Dark Matter searches at LHC

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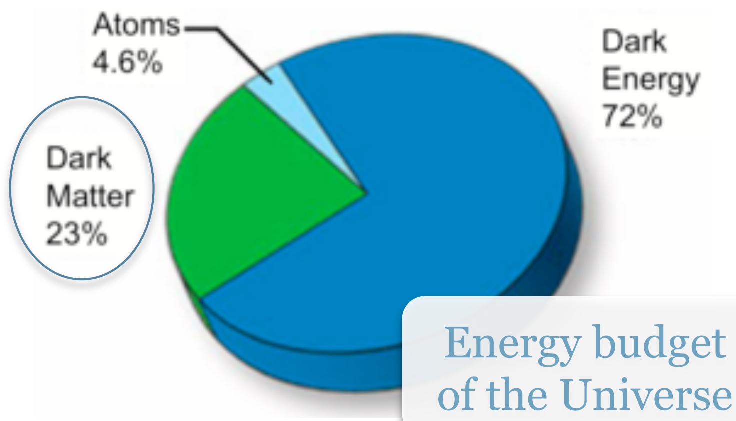
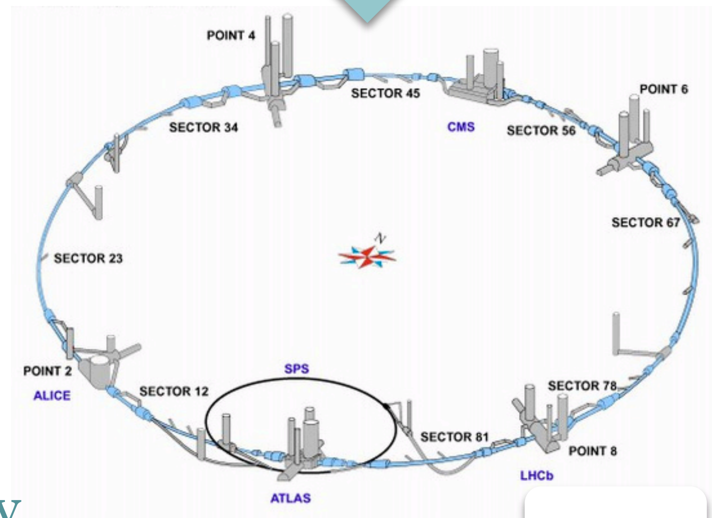
Outline

- Introduction
  - LHC, ATLAS, CMS achievements
  - dark matter, WIMPs & colliders
- Supersymmetry
  - R-parity; model framework
  - search strategy at LHC & discriminating variables
- Searches for SUSY with 7-TeV data
  - data-driven background estimation
  - MET-based inclusive signatures
- Prospects for 2011 run (~1 fb^{-1})
  - expected exclusion limits & discovery reach
- Conclusions & outlook
  - SUSY @ LHC
  - dark matter: colliders – cosmology interplay



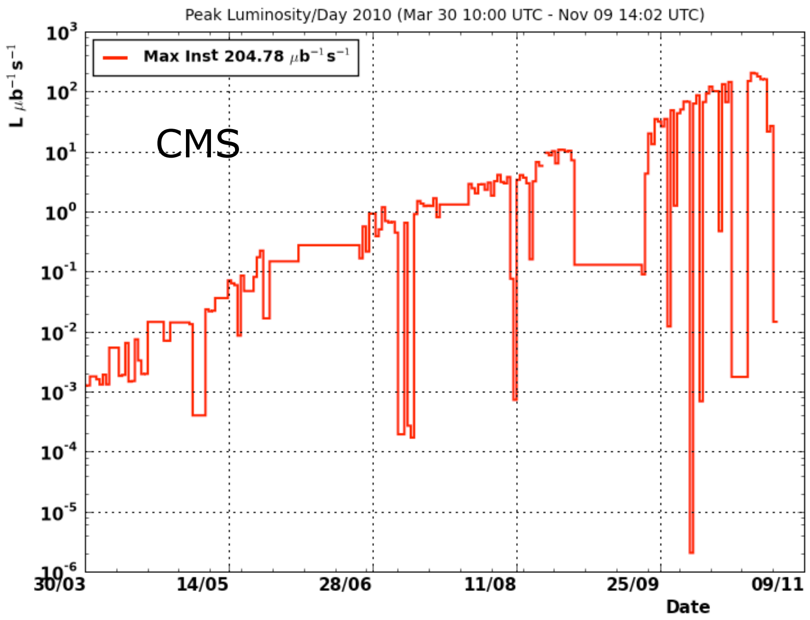
Energy budget of the Universe



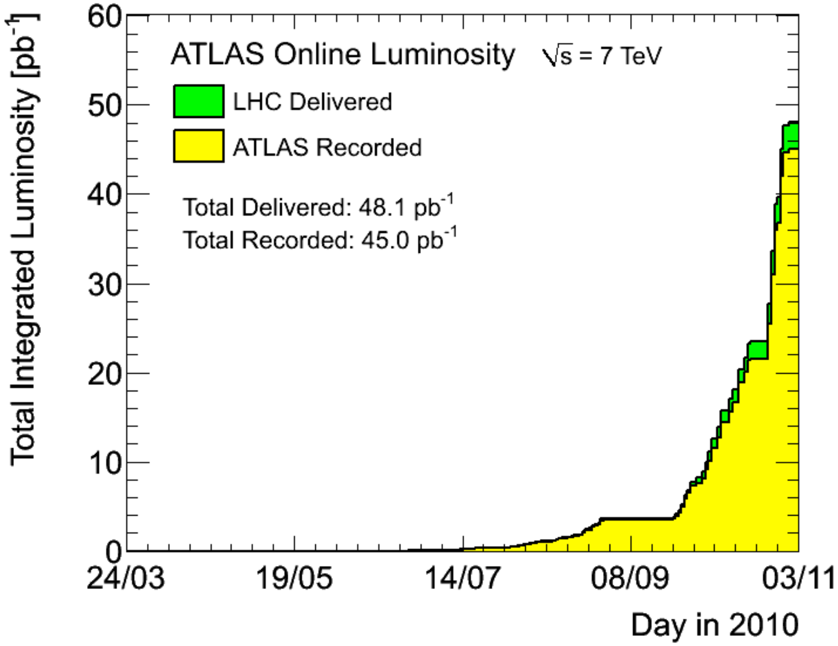
LHC

LHC operation

- Nov 2009: First collisions @ 900 GeV (SPS injection energy)
- Dec 2009: First collisions @ 2.36 TeV
  - exceeding Tevatron c.m.s. energy
- Since March 2010: 7-TeV collisions
  - final commissioning
  - first physics
- Nov-Dec 2010: Heavy ion collisions
  - Pb ions @ 2.76 TeV

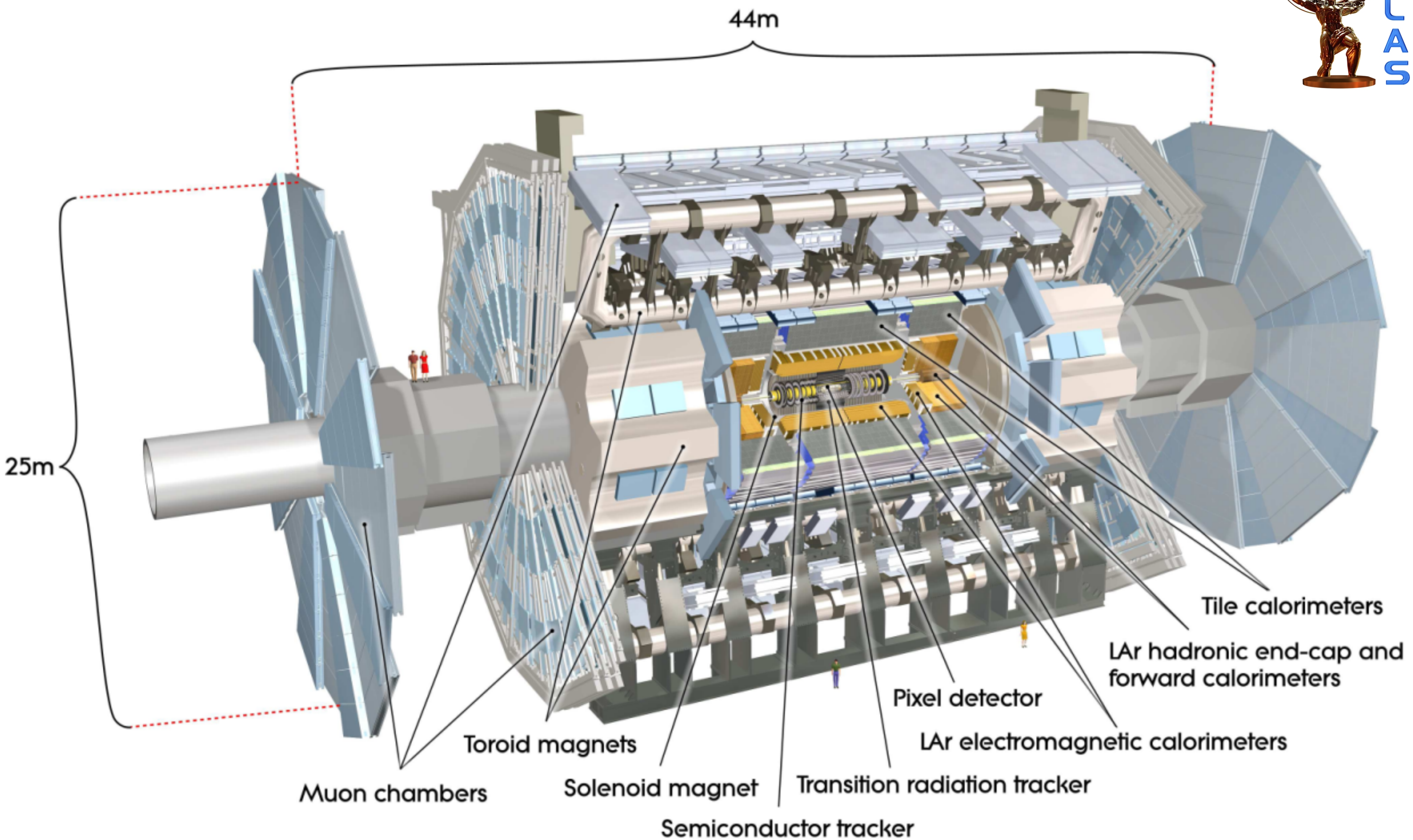


Peak Stable Luminosity Delivered	2.07×10^{32}
Maximum Luminosity Delivered in one fill	6304.61 nb^{-1}
Maximum Luminosity Delivered in one day	5983.78 nb^{-1}
Maximum Luminosity Delivered in 7 days	24637.08 nb^{-1}
Maximum Colliding Bunches	348
Maximum Average Events per Bunch Crossing	3.78
Longest Time in Stable Beams for one fill	30.3 hours

