

SUSY and Beyond the Standard Model a CMS e ATLAS



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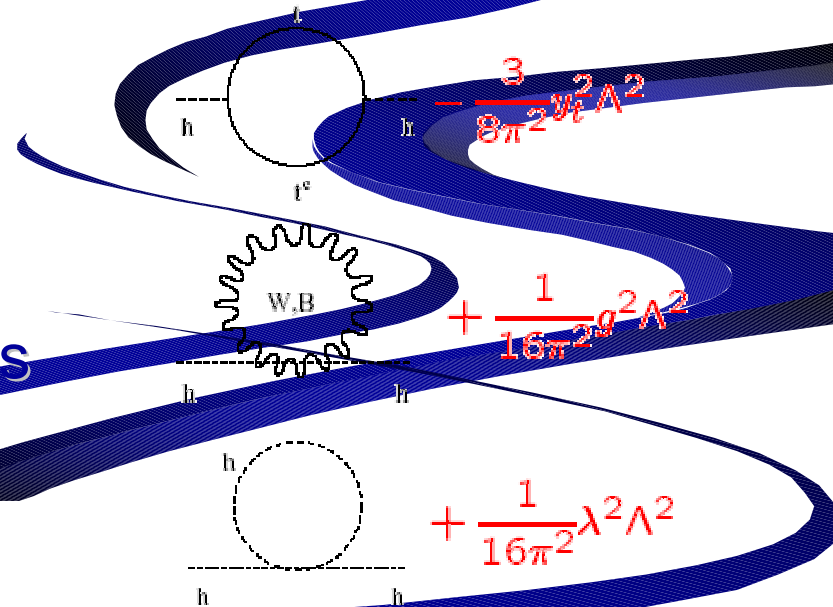
Necessità di andare oltre lo SM

- Ottima descrizione della Fisica dalla scala atomica a 10^{-18} m
- Estensione motivata dallo Hierarchy Problem
 - Planck scale (10^{19} GeV) \gg EW scale (10^2 GeV)
 - Le correzioni radiative portano la massa dell'Higgs alla scala più alta, a meno che uno spinto fine tuning dei parametri non dia delle cancellazioni

Possibili soluzioni:

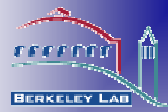
- **Supersimmetria**
- **Little Higgs**
- **Extra Dimensions**
- **Technicolor, Modelli Higgsless**
(non trattati in questo talk)

●



SUPERSYMMETRY

The image features a white background with abstract blue elements. A large, thick, wavy blue line starts from the top right and curves across the middle of the page. The word "SUPERSYMMETRY" is written in a bold, blue, sans-serif font, centered horizontally and partially overlaid by the wavy line. In the bottom left corner, there are three small blue dots connected by thin, curved lines, suggesting a path or trajectory.



SUSY: Trigger

- Obiettivo : ridurre i 40 MHz bx rate (~1 GHz pp) → O(100 Hz)
- Preservare la massima efficienza di segnale SUSY in canali jets + ETmiss
- Grosso rate QCD: trigger rate su nastro limitato dalla potenza di calcolo HLT

● Studio di ottimizzazione (CMS)

- Punti a limite della regione di scoperta di TeVatron
- R-conserving e R-violating
- Full simulation su segnali SUSY e fondi SM per valutare l'efficienza di trigger
- Efficienza ottimizzata per un rate O(10 Hz)

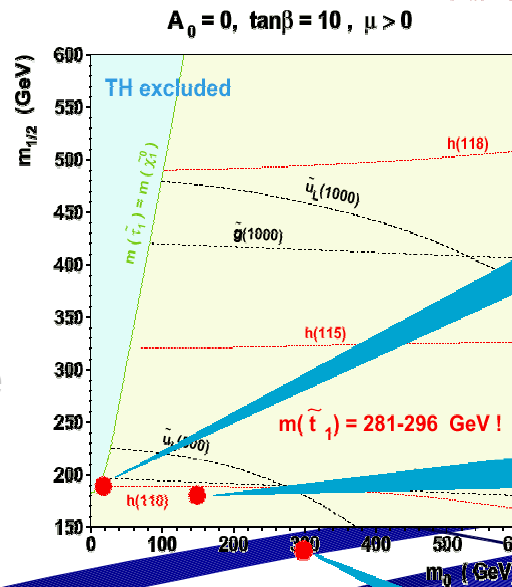
● Schemi possibili (low-lum):

- 1 jet con ET > 180 GeV & missing ET > 123 GeV
- 4 jets con ET > 113 GeV

● Efficienze:

- 60-70% R-conserving
- 25-45% R-violating

H.Baer et al., hep-ph/9802441; Phys.Rev.D58:075008, 1998



$m(\tilde{\chi}_1^0) = 70$ GeV $m(h) = 110$ GeV
 $m(\tilde{g}) = 466$ GeV $m(\tilde{u}_L) = 410$ GeV
 $\sigma \sim 181$ pb tau-enriched,
4 20,190 quite enough sleptons

$m(\tilde{\chi}_1^0) = 66$ GeV $m(h) = 110$ GeV
 $m(\tilde{g}) = 447$ GeV $m(\tilde{u}_L) = 415$ GeV
 $\sigma \sim 213$ pb nothing special
5 150,180

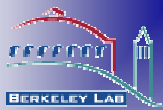
$m(\tilde{\chi}_1^0) = 45$ GeV $m(h) = 106$ GeV
 $m(\tilde{g}) = 349$ GeV $m(\tilde{u}_L) = 406$ GeV
 $\sigma \sim 500$ pb $\tilde{q} \rightarrow \tilde{g} + X$, $\tilde{g} \rightarrow 3$ body,
6 300,130 more jets, less MET

Require $\int L dt < 10 \text{ pb}^{-1}$



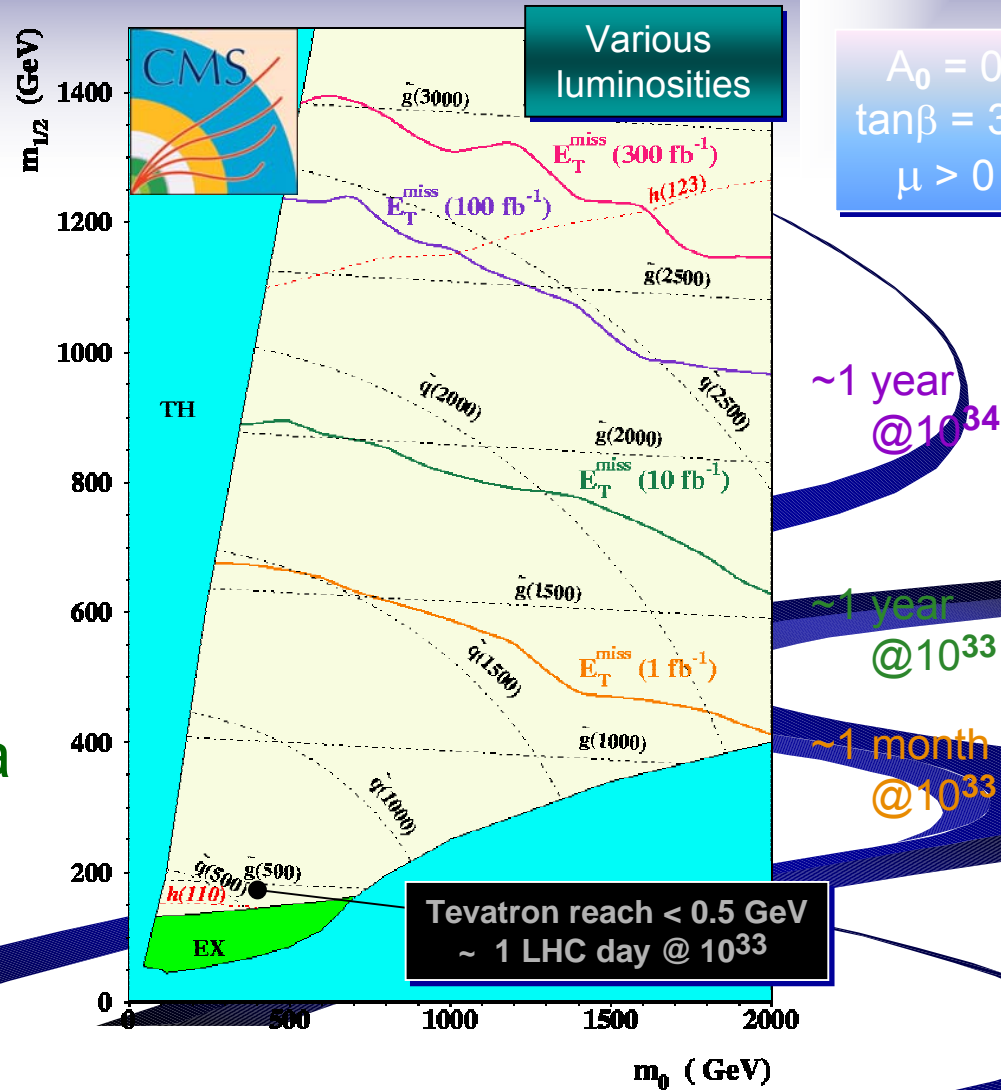


SUSY: Scoperta



$A_0 = 0$
 $\tan\beta = 35$
 $\mu > 0$

- **Jets+MET danno la migliore sensibilità**
- **Tempi limitati non dalla statistica, ma dalla comprensione delle prestazioni dei rivelatori**
 - Calibrazioni della scala di energia dei jet
 - Calibrazioni della missing energy
- **Occorrono grandi quantità di dati W,Z,tbbar per una corretta stima dei fondi**
- **Scoperta possibile fino a masse di $\sim q$ e $\sim g$ dell'ordine di 2.5-3 TeV con 300 fb^{-1}**



