Higgs→ZZ

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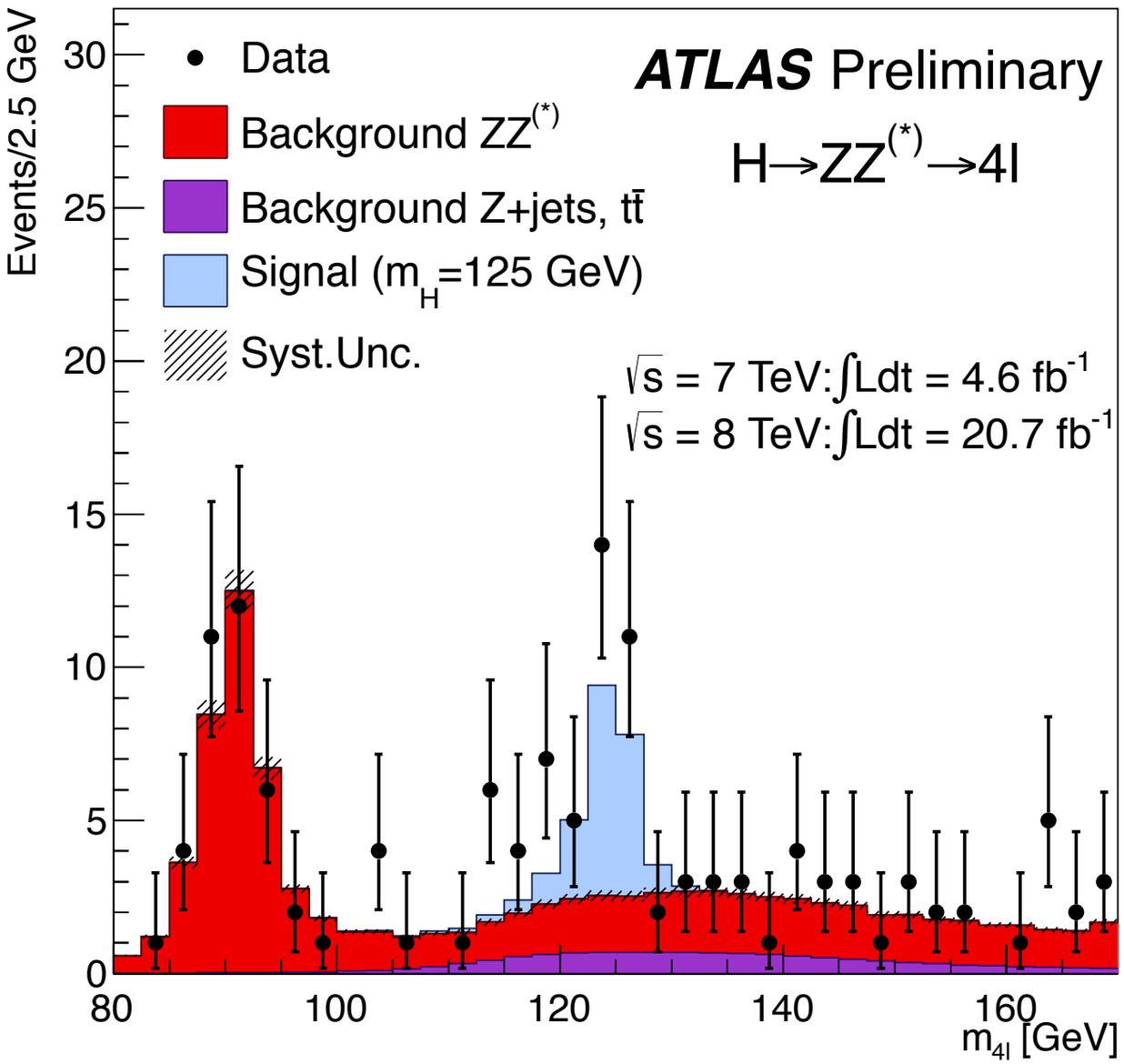
ATLAS-CONF-2013-013



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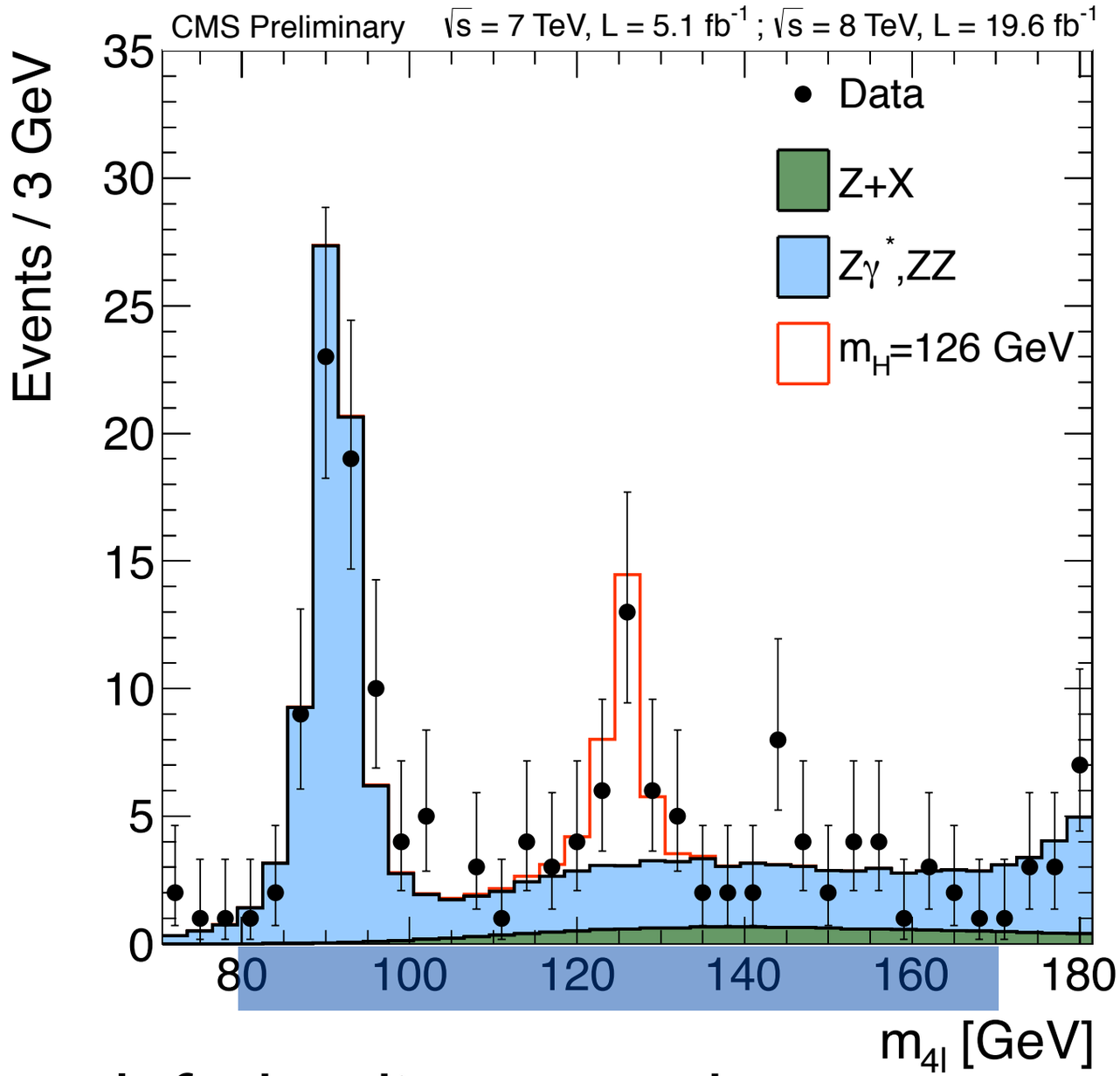


Focus on H→ZZ→4ℓ: we have left the discovery phase and we are now entering the measurement phase!

Talk overview

Review of latest results in the H→ZZ→4ℓ channel presented by ATLAS (on the left) and CMS (on the right) at Moriond

<u>General analysis strategies:</u>

lepton selection, signal modeling, background estimations, etc.

<u>Measurements:</u>

Significance, Mass and Signal Strength

Spin/CP

Couplings

High mass and other final states in the backup slides

H→ZZ→4ℓ: analysis strategy

Reconstruct 4 leptons in final state (electrons and muons)

p_T thresholds:

20, 15, 10, 7 (6 for muons)	20, 15, 7, 7 (5 for muons)

$M_{\ell\ell}$ cuts:

Closest di-lepton to M_Z^{PDG} (Z_1)

$50 < M_{Z1}$ [GeV/c²] < 106	$40 < M_{Z1}$ [GeV/c²] < 120

Remaining di-lepton (Z_2)

$12 < M_{Z2}$ [GeV/c²] < 115	$12 < M_{Z2}$ [GeV/c²] < 120

Isolation

Track Iso less than 15% (ΔR<0.2)	Isolation less than 40% (ΔR<0.4)
Calo Iso less than 20% (ΔR<0.2)	(charged and neutral particles from PF)

H→ZZ→4ℓ: object selection

*more in backup!

Electrons:

Identification: rectangular cuts

Coverage: |η| < 2.47

Reco+ID efficiency: 70%-90%*

Identification: boosted decision tree

Coverage: |η| < 2.5

Reco+ID efficiency+isolation: 60%-95%*

Muons:

Coverage: |η| < 2.7

Reco+ID efficiency: ~98%*

Coverage: |η| < 2.4

Reco+ID efficiency: >98%*

Jets:

Algorithm: Anti-Kt (ΔR=0.4)

p_T > 25 GeV/c (|η|<2.5)

p_T > 30 GeV/c (2.5<|η|<4.5)

Algorithm: Anti-Kt (ΔR=0.4)

p_T > 30 GeV/c (|η|<4.7)

H→ZZ→4ℓ: FSR correction

Applied to:

$Z_1 \to \mu\mu$, only if $66 < M_{\mu\mu}$ [GeV/c²] < 89 and $M_{\mu\mu\gamma} < 100$ GeV/c²

Both Z, both e and μ, if $M_{ll\gamma} < 100$ GeV/c² and closer to nominal Z mass

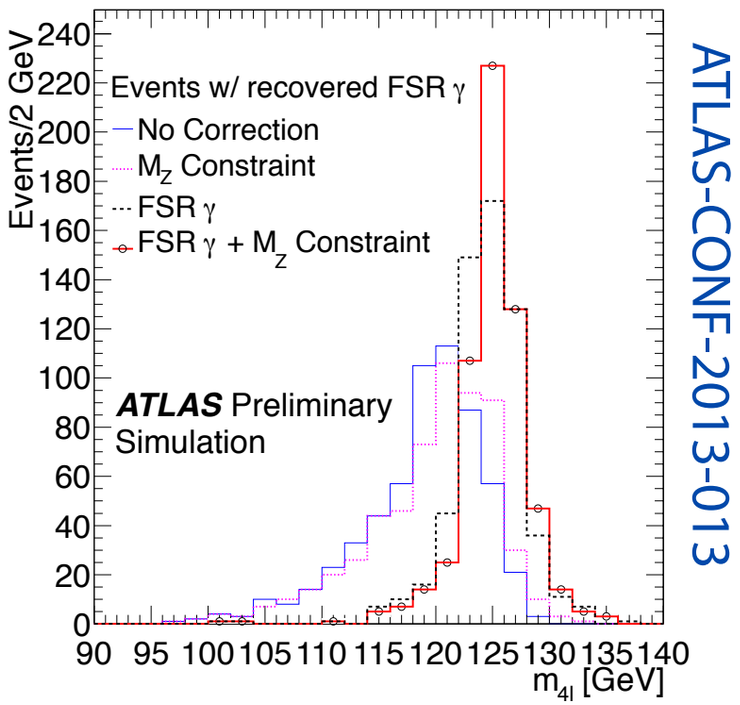
Photon selection:

$1 < E_T < 3.5$ GeV, $\Delta R < 0.08$, $f_1 > 0.2$

$E_T > 2$ GeV, $\Delta R < 0.07$; or

$E_T > 3.5$ GeV, $\Delta R < 0.15$, $f_1 > 0.1$

$E_T > 4$ GeV, $0.07 < \Delta R < 0.5$, isolated



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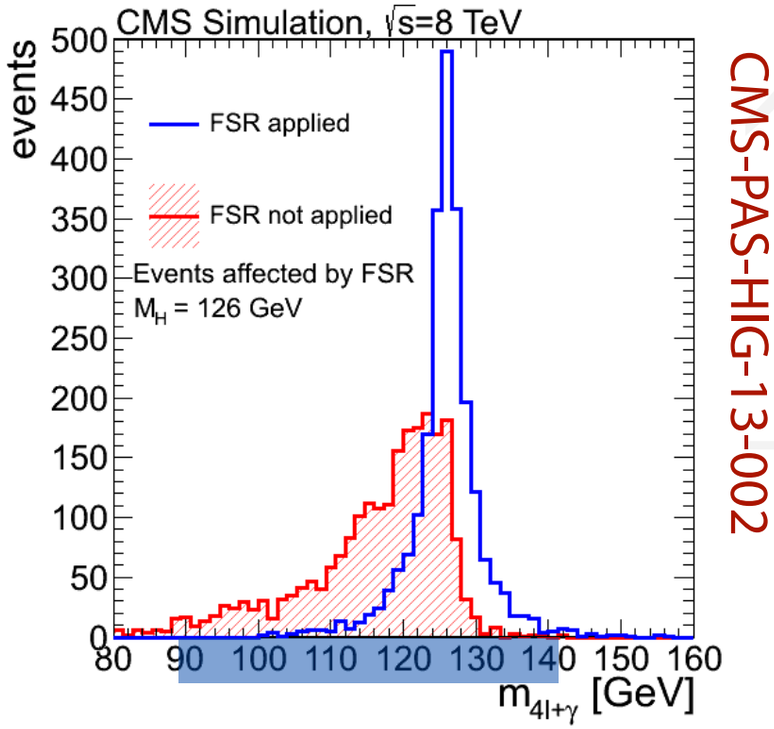

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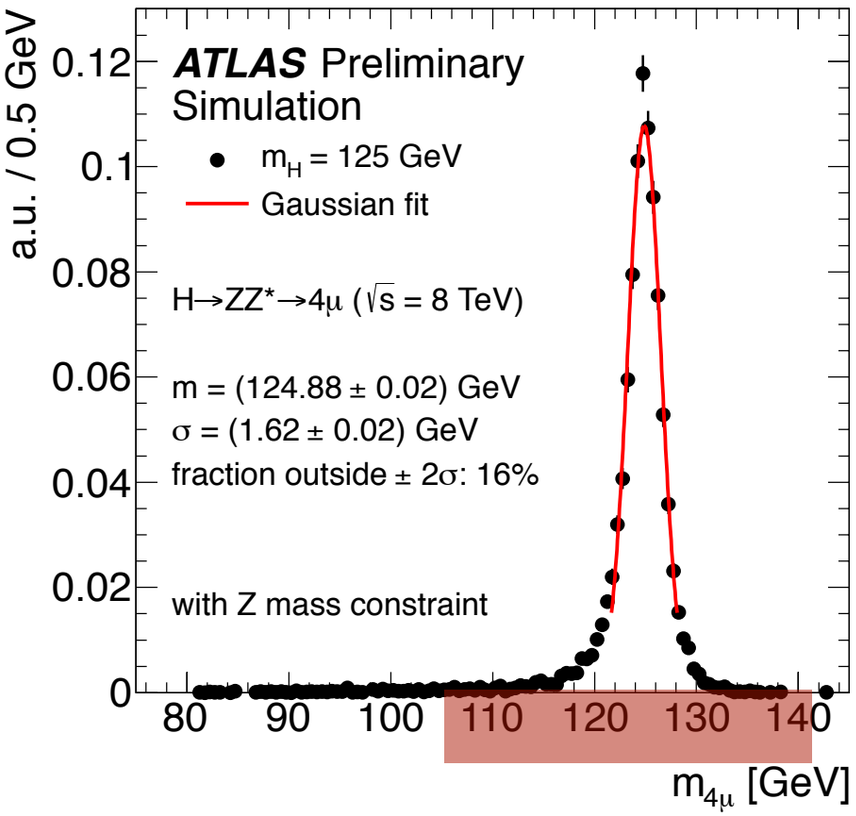
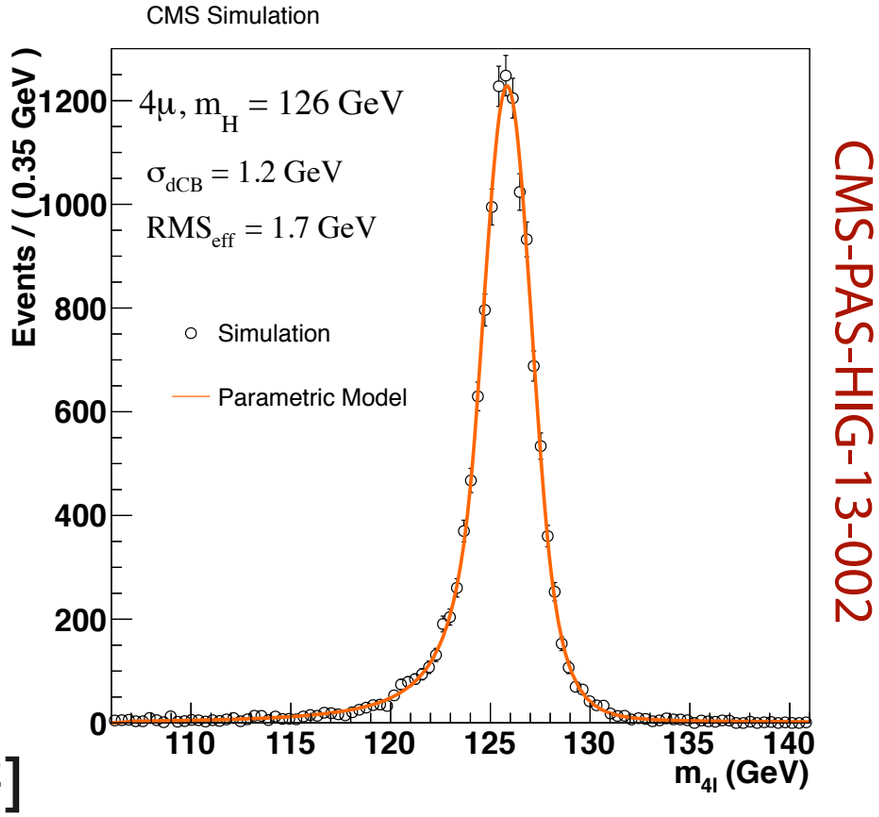
M_{4l} resolution

Mass constraint on Z_1 : refit momentum parameters of leptons, using covariance matrix and Z line shape



No refitting, strong magnetic field provides great resolution and M_{Z1} directly used in definition of K_D



Resolution [GeV/c²]

	4μ	2μ2e	4e
ATLAS	1.6	1.9	2.4
CMS	1.2	1.7	2.0

Backgrounds

Same strategy adopted by both experiments:

Irreducible background (ZZ): taken from Monte Carlo

Samples used: POWHEG+Pythia6 ($qq \to ZZ$), gg2zz+Pythia6 ($gg \to ZZ$),

Sherpa (ATLAS, for $ZZ^{(*)}qq'$)

Reducible backgrounds (tt, Z+jets):

$\Rrightarrow$ Measure yields in control region (Z+XX or Z+ℓ+X)

$\Rrightarrow$ Extrapolate to signal region with transfer factors taken from MC/data

(control regions built by relaxing and/or inverting

identification cuts or isolation cuts)

Results of event selection

	ATLAS (25.3 fb^{-1})	CMS (24.7 fb^{-1})	
M_H range [GeV/c^2]	**100-160**	**110-160**	
Signal (M_H=125)	6.8 ± 0.7	6.8 ± 0.8	**4μ**
ZZ	14.6 ± 0.6	13.8 ± 1.0	
Reducible Bkg.	2.1 ± 0.6	1.6 ± 0.6	
Total expected	**23.5 ± 1.1**	**22.2 ± 1.4**	
Observed	**35**	**23**	
Signal (M_H=125)	8.1 ± 0.9	8.9 ± 1.0	**2e2μ**
ZZ	17.2 ± 0.9	18.1 ± 1.3	
Reducible Bkg.	8.5 ± 0.2	4.0 ± 1.6	
Total expected	**33.8 ± 1.3**	**31.0 ± 2.3**	
Observed	**33**	**32**	
Signal (M_H=125)	3.3 ± 0.4	3.5 ± 0.5	**4e**
ZZ	6.2 ± 0.5	6.6 ± 0.8	
Reducible Bkg.	4.5 ± 0.8	2.5 ± 1.0	
Total expected	**14.0 ± 1.0**	**12.6 ± 1.4**	
Observed	**15**	**16**	

Some experimental systematics

Expected signal rate:

for $m_H = 125$ GeV/c^2	100 GeV/$c^2 < m_H < 1$ TeV/c^2
$4\mu = 0.8\%$	$4\mu = 2.9$-4.3%
$4e = 9.4\%$	$4e = 5.5$-11%

Expected rate for reducible backgrounds:

$4\mu = 30\%$	$4\mu = 40\%$
$4e = 20\%$	$4e = 40\%$

Mass shift induced by energy scale systematics:

$4\mu = 0.2$ %	$4\mu = 0.1\%$
$4e = 0.4$ %	$4e = 0.3$ %

Analysis workflow: ATLAS

Explained selection, then branching into each different topic:

Mass measurement

Inclusive fit to M_{4l}

(M_{4l} distribution modeled using templates from Monte Carlo)

Spin/CP

Two different approaches, BDT and J^P MELA (see later)

Couplings

Events split into ggF-like, VBF-like and VH-like categories

Analysis workflow: CMS

Use a signal/background kinematic discriminant:

$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, M_{Z1}, M_{Z2}|M_{4\ell}) = P_{sig}/(P_{sig} + P_{bkg})$$

***P* defined using matrix element techniques**

- Analytical parametrization, JHUGen, MCFM and Madgraph studied – similar performance
- Use JHUGen for signal, MCFM for ZZ
- Include interference in same-flavour final states
- cross-check with machine training techniques (BDT, BNN)

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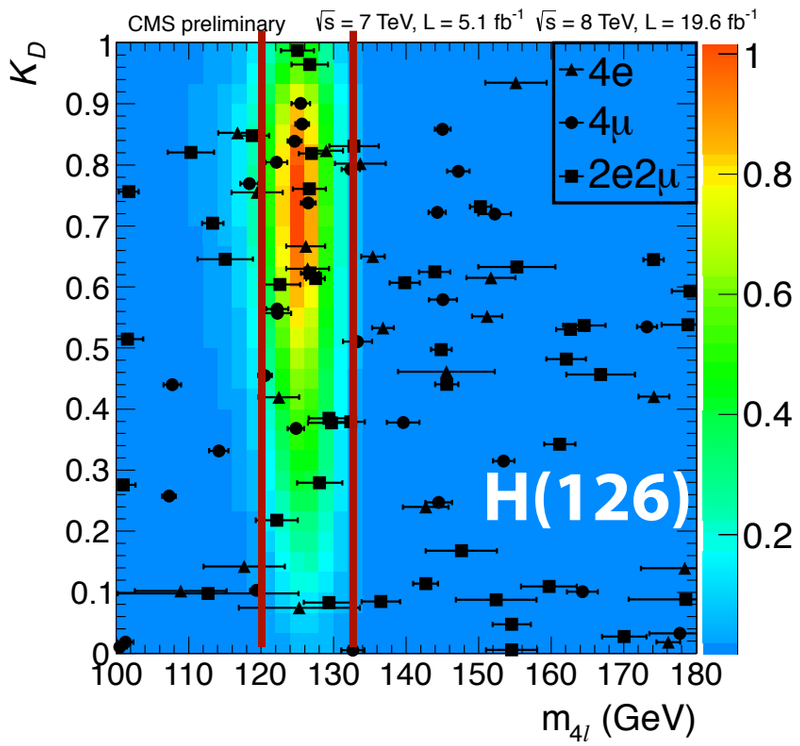
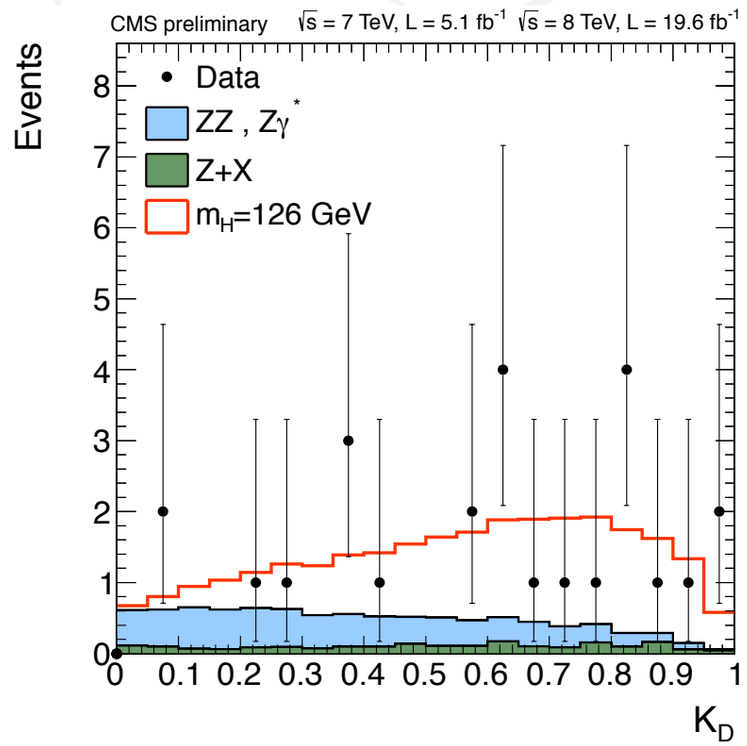




CMS-PAS-HIG-13-002

Analysis workflow: CMS

"3D" models: $P(M_{4\ell}, K_D, \xi) = P(M_{4\ell}|M_X) \times P(K_D|M_{4\ell}) \times P(\xi|M_{4\ell})$

