Higgs Searches with the ATLAS Experiment at the LHC

Bruce Mellado

University of Wisconsin-Madison

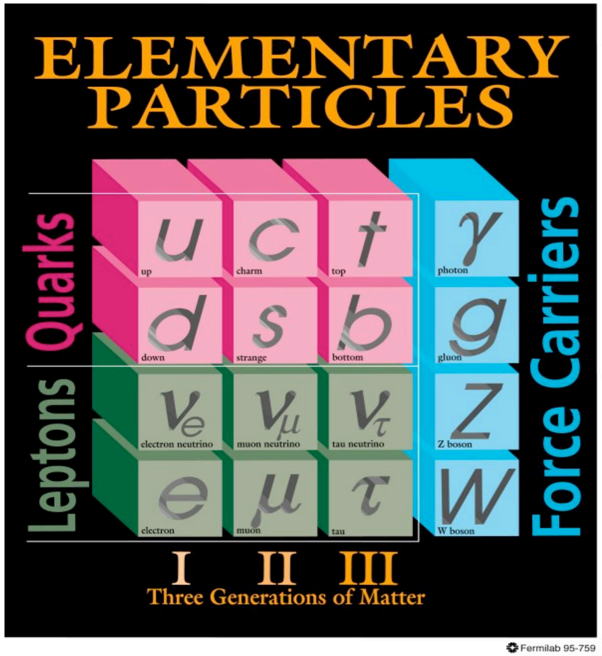
HEP Seminar, PSI 11/11/08

Outline

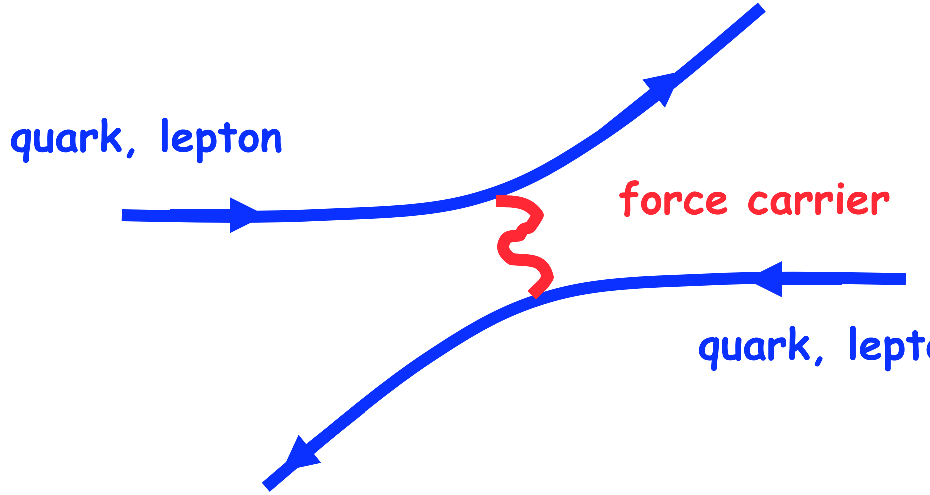
- Introduction
- Most relevant observation channels (SM)
  - $H \to \gamma\gamma$
  - $H \to \tau\tau$
  - $H \to ZZ^{(*)} \to 4l$
  - $H \to WW^{(*)} \to ll\nu\nu$
- MSSM Higgs
  - What can the Tevatron tell us?
  - Feasibility of searches

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



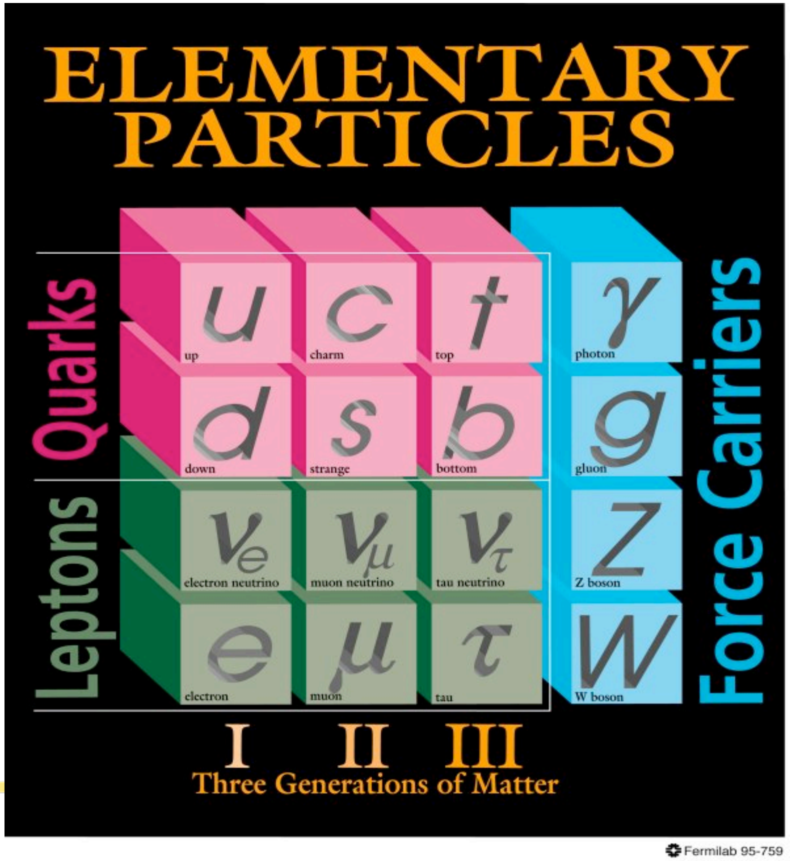
Force	Carrier
Strong	Gluons (g)
Electro-Weak	Electro-weak bosons (γ,W,Z)
Gravitation	?

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

What is the origin of the particle masses?

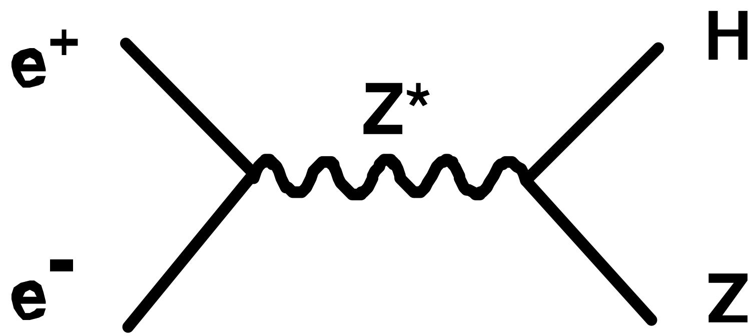
Why some particles are heavier than others?

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)

$e^+e^- \longrightarrow H\ Z$

$Z \to q\bar{q}$

$H \to b\bar{b}$

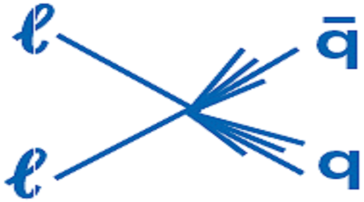
$\approx$54% of Total

$e^+e^- \longrightarrow H\ Z$

$Z \to \nu\bar{\nu}$

$H \to q\bar{q}$

$\approx$15%



$e^+e^- \longrightarrow HZ$

$Z \to \ell^+\ell^-$

$H \to q\bar{q}, \tau^+\tau^-$

$\approx$5%

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

$e^+e^- \longrightarrow H\ Z$

$Z \to \tau^+\tau^-$

$H \to q\bar{q},$

$\approx$ 2.6%

$e^+e^- \longrightarrow H\ Z$

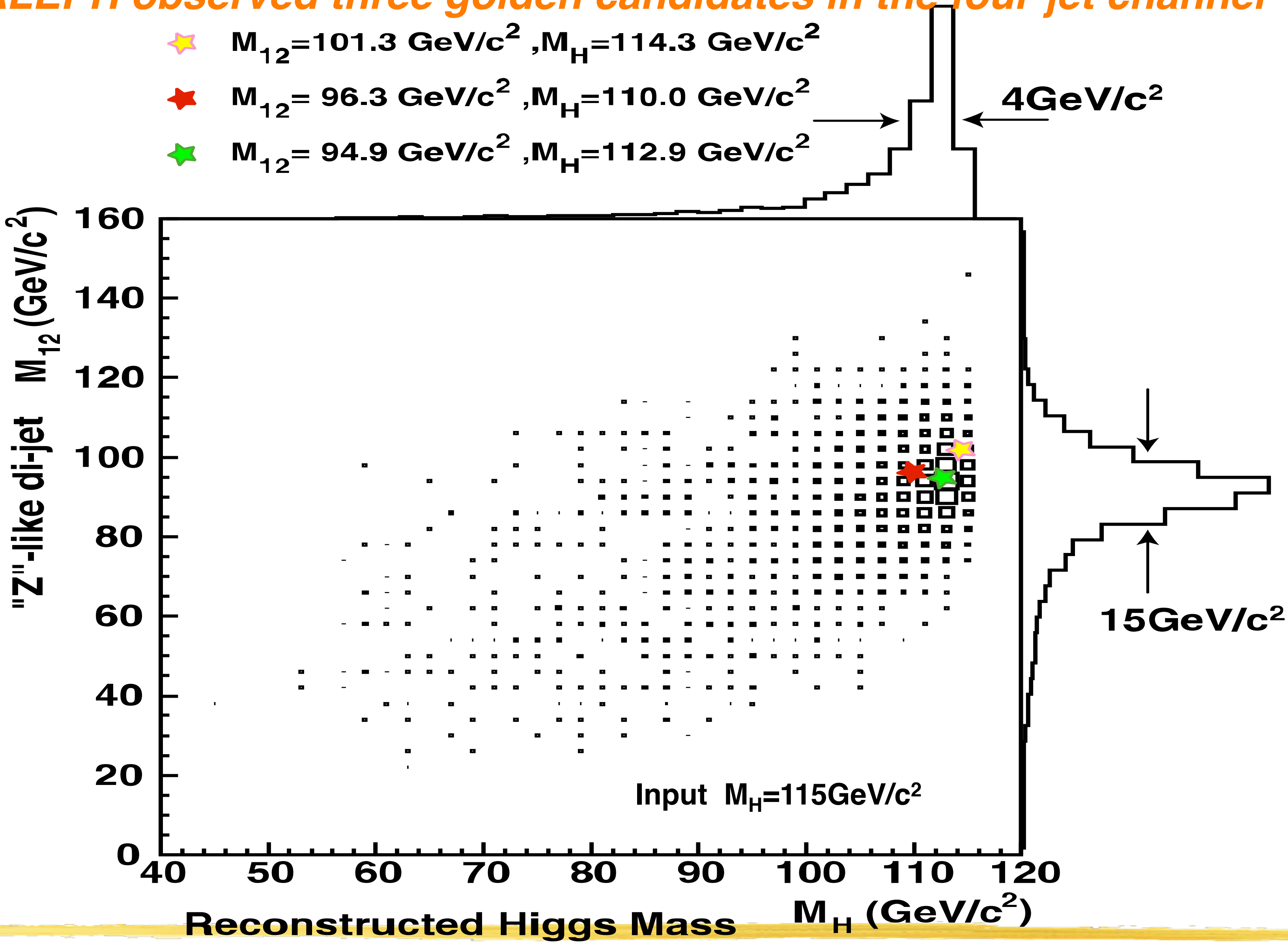
$Z \to q\bar{q}$

$H \to \tau^+\tau^-$

$\approx$ 5%

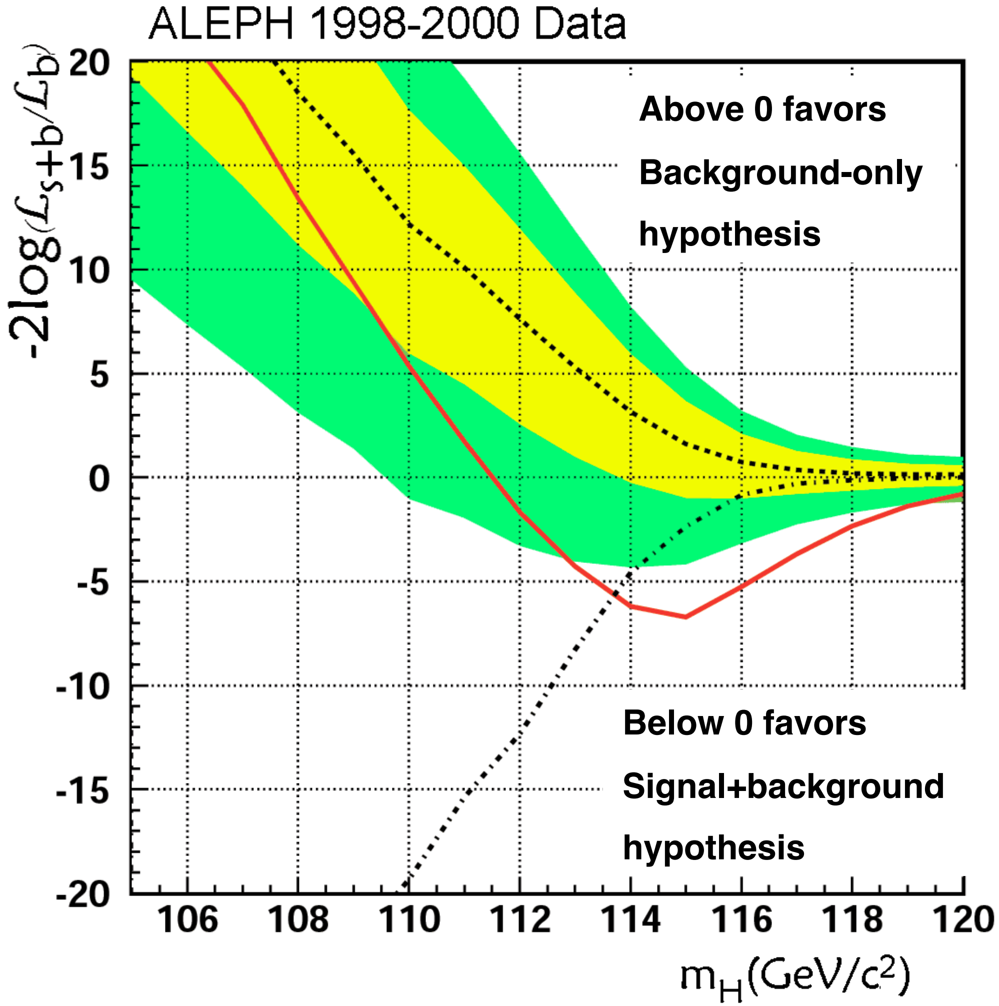
First Possible Hint for a Higgs boson (2000)

ALEPH observed three golden candidates in the four-jet channel

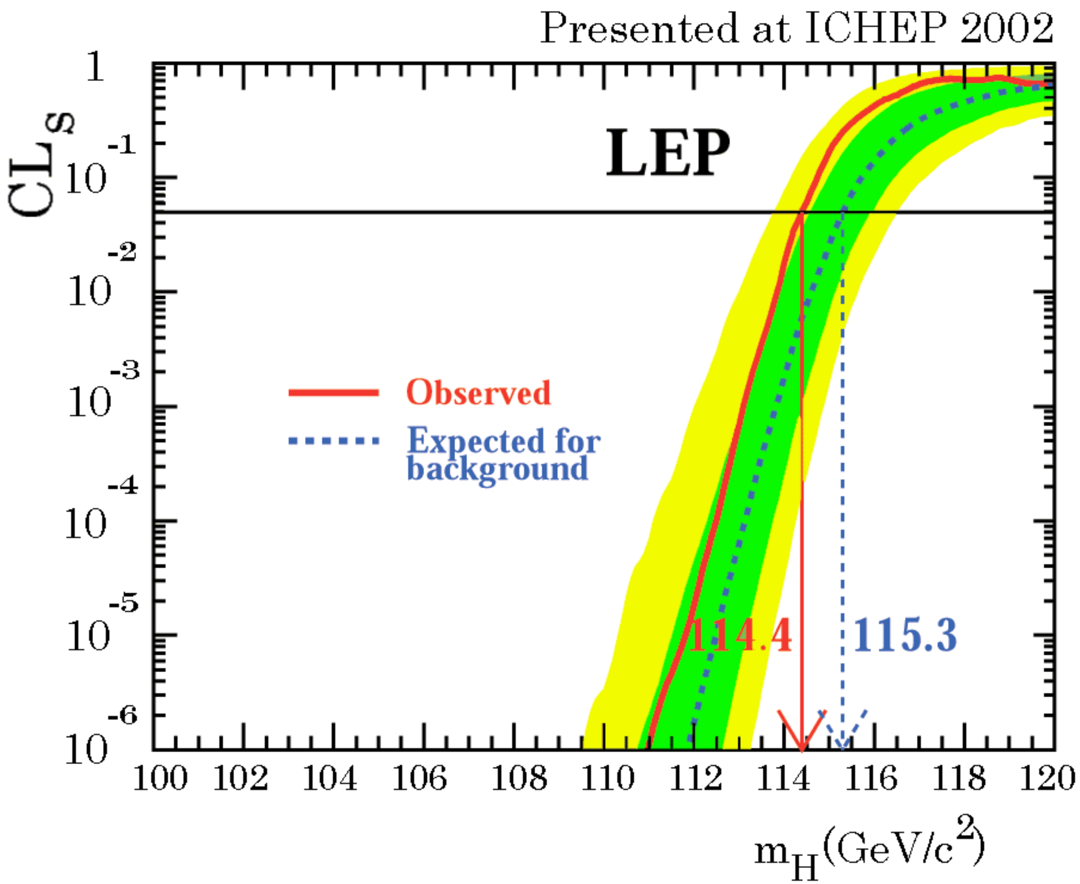


The LEP Limit

ALEPH observed an excess over background-only prediction with significance of 2.8σ at 115 GeV/c²



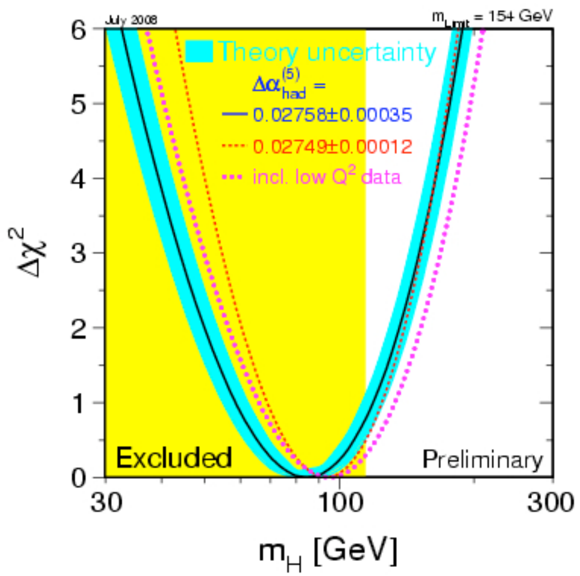
Overall significance of LEP experiments ~1.8 σ → limit setting M_H>114.4

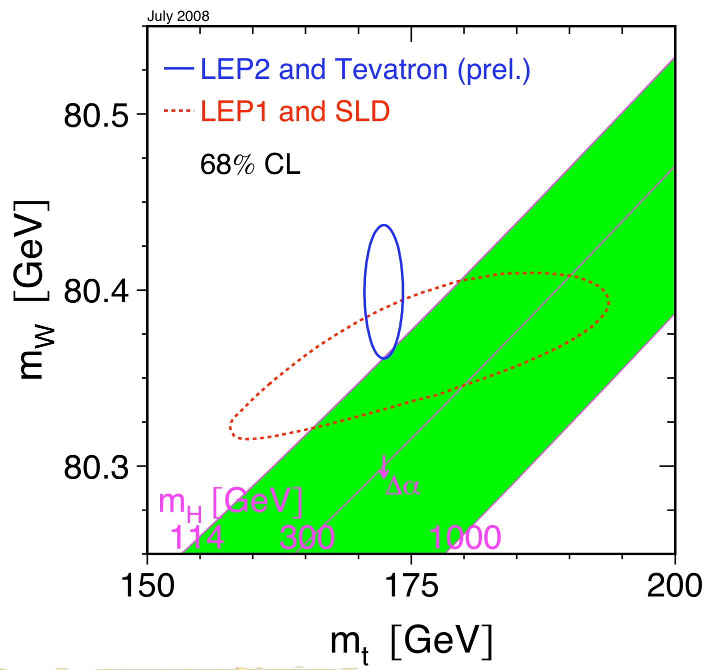


Electro-Weak Fits

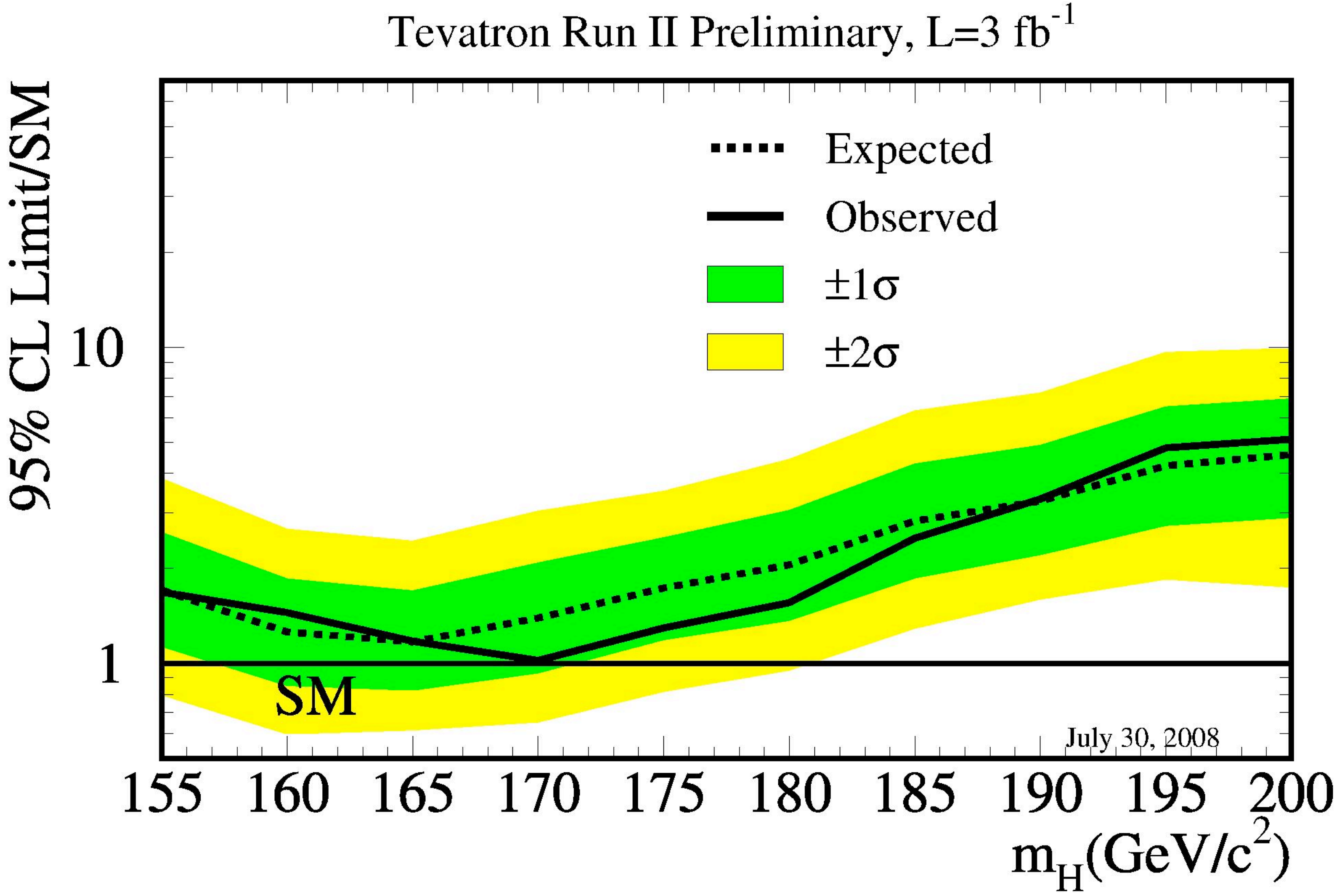
Experimental constraints so far:

