# MEM@NLO

Walter Giele, arXiv:1204.4424

# The Matrix Element Method at Next-to-Leading Order

In collaboration with
Ciaran Williams
and
John Campbell

Chicago 2012 Workshop on LHC Physics

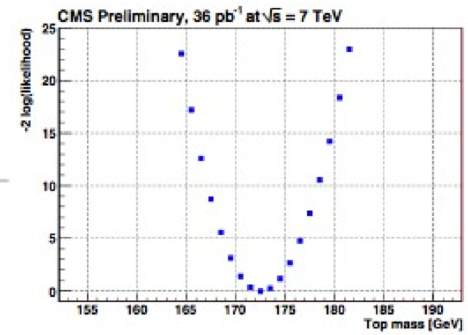
# Outline

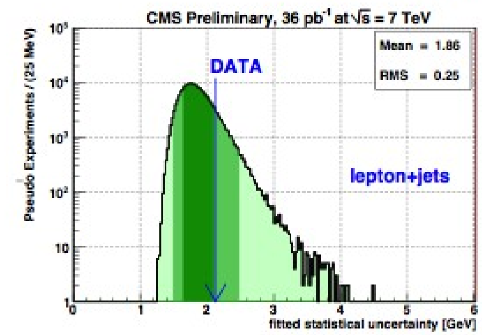
- Theoretical issues in MEM
- MEM@NLO method
- MEM@NLO examples
  - Z mass
  - W mass
  - PP $\rightarrow$ 4 leptons
- Outlook

# Introduction

- The Matrix Element Method has been used by the experimenters for a long time
  - Developed and used at Tevatron, also used at LHC.
  - Good at extracting model parameters.
- On the theoretical side not much attention has been given to this method
  - Only used in some manner with Leading Order.
  - Need for a proper definition of the method to all orders in perturbation theory (LO, NLO,..., LL,...).
  - Should minimize higher order corrections as much as possible.

# MEM in action!



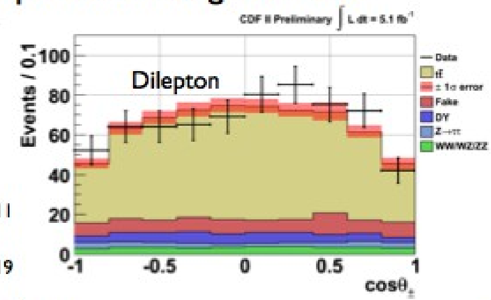

CMS:PAS TOP-10-009

## Measuring the Spin Correlation

- Results shown here assume spin quantized along beam axis
- CDF:
  - Template fits based on decay product angular distributions

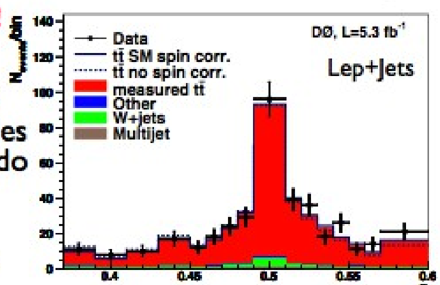
$\kappa^{CDF}_{Lep+Jet} = 0.72 \pm 0.69$ CDF Conf. Note 10211

$\kappa^{CDF}_{Dilepton} = 0.042 \pm 0.563$ CDF Conf. Note 10719




- D0: 3 σ Evidence For Spin Correlations!
  - New matrix element approach
    - Significantly increased sensitivity
  - Likelihood fit based on probabilities that events are signal events and do (or do not) contain SM spin correlation

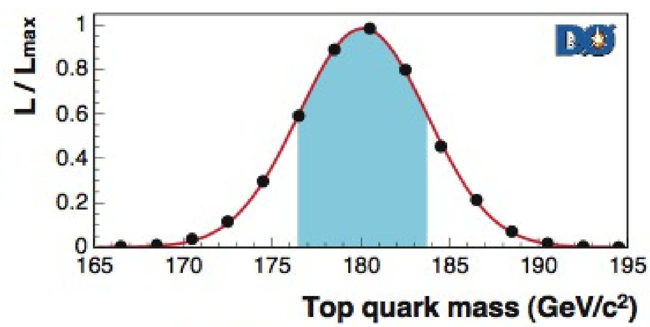
$\kappa^{D0}_{Combo(Dil,Lep+Jet)} = 0.66 \pm 0.23$




9 PRL **108**, 032004 (2012)

D. Mietlicki Moriond 2012

<=SM prediction 0.78(4)

