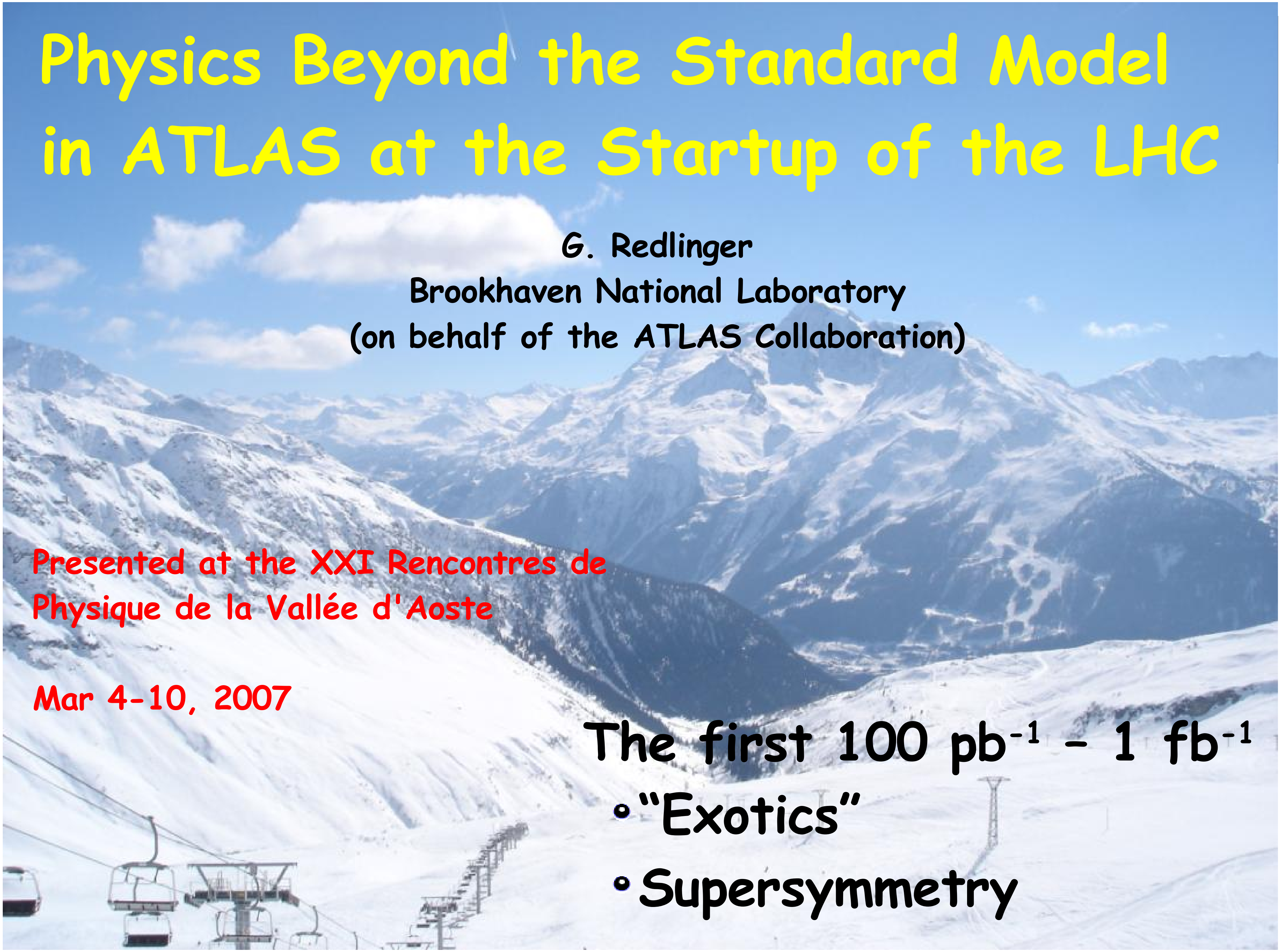


Physics Beyond the Standard Model in ATLAS at the Startup of the LHC

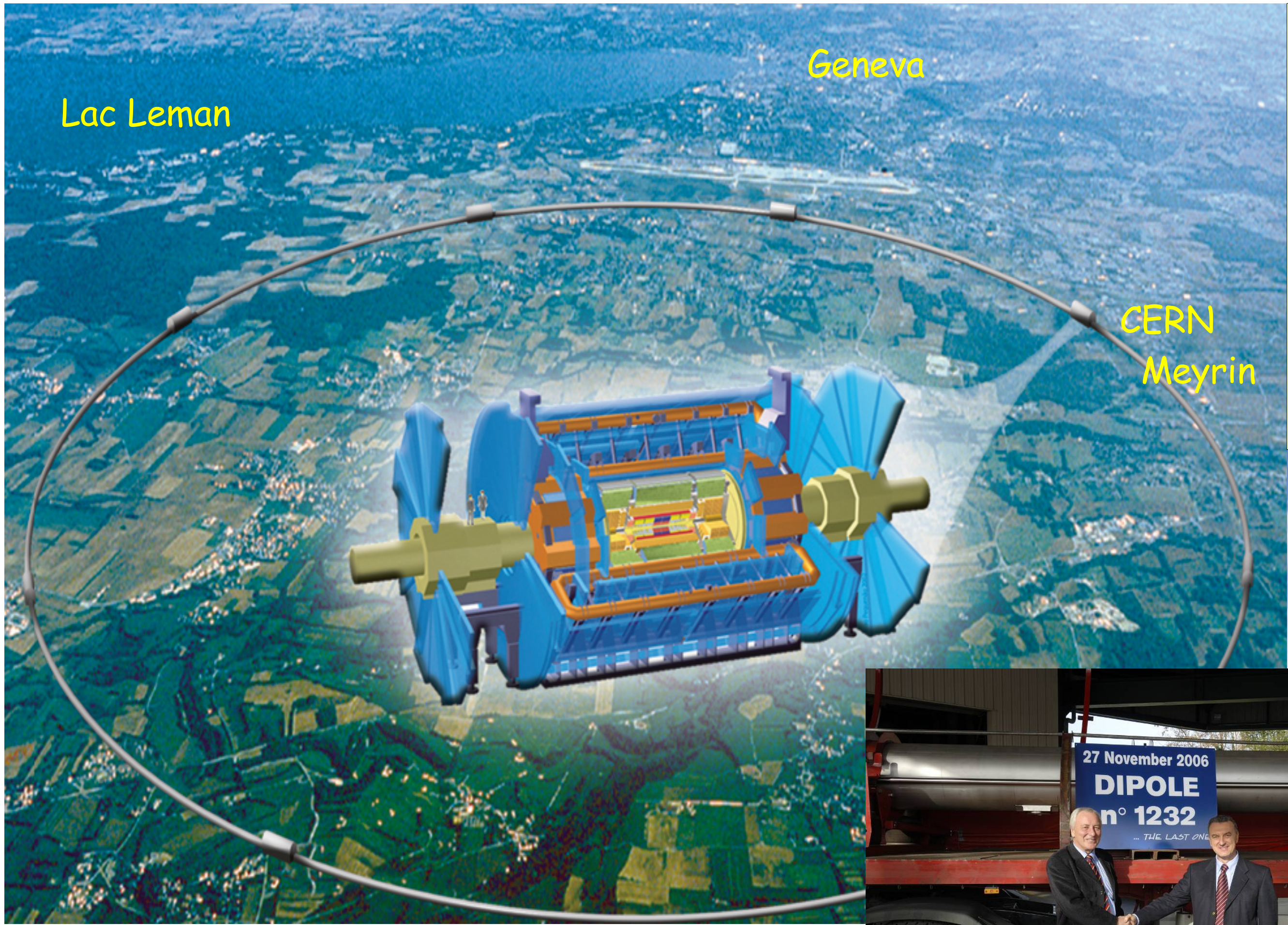
G. Redlinger
Brookhaven National Laboratory
(on behalf of the ATLAS Collaboration)

Presented at the XXI Rencontres de Physique de la Vallée d'Aoste

Mar 4-10, 2007

The first 100 pb^{-1} – 1 fb^{-1}

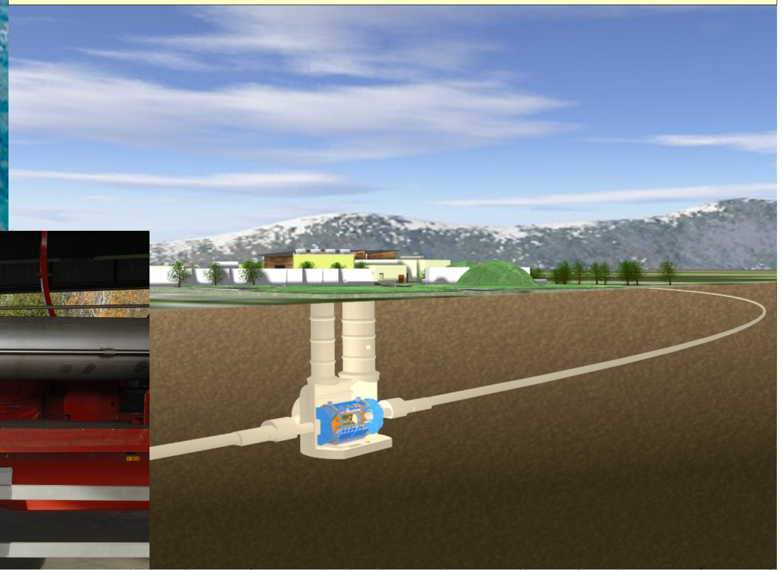
- "Exotics"
- Supersymmetry



pp collisions at $\sqrt{s}$ = 14 TeV

Design luminosity
10^{34} cm^{-2} sec^{-1}

(25ns between bunches)



End magnet delivery	**November 2006**
End installation	**April 2007**
Ring closure	**August 2007**
First beam (450+450 GeV)	**November 2007**
First physics run (14 TeV)	**Summer 2008**

[Evans 07] (Full references in last slide)

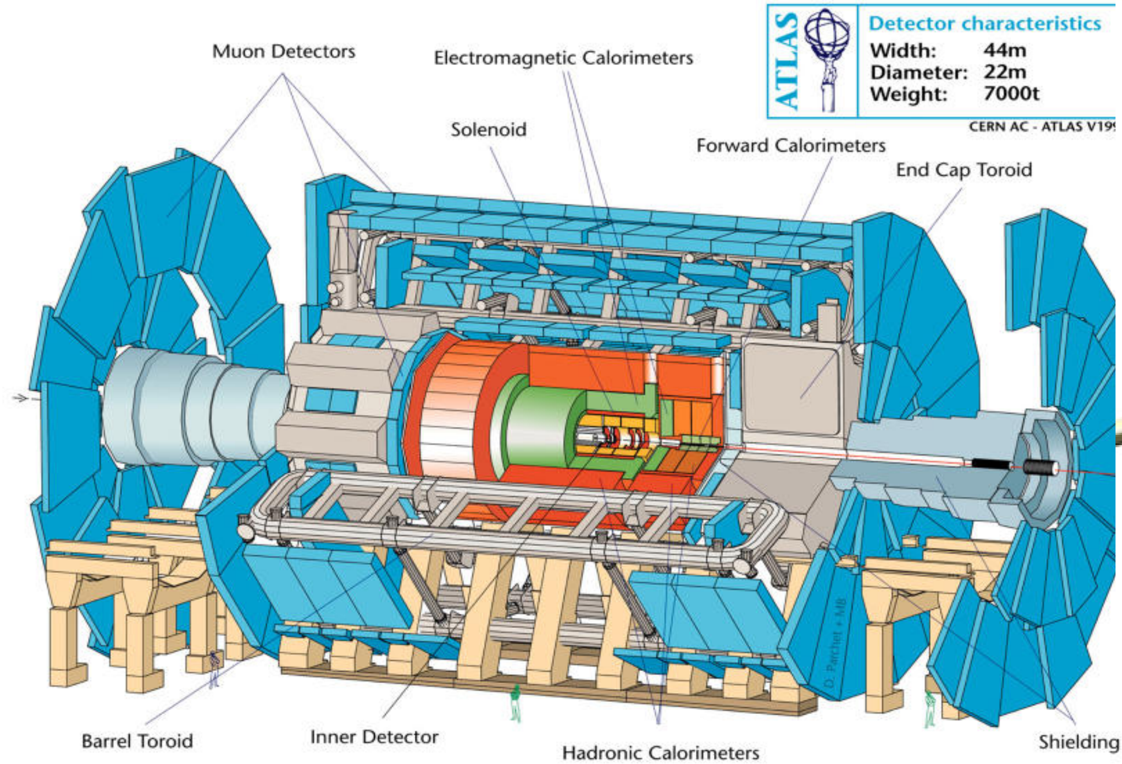
COUNTDOWN FOR TERMINATION

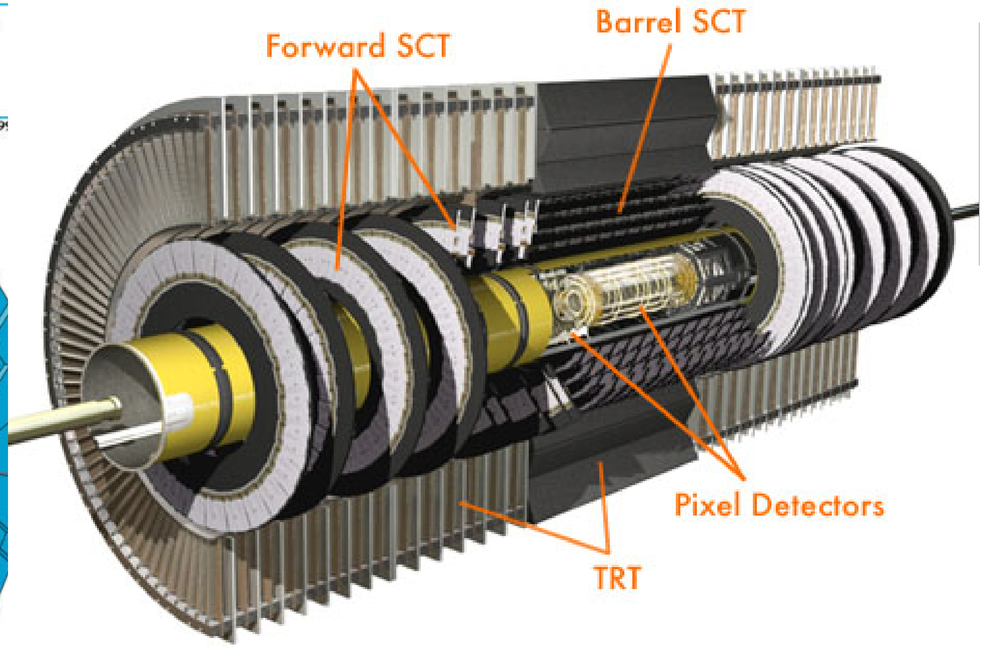
MAGNETS still to be tested FOR LHC LATTICE completion

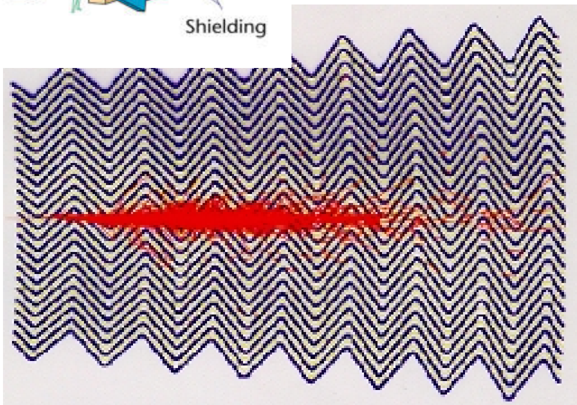
	DIPOLES (1232)	ARC SSS (360)	IR-SSS: 500 SERIES (32)	IR-SSS: 600 SERIES (82)
UPDATED ON	REPAIRED SUBSTITUTES INCLUDED'	REPAIRED SUBSTITUTES INCLUDED'		REPAIRED SUBSTITUTES INCLUDED'
19-Feb-07	1	0	0	0

