Dark matter searches at the LHC

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on behalf of the CMS and ATLAS collaborations

Caltech

International Workshop on Double Beta Decay and Underground Science, DBD2014
Hawaii's Big Island

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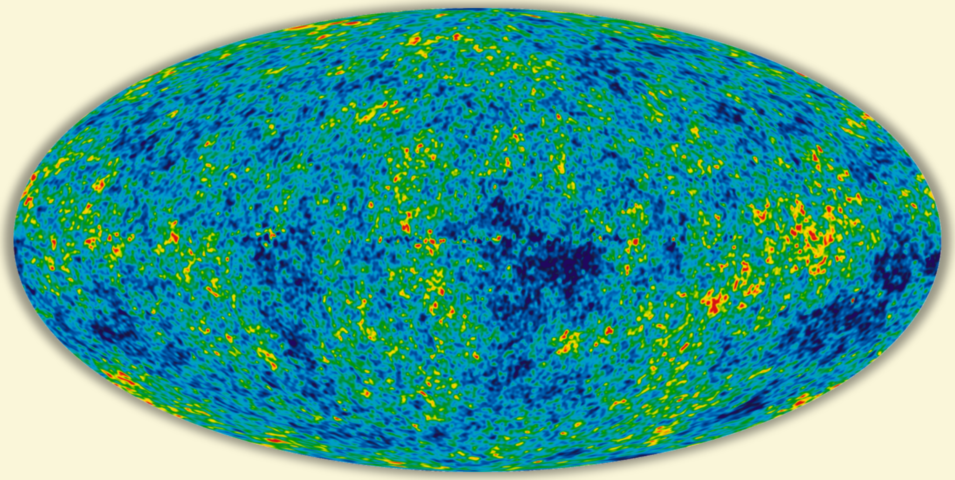
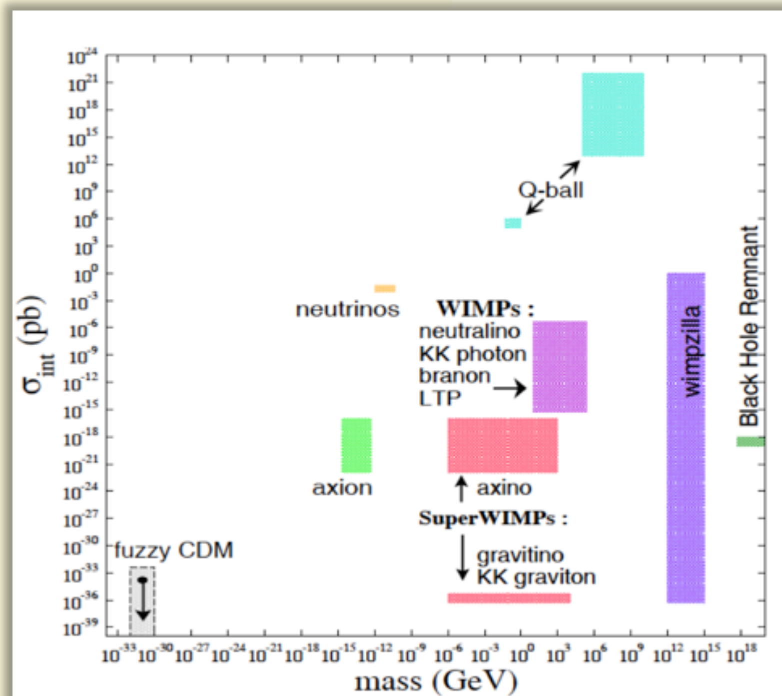
DM Candidates

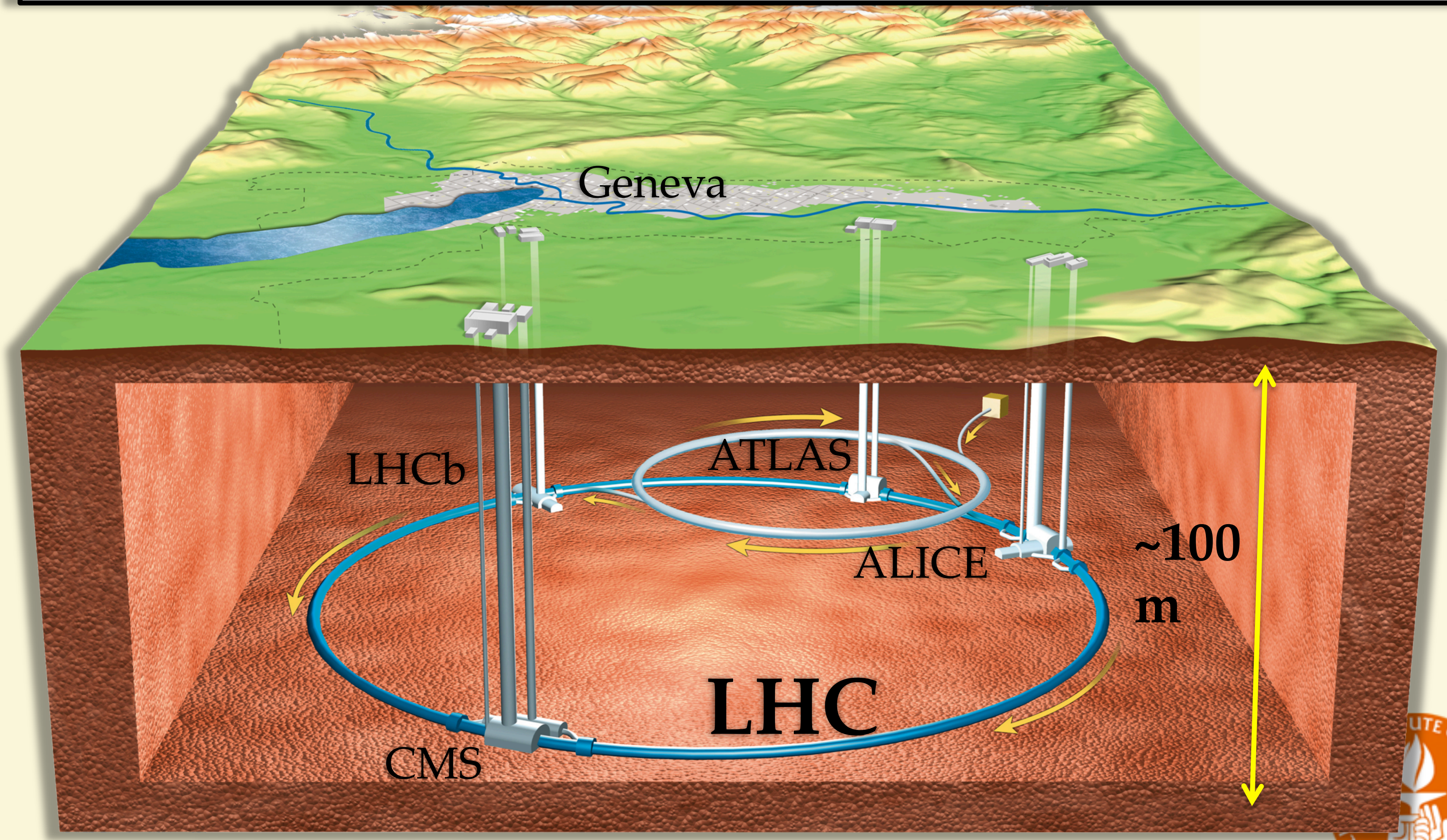




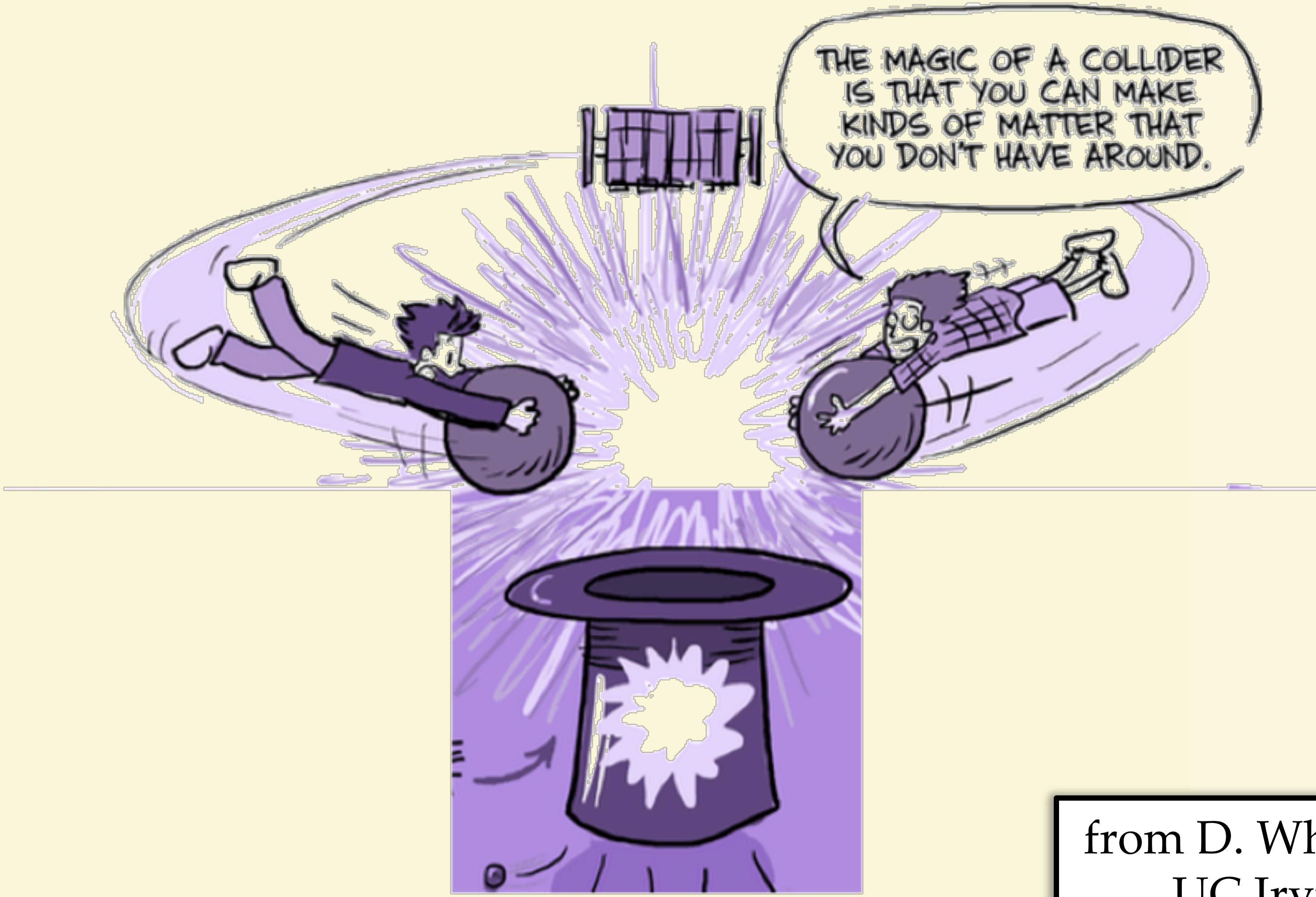
- *Many models of DM (J.Feng arXiv:1003.0904):*
  - WIMP: naturally arise in SUSY, UED; "WIMP" miracle → 0.1-1 TeV
  - Axion (Axino): solve strong-CP problem, can be very light
  - Gravitino: SUSY; can inherit WIMP miracle if NLSP
  - More *"exotic"*: primordial black holes, wimpzilla, sterile neutrino, etc…

The Large Hadron Collider

Proton-proton collisions at √s=7, 8 TeV (13-14 TeV in 2015)

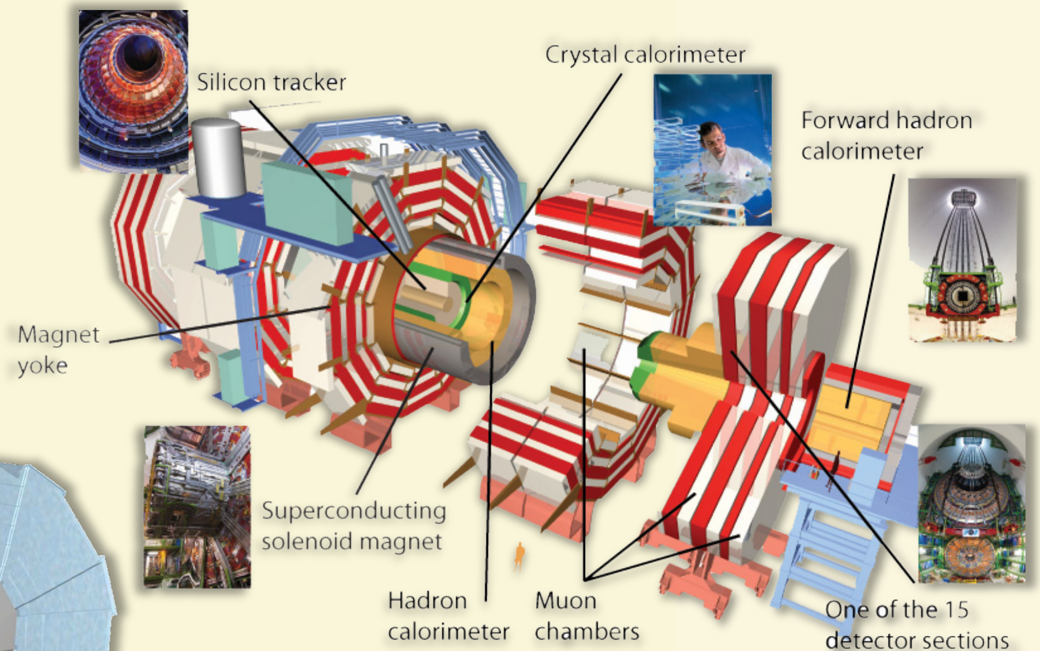


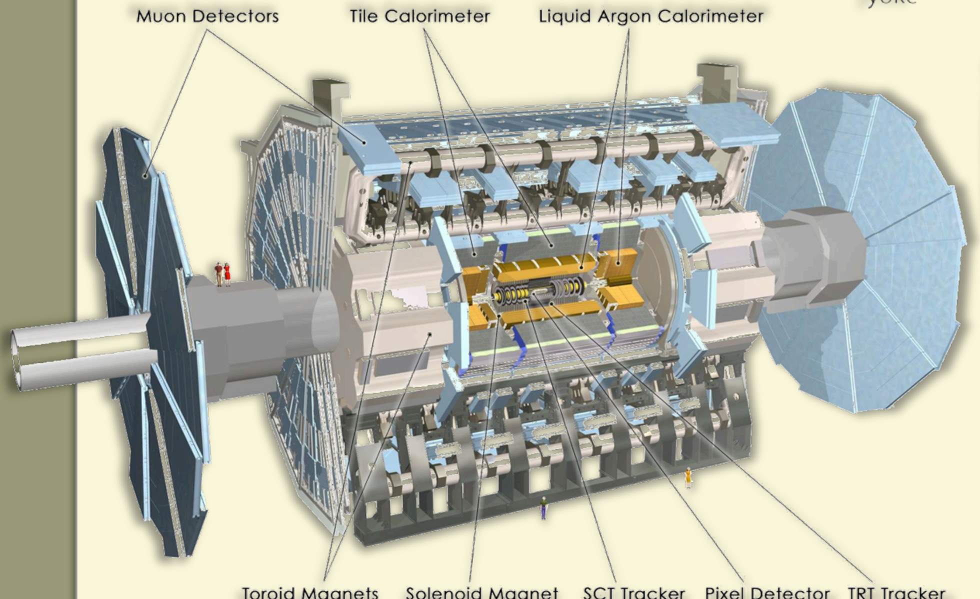
What are colliders good for?



