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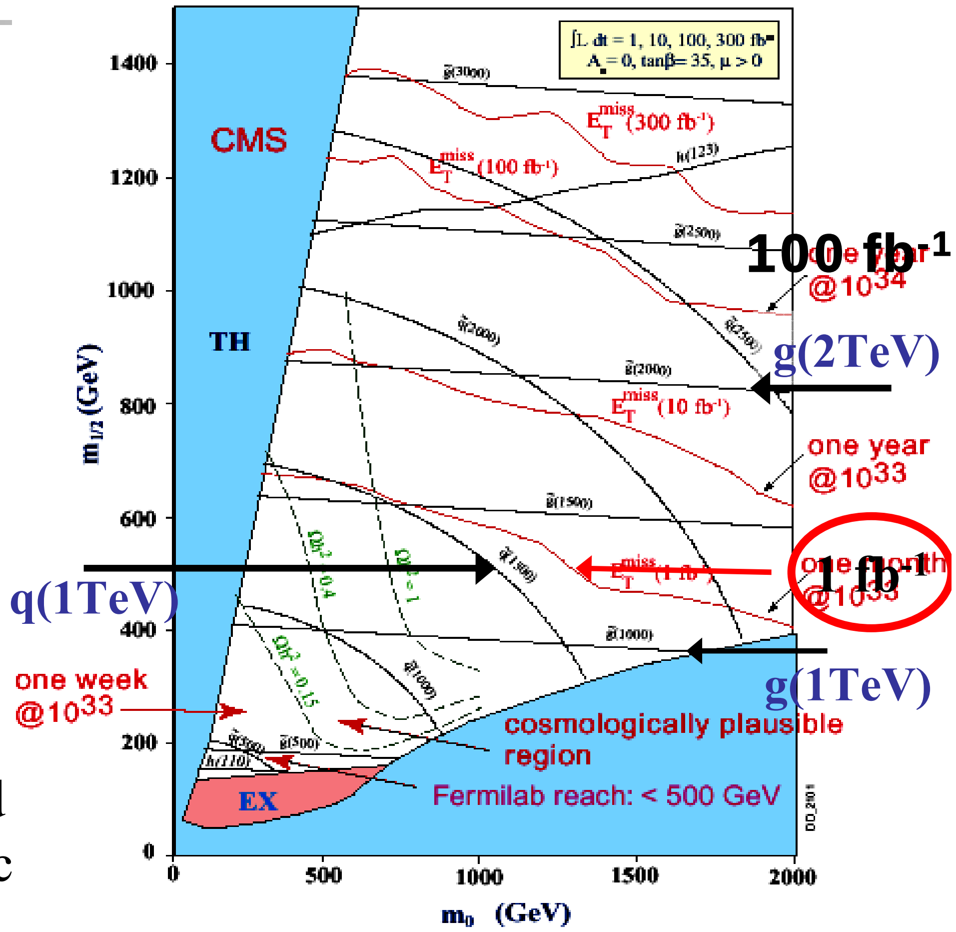
Perspectives for early discovery of SUSY in ATLAS and CMS

- Introduction
  - how SUSY events look like at the LHC
- SUSY searches (**review of analysis strategy and discovery potential**)
  - Trigger efficiency
  - Search strategy and reach in parameter space
- SUSY searches (**realistic background estimation, roadmap to discovery**)
  - Improved background computation: Matrix Element vs Parton Shower
  - Measurement of background from data: top, W+jets, Z+jets
  - Detector effects: E^{T}_{Miss} tails in QCD events, fake leptons
- The first mass measurements
- An other scenario: GMSB models

LHC discovery reach

• **LHC discovery potential** for Supersymmetry **well documented** since several years
ATLAS: Physics TDR, CERN/LHCC 99-14
CMS: J. Phys. G28 (2002) 469.

• **<u>1 fb^{-1}</u> of data already allows discovery if squark or gluino mass < 1.5 TeV**
(as it should, because of naturalness).
<u>ATLAS and CMS potentials similar</u>



• Those studies assumed a **perfectly known SM physics** (only stat. errors on background rate) and **ideal detector** (nominal asymptotic performance).

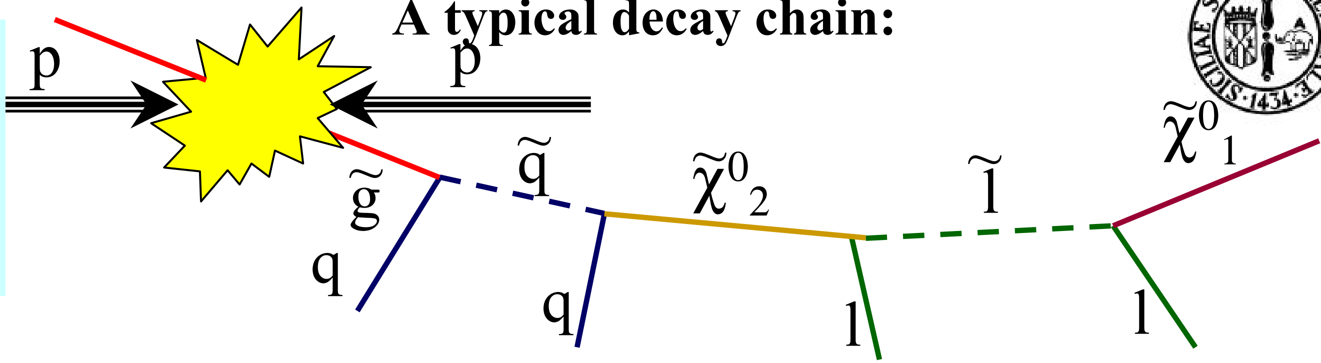
• SUSY discovery likely to depend not on statistic but on the **understanding of SM physics background and detector systematic** with early data.

• **In this talk, emphasis on these issues**

SUSY events topology

SUSY particles:
Scalars (s-quarks, sleptons)
Gaugino (gluino, 4 neutralinos, 2 charginos)
5 Higgs bosons

A typical decay chain:



In SUGRA models (see later for GMSB models) strongly interacting sparticles (squarks, gluinos) dominate production.

Cascade decays to the stable, weakly interacting lightest neutralino follows.

- **Event topology:**
  - **high p_T jets (from squark/gluino decay)**
  - **Large E_T^{miss} signature (from LSP)**
  - **High p_T leptons, b-jets, τ-jets (depending on model parameters)**
- **R-Parity Violating models: the LSP decays, more jets and less missing energy.**

The standard discovery plot

Most general search strategy:
jets + E_T^{miss} + n-leptons

- **Backgrounds:**

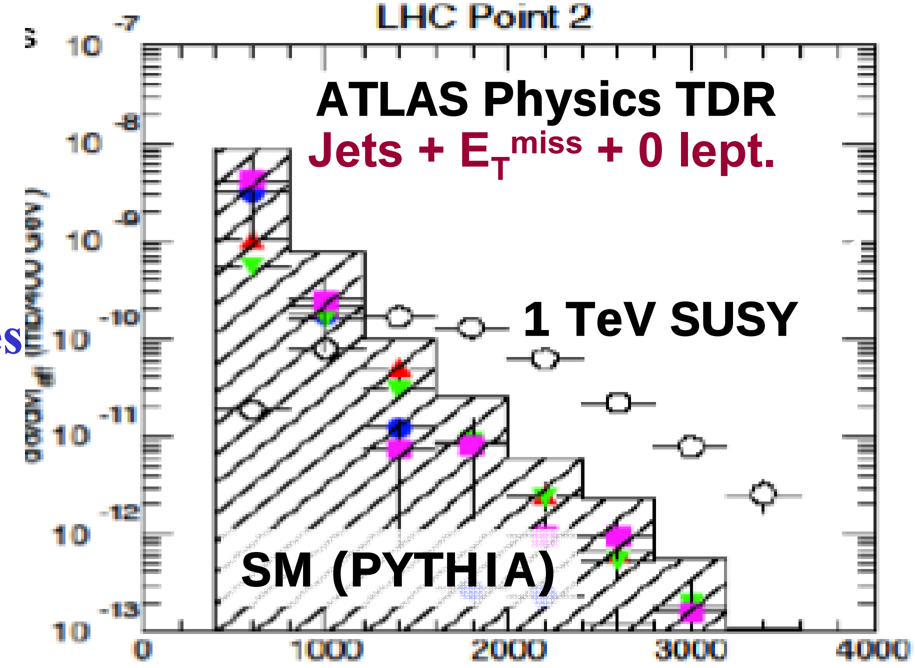
- **Real missing energy from SM processes with hard neutrino**

tt, W+jets, Z+jets

- **Fake missing energy from detector**

Jet energy resolution (expecially non-gaussian tails) critical

A good understanding of both SM physics and detector (missing energy expecially) critical to claim excess over SM predictions



$M_{eff} = \Sigma|p_T^i| + E_T^{miss}$ (GeV)

SUSY selection cuts used in the pictures:

- 1 jet with p_T>100 GeV, 4 jets with p_T>50 GeV
- E^T_{MISS} > max(100 GeV,0.2M_{eff})
- Transverse sfericity S_T>0.2
- No isolated muon or electron with p_T>20 GeV

CMS SUSY trigger benchmarks

- 6 benchmark points used to test **CMS** trigger performance
  - Represent difficult "case studies" for the trigger, non exhaustive test of the values of SUSY parameters.

Point	$\mathbf{m_0}$ **(GeV)**	$\mathbf{m_{1/2}}$ **(GeV)**	**σ (pb)**
4	20	190	181
5	150	180	213
6	300	150	500
7	250	1050	0.017
8	900	930	0.022
9	1500	700	0.059

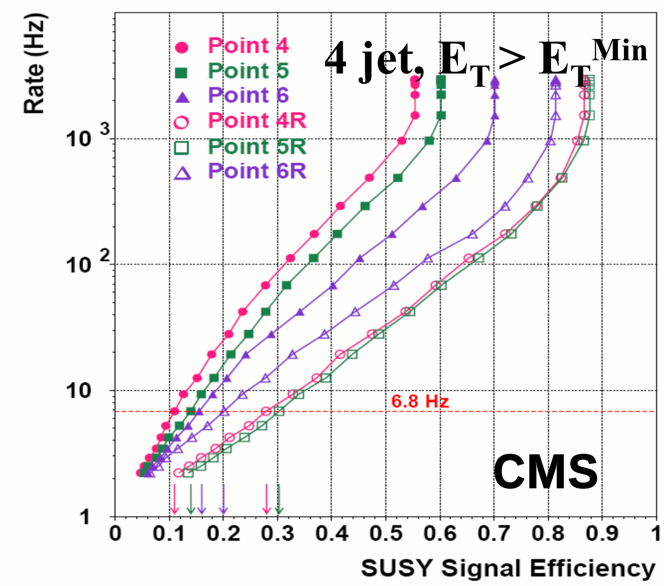
$A_0 = 0$, $\tan\beta = 10$, $\mu > 0$

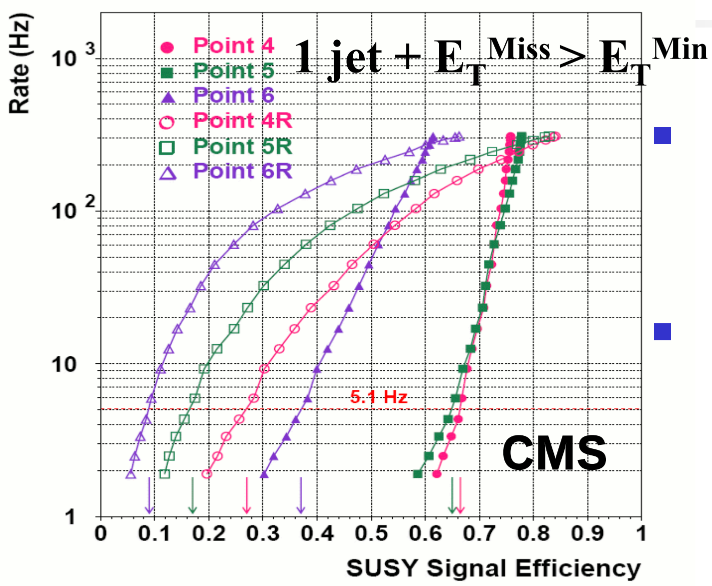
Low Mass (LM) (points 4, 5, 6):
- Low E_T^{Miss}
- Low P_T particles