Analytic: BW⊗DCB — 2D templates

ξ =

Mass measurement

Event-by-event M_{4l} estimated uncertainty

Significance, μ, Couplings

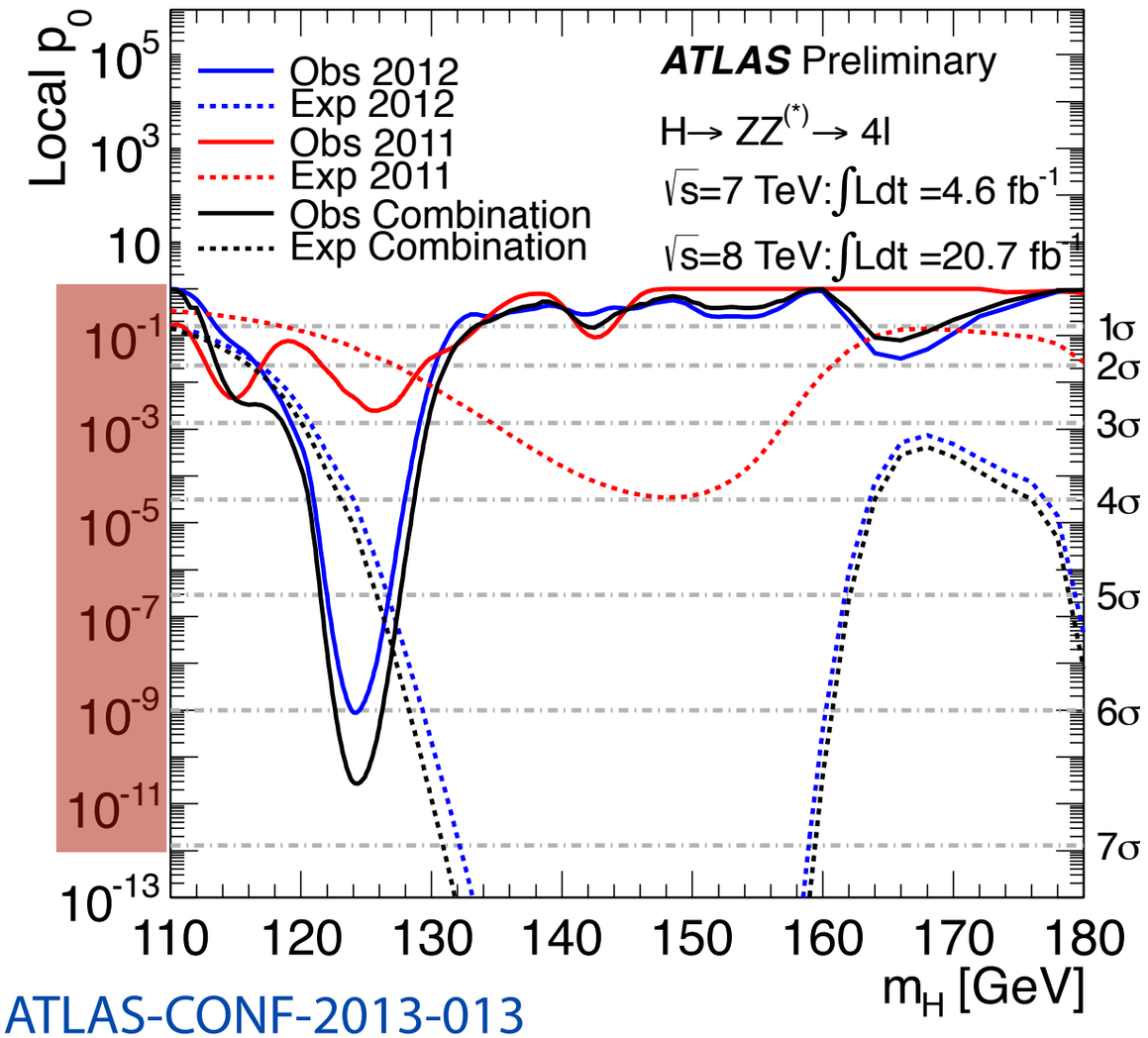
VBF sensitive variable:
- **Di-jet tag: V_D= linear combination of M_{JJ}, $\Delta\eta_{JJ}$**
- **Untagged: p_T/M_{4l} (Use HRes to reweight ggH p_T spectrum)**

Spin/CP

D_{JP}: SM vs J^P discriminant built from Matrix Element likelihood technique

Significance, Mass and Signal Strenght

Significance



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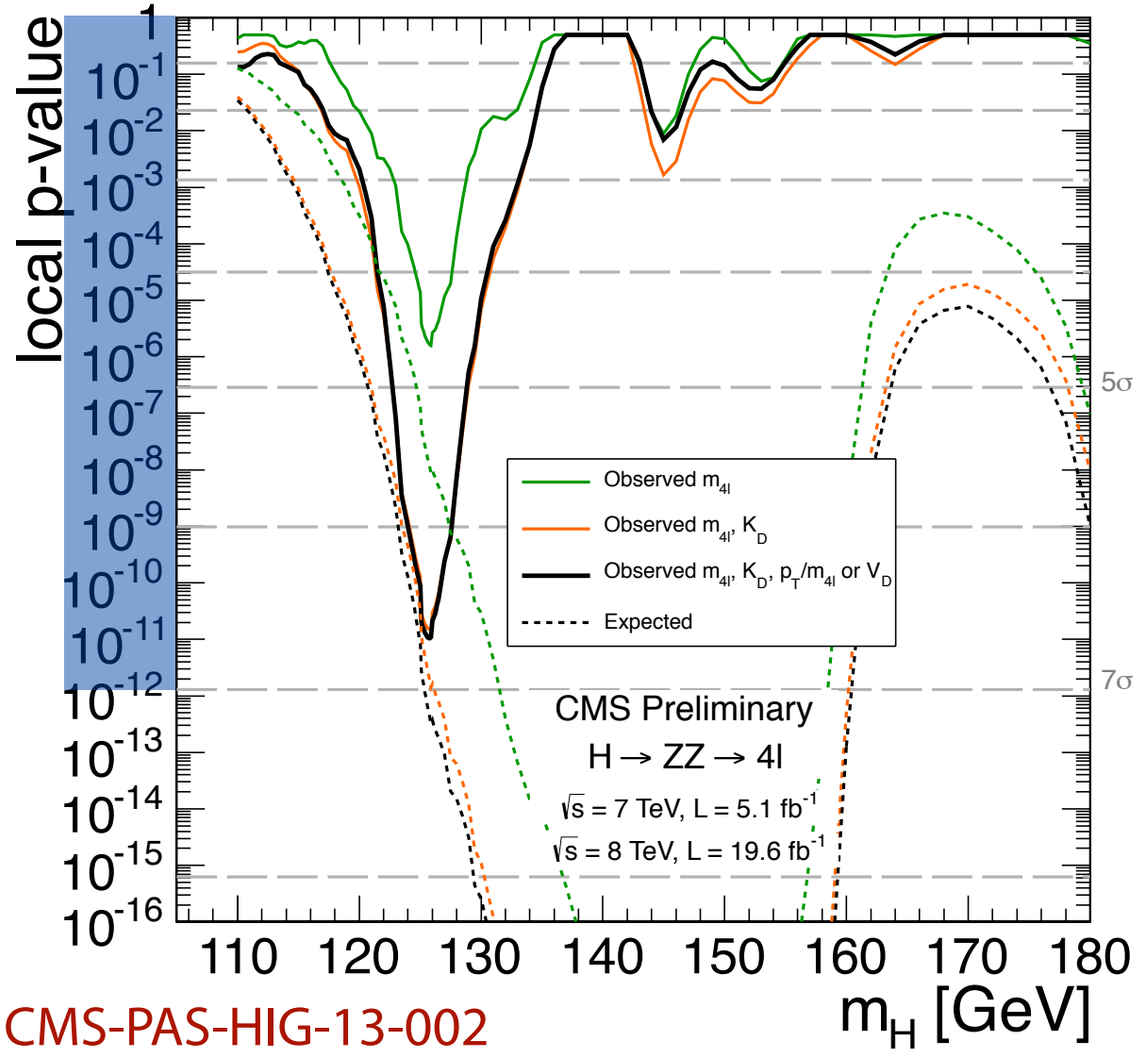
	Expected*	Observed
only M_{4l}	4.4 σ	6.6 σ

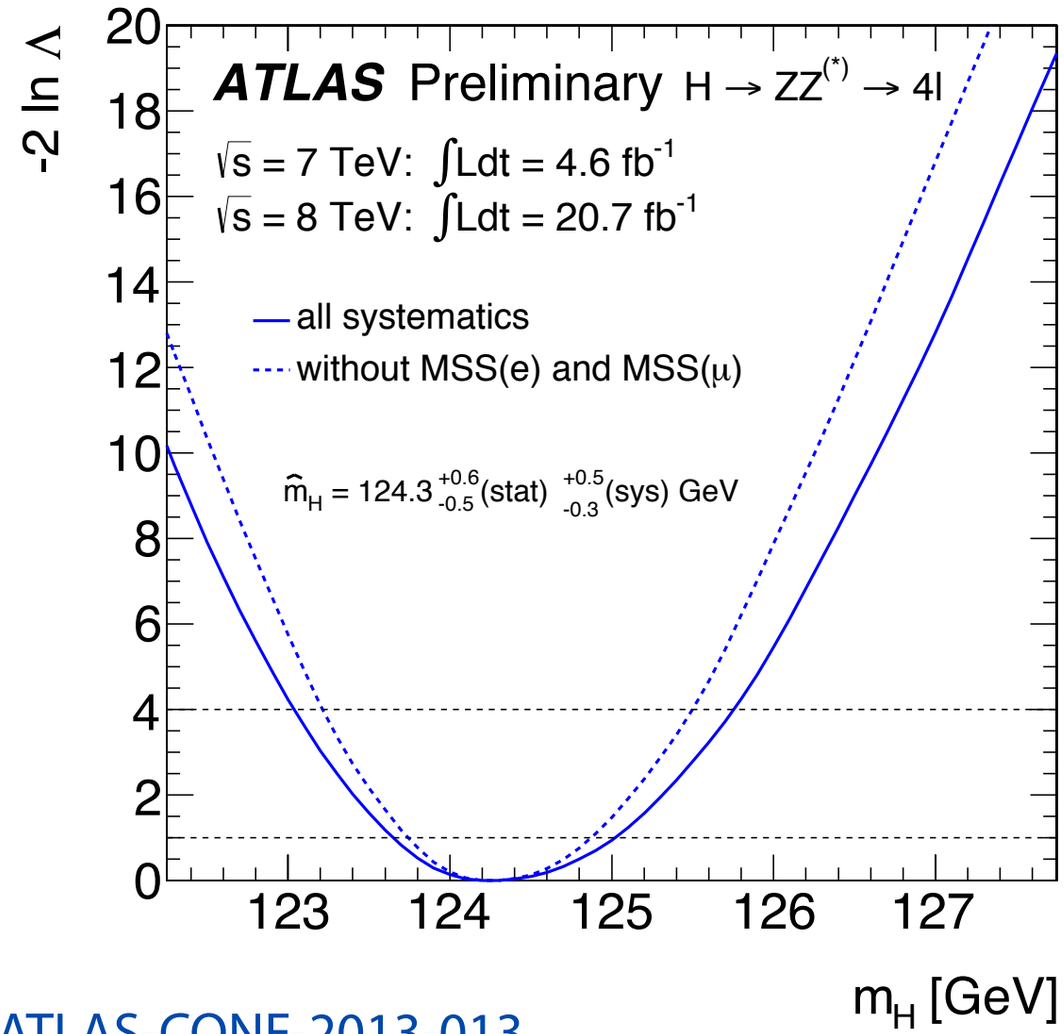
*evaluated at minimum p_0



CMS-PAS-HIG-13-002

	Expected*	Observed
only M_{4l}	5.6 σ	4.7 σ
with K_D and categories	7.2 σ	6.7 σ

Mass measurement



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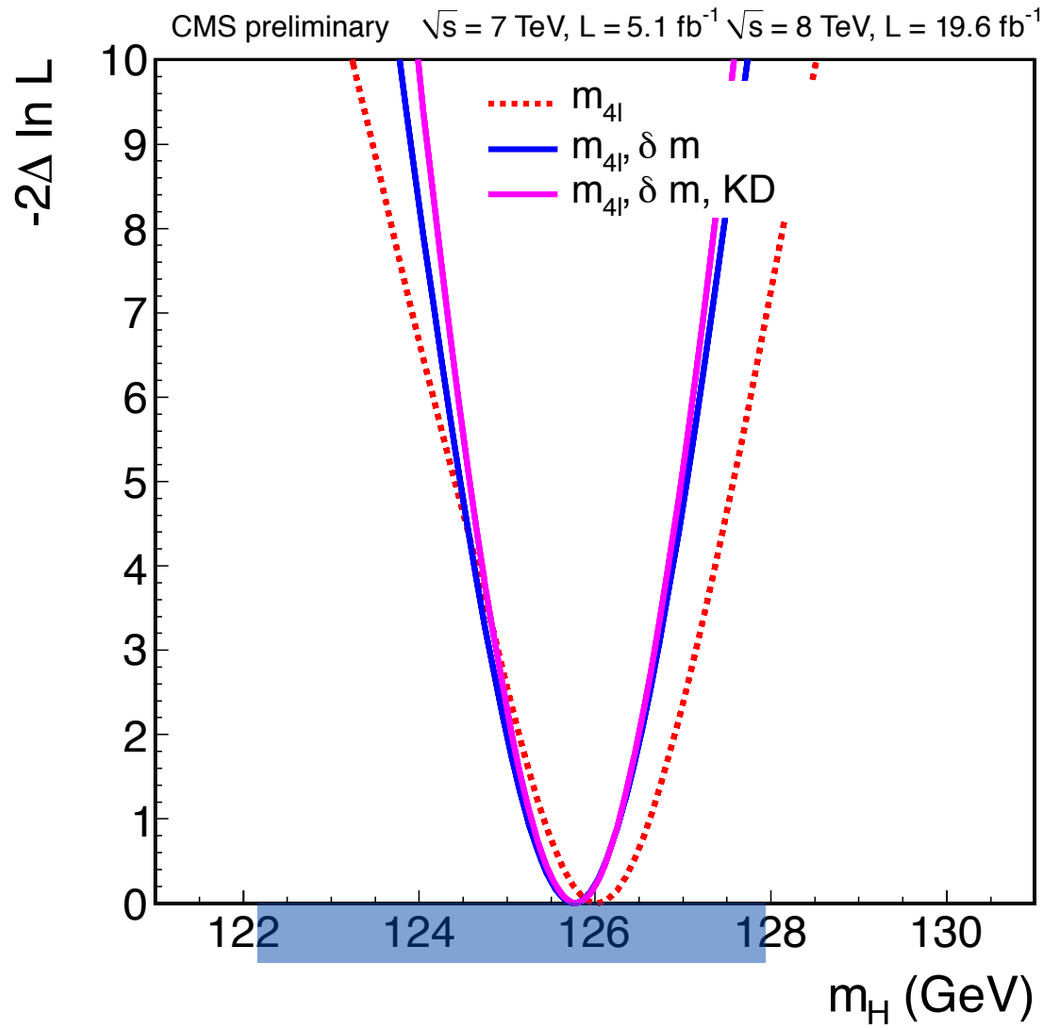


CMS-PAS-HIG-13-002

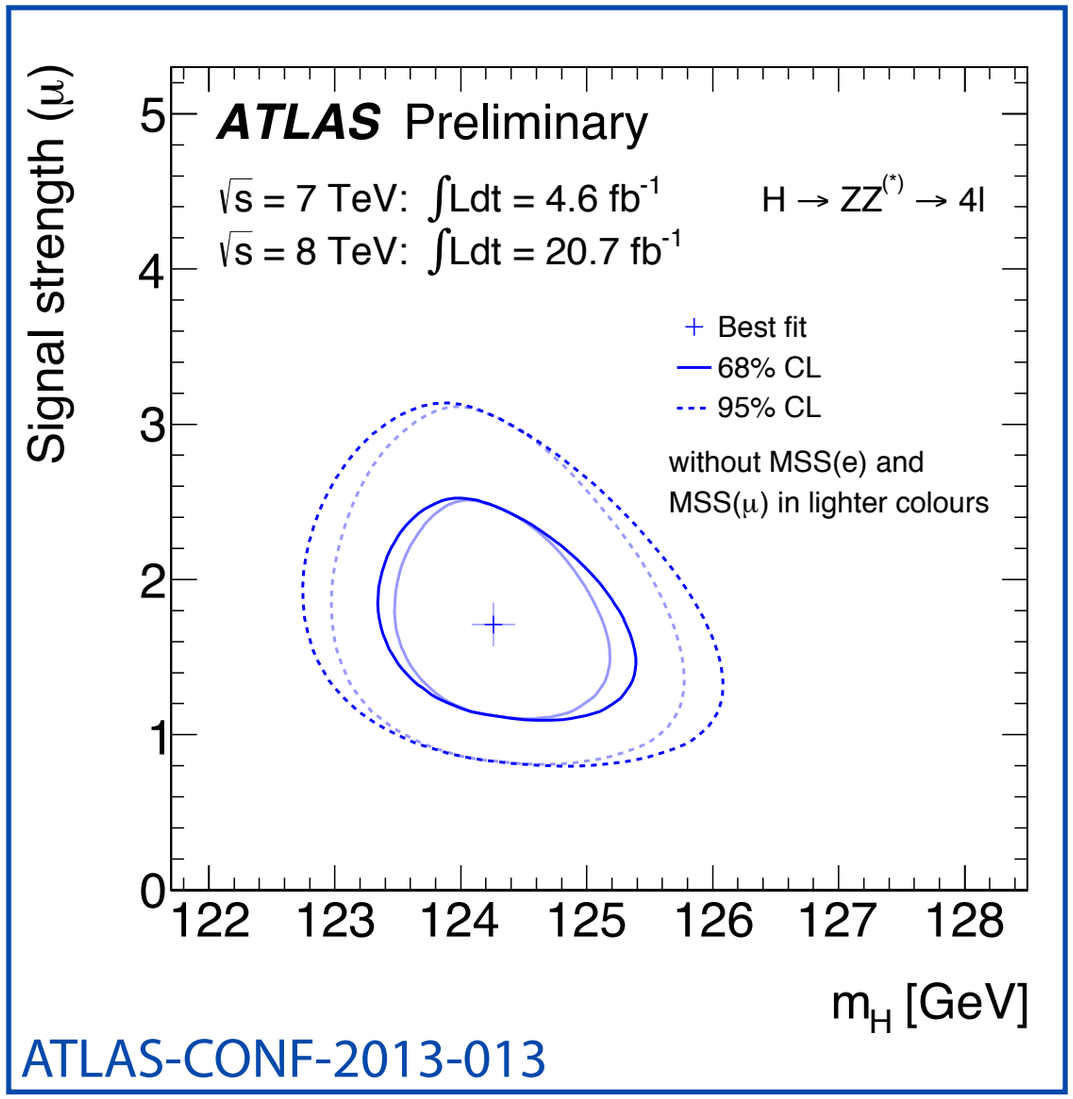
Inclusive fit to M_{4l}

Inclusive fit to M_{4l}, K_D and per-event errors

$M_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV/c²

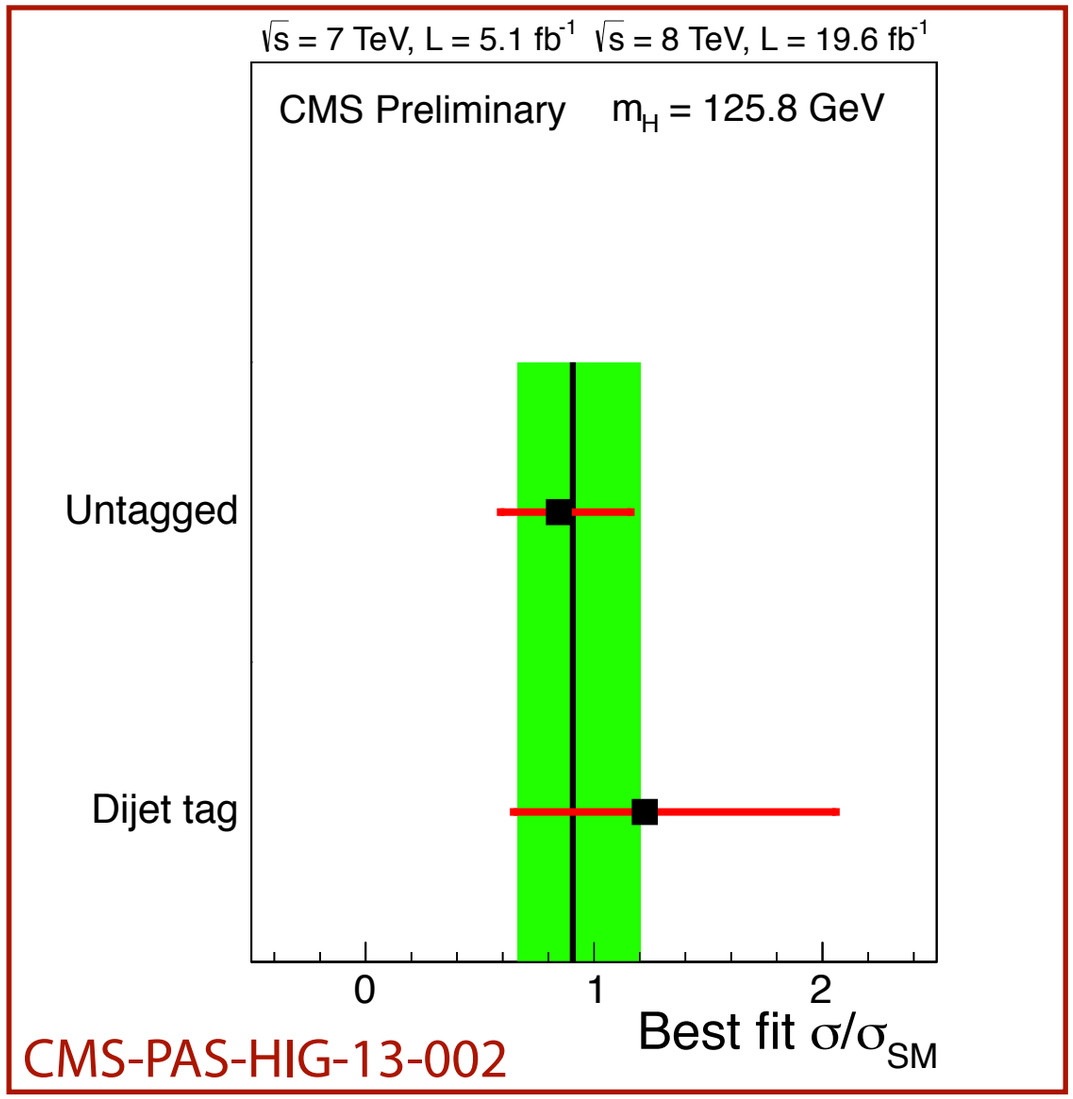
$M_H = 125.8 \pm 0.5 \pm 0.2$ GeV/c²

Signal strength



Inclusive fit to M_{4l}

μ at 124.3 GeV/c² : 1.7 $^{+0.5}_{-0.4}$



Inclusive fit to M_{4l}, K_D and

p_T/M_{4l} (V_D) for Category 1 (2)

μ at 125.8 GeV/c² : 0.91 $^{+0.3}_{-0.24}$

Spin/CP

Methods: ATLAS

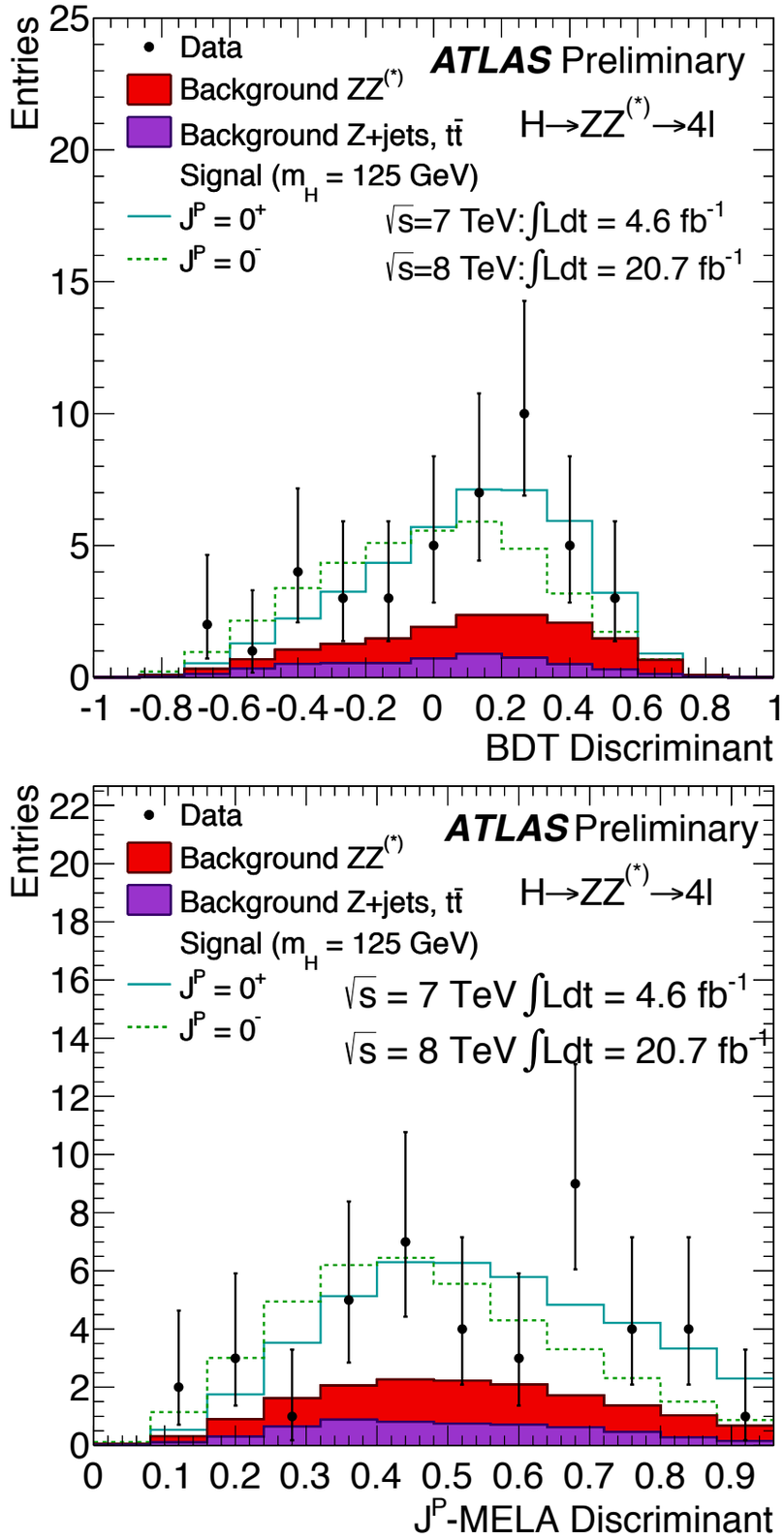
Two different approaches:

Boosted decision tree

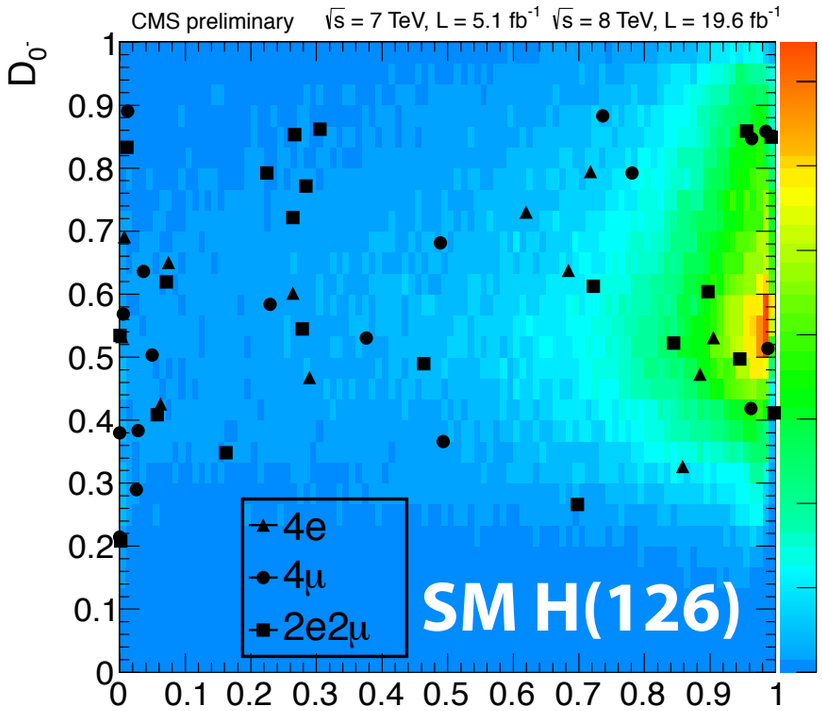
J^P discriminant formed for each pair of spin hypotheses to be tested

