Higgs Search Prospects for CMS

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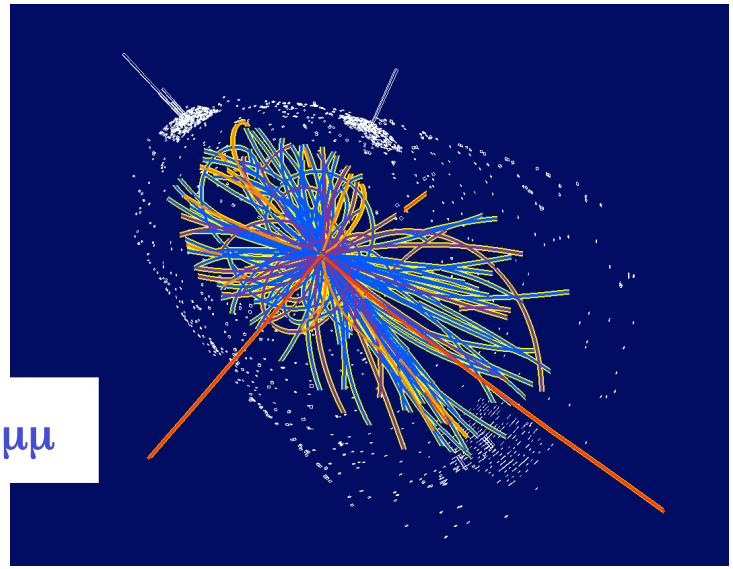


H->ZZ->ee μμ

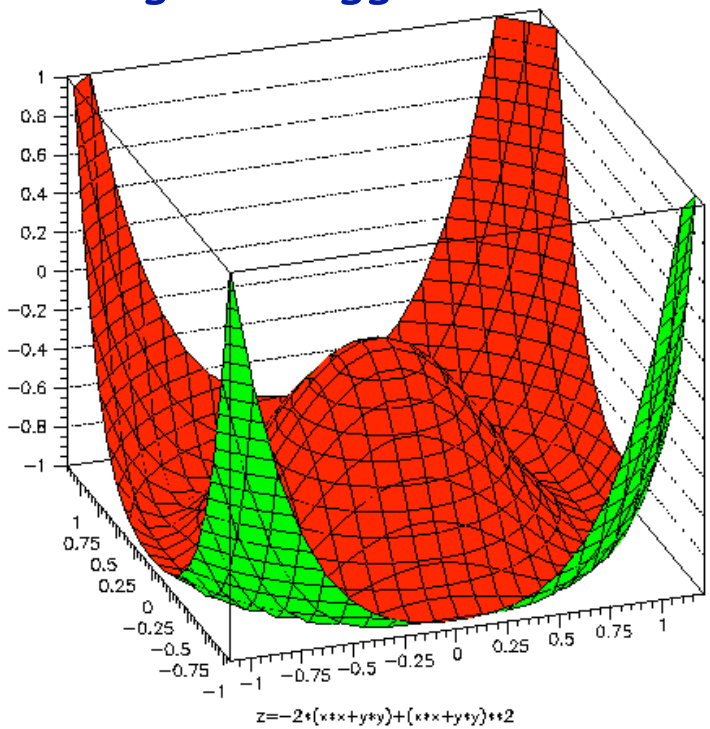
Electro-Weak Symmetry Breaking (EWSB)

- Why are the masses of the fundamental particles not equal to zero
  ⇒ Electroweak Symmetry breaking
  - EWSB mechanism requires (at least) one new particle
  - energy scale of EWSB must be ~ TeV to preserve unitarity of V-V (V=W, Z) scattering matrix
- Current wisdom: SB mechanism generates Goldstone bosons → longitudinal degrees of freedom for W & Z
  - But underlying nature of dynamics not known → traditionally:two possibilities: weakly-coupled and strongly-coupled dynamics

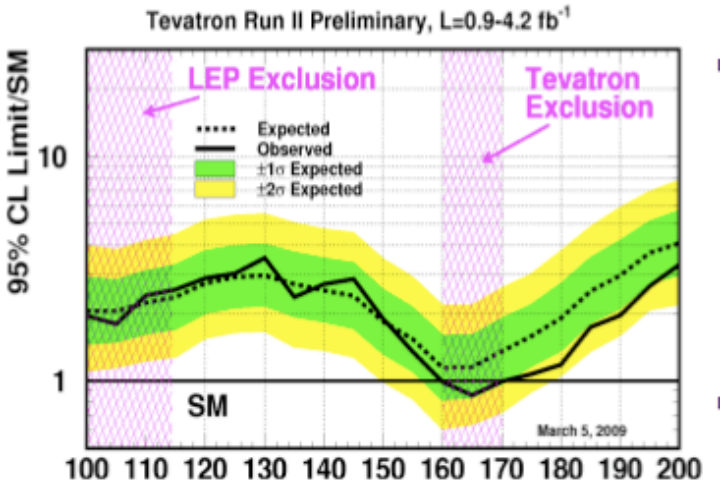
- Weakly-coupled: self-interacting scalar fields: E.g the BEH (Higgs) field
  - Self-interaction → non-vanishing vacuum expectation value
  - Then: interactions with bosons/fermions → gives mass to them
  - Must stabilize mass of the field → some additonal mechanism (SUSY?)
    - New ideas: whole new "world": extra space dimensions
- Strongly-coupled: new strong interaction at ~TeV scale
  - Fermion-antifermion pair condensates

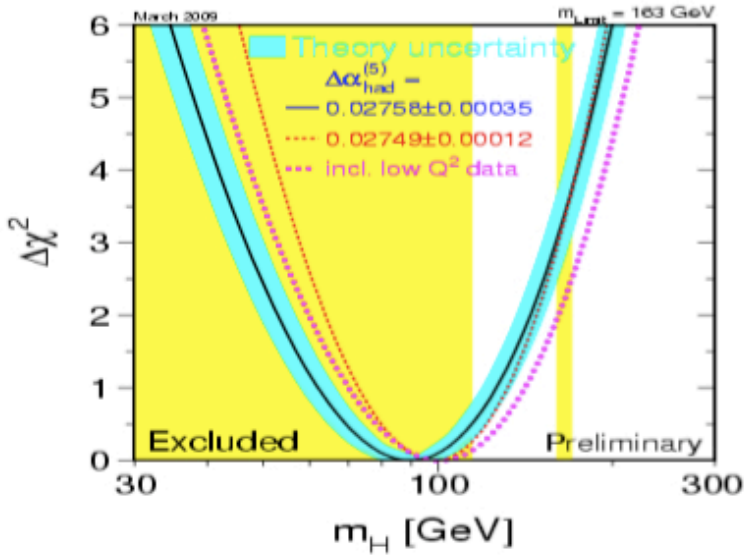
The BEH Mechanism!(*)

(*)Brout-Englert-Higgs

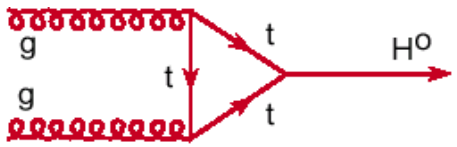


⇒At least one BEH particle, called "Higgs" from now on..

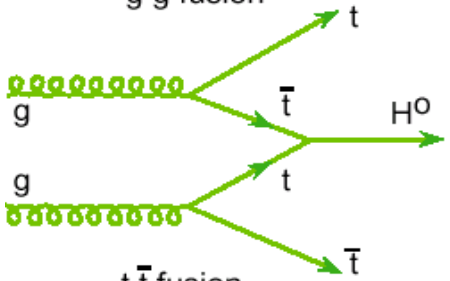




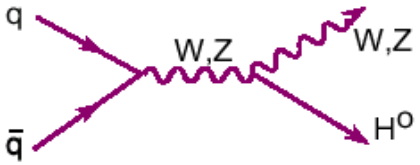
The SM Higgs @ the LHC



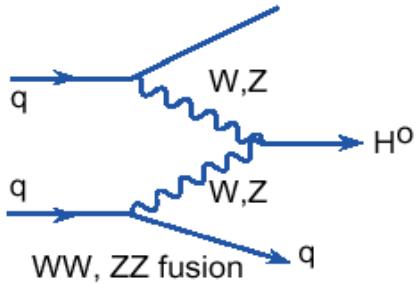
g g fusion



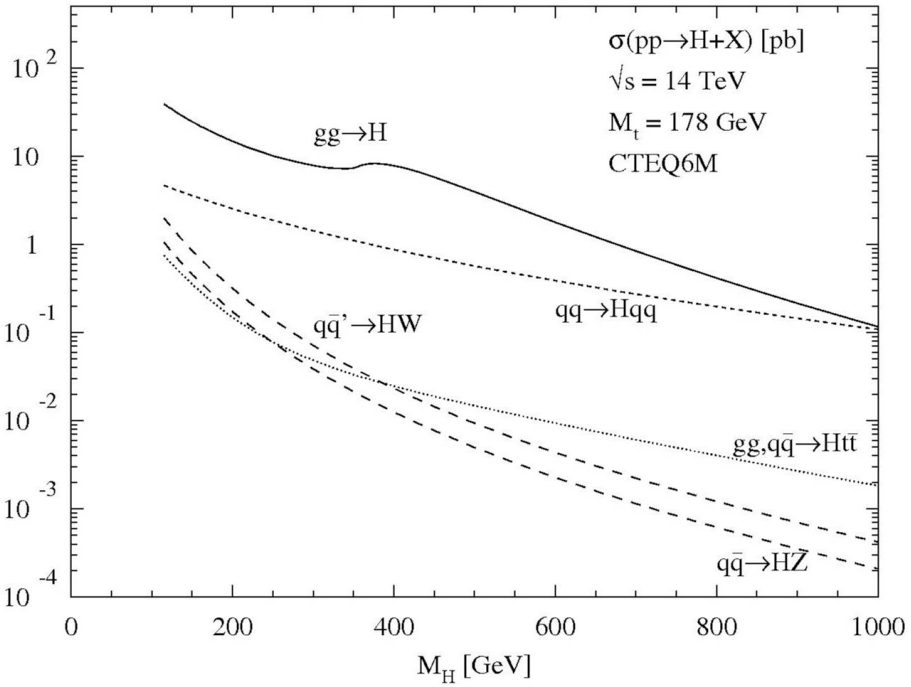
t t̄ fusion

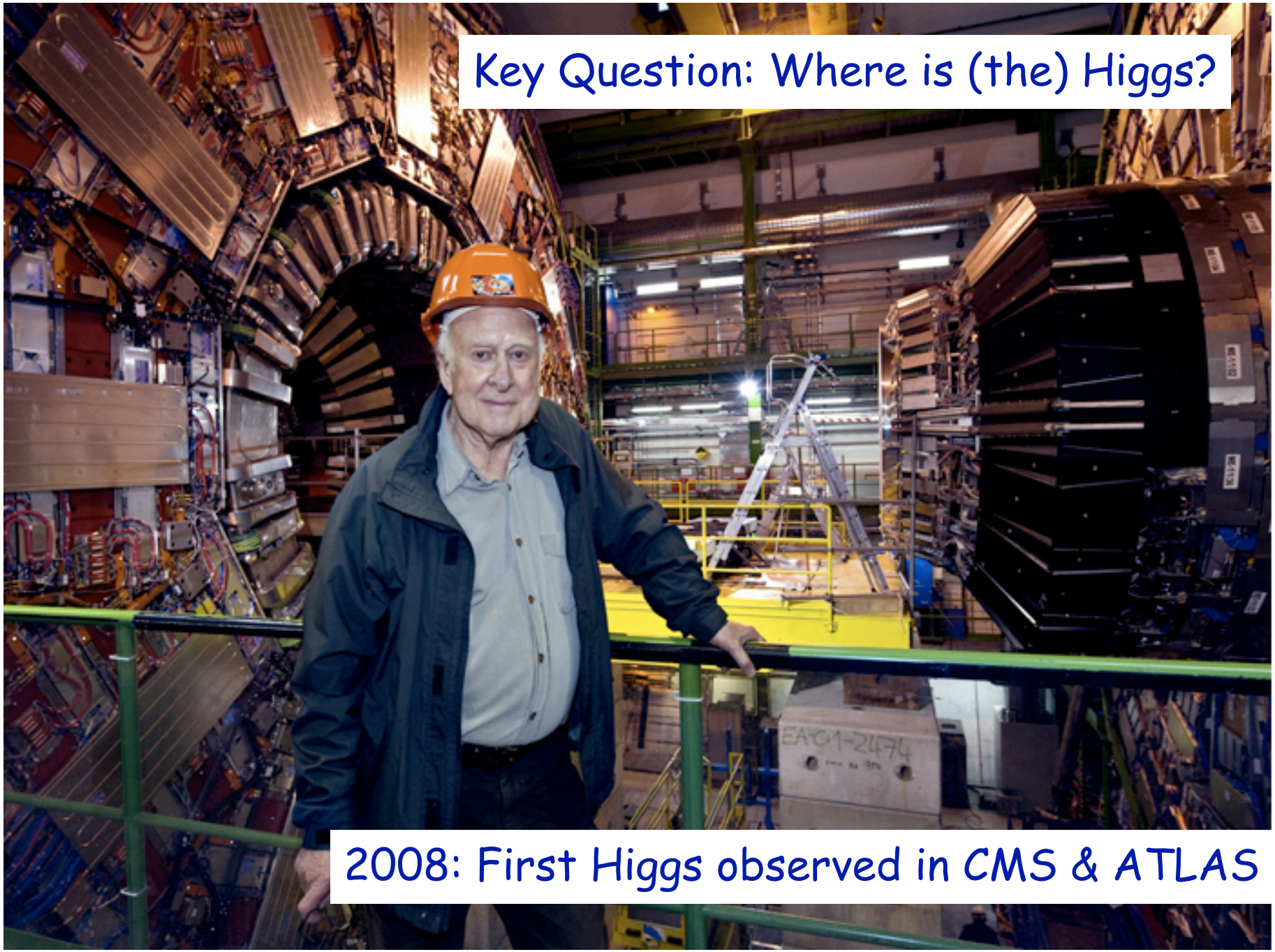


W, Z bremsstrahlung



WW, ZZ fusion

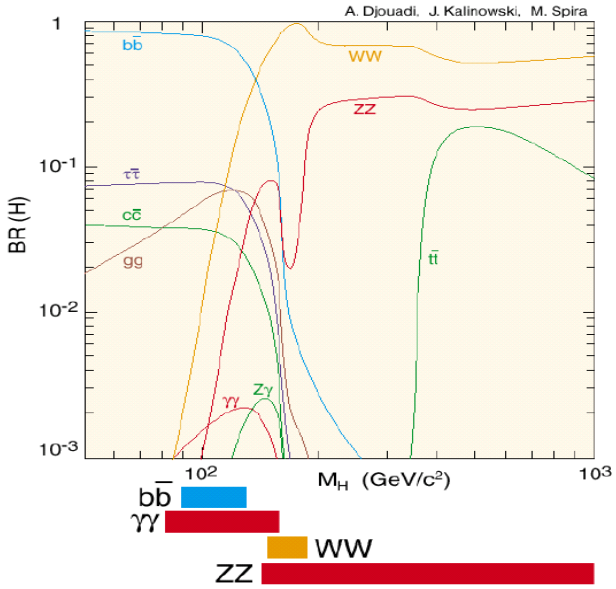



Key Question: Where is (the) Higgs?
2008: First Higgs observed in CMS & ATLAS

SM Higgs Search Channels

Low mass $M_H \lesssim 200$ GeV

Production DECAY	Inclusive	VBF	WH/ZH	ttH
$H \to \gamma\gamma$	YES	YES	YES	High lumi
$H \to bb$			YES?	High lumi
$H \to \tau\tau$		YES		
$H \to WW^*$	YES	YES	YES	
$H \to ZZ^*$, $Z \to \ell^+\ell^-$, ℓ=e,μ	YES			
$H \to Z\gamma$, $Z \to \ell^+\ell^-$, ℓ=e,μ	very low σ			