- Indirect measurements from fitting the EW data using new world average for M_{top}=172.4±1.2 GeV and M_w=80.399±0.025 GeV:
  - $m_H = 84^{+34}_{-26}$ GeV — **Data prefers low mass Higgs**
  - m_H<154 GeV @ 95%CL (including LEP exclusion m_H<185 GeV)

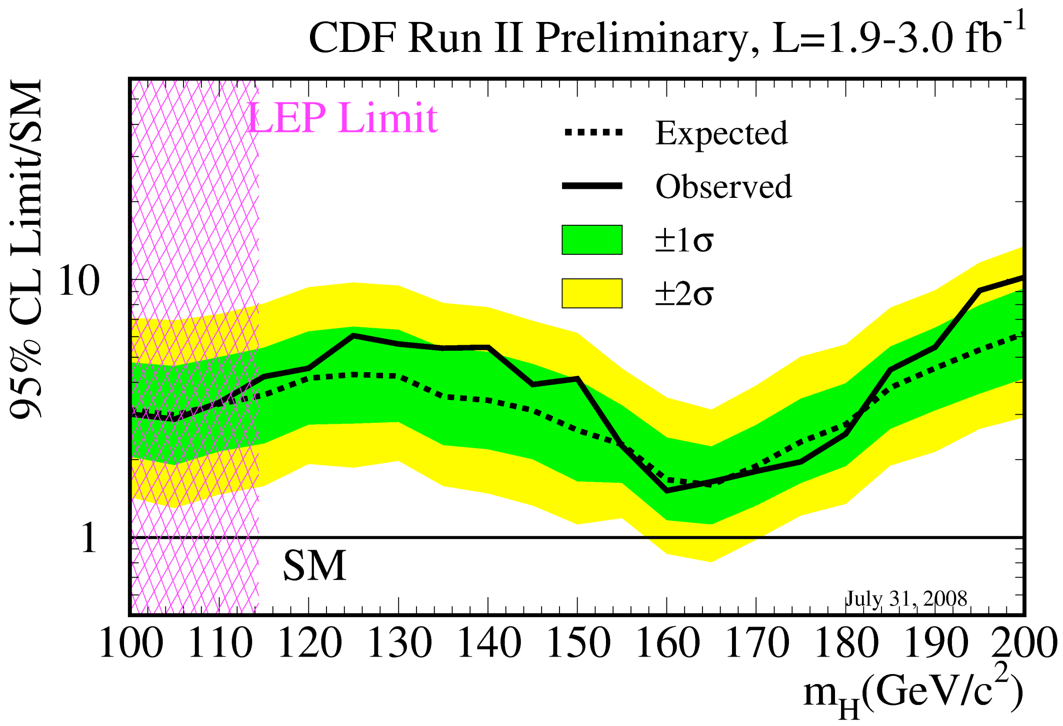


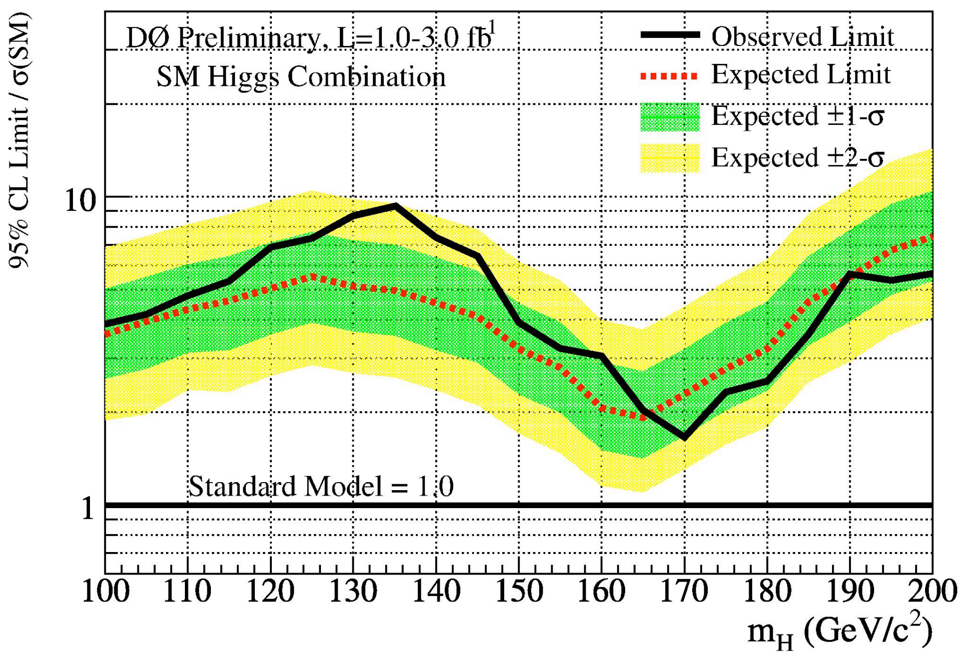


Present Tevatron Exclusion Limit



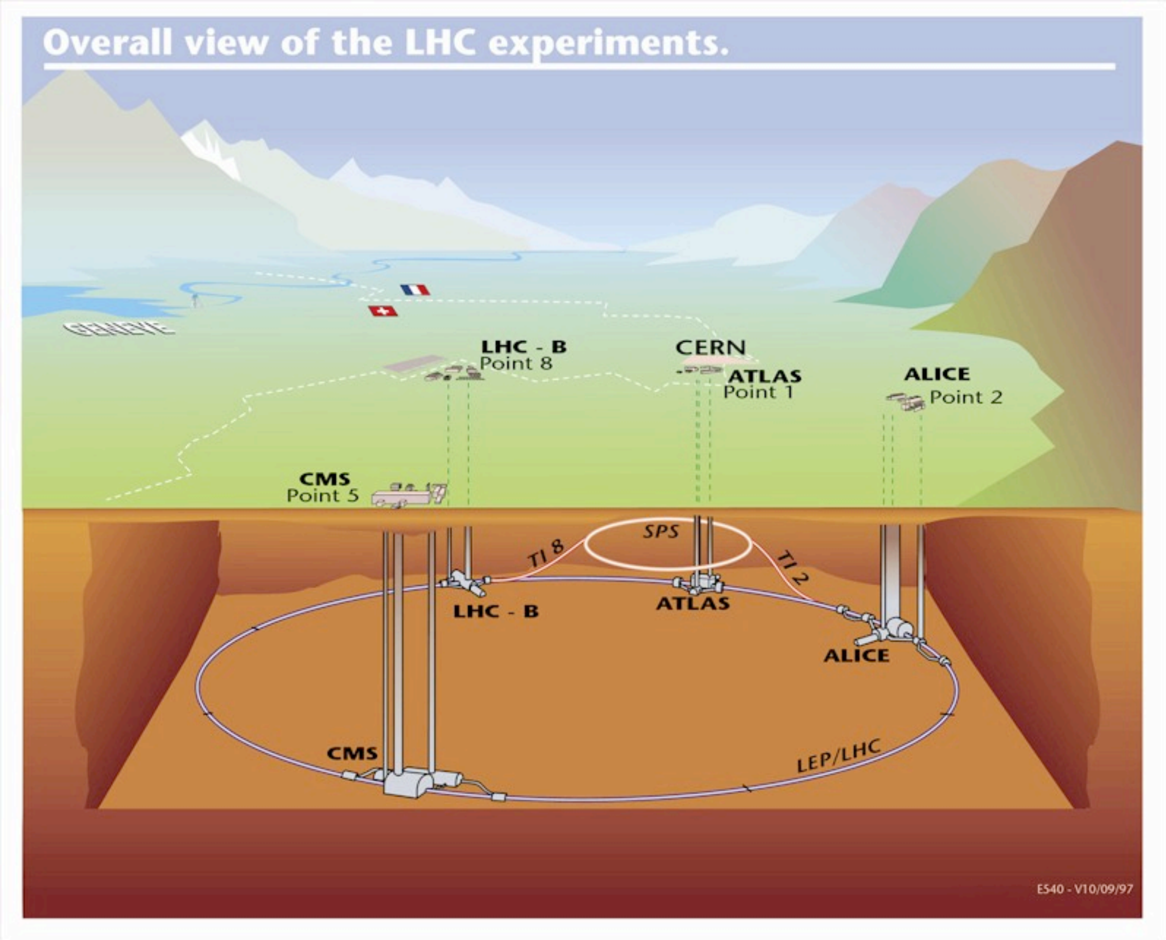
Present Tevatron Exclusion Limit

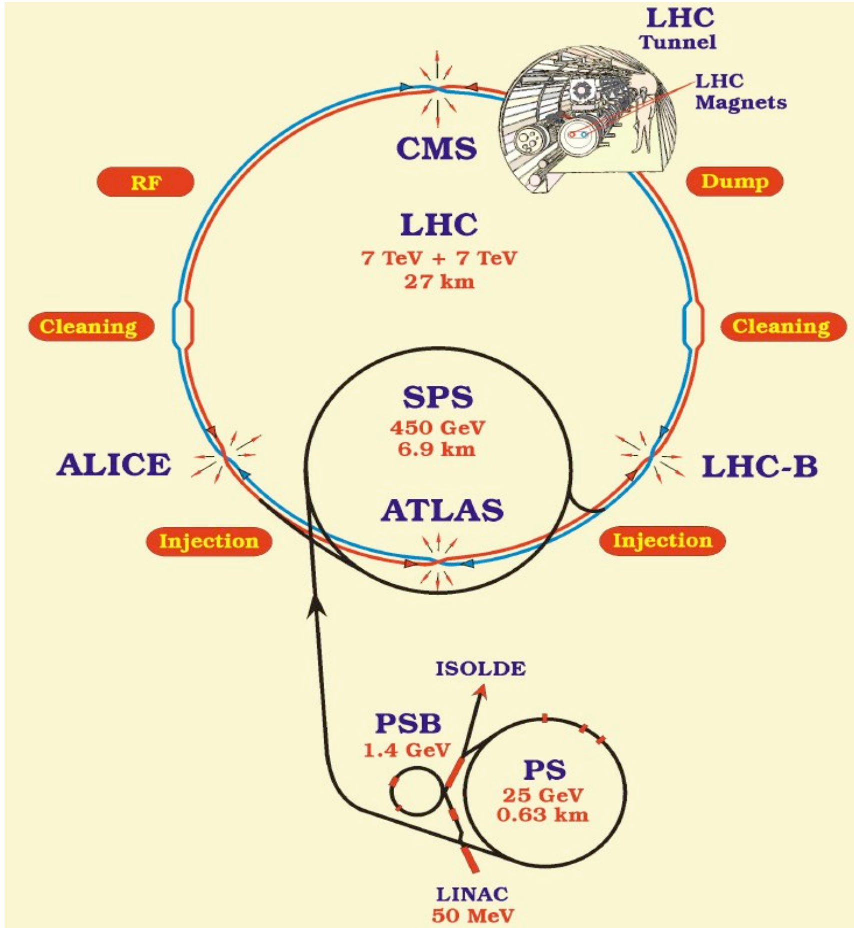




The LHC

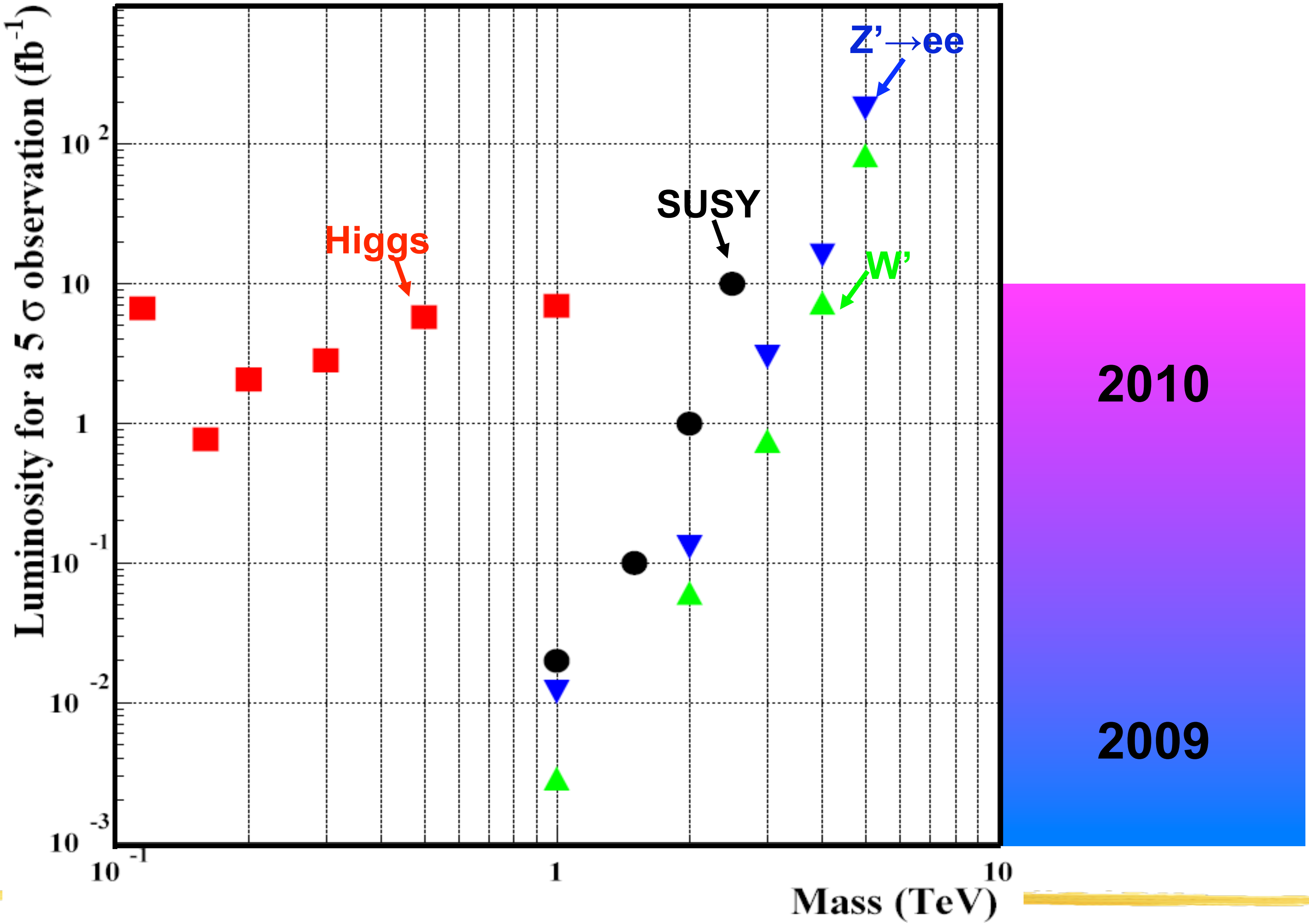
Center of mass E	14 TeV
Design Luminosity	10^{34} cm^{-2} s^{-1}
Luminosity Lifetime	10 h
Bunch spacing	25 ns





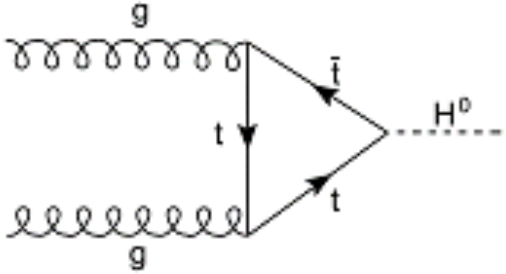
LHC Discovery Reach

Approximate discovery reach for one Experiment

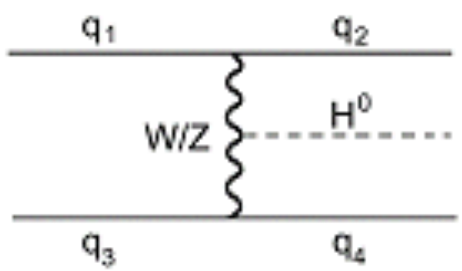


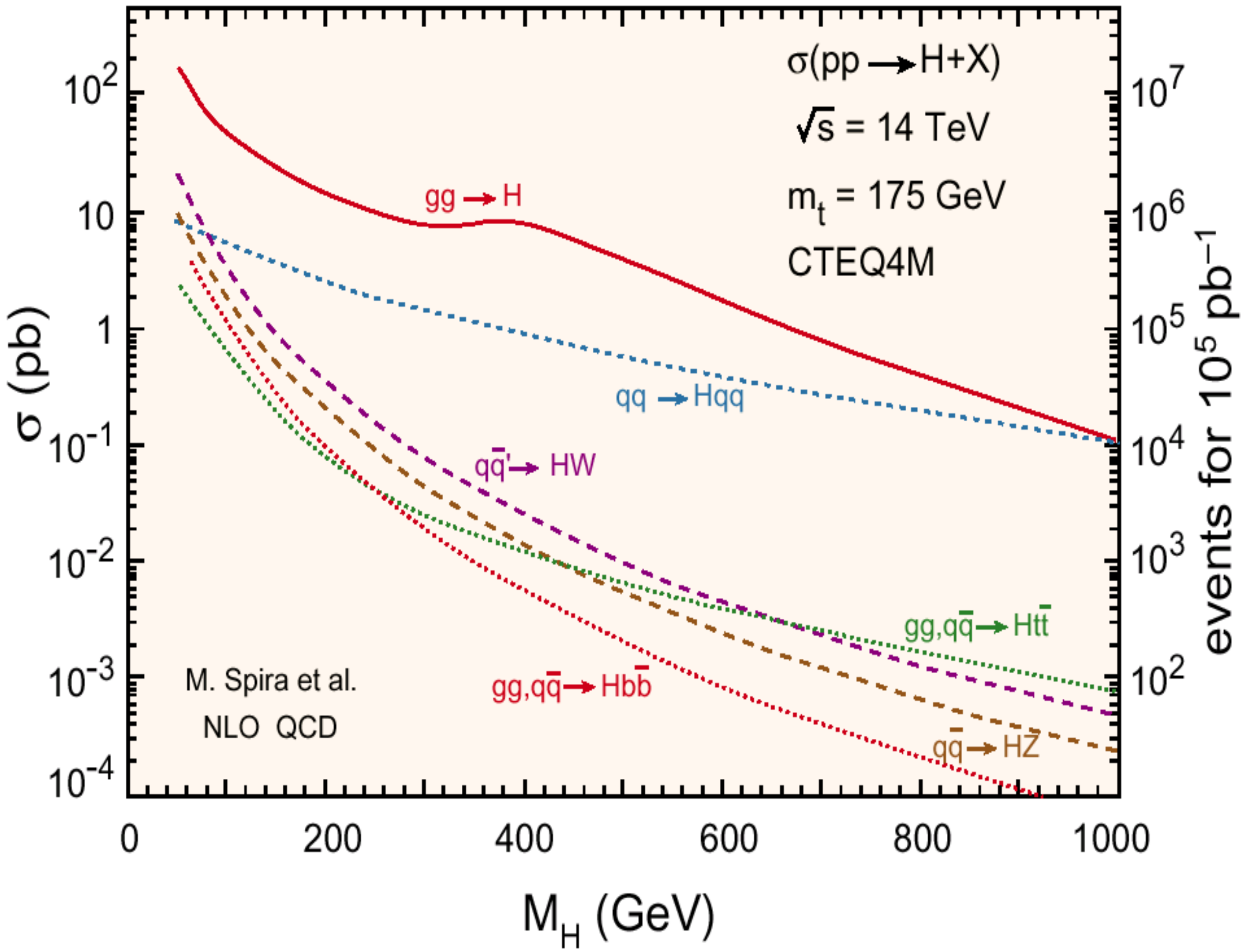
Higgs Production at LHC

Leading Process (gg fusion)

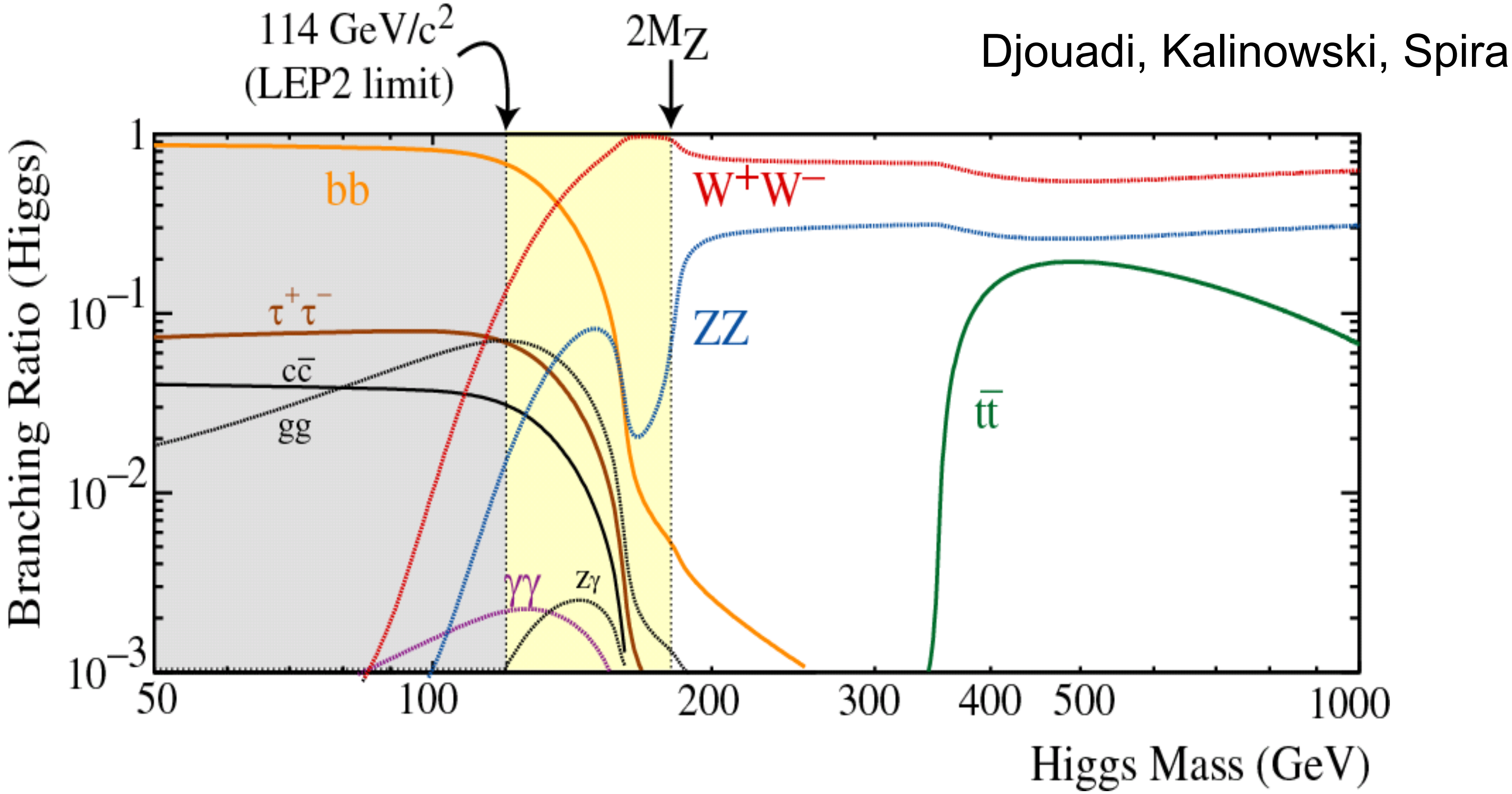


Sub-leading Process (VBF)





