

Ricerca di fenomeni supersimmetrici ad LHC con il rivelatore CMS

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28 Aprile 2011
IFAE - Perugia

Sommario:

Motivazioni per cercare Susy ad LHC

Ricerca di Susy in canali puramente adronici

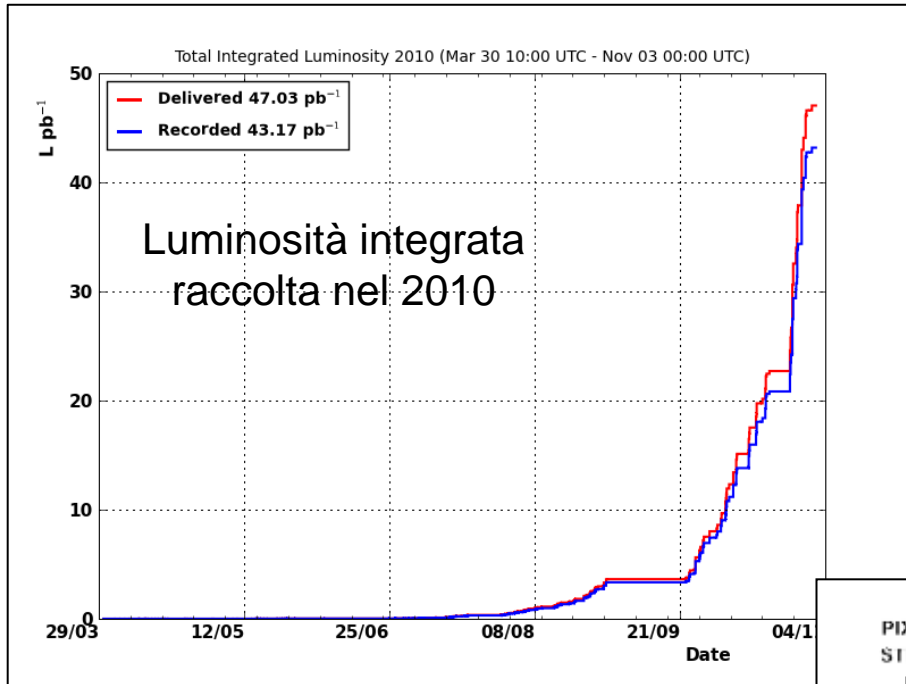
Ricerca di Susy in canali con leptoni nello stato finale

Ricerca di Susy in canali con fotoni nello stato finale

Supersimmetria

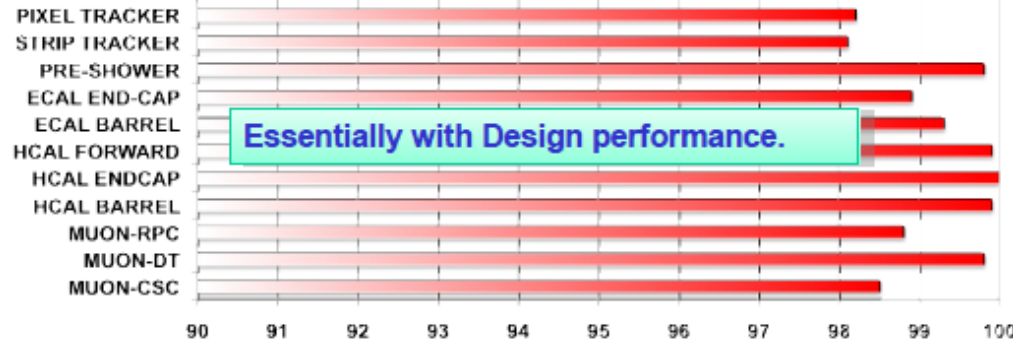
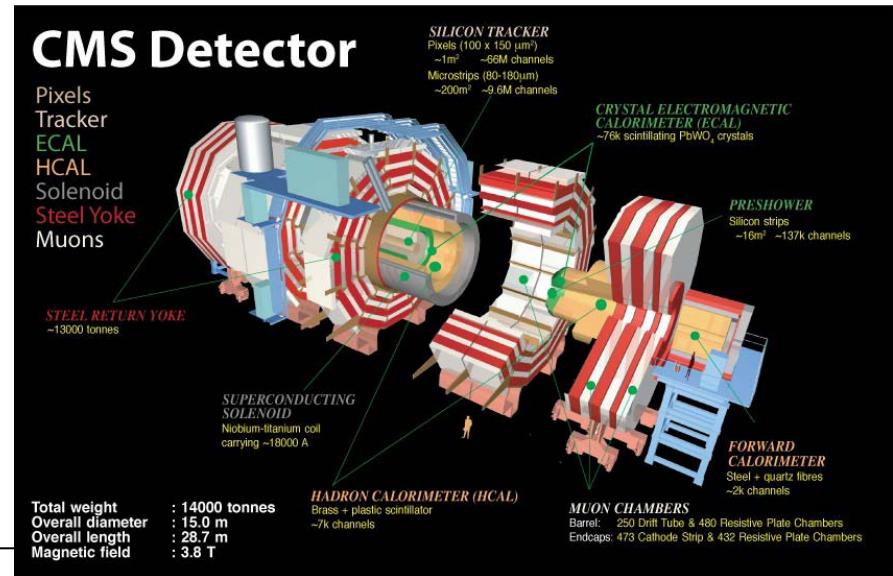
- **Simmetria tra bosoni e fermioni**
 - Ad ogni fermione SM corrisponde un partner bosonico supersimmetrico e vice-versa
- **Amata dai teorici perche':**
 - Risolve elegantemente il problema delle divergenze della massa dell'Higgs
 - Permette l'unificazione delle costanti di accoppiamento ad alta energia
 - Fornisce un candidato per la materia oscura
- **Amata dagli sperimentali perche':**
 - Ci sono nuove particelle da scoprire e caratterizzare
- **Ampia fenomenologia:**
 - Energia mancante + jet +(leptoni)
 - Energia mancante + fotoni
 - 5 higgs (M. Tosi - sessione SM ed oltre II)
 - Particelle con vita media lunga (M.Meneghelli - sessione dottorandi II)
 - ...

LHC e CMS



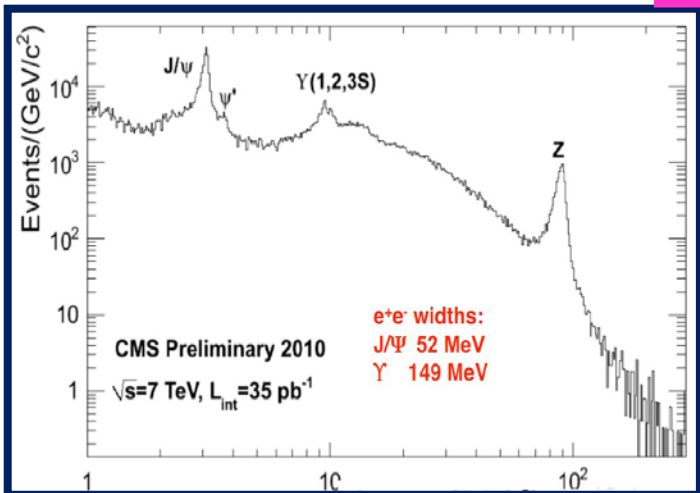
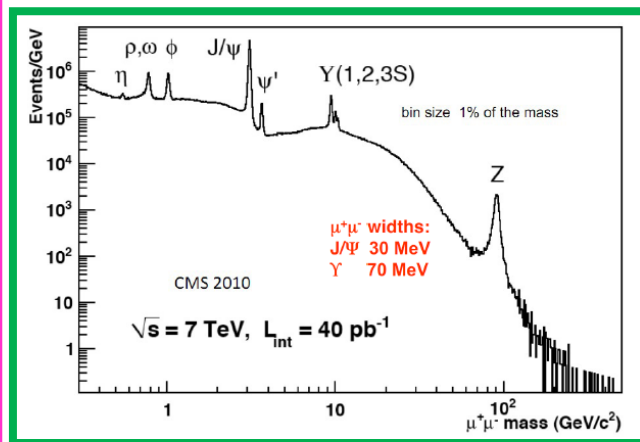
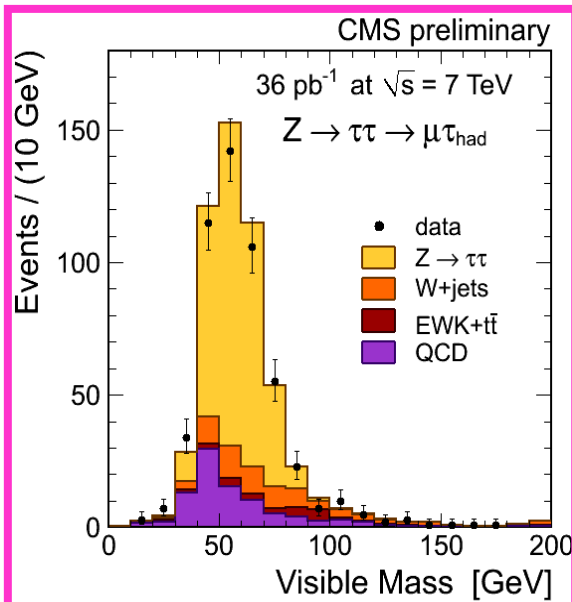
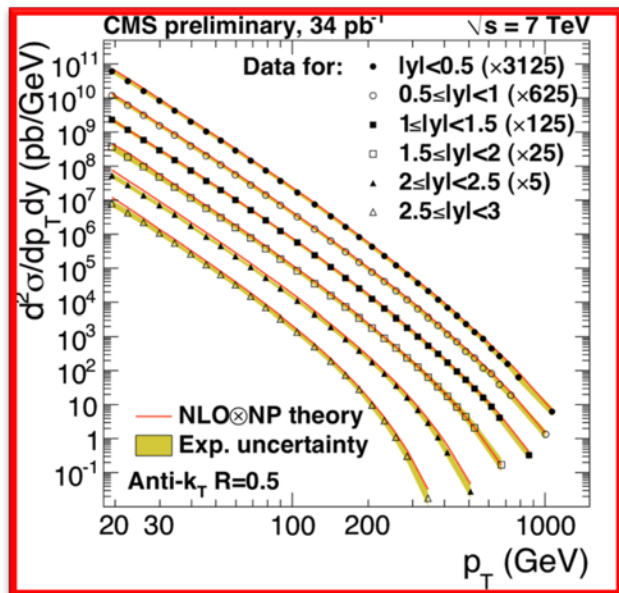
Collisioni protone-protone
LHC ha fornito 47 pb⁻¹,
CMS ha registrato 43 pb⁻¹
85% con tutti i sottorivelatori operativi (~36 pb⁻¹)

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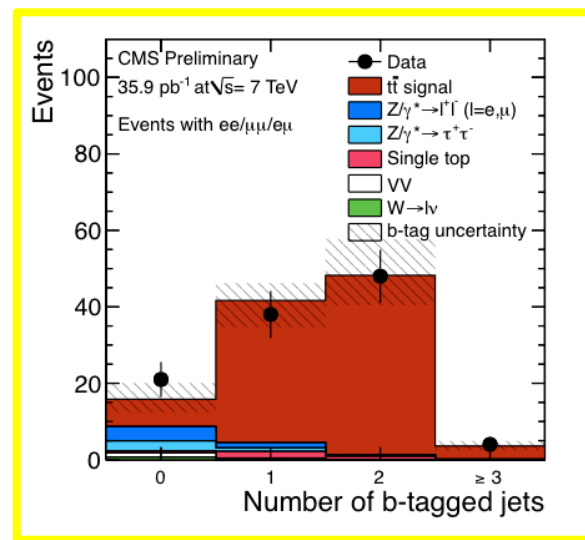


	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARRE L	HCAL ENDCAP P	HCAL FORWAR D	ECAL BARRE L	ECAL ENDCAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2

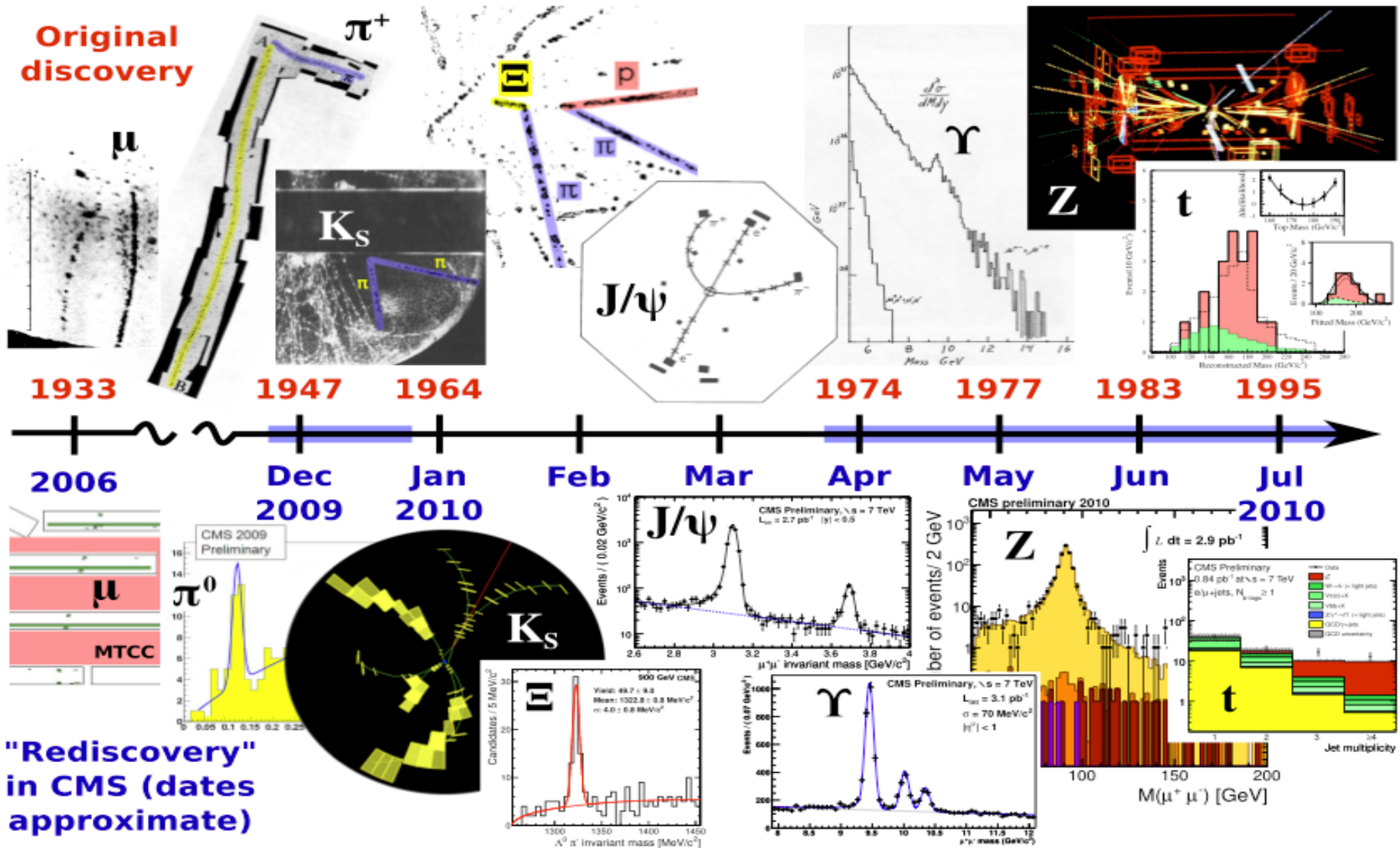
Oggetti fisici



Validazione della ricostruzione di **getti adronici**, **elettroni**, **muoni**, **getti da b-quark** tramite processi noti di fisica.