High Mass (HM) (points 7, 8, 9):
- High mass sparticles
- σ_{prod} very low

- 4, 5 and 6 excluded by LEP, but useful to test trigger performances
- The same points are also studied for R-parity violation, with $\chi_1^0 \rightarrow jjj$

Trigger performances





- If R-parity is conserved, the E^T_{miss} trigger have an high efficiency.
- Efficiency is lower for R-parity violation
  - Compensated by n-jets triggers

Cumulative Efficiency (%)

	Point					
	4	**5**	**6**	**4R**	**5R**	**6R**
L1	92	92	85	94	93	87
HLT	69	68	44	46	41	26

	Point					
	7	**8**	**9**	**7R**	**8R**	**9R**
L1	90	98	94	100	100	100
HLT	85	92	76	90	88	64

ATLAS HLT trigger relevant for SUSY: 4j110, μ10+e15i, **j70+xE70**, τ35i+xE45

Physics Analysis always use (usually much) more stringent cuts

1 jet p_T >70 GeV
E^T_{miss} > 70 GeV

Reach of different channels

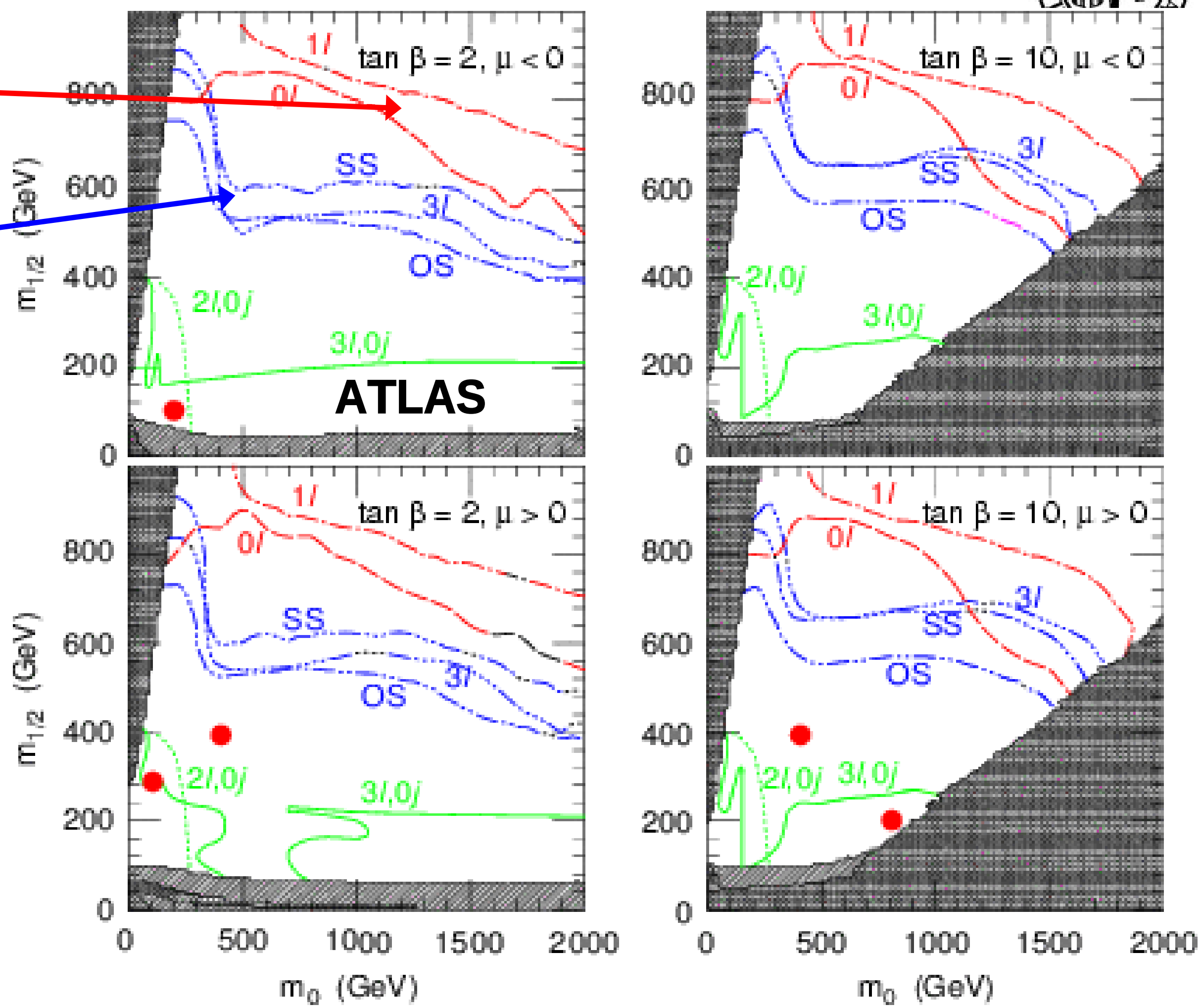
Inclusive E_T^{Miss} + jet:

- Best signature
- Important for high ∫L limit

Multi-lepton n(≥1) ℓ:

- Less powerful
- But may be very **useful for early discovery:**
  - Signal confirmed in several channels
  - Better S/B, leptons better measured/understood than jets at the beginning – **can be important in early searches**

Esempio: 2μSS



Example of an analysis: 2μSS

Promising channel: **(CMS study 2004)**

- High trigger efficiency for μ
- Clean, easy channel (even with tracker misalignments)
- Less background contamination than for E_T^{Miss} + N jets

Preselection: 2 μ SS with $P_T > 10$ GeV **reliable quite early**

Further cuts on jet and E^T_{miss} optimized for each point. More difficult to control with early data

Main backgrounds:

	tb	tqb	$\bar{t}b$	$\bar{t}qb$	ZZ	ZW	WW	$t\bar{t}$	$Zb\bar{b}$	All
σ, pb	0.212*	5.17*	0.129*	3.03*	18(NLO)	26.2	70.2	886(NLO)	232(NLO)*	
N1	2,120	51,700	1,290	30,300	180,000	262,000	702,000	8,860,000	2,320,000	
N2	112	1,798	71	1,067	256	727	39.7	142,691	12,924	160,000

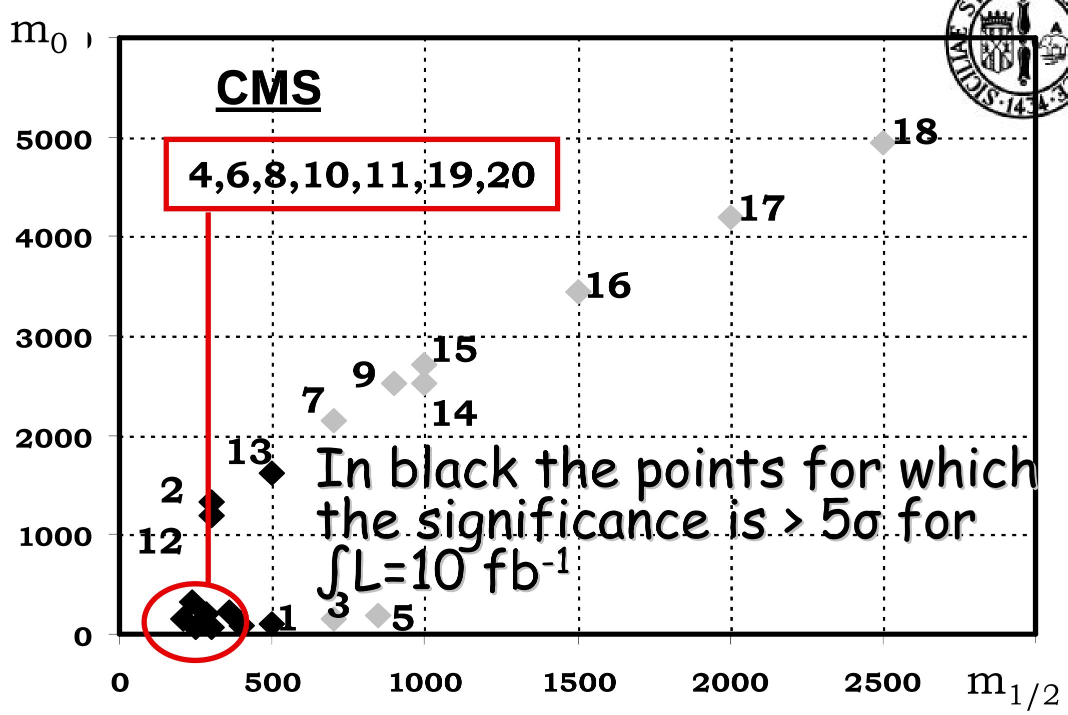
- **N1: Total number of events expected for $\int L = 10\ fb^{-1}$**
- **N2: Events passing preselection cuts**

Dominant background is from top. That's good – can be understood using data (see later)

2μSS results

Several points visible with $\int L << 10\ fb^{-1}$

For many points significance is >> 5



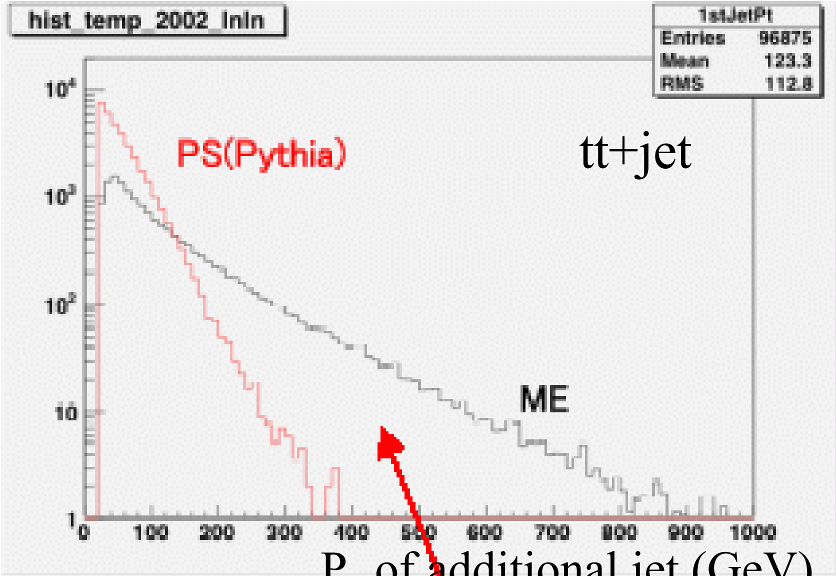
- **Study of results stability:**
  - **Both +30% SM and –30% SUSY**
  - **Only point #13 exits discovery zone.**

Preparing for real data

- **Most traditional studies** uses an **ideal detector** (no miscalibration, misalignments, etc.) and **SM background** is simulated with **parton-shower montecarlos** and **assumed to be "known"** (significance is $S/\sqrt{S+B}$)
- More realistic studies:
  - Montecarlo production with **Parton shower + Matrix element**
  - Take into account **uncertainties on background** cross section, **rely on data** as much as possible to evaluate SM contribution
  - Increasing realism of **detector effects**

Matrix elements and backgrounds

- Hard jet emission in SM processes is important for SUSY searches background
- Standard analysis use Parton Shower Montecarlo for SM processes: **badly underestimates hard jet emission.**
- Recent ATLAS background studies:
  - Generate hard process with exact ME computation (Alpgen, Sherpa, …)
  - Parton shower hadronization with HERWIG, PYTHIA
  - Solve double-counting problems with MLM matching



