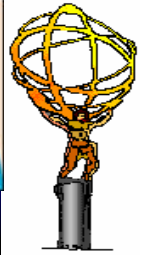


Tommaso Lari
Università and INFN Milano

Misura di massa delle sparticelle ad LHC



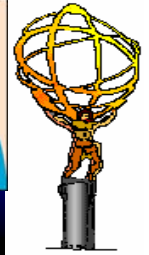
Supersimmetria a LHC



- Tuttavia il modello di “Fisica oltre il Modello Standard” piu’ promettente e studiato.
- **Scenario tipico**: produzione di s-particelle **colorate** (squarks e gluini) che decadono nella s-particella piu leggera (χ^0_1).
 - La massa di tali particelle dovrebbe essere minore di ca. 1 TeV per mantenere una delle principali motivazioni della teoria (stabilizzare la scala elettrodebole senza fine-tuning).
 - La particella SUSY piu leggera dovrebbe essere stabile e debolmente interagente per spiegare la materia oscura
- **Tipica segnatura**: getti, energia mancante, leptoni.



Cronologia SUSY a LHC



- **Fase 1 (Ricerche inclusive)**: Osservare un eccesso di eventi con getti + energia mancante + leptoni, convincersi che sono dovuti a “nuova fisica”.

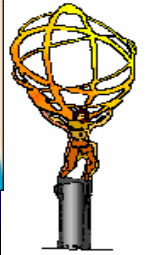
Attualmente: Studiare il potenziale di scoperta SUSY/ \sqrt{SM} delle analisi con uno scan dello spazio dei parametri (**talk Galanti**)

- **Fase 2 (Spettroscopia SUSY)**: Ricostruire i decadimenti e le masse delle s-particelle per determinare il meccanismo di rottura di supersimmetria ed i parametri della teoria.

Attualmente: Su un punto nello spazio dei parametri, sviluppare analisi per ricostruire le masse. Le analisi sono (dovrebbero essere) utili in una vasta regione dello spazio dei parametri, e non essere specifiche del modello particolare.



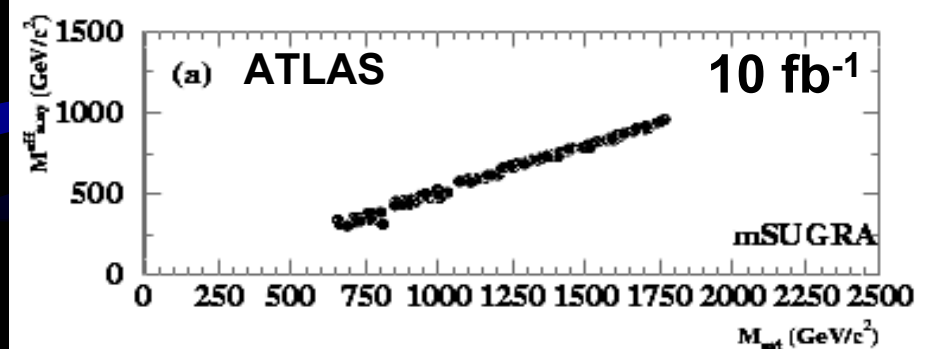
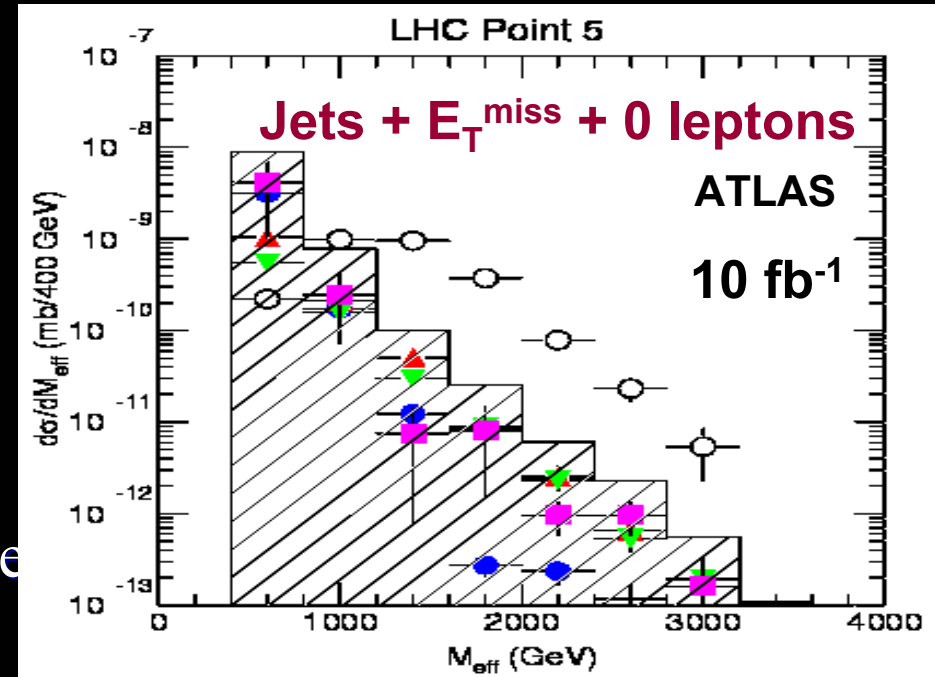
Ricerche inclusive



- Maggiori dettagli nel talk di Galanti.
- La “Massa efficace”:

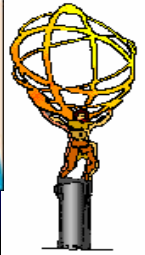
$$M_{\text{eff}} = \sum |p_{\text{T}}^i| + E_{\text{T}}^{\text{miss}}$$

e' utile per discriminare SM e SUSY e ha un picco fortemente correlato (almeno in mSUGRA) con la massa delle s-particelle primarie prodotte nella collisione pp.

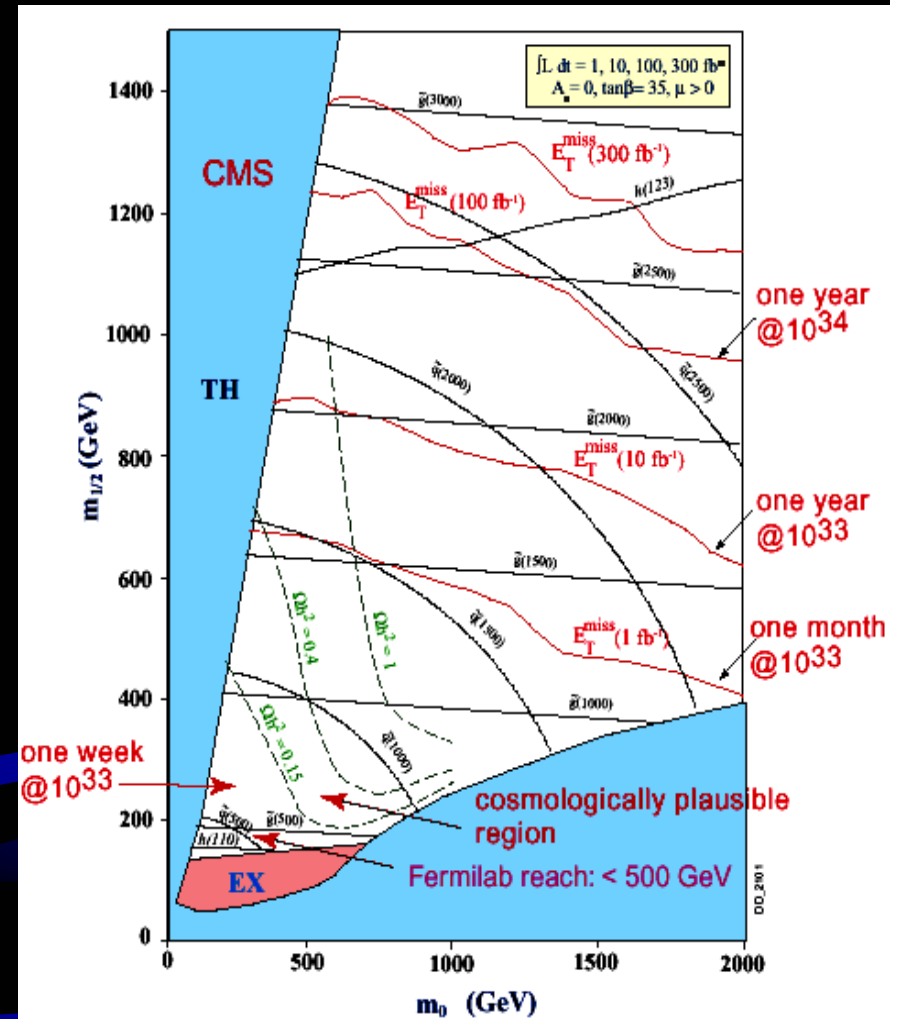




Potenziale di scoperta

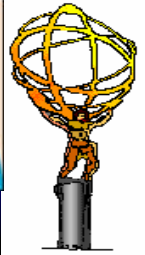


- Per $M(\text{SUSY}) < 1\text{TeV}$ la scoperta sara' potenzialmente molto rapida (limitata dal tempo necessario a capire i fondi del MS)





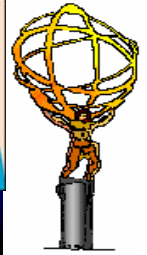
Ricerche esclusive



- Mi concentrerò sulle tecniche di ricostruzione per alcuni punti selezionati dello spazio dei parametri **mSUGRA**:
 - Punto 5 – ATLAS Physics TDR
 - Punto 5a - ATL-PHYS-2004-011 Simulazione completa
 - SPS1a – ATL-PHYS-2004-007
 - B (G,H) – CMS NOTE 2004-029
- Le stesse tecniche sono applicabili per molte altre (ma non tutte) scelte dei parametri.
- Non pretenderò di descrivere tutte le possibili analisi per tutti i possibili punti/modelli studiati!
(Vedi anche la presentazione di Galanti)

