Dark Matter results from Monojets at LHC

DM@LHC 2014

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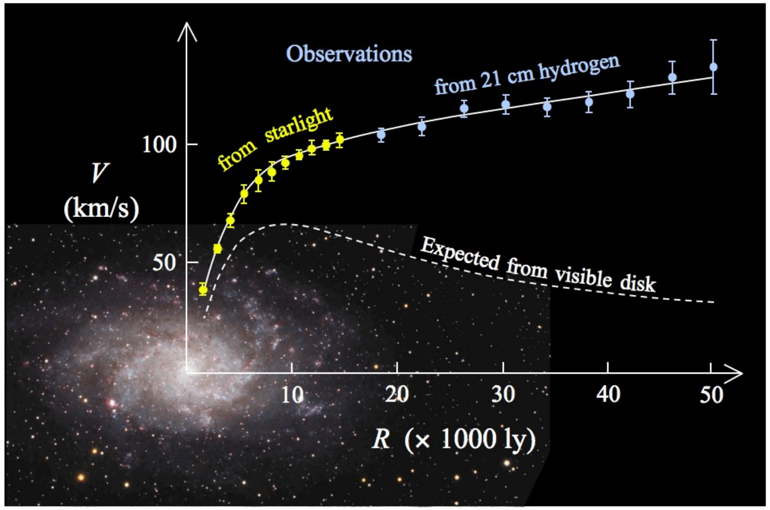
(on behalf of the ATLAS and CMS Collaborations)

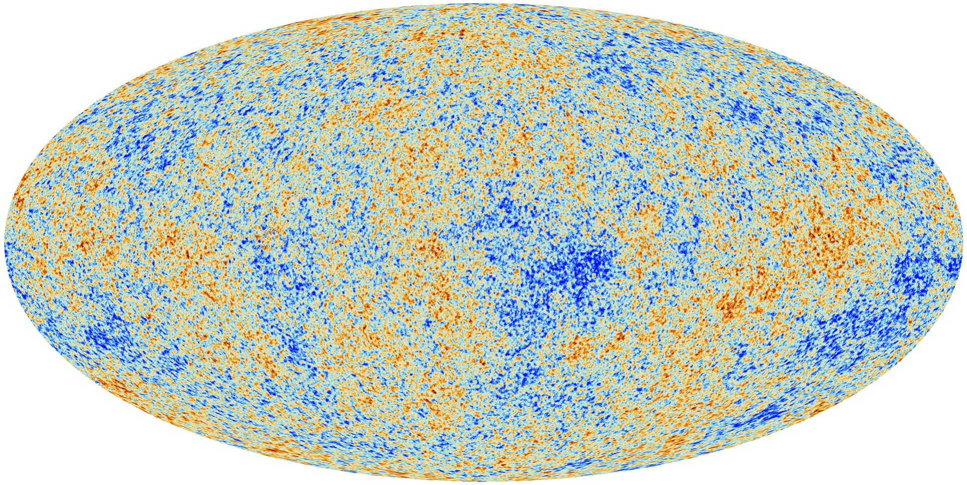
Dark matter: evidence

Galaxy rotation curves:

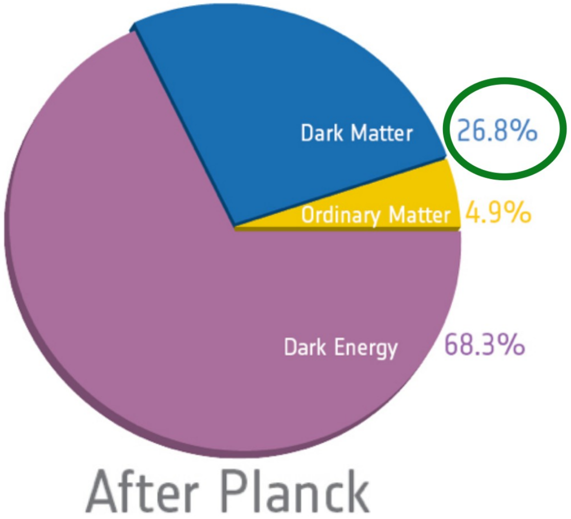


Gravitational lensing:

Cosmic microwave background:



fitting ΛCDM →



Dark matter: candidates

Weakly Interacting Massive Particles (WIMPs)

- **Weakly Interacting**: right relict abundance without fine-tuning
- **Massive**: cold (v≪c) dark matter won't smear large-scale structure of the universe
- Side product of various BSM theories (e.g. R-parity conserving SUSY)

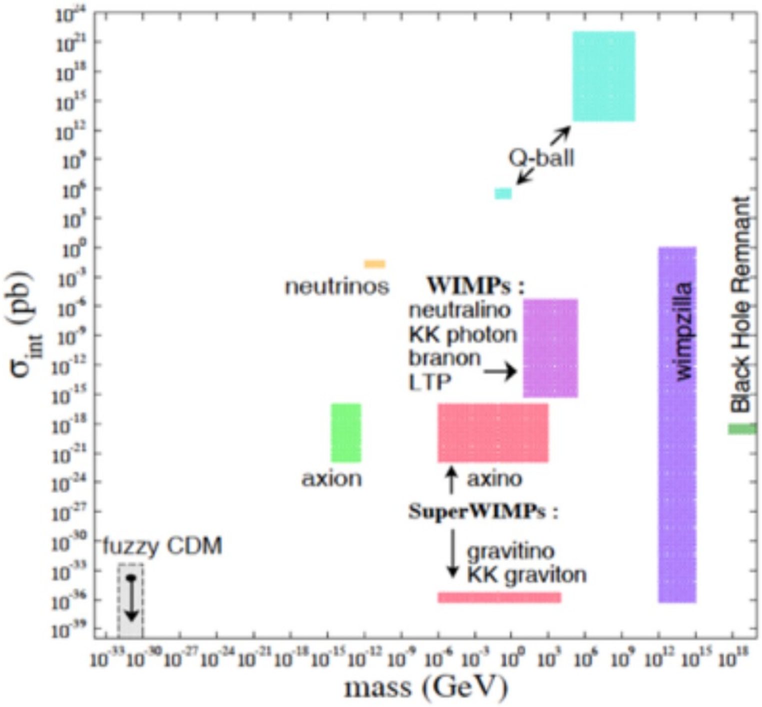
Sterile neutrinos

- Neutrinos in Standard Model are left-handed
  → right-handed analog would be invisible

Axions

- hypothetical $U_{PQ}(1)$ field solving strong CP problem

(making QCD Lagrangian CP-invariant)



Anything else fitting the minimal picture:

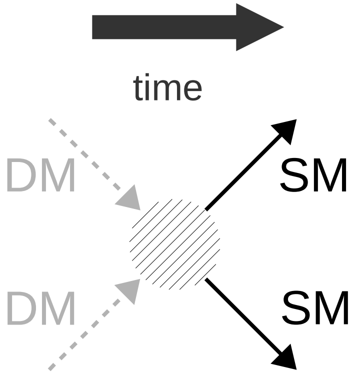
- single
- stable
- weakly interacting
- neutral

… but there are also options with a “hidden world” of multiple states and interactions

Dark matter: searches

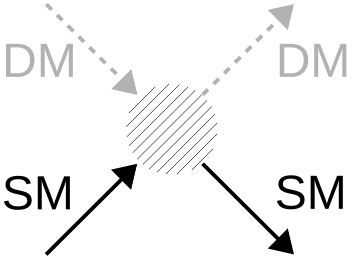
Indirect detection (annihilation of DM into SM particles):

- experiments: AMS, Pamela, Fermi
- anomalies seen (too many positrons, 130 GeV γ-ray line, 1402.6703) … no solid conclusion



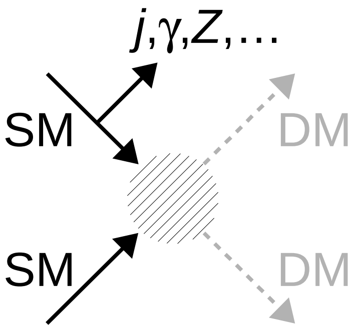
Direct detection (scattering of DM on atomic nuclei):

- experiments: SuperCDMS, CoGeNt, XENON100, LUX, …
- some hints seen (the 3 CDMS events, DAMA annual modulation, …), but not confirmed

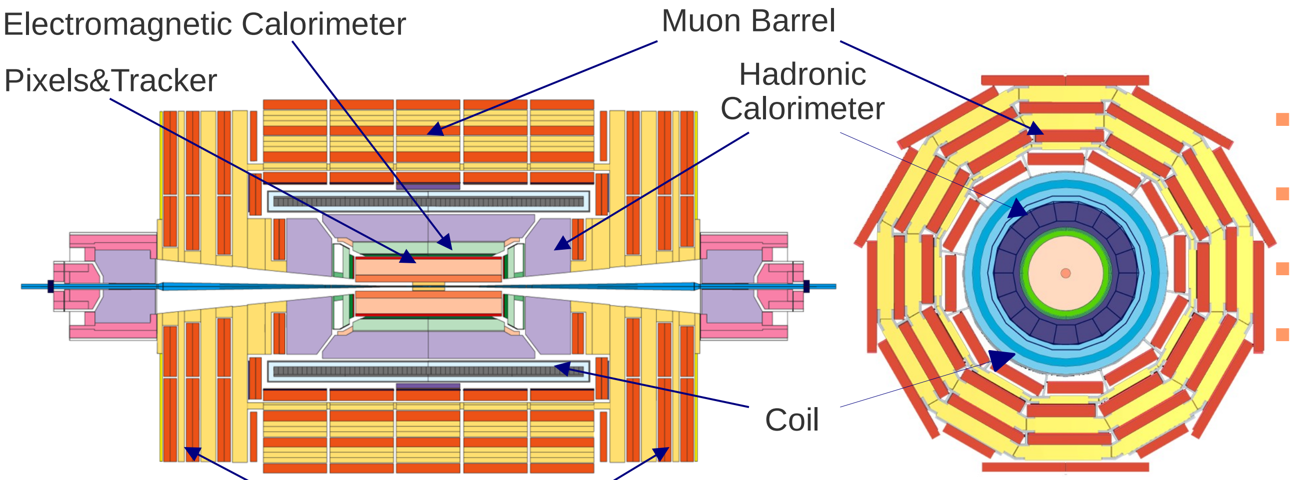


Collider experiments (annihilation of SM into DM particles)

- searches with $\not{E}_T$: mono-X (X=jet,γ,Z,t,H,…)
- different regime: high momentum transfer → can resolve mediator resonant production boosts sensitivity compared to the direct detection



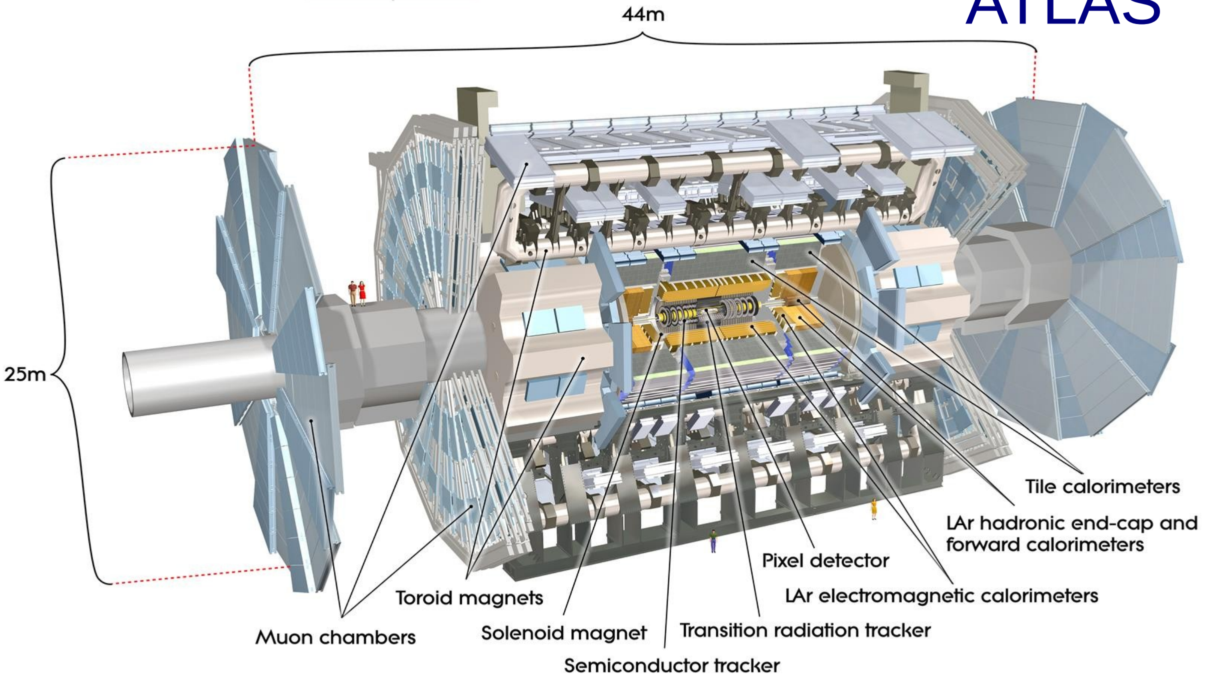
CMS and ATLAS detectors at LHC



CMS

- tracker: $\sigma(p_T)/p_T \sim 1.5 \cdot 10^{-4}\, p_T + .005$
- ECal: $\sigma_E/E \sim 3\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.5\%$
- HCal: $\sigma_E/E \sim 100\%/\sqrt{E[\mathrm{GeV}]} \oplus 5\%$
- trk+Mu: 1%@50GeV–10%@1TeV

