Searching for the Higgs at the LHC

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Boston University - PY 898 - Special Topics in LHC Physics
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Outline

- Theory & Background of Higgs Mechanism
- Production Modes
- Decay Modes
  - Discovery Channels
- Invisible Higgs

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- Theory & Background of Higgs Mechanism
- Production Modes
- Decay Modes
  - Discovery Channels

Emphasis on SM

- Invisible Higgs

The Higgs Mechanism

- Describes the way in which gauge bosons obtain a mass by interacting with the *Higgs Field*
  - Mechanism requires Higgs Field to have non-zero vacuum expectation value: *spontaneous symmetry breaking* of electroweak symmetry
- Successfully explains the mass ratio between $W^{\pm}$ / Z gauge bosons
  - Correctly predicted to 5 decimal places
  - Leptons and quarks also acquire mass as a result of interaction with the Higgs
- Higgs field has 4 degrees of freedom
  - 3 DOF mix with the $W^{\pm}$ / Z bosons, giving them mass
  - 4th DOF manifests as the Higgs boson (scalar)

Searching for the Higgs

- Higgs is difficult to search for since couplings to the Higgs are proportional to mass
  - Coupling is small for the light particles that are most copiously available
- Mass of the Higgs is unknown
  - SM + spontaneous symmetry breaking predicts the existence of Higgs boson(s) , but not mass
  - M_H depends on coefficient of self-interaction λ. No other observables depend on λ in a measurable way
- Current LEP limits on M_H
  - 114.4 GeV < M_H < 182 GeV (indirect)

Higgs Production Modes

- Gluon Fusion (GF) — $gg \rightarrow H$
  - Most dominant production mode (cross-section)
- Vector Boson Fusion (VBF) — $qq \rightarrow VV^* \rightarrow Hqq$
  - σ is x10 below GF but VBF gives *much cleaner* signal in detectors
- Associated Production with W,Z — $qq \rightarrow WH / ZH$
  - σ is x15-30 below GF, but allows for unique signatures using W/Z as *tag*
- Associated Production with Heavy Quarks — $qq,gg \rightarrow ttH$
  - σ is x30-60 below GF. Difficult jet/QCD backgrounds

Higgs Production Cross Sections at LHC

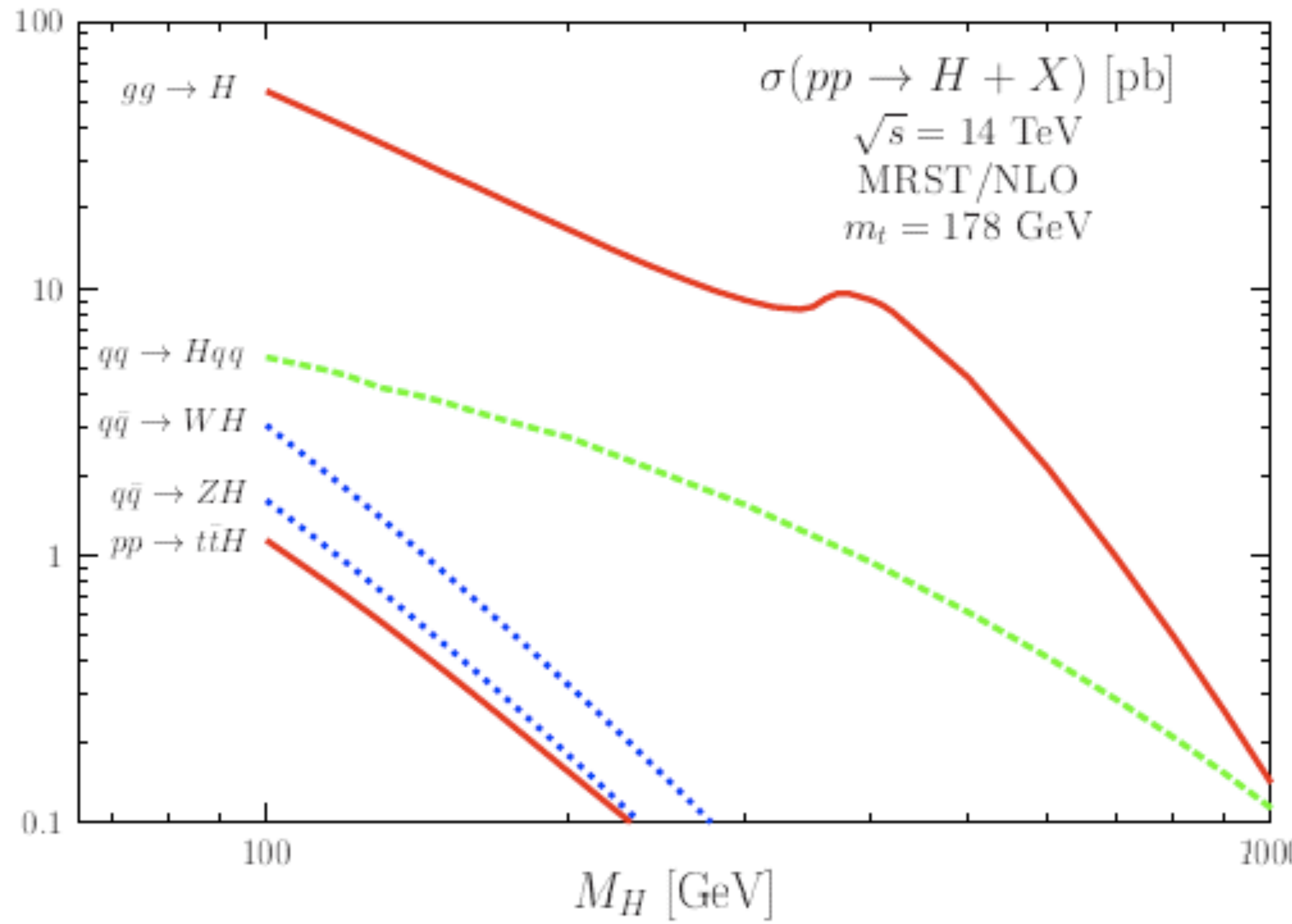
GF

VBF

AP (W,Z)

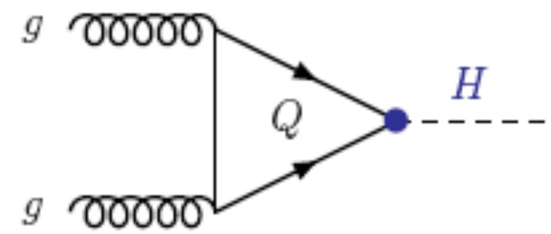
AP (t)

A. Djouadi [arXiv: hep-ph/0503172]



Gluon-Fusion Production

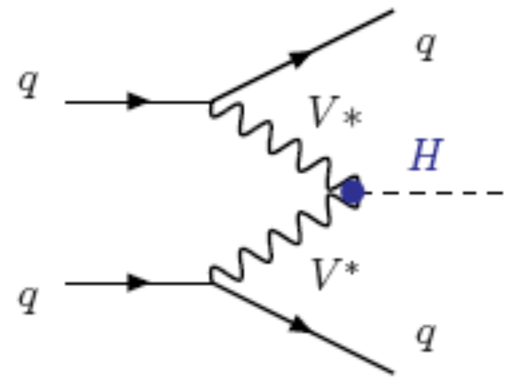
GF



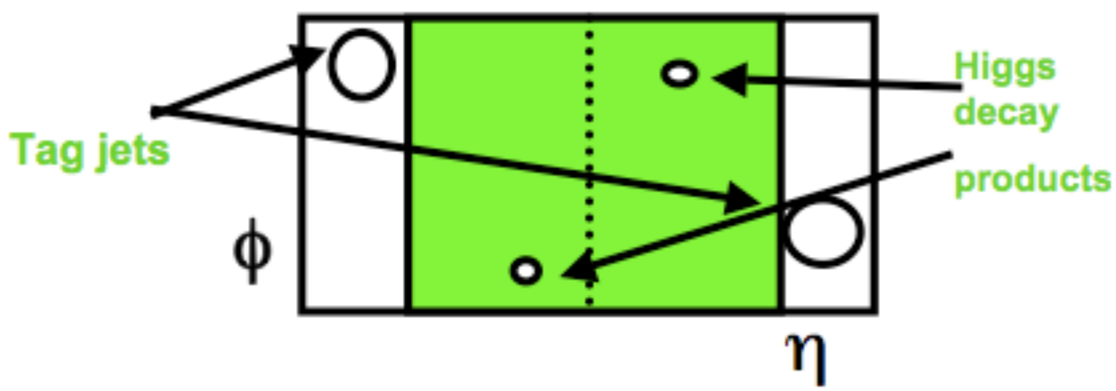
- ~10 orders of magnitude greater production σ in low-mass range
- Dominant production factor for $H \rightarrow \gamma\gamma$ based searches
  - As we will see, this is one of the *cleanest* decay modes in the low-mass (~140 GeV) range
- Lots of QCD background issues at LHC with gluon-fusion production
  - This is why, despite the dominant production cross-section, much effort has been made to calculate/understand the other less dominant production modes

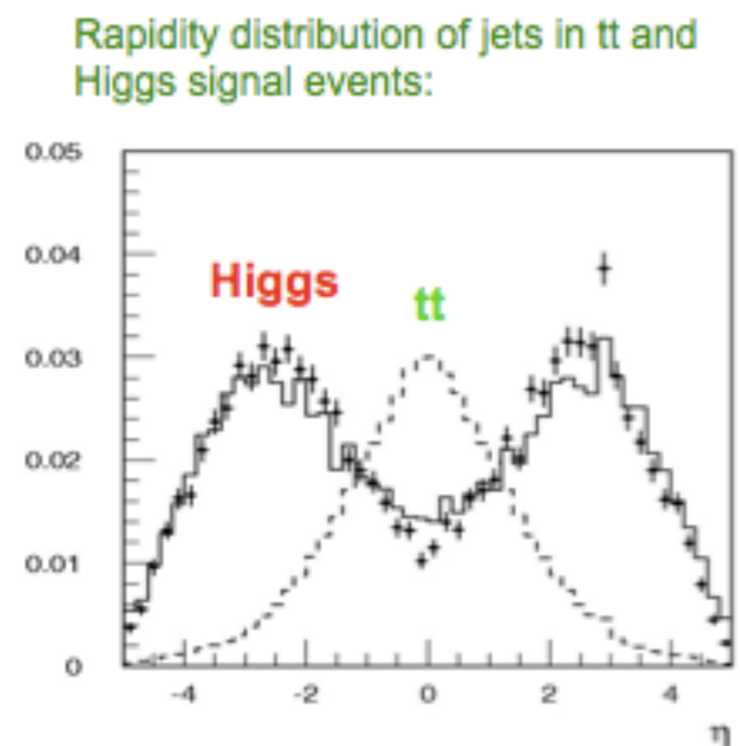
Vector Boson Fusion Production

VBF



- Provides distinctive signature via forward tagging jets
  - Good rejection of QCD background via central jet veto!

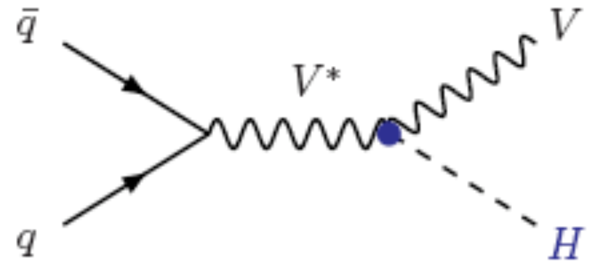




- Importance in low-mass region
  - Dominant production mode for $H \to \tau\tau$ decays (relevant in low-mass region)

Associated Production with W, Z

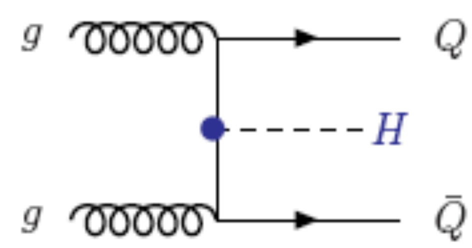
AP (W,Z)



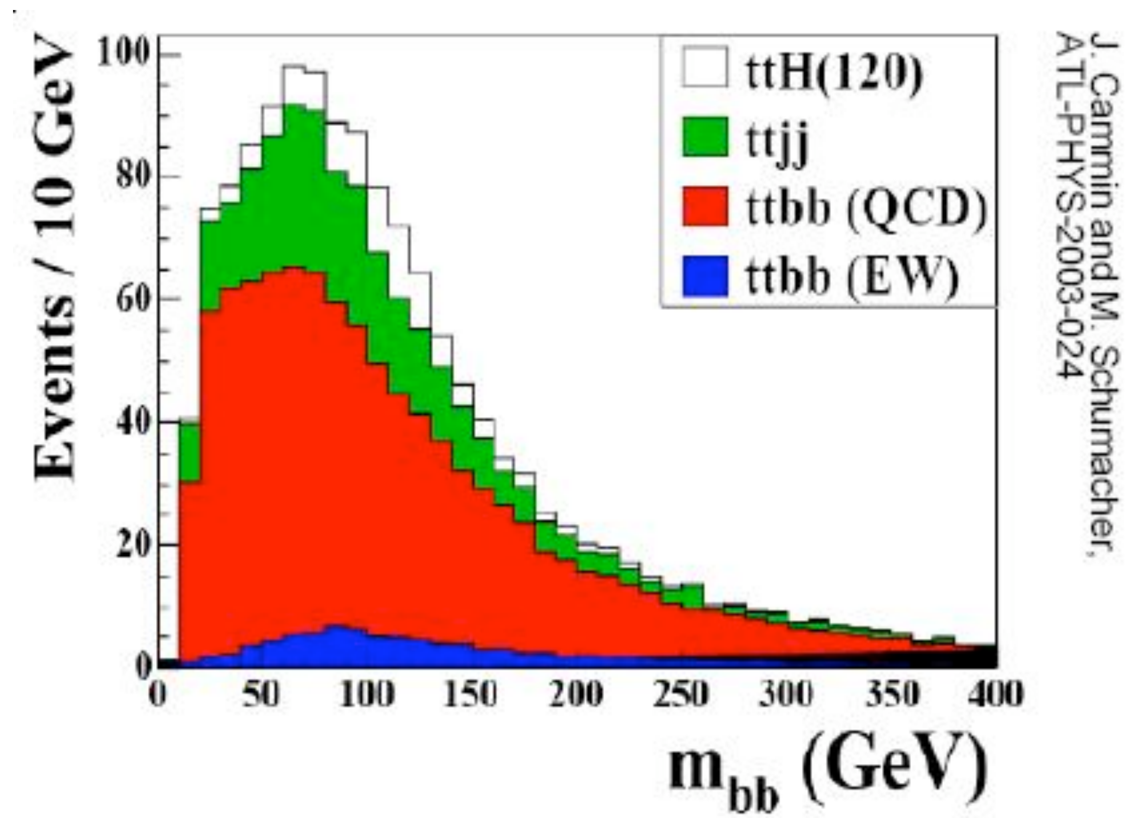
- Sometimes called *Higgs-strahlung*
- Clean signatures from leptonic decays of *W, Z*
  - However, possible high QCD background from hadronic decays of *W, Z*
  - Requires summation of *W, Z* leptonic decays to increase statistics due to low branching ratio of these decays

Associated Heavy Quark Production

AP (t)



