Misura della massa del bosone di Higgs con dati da collisioni *pp* collezionati dall'esperimento ATLAS nel Run 1 e Run 2 di presa dati

IFAE 2024

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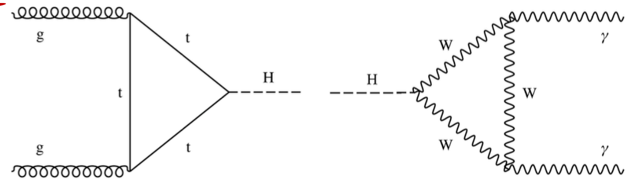
3-5 Aprile 2024

Le motivazioni dietro alla misura della massa del bosone di Higgs

La **massa del bosone di Higgs** m_H è un parametro fondamentale e libero del Modello Standard:

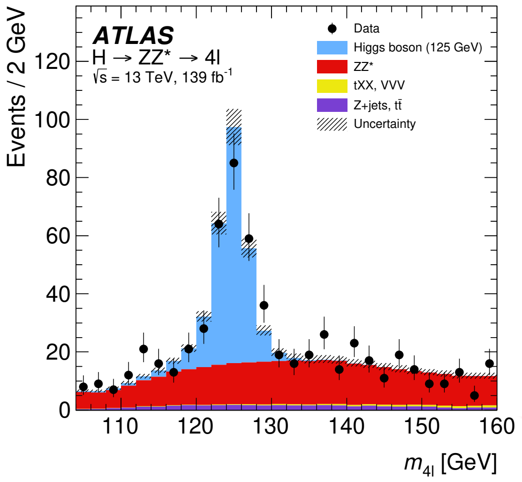
- Le *sezioni d'urto di produzione* σ e i *rapporti di ramificazione (decay branching ratios)* del bosone di Higgs, cioè gli **accoppiamenti** dell'Higgs con tutte le altre particelle, sono stabiliti solo quando m_H è fissato
- m_H ha un ruolo chiave nei **fit globali EW** e nella **stabilità del vuoto EW**

Esempi di diagrammi produzione o decadimento:

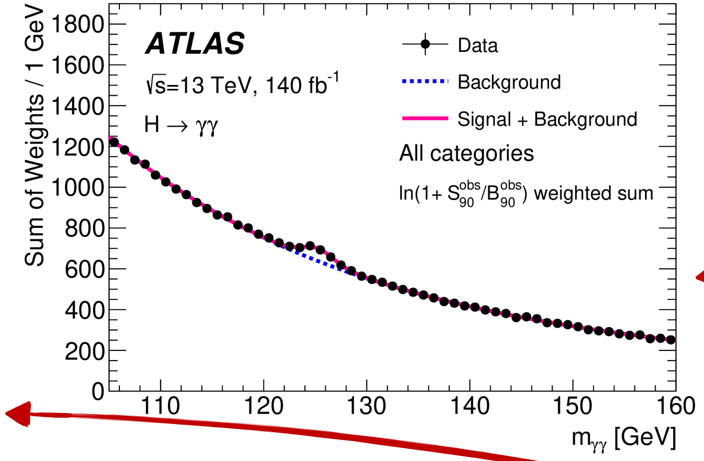


⇒ serve una **misura sperimentale** di m_H!

Phys. Lett. B 843 (2023) 137880



Phys. Lett. B (2023) arXiv:2308.07216



Le precedenti misure di ATLAS e CMS nei canali $H \to \gamma\gamma$ e $H \to ZZ^* \to 4l$:

- **Ricostruzione cinematica completa** dello stato finale
- **Migliore risoluzione in massa invariante** sul segnale

Misure di m_H:

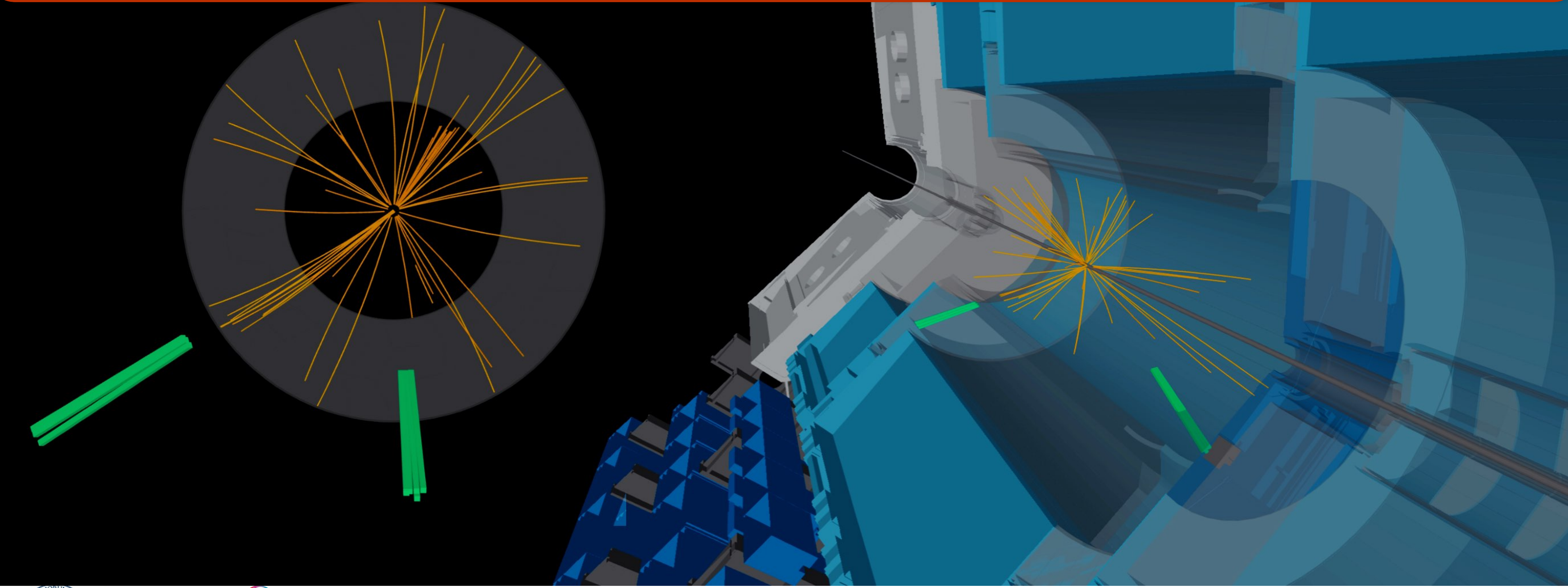
Esperimento	Canale	Anno	Precisione
ATLAS Run1	$H \to \gamma\gamma$	2012	0.4%
ATLAS + CMS Run1	$\gamma\gamma + 4l$	2015	0.19%
ATLAS Run1+Run2	$H \to 4l$	2022	0.14%
ATLAS Run2 / ATLAS Run1+Run2	$H \to \gamma\gamma$ / $\gamma\gamma + 4l$	2023	?% ($\gamma\gamma$), ?% ($\gamma\gamma$+$4l$)

Precisione delle misure di m_H:

ATLAS Run2 $H \to \gamma\gamma$ — ATLAS Run1+Run2 $\gamma\gamma + 4l$: Analisi presentate oggi!

UNIVERSITÀ DEGLI STUDI DI MILANO — ATLAS EXPERIMENT

Misura della massa del bosone di Higgs in decadimenti $H \to \gamma\gamma$ con 140 fb^{-1} da collisioni *pp* a $\sqrt{s} = 13$ TeV con l'esperimento ATLAS

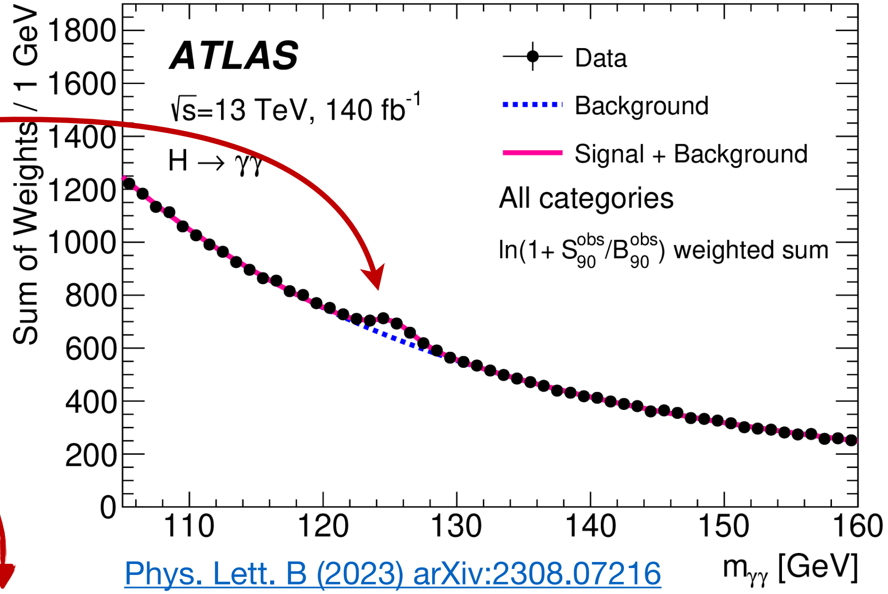


$H \rightarrow \gamma\gamma$ Run 2: la strategia dell'analisi

- **Dati**: dataset completo **Run 2** (2015-2018) collezionato da ATLAS a $\sqrt{s}$ = **13 TeV** per una luminosità totale integrata di **L = 140 fb^{-1}**
- **Obiettivo**: misurare m_H dalla posizione del segnale risonante

- **Selezione degli eventi** per ridurre il bkg γ-jet e di-jet cercando due fotoni di buona qualità (identificazione *tight,* isolati)

1) **Categorizzazione** degli eventi ottimizzata per ridurre l'incertezza totale sperimentale su m_H
2) Modello analitico del **segnale** $\propto m_H$, $\forall$ categoria
3) Modello analitico del **background** $\forall$ categoria
4) Incertezze **sistematiche** sperimentali (PES)
5) Incertezze sistematiche secondarie e dei modelli
6) **Modello statistico**, risultati attesi e osservati
   - Fit simultaneo di massima verosimiglianza su tutte le categorie sui dati
   - Valore di m_H ed errori dallo scan della *likelihood*
7) **Combinazione in $H \rightarrow \gamma\gamma$** Run1 + Run2

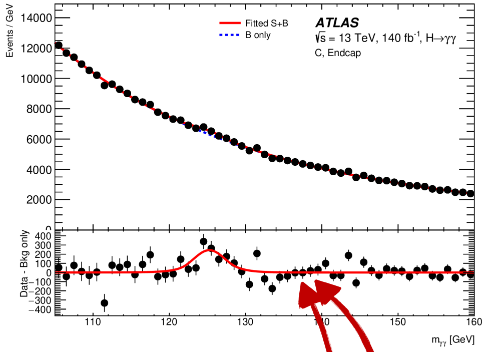


Phys. Lett. B (2023) arXiv:2308.07216

Selezione degli eventi	
Triggers per 2 fotoni	2015-2016: HLT_g35_loose_g25_loose + HLT_g120_loose 2017-2018: HLT_g35_medium_g25_medium + HLT_g140_loose
Preselezione dei fotoni	Loose ID, p_T > 25 GeV, $\lvert\eta\rvert$ < 2.37 evitando la regione del crack
Vertice a 2 fotoni da Rete Neurale	Migliora l'efficienza di classificazione dei vertici e della risoluzione in $m_{\gamma\gamma}$ fino all' 8%
Selezione finale sui γ	Tight ID, isolamento FixedCutLoose, $p_T^{\gamma}/m_{\gamma\gamma}$ >0.25(0.35), $m_{\gamma\gamma}$ in [105,160] GeV

1) $H \rightarrow \gamma\gamma$ Run 2: categorizzazione

[Phys. Lett. B (2023) arXiv:2308.07216]

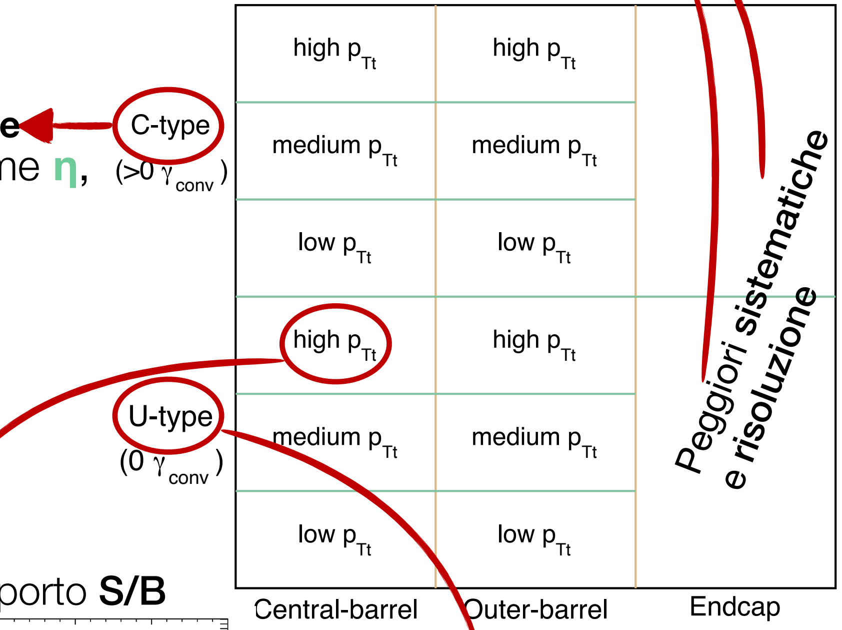


Obiettivo: dividere gli eventi in categorie mutualmente esclusive ottimizzate a **ridurre l'incertezza totale** su m_H

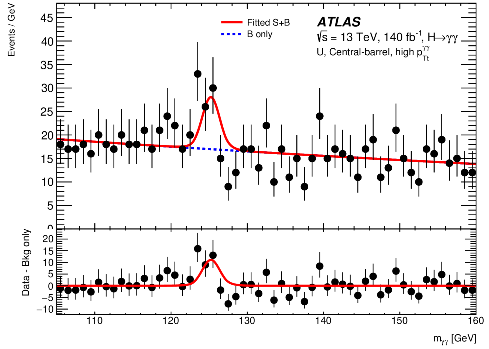
- Categorie con diversa **risoluzione su $m_{\gamma\gamma}$**, **sistematiche PES** e rapporto **S/B**
- Molte categorizzazioni testate, comparando modello S+B completo

Categorizzazione finale: **14** categorie basate sulle **variabili cinematiche** dei γ come **η**, **p_{Tt}** and stato di conversione

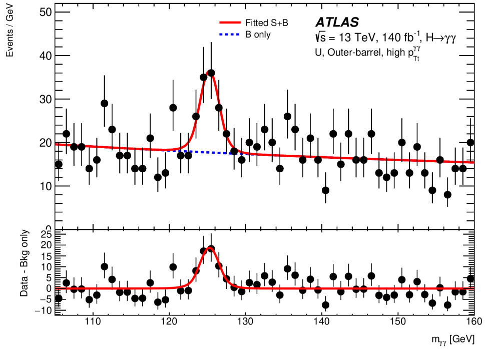
- Stato di conversione: 0 (tipo-U) or ≥ 1 (tipo-C) γ convertiti
- Pseudorapidità |η|: - Barrel centrale (entrambi γ |η| < 0.8)
  - Barrel esteso (≥ **1** γ in 0.8 < |η| < 1.37 & non nell'Endcap)
  - Endcap (≥ **1** γ in 1.52 < |η| < 2.37)
- p_{Tt}: Alto/Medio/Basso (limiti usati 70 e 130 GeV)



Buon rapporto **S/B**



Migliore **risoluzione**



Guadagno sull'incertezza totale su m_H dalla categorizzazione:

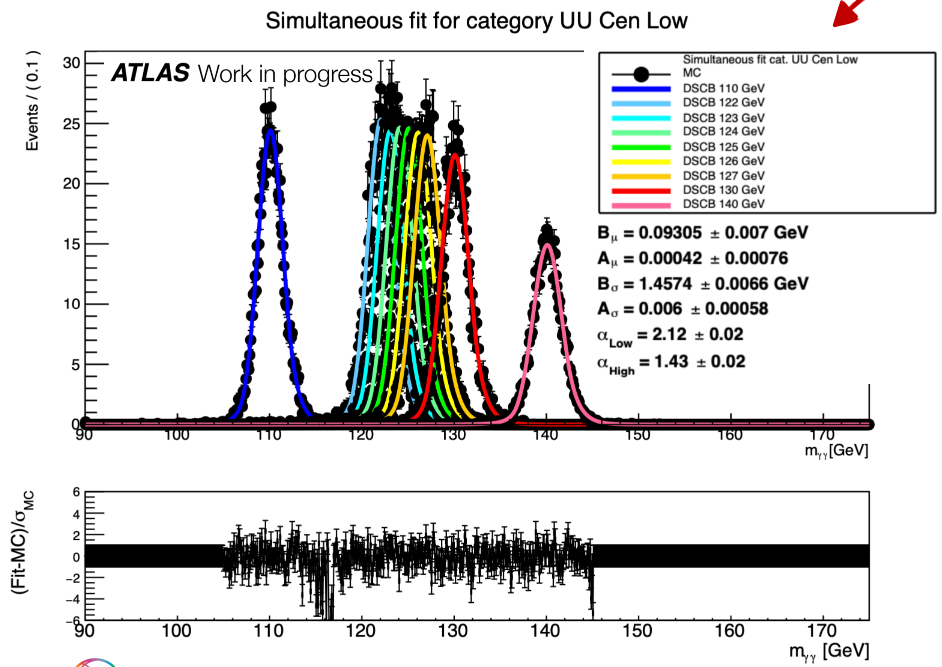
- -17% comparato alla misura inclusiva (1 categoria)
- -6% comparato con l'[analisi parziale Run 2] @36 fb^{-1} (31 categorie

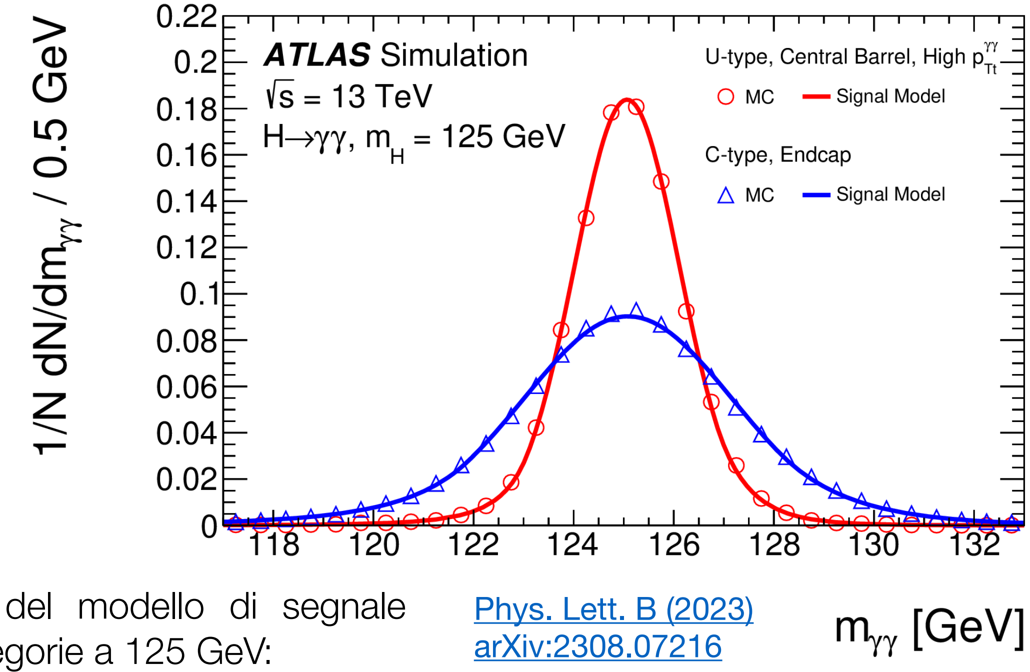
2) $H \to \gamma\gamma$ Run 2: modello di segnale $\propto m_H$

- Con **campioni simulati Monte Carlo di segnale** a 9 diversi valori di m_H tra 110 e 140 GeV
- La distribuzione $m_{\gamma\gamma}$ del segnale risonante è modellizzata con una funzione **Double-Sided Crystall Ball** (DSCB): picco gaussiano (μ_{CB}, σ_{CB}) e code descritte con leggi a potenza
- Per ottenere la dipendenza della forma di segnale da m_H, i parametri della DSCB sono parametrizzati con una funzione in m_H $\forall$ categoria: fit simultaneo sui 9 campioni MC per ottenere i valori dei parametri

$$\mu_{CB}(m_H) = m_H + B_{\mu_{CB}} + A_{\mu_{CB}}(m_H - 125\ \mathrm{GeV})$$
$$\sigma_{CB}(m_H) = B_{\sigma_{CB}} + A_{\sigma_{CB}}(m_H - 125\ \mathrm{GeV})$$
$$\alpha_{Low}(m_H) = \alpha_{Low} \qquad \alpha_{High}(m_H) = \alpha_{High}$$
$$n_{Low}(m_H) = n_{Low}|_{125\mathrm{GeV}} \qquad n_{High}(m_H) = n_{High}|_{125\mathrm{GeV}}$$

Esempio di fit simultaneo per 1 categoria:





Esempio del modello di segnale per 2 categorie a 125 GeV:

[Phys. Lett. B (2023)](arXiv:2308.07216)
arXiv:2308.07216

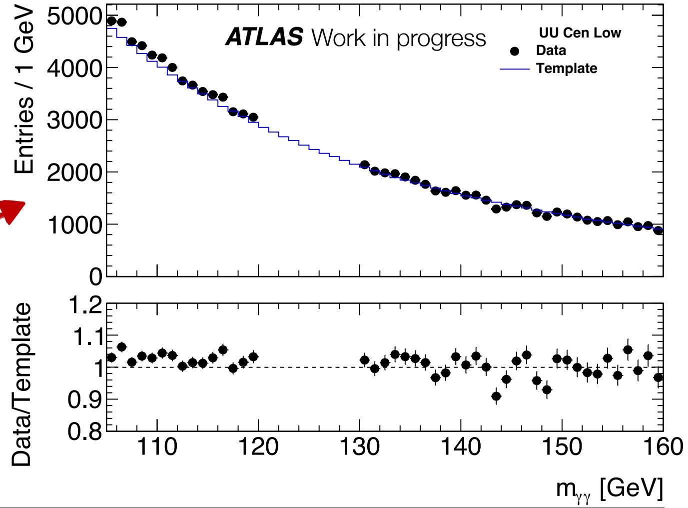
3) $H \rightarrow \gamma\gamma$ Run 2: modello di background

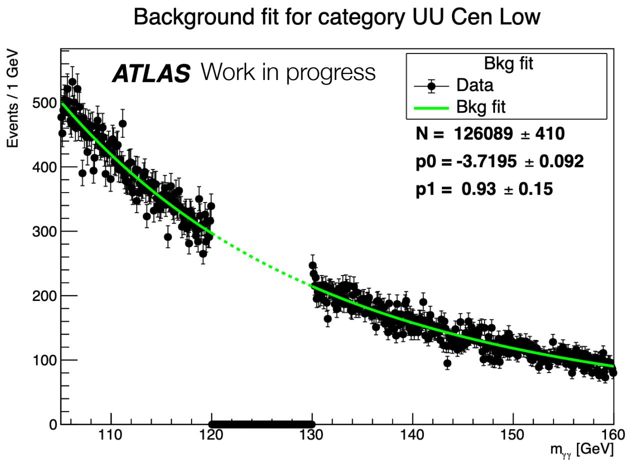
Il bkg $\gamma\gamma$ QCD non-risonante, $\gamma\gamma$ **irriducibile** ($\sim 80\,\%$) + γ-jet + di-jet **riducibile** ($\leq 20\,\%$), è modellizzato con funzioni analitiche ∀ categoria ed è quasi **completamente basato sui dati**

- La misura della massa **non** è molto sensibile al modello di bkg

Strategia ∀ categoria:

1. Misurare le frazioni dei bkg $\gamma\gamma$, γj e jj con un metodo ABCD
2. Costruire dei templates di solo background partendo da un campione $\gamma\gamma$, ripesando la distribuzione di $m_{\gamma\gamma}$ con le frazioni di γj and jj
3. Eseguire il test dello **Spurious Signal** per determinare la **funzione analitica + sistematica**: test di un set di funzioni analitiche (exp, leggi a potenza), scegliendo la funzione che minimizza il bias sul template di solo bkg col minimo numero of g.d.l.
4. **Parametri e normalizzazione** fittati sulle bande laterali dei dati in $m_{\gamma\gamma}$ ϵ [105, 160] GeV, escludendo la regione $m_{\gamma\gamma}$ ϵ [120, 130] GeV.



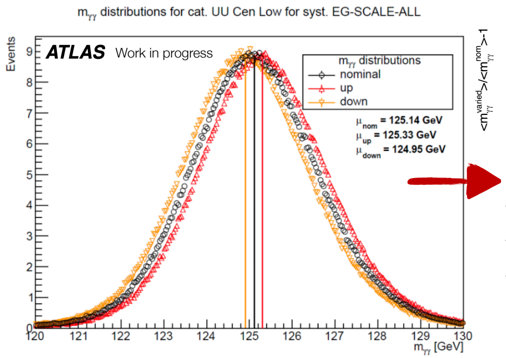


Category	m_H	n_S	Function	$p(\chi^2)$ %
UU Cen High	127.0	0.235	Exponential	27.1
UU Cen Med	123.0	5.31	Exponential	20.8
UU Cen Low	123.0	25	ExpPoly2	81.8
UU OutBarrel High	125.5	0.766	Pow	4.13
UU OutBarrel Med	126.0	4.92	ExpPoly2	53.1
UU OutBarrel Low	123.5	34.9	ExpPoly2	26.4
UU EndCap	123.0	63	ExpPoly2	15.6
Conv Cen High	126.5	-0.529	Pow	21.3
Conv Cen Med	123.5	6.99	Exponential	8.27
Conv Cen Low	124.5	21.2	ExpPoly2	40.5
Conv OutBarrel High	126.5	2.35	Exponential	12.8
Conv OutBarrel Med	126.5	6.97	ExpPoly2	69.1
Conv OutBarrel Low	125.5	28.7	ExpPoly2	59.4
Conv EndCap	126.5	137	ExpPoly2	1.53

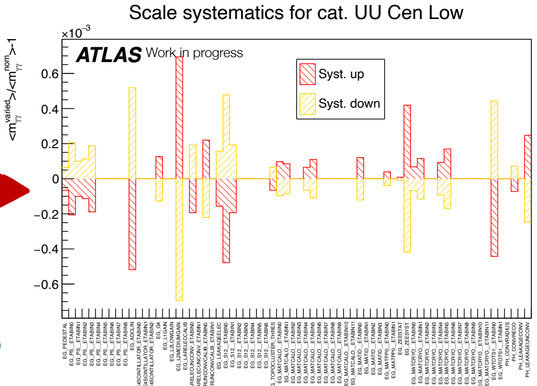
4) $H \to \gamma\gamma$ Run 2: incertezze sperimentali sistematiche principali, PES

Le principali incertezze sperimentali sistematiche sono le scale di energia dei fotoni (**PES**) che influenzano μ_{CB}, ∀ categoria:

- Beneficiano dalle **eccellenti raccomandazioni di calibrazione EGamma**
- **Procedura**: campioni MC ausiliari dove le variazioni sistematiche ($\pm 1\sigma$) sono applicate a monte e il loro effetto è propagato alla distribuzione di $m_{\gamma\gamma}$
- PES: 67 impatti valutati come variazione della media della distribuzione di $m_{\gamma\gamma}$



∀ impact



∀ category

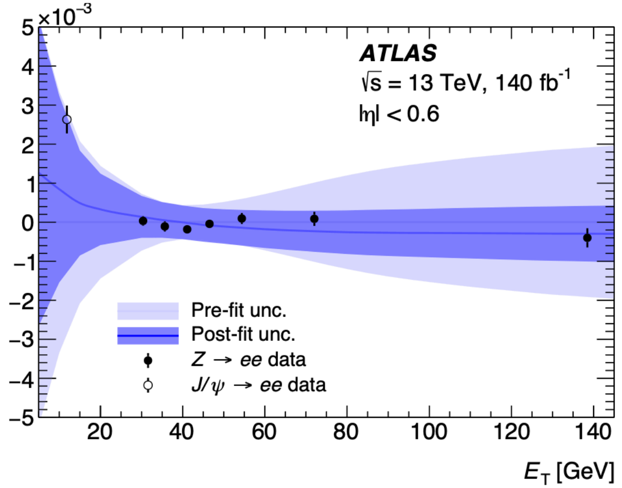
Riduzione ulteriore per le PES proviene dal **fit della linearità EGamma**:

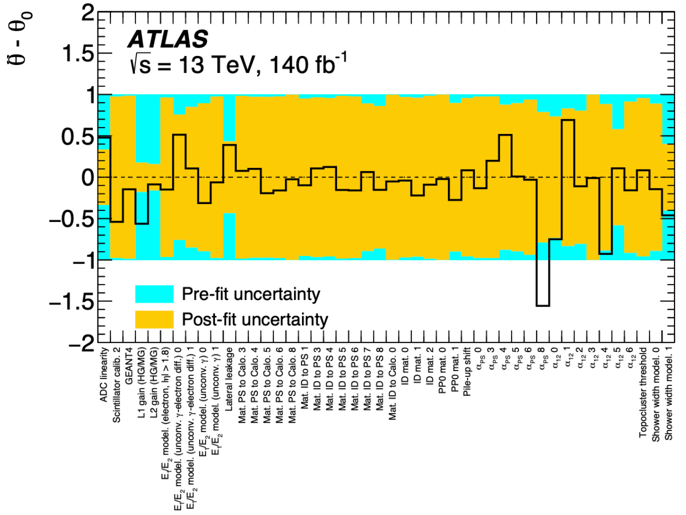
- Misura delle scale di energia residue con dipendenza dal p_T α' come funzione delle PES nominali (p_T-dipendenti) da eventi $Z \to ee$ in (p_T, η) bins

$$E_{\text{dati}} = E_{\text{MC}}[1 + \alpha(\eta)(1 + \alpha'(|\eta|, p_T))]$$

$$\alpha' \propto \sum_{k}^{N_{sys}} \theta_k$$

- Le nuove sistematiche sono ottenute da un fit della parametrizzazione delle scale sulle scale residue misurate
- L'output del fit consiste in incertezze sistematiche constrette e correlate





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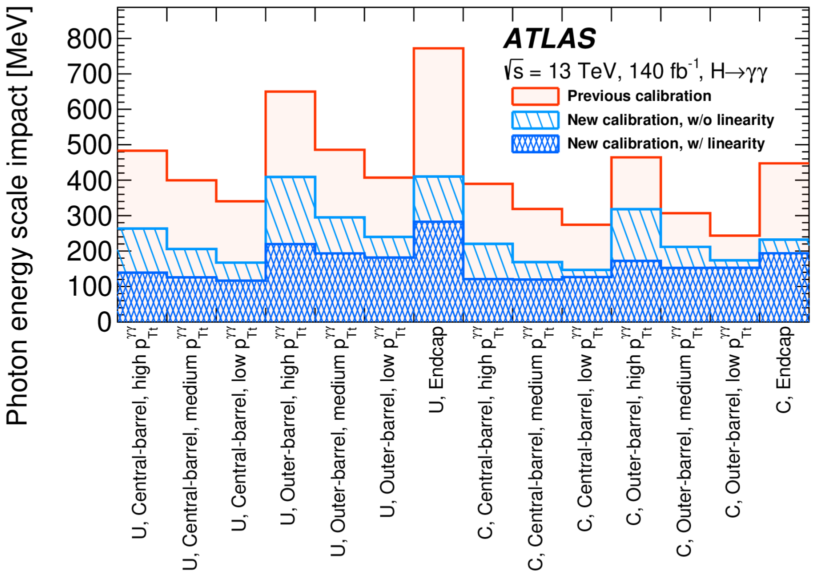
4) $H \rightarrow \gamma\gamma$ Run 2: incertezze sperimentali sistematiche principali, PES

L'informazione dal **fit della linearità EGamma** è propagata all'analisi della massa in $\gamma\gamma$:

- Applicando le scale di energia residue p_T-dipendenti per ogni fotone sui **dati** per ottenere i nuovi valori di $m_{\gamma\gamma}$
- Modificando i vincoli sui NPs nella funzione di **likelihood**, usando una Gaussiana multidimensionale con la matrice di covarianza del fit della linearità, al posto di tanti vincoli gaussiani 1D indipendenti

$$\prod_j G(0|\theta_j,1) \rightarrow G(0|\vec{\theta}, \sum n_{NP} x n_{NP})$$

La **riduzione finale delle incertezze sistematiche PES** è vicina a un **fattore 4** rispetto alle precedenti nell'analisi parziale Run 2 @ 36 fb^{-1}!