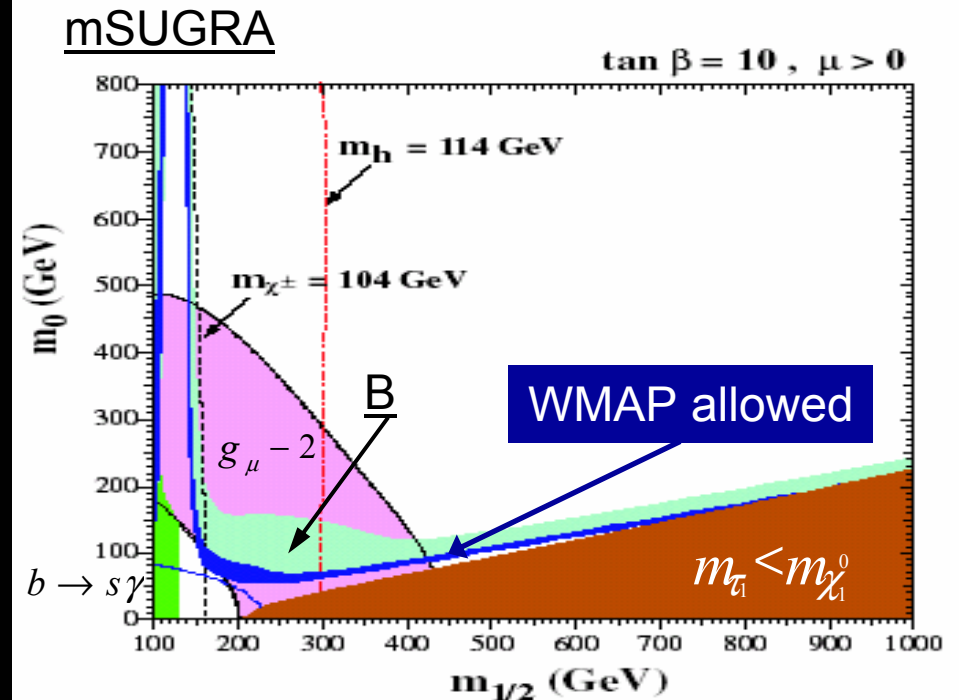


Un tipico scenario (mSUGRA)

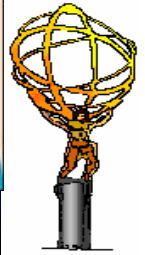


	<u>CMS</u>	<u>ATLAS</u>	<u>ATLAS</u>
Punto	B	SPS1a	5a
M_0	100	100	100
$M_{1/2}$	250	250	300
$\tan \beta$	10	10	6
M	+	+	+
A_0	0	-100	-300
$M(u)$	537		
σ (pb)	58		

All masses/energies in GeV

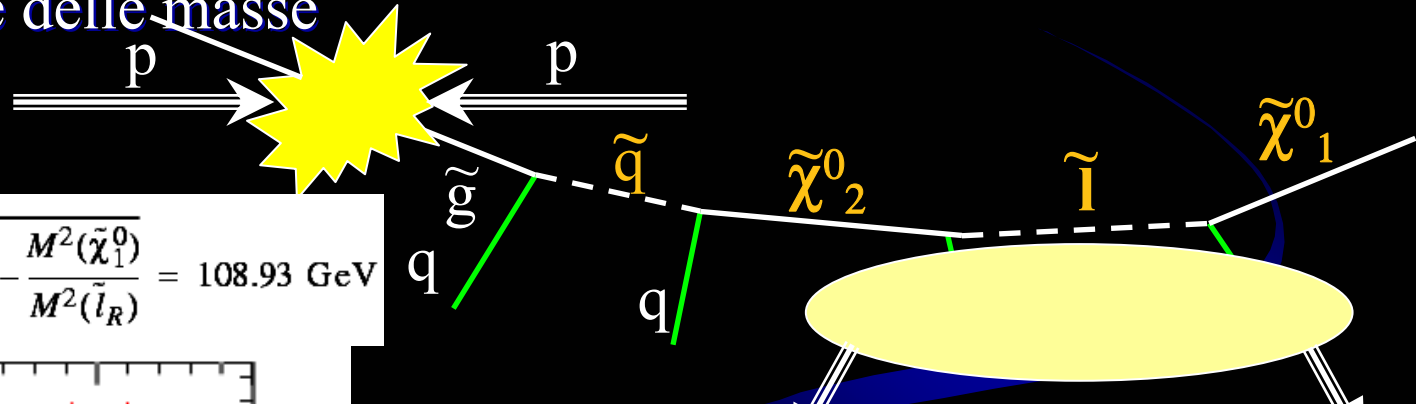


Questi punti sono scelti nella regione dello spazio dei parametri che da' una densita' ragionevole (non troppo alta) di materia oscura e a scale SUSY basse (naturalzza, alta sezione d'urto a LHC).

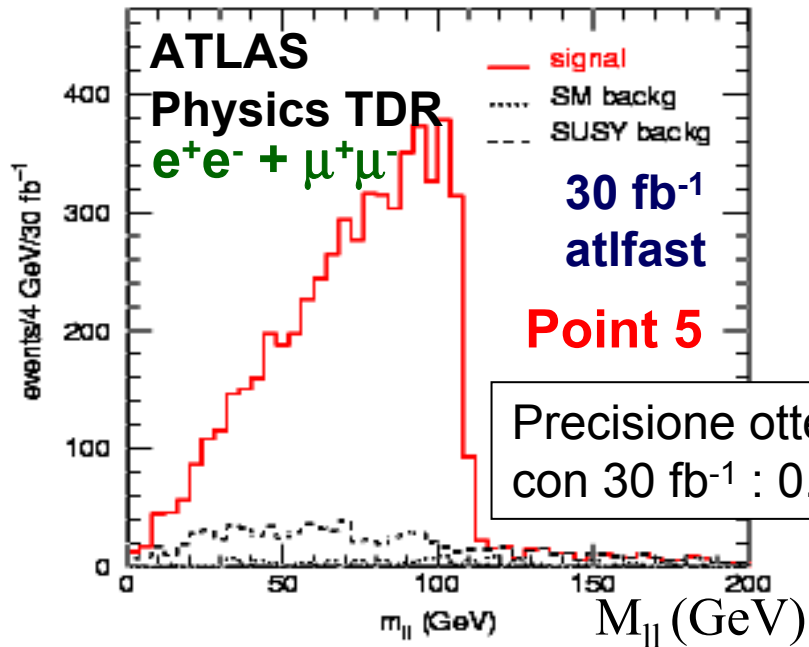


Il decadimento d'oro

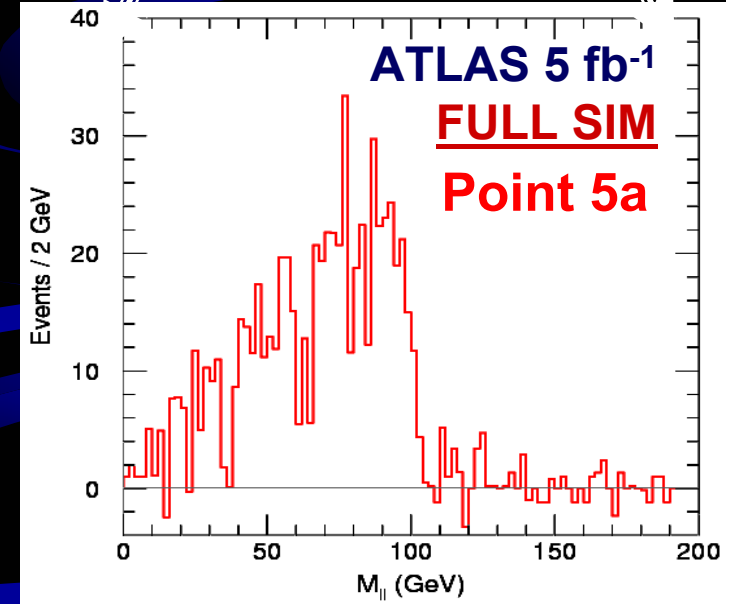
Il decadimento leptonic del neutralino
e' il tipico punto di partenza per la
ricostruzione delle masse



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

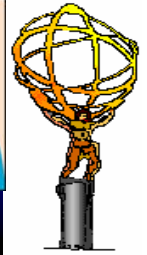


Precisione ottenibile sull'edge
con 30 fb⁻¹ : 0.5%

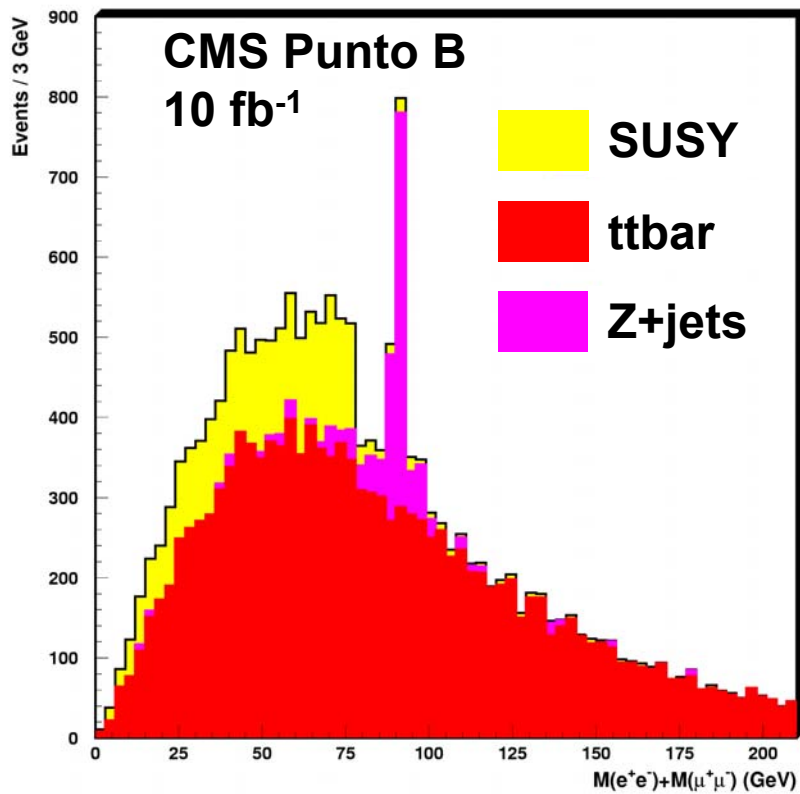




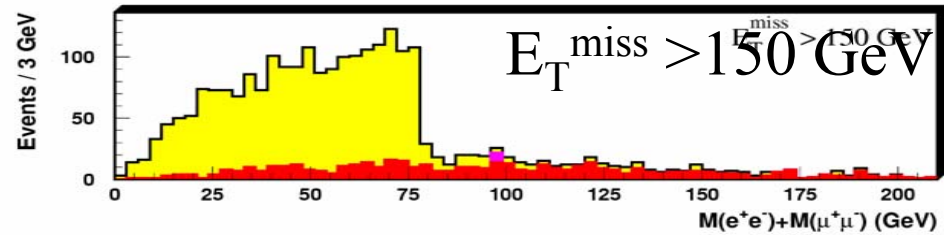
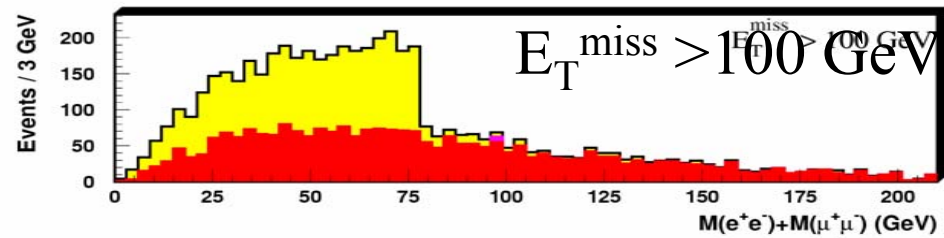
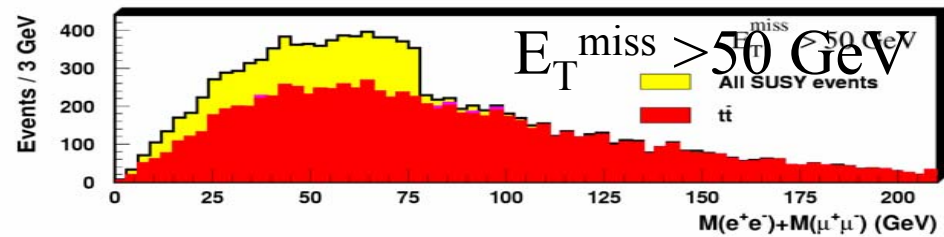
Selezione di eventi SUSY