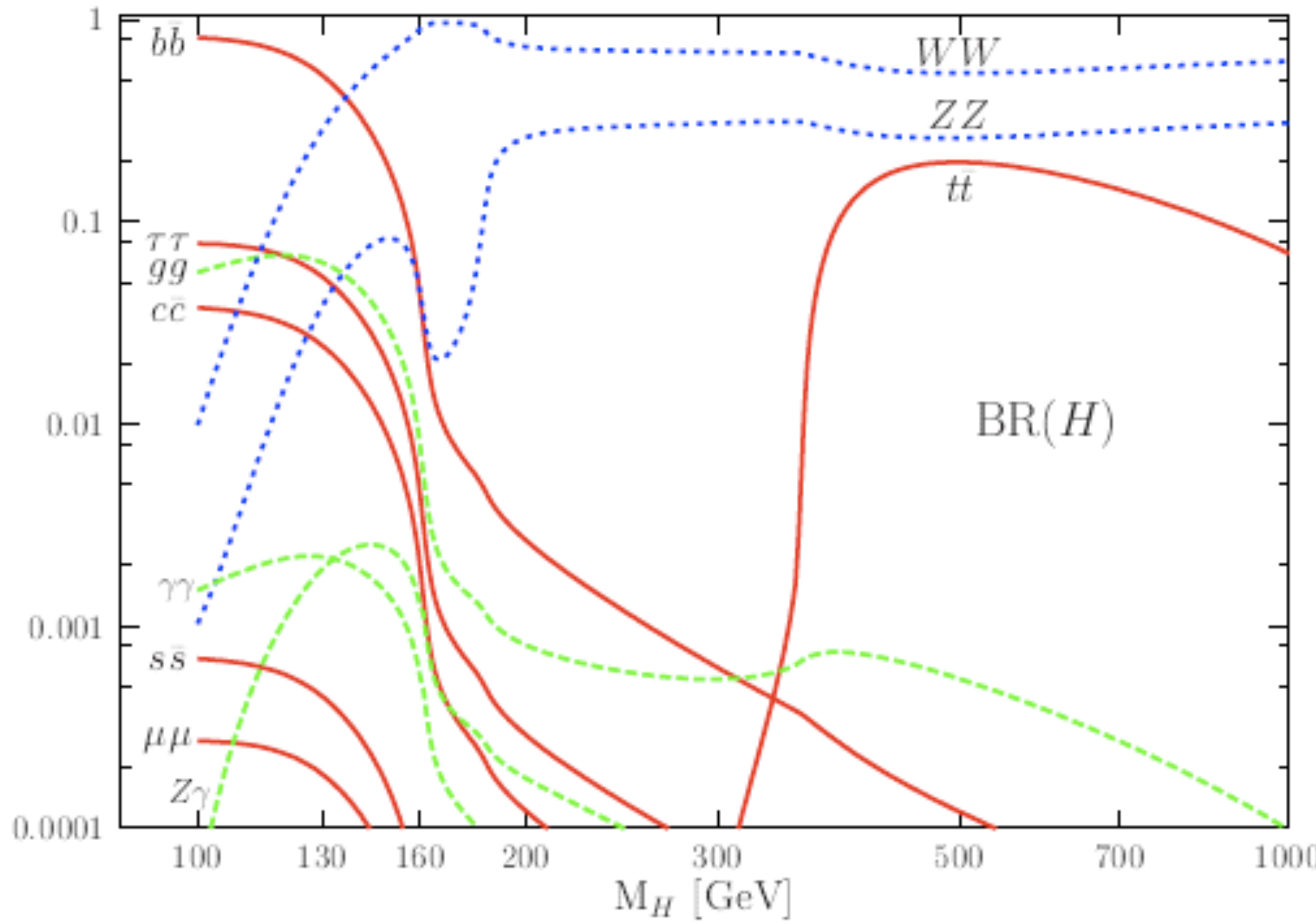
- Complex final states. Dominated by [*ttH* → *bb*]
  - bb state dominates BR at: 100 GeV < M_H < 120 GeV
  - Problem: dominant background: *tt + jets*
- Successful work with this channel requires
  - Good b-tagging!
  - Very good knowledge of jet background



Higgs Decay Modes

SM Higgs decay branching ratio as a function of M_H

A. Djouadi [arXiv: hep-ph/0503172]



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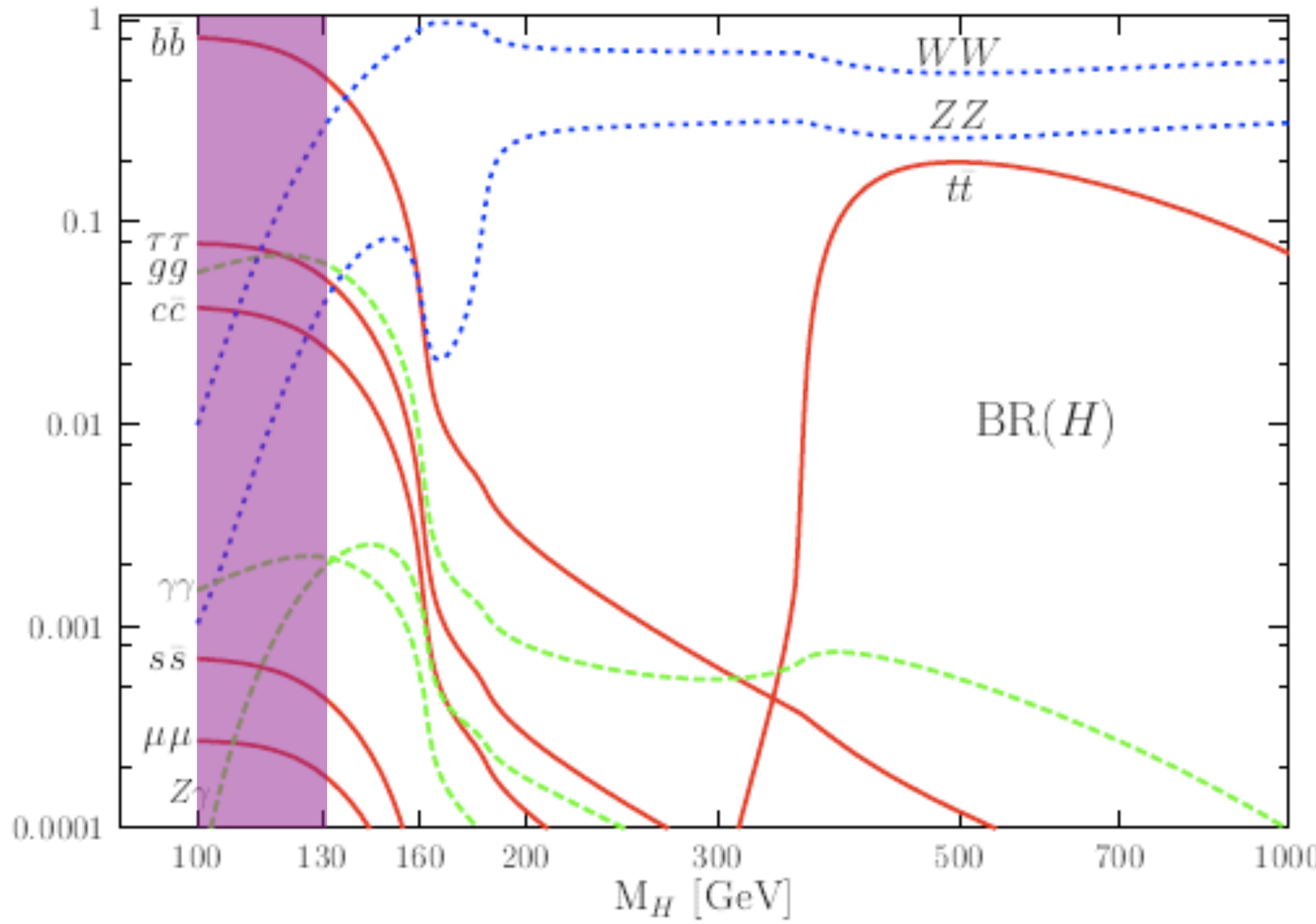

"low mass" range: 110 GeV ≤ M_H ≤ 130 GeV

Higgs Decay Modes

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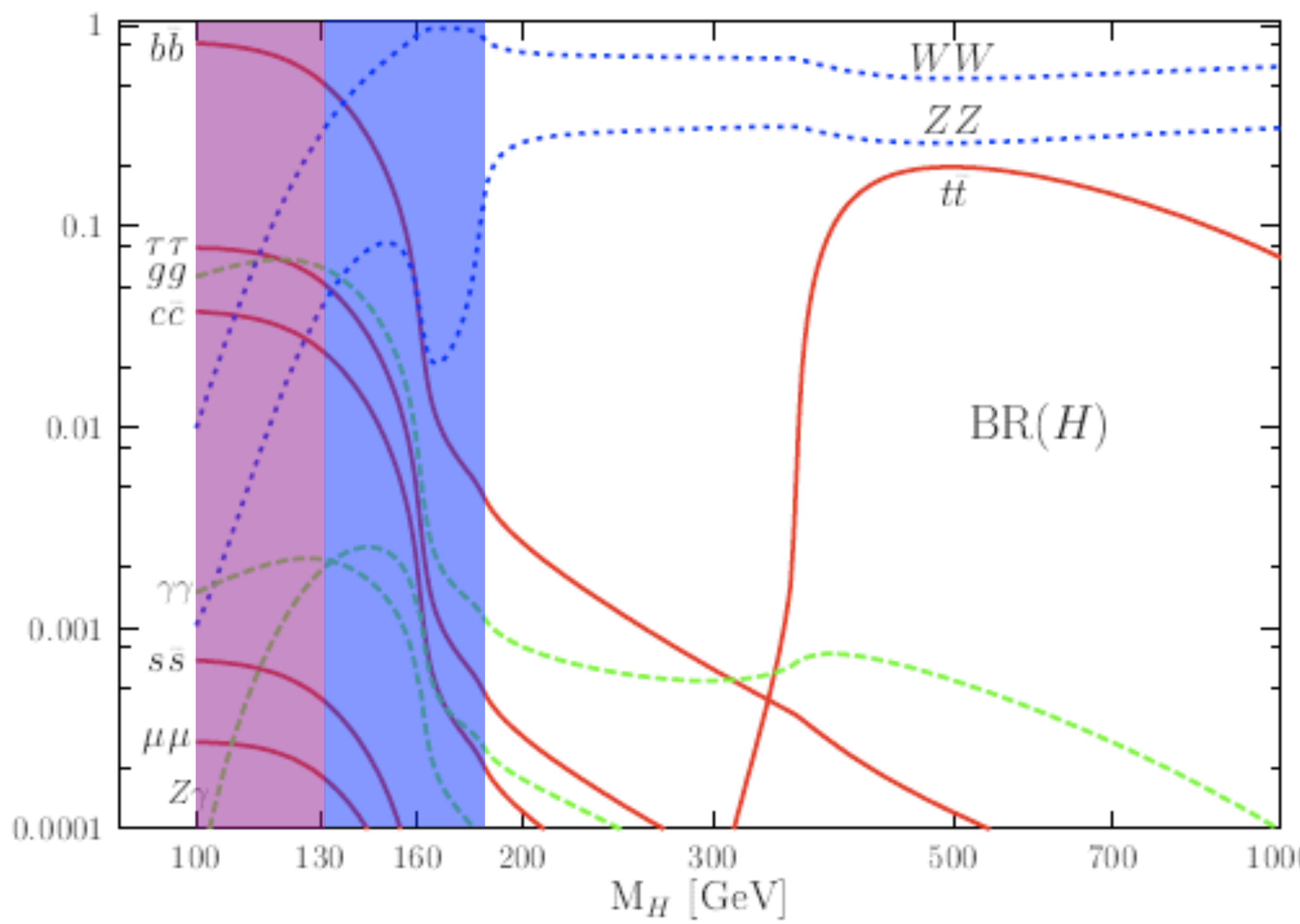

"low mass" range: 110 GeV ≤ M_H ≤ 130 GeV

"intermediate mass" range: 130 GeV ≤ M_H ≤ 180 GeV

Higgs Decay Modes

SM Higgs decay branching ratio as a function of M_H

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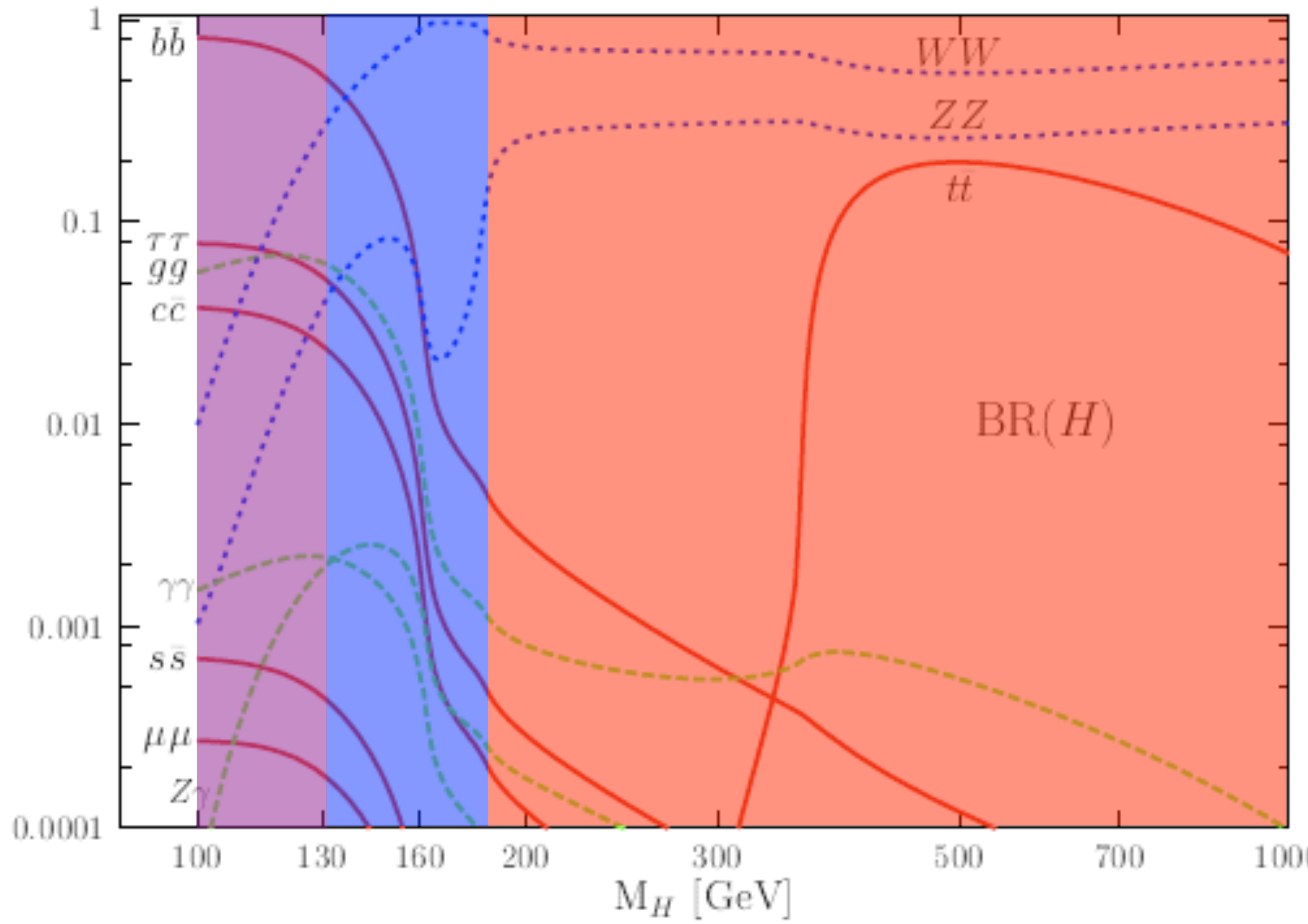


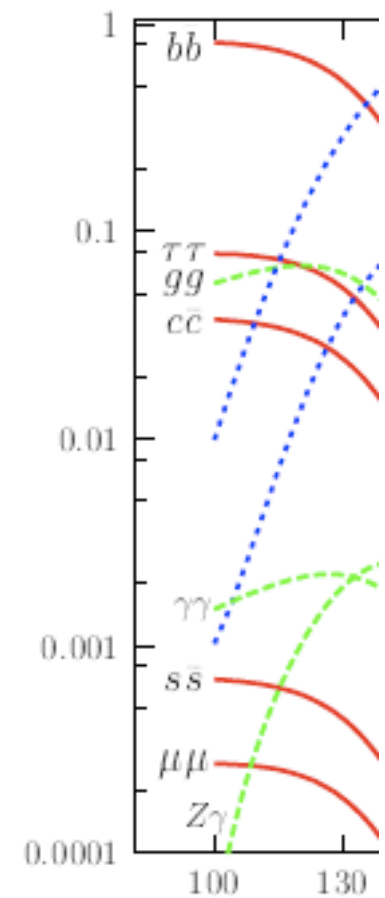
"low mass" range: 110 GeV ≤ M_H ≤ 130 GeV

