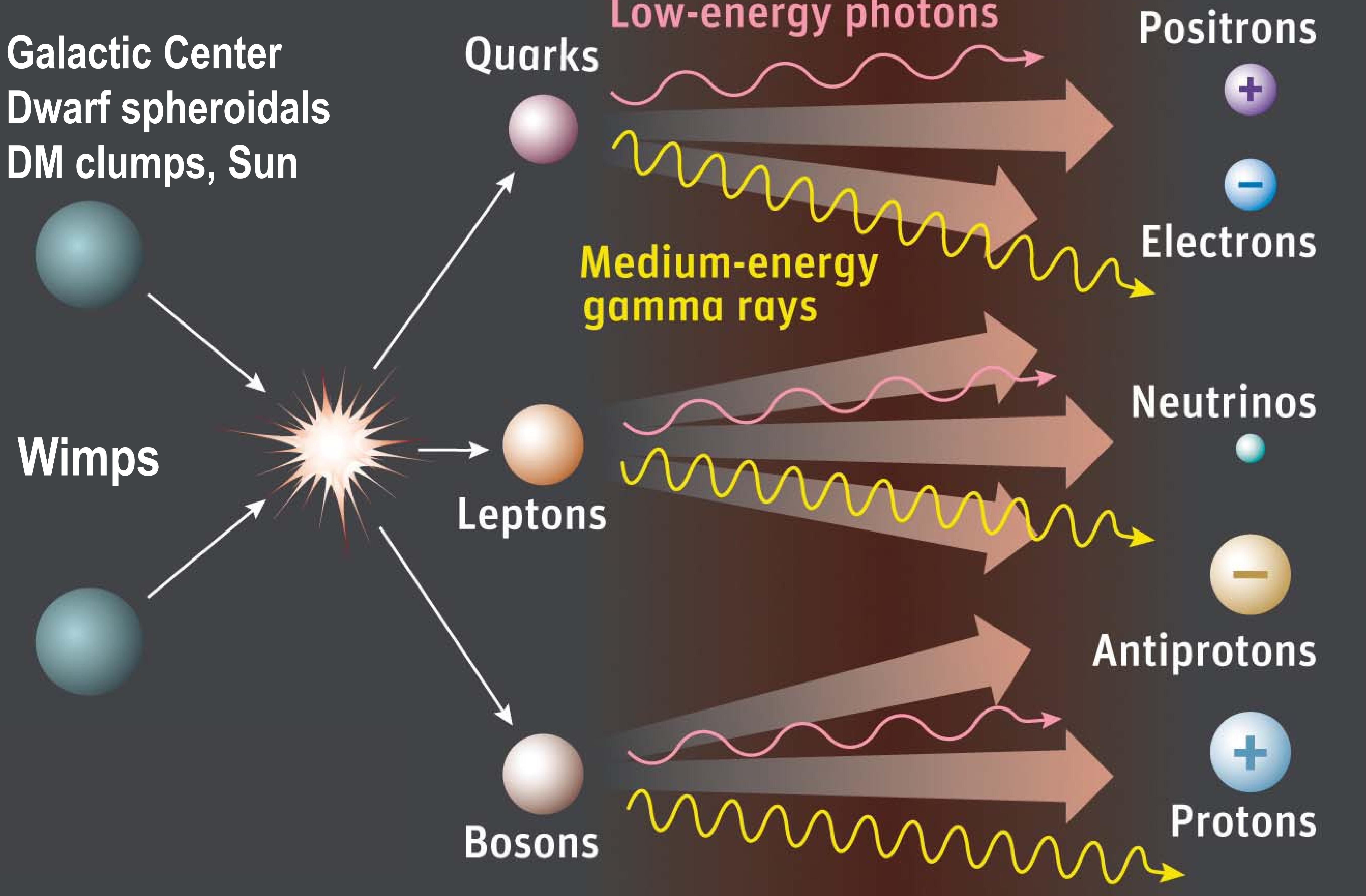


Indirect Detection *Direct Detection* *Production at Colliders*

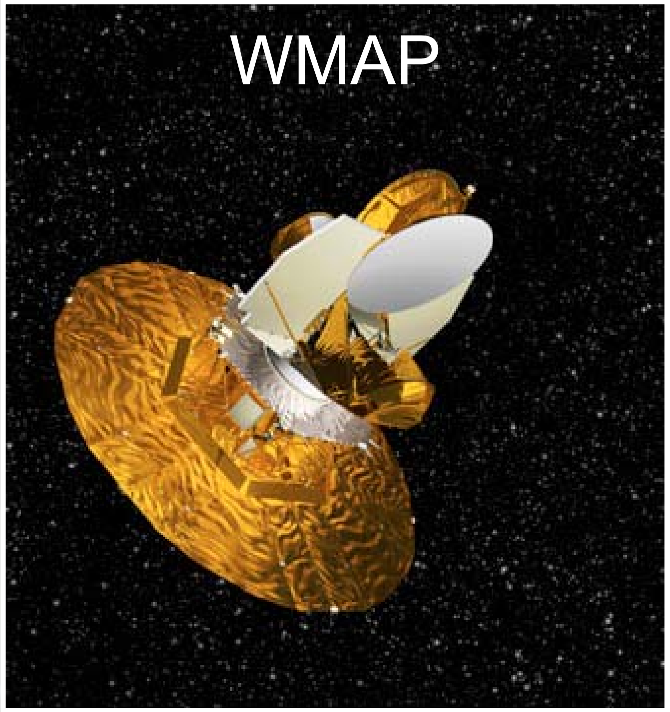
...We can probe the same interaction at the LHC

Indirect Detection

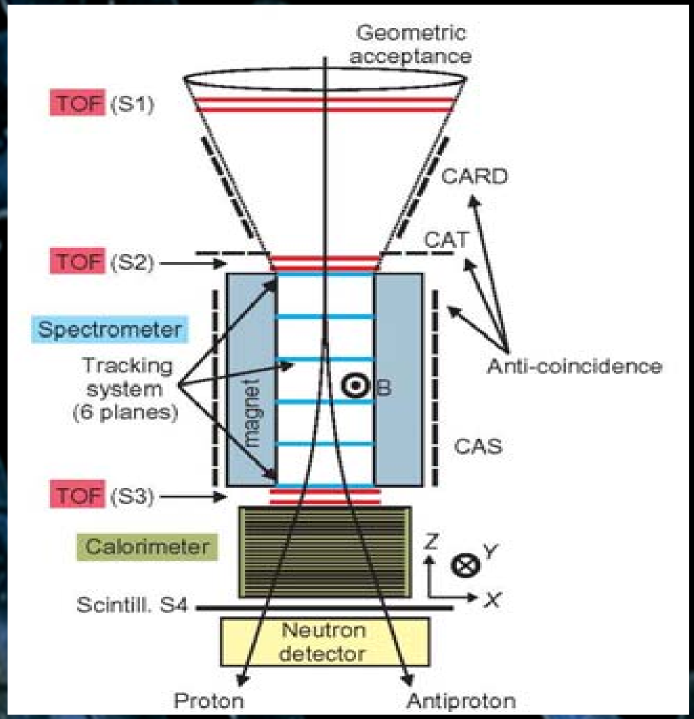
Galactic Center
Dwarf spheroidals
DM clumps, Sun



