

Higgs at the LHC

- Theoretical constraints on Higgs boson mass
- Constraints from pre-LHC era and LHC no-lose theorem
- Experimental detection of SM(-like) Higgs boson h

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Where are the masses ?

Problem with the SM: all particles are massless. Introduction of mass terms ruins the gauge invariance. Oops.

Solution proposed by Brout-Englert-Higgs:

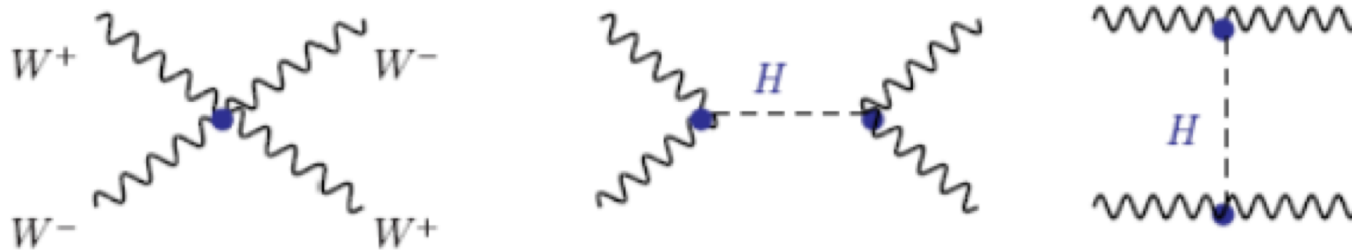
- assume the existence of a scalar field that pervades the universe
- particles interacting with this field acquire mass – the stronger the interaction, the larger the mass
- the particle associated with the Higgs field is the Higgs boson

2nd argument for extra scalar

Other – independent – argument for a new (effectively) scalar particle:

$\sigma (W^+W^- \rightarrow W^+W^-)$ diverges with energy!

We need something to cancel the divergence: scalar particle H



$$A(W^+W^- \rightarrow W^+W^-) \xrightarrow{s \gg M_W^2} \frac{1}{v^2} \left[s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2} \right]$$

Upper bound on scalar mass

In order not to violate unitarity, in the previous formula:

$$M_H \lesssim 870 \text{ GeV}$$

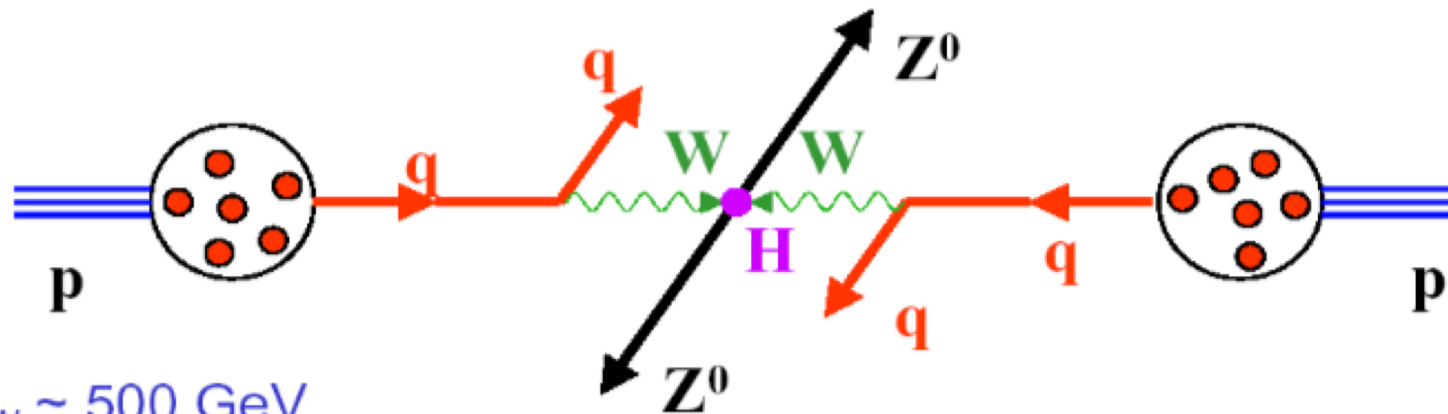
This argument lead to the minimum physics requirement for a post-LEP collider:

The next accelerator must be able to produce particles up to a mass of $\sim 1 \text{ TeV}$

Design goals of the LHC

Hadron colliders are broad-band exploratory machines

May need to study W_L - W_L scattering at a cm energy of ~ 1 TeV



- $\Rightarrow E_W \sim 500$ GeV
- $\Rightarrow E_{\text{quark}} \sim 1$ TeV
- $\Rightarrow E_{\text{proton}} \sim 6$ TeV

$\Rightarrow$ **pp collisions at 7 + 7 TeV**

14 TeV collider

Event Rate = $L \cdot \sigma \cdot BR$

e.g. $H(1 \text{ TeV}) \rightarrow ZZ \rightarrow 2e+2\mu$ or $4e$ or 4μ

For $L \sim 10^{34}$, Evts/yr = $10^{34} \cdot 10^{-37} \cdot 10^{-3} \cdot 10^7 \sim 10$ /yr !!

$L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

LHC no-lose theorem

Very strong arguments to design and construct the new LHC accelerator

LHC was expected to:

- either find a Higgs boson with mass $< 1\text{TeV}$
- or observe new physics in WW boson scattering at $\sim 1\text{TeV}$

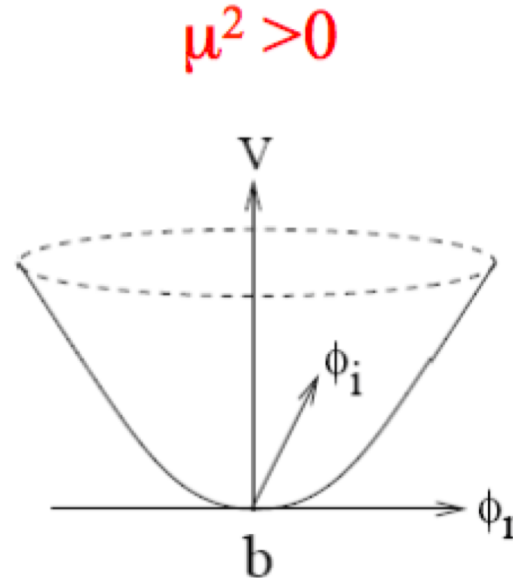
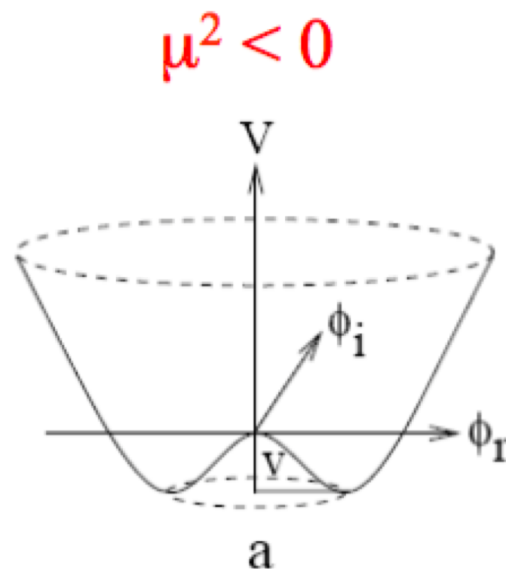
The former has already been observed (see next)

The minimal Higgs Mechanism

1964: Brout, Englert and Higgs propose to add a complex scalar doublet field to the Lagrangian

$$\mathcal{L} = (\partial^\mu \phi^\dagger)(\partial_\mu \phi) - \mu^2 |\phi|^2 - \lambda |\phi|^4$$

EWSB if μ^2 negative!



$$\rightarrow m_W = \frac{1}{2} g v \quad (v^2 = \frac{\mu^2}{\lambda})$$

$$m_Z = \frac{1}{2} \sqrt{g^2 + g'^2} v$$

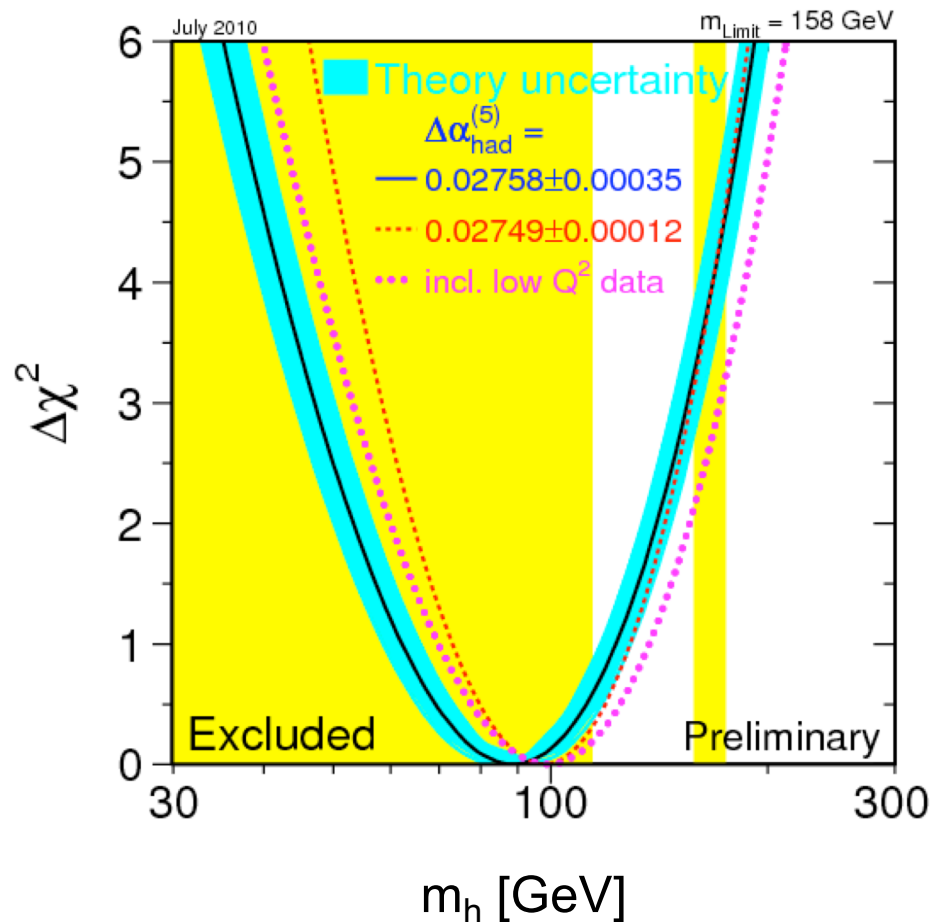
$$m_\gamma = 0.$$

and one extra boson with

$$m_H^2 = -\mu^2$$

Limits on SM Higgs boson mass before

From LEP and Tevatron (1983-2011) experiments:



Direct exclusion:

- $m_h > 114.4 \text{ GeV}$ (LEP)
- $m_h < 158 \text{ GeV}$ or $> 175 \text{ GeV}$ (Tevatron)

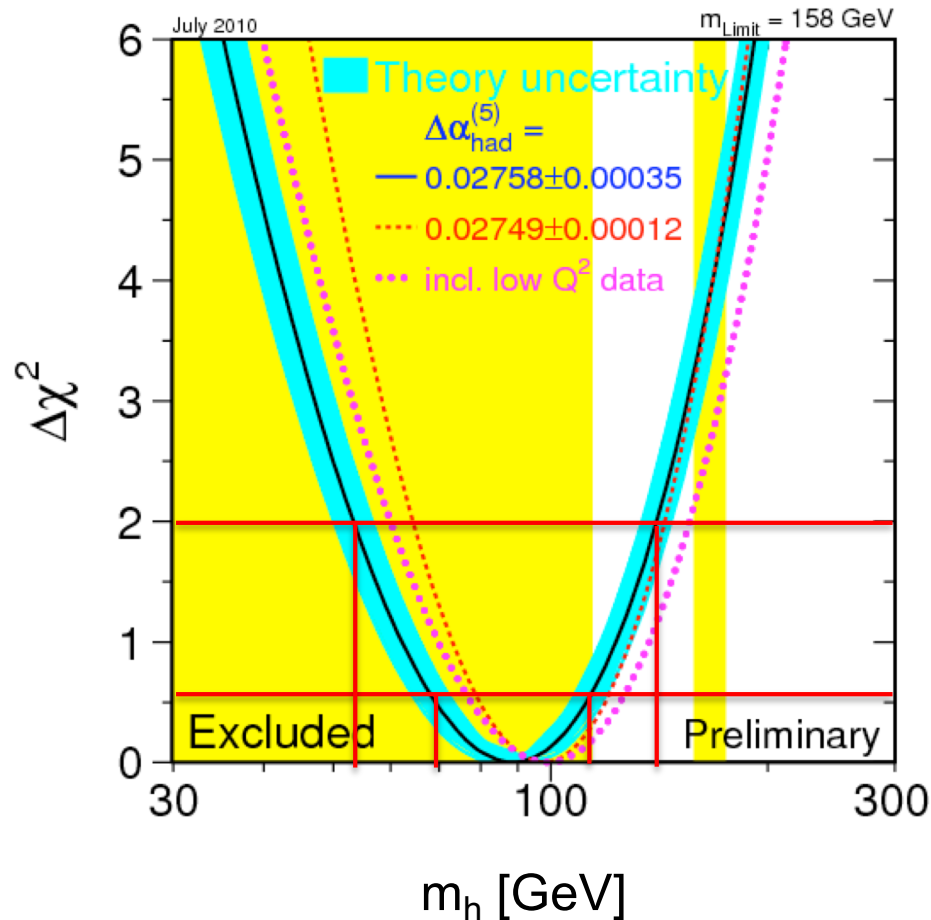
Preferred value from indirect measurements:

- $m_h = 89^{+35}_{-26} \text{ GeV}$

<https://inspirehep.net/record/880855/>

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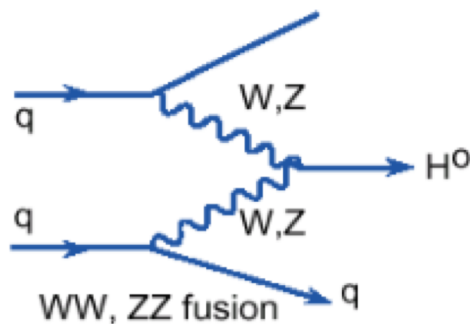
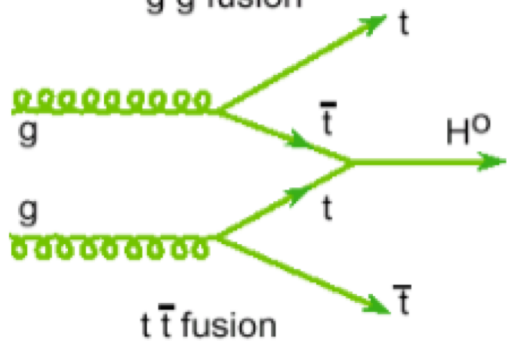
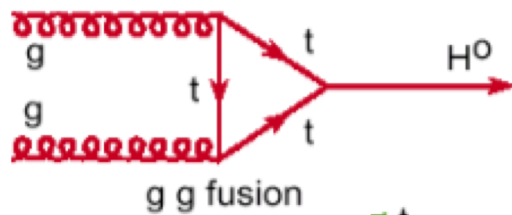
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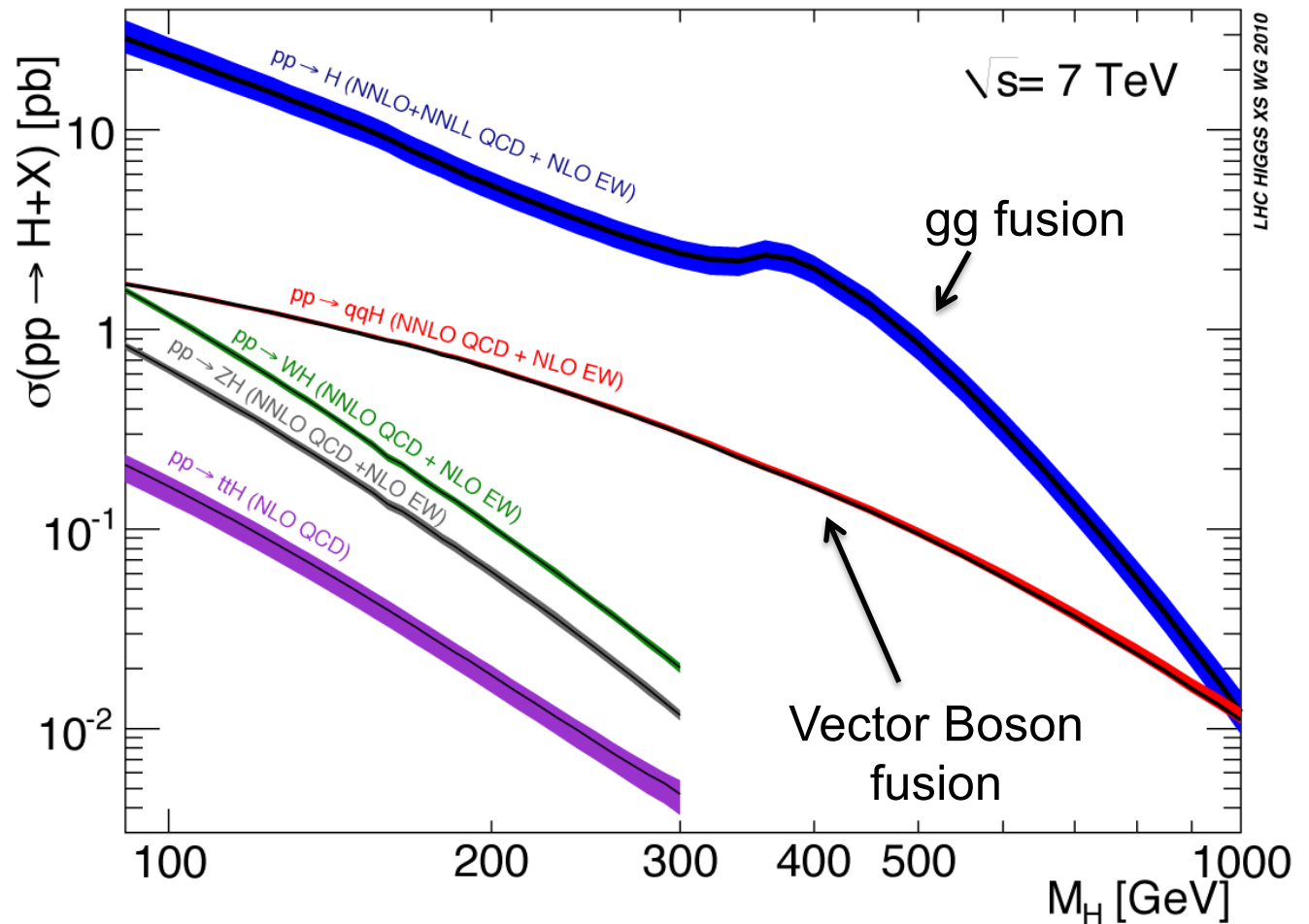
<https://inspirehep.net/record/880855/>