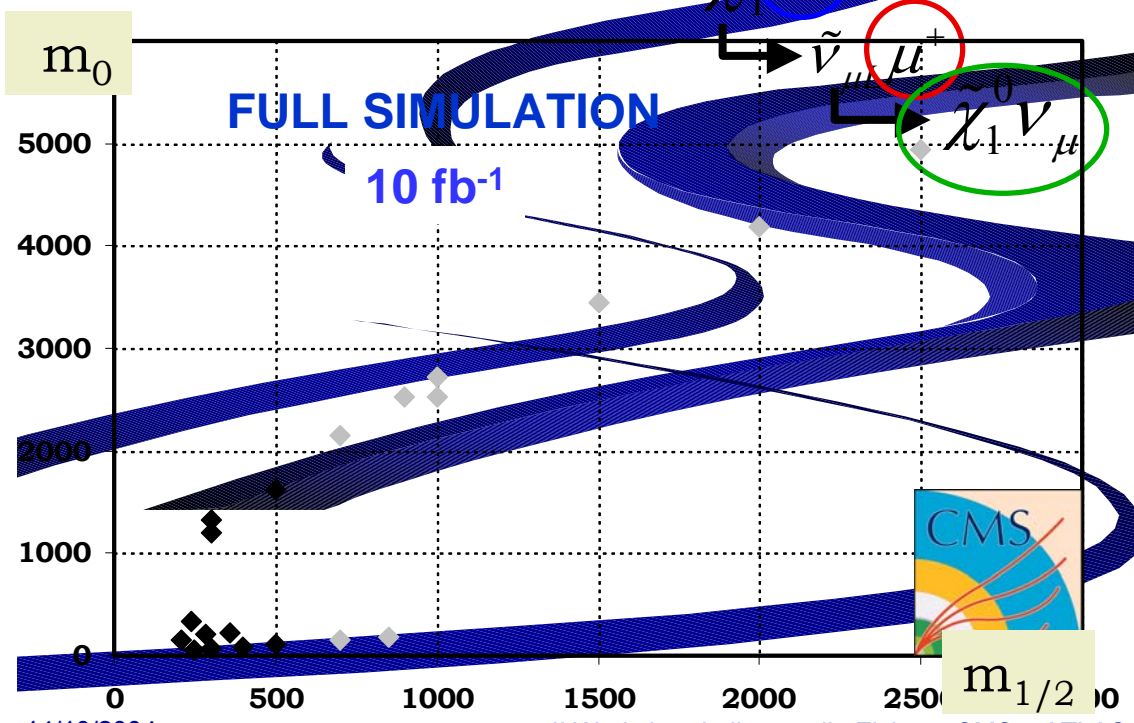
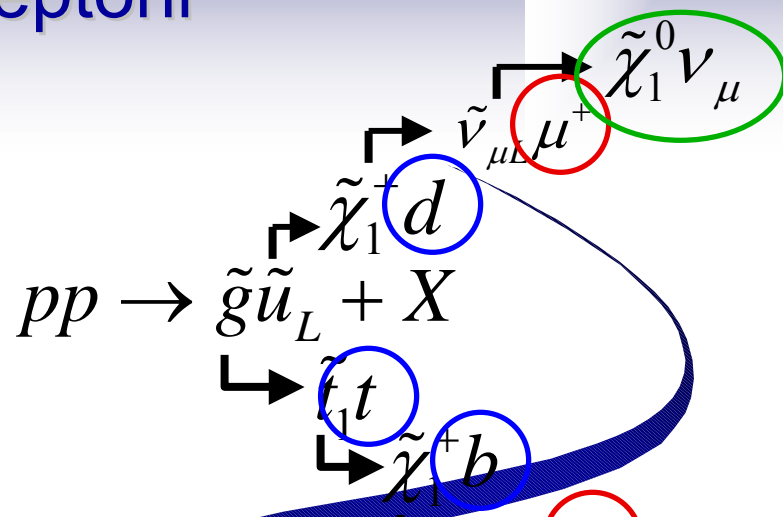
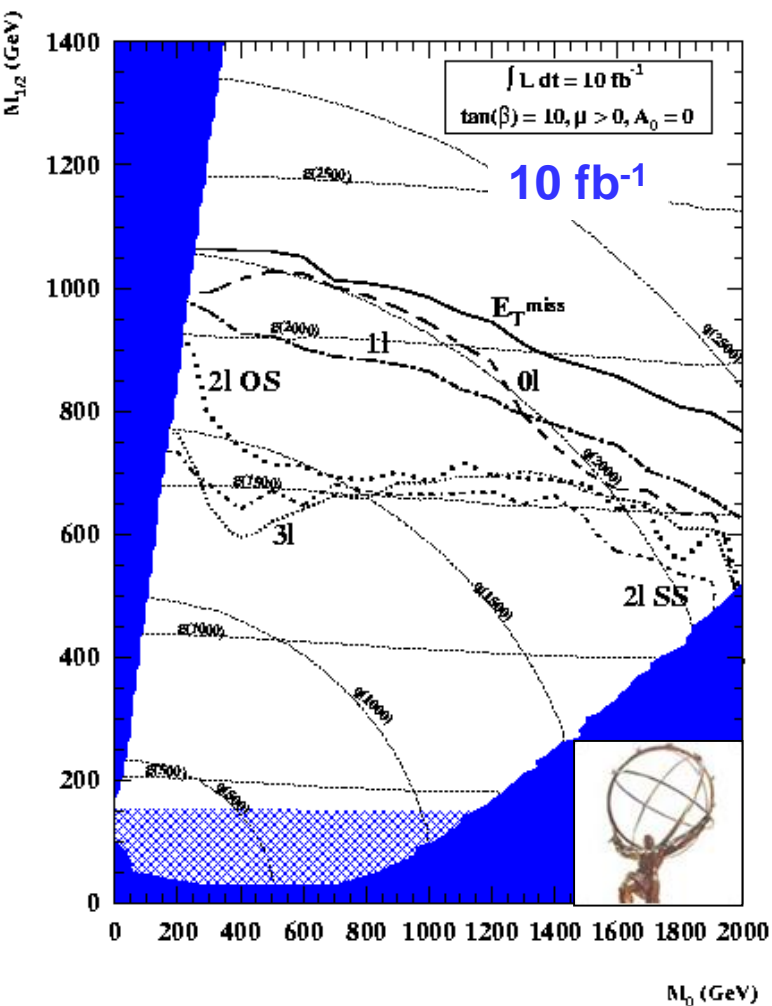
FAST SIMULATION



SUSY scoperta

● Analisi di supporto basate su leptoni

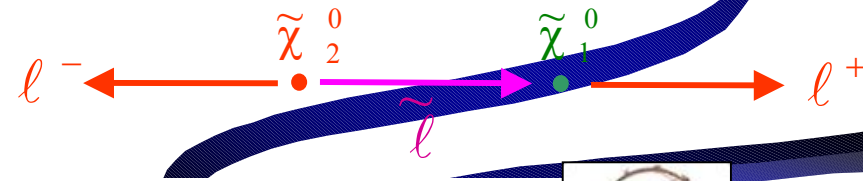
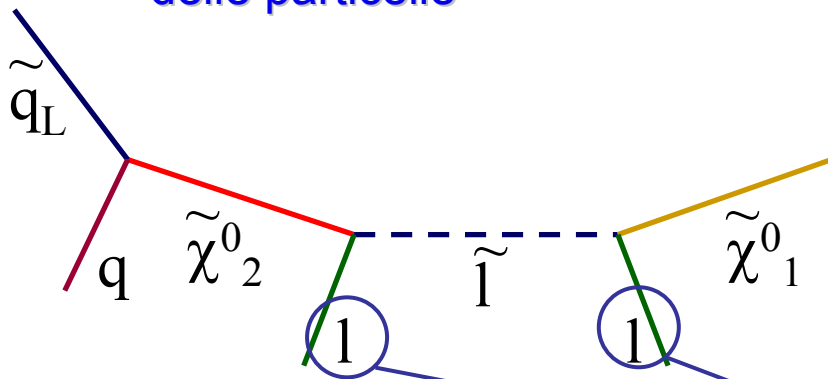
- trigger più efficiente
- migliore soppressione del fondo



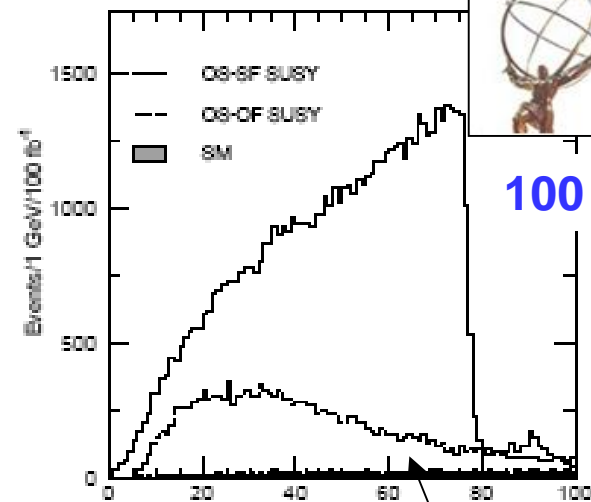


SUSY Misura dei parametri

- Scegliere alcuni punti di benchmark nello spazio dei parametri mSUGRA
- Identificare catene di decadimento in modo esclusivo
- Se una catena di almeno 3 two-body-decays può essere isolata, le masse e gli impulsi delle particelle possono essere misurate.
 - Edge e soglie nelle distribuzioni di massa invariante funzioni delle masse delle particelle



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



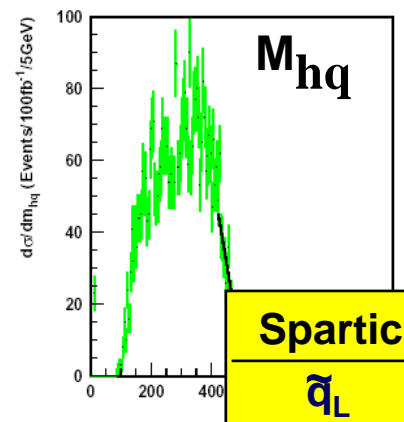
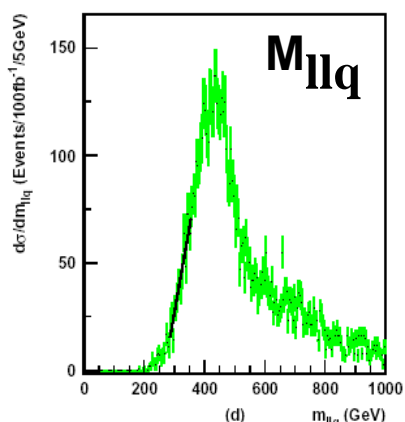
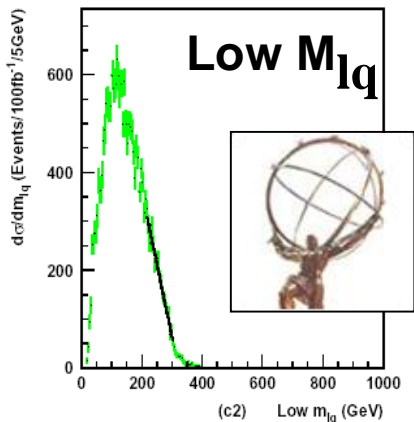
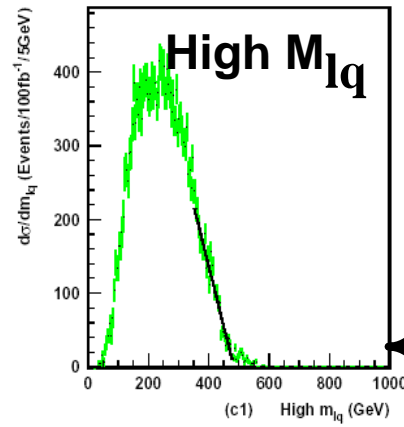
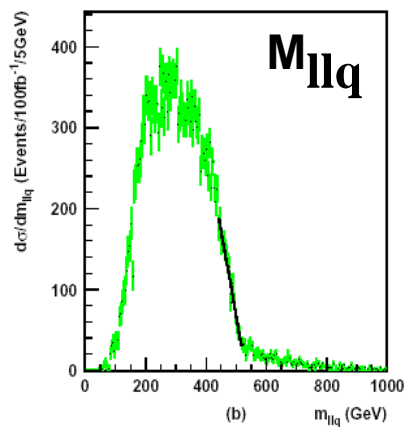
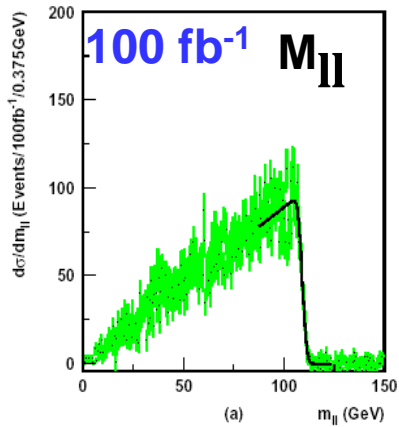
100 fb⁻¹

SM trascurabile



SUSY Misura dei Parametri

- ATLAS punto SPS1 ($m_0=100$, $m_{1/2}=250$, $\tan\beta=10$, $A_0=-100$, $\mu>0$)
- ATLFAST (fast simulation)



$$\begin{aligned}
 (m_{ll}^2)^{\text{edge}} &= \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2} \\
 (m_{ql}^2)^{\text{edge}} &= \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\chi}_2^0}^2} \\
 (m_{ql}^2)^{\text{min}} &= \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2)}{m_{\tilde{\chi}_2^0}^2} \\
 (m_{ql}^2)^{\text{max}} &= \frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{l}_R}^2}
 \end{aligned}$$

end-point misurati con errori dell'1÷2%

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

- Le incertezze sistematiche sulla scala di energia di jet e leptoni dominano sulle incertezze statistiche

- Sfruttare grande statistica di $Z \rightarrow ll$, $W \rightarrow jj$ per le calibrazioni

- Lepton scale:

- $Z \rightarrow ll$ (2 ev/s a 10^{33}), constraint sulla massa di Z

- LHC goal: 0.1%

- Sistemati dominanti:

- $Z \rightarrow ee$ – conoscenza del materiale nella parte interna del detector (goal 1%), modelling del bremsstrahlung (goal 10%)

- $Z \rightarrow \mu\mu$ – mapping del campo magnetico, allineamenti

- Jet scale:

- $Z(\rightarrow ll)+jet$, richiedendo $p_T(jet) = p_T(Z)$

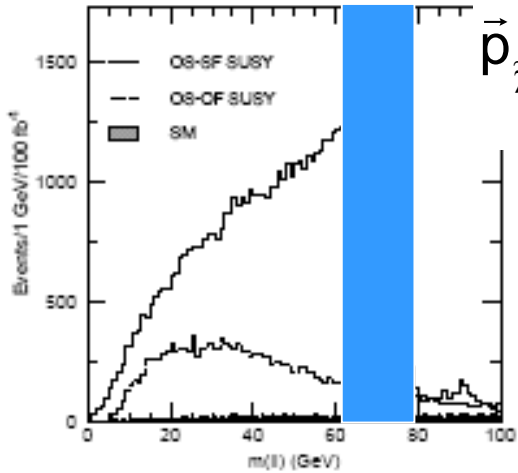
- $W \rightarrow jj$, in eventi $tt \rightarrow bWbW$, richiedendo $m_{jj} = m_W$

