Higgs Searches with the ATLAS Experiment at the LHC

Bruce Mellado

University of Wisconsin-Madison

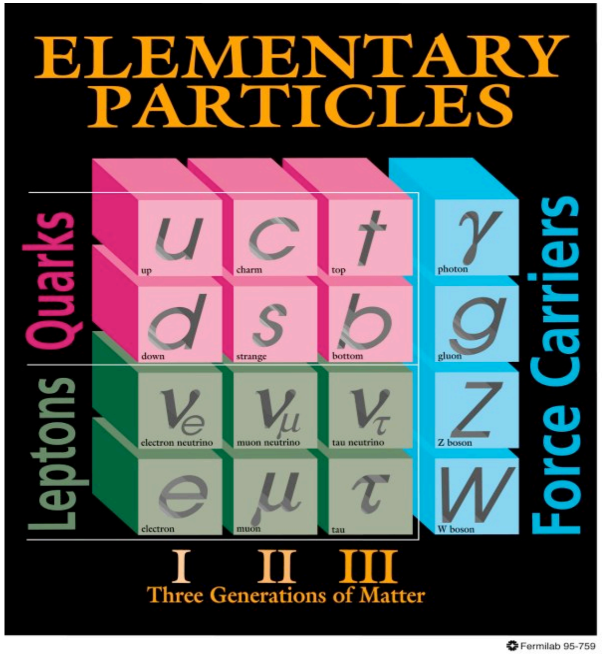
Finding the Light, Hidden Higgs, UCD
03/08/08

Outline

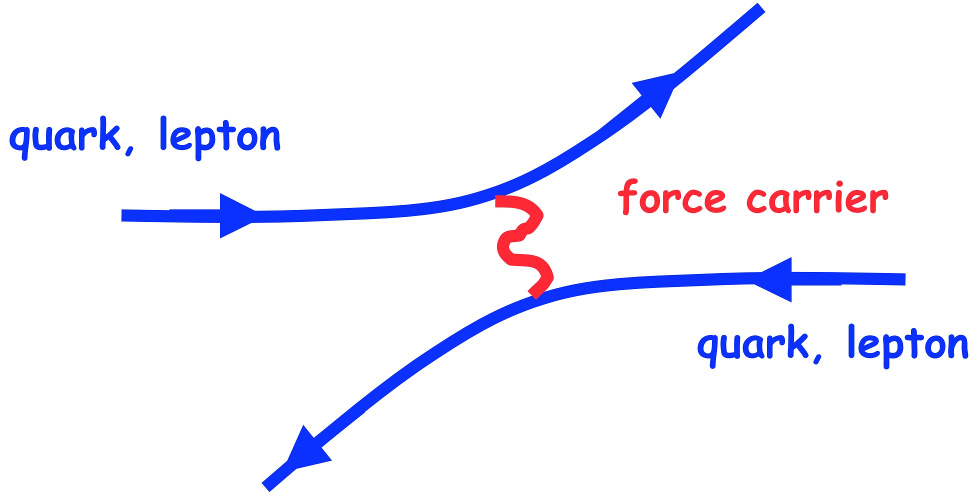
- Introduction
- Most relevant observation channels (SM)
  - $H \to \gamma\gamma$
  - $H \to \tau\tau$
  - $H \to ZZ^{(*)} \to 4l$
  - $H \to WW^{(*)} \to ll\nu\nu$
- MSSM Higgs
  - What can the Tevatron tell us?
  - Feasibility of searches

Focus on what we can do with 10 fb^{-1} of data at the LHC

Standard Model of Particle Physics



- Quarks and Leptons interact via the exchange of force carriers



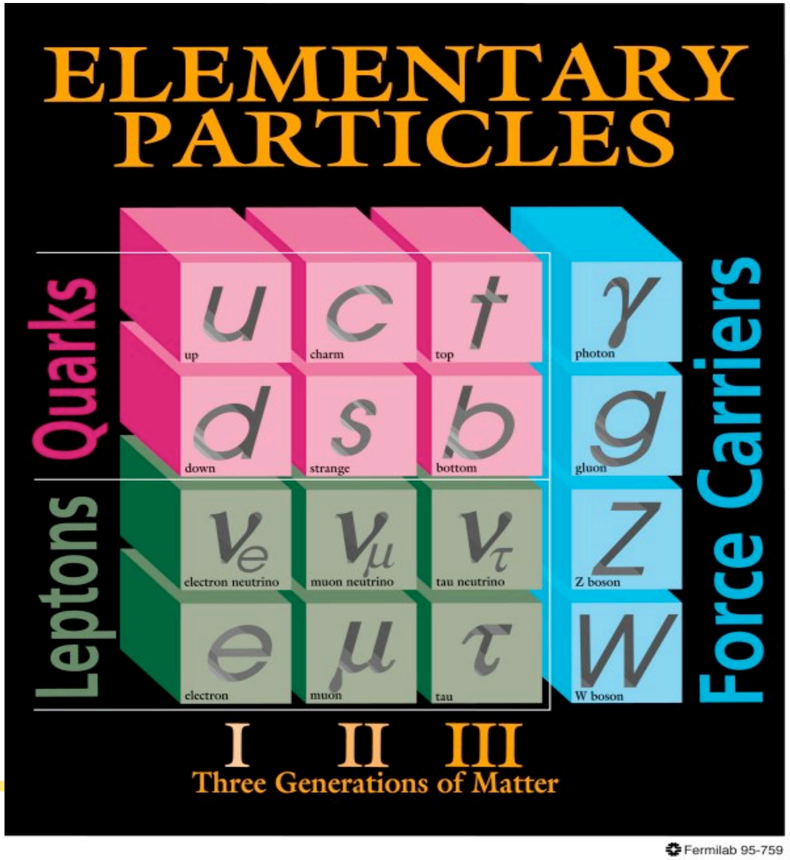
Force	Carrier
Strong	Gluons (g)
Electro-Weak	Electro-weak bosons (γ,W,Z)
Gravitation	?

A Higgs boson in predicted and required to give mass to particles

What is the origin of the particle masses?

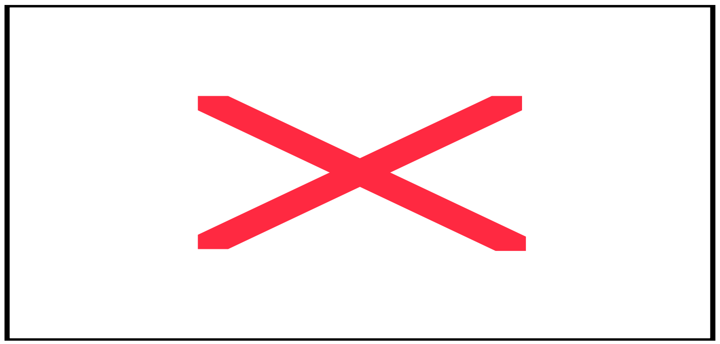
Why some particles are heavier than others?

The discovery of the Higgs boson should answer these questions



The Quest for the Higgs

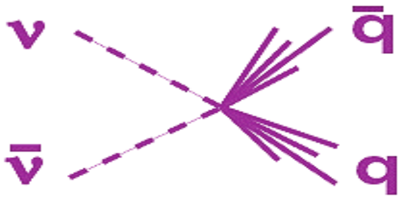
- Experimentalists have been looking for the Higgs since the 70's and 80's in decays of nuclei, π, K, B, Y, etc… yielding mass limit <5 GeV
- One of the goals of the LEP experiments (e^+e^- collisions 1989-2000) was to search for a Higgs boson. The most stringent limit to date comes from the LEP experiments



LEP Higgs Searches (M_H=115)

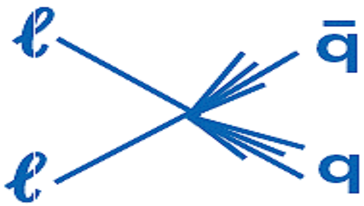
$e^+e^- \longrightarrow H\,Z$, with $Z \to q\bar{q}$ and $H \to b\bar{b}$

≈54% of Total



$e^+e^- \longrightarrow H\,Z$, with $Z \to \nu\bar{\nu}$ and $H \to q\bar{q}$

≈15%



$e^+e^- \longrightarrow HZ$, with $Z \to \ell^+\ell^-$ and $H \to q\bar{q}, \tau^+\tau^-$

≈5%

($\ell^\pm = e^\pm \mu^\pm$)

$e^+e^- \longrightarrow H\,Z$, with $Z \to \tau^+\tau^-$ and $H \to q\bar{q}$,

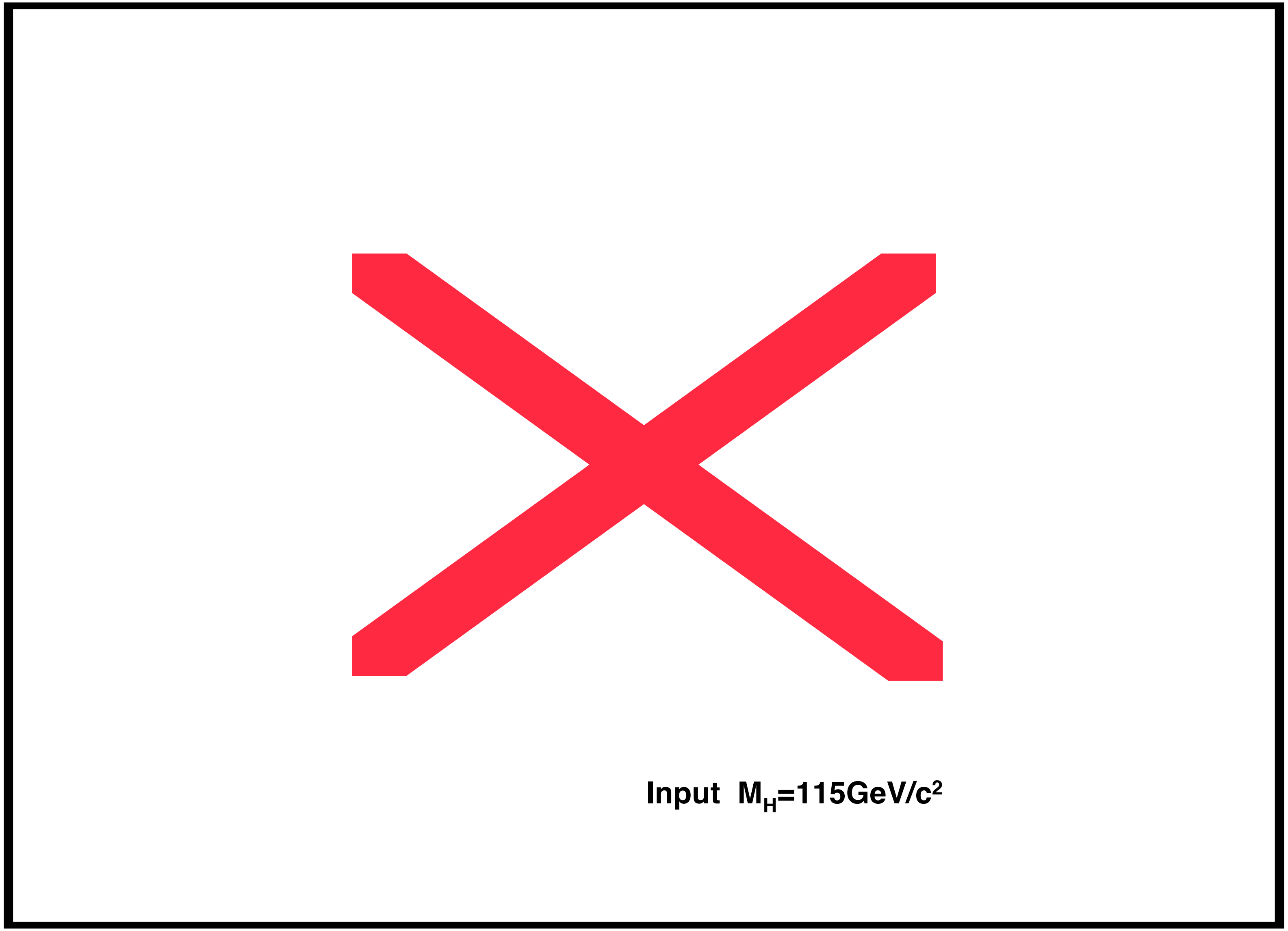
≈ 2.6%

$e^+e^- \longrightarrow H\,Z$, with $Z \to q\bar{q}$ and $H \to \tau^+\tau^-$

≈ 5%

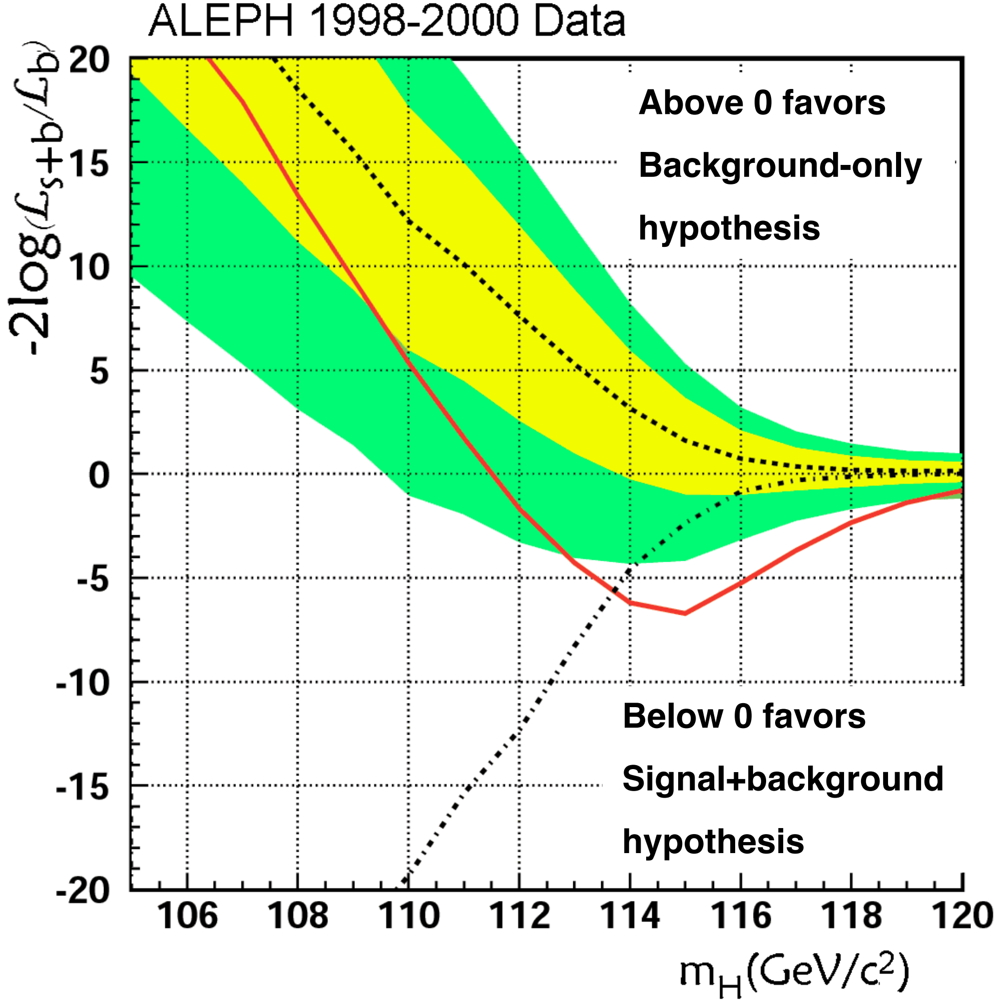
First Possible Hint for a Higgs boson (2000)

ALEPH observed three golden candidates in the four-jet channel

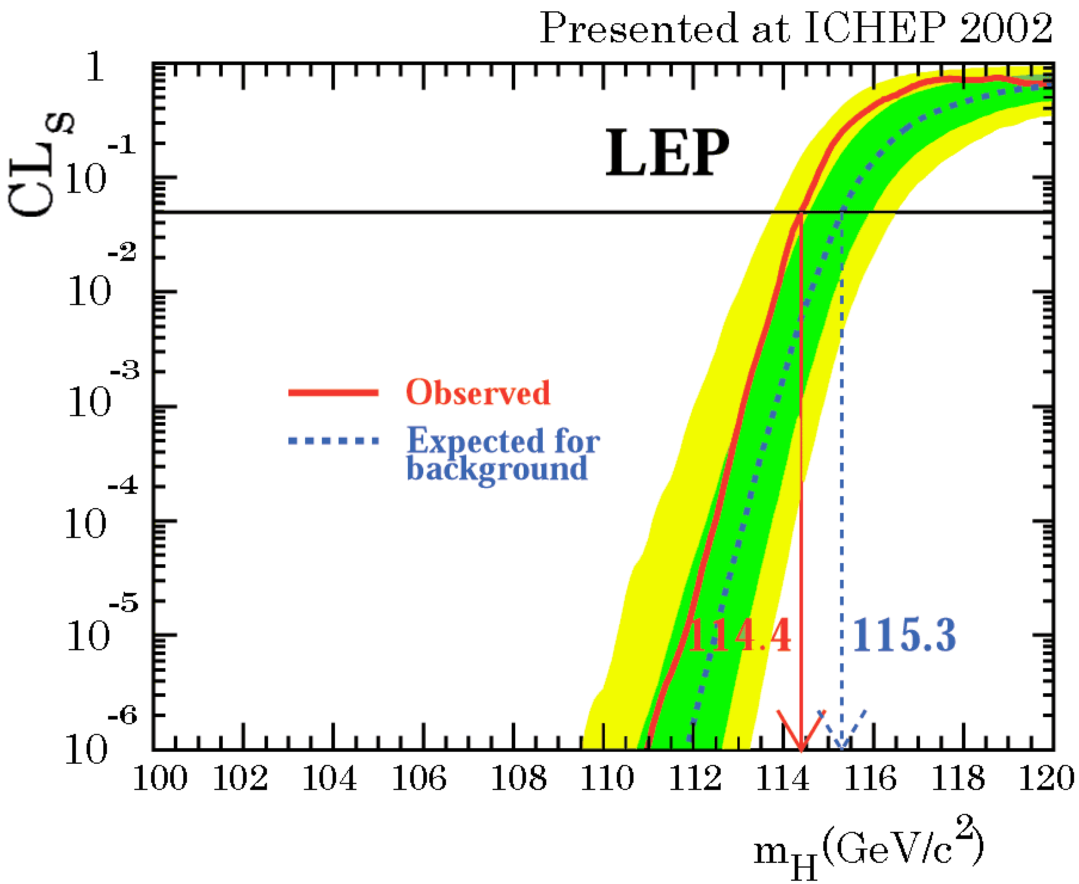


The LEP Limit

ALEPH observed an excess over background-only prediction with significance of 2.8σ at 115 GeV/c^2



Overall significance of LEP experiments ~1.8 σ → limit setting M_H>114.4



Electro-Weak Fits

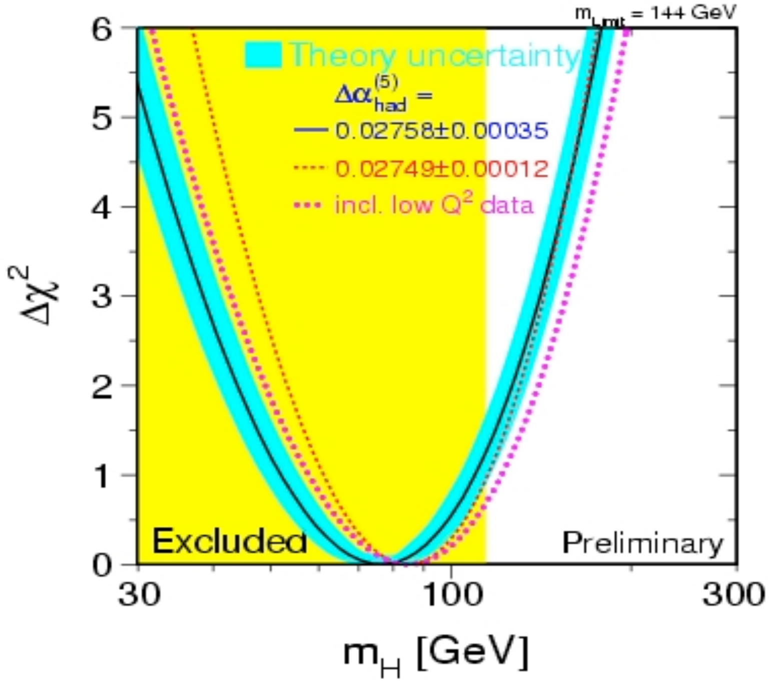
Experimental constraints so far:

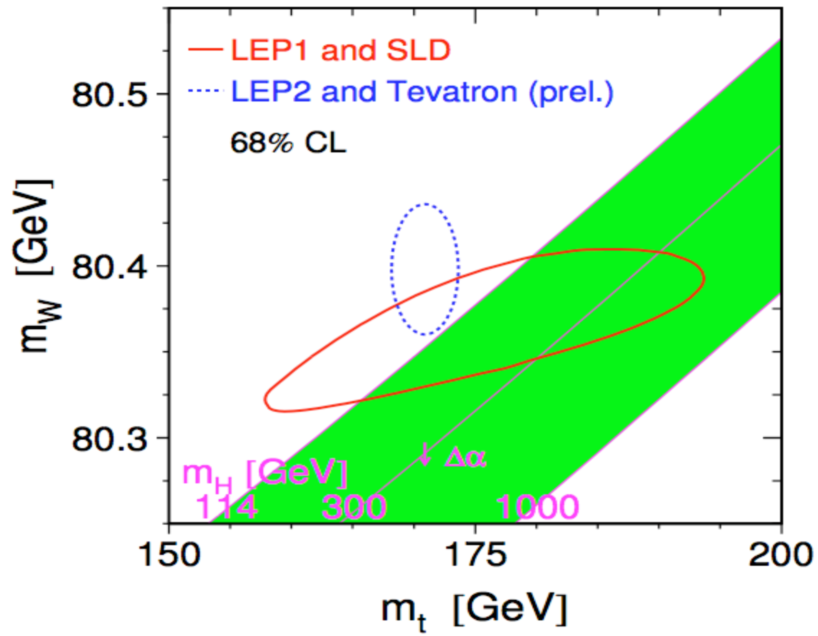
➢ Indirect measurements from fitting the EW data using new world average for M_{top}=170.9±1.8 GeV and M_w=80.398±0.025 GeV:

❖ $m_H = 76^{+33}_{-24}$ GeV

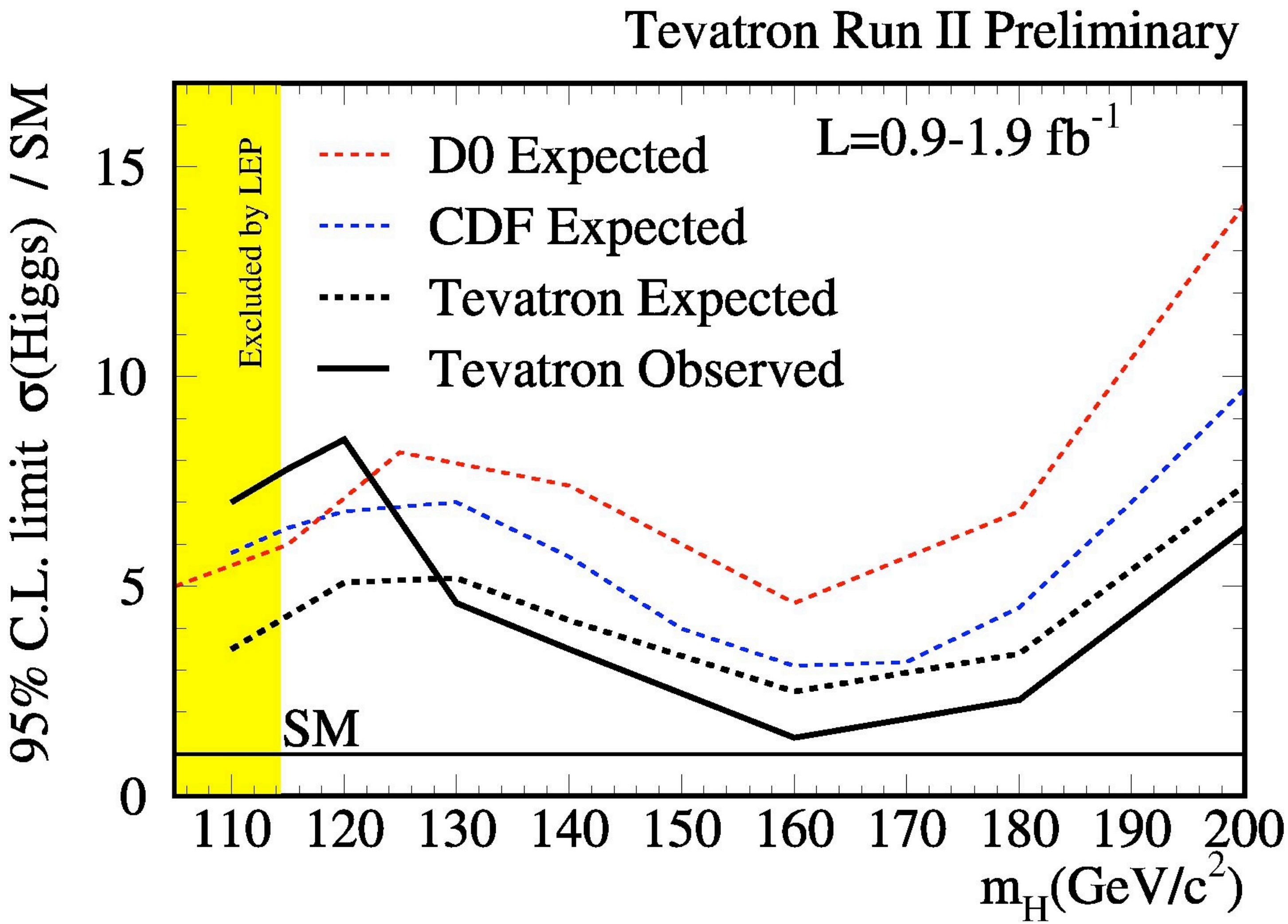
Data prefers low mass Higgs

❖ m_H<144 GeV @ 95%CL (including LEP exclusion m_H<182 GeV)





