

Osservazione di una risonanza alla massa
di circa 126 GeV nella ricerca del bosone
di Higgs del Modello Standard con
l'esperimento ATLAS

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10 luglio 2012

I dati da LHC 11-12:

2011:

$$\sqrt{s} = 7 \text{ TeV}$$

$$L_{\text{max}} = 3.6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

$$L = 5.6 \text{ fb}^{-1}$$

2012:

$$\sqrt{s} = 8 \text{ TeV}$$

$$L_{\text{max}} = 6.8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

$$L = 6.6 \text{ fb}^{-1}$$

(2012) $\approx 1.5 \times$ (2011)

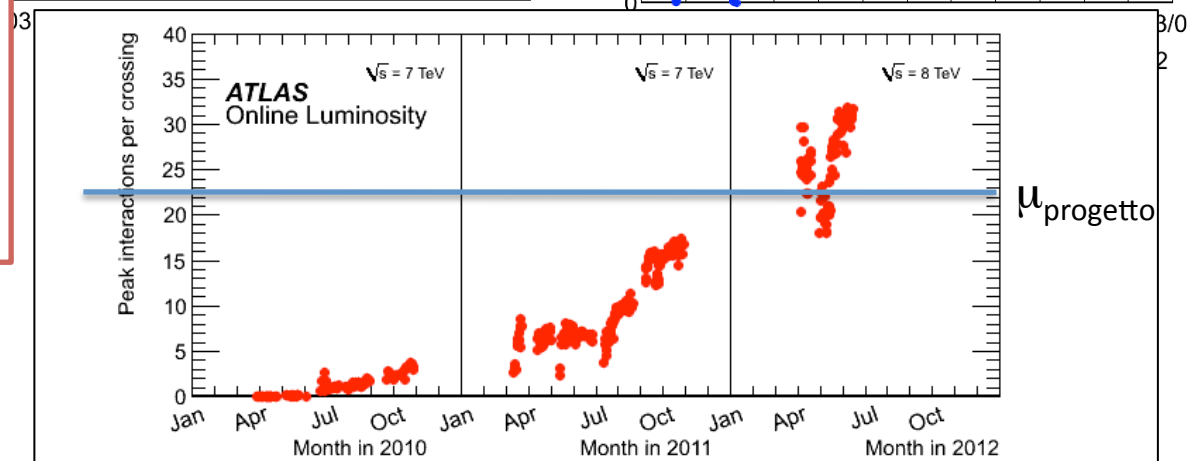
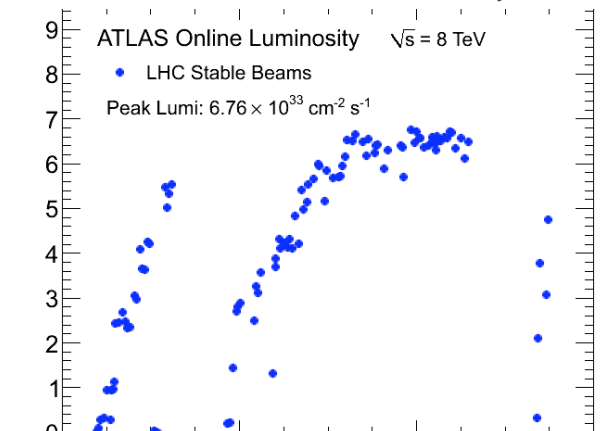
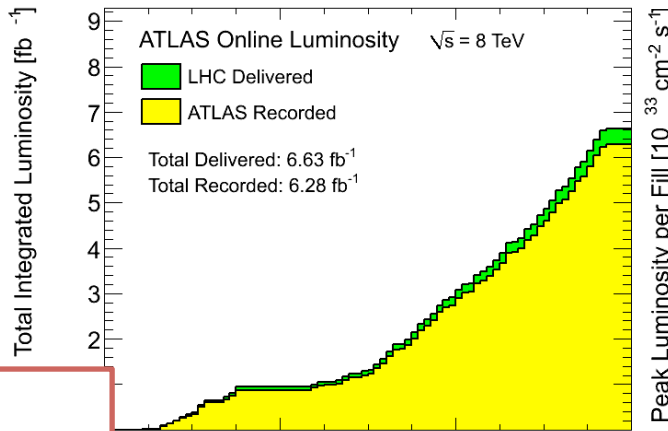
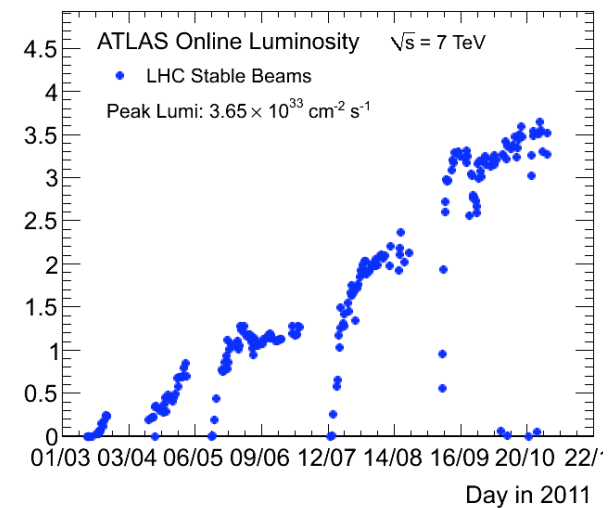
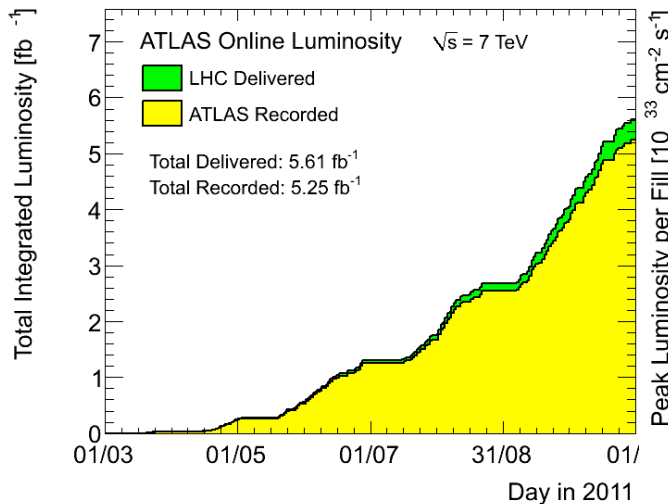
→ Efficienza ATLAS $\approx 90\%$
(Detector on AND DQ ok)

$$4.8 + 5.8 = 10.6 \text{ fb}^{-1}$$

→ Fine presa dati 18/06:
risultati "pronti" 10 giorni dopo.

Questione "pile-up":

Nel 2012 $\langle \mu \rangle > \mu_{\text{progetto}}$

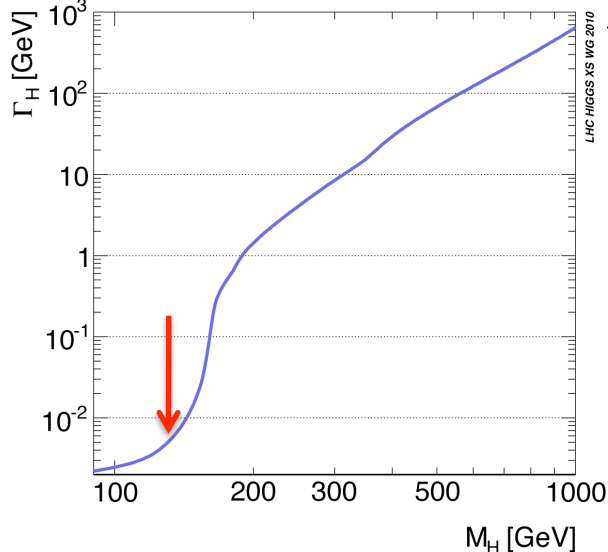
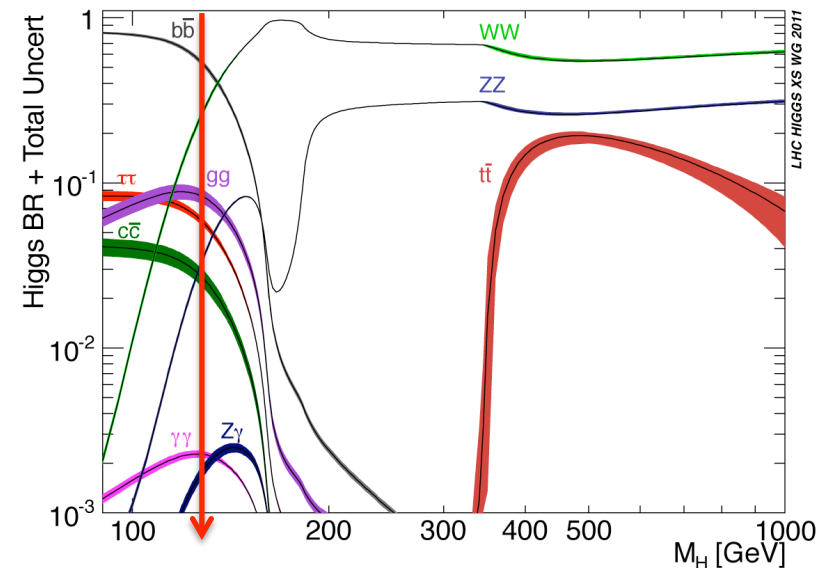
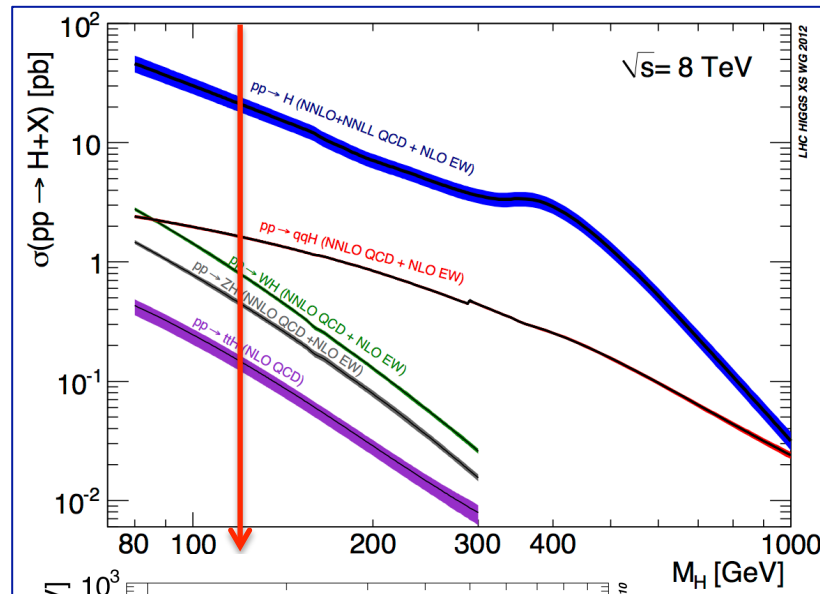


Come si cerca il bosone di Higgs in collisioni p-p a 7-8 TeV ?

Per ogni valore di M_H predizioni della teoria al $\approx 10\text{-}20\%$. @ $M_H = 125$ GeV:

Produzione in gluon-gluon fusione (VBF < 10% ma interessante);

Molti canali di decadimento attivi; Larghezza intrinseca molto piccola.



Conseguenze:

→ Higgs prodotto "da solo" (non associato);

→ Analisi "multi-canale" inevitabile !

→ golden channels ($\gamma\gamma$, ZZ) rari

→ alta accettazione !

→ Importanza della risoluzione in massa.

ATLAS luglio 2012: strategia per l'osservazione.

Presentiamo ed utilizziamo nella combinazione:

Per $H \rightarrow \gamma\gamma$ e $H \rightarrow ZZ^{(*)} \rightarrow 4l$ l'analisi completa del campione 2011 (con *analisi migliorata*) e del campione 2012;

Per gli altri canali (in particolare $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, $H \rightarrow \tau^+\tau^-$, $W/Z H \rightarrow bb$) i risultati basati sul campione 2011 (già pubblicati);

Analisi tradizionali, adatte per la "scoperta".

Perché ?

$H \rightarrow \gamma\gamma$ e $H \rightarrow ZZ^{(*)} \rightarrow 4l$ sono i "golden channels", analisi semplice, fondo stimato dai dati e dipendenza dal pile-up ben capita;

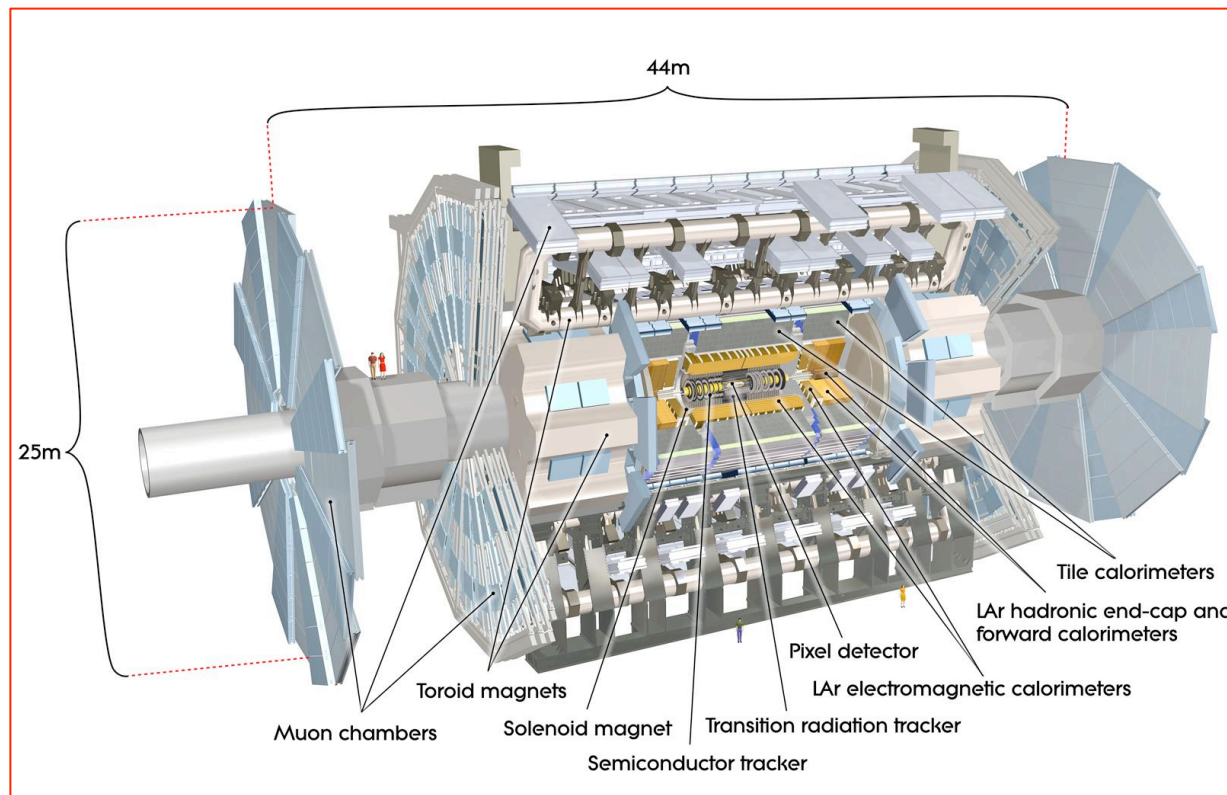
Gli altri canali dipendono da oggetti più sensibili alla problematica del pile-up e dell'alta luminosità (e.g. E_t^{miss} , *Jet reconstruction*, ...).

Next...

Nell'articolo di fine luglio, per il canale $H \rightarrow WW \rightarrow l\nu l\nu$ sarà aggiunta anche l'analisi 2012;

A seguire, update di $H \rightarrow \tau^+\tau^-$, $W/Z H \rightarrow bb$.

Il rivelatore ATLAS

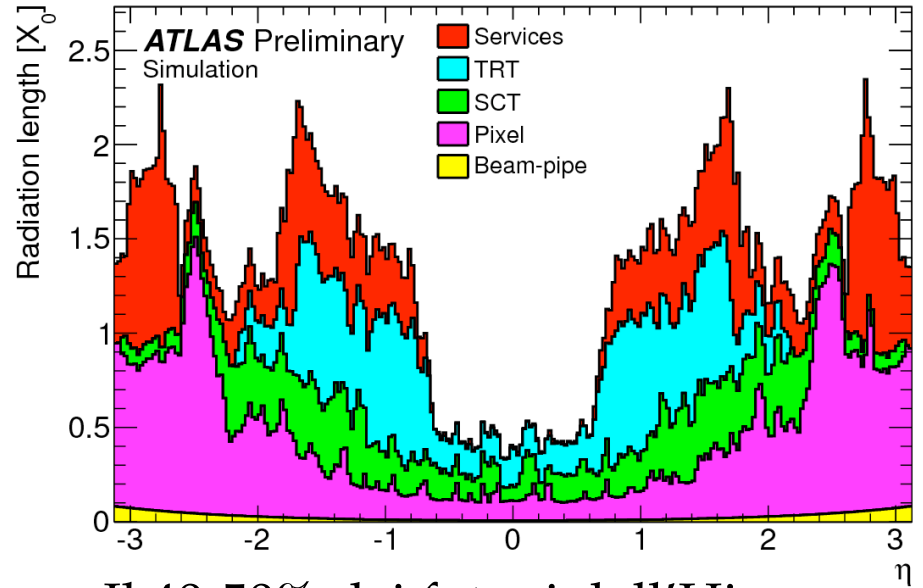
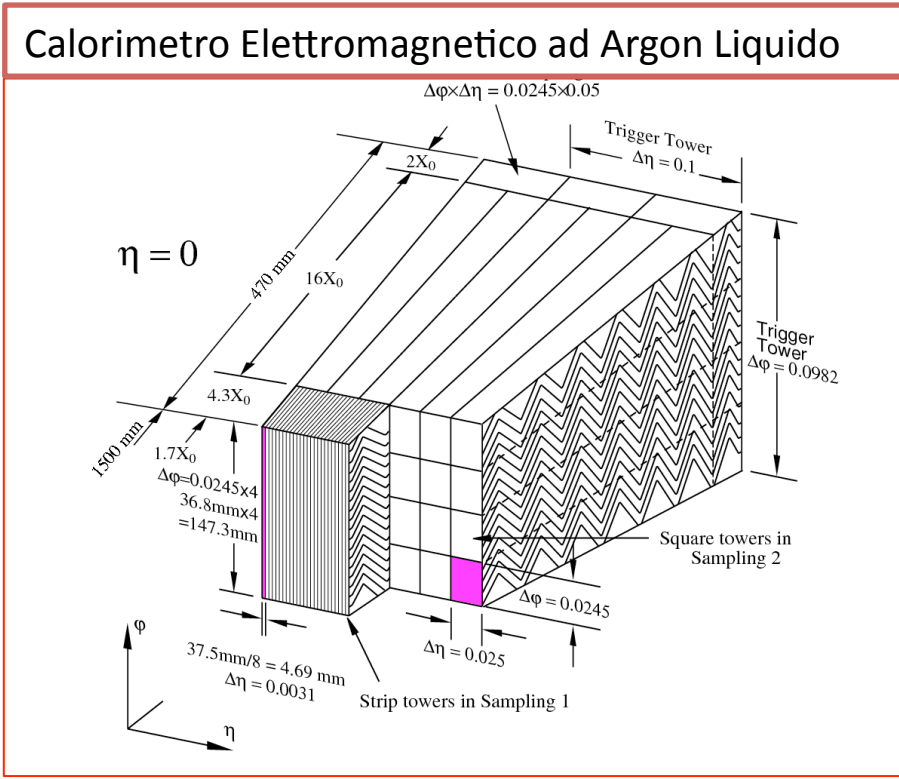


Item	pT threshold (GeV)	Rate (Hz) @ 5×10^{33}
incl. e	24	70
incl. μ	24	45
ee	12	8
$\mu\mu$	13	5
$\tau\tau$	29,20	12
$\gamma\gamma$	35,20	10
E_T^{miss}	80	17
5j	55	8

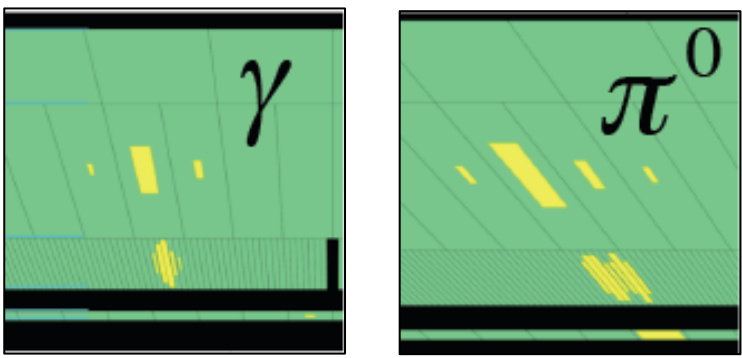
Tutte le parti del rivelatore entrano nei risultati che presentiamo.

Trigger molto “robusto” e versatile: rate $O(100 \text{ Hz})$ senza perdita rilevante sulla fisica di alto p_T .

