# WBF Higgs Physics at the LHC

## - What can be learned from the Tevatron -

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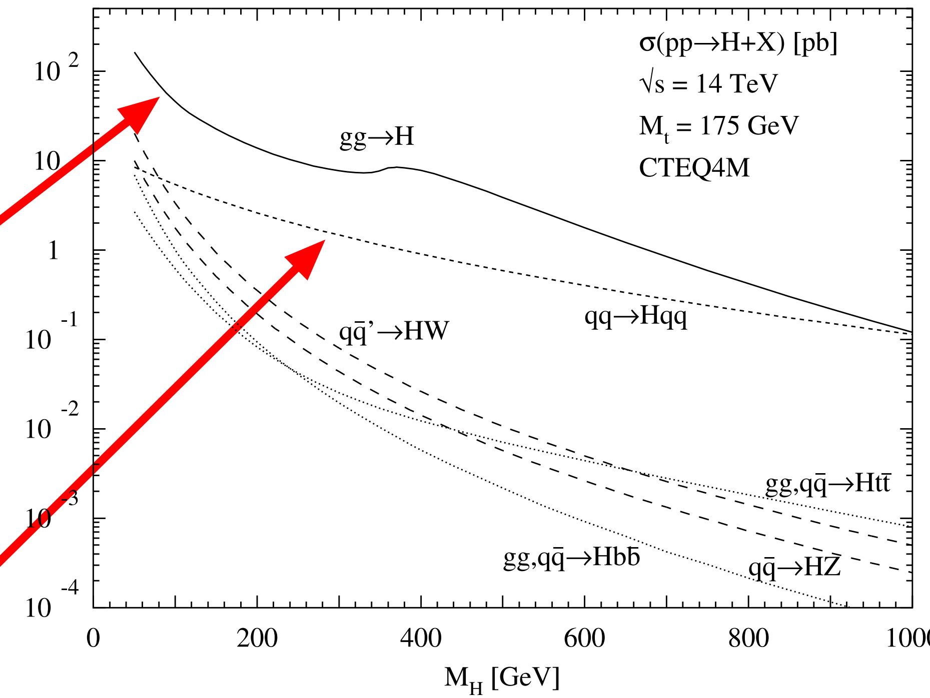
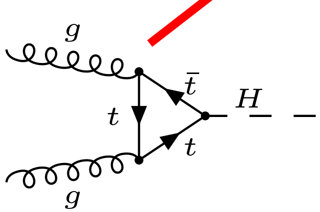
Fermilab, TeV4LHC, October 2005

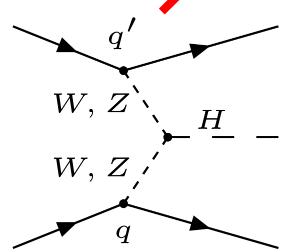
- **Introduction / Motivation**
- **Discovering the Higgs at the LHC**
  - Inclusive H $\longrightarrow \gamma\gamma$ and H $\longrightarrow$ ZZ
  - gg $\longrightarrow$ H $\longrightarrow$ WW
  - **WBF H $\longrightarrow \tau\tau$**
  - **WBF H $\longrightarrow$ WW**
- **Summary**

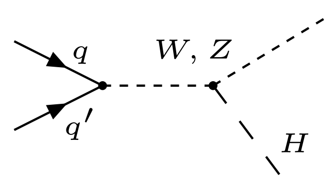
# Introduction - Higgs Boson Production at LHC

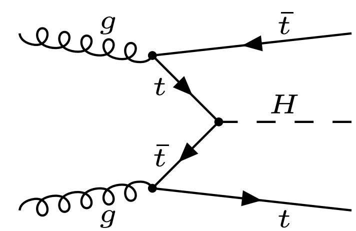
- Gluon Fusion large due to large gluon luminosity at LHC
- NLO cross sections known at 5% (WBF) to 15% (GF) level



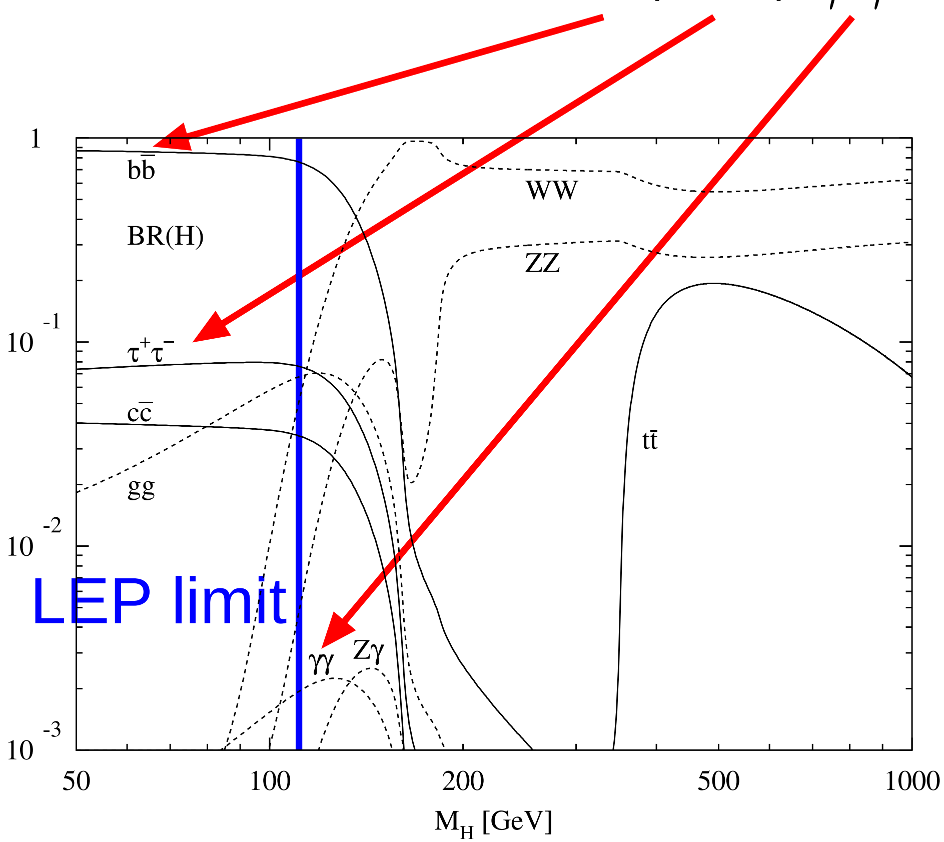




| | | | |
|---|---|---|---|
| Gluon-Fusion (GF) $(gg \to H)$ | Weak-Boson-Fusion (WBF) $(qq \to qq\,H)$ | $W$-, $Z$- Bremsstrahlung $(WH, ZH)$ | $t\bar{t}$ associated production $(t\bar{t}H)$ |

# Introduction - Higgs Boson Decays

$110$ GeV $\lesssim m_H \lesssim 150$ GeV :

- close to LEP limit, discovery is most problematic for LHC
- search for H $\longrightarrow$ bb, $\tau\tau$, $\gamma\gamma$

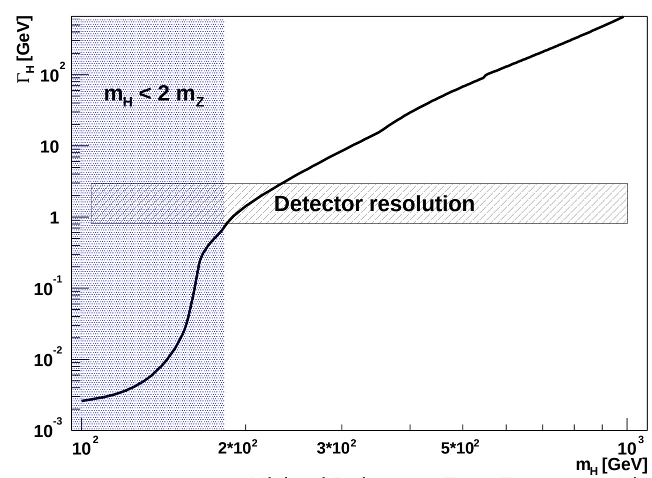



$135$ GeV $\lesssim m_H$ :

- search for H $\longrightarrow$ WW, ZZ

$180$ GeV $\lesssim m_H$ :

- H $\longrightarrow$ ZZ golden channel
- total width measureable



# Introduction - Higgs Boson Discovery Potential

**Main discovery channels:**

$m_H \gtrsim 2\,m_Z$ : GF : H $\longrightarrow$ ZZ

WBF : H $\longrightarrow$ ZZ

H $\longrightarrow$ WW

$m_H \lesssim 2\,m_Z$ : GF : H $\longrightarrow \gamma\gamma$

H $\longrightarrow$ ZZ

H $\longrightarrow$ WW

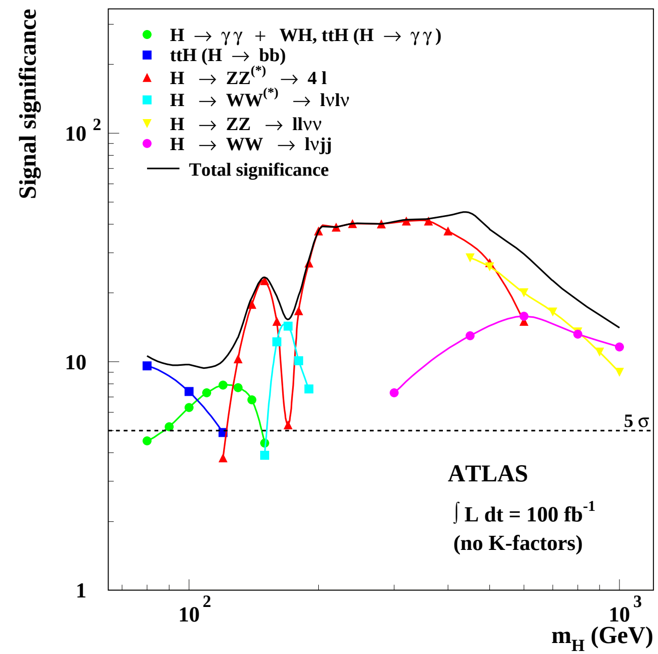
$t\bar{t}$ H : H $\longrightarrow b\bar{b}$