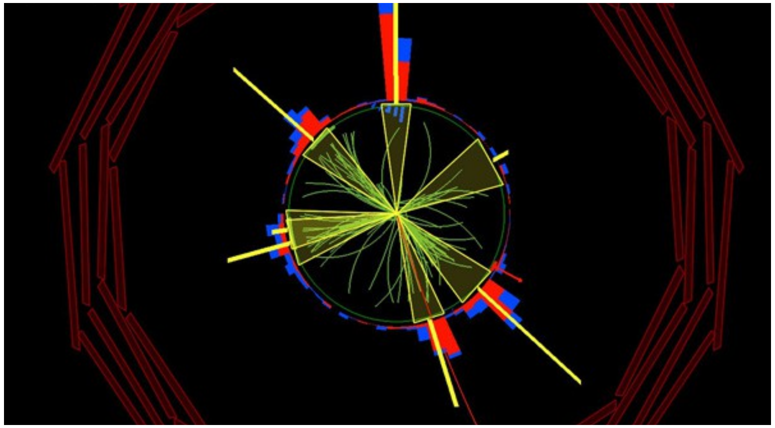



D0: Nature **429**, 638-642

- Slide from David Mietlicki's Moriond talk.

# MEM Issues

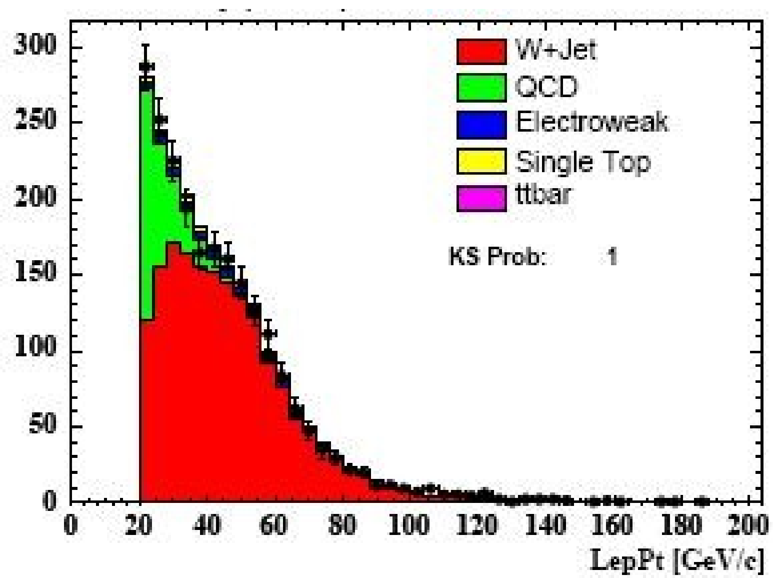
- The basis of the MeM method is simple:
  - Assign a probability to an observed event

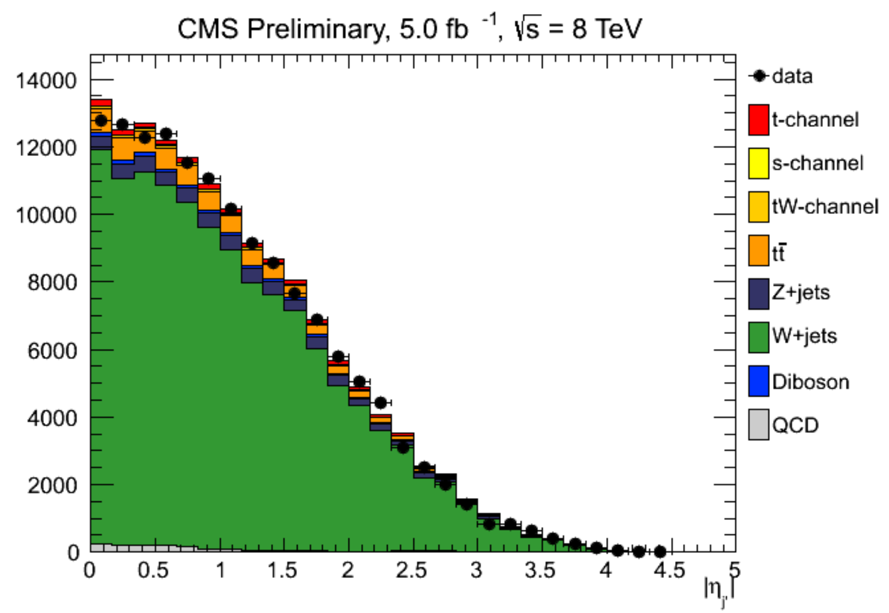


  - Fixed order pQCD should be able to give a sensible prediction provided it is only jet exclusive (i.e. we sum over all possible hadronic configurations leading to the jet final state).