- LHC goal: 1%

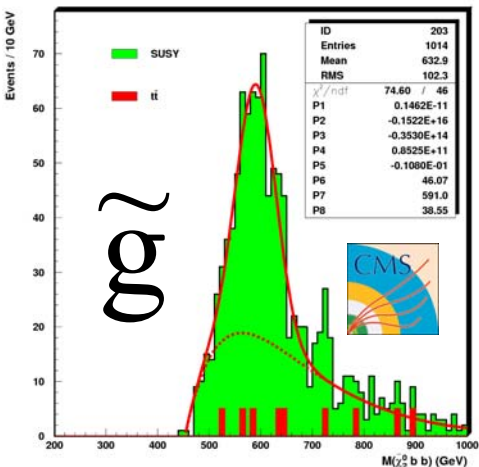
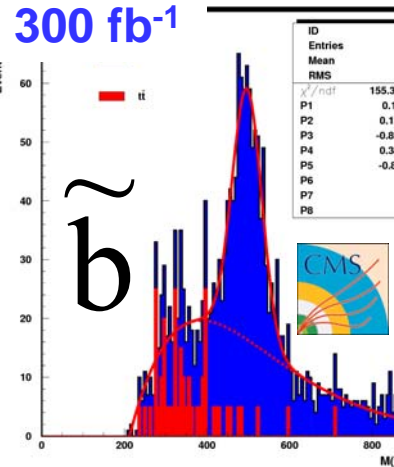
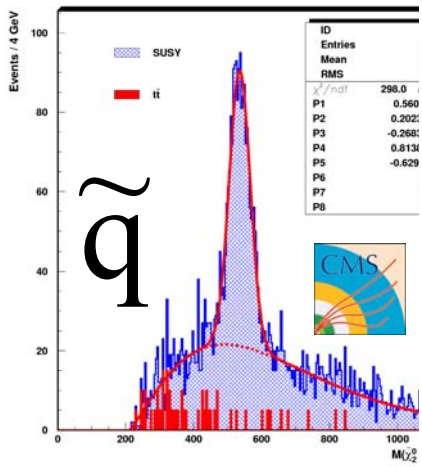
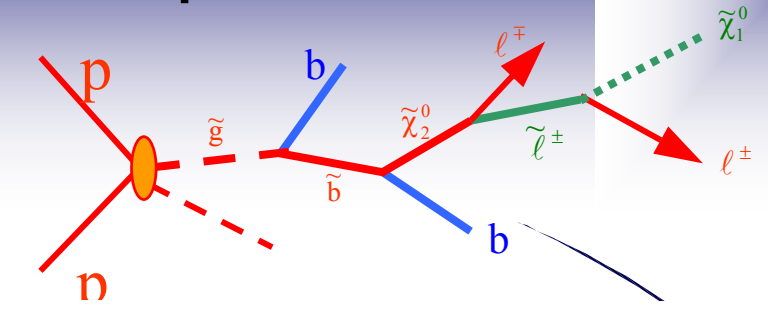
- Sistemati:

- Final State Radiation, cono per la ricostruzione del jet

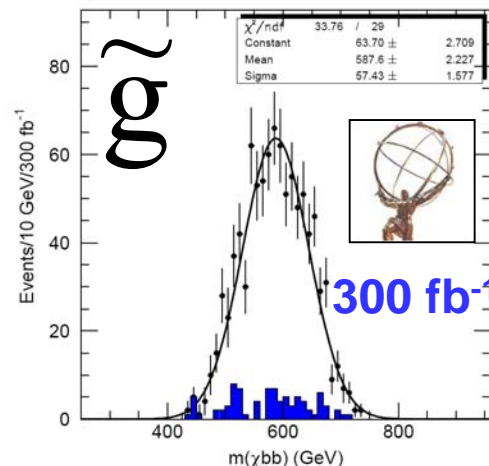
Ricostruzione delle S-particelle



$$\vec{p}_{\tilde{\chi}_2^0} = \left(1 + \frac{M_{\tilde{\chi}_1^0}}{M_{l^+l^-}} \right) \vec{p}_{l^+l^-}$$



- Ricostruzioni possibili già a 1-10 fb⁻¹
- Incertezze statistiche $\ll 1\%$ con 300 fb⁻¹
- Incertezze principali: energy scale e M(χ_1^0)



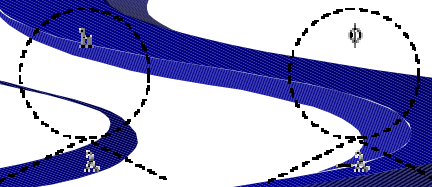
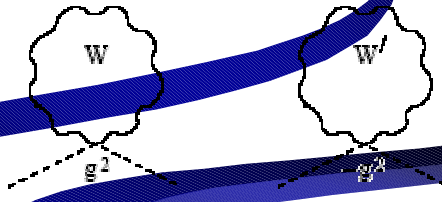
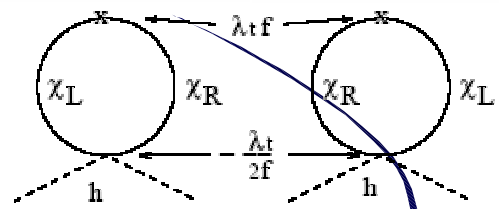
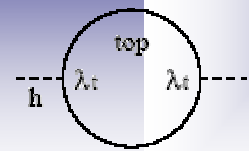
Little Higgs





Little Higgs

- Idea: cancellazione tra stati con uguale spin
- Naturale se inglobata in una simmetria più ampia
- Higgs pseudo-Goldstone di una simmetria globale
- Diversi modelli
 - Littlest Higgs:
 - $SU(5) \rightarrow SO(5)$
 - $[SU(2) \otimes U(1)] \otimes [SU(2) \otimes U(1)] \rightarrow SU(2) \otimes U(1)$



SUSY :

bosons

cancellations

fermions

Little Higgs :

gauge bosons

new gauge bosons

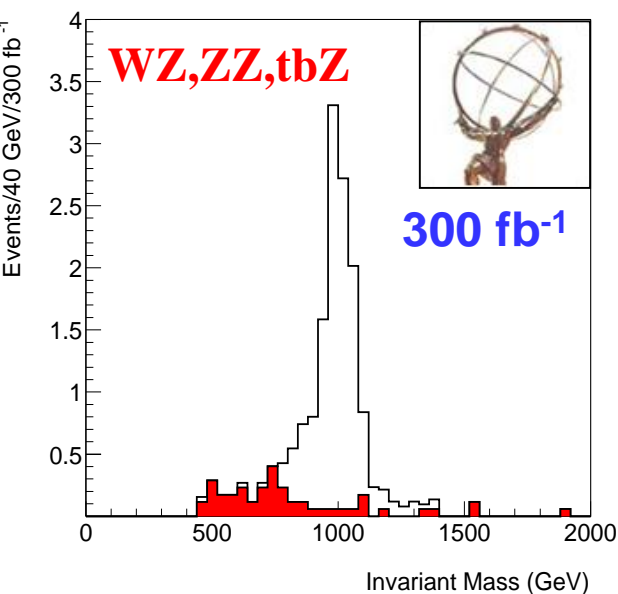
quarks

new quarks

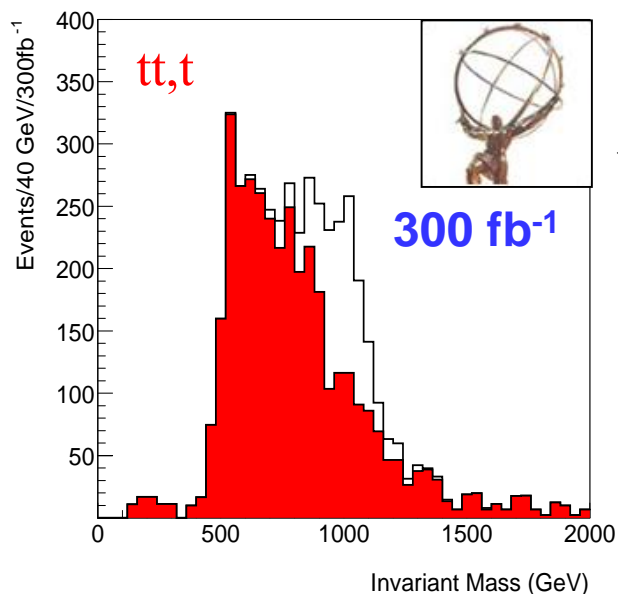
$$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

Little Higgs - T Quark Search

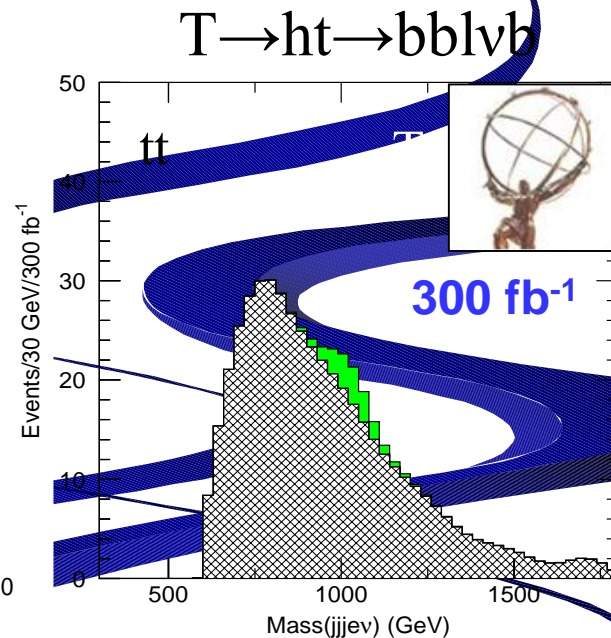
- Parametri: $M_T, \lambda_1/\lambda_2$
- ATLAS Fast simulation (hep-ph/0402037)
- Plot per 300 fb^{-1}
- Limite di scoperta 5σ per $\lambda_1/\lambda_2 = 1$ (2) e 300 fb^{-1}