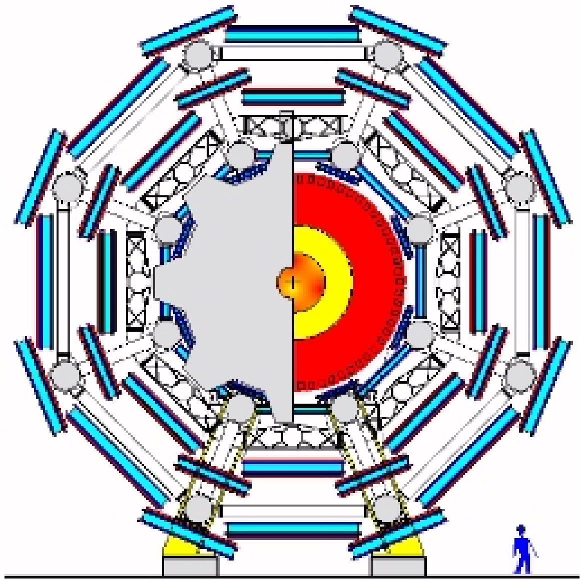
DAYS FROM CERN RE-OPENING 8-Jan-07	REMAINING MAGNETS FOR LHC LATTICE COMPLETION
41	1

http://lhc.web.cern.ch/lhc/









ID: $\sigma/p_T \approx 5\times10^{-4}\, p_T \oplus 0.001$

$\sigma(d_0)$=15μm at 20GeV

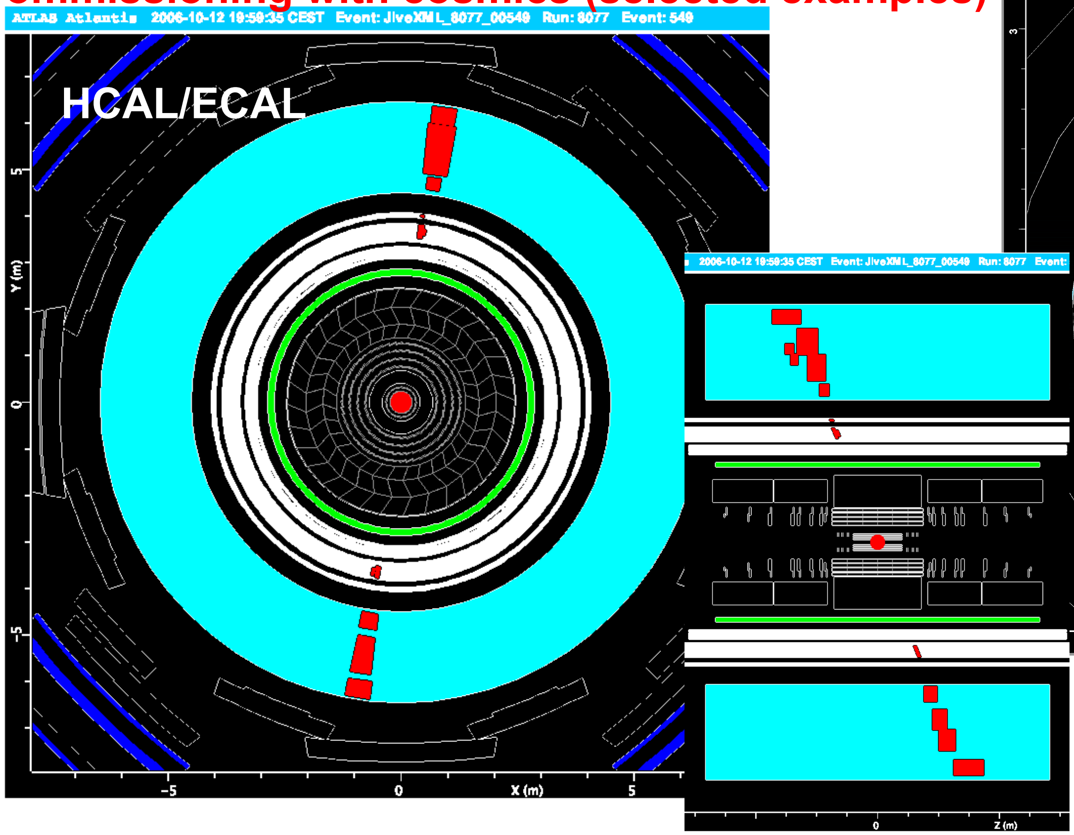
ECAL: $\sigma/E \approx 10\%/\sqrt{E(\mathrm{GeV})} \oplus 0.7\%$

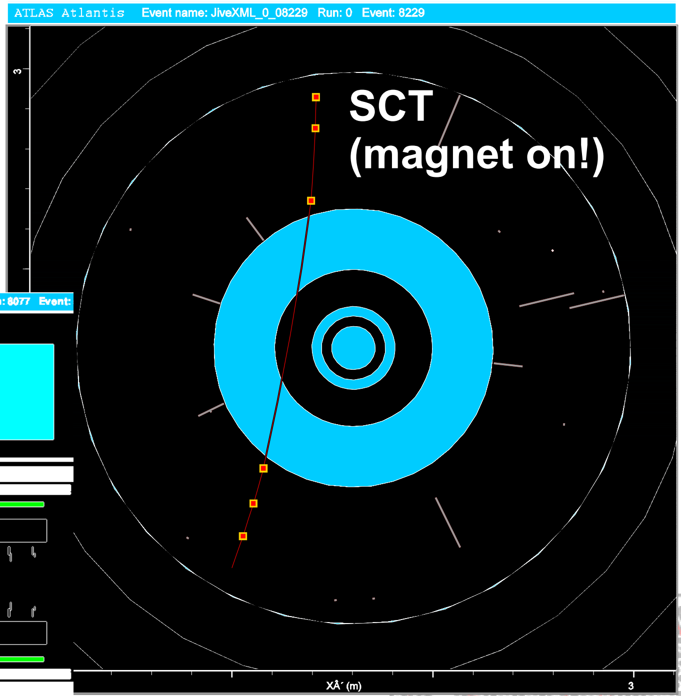
HCAL: $\sigma/E \approx 50\% / \sqrt{E(\mathrm{GeV})} \oplus 3\%$

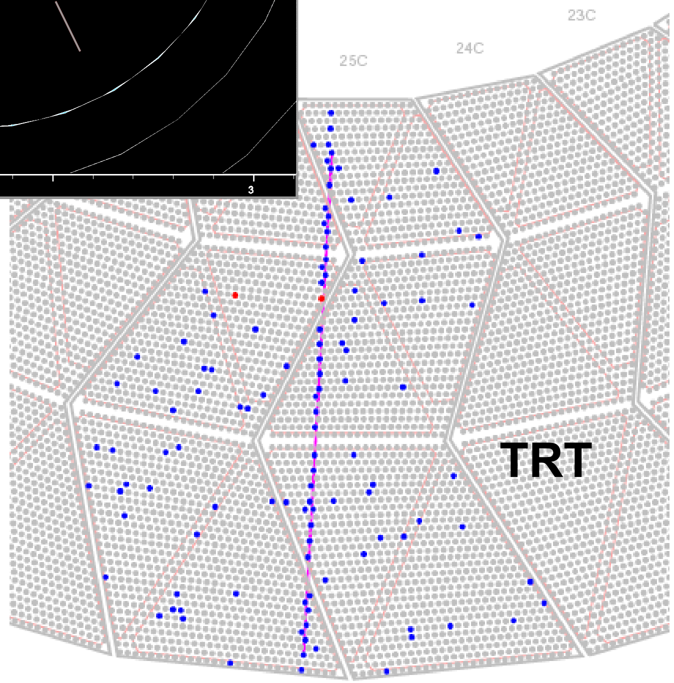
Muon: $\sigma/p_T \approx 10\%$ at 1 TeV/c

Detector Commissioning

Commissioning with cosmics (selected examples)





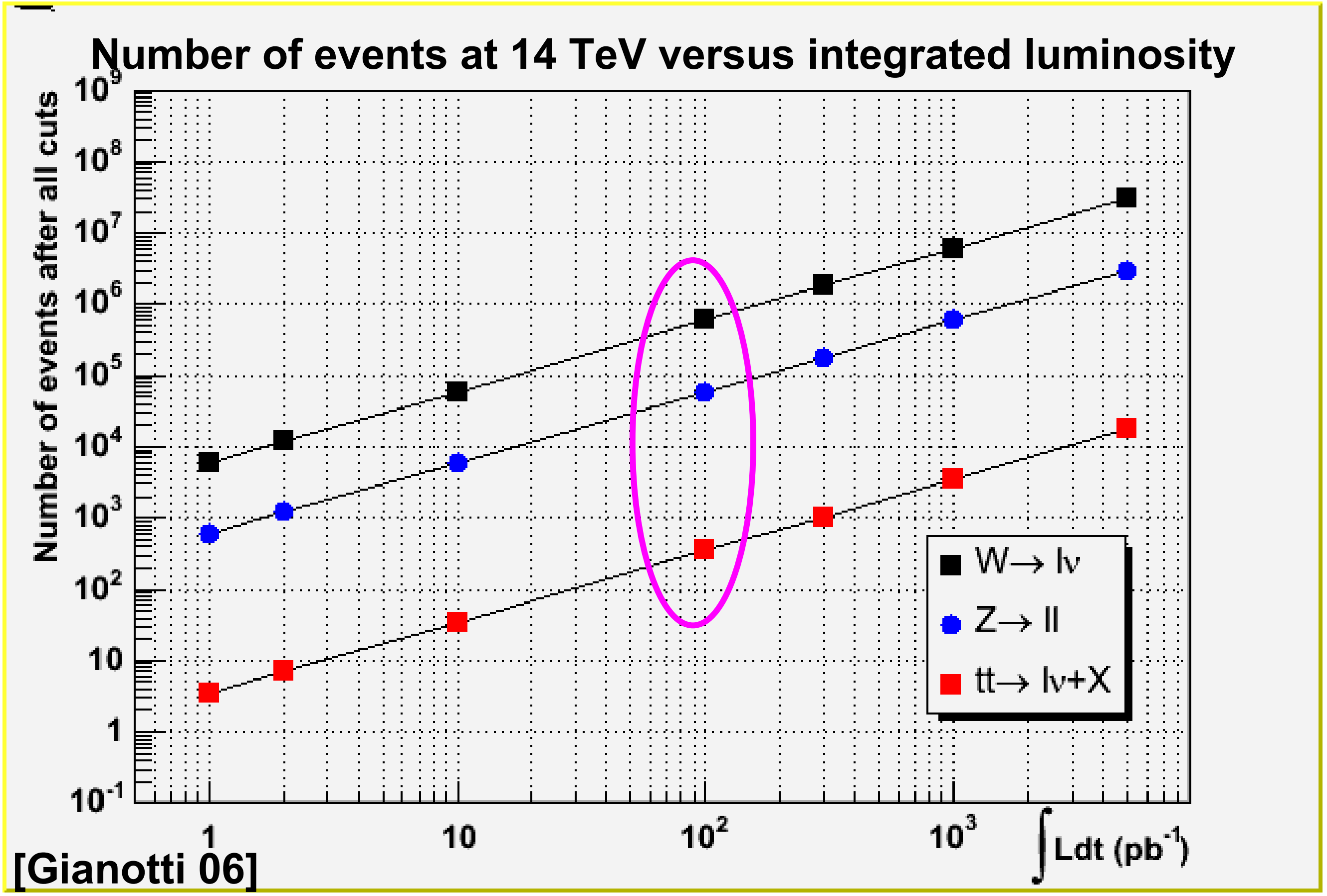


Guess at ATLAS "day 1 performance" [Gianotti 06]

ECAL uniformity	~ 1%
e/gamma scale	~ 2%
HCAL uniformity	~ 3%
Jet scale	< 10%
Tracker alignment	20-200 μm in rφ

"Standard candles"

Standard candles at the LHC are W/Z and (lesser extent) top. These provide basis for absolute calibration of the detector....



$l \equiv e$ or μ

Assumed selection efficiency:
$W \to l\nu$, $Z \to ll$: 20%
$tt \to l\nu+X$: 1.5% (no b-tag, inside mass bin)

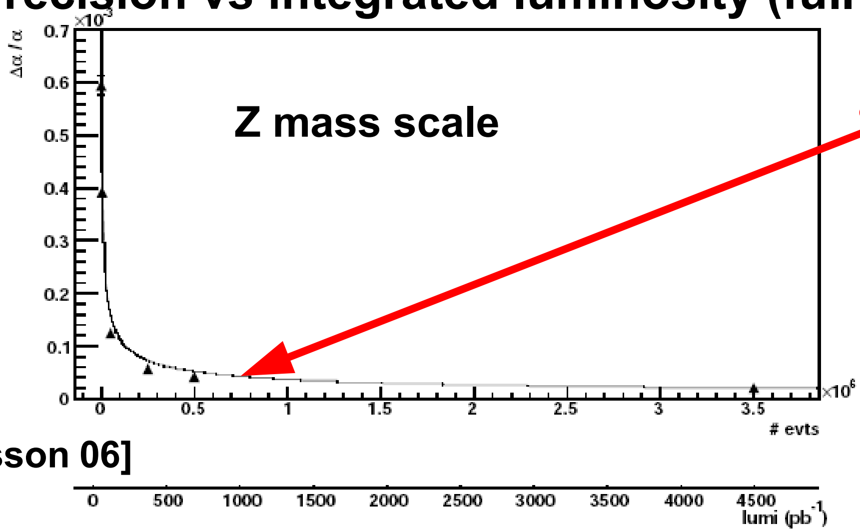
+ lots of minimum-bias and jets (10^{7} events in 2 weeks of data taking if 20% of trigger bandwidth allocated)

... in conjunction with various techniques to extend the calibrations to other objects, energies: pt balance (Z+jet, gamma+jet, jet+jet), W+jet, isolated tracks (low lumi), inclusive leptons, ...

