Prospects for Higgs searches in CMS with 1 fb^{-1} at 7 TeV and CMS performance validation with early data

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On behalf of the CMS Collaboration

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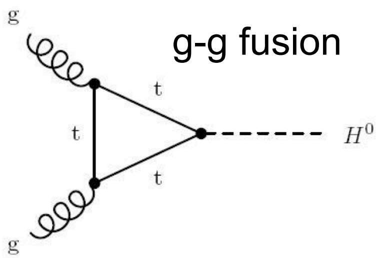
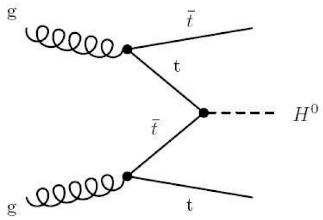
Higgs production at 7 TeV: LHC and TeVatron

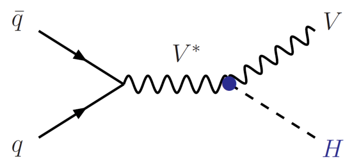
By the end of 2011:
LHC: L~ 1 fb^{-1}
TeVatron: L~10 fb^{-1}



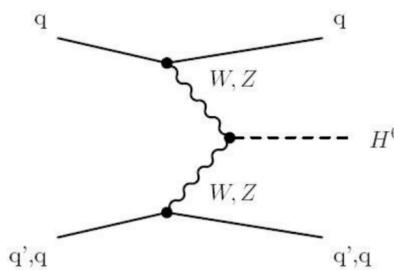
g-g fusion



associated production



Higgs-strahlung



vector boson fusion

For m_H such that H→WW, H→ZZ channels open up,

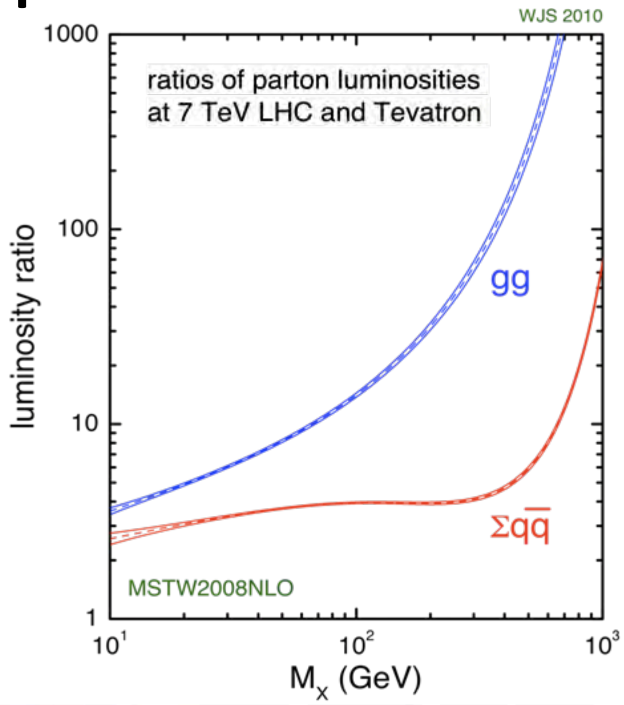
LHC can compete with TeVatron with 1 fb^{-1}

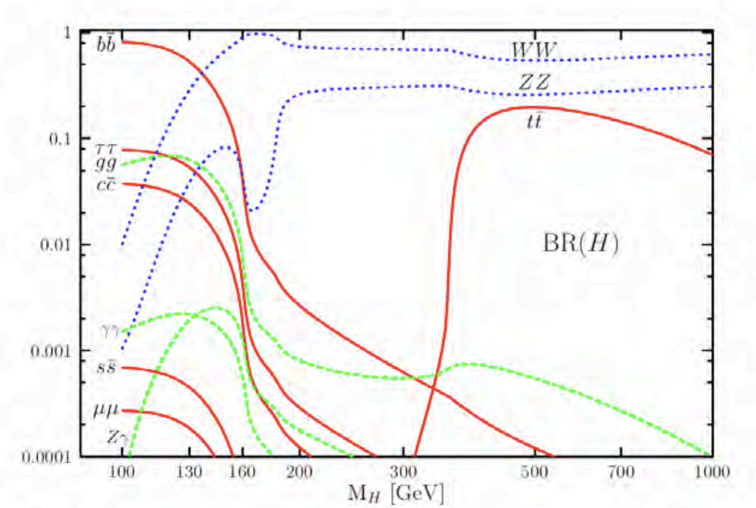
(gg enhances the signal, whereas the irreducible backgrounds come from $q\bar{q}$)

For low m_H values,

LHC S/N ratio is not competitive

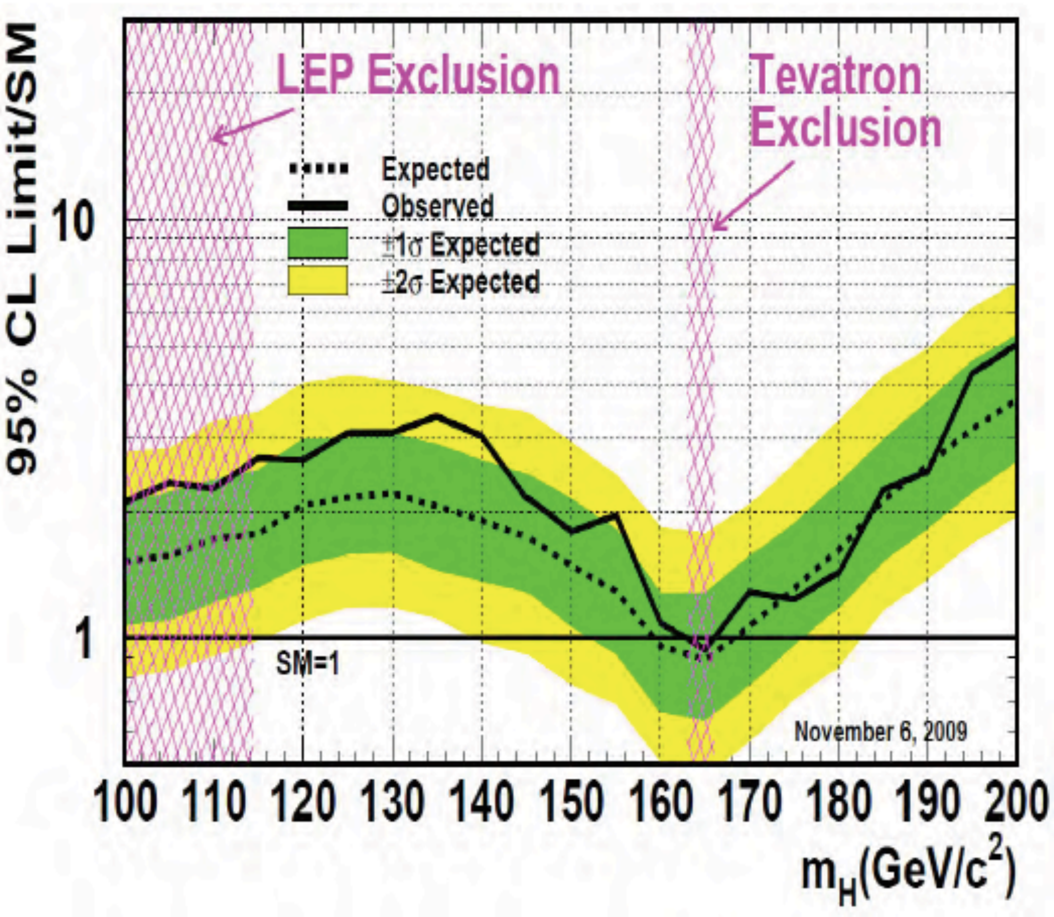
(gg favours $t\bar{t}$, W+$b\bar{b}$, Z+$b\bar{b}$ backgrounds; also gg→H→γγ rate is larger, but the QCD γγ background is huge)





Excluded regions

Reference: arXiv:1001.4162



- Exclusions at 95% C.L. from direct search:
  - LEP: $m_H < 114.4$ GeV
  - TeVatron run II: $162 < m_H < 166$ GeV
- LEP preferred fit values:
  - $m_H = 87_{-26}^{+35}$ GeV (68% C.L.)
  - $m_H < 157$ GeV (95% C.L.)

Projecting to 7 TeV

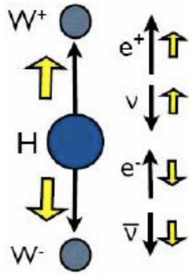
- The following results have been produced by performing a projection from 14 TeV to 7 TeV
  - event yields for signal and background at 14 TeV have been re-scaled by the ratio $\frac{\sigma(7\ TeV)}{\sigma(14\ TeV)}$
  - and projected for an integrated lumi of L=1 fb^{-1}
- No correction for higher acceptance of the detector has been applied
  - at 7 TeV, particles are less forward-boosted than at 14 TeV
  - the acceptance can be up to 20% higher
- The improvements of detector simulation and of reconstruction performances have not been taken into account
- Rescaling of systematic errors:
  - those evaluated from control samples scale as $1/\sqrt{N}$
  - some uncertainties (e.g. the theoretical ones) have been used without changes
  - other ones have been inflated to account for smaller datasets
- Statistical analysis:
  - based on re-scaled event counts and on re-evaluated systematic errors
  - Modified Frequentist method has been used for exclusion studies (95% C.L.)
  - Profile Likelihood method applied to significance calculations

$H \rightarrow WW^{(*)} \rightarrow 2l\ 2\nu$

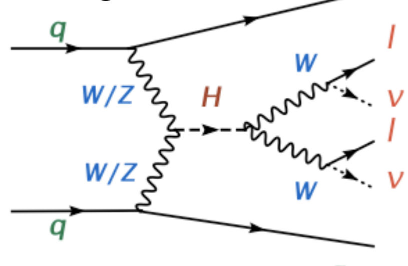
- Signature:
  - 2 high-p_T isolated leptons
  - MET
  - no central jets
- Because of MET, no m_H peak can be looked for
  - one has to use counting experiments…
  - …and the transverse mass:

$$M_T = \sqrt{(E_T(ll) + E_T(\nu\nu))^2 - (p_T(ll) + p_T(\nu\nu))^2}$$

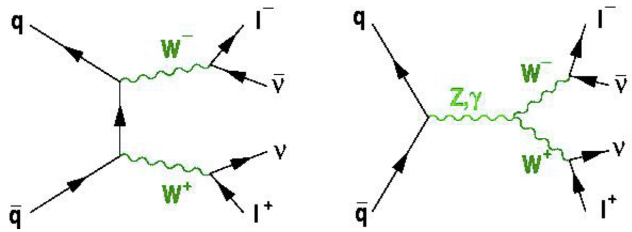
- Backgrounds:
  - WW, Wt, $t\bar{t}$, WZ, ZZ, Drell-Yan, ...
  - WW → cut on $\Delta\phi_{ll}$, the angle between the 2 isolated leptons in the transverse plane (larger for WW than for signal)
  - DY, WZ, ZZ → $m_{inv}(ll)$ peaks around m_Z for di-lepton pairs
  - reject events with central jets, to fight against $t\bar{t}$



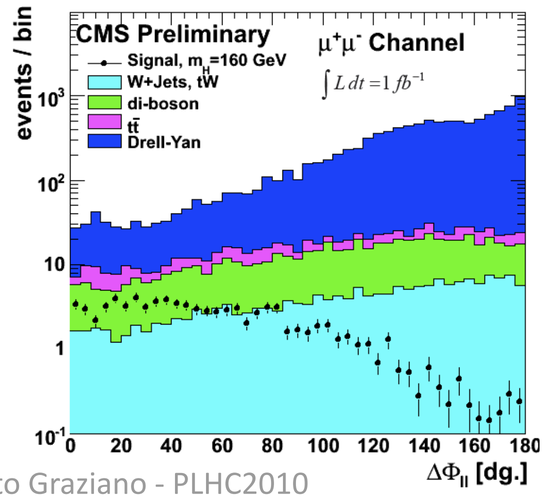
Signal:

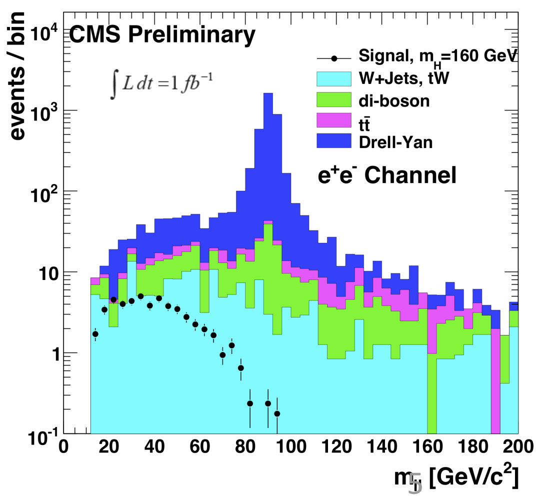


Irreducible backgrounds:

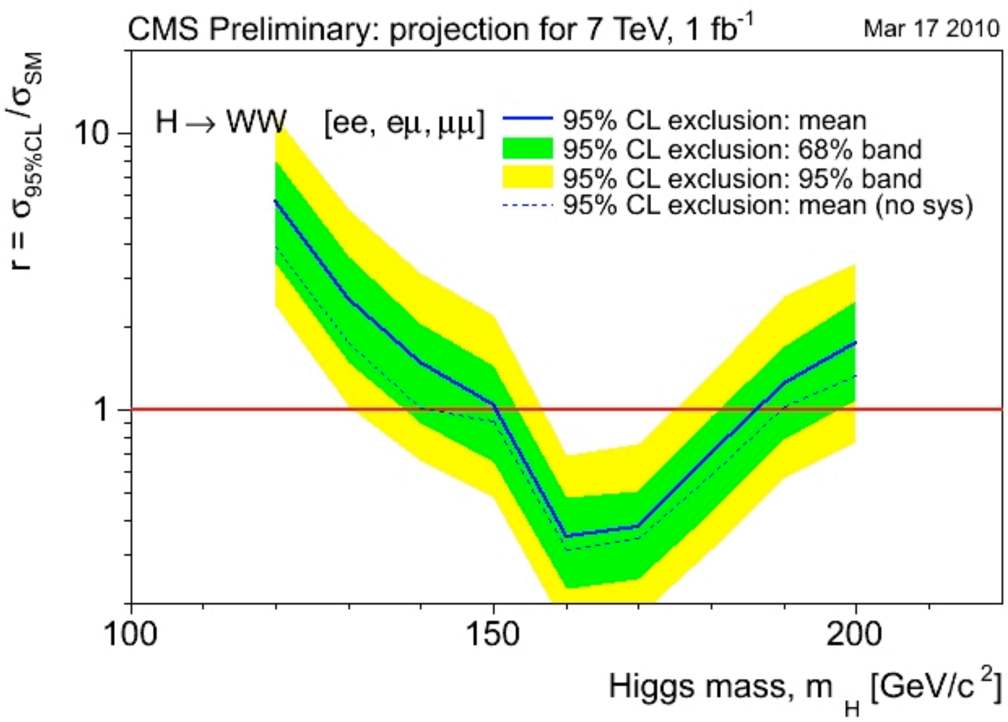


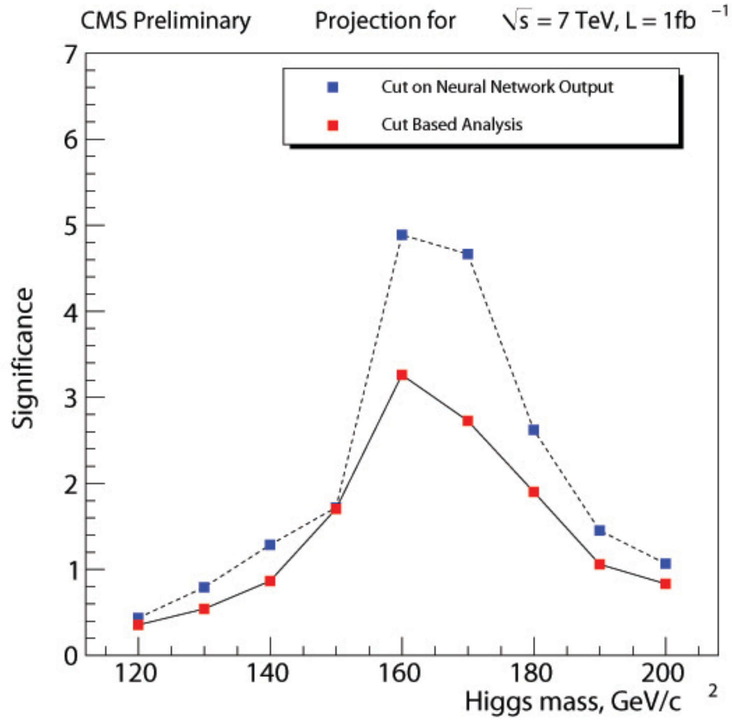
14 TeV results:





$H \to WW^{(*)} \to 2l\, 2\nu$





Exclusion range:
$150 < m_H < 185$ GeV

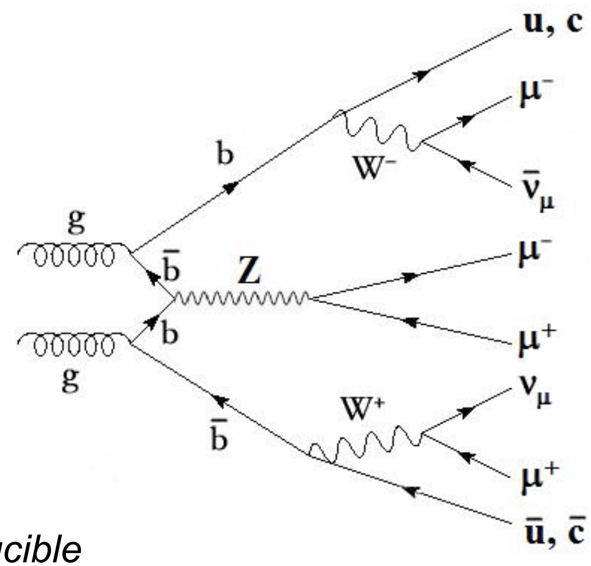
Sensitivity for claiming a discovery (~5 σ) is expected to be reached in the mass range **$160 < m_H < 170$ GeV**

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

- The 'golden channel':
  - 2 pairs of opposite-charge, same-flavour, high-p_T isolated leptons (4e, 4μ, 2e2μ)
  - if correctly matched, lepton pairs reconstruct 2 Z's: $m_{inv}(ll) = m_Z$

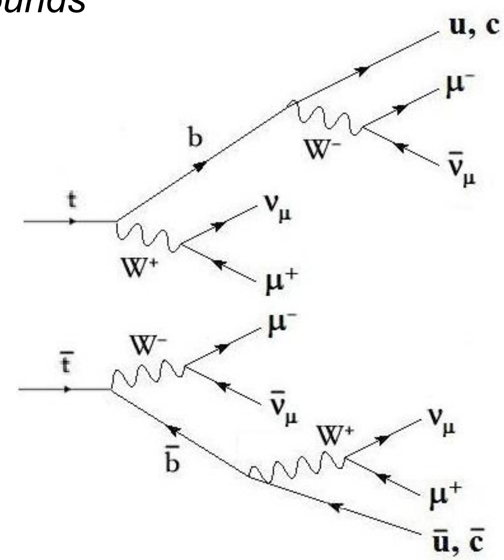
- Backgrounds:
  - ZZ ('irreducible'), $Zb\bar{b}$, $t\bar{t}$, W/Z + jets, QCD
  - ZZ: the main discriminating variable is m(4l)
  - $Zb\bar{b}$, $t\bar{t}$ have at least 2 jets (from b-decays) in the final state → **isolation cuts** are very powerful
  - $Zb\bar{b}$, $t\bar{t}$: leptons from b-decays do not point to the primary vertex → cuts on the **impact parameter significance** of leptons

$Zb\bar{b}$

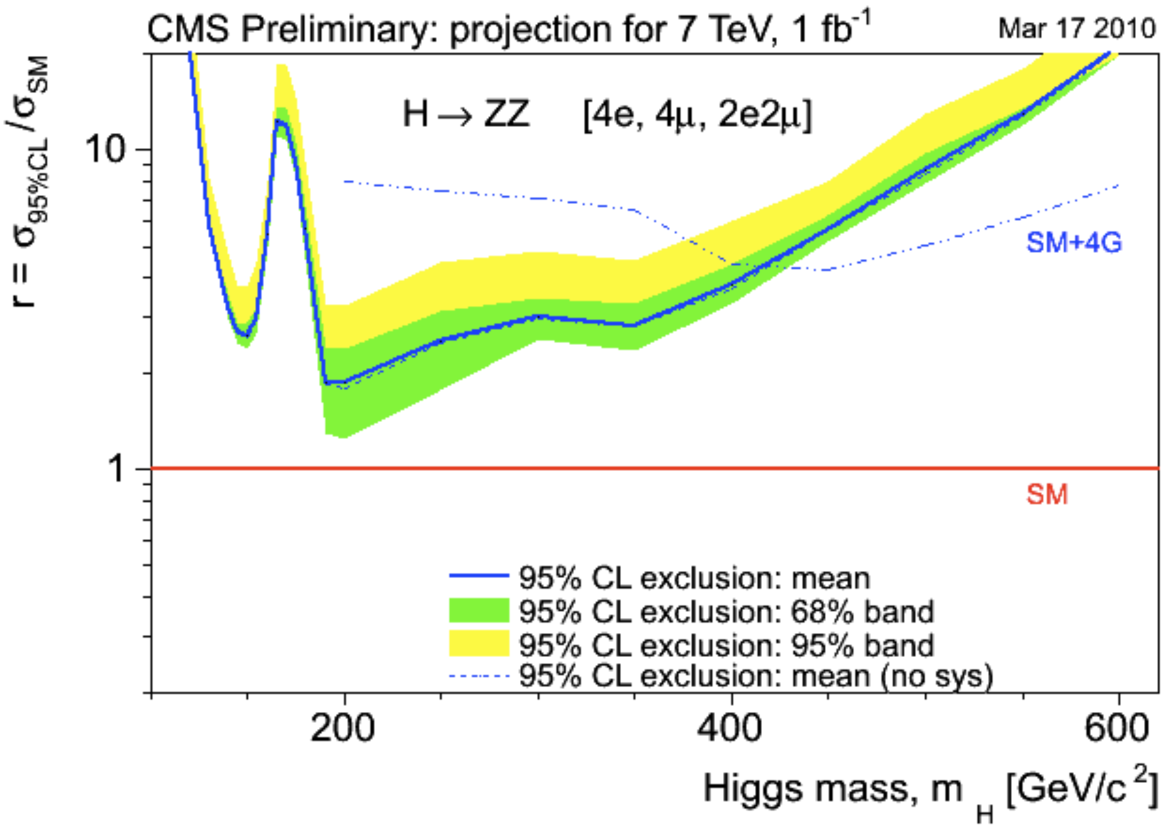


Reducible backgrounds

$t\bar{t}$



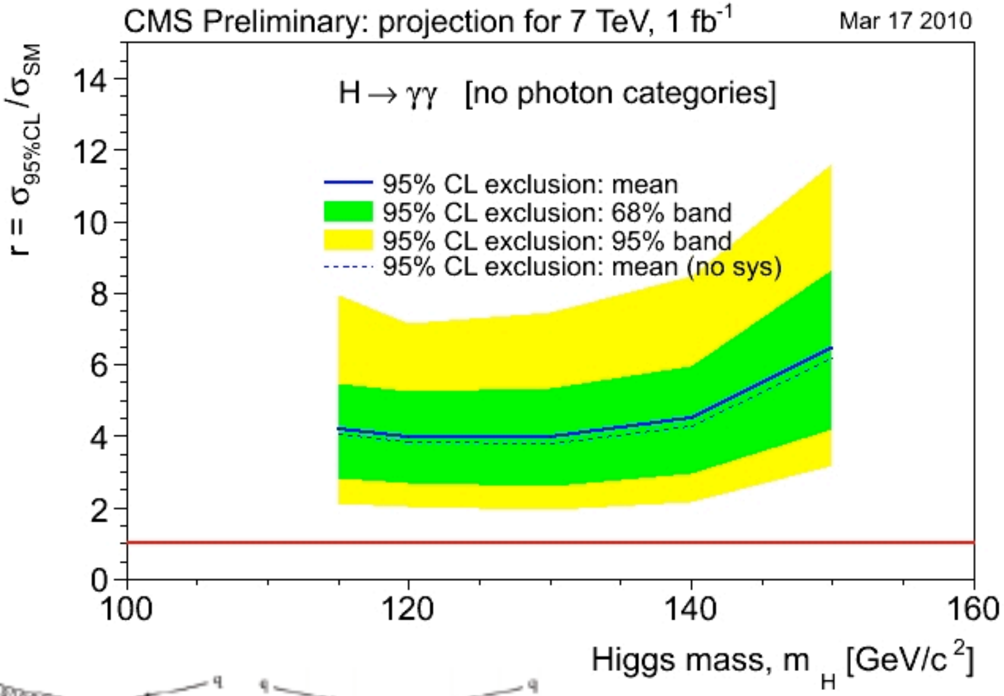
$H \to ZZ^{(*)} \to 4l$

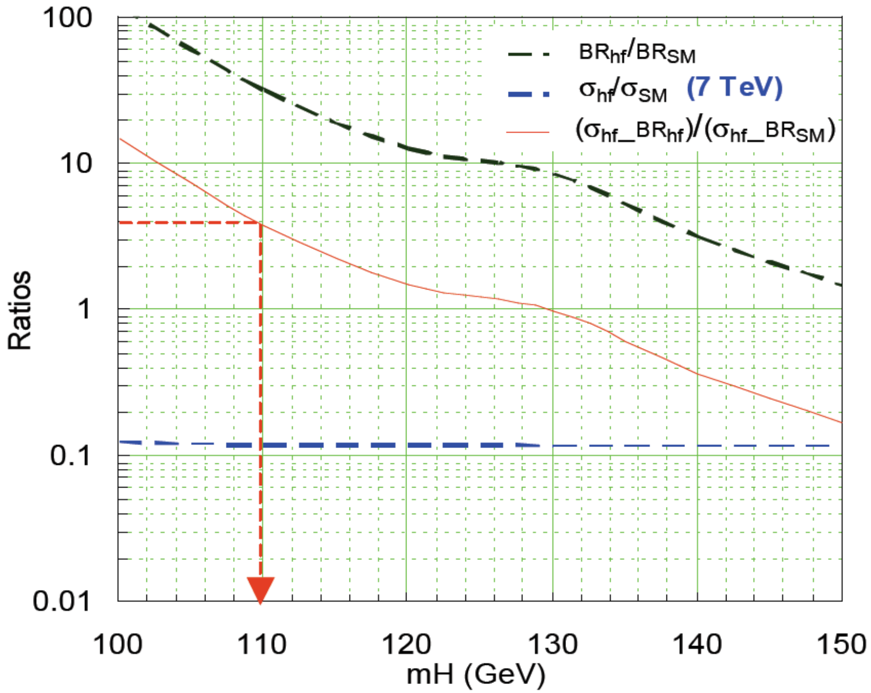


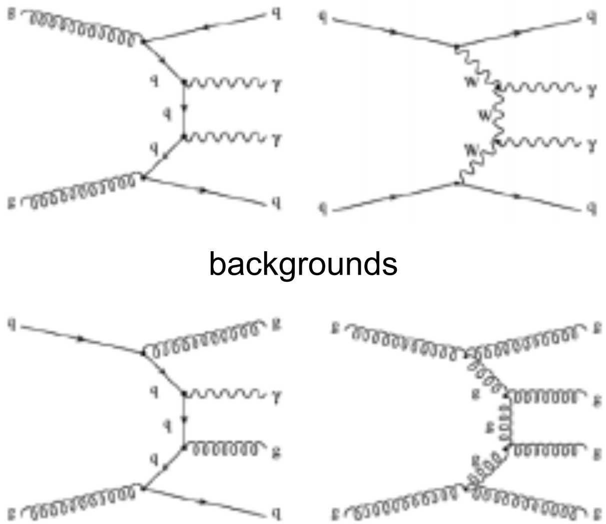
Exclusion is **out of reach** across the whole m_H range.

Should a fourth generation of quarks exist, the Higgs boson could be excluded in the range **m_H < ~420 GeV**

$H \rightarrow \gamma\gamma$







backgrounds

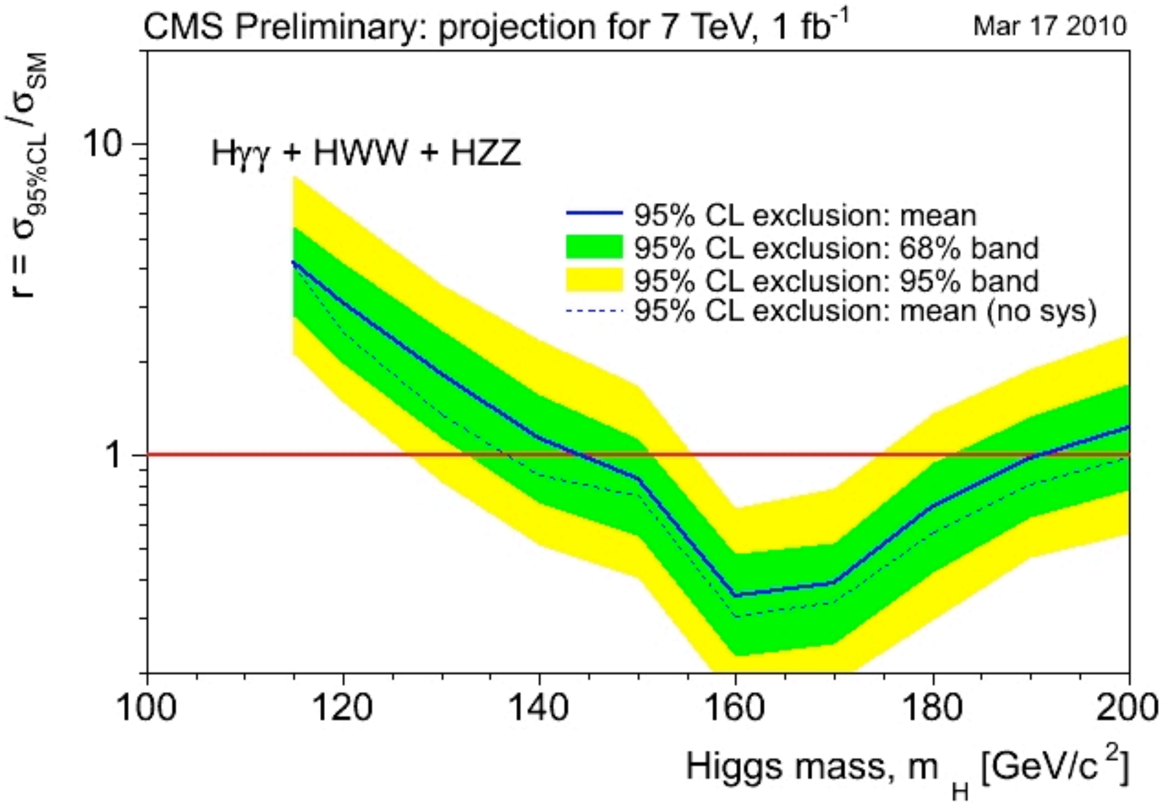
Features of the analysis:

- two isolated photons required
- looking for a γγ mass peak
- large QCD background, estimated from sidebands

Exclusion is **not possible** at 7 TeV with L=1 fb^{-1}

A fermiophobic Higgs might be excluded if **m_{hf} < 110 GeV**
(*because σ_{hf} x BR > 4 times the expected SM value*)

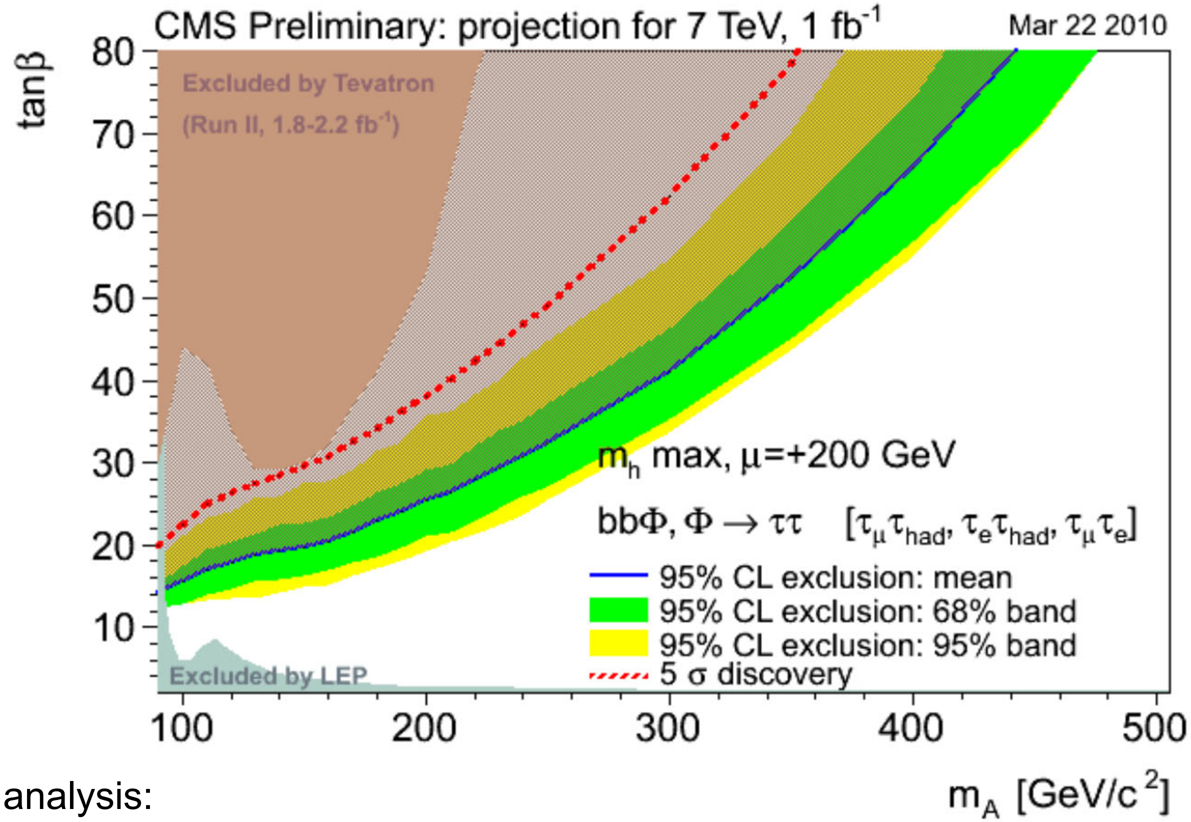
Combination of channels



By combining the results for the three channels shown before, one gets:

Expected exclusion range for the SM Higgs: **$145 < m_H < 190$ GeV**

MSSM: $p\,p \rightarrow b\,b\,\Phi \rightarrow b\,b\,\tau^+\tau^-$



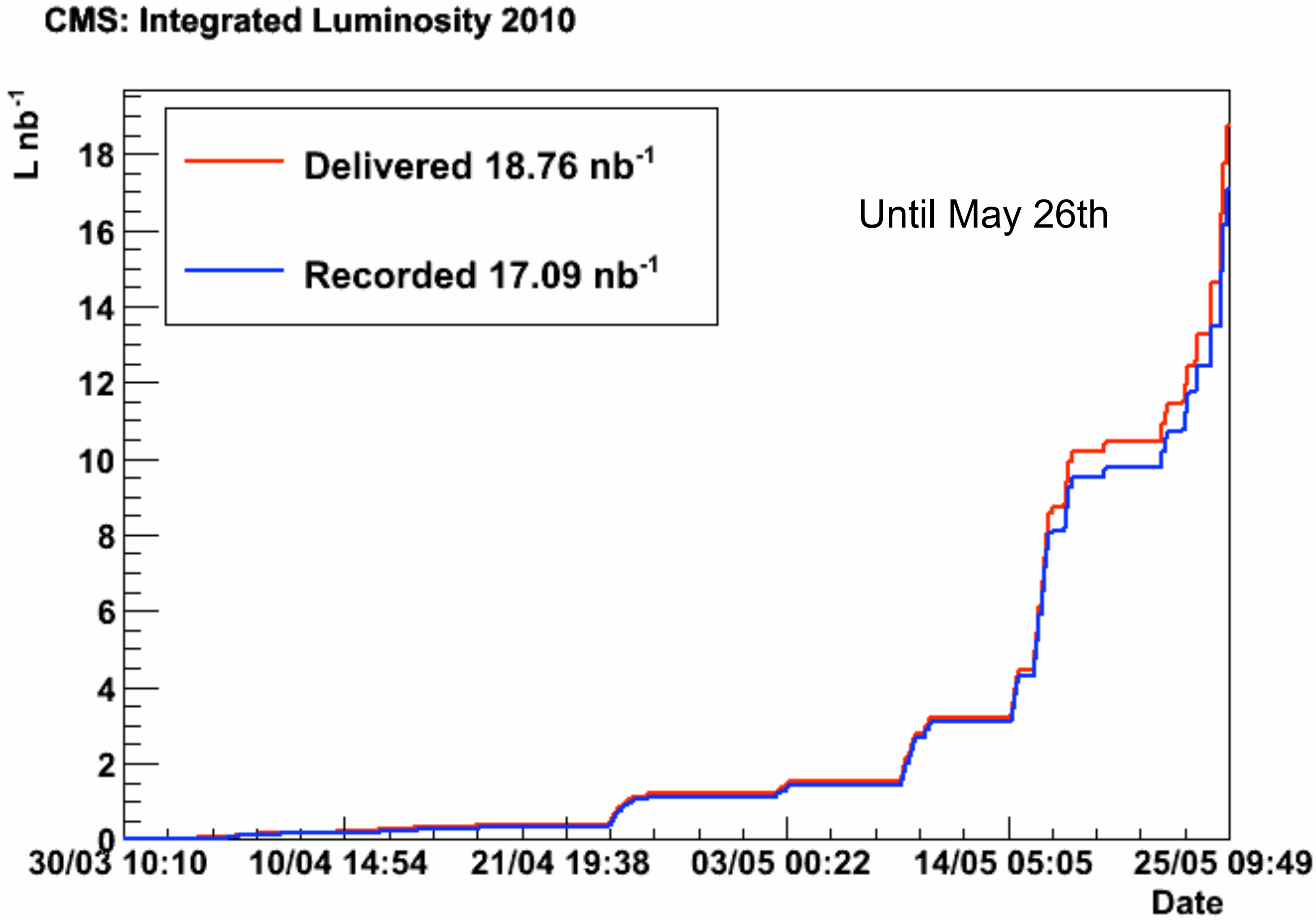
Features of the analysis:

- isolated pairs of (τ_μ, τ_e), (τ_{had}, τ_e), (τ_{had}, τ_μ)
- if MET, look at 1 tagged b-jet and veto other jets
- collinear approximation used to calculate ττ mass (ν's collinear to τ's)
- events counted in a sliding $m_{\tau\tau}$ window
- data-driven estimation of the main backgrounds: $t\bar{t}$, $Zb\bar{b}$, $Zc\bar{c}$

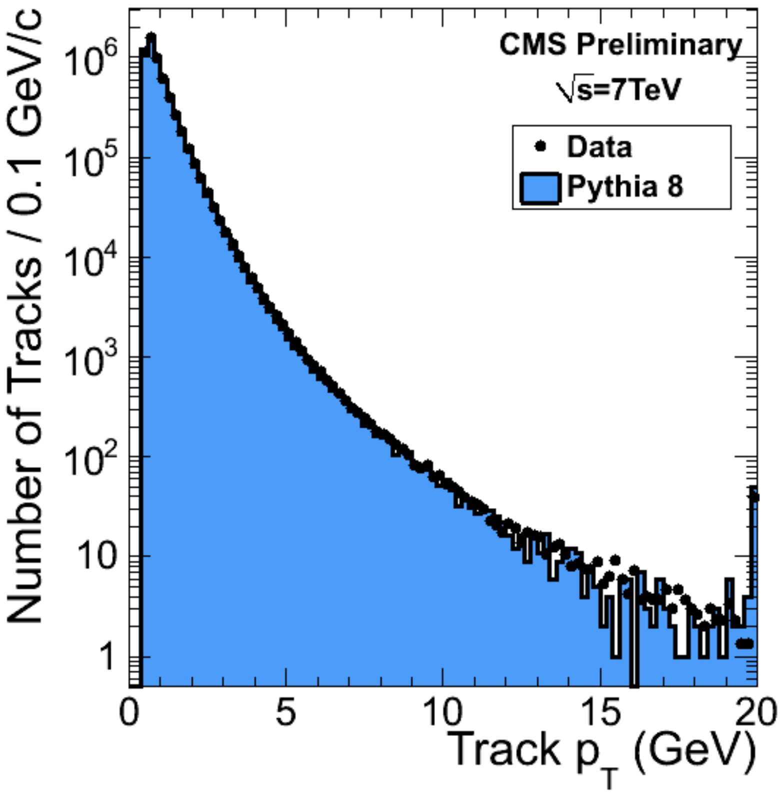
At m_A~90 GeV,

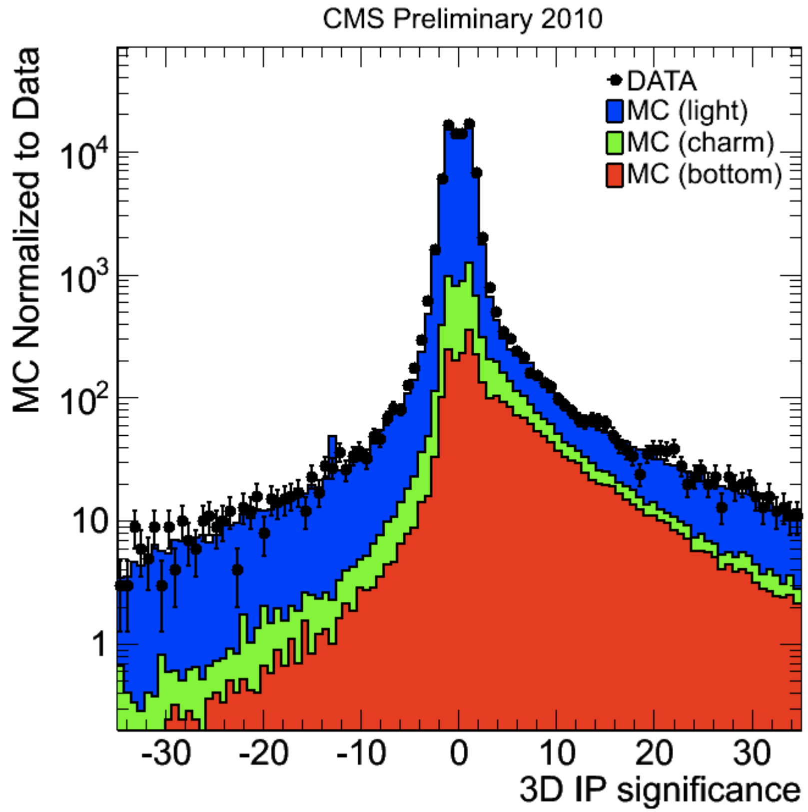
discovery possible for **tan(β)>20**,
exclusion for **tan(β)~15**

Validation from 7 TeV data



Validation at 7 TeV: tracking, b-tagging





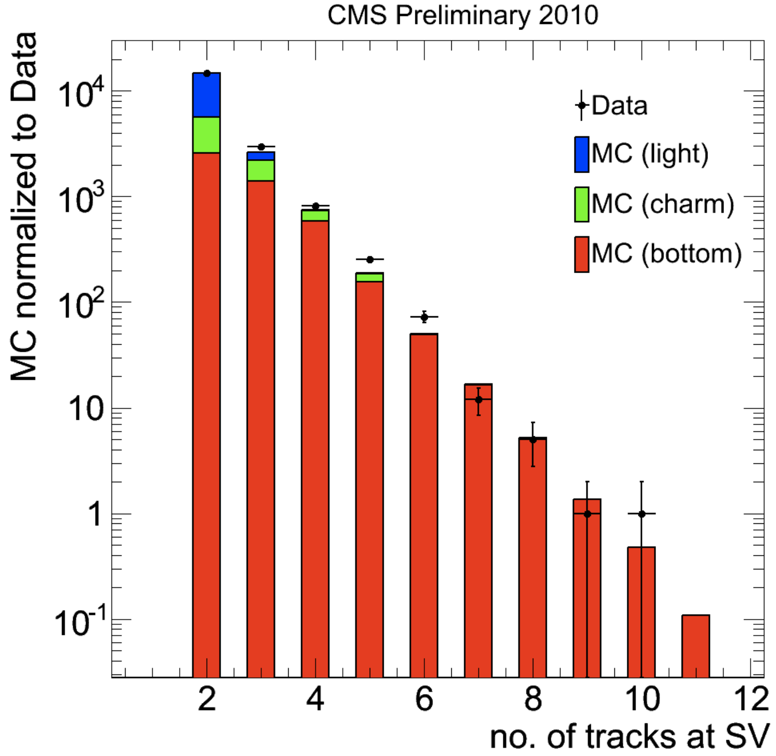
Selection for the p_T distribution:

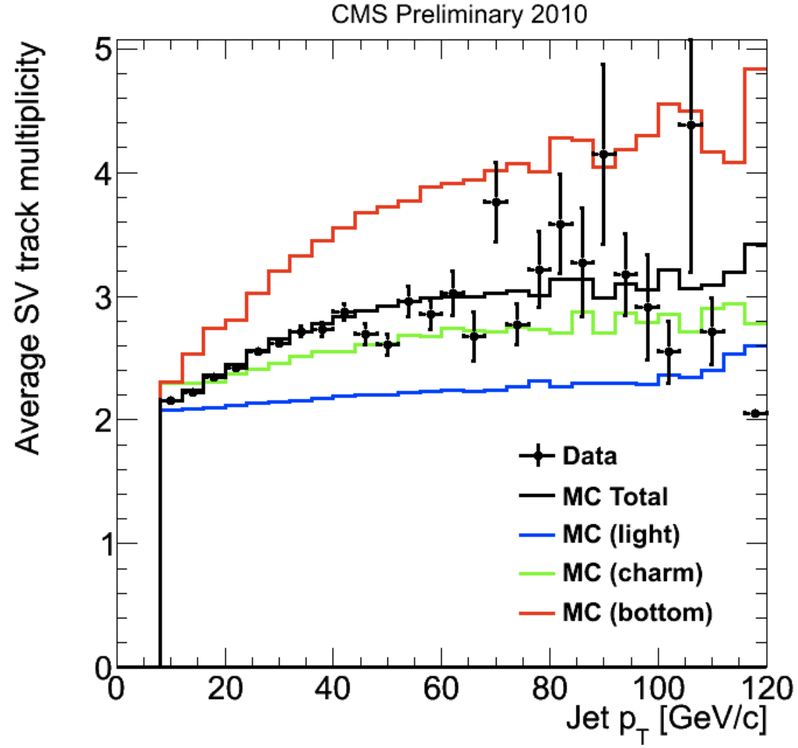
- one Primary Vertex with > 3 tracks
- |dz| < 15 cm, |dxy| < 2 cm
- beam-induced backgrounds rejected
- p_T > 0.5 GeV/c

Significance of the **signed 3D impact parameter** for all tracks selected for b-tagging, for jets with p_T > 40 GeV and $|\eta|$ < 1.5

Good agreement between data and MC

Validation at 7 TeV: secondary vertices

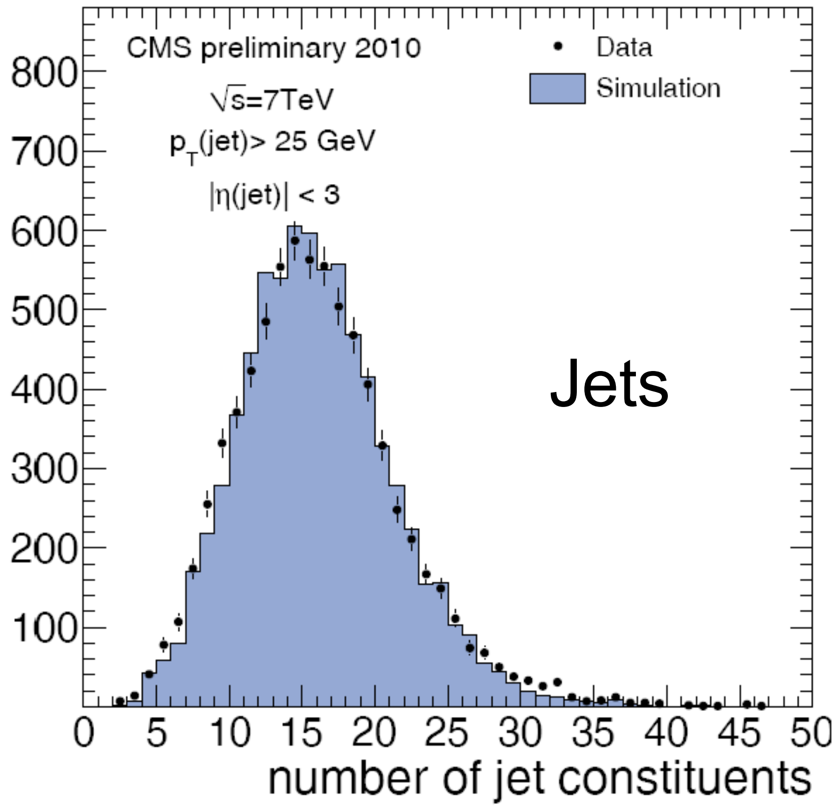


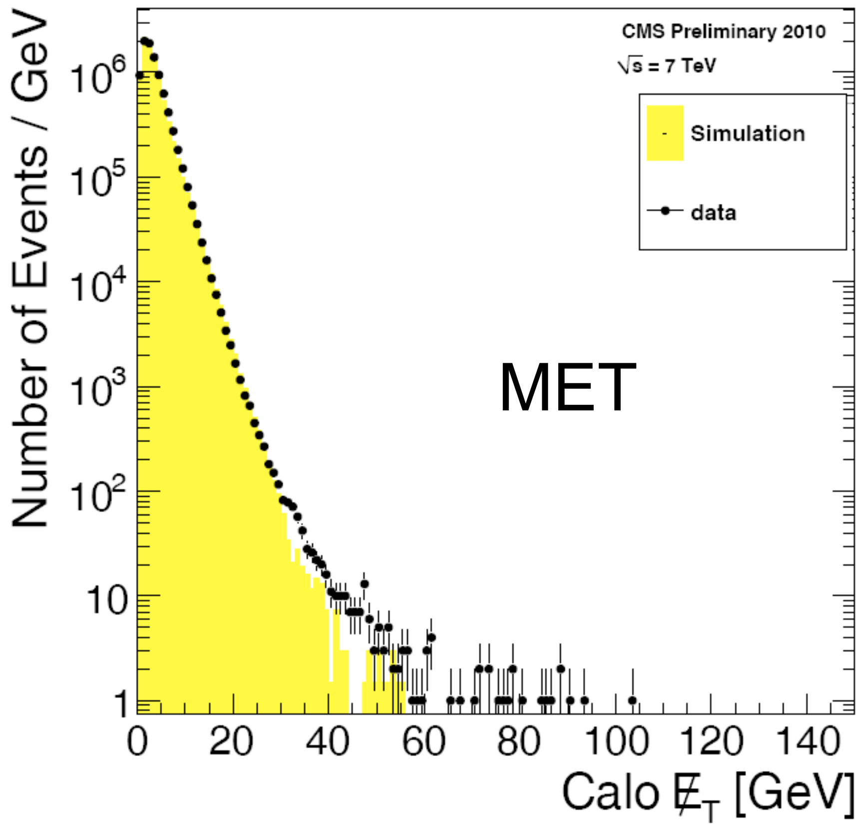


Left: track multiplicity of reconstructed secondary vertices
Right: average track multiplicity as a function of jet p_T

