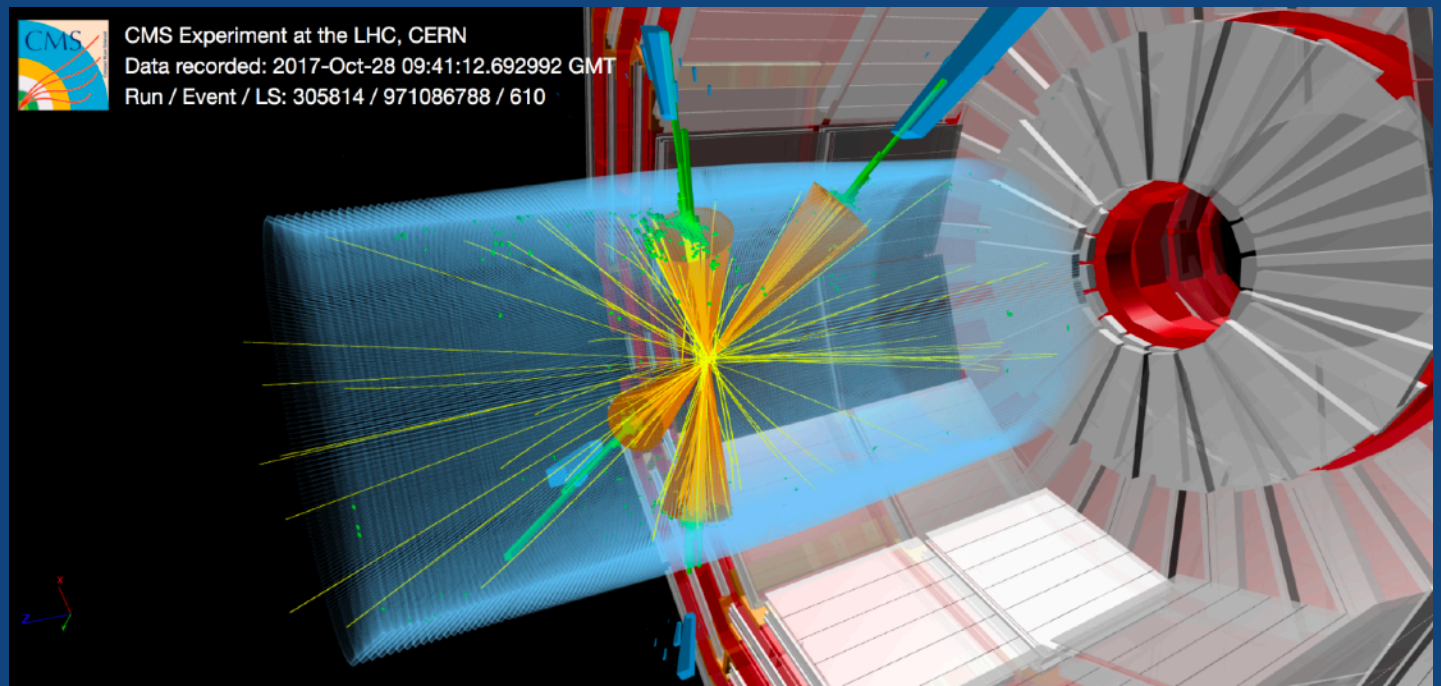
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Phenomenology of Physics Beyond the Standard Model

Exp Lecture 3: MSSM Higgs bosons search

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From last exp. lecture

- SUSY signature depend on the model assumed
  - RPC SUSY (MET + high pT jets/leptons), RPV SUSY (SUSY particle invariant mass reconstruction), Exotic SUSY (unconventional signatures)
- Interplay of different search channels to investigate the full model phase space
  - Event categorisation based on the signature helps in addressing specific models

In this lecture

- Recap on theory of SM and MSSM Higgs sector
- Detour on experimental detection of SM(-like) Higgs boson h0
  - Discovery channels: $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$
  - Higgs reconstruction techniques
  - Exclusion or discovery?
- Searches of the MSSM Higgs bosons at the LHC

Where are the masses ?

Problem with the SM: it only works for *massless gauge bosons*!
Introduction of mass terms ruins the gauge invariance!

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

Higgs in MSSM

In MSSM: 2 Higgs doublets needed (2HDM, 2 Higgs Doublet Model)

- to ensure anomaly-free theory
- to give mass to both up and down type fermions

2 Higgs fields →8 degrees of freedom

- 3 are used to make $W^{\pm}$ and Z^0 massive
- MSSM contains 5 physical Higgs states

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

$$tan\beta = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$$

- 2 charged scalar $H^{\pm}$
  Mixture of H_d^- and H_u^+, fixed by tanβ
- 1 neutral pseudo-scalar A^0
  Mixture of $Im(H_d^0)$ and $Im(H_u^0)$, fixed by tanβ
- 2 neutral scalars h^0 and H^0
  Mixture of $Re(H_d^0)$ and $Re(H_u^0)$, with mixing angle α

MSSM Higgs bosons:
h^0, H^0, A^0, $H^{\pm}$

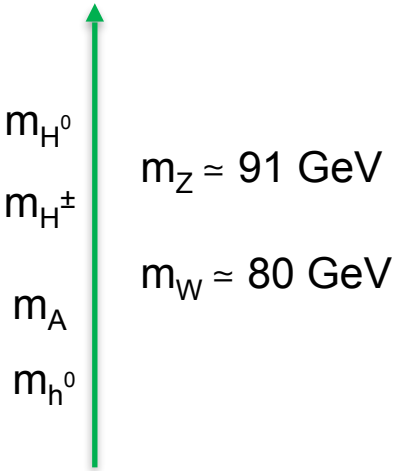
Higgs masses at tree level

- From scalar potential, tree-level masses are:

$$m^2_{H^\pm} = M^2_W + m^2_A$$

$$m^2_{H,h} = \frac{1}{2}(m^2_A + M^2_Z) \pm \frac{1}{2}\sqrt{(m^2_A + M^2_Z)^2 - 4m^2_A M^2_Z \cos^2 2\beta}$$

- Higgs masses depend on only 2 parameters: m_A and tanβ
- Mass hierarchy at tree level:
  - $0 \leq m_h \leq M_Z |\cos 2\beta|$
  - $m_h \leq m_A \leq m_{H^0}$
  - $m_{H^0} \geq M_Z$
  - $m_{H^\pm} \geq M_W$



- Expect light $h^0 \rightarrow$ observable at LEP2
  But radiative corrections are large, especially on m_h

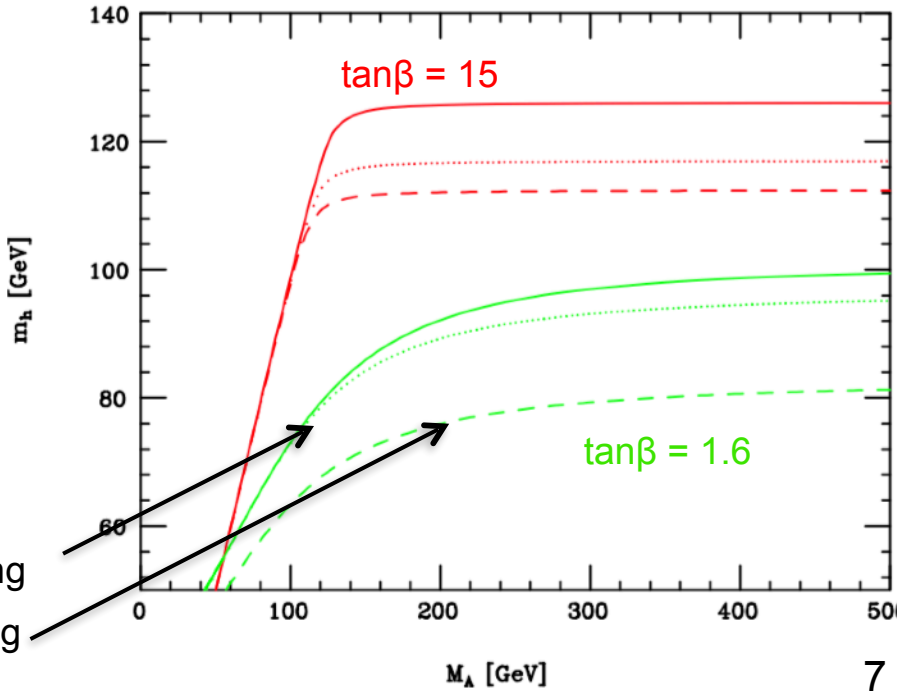
Higgs mass radiative corrections

- Top loop corrections
  - Dependency on top and stop masses (no cancellation)
  - And on stop mixing

- In MSSM, m_{h^0} has an upper bound
  - increases with $\tan\beta$
  - increases from minimal to maximal stop mixing

$$m_h \leq 130 \text{ GeV}$$

(for $M_{SUSY} = 1$ Tev, $m_t = 175$ GeV)



The SM (?) Higgs boson

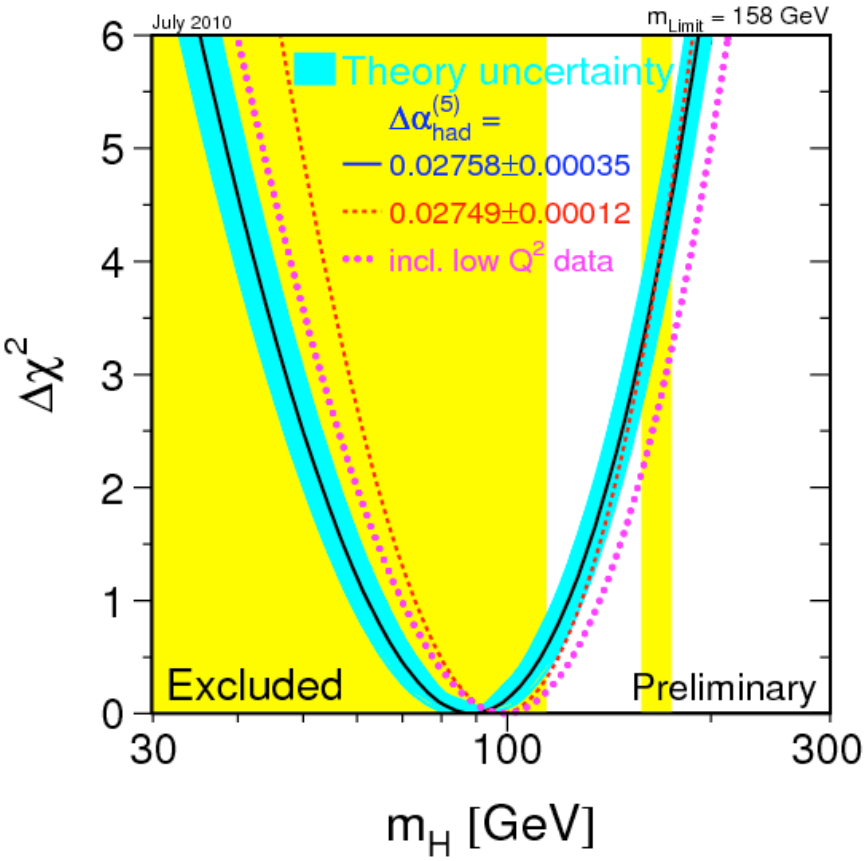


SM-like Higgs boson:

- How was it found ?
- Can it fit into the MSSM Higgs sector ?

Limits on SM Higgs boson mass before LHC

- From LEP and Tevatron (1983-2011) experiments:



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

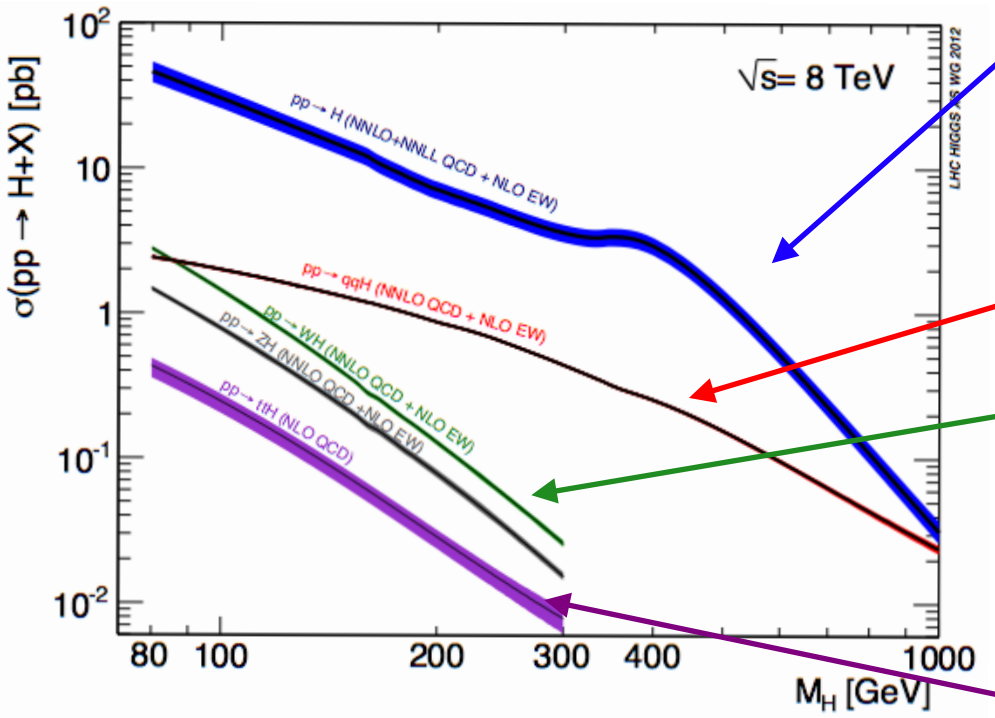
Constraints from direct searches:

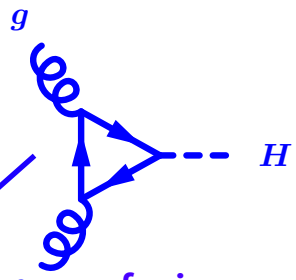
- m_H > 114.4 GeV (LEP)
- m_H < 158 GeV or > 175 GeV (Tevatron)

Preferred value from indirect measurements

- $m_H = 89^{+35}_{-26}$ GeV (global fit of EW precision data)

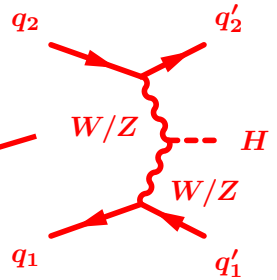
Higgs production at the LHC

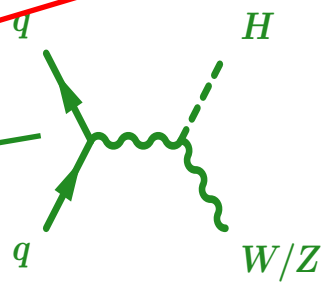




gg fusion

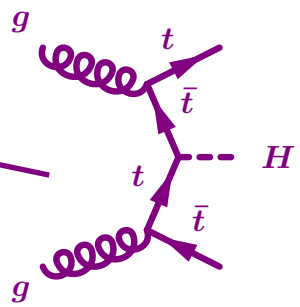
VBF (Vector Boson Fusion)





V associated production

tt associated production

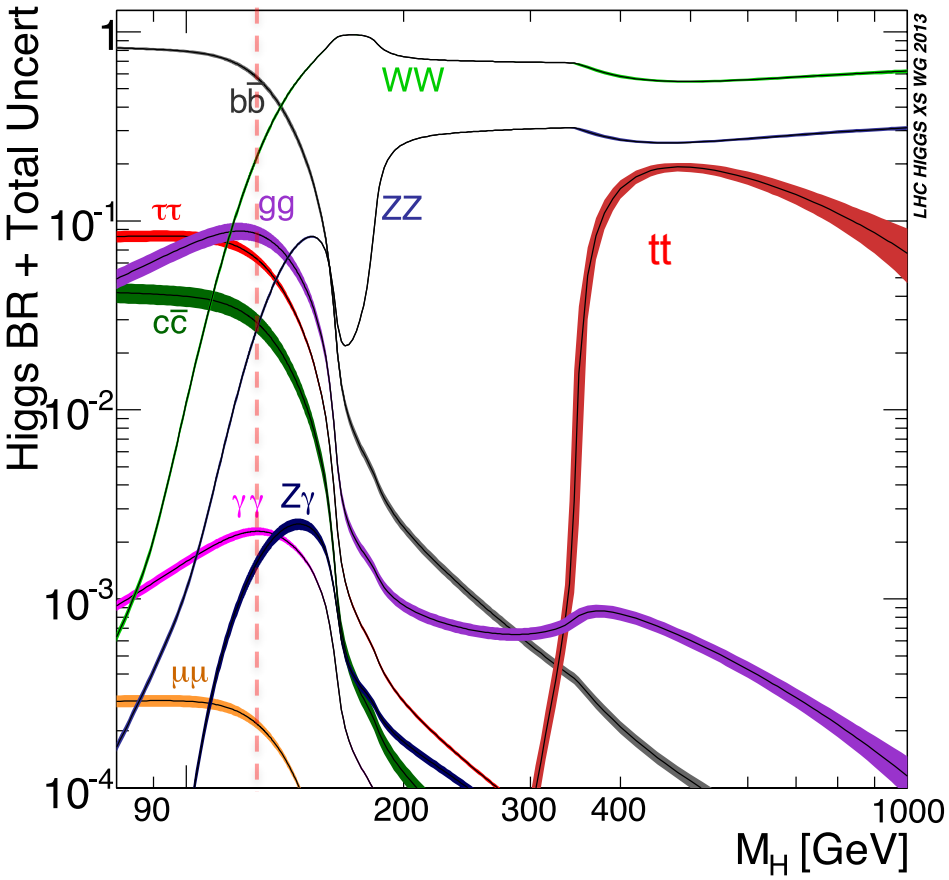


Production mechanisms:

- gg fusion, VV fusion, W and Z associated production, tt associated production

Gluon fusion is the dominant production mode

SM Higgs decay modes

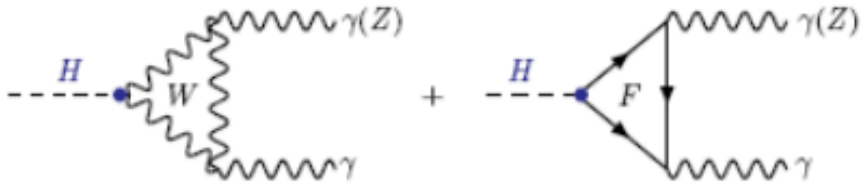


Higgs coupling increases with mass of fermion/boson

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

Dominant BR for H→bb (~58% @ 125 GeV) until WW and ZZ open up

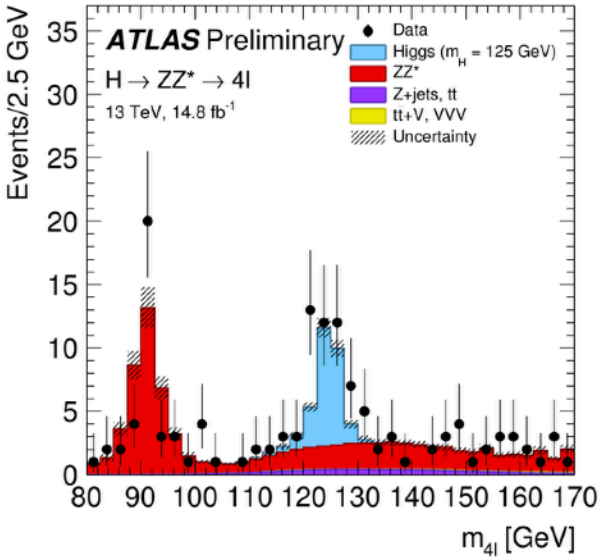
Decay into γγ through loops



Discovery channels

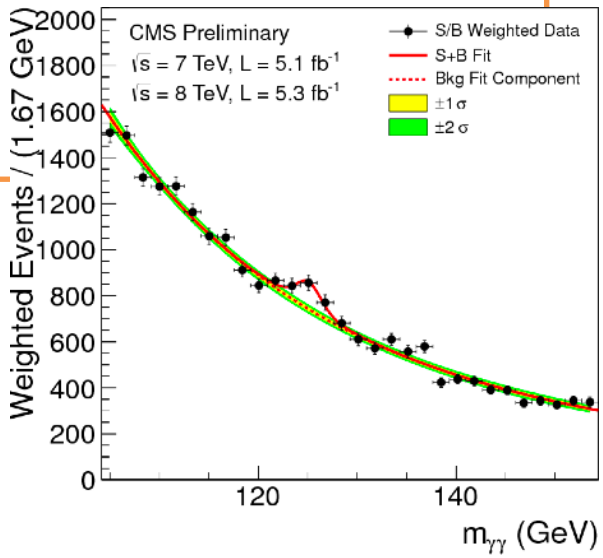
H→ZZ→4l

- Clean experimental signature: four isolated leptons
- Narrow resonance peak in four lepton mass spectrum