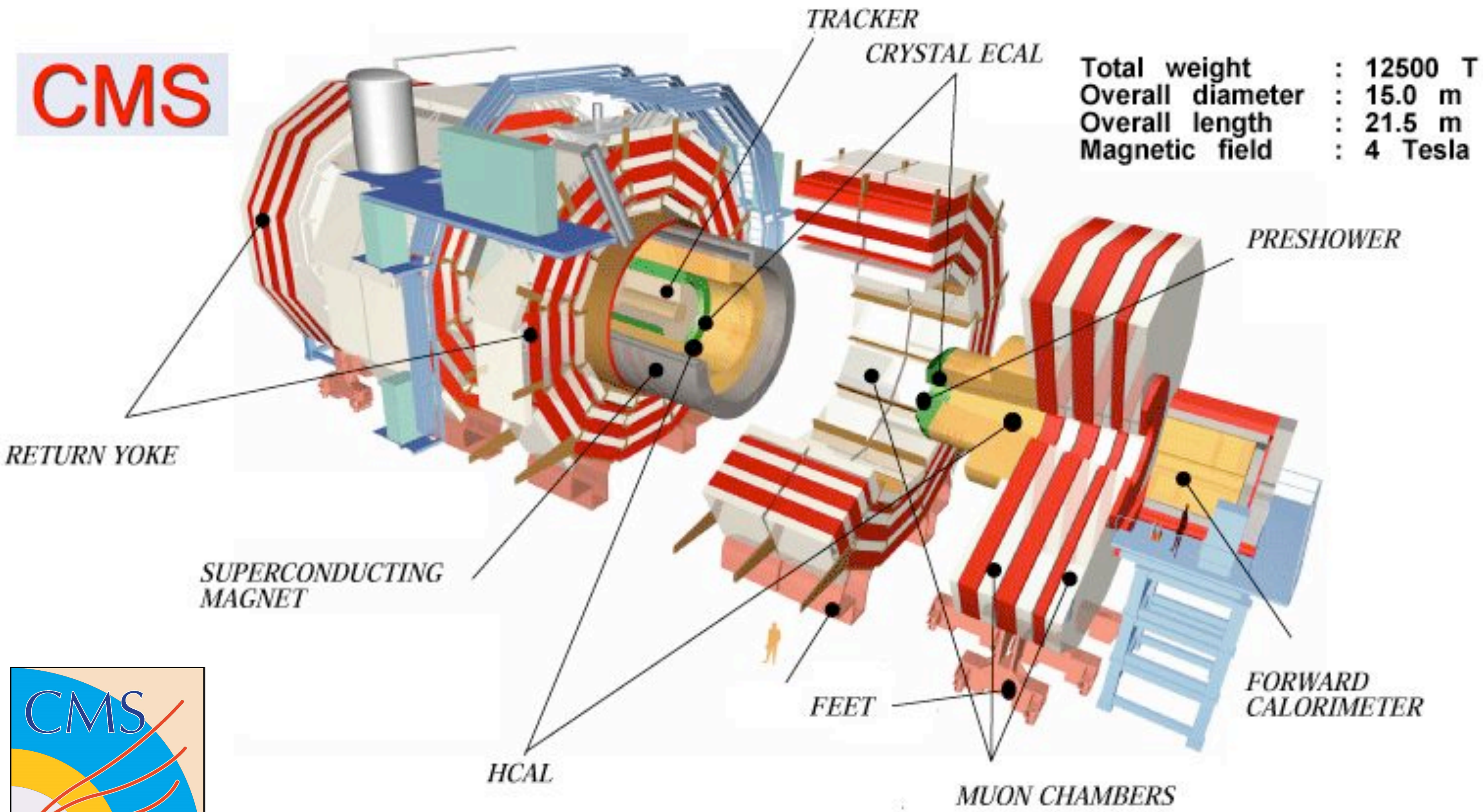


Excellent performance!

The ATLAS detector

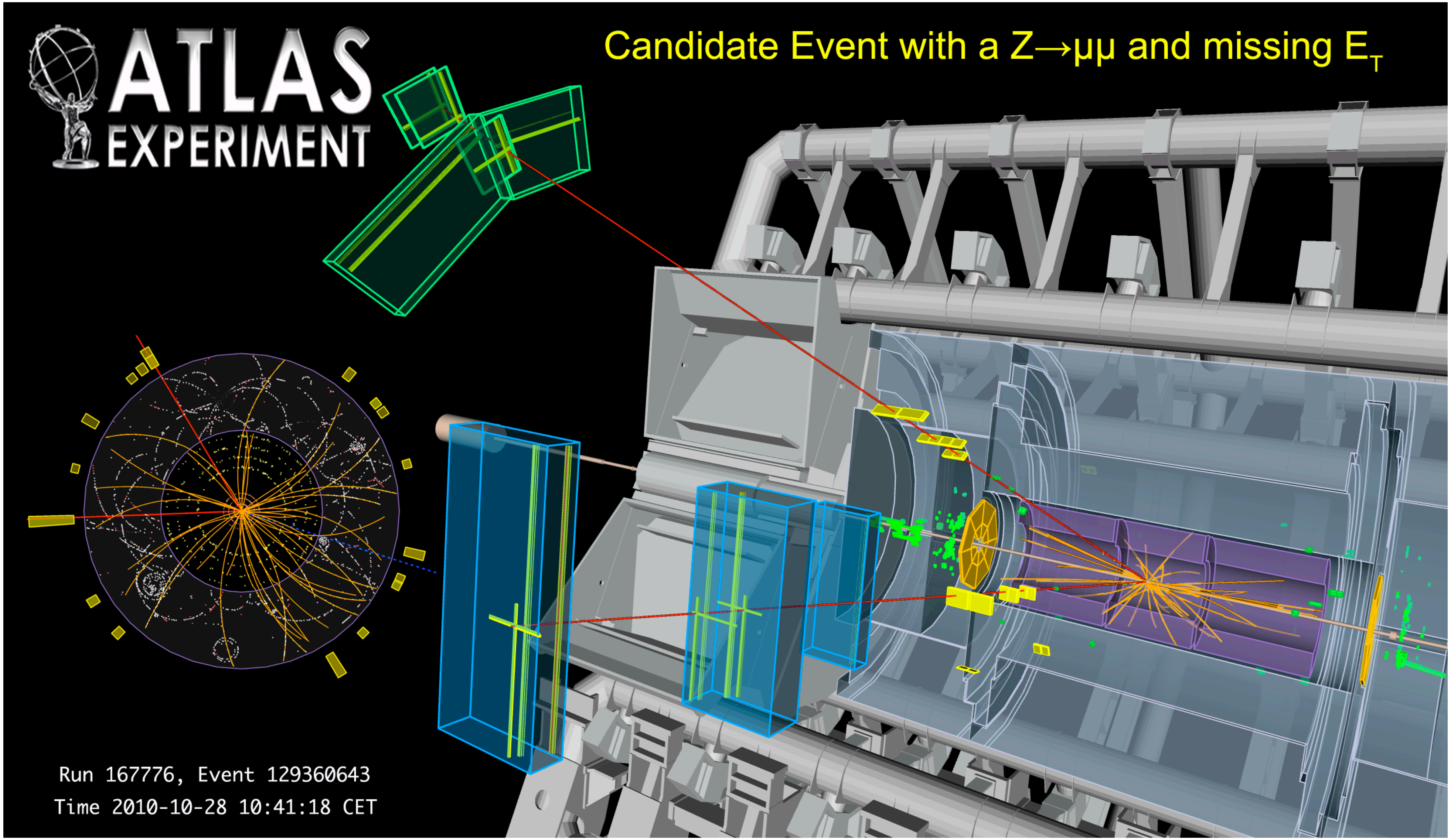


The CMS detector

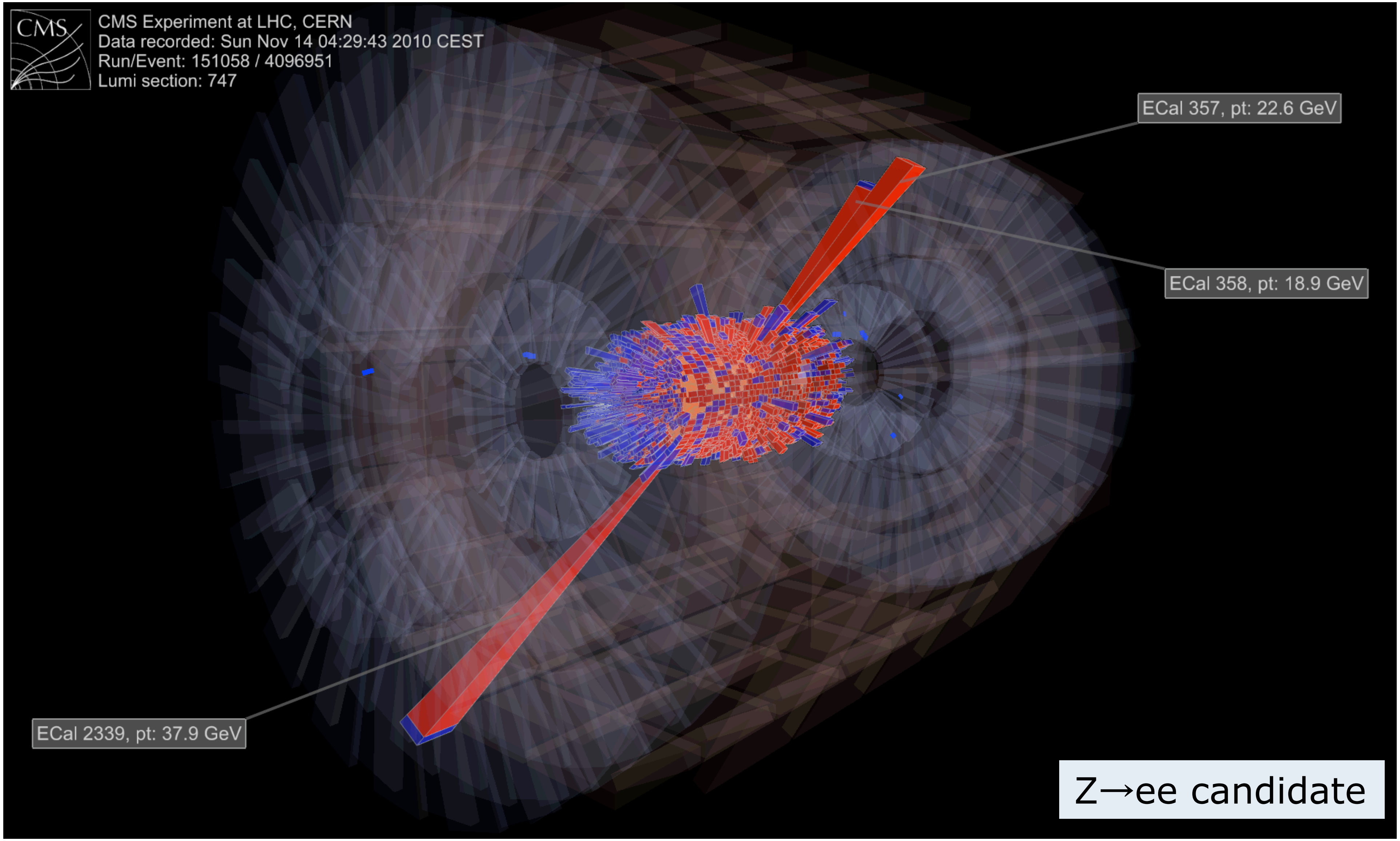


High missing energy event

E_T^{miss} = 161 GeV



Z bosons in heavy-ion collisions

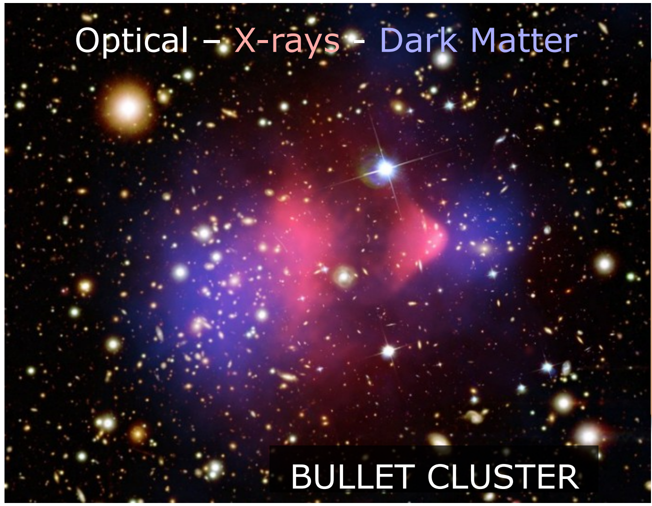


Z→ee candidate

Dark matter cosmological evidence

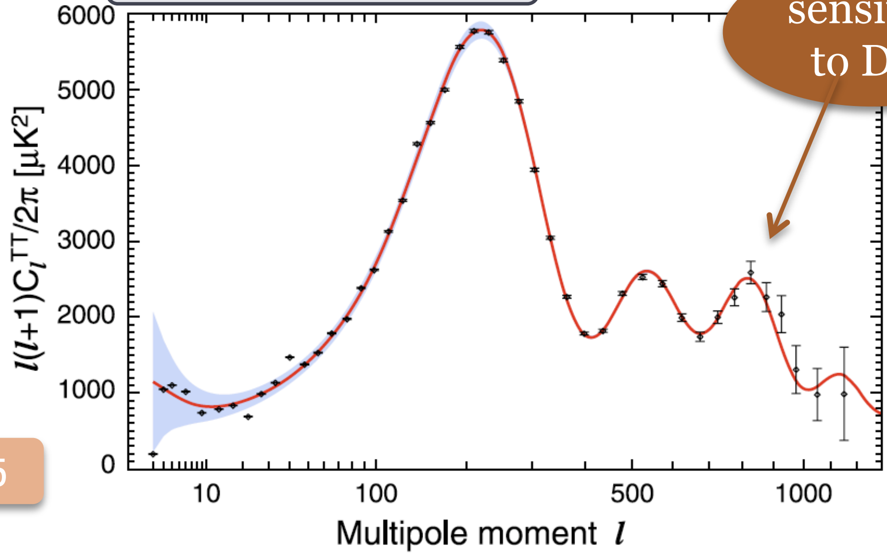
- Astrophysical observations (gravitational)
  - galaxy clusters rotation curves
  - velocity dispersions of galaxies
  - gravitational lensing
  - structure formation
    - ➔ Cold Dark Matter: non-relativistic matter
- Precise DM measurements
  - Cosmic Microwave Background (CMB)
  - + other (BAO, H_0, ...)
  - $\Omega_\chi \approx 0.23\%$