Main Decay Modes

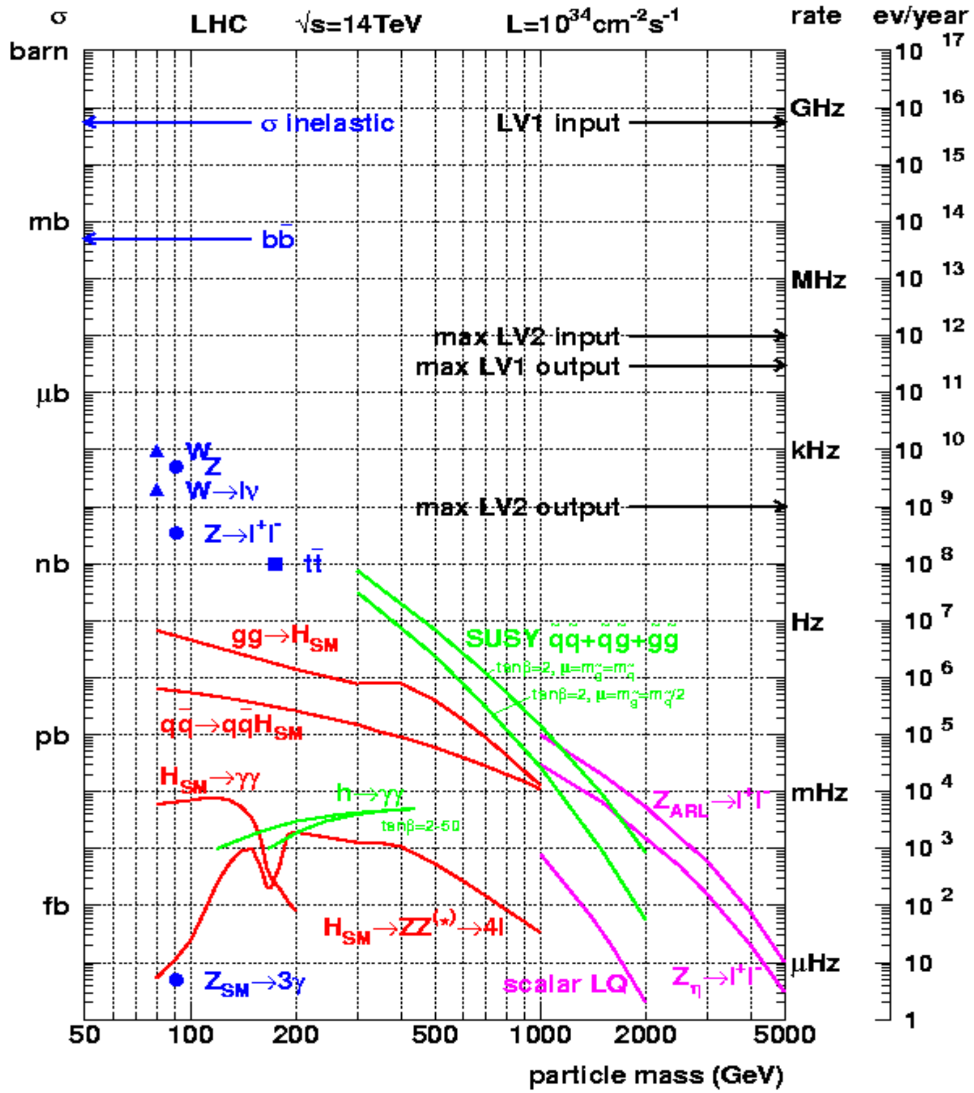


Close to LEP limit:
$H \rightarrow \gamma\gamma, \tau\tau, bb$

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

Cross-sections at LHC

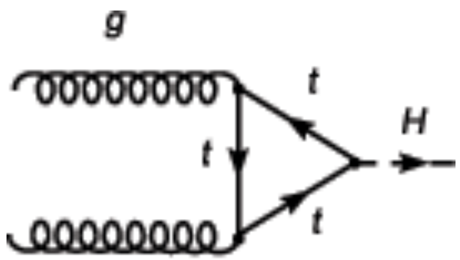
- Search for Higgs and new physics hindered by huge background rates
  - Known SM particles produced much more copiously
- This makes low mass Higgs especially challenging
  - Narrow resonances
  - Complex signatures
    - Higgs in association with tops and jets.

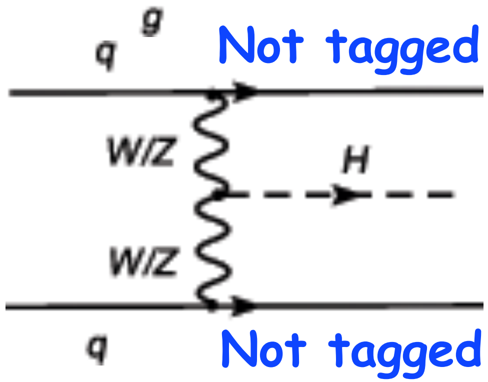


Low Mass Higgs Associated with Jets

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

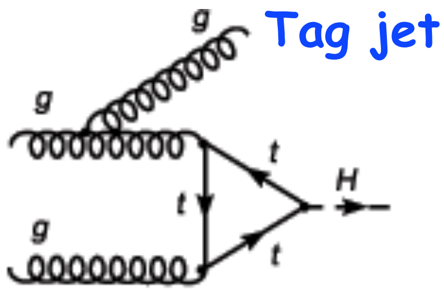
Inclusive

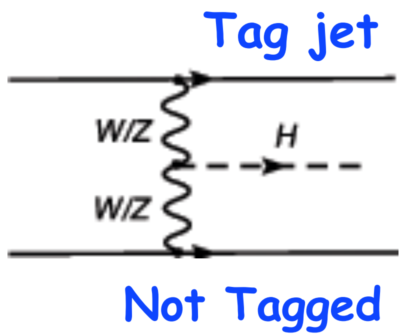




Analyses in TDR were mostly inclusive

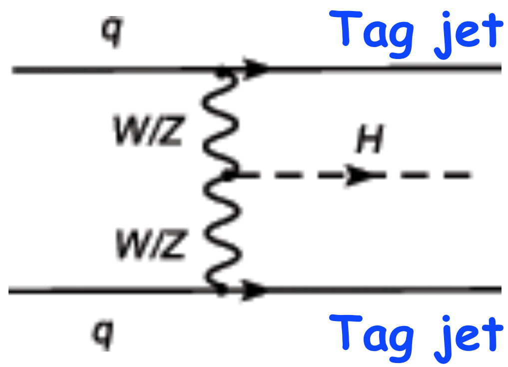
H+1jet

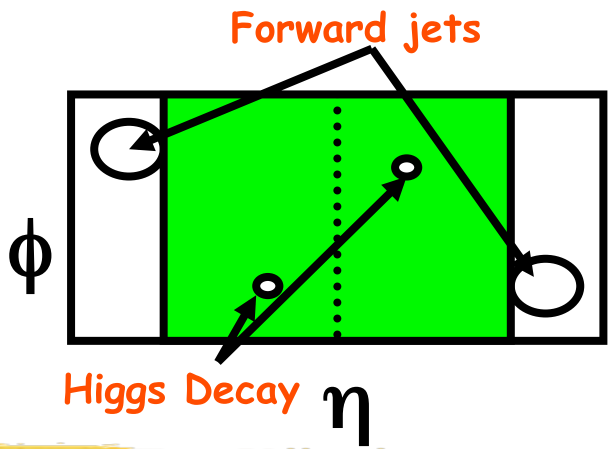




Applied to $H \to \gamma\gamma, \tau\tau, WW^{(*)}$

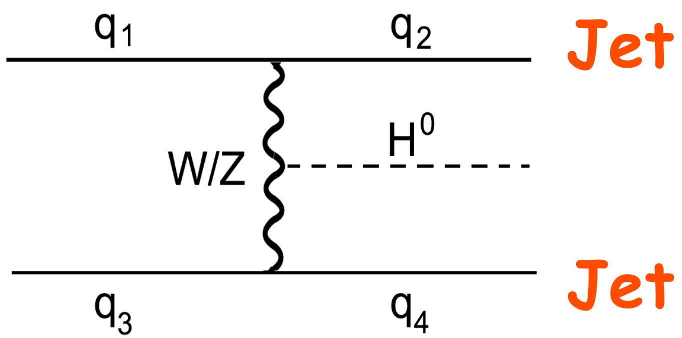
H+2jet





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)

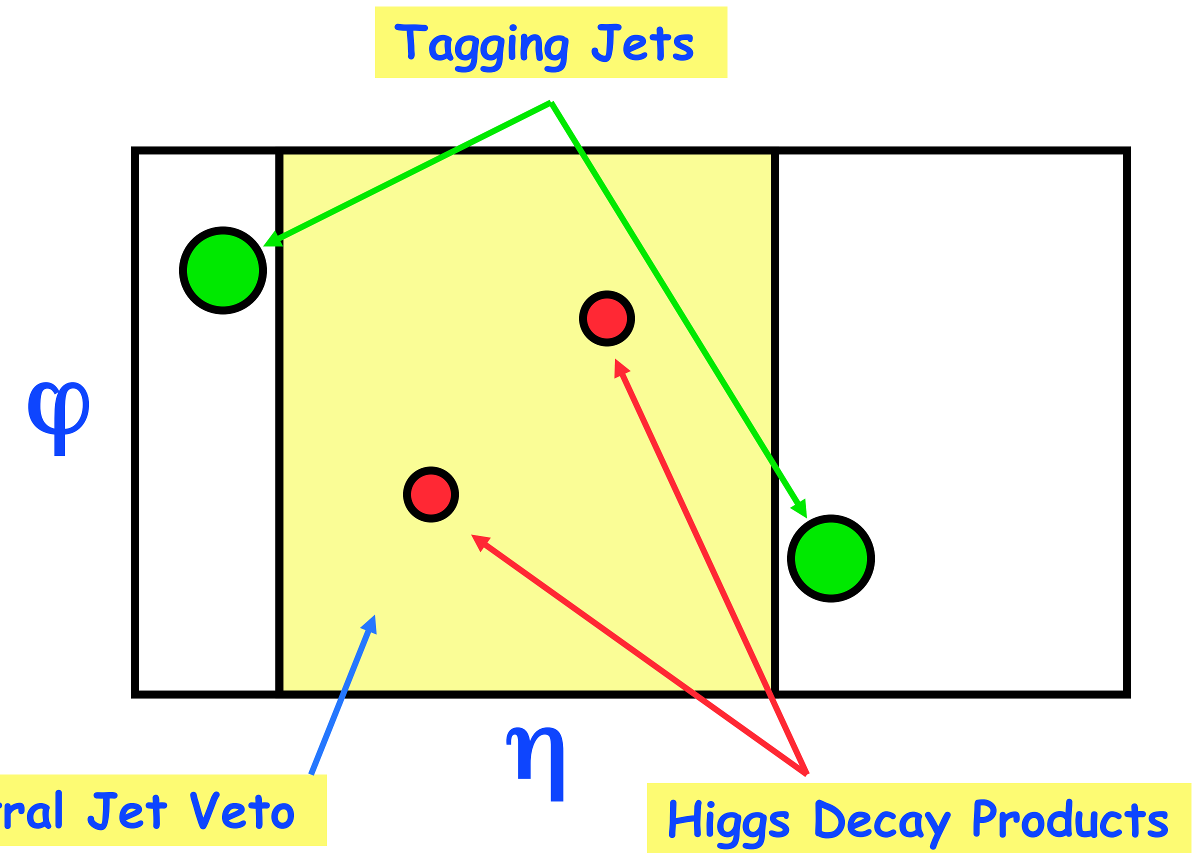


$\eta_{J1} \cdot \eta_{J2} < 0$

$\Delta\eta_{JJ} > 3.5 \div 4$

$M_{JJ} > 500 \div 700\text{GeV}$

c.j.v.



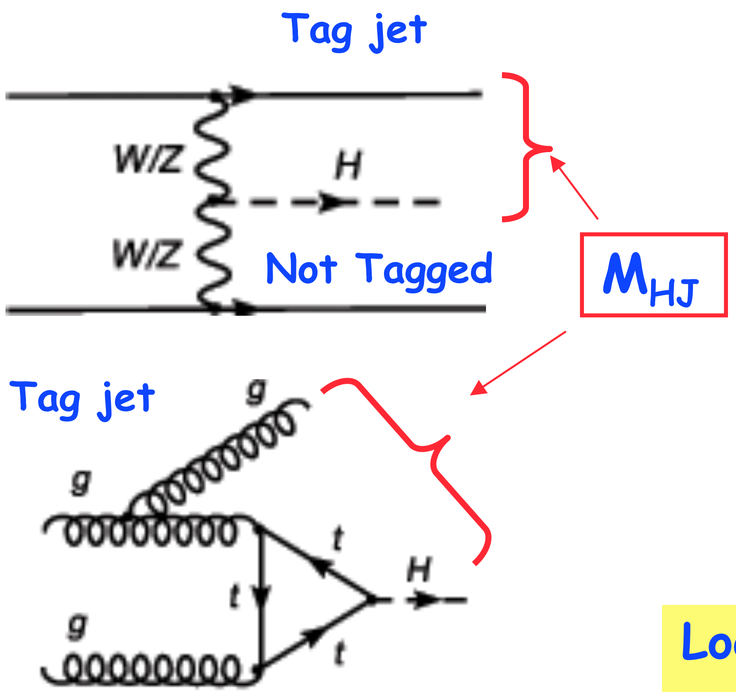
SM Higgs + ≥1jet at the LHC

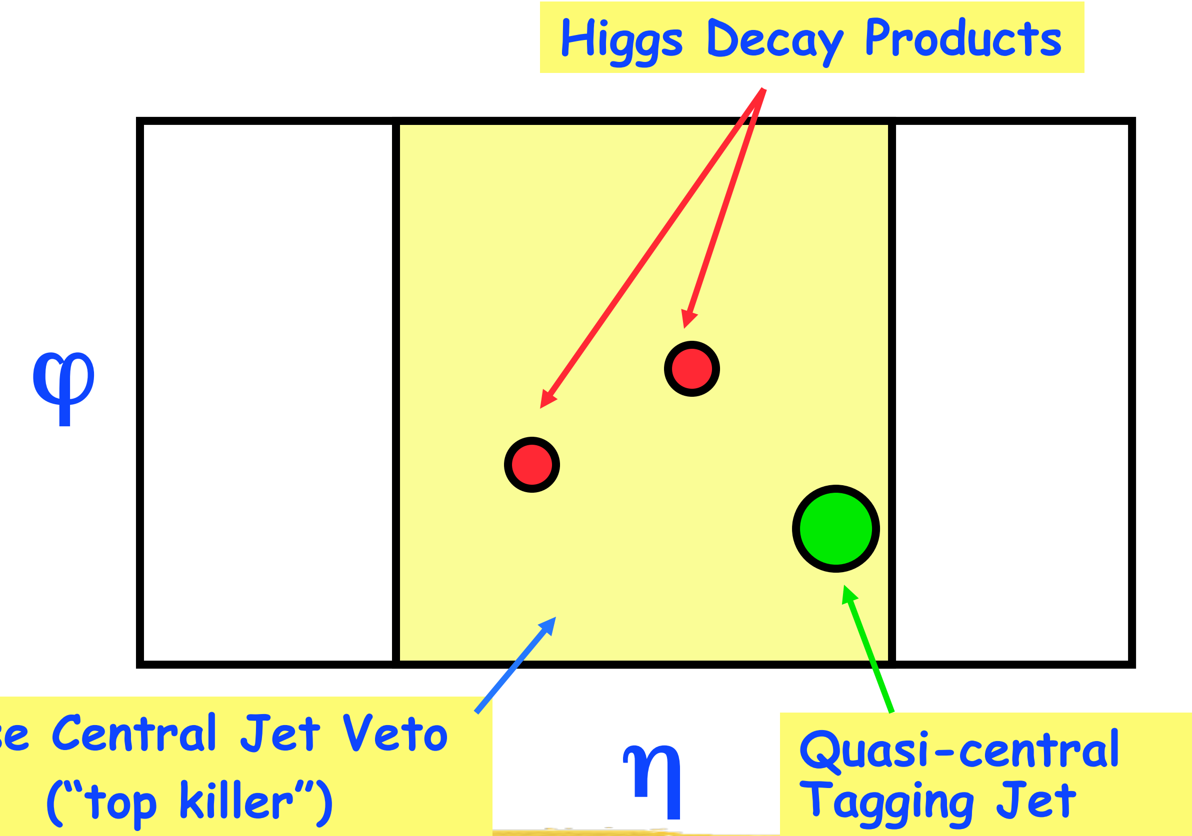
1. Large invariant mass of leading jet and Higgs candidate
2. Large P_T of Higgs candidate
3. Leading jet is more forward than in QCD background

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

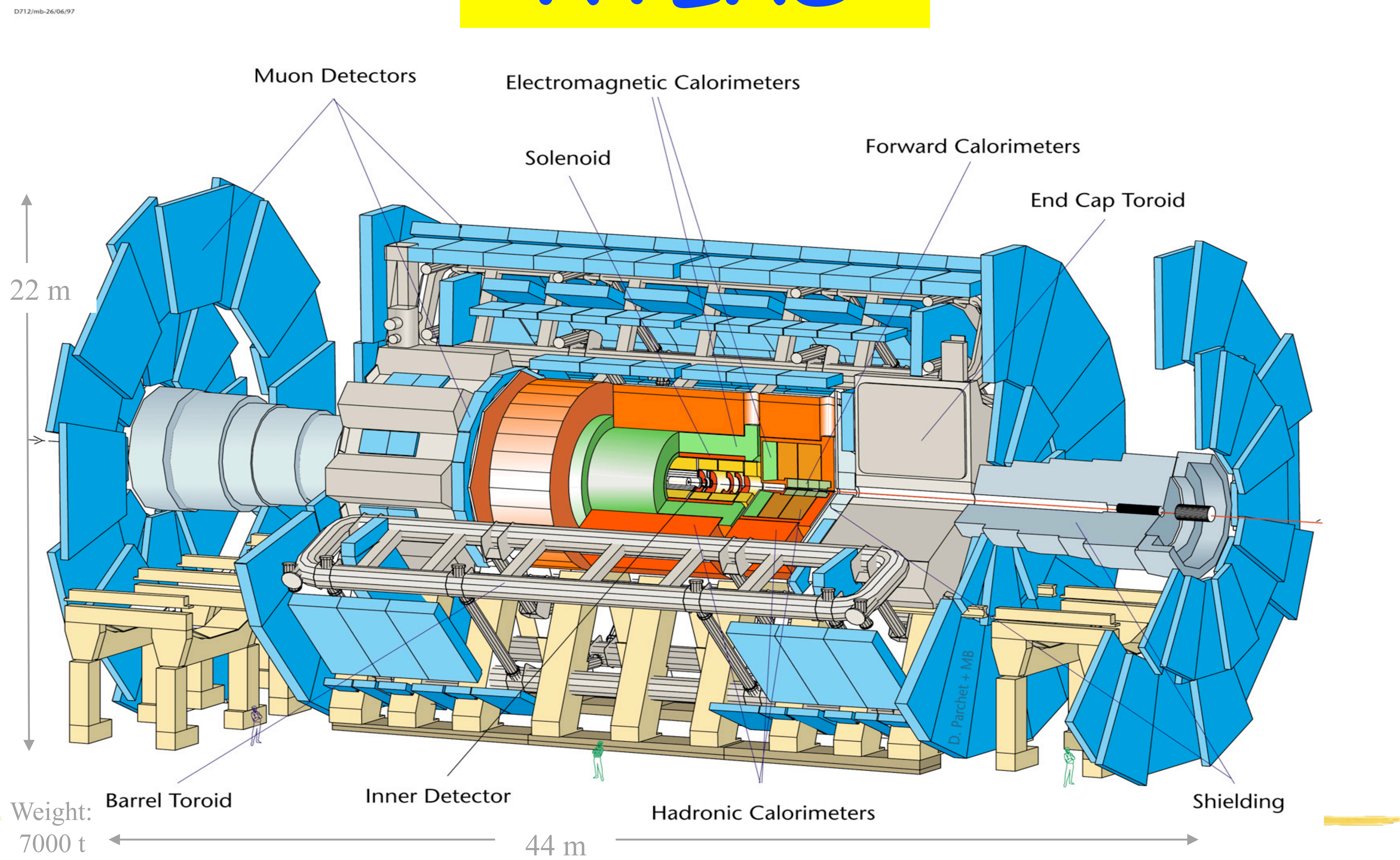
B.Mellado, W.Quayle and Sau Lan Wu Phys.Lett.B611:60-65,2005 for $H\rightarrow\tau\tau$

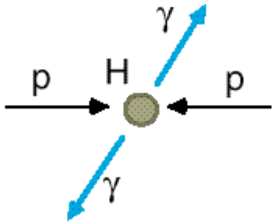
B.Mellado, W.Quayle and Sau lan Wu Phys.Rev.D76:093007,2007 for $H\rightarrow WW^{(*)}$