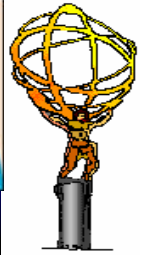
Si puo' far fuori il MS con tagli su getti ed energia mancante.
 Il fondo MS+SUSY residuo si puo' sottrarre con le coppie $e^+ \mu^- + \mu^+ e^-$



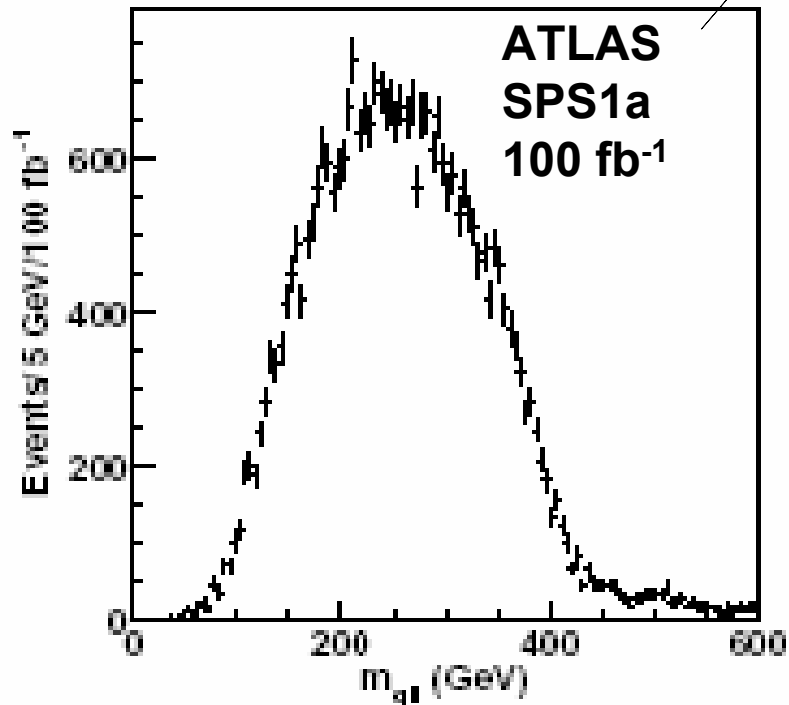
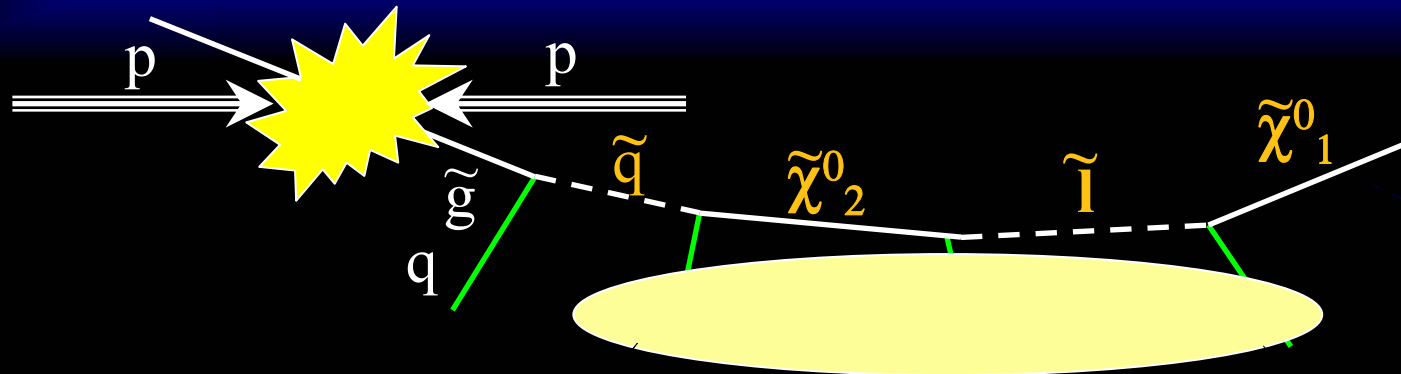
2 b-getti + 2 leptoni SFOS



2 b-getti + 2 leptoni SFOS + energia mancante

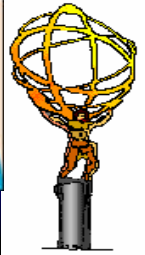


Ulteriori combinazioni: ql edge

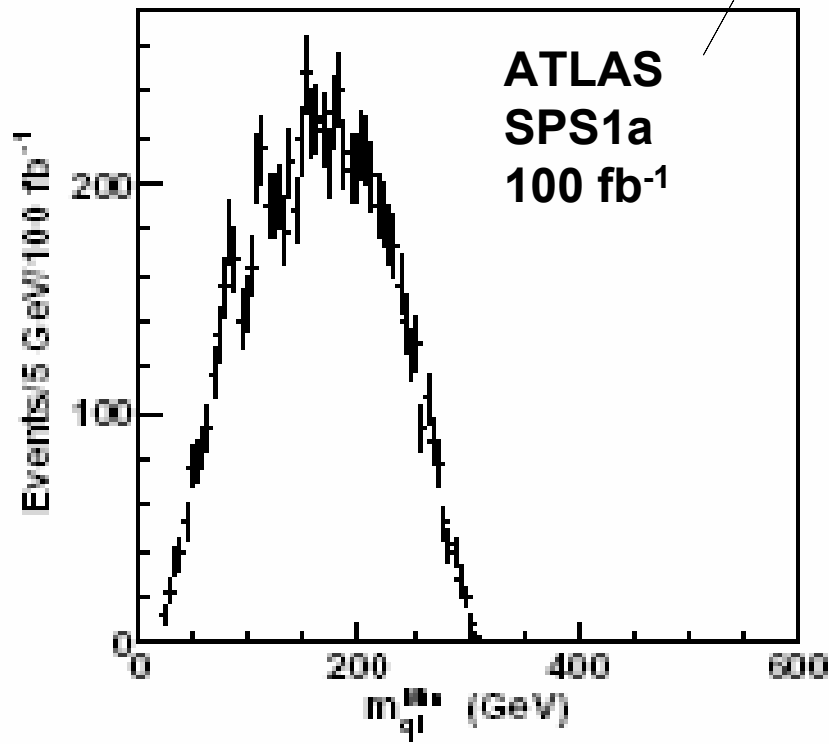
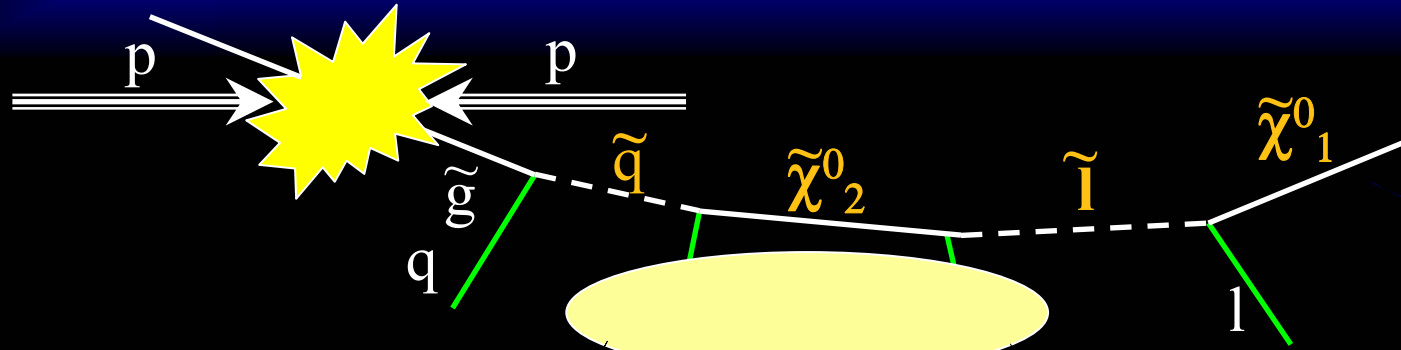


$$M_{llq}^{\max} = \left[\frac{(M_{qL}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2} \right]^{1/2}$$

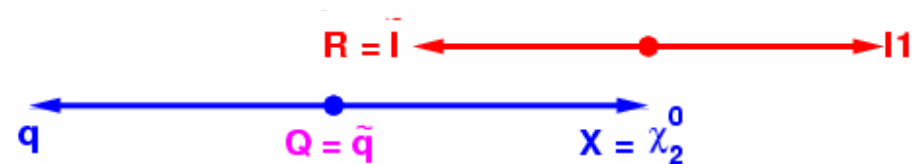
The two lepton are combined with one of the two hardest jets (the combination with the smaller invariant mass)