Indirect Detection

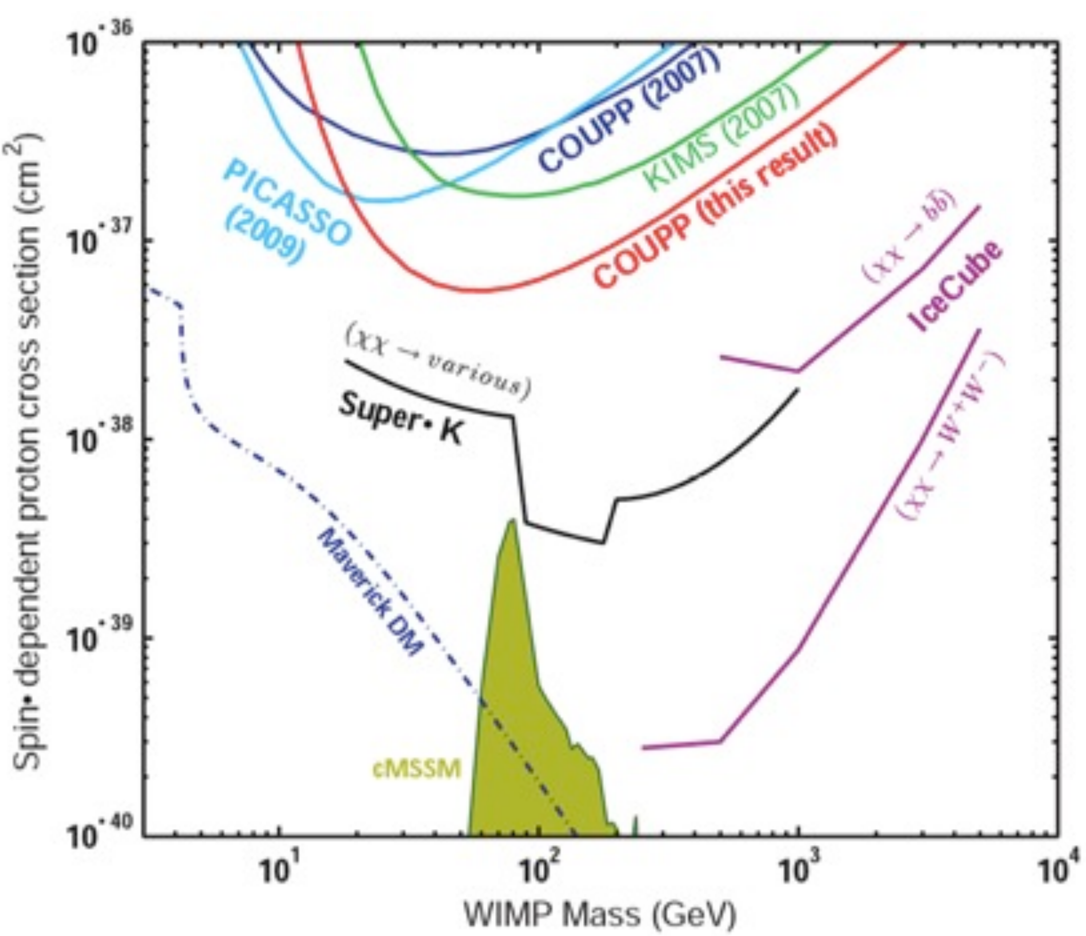


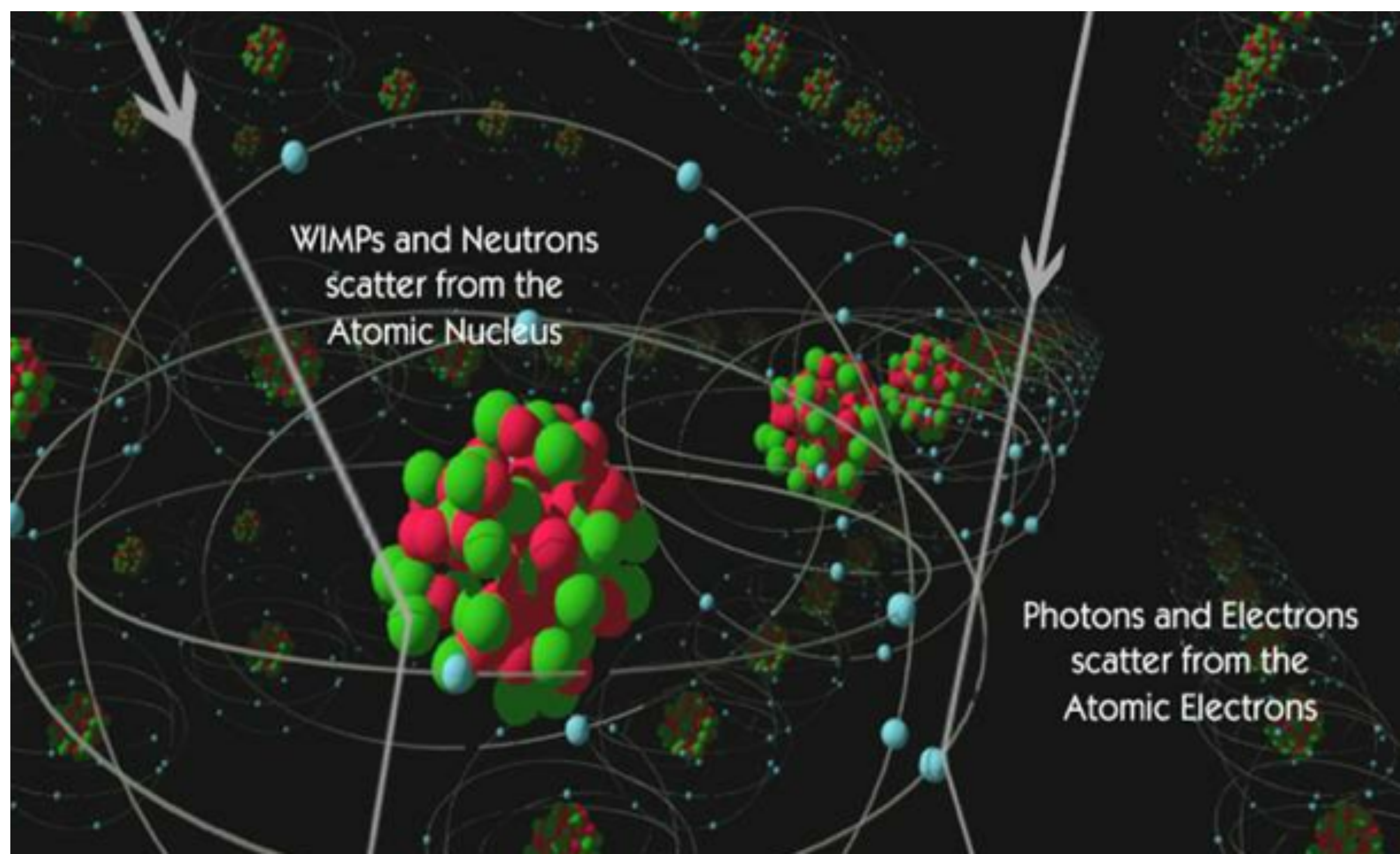
PAMELA



Direct Detection Experiments

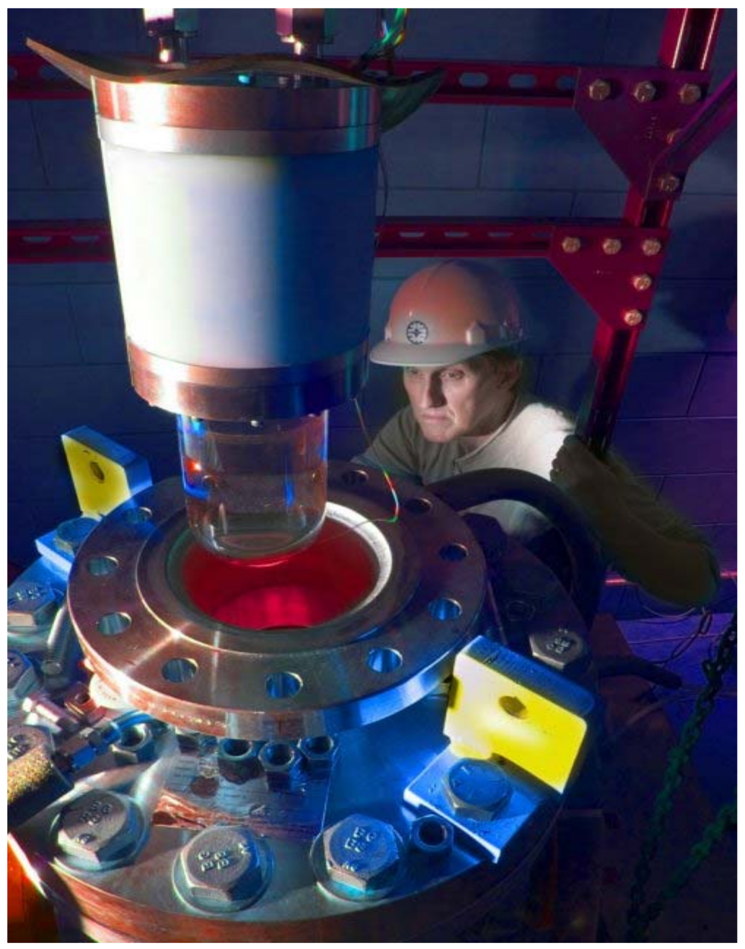
- Direct detection experiments
  - Extremely sensitive, extremely difficult... extremely successful!
  - Aim to observe recoil of dark matter off nucleus
  - Excesses observed by some experiments, not confirmed by others (10 GeV DM candidate?)
- Need for independent verification from non-astrophysical experiments
  - Low mass region not accessible to direct detection experiments
  - Limited by threshold effects, energy scale, bkgnds; spin-dependent couplings difficult...



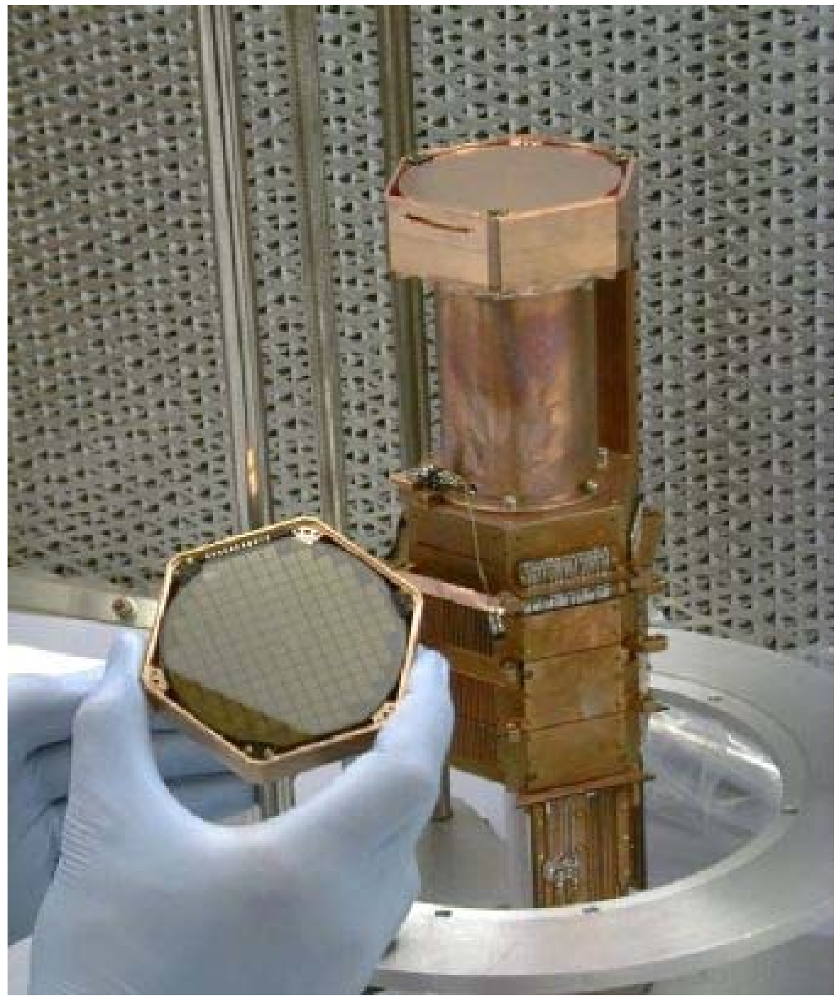


Direct Detection

COUPP



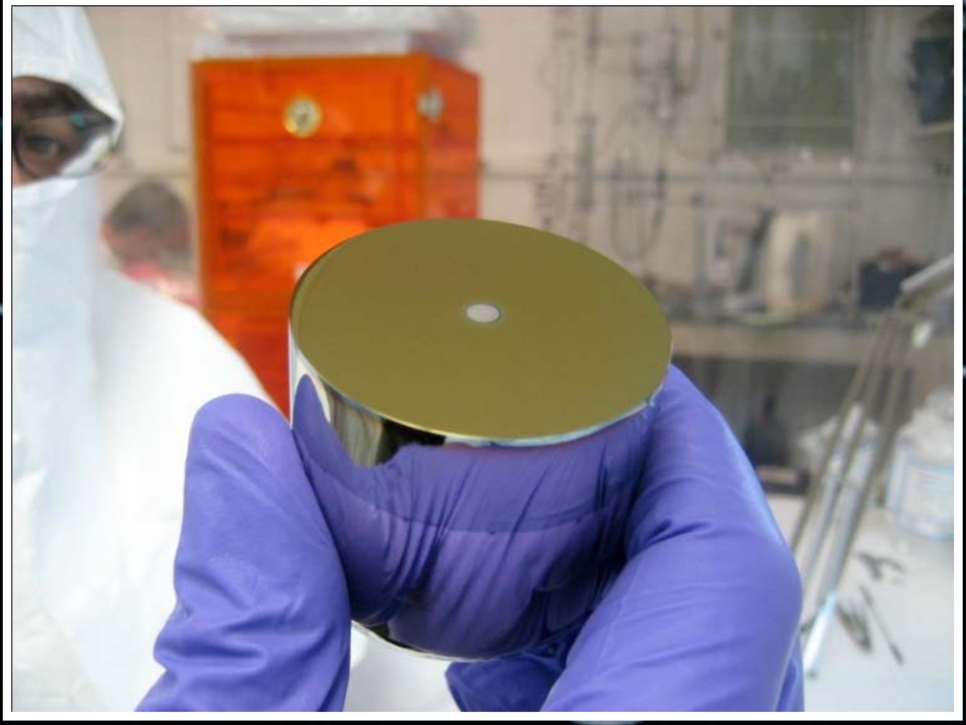
CDMS



CRESST

DAMA

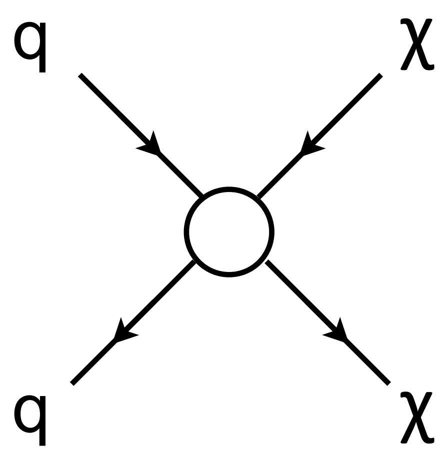
CoGeNT



(+ EDELWEISS, XENON, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, …)

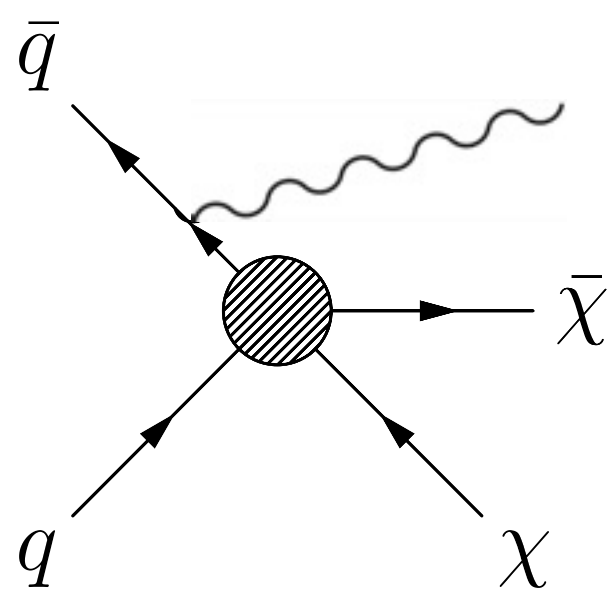
Production of Dark Matter at the LHC

- Search for evidence of pair-production of Dark Matter particles (χ)

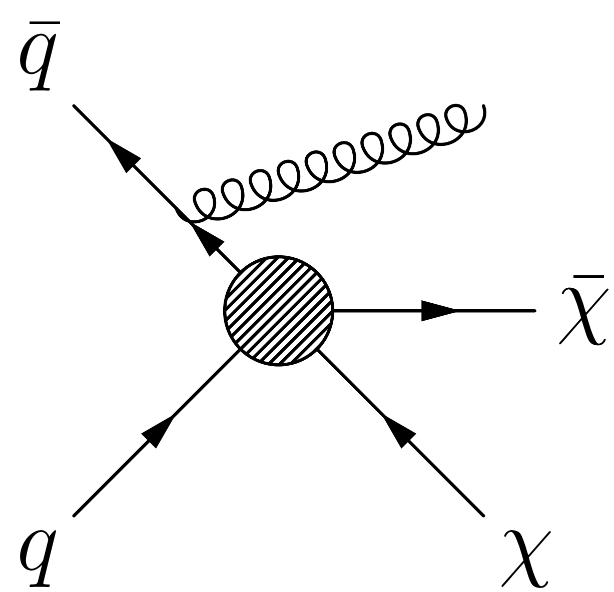


Production at Colliders (s-channel)

- Dark Matter production gives missing transverse energy (MET)
- Photons (or jets from a gluon) can be radiated from quarks, giving monophoton (or monojet) plus MET



Monophoton + MET



Monojet + MET

Phenomenology

- Pair-production of χ can be characterised by a contact interaction with operators

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

vector --> spin independent (SI)

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

axial-vector --> spin-dependent (SD)

- Cross section depends on the mass (m_χ) and the scale Λ (for couplings g_χ, g_q)

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

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

spin-independent and spin-dependent cross sections

$$\Lambda = M/\sqrt{g_\chi g_q} \qquad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

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

[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010)]

PHENOMENOLOGY REVISITED

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{X}\gamma^\mu\partial_\mu X - M_X\bar{X}X + \sum_q \sum_{i,j} \frac{G_{qij}}{\sqrt{2}} \; [\bar{X}\Gamma_i^X X]\,[\bar{q}\Gamma_q^j q]$$

Name	Type	G_X	Γ^X	Γ^q
M1	qq	$m_q/2M_*^3$	1	1
M2	qq	$im_q/2M_*^3$	γ_5	1
M3	qq	$im_q/2M_*^3$	1	γ_5
M4	qq	$m_q/2M_*^3$	γ_5	γ_5
M5	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	γ^μ
M6	qq	$1/2M_*^2$	$\gamma_5\gamma_\mu$	$\gamma_5\gamma^\mu$
M7	GG	$\alpha_s/8M_*^3$	1	-
M8	GG	$i\alpha_s/8M_*^3$	γ_5	-
M9	$G\tilde{G}$	$\alpha_s/8M_*^3$	1	-
M10	$G\tilde{G}$	$i\alpha_s/8M_*^3$	γ_5	-

Majorana WIMP

R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$

Spin zero WIMPs

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	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	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	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$
D15	$\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	M
D16	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi F_{\mu\nu}$	D

Dirac WIMPs

- Many operators/interactions can contribute
  - Can investigate each (list above from Tait et al...)
  - Or pick a few expected to be dominant (Harnik et al)
- Discussion of EFT validity at small Λ, large m_χ ...