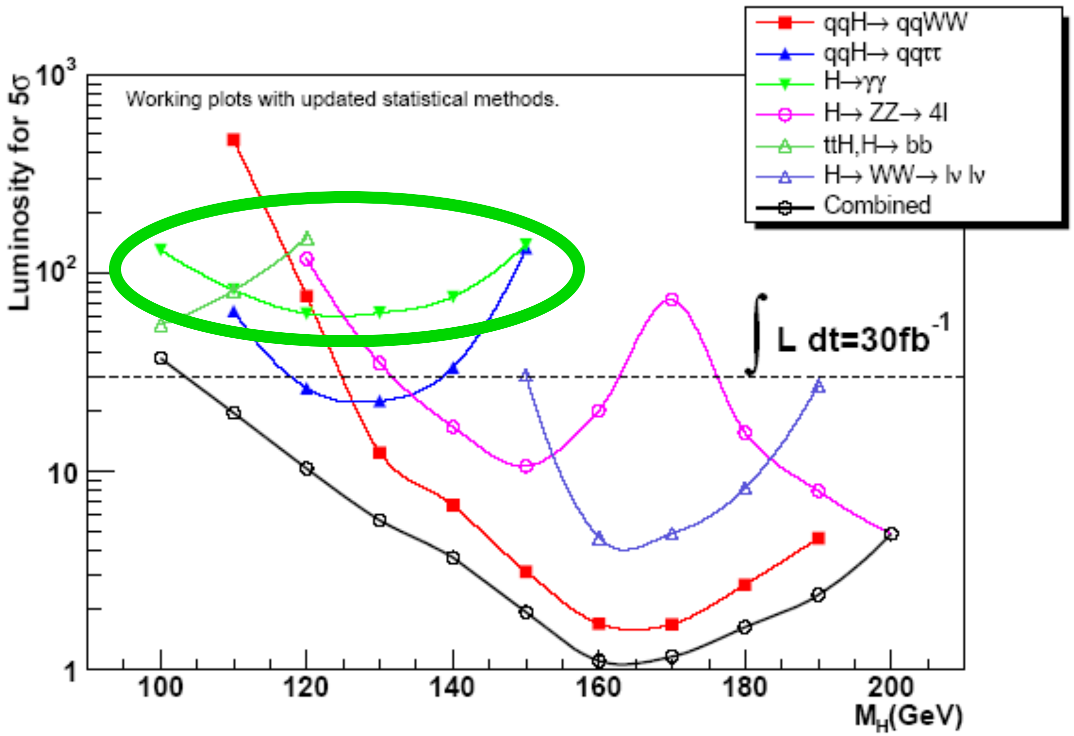


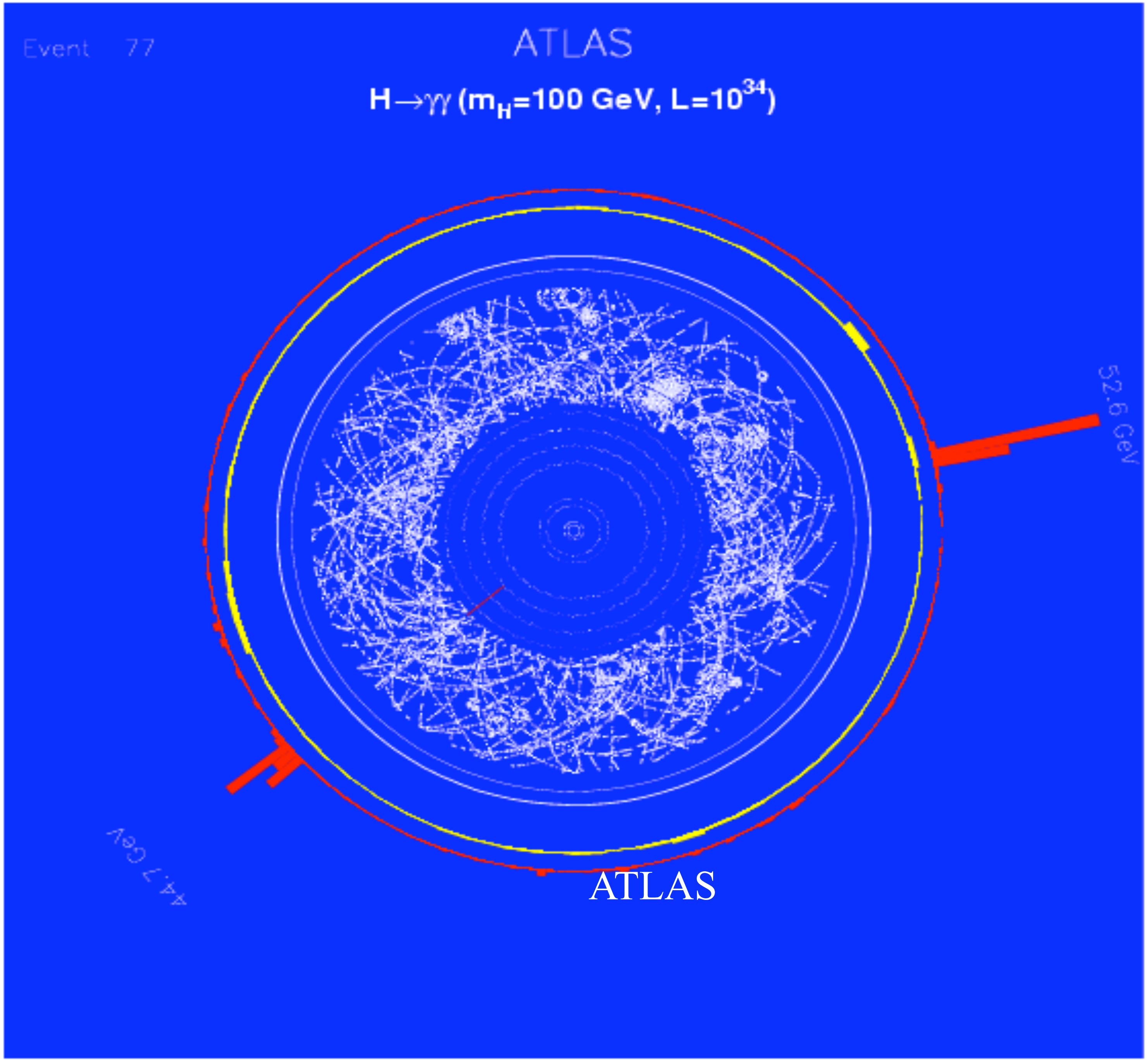
ATLAS


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

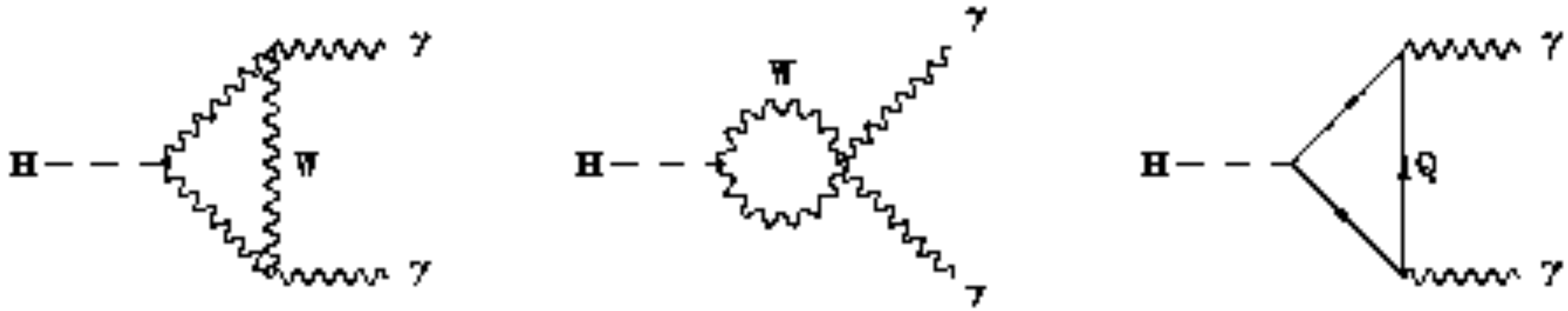


Low Mass SM Higgs: H→γγ

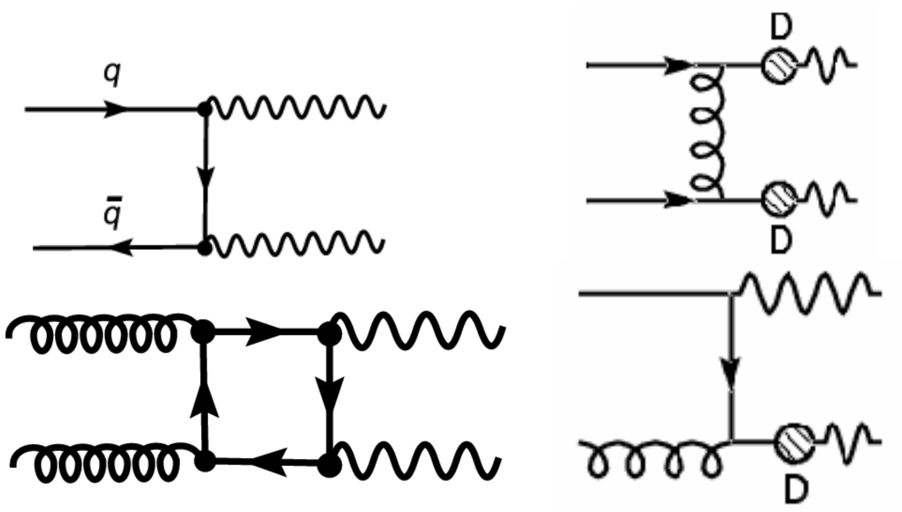



Event 77
ATLAS
H→γγ (m$_H$=100 GeV, L=10^{34})
52.6 GeV
44.7 GeV
ATLAS

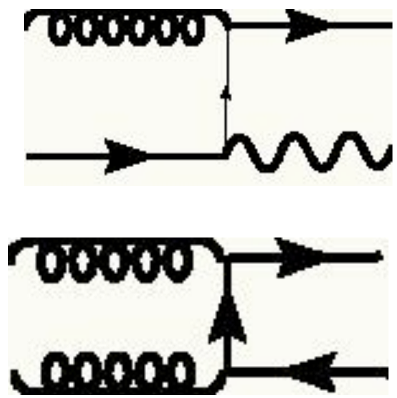
Higgs decay to $\gamma\gamma$



$\gamma\gamma$ Backgrounds

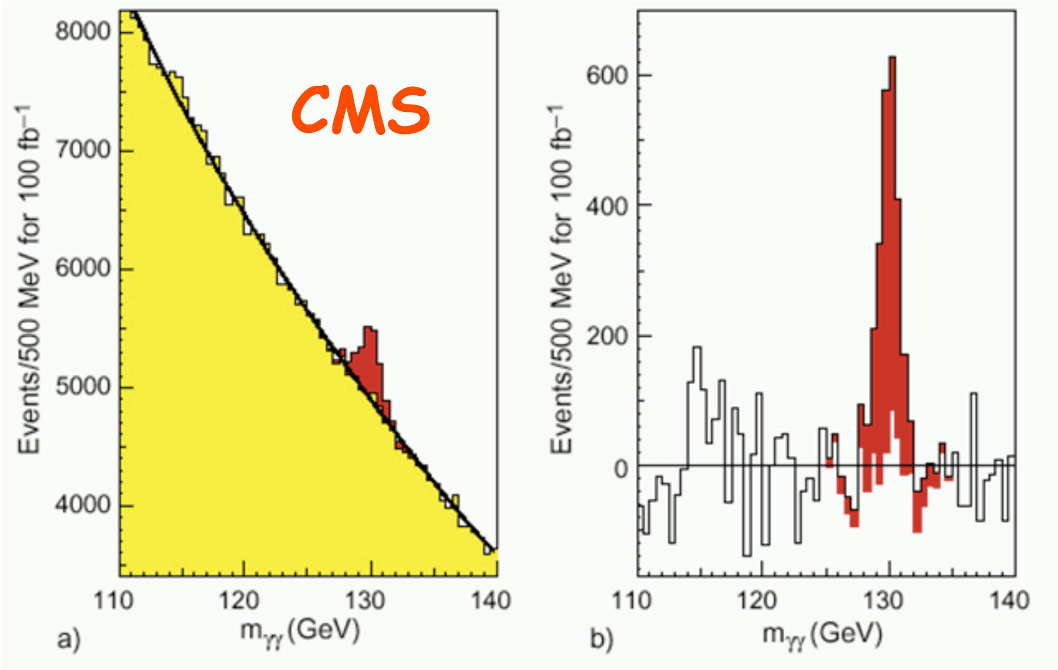


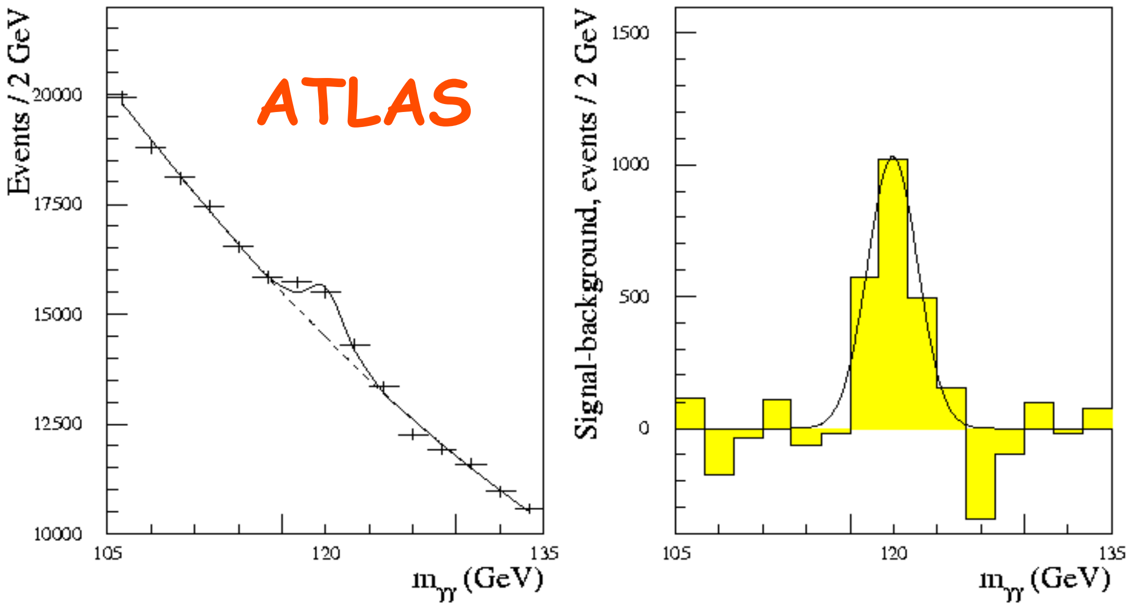
Reducible γj and jj Backgrounds



$q \rightarrow \pi^0$

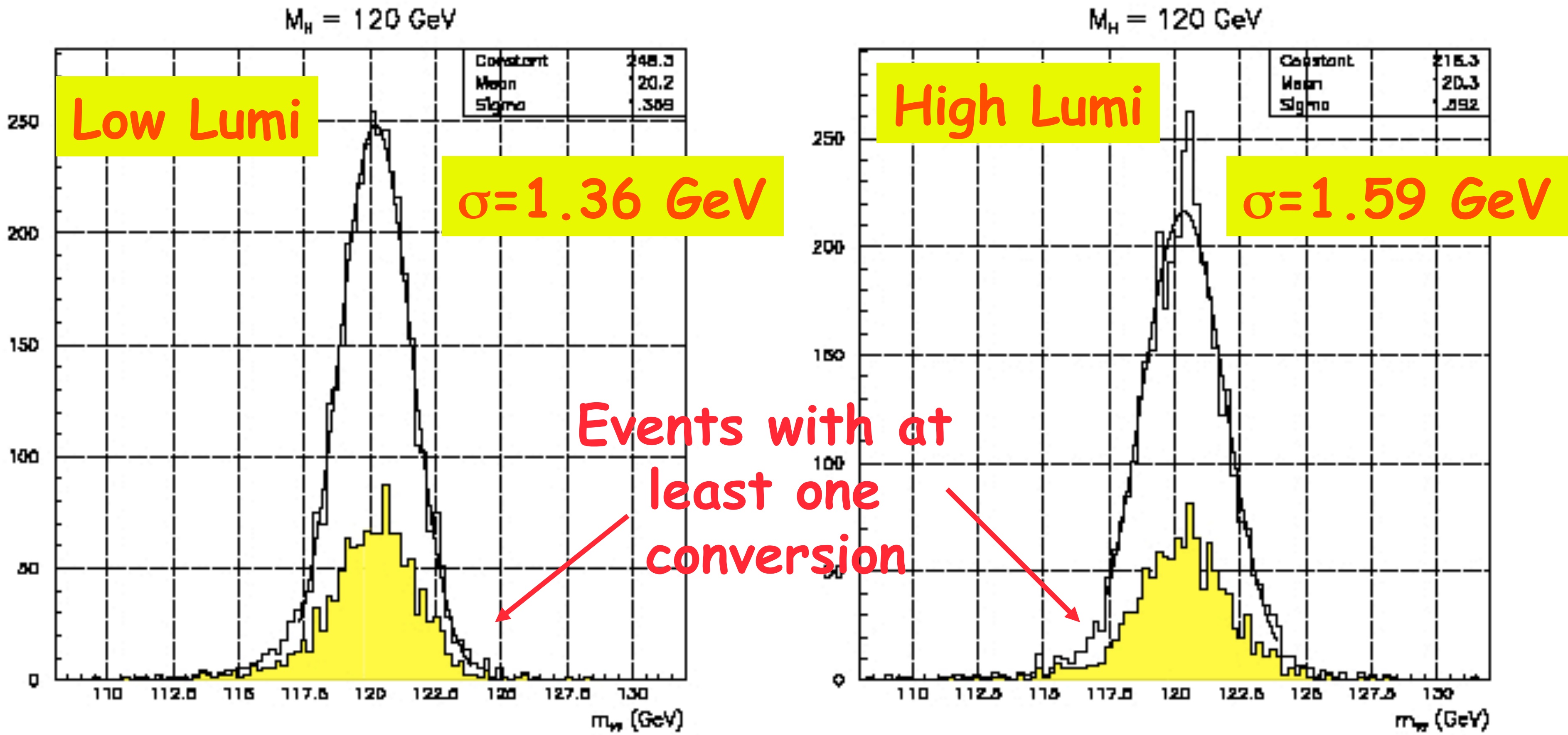
CMS and ATLAS analyses for 100 fb^{-1}





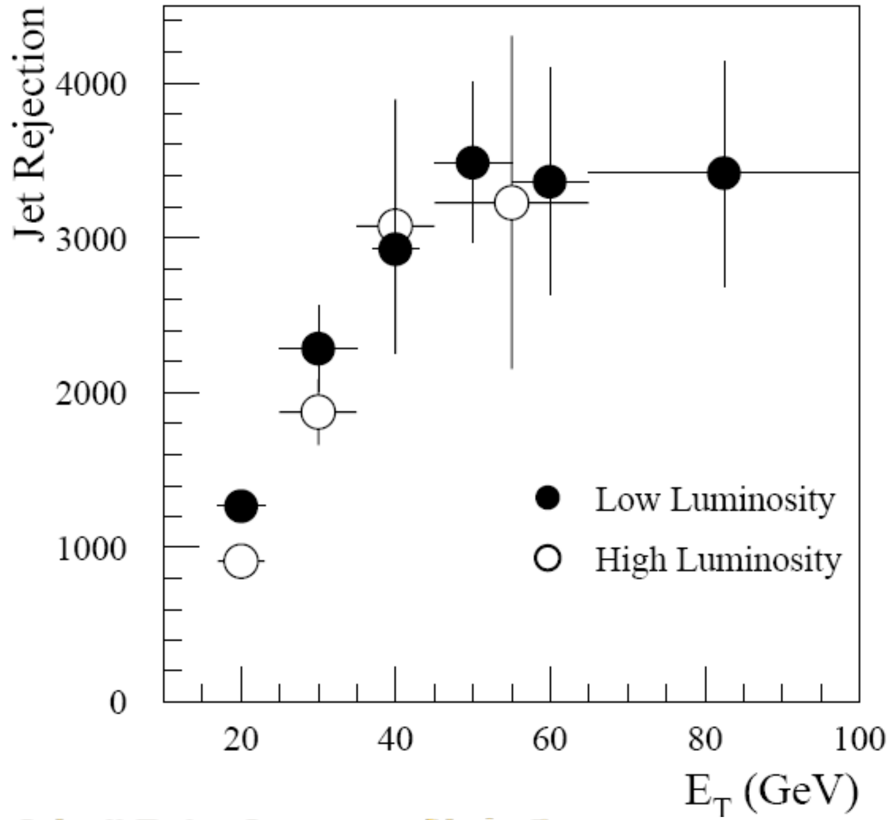
Higgs Mass Reconstruction

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



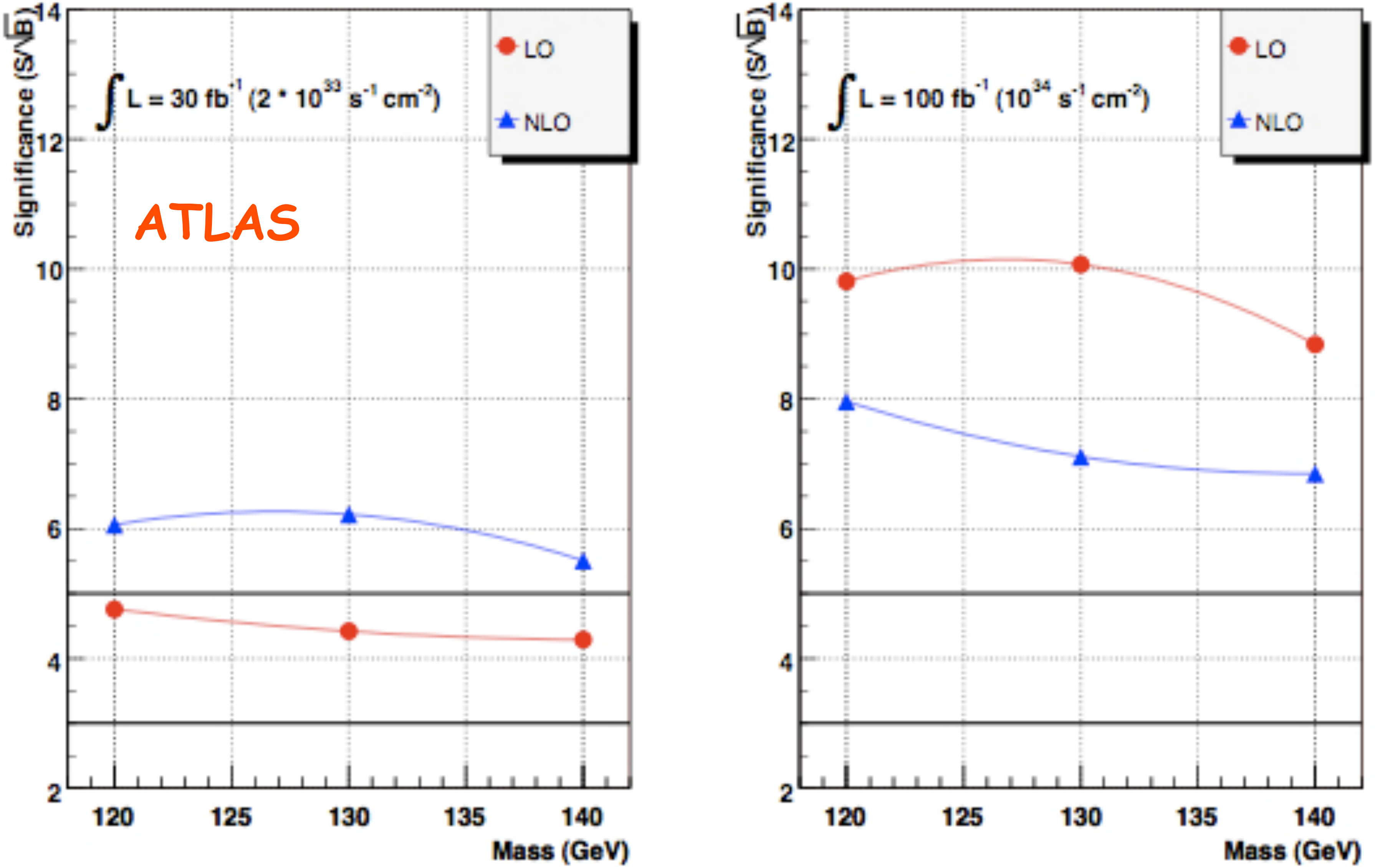
Photon Identification

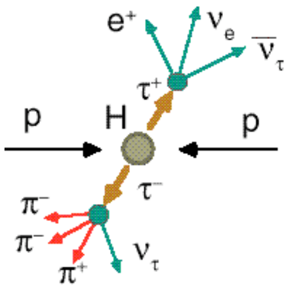
- To separate jets from photons is crucial for Higgs discovery
  - Need rejection of > 1000 against quark-initiated jets for ε_γ=80% to keep fake background about 20% of total background
  - Expect rejection against gluon-jets to be 4-5 times greater
- Jet rejection will be evaluated with data
  - Look 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



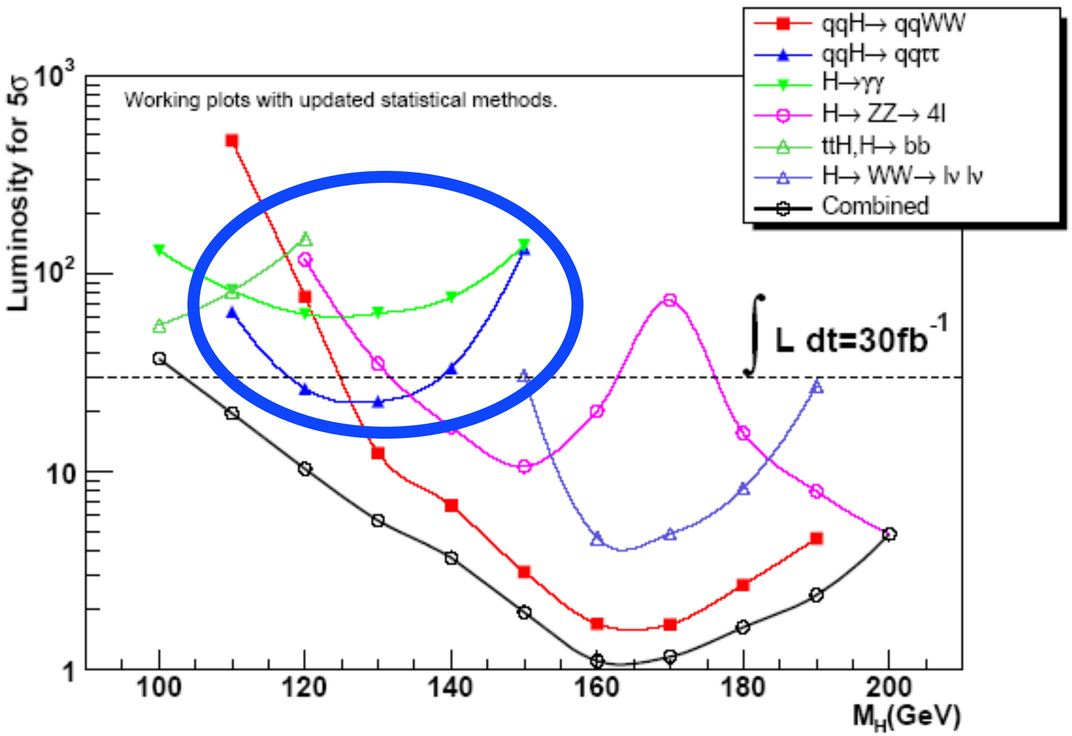
ATLAS TDR (1999)