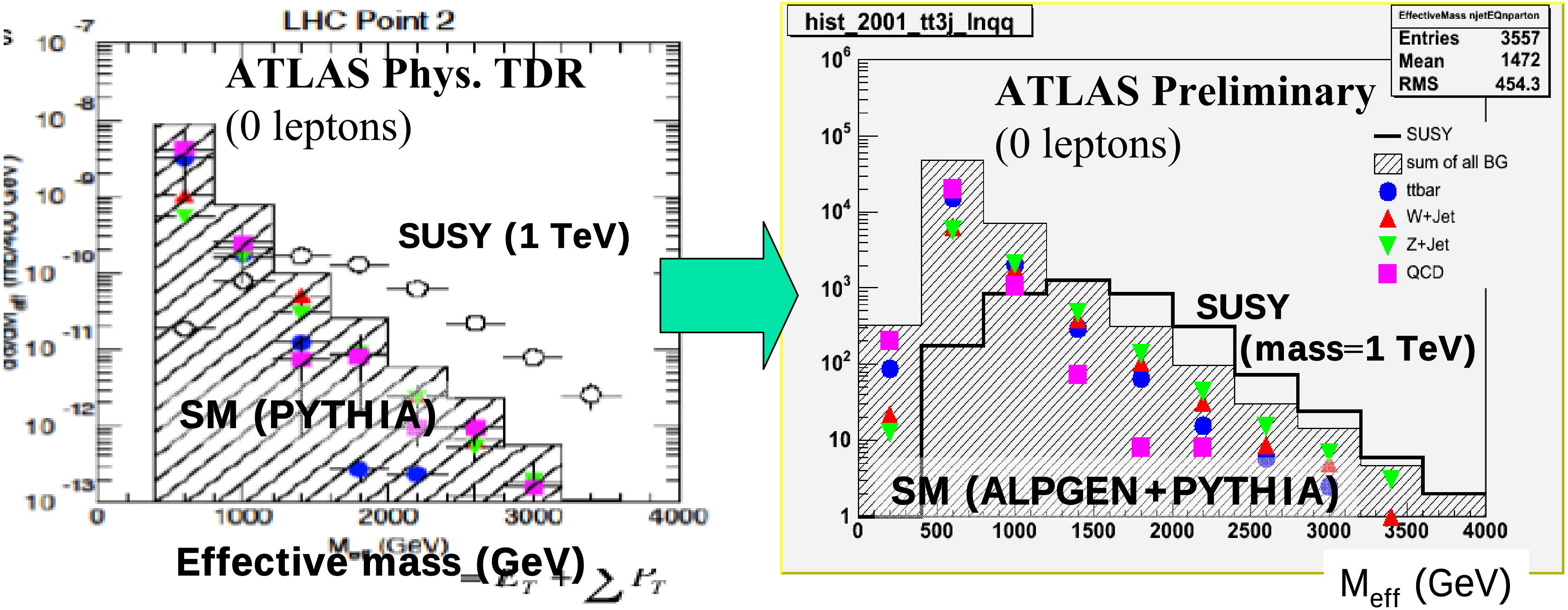
P_T of additional jet (GeV)

Parton shower is a good model in collinear region, but fails to describe hard jet emission

Backgrounds with MEs (1)

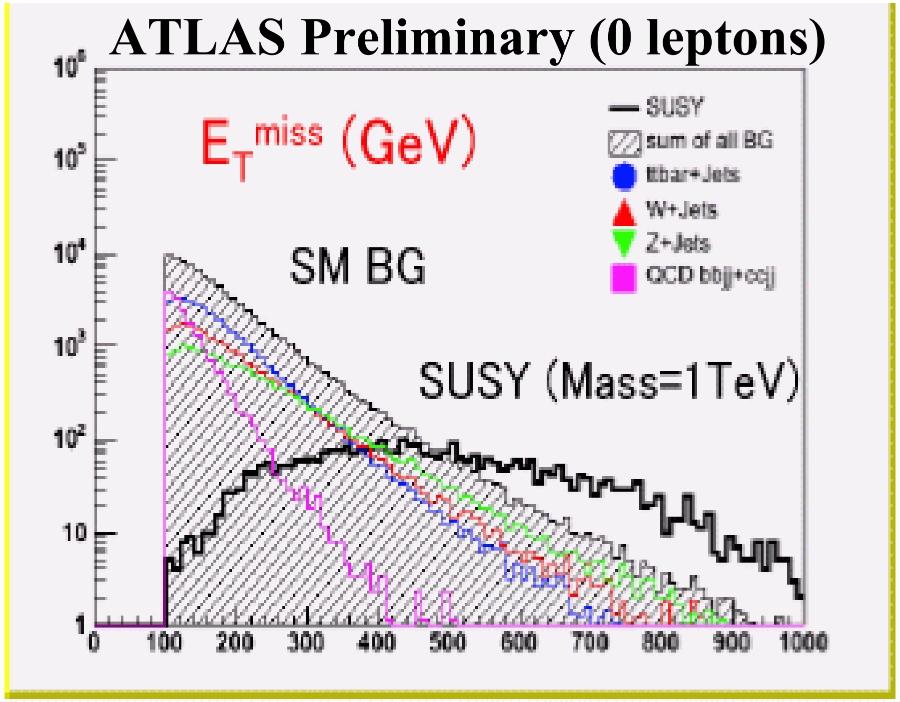
- **Background increases**

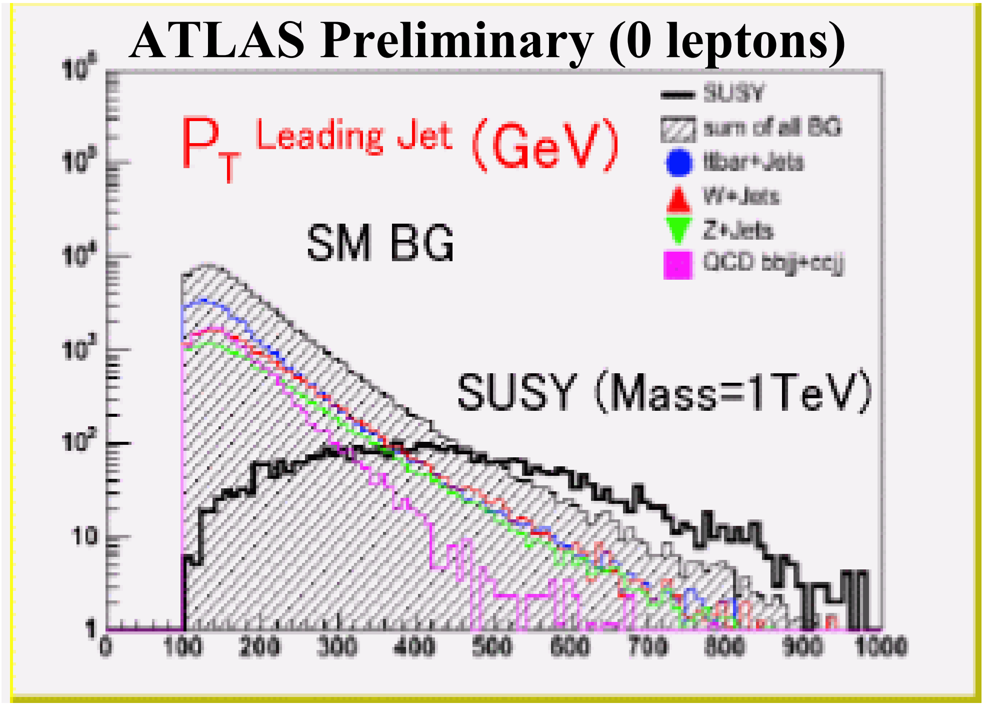
But **discovery of 1 TeV SUSY still easy** with only statistical errors



Backgrounds with MEs (2)

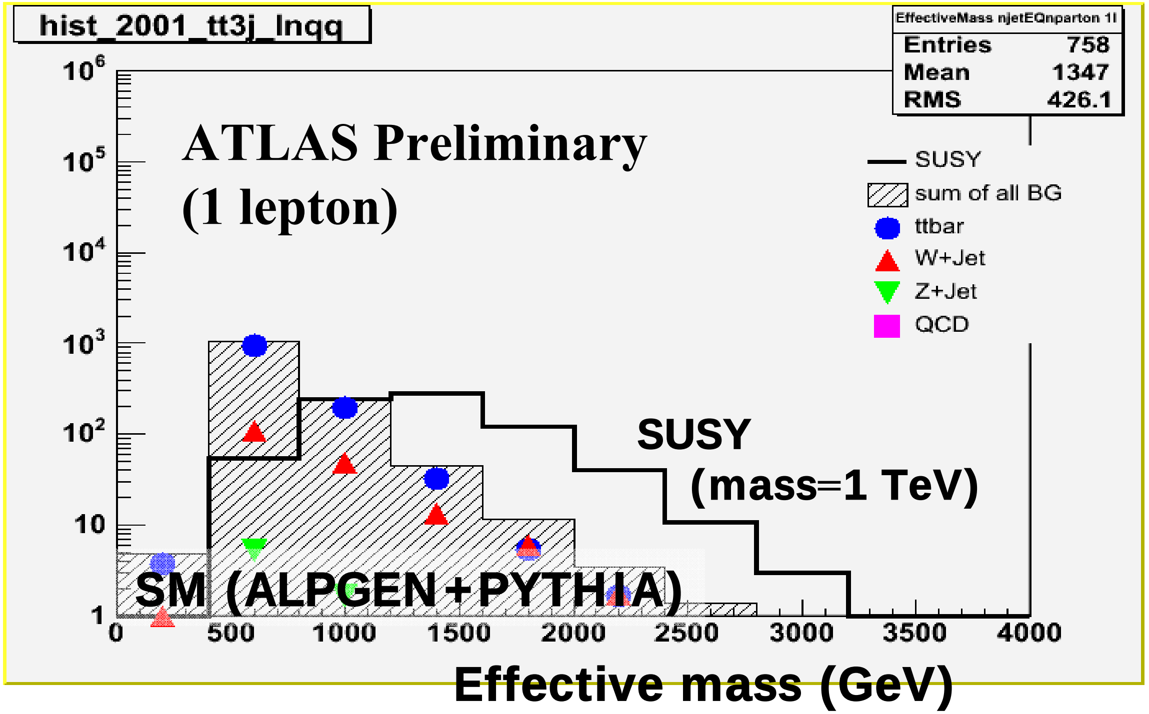
- Additional jet, but not missing energy in background process: importance of missing energy crucial





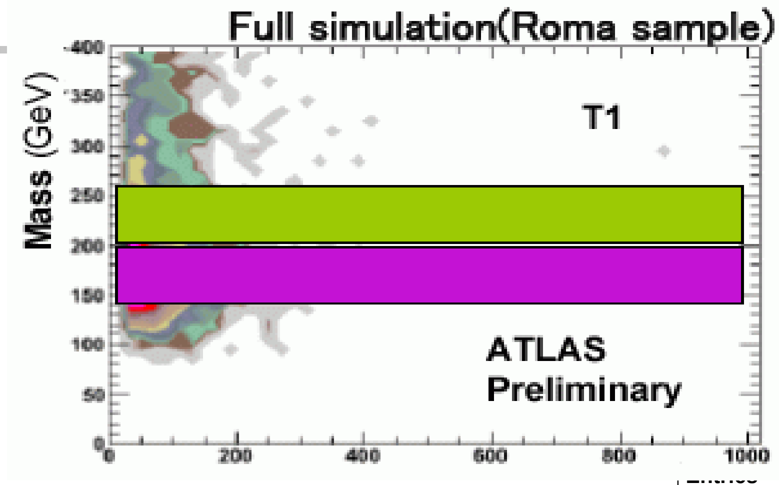
Backgrounds with MEs (3)