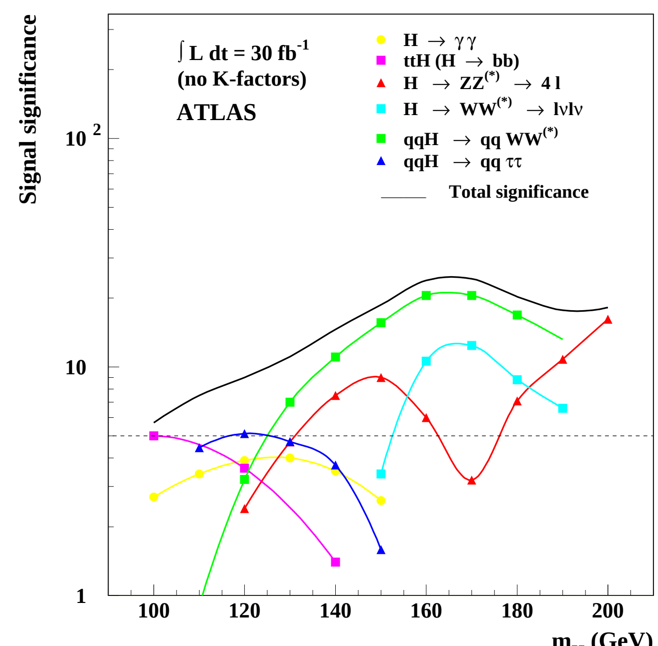
WBF : H $\longrightarrow$ WW

H $\longrightarrow \tau\tau$

**Dicovery Potential based on**

**LO predictions**



# Introduction - Early discovery of a light Higgs

## - where Tevatron enters the game -

**The most promising channels and the main challenges :**

(more details later)

- inclusive H $\longrightarrow \gamma\gamma$ :

  large background

- inclusive H $\longrightarrow$ ZZ :

  lepton isolation

- GF H $\longrightarrow$ WW :

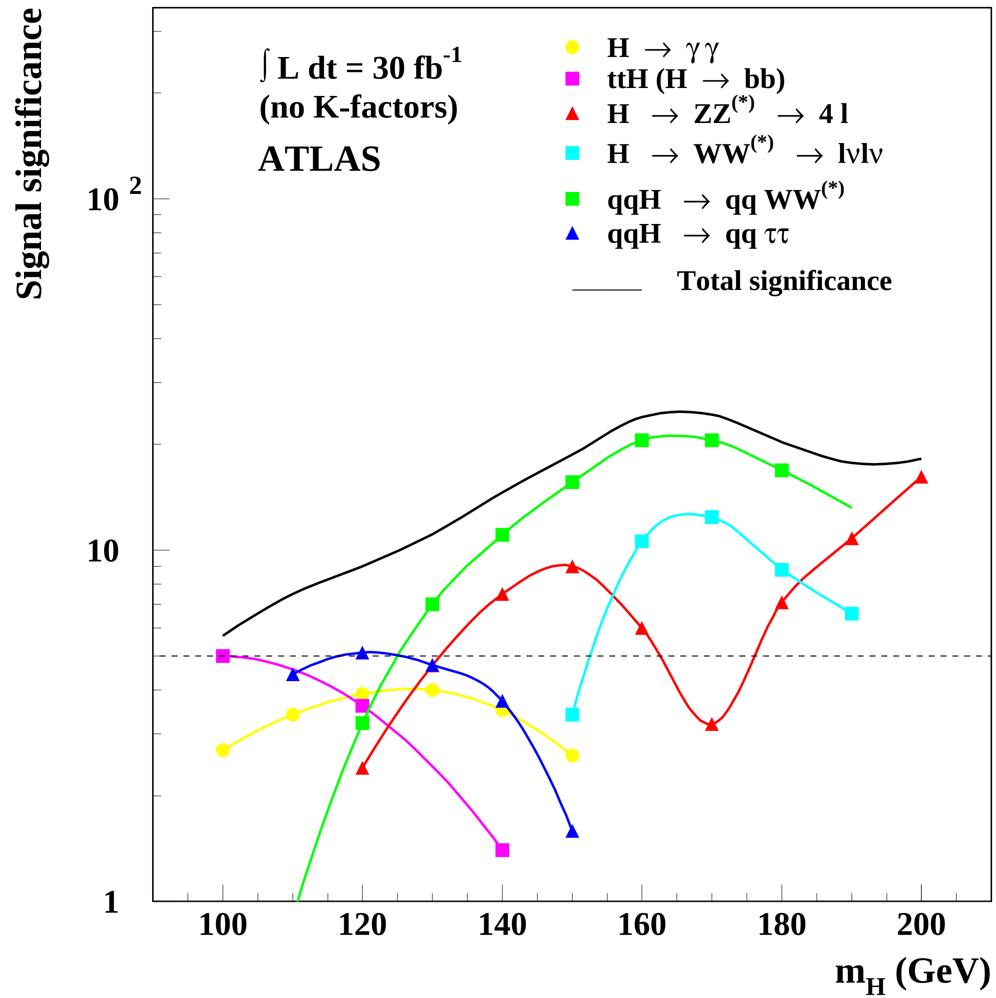
  background normalization

- WBF H $\longrightarrow \tau\tau$ :

- WBF H $\longrightarrow$ WW :

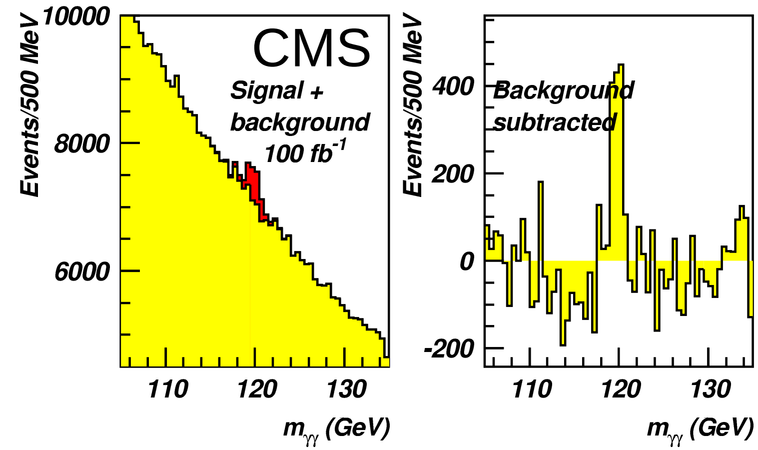
  tagging jets and jet veto

- or Tevatron is faster...



# $H \rightarrow \gamma\gamma$

**Challenges for the detector :**




- needs very good calorimeter

  mass resolution $\sigma_{\text{CMS}} \approx 800$ MeV

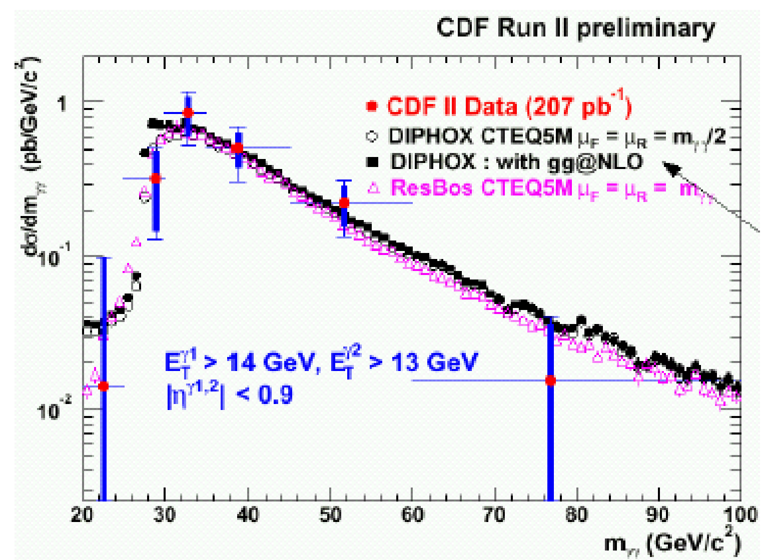
- needs very good photon/jet rejection

  (fake rate $\approx$ 1/10.000)

**Challenges for theory (NLO MC tested/tuned against Tevatron data):**

- $\gamma\gamma$, $\gamma$-jet and jet-jet background very difficult to estimate

- matching of photon isolation in theory and experiment not trivial




**But :**

- can take background from data !

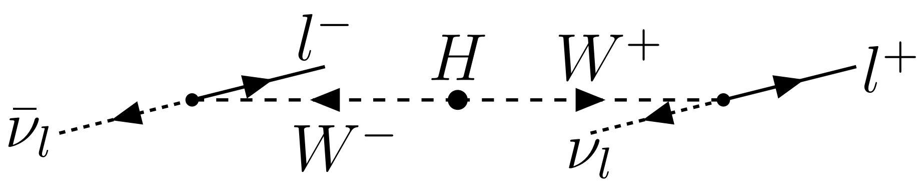
# H $\longrightarrow$ WW $\longrightarrow l\nu\ l\nu$

## Channel with largest statistical potential ($m_H$ $\approx$160 GeV):

- No Higgs resonance visible
- Main backgrounds: tt and WW

  learn from Tevatron: check W+jets/$\gamma$
- tt : reduce by jet veto, b-jet veto
- WW : different spin correlations

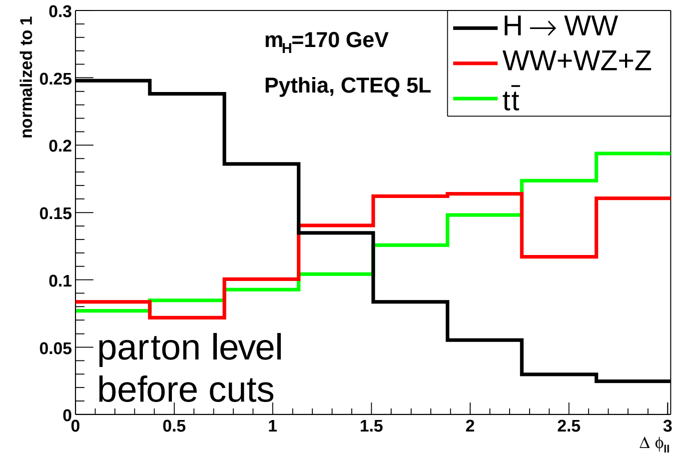
  most significant : $\Delta\phi$ of leptons




- Main theoretical challenge :

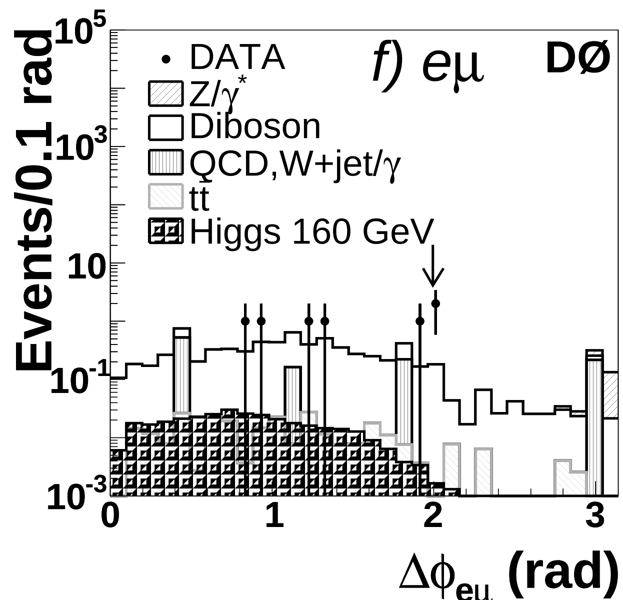
  - need to know shape of WW

  - need to know contribution from gg$\longrightarrow$WW
- Need to know bg. at $\approx$ 5% level !