H \rightarrow $\gamma\gamma$ Selezione di coppie di γ “isolati” in accettazione e di alta E_T :
 $E_T > 40, 30$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$;
 Misura della massa invariante $M_{\gamma\gamma}$. ($\sigma = 40 \div 50$ fb \rightarrow attesi $O(10^2)$ evts)
 Fondi: $\gamma\gamma$ dal continuo (75-80%), $1\gamma + 1$ fake jet (20%), 2 fake-jets (2%) $\rightarrow O(10^4)$ evts



Il 40-50% dei fotoni dall'Higgs “convertono”, ricostruiti con l'ID



Efficienza per coppie di γ da Higgs:
 Trigger 2g $\epsilon = 98.9 \div 99.6\%$
 Selezione $\epsilon = 38 \div 43\%$
 # eventi nei dati ($100 < M_{\gamma\gamma} < 160$ GeV):
 23788 (campione 2011)
 35271 (campione 2012)

Misura della massa invariante $M_{\gamma\gamma}$

$$M_{\gamma\gamma} = 2E_1E_2(1 - \cos\alpha)$$

Misura di energia:

Risoluzione $\approx 10\% / \sqrt{E} + 1\%$

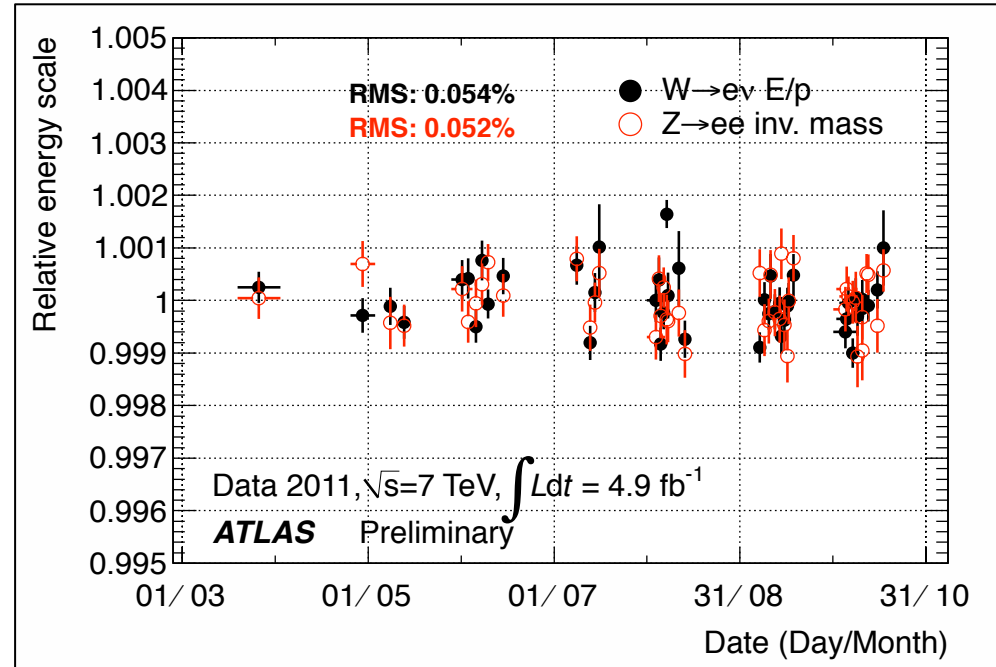
Stabilità della risposta $< 0.1\%$;

Calibrazione assoluta $< 0.3\%$.

Misura dell'apertura angolare α

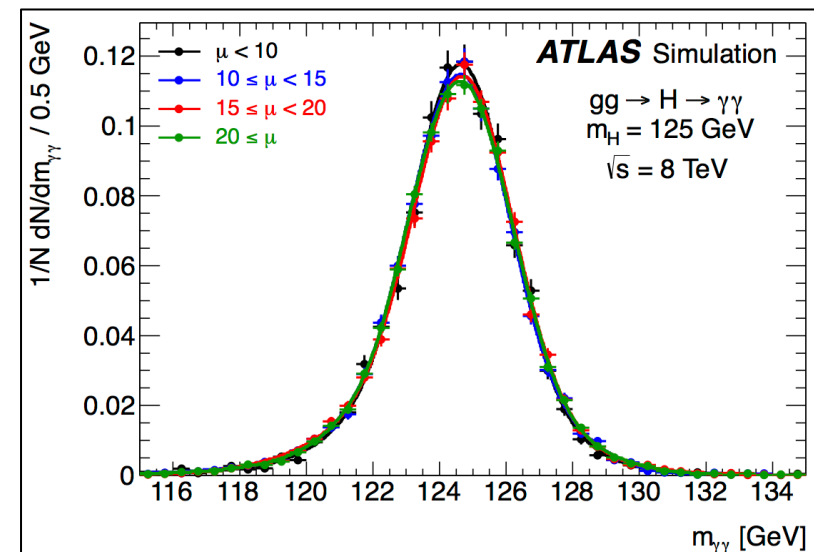
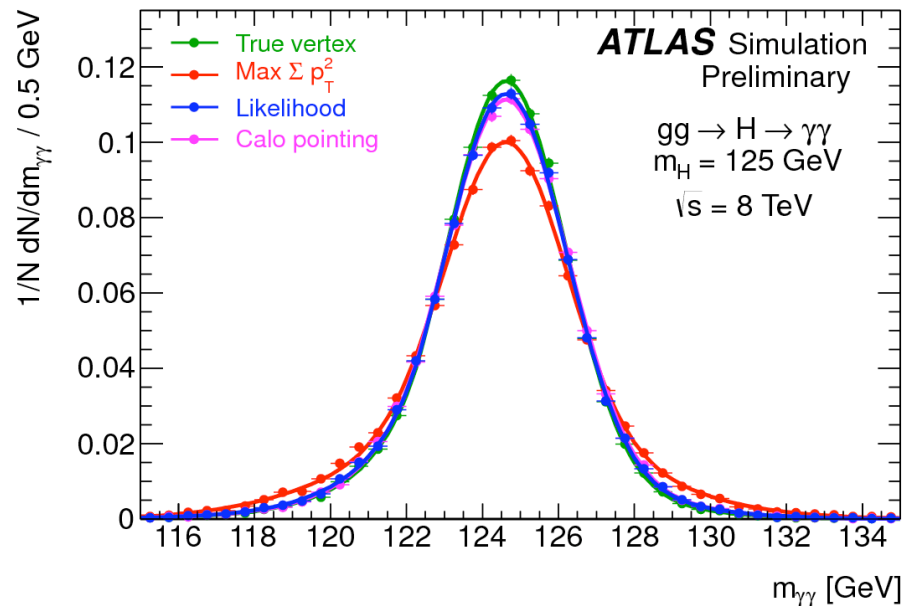
“Traiettorie” dei fotoni estrapolate alla linea dei fasci ($\sigma(Z) \approx 1.5$ cm)

+ Σp_T^2 delle tracce

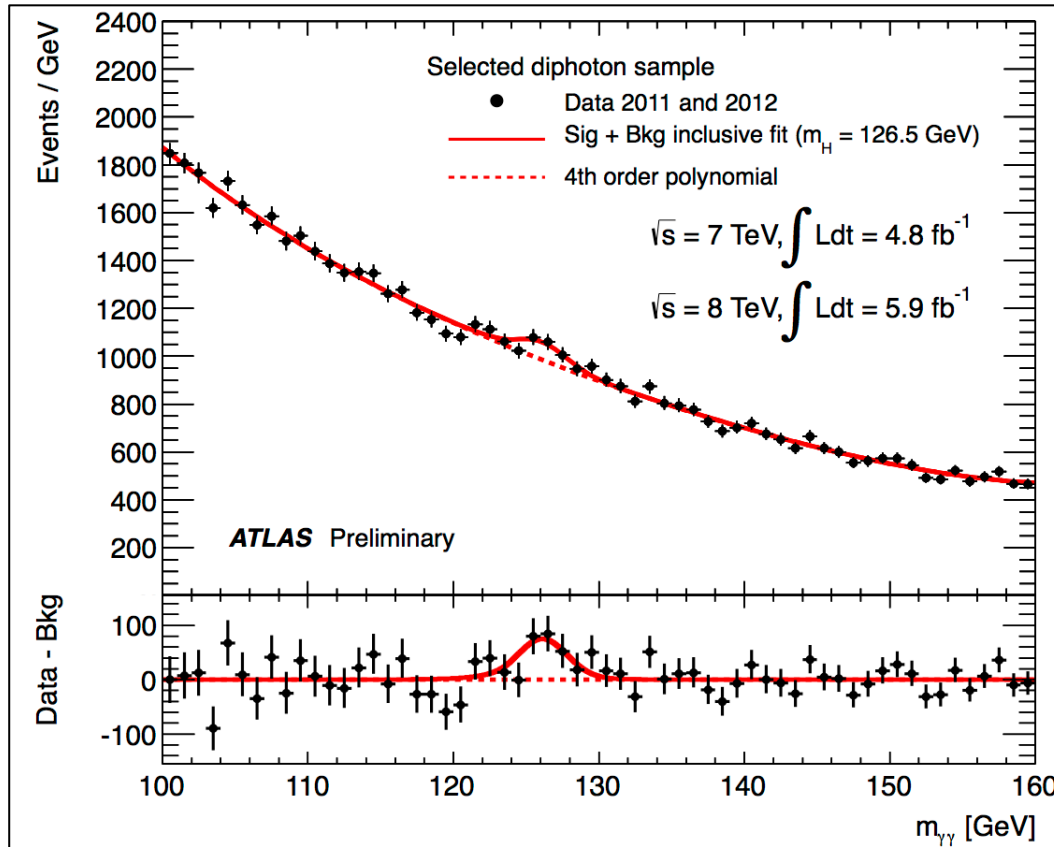


Risoluzione in $M_{\gamma\gamma}$: 1.4 ÷ 2.6 GeV

Indipendente da $\mu = N(\text{vertici})$

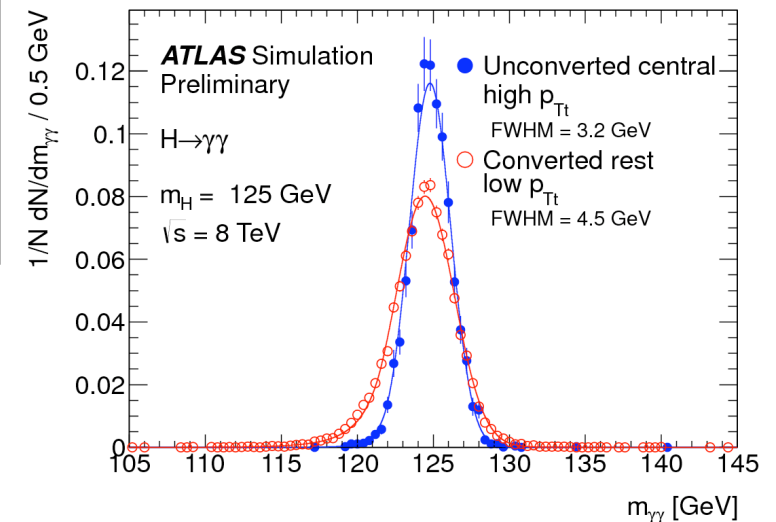


Spettro in massa invariante "raw" complessivo 2011 + 2012



Fit:

- fondo polinomiale
- segnale Gaussiana + CB



Suddivido il campione in **10 categorie**:

Convertito / non Convertito

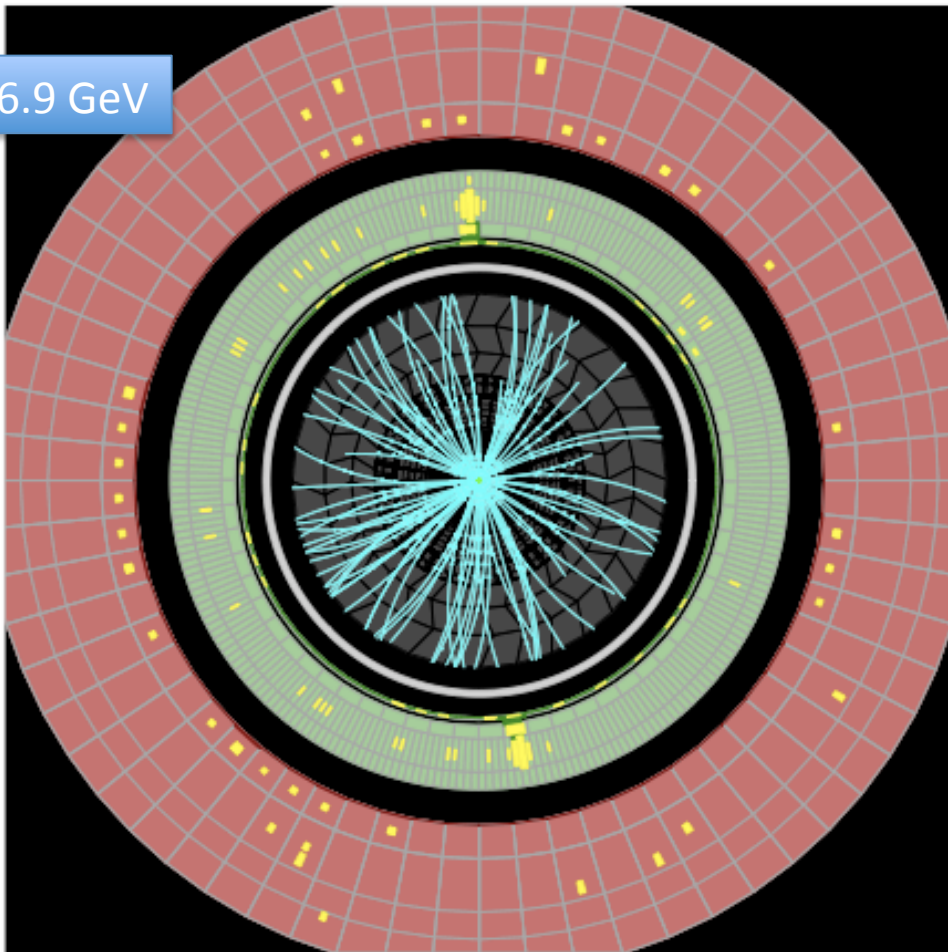
Centrale / periferico

Alto P_{Tt} / Basso P_{Tt}

VBF (presenza di 2 jet) (Introdotta in questa analisi)

→ 20 fit indipendenti (10x2) con diverse sensibilità → analisi statistica

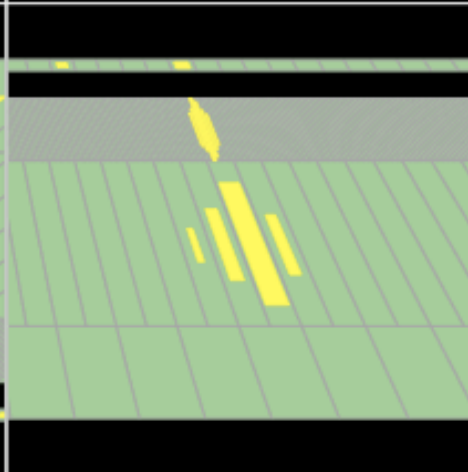
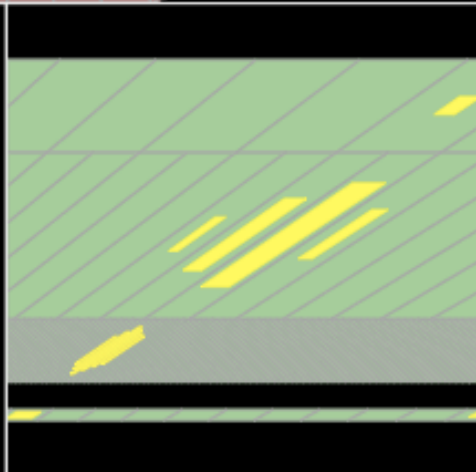
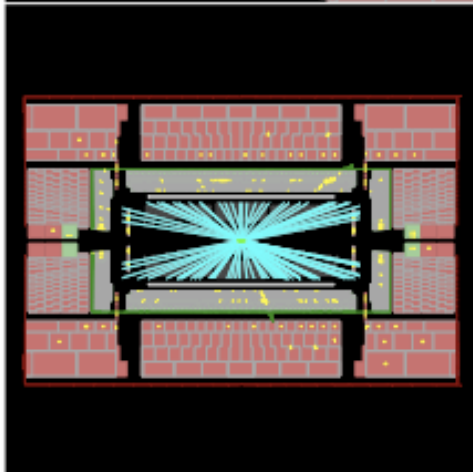
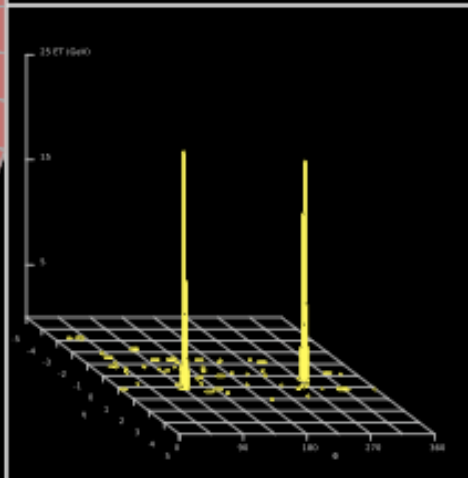
$M_{\gamma\gamma} = 126.9 \text{ GeV}$



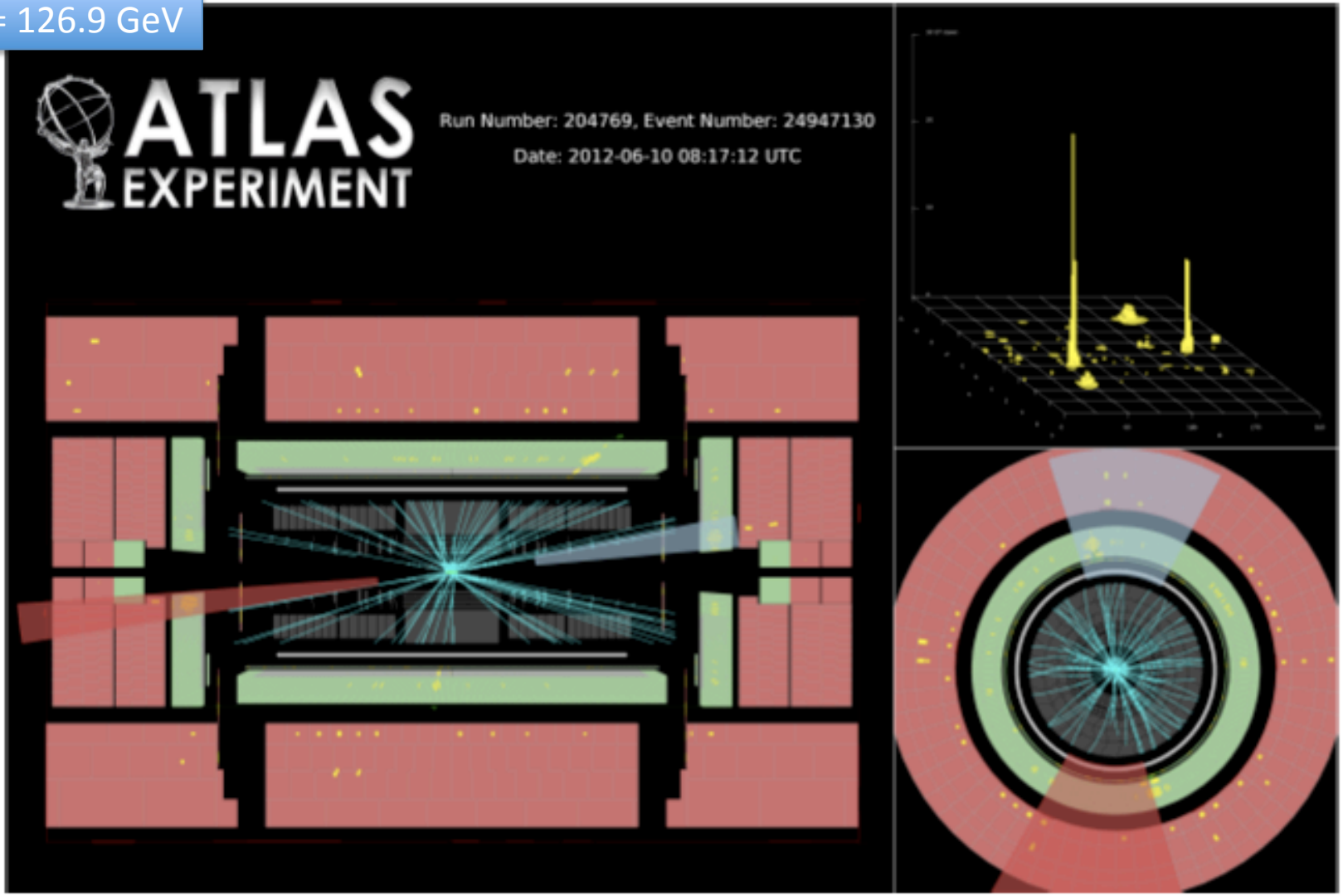
 **ATLAS**
EXPERIMENT

Run Number: 203779, Event Number: 56662314

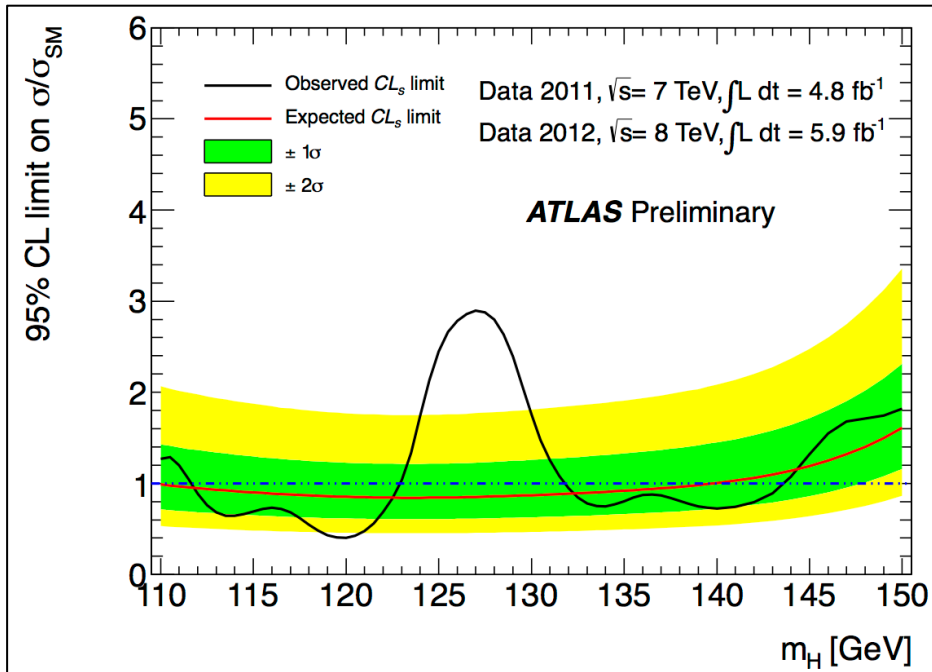
Date: 2012-05-23 22:19:29 CEST



$M_{\gamma\gamma} = 126.9 \text{ GeV}$



Analisi statistica (likelihood ratio + nuisance parameters per sistematiche):
 Grafico di “esclusione” basato sul metodo CL_s
 Grafico del p_0 -value locale

