Invisible Higgs Experimental Perspective

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Outline

- Physics Motivation
- Environmental Challenges
- Status of analyses
- Review analyses for the main production modes:
  - VBF
    - i. Trigger
    - ii. Jet Performance
    - iii. Underlying Events and Central Jet Veto
    - iv. Control Samples
  - ZH
    - i. Trigger
    - ii. Reconstruction Performance
- What can we say with $10fb^{-1}$?
- Few words on the ILC

Physics Motivation

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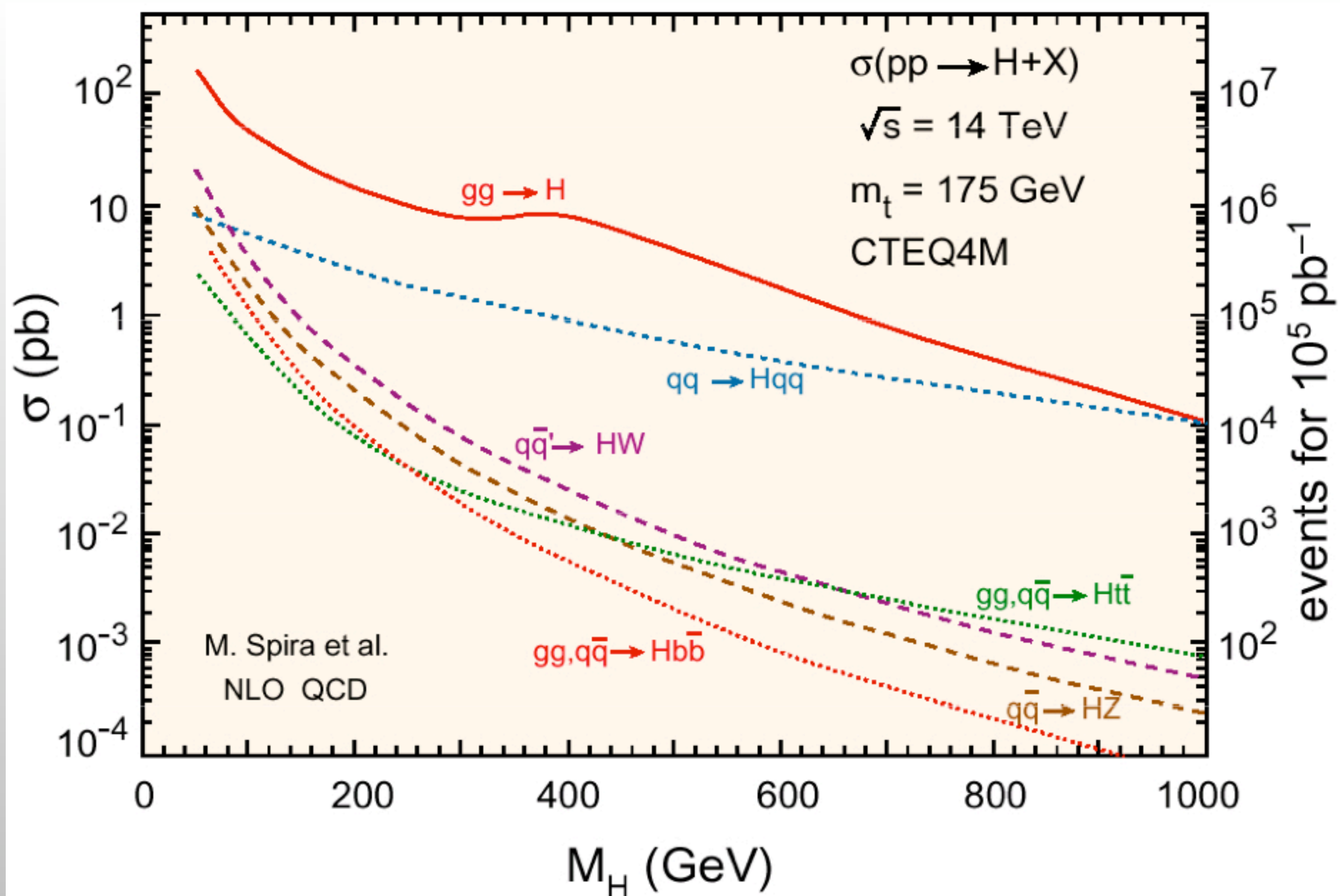
- The Standard Model (SM) Higgs has a very narrow decay width for $m_h<160$ GeV (below the WW threshold).
- The largest particle within the SM for which a light Higgs boson can decay is the b quark ($m_b\sim4.5$ GeV).
- Therefore, any new particle with less than half the Higgs mass which interacts with the Higgs boson could significantly modify decay branching fractions.
- If these new particles are weakly interacting, then $h\rightarrow$invisible can be a dominant decay.
- Models include: MSSM,NMSSM, Extra Dimension, 4-generation neutrinos, etc.

- Even if the Higgs is discovered through another decay channels the invisible Higgs search will be integral in understanding the Higgs sector especially if the visible channels are suppressed.

SM Higgs Production



Invisible Higgs Searches

Production Mode	Select List of Papers	Status
Gluon Fusion	--	Not feasible
Vector-Boson-Fusion	Eboli & Zeppenfeld (2000) Di Girolamo & Neukermans (2003) Hanninger, Schumacher, Wermes (2008) ATLAS Collaboration (2008)	Full Simulation Trigger at high luminosity still in question
WH	Godbole, Guchait, Mazumdar, Moretti, Roy (2003) Chudhury and Roy (2004) Gagnon (2003)	Not feasible Swamped by W+jets
ZH	Godbole, Guchait, Mazumdar, Moretti, Roy (2003) Gagnon (2003) Chudhury and Roy (2004) Davoudiasl, Tao, Logan (2004) Meisel, Dührssen, Heldmann, Jakobs (2006) ATLAS Collaboration (2008)	Full Simulation
ttH	Gunion (1994) Kersevan, Malawski, Richter-Was (2003)	Needs Full Simulation Analysis