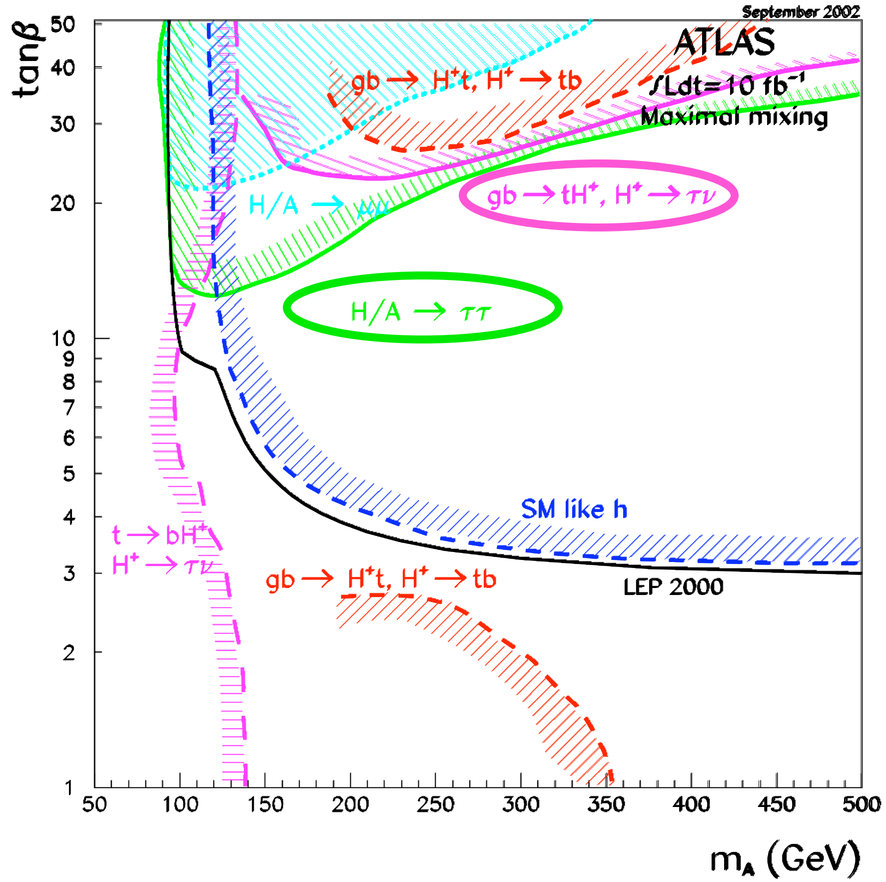
Inclusive H→γγ





$h, A \to \tau\tau$; $H^{\pm} \to \tau^{\pm}\nu$

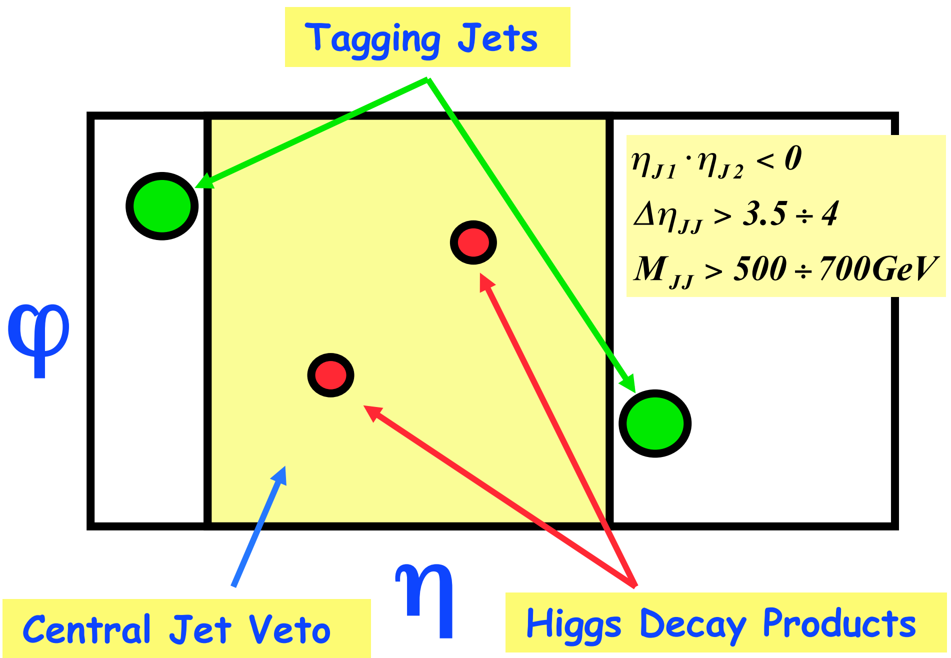




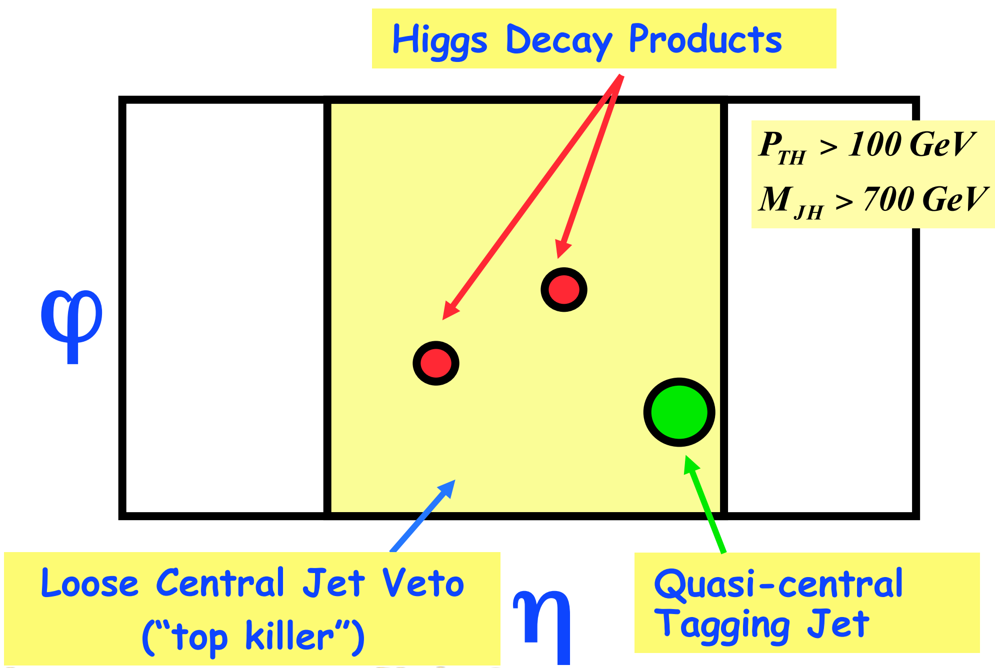
Low Mass SM $H\rightarrow\tau\tau$ + jets

- 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

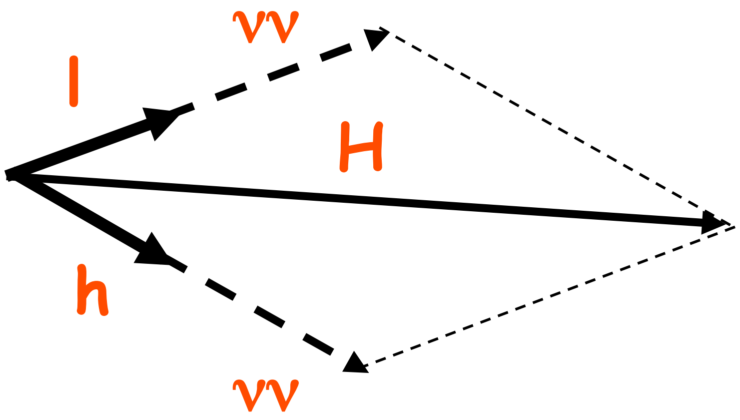
Tau decay products are collinear to tau direction

Fraction of τ momentum carried by visible τ decay

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

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

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



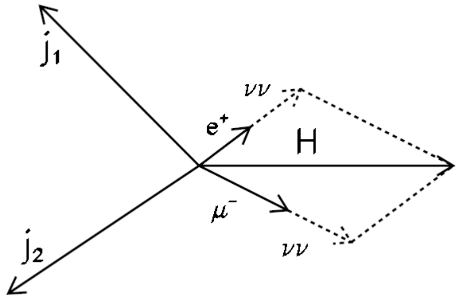
$$x_{\tau_1} = \frac{p_{T_{lep1},x} \cdot p_{T_{lep2},y} - p_{T_{lep1},y} \cdot p_{T_{lep2},x}}{p_{T_{Higgs},x} \cdot p_{T_{lep2},y} - p_{T_{Higgs},y} \cdot p_{T_{lep2},x}}$$

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

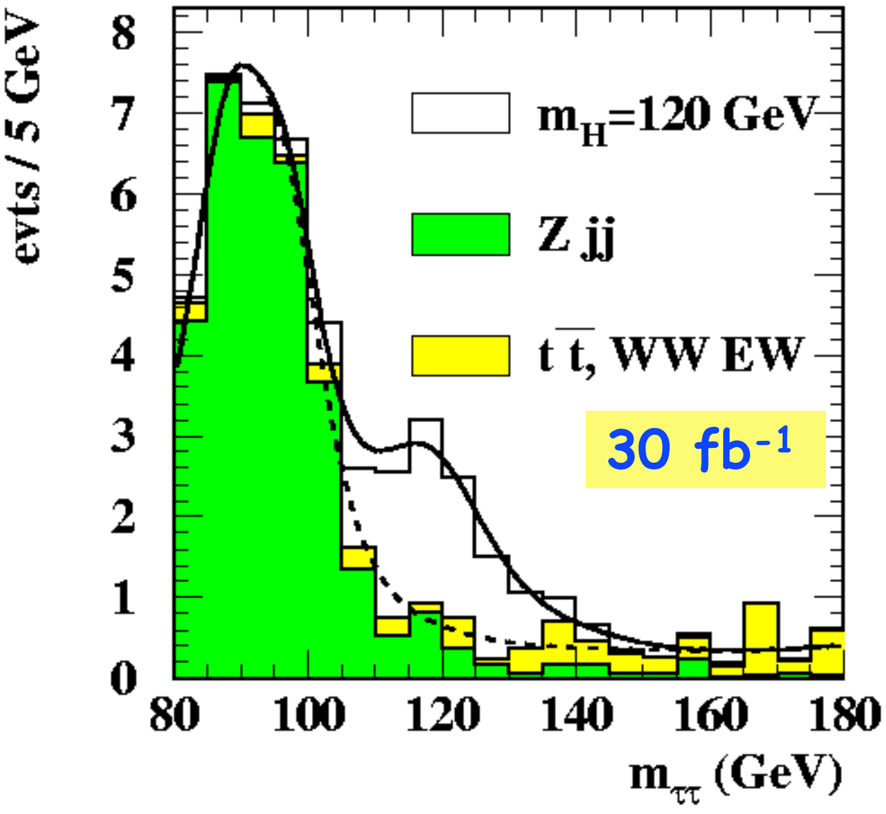
- $x_{\tau 1}$ and $x_{\tau 2}$ can be calculated if the missing E_T is known
- Good missing E_T reconstruction is essential

Low Mass SM H→ττ+jets

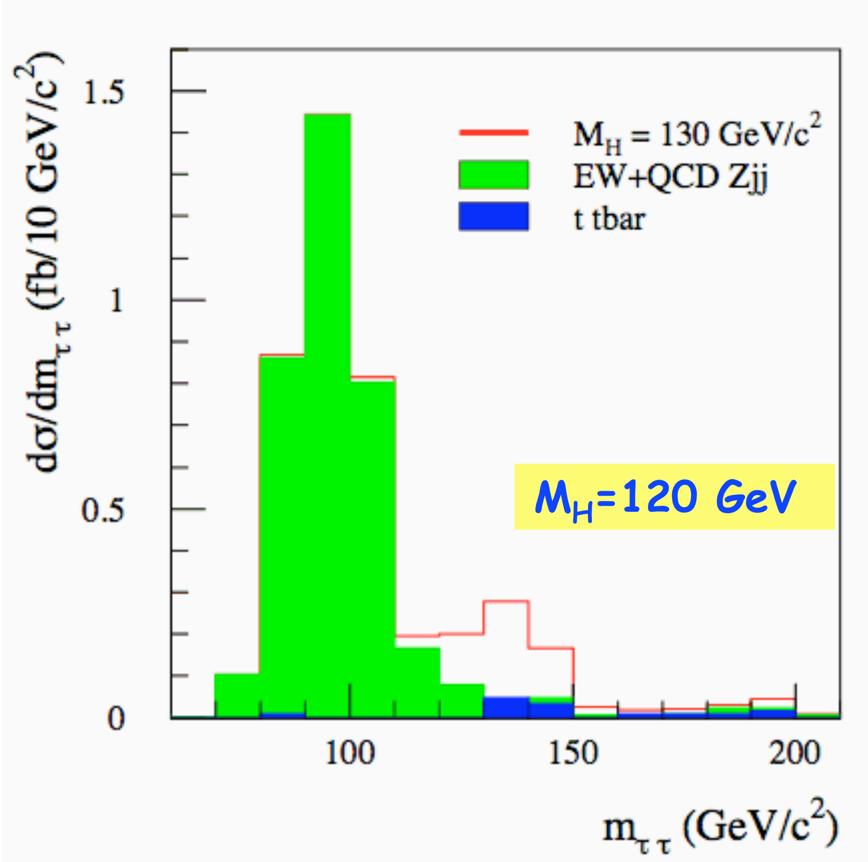
- Reconstruct Higgs mass with collinear approxim



H(→ττ→ll) +≥2jets



H(→ττ→lh) +≥1jet



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

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

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

MC extrap. is validated →

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

$85<M_{ll}<95$ GeV

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

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

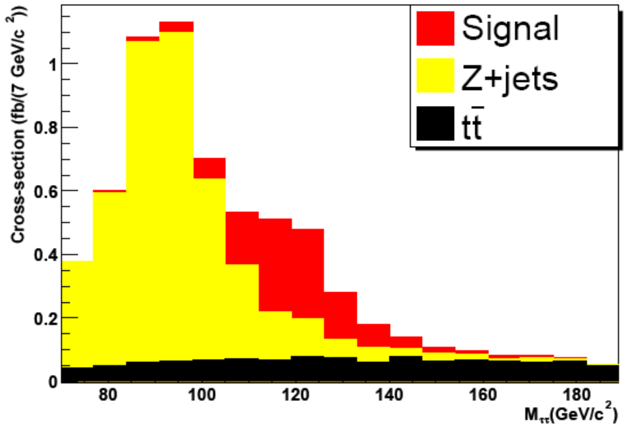
MC extrap. →

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

$M_{ll}<75$ GeV

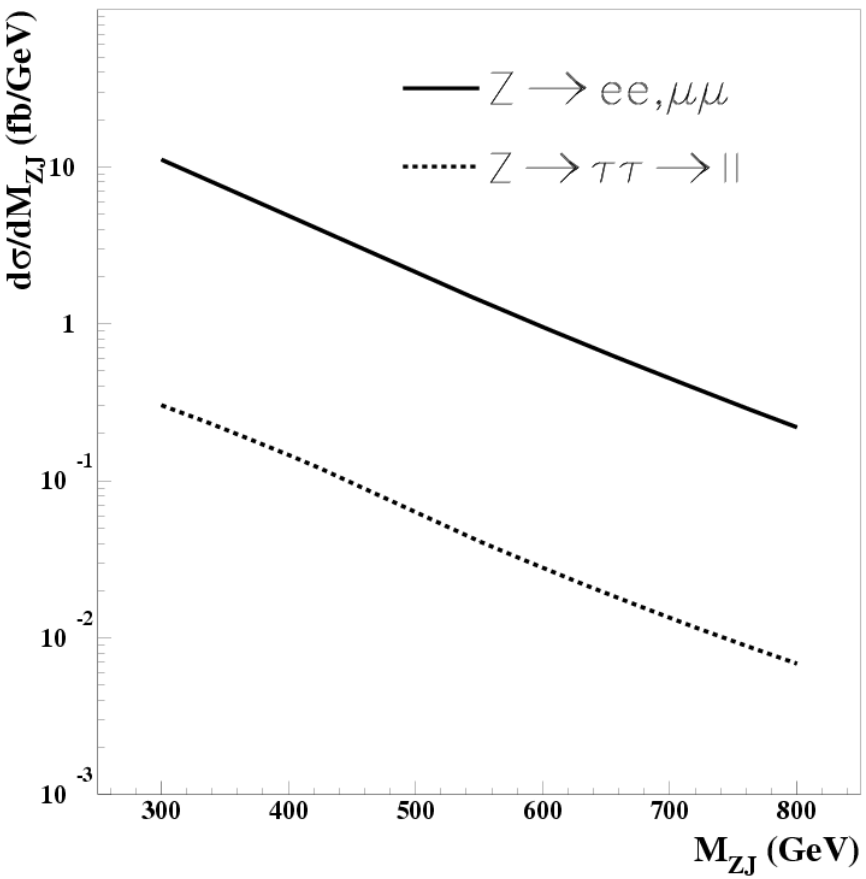
M_{HJ}, $\Delta\eta_{JJ}$ →

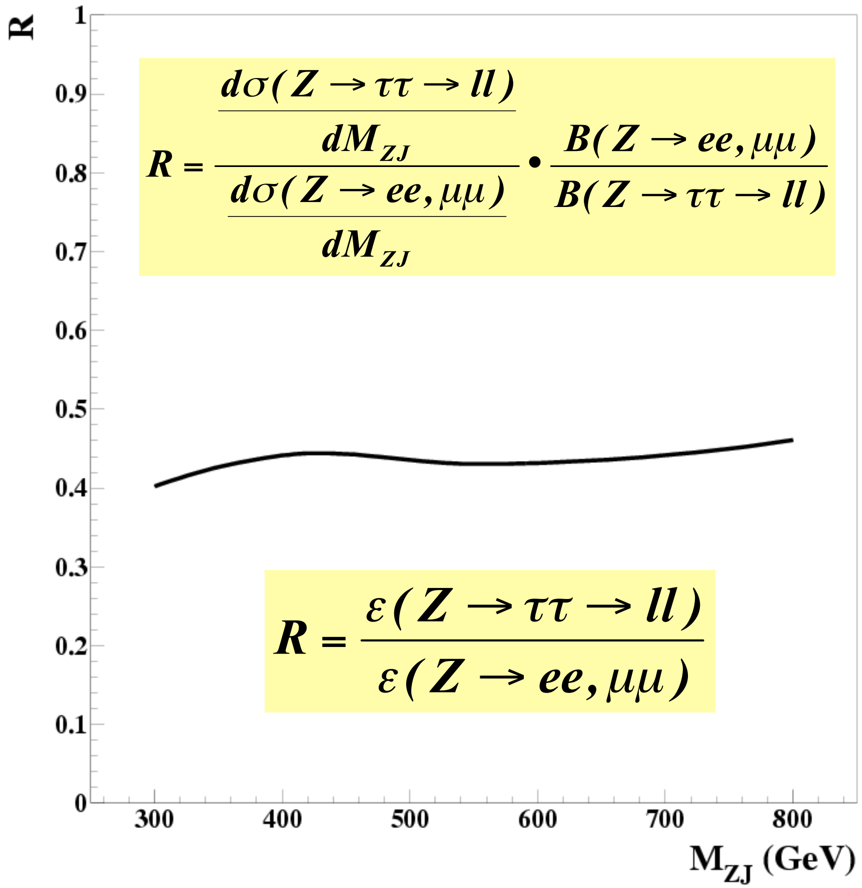
Determine shape and normalization of $Z\rightarrow\tau\tau$ background

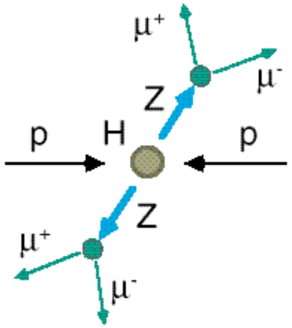


Normalization of $Z \to \tau\tau$ using $Z \to ee,\mu\mu$

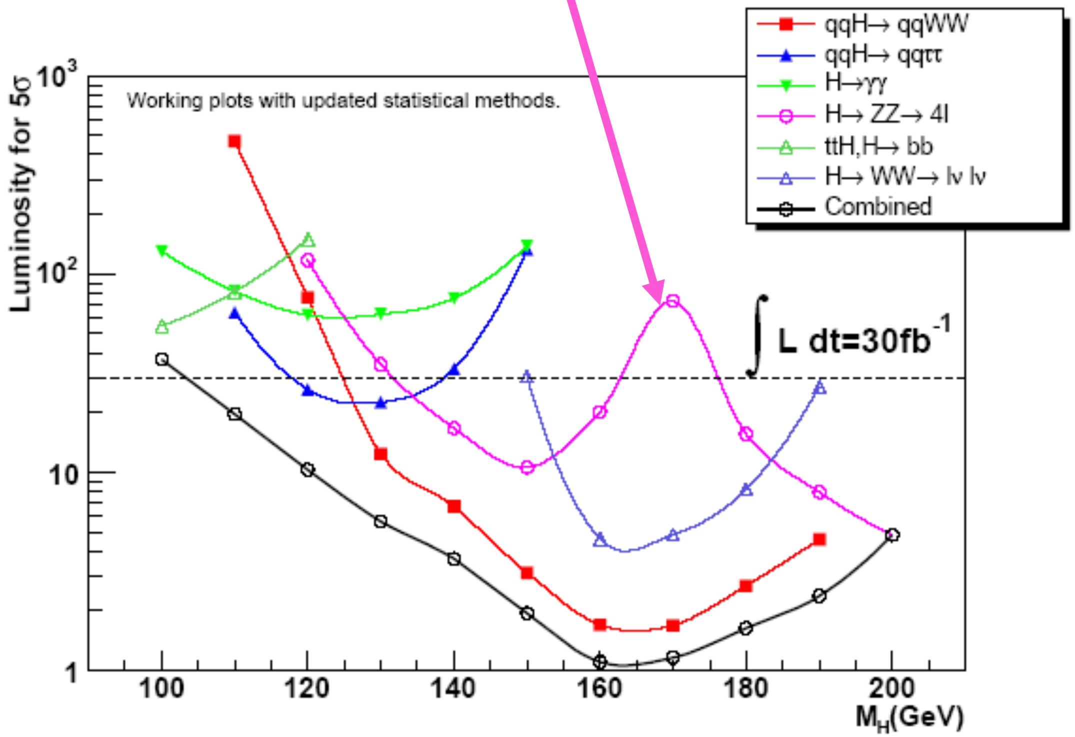
- $Z \to ee,\mu\mu$ offers about 35 times more statistics w.r.t to $Z \to \tau\tau \to ll$
  - Ratio of efficiencies depends weakly with M_{HJ} and can be easily determined with MC after validation with data