$M_T < 1050$ (1400) GeV



$M_T < 2000$ (2500) GeV

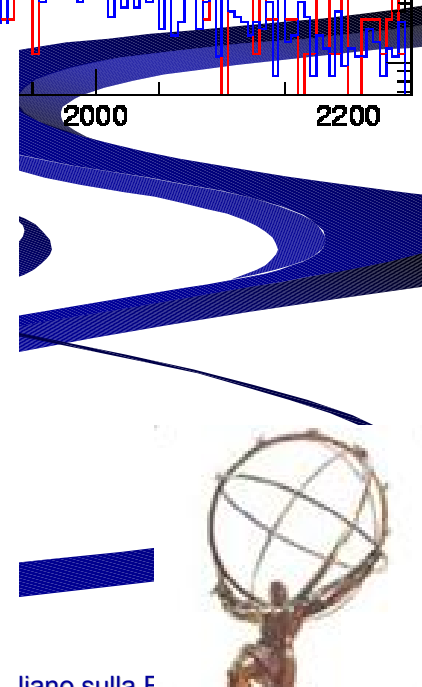
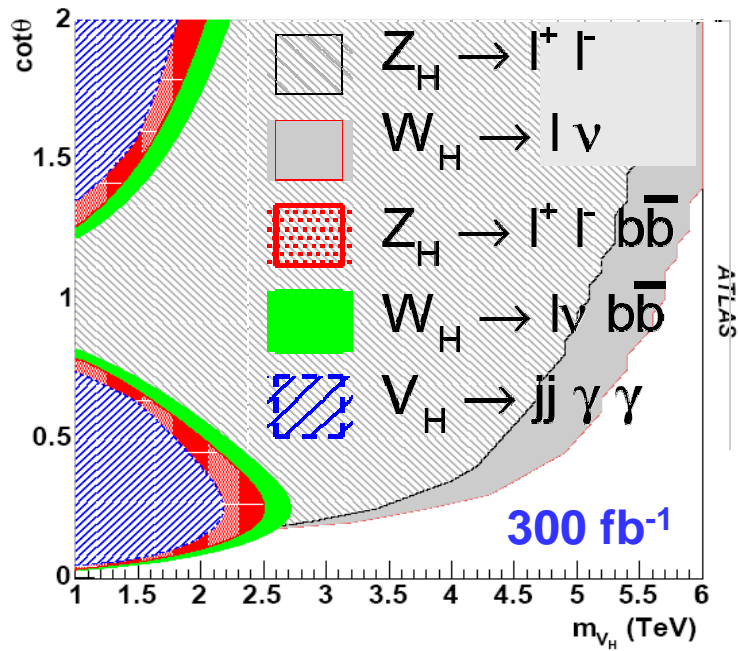
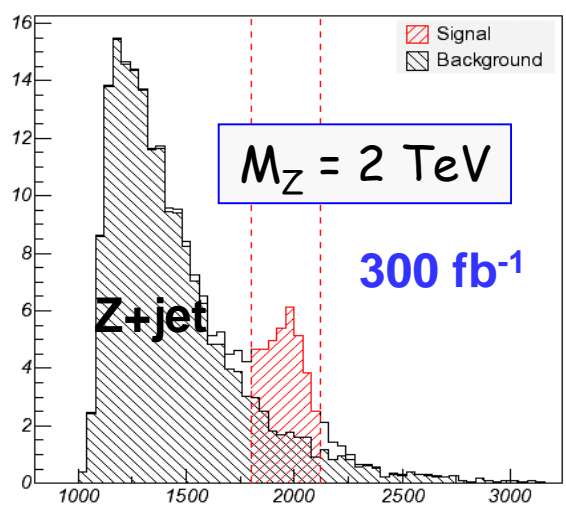
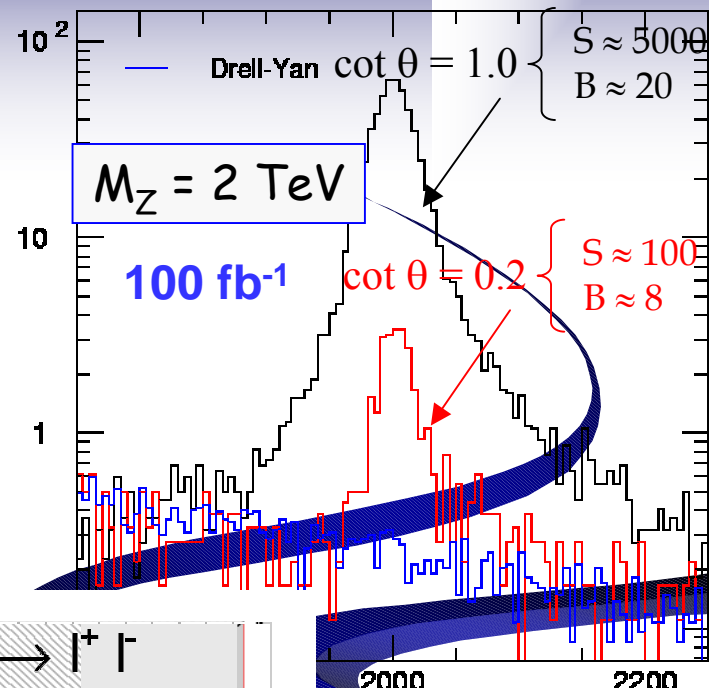


4σ for $M_T = 1000$ GeV
 3σ for $M_T = 700$ GeV

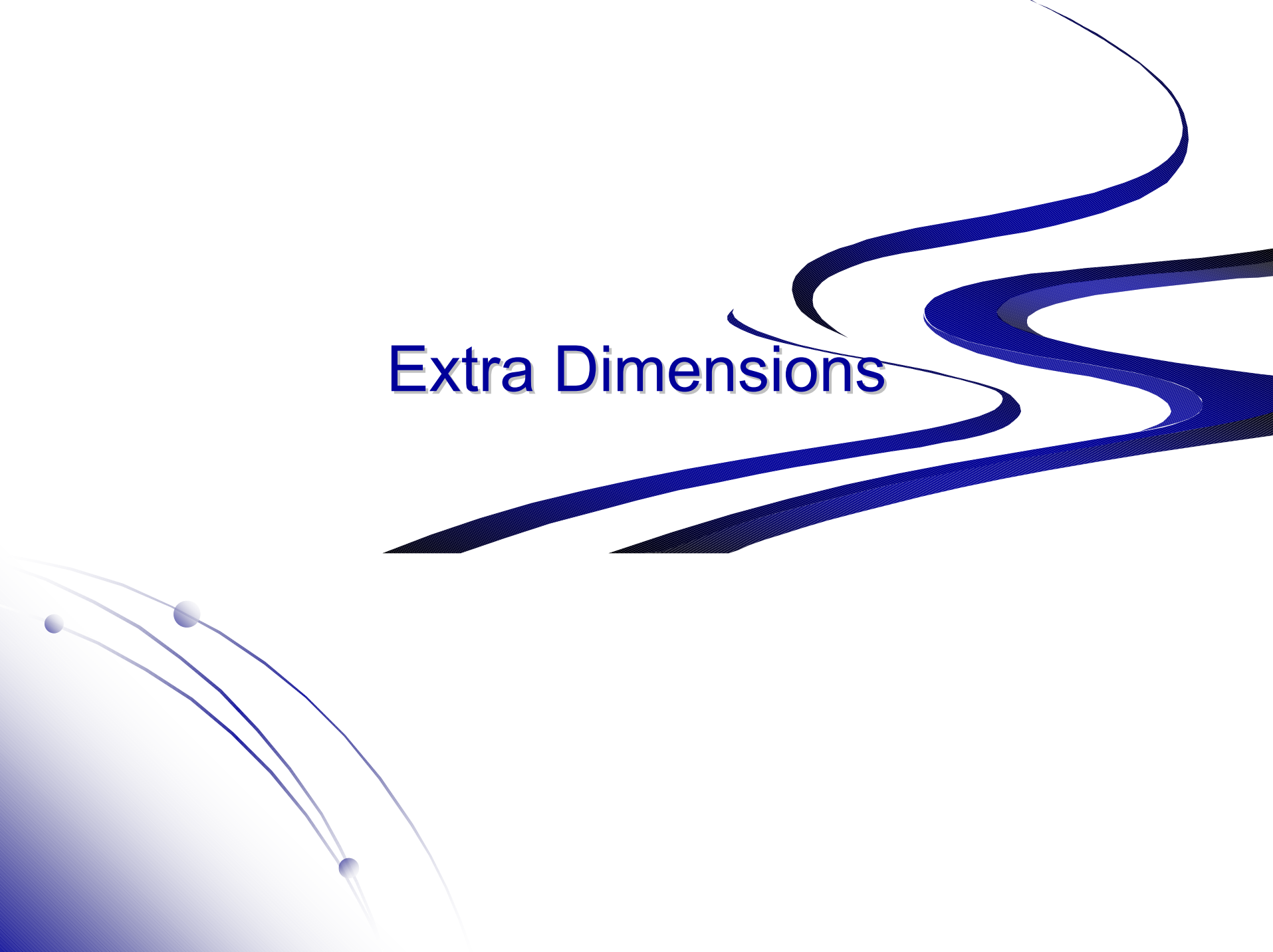


Little Higgs - Heavy Gauge Bosons

- Parametri: M , $\cot \theta$ (per Z_H), $\tan \theta'$ (per A_H)
- Scoperta:
 - $A_H, Z_H \rightarrow ee, \mu\mu$
 - $W_H \rightarrow e\nu, \mu\nu$
 - Fino a 5 TeV, tranne per piccoli $\cot \theta$ (W_H, Z_H) e per $\tan \theta' \approx 1.3$
 - Dalla $\sigma \Rightarrow$ misura di θ
- Canali specifici per LH:
 - $Z_H \rightarrow Zh \rightarrow llbb$
 - $W_H \rightarrow Wh \rightarrow lvbb$
 - $W_H/Z_H \rightarrow W/Z h \rightarrow qq\gamma\gamma$



Extra Dimensions

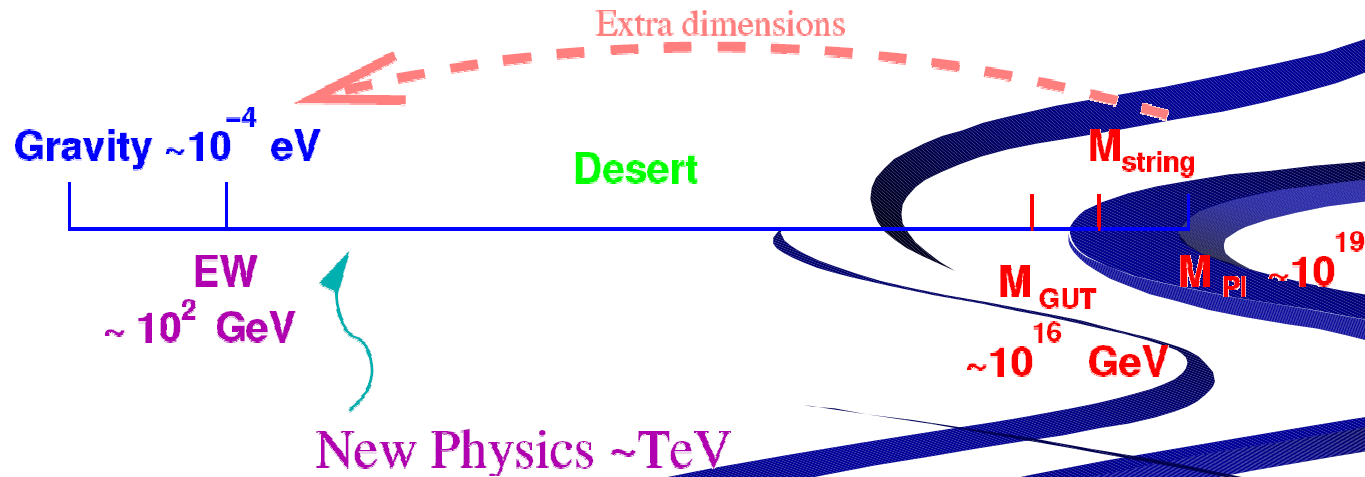




Extra Dimensions

Hierarchy problem risolto in modo “geometrico”:

- Interazione gravitazionale così debole solo perché “diluita” in n dimensioni
- Non abbiamo mai visto le dimensioni extra perché esistono a scala $R < 1 \text{ mm}$
- Verifiche dirette dell’interazione gravitazionale fino a $R \sim 1 \text{ mm}$



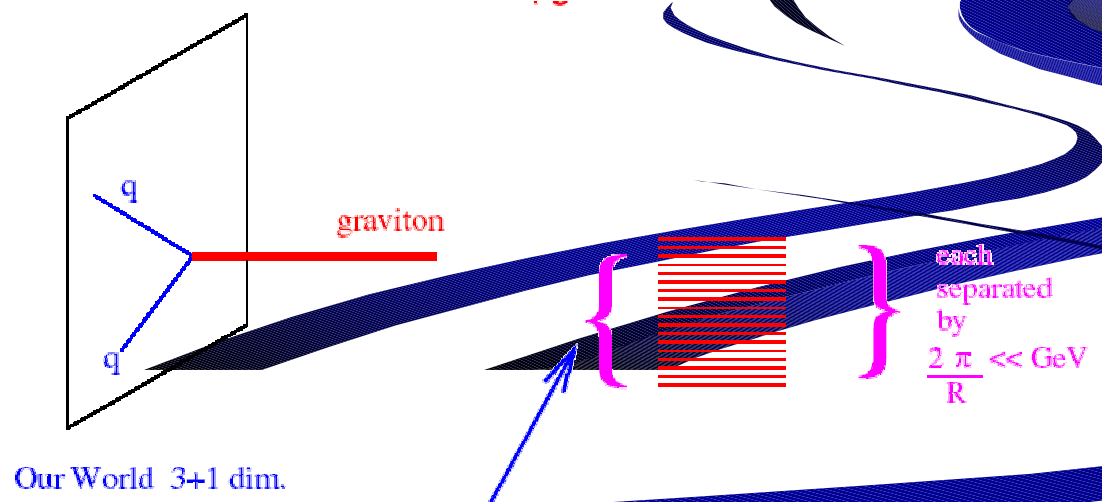
Molti modelli. LHC-friendly:

- ADD (Arkani-Hamed – Dimopoulos – Dvali)
- TeV-1 sized ED
- RS (Randall – Sundrum)



ADD

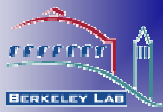
- n extra-dimension di size $\text{TeV}^{-1} \ll R_0 < 0.2 \text{ mm}$ (n=1 escluso, n=2 quasi escluso)
- Geometria “flat”
- Gravità nel bulk, va come $R^{-(2+n)}$ per $R < R_0$ ed è forte a scala M_D ($\sim \text{TeV}$)
- $M_D^{n+2} R_0^d = M_{\text{Planck}}$ $\rightarrow R_0 \sim 1 \text{ mm}$ (n=2) or 10 fm (n=6) (Large Extra Dimensions)
- SM particles nel “brane” (3+1 dimensioni)
- Eccitazioni Kaluza-Klein del gravitone di bassa energia. Coupling con le particelle SM debole e universale. Grande numero di stati (\sim continuo).