READING LIST

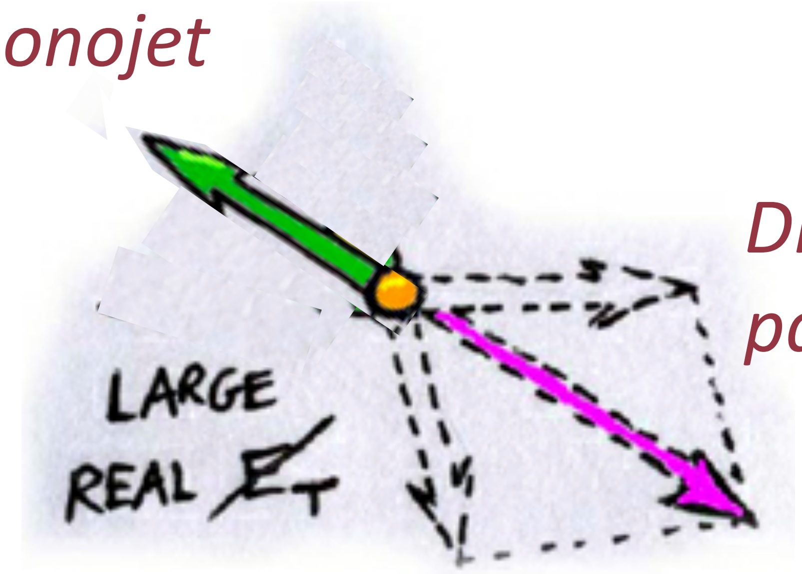
- Beltran,Hooper,Kolb,Krusberg,Tait, 1002.4137
- Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1005.1286
- Bai, Fox, Harnik, 1005.3797
- Goodman, Ibe, Rajaraman, Shepherd,Tait, 1008.1783
- Goodman, Ibe, Rajaraman, Shepherd,Tait,Yu, 1009.0008
- Fox, Harnik, Kopp,Tsai, 1103.0240
- Fortin,Tait, 1103.3289
- Cheung,Tseng,Yuan, 1104.5329
- Shoemaker,Vecchi, 1112.5457
- Haipeng An, Xiangdong Ji, Lian-Tao Wang
- Djouadi, Falkowski, Mambrini, Quevillion, 1205.3169

Detecting Ghosts: Missing Energy

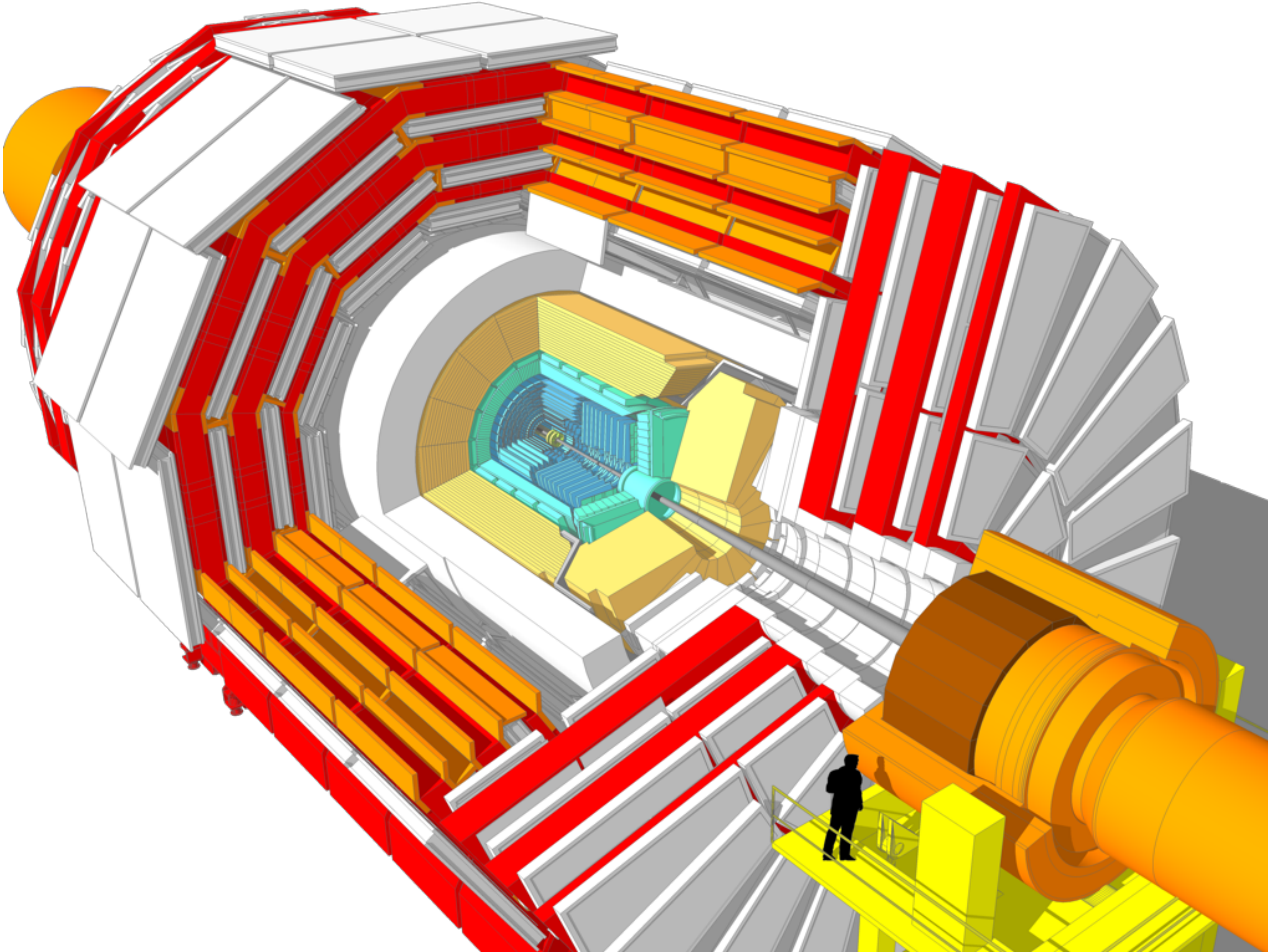
- DM particles interact very weakly... but sometimes come with extra radiation
  - Alas no “Ghost Detector”, we look for radiated γ/jets: *Missing transverse energy (MET)*
  - challenging to measure, sensitive to mis-measurements, detector effects, backgrounds
  - multiple interactions within the same bunch crossing adds extra headache to MET measurement