H→γγ

- Clean experimental signature: 2 high energy and isolated photons
- Narrow resonance in di-photon mass spectrum over a falling continuous background



Commonalities

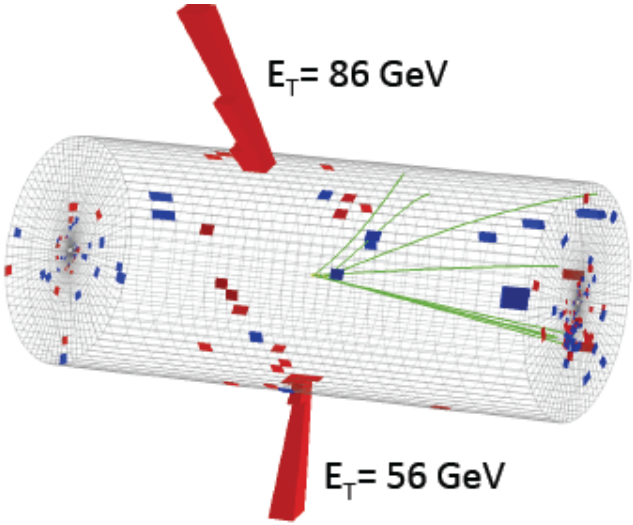
- Both channels suffer low BR
- Both allow mass peak reconstruction with very good resolution

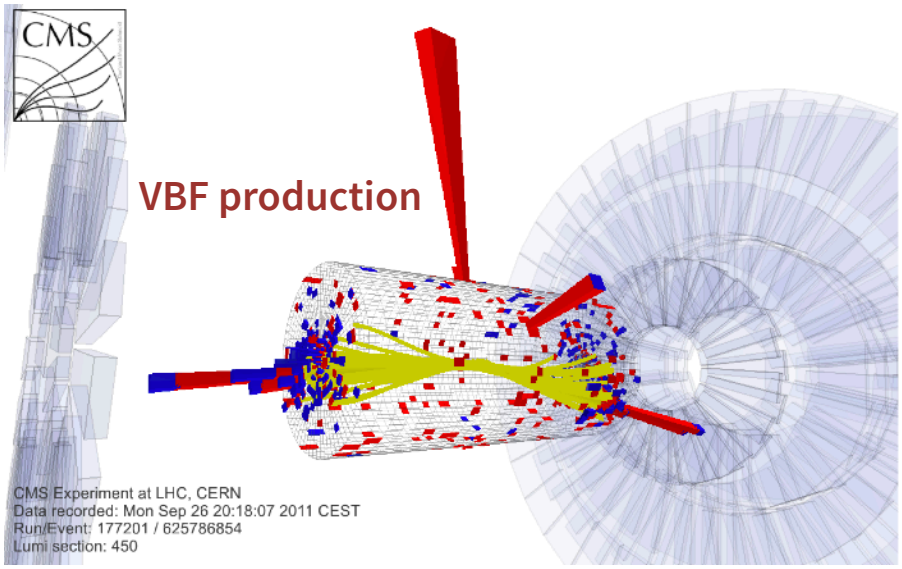
H→γγ

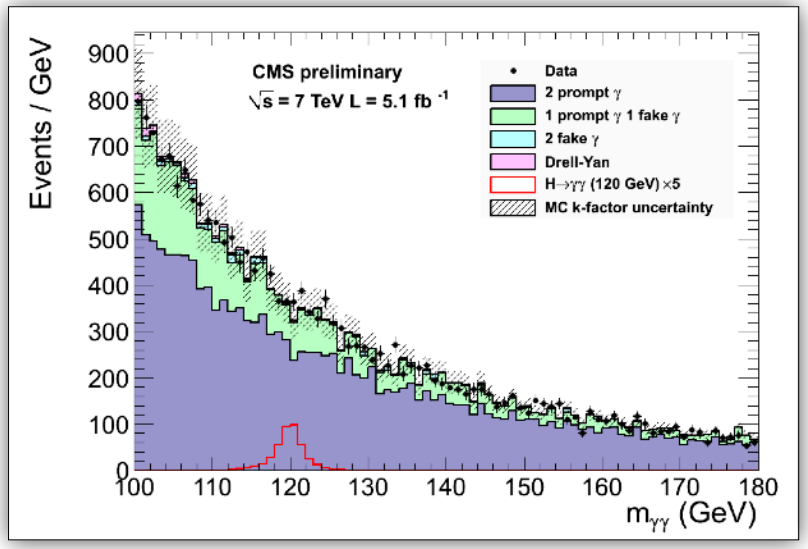
Eur. Phys. J. C (2014) 74:3076

Critical channel for the discovery of the Higgs

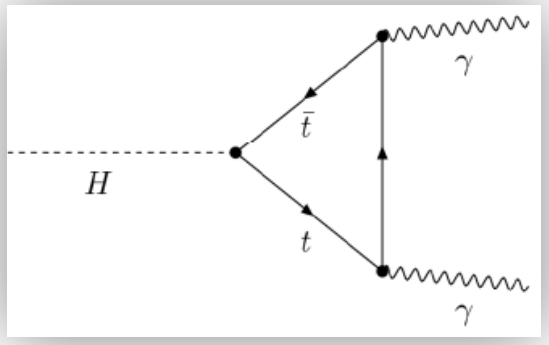
- Small BR (~0.2%) but very clear signature:
  - 2 isolated highly energetic photons
  - Search for a narrow peak over a falling background
    - very good mass resolution (~1-2%$m_{\gamma\gamma}$)
- VBF production channel helpful for background rejection
  - 2 forward jets from outgoing quarks







H→γγ - Backgrounds



$$\Gamma(H \to \gamma\gamma) = \frac{\alpha^2 m_H^3}{256\pi^3 v^2}\left|A_V\left(m_H^2/4m_W^2\right) - \sum_q A_f\left(m_H^2/4m_q^2\right)\right|^2$$

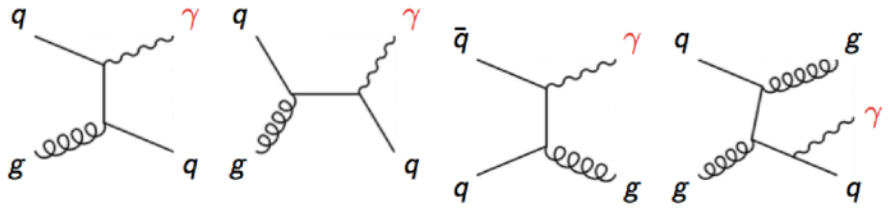
Photons do not couple directly to H because massless

Process takes place through a top (or W) loop

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

Reducible backgrounds

- Mainly due to jets identified as photons

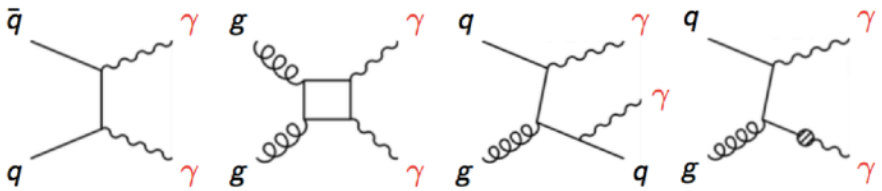


Need a very good γ-jet separation

Irreducible backgrounds

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

- γγ pair production from non-Higgs decays

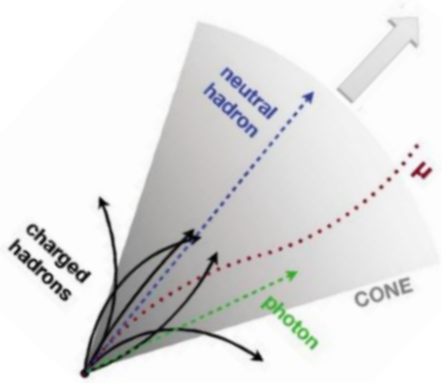


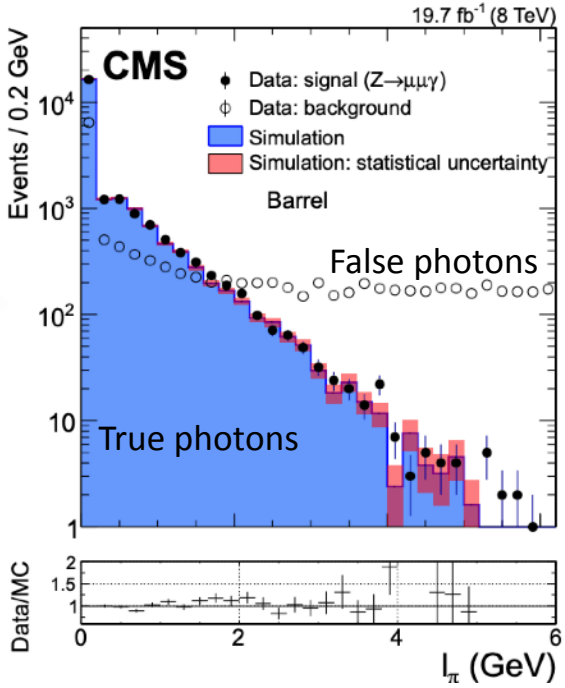
γ-jet separation

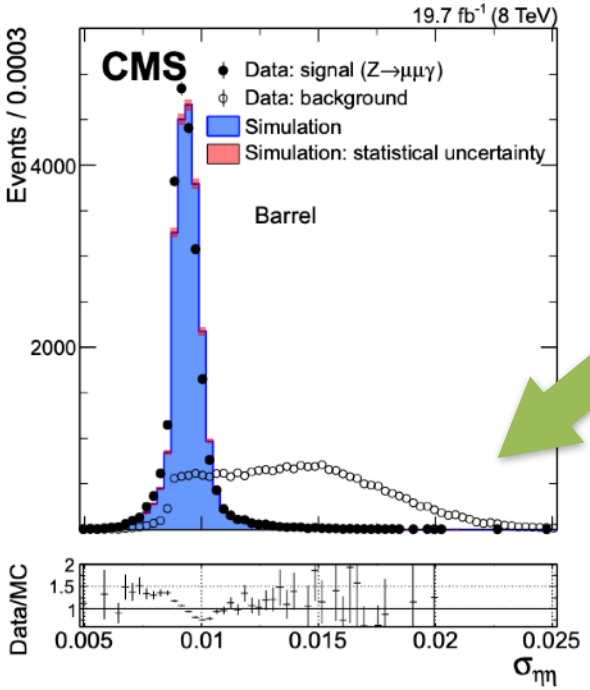
Isolation energy

- Sum the p_T of all particles reconstructed in a cone around main object
- low for prompt photons, larger for jets faking photons

direction of γ candidate







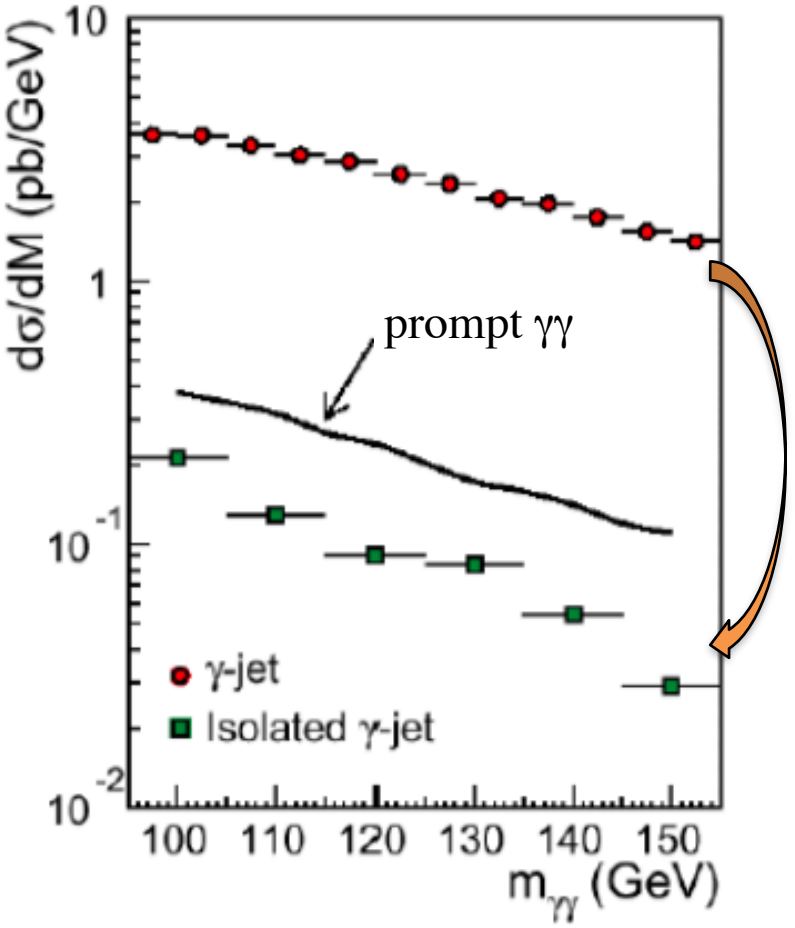
Identification

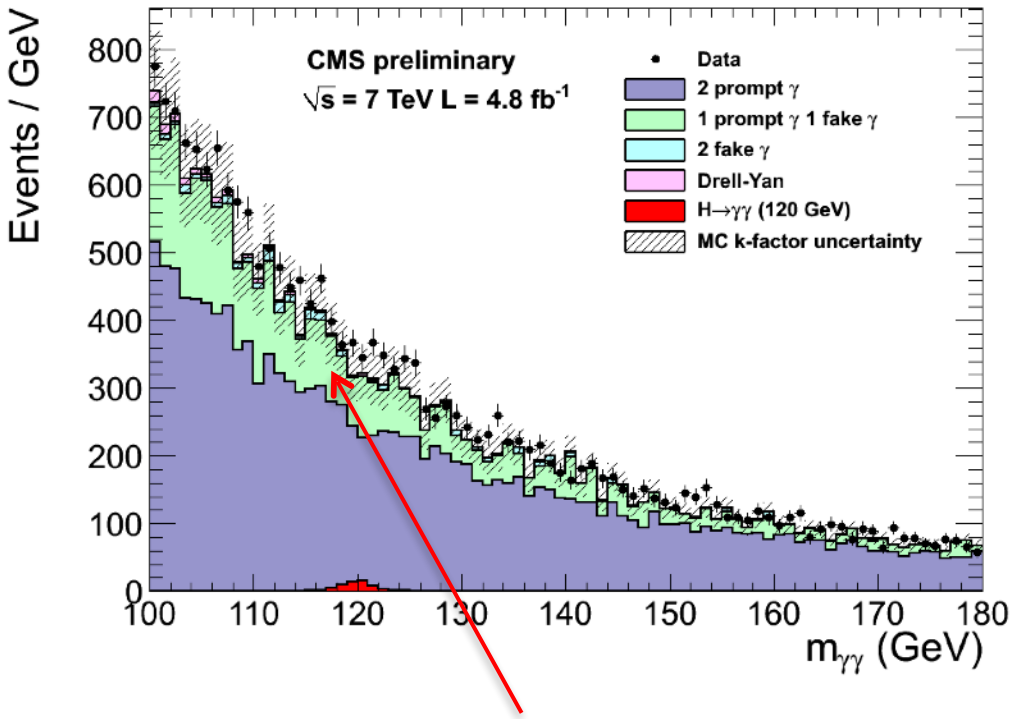
Variables describing the energy distribution in ECAL (shape of the shower)

E.g. $\sigma_{\eta\eta}$ ~ width of the shower in η, larger for background of jets faking photons

Combination of these requirements, often via machine learning techniques, provides excellent discrimination

