Higgs decays to bosons in CMS ($H\rightarrow\gamma\gamma$, $H\rightarrow WW$, $H\rightarrow ZZ$)

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Niels Bohr International Academy and Discovery Center, Copenhagen

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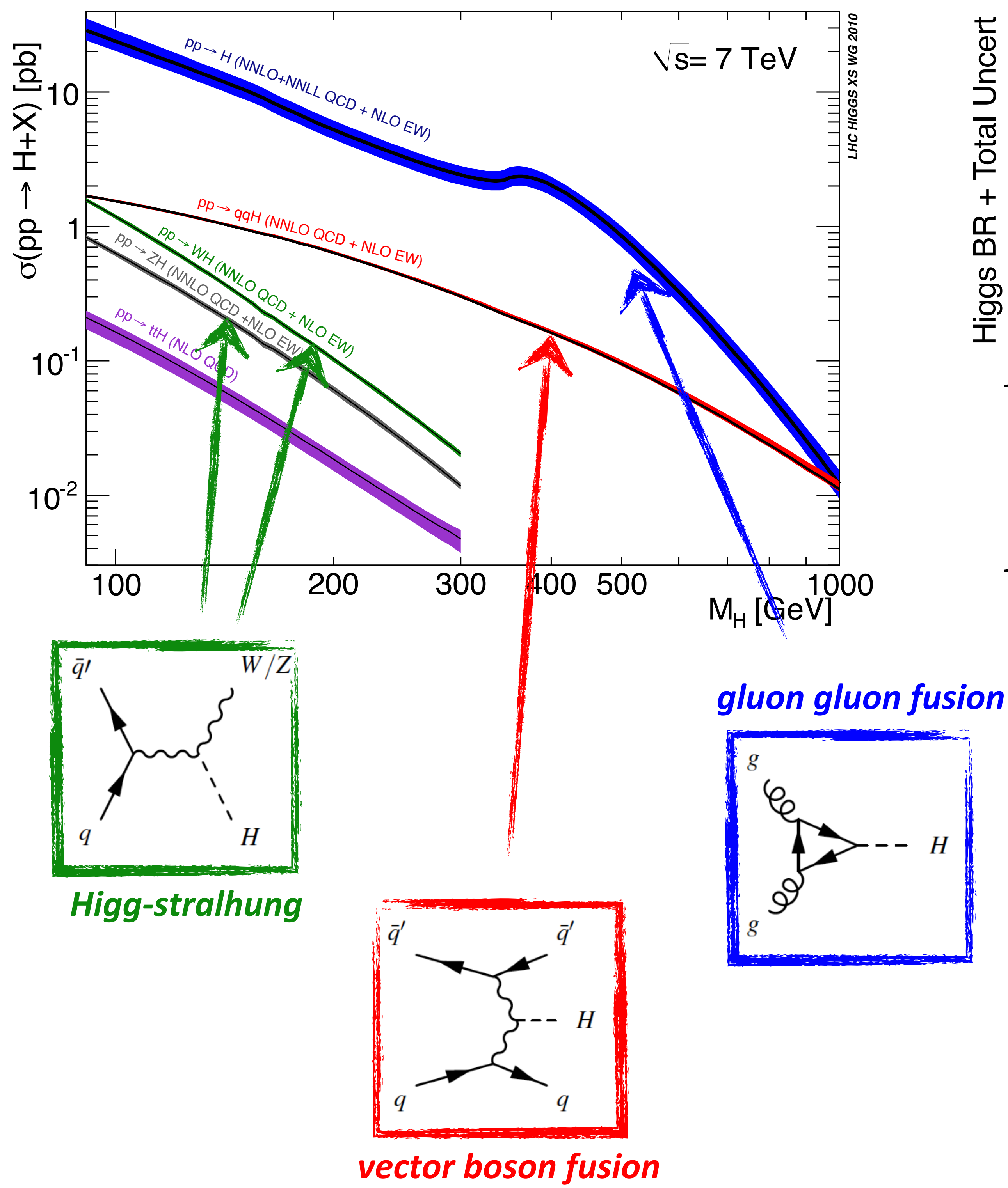
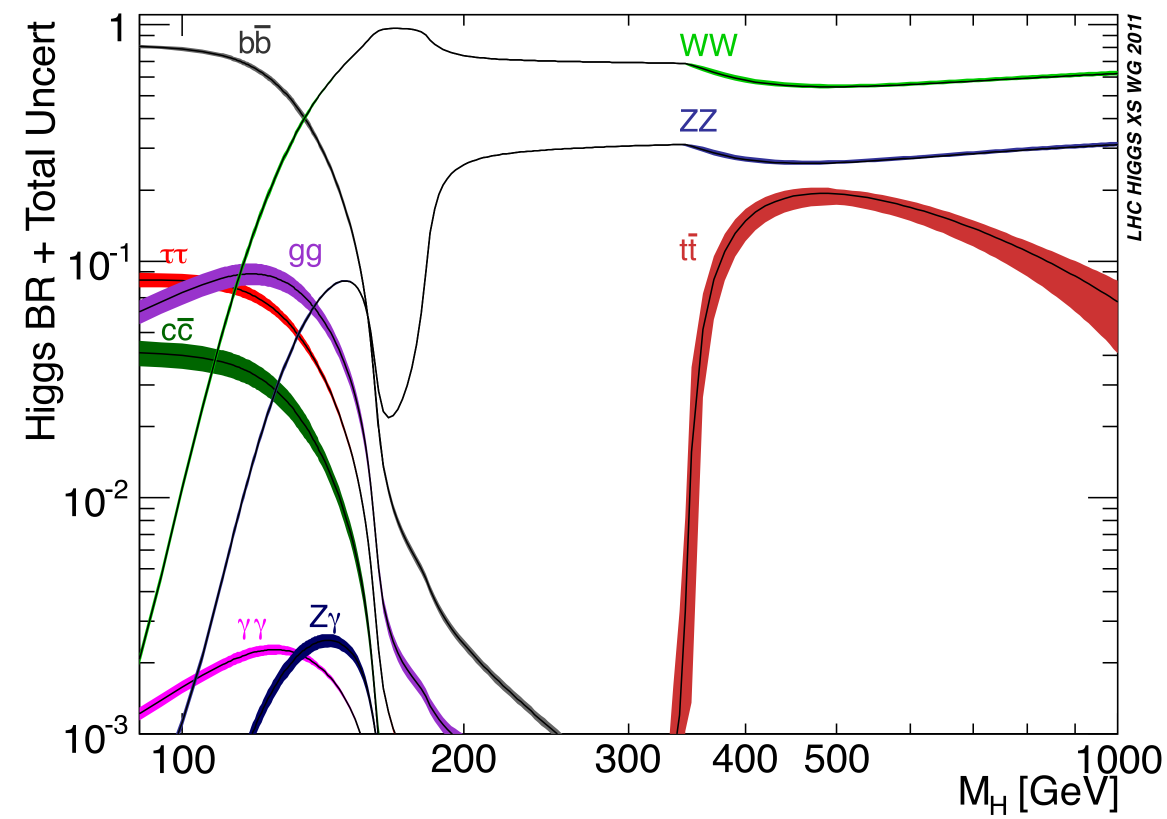
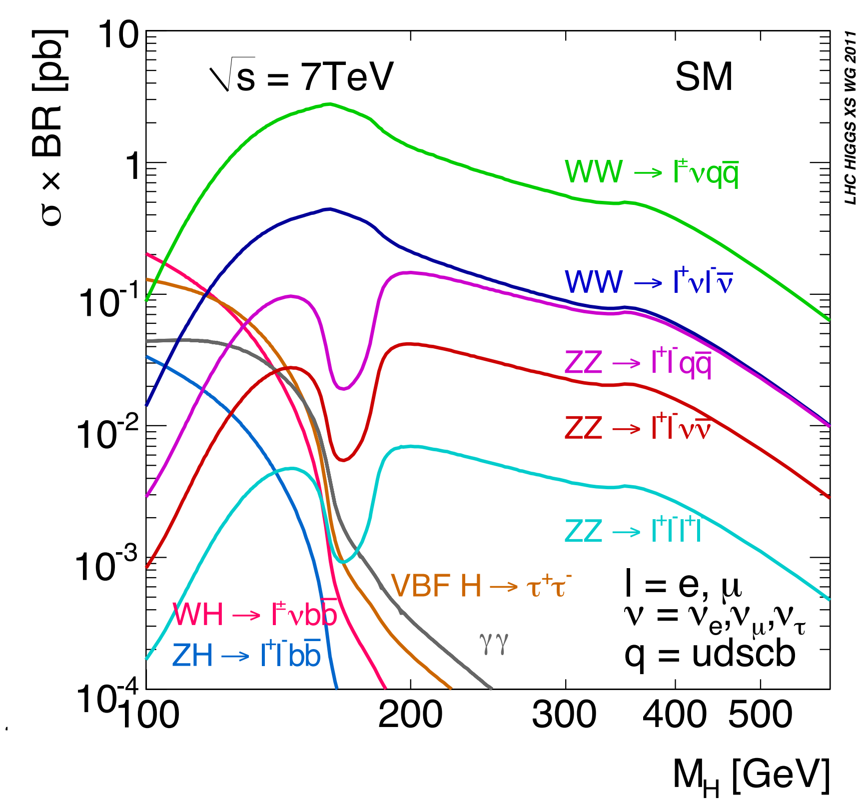
Higgs Production and Decays

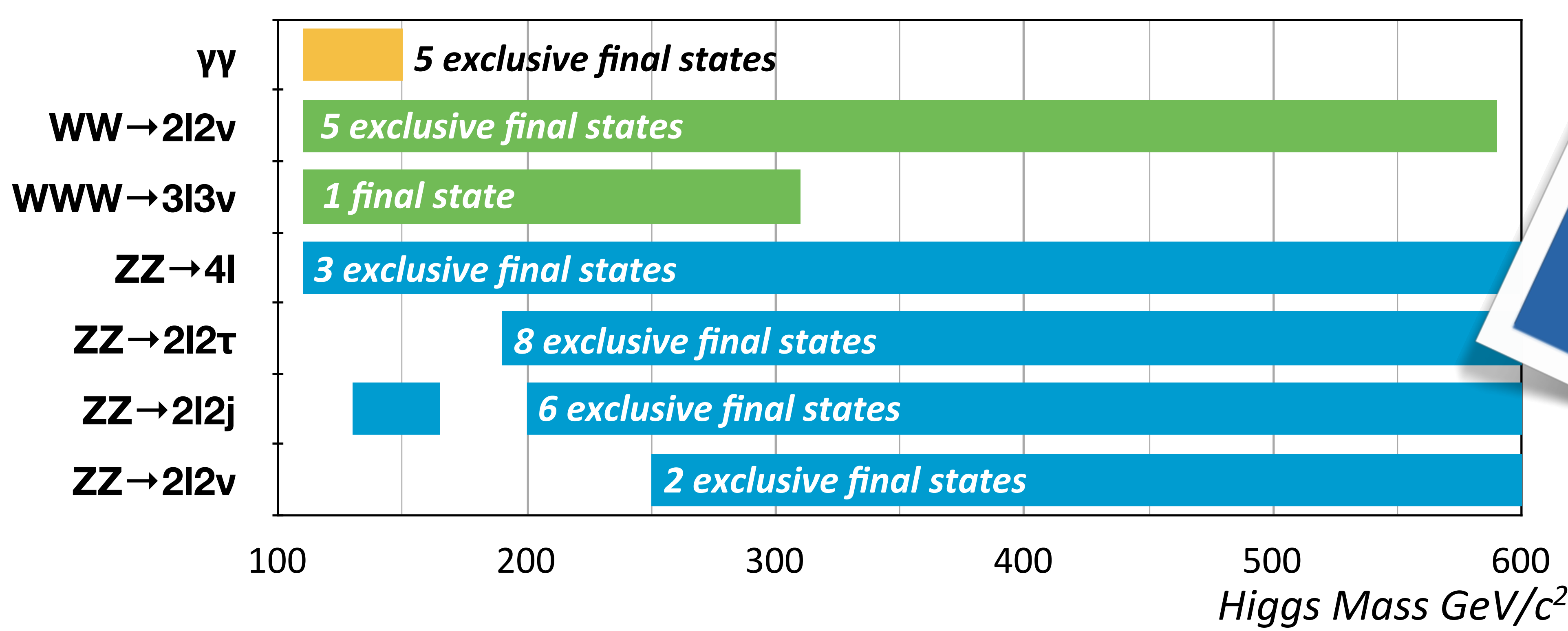






Higgs to Bosons Searches in CMS

Mode	Mass Range	Data Used (fb^{-1})	Mass resolution	CMS Document	
H →γγ	110-150	4.8	**1-3 %**	arXiv:1202.1487 HIG-12-001 (MVA) HIG-12-002 (FP)	
H →WW→2ℓ2ν	110-600	4.6	20%	arXiv:1202.1489	
H →WWW→3ℓ3ν	110-200	4.6	20%	HIG-11-034 (PAS)	*
H→ZZ→4l	110-600	4.7	**1-2%**	arXiv:1202.1997	
H→ZZ→2l2τ	190-600	4.7	10-15%	arXiv:1202.3617	*
H→ZZ→2l2j	130-165/200-600	4.6	3%	arXiv: 1202.1416	
H→ZZ→2l2ν	250-600	4.6	7%	arXiv:1202.3478	

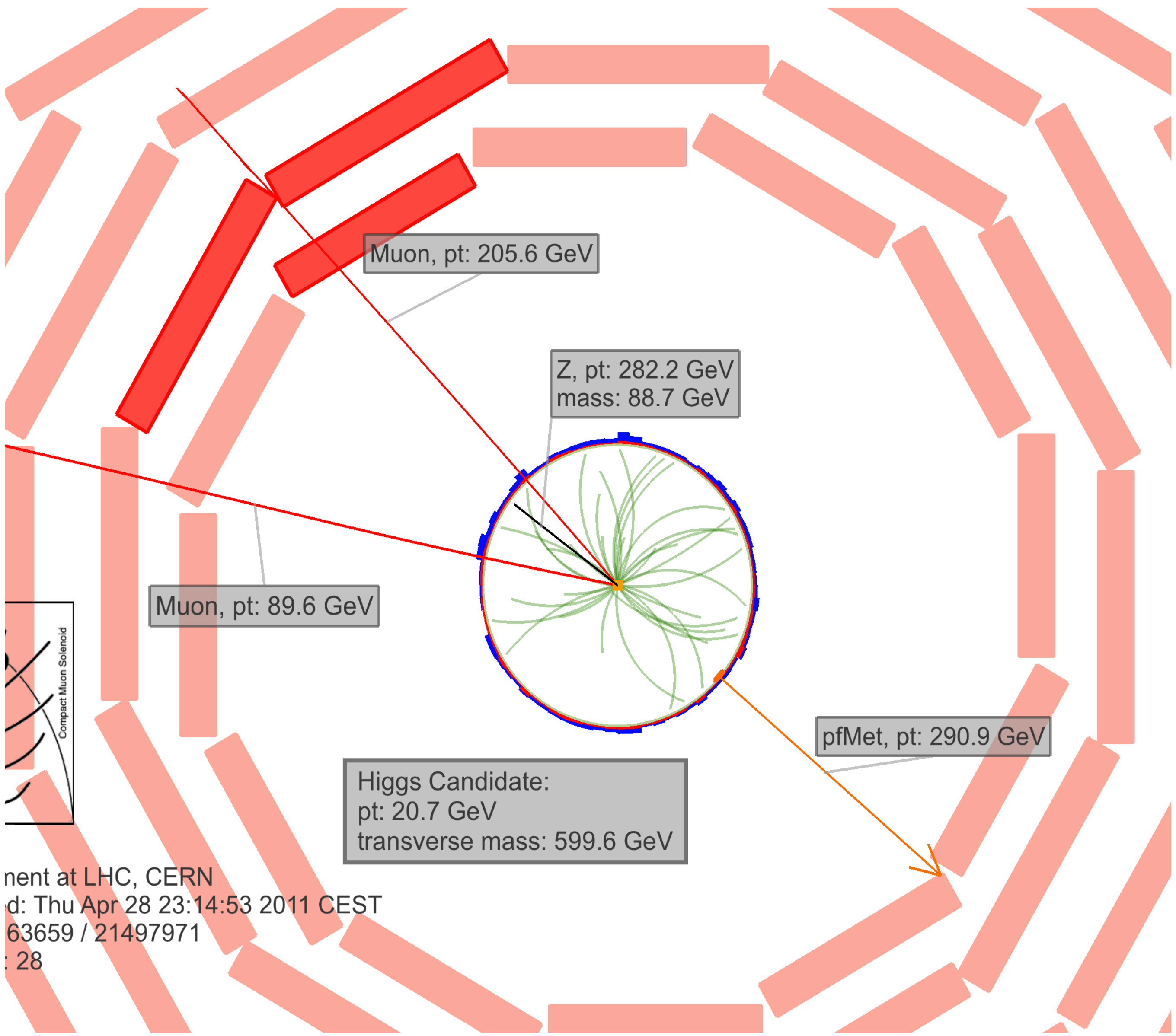


Fermionic channels in R.Mankel's talk

High Mass Range

$H \rightarrow ZZ \rightarrow 2\ell 2\nu$

Most sensitive channel for the high mass search



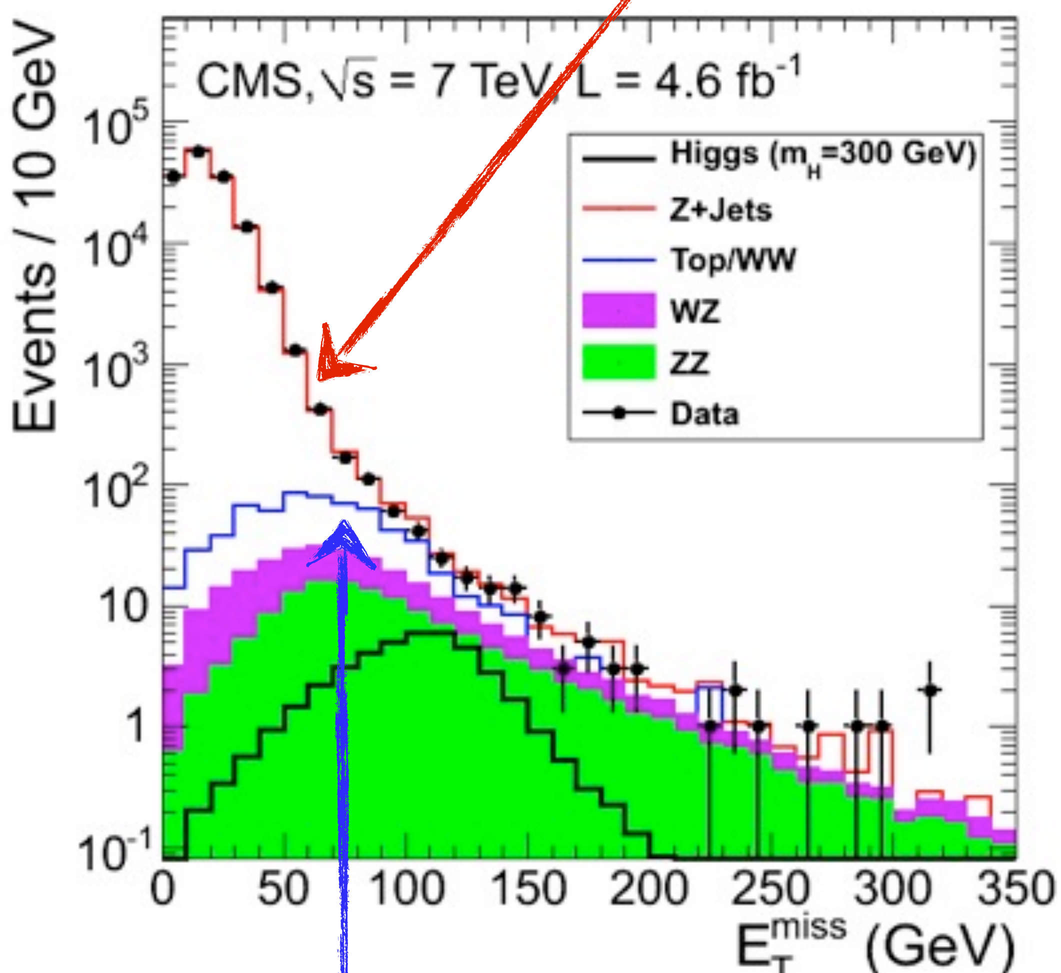
- Signature and selection
  - 2 isolated leptons $Z \rightarrow 2e/Z \rightarrow 2\mu$, matching the Z mass and boosted
  - large MET, not aligned with jets or leptons
  - b-jet veto
  - Final discriminant: M_T-shape
- Backgrounds
  - *ZZ*, irreducible
  - *Z*+jets: est. from γ-jets data
  - ttbar, *WW*, *W*+jets: est. from off Z-peak data
  - *WZ*
- Mass-resolution: 7%
- Two analysis, cut based and m_T-shape

arXiv 1202.3478
(submitted to JHEP)

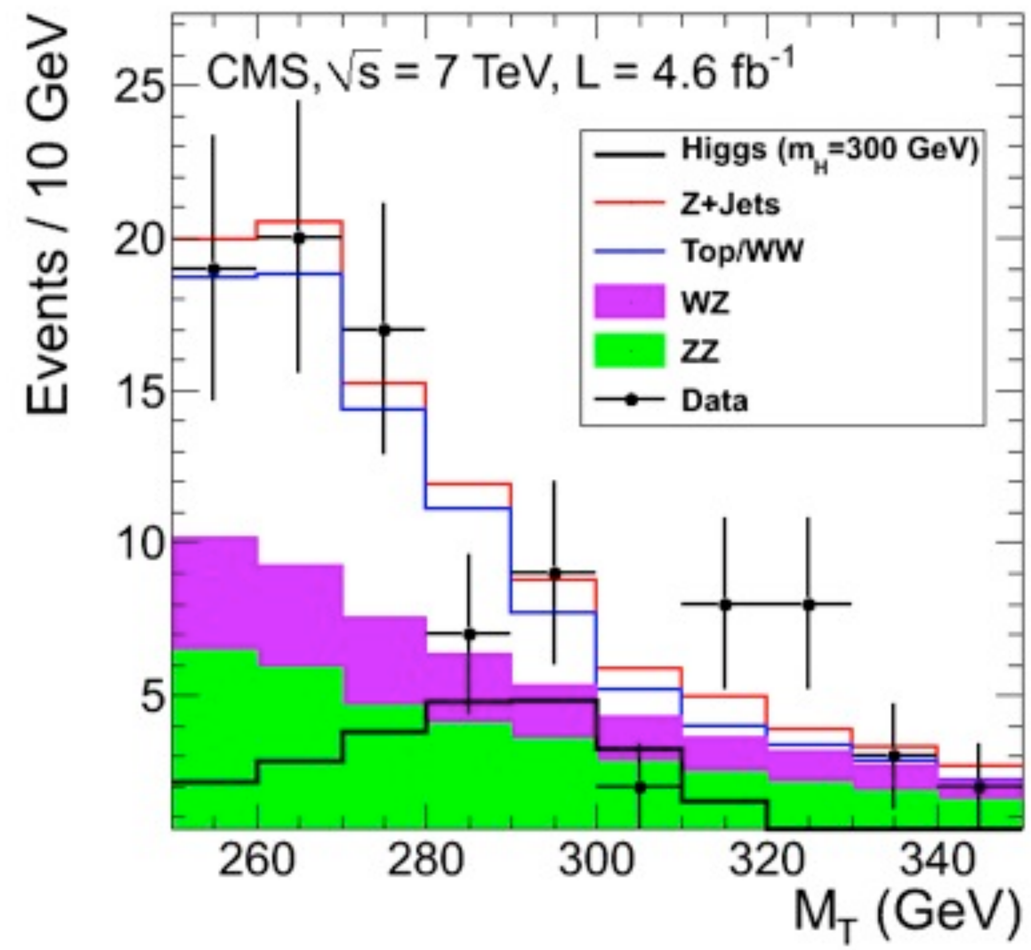
Distributions

H→ZZ→2ℓ2ν

Data-driven prediction for Z+jets background, using γ+jets events



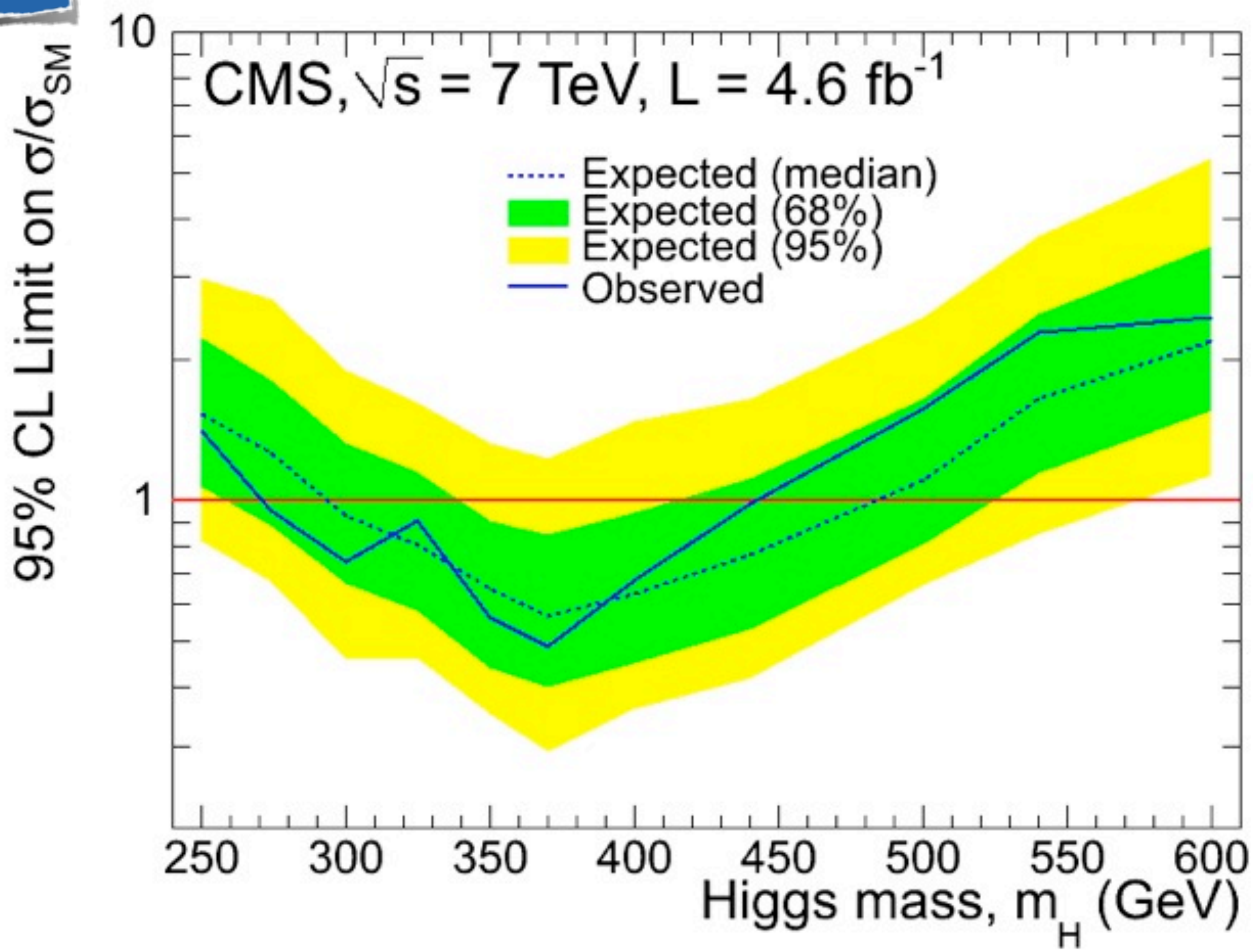
Data-driven prediction for ttbar/*WW* background, using m_Z sidebands