Both plots refer to jets with p_T > 10 GeV and $|\eta|$ < 2.4

Validation at 7 TeV: Jets, MET

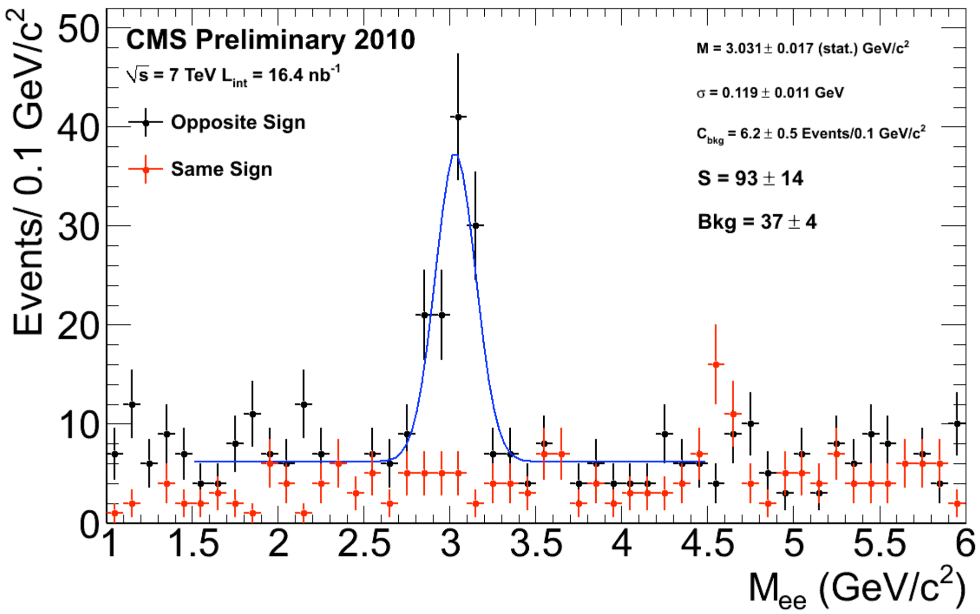




Also these two key points for Higgs physics show
an *overall good agreement* between data and MC

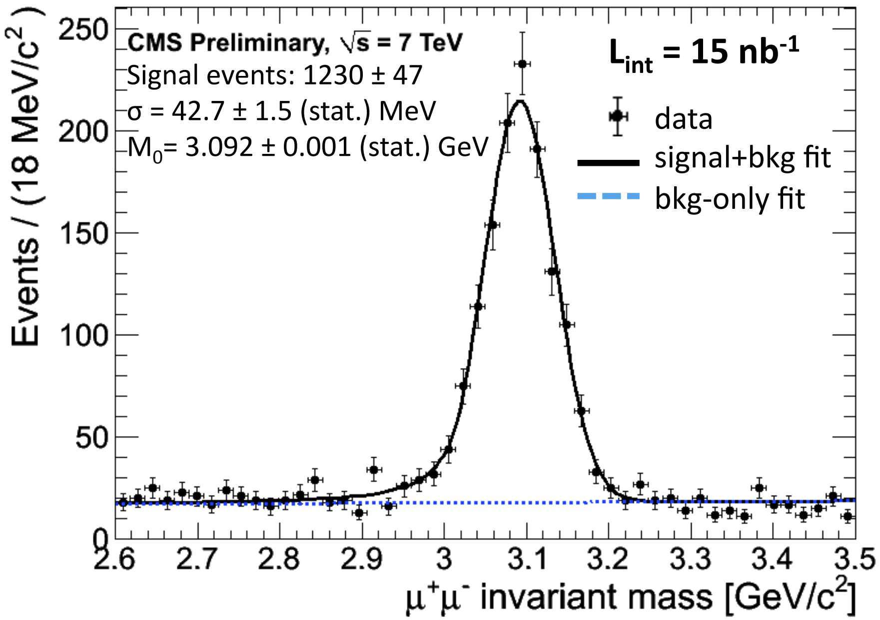
Validation at 7 TeV: $J/\psi \to ee$, $J/\psi \to \mu\mu$

$J/\psi \to ee$



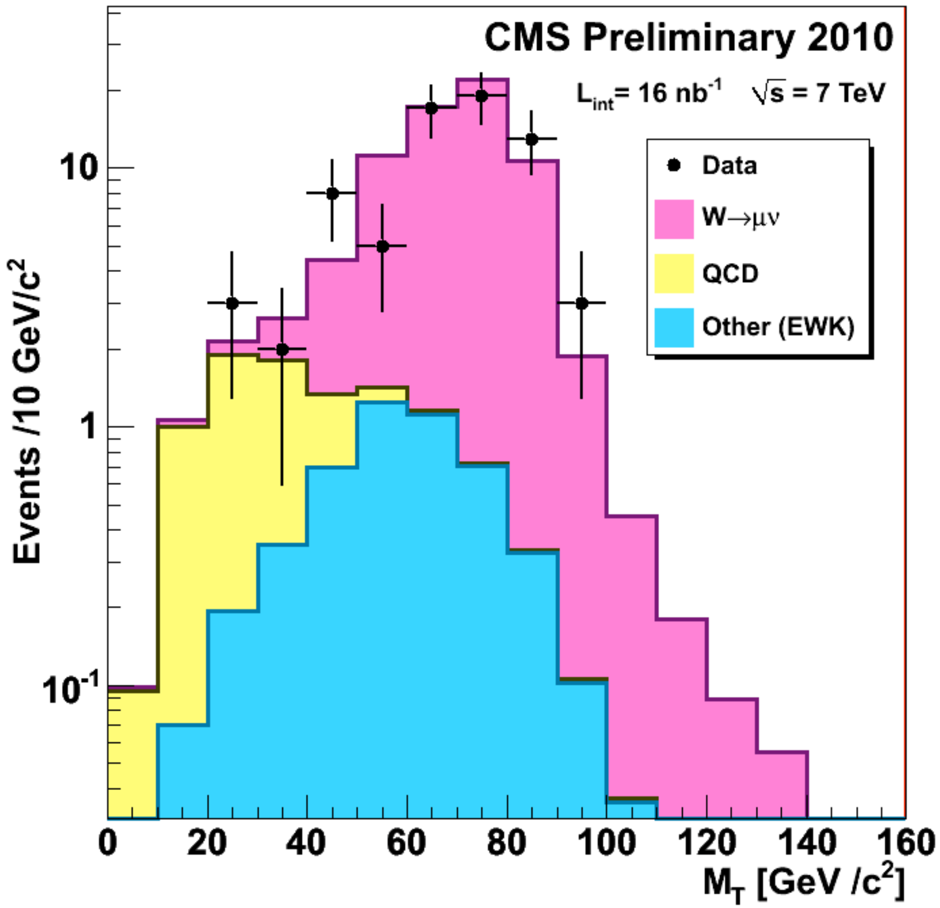
A binned likelihood fit of a **Gaussian** function and a **constant** has been performed in the mass range 1.5 < M(ee) < 4.5 GeV

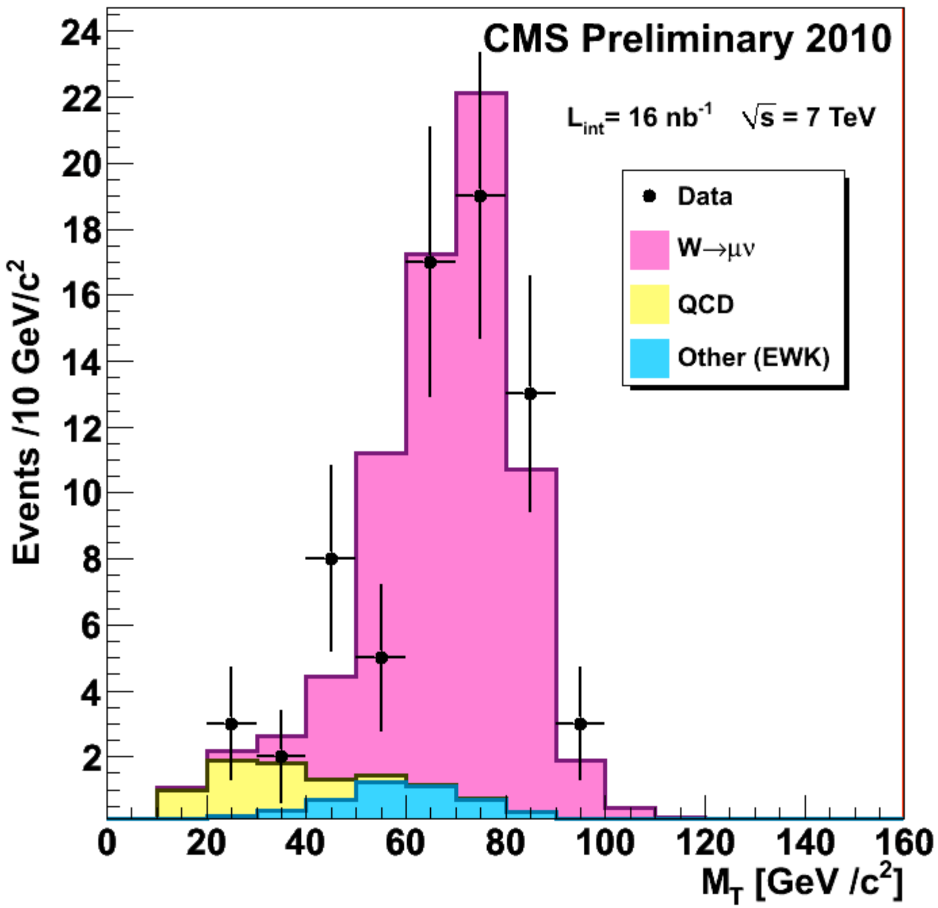
$J/\psi \to \mu\mu$



Extended ML fits are performed with an **exponential** for the background and a **crystal ball** function for the signal *(to account for radiative tails)*

$W \to \mu\nu$ M_T distribution

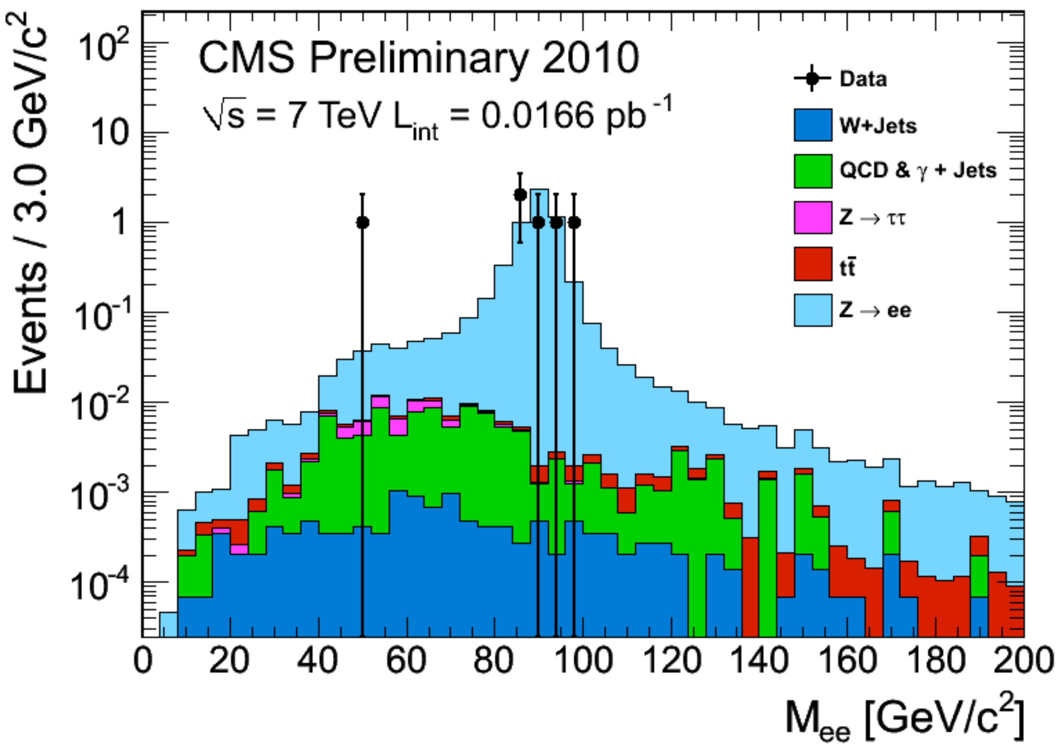




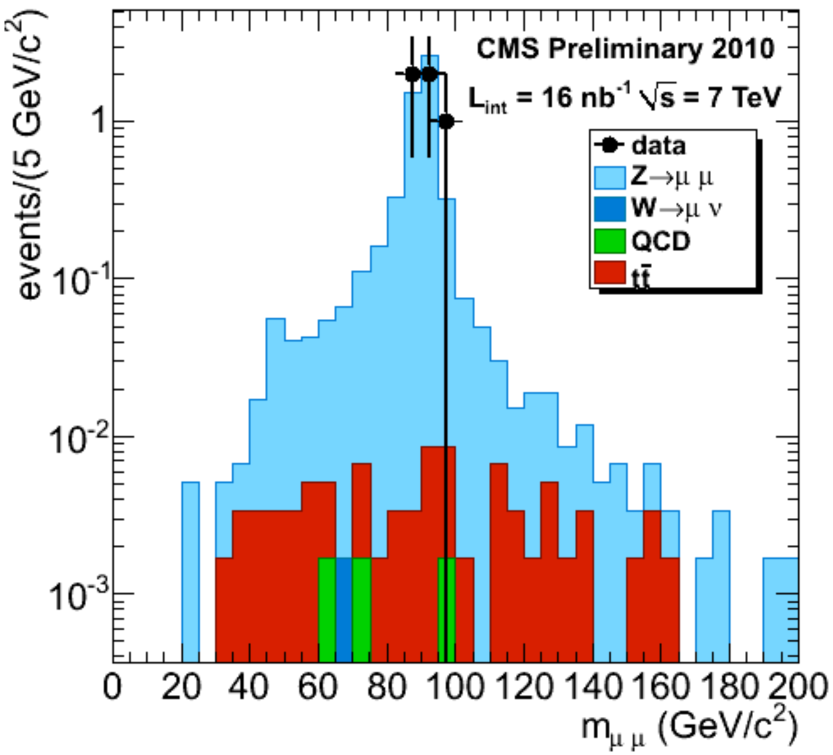
70 signal events in the plot, 57 of them with M_T > 50 GeV