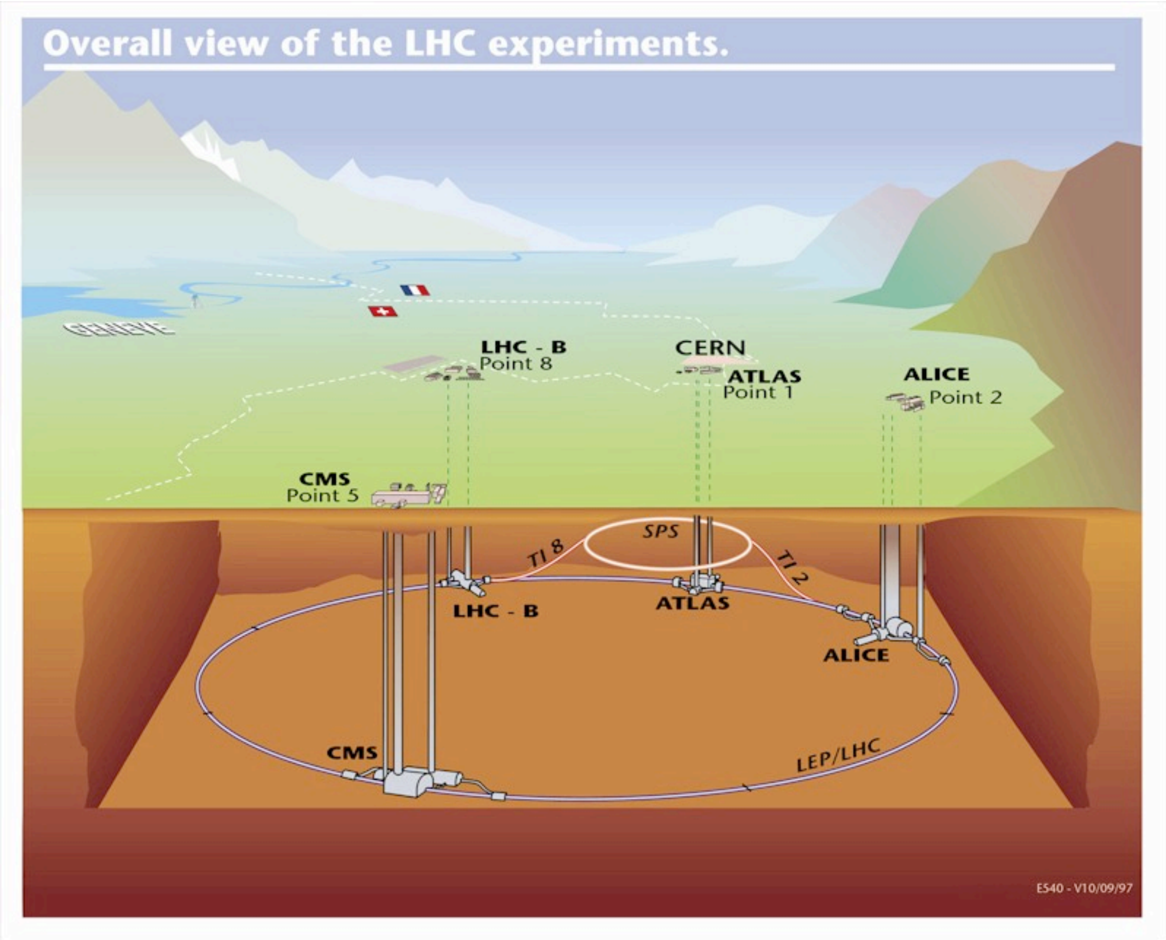
Present Tevatron Exclusion Limit

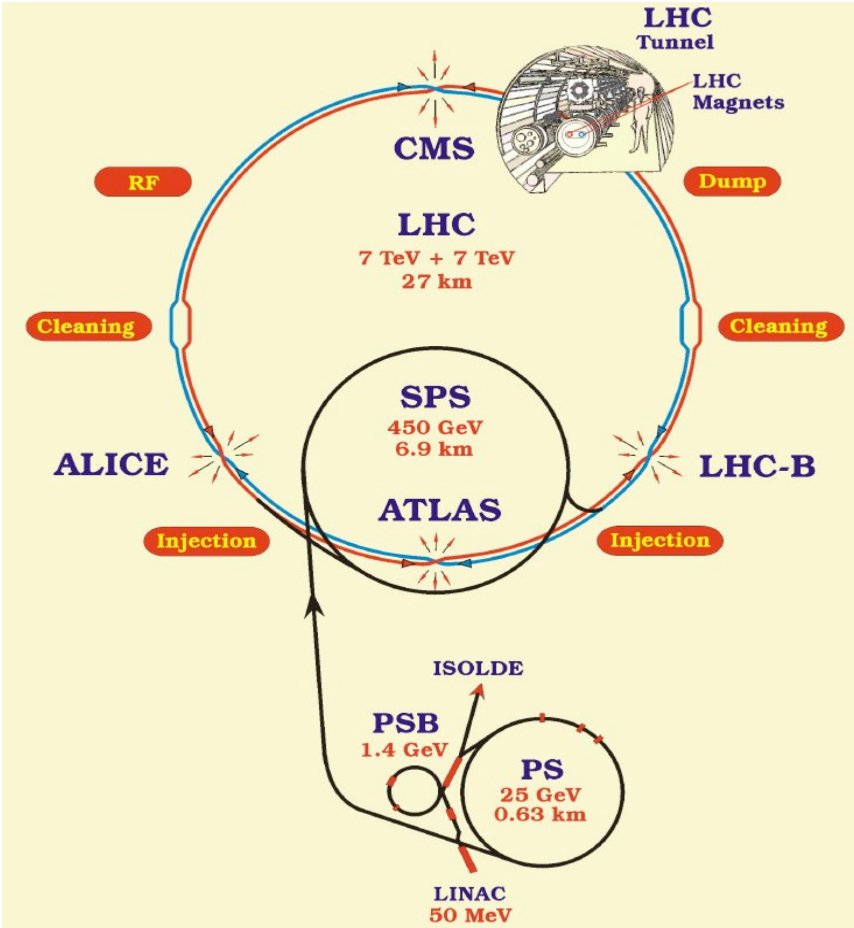


Note: the combined result is essentially equivalent to one experiment with 1.3 fb^{-1}, since both experiments have "complementary" statistics at low and high mass

The LHC

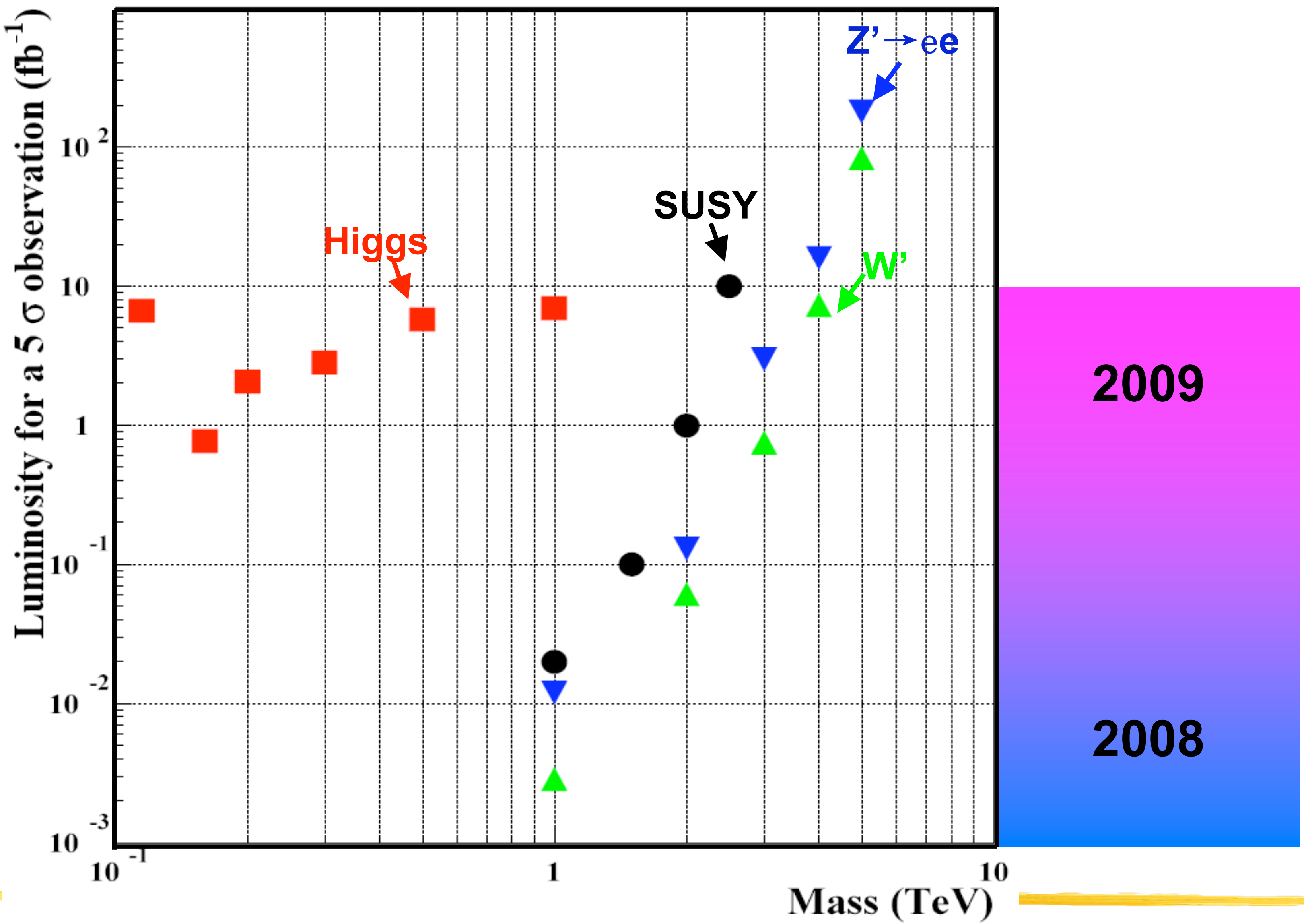
Center of mass E	14 TeV
Design Luminosity	10^{34} cm^{-2} s^{-1}
Luminosity Lifetime	10 h
Bunch spacing	25 ns





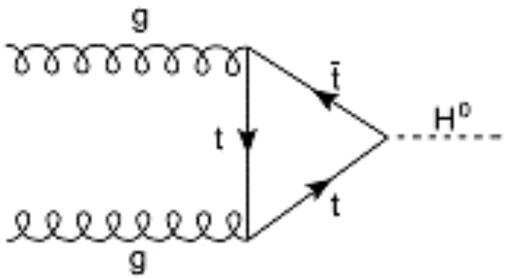
LHC Discovery Reach

Approximate discovery reach for one Experiment

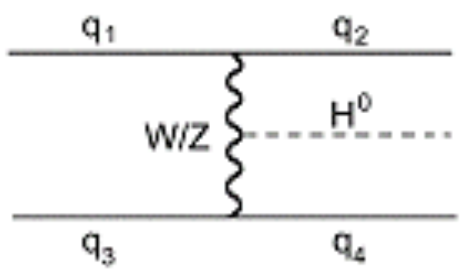


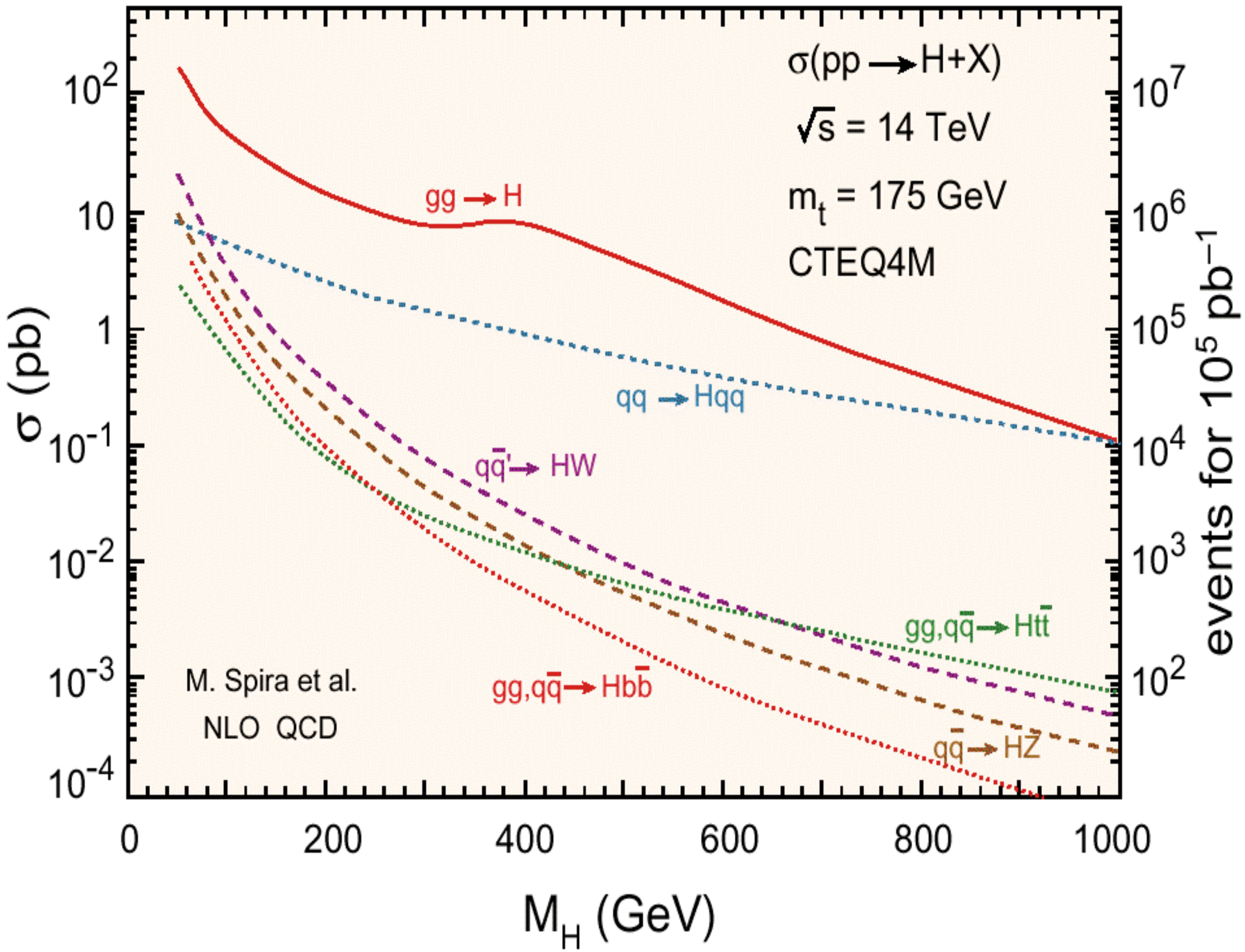
Higgs Production at LHC

Leading Process (gg fusion)



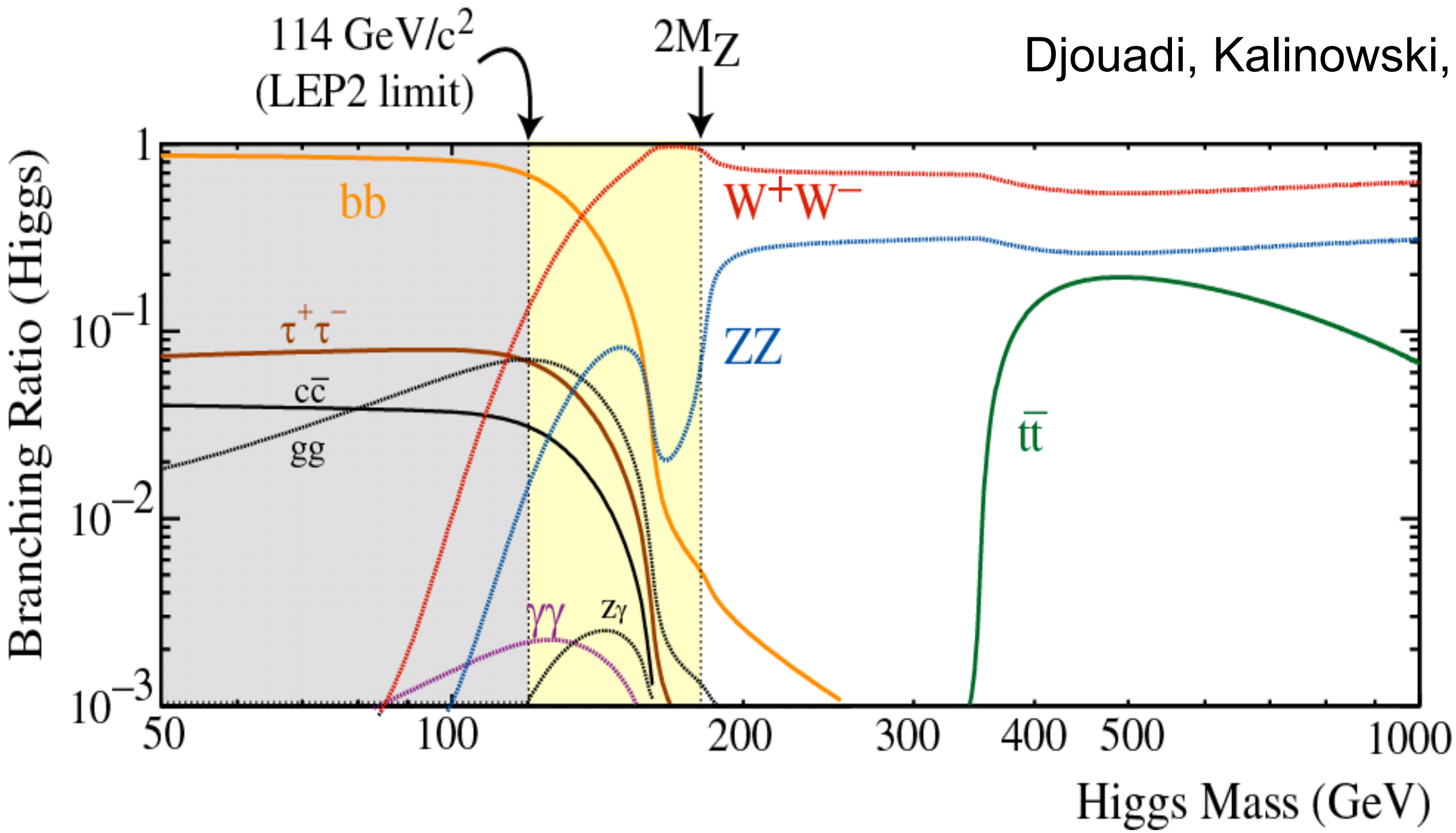
Sub-leading Process (VBF)





Main Decay Modes

Djouadi, Kalinowski, Spira

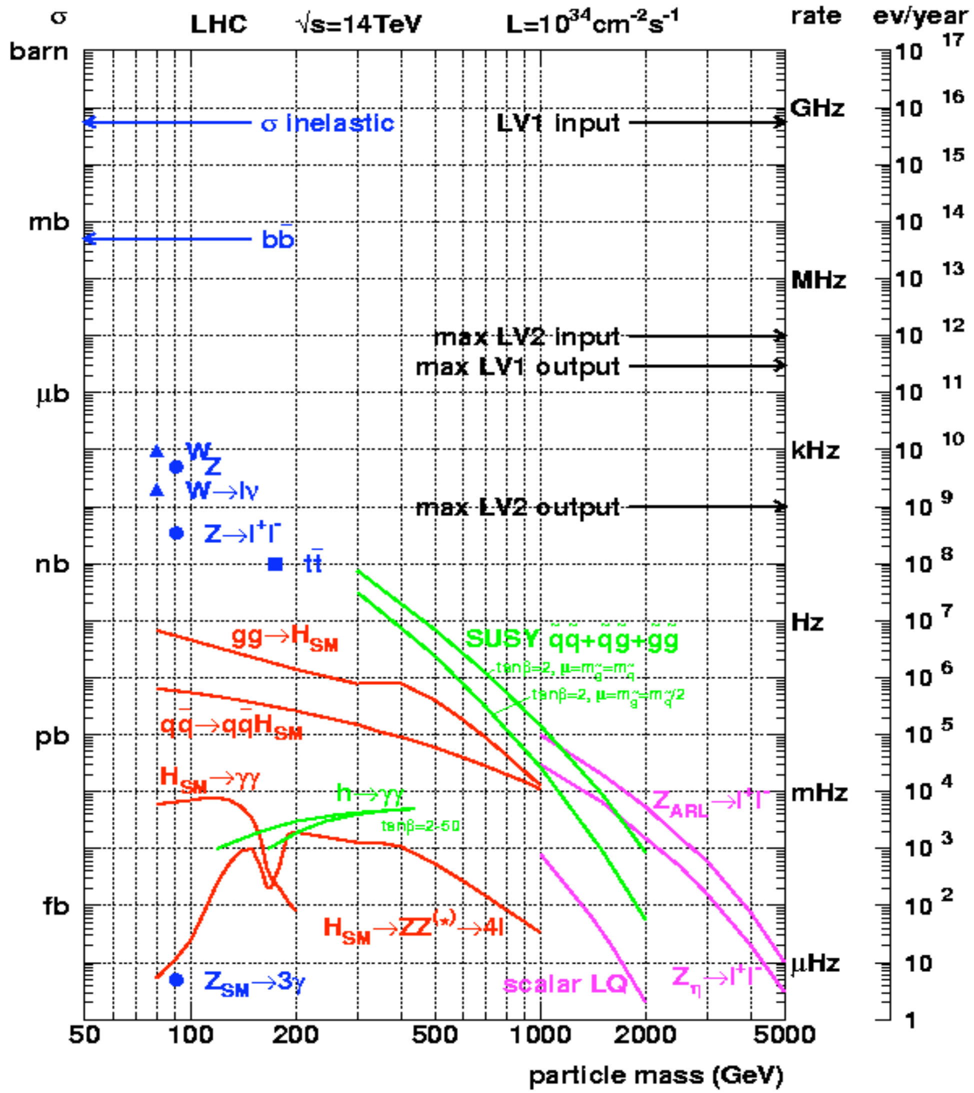


Close to LEP limit:
$H \rightarrow \gamma\gamma, \tau\tau, bb$

For M_H>140 GeV:
$H \rightarrow WW^{(*)}, ZZ^{(*)}$

Cross-sections at LHC

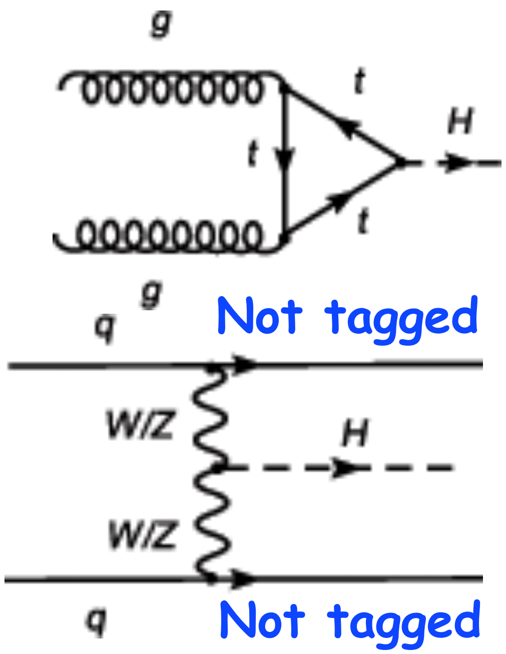
- Search for Higgs and new physics hindered by huge background rates
  - Known SM particles produced much more copiously
- This makes low mass Higgs especially <u>challenging</u>
  - Narrow resonances
  - Complex signatures
    - Higgs in association with tops and jets.



Low Mass Higgs Associated with Jets

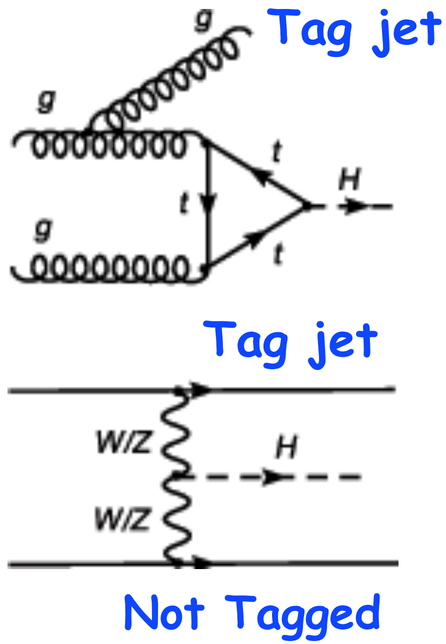
- Slicing phase space in regions with different S/B seems more optimal when inclusive analysis has little S/B

Inclusive



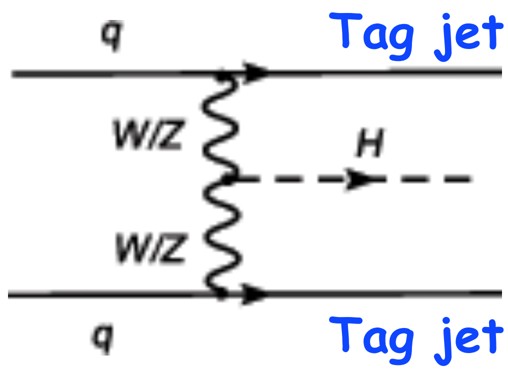
Analyses in TDR were mostly inclusive

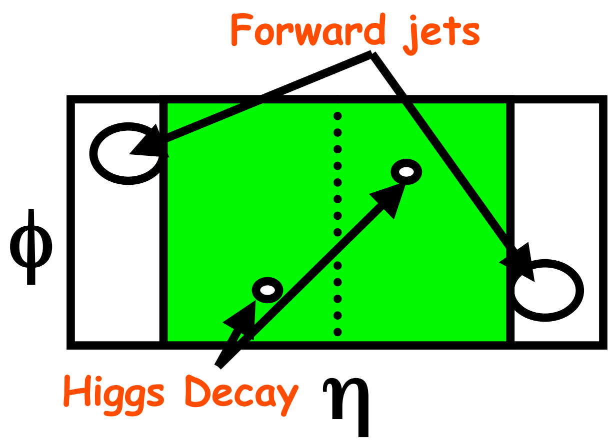
H+1jet



Applied to $H \rightarrow \gamma\gamma, \tau\tau, WW^{(*)}$

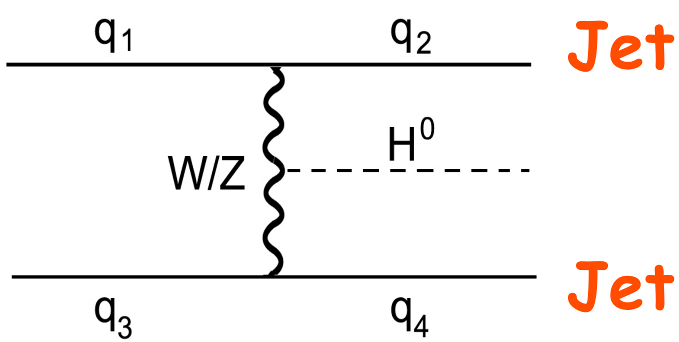
H+2jet

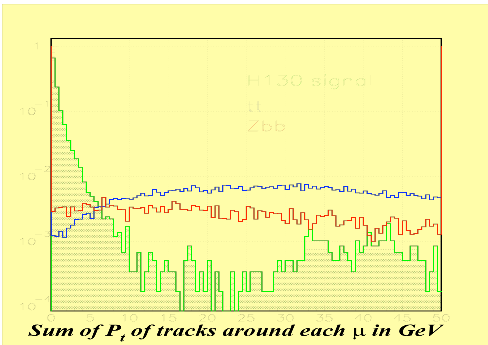


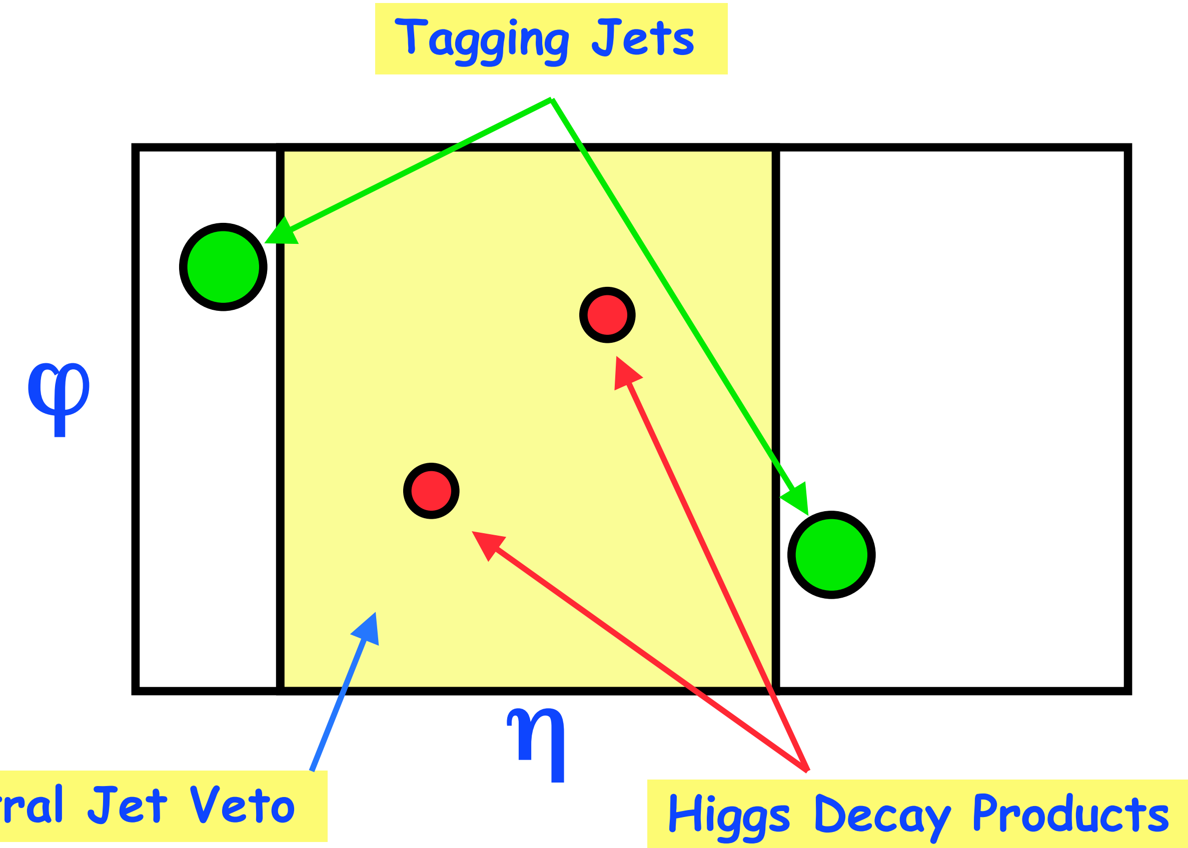


SM Higgs + ≥2jets at the LHC

- Wisconsin Pheno (D.Zeppenfeld, D.Rainwater, et al.) proposed to search for a Low Mass Higgs in association with two jets with jet veto
  - Central jet veto initially suggested in V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)