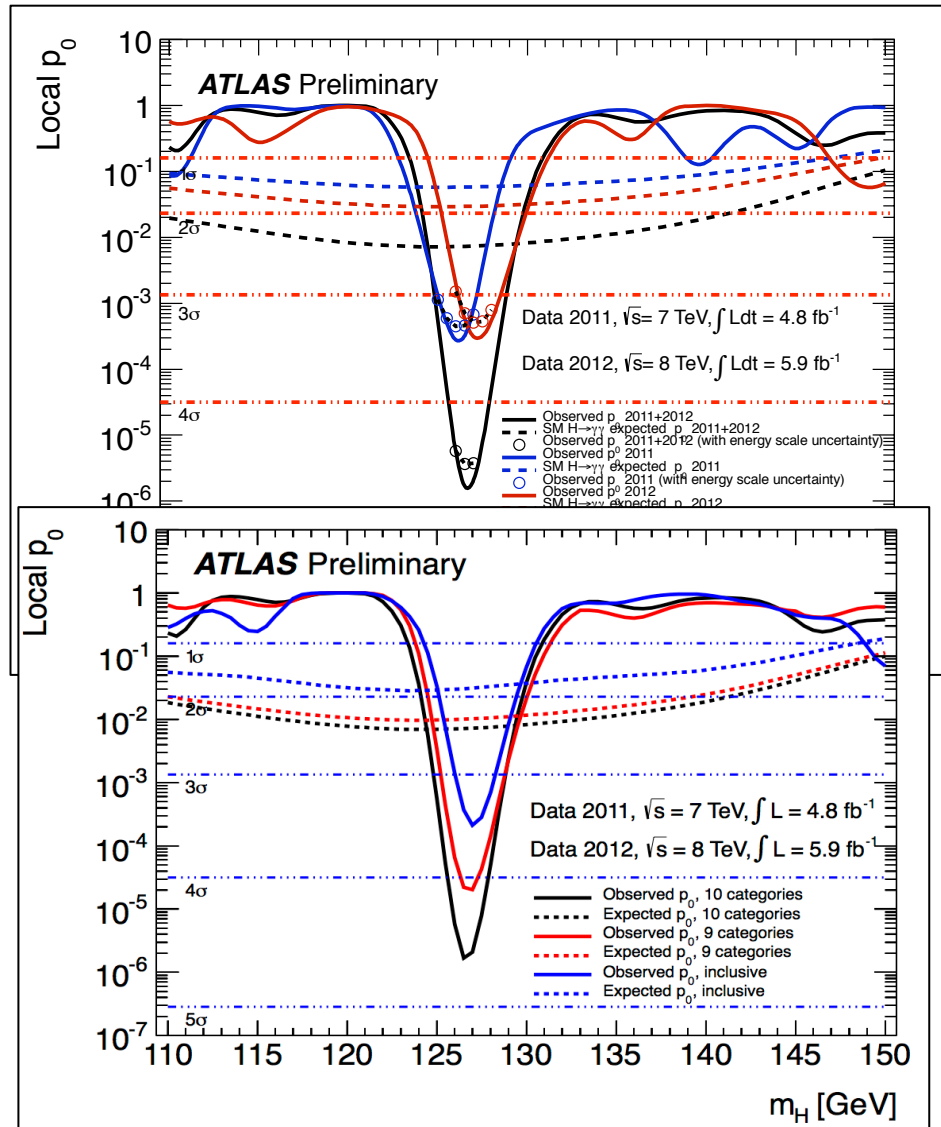


Esclusione @ 95% C.L.:

112 ÷ 122.5 GeV AND 132 ÷ 143 GeV
 (expected 110 ÷ 139 GeV)

Significatività @126.5 GeV:

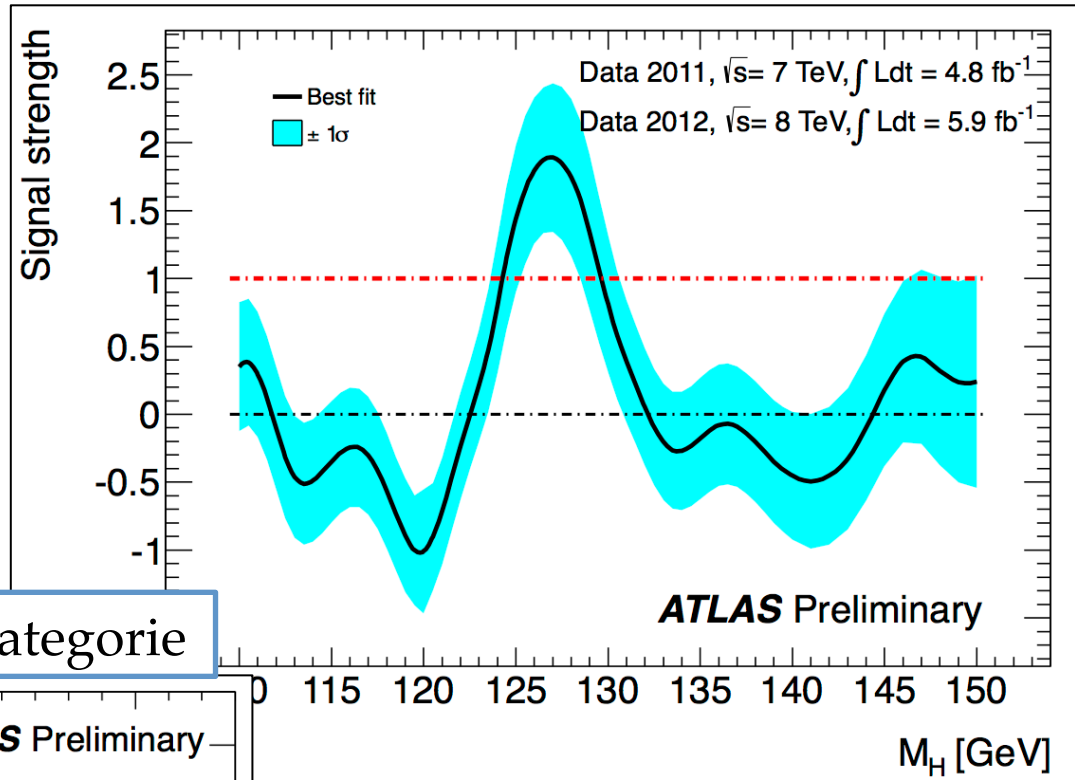
“locale” **4.5 σ (2.4 σ attesa SM)**
 “globale” **3.6 σ (LEE 110 – 150 GeV)**



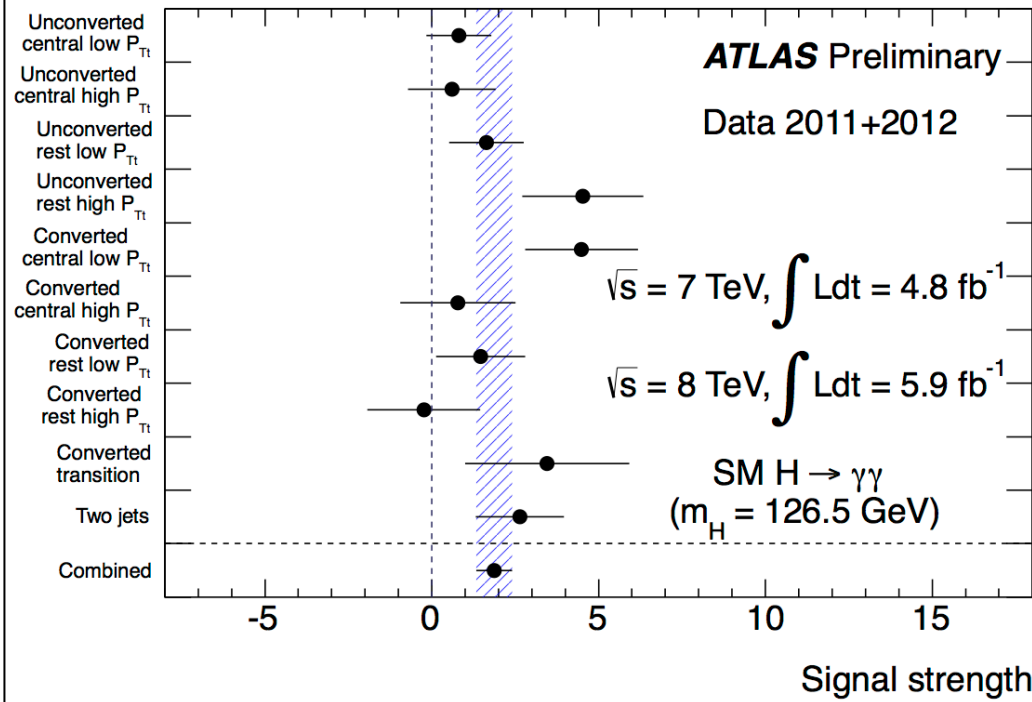
“Signal Strength” $\mu = \sigma / \sigma_{SM}$

Miglior Fit @ 126.5 GeV:

$$\mu = 1.9 \pm 0.5$$



“Signal Strength” dalle diverse categorie



H \rightarrow ZZ^(*) \rightarrow 4leptoni

Canale molto raro, $\sigma = 2.3 \div 2.9$ fb \rightarrow attesi O(10) evts;

Ma segnatura molto chiara (*golden channel*) e fondi limitati O(10²) evts;

Ricerca nell'intero intervallo di massa $110 < M_H < 600$ GeV

Stati finali con:

2 bosoni Z, uno reale, il secondo reale o virtuale (bassa M_H)

3 possibilità: 4e / 2e2 μ / 4 μ - (0.25 / 0.5 / 0.25)

Principali fondi:

pp \rightarrow ZZ^(*) \rightarrow 4leptoni ; dal continuo (irriducibile)

Z+jets ; (in particolare Z+bb) e tt (riducibili)

Trigger singolo o doppio leptone ($\epsilon(\text{trig}/\text{ricos}) \approx 99\%$)

Selezione dei candidati

2 coppie di leptoni, stesso "flavour", carica opposta;

leptoni con: $p_T > 20, 15, 10, 6$ (7) GeV; $|\eta_e| < 2.47, |\eta_\mu| < 2.7$;

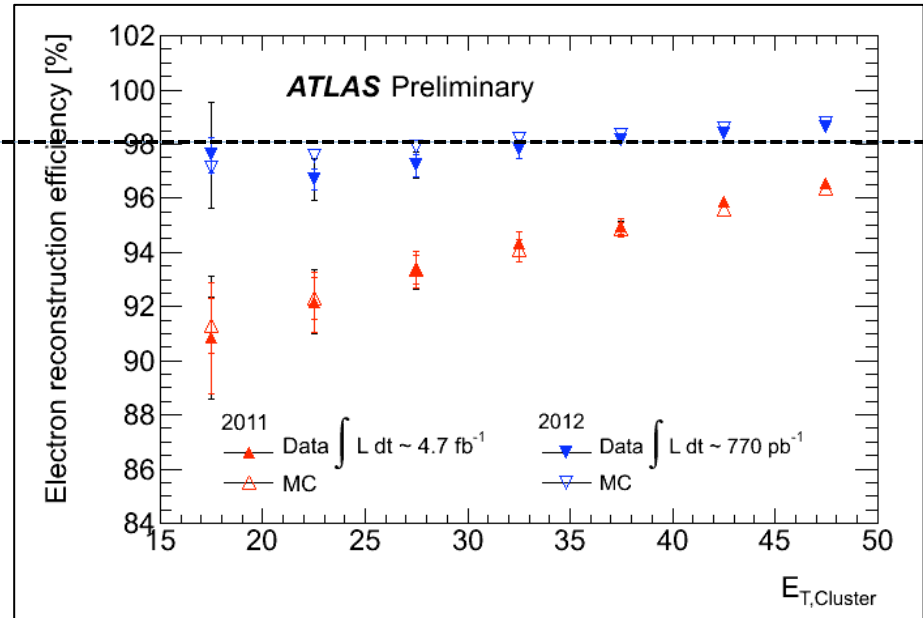
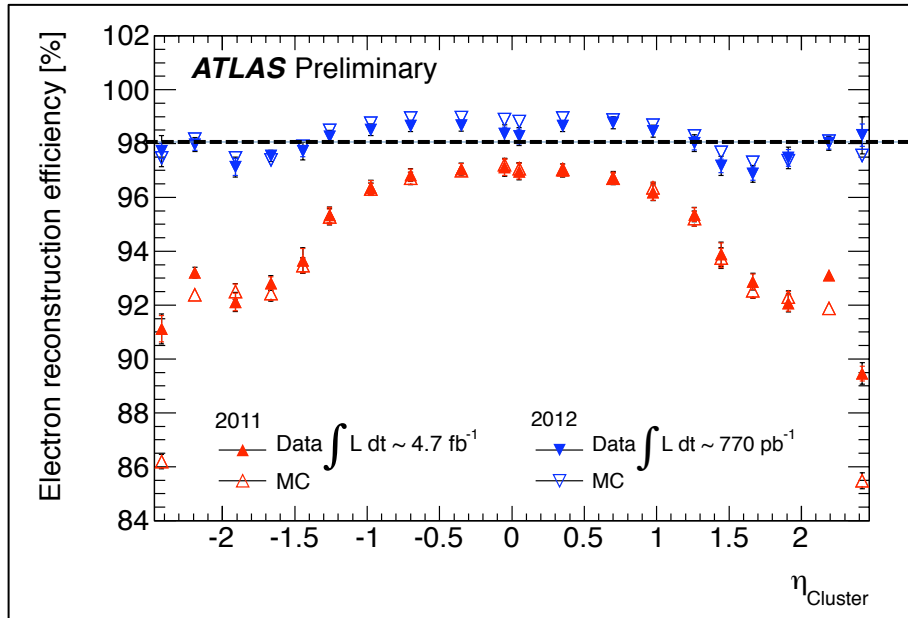
Masse delle Z: $50 < M_{12} < 106$ GeV AND $M_{\min}(M_{4l}) < M_{34} < 115$ GeV, $M_{ll} > 5$ GeV

leptoni "isolati" (ID e Calorimetro) e provenienti dal vertice primario

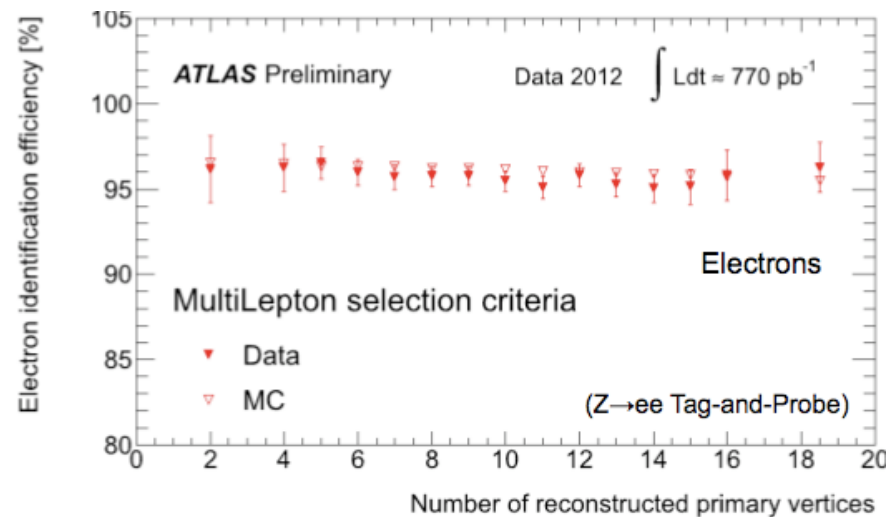
Efficienza	2011 (old)	2011 (new)	2012	
4 μ	27%	43%	41%	+40%
2e2 μ	18%	23%	27%	
4e	14%	17%	23%	+60%

Elettroni:

BREM recovery molto efficace su efficienza e risoluzione

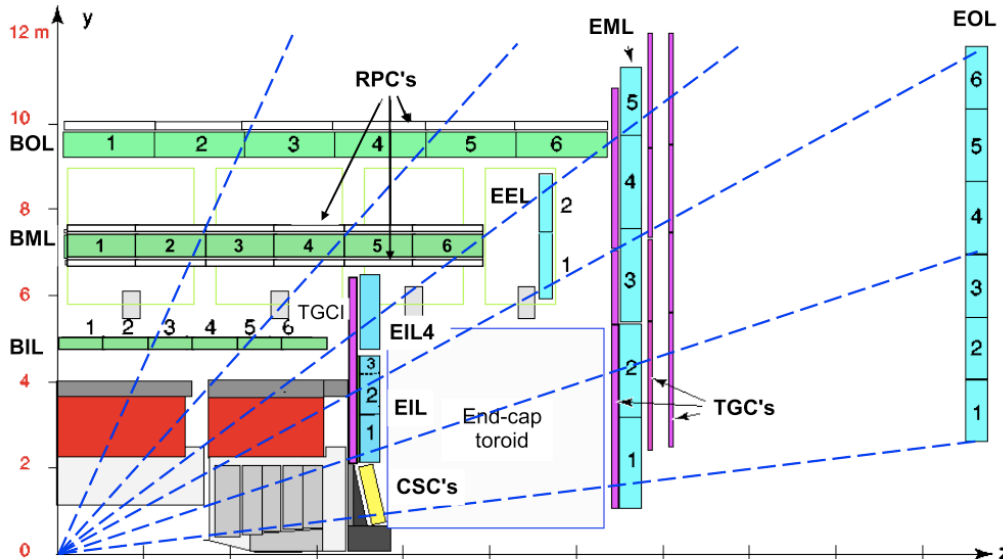


- Candidati elettroni ri-fittati tenendo conto della bremsstrahlung;
- Modificate le richieste per il matching con il cluster;
- L'efficienza (e le variabili di shape) sono \approx indipendenti da N_{vtx} .

