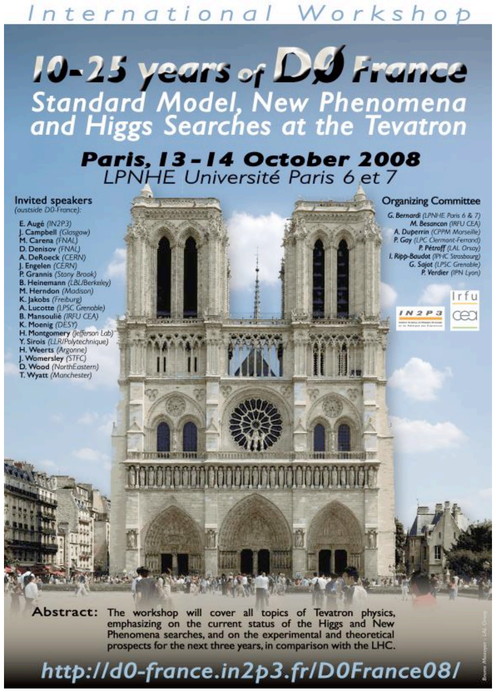
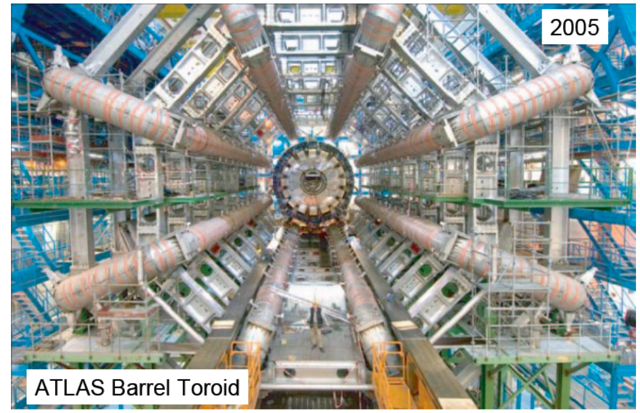
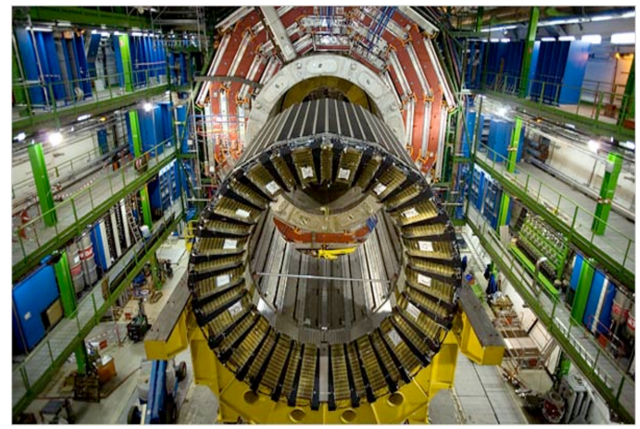
LHC: first 500 pb^{-1} for SUSY and beyond



- **Introduction**
- **Supersymmetry**
- **Beyond SUSY**
- **Conclusions**





Beate Heinemann

University of California, Berkeley and Lawrence Berkeley National Laboratory

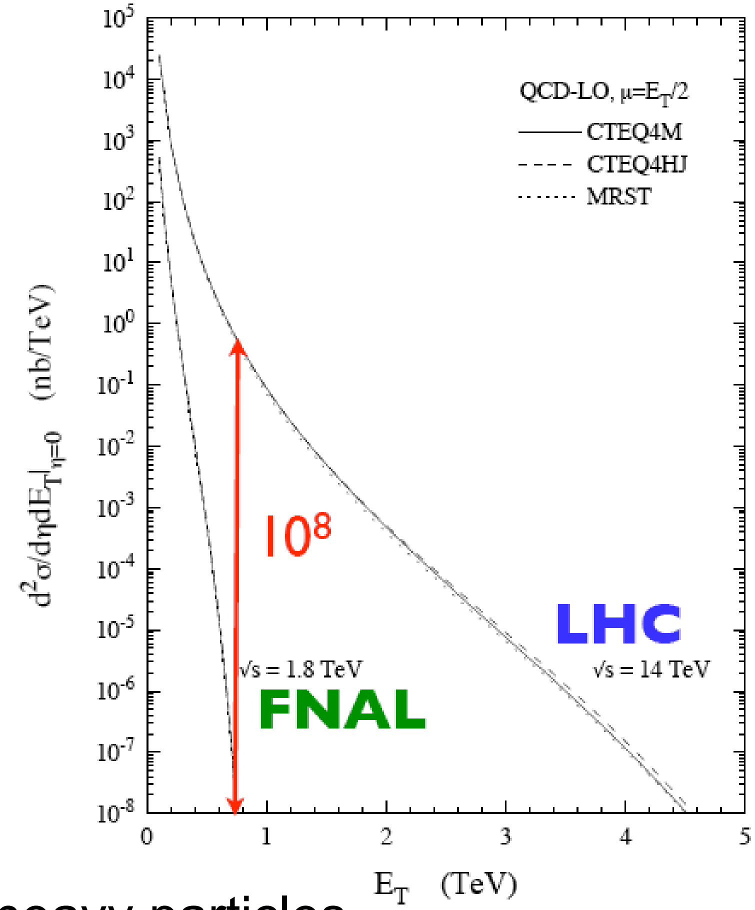
DØ France, Paris, October 2008

Physics Opportunities at LHC

Cross Sections of Physics Processes (pb)

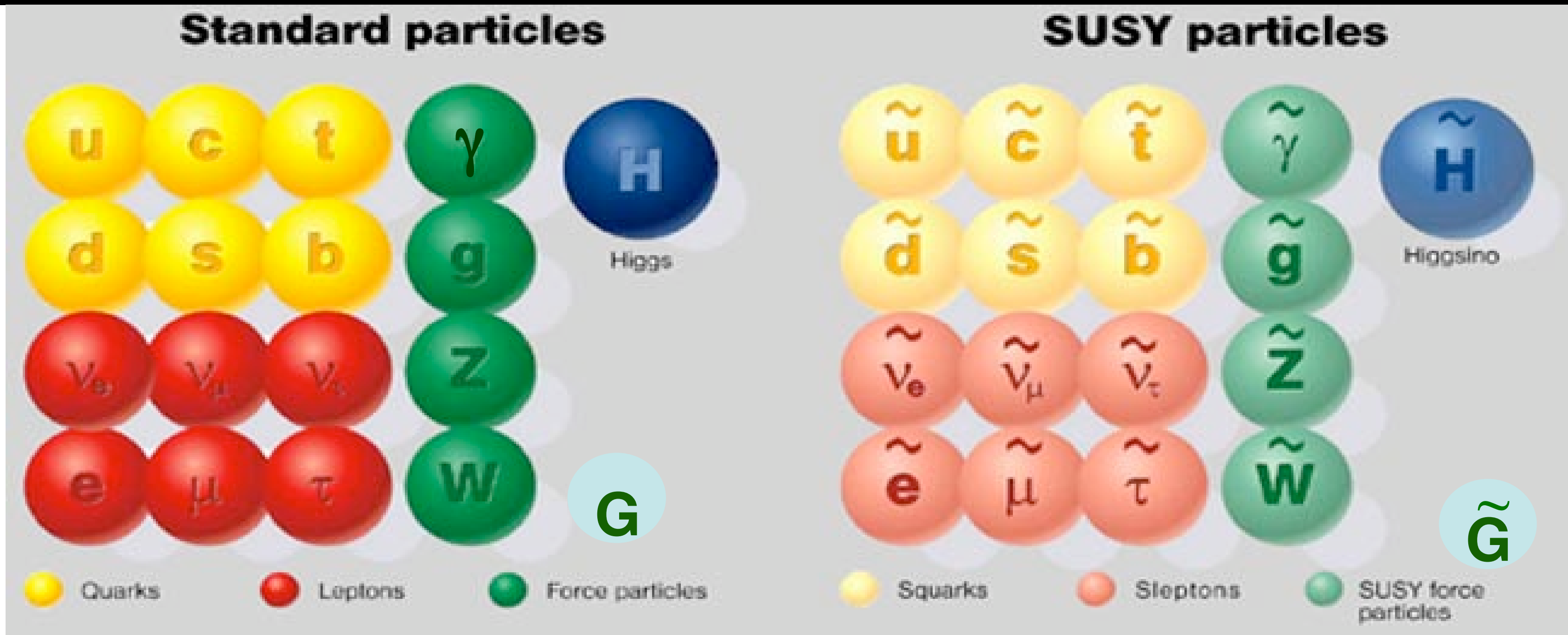
	Tevatron	LHC √s=14TeV	Ratio
W± (80 GeV)	2600	20000	~10
tt (2x172 GeV)	7	900	~100
gg->H (120 GeV)	1	40	~40
$\tilde{\chi}^+_1\tilde{\chi}^2_0$ (2x150 GeV)	0.1	1	~10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	~1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	~20000
Z' (1 TeV)	0.1	30	~300

Jet Cross Section

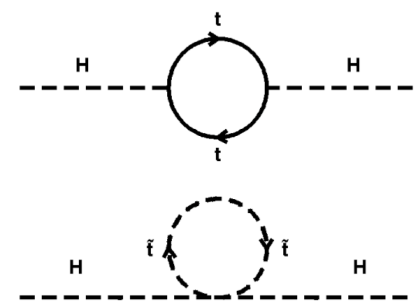


- Amazing increase for strongly interacting heavy particles
  - Opportunity!
- Cross sections typically 50% lower for √s=10 TeV

Supersymmetry (SUSY)

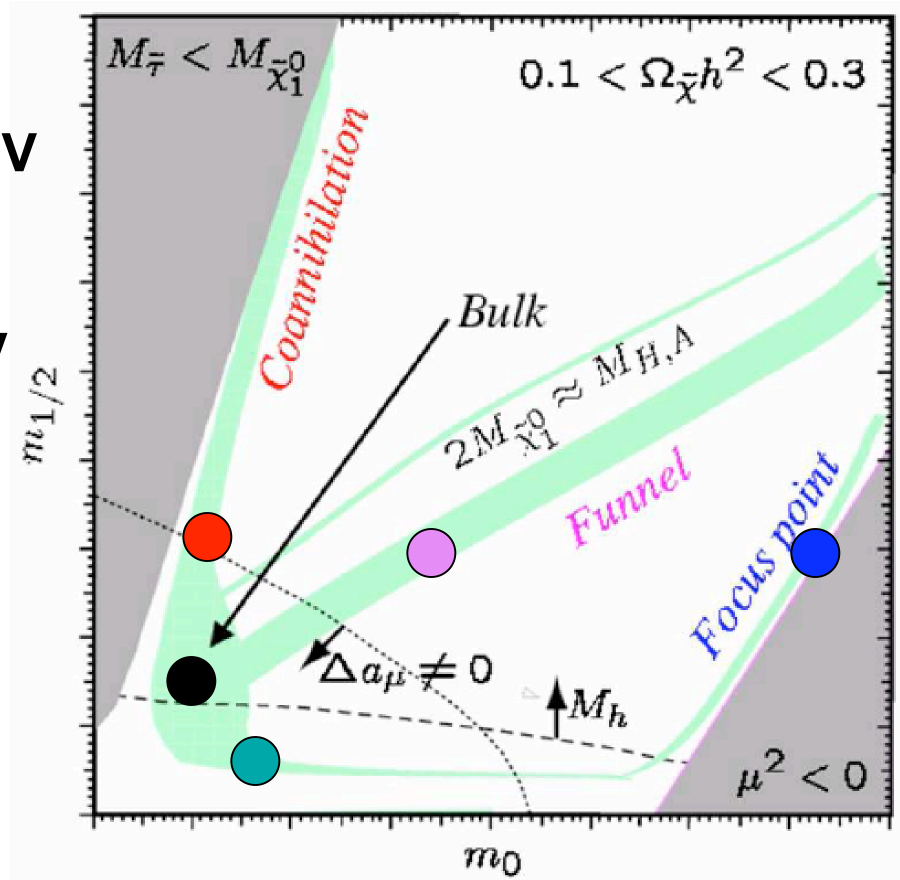


- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - **Sfermions** (squarks, selectron, smuon, ...): spin 0
    - **Gauginos** (chargino, neutralino, gluino,…): spin 1/2
- SUSY mass scale needs to be low to
  - Solve hierarchy problem
  - Achieve unification of strong and electroweak forces
  - Provide sensible dark matter candidate