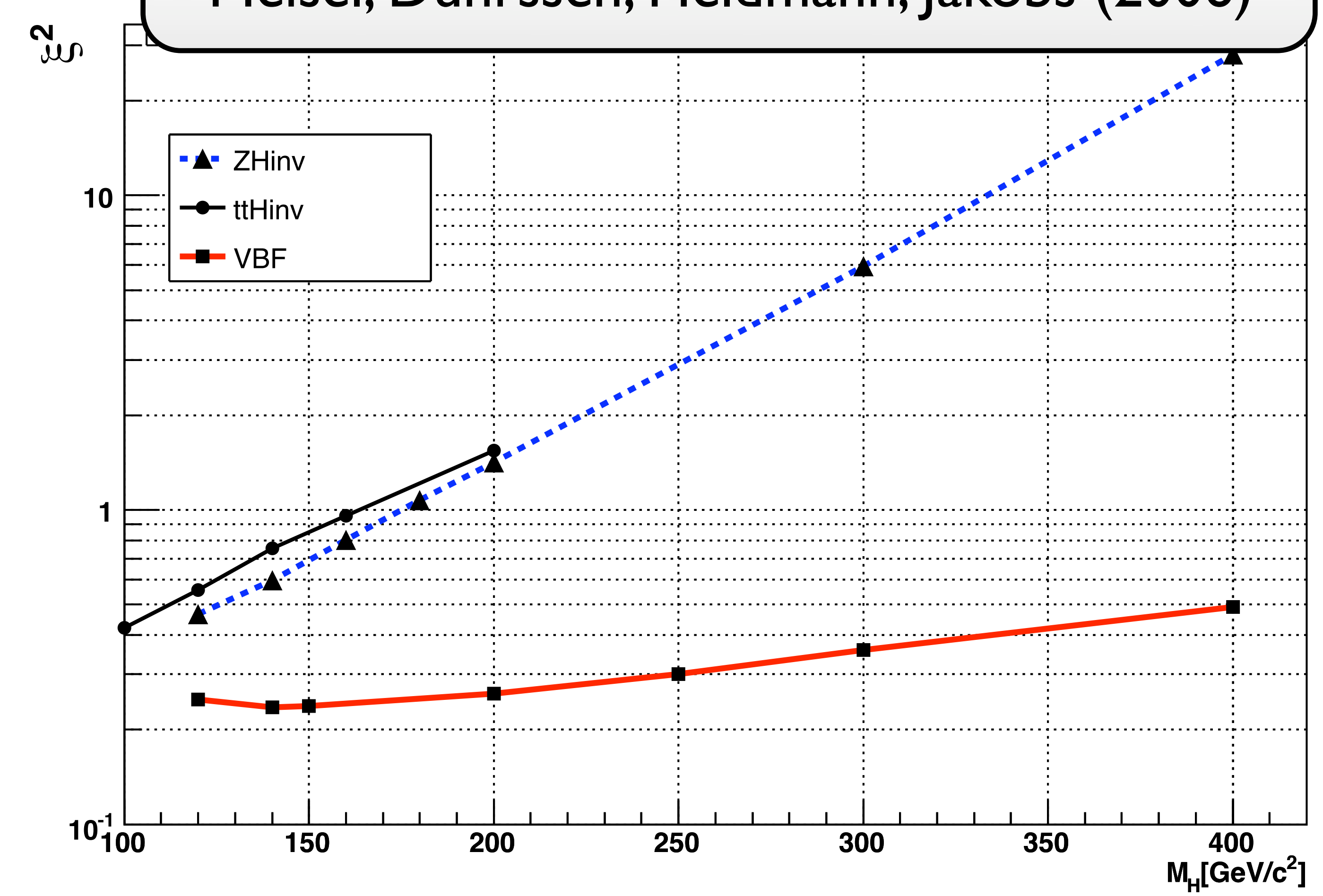
Defining Discovery Potential and Earlier Studies

In order to estimate the potential for invisible Higgs, a model dependent variable is defined as:

$$\xi^2 = Br(H \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$

Previous analysis using fast simulation of the ATLAS detector has been performed. Results for 95% confidence level limits with 30fb^{-1} of data are shown below.

Meisel, Dührssen, Heldmann, Jakobs (2006)



Environmental Challenges

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Collisional backgrounds

- Pile-up
- Underlying Event

Non-collisional backgrounds:

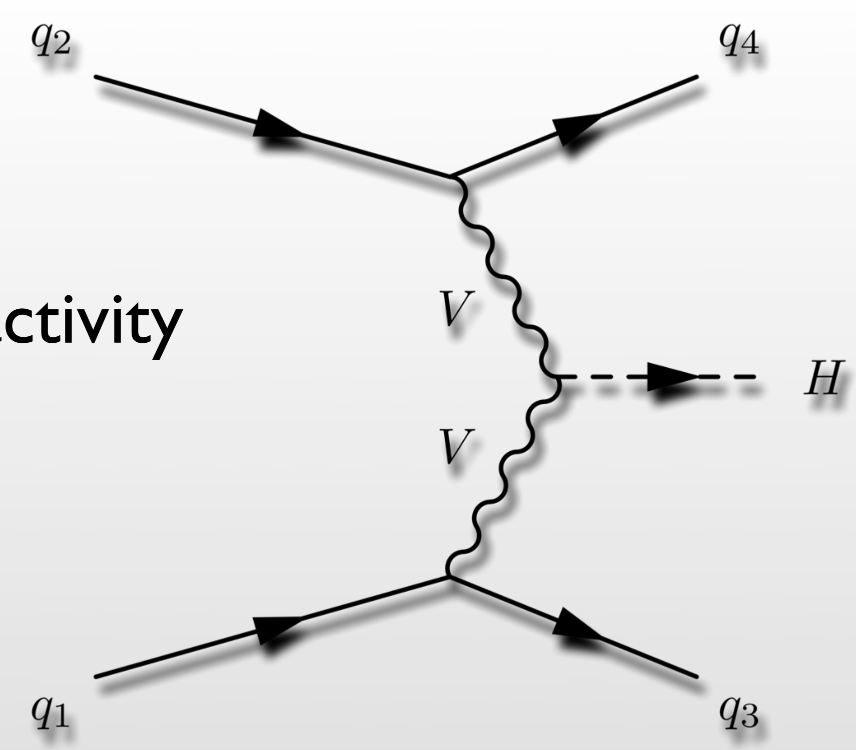
- Beam halo
- Cosmic muons

Detector Effects:

- Instrumental noise
- Hot/dead channels
- Detector calibration

Vector-Boson-Fusion

Signature characteristics:
- Two well separated outgoing jets
- Large amount of missing transverse energy.
- Absence of color exchange, leads to a reduced activity between the two outgoing jets.