Ulteriori combinazioni: ql min



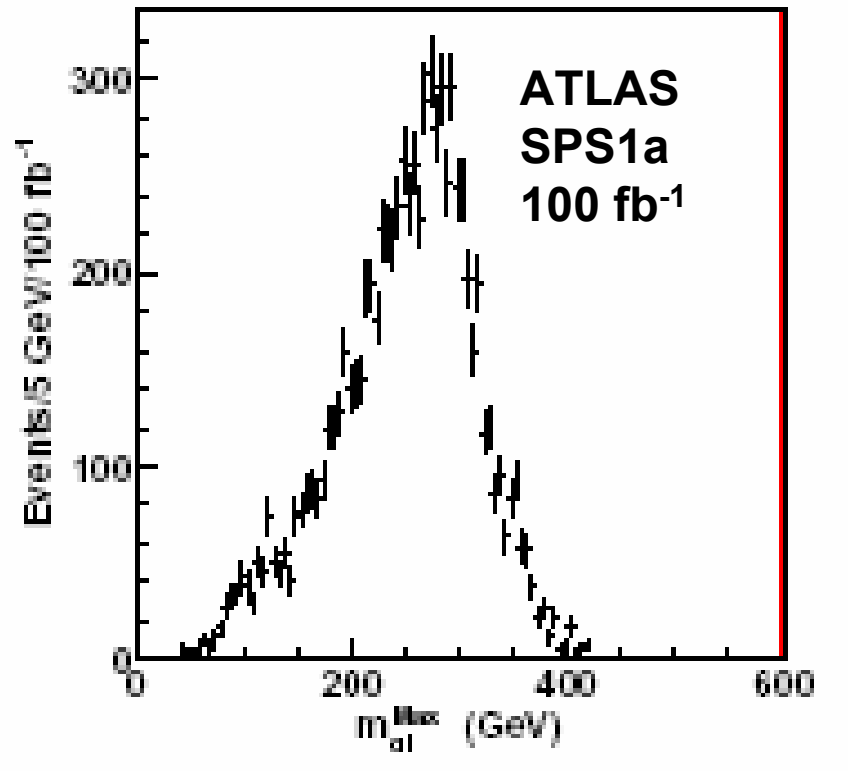
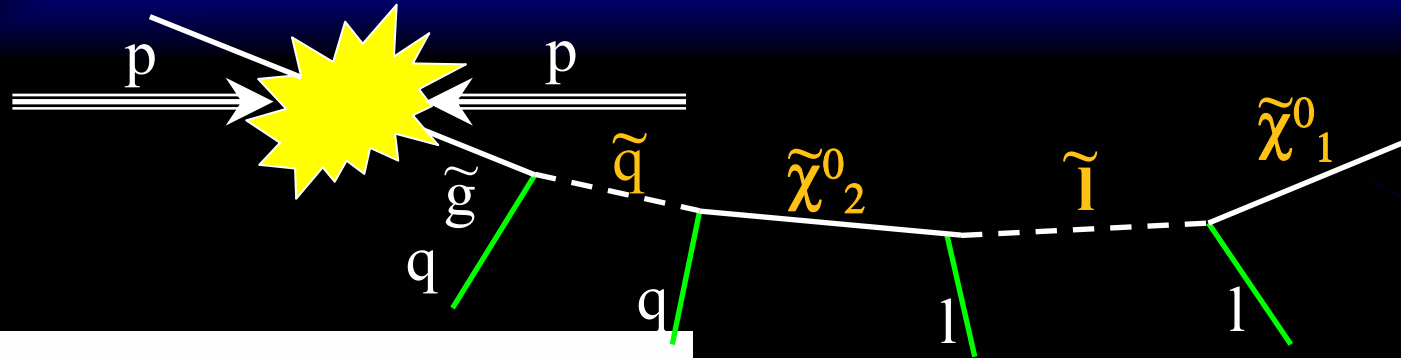
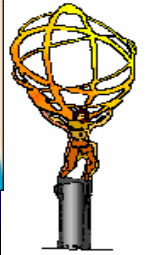
$$(m_{ql}^2)_{\min}^{\text{edge}} = \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)}{m_{\tilde{\chi}_2^0}^2}$$



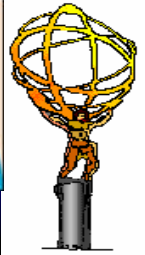
When only one qll combination is Below the edge (the ambiguity on the right jet) the two ql combinations (with lower and larger invariant mass) give two further edges.



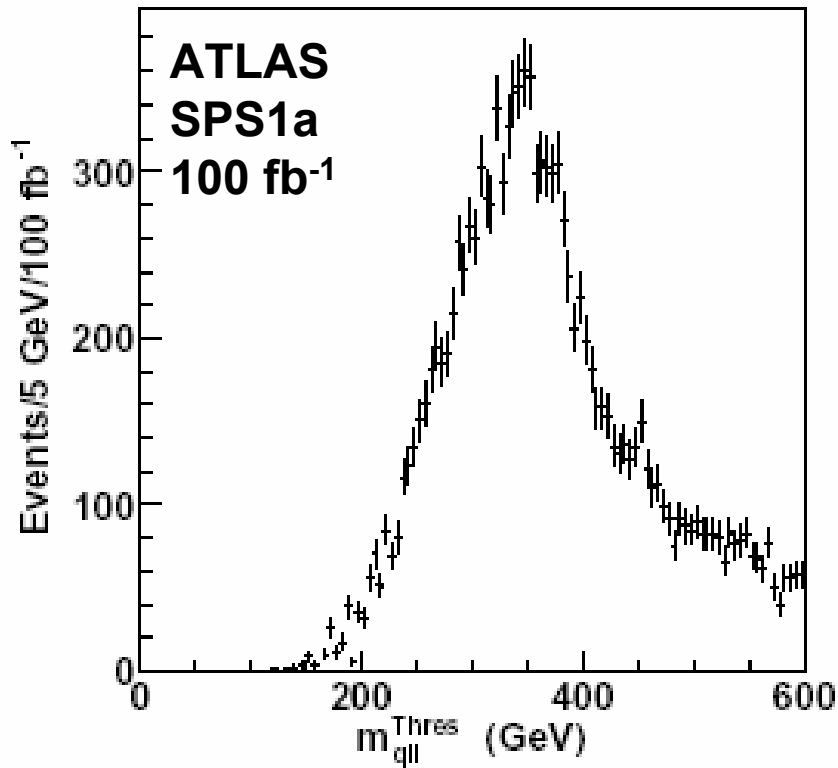
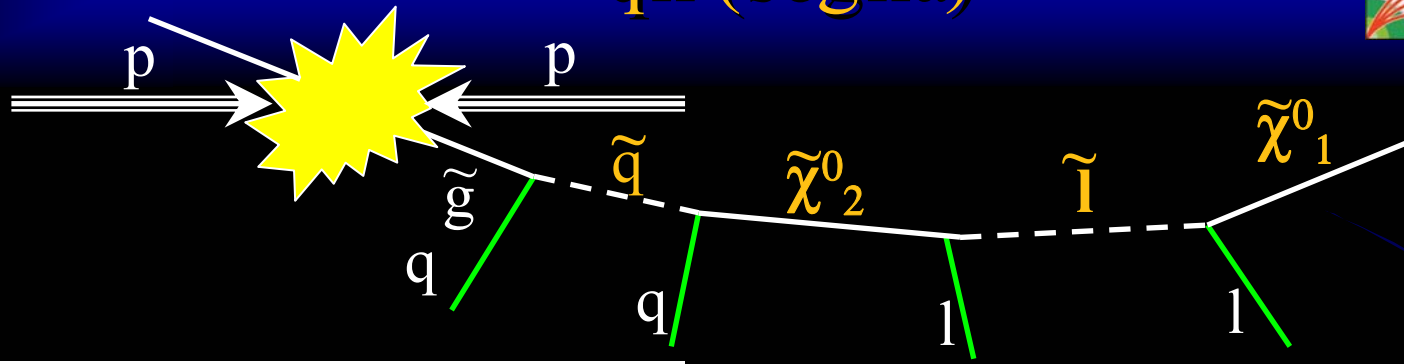
ql max



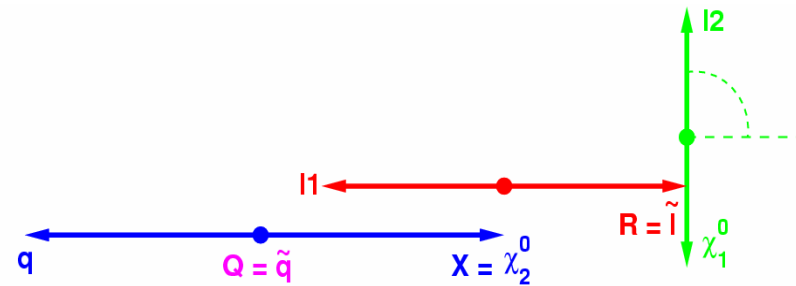
$$M_{lq}^{\max} = \left[\frac{(M_{q_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{l_R}^2)}{M_{\tilde{\chi}_2^0}^2} \right]^{1/2}$$



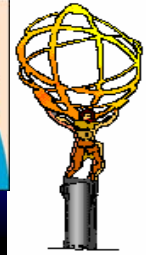
qll (soglia)



$$(m_{qll}^2)^{\text{thres}} = \frac{[(m_{\tilde{q}_L}^2 + m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2) - (m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)\sqrt{(m_{\tilde{\chi}_2^0}^2 + m_{\tilde{l}_R}^2)^2(m_{\tilde{l}_R}^2 + m_{\tilde{\chi}_1^0}^2)^2 - 16m_{\tilde{\chi}_2^0}^2 m_{\tilde{l}_R}^4 m_{\tilde{\chi}_1^0}^2} + 2m_{\tilde{l}_R}^2(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)]}{(4m_{\tilde{l}_R}^2 m_{\tilde{\chi}_2^0}^2)}$$



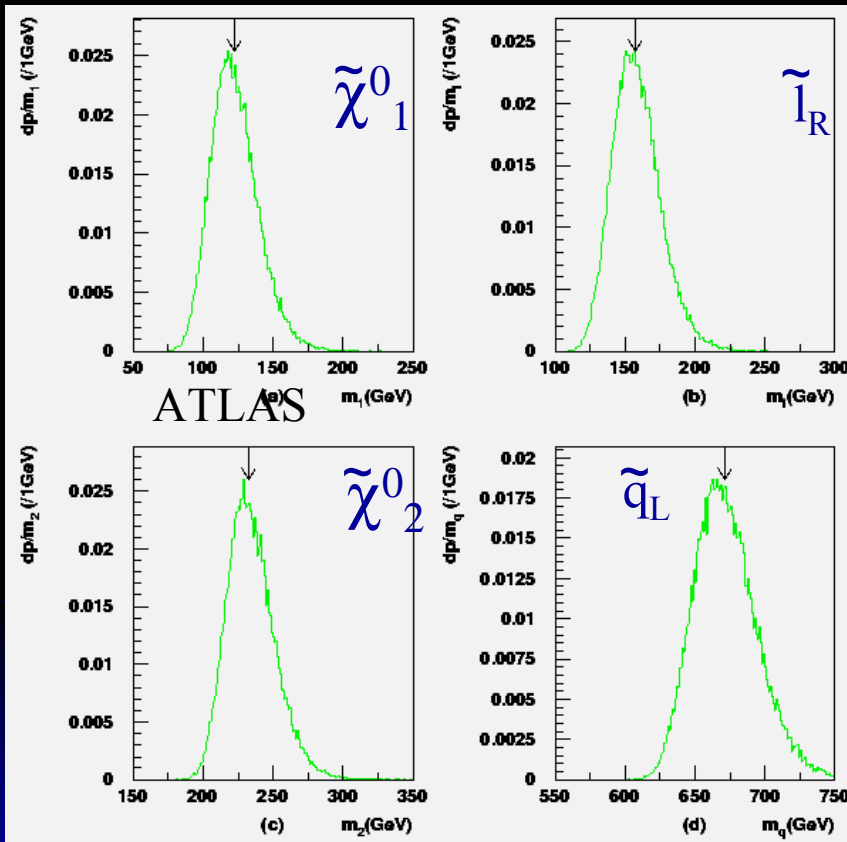
Minimum qll invariant mass, from the jet-dilepton combination with the larger invariant mass.