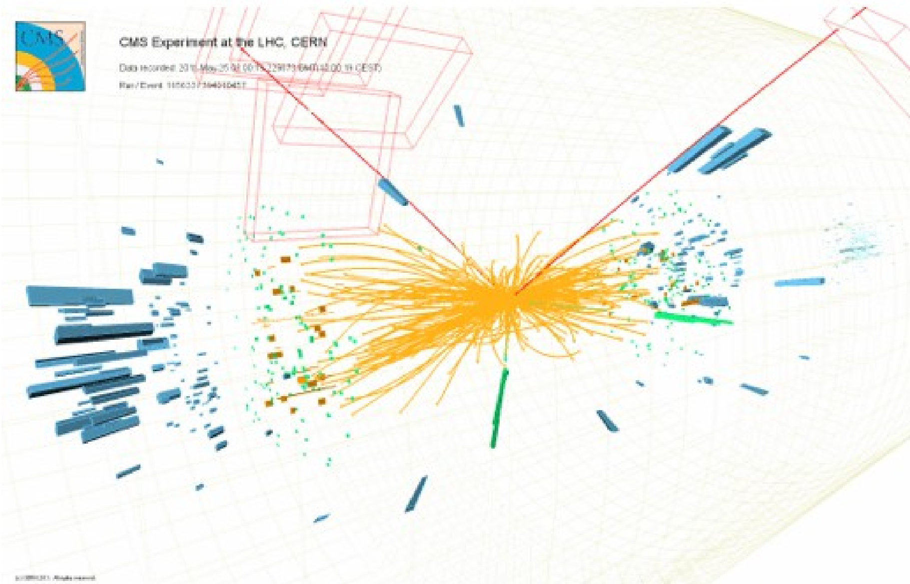
# MEM issues

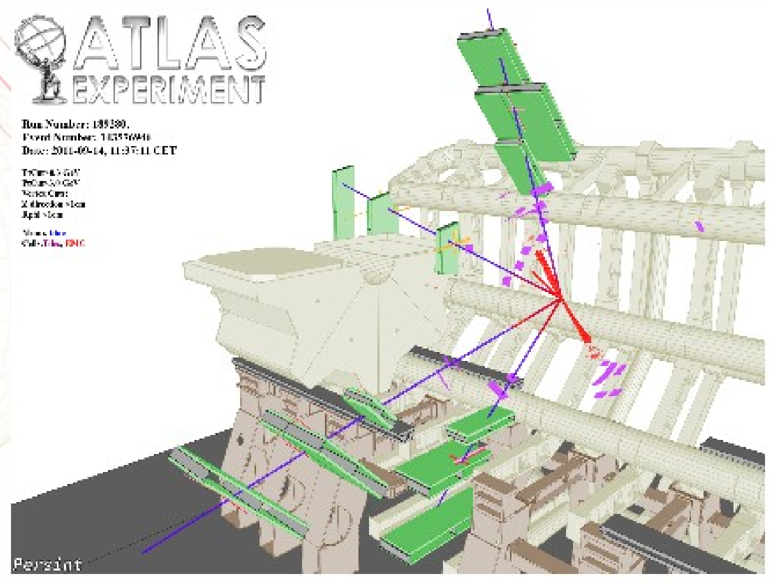
- Note that this is very different from a standard approach used in MC. We usually generate kinematic configurations with associated weights.
- These are binned for a comparison with data.

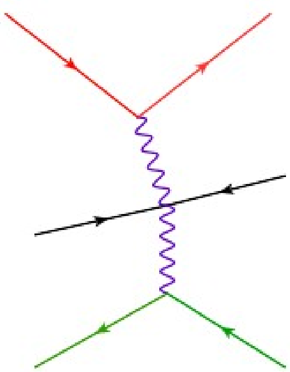


# MEM method



We want to weight an experimental event with a fixed order ME.

Experimental events contain more than the Born final state particles, we need to conserve momentum between the observed final state.

# MEM method

- A Leading Order event has 2 distinct features:
  - Jet momenta are massless (i.e. no FSR).
  - No unclustered hadrons (i.e. no ISR).
- In a real event the jets are massive and the final state objects are not Pt balanced due to unclustered energy.
- How to match real events onto the LO kinematics is not obvious.
  - (Solving this, is the same as defining MEM@NLO as NLO has ISR and FSR).