Main backgrounds:
- Z+jets
- W+jets
- QCD dijets

Primary Cuts:
- Tagged Jets: Jet pt, jet eta separation and product
- Missing Transverse Energy
- Missing Transverse Energy Isolation
- Central Jet Veto
- Tagged Jet φ Separation

Trigger Systems and VBF

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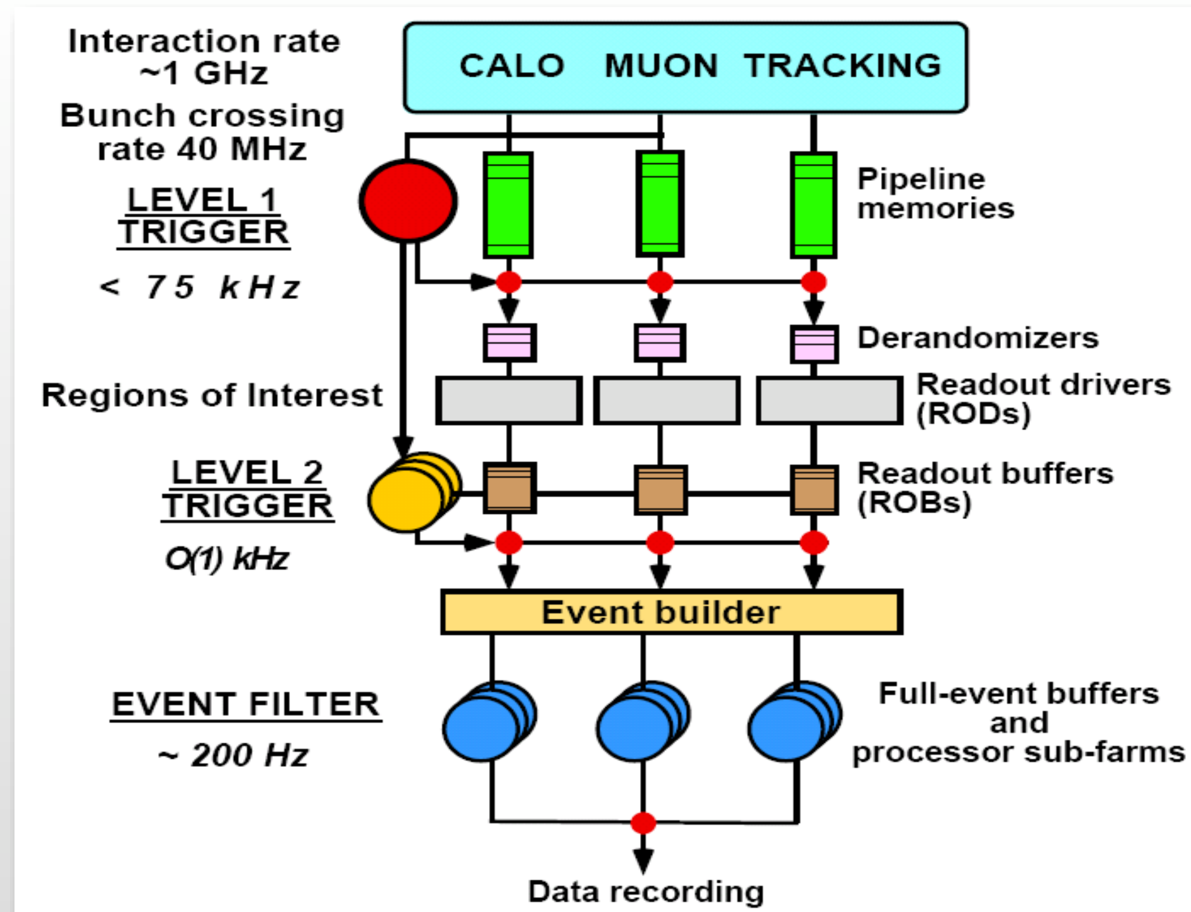
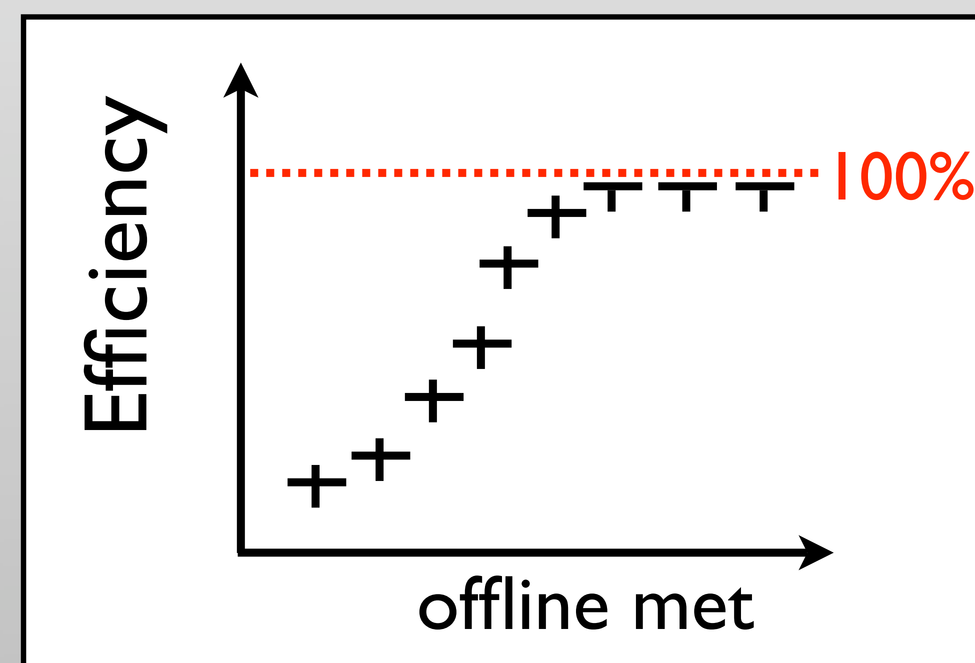
VBF Trigger Challenge

- Goal is to keep as much of the signal within the allowed trigger bandwidth.
- The VBF process has two jets and large missing energy. In a hadronic environment this is a problem.
- Increased luminosity requires larger trigger thresholds in order to manage the bandwidth.
- For low luminosity, we will use the lowest un-prescaled missing transverse energy trigger item, expected (hoping) to be at ~70 GeV, however. However, data will tell us the trigger rates.



VBF Trigger Efficiency

- Select a data sample from an unbiased trigger with respect to missing transverse energy trigger (muon trigger)
- Determine trigger efficiency by plotting a fraction of events which satisfied the missing transverse energy trigger with respect to the offline missing transverse energy (met).