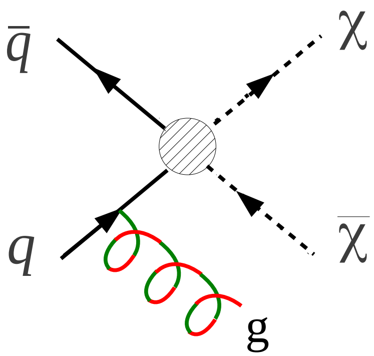
ATLAS



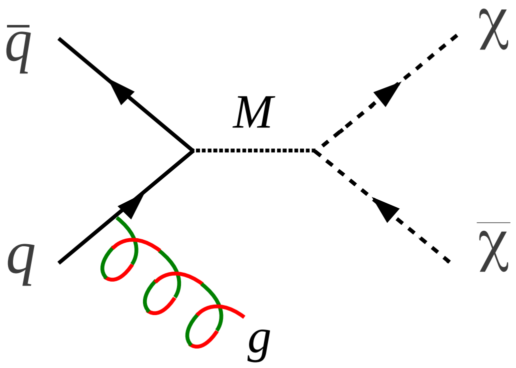
- tracker: $\sigma(p_T)/p_T \sim 5 \cdot 10^{-4}\, p_T + 0.01$
- ECal: $\sigma_E/E \sim 10\%/\sqrt{E[\mathrm{GeV}]} \oplus 0.7\%$
- HCal: $\sigma_E/E \sim 50\%/\sqrt{E[\mathrm{GeV}]} \oplus 3\%$
- trk+Mu: 2%@50GeV–10%@1TeV

Monojet theory

Can't resolve mediator → use Effective Field Theory of contact interaction at scale Λ:



Light mediator of mass M → use Simplified Theory:



$$O_V \sim \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$O_A \sim \frac{(\bar{\chi}\gamma_\mu\gamma^5\chi)(\bar{q}\gamma^\mu\gamma^5 q)}{\Lambda^2}$$

$$\Longleftrightarrow$$

$$\mathcal{L}_V \sim \frac{i g_\chi g_q}{q^2-M^2}(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)$$

$$\mathcal{L}_A \sim \frac{i g_\chi g_q}{q^2-M^2}(\bar{\chi}\gamma_\mu\gamma^5\chi)(\bar{q}\gamma^\mu\gamma^5 q)$$

Nomenclature for the interactions:

"V" → vector; "A" → axial-vector; "S" → scalar (describes gluon fusion with $O_S \sim \frac{\bar{\chi}\chi \quad \alpha_s (G^a_{\mu\nu})^2}{4\Lambda^3}$)

EFT and ST are equivalent for $q \ll M$ → $\Lambda = \frac{M}{\sqrt{g_\chi g_q}}$

Effective theories vs. simplified models

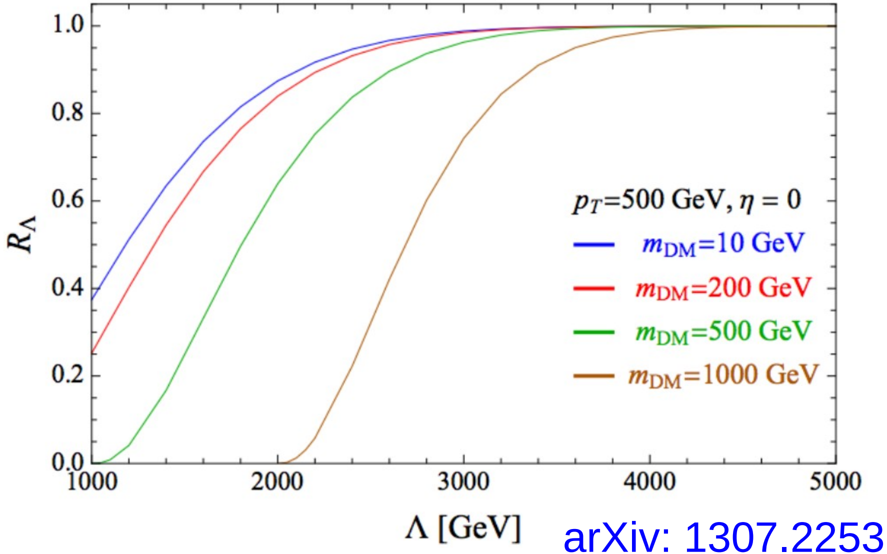
Effective Field Theory

- simple parameter space: m_χ and Λ
- breaks at $\Lambda \sim q \sim m_\chi$ (actually at $\Lambda < m_\chi/2\pi$)

Simplified Model:

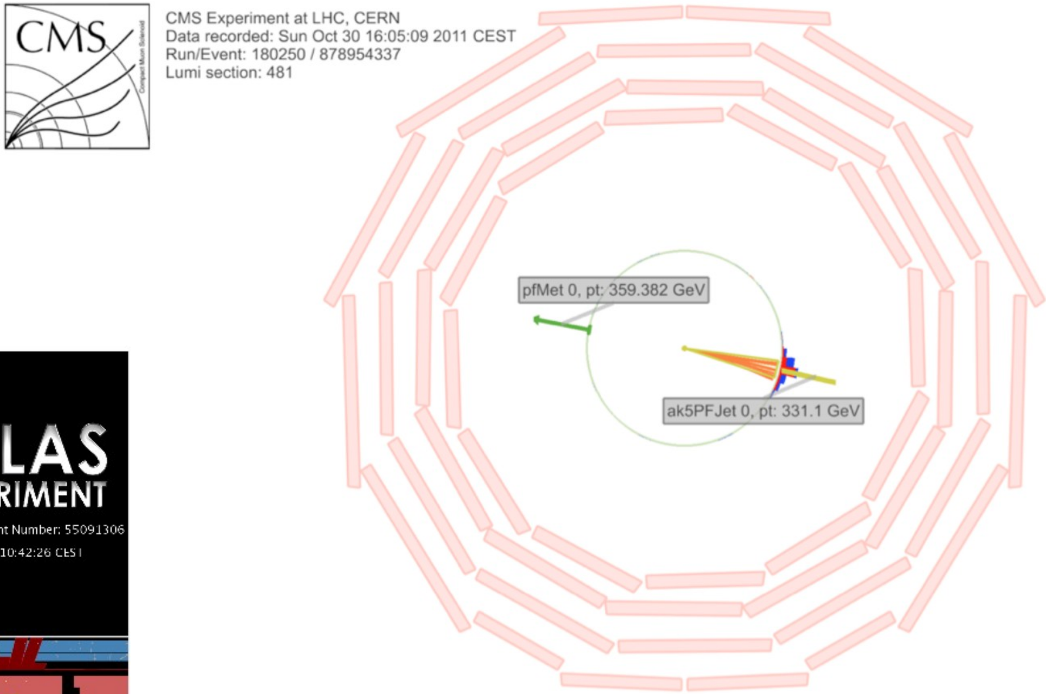
- UV-complete
- both: s- and t- channels
- complex parameter space: m_χ, M, g_χ, g_q

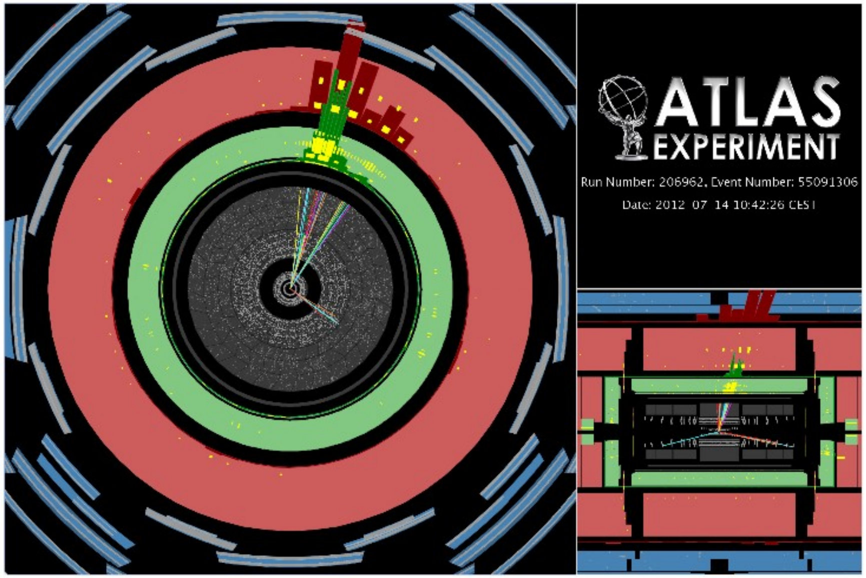
fraction of events with $q < \Lambda$:



arXiv: 1307.2253

Event topology: jet and $\not{E}_T$





$$p_T^{\text{jet1}} = 852\,\text{GeV},\ \text{E}_\text{T}^{\text{miss}} = 863\,\text{GeV}$$

Event selection

	ATLAS	CMS
trigger:	$\not{E}_T > 80$ GeV	$(\not{E}_T > 120)$ .OR. $(\not{E}_T > 105$ .AND. $p_T^{jet} > 80)$ (GeV)
signal jet:	central leading jet: $p_T > 120$ GeV, $\lvert\eta\rvert < 2.0$ at most 2 jets: $p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$	central leading jet: $p_T > 110$ GeV, $\lvert\eta\rvert < 2.4$ at most 2 jets: $p_T > 30$ GeV, $\lvert\eta\rvert < 4.5$
suppress EWK:	lepton veto: $p^e_T > 20$ GeV, $p^\mu_T > 7$ GeV	lepton veto: $p_T^{e,\mu} > 10$ GeV, $p_T^{\tau} > 20$ GeV
suppress QCD:	$\Delta\phi(\not{E}_T, \mathrm{jet2}) > 0.5$	$\Delta\phi(\mathrm{jet1}, \mathrm{jet2}) < 2.5$
optimization for the "invisible" component:	$(p_T^{jet1}, \not{E}_T) > 120, 220, 350, 500$ GeV	$\not{E}_T > 250, 300, 350, 400, 450, 500, 550$ GeV

Backgrounds

$Z\to\nu\nu$ + jet(s)	irreducible
$W\to\ell\nu$ + jet(s)	lost or non-isolated lepton or hadronic τ
$t\bar{t}$	e.g. fully leptonic decay with both leptons lost
$Z\to\ell\ell$ + jet(s)	lost both leptons or hadronic τ
multijet	mismeasured jet
single top	e.g. leptonic decay with undetected lepton
WW WZ ZZ	combinations of leptonic, hadronic, invisible decays
Non-collision	noise, beam halo, cosmics; smallest

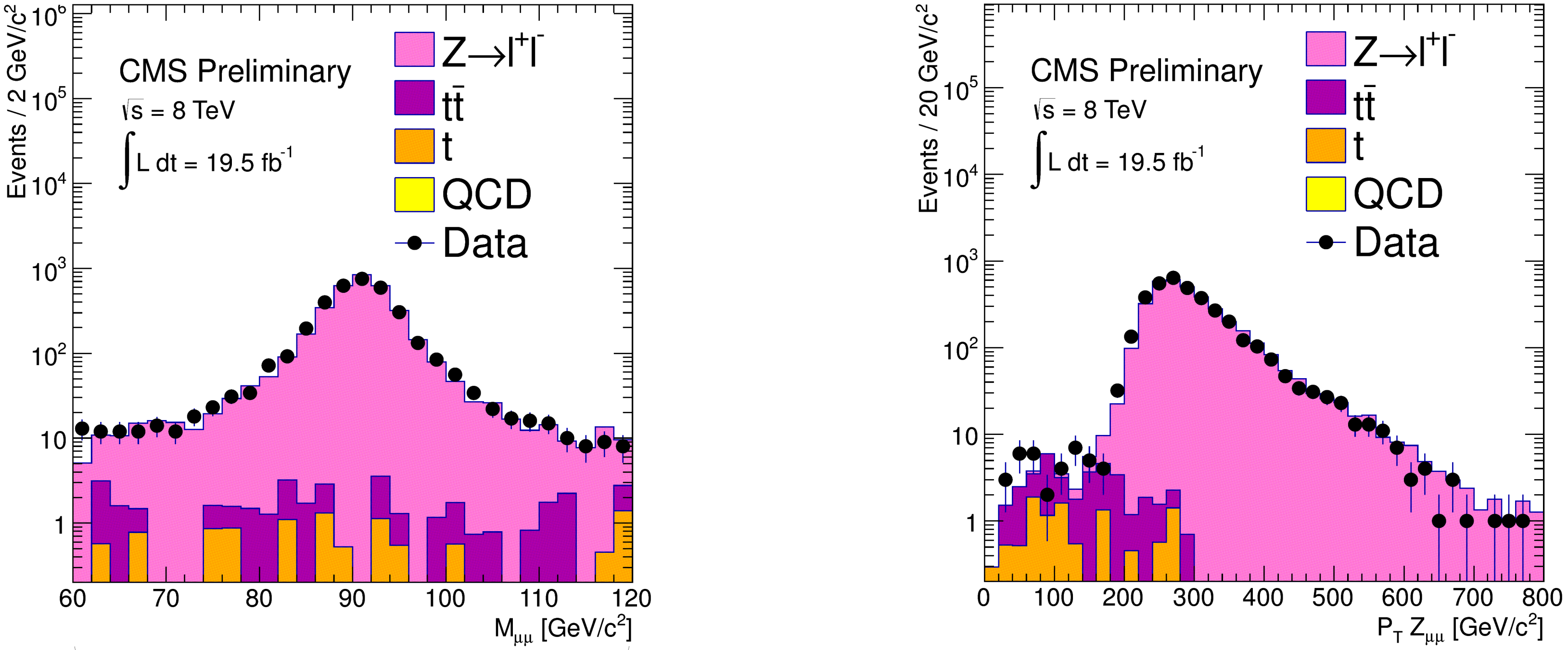
Additional jets in W/Z events originate from multijet process and are poorly simulated