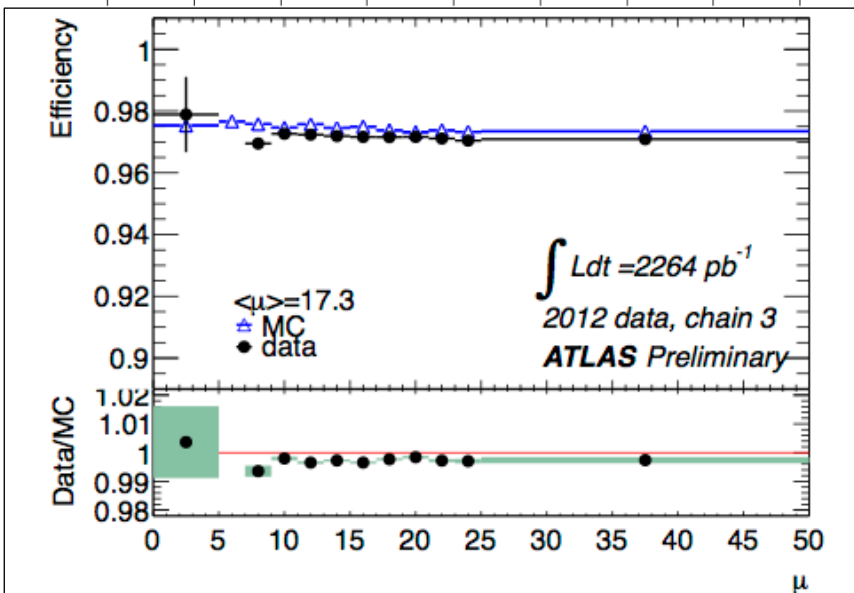


Muoni:

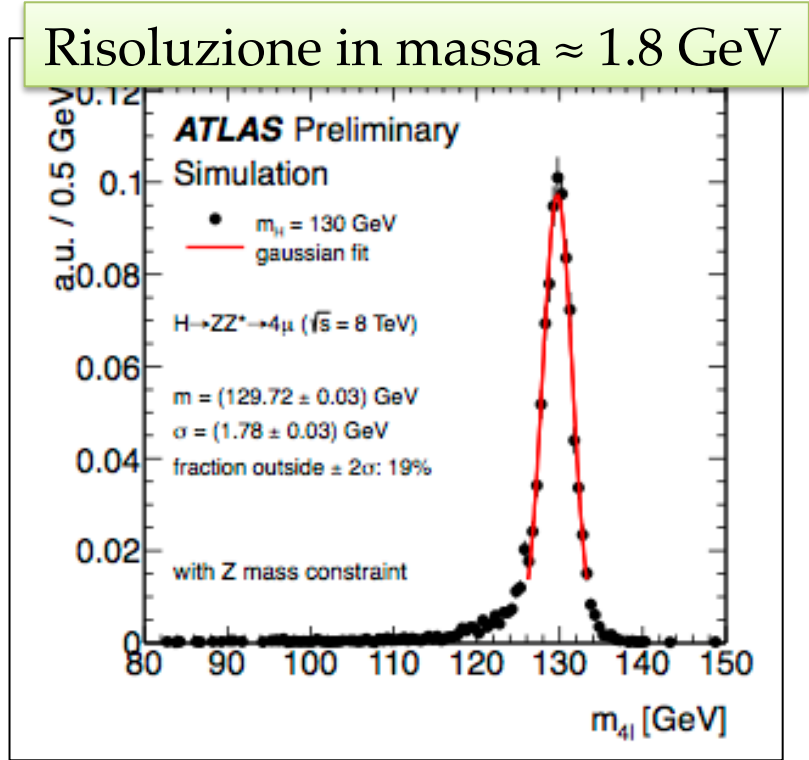
Estesa l'accettazione a muoni "standalone" e "calomuons"



Muoni combinati o tagged +
 Muoni standalone ($2.5 < |\eta| < 2.7$)
 Calomuons ($|\eta| < 0.1, p_T > 15 \text{ GeV}$)
 Abbassate soglie in p_T
 Ottimizzati tagli sulle masse Z
 → +40% rispetto a dicembre

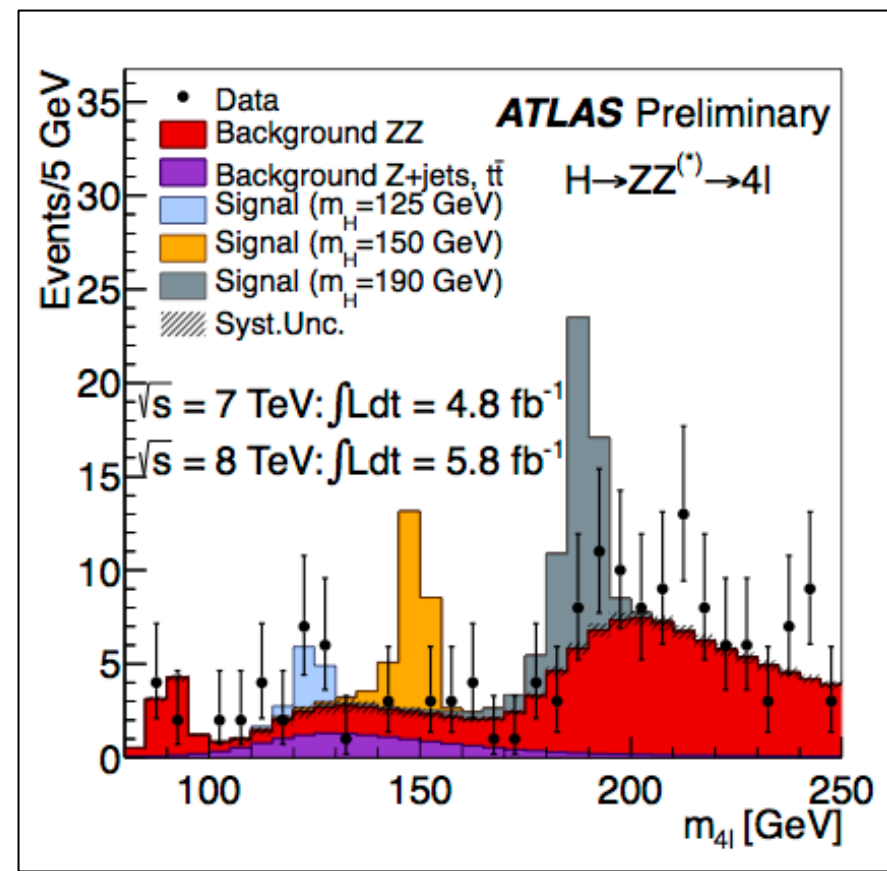
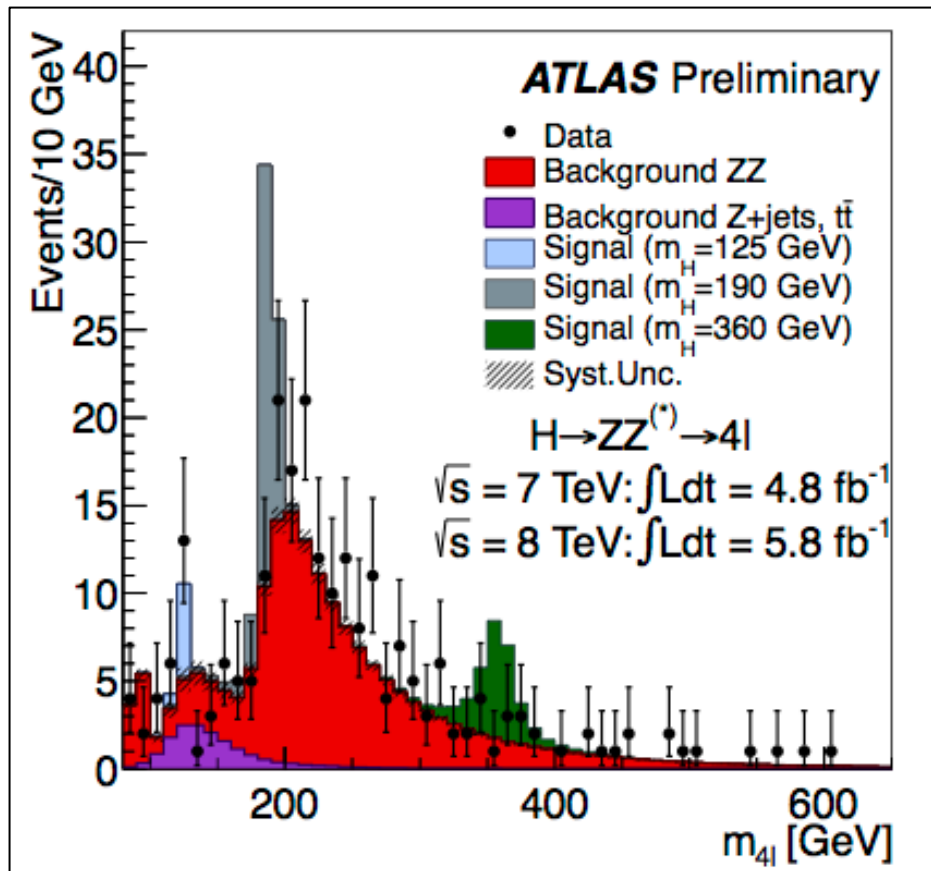


Efficienza "robusta" rispetto al pile-up



Risoluzione in massa $\approx 1.8 \text{ GeV}$

Risultati: selezionati 230 evts (88 + 142): spettro in massa invariante “raw”



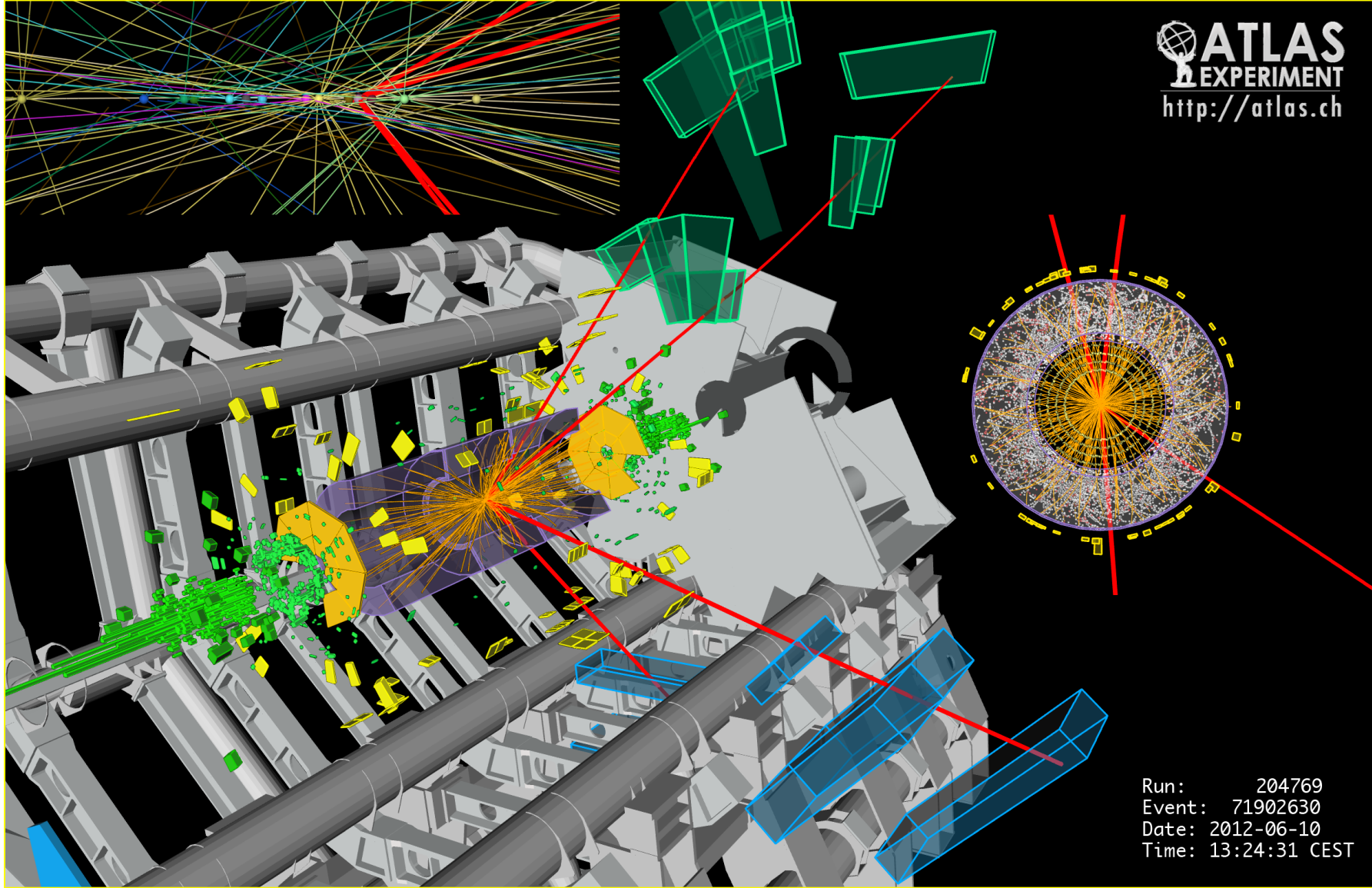
Fondo ZZ: forma e normalizzazione MC

Accordo entro 2σ norm. con dati,
effetto molto limitato a 125 GeV

Fondo Z+jets, tt: regioni di controllo + MC

Eventi in $M_{4l} = 125 \pm 5$ GeV			
	2011	2012	combined
exp.bckg.	2.1 ± 0.3	2.9 ± 0.4	5.1 ± 0.8
exp.signal	2.0 ± 0.3	3.3 ± 0.5	5.3 ± 0.8
data	4	9	13

Evento 4μ : $M_{4l} = 125.1 \text{ GeV}$



Evento 4e: $M_{4l} = 124.6$ GeV

ATLAS
EXPERIMENT

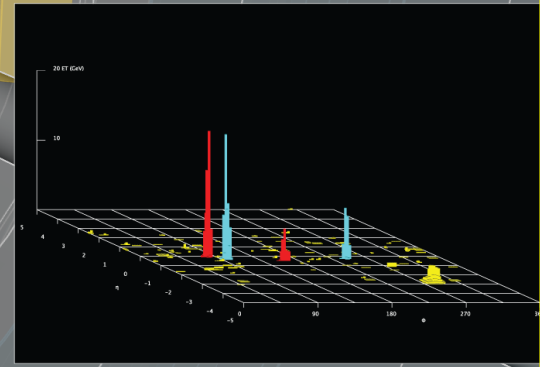
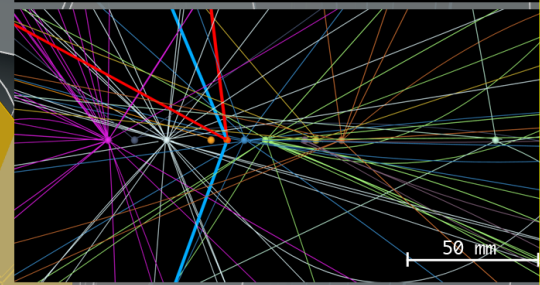
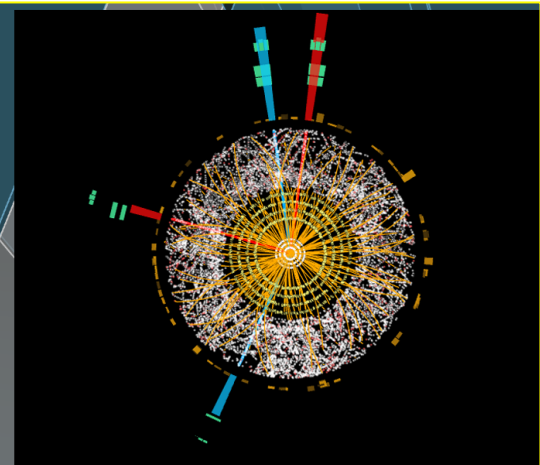
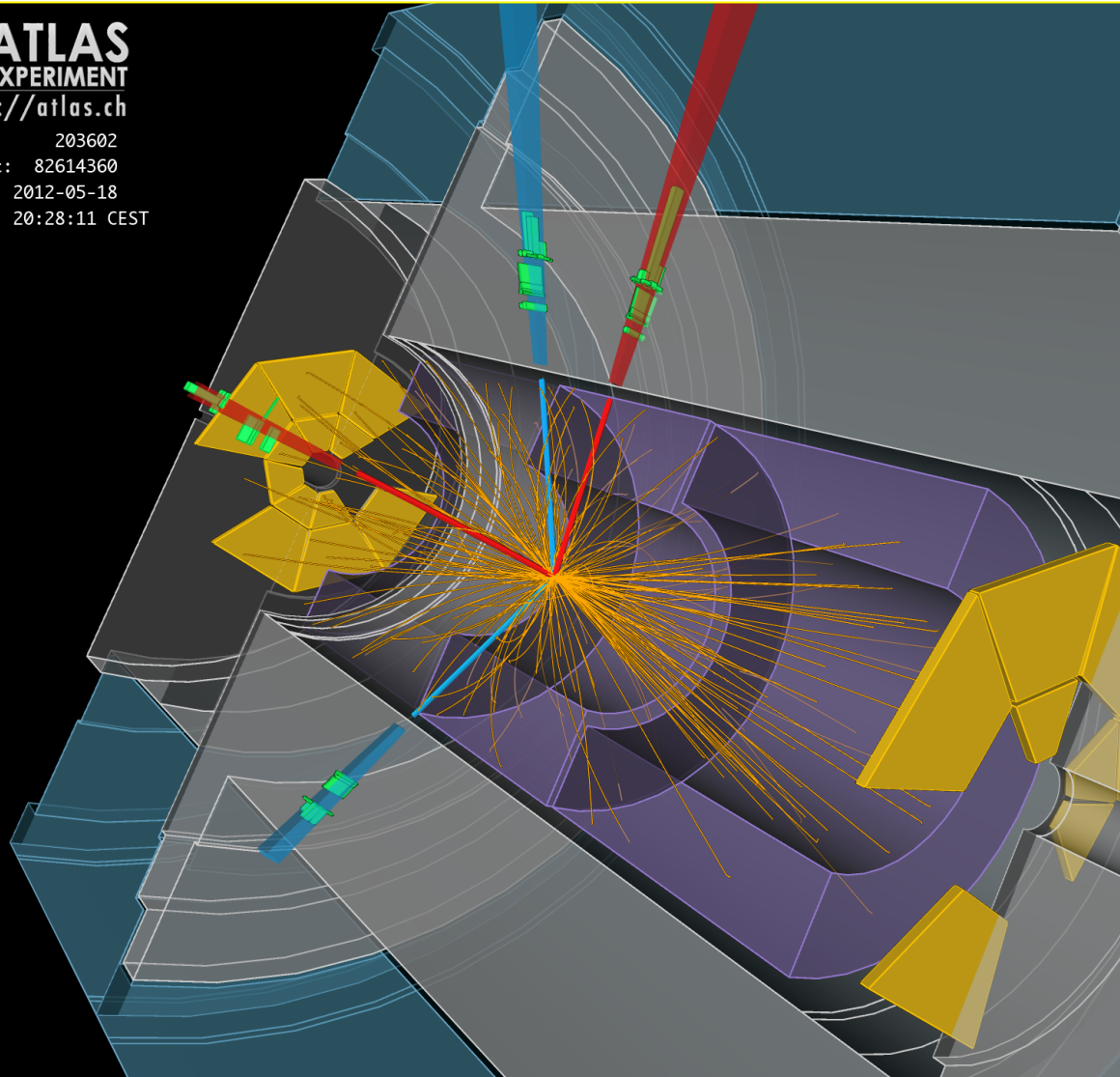
<http://atlas.ch>

Run: 203602

Event: 82614360

Date: 2012-05-18

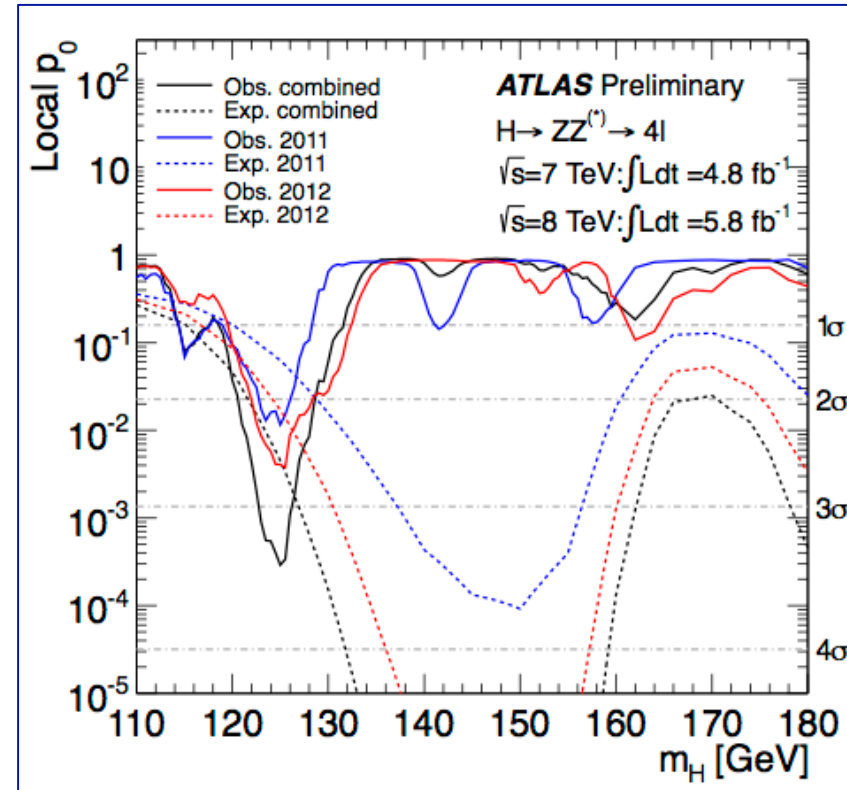
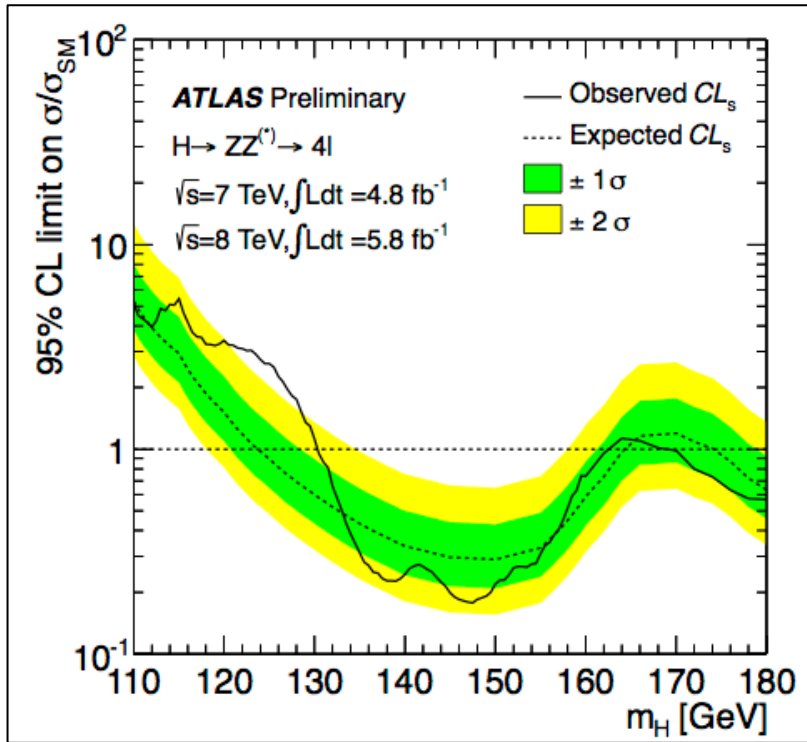
Time: 20:28:11 CEST