EM energy scale/resolution from Z→ee

Fit Z mass distribution to MC templates. Both electrons $|\eta| < 2.5$, pt > 20 GeV

Precision vs integrated luminosity (full simulation)



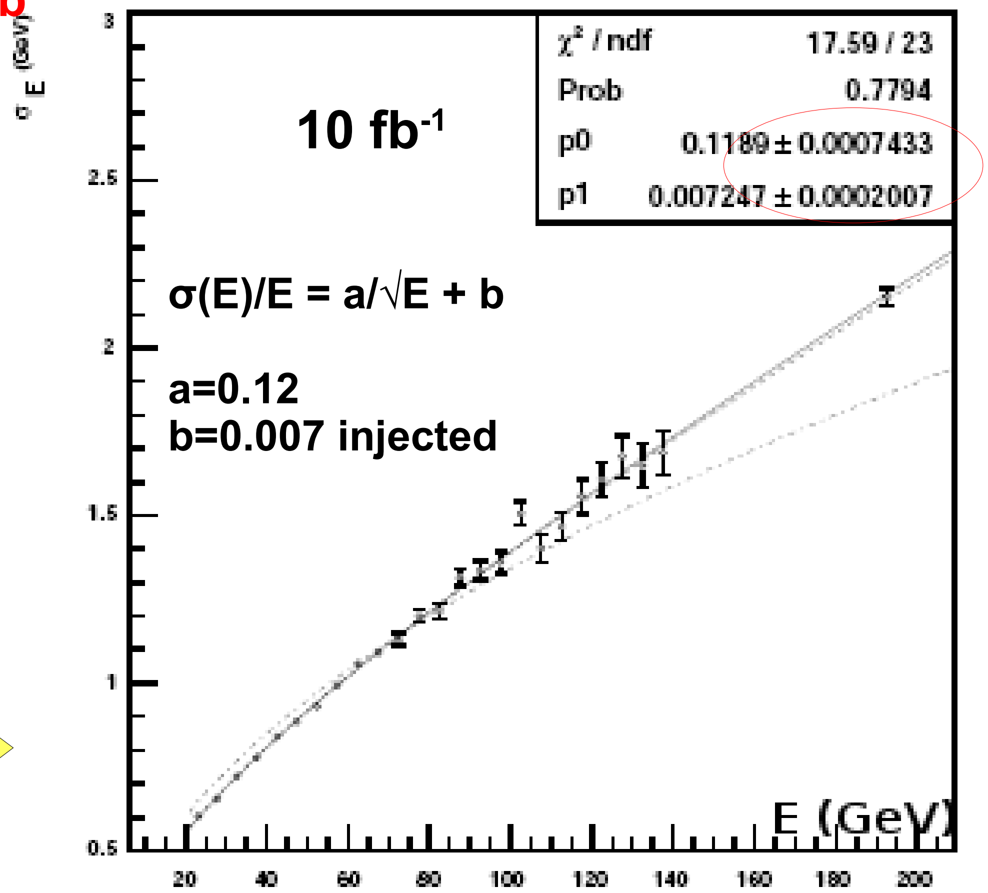
[Besson 06]

Relative precision on Z mass scale ≈ $4 \cdot 10^{-5}$ after 1 fb^{-1}

Energy-dependent analysis (fast sim only):

Relative precision (statistical) on electron energy resolution after 10 fb^{-1}:

- **Stochastic term 0.6%**
- **Constant term 3%**



Physics of first 100 pb^{-1}

ATLAS Physics TDR dates from 1999

- Getting a bit old
- Emphasis on “ultimate” physics reach

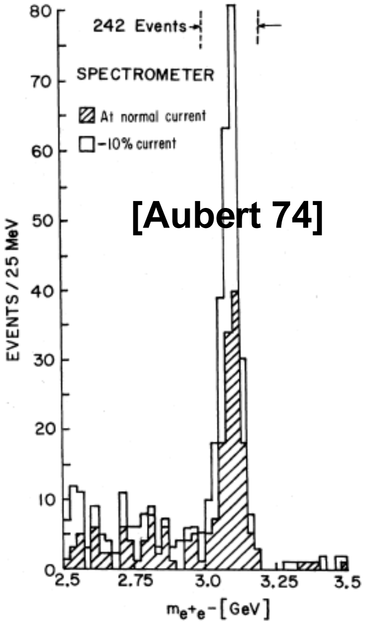
Now in the process of updating these estimates (so-called “CSC”) and preparing/exercising tools for data analysis

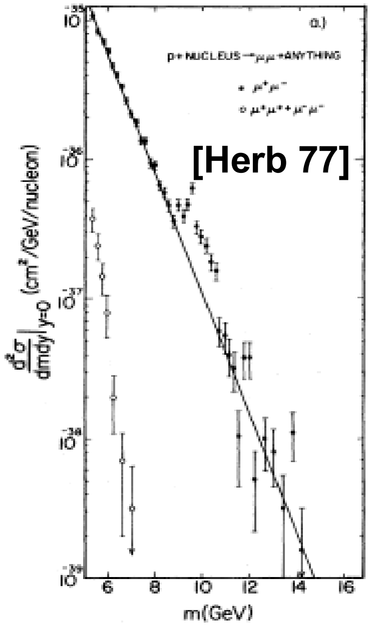
- Updated event generators
- Full GEANT detector simulation, more detailed geometry
- Focused on early physics scenarios $\int L\,dt \approx (0.1 \rightarrow 1)\ fb^{-1}$
- Initial results around May of this year, hoping to complete in the summer

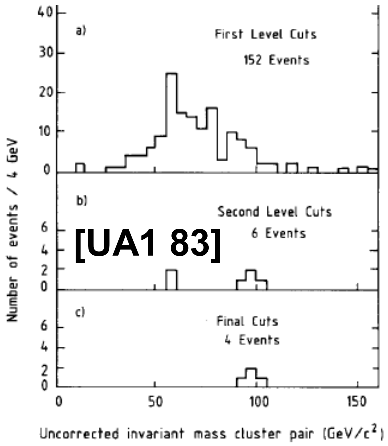
Concentrate here on a very few topics from “exotics” and SUSY (gluino/squark)

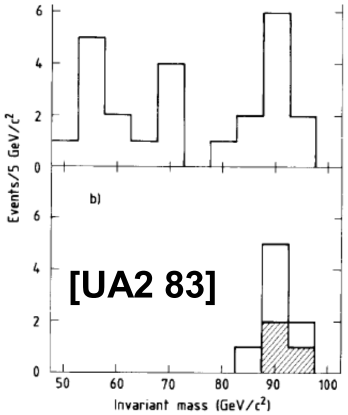
$\ell^+ \ell^-$ resonances

Historically, dilepton resonances have been key in understanding new physics.



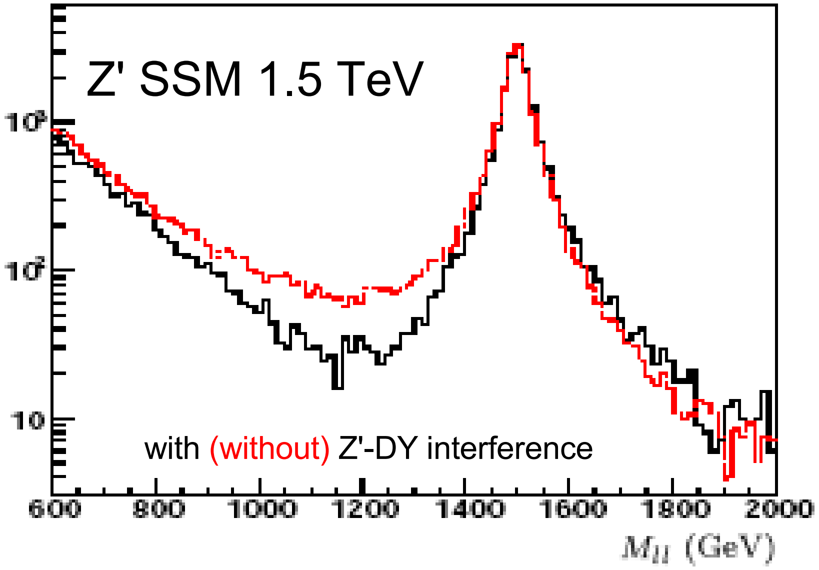






Today, dilepton resonances arise in many BSM scenarios such as:

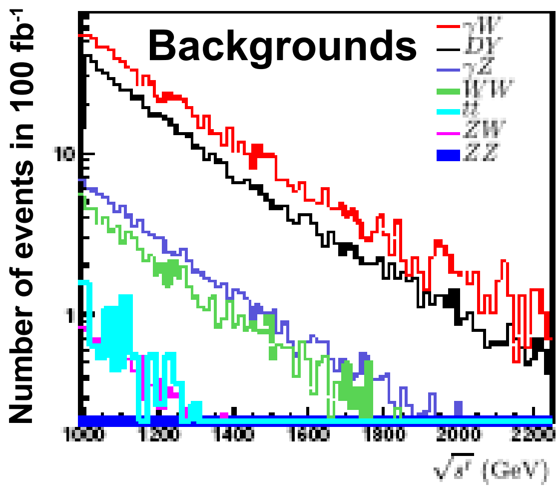
- Z' gauge boson from extended symmetry (GUTs)
- Z_H in Little Higgs models
- Kaluza-Klein excitation of
  - gauge boson (extra dimensions)
  - graviton (Randall-Sundrum)
- ...



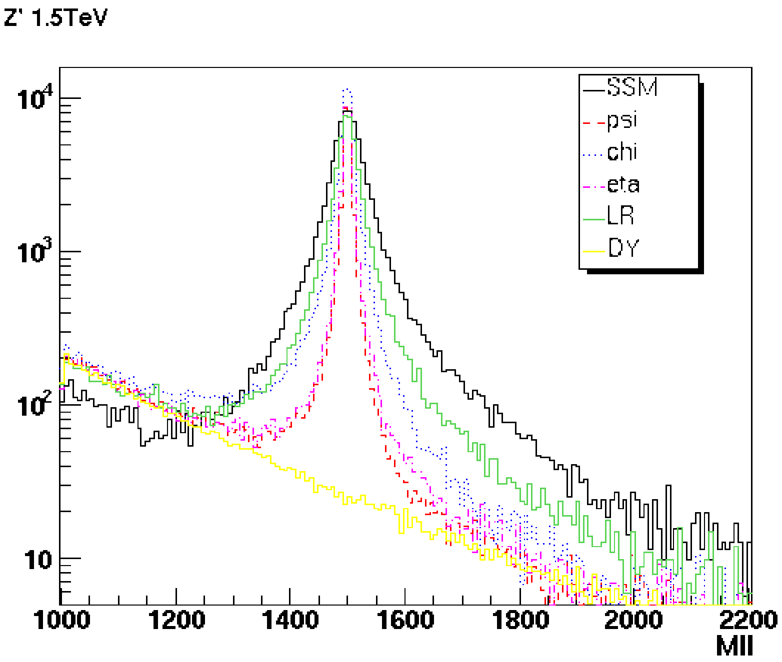
$\ell^+ \ell^-$ resonances (2)

Some general comments:

Drell-Yan is main background, and falls with M_{ee}
< 1 event for M=1.5 TeV in 1 fb^{-1}



Signal: typical benchmark is Z' with SM couplings
σ * BR(ee) ~ 160 fb for M=1.5 TeV
efficiency ~50% both electrons reco in |η| < 2.5
~80 events in 1 fb^{-1}



[Willocq 06]

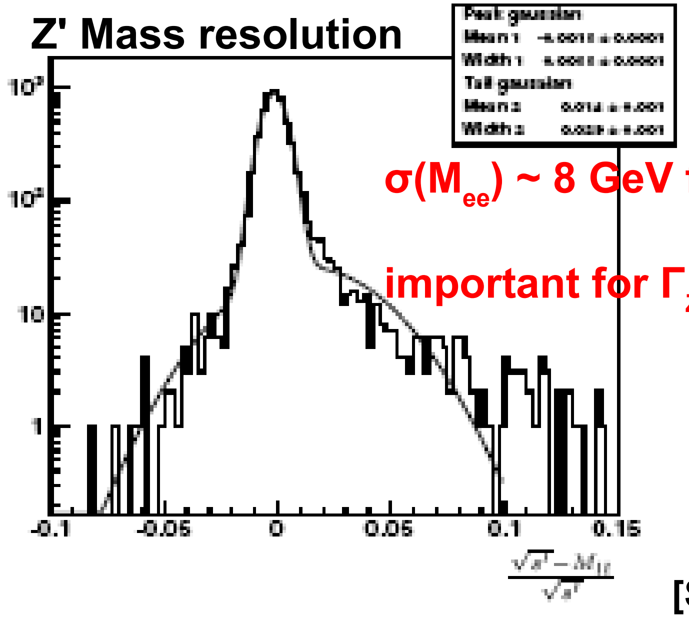
Z' width gives first handle on model discrimination

Ultimate mass reach ~ 5 TeV for Z'(SSM) with 100 fb^{-1}

$\ell^+ \ell^-$ resonances (3)

Measurements after discovery
- Distinguish between models via:
  - $\sigma \cdot \Gamma_{\ell\ell}$
  - Forward-backward asymmetry
- Measure spin
- Measure couplings

Z' Mass resolution

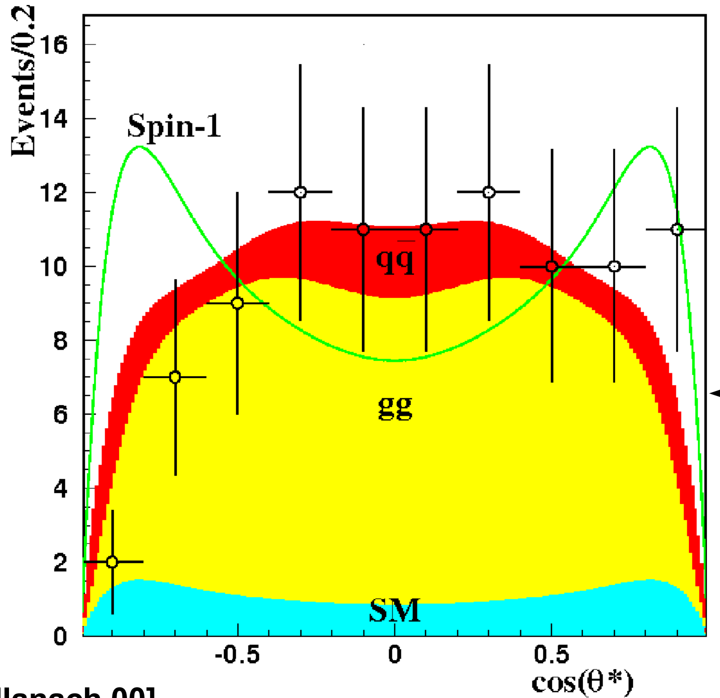


$\sigma(M_{ee})$ ~ 8 GeV for 1.5 TeV Z'

important for Γ_Z measurement

[Schaefer 05]

But these will take more time...



[Allanach 00]

Spin measurement via decay angle distribution

~50-100 events needed to distinguish spin-2 RS graviton from spin-1 Z'

Other early searches for 'exotics'

In ATLAS 'Exotics' refers to anything BSM besides SUSY and Higgs (SM, SUSY)

Other resonances...

- **lepton – jet resonances**
  - **Leptoquarks**
  - **R-parity violating SUSY**
  - **E6-inspired exotic quarks → W or Z + jet**
  - **Heavy leptons → W or Z + lepton**
- **lepton – MET resonances**
  - **W' gauge bosons**
  - **W_H Little Higgs**
- **photon-jet or photon-lepton resonances**
  - **excited quarks**
  - **excited leptons**

... and spectacular signatures such as many high pt leptons and jets

- **microscopic black holes from extra-dimensional models**

Searches for excesses in tails will take longer

- **e.g. Drell-Yan tail**
  - **Extra dimensions**
  - **Compositeness**

Early searches for SUSY

SUSY phenomenology is quite rich and can be overwhelming

Early searches rely on fairly general features:

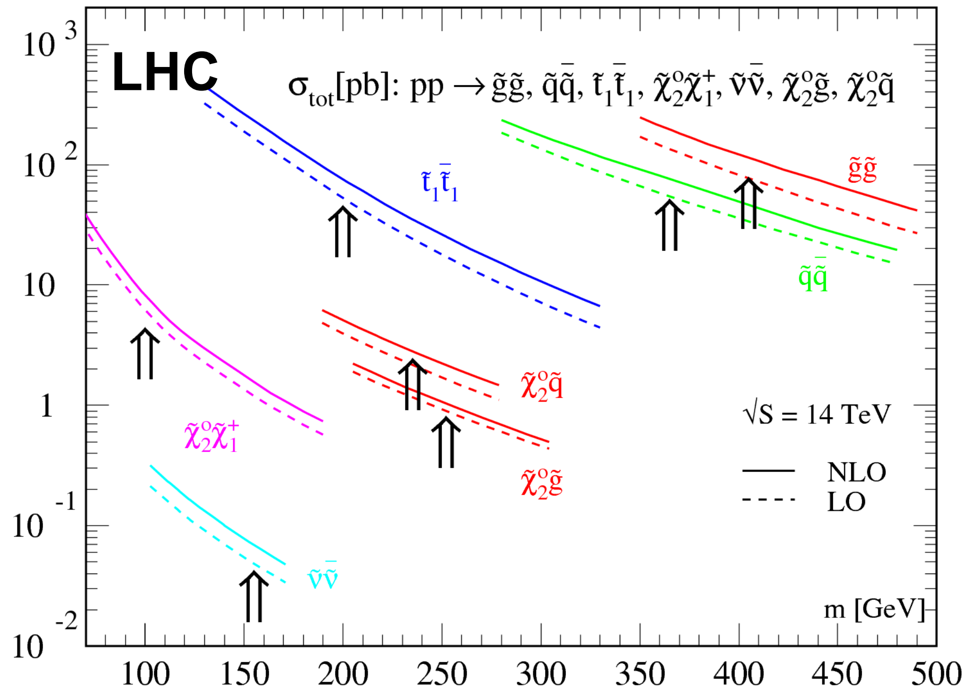
- **gluinos/squarks are produced via the strong interaction**
- **gluinos/squarks are the heaviest sparticles**
- **gluino/squark decays give rise to (energetic) jets**
- **neutralinos/charginos often decay via emission of leptons**
- **LSP is stable (R-parity conservation) and neutral, escaping detector**