Phys. Lett. B (2023) arXiv:2308.07216

5) Incertezze sistematiche secondarie: altre $\sim 10^2$ incertezze sono incluse nel modello, slide 27 in backup

6) $H \to \gamma\gamma$ Run 2: risultati attesi e **osservati** 📊

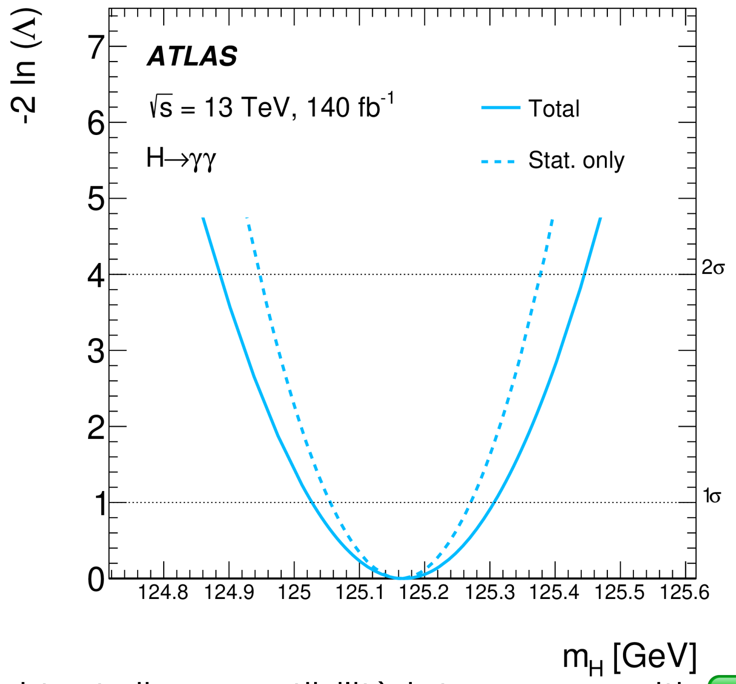
Il fit è eseguito simultaneamente sulle 14 categorie dell'analisi con **14 signal strengths** μs, uno per categoria

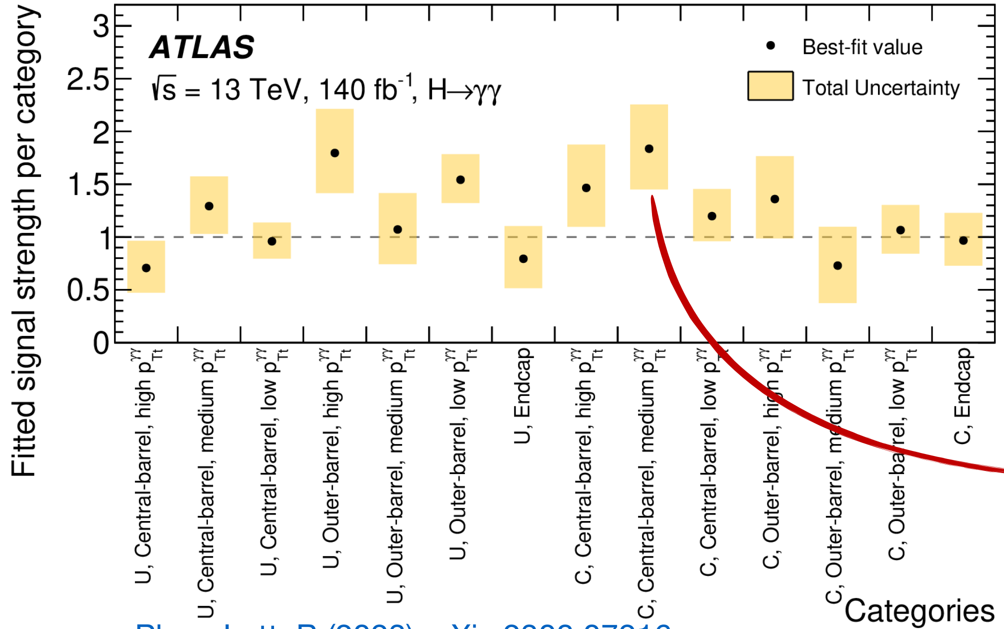
Risultato atteso per m_H: $m^{\text{Expected}}_{H\to\gamma\gamma,\text{Run2}} = 125.00 \pm 0.15$ GeV $= 125.00 \pm 0.12$ (stat.) ± 0.09 (syst.) GeV

Risultato osservato m_H dal rapporto di verosimiglianza (profile likelihood ratio):

$$m^{\text{Observed}}_{H\to\gamma\gamma,\text{Run2}} = 125.17 \pm 0.14 \text{ GeV} = 125.17 \pm 0.11 \text{ (stat.)} \pm 0.09 \text{ (syst.) GeV}$$

Precisione 0.11%! 🥳





All'uscita, era la misura più precisa of m_H da un singolo canale!

Massima "tensione" di $\sim 2.2\sigma$ in $\mu_{\text{ConvCenMed}}$

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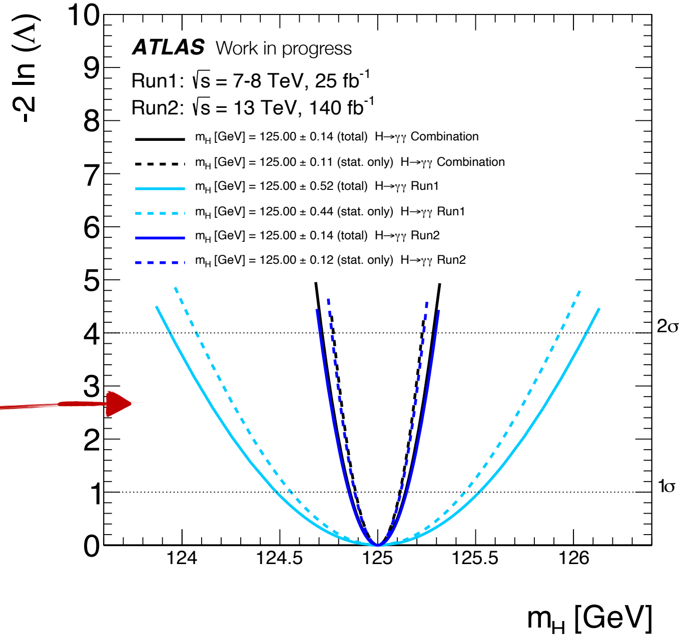
Tantissimi test di compatibilità interna eseguiti ✅ (backup slide 33)

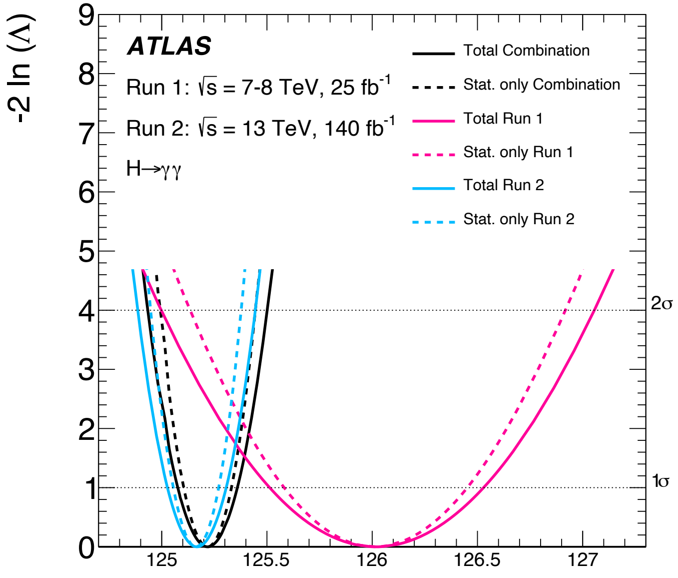
7) Combinazione H → $\gamma\gamma$ Run1+Run2

- H→γγ Run1: riprodotti risultati **attesi** (template) e **osservati** (dati Run1) usati nella combinazione Run1 di ATLAS e CMS. I risultati sono ottenuti fittando m_H e due signal strengths, uno per l'accoppiamento ai fermioni e uno ai bosoni vettori: μ_F and μ_V
- **Combinazione**: basata sul rapporto di verosimiglianza (profile likelihood ratio) definito in termini di m_H.
  - Gli spettri di massa invariante $m_{\gamma\gamma}$ dei due Runs sono fittati con una massa comune m_H combinando le funzioni di verosimiglianza individuali
  - Lo schema di correlazione è incluso nel modello
  - Le incertezze totali e statistiche sono ottenute dallo scan di likelihood



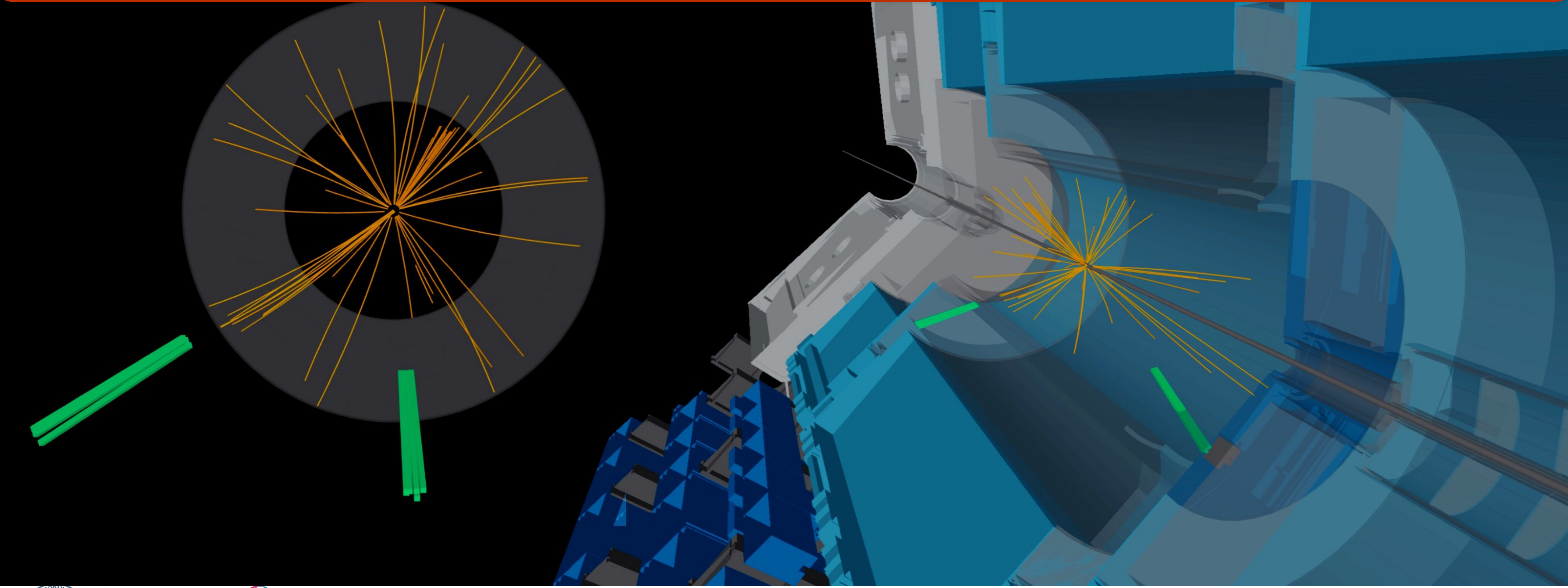
	Template				Dati			
		Incertezza [GeV]				Incertezza [GeV]		
Analisi	m_H	Totale	Stat.	Sist.	m_H	Total	Stat.	Sist.
H→γγ Run1	125.00	0.52	0.44	0.27	126.02	0.51	0.43	0.27
H→γγ Run2	125.00	0.15	0.12	0.09	125.17	0.14	0.11	0.09
H→γγ Run1+Run2	125.00	0.14	0.11	0.09	**125.22**	**0.14**	**0.11**	**0.09**

p-value = 11%



Phys. Lett. B (2023) arXiv:2308.07216

Misura combinata della massa del bosone di Higgs dai canali di decadimento $H \to \gamma\gamma$ e $H \to ZZ^* \to 4l$ con l'esperimento ATLAS usando dati da collisione pp a $\sqrt{s} = 7$, 8 and 13 TeV



$H \to \gamma\gamma$ + $H \to 4l$ Run1-Run2, inputs della combinazione

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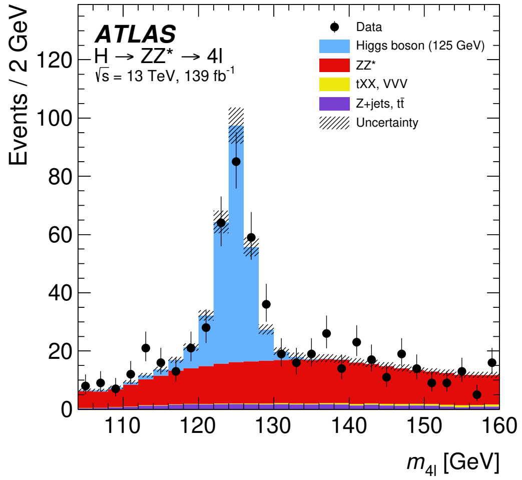
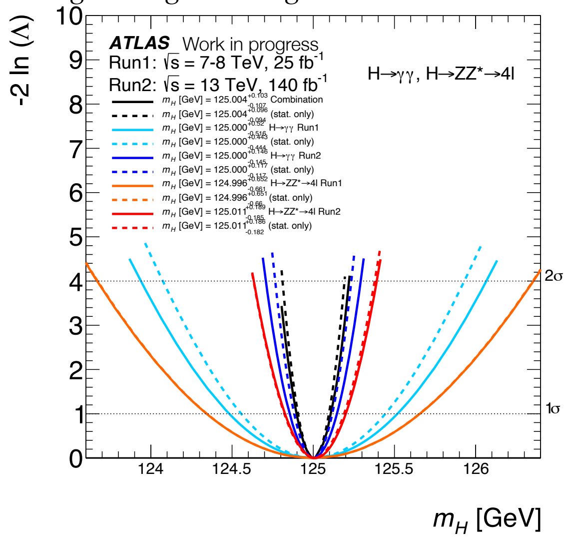
- H→γγ Run1 e H→γγ Run2: slides precedenti
- H→ZZ*→4l:
  - Eventi contenenti almeno 4 leptoni (l = e, μ) isolati provenienti da un vertice comune, che formano due coppie di leptoni con carica opposta ma stesso tipo. Requisiti cinematici
  - 4 canali: $4\mu,\ 2e2\mu,\ 2\mu 2e,\ 4e$
  - Bkg dominante = produzione non-risonante ZZ* ($\sim 90\ \%$ degli eventi di bkg)
  - Separazione tra segnale - background usando una BDT (Run1) o DNN (Run2)
  - Modello segnale + bkg fittato simultaneamente sulle 4 categorie. Dominato dall'incertezza stat.