Learn from Tevatron about WW:

$\sigma(WW)$=13.8 $^{+4.3}_{-3.8}$ $^{+1.2}_{-0.9}$ $\pm$ 0.9 pb




From H $\longrightarrow$ WW analysis

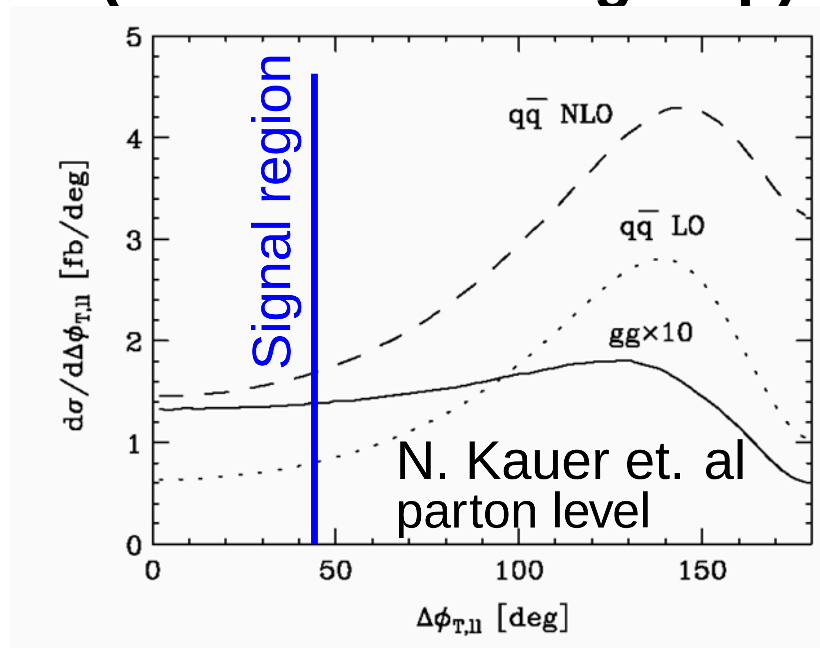
more WW events in $q\bar{q}\longrightarrow$ WW analysis ($\approx$320pb$^{-1}$)

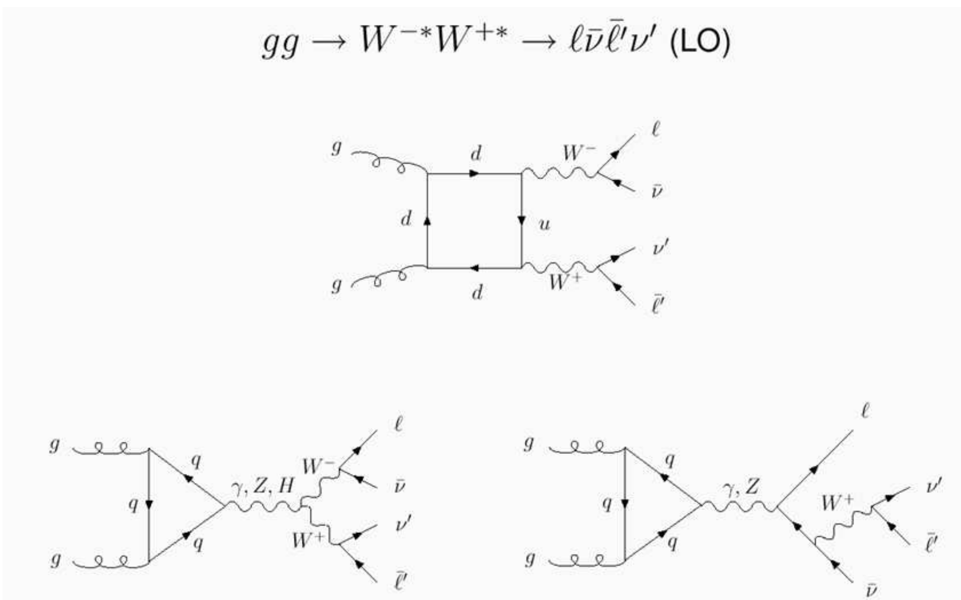
**(PRL 94: 151801)**

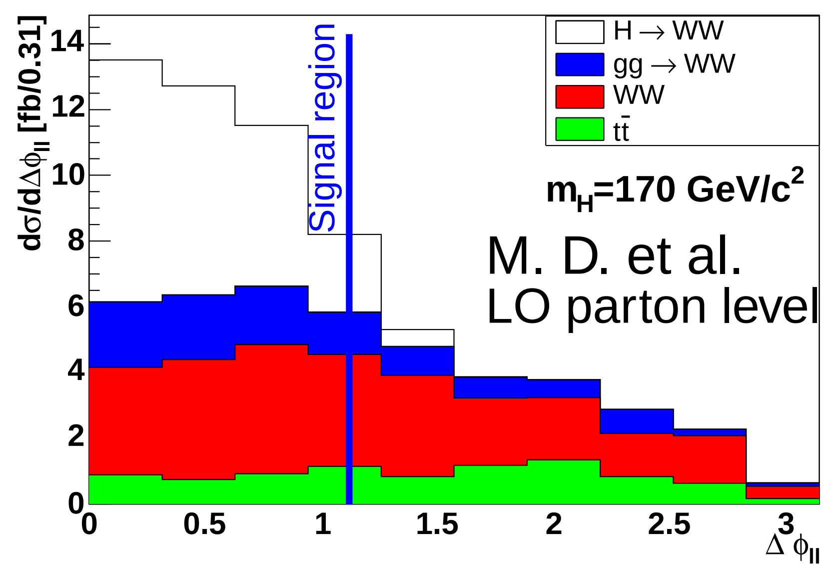
# H $\longrightarrow$ WW $\longrightarrow l\nu\ l\nu$ : gg $\longrightarrow$ WW background

## From Les Houches Workshop 2005 (dedicated workgroup)

- Part of NNLO for $q\bar{q} \rightarrow WW$
- $\sigma(gg \rightarrow WW)$ only 5% of $\sigma(WW)$ before cuts, but $\approx$ 30% after cuts $\longrightarrow$ very signal like
- too small at Tevatron

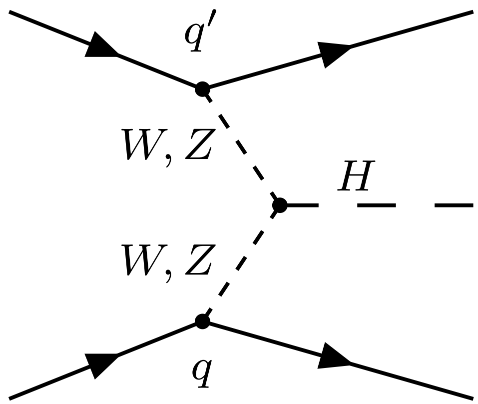


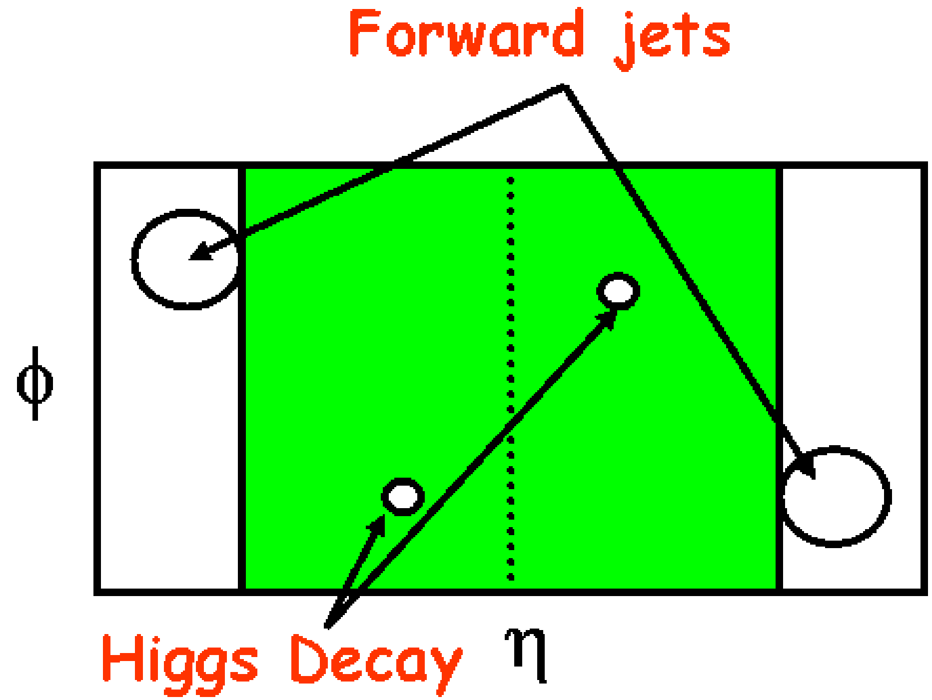



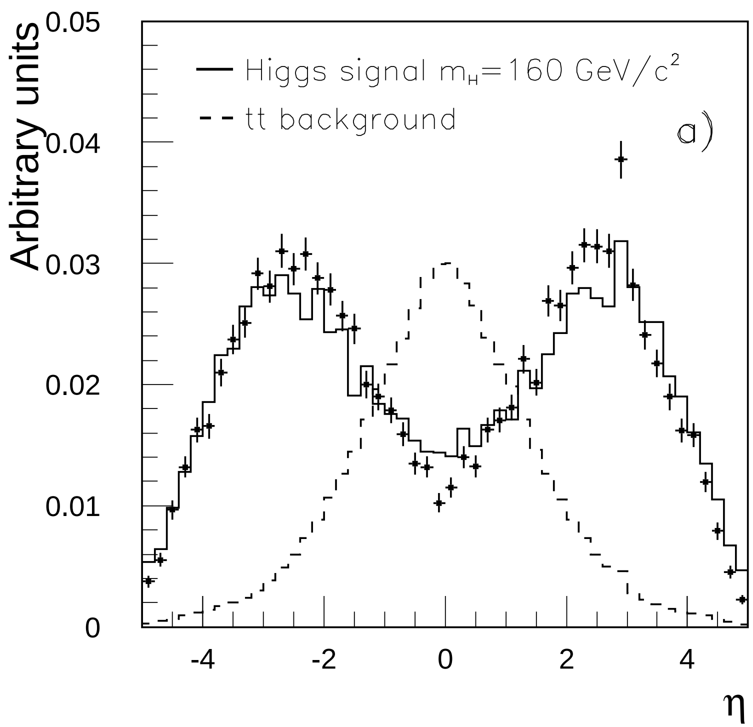




- Sytematic normalization of background is limiting this channel

# Weak Boson Fusion WBF (VBF)




Extra Signature:

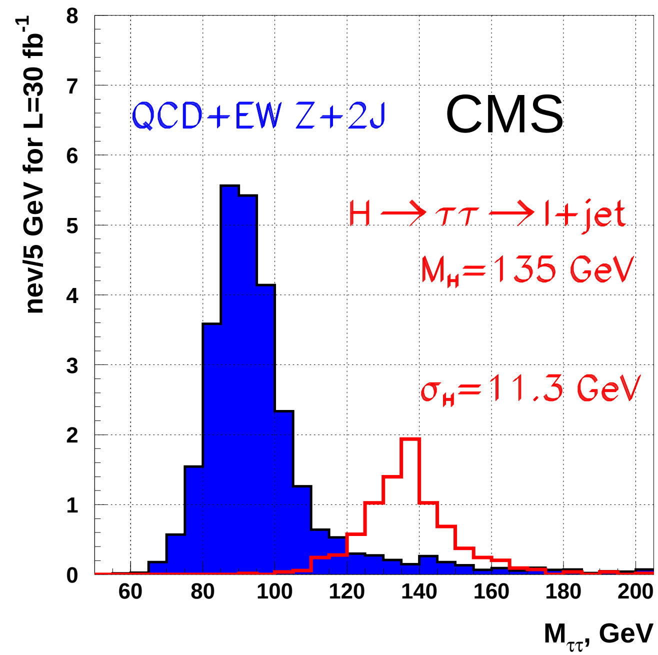
- 2 high $p_T$ forward jets (large $\Delta\eta$)
  $\longrightarrow$ tagging jets
- Jet veto in central region
- large $M_{jj} \approx$ 0.5 - 1 TeV
- Higgs decay products between tag jets

# WBF H $\longrightarrow \tau\tau$

- Dominant discovery channel for a light Higgs ($m_H \lesssim$135 GeV)
- Dominant background from Zjj
- Main experimental challenges :
  - forward jet reconstruction
  - pile up and central jet veto
  - Z $\longrightarrow \tau\tau$ shape
- Main theoretical challenge for the backgrounds :
  - correct description of tagging jets
  - correct description for 3rd jet
- But : shape of Z$\longrightarrow \tau\tau$ background can be taken from data

Most important jet cuts :

- $p_T(j_1) >$ 20 - 50 GeV
- $p_T(j_2) >$ 20 - 30 GeV
- $\Delta\eta(jj) >$ 3.5 - 4.5
- $M(jj) >$ 600-700 GeV
- jet veto : $p_T > 20$ GeV $|\eta_3| <$ 3.2 or $\eta_1 < \eta_3 < \eta_2$

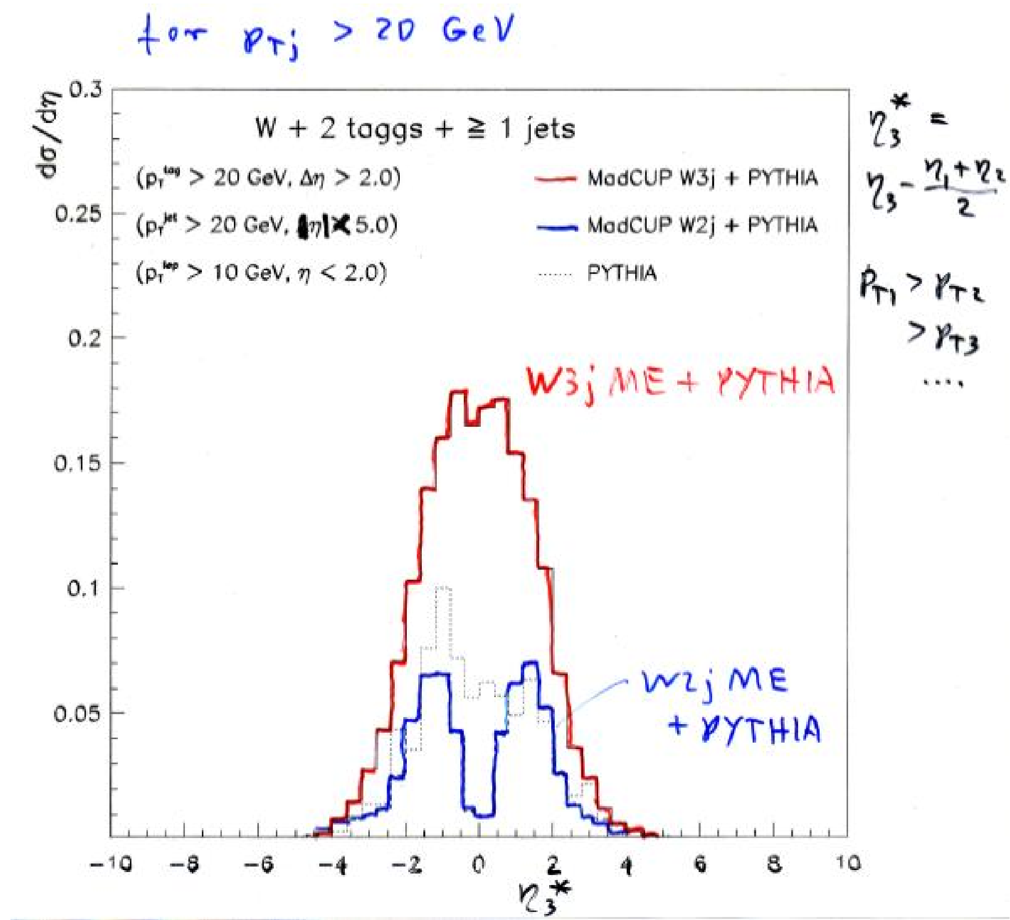


# Test of WBF like jets: Zeppenfeld plot

For the background MC we want

- tagging jets from matrix element (ME)
- 3rd jet (for jet veto) is soft : ME or parton shower (PS) ?
- define $\eta_3^* = \eta_3 - \frac{\eta_1+\eta_2}{2}$
- parton shower predicts 3rd jet close to tagging jets
- ME predicts central 3rd jet $\longrightarrow$ better background rejection

From D. Zeppenfeld, TeV4LHC 09/16/2004




$\longrightarrow$ **Combine both : CKKW or MLM matching of PS and ME**

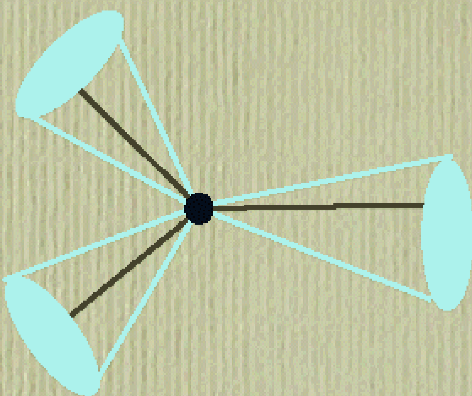
**Tevatron plays a key role : can test jet distributions in W/Z+N jets !**

# MLM matching (M. Mangano at TeV4LHC)

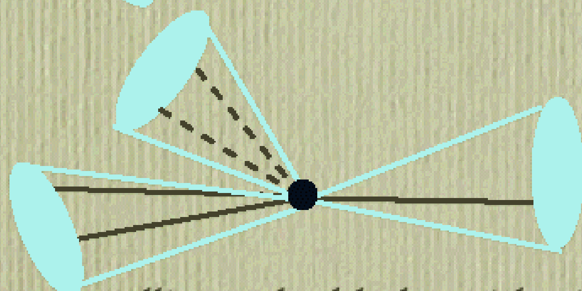
**Few examples of matching:**

— hard parton

- - - parton emitted by the shower



Event matched, $N_{jet}=N_{part}=3$, keep

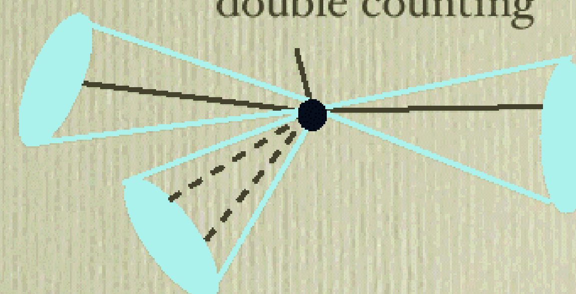


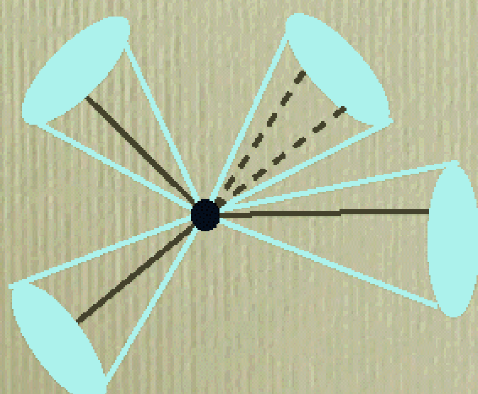
collinear double-logarithmic double counting

NOT matched, $N_{jet}=N_{part}=3$, but $N_{match}=2$

Throw away

soft single-logarithmic double counting





Event matched, $N_{jet}>N_{part}$, keep for inclusive sample, but throw away for exclusive samples.