▸ *MET a well-understood and well-measured quantity...*

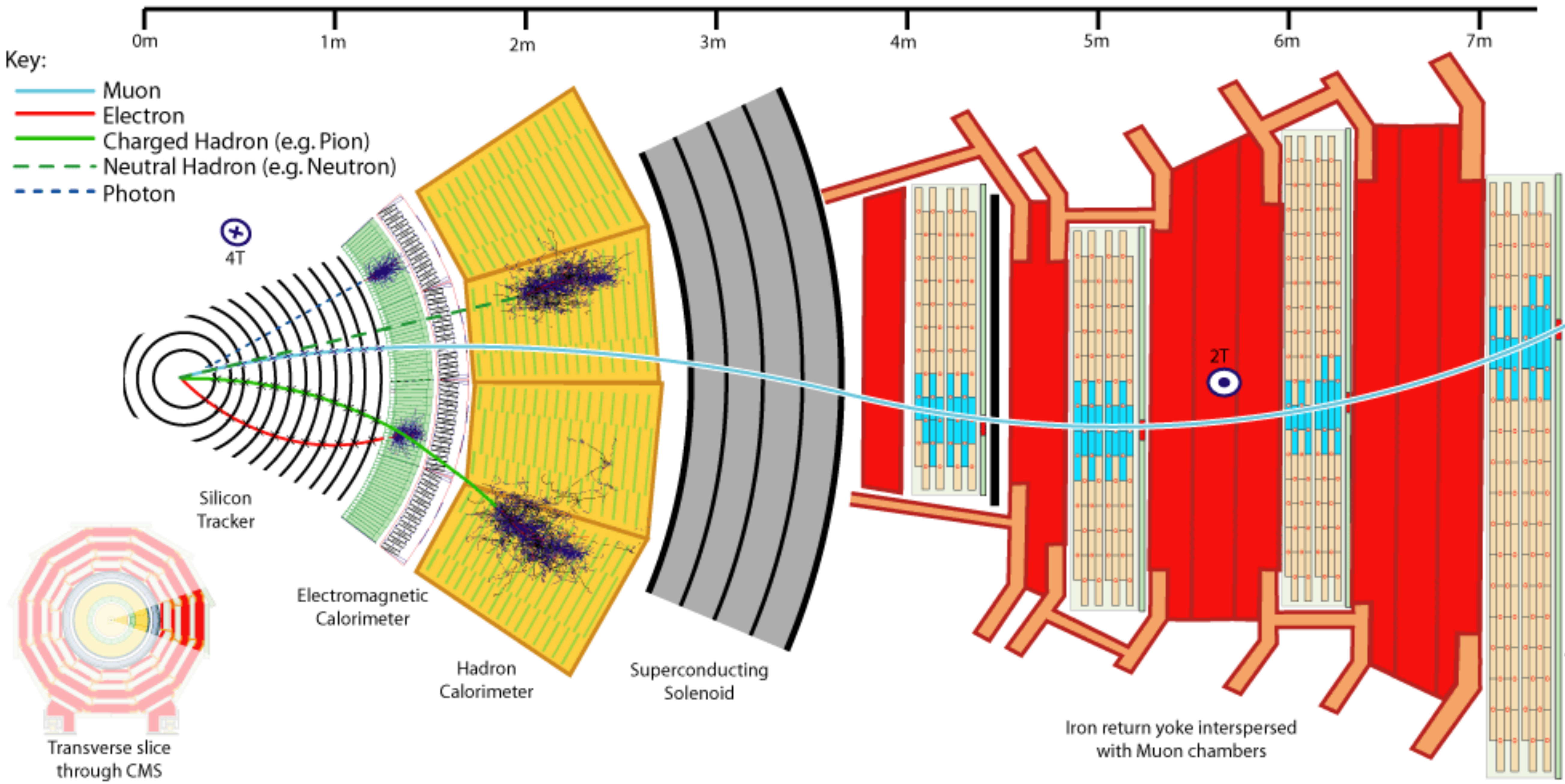
monojet



DM particles

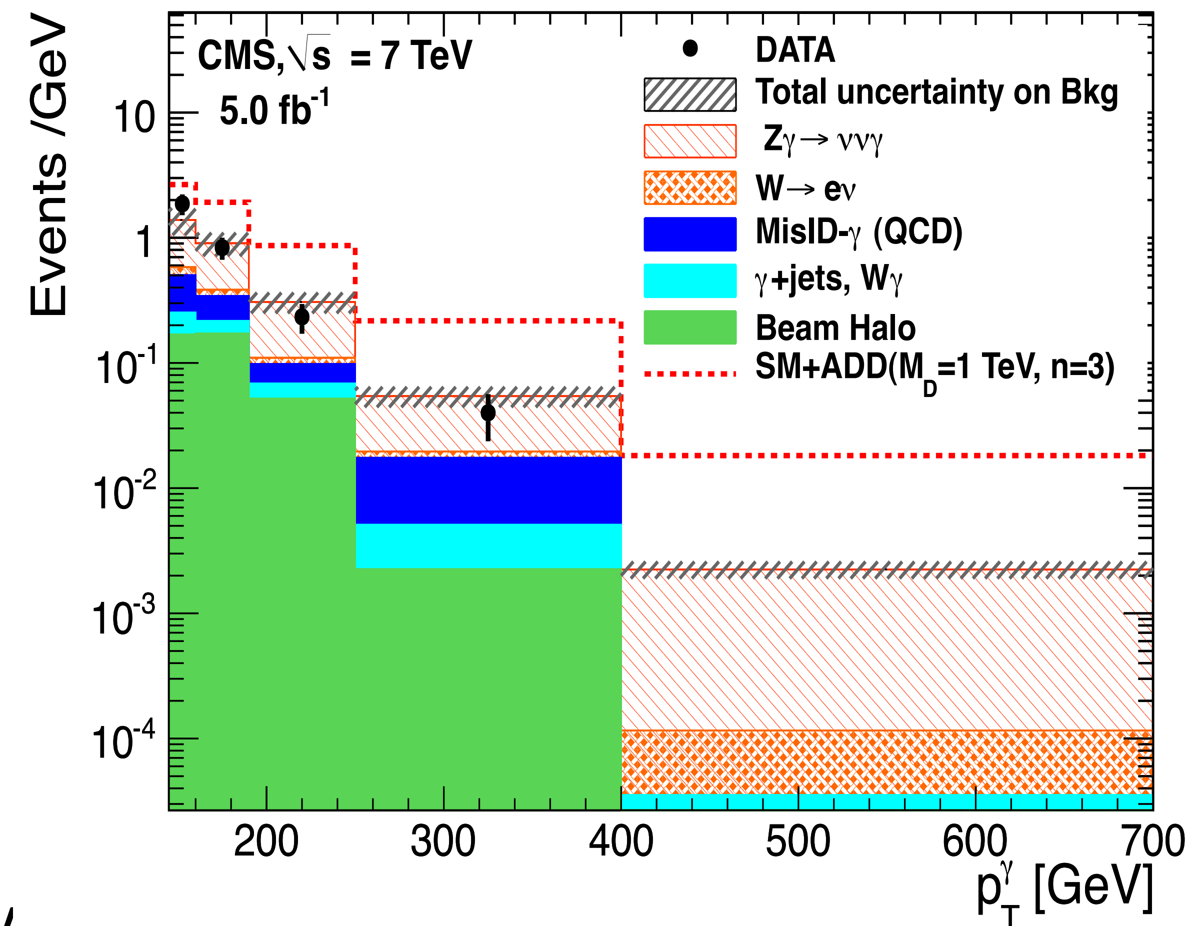


The CMS Detector



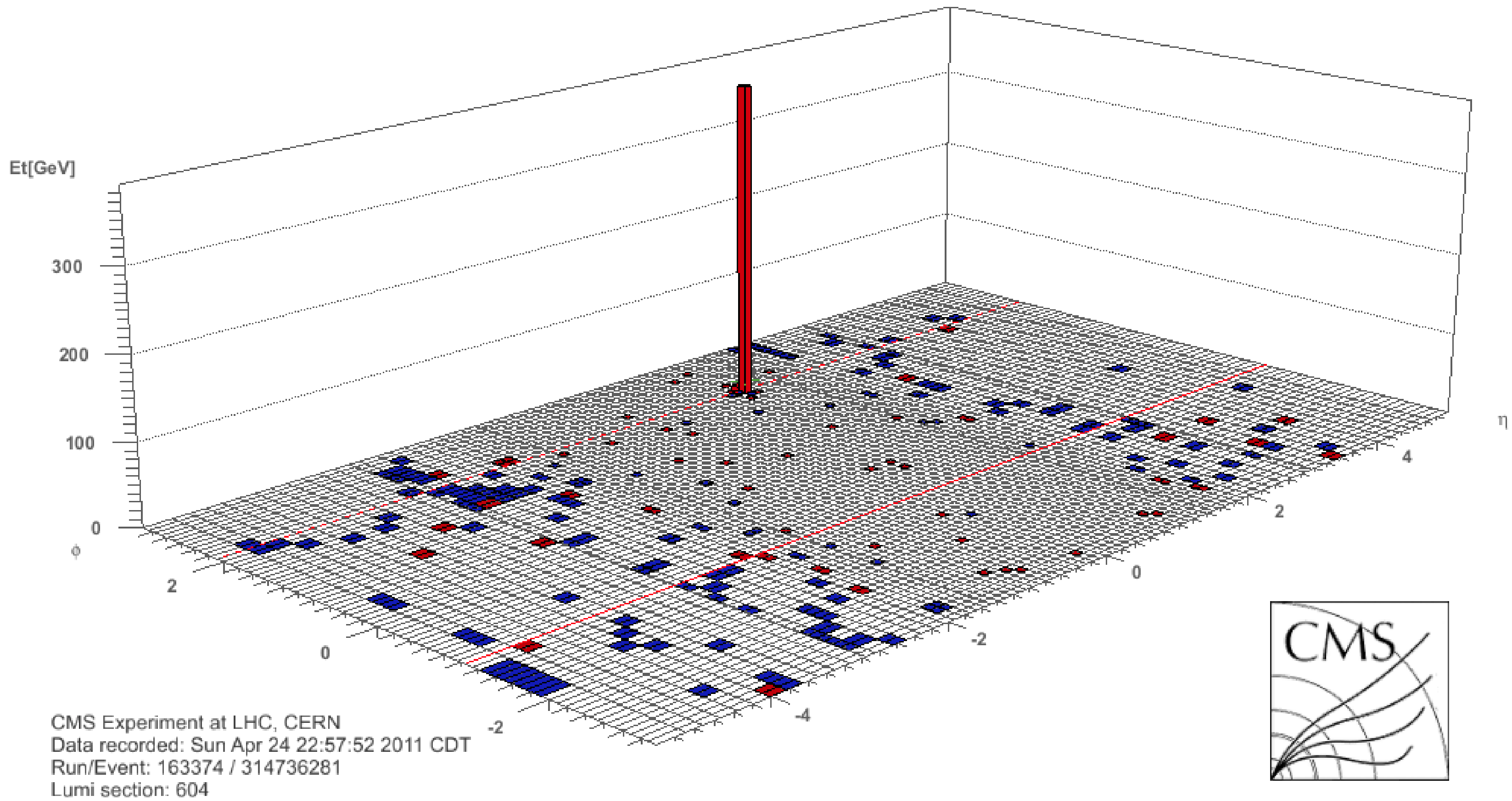
MONOPHOTON – SEARCH DETAILS

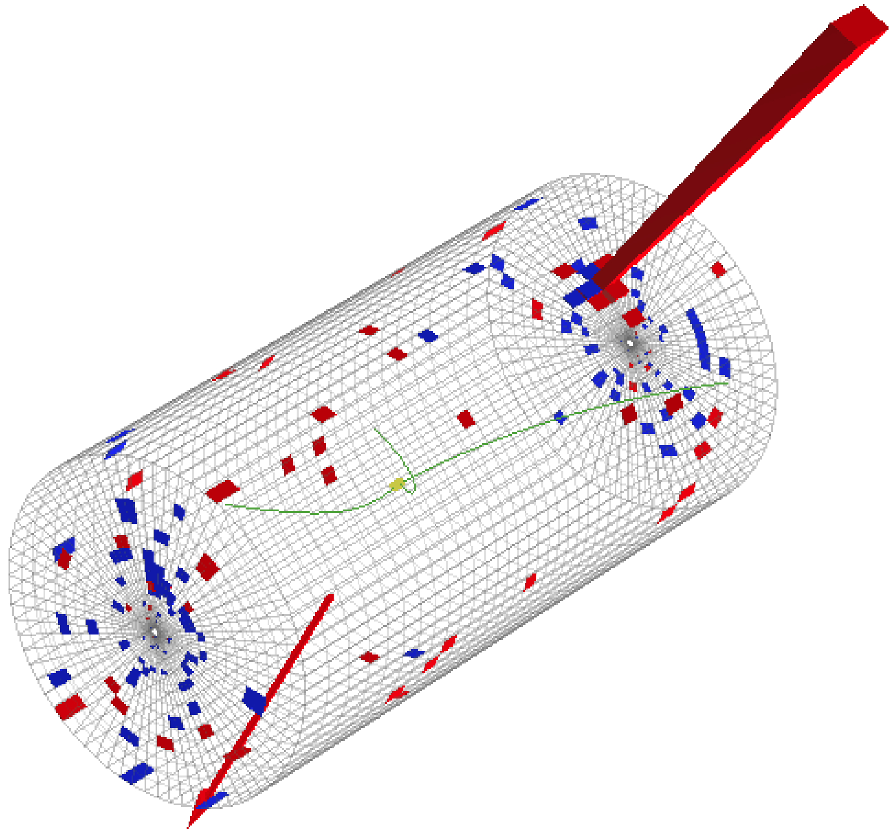
- Require a photon in an event with
  - High energy photon: $p_T(\gamma) > 145$ GeV/c
  - In the central part of the detector: $|\eta| < 1.442$
  - Shower shape consistent with γ: $\sigma_{i\eta i\eta} > 0.013$
  - MET > 130 GeV, using a particle flow method
    - *Single photon plus significant missing energy*

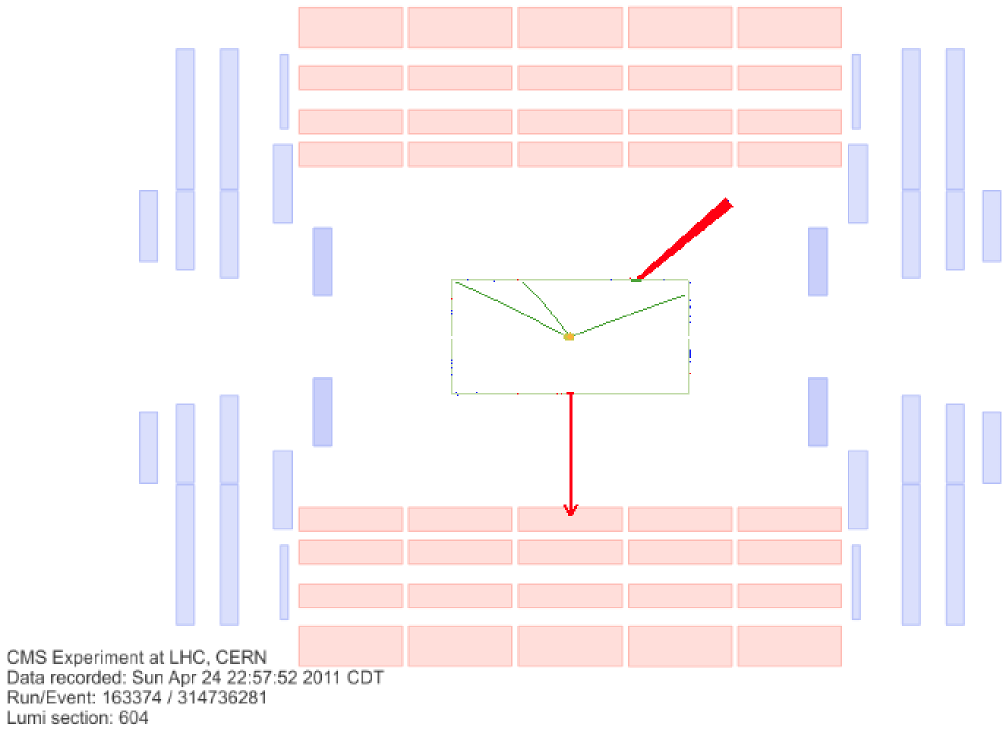


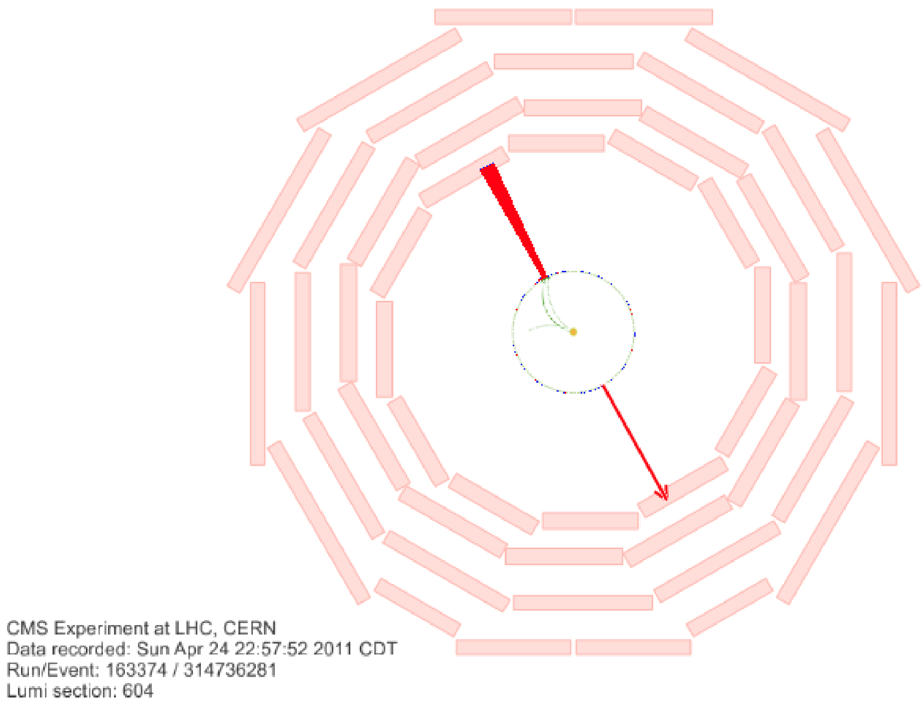
- Remove events with excessive nearby activity
  - No central jet: veto events with p_T(jet) > 40 GeV/c and $|\eta\text{jet}| < 3.0$
  - Veto events with nearby tracks or pixel stubs
  - Veto events with significant electromagnetic calorimeter activity ($\Delta R < 0.4$)
  - Veto events with significant hadronic activity ($\Delta R < 0.4$, $E_{HCAL}/E_{ECAL} < 0.05$)
  - All reconstructed vertices are used for isolation calculations.
    - *Aggressive isolation-based clean-up to ensure purity*

MONOPHOTON – EVENT DISPLAY









Monophoton – Backgrounds

- Backgrounds from pp collisions

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

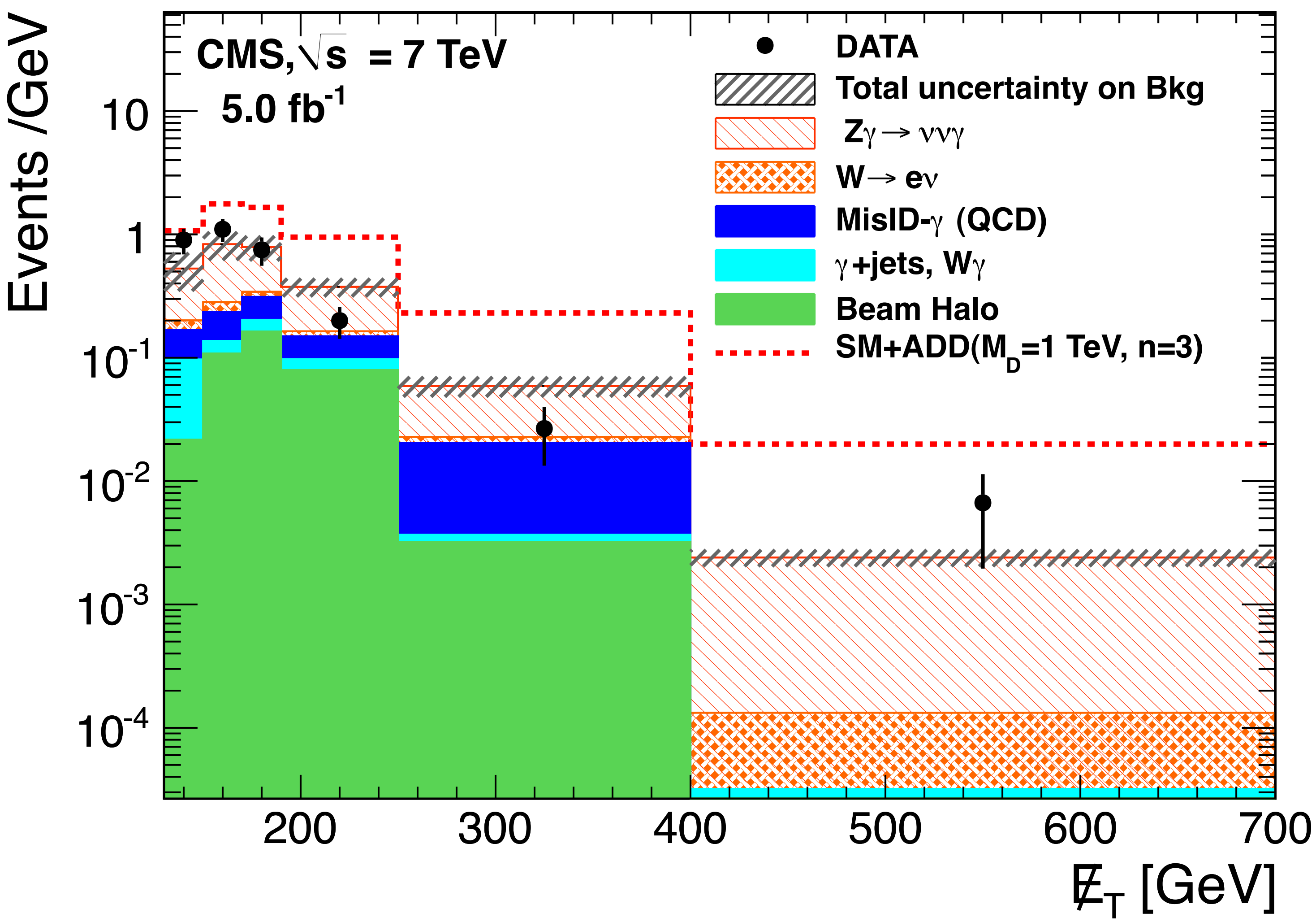
- Backgrounds unrelated to pp collisions