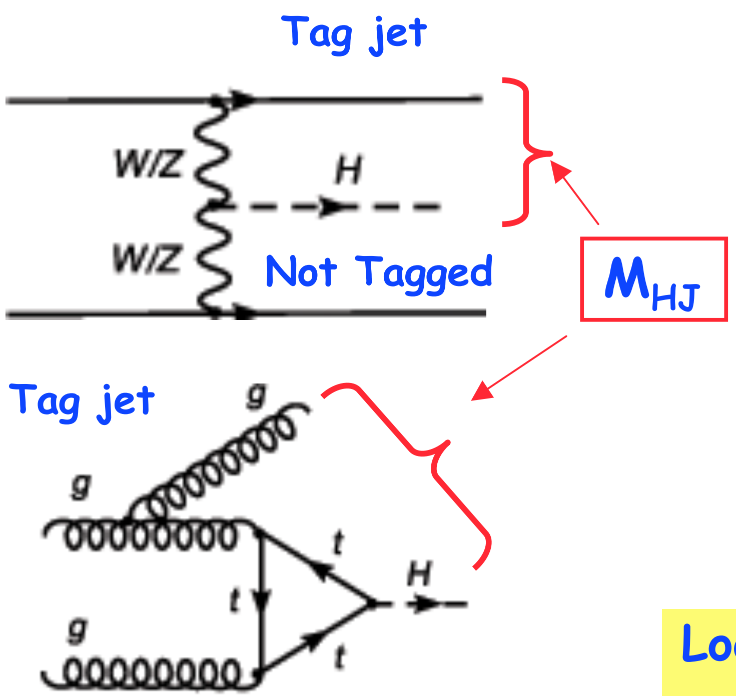
SM Higgs + ≥1jet at the LHC

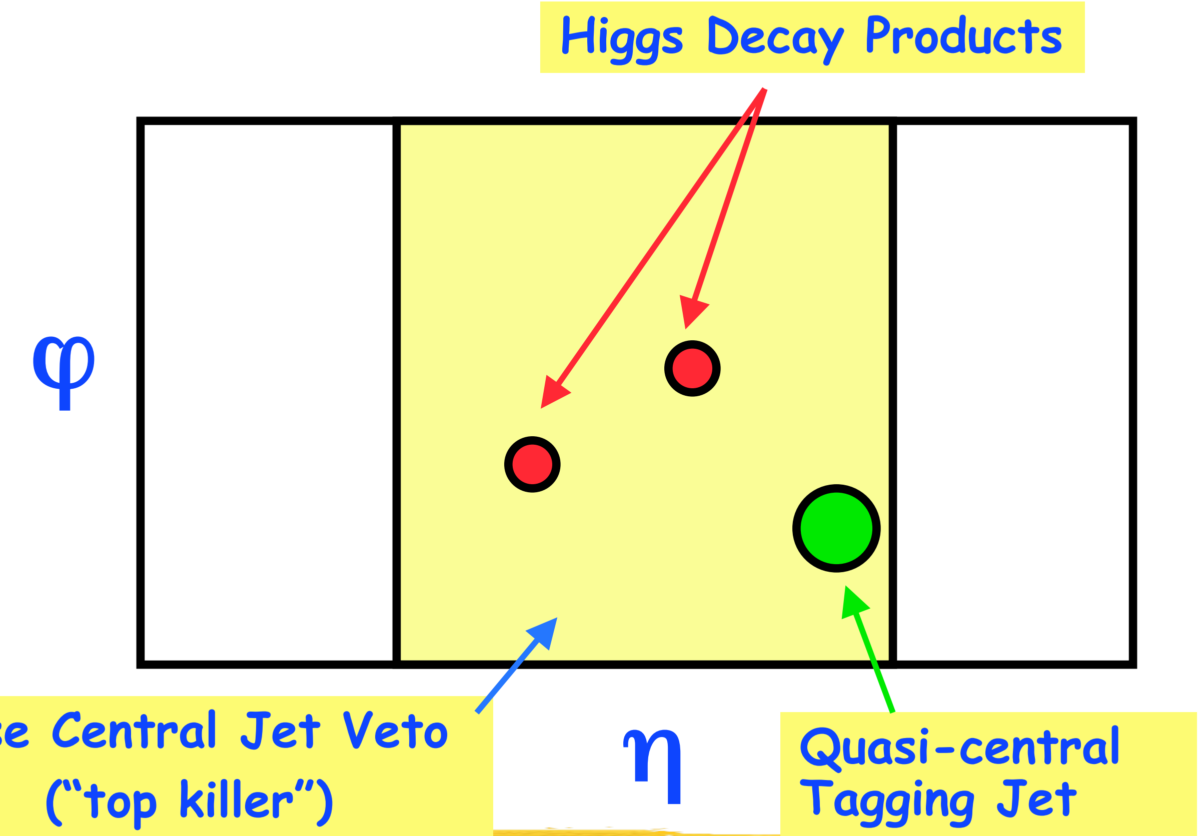
- Large invariant mass of leading jet and Higgs candidate
- Large P_T of Higgs candidate
- Leading jet is more forward than in QCD background

S.Abdullin et al PL B431 (1998) for $H\to\gamma\gamma$

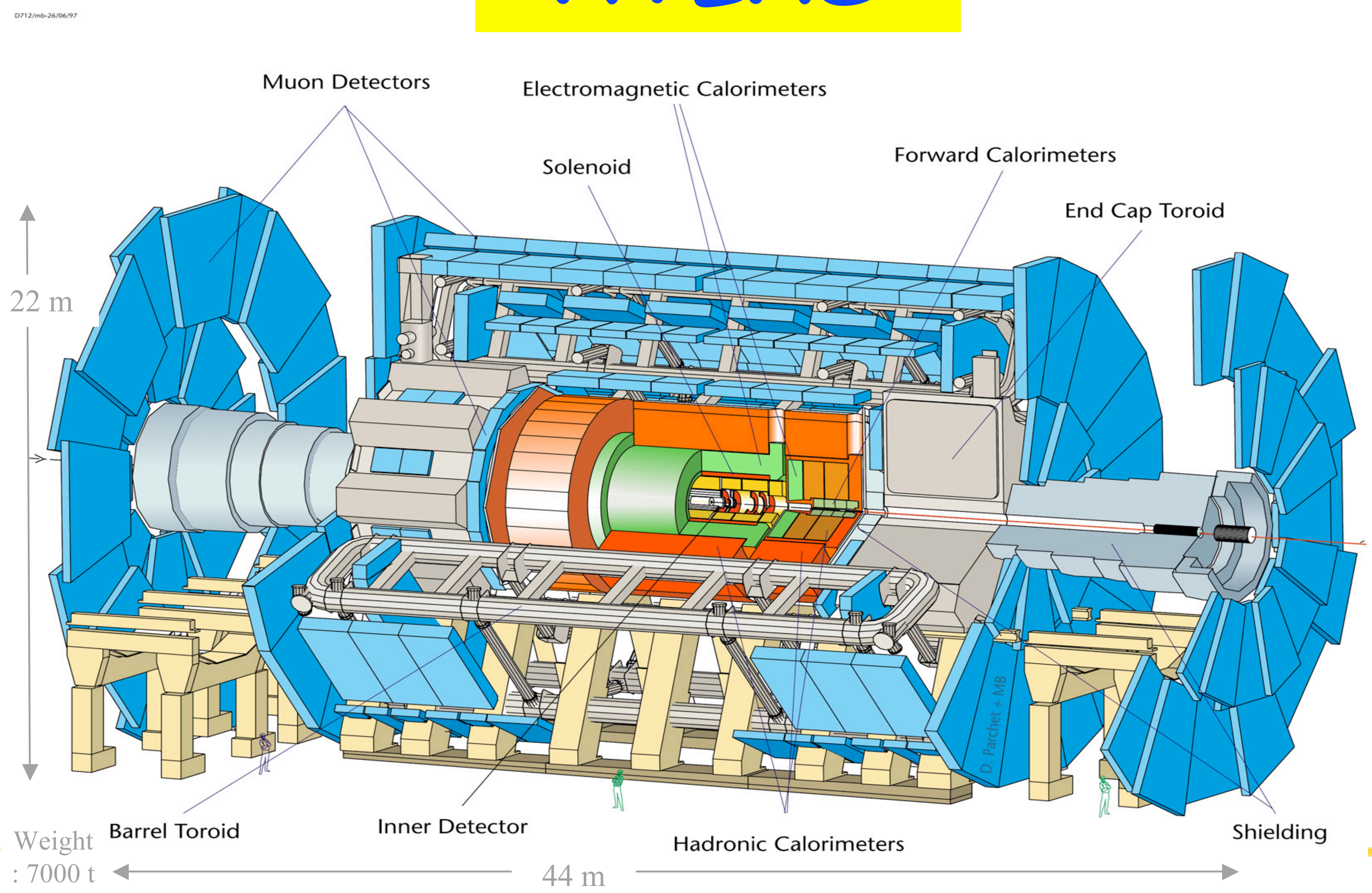
B.Mellado, W.Quayle and Sau Lan Wu Phys.Lett.B611:60-65,2005 for $H\to\tau\tau$

B.Mellado, W.Quayle and Sau lan Wu Phys.Rev.D76:093007,2007 for $H\to WW^{(*)}$

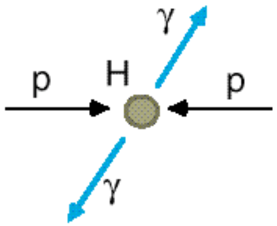




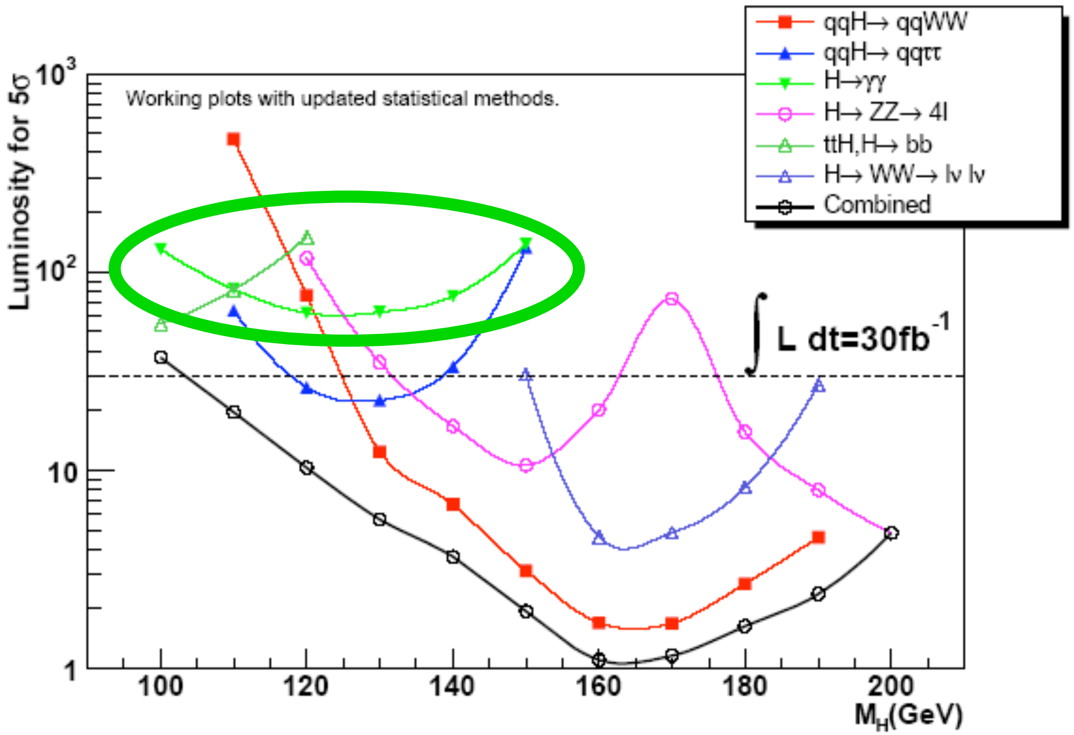
ATLAS

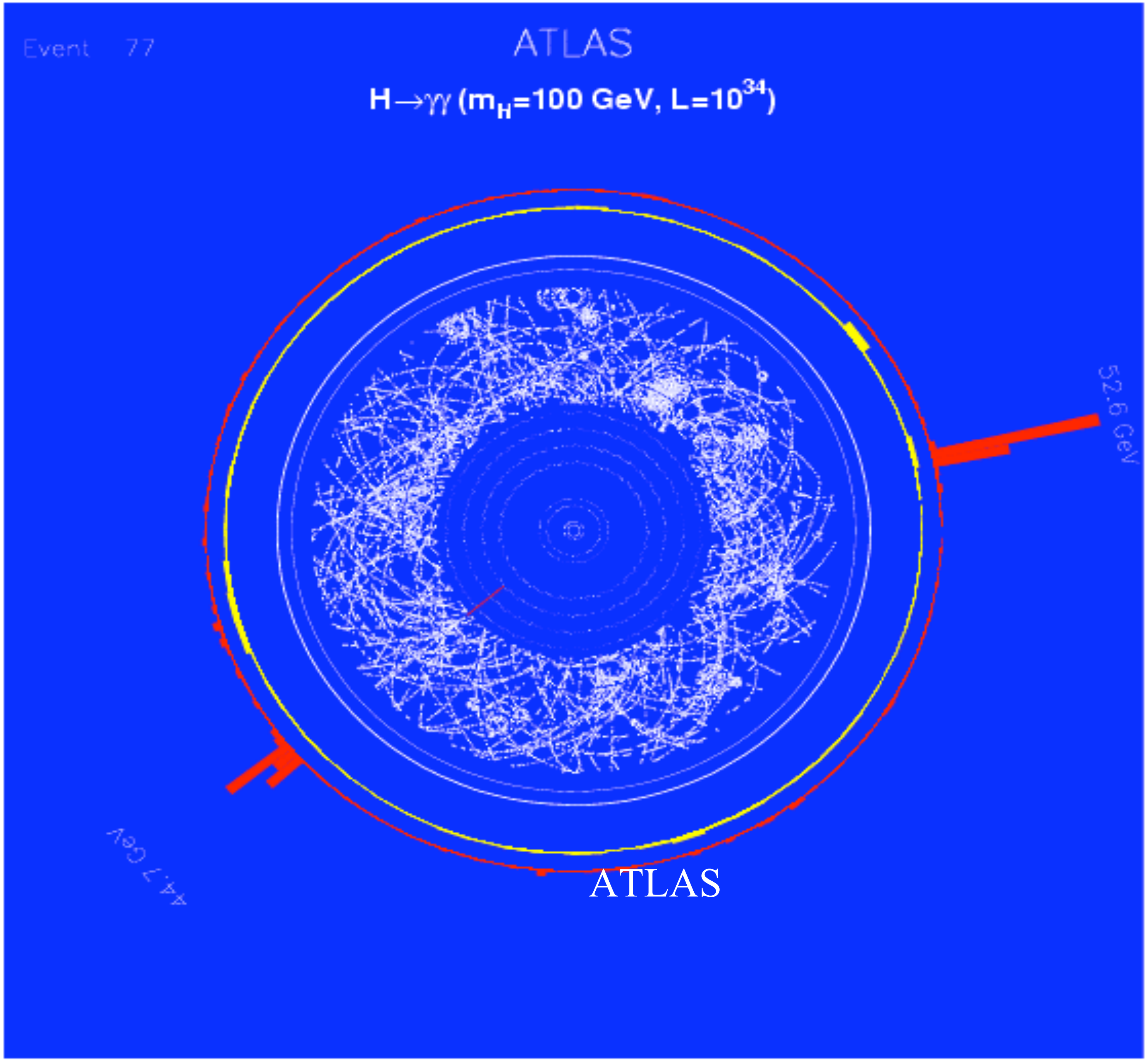


D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
22 m
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
Weight : 7000 t
44 m
D. Parchet + MB