Benchmarks in SUSY Parameter space

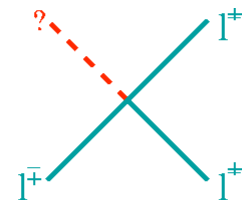
- **SU1: m($\tilde{g}$)≈830 GeV,m($\tilde{q}$)≈750 GeV**
  - Coannihilation region
- **SU2: m($\tilde{g}$)≈860 GeV,m($\tilde{q}$)≈3500 GeV**
  - Focus point
- **SU3: m($\tilde{g}$)≈720 GeV,m($\tilde{q}$)≈620 GeV**
  - Bulk point
- **SU4: m($\tilde{g}$)≈420 GeV,m($\tilde{q}$)≈420 GeV**
  - Just beyond Tevatron reach
- **SU6: m($\tilde{g}$)≈900 GeV,m($\tilde{q}$)≈870 GeV**
  - Funnel regions

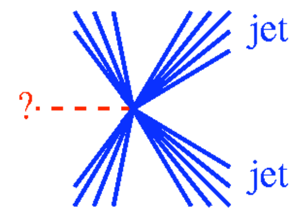


Attempt to span broad parameter space to understand model dependence

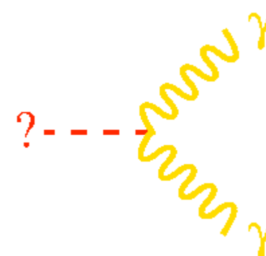
SUSY Comes in Many Flavors

- Breaking mechanism determines phenomenology and search strategy at colliders
  - mSUGRA/CMSSM
    - Neutralino is the LSP
    - Many different final states
    - Common scalar and gaugino masses



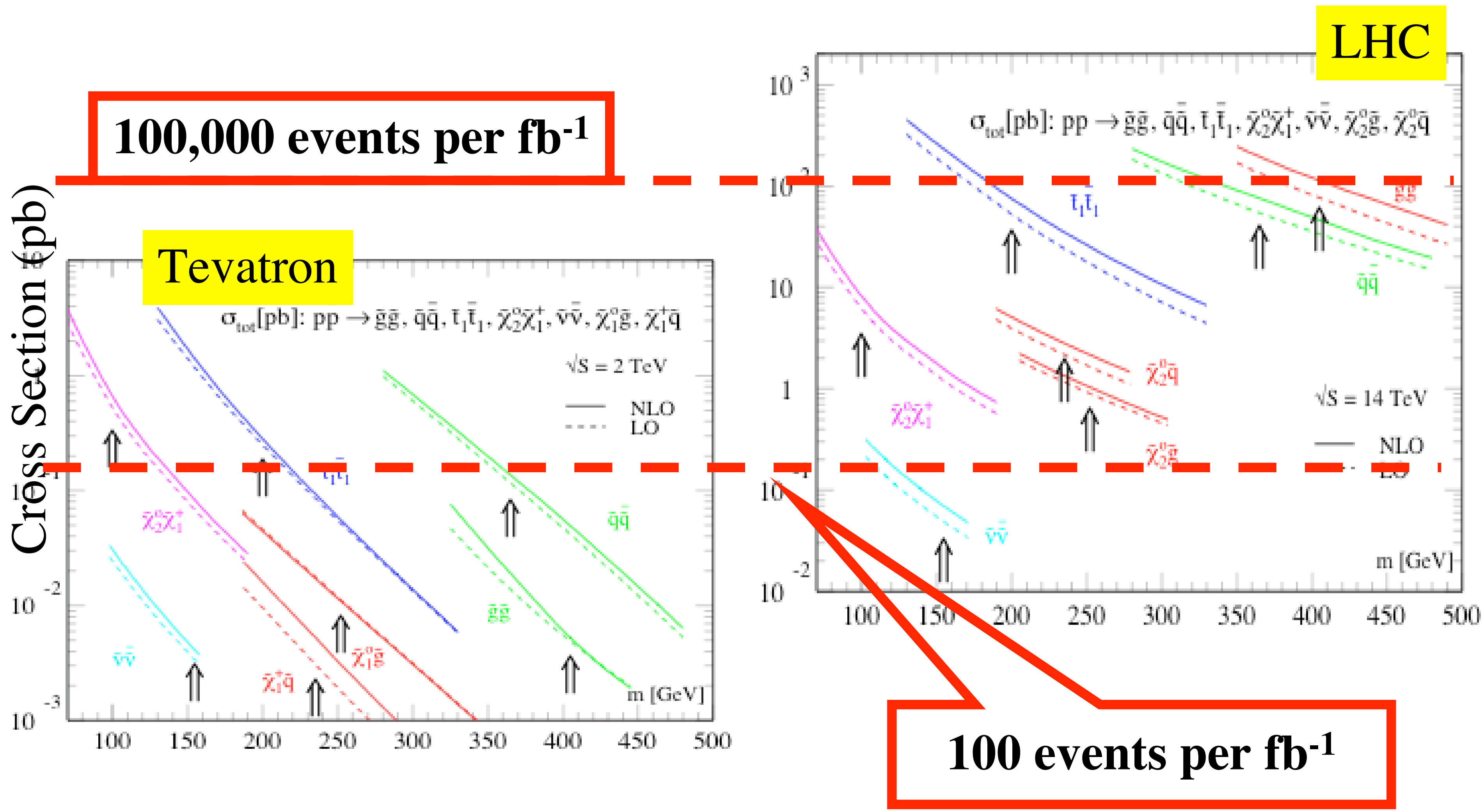


  - GMSB:
    - Gravitino is the LSP
    - Photon or tau final states expected



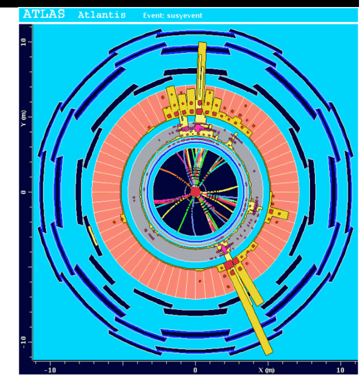
  - Other:
    - AMSB,Split-SUSY,…
- R-parity
  - Conserved: Sparticles produced in pairs
    - natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector

Sparticle Cross Sections: LHC vs Tevatron

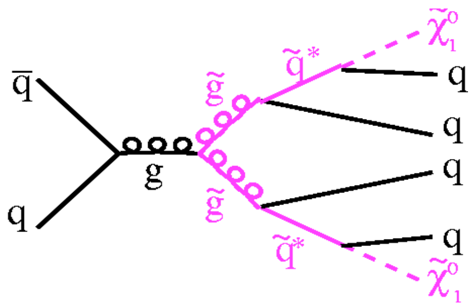


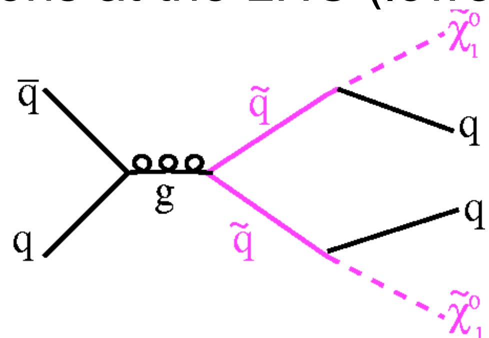
T. Plehn, PROSPINO

Squarks and Gluinos at the LHC

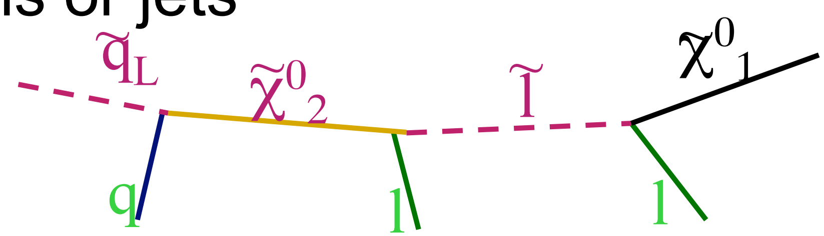


- Cross section nearly model-independent
  - for m($\tilde{g}$)=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g})/\ \sigma_{Tevatron}(\tilde{g}\tilde{g}) \approx 20{,}000$
  - for m($\tilde{q}$)=400 GeV: $\sigma_{LHC}(\tilde{q}\tilde{q})/\ \sigma_{Tevatron}(\tilde{q}\tilde{q}) \approx 1{,}000$
    - Since there are a lot more gluons at the LHC (lower x)

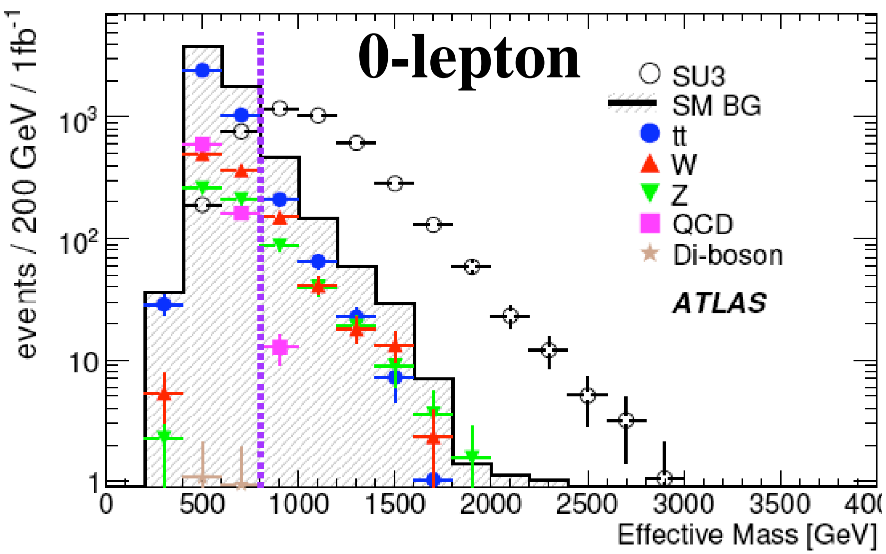


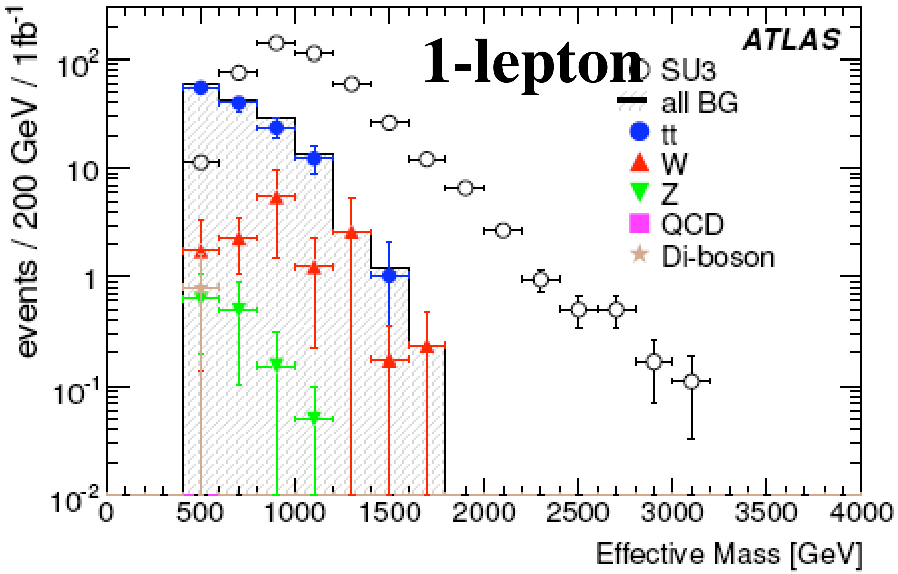


- At higher masses more phase space => decay in cascades
  - Results in additional leptons or jets
  - Very model-dependent