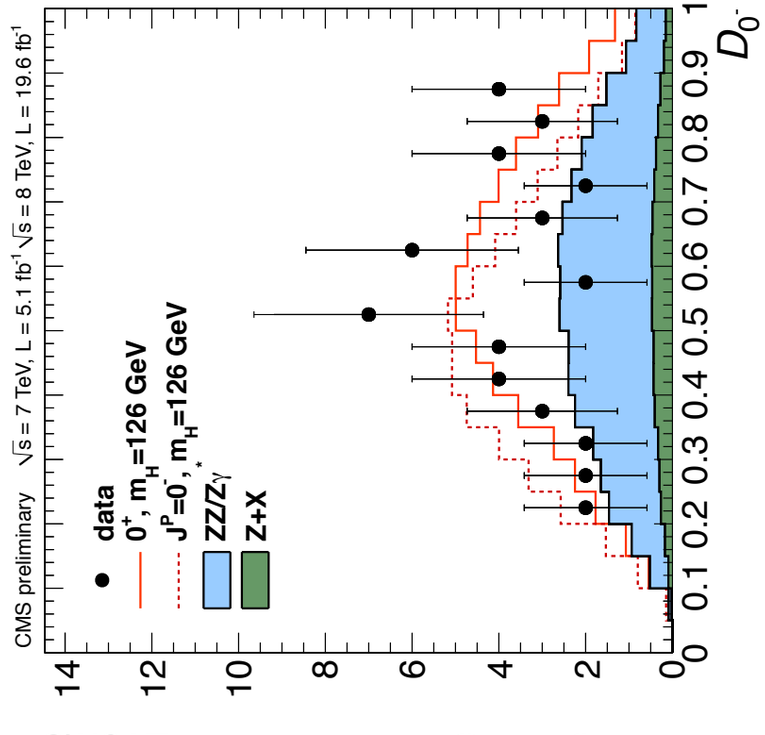
MELA approach

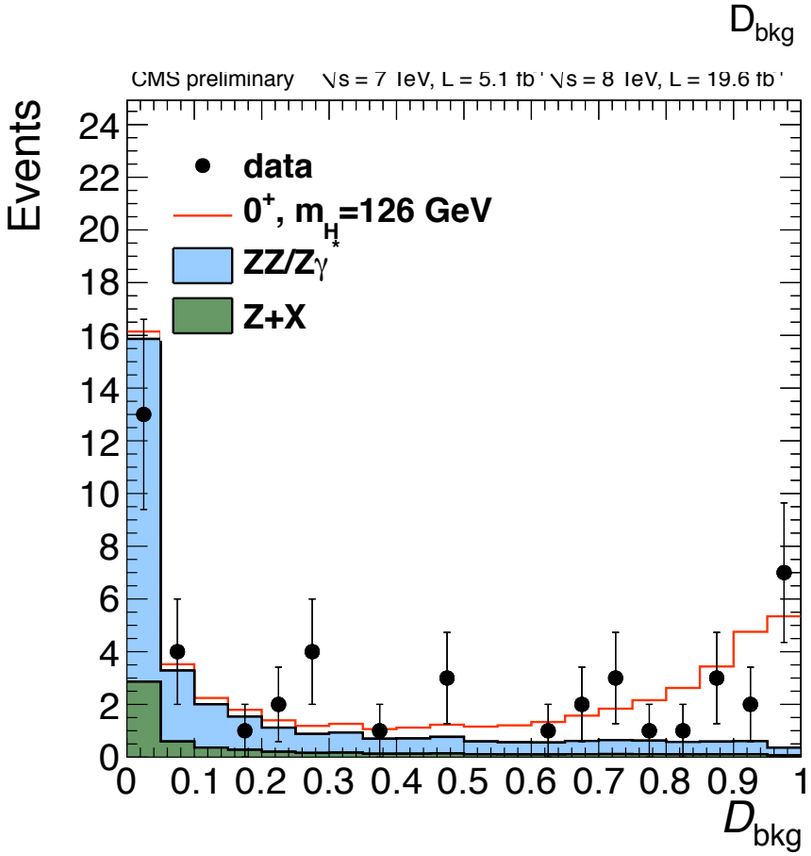
The theoretical decay rates for the variables used in the discriminant (angles, M_{12} and M_{34}) are corrected for detector acceptance and analysis selection



Methods: CMS







2D fit of events in $106<M_{4l}<141$ GeV/c^2:

- D_{bkg} = combination of M_{4l} and K_D (discriminates signal vs background)

- $D_{JP} = P_{SM} / (P_{SM} + P_{JP})$ (discriminates SM 0^+ vs J^P hypothesis)

In addition to hypothesis testing: first measurement of f_{a3} (indicates mixture of 0^+ and 0^-states)

Results

ATLAS (BDT)					ATLAS (j^P MELA)			
j^P	expected	obs. 0^+	obs. j^P	CL_S	expected	obs. 0^+	obs. j^P	CL_S
0^-	2.7σ	0.5σ	2.2σ	0.022	3.1σ	0.2σ	2.8σ	0.004
1^-	2.7σ	1.0σ	1.6σ	0.060	3.1σ	1.2σ	1.9σ	0.031
1^+	2.9σ	-0.1σ	3.1σ	0.002	2.7σ	0.0σ	2.8σ	0.006
2^+_{mgg}	1.3σ	-0.1σ	1.4σ	0.168	1.5σ	0.3σ	1.2σ	0.182
2^-	2.5σ	1.8σ	0.7σ	0.258	2.7σ	1.4σ	1.2σ	0.116

CMS				
j^P	expected	obs. 0^+	obs. j^P	CL_S
0^-	2.6σ	0.5σ	3.3σ	0.0016
0^+_m	1.7σ	0.0σ	1.7σ	0.081
1^-	2.8σ	1.4σ	>4.0σ	<0.001
1^+	2.3σ	1.7σ	>4.0σ	<0.001
2^+_{mgg}	1.8σ	0.8σ	2.7σ	0.015
2^+_{mqq}	1.7σ	1.8σ	4.0σ	<0.001

Couplings

Categorization details

If $n_{Jets} \geq 2$ and $\Delta\eta_{JJ} > 3$ and $M_{JJ} > 350$ GeV/c^2

⇓

VBF category

otherwise if additional lepton

(isolated and with $p_T > 8$ GeV/c) is found

⇓

VH category

otherwise

⇓

ggF category

Same categorization as before!

If $n_{Jets} \geq 2$

⇓

di-jet category

(V_D used for ggF/VBF separation)

otherwise

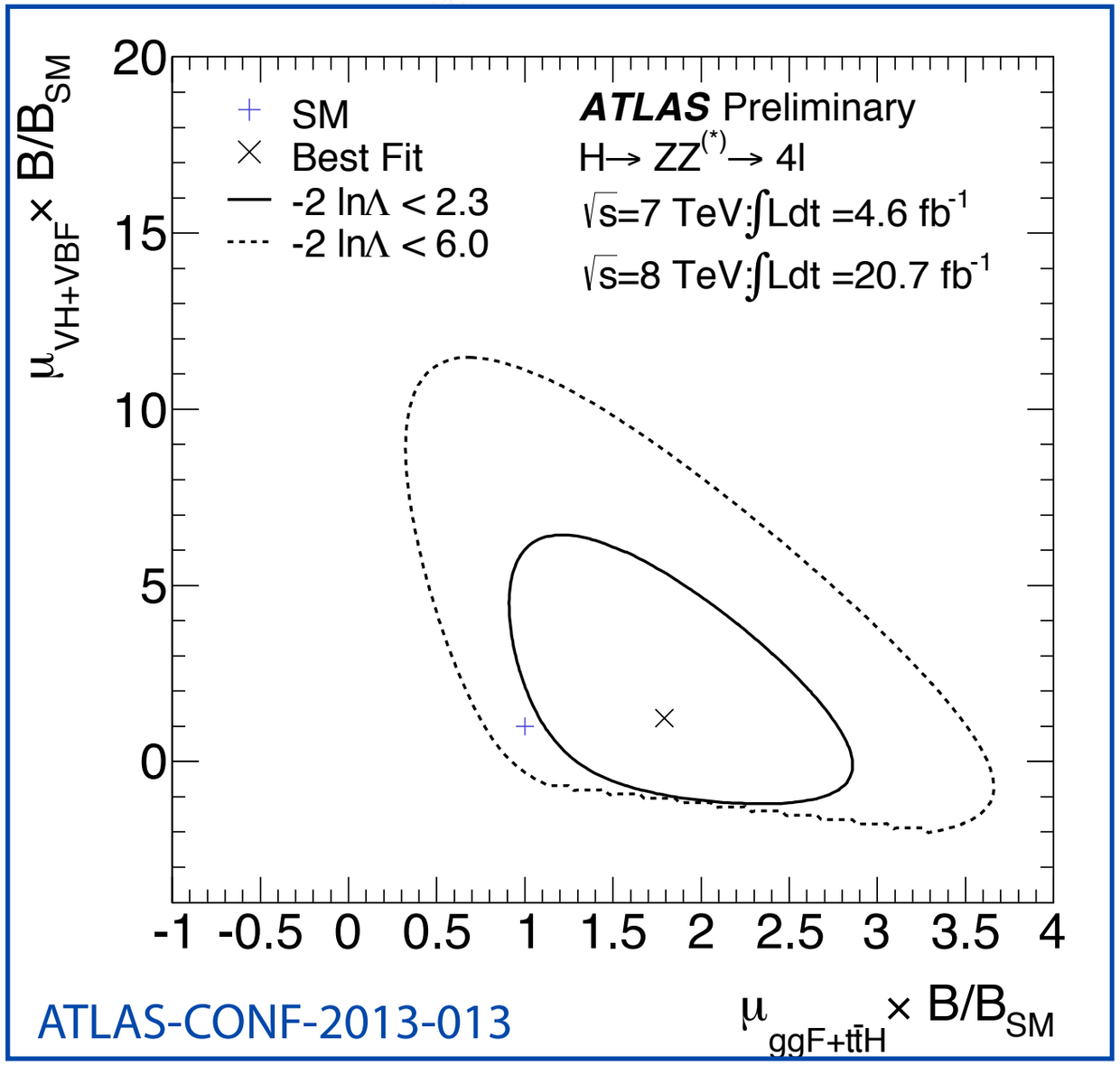
⇓

untagged category

(p_T/M_{4l} used for ggF/VBF separation)

Coupling results

Mass profiled



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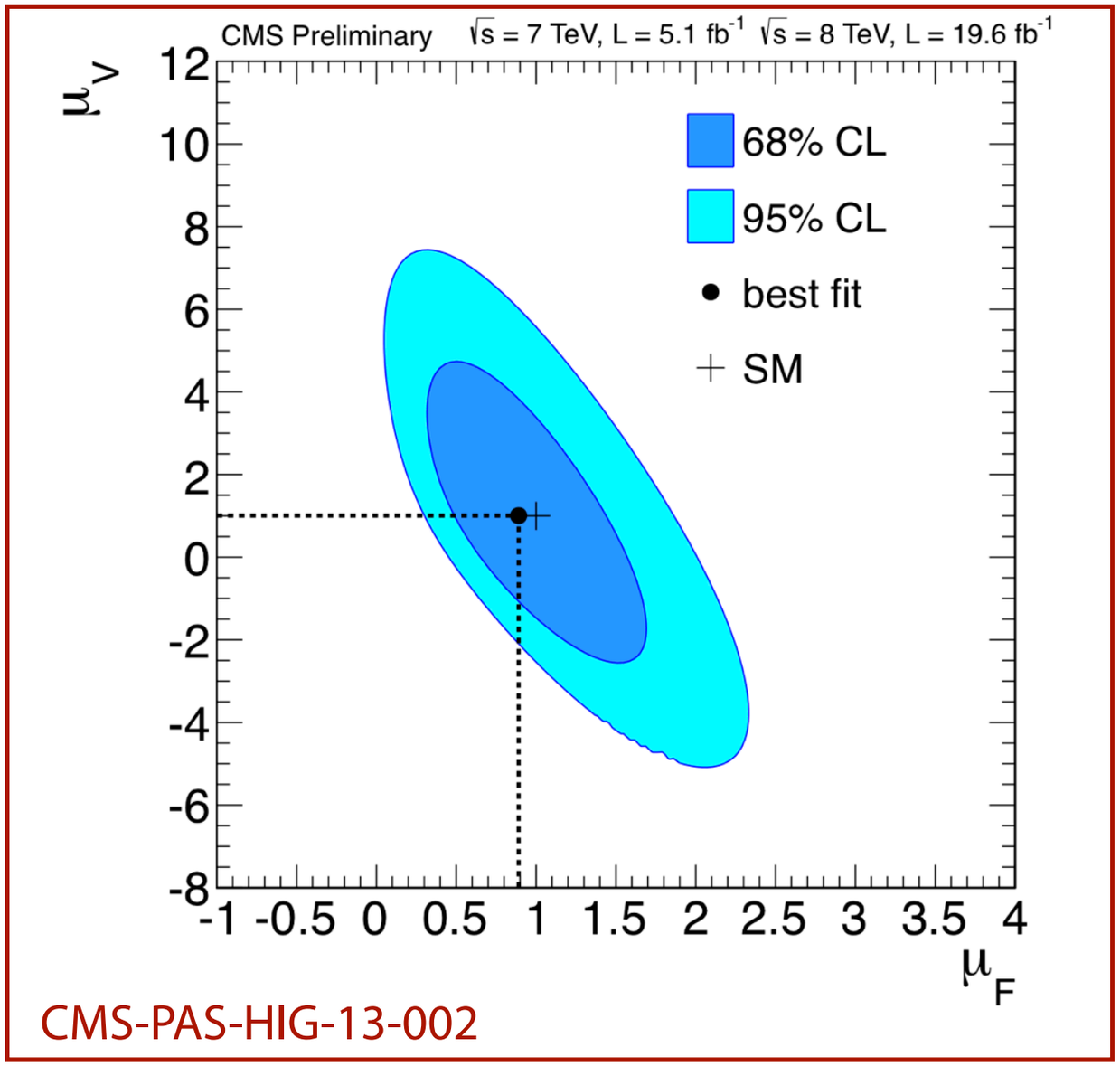
$\mu_F = 1.8^{+0.8}_{-0.5}$ $\mu_V = 1.2^{+3.8}_{-1.4}$

Mass fixed at best fit (125.8 GeV/c²)



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$\mu_F = 0.9^{+0.5}_{-0.4}$ $\mu_V = 1.0^{+2.4}_{-2.3}$

Conclusions

- The H→ZZ channel has played a major role in the Higgs discovery with Run 1 data

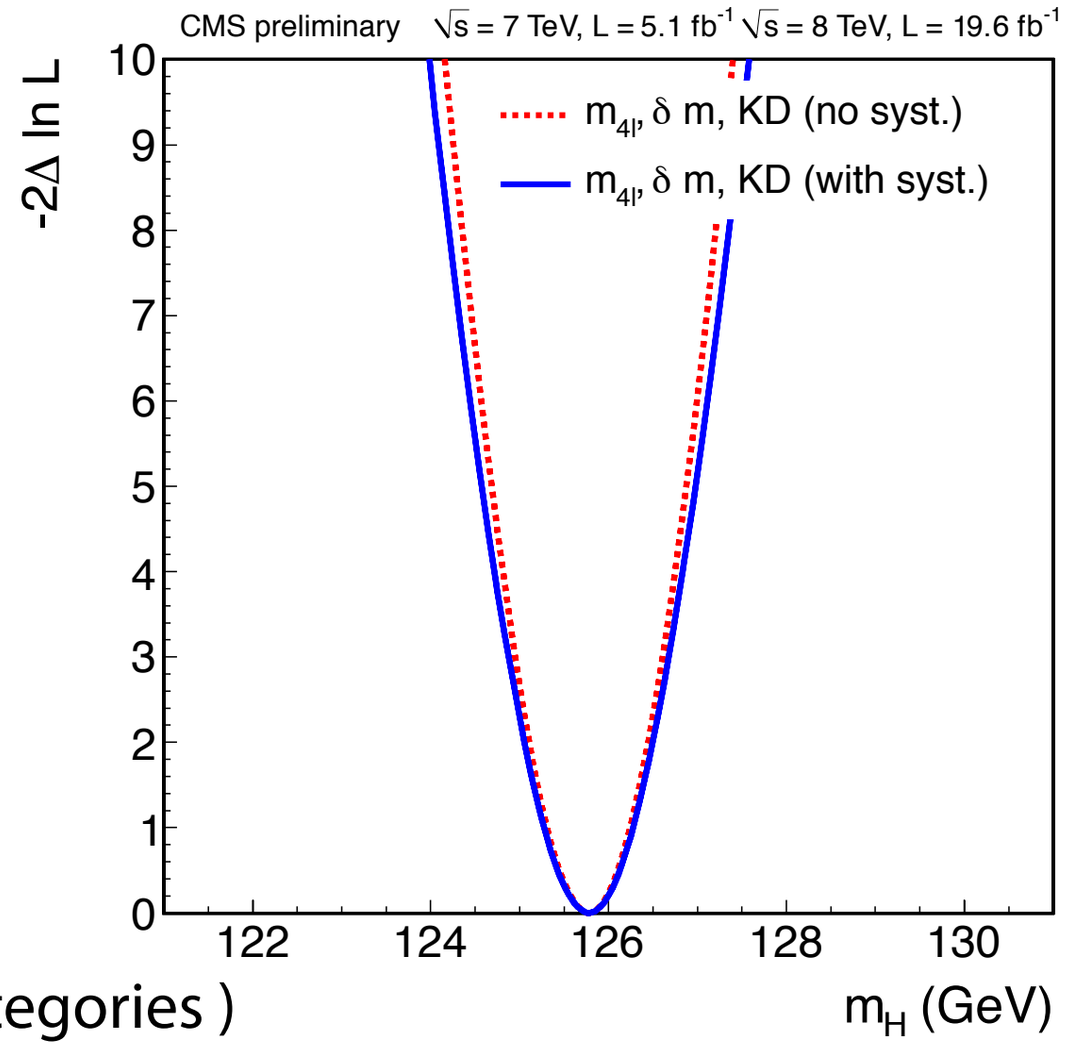
  The H→ZZ→4ℓ channel provides the best significance, can measure the Higgs mass with the highest precision and can shed light on the spin/CP of this particle

- Both collaborations put a lot of effort in these analyses and provided results which have been thoroughly cross-checked
- In general, this is an extremely mature analysis and there is not much room for improvement at the moment No substantial changes expected in the upcoming months!
- So far ATLAS and CMS have consistent results and so far we are both dominated by the statistical uncertainty
- What is interesting about this channel for the future?

Discussion

Systematics

- **This is a low-stat channel. Still fully dominated by statistics.**
  - Mass uncertainty could be still dominated by stat at the end of 2015…
  - Huge effort to keep energy scale uncertainties under control



- **Some critical theoretical uncertainties:**
  - gg→H + 2 jets (ggF contamination in VBF categories)
  - Knowledge of Higgs p_T spectrum

What next?

- **How will Run 2 data taking conditions affect our experimental results?**
  - Pile-up conditions affecting isolation, jets, electron resolution, etc.
  - Trigger conditions
  - Detector upgrades?
- **Do we need to review any of the methods/models used in obtaining our results?**
  - E.g. definition of FSR, Matrix element methods

What else?

- **What else can we do with more statistics at 14 TeV?**
  - J^P: move from hypothesis testing of pure J^P states to test/measure mixtures of different CP states (cf. f_{a3} measurement)
  - VH
  - Higgs Width
  - Search for multi-Higgses (including $H \to ZZ \to \ell\ell qq$ and $H \to ZZ \to \ell\ell\nu\nu$)
    - EW singlet mixing, 2HDM, ...

Backup

Lepton efficiencies

Muon Efficiency (ATLAS)

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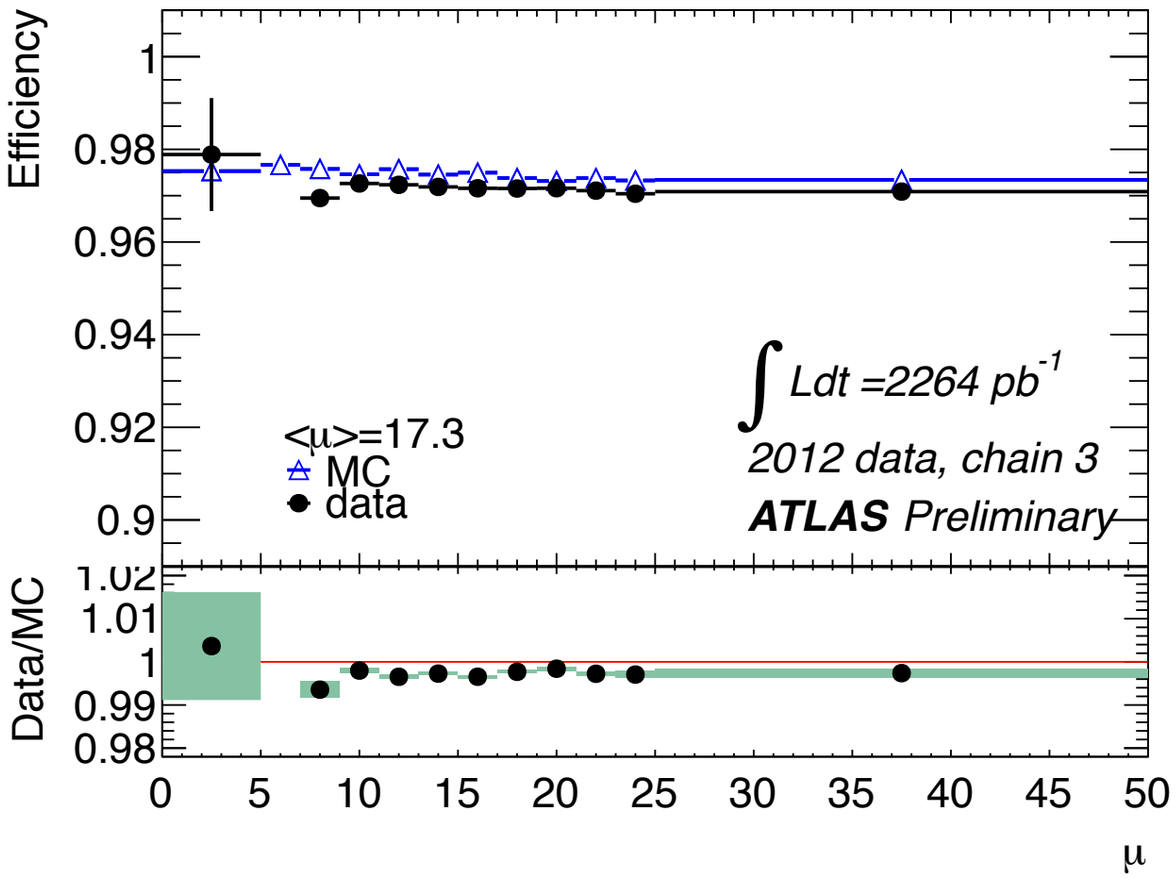

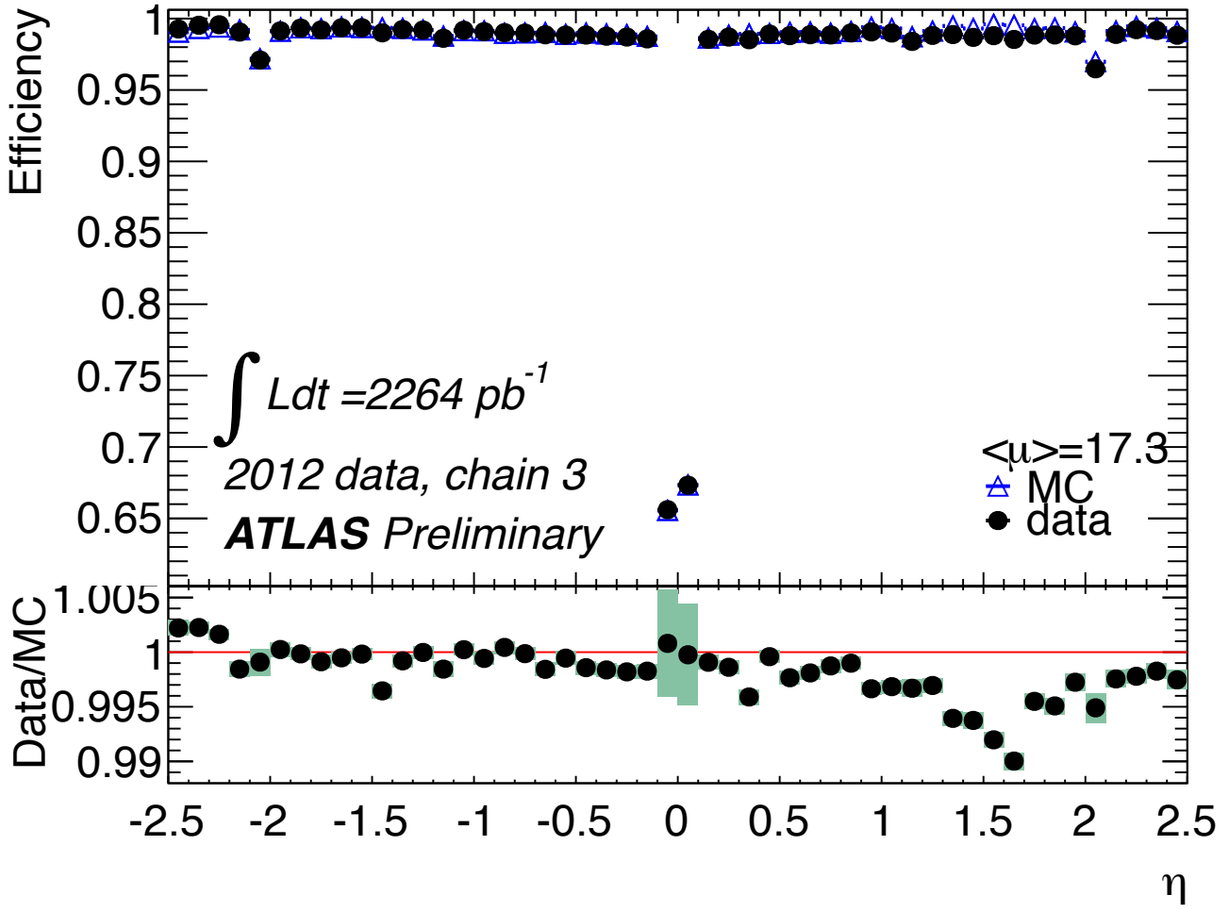

Muon Efficiency (CMS)