# MEM method

- LO tells us the jet mass is an internal property of a jet and should be integrated over
  - I.e. only the transverse momentum and rapidity of an event are fixed for an event.
  - This is conceptually easy to implement.
- LO tells us an event should be Pt balanced.
  - i.e. hadrons not associated with final state jets have to be taken into account. We need beam jets, so the ISR can be integrated out.
  - This needs more clarification.
  - (Note the unclustered hadrons are now of importance.)

# MEM method

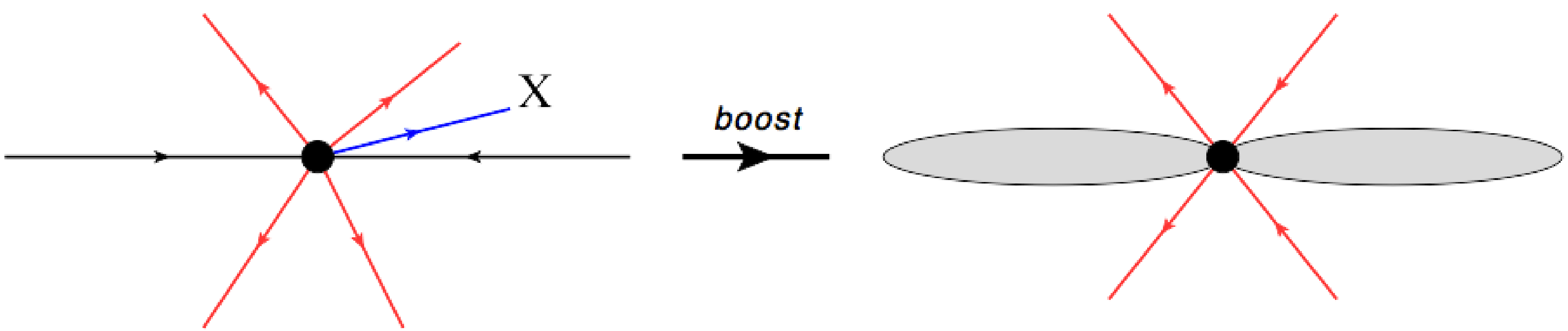
- Consider the production of an electorweak final state Q, on the experimental side this is measured as the desired final state, plus some addition recoil X.

$$Q + X$$

- We wish to model this as,

$$p_a + p_b \to Q$$

- One obvious mechanism to remove the excess recoil is to boost it into the initial state. I.e. we boost our final state Q such that its conserves momentum in the transverse plane. This has the obvious advantage of preserving all Lorentz invariants associated with our final state.