from D. Whiteson, UC Irvine

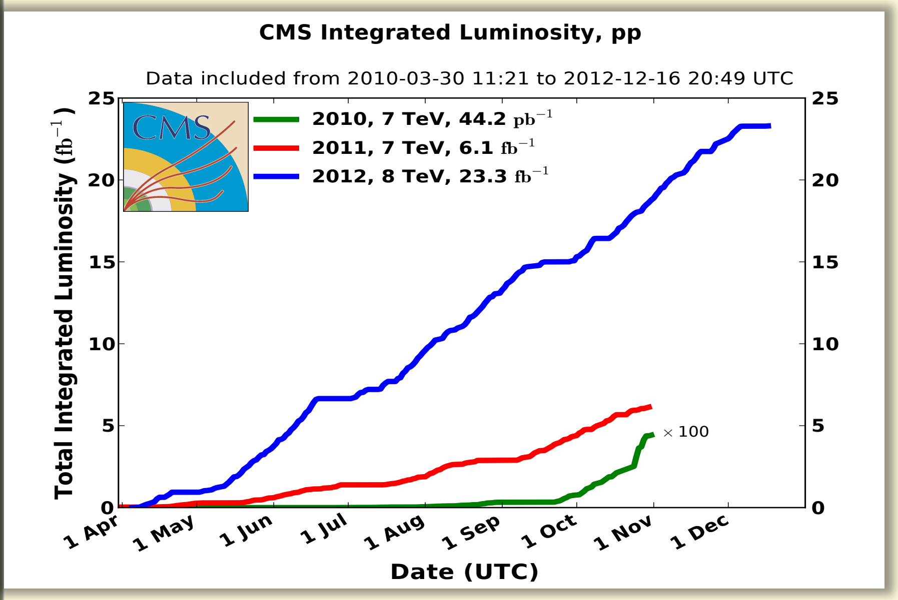
The CMS and ATLAS detectors

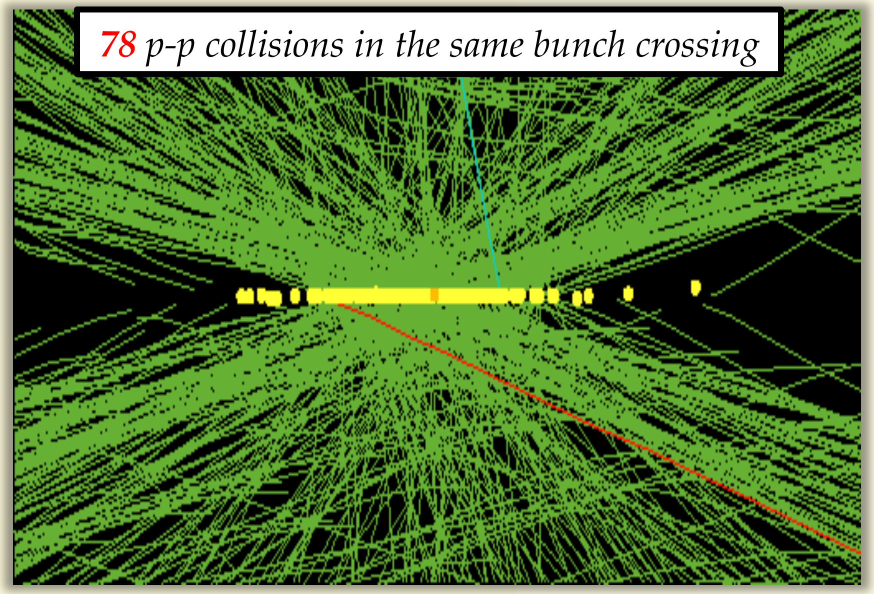




"General purpose" detectors to cover full physics program with LHC

LHC performance

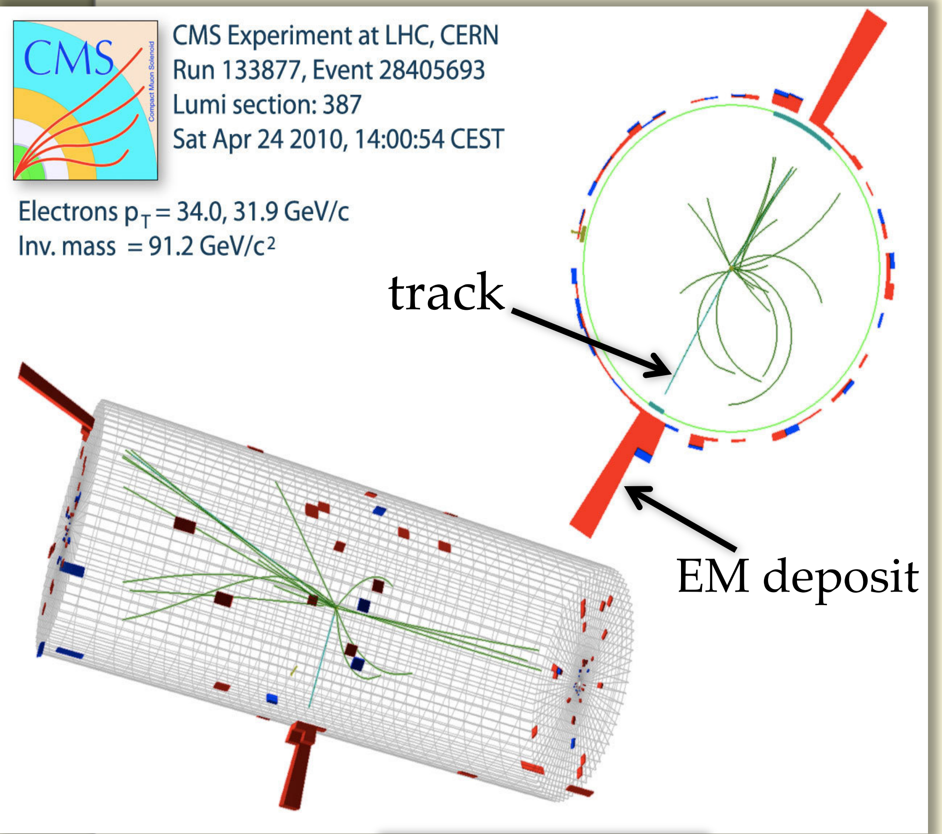




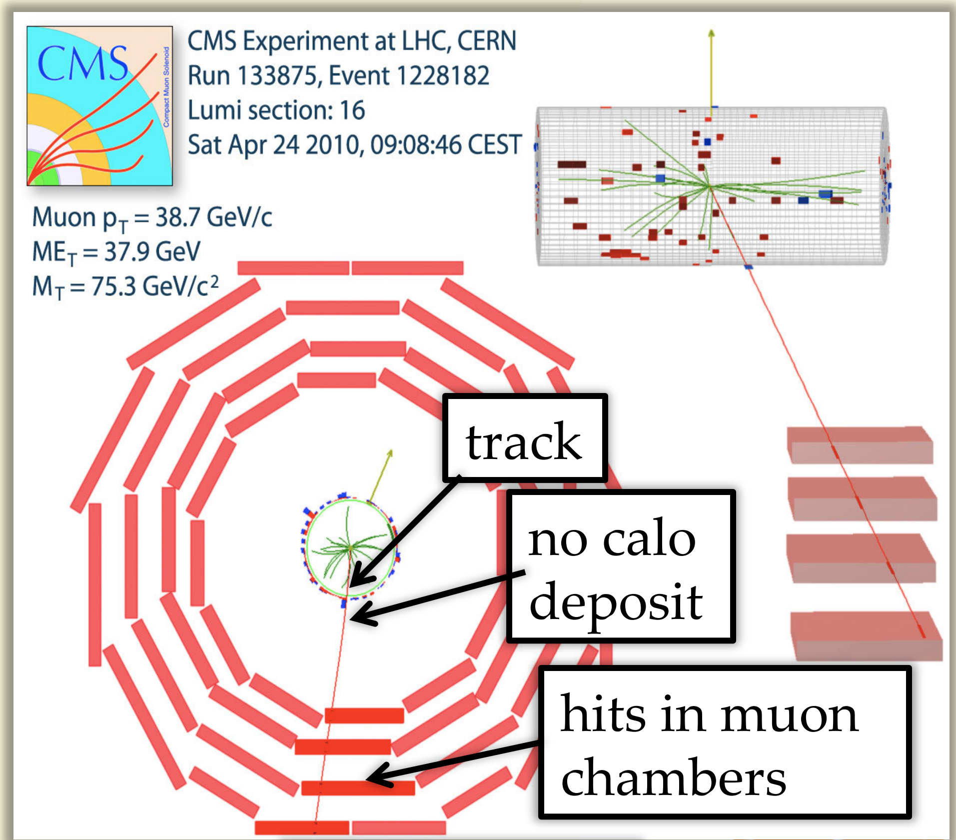
- Peak luminosity of **7.67** $nb^{-1}sec^{-1}$
- Inelastic proton-proton cross section at 8 TeV: ~70 mb
  - **~540M p-p** interactions per second @ peak luminosity (70x7.67)
  - **20M** times proton bunches cross each other per second (when bunch spacing is 50ns)
  - The average numbers of interaction per crossing (pile-up): **27**
- Approximately **15 PB/year** of data
  - Huge amount of data to process: **400M jobs/month** running on the Grid

Event reconstruction

- Charged leptons (e, μ, τ)



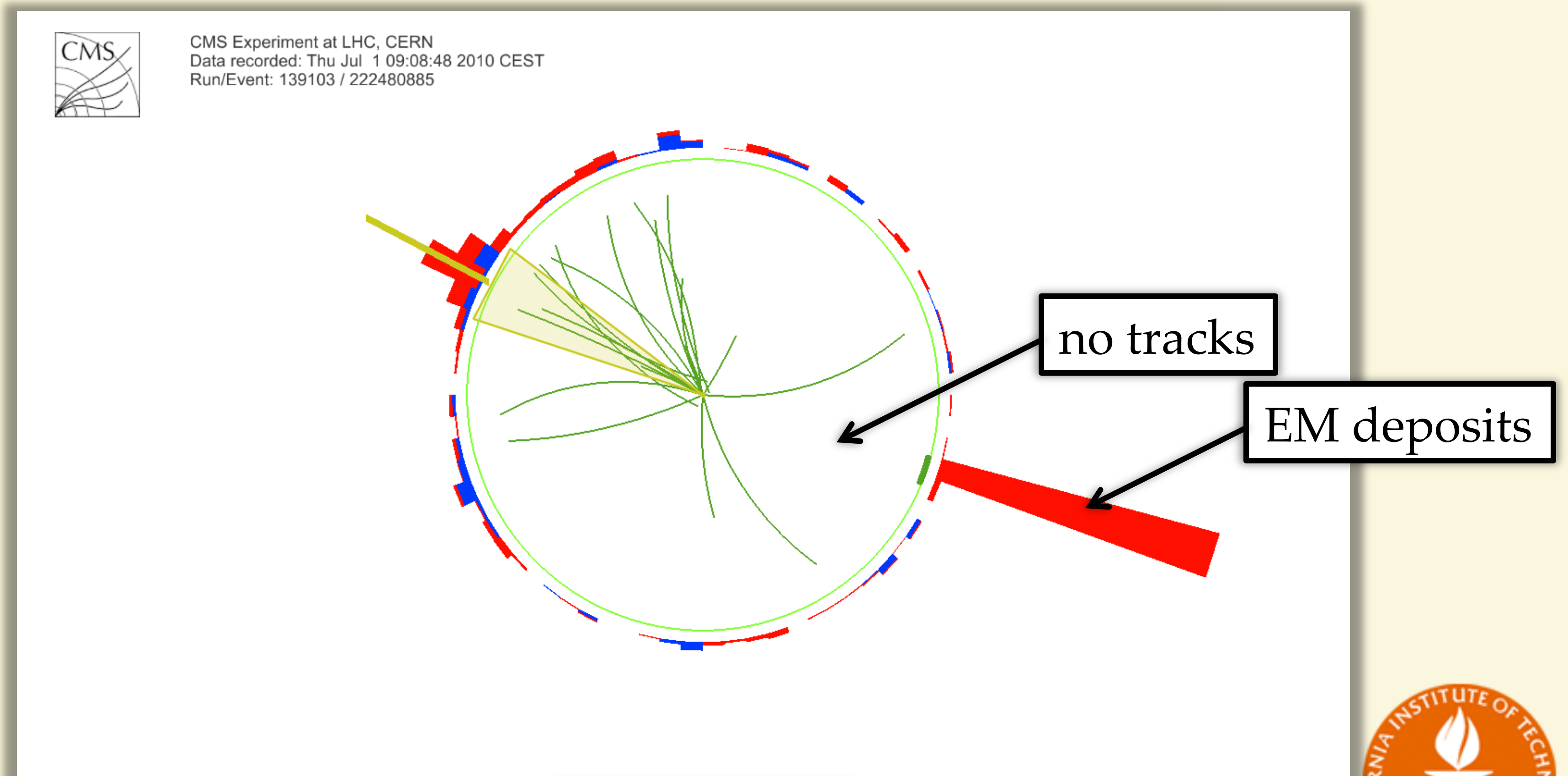
$Z \rightarrow ee$ event



$W \rightarrow \mu\nu$ event

Event reconstruction

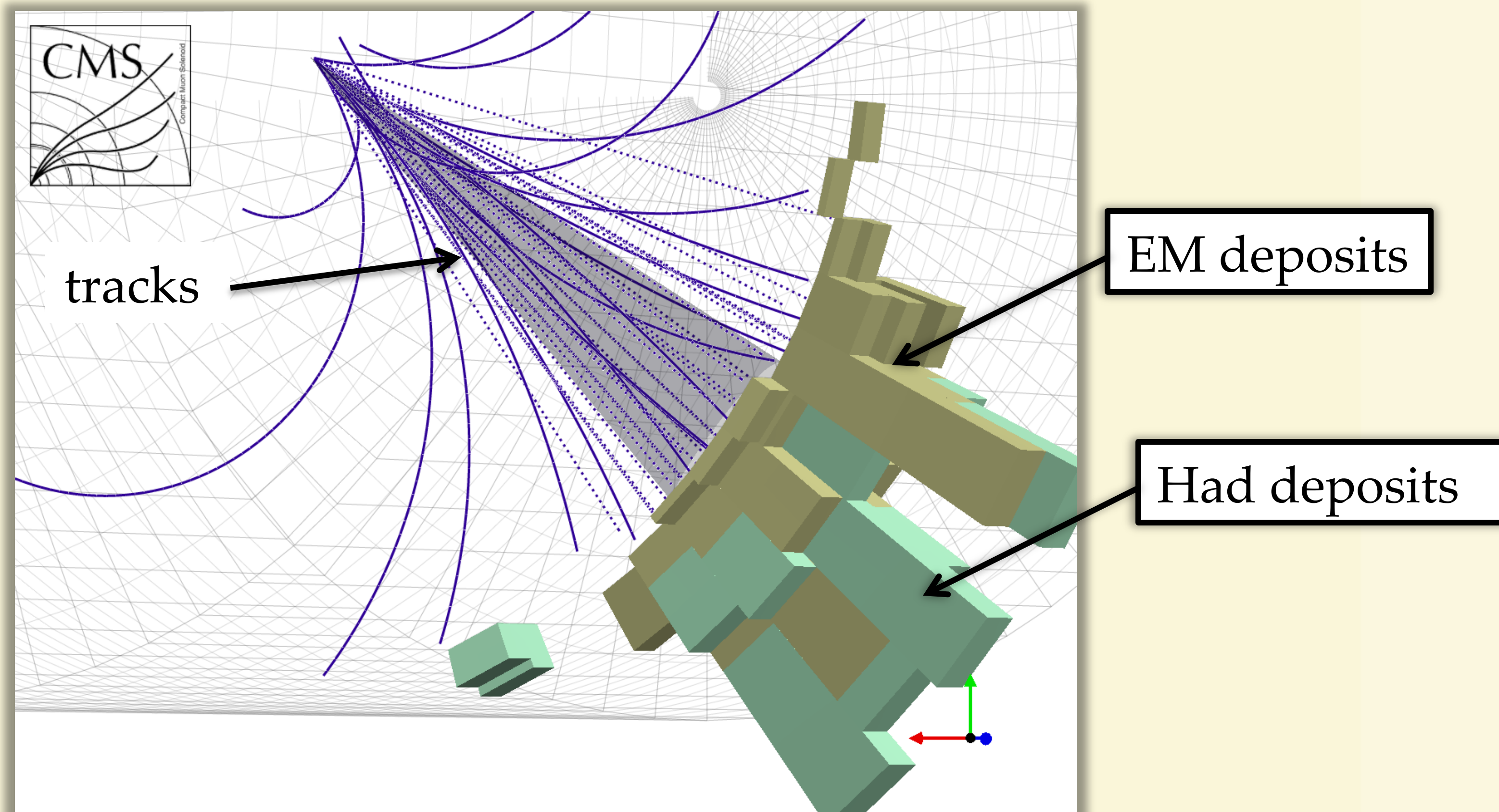
- Photons
  - Identify by shower-shape in ECAL, no/little energy in HCAL



γ+jet event

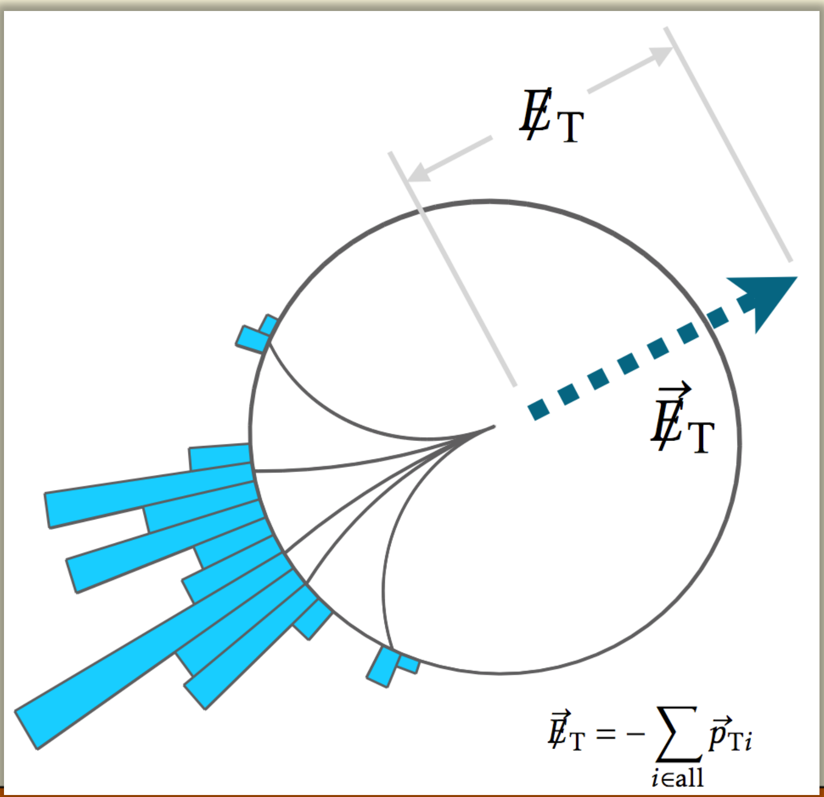
Event reconstruction

- Jets: collimated spray of stable particles
  - Clustered by jet-clustering algorithm (anti-k_T)
  - Can be *"tagged"* to identify origin (b-quark, boosted W)



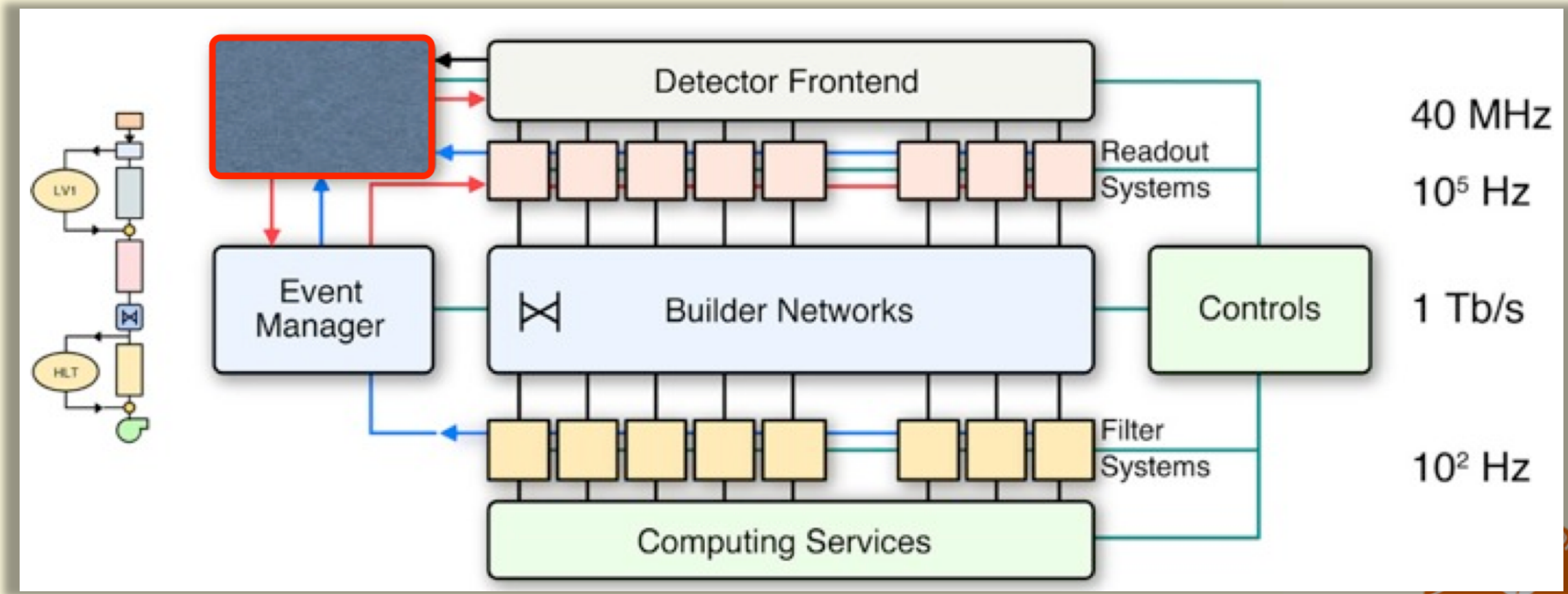
Event reconstruction

- Missing Transverse Energy (MET):
  - Weakly interacting stable particles, e.g. neutrinos, neutralino, etc
  - Vector sum of all measured particles' momenta
  - Cleaned from detector noise, cosmic muons, etc..