"intermediate mass" range: 130 GeV ≤ M_H ≤ 180 GeV

"high mass" range: 180 GeV ≤ M_H ≤ 1 TeV

The “low-mass” Range @ the LHC

- In range where: $M_H < 2M_{W,Z}$ fermionic decay modes dominate
- Higgs will decay to heaviest fermions allowed by energy conservation
- However, *qq* final states have too much QCD background at LHC to be useful as a search channel
    - This is why emphasis is placed on other channels ($H \to \tau\tau$, $H \to \gamma\gamma$) despite their lower branching ratios



Primary Search Channels @ LHC

- Four Lepton Decay: $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ $(4e, 4\mu, 2e2\mu)$
- Two Photon Decay: $H \rightarrow \gamma\gamma$
- Tau Pair Decay: $H \rightarrow \tau^{+} \tau^{-}$
- W-Boson Pair Decay: $H \rightarrow W^{+}W^{-} \rightarrow \ell\nu\ell\nu$ ($\ell = e^{\pm}$ or $\ell = \mu^{\pm}$)

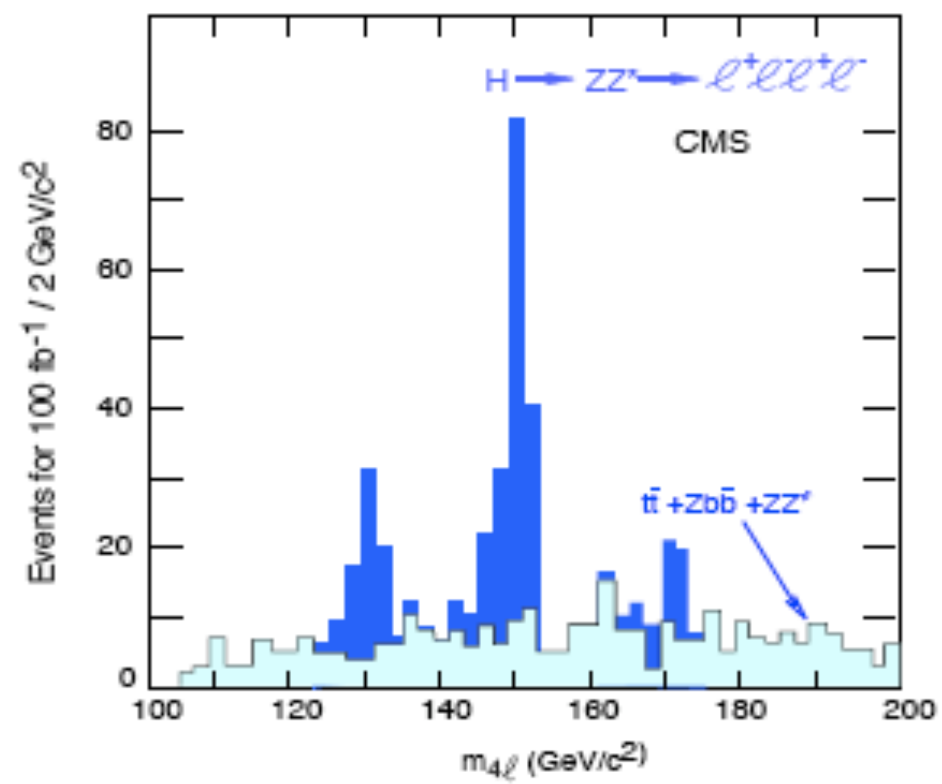
$H \rightarrow ZZ^{*} \rightarrow$ *4 lepton* Decays

- Provides clean signature for wide range of M_H above ~130 GeV
  - Except in range ($2m_W$, $2m_Z$) where branching ratio is dominated by $H \rightarrow W^{+} W^{-}$
- Background:
  - Irreducible: Direct ZZ^{*} and $Z\gamma^{*}$ production
  - Reducible: *tt, Zbb, ZW* production
- At least one *Z* is expected to be on mass shell
  - Two-lepton invariant mass is used to confirm this and reject false events
- Method relies heavily on:
  - lepton reconstruction
  - invariant-mass resolution

Background Suppression in 4 Lepton Decay

Backgrounds from ZZ^*, *tt*, *Zbb* processess are supressed via:

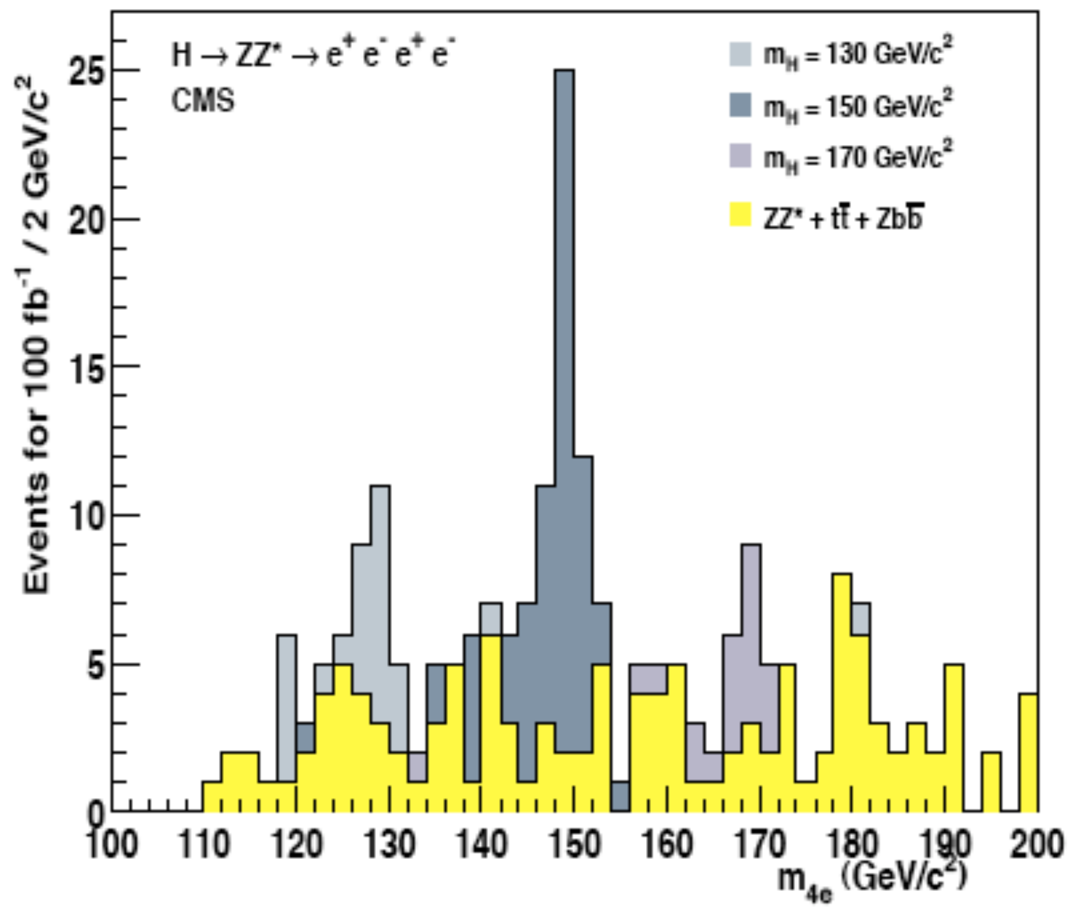
- Require leptons to be isolated in the tracker
- Cuts on 2-lepton & 4-lepton invariant mass
  - Require at least one of the 2-lepton invariant mass to be consistent with on-shell *Z*
- Require p_T threshold
  - For CMS typically p_T > 20GeV for largest p_T lepton



Four-lepton invariant mass of $H \to ZZ^* \to 4\ell$ signal with M_H = 130,150,170 GeV

S. Abdullin et. al., CMS Note 2003/033

$H \to ZZ^* \to 4e$ In "intermediate" M_H Range



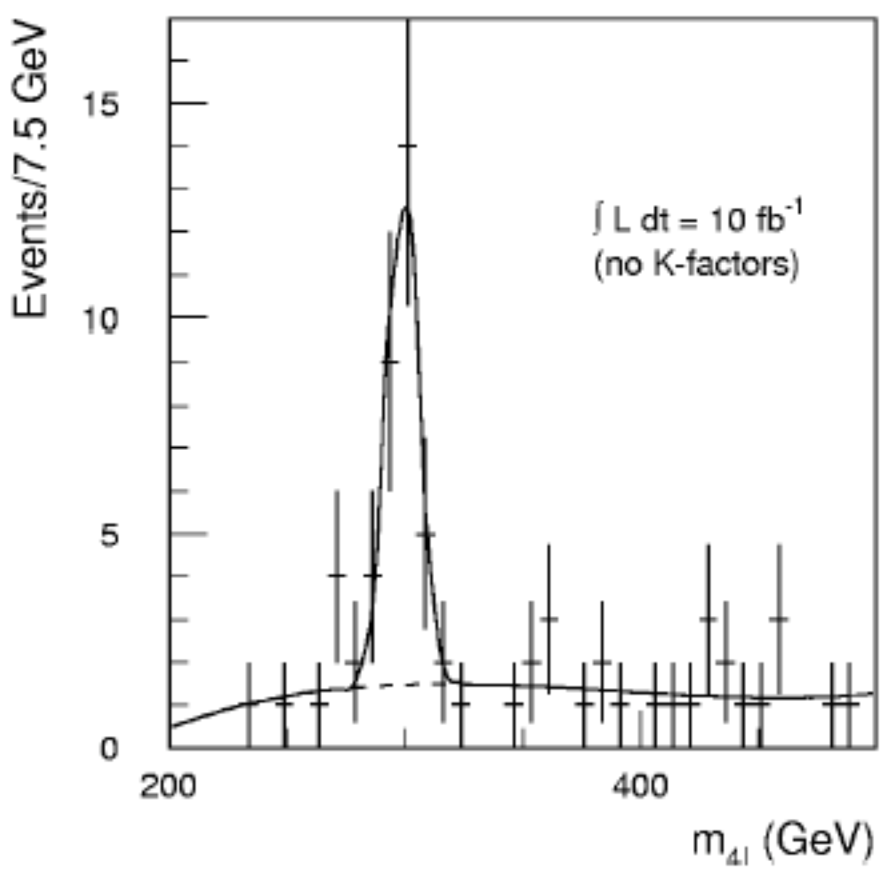
Four-electron invariant mass of $H \to ZZ^* \to 4e$ signal with M_H = 130,150,170 GeV

S. Abdullin et. al., CMS Note 2003/033

4 Lepton Decay in “high” M_H Region

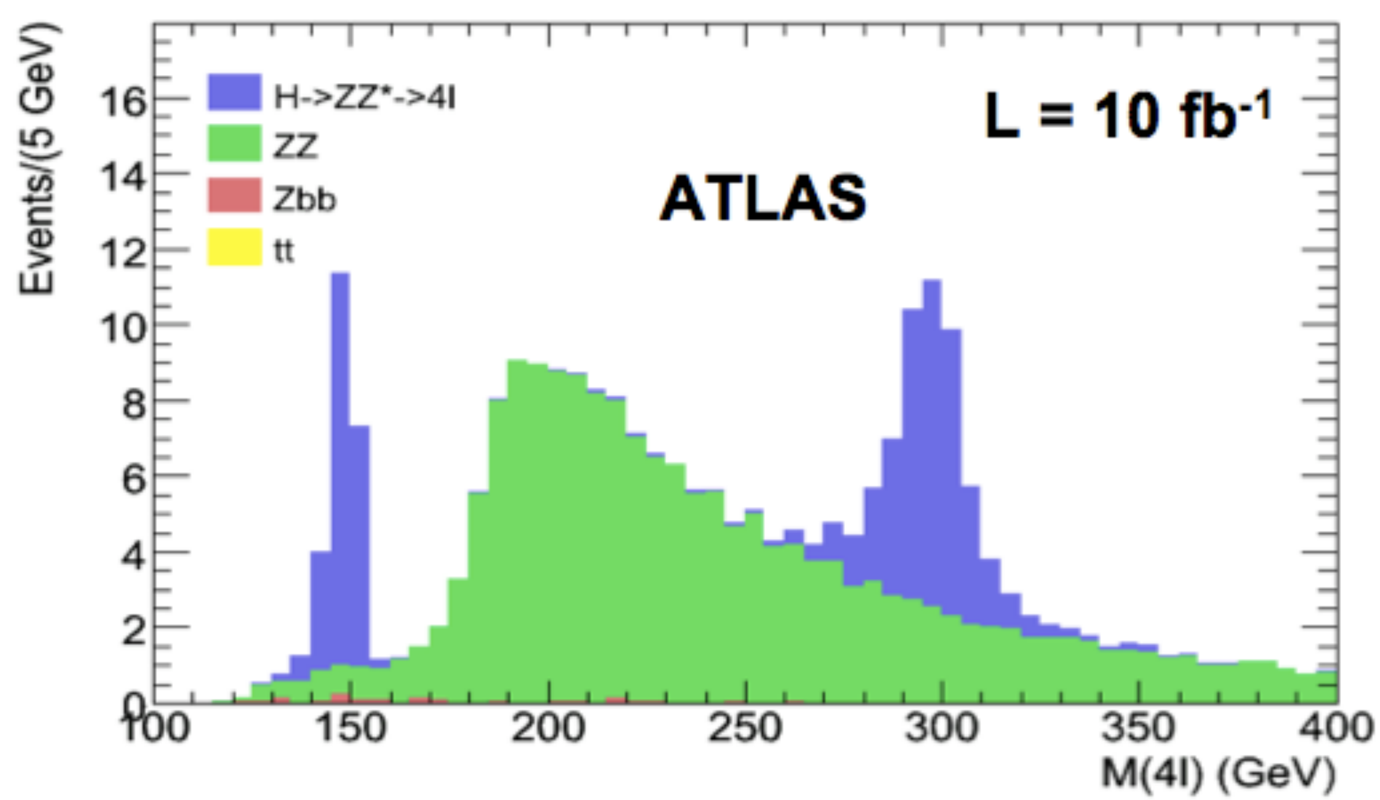
$H \to ZZ^{*} \to 4\ell$ signal presents an important discovery channel in “high” mass region as well

Buescher [arXiv: hep-ph/0504099]



Expected H→ZZ→4ℓ signal above background for M_H = 300 GeV in ATLAS experiment.