SM Higgs boson production @ LHC

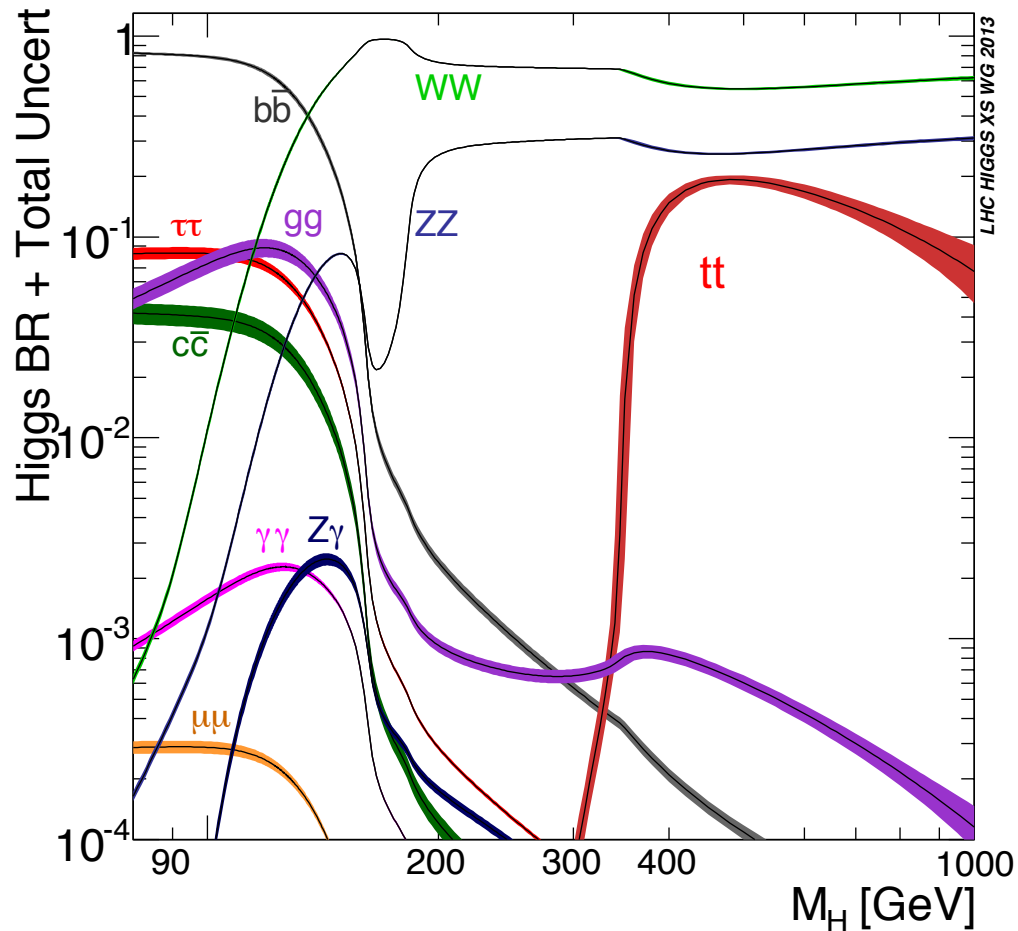


- Higgs coupling increases with mass of fermion/boson:

$$g_{Hf\bar{f}} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V^2}{v}$$



SM Higgs decay modes

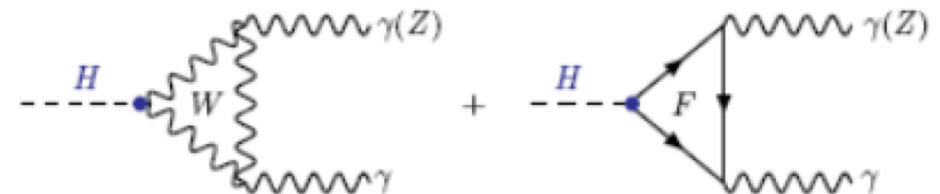


- Higgs coupling increases with mass of fermion/boson:

$$g_{Hf\bar{f}} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V^2}{v}$$

- Dominant BR is $H \rightarrow b\bar{b}$ until WW and ZZ modes open up

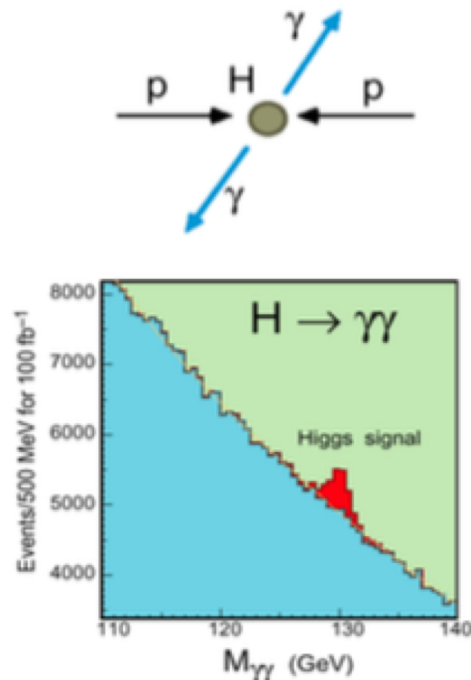
- decay into $\gamma\gamma$ through loops



Examples from LHC-design era

Higgs $\rightarrow \gamma\gamma$

Low $M_H < 140 \text{ GeV}/c^2$

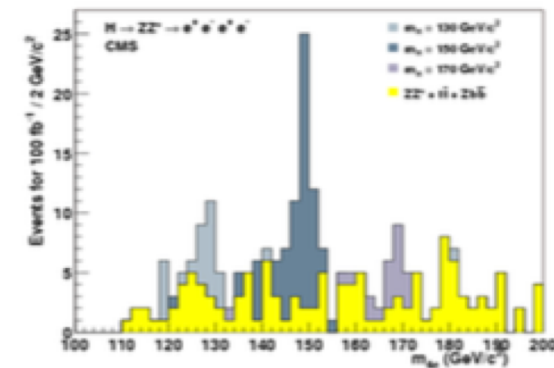
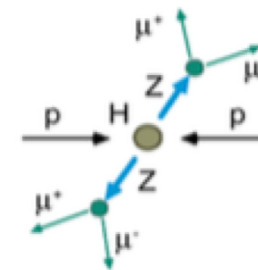


narrow signal over large-but-smooth background

L. Shchutska

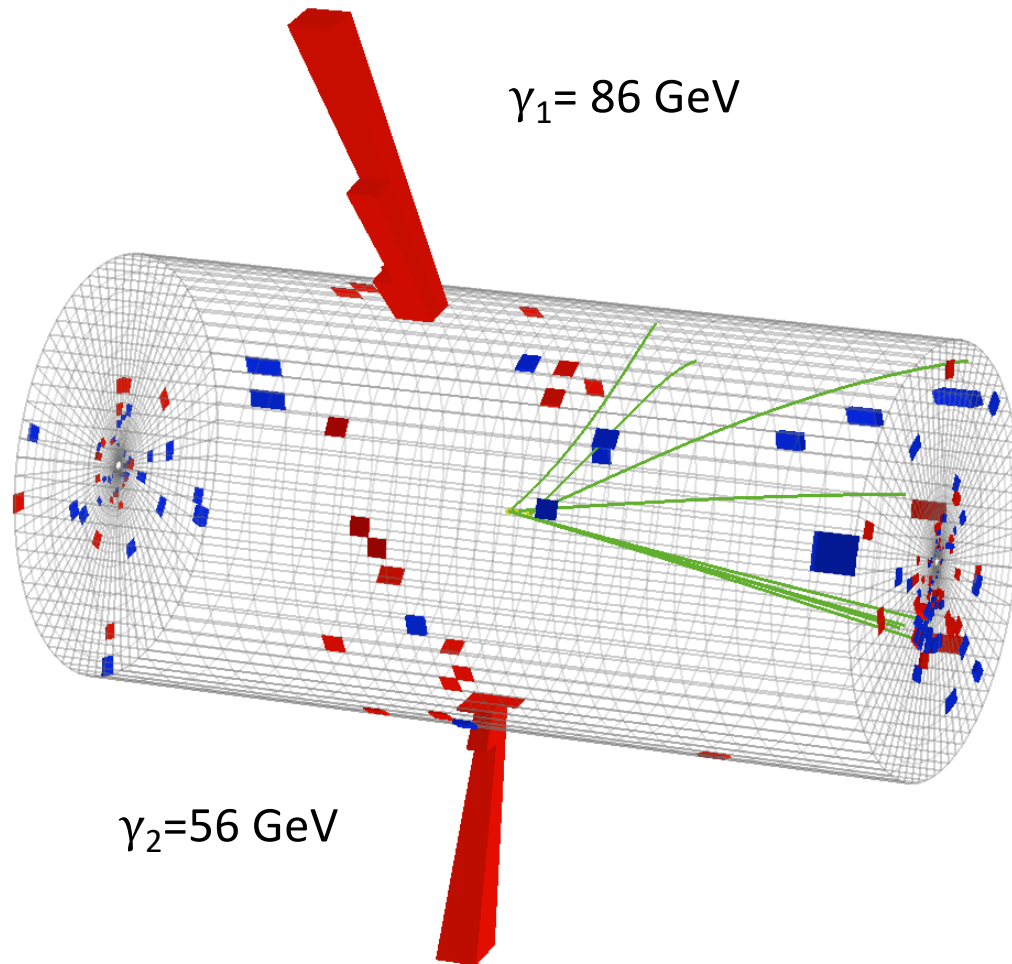
Higgs $\rightarrow ZZ \rightarrow 4l$

Medium $120 < M_H < 500 \text{ GeV}/c^2$



small-but-narrow signal over very small background

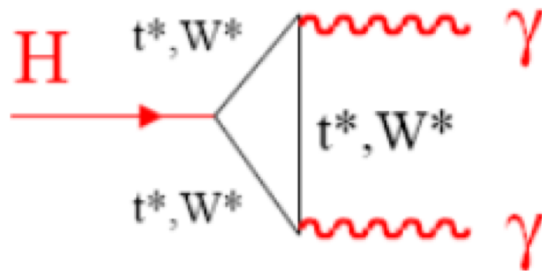
Higgs $\rightarrow \gamma\gamma$



Eur. Phys. J. C (2014) 74:3076

Higgs $\rightarrow \gamma\gamma$

Most promising channel in the range $m_H < 150$ GeV



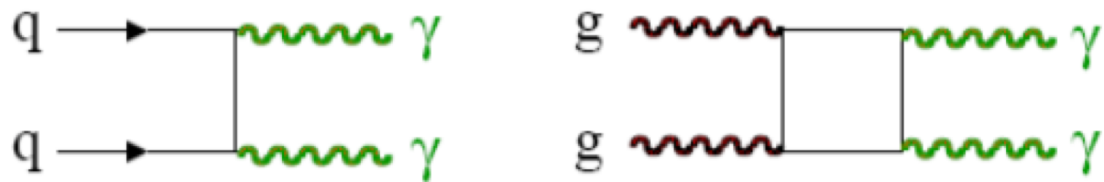
($\sigma.B \sim 50 \cdot 10^{-3}$ pb @ $m_H \sim 150$ GeV)

$\sigma.B$ can be modified by heavy undiscovered fundamental fermions or bosons

Higgs $\rightarrow \gamma\gamma$: backgrounds

Main Backgrounds

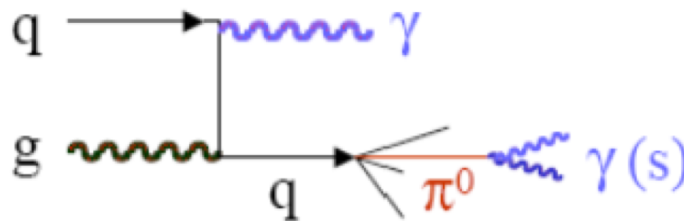
Irreducible: qq annihilation and gg 'box'



The diagram on the left shows two incoming quarks (q) meeting at a vertex, with two outgoing photons (γ) represented by green wavy lines. The diagram on the right shows two incoming gluons (g) meeting at a box loop, with two outgoing photons (γ) represented by green wavy lines.

$$\frac{\sigma(\gamma\gamma)}{\sigma(H \rightarrow \gamma\gamma)} \sim 60$$

Reducible: γ -jet and jet-jet



The diagram shows an incoming quark (q) and an incoming gluon (g) meeting at a vertex. One outgoing line is a photon (γ) represented by a blue wavy line. The other outgoing line is a quark (q) which then splits into a π⁰ (represented by a red line) and a photon (γ(s)) represented by a blue wavy line.

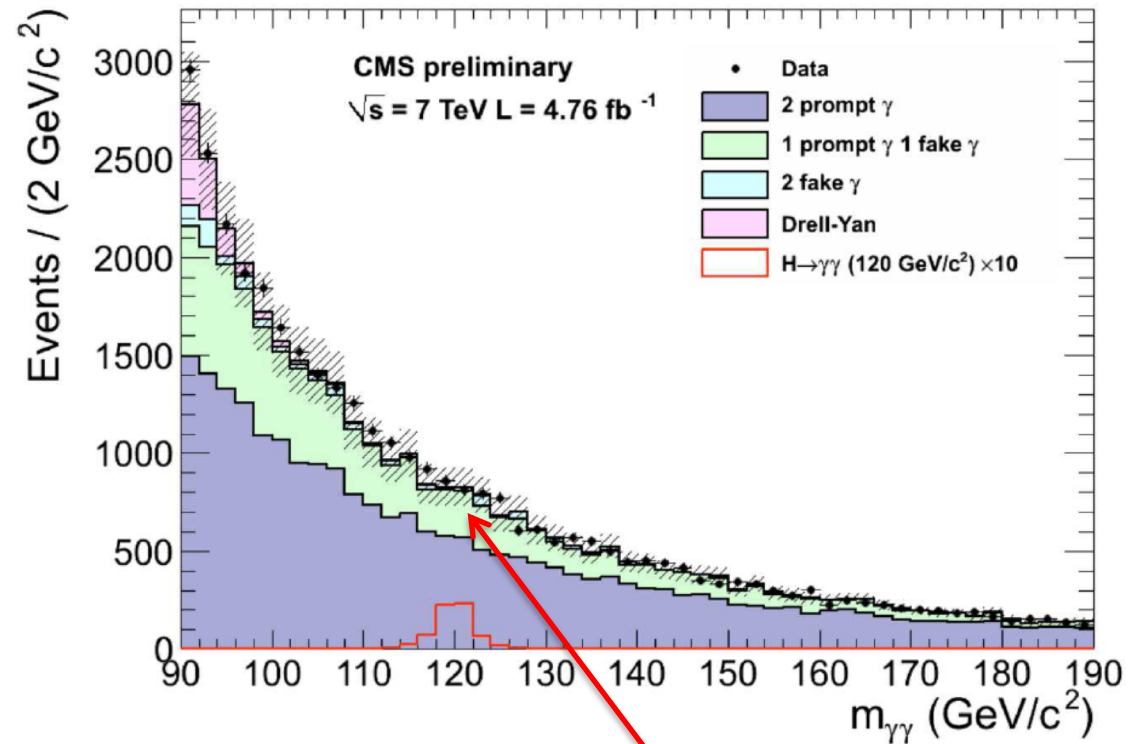
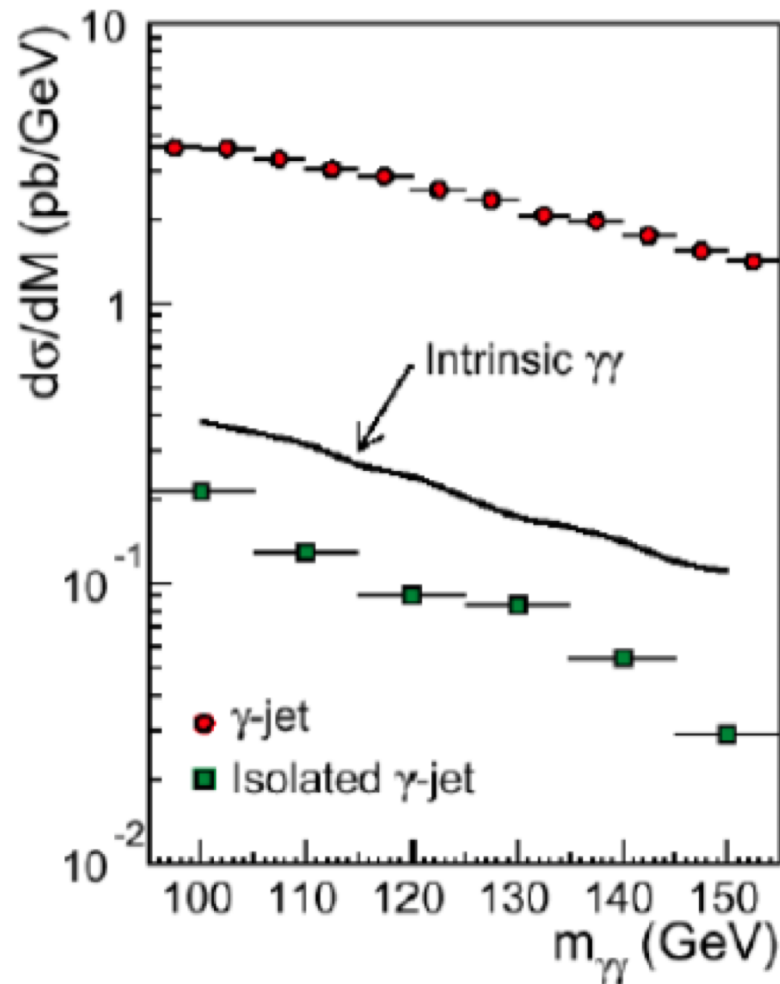
$$\frac{\sigma_{jj}}{\sigma(H \rightarrow \gamma\gamma)} \sim 10^8$$

Need of very good γ -jet separation

Obtained through:

- **photon isolation**
- **selection on calorimeter cluster-shape (photon ID)**

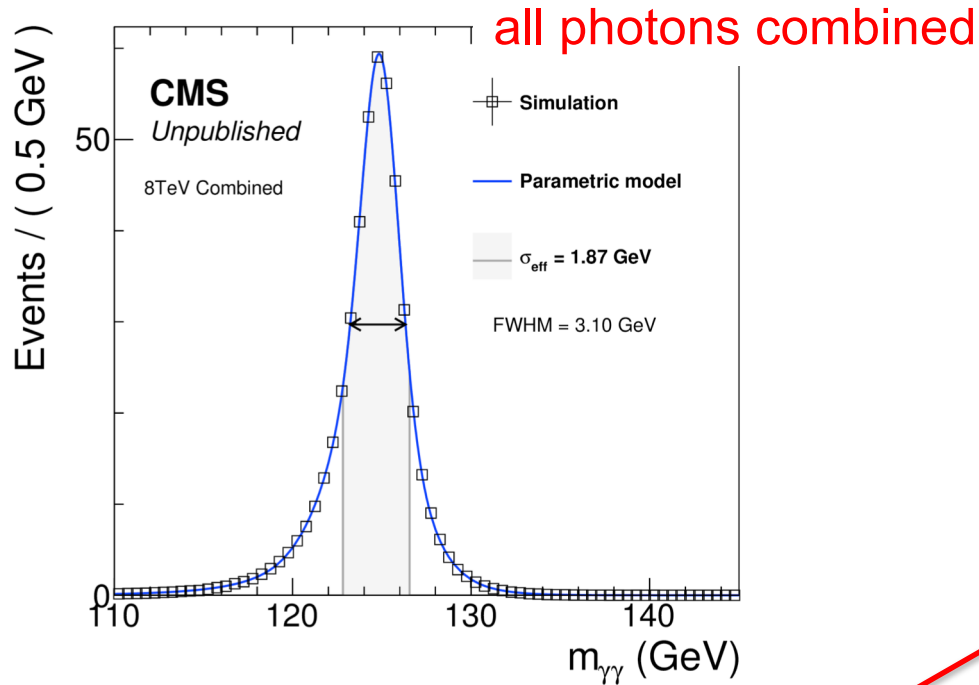
Higgs $\rightarrow \gamma\gamma$: isolation for bkg rejection



remaining fake-photon background
is about 30% of the total

Thanks to photon isolation and ID requirement:
(γ +jet & jet-jet) < irreducible background (i.e. prompt $\gamma\gamma$)

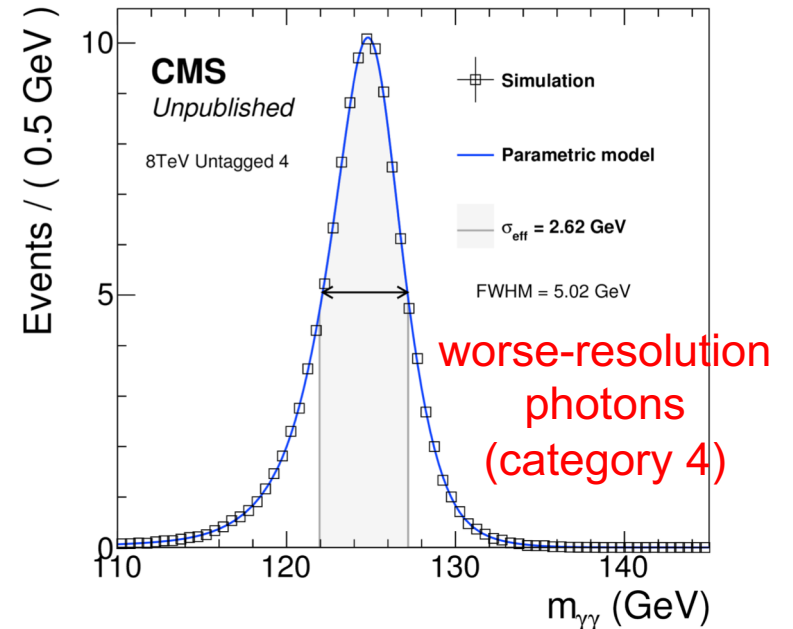
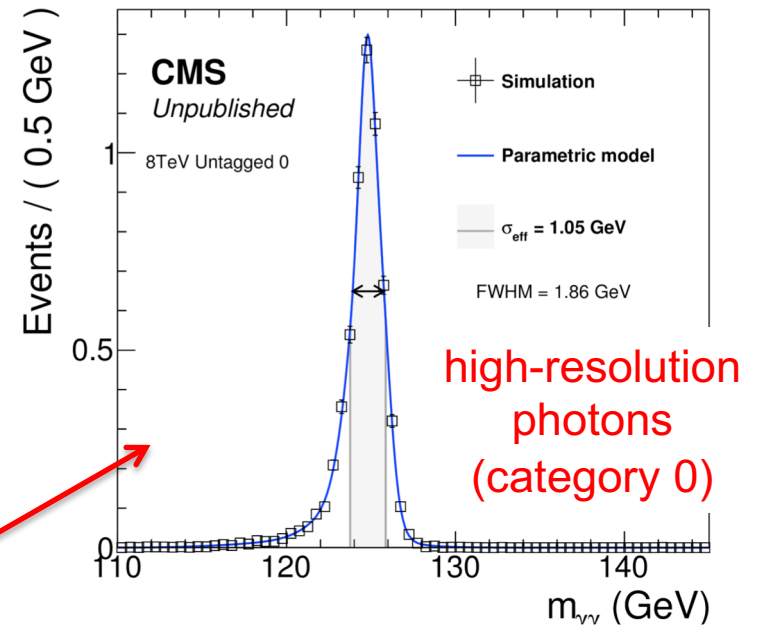
Higgs $\rightarrow \gamma\gamma$: photon categories