Each couples to the SM field with a strength

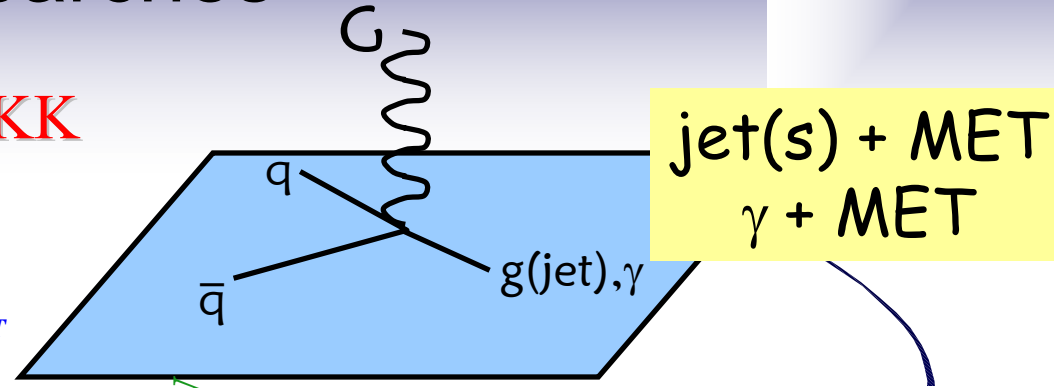


Large extra dimension: direct searches



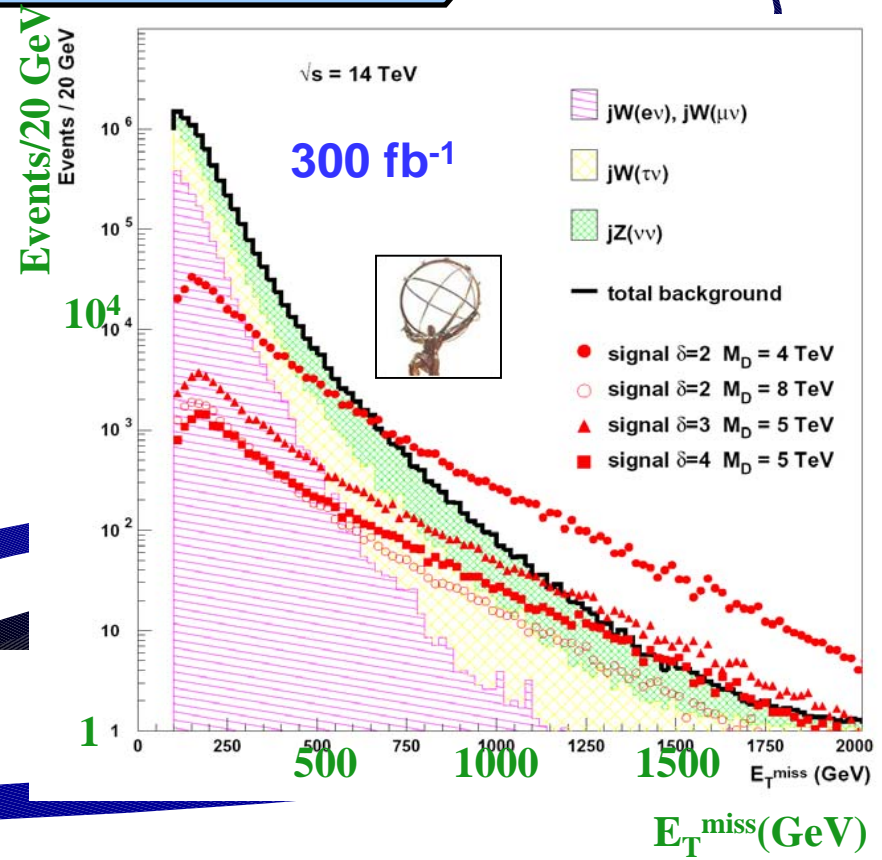
Produzione diretta di gravitoni KK

$$\left. \begin{aligned} \bar{q}q &\rightarrow gG^{(k)}, \gamma G^{(k)} \\ qg &\rightarrow qG^{(k)} \\ gg &\rightarrow gG^{(k)} \end{aligned} \right\} \text{jets} + \cancel{E}_T, \gamma + \cancel{E}_T$$



LEP+Tevatron+Hera limits \sim
1.4/0.6 TeV ($\delta=2/6$)

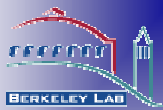
ATLAS search (L. Vacavant and I. Hinchliffe, J. Phys. G27, 1839)



δ	M_D^{max} (TeV)	
	LL, 30 fb^{-1}	HL, 100 fb^{-1}
2	7.7	9.1
3	6.2	7.0
4	5.2	6.0



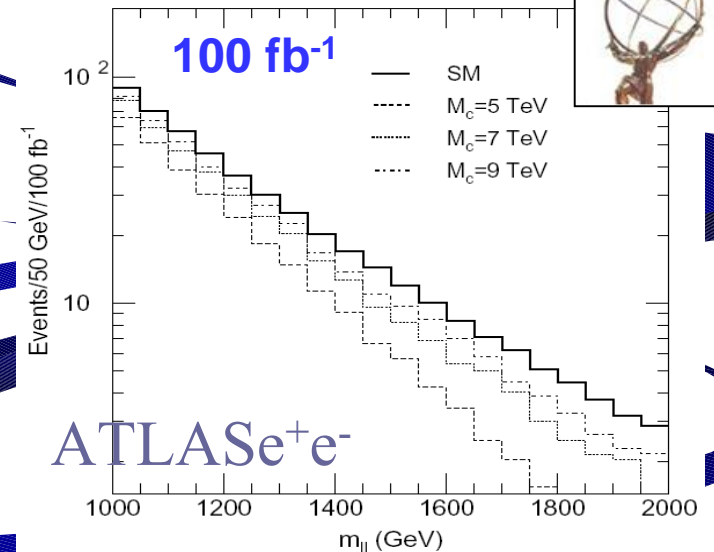
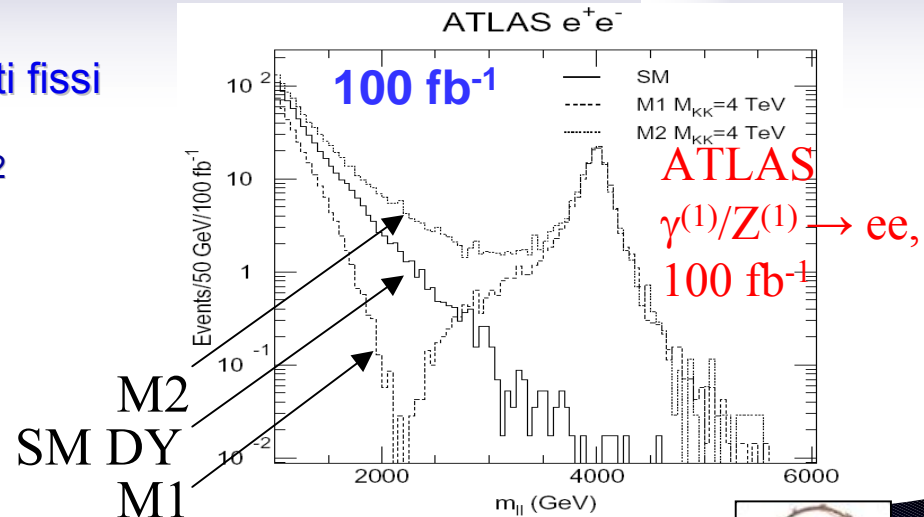
TeV⁻¹ sized Extra Dimensions



- Una ED
 - bosoni di gauge bosons nel bulk
 - Fermioni sulla 4D brane ad uno/due punti fissi nella 5^a dimensione (M1/M2 models).
- KK spectra for Z^(k), W^(k): $m_k^2 = m_0^2 + k^2 M_C^2$
 - EW data: $M_C > 4$ TeV
 - Solo la prima risonanza osservabile
- Scoperta con ee, μμ, eν, μν
- Misure di precisione con elettroni

$\Delta E/E$	2 TeV e	2 TeV μ
ATLAS	0.7 %	20 %
CMS	0.6 %	6%

- Sensitivity to peak (100 fb⁻¹, S/√B>5, S>10):
 - 5.8 TeV
- Reach (with interference in tail, el., 100 fb⁻¹):
 - 9.5 TeV
- Ultimate (with interference, el.+muons, 300 fb⁻¹):
 - 13.5 TeV

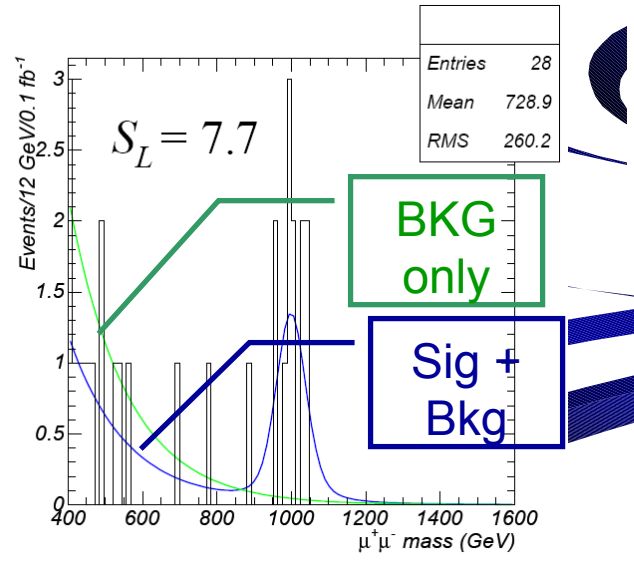
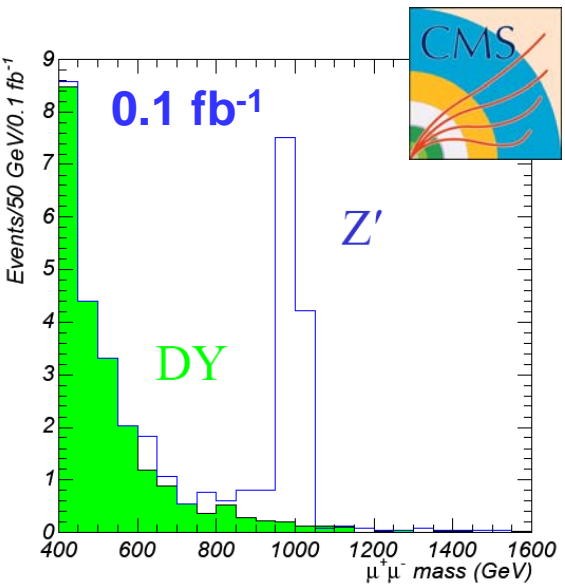
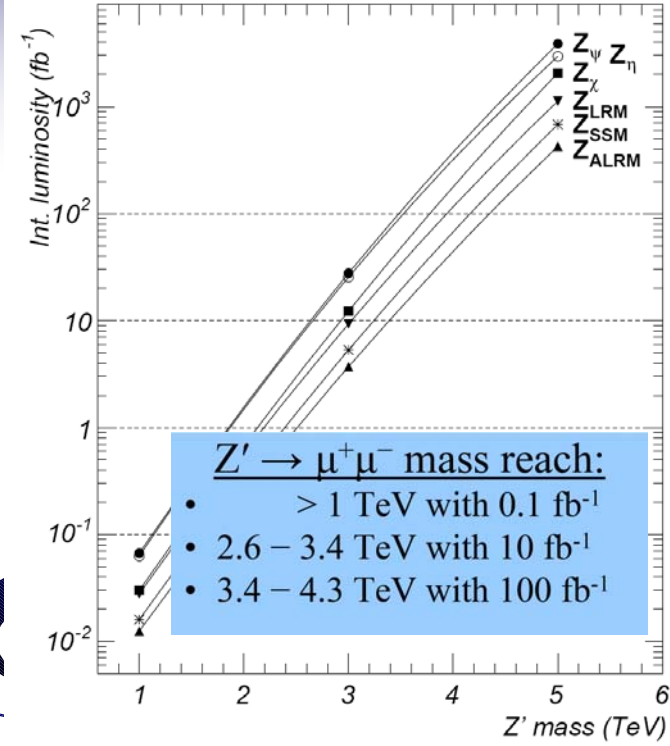