M_T after the very tight MET cut

Limits and Exclusion

H→ZZ→2ℓ2ν

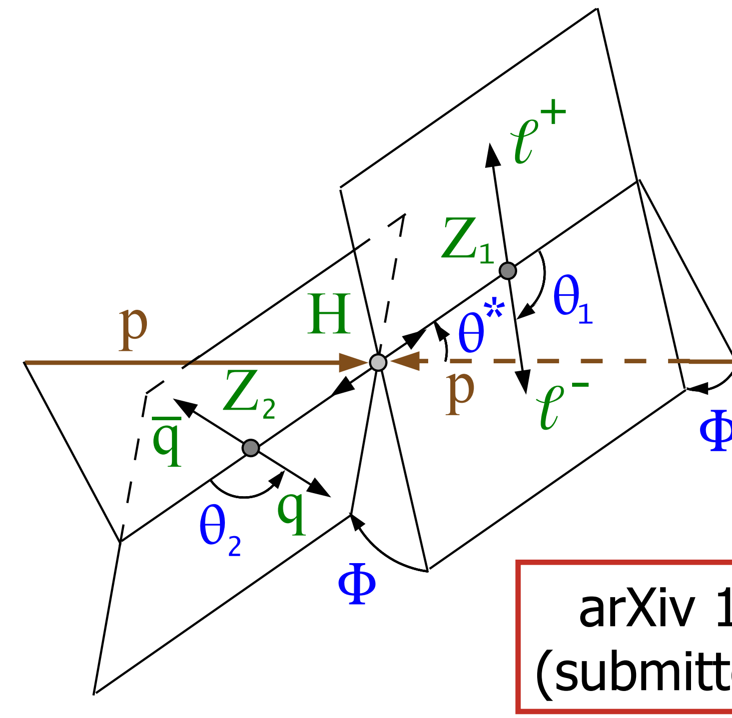


Expected: 290 < m_H < 490 GeV

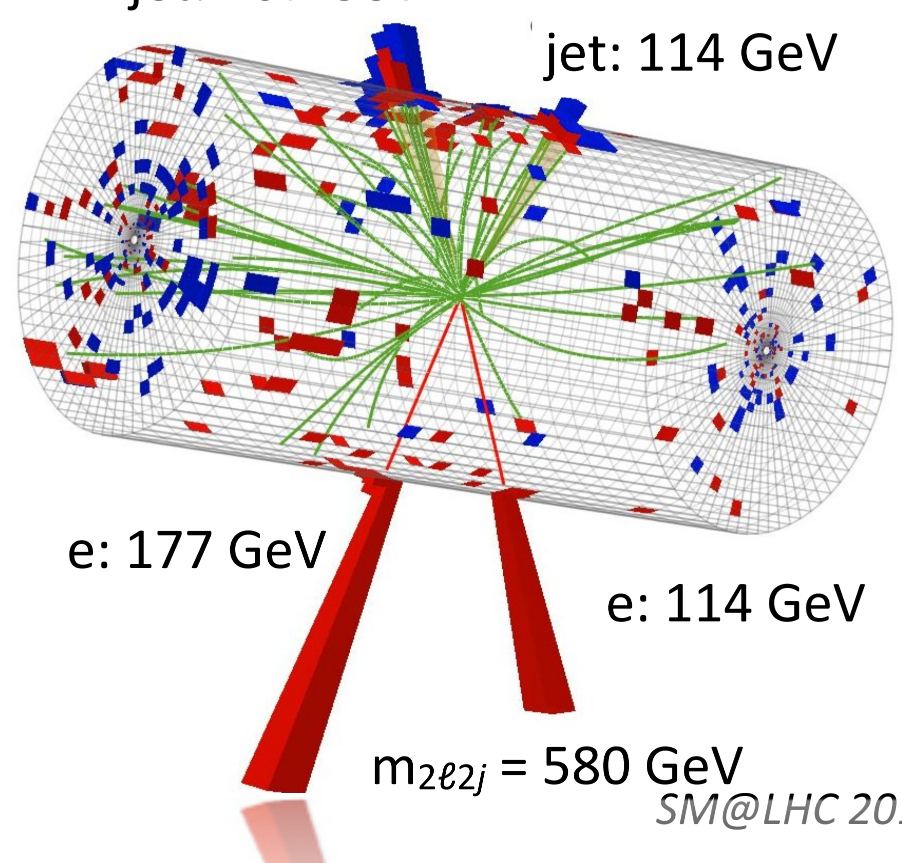
Observed: 270 < m_H < 440 GeV

H→ZZ→2ℓ2j

- Signature and selection
  - 2 opposite sign isolated prompt leptons (*Z*→2*e*/*Z*→2*μ*)
  - two jets: *Z*→*jj* with 0, 1, 2 b-tags
  - cut on angular topology likelihood discriminant
- Most of sensitivity from 2 b-tag category
- Final discriminant: $m_{\ell\ell jj}$ mass distribution
- Main backgrounds estimated from m_{jj} sidebands
  - *Z*+jets (including heavy flavor jets)
  - *WZ*, *ZZ*
  - ttbar, *WW*
- Mass resolution: 3%



arXiv 1202.1416
(submitted to JHEP)



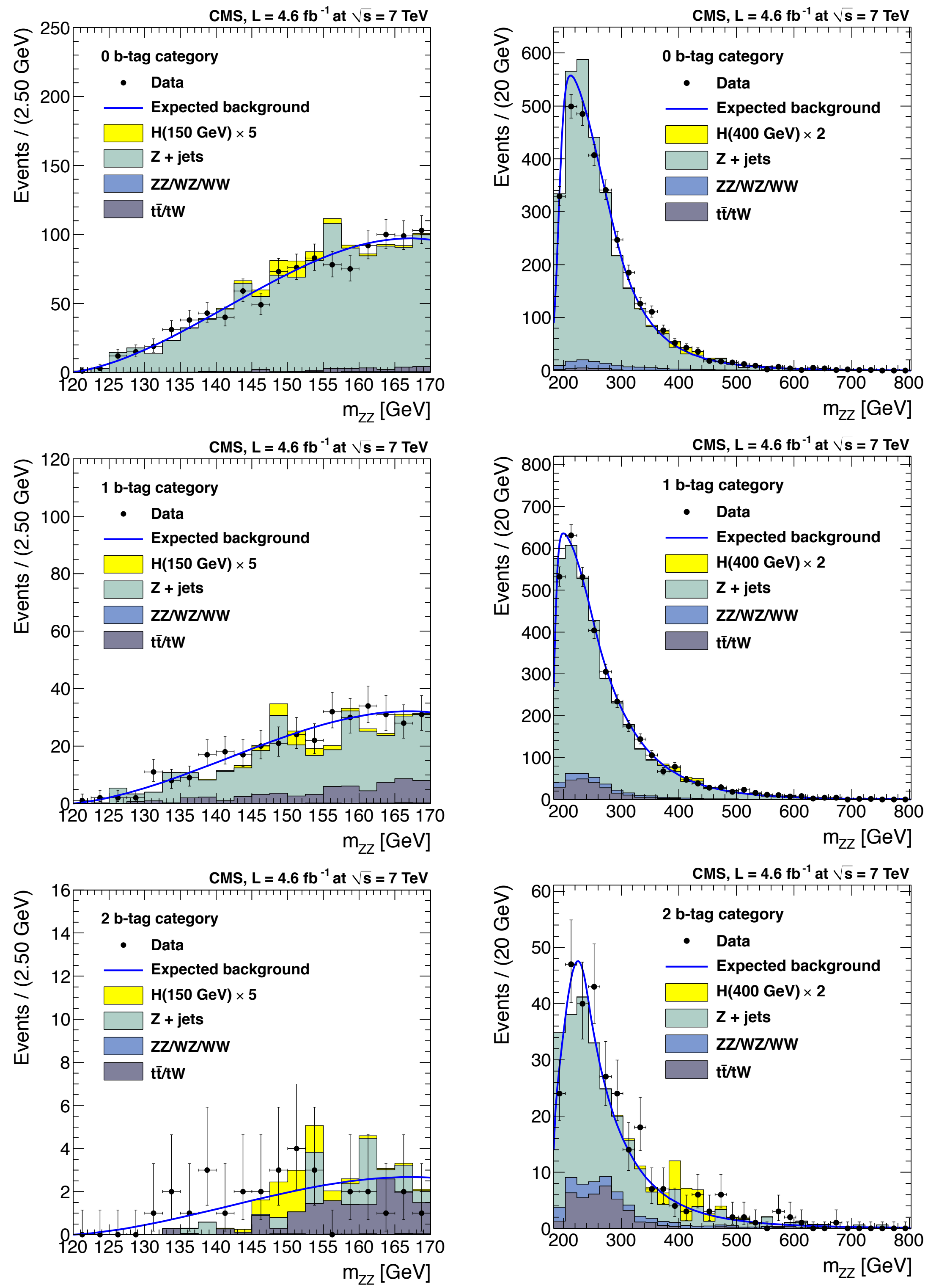
Distributions and Limits

$H \to ZZ \to 2\ell 2j$

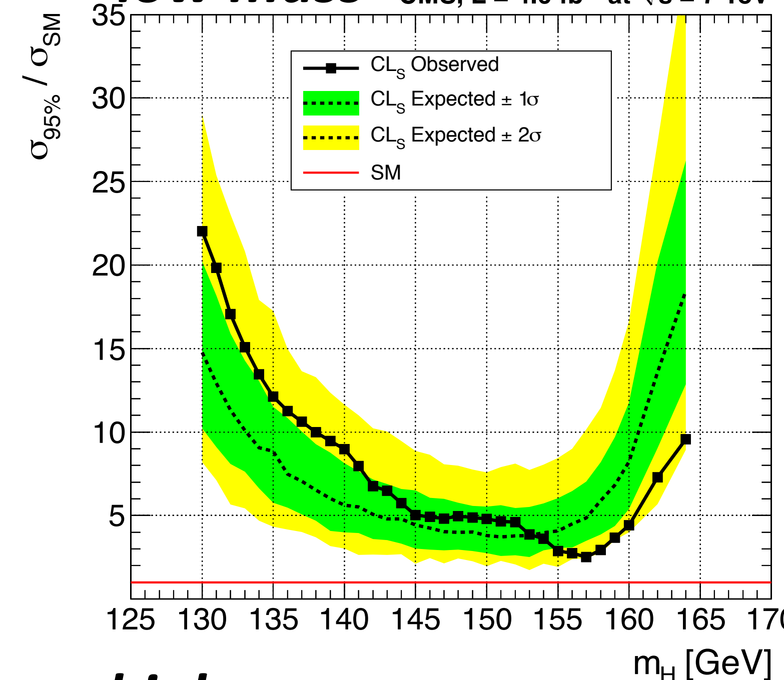
0 b-tag

1 b-tag

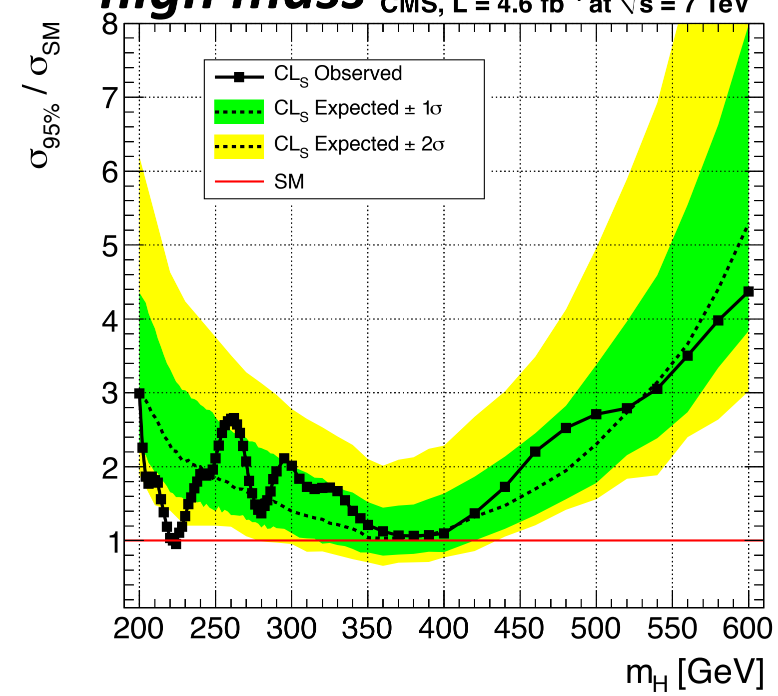
2 b-tag



low mass



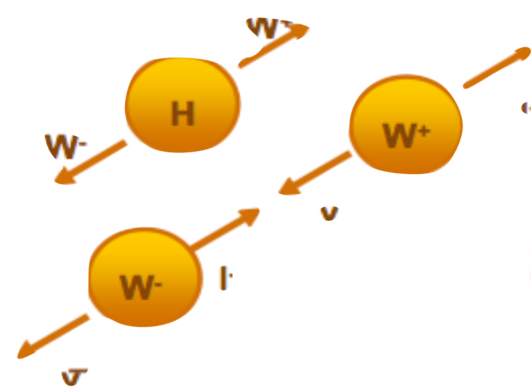
high mass

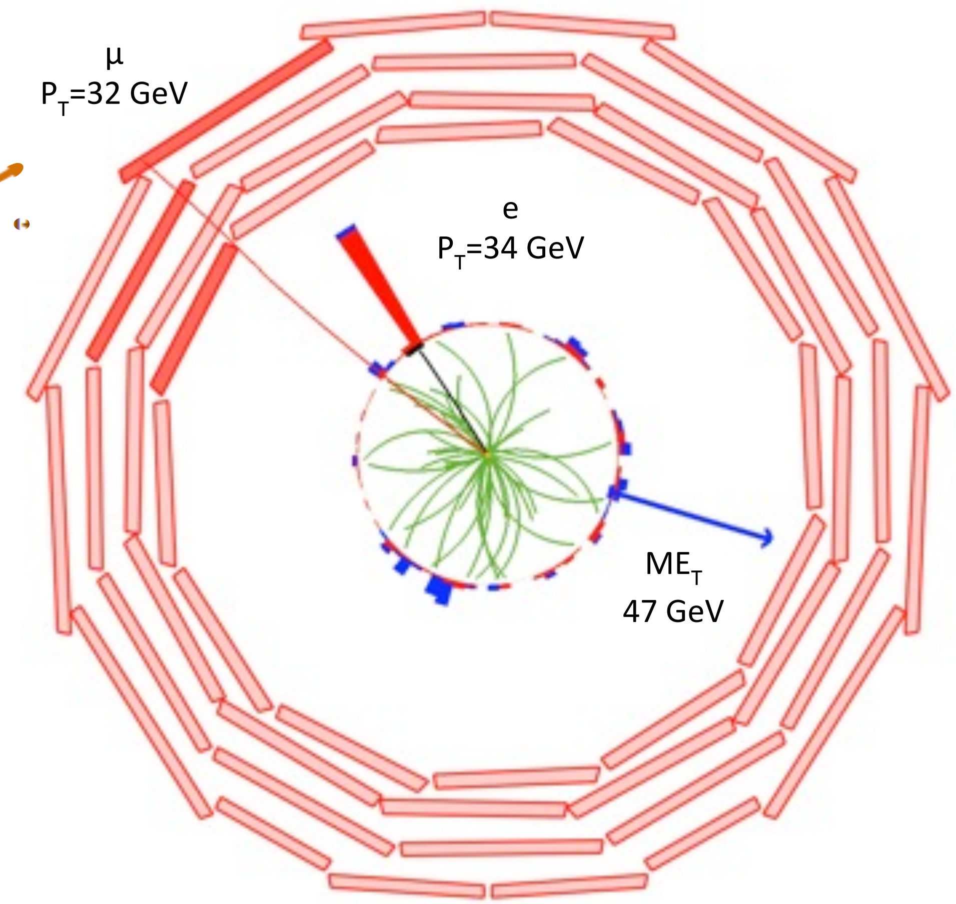


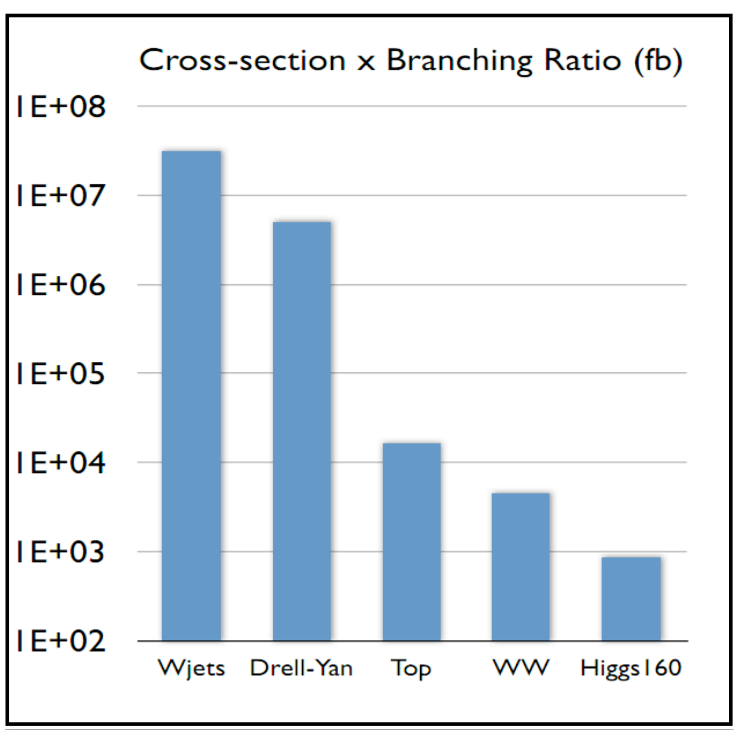
Full Mass Range

$H \to WW \to 2\ell 2\nu$

- Highest sensitivity for $m_H \approx 2m_W$
- Signature and selection
  - 2 opposite sign isolated leptons
  - high MET and no mass peak
  - small $\Delta\phi(\ell^+\ell^-)$
  - classification by number of jets (p_T>30 GeV)
  - Z-peak veto and b-jet veto







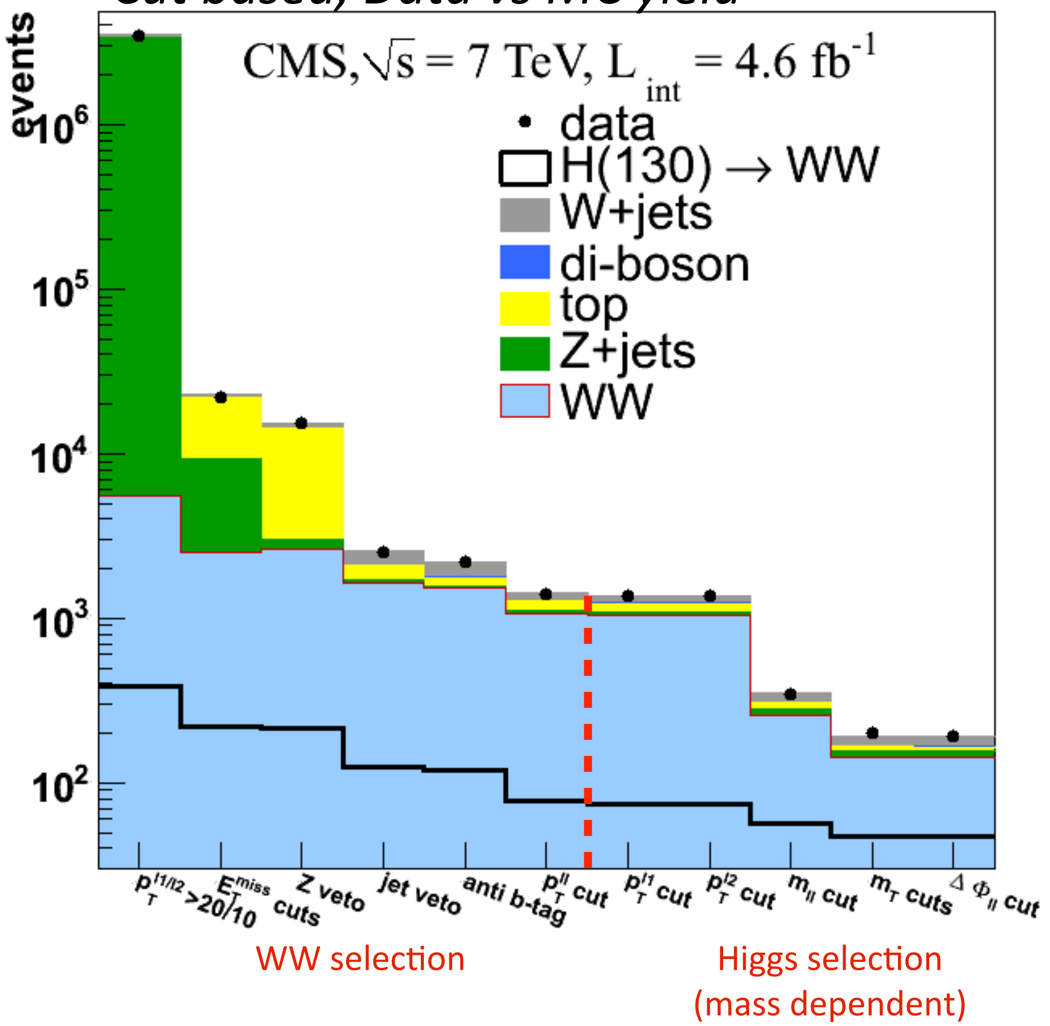
- The challenge is to remove & control large backgrounds
  - WW, irreducible, estimated from data
  - Z+jets, tt, W+jets: from data
  - WZ, ZZ from MC
- Two analyses: cut based and Boosted Decision Tree (BDT) shape

arXiv 1202.1489
(submitted to PLB)