Generic signature is therefore:
- **multiple jets, often energetic**
- **possibly some leptons (lower pt)**
- **missing Et**

In the R-parity violating scenario, the LSP decays.
- **If LSP decays outside detector, looks same as R-parity conserving case.**
- **If LSP decays promptly, we lose the missing Et signature. We also lose the feature of providing a candidate for dark matter. But we gain by the possibility of having more leptons or more jets or resonant mass peaks.**

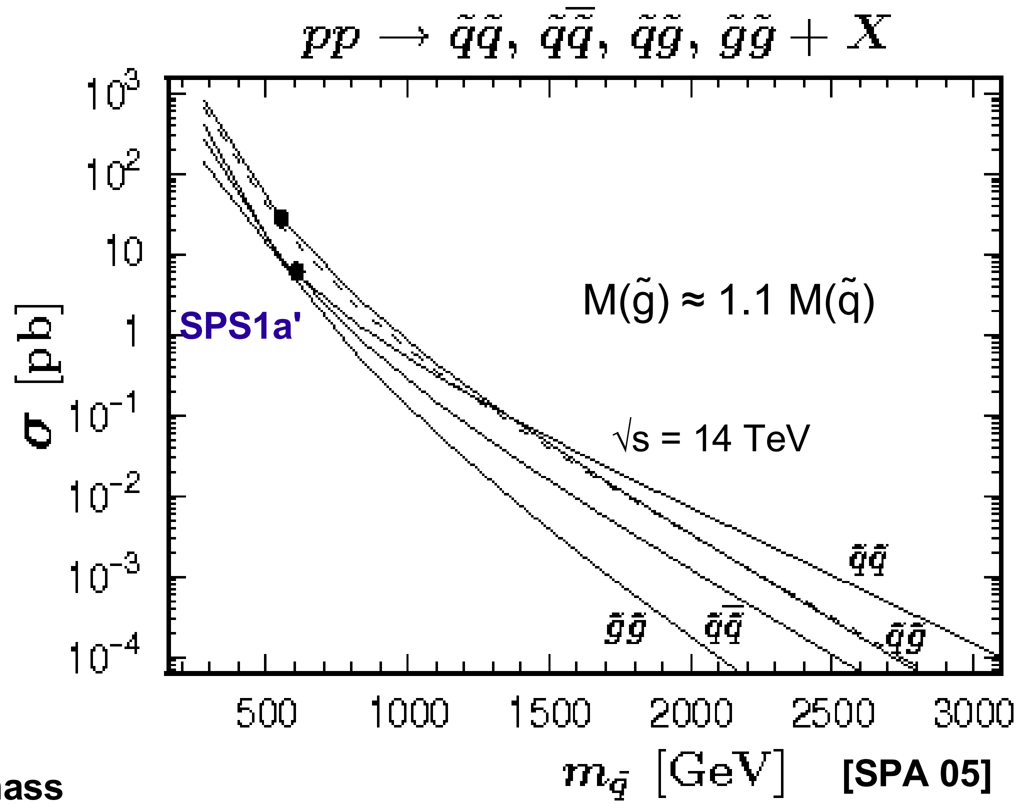
Sparticle production in the MSSM

- Dominated by squark and gluino production at the LHC
  - SUSY QCD - Strong couplings
- Cross sections calculated to NLO, typically in the pb range (depends on masses)
  - Masses depend on how SUSY is broken
  - But otherwise, cross section is model-independent



[Prospino]

average particle mass



[SPA 05]

SUSY studies in ATLAS

Most studies in ATLAS done in the context of Minimal Supersymmetric SM (MSSM) with R-parity conservation

SUSY breaking scenarios:

- mSUGRA - minimal SuperGravity (most studied)
- GMSB - Gauge Mediated SUSY Breaking
- AMSB - Anomaly Mediated SUSY Breaking

Can choose to apply constraints from relic dark matter density

Our strategy so far:

- Full detector simulations at selected points consistent with DM constraints and spanning different signatures
- Scans of parameter space with fast detector simulation
- Studies of “unusual” signatures:
  - Long-lived stau
  - “R-hadron”

Not believing that any of these models is a true description of Nature.
Aim is to cover a broad range of experimental signatures in a self-consistent way

Inclusive searches for SUSY

Large effort focused on inclusive searches for early days of LHC

- Jets + Missing Et + (0,1 or 2) leptons (e,μ)
  - Tau signatures important at large tanβ; under study, but less advanced
- Acoplanar dijets + Missing Et ($\tilde{q}_R \rightarrow q\tilde{\chi}_1^0$)

Emphasis on robust background estimates:

- ttbar, W/Z + jets, QCD multijets

Typical selection cuts (not optimized):

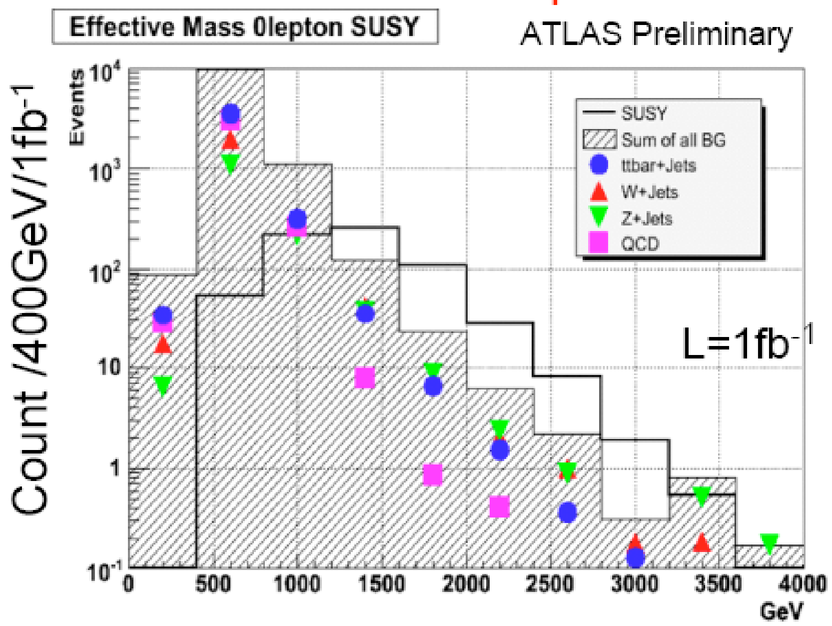
- ≥ 4 jets, leading jet pt > 100 GeV, other jets > 50 GeV
- Missing Et > 100 GeV
- Lepton pt > 15 GeV
- Transverse sphericity > 0.2
- Transverse mass > 100 GeV (1 lepton mode)

Look for excess at large values in HT (HT ≡ ∑pt(jets+leptons)) vs Etmiss plane
(or at large values of Meff = HT + Etmiss)

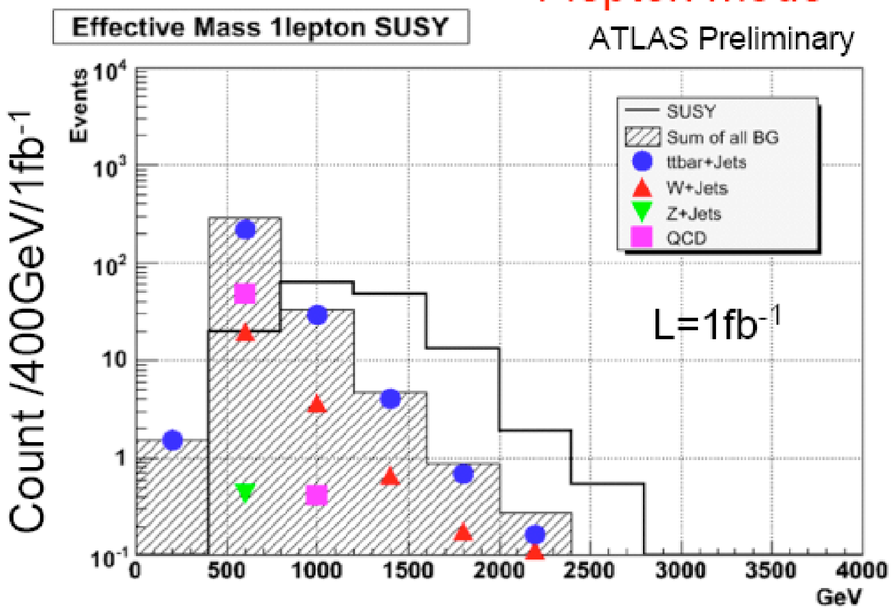
- Meff gives a measure of the gluino/squark mass
  [Hinchliffe 97, Tovey 01]

0 and 1-lepton (e,μ) channels

0 lepton mode



1 lepton mode



Roughly equal BG contributions from ttbar, W+jets, Z+jets

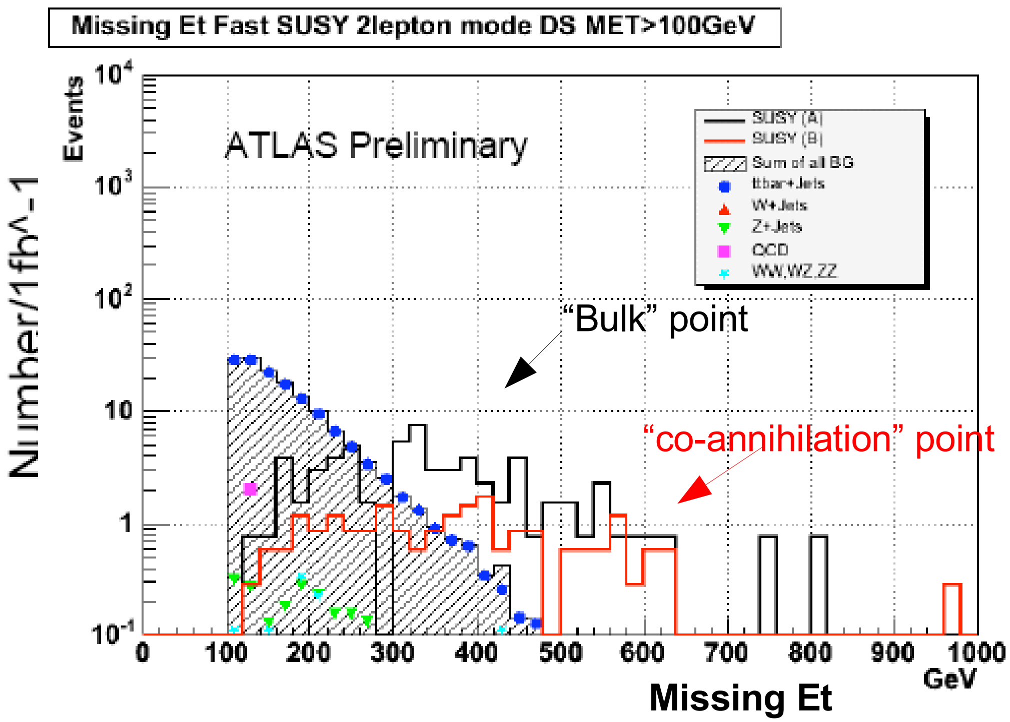
QCD multijet BG (with real or fake Etmiss) also significant; difficult to simulate

Lower statistics but bkg more manageable (mainly ttbar)

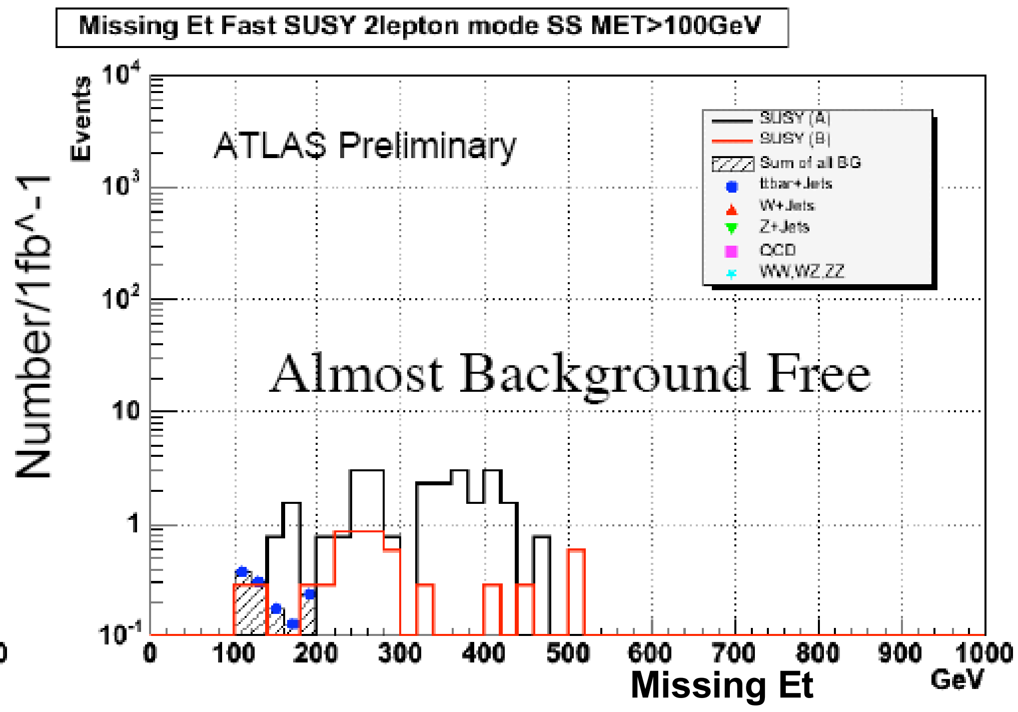
$M(\tilde{g}) \approx M(\tilde{q}) \approx 1$ TeV, $\tan\beta = 10$
Bkg from Alpgen 2.05
"Fast" detector simulation

2 lepton mode

Opposite sign dileptons



Same sign dileptons



Low statistics but potentially clean.