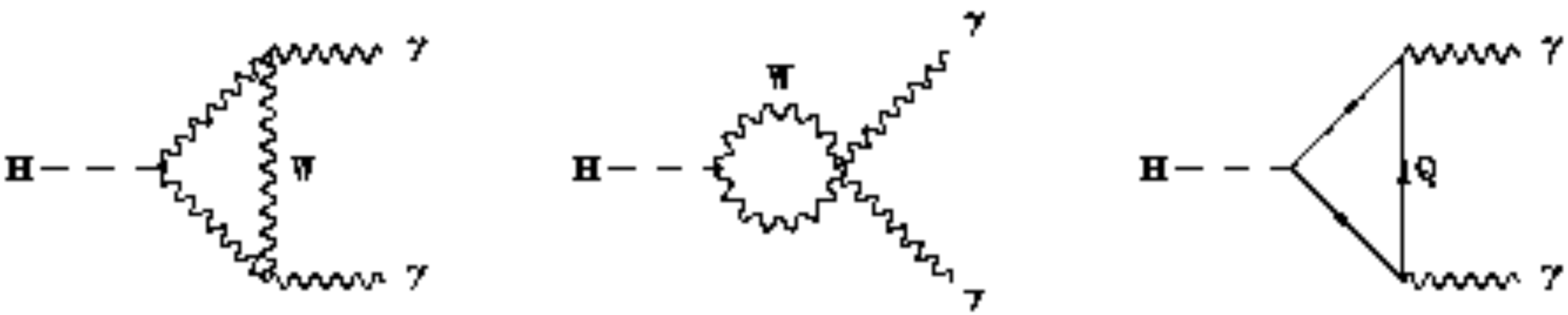


Low Mass SM Higgs: H→γγ

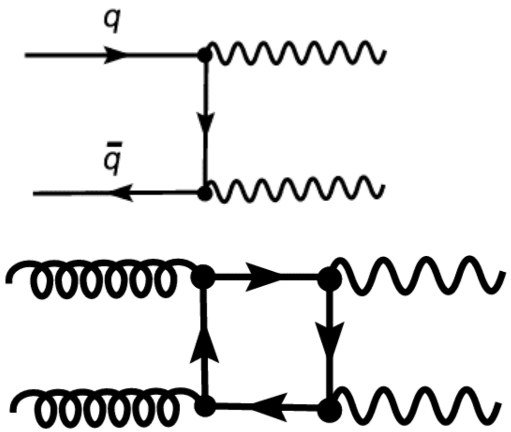


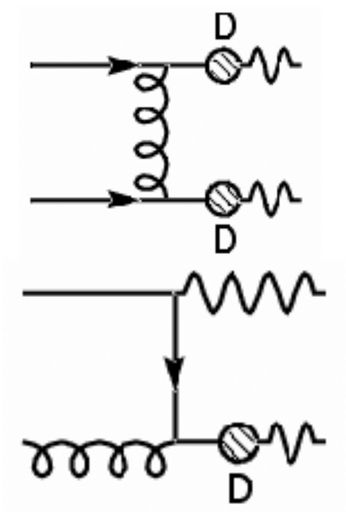

Event 77
ATLAS
H→γγ (m_H=100 GeV, L=10^34)
52.6 GeV
44.7 GeV
ATLAS

Higgs decay to γγ

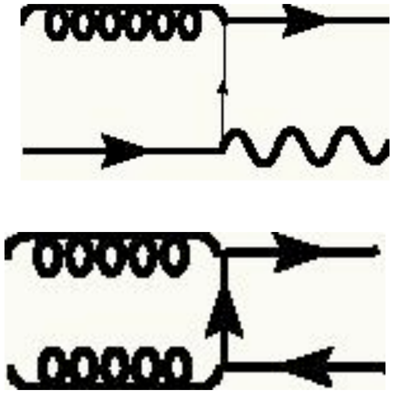


γγ Backgrounds



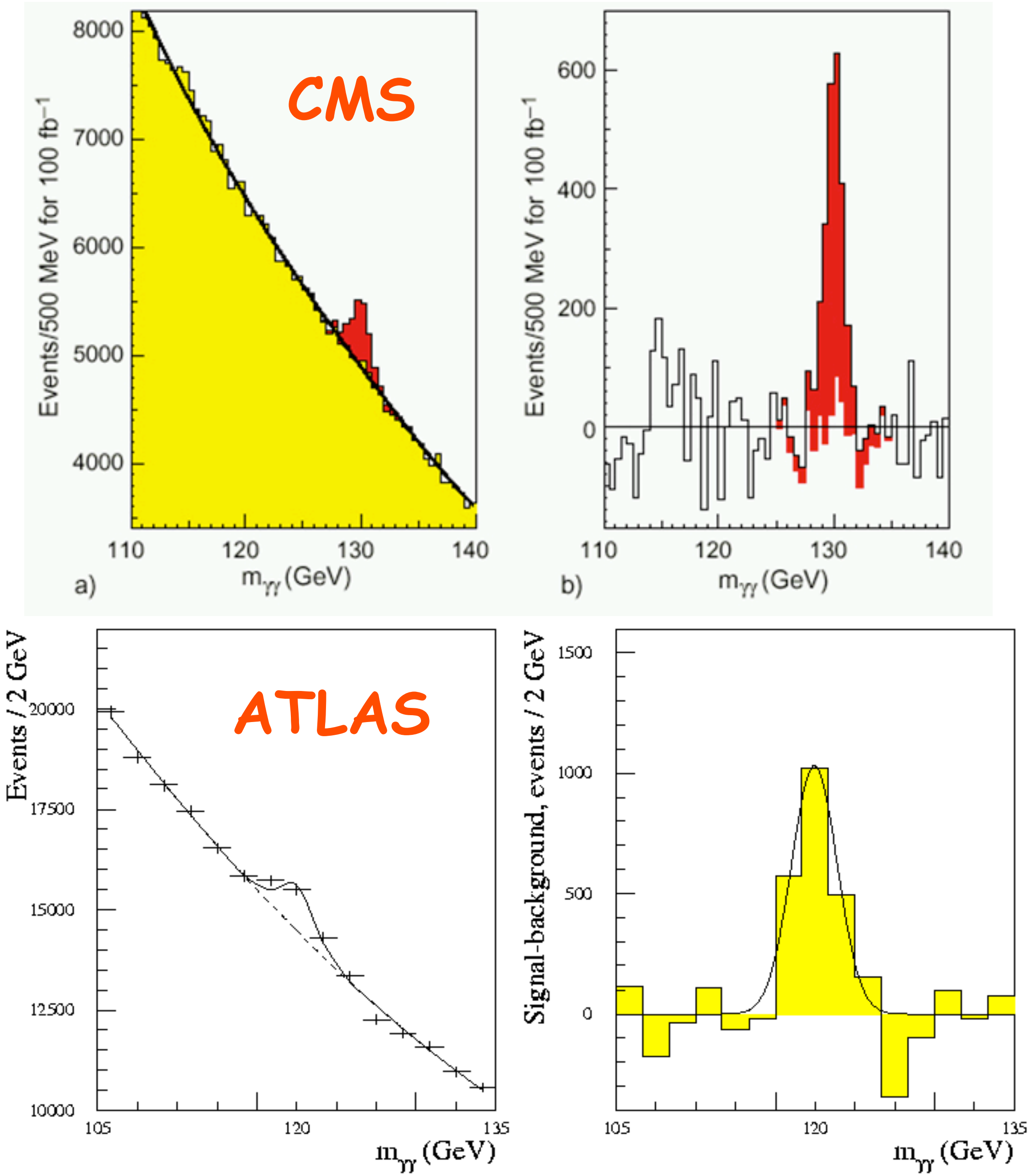


Reducible γj and jj Backgrounds



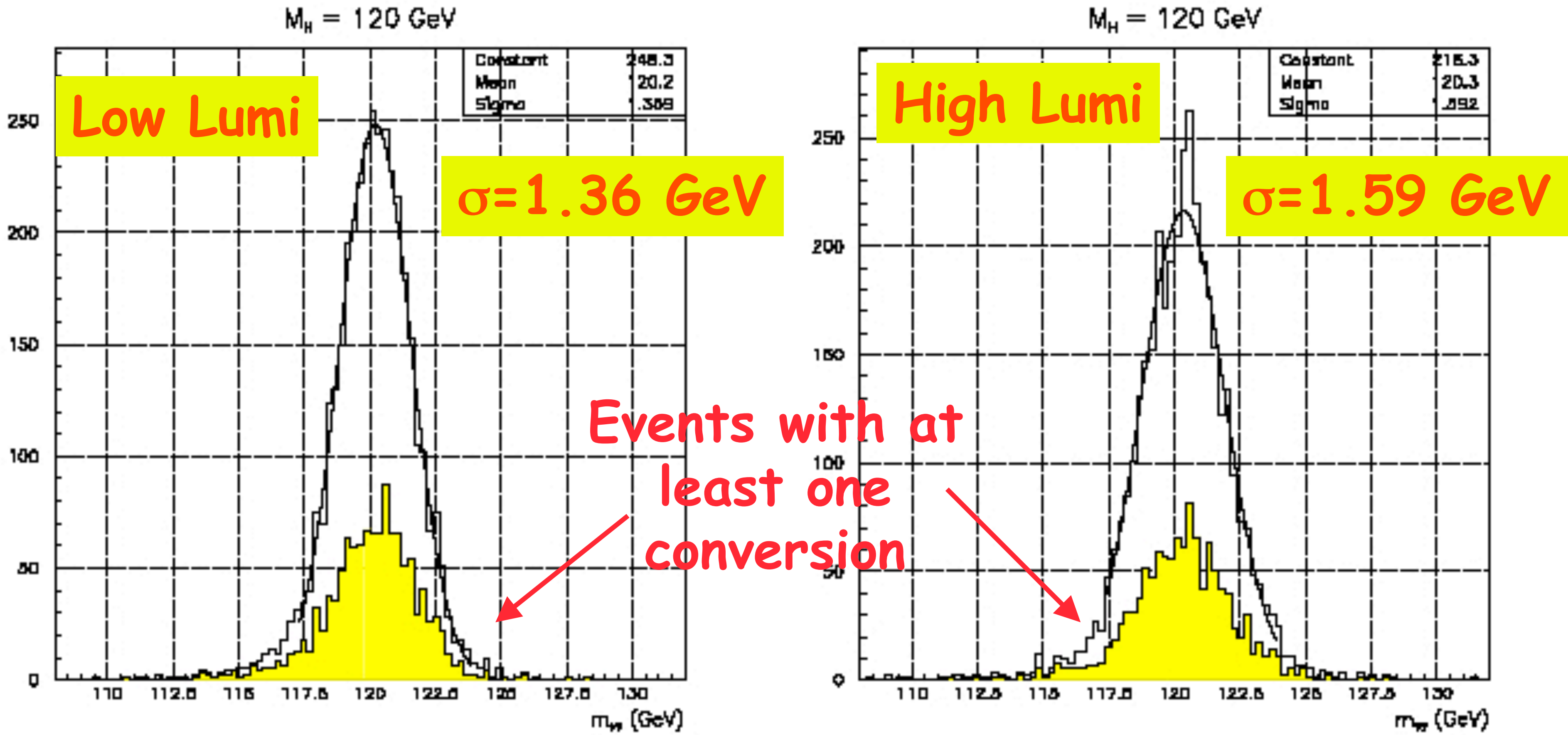
$q \rightarrow \pi^0$

CMS and ATLAS analyses for 100 fb-1



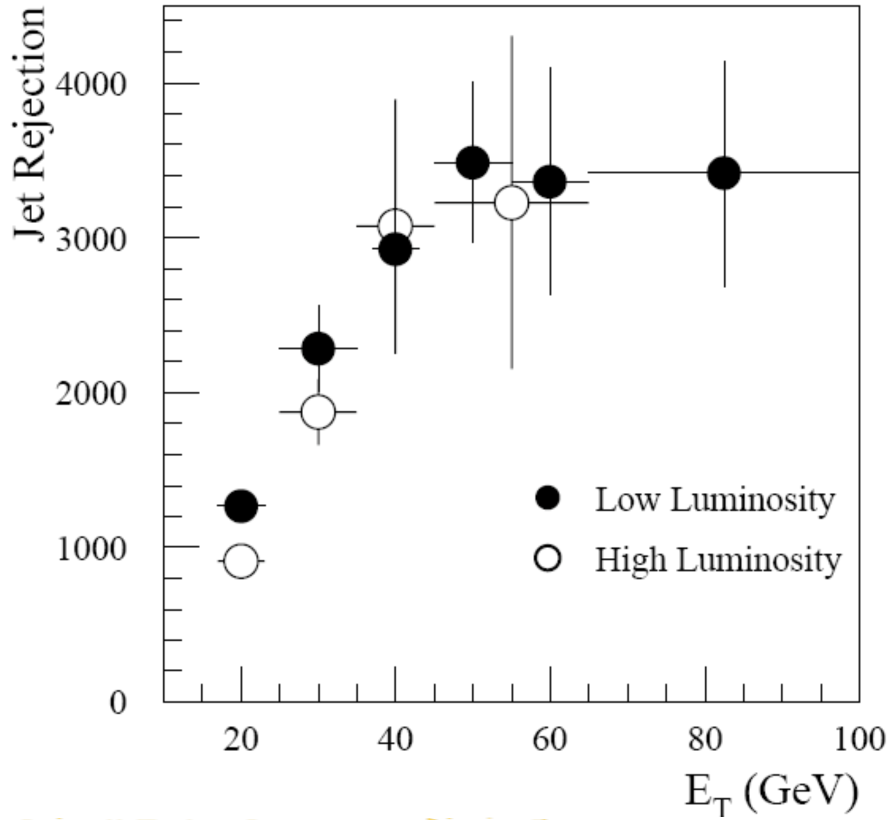
Higgs Mass Reconstruction

- In ATLAS Expect about 50% of events to have at least one converted photon, but can achieve <1.2% mass resolution



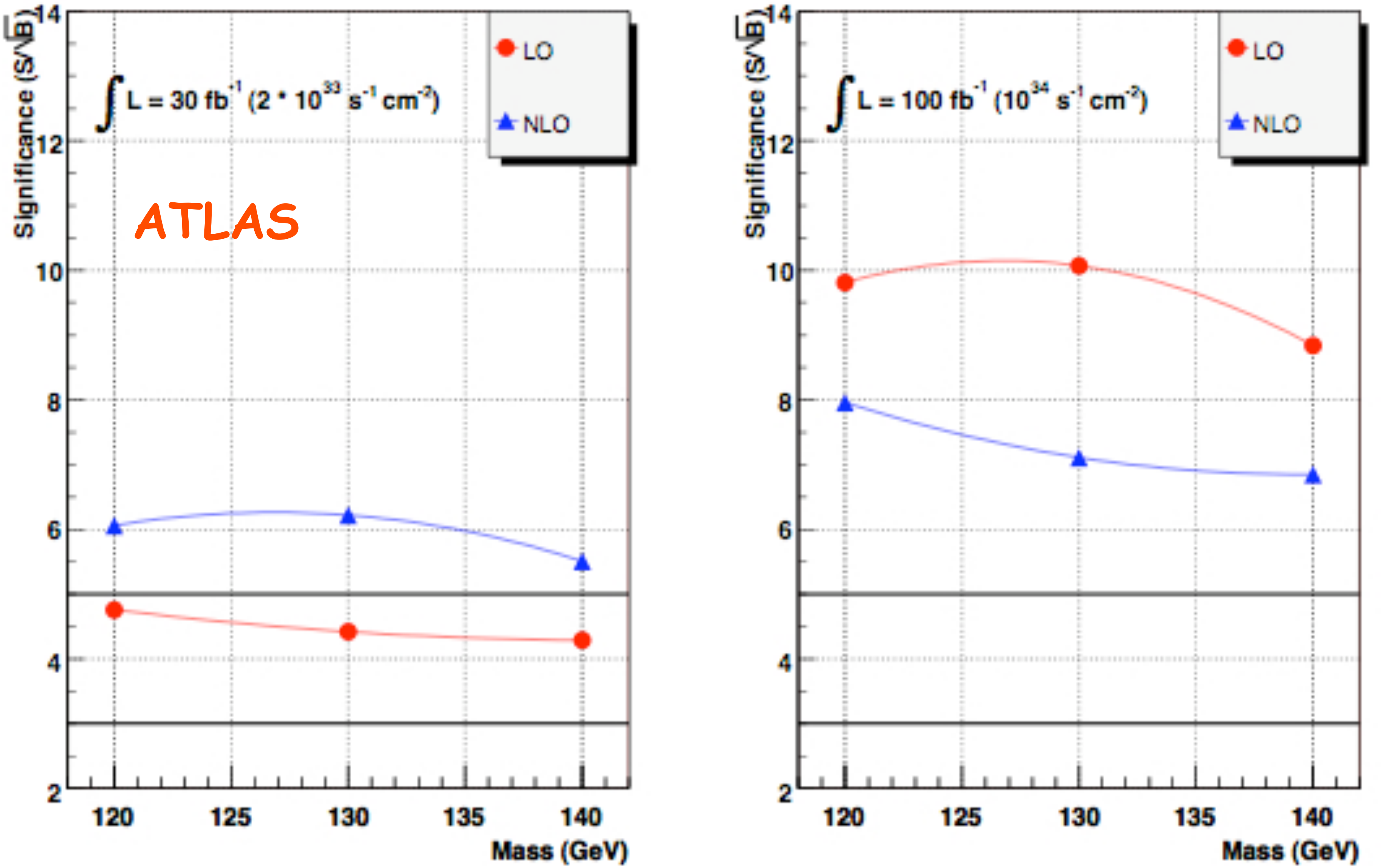
Photon Identification

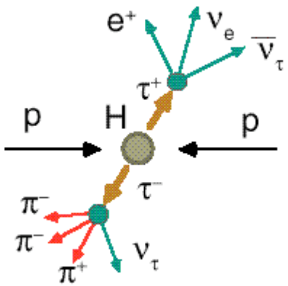
- To separate jets from photons is crucial for Higgs discovery
  - Need rejection of > 1000 against quark-initiated jets for ε_γ=80% to keep fake background about 20% of total background
  - Expect rejection against gluon-jets to be 4-5 times greater
- Jet rejection will be evaluated with data
  - Look into sub-leading jets in multi-jet final states with different P_T thresholds
    - Avoid trigger bias
    - Apply trigger pre-scaling if needed
    - Correct for contribution from prompt photons



ATLAS TDR (1999)

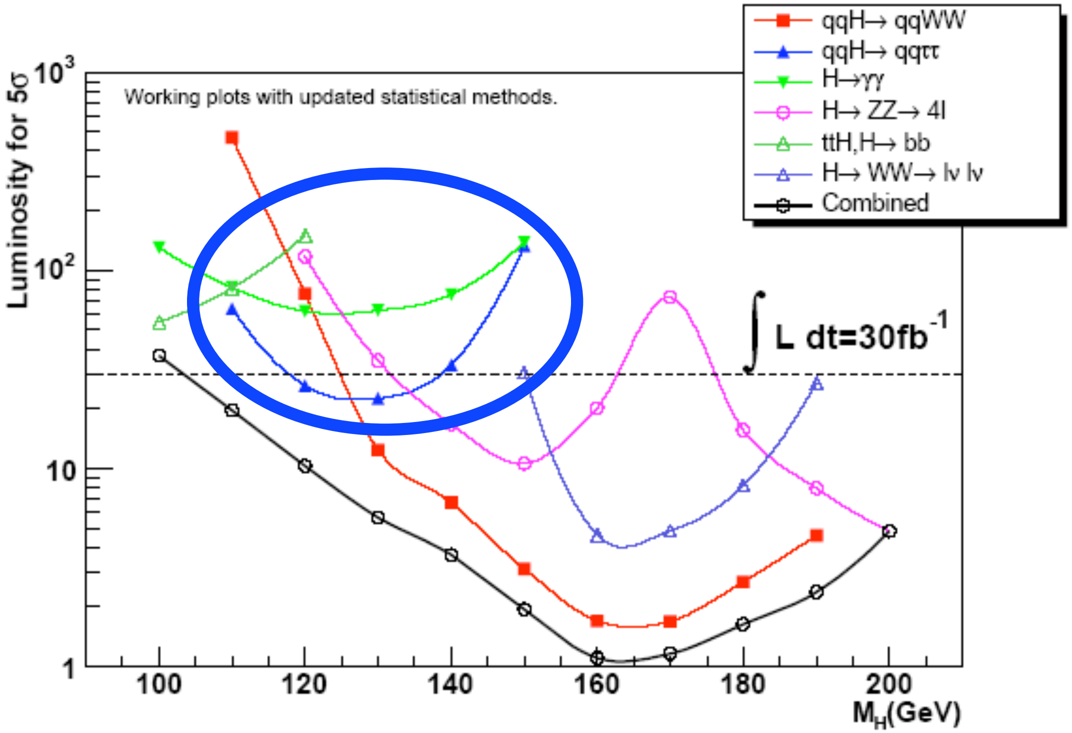
Inclusive H→γγ



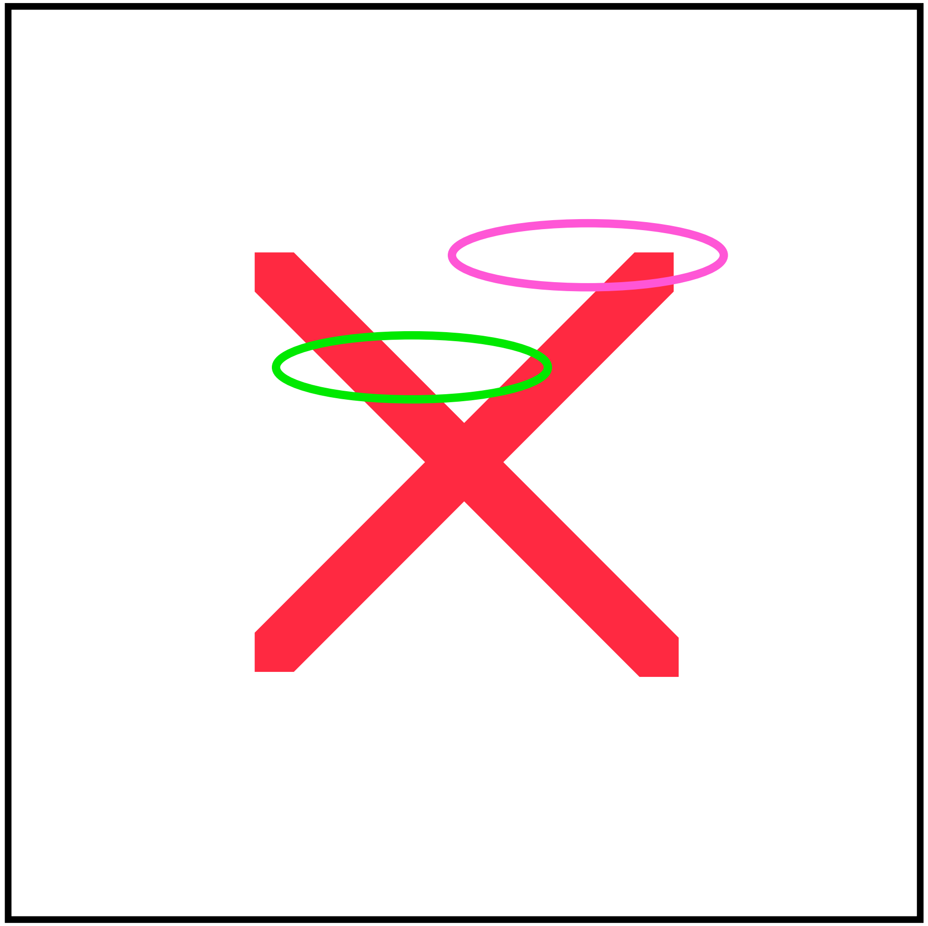


p
H
p

h,A→ττ; H±→τ±ν



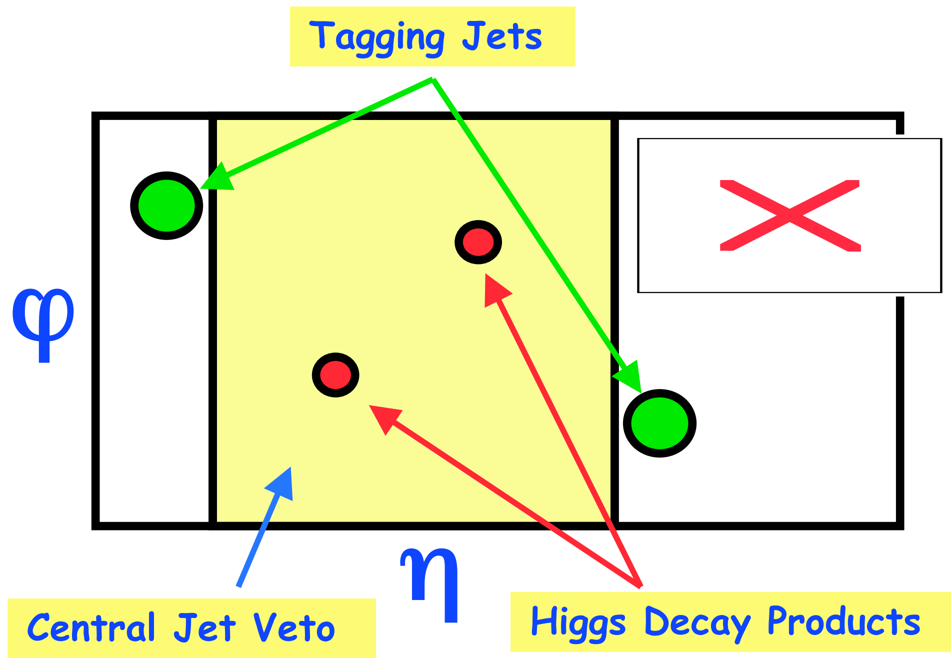
Working plots with updated statistical methods.
qqH→ qqWW
qqH→ qqττ
H→γγ
H→ ZZ→ 4l
ttH,H→ bb
H→ WW→ lν lν
Combined
∫ L dt=30fb^-1
Luminosity for 5σ
M_H(GeV)



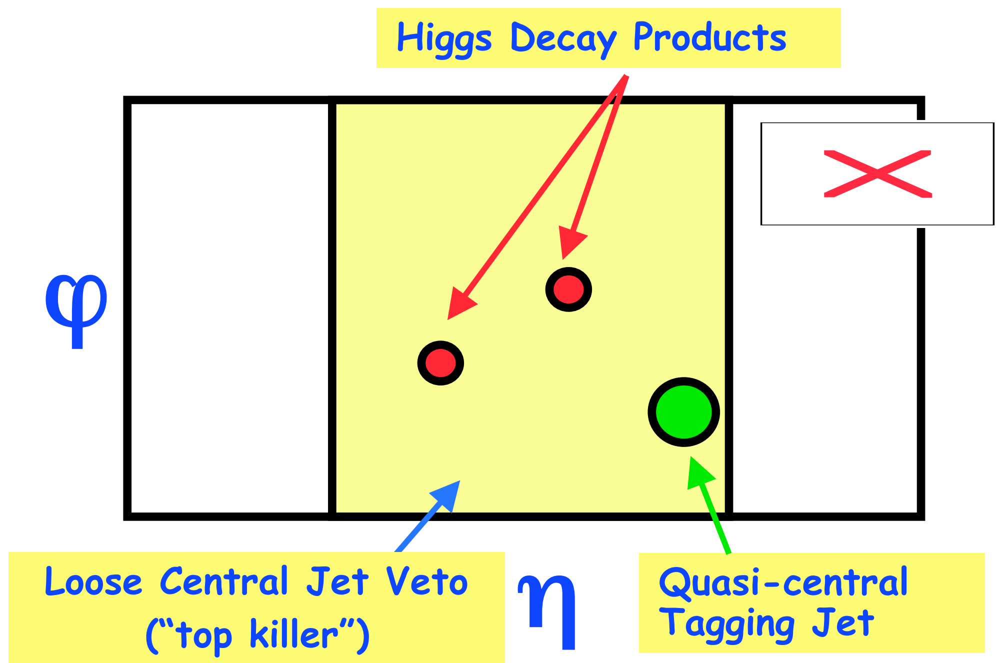
Low Mass SM $H \rightarrow \tau\tau$ + jets

- Because of the poor Higgs mass resolution obtained with $H \rightarrow \tau\tau$, inclusive analysis not possible. Need to reduce QCD backgrounds by using distinct topology of jets produced in association with Higgs

$H \rightarrow \tau\tau$ + ≥2 jets



$H \rightarrow \tau\tau$ + ≥1 jets

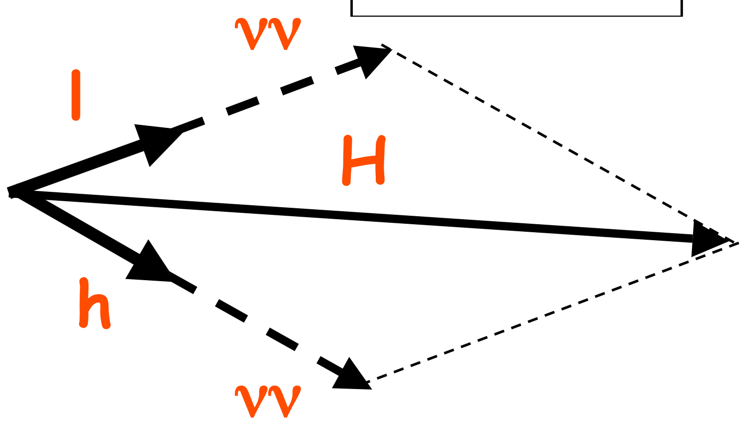


H→ττ Mass Reconstruction

- In order to reconstruct the Z mass need to use the collinear approximation

Tau decay products are collinear to tau direction

Fraction of τ momentum carried by visible τ decay



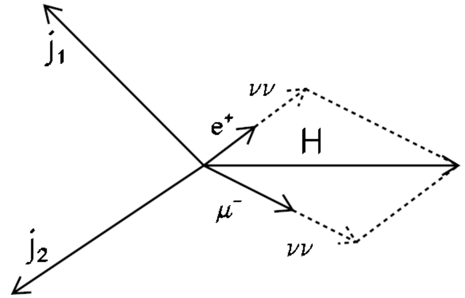
$$x_{\tau_1} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},x} \cdot p_{T_{lep2},y} - p_{T_{Higgs},y} \cdot p_{T_{lep2},x}}$$

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

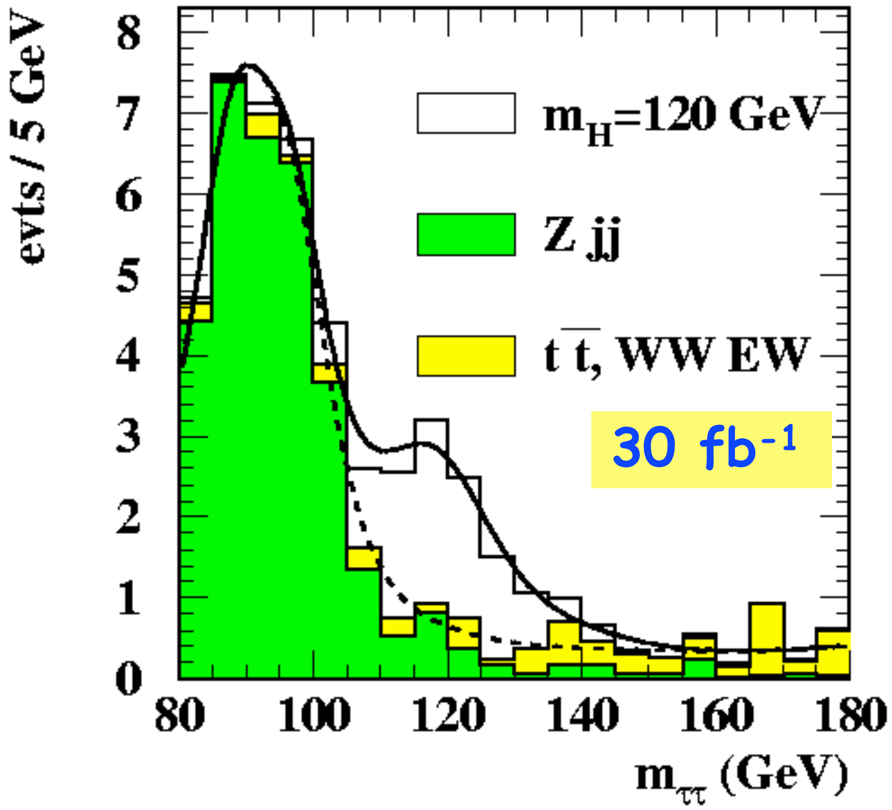
- $x_{\tau 1}$ and $x_{\tau 2}$ can be calculated if the missing E_T is known
- Good missing E_T reconstruction is essential

Low Mass SM $H \rightarrow \tau\tau$+jets

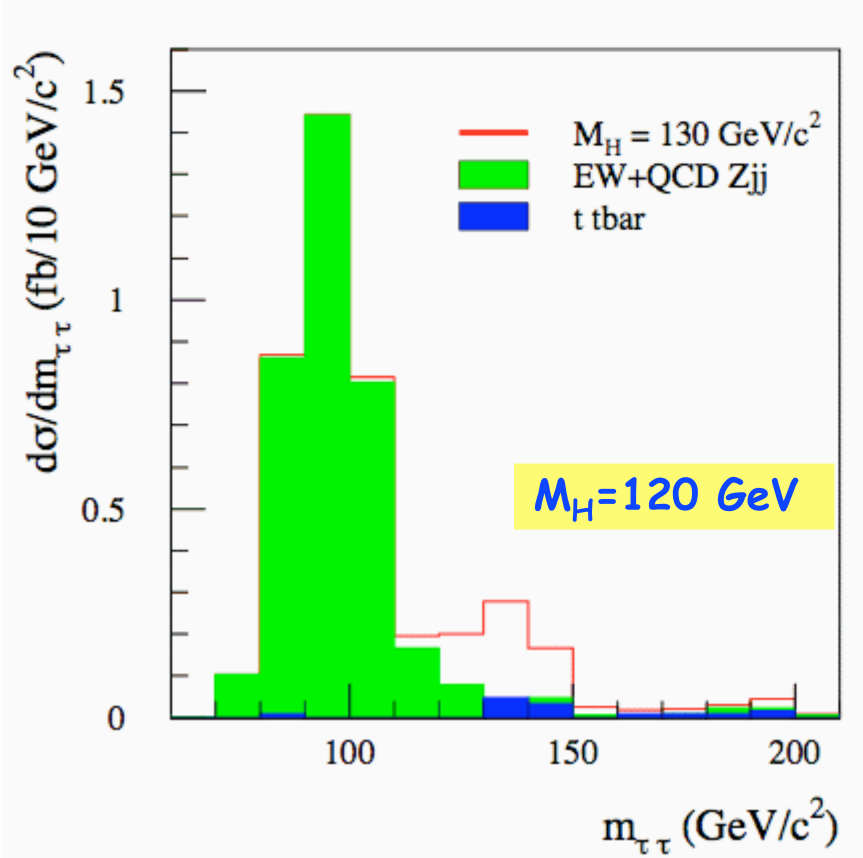
- Reconstruct Higgs mass with collinear approxim



$H(\rightarrow\tau\tau\rightarrow ll)$ +≥2jets



$H(\rightarrow\tau\tau\rightarrow lh)$ +≥1jet



Two independent ways of extracting $Z\to\tau\tau$ shape

- Data driven and MC driven
- Similar procedure has been defined for $H\to WW^{(*)}$