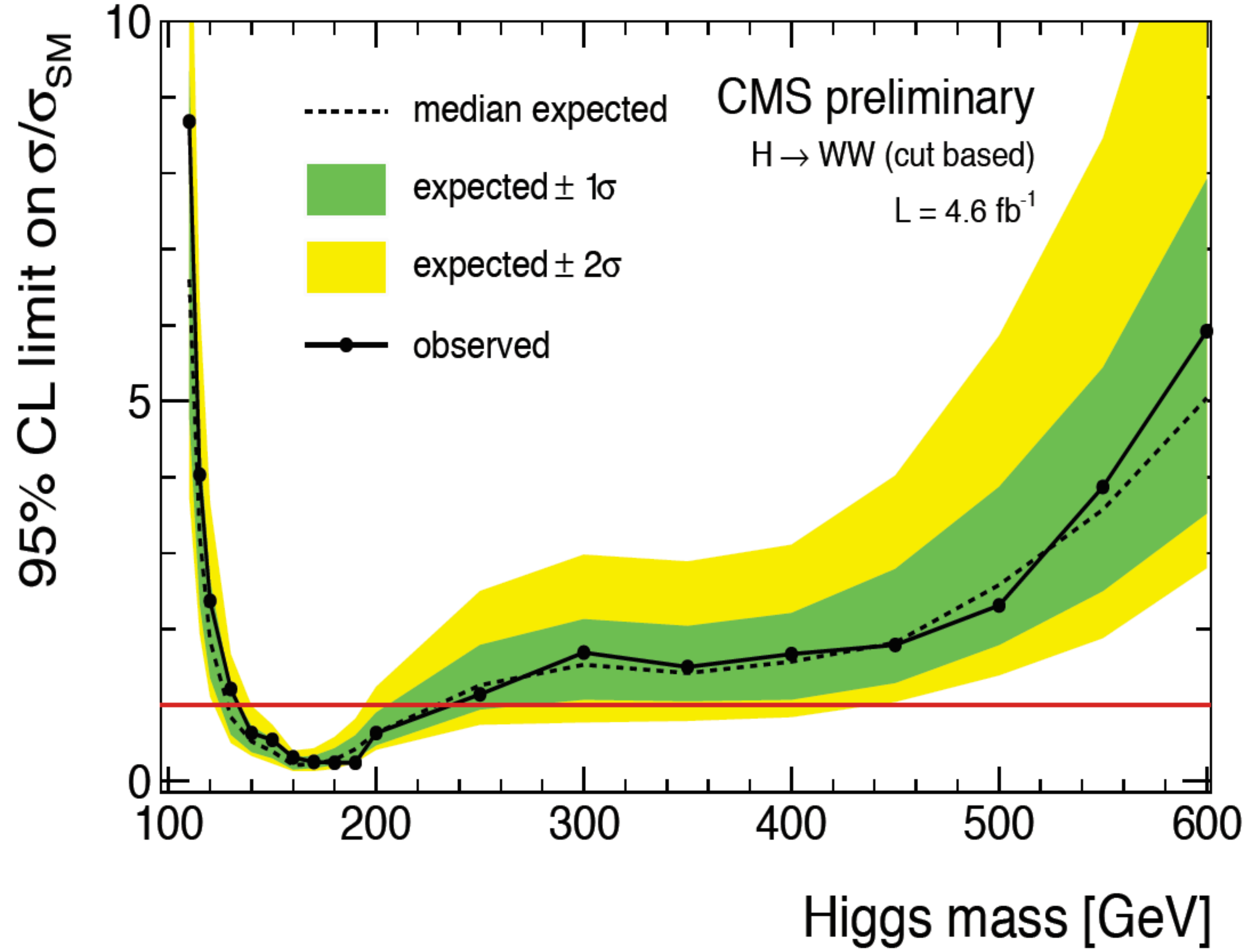
Cut based

H→WW

Cut based, Data vs MC yield



Data described well by the MC



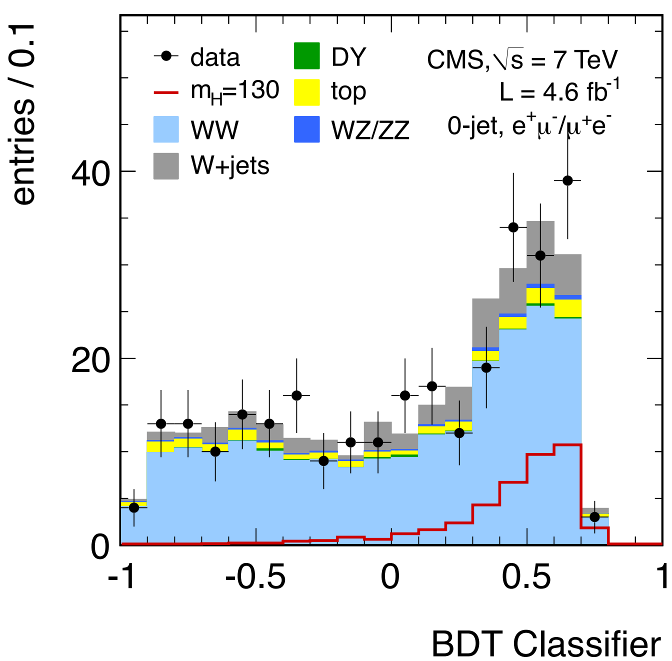
Expected: 129 < m_H < 236 GeV

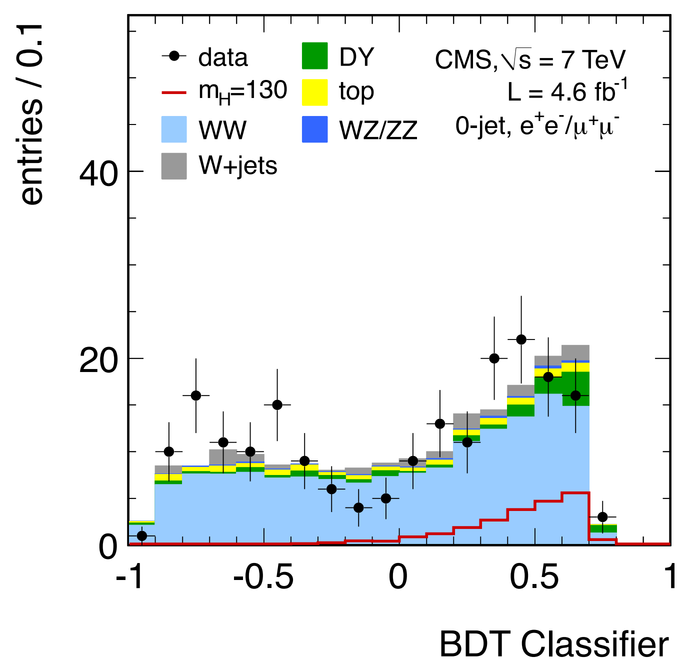
Observed: 132 < m_H < 238 GeV

MVA Analysis 0,1 jets

H→WW

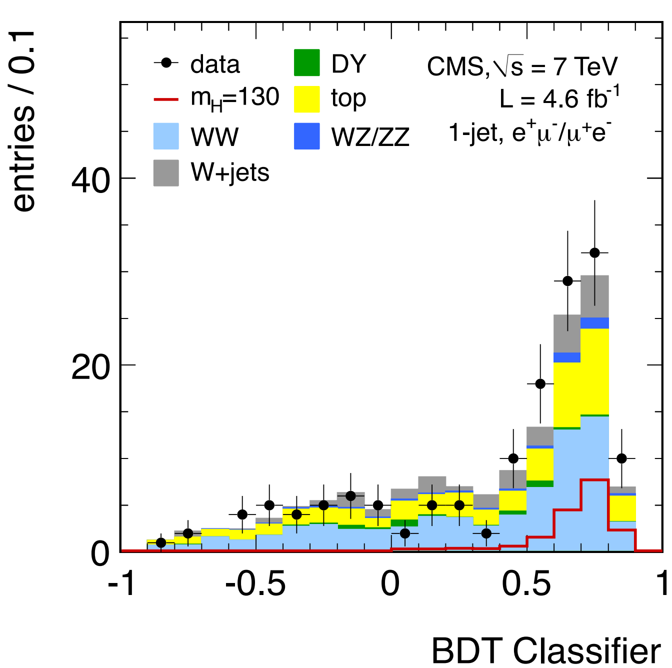
0-jet eμ

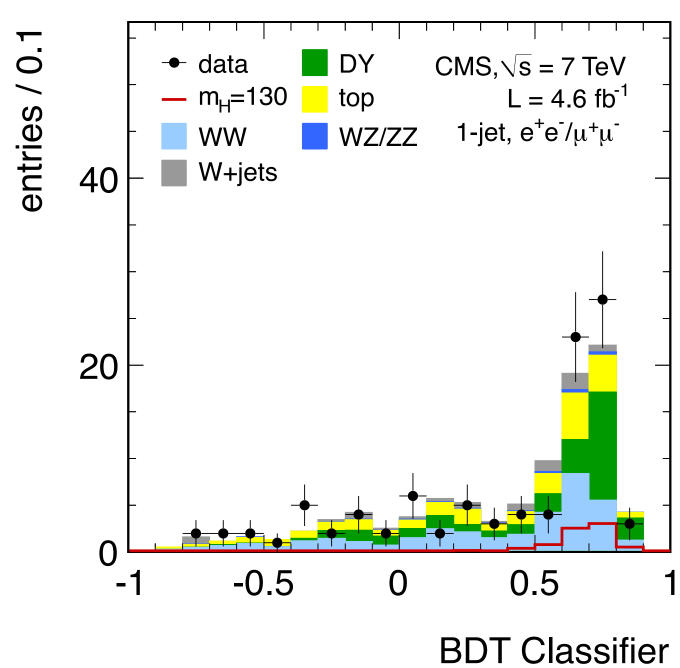




0-jet ee,μμ

1-jet eμ

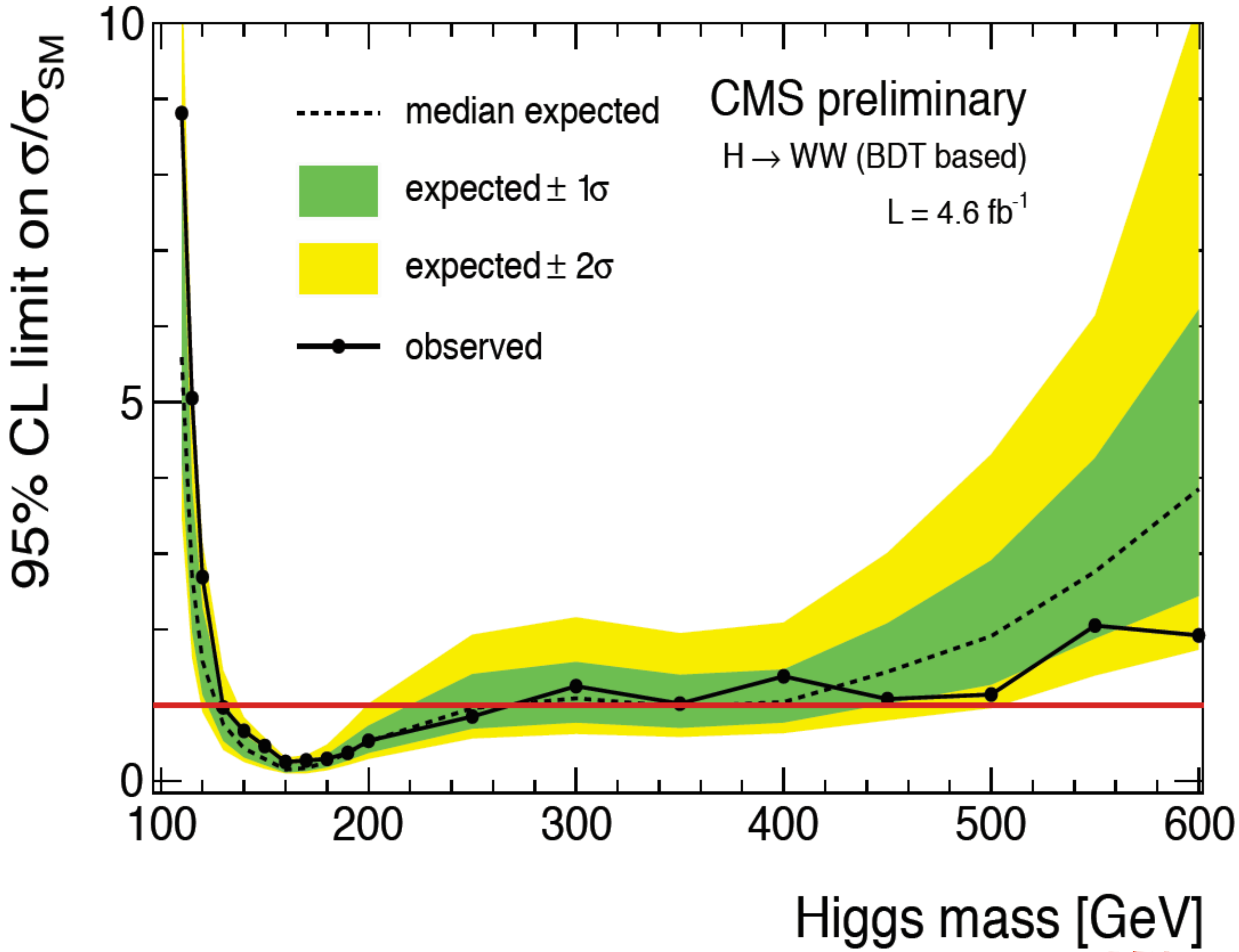




1-jet ee, μμ

- BDT trained on pT_ℓ, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$ and $mT_{\ell\ell}$, mT_ℓ at each mass point against *WW* continuum
- BDT shape analysis
- Overall Uncertainties
  - signal efficiency ~20%
  - backgrounds ~20%
- Additional $m_{\ell\ell}$ shape and matrix element analysis used as cross-check

MVA Exclusion Limit

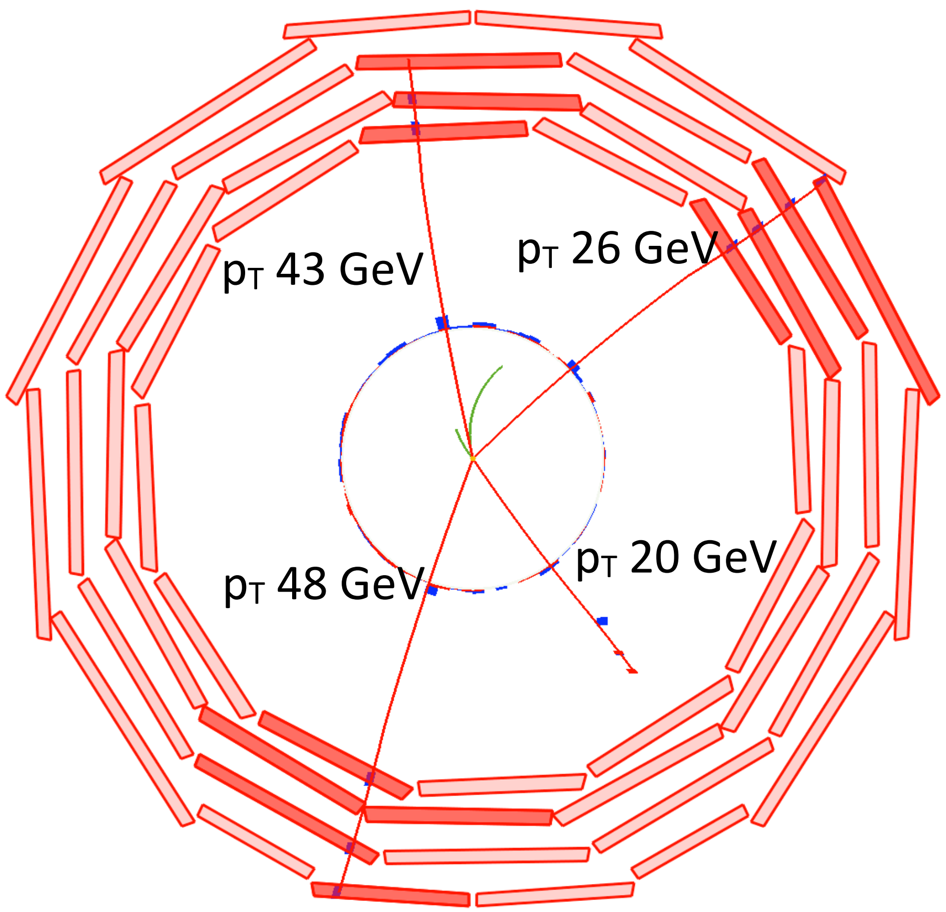


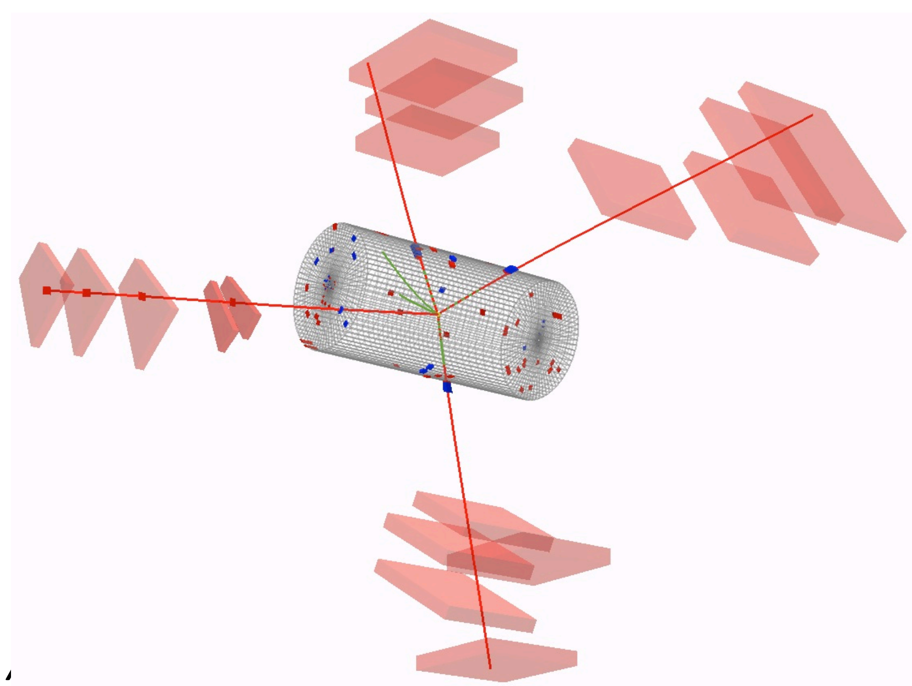
arXiv:1202.1489

Expected: 127 < m_H < 270 GeV

Observed: 129 < m_H < 270 GeV

H→ZZ→4ℓ: the Golden Channel



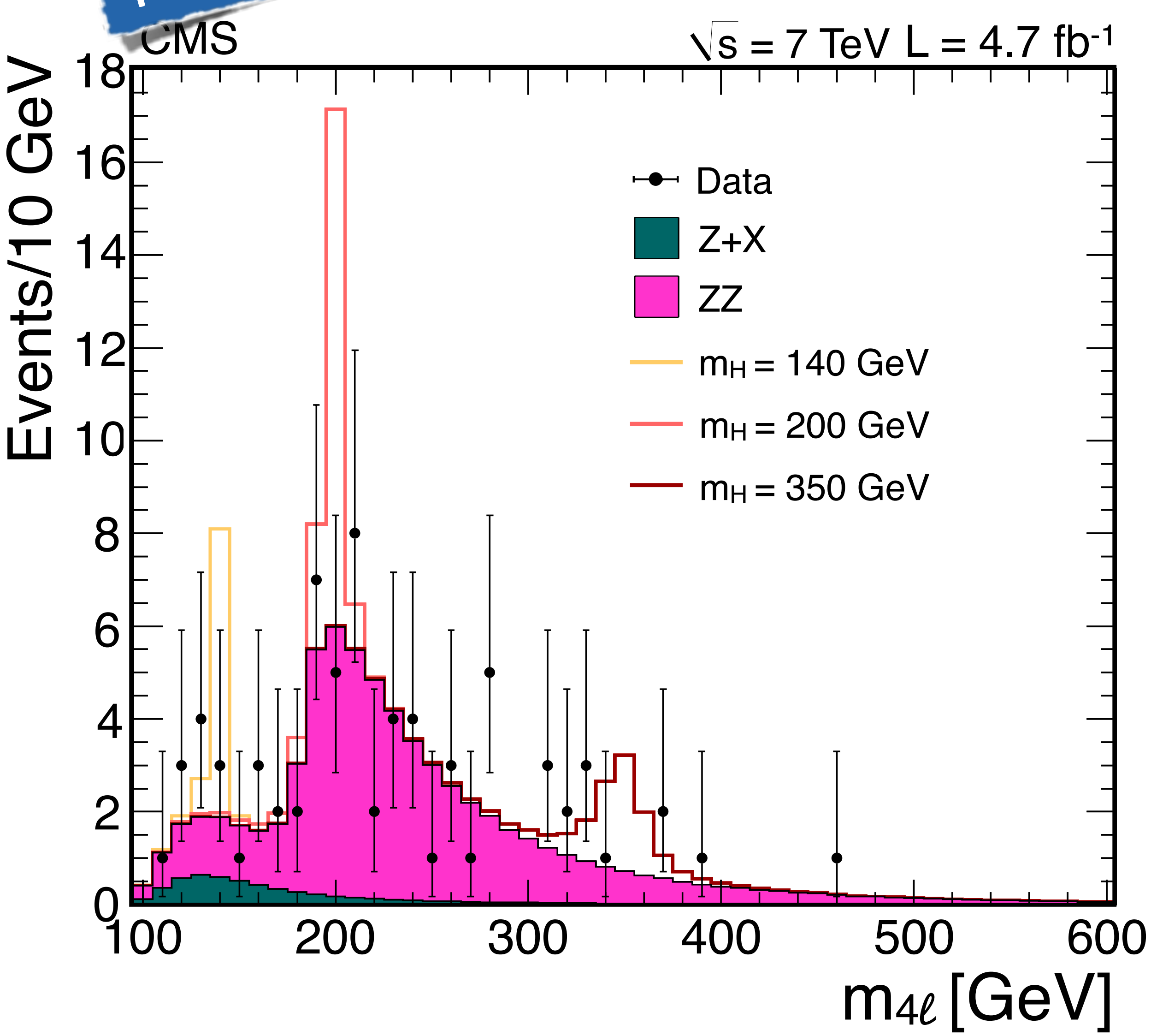


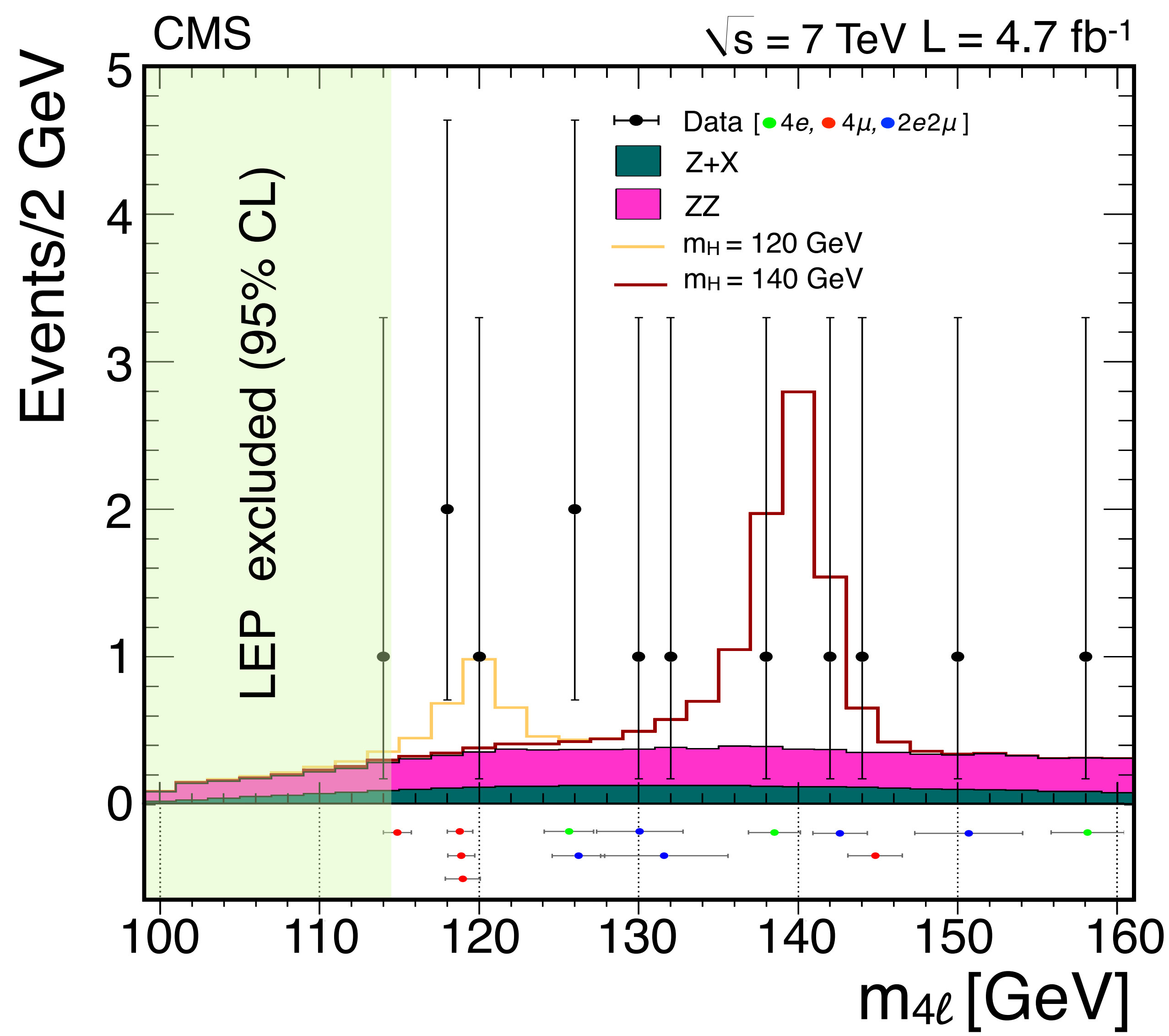
arXiv 1202.1997
(submitted to PRL)

- Signature
  - 4 isolated lepton from common vertex
  - narrow mass peak
- Fully reconstructed, mass resolution ~1-2%
- Main backgrounds:
  - ZZ continuum, irreducible
  - tt→2ℓ2ν2b, Z+bb reducible, est. from data
- Event Selection:
  - same flavor, opposite charge
  - (50/60) < m_{Z1} < 120 GeV, (12/60) < m_{Z2} < 120 GeV
  - $m_{4\ell}$ > 100 GeV
- ZZ continuum:
  - Shape known at NLO, corrected for gg→*ZZ*→4ℓ evaluated with MCFM
  - Rate obtained from Z yield in data & theoretical prediction for ratio of ZZ to Z cross sections