Bkg dominated by tt → bbℓνℓν

$M(\tilde{g}) \approx M(\tilde{q}) \approx 0.9$ TeV

Background estimation

Monte Carlo based

- Early indications are that generator-level uncertainties mainly affect the normalization of backgrounds and not shapes
- Supplement with measurements of cross sections for W/Z+jets, ttbar, QCD multijets
- Systematics of detector simulation? (esp tails for QCD bkg)

"Data driven"

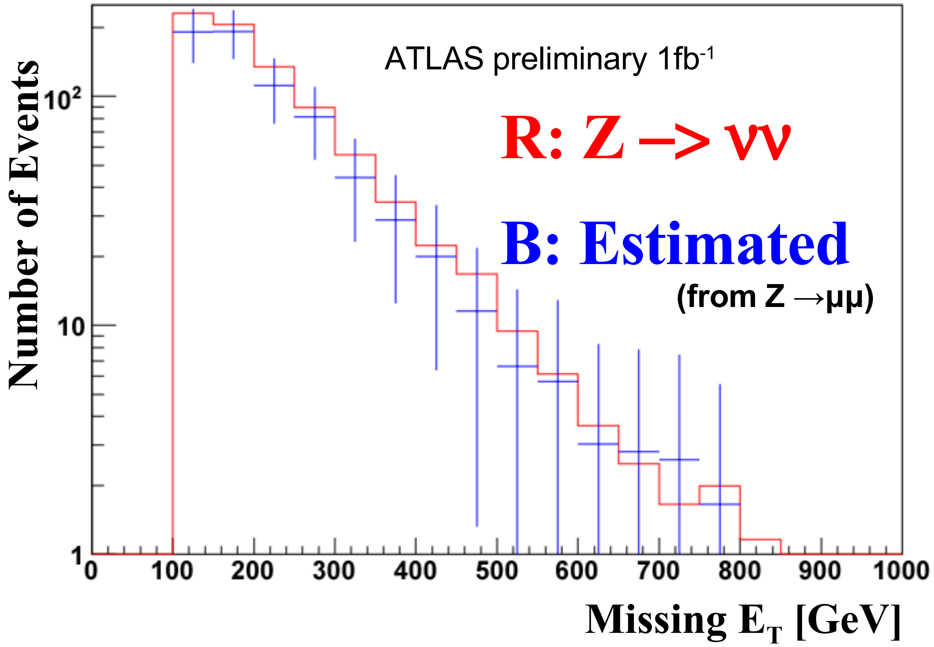
- Isolate the background process of interest, extrapolate into signal region via shapes estimated in some control region
- Isolate process similar to the background process of interest, replace reconstructed objects with MC-generated decays
  - trivial case: replace $Z \to ee$ with $Z \to \nu\nu$
  - harder examples: replace $W \to e\nu$ with $W \to \tau\nu$
    $t \to bjj$ with $t \to b\ell\nu$

Interaction between all methods

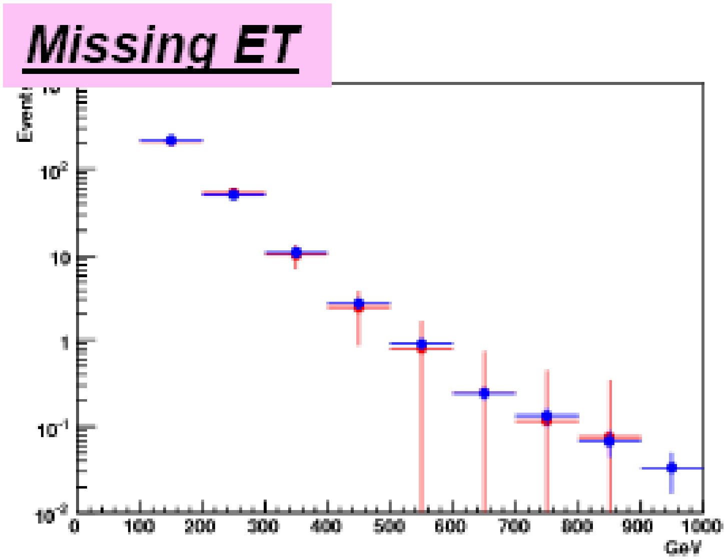
Data-driven background estimation

Examples of data-driven estimations:

0-lepton mode: Z+jets



1-lepton mode: ttbar + W+jets



Works well. Statistics limited
W(μν)+jets as a control sample may also work with higher statistics, but need a handle on contamination from ttbar

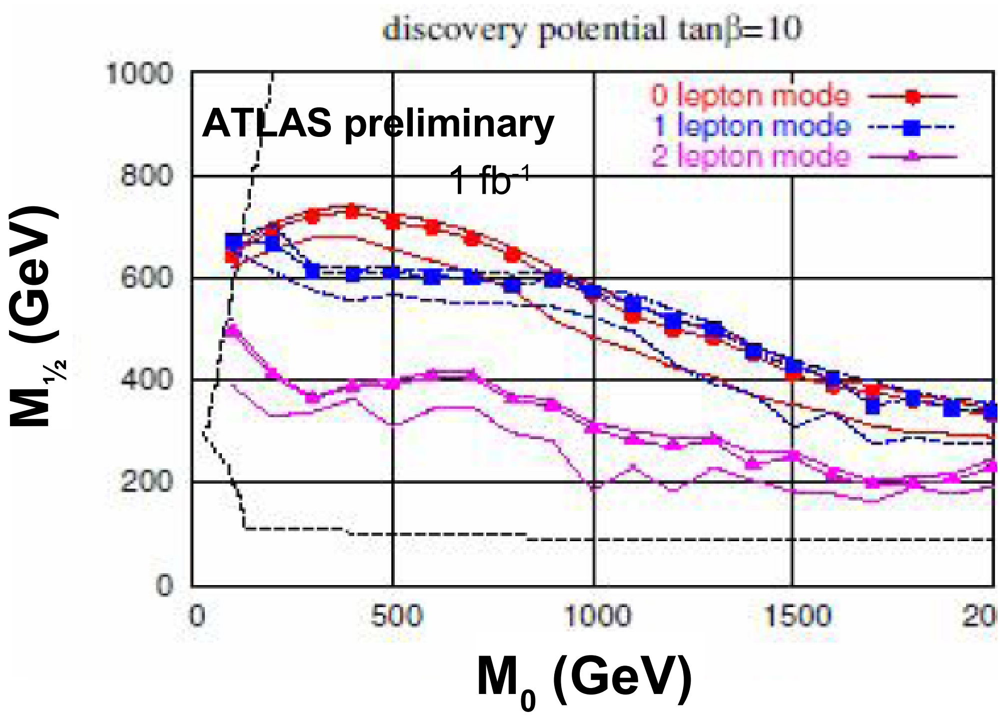
Use same technique for W(τν)+jets?

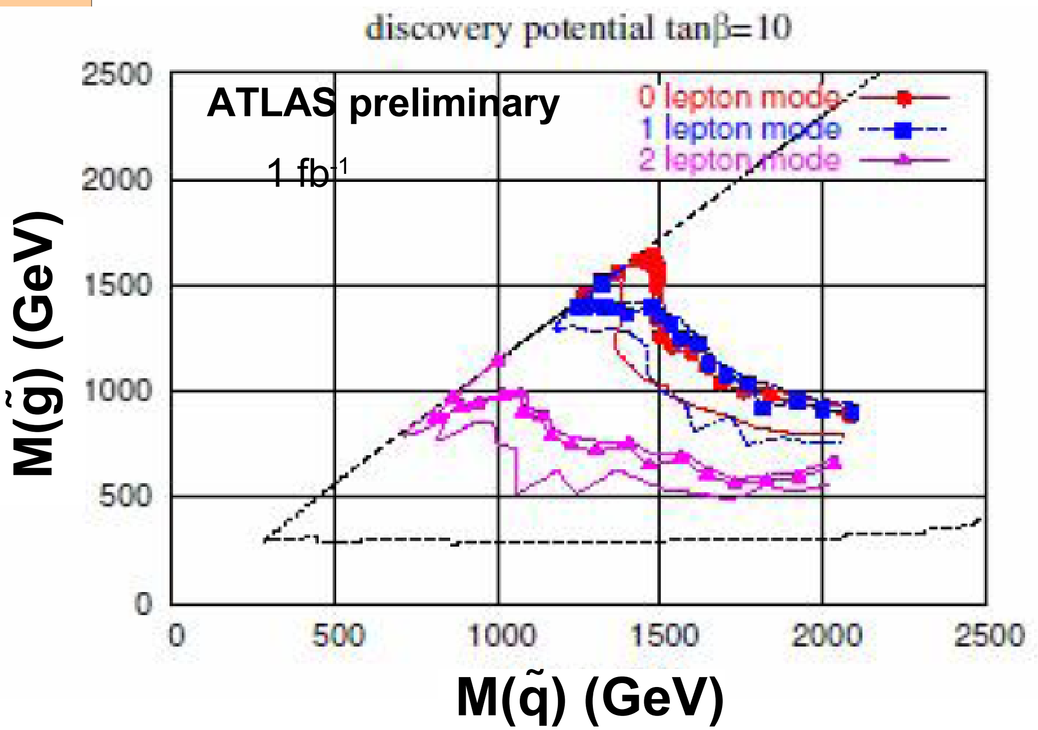
- **Measure MET distribution for sample with M_T < 100 GeV**
- **Normalize to M_T > 100 GeV sample in the region MET=[100,200] GeV**

Discovery potential in mSugra framework

Discovery potential for 1 fb^{-1}
(after optimization of Et_{miss} and Jet pt cuts)

$A_0 = 0, \mu > 0$



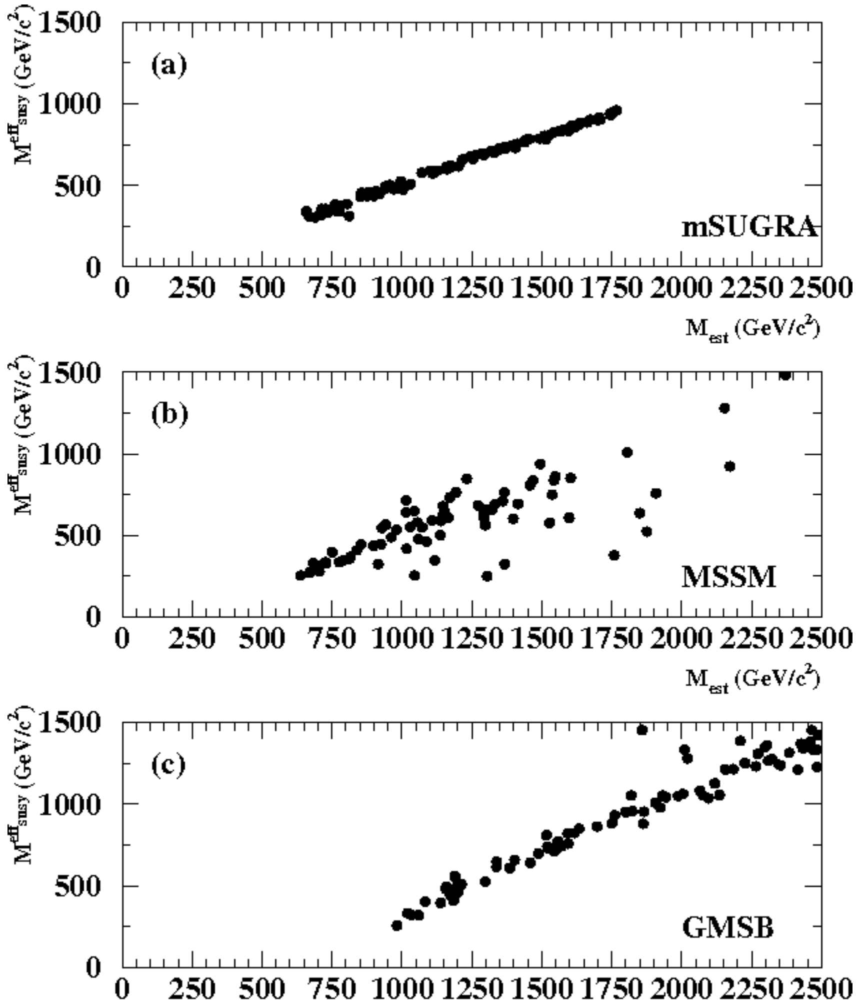


S ≥ 10 and S/√B > 5
2-lepton channel: opposite sign only
Fast simulation.
Generator-level systematic uncertainties included.

Early post-discovery measurements

Discovery of an excess will unfortunately not be a smoking gun for SUSY
However, we can start to extract more information in the SUSY context

- **Yield in different channels**
- **Estimation of the SUSY mass scale** →
- **Searches for exclusive decay modes**



[Tovey 01]

Correlation between effective mass and SUSY mass scale studied in 0 leptons + jets + Etmiss channel

$M_{susy} = \sum_i \sigma_i m_i \,/\, \sum_i \sigma_i$

$M^{eff}_{susy} \equiv M_{susy} - M_\chi^2 / M_{susy}$

$M_{est} = \sum pt(jets) + Etmiss$

~15% (40%) precision on M^{eff}_{susy} after 10 fb^{-1}
for mSugra (cMSSM) models

Conclusion

ATLAS is approaching the installation "end game". Commissioning is well underway. Planning to close the beampipe late summer for commissioning with beam near the end of the year.

First physics run at 14 TeV in summer 2008.

Initial emphasis on understanding detector performance and Standard Model processes

But if we are lucky, there are many possibilities for early (0.1 – 1 fb^{-1}) discovery of BSM physics

Resonances: dilepton, lepton+jet, lepton+MET, lepton+photon, jet+photon, ... ("easy")

Excess riding on long tail will take longer to establish

Supersymmetry

- Establishing a robust background estimation strategy will be the near term focus
- Could start to probe SUSY at the 1 TeV scale in early running with inclusive searches in (0,1, or 2 lepton) + jets + Etmiss channels

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S.Asai, K.Oe, O. Jinnouchi, H.Okawa, N.Kanaya, Y.Tomishima, T.Sasaki, D.Lissauer

Extra material

Brief summary of ATLAS status

Magnets:

- **Barrel solenoid: installed, commissioning complete, B field mapped**
- **Barrel toroid: installed, commissioning complete**
- **Endcap toroids: side A: integration in cryostat completed, ready for installation in April**
  side C: ready for installation May/June

Muon systems:

- **Barrel: 95% of chambers installed, commissioning started**
- **Endcap side C: TGC1 wheel completed, MDT wheel ongoing**
- **Endcap side A: Tooling for TGC1 ongoing**

Calorimeter:

- **Barrel: installation and services completed, LAr cooled down and kept cold, cosmic ray commissioning ongoing**
- **Endcap: mechanical installation complete, services ongoing, LAr side A being cooled down, side C cool down start in March, commissioning started**

Inner detector:

- **Barrel SCT and TRT installed and commissioning**

Beam pipes:

- **ready for installation**

Brief summary of ATLAS status (2)

Counting room electronics:

- **Cabling and electronics installation ongoing**
- **Slow control well advanced**

Trigger and DAQ:

- **Incremental installation started in 2006 and ending (deferred) in 2009**
- **Installation/commissioning of 2006 layer completed**

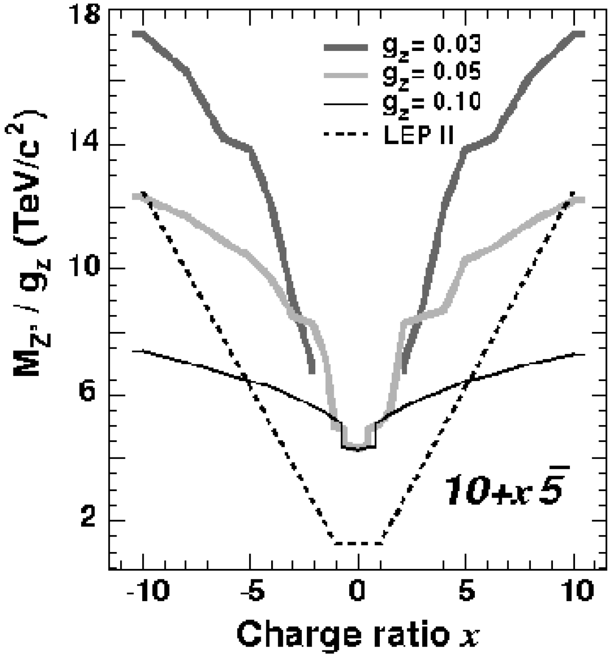
More general Z' (gauge boson) analysis

CDDT [Carena 04] classified Z' models into four families, each specified by
- M(Z')
- gauge coupling
- ratio of U(1) charges

Simple counting analysis in M_{ee}

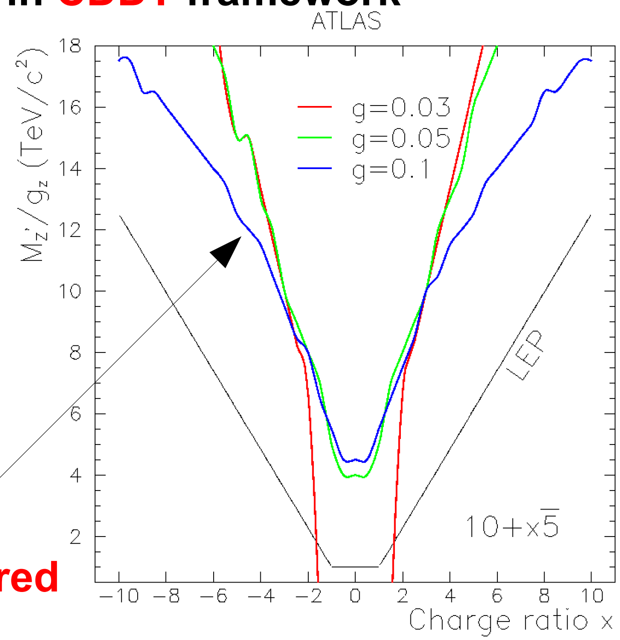
Z' detection efficiency depends mainly on Z' mass
- Symmetric detection in cosθ* reduces model dependence
- Residual model dependence from relative couplings to u/d (via u,d PDF differences)