Reconstruction + Identification

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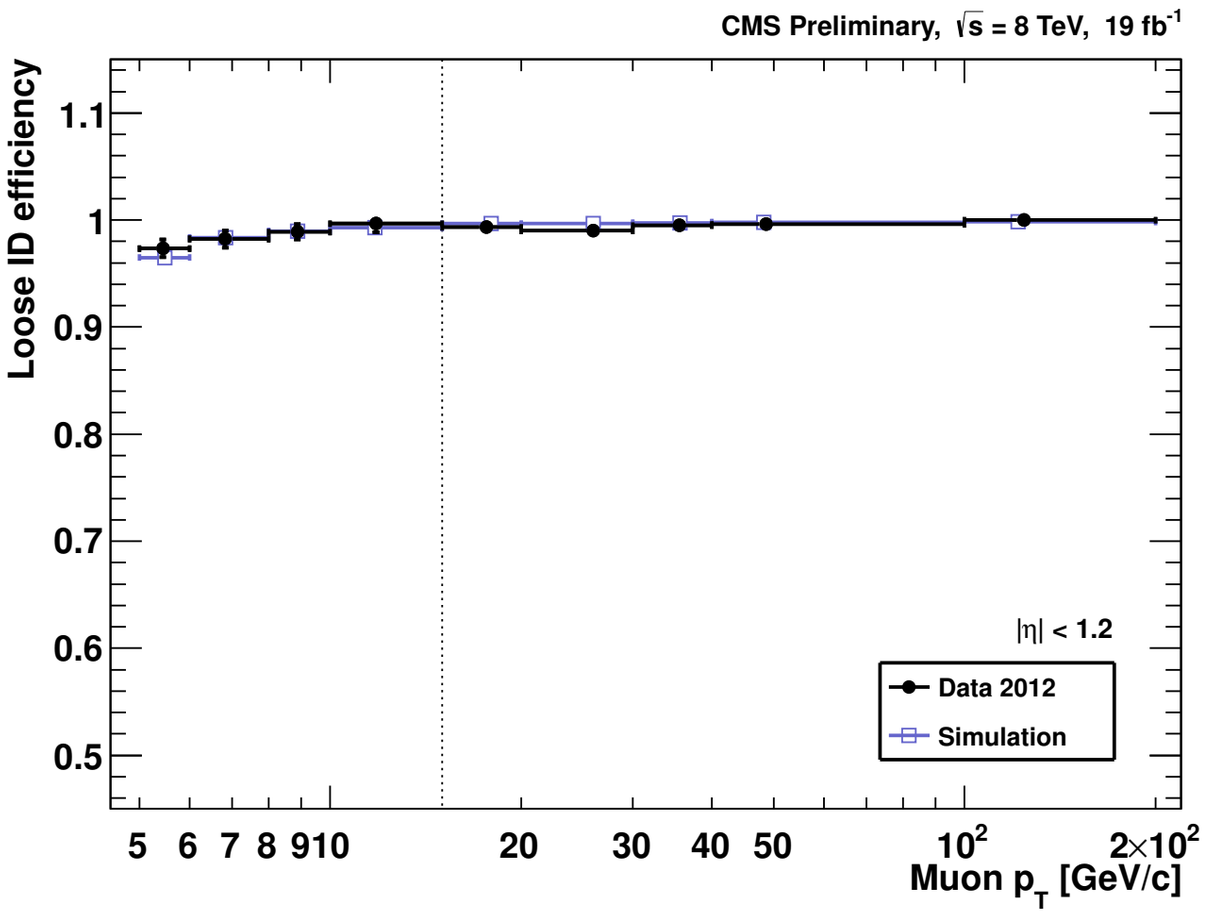
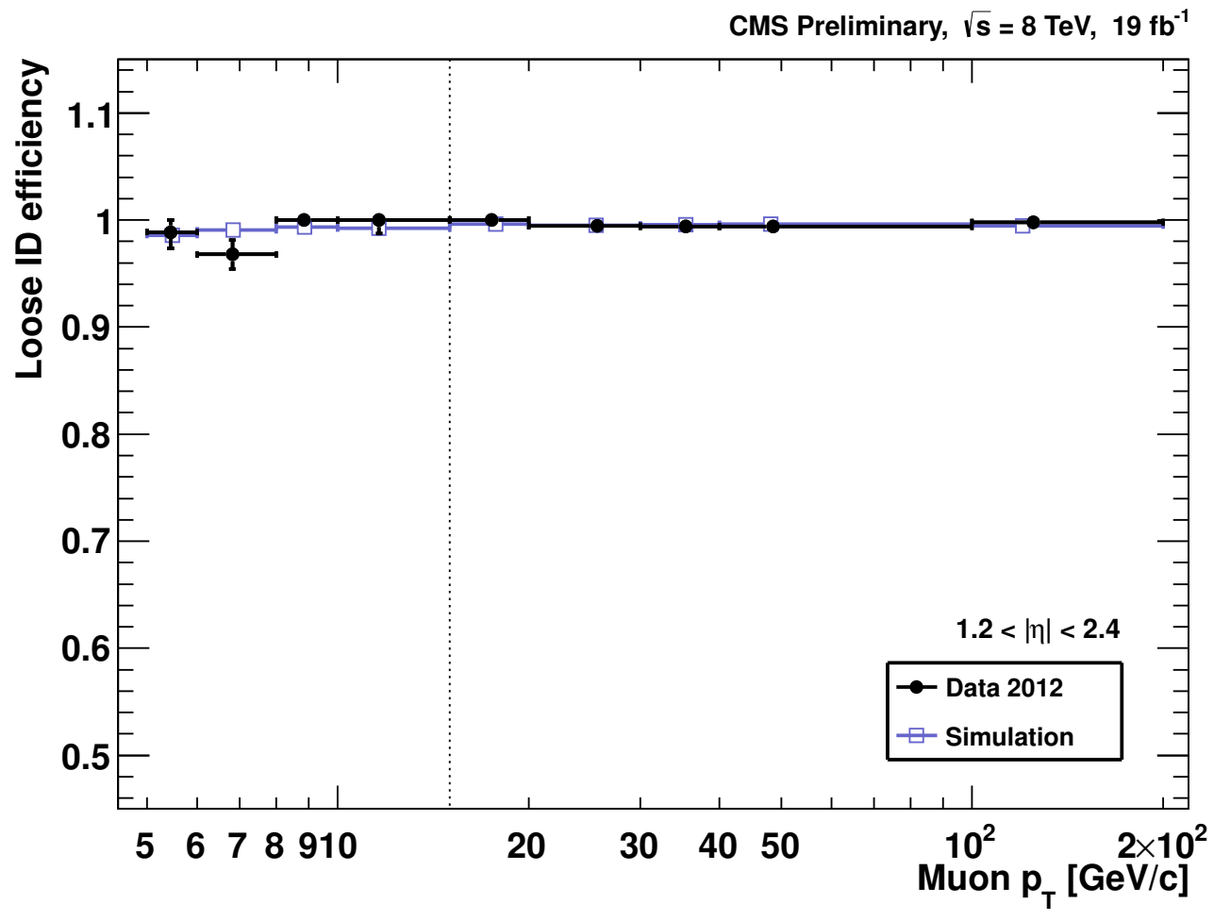
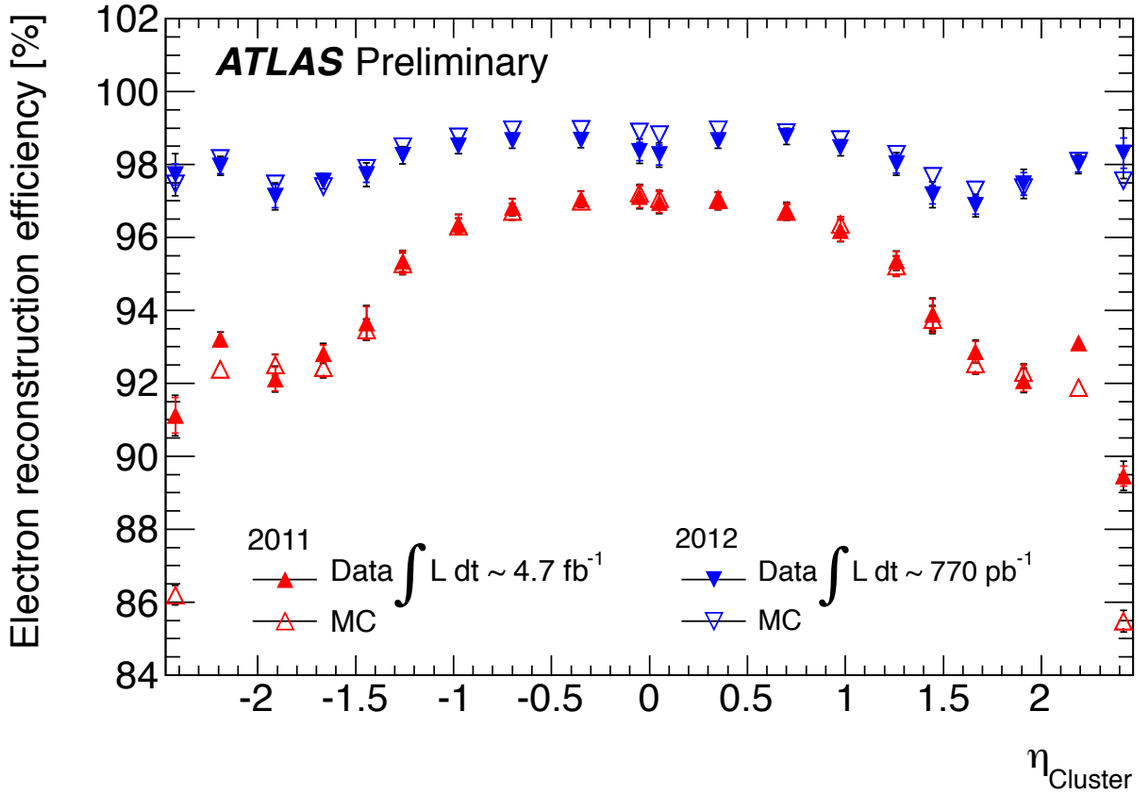
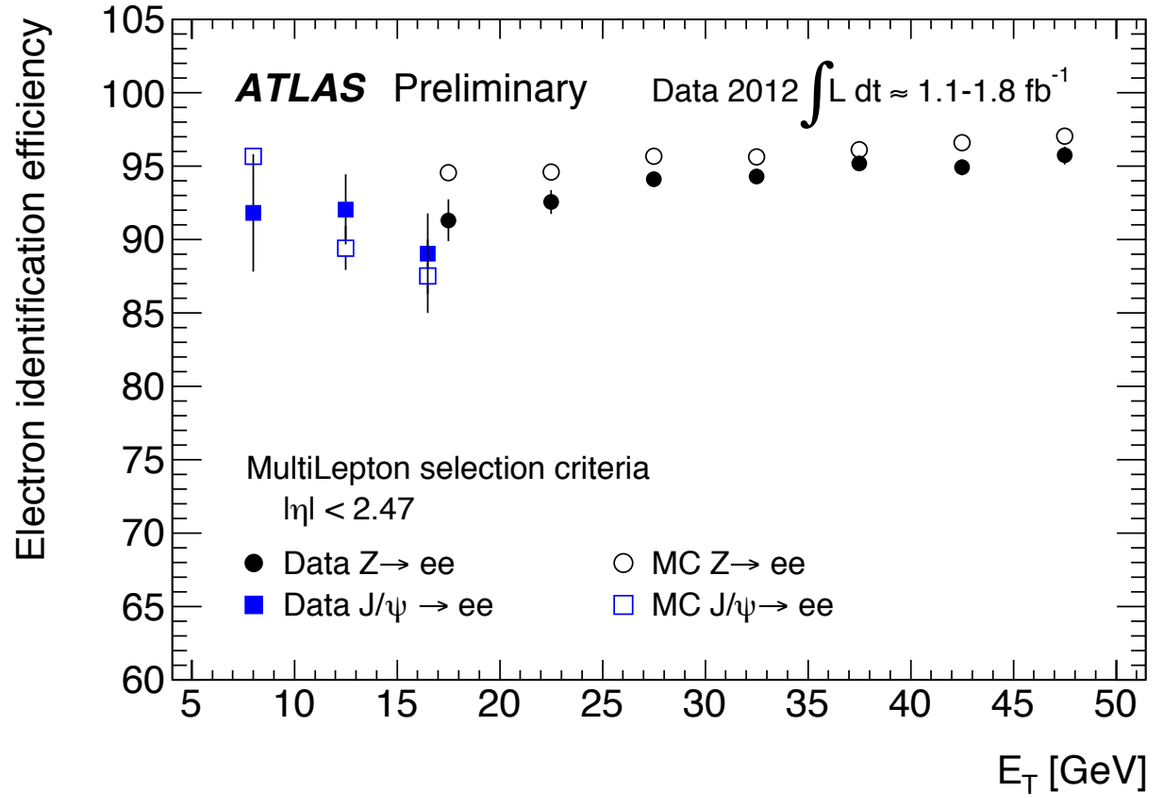




Electron Efficiency (ATLAS)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/EGAMMA/PublicPlots/20120611/ElectronEfficiency2012/ATL-COM-PHYS-2011-783/ATL-COM-PHYS-2011-783.pdf





Electron Efficiency (CMS)

Reconstruction + Identification + Isolation + SIP

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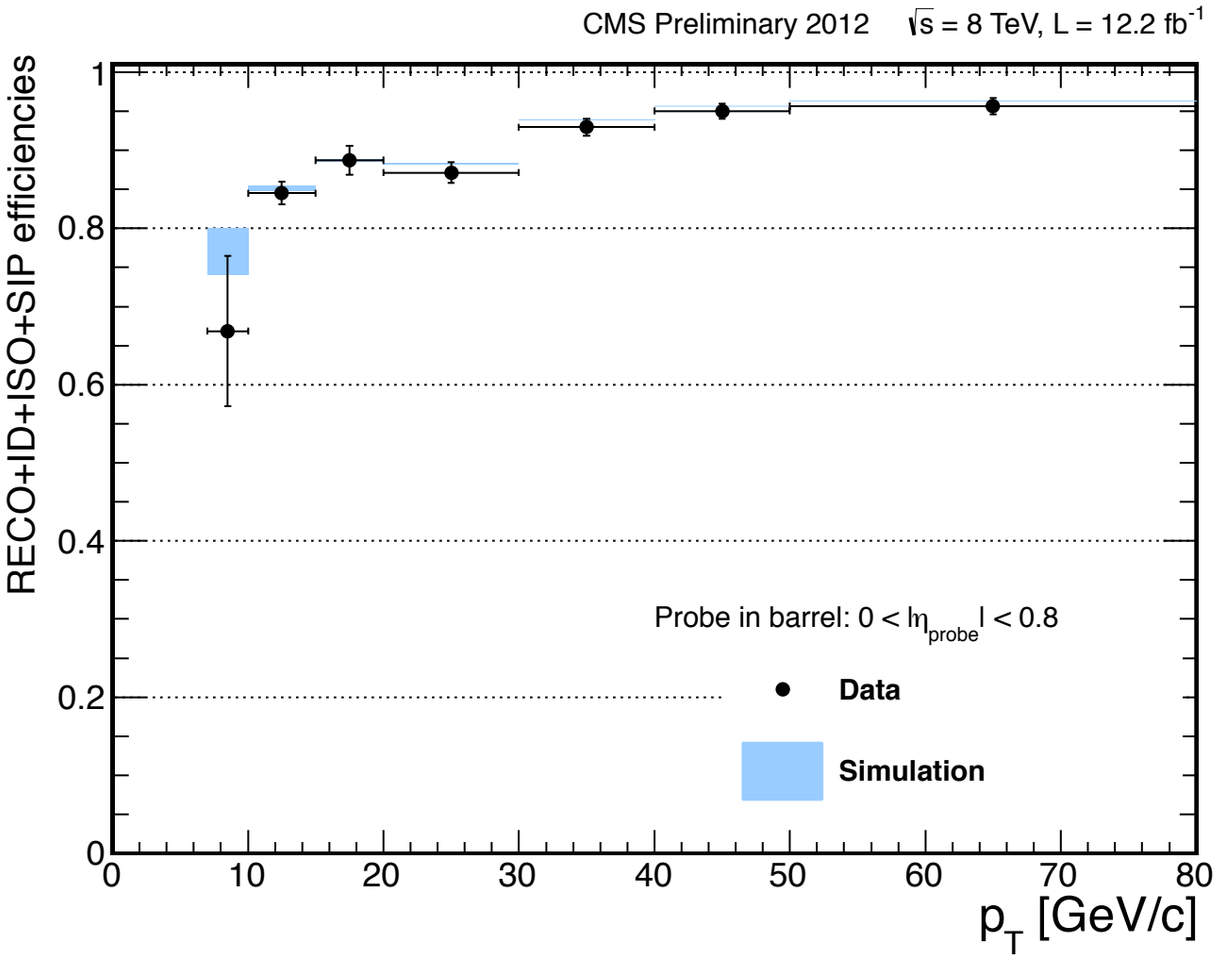
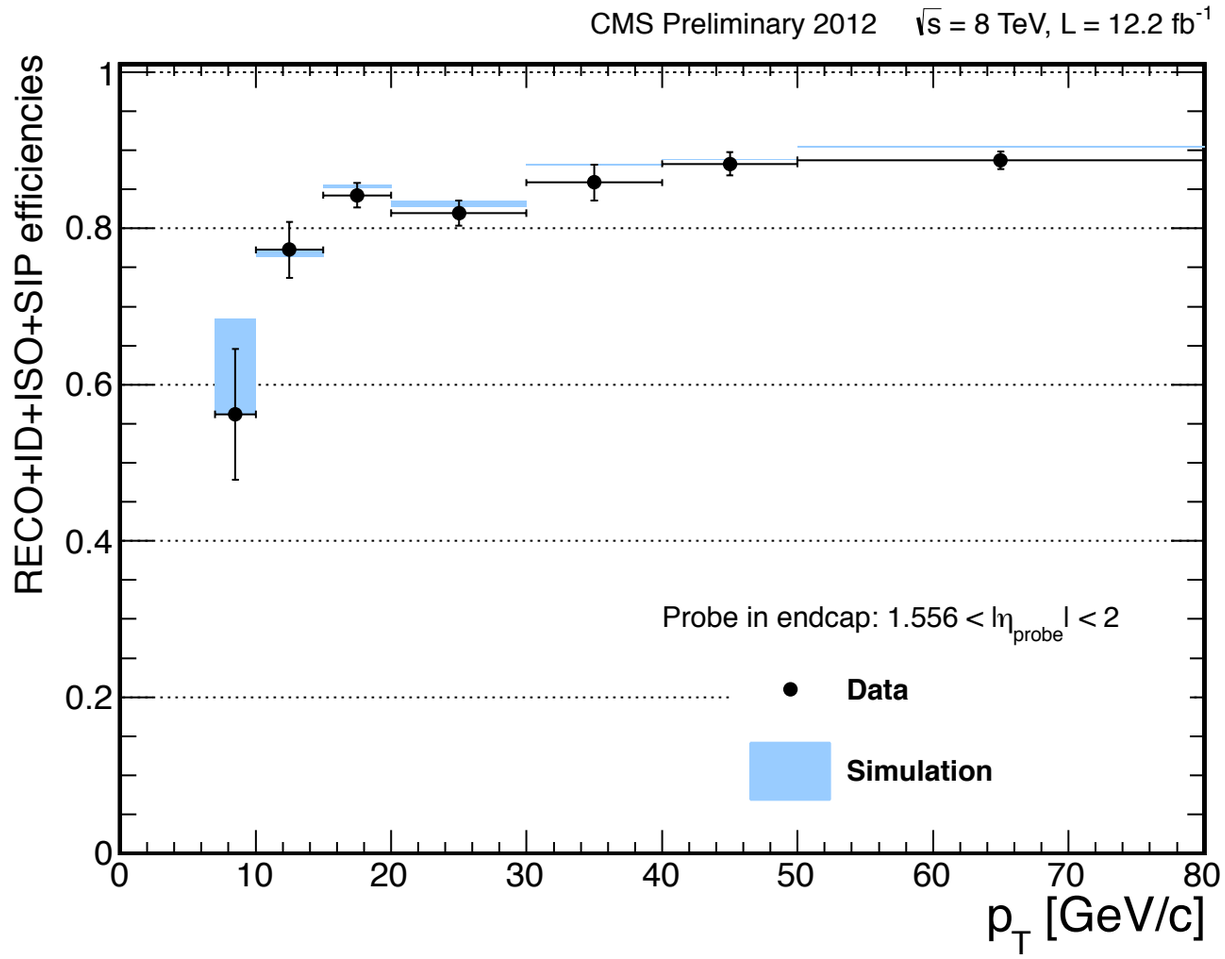
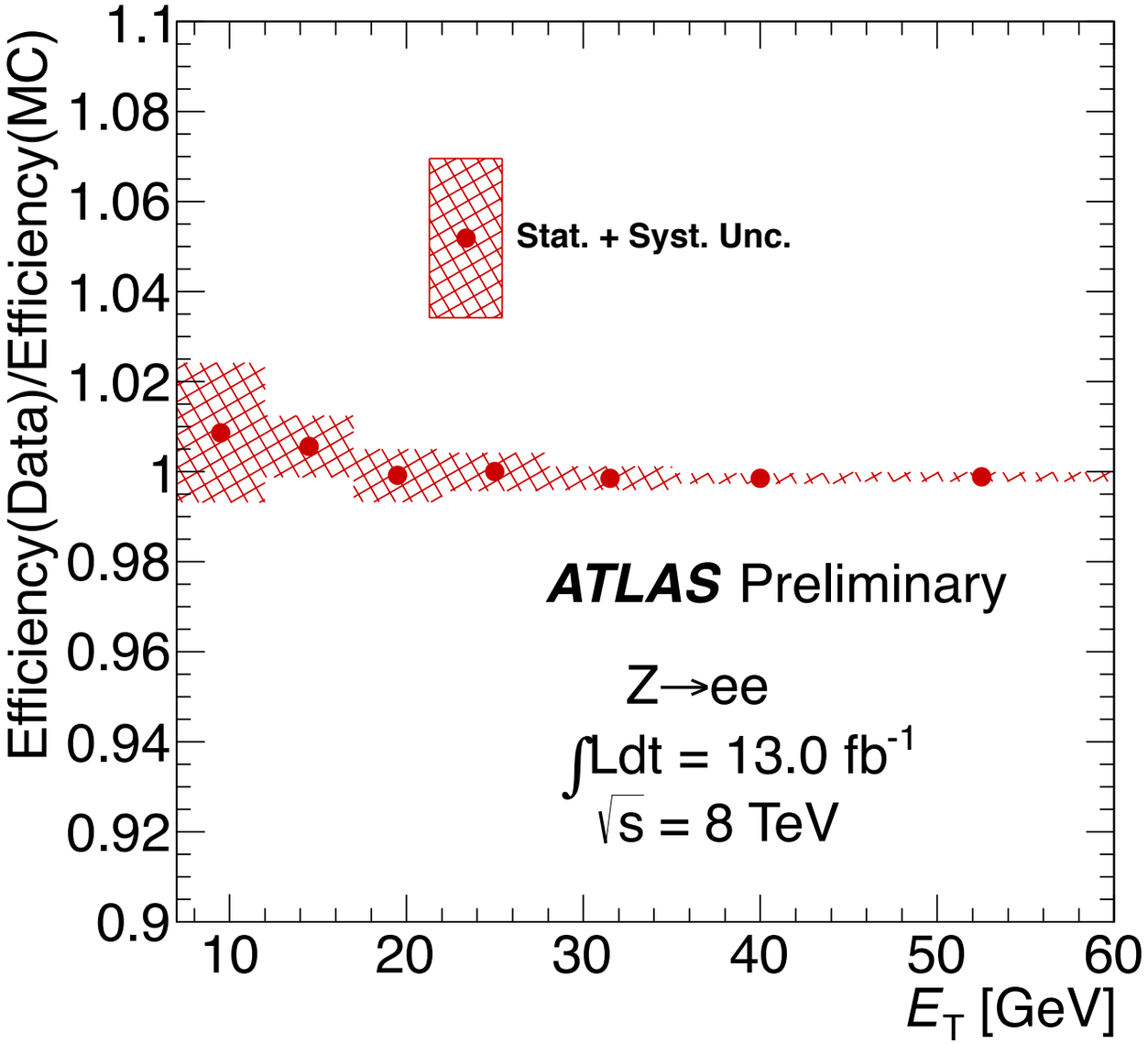
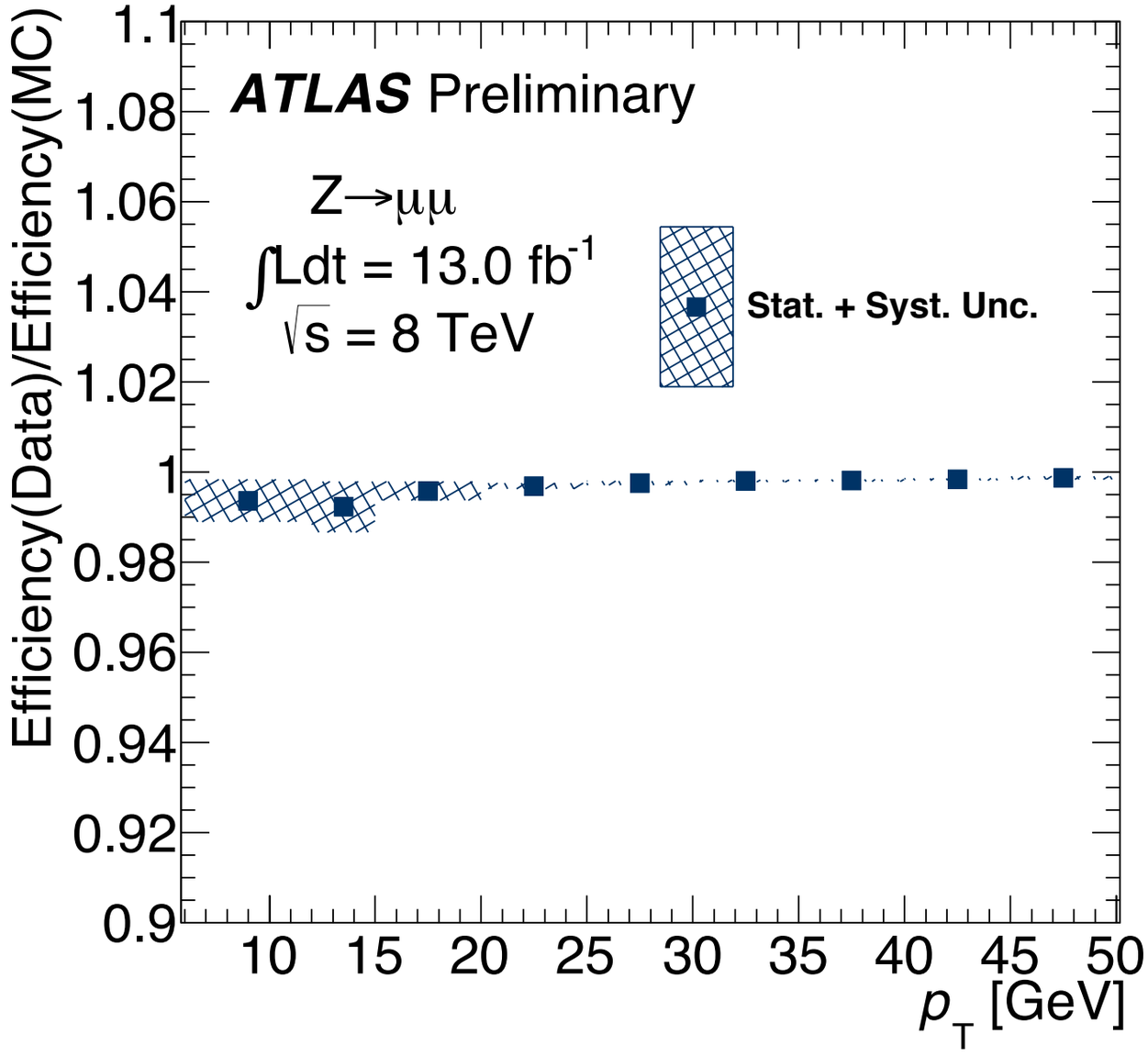