Analisi statistica (likelihood ratio + nuisance parameters per sistematiche):

Grafico di “esclusione” basato sul metodo CL_s

Grafico del p_0 -value locale



Esclusione @ 95% C.L.:

131 ÷ 162 GeV AND 170 ÷ 460 GeV (expected: 124 ÷ 174 AND 176 ÷ 500 GeV)

Significatività @125 GeV:

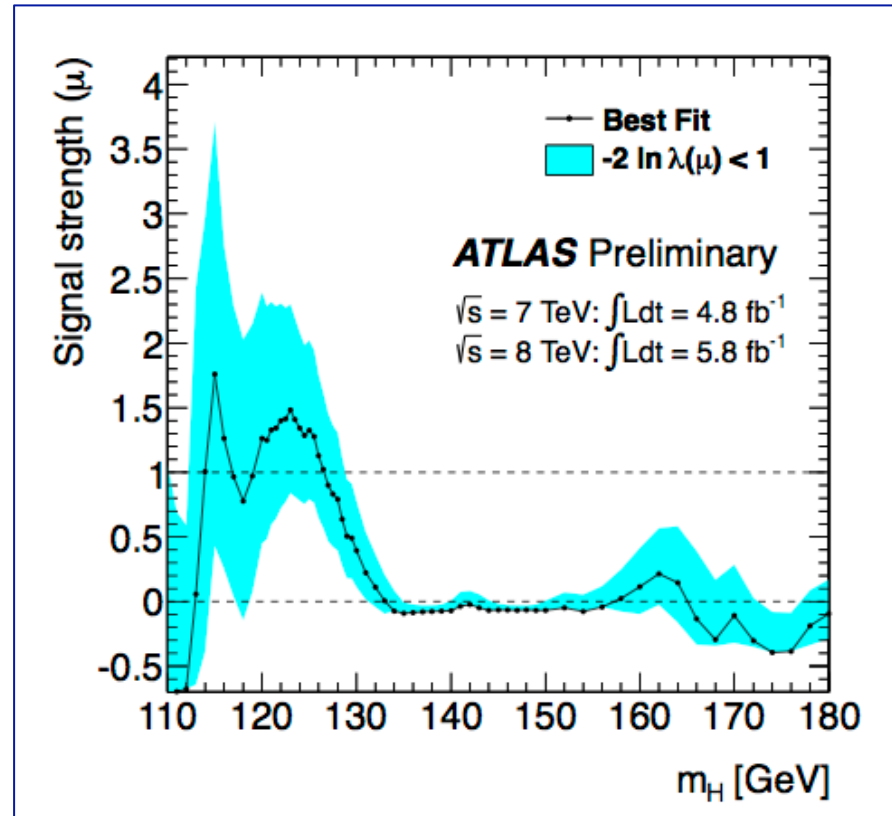
“locale” **3.4 σ (2.6 σ attesa SM)**

“globale” 2.1 σ (LEE 110 – 600 GeV)

“Signal Strength” $\mu = \sigma / \sigma_{SM}$

Miglior Fit @ 125.0 GeV:

$$\mu = 1.3 \pm 0.6$$

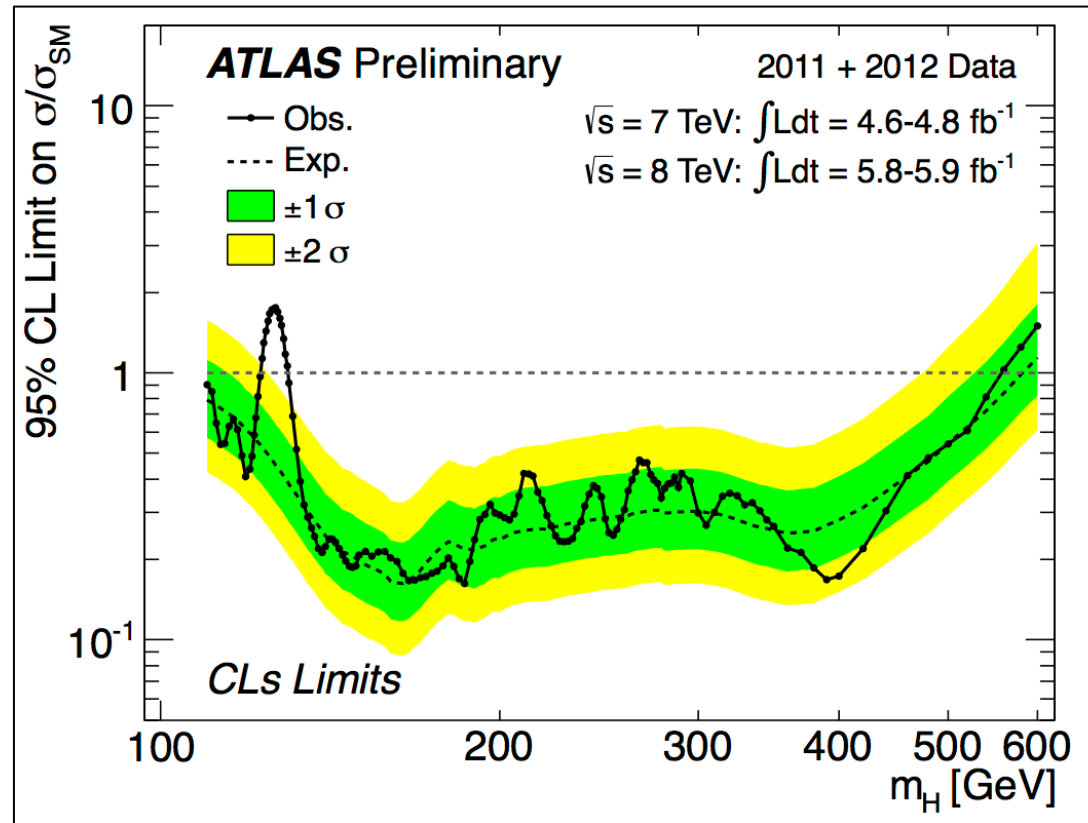


Combinazione - I

$H \rightarrow \gamma\gamma$, 4l

Tutti gli altri canali, solo dati 2011 analisi pubblicata

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$
$H \rightarrow WW \rightarrow l\nu qq$
$H \rightarrow ZZ \rightarrow ll\nu\nu$
$H \rightarrow ZZ^{(*)} \rightarrow llqq$
$H \rightarrow \tau\tau$
$WH \rightarrow l\nu bb$
$ZH \rightarrow llbb$
$ZH \rightarrow \nu\nu bb$



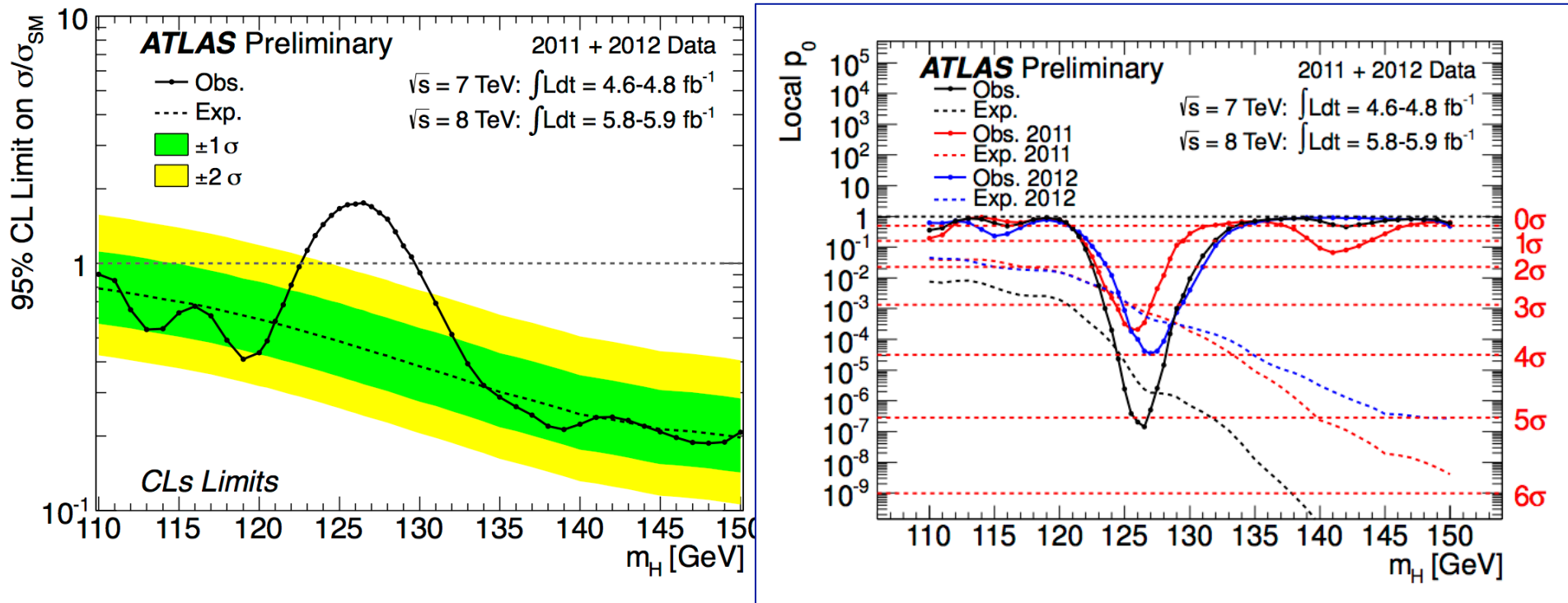
Esclusione:

@ 95% C.L. **110.0 ÷ 122.6** AND **129.7 ÷ 557.6** GeV (110 ÷ 582 GeV exp.)

@ 99% C.L. **111.7 ÷ 121.8** AND **130.7 ÷ 522.6** GeV

Combinazione - II

Significatività del segnale @ 126 GeV



La probabilità che un esperimento di solo fondo fluttui come o più dei dati corrisponde a 5.1 deviazioni standard gaussiane.

L'effetto delle sistematiche su Scala e Risoluzione in Energia $\rightarrow 5.0$

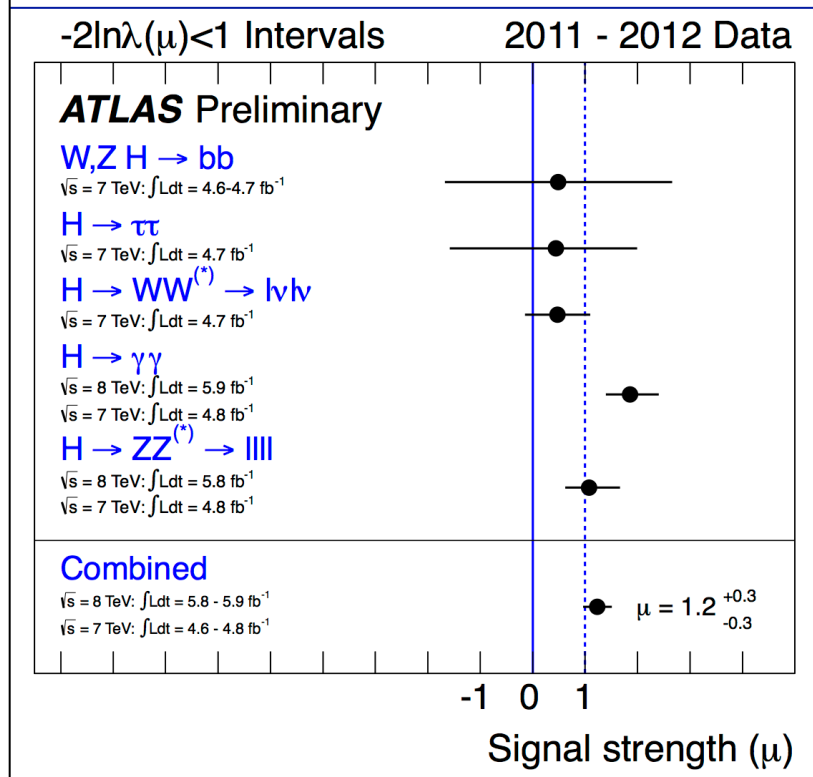
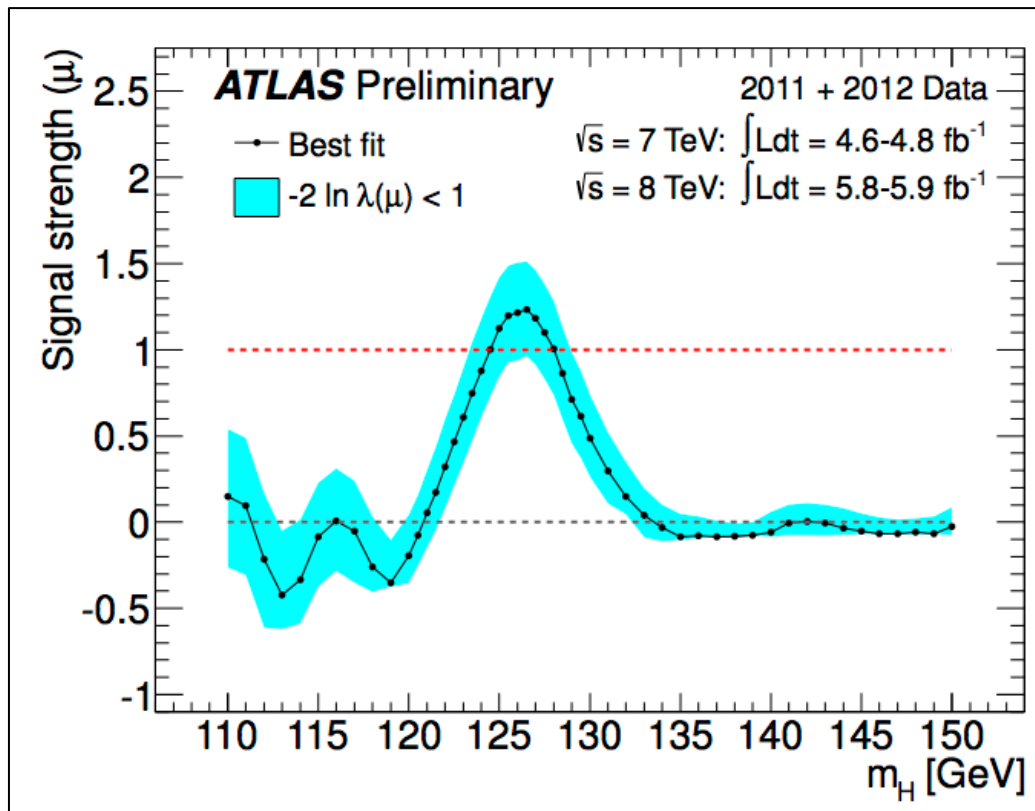
p_0 -value @ 126.5 GeV = 5.0 σ (expected 4.6 σ)

Combinazione - III

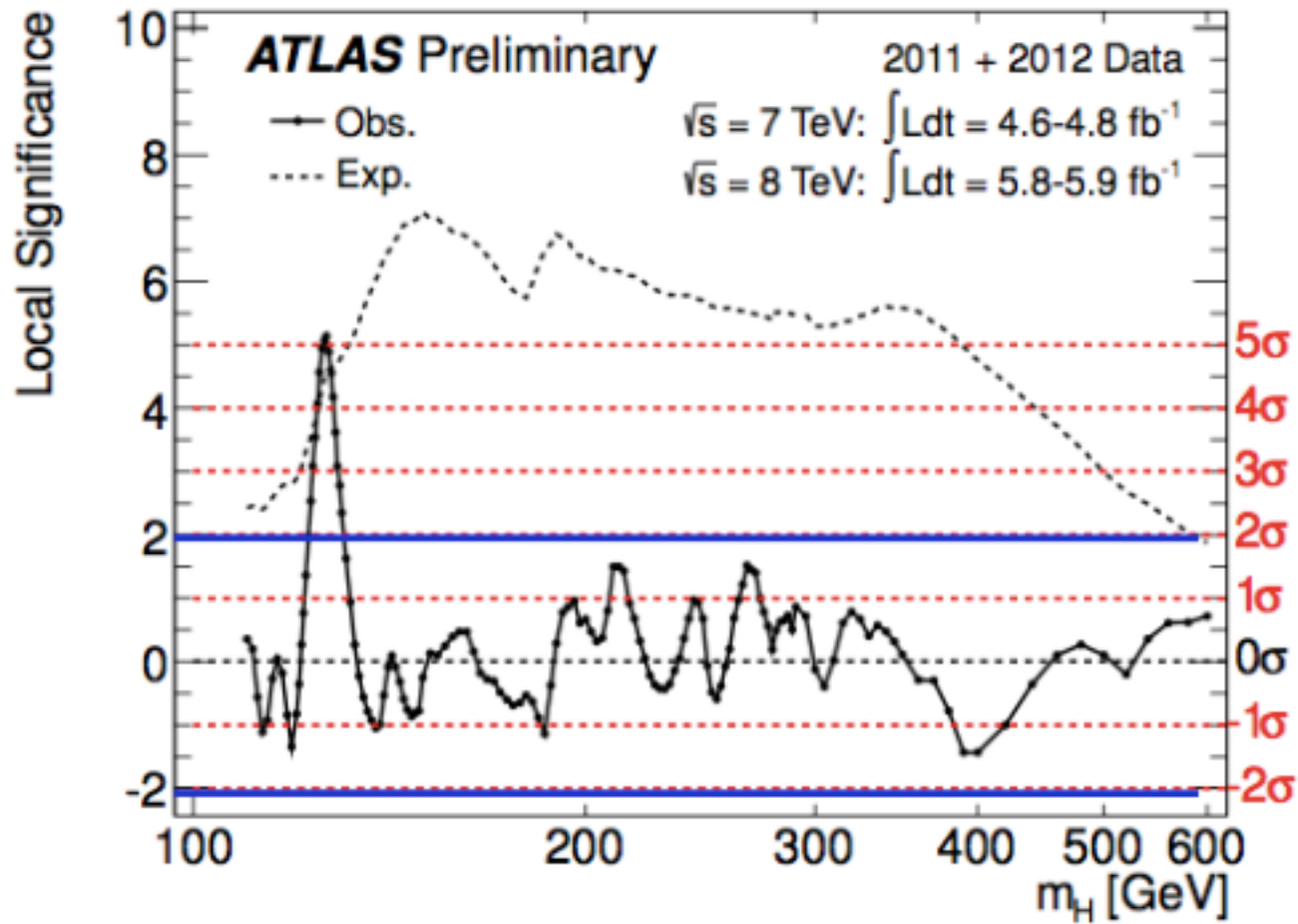
“Signal Strength” $\mu = \sigma / \sigma_{SM}$

Miglior Fit @ 126.5 GeV:

$$\mu = 1.2 \pm 0.3$$



Significatività dell'eccesso su tutta la finestra di massa esplorata:
quella a 126 GeV è l'unica fluttuazione che osserviamo !