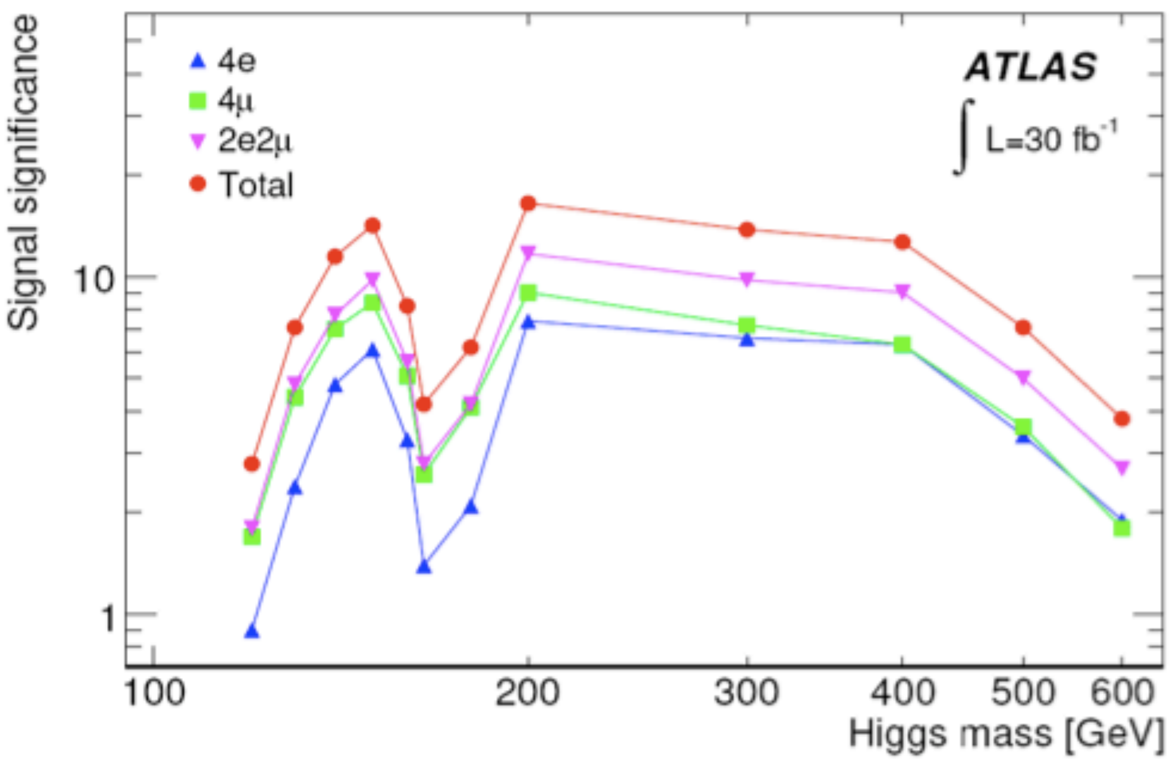
K. Assamagan

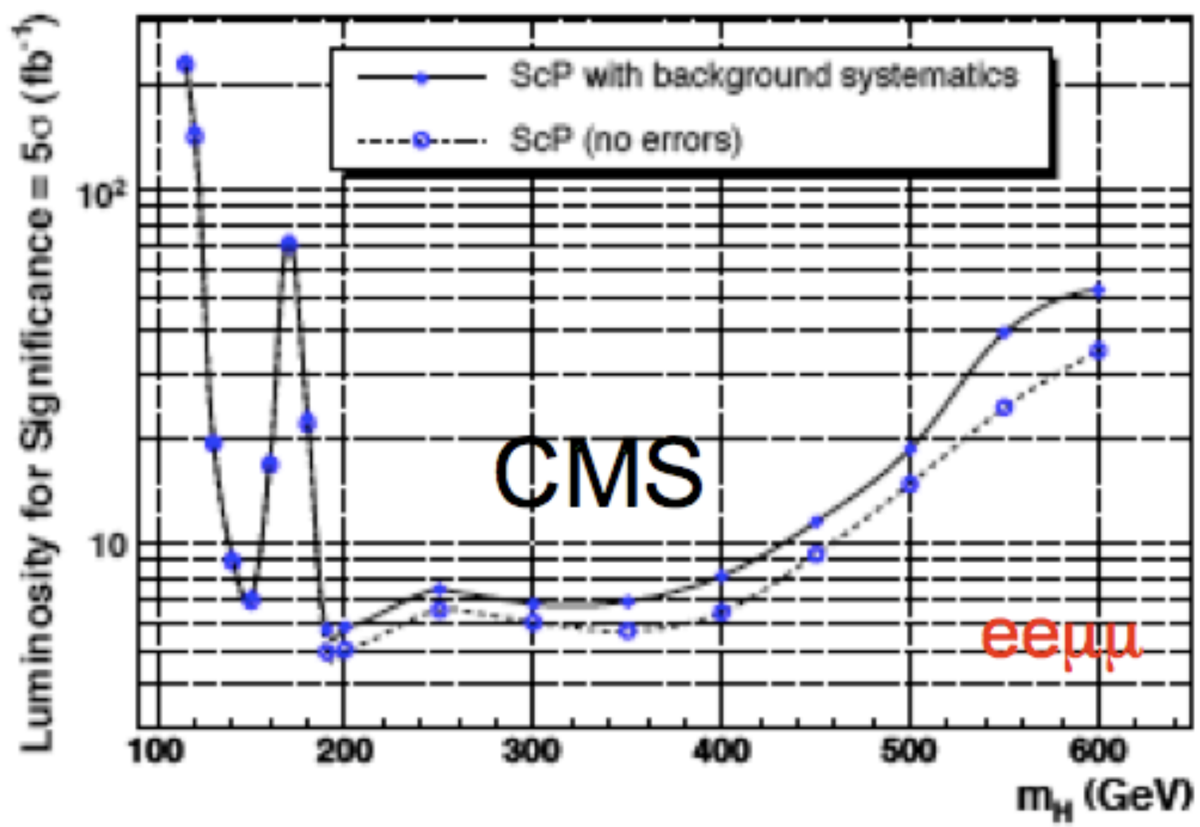


Expected H→ZZ→4ℓ signal for range of M_H in ATLAS experiment.

Discovery Potential of 4 Lepton Decay

K. Assamagan





Very high discovery potential in $H \rightarrow ZZ^{*} \rightarrow 4\ell$ channel

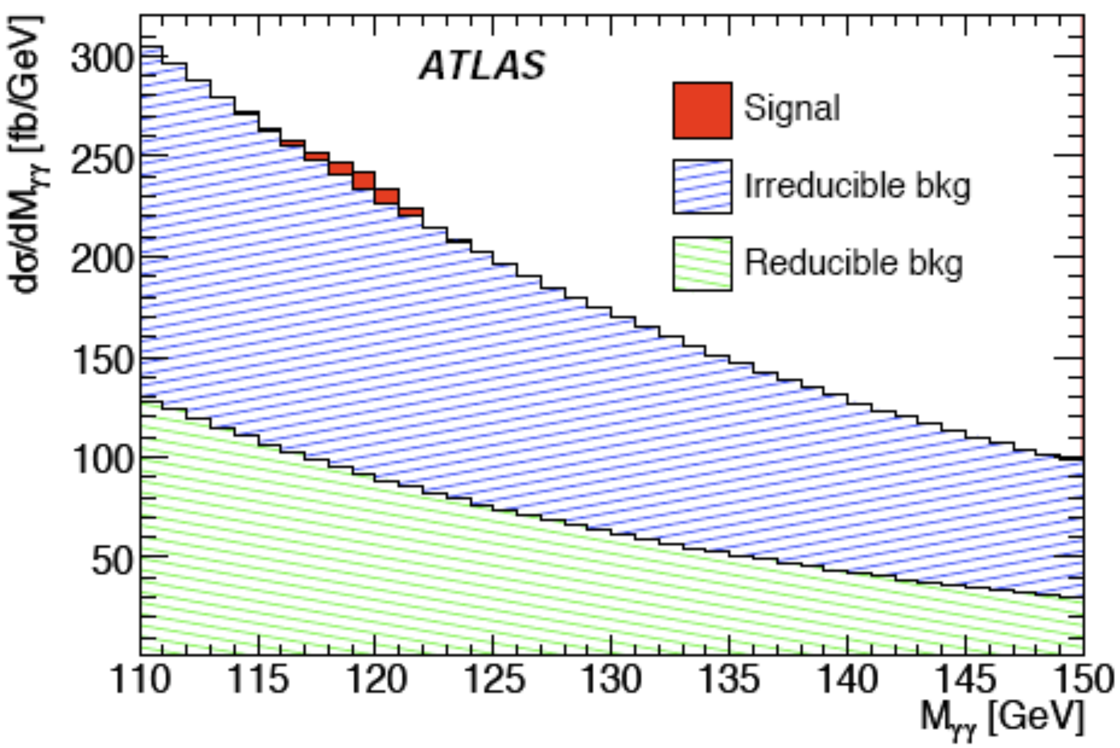
$H \rightarrow \gamma\gamma$ Decays

- Decay mode only detectable in region: 80 GeV < M_H < 150 GeV
- Requires excellent energy and angular resolution!
- Method relies on detecting mass peak above:
  - Irreducible background from prompt $\gamma\gamma$ continuum
  - Reducible background from direct γ production + QCD jet production
- Simulation studies have brought sources of reducible background to ~20% of irreducible background
- Efficiency and purity of this method depend heavily on minimum-bias event model and p_T spectrum of H
  - high p_T tracks used to distinguish Higgs events from pileup

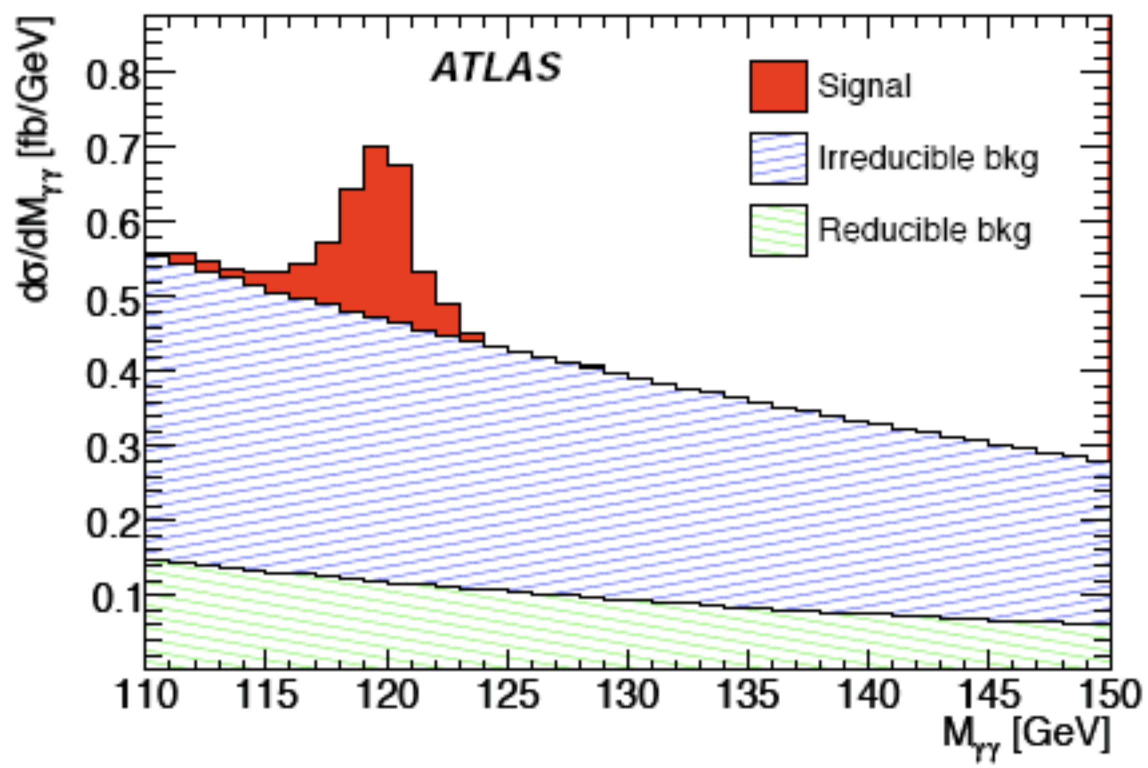
$H \to \gamma\gamma$ - Event Selection

Signal Process	Cross-section (fb)	Background Process	Cross-section (fb)
$gg \to H$	21	$\gamma\gamma$	562
VBF H	2.7	Reducible γj	318
ttH	0.35	Reducible jj	49
VH	1.3	$Z \to e^+e^-$	18

Expected cross-sections for different signal (M_H = 120 GeV) and background processes within a mass window of $m_{\gamma\gamma} = \pm 1.4\sigma$



Diphoton mass spectrum with fiducial and p_T cuts applied.

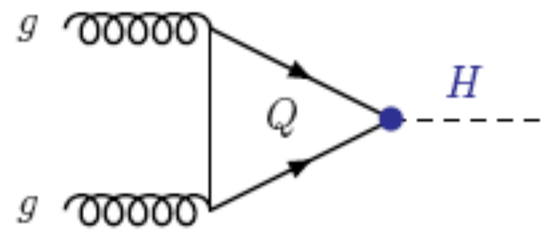


Diphoton mass spectrum based on event selection requiring the presence of two tagging jets

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020

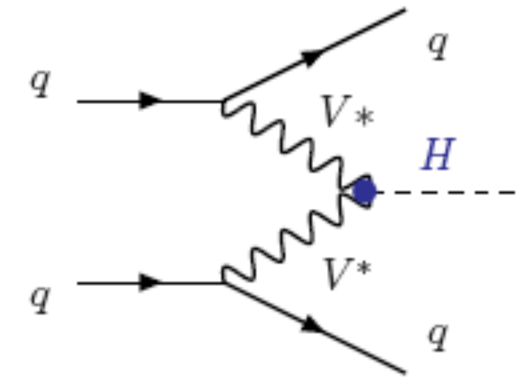
$H \rightarrow \gamma\gamma$ - Inclusive vs VBF