Showers induced by cosmics	identified and removed
Neutron-induced signals	identified and removed
Beam halo	mostly removed; a residual contribution estimated

- Backgrounds estimated from MC and data-driven techniques

  - *Look for excess of events above background (counting experiment)*

Monophoton – Search 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 – good agreement with Standard Model and background expectations*

Monophoton – Dark Matter Signal

- Signal Generation
  - Dark Matter model follows effective theory outlined in earlier slide
  - Madgraph4 + Pythia6 generation with 10 TeV mediator mass
  - Similar sensitivity to spin-dependent and spin-independent (no A^2 factor)
- Acceptance times efficiency for Dark Matter signal
  - Acc. × ε ≈ 0.3, for both vector operator and axial-vector operator
  - Kinematics mainly from ISR photon; Acc. × ε is fairly constant in the range m_χ = 1-1000 GeV
- Systematic uncertainties
  - Stats. uncertainty 1.7%
  - Photon PT uncertainty 2.3%
  - Jet Energy Scale 1.2%
  - MET modelling 0.5%
  - Pile-up modelling 2.4%

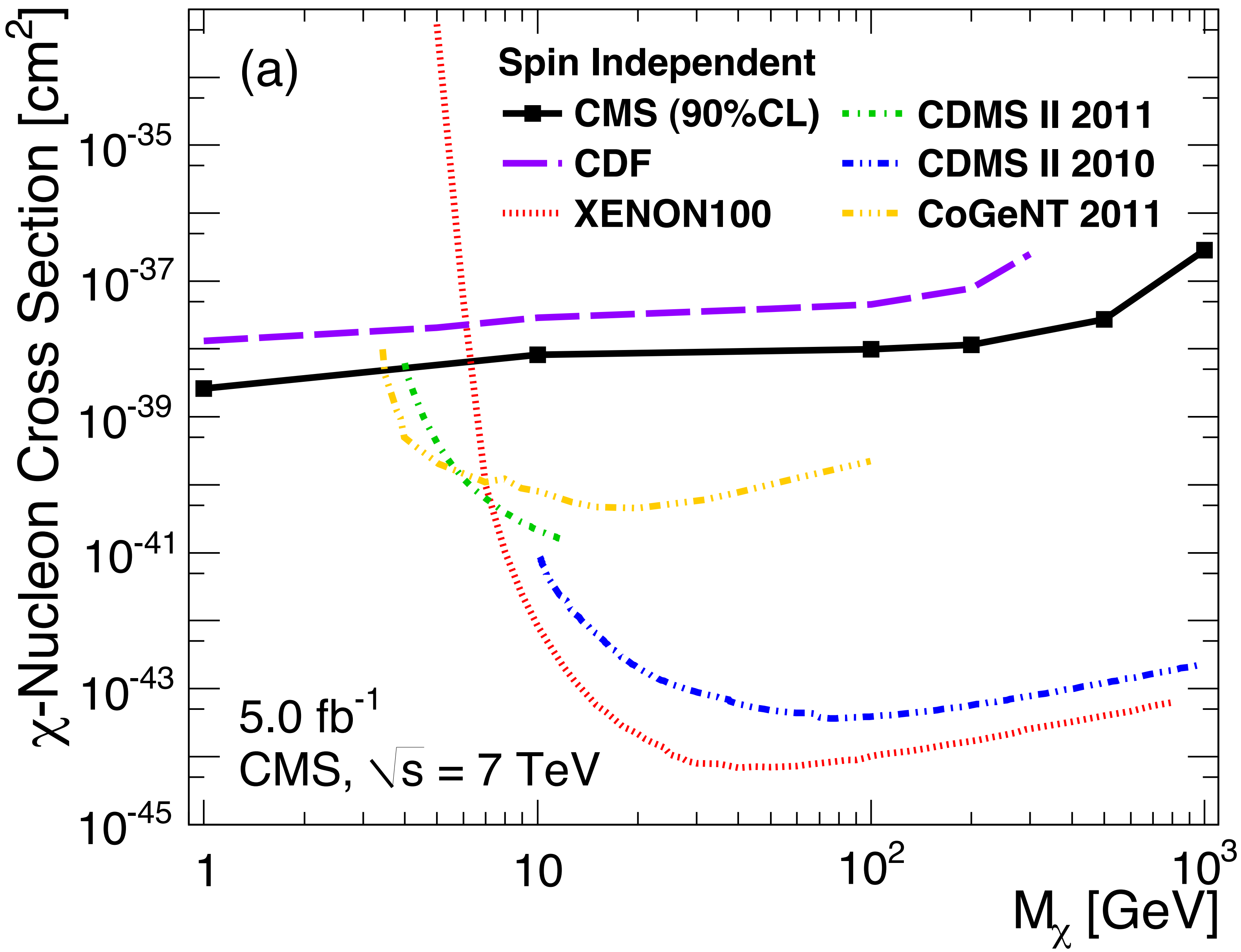
▸ *Good efficiency and modest systematics*

Monophoton – Limit Setting

- Limit-setting
  - CLs limits calculated for an integrated luminosity of 4.67 fb^{-1}
  - 71.9 ± 9.1 expected and 73 observed
  - 90% CL limits shown below, "expected" limits in parenthesis (95% also available)
- Extraction of χ-nucleon cross section
  - Upper limits on cross sections give lower limits on Λ, assuming a Λ^{-4} behaviour
  - Lower limits on Λ then used to plot χ-nucleon cross section limits versus DM mass

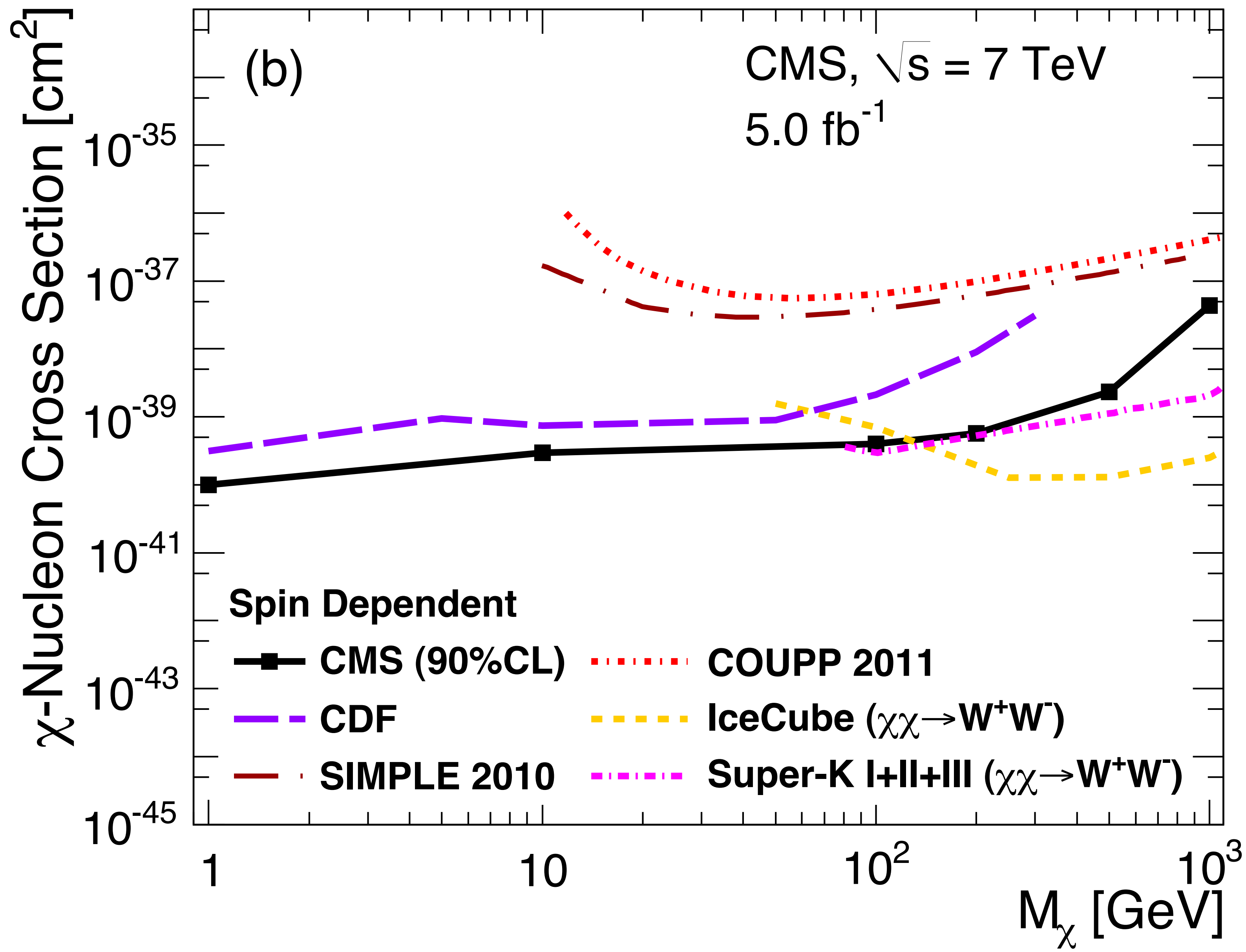
	Spin Independent		*Spin Dependent*	
M_χ [GeV]	Vector		Axial-Vector	
	σ [fb]	Λ [GeV]	σ [fb]	Λ [GeV]
1	14.3 (14.7)	572 (568)	14.9 (15.4)	565 (561)
10	14.3 (14.7)	571 (567)	14.1 (14.5)	573 (569)
100	15.4 (15.3)	558 (558)	13.9 (14.3)	554 (550)
200	14.3 (14.7)	549 (545)	14.0 (14.5)	508 (504)
500	13.6 (14.0)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

MONOPHOTON – SPIN-INDEPENDENT LIMITS



[CDMS II: Science 327 (2010) 1619]
[CDMS 2011: PRL 106 (2011) 131302]
[XENON100: Phys. Rev. Lett 17 (2011) 131302]
[CoGeNT: Phys. Rev. Lett. 106 (2011) 131301]

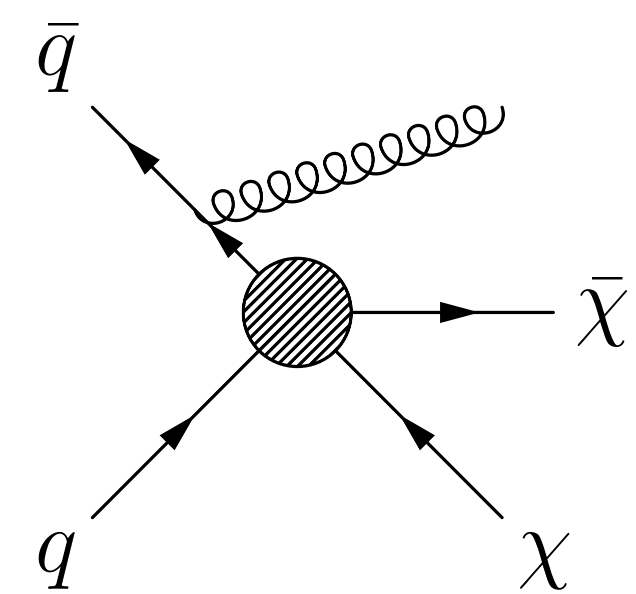
MONOPHOTON – SPIN-DEPENDENT LIMITS



[SIMPLE: PRL 105 (2010) 211301]
[COUPP: PRL 106 (2011) 021303]
[IceCube: PRD 85 (2012) 042002]
[Super-K: ApJ 742 (2011) 78]
[CDF: arXiv:1203.0742 (submitted to PRL)]

MONOJET – SEARCH DETAILS

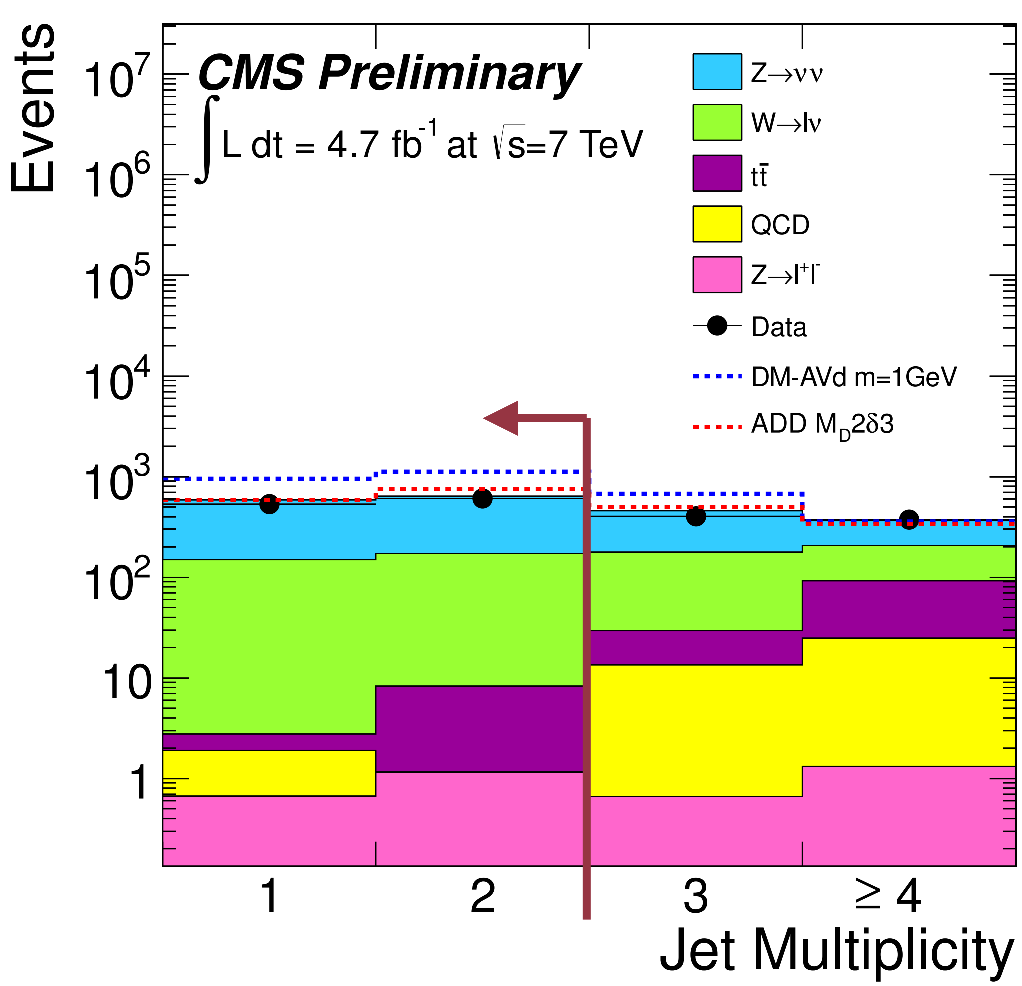
- Select sample of Monojet+MET events (keeping muons)
  - Basic cuts on jet constituents– charged and neutral HAD and EM fractions
  - Removes cosmics, instrumental backgrounds, mismeasured jets
- Basic topological selection
  - MET > 200 GeV, # of Jets = 1 or 2
  - Particle flow jets; anti-k_T with R = 0.5
  - Leading Jet: pT > 110 GeV, $|\eta|<2.4$
  - Second Jet: pT > 30 GeV
  - $\Delta\varphi$(jet1,jet2) < 2.5
- Monojet Signal Sample (Lepton Rejection)
  - Reject events with e, μ isolated in a cone of ΔR = 0.3
  - Reject events with tracks isolated in a cone of ΔR = 0.3
  - MET > 350 GeV for DM search
- Data-driven Background Estimation (Lepton Identification)
  - Isolated muon > 20 GeV/c
  - Obtain Z+jet sample from M(μμ), W+jet sample from $p_T(\mu)$+MET