Riscoperta dello Standard Model



Strategia di ricerca di Susy

- Ricerca basata su caratteristiche generali:
 - Energia mancante (modelli con R-parità conservata)
 - Alta attività adronica (dal decadimento di gluini e squark)
- Ricerca suddivisa in base alle possibili topologie finali

0-leptoni	1-leptone	OSDL	SSDL	≥ 3 leptoni	2-fotoni	γ +leptone
Alta sezione d'urto. Fondo da QCD	Fondo da W+jet e tt	Fondo da Z+jet e tt. Analisi della massa(l^+l^-)	Assenza di fondo da SM	Richiesta di almeno 3 leptoni +MET	Stato finale favorito in modelli GMSB	Richiesta del leptone riduce il fondo QCD

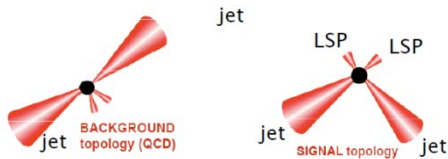
Ricerca di susy in stati finali puramente adronici

3 analisi complementari:

- α_T
 - Primo articolo di LHC su Susy
 - 50 citazioni
 - Utilizza le proprietà cinematiche del fondo da QCD
- **Eccesso di MET**
 - Alta efficienza di rivelazione
 - Necessita una comprensione dettagliata del rivelatore
- **Razor**
 - Utilizza le proprietà cinematiche della produzione di due particelle massive

α_T

$$\alpha_T = \frac{E_{Tj2}}{M_{Tj1j2}} = \frac{\sqrt{E_{Tj2}/E_{Tj1}}}{\sqrt{2(1 - \cos\Delta\varphi)}}$$



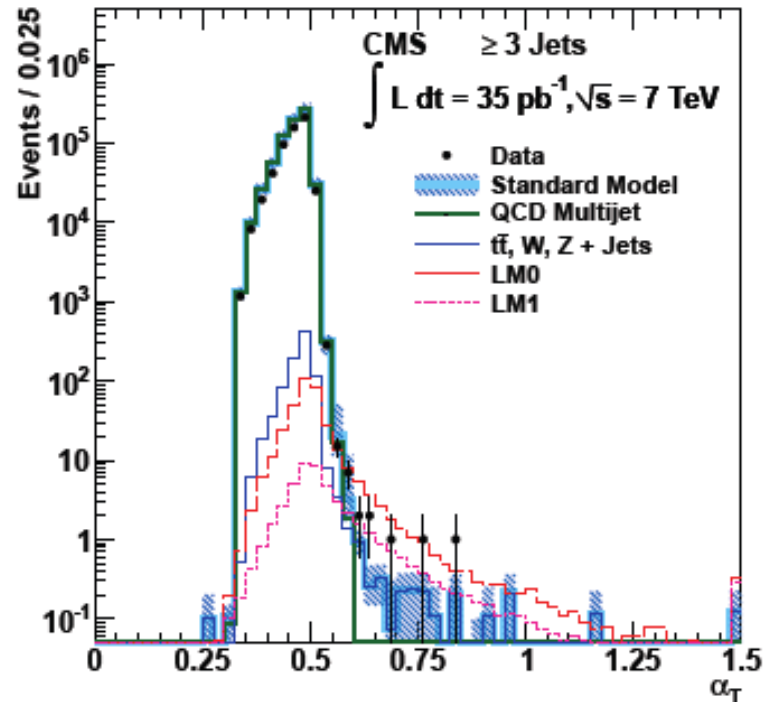
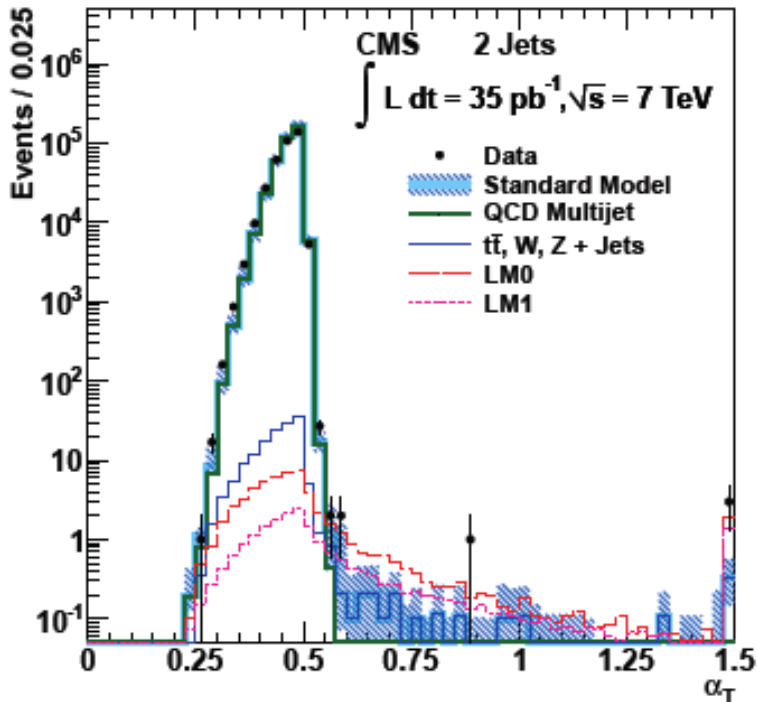
HT > 350 GeV

$\alpha_T > 0.55$

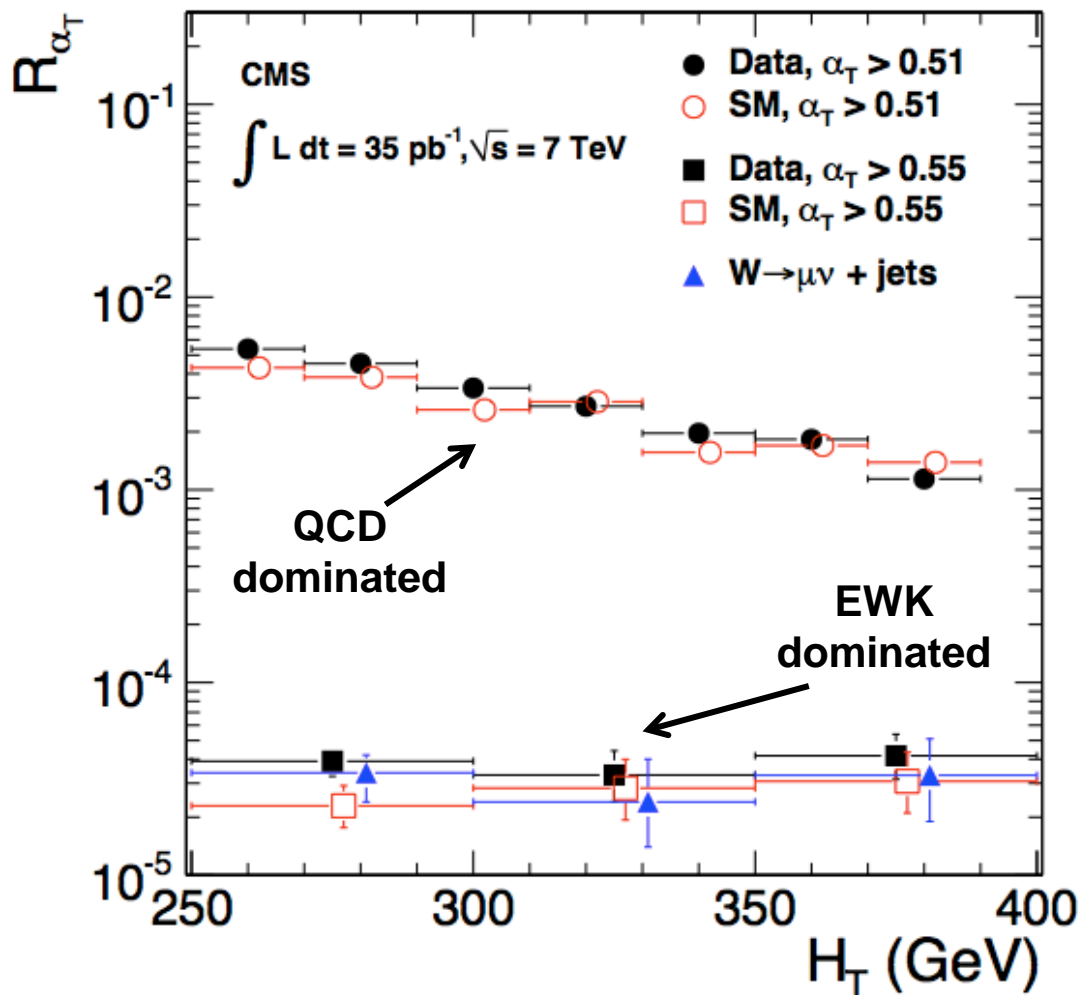
0 fotoni

0 leptoni

13 eventi osservati



Stima inclusiva del fondo



$$R_{\alpha_T} = N(\alpha_T > x) / N(\alpha_T < x)$$

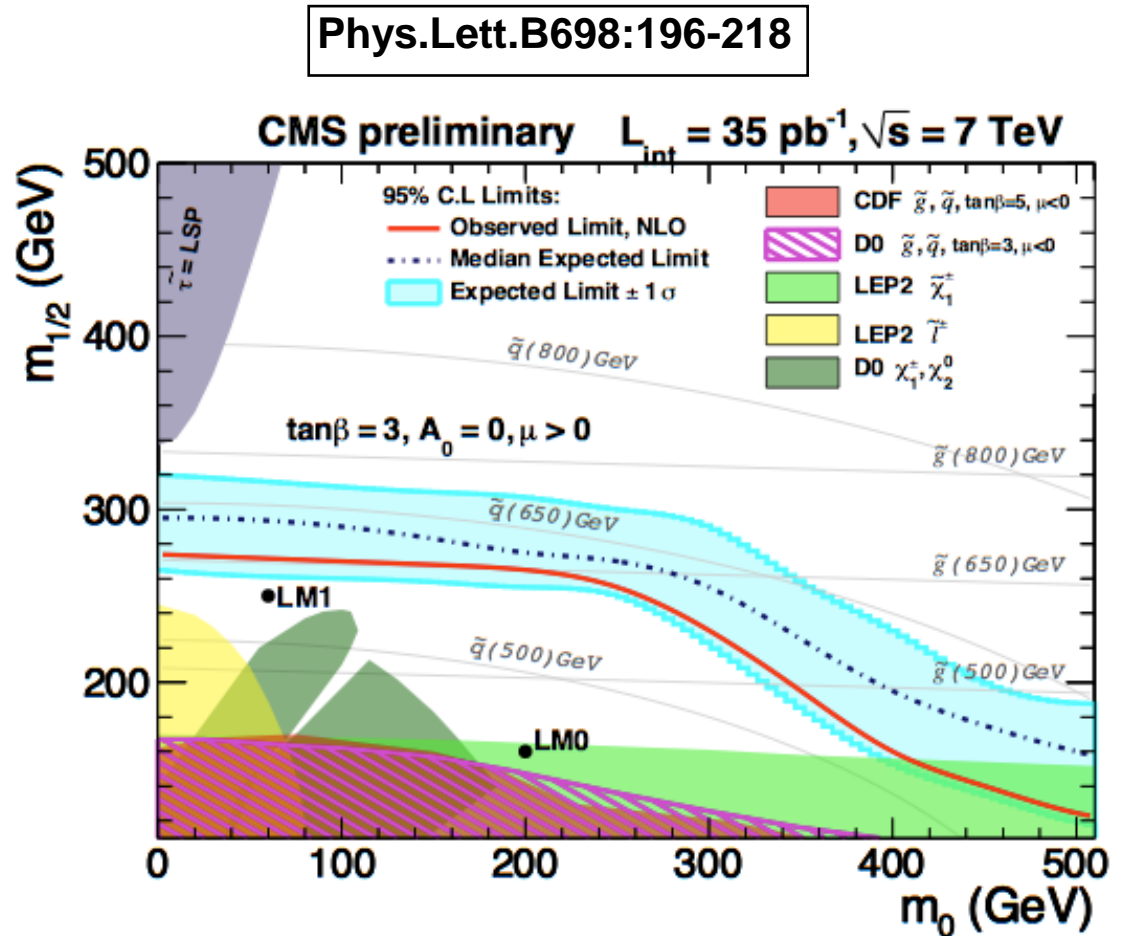
Il valore di R_{α_T} è misurato in una regione dove non ci aspettiamo segnale (bassi valori di H_T) ed estrapolato nella regione di segnale ($H_T > 350 \text{ GeV}$)