Intermediate mass
(200 GeV ≲ M_H ≲700 GeV)

inclusive $H \to WW$
inclusive $H \to ZZ$

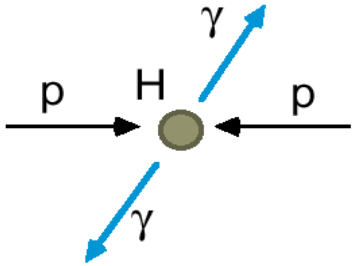
High mass ($M_H \gtrsim 700$ GeV)

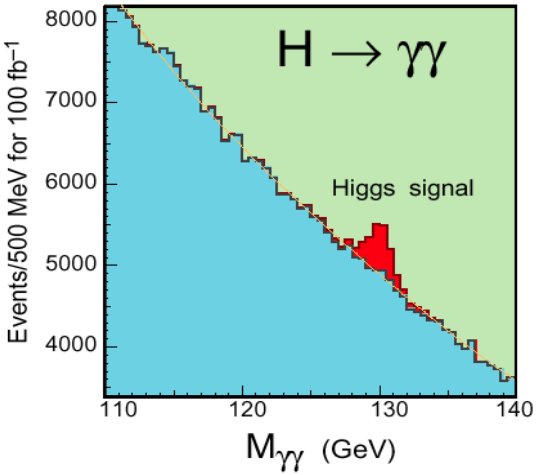
VBF $qqH \to ZZ \to \ell\ell\,\nu\,\nu$
VBF $qqH \to WW \to \ell\,\nu\,jj$

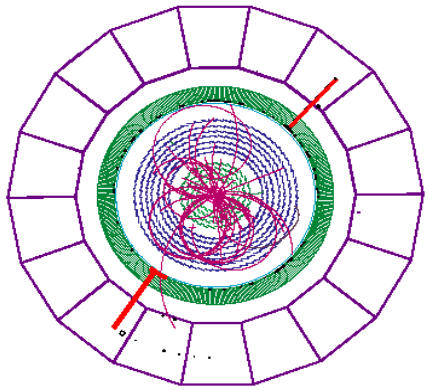
$H \to \gamma\,\gamma$ and $H \to ZZ^* \to 4\ell$ are the only channels with a very good mass resolution ~1%

Higgs Searches

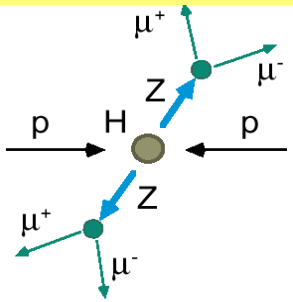
Low M_H < 140 GeV/c²

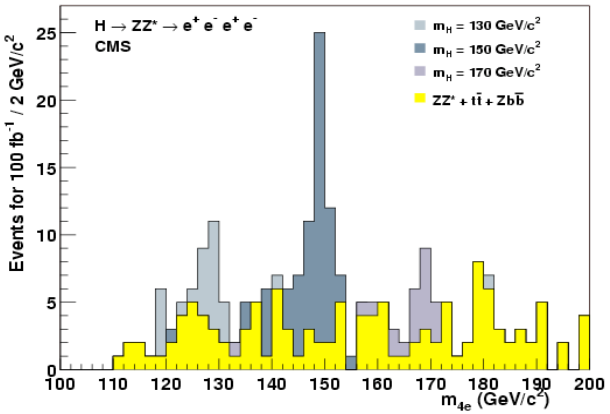


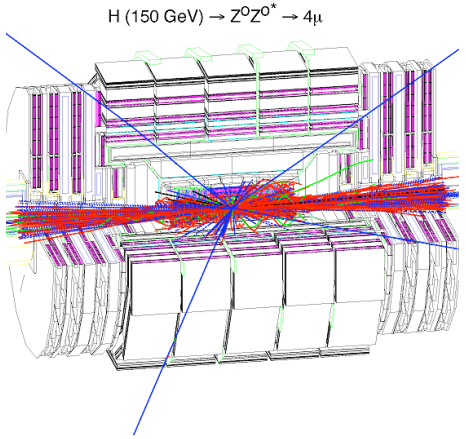




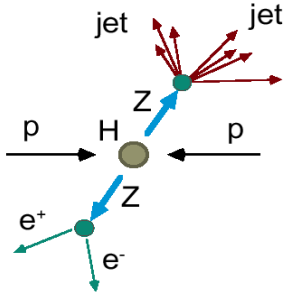
Medium 130<M_H<500 GeV/c²

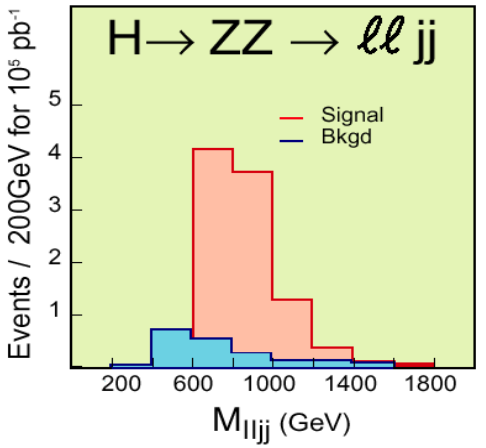


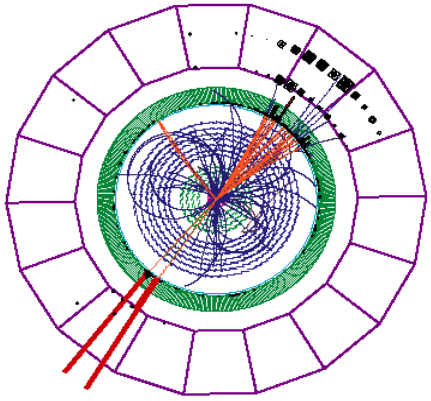




High M_H > ~500 GeV/c²



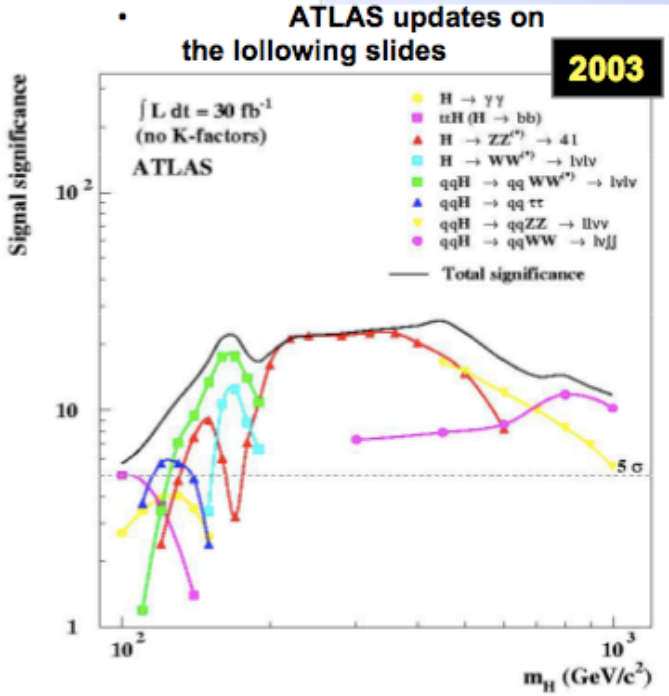


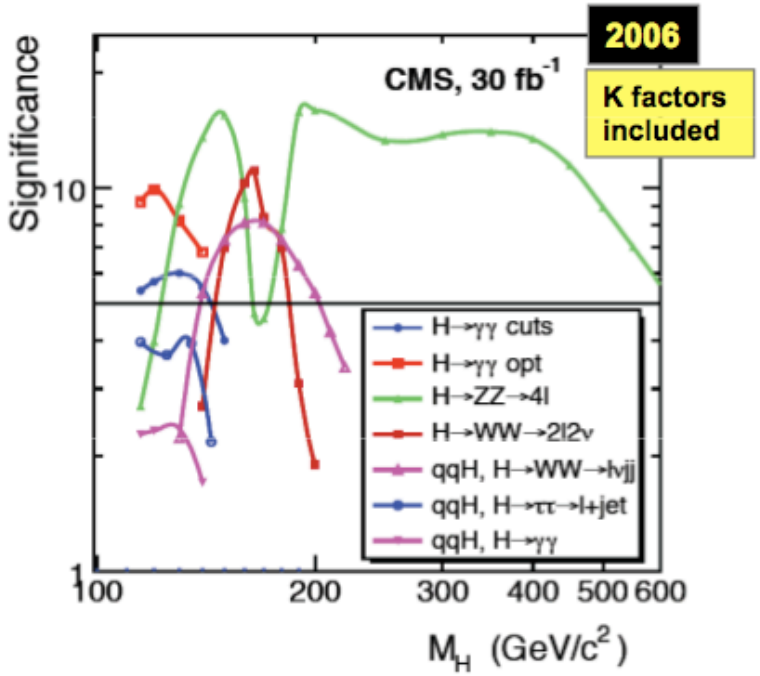


High Luminosity Studies

Assume O(10) fb^{-1} or more

SM: Higgs @ LHC: prospects ~ 2006





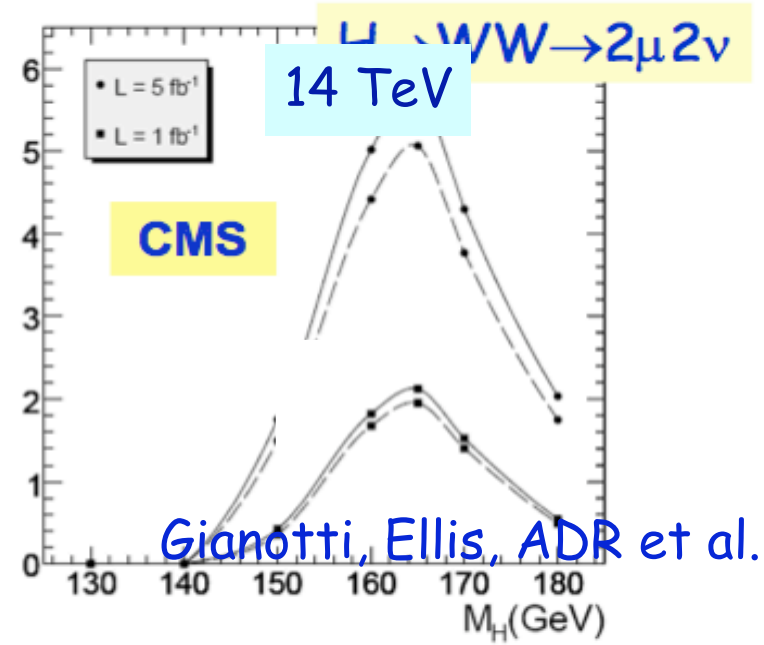
Lead channels (forerunners)

mass	~120	~140	~160	190-600
ATLAS 2003	VBF, H→ττ incl., H→γγ	VBF, H→WW*	VBF, H→WW	incl., H→ZZ
CMS	incl., H→γγ	incl., H→ZZ*	incl., H→WW	

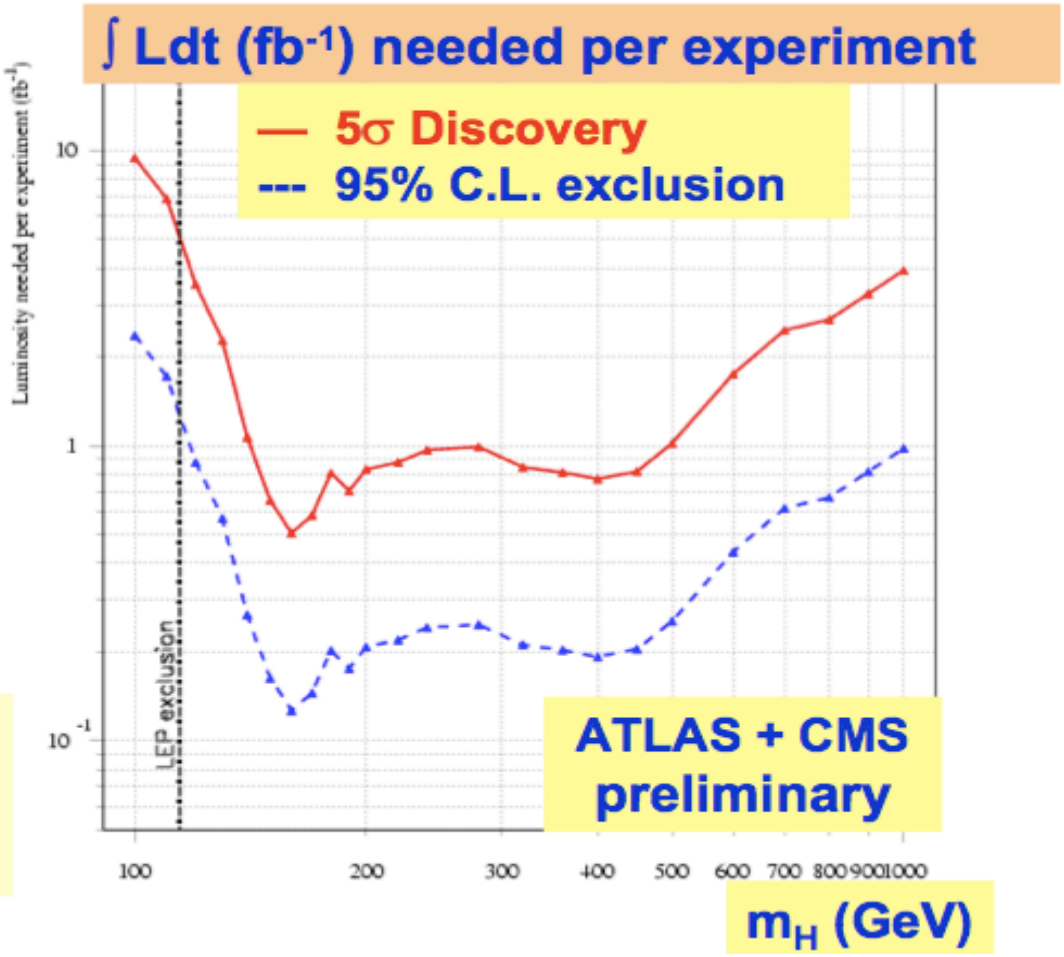
CMS has to extended the VBF qq→qqH, H→ττ and WW* inclusive channel