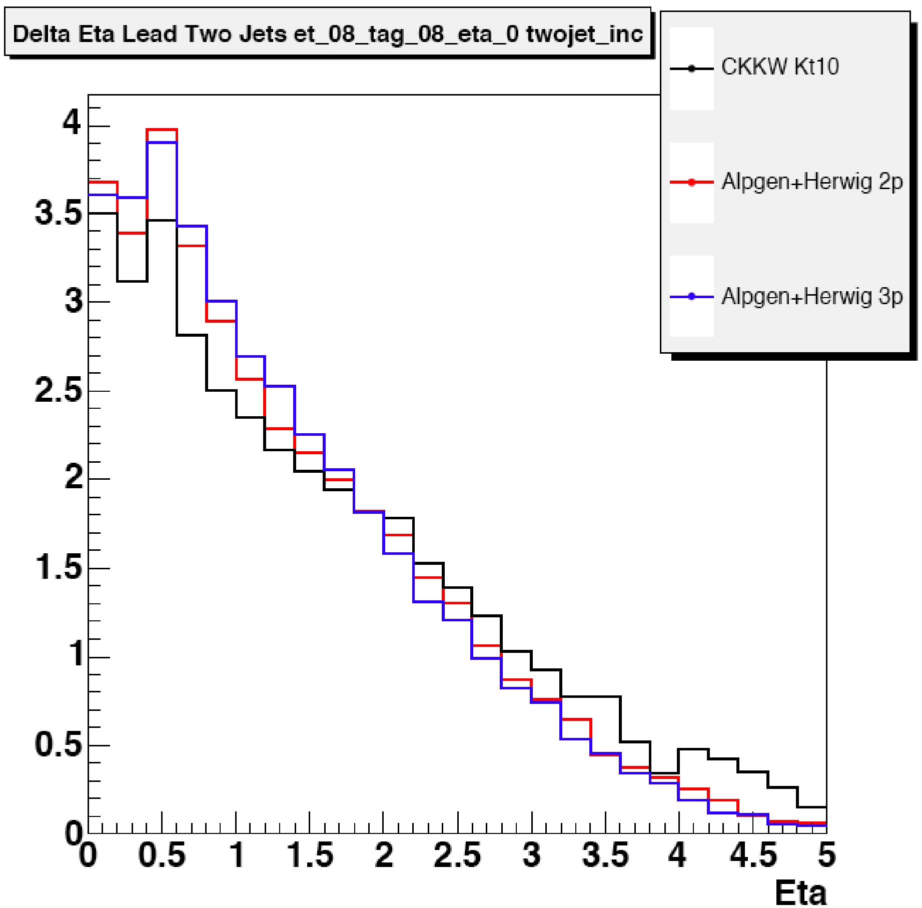
8

# W + jets at CDF

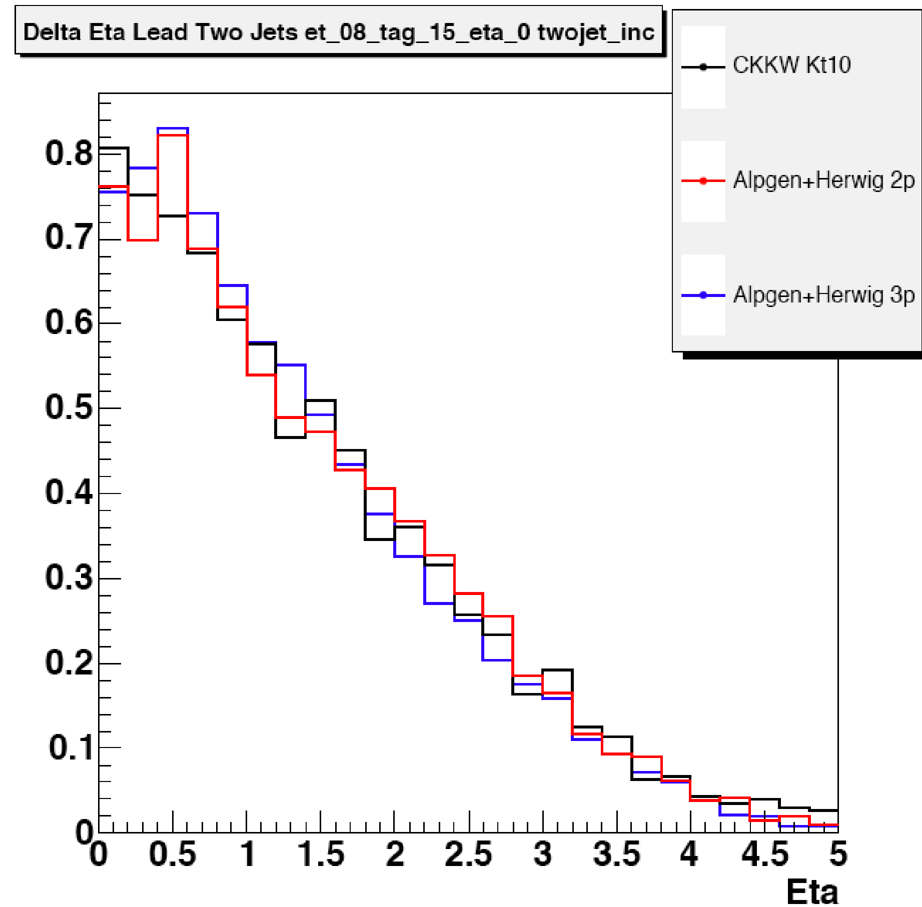
- WBF H not visible at Tevatron, but backgrounds for WBF can be tested
- Analysis of W+jets events at CDF performed (B. Cooper and J. Huston), results will be released soon
  - select events with two jets at large $\eta$ seperation
  - look at the 3rd jet (if any)
- Test data against various MC prediction
  - Alpgen + Herwig (no MLM matching)
  - Matched W + N jet events produced by S. Mrenna (Madgraph/Madevent + Pythia)
  - MCFM W +2 jets at NLO (W + 3 jets at LO)