Higgs →γγ: γ-jet rejection

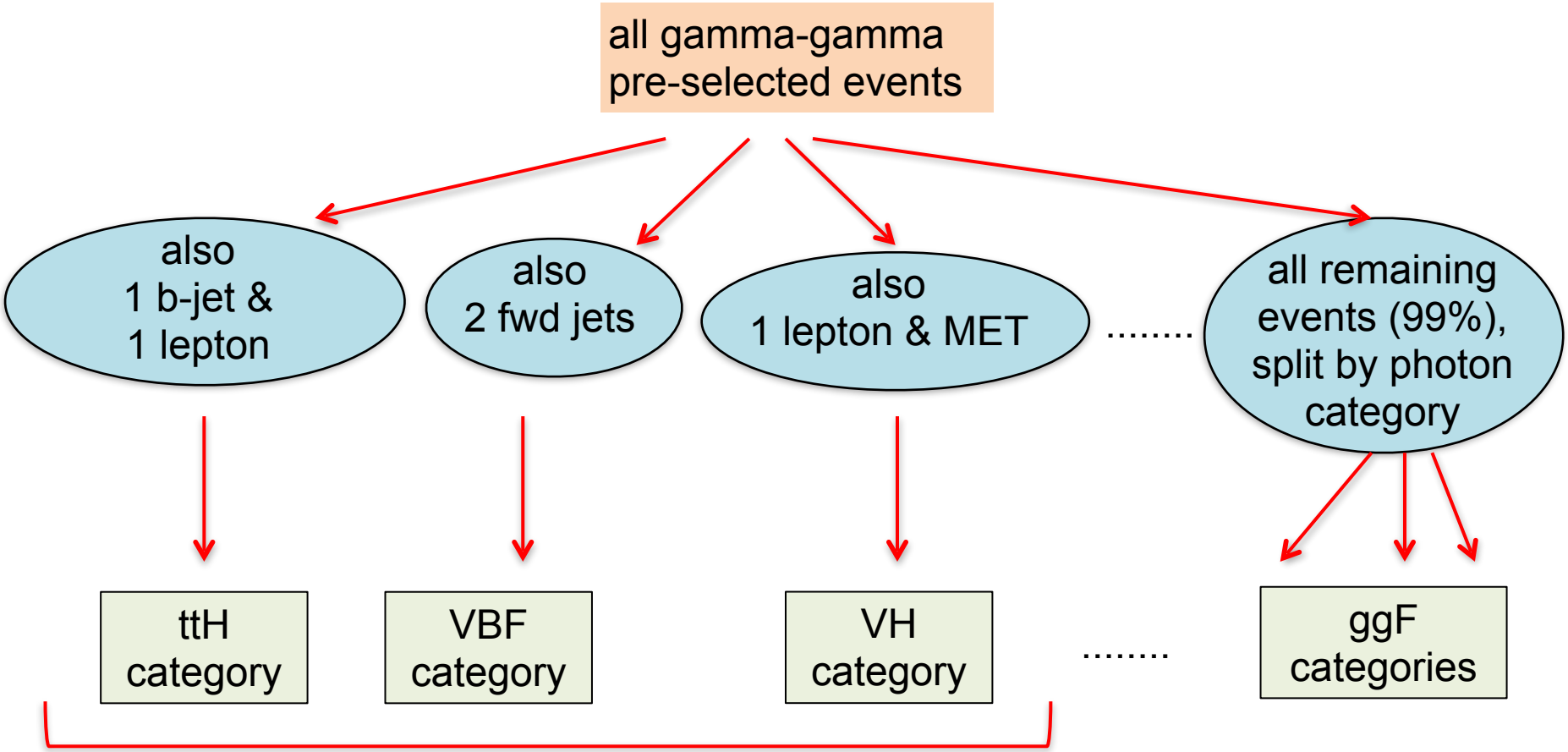




remaining background from jet-emulating-photons is about 30% of the total

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

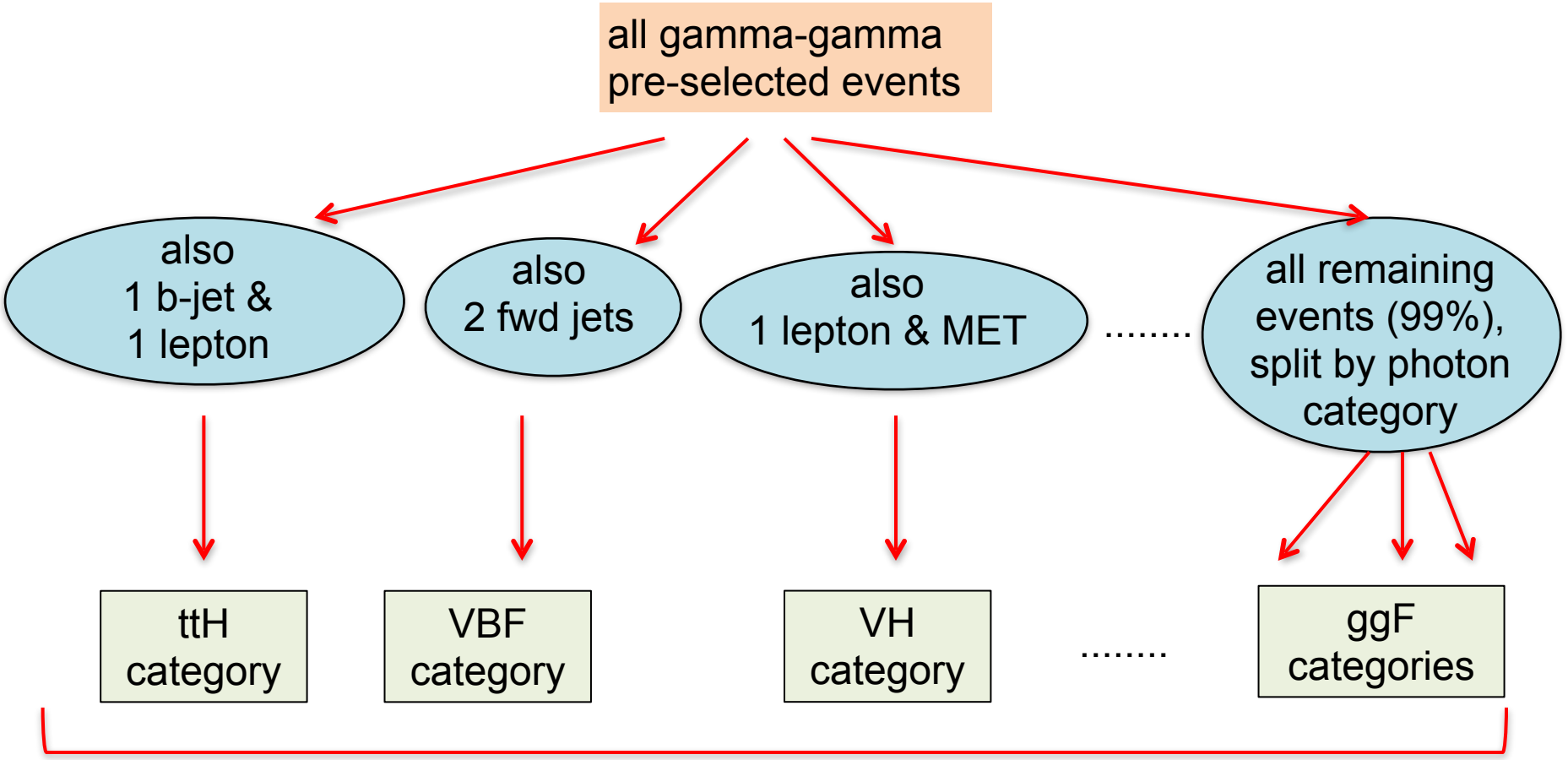
Higgs →γγ: event topology categories



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

better signal/bkg ratio

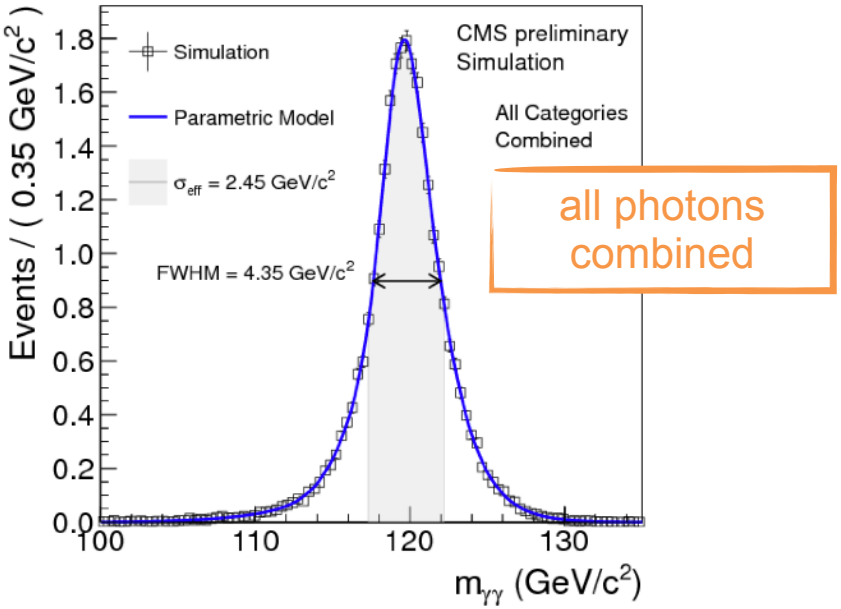
Higgs →γγ: event topology categories



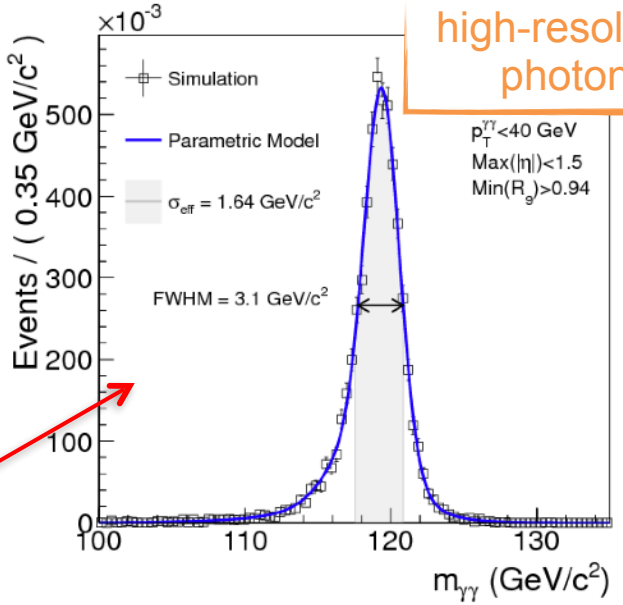
probing cross-section of different production processes

probing the coupling of the Higgs boson to different particles

Higgs →γγ: photon categories

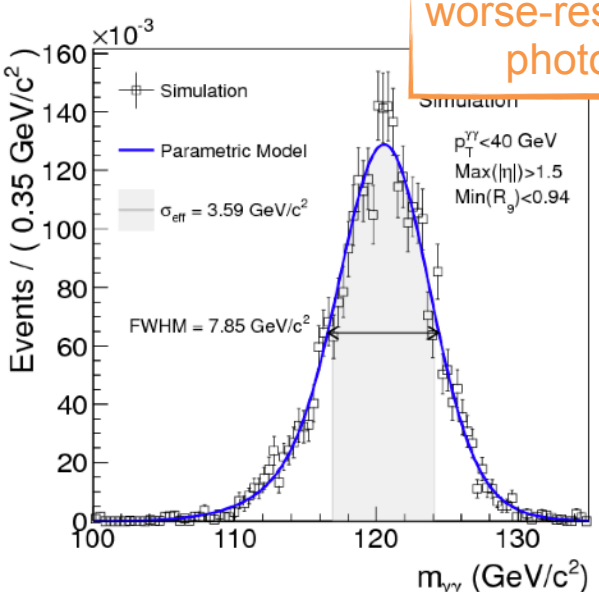


all photons combined



high-resolution photons

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

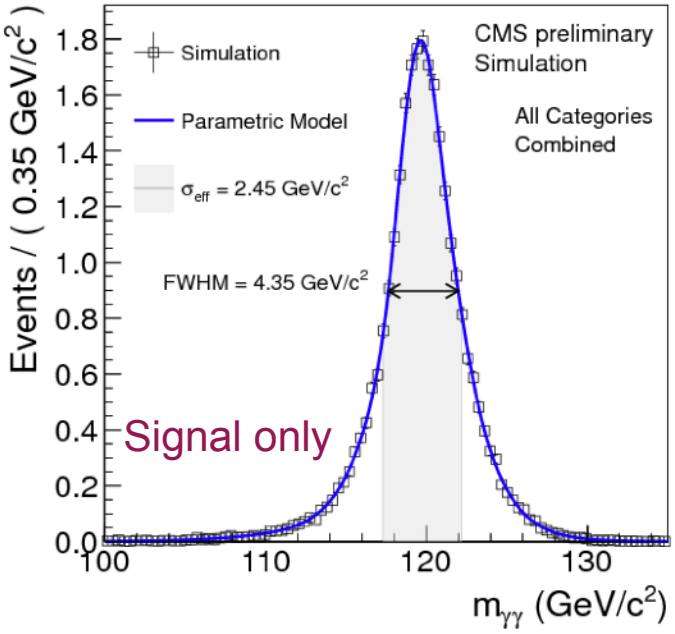


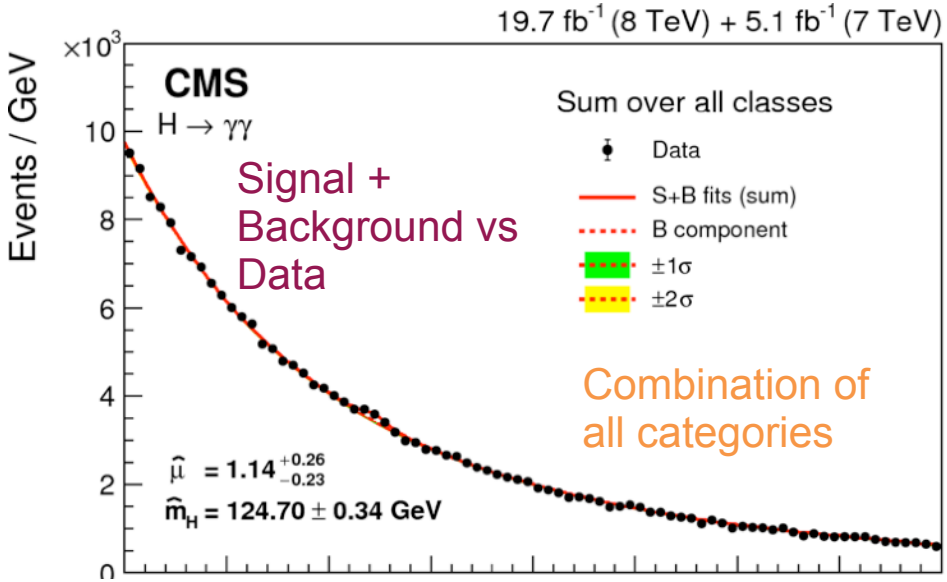
worse-resolution photons

Narrower signal peak, better signal/bkg ratio

H→γγ - Signal and background modelling

- Signal is parametrised from MC simulation
  - Crystal Ball + Gaussian
- Background is estimated by fitting a polynomial function to data in the full mass range

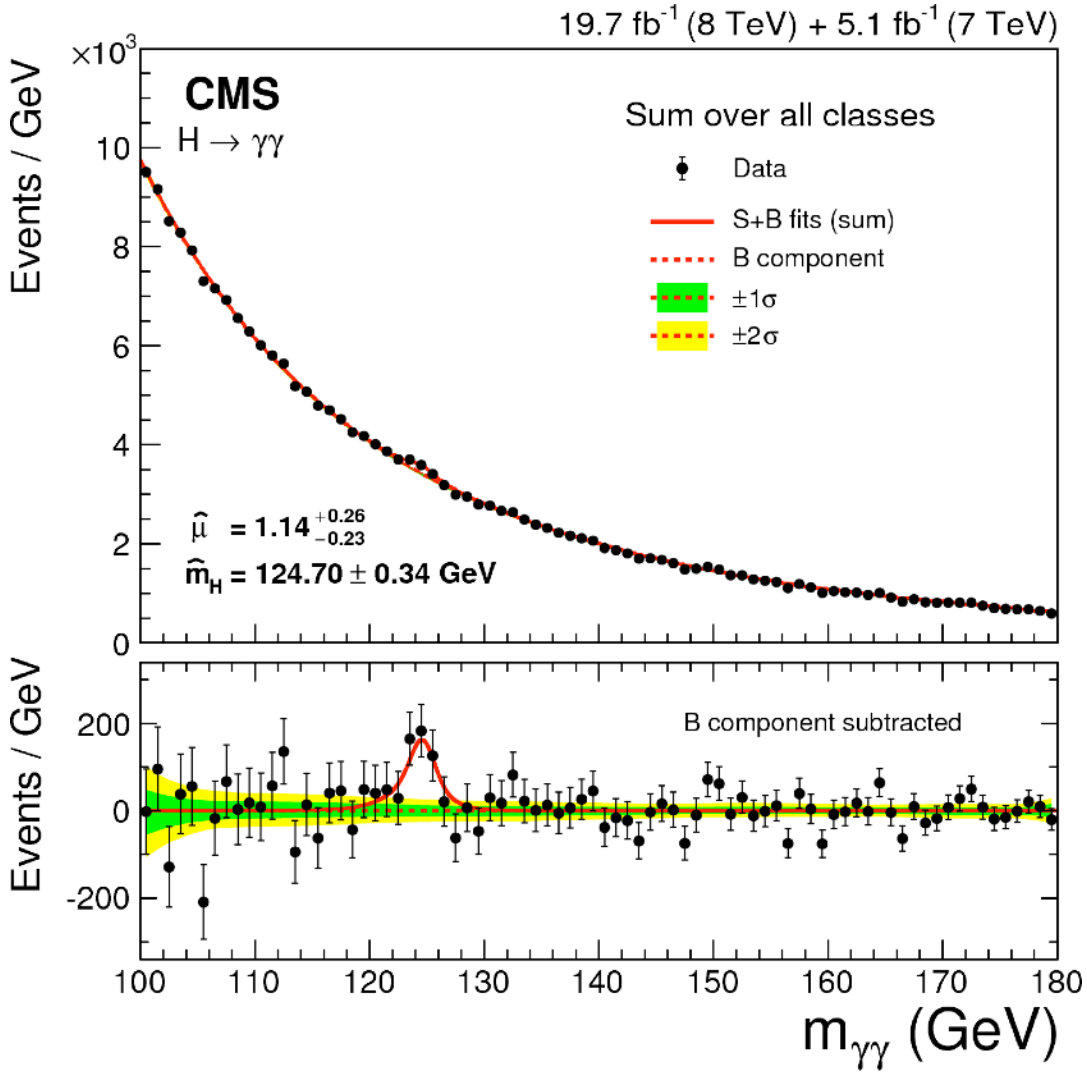




Fit $m_{\gamma\gamma}$ distribution in data to expected B+μS distribution in all categories:

- μ is a free parameter in the fit that parametrizes the signal hypothesis

Higgs →γγ: results

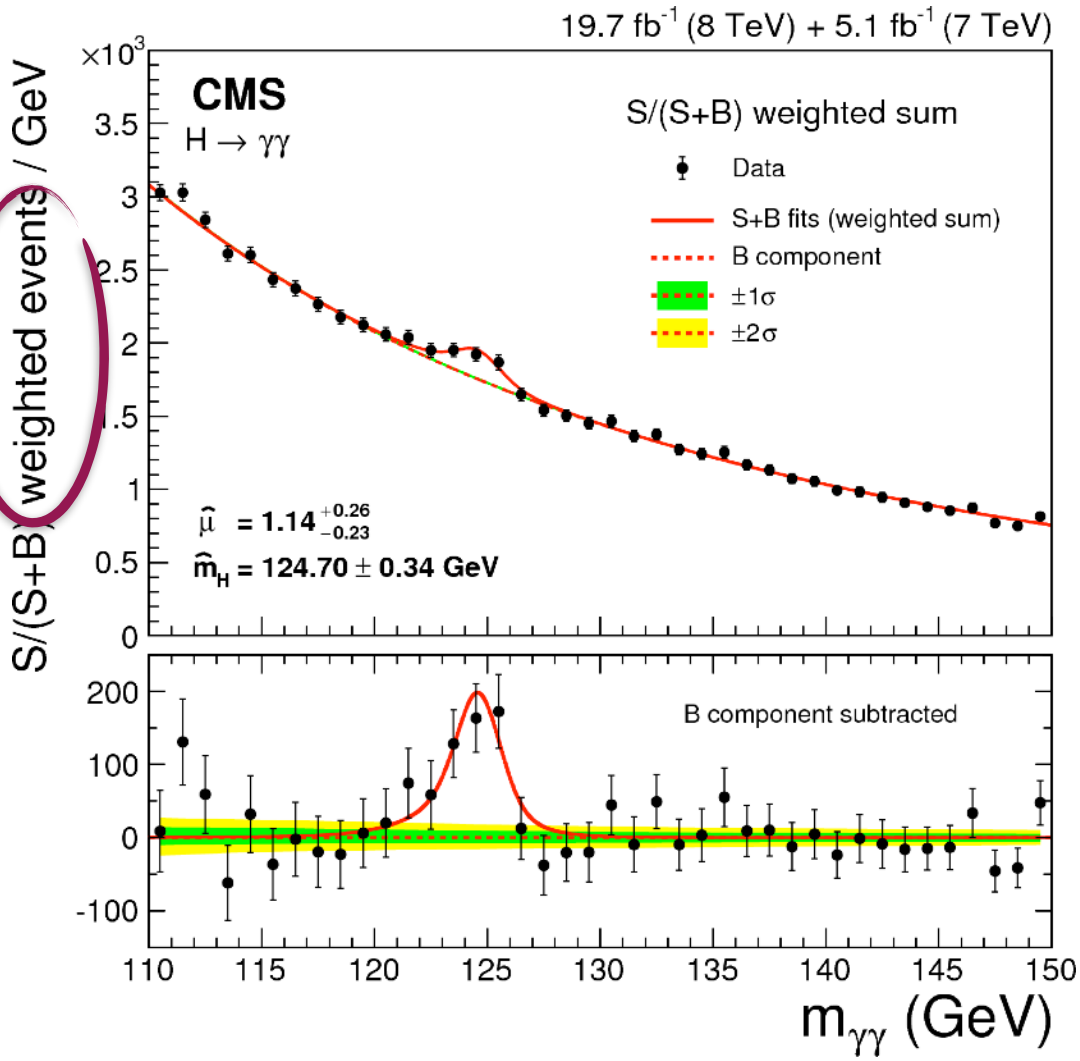


Perform maximum likelihood fit to the B+μS distribution in all categories simultaneously

⇒ extract best-fit value of μ : $\hat{\mu}$

- $\hat{\mu}$ = 1 : observation is in line with SM prediction
- $\hat{\mu}$ = 2 : observation favors 2 x SM prediction

Higgs →γγ: results



Not all events are "equal" in the statistical analysis.