CDF 95% CL exclusion contours ($\int L\,dt$ = 450 pb^{-1})



[CDF 06]

ATLAS Z' → e^+e^- discovery reach ($\int L\,dt$ = 400 pb^{-1}) in CDDT framework



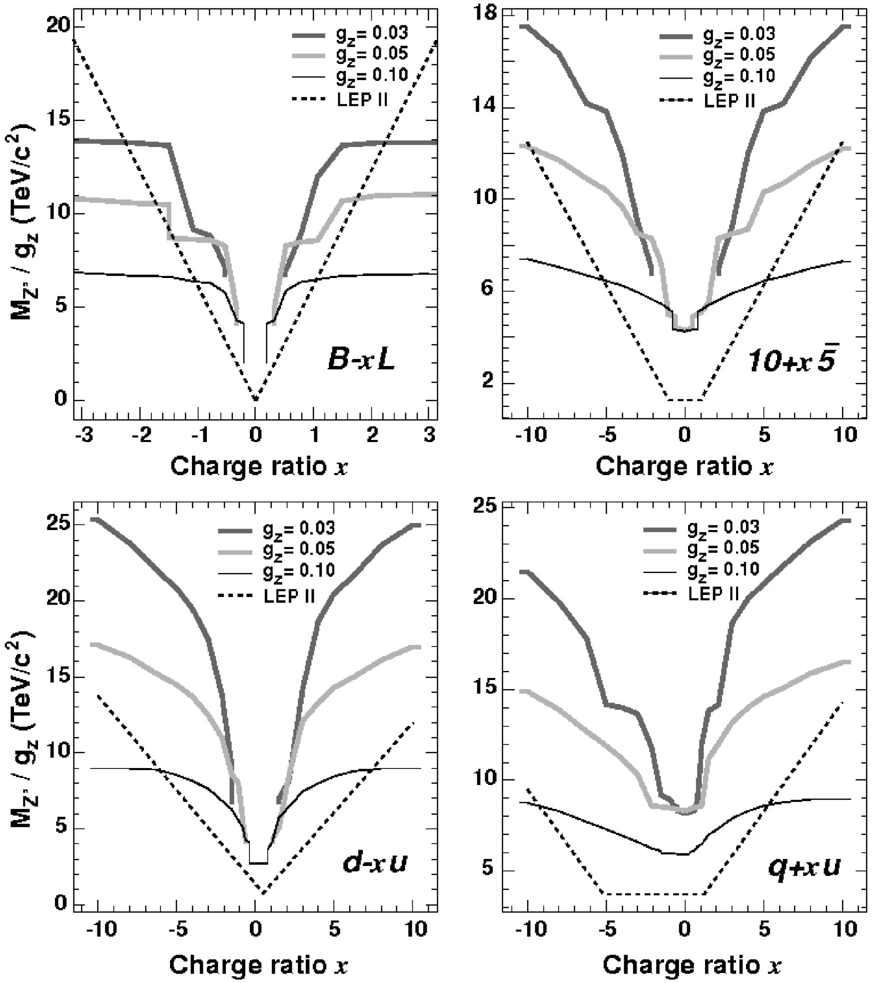
Includes $U(1)_\psi$ $U(1)_\eta$ and $U(1)_\chi$ models

Area below the curves would be discovered

[Ledroit 06]

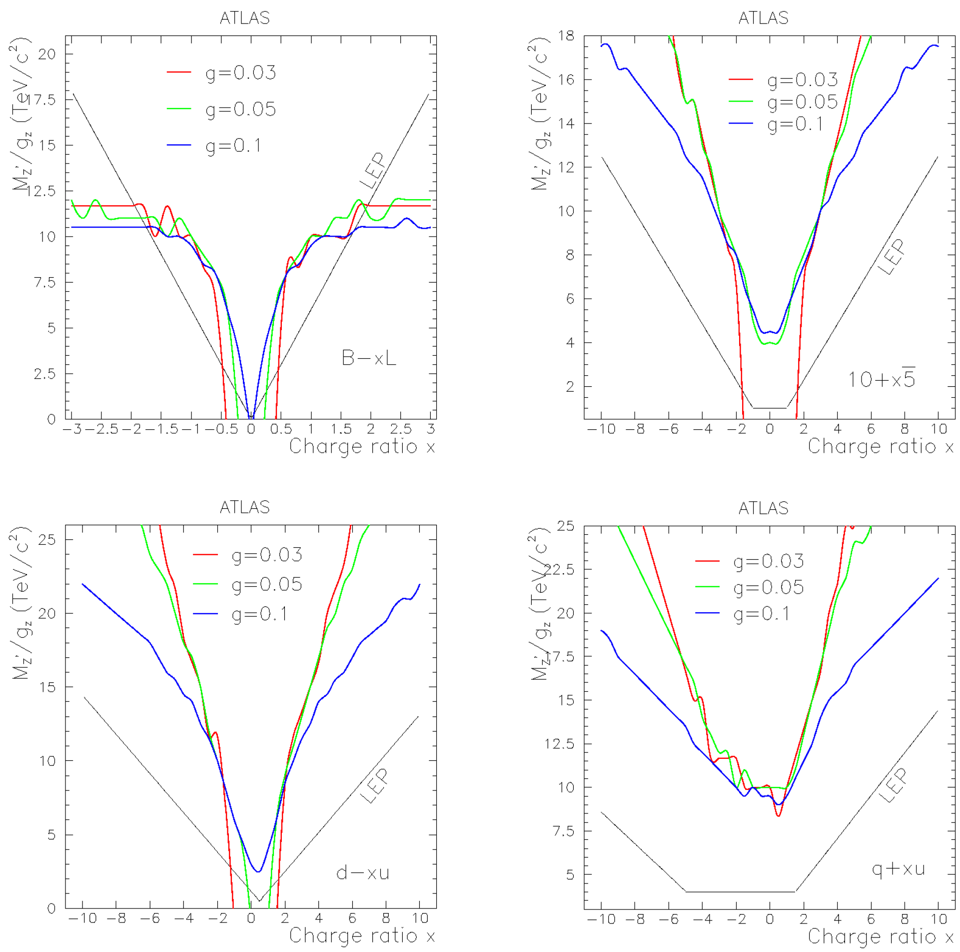
CDDT analysis

CDF Z' exclusion contours (∫L dt = 450 pb^{-1})



[CDF 06]

ATLAS Z' → e$^+$e$^-$ discovery reach (∫L dt = 400 pb^{-1})



[Ledroit 06]

$\ell^+ \ell^-$ resonances – post discovery

Measurements after discovery (these will take some time)

- **Distinguish between models via:**
  - **$\sigma \bullet \Gamma_{\ell\ell}$**
  - **Forward-backward asymmetry**
- **Measure spin**
- **Measure couplings**

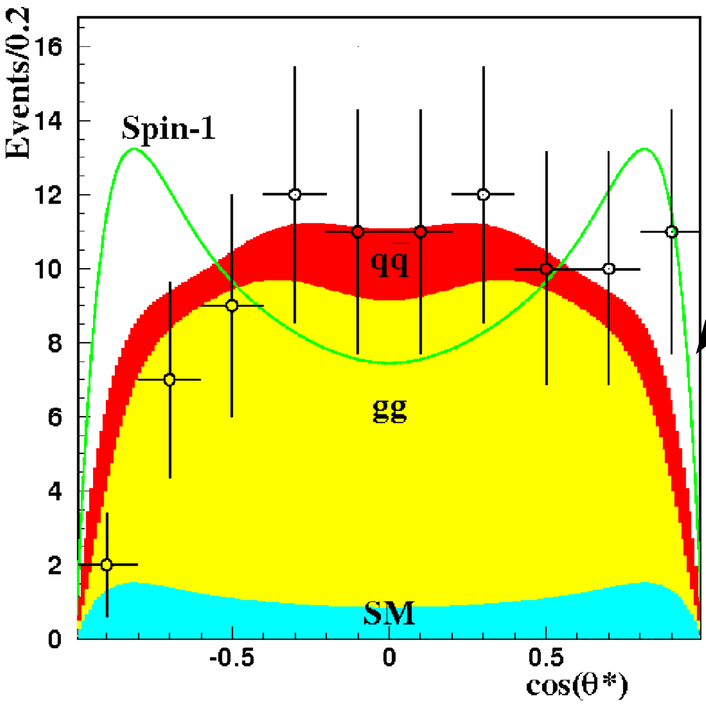
		σ_{ll}^{gen}(fb)	σ_{ll}^{rec}(fb)	$\sigma_{ll}^{rec} \times \Gamma_{rec}$(fb.GeV)
$M = 1.5$ TeV	SSM	78.4±0.8	78.8±1.8	3668±138
	ψ	22.6±0.3	22.7±0.6	178±13
	χ	47.6±0.6	48.4±1.3	828±48
	η	26.2±0.3	25.1±0.6	223±15
	LR	50.8±0.6	51.1±1.3	1515±75
$M = 4$ TeV	SSM	0.16±0.02	0.15±0.03	14±6
	KK	2.2±0.07	2.2±0.12	376±37

[Schaefer 05]

Sample size: approx 10k events in peak region for each sample
Corresponds to ~100 – 500 fb^{-1}

Z' spin determination

1.5 TeV Kaluza-Klein RS graviton:



[Allanach 00]

Min. number signal evts needed to distinguish spin-2 RS graviton from Drell-Yan

m_G (GeV)	N_S^{min} 90% CL	95% CL	99% CL
500	140	141	226
1000	59	70	99
1500	43	48	70
1700	41	48	65
1800	29	33	58
1900	32	40	64
2000	36	41	69
2100	31	45	59
2200	29	33	55

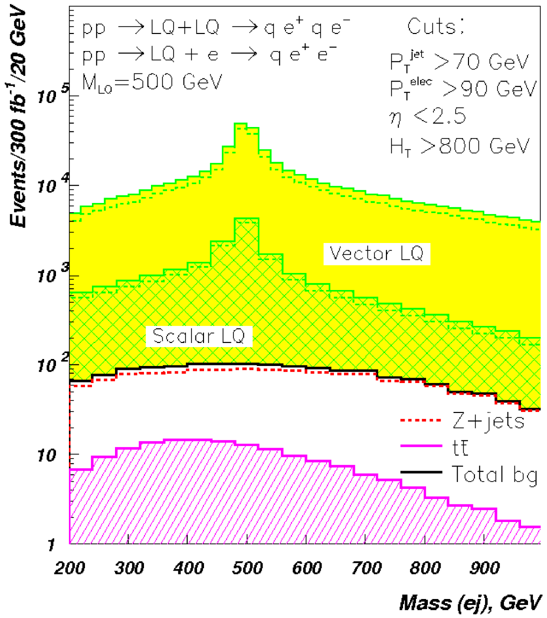
High because require $N_{sig} > 5\sqrt{N_{DY}}$

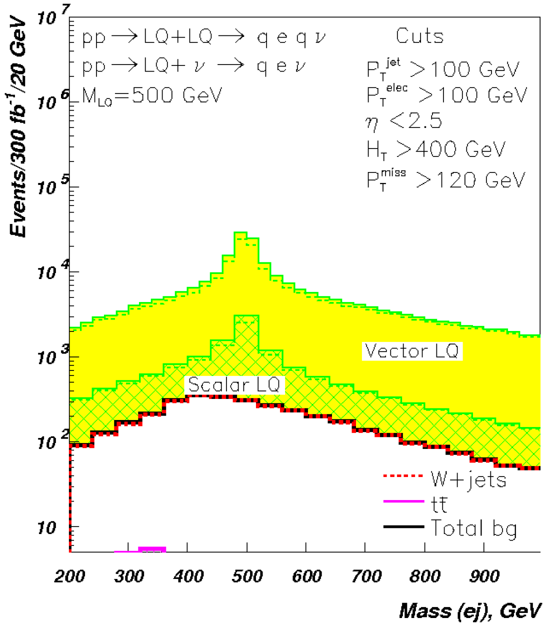
ℓ,jet resonances

"Classic" signal of leptoquark production.
Also RPV SUSY, composite models, ...

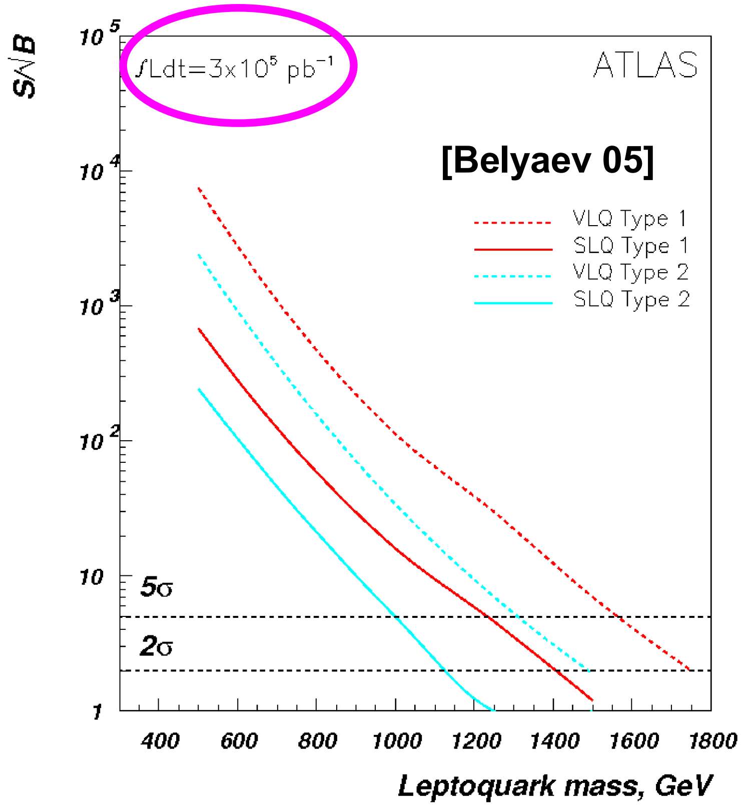
Pair production via mainly gg fusion
Single LQ production from qg fusion ← **Calculated at NLO**

Implemented most general form of scalar and vector LQ interactions and studied with fast detector simulation





λ_{eff} = e (~0.31) $\kappa_G = 1, \lambda_G = 0$



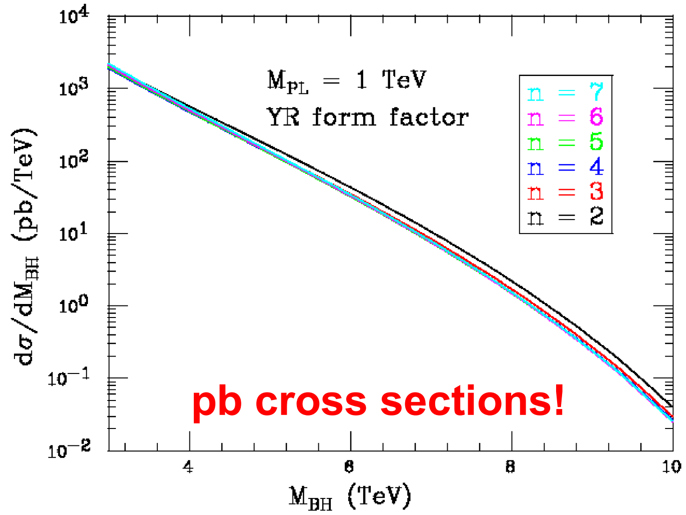
Some numbers for 1 fb^{-1}

	channel	mass (GeV)	bkg	signal
scalar LQ	2ℓ + jets	500	2	55
vector LQ	2ℓ + jets	750	< 1	40
scalar LQ	ℓ + jets + MET	500	6	35
vector LQ	ℓ + jets + MET	750	2	20