Est. Bkg=

$$9.4^{+4.8}_{-4.0}(\text{stat.}) \pm 1.0(\text{syst.})$$

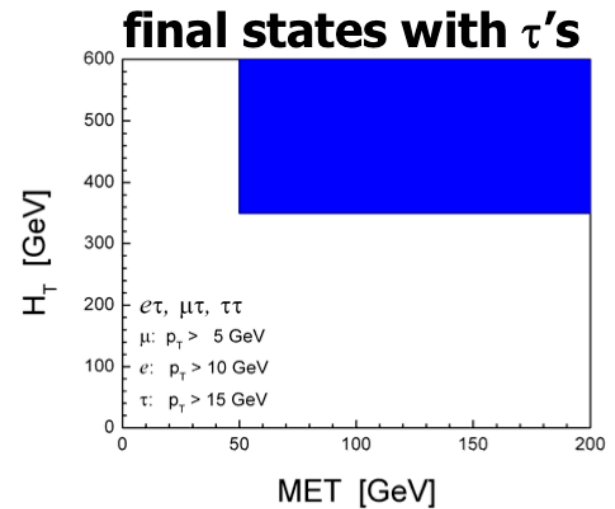
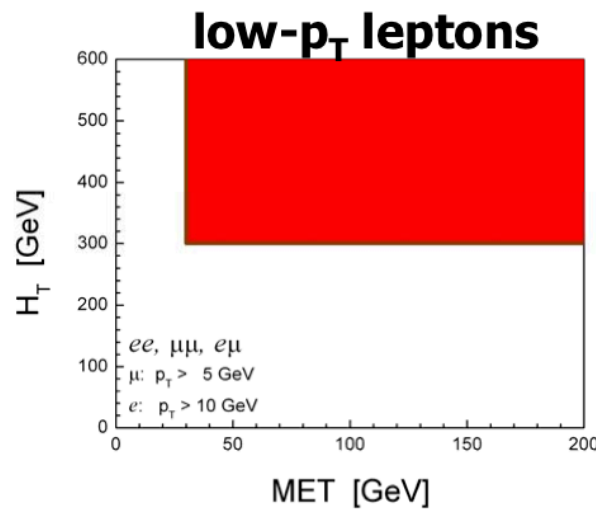
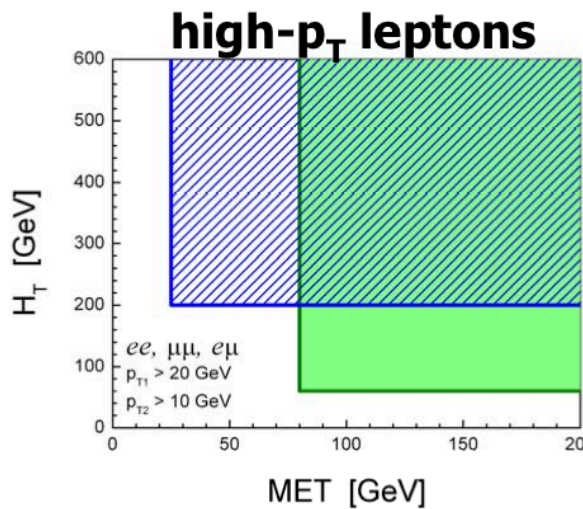
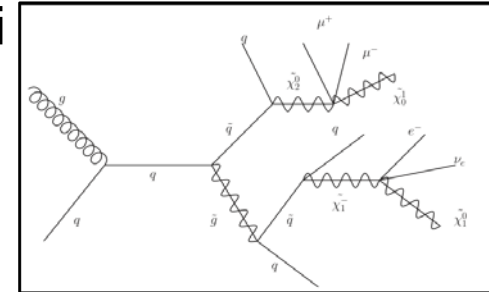
Hadronic search with α_τ

- I risultati sono stati interpretati in CMSSM favorendo così il confronto con altri esperimenti
- $\tan\beta=3$ $A_0=0$ $\mu>0$
- Rispetto agli esperimenti del Tevatron, la regione esclusa è stata estesa



Ricerca di leptoni con lo stesso segno

- Questo stato finale appare naturalmente in molti modelli susy
- Topologia assente nello Standard
- Ricerca utilizzando tutti i leptoni e 4 regioni di segnale nel piano MET, HT



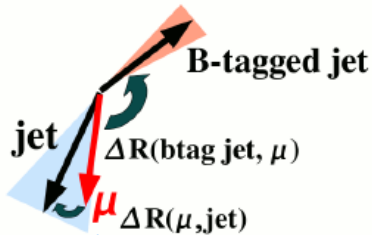
Fondi principali

t \bar{t} bar: un l isolato dal W ed uno dal decadimento semileptonico nel jet da b-quark

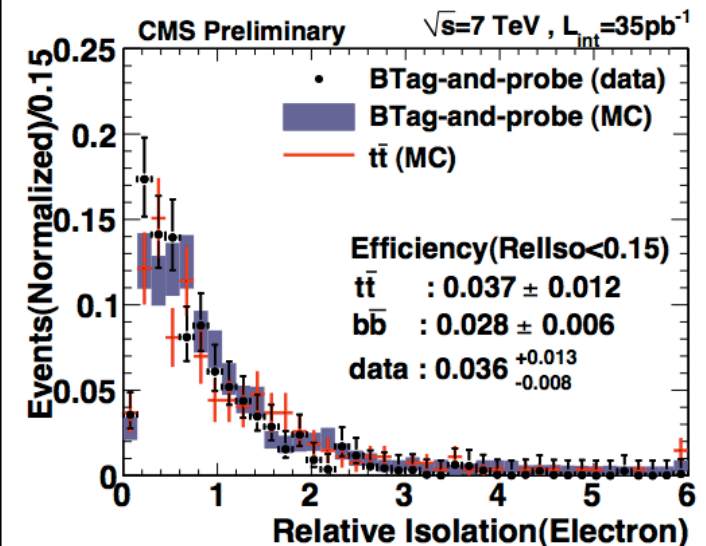
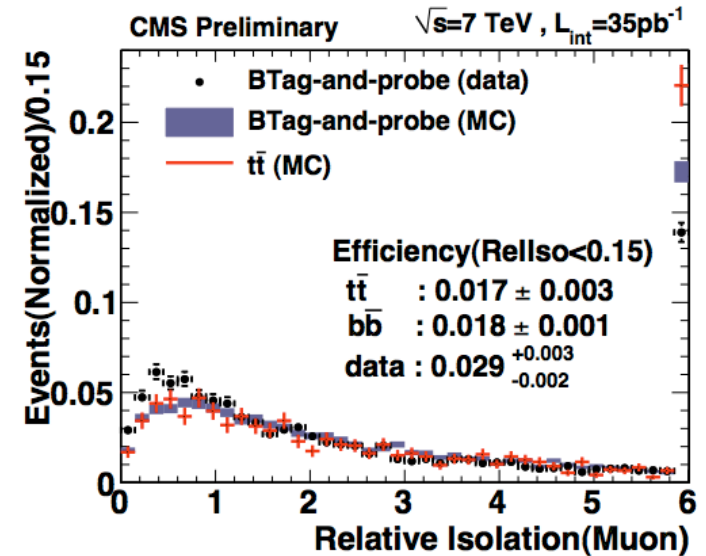
QCD: importante per gli stati finali con decadimenti adronici del τ

Fondo da ttbar

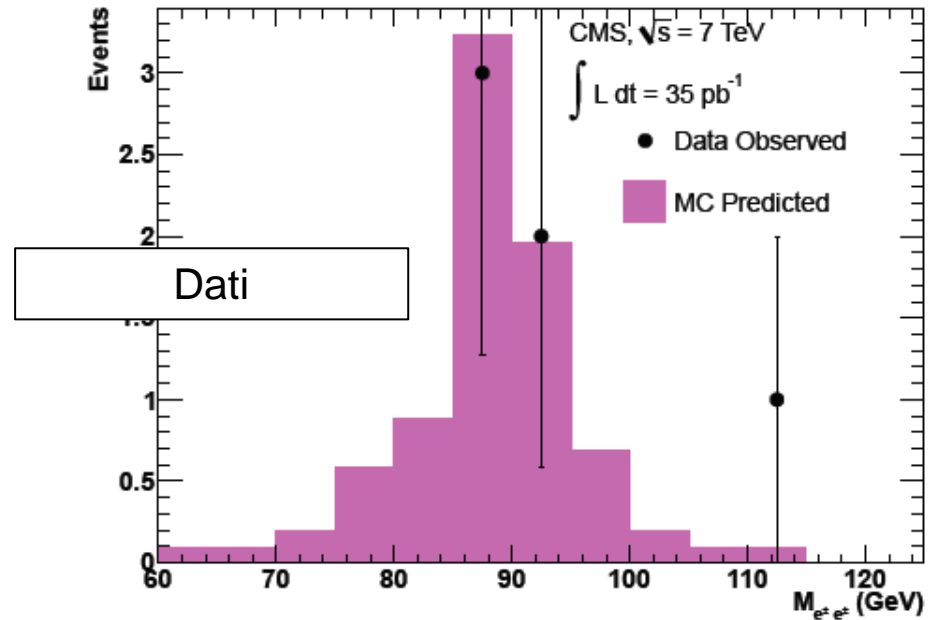
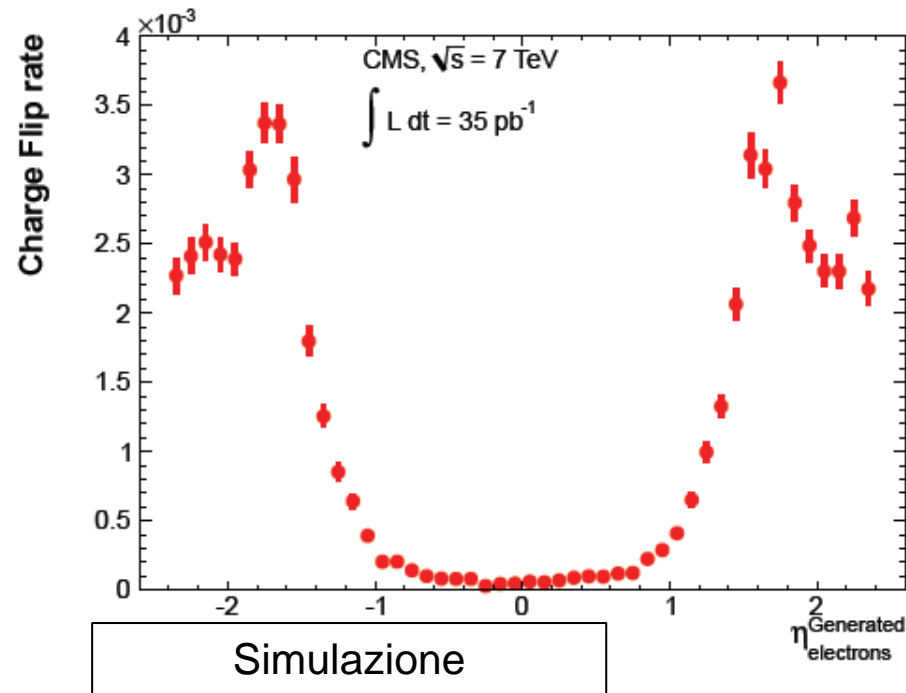
- Tag&Probe con eventi bb(QCD) per misurare l'efficienza di isolamento dei leptoni in jet da b-quark



- Distribuzione dei b-jet in bb e in tt e' differente \rightarrow Efficienza va ripesata
- Efficienza di isolamento per determinare il fondo da ttbar



Fondo da elettroni con il segno della carica sbagliata

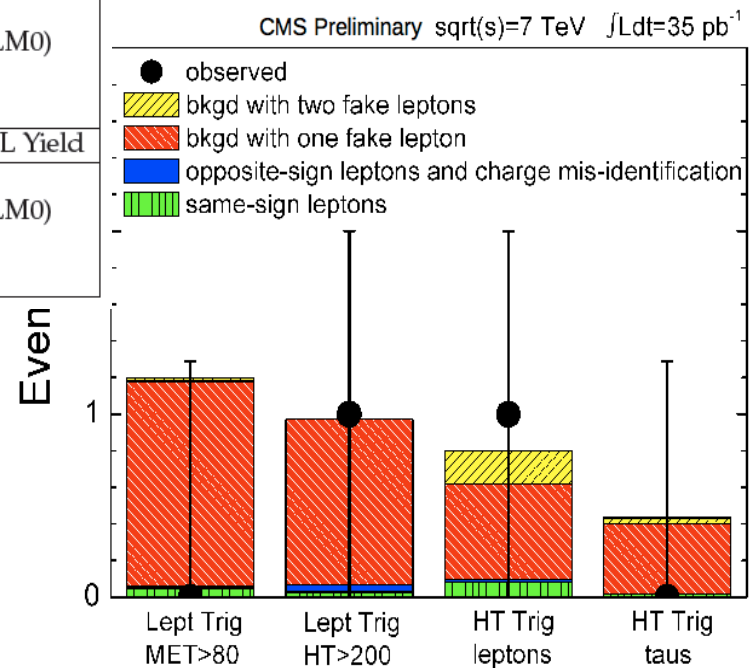


Eventi con $Z \rightarrow ee$ dello stesso segno : 5
 Eventi con $Z \rightarrow ee$ di segno opposto: 3642

La probabilità di sbagliare il segno della carica è $\langle \epsilon \rangle = 0.5 \cdot (5/3642) = 0.0007$
 e viene applicato al numero di eventi con due leptoni isolati
 $ee/e\mu$ (+HT, +MET)