Search Analyses: 0, 1, 2 leptons+jets



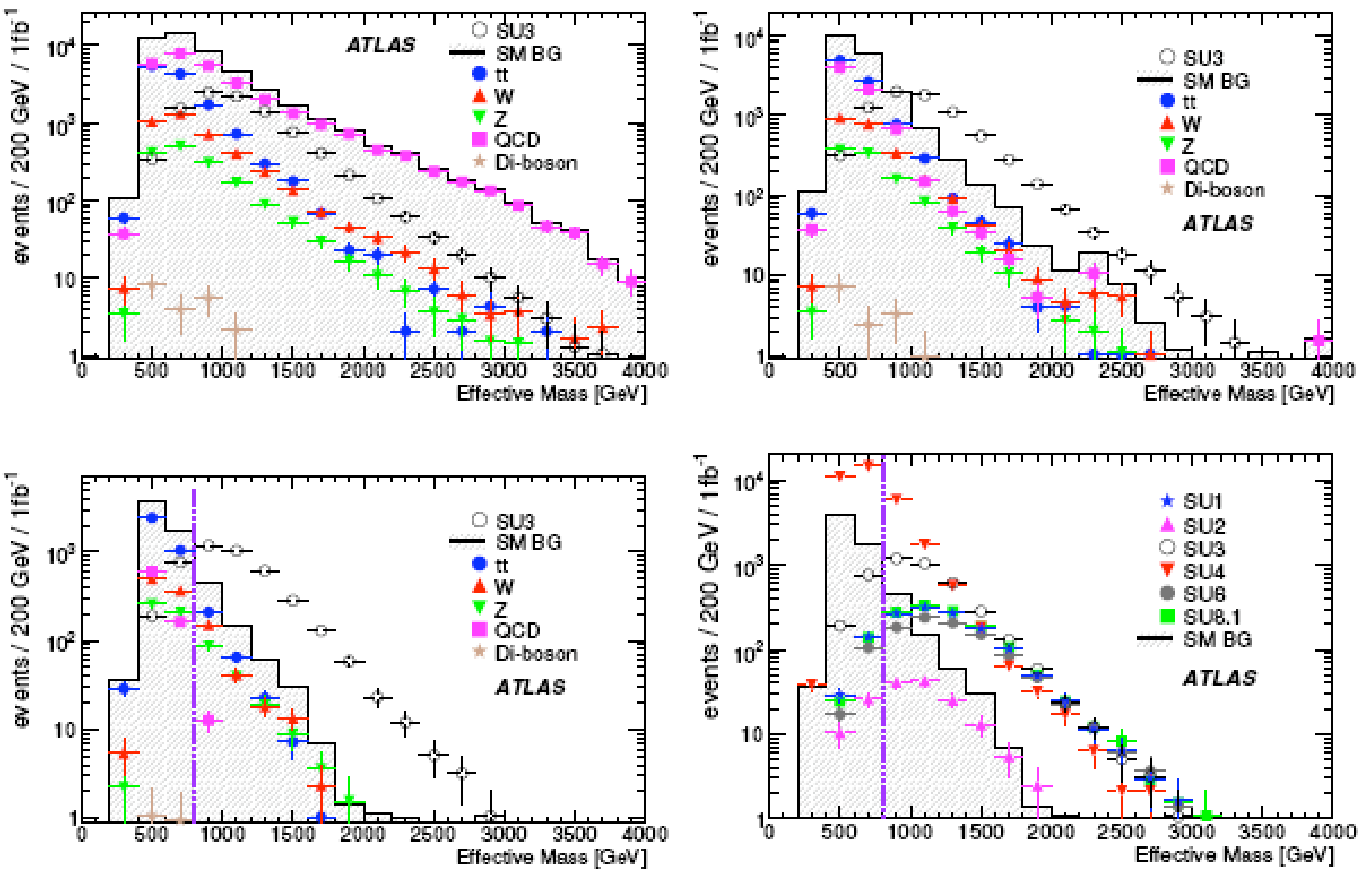


- Signal can appear in many search analyses simultaneously
  - Depends on model details
  - Important to do all of them
- Top is most severe background

2-lepton

Sample	Nevent/fb^{-1}
SU1 m($\tilde{g}$)≈860 GeV	72.6
SU2 m($\tilde{g}$)≈830 GeV	18.8
SU3 m($\tilde{g}$)≈720 GeV	159.8
SU4 m($\tilde{g}$)≈420 GeV)	809.5
Top	81.5
Other backgrounds	3.2

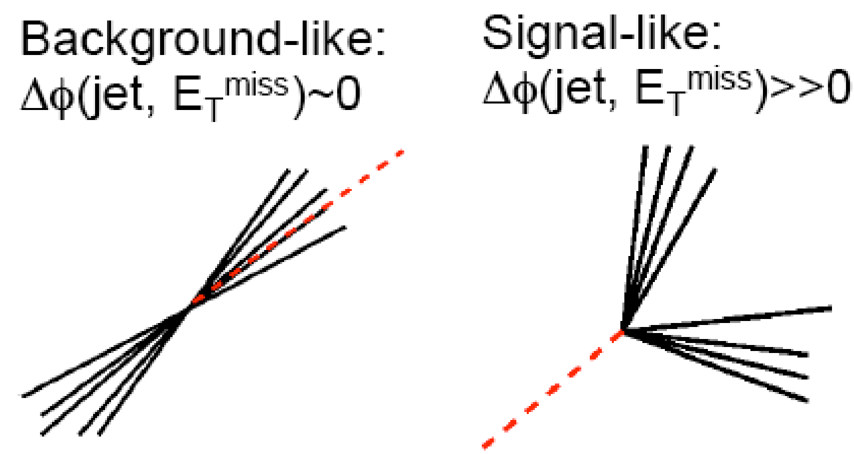
0-lepton analysis: Details

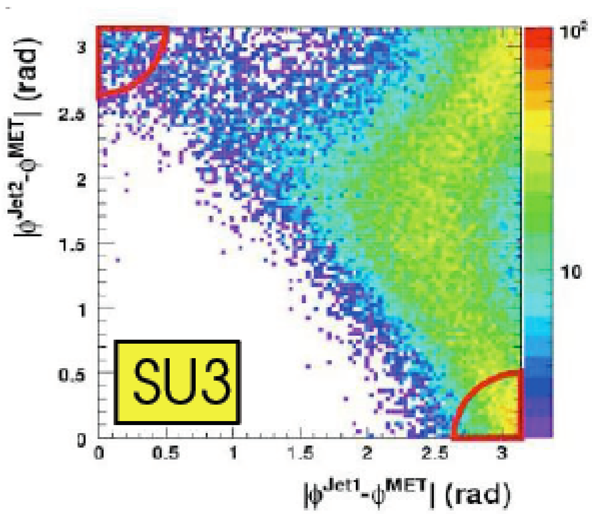


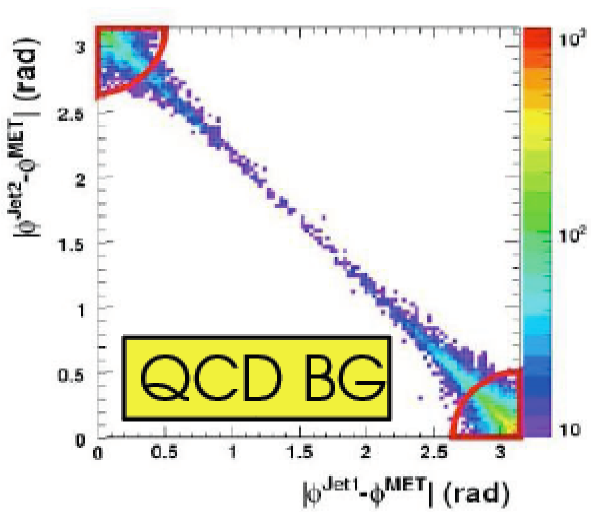
- 4 energetic jets and E_T^{miss}>100 GeV
- E_T^{miss}>0.2 M_{eff} where $M_{eff}=\sum_i E_{T,i}+E_t^{miss}$
- Sphericity>0.2, phi-correlation cuts, lepton veto

QCD Multi-jet

- Require large $\Delta\phi$
  - Between missing E_T and jets and between jets
  - Suppresses QCD dijet background due to jet mismeasurements







- Many studies on how to determine this background with data
  - Not yet clear to me how well any of them will work
  - We'll see!

Hermetic and well understood calorimeter critical for this

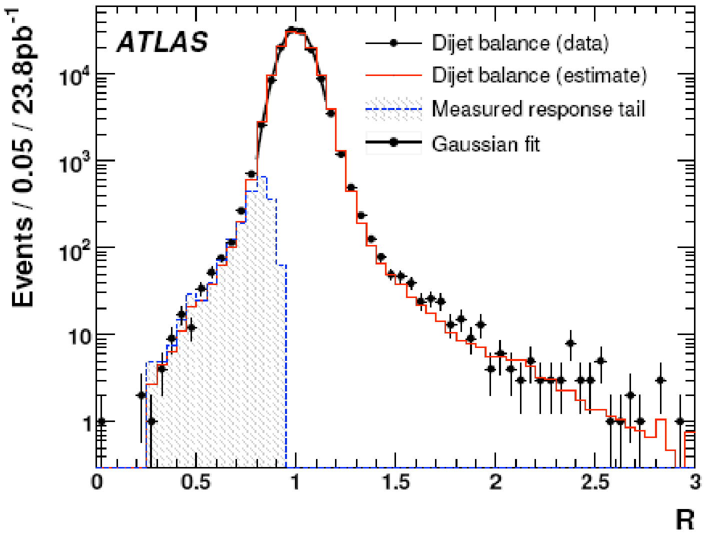
Methods to estimate remaining QCD multi-jet Background

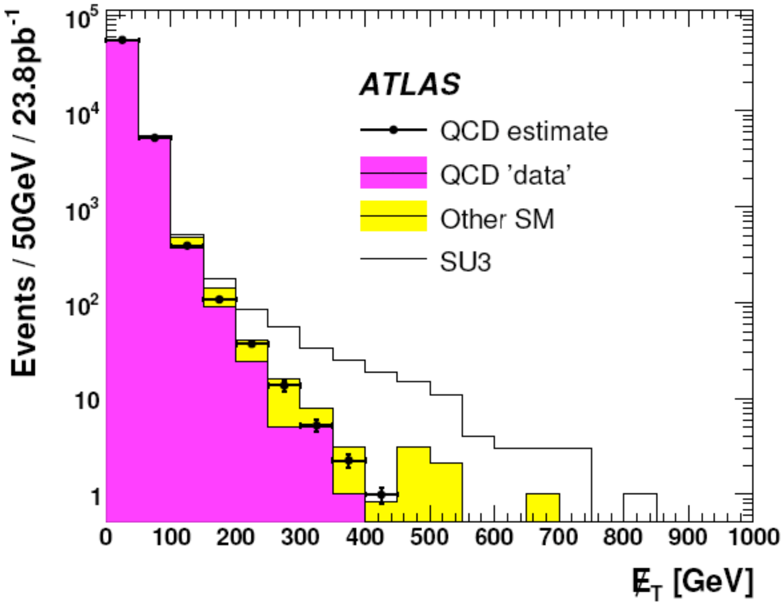
- Measure gaussian and non-gaussian contributions from data in dijet events

$$R_3(j) = 1 + \frac{\not{\mathbf{p}}_T \cdot \mathbf{p}_T(j')}{|\mathbf{p}_T(j')|^2}$$

- Technique practiced in MC
  - Works well!
  - Many alternative methods
- Will see with real data

- Clearly the single most difficult background to control!