Additional selections control (ATLAS)

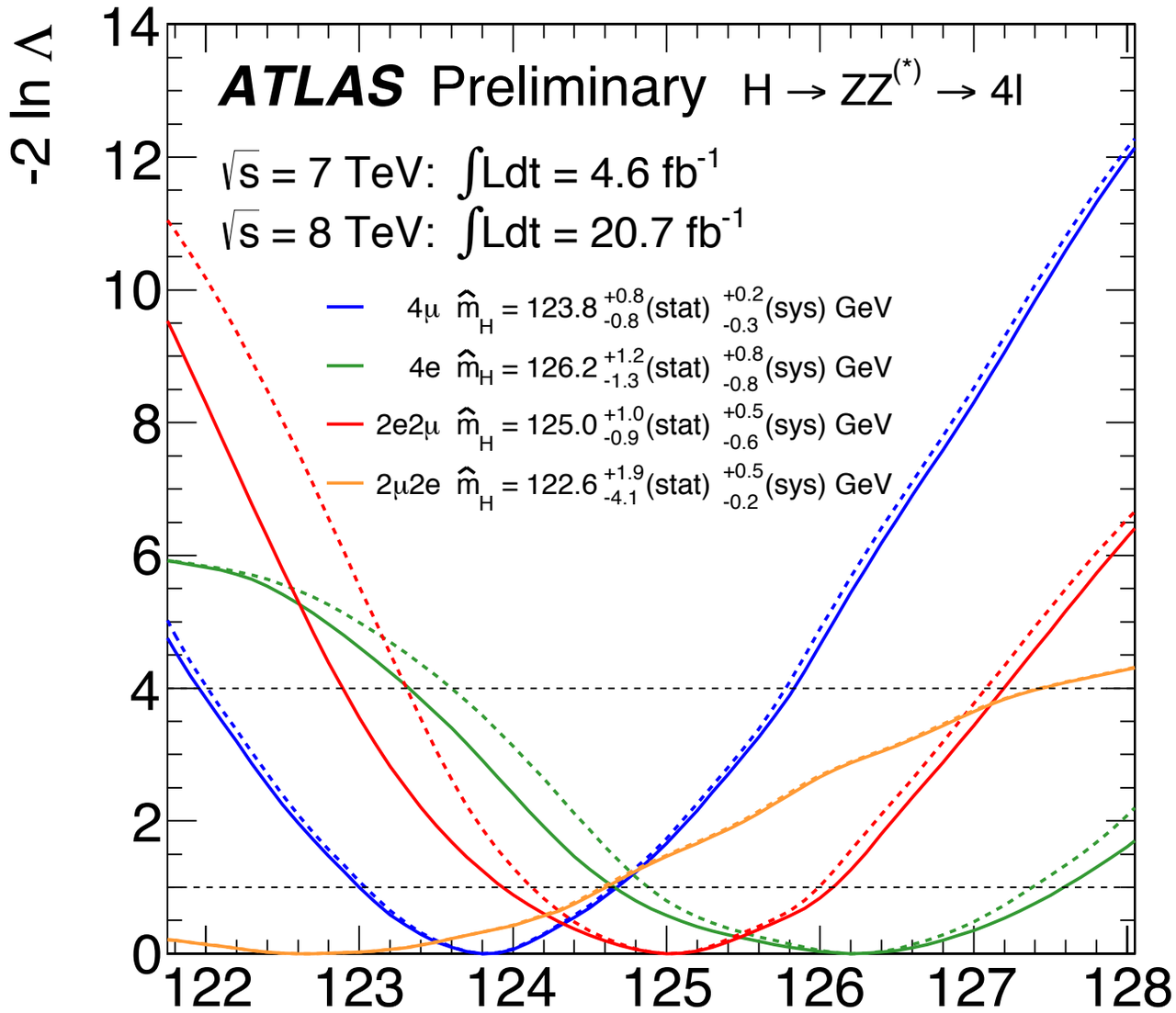
ATLAS-CONF-2012-169





Mass measurement, cross-checks

Mass measurement in different channels



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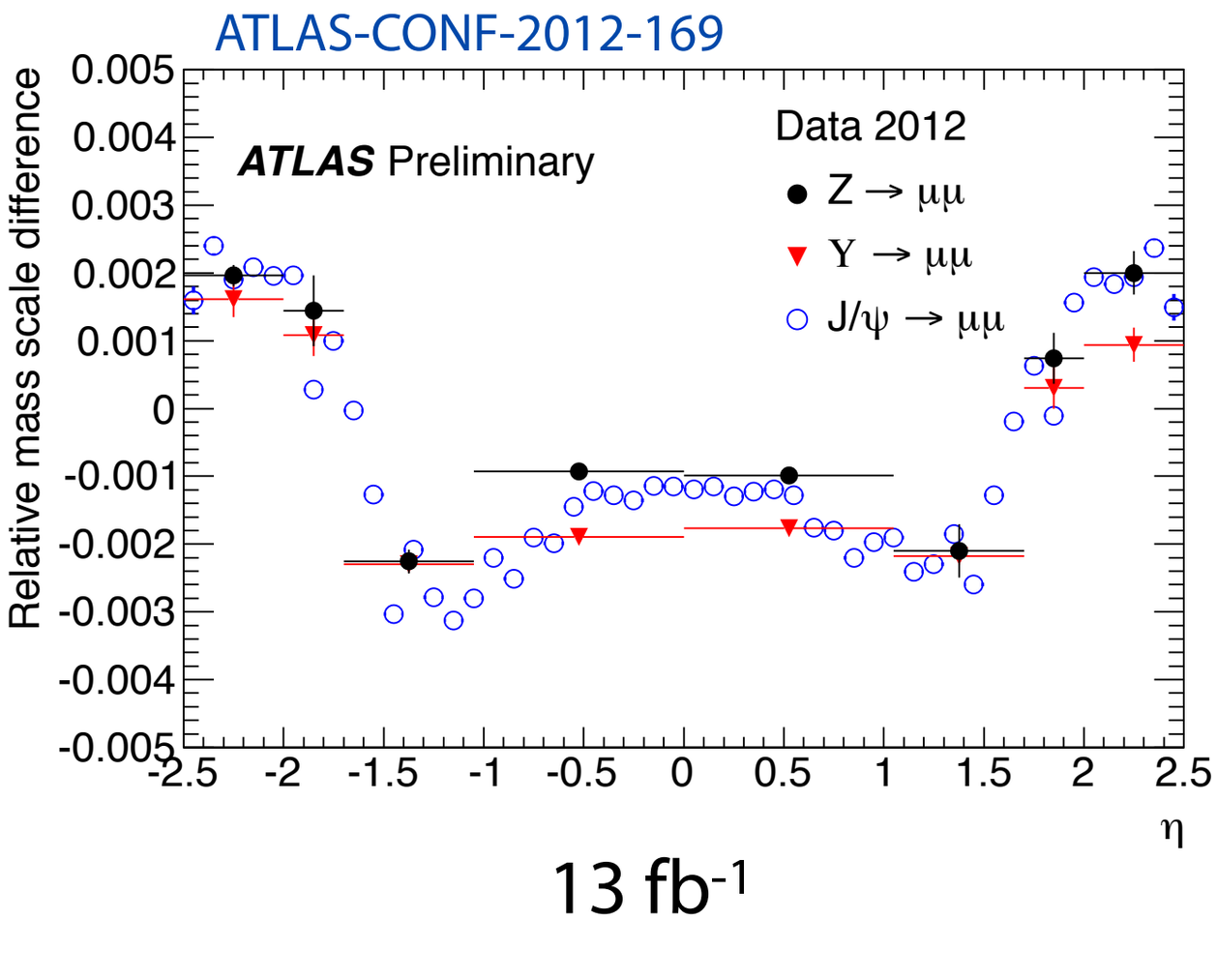
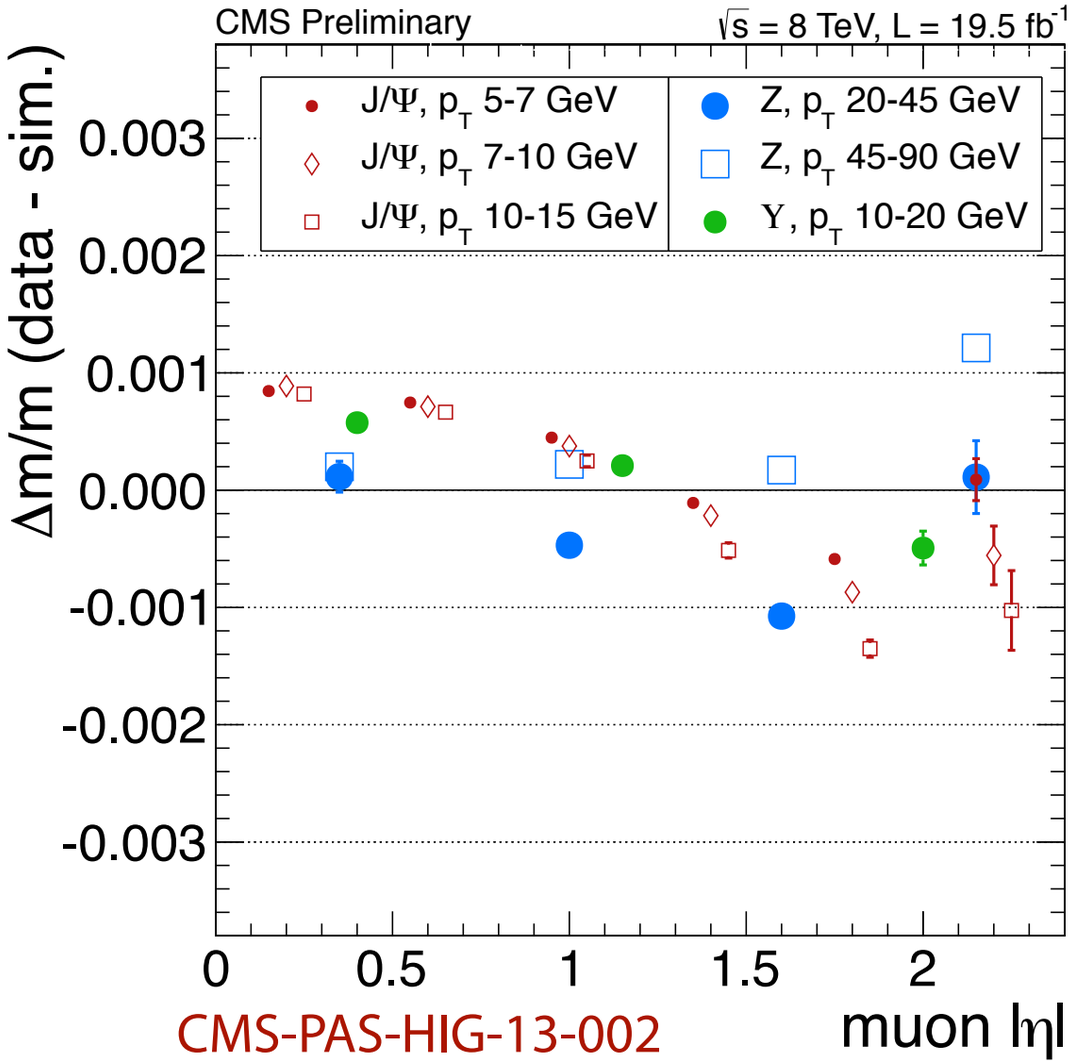
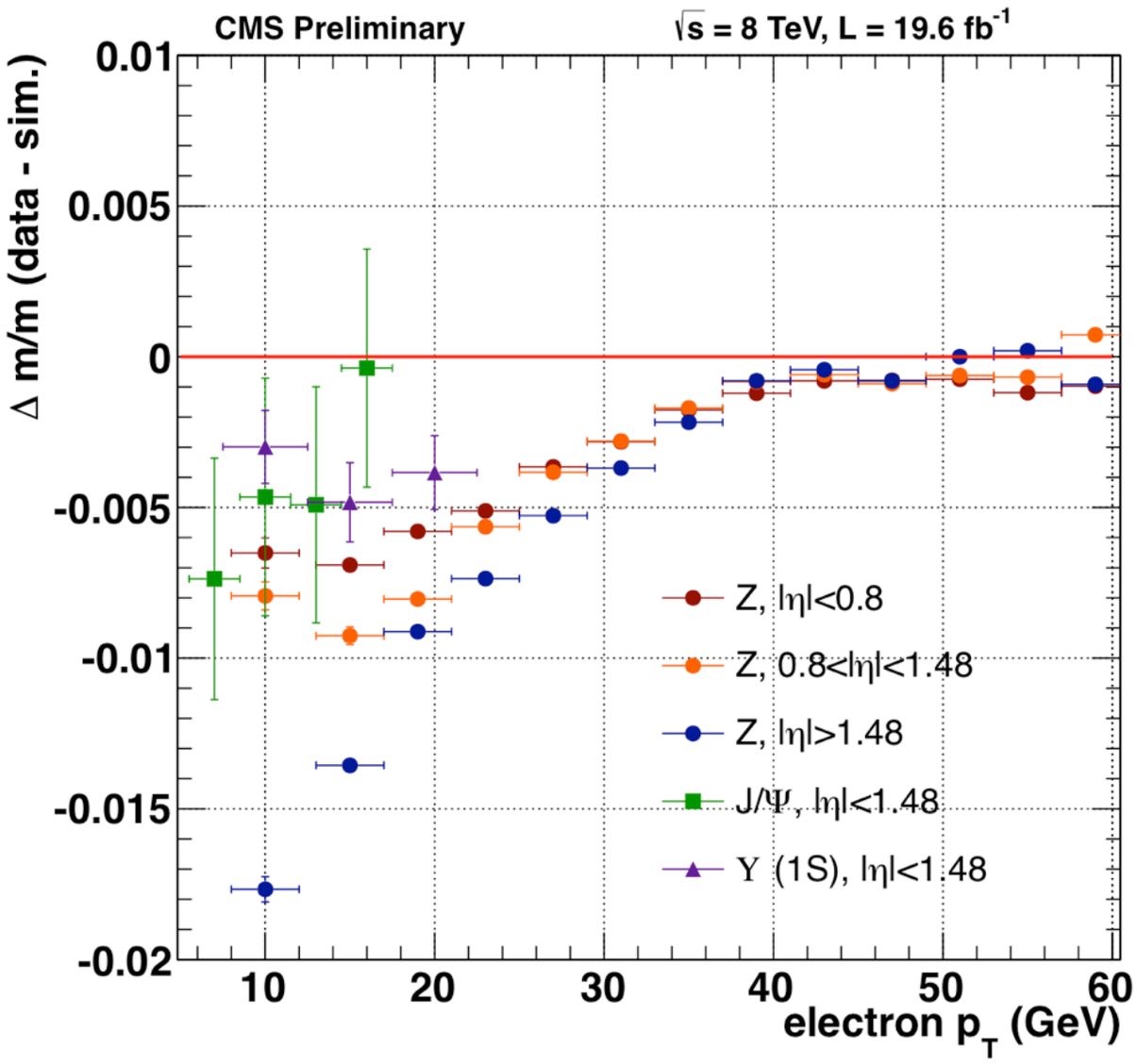
Relative mass scale difference