The first $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ events

$Z \rightarrow ee$



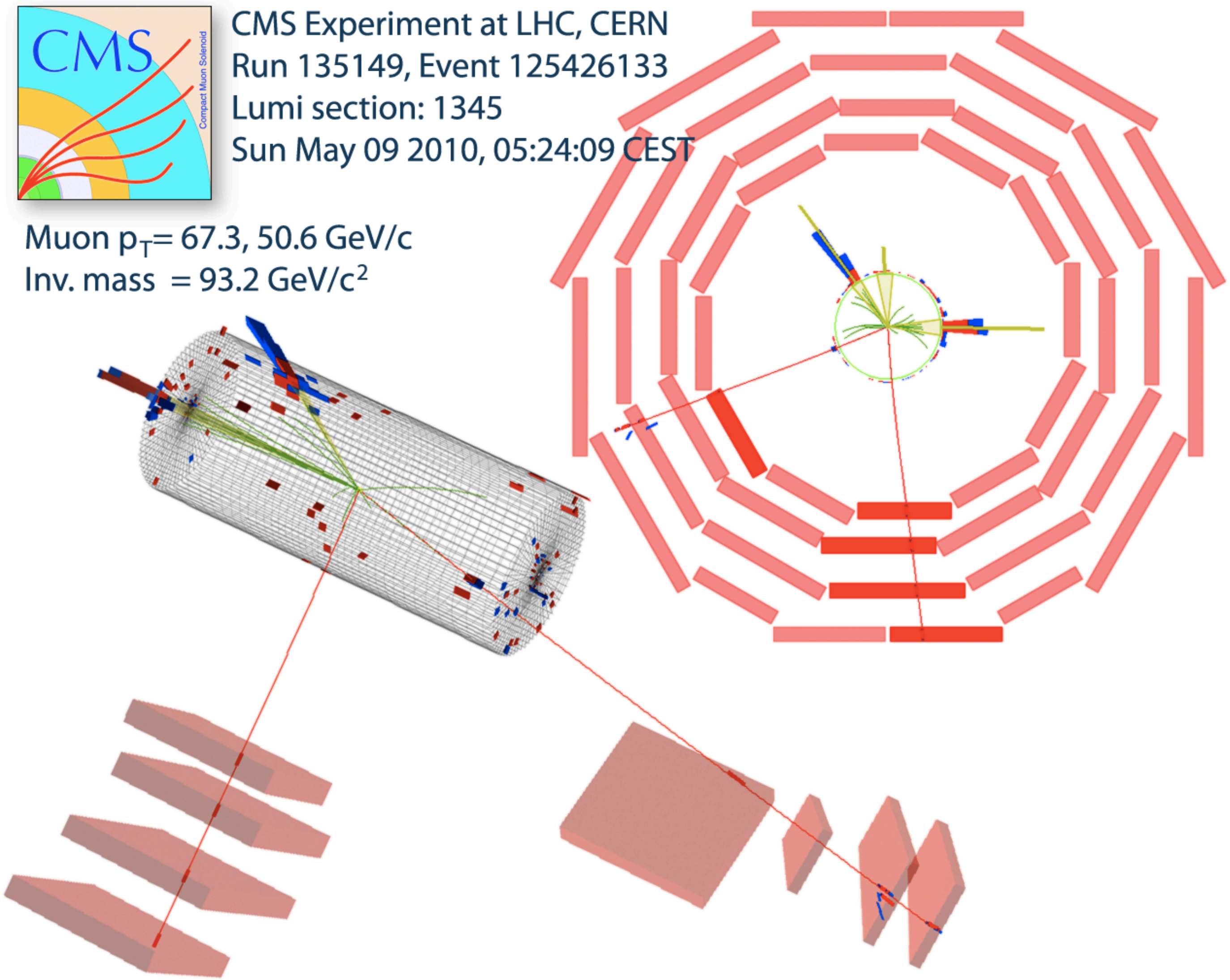
$Z \rightarrow \mu\mu$



- Number of observed Z→ee candidates: 5
- Both electrons are required to pass a loose cut-based electron Id and isolation selection

Muon selection: ID, isolation, p_T>20 GeV

$Z \rightarrow \mu\mu$ candidates: event display

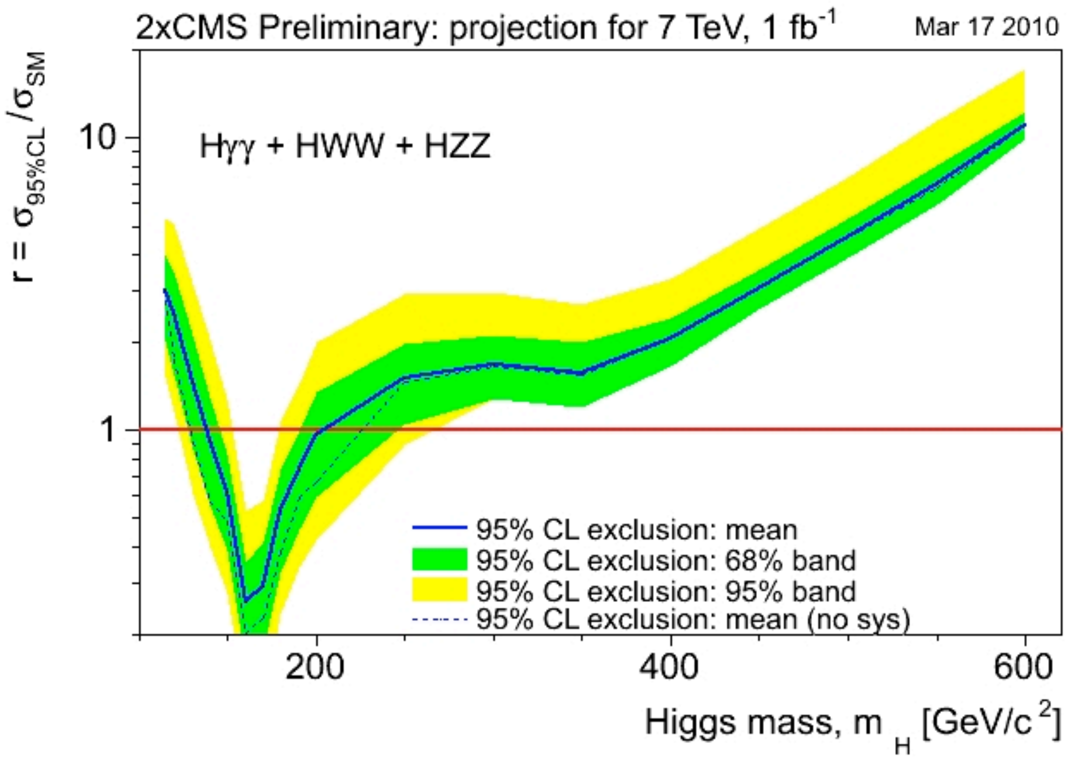


Conclusions

- The expected exclusion limits and discovery sensitivity for Higgs searches have been evaluated in the 7 TeV, 1 fb^{-1} scenario
  - Exclusion range for SM Higgs is **$140 < m_H < 200$ GeV**
  - Discovery range for SM Higgs is **$160 < m_H < 170$ GeV**
  - For MSSM Higgs and low m_A values, exclusion range down to tan(β)~15 …
  - … discovery down to tan(β)~20
- Several key points of these Higgs analyses are being validated with 7 TeV data
  - b-tagging, alignment, jets, MET, energy and momentum calibration…
  - SM is being rediscovered: resonances like π^0, K_s, J/ψ have been measured
  - some W, Z candidates have been observed
  - excellent overall agreement between CMS simulation and data
- Looking forward to having more data for Higgs searches!

BACKUP

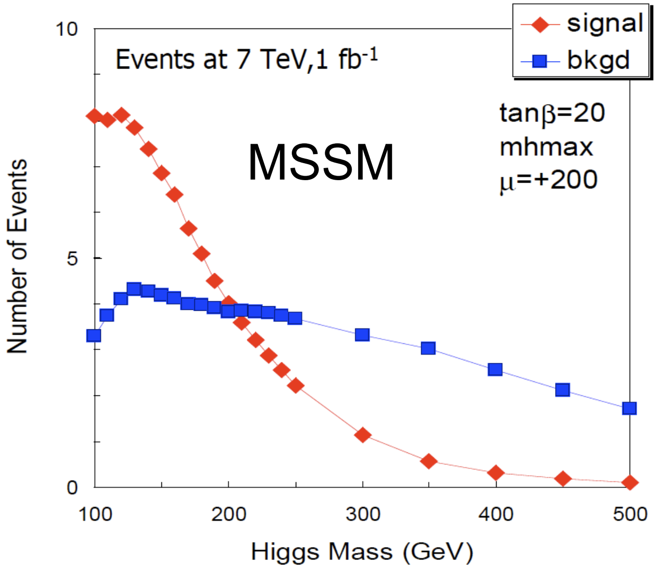
Combination: “2 x CMS”

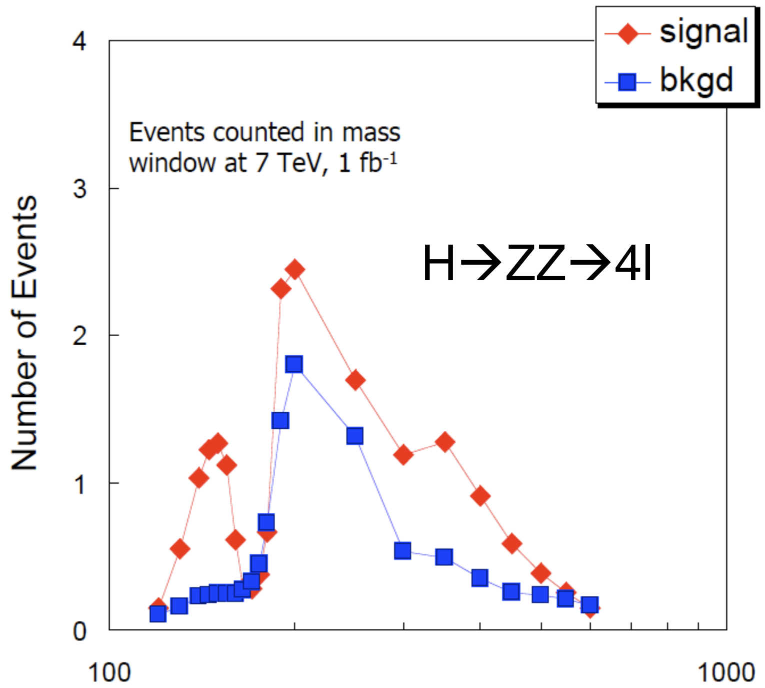


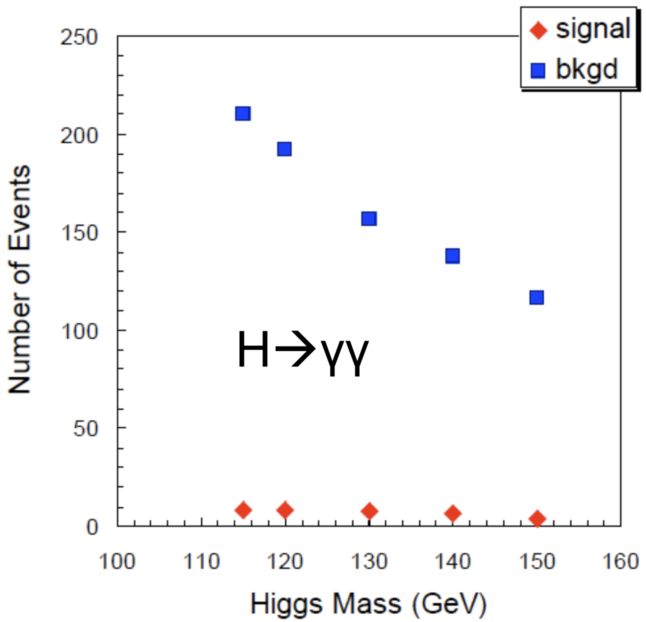
Combining the channels, but under the hypothesis of twice as much data, can provide an estimate of the combined CMS + ATLAS exclusion limits with L=1 fb^{-1}:

Expected exclusion range for the SM Higgs: **$140 < m_H < 200$ GeV**
Expected discovery range: **$160 < m_H < 170$ GeV**
If 4 fermion generations exist, then the excluded range is **$m_H <$ ~570 GeV**

Events for each channel







References

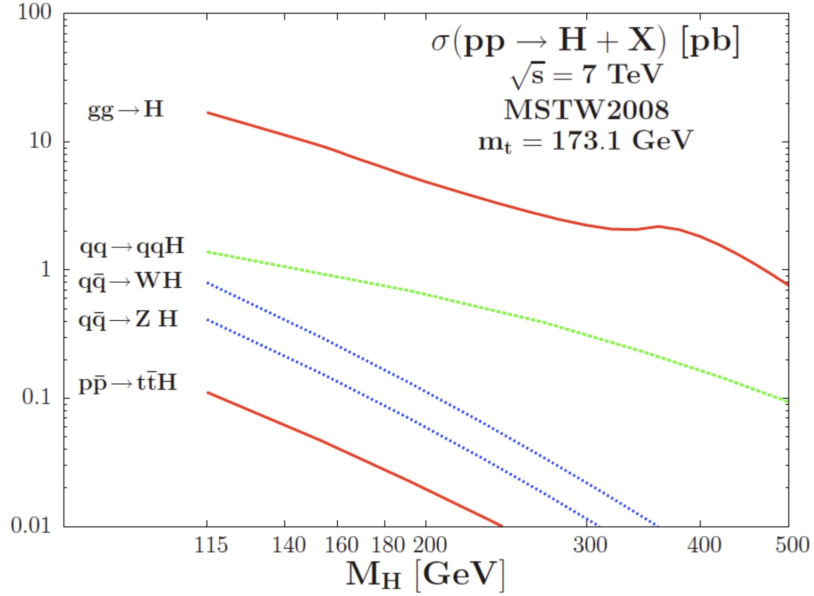
HWW…………………………………… Reference: PAS HIG-08/006

HZZ………….. References: PAS HIG-08/003 NOTE 2006/115, 2006/122, 2006/136

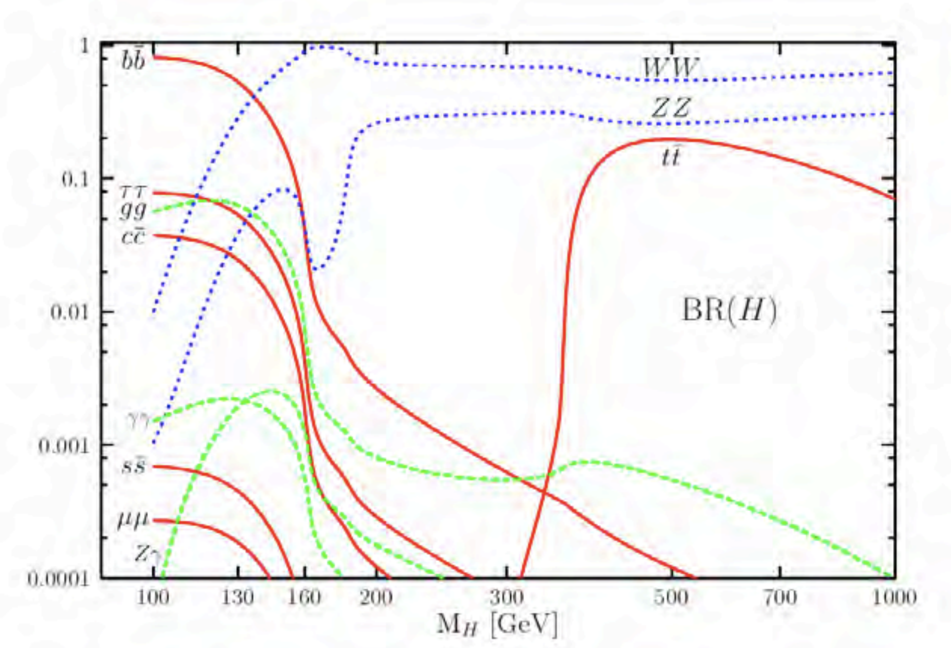
Hγγ………………………….. Reference: NOTE 2006/122

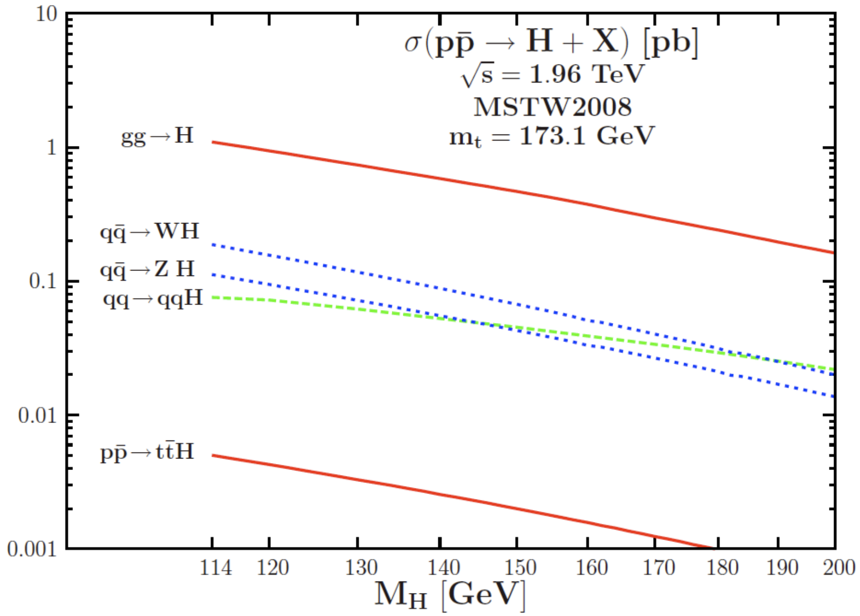
MSSM……………………………………… References: NOTE 2006/075, 2006/101, 2006/105