Ricerca di eventi con leptoni dello stesso segno

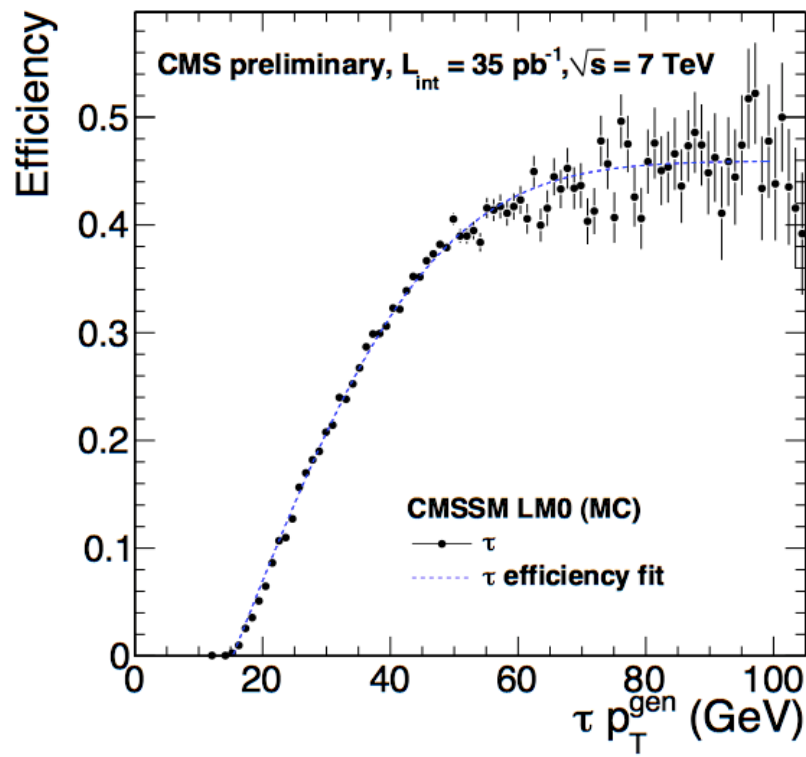
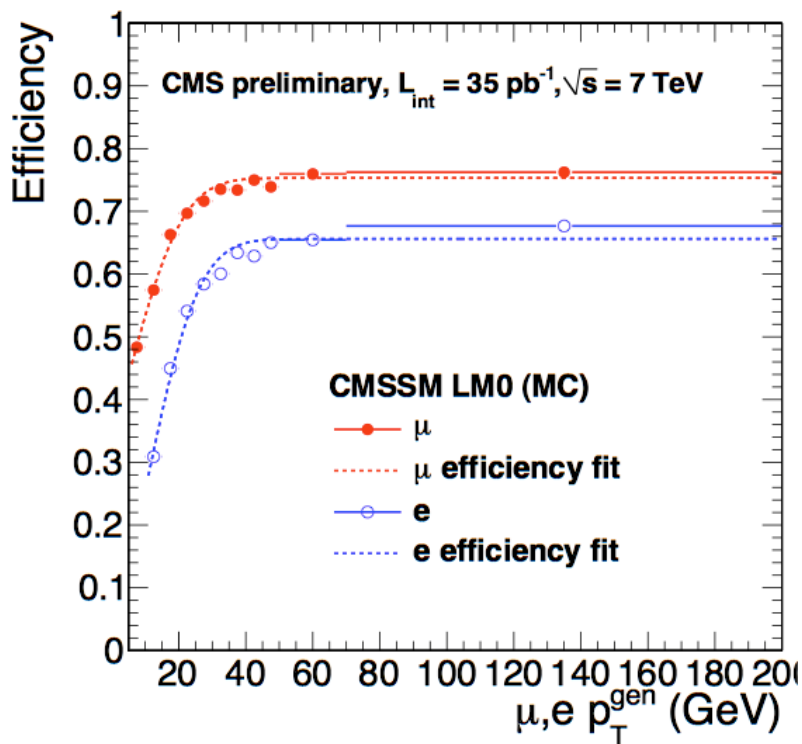
Search Region	ee	$\mu\mu$	$e\mu$	total	95% C.L. UL Yield
Lepton Trigger					
$E_T > 80$ GeV MC	0.05	0.07	0.23	0.35	(7.3 for LM0)
BG predicted	0.23 ± 0.35	0.23 ± 0.26	0.74 ± 0.55	1.2 ± 0.8	
observed	0	0	0	0	3.1
$H_T > 200$ GeV MC	0.04	0.10	0.17	0.32	(9.6 for LM0)
BG predicted	0.71 ± 0.58	0.01 ± 0.24	0.25 ± 0.27	0.97 ± 0.74	
observed	0	0	1	1	4.4
H_T Trigger					
Low- p_T MC	0.05	0.16	0.21	0.41	(9.1 for LM0)
BG predicted	0.10 ± 0.07	0.30 ± 0.13	0.40 ± 0.18	0.80 ± 0.31	
observed	1	0	0	1	4.5
	$e\tau$	$\mu\tau$	$\tau\tau$	total	95% C.L. UL Yield
τ enriched MC	0.36	0.47	0.08	0.91	(2.0 for LM0)
BG predicted	0.10 ± 0.10	0.17 ± 0.14	0.02 ± 0.01	0.29 ± 0.17	
observed	0	0	0	0	3.4



Input per teorici

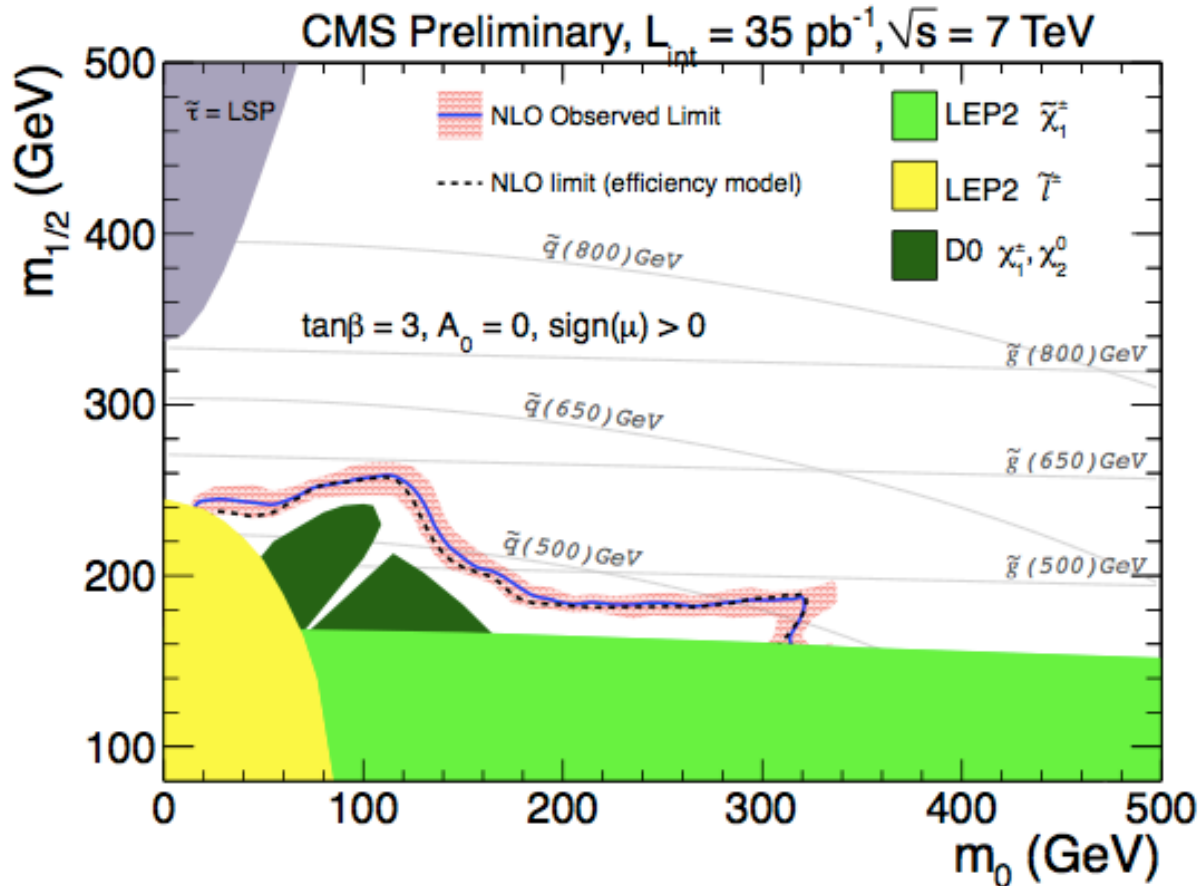
Nell'articolo vengono descritte in dettaglio le accettanze, le efficienze di ricostruzione dei leptoni, le risoluzioni di HT e MHT

Ogni teorico può testare il proprio modello senza dover passare attraverso la simulazione del rivelatore



Limiti in CMSSM

arxiv:1104.3168



I limiti in CMSSM superano i precedenti risultati ottenuti da Tevatron

I limiti ottenuti con la simulazione di CMS sono in ottimo accordo con quelli ottenuti con il “metodo delle efficienze”

Eventi con 2γ +jet+MET

arxiv:1103.0953

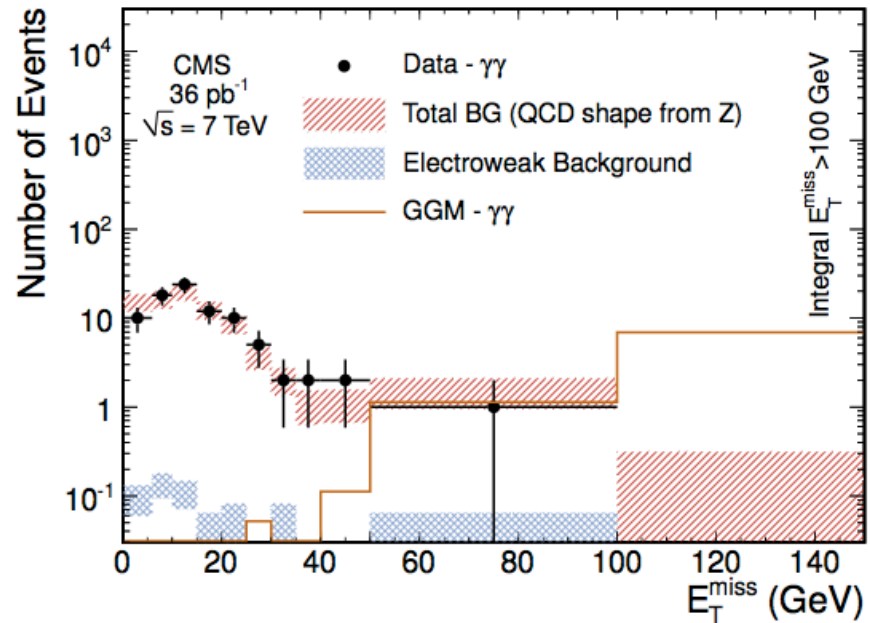
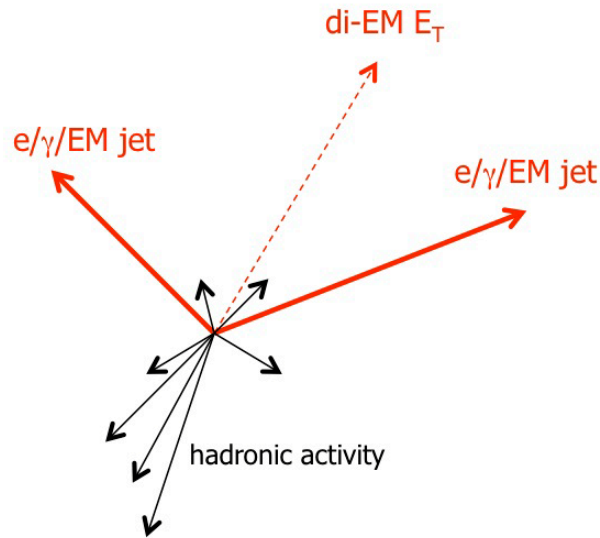
- Selezione

- 2 fotoni isolati $P_{T\gamma} > 30$ GeV e $|\eta_\gamma| < 1.4$
- Elettroni e fotoni si distinguono per la presenza di una traccia
- 1 jet $E_T > 30$ GeV
- MET > 50 GeV

- Fondo

- Produzione di fotoni da QCD + MET mismeasurement
 - Misurata nei dati (rinculo in eventi con $Z \rightarrow ee$)
- Elettroni identificati come fotoni (es. $W(e\nu)$ +jet)
 - La probabilità di identificare un elettrone come un fotone ($f_{e \rightarrow \gamma}$) viene misurata nei dati
 - Numero di eventi con $e+\gamma$ +jet+MET viene riscalato per il fattore $f_{e \rightarrow \gamma}$