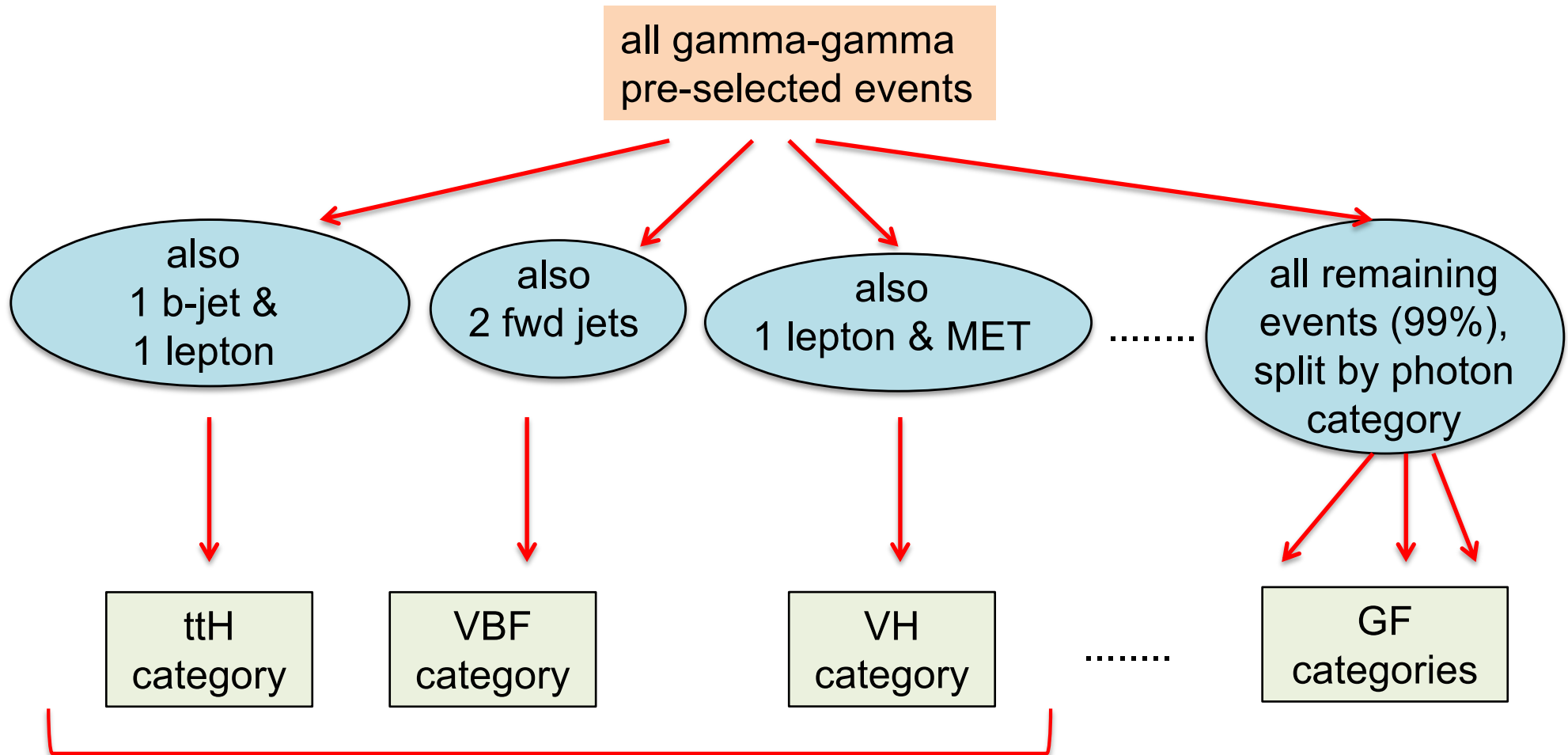
Instead of lumping all photons together, split higher- and worse-resolution categories



Narrower signal peak, then better signal/bkg ratio



Higgs $\rightarrow \gamma\gamma$: event topology categories

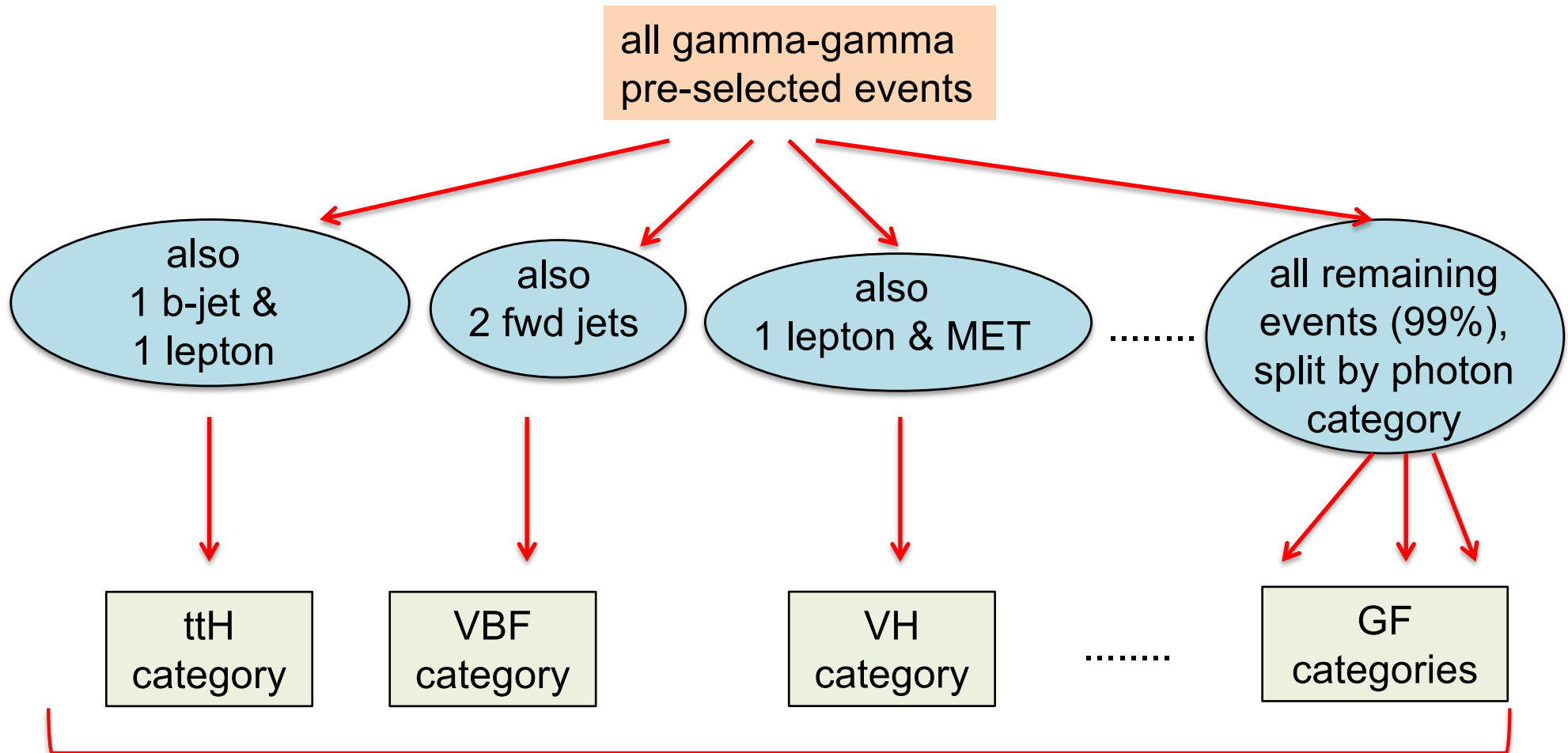


these extra requirements reduce the background (gamma-gamma prompt production) more than signal



better signal/bkg ratio

Higgs $\rightarrow \gamma\gamma$: event topology categories

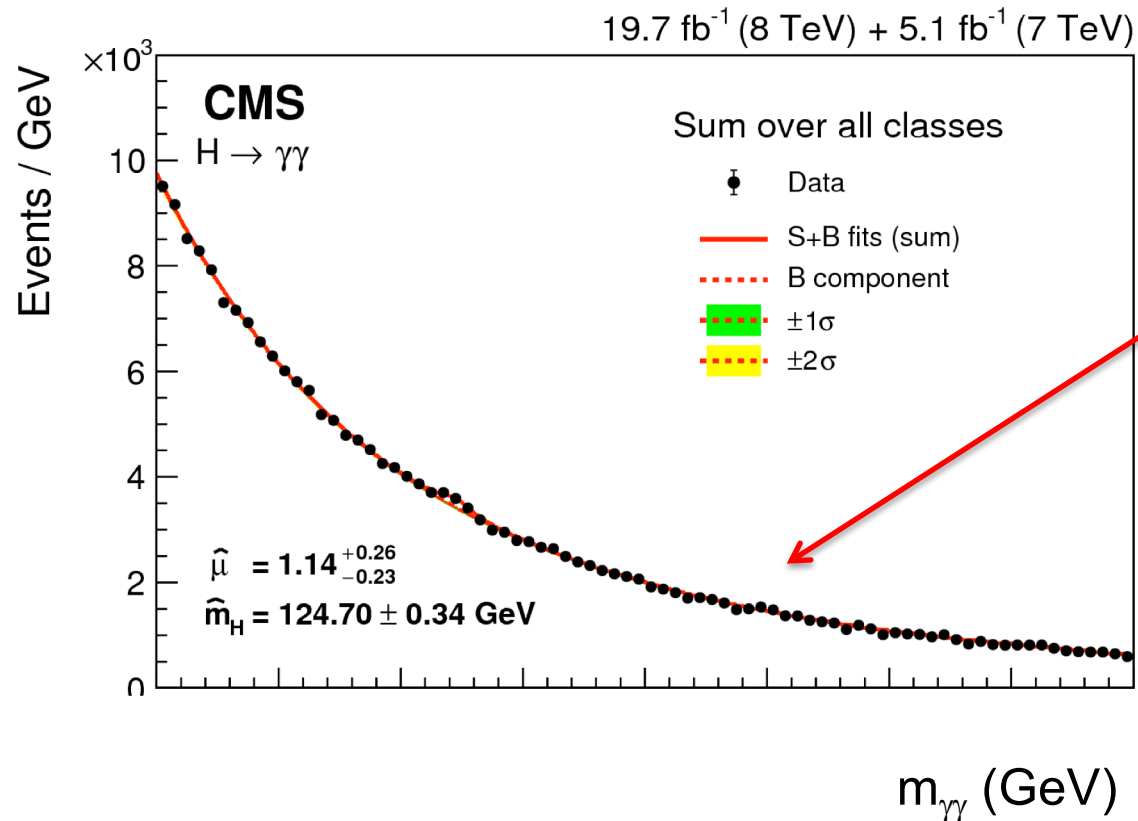


**probing cross-section
of different production
processes**



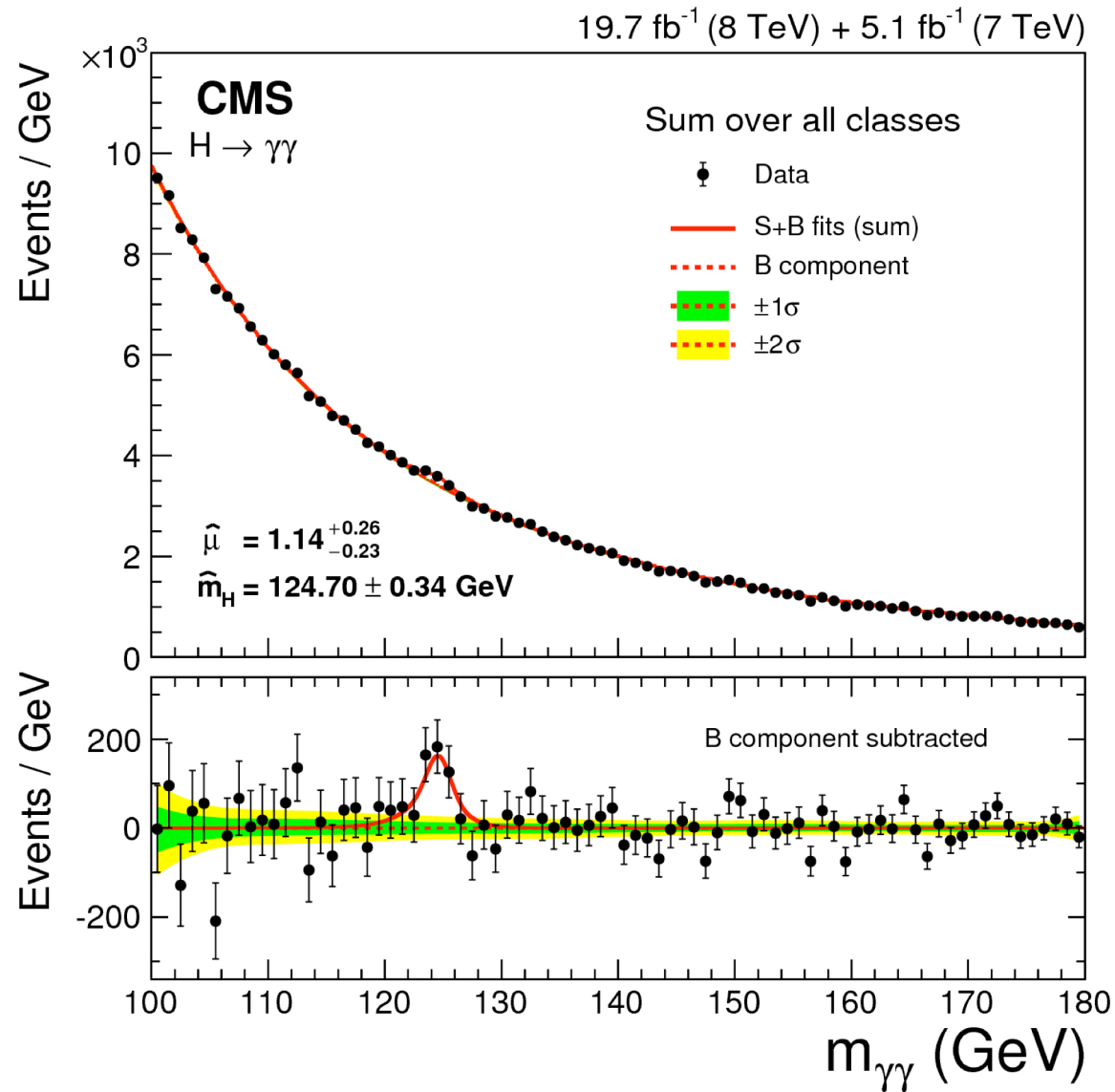
**probing the coupling of the Higgs
boson to different particles**

Higgs $\rightarrow \gamma\gamma$: results

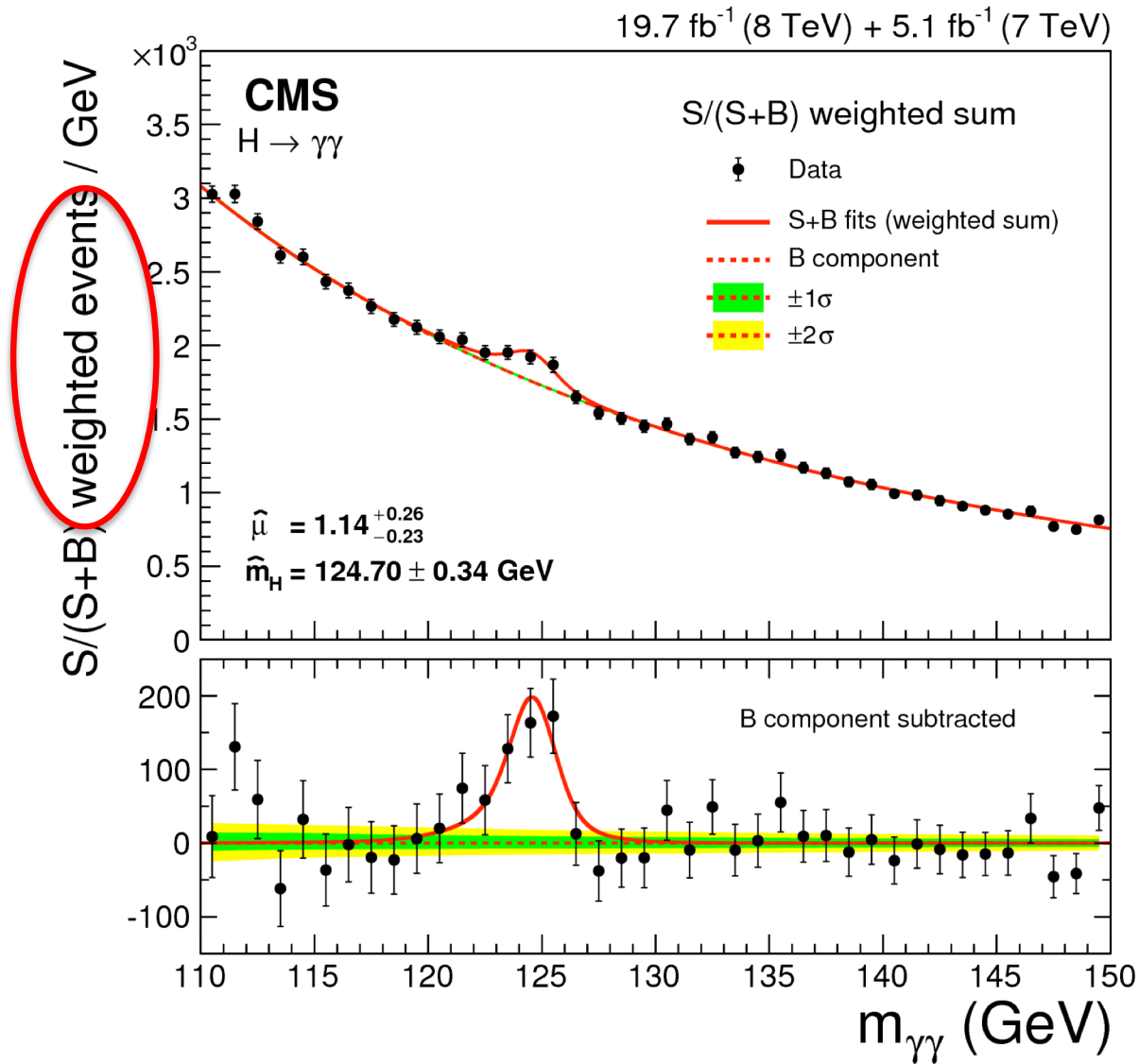


Background is extracted directly from data fitting the smooth $\gamma\gamma$ invariant mass distribution

Higgs $\rightarrow \gamma\gamma$: results



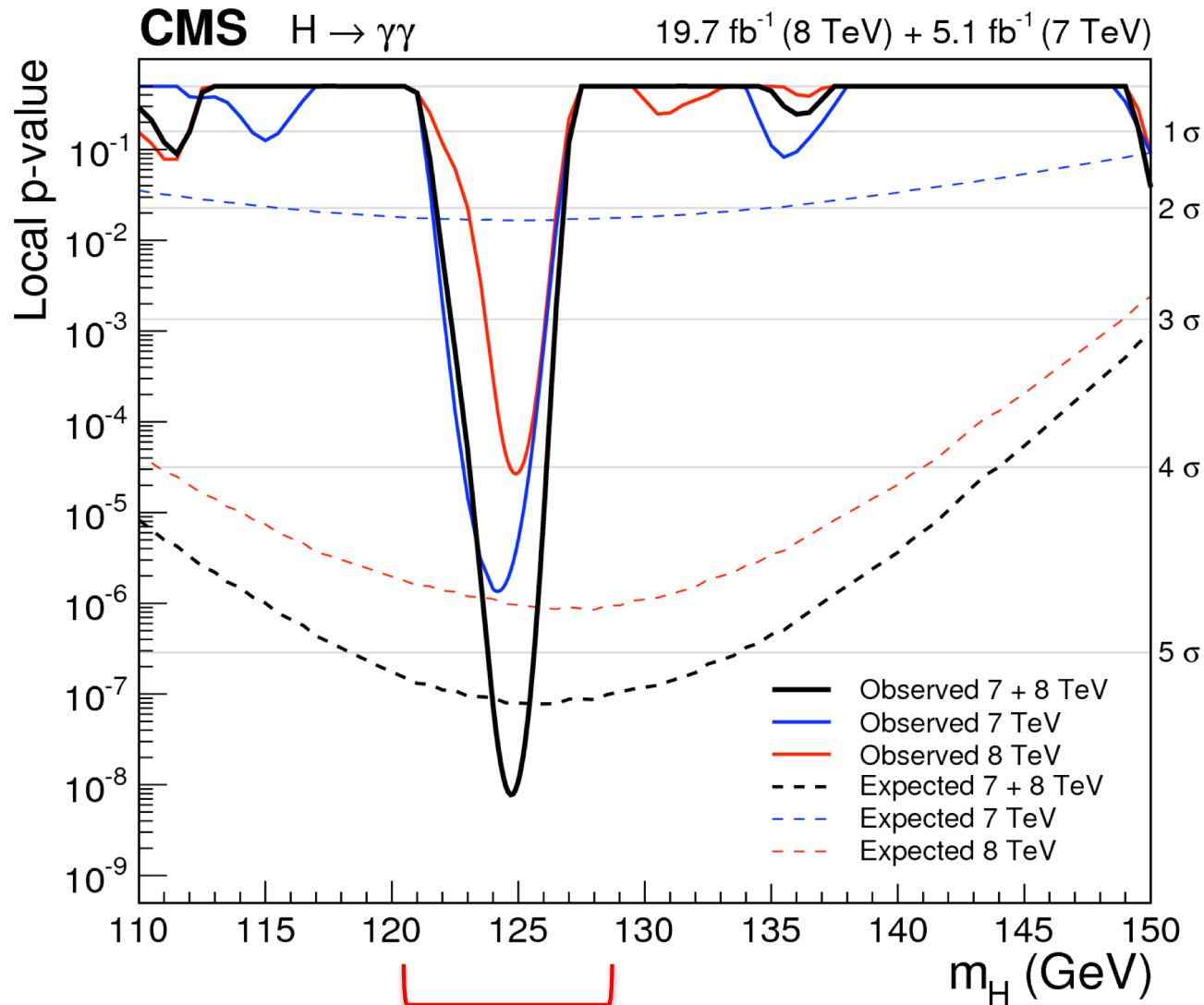
Higgs $\rightarrow \gamma\gamma$: results



Not all events are
“equal” in the
statistical analysis.