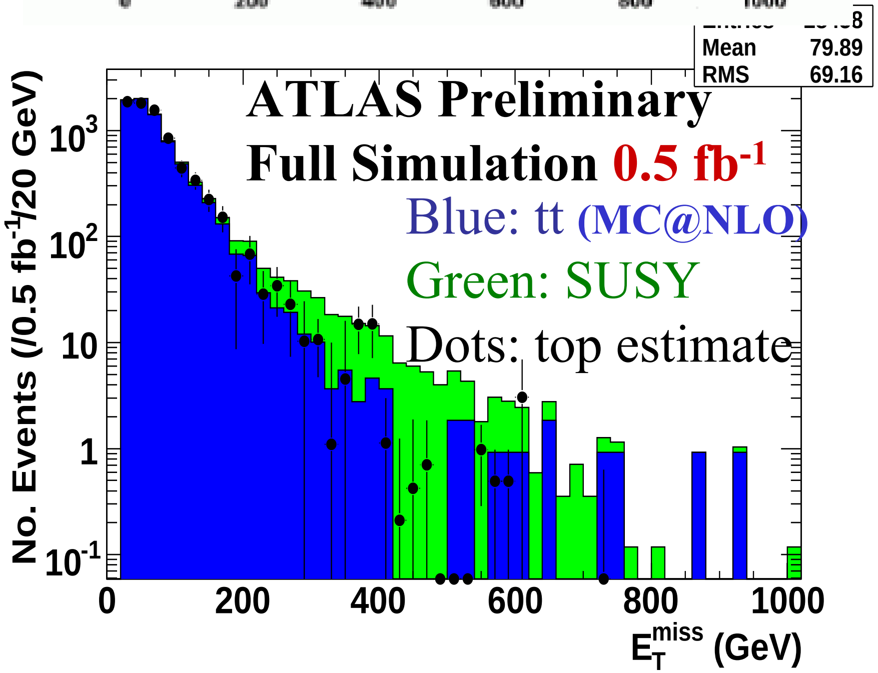
1-lepton channel more promising than 0-lepton
- Background decreases more than signal
- Dominant background is top, more controllable than QCD jets (see later)



Background from data

- Top mass reasonably uncorrelated with E^T_{MISS}
- Select events with m(lj) in top window (with W mass constraint – **no b-tag used**). Estimate combinatorial background with sideband subtraction.
- Normalize to low E^T_{Miss} region (where SUSY small)
- **Procedure gives estimate consistent with top distribution also when SUSY is present**
- Z+jets: big contribution from $Z \rightarrow \nu\nu$
  - Can use $Z \rightarrow ee$, apply same cuts as analysis, substitute $E^T(ee)$ with E^T_{miss} and rescale by BRs.

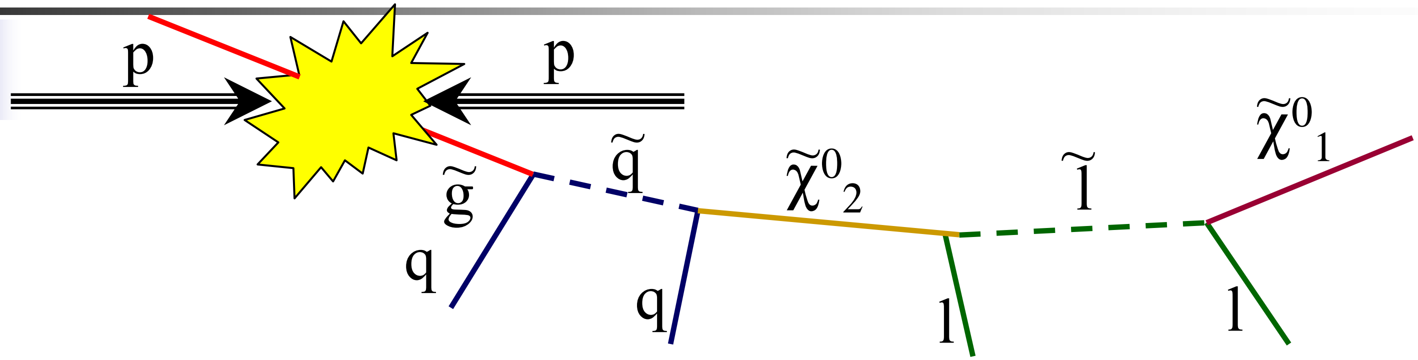




Background from detector

- Jet resolution not critical for SUSY searches, **non-gaussian tails** are much more critical
  - Can **map badly behaving cells** (ϕ simmetry, Z+jets balance, …)
  - **Avoid problemating regions** (events with jet in crack)
  - **Veto events** with E^T_{miss} vector along a jet
- Modeling of detector response in simulation
  - Problem: jet cross section very large, problems from a very small fraction of events in tails – difficult to produce the required statistic in full simulation
- Light Jets misidentified as leptons can contribute to 1-lepton channel background
- Lepton efficiency less critical
  - But reduces significance of 1-lepton channel if low
  - Also 3-lepton channel may be promising for discovery
  - Must be understood for reconstruction of specific decays (see exclusive analysis later)

SUSY mass spectroscopy



- **After discovery: reconstruction of SUSY masses**.

Two undetected LSP: no mass from one specific decay. Measure mass combinations from kinematics endpoints/thresholds. With long enough decay chain, enough relations to get all masses.

- A point in parameter space is chosen, and decay chains are reconstructed.
  - Analysis should be applicable whenever the specific decay do exist.
  - **Leptonic (e/μ) decay of χ^0_2 "golden channel" to start reconstruction.**

  Can also be a good channel for discovery

- Some benchmark points favoured by cosmology studied in detail with full simulation

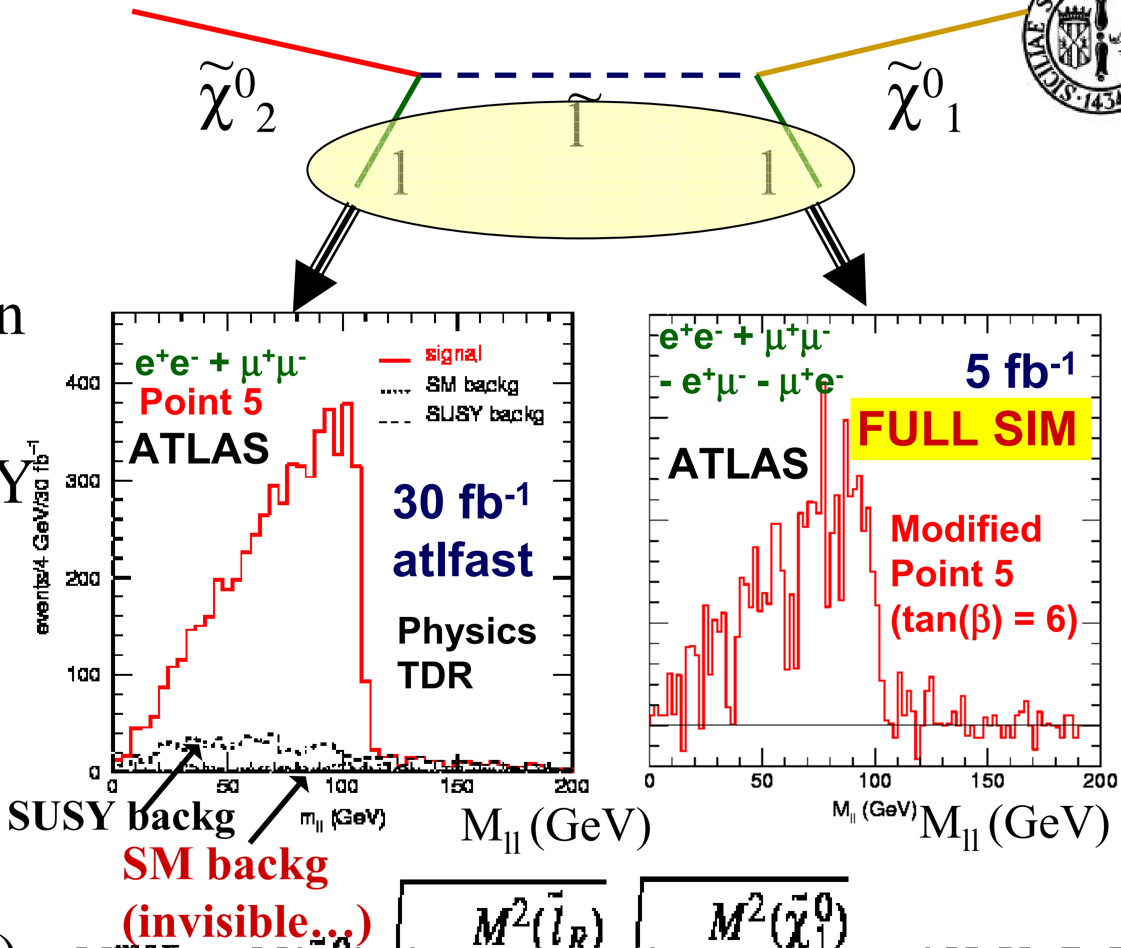
Dilepton Edge

- **Clear signature, easy to trigger:** starting point of many mass reconstruction analyses.
- Can perform SM & SUSY background subtraction using OF distribution

  $e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$

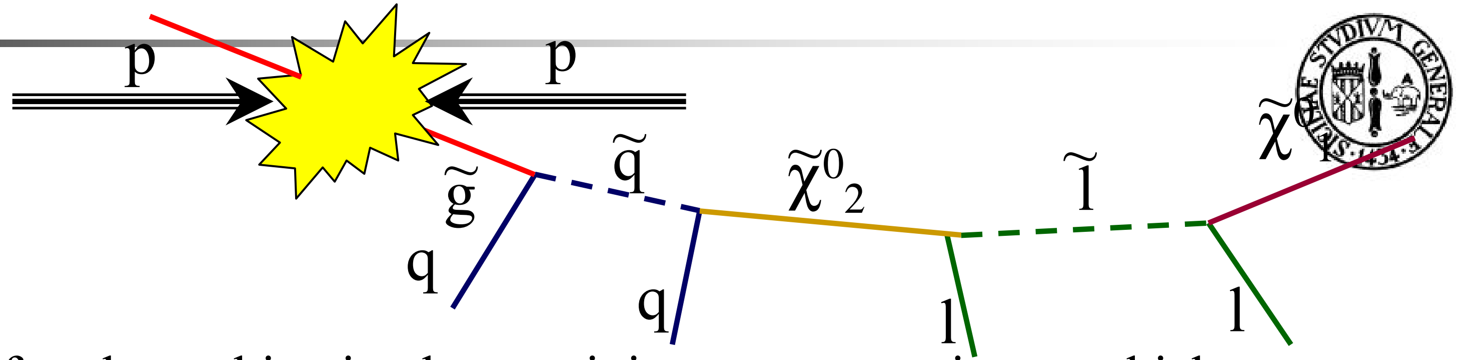
- Position of edge (LHC Point 5) measured with precision ~ 0.5% (30 fb^{-1}).