High weight to most sensitive categories, lower weight to less sensitive categories

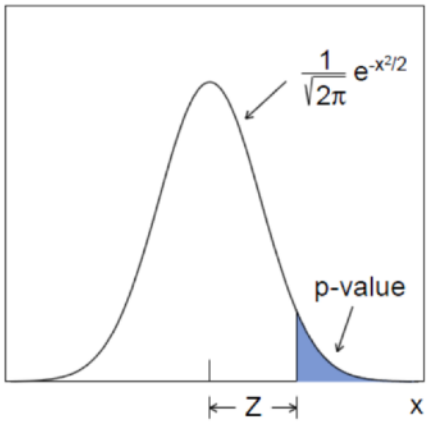
Nice peak over a falling background

Claiming a discovery

We can claim discovery if we measure a signal yield sufficiently inconsistent with zero.

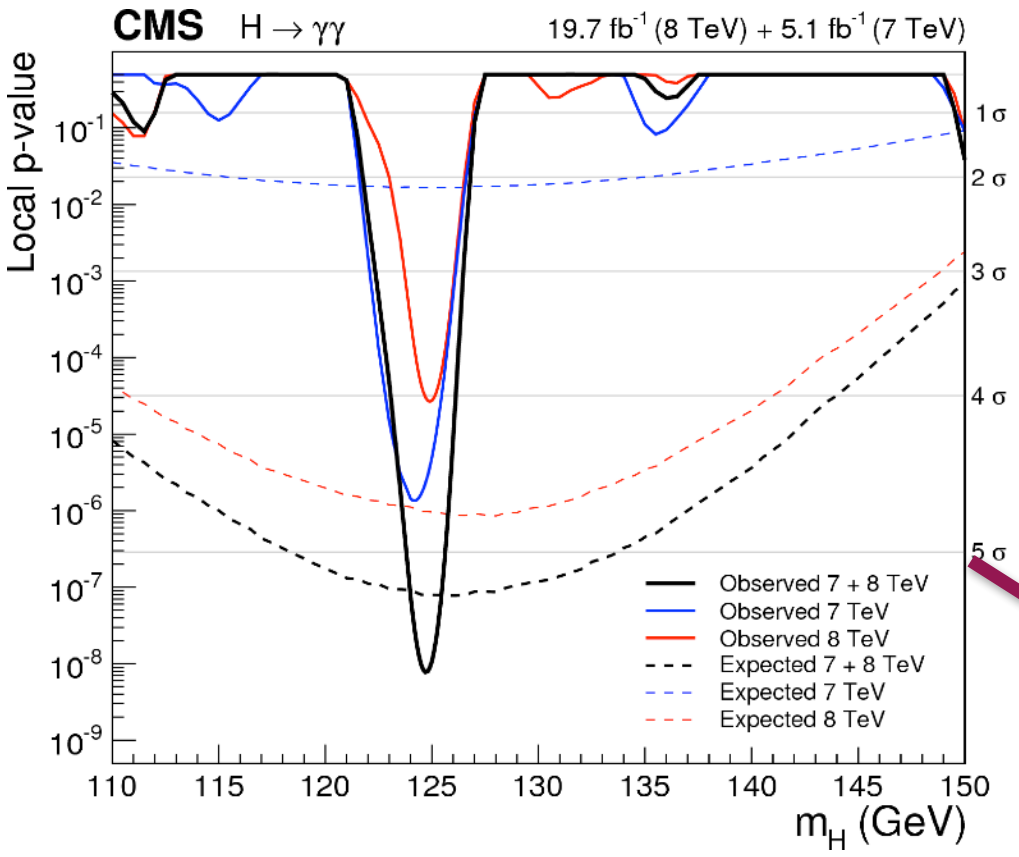
What does it mean sufficiently?

- We can quantify how relevant is the excess by stating what is its ***significance*** *or* ***p-value***
  - ***p - value:*** probability that the observed excess is due to a background fluctuation $$p = \int_{n\sigma}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \mathrm{d}x = 1 - \frac{1}{2}\mathrm{erf}\left(\frac{n}{\sqrt{2}}\right)$$
  - Often preferred to quote "nσ" significance
- It is common habit to claim:
  - *Evidence of:* if significance is > **3 σ**
  - *Observation*: if significance is > **5 σ** (i.e. prob for bkg fluctuation = 2.87 x 10^{-7})



Z significance

Higgs →γγ: results



$Z\ (\sigma)$	p
1.00	1.59×10^{-1}
1.28	1.00×10^{-1}
1.64	5.00×10^{-2}
2.00	2.28×10^{-2}
2.32	1.00×10^{-2}
3.00	1.35×10^{-3}
3.09	1.00×10^{-3}
3.71	1.00×10^{-4}
4.00	3.17×10^{-5}
5.00	2.87×10^{-7}
6.00	9.87×10^{-10}

What if we do not observe a significant excess?

Not always experiments lead to discoveries:

- The signal may indeed not be there
- Or the collected dataset is not enough to claim a discovery

We can still say something by **setting upper limits**

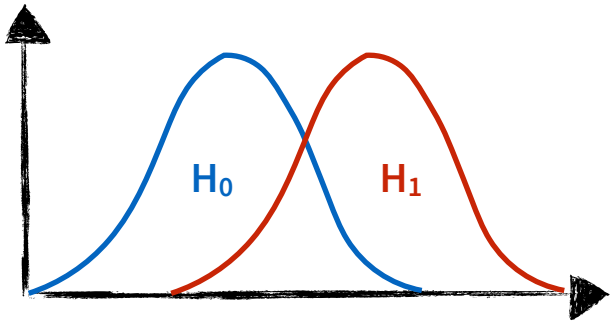
One possible definition of upper limit: *"largest value of the signal s for which the probability of a signal under-fluctuation smaller or equal to what has been observed is less than a given level (usually 10% or 5%)"*

- Upper limits for an exclusion are set requiring:
  - $p<0.05$ (95%CL) or $p<0.10$ (95%CL)
  - In this case *p* indicates the probability of a signal underfluctuation

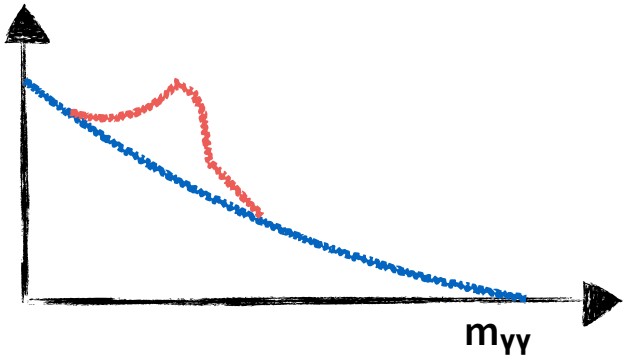
Statistical Interpretation of Higgs searches

Null Hypothesis (H_0) vs alternative hypothesis (H_1, Existence of Higgs)

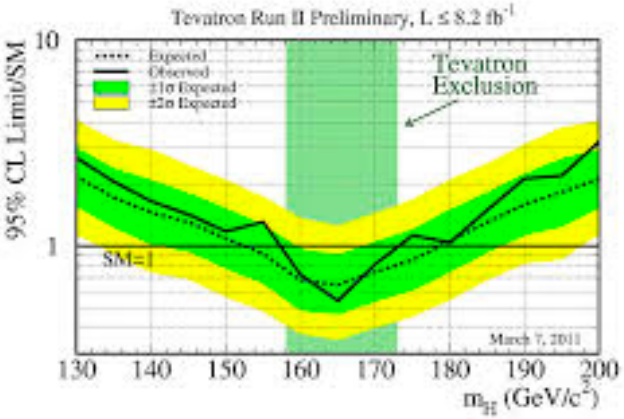
Need to quantify the level at which each hypothesis is accepted or rejected



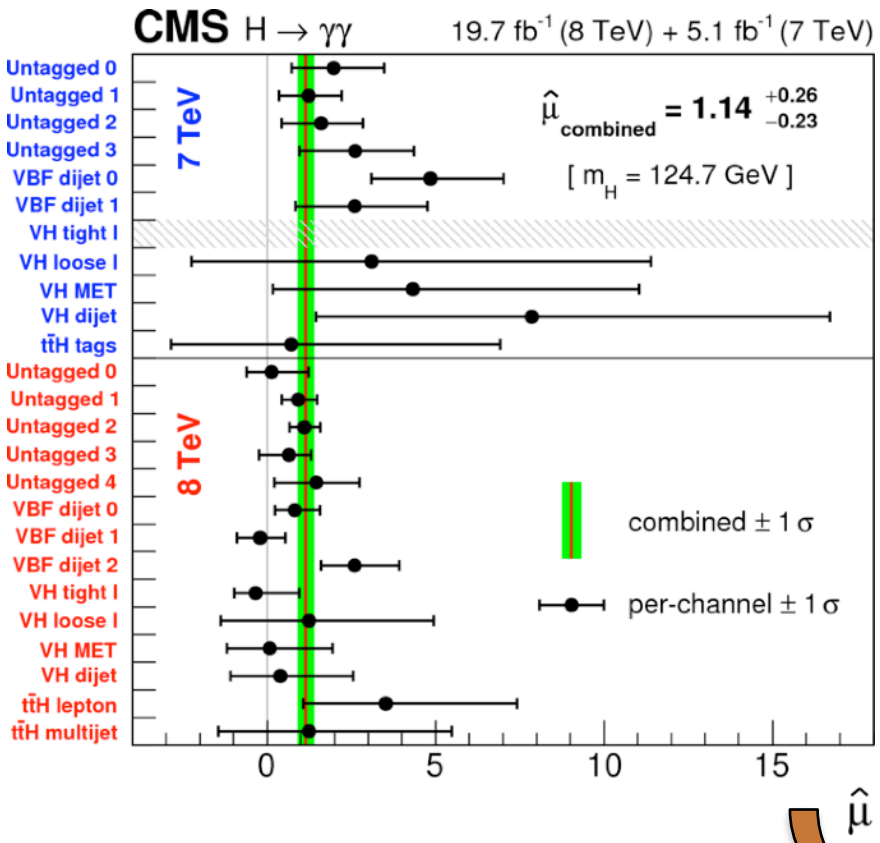
Identify the experimental observables and define a statistical test and the parameters of the model

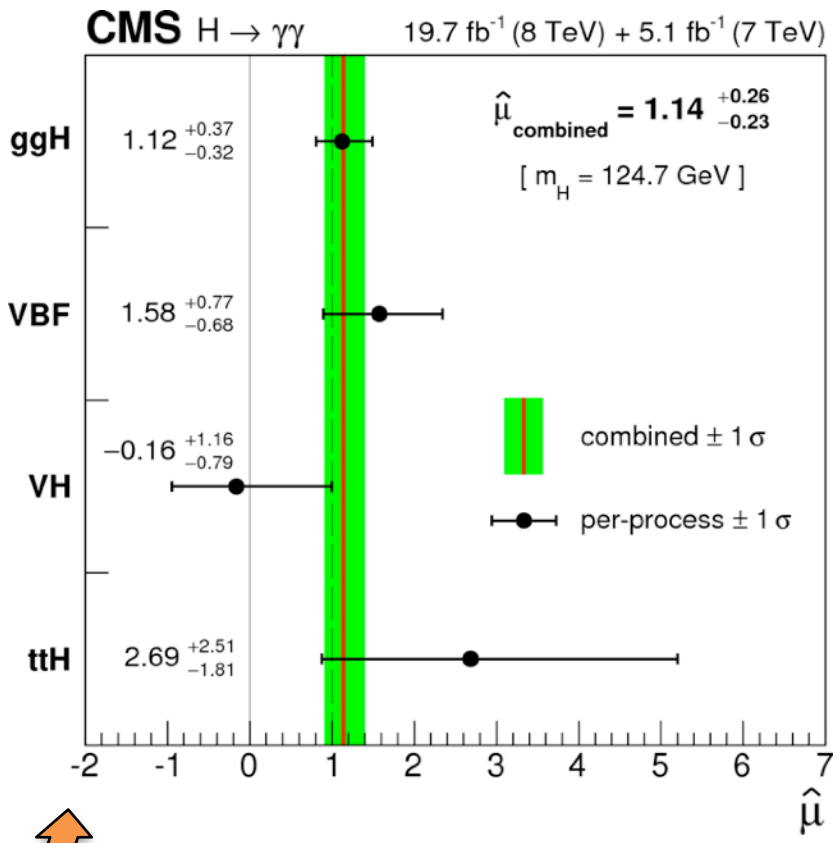


Compute the confidence level for exclusion or the significance of the excess



Is it a SM-like Higgs boson ?





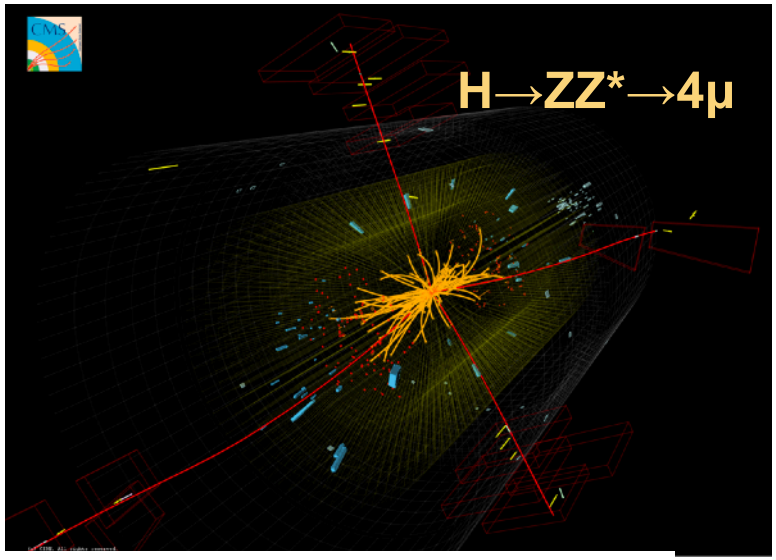
obtained by performing fit in individual categories

then combine different categories by production type

H→ZZ*→4l

The golden channel

- Very clean signature
  - four isolated leptons (*e* or μ)
- And very small background
- Challenges: requires high lepton identification/reconstruction/ isolation efficiency