Control Sample 1
$Z\to ee,\mu\mu$
Loose cuts on Jets

MC extrap. is validated →

Control Sample 3
$Z\to ee,\mu\mu$
Tight cuts on Jets

$85<M_{ll}<95$ GeV

↓ Replace $Z\to ee,\mu\mu$ by $Z\to\tau\tau$

Control Sample 2
$Z\to\tau\tau$
Loose cuts on Jets

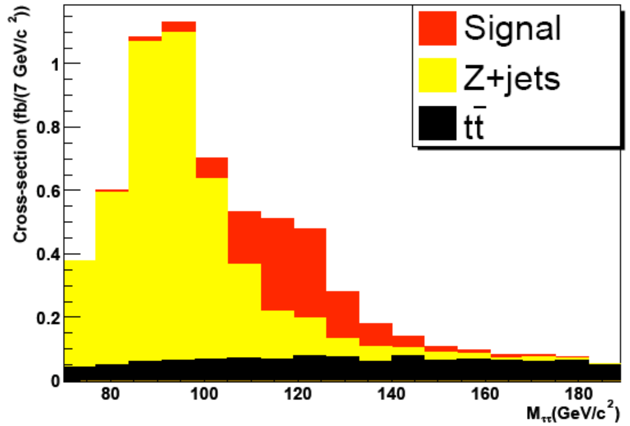
MC extrap. →

Signal Region
$Z\to\tau\tau$
Tight cuts on Jets

$M_{ll}<75$ GeV

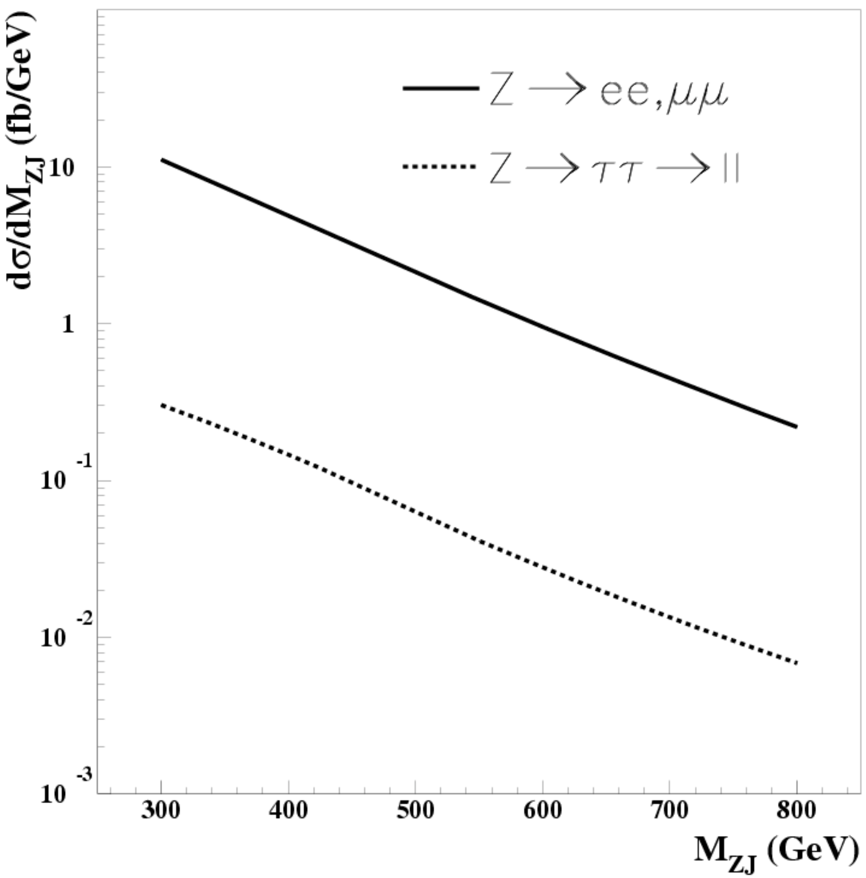
M_{HJ}, $\Delta\eta_{JJ}$ →

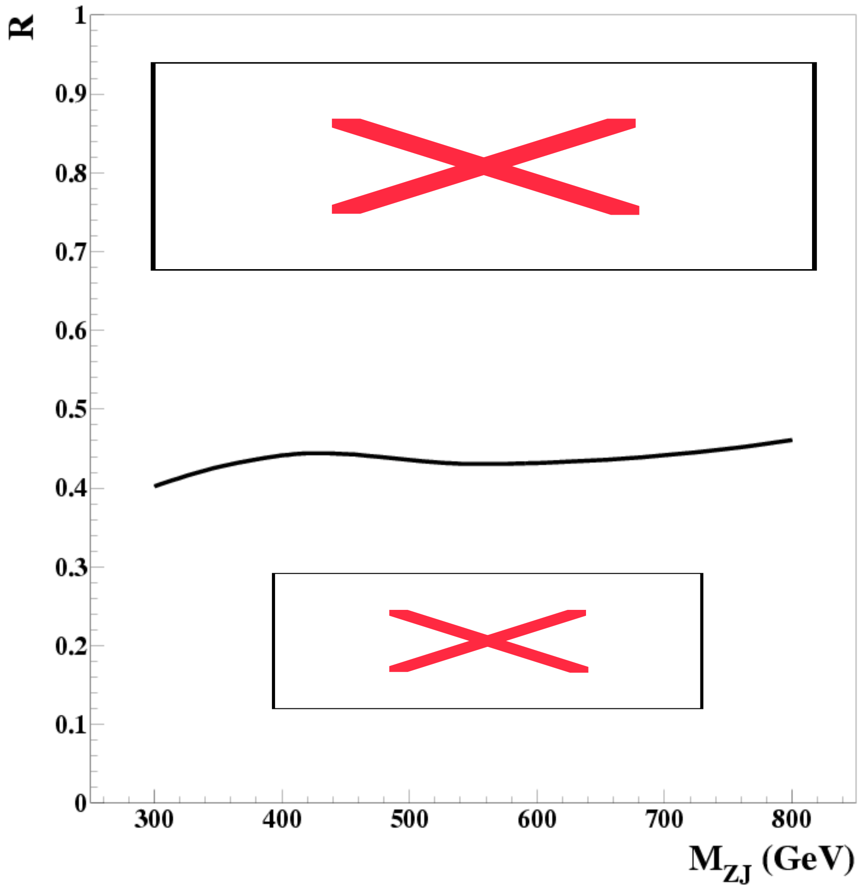
Determine shape and normalization of $Z\to\tau\tau$ background

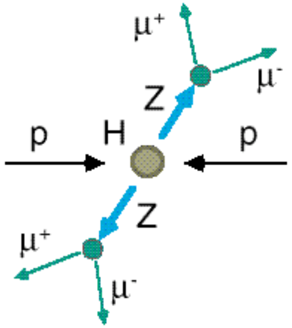


Normalization of $Z\rightarrow\tau\tau$ using $Z\rightarrow ee,\mu\mu$

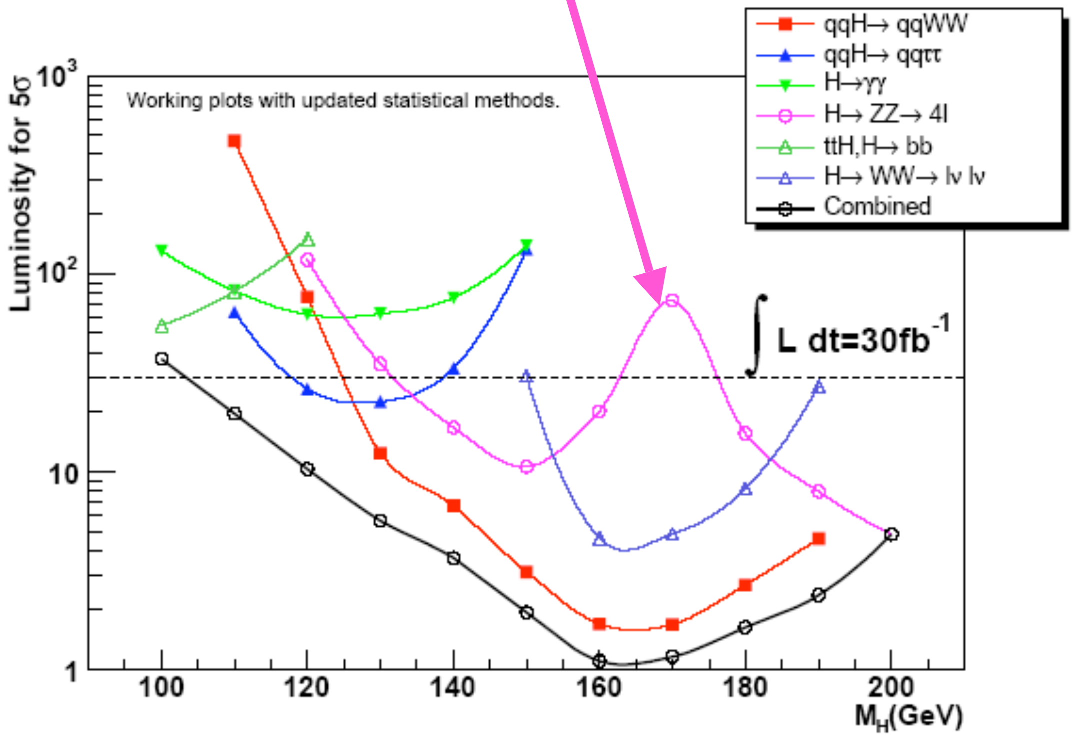
- $Z\rightarrow ee,\mu\mu$ offers about 35 times more statistics w.r.t to $Z\rightarrow\tau\tau\rightarrow ll$
  - Ratio of efficiencies depends weakly with M_{HJ} and can be easily determined with MC after validation with data



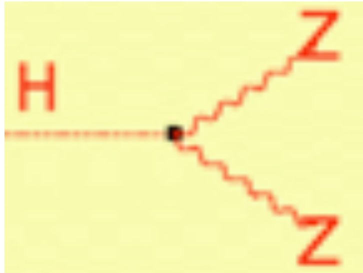




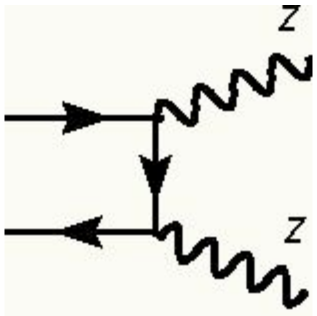
SM Higgs: H→ ZZ(*)→4l

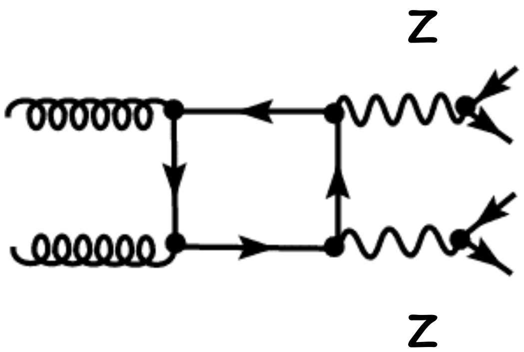


Higgs decay to Z^0Z^0

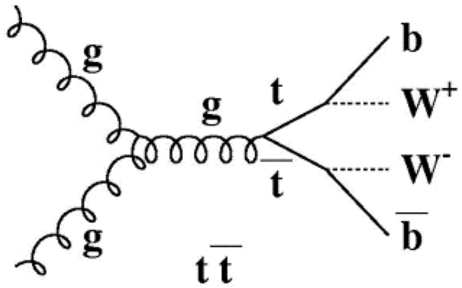


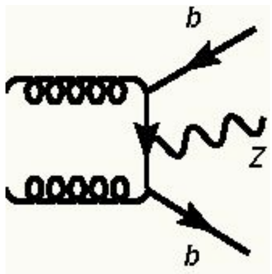
Irreducible Z^0Z^0 backgrounds



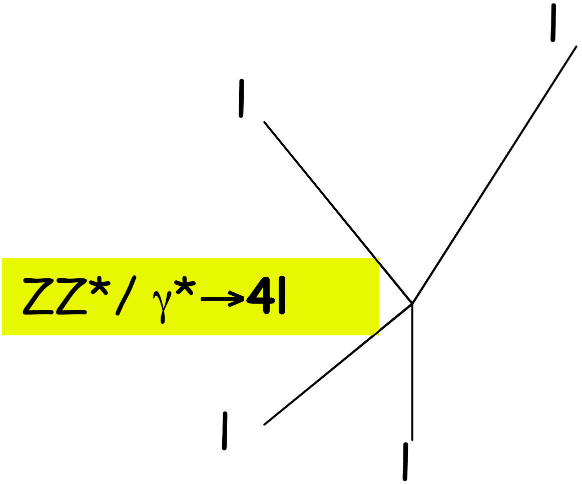


Reducible 4l backgrounds

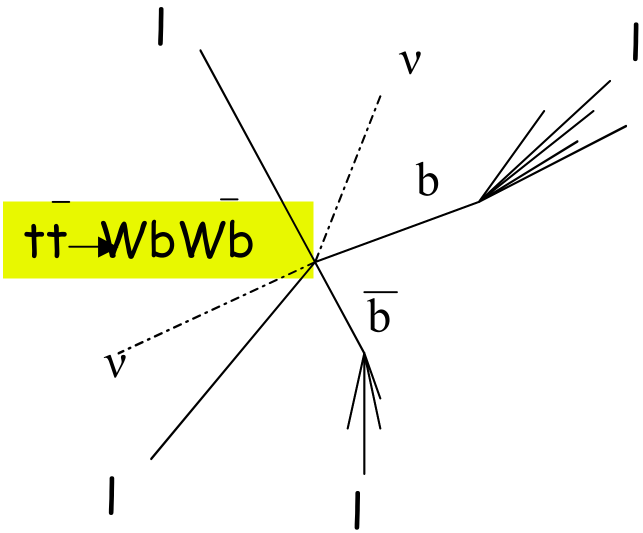




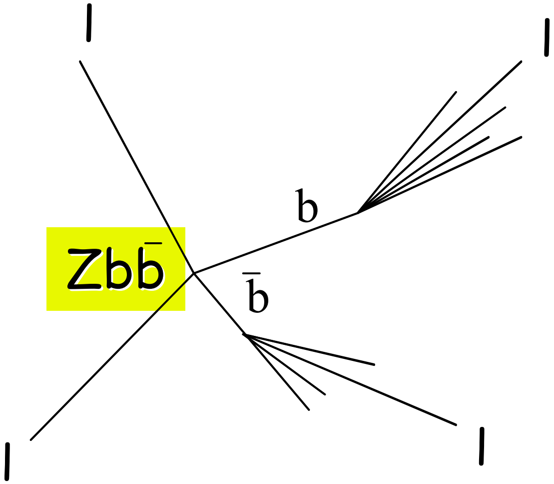
Backgrounds Higgs→ZZ$^{(*)}$→4l (l=eμ)



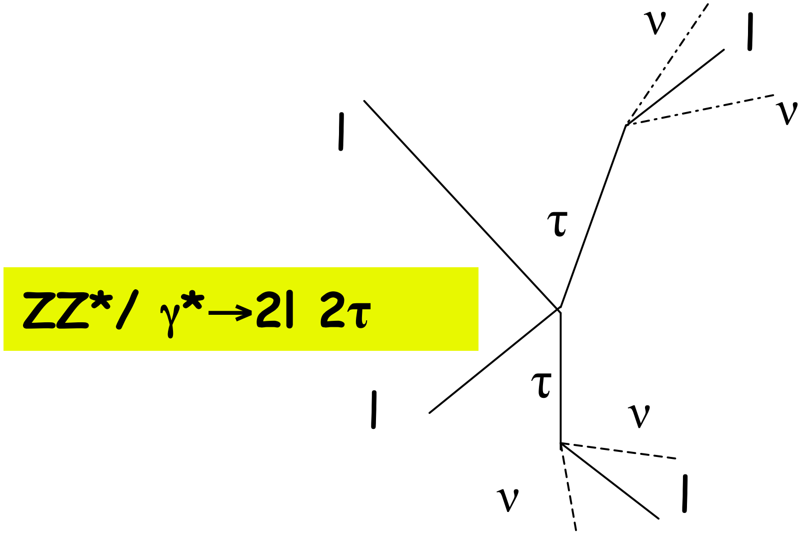
Continuum
Irreducible



Non-Resonant
reducible

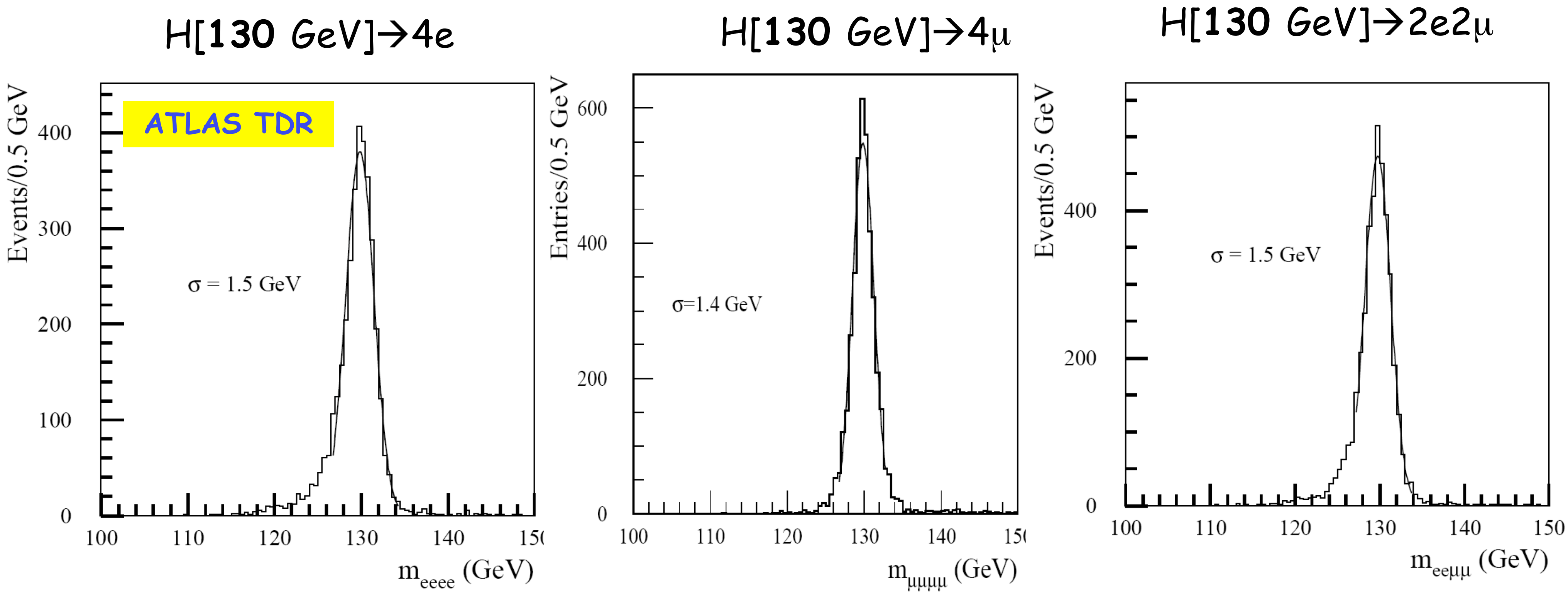


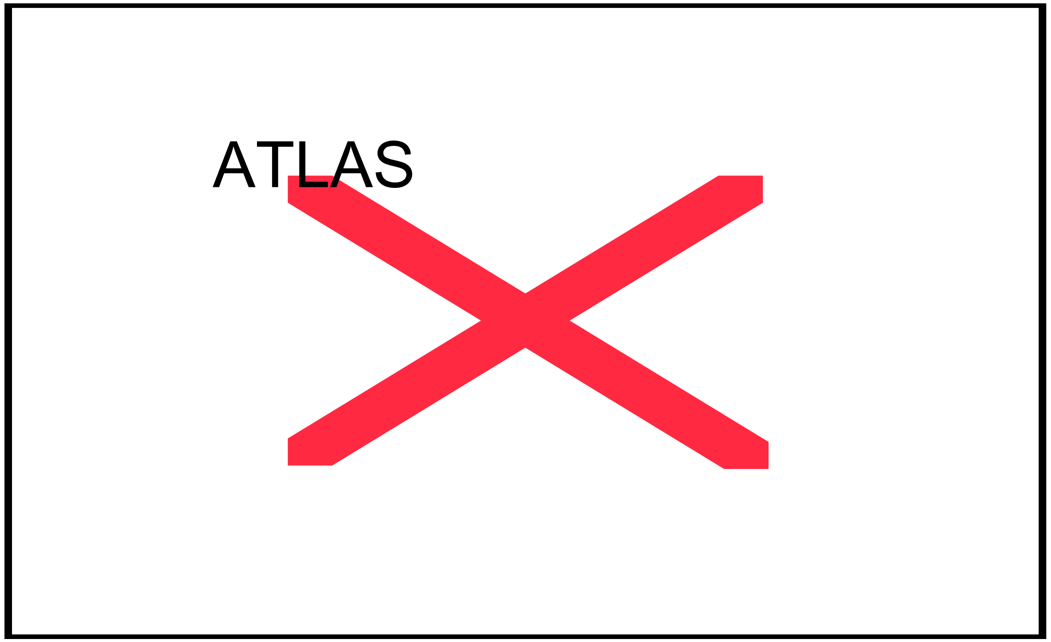
Resonant
reducible

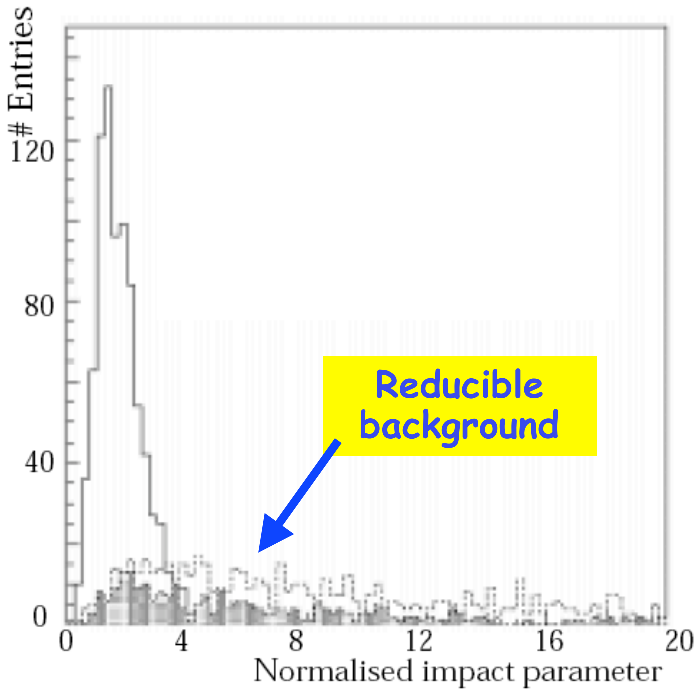


SM Higgs→ZZ$^{(*)}$→4l

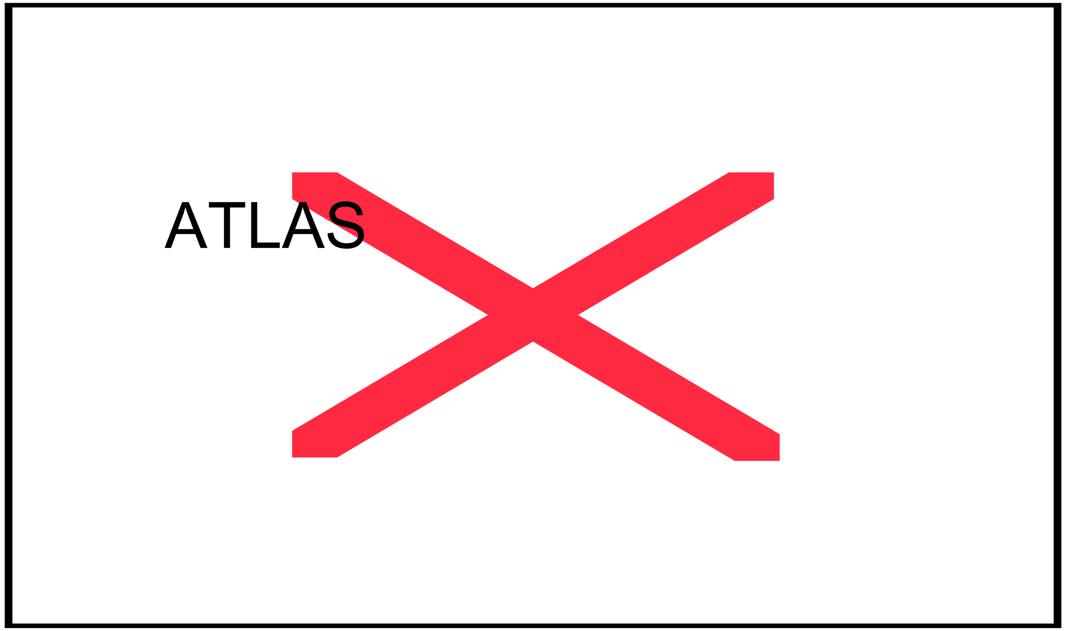
- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background > 1
  - Major issue: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background Zbb,tt→4l