Polesello et al. 1997



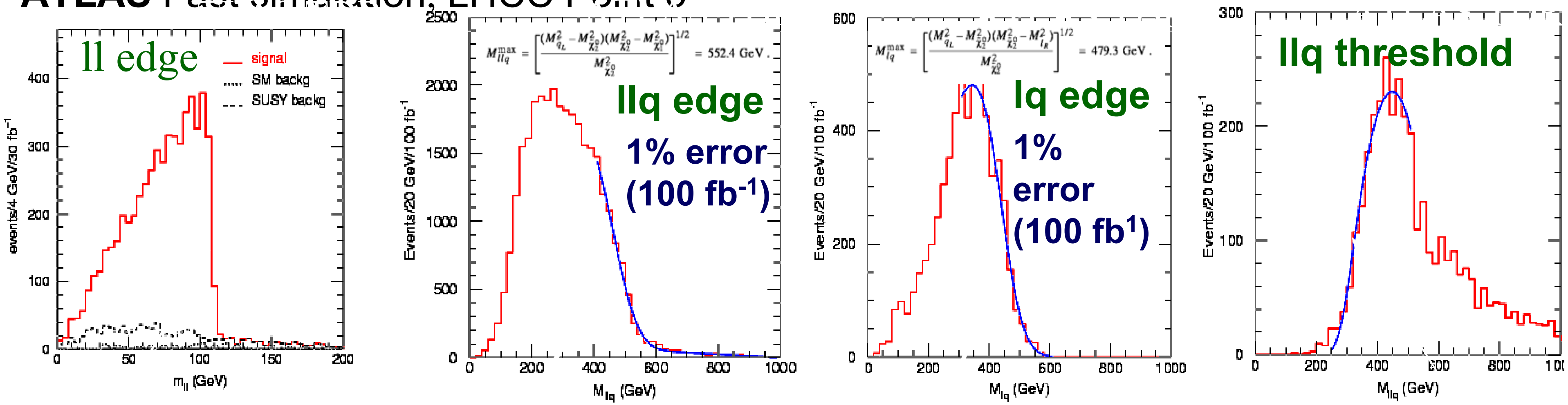
$$M_{ll}^{max} = M(\tilde\chi^0_2)\sqrt{1-\frac{M^2(\tilde l_R)}{M^2(\tilde\chi^0_2)}}\sqrt{1-\frac{M^2(\tilde\chi^0_1)}{M^2(\tilde l_R)}} = 108.93\ \text{GeV}$$

Mass reconstruction: a typical decay chain



The invariant mass of each combination has a minimum or a maximum which provides one constraint on the masses of $\tilde{\chi}^0_1$ $\tilde{\chi}^0_2$ $\tilde{l}$ $\tilde{q}$

ATLAS Fast simulation, LHCC Point 5



$$M_{ll}^{max} = M(\tilde{\chi}^0_2)\sqrt{1 - \frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}^0_2)}}\sqrt{1 - \frac{M^2(\tilde{\chi}^0_1)}{M^2(\tilde{l}_R)}}$$

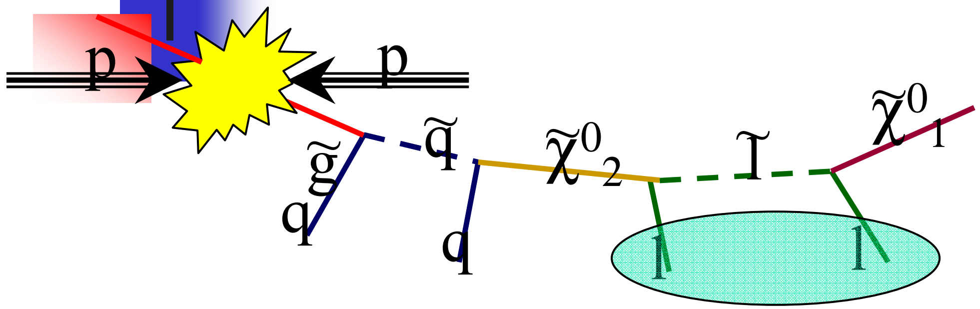
$$M_{llq}^{max} = \left[\frac{(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2})(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{\chi}^0_2}}\right]^{1/2}$$

$$M_{lq}^{max} = \left[\frac{(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2})(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{l}_R})}{M^2_{\tilde{\chi}^0_2}}\right]^{1/2}$$

$$(m_{llq}^{min})^2 = \Big\{\,[\,2\tilde{l}(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi}) + (\tilde{q}+\tilde{\xi})(\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi}) - (\tilde{q}-\tilde{\xi})\sqrt{(\tilde{\xi}+\tilde{l})^2(\tilde{l}+\tilde{\chi})^2 - 16\tilde{\xi}\tilde{l}^2\tilde{\chi}}\,]/(4\tilde{l}\tilde{\xi})$$

Formulas in Allanach et al., hep-ph/0007009

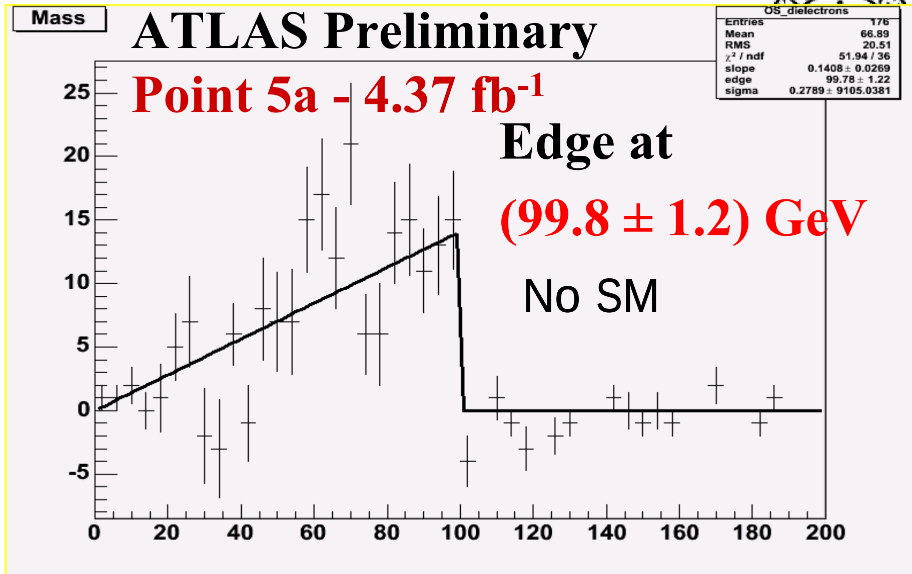
Full simulation: 2-lepton edge

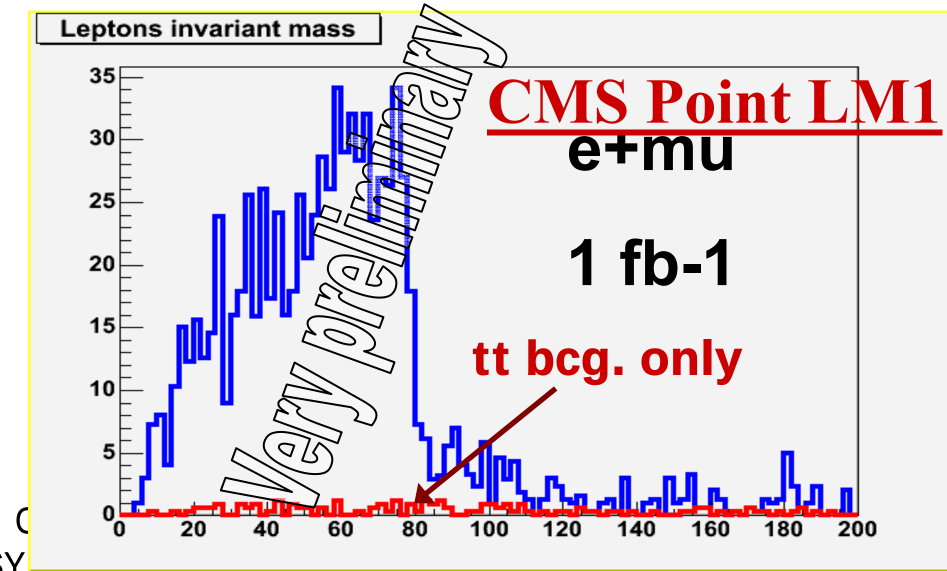


(e+e-) + β²(η) (μ+μ-) – β(η) (e+μ-)

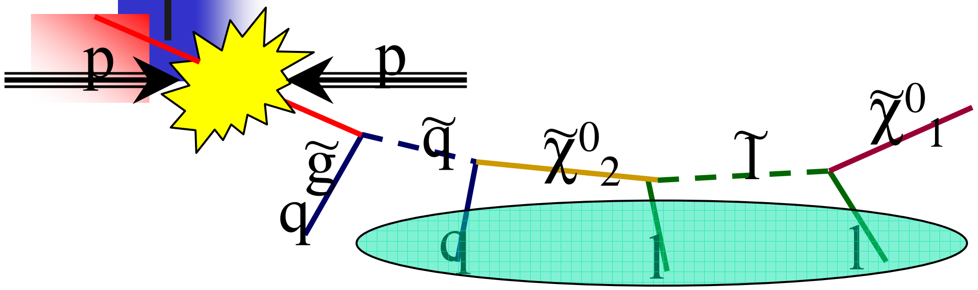
β is the acceptance correction factor for different e/μ efficiencies (from Z decays?)

The edge in dilepton invariant mass is a clear signature, with a very high S/B ratio



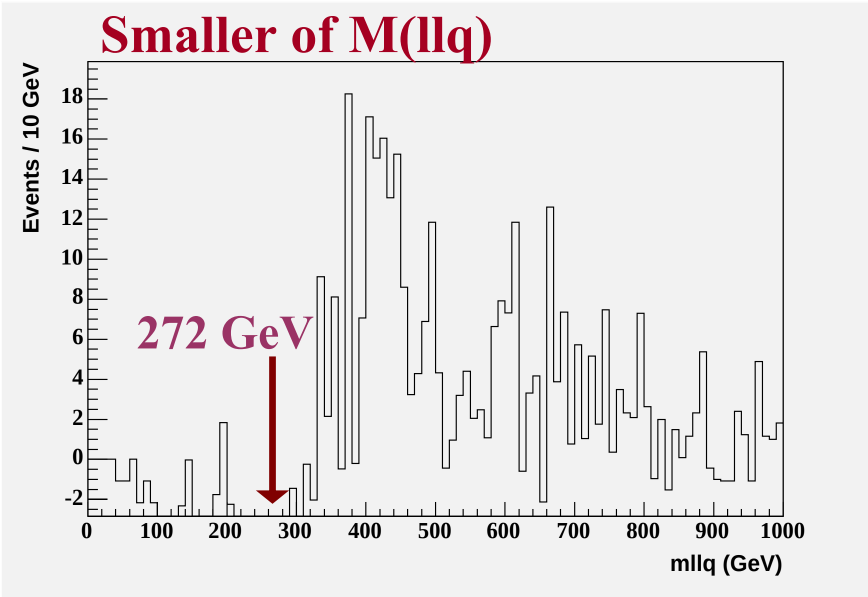


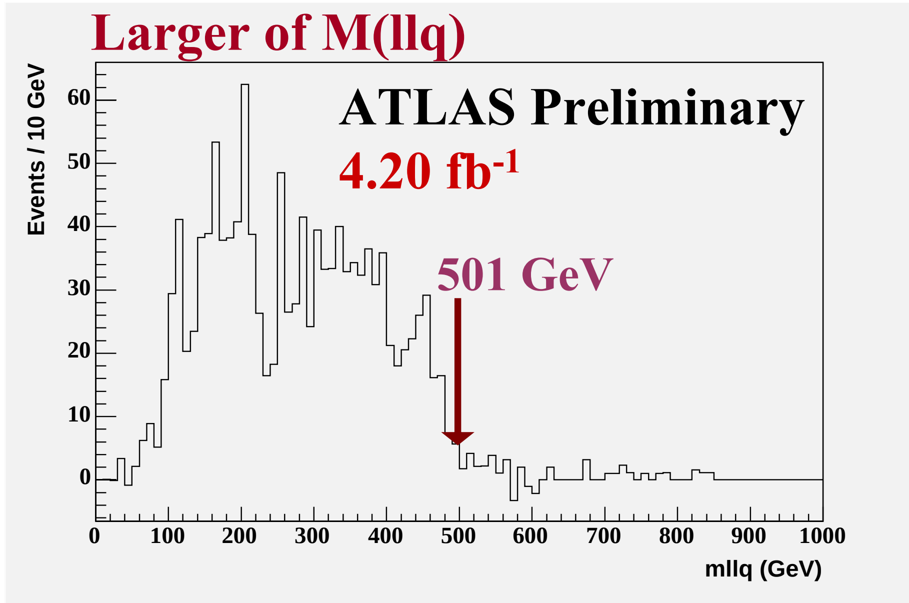
Jet+lepton combinations



Several edges (mass relations between SUSY particles) **may be visible with only a few fb^{-1} of data.**