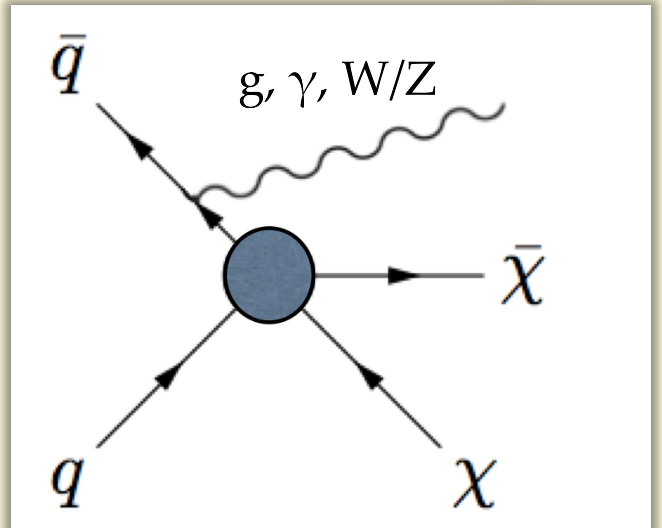
Event selection

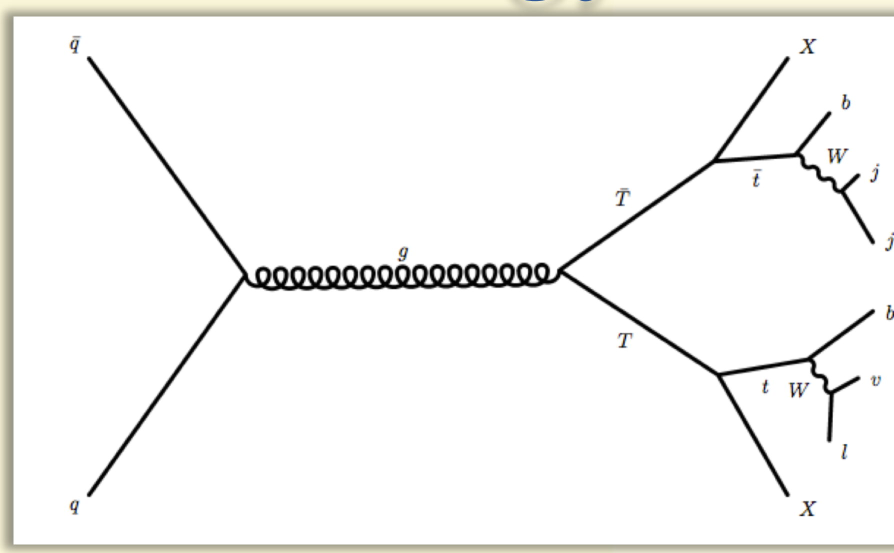
- Bunches of protons (~10^{11} protons in each bunch) cross each other at CMS/ ATLAS at 20~40 MHz
- Trigger system to select only interesting events for further processing
  - Tiered system of triggering (2 levels at CMS, 3 levels at ATLAS)
  - Reduce the output rate down to ~500 Hz



CMS Trigger and DAQ

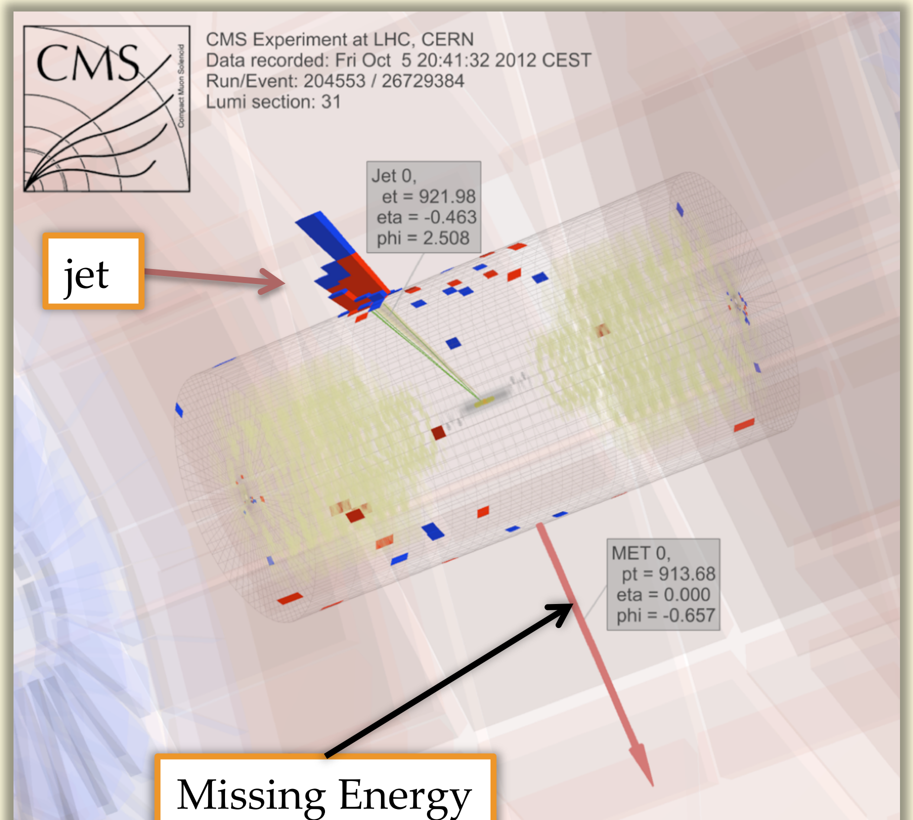
LHC phenomenology



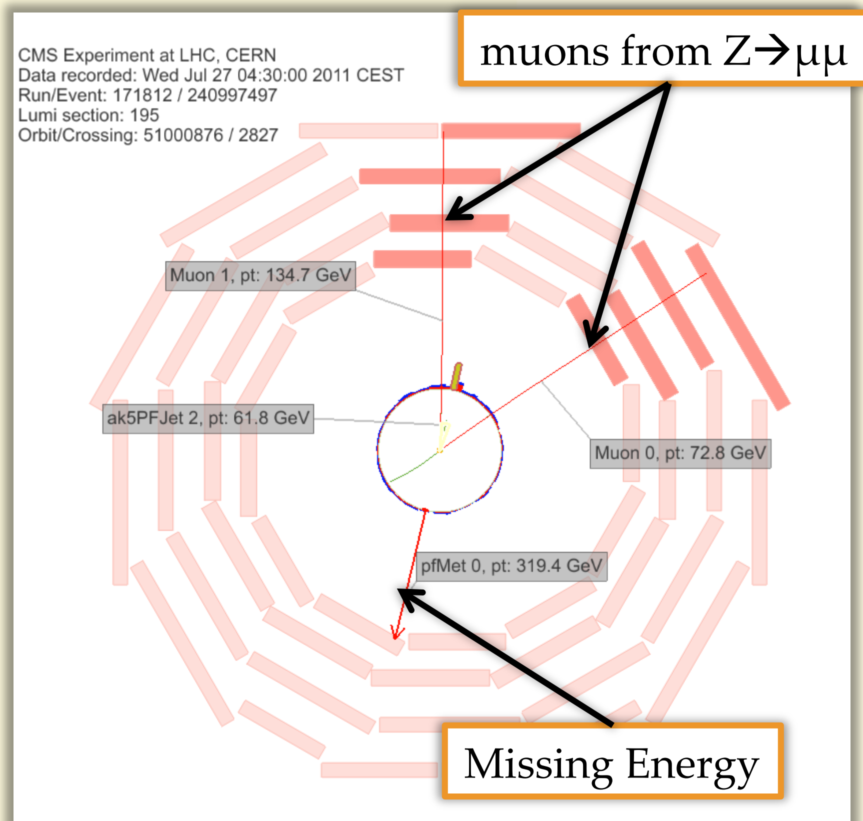


- Assumption: **DM interacts with the SM particles**
- In framework of EFT, *usually* assume DM is a Dirac
  - Identify DM candidate events by tagging ISR jet/photon/W or Z
  - Coupling between SM and DM can be evaluated, results can be compared with direct detection results
- Colored production followed by decays to WIMPs
  - Many SUSY searches in CMS and ATLAS (*not covered here*)

Experimental signatures



Mono-jet event in CMS

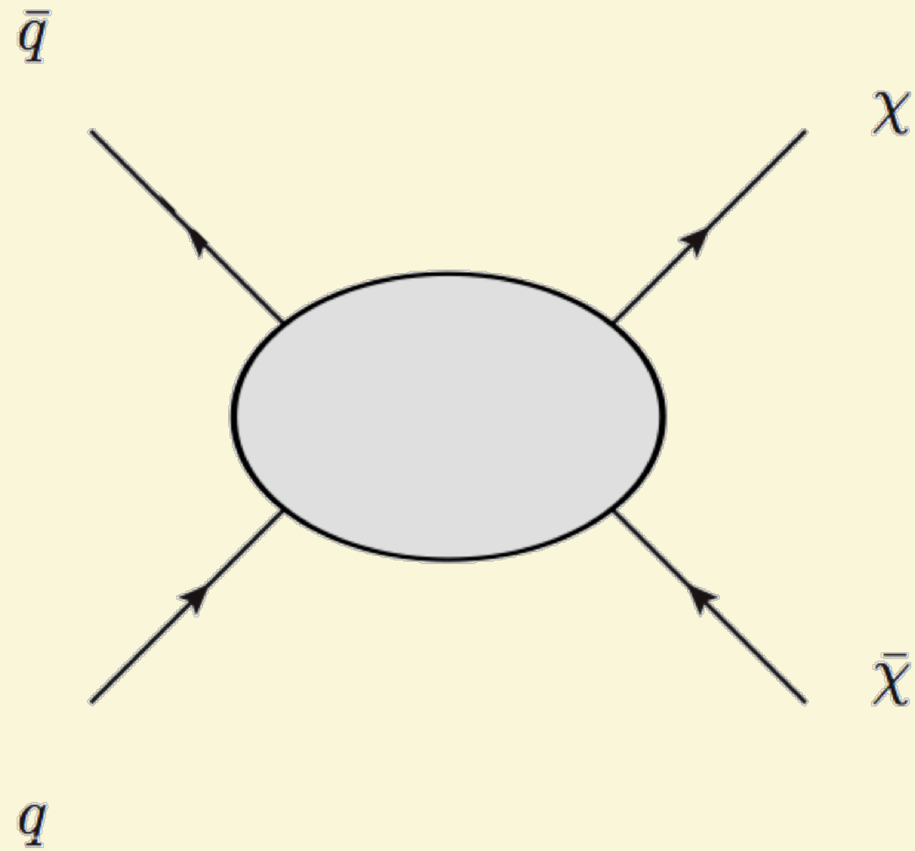


Mono-Z event in CMS

10.5fb^{-1} @ 8TeV, ATLAS-CONF-2012-147

19.5 fb^{-1} @ 8TeV, CMS arXiv:1408.3583

Monojet searches

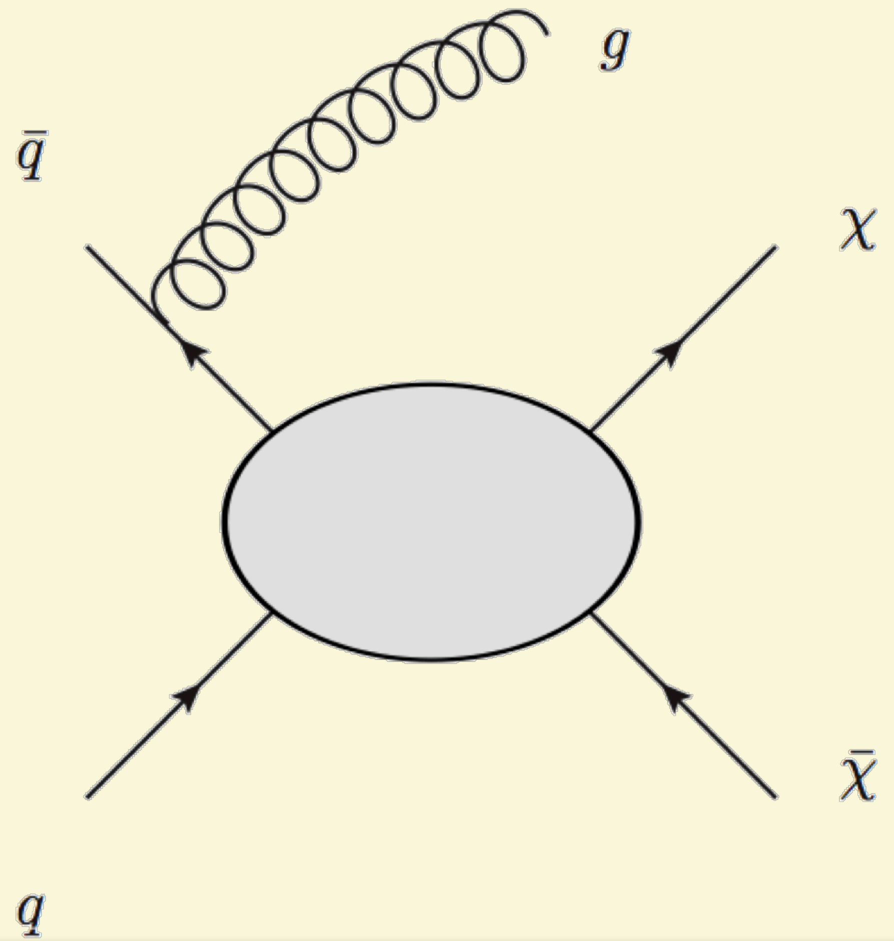


quarks annihilate to produce a pair of DM particles
Detector signature: nothing, can't trigger or identify

10.5fb^{-1} @ 8TeV, ATLAS-CONF-2012-147

19.5 fb^{-1} @ 8TeV, CMS arXiv:1408.3583

Monojet searches

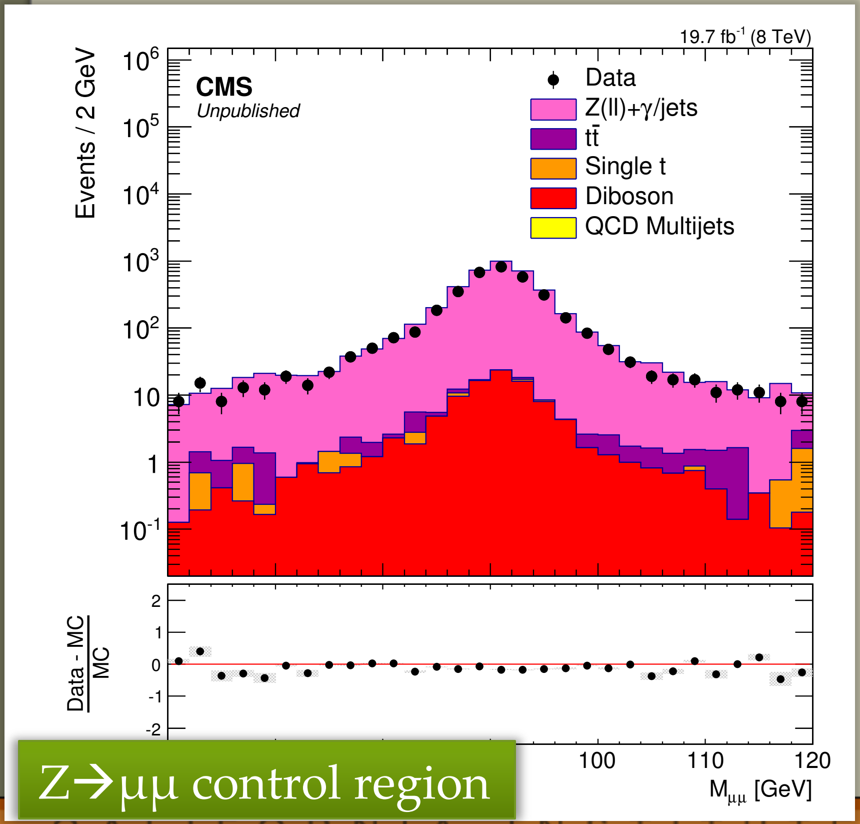


Initial state radiation of a gluon allows to trigger and identify candidate events

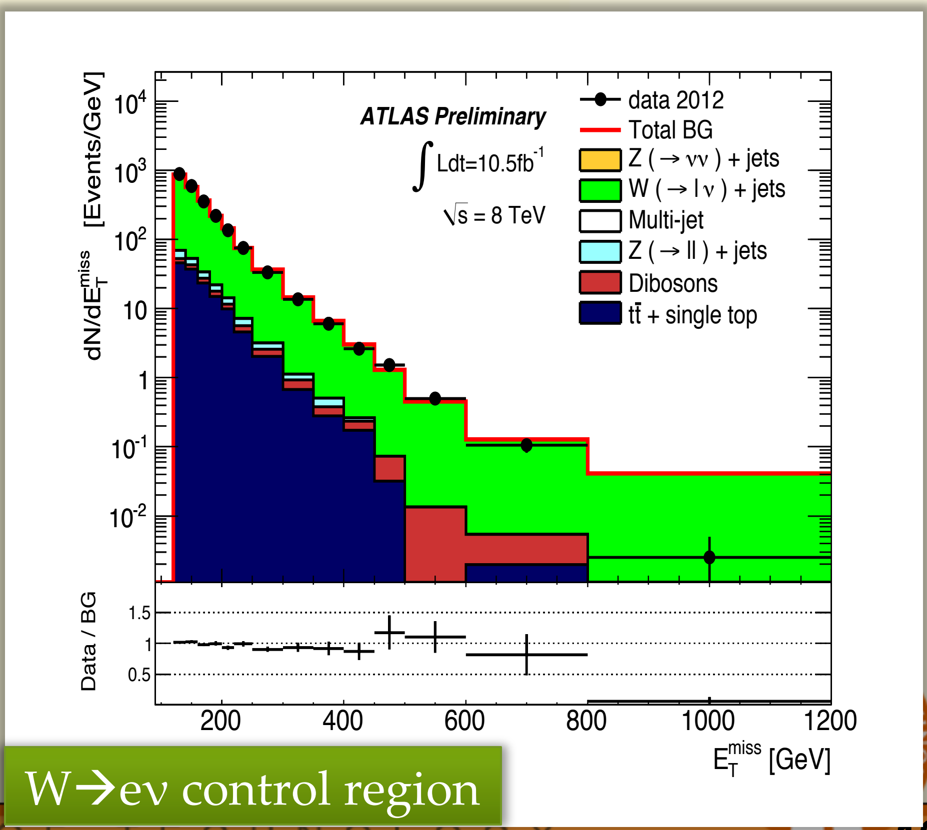
10.5fb^{-1} @ 8TeV, ATLAS-CONF-2012-147 19.5 fb^{-1} @ 8TeV, CMS arXiv:1408.3583

Monojet searches

- Main backgrounds from Z→νν and W→*l*ν (lepton is lost, τ hadronic)
  - Z→νν is estimated from Z→μμ: similar kinematic characteristics (CMS) or from data/MC ratio in enriched control sample (ATLAS)
  - W→*l*ν from W→*μ*ν, understand the Data/MC scale factors



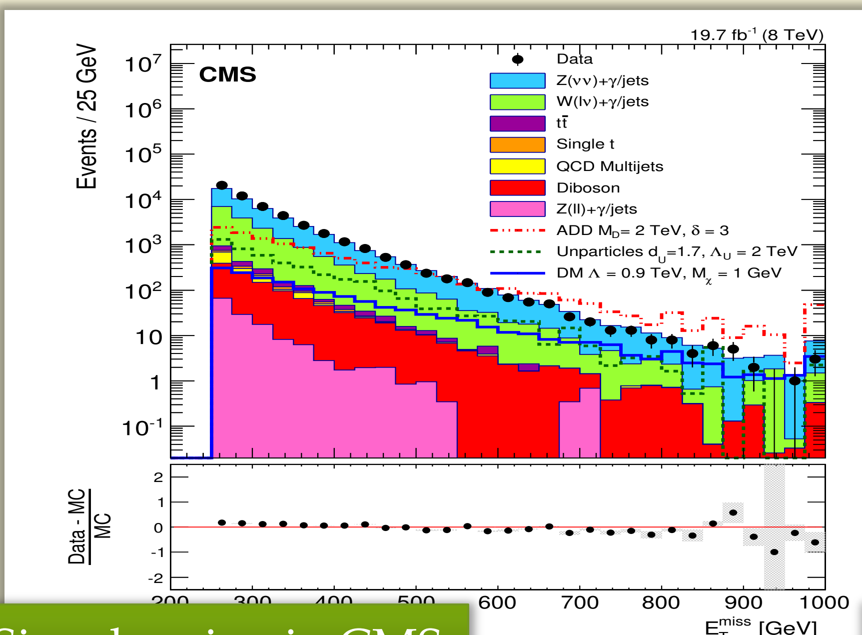
Z→μμ control region



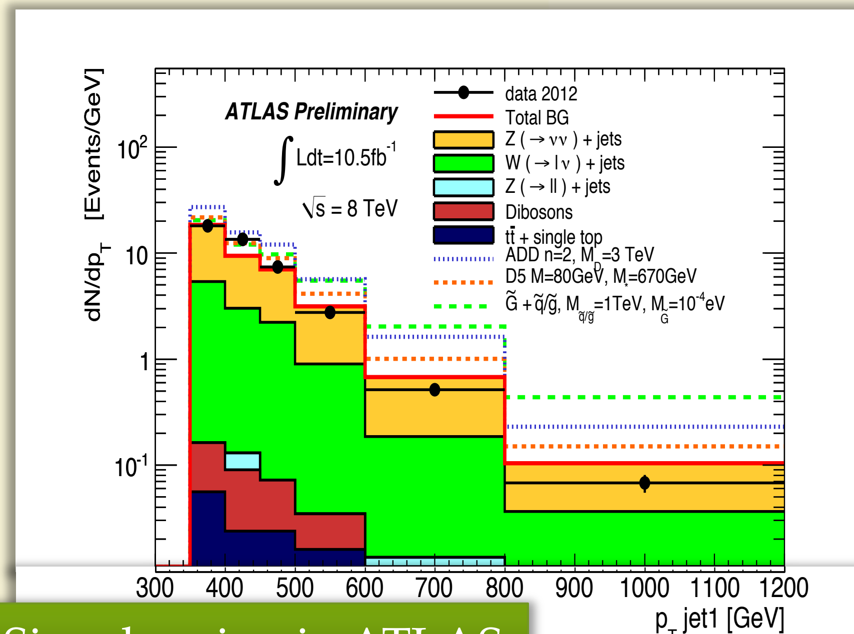
W→eν control region

Monojet results

- Event selections in CMS (ATLAS):
  - $p_T(j_1) > 110$ (120) GeV in $|\eta| < 2.4$ (2.0); no more than 2 jets with $p_T > 30$ GeV in $|\eta| < 4.5$
  - Reject events with signatures of anomalous calorimeter noise
  - no isolated charged leptons with $p_T > 10 \sim 20$ GeV
- Several signal regions defined:
  - CMS: MET > 250-550 GeV; ATLAS: $p_T(j1) > 120$-500, MET>120-500 GeV



Signal region in CMS



Signal region in ATLAS

10.5fb^{-1} @ 8TeV, ATLAS-CONF-2012-147

19.5 fb^{-1} @ 8TeV, CMS arXiv:1408.3583

Monojet results

E_T^{miss} (GeV) →	>250	>300	>350	>400	>450	>500	>550
Z($\nu\nu$)+jets	32100 ± 1600	12700 ± 720	5450 ± 360	2740 ± 220	1460 ± 140	747 ± 96	362 ± 64
W+jets	17600 ± 900	6060 ± 320	2380 ± 130	1030 ± 65	501 ± 36	249 ± 22	123 ± 13
$t\bar{t}$	446 ± 220	167 ± 84	69 ± 35	31 ± 16	15 ± 7.7	6.6 ± 3.3	2.8 ± 1.4
Z($\ell\ell$)+jets	139 ± 70	44 ± 22	18 ± 9.0	8.9 ± 4.4	5.2 ± 2.6	2.3 ± 1.2	1.0 ± 0.5
Single t	155 ± 77	53 ± 26	18 ± 9.1	6.1 ± 3.1	0.9 ± 0.4	—	—
QCD multijets	443 ± 270	94 ± 57	29 ± 18	4.9 ± 3.0	2.0 ± 1.2	1.0 ± 0.6	0.5 ± 0.3
Diboson	980 ± 490	440 ± 220	220 ± 110	118 ± 59	65 ± 33	36 ± 18	20 ± 10
Total SM	51800 ± 2000	19600 ± 830	8190 ± 400	3930 ± 230	2050 ± 150	1040 ± 100	509 ± 66
Data	52200	19800	8320	3830	1830	934	519

CMS

Background Predictions ± (stat.data)± (stat.MC) ± (syst.)