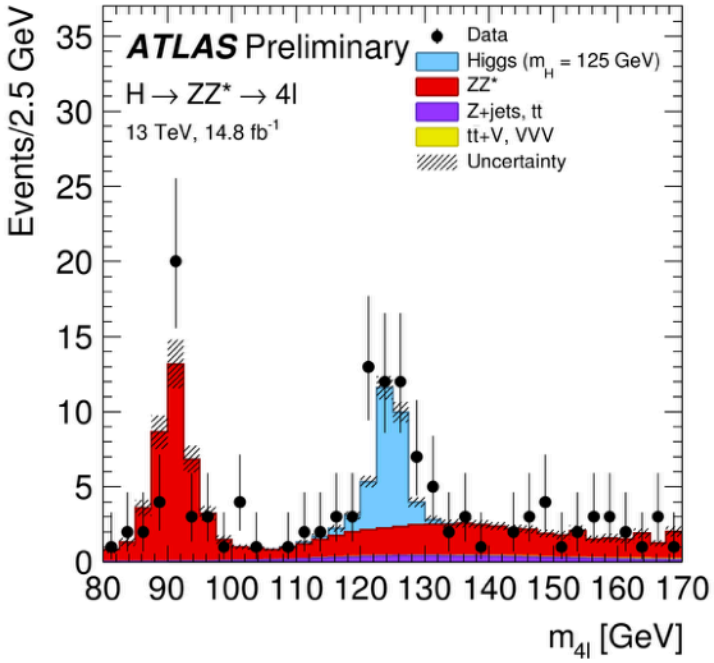


Reducible background

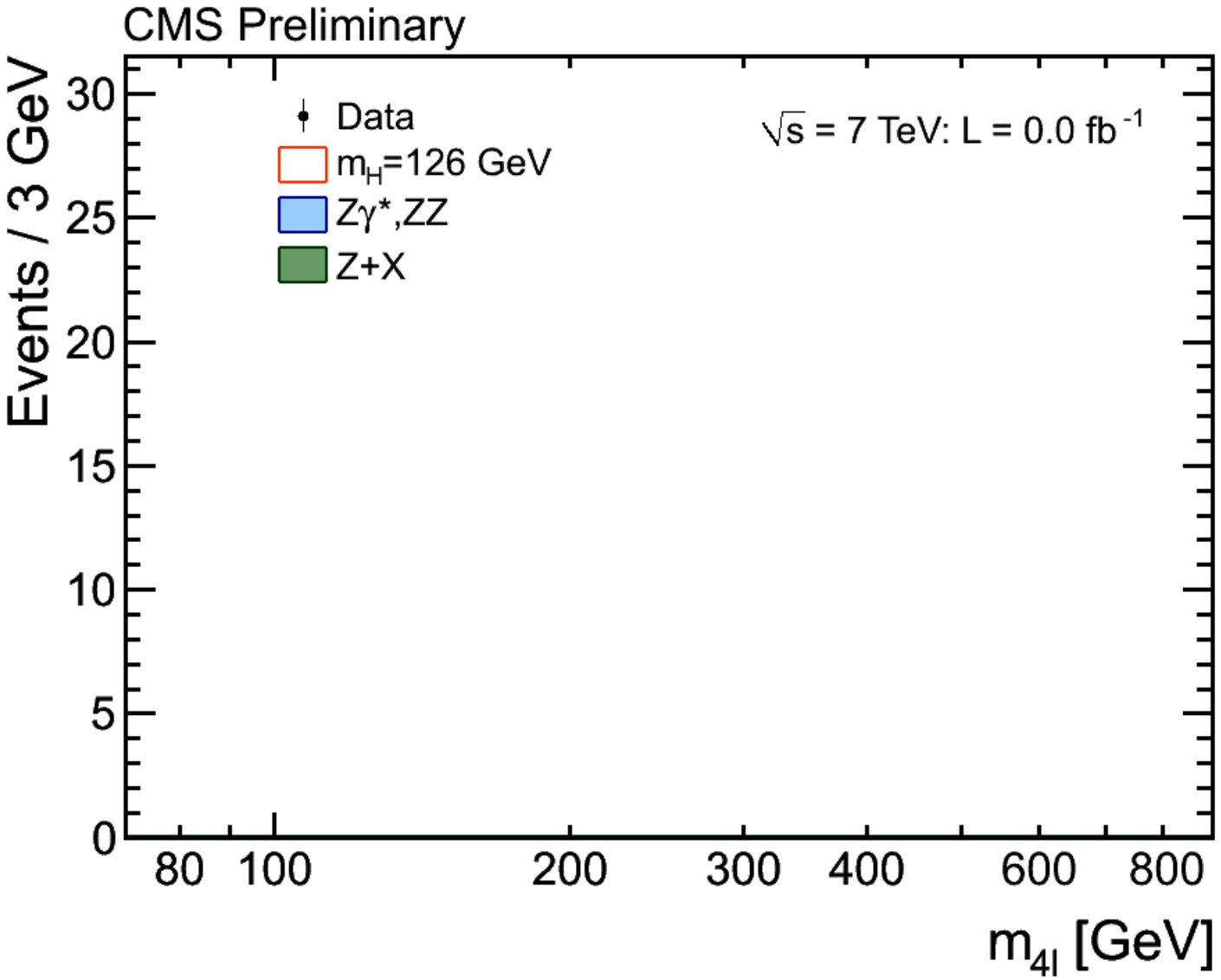
- Z+bb, tt, tt+ jets. Z+jets, WZ+jets

Irreducible background

- ZZ*

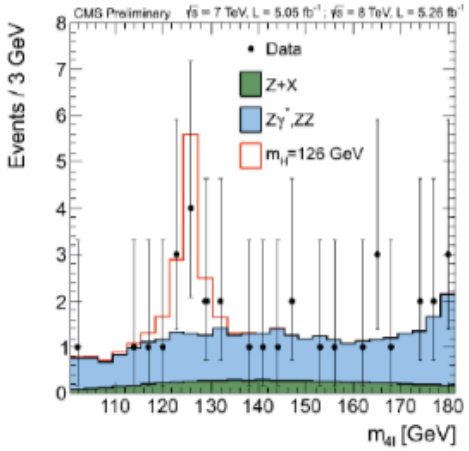


4 lepton invariant mass spectrum

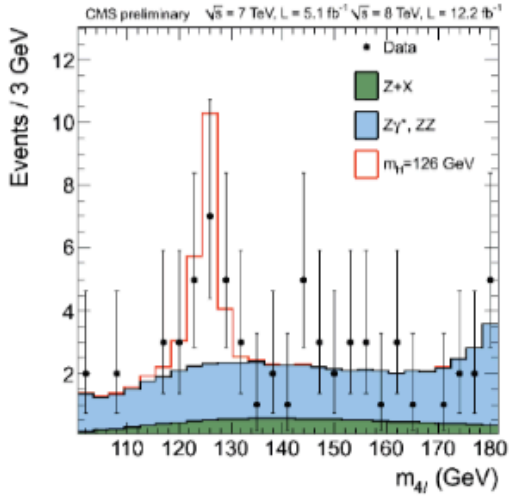


H → ZZ(*)→ 4l

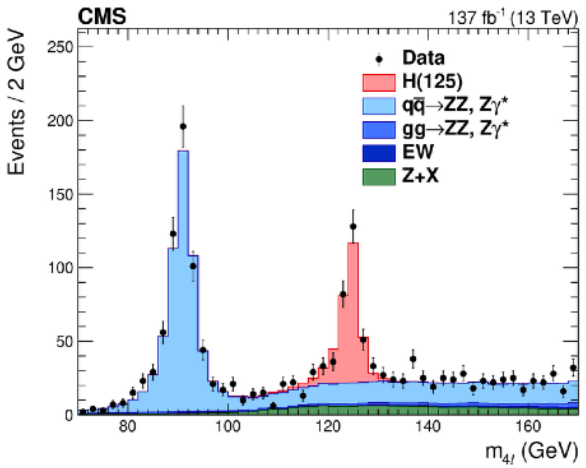
First Observation



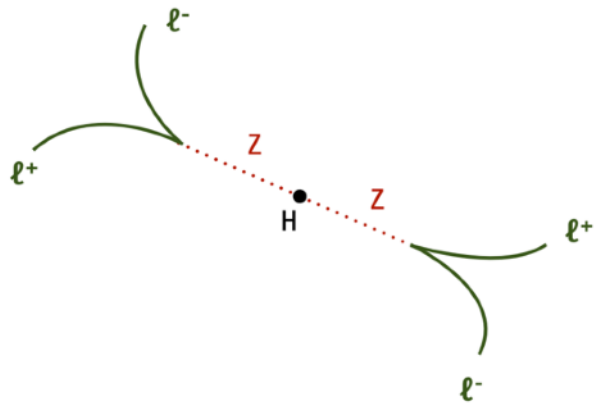
Increasing statistics



Full Run-2 data



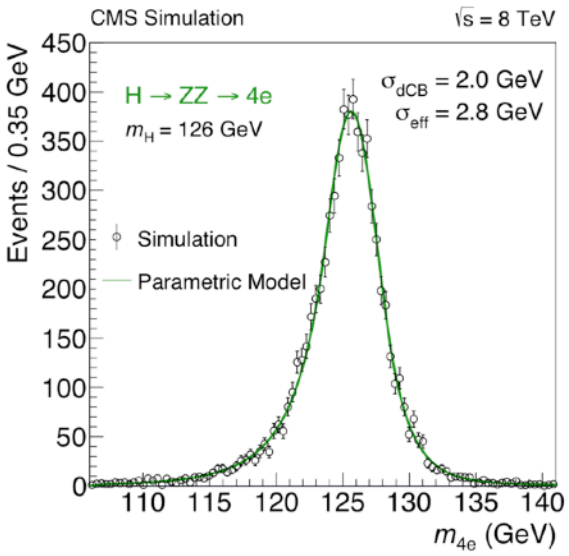
increasing amount of data collected...

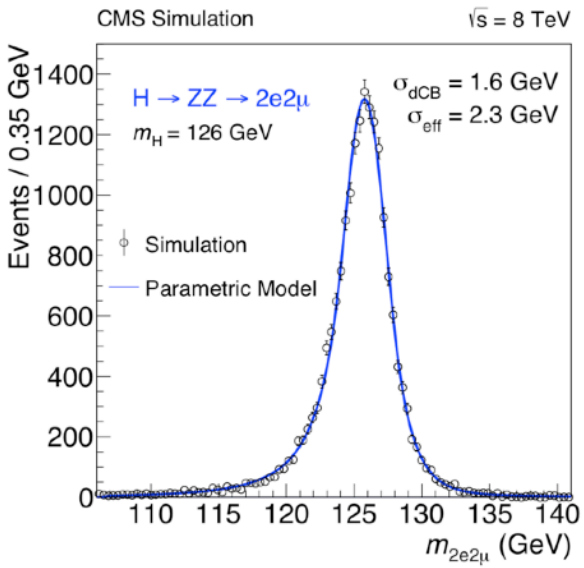


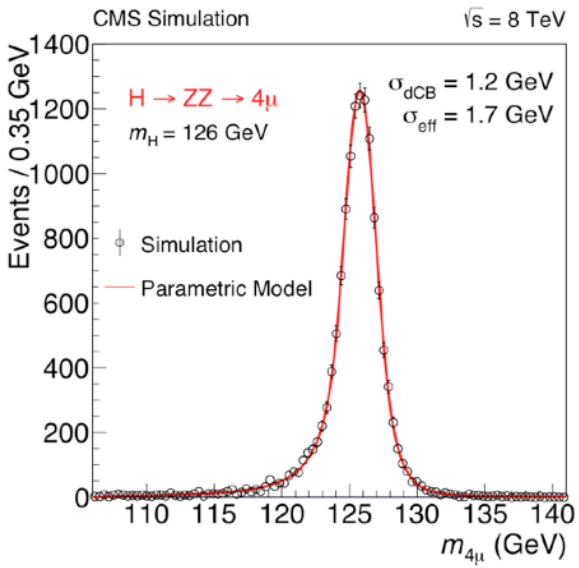
- Two pairs of SF, OS lepton
- Compatible with a ZZ system

A narrow resonance on top of a smooth background in the 4-lepton invariant mass distribution

H → ZZ(*) → 4l: event categories





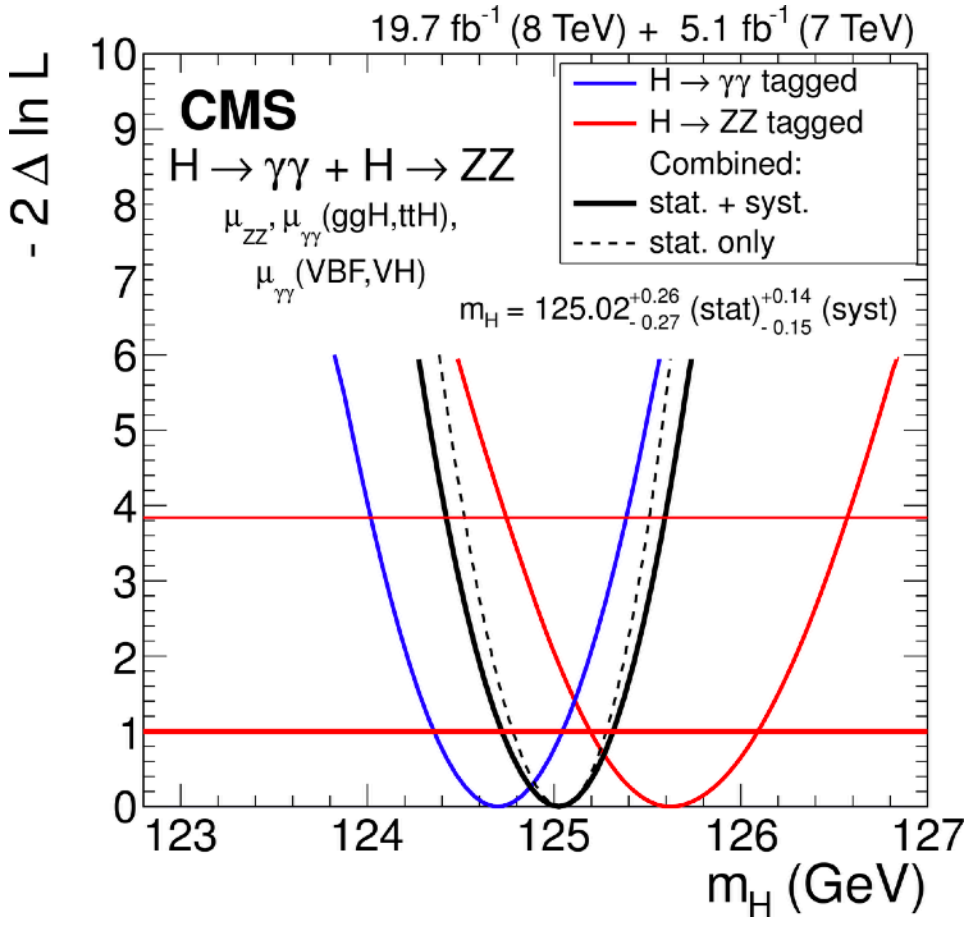


Improving mass resolution moving from electrons to muons.
(Muons are basically not affected by bremsstrahlung)

As for H→γγ search, narrower the signal peak, better the signal/bkg ratio

events are split in different lepton categories

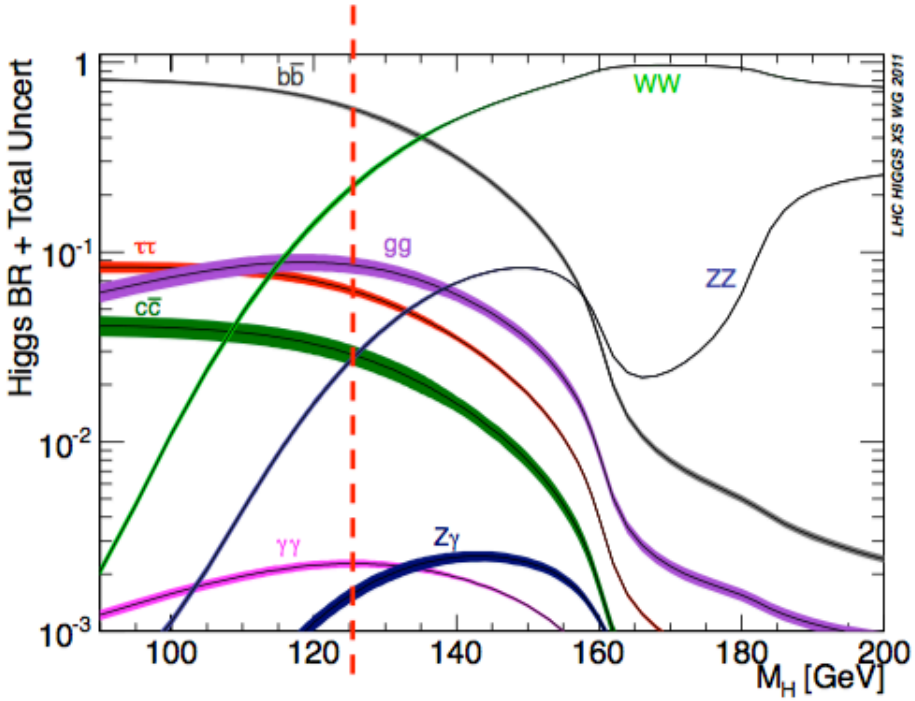
Higgs mass: combination of γγ and 4l channels



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

arxiv:1412.8662

Other channels

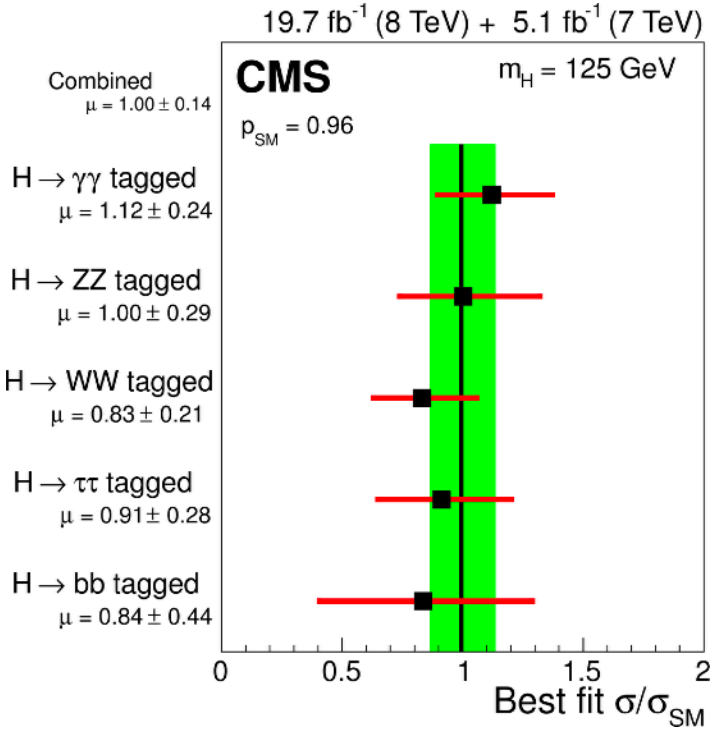


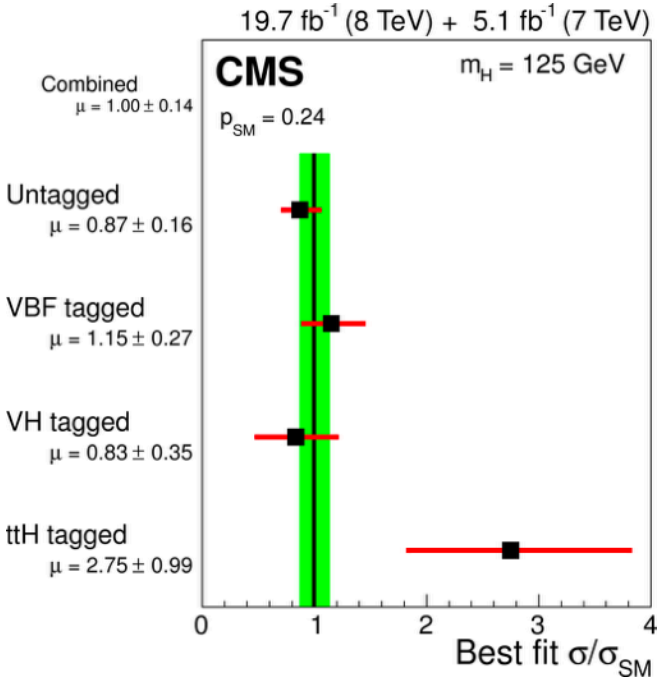
	σ_M/M
• bb	10%
• ττ	10%
• WW	20%
• ZZ	1-2%
• γγ	1-2%

Ingredients that influence the sensitivity of a channel:

- how much signal compared to background
- performance of the physics objects ⇒ resolution of the invariant mass

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)

Back to the MSSM road

MSSM



SM Higgs

MSSM

SM Higgs boson ?

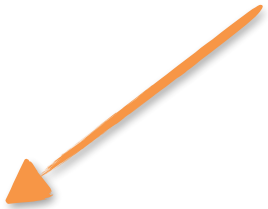
Within uncertainties, new discovered particle is compatible with SM 0^+ Higgs boson

In MSSM the lightest neutral higgs boson has SM-like properties (production cross-sections, BRs, spin-parity) in the decoupling regime ($m_A >> m_Z$) or for intermediate m_A and large tgβ

Discovered SM-like boson can fit into the MSSM

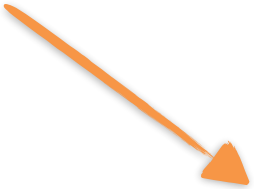
From SM-like Higgs boson to MSSM ones

For a SUSY interpretation, focus is then on two different fronts:



Measure deviations in couplings/ properties
of the discovered boson which are NOT compatible with SM predictions.

This will require very high luminosity



Directly detect the other MSSM Higgs bosons: H^0, A, $H^\pm$



remaining slides about this

Neutral MSSM Higgses

Neutral MSSM Higgs couplings to fermions

- for h/H/A coupling proportional to mass ⇒ 3rd generation favoured
- in the decoupling limit ($m_A >> m_Z$):
  - couplings of A same as couplings of H
  - A/H couplings to down-type fermions are enhanced (unlike h)

$$g_{h^0 t\bar{t}} \propto m_t \frac{\cos\alpha}{\sin\beta} \sim m_t \qquad g_{h^0 b\bar{b}} \propto m_b \frac{-\sin\alpha}{\cos\beta} \sim m_b\,(-1)$$

$$g_{H^0 t\bar{t}} \propto m_t \frac{\sin\alpha}{\sin\beta} \sim m_t \cot\beta \qquad g_{H^0 b\bar{b}} \propto m_b \frac{\cos\alpha}{\cos\beta} \sim m_b \tan\beta$$

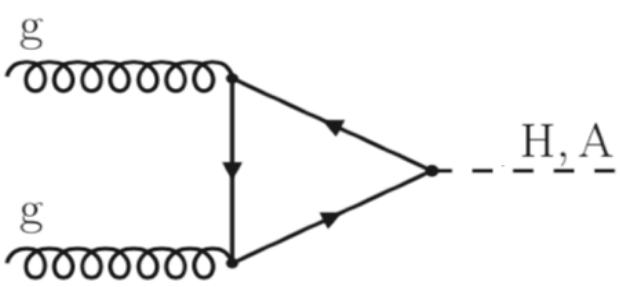
$$g_{A^0 t\bar{t}} \propto m_t \cot\beta \qquad g_{A^0 b\bar{b}} \propto m_b \tan\beta$$

in the decoupling limit: $\alpha \sim \beta - \pi/2$

couplings of A/H to b-quarks and tau-leptons important

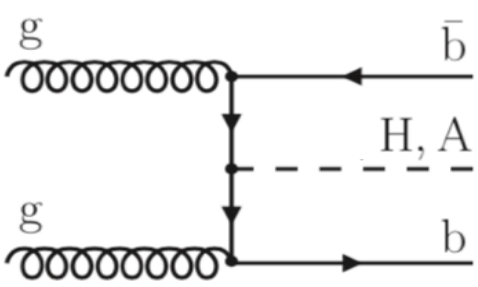
A/H production

Main production mechanisms for A/H



gg fusion

gg-fusion dominant
at intermediate tgβ

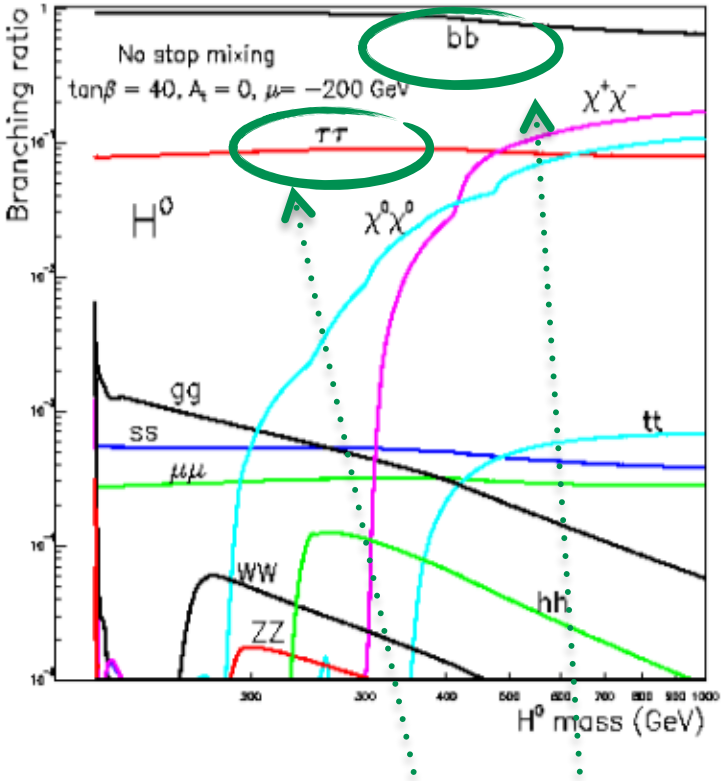


b-associated

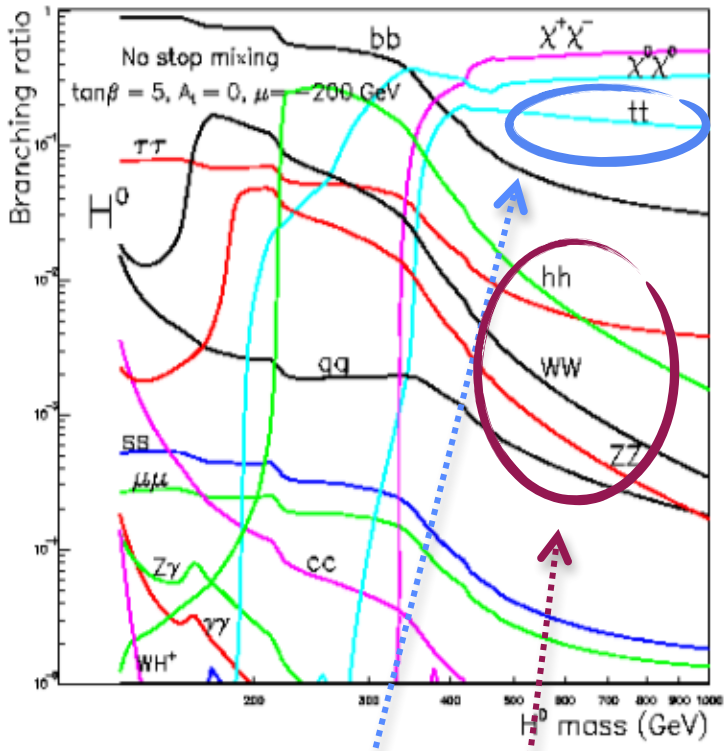
b-quark associated dominant
at large tgβ