- H→ZZ*→4l Run1: riprodotti risultati attesi (template) e osservati (dati Run1) usati nella combinazione Run1 di ATLAS e CMS, fittando 1 μ

- H→ZZ*→4l Run2: Resultati fittando 4 signal strengths + 4 normalizzazioni del bkg: $\mu_{sig}^{4\mu}, \mu_{sig}^{2\mu 2e}, \mu_{sig}^{2e2\mu}, \mu_{sig}^{4e}, \mu_{bkg}^{4\mu}, \mu_{bkg}^{2\mu 2e}, \mu_{bkg}^{2e2\mu}, \mu_{bkg}^{4e}$

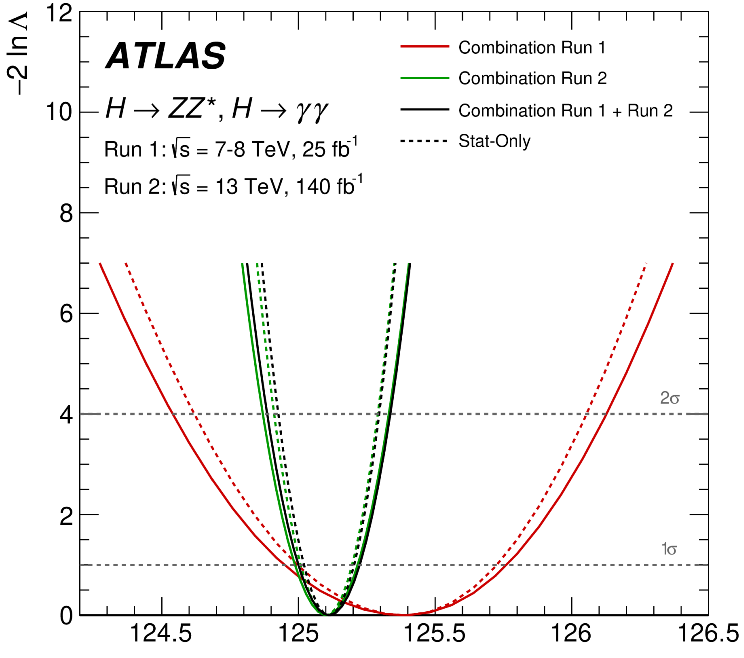
	Template				Dati			
		Incertezza [GeV]				Incertezza [GeV]		
Analisi	m_H	Totale	Stat.	Sist.	m_H	Totale	Stat.	Sist.
H→ZZ*→4l Run1	125.00	0.66	0.66	0.04	124.51	0.53	0.53	0.03
H→ZZ*→4l Run2	125.01	0.19	0.19	0.03	124.99	0.18	0.18	0.03



Combinazione H → $\gamma\gamma$ + H → 4l Run1-Run2 - risultati osservati

	m_H	Incertezza [GeV] Totale	Stat.	Sist.	m_H	Incertezza [GeV] Totale	Stat.	Sist.	m_H	Incertezza [GeV] Totale	Stat.	Sist.
	H→γγ				**H→4l**				**Combinazione: ≠ canale, = Run**			
Run1	126.02	0.51	0.44	0.27	124.51	0.53	0.53	0.03	125.38	0.43	0.39	0.19
Run2	125.17	0.14	0.11	0.09	124.99	0.18	0.18	0.03	**125.10**	**0.11**	**0.09**	**0.07**
Combinazione: = canale, ≠ Run	125.22	0.14	0.11	0.09	124.94	0.18	0.17	0.03	**125.11**	**0.11**	**0.09**	**0.06**

$\gamma\gamma$ Run1+Run2
combinazione di slide 12



Phys. Rev. Lett. arXiv:2308.04775

Combinazione: incertezza totale ~ 110 MeV, **precisione < 1‰**!! 🥳

Conclusioni

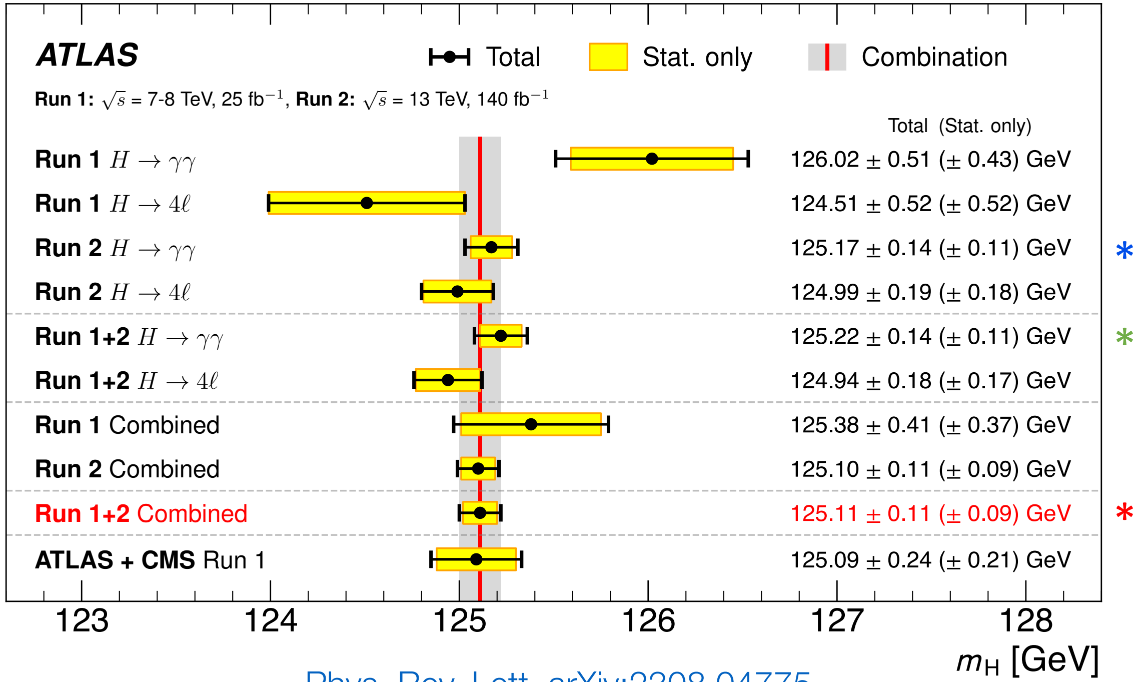
Run2 $\gamma\gamma$ risultati osservati $m^{\text{Observed}}_{H\to\gamma\gamma,\text{Run2}} = 125.17 \pm 0.14\ \text{GeV} = 125.17 \pm 0.11\ (\text{stat.}) \pm 0.09\ (\text{syst.})\ \text{GeV}$ * **precisione 0.11%**

Run1+Run2 $\gamma\gamma$, risultati osservati della combinazione:

$$m^{\text{Observed}}_{H\to\gamma\gamma,\text{Run1+Run2}} = 125.22 \pm 0.14\ \text{GeV} = 125.22 \pm 0.11\ (\text{stat.}) \pm 0.09\ (\text{syst.})\ \text{GeV}$$ *

Run1+Run2 $\gamma\gamma$ + *4l*, risultati osservati della combinazione:

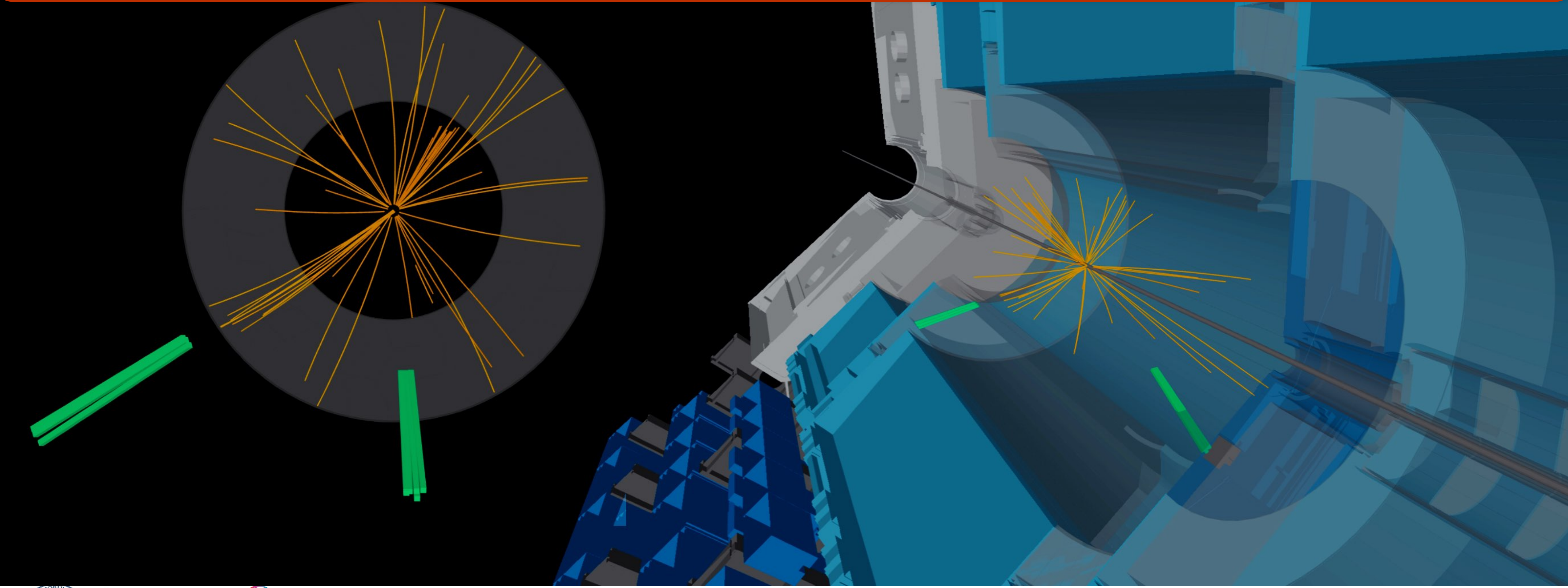
$$m^{\text{Observed}}_{H\to\gamma\gamma+4l,\text{Run1+Run2}} = 125.11 \pm 0.11\ \text{GeV} = 125.11 \pm 0.09\ (\text{stat.}) \pm 0.06\ (\text{syst.})\ \text{GeV}$$ * **precisione 0.09%!**



Misura più precisa ad oggi!

[Phys. Rev. Lett. arXiv:2308.04775]

Backup



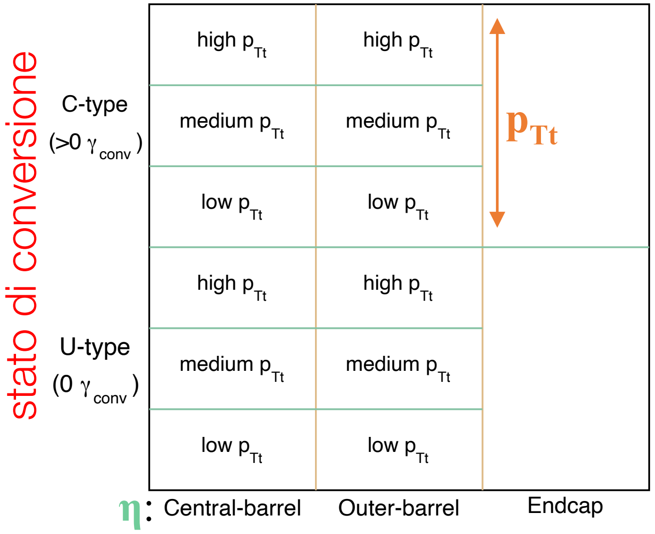
1) $H \rightarrow \gamma\gamma$ Run 2: categorizzazione

Obiettivo: dividere gli eventi in categorie mutualmente esclusive ottimizzate a **ridurre l'incertezza totale** su m_H

- Categorie con diversa **risoluzione su $m_{\gamma\gamma}$, sistematiche PES** e rapporto **S/B**
- Molte categorizzazioni testate, comparando modello S+B completo + incertezze sistematiche PES

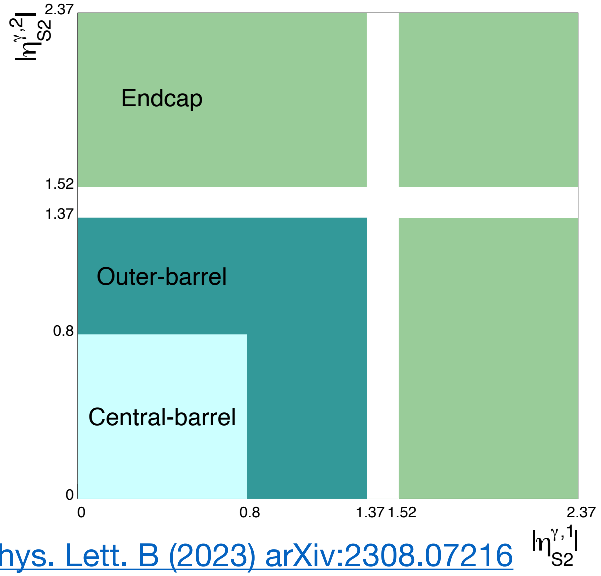
Categorizzazione finale: **14** categorie badate sulle **variabili cinematiche** dei γ come **η**, **p_{Tt}** and stato di conversione

- Stato di conversione: 0 (tipo-U) or ≥ 1 (tipo-C) γ convertiti
- Pseudorapidità |η|: - Barrel centrale (entrambi γ |η| < 0.8)
  - Barrel esteso (≥ 1 γ in 0.8 < |η| < 1.37 & non nell'Endcap)
  - Endcap (≥ 1 γ in 1.52 < |η| < 2.37)
- **p_{Tt}**: Alto/Medio/Basso (limiti usati 70 e 130 GeV)



Guadagno sull'incertezza totale su m_H dalla categorizzazione:

- -17% comparato alla misura inclusiva (1 categoria)
- -6% comparato con l'analisi parziale Run 2 @36 fb^{-1} (31 categorie)



Phys. Lett. B (2023) arXiv:2308.07216

The Standard Model Higgs boson

- The Standard Model (SM) of particle physics is a quantum field theory:
  - classify all the known elementary particles
  - describe strong and electroweak interactions: $SU(2)_L \times U(1)_Y \times SU(3)_C$

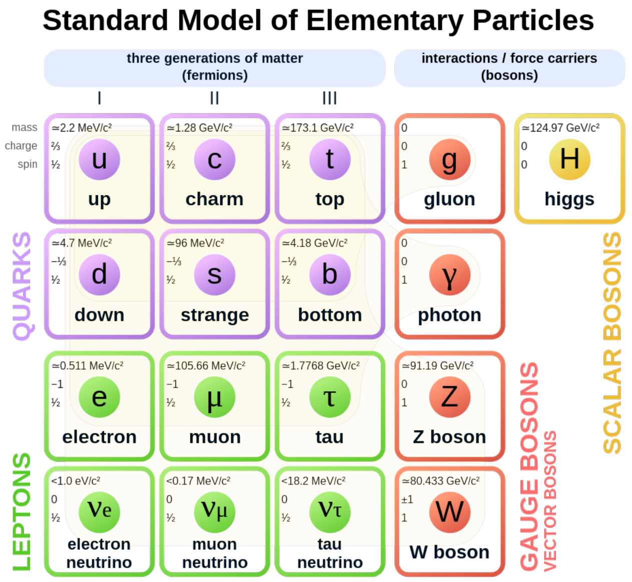
Problem: The introduction of mass terms for the gauge bosons $W^{\pm}$ and Z in the SM Lagrangian would **violate** the local gauge invariance of the theory.