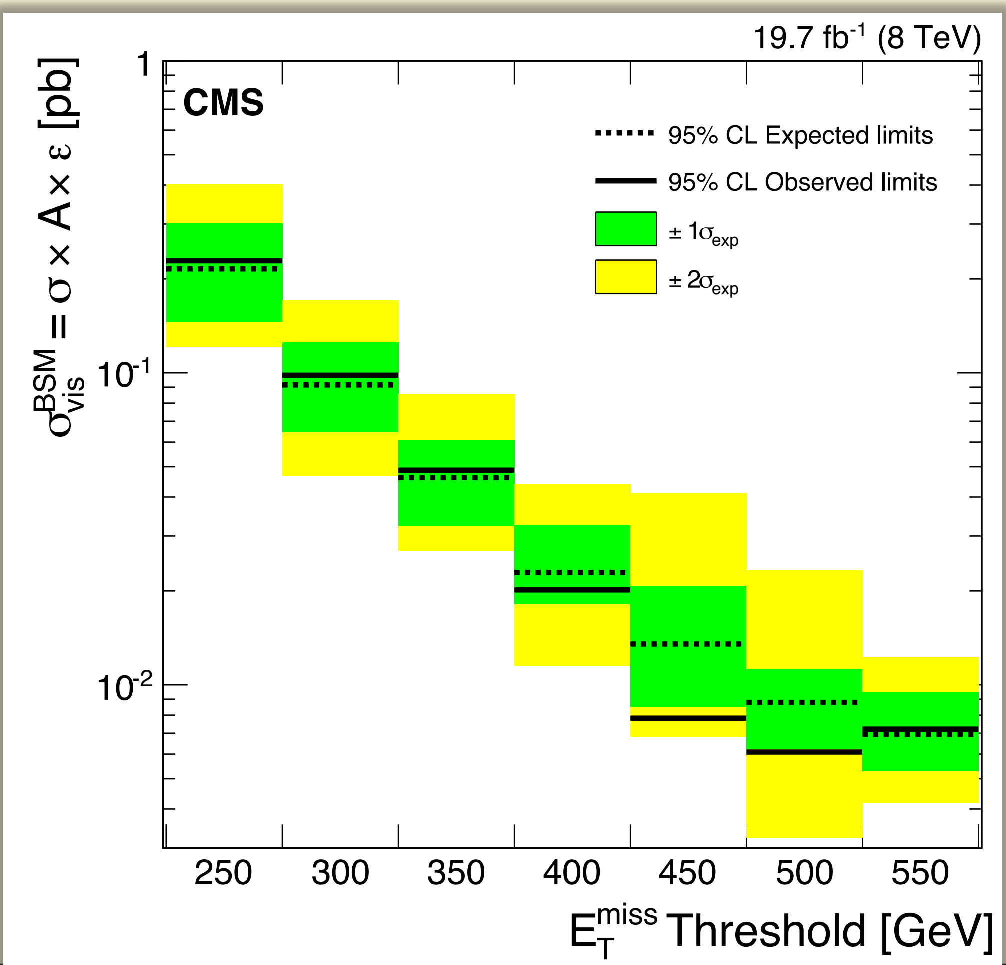
	SR1	SR2	SR3	SR4
$Z(\rightarrow \nu\nu)$+jets	173600 ± 500 ± 1300 ± 5500	15600 ± 200 ± 300 ± 500	1520 ± 50 ± 90 ± 60	270 ± 30 ± 40 ± 20
$W \rightarrow \tau\nu$+jets	87400 ± 300 ± 800 ± 3700	5580 ± 60 ± 190 ± 300	370 ± 10 ± 40 ± 30	39 ± 4 ± 11 ± 2
$W \rightarrow e\nu$+jets	36700 ± 200 ± 500 ± 1500	1880 ± 30 ± 100 ± 100	112 ± 5 ± 18 ± 9	16 ± 2 ± 6 ± 2
$W \rightarrow \mu\nu$+jets	34200 ± 100 ± 400 ± 1600	2050 ± 20 ± 100 ± 130	158 ± 5 ± 21 ± 14	42 ± 4 ± 13 ± 8
$Z \rightarrow \tau\tau$+jets	1263 ± 7 ± 44 ± 92	54 ± 1 ± 9 ± 5	1.3 ± 0.1 ± 1.3 ± 0.2	1.4 ± 0.2 ± 1.5 ± 0.2
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$+jets	783 ± 2 ± 35 ± 53	26 ± 0 ± 6 ± 1	2.7 ± 0.1 ± 1.9 ± 0.3	–
$Z/\gamma^*(\rightarrow e^+e^-)$+jets	–	–	–	–
Multijet	6400 ± 90 ± 5500	200 ± 20 ± 200	–	–
tt + single t	2660 ± 60 ± 530	120 ± 10 ± 20	7 ± 3 ± 1	1.2 ± 1.2 ± 0.2
Dibosons	815 ± 9 ± 163	83 ± 3 ± 17	14 ± 1 ± 3	3 ± 1 ± 1
Non-collision background	640 ± 40 ± 60	22 ± 7 ± 2	–	–
Total background	344400 ± 900 ± 2200 ± 12600	25600 ± 240 ± 500 ± 900	2180 ± 70 ± 120 ± 100	380 ± 30 ± 60 ± 30
Data	350932	25515	2353	268

ATLAS

10.5fb^{-1} @ 8TeV, ATLAS-CONF-2012-147 19.5 fb^{-1} @ 8TeV, CMS arXiv:1408.3583

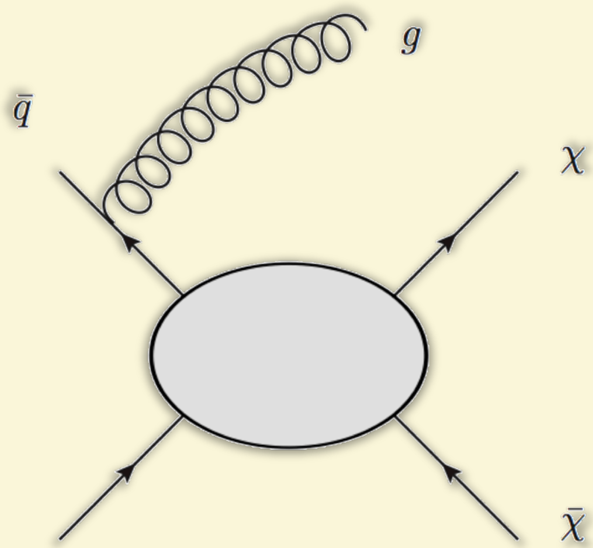
Interpreting results

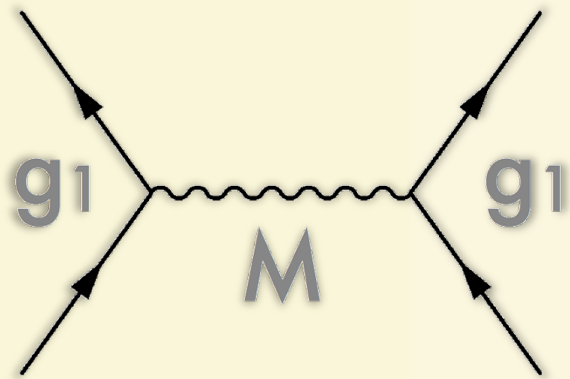
- Can interpret results in a model-independent way: set limits on BSM physics cross-section



Setting limits

- To compare with DM-nucleon limits, need to make assumptions
  - Interactions are vector, axial-vector, or scalar; DM is Dirac particle
  - Generate simulated events: assume interaction of form qqχχ or ggχχ

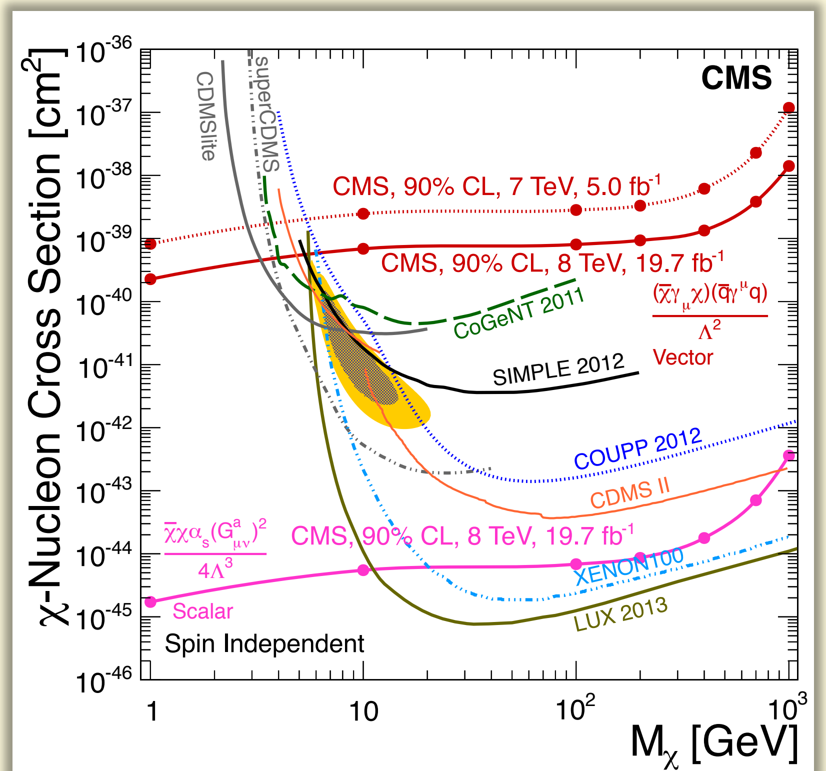


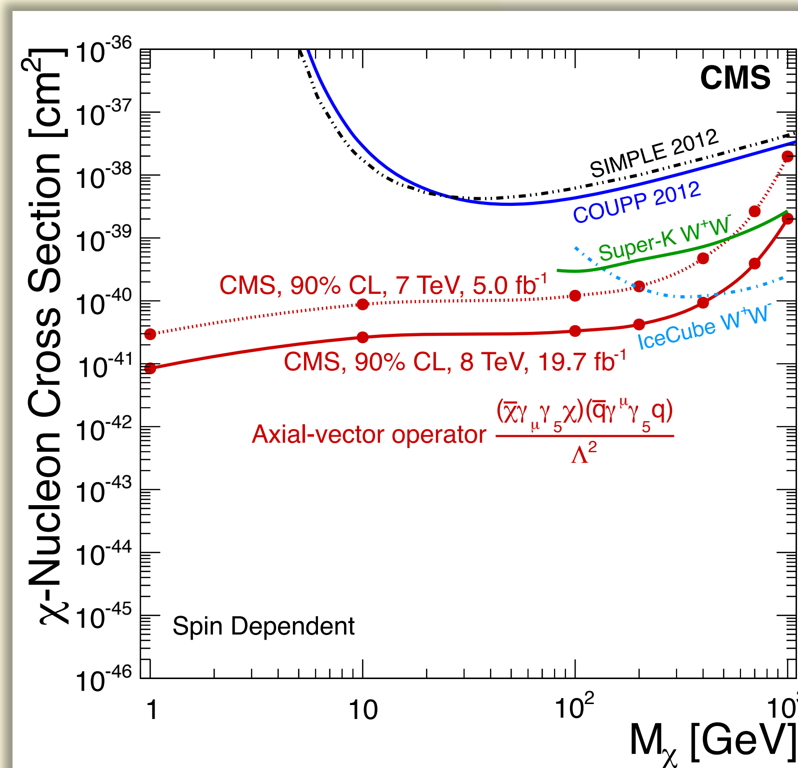


10.5fb^{-1} @ 8TeV, ATLAS-CONF-2012-147   19.5 fb^{-1} @ 8TeV, CMS arXiv:1408.3583

Effective Field Theory limits

- Assume the Mediator mass M is very large (>few TeV)
  - Set limits on cutoff scale Λ
  - Translate to limits on $\sigma_{\chi N}$ which can be compared to direct detection

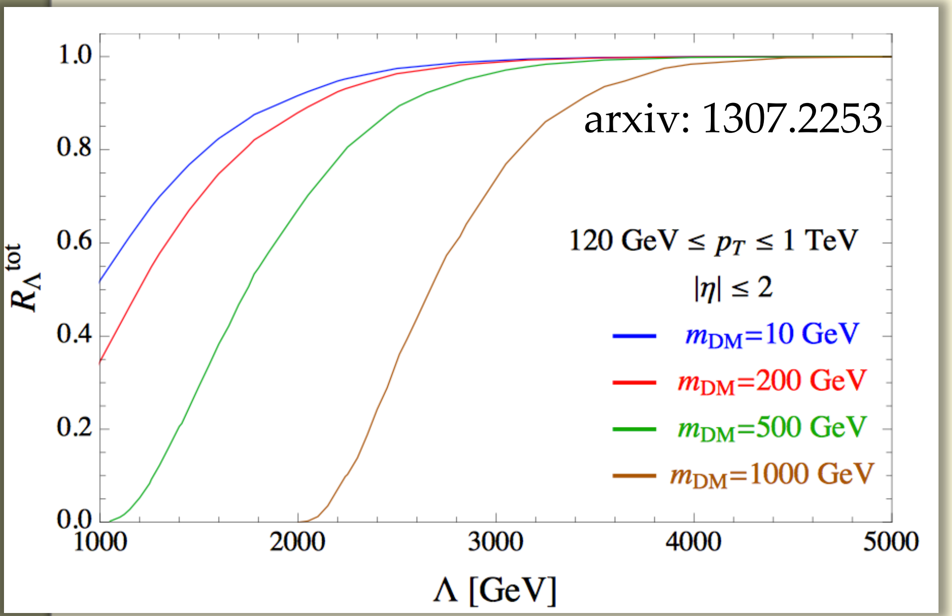




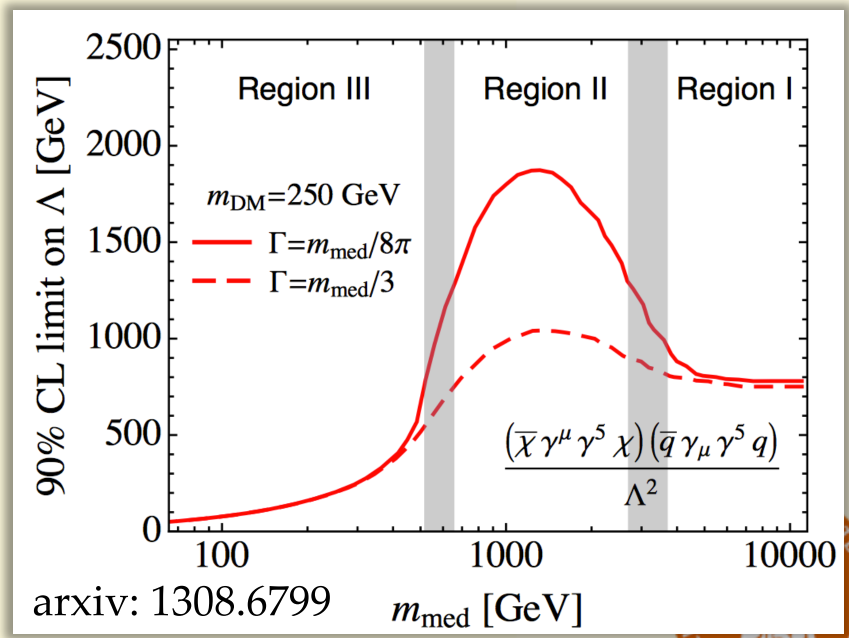
Best limits below **3.5** GeV for SI DM (hard for the DD experiments)

Light Mediators

- EFTs only applicable if M is very large, i.e. if $Q < \Lambda$

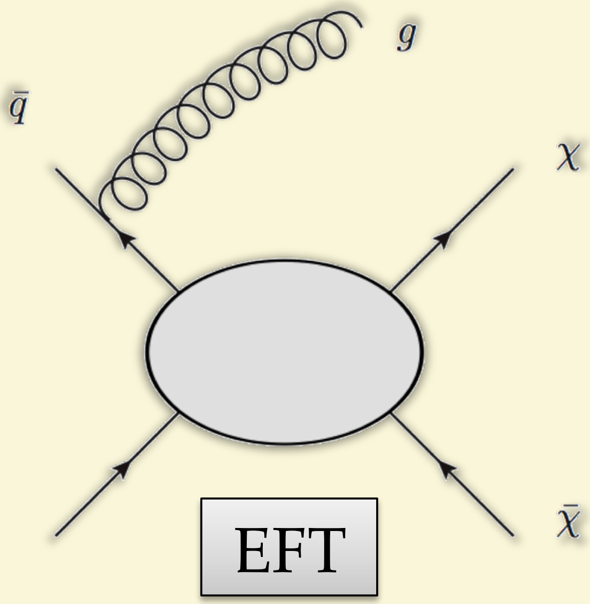


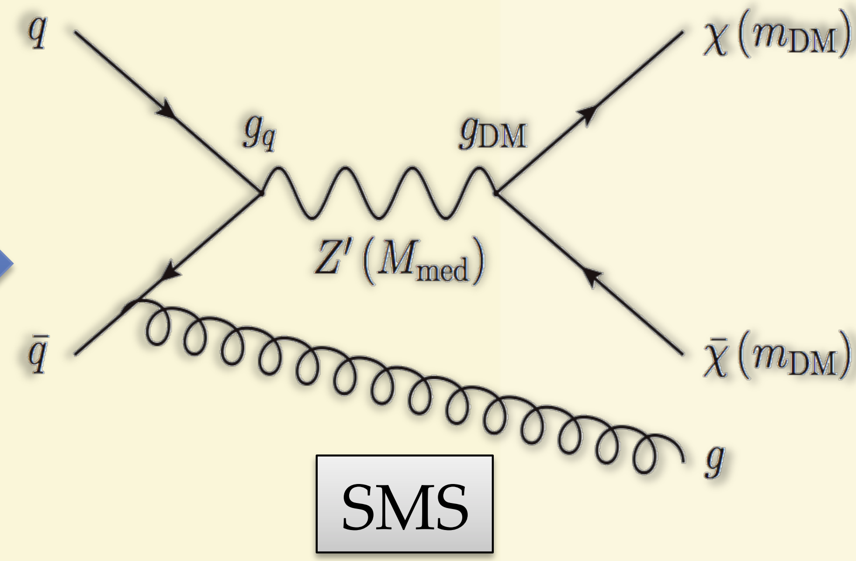
R: fraction of events with $Q<\Lambda$



- Region I: EFT limit holds
  Region II: Better than EFT
- Region III: Worse than EFT (off-shell)