Fondo da QCD



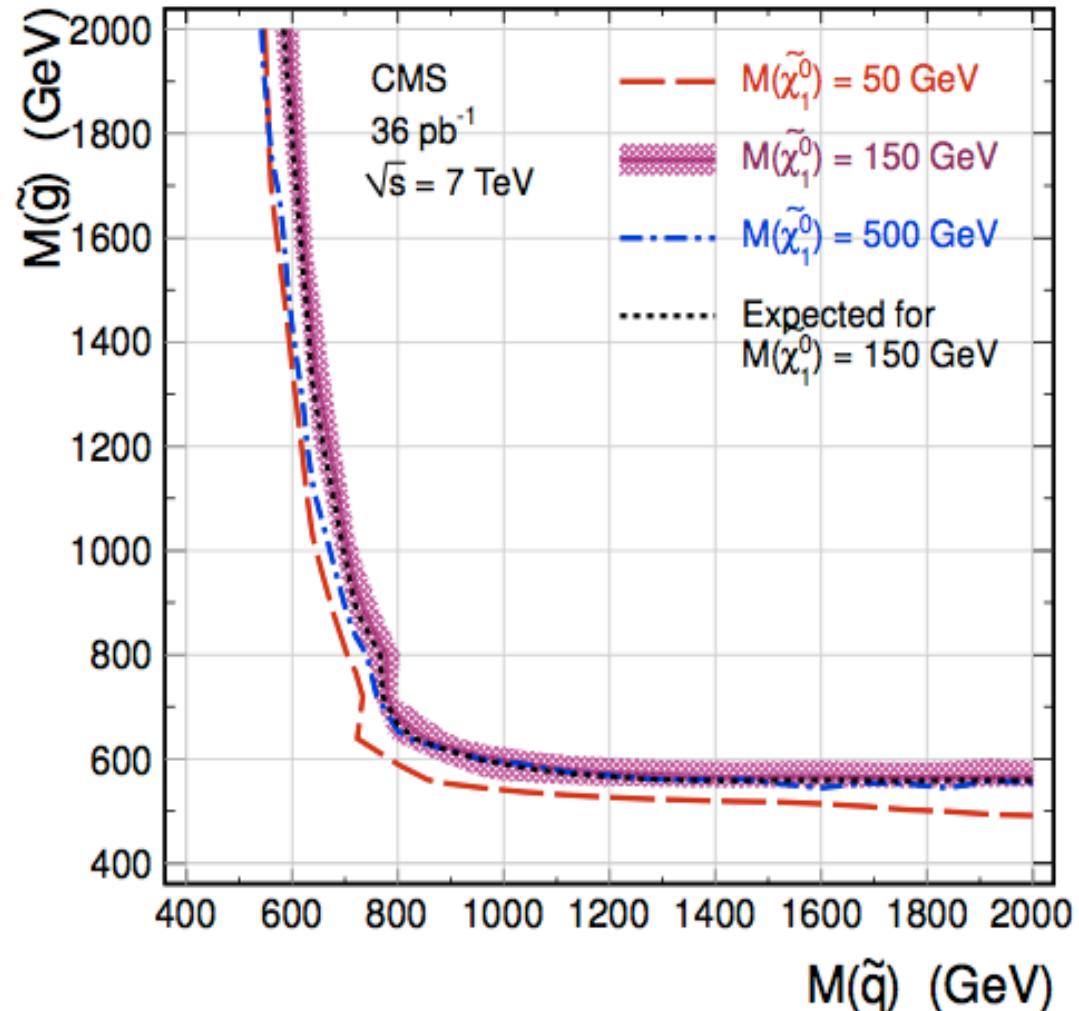
- Oggetti EM hanno una risoluzione energetica migliore dei getti adronici → la risoluzione dell'energia mancante è dominata dalla risoluzione adronica
- Risoluzione adronica e' misurata in eventi $Z \rightarrow ee$ in funzione di Z_{Pt}
- La risposta adronica viene ripesata secondo lo spettro in E_T del sistema $\gamma\gamma$
- Campione di controllo viene normalizzato a bassi valori di MET (< 20 GeV)

Eventi con $2\gamma+\text{jet}+\text{MET}$

1 evento osservato

Eventi aspettati = 1.2 ± 0.8

- Interpretazioni in GGM
- $\text{Br}(\chi^0 \rightarrow G\gamma) = 100\%$
- Limiti superiori tra 0.5 e 1.1 pb



Conclusioni

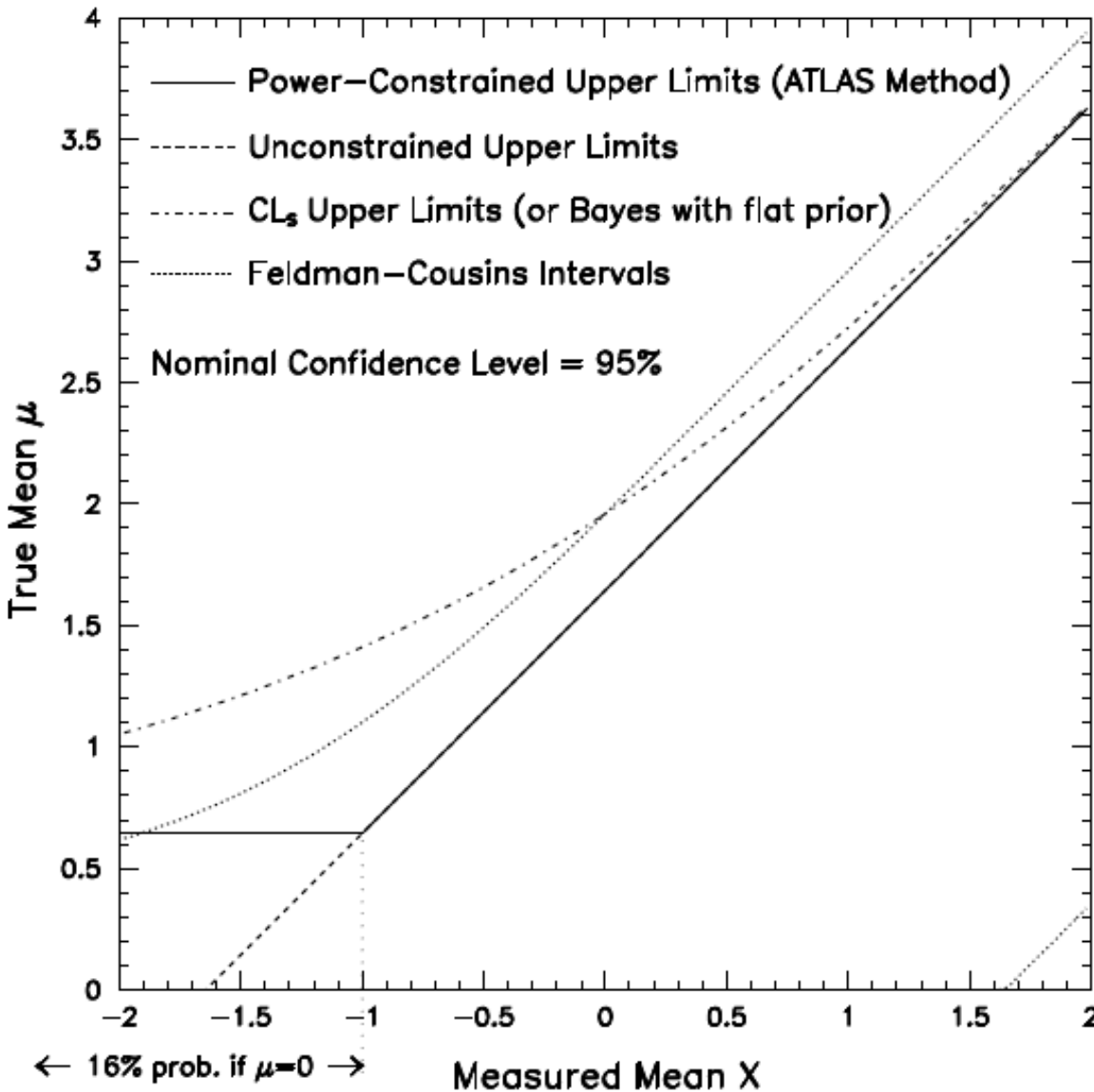
- 16 documenti pubblici (articoli e PAS) relativi alla ricerca di fenomeni supersimmetrici
- Sfortunatamente nessuna di queste ricerche ha osservato segnali di nuova fisica
- Con 35 pb^{-1} i limiti di TeVatron sono stati superati in molti modelli
- Nel 2011/2012 ci attendiamo molti più dati...

Back-up

Intervals and Limits for a Physically Bounded μ

- Prototype: measurement x is unbiased Gaussian estimate of μ . (Let $\hat{\sigma}=1$.)
What is 95% C.L. Upper Limit (UL)?
- 1986: Six methods for UL surveyed by V. Highland (VH) include U.L. = $\max(0, x + 1.64)$ and U.L. = $\max(0, x) + 1.64$.
- RPP 1986: Bayesian: uniform prior on the mean μ for $\mu \geq 0$, prior prob = 0 for $\mu < 0$. (VH's other five not mentioned.)
- 1994,96: 3 ad-hoc frequentist recipes, one using $\max(x, 0)$.
- 1998: Feldman & Cousins (FC) "Unified Approach" in (Kendall and Stuart) replaces ad hoc frequentist
- 2002: CL_s from LEP added to Bayesian and FC.
- CMS Statistics Committee recommends using (at least) one of the three (red) methods in 2002-present PDG RPP.
- ATLAS SC method implies U.L. = $\max(0, x + 1.64)$ before power constraint (PC), U.L. = $\max(-1, x) + 1.64$ after PC.

Comparison of ATLAS PCL with the three methods in PDG



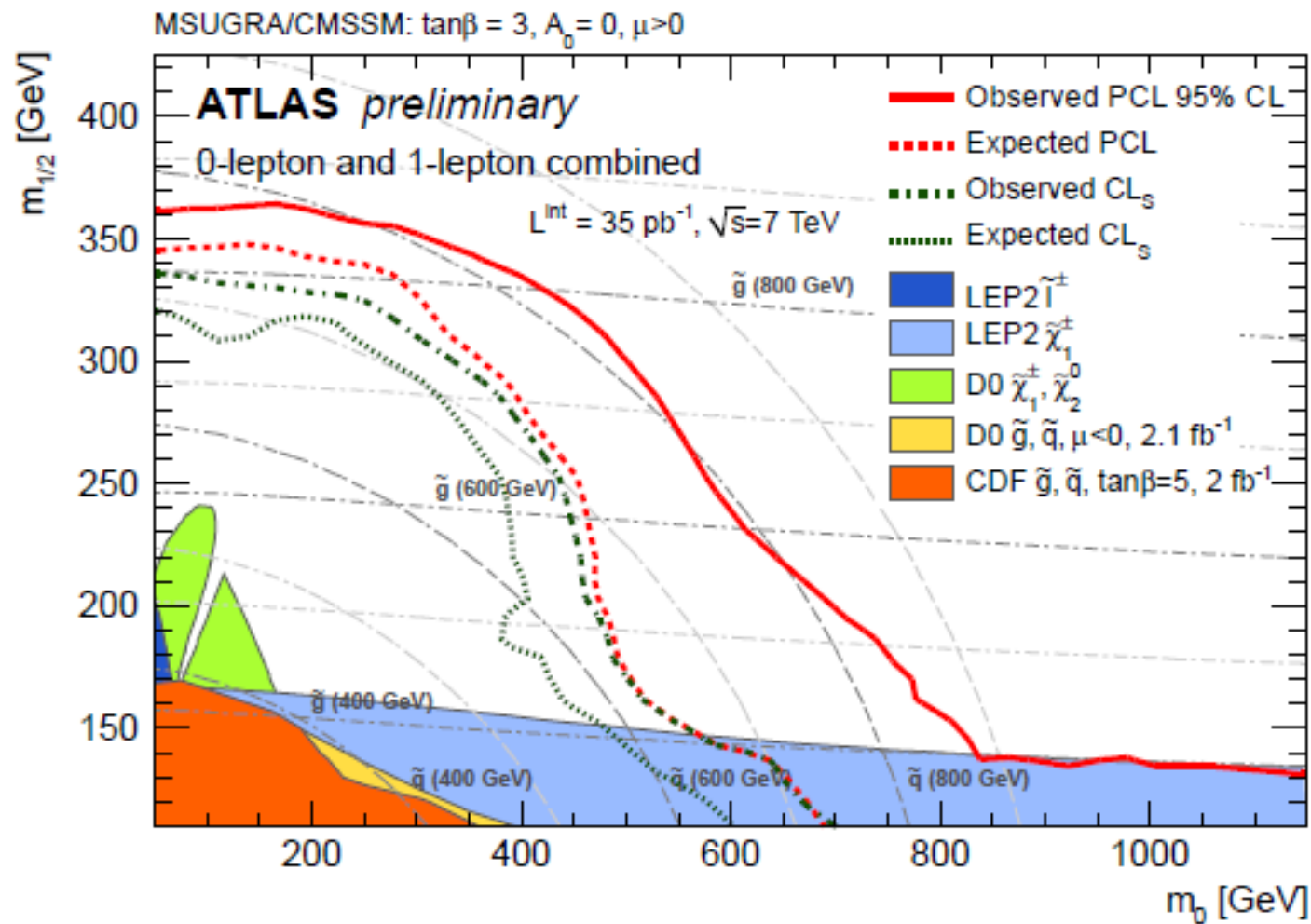
(Atlas unconstrained U.L. is zero, not null, for $x < -1.64$)

ATLAS PCL re-opens discussion on use of diagonal line along with ad hoc constraint, out of favor for many years, not recommended by CMS SC.

CMS and ATLAS SC's are reviewing arguments and what has been learned in 25+ years. Academic statisticians have commented as well.