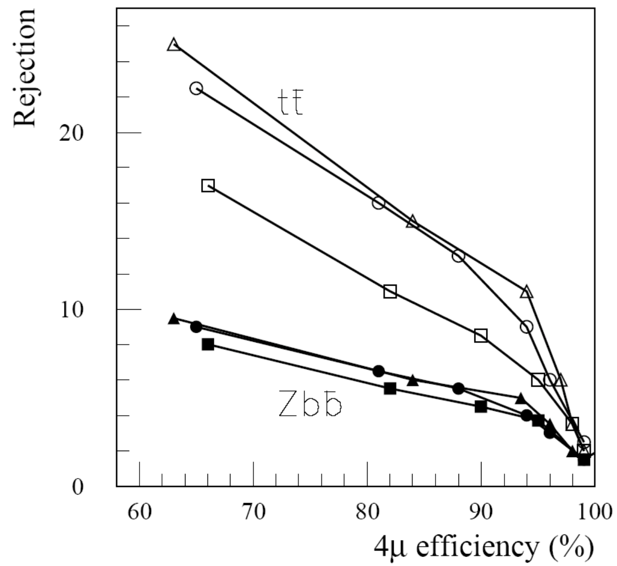




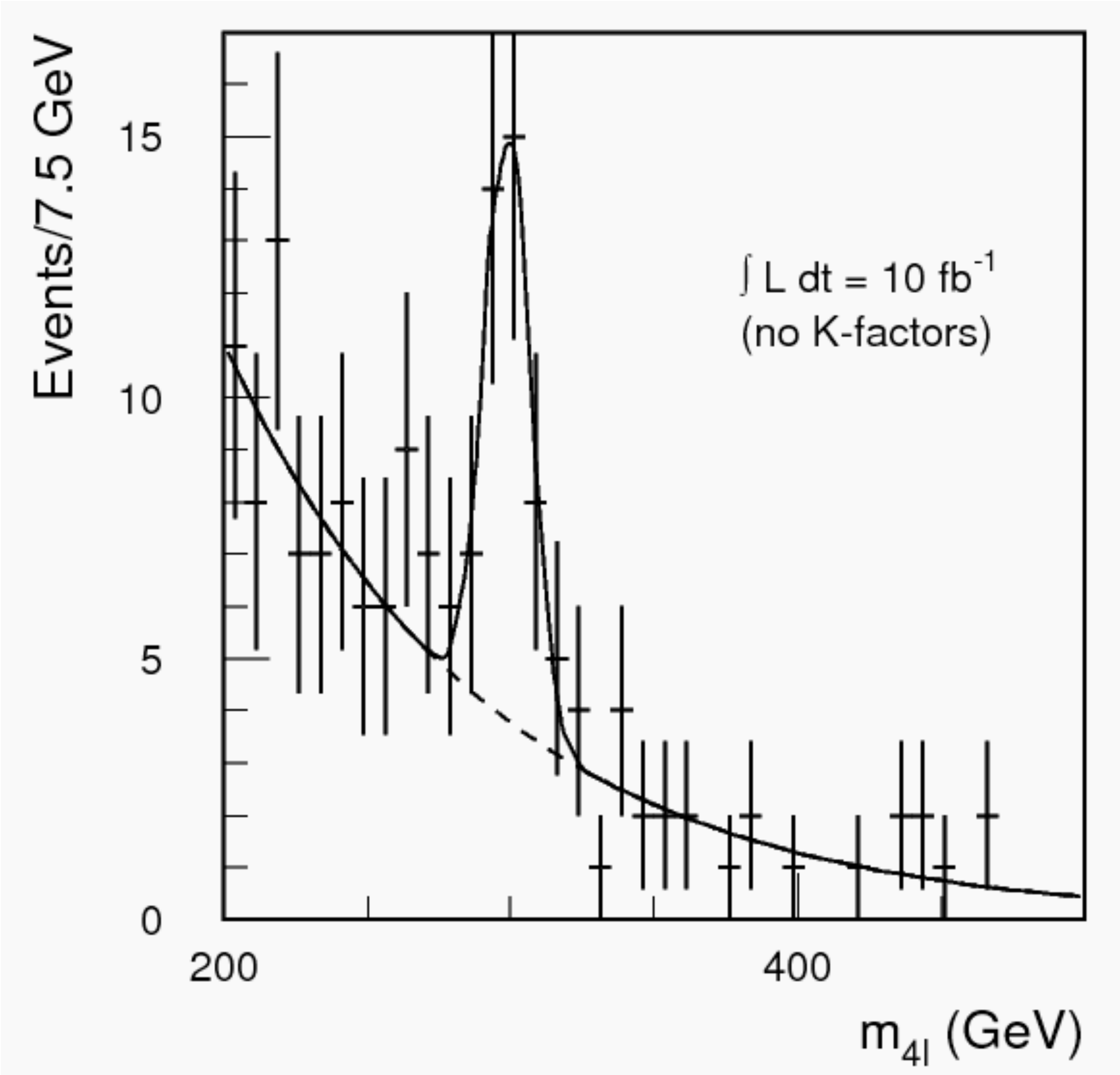


ATLAS TDR

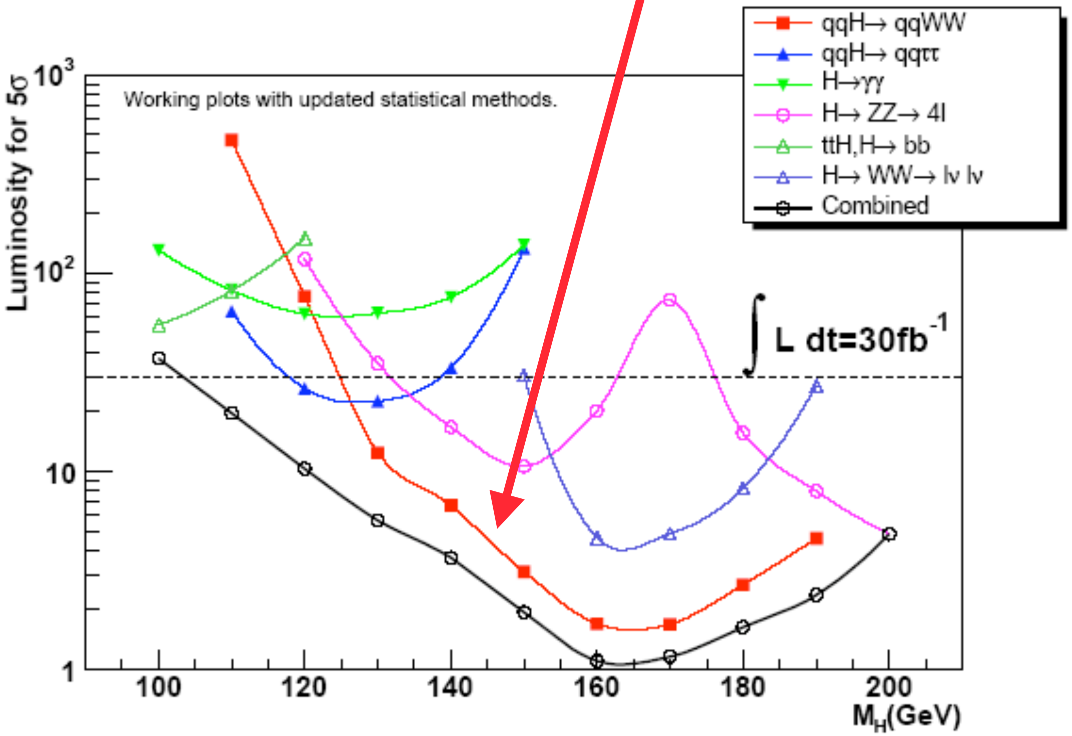




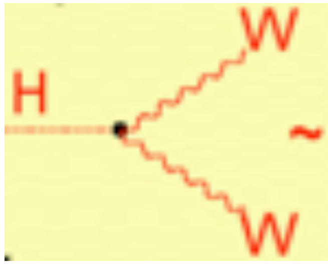
ATLAS TDR


Events/7.5 GeV
15
10
5
0
200
400
m41 (GeV)
∫ L dt = 10 fb-1
(no K-factors)

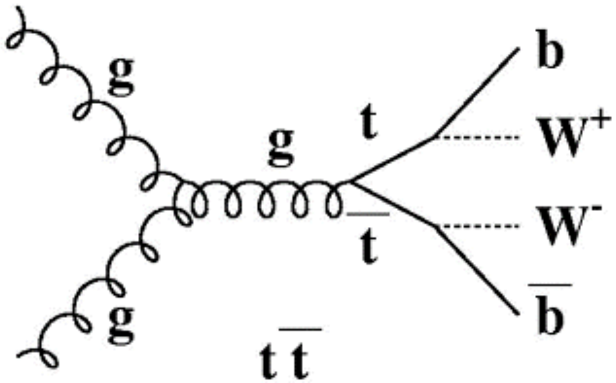
SM Higgs: H→ WW(*)→2l2ν

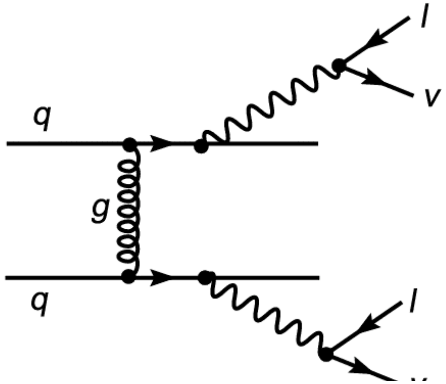


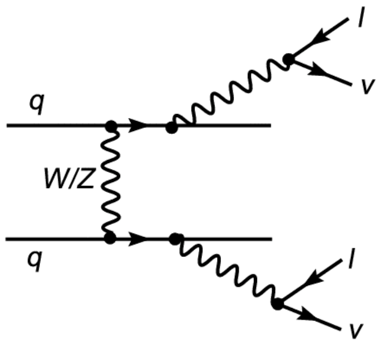
Higgs decay to W^+W^-



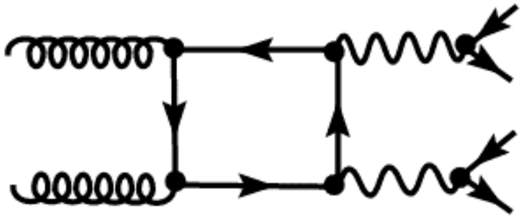
W^+W^- backgrounds





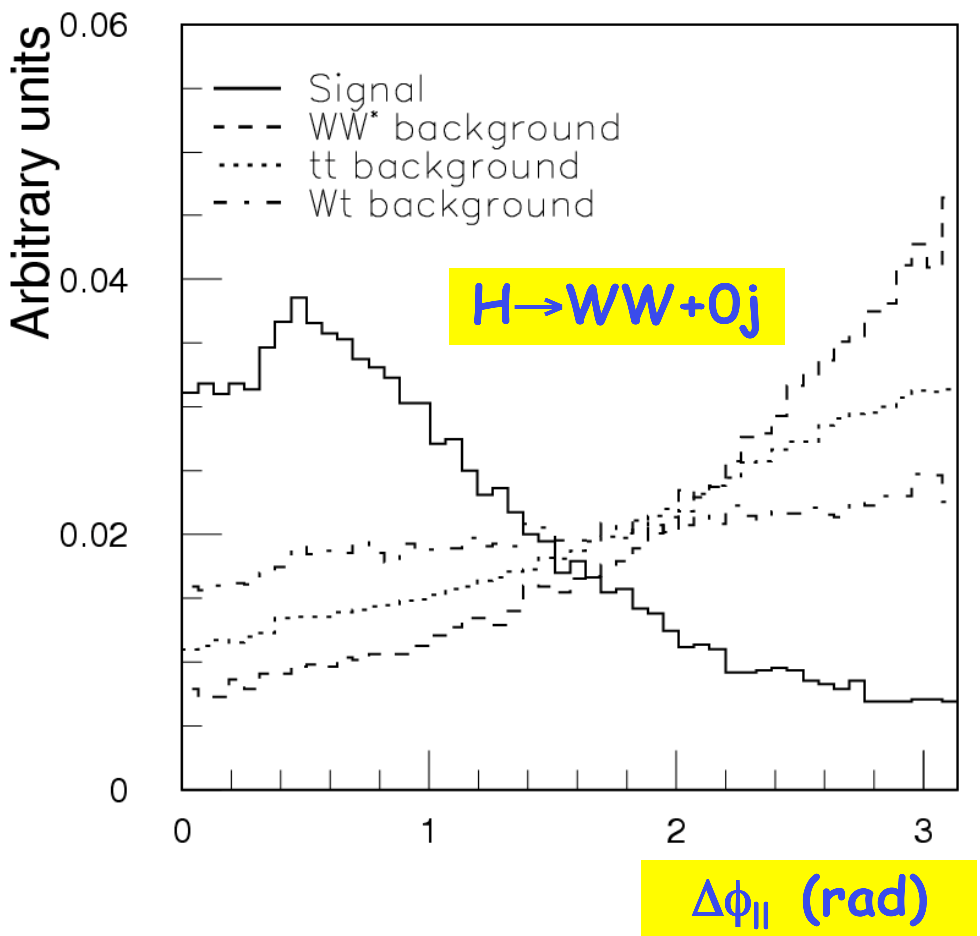


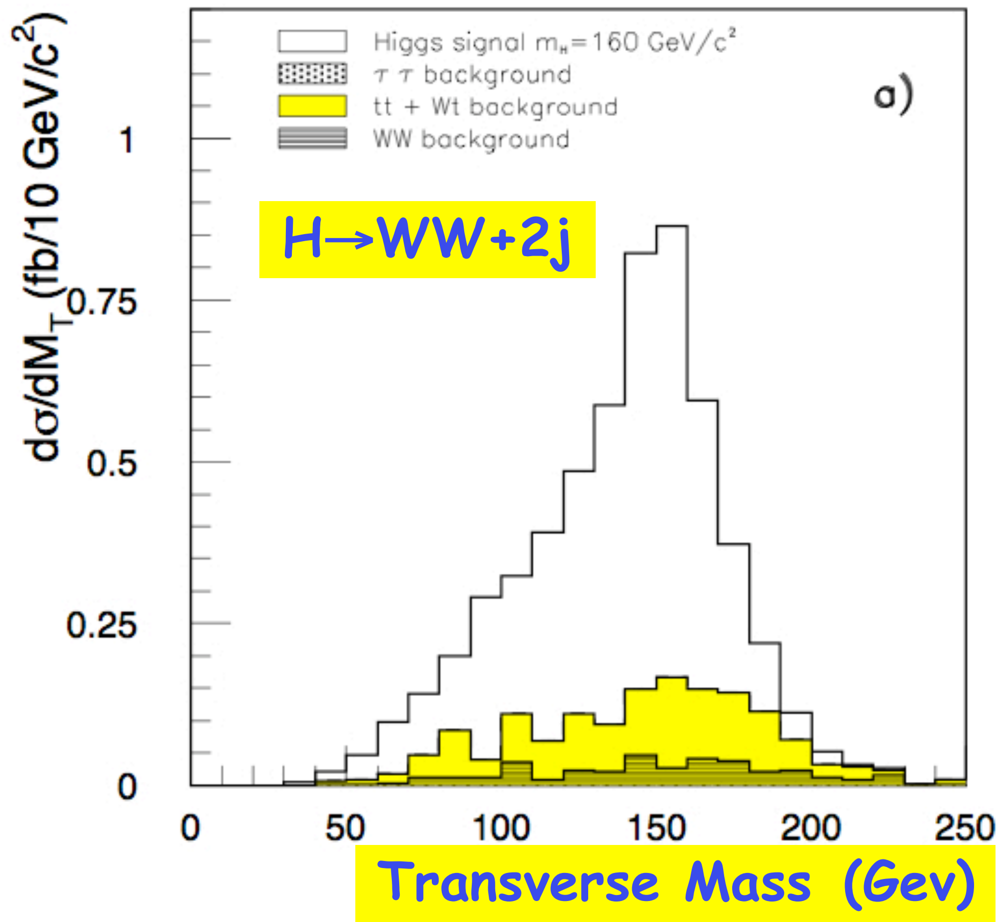
+ Single top
& non-resonant WWbb



SM Higgs $H \rightarrow WW^{(*)} \rightarrow 2l2\nu$

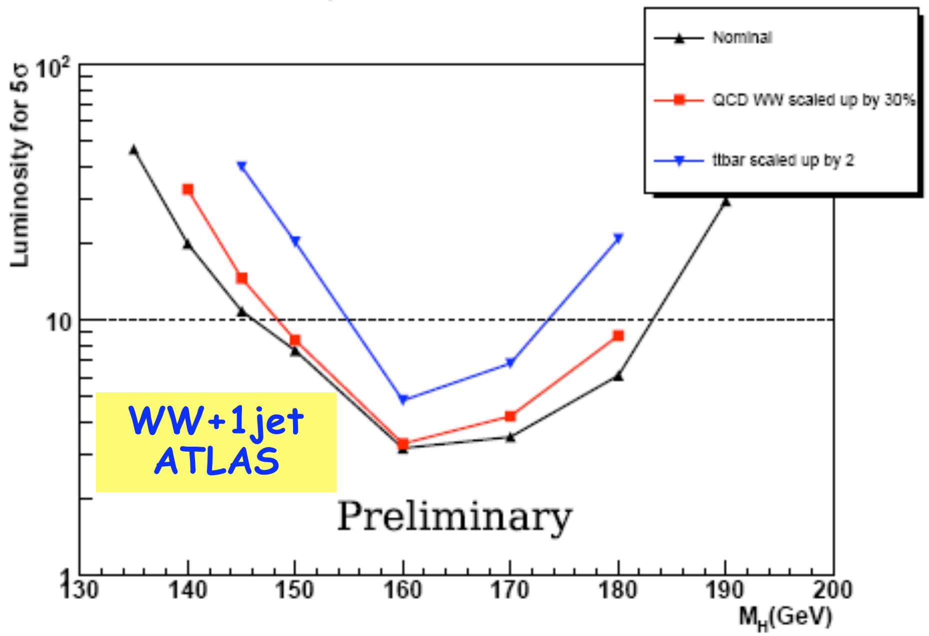
- Strong potential due to large signal yield, but no narrow resonance. Left basically with event counting experiment

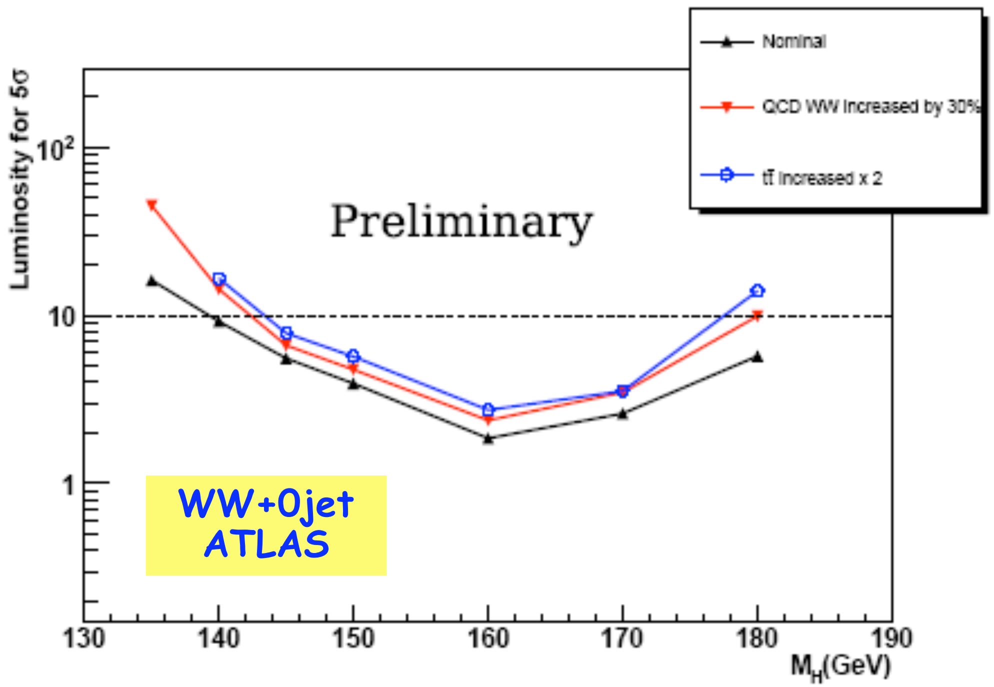


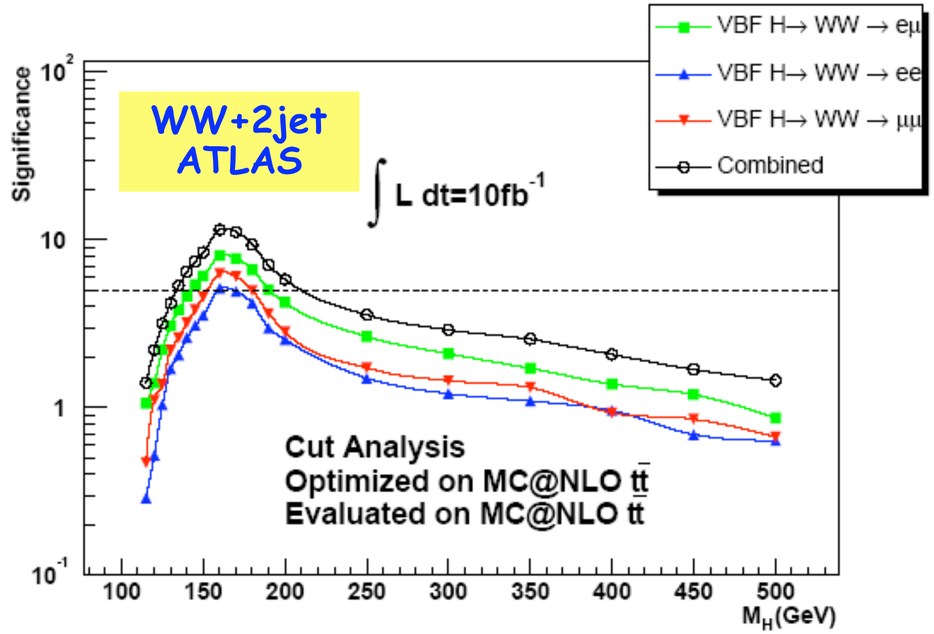


SM H→WW +0,1,2 jets

- Defined three independent analysis, depending on the number of tagged jets
  - Systematic errors added in significance calculation





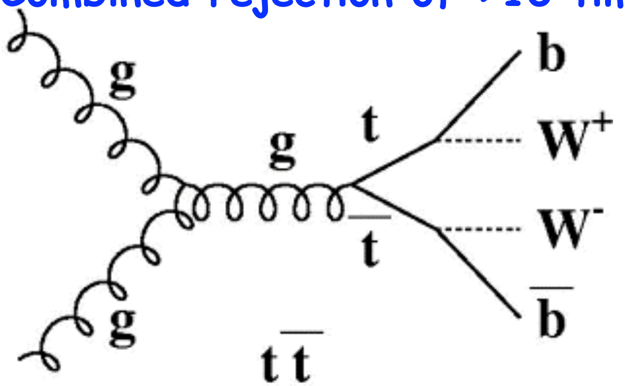


Background Suppression and Extraction

- Not able to use side-bands to subtract background. This makes signal extraction more challenging. Need to rely on data rather than on theoretical predictions
- Definition & understanding of control samples is crucial

ttbar suppression

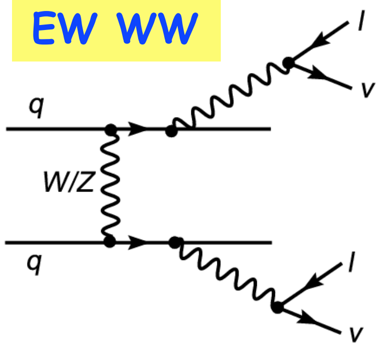
- Jet veto (understand low P_T jets)
- Semi-inclusive b-tagging or "top killing" algorithm
- Combined rejection of >10 times



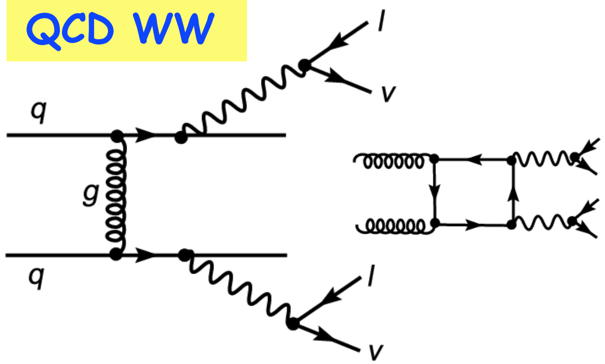
Non-resonant WW suppression

- $\Delta\phi_{ll}$ and $M_{ll,}$ very important variables
- Transverse momentum of WW system
  - Higgs production is harder
  - Missing E_T reconstruction plays a role