GF

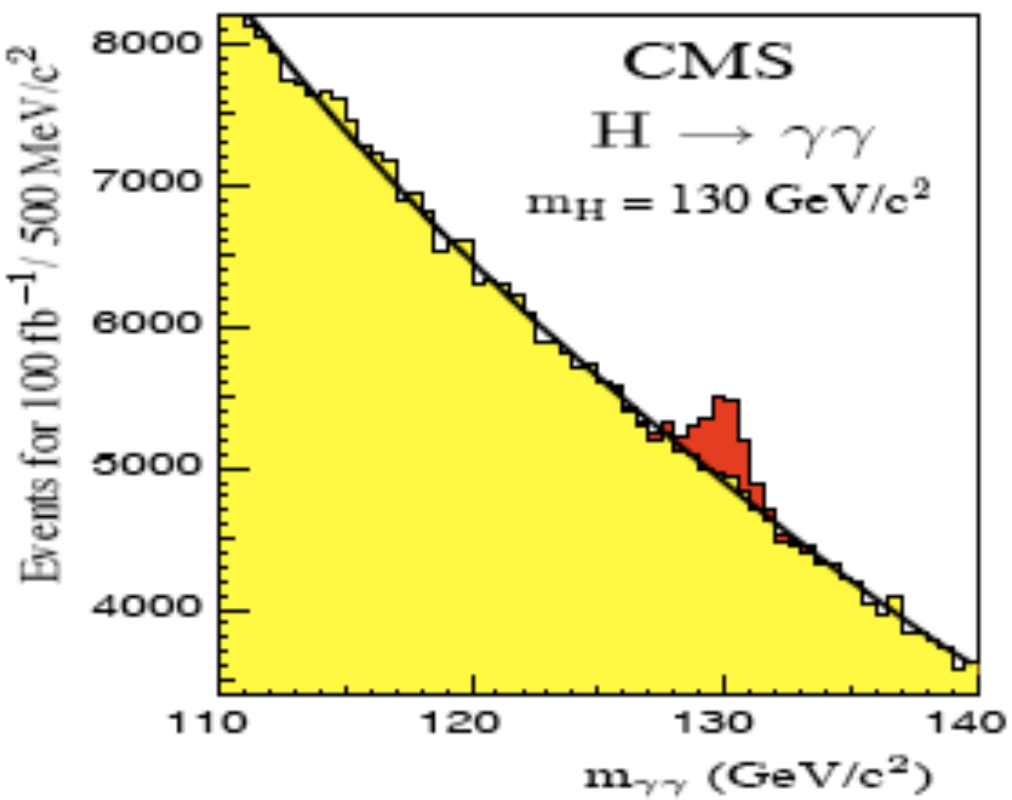


~83% of σ_H

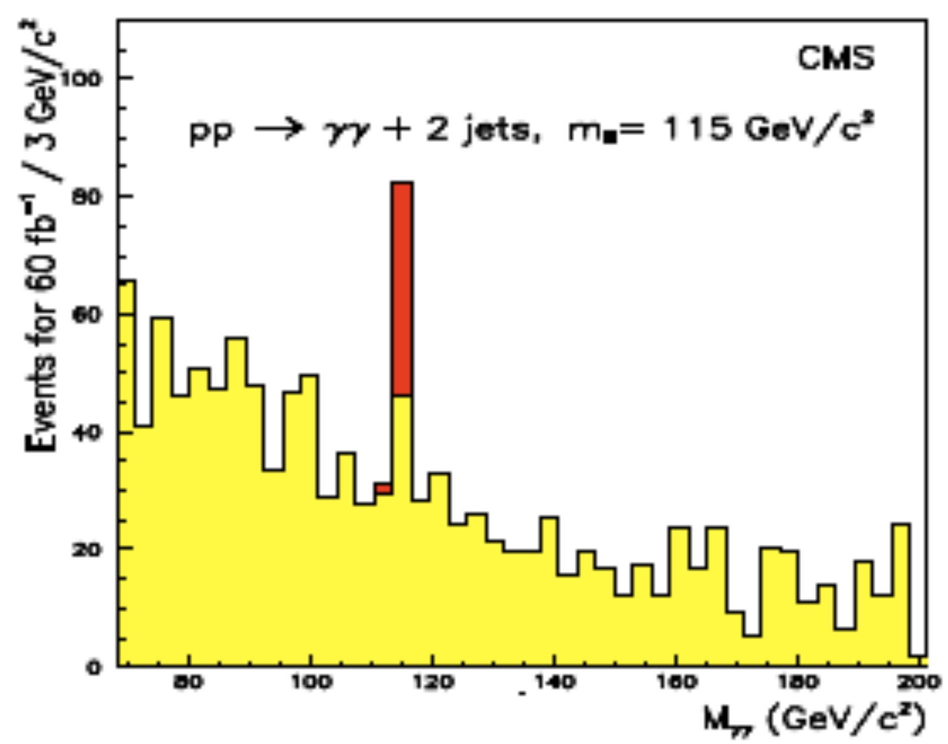
VBF



~10% of σ_H



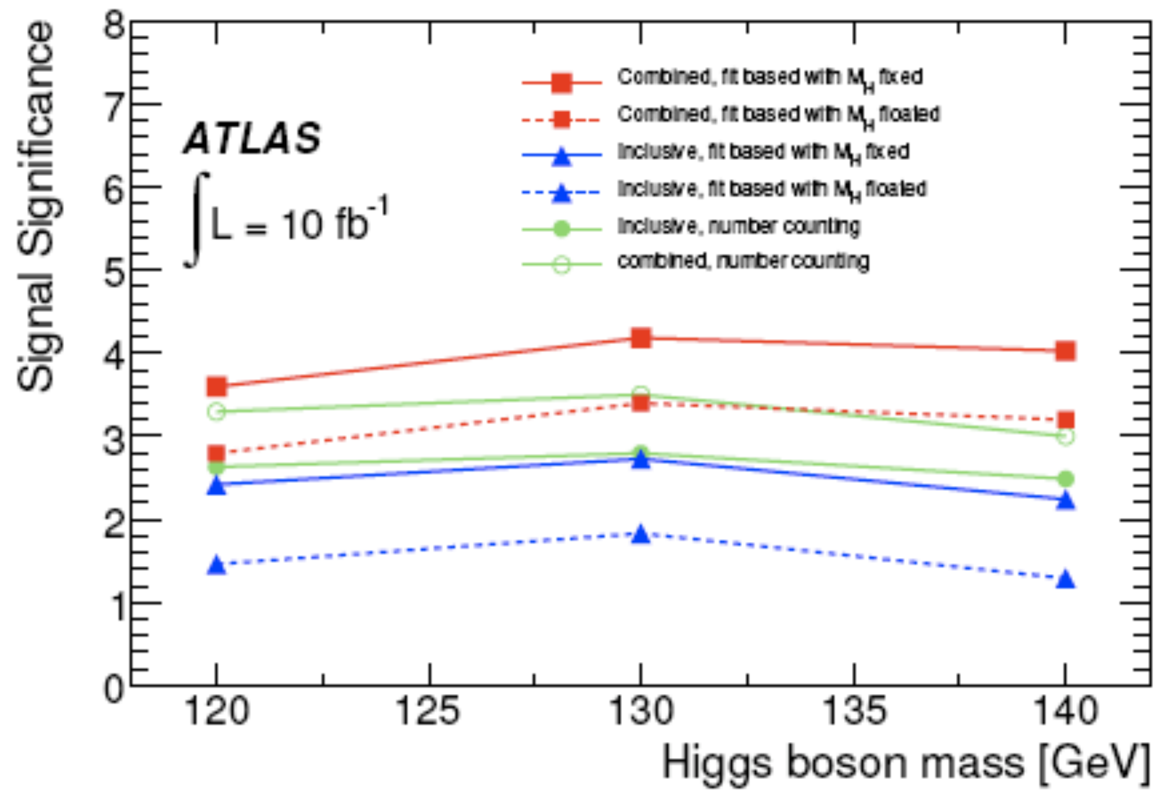
Di-photon invariant mass distribution for inclusive $H \rightarrow \gamma\gamma$ signal. Yellow represents irreducible prompt $\gamma\gamma$ production and $j\gamma$ QCD processes



Di-photon invariant mass distribution for VBF, $H \rightarrow \gamma\gamma$. Yellow represents irreducible $jj\gamma\gamma$ background

S. Abdullin et. al., CMS Note 2003/033

$H \to \gamma\gamma$ - Discovery Potential



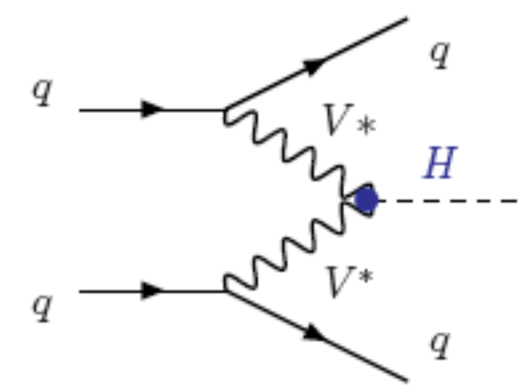
Expected signal significance for a Higgs boson using the $H \to \gamma\gamma$ decay for $10 fb^{-1}$ of integrated luminosity as a function of the mass using a variety of analysis/fit methods.

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020

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

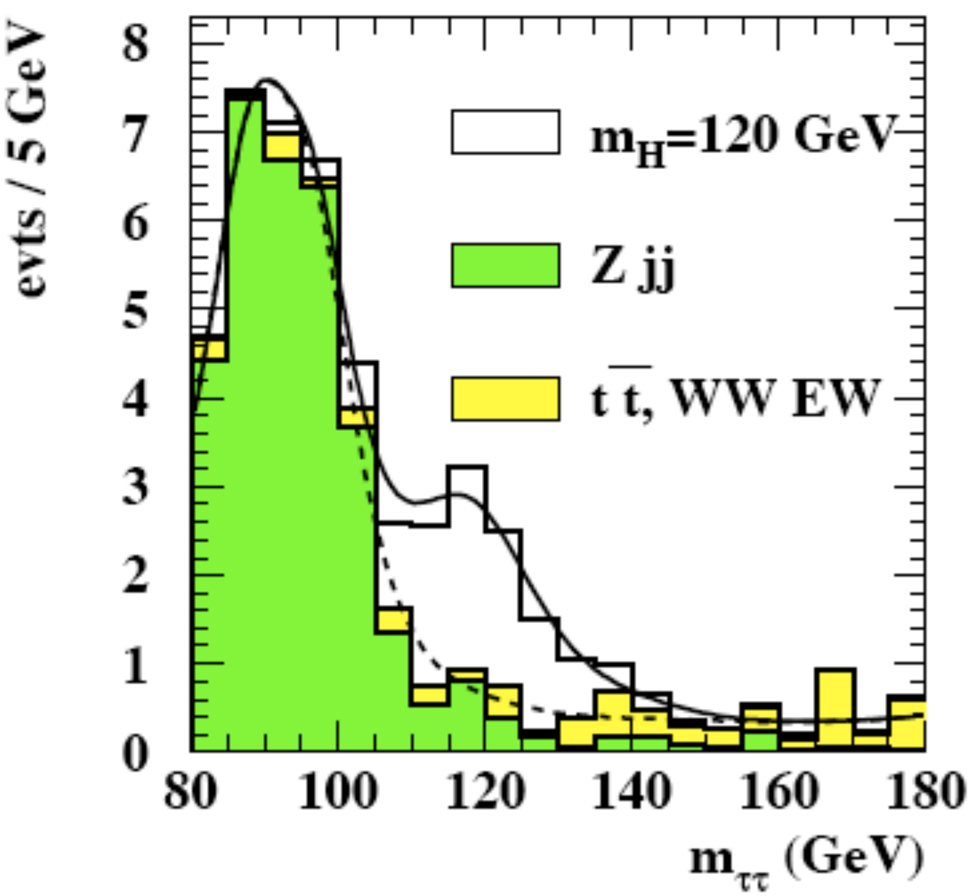
- Provides one of the best sensitivities in "low" M_H range
- Searches based on
  - double leptonic decay: $qqH \rightarrow qq\tau\tau \rightarrow qql\nu\bar{\nu}l\nu\bar{\nu}$
  - lepton-hadron decay: $qqH \rightarrow qq\tau\tau \rightarrow qql\nu\bar{\nu} + \text{had} + \nu$
- $\tau\tau$ invariant mass reconstruction based on collinear approximation
  - Assume τ directions are collinear to measured decay products
- Primary background from *Z+jets* with $Z \rightarrow \tau^+ \tau^-$
  - Other backgrounds: *W+jets, tt, di-jets*
- Analysis methods rely on VBF
  - Lack of color flow between interacting partons results in diminished hardonic activity in barrel region
  - Forward tagging jets used to reject SM background

VBF



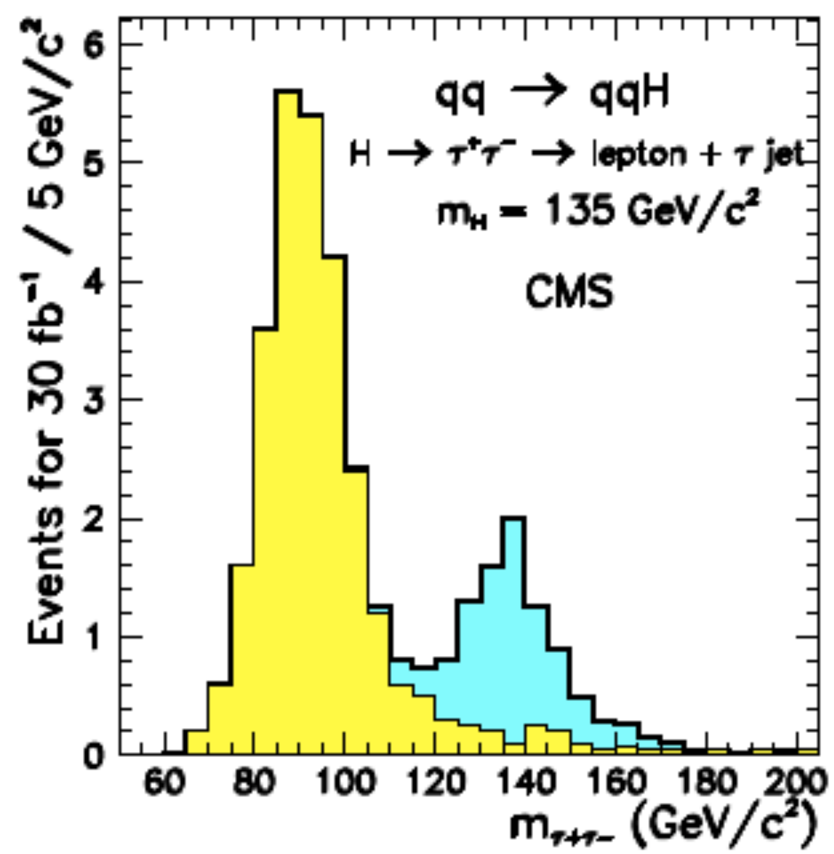
$H \rightarrow \tau^+\tau^-$ - Signal vs Background

Buescher [arXiv: hep-ph/0504099]



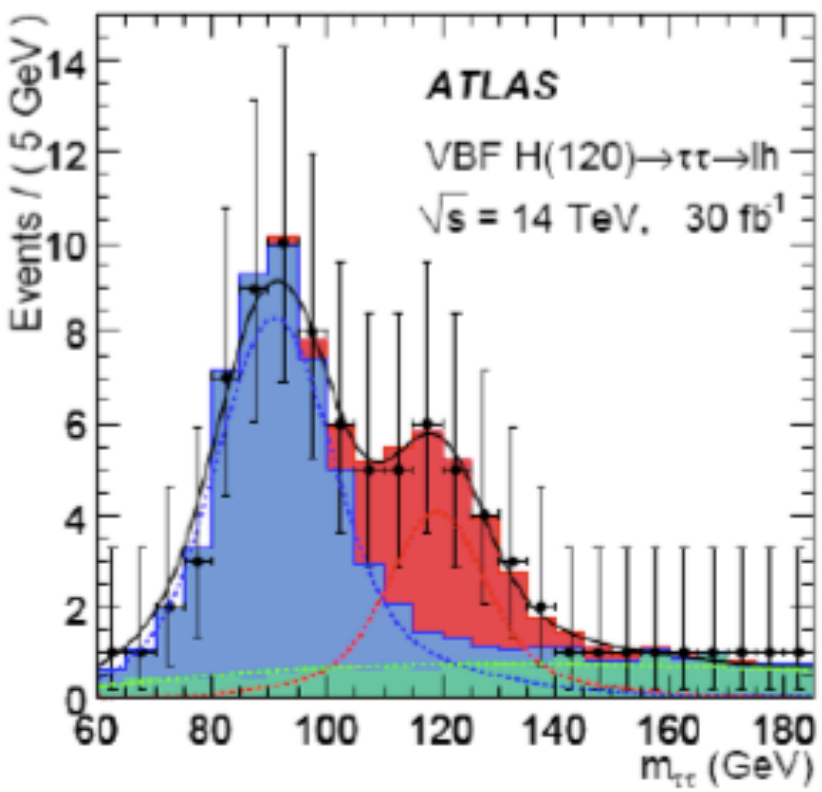
Reconstructed ττ invariant mass for M_H of 120 GeV in the eμ channel after application of all cuts (except mass window)

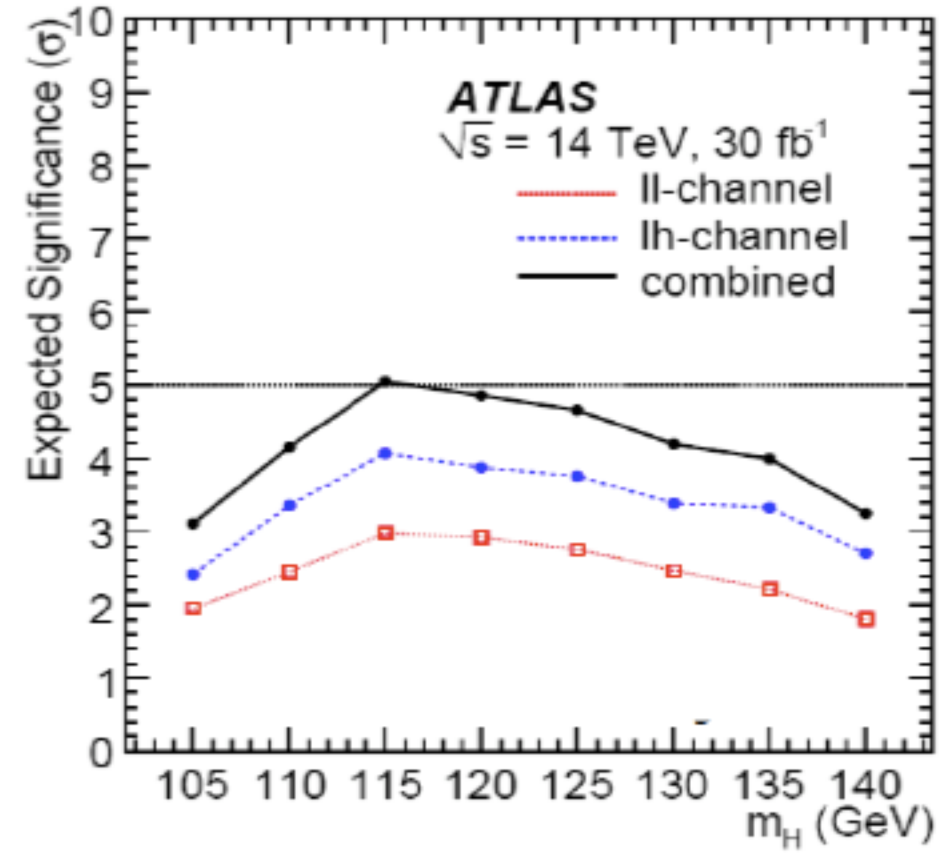
Buescher [arXiv: hep-ph/0504099]