D Larson et al [WMAP], arXIv:1001.4635



Bradac et al, ApJ 652 (2006) 937

CMB power spectrum



sensitive to DM

Dark matter candidates

Weakly Interacting Massive Particles (**WIMPs**)

- 1 GeV < m_χ < 50 TeV
- thermal relics from Big Bang
- being *stable* and *weakly*-interacting only, if produced at a collider, escape detection
  ➔ **large missing energy**
- possible WIMPs
  - **lightest supersymmetric particle** (neutralino, mass $\mathcal{O}$(100 GeV))
  - Kaluza-Klein states (UED, warped GUTs)
  - T-odd states in "Little Higgs"
  - axino, gravitino (extremely WIPs) ➔ search for long-lived charged particles

WIMP miracle

thermally-averaged WIMP annihilation cross section ~ EW cross section for annihilation of non-relativistic particles

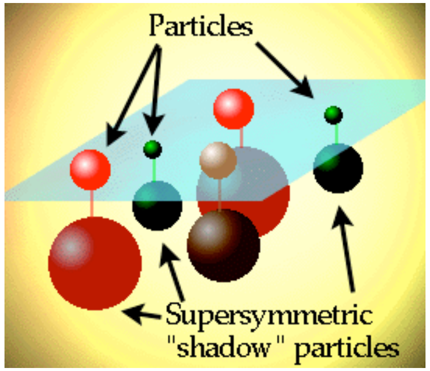
Other DM explanations

- axions (solve strong CP problem)
- non-thermal (superheavy) relics
- wimpzillas, cryptons, …

focus on SUSY in this talk

search strategy at LHC similar to that of SUSY

Supersymmetry (SUSY)

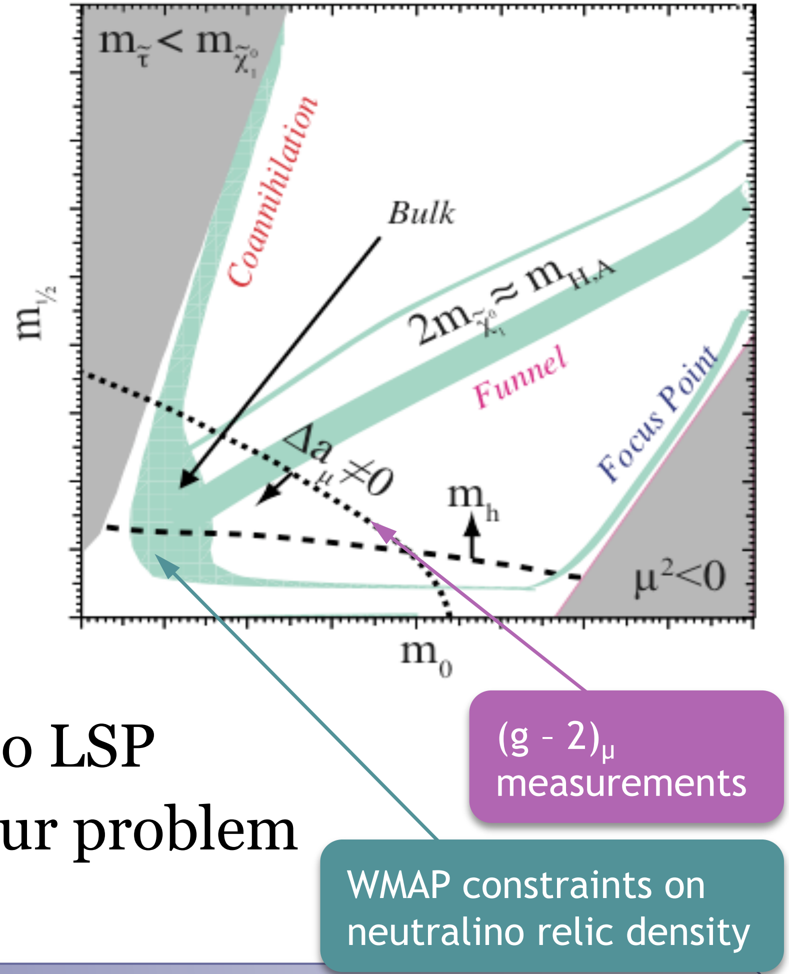


- SUSY = global symmetry between fermions & bosons
  - all SM particles have SUSY-partners with spin difference of ±1/2
- Theoretical motivation *(besides DM)*
  - Higgs mass stabilisation against loop corrections (*fine-tuning* problem)
  - unification of gauge couplings at single scale
- R-parity: $R = (-1)^{3(B-L)+2s} \longrightarrow R = \begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$
  - R-parity conservation *hinted* but not required by proton stability
- If R-parity is conserved ➔ lightest SUSY-particle (LSP) is stable
  - should be colorless and neutral
  - WIMP – dark matter candidate

SUSY model framework

- Minimal SuperSymmetric Standard Model (**MSSM**) contains >100 free parameters
  → assume specific physics-motivated model for systematic studies
- **mSUGRA**: minimal SuperGravity
  - universal masses and couplings at GUT scale
  - LSP: lightest neutralino $\tilde{\chi}_1^0$
- **GMSB**: gauge messengers; light gravitino LSP
- **AMSB**: anomalies in SUGRA L; no flavour problem
- **pMSSM**: 19 parameters

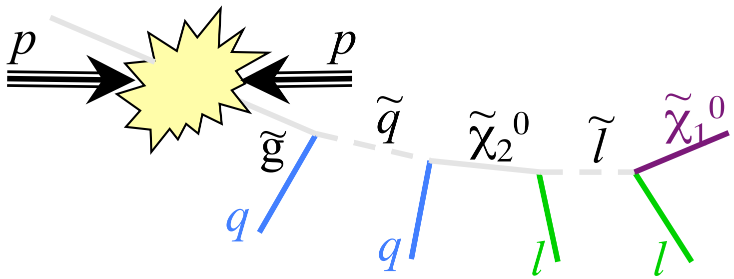
qualitative picture – no mass scale

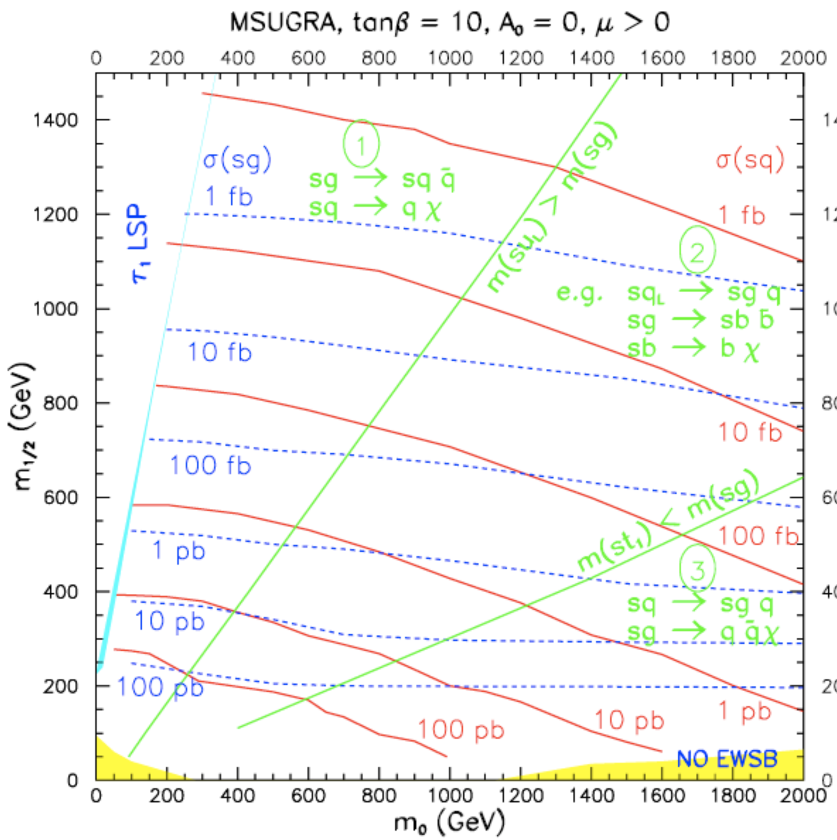


Inclusive searches at LHC:
model independent; not optimized for specific decay chains

SUSY signature at LHC

- Relatively large cross sections
- Strongly interacting sparticles ($\tilde{q}$, $\tilde{g}$) dominate production
- Long cascade decay into the LSP





CMS Coll., J. Phys. G, 34 (2007) 995

- **Golden discovery channel**: multi jets + missing E_T + (leptons)
- Divide search in channels with different #leptons (exclusive) and #jets (inclusive)
- Other modes also investigated: b-jets, photons, tau leptons

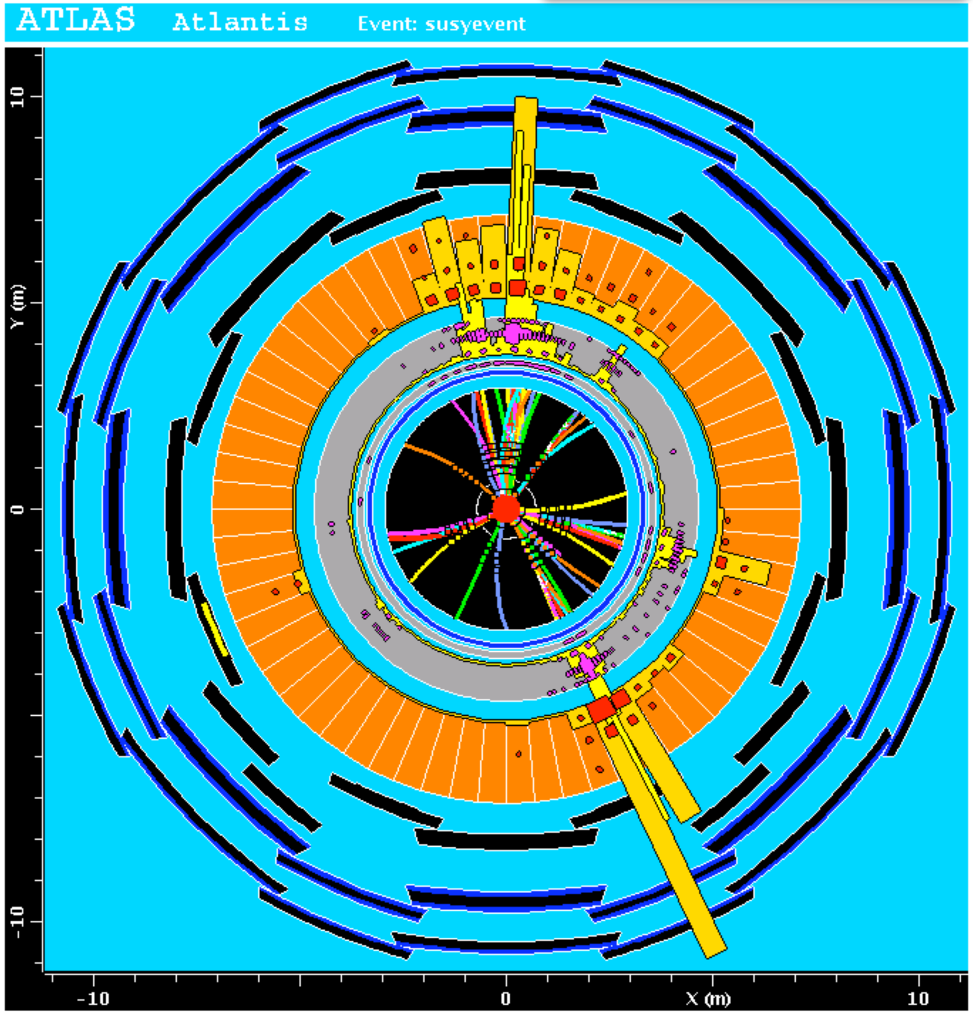
Data-driven background estimation
- check control regions
- understand SM-processes tails in SUSY-sensitive observables