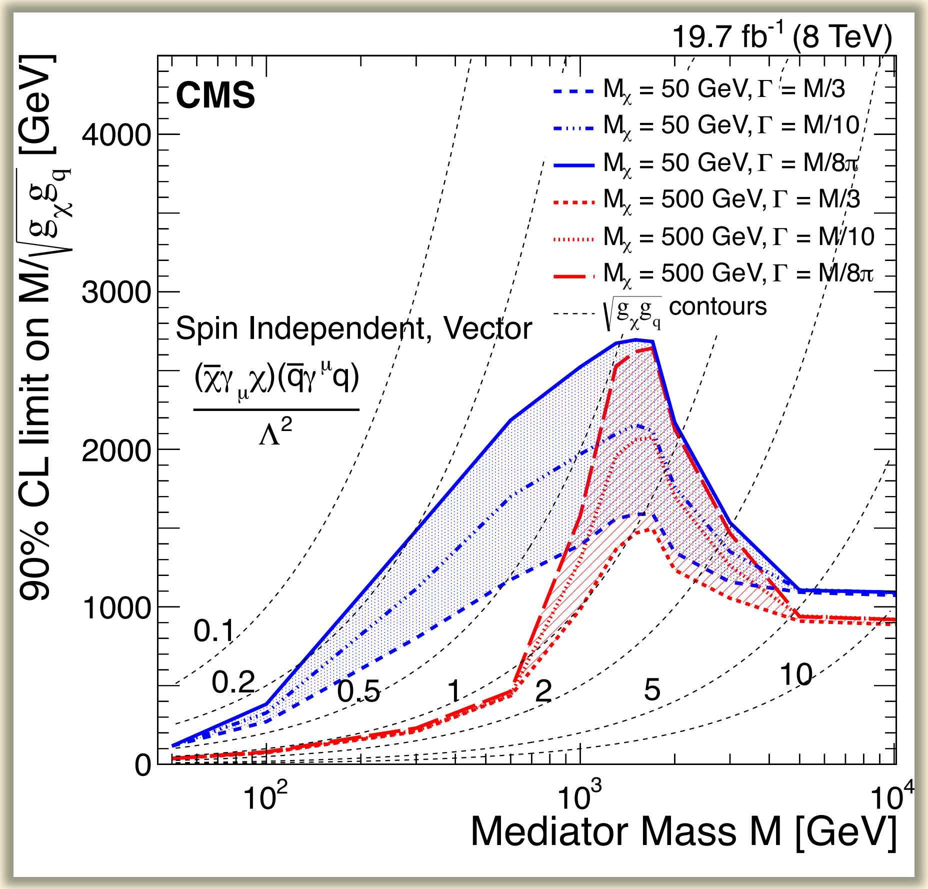
Simplified models





- Consider explicit models: specify particles and their masses
  - s-channel mediator with vector interactions
  - Vary the masses of DM, and mediator mass and widths

Simplified models

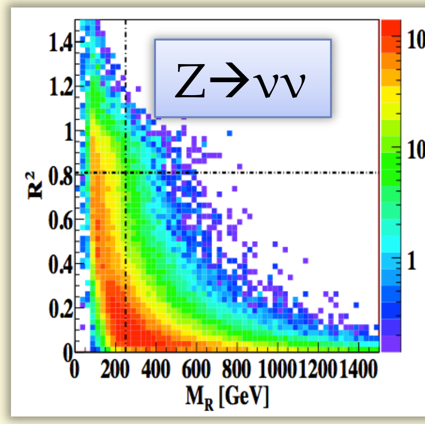


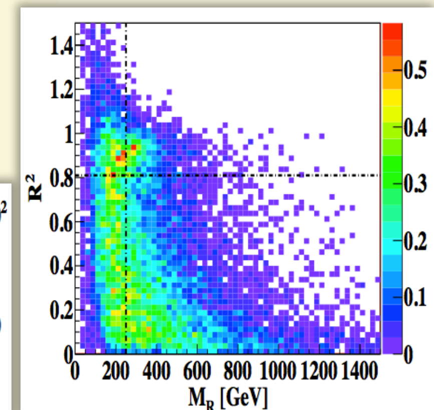
- Results asymptote those with EFT at M>~5 TeV
- For $2m_\chi$ << M <~ 5 TeV, improved limits due to resonant enhancement
- Worse limits at lower M: mediator cannot decay to $\chi\chi$

arXiv:1203.1662

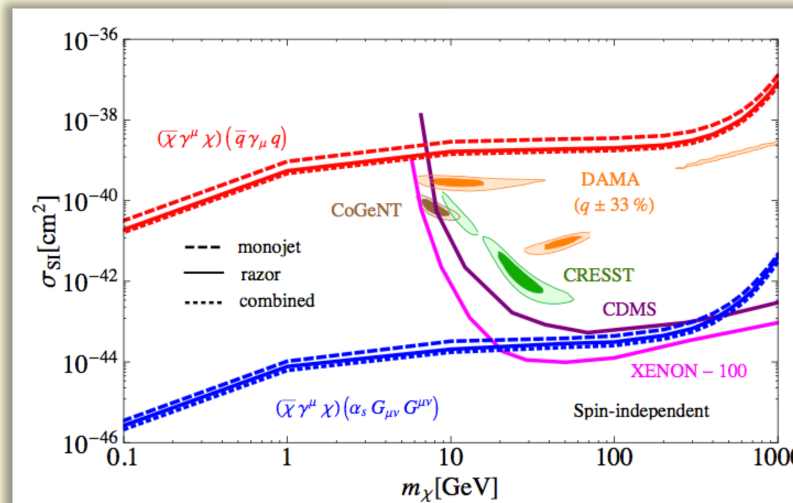
Razor approach

- CMS developed Razor variables for SUSY searches
- Turns out to have a significant sensitivity to ISR jet+MET topology
  - Allow second jet in the event
  - Large non-overlap in the samples
- If DM scalar coupling with SM, strength ~m_q: b- and t-tag selection
- Official CMS analysis to be released soon





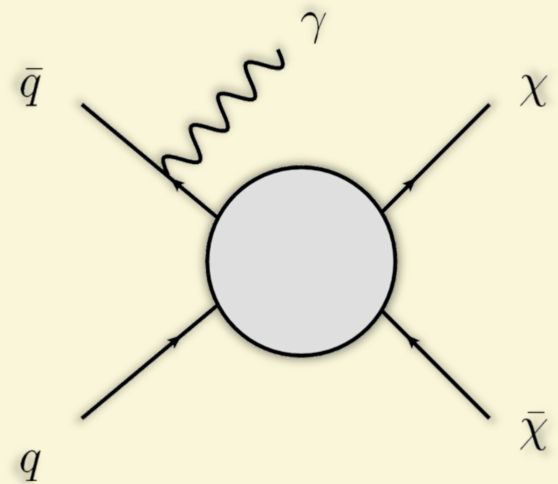
Signal (M_χ = 100 GeV, Λ = 644 GeV)

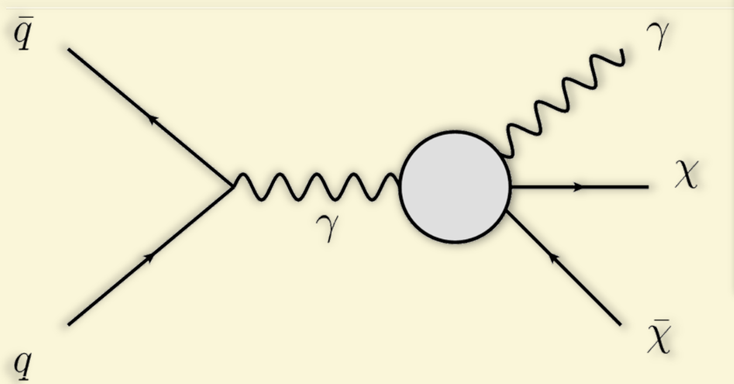


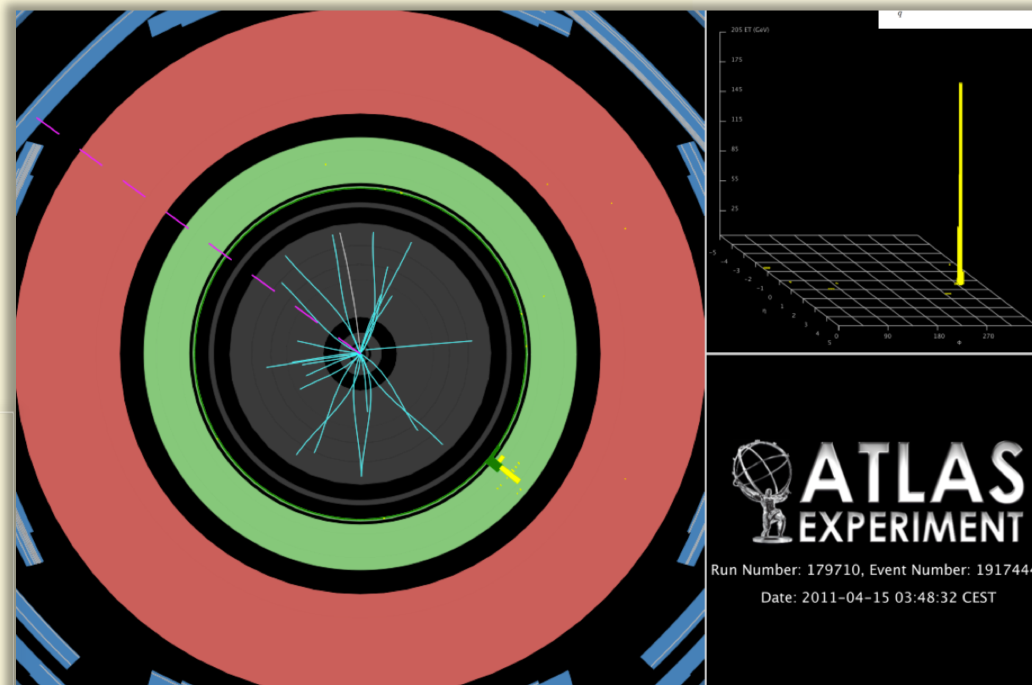
20.3 fb^{-1} @ 8TeV, ATLAS-CONF-2014-051

19.5 fb^{-1} @ 8TeV, CMS-PAS-EXO-12-047

Mono-photon searches



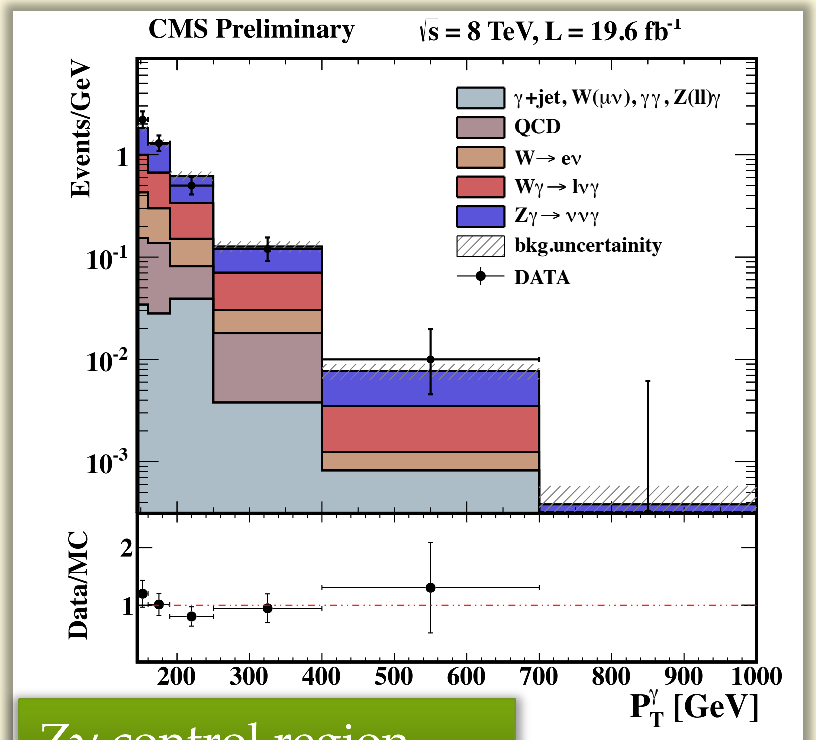




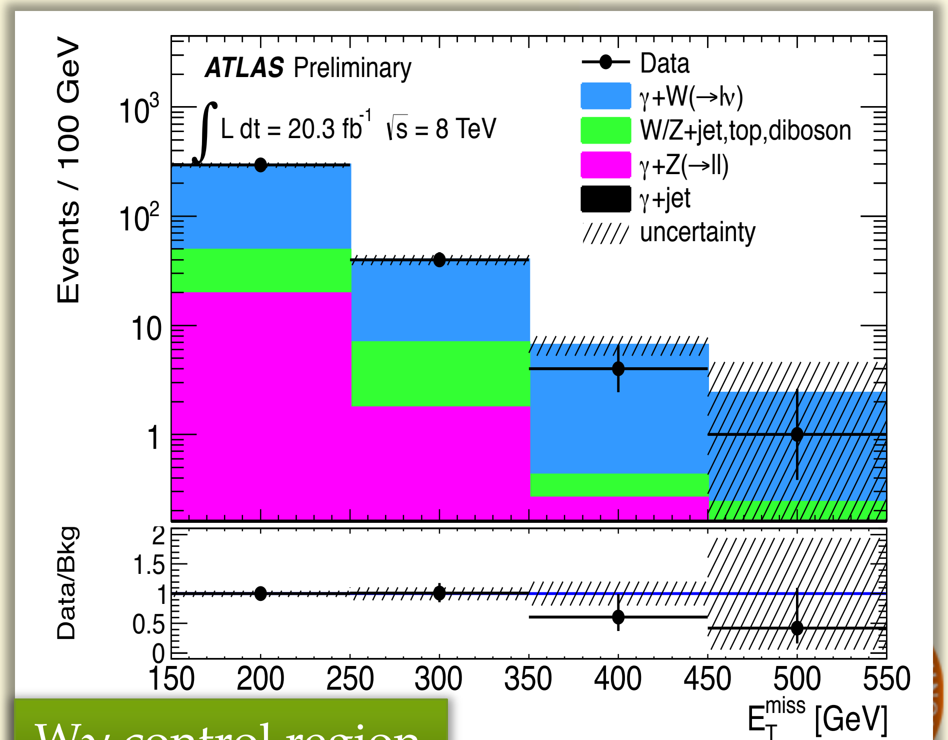
Initial state radiation of a photon allows to trigger and identify candidate events

Mono-photon searches

- Main backgrounds from Z→νν + γ with photon from ISR
  - Secondary backgrounds from Z→llγ, W→lνγ, W/Z+jets
- Estimate W/Z from MC simulation to predict shapes, validate in CR
- Measure fake rates in Z→ee and γ+jets data to model fakes



Zγ control region

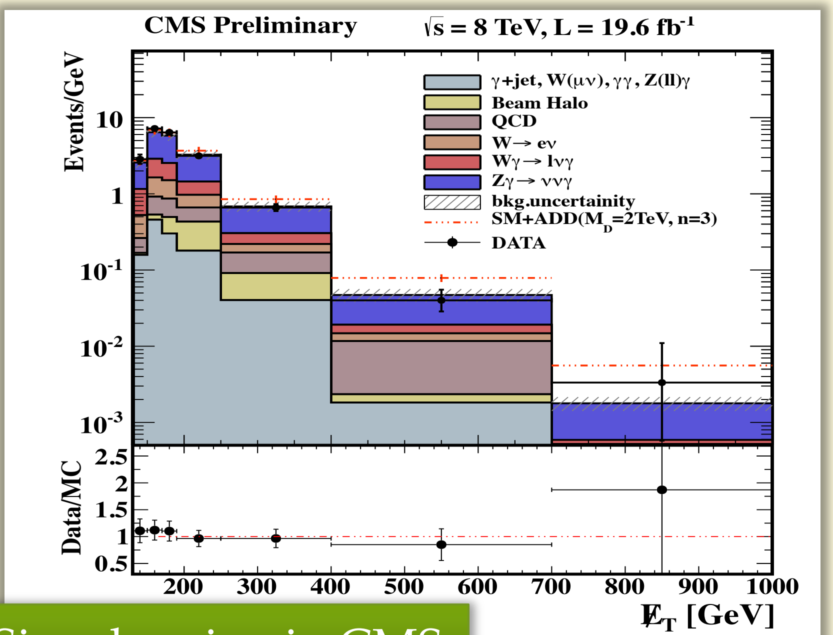


Wγ control region

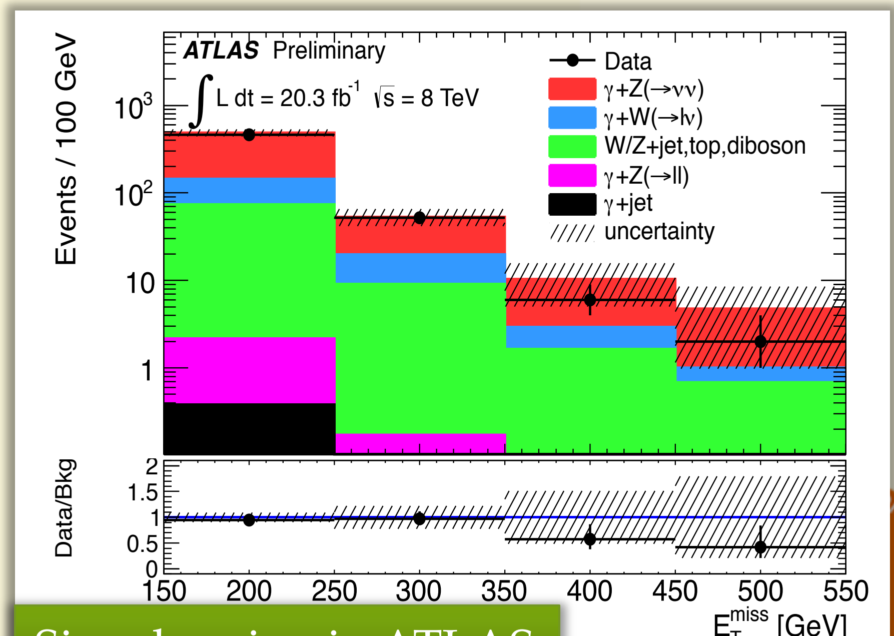
20.3 fb^{-1} @ 8TeV, ATLAS-CONF-2014-051 | 19.5 fb^{-1} @ 8TeV, CMS-PAS-EXO-12-047

Mono-photon results

- Event selections in CMS (ATLAS):
  - $p_T(\gamma)$>145 (125) GeV; no more than 2 jets with p_T>30 GeV in $|\eta|$< 4.5
  - Reject events with signatures of anomalous calorimeter noise
  - no isolated charged leptons with p_T > 6-10 GeV, large $\Delta\phi$ between γ and MET
- Several signal regions defined:
  - CMS: χ2 minimized MET > 120 GeV; ATLAS: MET > 150 GeV