Combining experiments…

Possible observation (a
part of parameter space



ace will be on understanding
f detector, physics objects
nd bkg measurement

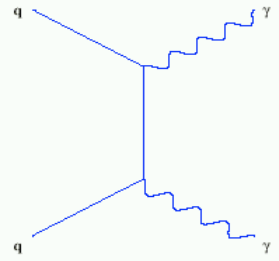


Note: ATLAS+CMS combination at an early stage is taken very seriously

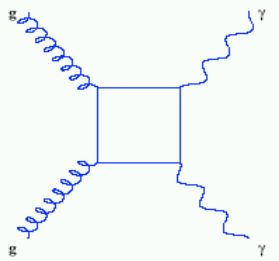
Higgs →γγ

Still a main search channel. Summary in the PTDR (2006)

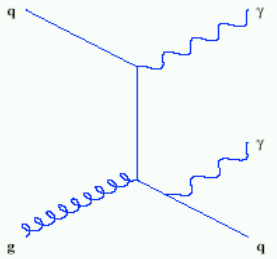
- More complete study of the backgrounds, K factors
- Optimized analysis (Neural Network)



born



box



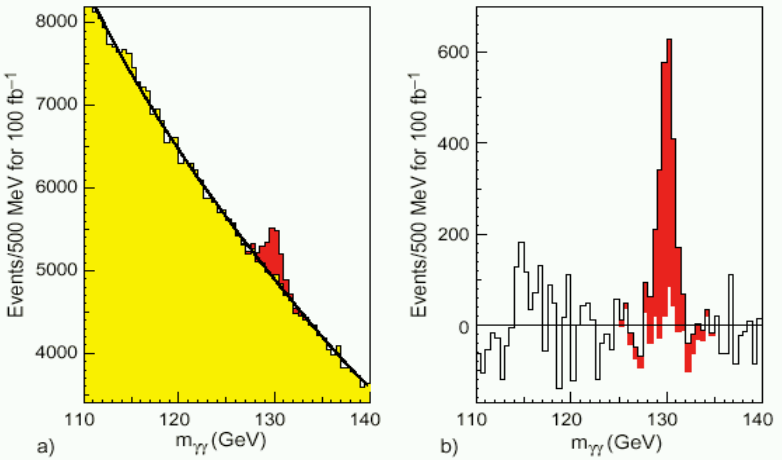
isol. brem

γ+j, j->π^0

j+j, jj->$2\pi^0$

was not in ECAL TDR

ECAL TDR plots, L=10^{34}cm^{-2}s^{-1}



	ECAL TDR K factors	current K factors: DIPHOX(NLO) / PYTHIA
born	1	1.50 , uncertainty 10-20 %
box	1.85	1.20, uncertainty 10-20 % (Dixon et al)
isolated brem	1	1.72, uncertainty 20-30 %
γ+j, j->π^0	not simulated	1.00, uncertainty 30-40 %
j+j, jj->$2\pi^0$	not simulated	unknown; work in progress

CMS H→γγ Analysis

Optimized analysis
Use event kinematics, event classification etc..
⇒ Improve sensitivity by factor 1.4-2

Use Mass and a Neural Net

[NN inputs: $E_{T1}/M\gamma\gamma$, $E_{T2}/M\gamma\gamma$, $|\eta_1 - \eta_2|$, P_L (pair), Isol. of γ]

to separate signal from the backgrounds

Plot each event versus:

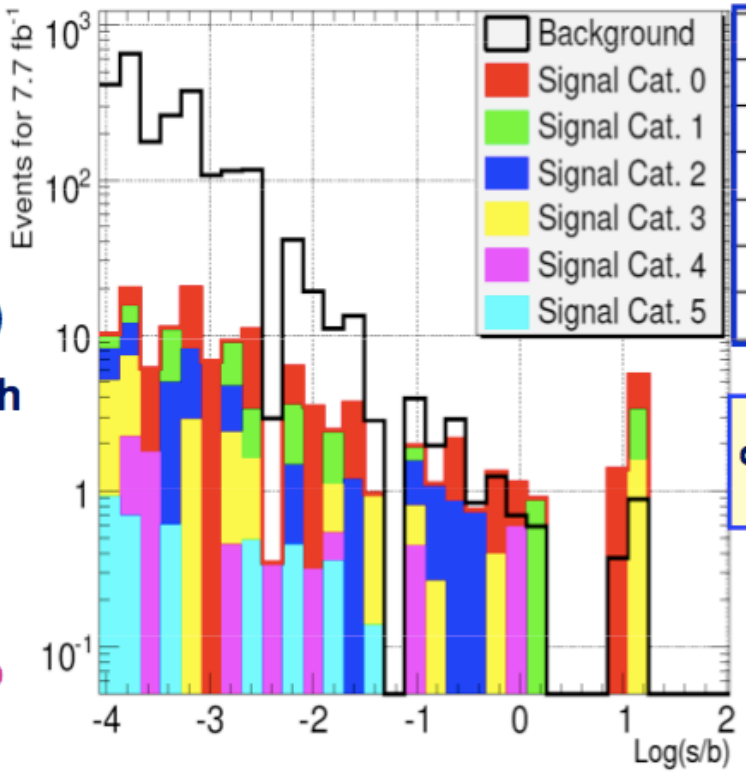
Ln (s/b) = Ln(s/b$_{Mass}$ X s/b$_{Kin}$)

for the background and each of 6 signal categories:

0: R9 > 0.948 Barrel
1: 0.948 > R9 > 0.9 Barrel
2: 0.9 > R9 Barrel
3: R9 > 0.948, 1 in ECap
4: 0.948 > R9 > 0.9, 1 in ECap
5: 0.9 > R9, 1 in ECap

Jet and π^0 bckgds. tend to go into lower R9 categories

M_H = 120 GeV, L= 7.7 pb^{-1}



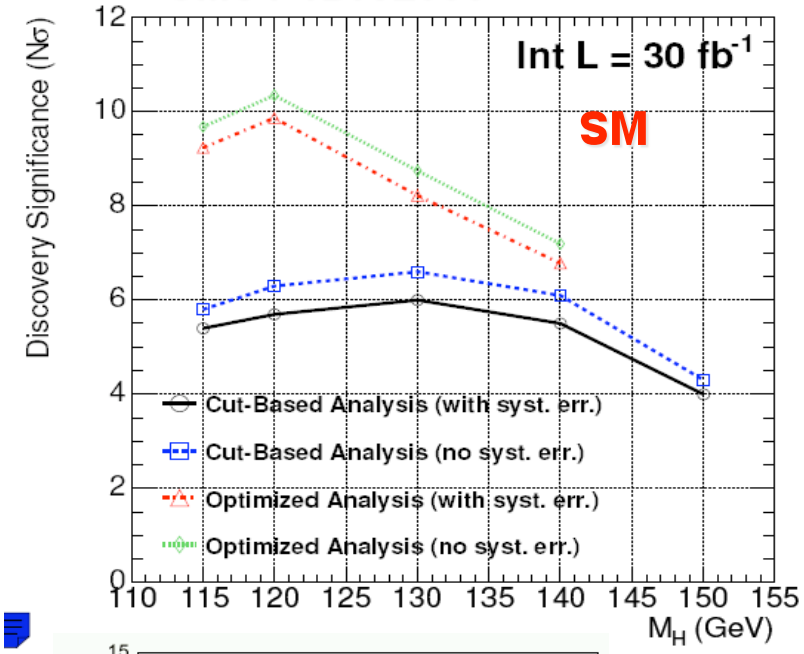
Signal %	LLR %
27.8	48.0
16.1	24.8
21.7	11.9
16.6	9.7
9.0	4.1
8.8	1.5

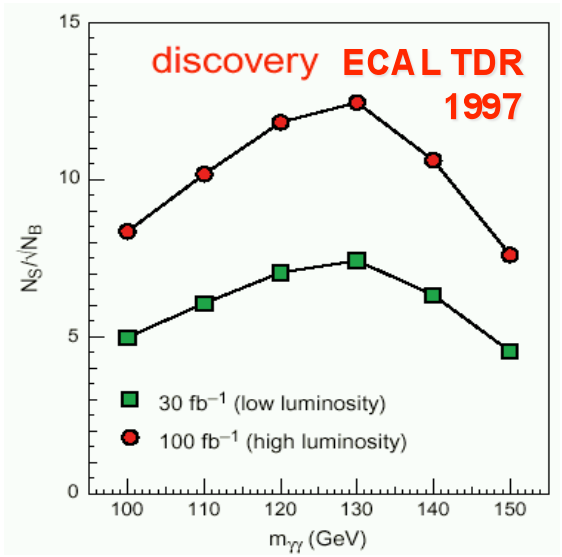
Contribution of each category to signal & LLR

See CMS NOTE-2006/112

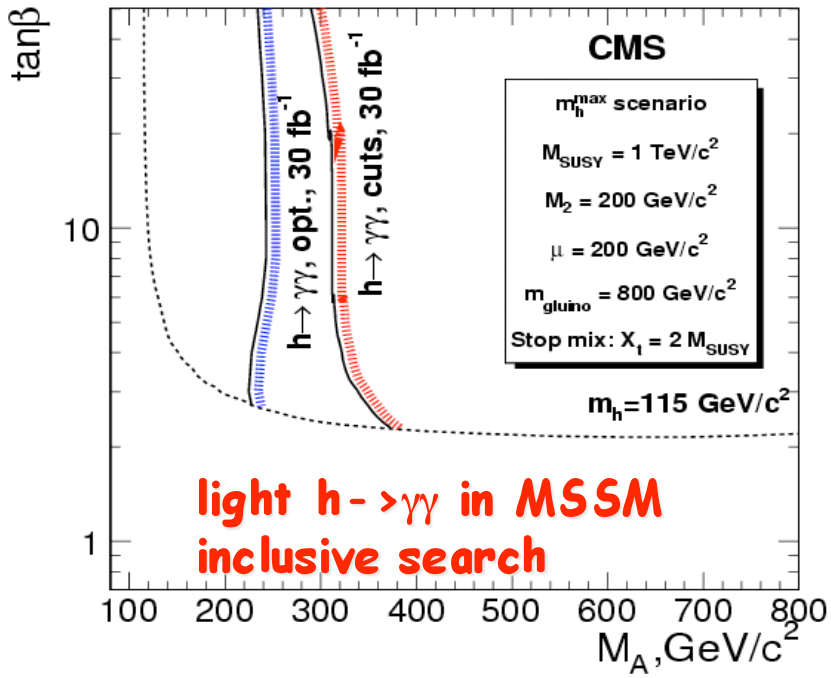
Discovery potential for Higgs→γγ

CMS PTDR 2006





CMS PTDR 2006

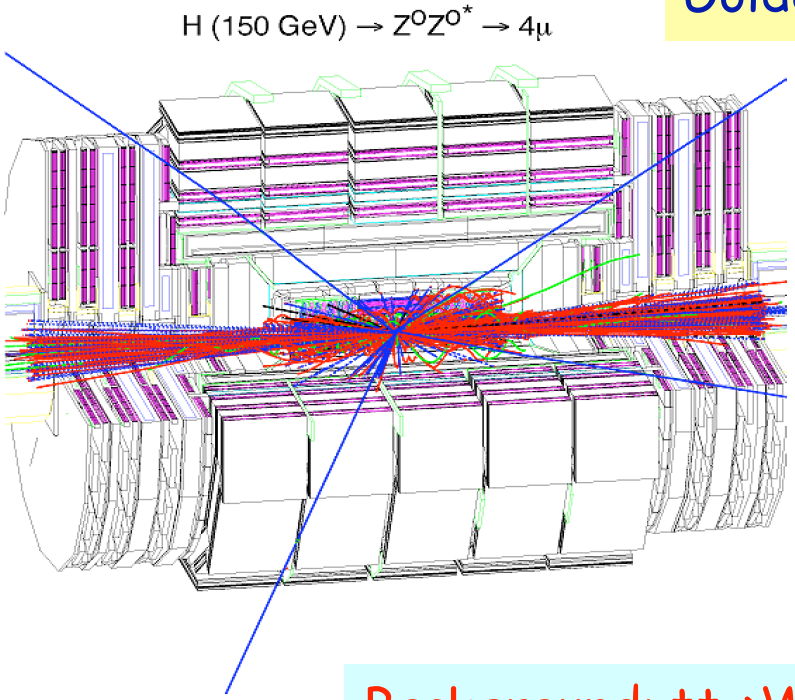


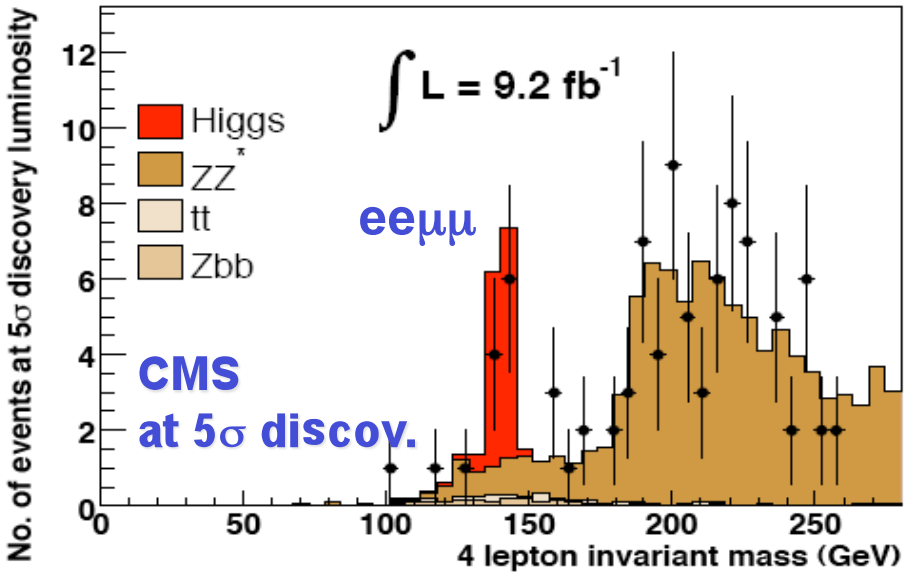
Significance for SM Higgs M_H=130 GeV for 30 fb^{-1}

ECAL TDR	Phys TDR 2006	
count. exp	cut based	optimized
~ 7.5	6.0	8.2

Higgs →ZZ→μμμμ,μμee, eeee

Golden mode: allows to fully reconstruct the Higgs





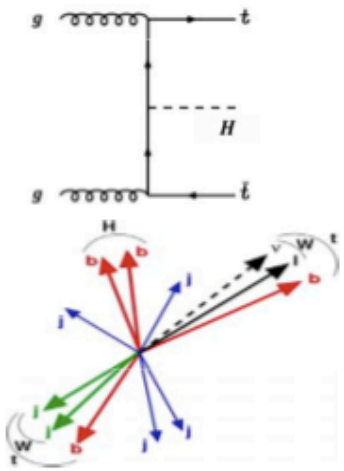
Background: tt->WbWb->llννbb,
ZZ->4l, llbb ("Zbb")