→ W/Z + jet(s) backgrounds are estimated from data and other productions from MC

$Z\rightarrow\nu\nu$ + jet(s) by CMS

Count similar $Z\rightarrow\mu\mu$ + jet(s) events and “pretend” that $\mu = \nu$: $\not{E}_T = \left|\vec{\not{E}}_T + \sum \vec{p}_T^{\,\mu}\right|$

$\not{E}_T > 250$ GeV:

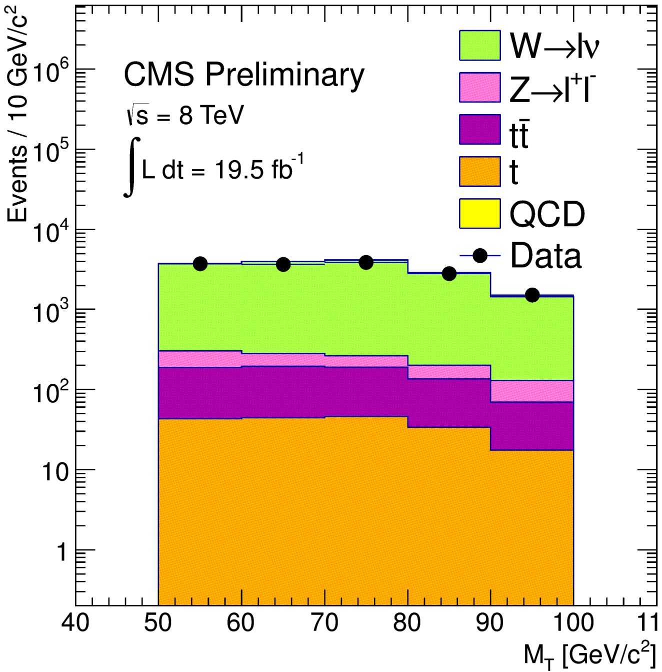


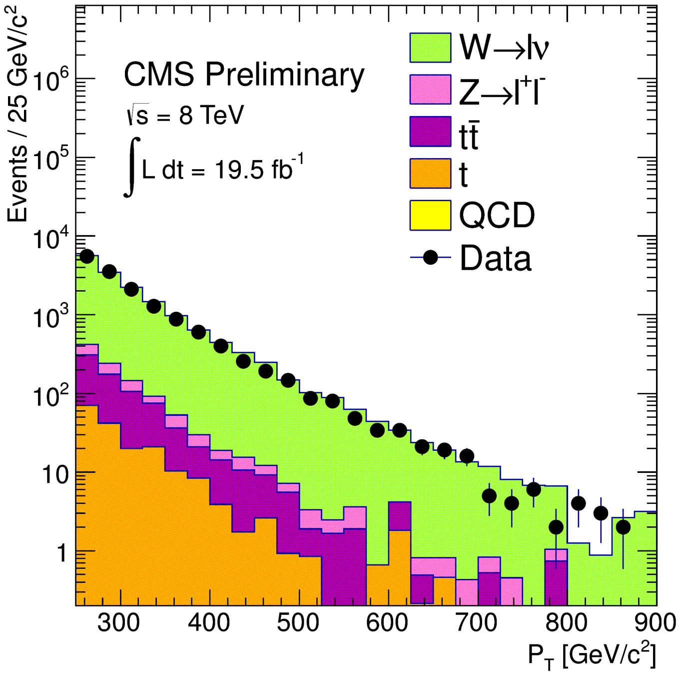
from MC

$$N(\nu\bar{\nu}) = \frac{N(\mu^{+}\mu^{-}) - N(non-Z)}{A\times\epsilon(\mu\mu)} \cdot \frac{\mathcal{B}(Z\rightarrow\nu\bar{\nu})}{\mathcal{B}(Z\rightarrow\mu\mu)}$$

$W \to \nu$ lost ℓ + jet(s) by CMS

Count similar $W \to \mu\nu$+jet(s) events; in MC find how often ℓ escapes detection





probability to miss

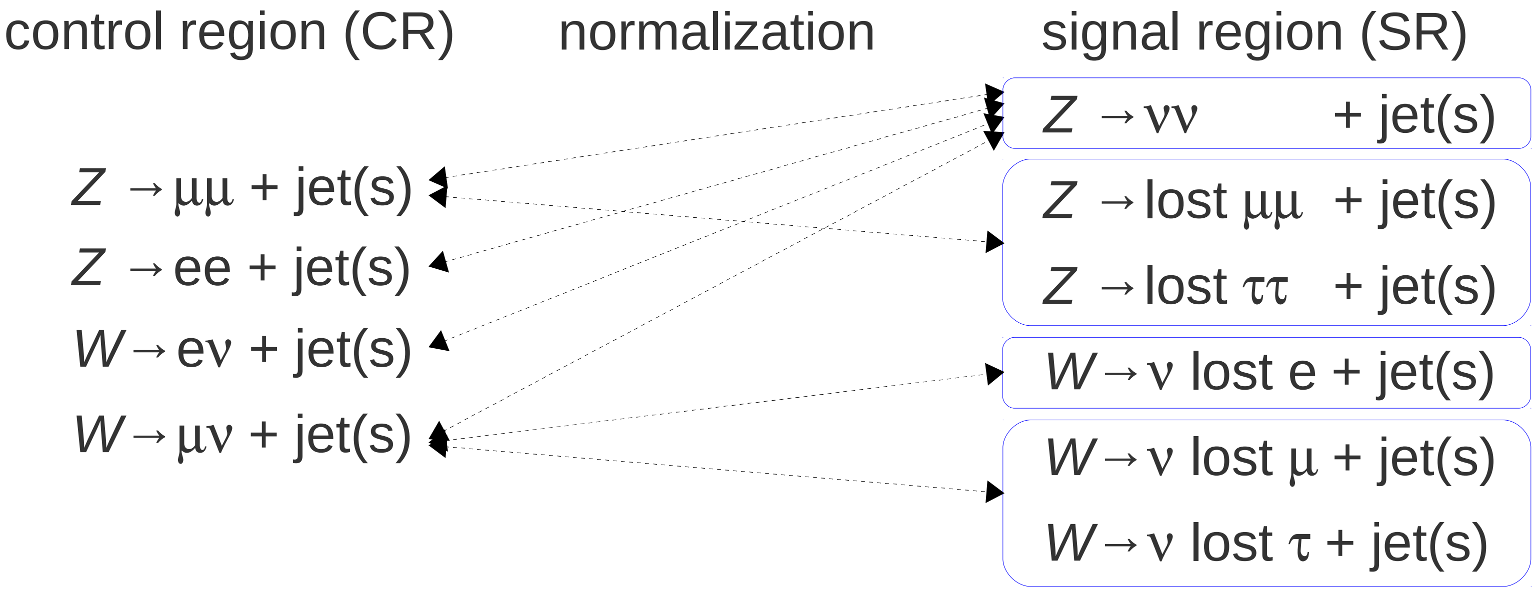
$$N(W)=\frac{N(W\to\mu\bar{\nu})-N(non-W)}{A\times\epsilon(\mu)},\qquad N(W\to\bar{\nu}\,lost\,\ell)=\overbrace{[1-A'\times\epsilon'(\ell)]}\cdot N(W),$$

from MC

probability
to detect

Data-driven *V*+jets backgrounds by ATLAS

Processes on the left fix normalization of backgrounds on the right:



control region (CR) normalization signal region (SR)

$Z \rightarrow \mu\mu$ + jet(s)

$Z \rightarrow ee$ + jet(s)

$W \rightarrow e\nu$ + jet(s)

$W \rightarrow \mu\nu$ + jet(s)

$Z \rightarrow \nu\nu$ + jet(s)

$Z \rightarrow$ lost $\mu\mu$ + jet(s)

$Z \rightarrow$ lost $\tau\tau$ + jet(s)

$W \rightarrow \nu$ lost e + jet(s)

$W \rightarrow \nu$ lost μ + jet(s)

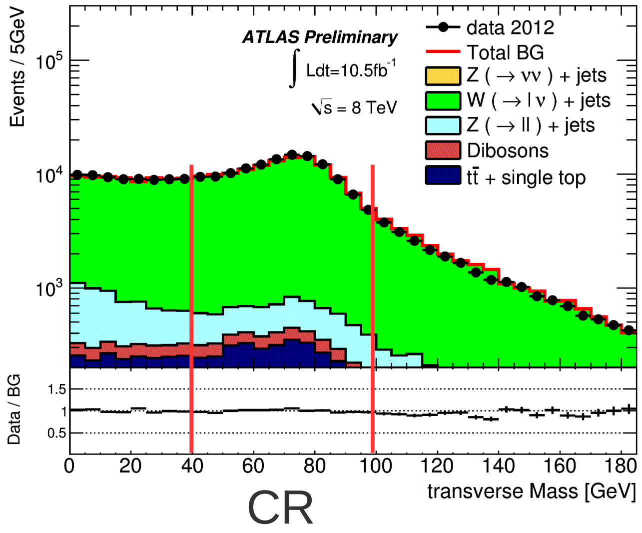
$W \rightarrow \nu$ lost τ + jet(s)

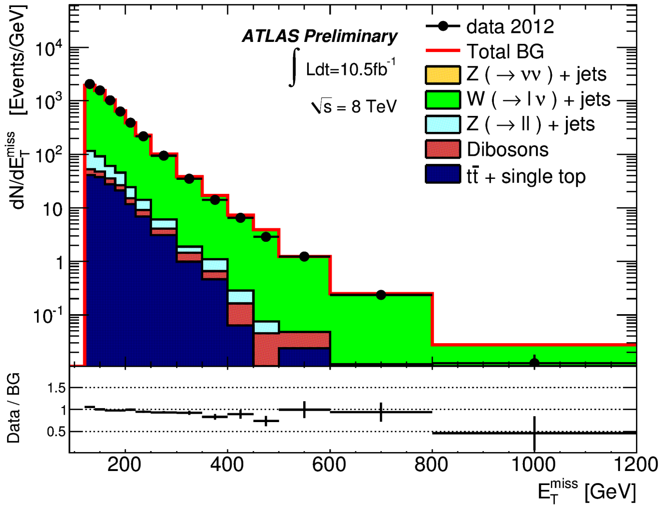
- Similar approach: number of *Z* or *W* events detected by their e and μ decays set the scale on number of *Z* and *W* events, that escape the detection, for example:

$$N_{SR}^{data}(Z \rightarrow \nu\nu + jets) = (N_{CR}^{data}(W \rightarrow \mu\nu + jets) - N_{CR}^{MC}(non - W)) \times \frac{N_{SR}^{MC}(Z \rightarrow \nu\nu + jets)}{N_{CR}^{MC}(W \rightarrow \mu\nu + jets)}$$

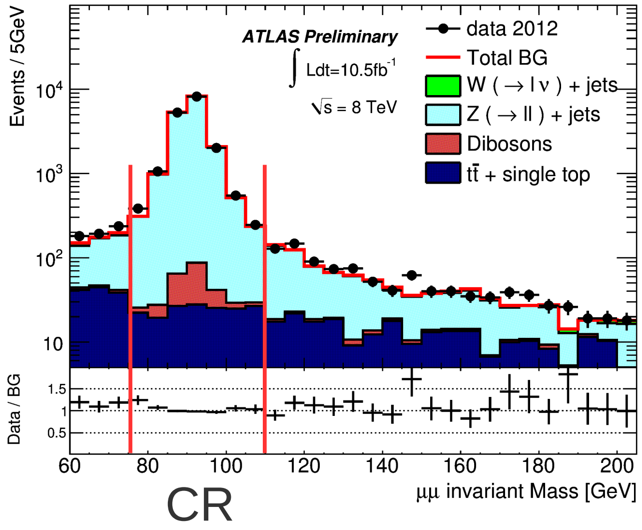
- $Z \rightarrow \nu\nu$+jets yield is given by “sum” of 4 estimates, weighted by relative uncertainties