Good jet resolution (and missing energy used in cuts) **more critical**





GMSB scenario

In gauge mediated supersymmetry breaking models, the lightest SUSY particle is the **gravitino**.
Phenomenology depends on nature and lifetime of the second lightest state:

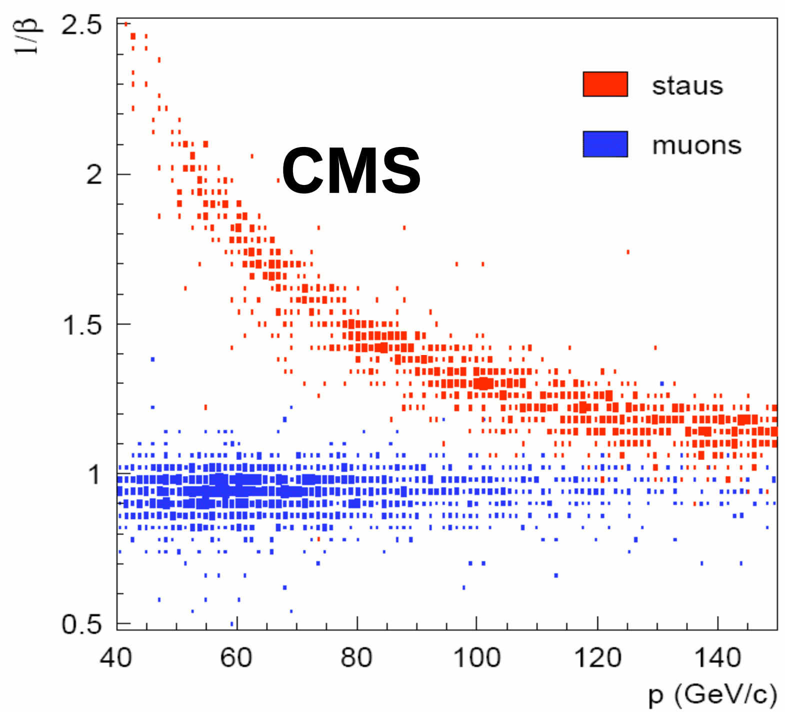
	$\tilde{\tau}_1$ is NLSP	**$\tilde{N}_1$ is NLSP**
cτ>>L	Like an heavy μ	Like mSUGRA
cτ~L	NLSP decays in the detector, possible lifetime measurements	
cτ<<L	Decay into 2τ	Decay into 2γ

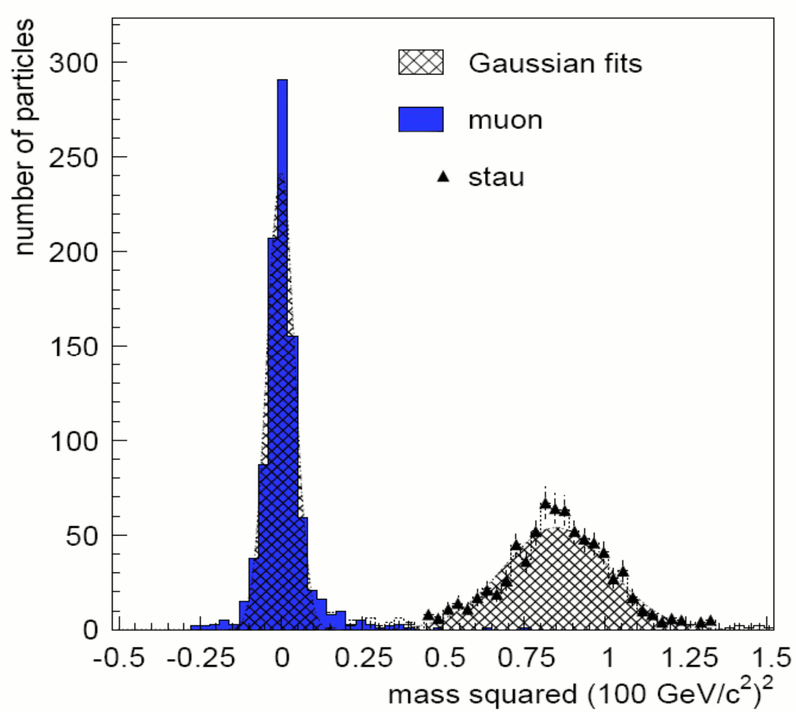
L=detector size

- **τ trigger and reconstruction** in early data not trivial
- **Decay into 2γ promising** (good ECAL performance early enough?)
- **Lifetime measurements**: need to understand **vertexing** in early data
  - For longer lifetimes, need to understand **background:**
    - Hard radiation from high-p_T cosmic muons
    - Delayed hadronic showers (K^0_L and neutrons)

GMSB

- Heavy slow "stable" leptons can be tagged with Time-Of-Flight measurements in muon drift tubes.
- Timing/triggering issues most critical?





Also similar ATLAS studies (Phys. TDR)

Conclusions

• Supersymmetry is one of the most promising extensions of the Standard Model.

• **In most models, a few fb-1 of data will allow the LHC experiments to measure a clear excess over the SM contribution and reconstruct several mass relations.** Whether we can achieve this within the first year of physics run will depend on the ability of the experiments to understand their detector and the SM processes in a short time.

• **Recent ATLAS and CMS studies focus on**

• Understanding of SM backgrounds with the use of the **latest Montecarlo tools,** and development of strategies to **validate the MC predictions with data.**

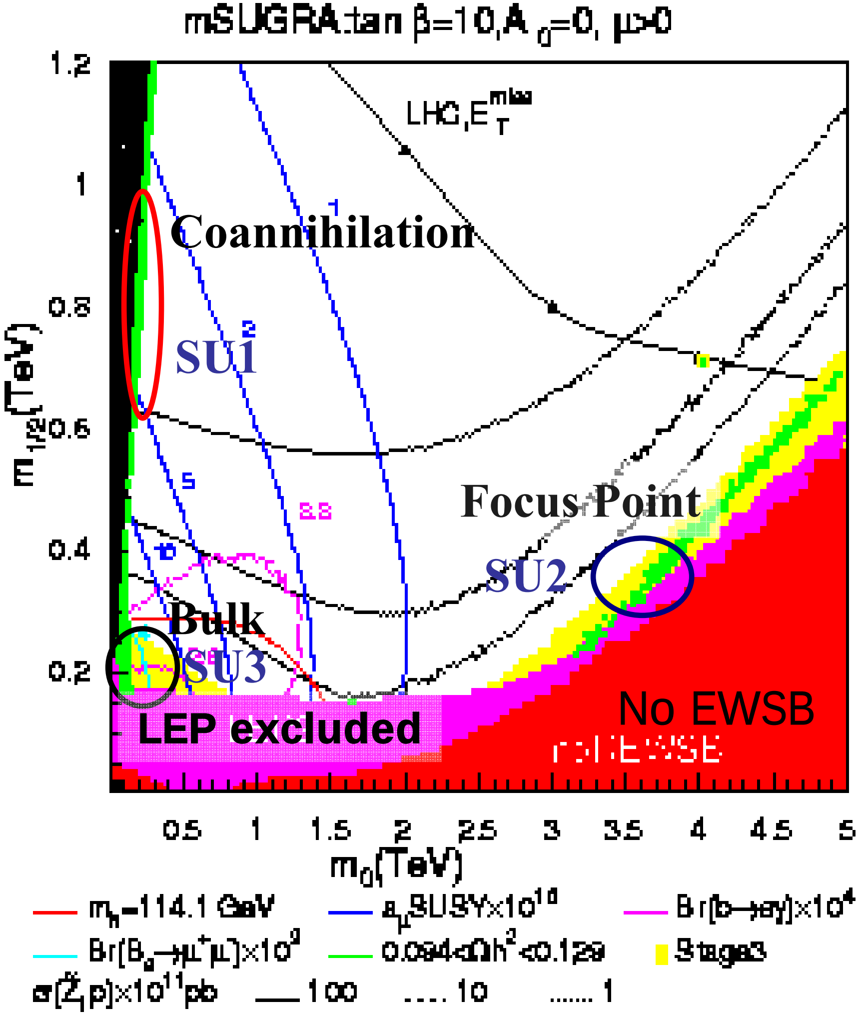
• **Large scale** productions of **full simulation** data, are used to study **detector systematic** and prepare for real data analysis.

•Looking eagerly forward to the first data!

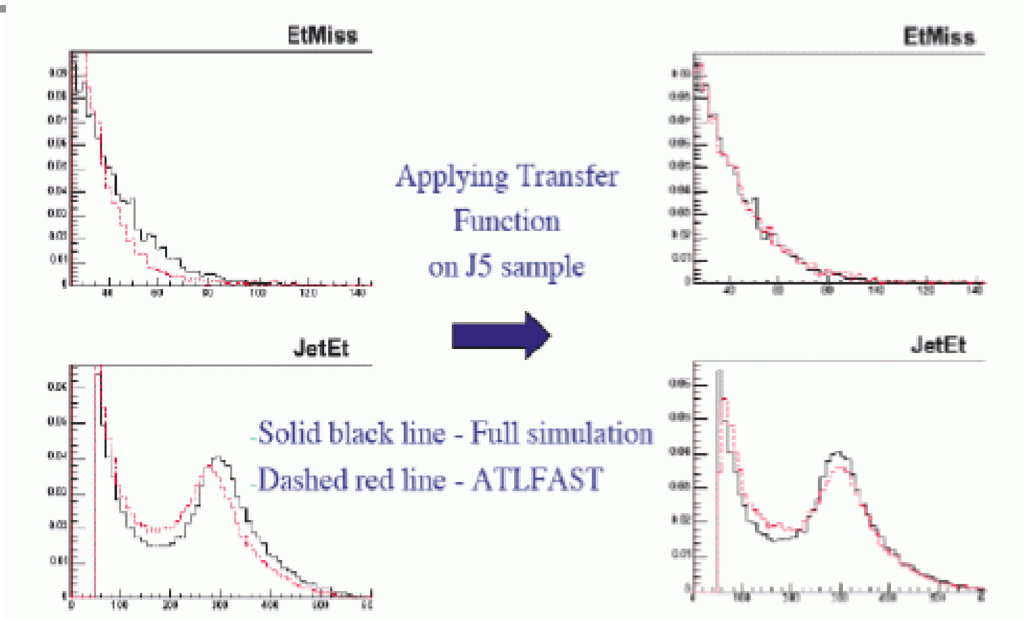
Backup slides

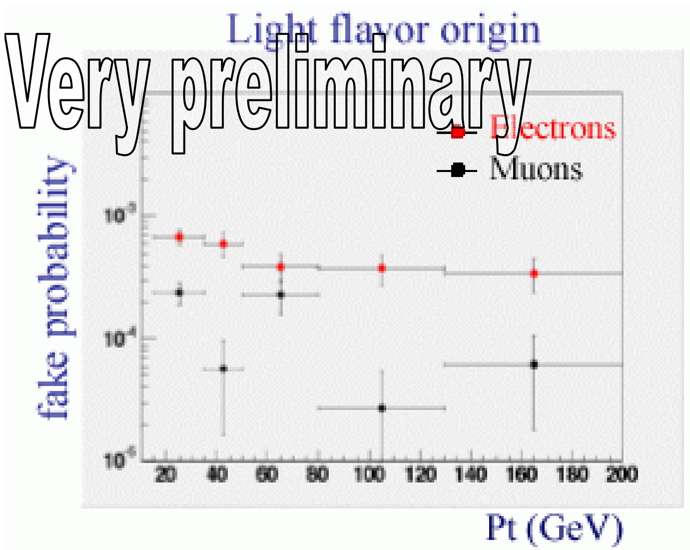
ATLAS Full simulation studies

- Goals: test software for data reconstruction and analysis, computing grid production. Study detector-related systematic. Validate fast simulation results.
- 10M events produced in ATLAS Data challenge of 2005.
- Five mSUGRA models studied. Focus on cosmologically interesting regions.
- Typical statistic of 10 fb^{-1}
- Some 10M events to be produced in full simulation in first half of 2005 with more realism (misaligned detector, calibrations, …) – focus on first 100 pb^{-1} of data