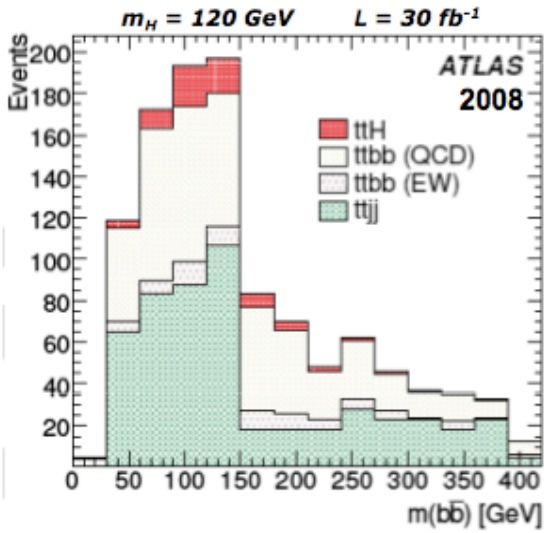
Selections :

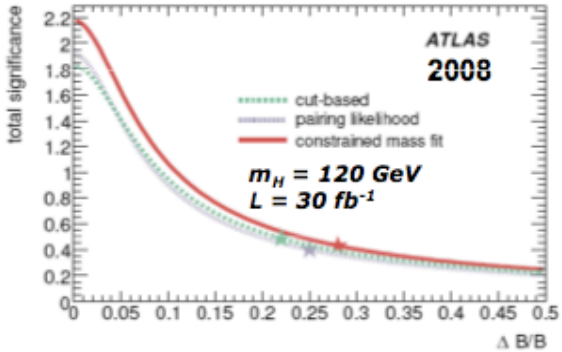
- lepton isolation in tracker and calo
- lepton impact parameter, μμ, ee vertex
- mass windows $M_{Z(*)}$, M_H

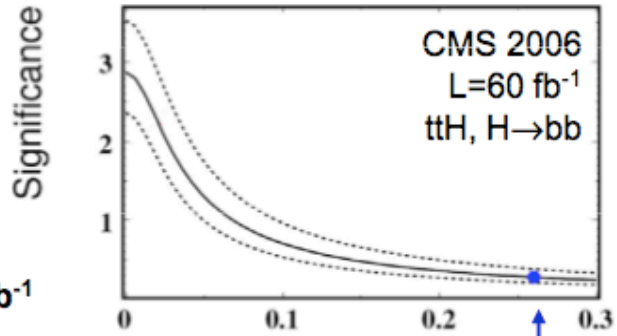
The Channel ttH with H→bb ⇒ R.I.P?

ttH is (was?) the best bet to see H→bb









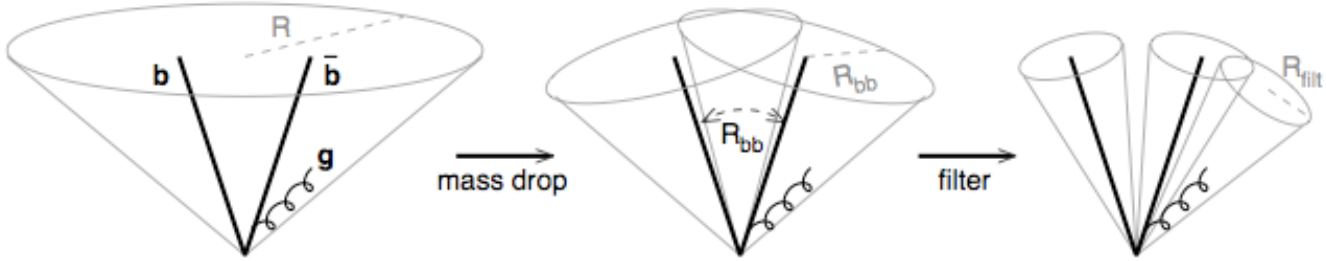
- **Early projections:** might be observable already at L=30 fb^{-1}
- **CMS-2006 analysis:**
  - systematic error control at a percent level is needed—not feasible...
- **ATLAS-2008 analysis:**
  - same conclusions

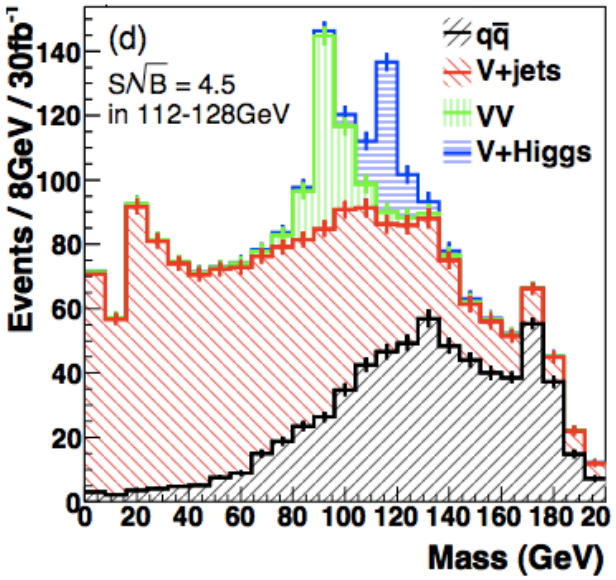
current estimate of background uncertainties
jet energy scale (3-10%)
jet energy resolution (10%)
b/c-tag efficiency (4%)
uds/g-tag efficiency (10%)
luminosity (3%)

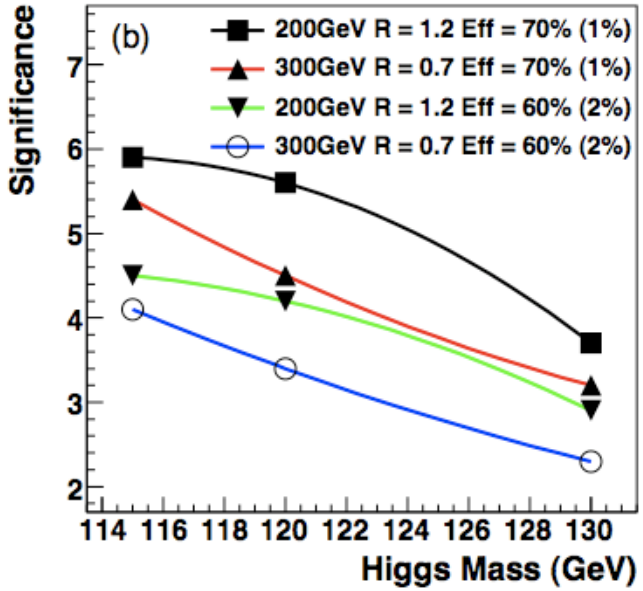
Perhaps ttH with H→γγ will be observable but with O(100) fb^{-1}

So is H→bb Hopeless? Maybe not…

- New idea from Butterworth et al. arXiv:0802.2470
- Use high P_T associated WH production
- Use subjet analysis techniques & recover WH for O(30 fb^{-1})



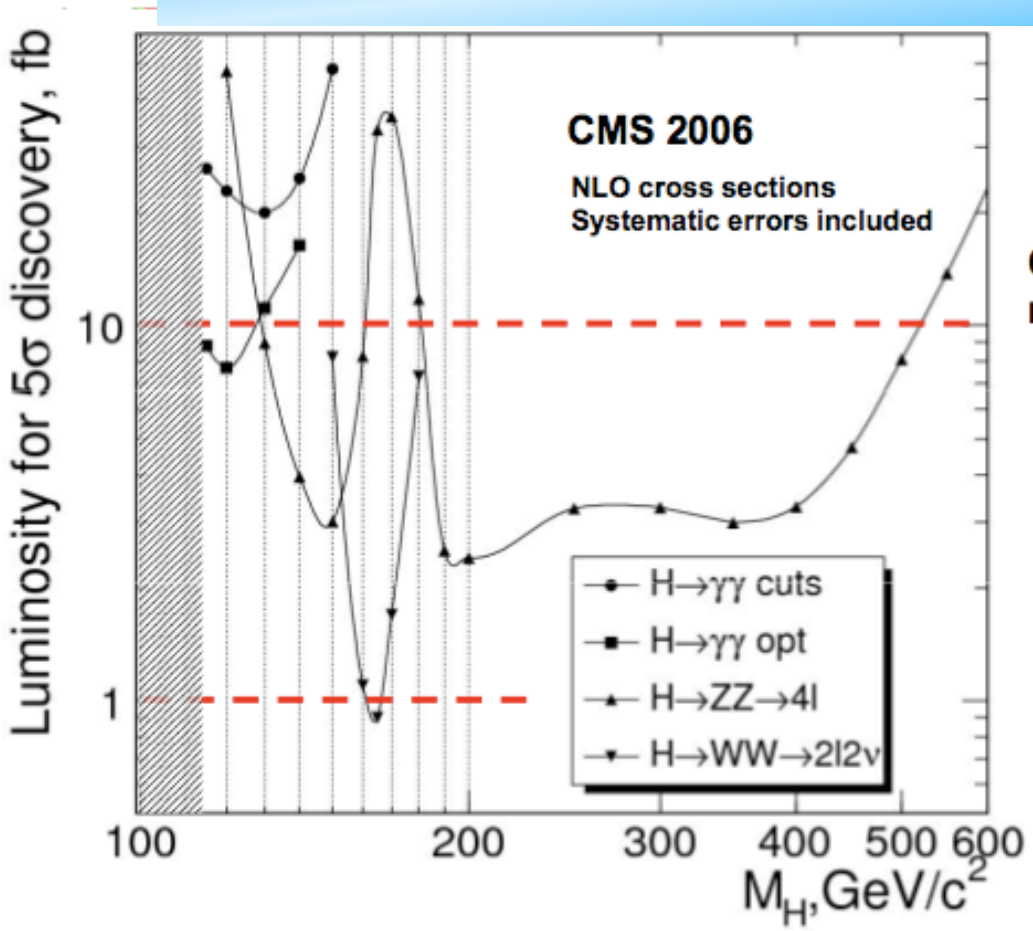




Detailed detector studies needed

+Exclusive production

CMS Reach Summary



CMS and ATLAS different at low mass region, ~agree elsewhere

Most important channels

Benchmark luminosities:

- **0.1 fb^{-1}: exclusion limits will start carving into SM Higgs cross section**
- **1 fb^{-1}: discoveries become possible if M_H~160-170 GeV**
- **10 fb^{-1}: SM Higgs is discovered (or excluded) including low mass range (CMS)**

First Physics in 2010

$\Rightarrow$30-50 pb^{-1} at 7 TeV ?

$\Rightarrow$200 pb^{-1} at 10 TeV ?

First, we have to "re-discover" the Standard Model
to be prepared for Higgs discovery:
QCD jets, W/Z(+jets), tt~, WW, ZZ, ….

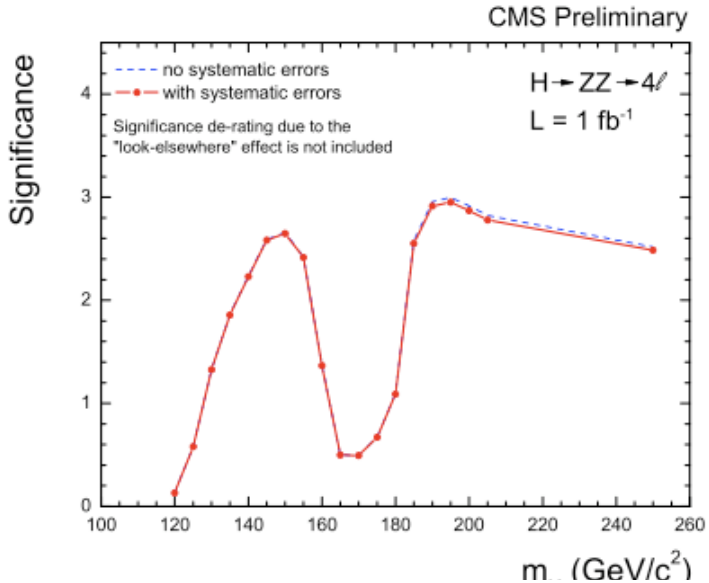
Zbb,Zcc, Wbb, Wcc, W/Z+n, Z to tau decays…

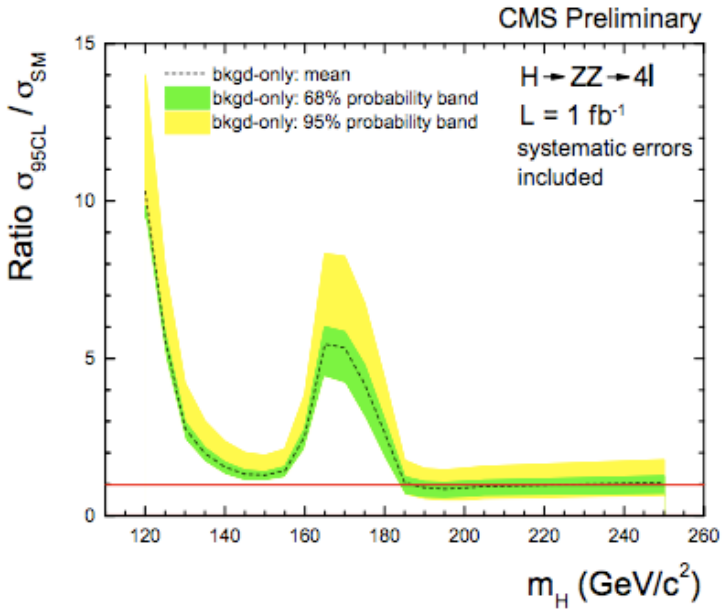
Early data: H → ZZ → leptons

14 TeV

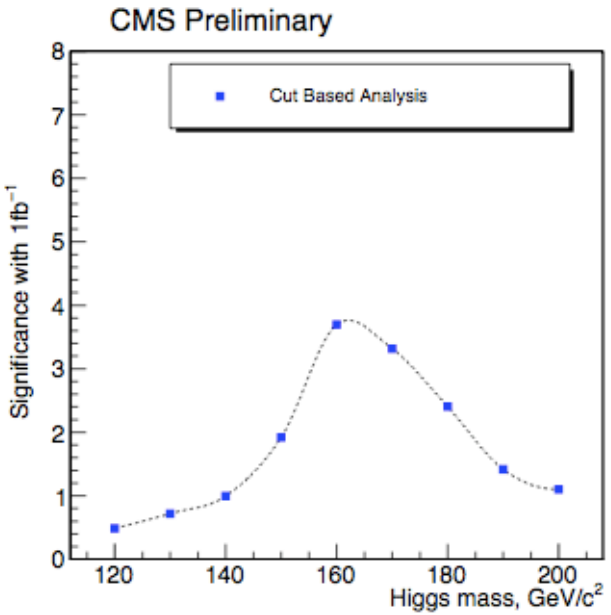
m_H (GeV/c^2)	Events at 1 fb^{-1}		Significance	$R_{95\%\ C.L.}$
	N_{s+b}	N_b		
120	0.52	0.19	0.13	10.3
130	1.56	0.29	1.32	2.79
140	2.85	0.42	2.22	1.55
150	3.52	0.47	2.64	1.29
160	1.98	0.47	1.36	2.53
170	1.34	0.61	0.50	5.35
180	3.16	1.38	1.09	2.64
190	9.24	2.74	2.92	0.89
200	10.6	3.52	2.87	0.89
250	8.02	2.66	2.49	1.06