Missing transverse energy MET (or E_T^{miss})

$$E_T^{miss} = \left| -\sum_i \vec{p}_x^{\,i} - \sum_i \vec{p}_y^{\,i} \right|$$

- = imbalance of total measured transverse momentum
  - true MET indicates *invisible*, i.e. weakly interacting, particles
    - e.g. neutrinos, WIMPs
  - may be defined/measured by various ways
    - calorimetric clusters, MET
    - calorimetric jets, MHT
    - tracks, MPT
- Crucial in SUSY searches is understanding and *cleaning* the sample from sources of fake MET
  - detector cracks
  - jet mis-measurement
  - …

simulated event



Other discriminating variables

- Effective mass, $\mathbf{M_{eff}}$
  - scalar sum of MET and p_T of selected jets and leptons
  - correlates with SUSY mass scale

$$M_{\text{eff}} = \sum_{\text{jets}} p_{\text{T}} + \sum_{\text{leptons}} p_{\text{T}} + E_{\text{T}}^{miss}$$

- Transverse mass, $\mathbf{m_T}$
  - constructed from highest-p_T lepton and E_T^{miss}

$$m_T^2 \equiv 2\left|\vec{p}_T^{\,\ell}\right|\left|\vec{E}_T^{miss}\right| - 2\vec{p}_T^{\,\ell}\vec{E}_T^{miss}$$

- $\mathbf{H_T}$: scalar sum over p_T of the selected jets

$$H_T = \sum_{jets\ j} p_{Tj}$$

- Missing transverse momentum, **MHT**

$$MHT \equiv \left|\sum_{jets\ j}(-\vec{p}_{Tj})\right|$$

- $\boldsymbol{\alpha_T}$: introduced to characterize di-jet events:
  - $\alpha_T \approx 0.5$: well-measured QCD events
  - $\alpha_T < 0.5$: QCD events with mis-measured jet
  - $\alpha_T > 0.5$: lost third jet; true MET; SUSY, W, ttbar, …
  - generalized to *n*-jets events

$$\alpha_T = \frac{\sqrt{p_{T2}/p_{T1}}}{\sqrt{2(1-\cos\Delta\phi)}}, \quad \text{for 2 jets}$$

$$\alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{\sqrt{H_T^2 - (MHT)^2}}, \quad \text{for } n \text{ jets}$$

- Transverse sphericity, $\mathbf{S_T}$
  - related to geometrical distribution of reconstructed objects
  - SUSY events more `spherical' than SM ones

Searches with 7-TeV data

ATLAS/CMS data analysis with luminosity up to 300 nb^{-1} on R-parity conserving SUSY

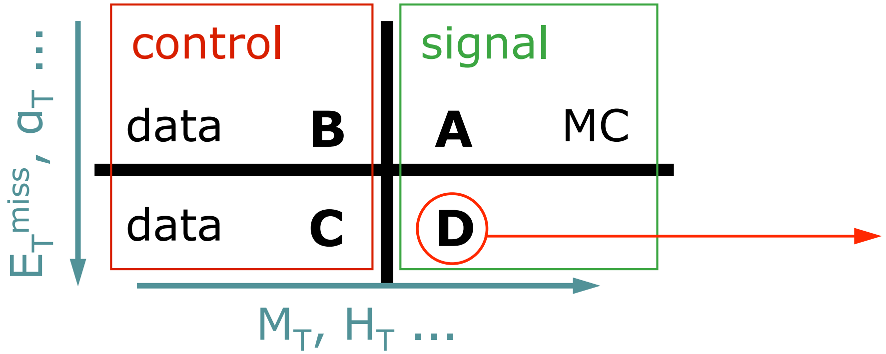
- ICHEP results mostly
- no exclusion limits set yet

NOT COVERED: searches for long lived sparticles

- not relevant for Dark Matter
- new exclusion limits already set (R-hadrons)

Background estimation from data

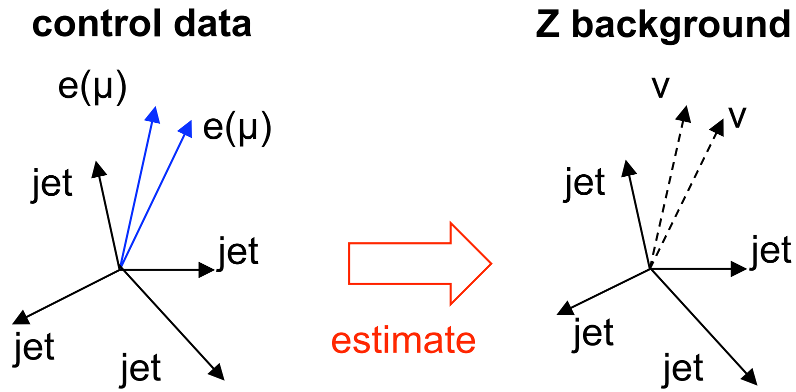
- Estimate background in *control* sample and propagate measurement to *signal* sample, e.g. **ABCD method**



D = A × C/B

Requirements
- control region close to signal region
- low SUSY contamination

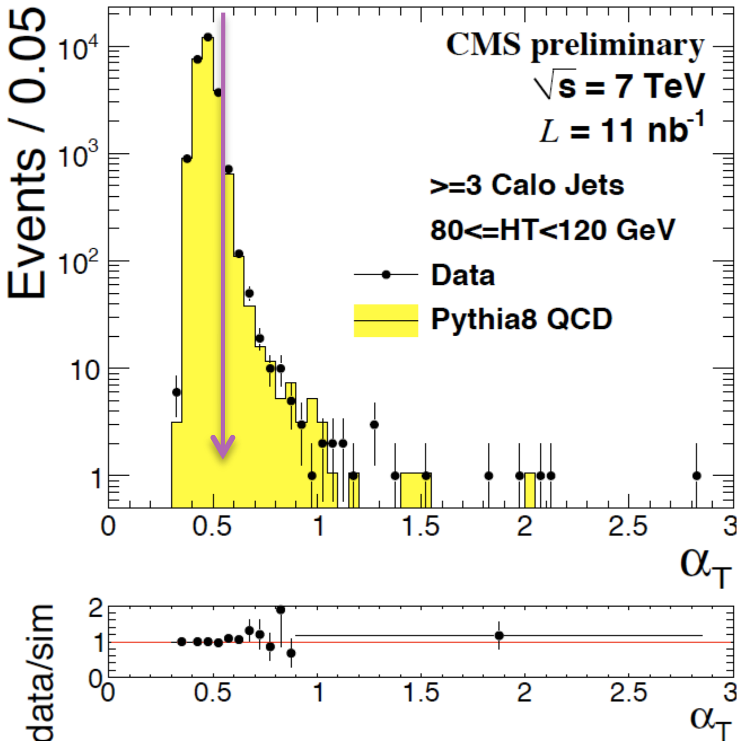
- Example: Replace method for $Z \to \nu\nu$ background
  - estimate E_T^{miss} distribution of $Z \to \nu\nu$ from $p_T(\ell^+\ell^-)$ distribution of $Z \to \ell^+\ell^-$
  - apply corrections for lepton reconstruction efficiency and coverage, additional cuts, …

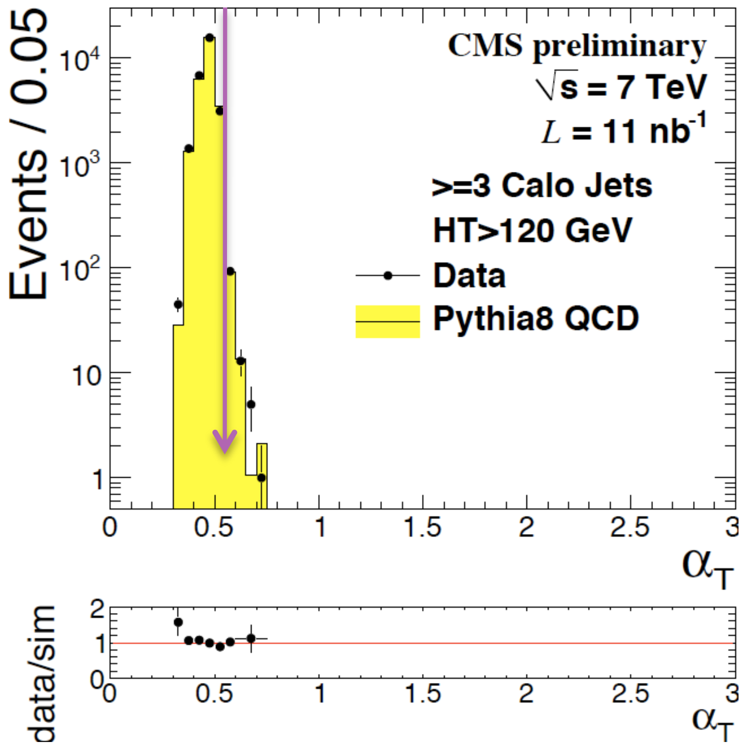


QCD background estimation with α_T

- QCD background
  - large cross section; poorly known properties
  - sensitive to detector performance
- MC agreement in control sample far from signal region (high HT>350 GeV)
- Study of $\alpha_T > 0.55$ rejection power as H_T threshold increases shows robust behaviour of α_T cut

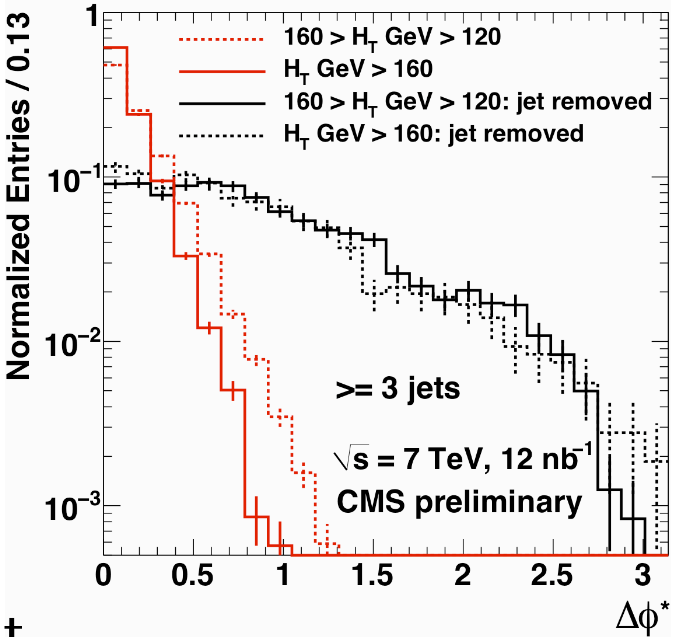
CMS PAS SUS-10-001 (2010)

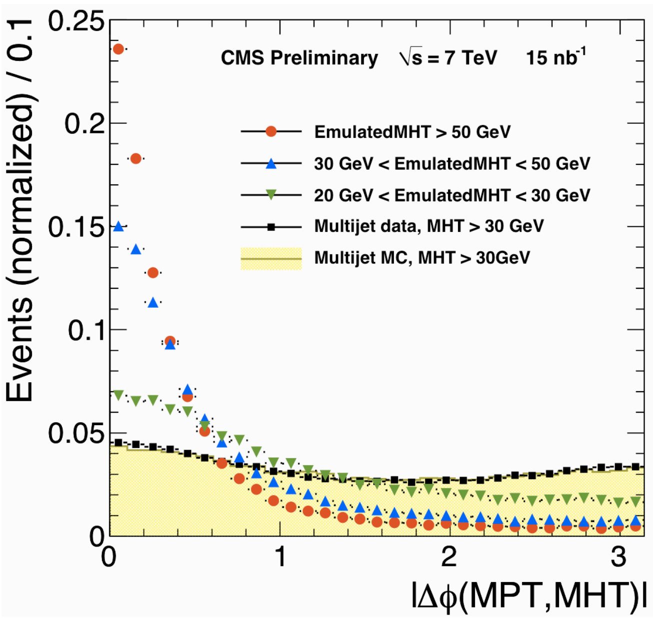




Suppressing fake MET in jet events

- $\Delta\varphi^* = \Delta\varphi(\text{MHT, jets})$ cut
  - in jet samples MHT may coincide with a mis-measured jet
  - $\Delta\varphi^*$ peaks at zero; narrower for increasing HT
- SUSY or true-MET events
  - uniform $\Delta\varphi^*$ distribution
  - emulate SUSY by randomly removing one jet