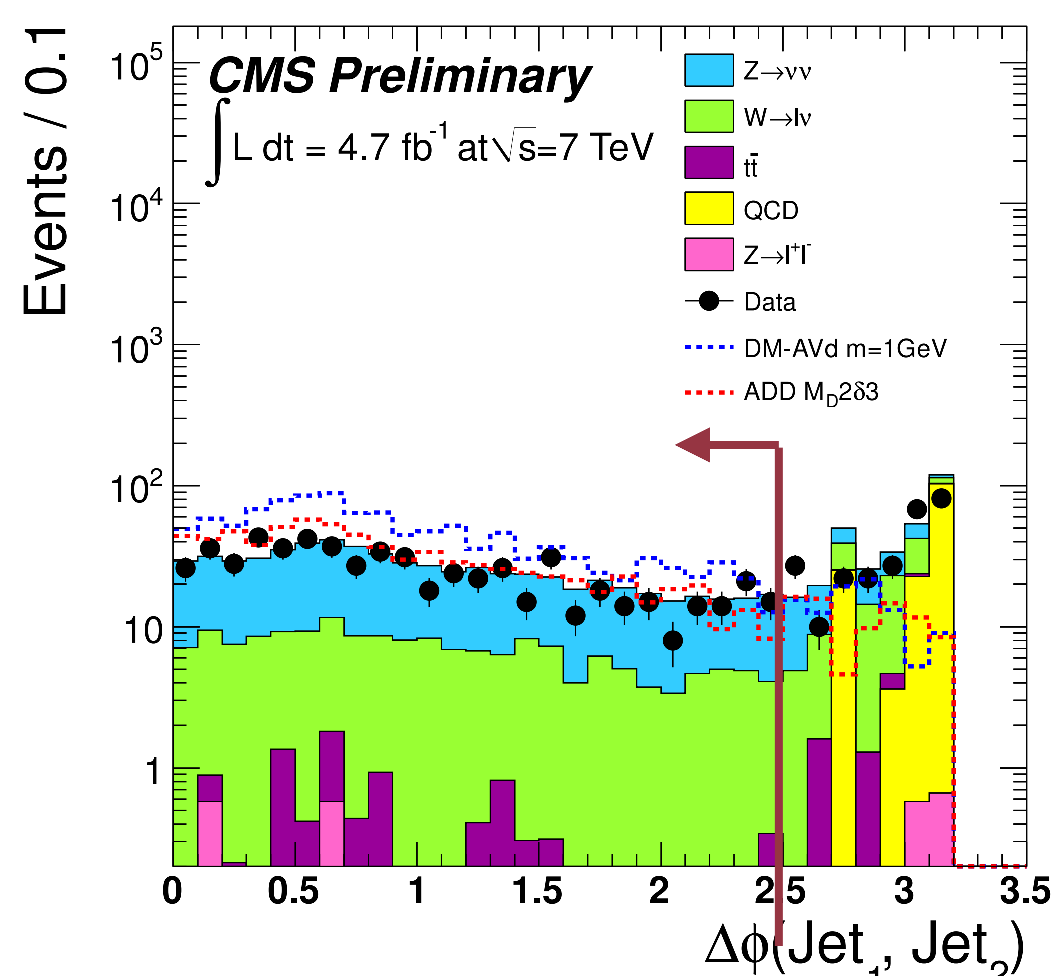


MONOJET – BASIC SELECTION

- Basic topological selection
  - MET > 200 GeV, # of Jets = 1 or 2
  - Leading Jet: pT > 110 GeV, |η|<2.4
  - Second Jet: pT > 30 GeV
  - Δφ(jet1,jet2) < 2.5

QCD rejection accomplished by topological cuts



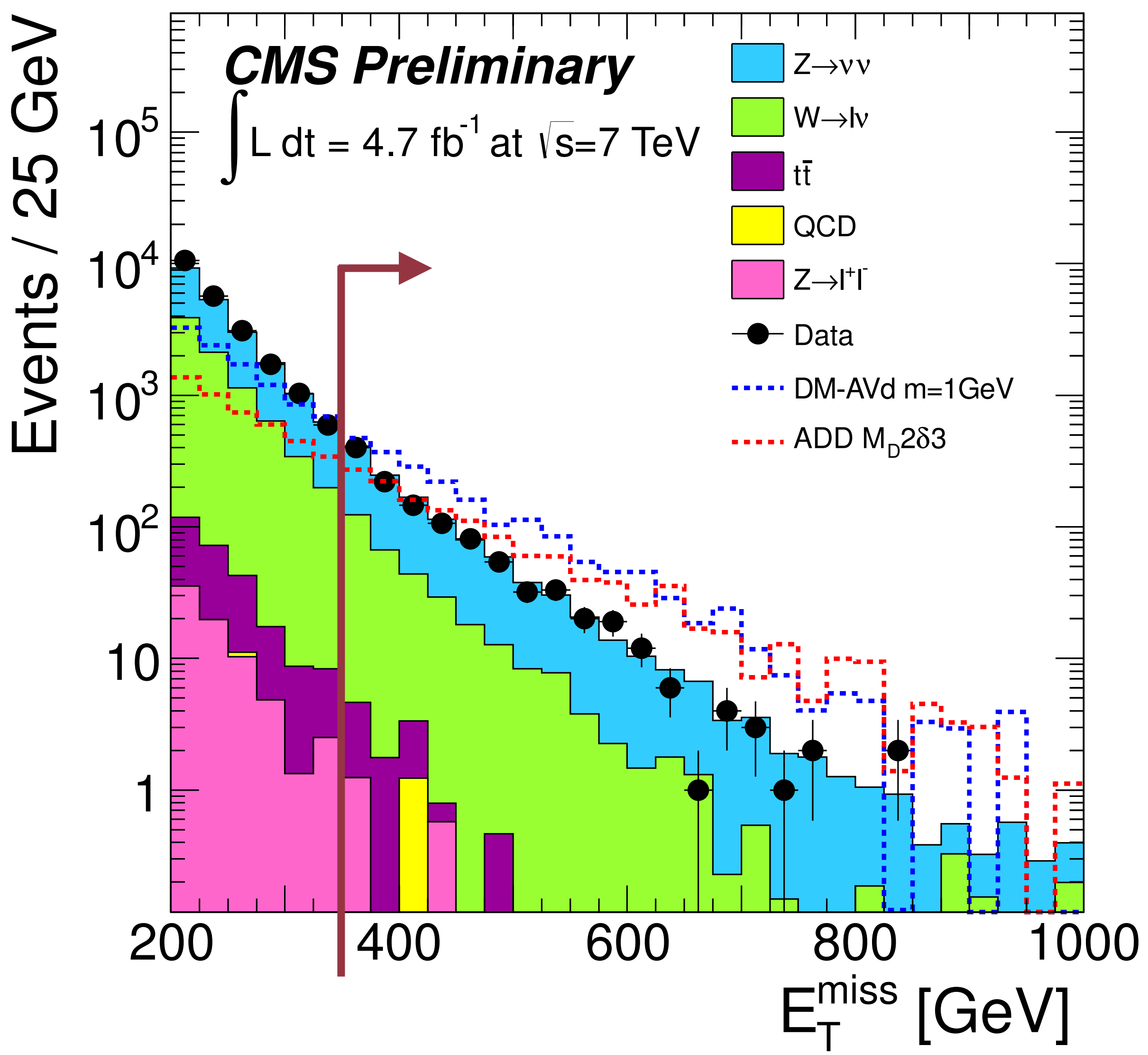


Monojet – Data Sample

- Final monojet signal sample obtained by
  - Rejecting events with isolated e, μ
  - Rejecting events with isolated tracks

- Good agreement for full MET range
  - Sensitivity to new physics (DM, ADD) in the tails
  - Optimise search for best expected sensitivity to new physics
  - MET > 350 GeV for DM search

    ‣ *Search high MET events for DM*



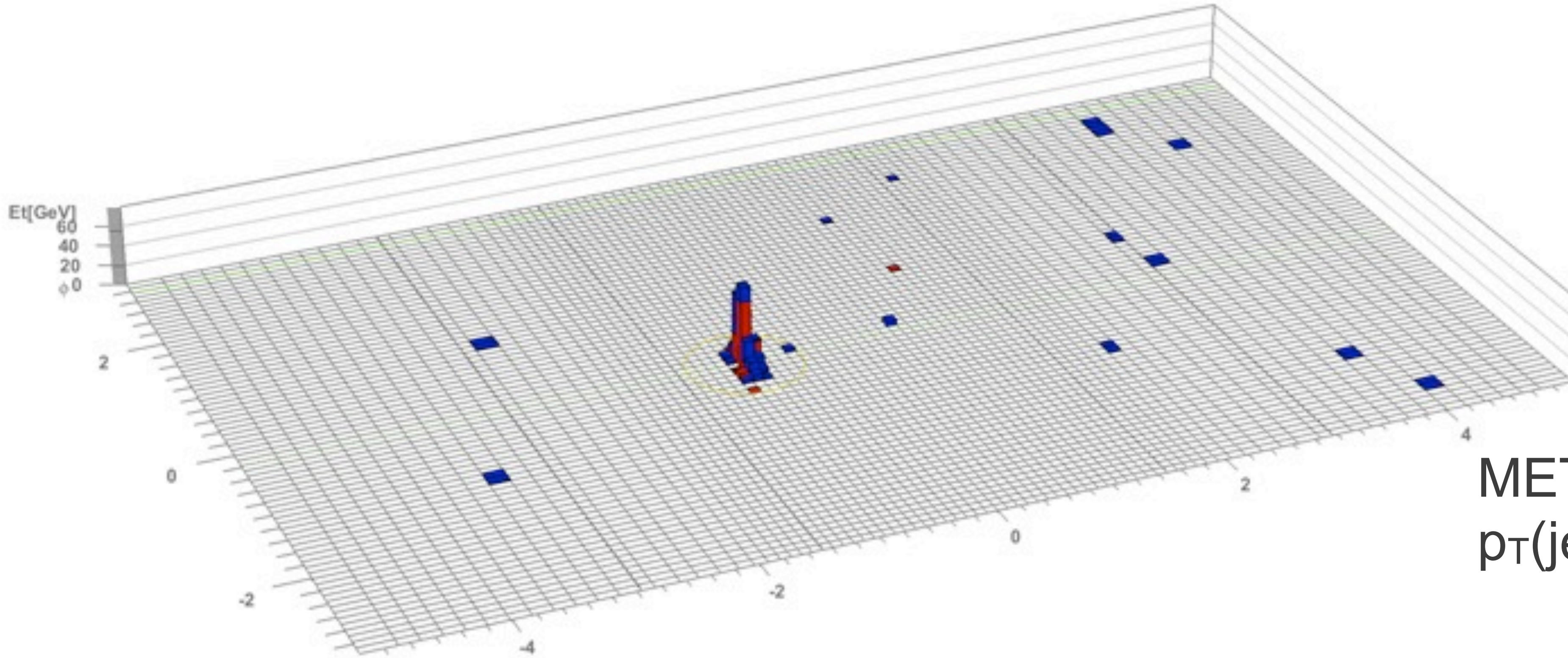
MONOJET – ANALYSIS CUT FLOW

- Primary backgrounds normalised to data-driven estimation
- Remaining bkgnds after full event selection: Z(vv) (≈70%), W+jets (≈30%),
- Other backgrounds from QCD, top, Z+jets negligible (≈1%) – estimated from MC