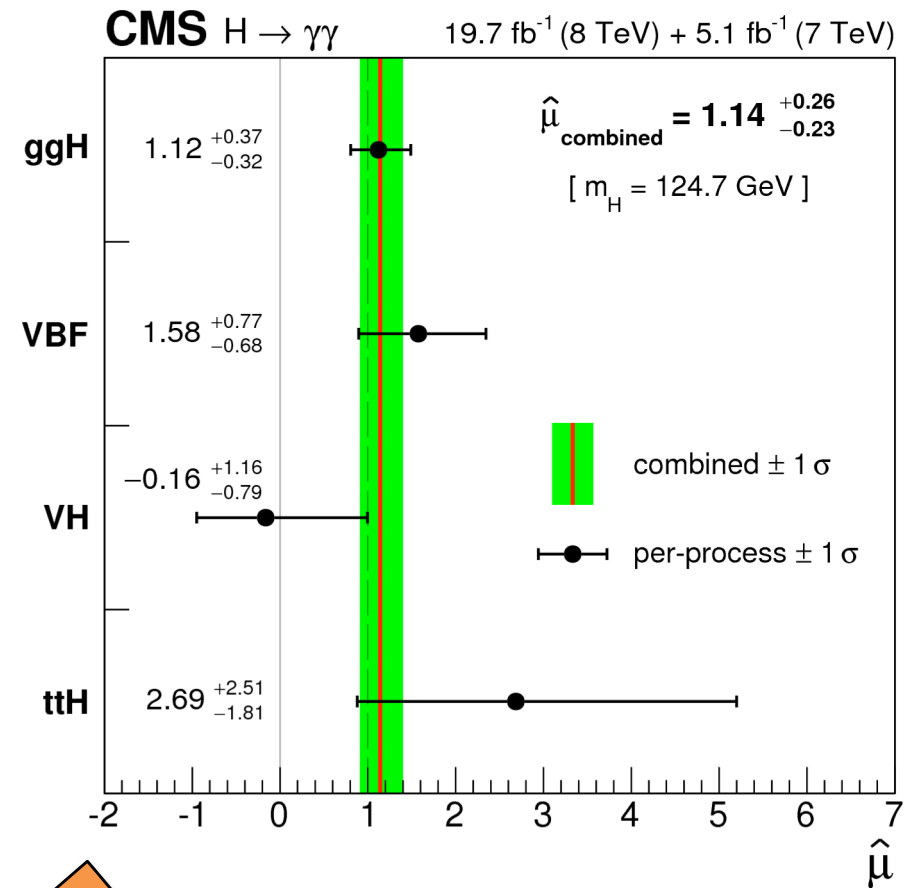
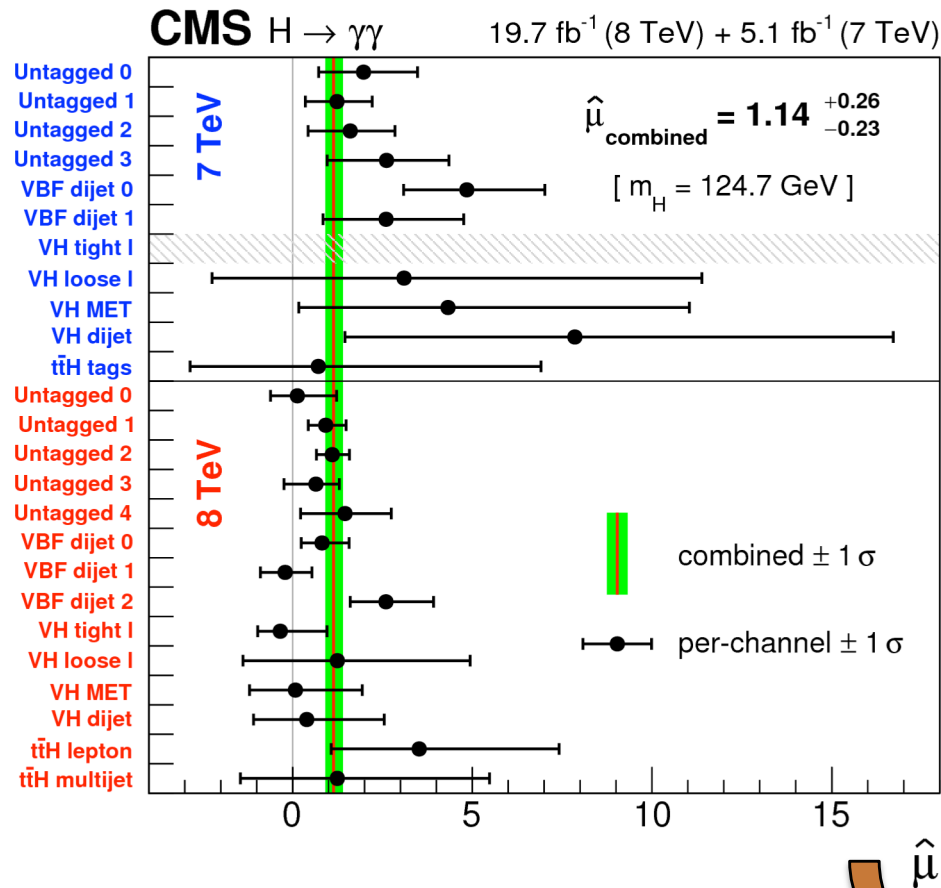
Some have a larger
“weight”

Higgs $\rightarrow \gamma\gamma$: results



width of the p-value dip is related to width of the $\gamma\gamma$ invariant-mass peak

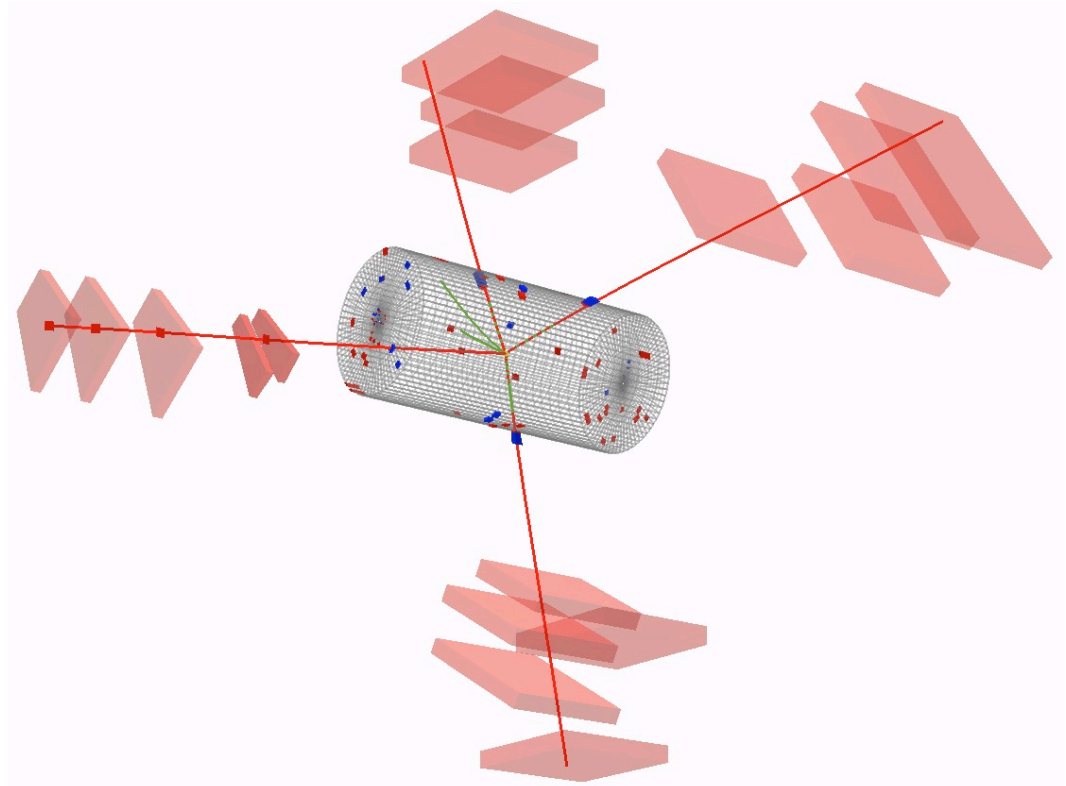
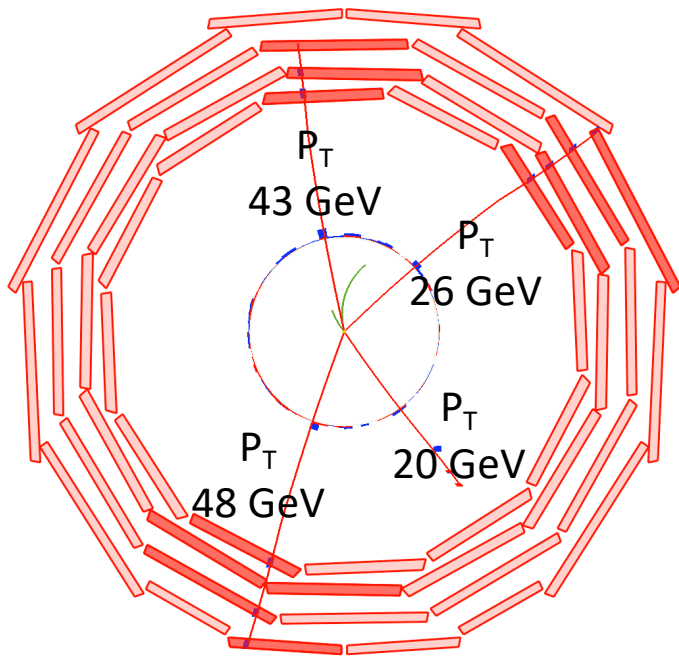
Is it a SM-like Higgs boson ?



combining different event category by production type

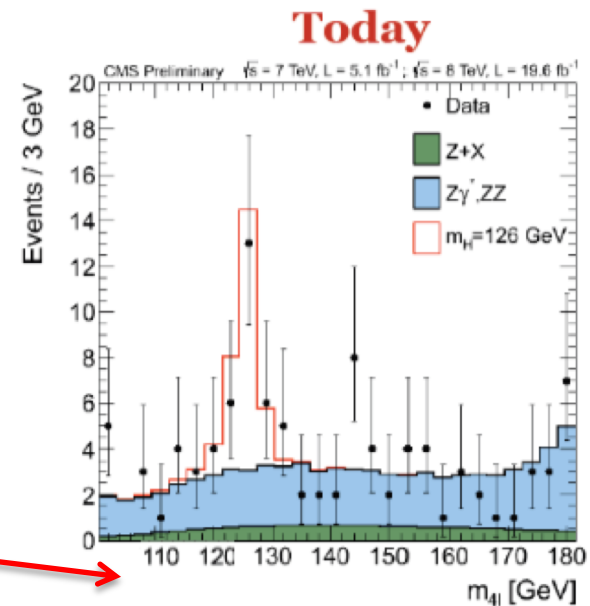
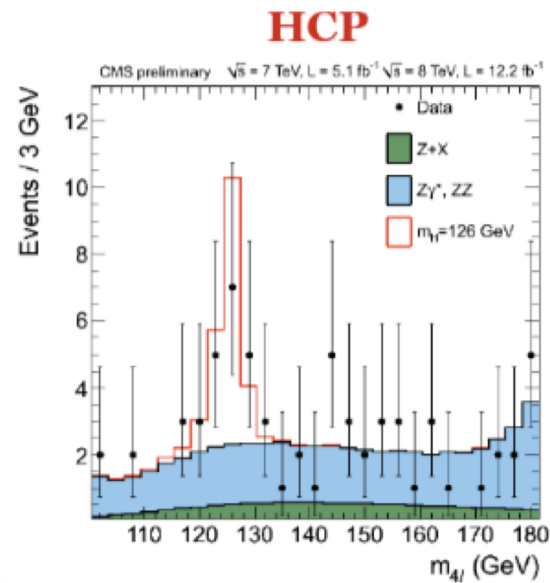
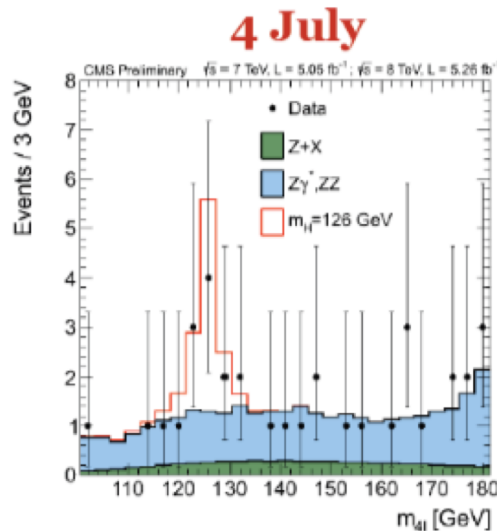
Definition: μ = ratio of measured- / SM- cross-section

$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$



10.1103/PhysRevD.89.092007

$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$

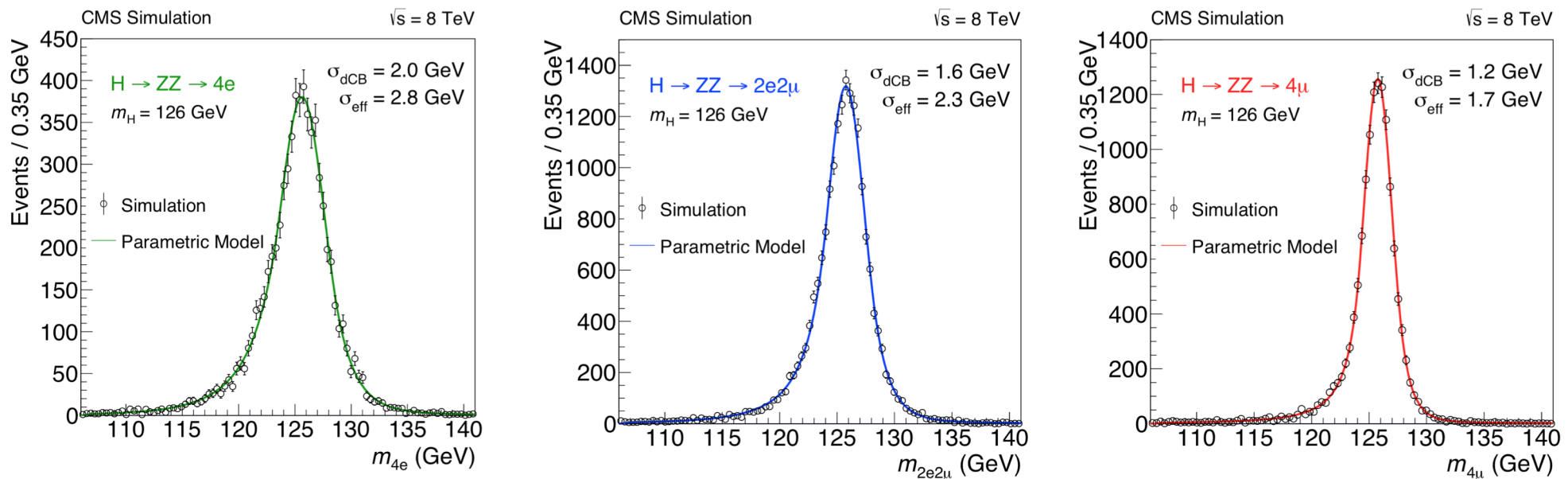


increasing amount of data
collected...

Narrow signal peak and very little
SM background imply again:

- good S/B ratio
- very precise measurement of
particle mass

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: event categories



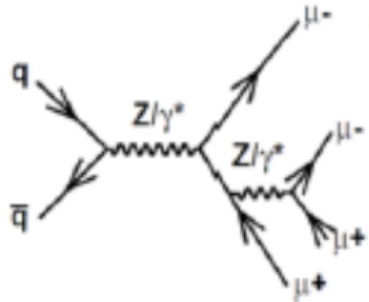
Improving mass resolution moving from electrons to muons.
(Muons are basically not affected by bremsstrahlung)

As for $H \rightarrow \gamma\gamma$ search, narrower the signal peak, better the signal/bkg ratio

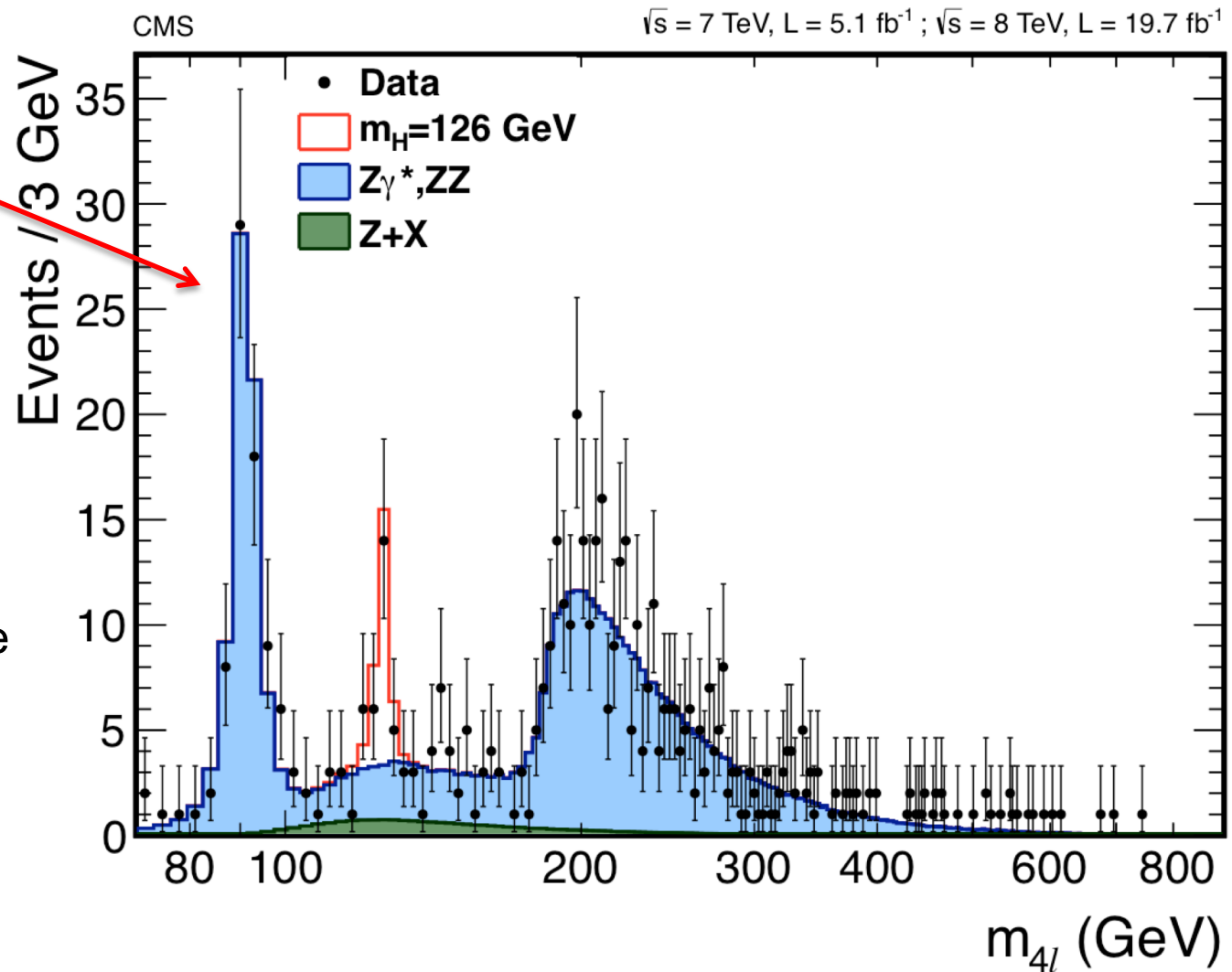


events are split in different lepton categories

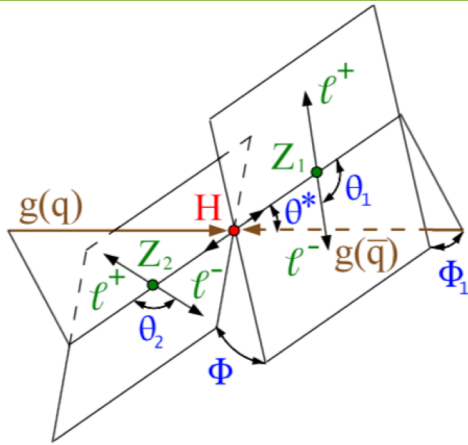
$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$