ATLAS Detector studies





- **Detailed studies of detector effects ongoing in ATLAS.**
- Jet energy response, lepton efficiency and fake rates studied with full simulation can be implemented in fast simulation to get high statistic samples with realistic detector response

Ricerca di nuova fisica con tau

- Trigger per tau (decadimento adronico)
  - **Il trigger sfrutta il fatto che i tau-jet hanno bassa molteplicità e sono generalmente ben collimati**
- Trigger L1: si cercano jet stretti:
  - Alta E_T in gruppi di 4x4 torri calorimetriche (almeno 90 GeV per eventi con 1 tau, almeno 60 GeV per eventi con 2 tau)- bassa E_T in tutti i gruppi 4x4 circostanti
- Trigger L2: cut aggiuntivo sull'isolamento nel calorimetro elettromagnetico:
  - $\Sigma E_T(R<0.4)$ - $\Sigma E_T(R<0.13) < 5$ GeV [R=Raggio in η,φ attorno all'asse del jet]
- High Level Trigger: isolamento nel tracciatore
  - Studiate performance usando il rivelatore a pixel (o pixel + microstrisce)
  - La traccia con più alto P_T all'interno del cono del jet (R_M=0.1) può avere altre tracce vicine entro il cono "di segnale" (R_S=0.05) ma non tra questo e il cono "di isolamento" (R_I=0.2÷0.6)
  - Efficienze ottenute: attorno al 40% per eventi con 2tau e R_I=0.3

- Risultati ottenuti in caso di detector "perfetto"
- Effetti del disallineamento iniziale del tracciatore:
  - P_T poco affetto da errori
  - Altri parametri di traccia con risoluzioni molto peggiori
  - Deterioramento dell'efficienza di trigger probabile, ma non quantificato

Disallineamento del tracker: effetti sulla ricostruzione delle tracce

- Studi fatti usando muoni; tracciatore completo
- Misure di P_T
  - La determinazione della media è precisa anche in uno scenario di First Data Taking
  - Il misalignment degrada soprattutto la risoluzione
    - No misalignment: risoluzione = 2% fino a η=1.75
    - First Data Taking: risoluzione = 4 – 5% fino a η=1.75
    - LongTerm: Nessun degrado significativo
    - Per η>1.75 degradazione lineare al crescere di η
- Altri parametri di traccia (First Data Taking)
  - Grosso degrado nella risoluzione di ϕ e d0 (fattori 4 e 6 rispetto all'allineamento perfetto)
    - Per d0 domina l'errore dovuto al misalignment del primo strato di pixel
  - Degrado meno significativo per z0 e cot(θ)
  - Per d0, z0 e cot(θ) risoluzione peggiora all'aumentare di η
- Gli effetti del disallineamento sono più marcati all'aumentare del P_T del muone

Disallineamento del tracker: effetti sulla determinazione del vertice primario

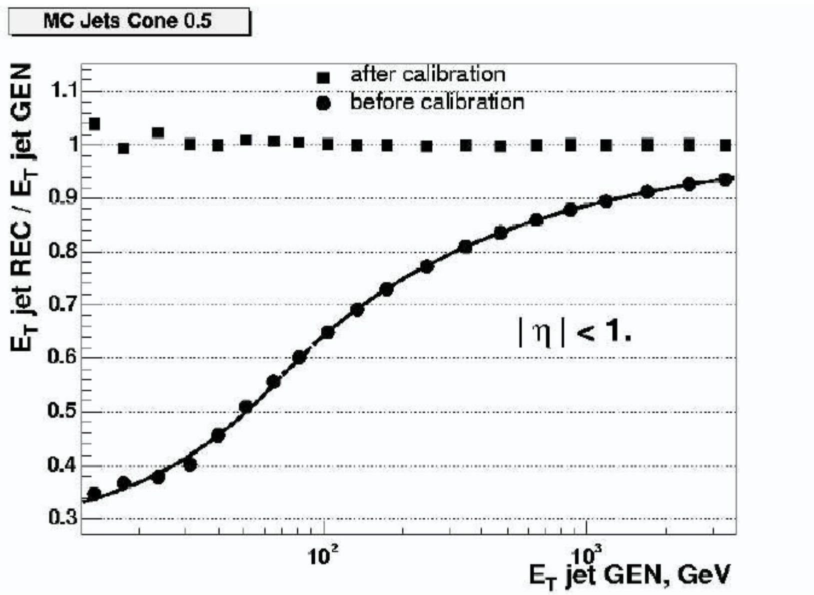
- Simulati vari canali fisici (NO SUSY purtroppo), per simulare varie condizioni di molteplicità nel tracciatore
  - $B_S^0 \rightarrow J/\psi\ \phi$
  - ttH
  - DY
- In generale il disallineamento sembra avere effetti trascurabili sull'efficienza e la purezza di assegnazione delle tracce al vertice primario

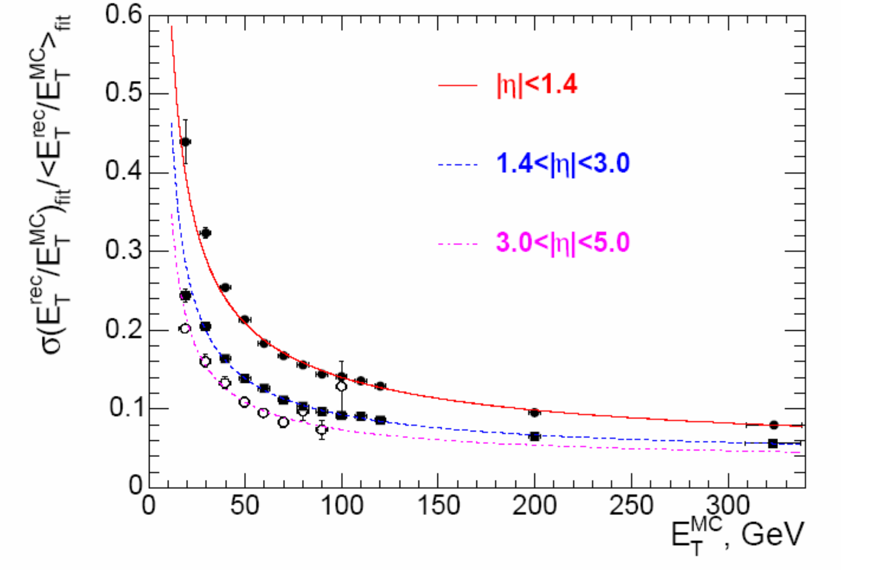
Calibrazione del calorimetro elettromagnetico

- Precisione di progetto <0.5%
- Circa il 25% degli elementi saranno precalibrati nel test-beam (precisione migliore del 5%)
- L'intercalibrazione ai livelli nominali e la determinazione della scala assoluta di energie si può raggiungere in breve tempo (circa 2 mesi di data taking) usando misure di E/P per elettroni da decadimenti di W o la posizione del picco della massa invariante e^+e^- nel decadimento $Z \rightarrow ee$
- Tenuto conto del disallineamento del tracciatore ci vorrà probabilmente più tempo
- La calibrazione di ECAL non sembra comunque essere un grosso issue per le misure di fisica

Calibrazione dell'energia dei jet (1)

- Risposta in E (o in E_T) del calorimetro parametrizzata da k_{jet}:
  $E_{jet}^{Real}=E_{jet}^{Rec}/k_{jet}$
- Calibrazione con jet di generatore
  - Sopra: Rapporto tra E_T^{RecJet} e E_T^{GenJet} nel barrel prima e dopo la calibrazione
  - Sotto: Risoluzione in funzione E_T per varie η (DOPO la calibrazione)



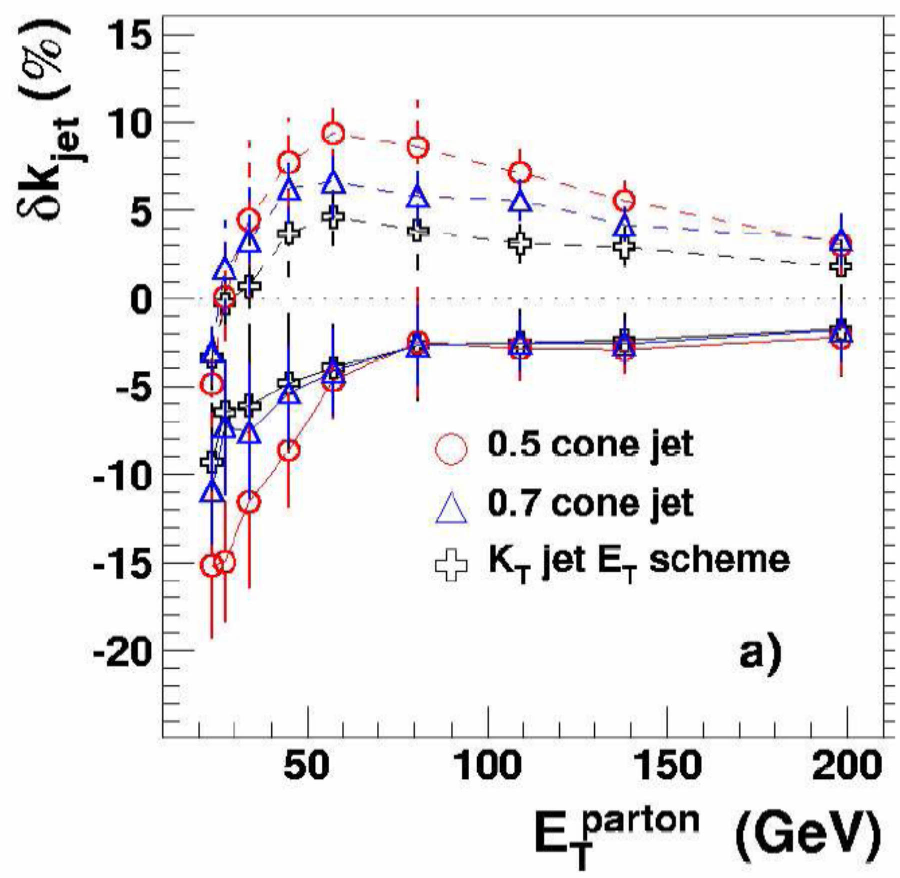


Calibrazione dell'energia dei jet (2)

- Calibrazione con algoritmi basati sui jet:
  - Si usa la topologia γ+jet
  - Si bilancia P_T del γ (noto dal calorimetro EM) e quello del jet (ipotesi di emissione back-to-back)
  - In prima approssimazione

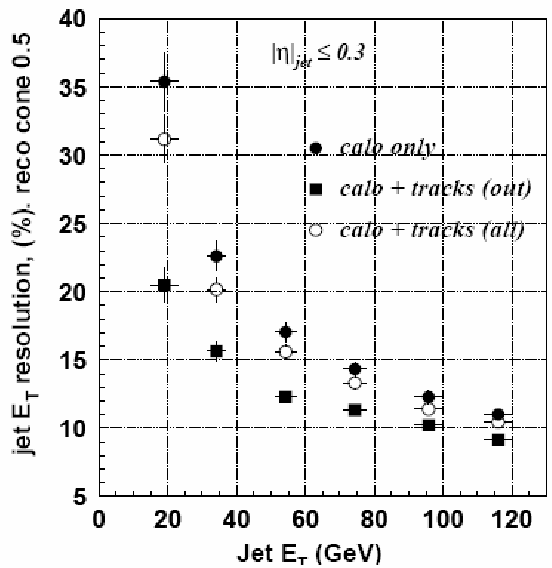
$$k_{jet}=P_T^{RecJet}/P_T^{\gamma}$$

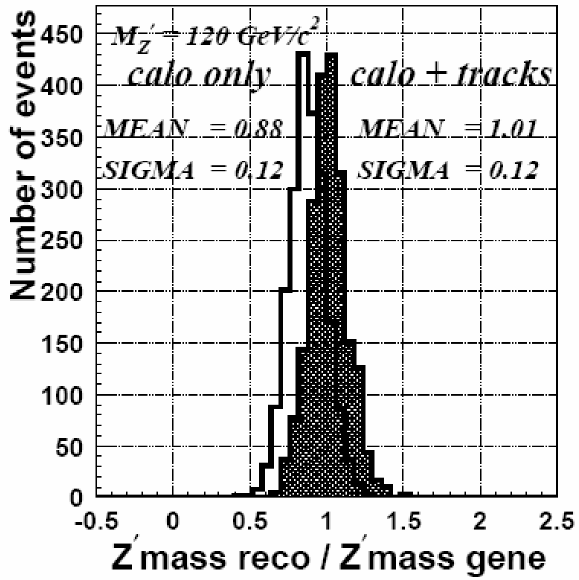
- Se il sistema γ+jet ha $P_T \neq 0$, si sposta la media della distribuzione di k_{jet}, ma non la posizione del picco
  - Fit gaussiano nell'intorno del picco
- Errori sistematici dovuti alla contaminazione di jet da gluoni
  - In figura, errore relativo su k_{jet} per 3 tipi di jet, con (linee tratteggiate) o senza (linee continue) includere i jet da gluoni tra quelli usati per la calibrazione