Relative mass scale difference

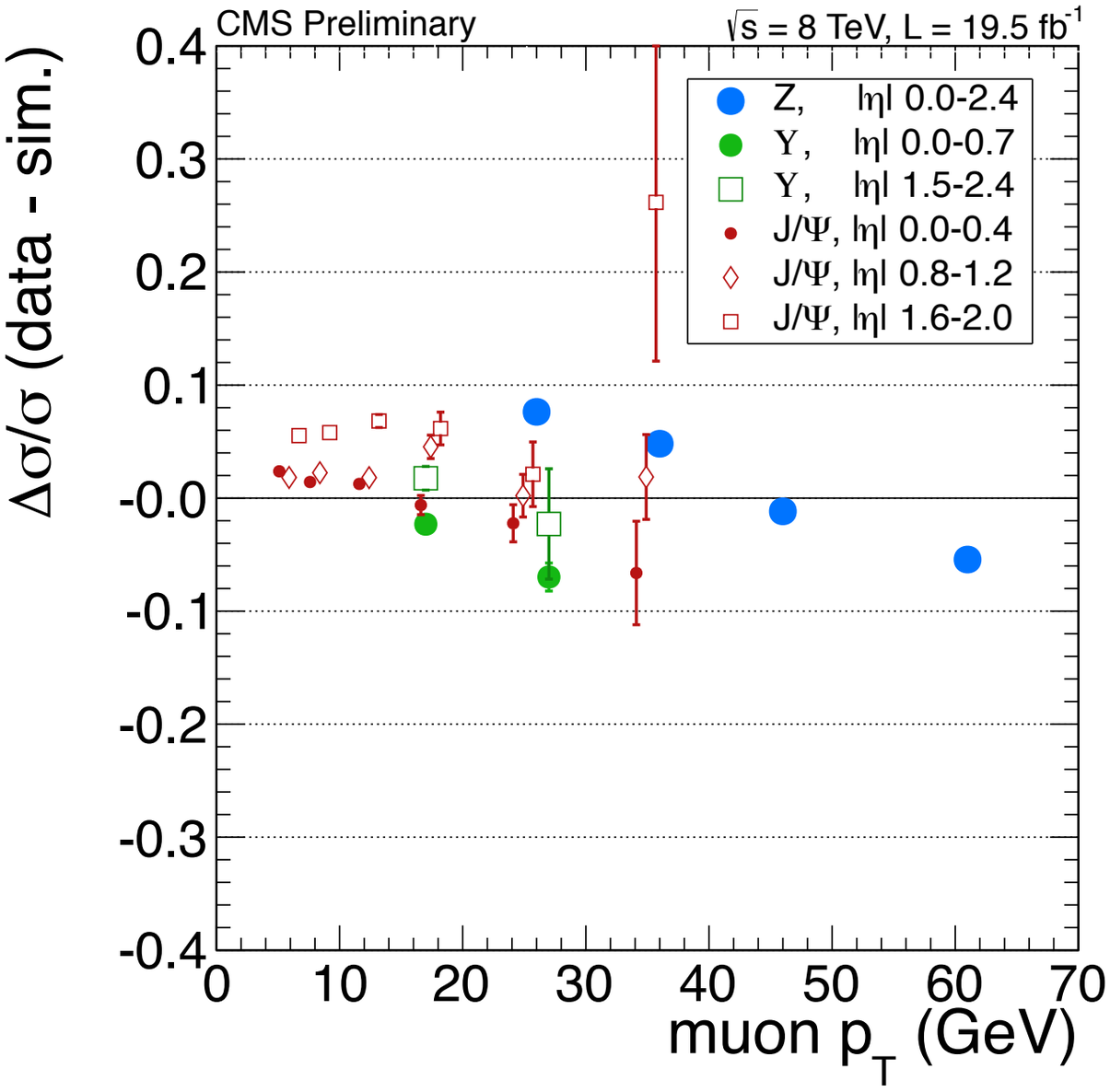


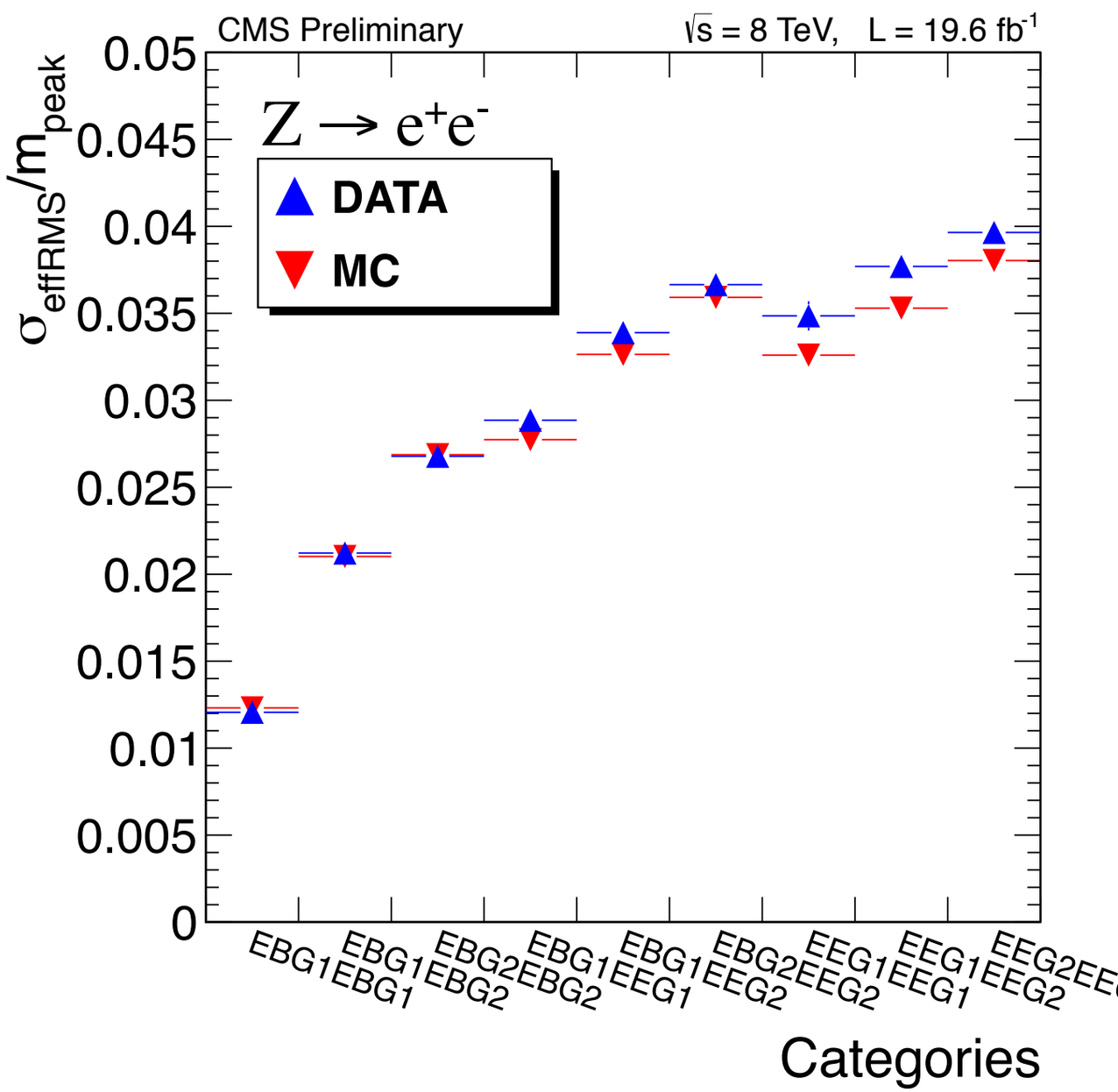
CMS-PAS-HIG-13-002

Resolution validation

CMS only

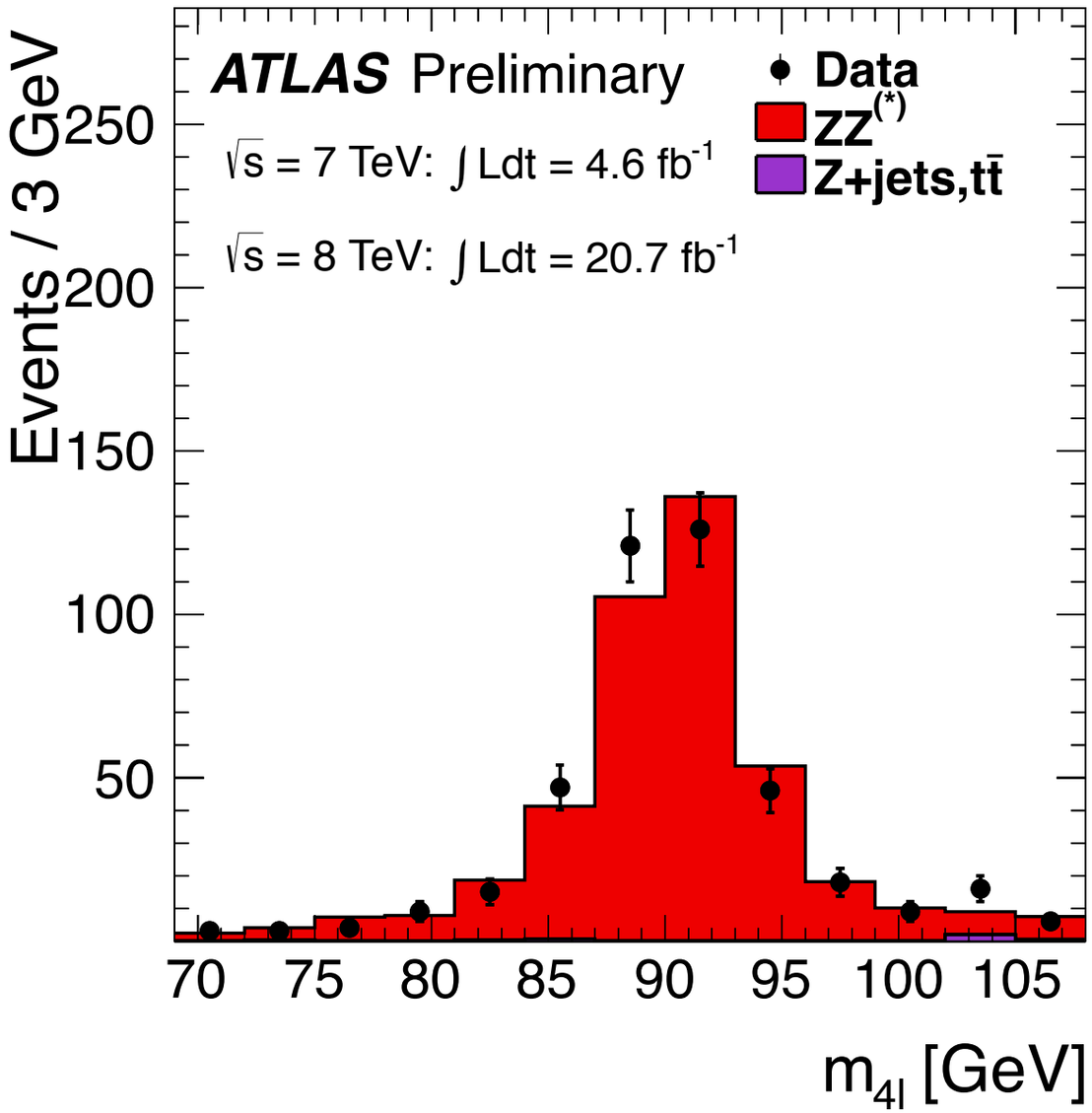
CMS-PAS-HIG-13-002

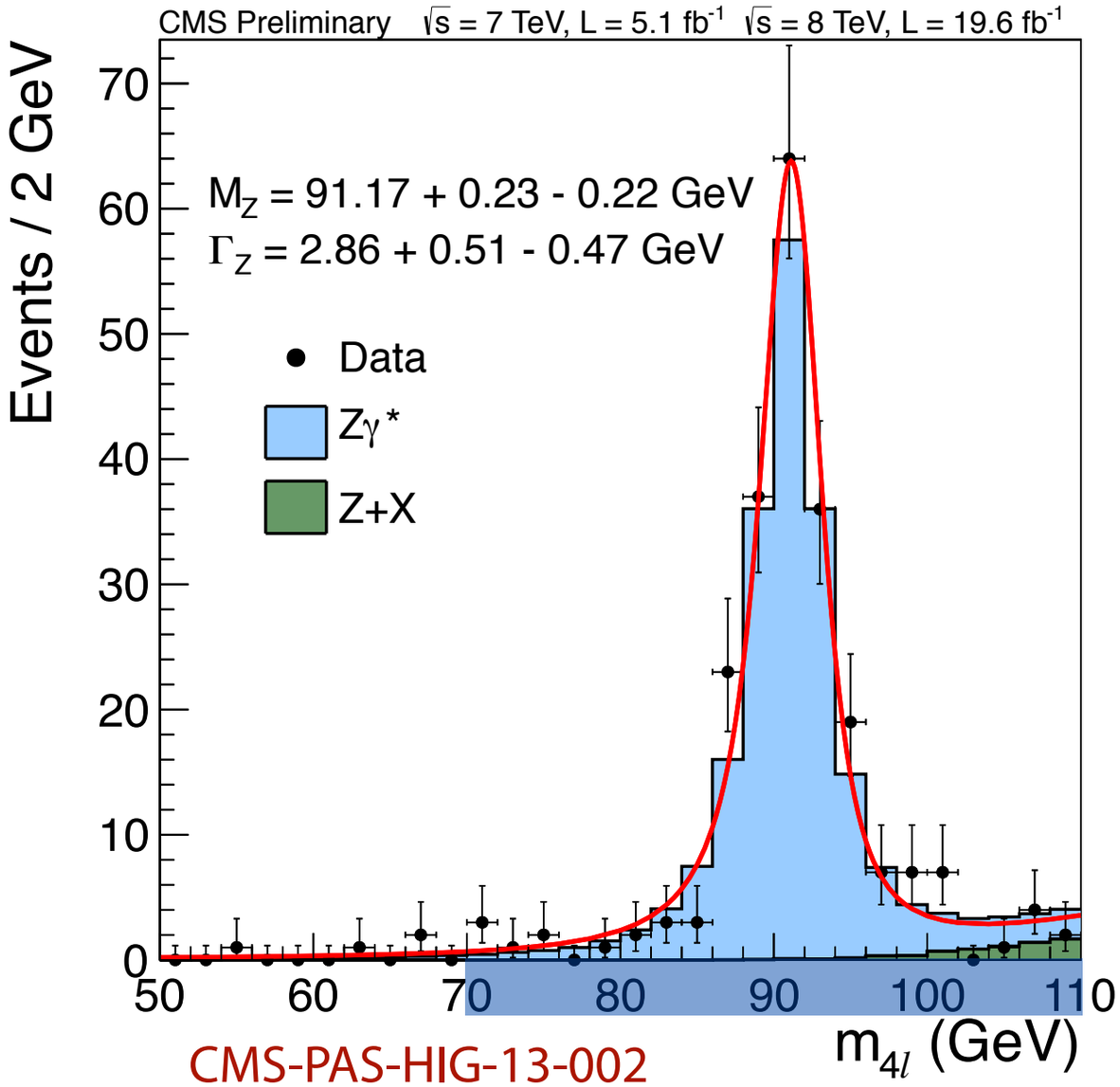




Single resonant Z

ATLAS-CONF-2013-013



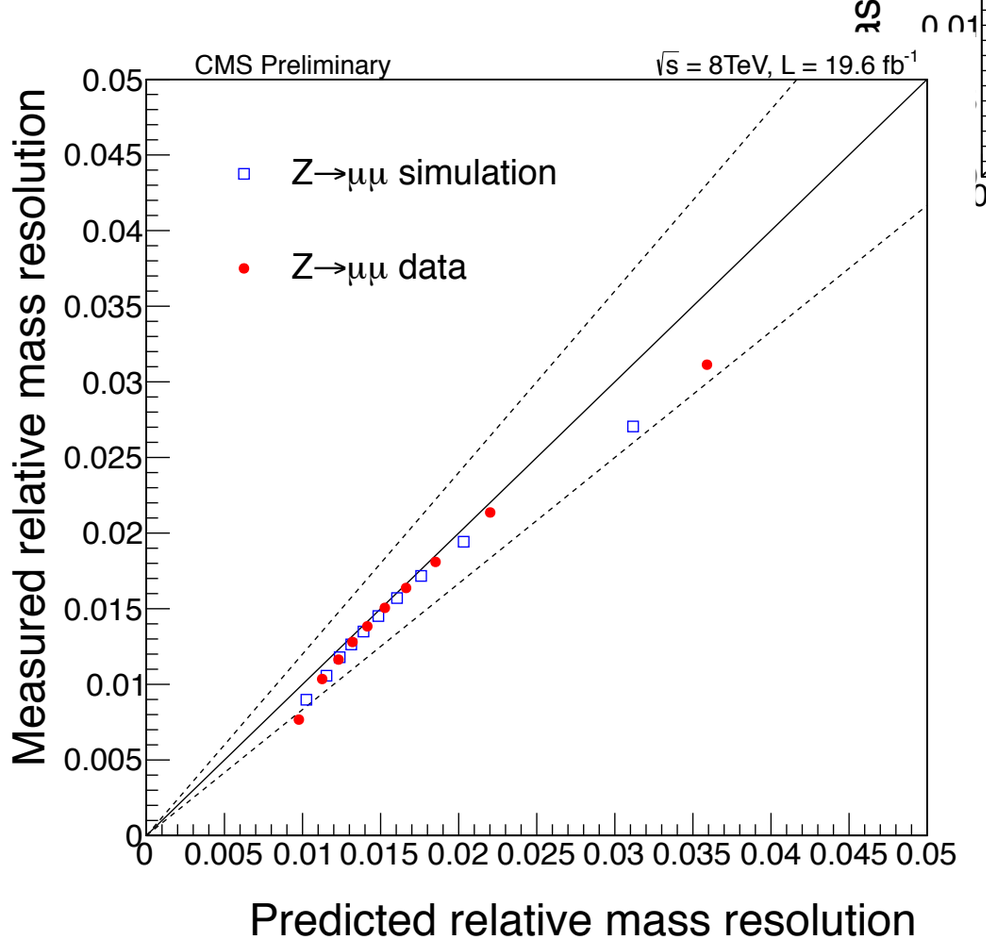


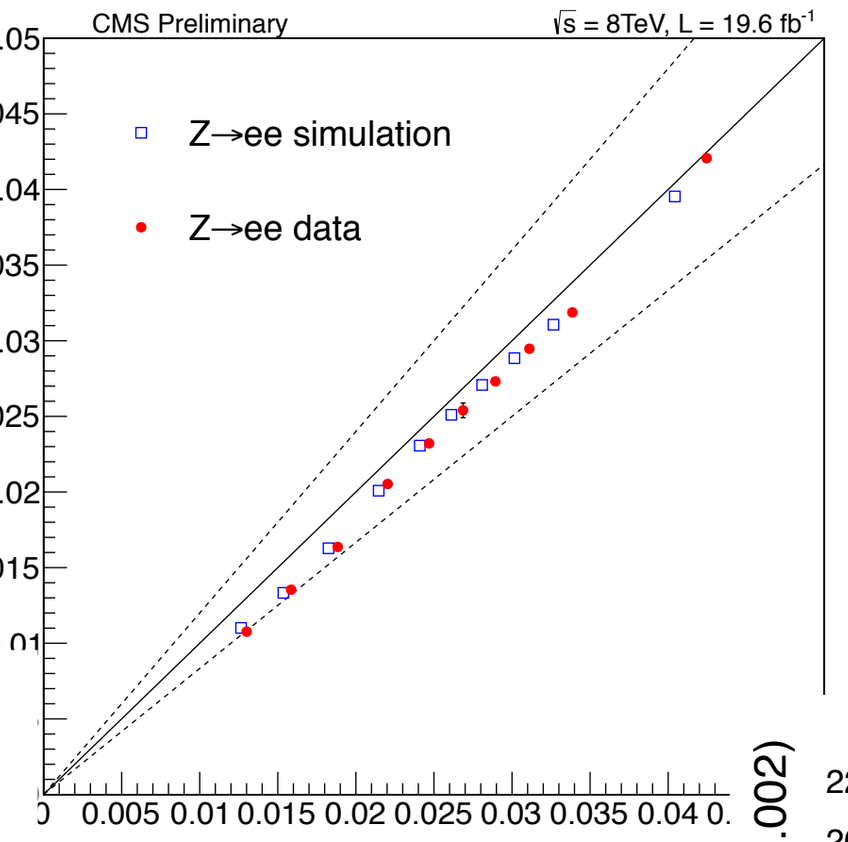
CMS-PAS-HIG-13-002

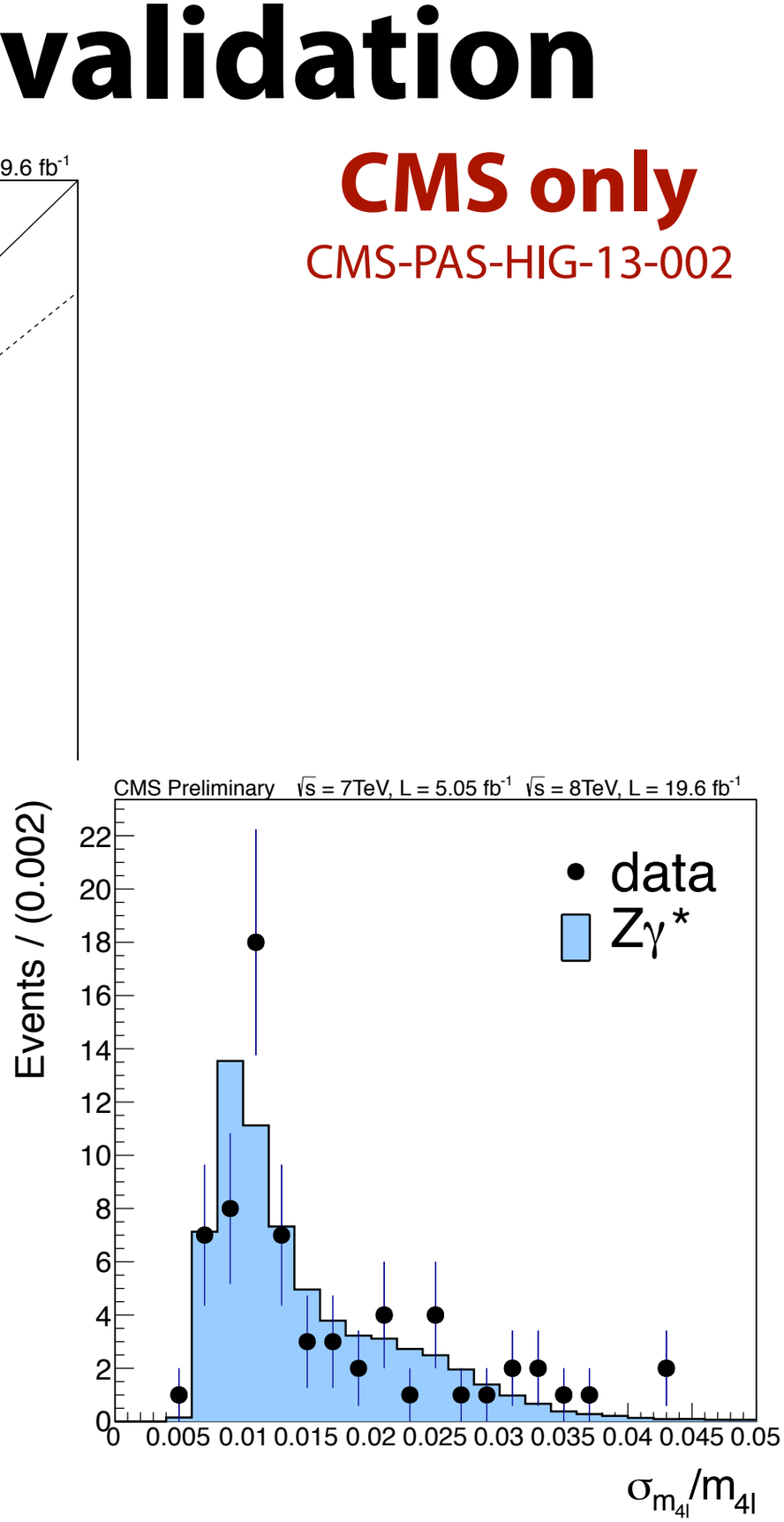
Event by event errors validation

CMS only

CMS-PAS-HIG-13-002



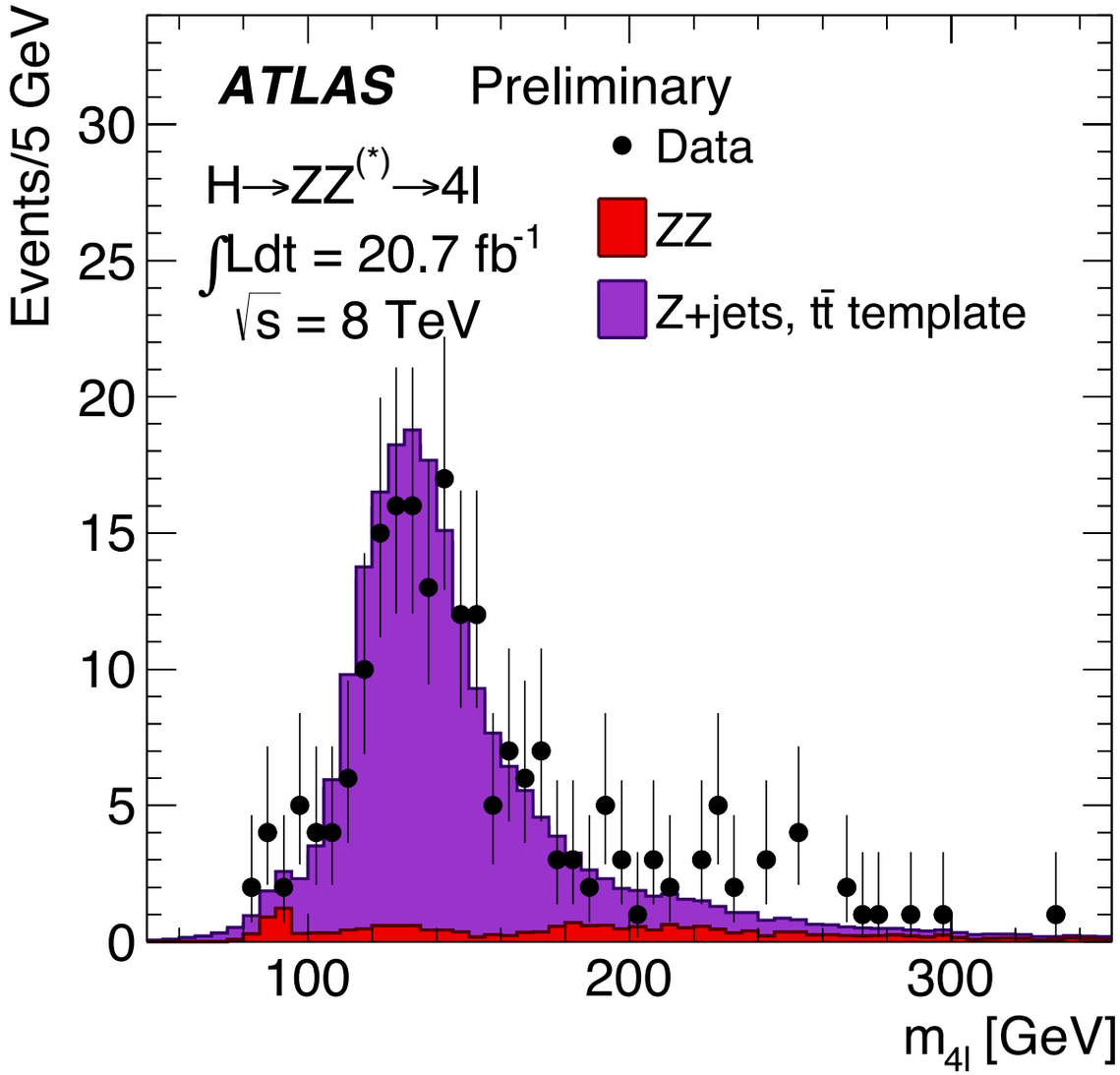


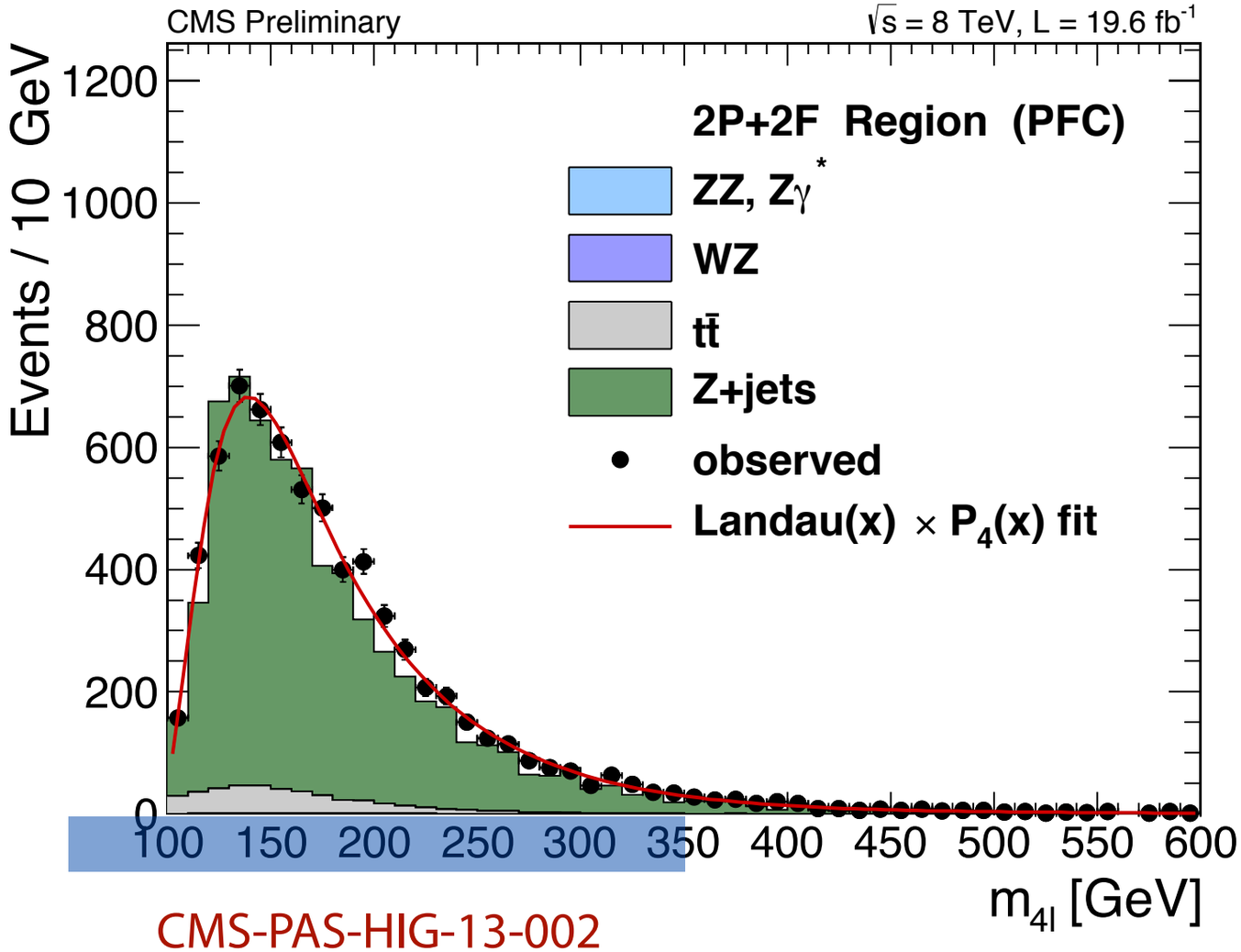


Backgrounds

Reducible backgrounds shape

ATLAS-CONF-2013-013





CMS-PAS-HIG-13-002

Complete spectrum

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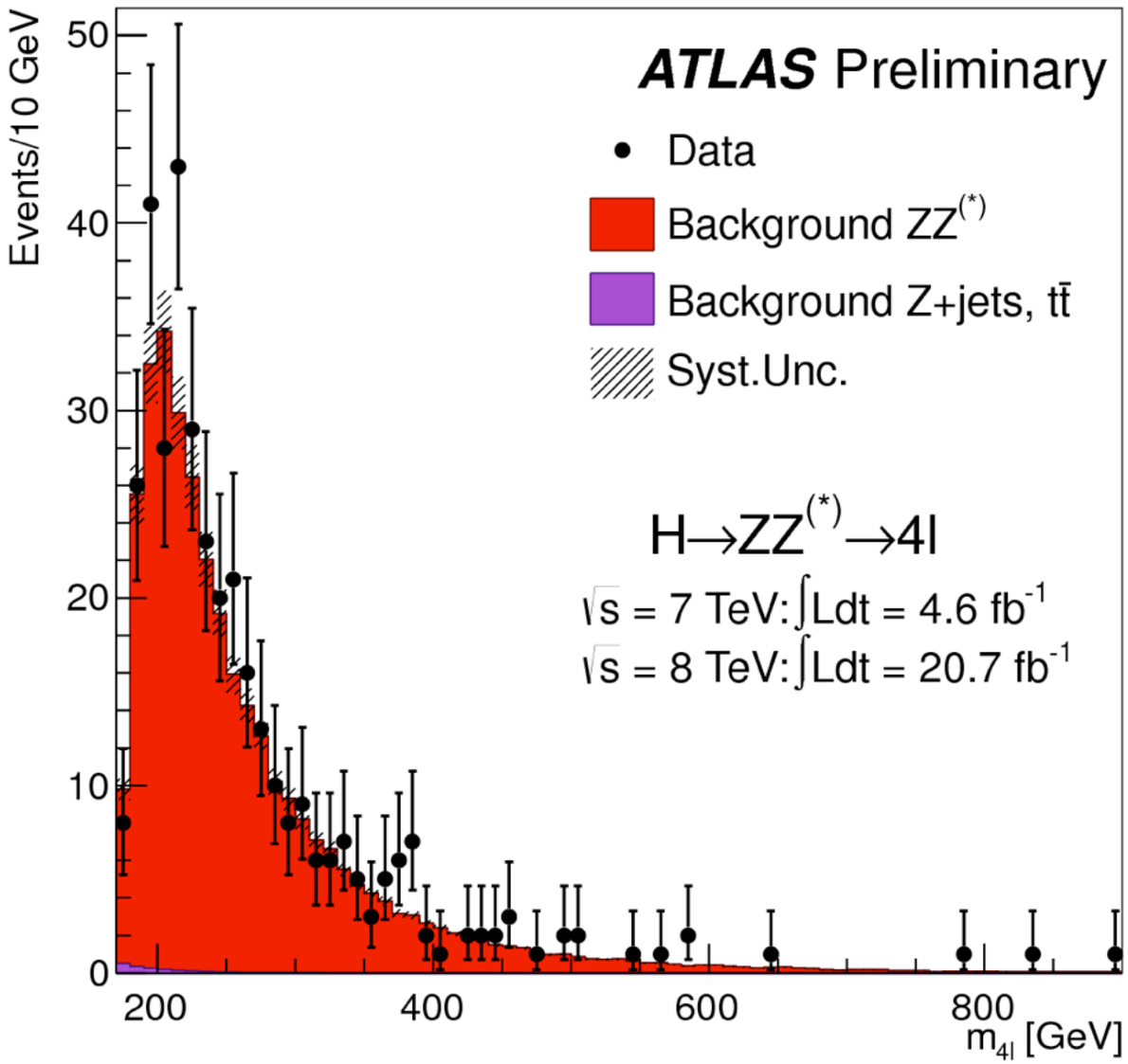
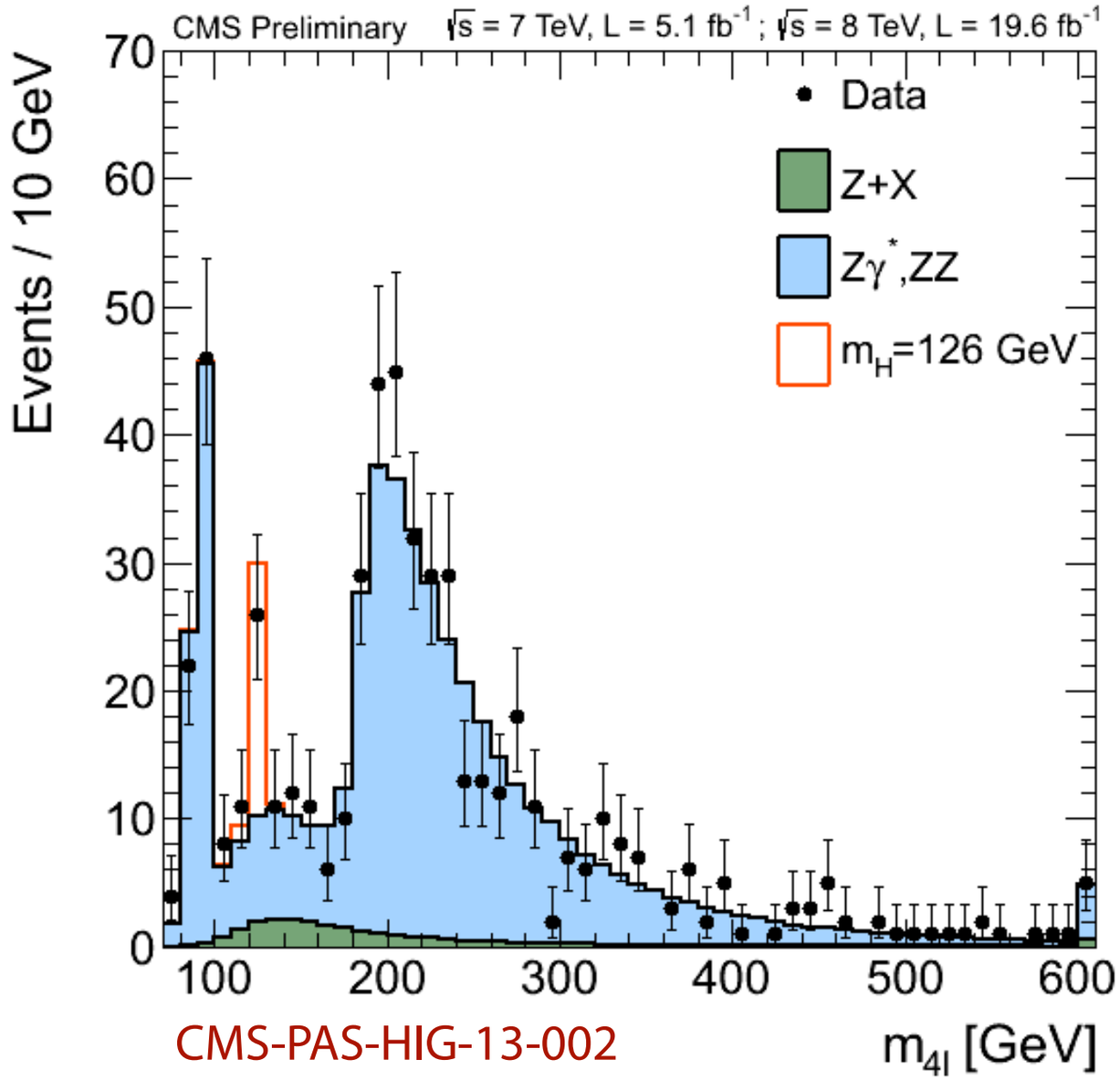
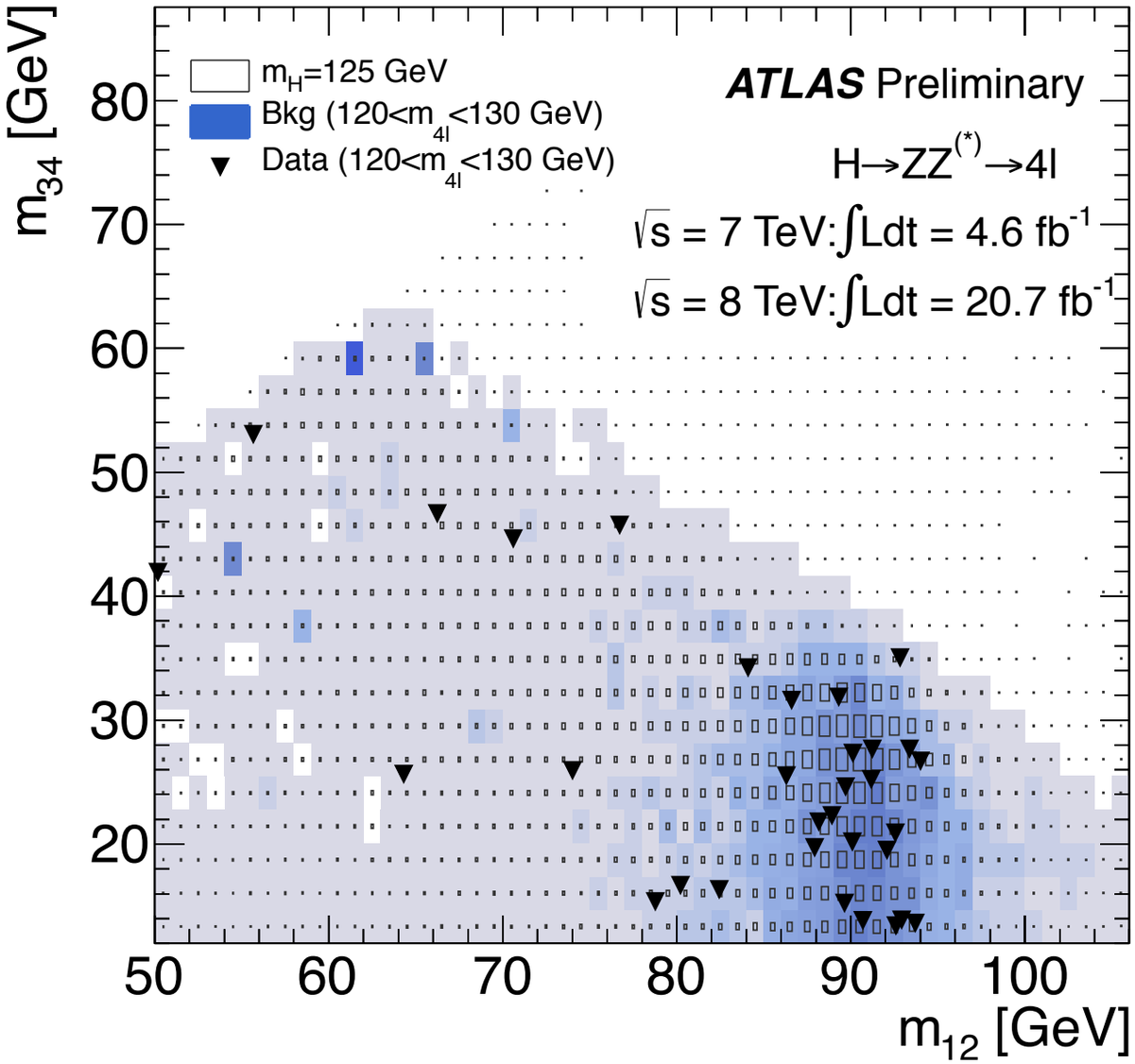