Altri modelli di Z pesanti



- Studio CMS per Z' generico
- $Z' \rightarrow \mu^+ \mu^-$, BR(6-8%)
- Z_{SSM} , Z_{ψ} , Z_{η} , Z_{χ} , Z_{LRM} , Z_{ALRM}
- Limiti sulla massa
 - Attuale: 600-800 GeV
 - Previsto per LHC start-up: 1 TeV



N.B.: syst. uncertainties are not taken into account

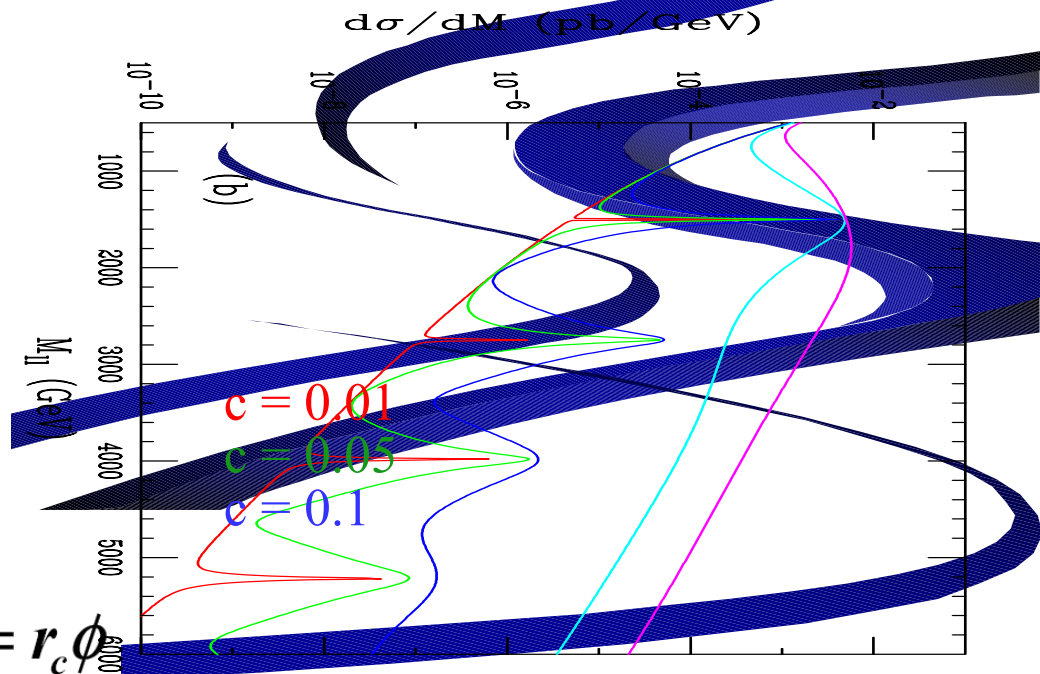
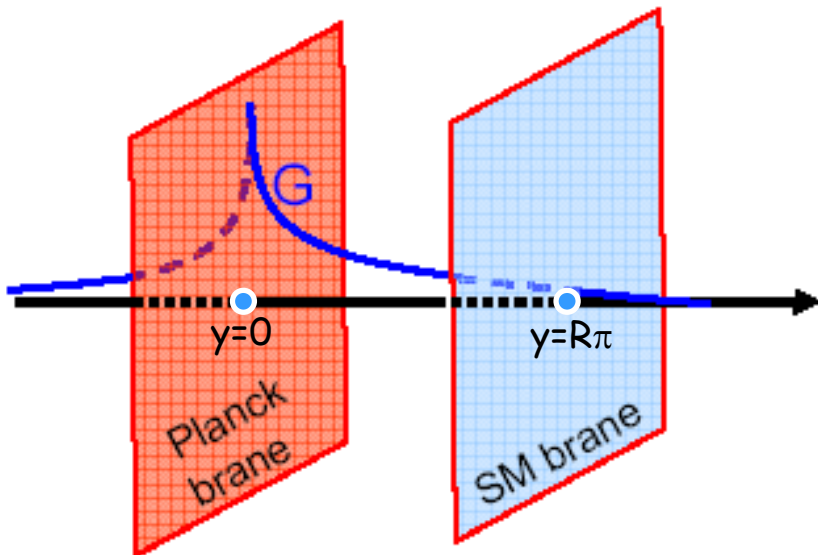
- Perfect alignment, calibration, B field, etc.;
- Background shape, functional forms of pdf's, mass resolution perfectly known.

FULL SIMULATION



RS – Randall Sundrum

- 2 brane (TeV brane e Plank brane) connesse da una 5^a dimensione a geometria curva
- Gravità nel bulk
- Gravity scale $\Lambda_\pi \sim M_{Pl} e^{-kr\pi} \sim \text{TeV}$ se $kr \sim 12$, scala dei processi sulla TeV-brane ($y = \pi R$)
- Curvatura $0.01 < c = k/M_{Pl} < 0.1$
- Eccitazioni KK del gravitone: $M_n = kx_n e^{-kr\pi}$ con $J_1(x_n) = 0$, $M_1 = 0.83 c \Lambda_\pi$
- Coupling degli stati KK $\sim 1/\Lambda_\pi$

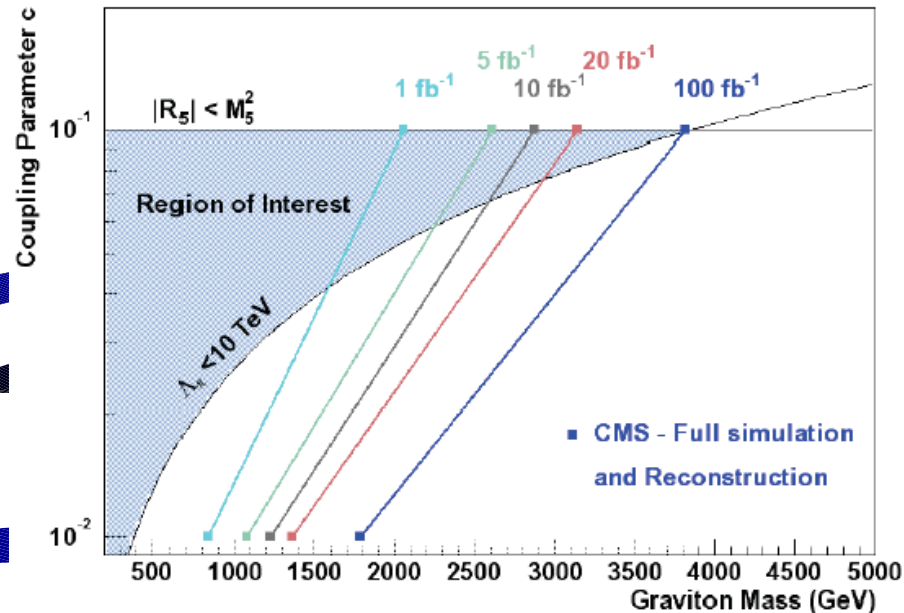
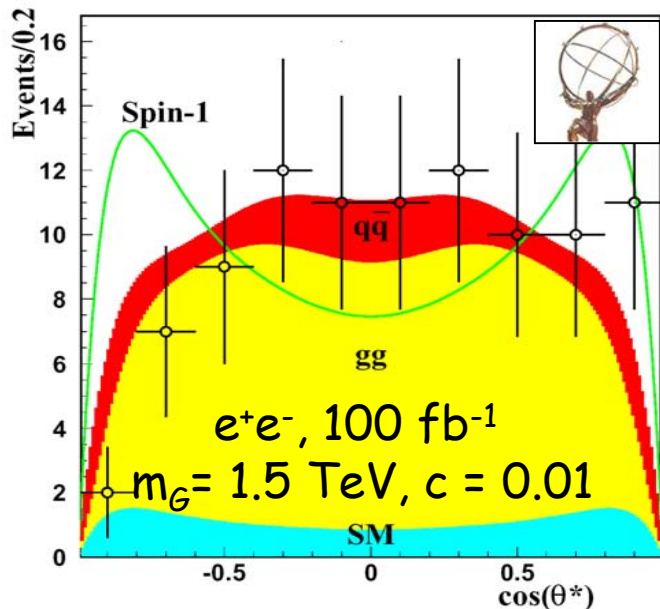
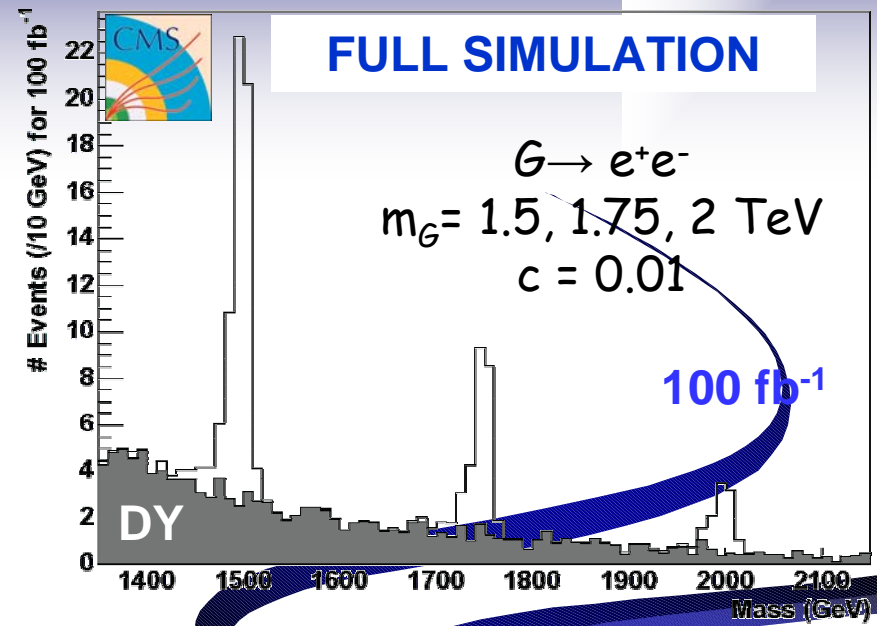


$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2, \quad y = r_c \phi$$



RS - Gravitone

- Canali di scoperta: $G \rightarrow ee, \mu\mu, \gamma\gamma$
- Regione di interesse totalmente coperta con 100 fb^{-1}
- Possibilità di misurare i parametri da M, Γ e σ
- Misura dello spin in un'ampia regione (end-caps needed!)
 - θ^* angolo tra il fascio e il leptone nel centro di massa del dileptone





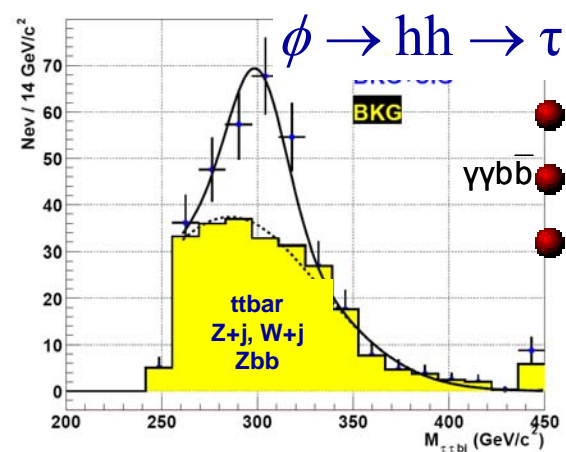
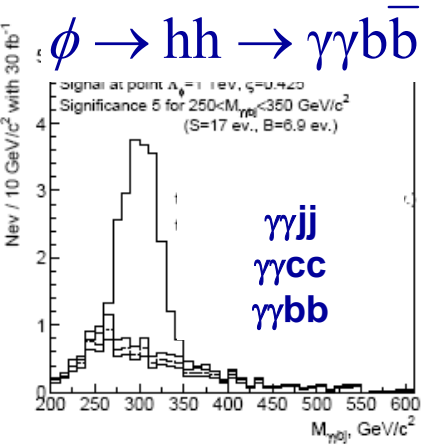
RS - Radion