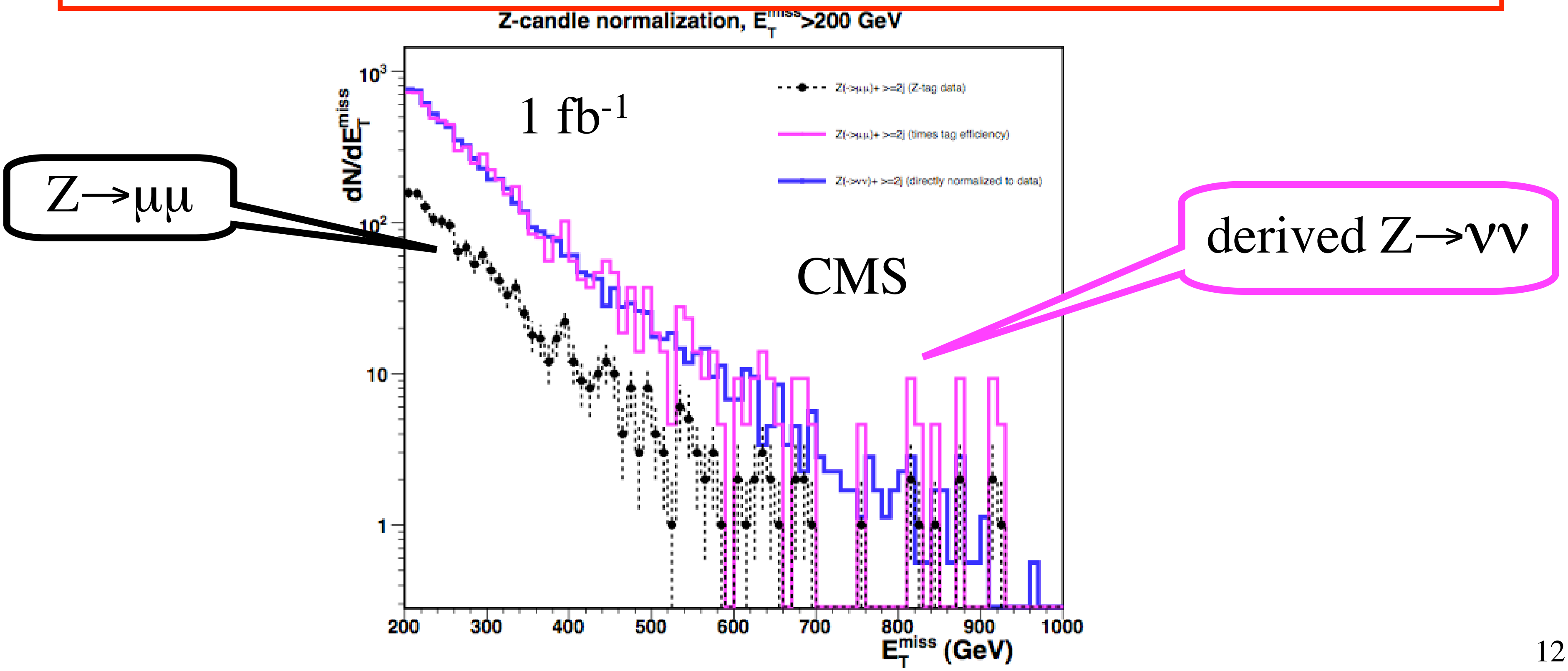




Using Z(→ll)+jets for estimating W/Z+jet background

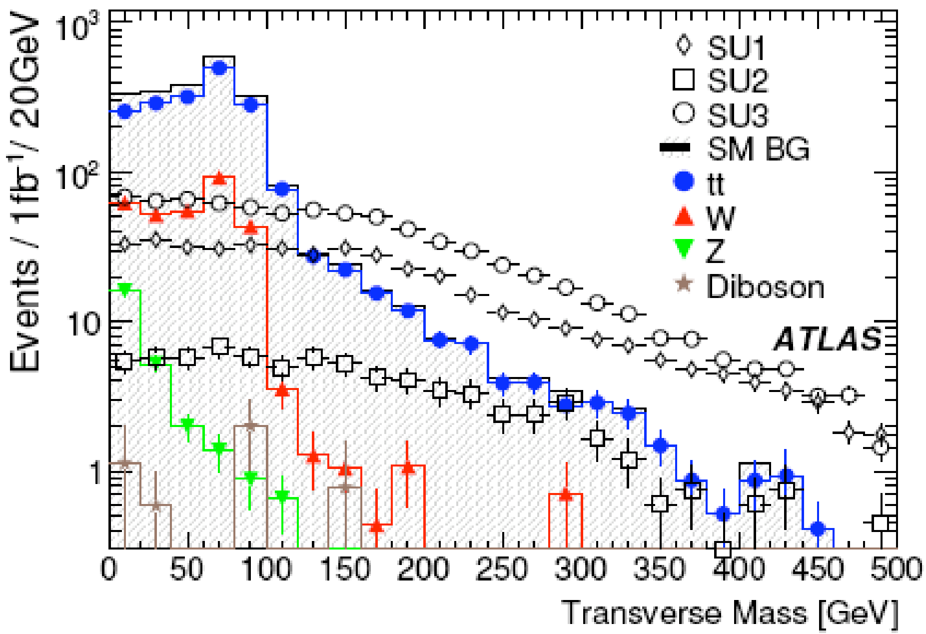
- Use Z(→ll)+jets to extrapolate to Z(→νν)+jets
  - $ME_T \sim p_T(Z)$

$$N_{Z\to\nu\bar{\nu}}(E_T^{\rm miss}) = N_{Z\to\ell^+\ell^-}(p_T(\ell^+\ell^-)) \times c_{\rm Kin}(p_T(Z)) \times c_{\rm Fidu}(p_T(Z)) \times \frac{{\rm Br}(Z\to\nu\bar{\nu})}{{\rm Br}(Z\to\ell^+\ell^-)},$$

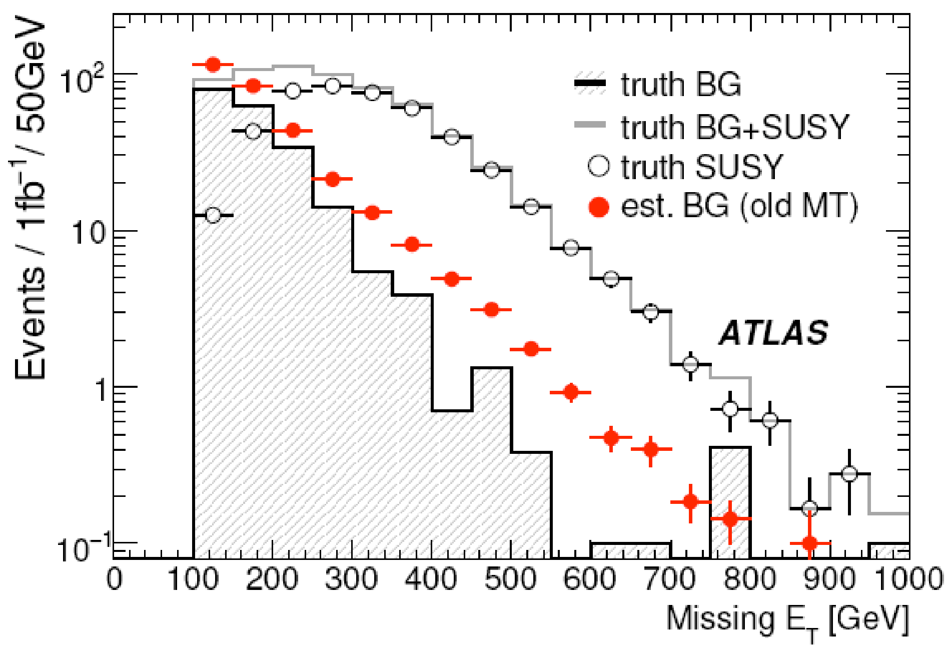


Top and W+jets background estimate

- Use region of low $m_T(W)$
  - Extrapolate to signal region using MC
  - But may be contaminated by SUSY => overestimate BG
    - If SUSY signal is large
    - Iterating required