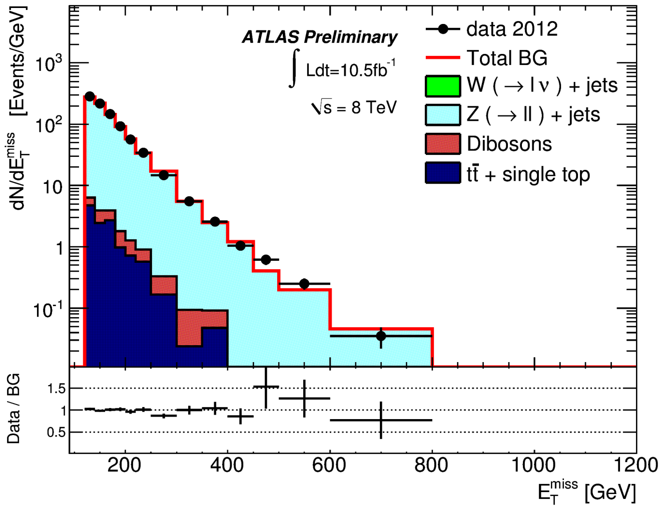
Data-MC shapes for *W* and *Z* in ATLAS





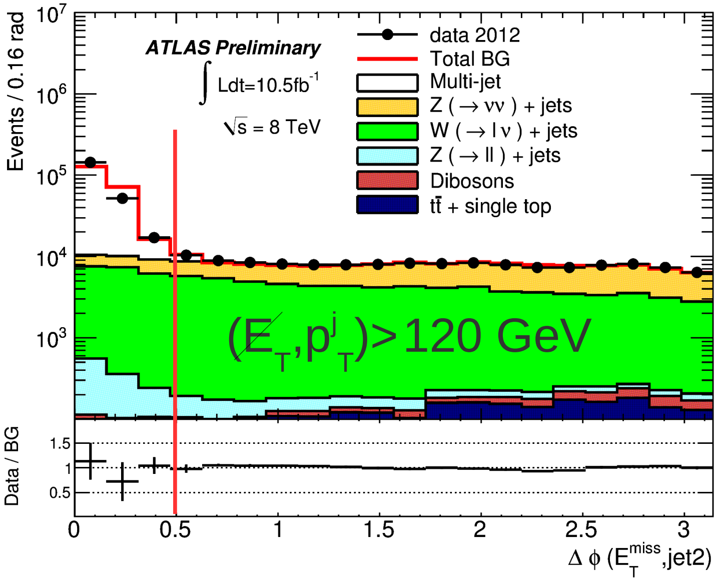
Muons, ($\not{E}_T$,p^j_T)>120 GeV, good agreement:



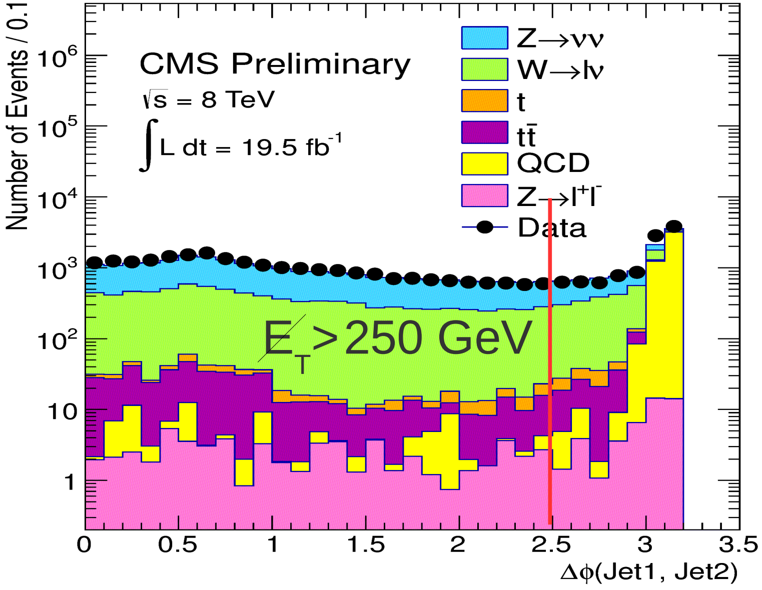


Multijet background

ATLAS:



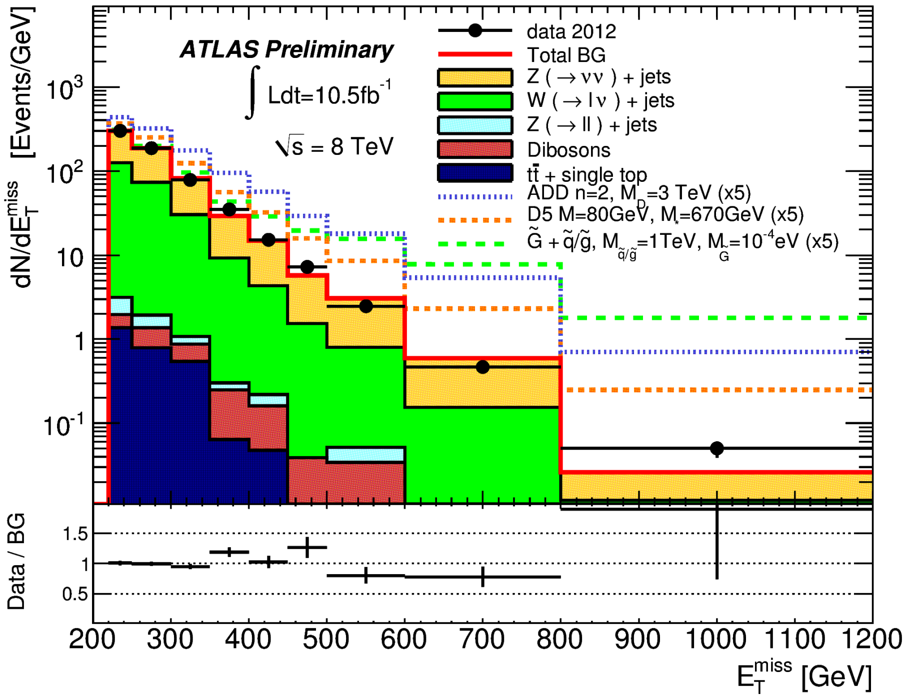
CMS:



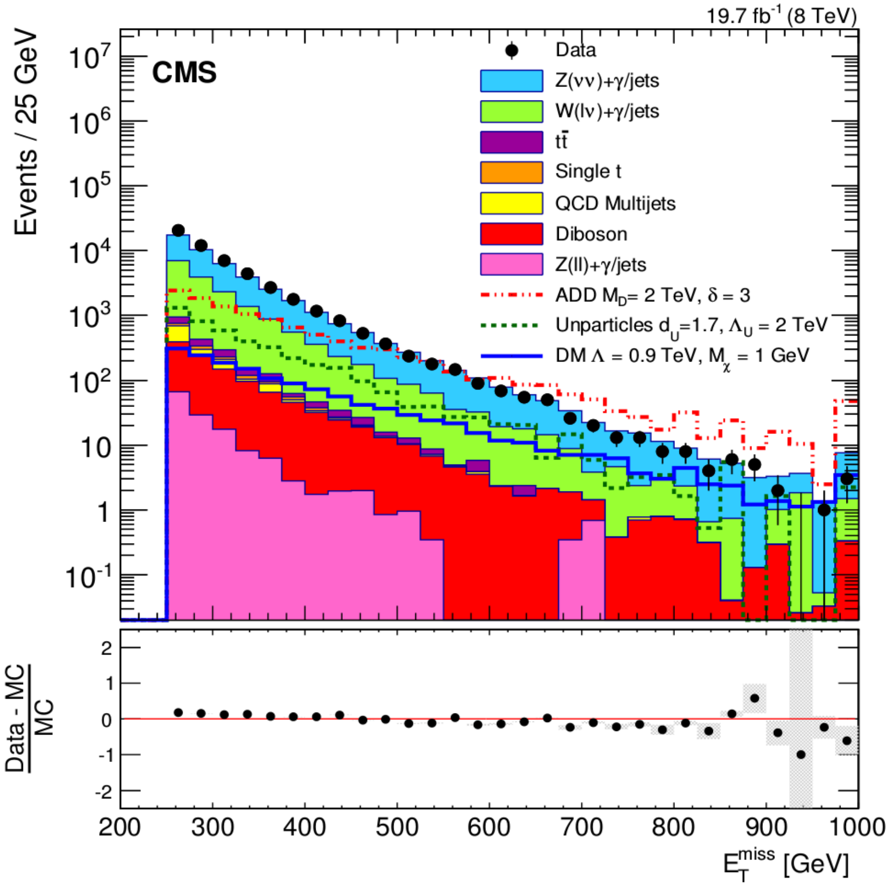
Multijet background is eliminated with collinearity cuts

Results

ATLAS-CONF-2012-147:



CMS-EXO-12-048:



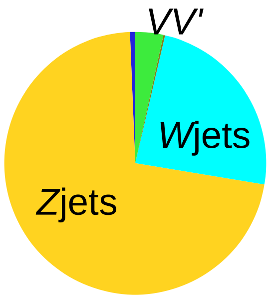
Data are consistent with SM expectations

Uncertainties

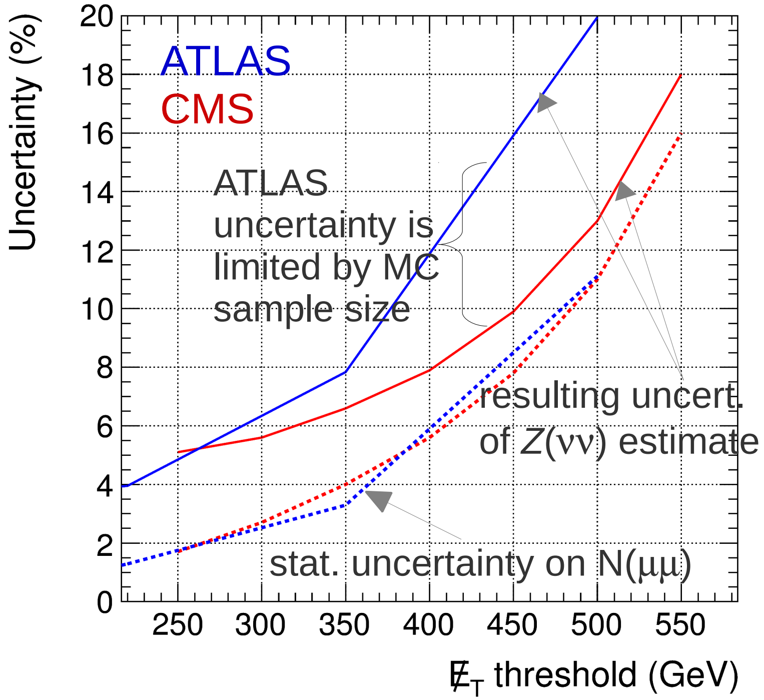
Leading uncertainties:

- number of single and double lepton events in control regions
- particle identification (uncertainty on the selection efficiency)
- simulated backgrounds:
  - renormalization and factorization scales
  - jet energy scale and resolution
  - initial/final state radiation (ME/PS jet matching)
  - parton distribution functions
  - ...