Expected and Observed Yields

H→ZZ→4ℓ





$m_{4\ell}$ **> 100 GeV/c²**

Exp. events: 67.1 ± 6.0

Obs. events: 72

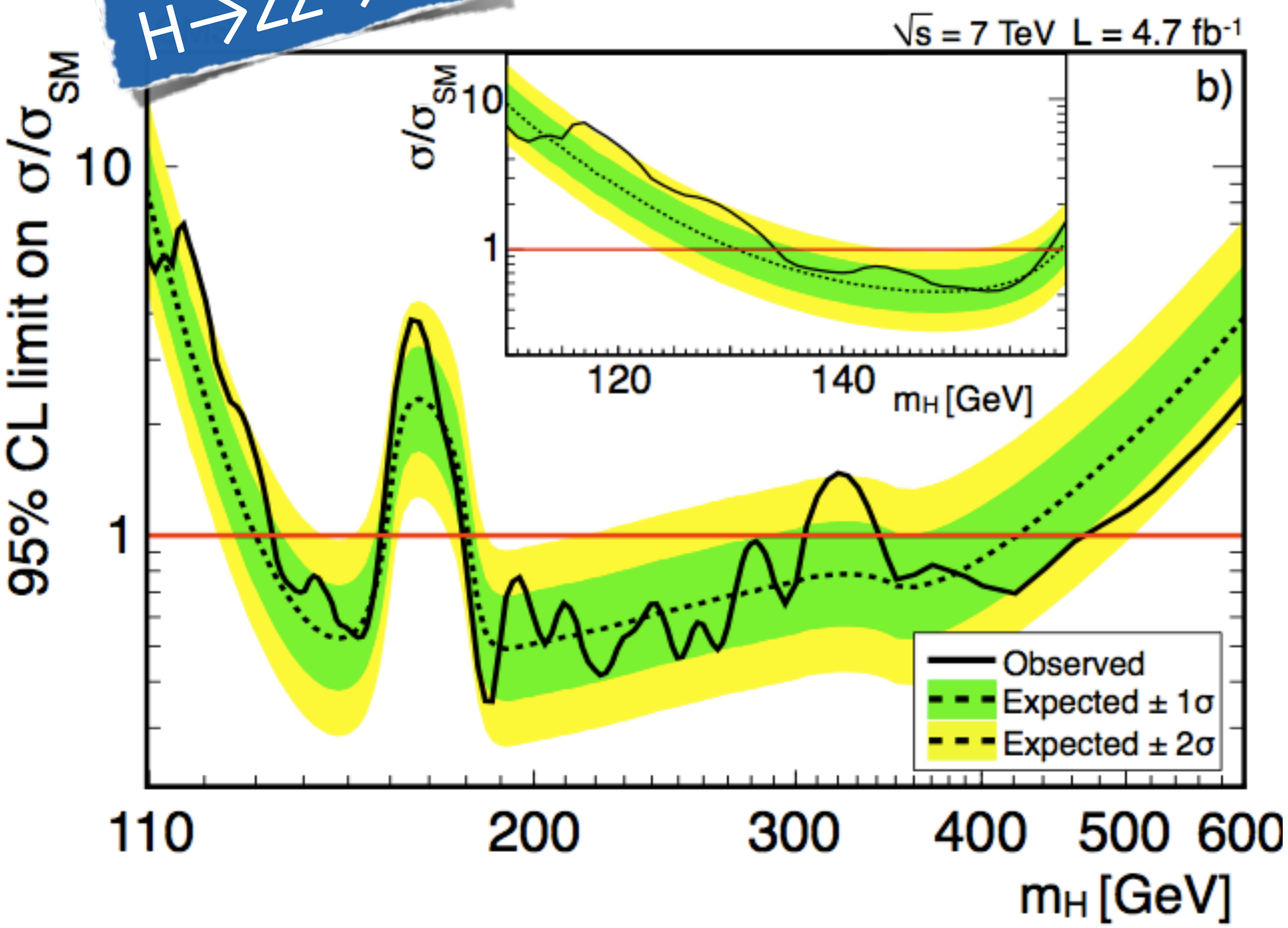
100 < $m_{4\ell}$ **< 160 GeV**

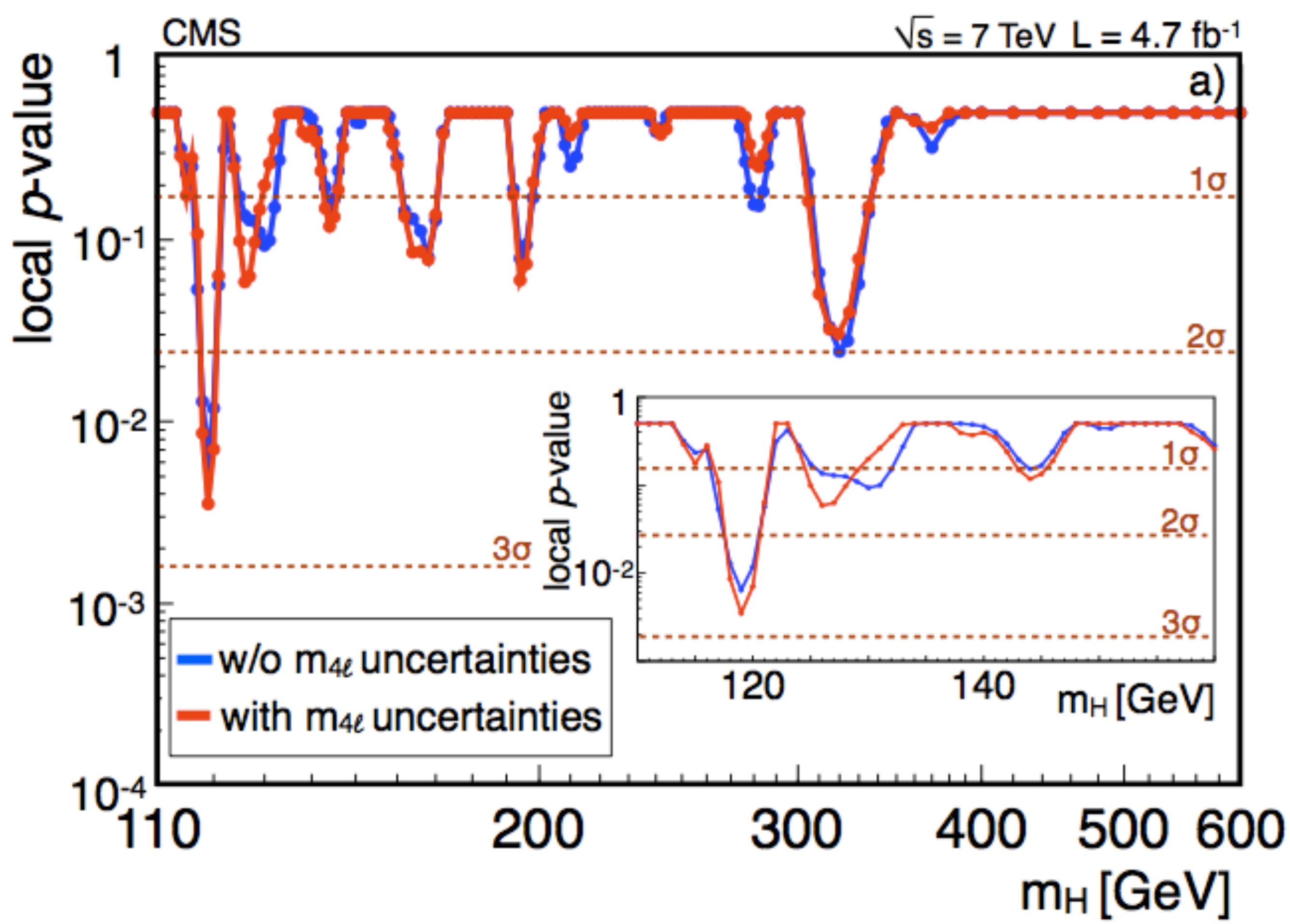
Expected events: 9.5 ± 1.3

Observed events: 13

Exclusion Limits and p-values

H→ZZ→4ℓ



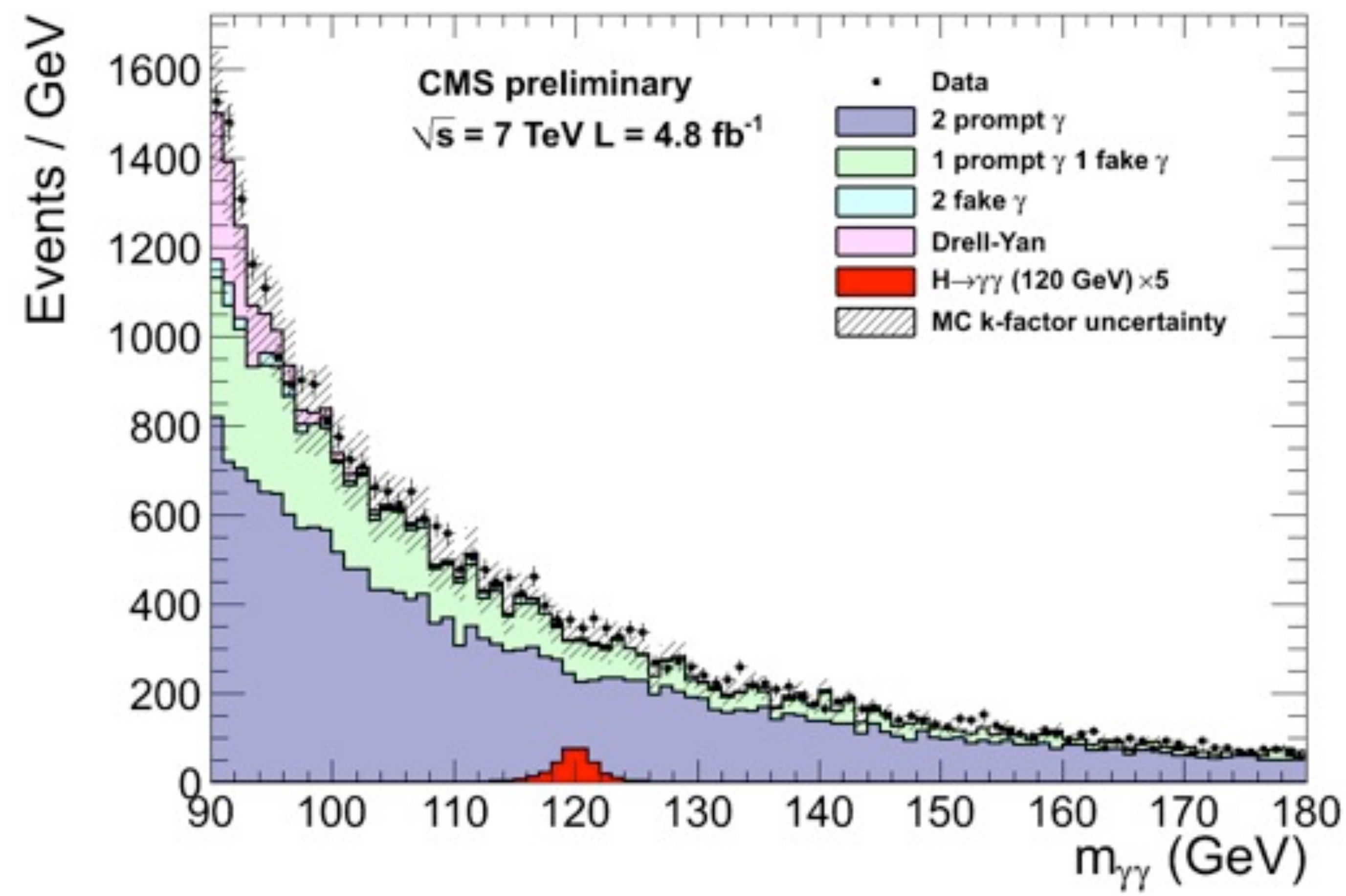


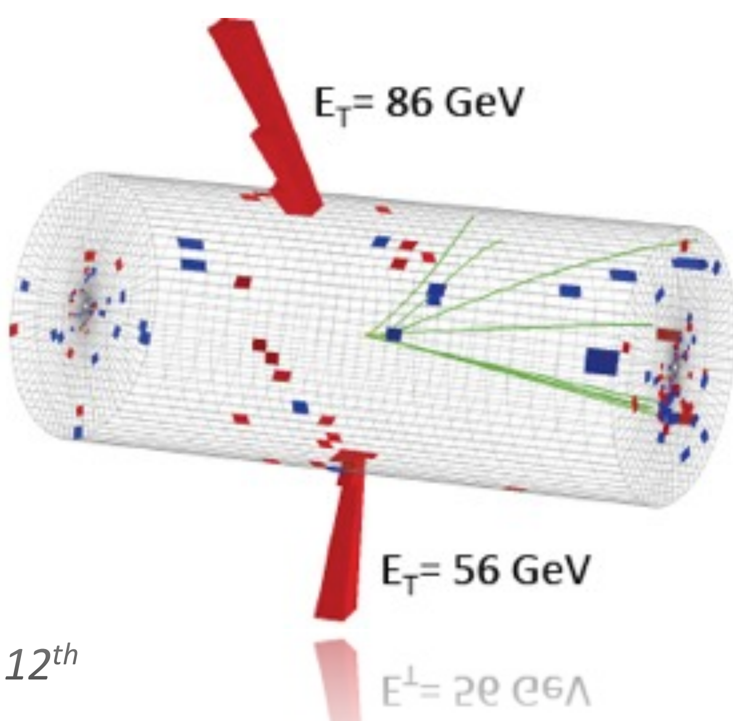
- Exclusion ranges: [134,158],[180,305],[340,465]
- Largest excess: 2.5σ at 119 GeV (1.6σ after LEE in 110-160 GeV)
- Also, local p-value = 1.5σ at 126 GeV and ~2σ at 320 GeV

Low Mass Range

H→γγ

- Very good mass resolution 1-2%
- Narrow mass peak
- Signature
  - 2 isolated high-E_T photons
  - Small peak over smooth background
  - 2 additional jets for the VBF channel
- Main backgrounds
  - Reducible: fake photons (γ+jet, Drell-Yan to electrons)
  - Irreducible: γγ QCD production

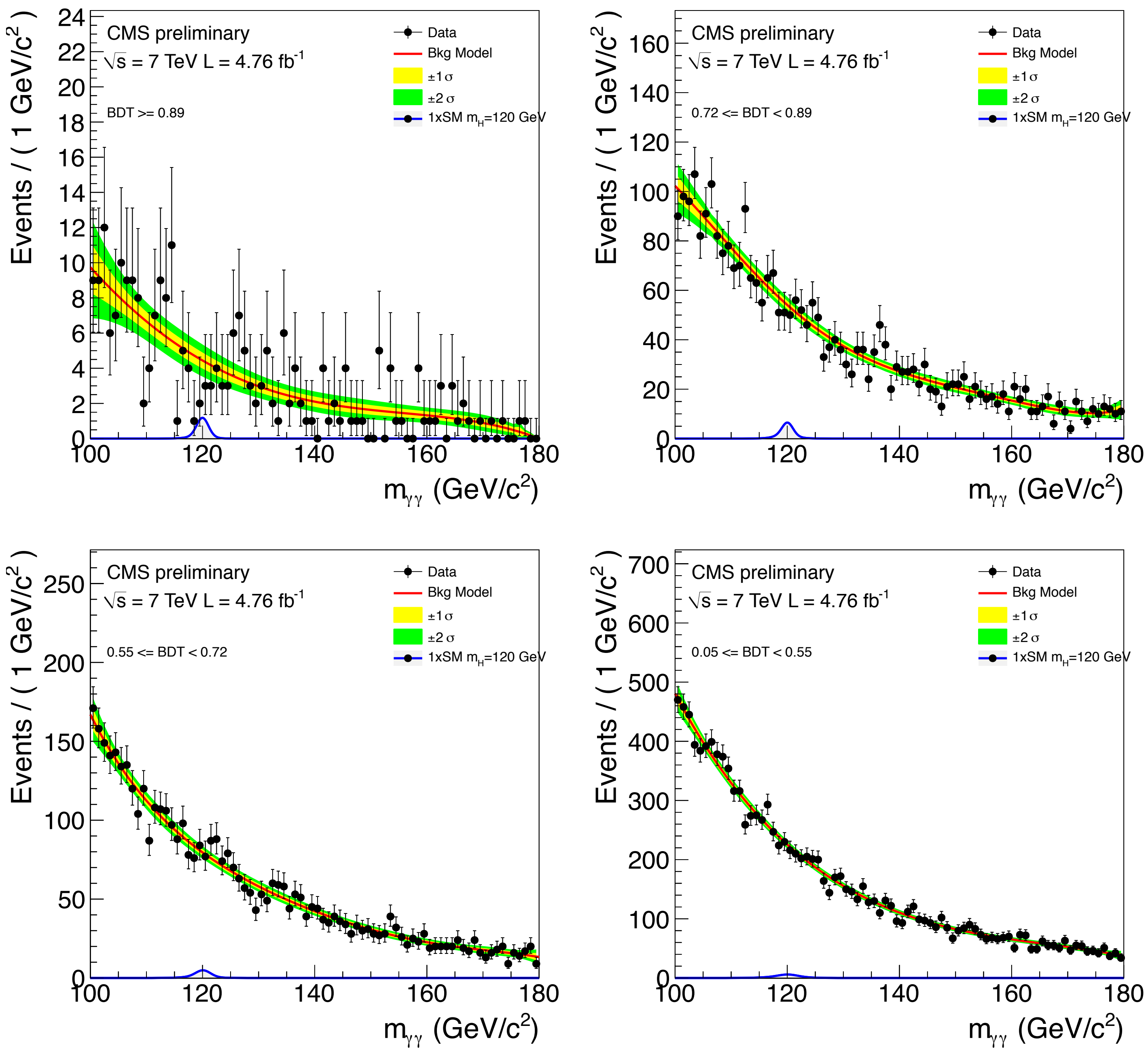




- Two analysis
  - Cut in categories
  - MVA analysis
    - Event by event mass resolution, photon-ID discriminant, di–photon kinematic and vertex probability combined in a BDT

MVA Analysis

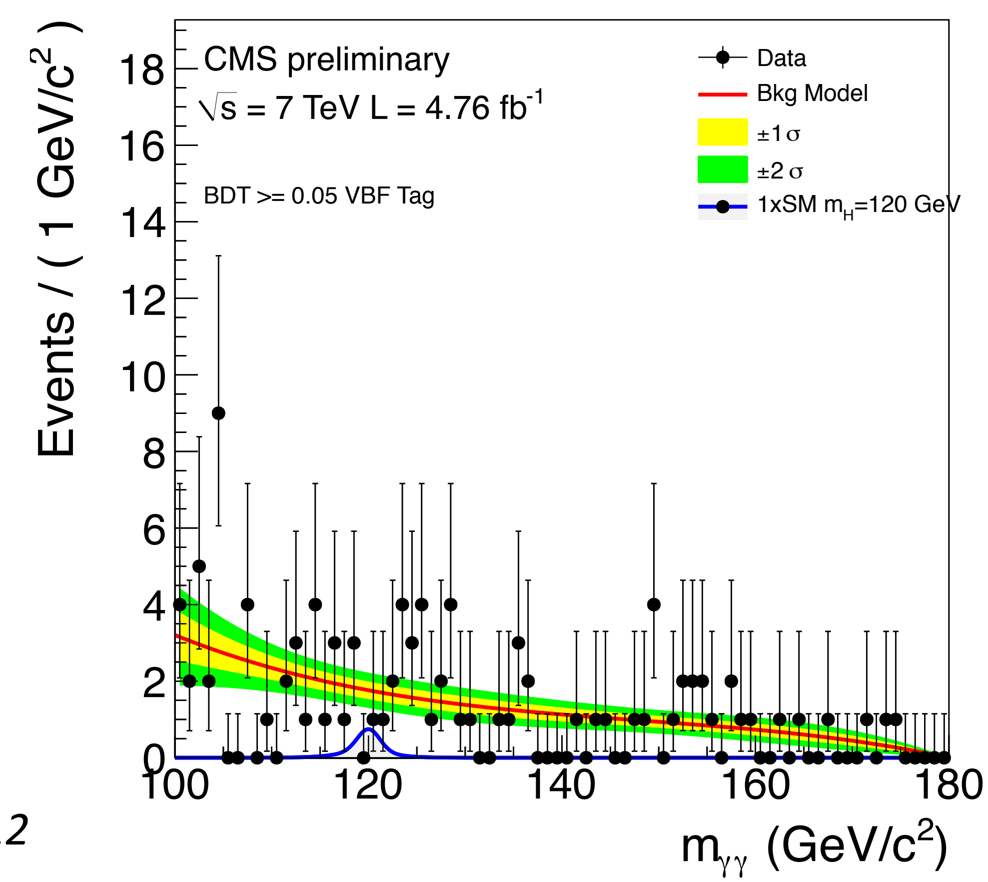
H→γγ

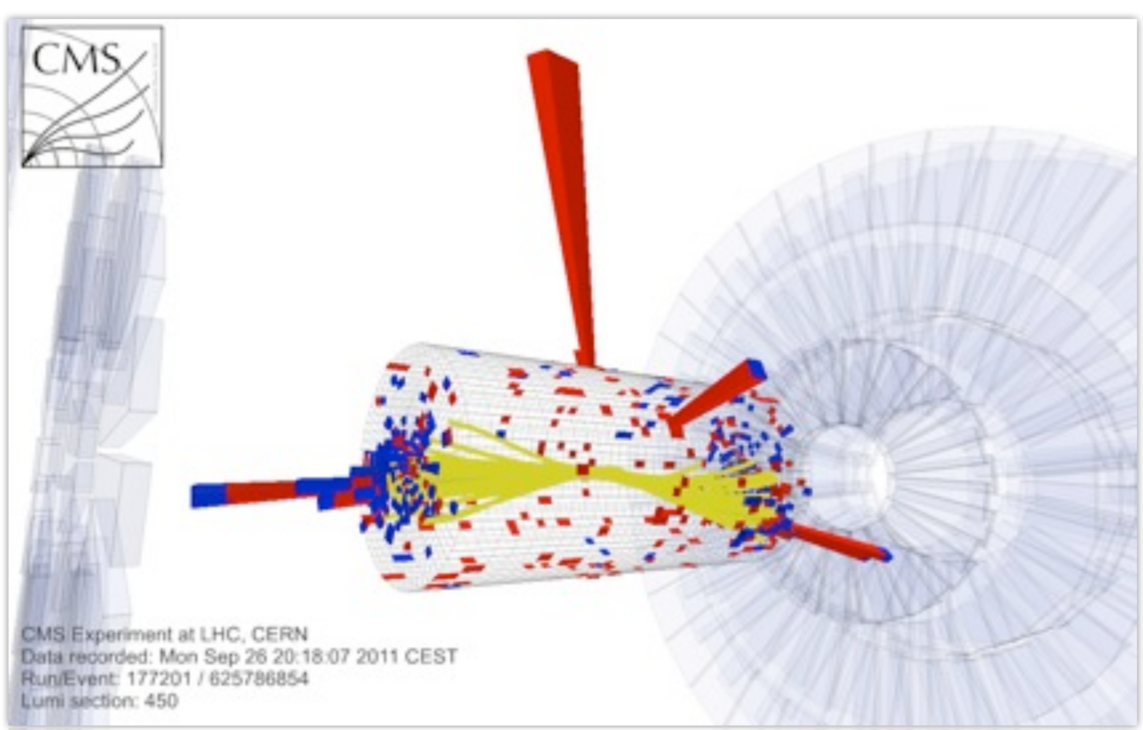


- 4 Non-VBF event classes split based on the di-photon BDT classifier output
- Background shape fitted by a 5th order polynomial constrained to be positive.
  - Possible bias is always <20% of the stat. err.
  - Different background estimations give compatible results

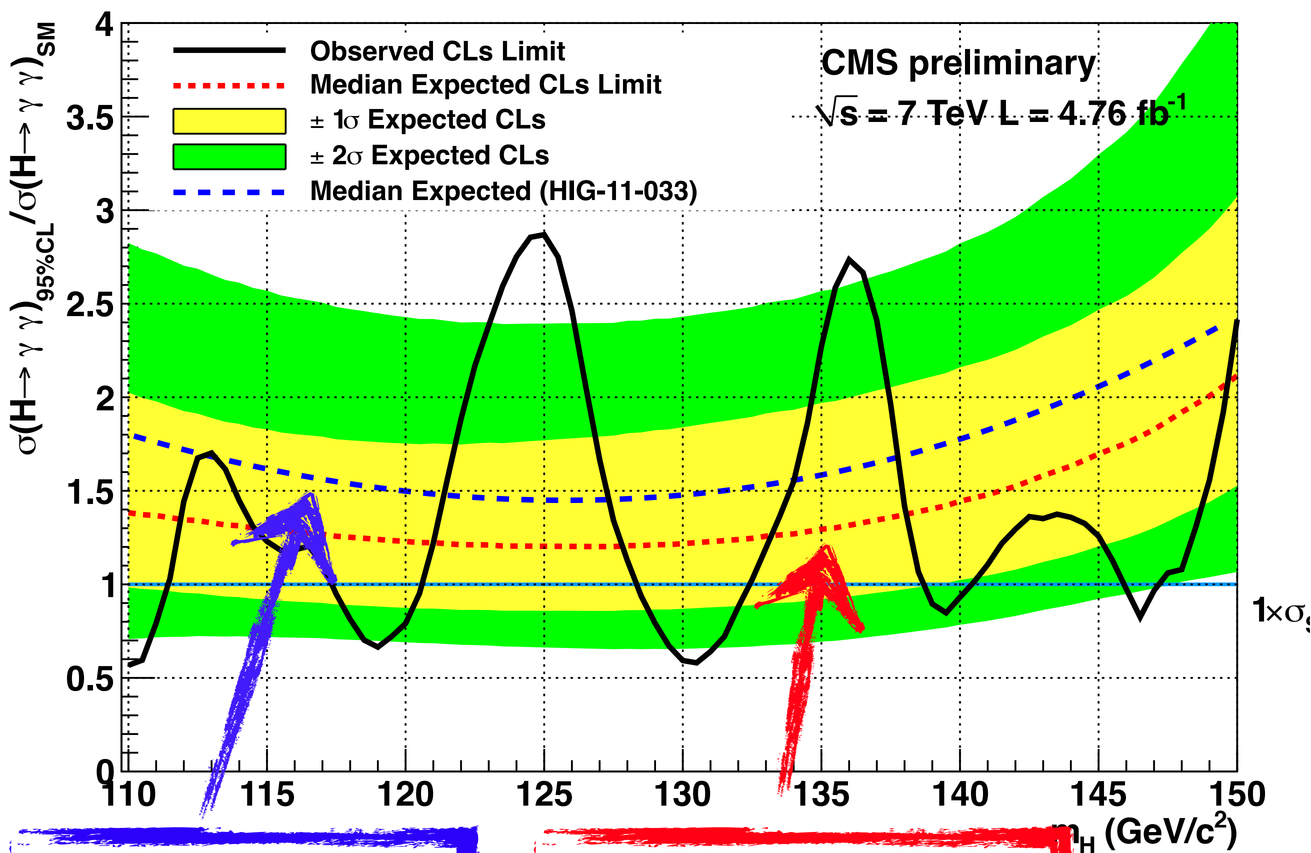
VBF analysis

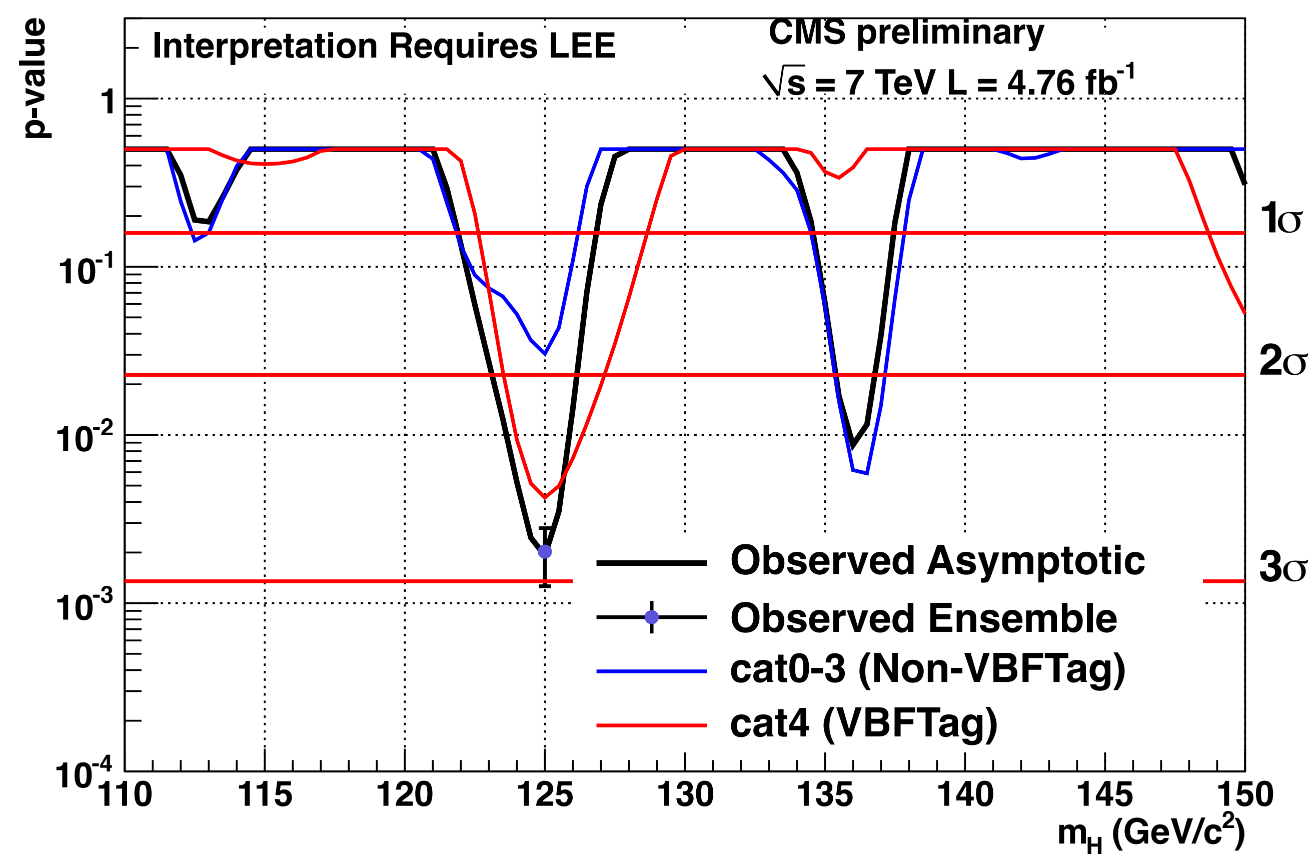
- Two jets with p_T>30/20 GeV with $\Delta\eta$>3.5
- Using an exclusive dijet tag class improves the sensitivity by 10%
  - The dijet tag selection has high S/B, ~1/3
- Photon identification is the same as for the other classes
  - Tighter cut on the leading photon ($p_T/m_{\gamma\gamma}$> 55/120)