Higgs at 7 TeV



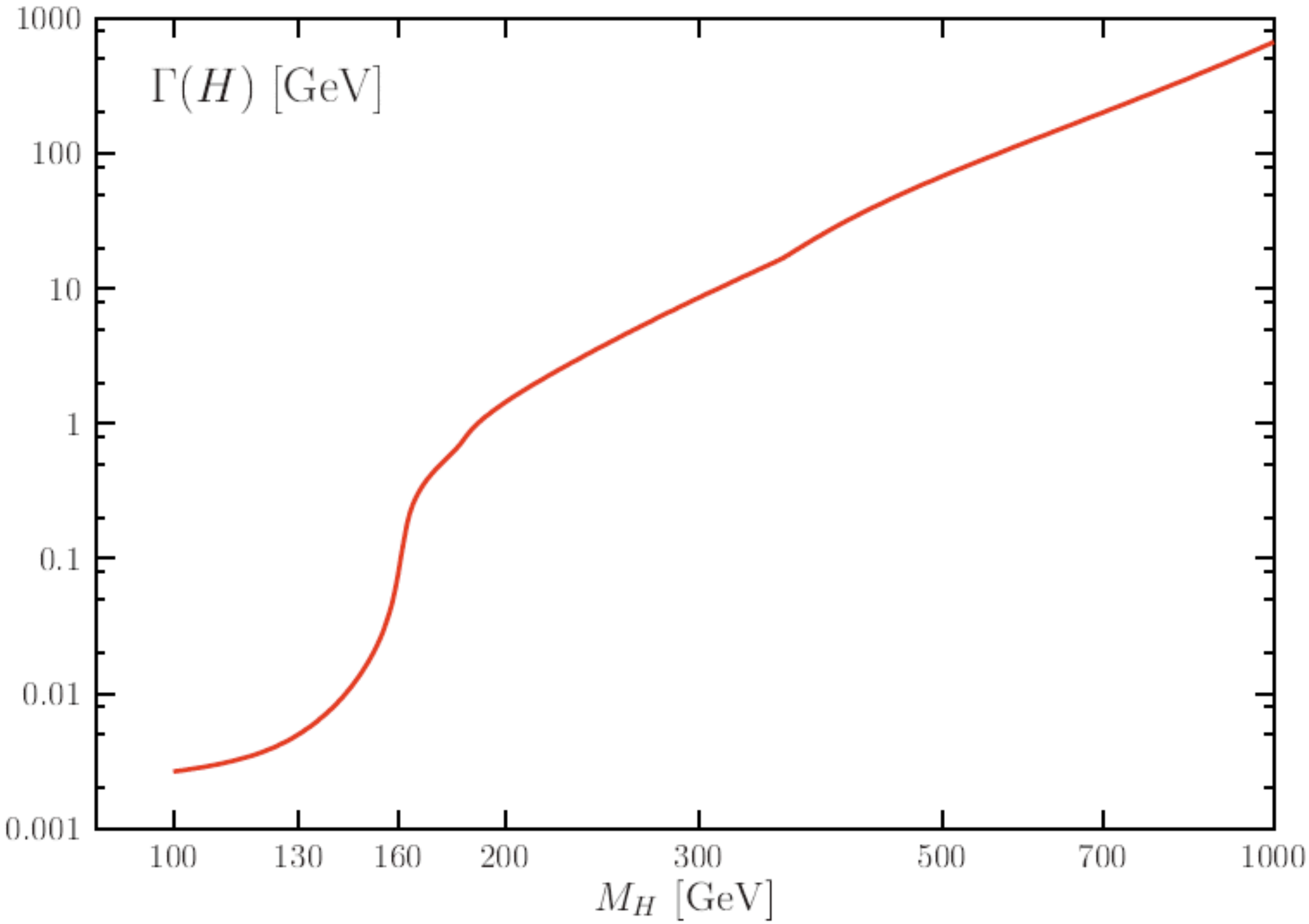
LHC





TeVatron

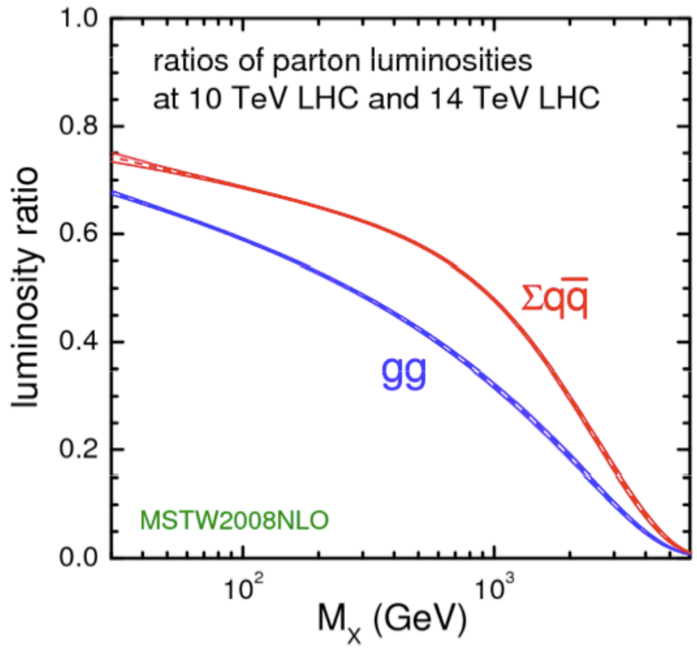
Higgs width vs mass



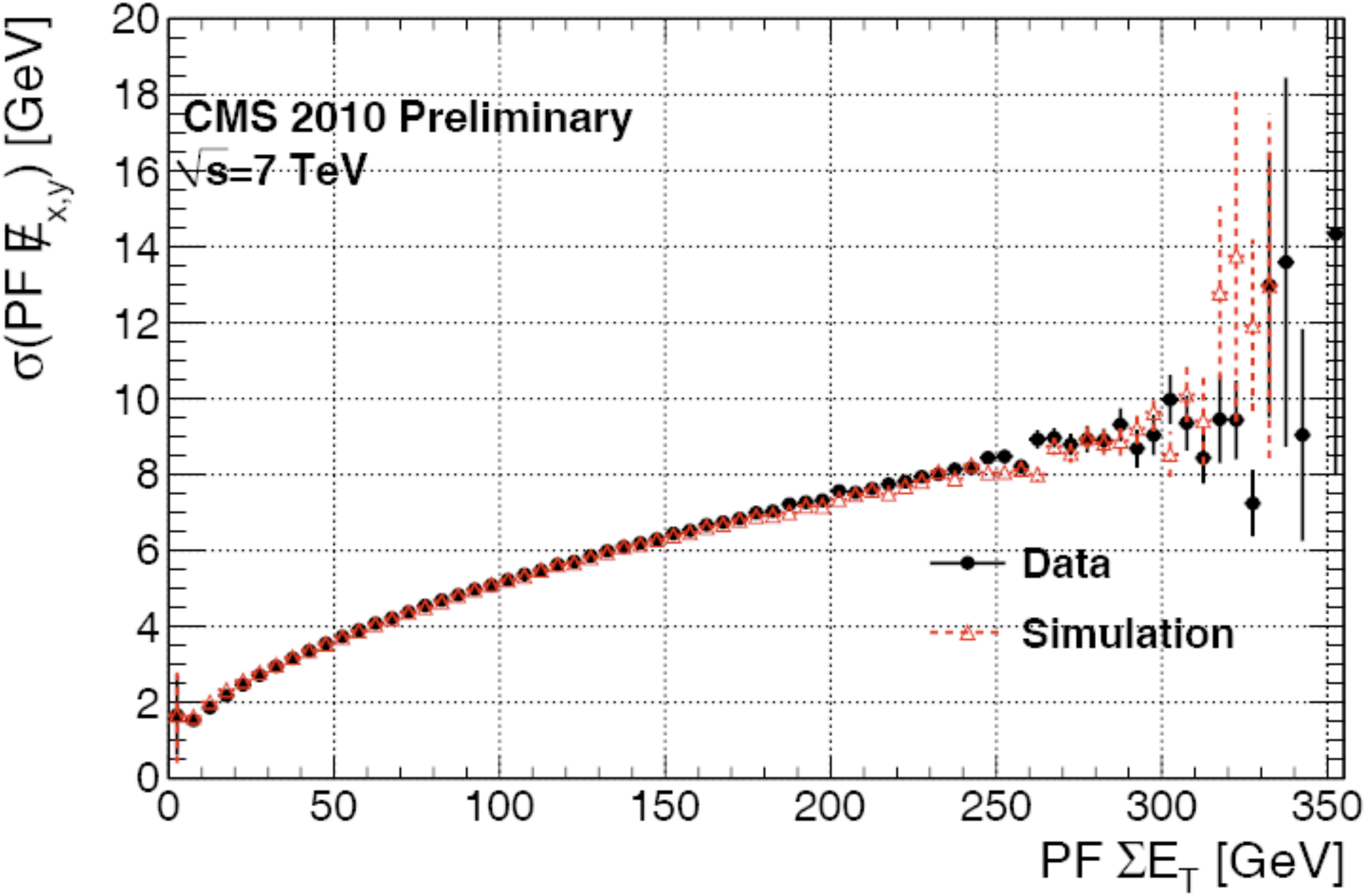
Ratio of Xsections at $\sqrt{s}$ = 14, 10, 7 TeV

Process	σ(10 TeV)/σ(14 TeV)	σ(7 TeV)/σ(10 TeV)	σ(7 TeV)/σ(14 TeV)
H (m=160)	0.54	0.50	0.27
WW, ZZ, WZ	0.65	0.62	0.40
tt	0.45	0.39	0.18
tW	0.45	0.39	0.18
W, Z	0.68	0.66	0.45

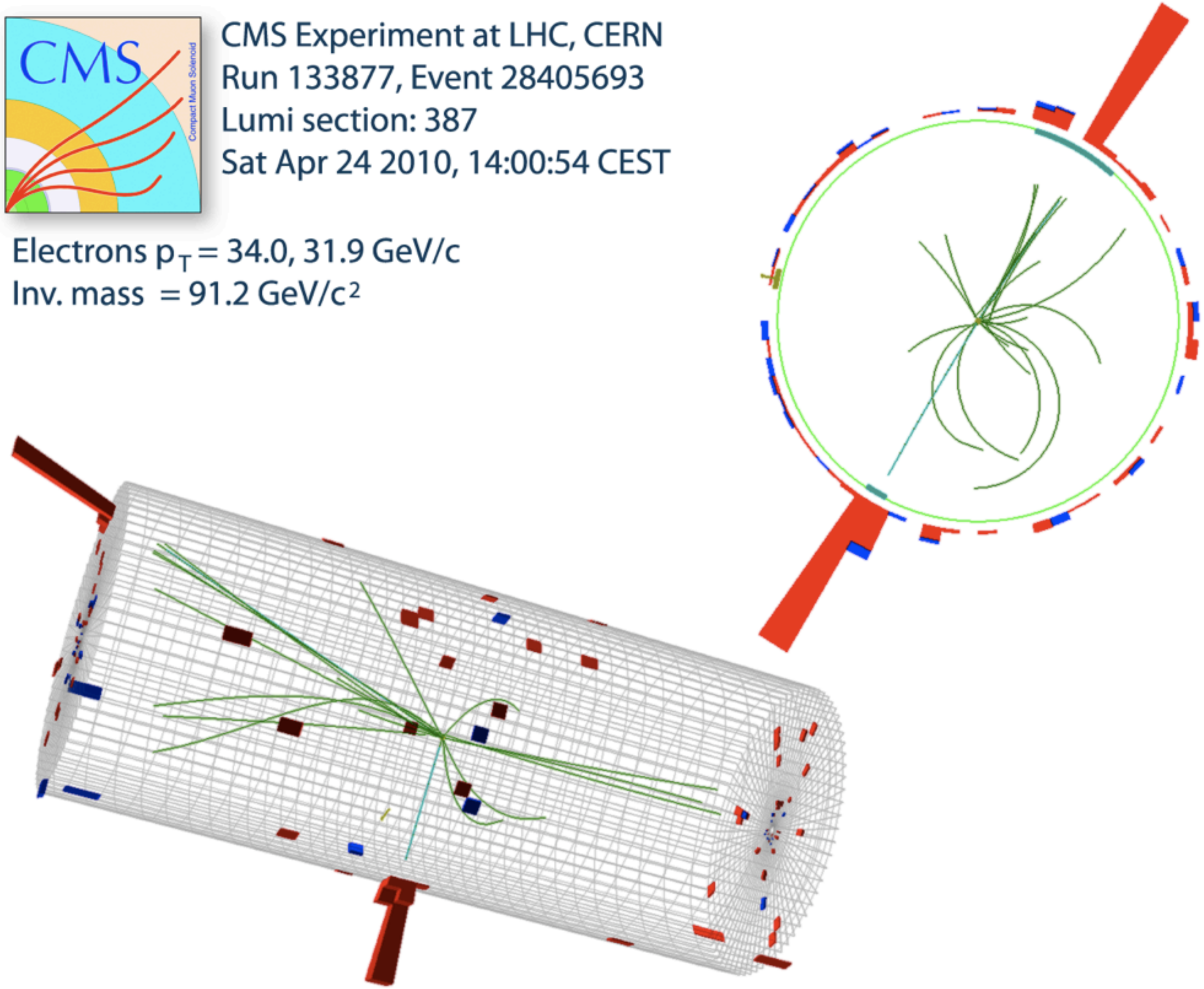
LHC at 10 TeV



MET resolution

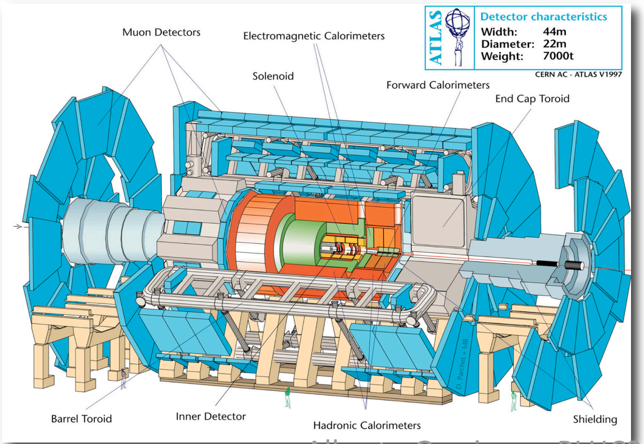


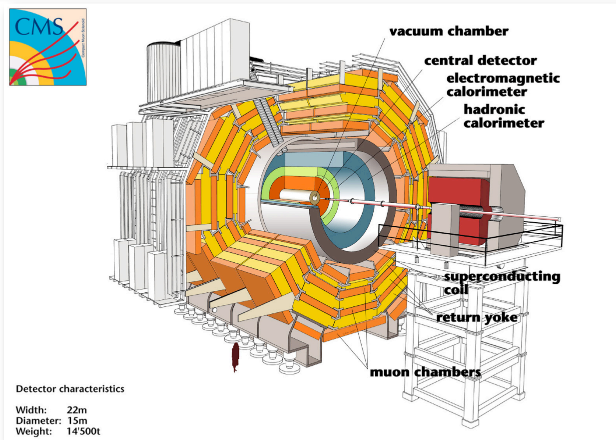
$Z \rightarrow ee$ candidates: event display