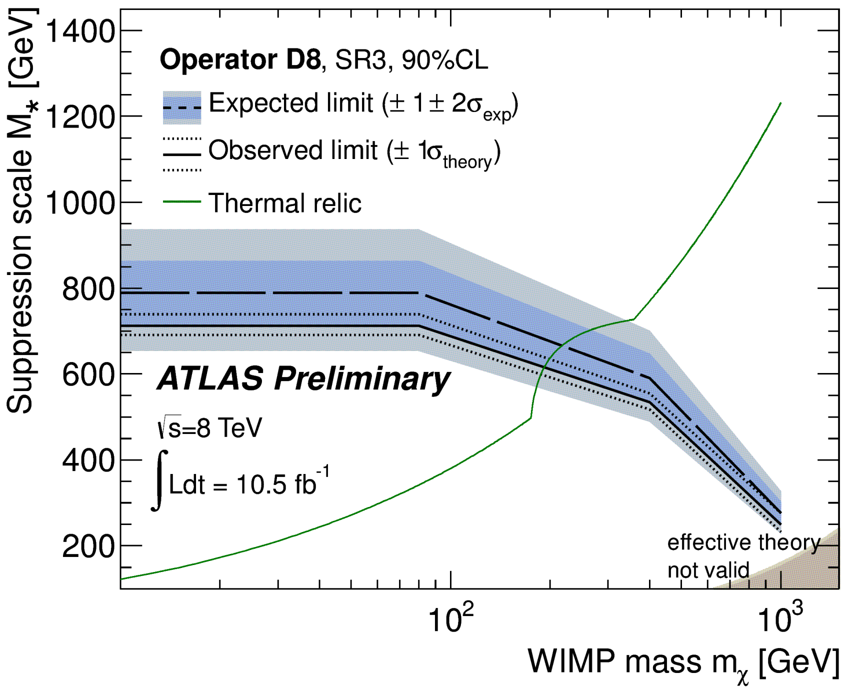
Background composition at $\not{E}_T > 500\,\mathrm{GeV}$ (leading is *Z*+jets):

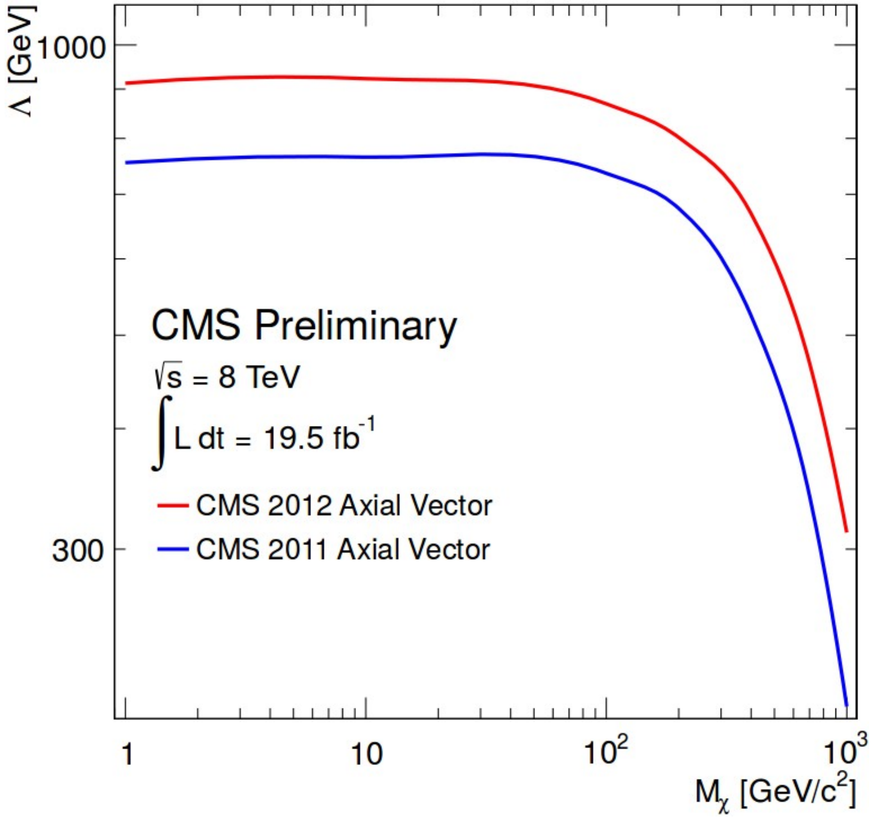


$Z \rightarrow \nu\nu$+jets background uncertainty:



Limits on the EFT parameters



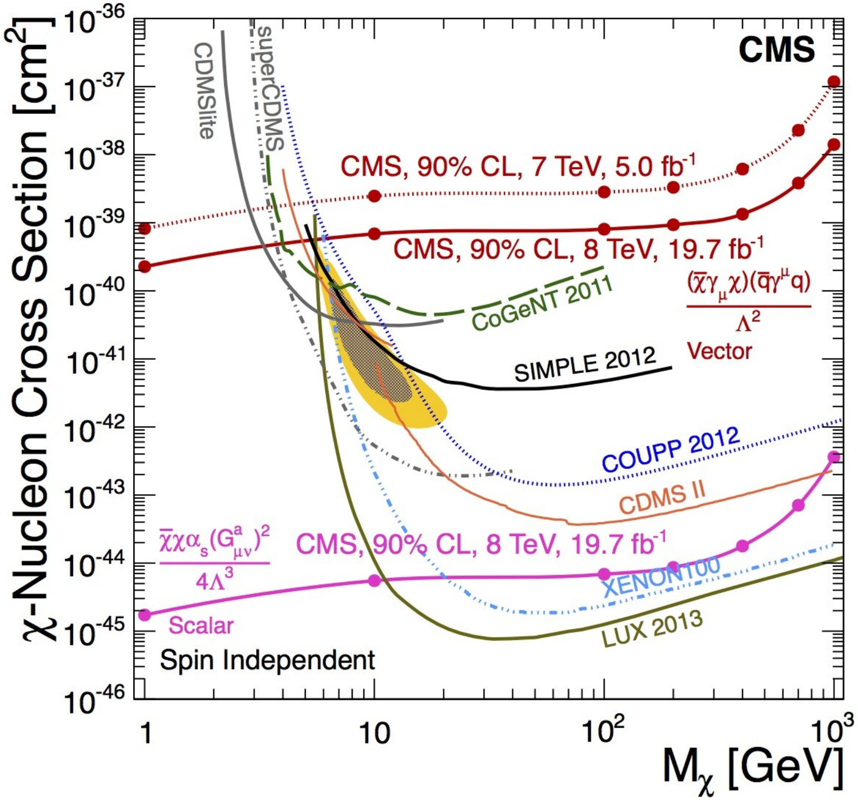


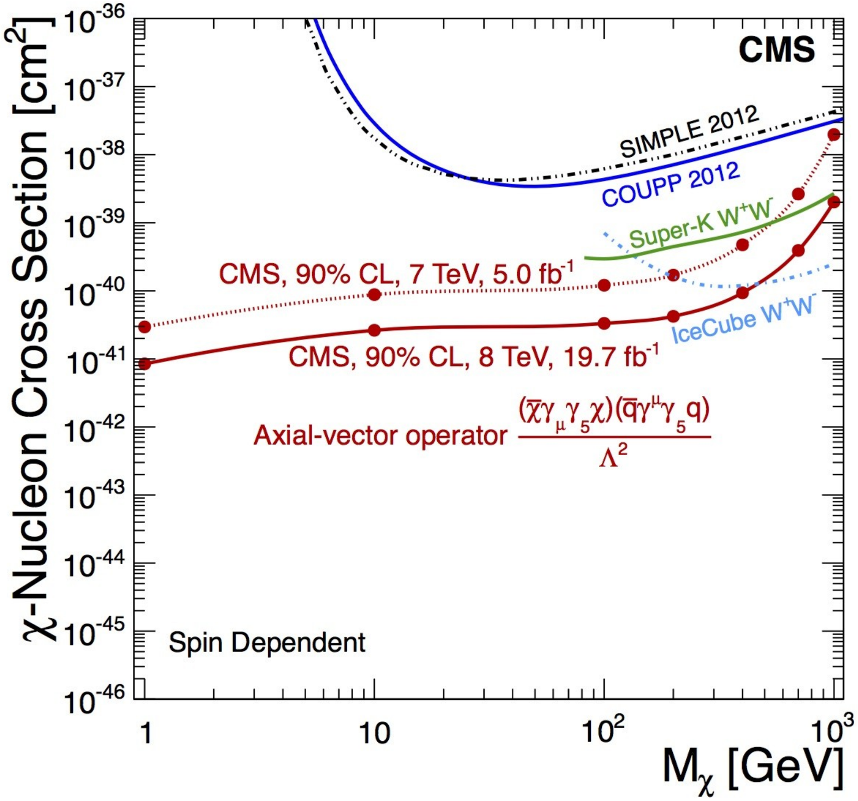
For a wide range of χ mass the limit on Λ is around 1 TeV

WIMP interpretation (CMS only for 8 TeV)

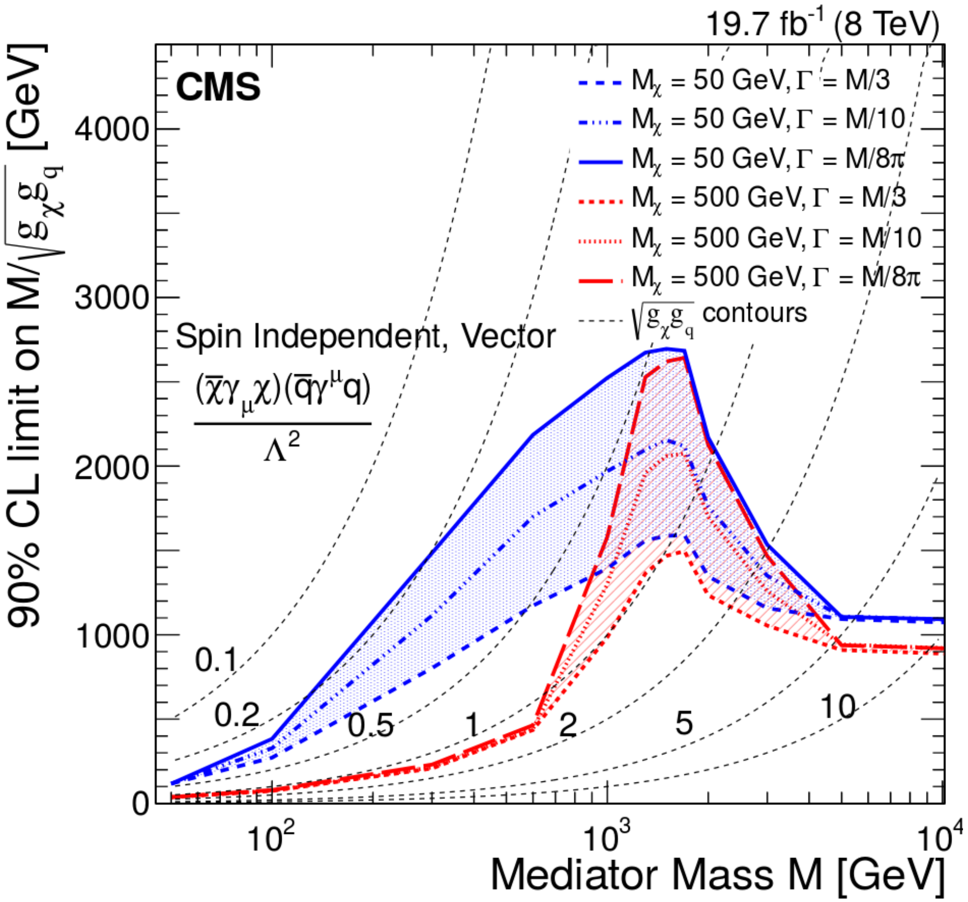
Direct detection experiments use same EFT theory

→ limits on Λ can be translated to limits on $\sigma_{\chi N}$ for direct comparison





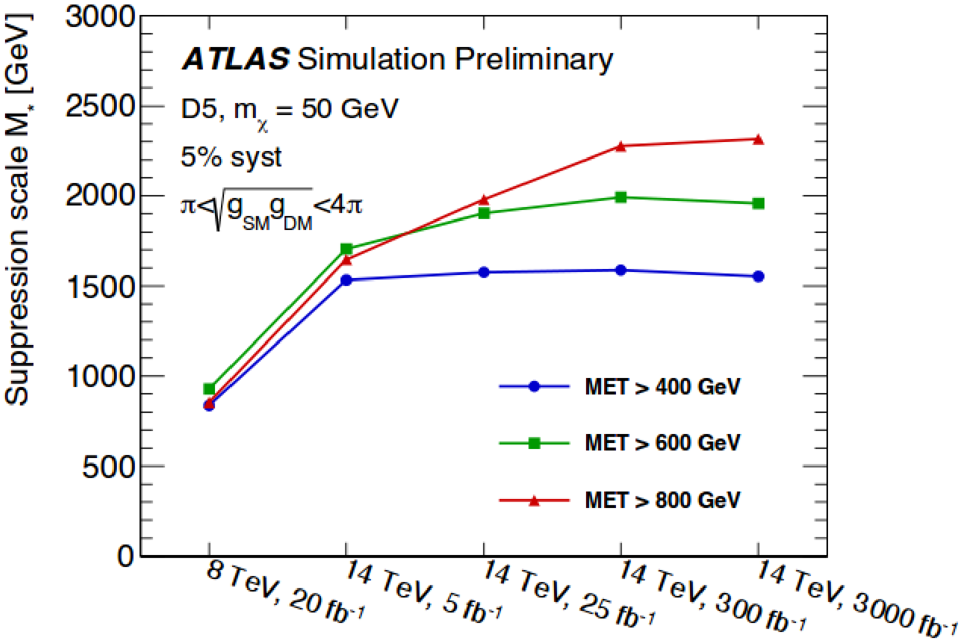
Limits on Simplified Model parameters

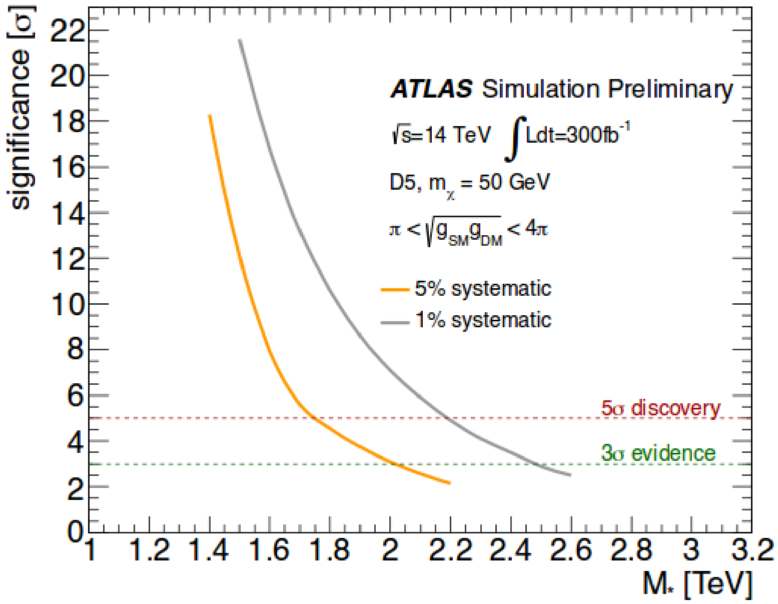


- No concerns for light mediator
- In the plot: light mediator or large couplings are ruled out (bottom area)

Future of monojets (from David Šálek's talk)

- Already first data from Run-II will bring improvements in sensitivity to DM.
  - Exclusion limits can be improved by factor of 2 with first few fb^{-1}.
  - 5σ discovery potential for M* ~ 1.7 TeV with 300 fb^{-1}.