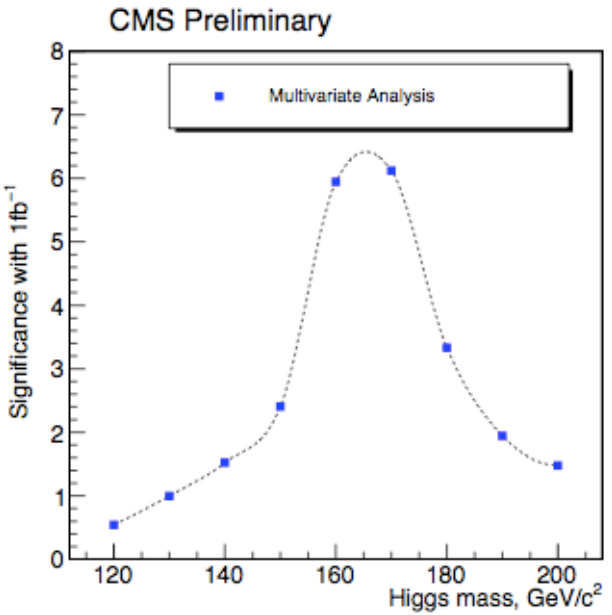
- Cuts optimized for startup luminosity
- Assume 1 fb^{-1}
- 95% CL limits probe SM region





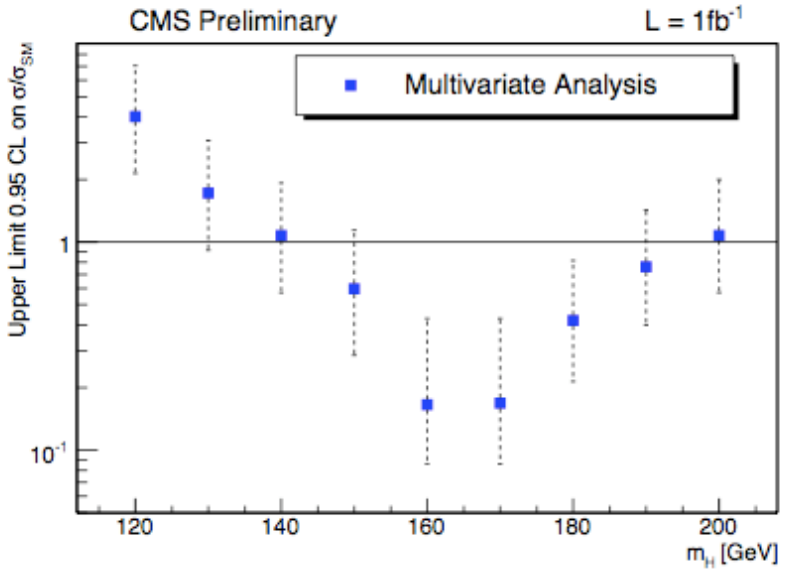
Early data: H→WW





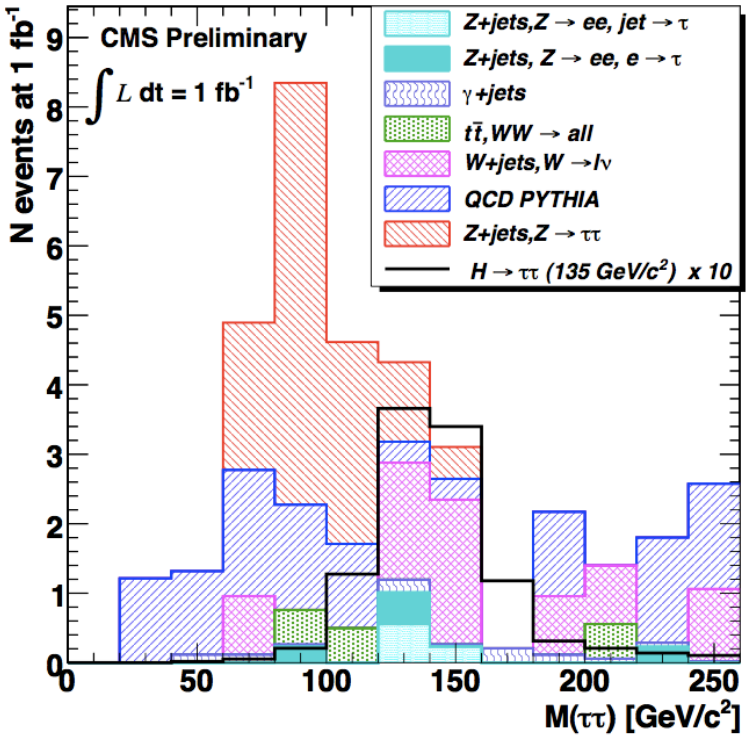
14 TeV

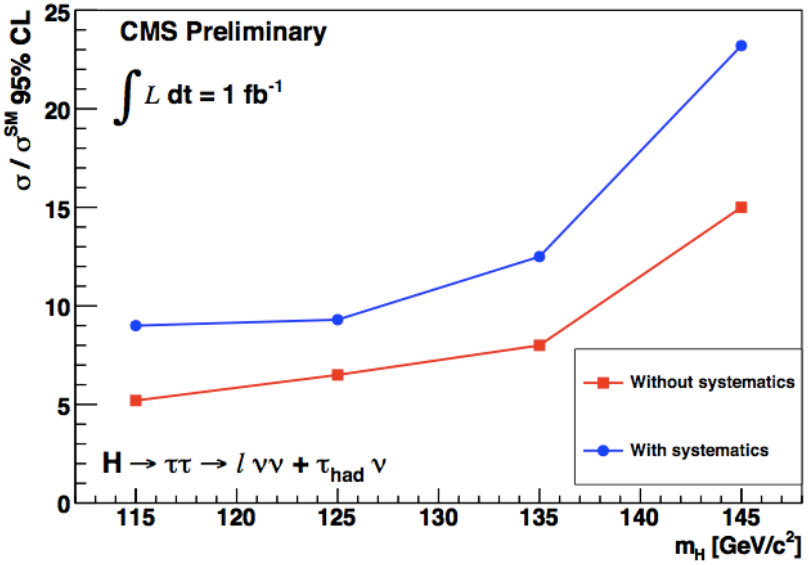
- Cuts optimized for startup luminosity
- Assume 1 fb^{-1}
- 95% CL limits probe SM region

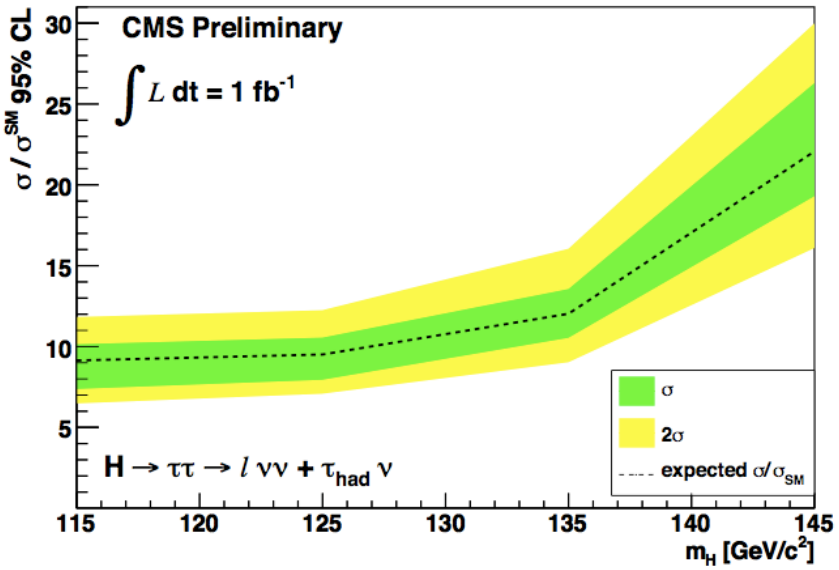


Early Data: VBF with H→ττ

14 TeV

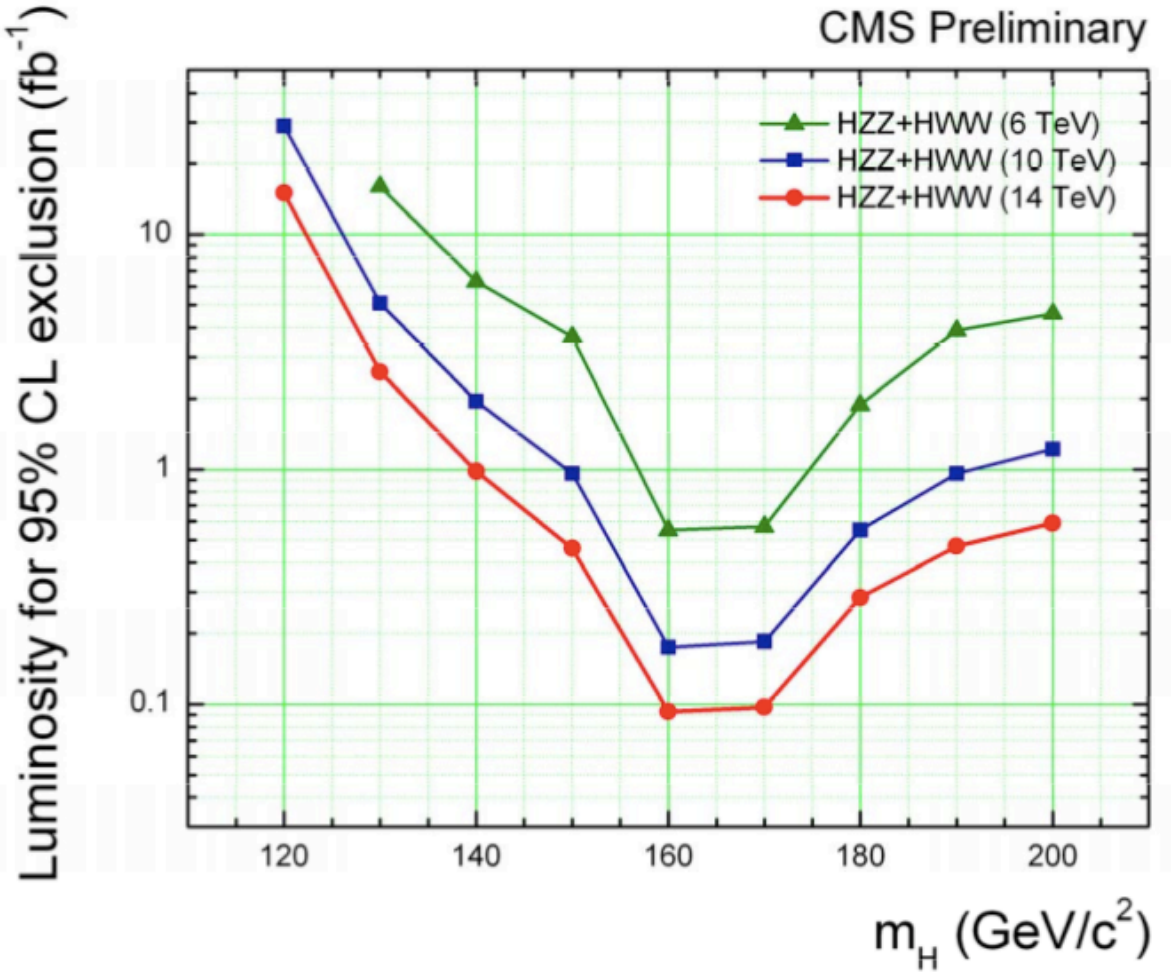






- Cuts optimized for startup luminosity
- Assume 1 fb^{-1}
- 95% CL limits probe SM region

Early Searches/Reduced Energy



Luminosity needed for 95% CL exclusion

At 6 TeV you need 7 times more data than at 14 TeV

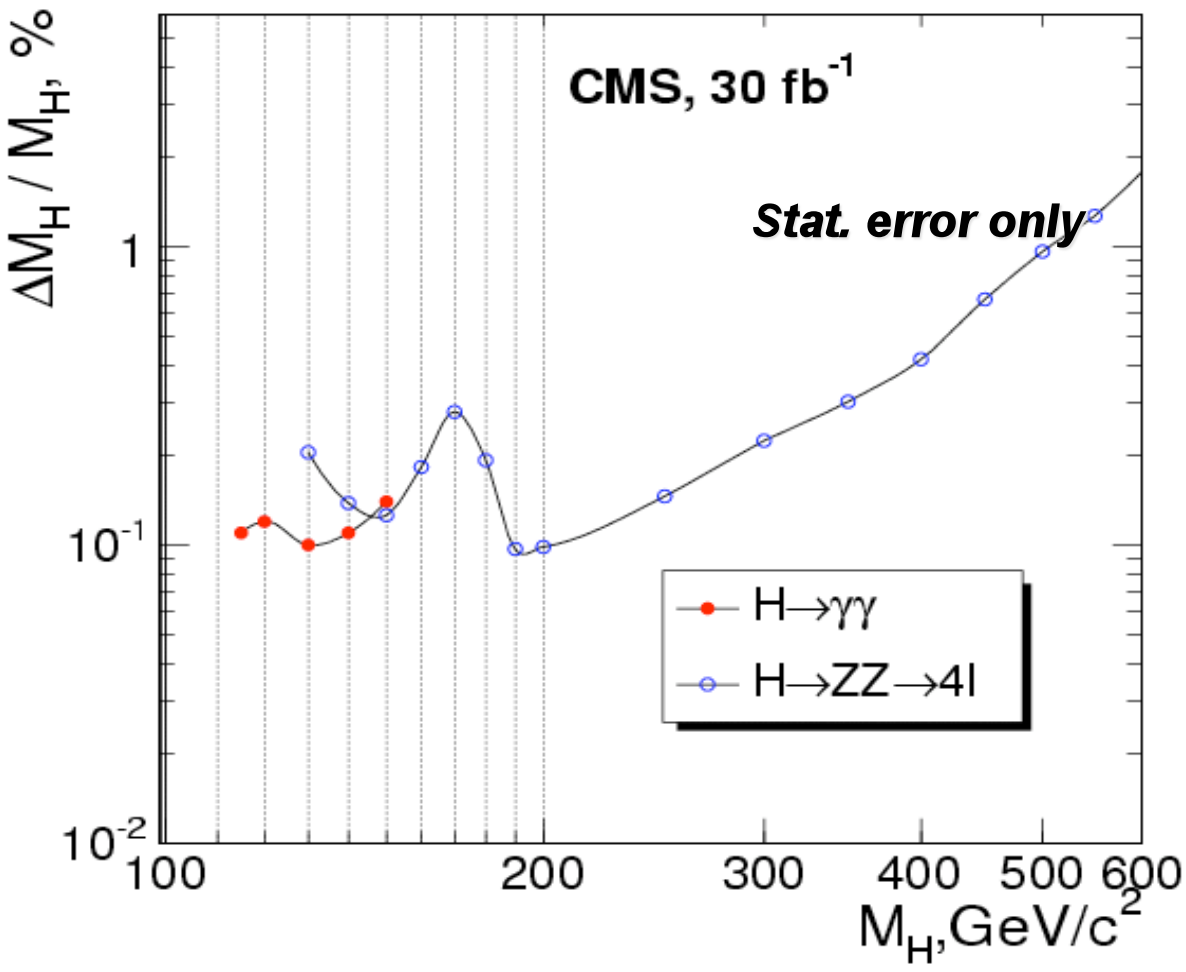
2010 will not be "the Year of the Higgs" for LHC…

Determining properties of the Higgs

Very High Luminosity

Higgs Mass Measurements

Using the golden channels into $\gamma\gamma$ and ZZ



Statistical error only

Ratios of couplings

How to learn something on the Couplings of the Higss to the Bosons and fermions?