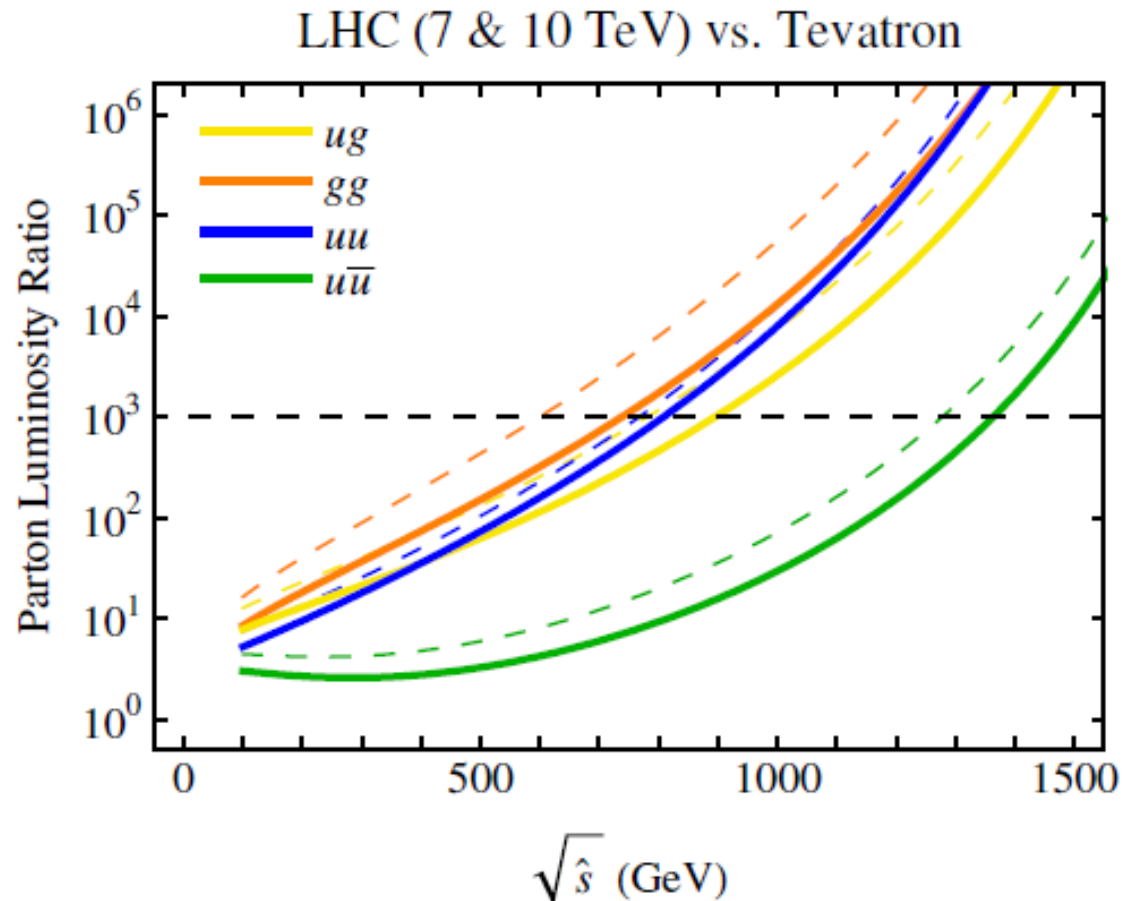
Just tip of iceberg: Poisson example brings in other issues. Nuisance parameters yet more. Choice of test statistic varies.

Atlas



LHC vs TeVatron

Ratio of parton luminosities at the LHC and the TeVatron exceeds the inverse ratio of integrated luminosities ($\sim 100 = 5 \text{ fb}^{-1} / 50 \text{ pb}^{-1}$) for mass scale $>500\text{-}600 \text{ GeV}$ (gg, qq) and 1150 GeV (qq)



SUSY phenomenology

Breaking mechanism and R-parity determines
phenomenology and the **search strategy**

In R-parity conserving scenarios, $\tilde{\chi}_1^0$ (or $\tilde{\nu}$) is LSP.
Signatures:
Missing E_T + jets (+ leptons)

Generic MSSM
MSUGRA/CMSSM
GMSB, GGM

Exploit unbalanced momentum from LSP

Gravitino very light (\ll MeV) \rightarrow is the LSP. Neutralino can be NLSP:

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$

Signatures (R-parity cons.):

Missing $E_T + 2\gamma$ (+lepton/jets)

AMSB

Split-SUSY
RPV-scenarios

....

Depending on the mass spectrum if small $\tilde{\chi}^\pm - \tilde{\chi}_1^0$ mass difference, long-lived charginos expected
Signatures:
displaced vertex kinked tracks

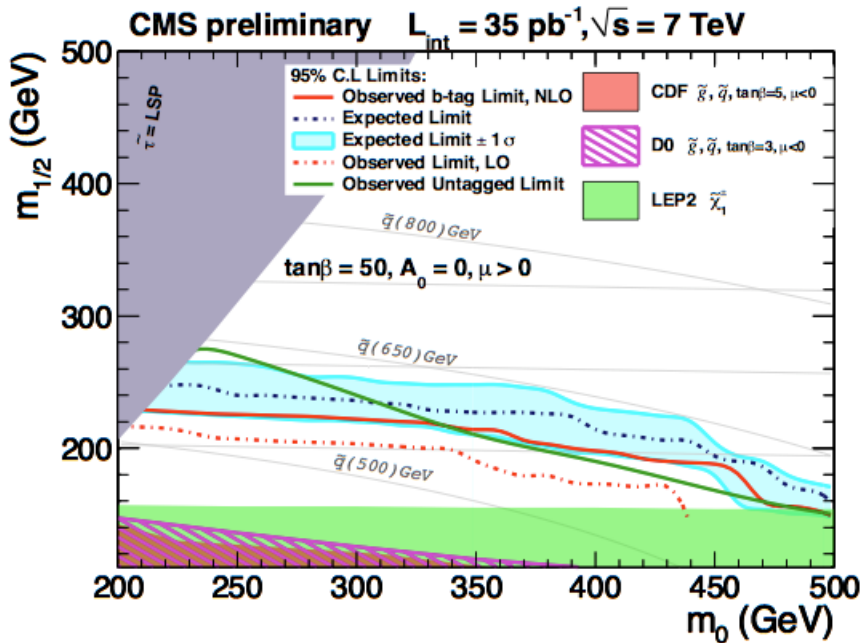
Dedicated techniques

squarks/gluinos heavy
Typical signatures:
Long-Lived / quasi stable particles (R-hadrons)

If R-parity not conserved, search for resonances

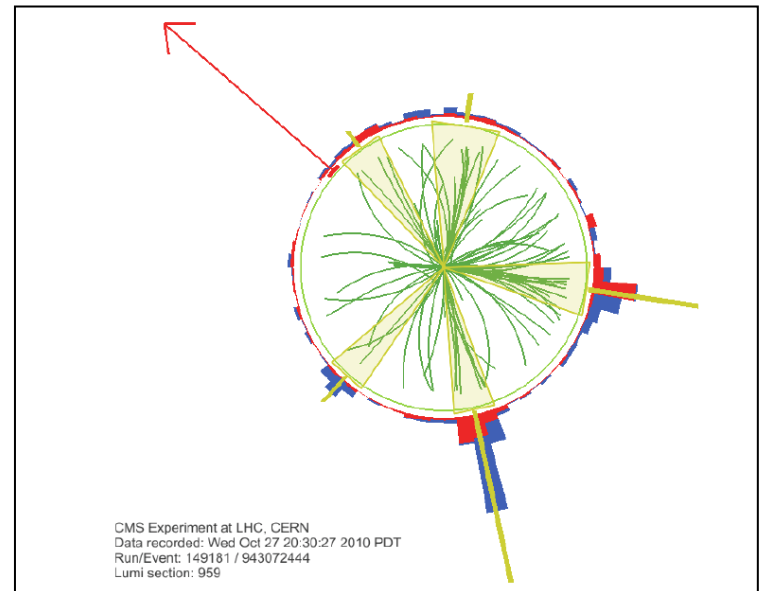
$\alpha_T + b\text{-tag}$

CMS-SUS-10-011



1 evento osservato
 $0.33^{+0.43}_{-0.33}$ (stat) ± 0.13 (syst) eventi
di fondo aspettati

- Stesse metodologie dell'analisi α_T
- La richiesta di un jet da b-quark riduce il fondo da QCD e W+jet
- Questa ricerca è sensibile ai modelli con molti b-quark nello stato finale (alto $\tan\beta$)

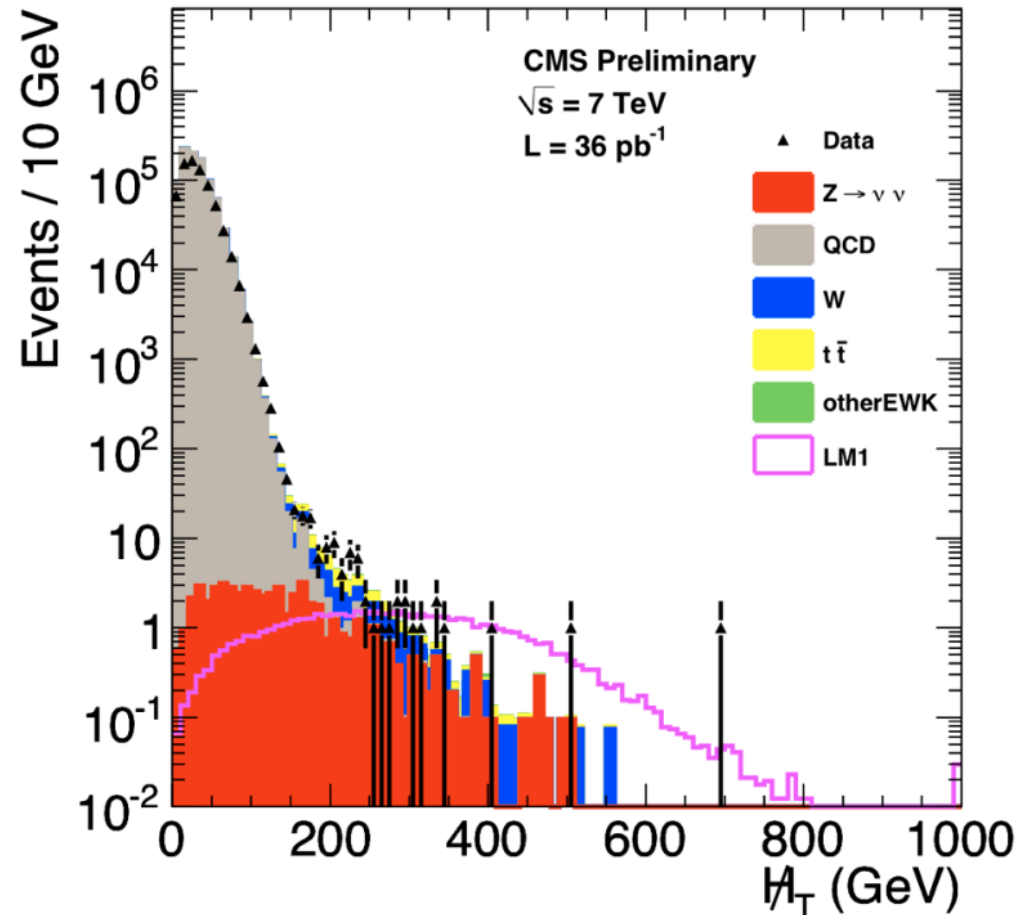
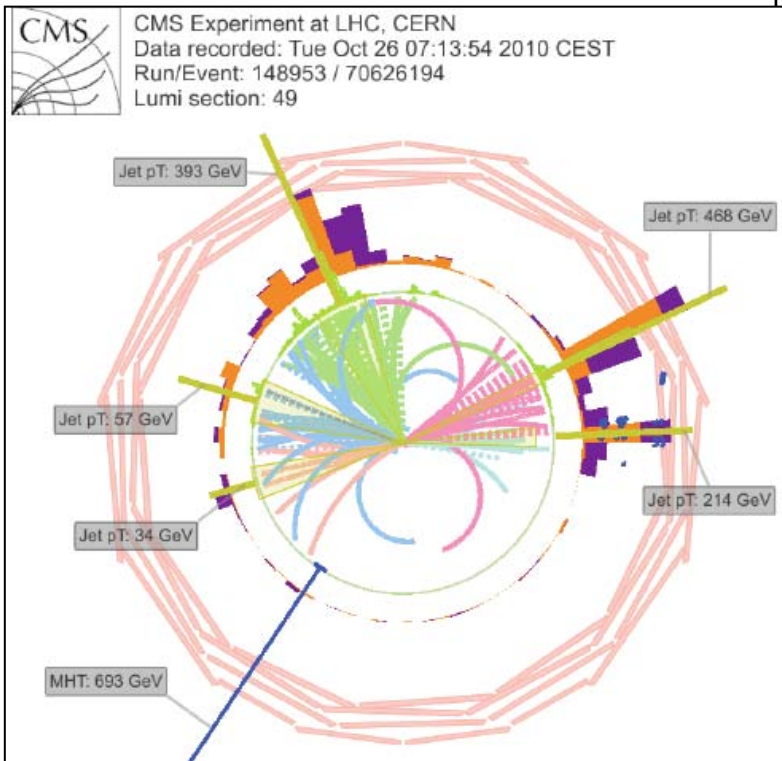


Hadronic search with missing energy

- $N_{\text{jets}50} > 2$
- $H_T > 300$ GeV
- $MHT > 150$ GeV
- No Leptons

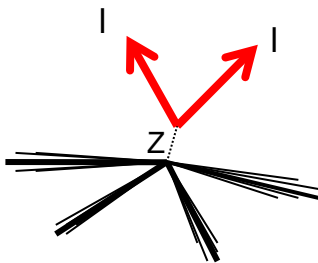
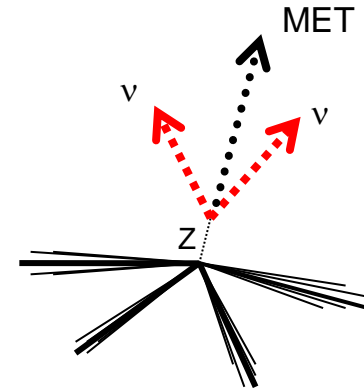
15 observed events

CMS-SUS-10-005



Fondo da $Z \rightarrow \nu\nu$

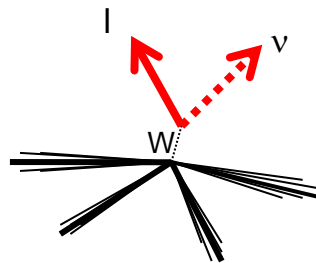
- $Z \rightarrow \nu\nu + \text{jets} \rightarrow$ Fondo irriducibile
- $Z \rightarrow \nu\nu$ viene rimpiazzato da altri processi