Masse

Avendo 5 relazioni per quattro masse e' possibile risolvere le equazioni (forti correlazioni tra i valori delle masse).

ATLAS, 100 fb⁻¹

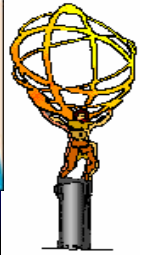


Edge	Nominal Value	Fit Value	Syst. Error Energy Scale	Statistical Error
$m(l\bar{l})^{\text{edge}}$	77.077	77.024	0.08	0.05
$m(q\bar{l})^{\text{edge}}$	431.1	431.3	4.3	2.4
$m(q\bar{l})_{\text{min}}^{\text{edge}}$	302.1	300.8	3.0	1.5
$m(q\bar{l})_{\text{max}}^{\text{edge}}$	380.3	379.4	3.8	1.8
$m(q\bar{l})^{\text{thres}}$	203.0	204.6	2.0	2.8
$m(b\bar{l})^{\text{thres}}$	183.1	181.1	1.8	6.3

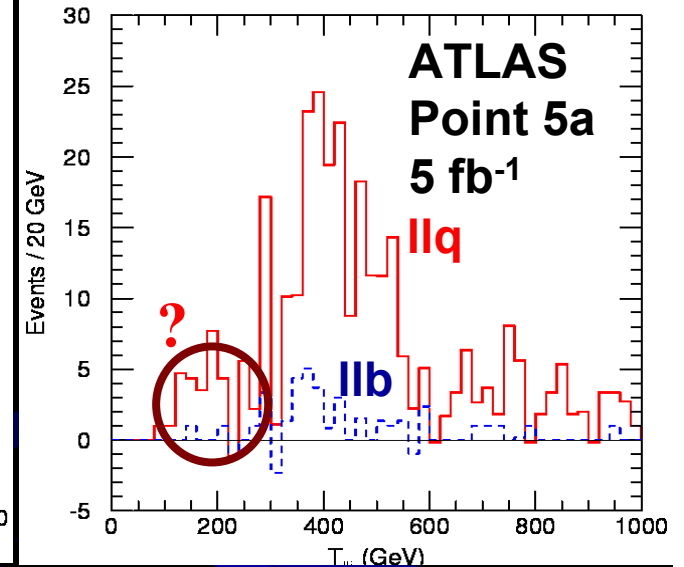
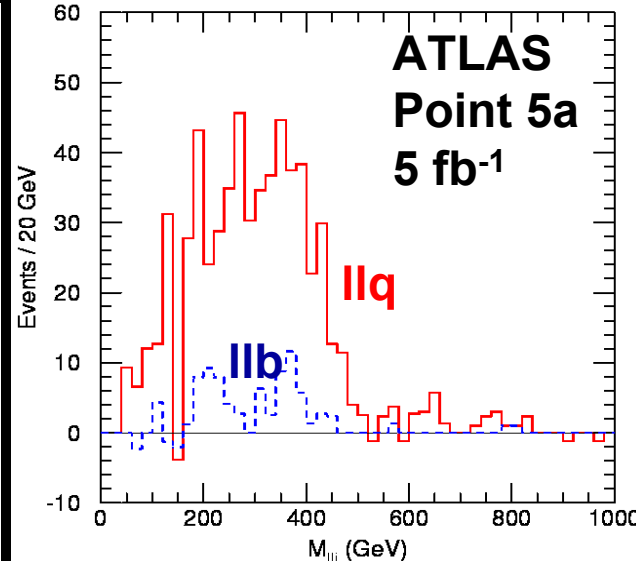
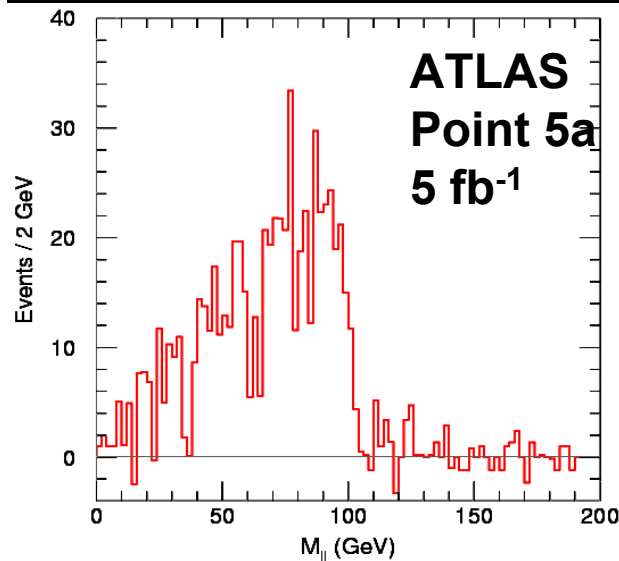
Sparticle	Expected precision (100 fb ⁻¹)
\tilde{q}_L	$\pm 3\%$
$\tilde{\chi}_2^0$	$\pm 6\%$
\tilde{l}_R	$\pm 9\%$
$\tilde{\chi}_1^0$	$\pm 12\%$



SUSY 2008?



Results with detailed simulation



ll edge

llq edge

llq threshold

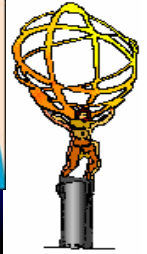
Si possono ottenere risultati significativi anche con pochi fb⁻¹

La simulazione dettagliata da' generalmente i risultati attesi dagli studi in simulazione veloce

Tre relazioni su quattro masse. Anche l'edge τ e $m(q_R)$ possono essere ricostruiti.



Risalire la catena di decadimento



Una volta che la massa del χ^0_1 e' conosciuta, e' possibile ottenere l'impulso del χ^0_2 usando

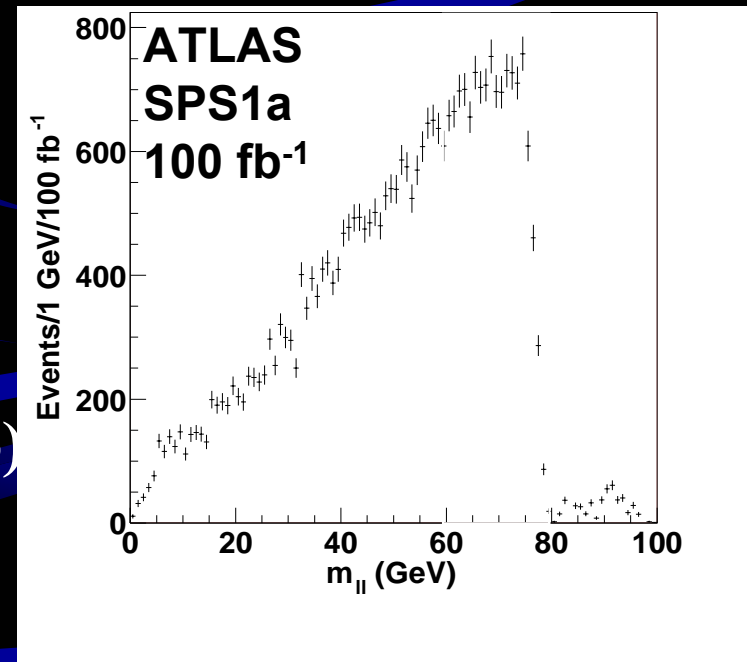
$$p(\chi^0_2) = (1 - m(\chi^0_1)/m(l\bar{l})) p_{ll}$$

valida per coppie di leptoni con massa invariante vicino all'edge.

Il χ^0_2 puo' essere combinato con getti b per ottenere la massa del gluino e dello sbottom:

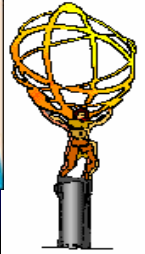
$$\tilde{g} \rightarrow \tilde{b}b \rightarrow bb\chi^0_2$$

La combinazione con getti non belli (veto) da' la massa degli squark udcs (CMS).





Gluino e sbottom: ATLAS



Combinazioni corrette.
 $m(\tilde{g})$ e $m(\tilde{b})$ correlati.
 L'errore dominante viene dall'impulso del χ^0_2)

Bad $\tilde{\chi}^0_2 b$ combinations (b-jet is from gluino decay)

$M(\chi^0 b)$

a reasonable statistics for the analysis. We plot in Fig 4 the flavour-subtracted distribution of $m(\tilde{\chi}^0_2 b)$ versus $m(\tilde{\chi}^0_2 bb)$, for both b jets, assuming the nominal values for $m(\tilde{\chi}^0_1)$ and $m(\tilde{\chi}^0_2)$. Two well-separated regions appear in the plot, of which one corresponds to the

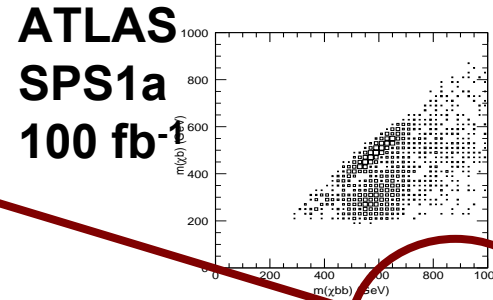


Figure 4: Distribution of $m(\tilde{\chi}^0_2 b)$ versus $m(\tilde{\chi}^0_2 bb)$ for events passing the selections.

correct $\tilde{\chi}^0_2 b$ pair for the reconstruction of the \tilde{b} , and shows a strong correlation between the \tilde{g} and the \tilde{b} mass. The second region corresponds to the situation in which $m(\tilde{\chi}^0_2 b)$ is calculated taking the b -jet from the $\tilde{g} \rightarrow b\bar{b}$ decay. We select the interesting region on the 2-dimensional plot by requiring $380 < m(\tilde{\chi}^0_2 b) < 600$ GeV and $m(\tilde{\chi}^0_2 bb) - m(\tilde{\chi}^0_2 b) > 150$ GeV. The main residual background consists where the cascade is initiated by OS-SF the lepton pair originates from a squark of the first four generations and the leading b is part of a $\tilde{g} \rightarrow b\bar{b}$ cascade. We suppress this background by requiring that the invariant mass of the $\tilde{\chi}^0_2$ with the leading jet not tagged as b is outside of the interval 400 GeV to 600 GeV. The $m(\tilde{\chi}^0_2 bb)$ after these cuts is shown in Fig. 5. Superimposed in blue is the residual background. The width of the distribution is dominated by the $\tilde{\chi}^0_2$ momentum mismeasurement. The statistical uncertainty on the peak position is ~ 4 GeV for 100 fb^{-1} and ~ 2.5 GeV for 300 fb^{-1} , and the central value is ~ 10 GeV smaller than the nominal \tilde{g} mass. The displacement of the fit value from the nominal value is related to an underestimate of the energy of part of the b jets.