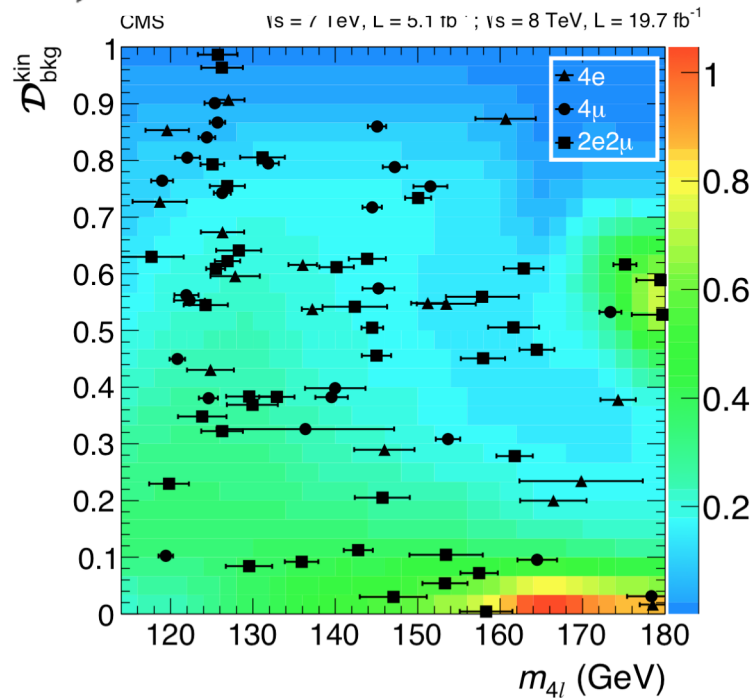
$Z \rightarrow 4l$ events are a handy SM “candle” that is used to validate the calibration of the lepton momentum reconstruction, in the relevant range of lepton momenta



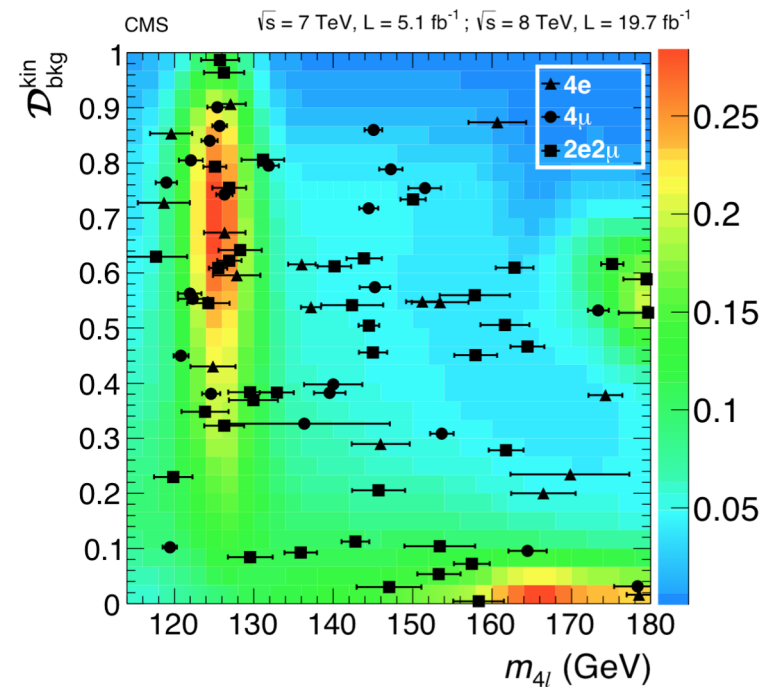
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: kinematical discriminator



Directions of final 4 leptons are correlated. Angles ϕ_1, θ_1, ϕ_2 , etc.. can be combined into a kinematical discriminator that separates signal (values~1) from background (values~0)

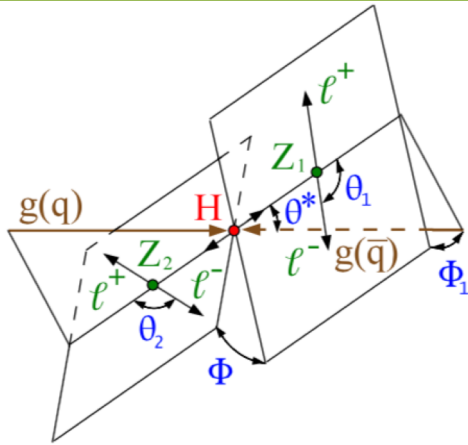


background expected distribution

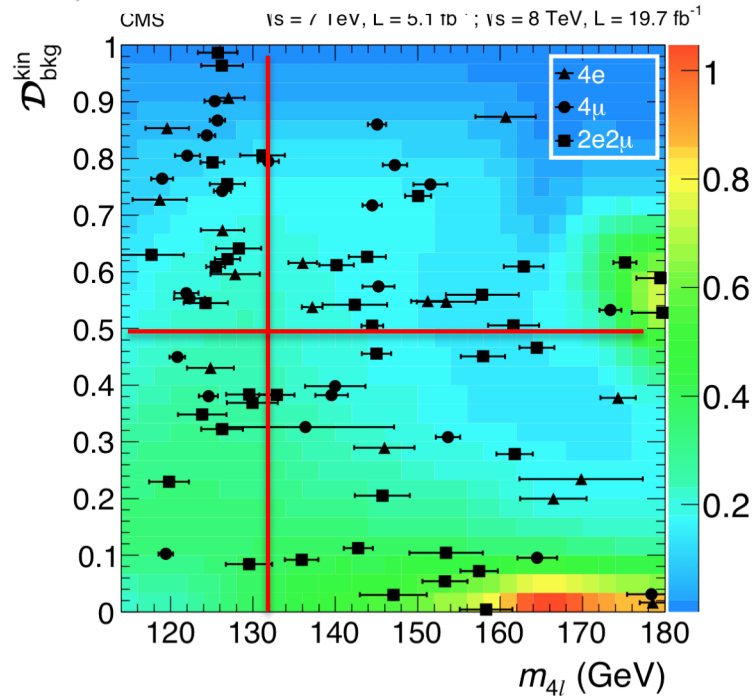


Higgs signal + background expected distribution

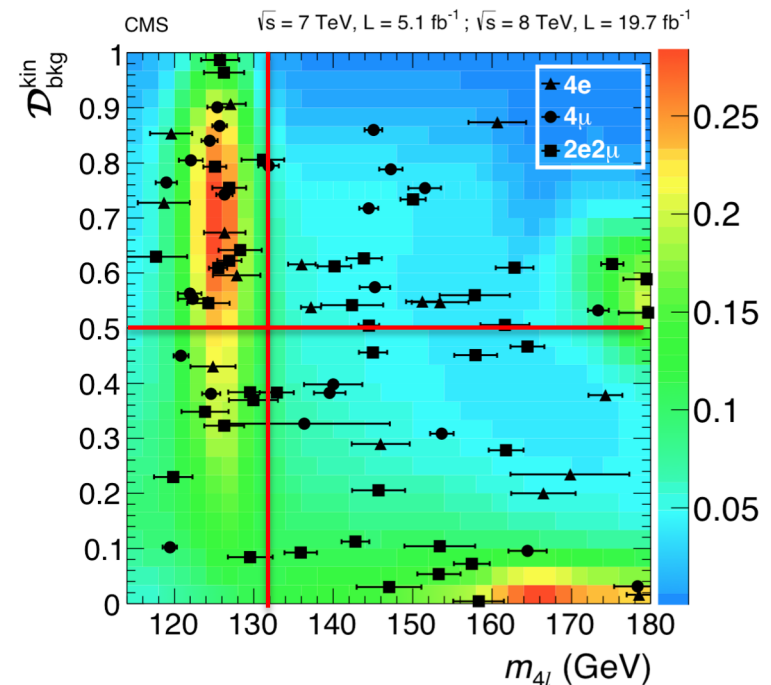
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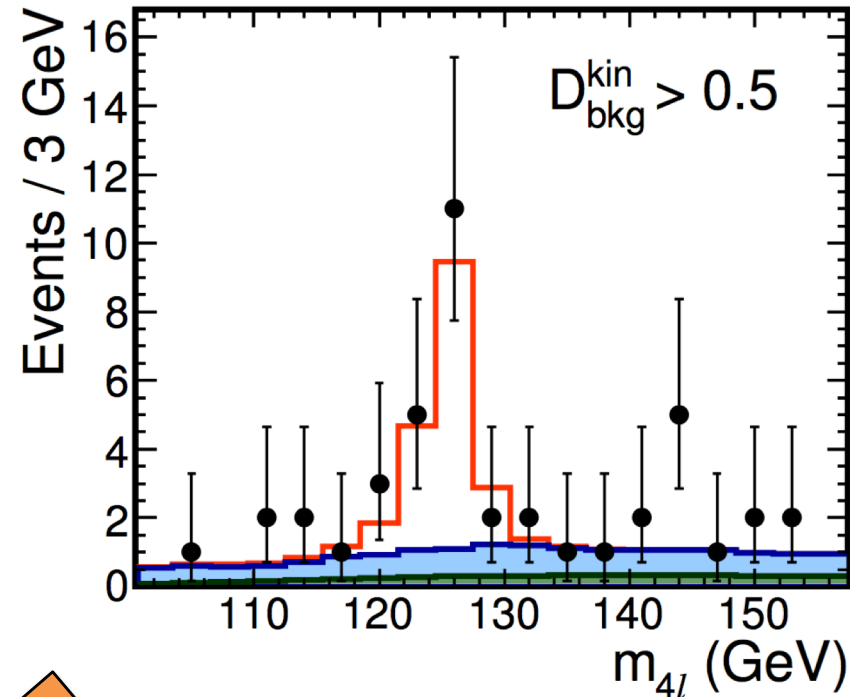
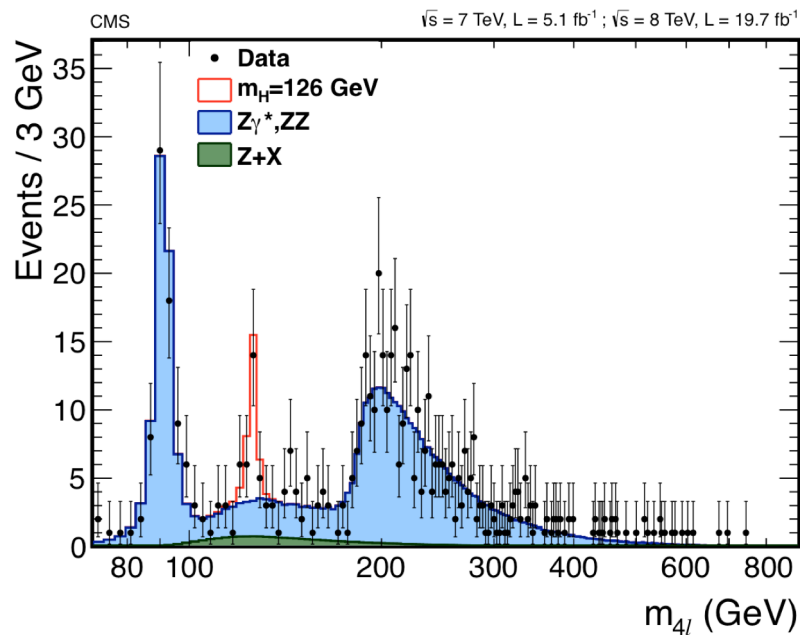


background expected distribution



Higgs signal + background expected distribution

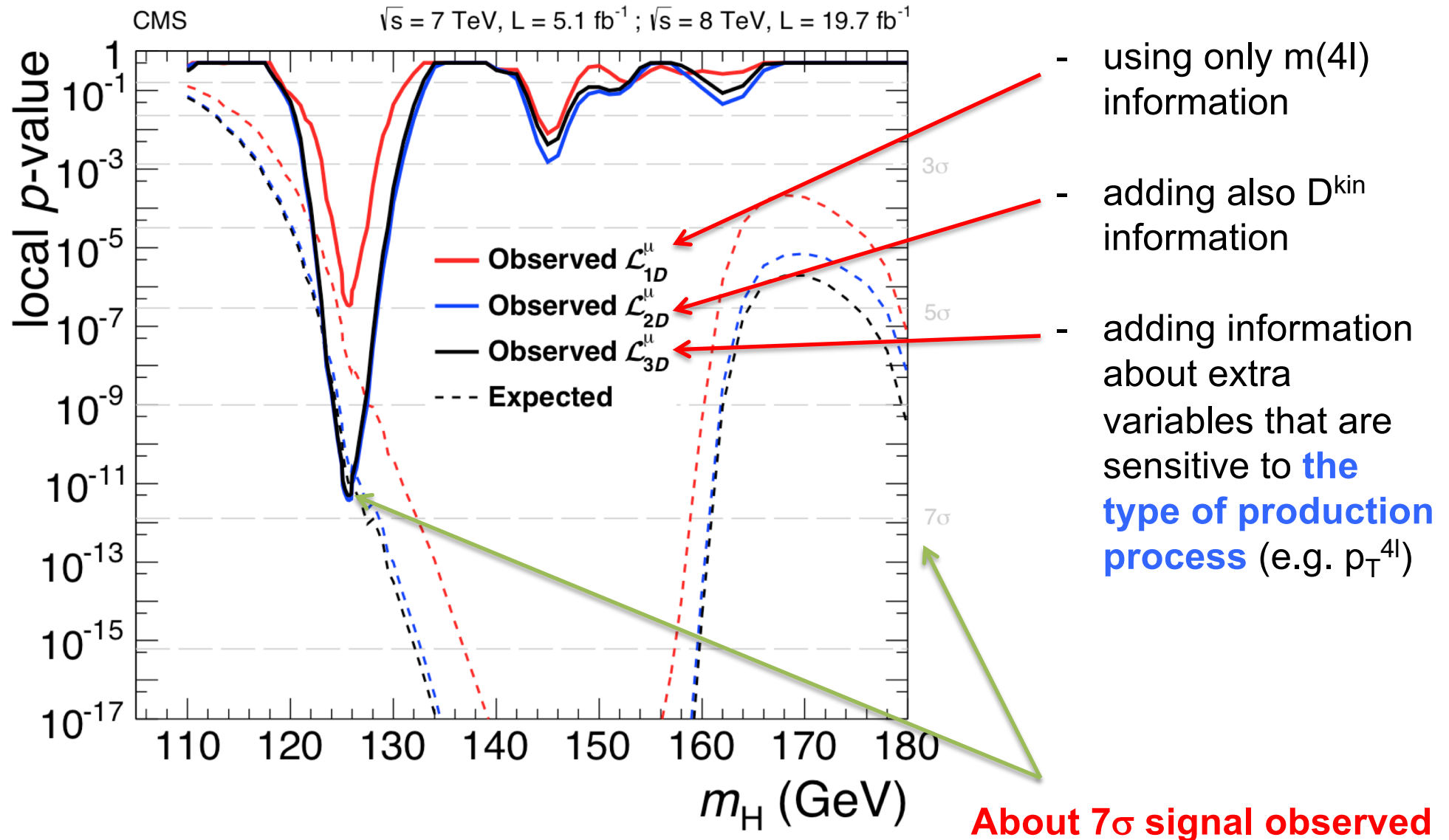
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: kinematical discriminator



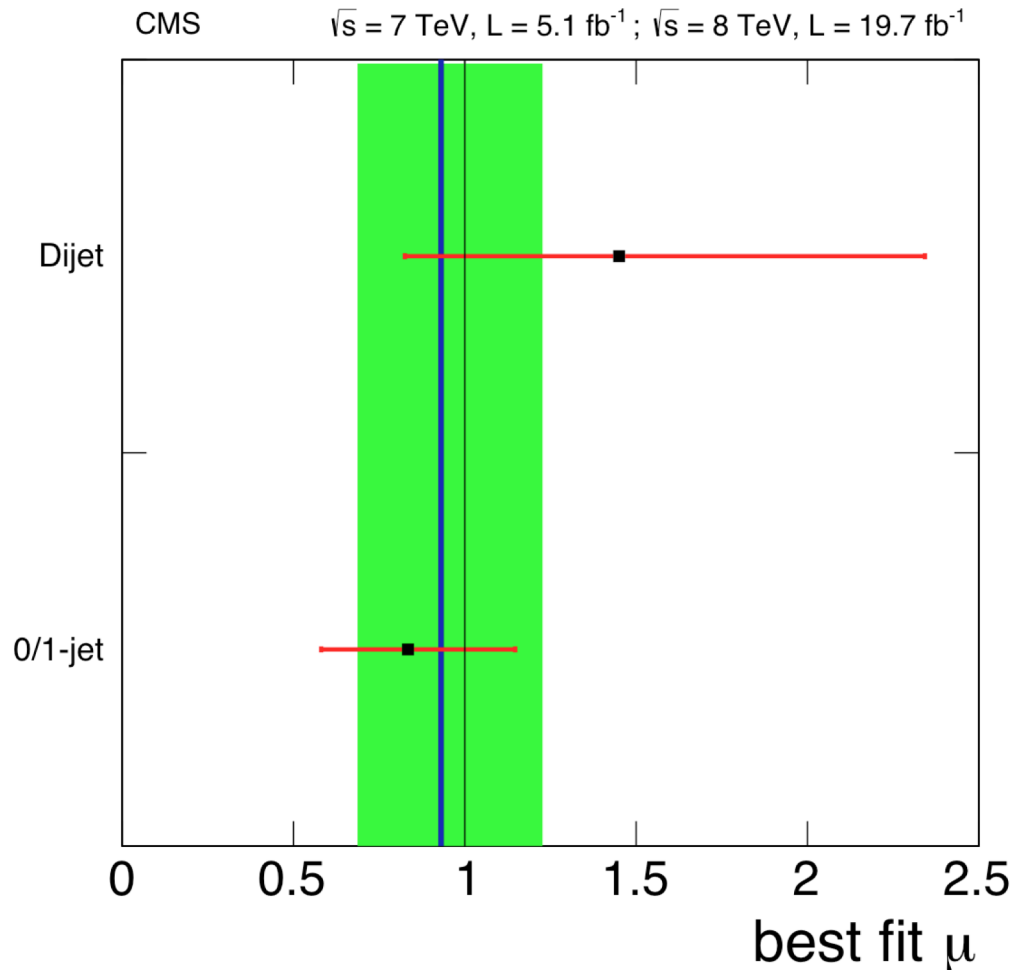
Only for illustration purposes: $m(4l)$ distribution after requiring kinematical discriminator value > 0.5

NB: in the actual statistical analysis of data, shapes of $m(4l)$ and D^{kin} are simultaneously fit to the data, without explicitly cutting on either of the two variables

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: results



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: results

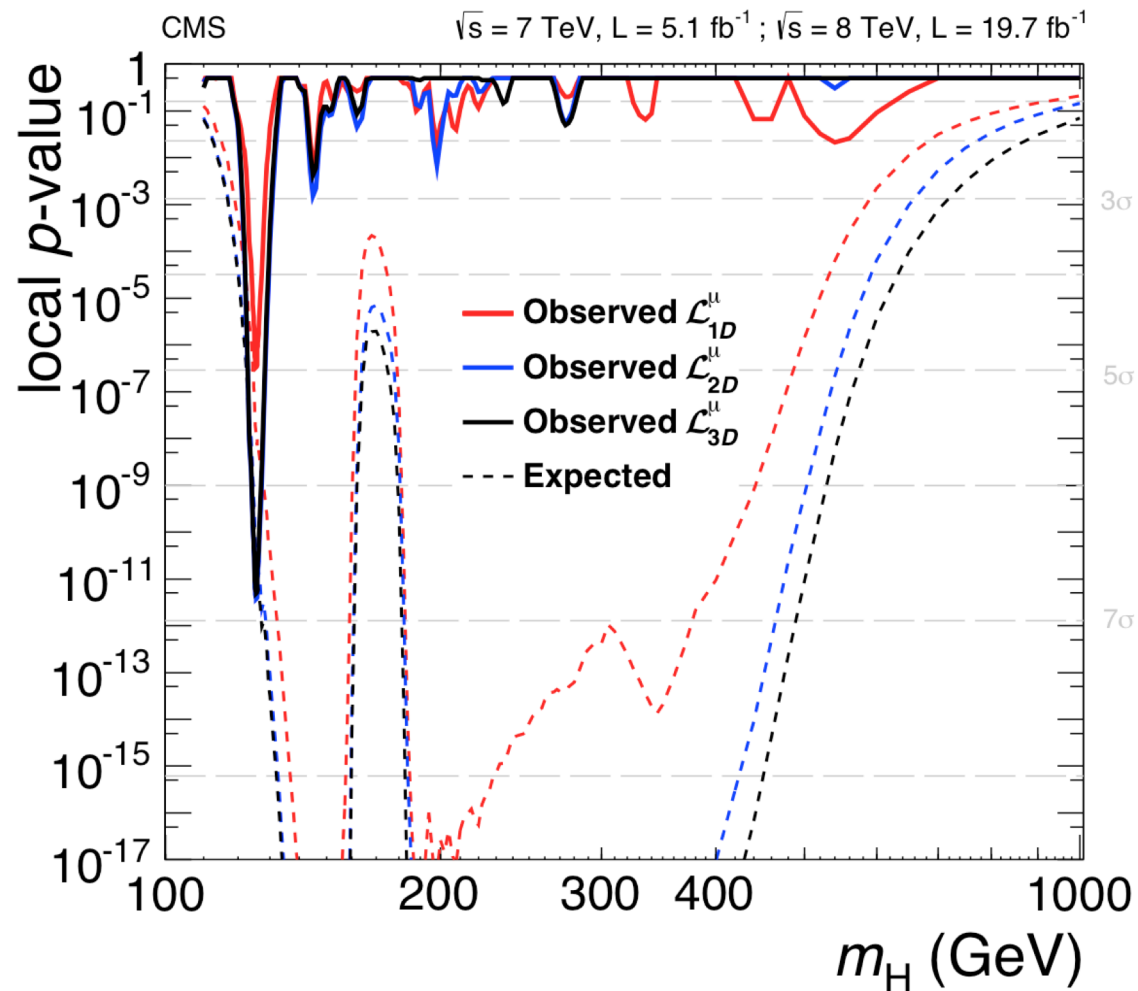


- Di-jet events sensitive to VBF Higgs boson production

- Most of the events produced by gluon-fusion (0/1 jet category)