Many high pt objects: micro black holes

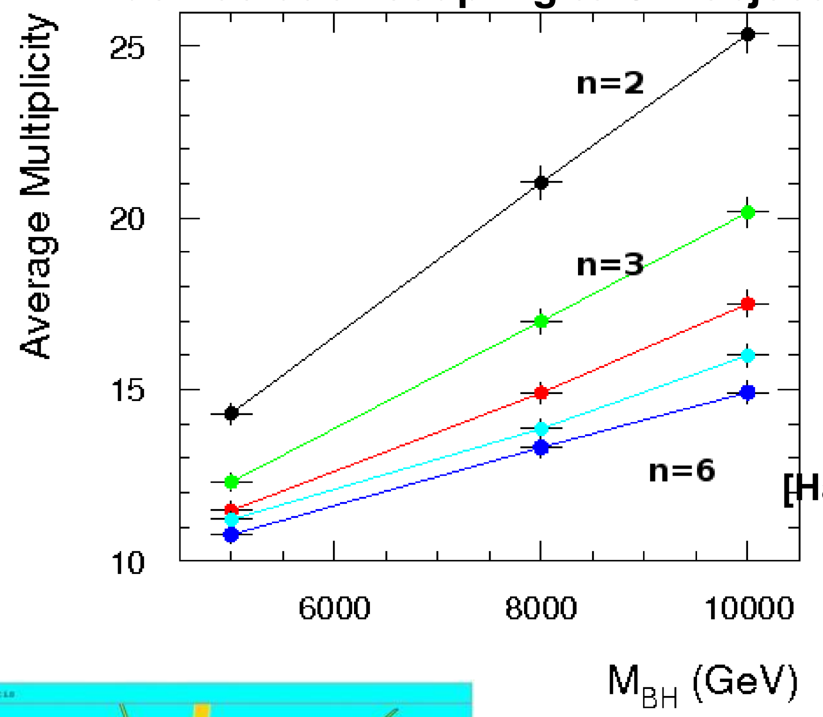
Theories of large extra dimensions
- Planck mass could be on TeV scale
- Microscopic black holes could be produced when E_{CM} > Planck scale
- BH decay (roughly black body) via Hawking radiation

Cross section estimations at LHC
- Can be motivated by (semi) classical geometric arguments when $M_{BH} >> M_{PL}$: $\sigma \sim \pi R_S^2$
- Need theory of quantum gravity as M_{BH} approaches M_{PL}

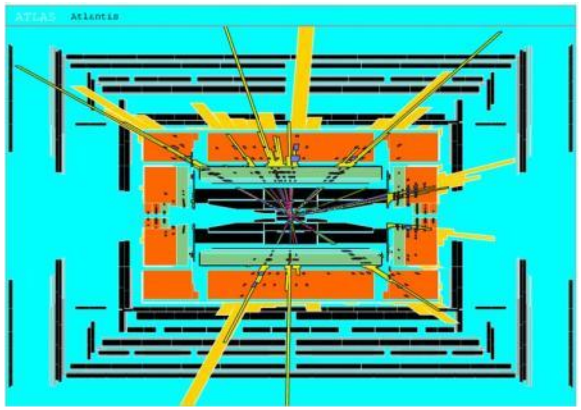


[Webber 05]

“democratic” coupling to SM objects



[Harris 04]

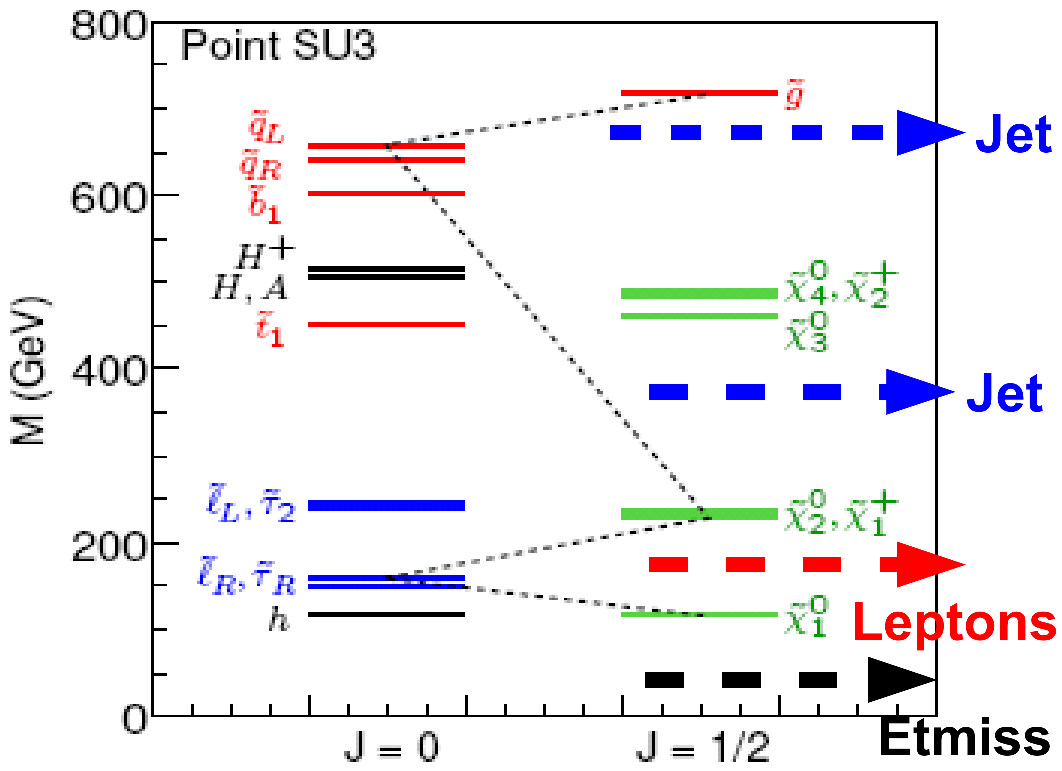


Sparticle decay

Although masses depend on how SUSY is broken, there is a folklore about features that are thought to be more general [Martin 06]

- $m(\tilde{g}) > m(\tilde{\chi}^0), m(\tilde{\chi}^\pm)$
- For light squarks
  - $m(\tilde{q}) > m(\tilde{\ell})$
  - $m(\tilde{q}_L) > m(\tilde{q}_R)$
  - $m(\tilde{q}) > 0.8\, m(\tilde{g})$ (mSugra)
  - $m(\tilde{q}) > 0.6\, m(\tilde{g})$ (GMSB, $N_5 \leq 4$)
- $\tilde{t}_1$ and $\tilde{b}_1$ are the lightest squarks
- Lightest charged slepton is $\tilde{\tau}_1$
- $m(\tilde{e}_L) > m(\tilde{e}_R)$, $m(\tilde{\mu}_L) > m(\tilde{\mu}_R)$

Mass spectrum at "generic" mSUGRA point
(m_0 = 100 GeV, $m_{½}$ = 300 GeV, A_0 = -300, tanβ=10, μ>0)

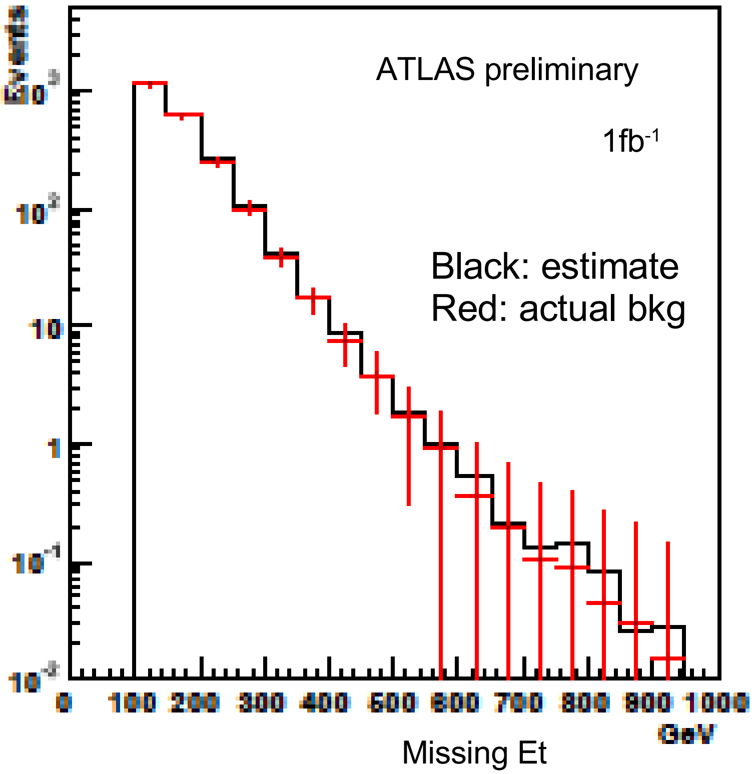


Generic signature involves energetic jets, possibly some leptons (usually lower energy) and missing Et

Background estimation 0-lepton mode

Examples of data-driven estimations:

ttbar



tt → bbqqτν dominates
Estimate with tt →bbqqℓν selected with M_T<100 GeV
Normalize with MET=[100,200]

Must control contamination from W+jets

Background estimation 1-lepton mode

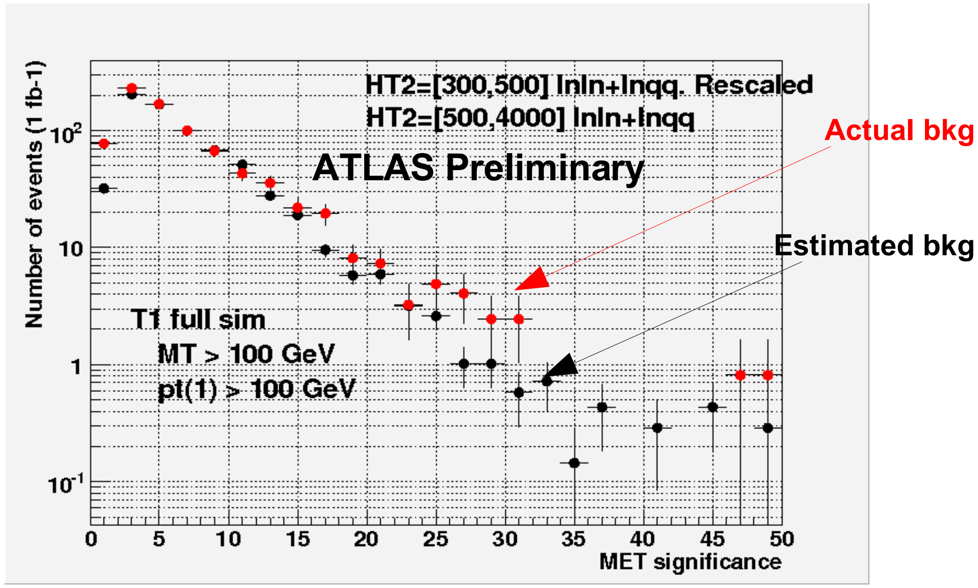
Main background is tt → bbℓνℓν after M_T > 100 GeV

Currently under study

- Bkg suppression via veto of 2nd lepton
- Estimation of bkg via "sideband" and "decay resimulation" methods

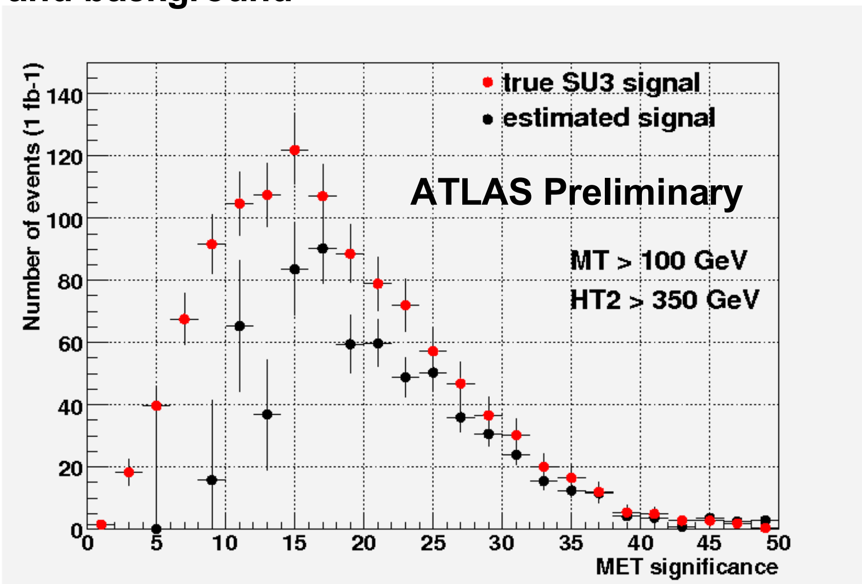
Alternative sideband method:

- Select bbℓνℓν sample with MT > 100 GeV
- Estimate MET shape using control sample selected with HT2.



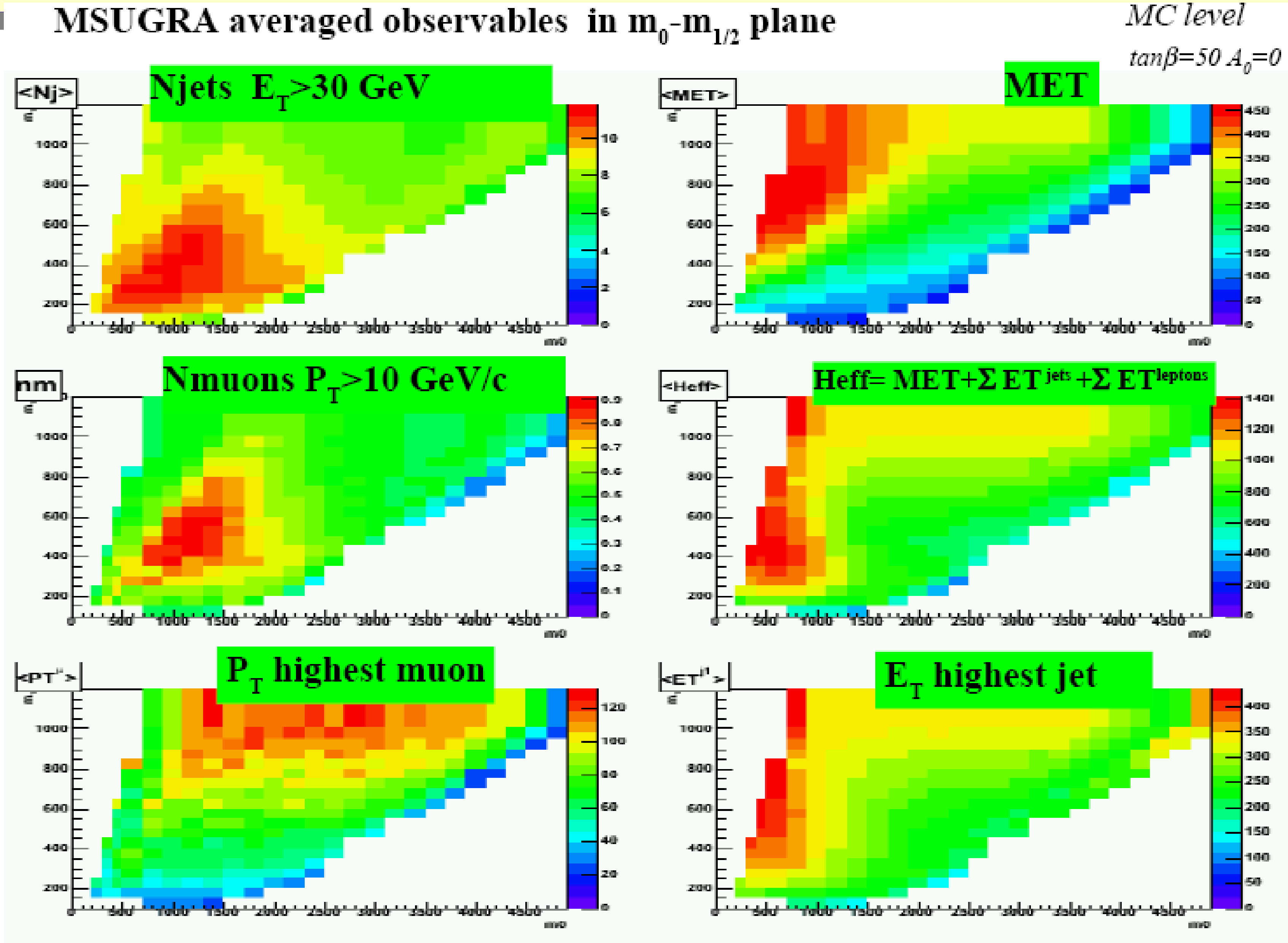
Also useful for ttbar bkg in 2-lepton channel