Reconstructed ττ invariant mass for M_H of 135 GeV in the ℓ+*had*ron channel after application of all cuts (except mass window)

Discovery Potential of $H \rightarrow \tau^+\tau^-$ Channel





Discovery in "low" M_H region possible with 30 fb^{-1}

Expected Performance of the ATLAS Experiment, CERN-OPEN-2008-020

W Boson Pair Decay

$$H \rightarrow W^+W^- \rightarrow l\nu l\nu$$

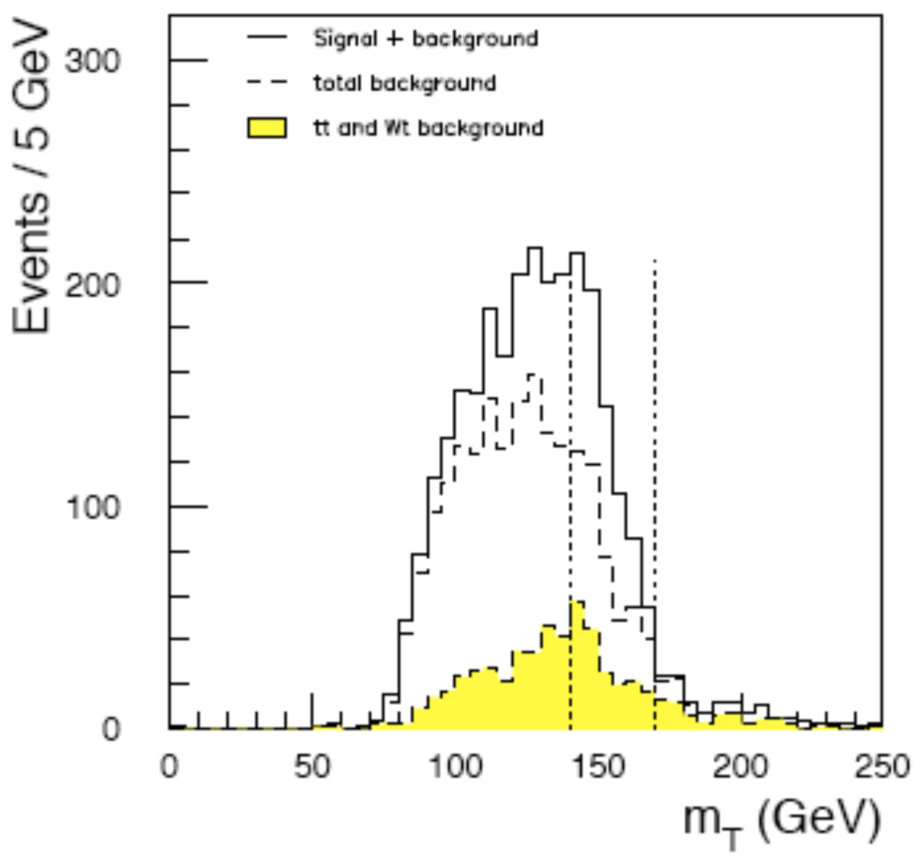
- Provides most sensitive search in range: $2m_W < M_H < 2m_Z$
  - Due to dominating $H \rightarrow WW$ branching ratio in this mass range (~95%)
- Primary source of background from direct W^+W^- production (and *tt* production)
  - Strongly reduced by cuts based on angular correlation of the *W* decay products due to spin correlation of the two *W* bosons in *H* frame (Lepton Opening Angle)
  - *tt* background reduced via veto on central jets
  - Can also extend search to utilize VBF production (tagging jets in final state)
- Problem: Cannot reconstruct Higgs mass peak due to neutrinos in final state!

W Boson Decay - Neutrinos in Final State

- Presence of high p_T neutrinos makes reconstruction of Higgs mass peak unfeasible.
- Excess of events above expected backgrounds used to establish presence of Higgs
- Transverse mass based on lepton p_T and missing E_T is used to discriminate between signal and background
  - In the inclusive channel:

$$m_T = \sqrt{2 P_T^{ll} \not{E}_T (1 - \cos\Delta\varphi)}$$

Buescher [arXiv: hep-ph/0504099]

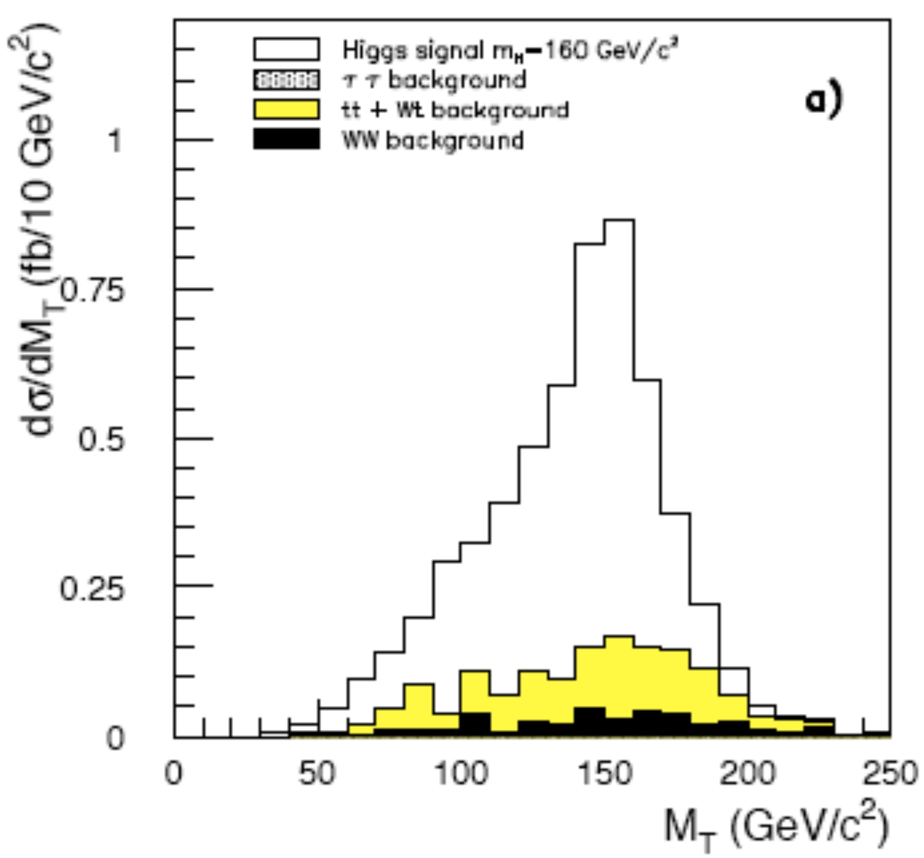


Transverse mass distribution for summed H→WW→lνlν signal with M_H of 150 GeV

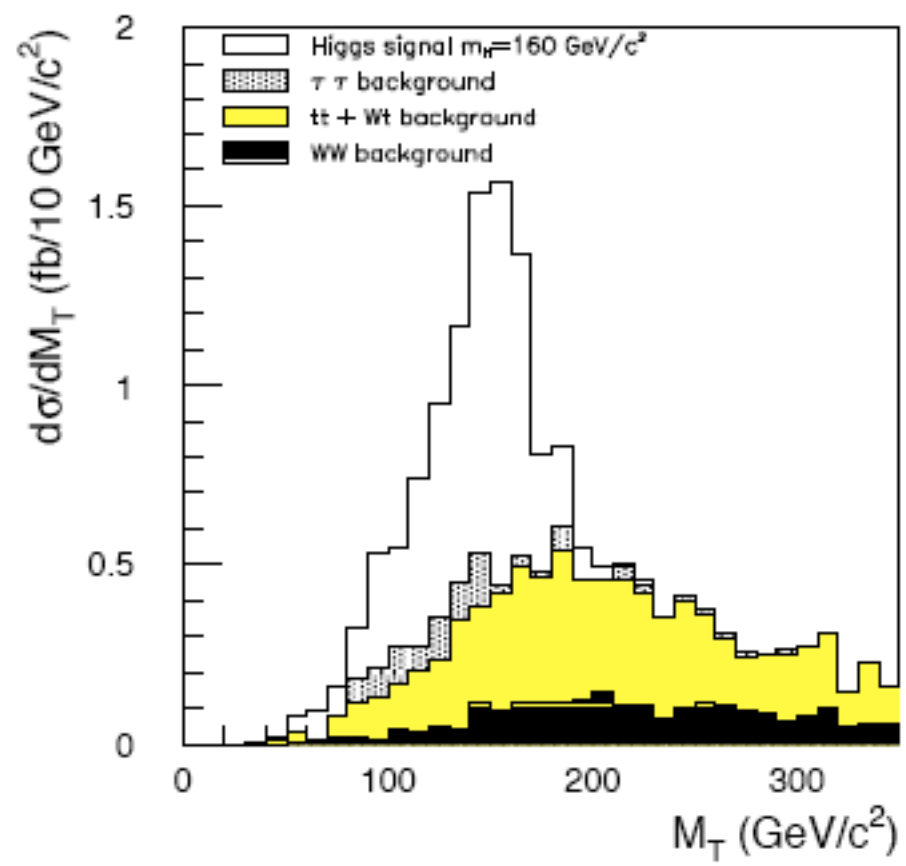
W Boson Decay - VBF Event Selection

VBF

- Further signal enhancement obtained via VBF production mode
  - Presence of tagging jets and veto on central jet activity allow additional suppression of background
  - Result: Signal sensitivity less affected by prediction of background rates
- Here, transverse mass defined as: $m_T = \sqrt{\left(E_T^{ll} + E_T^{\nu\nu}\right)^2 + \left(\vec{p}_T^{\,ll} + \vec{\not{p}}_T\right)^2}$



Buescher [arXiv:hep-ph/0504099]

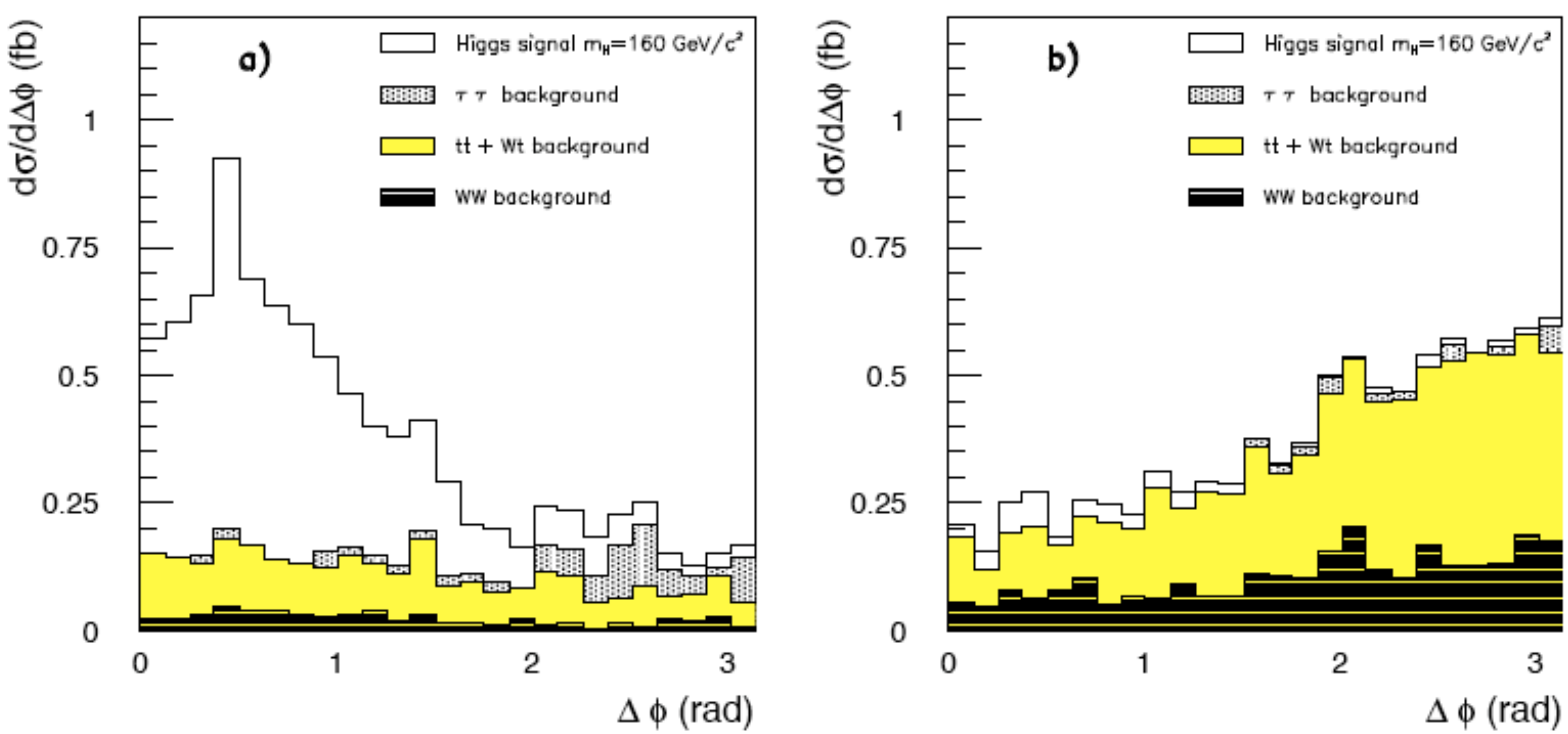


Distribution of transverse mass for M_H of 160 GeV and backgrounds in the eμ channel.
Right plot shows same distribution after relaxing kinematic cuts.