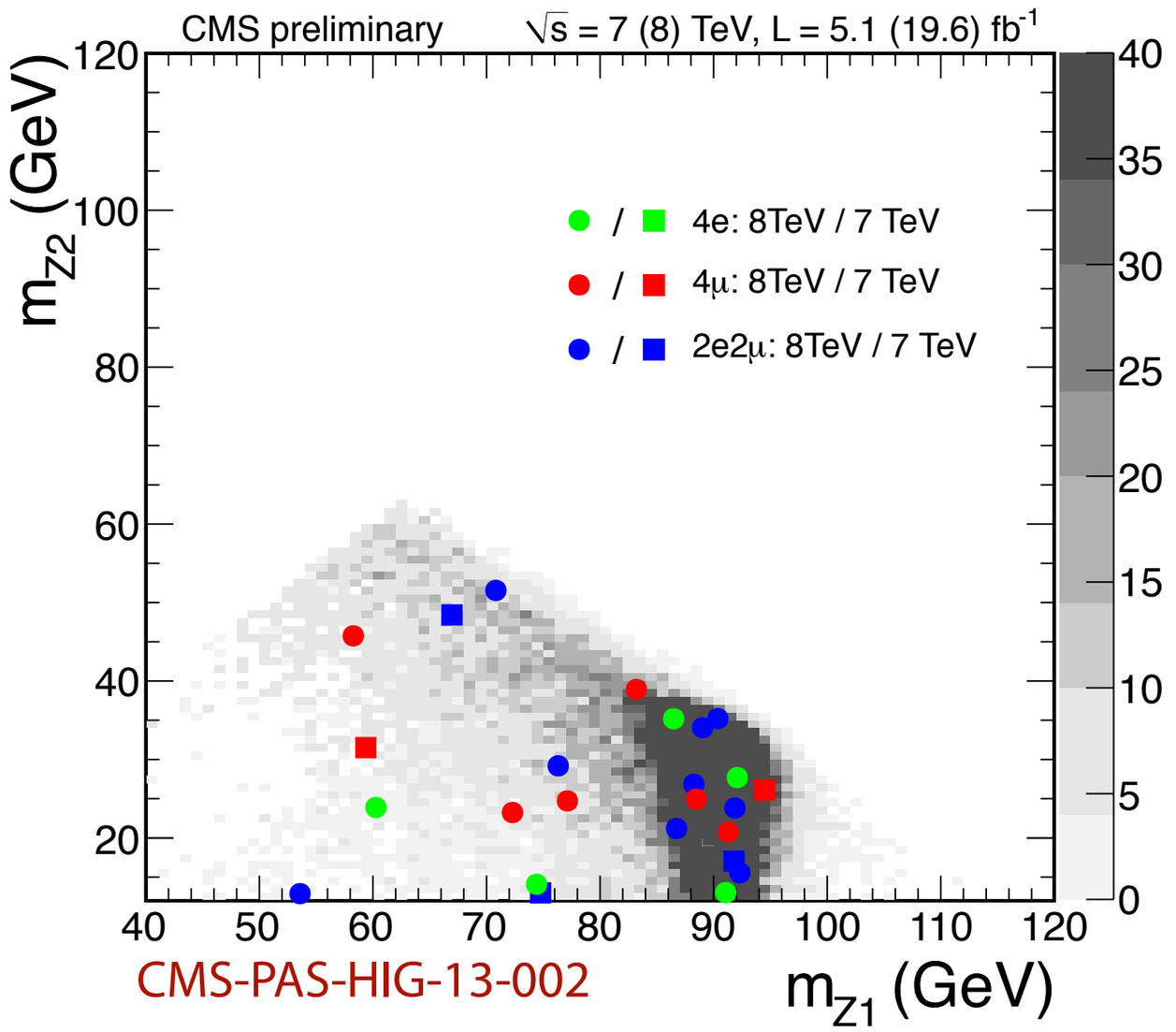


CMS-PAS-HIG-13-002

M_{Z1} vs M_{Z2}

ATLAS-CONF-2013-013





Results of event selection

	ATLAS (25.3 fb^{-1})	CMS (24.7 fb^{-1})	
M_H range [GeV/c^2]	100-1000	110-1000	
Signal (M_H=125)	6.8	6.8	**4μ**
ZZ	124	118.9	
Reducible Bkg.	2.8	3.8	

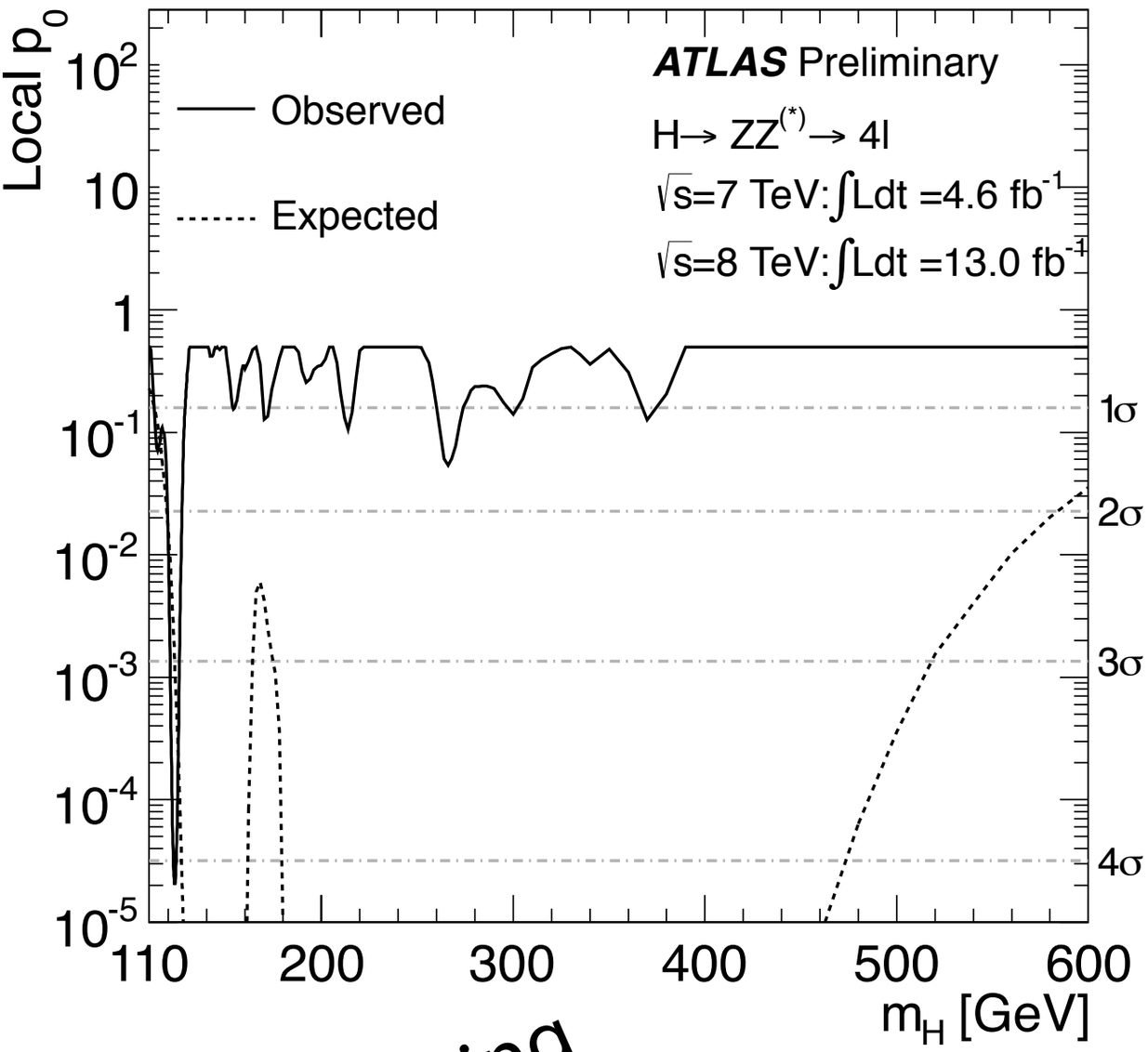
Signal (M_H=125)	8.1	8.9	**2e2μ**
ZZ	187.8	192.8	
Reducible Bkg.	10.6	9.9	

Signal (M_H=125)	3.3	3.5	**4e**
ZZ	71.5	78.9	
Reducible Bkg.	5.7	6.5	

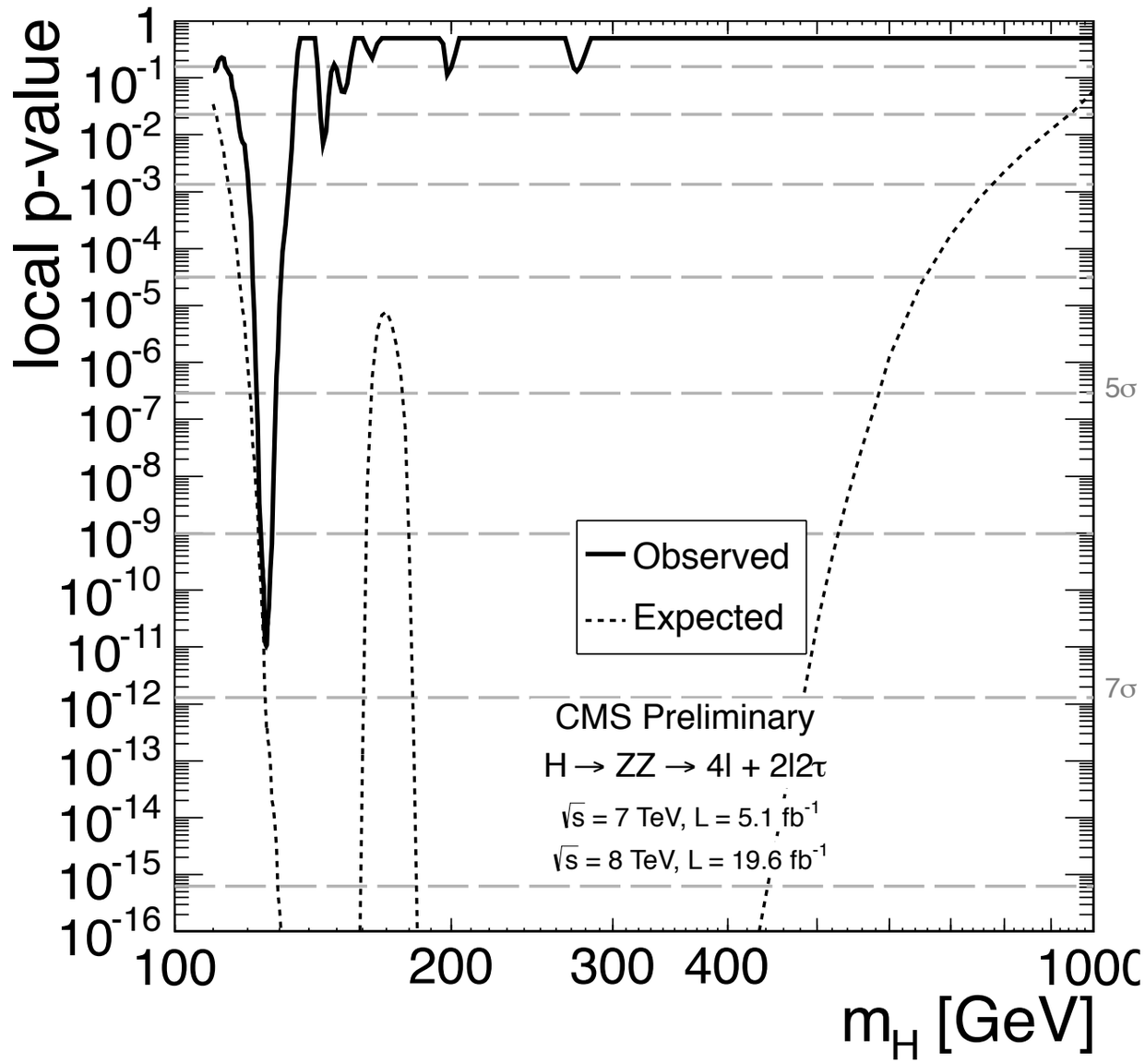
High mass

High mass

ATLAS-CONF-2012-169



CMS-PAS-HIG-13-002

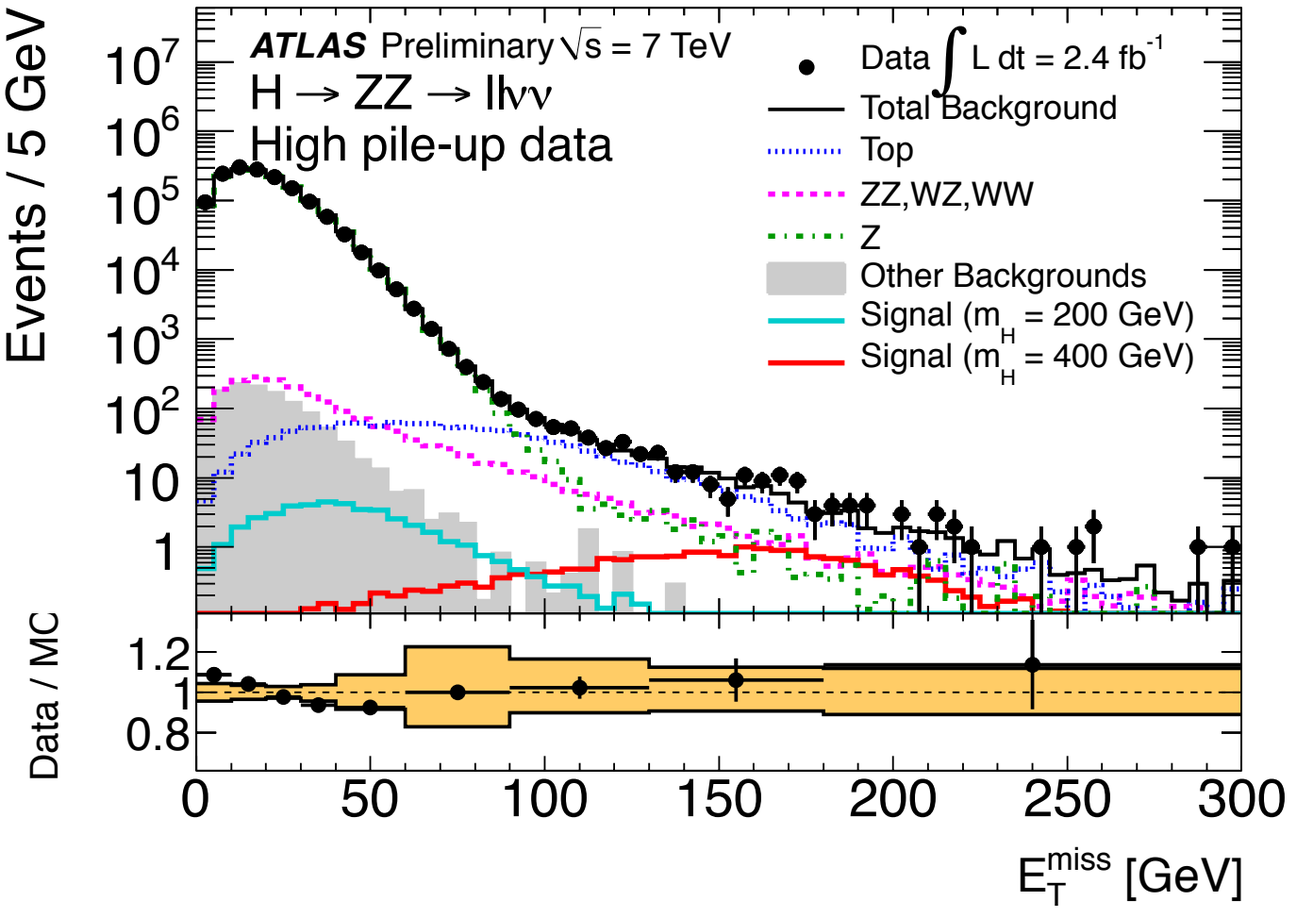


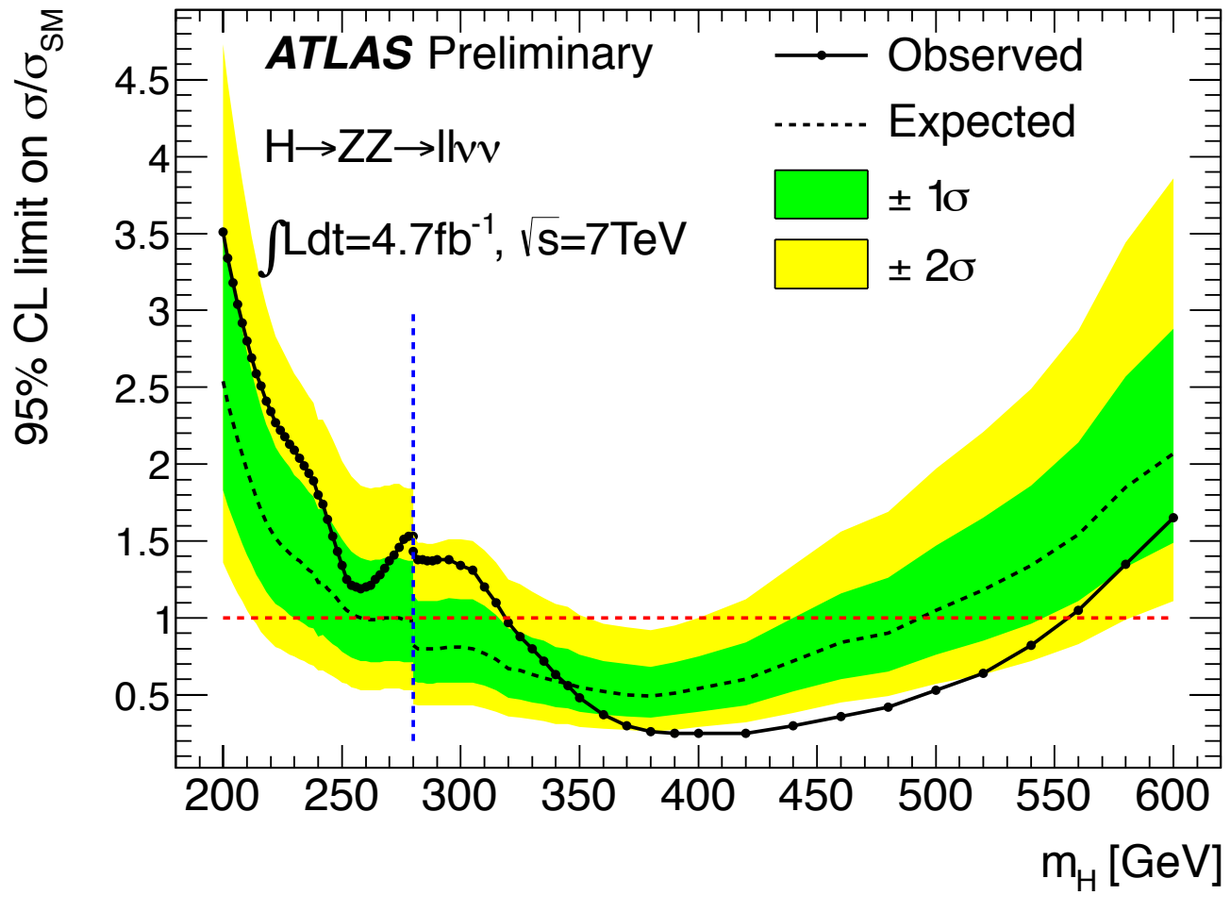
Also contributing at high mass:

2l2τ	-	CMS-HIG-13-002
2l2q	ATLAS-CONF-2012-017	CMS-HIG-12-034
2l2ν	ATLAS-CONF-2012-016	CMS-HIG-12-034

H→ZZ→ℓℓνν (ATLAS)

ATLAS-CONF-2012-016





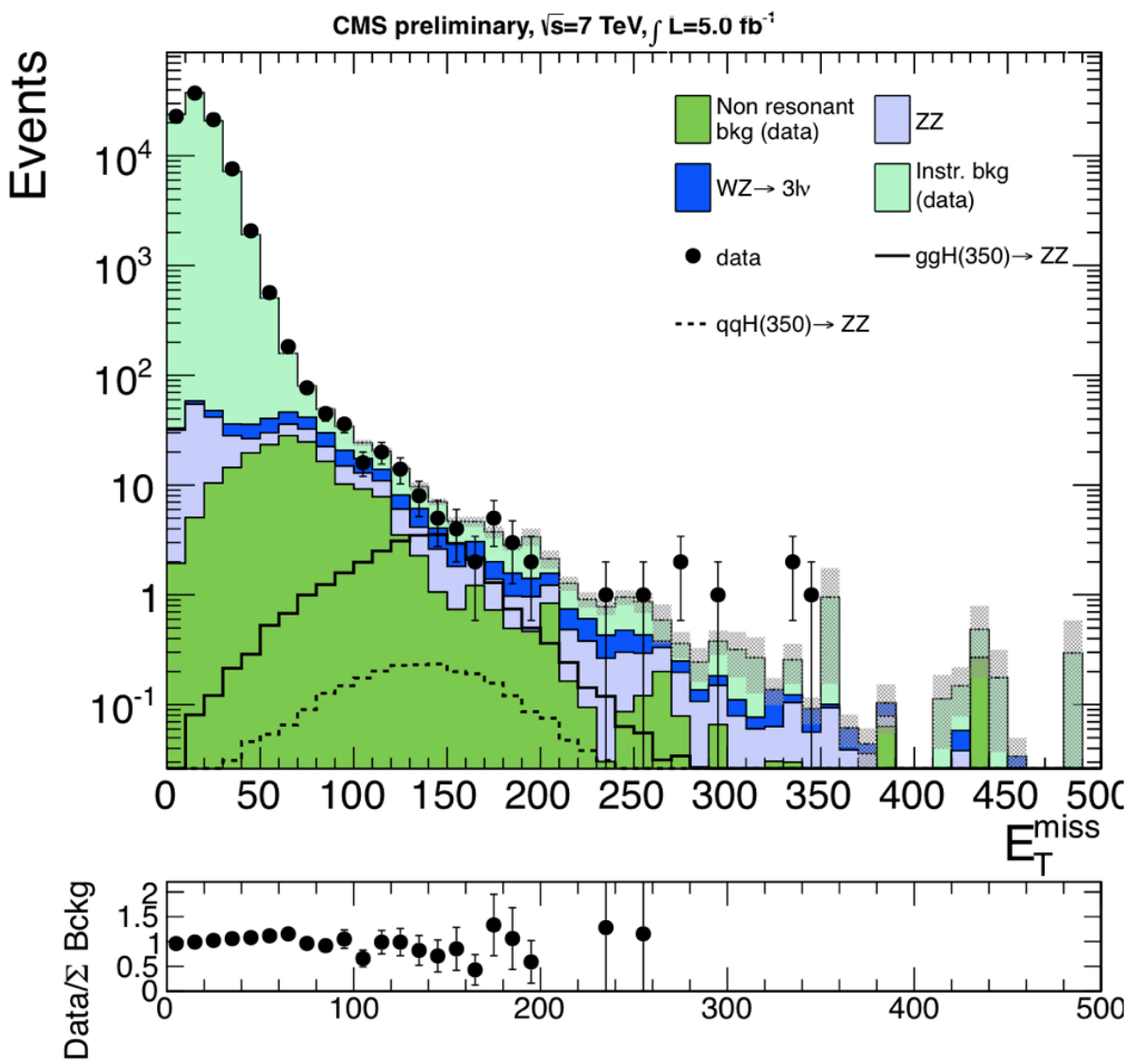
Two leptons from a Z boson, large E_T^{miss}