This is important to establish that We are really looking at the Higgs

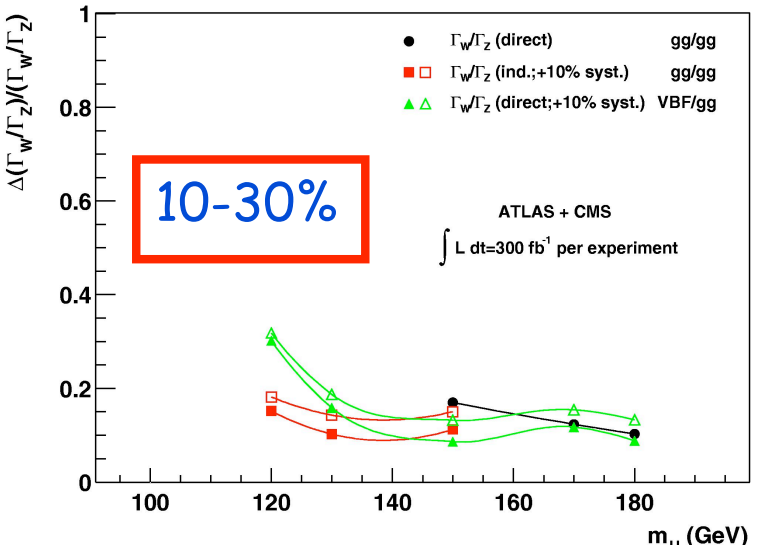
Coupling ~ mass of the particle!

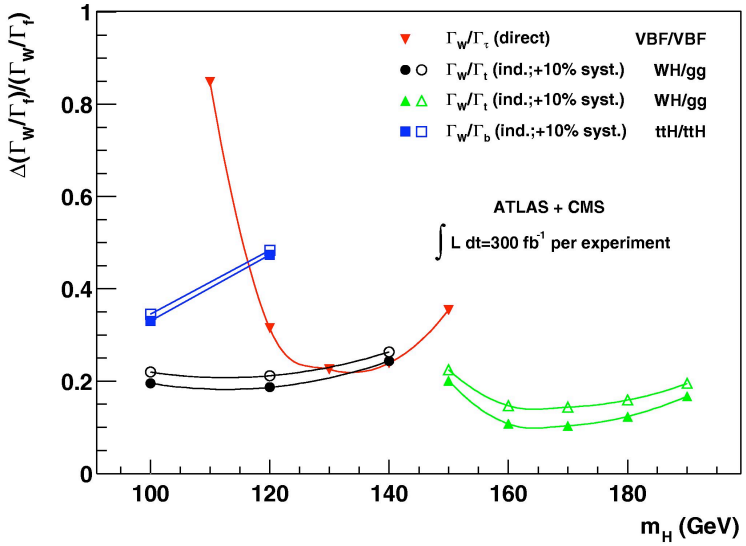
LHC solution: measure ratios

Example

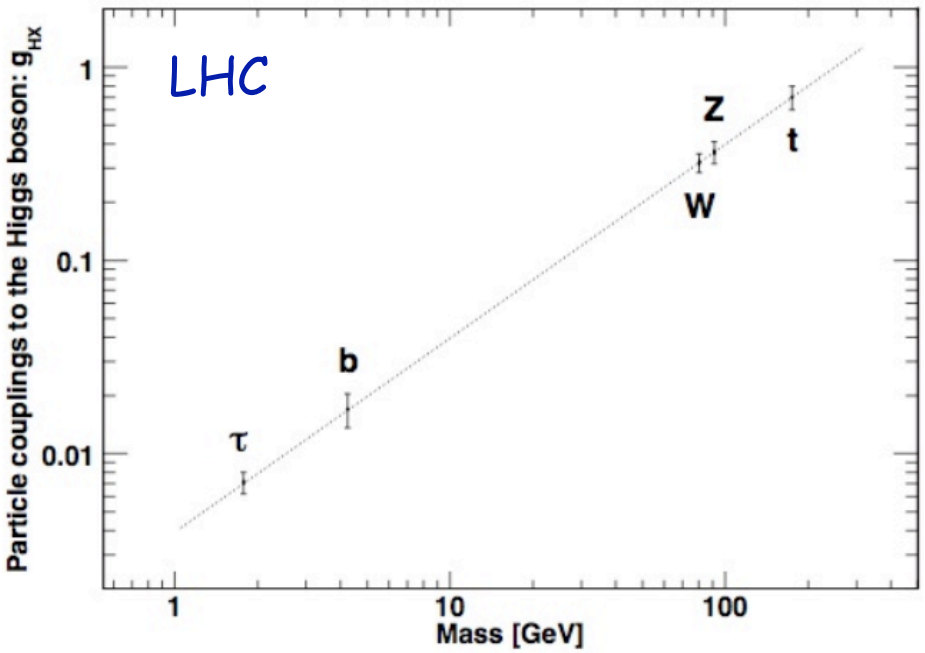
$$- \frac{\sigma \times BR(H \to WW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$

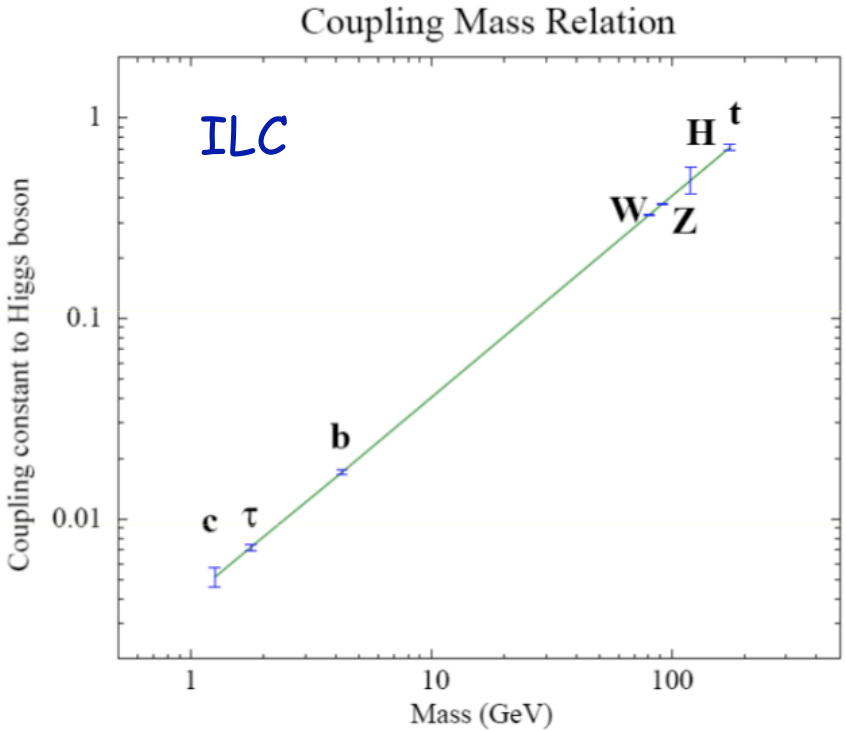
$$- \frac{\sigma \times BR(H \to \gamma\gamma)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_g \Gamma_Z} \sim \frac{\Gamma_W}{\Gamma_Z}$$





Coupling Mass Relation



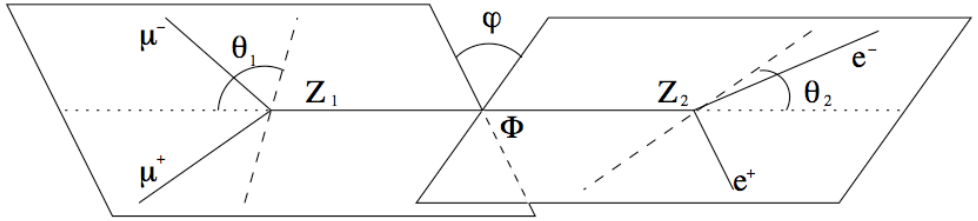


NB before the ttH "disappeared"

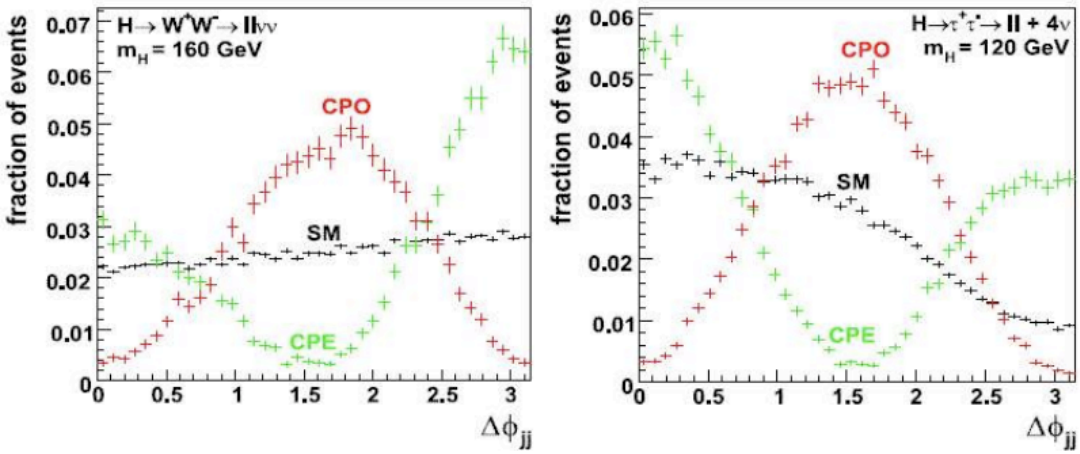
Gianotti, Ellis, ADR et al.

Spin/CP information on the Higgs

- In ZZ decays (if Higgs heavy ie > 200 GeV)



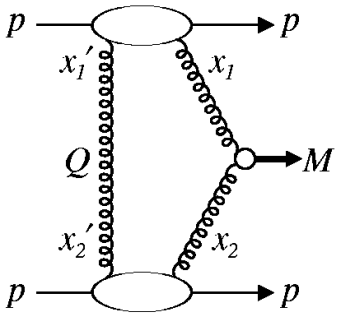
- In VBF ->WW decays

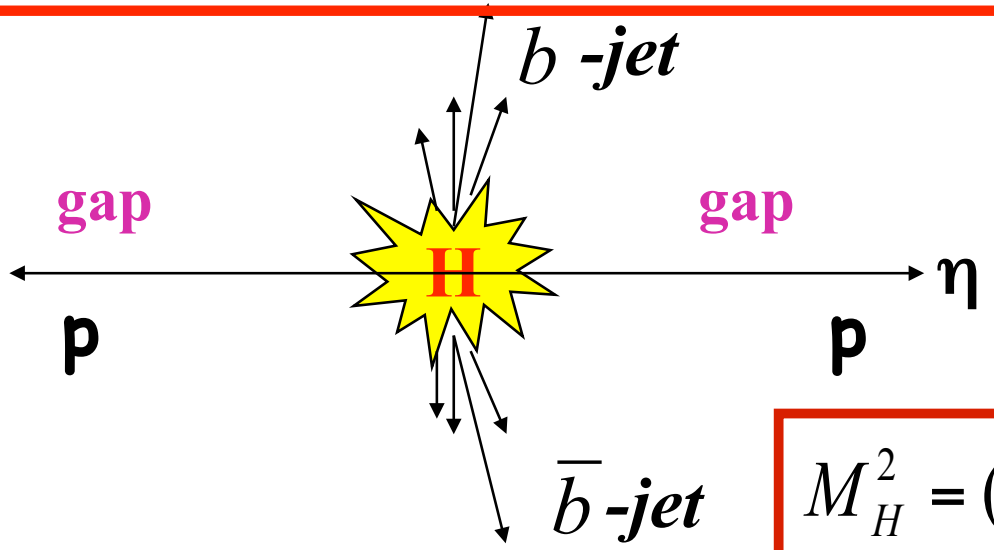


- In decays to taus?
- Exclusive production?

Central Exclusive Higgs Production

Central Exclusive Higgs production pp→ p H p : 2-10 fb (SM)
~10-100 fb (MSSM)

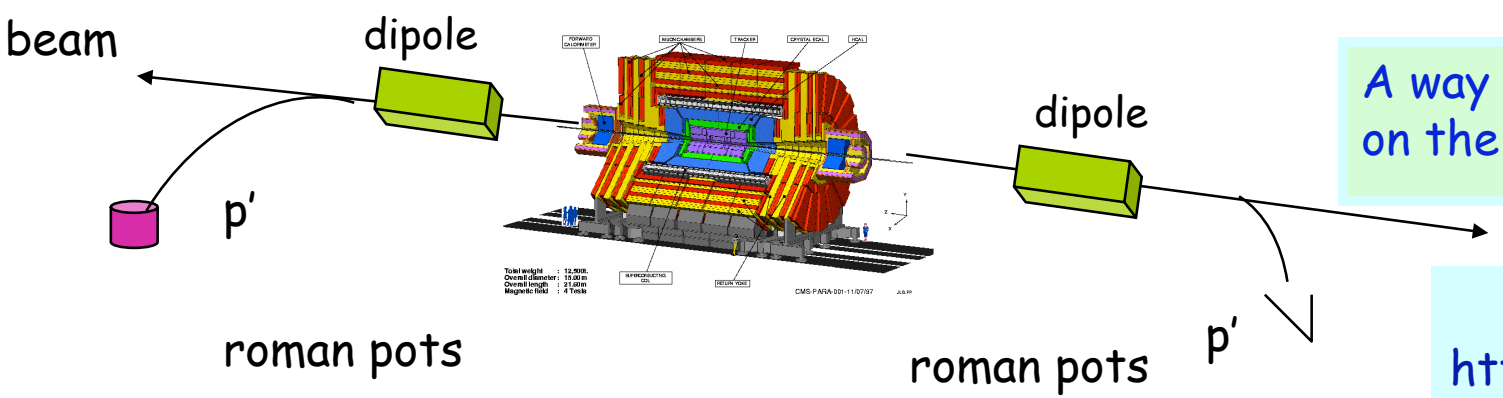




E.g. V. Khoze et al
ADR et al.
M. Boonekamp et al.
B. Cox et al.
V. Petrov et al...
Brodsky et al.