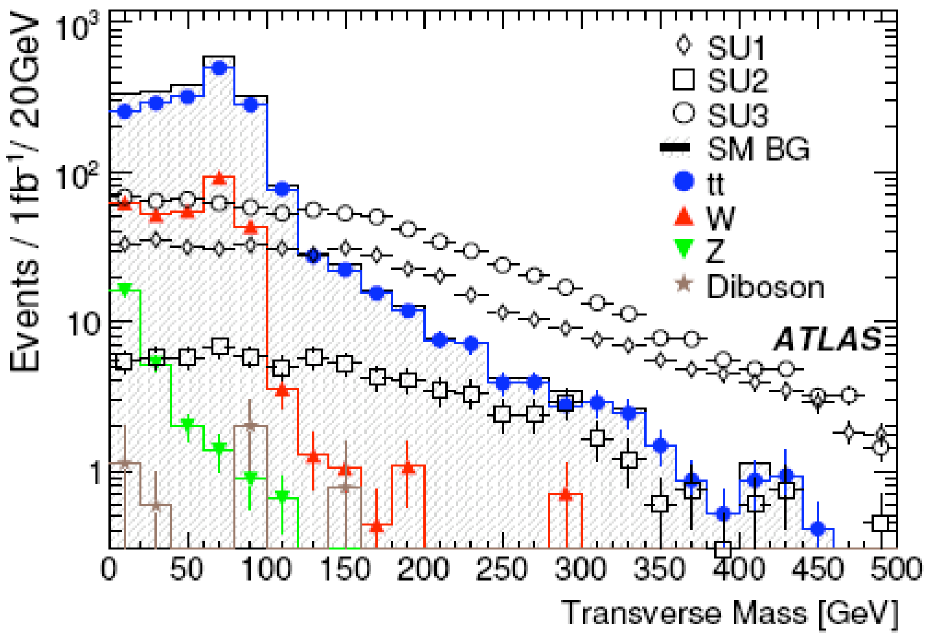


BG estimate: 1st iteration

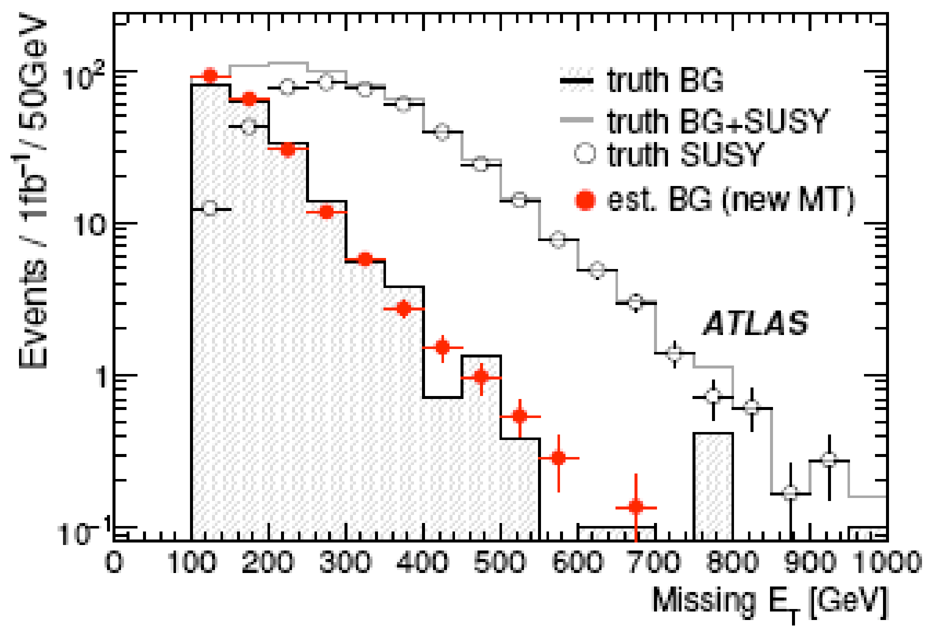


Top and W+jets background estimate

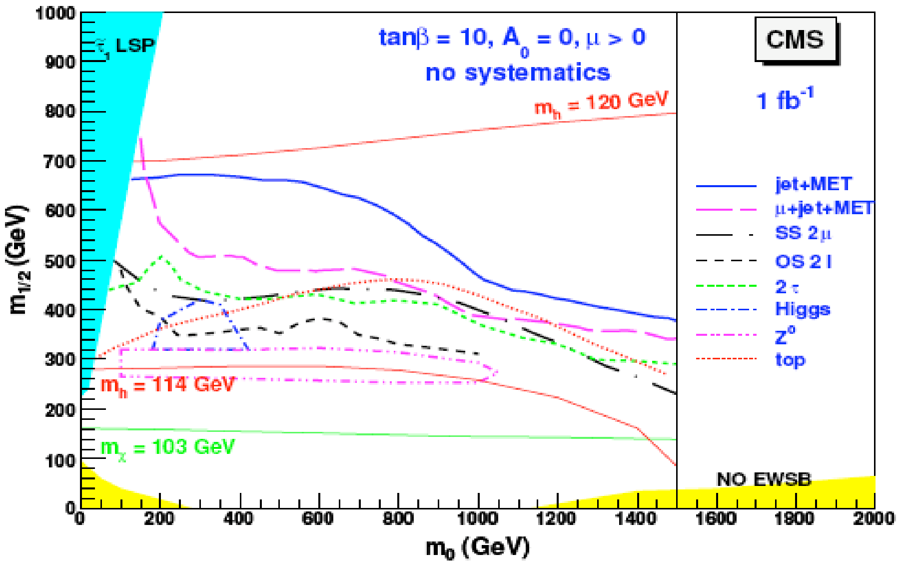
- Use region of low $m_T(W)$
  - Extrapolate to signal region using MC
  - But may be contaminated by SUSY => overestimate BG
    - If SUSY signal is large
    - Iterating required

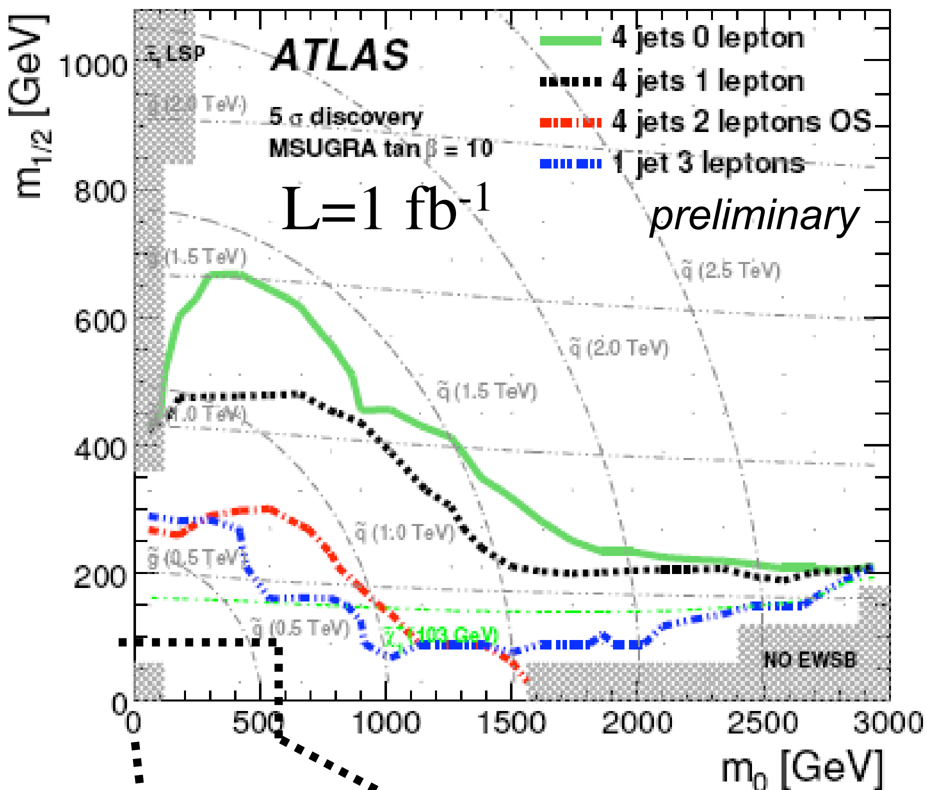


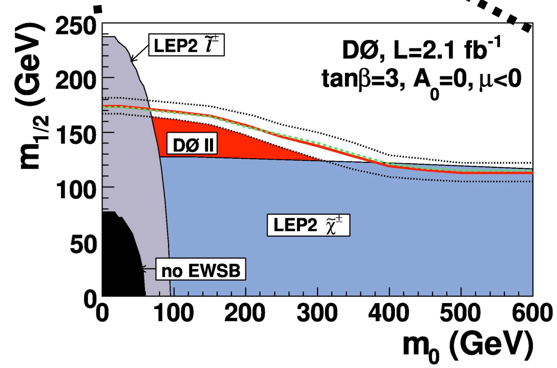
BG estimate after iterating



LHC SUSY Discovery Reach



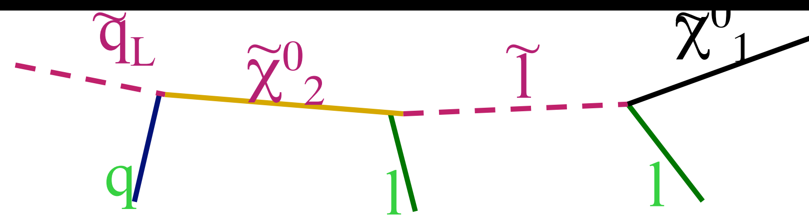




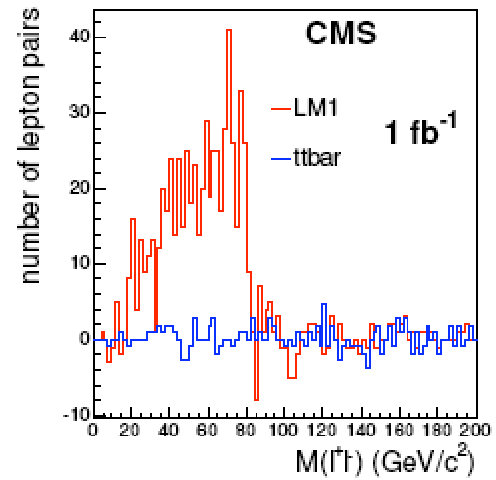
- With 1 fb^{-1}:
  - Sensitive to $m(\tilde{g})<0.5\text{-}1.5$ TeV/c^2
  - Depending on squark mass
- Current limits:
  - $m(\tilde{g})>300\text{-}400$ GeV/c^2
- Amazing potential!
  - If data can be understood
  - If current MC background predictions are ≈ correct

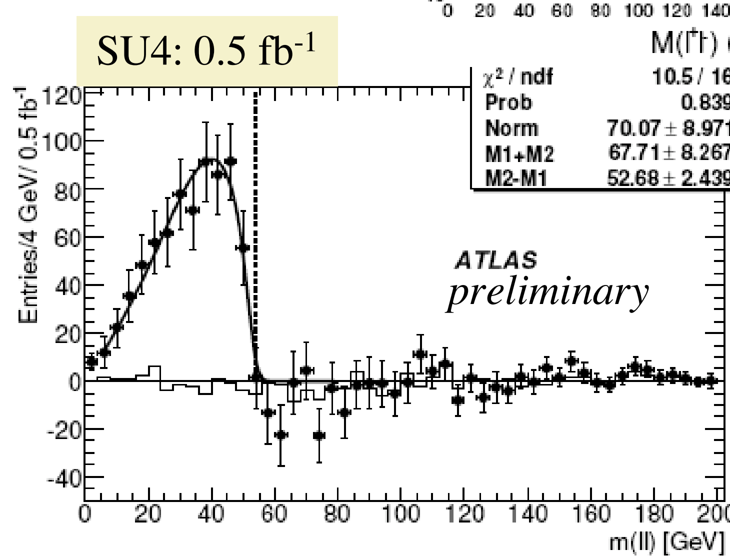
What kind of SUSY is it?

- We will need to do SUSY spectroscopy!
  - Rate of 0 vs 1 vs 2 vs n leptons
    - Sensitive to neutralino masses
  - Rate of tau-leptons:
    - Sensitive to tanβ
  - Kinematic edges
    - obtain mass values
  - Trileptons
    - Examine chargino/ neutralino couplings
  - Detailed examination of inclusive spectra



$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$

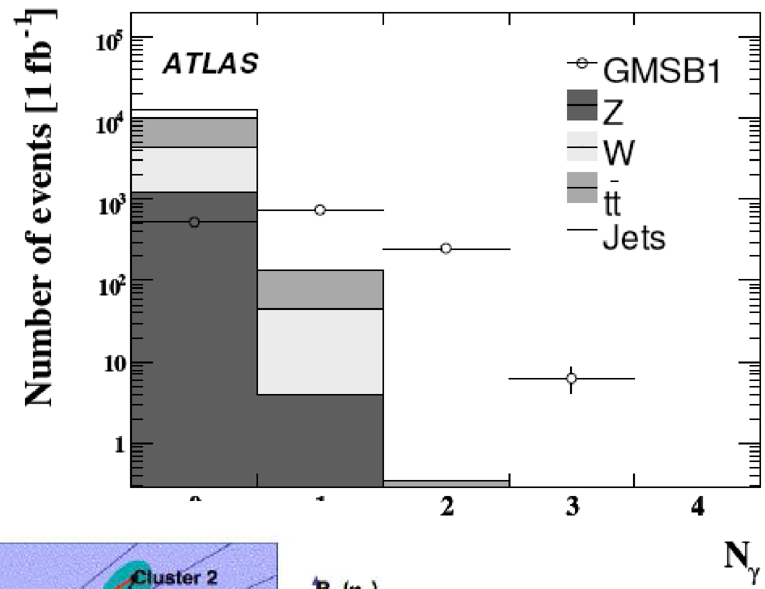


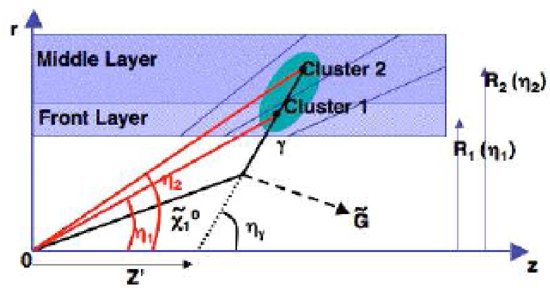


That would be a lot of fun!!