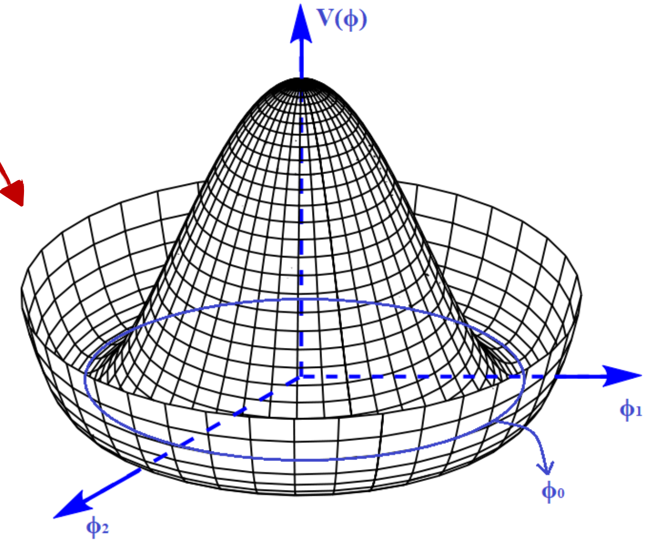
Solution: the ***Higgs mechanism*** (1964) and the *spontaneous symmetry breaking* allow to give mass to the particles dynamically, through the interaction with a scalar field Φ. Self-interaction term through V(Φ):

$$V(\Phi) = \lambda(\Phi^{\dagger}\Phi)^2 - \mu^2(\Phi^{\dagger}\Phi)$$

V(Φ) has infinite minima → Φ aquires one ground state → this choice *spontaneously break the symmetry* of the configuration → mass terms arise! ✅

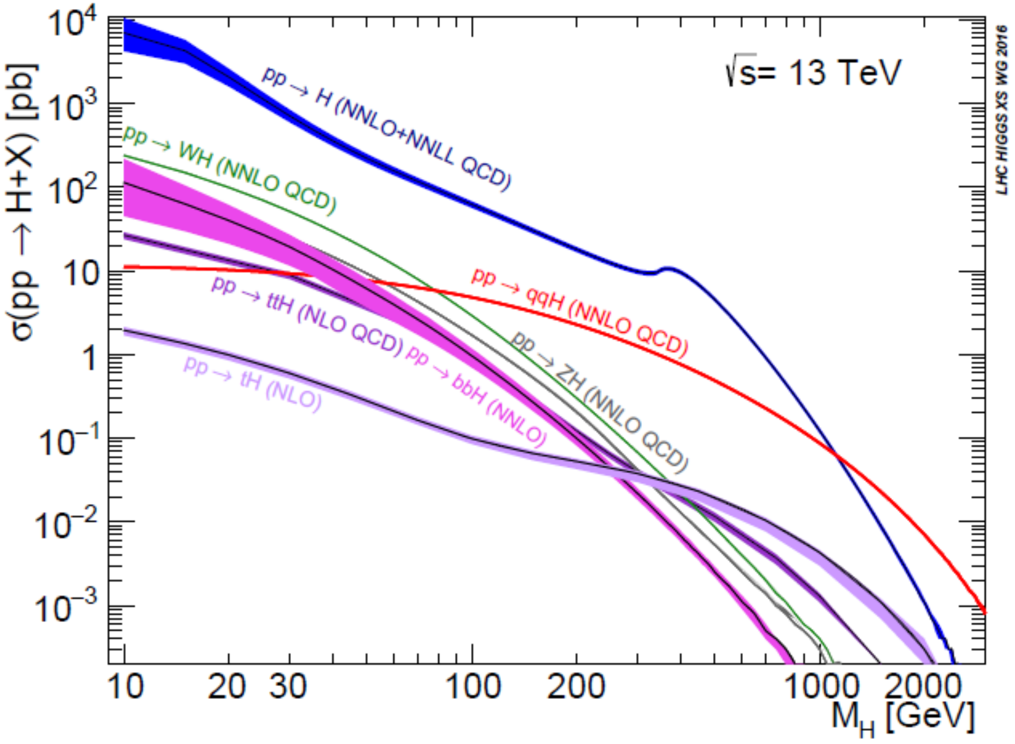
- The quantum of the field is the **Higgs boson** H, a massive scalar particle

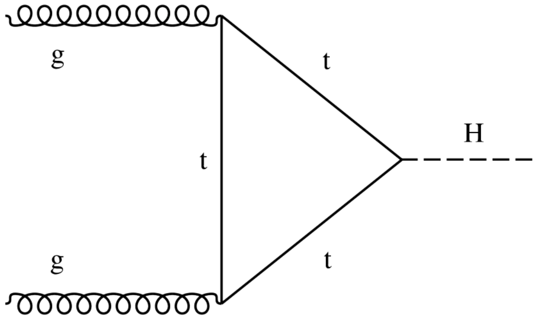




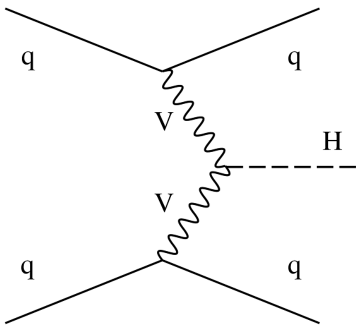
Production cross sections and decay Branching ratios

- **Cross sections:** considering $\sqrt{s}$ = 13 TeV and m_H ~ 125 GeV, the total cross section is σ_H~56 pb

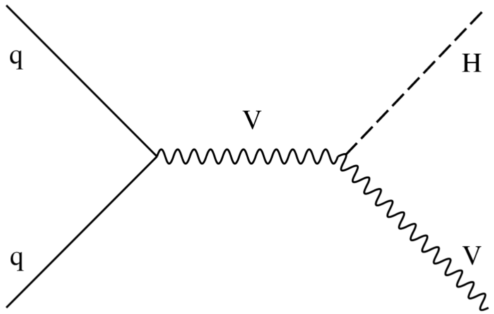




ggF, σ_{ggF}~48.5 pb

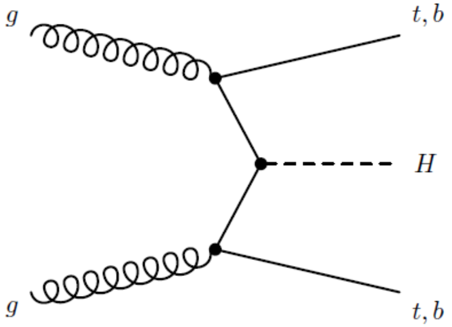


VBF, σ_{VBF}~3.8 pb



VH = WH or ZH, σ_{WH}~1.4 pb

σ_{ZH}~0.88 pb



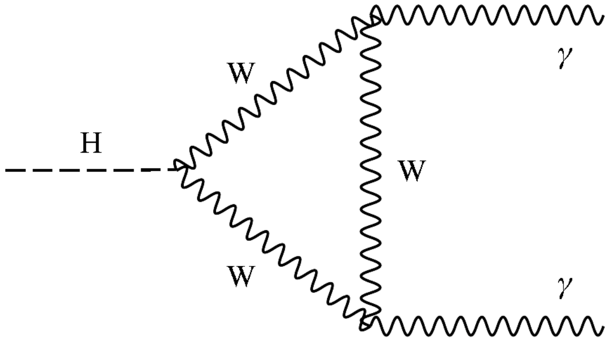
$t\bar{t}$H and $b\bar{b}$H, σ_{ttH}~0.51 pb

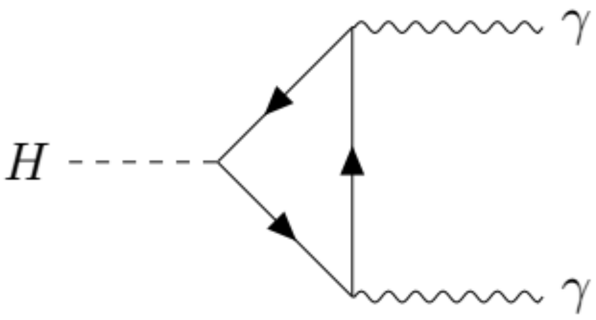
σ_{bbH}~0.49 pb

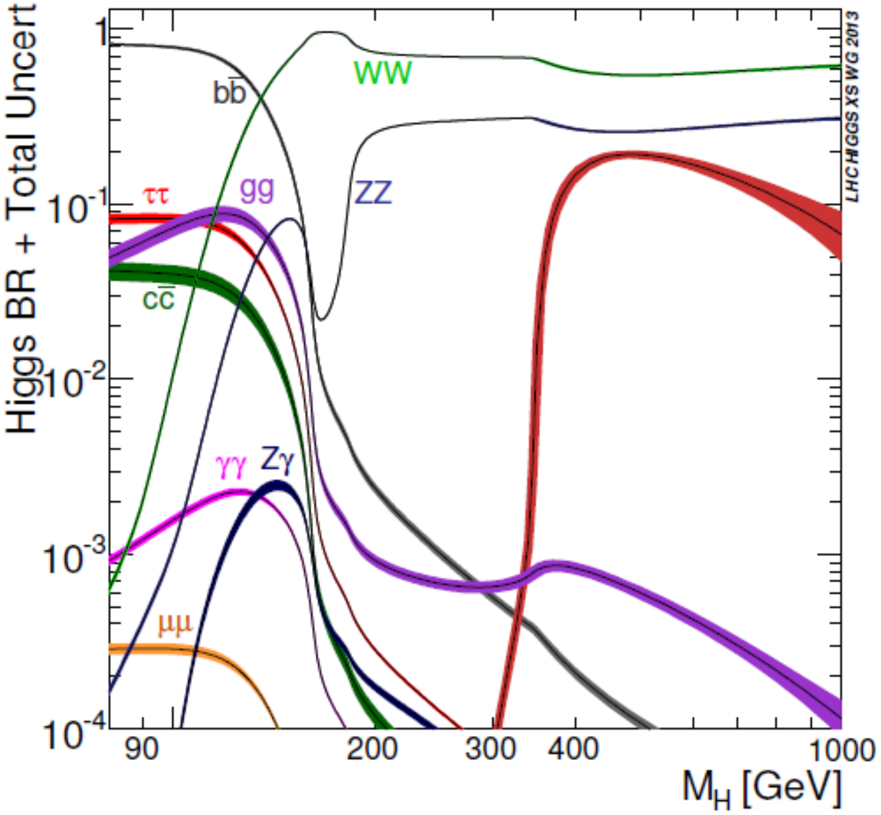
Production cross sections and decay Branching ratios

- **Branching ratios:** $BR(H \to X_i) = \dfrac{\Gamma(H \to X_i)}{\sum_i \Gamma(H \to X_i)}$

  - $H \to b\bar{b}$: BR ~ 58.1 %
  - H → WW*(→lνlν): BR ~ 21.5 %
  - …
  - H → ZZ*: BR ~ 2.6 %
    ZZ*→ 4l: BR ~ 0.0125%
  - H → γγ: BR ~ 0.227%

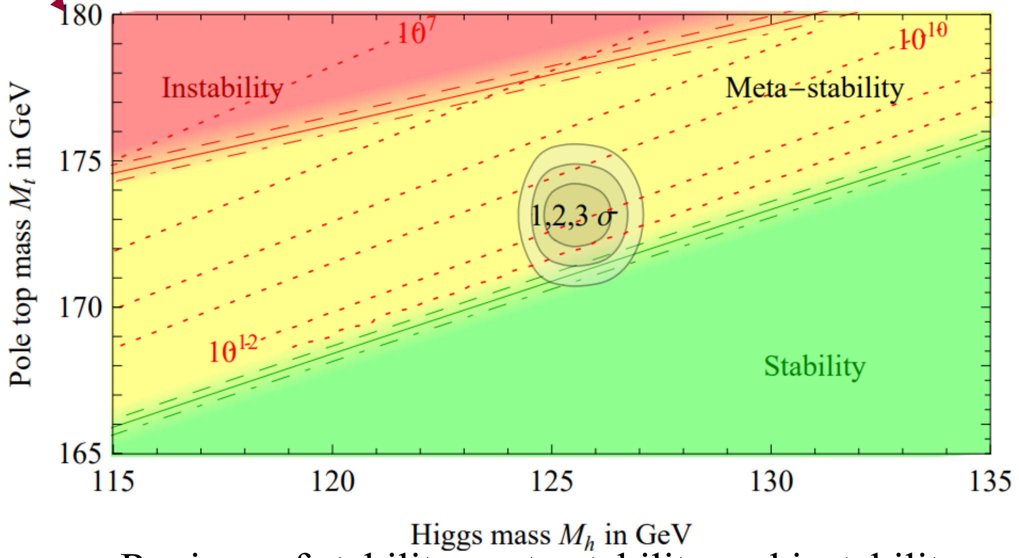




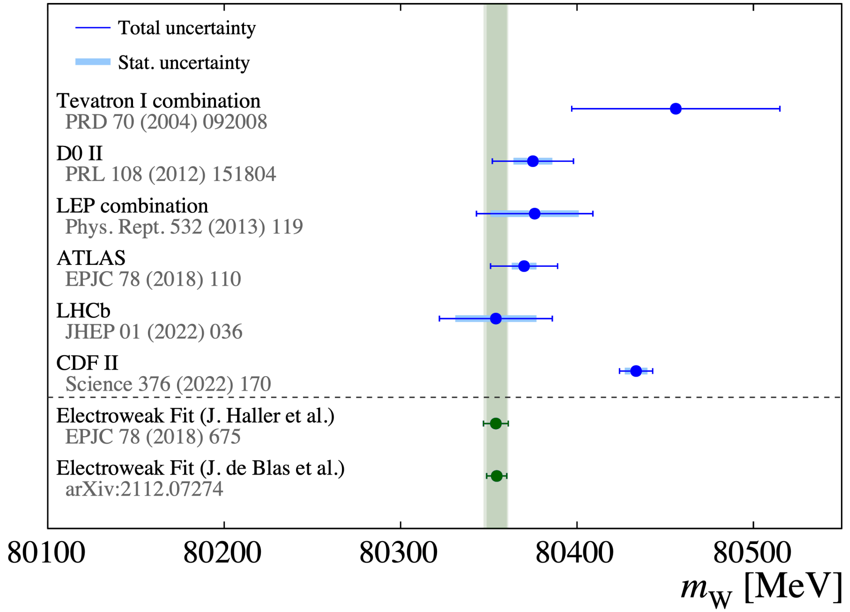


Vacuum stability and EW fits

- **Vacuum stability**: The value of the Higgs mass determines the vacuum stability, i.e. the Higgs potential might be unbounded below or exhibit lower additional minima given a certain m_H below the Planck scale



Regions of stability, meta-stability and instability of the SM vacuum in the m_t - m_H plane



- **Global EW fits**: they test the internal consistency of the SM. The SM prediction of the W gauge boson mass m_W from the electroweak fit including the Higgs boson mass as input, gives $m_W = 80.354 \pm 0.007$ GeV. This theoretical result is compatible with ATLAS measurement but in severe tension (7σ) with CDF result of $m_W = 80.43350 \pm 0.0094$ GeV

1) Event categorisation – Past categorisations

Event categorisation: selected events are divided in mutually exclusive categories optimised to reduce the total expected uncertainty on m_H. Regions with different:

- signal-to-bkg ratio $\frac{S}{B}$ and significance $Z \sim \frac{S}{\sqrt{B}}$
- invariant mass **resolution** (σ) of the $m_{\gamma\gamma}$ peak
- **systematic** uncertainties on photon energy scale (PES)

} γ kinematic variables as η, p_{Tt}, conversion status

Run1, 7/8 TeV, 25 fb^{-1} [Run1]

η:	Central	Rest	Trans
UU=2γUnconv	High / Low	High / Low	
Conv, $\geq$ 1γ Conv	High / Low	High / Low	

10 categories

- Central: both γ with $|\eta|<0.75$
- Trans: one γ with $1.3 < |\eta| < 1.75$
- Rest: all the other events
- High/Low: events with $p_{Tt}^{\gamma\gamma} \gtrless 70$ GeV