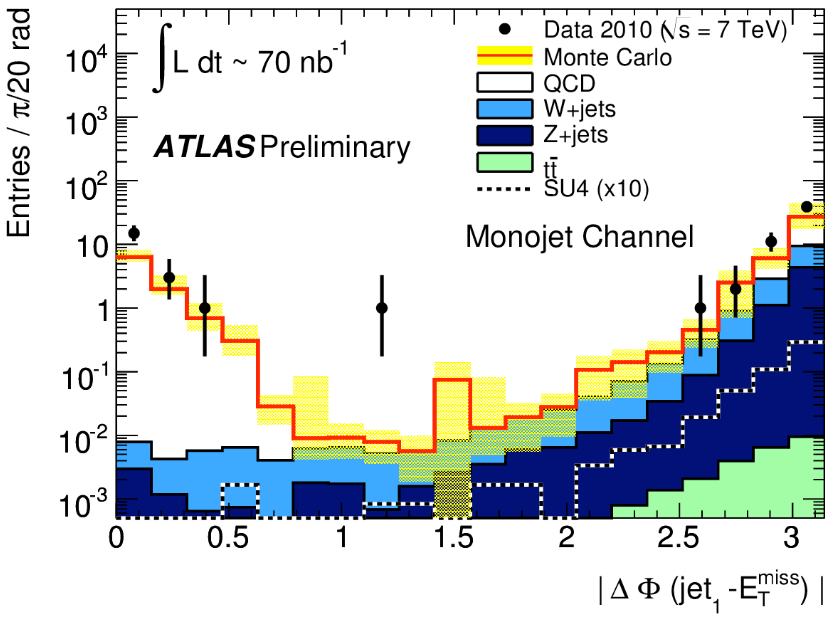
- $\Delta\varphi(\text{MPT,MHT})$ cut
  - in events with real MET, MPT and MHT coincide
  - in events with fake MET (such as QCD) MPT and MHT are uncorrelated
- Expectations confirmed by data

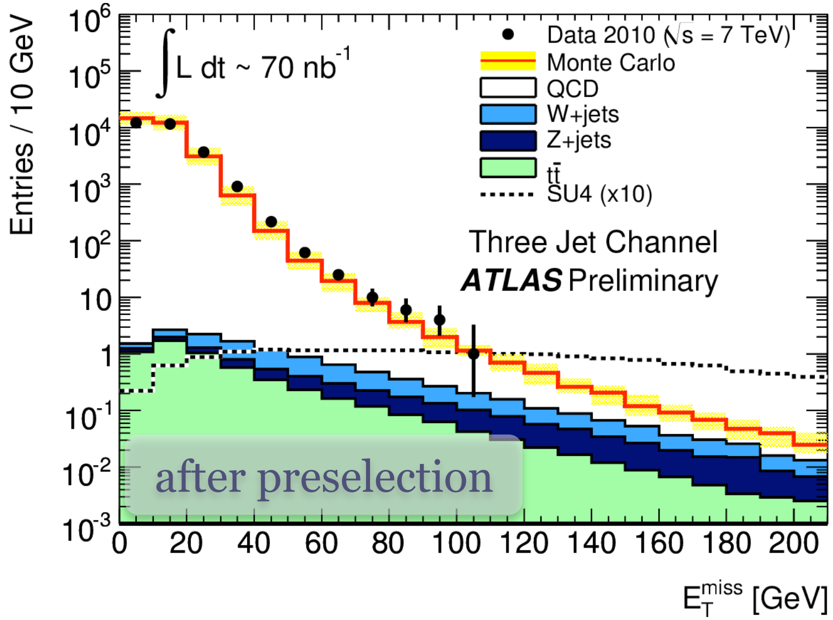
CMS PAS SUS-10-001 (2010)

0-lepton + MET (I)

- QCD normalized in control region p_T(jet1) > 70 GeV, p_T(jet2) >30 GeV
- Mono-jet channel
  - require one jet, p_T > 70 GeV and veto additional jets with p_T > 30 GeV
  - $\Delta\varphi$(MET, jet) ≈ 0 for QCD events
- Three-jet channel
  - require three jets with p_T > (70, 30, 30) GeV and MET > 0.25 Meff
  - no data events where 1.9 ± 0.9 are expected from MC
- Agreement between ATLAS data and SM simulation ➔ jets are well understood

ATLAS-CONF-2010-065





0-lepton + MET (II)

- Two-jet channel
  - MET > max{40 GeV,0.3 M_{eff}}, $\Delta\phi$(MET,jets) < 0.2
  - 4 events found where 6.6 ± 3 are expected
- Four-jets
  - 3rd and 4th jet of 30 GeV and loosen to MET > 0.2 M_{eff}
  - 1 event is found where 1.0 ± 0.6 are expected
- All data distributions consistent with normalized MC

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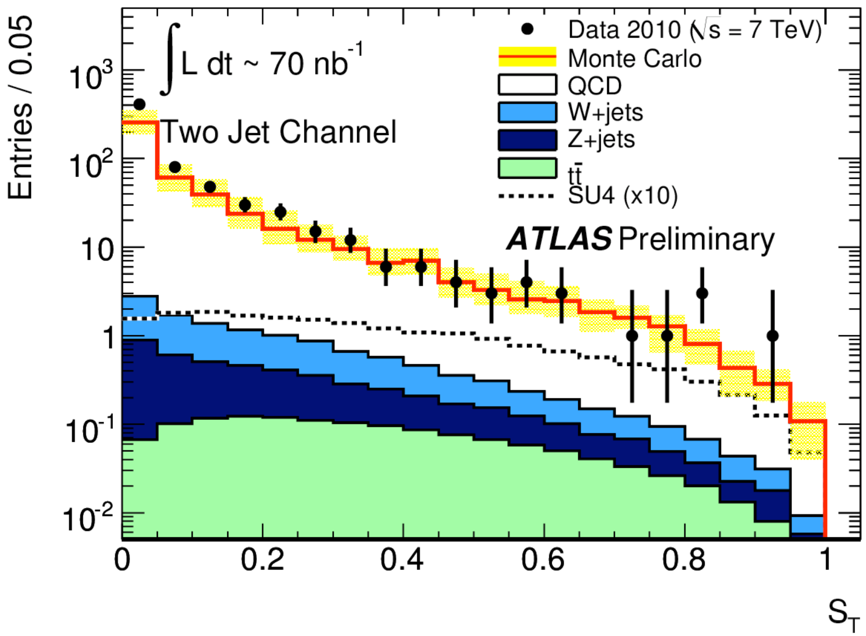
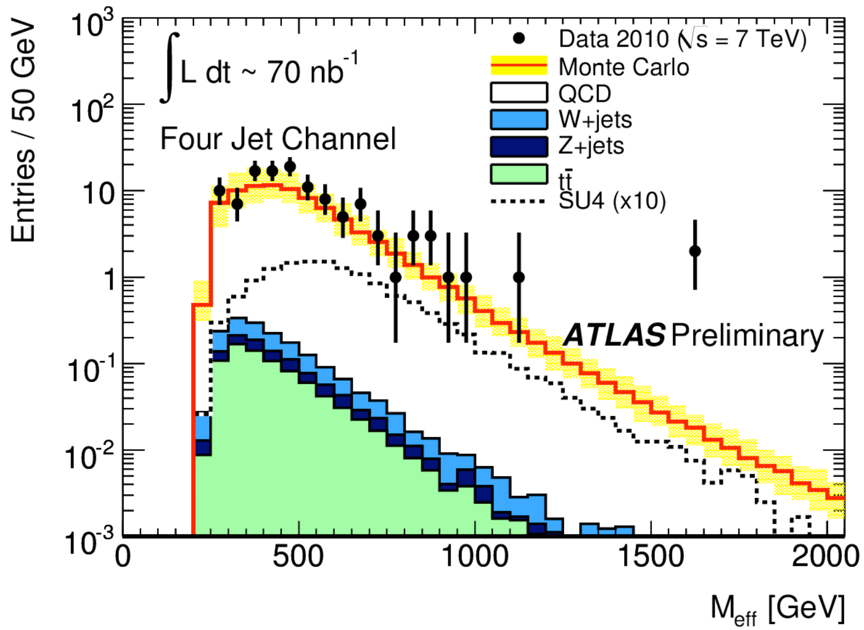
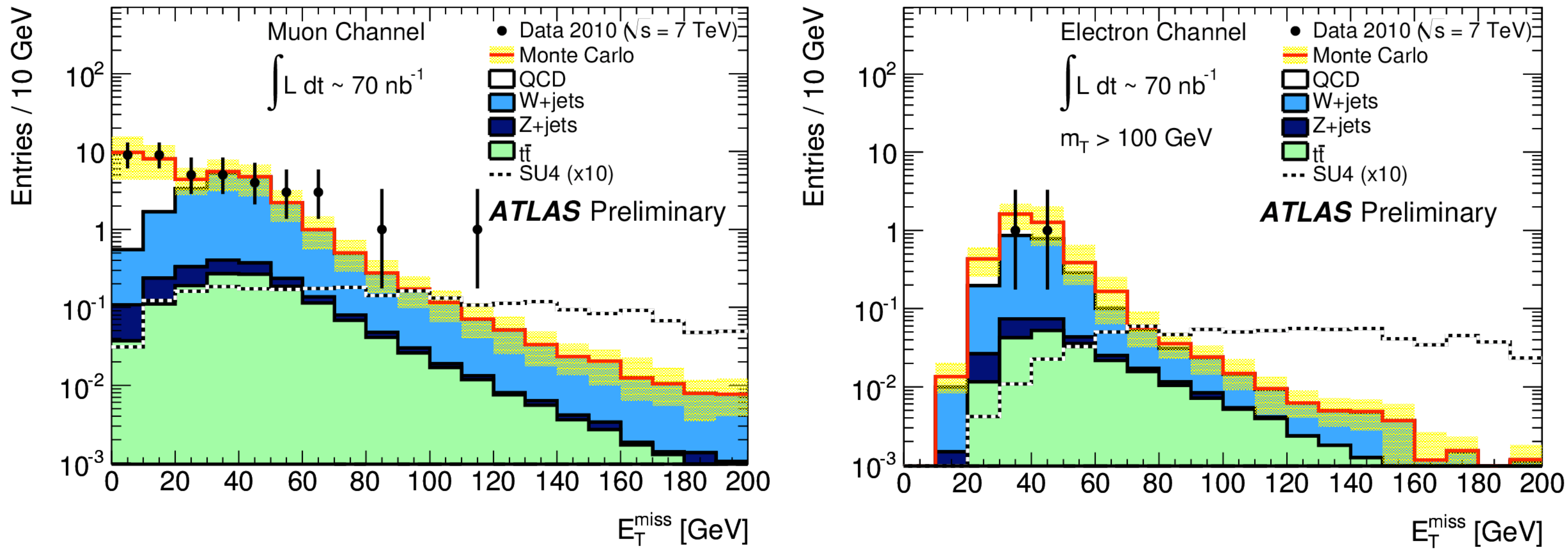




One-lepton selection — MET

- Split into e and μ channels
- MC normalization in control regions
  - Pythia QCD: MET < 40 GeV; m_T< 40 GeV
  - Alpgen W+jets: 30 GeV< MET <50 GeV; 40 < m_T < 80 GeV
- Event selection after standard cleaning cuts
  - ℓ with p_T > 20 GeV and veto more ℓ with p_T > 10 GeV
  - two or more jets with p_T > 30 GeV