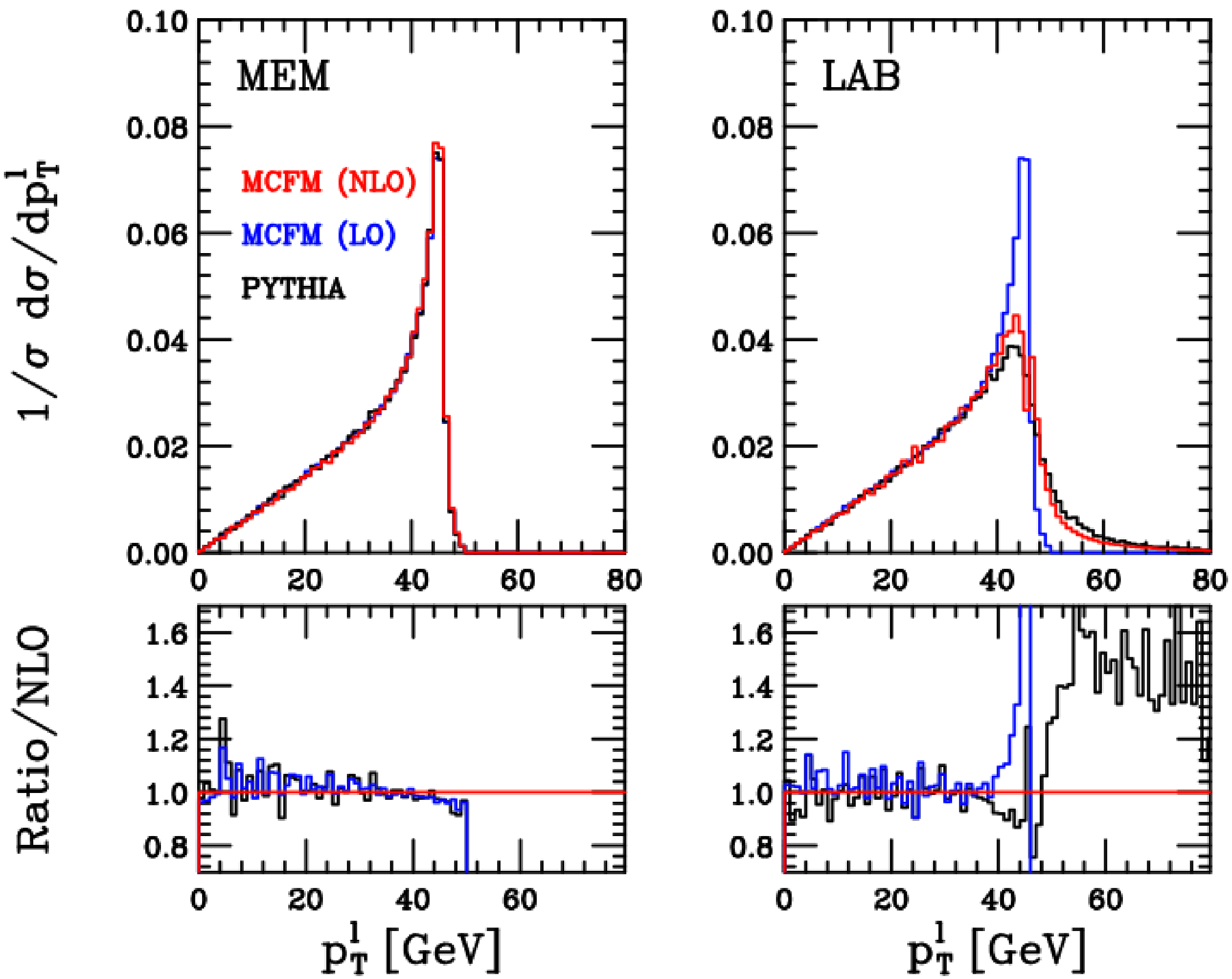
# MEM method

- This does not fix the longitudinal component of the Lorentz transformation.
- As a result we have to sum over the longitudinal boosts.
  - i.e. all events connected through a longitudinal boost are equivalent and averaged over.
- Note that all unclustered hadrons are added to the boost vector. Its transverse component determines the Lorentz Transformation to the MeM frame where the observables are defined.
- In the MeM frame there can still be missing energy due to a neutrino.

# MEM method

- We now have a procedure to match an event onto the LO kinematics.
  - The MeM frame momenta are the ones used in comparing experiment to theory (not the lab momenta).
- This procedure can be applied also to map a NLO event onto the LO kinematics.
  - This enables us to integrate out the FSR and ISR radiation of a given event to give us the NLO probability of the particular event.
- This is implemented into the code NLOME (based on MCFM). Jets are not yet included in the code.

# MEM example: MEM frame




Basic example: Z=>2l

Compare the shapes of the pT distribution in the two frames for 3 different theory predictions.