Potential VBF Trigger Solutions at Higher Luminosity (10^33-10^35)

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Adding more items to the trigger requirement

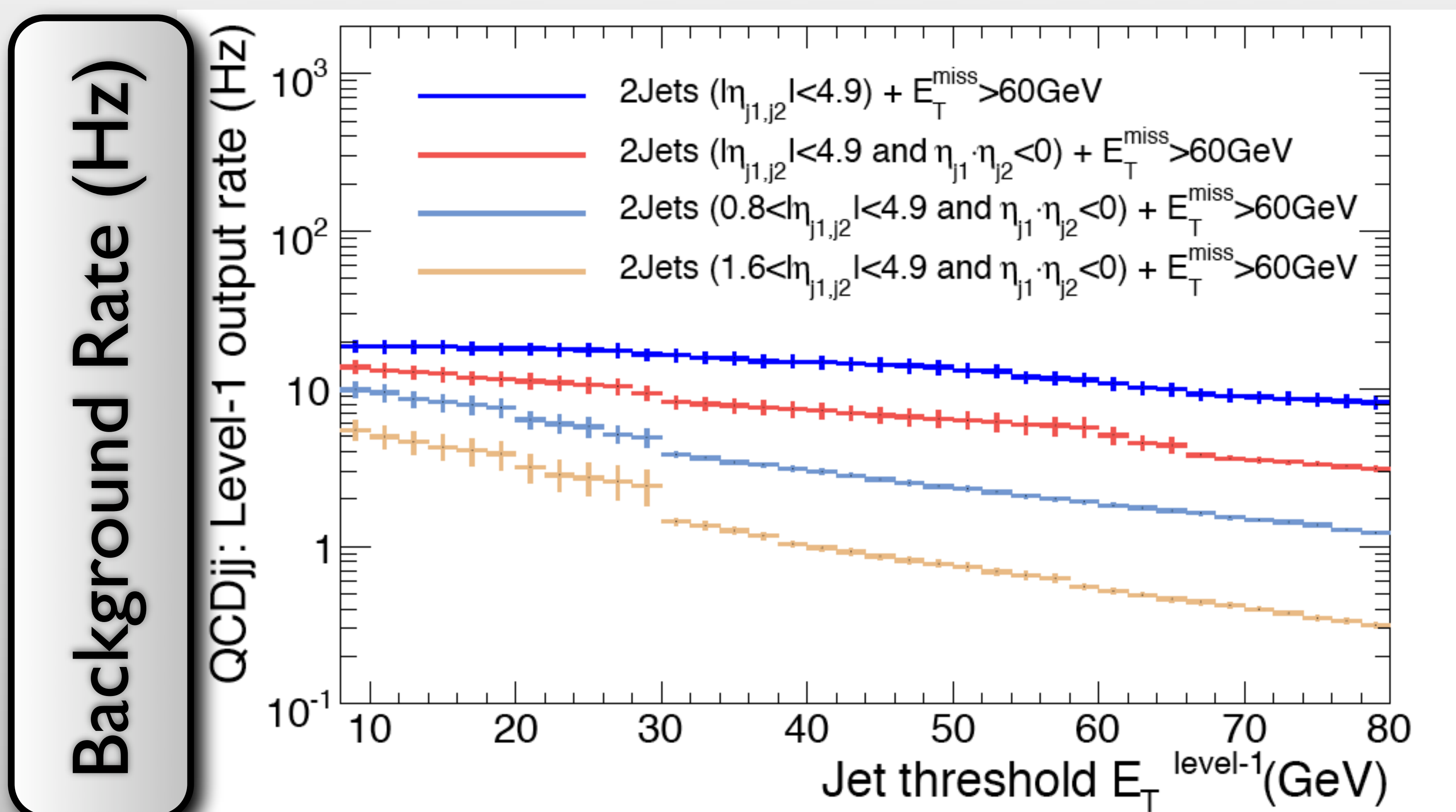
- A single missing transverse energy trigger might not be sufficient.
- One can include additional requirements to the trigger, such as jets.
- Example below using linear scaling (not correct!)

Trigger Item @ LVL 1	Acceptance [%] Norm. Offline Cuts	QCD Dijet Rate [Hz] $\mathscr{L}$=10^31	QCD Dijet Rate [Hz] $\mathscr{L}$=10^33
Missing transverse energy (met)>70GeV	98	1.5	150
Forward Jet with pt>23GeV+met>70GeV	78	0.9	90
Central Jet with pt>23GeV+met>70GeV	83	1.4	140
met>100GeV	84	0.2	20
Forward and Central Jet with pt>23GeV +met>100GeV	55	~0	2

Potential VBF Trigger Solutions at Higher Luminosity (10^33-10^35)

Topological trigger

- A dedicated trigger study was performed to understand the potential benefits of changing the jet trigger eta definition and jet eta separation
- Topological triggers reduces the background rate.
- Results are shown for $\mathscr{L}$=2*10^33 using the ATLAS detector.

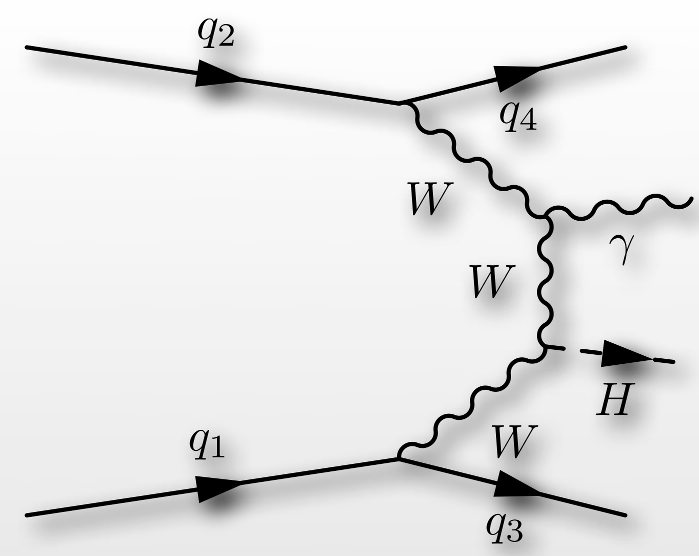


Hanninger, Schumacher, Wermes (2008)

Potential VBF Trigger Solutions at Higher Luminosity (10^33-10^35)

Investigate VBF+photon process

- Associate a photon to the VBF process
- This might provides a better trigger
- This reduces the effective cross-section by ~100
- Opens the phase space
- We will have to look at both the new thresholds and the potential pre-scale at higher luminosity to determine if this is a viable option.