Calibrazione dell'energia dei jet (3)

- Calibrazione con le tracce:
  - Sostituire all'E_T misurata nel calorimetro il P_T delle tracce che all'ingresso del calorimetro sono dentro al cono del jet
- Sopra: risoluzione migliorata di un fattore 1.7 per jet da 20 GeV e del 15% per jet da 100 GeV
- Sotto: scala di massa di un generico oggetto X →jj quasi del tutto ripristinata dopo la correzione





Calibrazione dell'energia dei jet (4)

- Osservazioni:
- Per quanto ci riguarda puoi leggere le slide sulla calibrazione "al contrario", cioè vedendo qual è la degradazione nella scala di energia e nella risoluzione rispetto ai valori nominali (post calibrazioni) che ci si aspetta all'inizio
- I risultati più drammatici si hanno per jet soffici, con grosse perdite di risoluzione e una scala molto ridotta. Anche nel range tipico di jet da eventi SUSY (grosso modo 100 – 500 GeV), pur avendo una buona risoluzione, c'è però da aspettarsi un sistematico non trascurabile (meno 20 – 30% rispetto al valore corretto)

SUSY Higgs sector

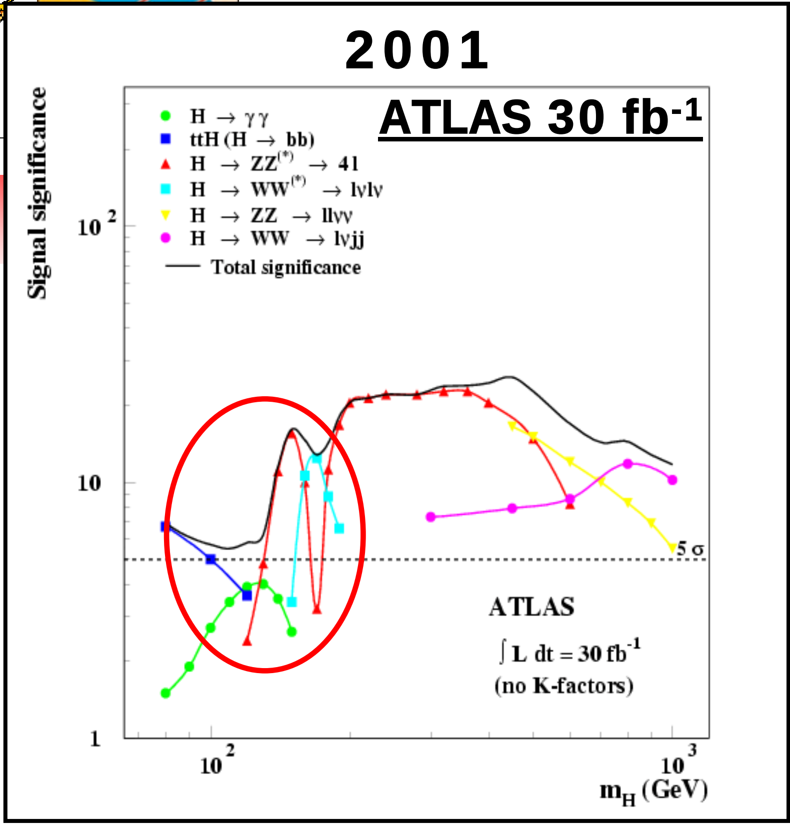
2 doublets, 5 physical states: h^0,H^0,A^0,$H^\pm$ (mix if CPV)

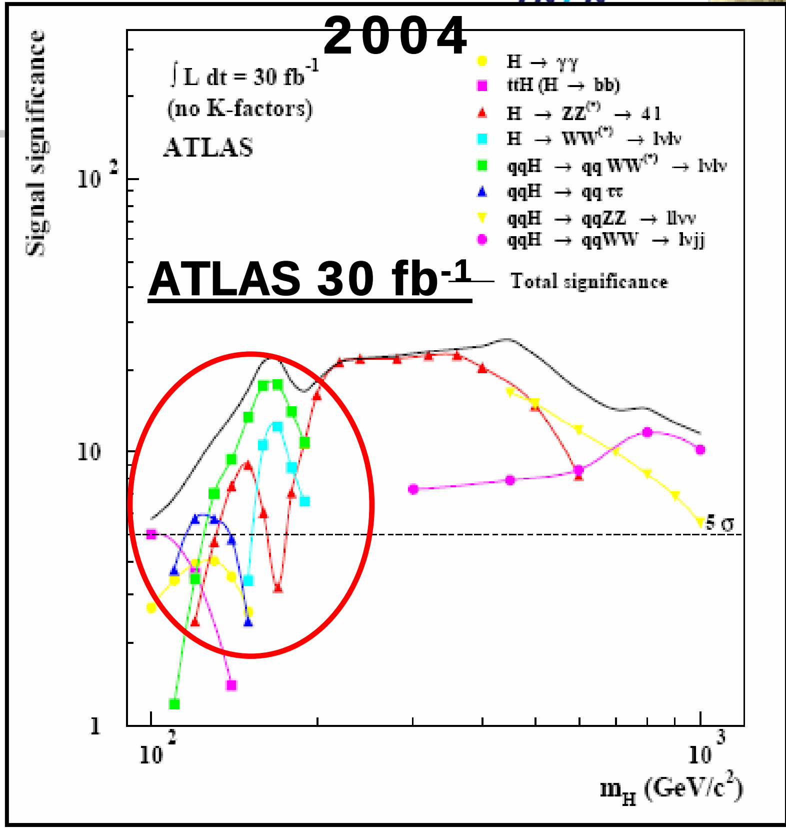
h light, SM-like. m < 133 GeV

Lots of free parameters in MSSM

- Often assume heavy SUSY states (no Higgs decay into SUSY nor Higgs production in SUSY decays)
- Define banchmark scenarios. Example: **Carena et al. , Eur.Phys.J.C26,601**
  - MASSH – maximum h mass allowed by theory
  - **Nomixing** – small h mass (difficult for LHC)
  - gluophobic – reduces hg coupling (and LHC production xSection)
  - **Small** α – reduces hbb and h$\tau\tau$ couplings (harms some discovery channels)

SM Discovery Potential: New and Updated Analysis



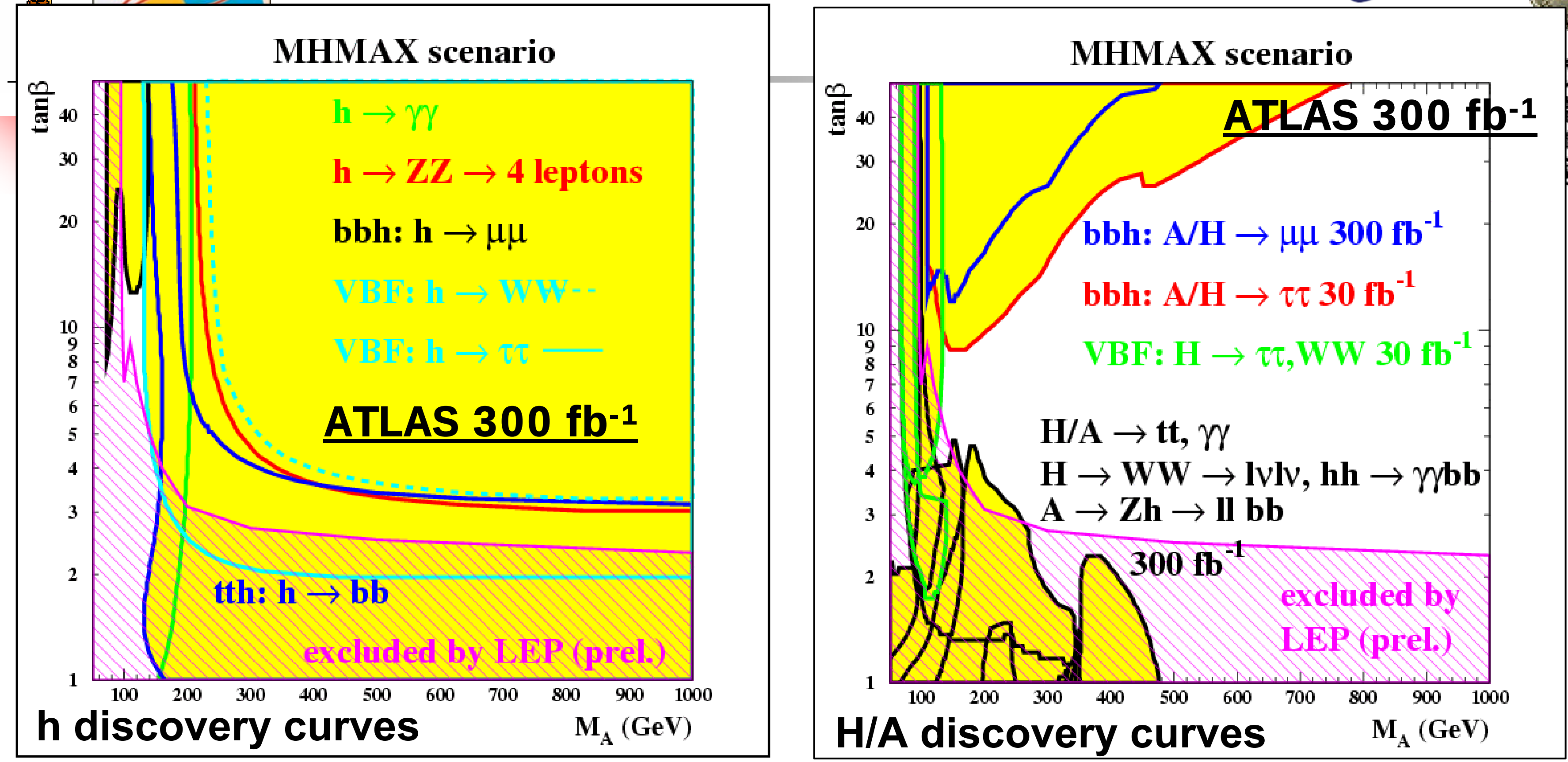


new : Vector Boson Fusion (VBF), H→ ττ and H →WW

affects discovery potential for light Higgs (relevant for the h boson in SUSY)

Issues for early data taking: tau reconstruction, forward jet reconstruction and trigger, veto on central jets (underlying event, ...)

SUSY Higgs scans



LEP limit depends on top mass (here m_{top} = 175 GeV). No tanβ limit for m_t > 183 GeV

Statistic is 30 fb^{-1} or 300 fb^{-1} depending on channels. Stat. errors only.

Always at least one Higgs is seen (also for the other scenarios).

Over a large parameter space, only h is observable and discrimination from SM Higgs is very difficult.

Other SUSY-Higgs studies

Higgs in cascade decays. Peak in bb invariant mass distribution – with SUSY cuts may be much easier to see than SM Higgs.