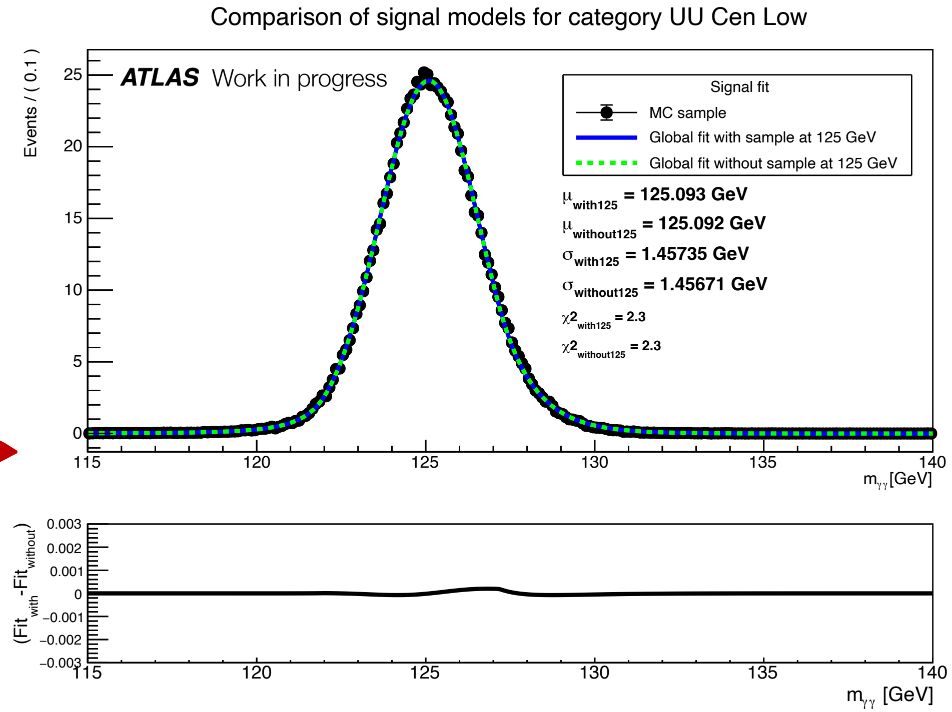
Partial Run2, 13 TeV, 36 fb^{-1} [Run2@36ifb]

31 categories from STXS 2016 coupling analysis, 4% worst wrt to Run1 categorisation:

- 10 ggH categories, with ggH 0J split in CEN/FWD regions;
- 4 VBF categories;
- 8 categories for the associate production with a vector boson (W and Z);
- 9 categories for the associate production with a $t\bar{t}$ or single t

2) Signal model $\propto m_H$

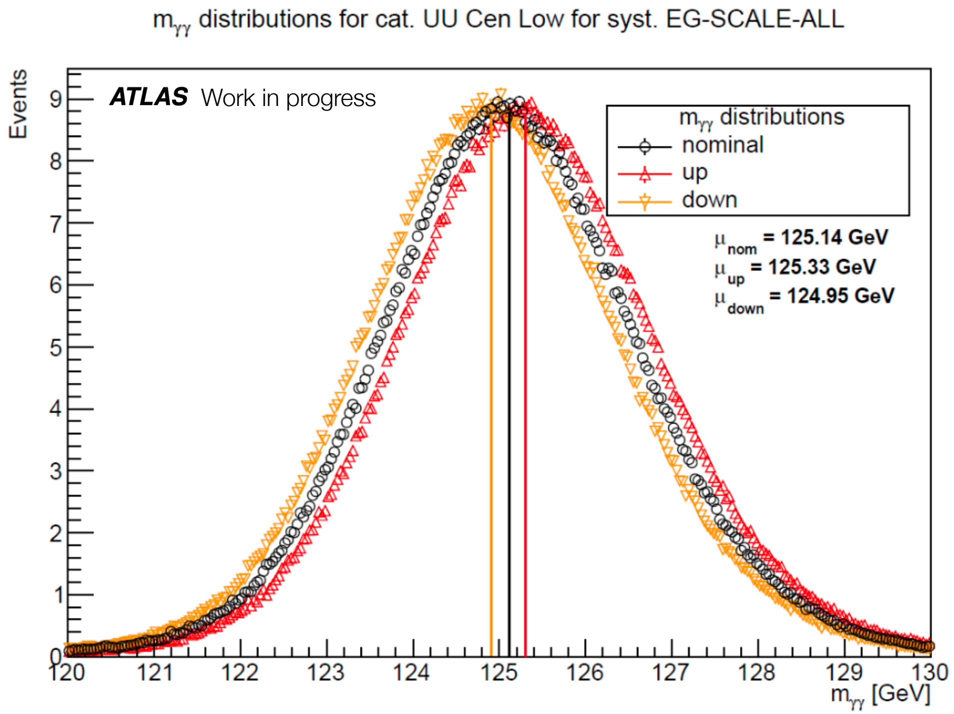
- Different **checks** performed:
  - χ^2 to evaluate the goodness of the fit, see backup slide 32
  - **Closure test**: the simultaneous fit is repeated ignoring the $m_H = 125$ GeV sample. The resulting signal model is extrapolated to 125 GeV and compared with the nominal signal model obtained fitting simultaneously all the 9 MC samples.
    - ✦ Similar χ^2 and fitted parameters $\forall$ category $\Rightarrow$the fitting procedure is not so dominated by the 125 GeV sample
  - Check the impact of considering n_{Low} and n_{High} as constants in the *simultaneous fit*: the fit $\forall$ category was repeated leaving free also n_{Low} and n_{High}.
    - ✦ the peak parameters do not change significantly and they are usually compatible within the uncertainties, see backup slide 33

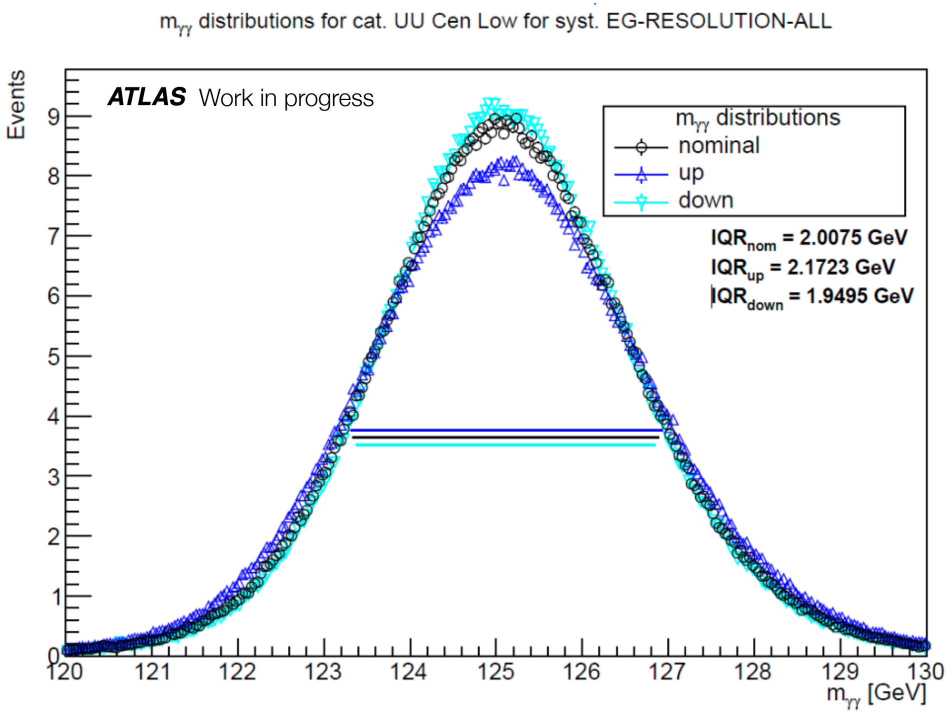


$$\mu_{\text{CB}}(m_H) = m_H + B_{\mu_{\text{CB}}} + A_{\mu_{\text{CB}}}(m_H - 125\text{ GeV})$$
$$\sigma_{\text{CB}}(m_H) = B_{\sigma_{\text{CB}}} + A_{\sigma_{\text{CB}}}(m_H - 125\text{ GeV})$$
$$\alpha_{\text{Low}}(m_H) = \alpha_{\text{Low}}$$
$$\alpha_{\text{High}}(m_H) = \alpha_{\text{High}}$$
$$n_{\text{Low}}(m_H) = n_{\text{Low}}|_{125\text{GeV}}$$
$$n_{\text{High}}(m_H) = n_{\text{High}}|_{125\text{GeV}}$$

4) Main experimental systematic uncertainties: PES and PER

- Photon energy scale (**PES**) and photon energy resolution (**PER**) systematics affect μ_{CB} and σ_{CB}, ∀ category:
  - Procedure: auxiliary MC samples where the syst. variations ($\pm 1\sigma$) are applied upstream and their effect is propagated to the $m_{\gamma\gamma}$ distribution
  - PES: 67 NPs computed as variation of the mean of the $m_{\gamma\gamma}$ distribution $\delta_{PES}(\pm 1\sigma) = \frac{\langle m_{\gamma\gamma}^{\pm 1\sigma} \rangle}{\langle m_{\gamma\gamma}^{nom} \rangle} - 1$
  - PER: 9 NPs (grouped in 5 NPs to match Run1 scheme) as variation of the inter-quartile of the $m_{\gamma\gamma}$ distribution $\delta_{PER}(\pm 1\sigma) = \frac{IQR^{\pm 1\sigma}}{IQR^{nom}} - 1$





4) Main experimental systematic uncertainties: PES and PER

- Photon energy scale (**PES**) and photon energy resolution (**PER**) systematics affect μ_{CB} and σ_{CB}, $\forall$ category:
  - Procedure: auxiliary MC samples where the syst. variations ($\pm 1\sigma$) are applied upstream and their effect is propagated to the $m_{\gamma\gamma}$ distribution
  - PES: 67 NPs computed as variation of the mean of the $m_{\gamma\gamma}$ distribution $$\delta_{PES}(\pm 1\sigma) = \frac{\langle m_{\gamma\gamma}^{\pm 1\sigma} \rangle}{\langle m_{\gamma\gamma}^{nom} \rangle} - 1$$
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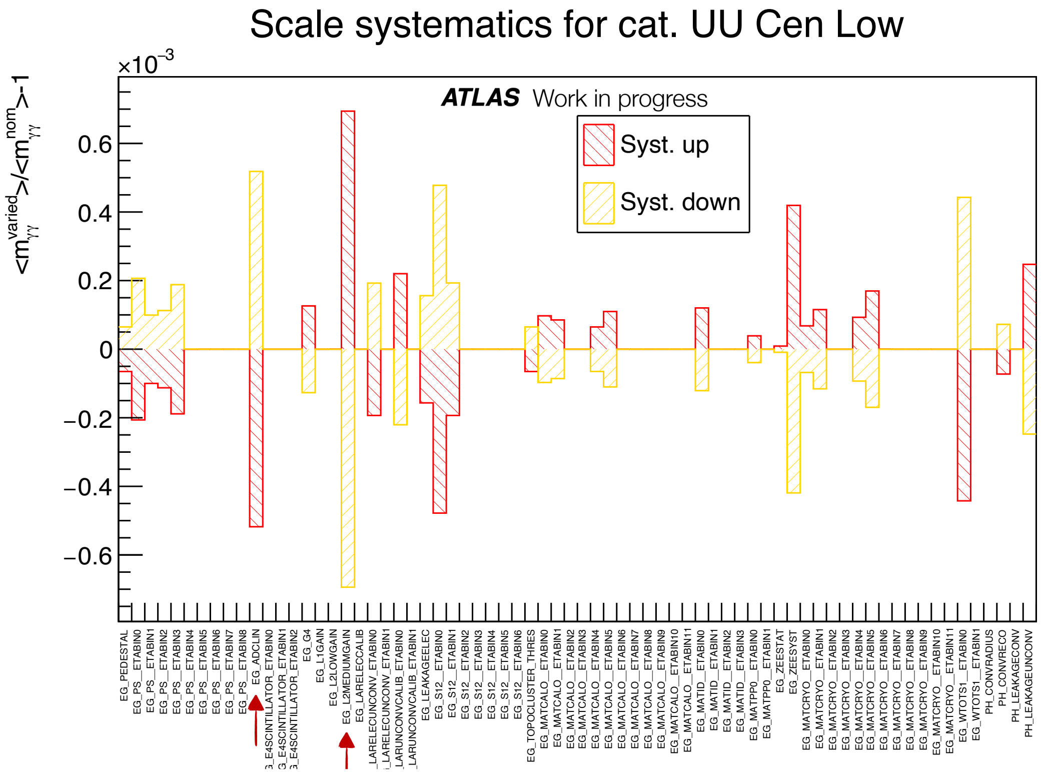
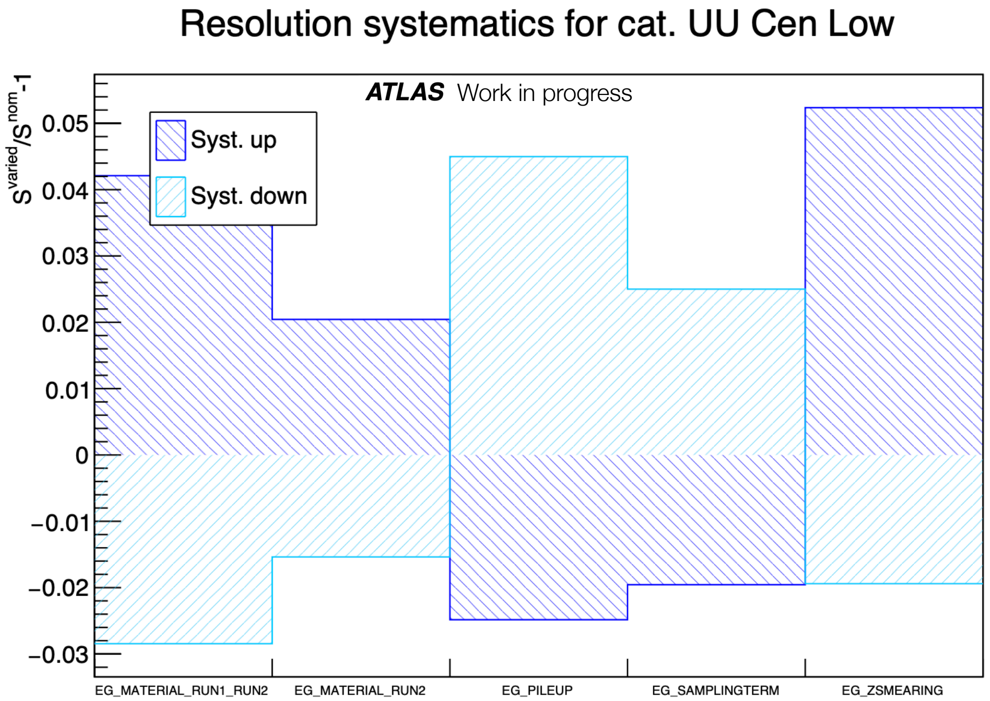




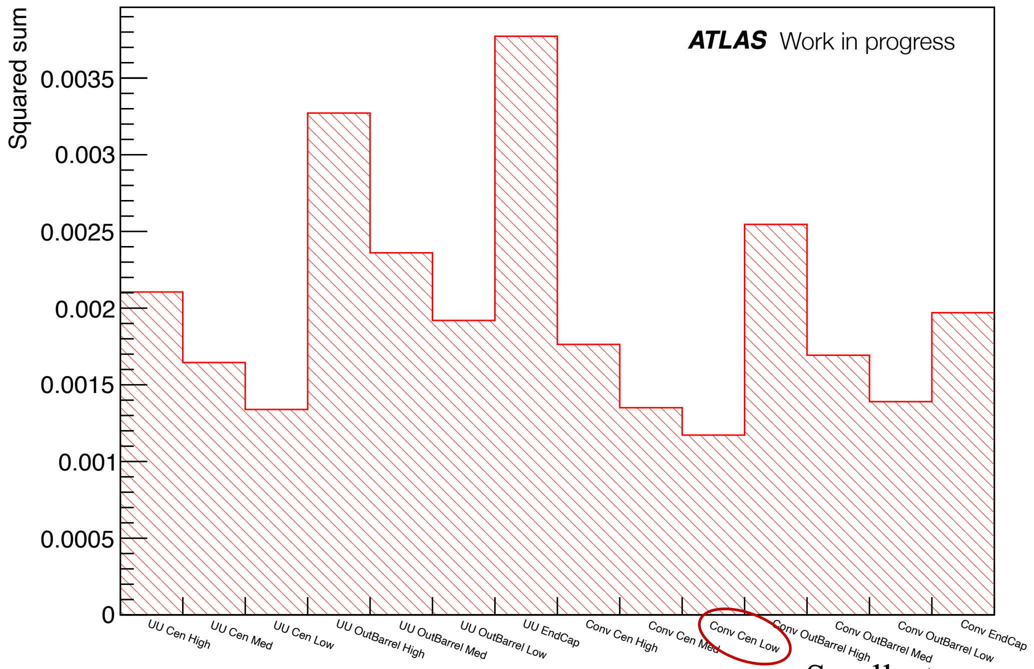
4) Main experimental systematic uncertainties: PES and PER