A/H branching ratios

high tan β



low tan β



- BR into bb and ττ favoured for high tanβ

- BR into ttbar open up for low tanβ and high mass
- BR to hh, WW, ZZ can become important

* plots shown for H^0, similar considerations for A^0

Conventional MSSM A/H channels

Conventional searches (intermediate/high tgβ):

- A/H → ττ
- A/H → μμ
- A/H → bb

Searches targeting low tgβ:

- H → WW
- H → hh(bbγγ)
- H → hh(bbττ)
- A → Zh(ττ)
- A/H → tt
- (…)

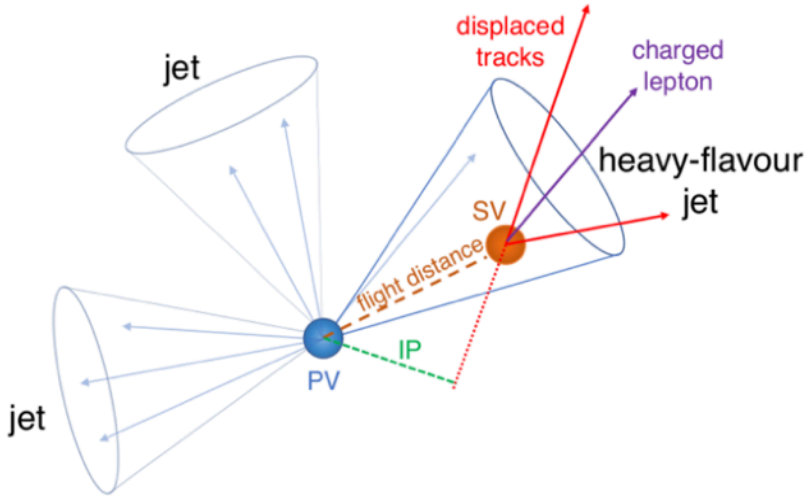
B-flavoured jets

We have seen last time that quarks and gluons undergo fragmentation and hadronization producing *Jets*

B-jets are jets originating from b-quark fragmenting into B-hadrons

B-jets vs uds/gluon-jets:

- longer lifetime τ~1.5ps
  - secondary vertices (SV) up to ~1 cm from PV
- ~ 20% of decays to leptons
  - leptons-in-jet
- larger mass of B-hadrons
  - larger reconstructed mass at secondary vertex (SV)



Identification of b-jets largely based on machine learning based discriminators

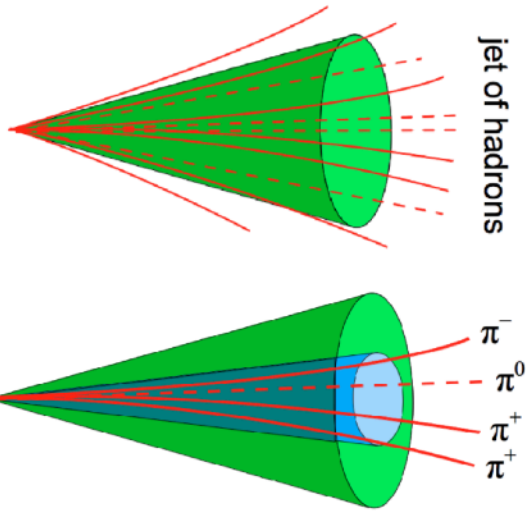
Tau leptons

Tau is the only lepton heavy enough to decay to hadrons

	Decay Mode	Resonance	B [%]
leptonic decays	$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
	$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
1 - prong decays	$\tau^- \to \pi^- \nu_\tau$	$\pi(140)$	11.6
	$\tau^- \to \pi^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
	$\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
3 - prongs decays	$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	$a_1(1260)$	9.8
	$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		4.8
	Other hadronic modes		1.7
	All hadronic modes		64.8

Tau hadronic differs from q/gluon-jets

- Lower multiplicity: 1-3 $\pi^\pm$ + 0-2 π^0
- Longer lifetime than light hadrons but shorter than b/c-hadrons
- τ not colored ⇒ isolated



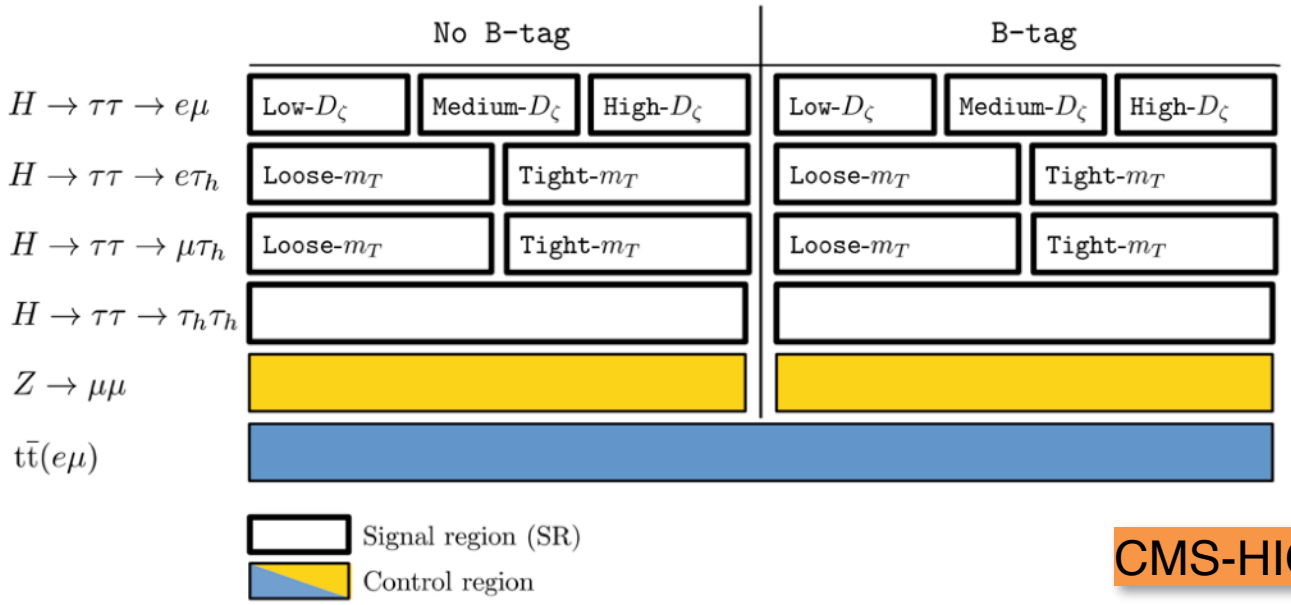
Identification of taus largely based on machine learning discriminators

Tau leptonic decays reconstructed with usual techniques for electrons and muons

A/H → ττ: Categorization

- Split events into categories depending on tau decays:
  - use the 4 most sensitive channels: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
- Further categorization based on:
  - presence of b-jets ⇒ **target b-associated production**
  - transverse mass m_T in $e\tau_h$, $\mu\tau_h$; signal expected at low m_T

$$m_{\mathrm{T}}^{\mathrm{e}(\mu)} = \sqrt{2\, p_{\mathrm{T}}^{\mathrm{e}(\mu)}\, p_{\mathrm{T}}^{\mathrm{miss}}\, (1 - \cos\Delta\phi)}.$$



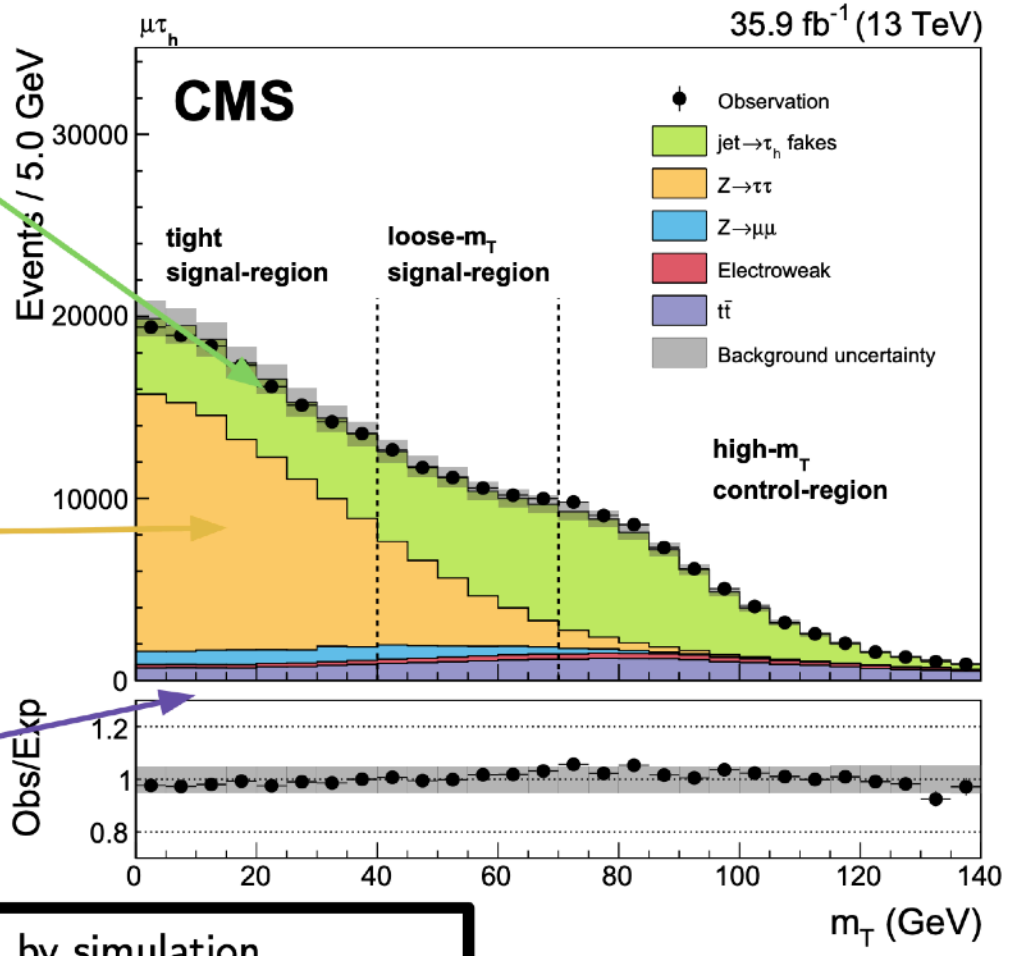
CMS-HIG-17-020

A/H →ττ: Backgrounds

Reducible backgrounds:
–Hadronic taus faked by jets in μτ, eτ, ττ channel → estimated by the fake factor method

Irreducible backgrounds:
–$Z \to \tau\tau$
–$t\bar{t}$, single-top, diboson with genuine taus
–Taken from simulation in all 4 channels

Background estimation



Smaller backgrounds → estimated by simulation

A/H →ττ: discriminating variable

Best discriminating power found by building total transverse mass mTtot :

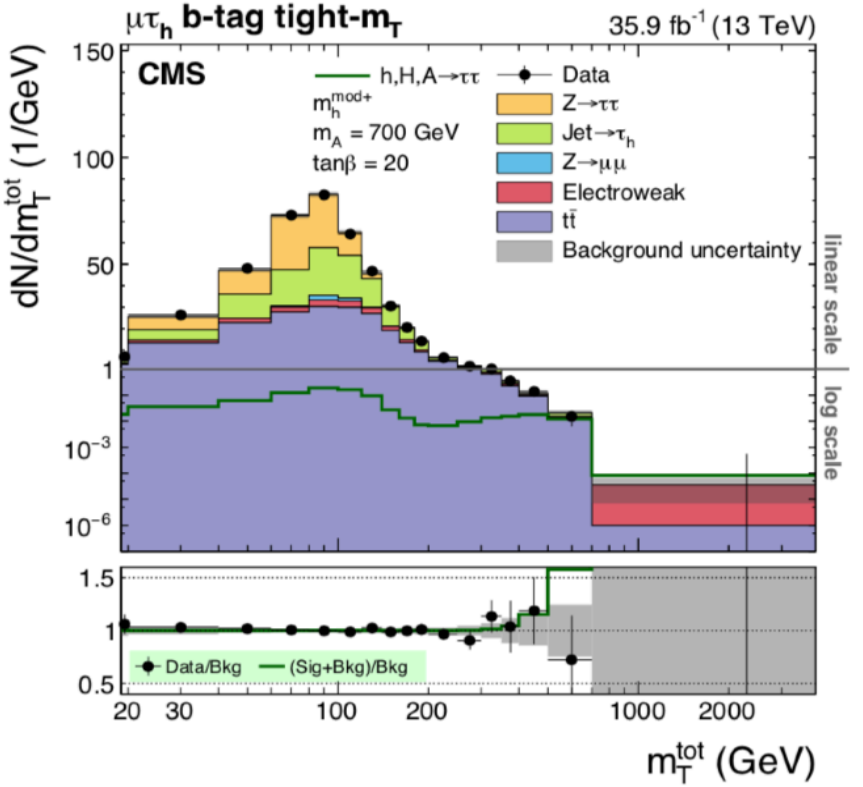
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\tau_2}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_2}, p_{\mathrm{T}}^{\mathrm{miss}})},$$

$$m_{\mathrm{T}} = \sqrt{2\, p_{\mathrm{T}}\, p'_{\mathrm{T}}\, [1 - \cos(\Delta\phi)]}$$

Worse resolution than invariant mass mττ, but better discrimination against multi-jet

- Two peak structure of the signal:
- Light h ~ 125 GeV
- nearly mass-degenerate A/H at 700 GeV

- Simultaneous fit of m_T^{tot} in all categories



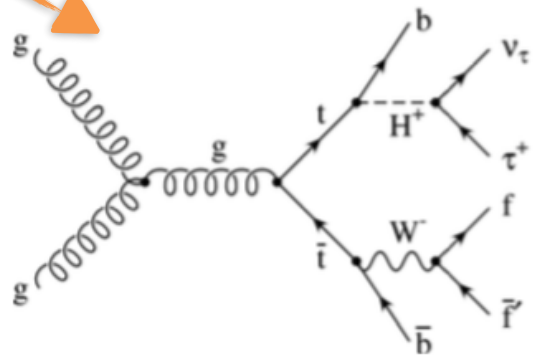
Charged Higgs bosons searches

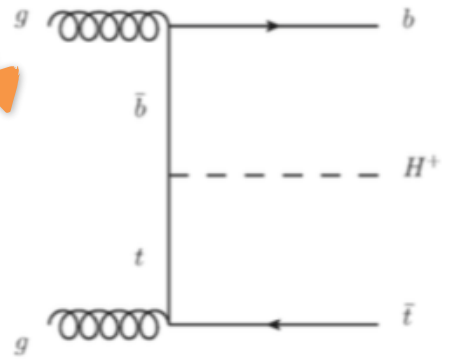
Production

- mH± < mt : H± produced from top decay
- mH± > mt : H± produced in association with top/bottom

Decay

- mH± < mt : BR(H±→$\tau\nu$) dominant
- mH± > mt : BR(H±→tb) dominant





CMS has searches in both channels,
$H^+ \rightarrow \tau\nu$ leading channel

Charged Higgs bosons searches

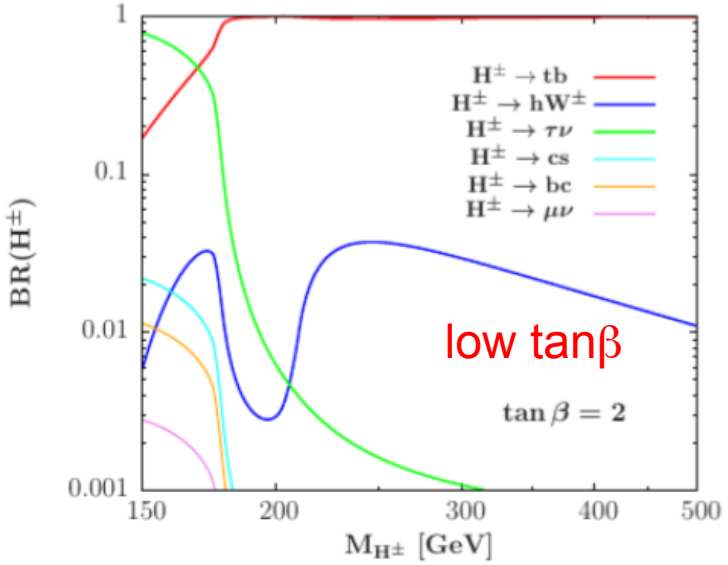
Production

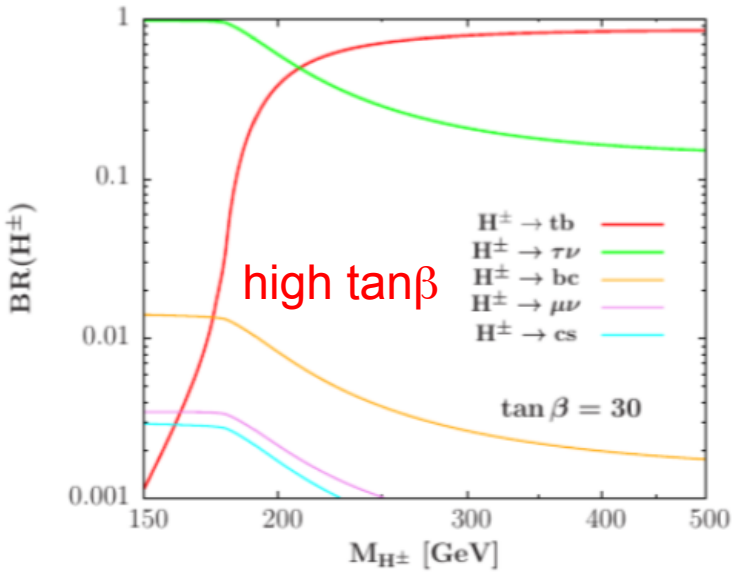
- mH± < mt : H± produced from top decay
- mH± > mt : H± produced in association with top/bottom