$Z \rightarrow ll + \text{jets}$

Strength: very clean

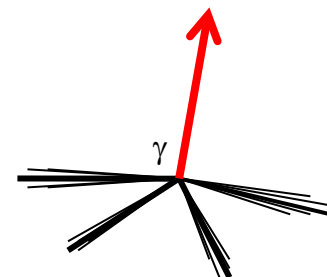
Weakness: low statistics



$W \rightarrow l\nu + \text{jets}$

Strength: larger statistics

Weakness: background from SM and SUSY



$\gamma + \text{jets}$

Strength: large statistics and clean at high E_T

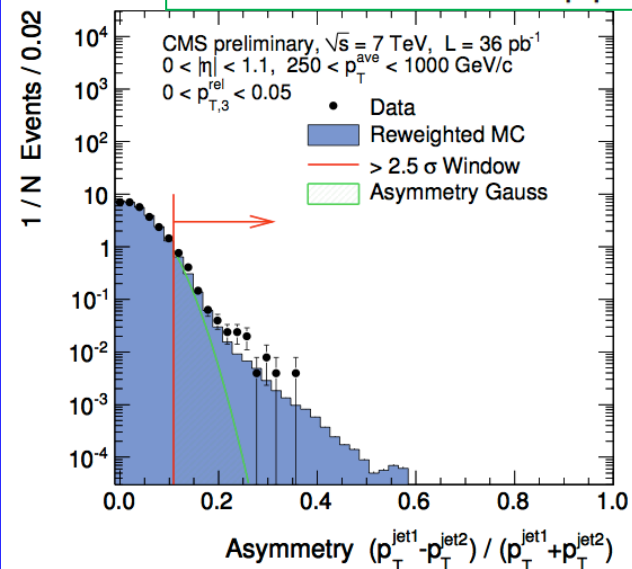
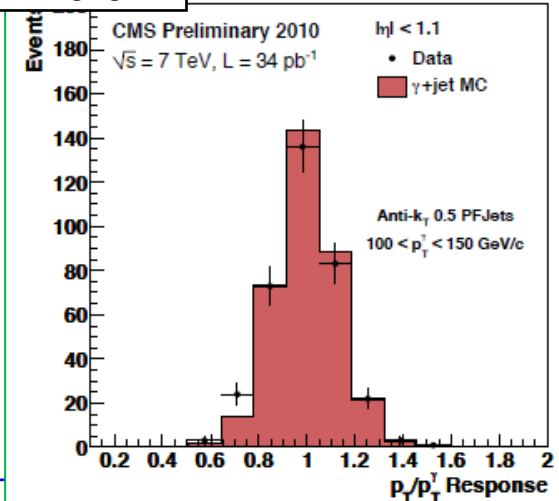
Weakness: background at low E_T , theoretical errors

Multi-jet QCD background

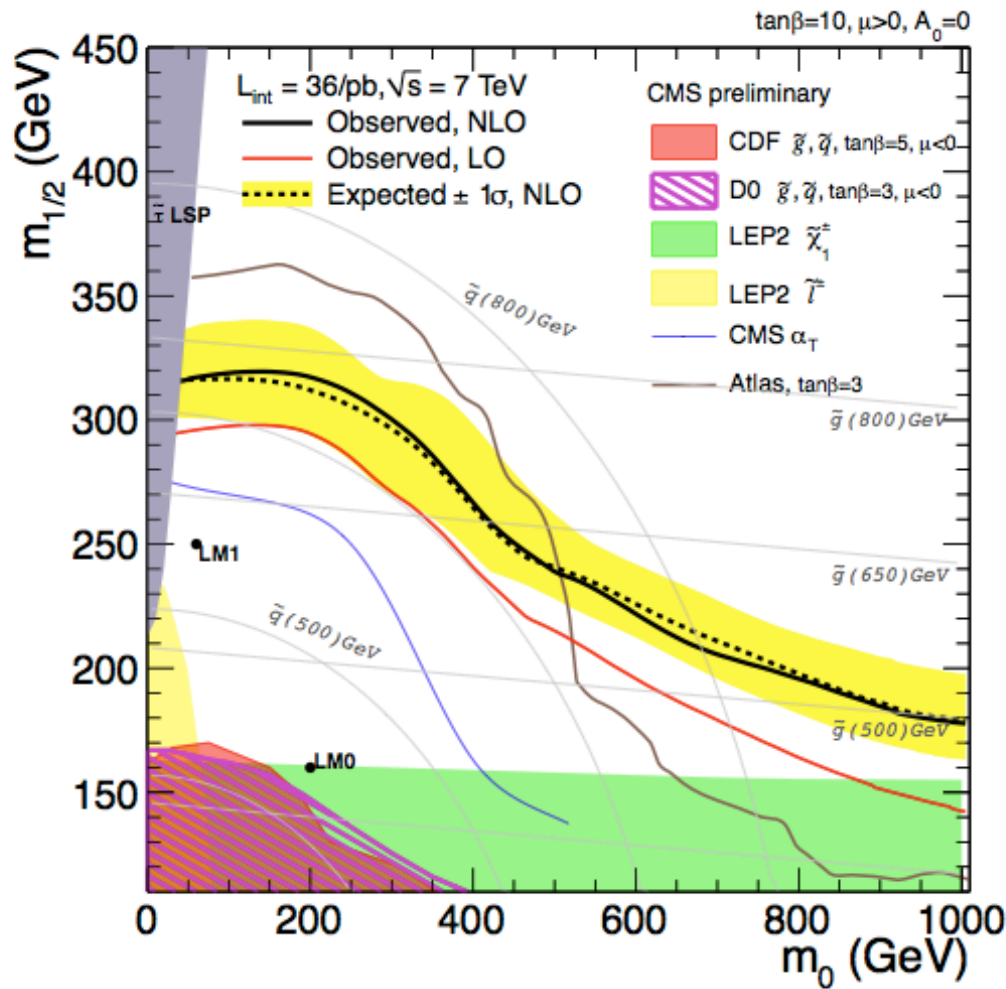
- Jet energy response from data γ +jets (core) and di-jets (non-gaussian tails)
- Jet energy response is applied to a “seed jet sample” to predict the high MHT tails
- Seed jet sample obtained by rebalancing multi-jet sample
- EWK component negligible

bkg estimate = 19.0 ± 3.6

CMS-JME-10-014



Hadronic search with missing energy



Results expressed in terms of 95% C.L. in CMSSM

Extends limit from α_T search and Tevatron

Hadronic search with “Razor”

- The “Razor” variables: M_R and R

arXiv:1006.2727

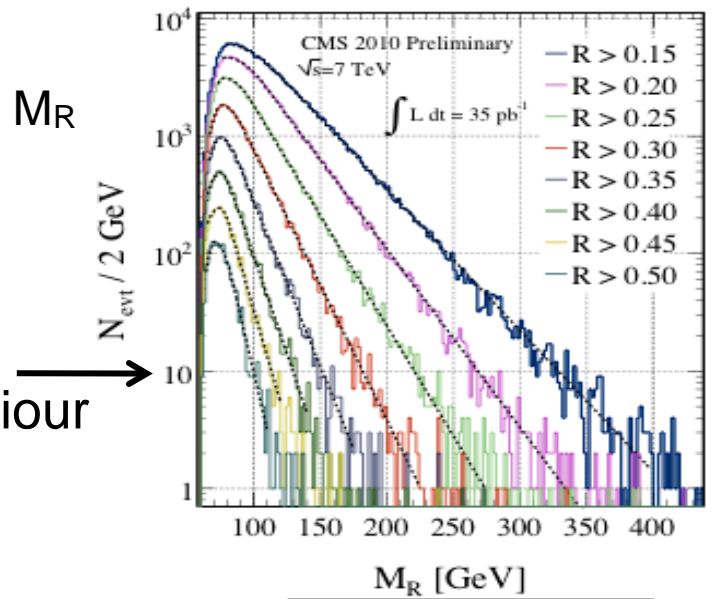
- Designed to characterise pair-production of heavy particles
- Combine all particles into two hemispheres and boost back to rest frame
- M_R is a measure of the mass and peaks at the scale of the production

$$M_R = \frac{M_{\tilde{q}}^2 - M_{\chi}^2}{M_{\tilde{q}}}$$

- M_{R^T} averaged transverse mass with endpoint M_R
- R then the ratio M_R/M_{R^T}

- For non-signal events M_R distribution after R cut shows exponential scaling behaviour

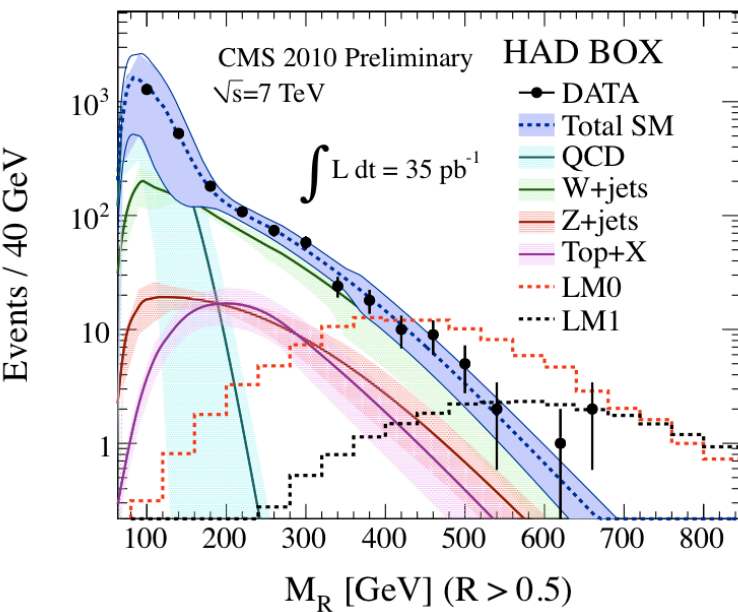
QCD simulation



Hadronic search with “Razor”