- Scalare che rappresenta fluttuazioni nella metrica della 5° dimensione
- Possibilmente più leggero di $G^{(1)}$
- Può mixare con l'Higgs: ξ
- Higgs-like couplings
- Parametri: ξ , m_ϕ , m_H , Λ_ϕ

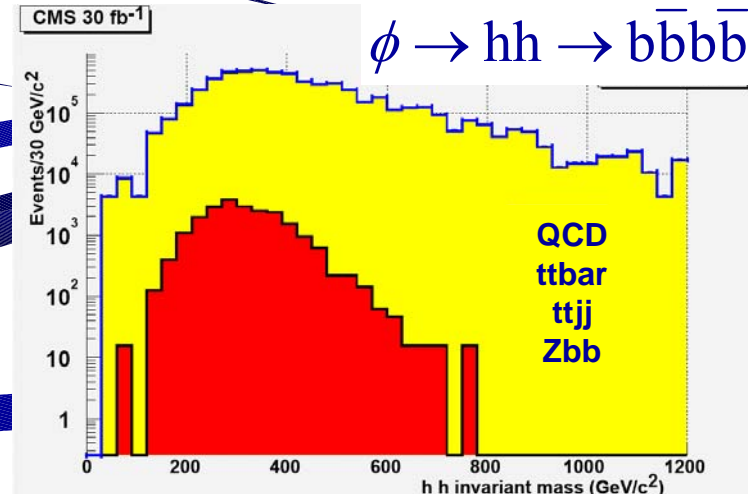
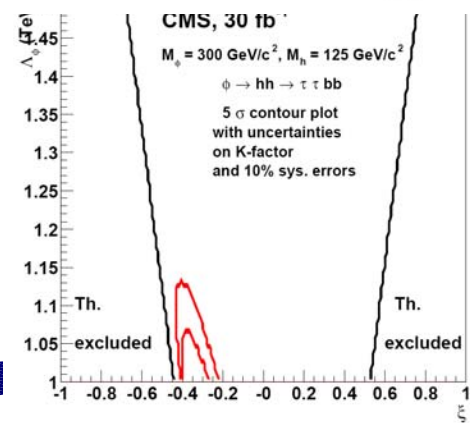
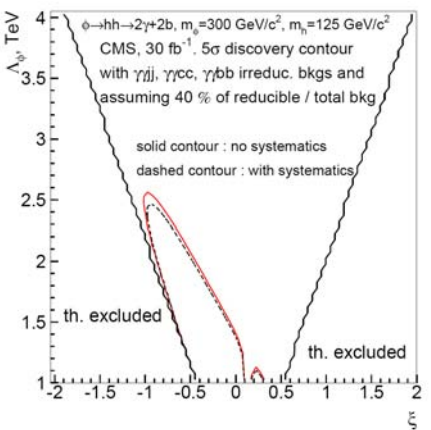


FULL SIMULATION

Working point:
 $M_\phi = 300 \text{ GeV}/c^2$, $m_H = 125 \text{ GeV}/c^2$
 $\xi = -1/3$, $\Lambda_\phi = 1 \text{ TeV}$
 Scan in (ξ, Λ_ϕ) plane
30 fb⁻¹

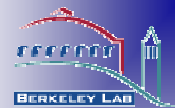


$\gamma\gamma b\bar{b}$: ampia regione nel piano (Λ, ξ)
 $\tau\tau b\bar{b}$: conferma
 $b\bar{b}b\bar{b}$: accurata conoscenza del bkg ($< 0.1\%$)





Conclusioni



- LHC macchina ideale per vedere nuova fisica
- **Supersimmetria**
 - scoperta possibile in ampie regioni dello spazio dei parametri
 - scoperta possibile con bassa luminosità integrata
 - possibilità di misurare le masse e di ricostruire i picchi in certe regioni dello spazio dei parametri
 - più modelli presi in esame
- **Little Higgs**
 - Scoperta possibile per T , W_H , Z_H (dopo diversi anni di presa dati)
 - Possibilità di osservare i decadimenti specifici del modello per W_H e Z_H
- **Extra-Dimensions**
 - Diversi modelli presi in esame (ADD, TeV-1, RS)
 - Possibilità di scoperta fino ad alte scale (masse)
 - Osservazione diretta di gravitoni, bosoni pesanti, radioni



Additional slides

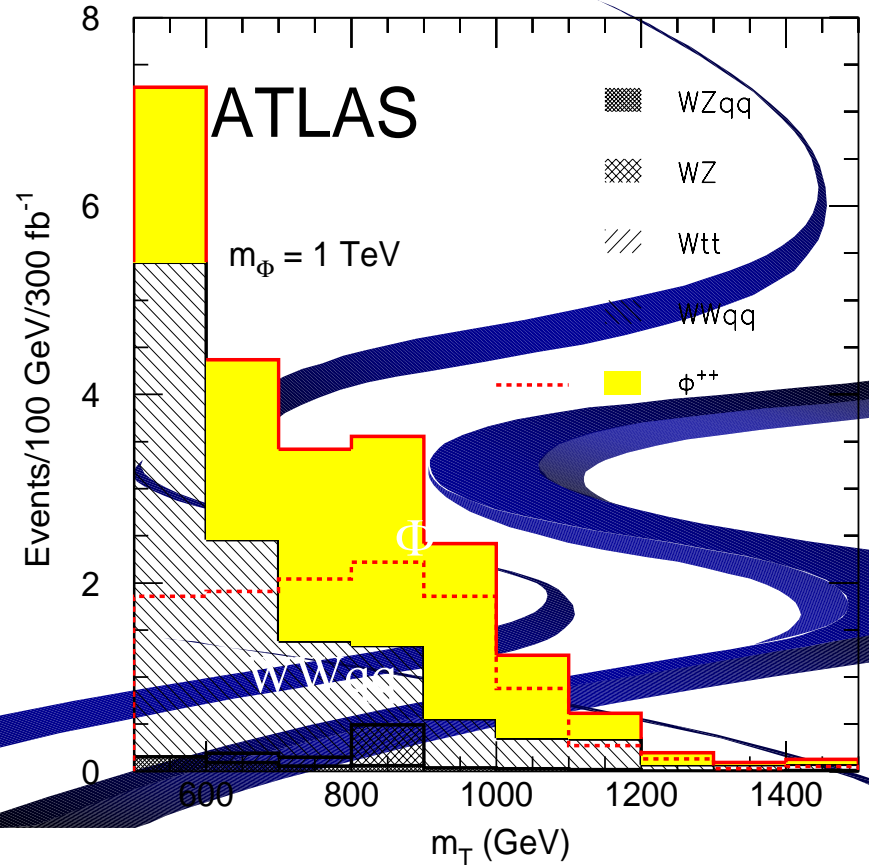




Heavy Higgs

- Less constrained in mass
- $qq \rightarrow \phi^{++}\phi^{--} \rightarrow 4l$ (too small cross section)
- $qq \rightarrow q'q'\phi^{++} \rightarrow q'q'W^+W^+ \rightarrow q'q'lv$
- Coupling ϕWW depends on v' (VEV of Higgs triplet)
- From EW data $v' < 15$ MeV
- For $m_\phi = 1000$ (1500) GeV discovery requires $v' > 29$ (54) MeV
- Φ^+ and Φ^0 probably even more difficult

hep-ph/0402037





Effetti di saturazione in ECAL

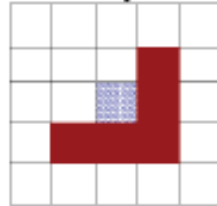
- Elettroni molto energetici: saturazione nell'elettronica di ECAL
- Sviluppo di un algoritmo di correzione

Idea for correction:

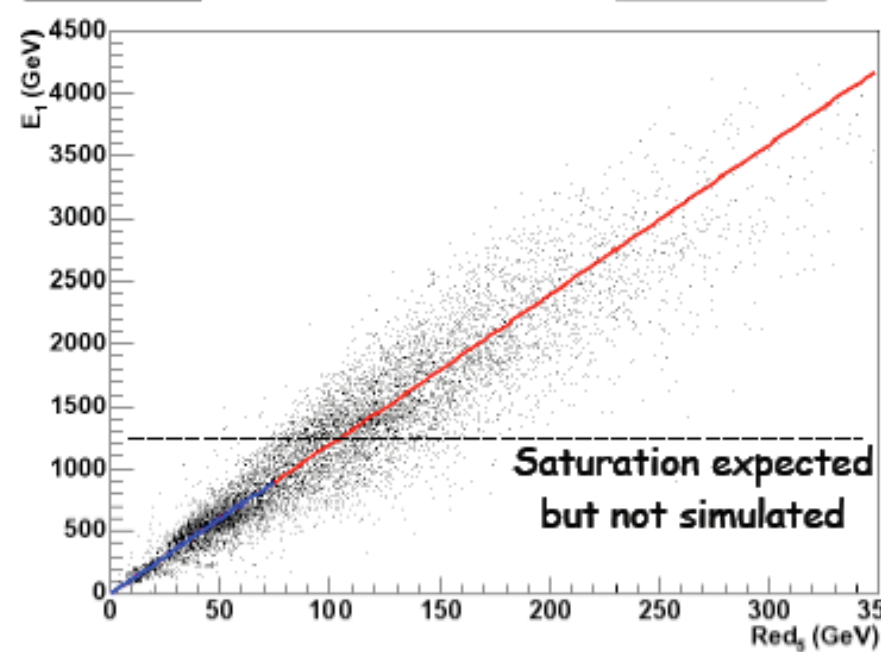
Correlation between

$$Red_5 = E_9 - E_4 \text{ and } E_1$$

5x5 crystals



E_1 vs Red_5

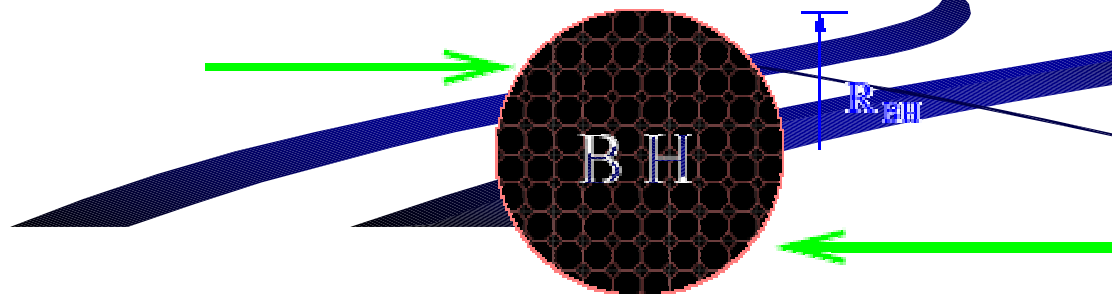




Black Holes

- Se $\sqrt{s} > M_{Pl}$ (gravity scale) è possibile la produzione di black holes.
- $\sigma \sim \pi R_s^2$ (grande, ma soppressa dalla parton pdf)
 - $\sigma_{tot} = 0.5 \text{ nb}$ ($M_p = 2 \text{ TeV}$, $\delta=7$)
 - $\sigma_{tot} = 120 \text{ fb}$ ($M_p = 6 \text{ TeV}$, $\delta=3$)
- Incertezze per la mancanza di una quantum gravity theory
- Decadimenti per Hawking radiation con $T \sim 100 \text{ GeV}$ (10^{15} K)
- Molteplicità ~ 10 , tutte le particelle con $m \ll T$ prodotte con uguale probabilità

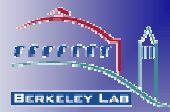
Production cross sections



$$\sigma(M_{BH}^2) \approx \pi R_{BH}^2$$



Black Holes



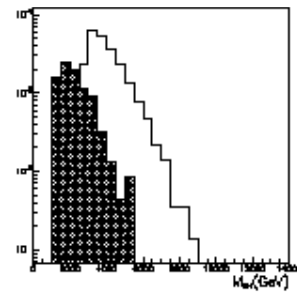
BH detection:

- Tag event with at least 4 jets + photon or electron → SM background small
- M_{BH} reconstructed for each event