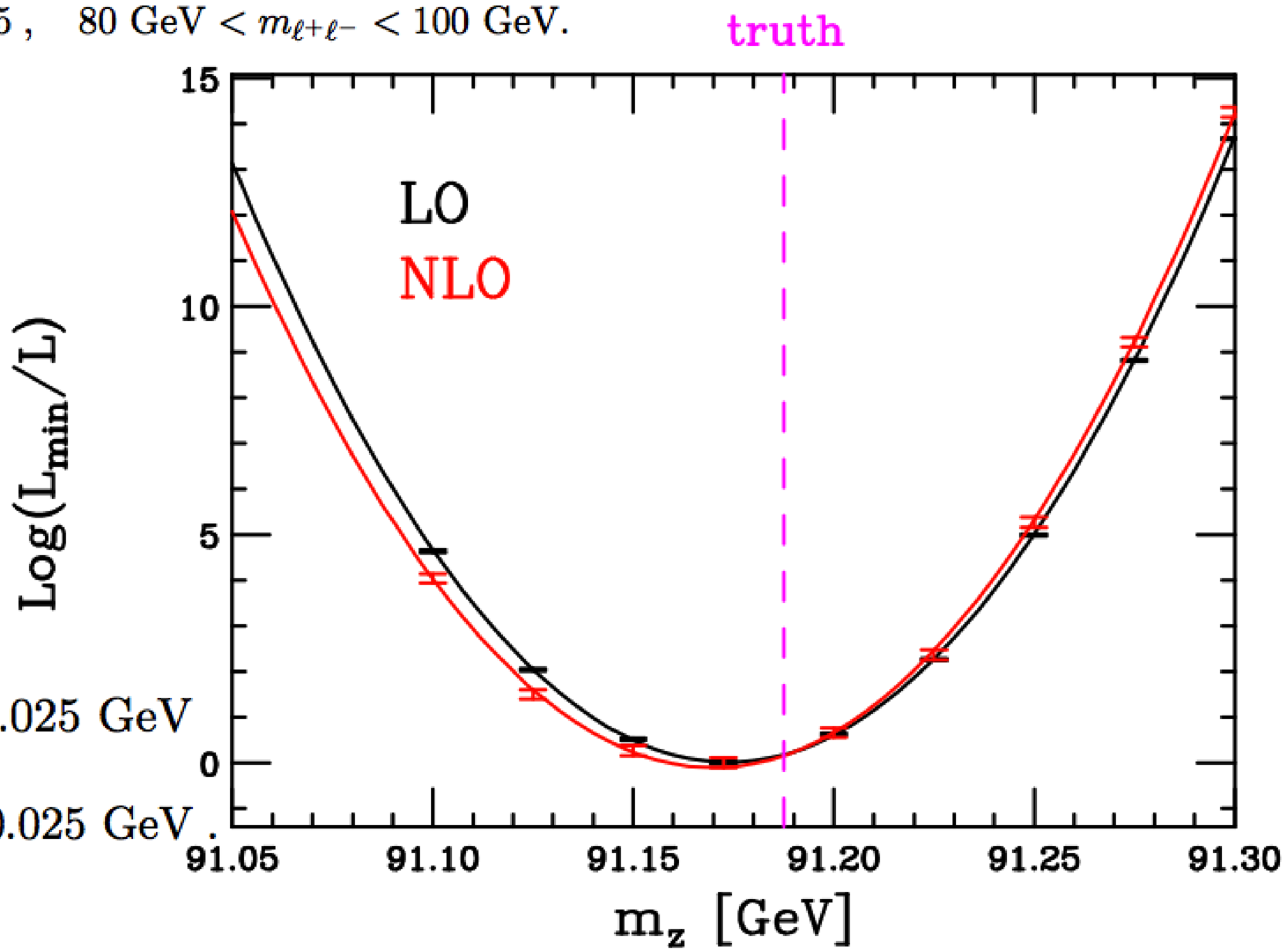
Since the MEM frame naturally removes recoil, the three predictions become similar, NLO corrections are small and of order 10%.

# Example : measuring the mass of the Z boson

$p_T^\ell > 15$ GeV , $|\eta_\ell| < 2.5$ , 80 GeV $< m_{\ell^+\ell^-} <$ 100 GeV.

Generate 5000 events with Pythia and try to measure the Z mass.

We know NLO corrections are very small (saw almost identical MEM frame kinematics).




LO: $m_Z = 91.170 \pm 0.025$ GeV

NLO: $m_Z = 91.174 \pm 0.025$ GeV .

# MET example : W mass from Pythia

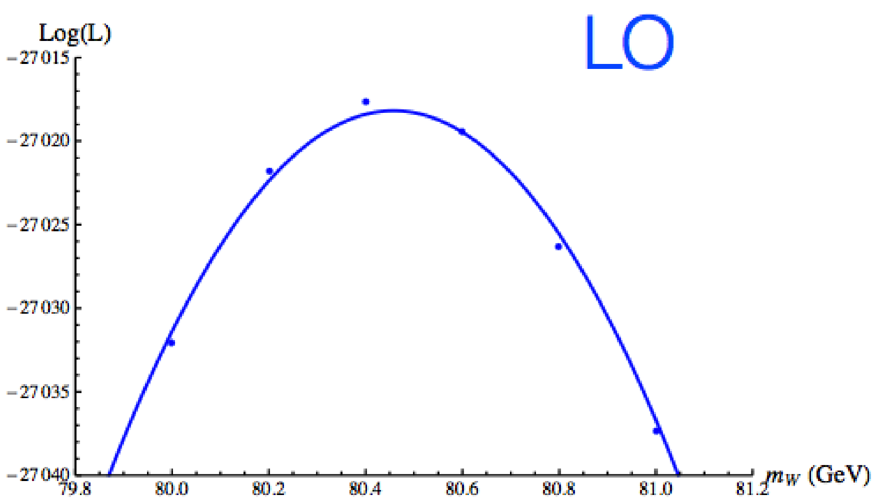
- We use 4000 (8 TeV) Pythia events to test our code at LO and NLO.