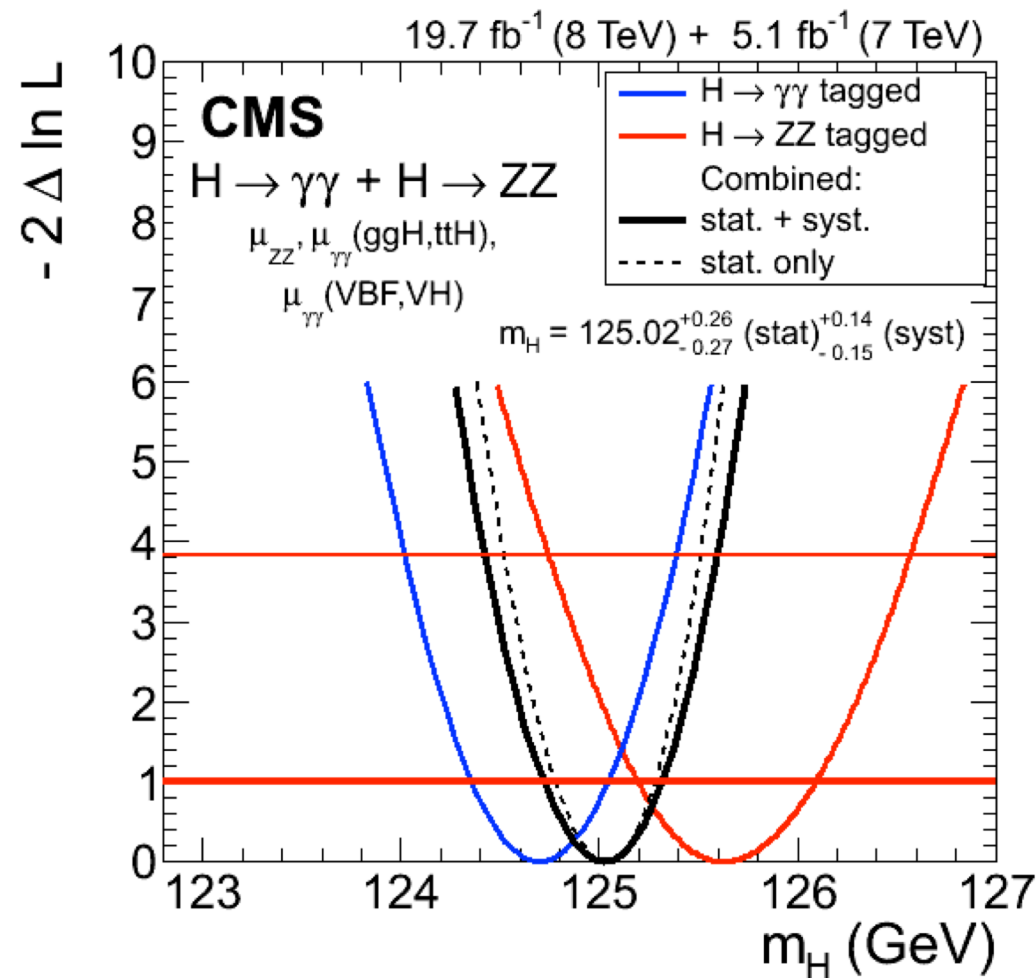
→ smaller statistical uncertainty on μ for second category of events

Other signals in 4l final state?



No other excess larger than 3σ observed up to $\sim 700 \text{ GeV}$

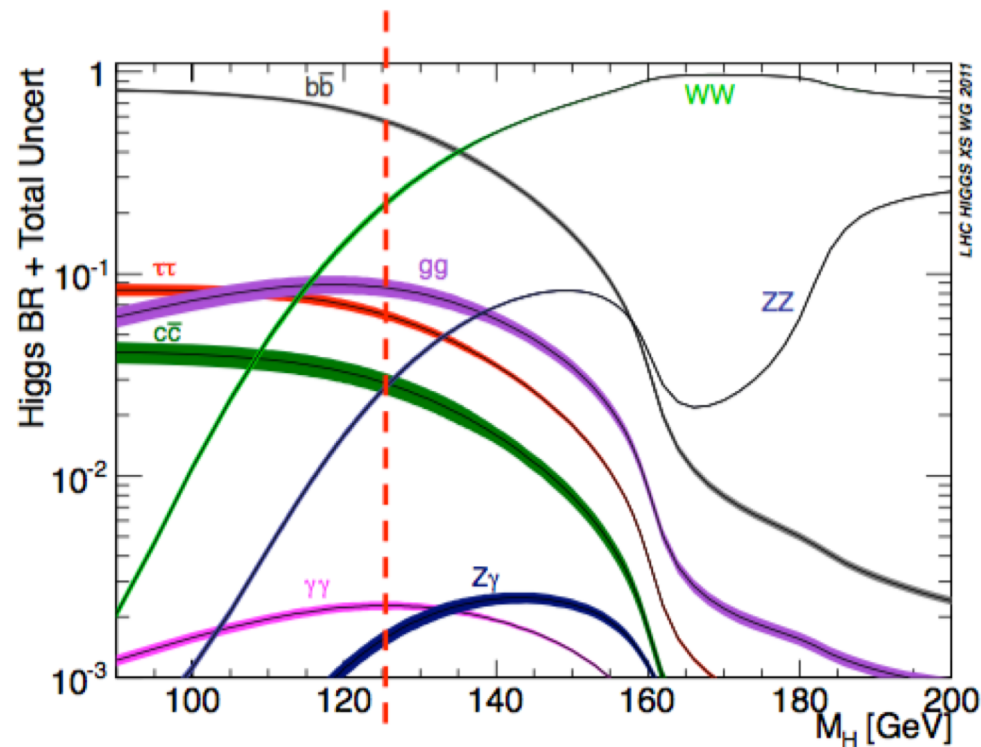
Higgs mass: combination of $\gamma\gamma$ and 4l channels



measured $m_H = 125.02^{+0.26}_{-0.27} \text{ (stat)}^{+0.14}_{-0.15} \text{ (syst)} \text{ GeV}$

[arxiv:1412.86662](https://arxiv.org/abs/1412.86662)

Other channels



	Exp Sig @125.7	σ_M/M
• bb	2.2σ	10%
• $\tau\tau$	2.6σ	10%
• WW	5.3σ	20%
• ZZ	7.1σ	1-2%
• $\gamma\gamma$	3.9σ	1-2%

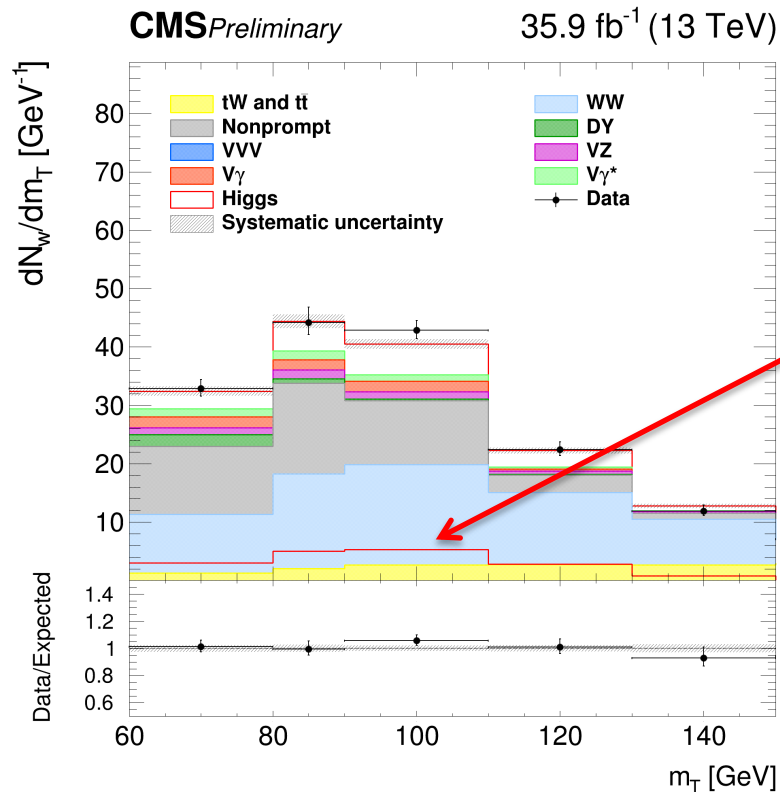
H $\rightarrow$ WW

Large cross section but poor mass resolution due to 2 neutrinos

- ◆ Same Flavour / Different flavour categories + #Jet categories

HIG-16-042

Eg: different lepton-flavour, 0-jet events



Events for 125 GeV Higgs boson signal are expected to be spread over wide range of m_T values.

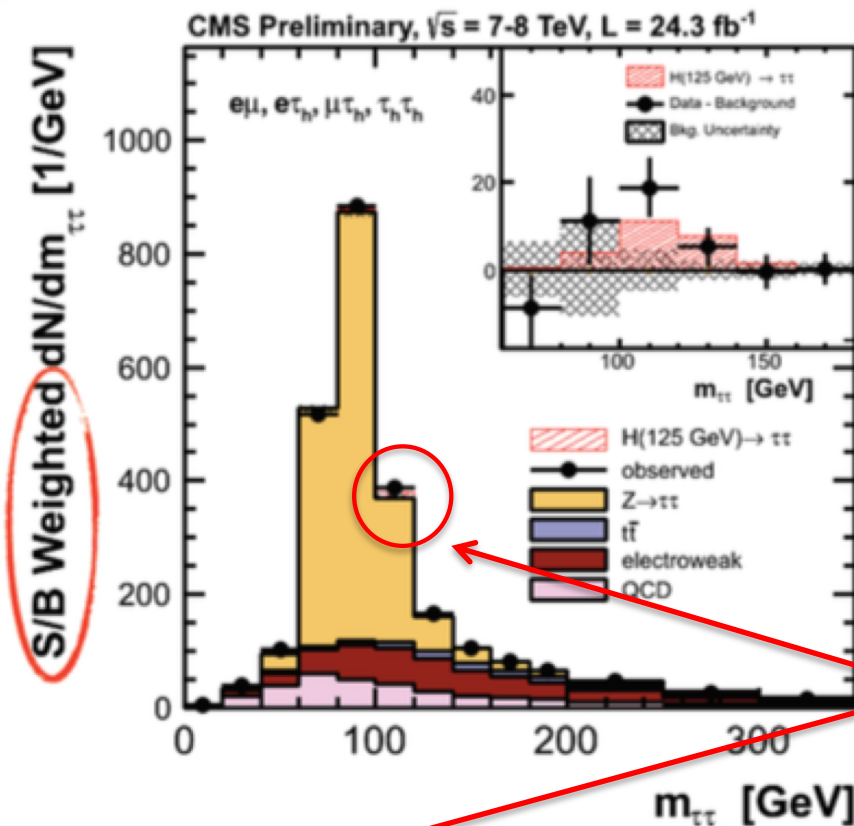
Then, worse “mass resolution”

9.1 σ @ $m_H = 125$ GeV

$\mu = 1.28 \pm 0.18$

$H \rightarrow \tau\tau$

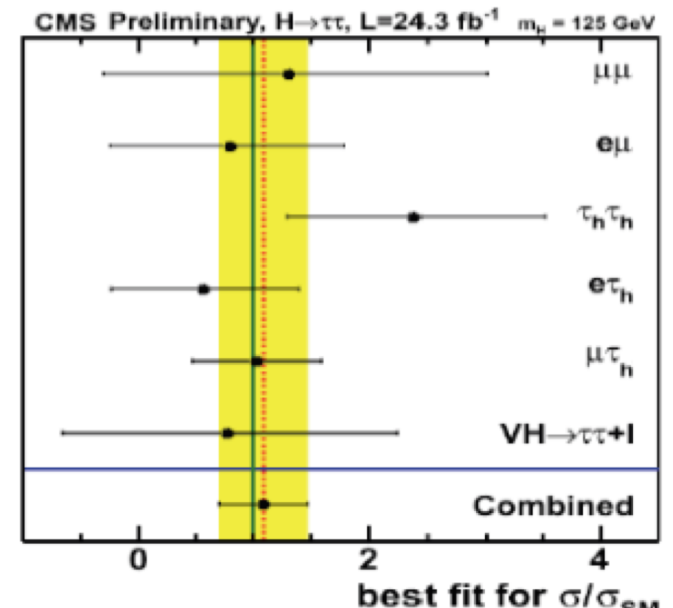
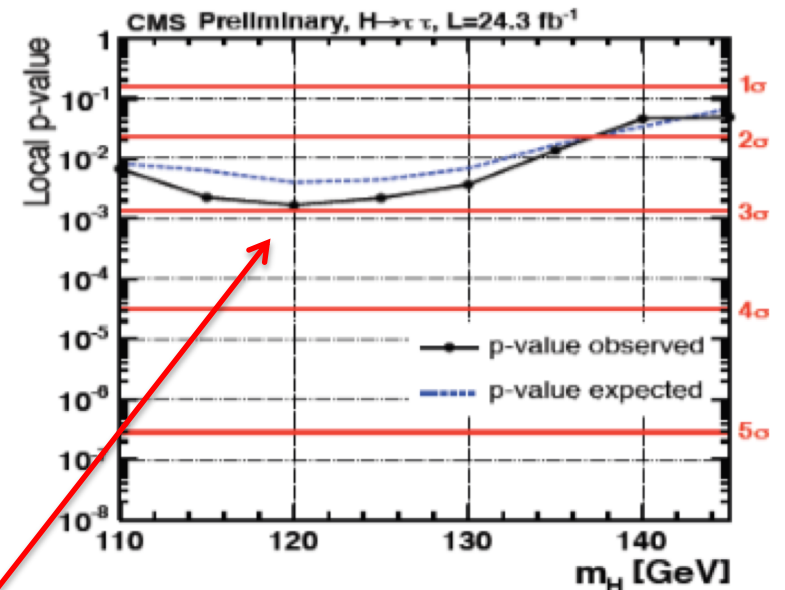
gg, VBF, VH production



2.93 σ @ $m_H = 120$ GeV
2.85 σ @ $m_H = 125$ GeV

tiny signal!

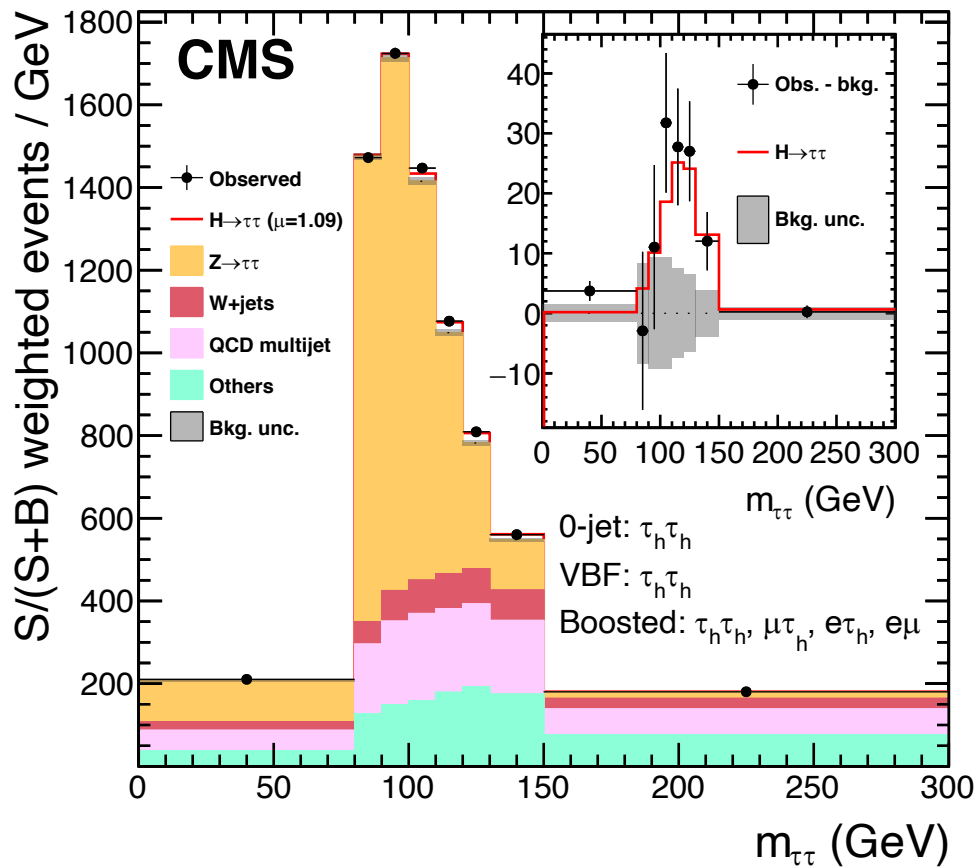
$\mu = 1.1 \pm 0.4$



H $\rightarrow$ $\tau\tau$ @ 13 TeV: observation

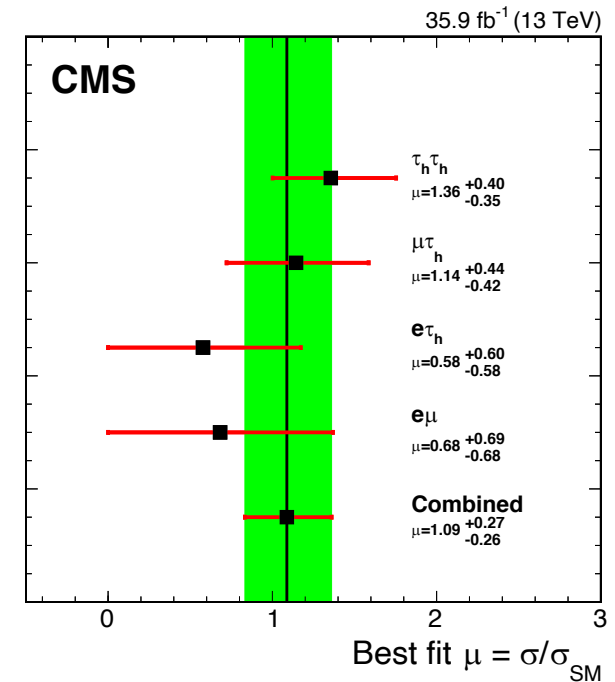
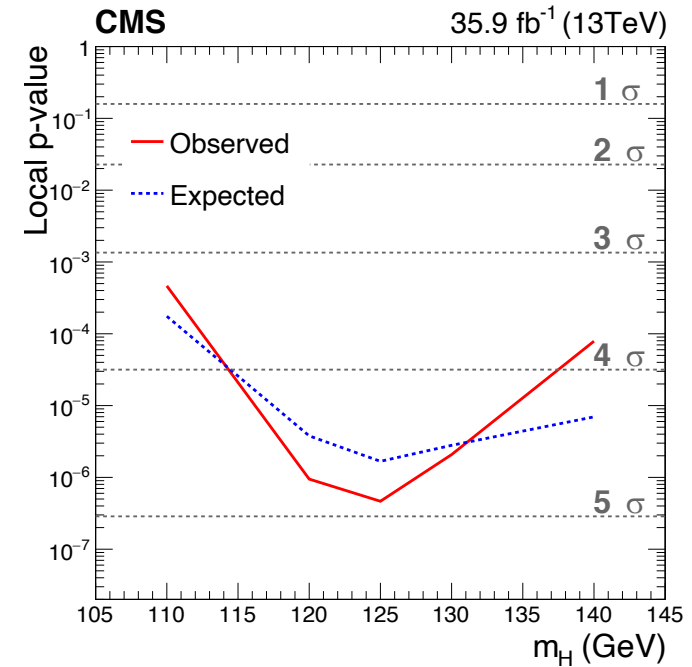
Phys. Lett. B 779 (2018) 283

35.9 fb⁻¹ (13 TeV)