ATLAS-CONF-2010-066

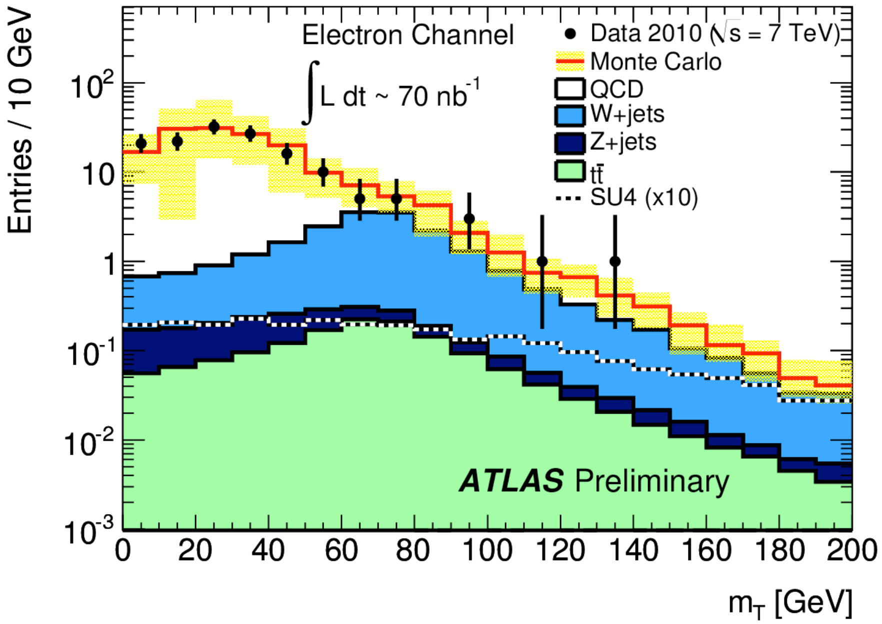


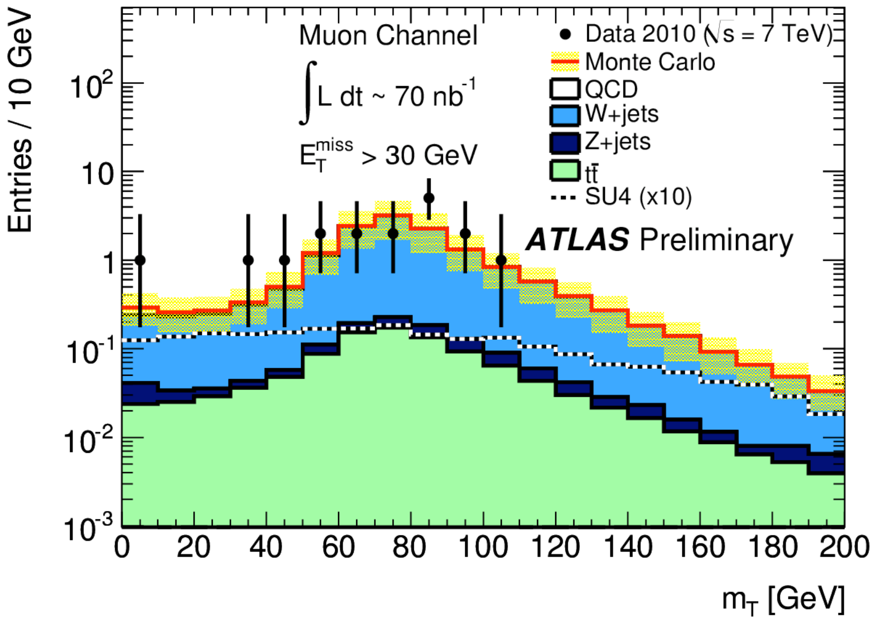
One-lepton selection — m_T

ATLAS-CONF-2010-066

Yellow band: jet energy scale uncertainly

- After preselection – no MET, m_T cuts
- Electron channel
  - QCD background dominates
  - 143 events in data compared to 157 ± 85 from MC
- Muon channel
  - W+jets largest contribution at high m_T; QCD important at low m_T values
  - 40 events in data compared to 37 ± 14 from MC





One-lepton selection — M_{eff}

- Additional cut: MET > 30 GeV
- Electron channel
  - 13 events in data compared to 16 ± 7 from MC
  - with m_T > 100 GeV: 2 data events survive compared with 3.6 ± 1.6
- Muon channel
  - 17 events in data compared to 15 ± 7 from MC
  - with m_T > 100 GeV: 1 data event survives compared with 2.8 ± 1.2

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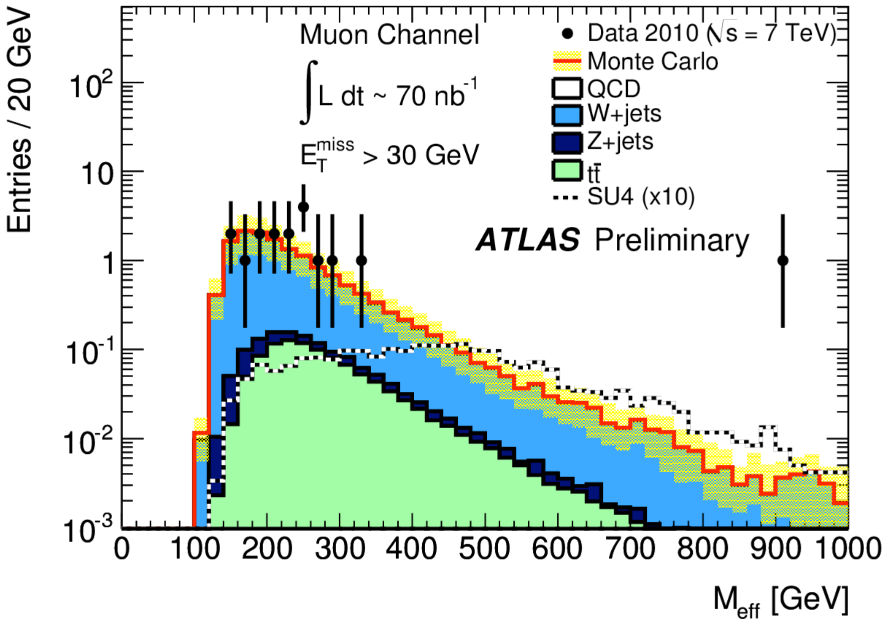

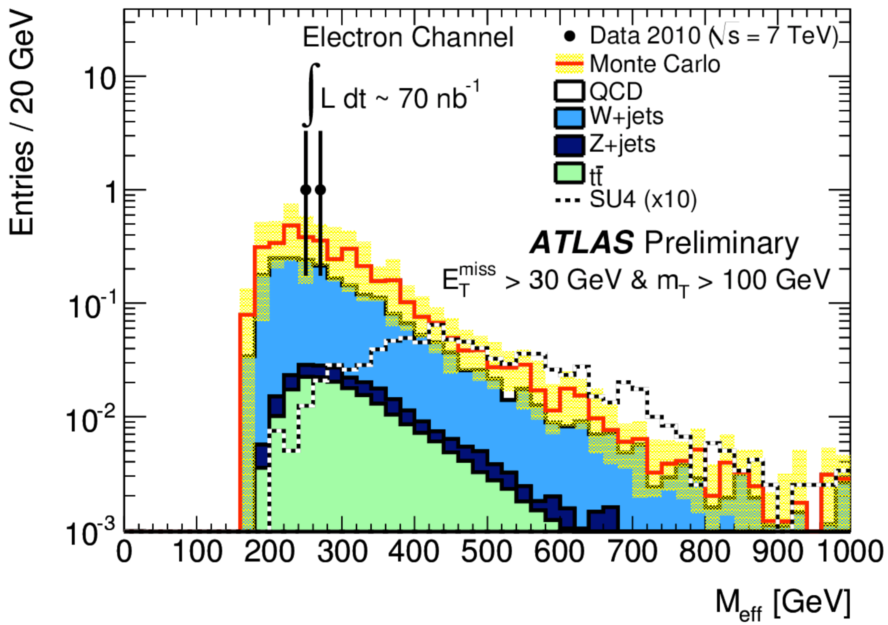

2-lepton + MET channel

- Selection cuts
  - exactly two leptons, p_T > (20 GeV, 10 GeV)
  - $M_{\ell\ell}$ > 5 GeV
  - MET > 30 GeV
- Events subdivided in opposite-sign (OS) and same-sign (SS) lepton pairs
- Observed events consistent with SM expectations

Opposite-sign leptons
- observed 2
- expected 2.0 ± 0.8

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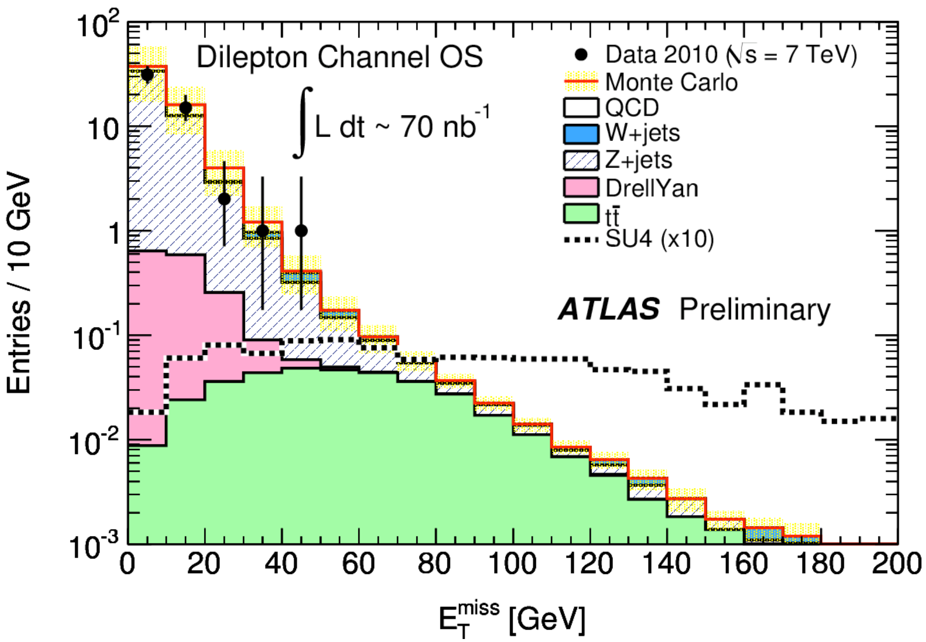
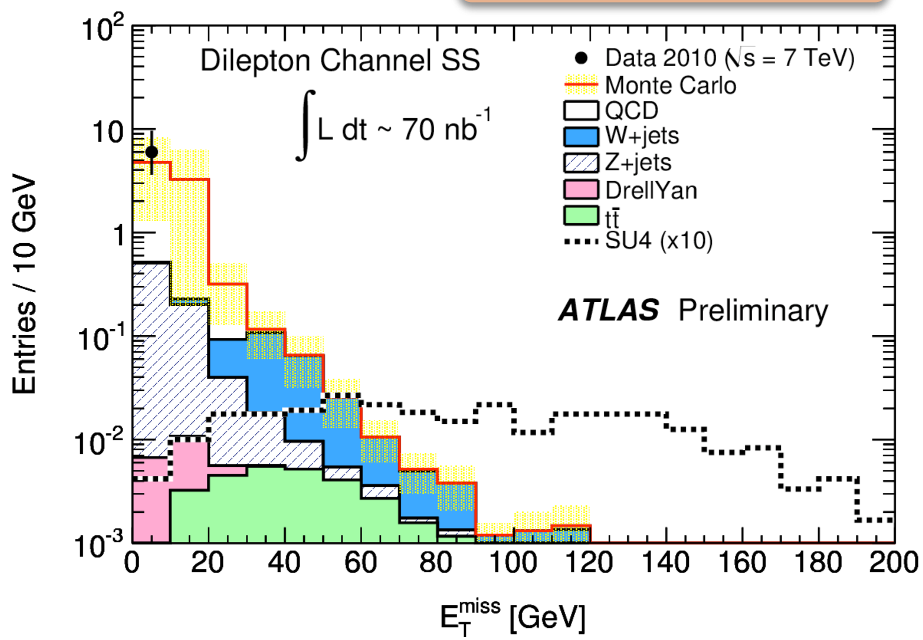
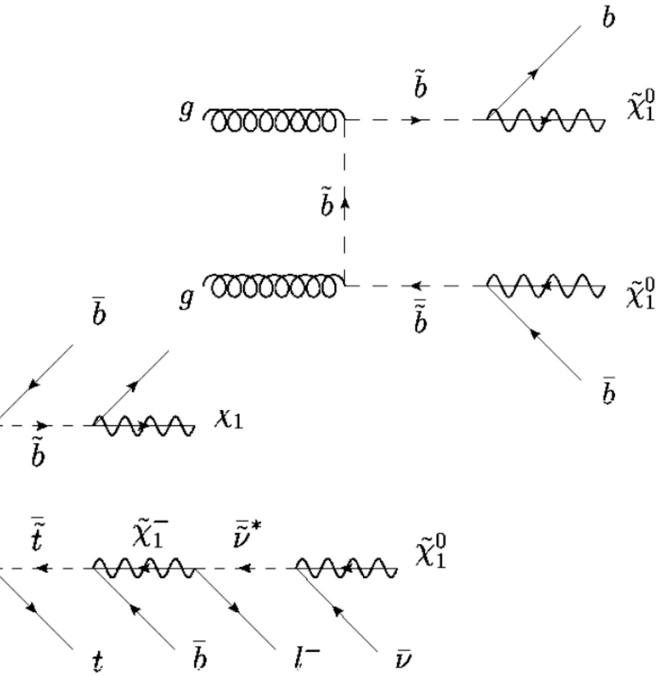