Decay

- mH± < mt : BR(H±→τν) dominant
- mH± > mt : BR(H±→tb) dominant

CMS has searches in both channels,
$H^+ \to \tau\nu$ leading channel





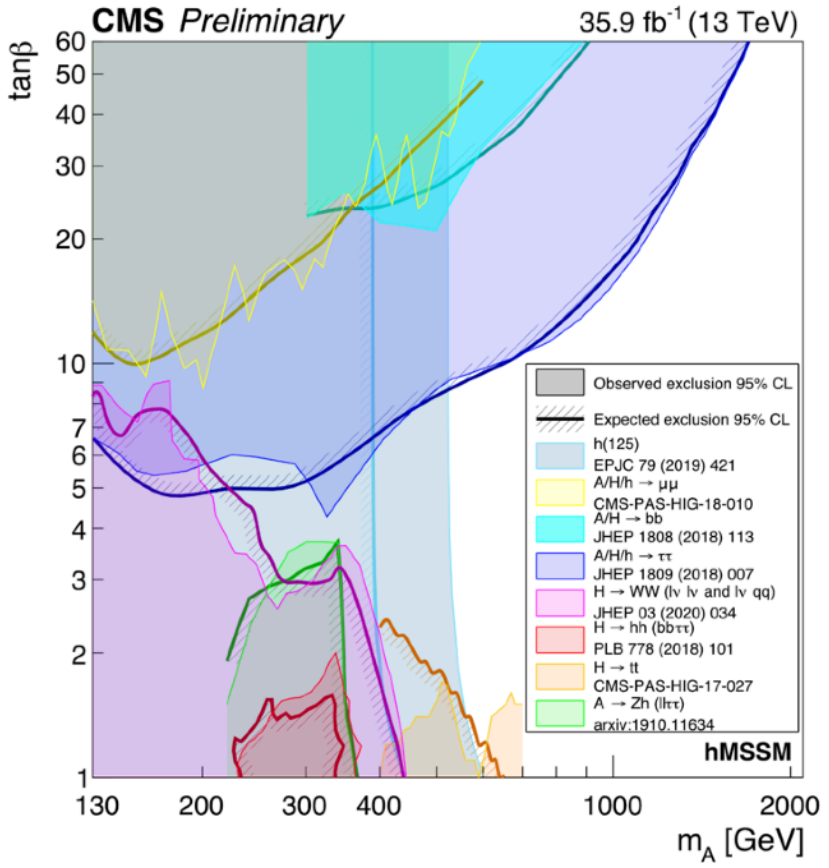
Landscape of MSSM Higgs search

Results presented in the hMSSM framework

- incorporates the discovered higgs as h0

Experimental status of the searches by CMS

- ττ channel dominant for intermediate-high tgβ
- WW channel dominant at low tgβ
- light blue line indicates indirect constrain from higgs coupling measurements



Summary

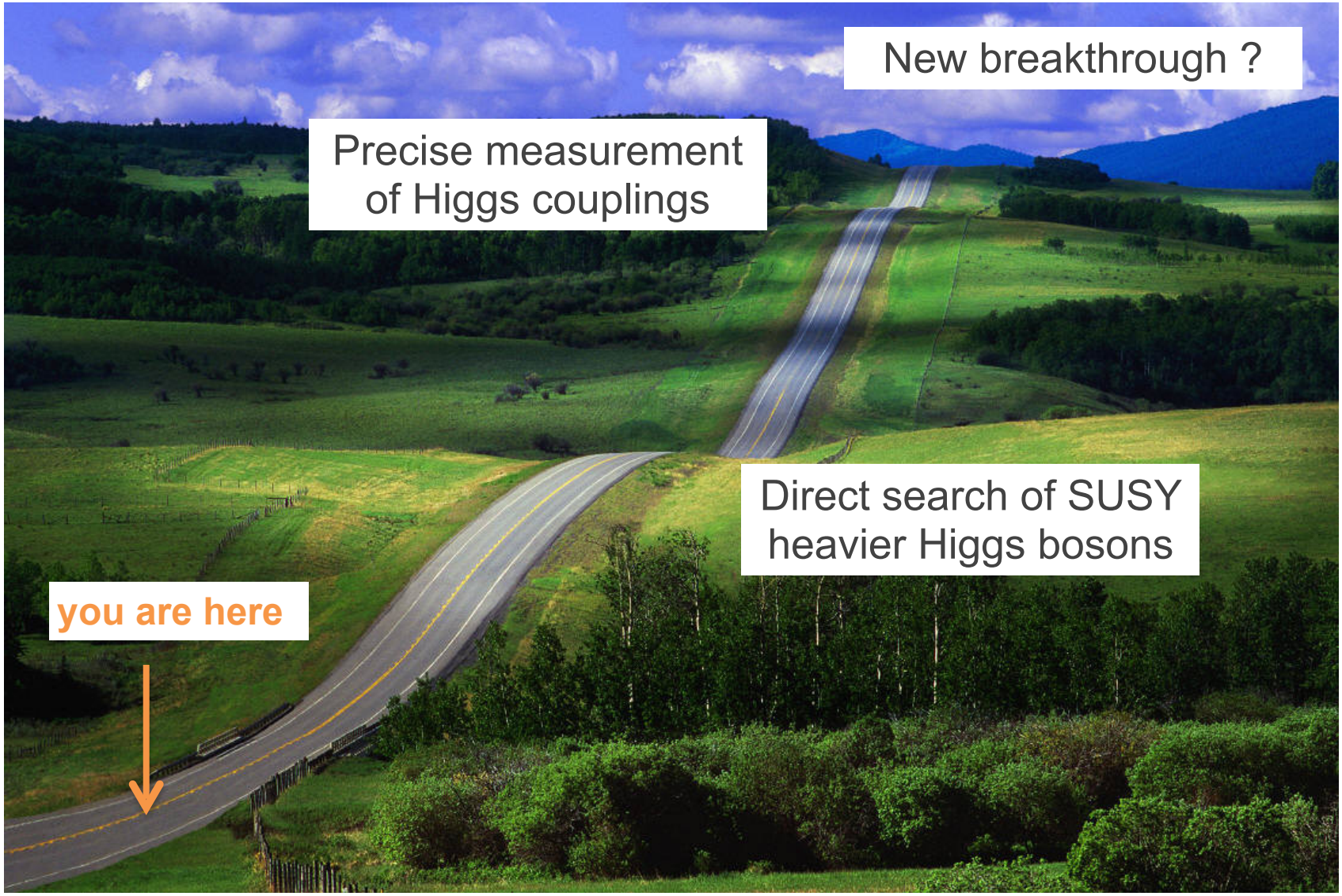
SM Higgs boson ?



First of a series of SUSY Higgs bosons ?

A 125 GeV SM-like Higgs boson was discovered

Summary


New breakthrough ?
Precise measurement of Higgs couplings
Direct search of SUSY heavier Higgs bosons
you are here

Key concepts in search design

Important aspects to design searches for a signal:

- rates of decay channels
- types of backgrounds and handles to kill them
- discriminating variables between signal and background (e.g. invariant mass spectrum vs MET spectrum vs score of a multi-variate classifier)
- event categorisation
- background estimation methods
- statistical interpretation: discovery (reject B-only hypothesis) or exclusion (reject S+B hypothesis)

Bibliography

All lectures

- Easy to read and accurate overview of the physics at the LHC:
  - “Physics at the LHC Run-2 and Beyond”, Andreas Hoecker, Lecture notes from the 2016 European School of High-Energy Physics, https://arxiv.org/pdf/1611.07864.pdf

SM/MSSM higgs bosons:

- Original papers, linked in the slides
- “Status of Higgs Boson Physics” , PDG 2018, http://pdg.lbl.gov/2018/reviews/rpp2018-rev-higgs-boson.pdf
  - VII.1 for MSSM higgs bosons
  - III.1 III.2, IV for SM Higgs boson

Additional material

Significance and corresponding p-value

$Z\ (\sigma)$	p
1.00	1.59×10^{-1}
1.28	1.00×10^{-1}
1.64	5.00×10^{-2}
2.00	2.28×10^{-2}
2.32	1.00×10^{-2}
3.00	1.35×10^{-3}
3.09	1.00×10^{-3}
3.71	1.00×10^{-4}
4.00	3.17×10^{-5}
5.00	2.87×10^{-7}
6.00	9.87×10^{-10}

The CLs method

Signal strength $\mu = \sigma/\sigma_{SM}$

test statistic q_μ

$$q_\mu = -2\ln\frac{L(obs|\mu,\hat{\theta}_\mu)}{L(obs|\hat{\mu},\hat{\theta})} \qquad 0 < \hat{\mu} < \mu$$

CL_{s+b} (s+b hypothesis)

$$\mathrm{CL_{s+b}} = P(q_\mu \geq q_\mu^{obs}|\mu \neq 0)$$

CL_b (b-only hypothesis)

$$\mathrm{CL_b} = P(q_\mu \geq q_\mu^{obs}|\mu = 0)$$

CL_s

$$\mathrm{CL_s} = \frac{CL_{s+b}}{CL_b}$$

The **exclusion of a SM Higgs boson** is defined by the following condition:

- **$CL_s(\mu = 1) \leq \alpha$** at **$1-\alpha = 95\%$** confidence level, C.L.

We can say that $s < s^{up}$ at 95% C L (or 90% CL)

Likelihoods

$$L(obs, \tilde{\theta}|\mu, \theta) = \prod_{c=1}^{N_{ch}} L_c(obs_c|\mu, \theta) \times \prod_{i=1}^{N_\theta} p_i(\tilde{\theta}_i|\theta_i)$$

If we are combining more channels, the overall likelihood is the product of the likelihood functions of each channel (L_c)

product of the response function of the measurement associated to the nuisance parameters (systematic uncertainties)

In case of a counting experiment

$$L(obs|\mu, \theta) = Poisson(n_{obs}, \mu \cdot s(\theta) + b(\theta))$$

Inputs:

- Signal yield, **s(θ)**
- Background yield, **b(θ)**
- Observed data, **n_{obs}**
- Systematic uncertainties on yields, **θ**

Likelihoods

$$L(obs, \tilde{\theta}|\mu, \theta) = \prod_{c=1}^{N_{ch}} L_c(obs_c|\mu, \theta) \times \prod_{i=1}^{N_\theta} p_i(\tilde{\theta}_i|\theta_i)$$

If we are combining more channels, the overall likelihood is the product of the likelihood functions of each channel (L_c)

product of the response function of the measurement associated to the nuisance parameters (systematic uncertainties)

Including informations from the shape

$$L(obs|\mu, \theta) = Poisson(n_{obs}, \mu \cdot s(\theta) + b(\theta)) \prod_{i=1}^{n_{obs}} f(x_i|\mu, \theta)$$

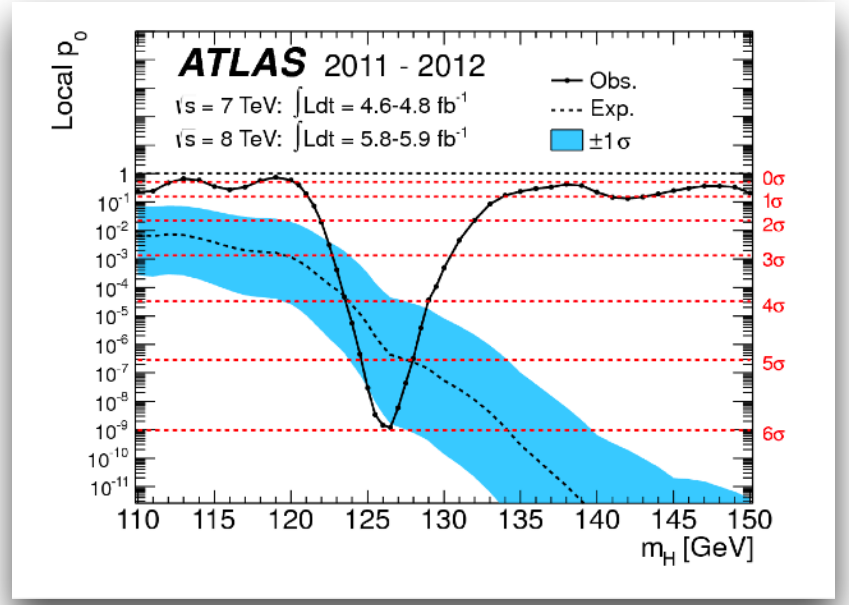
$$f(x_i|\mu, \theta) = \mu s(\theta) f_s(x_i, \theta) + b(\theta) f_b(x_i, \theta)$$

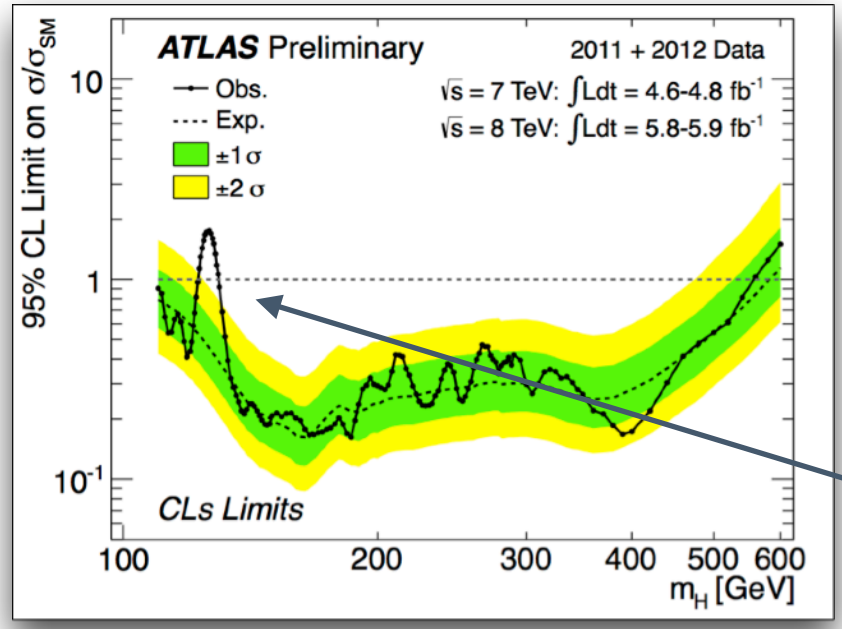
Inputs:

- Signal yield and shape, **$s(\theta)$** and **$f_s(x, \theta)$**
- Background yield and shape, **$b(\theta)$** and **$f_b(x, \theta)$**
- Observed data, **n_{obs}**
- Systematic uncertainties on yield and shape, **θ**

Combining all channels together

- Combining together results from Higgs boson searches in 5 decay modes: **H→γγ, H→ZZ, H→WW, H→bb, H→ττ**
- Early Summer 2012: sufficient statistics collected to claim the **observation of a new boson**

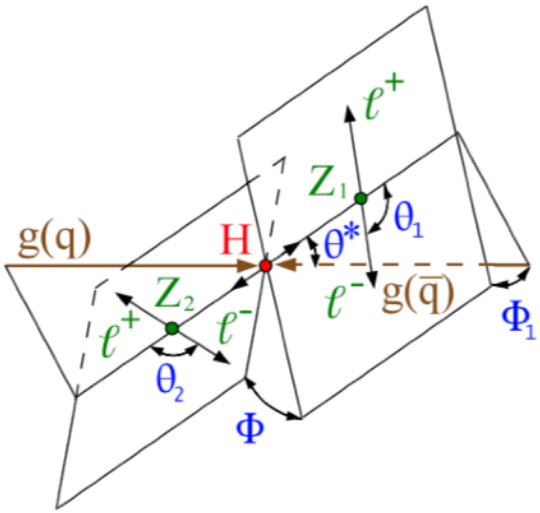




Observed excess of 7 σ around 125 GeV

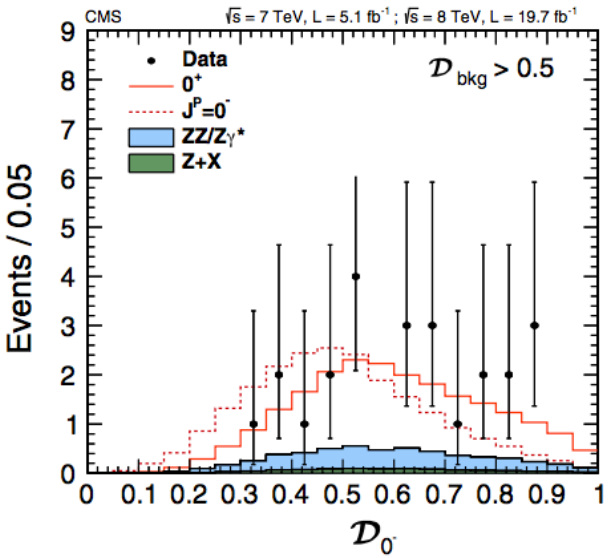
Clear excess in the upper limit plot ~ 125 GeV

H →4l - Spin and parity

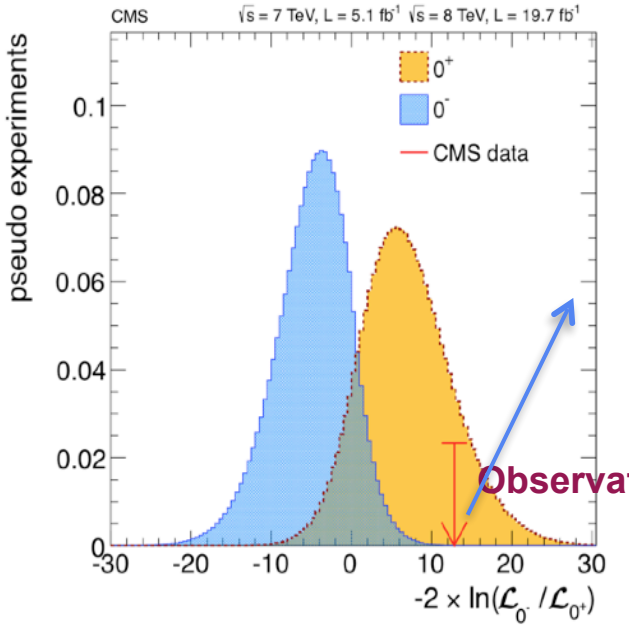


Kinematics of 4l final states of H→ZZ decay 4l can tell something about which is the best spin-parity (J^P) hypothesis