Trigger Efficiency and Complicated Triggers

- We need to understand how each trigger item performs in order to determine the trigger efficiency.
- For a single trigger item this is relatively easy (I hope).
- By adding more trigger items, the trigger efficiency becomes more complicated to unfold.
- Additional topological requirements complicate the issue even more.

Trigger Conclusion

- Data is needed to understand the rate at low luminosity and to work towards higher luminosity.
- We should consider all possible option and try to use the simplest trigger available.

Experimental Systematic Uncertainties

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VBF Jet Energy Scale and Resolution

- The systematic uncertainties associated with jets and transverse missing energy were investigated using accepted performance estimations.
- The real performance will only be known with data!
- The systematic uncertainty for the jet energy resolution was estimated by smearing the momentum of the jets using a Gaussian distribution.
- Jet energy scale systematic uncertainty was estimated by linearly scaling the energy.
- The missing transverse energy was re-calculated to account for the changes in the jet energy scale/resolution.

Systematics	Higgs boson 130 GeV	Background	
		Cut-Based	Shape
Jet energy resolution: $\sigma(E) = 0.45\sqrt{E}$ for $\lvert\eta\rvert < 3.2$; $\sigma(E) = 0.63\sqrt{E}$ for $\lvert\eta\rvert > 3.2$	0.8 %	5.3 %	4.5 %
Jets energy scale: $\pm 7\%$ for $\lvert\eta\rvert < 3.2$; $\pm 15\%$ for $\lvert\eta\rvert > 3.2$	10.0 %	19.5 %	2.8 %
Total	10.5 %	20.4 %	5.3 %

Underlying Events & Central Jet Veto

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Large uncertainty in UE

- Large difference in the Underlying Events predictions between Monte-Carlo generators.
- This has a large effect on central jet veto cut
- Central jet veto rejects events that has an extra jet with a pt>35GeV in |eta| < 3.

Selection Cuts	HERWIG 130 GeV	PYTHIA 130 GeV
Initial $\sigma(fb)$	3.93×10^3 (1.000)	3.93×10^3 (1.000)
Pre-Cut ($\not{E}_T > 80$GeV)	1.76×10^3 (0.448)	1.78×10^3 (0.453)
+ Tagged Jets	4.07×10^2 (0.231)	4.10×10^3 (0.230)
+ M_{jj}	2.45×10^2 (0.602)	2.45×10^3 (0.598)
+ $\not{E}_T > 100$GeV	2.05×10^2 (0.837)	2.14×10^3 (0.873)
+ Lepton Veto	2.05×10^2 (1.000)	2.12×10^2 (0.991)
+ $I > 1\ rad$	1.84×10^2 (0.898)	1.80×10^2 (0.849)
+ Central Jet Veto	1.59×10^2 (0.864)	1.07×10^2 (0.594)
+ $\phi_{jj} < 1\ rad$	7.43×10^1 (0.467)	4.93×10^1 (0.461)

factor of ~1.5

Control Samples (Data-Driven Methods)

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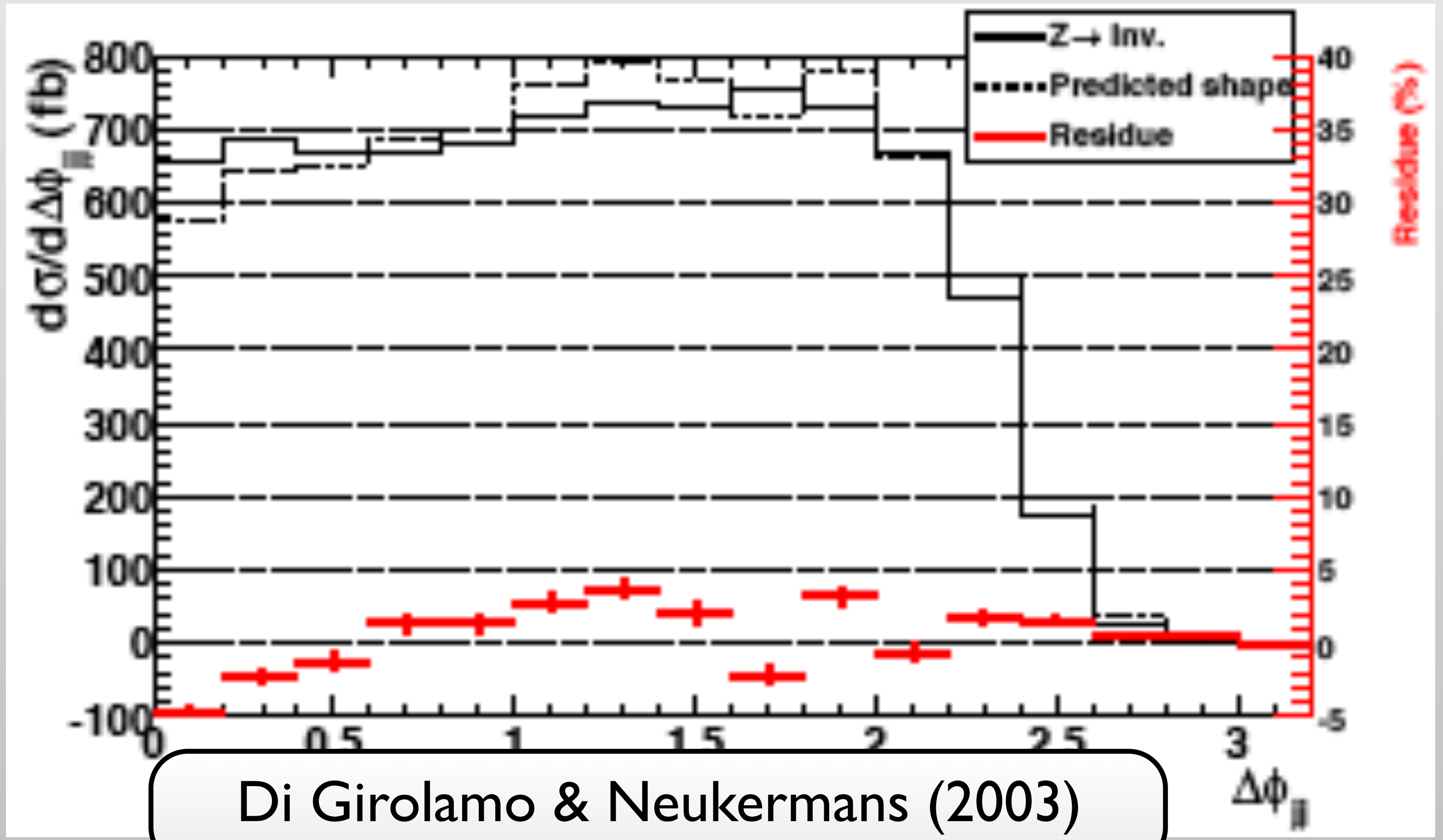
Predicting the Z+jets (or W+jets)