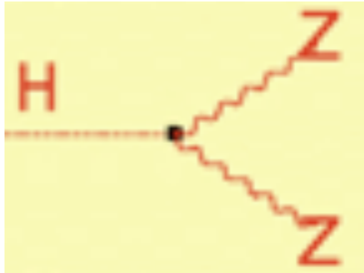




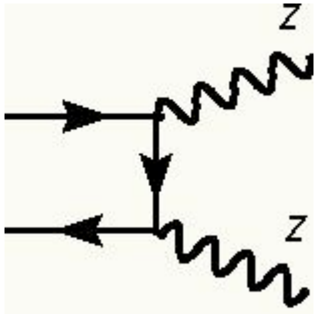
SM Higgs: $H \rightarrow ZZ^{(*)} \rightarrow 4l$

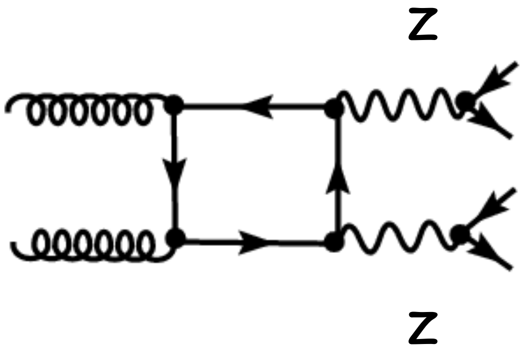


Higgs decay to Z^0Z^0

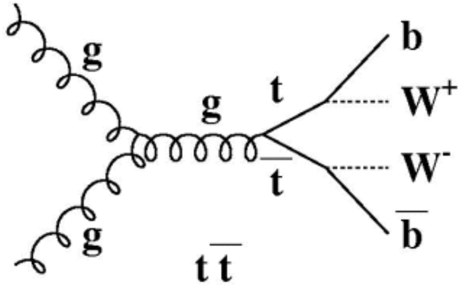


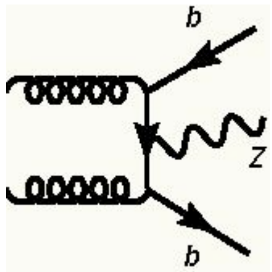
Irreducible Z^0Z^0 backgrounds



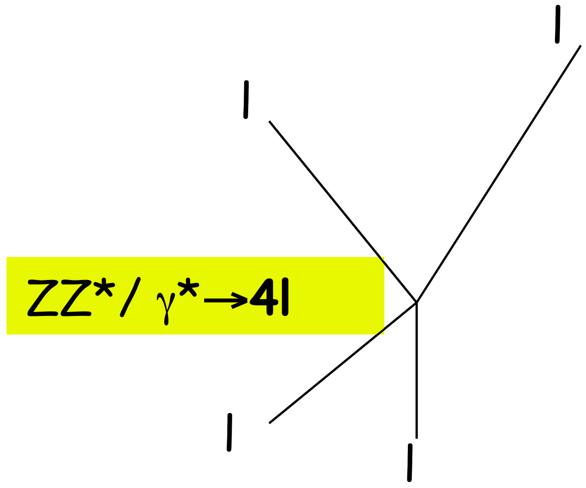


Reducible 4l backgrounds

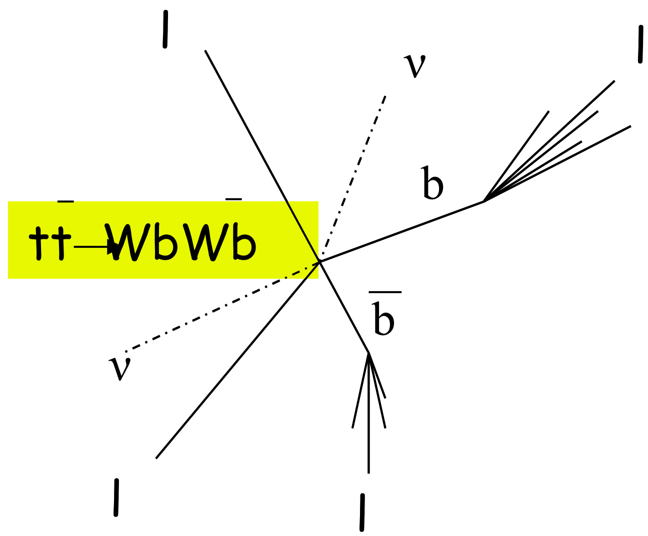




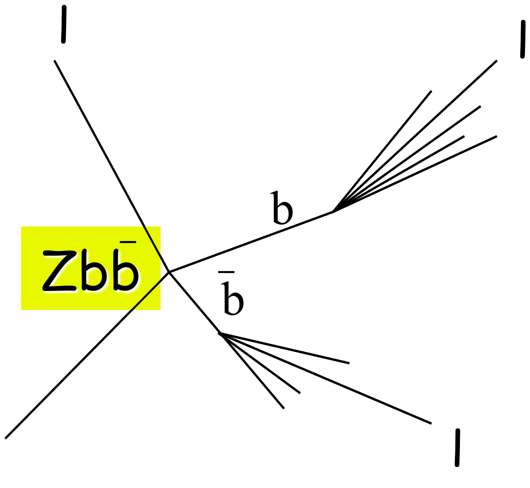
Backgrounds Higgs→ZZ$^{(*)}$→4l (l=eμ)



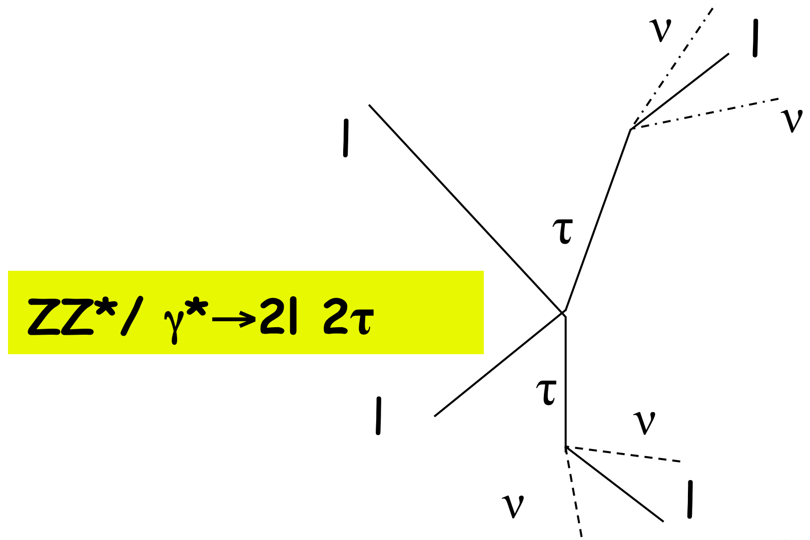
Continuum Irreducible



Non-Resonant reducible



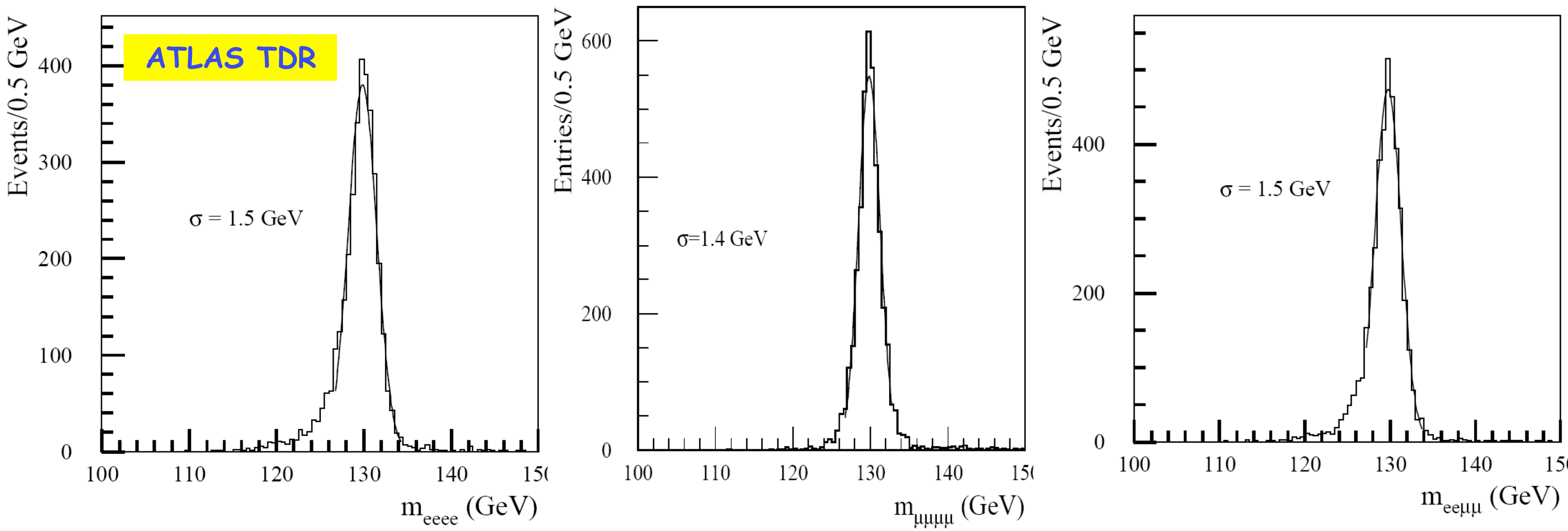
Resonant reducible

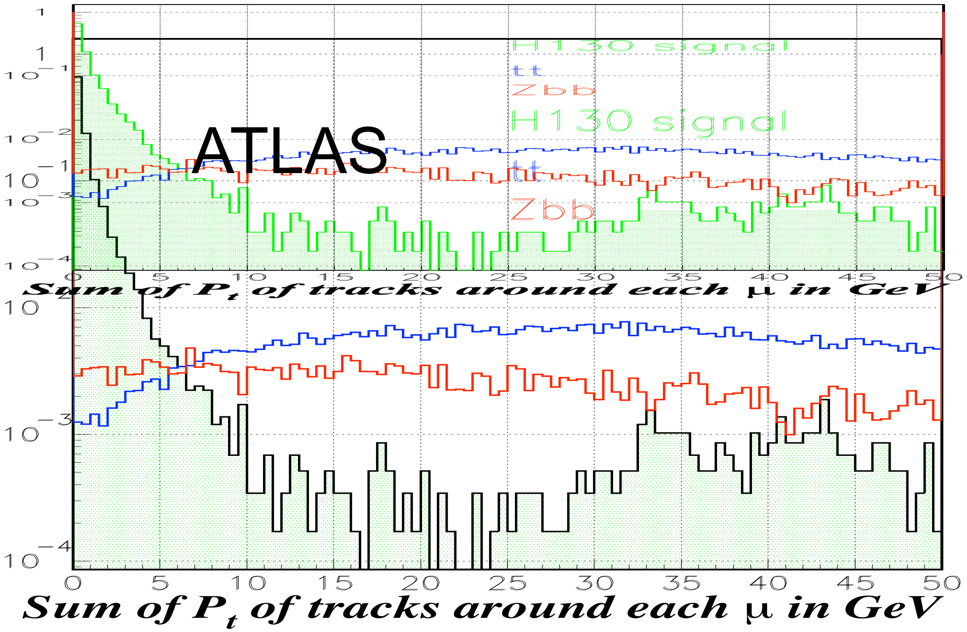


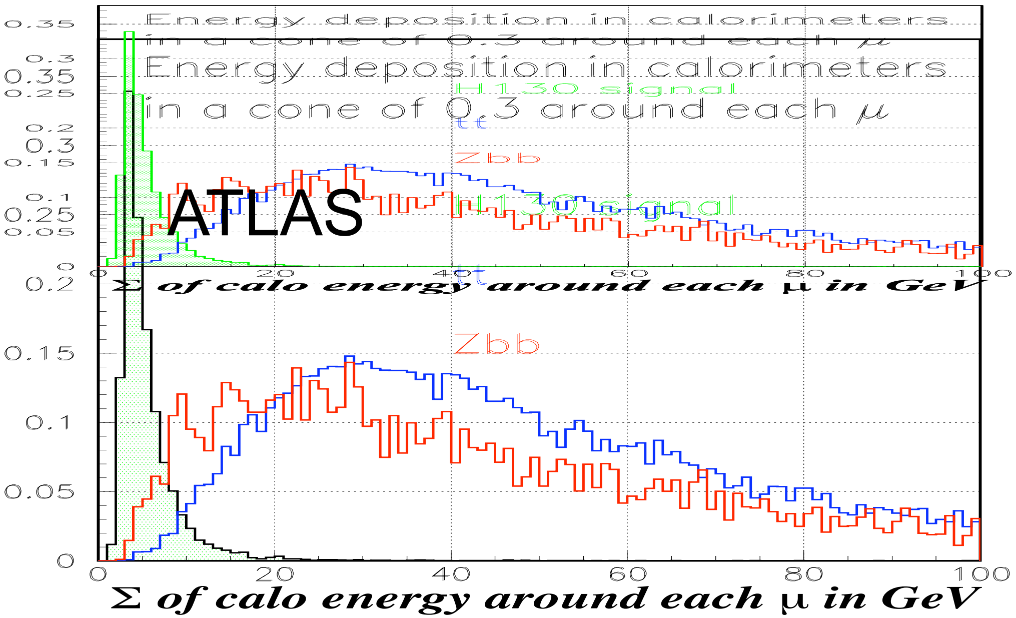
SM Higgs→ZZ$^{(*)}$→4l

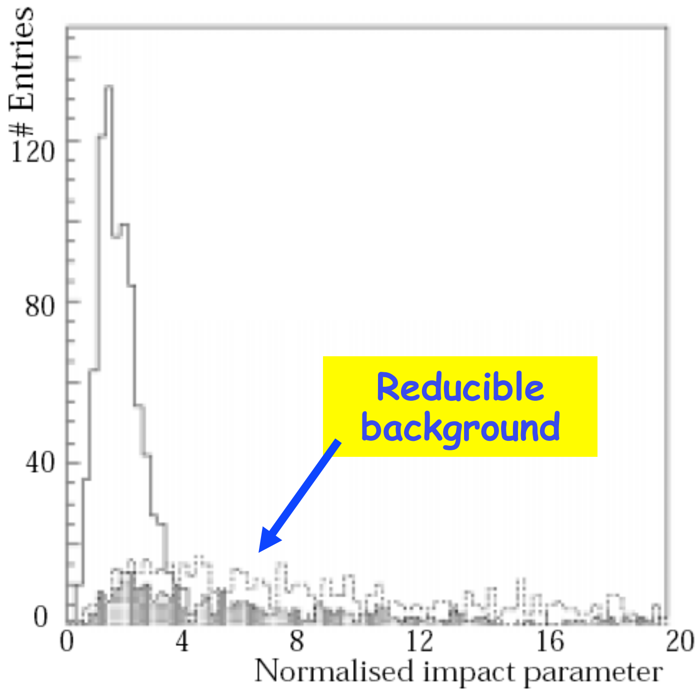
- Able to reconstruct a narrow resonance, with mass resolution close to 1%. Can achieve excellent signal-to-background > 1
  - **Major issue: Lepton ID and rejection of semi-leptonic decays of B decays. Suppress reducible background Zbb,tt→4l**

H[130 GeV]→4e H[130 GeV]→4μ H[130 GeV]→2e2μ

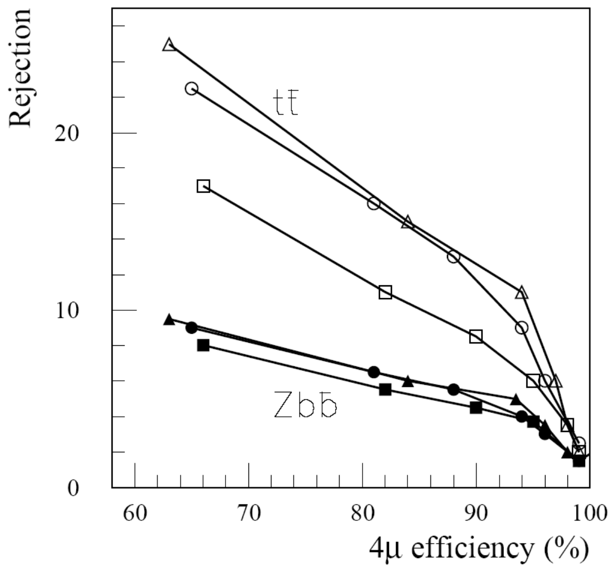




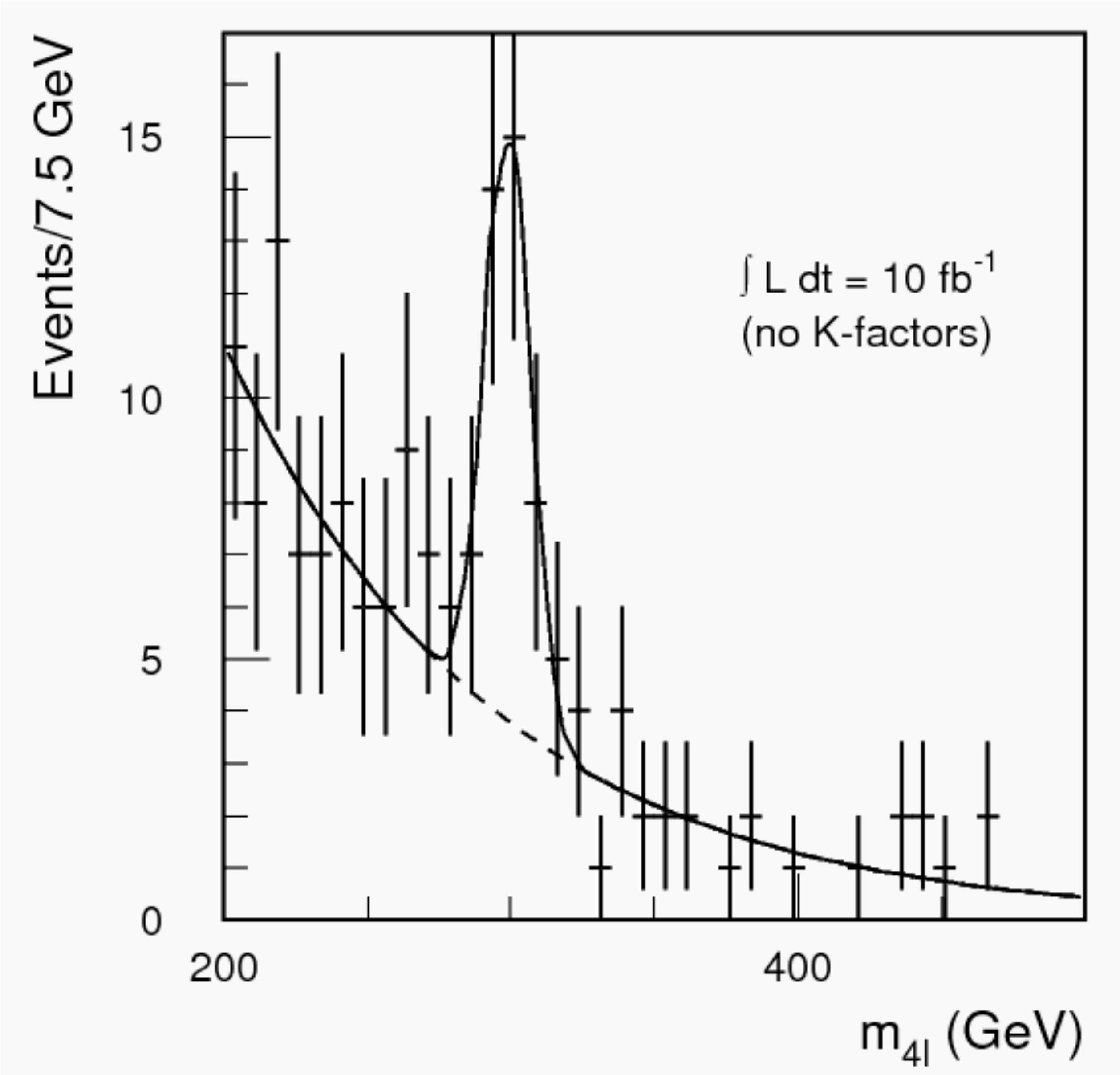




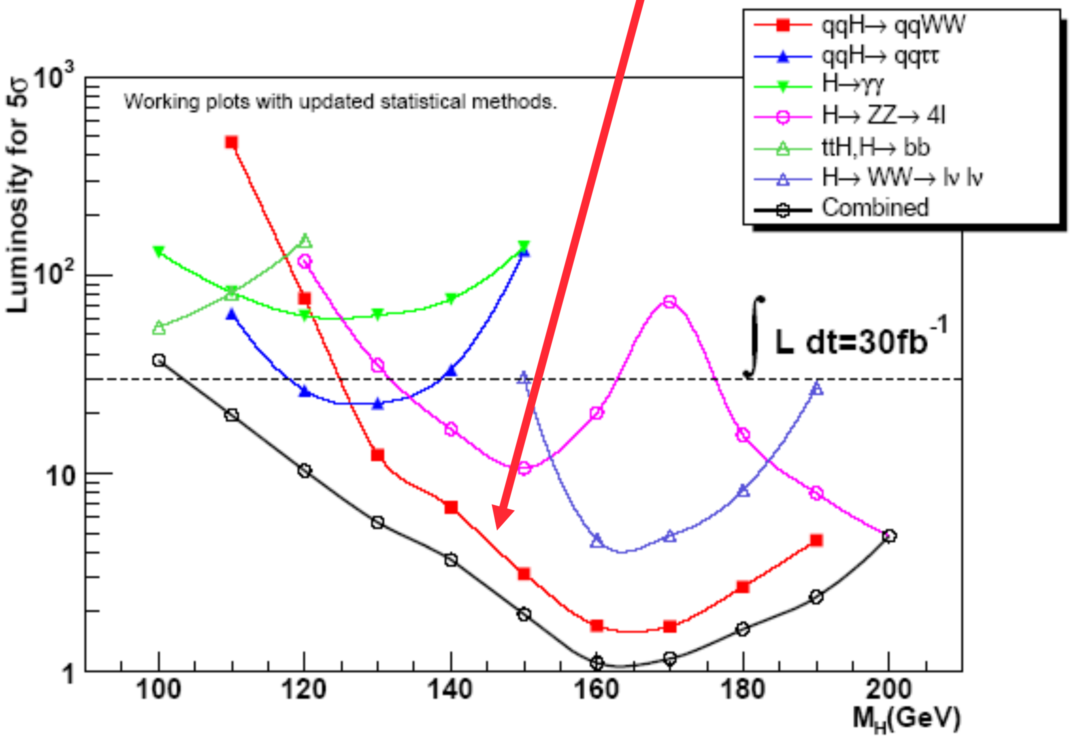
ATLAS TDR



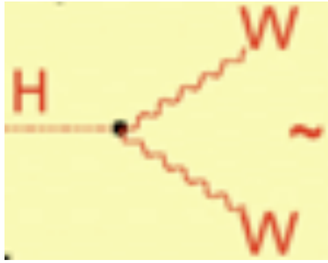
ATLAS TDR


Events/7.5 GeV
15
10
5
0
200
400
m_{4l} (GeV)
∫ L dt = 10 fb^{-1}
(no K-factors)