Signal region in CMS



Signal region in ATLAS

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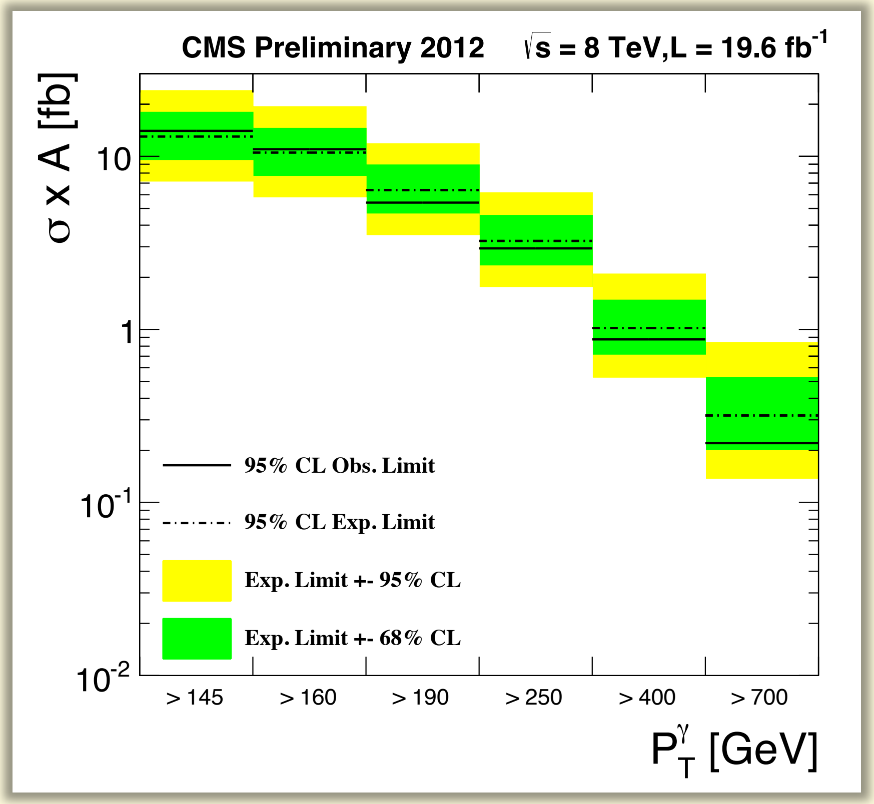
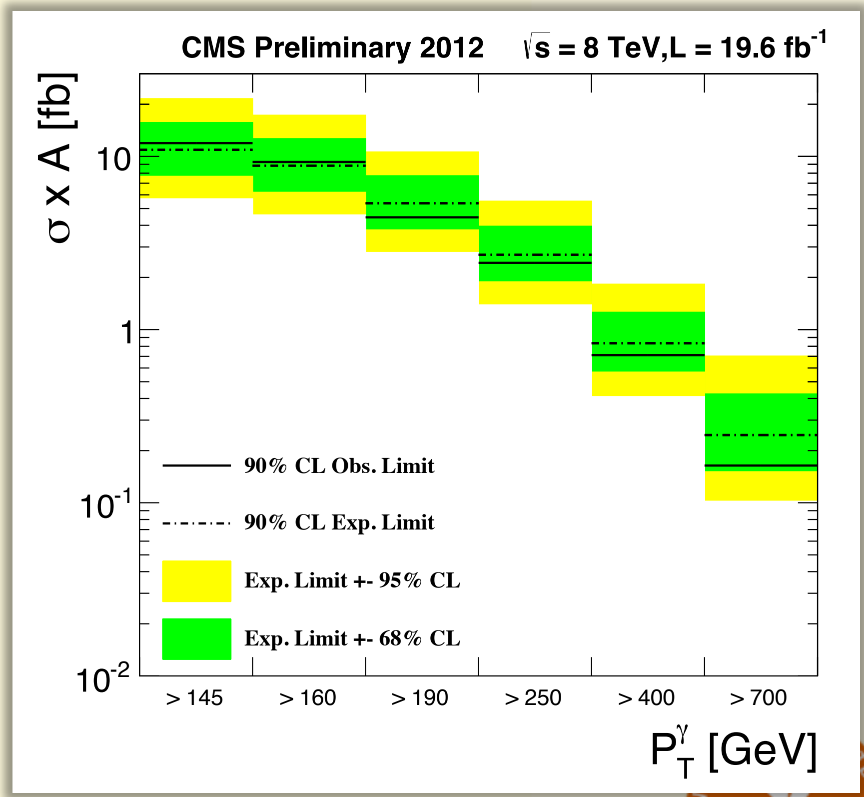
Interpreting results

- Interpret results in a model-independent way: set limits on BSM physics cross-section





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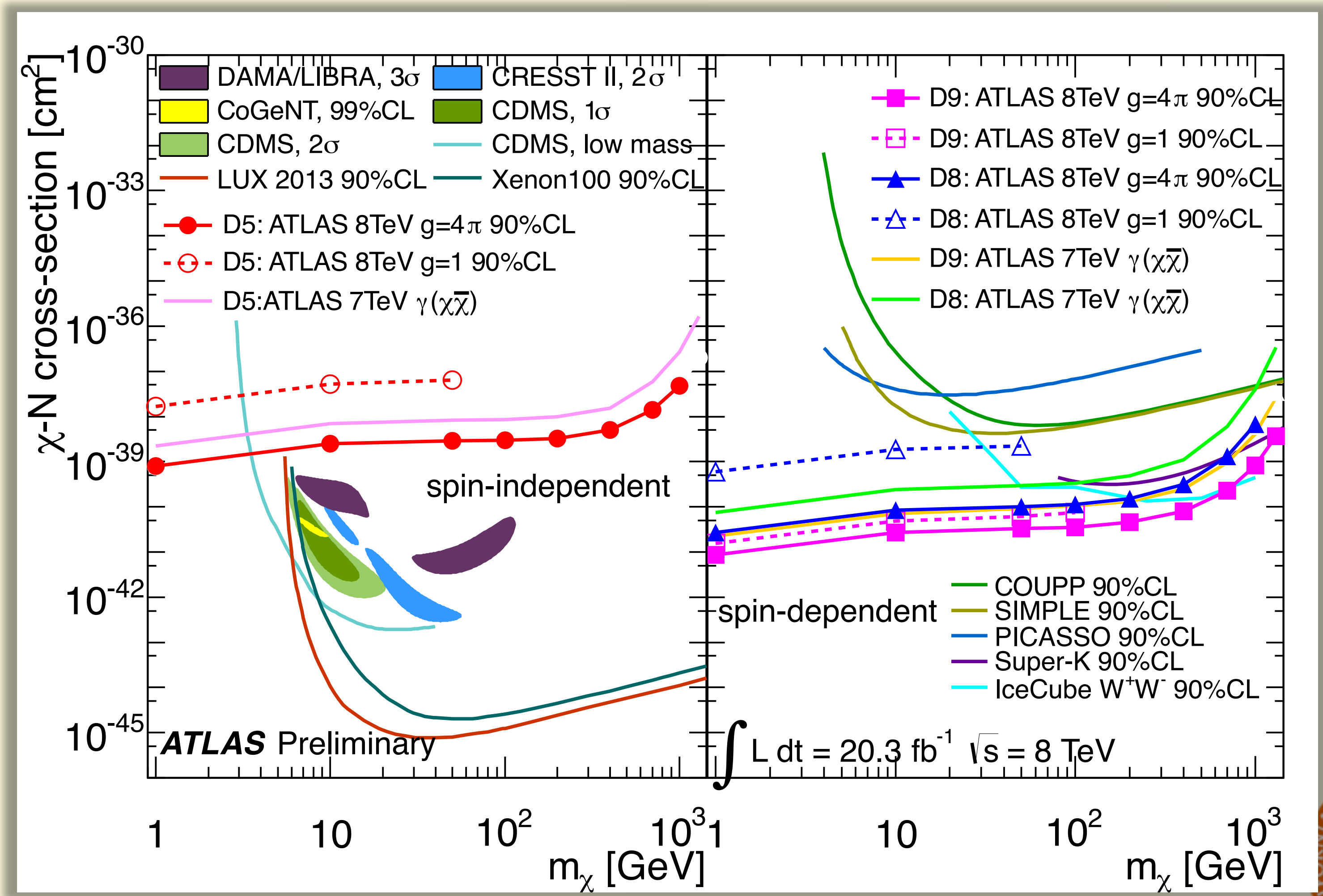
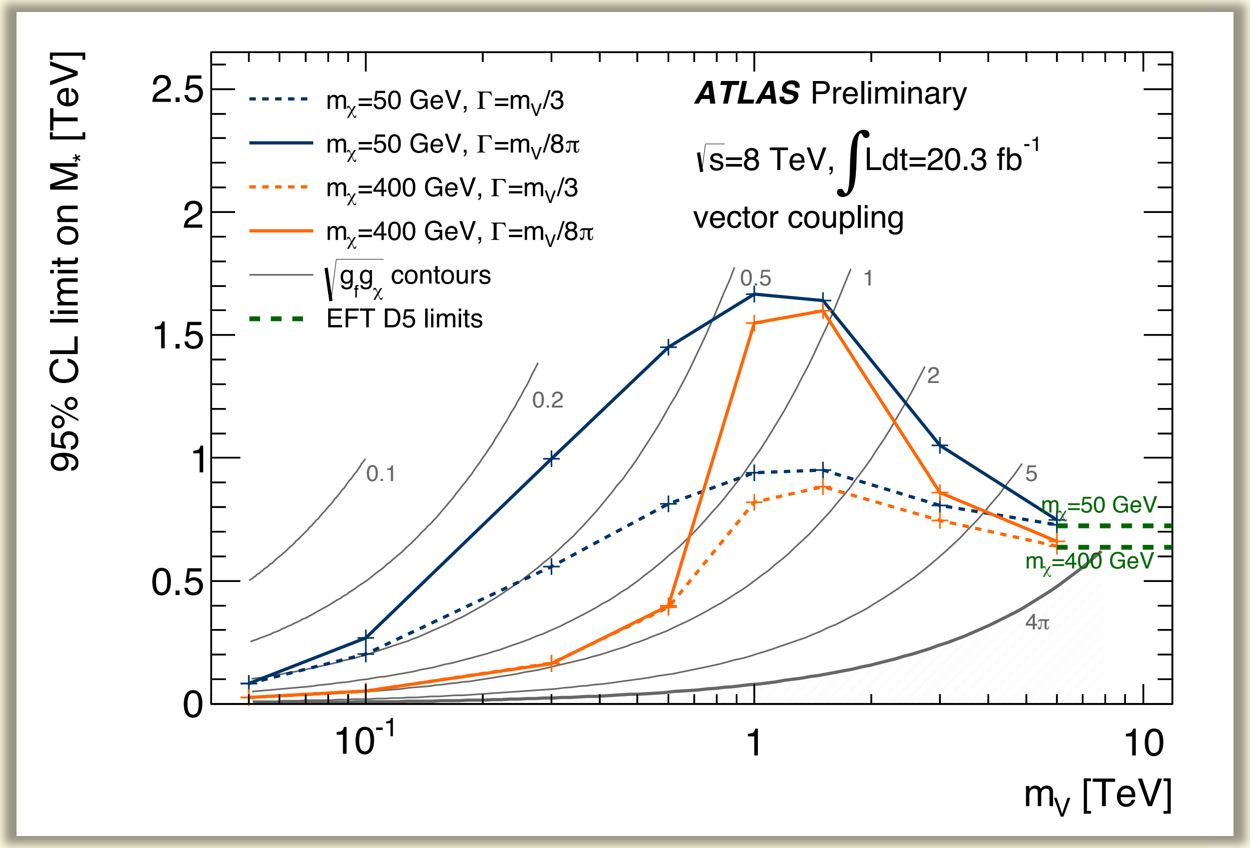
Effective Field Theory limits

- Assume the Mediator mass M is very large (>few TeV)



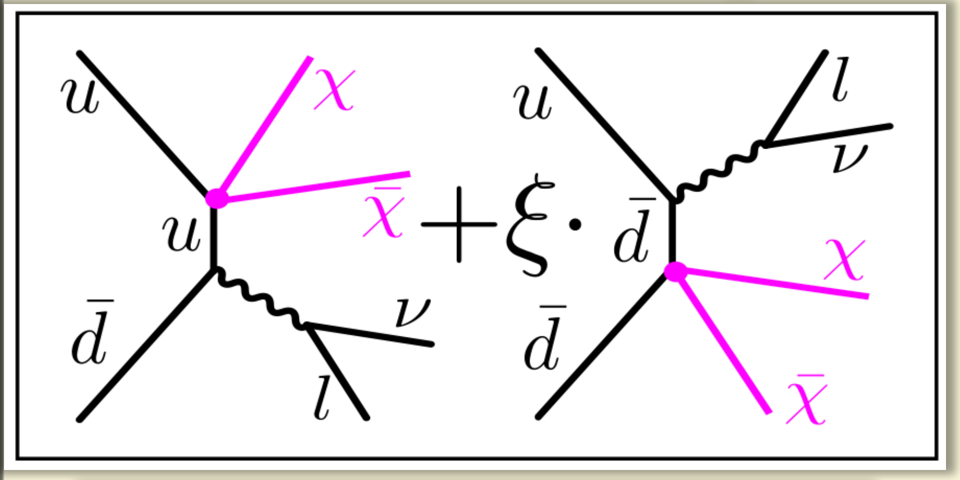
20.3 fb^{-1} @ 8TeV, ATLAS-CONF-2014-051 19.5 fb^{-1} @ 8TeV, CMS-PAS-EXO-12-047

Simplified models

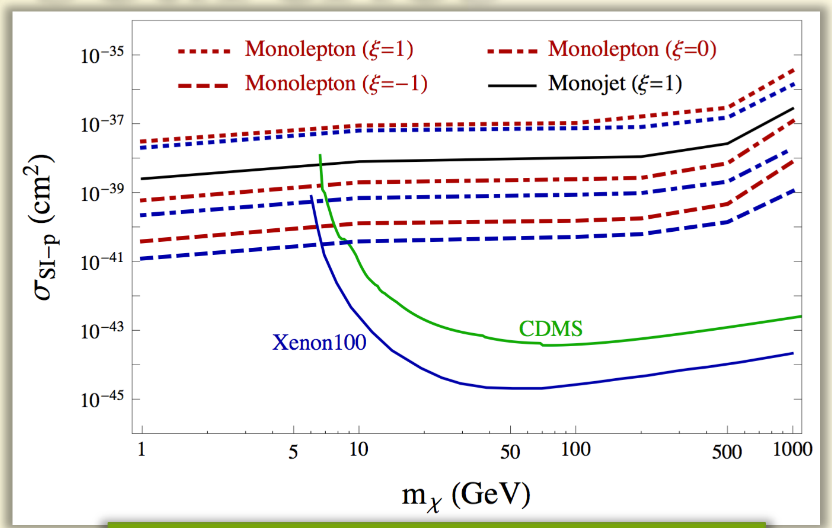


- Similar procedure as for mono-jet searches, consider s-channel Z′-like model with vector interactions

Mono-lepton searches



Interference between diagrams with W



Interpretation of CMS W' results
Y.Bai, T.Tait: arXiv:1208.4361

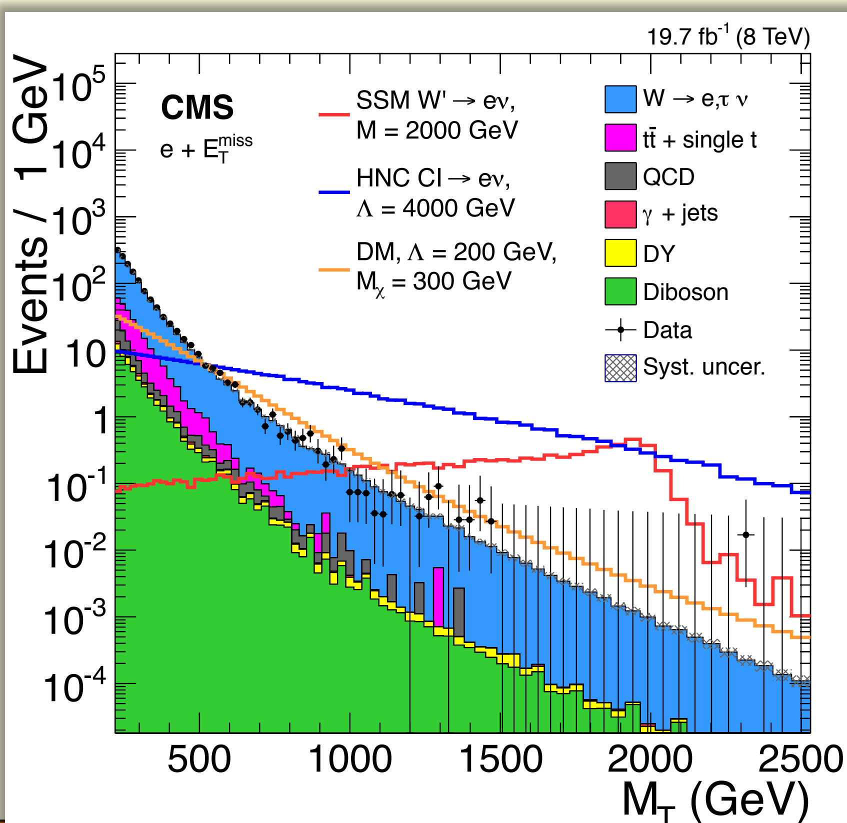
- Monojet and monophoton searches assume equal couplings of the DM particles to up- and down-type quarks
- Higher dimensional operators can alter this relation, yielding other values of ξ (e.g. ξ=-1, 0, -1)
  - ξ=+1 corresponds to destructive interference, ξ=-1 to constructive
  - Can have higher sensitivity than monojet searches

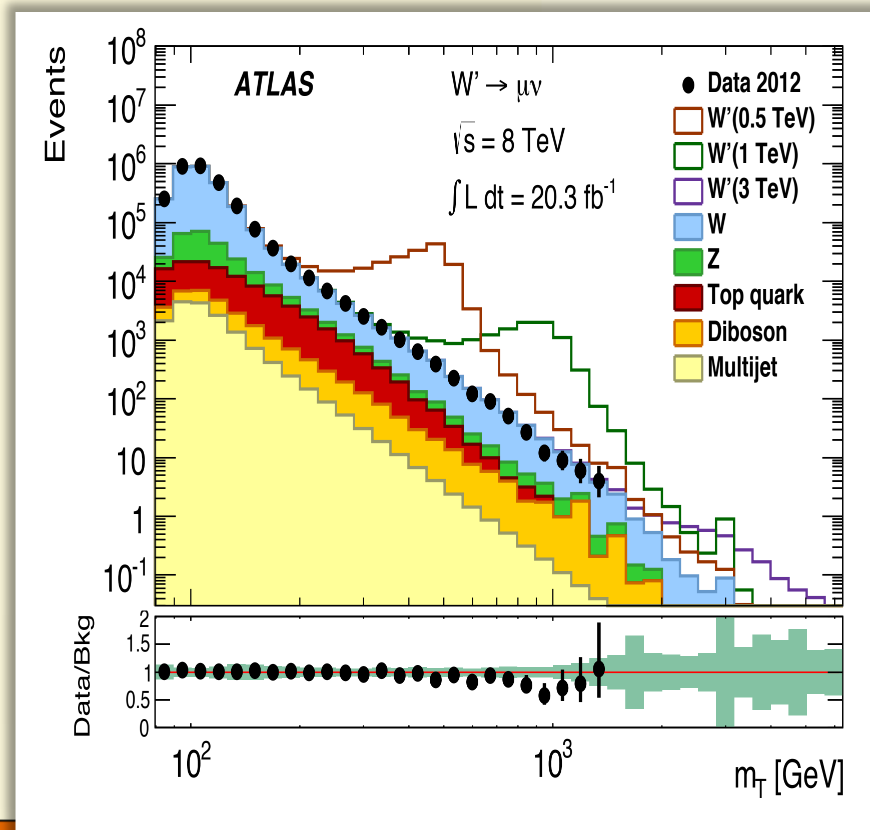
20.0 fb^{-1} @ 8TeV, ATLAS JHEP09(2014)037