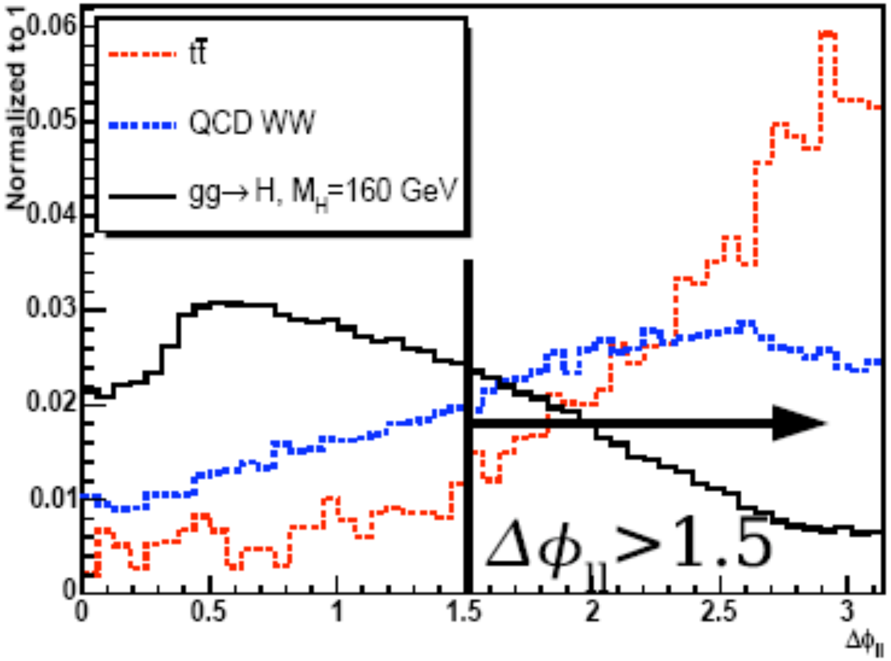
EW WW

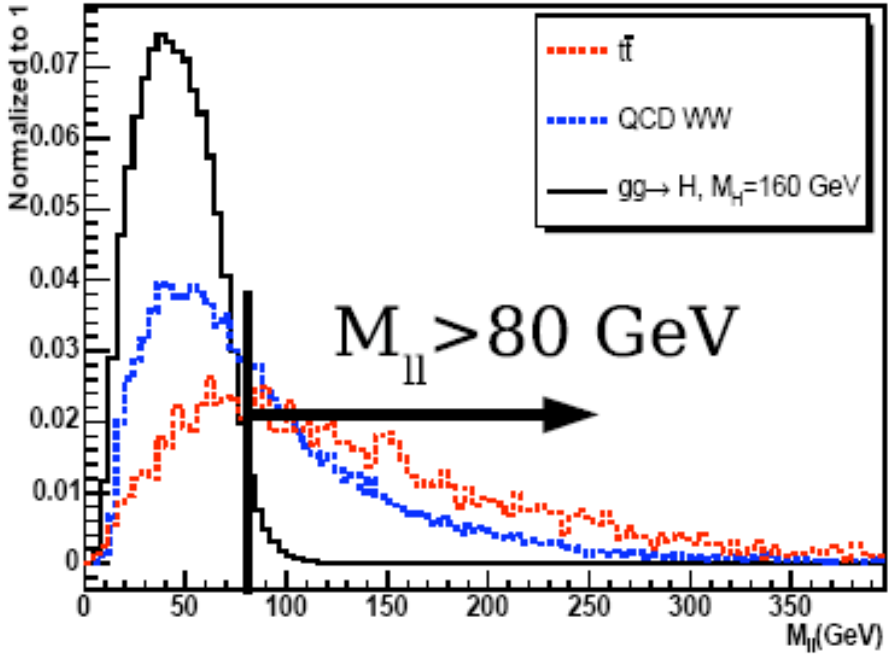


QCD WW



Control Samples for $H \rightarrow WW^{(*)}$

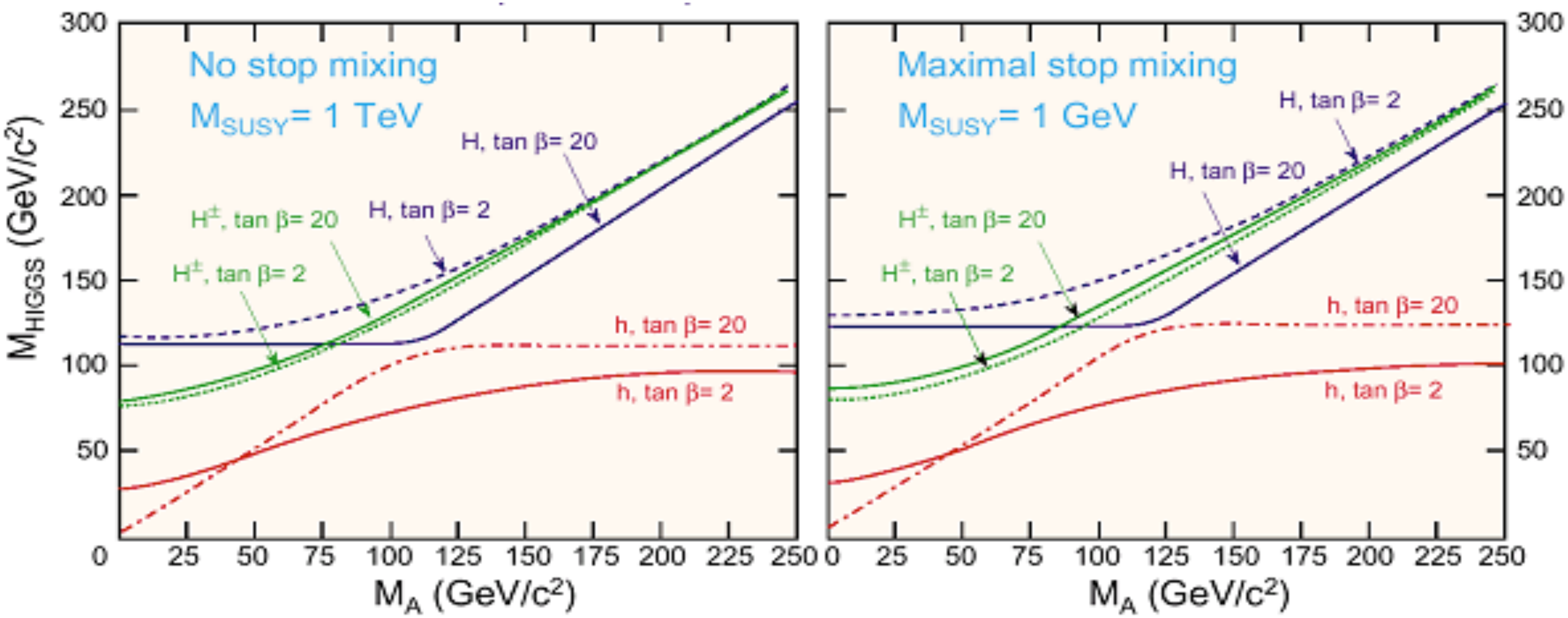




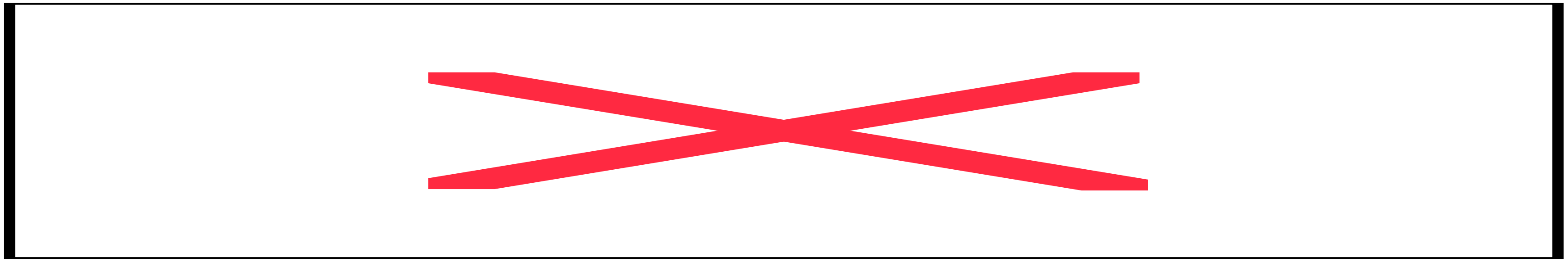
- Main control sample is defined with two cuts
  - $\Delta\phi_{ll}$>1.5 rad. and M_{ll}>80 GeV
- Because of tt contamination in main control sample, need b-tagged sample (M_{ll} cut is removed)

MSSM Higgs

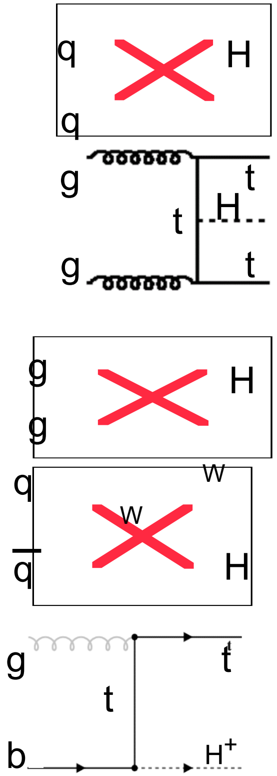
- Minimal super-symmetric extension of Higgs sector
  - Five Higgs: h (light), H, A, $H^{\pm}$ (heavy)
  - Parameter space reduced to two: M_A, $\tan\beta$
  - Theoretical limit on light MSSM Higgs: h<135 GeV

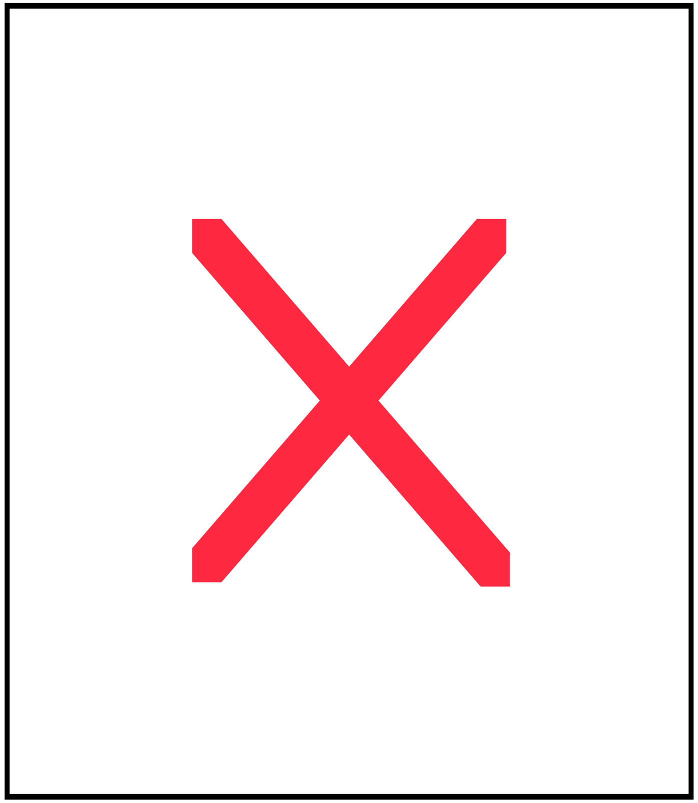


MSSM Higgs (cont)

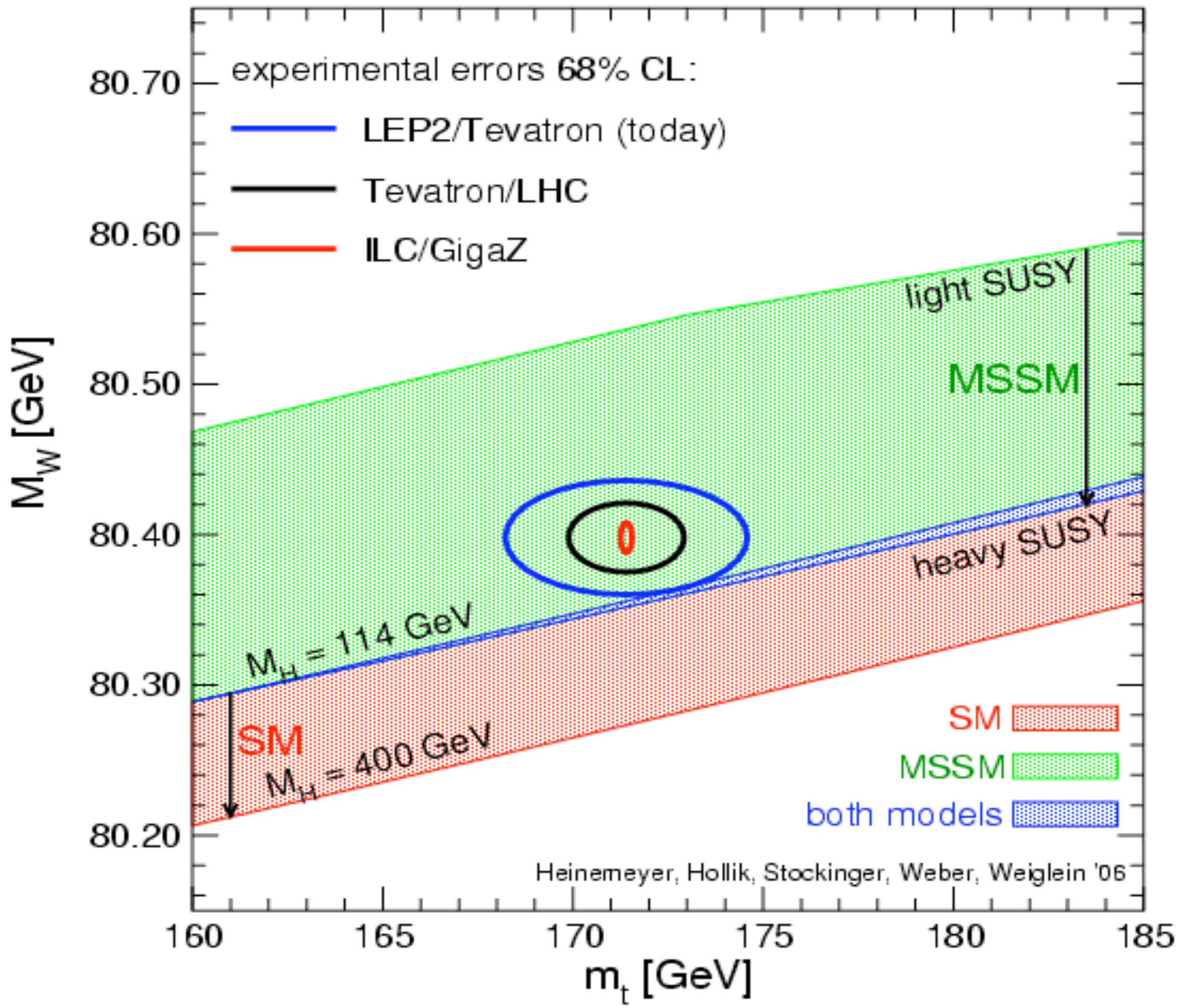


- **Large number of discovery modes:**
  - **SUSY particles heavy:**
    - SM-like: $h \to \gamma\gamma, bb, \tau\tau, WW$; $H \to 4l$
    - MSSM-specific: $A/H \to \mu\mu, \tau\tau, tt$; $H \to hh$, $A \to Zh$; $H^{\pm} \to \tau^{\pm}\nu$
  - **SUSY accessible:**
    - $H/A \to \chi^0_2 \chi^0_2$, $\chi^0_2 \to h\ \chi^0_1$
    - Small impact on Higgs branching ratio to SM particles





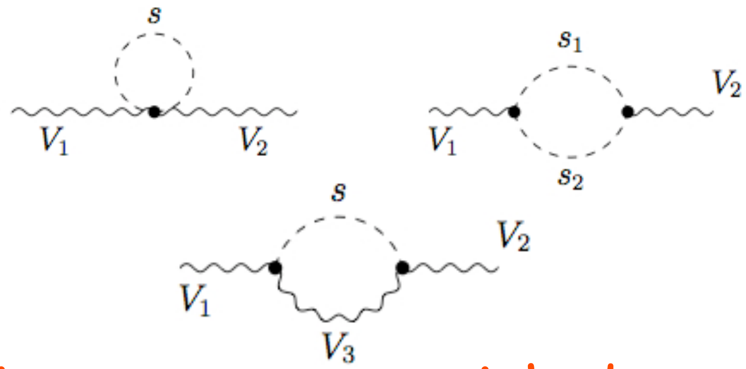
Does the data favor a MSSM Higgs?



M_t = 171.4 GeV
M_W = 80.398 GeV

Slepton/squark
one loop corrections

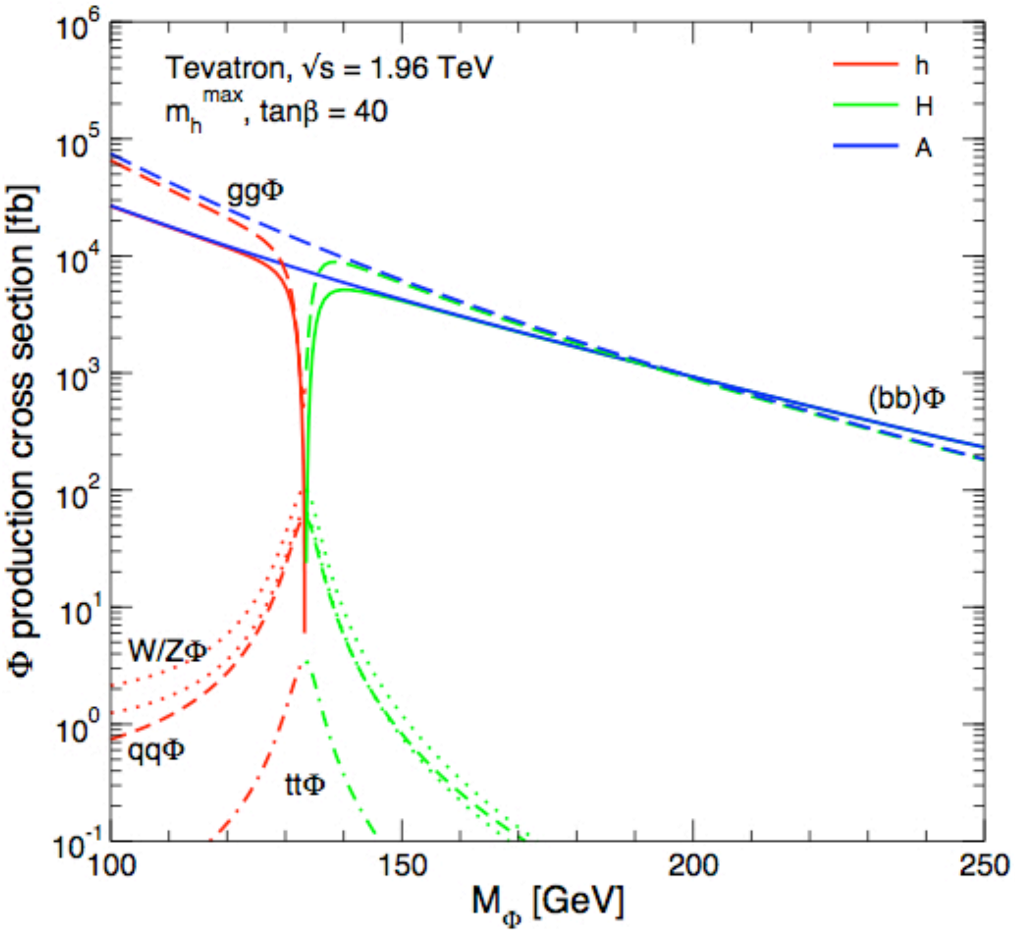
Contributions from
MSSM Higgs bosons



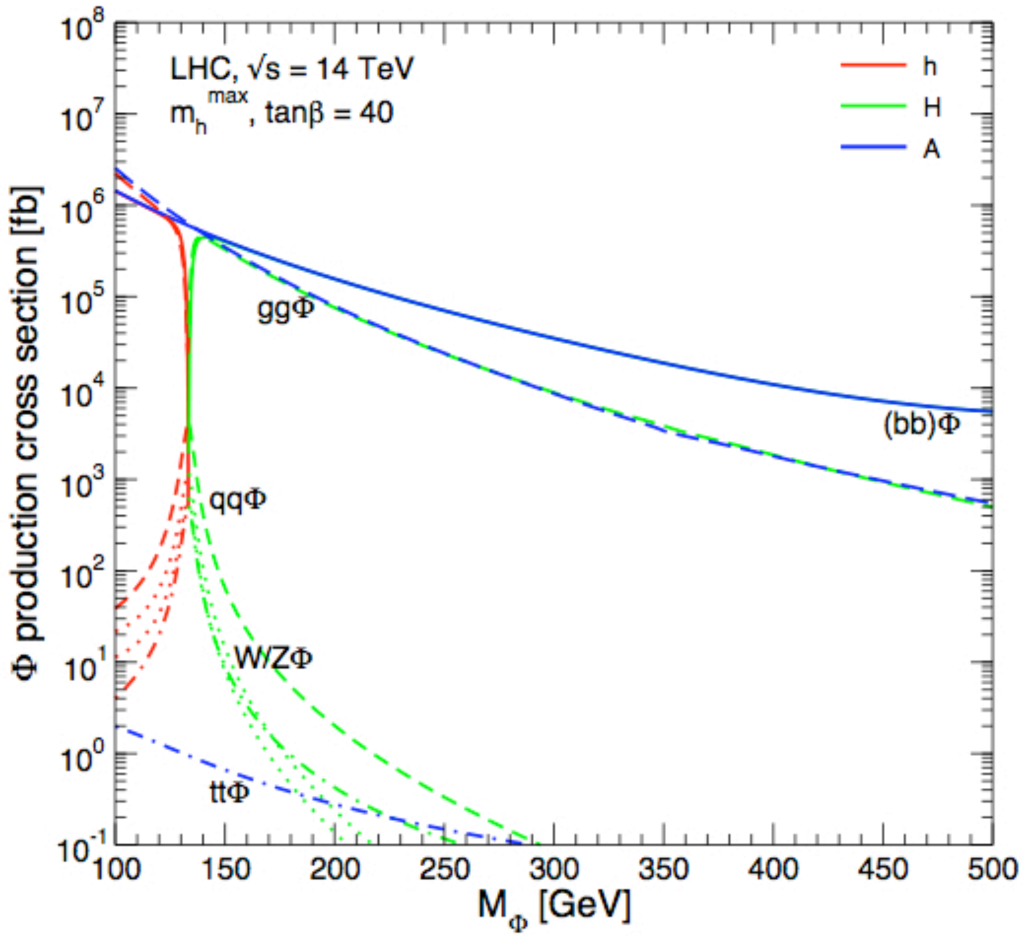
Caution: This is not the only way of achieving agreement with data

MSSM Higgs Cross-sections
(large tanβ)