# W + jets at CDF : $\Delta\eta$ of tag jets

## $\Delta\eta$ of tag jets for two different tag jet $E_T$ cuts



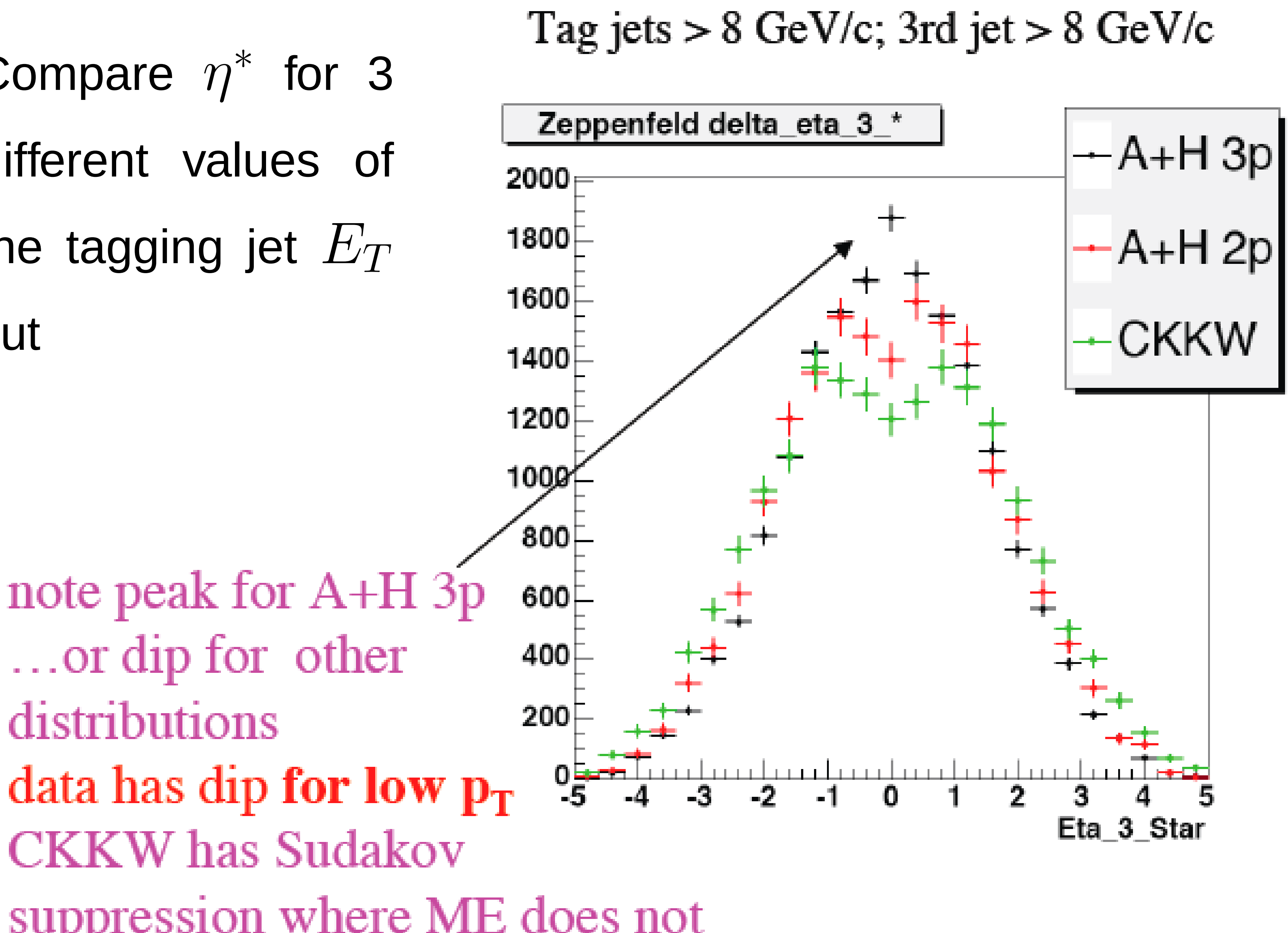

$E_T$ of tag jets $> 8$ GeV




$E_T$ of tag jets $> 15$ GeV

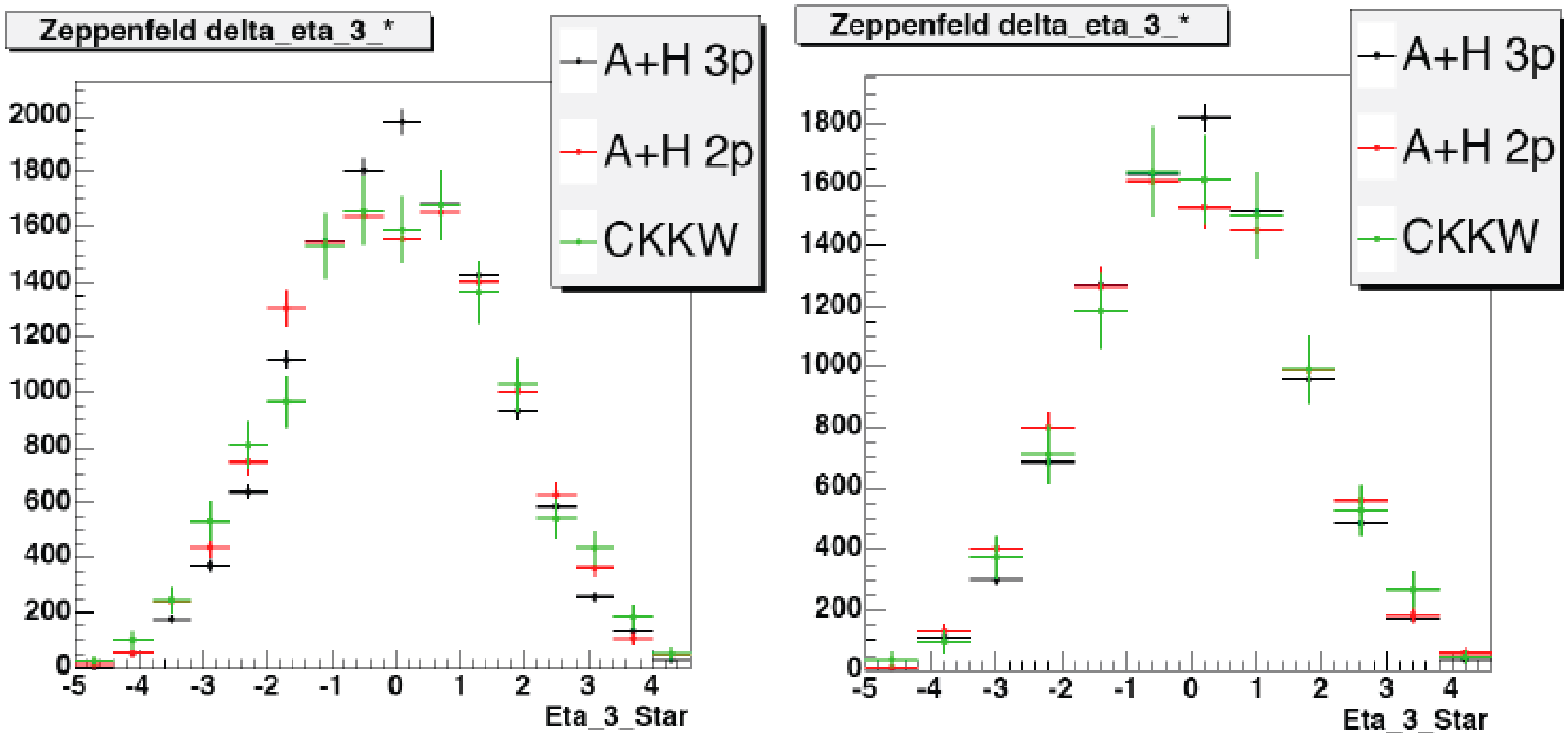
# W + jets at CDF : $\eta^*$ for $\Delta\eta > 1$

Compare $\eta^*$ for 3 different values of the tagging jet $E_T$ cut



# W + jets at CDF : $\eta^*$ for $\Delta\eta > 1$

Tag jets > 15 GeV/c; 3rd jet > 8 GeV/c | Tag jets > 20 GeV/c; 3rd jet > 8 GeV/c



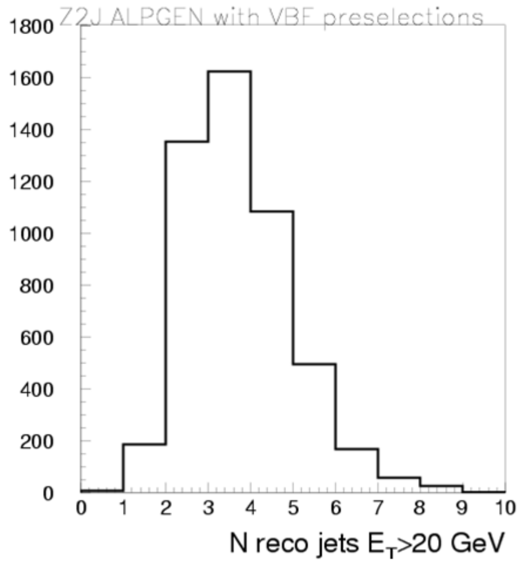

Dip fills in as tag jet $E_T$ increases

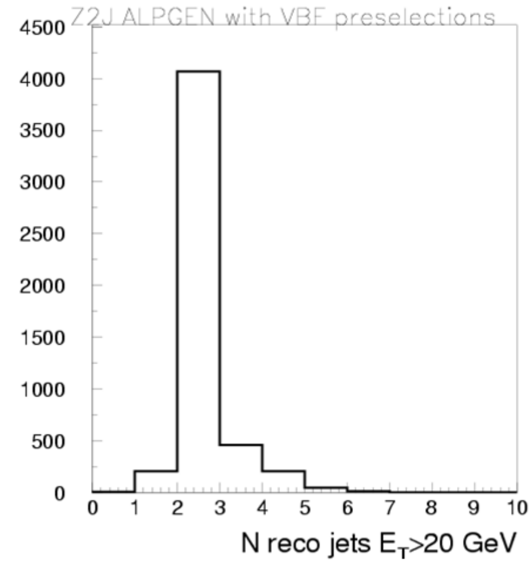
- Just some examples, a lot of interesting work in progress...

  Want more ? Please have a look at Joey Hustons talk this afternoon

# At LHC : MLM Z+2j exclusive (CMS preliminary*)

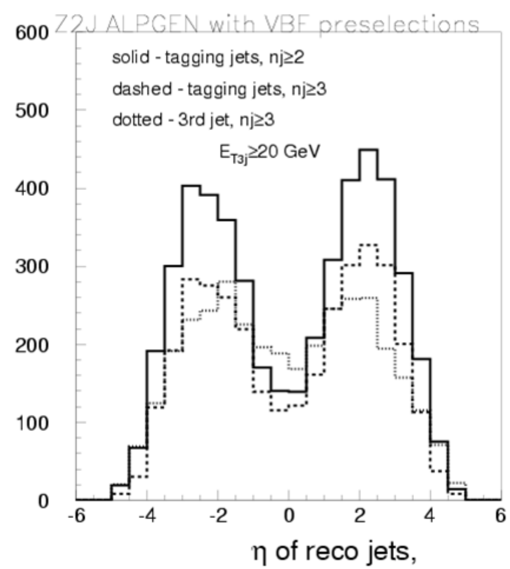
ALPGEN+PYTHIA Z+2j before and after MLM exclusive matching

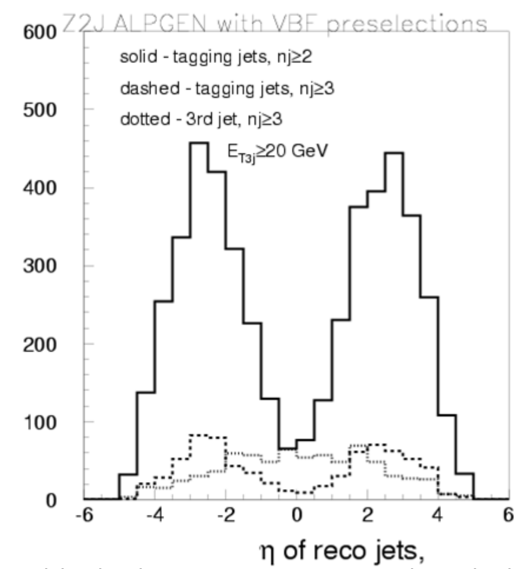



before MLM matching, $\sigma$=5.91pb

after MLM matching, $\sigma$=1.04pb

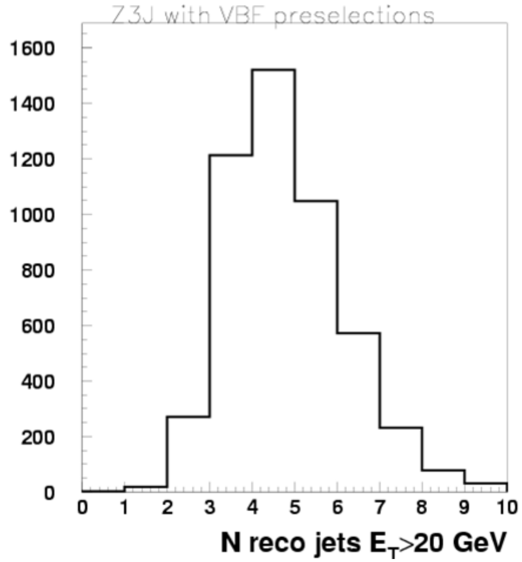


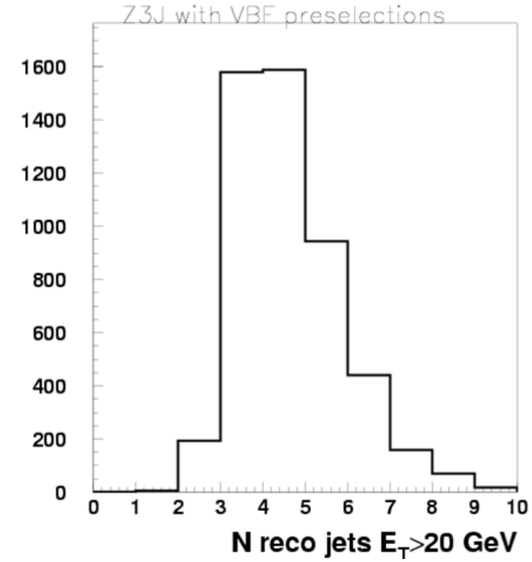




* Thanks to A. Nikitenko

# MLM Z+3j inclusive (CMS preliminary)

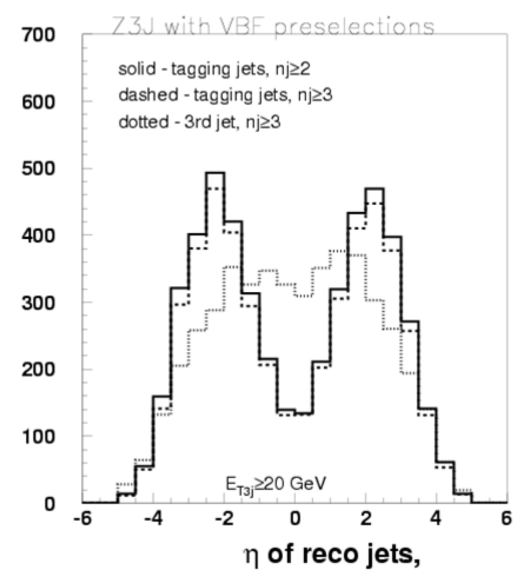
ALPGEN+PYTHIA Z+3j before and after MLM inclusive matching