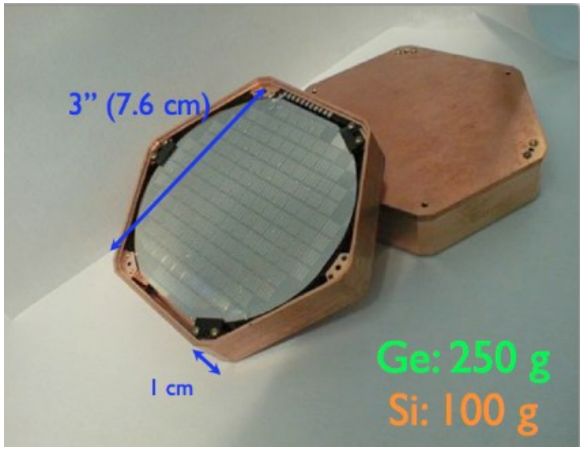
(more in Andrea DI Simone's talk ...)

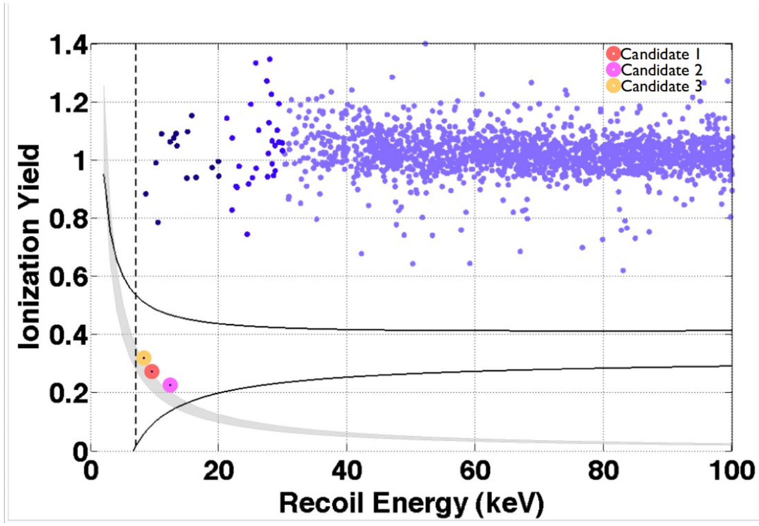
Summary

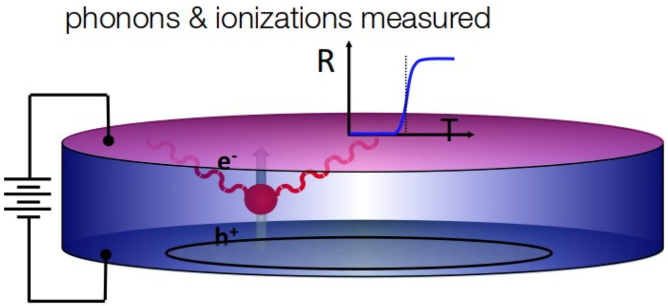
- Collider searches take advantage of a different energy regime compared to the direct and indirect detection searches ($\sqrt{s}$ vs. T_{DM} and m_{DM})
- Monojets wins in searches for few GeV WIMPs or axial-vector interaction
- Current limit on the suppression scale Λ is ~1 TeV for up to m_{WIMP}~10^2GeV

BACKUP

Direct searches

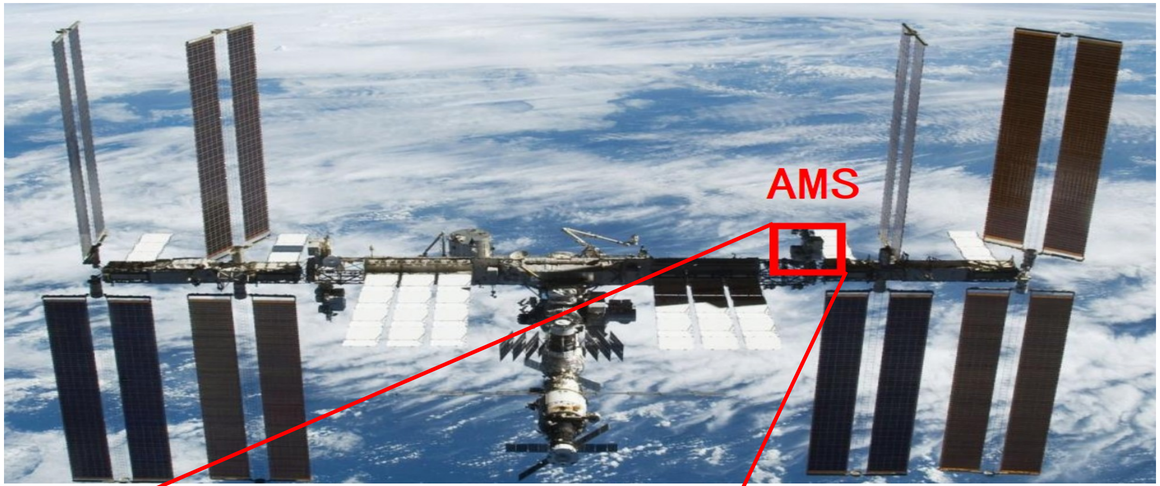


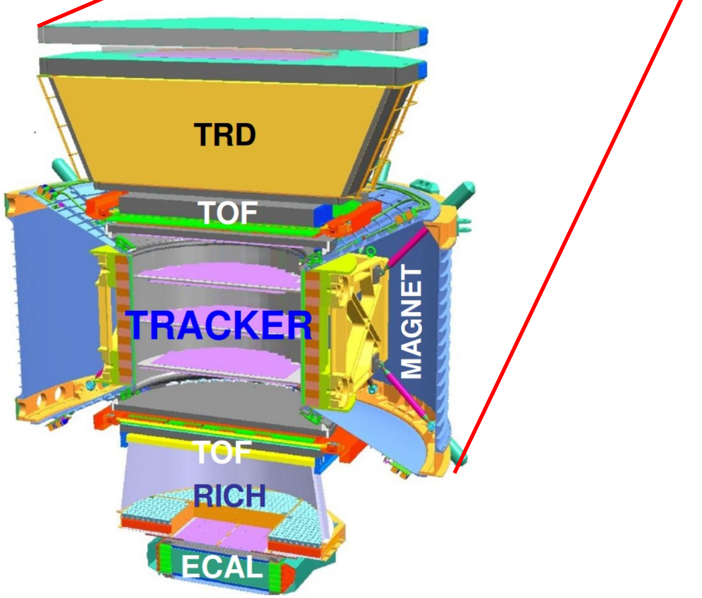




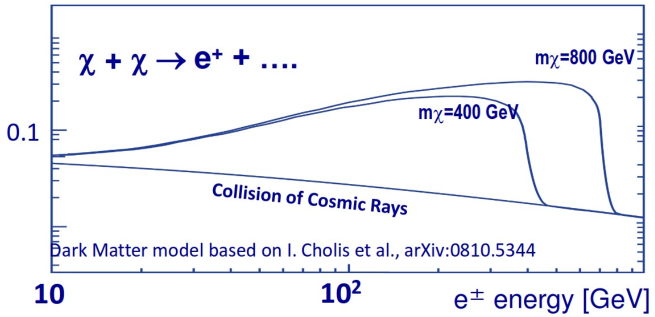
- 3 events in signal region at 140 kg-day exposure.
- Likelihood test favors WIMP+background at ~3σ
- The maximum likelihood occurs at m_{WIMP}= 8.6 GeV and $\sigma_{SI}=1.9\times10^{-41}$ cm^2

Indirect searches

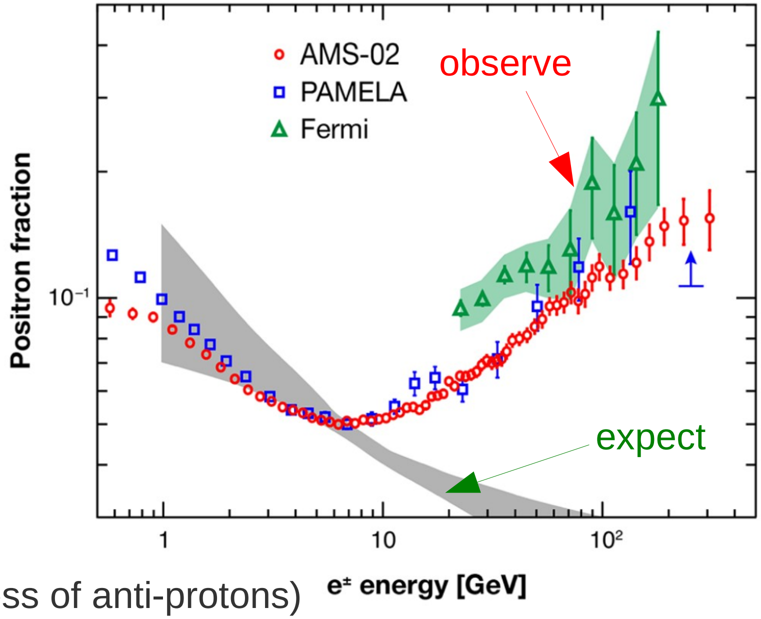




Model example:



AMS confirms PAMELA and Fermi:



Very interesting results, but many puzzles remain (e.g. no excess of anti-protons)

Monojets in year 2012

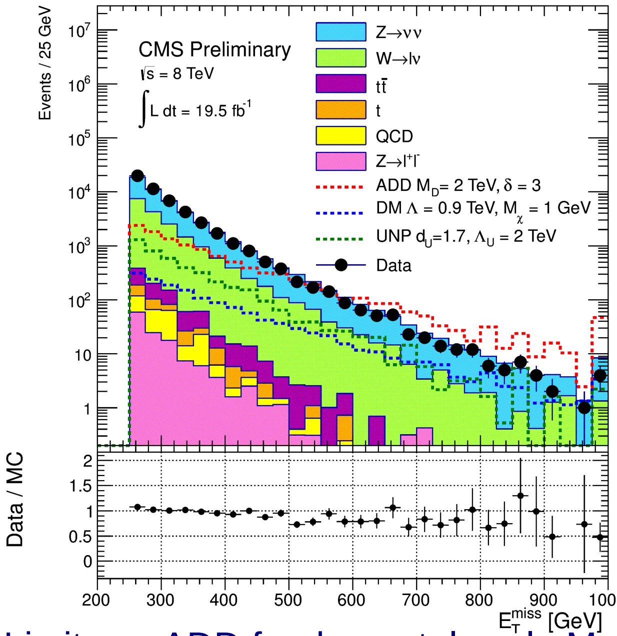
CMS-EXO-12-048, ATLAS-CONF-2012-147: excess of high $\not{E}_T$ events with 1 or 2 high p_T jets

- Non-collision bg. (noise, beam halo, ...) is cut based on balance of jet's deposits in tracker and calorimeter
- Leading SM backgrounds, Z(→νν)+jets and W(→ℓν)+jets, are derived from data requiring extra muon:

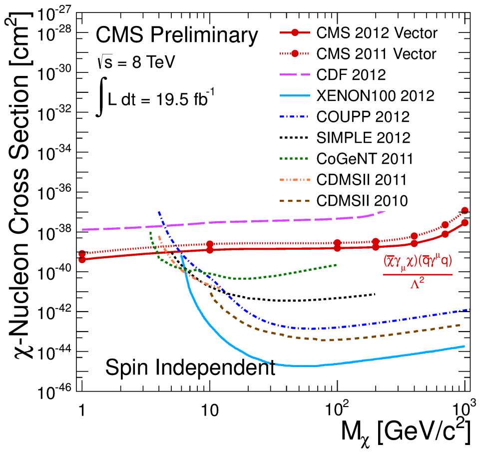
$$N(Z\to\nu\bar{\nu})=\frac{N(Z\to\mu\mu)-N(bg)}{A\times\epsilon}\cdot\frac{Br(Z\to\nu\bar{\nu})}{Br(Z\to\mu\mu)}$$