W Boson Decay - Lepton Opening Angle

- Presence of $H \rightarrow WW$ signal can also be determined via the difference of the azimuthal angle between the two leptons in the final state.
  - Expect to see structure at small $\Delta\Phi$ characteristic of spin-0 resonance

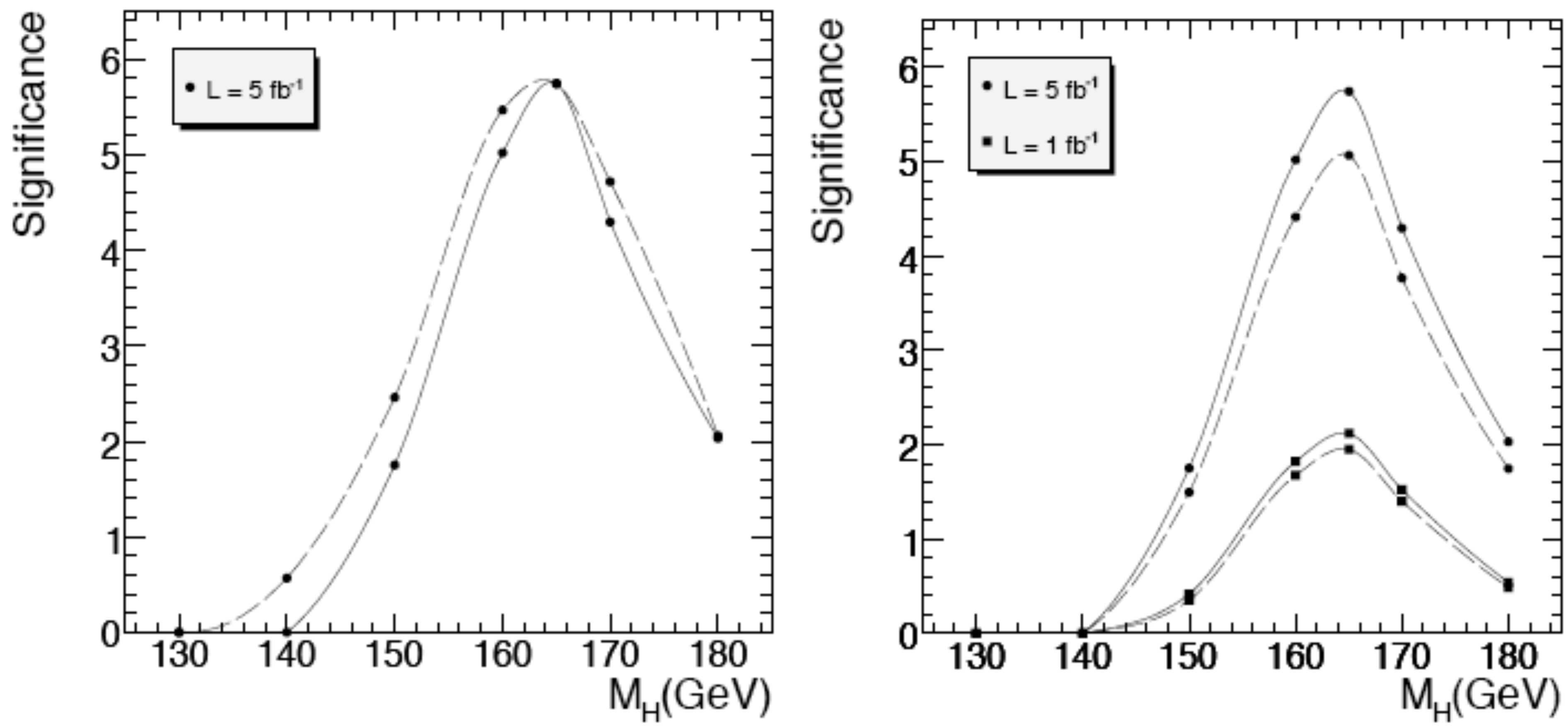
$m_T < 175$ GeV $m_T > 175$ GeV



Distribution of azimuthal opening angle $\Delta\Phi$ between two leptons for events in the signal region (left) and events outside of the signal region (right)

Buescher [arXiv: hep-ph/0504099]

W Boson Decay - Discovery Potential



Significance as a function of different Higgs masses with a luminosity of 5 fb^{-1}, solid line for kinematic cuts optimized at M_H = 165 GeV, dashed line for kinematic cuts optimized as a function of the Higgs mass

Discovery potential in $2m_W < M_H < 2m_Z$ range with 5 fb^{-1}

V. Drollinger et. al., CMS Note 2006/055

Invisible Higgs Decays

- Several extensions to SM allow for the Higgs boson (or the lightest scalar which plays its role if several are present) to have substantial branching ratios to invisible decay products
- In such models, the light Higgs will decay to *Goldstone bosons*, *Majorons*, or a pair of the *lightest SUSY particles (LSP)*
  - None of these interact with the detector
- Occurs in a variety of SUSY extensions to SM:
  - light neutralinos, spontaneously broken lepton number, radiatively generated neutrino masses, additional singlet scalars, right handed neutrinos in the extra dimensions of TeV scale
- Ex SUSY: Current limits on M_H in general SUSY model kinematically allow for a decay into two LSPs with a BR as high as 0.7
- Ex Models with 4th gen. leptons allow for $H \to \nu\nu'$ decays

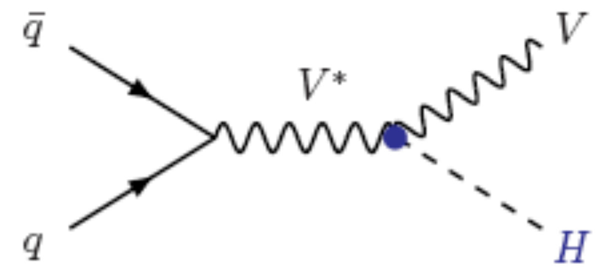
Invisible Higgs - Impact on SM Physics

- Only invisible Higgs decay in SM via: $H \rightarrow ZZ^{*} \rightarrow 4\nu$
  - BR ~ 1% for M_H > 180 GeV and smaller for lower M_H
- In BSM scenarios invisible Higgs decays can have substantial BR in "intermediate" mass range: 115 GeV < M_H < 180 GeV
- Detection of Higgs in "intermediate" range relies heavily on
  - $WW \rightarrow (\ell\nu)\,(\ell\nu)$
  - $ZZ^{*} \rightarrow 4\ell$
- Reduction of these BRs due to substantial invisible decays could impede/prevent detection of the Higgs
- Presence of invisible Higgs decay modes would require development of new search strategies in the "intermediate" mass range (or beyond)

Invisible Higgs - Search Strategies

- Invisible Higgs detection in dominant GF production not feasible
  - Would have to consider *gg* → *H* + *jet* signatures containing a monojet with large E_T and substantial missing E_T for the event.
  - Such signals overwhelmed by QCD background
- VBF channel combined with tagging jets to reduce QCD background presents viable option
  - Recently shown to be able to probe down to BR ~ 25% with 30 fb^{-1} [CMS AN -2008/083]
  - Can serve to complement AP channel with high statistics
- Associated production with *W* / *Z* provides clean signature by exploiting leptonic decays of *W* / *Z*

AP (W,Z)



Invisible Higgs - WH vs ZH Channel

- Two options for invisible Higgs decays in associated VB production
  - *qq' → W* → W + H → (ℓν) + invisible*
    - Signature: single lepton + missing E_T
  - *qq' → Z* → Z + H → (ℓ⁺ℓ⁻) + invisible*
    - Signature: di-lepton + missing E_T
- Production rate of WH ~5-6 greater than ZH in "intermediate" mass range
- However, background in WH due to off-shell W* production overwhelms signal
  - Not a problem for ZH channel since mass-cuts can be made based on di-lepton invariant mass
- ZH channel favored for search despite relatively lower production rate

Invisible Higgs - Background in WH Signal

$qq' \rightarrow W^{*} \rightarrow W + H$
$W \searrow \ell\nu$, $H \searrow$ invisible

- Charged Drell-Yan (DY) production via: $qq' \rightarrow W^{(*)} \rightarrow \ell\nu$
- Neutrino decay of Z: $qq' \rightarrow WZ \rightarrow (\ell\nu)(\nu\nu)$
  - Irreducible, yet low BR in SM
- Lepton ID failure: $qq' \rightarrow WW' \rightarrow (\ell\nu)(\ell'\nu')$
  - If one of the leptons is outside the fiducial volume, it will misrepresent missing E_T
- Jet ID failure: $qq' \rightarrow W \rightarrow \ell\nu + jet$
  - Failure to identify the jet results in misidentification as missing E_T
- Jet misidentification: $qq' \rightarrow Z + jets \rightarrow (\nu\nu') + jets$
  - Jet misidentified as lepton gives false signal

Invisible Higgs - Background in ZH Signal

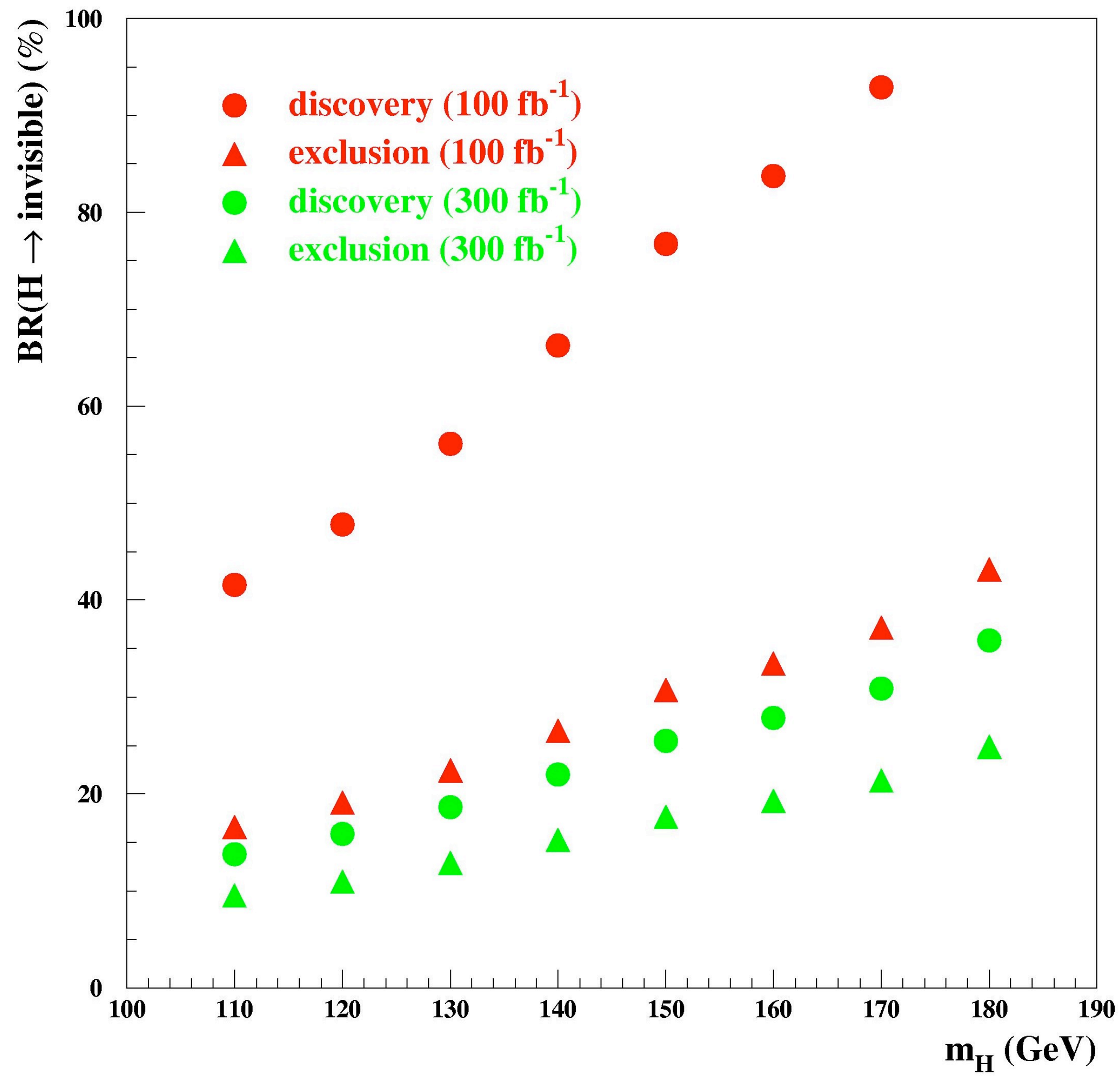
$qq' \to Z^* \to Z + H$, with $Z \to \ell^+ \ell^-$ and $H \to$ invisible

- DY production: $qq' \to Z^* \to (\ell^+\ell^-) + jets$
  - Failure to ID jets results in false missing E_T signature
- Irreducible neutrino decay of Z: $qq' \to ZZ' \to (\ell^+\ell^-)(\nu\nu')$
- Lepton ID failure: $qq' \to WZ \to (\ell\nu)(\ell^+\ell^-)$
  - Failure to identify one lepton results in false signal
- WW production: $qq' \to WW \to (\ell\nu)\ (\ell\nu)$

Invisible Higgs - Cuts in ZH Channel

- Select events with exactly two leptons, same flavor and opposite sign
  - Kinematic requirement: $|M_{\ell\ell} - M_Z| < 10\ GeV$
  - Transverse energy threshold: $E_T^{\ell} > 10\ GeV$
  - Fiducial cut: $|\eta^{\ell}| < 3$
- Hadronic veto on jets in the barrel region
  - Reject jets with $E_T^j > 30\ GeV$ or $|\eta^j| < 4$
- Enforce missing transverse momentum threshold
  - Requite: missing $p_T > 30\ GeV$