Non-standard SUSY

- Inclusive jets+E_T analysis should work for any model
  - If squarks/gluinos are light enough
  - If LSP is stable
- Alternative searches with photons:
  - In GMSB models:
    - Next-to-lightest particle is
      - neutralino→ $\gamma\tilde{G}$
      - pp→ $\tilde{\chi}\tilde{\chi}$ →$\gamma\gamma\tilde{G}\tilde{G}$
    - **jets+$\not\!\!E_T$+photons**
    - **Non-pointing photons**
      - Decay of slow heavy neutralino

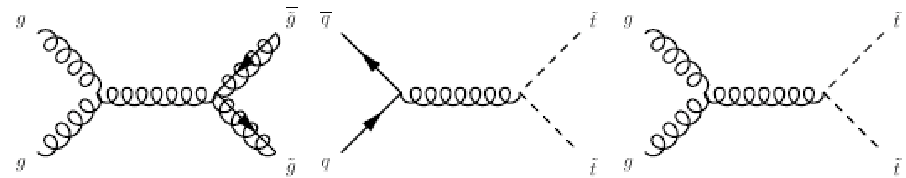


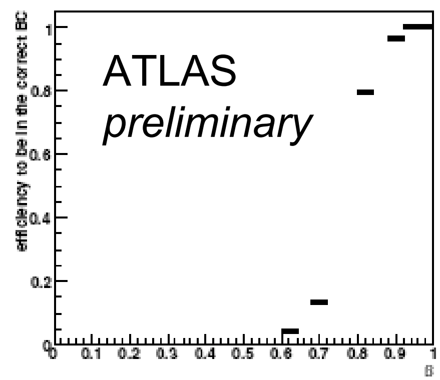


$\int Ldt$=1 fb^{-1}	>=2 photon selection
background	0.1
Signal (prompt)	252.9
Signal (non-prompt)	12.5

Long-lived stable charged particle

- Occur e.g. in
  - Split-SUSY: “R-hadron”
  - GMSB: stau
- Detect
  - Charged particles with β<<1 that get detected by muon system
- Challenge:
  - Detectors are huge and BC’s only 25 ns
    - Efficiency very low for β<0.6
- Discovery up to ~1 TeV possible with ~1 fb^{-1}



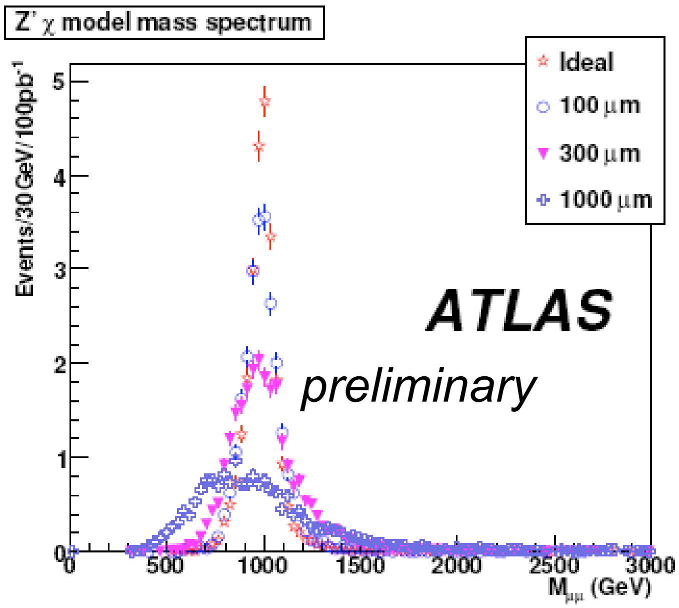


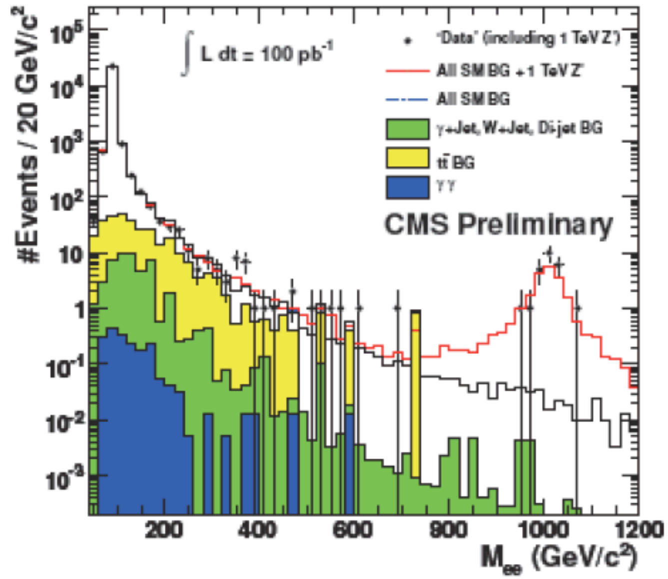
ATLAS
preliminary

Sample	Rate (Events/fb^{-1})
$m(\tilde{g})$=0.3 TeV	6440
$m(\tilde{g})$=1.0 TeV	10.7
backgrounds	1.7

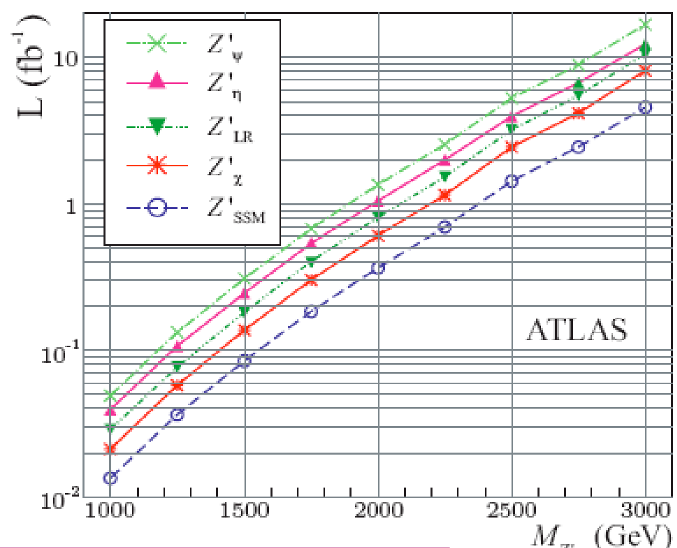
Beyond SUSY

Z´ type particles should be easy!



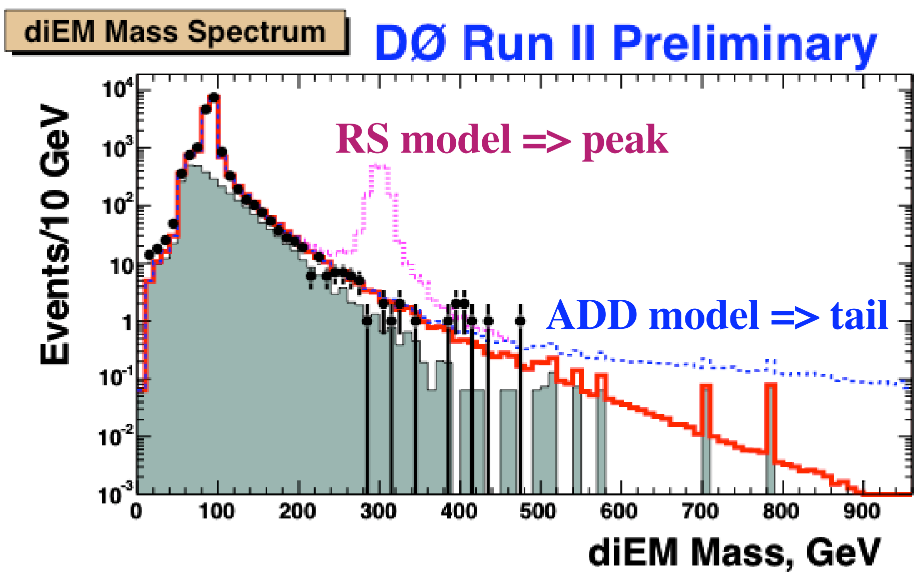


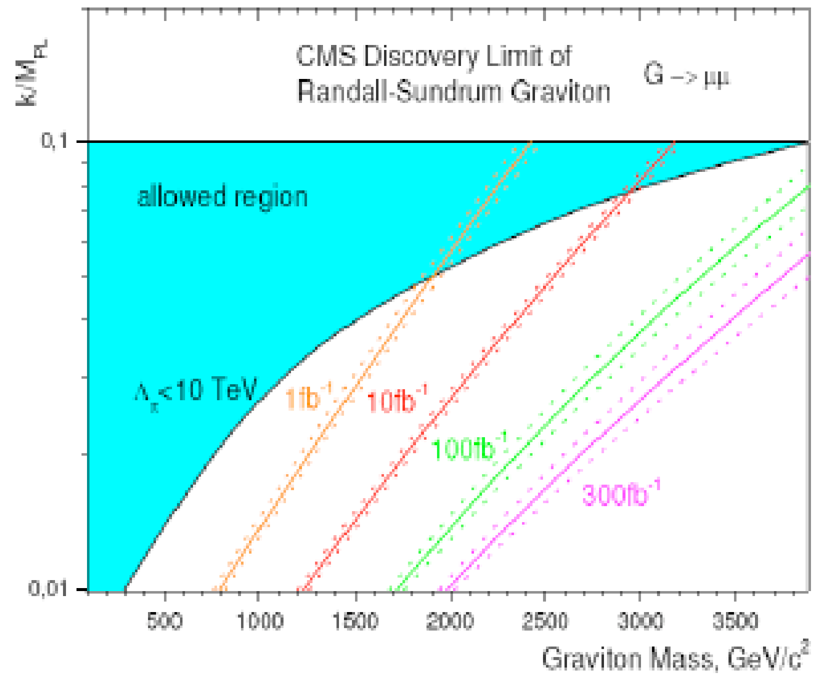
- Signal creates clear peak
  - Easier for electrons than muons though
  - Muons suffer from worsening resolution at high momentum
- Main background is well understood theoretically
- Conclusions similar for any heavy particle decaying to ee,μμ,γγ



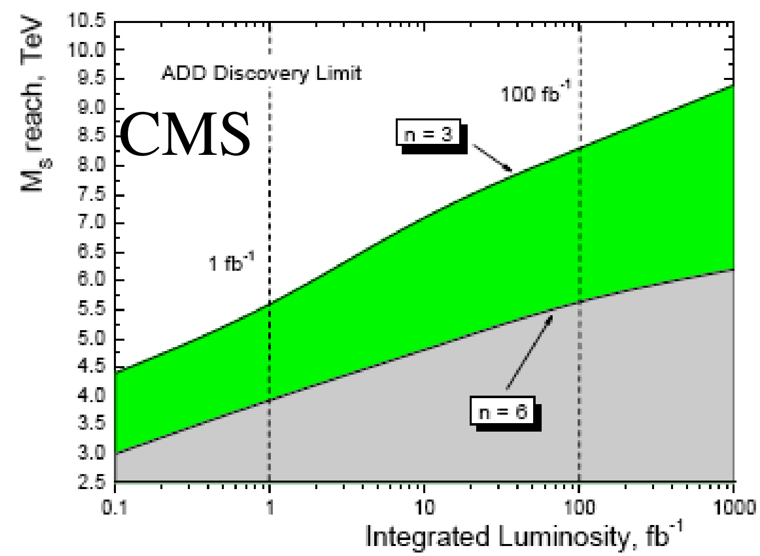
Probe ~1 TeV range already with <100 pb^{-1}

Extra Dimensions: Large or Warped?