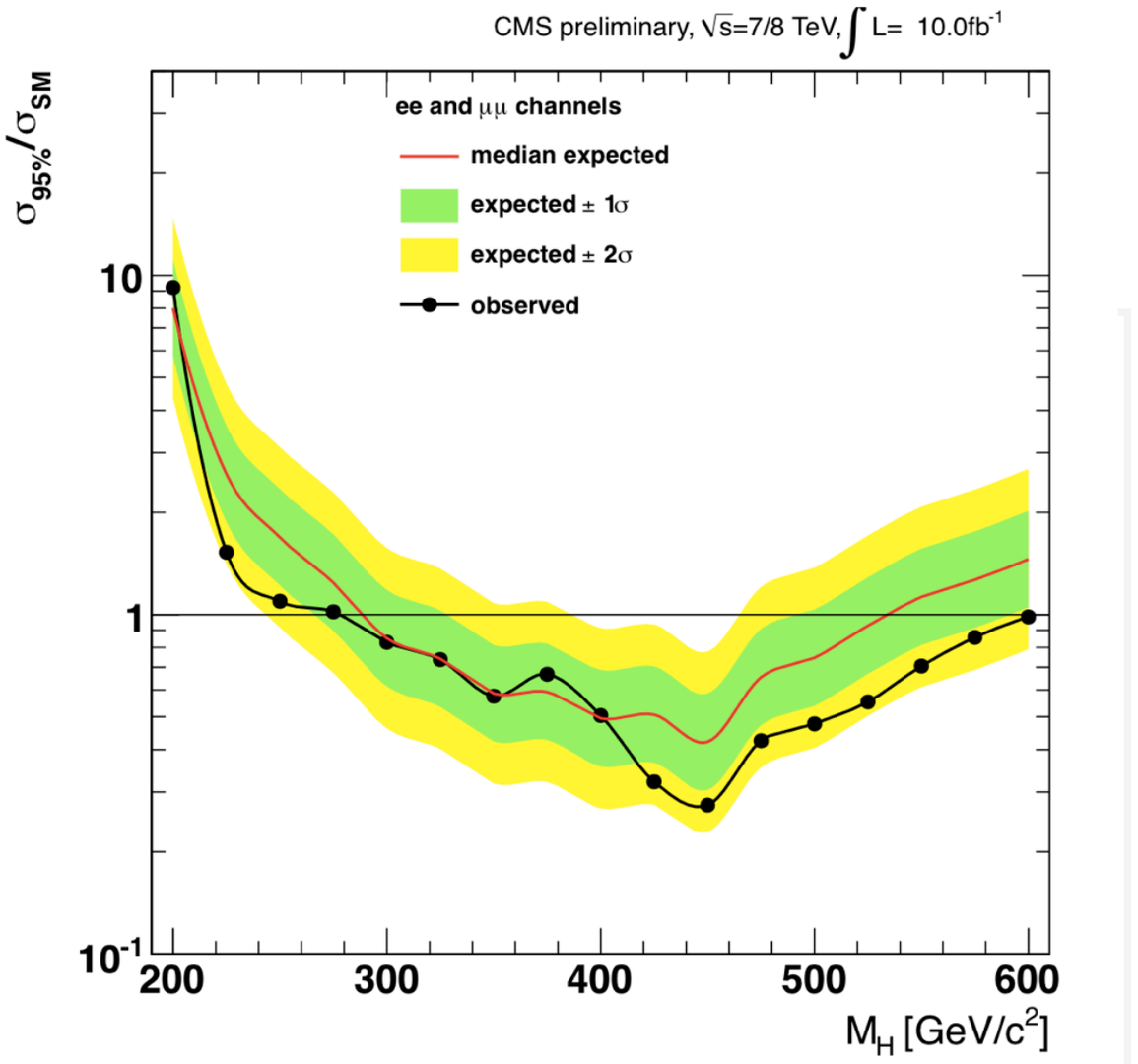
Using m_T as final variable

Split in categories: electrons/muons

H→ZZ→ℓℓνν (CMS)

CMS-PAS-HIG-12-023





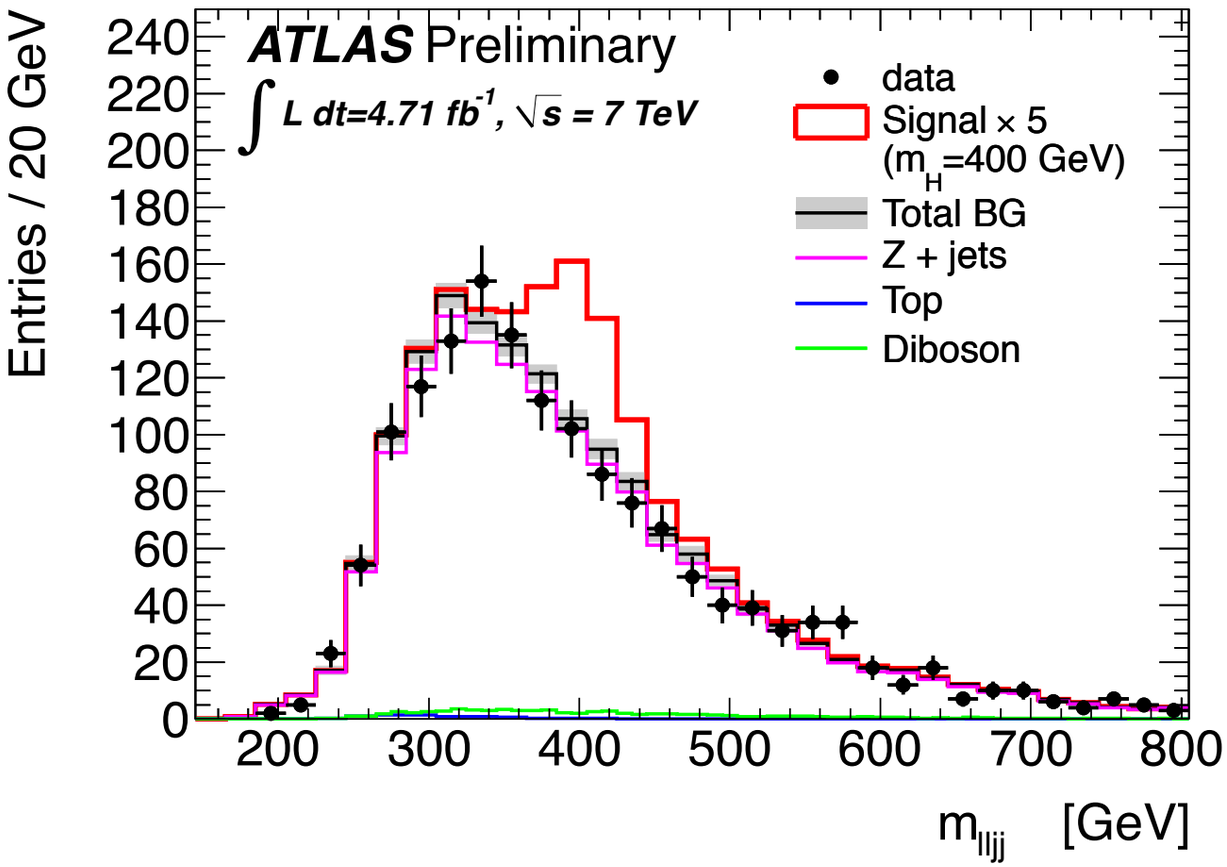
Two leptons from a Z boson, large E_T^{miss}

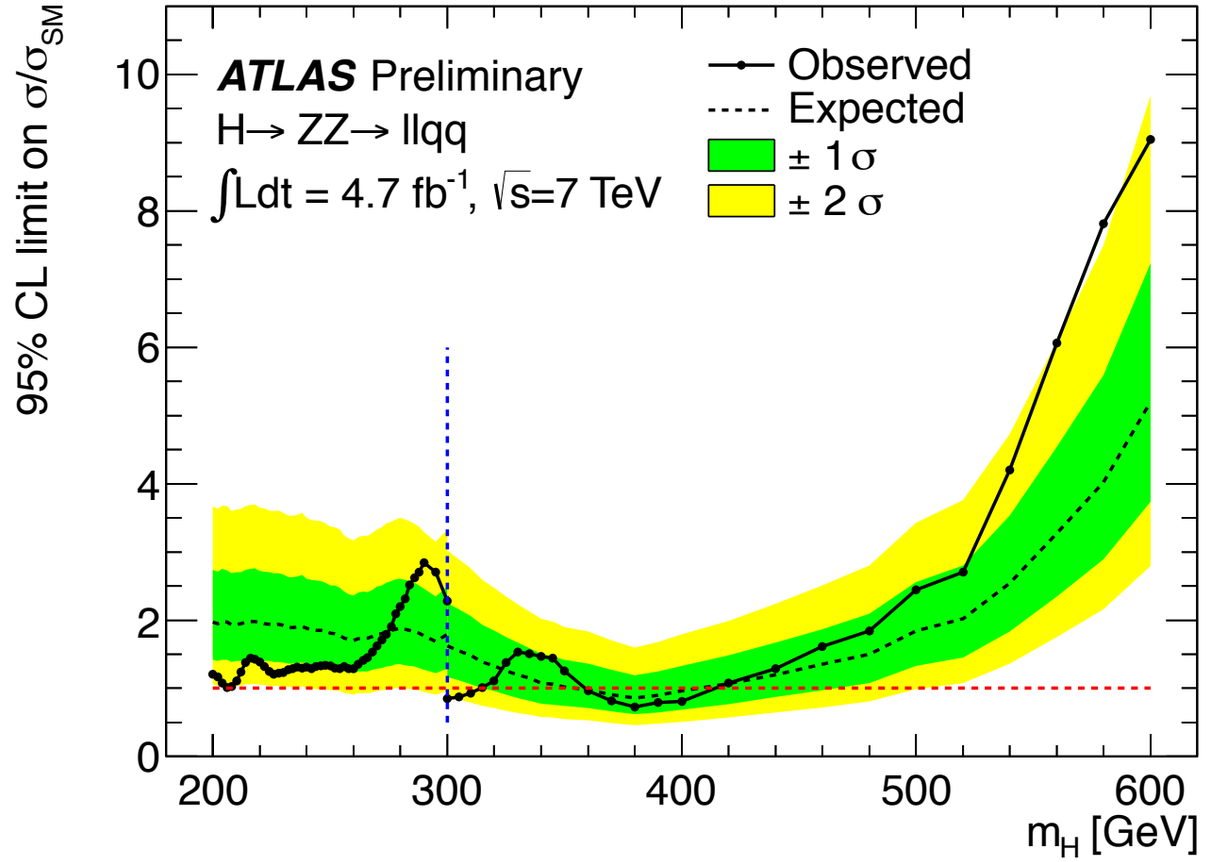
Using m_T as final variable

Split in several categories: electrons/muons, 0/1/2 jets

H→ZZ→ℓℓqq (ATLAS)

ATLAS-CONF-2012-017





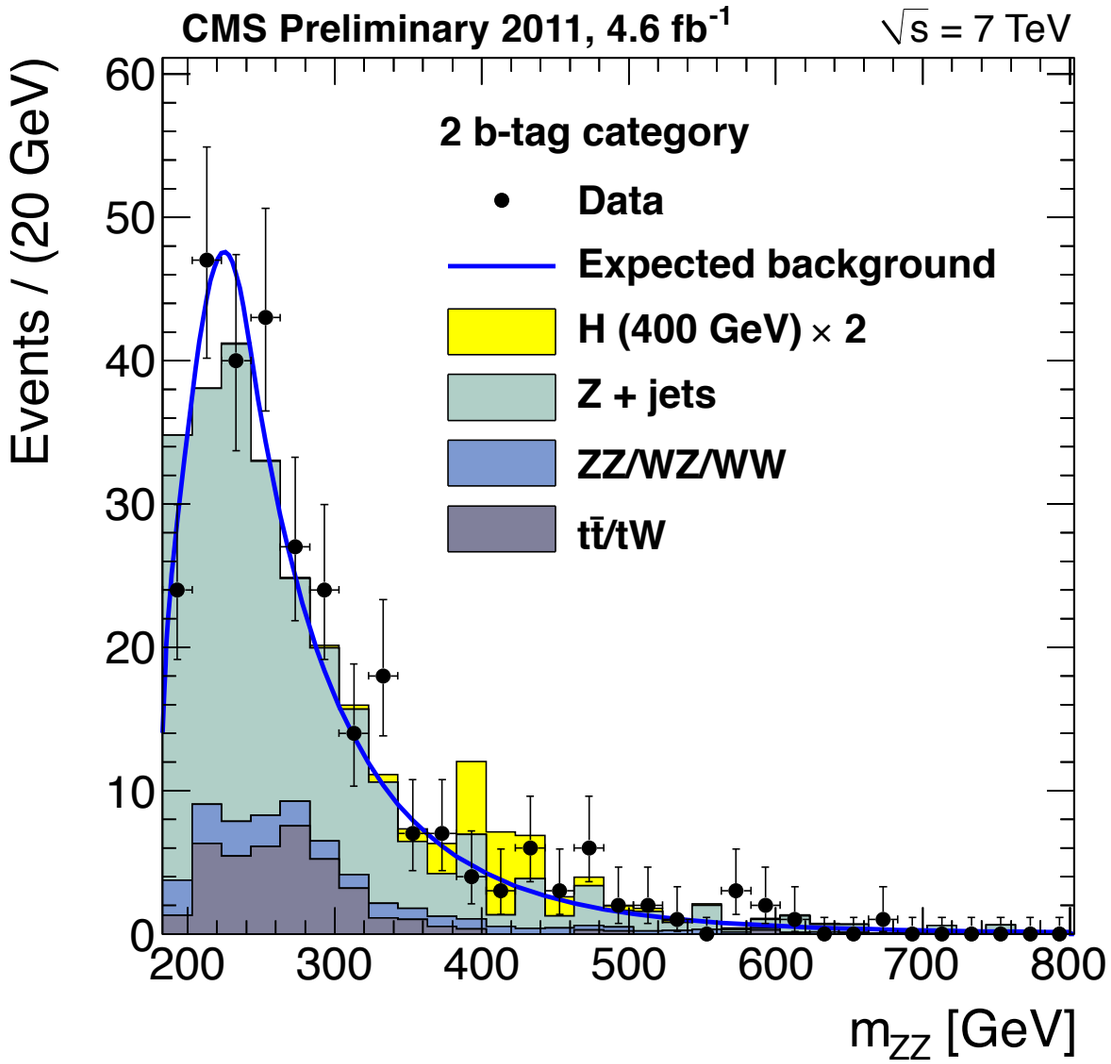
Two leptons from a Z boson, two jets from another Z boson

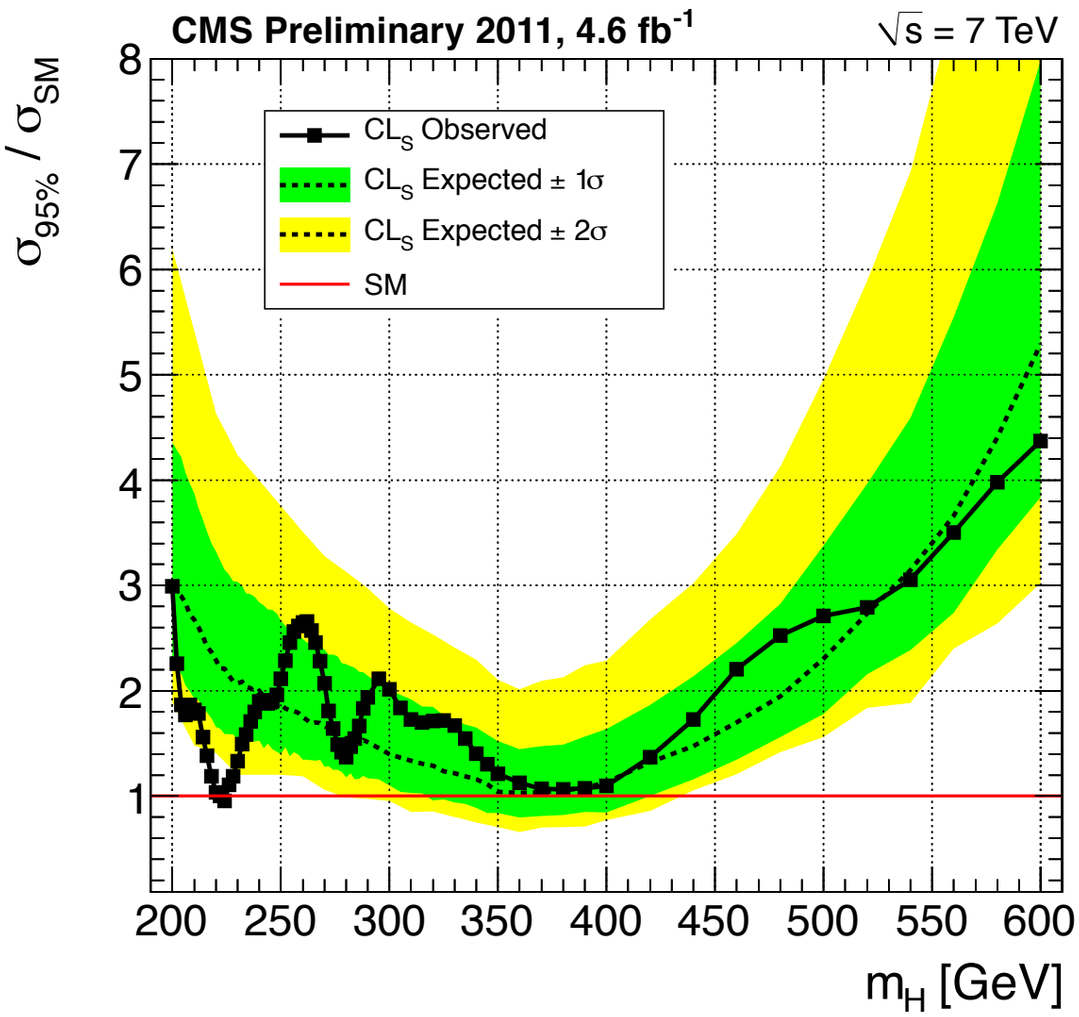
Using m_{2l2q} as final variable

Split in several categories: electrons/muons, 0 or at least 1 b-jet

H→ZZ→ℓℓqq (CMS)

CMS-PAS-HIG-11-027





Two leptons from a Z boson, two jets from another Z boson

Using m_{2l2q} as final variable

Split in several categories: electrons/muons, 0/1/2 b-jets

Other

Fermiophobic Higgs

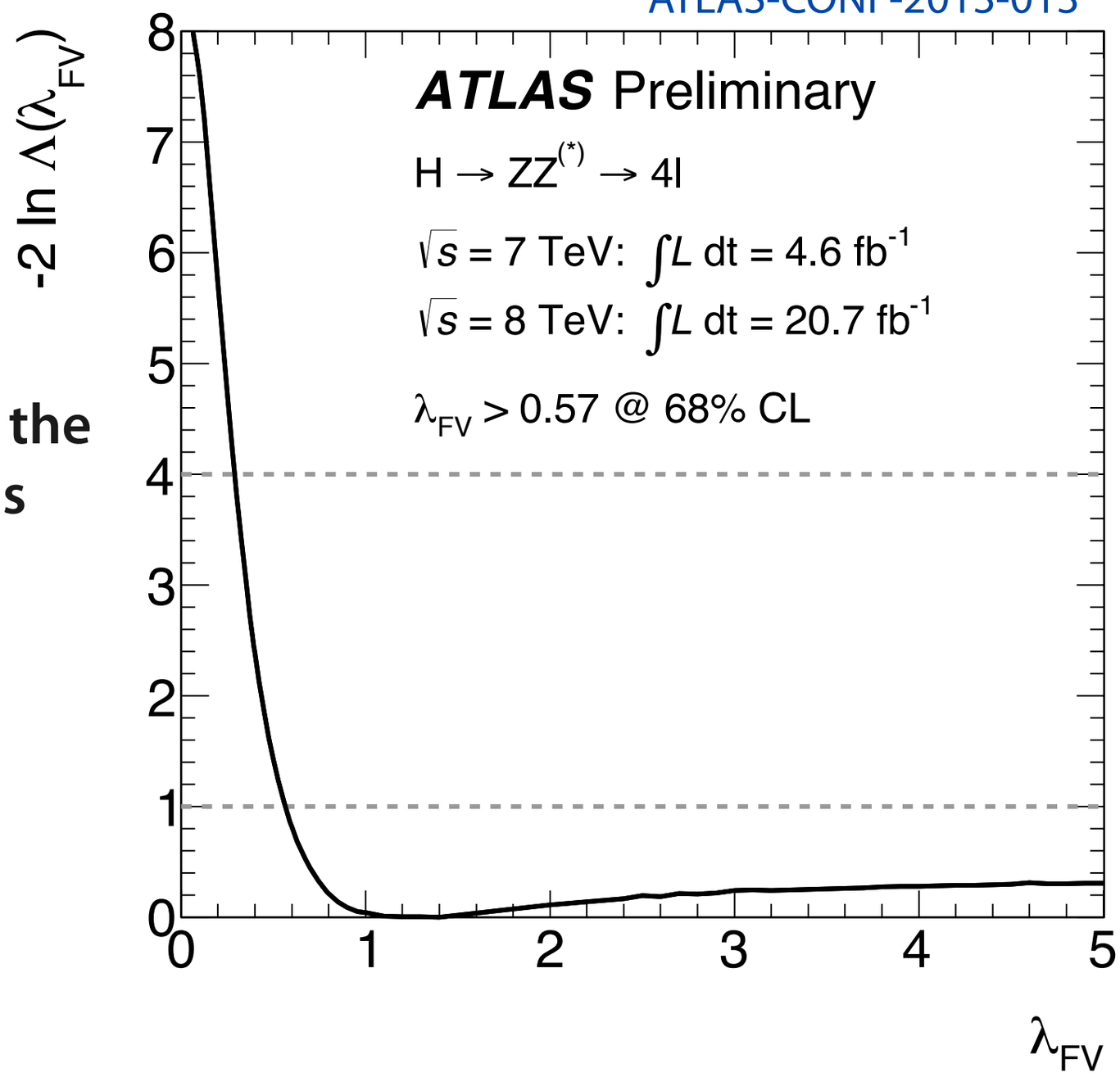
ATLAS only

ATLAS-CONF-2013-013

Also done in ATLAS:

measurement of the ratio between the coupling to fermions (F) and bosons (V): λ_{FV}

Already starting to rule out fermiophobic scenarios!

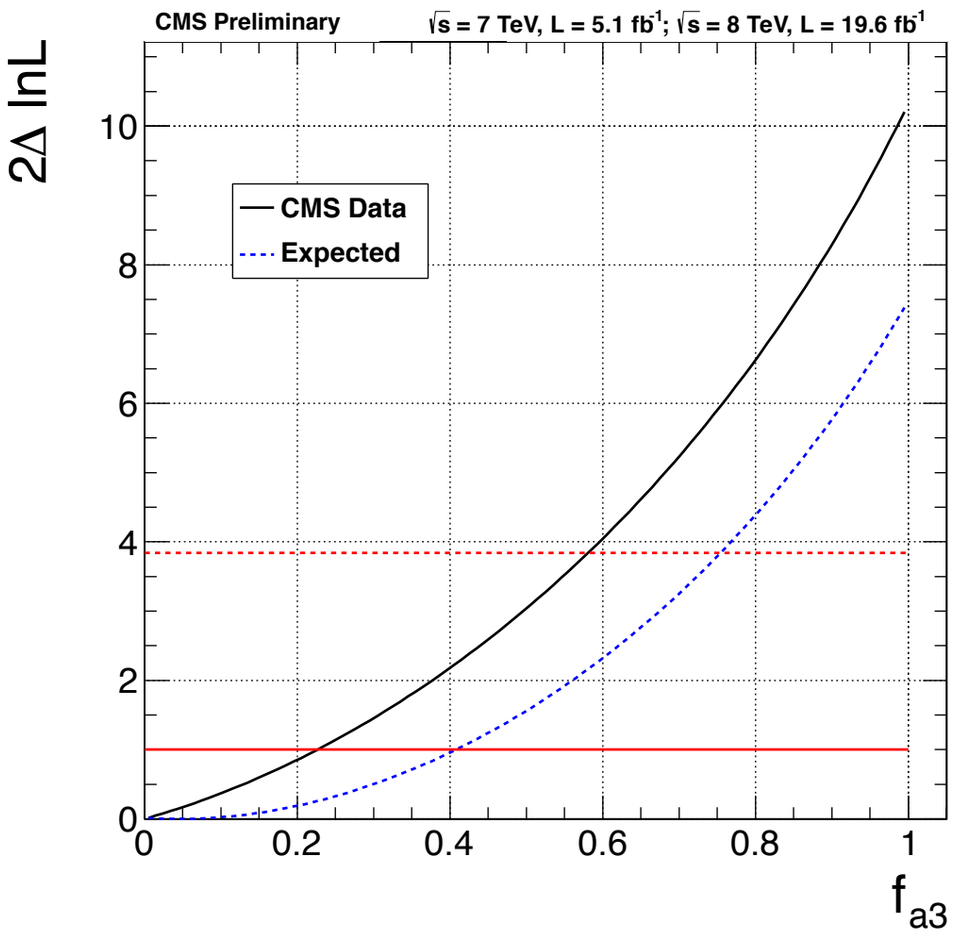


Measurement of f_{a3}

CMS only

CMS-PAS-HIG-13-002

$$A(X \to V_1 V_2) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$$



$$f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$

$$f_{a3} = 0.00^{+0.23}_{-0.00}$$

$$f_{a3} < 0.58 \ @ \ 95\% \ \mathrm{CL}$$