- SM requires H to be a CP-even scalar (0^+)
- Other hypothesis are tested:
  - 0^- excluded at 99.95% C.L.
  - $1^+,1^-$ / $2^+,2^-$ excluded with higher / similar level of confidence
-



example discriminant

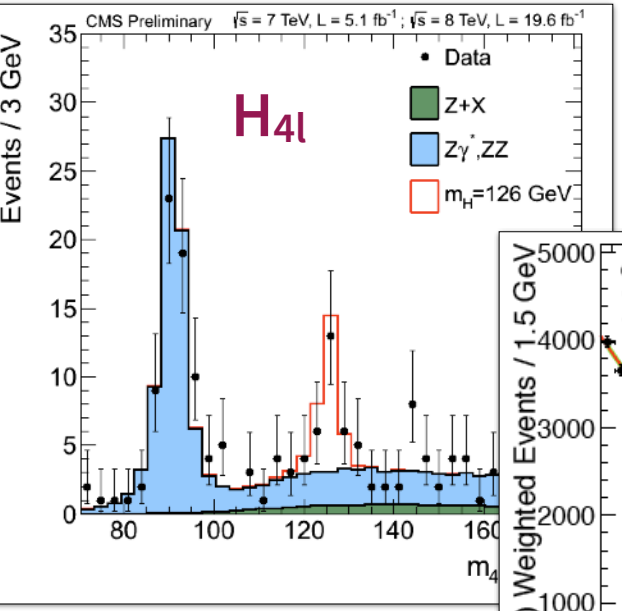


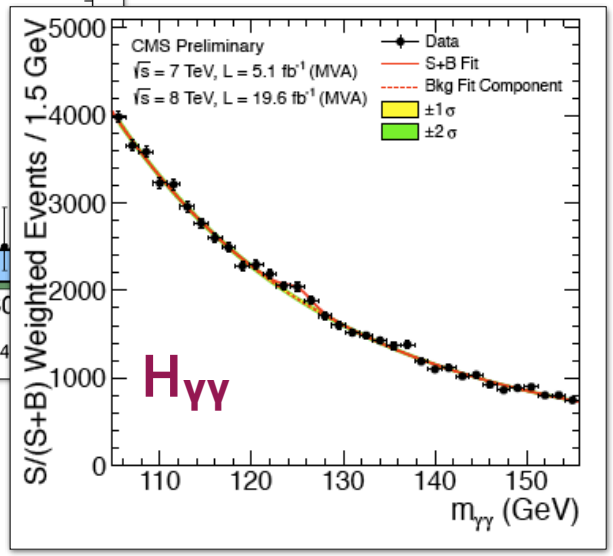
combining all discriminants

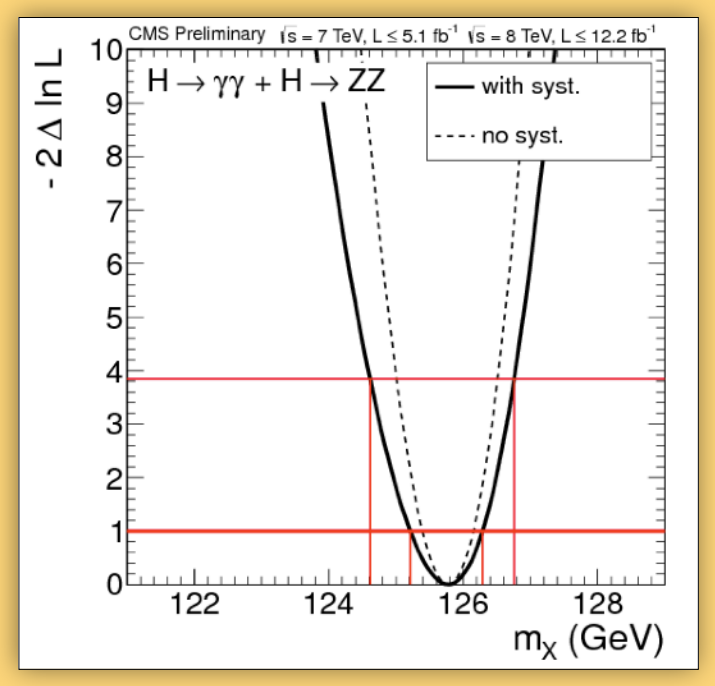
p-value = 0.05%
probability to observe in a future experiment a larger incompatibility with the 0- hypothesis

Mass measurement of the new boson

High resolution channels, H→γγ and H→ZZ→4l, allowed already in early 2012 to get a good estimate of Higgs boson mass





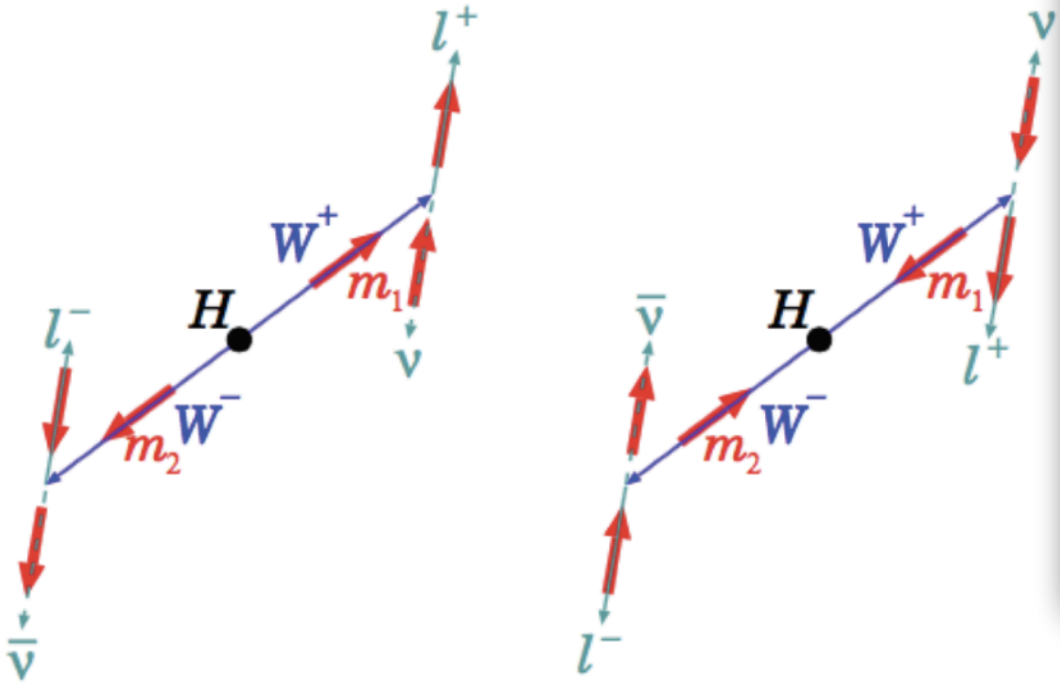


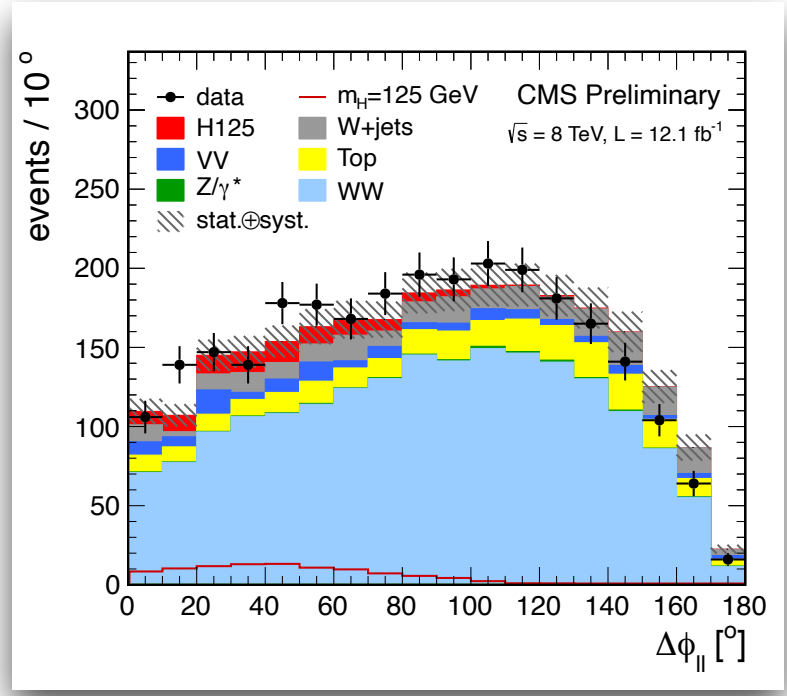
Measurement of the observed boson mass:

$m_H = 125.8 \pm 0.4^{(stat)} \pm 0.4^{(syst)}$ GeV

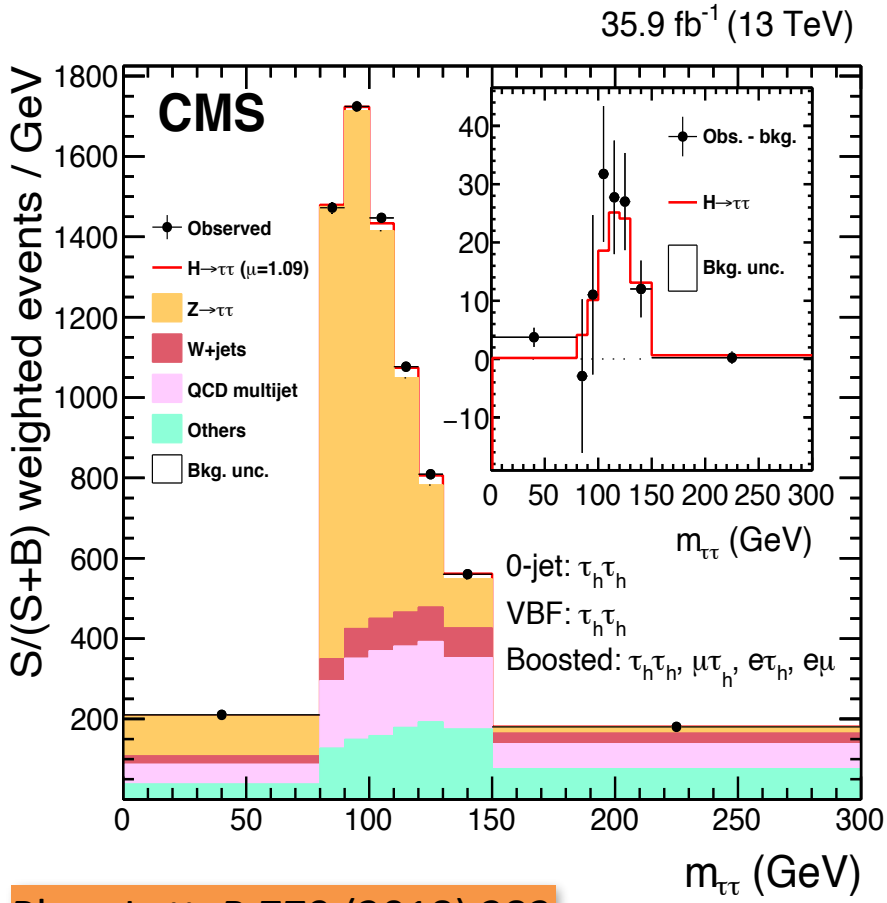
H→WW→ℓνℓν: spin properties

If the Higgs boson **has spin 0**, the **two leptons** expected to be **emitted in the same direction** (small azimuthal opening between the two)





H →ττ @ 13 TeV



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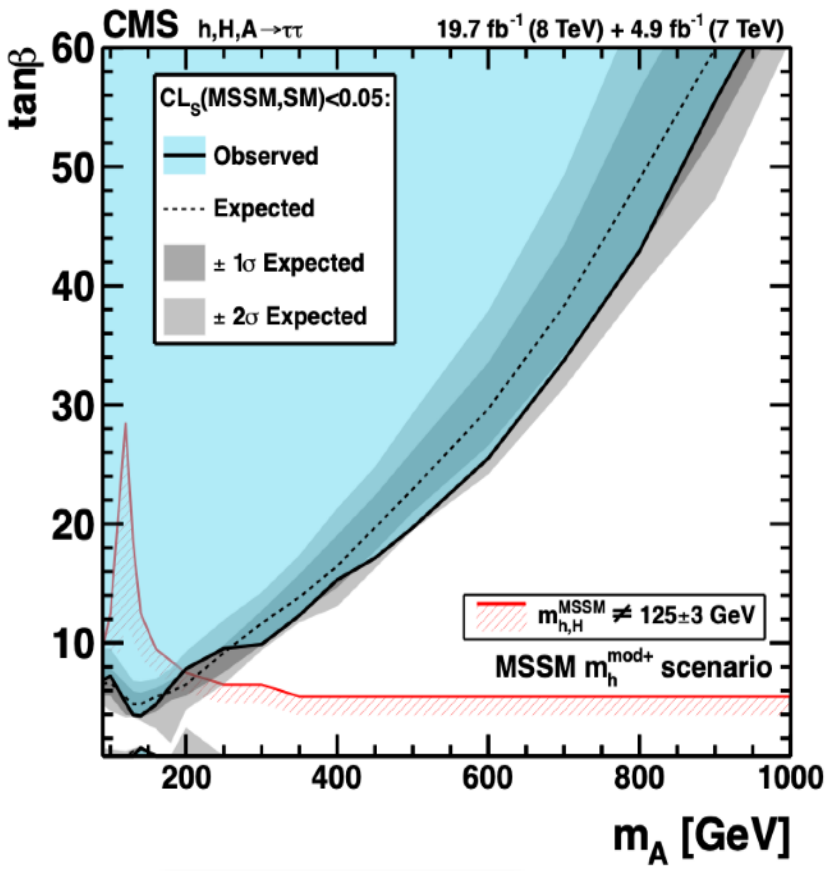
Significant cross section
but again a poor mass resolution

4.9σ @ m_H = 125 GeV

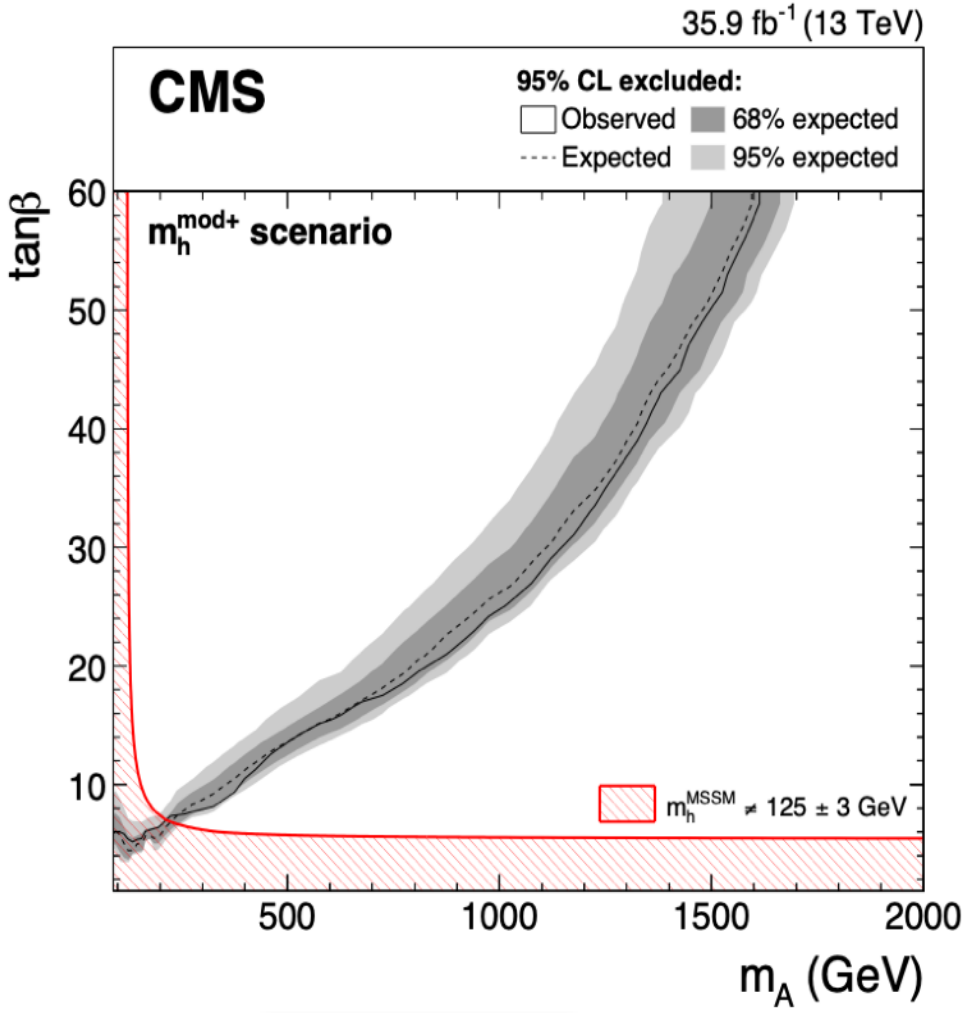
μ = 1.09 ± 0.27

exceed 5 sigma when combined
with 7+8 TeV analysis

A/H → ττ: interpretation



JHEP10(2014)160



JHEP09(2018)007

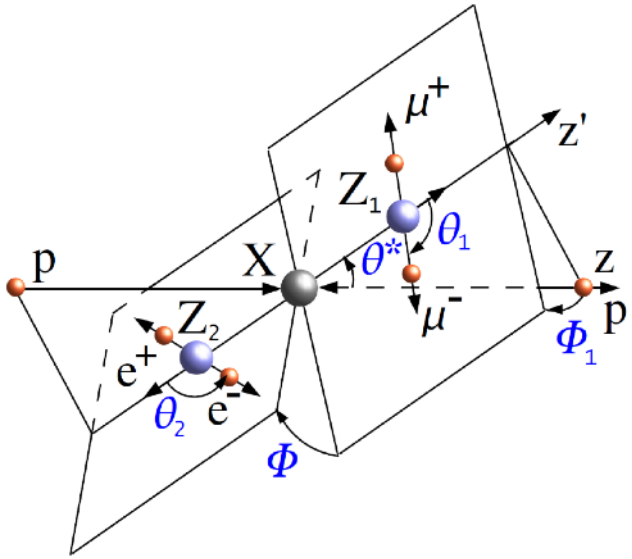
H→ZZ*→4l: Kinematical discriminant

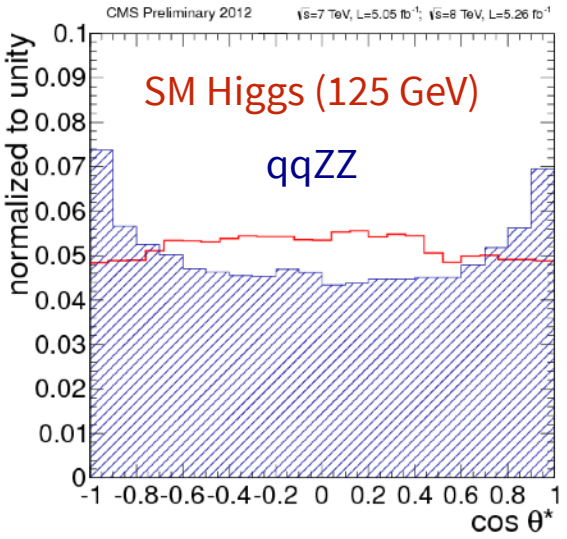
Matrix **E**lement **L**ikelihood **A**nalysis (**MELA**)

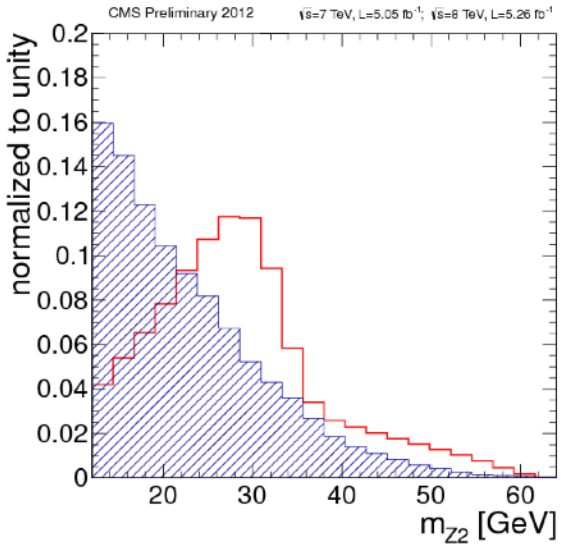
uses kinematic inputs for signal to background discrimination

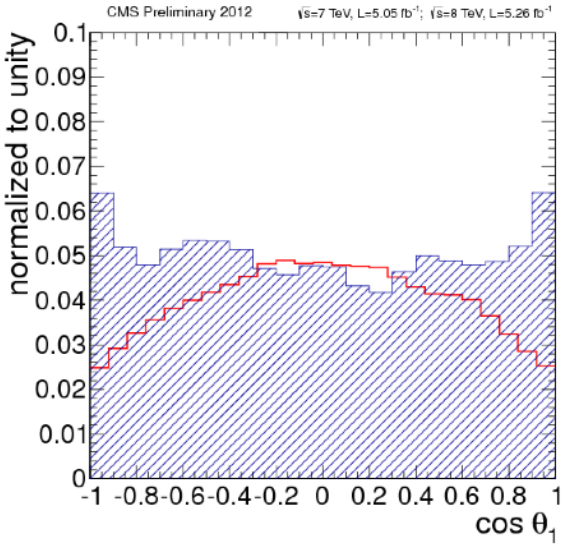
{m_1, m_2, θ_1, θ_2, θ^*, Φ, Φ_1}

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$









H→ZZ*→4l: Kinematical discriminant

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)