Search with b-jets

- b-tagging based on secondary-vertex tagger
  - $\varepsilon_{\text{b-tagging}} \sim O(50\%)$
- 0-lepton mode
  - $\geq$ 2 or 3 jets (p_T >70, 30, 30 GeV)
  - $\geq$ 1 b-tagged jet
  - rejection of light quark jets at 98-99% & charm jets at 80-90%
- Good agreement MC–data in full range



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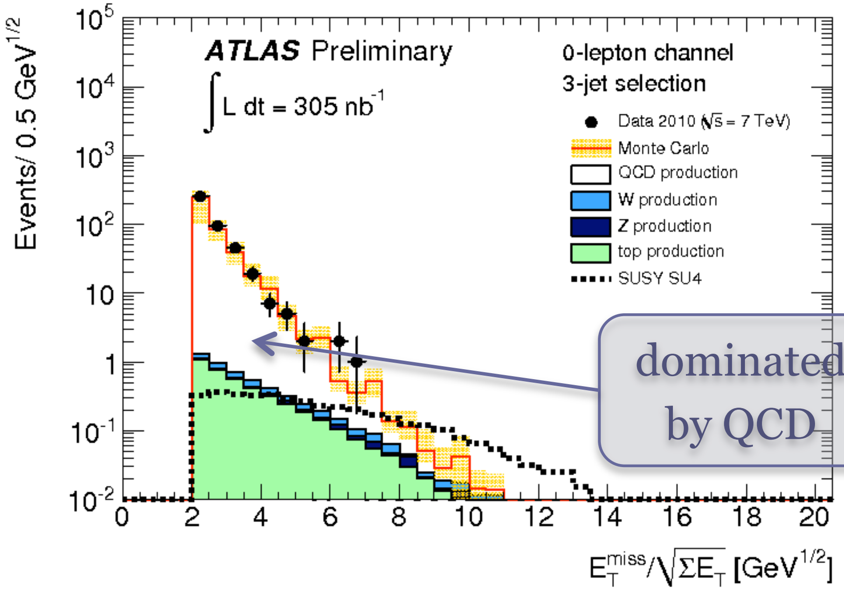
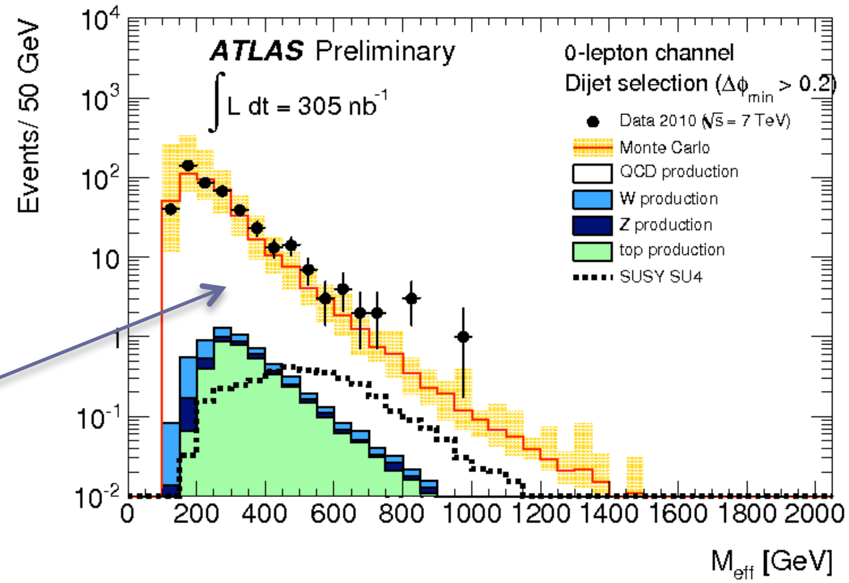


dominated by QCD



b-jets + 1 lepton channel

- Applied cuts as 0-lepton except
  - 2 jets (p_T>30 GeV ,p_T> 30 GeV)
  - ≥1 lepton (p_T>20 GeV)
- Reasonable agreement data – MC
  - SM background reduced to few events
  - top production dominates
  - no sensitivity to mSUGRA signal yet

electron channel
- observed 4
- expected 4.8 (+1.7) (-1.5)

muon channel
- observed 8
- expected 4.7 (+1.7) (-1.5)

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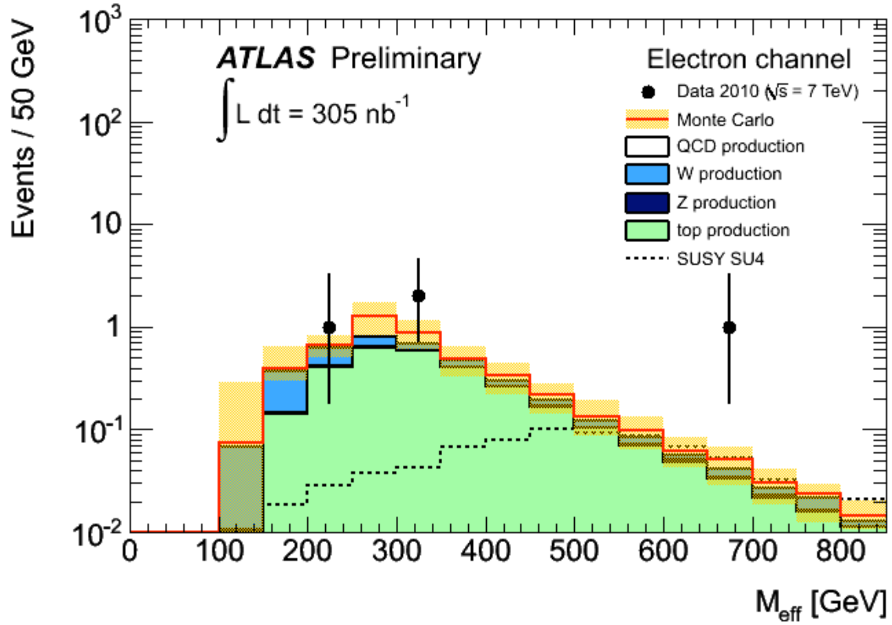
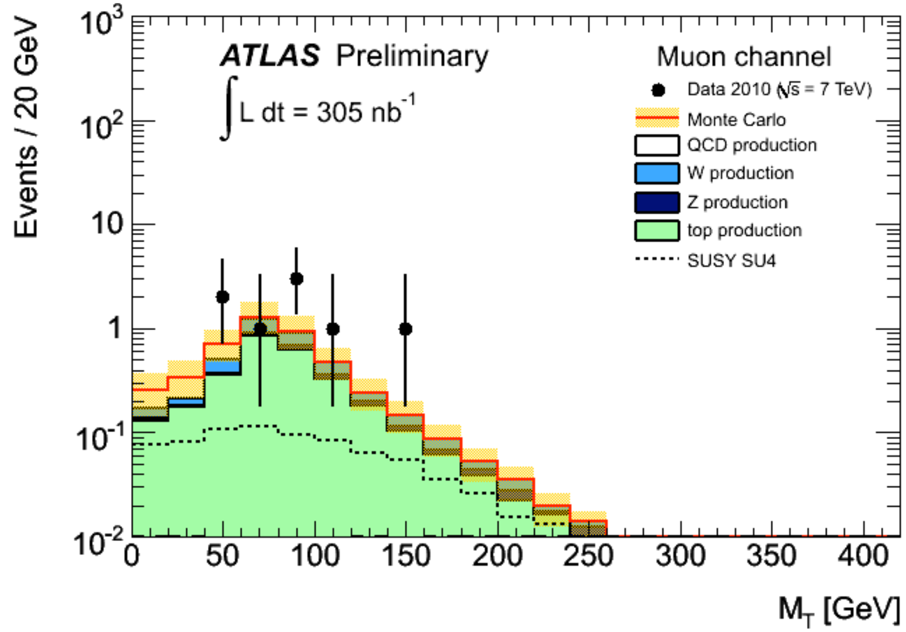


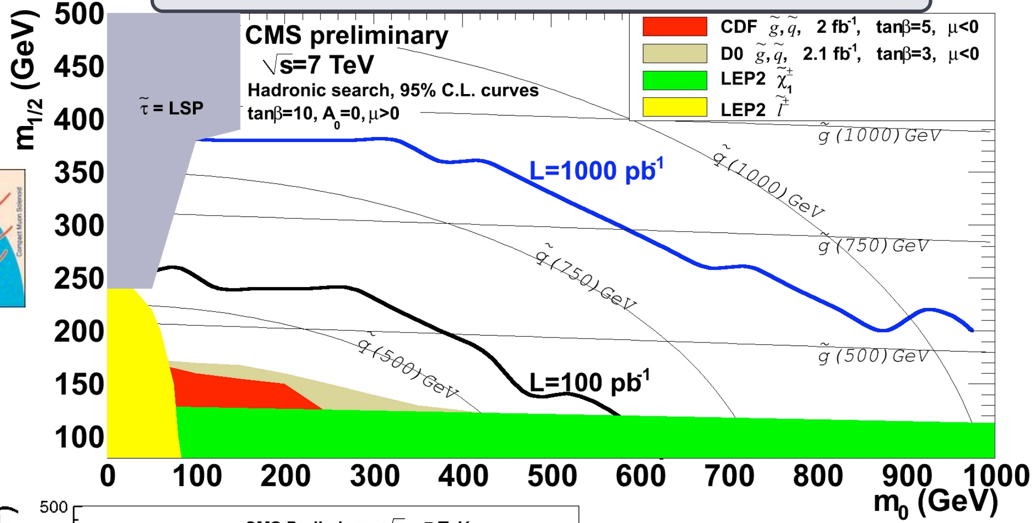


Prospects for end of 2011

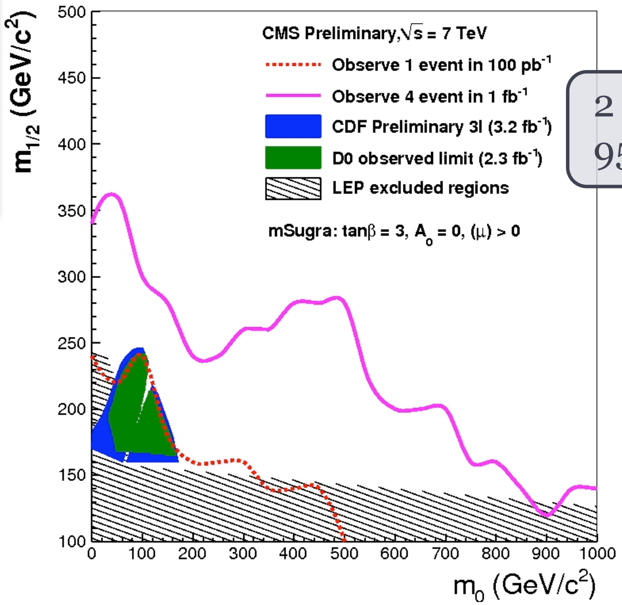
- SUSY discovery reach & exclusion limits for ~1 fb^{-1} and $\sqrt{s}$ = 7 TeV
- 2011 run at $\sqrt{s}$ = 8 TeV
    - to be decided at Chamonix (January 24 –28 2011)