20.0 fb^{-1} @ 8TeV, CMS arXiv:1408.2745

Mono-lepton search

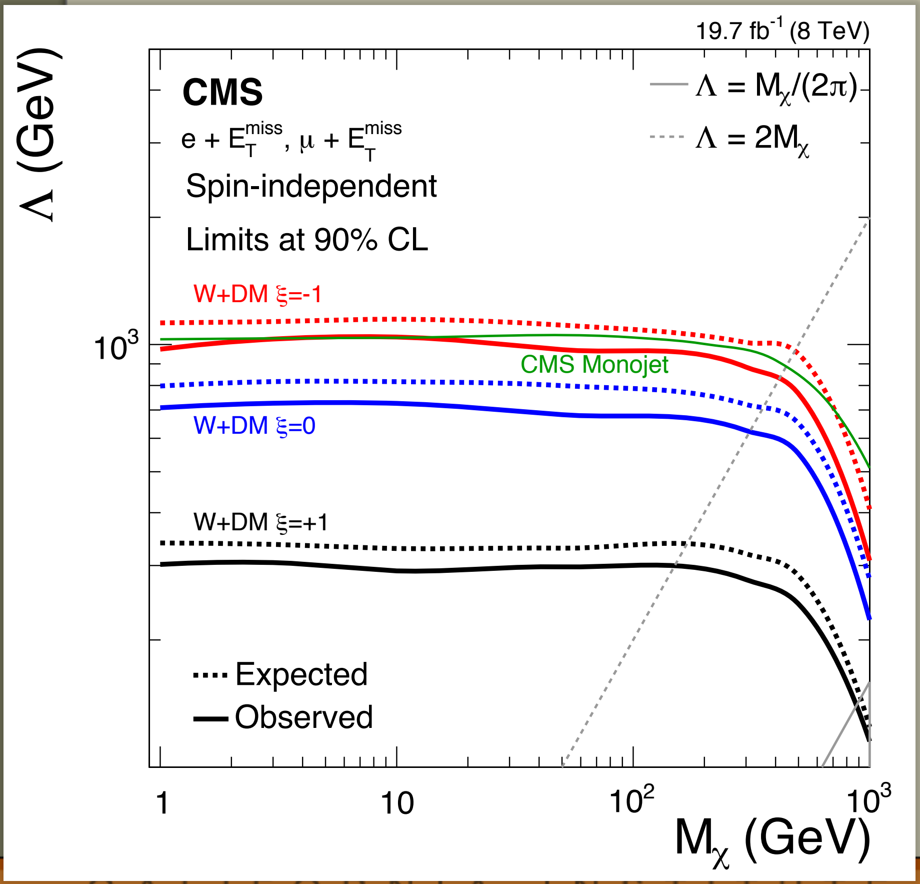
- Select events with one high p_T muon (ele) > 45 (100) GeV
- Back-to-back kinematics $0.4<p_T(\ell)/MET<1.5$; $\Delta\phi(\ell,\nu)>0.8\pi$
- Backgrounds determined from simulation, as in W′ search

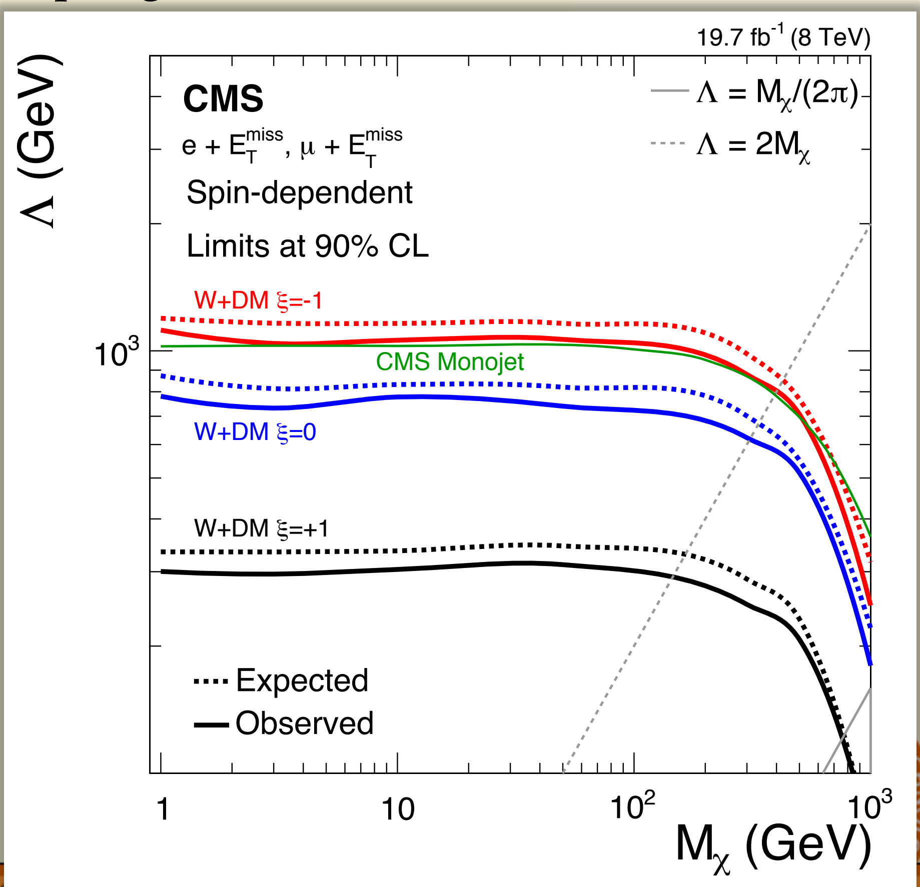




Mono-lepton limits

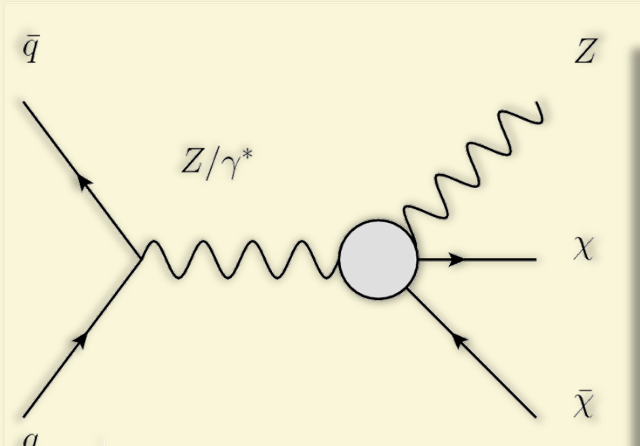
- Data consistent with SM expectations, set exclusion limits
- Excluded Λ <1000/700/300 GeV for ξ=-1/0/+1
  - for both vector and axial-vector coupling.

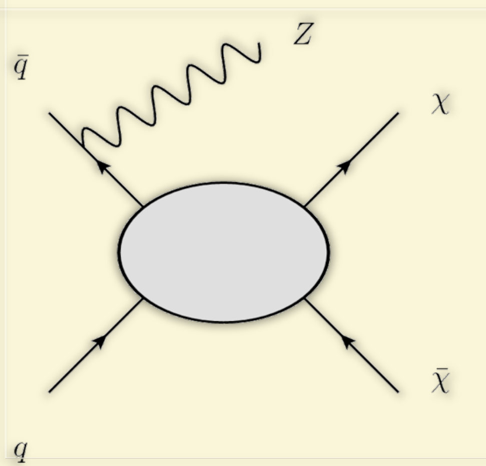


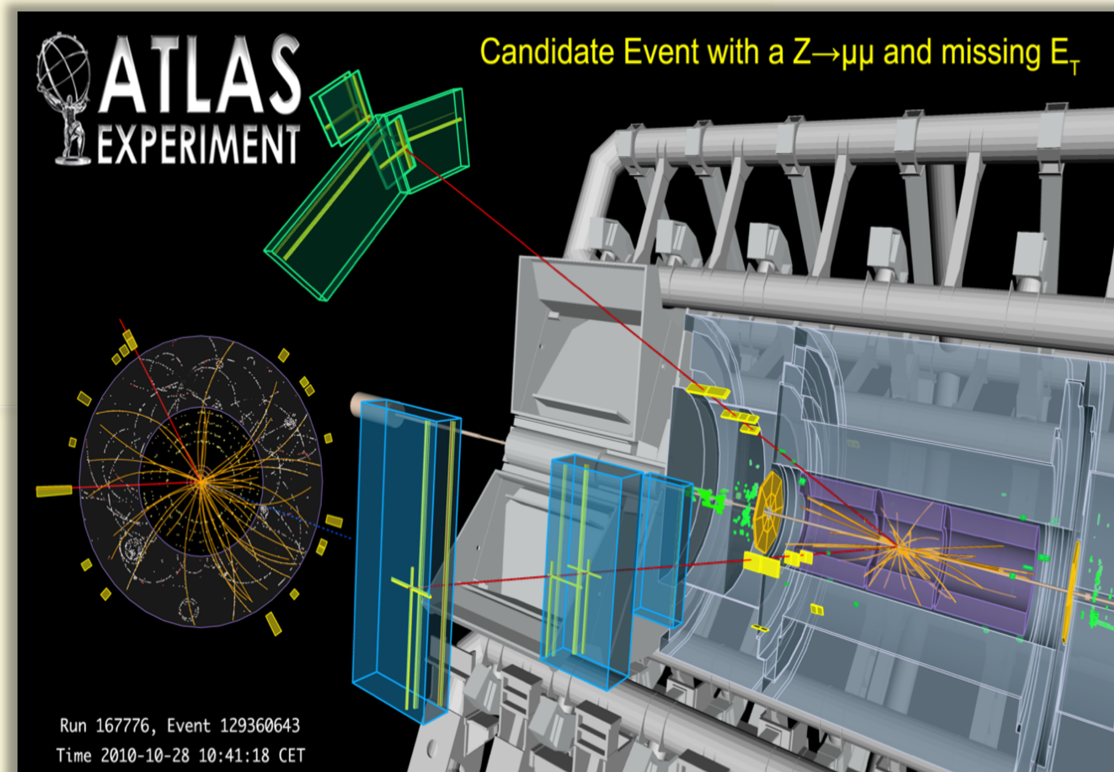


$20.3\ fb^{-1}$ @ 8TeV, ATLAS *Phys. Rev. D. 90, 012004 (2014)*

Mono-Z searches



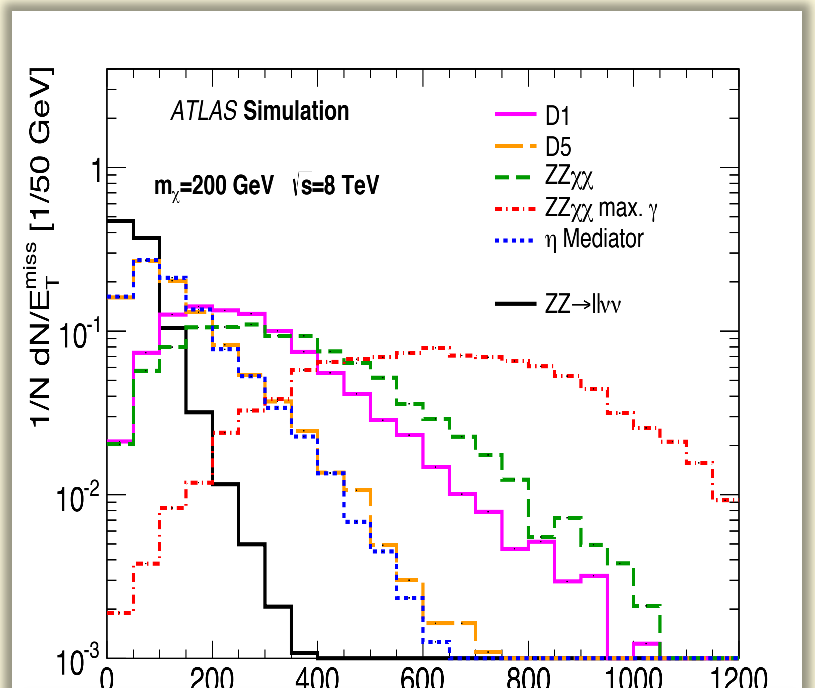




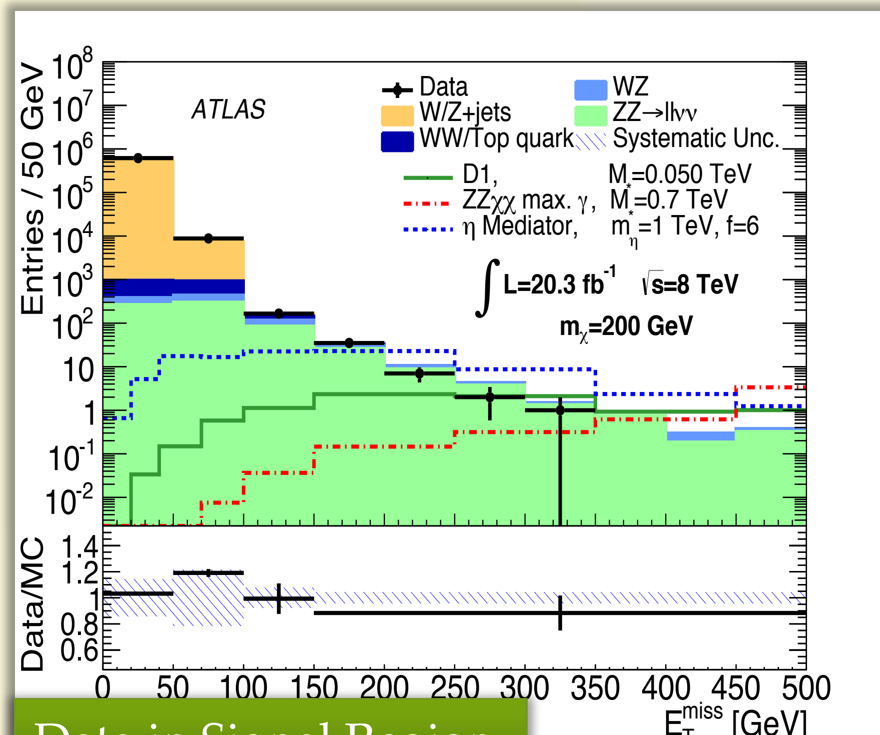
Initial state radiation of a Z boson, or if Z couple directly to the WIMP: select events with Z→ee (μμ)

Mono-Z searches

- Main irreducible backgrounds from ZZ→llνν, WW→lνlν
  - Secondary backgrounds from WZ, ZZ→llqq', W/Z+jets
- Estimate ZZ/WZ backgrounds with MC simulation
- WW/ttbar and other backgrounds estimated from data in eμ sample



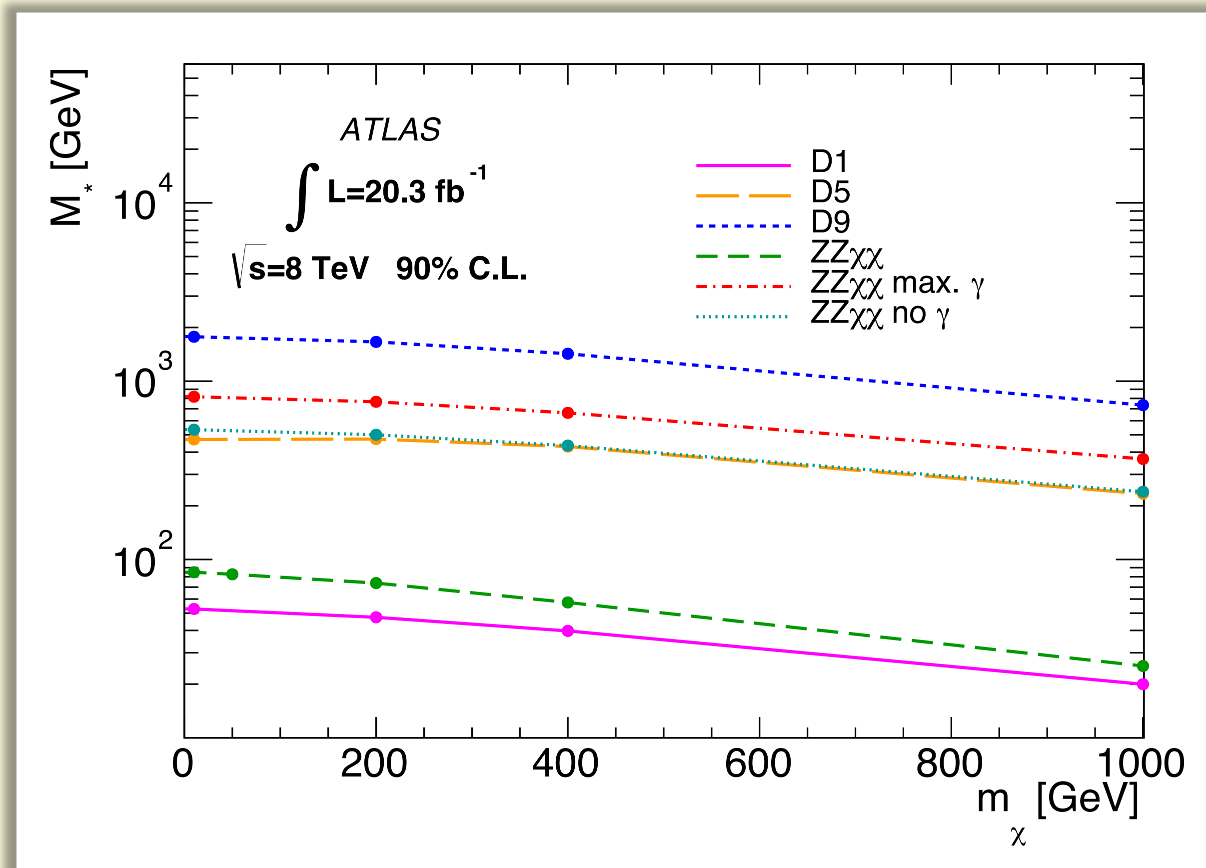
MET in signal and backgrounds

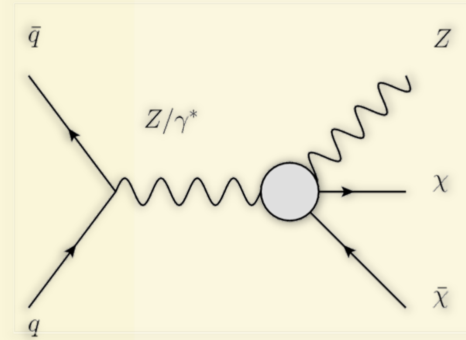


Data in Signal Region

20.3 fb^{-1} @ 8TeV, ATLAS *Phys. Rev. D. 90, 012004 (2014)*

Mono-Z limits

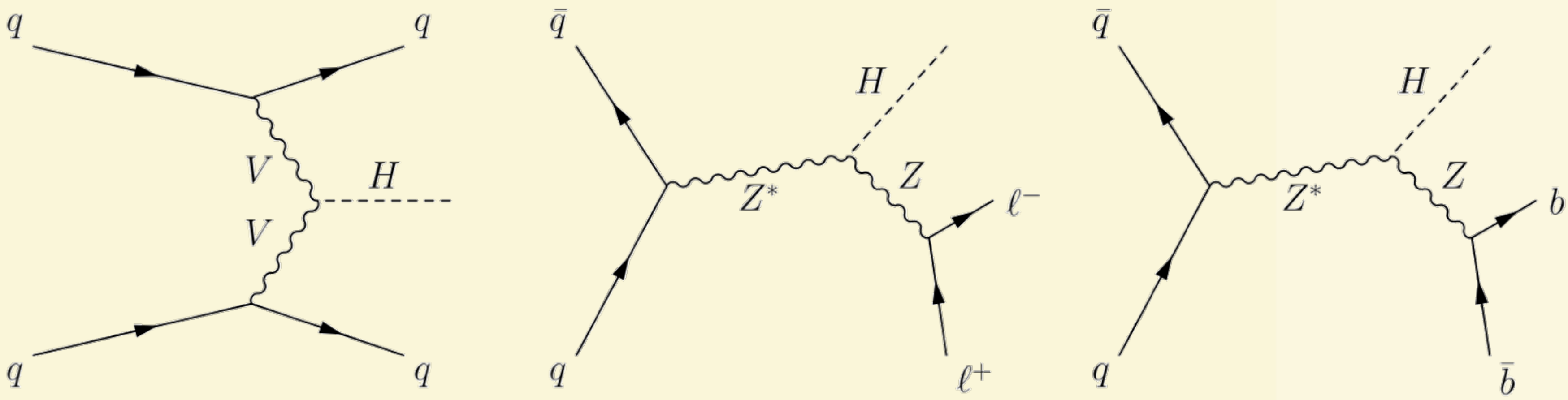




- First time considered in searches in LHC
- Similar searches performed with boosted W/Z hadronic decays, complementarity in phase-space coverage

Invisible Higgs Decays

- We have a new particle, h(125)
  - Use it as a "scout" to search for other particles and/or new interactions