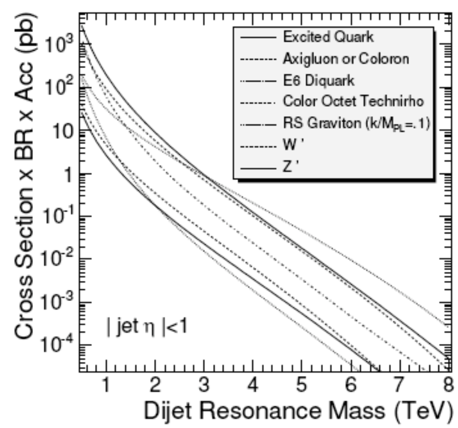


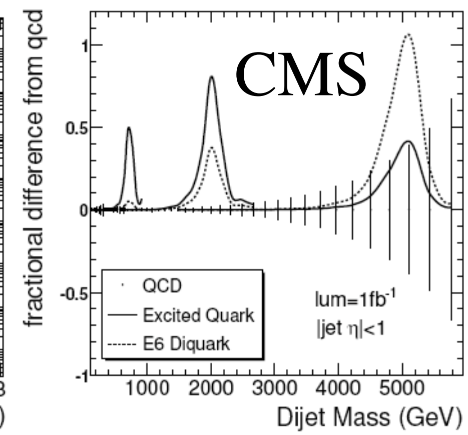
- Dilepton and diphoton mass spectra:
  - Probe RS model up to M_G=2.3 TeV with 1 fb^{-1}
    - Current limit: ~0.9 TeV (CDF/DØ)
  - Probe ADD model up to M_S=3.5 TeV with 1 fb^{-1} for n=3
    - Current limit: ~1.4 TeV (DØ)
- This is also quite easy and quick

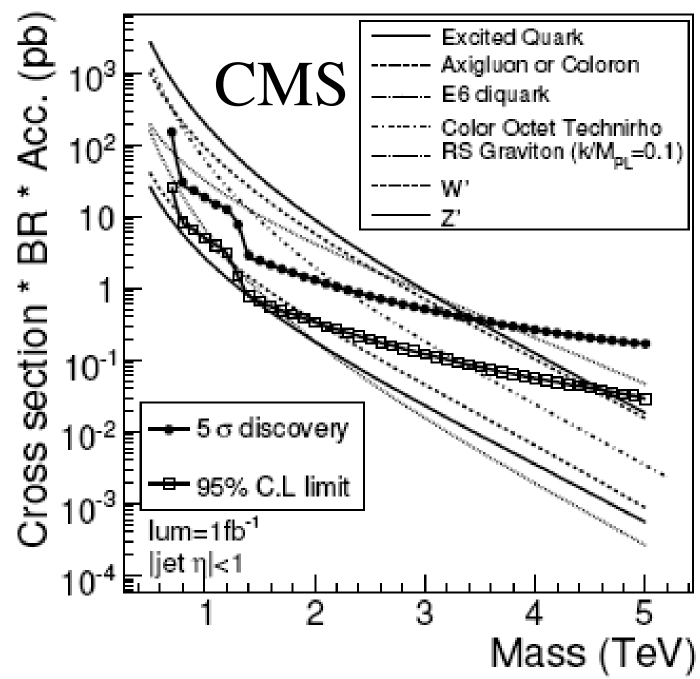


Dijet Resonances

- Predicted by many extensions of the Standard Model
- Search for resonance in dijet mass spectrum
  - On steeply falling spectrum
  - Requires good understanding of calorimeter resolution
- With 1 fb^{-1} e.g. sensitive to 3.5 TeV axigluon or q*
  - Tevatron limit: 1.2 TeV

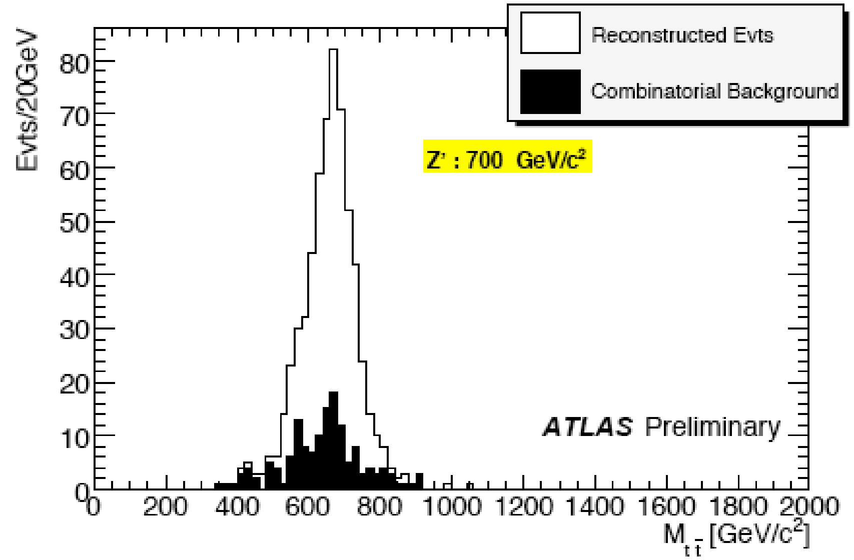


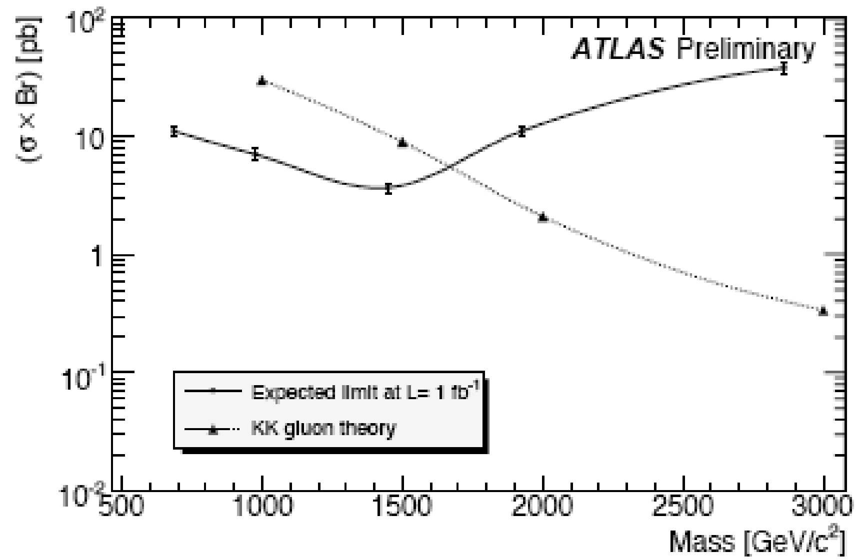




tt resonance

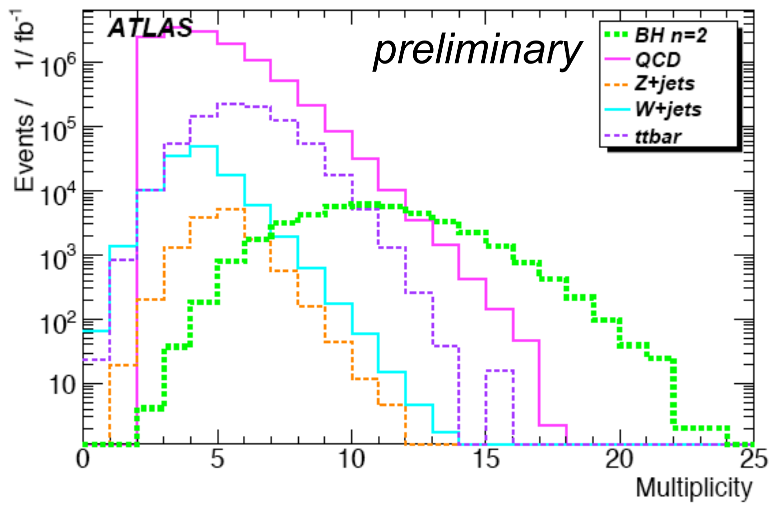
- Resonance production of top quark pairs
  - Recent theoretical interest
  - KK Gluon in Randall-Sundrum models
    - Decays 95% into top pairs
- Mass resolution about 6%
- Reach
  - up to 1.5 TeV with 1 fb^{-1}

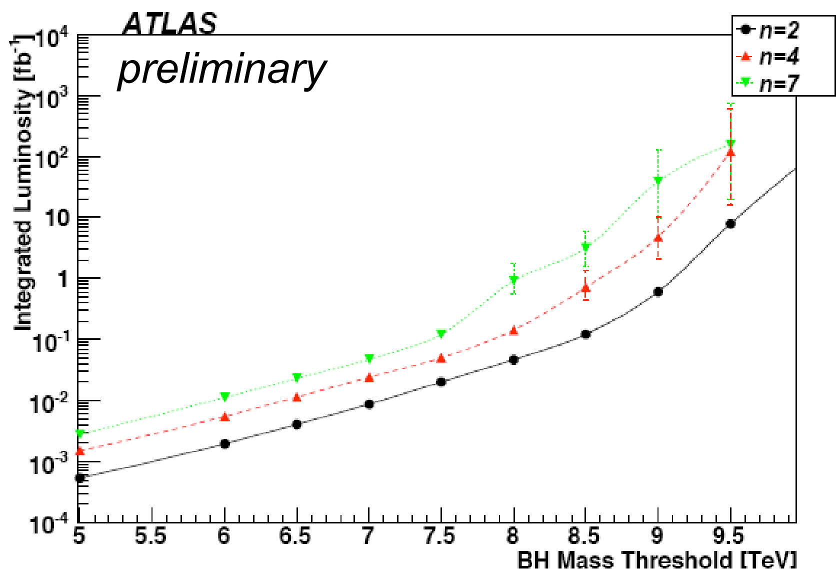




Black Holes

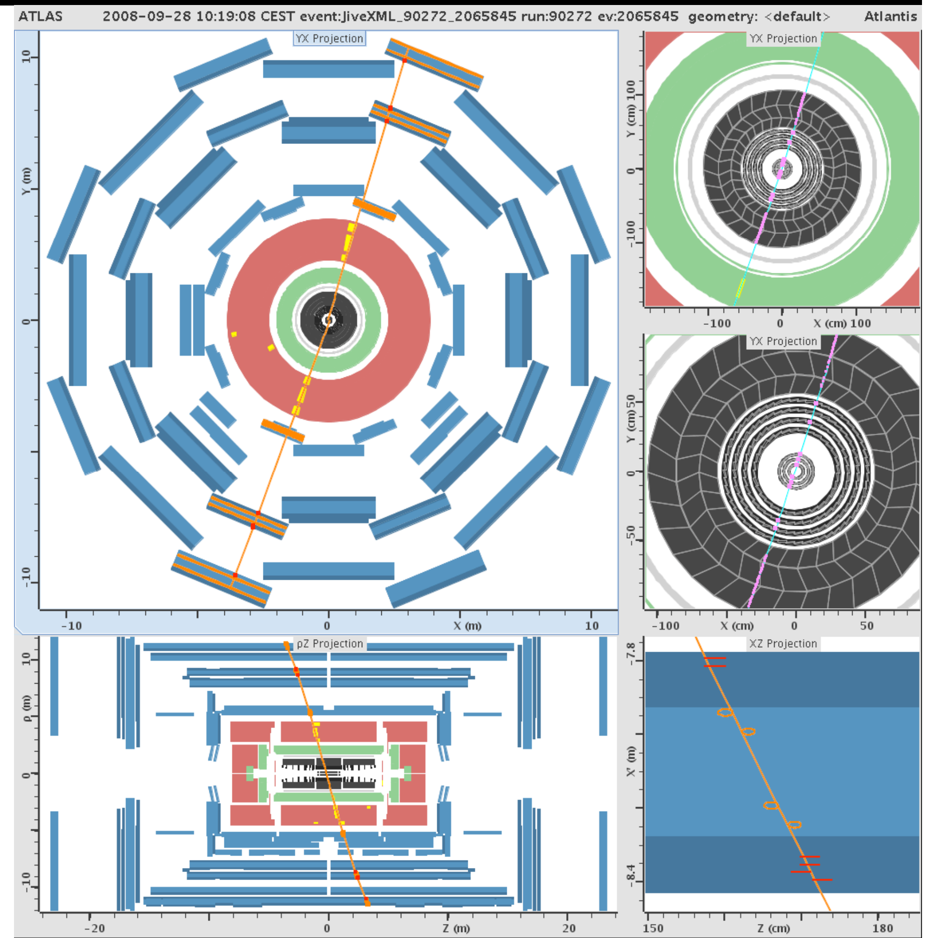
- Might be produced if the effective Planck scale is low due to Extra Dimensions
- Cross section could be large but is very uncertain
  - Here: $\hat{\sigma}_{ab\to \mathrm{BH}} = \pi r_{\mathrm{h}}^2$
  - r_h ≈Schwarzschild radius
- Evaporate via Hawking radiation
  - High multiplicity events
- Discovery possible for low luminosity



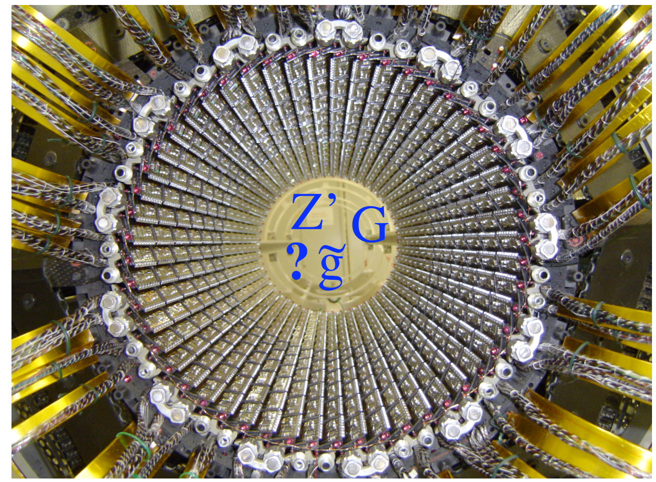


Conclusions

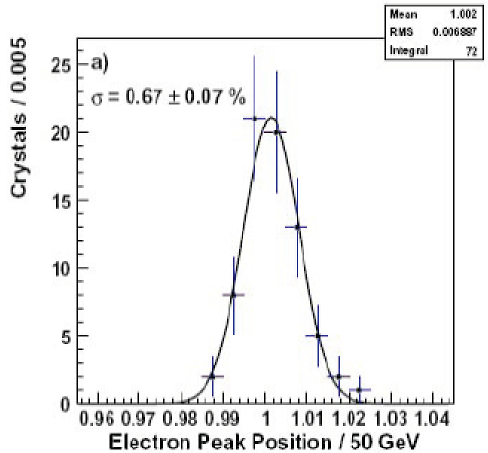
- **LHC probes new physics beyond the Tevatron with 500 pb^{-1}, e.g.**
  - gluinos at m~500-1000 GeV
  - Z'/KKG at m~1-1.5 TeV
  - ….
- **Let's hope**
  - There is new physics to be discovered
  - The beam comes soon
    - At $\sqrt{s}$= 10 TeV cross sections are about 50% lower
  - The detectors work well
    - Ongoing commissioning with cosmic rays very useful!