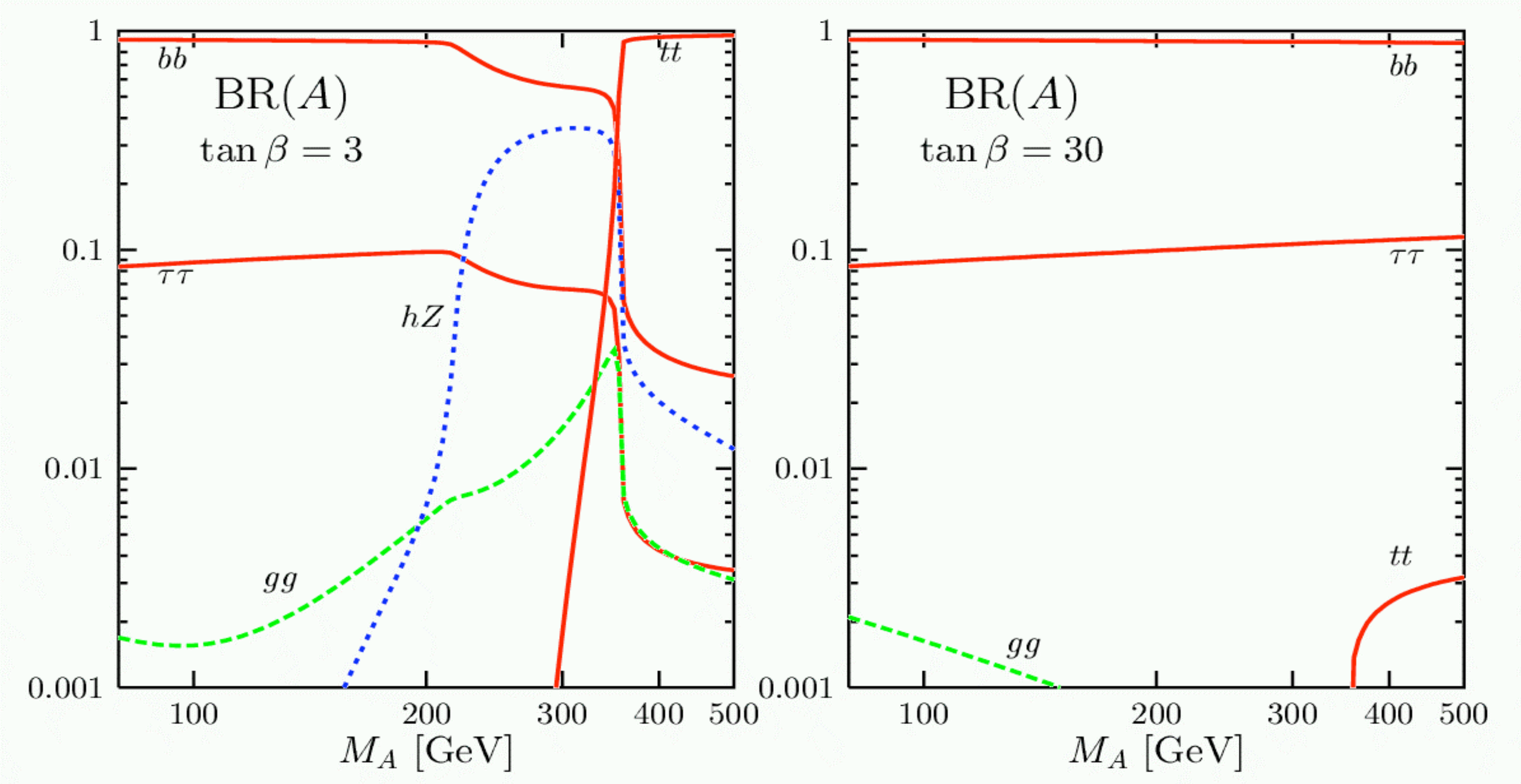
Tevatron



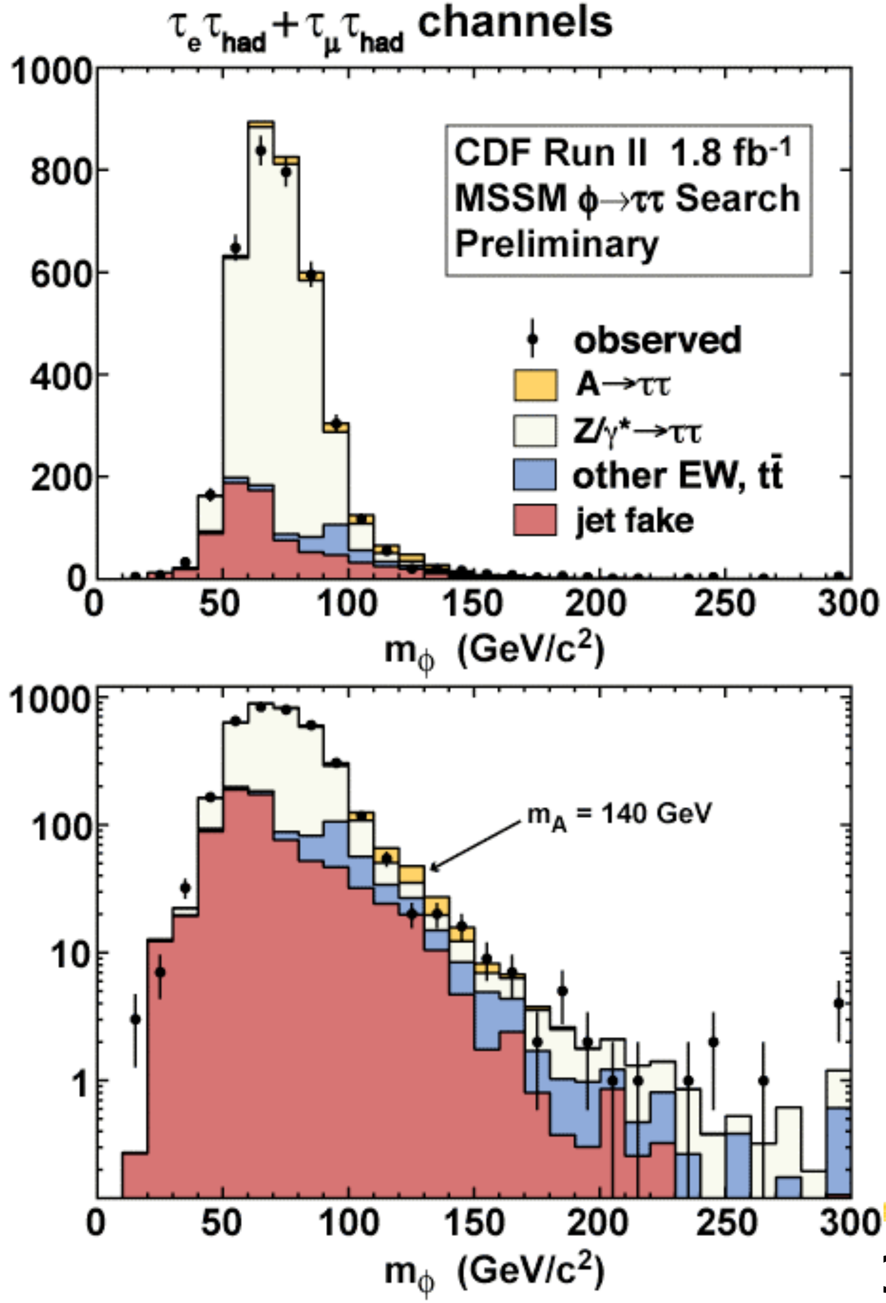
LHC

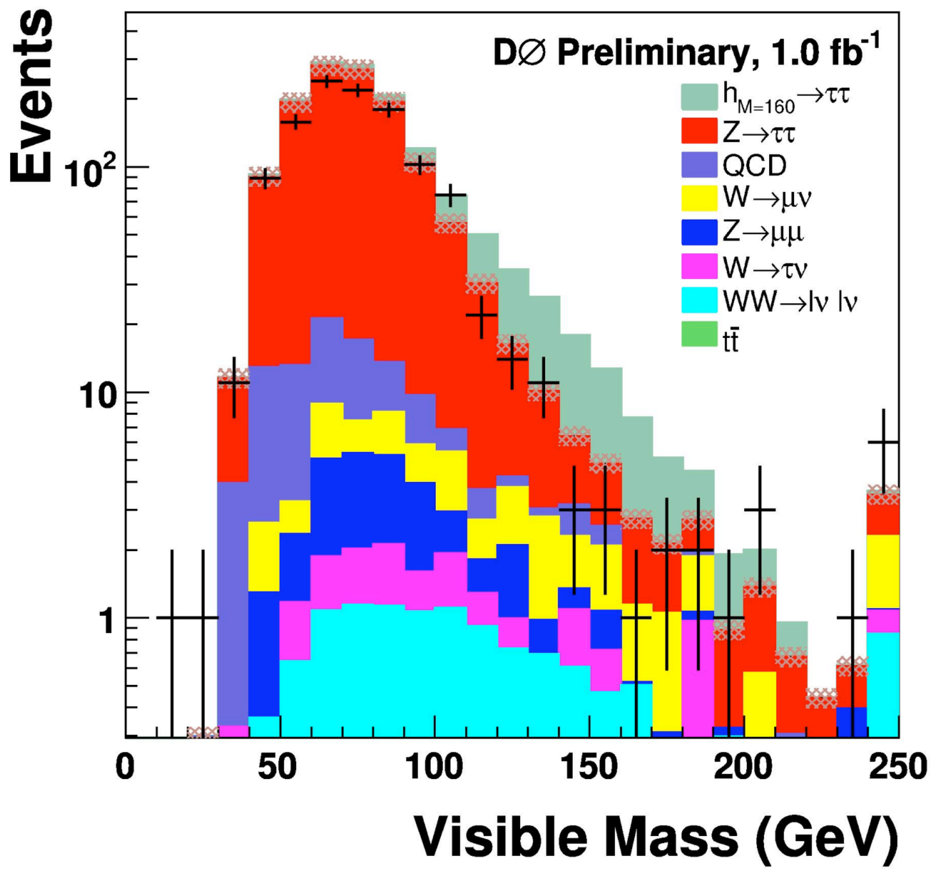


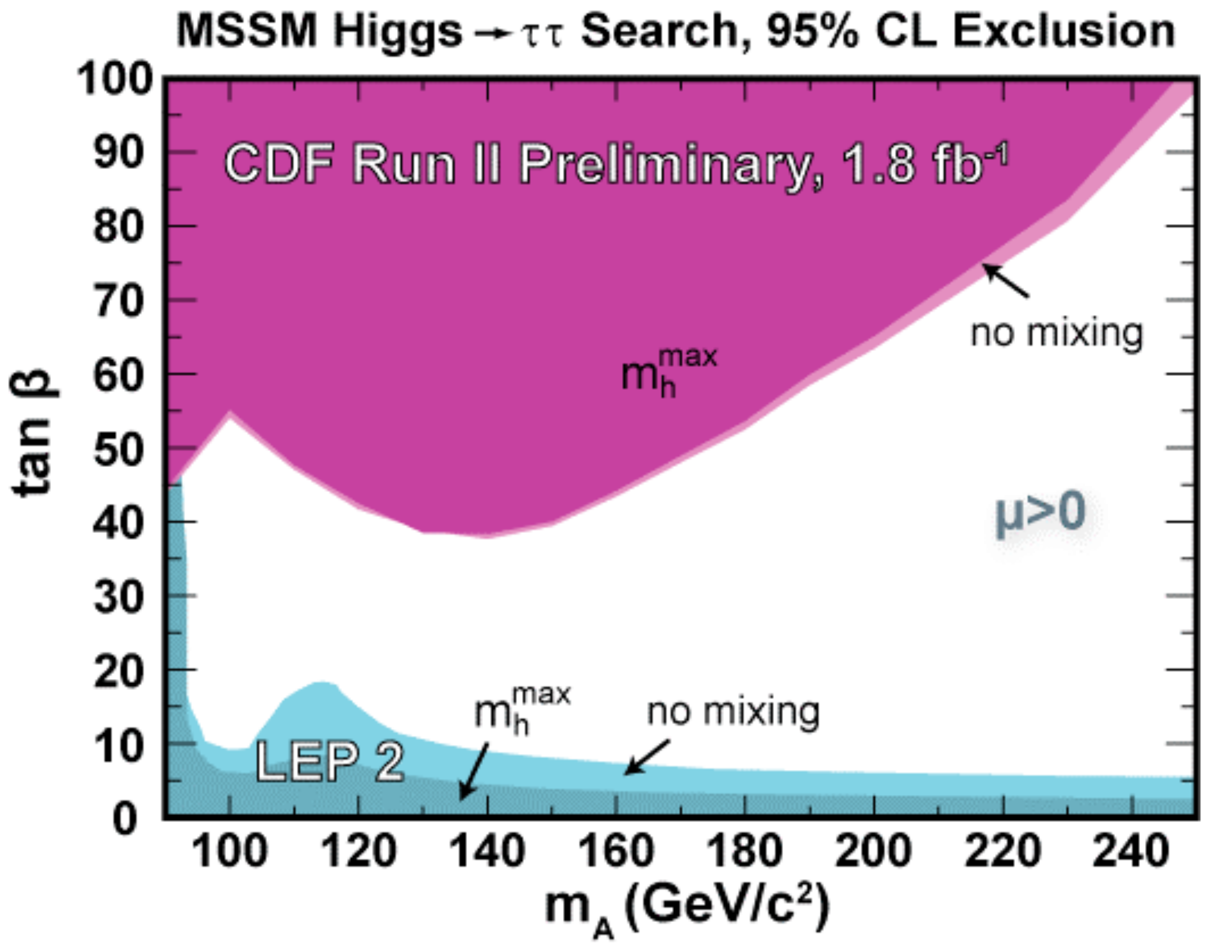
Heavy CP-odd Higgs boson (A) branching ratios

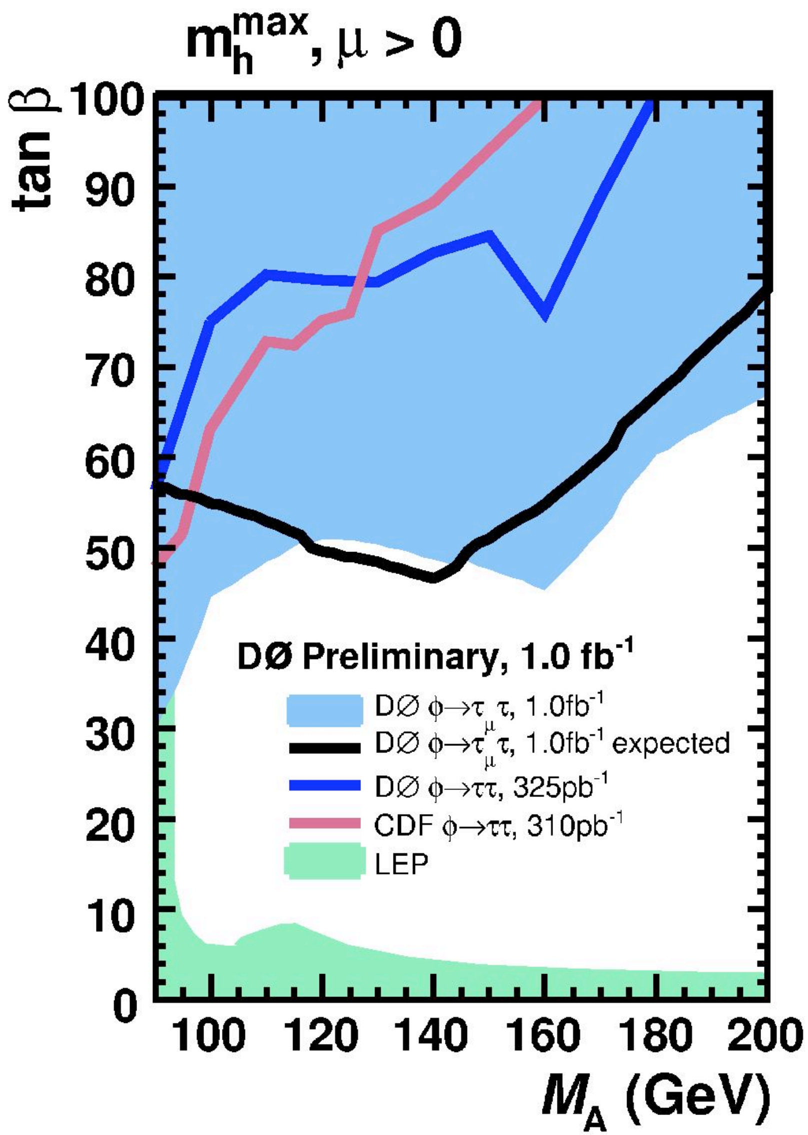


MSSM Higgs Search at the Tevatron

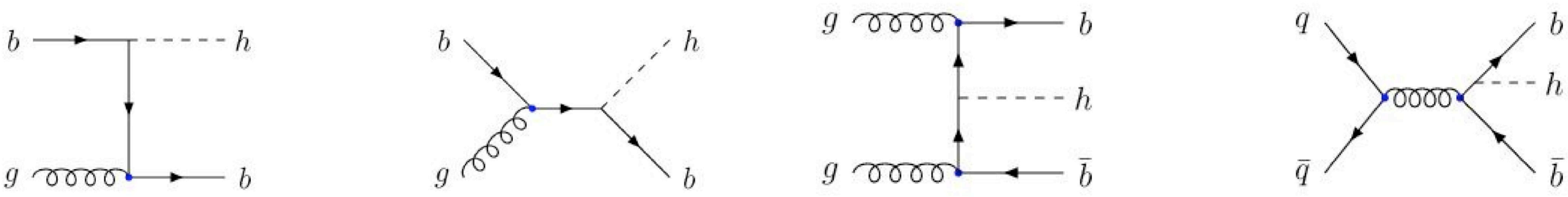


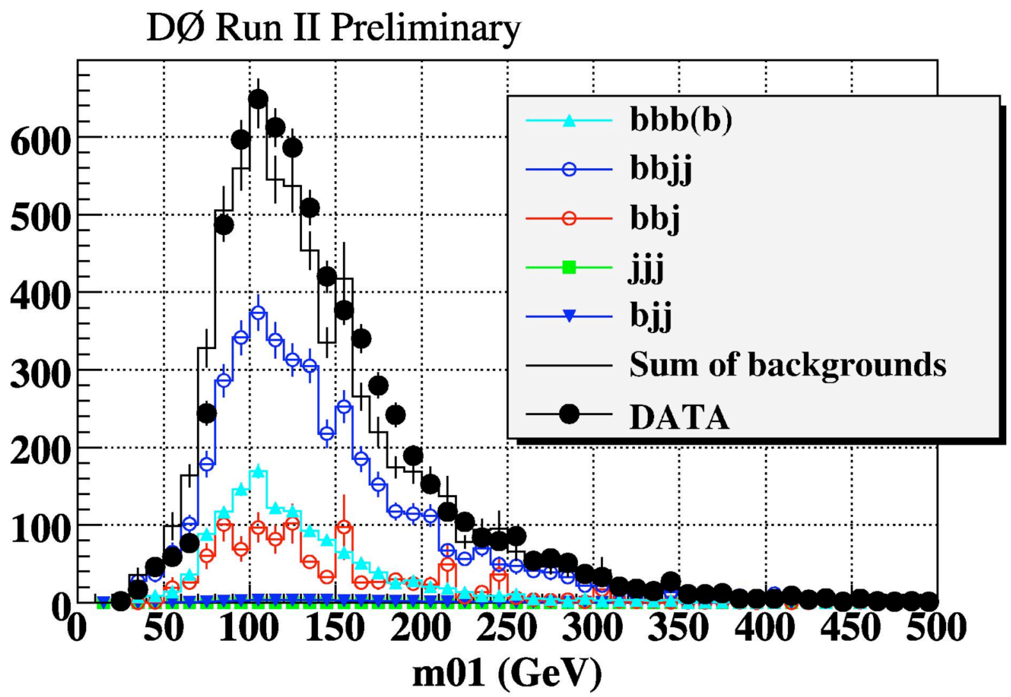


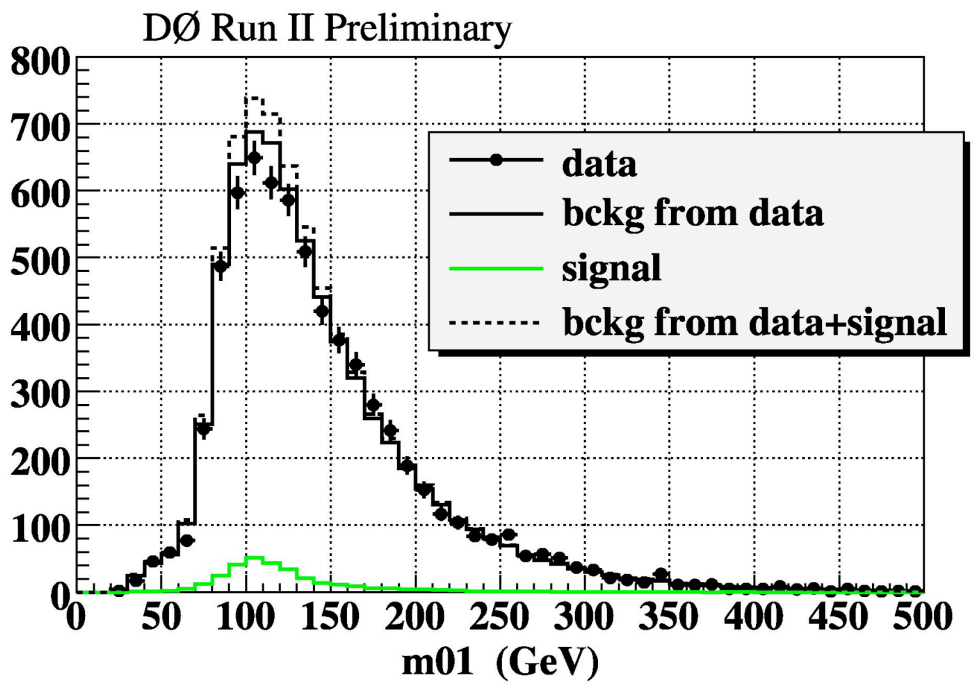

MSSM Higgs → ττ Search, 95% CL Exclusion
CDF Run II Preliminary, 1.8 fb-1
m_h^{max}
no mixing
μ>0
LEP 2
m_h^{max}
no mixing
tan β
m_A (GeV/c²)
100
90
80
70
60
50
40
30
20
10
0
100
120
140
160
180
200
220
240


m_h^{max}, μ > 0
tan β
DØ Preliminary, 1.0 fb-1
DØ φ→τ τ, 1.0fb-1
DØ φ→τ τ, 1.0fb-1 expected
DØ φ→ττ, 325pb-1
CDF φ→ττ, 310pb-1
LEP
M_A (GeV)
100
90
80
70
60
50
40
30
20
10
0
100
120
140
160
180
200

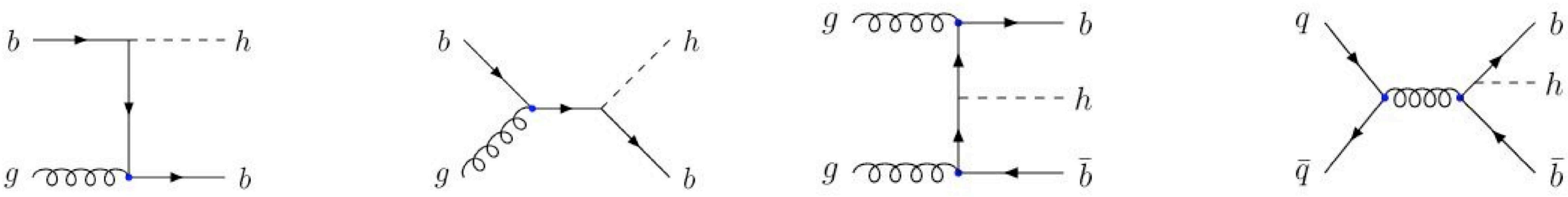
D0 3b-jet Analysis

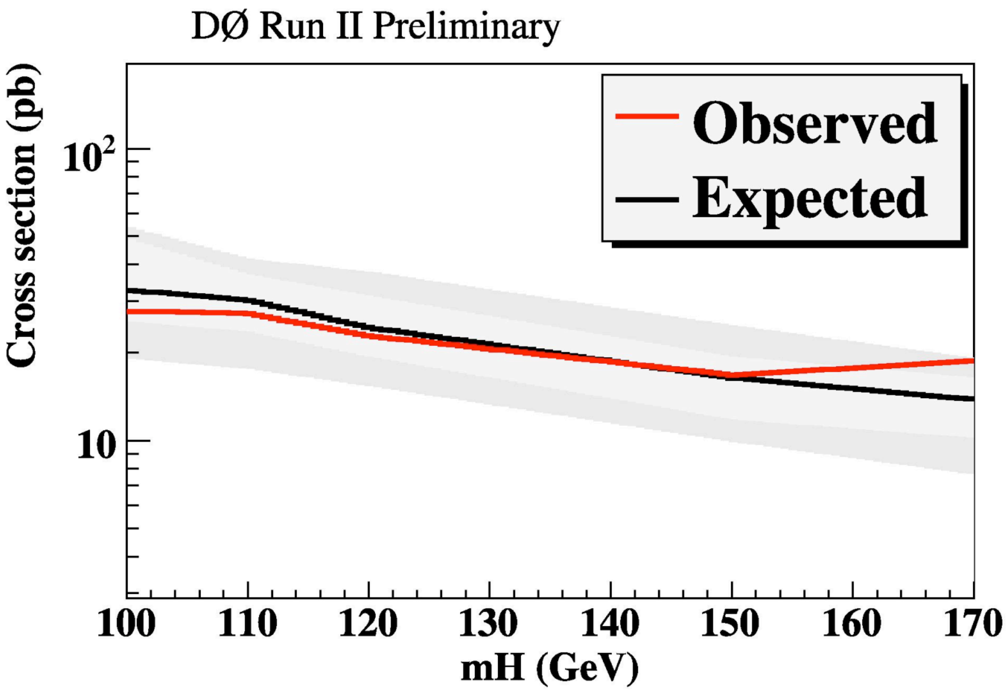


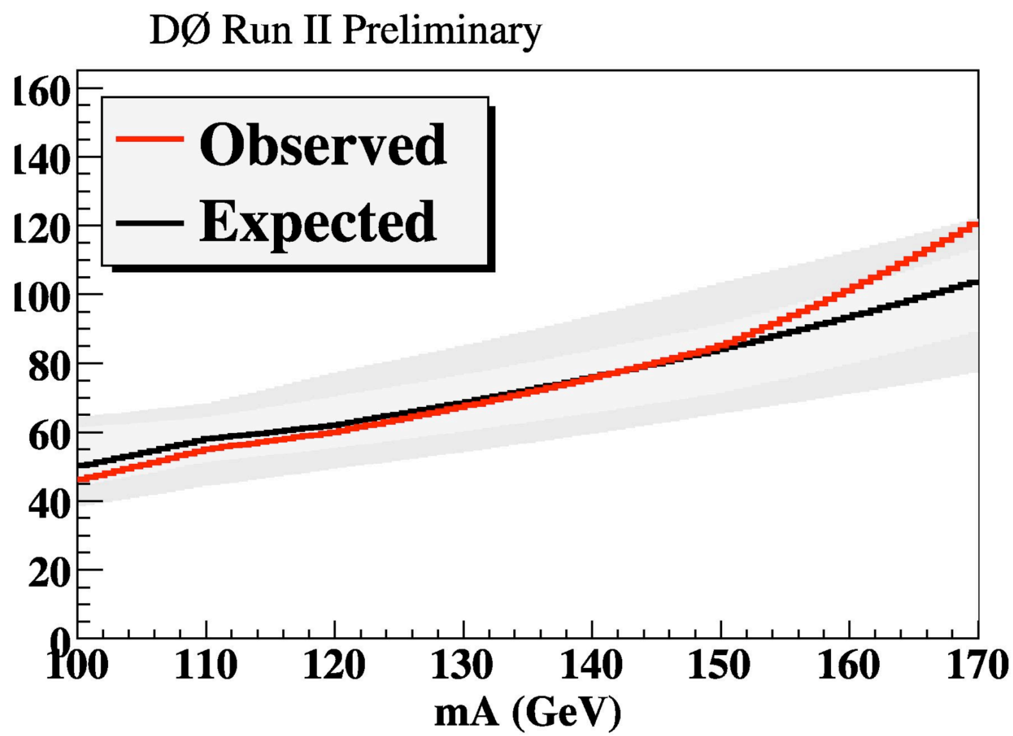




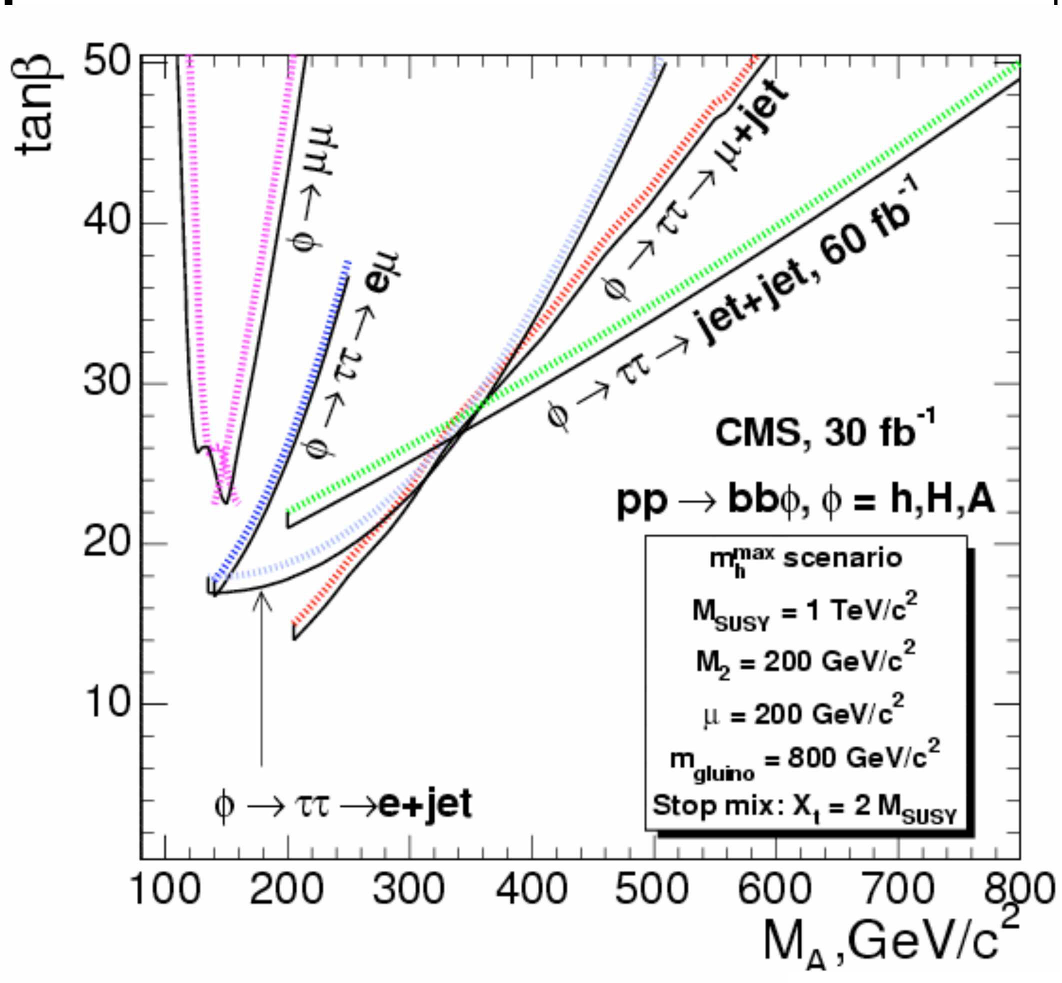
D0 3b-jet Analysis

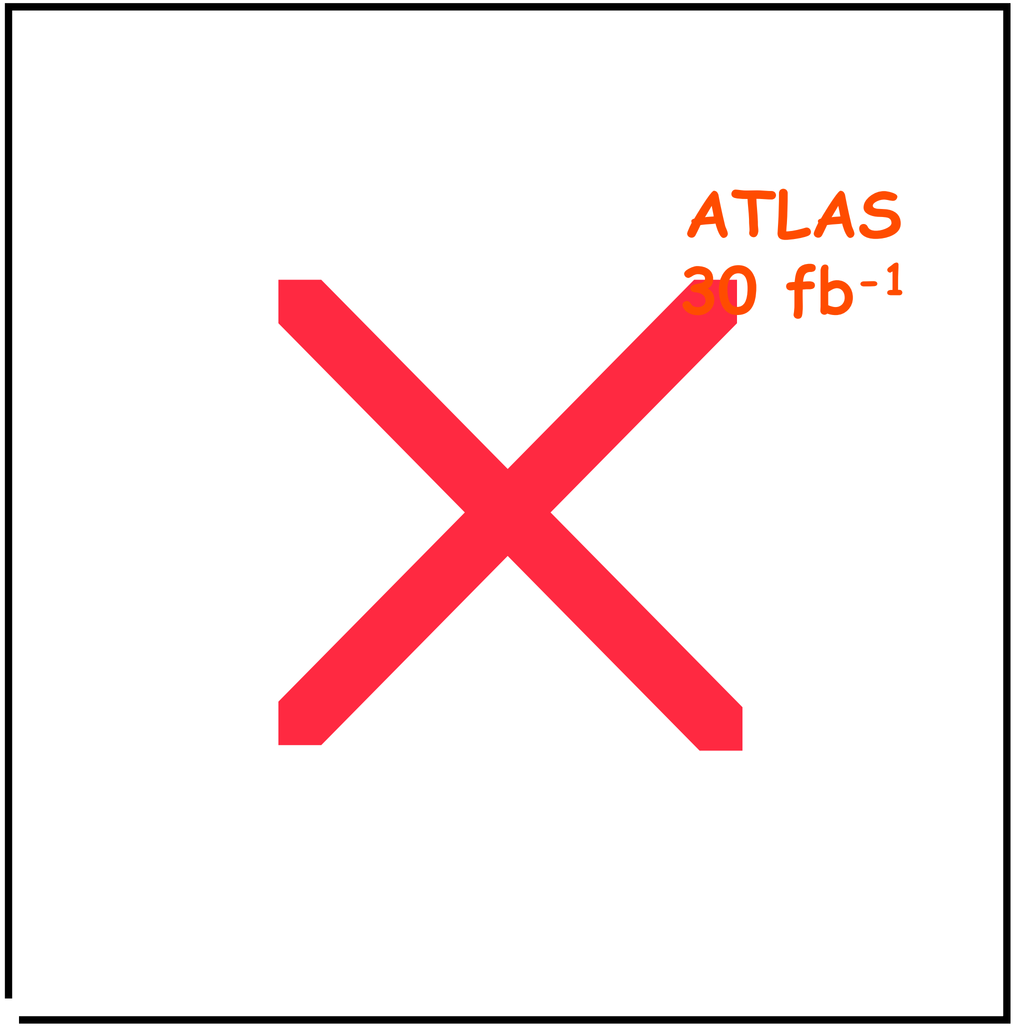






LHC Discovery Potential





Outlook and Conclusions

- The search for a Higgs boson is a priority of CMS and ATLAS. One experiment should be able to observe a SM Higgs with O(10) fb^{-1} and also cover most of the MSSM plane
- Higgs searches at the LHC comprise a large number of final states involving all the signatures that the CMS and ATLAS detectors can reconstruct
  - Electrons, muons, photons, τ, jets, b-jets
  - Need to understand V,VV, (V=Z,W), tt, $\gamma\gamma$, jγ and their production in association with jets
- Higgs searches at the LHC promise is a rich program that promises to turn the LHC era into fascinating times for High Energy Physics