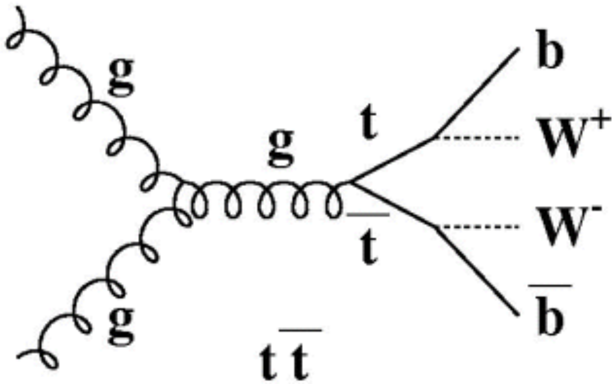
SM Higgs: $H \to WW^{(*)} \to 2l2\nu$

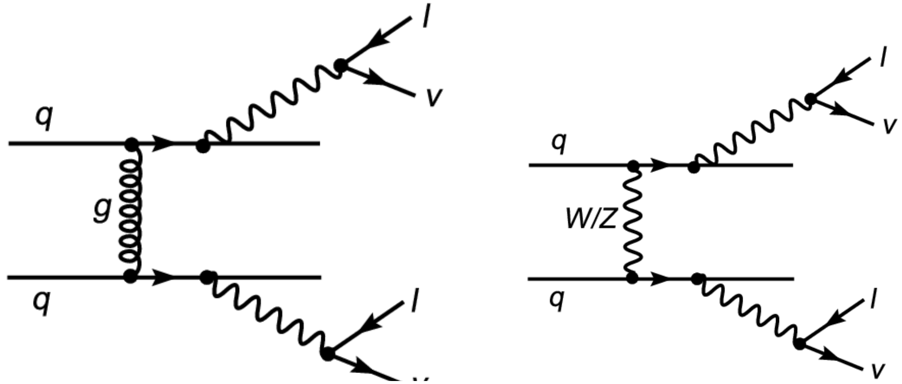


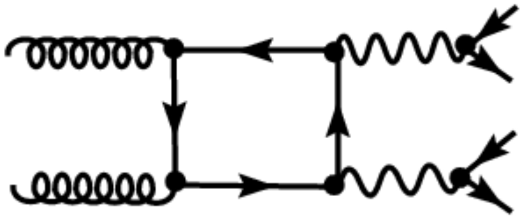
Higgs decay to W^+W^-



W^+W^- backgrounds



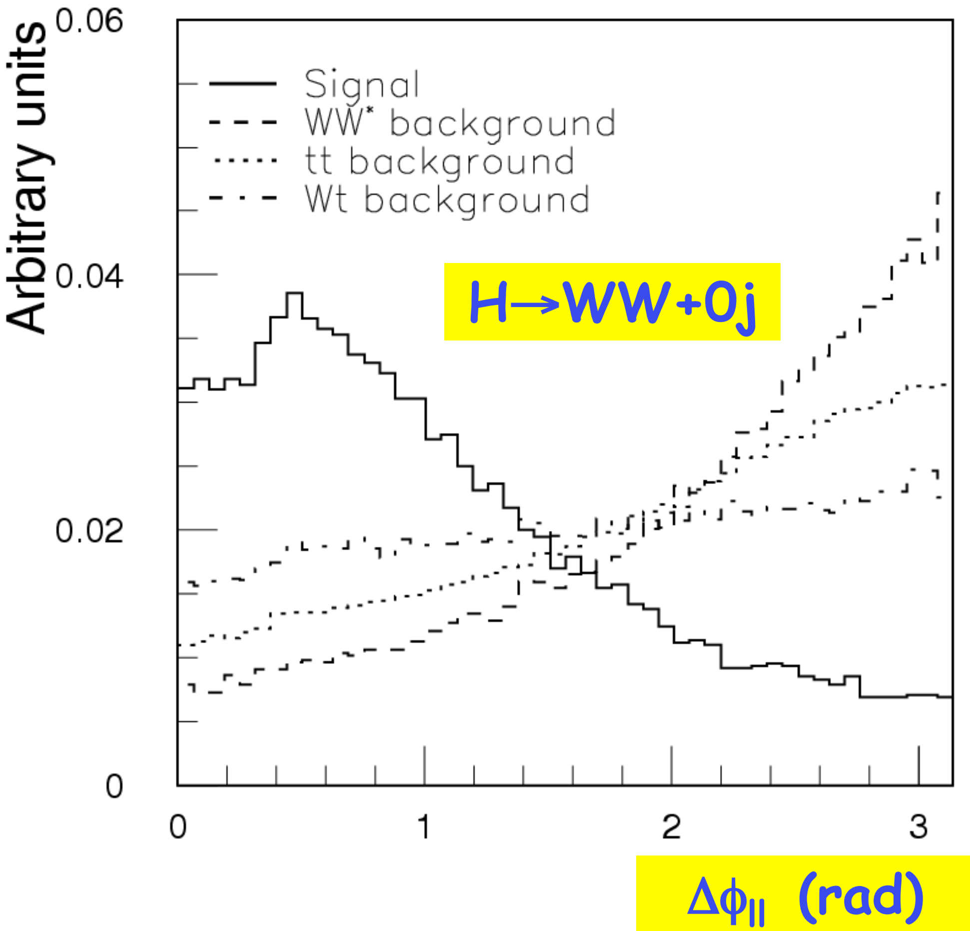


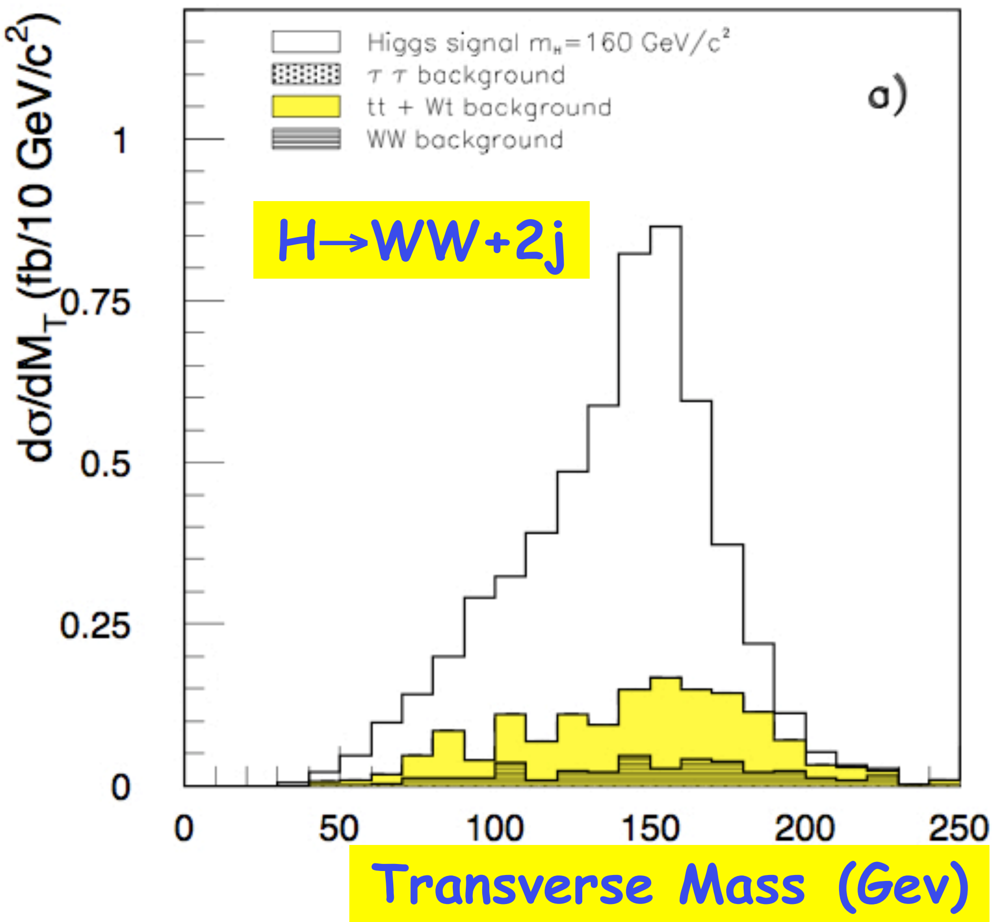


+ Single top
& non-resonant WWbb

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

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



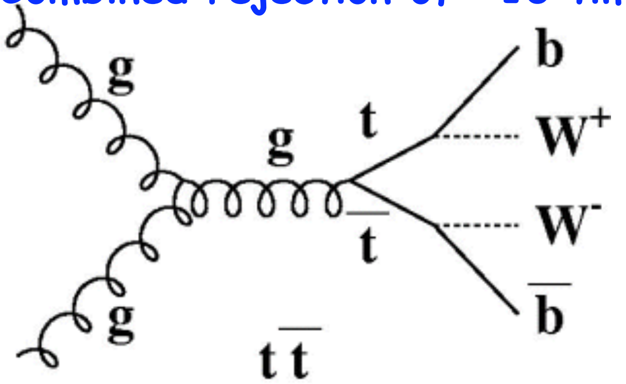


Background Suppression and Extraction

- 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

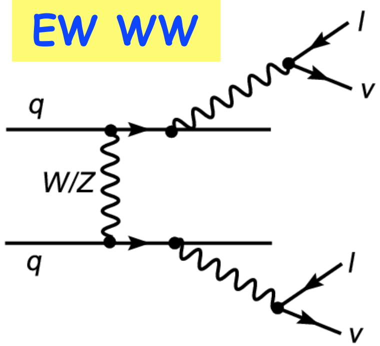
- Jet veto (understand low P_T jets)
- Semi-inclusive b-tagging or "top killing" algorithm
- Combined rejection of >10 times



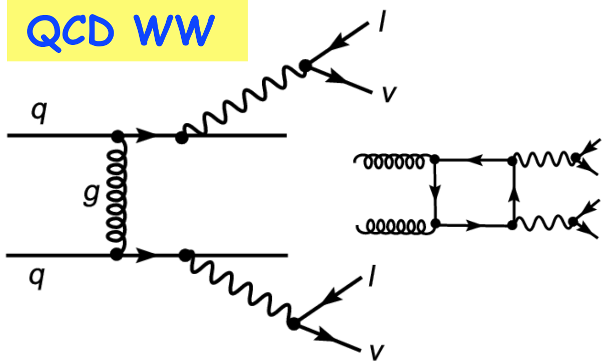
Non-resonant WW suppression

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

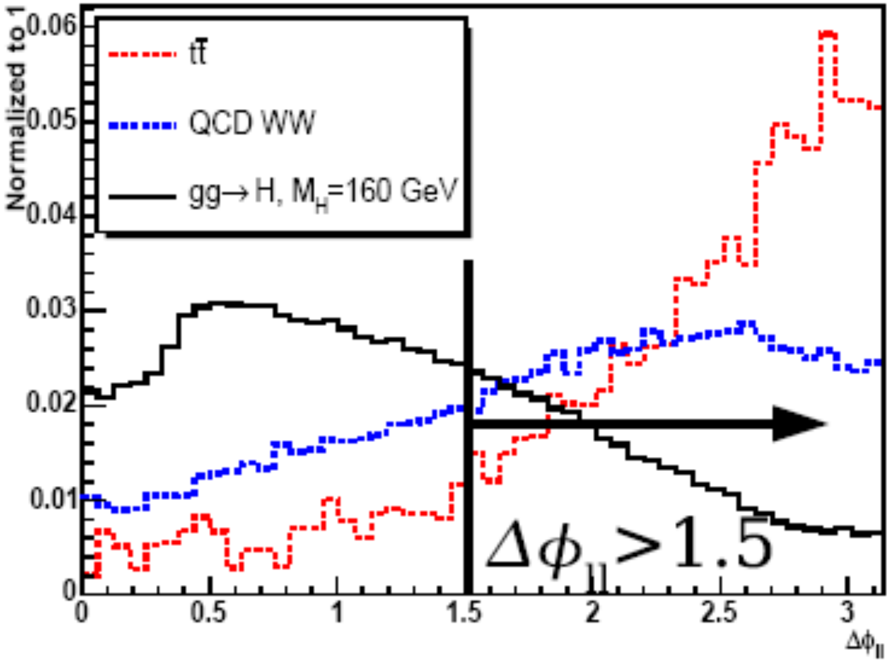
EW WW

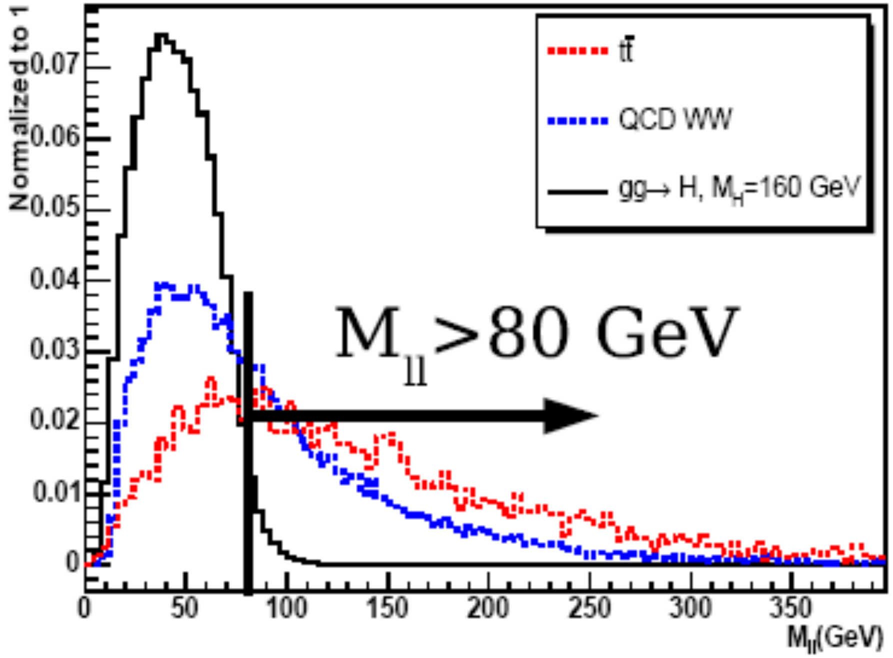


QCD WW



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

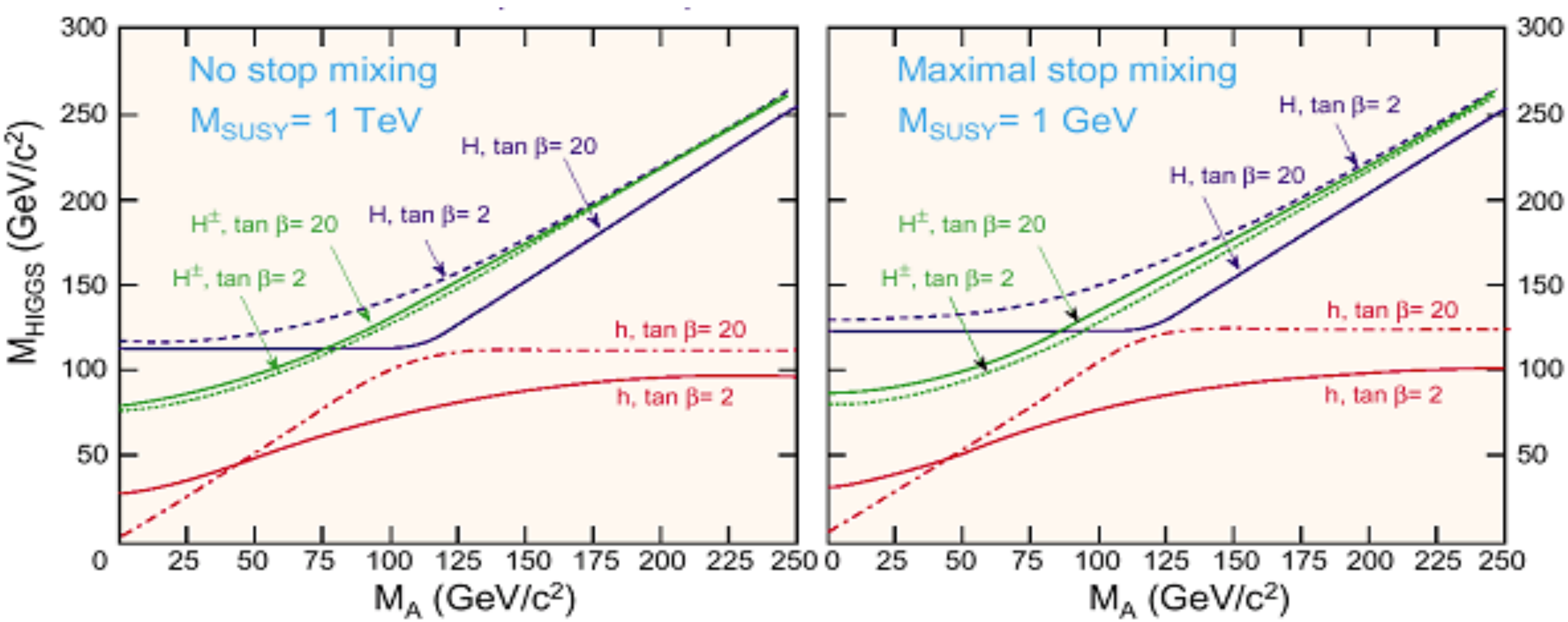




- **Main control sample is defined with two cuts**
  - $\Delta\phi_{ll}>1.5$ rad. and $M_{ll}>80$ GeV
- **Because of tt contamination in main control sample, need b-tagged sample (M_{ll} cut is removed)**

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, tanβ
  - Theoretical limit on light MSSM Higgs: h<135 GeV

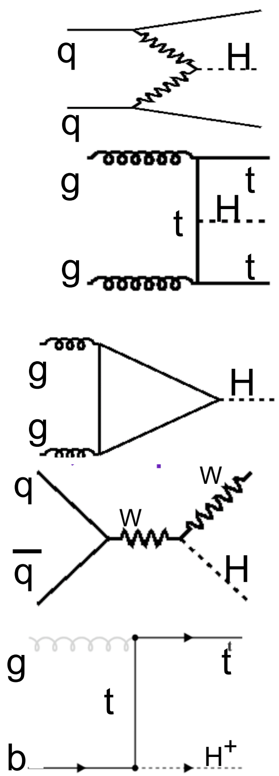


MSSM Higgs (cont)

	up type quark	down type quark/ charged lepton	W and Z boson
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\alpha-\beta)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\alpha-\beta)$
A	$\cot\beta$	$\tan\beta$	none

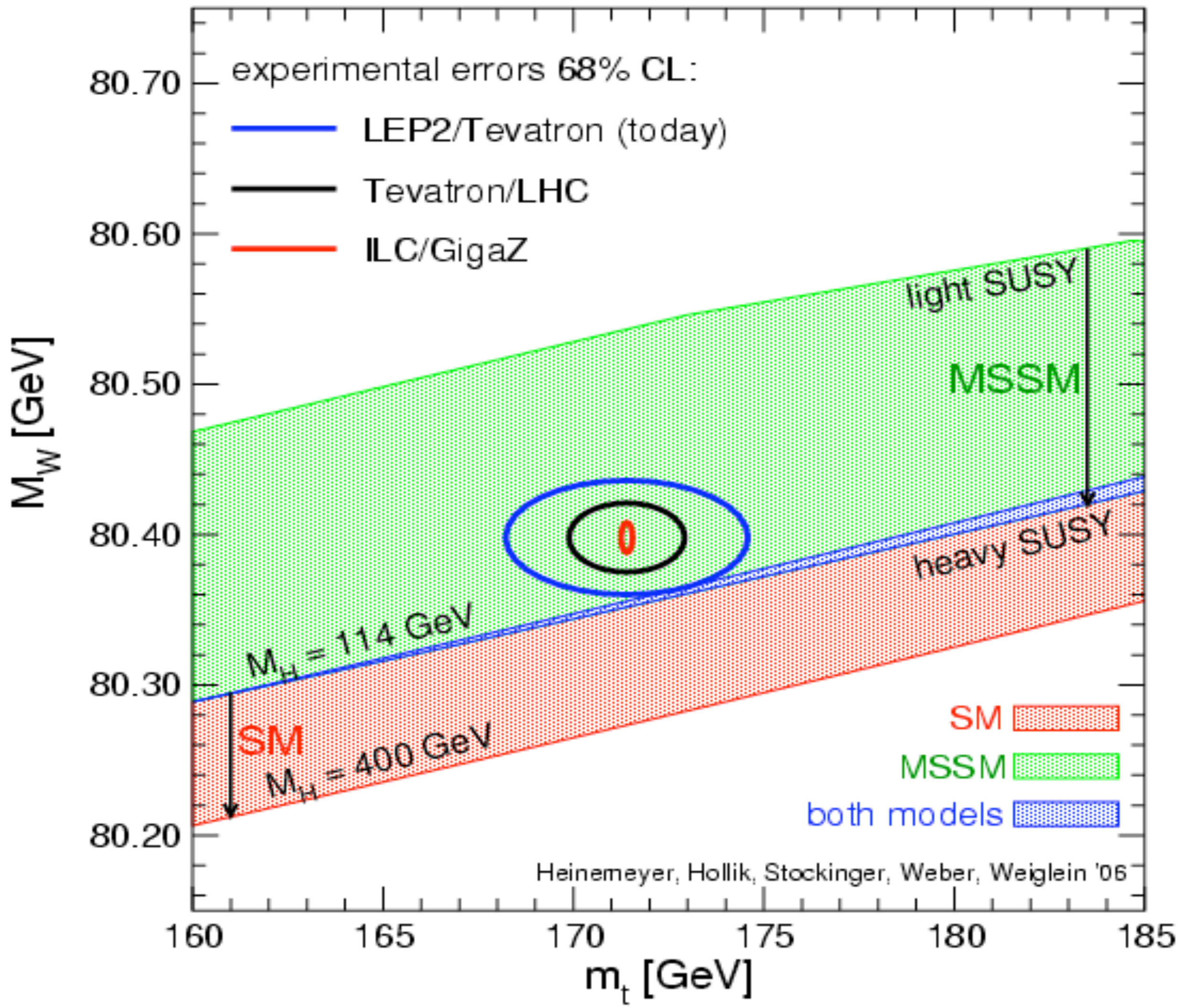
$$\text{VBF}: \quad \sigma_{MSSM}(h) \quad = \sin^2(\alpha-\beta)\times\sigma_{SM}$$

- **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



Search channel	Mass range
$VBF: H\to\tau\tau$	110 GeV to 180 GeV
$VBF: H\to WW$	110 GeV to 250 GeV
$VBF: H\to\gamma\gamma$	110 GeV to 180 GeV
$ttH, H\to bb$	110 GeV to 150 GeV
$GGF/bbh, H\to\mu\mu$	70 to 1000 GeV
$GGF/bbh, H\to\tau\tau\to lep.had.$	110 to 1000 GeV
$GGF/bbh, H\to\tau\tau\to had.had.$	450 to 1000 GeV
$H\to ZZ\to\ell\ell\ell\ell$	100 GeV to 420 GeV
$GGF, H/A\to tt$	450 to 600 GeV
$H/A\to\gamma\gamma$	60 to 400 GeV
$WH\to\ell\nu bb$	70 to 130 GeV
$GGF: H\to WW\to\ell\nu\ell\nu$	140 to 200 GeV
$WH\to\ell\nu WW\to\ell\nu\ell\nu\ell\nu$	140 to 200 GeV
$GGF: H\to hh\to\gamma\gamma bb$	100 360, 40 to 130 GeV
$GGF: A\to Zh\to\ell\ell bb$	100 360, 40 to 130 GeV
$tt\to H^\pm bWb\to\tau\nu\ell\nu b$	70 to 170 GeV
$tt\to H^\pm bWb\to\tau\nu bqqb$	70 to 170 GeV
$gb\to H^\pm t: H^\pm\to\tau\nu, tb$	180 t0 1000 GeV

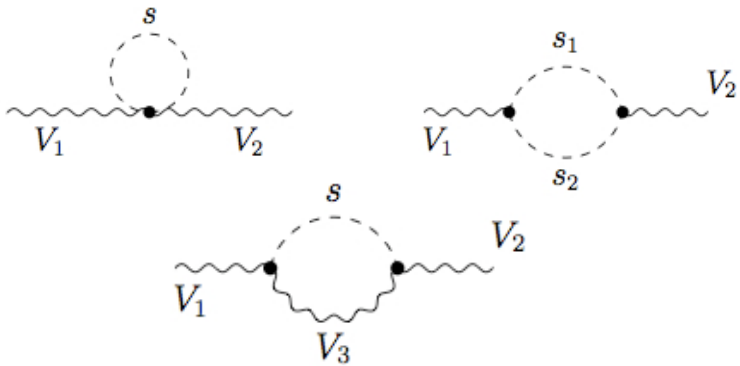
Does the data favor a MSSM Higgs?