For this analysis we assume that both $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ would be measured with the technique described in the previous section. As already discussed above, this results in a strong correlation between the measured $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ masses which can be parametrized as:

$$m(\tilde{\chi}^0_2) = 82.85 + 0.977 \times m(\tilde{\chi}^0_1)$$

Therefore, to evaluate the dependence of the measured gluino mass on the assumed $\tilde{\chi}^0_1$ and $\tilde{\chi}^0_2$ masses, we varied only the $\tilde{\chi}^0_1$ mass between 76 and 116 GeV, and the $\tilde{\chi}^0_2$ mass

$M(\chi^0 bb)$



Massa del gluino (ATLAS)

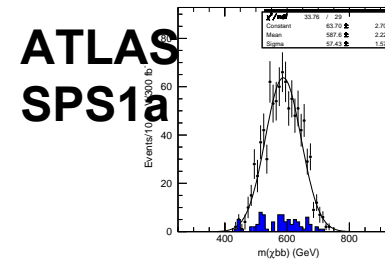
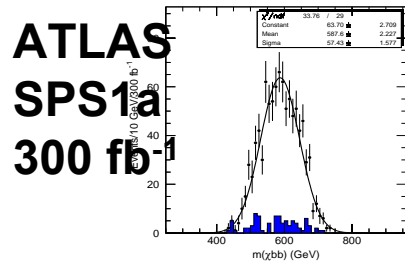
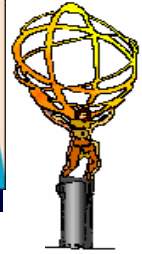


Figure 5: $m(\chi_{bb}^0)$ after all cuts. The residual SUSY background is shown in blue. Superimposed is a gaussian fit. The distribution is shown for an integrated statistics of 300 fb^{-1} .

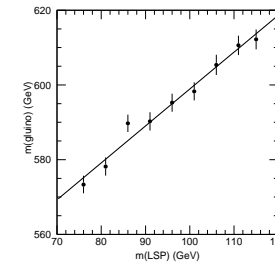


Figure 6: Estimated $m(\tilde{g})$ as a function of the $m(\chi_{11}^0)$ assumed as input of the fit.

8

Massa del gluino.

Dipendenza dalla massa della LSP.

Quella che e' realmente misurata e' la differenza:

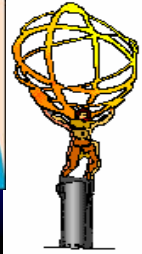
$$m(\tilde{g}) - 0.99m(\chi_{11}^0) = (500.0 \pm 6.4) \text{ GeV} \quad \text{with } 300 \text{ fb}^{-1}$$

Error is statistical plus (**dominant**) 1% uncertainty on jet energy scale

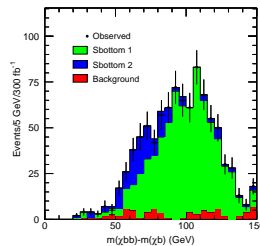
Central value 10 GeV lower than nominal because b-jet energy underestimated



Massa dello sbottom



$m(\tilde{\chi}^0_2 \text{ bb})$ and $m(\tilde{\chi}^0_2 \text{ b})$ strongly correlated : use the difference



ATLAS
SPS1a
300 fb⁻¹

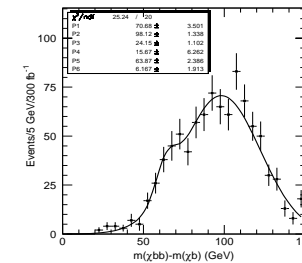


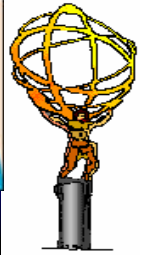
Figure 8: Distribution of $m(\tilde{\chi}^0_2 \text{ bb}) - m(\tilde{\chi}^0_2 \text{ b})$ for an integrated luminosity of 300 fb⁻¹. Superimposed is the fit performed assuming the sum of two gaussian distributions.

10

Con 300 fb⁻¹ potrebbe essere possibile separare i picchi dei due $\tilde{\text{b}}$

$$m(\tilde{\text{g}}) - m(\tilde{\text{b}}_1) = (103.3 \pm 1.8) \text{ GeV}$$

$$m(\tilde{\text{g}}) - m(\tilde{\text{b}}_2) = (70.6 \pm 2.6) \text{ GeV}$$

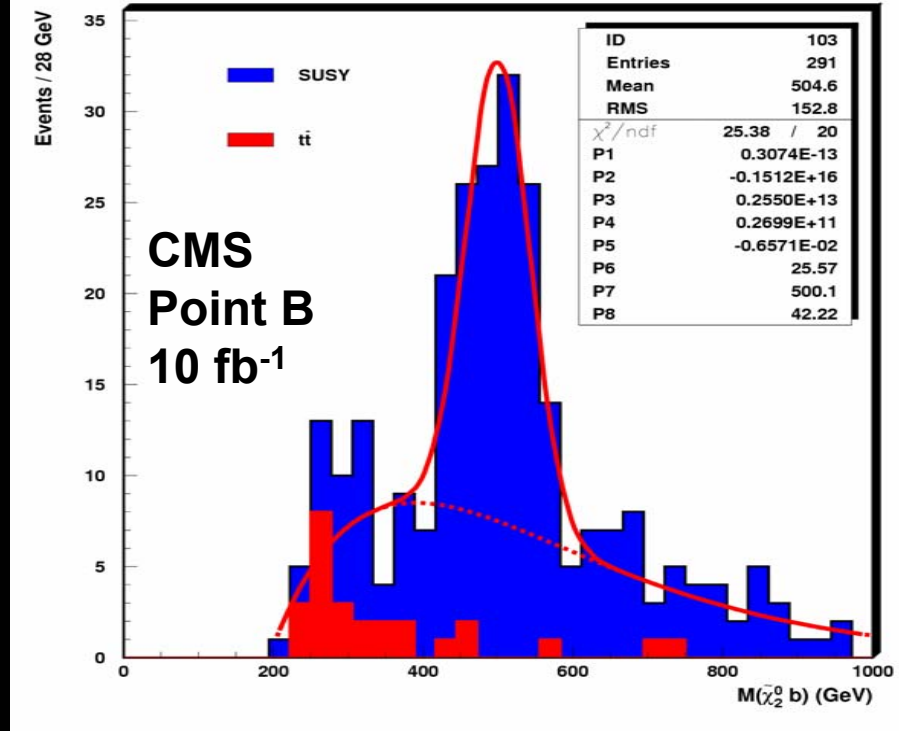
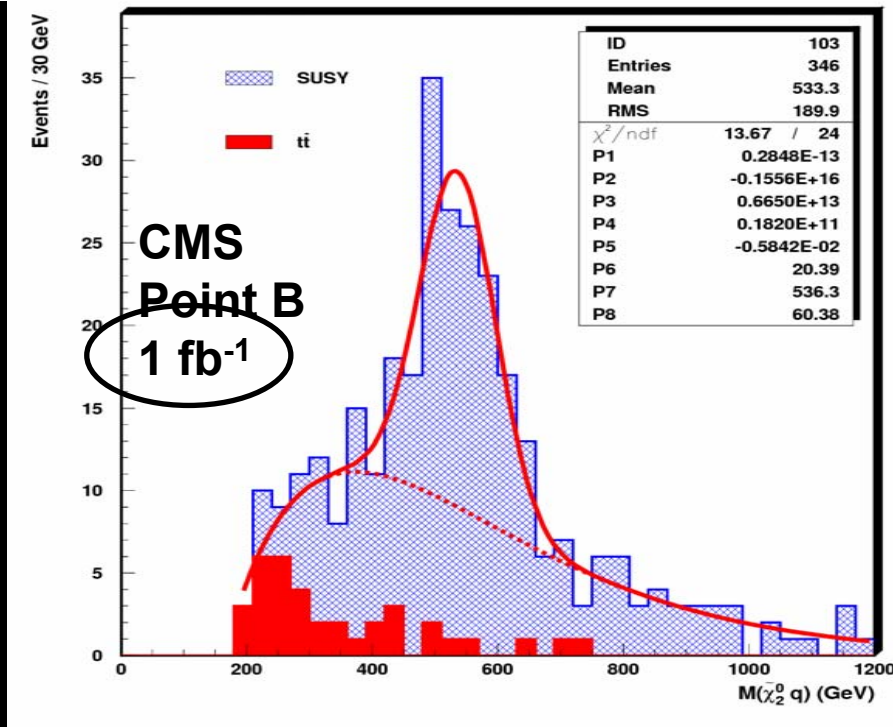


Squarks e sbottom (CMS)

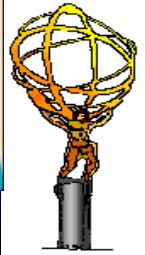


$$m(\tilde{q}) = (536 \pm 10) \text{ GeV}$$

$$m(\tilde{b}) = (500 \pm 7) \text{ GeV}$$



Anche CMS assume nota $m(\chi^0_1)$, rispetto alla quale $m(\tilde{q})$ varia linearmente (ma il coefficiente e' 1.6 mentre ATLAS trova ~1.0). $m(\chi^0_1)$ domina l'errore su $m(\tilde{q})$ e $m(\tilde{b})$ – gli errori di cui sopra sono in realta' sulla differenza delle masse e sono solo statistici.



Risoluzione sulle masse

Solo errori statistici (in GeV) normalizzati a 10 fb^{-1}

	ATLAS SPS1a	CMS Punto B
$M_0 = m(\chi^0_1)$	26	
$m(q)$		$3 \oplus 1.7\Delta M_0$
$m(g)$	$13 \oplus \Delta M_0$	$7 \oplus 1.6\Delta M_0$
$m(g)-m(b)$	5	3

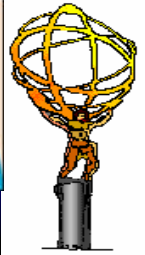
**Notare che sono
Due punti diversi!**

L'errore sulla massa del neutralino e' il contributo dominante all'incertezza sulle altre masse (il linear collider aiuterebbe...).