$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

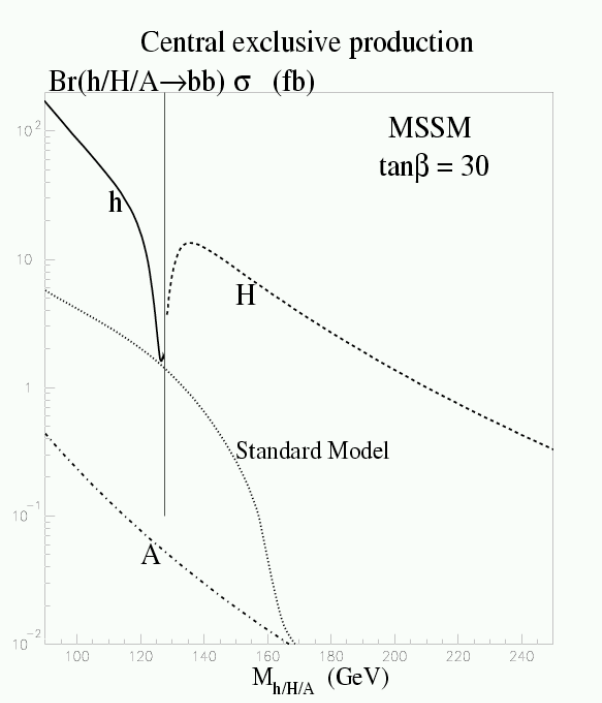
ΔM = O(1.0 - 2.0) GeV



A way to get information on the spin of the Higgs

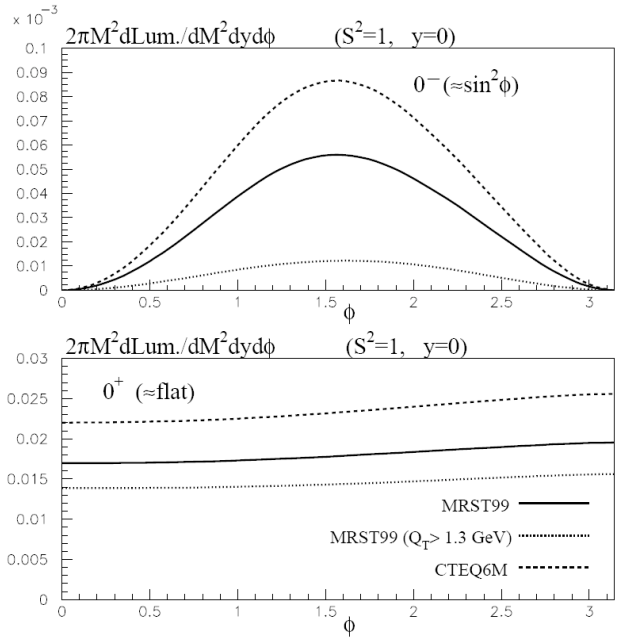
FP420 R&D Project
http://www.fp420.com

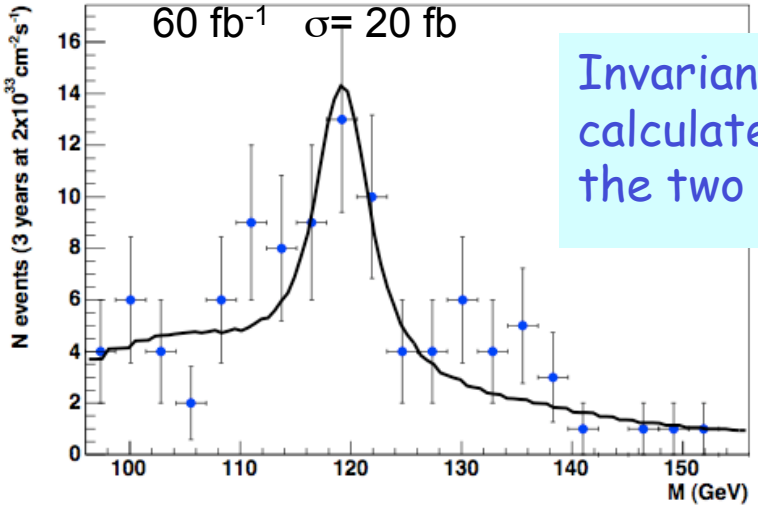
Exclusive Higgs: H→bb



RDMS

Khoze et al.,
hep-ph/0307064





Invariant mass calculated with the two protons

Azimuthal correlation between the tagged protons
Differentiate O^+ from O^-

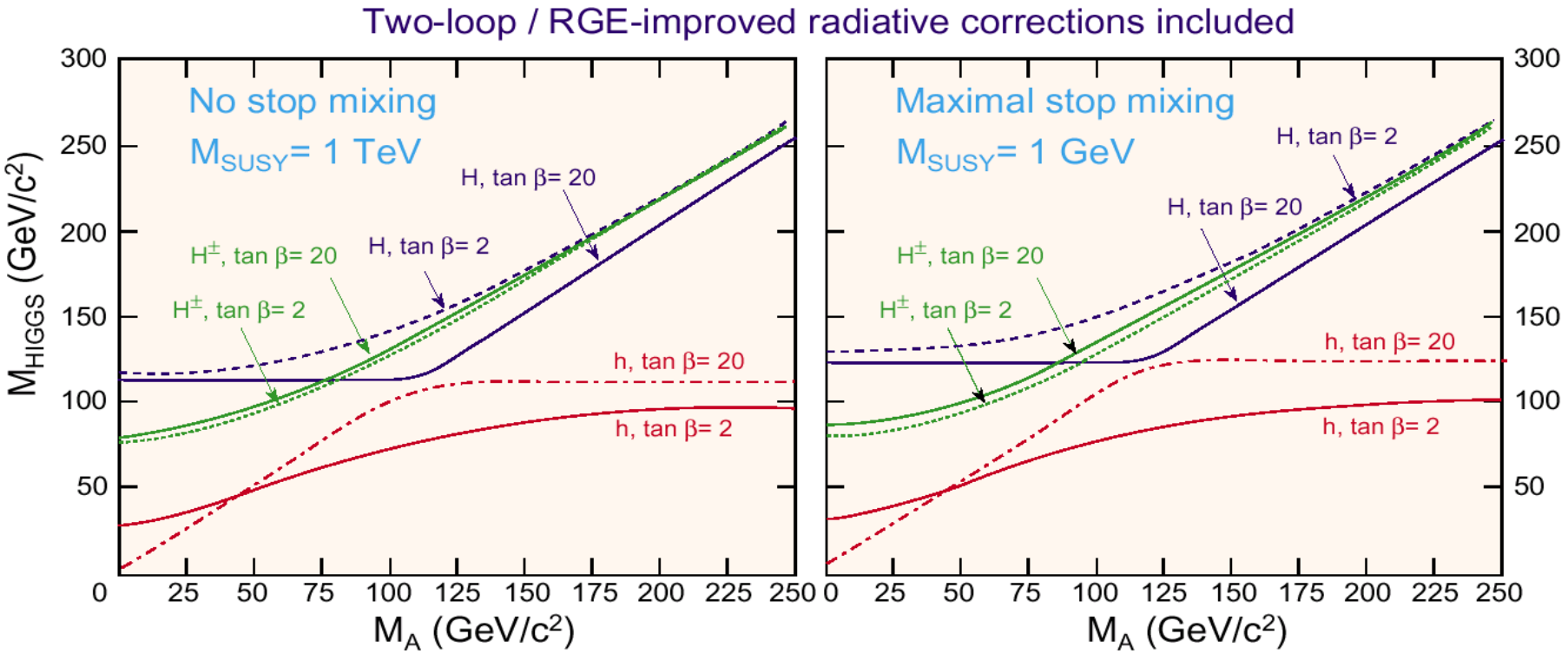
A way to get information on the spin of the Higgs
⇒ADDED VALUE TO LHC

Beyond the Standard Model

Usually more that one Higgs
E.g. Supersymmetry:

5 physical Higgs bosons
2 charged : H^+ and H^-
2 CP even neutral : H and h
1 CP odd neutral : A

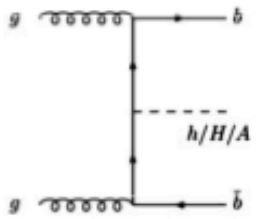
Mass spectra for M_{SUSY}=1TeV
The good news: M_h<135 GeV/c^2



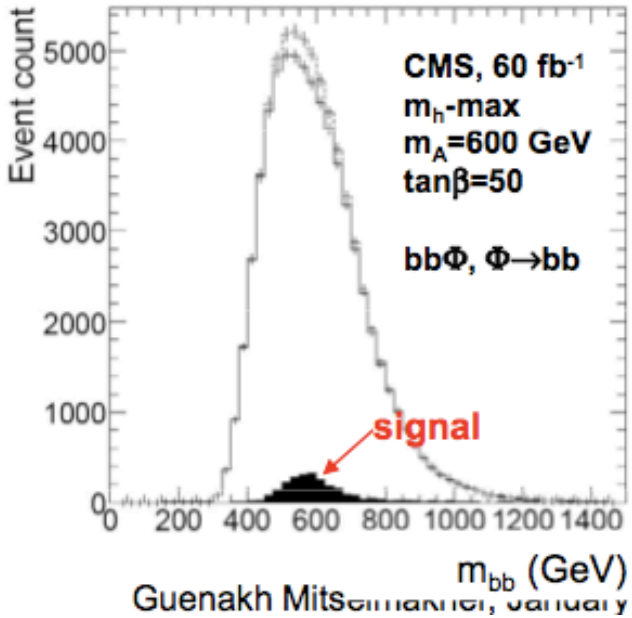
tanβ = v1/v2 v1 vacuum expectation of first higgs, v2 of the other

Heavy Neutral Higgs

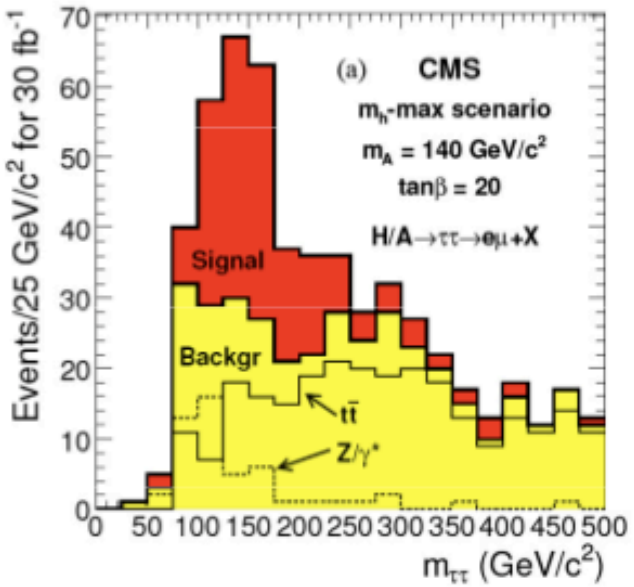
- given the H/A mass degeneracy, they are often referred to as Φ
- production in association with bb (especially good at large tanβ)
- Decays (large tanβ):
  - bb-decay mode (~90%) is overwhelmed with QCD background
  - ττ-decay mode (~10%) is the best bet
  - μμ-decays (~0.03%) allow for direct measurement of Γ