ATLAS and CMS

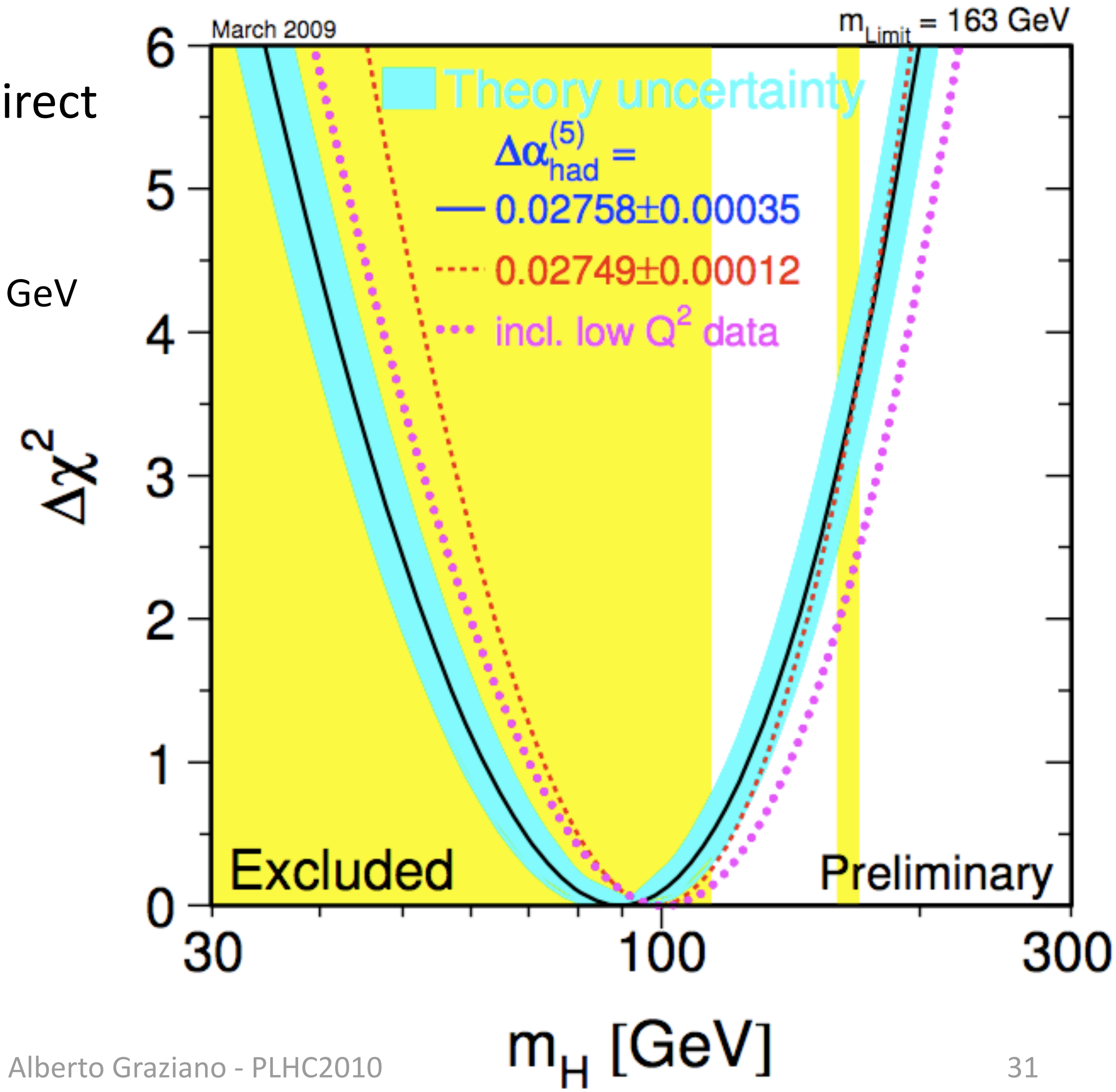
	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} + 0.005$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Cu+scintillator (5.8λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (ID+MS)	$\sigma/p_T \approx 1\%$ @ 50GeV to 5% @ 1TeV (ID+MS)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)





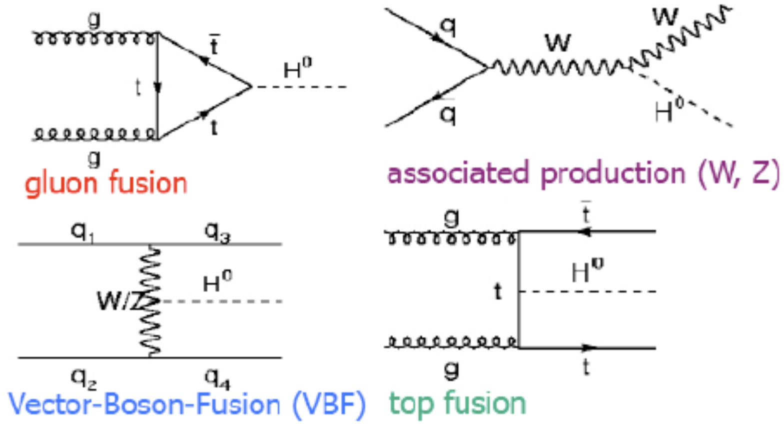
The Higgs mass

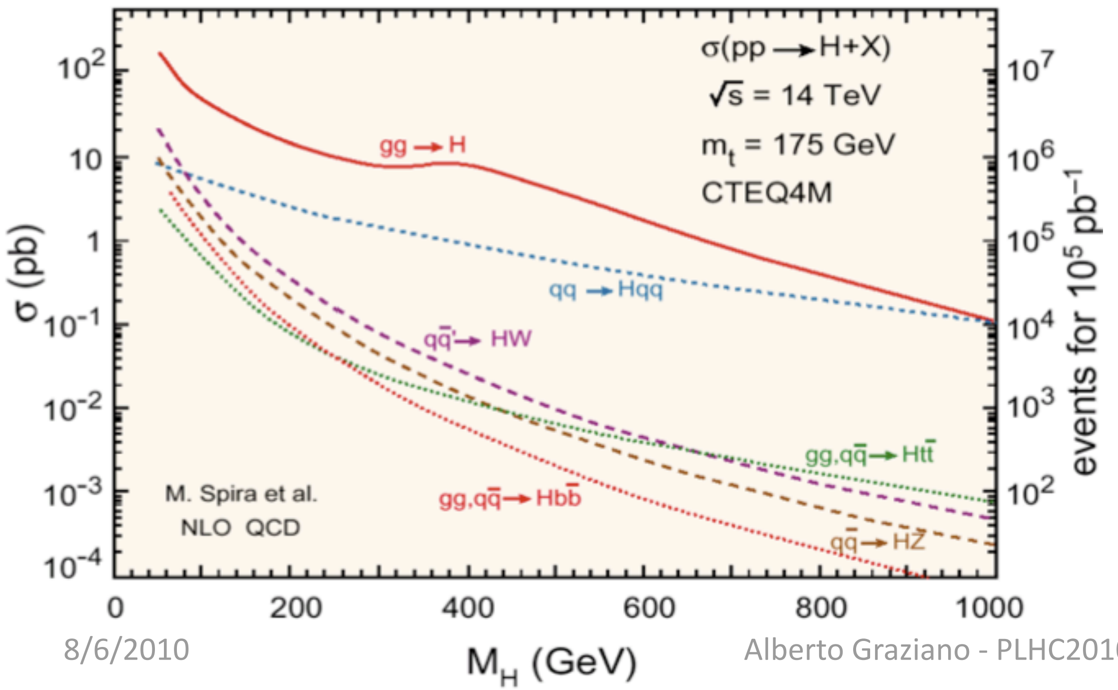
- Exclusions at 95% C.L. from direct search:
  - LEP: $m_H < 114.4$ GeV
  - TeVatron run II: $160 < m_H < 170$ GeV
- LEP preferred fit values:
  - $m_H = 87_{-26}^{+35}$ GeV (68% C.L.)
  - $m_H < 157$ GeV (95% C.L.)
- Unitarity constraint:
  - $m_H < 1$ TeV

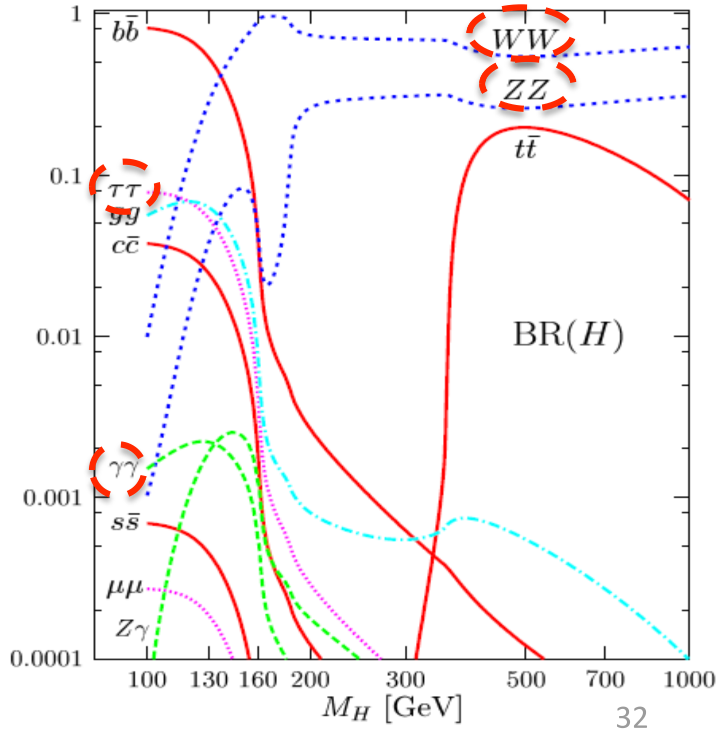


Higgs production and decays

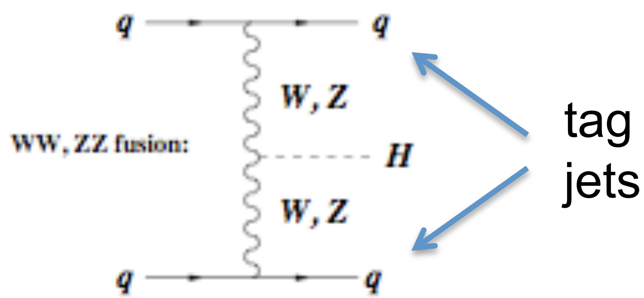
- g-g fusion is the main production channel at LHC
- Decay modes:
  - $b\bar{b}$ suffers from the huge QCD background
  - $\tau^+\tau^-$ is promising at low m_H values
  - $\gamma\gamma$ is relatively easy to detect, despite the very low BR
  - WW is the dominant channel for m_H > 140 GeV (BR ≈ 1 at m_H = 160 GeV)
  - ZZ has a lower BR than WW, but a clearer signature



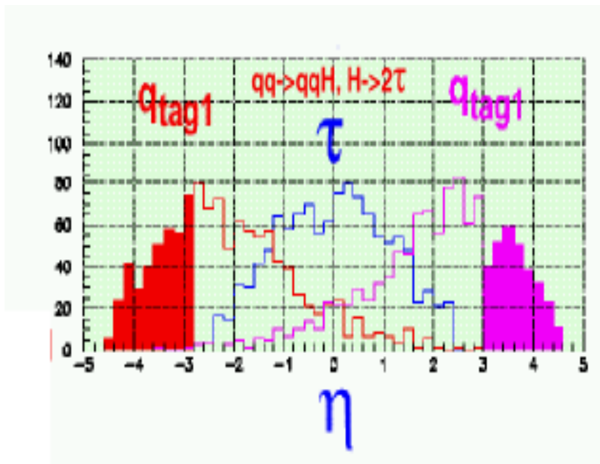


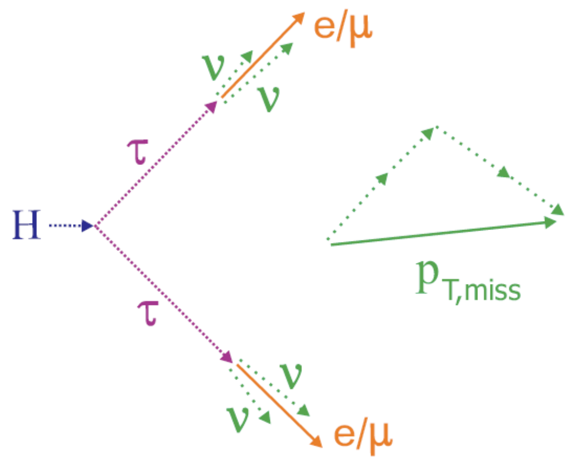


$VBF\ \ H \rightarrow \tau^+\tau^-$



- 3 final states: lepton-lepton, lepton-hadron, hadron-hadron
- Signature:
  - 2 leptons or τ-jets in the central region
  - MET
  - 2 forward tag jets in opposite hemispheres (used as tag)
- The invariant mass M(ττ) can be calculated in the collinear approximation:
  - ν's collinear to τ's
- Backgrounds:
  - QCD, reduced with the Central Jet Veto (no colour flow between the 2 tag jets)
  - W/Z + jets
  - $Z/\gamma^* \rightarrow \tau^+\tau^-$, estimated from $Z \rightarrow \mu^+\mu^-$
  - $t\bar{t}$, suppressed by performing b-jet ID





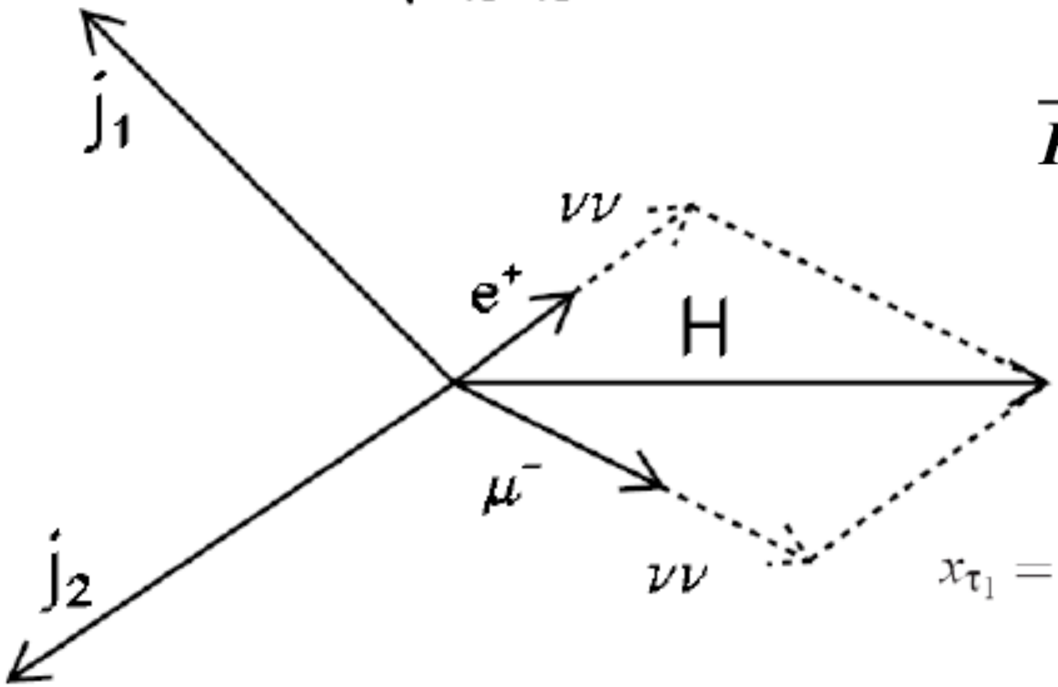
$VBF\ \ H \rightarrow \tau^+\tau^-$

$$M_{\tau\tau} \approx \frac{M_{ll}}{\sqrt{x_{\tau 1} x_{\tau 2}}}$$

$$\vec{P}_\tau = \frac{\vec{P}_l}{x_\tau}$$

fraction of τ momentum carried by the lepton

$$\vec{P}_{T\tau 1} + \vec{P}_{T\tau 2} = \vec{P}_{Tl1} + \vec{P}_{Tl2} + \vec{P}_{Tmiss}$$



$$x_{\tau_1} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},x} \cdot p_{T_{lep2},y} - p_{T_{Higgs},y} \cdot p_{T_{lep2},x}}$$

$$x_{\tau_2} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},y} \cdot p_{T_{lep1},x} - p_{T_{Higgs},x} \cdot p_{T_{lep1},y}}$$