Limits and Exclusion





Expected exclusion: cut based analysis

Expected exclusion: MVA

- Largest excess around 125 GeV
  - Local significance 2.9σ
  - Global significance 1.6σ, estimated with Look Elsewhere Effect (LEE) in the mass range 110-150 GeV via toy experiments

Expected exclusion about 1.2-2.1 times SM Higgs

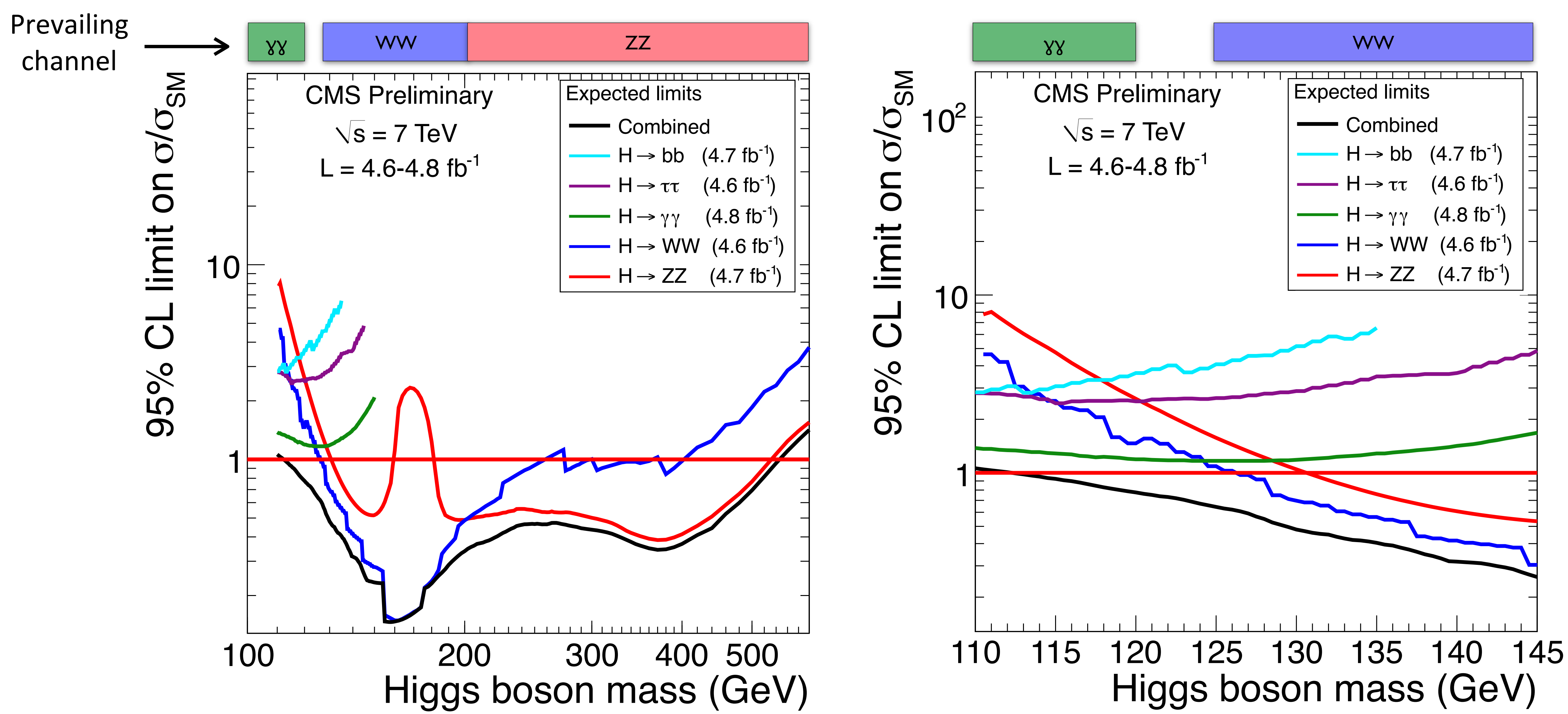
Observed exclusion in the ranges:

[110–111], [117.5–120.5], [128.5–132.0], [139.0–140.0] and [146.0–147.0] GeV.

The Combination

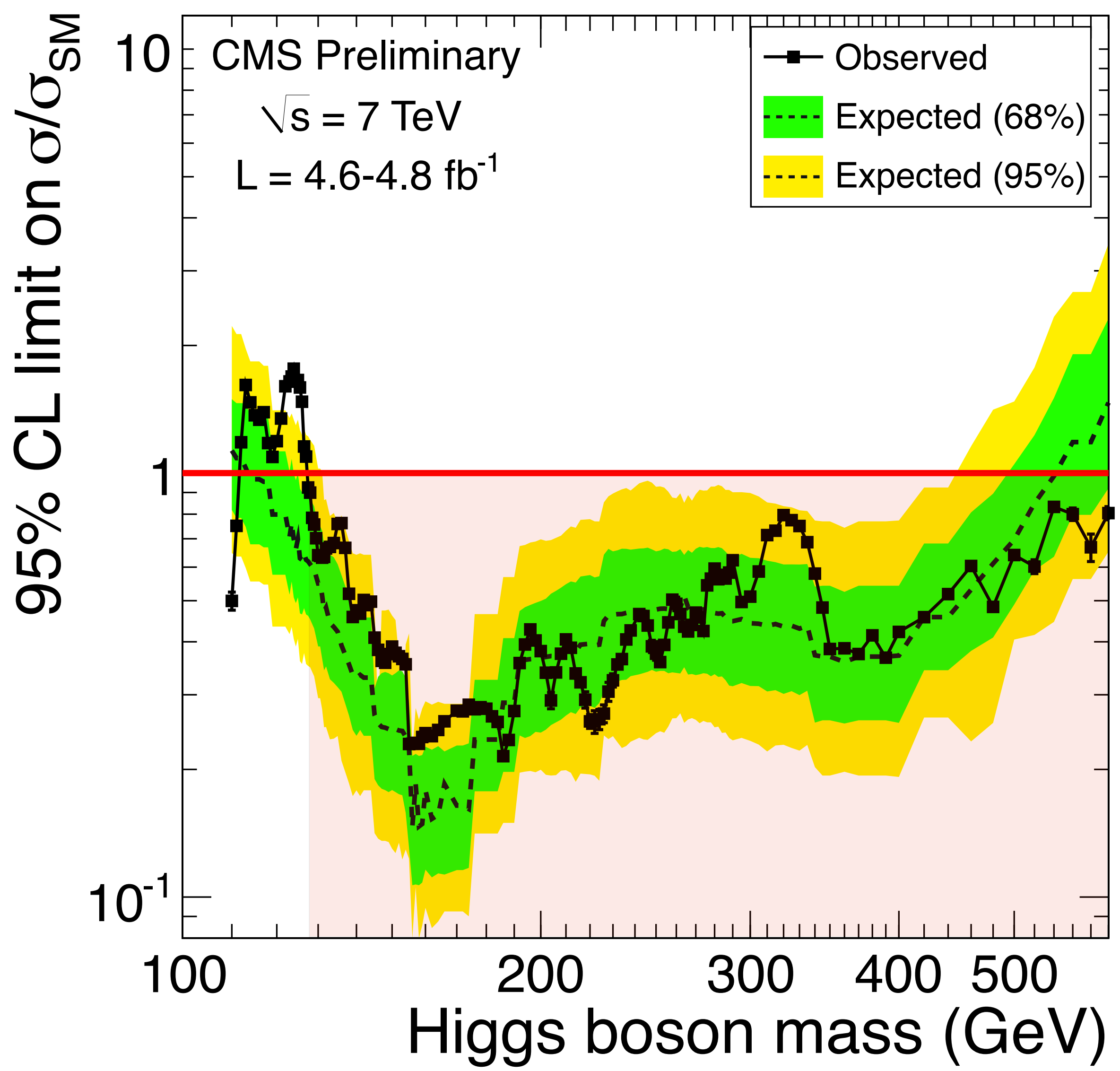
fermionics included

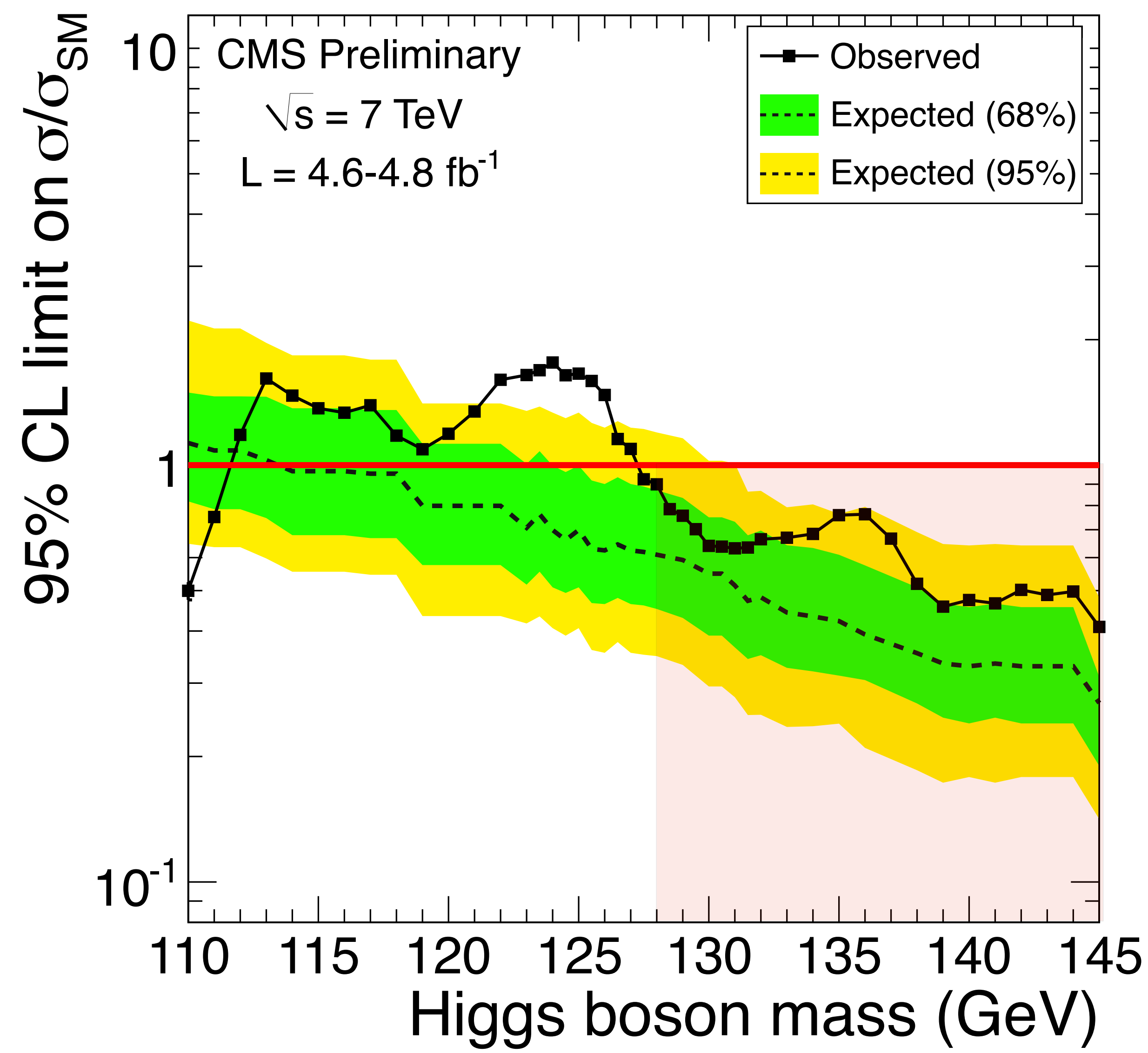
Expected Sensitivity with 4.7 fb^{-1}



95% CL expected exclusion: 114.5—543 GeV

95% CL Exclusion Limit on $\mu = \sigma/\sigma_{SM}$



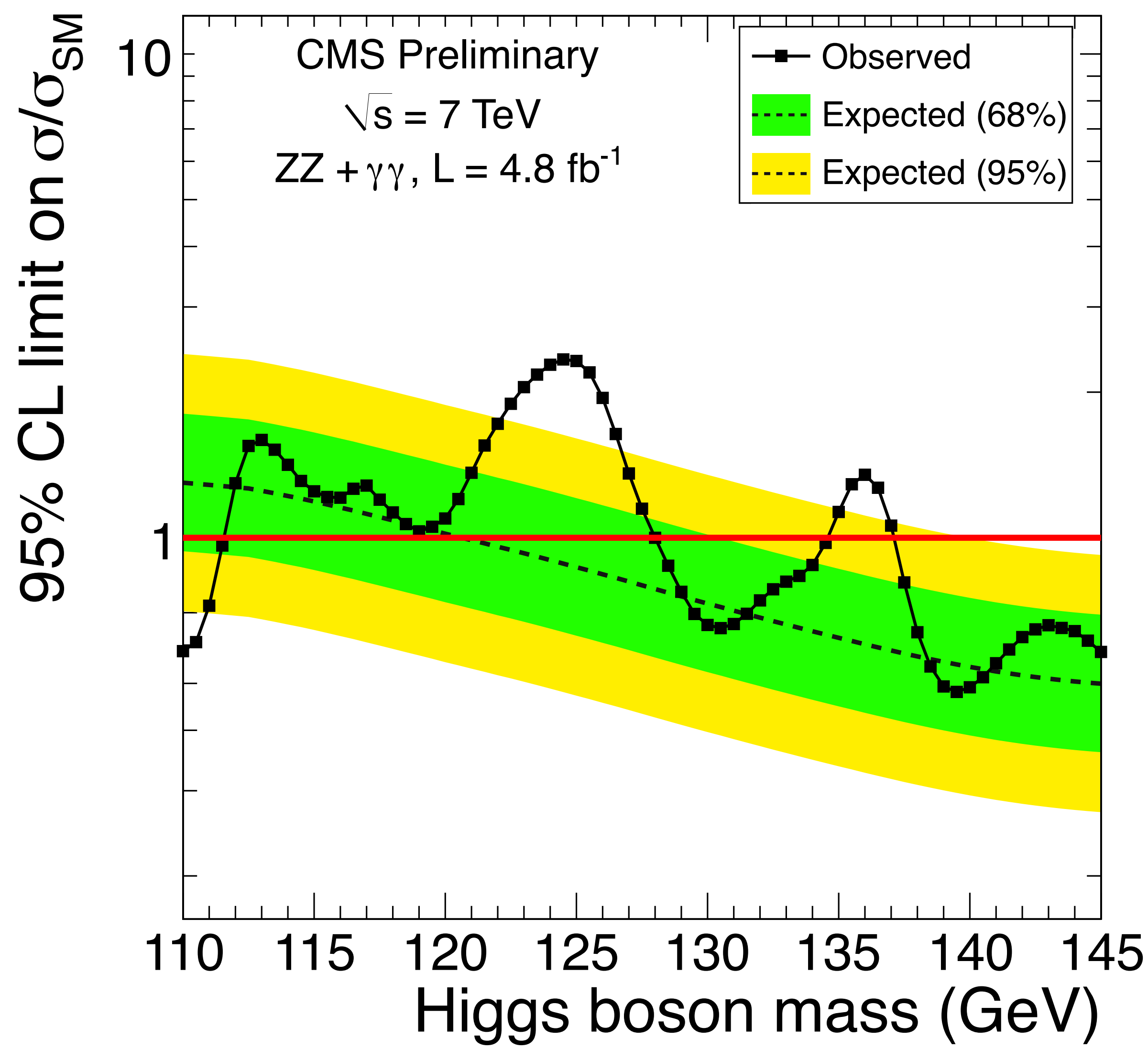


Expected exclusion: 114.5—543 GeV

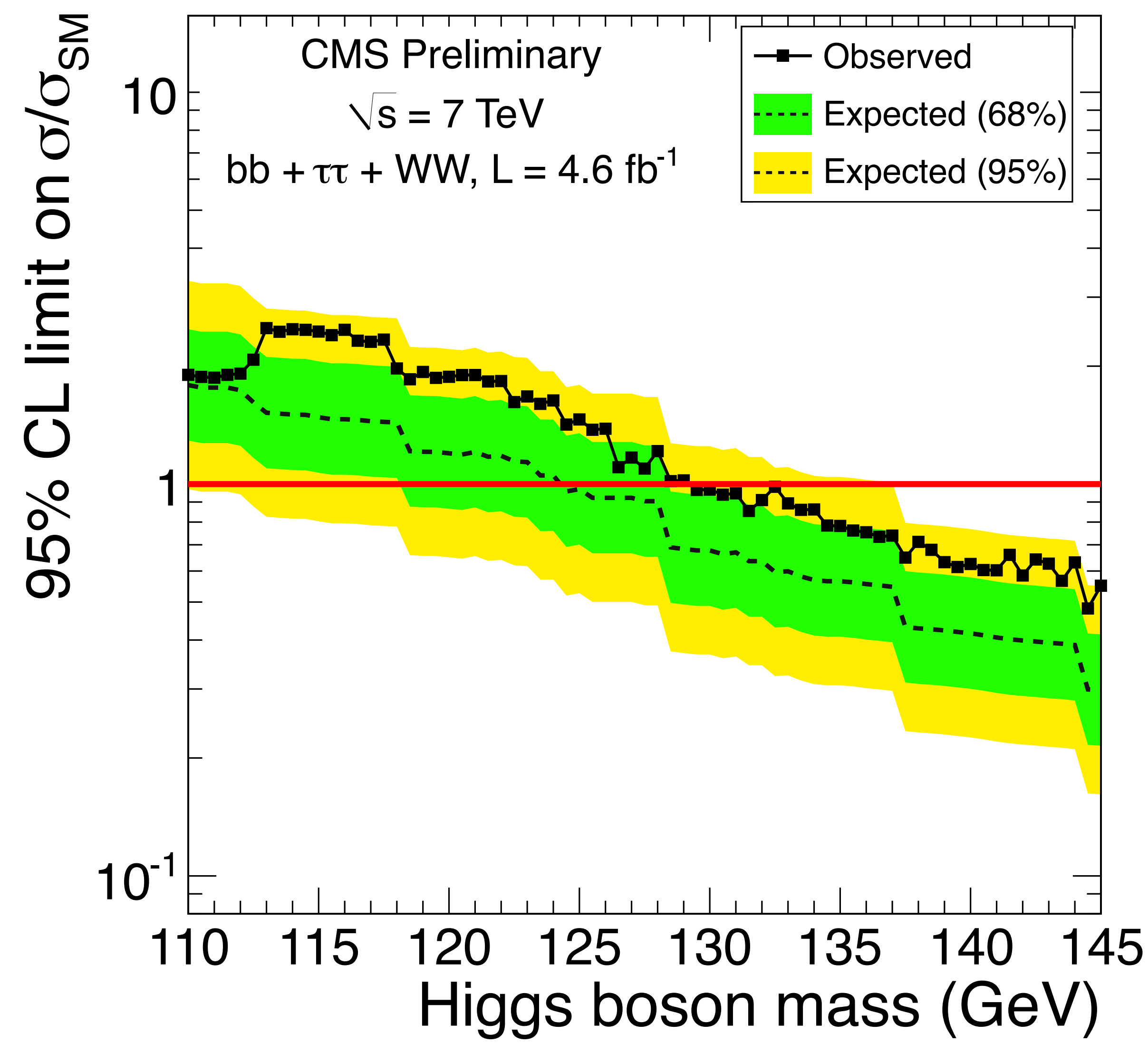
Observed exclusion: 127.5—600 GeV

By High & Low Mass Resolution Channels

High mass resolution channels: γγ + 4l

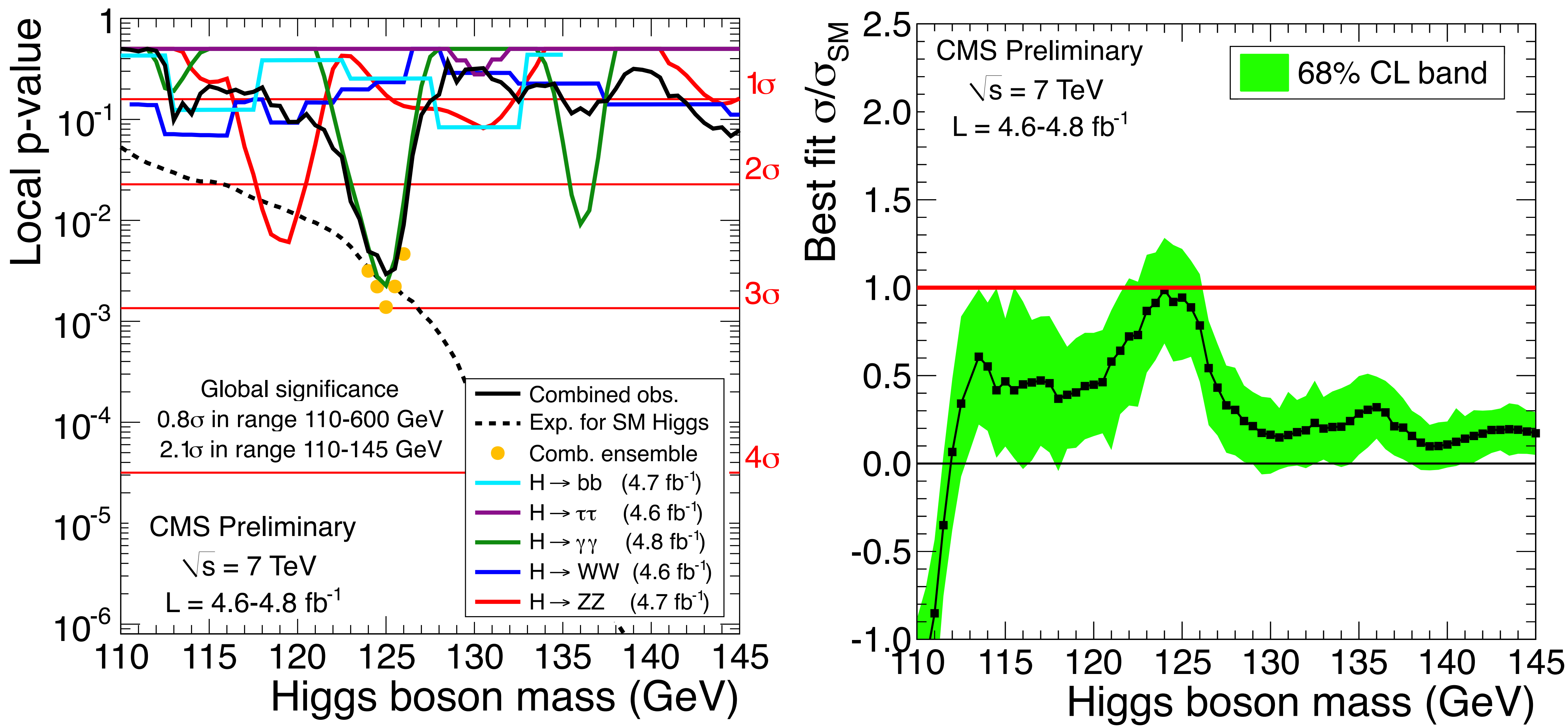


Poor mass resolution channels: WW + ττ + bb



- The two sets have nearly identical sensitivity
- The γγ+4ℓ group shows a localized excess >2σ around mH=121-125 GeV
- The WW+ττ+bb group shows a broad excess, reaching 2σ around 115-125 GeV