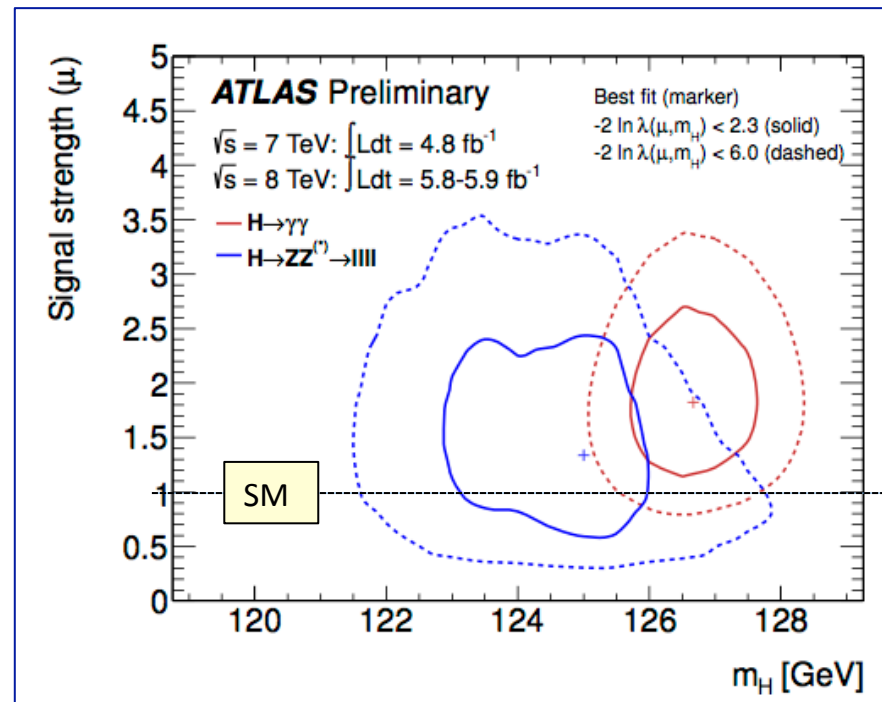


Ricapitolando: Significatività dell'osservazione

	local signif. (σ)	signal strength $\mu = \sigma/\sigma_{SM}$
$H \rightarrow \gamma\gamma$	4.5 (2.4)	1.9 ± 0.5 (126.5 GeV)
$H \rightarrow 4l$	3.4 (2.6)	1.3 ± 0.6 (125.0 GeV)
combinazione	5.0 (4.6)	1.2 ± 0.3 (126.5 GeV)

Consistenza tra i due principali canali

$p=20\%$
prob. di avere una
differenza di massa
 \geq questa osservata
 \rightarrow consistenti.



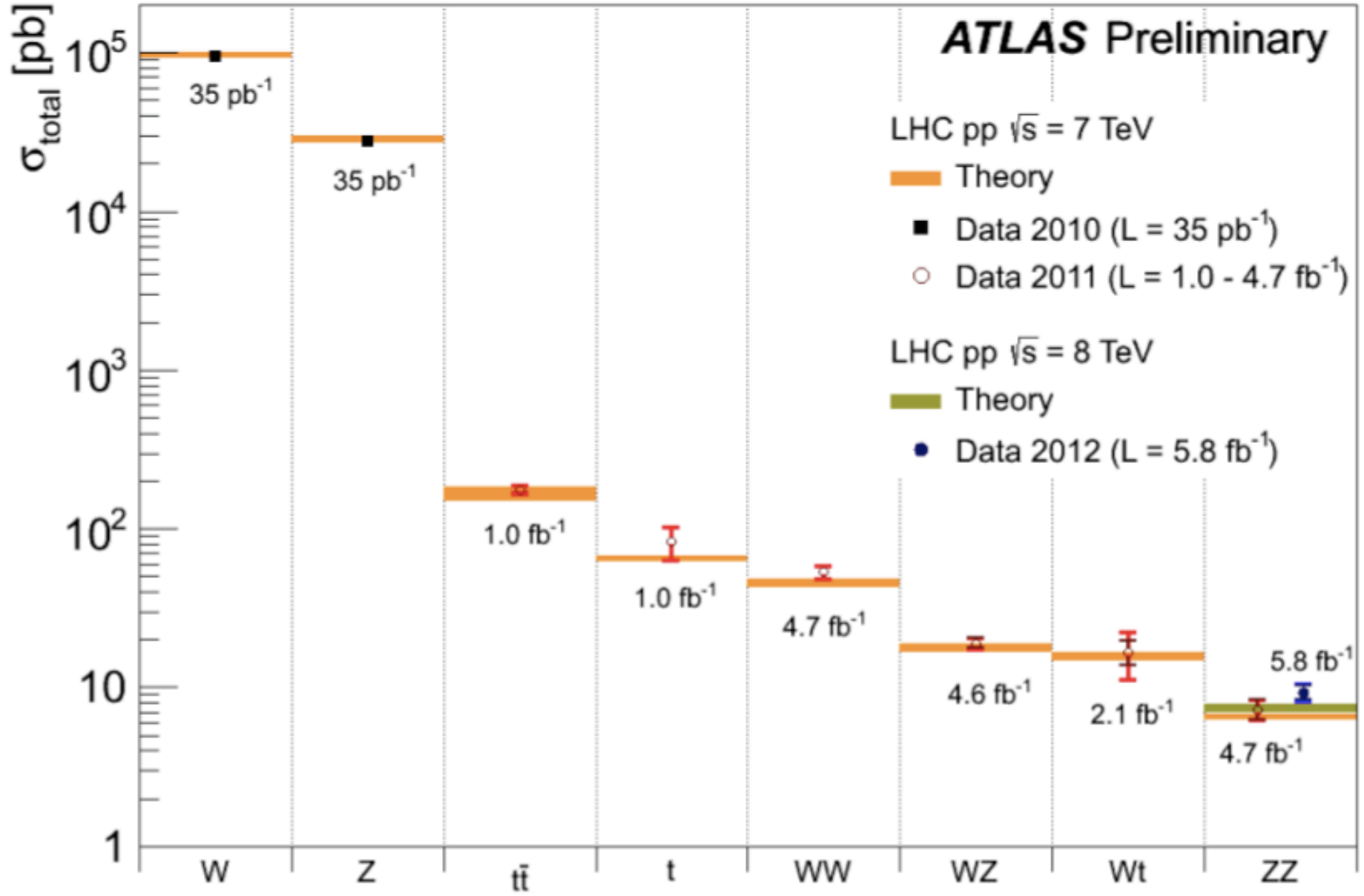
Conclusioni.

- ATLAS esclude il bosone di Higgs SM in tutto l'intervallo di massa esplorato eccetto la regione $122.7 \div 129.0$ GeV;
- ATLAS osserva un eccesso di eventi rispetto al fondo in due canali indipendenti alla stessa massa $M \approx 126$ GeV e coerentemente tra 2011 e 2012.
- L'eccesso ha una **significatività di 5 "sigma"** (4.6 attese SM).
- Le sezioni d'urto sono consistenti con le predizioni SM per il bosone di Higgs
- Il decadimento in $\gamma\gamma$ implica **che si tratta di un bosone** (spin=0, 2, ...)

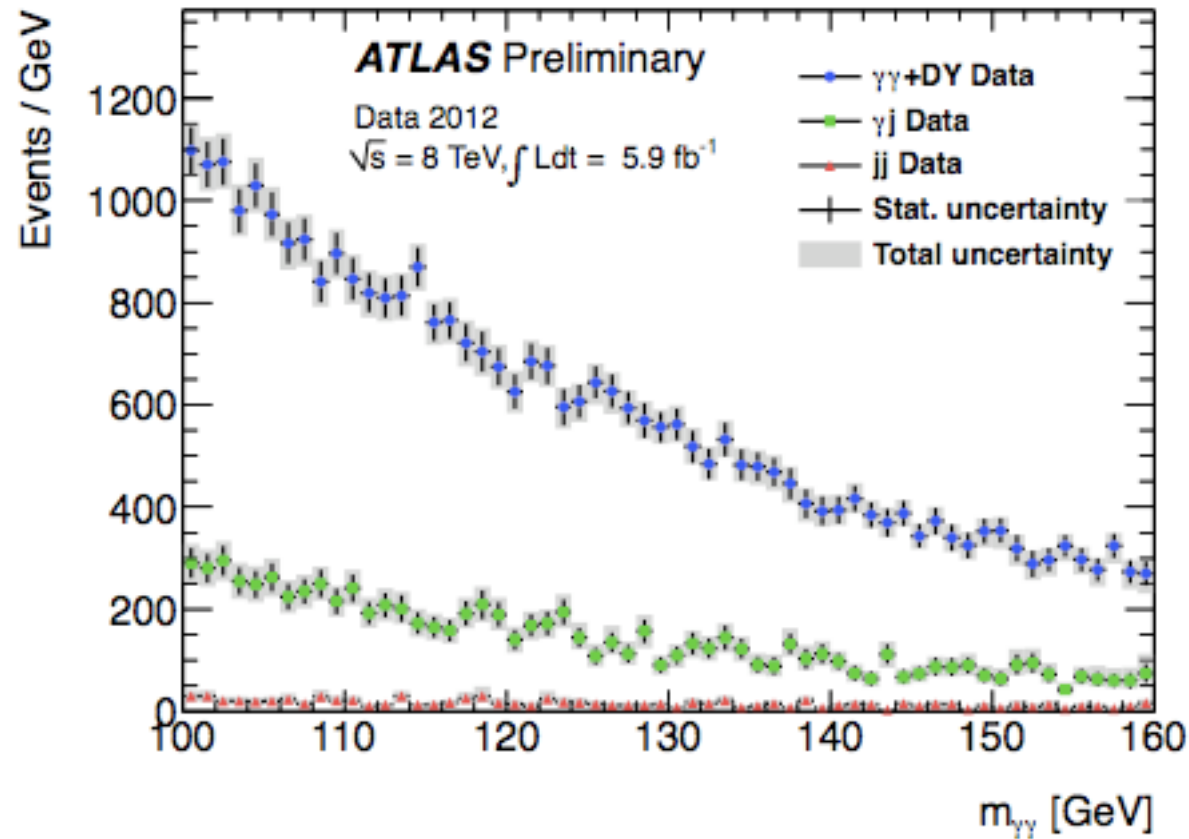
• Prossimi passi:

1. **Ampi margini di miglioramento delle tecniche di analisi**
2. **Statistica di 20-30 fb⁻¹ a 8 TeV a fine anno realistica**
 - ➔ **Consolidamento dell'osservazione**
 - ➔ **Estensione al canale WW e ai canali fermionici**
 - ➔ **Studio delle proprietà della particella osservata**

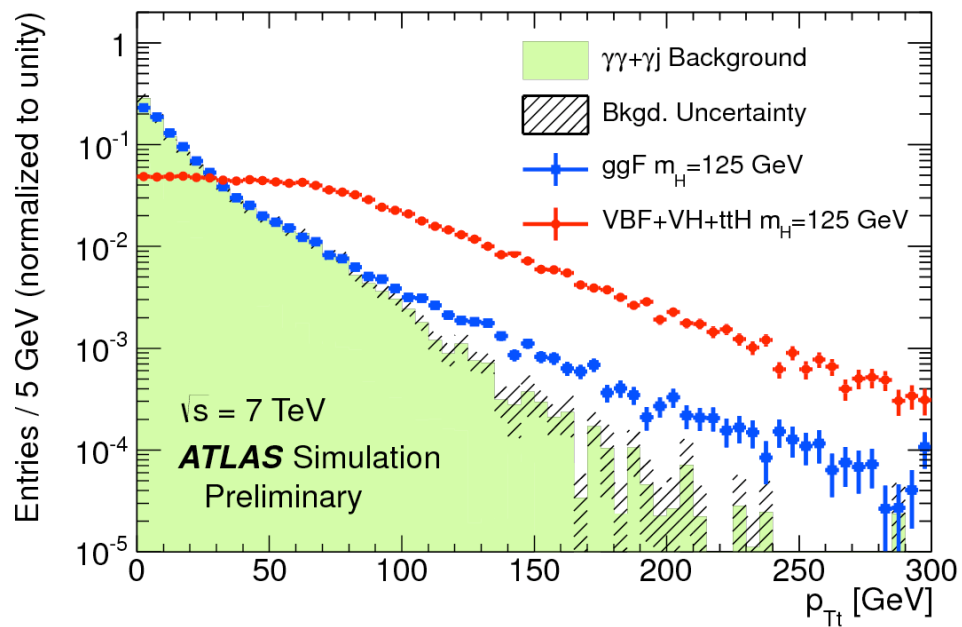
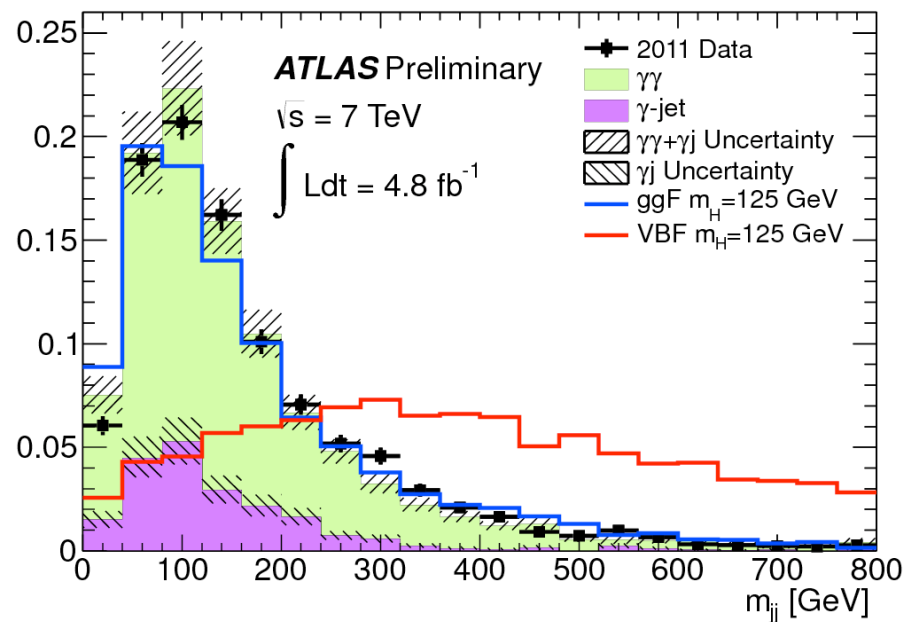
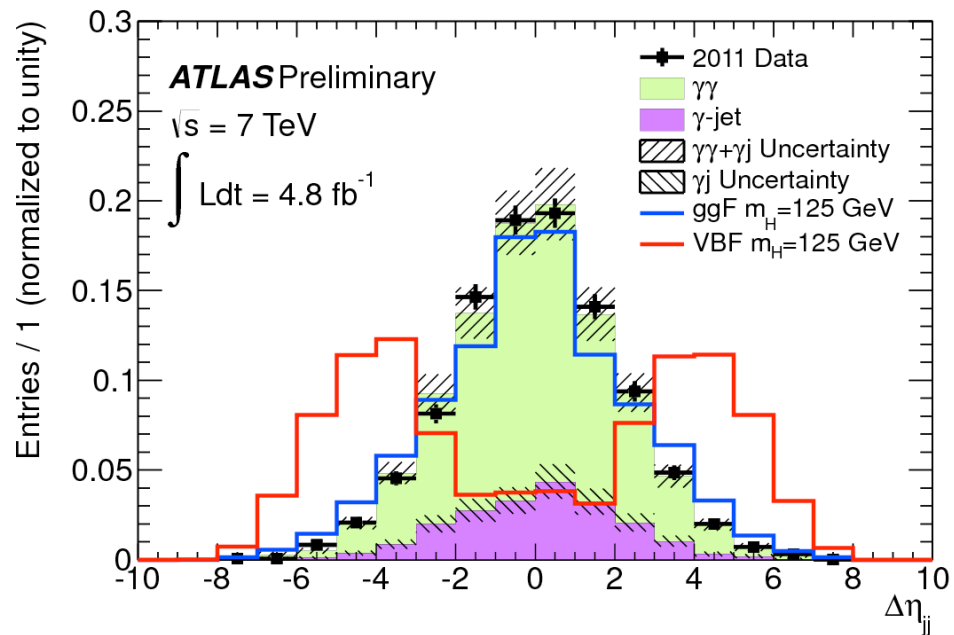
Backup

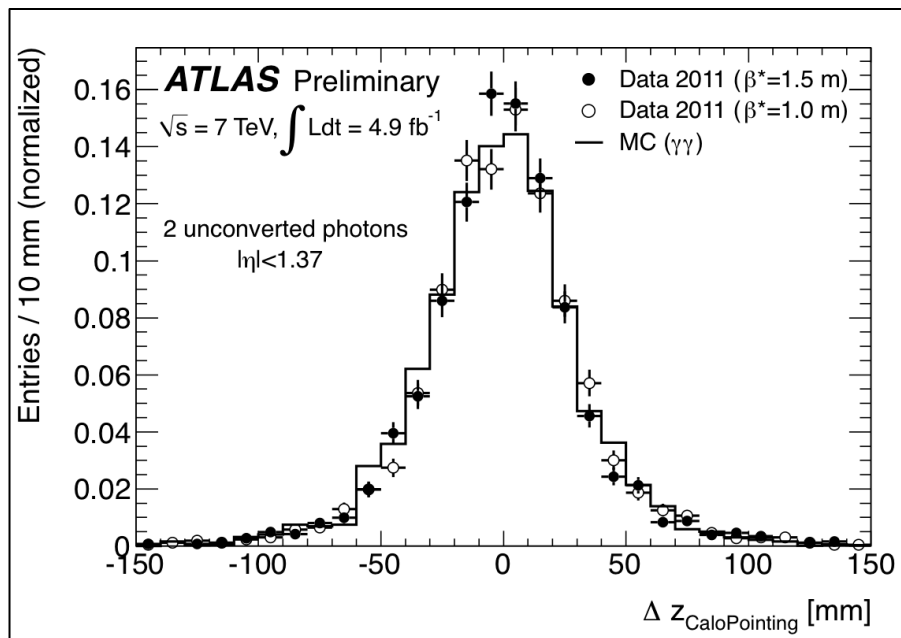


Determinazione “data-driven” della composizione del campione

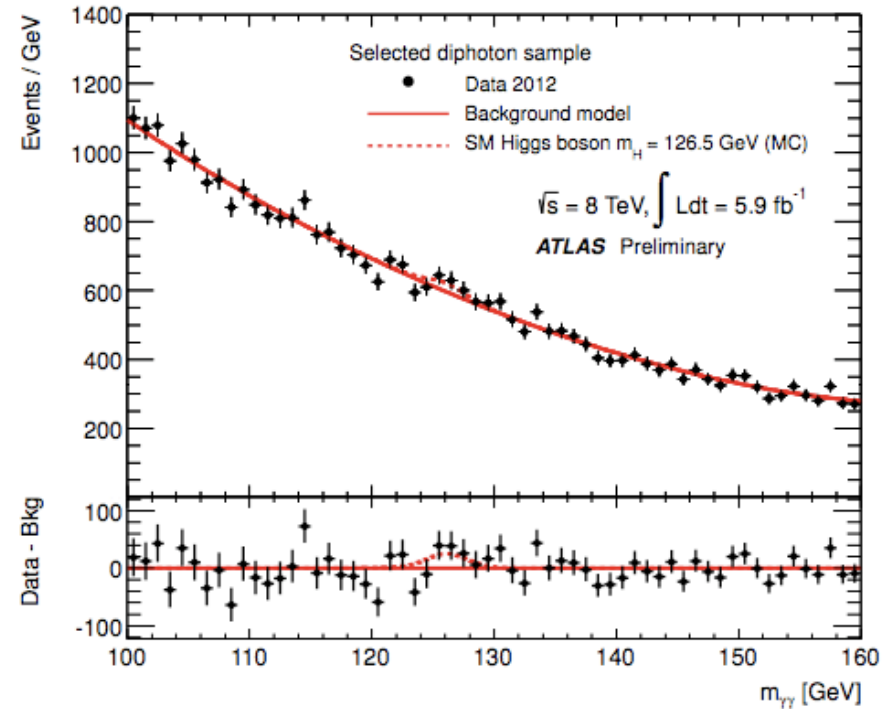
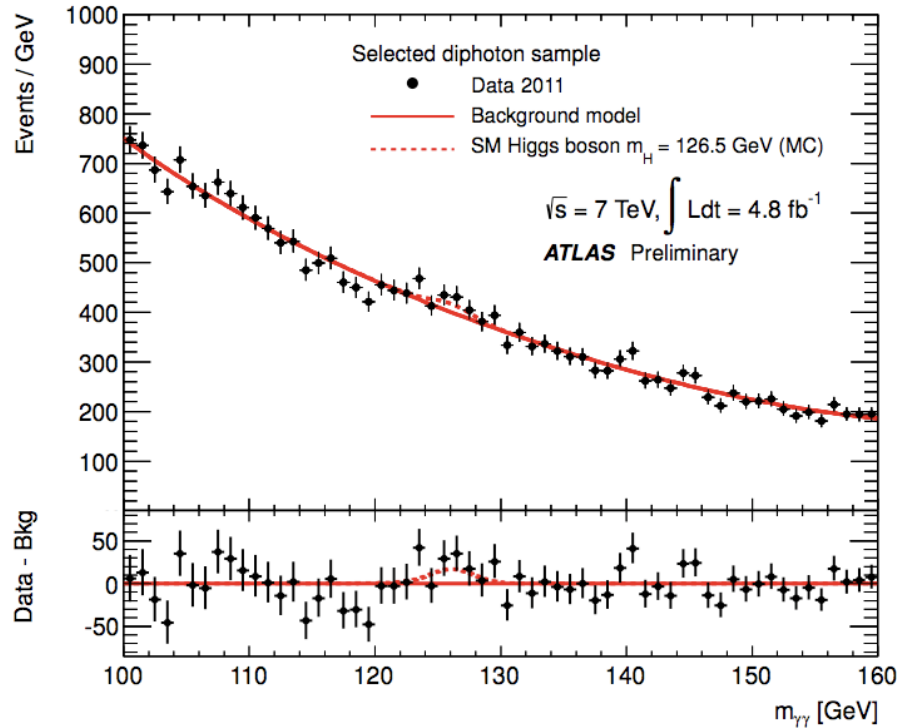