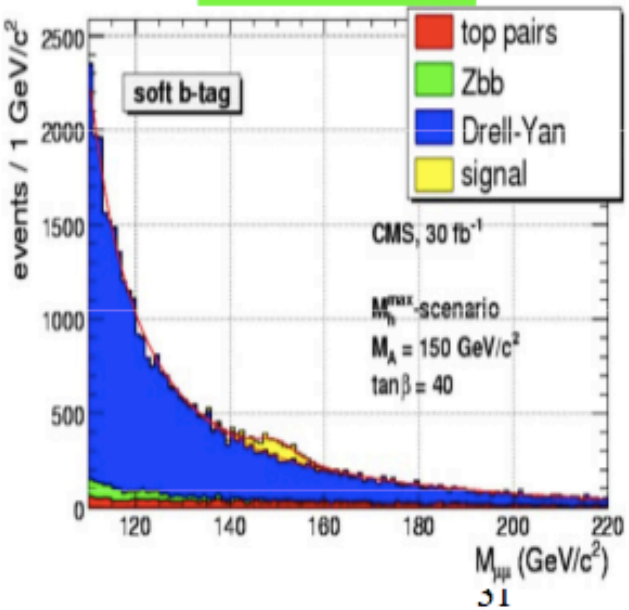
bbΦ, Φ→bb



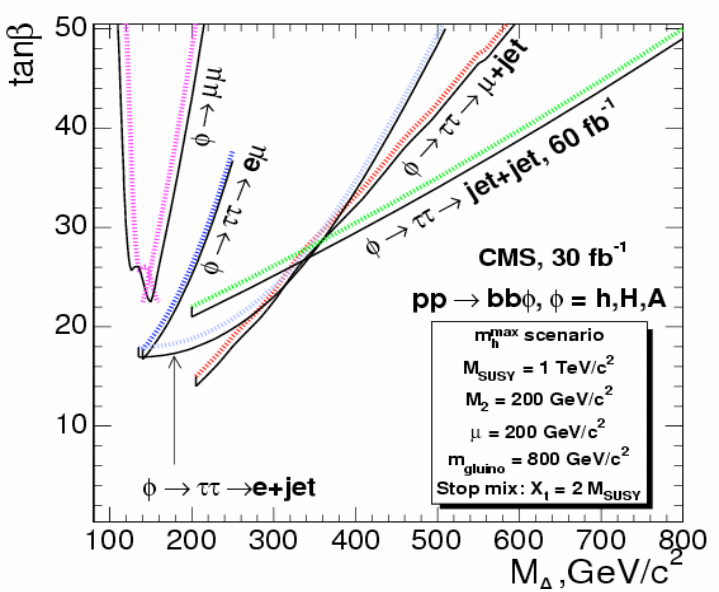
bbΦ, Φ→ττ



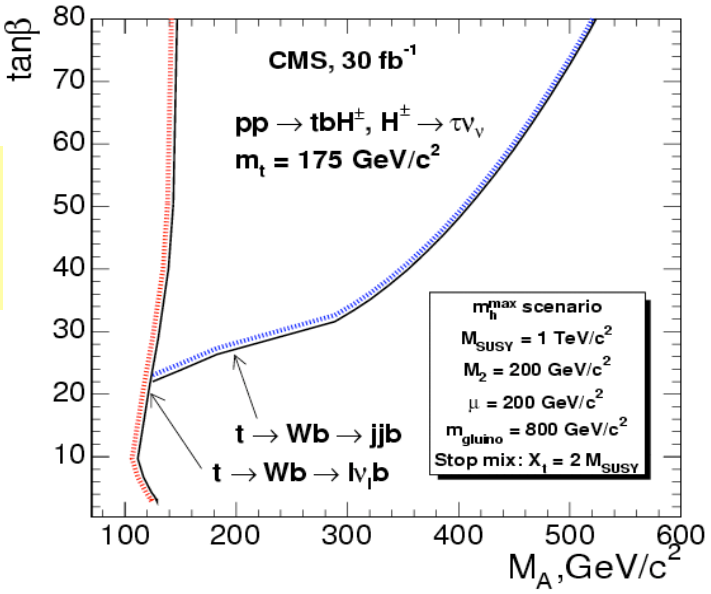
bbΦ, Φ→μμ

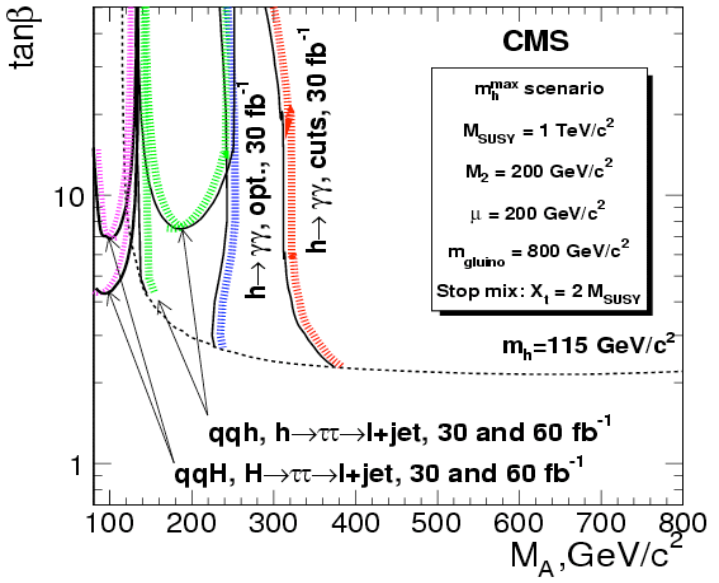


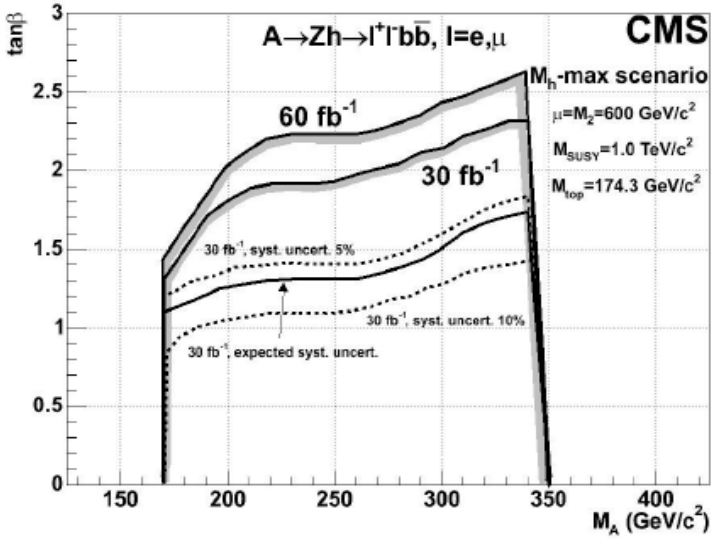
CMS Reach



14 TeV
30-60 fb^{-1}

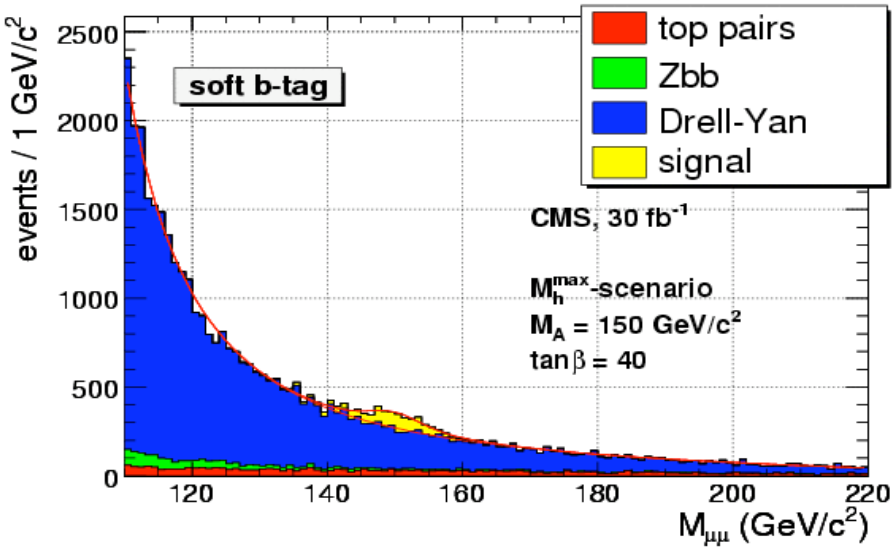


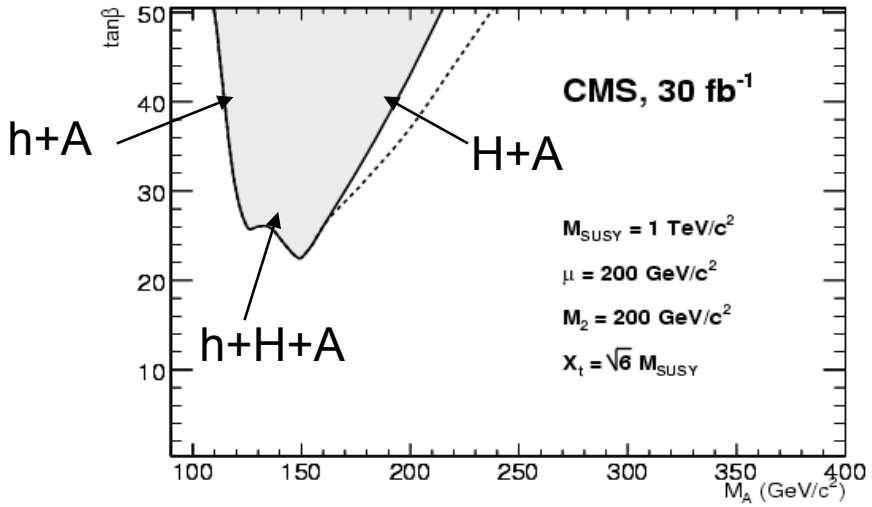




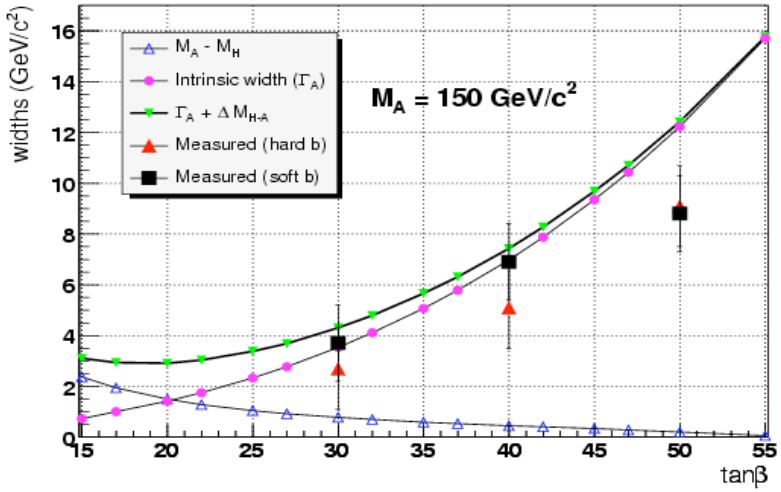
pp→bbϕ→bbμμ

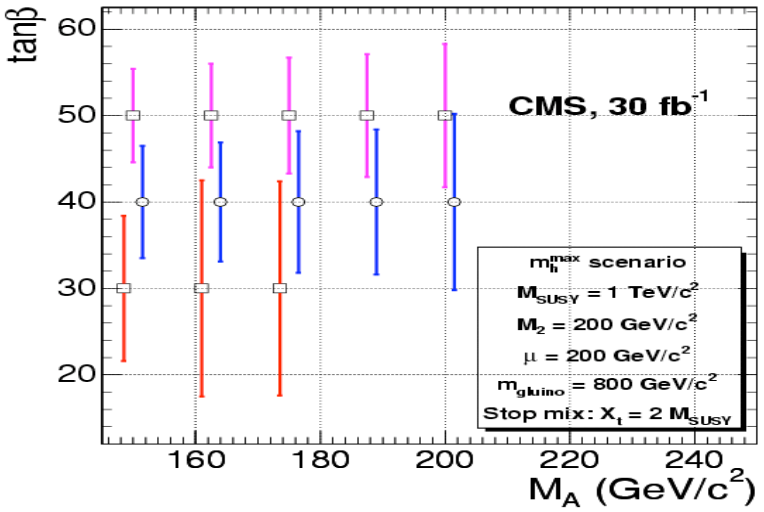
Discovery reach at low M_A, "intensive coupling" and decoupling regimes





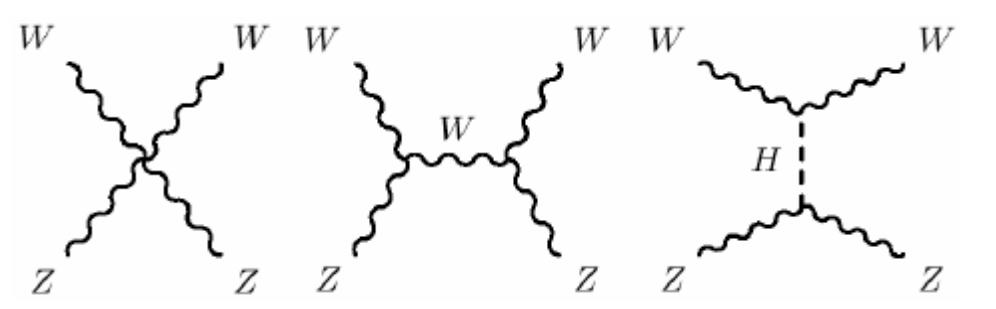
Possible constraint on tanβ by measuring width of A/H->μμ



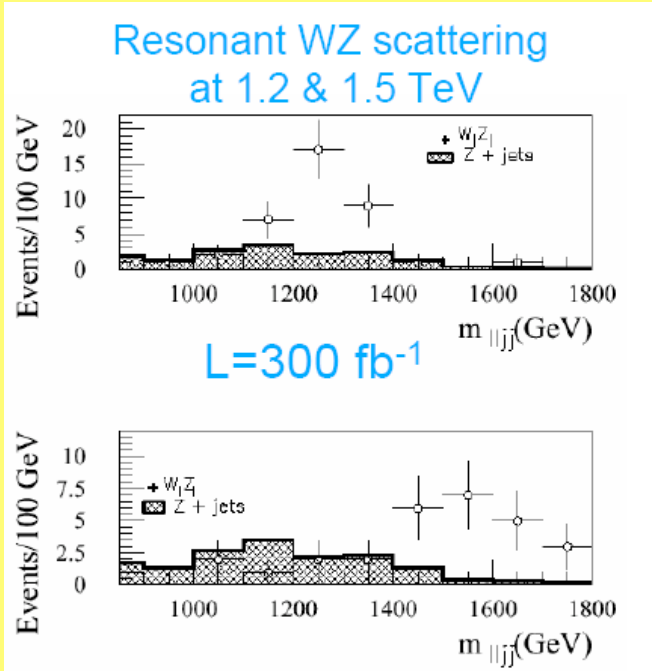


EWSB: What if no Higgs exists?

Vector Boson scattering amplitudes violate unitarity for s~ 1TeV
New physics must enter to cure this problem



- Examples
  - Strongly interacting vector bosons
    - Study WW,WZ,ZZ scattering
  - Technicolor
    - New particles (Techni-ρ, techni-π,…)



Mantra: LHC will either discover Higgs or find new dynamics ~ 1 TeV

No Higgs...

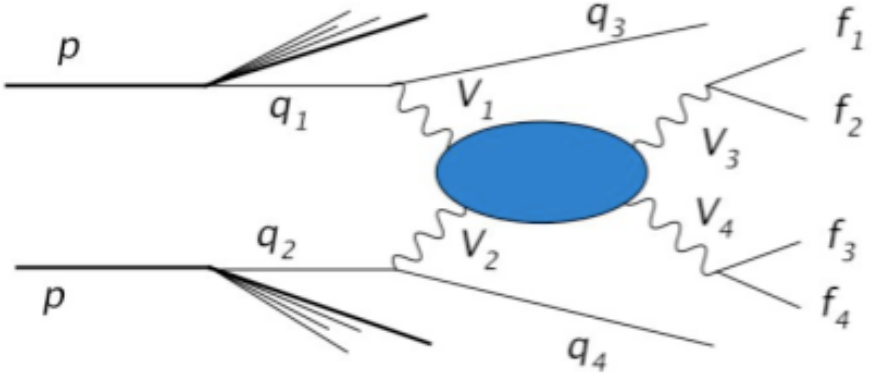
- EW theory uses an AD HOC minimal Higgs sector ...
- Higgs mass has quadratic divergences ⇒ naturalness and fine tunning "problems"
- Higgs creates a vacuum energy density $\rho_H = m_H^2 v^2/8 > 10^8 GeV^4$ (GR cosmological constant). Observation suggests that $\rho_{vac} < 10^{-46} GeV^4$!
- EW theory might be just a "low energy" effective theory. (In superconductivity Ginzburg-Landau potential is derived from fundamental BCS theory)

CMS note 2007/05

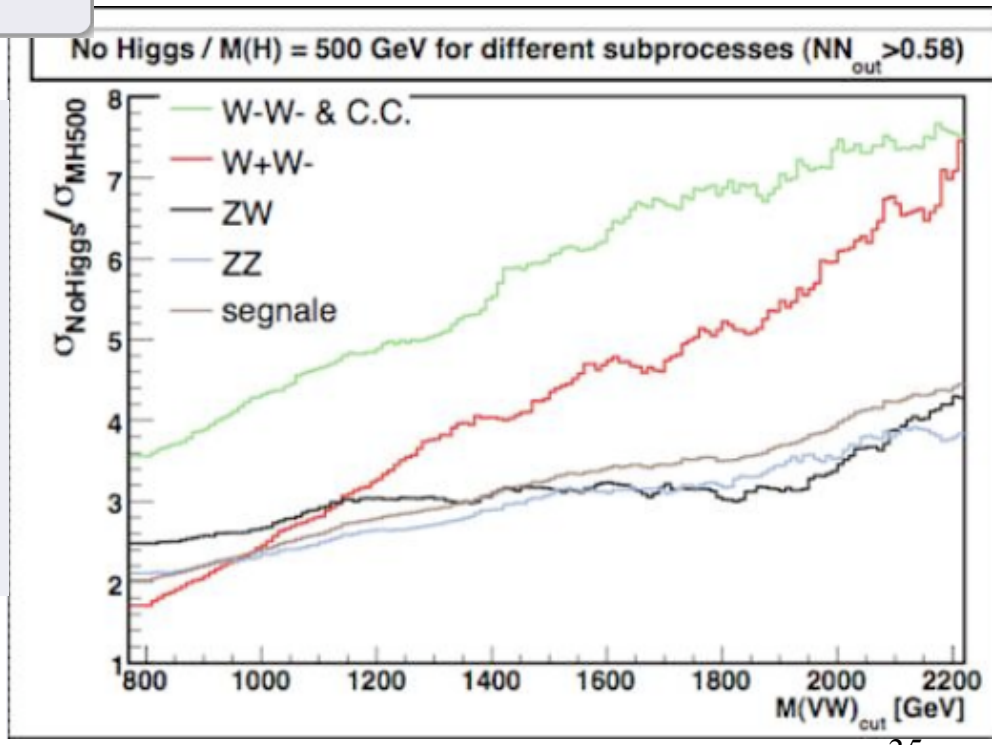
Will need a lot of luminosity

(> 60 fb^{-1})

Perhaps even SLHC



ATLAS: 50-300 fb^{-1} needed depending on the process



Summary: What can the LHC do?

- LHC will discover the SM Higgs in the full region up to 1 TeV or exclude its existence (1-10 fb^{-1}). If no Higgs, other new phenomena in VV →VV should be observed around 1 TeV, but may need high luminosity
- The LHC will measure with full luminosity (≥100 fb^{-1})
  - The Higgs mass with 0.1-1% precision
  - The Higgs width, for m_H> 200 GeV, with ~5-8% precision
  - Cross sections x branching ratios with 5-20% precision
  - Ratios of couplings with 10-30% precision
  - Absolute couplings only with additional assumptions
  - Spin information in the ZZ channel for m_H>200 GeV and VBF→WW
  - CP information from exclusive central production: pp→pHp
  - However: no information on the Higgs potential

..⇒will get a pretty good picture of the Higgs @ LHC
More detailed information from a Linear Collider