Quantifying The Low Mass Excess



- Minimum p-value observed at 125 GeV with local significance:
  - 2.8 σ – Similar significance expected from signal
- Estimated global significance:
  - 0.8 σ in [110–600] GeV, 2.1 σ in [110–145] GeV
- Not inconsistent (±1σ) with SM Higgs

Summary

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- $H \rightarrow \gamma\gamma$, $H \rightarrow WW$, $H \rightarrow ZZ$ in 7 independent modes, cover the full mass range 110–600 GeV
- In combination with the fermionic channels
  - **Expected 95% CL** exclusion range, in absence of Higgs, is **117–543 GeV**
  - **Observed 95% CL** exclusion range is: **127–600** GeV
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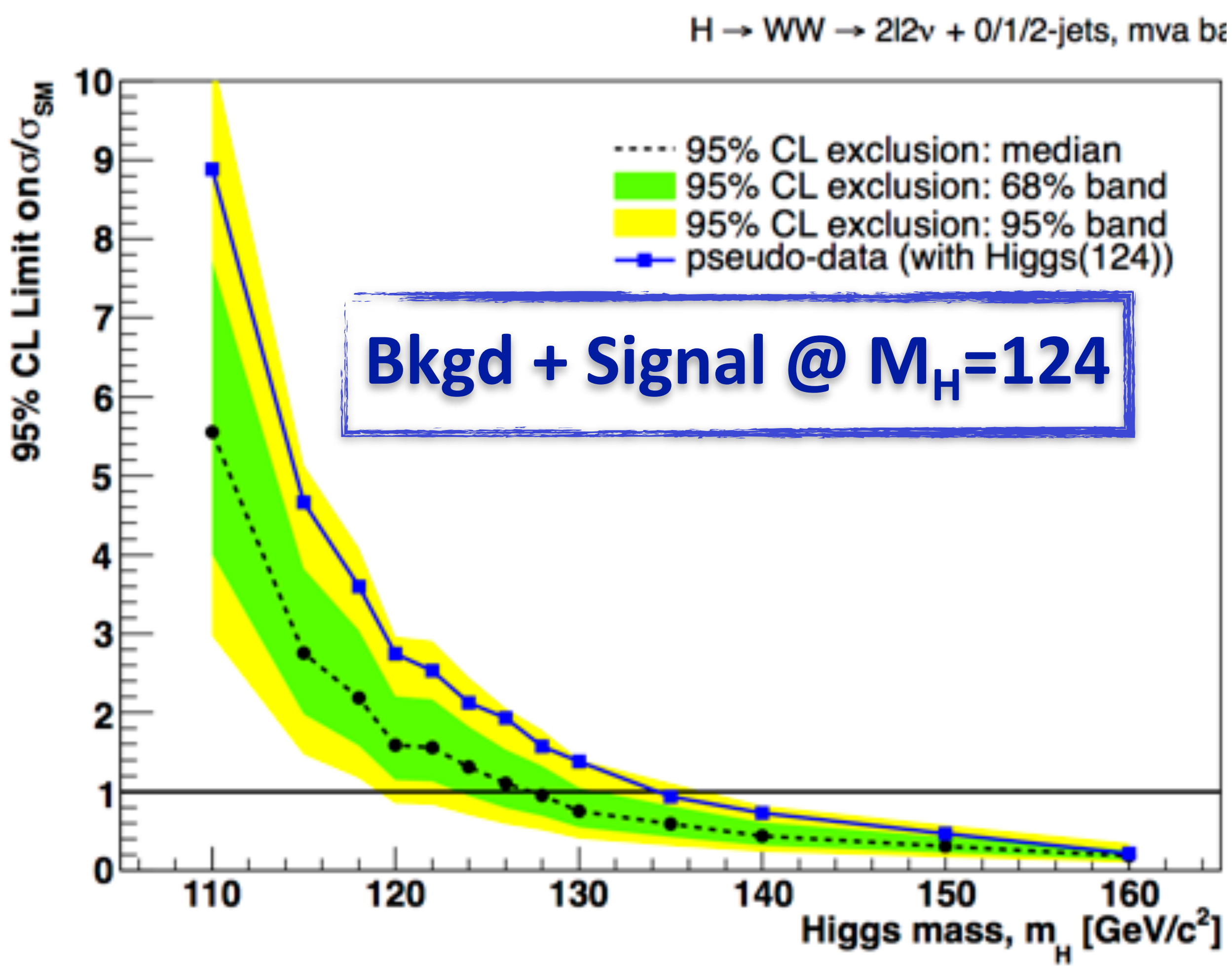
- An excess in the low mass range seen
  - More data are required to determine the source of this excess.
- The collisions at 8 TeV has just started
- The SM Higgs boson won't be able to run for long...
  (but keep your fingers crossed)

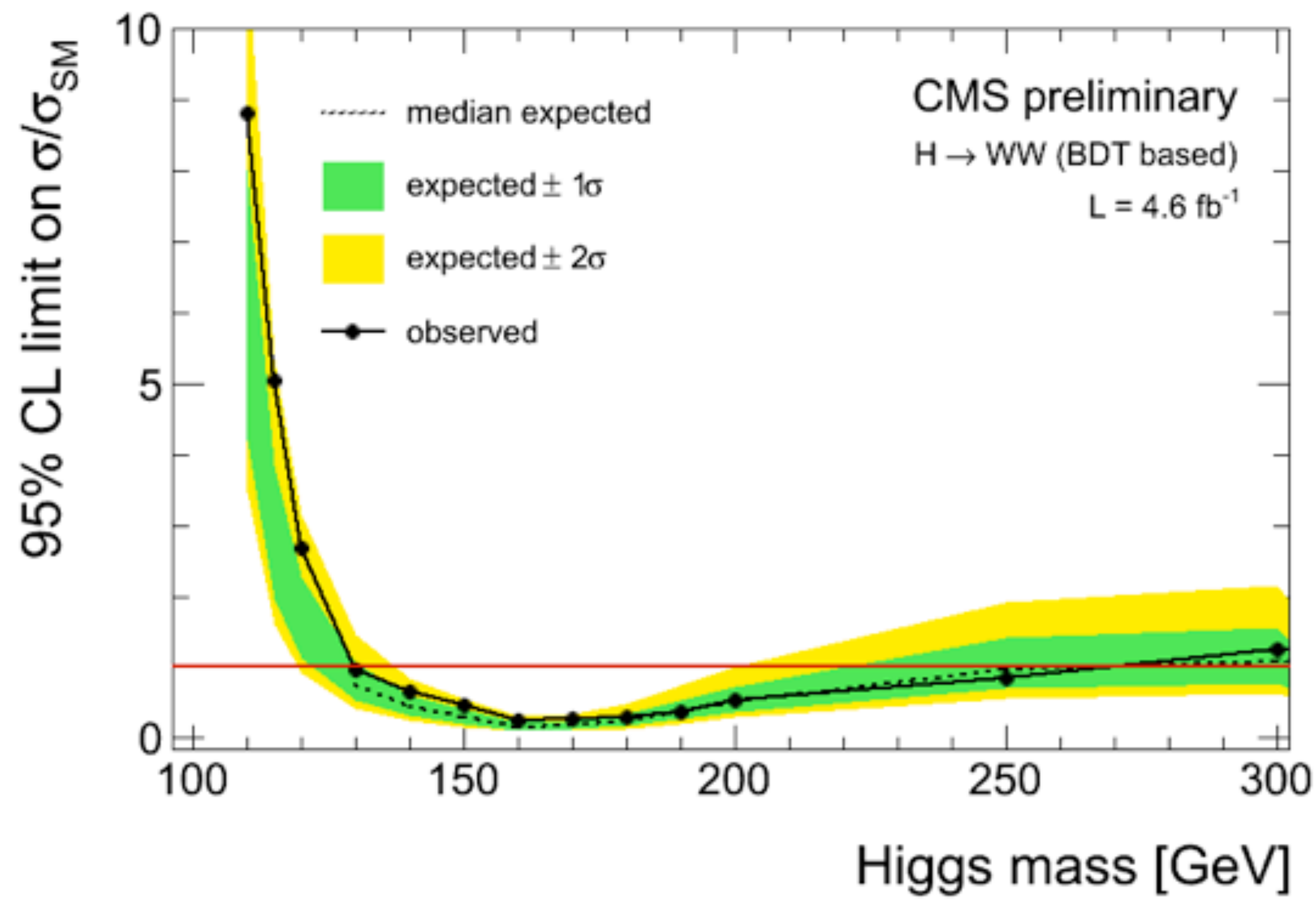
Backup

Backup

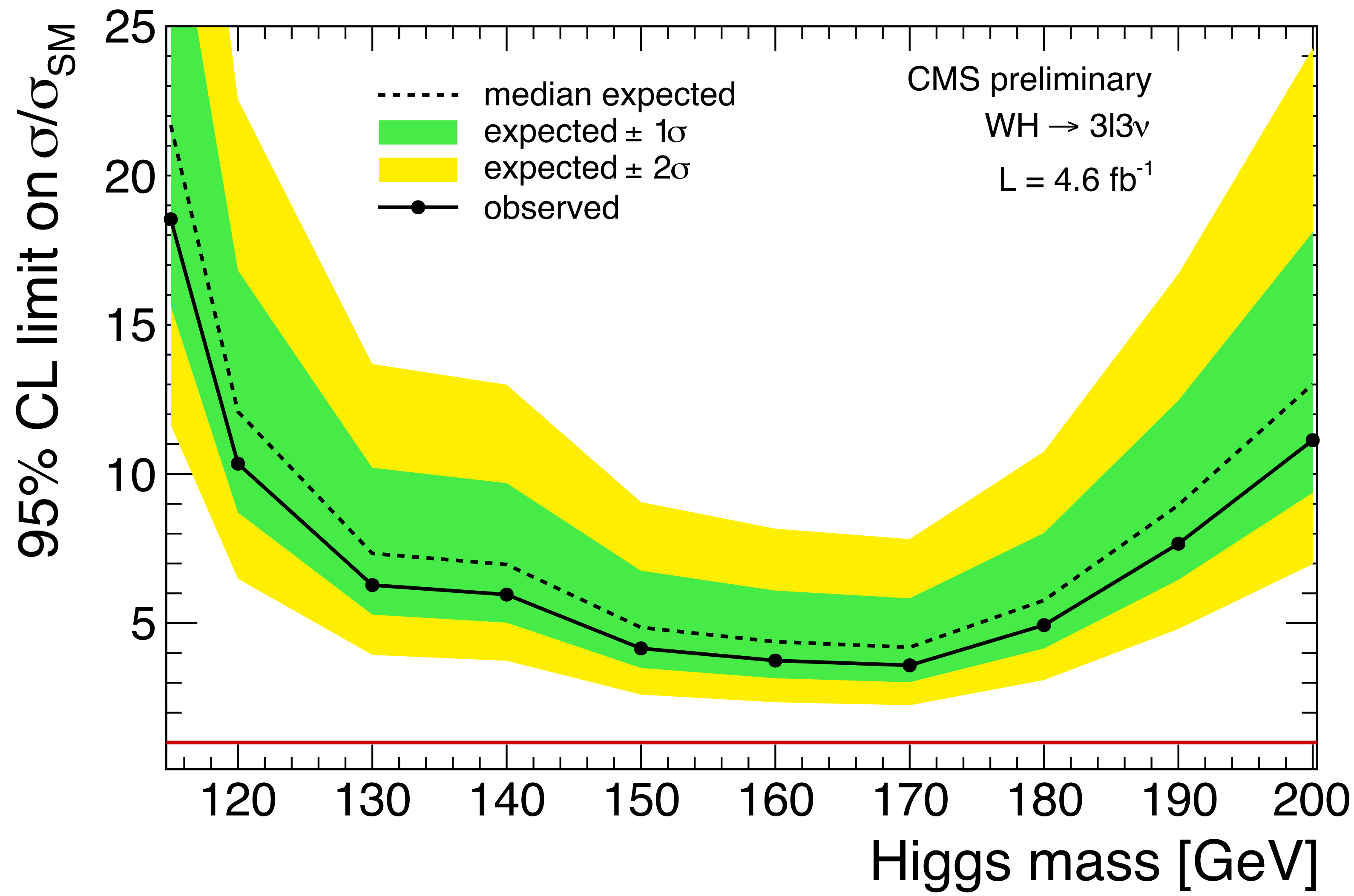
H→WW

Inject a SM like Higgs signal over predicted backgrounds





CMS document HIG-11-034



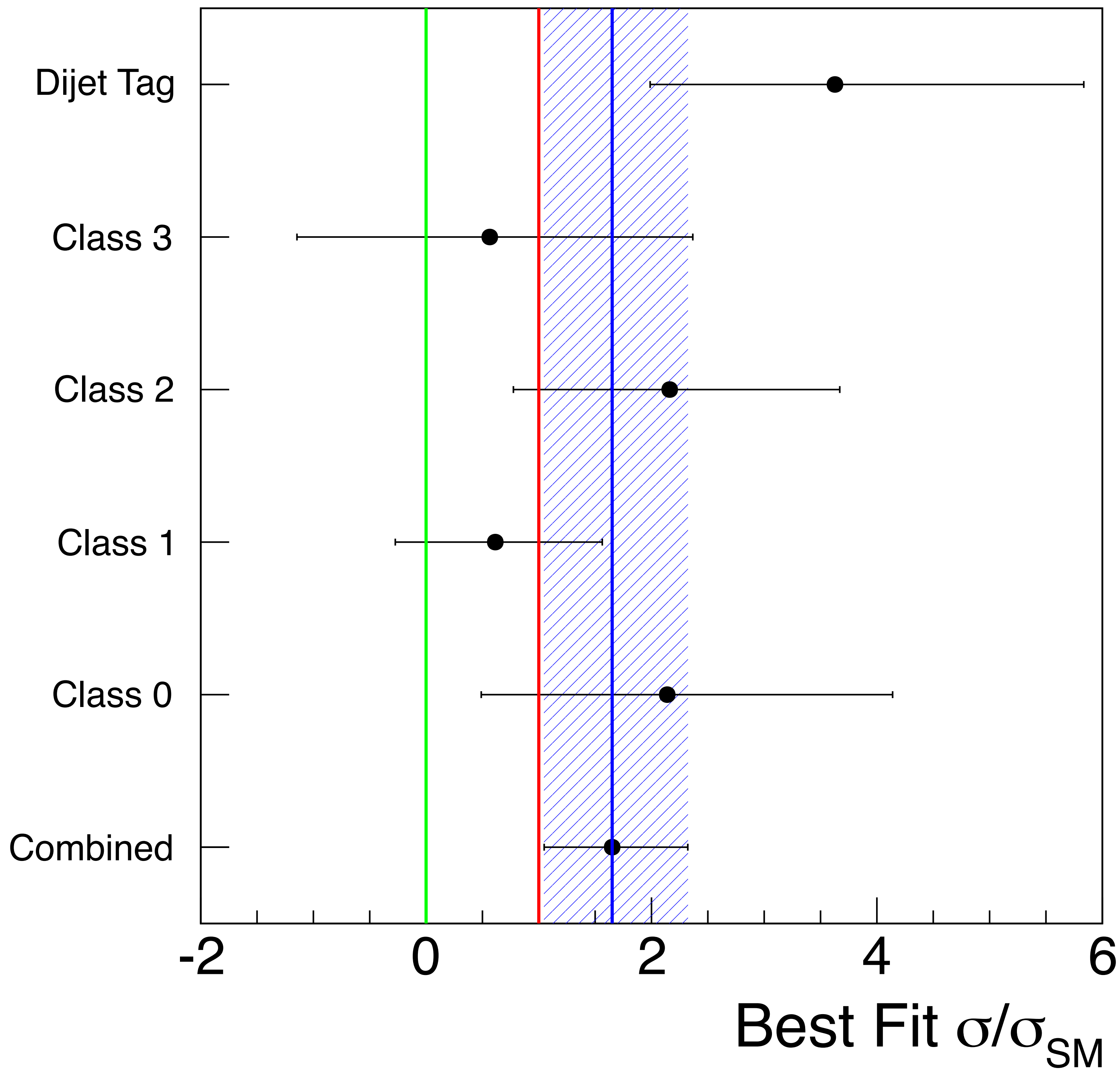
- Signature
  - 3 isolated leptons
  - high ME_T
- Backgrounds
  - WZ, ZZ, top and Z/γ*+jet
- Selection similar to the H→*WW* analysis
  - Mass independent cut and count
  - Main backgrounds estimated from data

stage	WH (120) $H \to \tau\tau$	WH (120) $H \to WW$	data	all bkg.
3-lepton preselection	2.1 ± 0.0	3.5 ± 0.1	950	968.3 ± 11.9
min-MET > 40 GeV	1.0 ± 0.0	1.8 ± 0.1	244	270.5 ± 4.4
Z removal	0.4 ± 0.0	1.0 ± 0.1	40	47.9 ± 3.1
top veto	0.1 ± 0.0	0.6 ± 0.1	12	14.2 ± 1.3
$\Delta R_{\ell^+\ell^-}$ & $m_{\ell\ell}$	0.1 ± 0.0	0.5 ± 0.1	7	8.4 ± 0.9

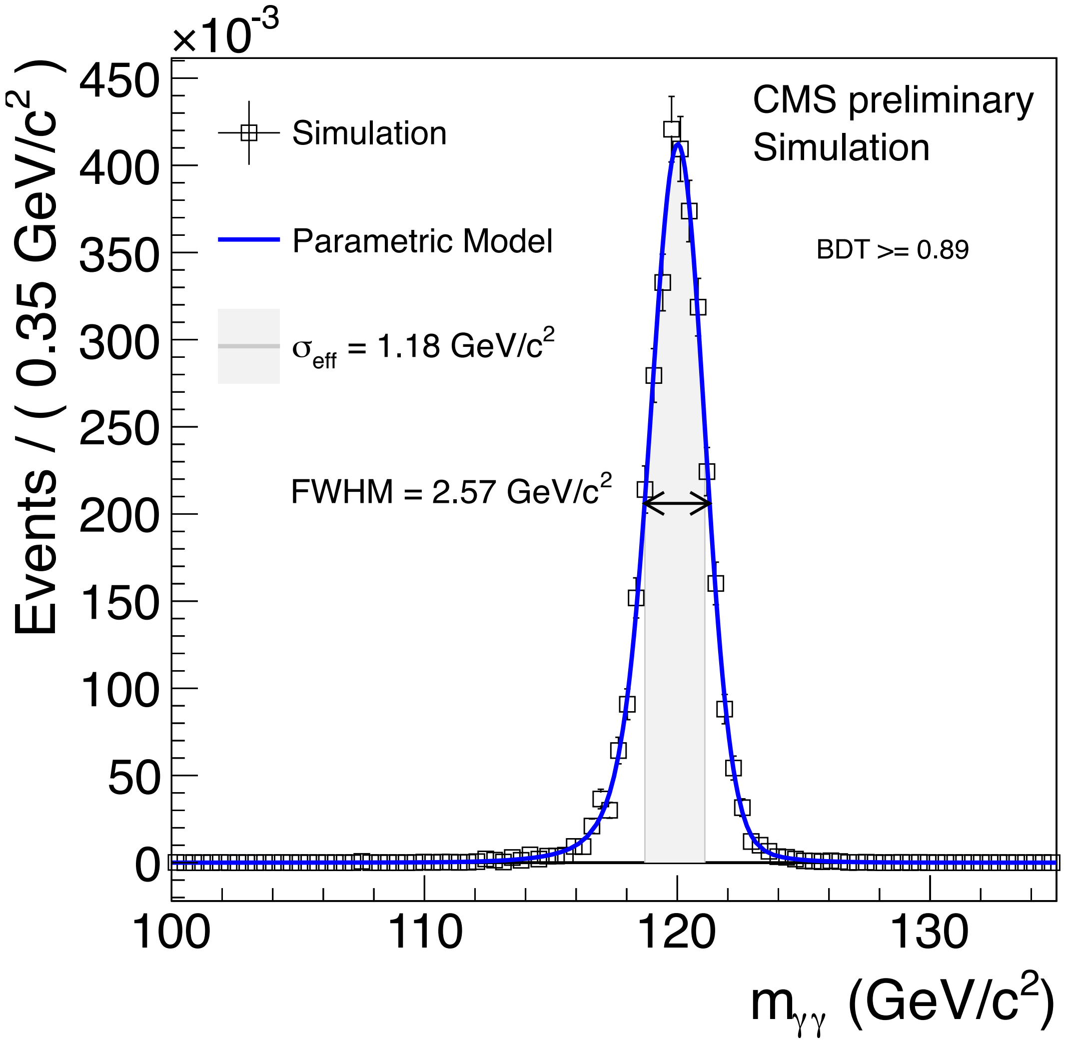
Backup

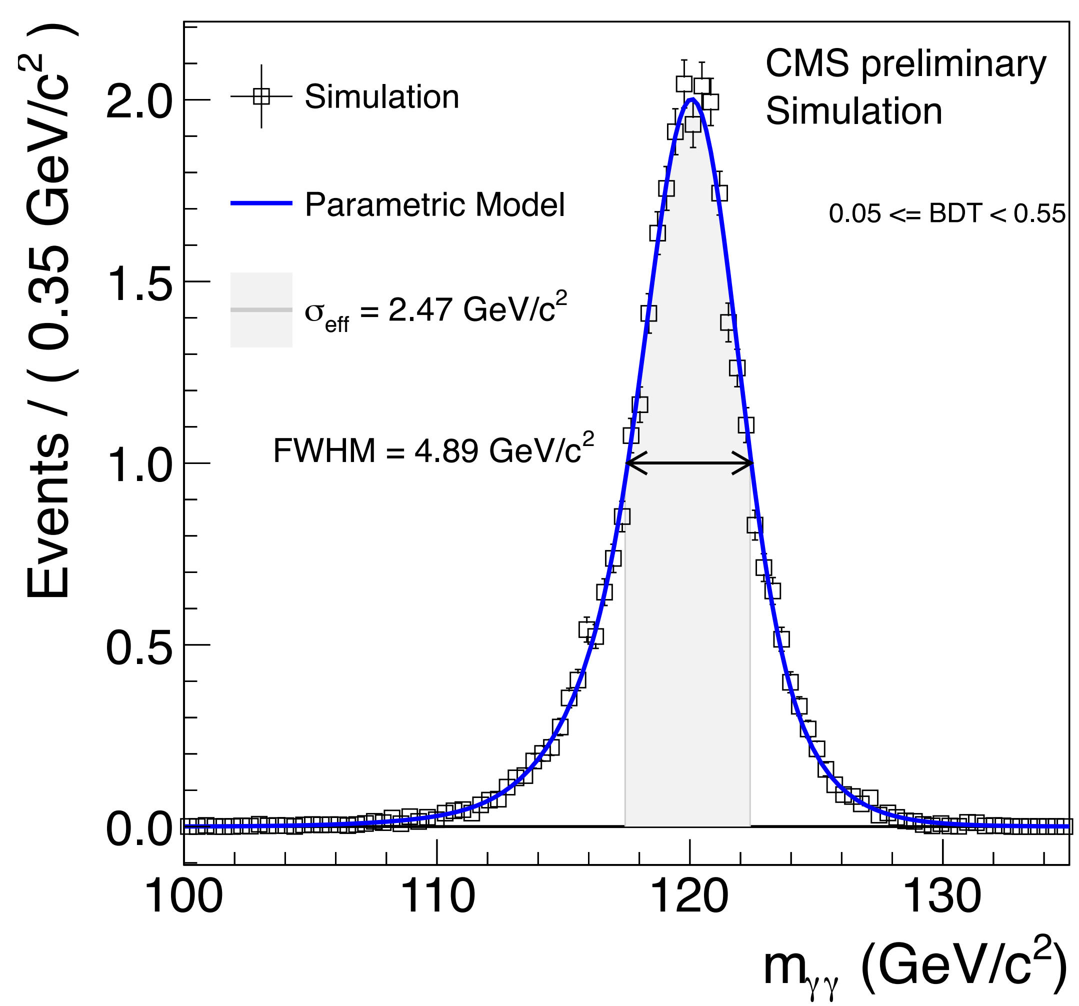
$H \rightarrow \gamma\gamma$

Best-fit results



$m_{\gamma\gamma}$ Resolution in the BDT Categories





	both γ in barrel		one or two γ in endcap	
	$min(R_9)$ >0.94	$min(R_9)$ <0.94	$min(R_9)$ >0.94	$min(R_9)$ <0.94
	unconverted γ		unconverted γ	
signal	31.1%	40.3%	12.2%	16.4%
data	23.0%	33.8%	17.8%	25.4%
resol. σ_{eff}	1.4 GeV	1.8 GeV	2.8 GeV	3.2 GeV