	$\gamma\gamma$ +DY	γ -jet	jet-jet
7 TeV (NN ID)	$(80 \pm 4)\%$	$(19 \pm 3)\%$	$(1.8 \pm 0.5)\%$
8 TeV (Cut ID)	$(75 \pm 3)\%$	$(22 \pm 2)\%$	$(2.6 \pm 0.5)\%$





Spettri in massa invariante “raw”: campioni 2011 e 2012 (ricerca limitata alla regione $110 < M_{\gamma\gamma} < 150$)



Background:

Parametrizzazioni ottenute da fit a campioni MC di puro fondo
Parametri aggiustati dal fit dei dati di “puro-background”

Nella zona di 125 GeV si osservano fluttuazioni positive

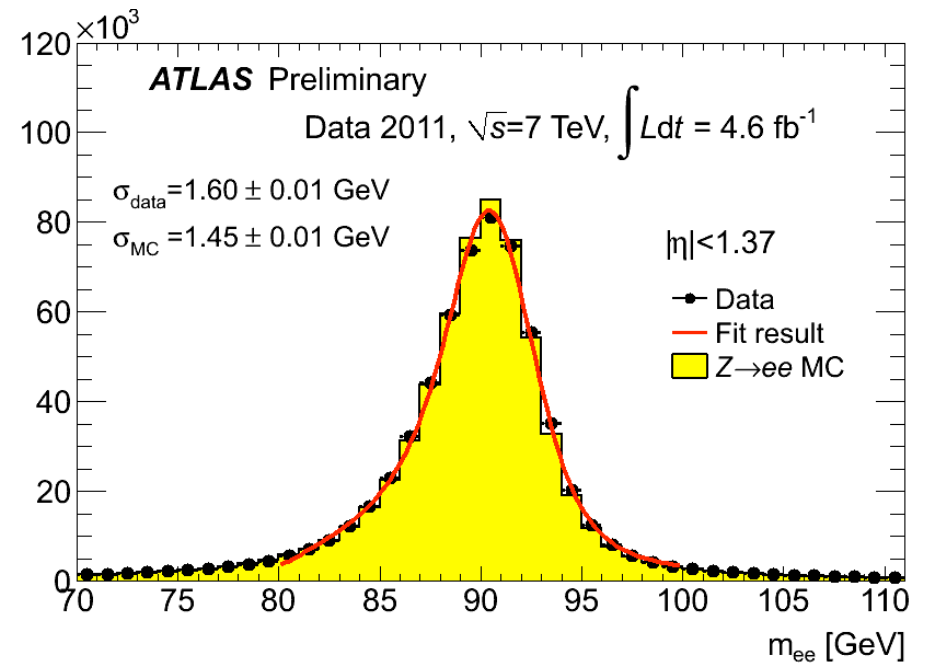
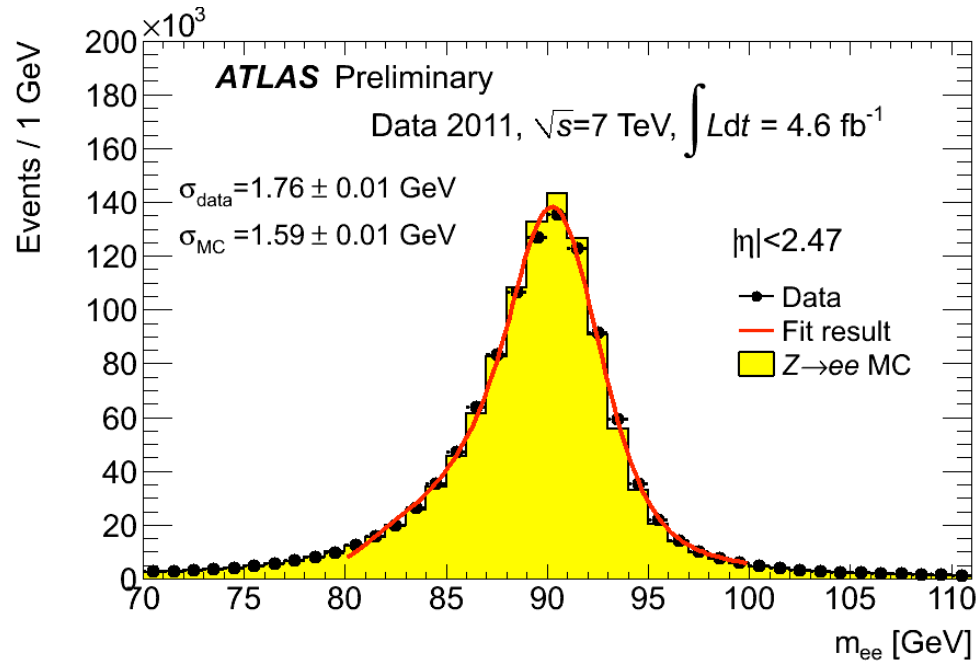
Table 2: Number of expected signal S and background events B in mass a window around $m_H = 126.5$ GeV that would contain 90% of the expected signal events, along with the observed number of events in this window. In addition, σ_{CB} , the Gaussian width of the Crystal Ball function describing the invariant mass distribution (see Sec. 6), and the FWHM of the distribution, are given. The numbers are given for the data and simulation at $\sqrt{s} = 8$ TeV for different categories and the inclusive sample.

Category	σ_{CB} [GeV]	FWHM [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]
Inclusive	1.63	3.87	3693	100.4	3635
Unconverted central, low p_{Tt}	1.45	3.42	235	13.0	215
Unconverted central, high p_{Tt}	1.37	3.23	15	2.3	14
Unconverted rest, low p_{Tt}	1.57	3.72	1131	28.3	1133
Unconverted rest, high p_{Tt}	1.51	3.55	75	4.8	68
Converted central, low p_{Tt}	1.67	3.94	208	8.2	193
Converted central, high p_{Tt}	1.50	3.54	13	1.5	10
Converted rest, low p_{Tt}	1.93	4.54	1350	24.6	1346
Converted rest, high p_{Tt}	1.68	3.96	69	4.1	72
Converted transition	2.65	6.24	880	11.7	845
2-jets	1.57	3.70	18	2.6	12

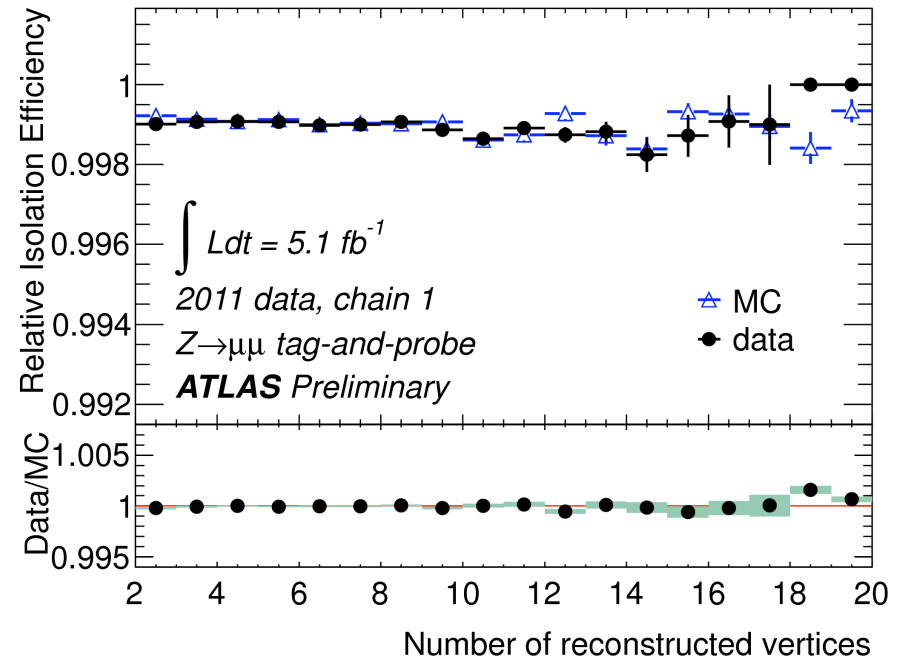
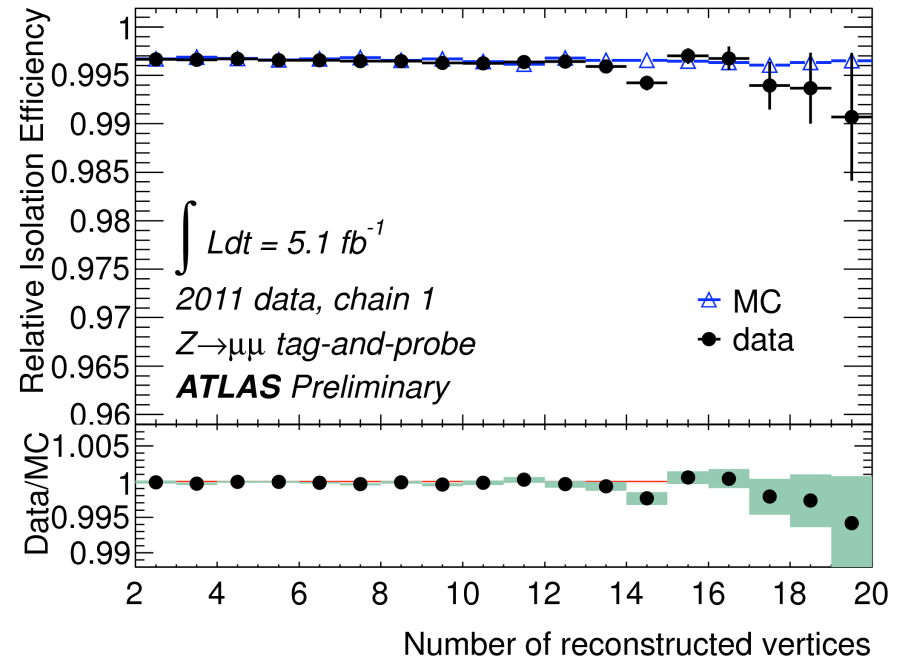
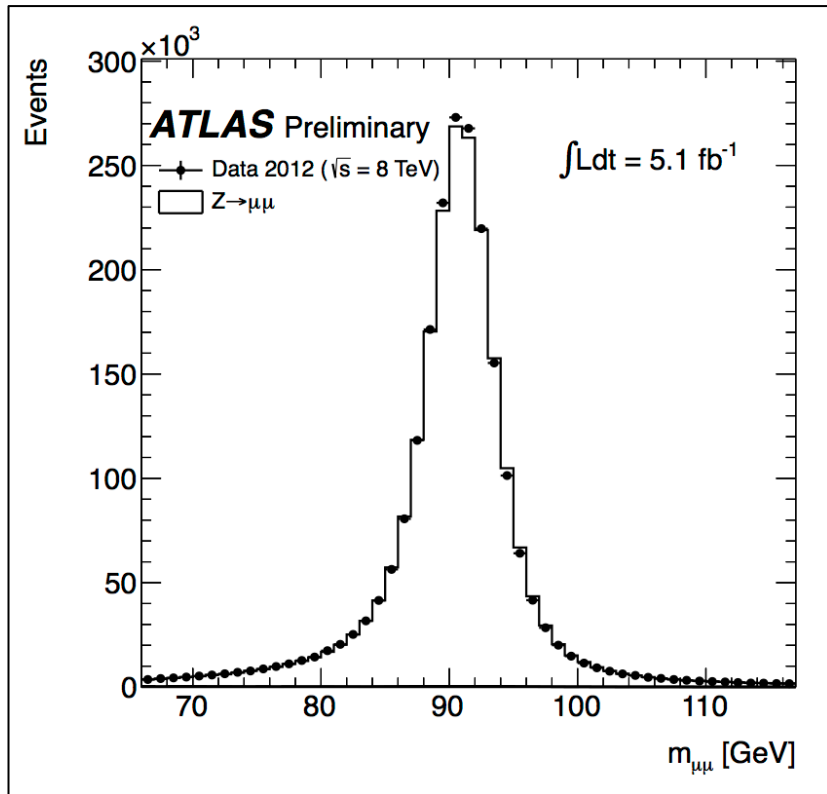
Table 6: Number of expected signal events per category at $m_H = 126.5$ GeV, at $\sqrt{s} = 7$ TeV (top) and $\sqrt{s} = 8$ TeV (bottom) and breakdown by production process.

\sqrt{s}	Category	Events	$gg \rightarrow H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]
7 TeV	Inclusive	79.3	87.8	7.3	2.9	1.6	0.4
	Unconverted central, low p_{Tt}	10.4	92.9	4.0	1.8	1.0	0.2
	Unconverted central, high p_{Tt}	1.5	66.5	15.7	9.9	5.7	2.4
	Unconverted rest, low p_{Tt}	21.6	92.8	3.9	2	1.1	0.2
	Unconverted rest, high p_{Tt}	2.7	65.4	16.1	10.8	6.1	1.8
	Converted central, low p_{Tt}	6.7	92.8	4.0	1.9	1.0	0.2
	Converted central, high p_{Tt}	1.0	66.6	15.3	10	5.7	2.5
	Converted rest, low p_{Tt}	21.0	92.8	3.8	2.0	1.1	0.2
	Converted rest, high p_{Tt}	2.7	65.3	16.0	11.0	5.9	1.8
	Converted transition	9.5	89.4	5.2	3.3	1.7	0.3
	2-jets	2.2	22.5	76.7	0.4	0.2	0.1
8 TeV	Inclusive	111.6	88.5	7.4	2.7	1.6	0.5
	Unconverted central, low p_{Tt}	14.4	92.9	4.2	1.7	1.0	0.2
	Unconverted central, high p_{Tt}	2.5	72.5	14.1	6.9	4.2	2.3
	Unconverted rest, low p_{Tt}	31.4	92.5	4.1	2.0	1.1	0.2
	Unconverted rest, high p_{Tt}	5.3	72.1	13.8	7.8	4.6	1.7
	Converted central, low p_{Tt}	9.1	92.8	4.3	1.7	1.0	0.3
	Converted central, high p_{Tt}	1.6	72.7	13.7	7.1	4.1	2.3
	Converted rest, low p_{Tt}	27.3	92.5	4.2	2.0	1.1	0.2
	Converted rest, high p_{Tt}	4.6	70.8	14.4	8.3	4.7	1.7
	Converted transition	13.0	88.8	6.0	3.1	1.8	0.4
	2-jets	2.9	30.4	68.4	0.4	0.2	0.2

$Z \rightarrow ee$ lineshape e confronto con la simulazione



Performance muoni: Isolamento Risoluzione



H4l: valutazione del fondo "riducibile": Z+jets, ttbar

Logica:

campione "background-enriched" su dati
MC per estrapolare a regione di segnale

(1) $ll+\mu\mu$: dominano Zbb e ttbar

→ per la coppia di muoni sub-leading:

NO richiesta isolamento

1 μ NO puntamento al vertice

Spettro M12 discriminante tra le due
componenti

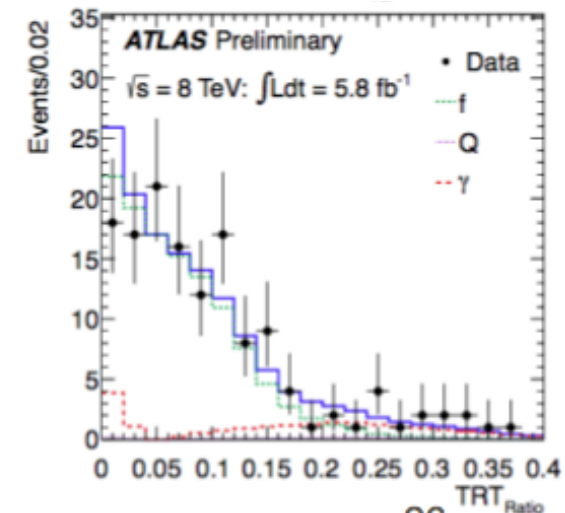
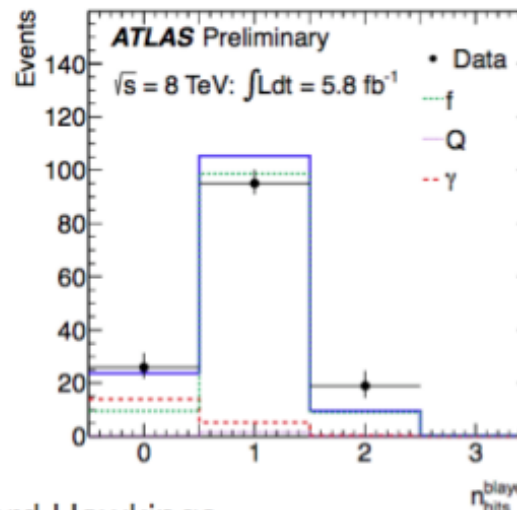
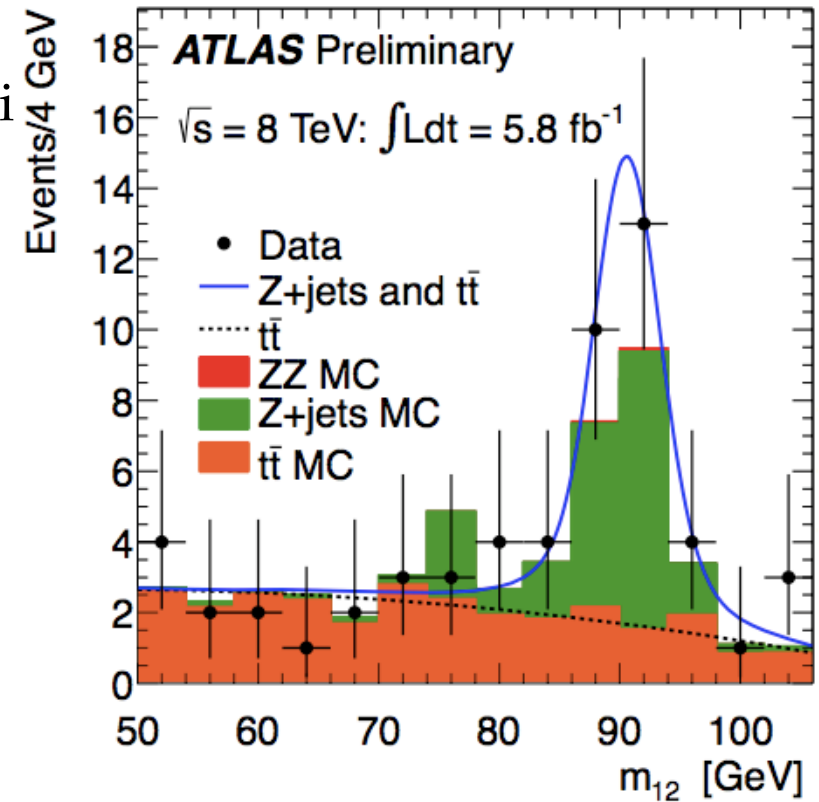
(2) $ll+ee$: domina Z+jets "γ fake e"