- One of the key backgrounds for this analysis is Z(→$\nu\nu$)+2jets
- We can use the Z(→ll)+2jets to estimate the background from the Z(→$\nu\nu$)+2jets
- In this example, we investigate the tagged jet φ separation variable

$$\left[\frac{d\sigma}{d\phi_{jj}}\right]_{pred} = R\left[\frac{d\sigma}{d\phi_{jj}}\right]_{meas} = \frac{1}{\epsilon_{2\ell}}\frac{Br(Z\to\nu\nu)}{Br(Z\to\ell\ell)}(1+f)\left[\frac{d\sigma}{d\phi_{jj}}\right]_{meas}$$

Results for Z+jets

- Previous fast simulation results place the uncertainty of the Z+jet background at ~6% for 10fb^{-1} of data.
- Need to consider detector effects!
- Full simulation analysis is needed.

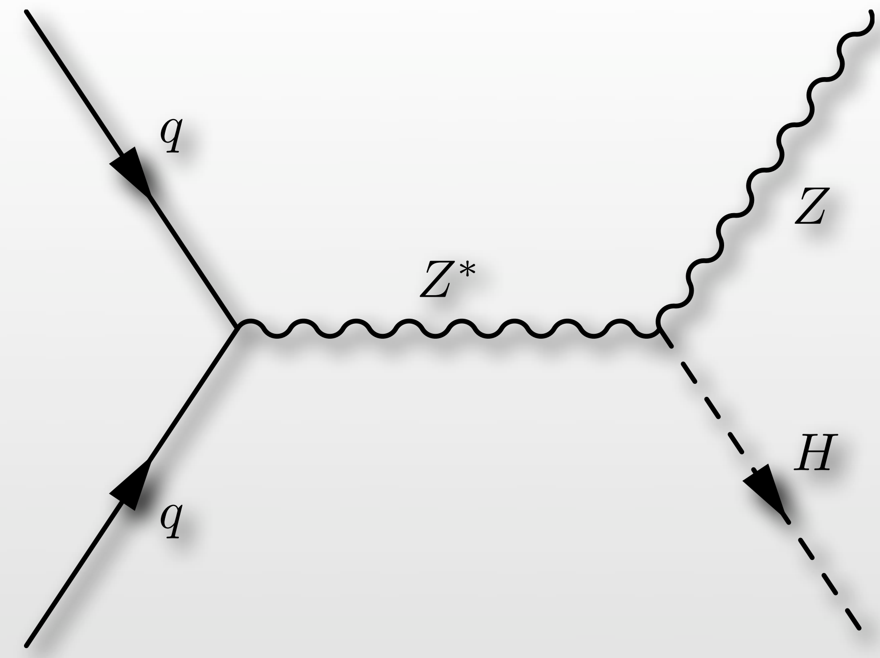


Di Girolamo & Neukermans (2003)

ZH Associated Production

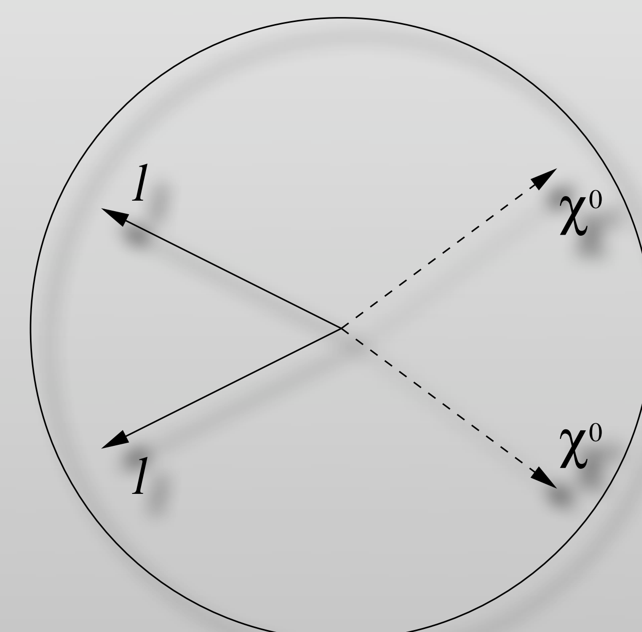
Signature characteristics:

- The ZH production mode relies on di-leptons coming from the associated Z and large missing transverse energy.
- However, this comes at a cost of lowering the effective cross-section, Br(Z->leptons)~6.7%.
- In addition, the lepton detector acceptance reduces the effective cross-section even more.



Trigger:

- The leptons allow for clean triggers, such as:
  - Single lepton trigger
  - Di-lepton trigger



Main backgrounds:

- ZZ→*llvv*, WW, ZW, Z+jets, tt

HZ Trigger

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Possible Triggers for LHC

- We expect some degraded performance of algorithms with increased luminosity.
- Muon trigger isn't expected to change much from low to high luminosity.
- Electron trigger is expected to change but hopefully not significantly
- Ballpark trigger at various luminosities:

Available Triggers for $\mathscr{L}$=10^31	Available Triggers for $\mathscr{L}$=10^33
di-lepton with pt~10 GeV	di-lepton with pt~10 GeV
single muon with pt~20 GeV	single muon with pt~20 GeV
single electron with pt~12 GeV	single electron with pt~20 GeV

Bottom line

- The ZH trigger appears in good shape.

Experimental Systematic Uncertainties

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- Similar to the VBF analysis, various systematic uncertainties associated to the leptons, jets, and transverse missing energy were investigated.
- The missing transverse energy was re-calculated to account for the changes in the reconstructed particles energy scale/resolution.