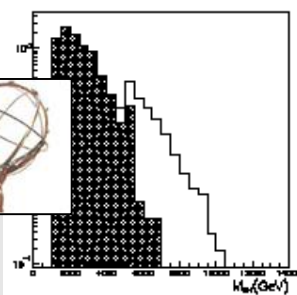
Higgs Discovery from BH decays:

- High production rate of BH + democratic decay of BH: $M_P \sim 2 \text{ TeV}$ and $n=3 \rightarrow \sigma_{BH} = 450 \text{ pb} \rightarrow 1 \text{ light Higgs every } 3 \text{ s}$

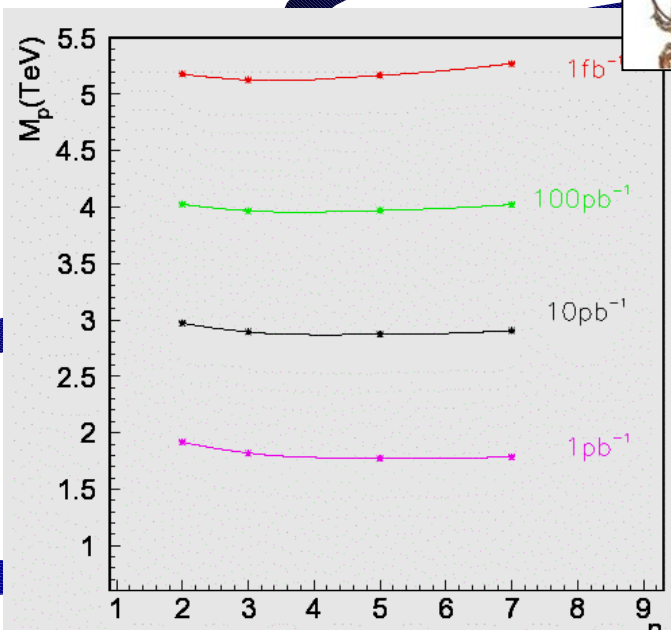
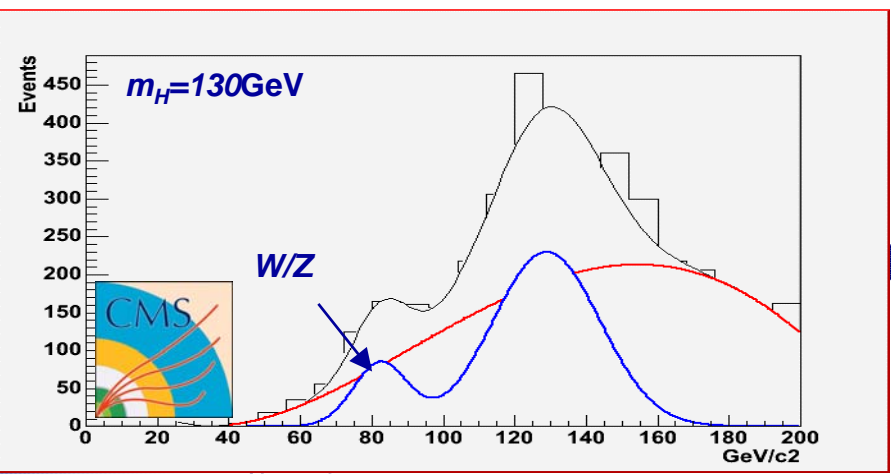
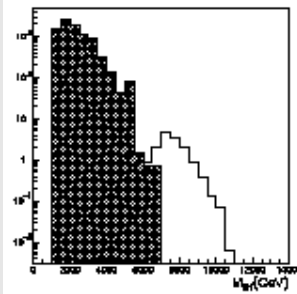
$M_P = 3 \text{ TeV}$



$M_P = 5 \text{ TeV}$

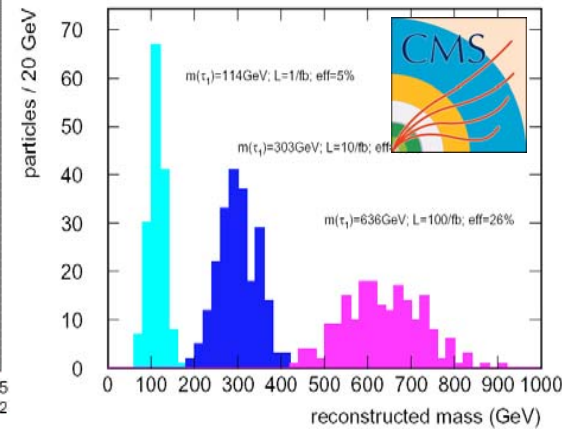
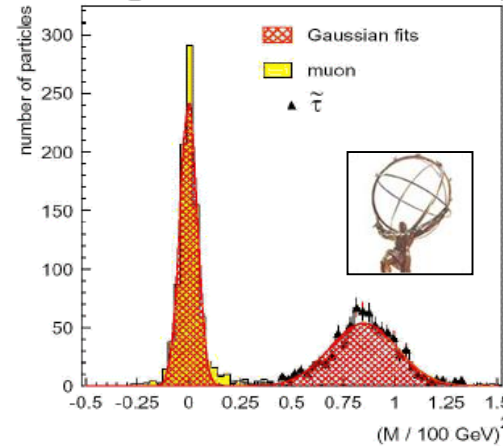
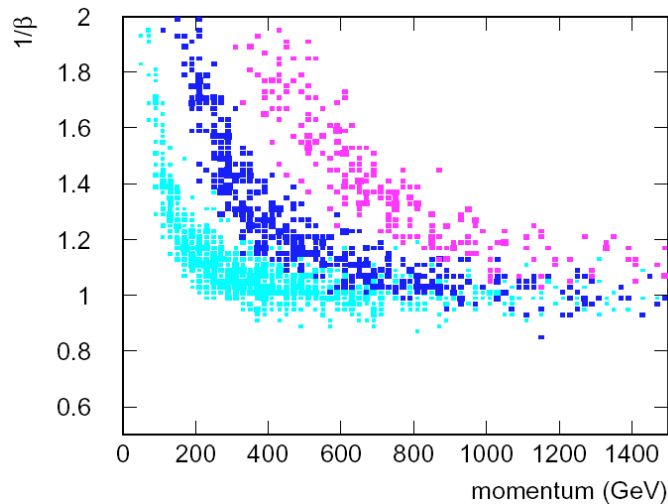


$M_P = 7 \text{ TeV}$



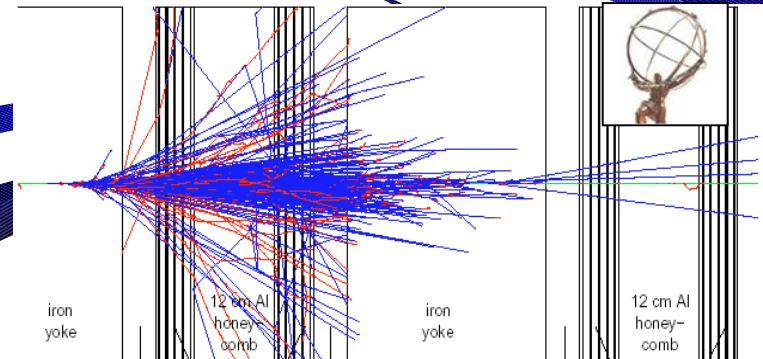
$\tilde{\tau}$ -NLSP

- uso del muon system per misurare il time-of-flight di leptoni pesanti
- Massa dello $\tilde{\tau}$ misurabile in range 90-700 GeV per 100 fb^{-1}



$\tilde{\chi}$ -NLSP

- Sciami elettromagnetici non puntati al vertice
- Per grandi $c\tau$: sciami elettromagnetici nel muon system

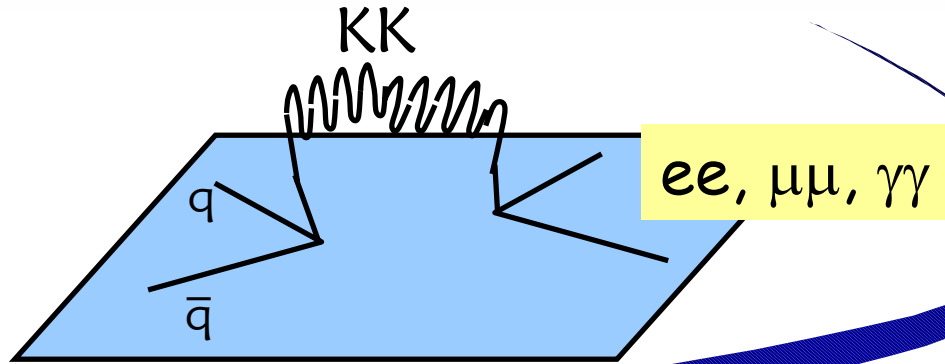




Large ED: indirect searches

- Lo scambio virtuale di gravitoni modifica la σ di Drell-Yan e le asimmetrie
- Divergenza UV, mancata conoscenza della teoria completa – uso di un cut-off M_S

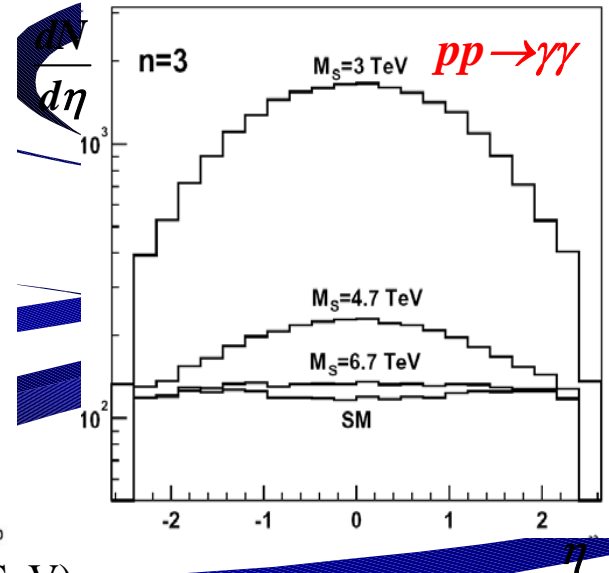
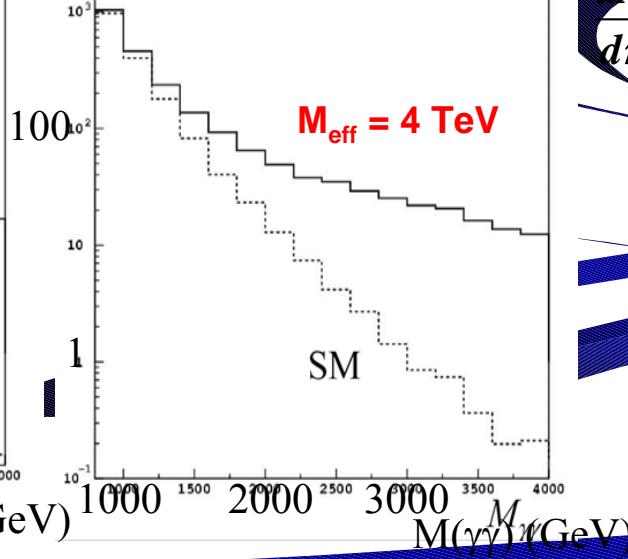
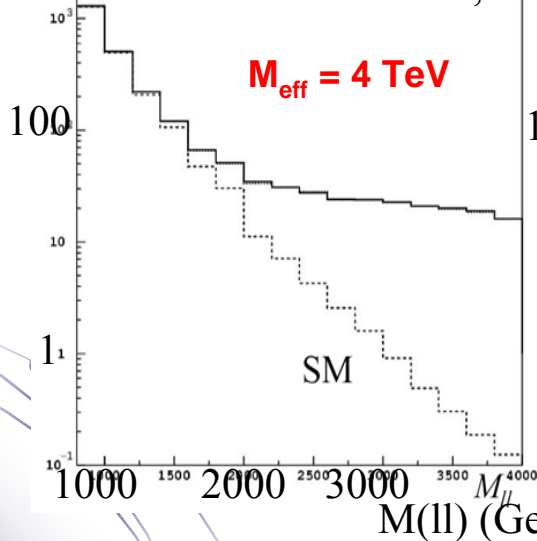
ATLAS, 100 fb^{-1}
 $M_S < 5.1 \text{ TeV}$ $l\bar{l}$
 $M_S < 6.6 \text{ TeV}$ $\gamma\gamma$



$l\bar{l}$

$\gamma\gamma$

V. Kabachenko et al., ATLAS-PHYS-2001-012



● Una variazione di una fattore 2 del background muove le curve di qualche decina di GeV