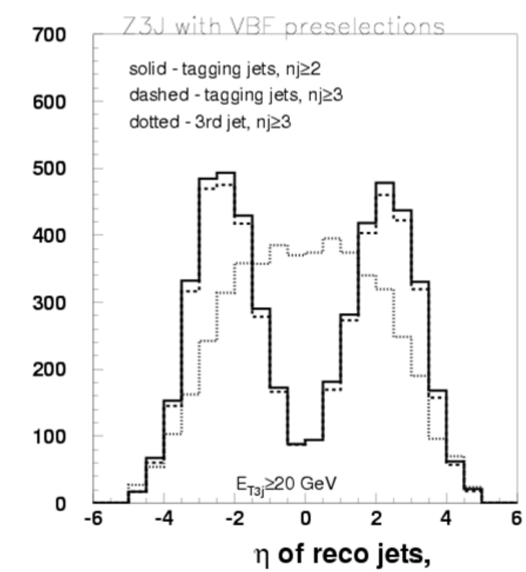



before MLM matching, $\sigma$=5.42pb

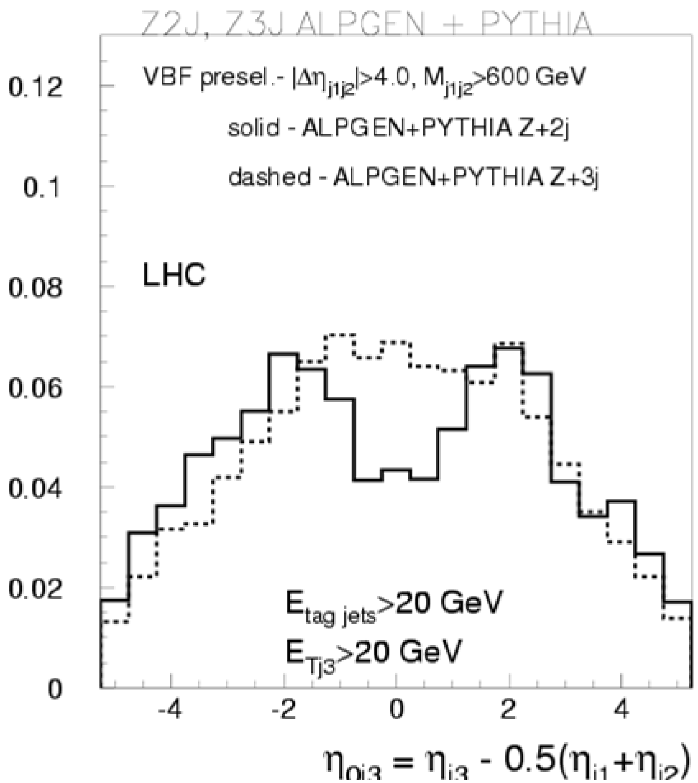
after MLM matching, $\sigma$=2.52pb

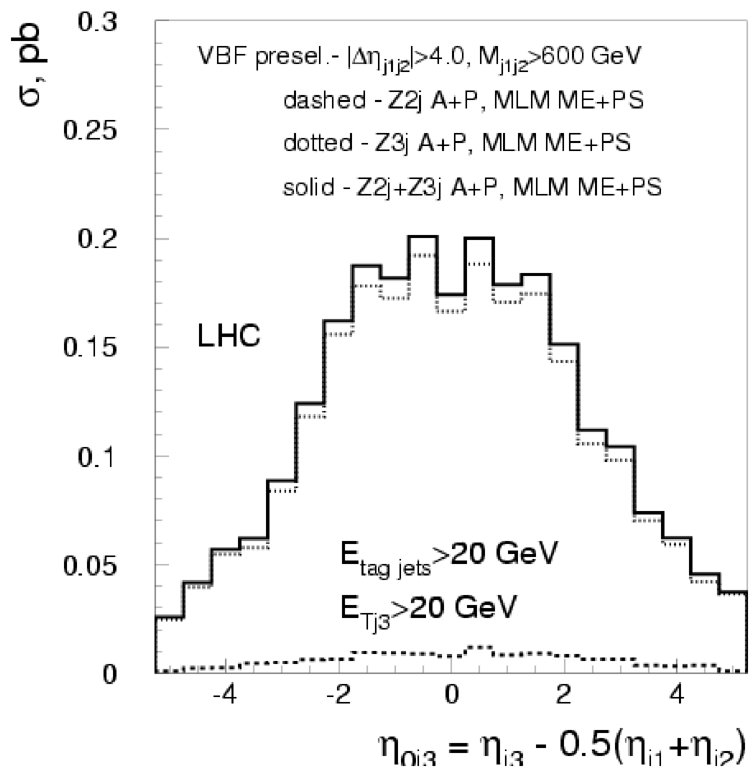


# MLM Z+2j/3j: $\eta^*$ distribution (CMS preliminary)

Zeppenfeld plot $\eta^* = \eta_3 - \frac{\eta_1+\eta_2}{2}$




Without MLM matching

3rd jet from parton shower or

Matrix Element

After MLM matching

3rd jet more central :

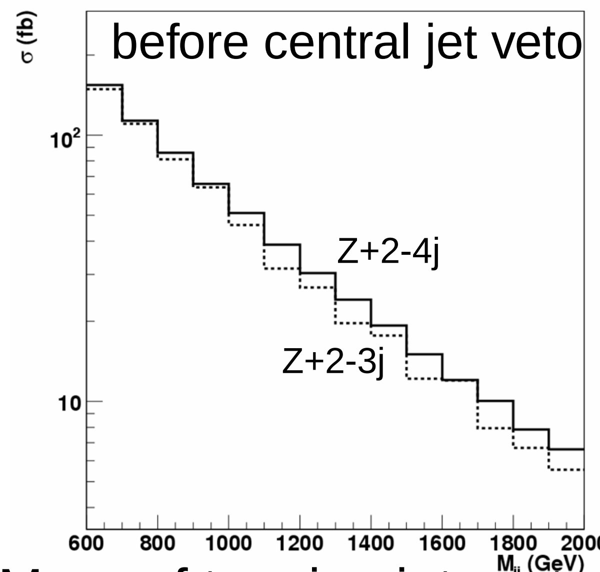
$\longrightarrow$ better rejection against QCD bg.

# Z+2j-4j : Stability check (ATLAS preliminary*)

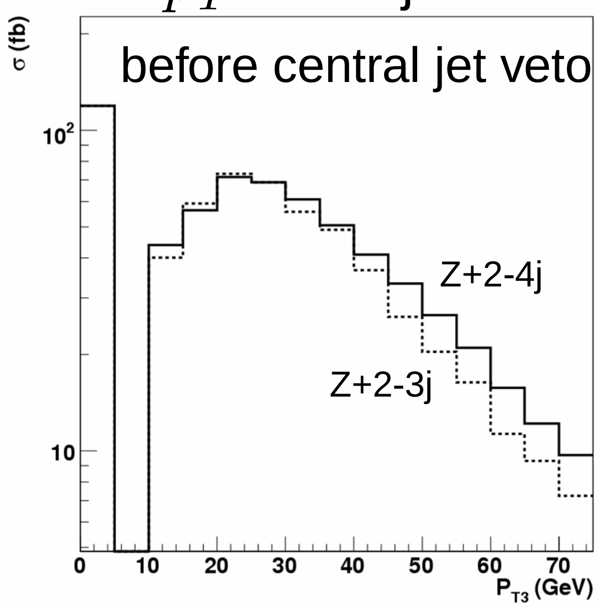
ALPGEN+PYTHIA Z+2j/3j with MLM and Z+2j/3j/4j with MLM

Check if approach is consistent : add more jets

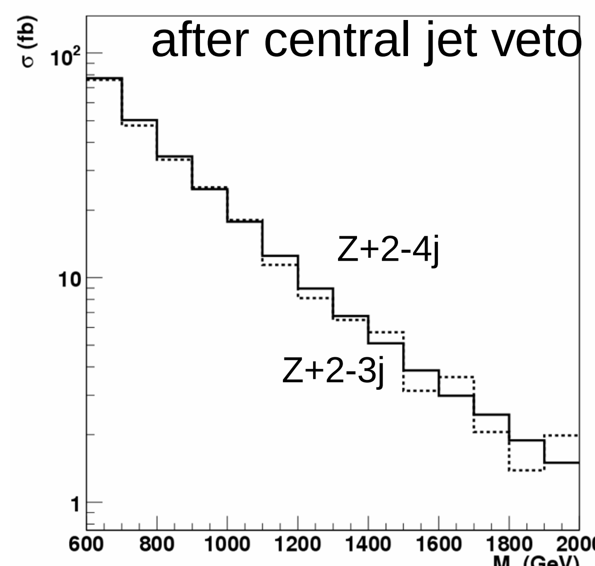
- Preliminary study based on ATLFAST
- compare MLM Z+2j-3j with MLM Z+2j-4j after tag jet selection and cuts
- after central jet veto no contribution from Z+4j left




$p_T$ of 3rd jet




Mass of tagging jet system



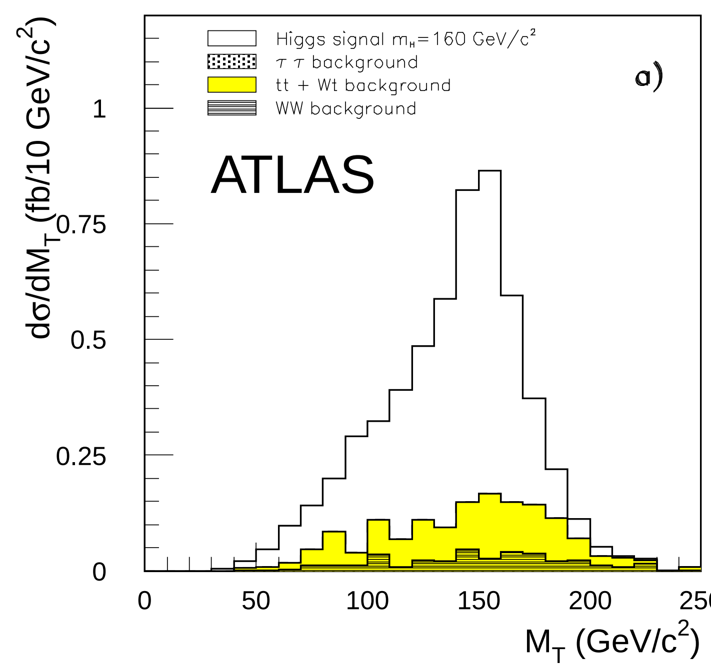

* Thanks to B. Mellado

# WBF H $\longrightarrow$ WW $\longrightarrow l\nu\ l\nu$

- Dominant Higgs discovery mode for 130$\lesssim m_H \lesssim$190 GeV
- Dominant background from $t\bar{t}$ and electroweak WW production
- Main experimental challenges :
  - forward jet reconstruction
  - pile up and central jet veto
- Main theoretical challenge for the backgrounds :
  - correct description of tagging jets
  - correct description for 3rd jet