M_t = 171.4 GeV
M_W = 80.398 GeV

Slepton/squark one loop corrections

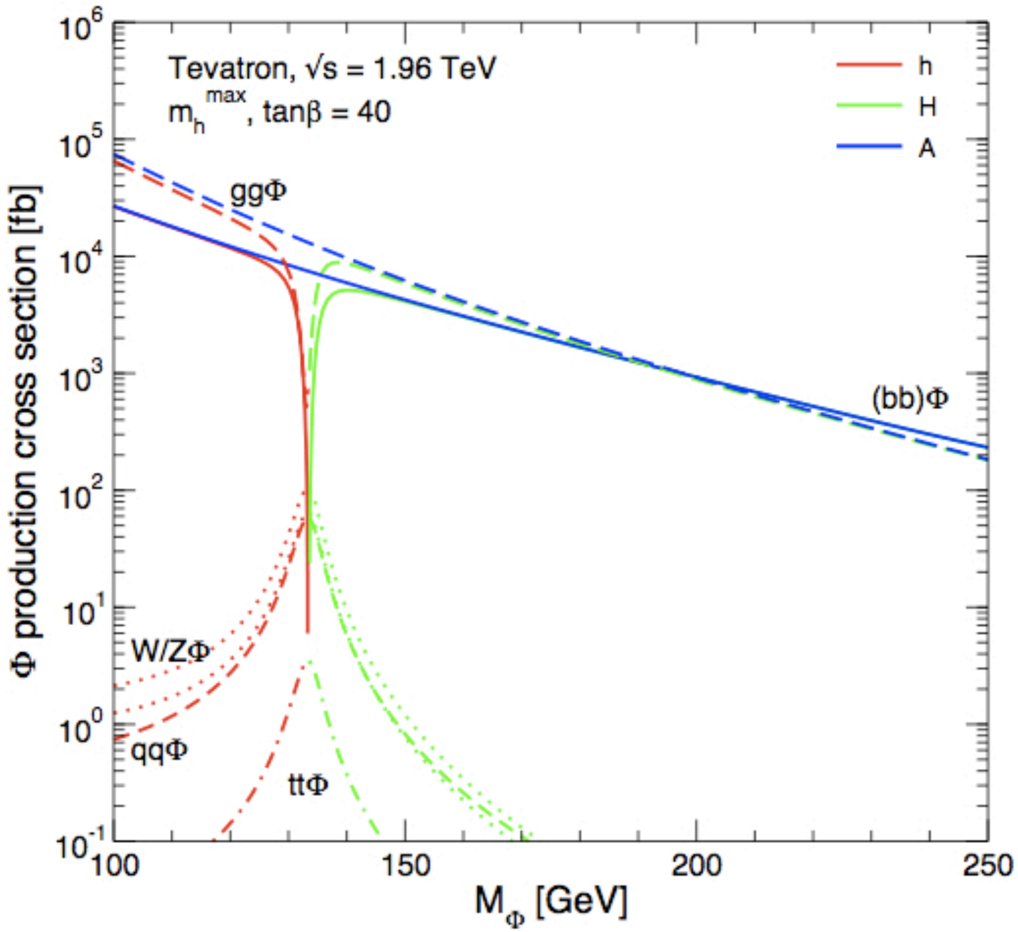
Contributions from MSSM Higgs bosons



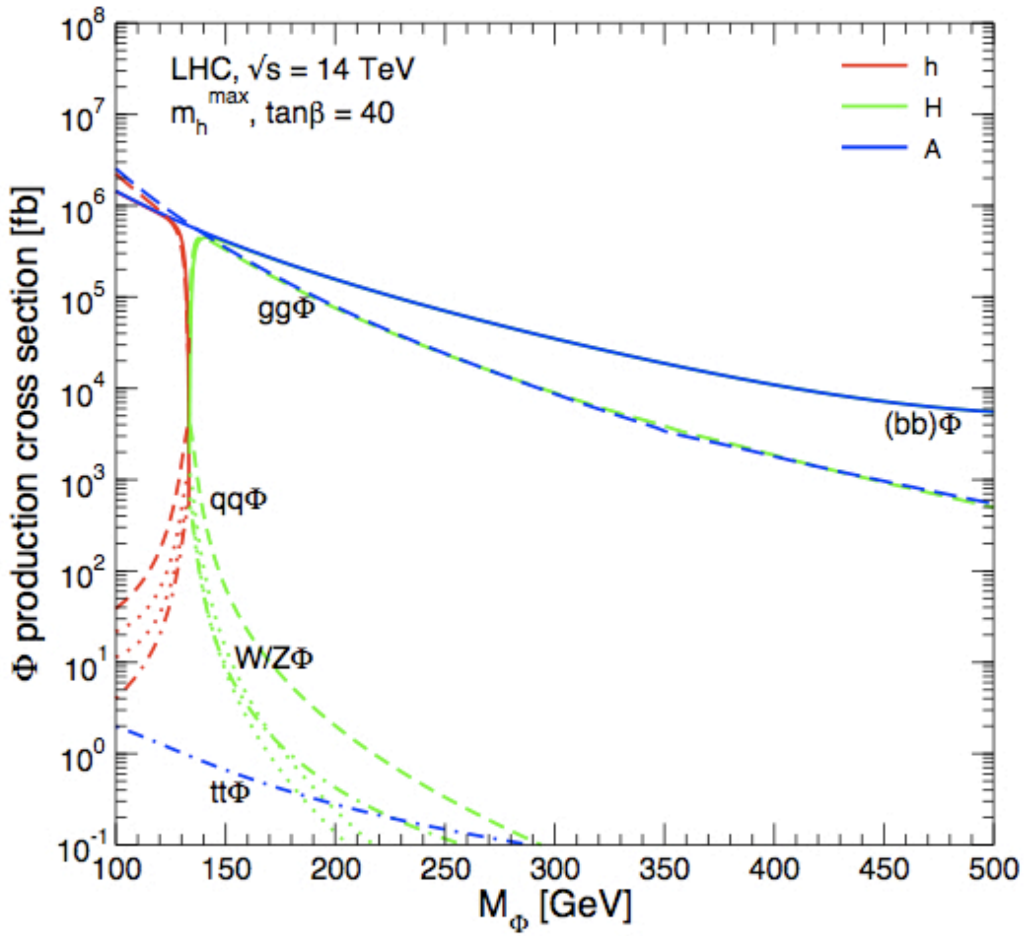
Caution: This is not the only way of achieving agreement with data

MSSM Higgs Cross-sections
(large tanβ)

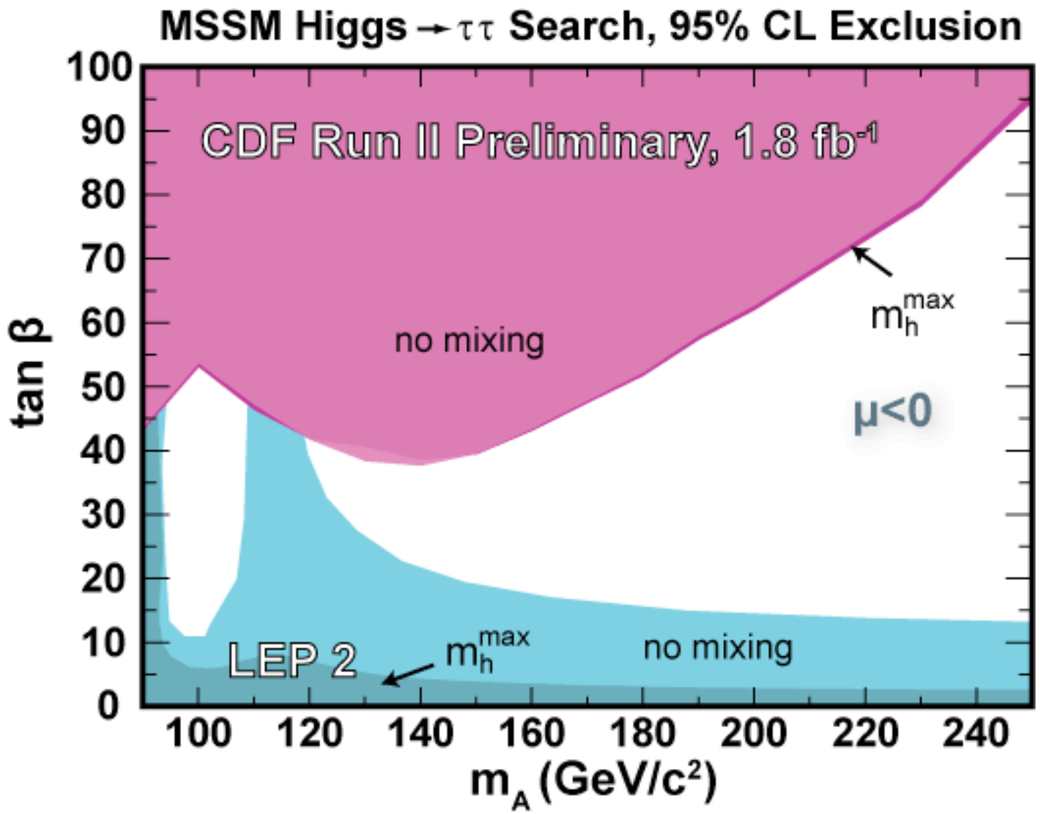
Tevatron

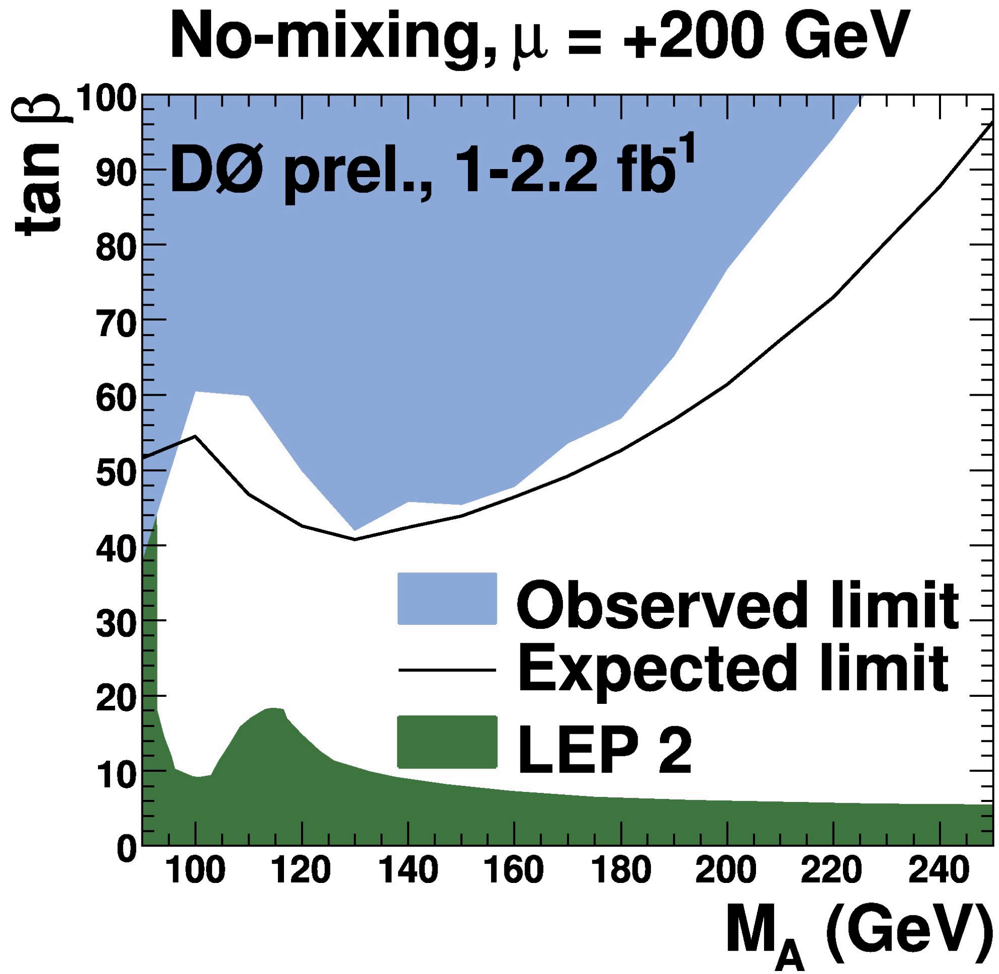


LHC

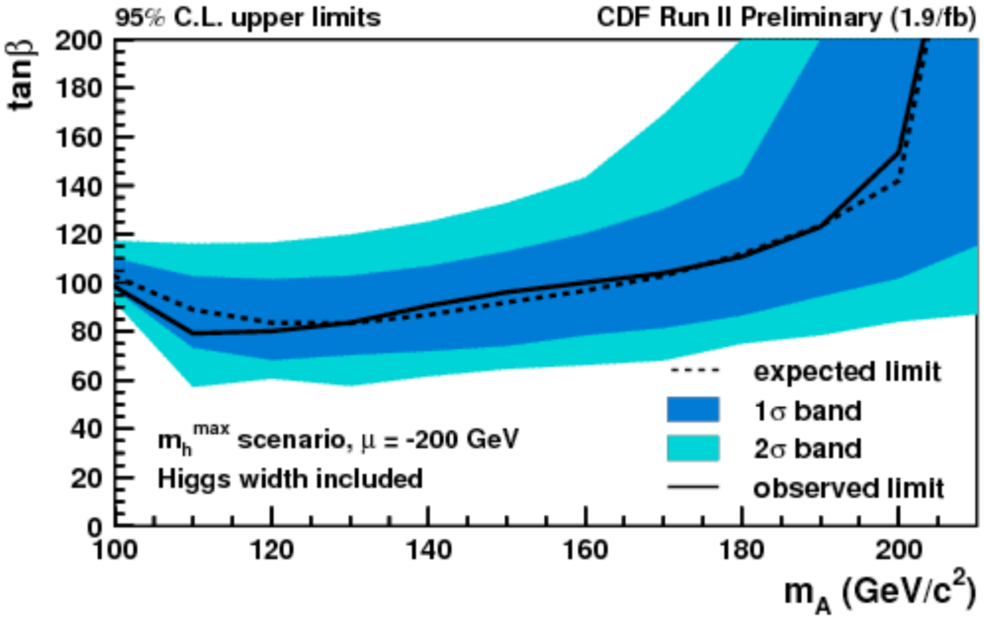


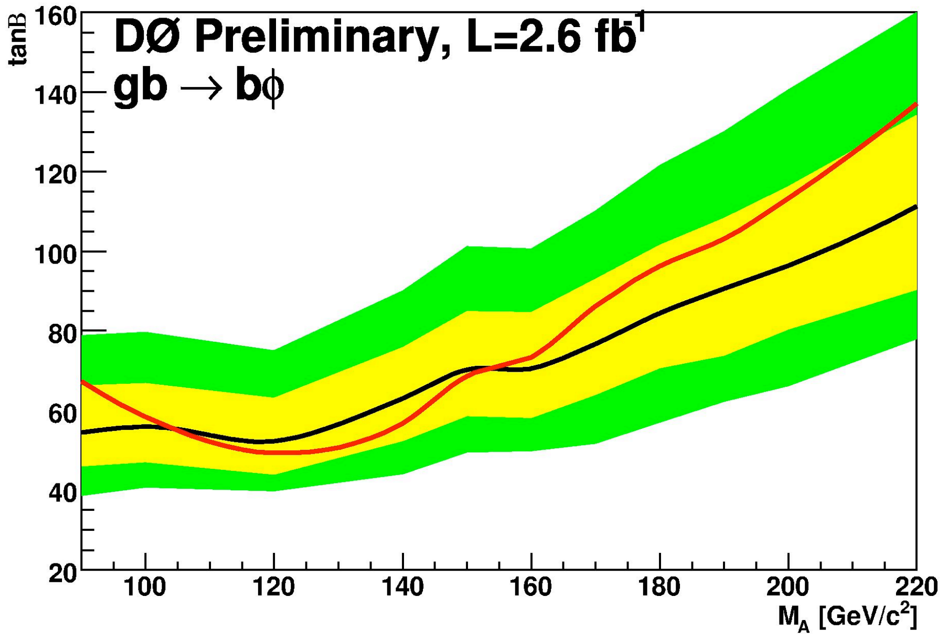
Search for MSSM Higgs boson production in di-tau final states



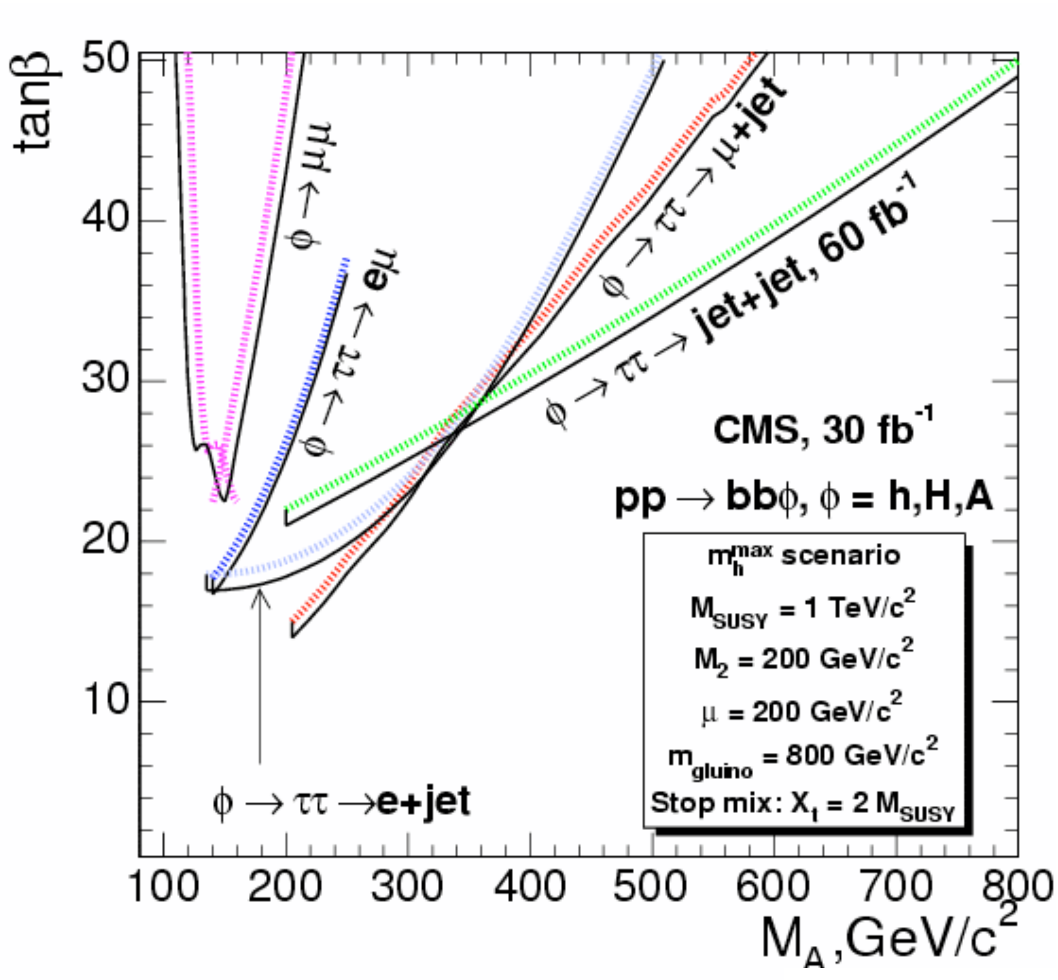


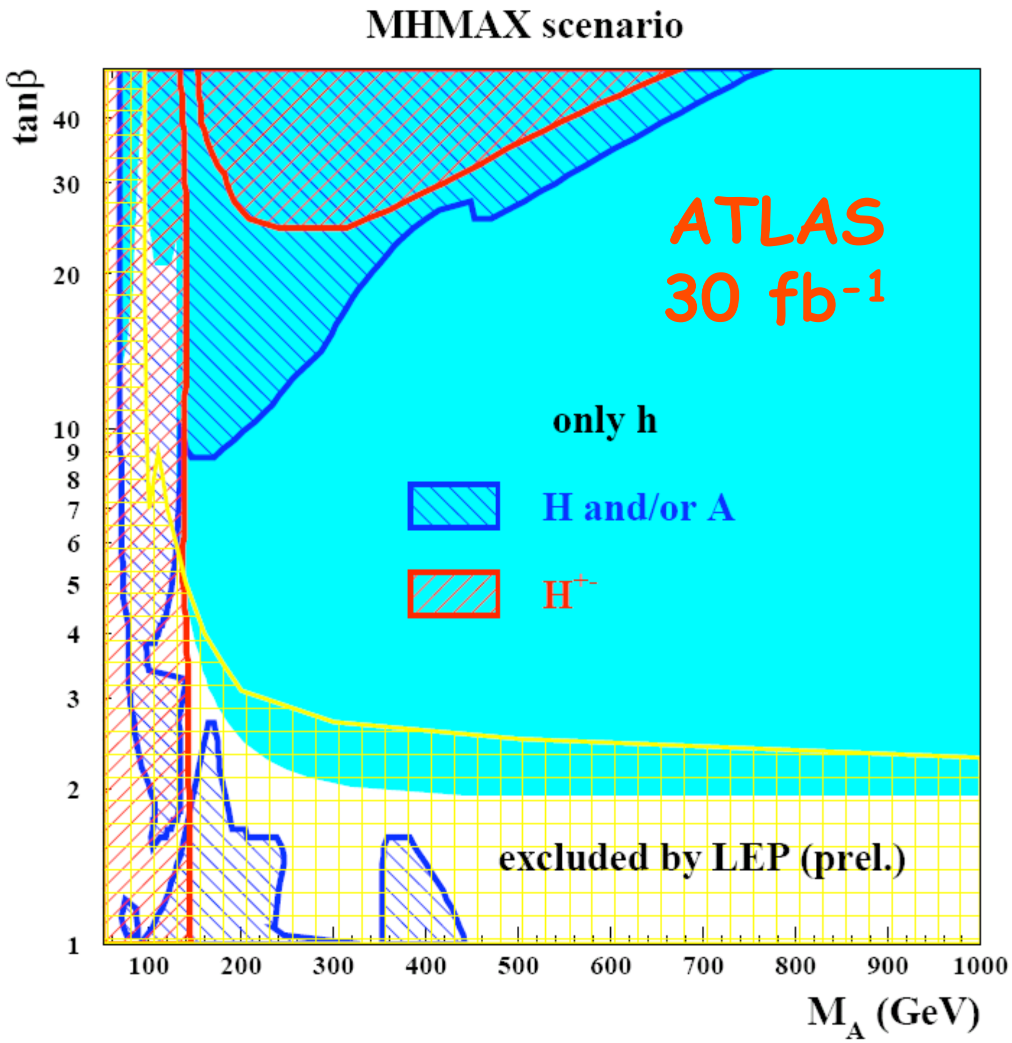
Search for MSSM Higgs boson with 3b in final state





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