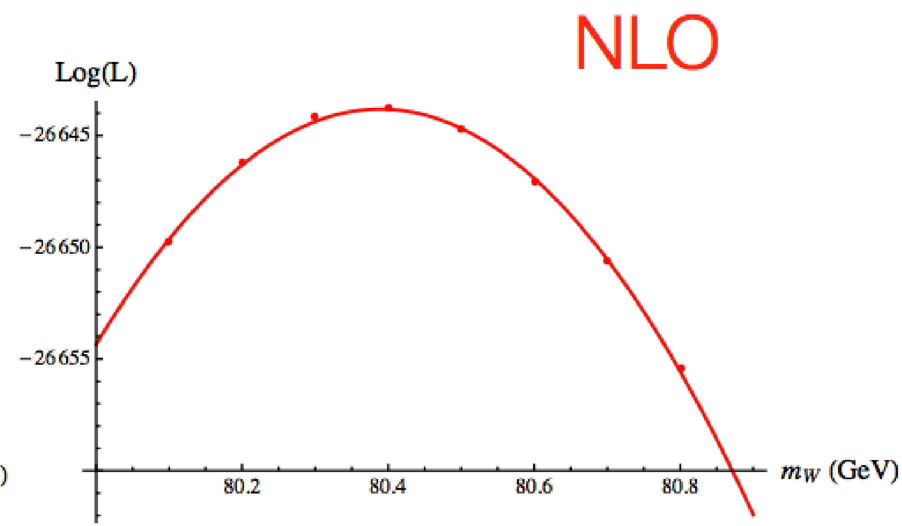
- Truth value = 80.399 GeV

$$\text{LO} \quad m_W = 80.46 \pm 0.09 \text{ GeV} \qquad \text{NLO} \quad m_W = 80.39 \pm 0.08 \text{ GeV}$$

Note: LO needs more MC precision for better fit!,

Losing some final state information has increased the uncertainty $\frac{\delta_W}{\delta_Z} \approx 3$



# Example H=>ZZ=>4l

- Use SHERPA to generate 4 lepton events with NLO+PS.

- Define

$$\mathcal{L}_{S+B}(\mu, N) = \frac{e^{-\mu}\mu^N}{N!}\prod_{i=1}^{N}\mathcal{P}(\mathbf{x_i}|S = m_H)\ ,$$

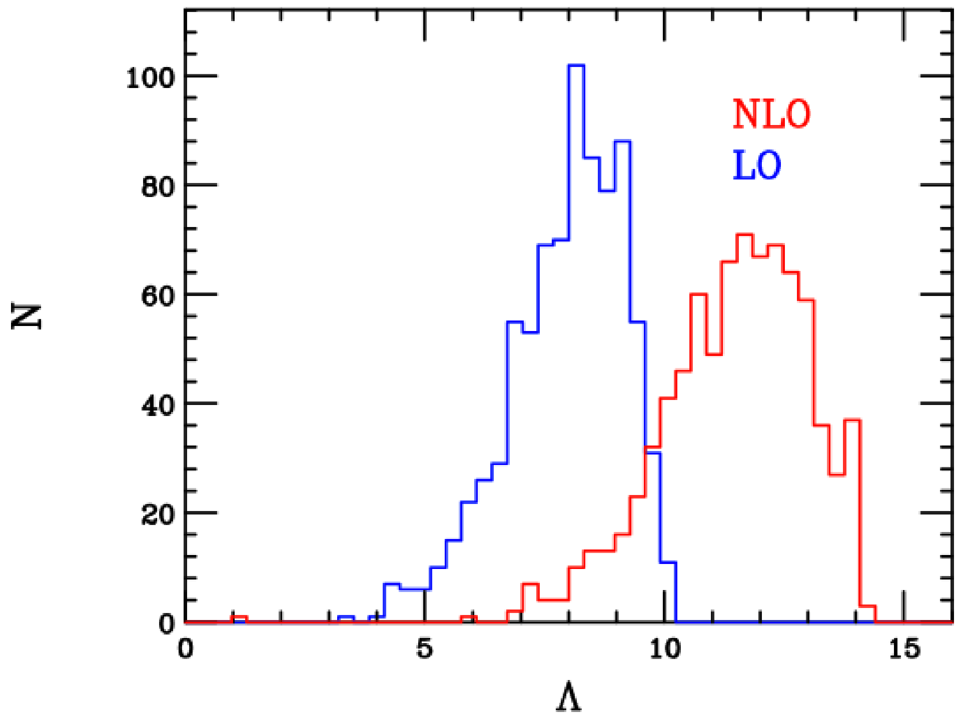
$$\mathcal{P}^{LO}(\mathbf{x}_i|S = m_H) = \frac{1}{(\sigma_S^{LO} + \sigma_B^{LO})}\Big(B_S(\mathbf{x}_i) + B_B(\mathbf{x}_i)\Big)\ ,$$