4.9 σ @ $m_H = 125$ GeV

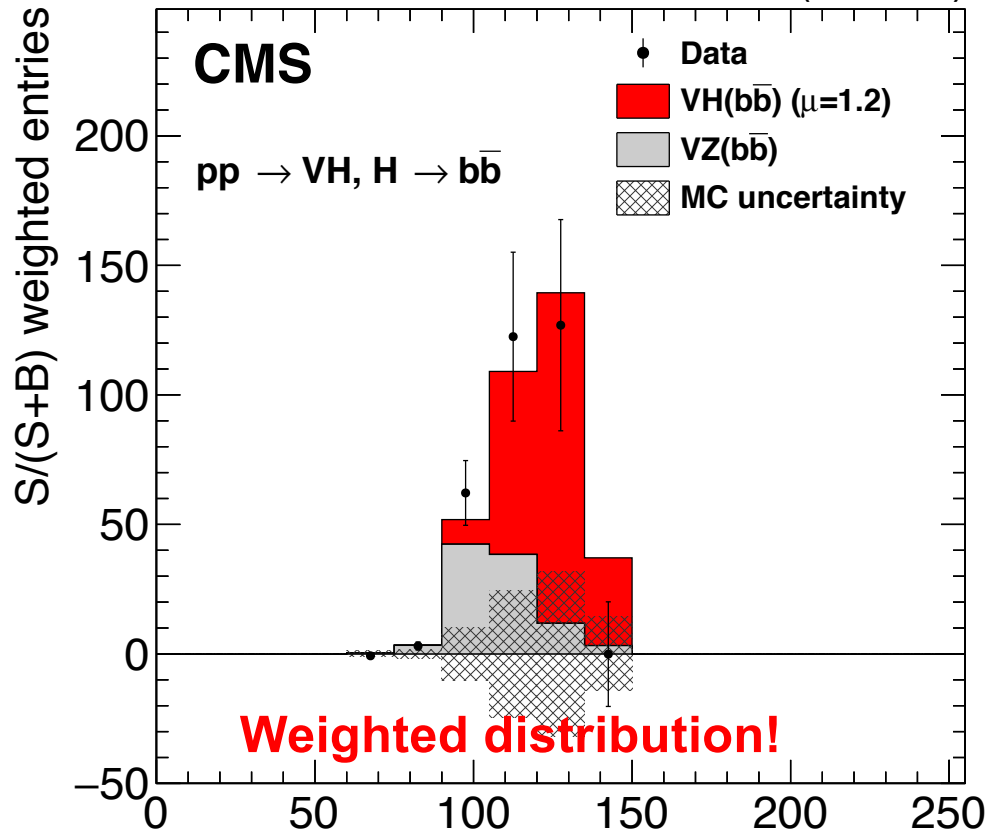
$\mu = 1.09 \pm 0.27$



H → bb

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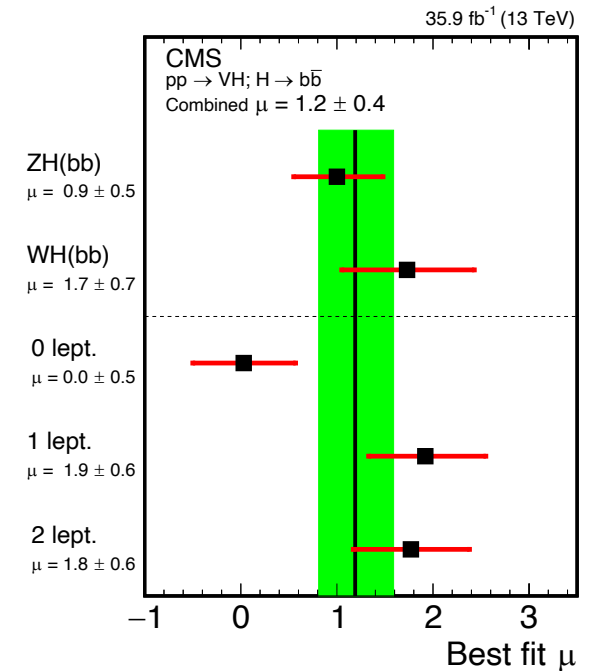
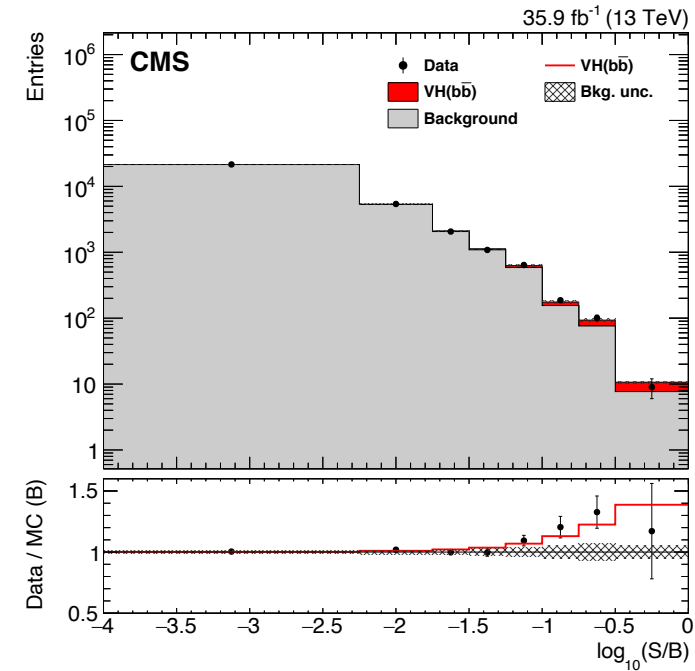
35.9 fb⁻¹ (13 TeV)



3.8 σ @ mH = 125 GeV M_{jj} [GeV]

$\mu = 1.06 \pm 0.29$ (combined with Run 1)

Despite the large H → bb BR, signal has not been “observed” in this channel yet.
More integrated luminosity is required

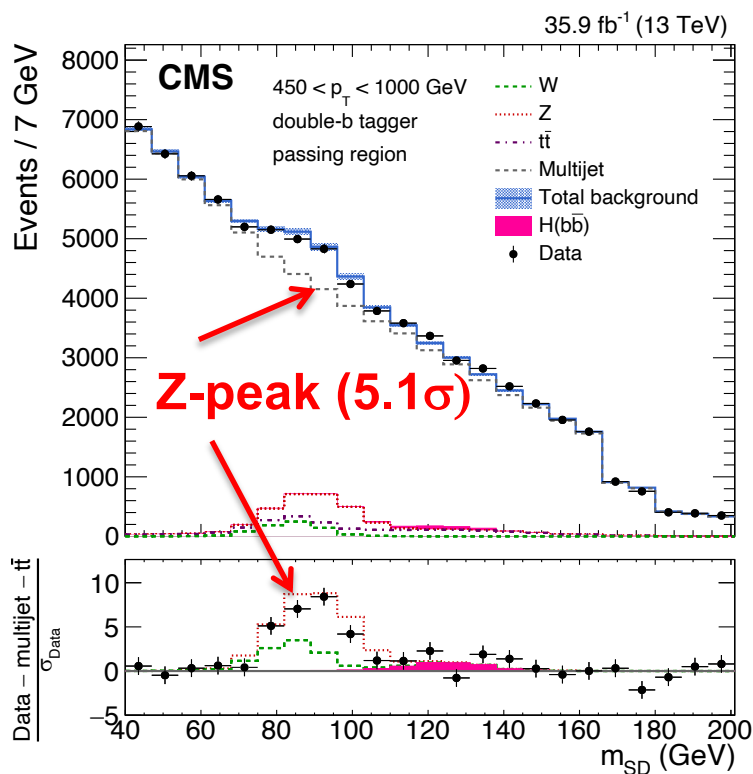
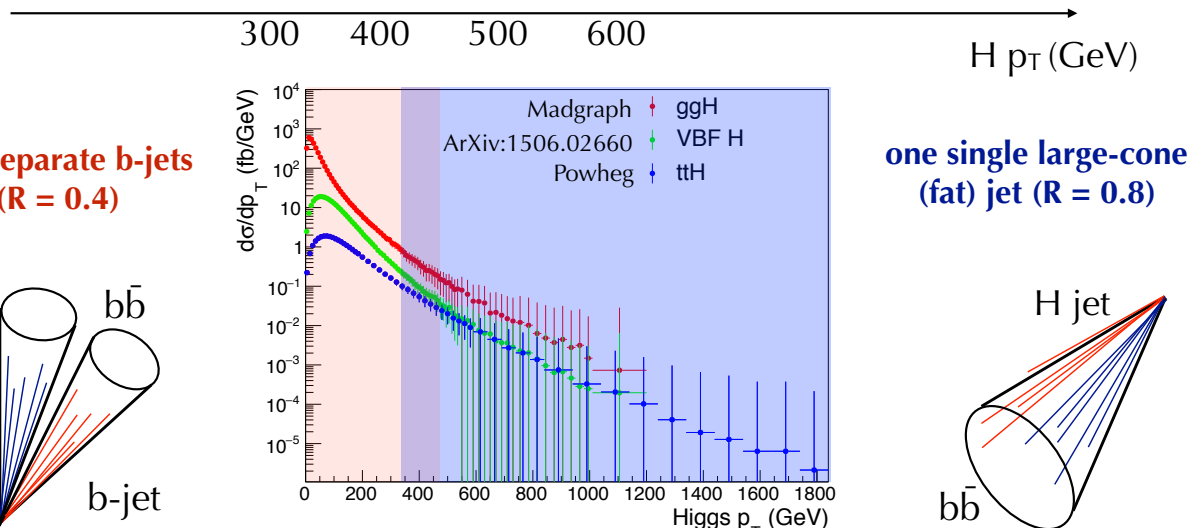


H → bb: using smarter ideas

Phys. Rev. Lett. 120, 071802 (2018)

$$dR(bb) \sim 2m_H/p_T$$

Take events with boosted H(bb)
Use substructure variables to
suppress SM gg→bb

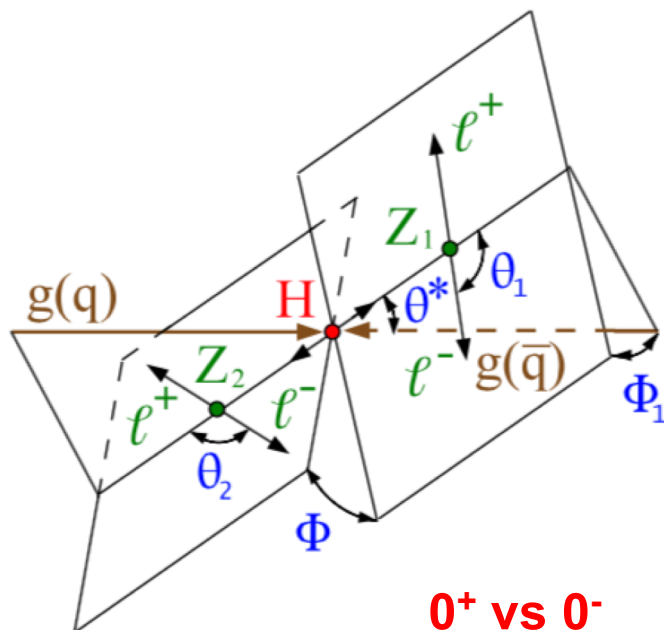


H(bb) is not observed yet:

1.5σ @ m_H = 125 GeV for p_T > 450 GeV

But for the first time Z(bb) is seen in a single jet topology!

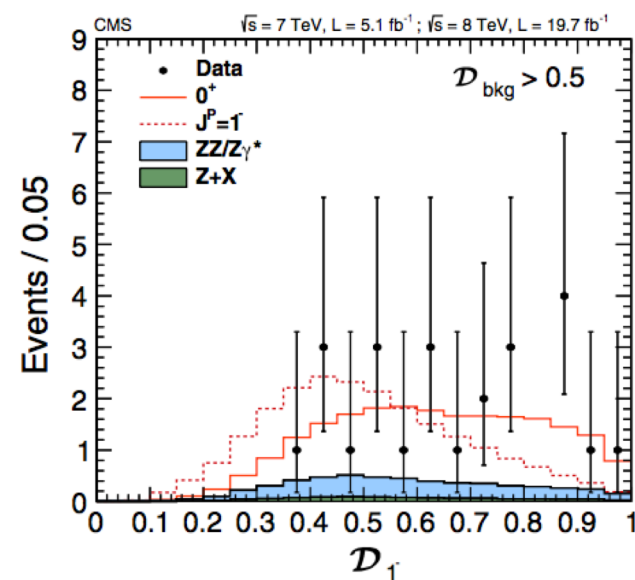
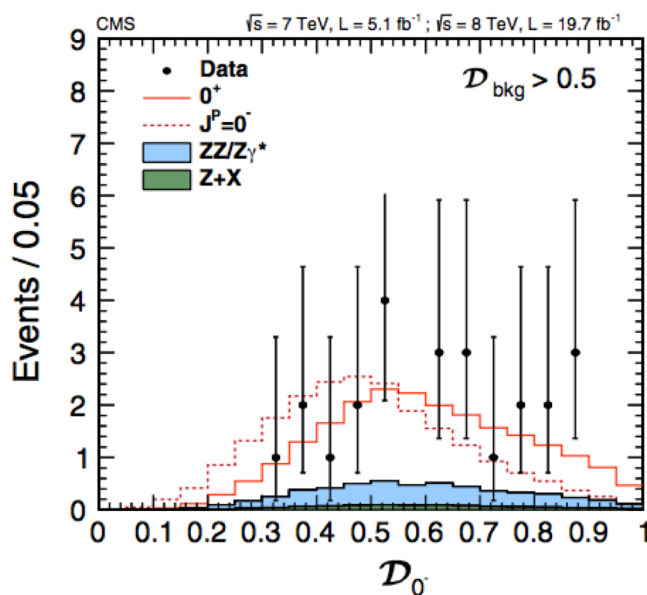
Spin and parity



$0^+ \text{ vs } 0^-$

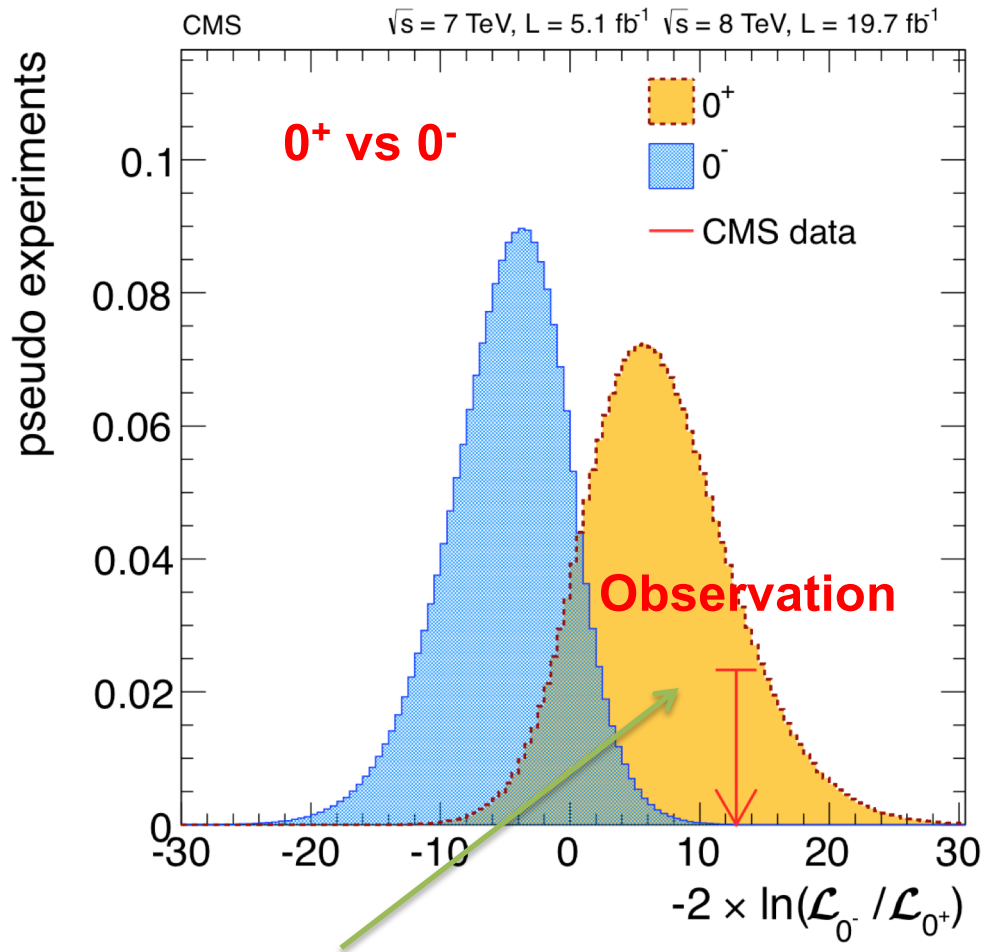
$H \rightarrow ZZ \rightarrow 4l$ events can be used also to construct kinematical variables that discriminate different spin-parity hypotheses for the new H particle

$0^+ \text{ vs } 1^-$



Spin and parity

$H \rightarrow ZZ \rightarrow 4l$ events



0.05% probability to observe what
seen in data given 0⁻ hypo

10.1103/PhysRevD.89.092007

Nota bene:

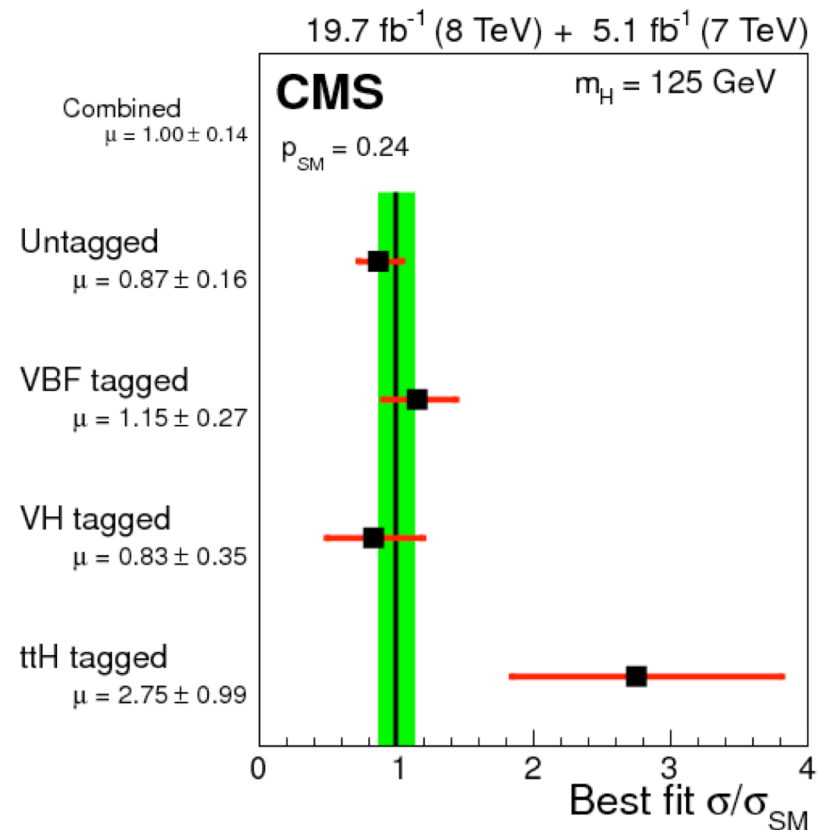
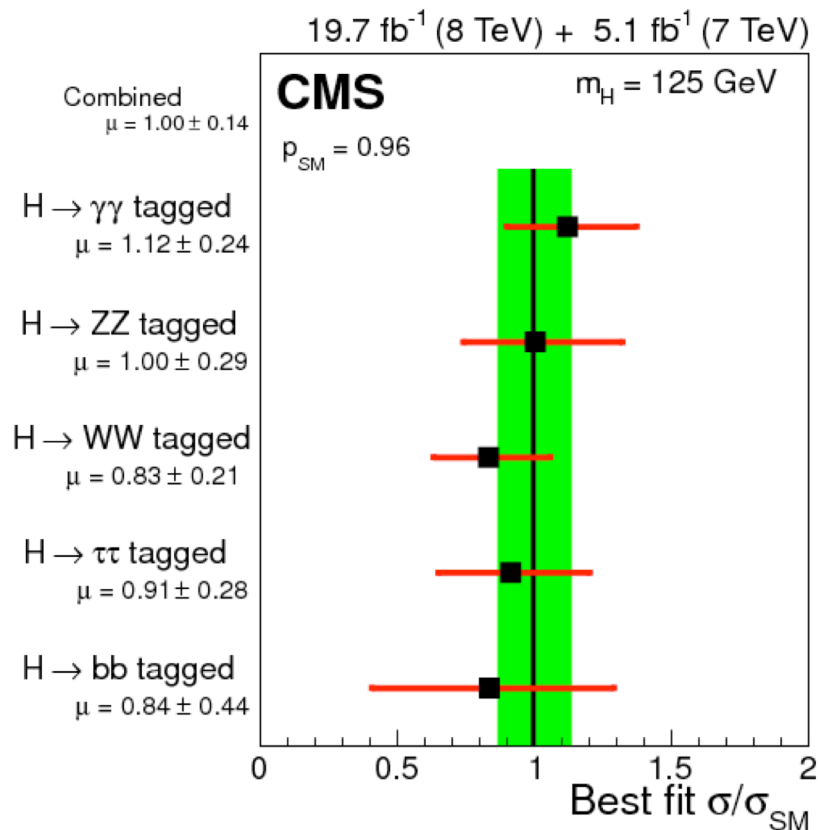
log-likelihood ratio maps the outcome of all events collected in an experiment (see previous slide) into a single number.

The two distributions are obtained repeating MANY pseudo-experiments, in simulation, under the 0⁺ and 0⁻ hypotheses, respectively.

Following similar procedure:

- other spin=1 hypotheses excluded at >99.9% CL
- spin=2 hypotheses excluded at 95% CL

SM Higgs boson ?