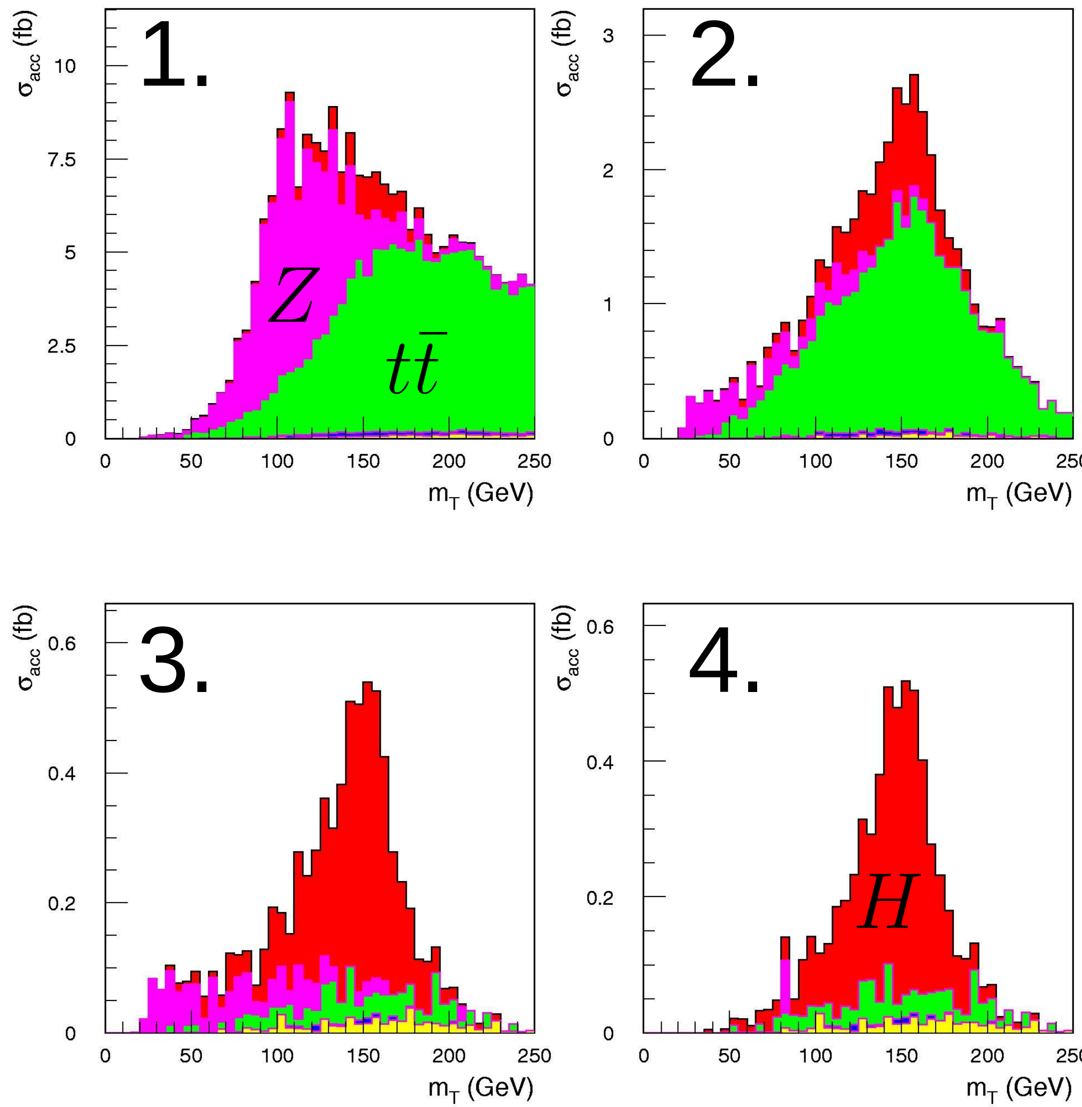
Most important jet cuts :

- $p_T(j_1) > 40$ GeV
- $p_T(j_2) > 20$ GeV
- $\Delta\eta(jj) > 3.8$
- $M(jj) > 550$ GeV
- jet veto : $p_T > 20$ GeV $|\eta_3| < 3.2$



# WBF H $\longrightarrow$ WW : Importance of jet veto

1. After lepton and tag jet requirements
2. Lepton angular and mass cuts
3. Momentum balance and central jet veto
4. Drell Yan (Z) rejection




$$M_T = \sqrt{(E_T^{ll} + E_T^{\nu\nu})^2 - (\vec{p}_T^{\,e\mu} + \vec{p}_T^{\,\text{miss}})^2}$$

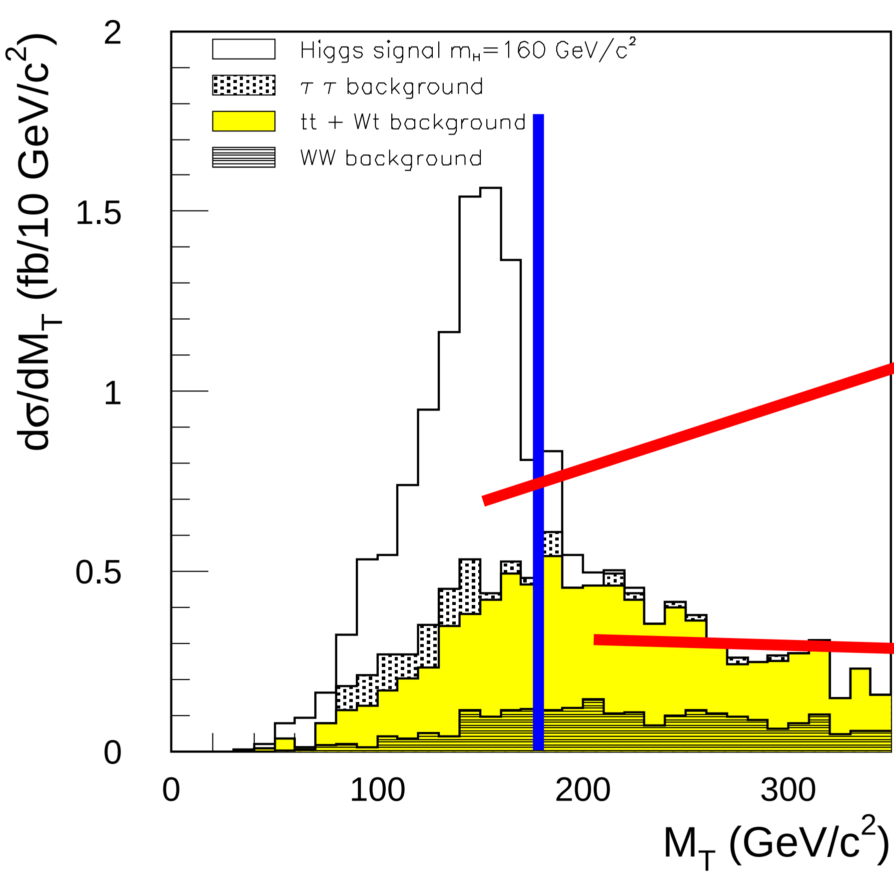
# WBF H $\longrightarrow$ WW : $t\bar{t}$ background

- Different situation than for Zjj : two b-jets from top-decay
- The combination of tag jet selection and central jet veto leads to a very specific topology:
  - one b-jet and one non b-jet are selected as tag jets
  - central jet veto either from second b-jet or radiation jet
- Detailed study started by B. Mellado, M. Duehrssen, J. Huston, S. Mrenna, ...
- Use of different MC Generators : Sherpa, Madgraph + Pythia + MLM by S. Mrenna, MC@NLO, ...

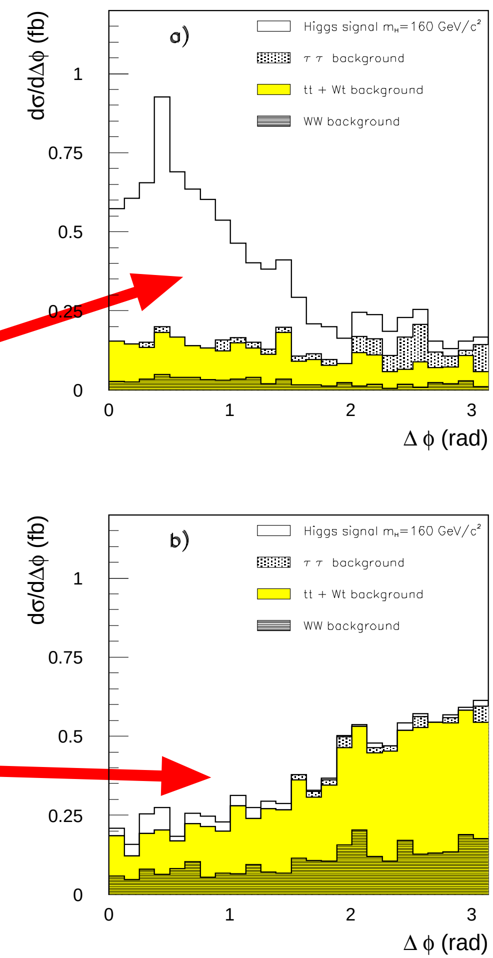
# WBF H $\longrightarrow$ WW : background normalization

- Cuts reduce tt background by more than a factor 10.000
- Only trust the Monte Carlo? Normalization from data needed!
- Normalize bg. to region in $M_T$ with small signal contribution

  (after jet cuts, before lepton cuts)




Strong angular correlation $\Delta\phi_{ll}$ in signal



# Higgs at Tevatron and LHC (besides who is first)

- So far concentrated on topics where Tevatron can help to understand LHC Higgs backgrounds
- Suppose the Higgs is really light, Tevatron might see first indications for H $\longrightarrow$ bb while LHC is seeing something in H$\longrightarrow \tau\tau$, $\gamma\gamma$, WW or ZZ
- But combining information on H $\longrightarrow$ bb from Tevatron with whatever LHC sees might give very valuable information for understanding Higgs physics

# Summary and Outlook

- I am sure I have forgotten to mention many studies...
- In the beginning of the LHC the focus of Higgs physics will be on understanding Standard Model backgrounds
- Todays measurements at the Tevatron give very valuable information on how accurate current predictions are
- Key issue is to understand W/Z, WW, tt backgrounds + jets
  - How often and in which topology are tag jets selected?
  - How effective is the central jet veto?
- And of course, LHC can learn a lot for lepton ID, jets, missing E$_T$, b-tag, $\tau$-tag, ...

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