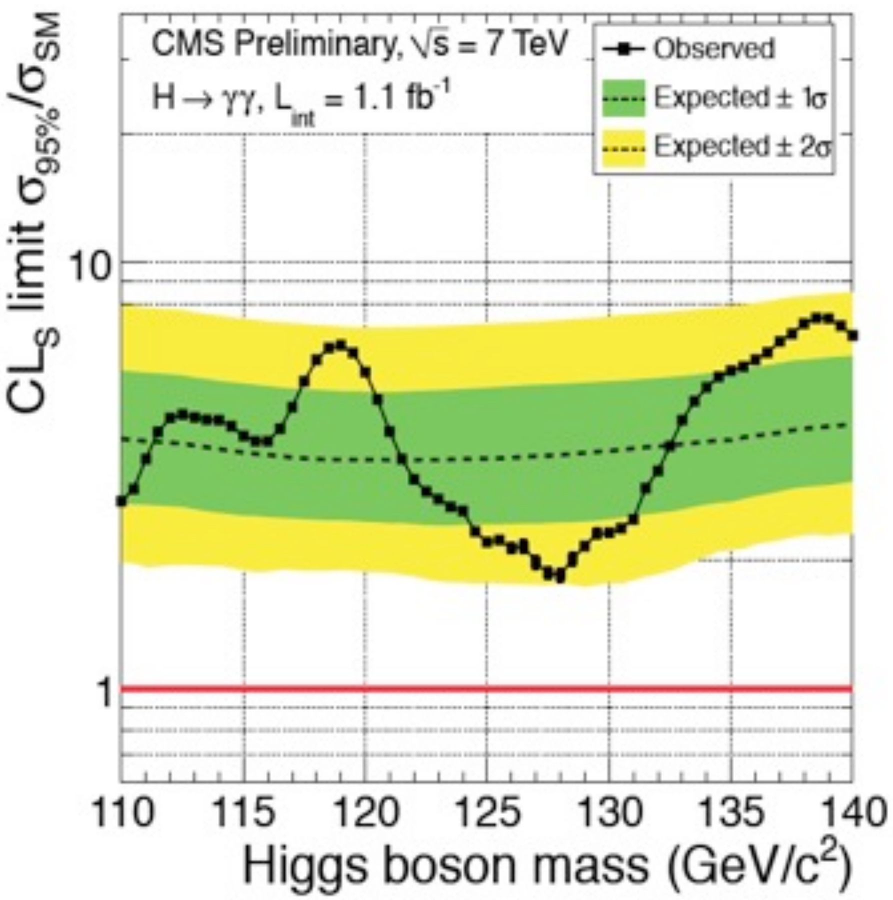
H→γγ : Systematic Uncertainties

ETH Zürich

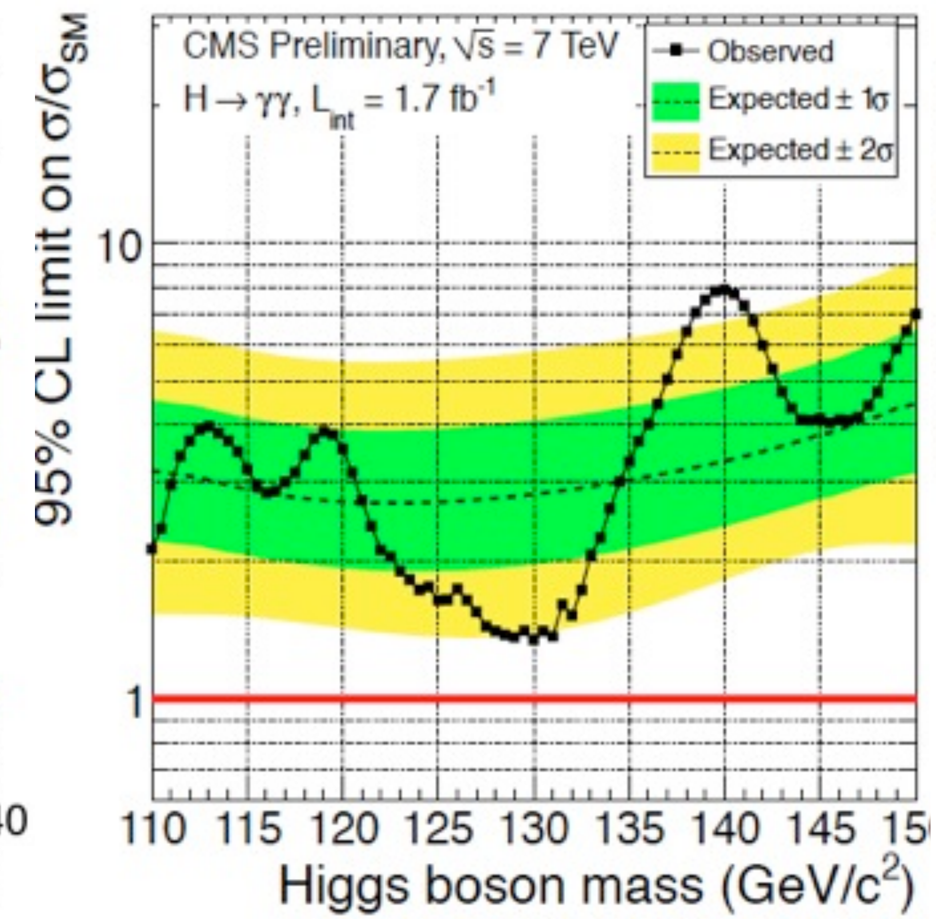
Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon identification efficiency		1.0%	2.6%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.61%	0.91%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.53%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Photon identification BDT	(Effect of up to 11% event class migration.)	± 0.025 (shape shift)	
Photon energy resolution BDT	(Effect of up to 8% event class migration.)	$\pm 10\%$ (shape scaling)	
Per event			
Integrated luminosity		4.5%	
Vertex finding efficiency		0.4%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	70%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Associated production with $t\bar{t}$		+3.6% -9.5%	8.5%
Scale and PDF uncertainties	(Effect of up to 16% event class migration.)	(y, p_T)-differential	

H->γγ:Evolution Of Search Limits

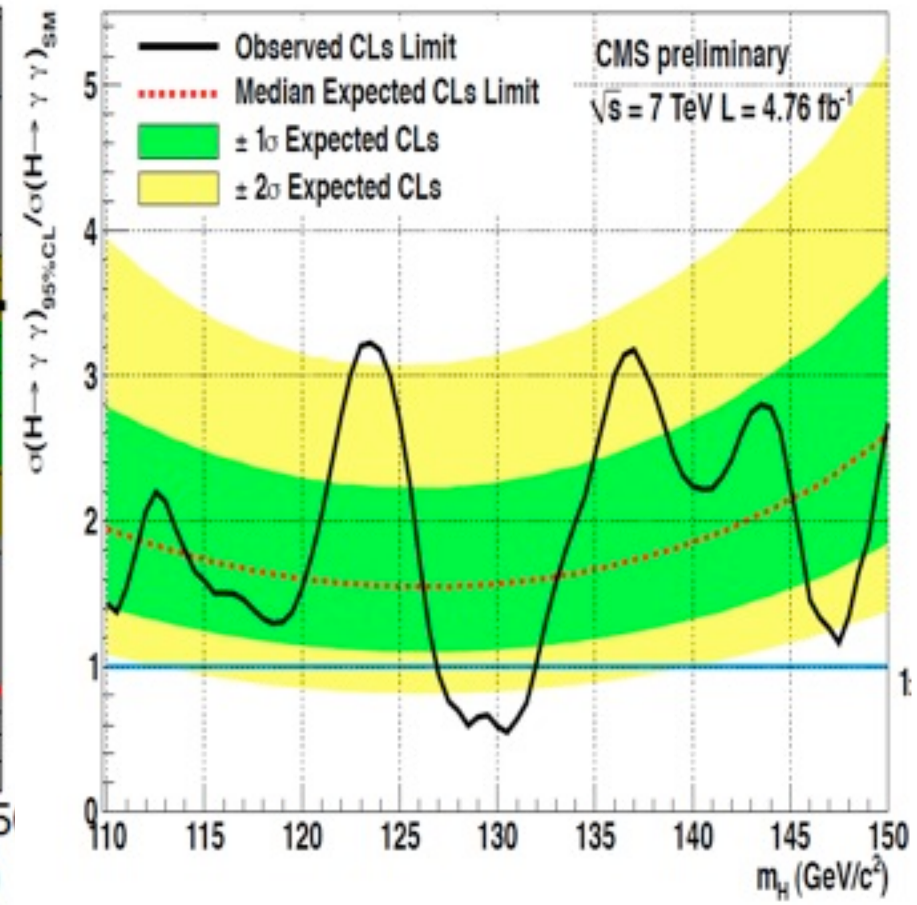
EPS'11



LP'11



2011

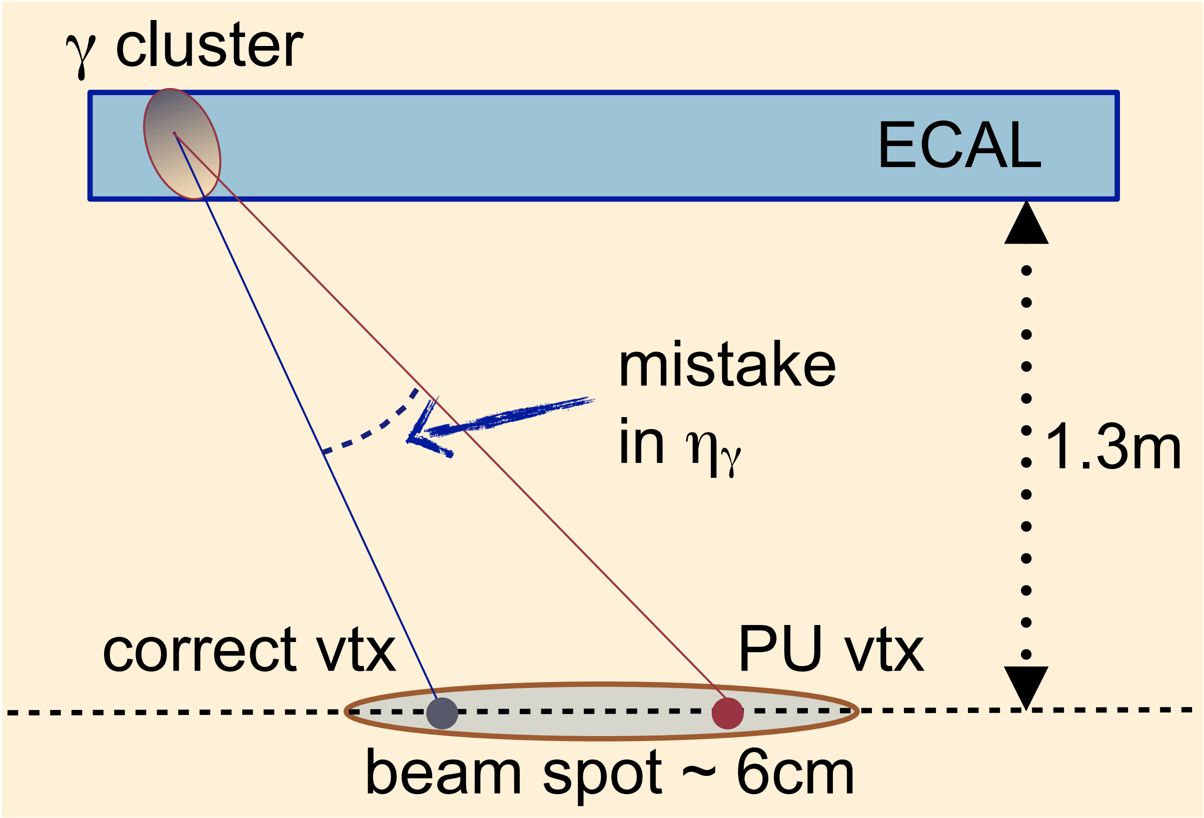


H →γγ : Studies of Background Model

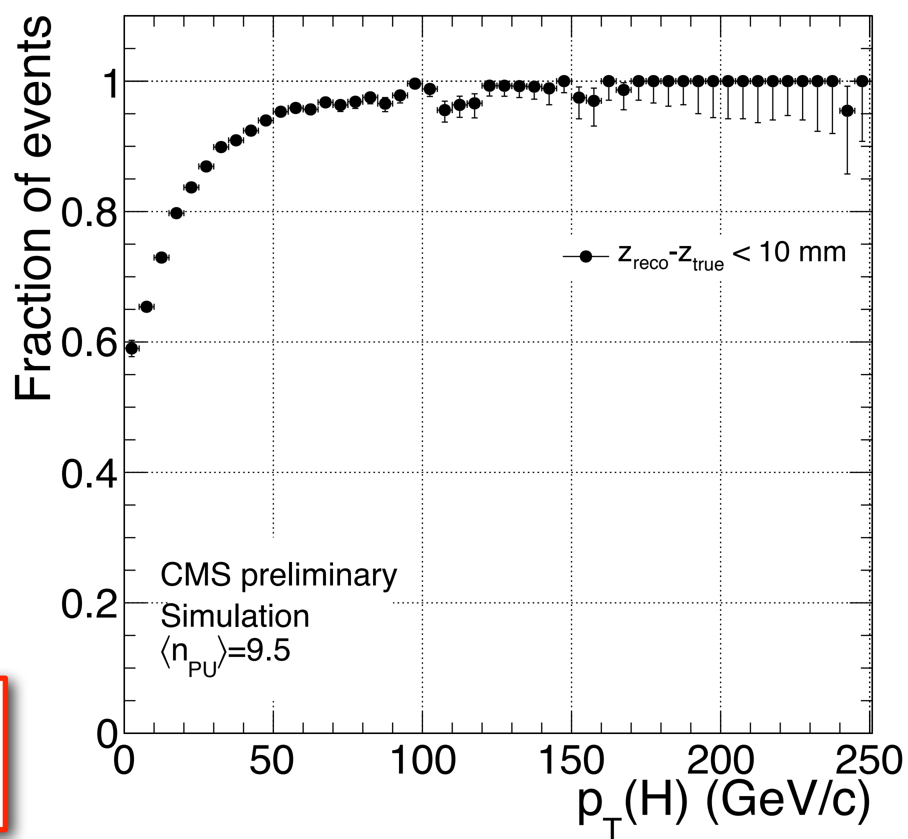
- The distribution of background events in $M_{\gamma\gamma}$ is assumed to behave as a continuous function. Since no prior knowledge is assumed of the specific form of this function we choose a parameterization which is demonstrably flexible enough to describe any reasonable form without introducing a bias. Studied several test functional forms all of which provide good fits to MC and data.
- Choose some functional form as truth model (used here 2nd Order polynomial, double exponential, double power law and 4-term “partial Laurent series")
- Fit chosen truth form to background MC scaled to $5fb^{-1}$ and throw **background only** toys.
- Fit test functional form + signal model and evaluate signal strength μ (in units of σ_{SM})
- **Bias defined as mean value of signal strength μ, should be 0 for background only toys**

H →γγ Event Vertex Determination

- **“large” pile-up conditions**
  - ➪ $\langle N_{PU} \rangle \sim 10$
- di-photon invariant **mass resolution affected by vertex** choice
- **vextex determination** based on
  - **tracks belonging to vertex** combined **with di-photon kinematics**
    - use of $\Sigma p_T{}^2{}_{trk}$ and p_T balancing
  - **conversion-track** finding and projection on beam spot
- performance **cross-checked using $Z \rightarrow \mu^+\mu^-$** after removing muon tracks



2011A	2011B	2011
86.3% ± 0.2% ± 0.4%	79.8% ± 0.2% ± 0.5%	83.0% ± 0.2% ± 0.4%

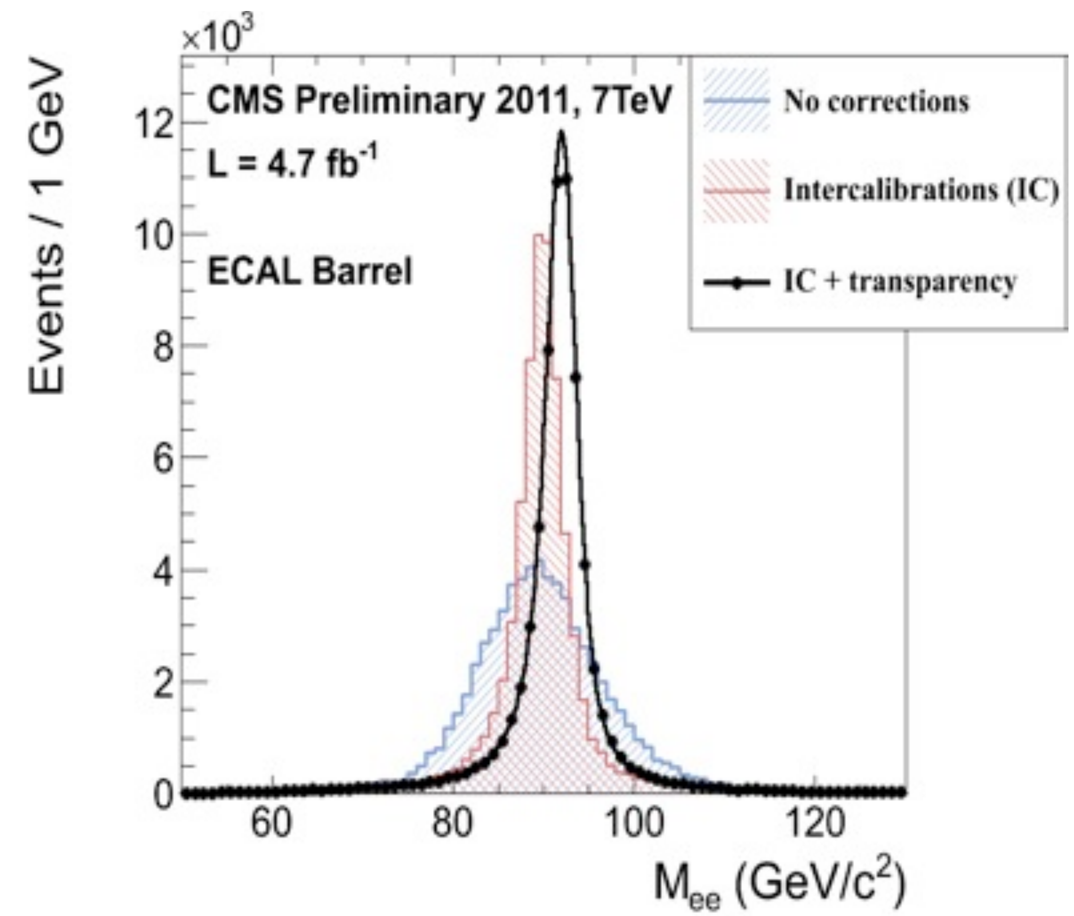


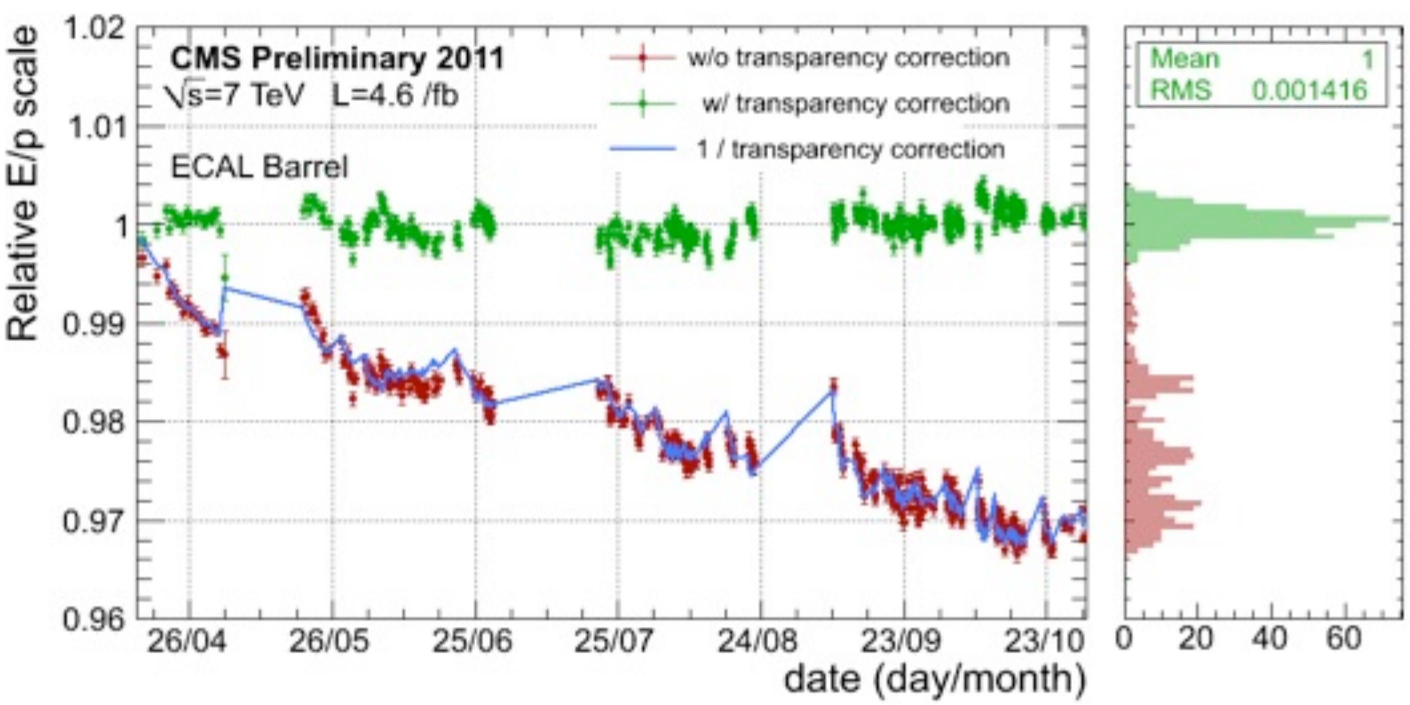
Photon Energy Scale & Resolution

Energy resolution studied with *Z→ee, W→eν* , *π⁰* inter-calibrations and laser signals for transparency corrections

Resolution in data improves typically by 10% in barrel (|η|<1, R9>0.94) w.r.t LP'11 data

Instrumental resolution in the best category = 0.99 ±0.01 GeV





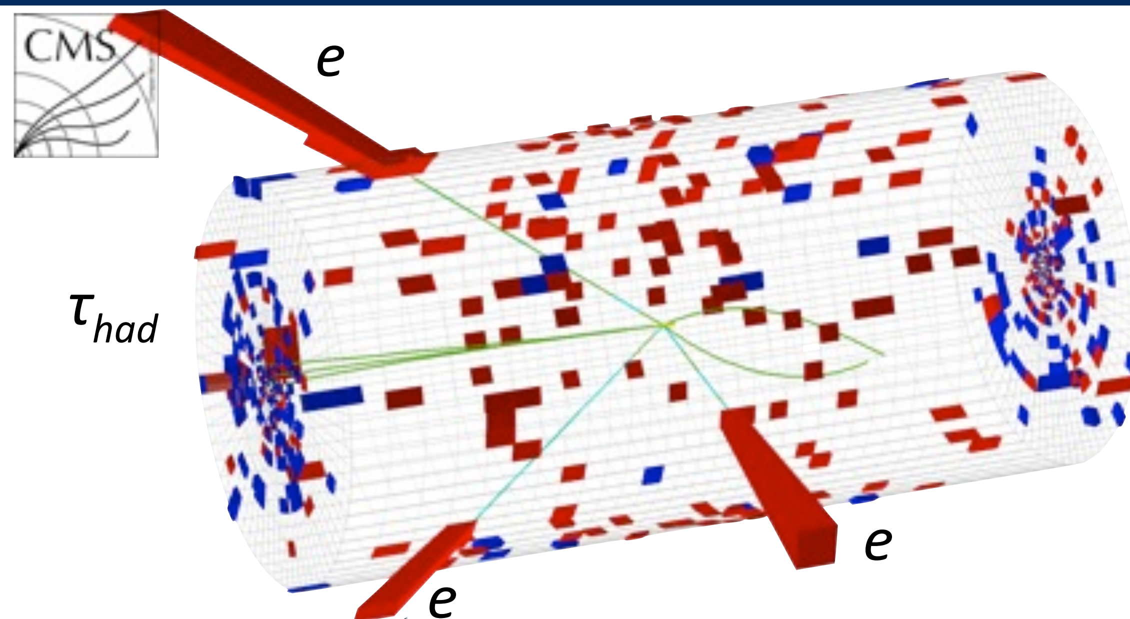
Energy scale for *W→eν* and *Z→ee* stable throughout 2011 at the level of 0.2% in barrel and 0.7% in endcap