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

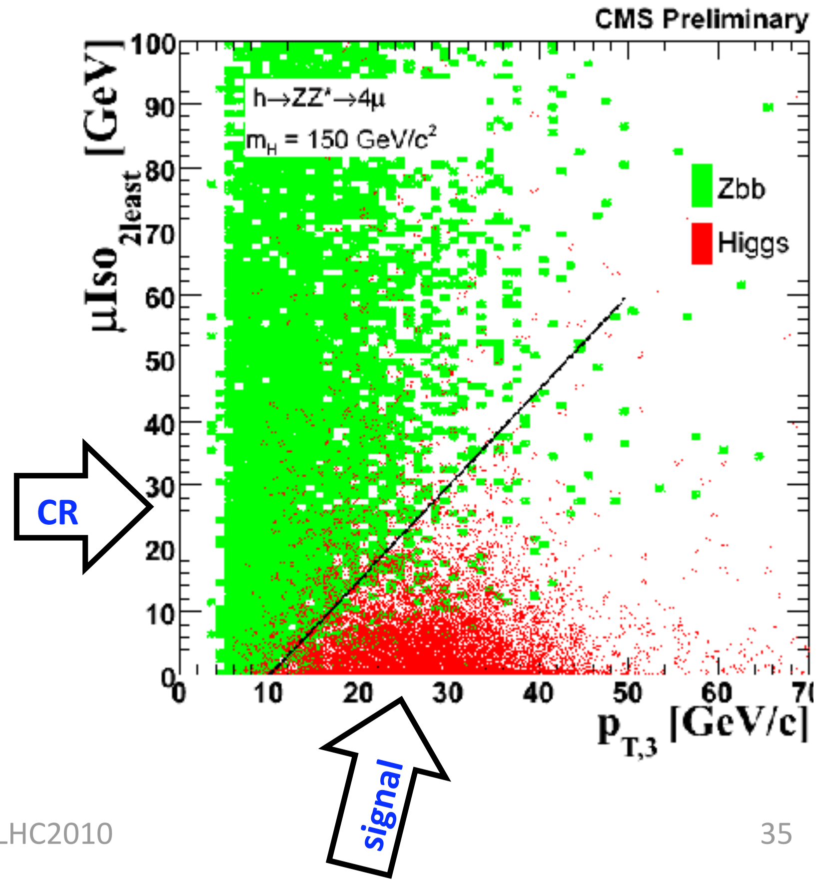
An example: CMS data-driven methods to control the background

- ZZ → 4l: normalization to Z → ll

from MC one gets:

$$\rho(m_H) = \frac{N_{ZZ}^{theory}(\Delta m) \cdot \varepsilon_{ZZ}}{N_Z^{theory} \cdot \varepsilon_Z} \quad \Rightarrow \quad N_{ZZ}^{predicted}(\Delta m) = \rho(m_H) \cdot N_Z^{measured}$$

- Zb$\bar{b}$: normalization to sidebands
  - Zb$\bar{b}$ background can be estimated in a control region (CR)
  - A constraint to the Z mass is set, to suppress t$\bar{t}$ contributions in this region
  - An extrapolation from the control region to the signal one is made
  - The final uncertainty is ~35% at L=1 fb^{-1}

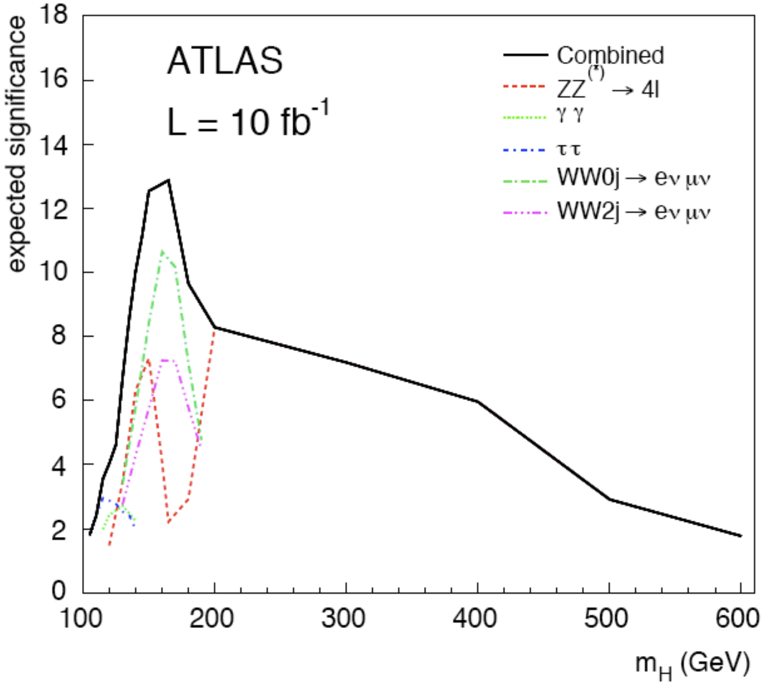


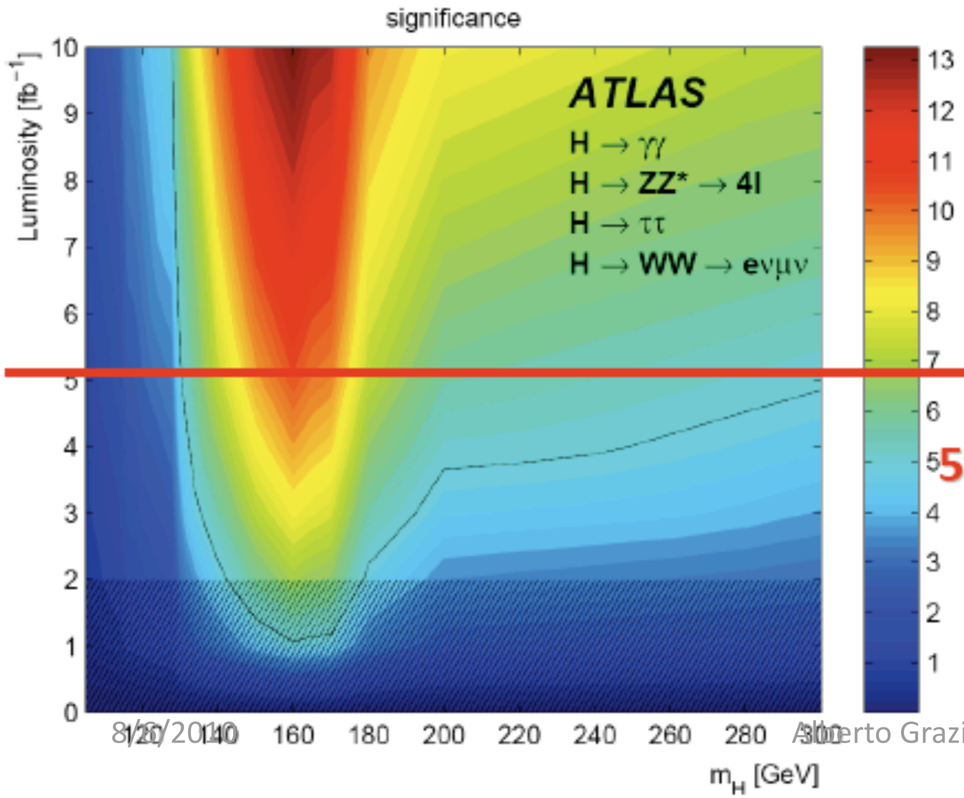
μIso_{2least}: sum of the isolation variable for the 2 least isolated leptons

$p_{T,3}$: p_T of the 3rd lepton (after sorting by decreasing p_T)

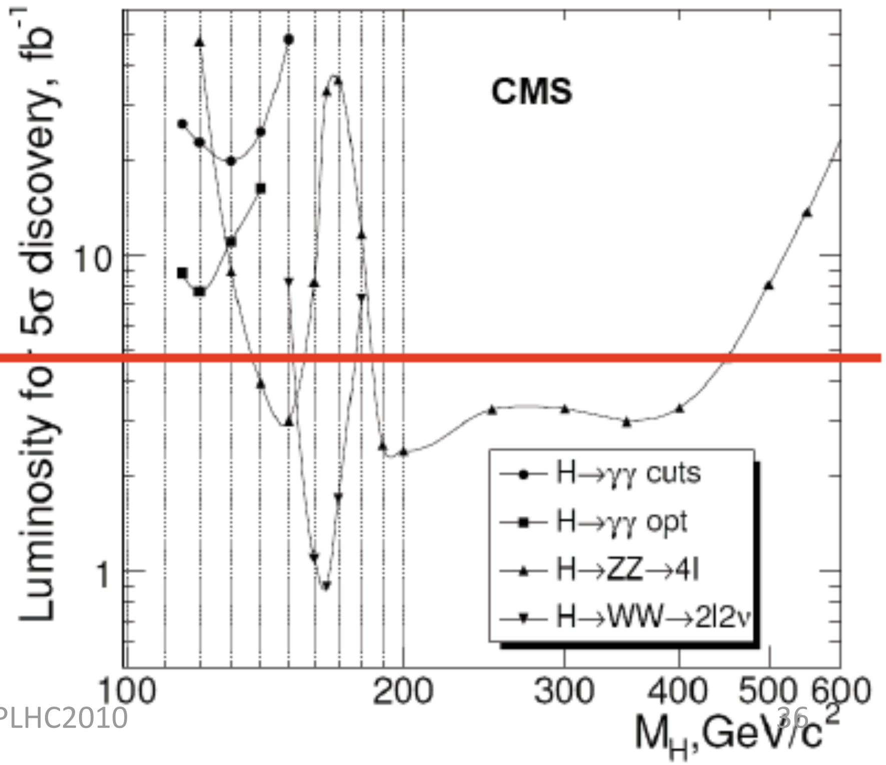
Channel combination: discovery (14 TeV analysis)

- ATLAS and CMS combined analyses can make a 5σ discovery possible in the range $140 < m_H < 450$ GeV with $L=5\ fb^{-1}$
- At low L, the main discovery channels are WW (around $m_H \sim 2\ m_W$) and ZZ



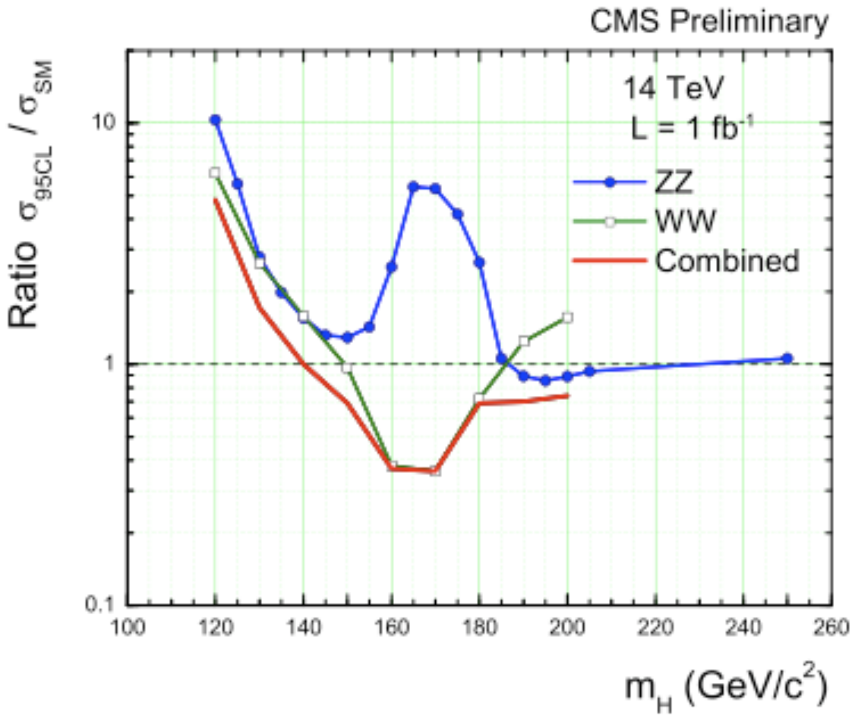


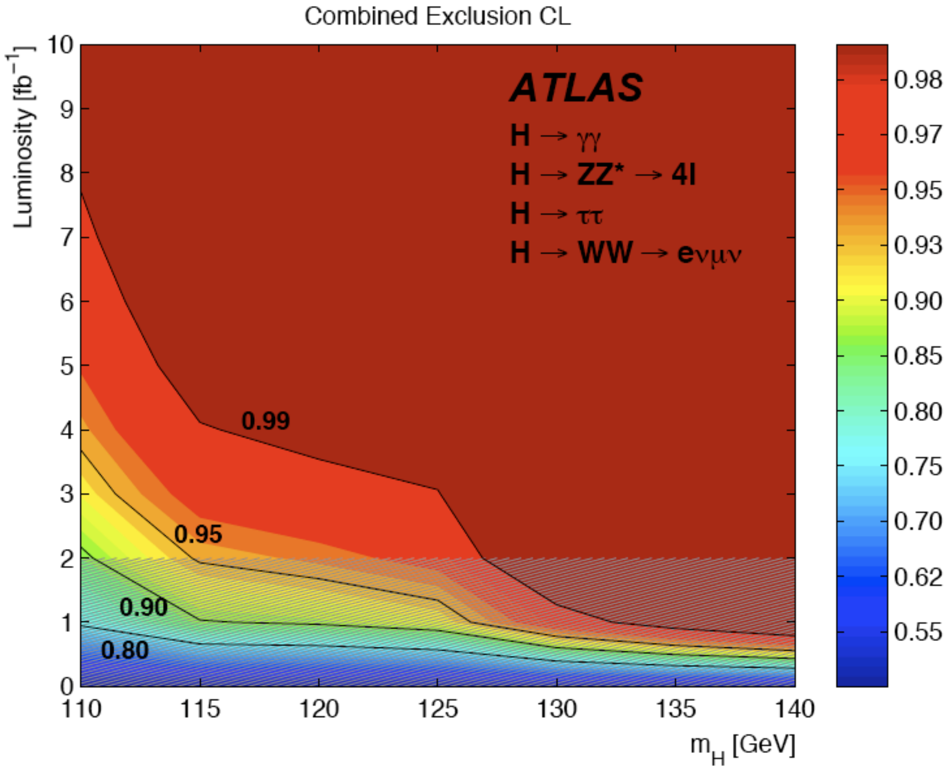
5fb-1

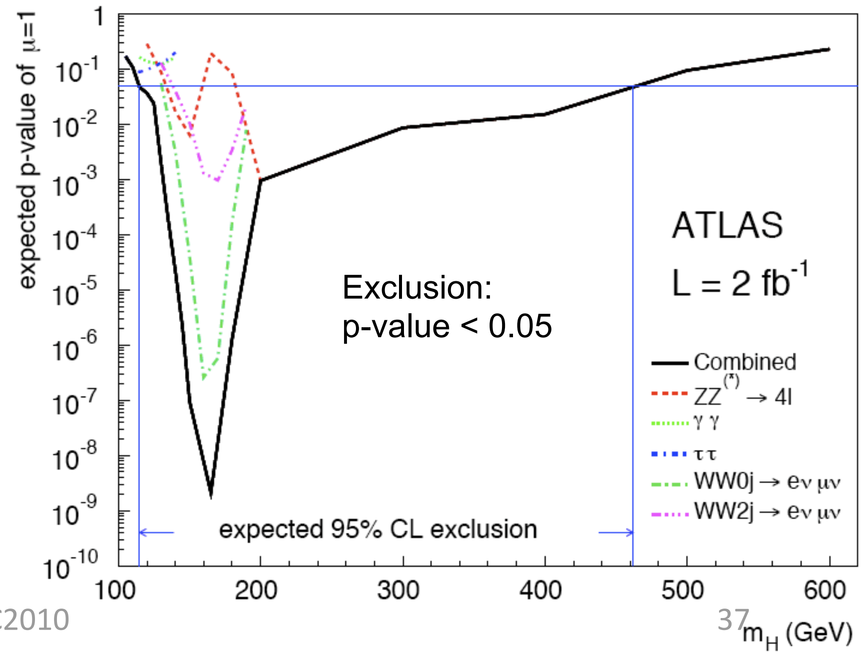


Channel combination: exclusion (14 TeV analysis)

- By combining WW and ZZ channels, CMS can exclude the Higgs at 95% C.L. in the mass range $140 < m_H < 230$ GeV with $L=1\ fb^{-1}$
- ATLAS can do the same in the mass range $115 < m_H < 460$ GeV with $L=2\ fb^{-1}$







Different $\sqrt{s}$ scenarios

- The LHC has started running at $\sqrt{s}$ = 7 TeV
- W.r.t. $\sqrt{s}$ = 14 TeV, both signal and bkg Xsections get lower
  - the signal one drops more steeply than the bkg one, because signal is mostly produced via gg fusion, whereas bkg via qq fusion
- Higgs production cross section: σ(10 TeV) ~ 0.5 σ(14 TeV)
- A larger integrated luminosity will be needed, both for discovery and for exclusion
  - e.g. at CMS, for 95% C.L. exclusion, L(6 TeV) ~ 10 L(14 TeV))

Process	$\frac{\sigma_{\sqrt{s}=10TeV}}{\sigma_{\sqrt{s}=14TeV}}$	$\frac{\sigma_{\sqrt{s}=6TeV}}{\sigma_{\sqrt{s}=14TeV}}$
$t\bar{t}$	0.450	0.113
Wt	0.450	0.113
WW	0.650	0.320
WZ	0.650	0.320
ZZ	0.650	0.320
$Z \to \ell\ell$	0.681	0.371
$W \to \ell\nu$	0.681	0.371
$gg \to H$	0.540	0.190

Example : HWW + HZZ combined

∫L for 5σ	14 TeV	10 TeV
m_H=200 GeV	0.6 fb-1	1.3 fb-1