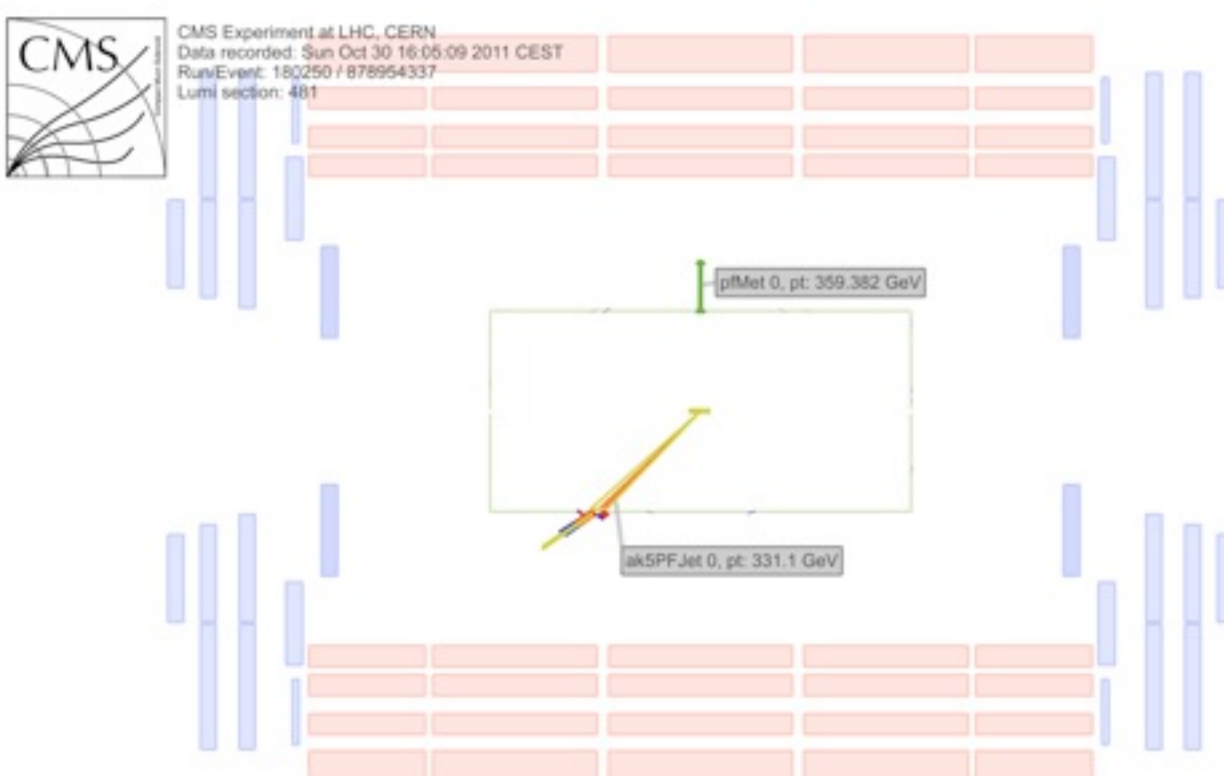
  - *Good agreement between data and SM backgrounds*

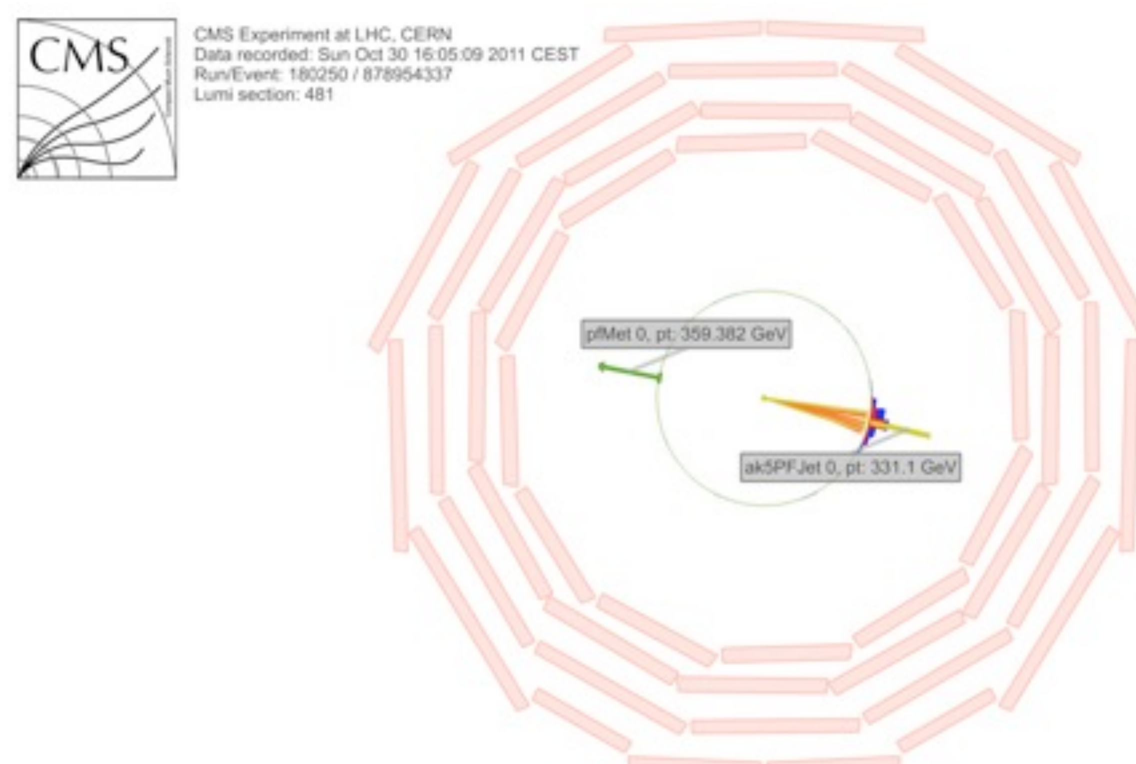
Requirement	W+jets	$Z(\nu\nu)$ +jets	$Z(\ell\ell)$ +jets	$t\bar{t}$	Single t	QCD multijet	Total bgd	Data
$E_T^{miss} > 200$ GeV	55269	30312	4914	12455	1090	14959	118999	104485
$p_T(j_1) > 110$ GeV/c, $\lvert\eta(j_1)\rvert < 2.4$	52100	28267	4590	11107	968	14743	111775	100658
$N_{jets} \leq 2$	37112	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

A Monojet Event



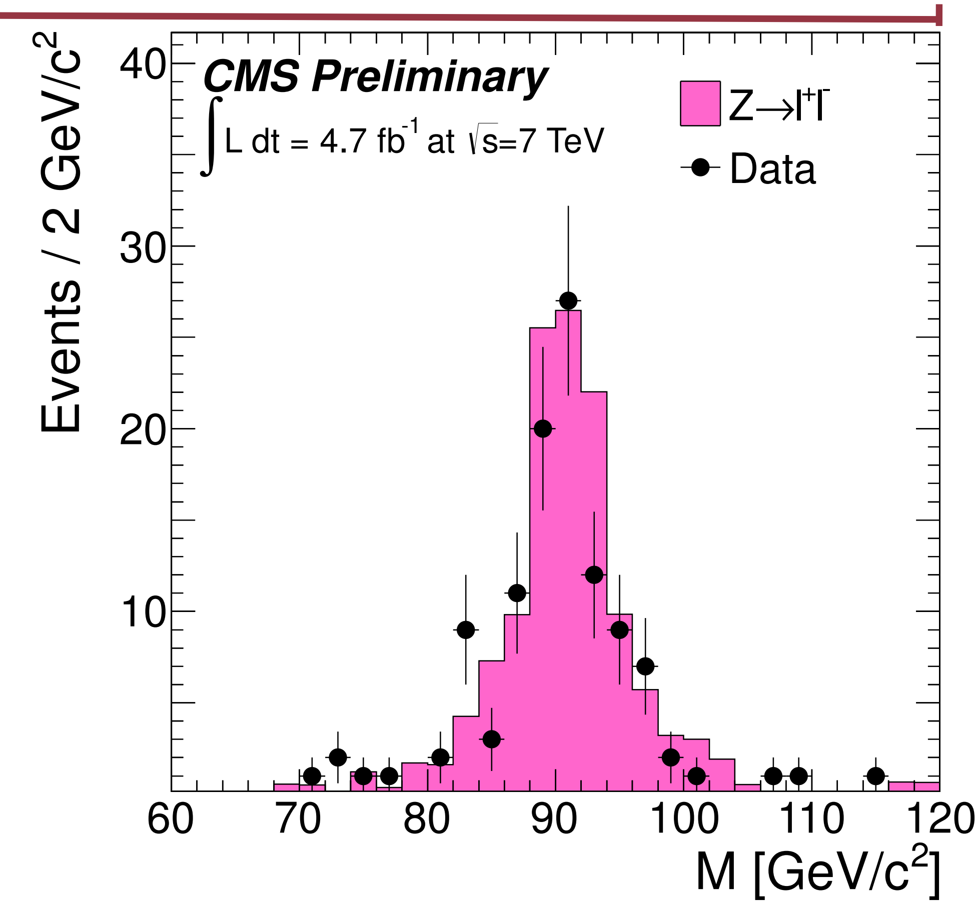
MET = 359 GeV
p_T(jet1) = 331 GeV



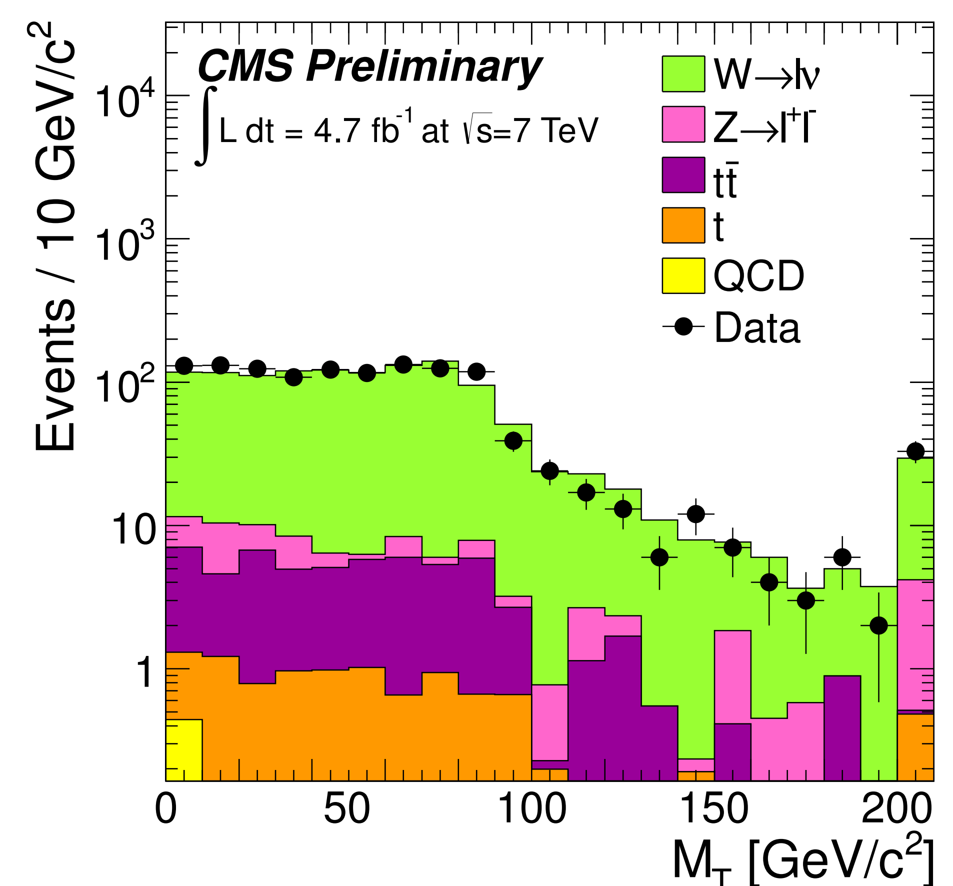


MONOJET – BACKGROUND NORMALISATION

- Data-driven estimation of Z+jets → νν+jets
  - Z+jets → μμ+jets control sample derived directly from our monojet data sample
  - Require two muons passing selection
  - Invariant mass 60-120 GeV, opposite sign
  - Uncertainty in method is 10.4% mainly from stats (9.5%)



- Similar for W+jets → νl+jets, where lepton is "lost"
  - lepton lost if outside detector acceptance or not reconstructed/isolated
  - Require single lepton and M_T between 50-100 GeV
  - Primary uncertainties from error on acceptance (7.7 %) and selection efficiency (6.8 %)
  - Uncertainty in method is 11.3%



Data-driven measure of main backgrounds

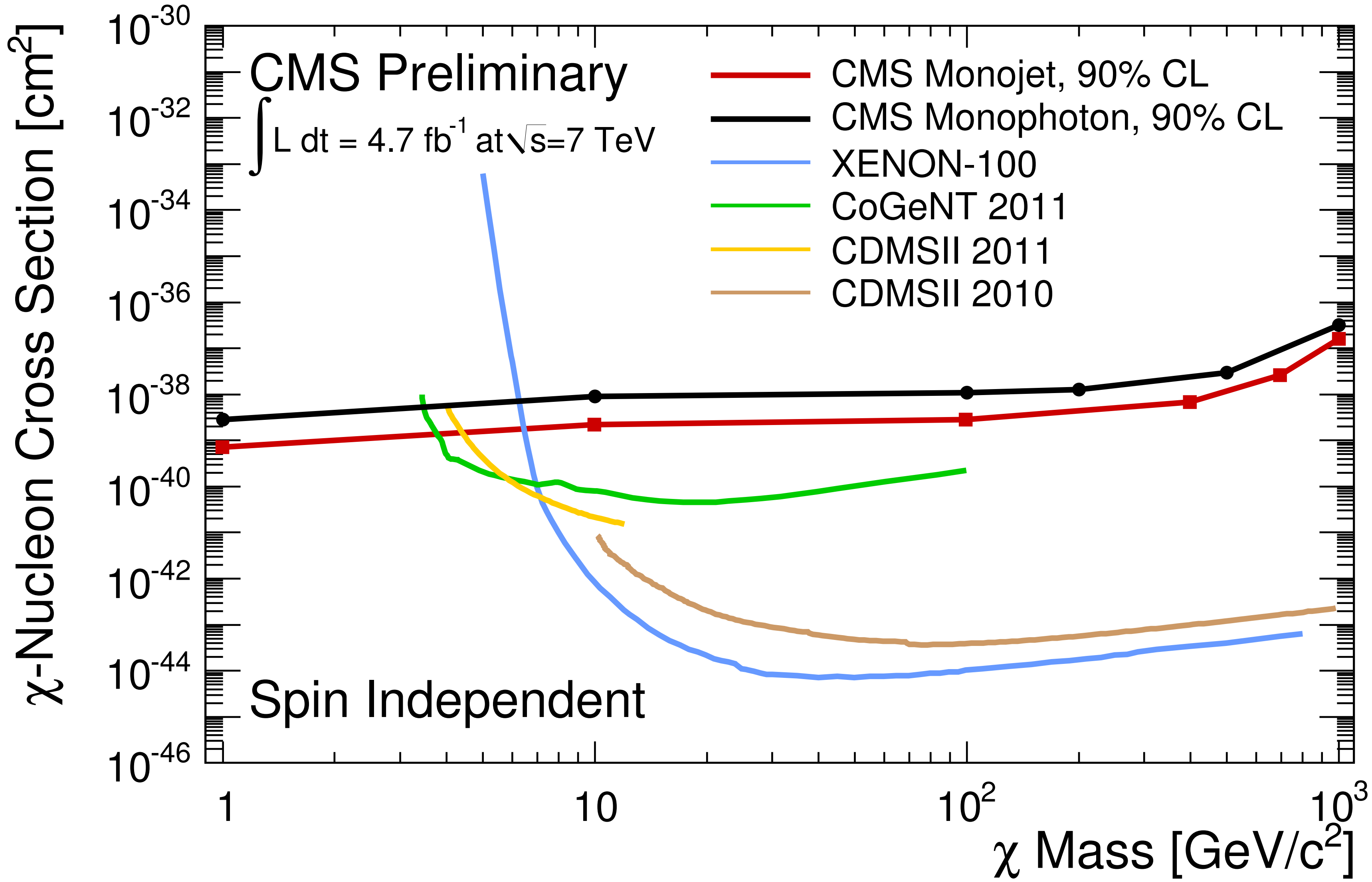
Monojet – Dark Matter Signal

- Monojet Signal Generation
  - Madgraph4 + Pythia6 generation with 40 TeV mediator mass
- Systematic uncertainties ≤15%, main contributions from
  - Jet Energy Scale ~10%
  - PDF (PDF4LHC) 2-4%
  - Jet Energy Resolution 2%
  - Luminosity 4.5%
- Final numbers for MET > 350 GeV: 1224 ± 101 background, 1142 data