Ad alta statistica l'errore sulla scala di energia dei getti (1%) diventa dominante sull'errore statistico.



Right-handed squark



\tilde{q}_R does not couple to Wino
 $\tilde{\chi}^0_1$ is nearly a Bino
 $\tilde{\chi}^0_2$ is nearly a Wino

$\left. \begin{array}{l} \text{ } \\ \text{ } \\ \text{ } \end{array} \right\} \rightarrow \tilde{q}_R \rightarrow q \tilde{\chi}^0_1$

Il momento trasverso dei due getti piu' energetici e' combinato con il momento trasverso mancante come segue:

$$M_{T2}^2 = \min_{\vec{p}_1 + \vec{p}_2 = \vec{p}_T} \left[\max \left\{ m_T^2(\vec{p}_T^{\ell_1}, \vec{p}_1), m_T^2(\vec{p}_T^{\ell_2}, \vec{p}_2) \right\} \right]$$

Il massimo e' $m(\tilde{q}_R) - m(\tilde{\chi}^0_1)$
 $m(\tilde{q}_R) - m(\tilde{\chi}^0_1) = (424.2 \pm 10.9) \text{ GeV}$

Note: can reconstruct $\tilde{l}_L \rightarrow l \tilde{\chi}^0_1$
 with same technique

$$m(\tilde{l}_L) - m(\tilde{\chi}^0_1) = (106.1 \pm 1.6) \text{ GeV}$$

**ATLAS
SPS1a
30 fb⁻¹**

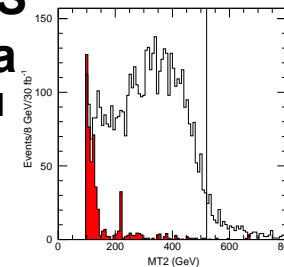


Figure 14: Distribution of M_{T2} for the events passing the cuts. In red is shown the Standard Model background. The integrated statistics in the plot is 30 fb⁻¹.

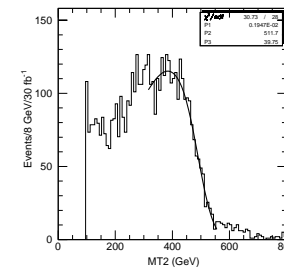
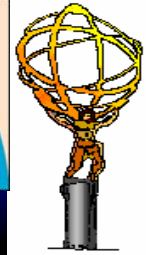


Figure 15: Distribution of M_{T2} for events passing the cuts. Superimposed is the fit described in the text.



(Alcune) Altre misure



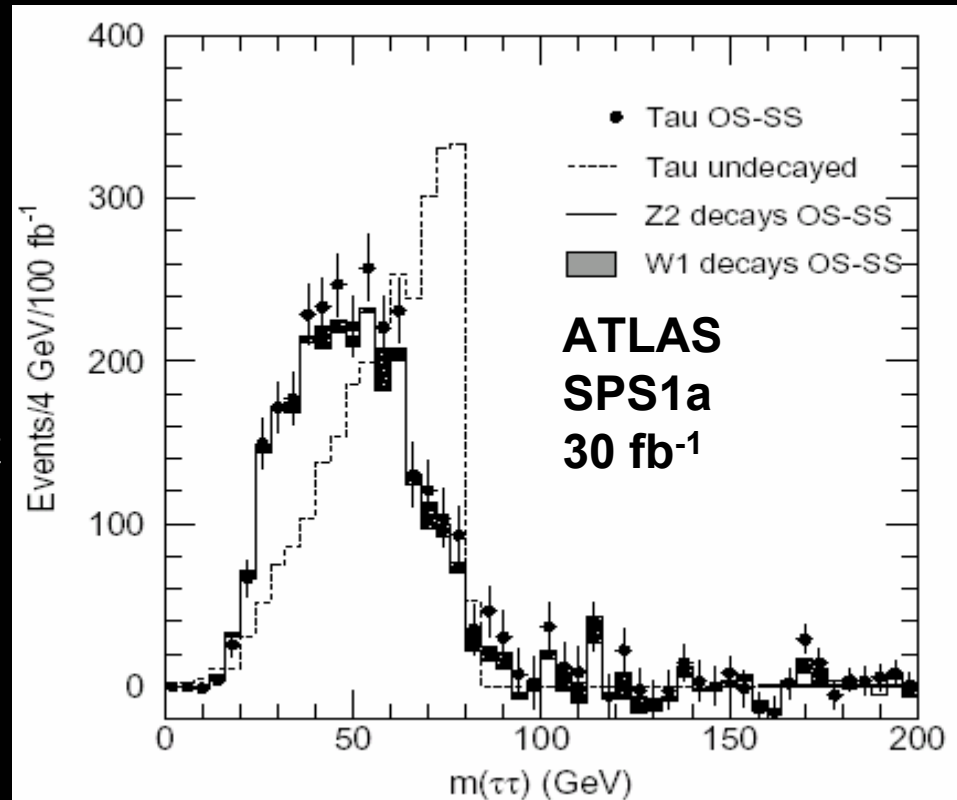
$$\chi^0_2 \rightarrow \tau\tau \rightarrow \chi^0_1 \tau\tau$$

Diventa dominante ad alti $\tan\beta$, sopprimendo il decadimento in elettroni/muoni.

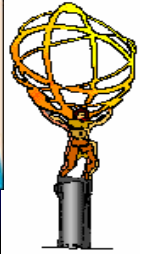
Si puo' comunque trovare l'endpoint con una precisione di alcuni GeV.

$$\chi^0_2 \rightarrow h \chi^0_1 \rightarrow bb \chi^0_1$$

Il picco di massa invariante bb puo' essere ricostruito ed usato per ulteriori combinazioni di masse.



Massa invariante $\tau\tau$



Altri punti dello spazio dei parametri

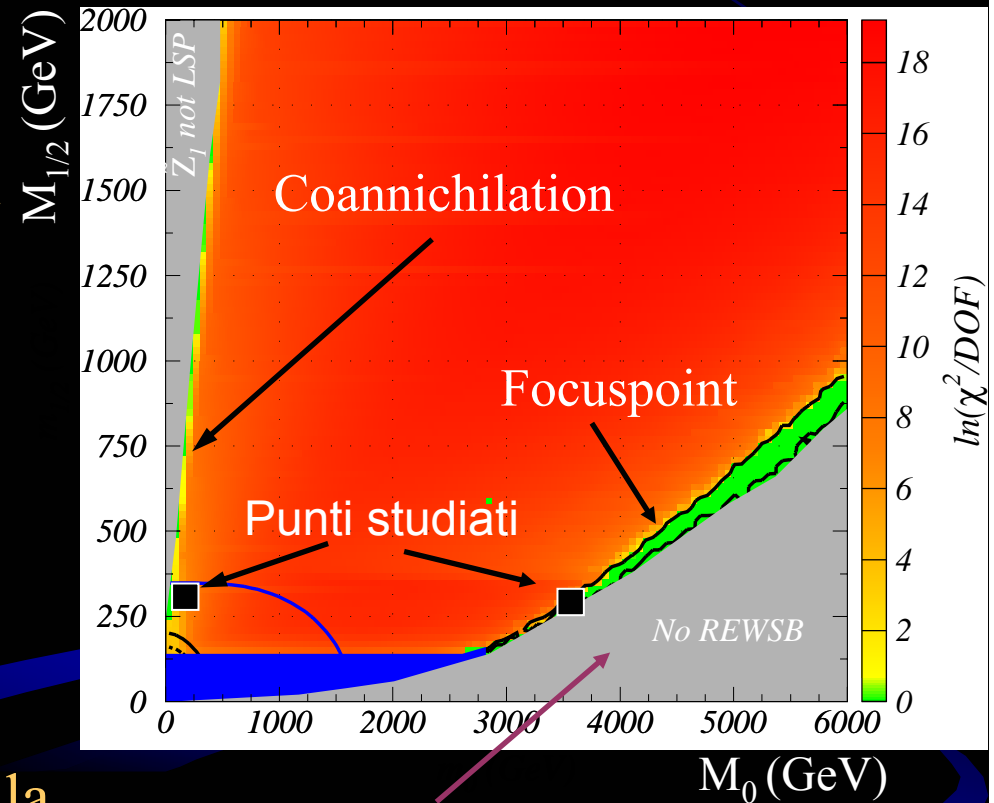
Large scalar mass: heavy squarks and sleptons.

Relatively low gaugino mass.

Low μ , large Higgsino/Bino mixing \Rightarrow low density of relic neutralinos, compatible with WMAP limits.

Limiti piu' stringenti sull'Higgs e misure piu' precise della densita' di materia oscura hanno notevolmente ridotto lo spazio dei parametri disponibile.

Di recente alcuni punti meno facili sono stati studiati da ATLAS nelle code ad alte scale di massa della regione mSUGRA compatibile con la densita' di Materia Oscura.