$$\mathcal{P}^{NLO}(\mathbf{x}_i|S = m_H) = \frac{1}{(\sigma_S^{NLO} + \sigma_B^{NLO})}\Big(V_S(\mathbf{x}_i) + V_B(\mathbf{x}_i) + R_S(\mathbf{x}_i) + R_B(\mathbf{x}_i)\Big)\ .$$

$$\Lambda = \log(\mathcal{L}_B/\mathcal{L}_{S+B})$$

- Here $\mu$ denotes the expected number of events (for a given signal +background hypothesis (with a fixed background expectation of 200) and N is the actual number of observed events.

# Example H=>ZZ=>4l

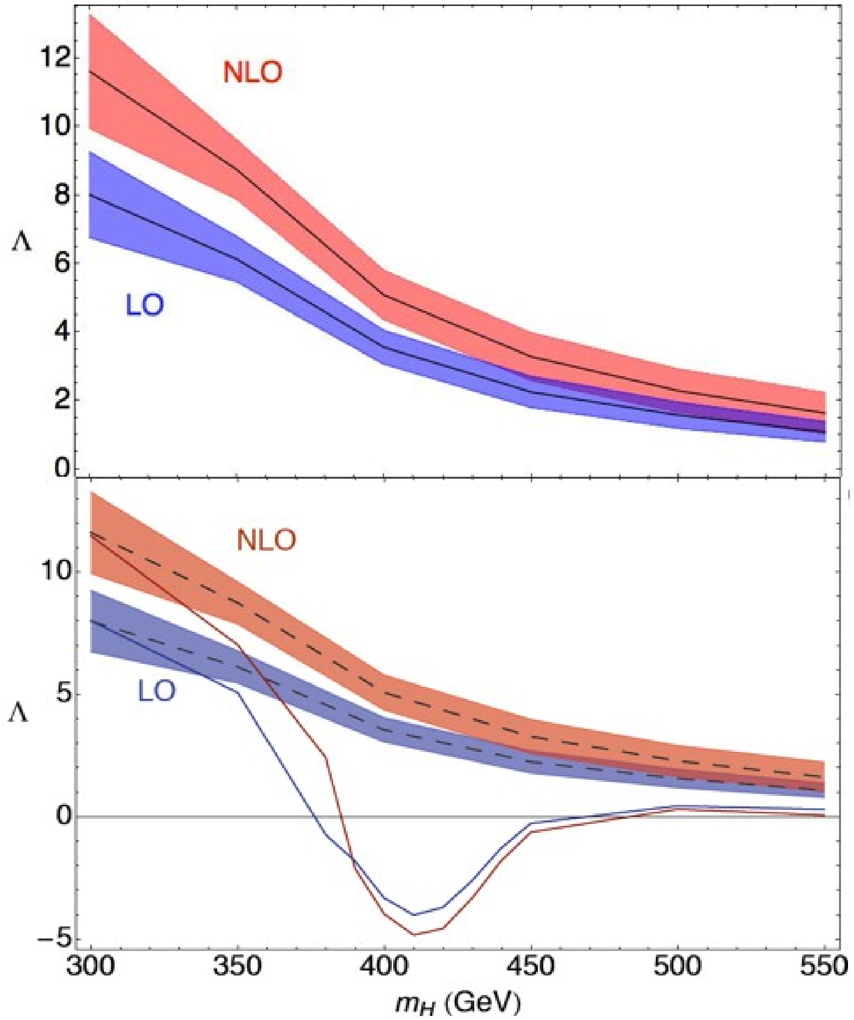



We generate pseudo experiments with no signal and proceed to set limits.

This plot shows results from around 1000 p-experiments at LO and NLO, for a hypothesis of mh=300 GeV.

Note in this example I'm going to keep mh > 300 to safely neglect experimental resolution effects.

# Example H=>ZZ=>4l




Calculate the expected limit from our p-experiments then the standard deviation to get measure of the spread.

Top plot shows expected results in the presence of no Higgs. The bottom plot indicates an experiment with an injected signal at mh=425 GeV.

# Conclusions and Future

- We have developed a theoretically well based method to calculate MEM-based likelihood.
- The available code includes ISR, the FSR will be included soon.
- The proper definition of the MEM method gives small radiative corrections to the exclusive events.
- This method elevates the MEM method to a theoretically well founded method.
- The next target is the top cross section in the MEM@NLO framework.