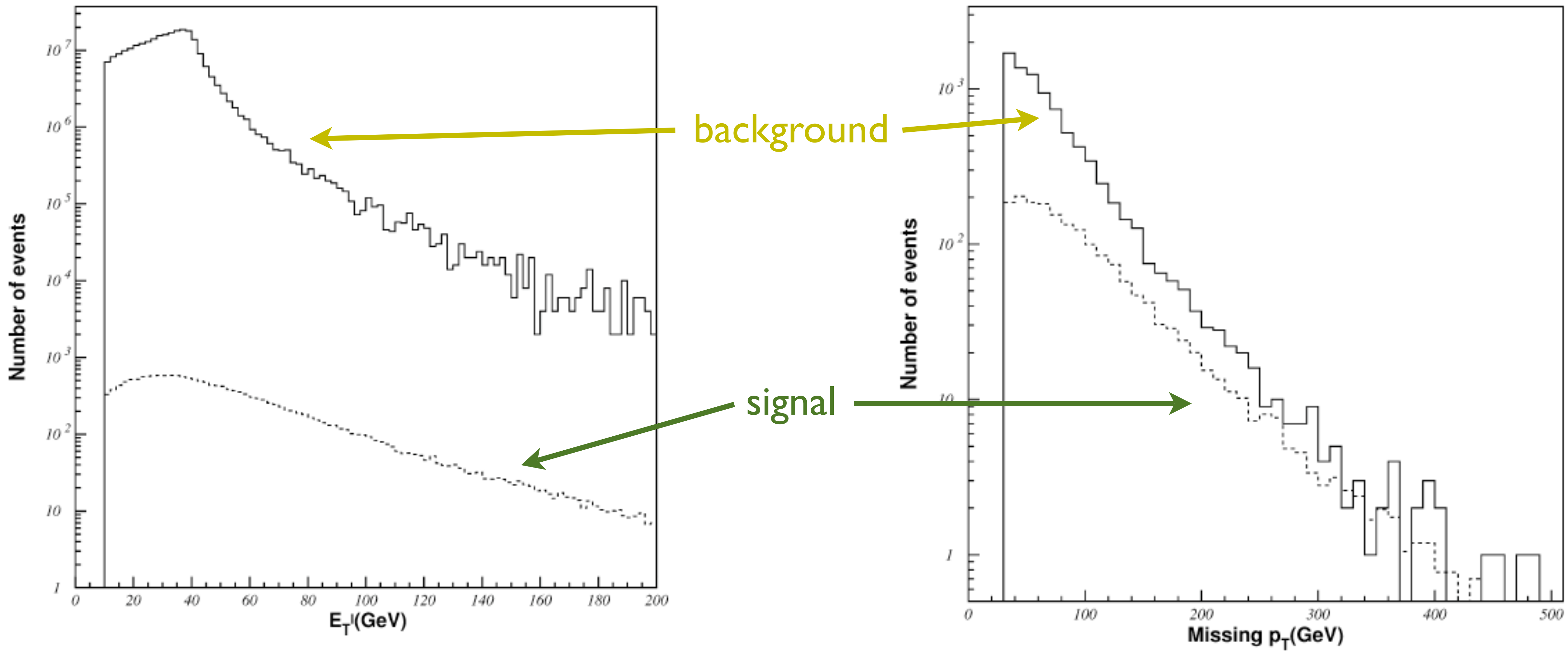
Invisible Higgs - ZH BR Limits



P. Gagnon - ATLAS Physics Workshop - May 2003

Invisible Higgs - WH vs ZH

WH　　　　　　　　　　　　　　ZH



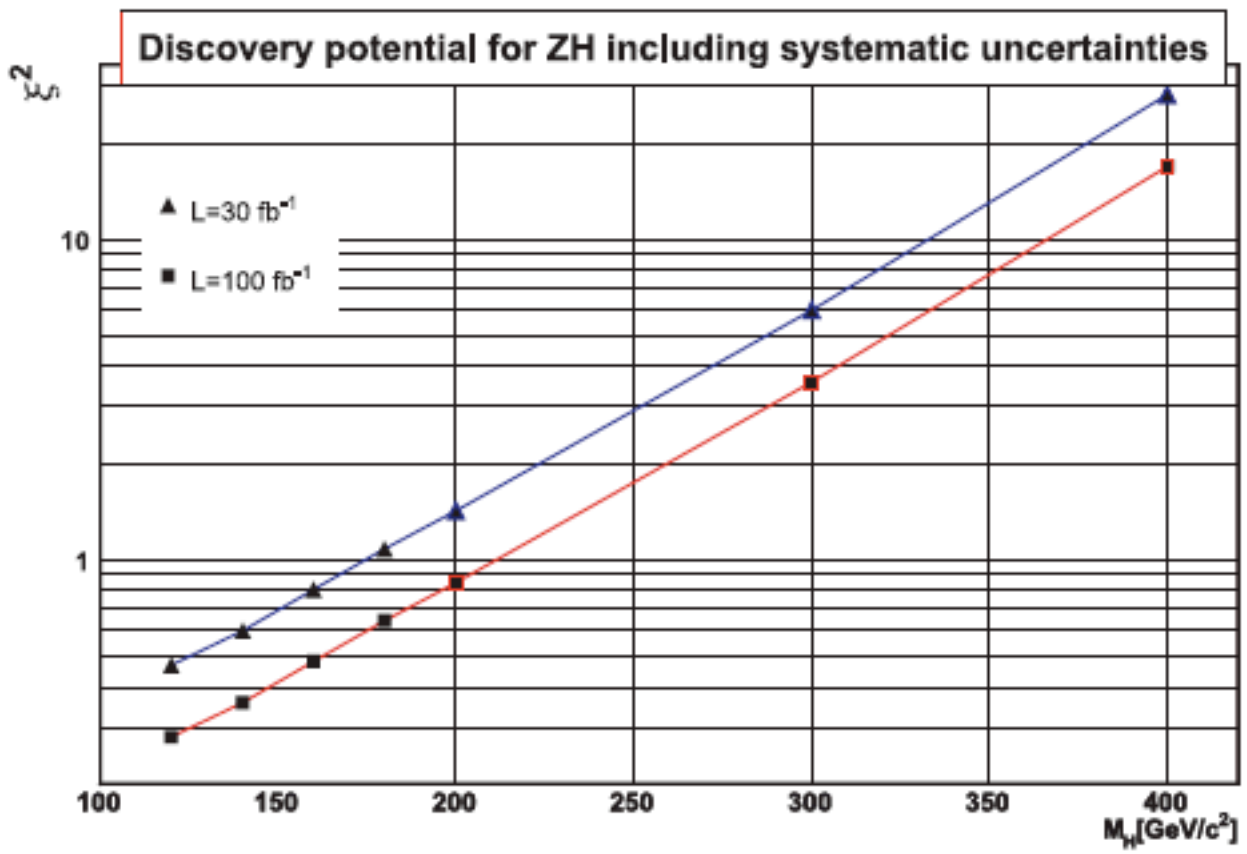
$E_T{}^{\ell}$ distribution for signal (dashed) and background (solid) in WH channel for 100 fb^{-1}

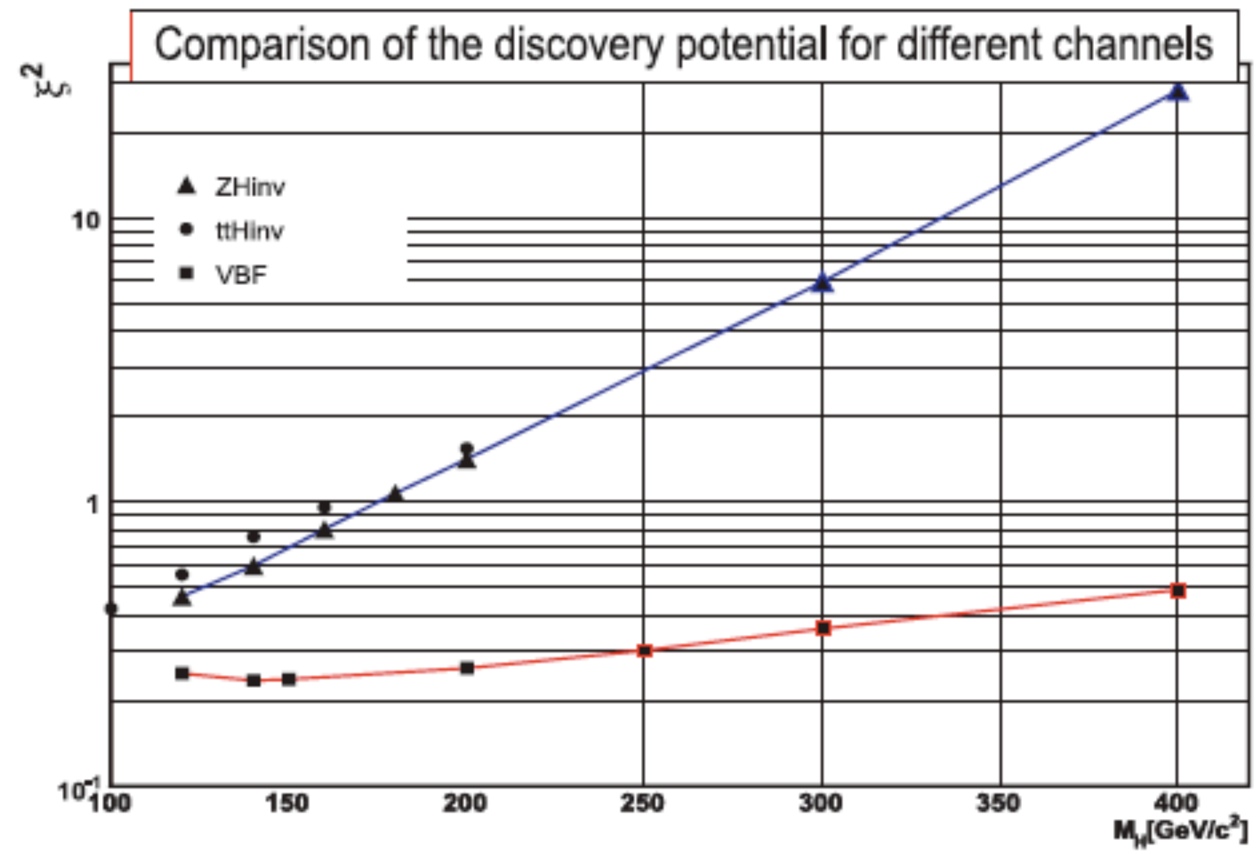
Missing p_T distribution for signal (dashed) and background (solid) in ZH channel for 100 fb^{-1}

Signal for ZH channel comparable to background (due to ZZ and WZ cross sections). Better signal ratio expected once LHC measures these cross sections.

R.M. Godbole et. al., Phys Lett. B. 571 (2003) 184-192

Invisible Higgs - Discovery Potential





ATLAS sensitivity at 95% CL for 30 fb^{-1} of integrated luminosity

$$\xi^2 = \frac{\sigma(H) \times \mathrm{BR}(H \to \mathrm{inv.})}{\sigma_{\mathrm{SM}}(H)}$$

$\xi^2 < 1$: Observation of invisible Higgs possible with SM σ

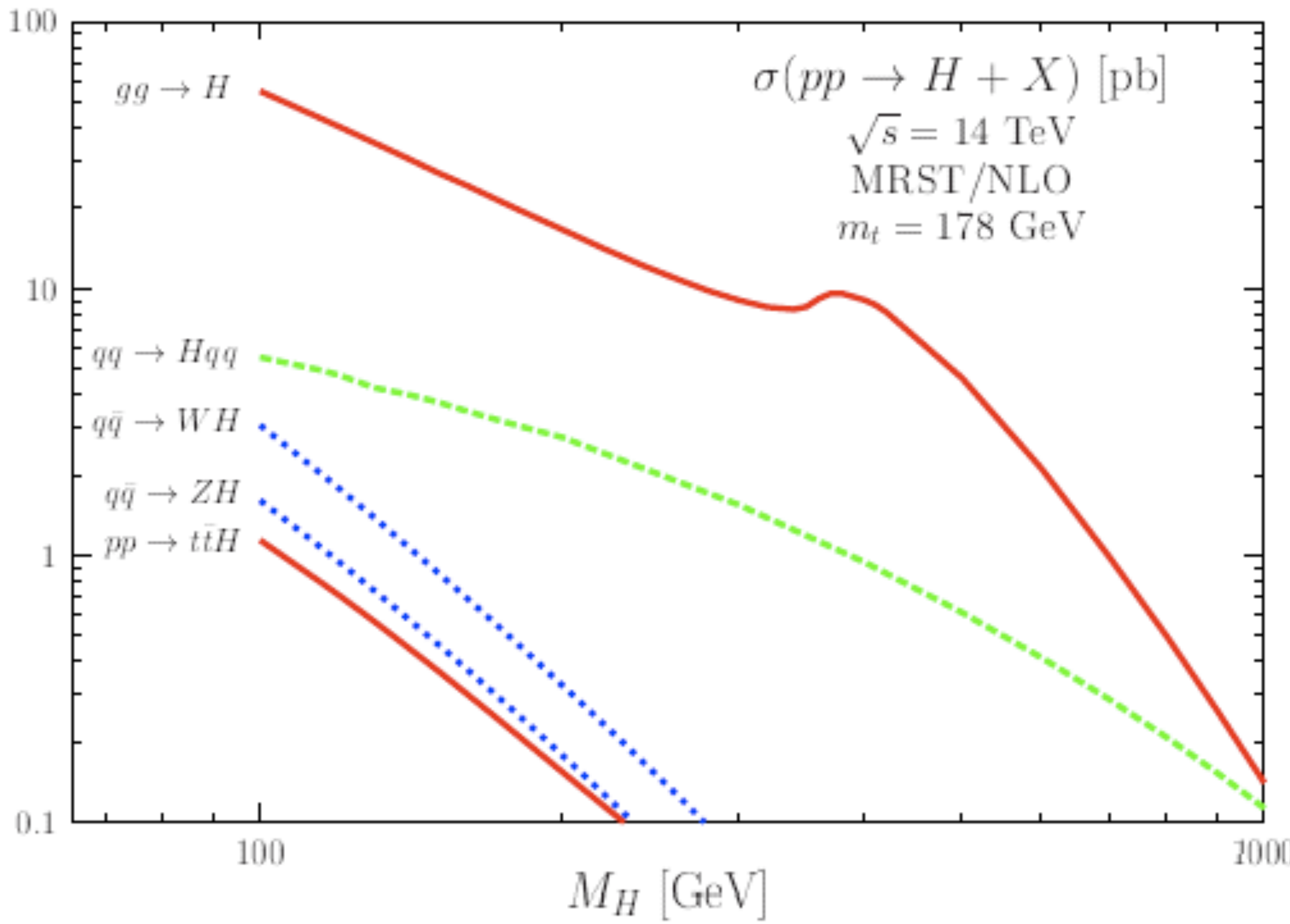
$\xi^2 > 1$: Observation of invisible Higgs requires enhanced σ

M. Heldmann, Acta Physica Polonica B, vol. 38, Issue 3

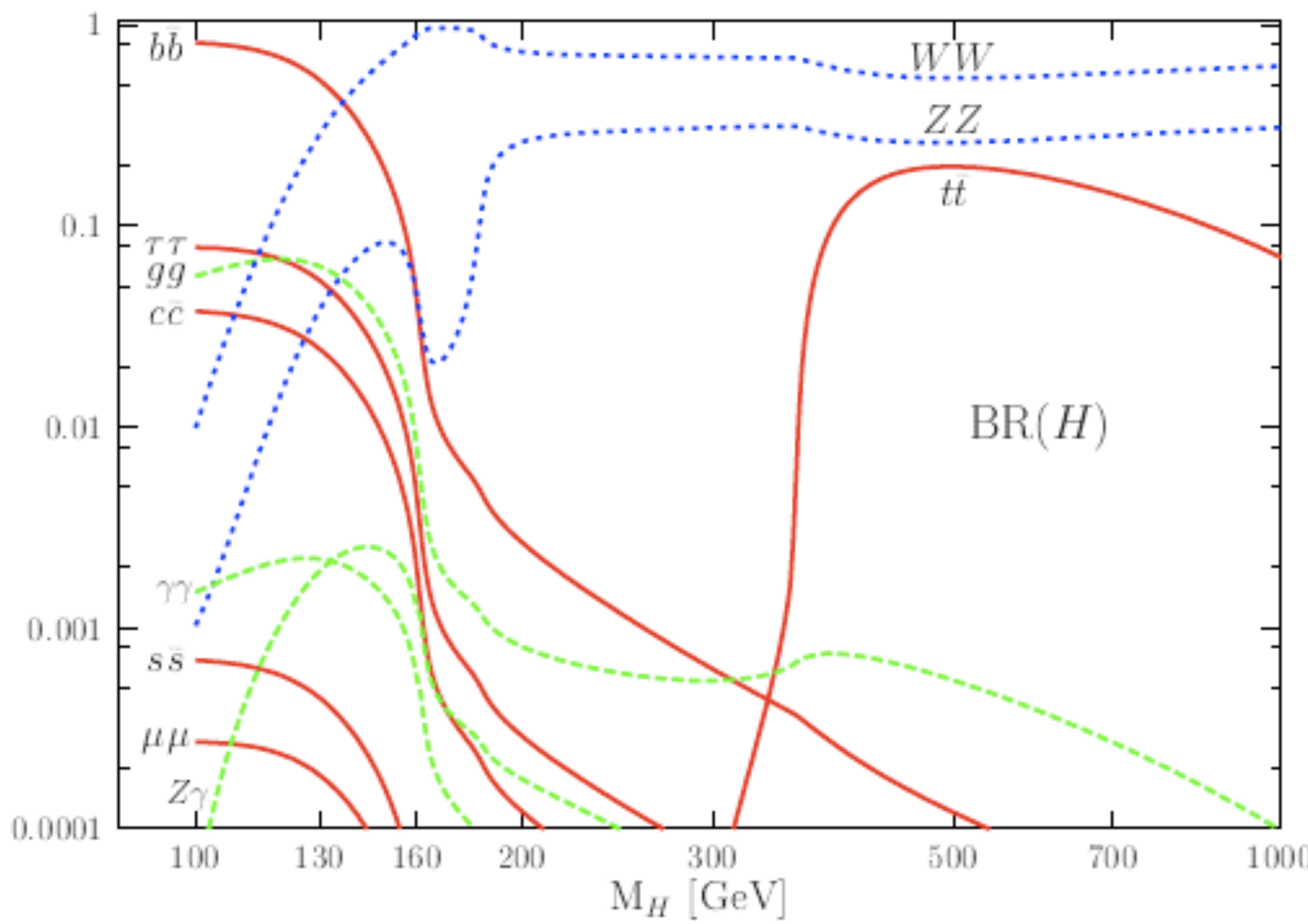
Conclusions

- The Search for Higgs boson(s) is a complex problem requiring multifaceted approach
  - All search channels needed to probe entire mass range
  - No single channel alone will suffice, since discovery of a Higgs boson in one mass region does not exclude existence in other regions
- Background considerations strongly affect signal significance at LHC
  - Signals with diminished production rates can play substantial roles
- Invisible Higgs searches are important tools for:
  - Verifying SM predictions
  - Providing early indication for new physics

Backup Slides



$\sigma(pp \to H + X)$ [pb]
$\sqrt{s} = 14$ TeV
MRST/NLO
$m_t = 178$ GeV
$gg \to H$
$qq \to Hqq$
$q\bar{q} \to WH$
$q\bar{q} \to ZH$
$pp \to t\bar{t}H$
100
10
1
0.1
100
1000
M_H [GeV]


BR(H)
WW
ZZ
$t\bar{t}$
$b\bar{b}$
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$s\bar{s}$
$\mu\mu$
$Z\gamma$
1
0.1
0.01
0.001
0.0001
100
130
160
200
300
500
700
1000
M_H [GeV]