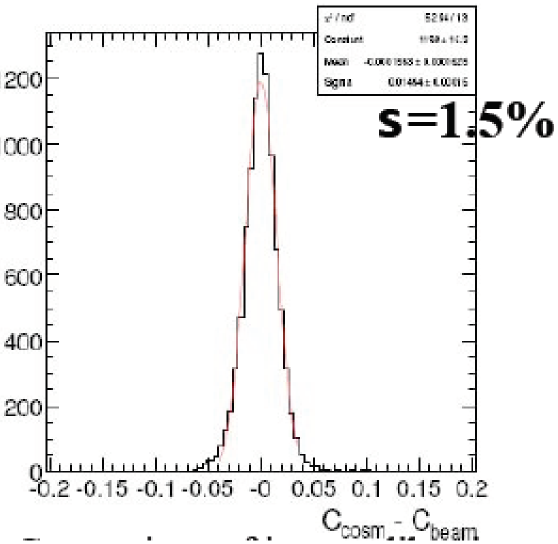
[redacted]

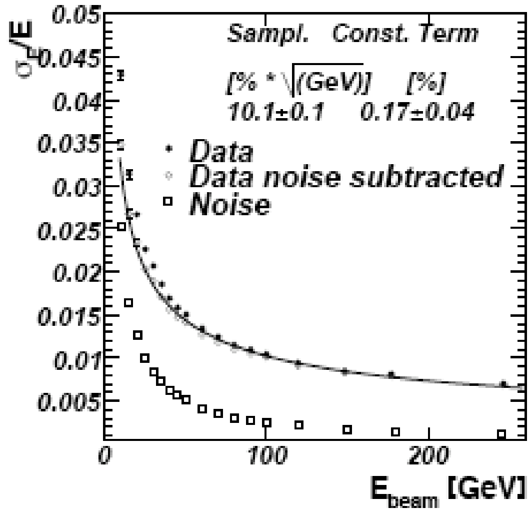


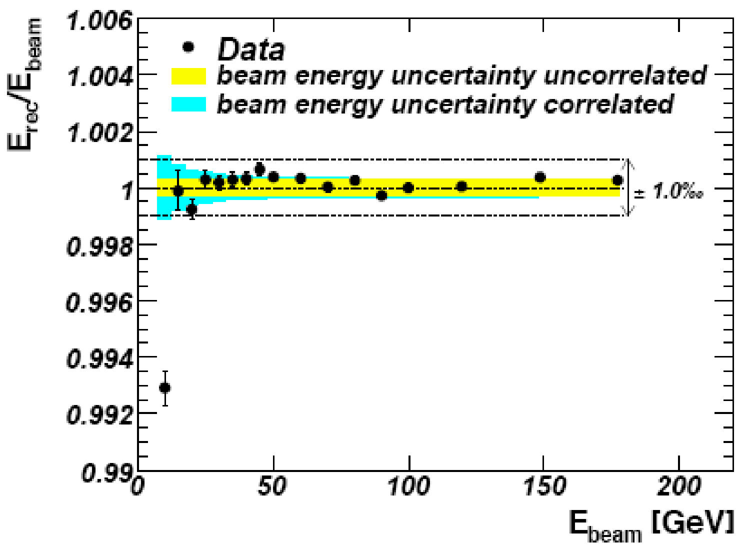
Test Beam + No Beam Results

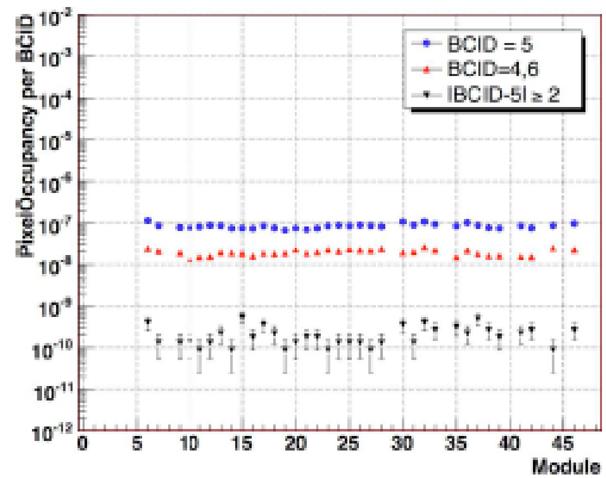


50 GeV electrons



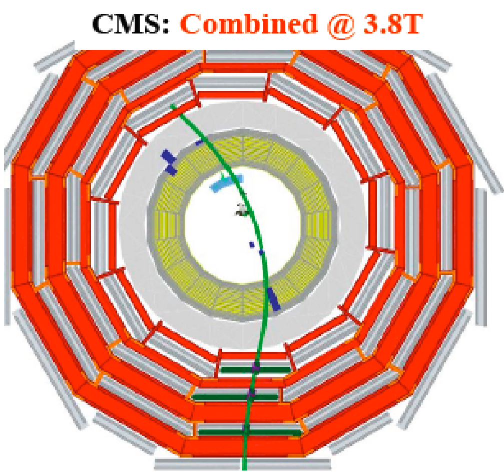


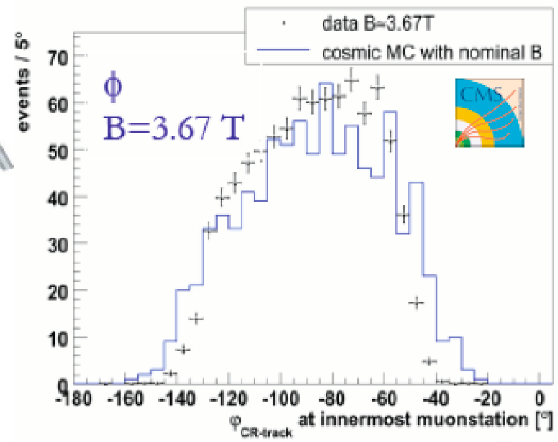


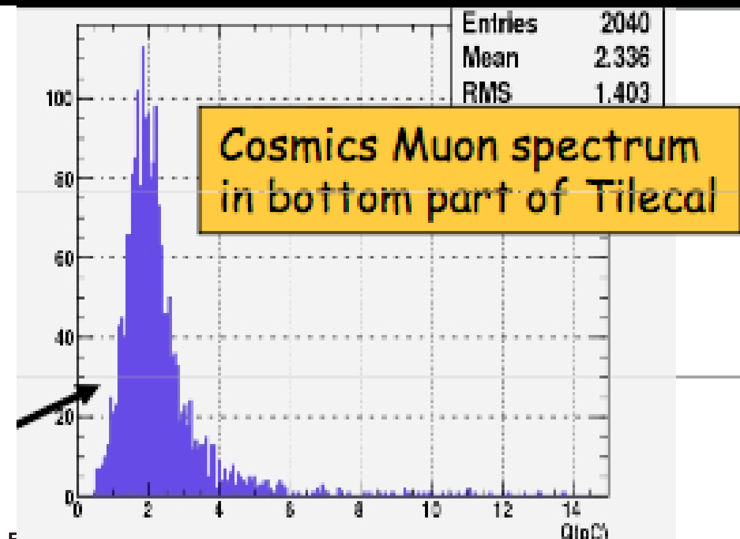


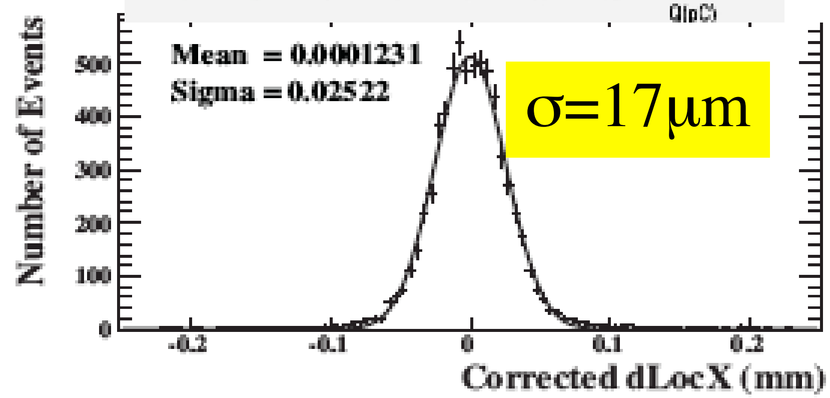
Wonderful detectors have been built!

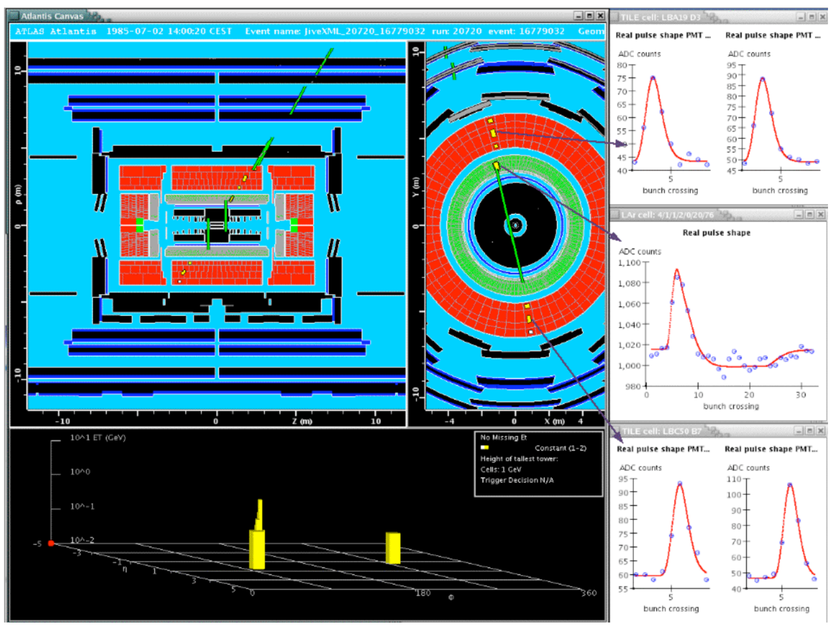
Cosmic Muon Data











Gain also quantitative understanding:
- e.g. alignment of tracking detectors
- e.g. MIP signal in calorimeters

A Typical Sparticle Mass Spectrum

- **Squarks/gluinos**
  - Biggest increase in cross section w.r.t Tevatron
  - Jets+ET (+leptons) signature
- **Gauginos**, **sleptons**
  - No large increase w.r.t. Tevatron
  - May be important if squarks/gluinos very heavy