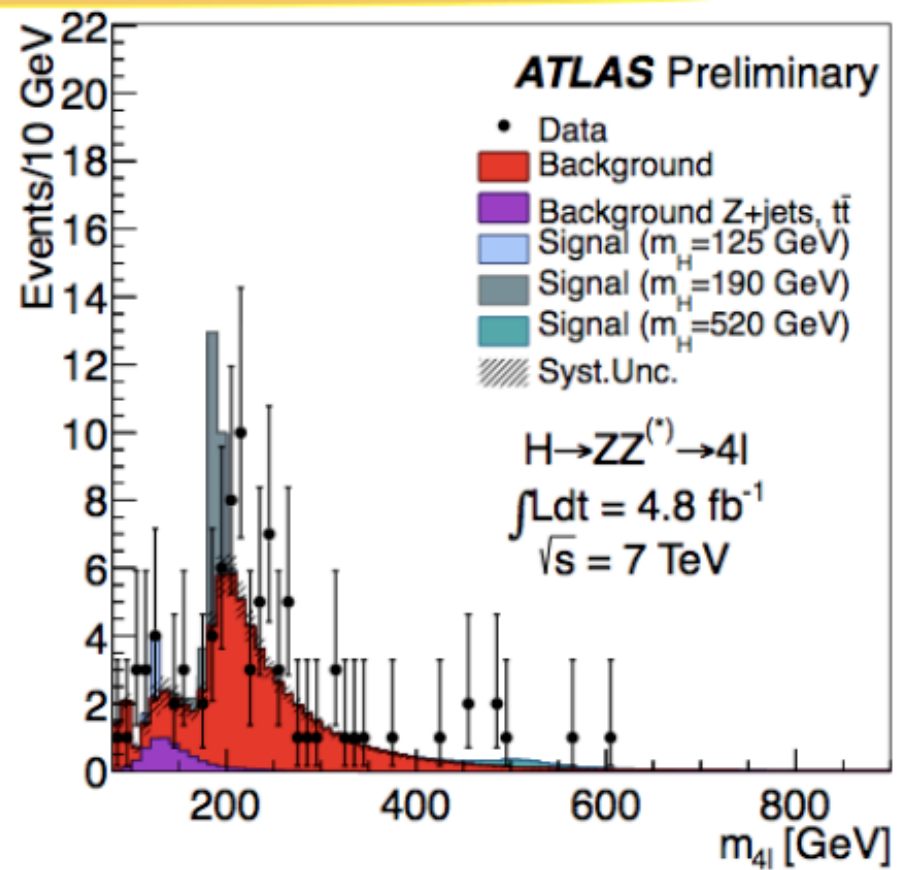
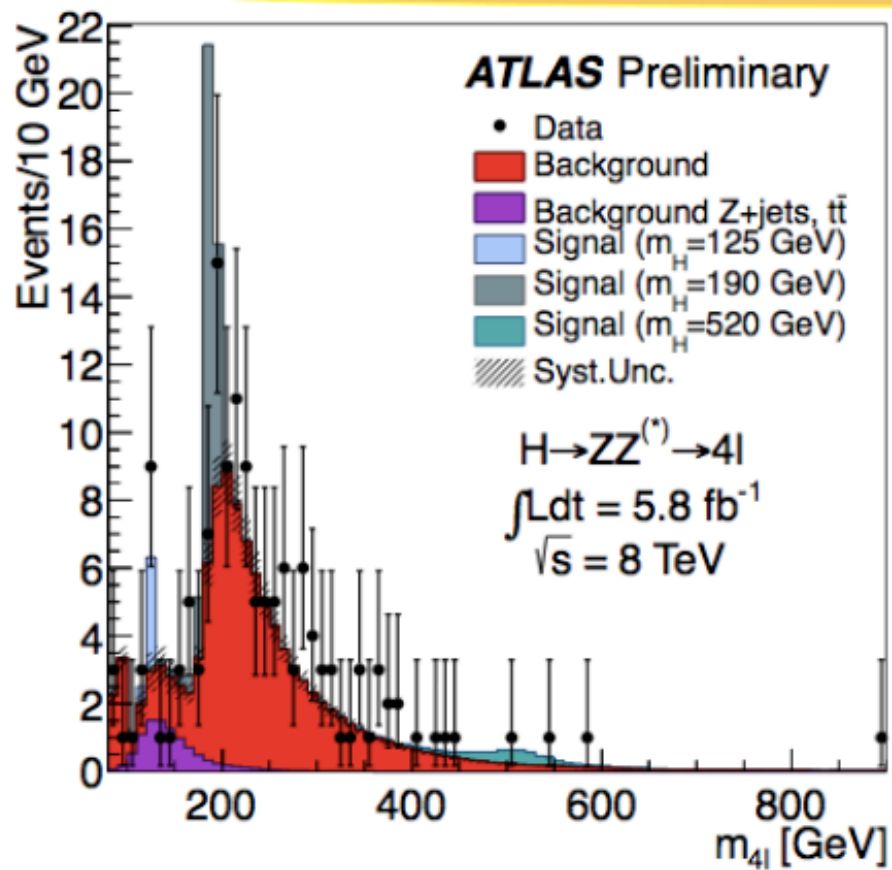
→ per la coppia di elettroni sub-leading:

NO B-layer hits

Alto TRT-ratio

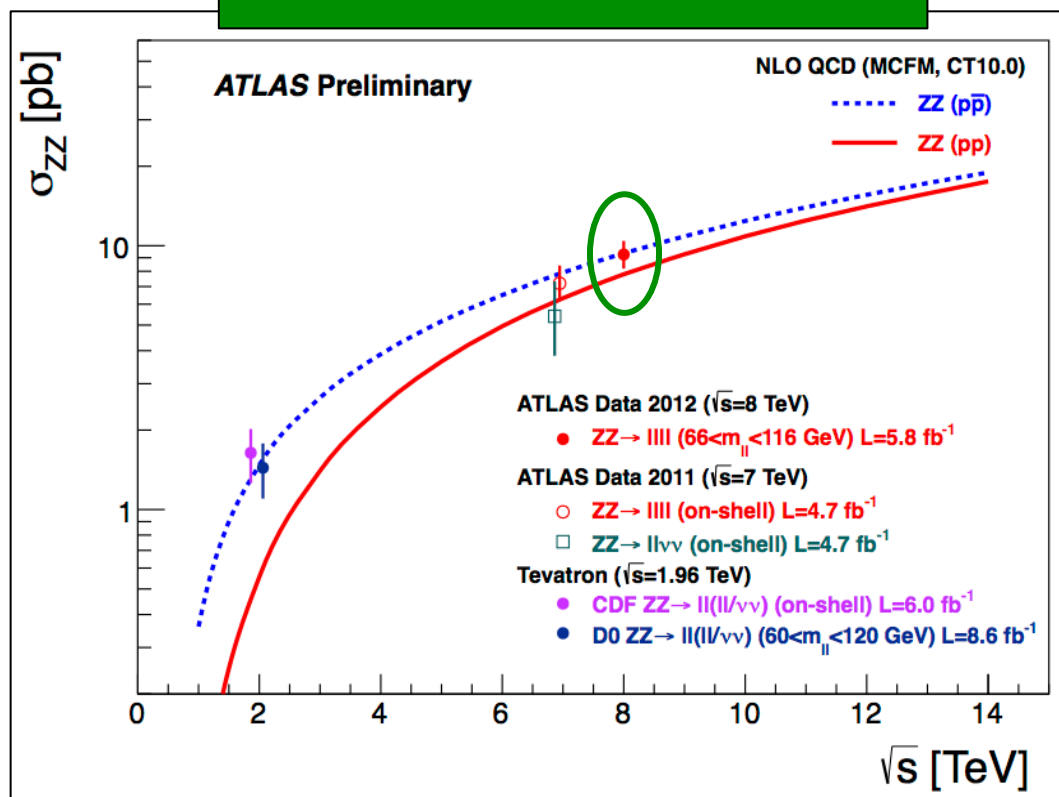
Controllo con selezione
"same-sign"





Misura della sezione d'urto $pp \rightarrow ZZ$ a 7 TeV e 8 TeV:
 Nel canale $ZZ \rightarrow 4l$ $\sigma(ZZ) > \sigma_{SM}(ZZ)$

Measured $\sigma(ZZ) = 9.3 \pm 1.2$ pb
 SM (NLO) $\sigma(ZZ) = 7.4 \pm 0.4$ pb

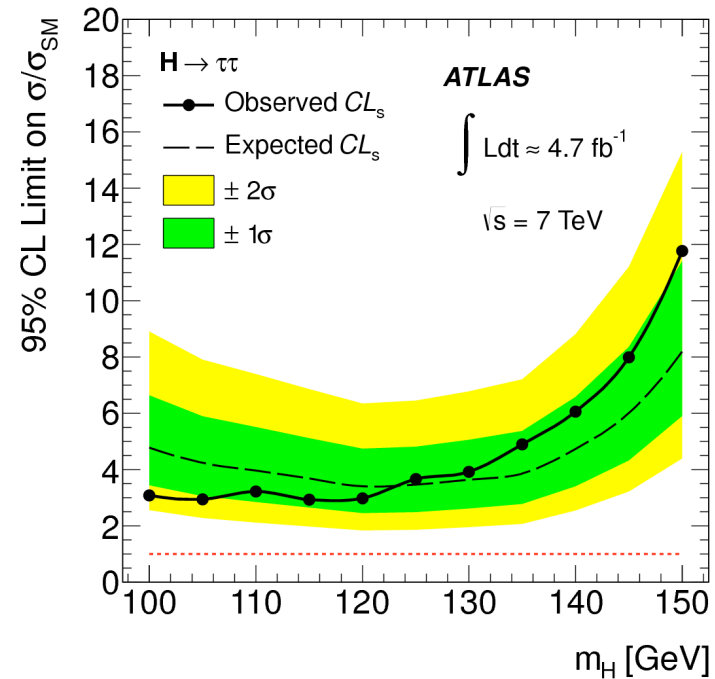
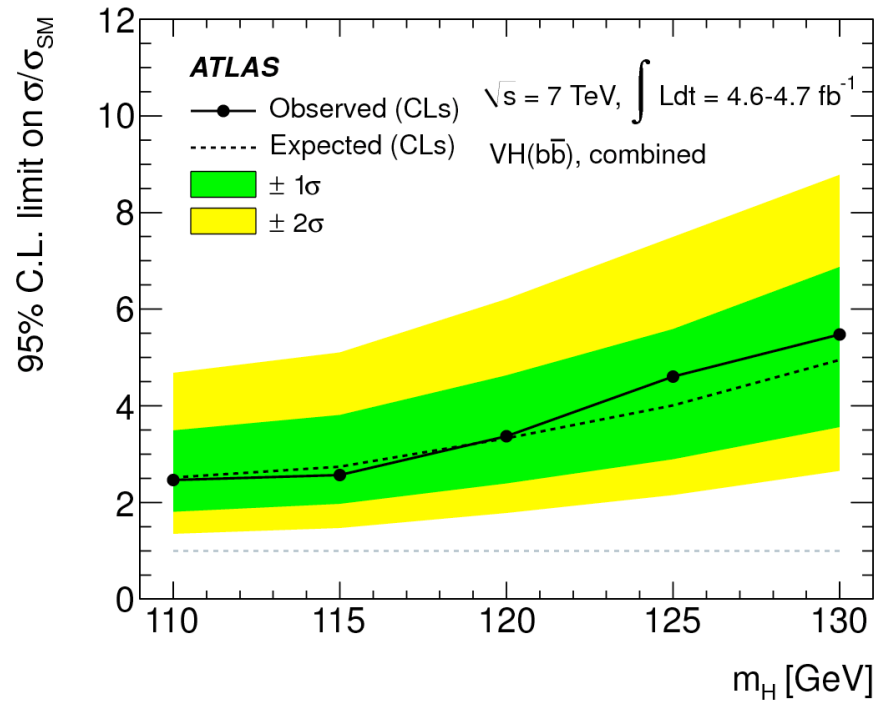
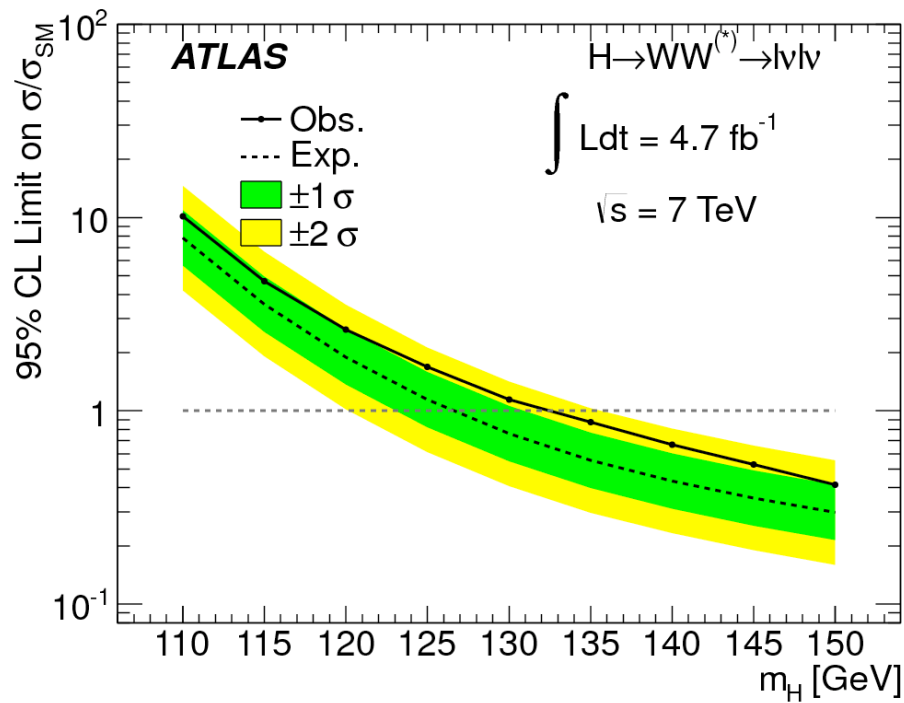


Limiti pubblicati (dati 2011)

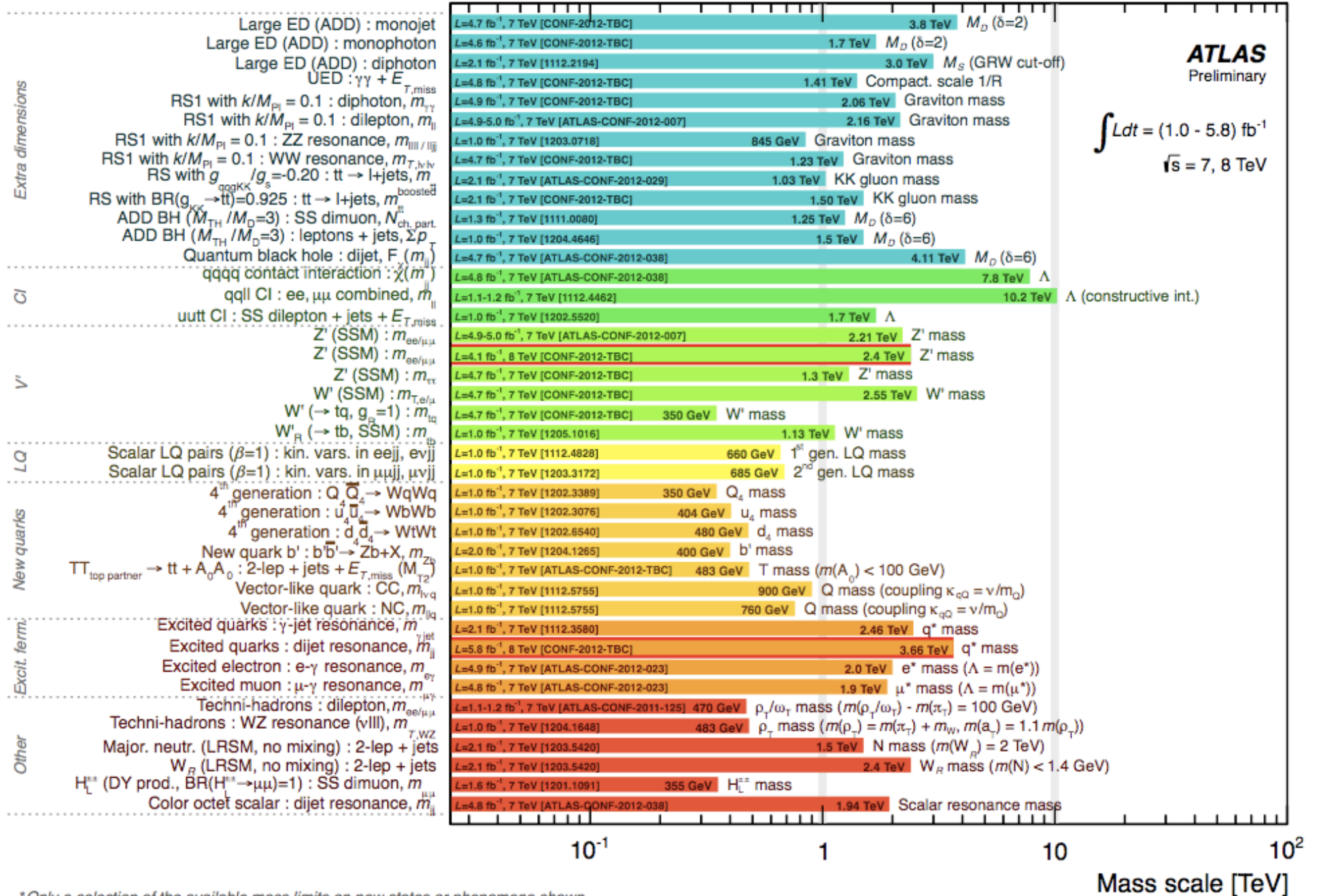
$$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$$

$$VH \rightarrow b\bar{b}$$

$$H \rightarrow \tau\tau$$

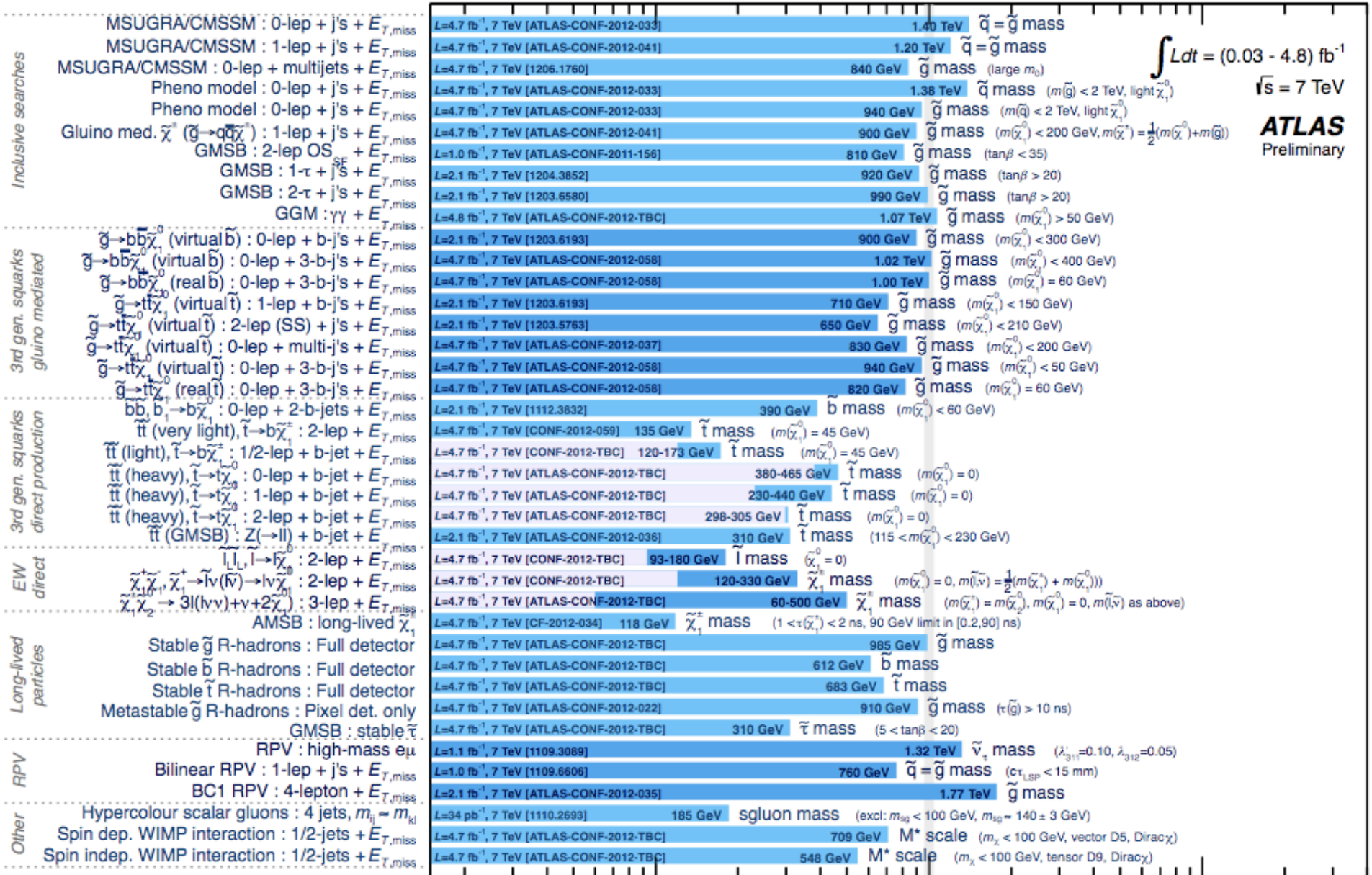


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: ICHEP 2012)



*Only a selection of the available mass limits on new states or phenomena shown

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: ICHEP 2012)



*Only a selection of the available mass limits on new states or phenomena shown

Mass scale [TeV]

- 3 neutral Higgs bosons Φ in MSSM: h , H and A
 - Production via gluon fusion and b -quark annihilation
 - Cross-sections rise with $\tan\beta$, b -assoc. becomes dominant
 - Decay into b - \bar{b} (90%), $\tau\tau$ (10%), $\mu\mu$ (0.04%)
- Search in both b -tagged and b -vetoed samples
 - $\mu\mu$: clean signature, good mass resolution, but low rates
 - $\tau\tau$: Similar to SM $H \rightarrow \tau\tau$ but with b -tagged/vetoed sel
 - Set limits in $(m_A, \tan\beta)$ plane and generically on $\sigma \cdot \text{BR}$