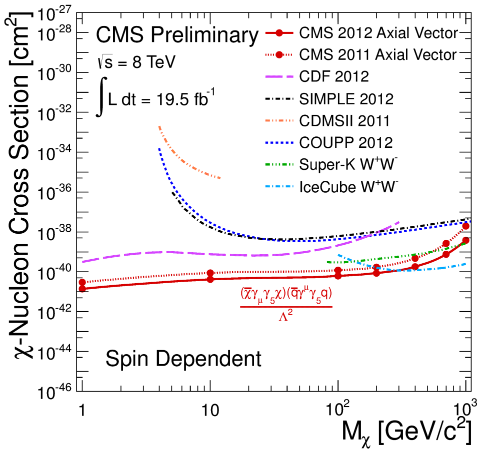
and

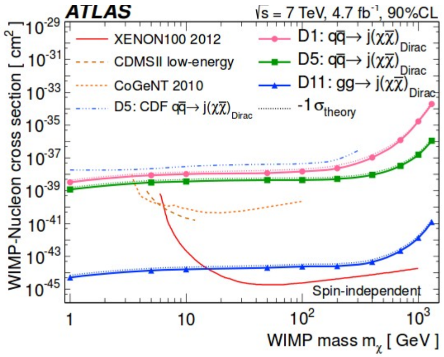
$$N(W\to lost\, l\bar{\nu})=(1-A\times\epsilon)\cdot N_{total}\,,\ N_{total}=\frac{N(W\to l\bar{\nu})-N(bg)}{A'\times\epsilon'}$$

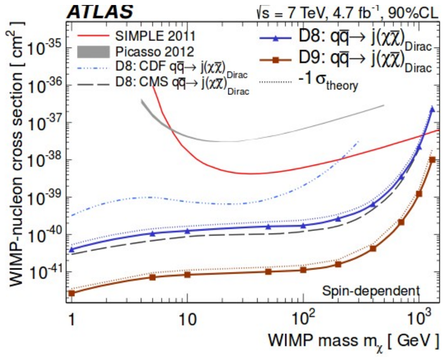


Limits on WIMP pair production:









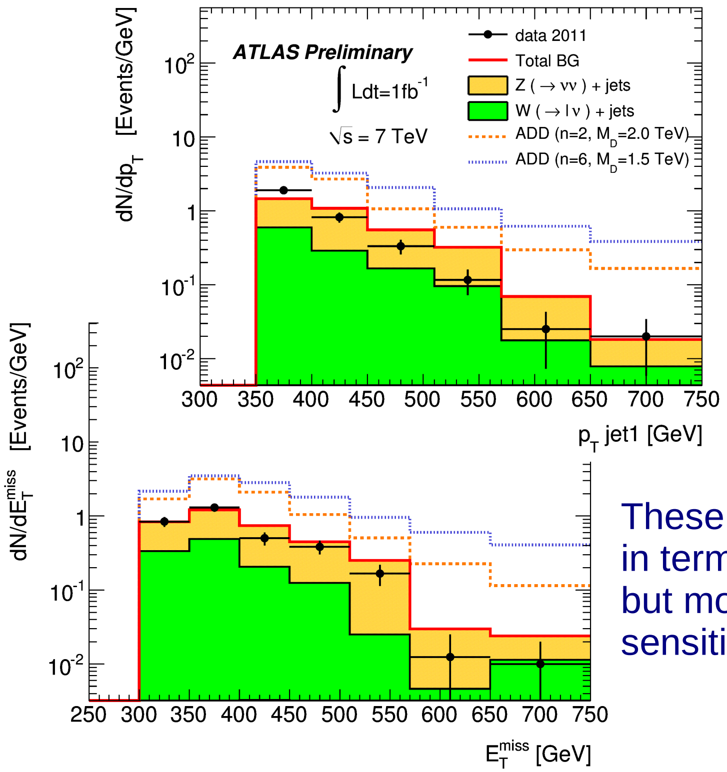
Limits on ADD fundamental scale M_D (TeV):

N^{dim}	2	3	4	5	6
LO	5.1	3.9	3.4	3.1	2.9
NLO	5.7	4.3	3.7	3.3	3.1

Monojets in year 2011

- ATLAS-CONF-2011-096 and CMS-EXO-11-059 analyses probe excess of high (>0.1-0.4TeV) $\not{E}_T$ events in association with =1 high p_T jet (ATLAS) or 1 or 2 high p_T jets (CMS), vetoing events with leptons
- Non-collision bg. (noise, beam halo, ...) is cut based on balance of jet's deposits in tracker and calorimeter
- Leading SM backgrounds, $Z(\to\nu\nu)$+jets and $W(\to\ell\nu)$+jets, are derived from data with all but lepton veto cuts:

$N(Z\to\nu\bar{\nu})=\frac{N(Z\to\mu\mu)-N(bg)}{A\times\epsilon}\cdot\frac{Br(Z\to\nu\bar{\nu})}{Br(Z\to\mu\mu)}$ and $N(W\to lost\, l\bar{\nu})=(1-A\times\epsilon)\cdot N_{total}$, $N_{total}=\frac{N(W\to l\bar{\nu})-N(bg)}{A'\times\epsilon'}$

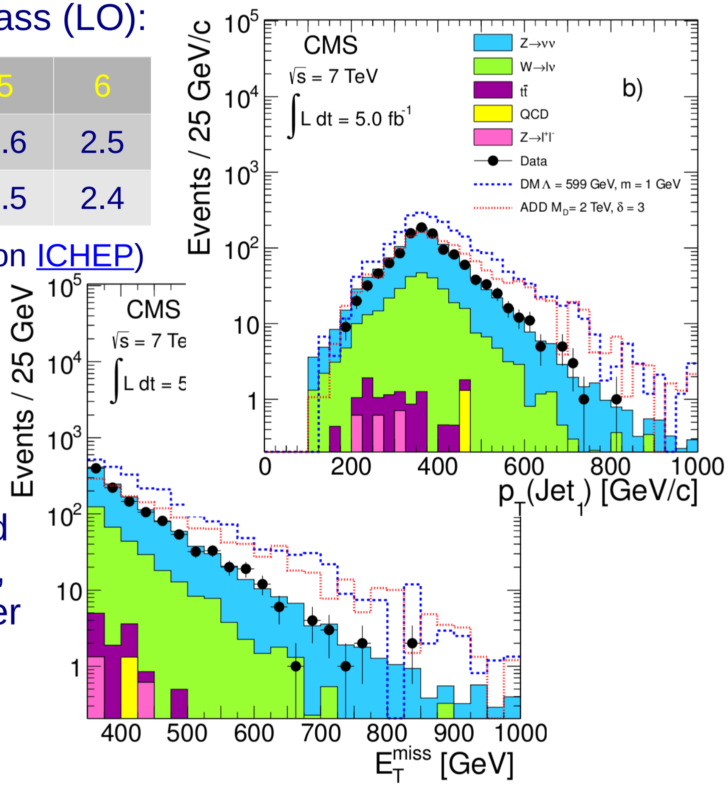


Limits on ADD graviton mass (LO):

N^{dim}	2	3	4	5	6
ATL*	4.2	3.3	2.9	2.6	2.5
CMS	4.1	3.2	2.8	2.5	2.4

(*ATLAS 4.6fb^{-1} result, shown on ICHEP)

These results are also interpreted in terms of WIMP pair production, but monophoton search has better sensitivity to WIMPs



Monojets: ADD graviton interpretation

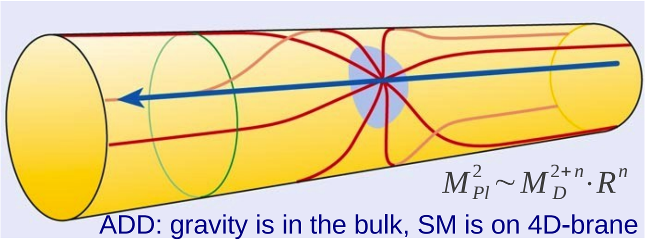
- Large Extra Dimensions (ADD framework):
  - $M_{Pl}^2 \sim M_D^{2+n} \cdot R^n$, where

    M_{Pl} – 4D Plank mass,

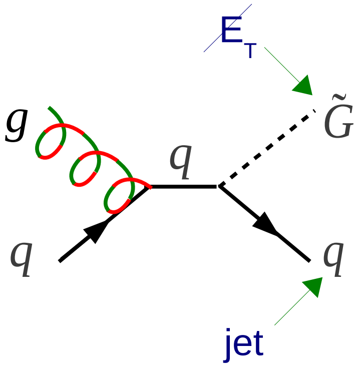
    n – # of extra dimensions,

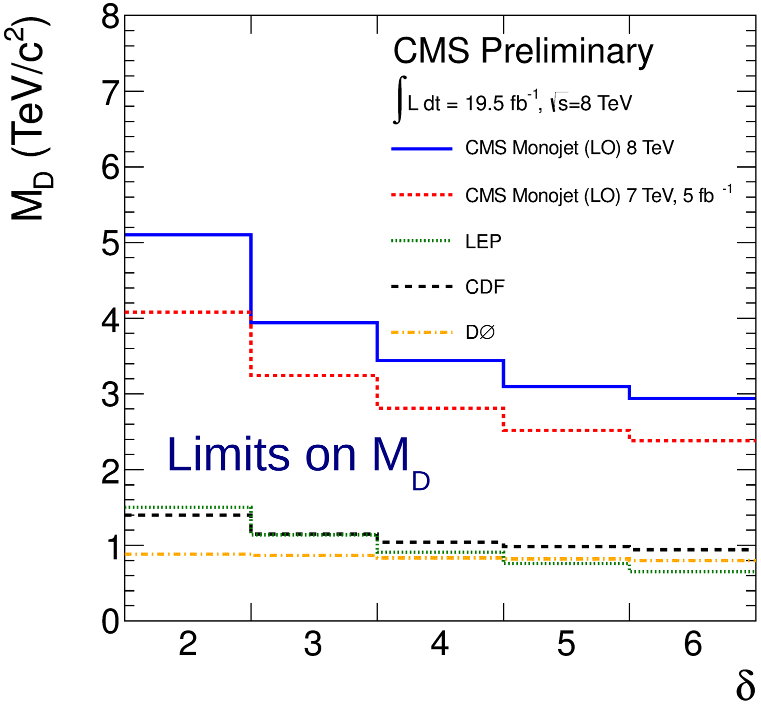
    R – size of extra dimensions,

    M_D – fundamental Plank scale



ADD: gravity is in the bulk, SM is on 4D-brane





Useful material

https://cds.cern.ch/record/1746770/files/ATL-PHYS-SLIDE-2014-508.pdf

https://indico.cern.ch/event/297618/session/0/contribution/5/material/slides/0.pdf

http://arxiv.org/pdf/1408.3583v1.pdf

https://kicp-workshops.uchicago.edu/DM-LHC2013/depot/talk-schramm-steven__1.pdf

https://svnweb.cern.ch/cern/wsvn/tdr2/notes/EXO-12-048/trunk/figures/

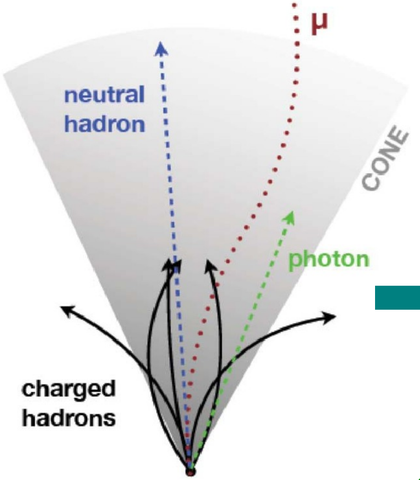
https://svnweb.cern.ch/cern/wsvn/tdr2/papers/EXO-12-048/trunk/figures/

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-147/

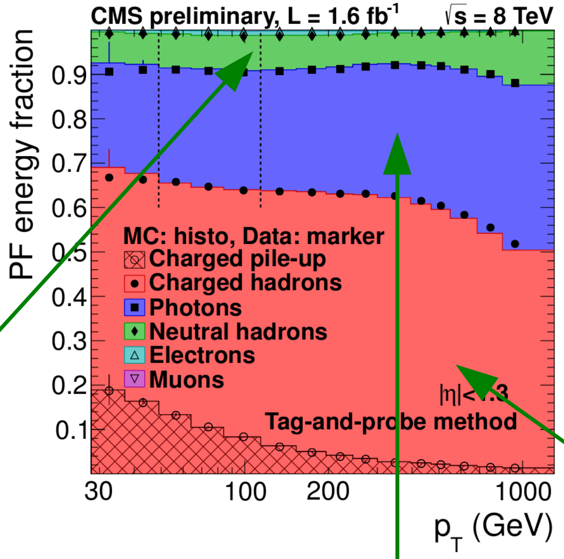
http://arxiv.org/pdf/1210.4491v2.pdf

Physics objects: jets

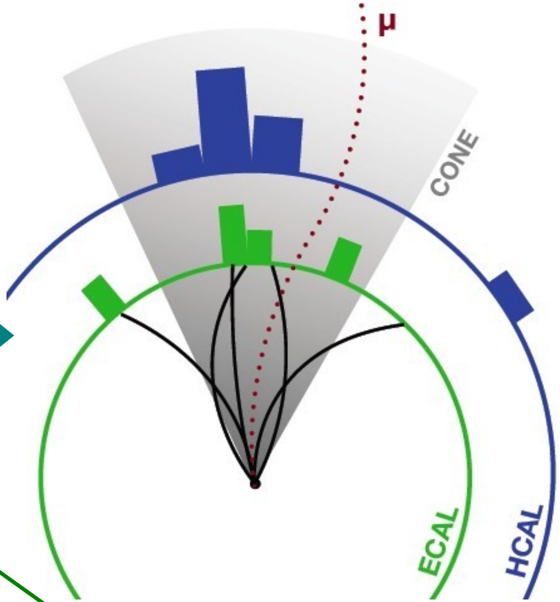
Jet:

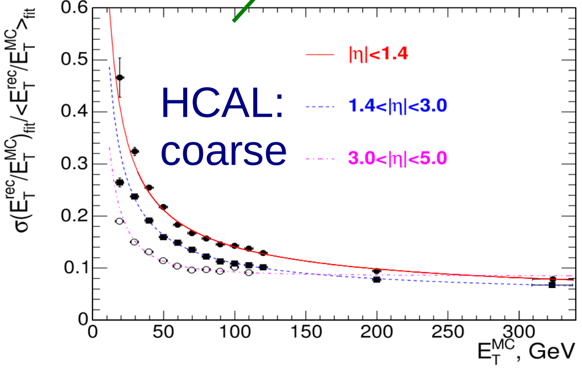


Jet composition:

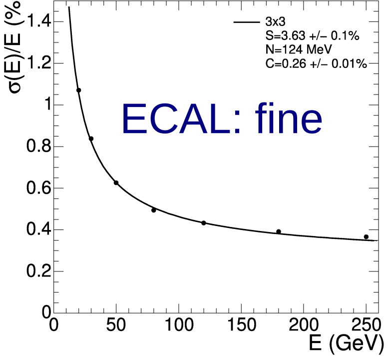


Deposits in subdetectors:

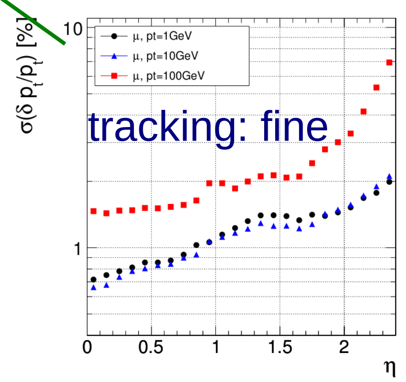




HCAL: coarse



ECAL: fine



tracking: fine

Particle Flow reconstruction takes advantage of best information available to construct a jet

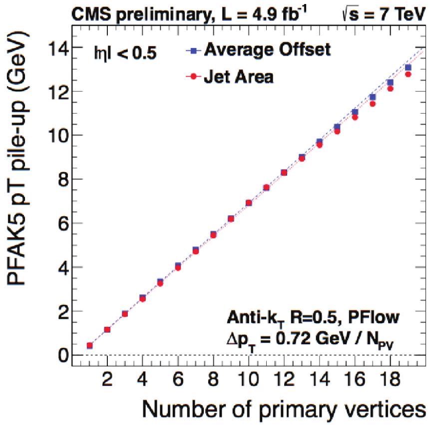
Jet resolution

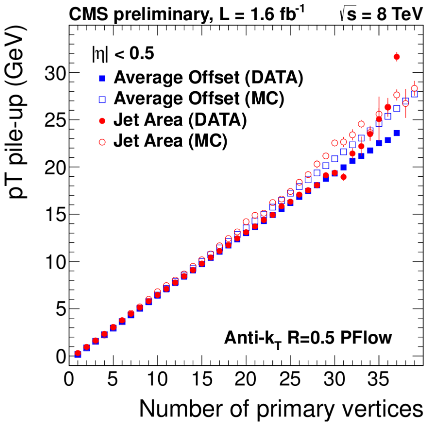
Offline jet energy calibration (same is used in ATLAS):

- offset expected pile-up deposits within jet area:
- relative (spatial-η) calibration:

  using di-jet balance correct jet response for arbitrary η wrt. jet response in the central region
- absolute (energy scale) calibration:

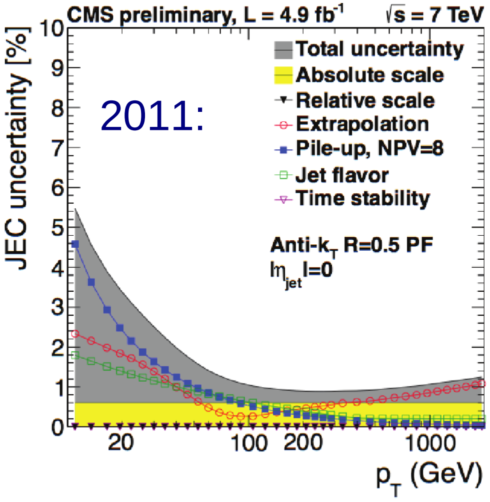
  using Z/γ + jet event balance set the absolute jet response scale using Z→ee/μμ p_T measurement

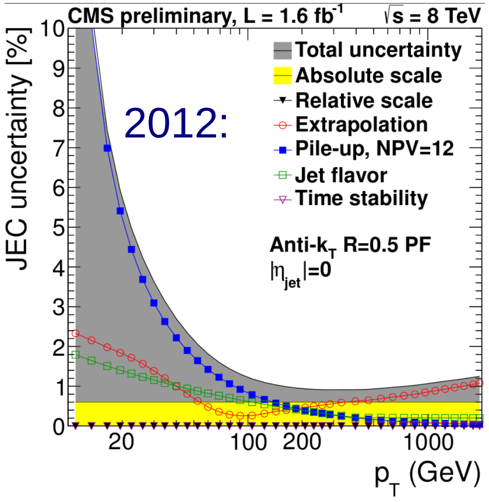




Resulting jet energy uncertainty:

- jet energy scale is known at ~2%





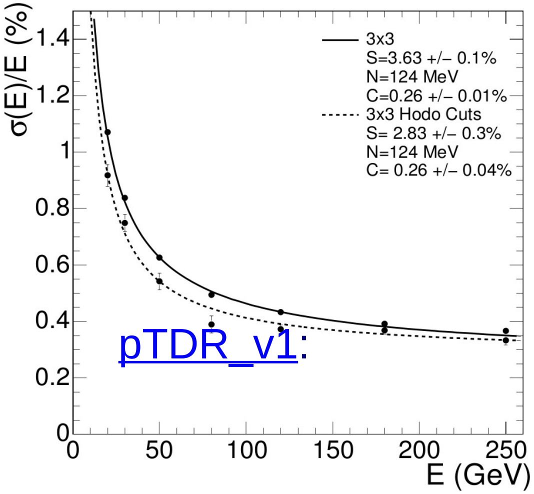
Physics objects: electrons and muons

Electron:

- essentially it is a track matched to an EM cluster with $E_{cal}/p_{trk} \sim 1$

  (current MVA ID scheme uses ~20 handles controlling matching, cluster shape, track quality, ...)
- p_T assignment: relies on ECAL energy resolution:

  (2012: $\delta p^e_T/p^e_T = \delta m_Z/m_Z =$ 1-2.6 GeV / 91GeV ~ 1-3% tr1%)

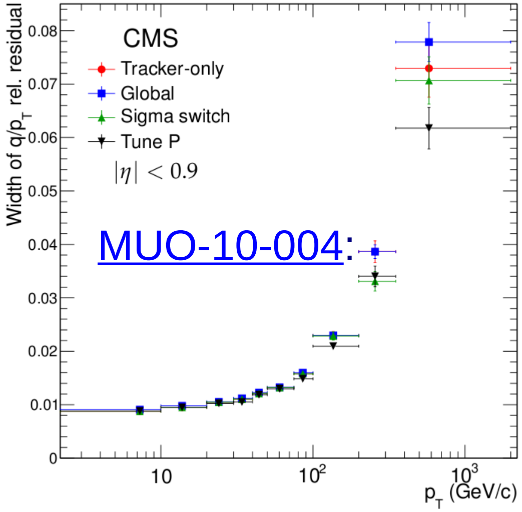


pTDR_v1:

Muon:

- essentially this is a track matched to hit(s) in the muon system
- p_T assignment: tracker + muon hits for a really stiff tracks:

  (for electrons resolution flattens; for muons it degrades with p_T)

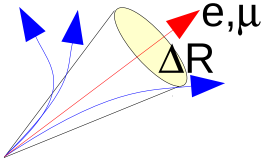


MUO-10-004:

Lepton isolation (discriminating jets with leptons and prompt leptons):

- tracker: $Iso_{TRK} = \Sigma p^{trk}_T$, tracks of same vertex in cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$
- calorimeter: $Iso_{ECAL,HCAL} = \Sigma e_i$ corrected for the track's p_T and pile-up
- combined: $Iso_{comb} = \Sigma(\alpha\, Iso_{TRK} + \beta\, Iso_{ECAL} + \gamma\, Iso_{HCAL})$

  (often the choice of α, β, and γ is analysis dependent)



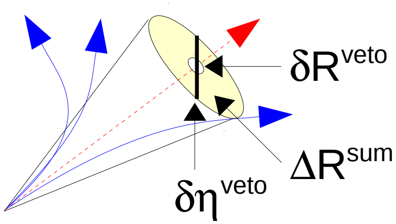
Physics objects: photon

Prompt photon's signature:

- no trices in tracker
- clustered deposits in ECAL
- little (or no) deposits in HCAL

Basics of photon identification:

- $Iso_{TRK} = \Sigma p^{trk}_T$ in cone $0.04<\Delta R<0.4$
- $Iso_{ECAL} = \Sigma e_i$ in a similar size cone
- $Iso_{HCAL} = \Sigma e_i$ in cone $0.15<\Delta R<0.4$
- $H/E = E^{ECAL}/E^{HCAL}$ in cone $\Delta R<0.15$
- $\sigma_{i\eta i\eta}$ – cluster shape in η-projection (highly localized for e/γ)

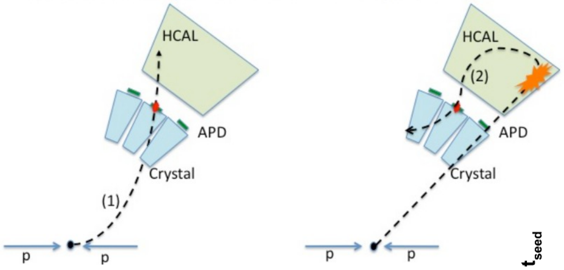


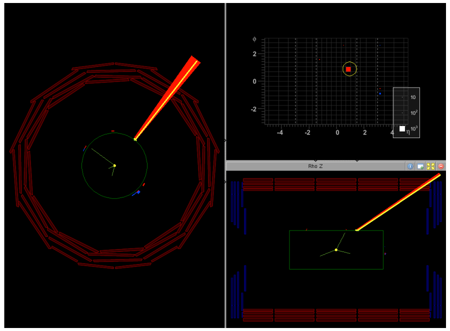
CMS features:

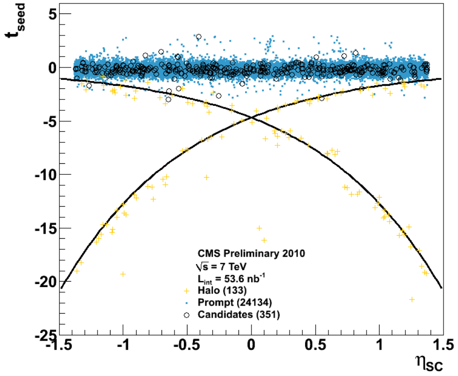
- very fast ECAL: 80% of light within 25ns (<1ns time resolution for impact time!)
- relatively high material budget: ~$1X_0$ before ECAL (brem and conversion: $e \rightarrow e\gamma$ and $\gamma \rightarrow e^+e^-$)

Instrumental backgrounds:

- spikes – vetoed by shower shape and timing:
- cosmics – primary vertex requirement
- beam halo – vetoed by endcap muon chambers and time of impact (negative time)







Physics object: missing E_T

- In CMS we use PF MET which is a negative of a vector sum of all momenta of PF particles
- Calibrated with standard SM candle: boosted Z/γ→μμ
  - MET scale is the average: $\left(u_{\parallel}/q_T \right)$
  - MET resolution is RMS width: $\sigma(u_{\perp}), \sigma(-u_{\parallel} - q_T)$
- Various types of offline MET corrections, e.g.:
  - Type1: propagates jet energy correction: $\vec{E}_T^{corr} = \vec{E}_T^{raw} + \Sigma(\vec{p}_T^{calib} - \vec{p}_T^{raw})$
  - MET ϕ: correction for the shift in x-y plane, induced by calorimeter noise (strongly pile-up dependent)