- Photon energy scale (**PES**) and photon energy resolution (**PER**) systematics affect μ_{CB} and σ_{CB}, ∀ category:
  - Procedure: auxiliary MC samples where the syst. variations ($\pm 1\sigma$) are applied upstream and their effect is propagated to the $m_{\gamma\gamma}$ distribution
  - PES: 67 NPs computed as variation of the mean of the $m_{\gamma\gamma}$ distribution
  - PER: 9 NPs (grouped in 5 NPs to match Run1 scheme) as variation of the inter-quartile of the $m_{\gamma\gamma}$ distribution

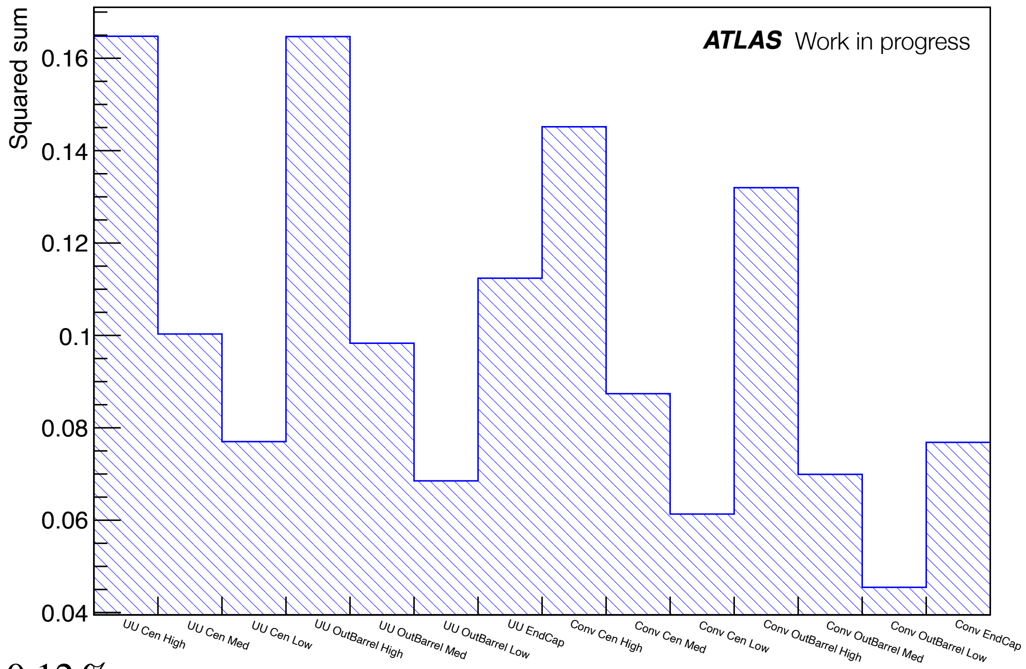
PES impact on m_H
~173 MeV

PER impact on m_H
~ 3 MeV

Squared sum of scale systematics up



Squared sum of resolution systematics up



Smallest unc. ~ 0.12 %

- better syst. for Conv wrt to corresponding UU

5) $H \rightarrow \gamma\gamma$ Run 2: secondary systematic uncertainties

Additional and secondary systematic uncertainties are included in the likelihood model

- **Signal and background modelling**: an inaccurate model can cause a bias in the m_H measurement
  - Evaluated by injecting sig (bkg) MC sample over a bkg (sig) Asimov ∀ category, then refit with S+B model and compute m_H shift
  - Effect uncorrelated among categories, impact of **5 (18) MeV** for signal (background)
- **Interference** between $\mathrm{gg} \rightarrow \gamma\gamma$ and $\mathrm{gg}\rightarrow\mathrm{H}\rightarrow\gamma\gamma$ processes causes a shift of the m_H
  - Evaluated by injecting interference MC sample over a S+B Asimov ∀ category, then refit with S+B model and compute m_H shift
  - Effect correlated among categories, expected **26 MeV** impact
- Photon energy **resolution** (PER): evaluated as interquartile difference of $m_{\gamma\gamma}$ distribution per category, applied on width of DSCB
- Photon **conversion reconstruction** affecting category migrations
  - Estimated with data/MC comparison in $Z \rightarrow ll\gamma$ events, correlated to corresponding scale effect
- **NN vertex selection** effect on m_H (5 MeV)
  - Estimated with data/MC comparison in $Z \rightarrow ee$ events where *e* are treated as unconverted photons
- Luminosity / BR $\gamma\gamma$ / QCD scale / PDF + α_s / Parton shower / Spurious signal / Yield
  - All included and with ∼ null impact on m_H

5) Secondary and modelling systematics uncertainties

- **Modelling systematic uncertainties**: an inaccurate model can cause a bias in the mass measurement

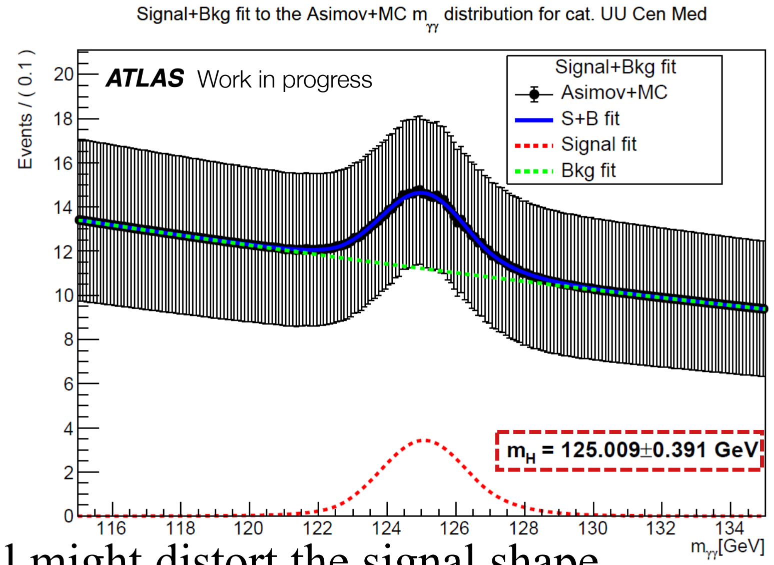
  - **Signal** and **background** biases: signal (background) injection tests for each category:
    - replace signal(bkg) Asimov components with MC, then refit with analytical S+B model
    - include biases as systematic uncertainties in the likelihood
    - Signal bias: **4 MeV** effect, uncorrelated among categories
    - Background bias: **29 MeV** effect, uncorrelated among categories

  - Bias due to the neglecting the **interference** between $gg \rightarrow \gamma\gamma$ bkg and $gg \rightarrow H \rightarrow \gamma\gamma$ signal:
    - Inject interference MC samples ($\Gamma = \Gamma_{SM}$) on top of Asimov S+B dataset
    - Re-fit with standard S+B model, compute the bias for each category, include bias in likelihood as an uncertainty
    - Interference bias: **34 MeV** effect, correlated among categories

Bias	**Impact on m_H [MeV]**
Signal	$\pm$ 4
Background	$\pm$ 29
Interference	$\pm$ 34

5) Modelling systematics uncertainties

- **Signal modelling bias on m_H**: parameters of the signal model are fixed to the values obtained in the signal fit
  → an inaccurate signal model can cause a bias in the mass measurement
  - Fit dataset formed by signal (MC) and bkg (Asimov) with the analytical S+B model
  - Evaluate the bias as relative shift between the fitted and injected (125 GeV) m_H
  - Bootstrap to check the statistical significance



Similar procedure:

- **Background modelling bias on m_H:** dataset = signal (Asimov) + bkg (template)

- **Interference bias on m_H** : interference between gg → γγ bkg and gg→H→γγ signal might distort the signal shape, the interference is **not** taken into account in the model → **neglecting** it can cause a bias in the mass measurement

Bias	Impact on m_H [MeV]
Signal	± 4
Background	± 29
Interference	± 34

fit on dataset = signal+bkg (Asimov) + interference (MC with $\Gamma_H^{SM} = 4.07$ MeV)

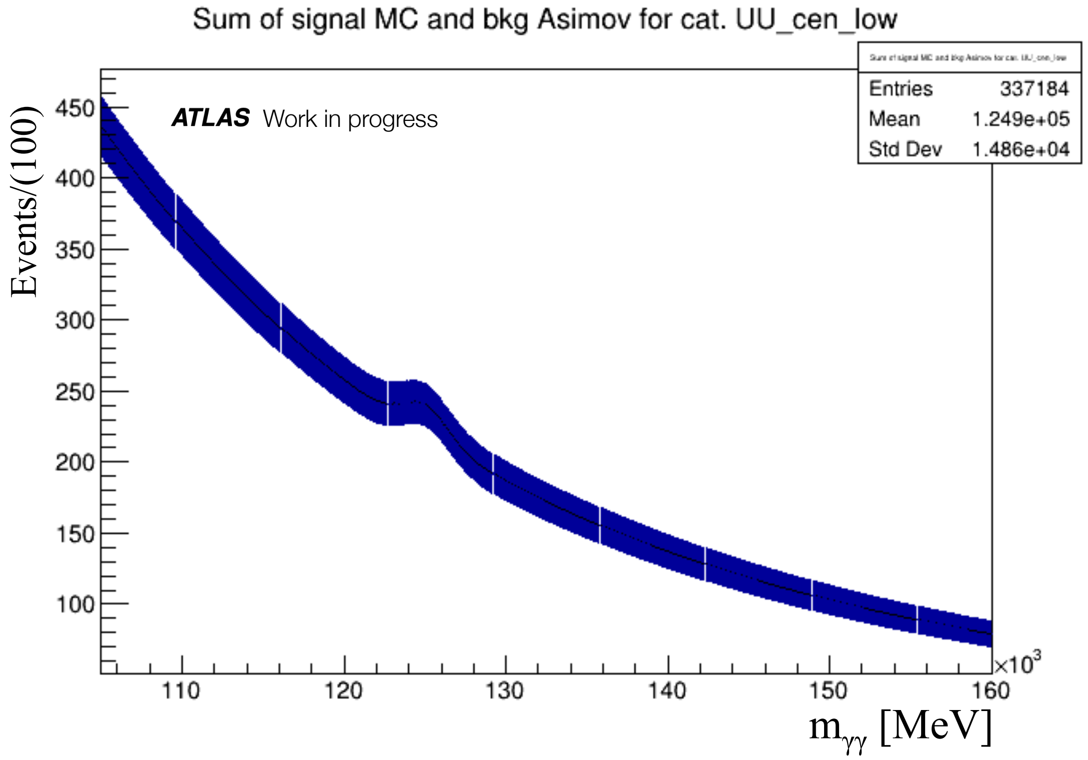
5) Signal modelling uncertainty – signal injection test

- **Motivation**: the parameters of the signal model are fixed to the values obtained in a simultaneous fit (see backup slides)
  → an inaccurate signal model can cause a bias in the mass measurement

- **Procedure** to evaluate this bias for each category, **signal injection test**:

1. sample = background Asimov + signal MC at $m_H = 125$ GeV.

   - Bkg shape parameters for each category from a fit on data sidebands in $m_{\gamma\gamma} \in [105$ GeV, 160 GeV$]$ blinding the range [120 GeV, 130 GeV]
   - Functional form of the bkg model selected by the SS test.



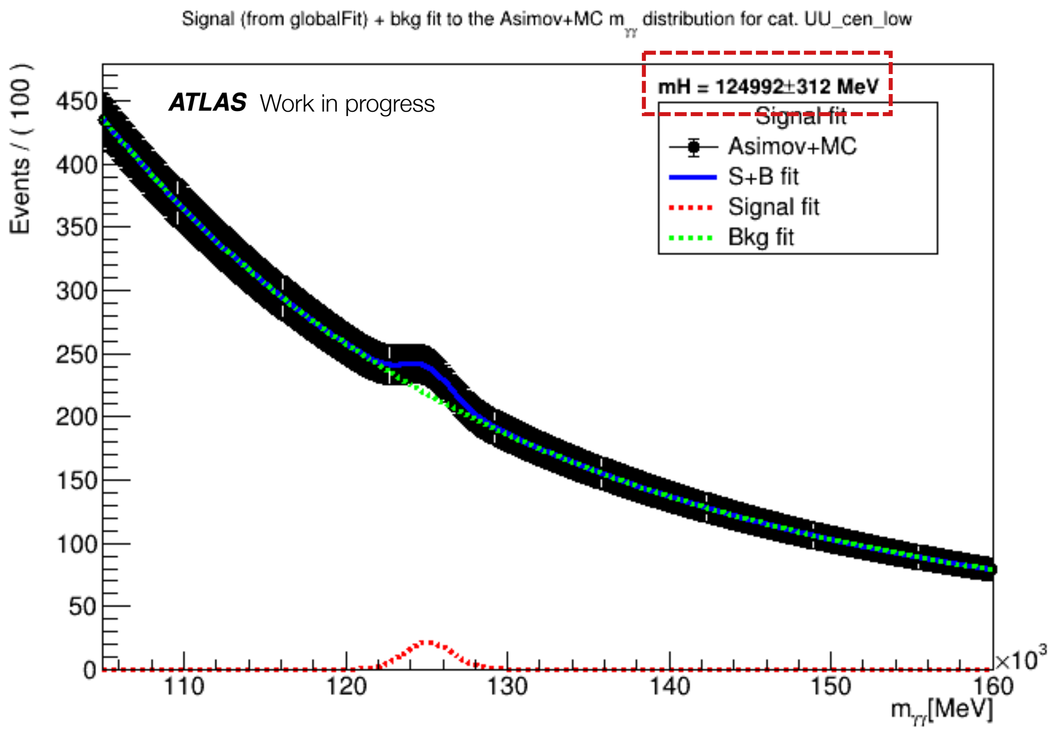
5) Signal modelling uncertainty – signal injection test

- **Motivation**: the parameters of the signal model are fixed to the values obtained in a simultaneous fit (see backup slides) → an inaccurate signal model can cause a bias in the mass measurement

- **Procedure** to evaluate this bias for each category, **signal injection test**:

1. sample = background Asimov + signal MC at m_H = 125 GeV.
2. Fit on the obtained sample with the nominal signal plus background model: fitted parameter $\mathbf{m_H}$
3. Signal bias = relative shift between the fitted and injected (m_H = 125 GeV) Higgs boson mass.

e.g. for cat. UU cen low:
SigBias = (124992 – 125000) MeV = -8 MeV



5) Signal modelling uncertainty – signal injection test

- **Motivation**: the parameters of the signal model are fixed to the values obtained in a simultaneous fit (see backup slides) $\longrightarrow$ an inaccurate signal model can cause a bias in the mass measurement

- **Procedure** to evaluate this bias for each category, **signal injection test**:

1. sample = background Asimov + signal MC at $m_H = 125$ GeV.
2. Fit on the obtained sample with the nominal signal plus background model: fitted parameter $\mathbf{m_H}$
3. Signal bias = relative shift between the fitted and injected (m_H = 125 GeV) Higgs boson mass.
4. Estimated for each category: |SigBias| ≈ 0 – 30 MeV