Exclusion & discovery for 1 fb^{-1} @ 7 TeV

All-hadronic channel 95% exclusion limits

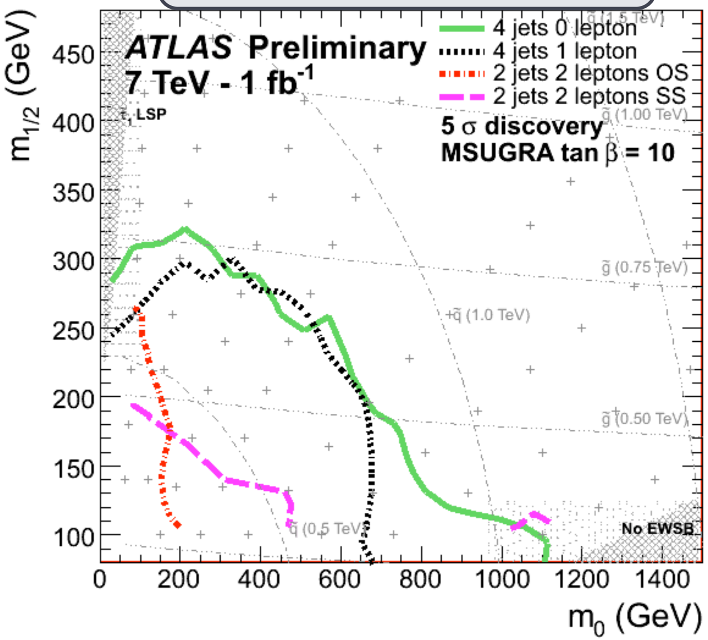


CMS-NOTE-2010-008



2 SS lepton channel 95% exclusion limits

5σ discovery reach for 0,1 and 2 lepton channels



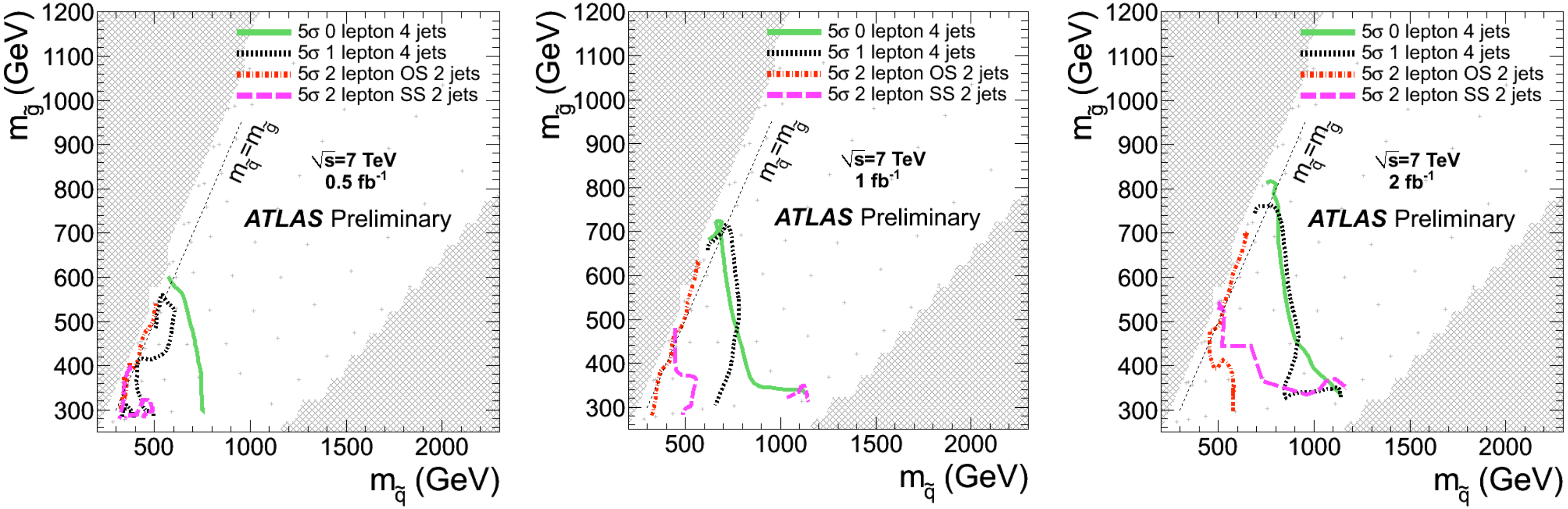
ATLAS-PHYS-PUB-2010-010

- 0-lepton and 1-lepton channels most powerful
- With 100 pb^{-1} ATLAS and CMS can significantly exceed current Tevatron & LEP exclusion limits

simulation studies

Evolution up to 2 fb^{-1}

ATLAS-PHYS-PUB-2010-010



- With 1 fb^{-1} squark and gluino masses up to 600-700 GeV can be discovered
- Systematic uncertainties included
- Caveat: excess of events is not enough
  - possibly other physics beyond the Standard Model
  - further precision measurements required

simulation studies

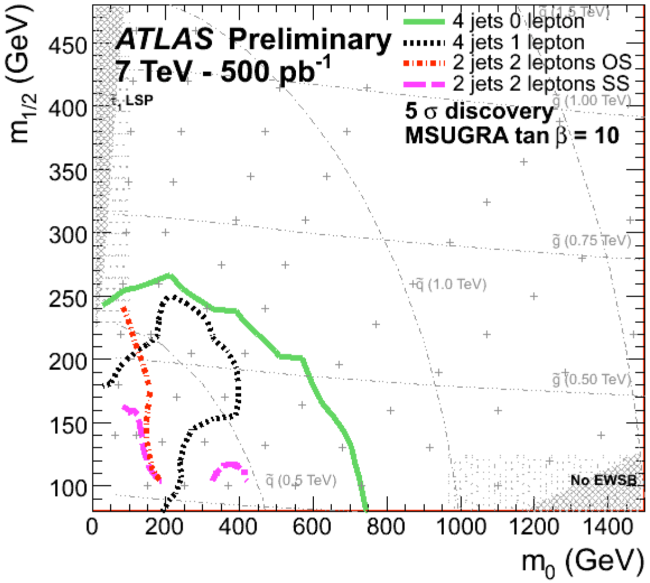
Conclusions on SUSY @ LHC

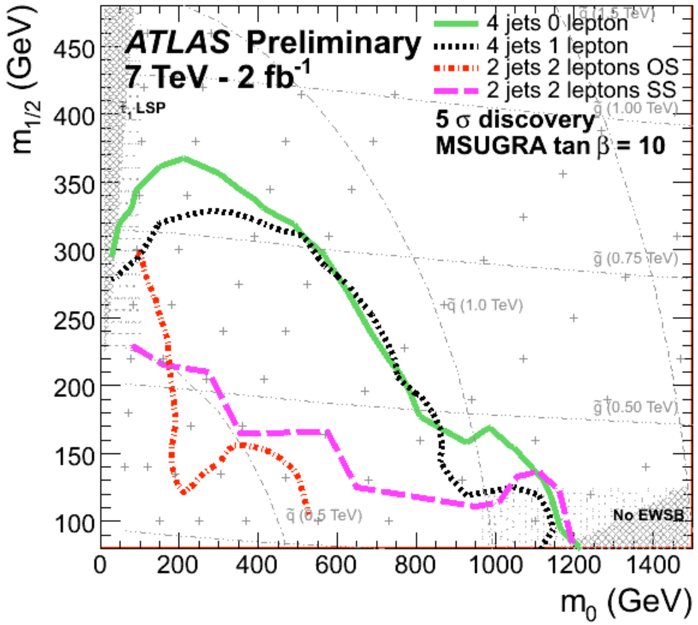
- ATLAS and CMS performed first analyses with luminosity up to 300 nb^{-1}
  - good understanding of detector performance & physics objects
  - background processes well under control
  - no significant deviations from SM seen so far
- New results competing with Tevatron can be obtained with 2010 data: ~40 pb^{-1} ($\approx$ 500 × ICHEP!)
- Monte Carlo studies for 1 fb^{-1} show that LHC with $\sqrt{s}$ = 7 TeV has sensitivity to
  - SUSY parameter space well beyond the Tevatron limits
  - SUSY with squark, gluino masses up to 700 GeV can be discovered

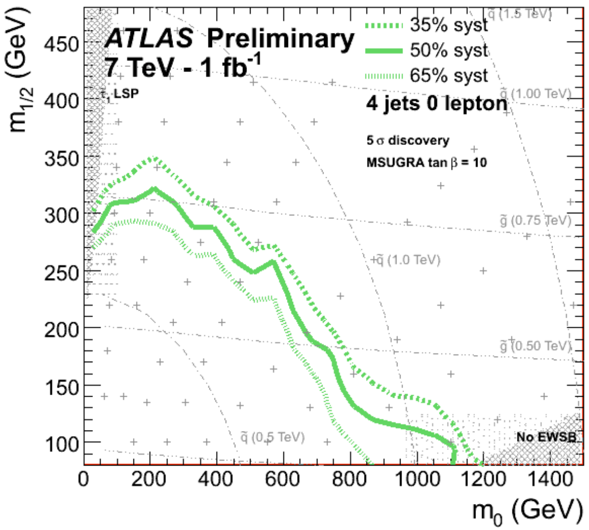
Outlook on Dark Matter & LHC

- Discovery: search for deviation from SM in inclusive signatures like missing energy + jets (+leptons)
- Scheme developed for SUSY, but applicable to other BSM scenarios, e.g. UED, T-parity Little Higgs, …
- LHC capable of discovering generic WIMP dark matter
  - non-trivial to prove that it has the right properties
  - ➔ LHC upgrade, ILC: extend LHC observations
    - improve on LHC capability of identifying DM model
    - more precise determination of model parameters
- Complementarity between LHC and astroparticle detectors
  - uncorrelated systematics
  - measure different parameters
- Continuous interplay between particle physics experiments (LHC, LHC upgrade, ILC) and cosmological observations

Back up slides…


ATLAS Preliminary
7 TeV - 500 pb^{-1}
4 jets 0 lepton
4 jets 1 lepton
2 jets 2 leptons OS
2 jets 2 leptons SS
5 σ discovery
MSUGRA tan β = 10
No EWSB
$m_{1/2}$ (GeV)
m_0 (GeV)


ATLAS Preliminary
7 TeV - 2 fb^{-1}
4 jets 0 lepton
4 jets 1 lepton
2 jets 2 leptons OS
2 jets 2 leptons SS
5 σ discovery
MSUGRA tan β = 10
No EWSB
$m_{1/2}$ (GeV)
m_0 (GeV)


ATLAS Preliminary
7 TeV - 1 fb^{-1}
35% syst
50% syst
65% syst
4 jets 0 lepton
5 σ discovery
MSUGRA tan β = 10
No EWSB
$m_{1/2}$ (GeV)
m_0 (GeV)

SUSY particle spectrum

spin $\frac{1}{2}$	spin 0	spin 1	spin $\frac{1}{2}$
quark q_L, q_R	$\boxed{\text{squark } \tilde{q}_L, \tilde{q}_R}$	W_3, B	$\tilde{W}_3$, $\tilde{B}$
lepton ℓ_L, ℓ_R	$\boxed{\text{slepton } \tilde{\ell}_L, \tilde{\ell}_R}$	$W^\pm$	$\tilde{W}^\pm$
$\boxed{\text{higgsino } \tilde{H}_1, \tilde{H}_2}$	Higgs H_1, H_2	gluon g	gluino $\tilde{g}$

graviton (spin 2) $\leftrightarrow$ $\boxed{\text{gravitino (spin 3/2)}}$

charginos

$$\tilde{W}^\pm,\ \tilde{H}^\pm \iff \boxed{\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm}$$

$$\tilde{B},\ \tilde{W}_3,\ \tilde{H}_1,\ \tilde{H}_2 \iff \boxed{\tilde{\chi}_1^0, \ldots, \tilde{\chi}_4^0}$$

neutralinos