- $N_{\text{jets}30} \geq 2$
- $R > 0.5$
- $M_R > 500 \text{ GeV}$

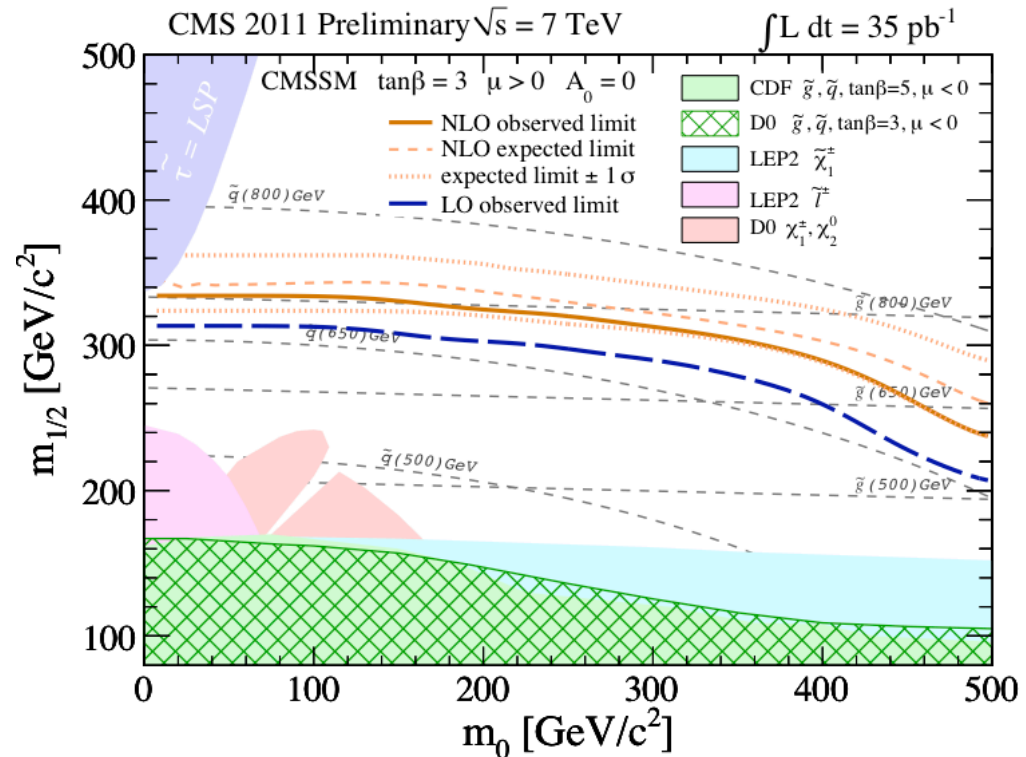
7 observed events



Only low M_R regions used to determine backgrounds

Bkg estimate = 5.5 ± 1.4

Similar limits to jets+MHT analysis

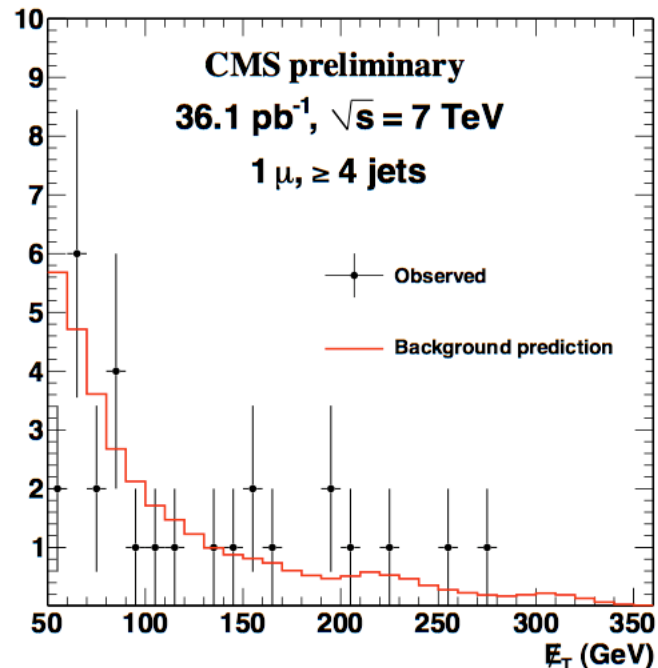


Search in single lepton events

CMS-SUS-10-006

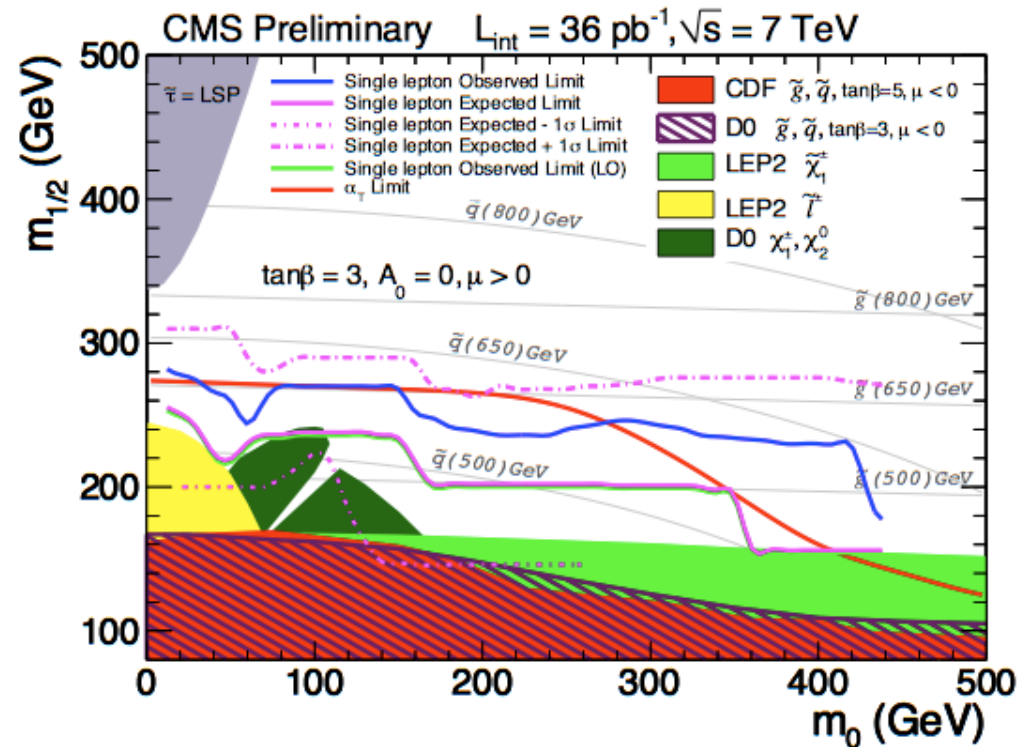
- $N_{\text{jets}20} \geq 4$
- 1 isolated electron or muon $p_{\text{T}} > 20$ GeV
- $H_{\text{T}} > 500$ GeV
- $M_{\text{ET}} > 250$ GeV
- 2 observed events in $\mu + \text{jets} + \text{MET}$
- 0 observed events in $e + \text{jets} + \text{MET}$

Main background sources are $W + \text{jets}$ and $t\bar{t}$ events estimated directly from data. Exploit the fact that for W decays the charged lepton and neutrino p_{T} spectra are on average approximately the same



Results and interpretation

Sample	$\ell = \mu$	$\ell = e$
Predicted SM 1 ℓ	1.7 ± 1.4	1.2 ± 1.0
Predicted SM dilepton	$0.0^{+0.8}_{-0.0}$	$0.0^{+0.6}_{-0.0}$
Predicted single τ	0.29 ± 0.22	$0.32^{+0.38}_{-0.32}$
Predicted QCD background	0.09 ± 0.09	$0.0^{+0.16}_{-0.0}$
Total predicted SM	2.1 ± 1.5	1.5 ± 1.2
Observed signal region	2	0

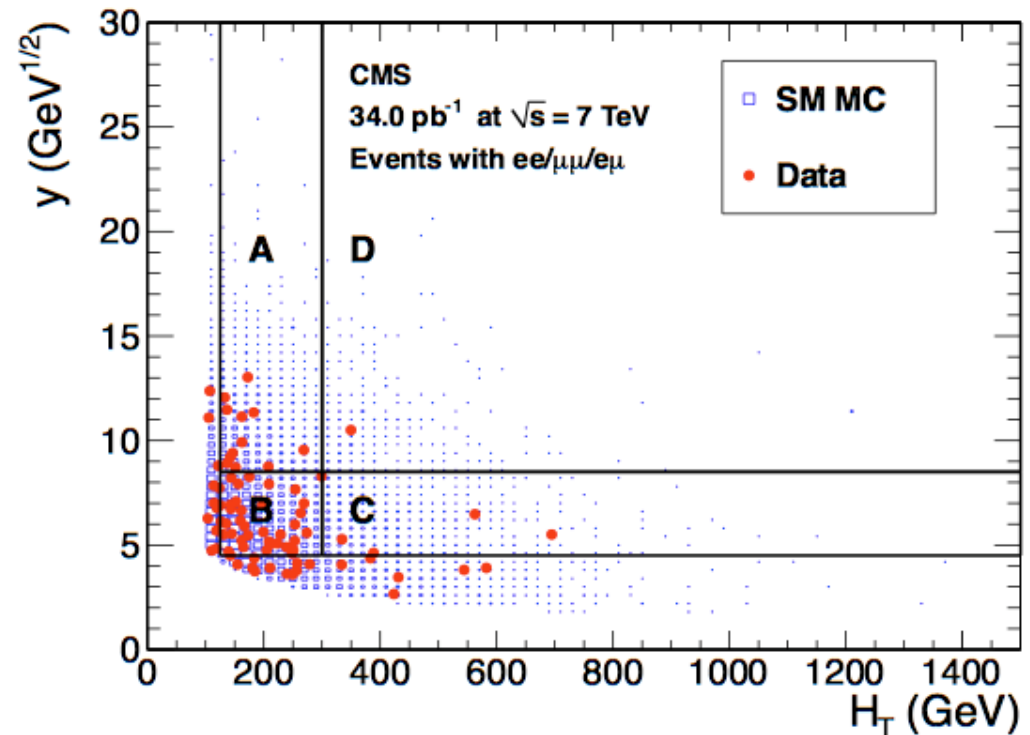


Limit similar to hadronic α_τ search in
CMSSM

Opposite-sign dilepton search

- Adding a second lepton rejects W +jets leaving mostly top background
- Two isolated leptons (e or μ); one with $p_T > 20$ GeV, other with $p_T > 10$ GeV
- Veto same-flavour pairs in Z mass window and $m_{ll} < 10$ GeV
- $N_{\text{jets}30} > 2$
- $H_T > 300$ GeV
- $Y = \text{MET} / \sqrt{H_T} > 8.5 \sqrt{\text{GeV}}$

arxiv:1103.1348

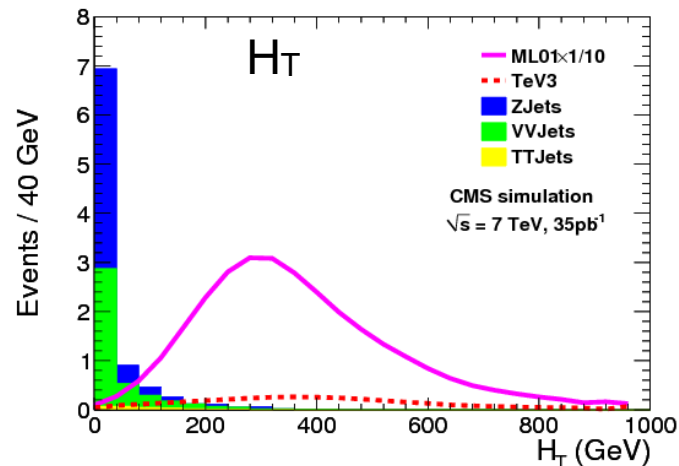
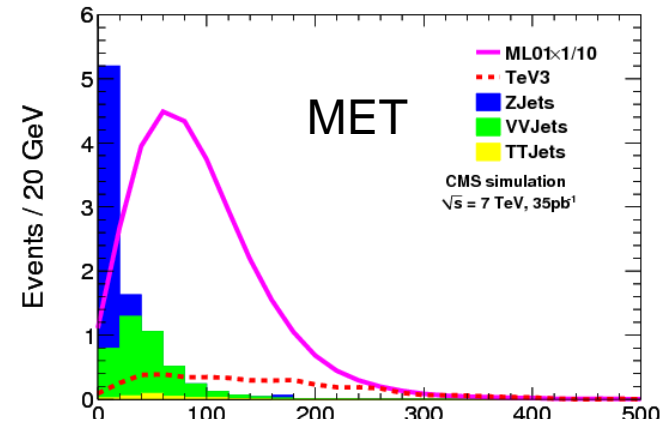


D signal region, ABC background regions
ABCD/matrix method
Background in D = A * C / B

Multi-lepton search

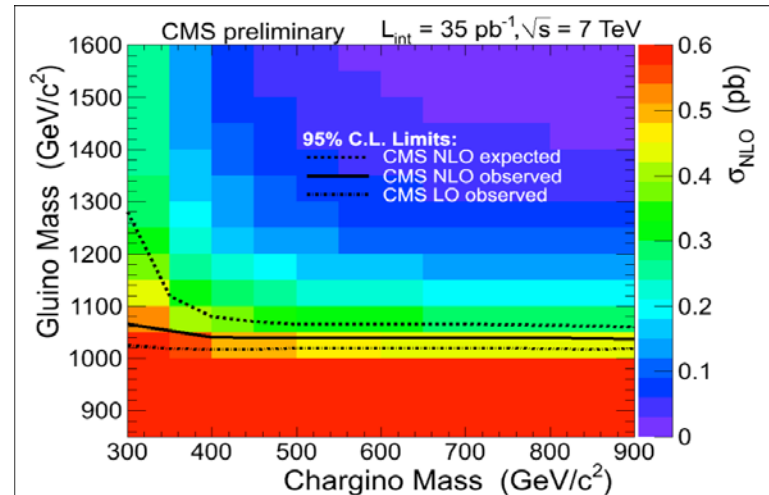
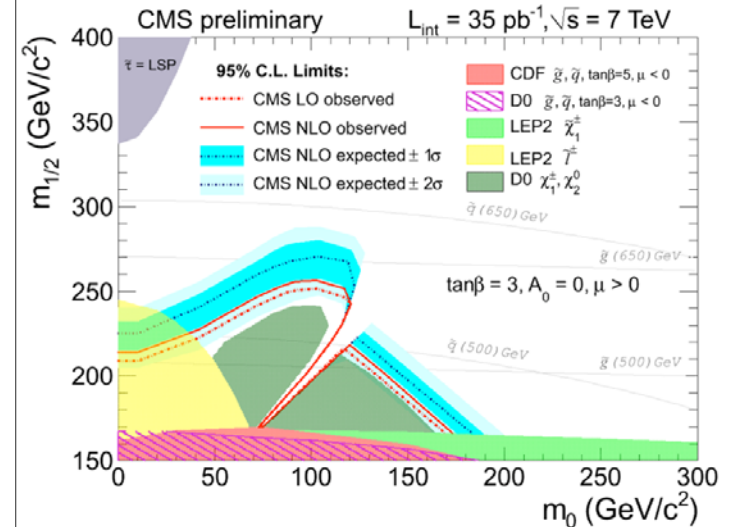
- Baseline
 - At least three leptons (e, μ, τ) with p_T thresholds from 8 GeV
 - Require one non- τ lepton (trigger)
- Two final selections
 - $MET > 50$ GeV
 - $H_T > 200$ GeV
- Backgrounds:
 - $WZ+Jets, ZZ+Jets, t\bar{t}$ estimated from simulation
 - $Z+Jets, WW+Jets, W+Jets, QCD$ estimated from data

CMS-SUS-10-008



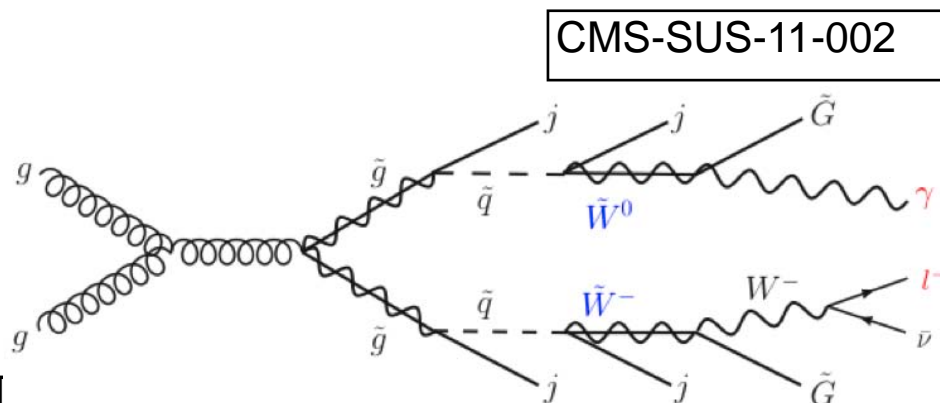
Multi-lepton search

- 55 exclusive channels combined statistically to give final result
- No excess observed
- Set limits in CMSSM for comparison with previous expts.
- Also consider more phenomenological interpretation in GGM model
- Multi-lepton signatures also arise naturally in co-NLSP model with mass degenerate sleptons decaying to leptons and Gravitino



Lepton + photon search

If wino and bino are mass degenerate NLSPs then di-photon signature replaced by lepton+photon signature.



- Isolated lepton (e or μ) with p_T
- Isolated photon with $p_T > 30$ GeV
- $MET > 100$ GeV
- Dominant background is $W\gamma$
 - Cross section measured by CMS [CMS EWK-10-008]
 - Taken from simulation

	Observed	BKG estimate
$\gamma + \mu + MET$	1	1.7 ± 0.4
$\gamma + e + MET$	1	1.6 ± 0.4