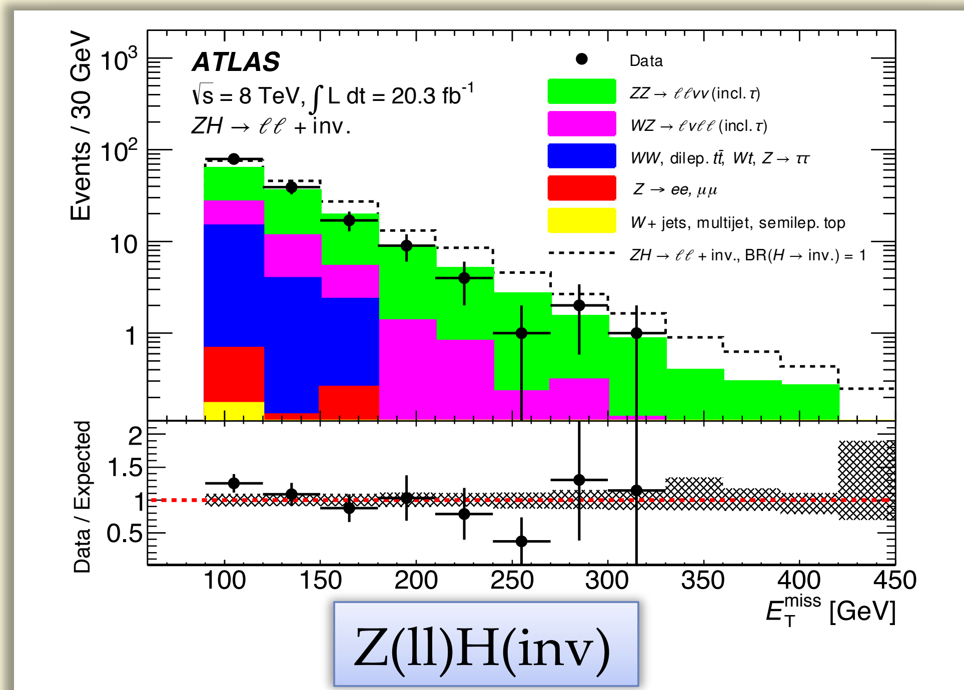


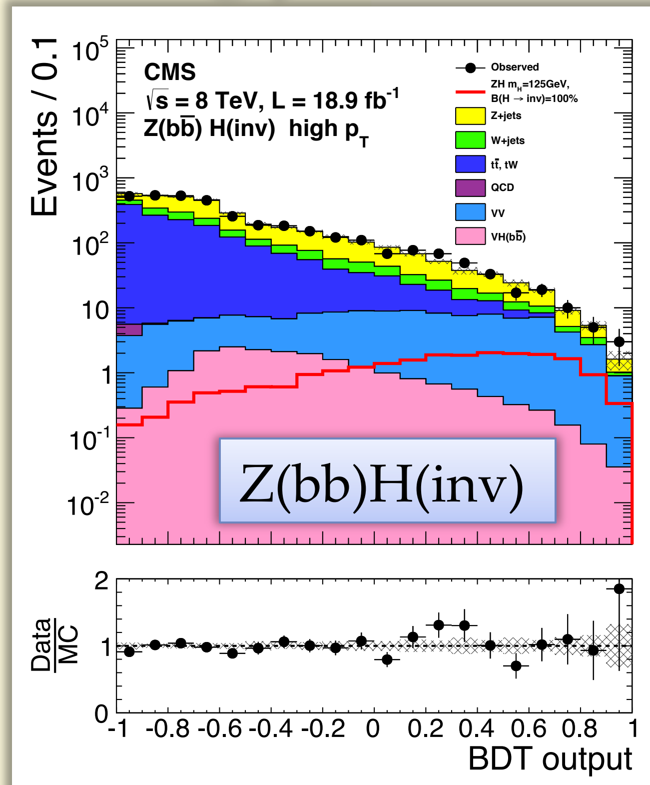
- Search for Higgs decays to invisible in these channels
  - Invisible decays of h are possible e.g. in SUSY, "Higgs-portal"
  - CMS and ATLAS performed searches VBF, Z(ll)H, and Z(bb)H final states

4.5 fb^{-1} @ 7 TeV, 20.3 fb^{-1} @ 8TeV
ATLAS PRL 112, 201802 (2014)

4.9 fb^{-1} @ 7 TeV, 19.7 fb^{-1} @ 8TeV
CMS Eur. Phys. J. C 74 (2014)

Z + Missing Energy

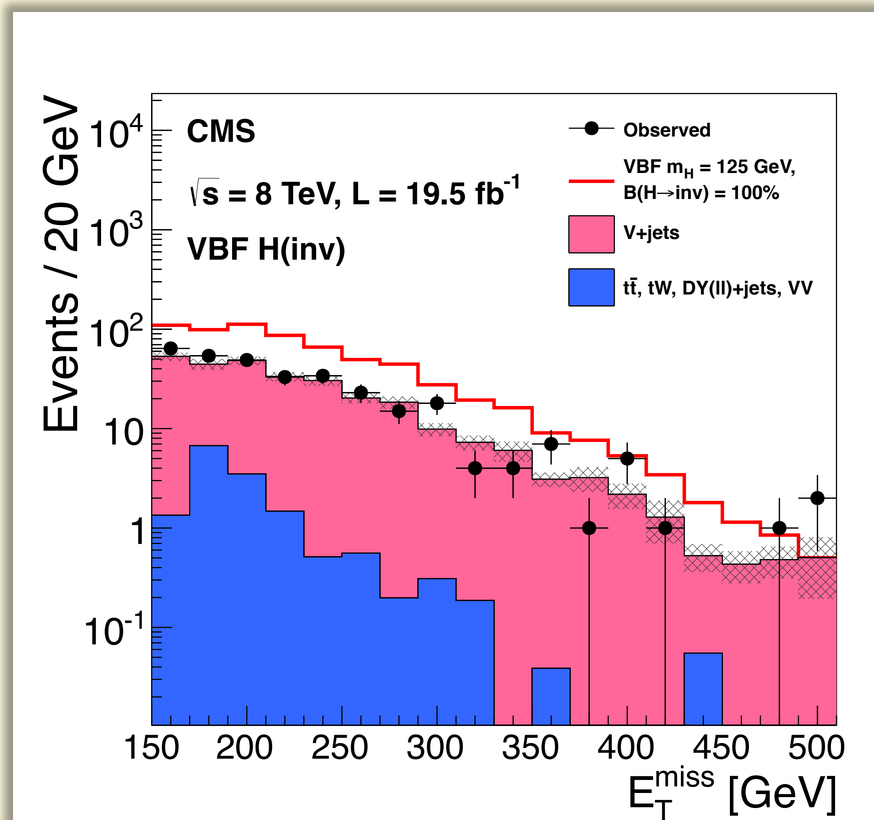


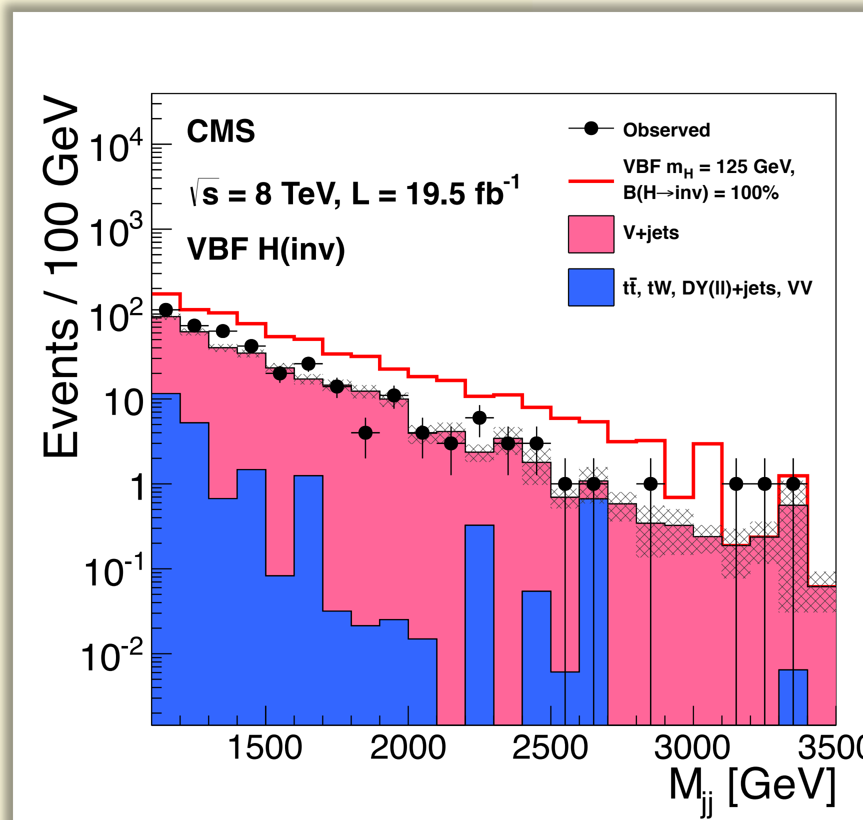


- BDT discriminant is used in the Zbb analysis to suppress large backgrounds
- Data agrees with background-only hypothesis

4.9 fb^{-1} @ 7 TeV, 19.7 fb^{-1} @ 8TeV
CMS Eur. Phys. J. C 74 (2014)

Vector boson fusion



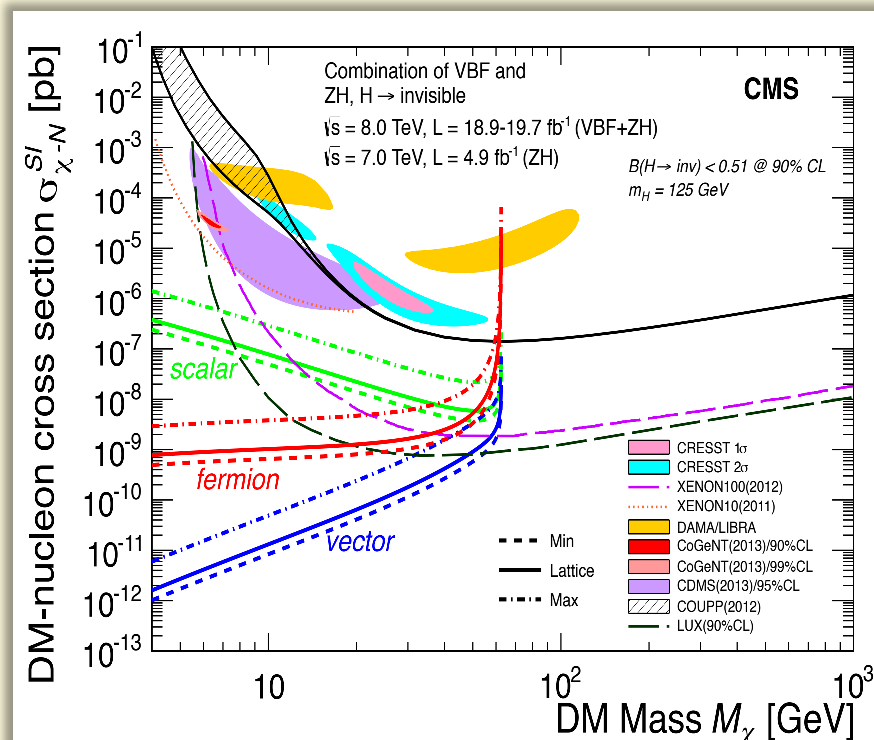


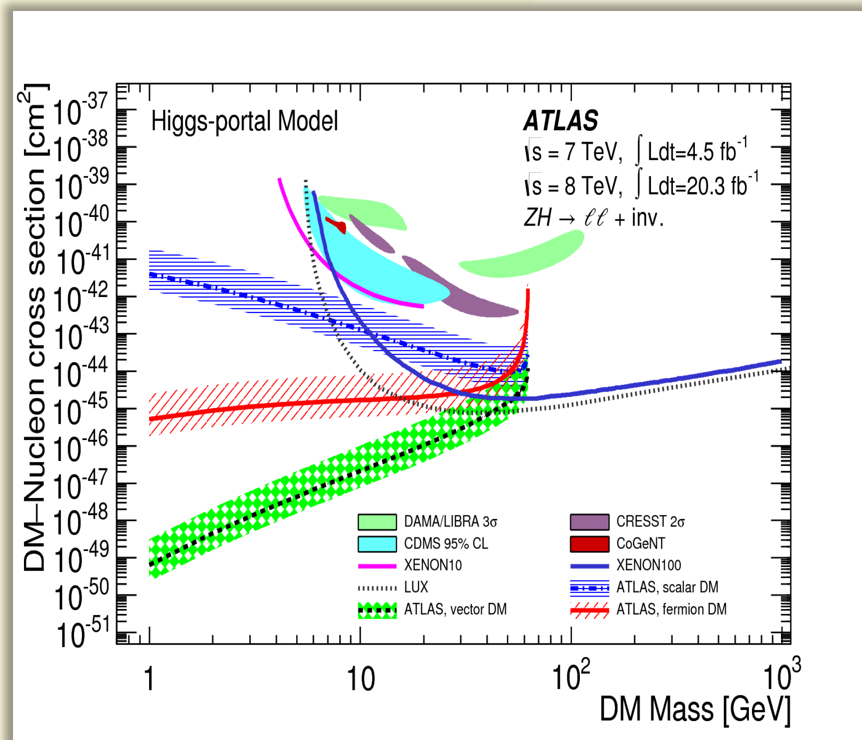
- Signature of the events: large MET and two forward jets

4.5 fb^{-1} @ 7 TeV, 20.3 fb^{-1} @ 8TeV
ATLAS PRL 112, 201802 (2014)

4.9 fb^{-1} @ 7 TeV, 19.7 fb^{-1} @ 8TeV
CMS Eur. Phys. J. C 74 (2014)

Higgs → invisible limits

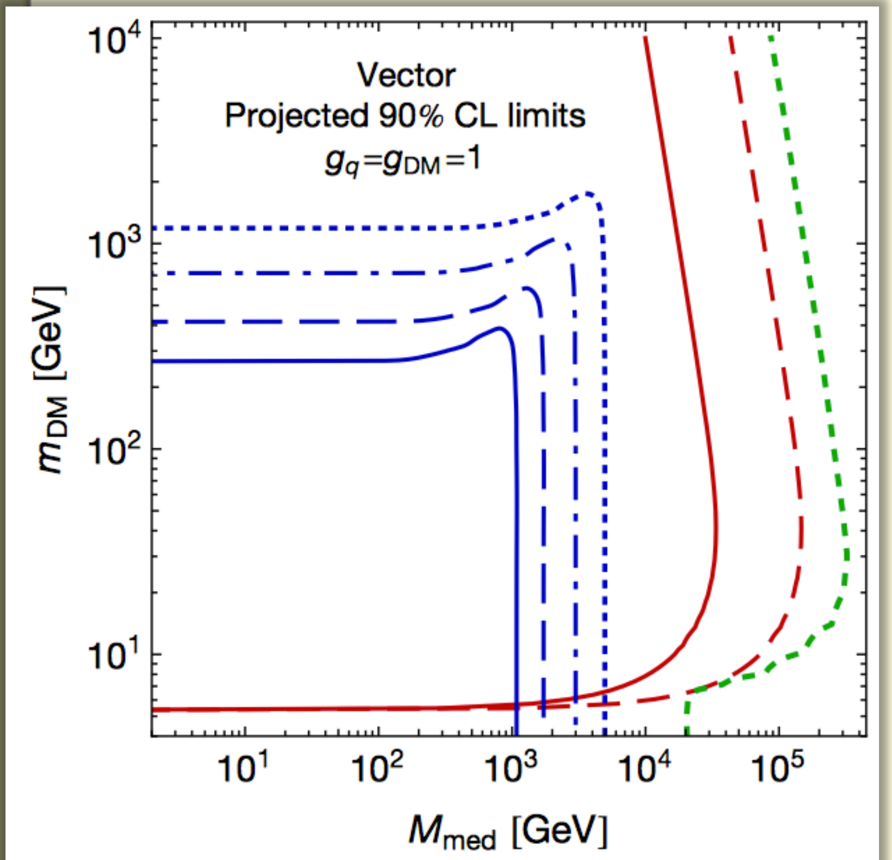


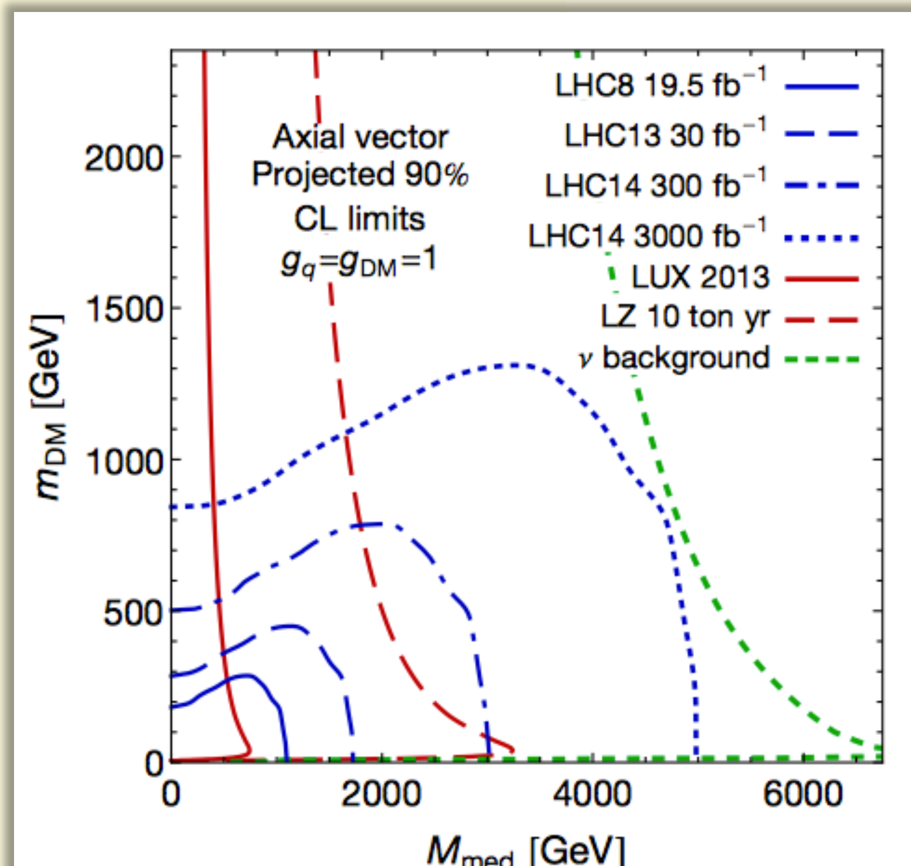


- ATLAS: BR(inv) < 0.75 (expected 0.62) @ 95%C.L.
- CMS: BR(inv) < 0.58 (expected 0.44) @ 95% C.L.

arXiv:1407.8257

Expectations for LHC13-14





- Extrapolating current results into future expect significant extension of the reach

Conclusion

- LHC experiments provide broadly sensitive searches
- Predictions for SM backgrounds consistent with data
    - Set limits on DM production cross-section
- Results interpreted in EFT framework
    - Interpret in terms of χ-nucleon cross-section limits
    - Provide competitive and complimentary results to DM searches, in some cases world best limits
    - Recently progress in interpreting results in terms of Simplified Models
- Substantial improvement expected from LHC Run2 @ 14 teV

Backup

DM operators

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
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	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
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	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

TABLE I: Operators coupling WIMPs to SM particles. The operator names beginning with D, C, R apply to WIMPS that are Dirac fermions, complex scalars or real scalars respectively.

ATLAS/CMS performance overview

	ATLAS (7 ktons)	CMS (12.5 ktons)
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • $B = 2$ T • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • $B = 3.8$ T • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	• 4 Magnets • Solenoid + Air-core muon toroids • Calorimeters outside solenoid field	• 1 Magnet • Solenoid • Calorimeters inside field
EM CALORIMETER	• Pb / Liquid Ar sampling accordion • $\sigma(E) \sim 10\text{–}12\% / \sqrt{E} \oplus 0.2\text{–}0.35\%$ • Longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E) \sim 3\text{–}5.5\% / \sqrt{E} \oplus 0.5\%$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. tiles (EC: Cu-liquid Ar) • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel)	• Cu (EC: brass) / Scint. tiles • Tail catchers outside solenoid • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	• Drift tubes & CSC (fwd) + RPC/TGC • $\sigma(p_T) \sim 10.5\%$ / 10.4% (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes & CSC (EC) + RPC • $\sigma(p_T) \sim 13\%$ / 4.5% (1 TeV, $\eta = 0$) (standalone / combined with tracker)

Source: Froidevaux-Sphicas, Ann Rev 56, 375 (2006)