- The overall systematic uncertainty for this channel is significantly smaller than that of the VBF analysis
- The largest systematic uncertainty associated with the reconstruction in this study originates from the leptons.

	signal	background
electron reconstruction efficiency	$\pm$0.2%	$\pm$0.2%
electron p_T resolution ($\pm$0.73%)	+0.5%	+1.7%
electron energy scale ($\pm$0.5%)	+1.1%	+2.1%
sub-total for electrons (43% of events)	+1.2% -0.2%	+2.7% - 0.2%
muon reconstruction efficiency	$\pm$1.0%	$\pm$1.0%
muon p_T resolution (see formula in text)	+1.1%	+1.9%
muon energy scale ($\pm$1%)	+1.0%	+2.2%
sub-total for muons (57% of events)	+1.8% - 1.0%	+3.1% - 1.0%
combined contributions for leptons	+1.5% - 0.7%	+2.9% - 0.7%
jet energy scale ($\pm$7% or $\pm$15%)	+0.8%	+0.2% - 2.2%
jet energy resolution effect on E_T^{miss}	-2.2%	-0.4%
luminosity	-	$\pm$3.0%
cross-section	-	$\pm$5.8%
filter effects	$\pm$1.4%	$\pm$1.4%
Boosted Decision Tree training effects	$\pm$0.2%	$\pm$0.7%
total	+2.2% - 2.6 %	+7.3% - 7.1%

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Additional Comments

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Control Samples

- Similar to VBF, several control samples will be used, such as ZZ where both Z's decay leptonically.
- Analysis on Z+jets can start very early, tt a little later and ZZ and WW much later.
- Problem with statistics for control samples even at 30 fb^{-1} of data. After some loose selection cuts only 85 events for $ZZ \rightarrow llll$ survive. This corresponds to ~11% statistical error.

Latest MC Results using Full Simulation

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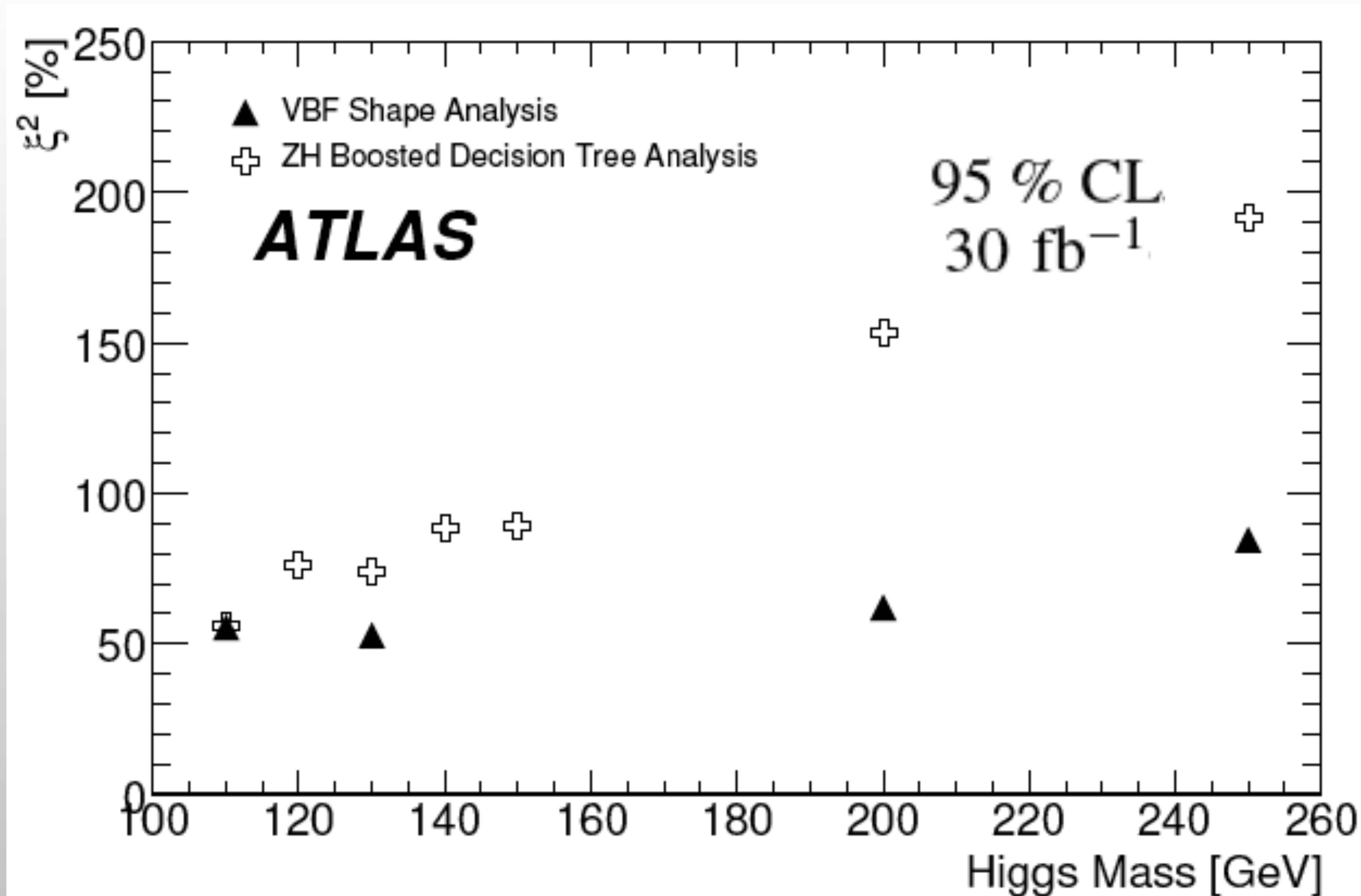
$$\xi^2 = Br(H \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$



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What can we say with 10 fb^{-1} of data and beyond?

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- If we naively scale the existing results to 10 fb^{-1} and 500 fb^{-1} results:

$$\xi^2 = Br(H \to inv.)\frac{\sigma_{BSM}}{\sigma_{SM}}$$

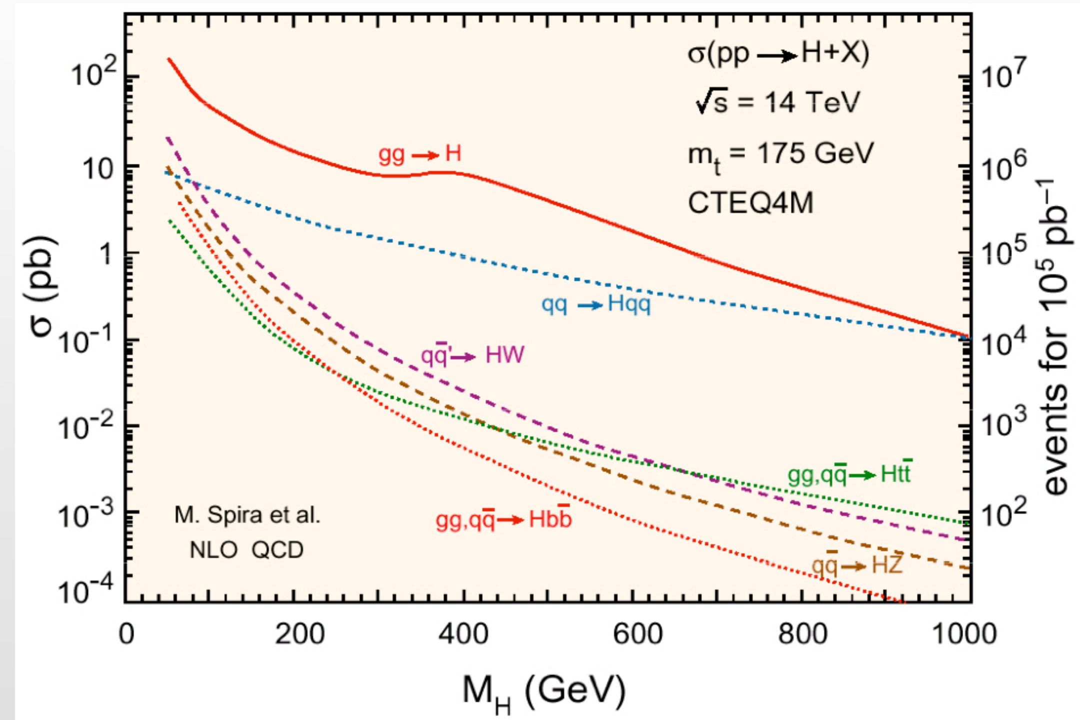
Preliminary, does not scale as $\mathscr{L}^{-1/2}$

Mass [GeV]	ξ^2 for VBF 10/30/500 [fb^{-1}]	ξ^2 for ZH 10/30/500 [fb^{-1}]
110	95/55/14	99/57/18
130	95/55/14	128/74/23
200	105/60/15	260/150/35

- There might be a very small chance we can say something at 10 fb^{-1}, however, systematic uncertainties do not scale as $\mathscr{L}^{-1/2}$!
- In addition, we can see that with 500 fb^{-1} we could probe down to ~10-35%.
- It is hard to speculate on the performance of these analyses at SLHC since the environment at LHC has yet to be understood and we need data to guide us on several key effects, such as the pile-up and UE.

Mass Reconstruction

- The mass of the invisible Higgs may be accessible through the production process.
- The signal rate depends on the mass of the Higgs.
- The steeply falling ZH production mode is more Higgs mass dependent than the VBF mode, however it has a small production cross-sections (low stats)
- Results from a parton level study are presented below.



Summary of m_H extraction 1σ uncertainty with 100 fb^{-1}:

	$m_H = 120$ GeV	140 GeV	160 GeV
$Z + H_{\text{inv}}$, $\xi^2 = 1$	12 GeV	12 GeV	14 GeV
VBF, $\xi^2 = 1$	32 GeV	32 GeV	31 GeV
Ratio method	14 GeV	16 GeV	18 GeV

Davoudias, Tao, Logan (2004)

ILC & Invisible Higgs

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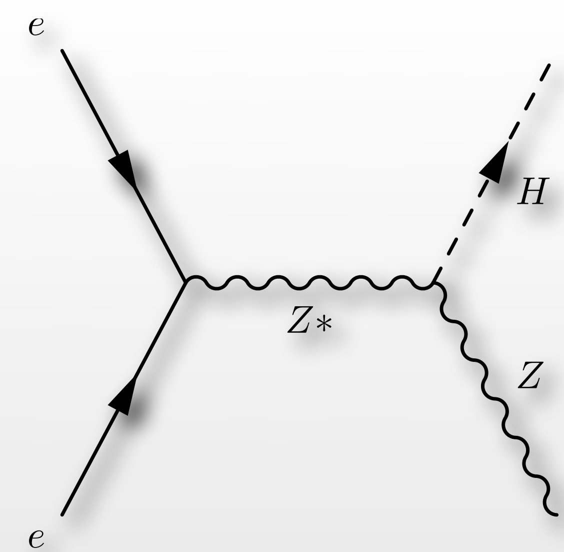
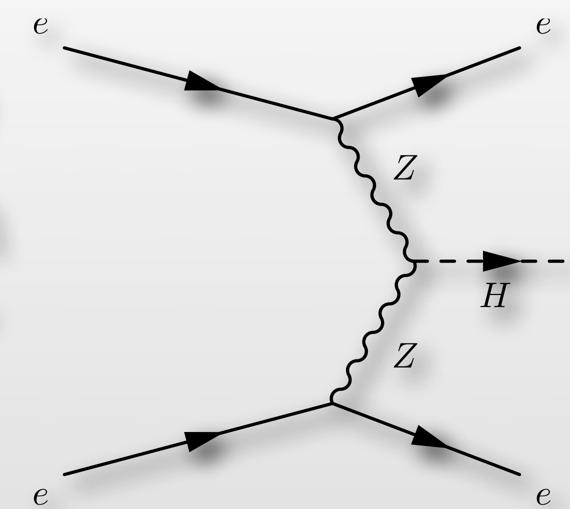
Production Modes

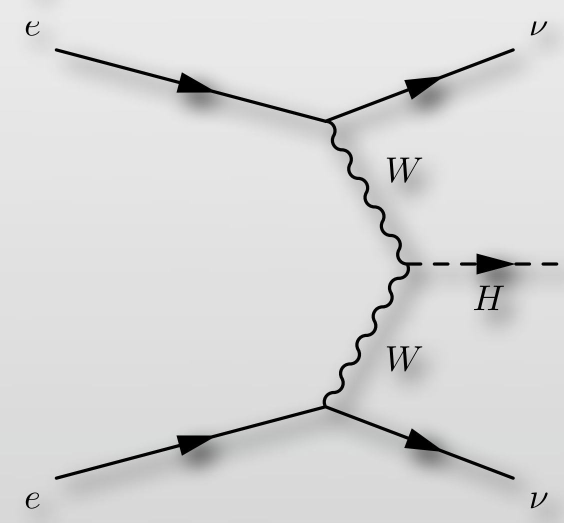
- ee→ZH: Probes the ZZH coupling
- ee→*νν*H: Probe the WWH coupling
- ee→eeH: Probes the ZZH coupling





Mass Resolution

- The mass resolution is expected to be significantly improved using the recoil method. Studies suggest it should be in the 10's of MeV.



Branching Fraction

- The results from Z(→qq)H, by Schumacher (2003), indicate the potential discovery reach at a collision energy of 350 GeV and 500 fb-1 of data

Mass [GeV]	ZH @ILC 2 sigma	VBF @ LHC 95%CL
120	~1%	~14%
140	<1%	~14%
160	<1%	~15%