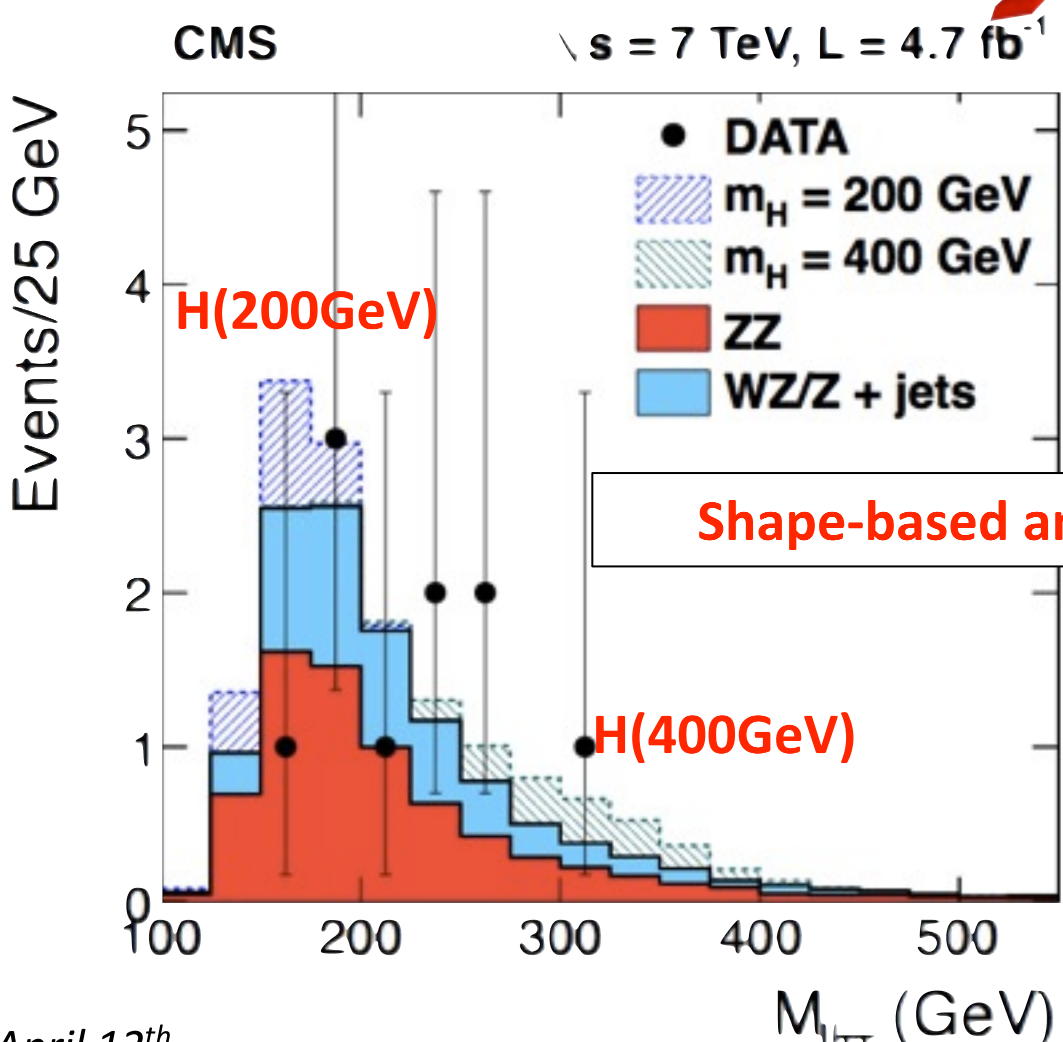
Backup

H->ZZ

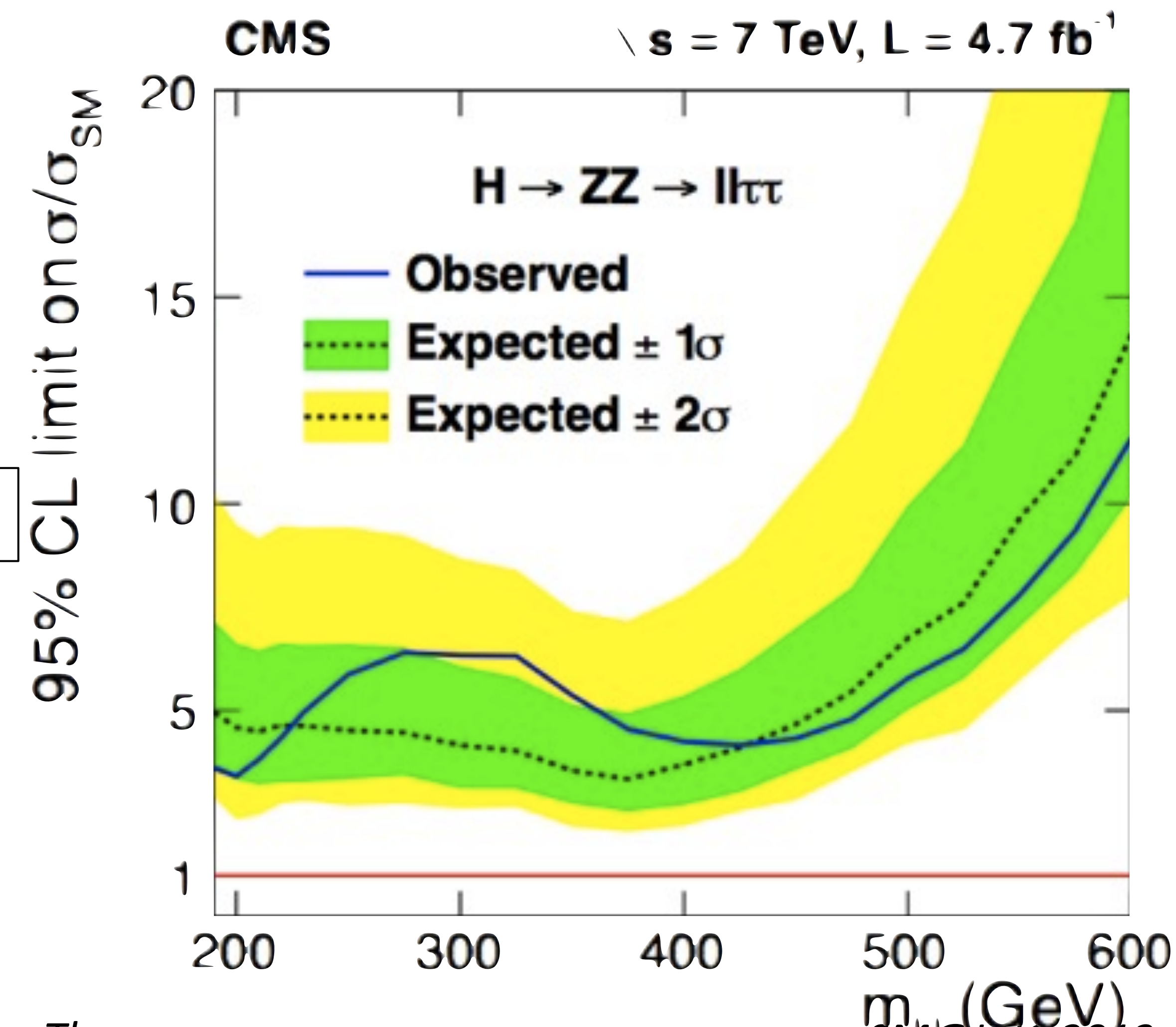
H→ZZ→2ℓ2τ

H→ZZ→*eee*τ candidate



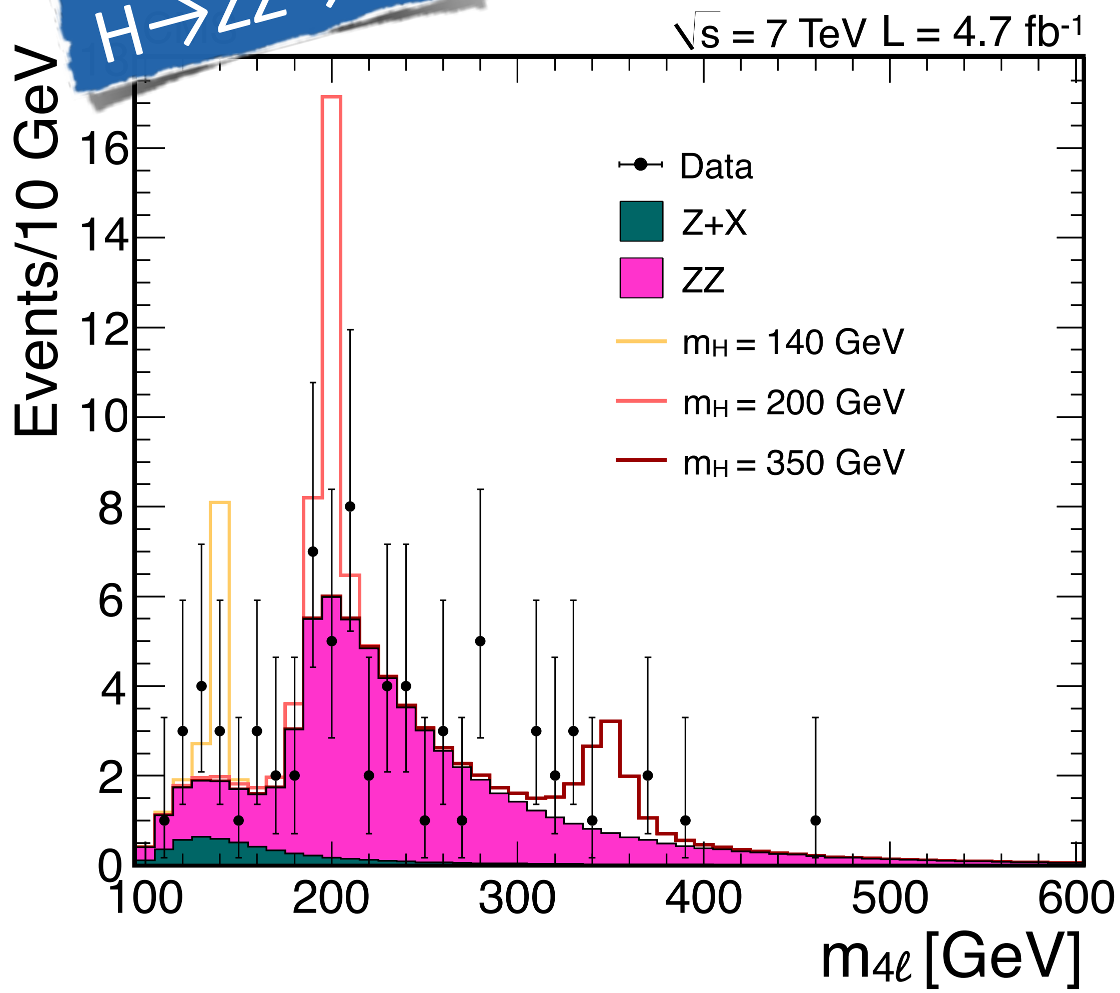


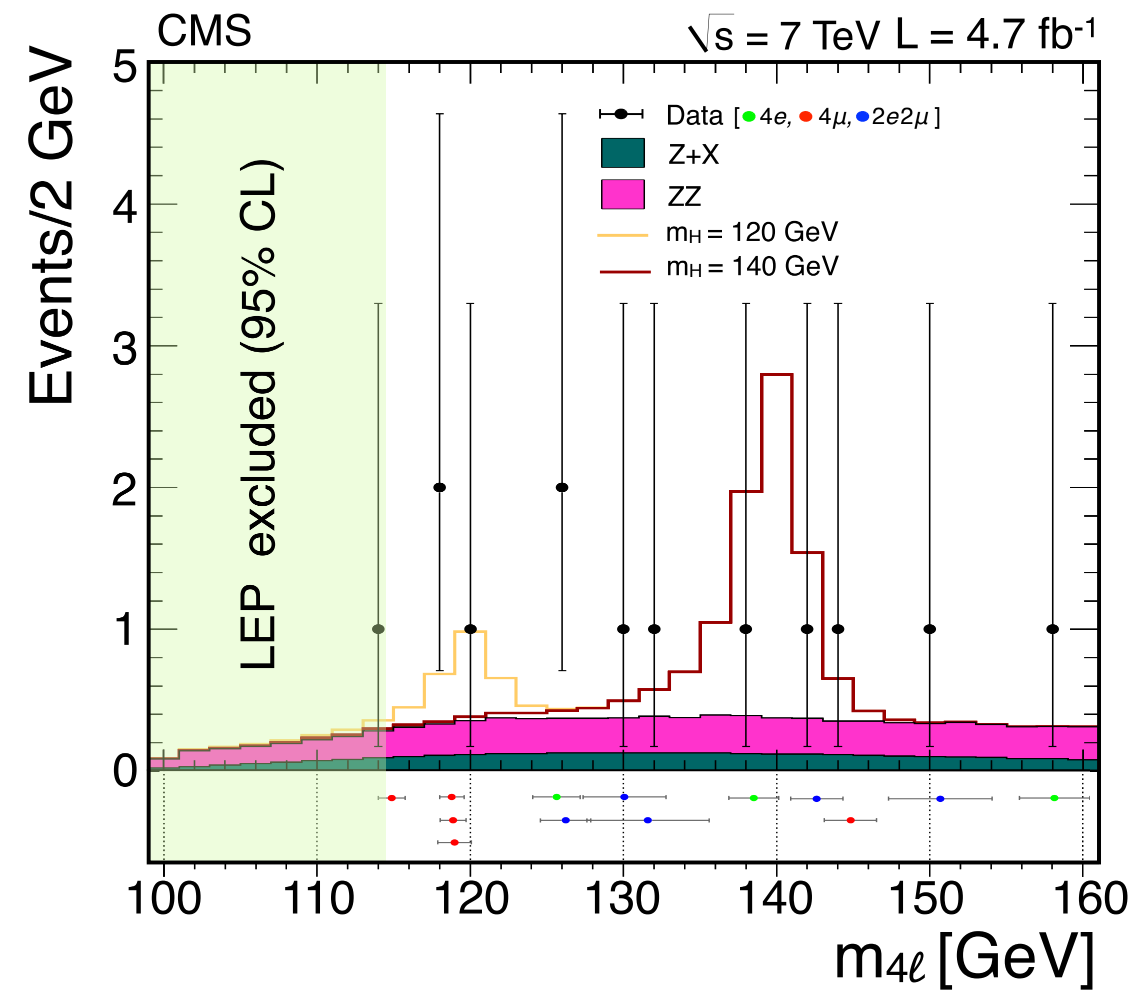
Shape-based analysis



Expected and observed yields

H→ZZ→4ℓ

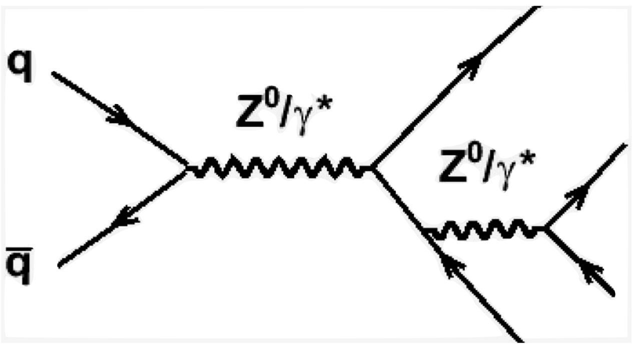


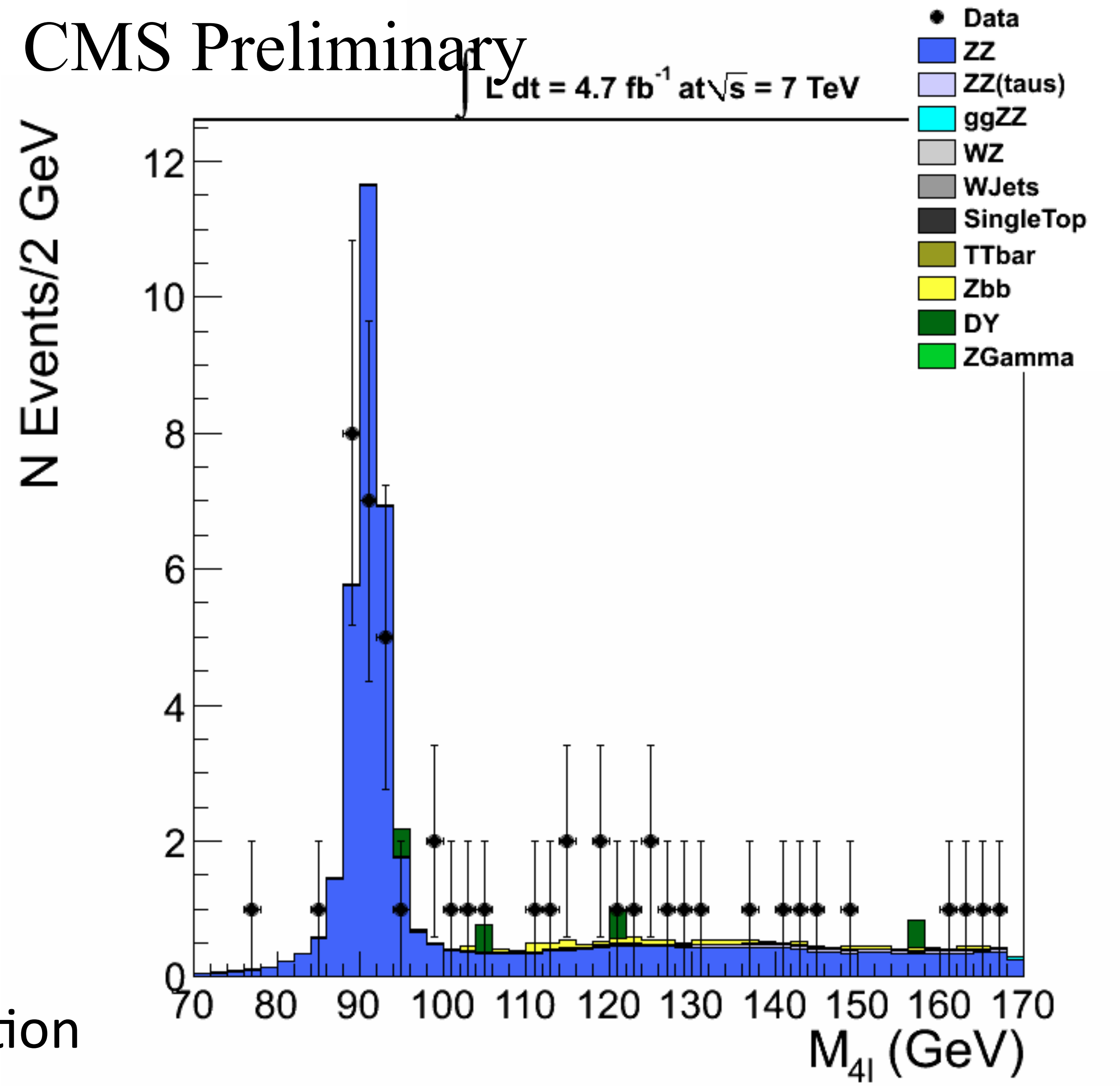


Channel	4e	4μ	$2e2\mu$
ZZ background	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_{H} = 120\,GeV$	0.25	0.62	0.68
$m_{H} = 140\,GeV$	1.32	2.48	3.37
$m_{H} = 350\,GeV$	1.95	2.61	4.64
Observed	12	23	37

Final state	$4e$	4μ	$2e2\mu$
Obs. Events	3	5	5
Exp. Events	1.7	3.3	4.5

Observation of Z→4ℓ





Di-lepton mass cut relaxed to 4 GeV

Standard Candle for H→ZZ→4l search

- direct calibration of $m_{4\ell}$ scale
- direct measurement of $m_{4\ell}$ resolution
- $m_{4\ell}$=91.3±0.6 GeV (stat)

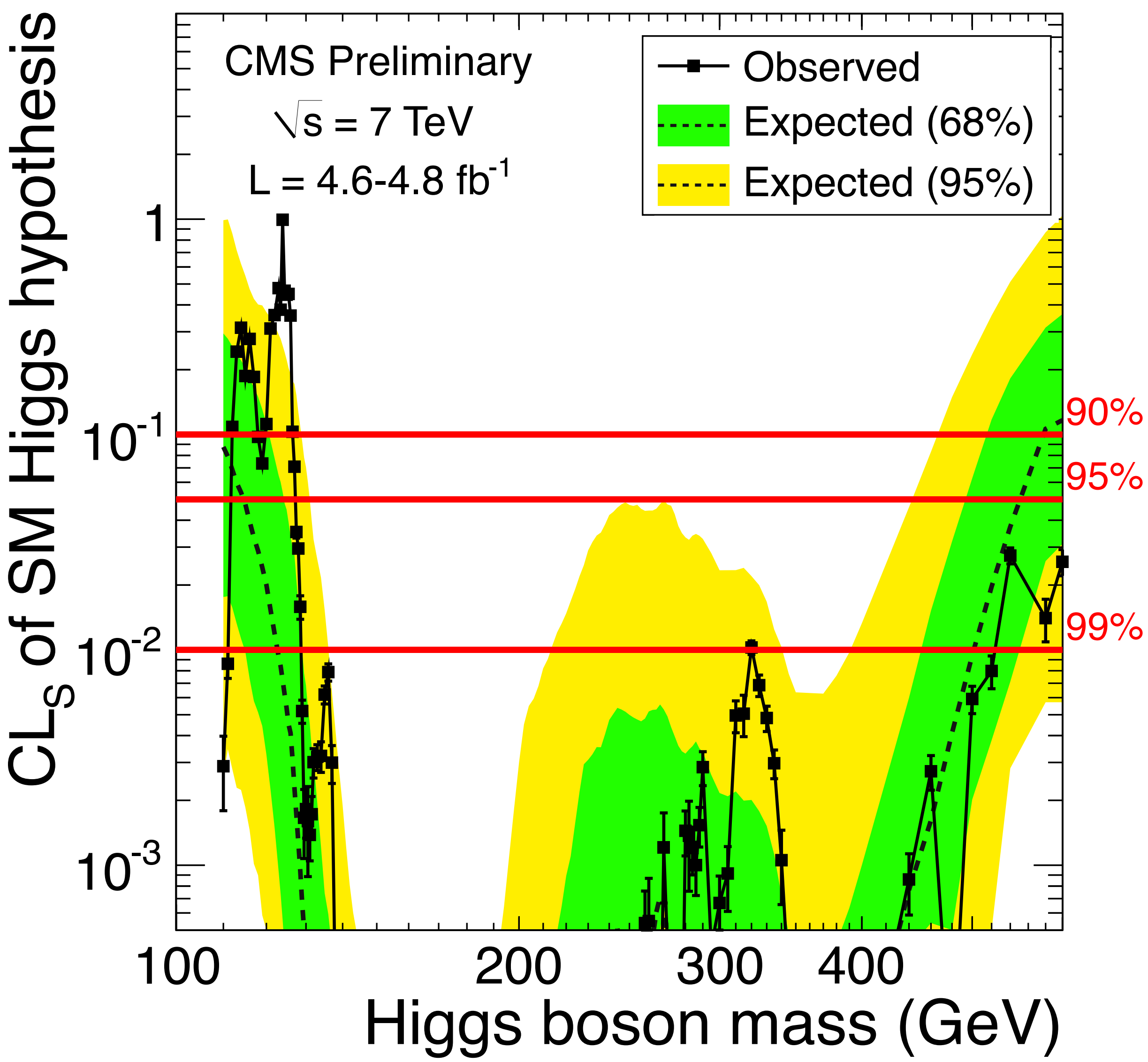
M_T definition

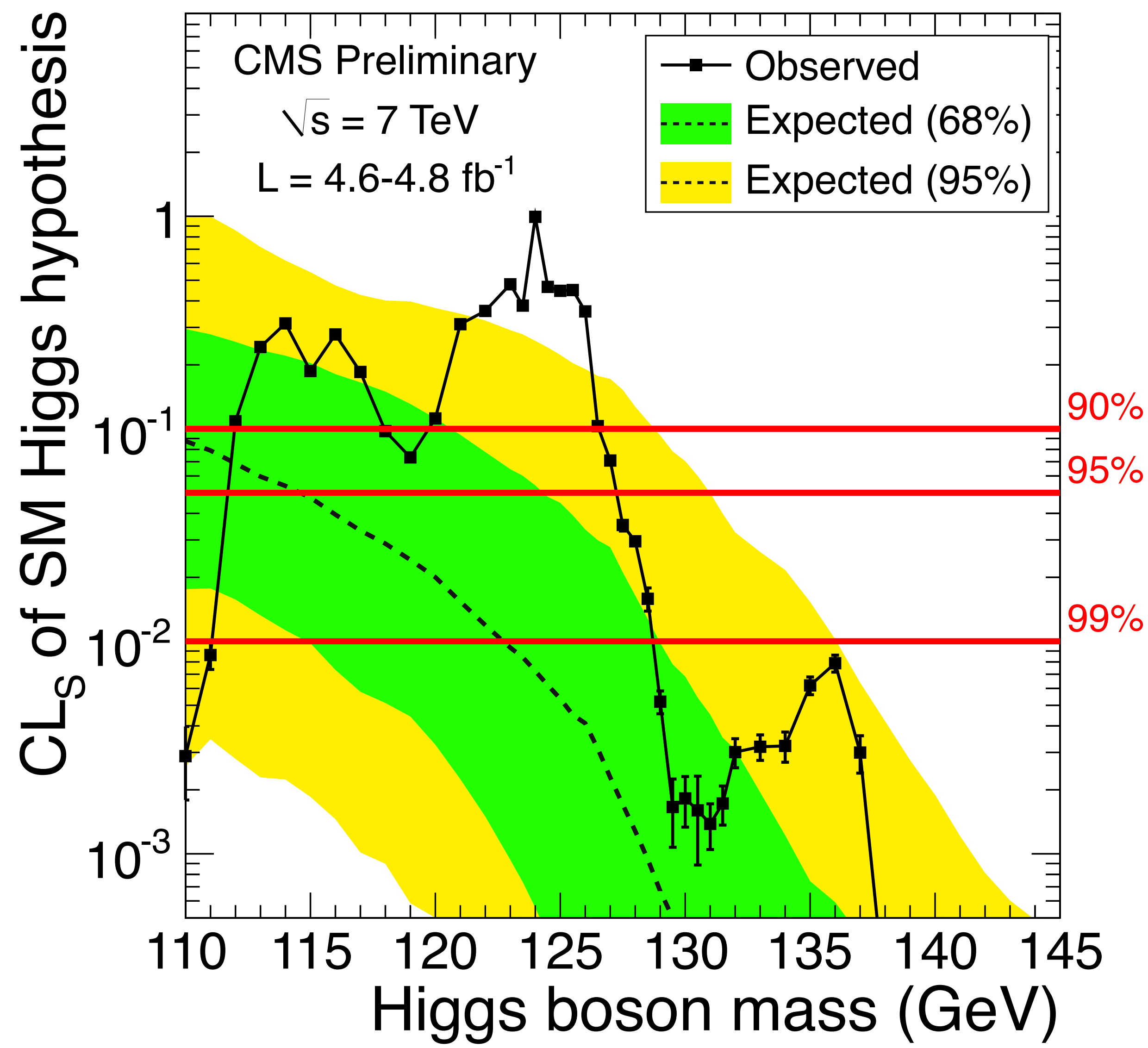
$$M_T^2 = \left(\sqrt{{P_{TZ}}^2 + {M_Z}^2} + \sqrt{MET^2 + {M_Z}^2}\right)^2 - (\vec{P}_{TZ} + M\vec{E}T)^2$$

Backup

Combination

Observed Exclusion Confidence Levels





95% CL observed exclusion: 127.5—600 GeV

99% CL observed exclusion: 129 —525 GeV

Observed Rate Of Excesses at m_H=119.5, 124 GeV