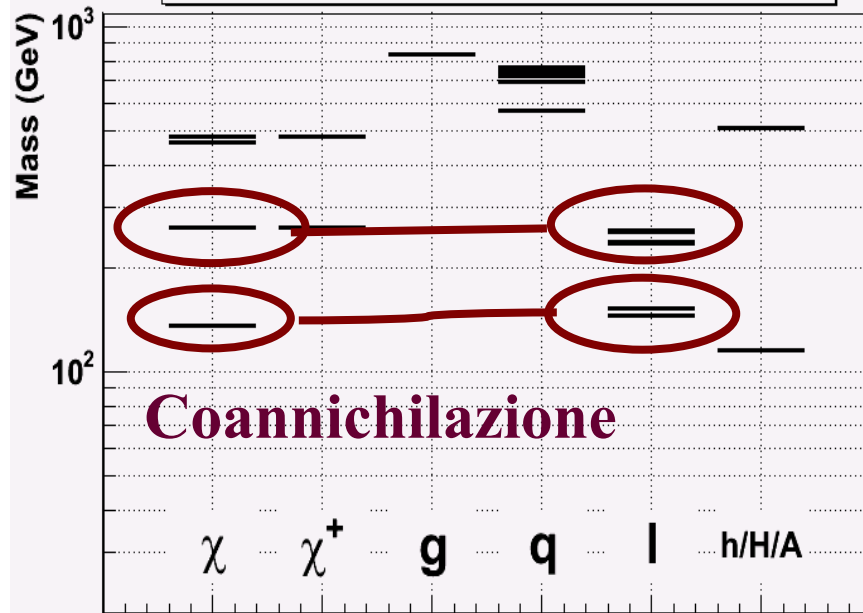
No EWSB solution



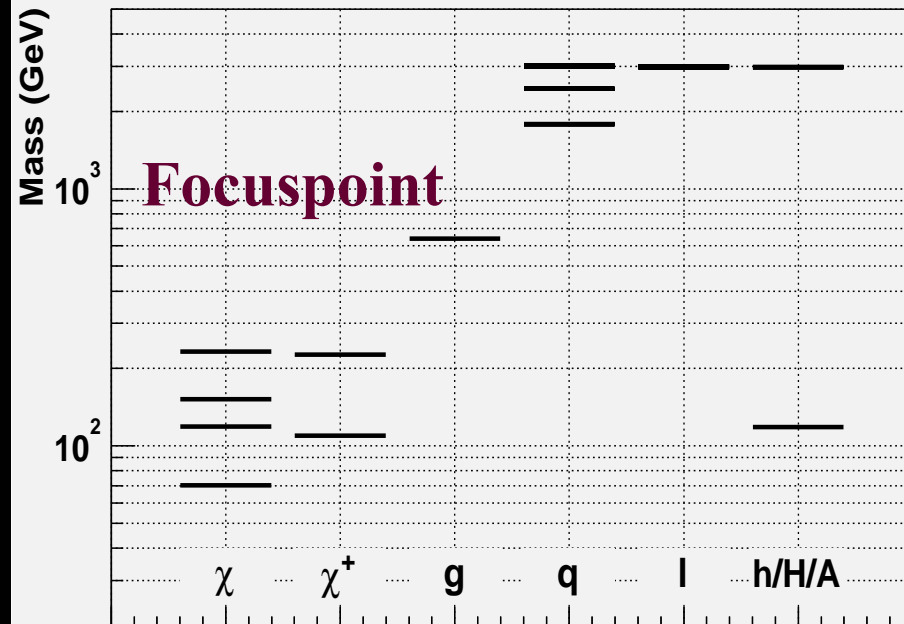
Spettro di massa



ISAJET, $m_0=70.0$, $m_{1/2}=350.0$, $A_0=0$, $\tan\beta=10.0$, $\text{sgn}(\mu)=+$, $m_t=175$

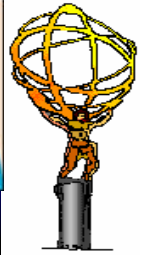


ISAJET, $m_0=3000$, $m_{1/2}=215$, $A_0=0$, $\tan\beta=10$, $\text{sgn}(\mu)=+$, $m_t=175$



Caratteristica peculiare:
 sleptoni vicini in massa ai due
 neutralini piu' leggeri: leptoni
 lenti nel decadimento del χ^0_2 .

Squark e sleptoni pesanti (~ 3 TeV).
 Higgs pesanti - eccetto h
 Gluino leggero (830 GeV), decade in
 chargini e neutralini



Punto di coannichilazione

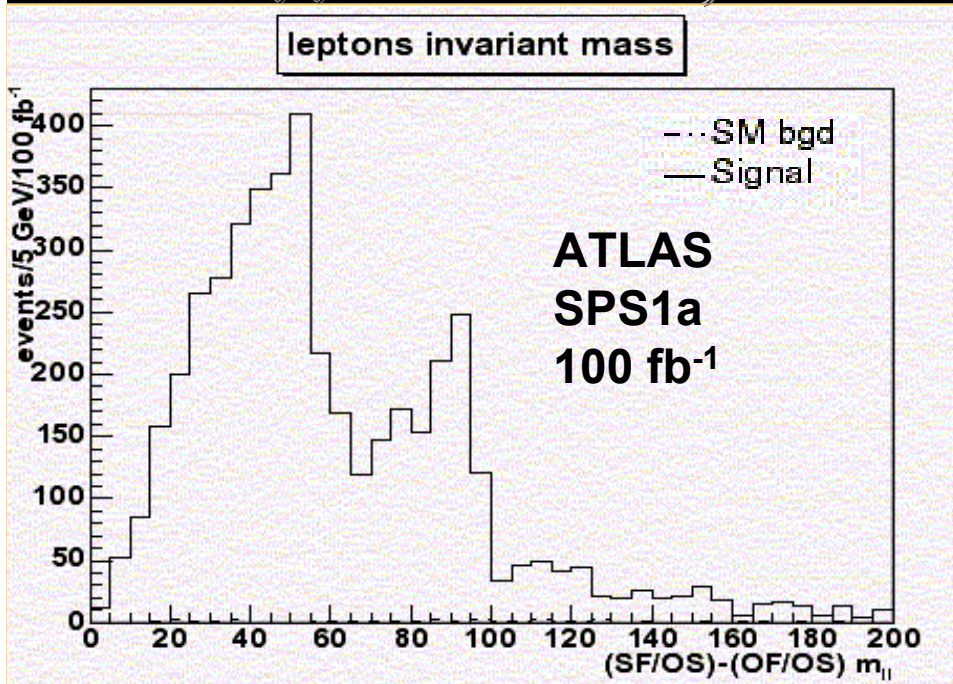


$$m_{\ell^+\ell^-}^{\max} \approx 57\text{ GeV}, 101\text{ GeV}$$

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 + q \quad 32\%$$

$$\tilde{\chi}_2^0 \rightarrow \ell_{L,R}^\pm + \ell^\mp \quad 6\%, 3\%$$

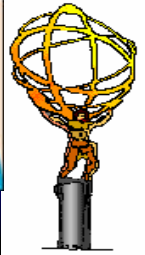
$$\ell_{L,R}^\pm \rightarrow \ell^\pm + \tilde{\chi}_1^0 \quad 100\%$$



E' possibile ricostruire anche l'edge τ e diversi edge leptone-getti.

Questo punto verra' studiato anche con la simulazione dettagliata nei prossimi mesi (10 fb⁻¹), verificando le prestazioni di ricostruzione di leptoni lenti.

- $xE_T > 200\text{ GeV}$
- 2 SF/OS leptons $P_{t_1} > 20\text{ GeV}, P_{t_2} > 10\text{ GeV}$
- ≥ 1 jets with $P_t > 150\text{ GeV}$
- OS/OF subtraction

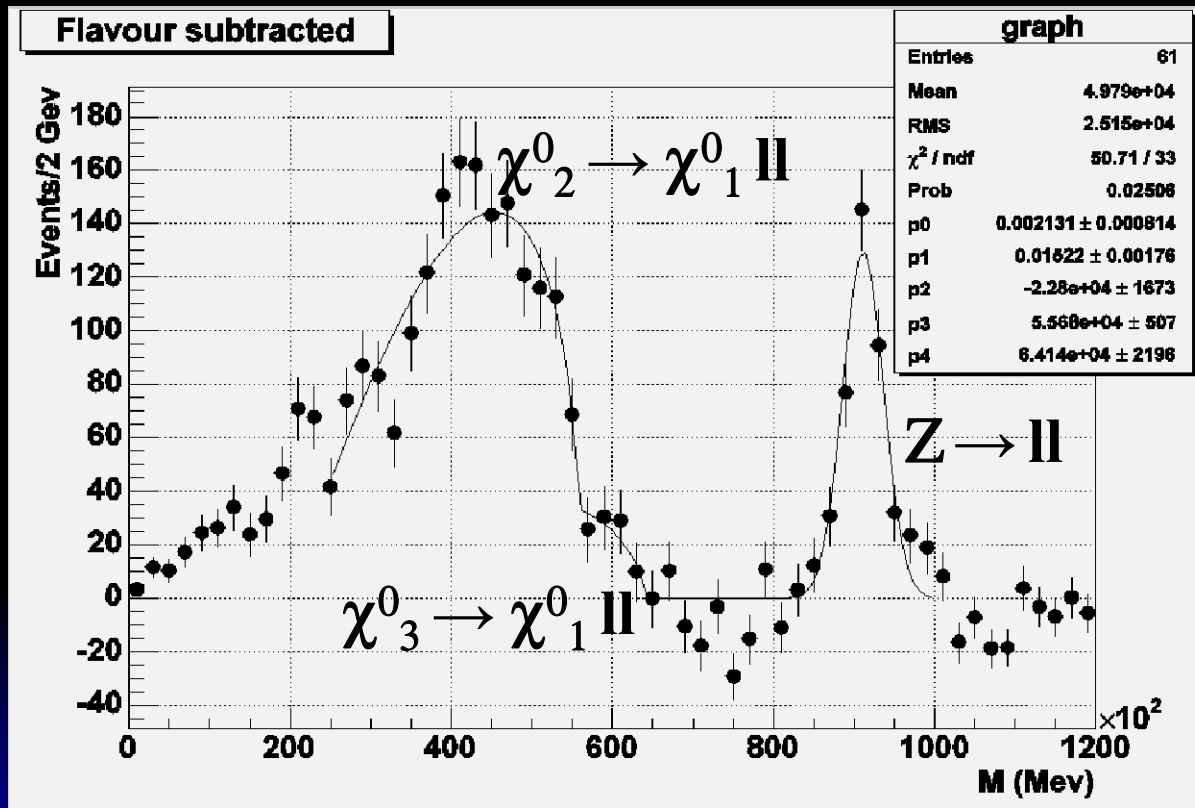


Focus-point



Decadimento diretto $\chi^0_n \rightarrow \chi^0_1 \ell\ell$

I due edges danno $m(\chi^0_n) - m(\chi^0_1)$. Altre informazioni potrebbero essere ottenute dalla forma della distribuzione e dal rapporto (BRs) tra i diversi decadimenti.

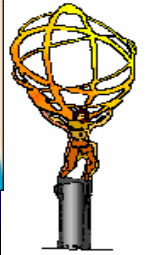


Il picco della massa efficace e la ricostruzione della massa invariante $t\bar{b}$ e $t\bar{t}$ da $g \rightarrow \chi t\bar{b}$ ($t\bar{t}$) permettono di stimare la massa del gluino.

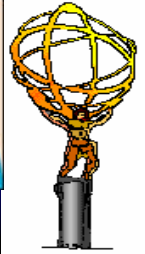
Anche questo punto verrà studiato con la simulazione dettagliata.



Conclusioni



- Per punti favorevoli dello spazio dei parametri, LHC sarà in grado di ricostruire gran parte dello spettro SUSY con precisioni dell'ordine di alcuni GeV. Diverse (combinazioni di) masse potrebbero essere ottenute già nel primo anno.
- La maggior parte degli studi fino ad ora sono stati fatti con la simulazione veloce. L'enfasi si sta spostando sulla simulazione dettagliata, lo studio degli effetti sistematici, la stima dei fondi a partire dai dati, la migrazione delle analisi nello stesso framework usato per la ricostruzione.....
- Nuove regioni dello spazio dei parametri, che rispettano i nuovi limiti sulla densità di materia oscura, stanno venendo studiati.



Backup slides