$m_H^{injected} = 125$ GeV

Category	Nominal fit		
	m_H^{fitted} [GeV]	bias [GeV]	bias [‰]
UU Cen High	124.975	-0.025	-0.20
UU Cen Med	125.009	0.009	0.07
UU Cen Low	125.005	0.005	0.04
UU OutBarrel High	124.971	-0.029	-0.23
UU OutBarrel Med	125.035	0.035	0.28
UU OutBarrel Low	125.008	0.008	0.06
UU EndCap	125.016	0.016	0.13
Conv Cen High	125.000	0.000	0.00
Conv Cen Med	124.997	-0.003	-0.02
Conv Cen Low	125.012	0.012	0.10
Conv OutBarrel High	125.030	0.030	0.24
Conv OutBarrel Med	124.986	-0.014	-0.12
Conv OutBarrel Low	125.016	0.016	0.13
Conv EndCap	125.018	0.018	0.14

6) $H \rightarrow \gamma\gamma$ Run 2: expected and **observed** results 📊

- Checks with **different fit configurations**: ✅
  - Without linearity
  - Different μ configurations (1 global μ or μ_F+μ_V or $\mu_{ggH} + \mu_{VBF} + \mu_{rest}$)
- **Internal compatibility studies**

Test 1: **general compatibility** of m_H in all the categories with global m_H value. Instead of only m_H, insert in our model $m_H + \Delta_{cat}$ $\forall$ category, 14 Δs

- Null hypothesis: *"mass is the same in each category"* → $\forall \Delta_{cat} = 0$
- Alternative hypothesis 1: *"the values of m_H in all the cat. are different"* → Fit with all the 14 Δs free

$$q_0 = -2\log \frac{L(\Delta_1 = 0, \Delta_2 = 0, \dots \Delta_n = 0, \hat{\hat{m}}_H)}{L(\hat{\Delta}_1, \hat{\Delta}_2, \dots, \hat{\Delta}_n, \hat{m}_H)}$$

→ Global p-value = χ^2 distribution with 13 d.o.f. = **0.077**

Compatibility checks	Global p-value %
Test 1: **general compatibility** of m_H in all the categories with global m_H value	7.7
Test 2: compatibility of groups of categories: **conv vs. unconv**	48
Test 3: compatibility of groups of categories: **η** vs η regions (Central, OutBarrel, Endcap)	43
Test 4: compatibility of groups of categories: **pTt** vs pTt regions (High, Low, Med)	5.7
Test 5: compatibility of different **pileup** regions (using a pileup based categorisation, 5 categories)	43
Test 6: compatibility of different **years** (using a years based categorisation, 2015+2016 vs 2017 vs 2018)	31

all p-values > 5% ✅

Compatibility checks on unblinded data

Test 1: **general compatibility** of m_H in all the categories with global m_H value.
Instead of only m_H, insert in the ws $m_H + \delta_{cat}$ $\forall$ category, 14 δs

- Null hypothesis: *"mass is the same in each category"* $\rightarrow \forall \delta_{cat} = 0$

- Alternative hypothesis 1: *"the values of m_H in all the cat. are different"*
  Fit with all the 14 δs free

$$q_0 = -2 \log \frac{L(\Delta_1 = 0, \Delta_2 = 0, \ldots \Delta_n = 0, \hat{\hat{m}}_H)}{L(\hat{\Delta}_1, \hat{\Delta}_2, \ldots, \hat{\Delta}_n, \hat{m}_H)}$$

↓

Global p-value = χ^2 distribution with 13 d.o.f. = **0.077**

- Alternative hypothesis 2: *"only m_H in category i is different"*

$$q_0^{(1)} = -2 \log \frac{L(\Delta_1 = 0, \Delta_2 = 0, \ldots \Delta_n = 0, \hat{\hat{m}}_H)}{L(\hat{\Delta}_1, \Delta_2 = 0, \ldots, \Delta_n = 0, \hat{m}_H)}$$

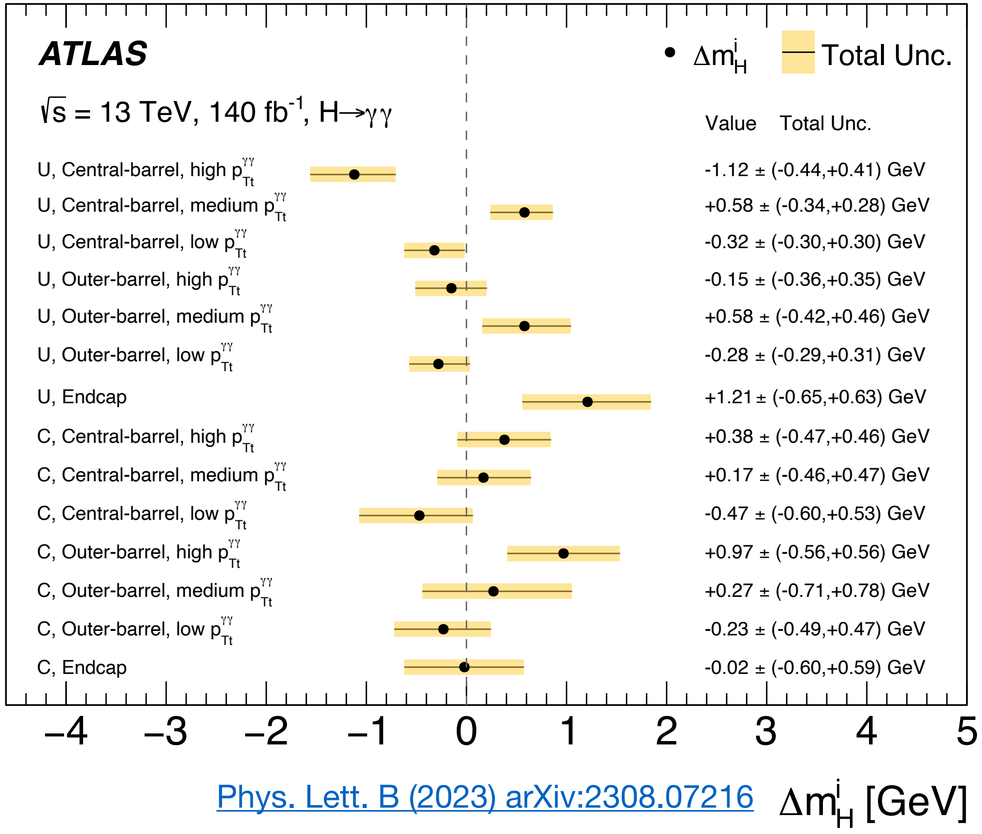
  p-value of each δ for each category: compatibility of each category with global m_H, all > 0.05 except for UU Cen High

Category	p-value category
UU Cen High	0.01
UU Cen Med	0,11
UU Cen Low	0,29
UU OutBarrel High	0,66
UU OutBarrel Med	0,18
UU OutBarrel Low	0,36
UU EndCap	0,07
Conv Cen High	0,41
Conv Cen Med	0,71
Conv Cen Low	0,38
Conv OutBarrel High	0,10
Conv OutBarrel Med	0,70
Conv OutBarrel Low	0,61
Conv EndCap	0,99

Compatibility checks on unblinded data

Test 1: **general compatibility** of m_H in all the categories with global m_H value.
Instead of only m_H, insert in the ws $m_H + \delta_{cat}$ $\forall$ category, 14 δs

Obtained with all δs free, alternative hypothesis 1



Phys. Lett. B (2023) arXiv:2308.07216

Obtained with 1 δ free at a time

Category	p-value category
UU Cen High	0.01
UU Cen Med	0,11
UU Cen Low	0,29
UU OutBarrel High	0,66
UU OutBarrel Med	0,18
UU OutBarrel Low	0,36
UU EndCap	0,07
Conv Cen High	0,41
Conv Cen Med	0,71
Conv Cen Low	0,38
Conv OutBarrel High	0,10
Conv OutBarrel Med	0,70
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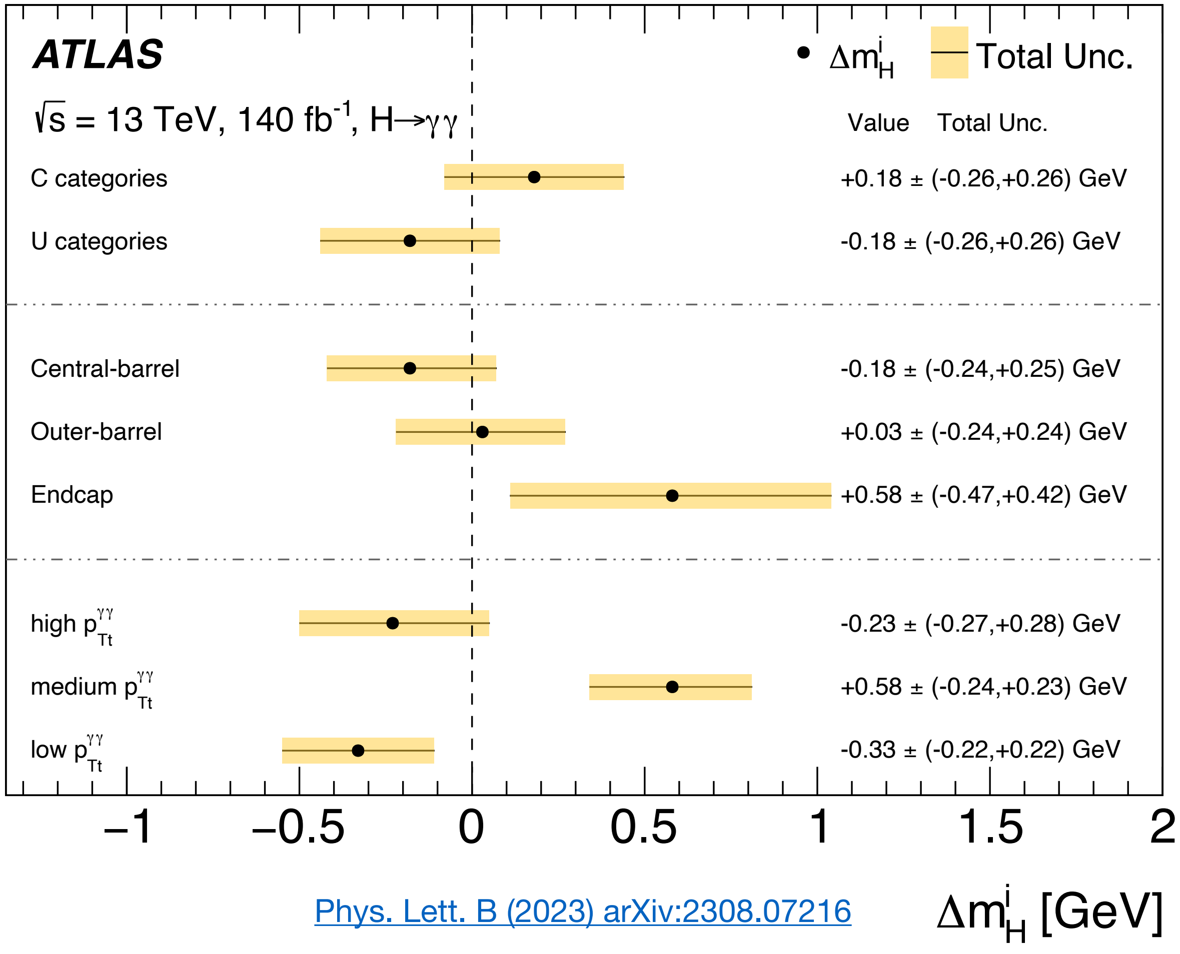
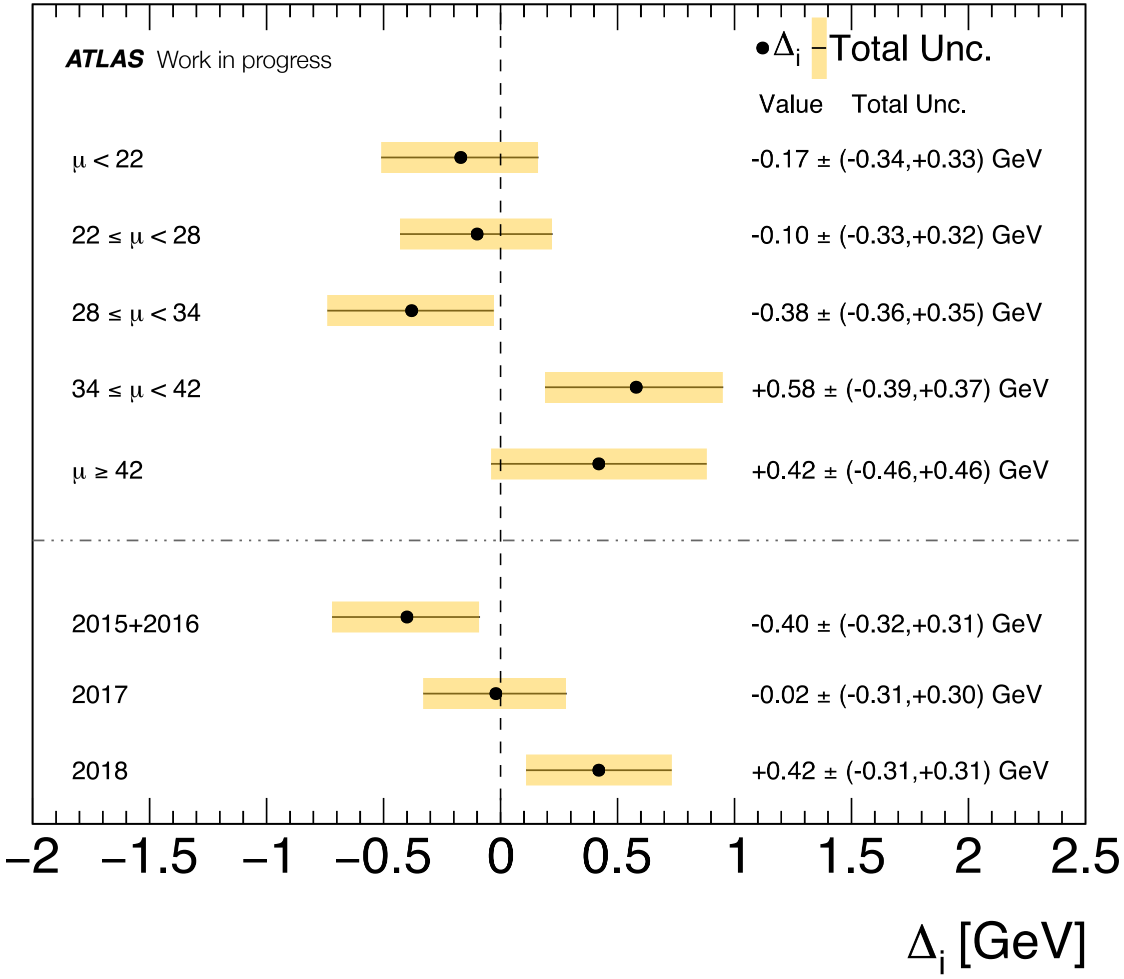
Conv EndCap	0,99

Compatibility checks on unblinded data



Phys. Lett. B (2023) arXiv:2308.07216



Higgs boson Run2 mass measurement $H \rightarrow \gamma\gamma$: systematic uncertainties

Experimental systematic uncertainties: the **energy calibration procedure** on the photons has an impact on m_H measurement

- **LAr cell non-linearity**: non-linearity of Layer2 gain cell energy measurement and to the uncertainty on the intercalibration between the different readout gains
- **Layer calibration**: accounts for the impact of the Layer1 and Layer2 (EM calorimeter) intercalibration on the reconstructed particle energy. The scale factors $\alpha_{1/2}$ used to intercalibrate the first two layers of the electromagnetic calorimeter are evaluated as a function of $|\eta|$ and E_T
- **Material**: the Inner Detector, the cryostat and calorimeter material uncertainties are obtained by comparing the energy response in Monte Carlo samples simulated with nominal and modified detector geometry. The difference in the energy response are scaled comparing the material variation of the corresponding distorted simulated sample with the actual material measurement uncertainties, yielding to the energy scale uncertainties
- **$Z \rightarrow e^+e^-$ calibration:** Z-based calibration fixes the energy scale and its uncertainty for electrons with transverse energy close to the average of those produced in Z decays ($p_T \sim$ 40 GeV). Photons produced in $H \rightarrow \gamma\gamma$ decay have a harder p_T spectrum so the uncertainties have to be extrapolated and the impact is generally larger