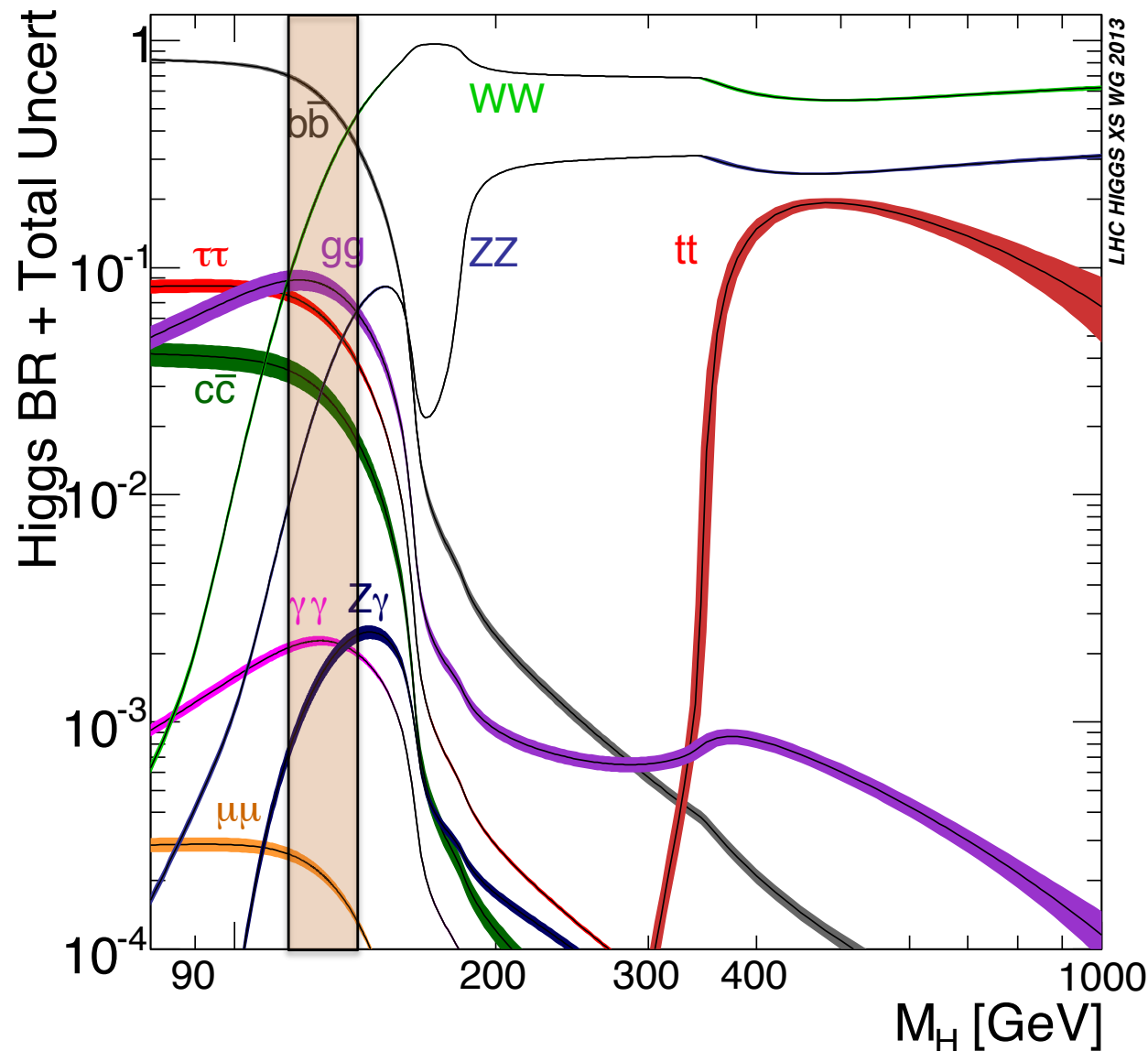


From combination of all channels:

$$\mu = 1.00 \pm 0.09 \text{ (stat)} {}^{+0.08}_{-0.07} \text{ (theo)} \pm 0.07 \text{ (syst)}$$

Signal strength consistent with SM prediction, as well as with many BSM predictions (e.g. MSSM) !!

Again on SM Higgs decay modes

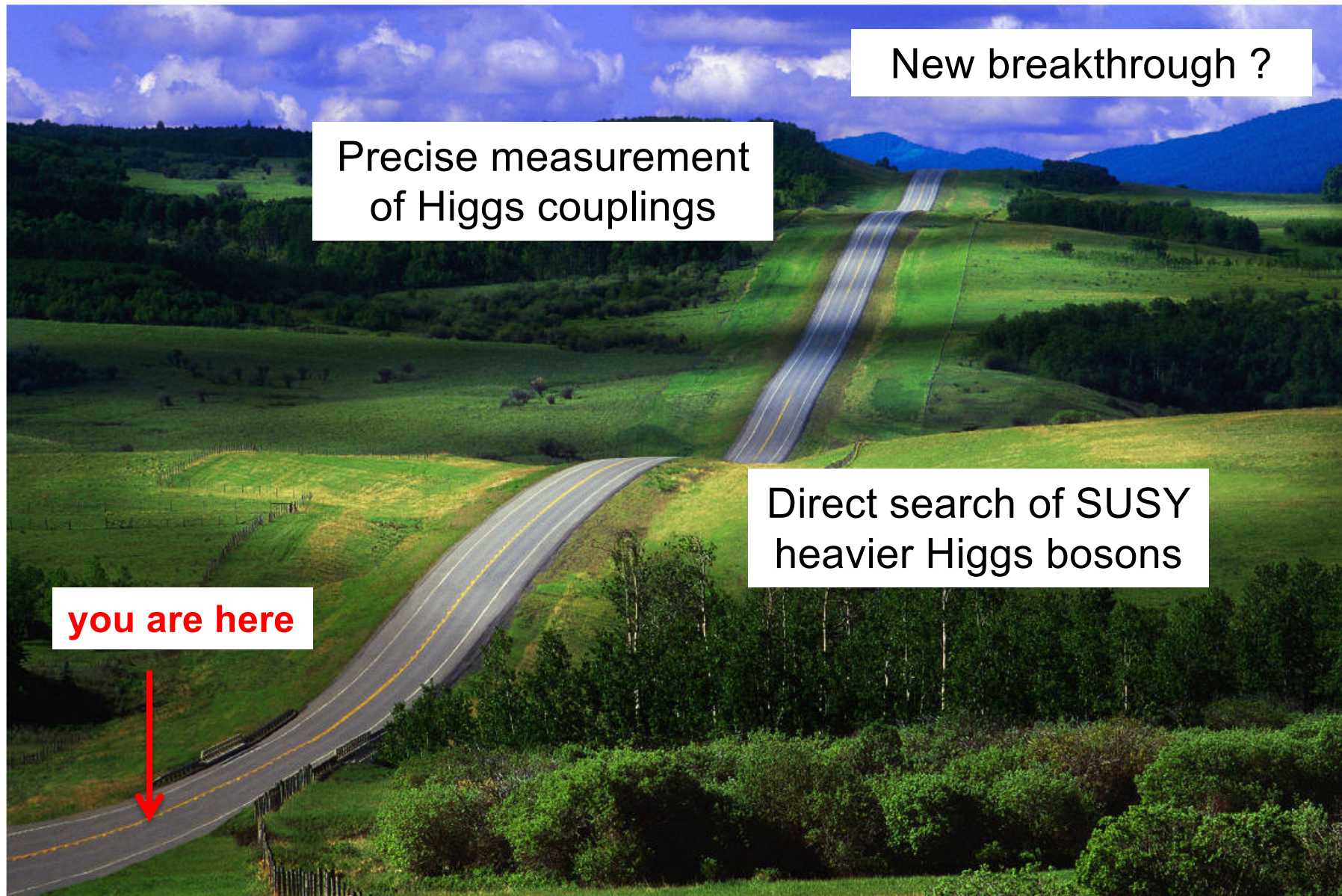


125 GeV is a luck number for the Higgs mass:

Many different decay chains could be probed...

... many different Higgs couplings could be studied

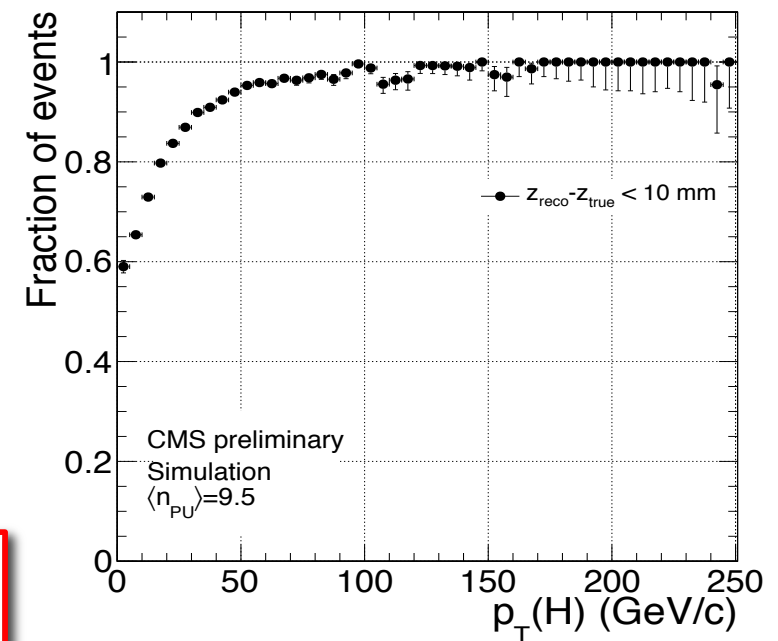
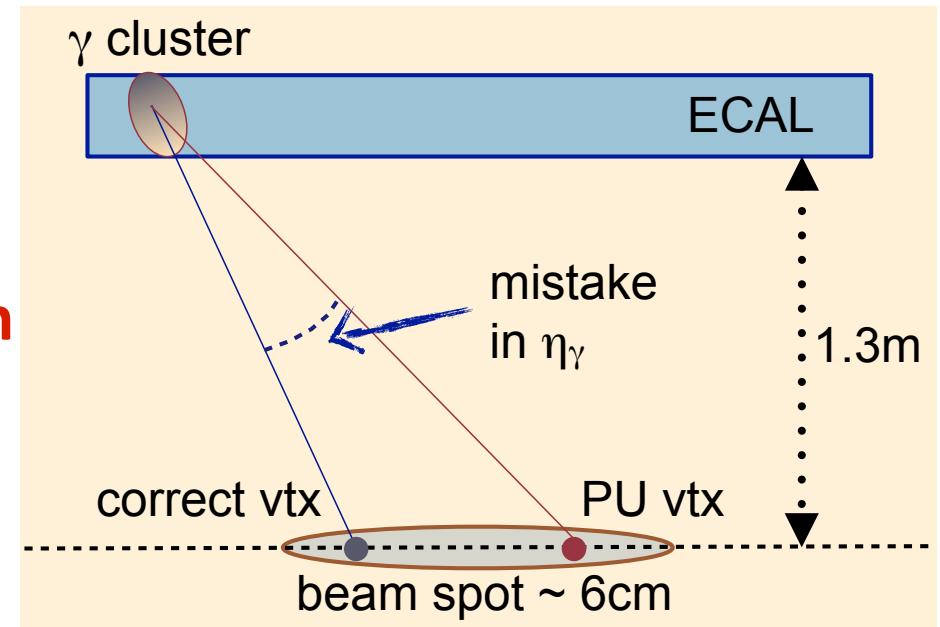
Summary



Backup slides

$H \rightarrow \gamma\gamma$ Event Vertex Determination

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



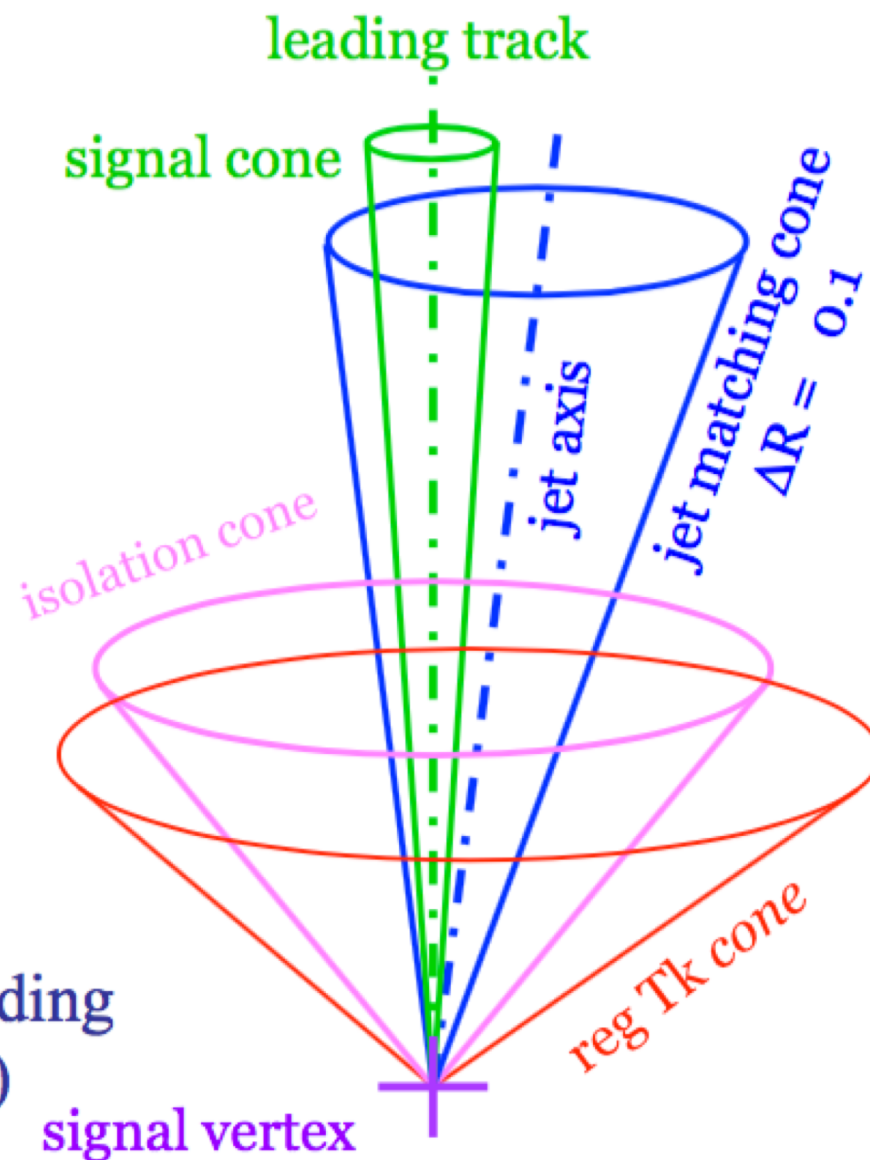
2011A	2011B	2011
$86.3\% \pm 0.2\% \pm 0.4\%$	$79.8\% \pm 0.2\% \pm 0.5\%$	$83.0\% \pm 0.2\% \pm 0.4\%$

tau-jet selection

- remember τ branching ratios:
 - $\tau \rightarrow l \nu_l \nu_\tau : 35\%$
 - $\tau \rightarrow \pi^\pm + n \pi^0 \text{'s} : 50\%$
 - $\tau \rightarrow 3\pi^\pm + n \pi^0 \text{'s} : 15\%$
- prefer hadronic decays (for mass rec.) but QCD background is huge

Dedicated τ trigger for this

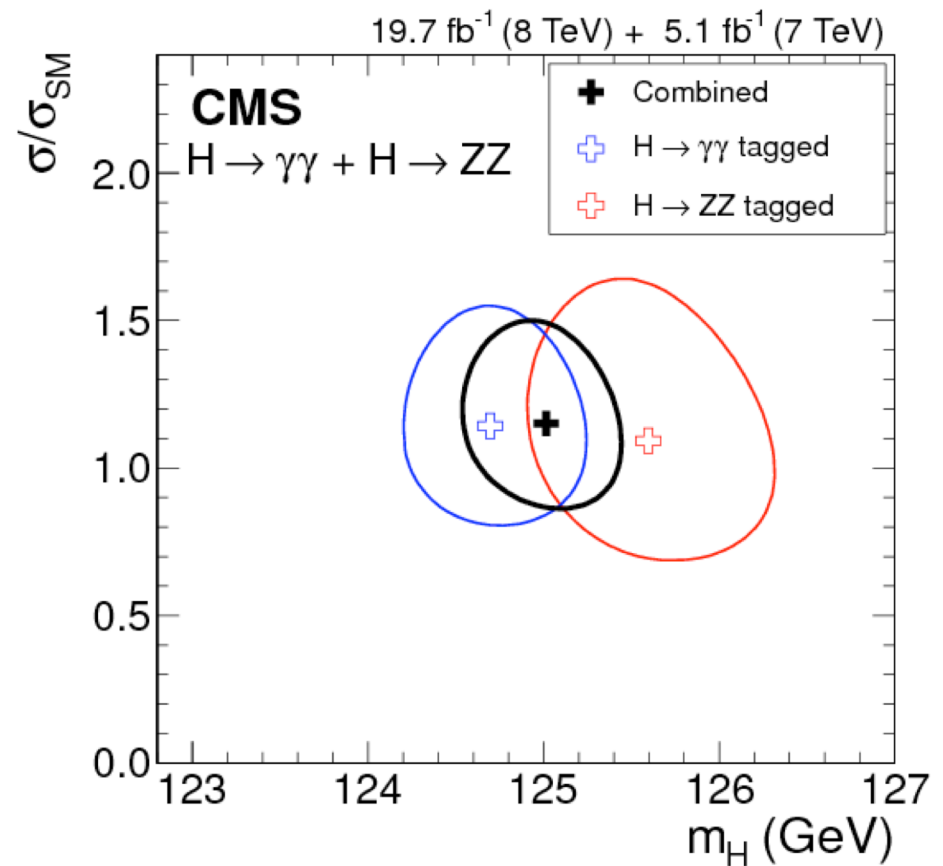
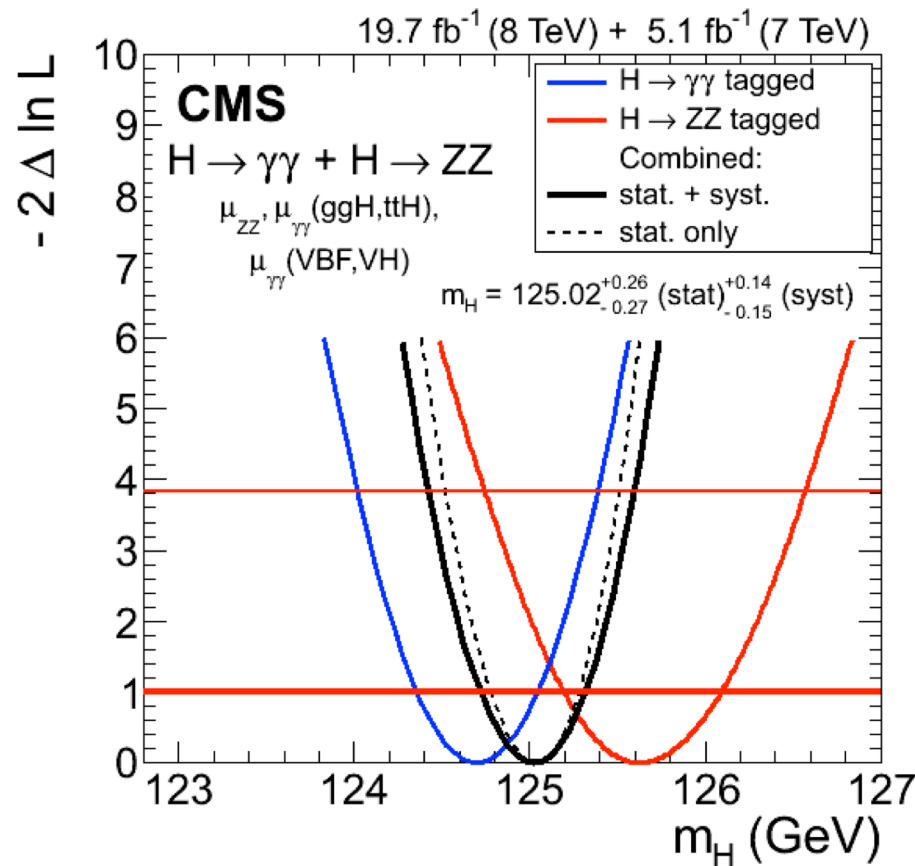
→ look for narrow jet (L1) with leading charged track ($\pi^\pm$) (L3)



Higgs $\rightarrow \gamma\gamma$: event topology categories

Label	No. of classes		Main requirements
	7 TeV	8 TeV	
$t\bar{t}H$ lepton tag	*	1	$p_T^{\gamma^1} > m_{\gamma\gamma}/2$ 1 b-tagged jet + 1 electron or muon
VH tight ℓ tag	1	1	$p_T^{\gamma^1} > 3m_{\gamma\gamma}/8$ [e or μ , $p_T > 20$ GeV, and $E_T^{\text{miss}} > 45$ GeV] or [2e or 2μ , $p_T^\ell > 10$ GeV; $70 < m_{\ell\ell} < 110$ GeV]
VH loose ℓ tag	1	1	$p_T^{\gamma^1} > 3m_{\gamma\gamma}/8$ e or μ , $p_T > 20$ GeV
VBF dijet tag 0–2	2	3	$p_T^{\gamma^1} > m_{\gamma\gamma}/2$ 2 jets; classified using combined diphoton-dijet BDT
VH E_T^{miss} tag	1	1	$p_T^{\gamma^1} > 3m_{\gamma\gamma}/8$ $E_T^{\text{miss}} > 70$ GeV
$t\bar{t}H$ multijet tag	*	1	$p_T^{\gamma^1} > m_{\gamma\gamma}/2$ 1 b-tagged jet + 4 more jets
VH dijet tag	1	1	$p_T^{\gamma^1} > m_{\gamma\gamma}/2$ jet pair, $p_T^j > 40$ GeV and $60 < m_{jj} < 120$ GeV
Untagged 0–4	4	5	The remaining events, classified using diphoton BDT

Higgs mass: combination of $\gamma\gamma$ and 4l channels



measured m_H $125.02^{+0.26}_{-0.27} \text{ (stat)}^{+0.14}_{-0.15} \text{ (syst)} \text{ GeV}$
 =

arxiv:1412.86662