Signal extraction from mixed sample of signal and background



Method is robust against "contamination" of background samples by SUSY signal

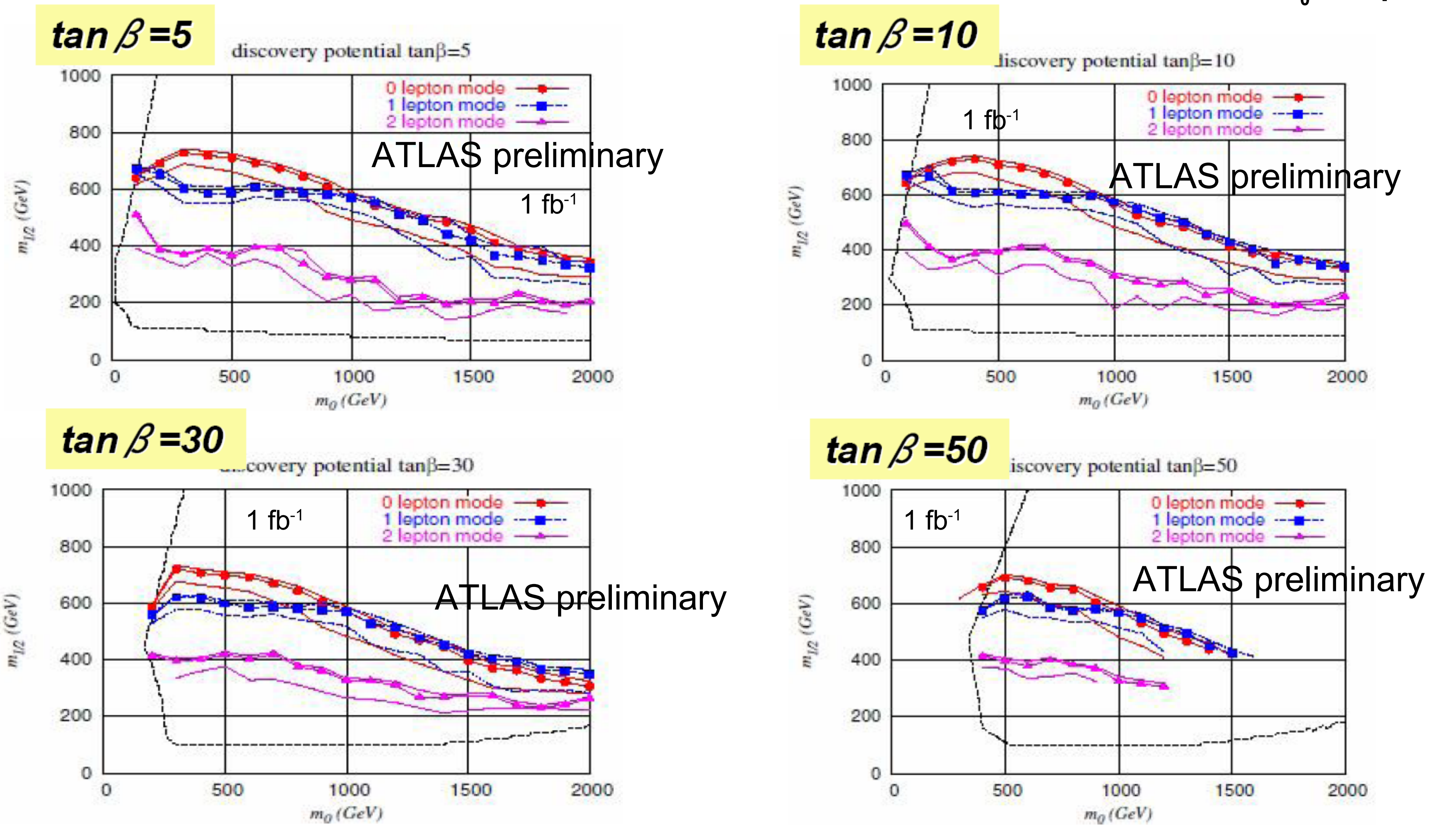
Event characteristics in mSUGRA



[Zhukov 06]

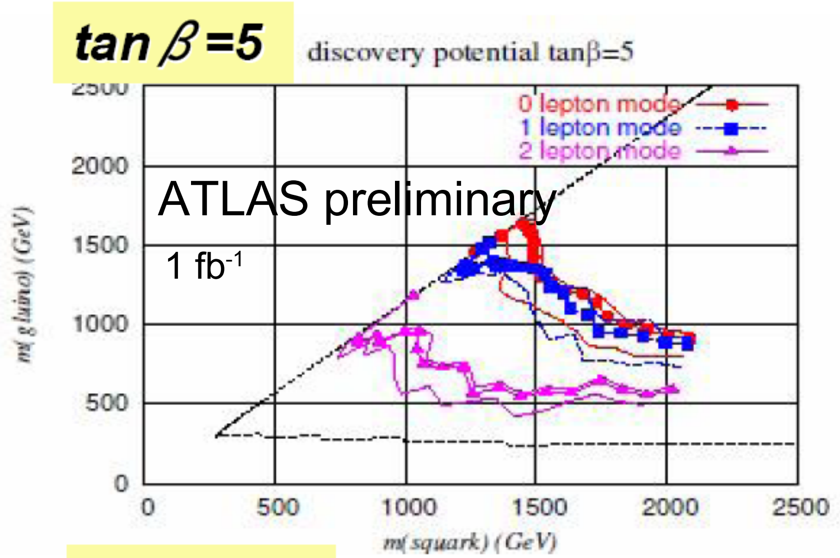
tanβ dependence

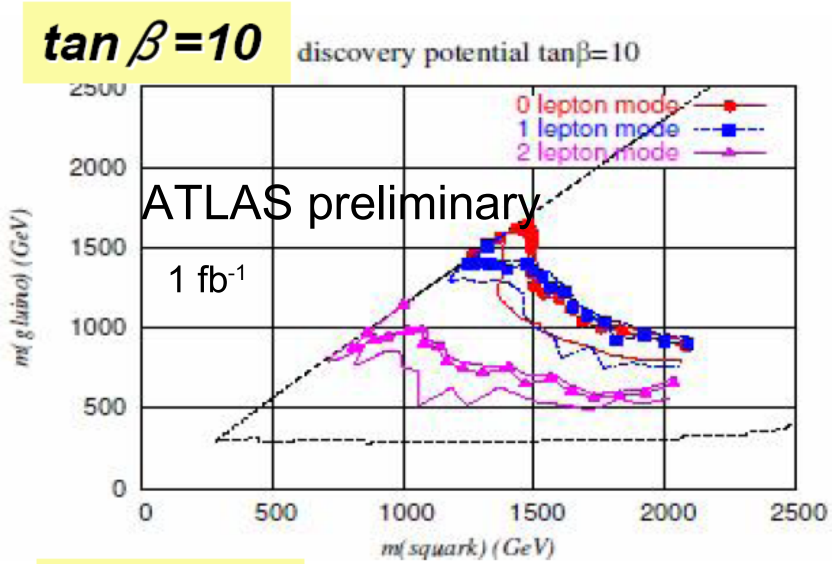
A_0 = 0, μ>0

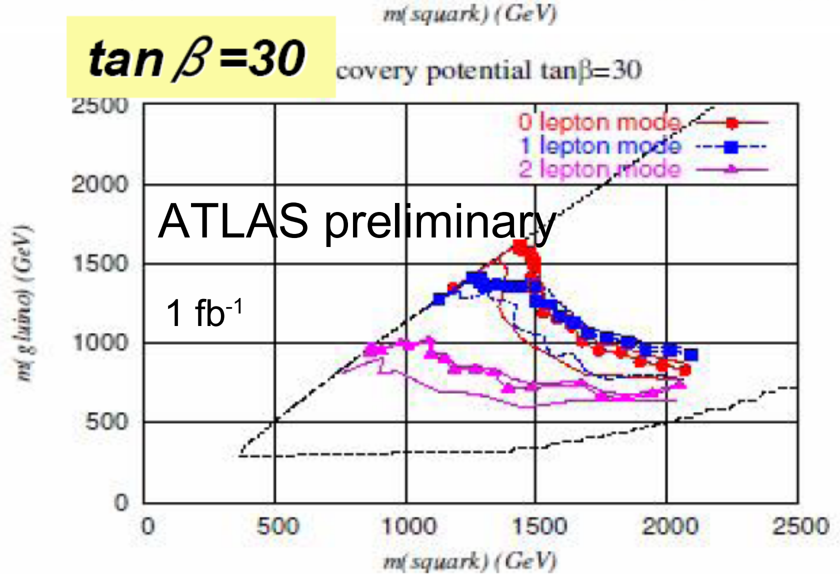


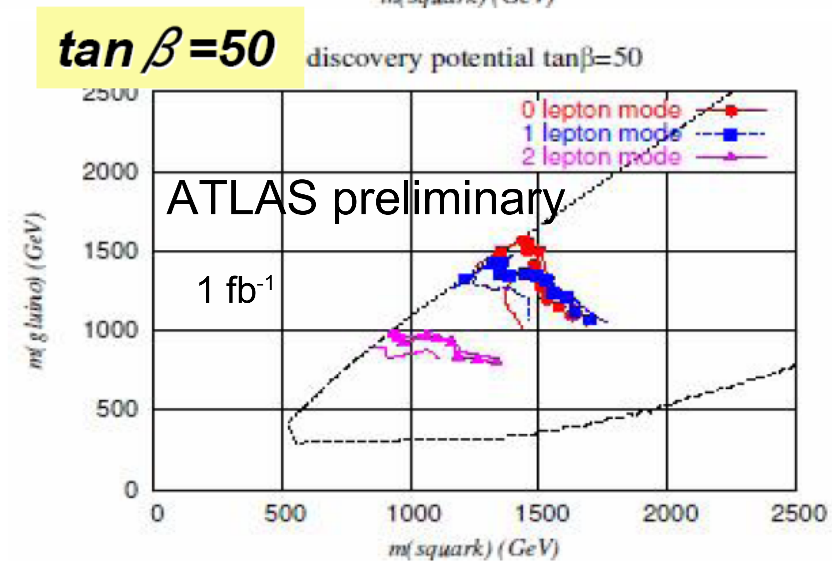
tanβ dependence (2)

$A_0 = 0$, $\mu>0$









Systematic uncertainties

Background generator-level uncertainties considered so far

Parameter	Default	Variation	Δbkg W+jets (%)	Δbkg ttbar (%)
Parton pt cut	> 40 GeV	> 15 GeV	+161	+107
ME generation ΔR	0.7	0.35	-8	-10
Factorization scale	$Q^2 = M^2 + Pt^2$	Q^2 = avg(pt^2 of jets)	+9	
α_S scale	pt of jet	0.5 x pt of jet	+74	+69
PDF	CTEQ6L	MRST2001J	+18	+36
MLM matching pt	15 GeV	40 GeV	-7	-2
MLM matching ΔR	0.35	0.7	+7	+3

SUSY signal uncertainties considered so far
luminosity: 5%   Etmiss scale: 5%   Jet energy scale: 5%

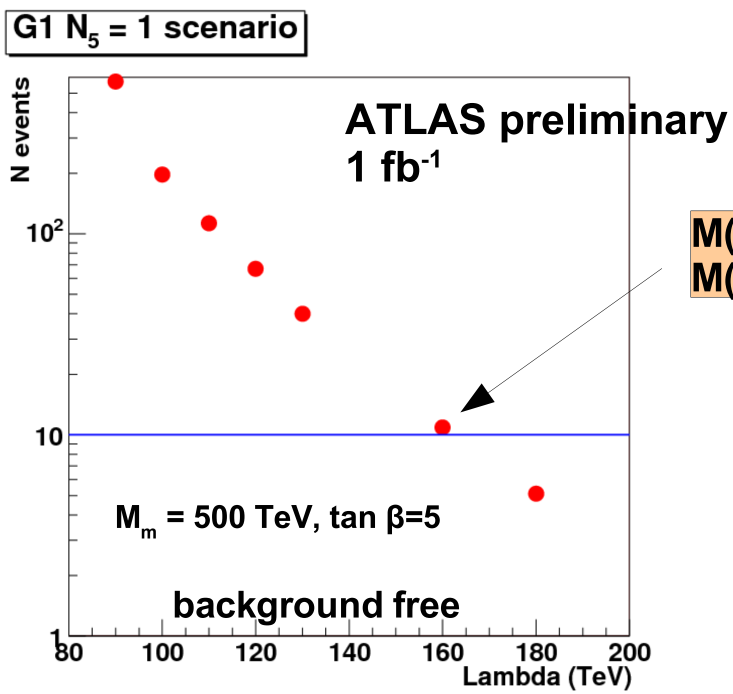
GMSB scenarios

In GMSB models, gravitino is LSP

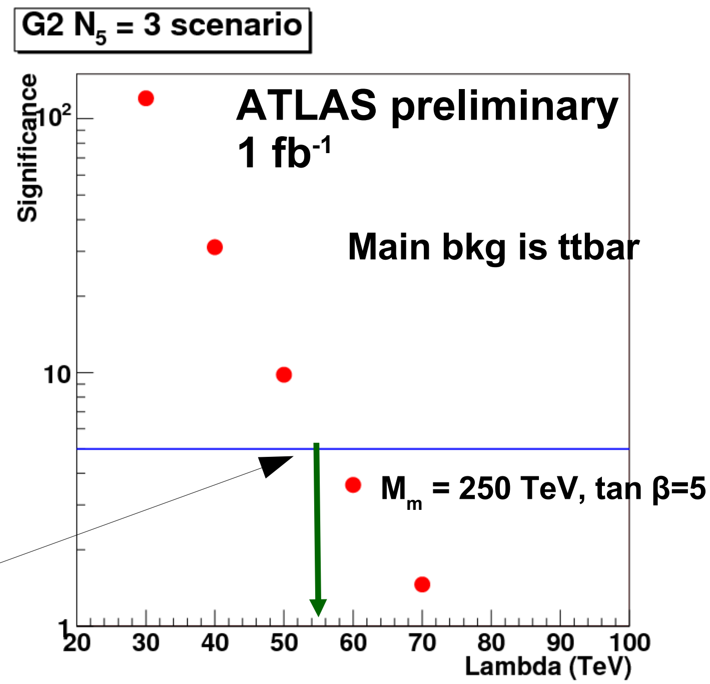
Four distinct scenarios:

- NLSP is $\tilde{\chi}_1^0 \rightarrow \gamma + \tilde{G}$ (two hard photons in addition to usual ℓ + jets + MET)
- NLSP is $\tilde{\ell}_R \rightarrow \ell + \tilde{G}$ (opposite sign, same-flavor leptons)
- NLSP has short lifetime
- NLSP has long lifetime

Short NLSP lifetime case studied, with non-optimized cuts



M(gluino) ≈ 1250 GeV
M(squark) ≈ 1700 GeV



M(gluino) ≈ 1225 GeV
M(squark) ≈ 1190 GeV