  - *Good efficiency and modest systematics → limit-setting as before*

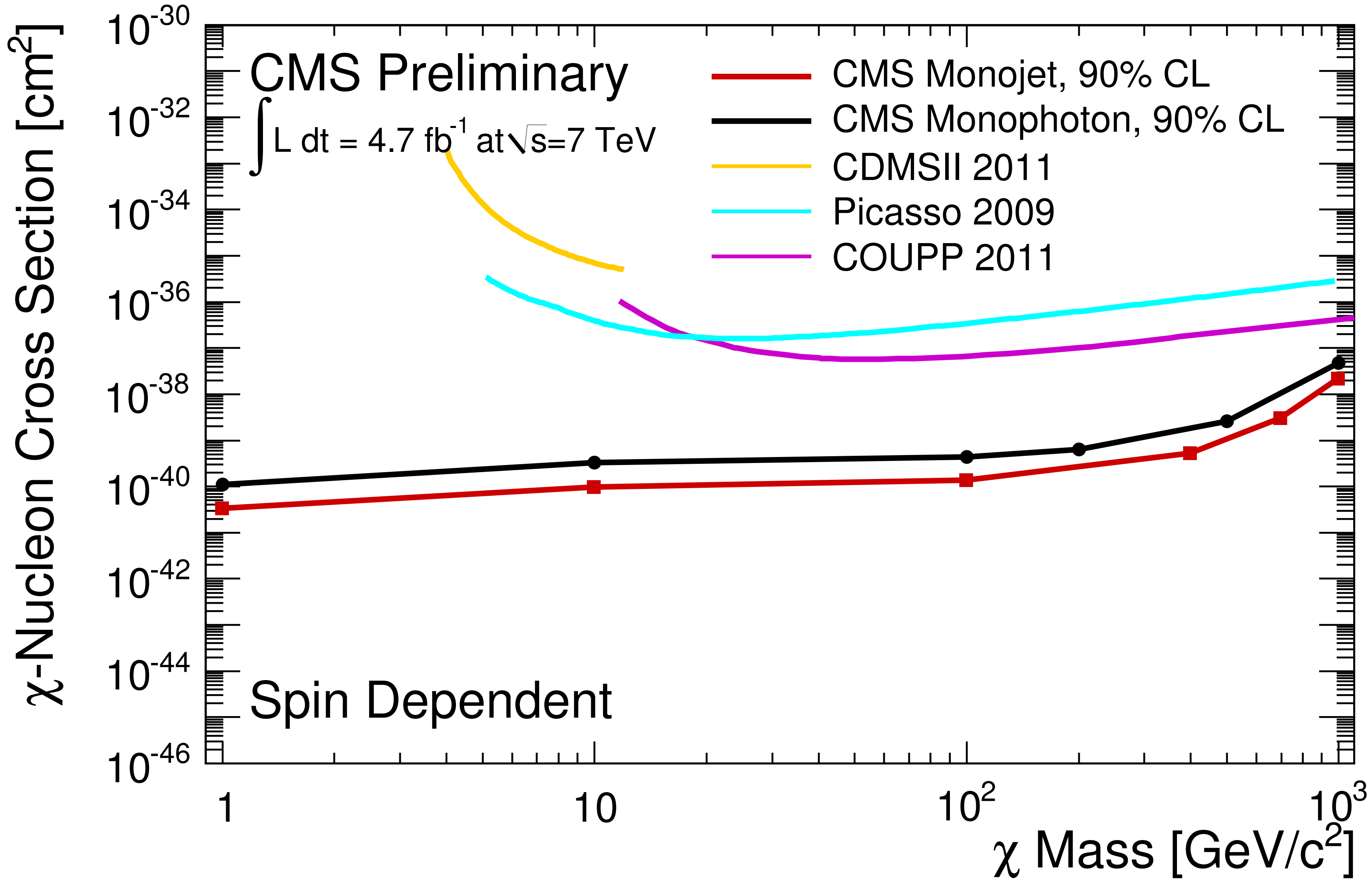
	Spin-dependent		Spin-independent	
M_χ (GeV/c^2)	σ(cm^2)	Λ(GeV)	σ(cm^2)	Λ(GeV)
1	3.37×10^{-41}	730	7.20×10^{-40}	776
10	9.83×10^{-41}	744	2.12×10^{-39}	789
100	1.33×10^{-40}	718	2.65×10^{-39}	776
400	5.14×10^{-40}	514	6.66×10^{-39}	619
700	2.95×10^{-39}	332	2.62×10^{-38}	440
1000	2.15×10^{-38}	202	1.57×10^{-37}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

DARK MATTER SPIN-INDEPENDENT LIMITS



- *Best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by direct detection experiments*

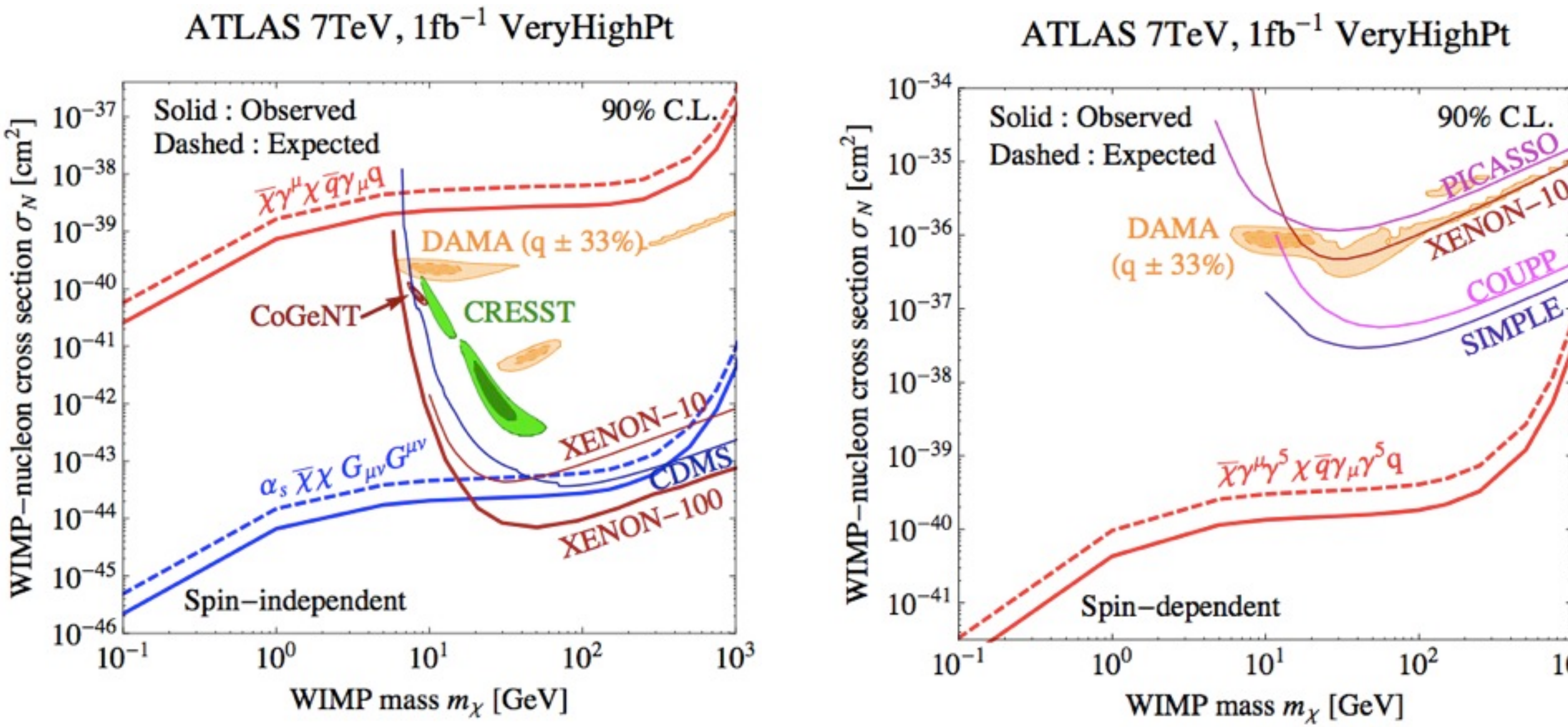
DARK MATTER SPIN-DEPENDENT LIMITS



- *Limits represent the most stringent constraints by several orders of magnitude over entire 1-1000 GeV mass range*

ATLAS Results Coming Very Soon!

- Expectations of excellent ATLAS limits from theory colleagues...
- ATLAS now looking at "monojets" with more than one jet



[Fox, Harnik, Kopp, Tsai: arXiv:1109.4398v1]

DARK MATTER LIMITS FROM CDF

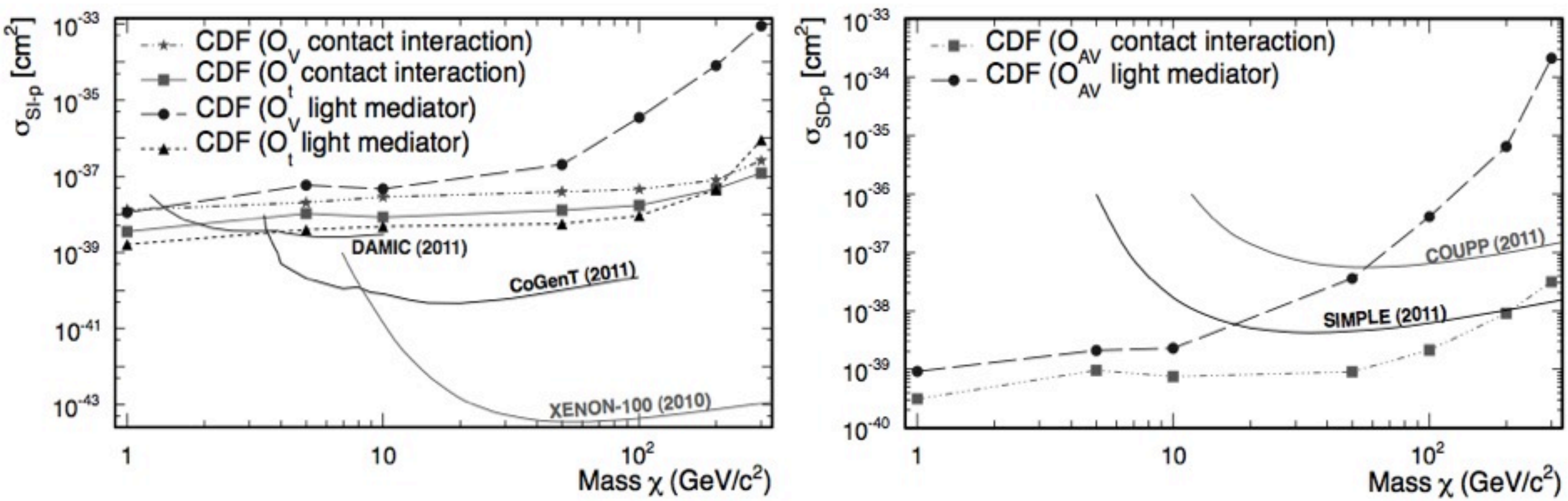


FIG. 2: Comparison of CDF results to recent results from DAMIC [34], CoGeNT [4], XENON-100 [35], SIMPLE [36], and COUPP [37]. Spin-independent (left) and spin-dependent (right) bounds are shown for the operators (defined in text) $\mathcal{O}_{AV}$, $\mathcal{O}_V$, and $\mathcal{O}_t$, assuming contact interactions. For comparison we also display CDF bounds assuming light mediators.

- *Limits from CDF posted in early March…*

[http://arxiv.org/abs/1203.0742]

Conclusions

Presented CMS searches for new physics in monojet and monophoton channels using 2011 dataset (~5 fb^{-1}).

Predictions for SM background consistent with observed data, *no excess* found. Limits set on Dark Matter production, resulting in a significant extension of previously excluded parameter space:

- *For spin-independent models, limits for low mass DM below 3.5 GeV, a region as yet unexplored by the direct-detection experiments.*
- *For spin-dependent models, limits represent stringent constraints over the entire 1-1000 GeV mass range studied.*

Further reading: EXO-11-059 (monojet) and EXO-11-096 (monophoton) at https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO