W and Z Boson Production at NNLO with *FEWZ* 2.0

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arXiv:1011.3540 [hep-ph] and WIP

Loopfest X, 5/12/11

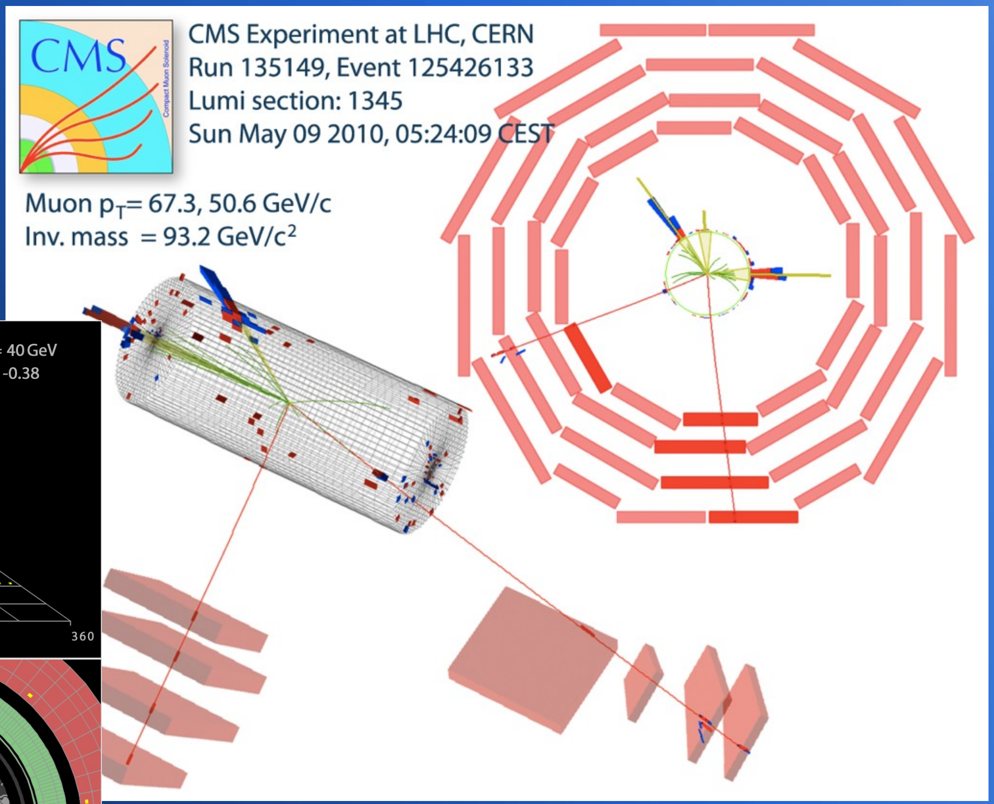
Outline

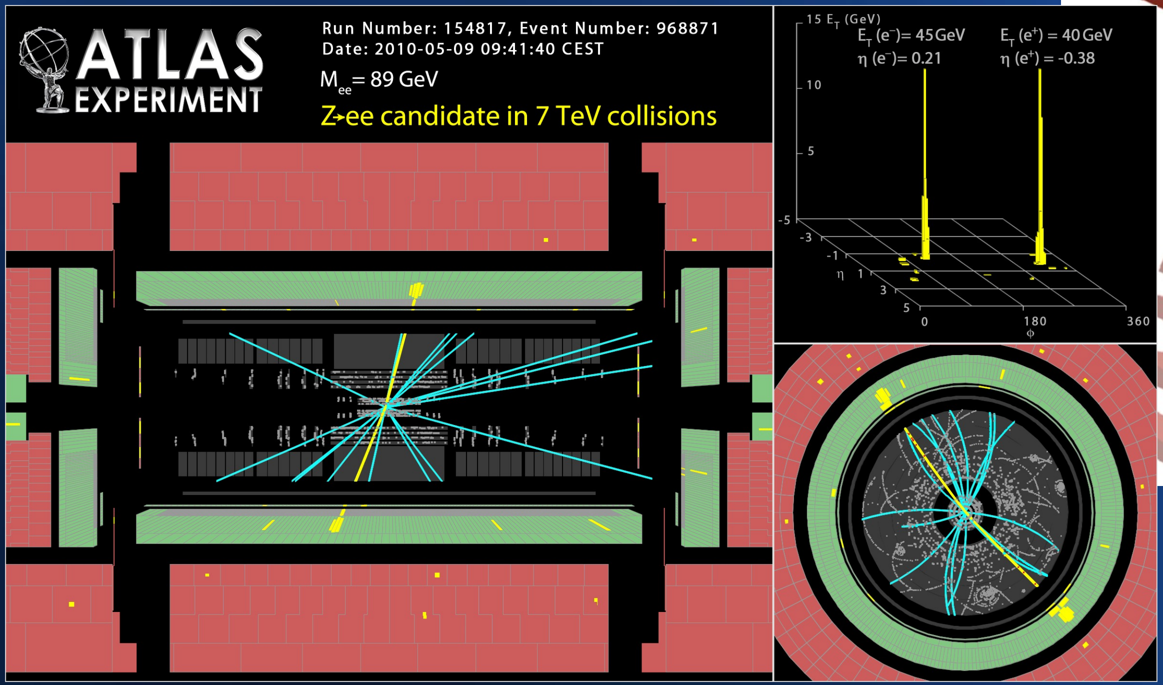
- Z and W bosons at the LHC
- Why NNLO?
- An introduction to FEWZ
- New and improved!
- The new FEWZ at work
- Return of the W
- Summary

Z bosons at the LHC

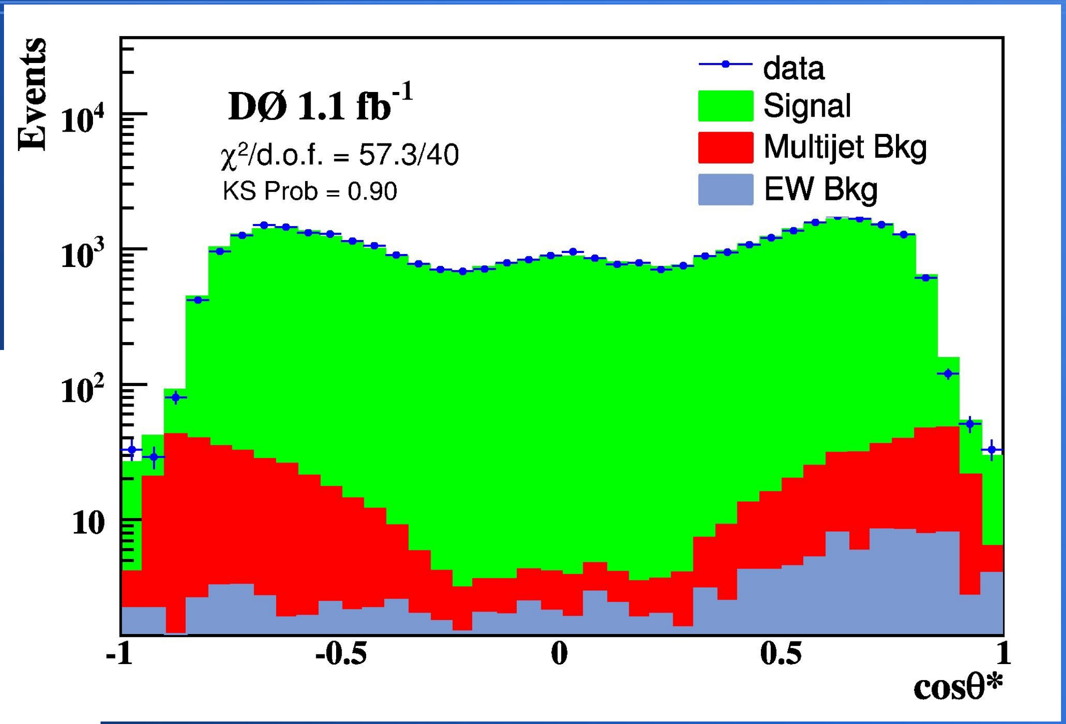
- No new physics yet, but 'rediscovery' of standard model complete at LHC
- Naturally, Z was found

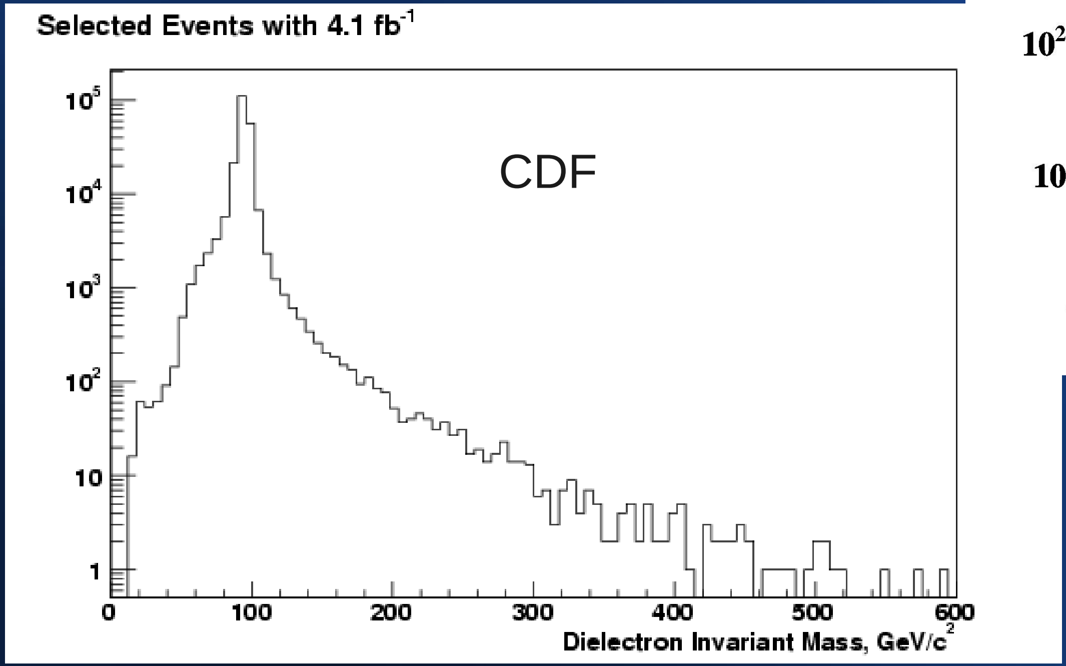
Z candidates



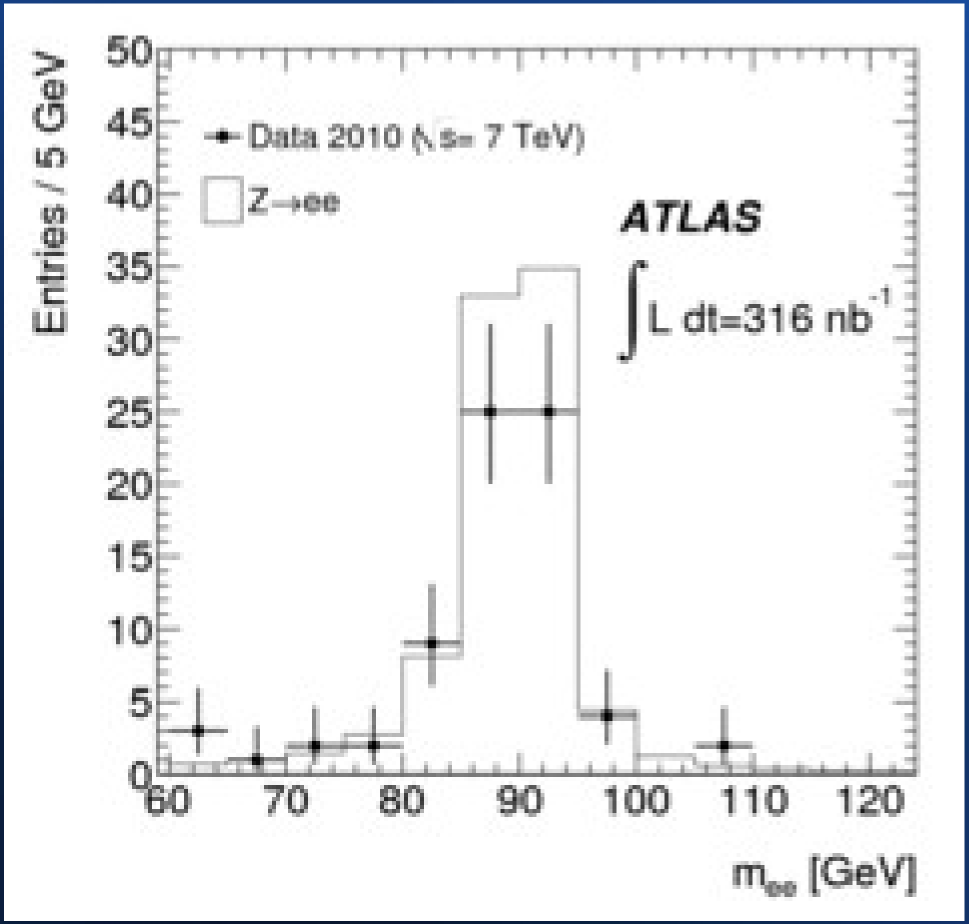


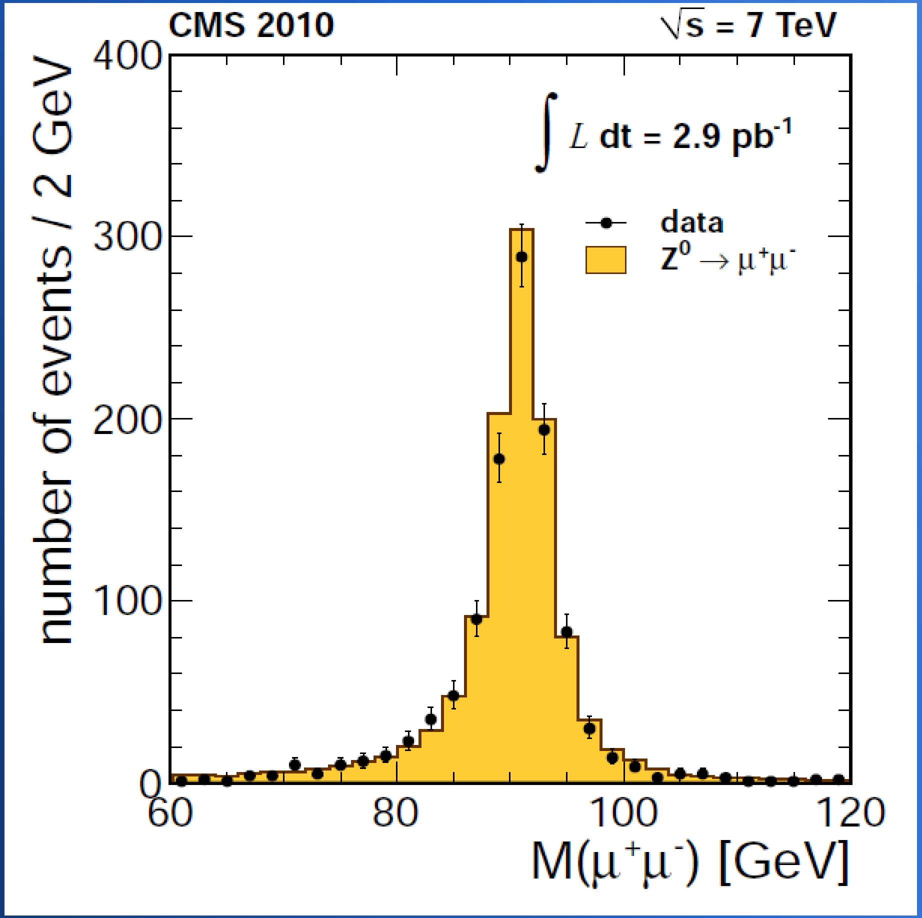
Real Data... Tevatron





Real data... LHC!





Early Z results

- ATLAS: $\sigma \times Br(ll) = 0.84 \pm 0.06(stat) \pm 0.05(sys) \pm 0.09(lum)\, nb$ (66 – 116 GeV)
- CMS: $\sigma \times Br(ll) = 0.975 \pm 0.007(stat) \pm 0.007(sys) \pm 0.039(lum)\, nb$ (60 – 120 GeV)
- Tens of thousands of events by now!

Early W results

- ATLAS: $\sigma \times Br(ll) = 9.96 \pm 0.23(stat) \pm 0.5(sys) \pm 1.1(lum)\, nb$
- CMS: $\sigma \times Br(ll) = 10.31 \pm 0.002(stat) \pm 0.009(sys) \pm 0.41(lum)\, nb$
- Hundreds of thousands of events by now!

Why look at the Z?

- Lots of them, millions at design luminosity
- Clean signal, stands above QCD
- Use as standard candle/luminosity measure
- Use to constrain PDFs

Z as standard candle

- Easy to measure
- Well-known properties (M_Z, Γ_Z) – calibrate
- σ_Z – Luminosity measure Dittmar

Z Physics

- Measure electroweak parameters from distributions -- $\sin^2\theta_W$
- Perturbative QCD – p_T spectrum
- Measure PDFs with rapidity distributions

$$x_1 \simeq \frac{M_Z}{\sqrt{s}} e^{Y_Z} \qquad x_2 \simeq \frac{M_Z}{\sqrt{s}} e^{-Y_Z}$$

W Physics

- Charge asymmetry $\rightarrow$ PDFs
- W mass for electroweak precision, indirect constraints on new physics

Why NNLO?

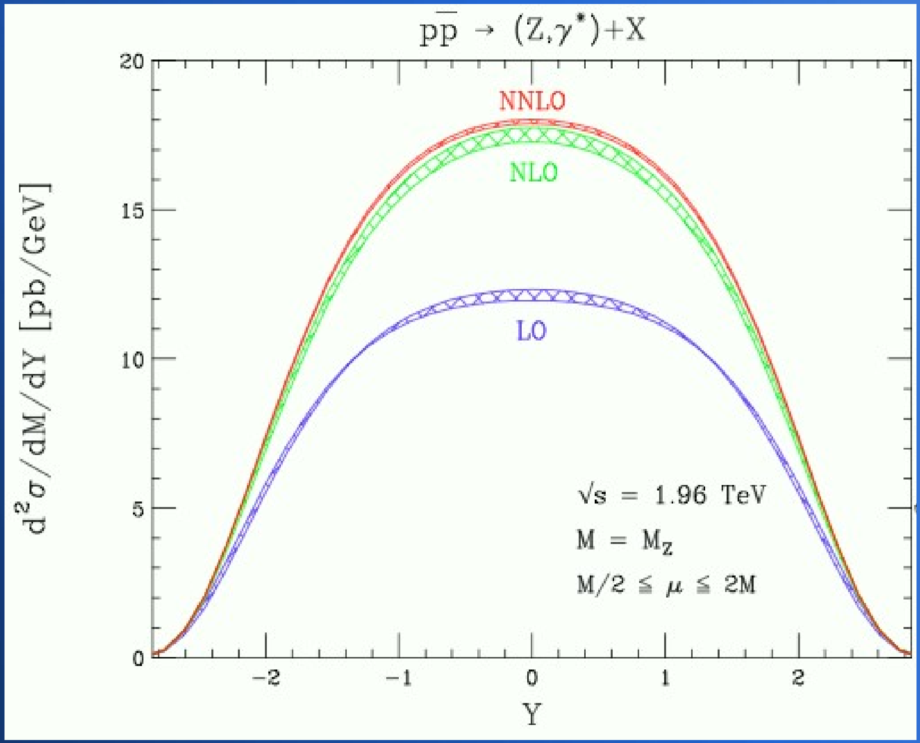
- NLO DY well-known, but remaining theory errors O(10%)
- As much statistics as you want, systematics much smaller than theory error
- Some observables only start at NLO (p_T, $\Delta\phi$)

Why NNLO?

- Precise measurements require precise theory
  - PDFs
  - Luminosity
  - Electroweak competitive with LEP
- Experimental physics should never be theory-limited
- Fortunately, NNLO has been available for DY for a while Hamberg, van Neerven, Matsuura

Differential NNLO

- Can we just use a K-factor?
- Distributions and acceptances have differing higher-order corrections



Anastasiou, Dixon, Melnikov, Petriello

FEWZ basics

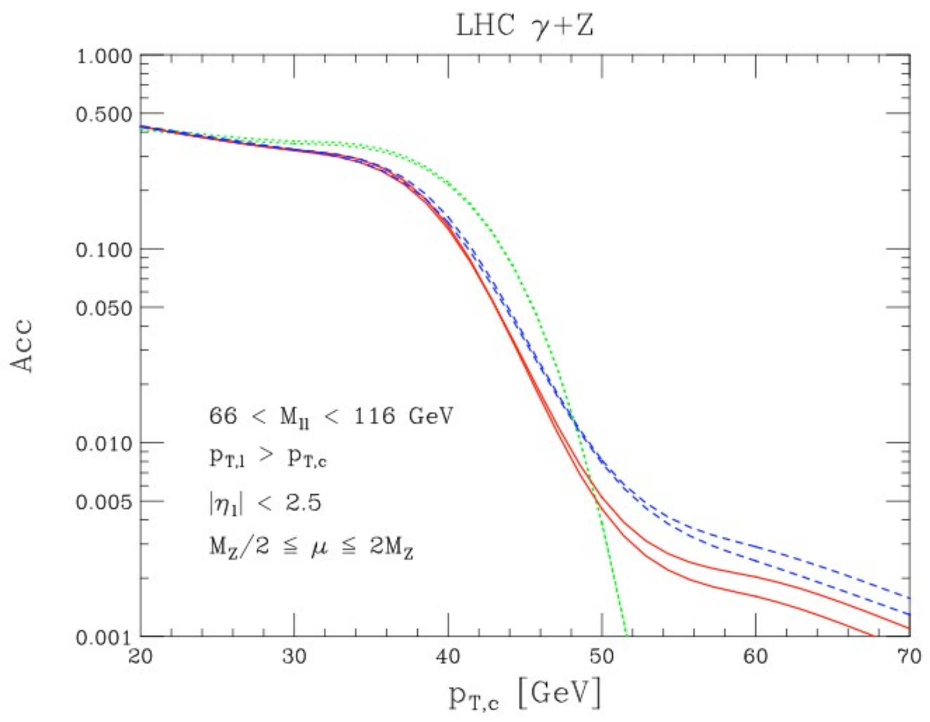
- Computes W/Z cross section for hadron colliders
- Fully exclusive in leptonic phase space at every order
  - Leptonic decays contain full W/Z spin correlations
  - Cuts on leptons, not Z

Old FEWZ code details

- Fortran 77 numerical program
- Two executables, FEWZw and FEWZz, for W & Z
- Some run parameters selectable in input file
  - Collider type
  - Perturbative order
  - Numerical integration parameters

Old FEWZ at work

- Fully differential distributions with realistic detector cuts!



Basics of the calculation
(Melnikov, Petriello)

- Differential cross section given by factorization:

$$d\sigma = \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\sigma_{ij}$$

- Each piece has many components
  - Partonic cross section to $O(\alpha_s^2)$ (gg, gq, qq)
  - PDF counterterms
- Singularities everywhere
  - Renormalization
  - Soft/collinear, PDFs

Pieces of the calculation

- NNLO:
  - Double-virtual
  - Real-virtual
  - Real-real
- First two pieces dealt with using AIR Anastasiou, Lazopoulos
  - Reduces loop integrals (including multi-loop) to less complicated forms using IBP identities

Pieces of the calculation

- Real-real parts require a method to deal with IR (soft/collinear) singularities
- Sector decomposition Binoth, Heinrich; Anastasiou, Melnikov, Petriello
  - Map denominators into hypercube variables to be integrated over
  - Make sure each variable is singular in only one limit by remapping as necessary
  - Expand $x^{-1+\epsilon}=\frac{\delta(x)}{\epsilon}+\sum_{n=0}^{\infty}\frac{\epsilon}{n!}\left[\frac{\ln(x)}{x}\right]_+$

Putting the pieces together

- Approximately 200 pieces corresponding to
  - different partonic channels (qq, qg, gg)
  - real radiation sectors from decomposition
  - soft/collinear counterterms+virtual pieces
- Poles in each up to ϵ^{-4}, cancel numerically
- Rest summed and interfaced with PDFs in numerical integrator

Drawbacks of old FEWZ

- Only one number per run
- Lengthy runtime, especially for harsh cuts
- Cuts hard-coded in Fortran by user
- Some numbers hard-coded, such as EW parameters
- Any of these changes require recompilation

Improved FEWZ

- Split different sectors and calculate independently
  - Sectors have different PDFs and kinematics, let integrator adapt separately
    - Exception: some sectors anticorrelate
  - Calculations basically independent, can use parallelism

Improved FEWZ

- Each call of phase space from numerical integrator corresponds to real kinematics
  - Bin each evaluation on-the-fly
  - Reweight each evaluation for different PDF eigenvector sets – free PDF errors!
  - FEWZ now produces user-selectable histograms with PDF errors with little overhead

Improved FEWZ

- Practically everything a user would want is moved to a text input file
  - No more Fortran coding, recompilation
- Practically everything a user would want is provided in a text output file
  - Kinematic distributions, scripts for PDF errors
- Scripts provided for multicore runs, *Condor* cluster runs, combining runs

User-selectable cuts

- Invariant mass
- Jet reconstruction (anti-k_T, cone), isolation
- Transverse momentum (lepton, Z, jets)
- Rapidity (lepton, Z, jets)
- Etc.

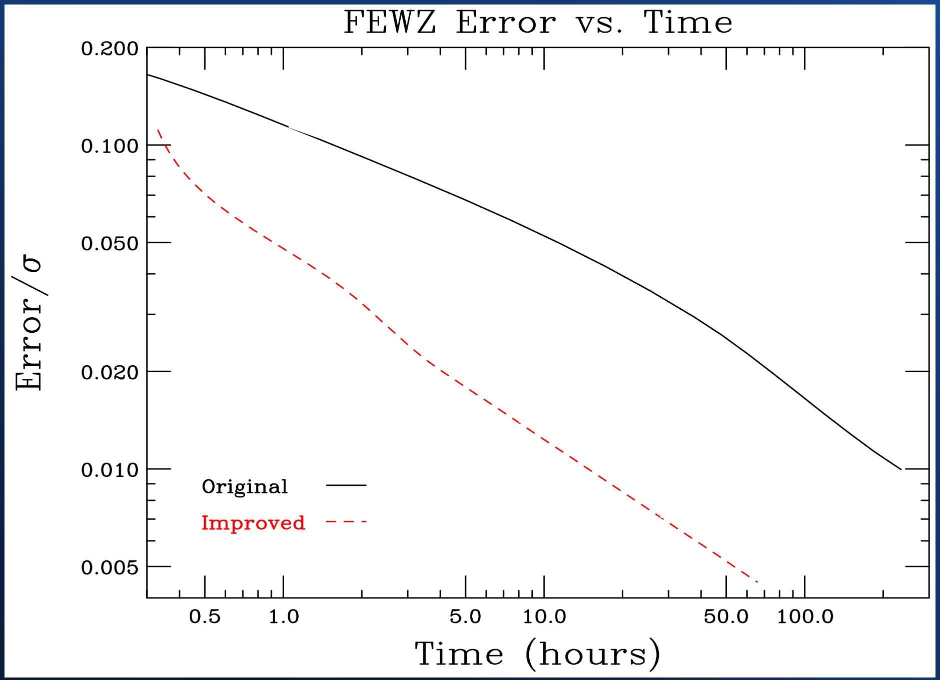
User-selectable histograms

- Lepton, Z, jet transverse momentum
- Lepton, Z, jet rapidity
- Dilepton invariant mass
- ΔR
- H_T
- etc.

Available PDFs

- MSTW
- CTEQ
- JR
- ABKM
- NNPDF
- i.e, all of them

Performance



- Faster, even per-core
- Numerical precision sub-dominant in a day, not weeks
- Hundreds of numbers instead of one

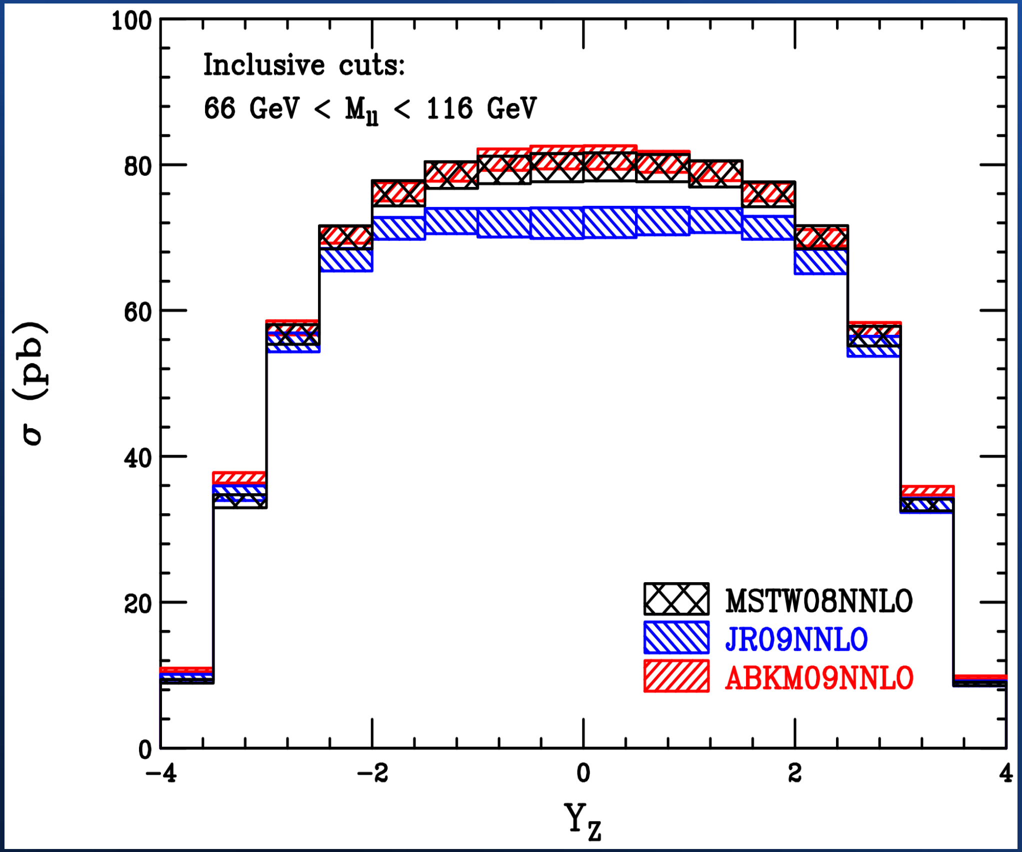
LHC 7 TeV benchmarks

- Inclusive numbers:
  - MSTW: $\sigma = 963.7 \pm^{4.9}_{6.8} (scale) \pm^{24.3}_{17.9} (PDF) \pm 0.5 (tech)\, pb$
  - ABKM: $\sigma = 980.5 \pm 15.6\, pb$
  - JR: $\sigma = 907.3 \pm^{17.9}_{20.9}\, pb$

LHC 7 TeV benchmarks

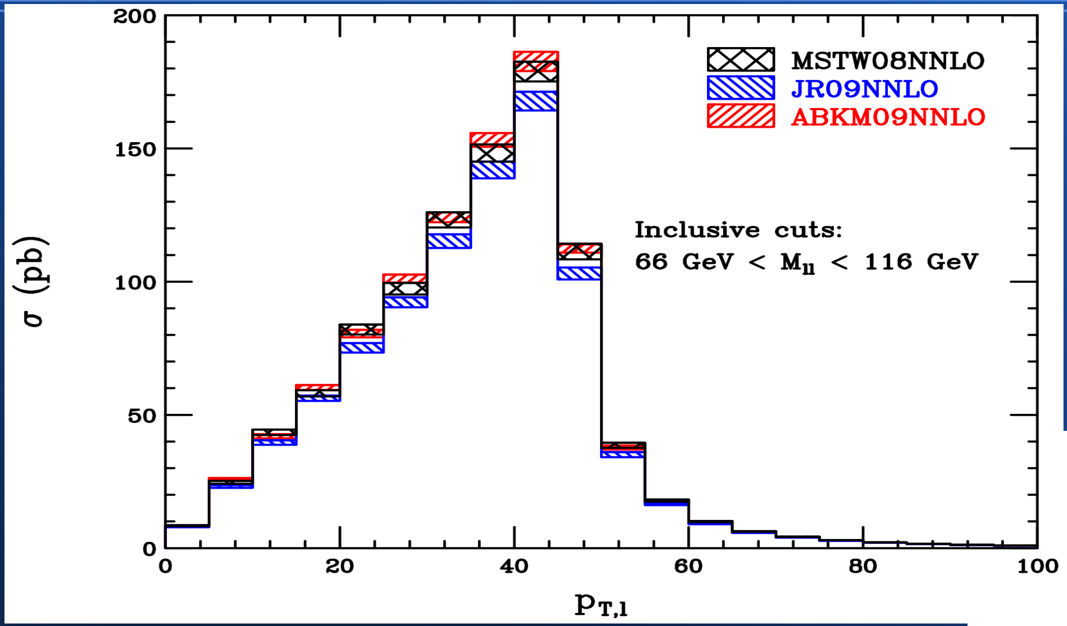
- Standard cuts:
  - $p_T^{lep} > 25$ GeV
  - $|\eta^{lep}| < 2.5$
  - 66 GeV $< M_{ll} <$ 116 GeV
  - $\Delta R > 0.5$
  - MSTW: $\sigma = 436.0 \pm^{11.5}_{8.7}\ pb$
  - ABKM: $\sigma = 445.6 \pm 7.6\ pb$
  - JR: $\sigma = 404.3 \pm^{7.9}_{11}\ pb$

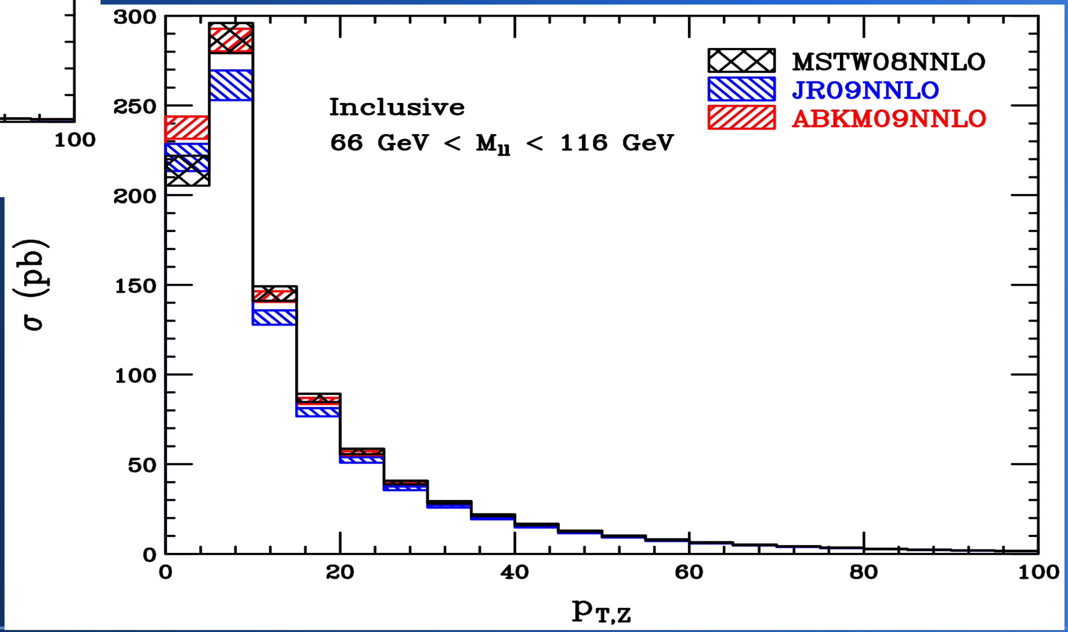
Inclusive distributions



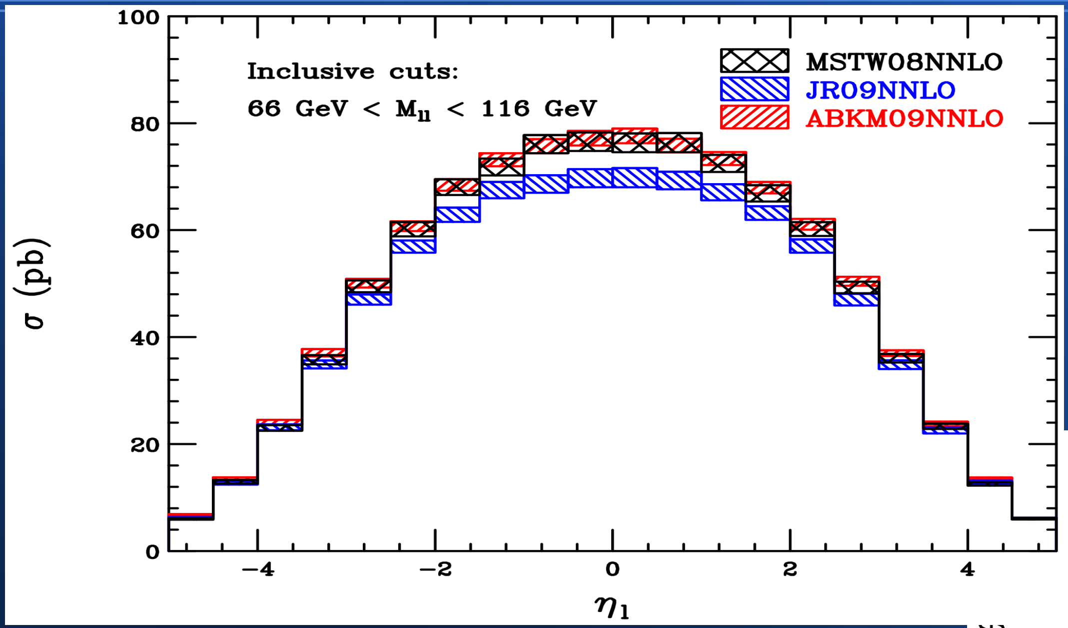
- Note JR consistently lower

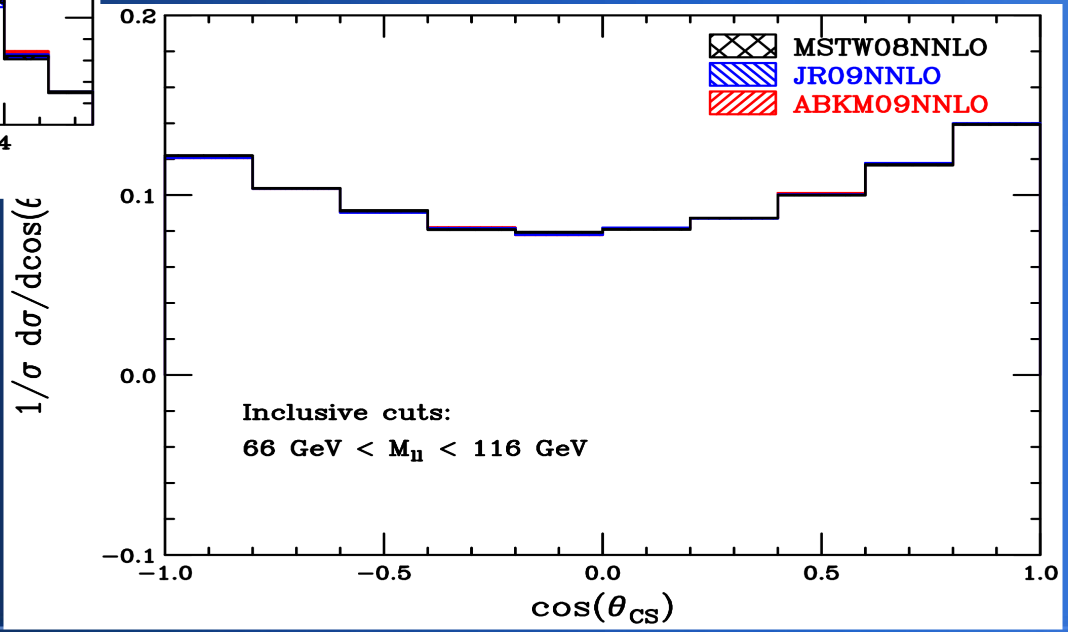
Inclusive distributions





Inclusive distributions





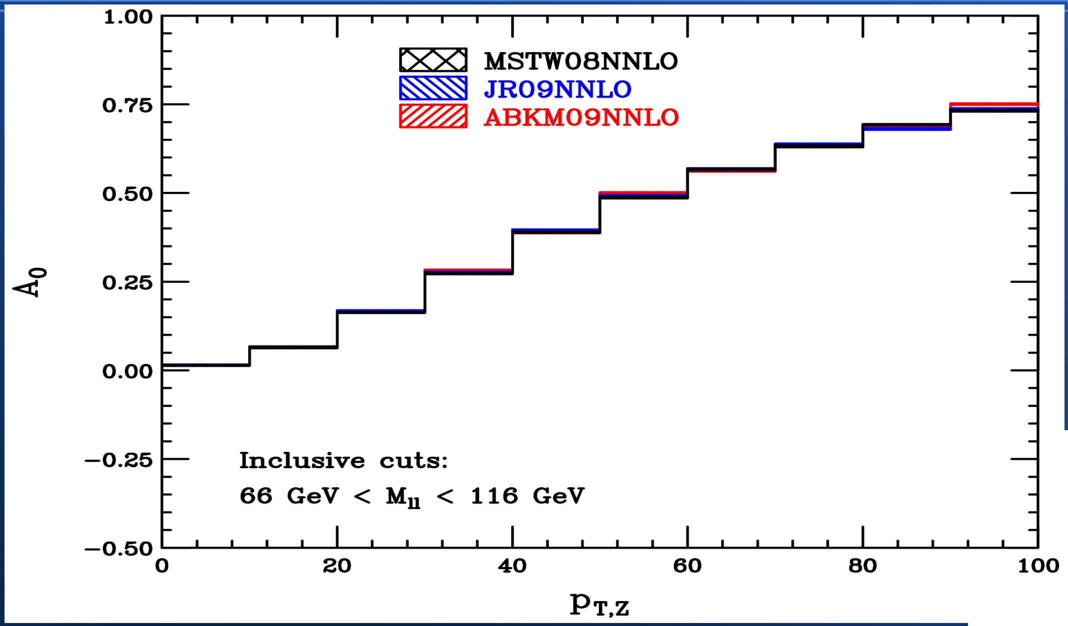
Collins-Soper angles

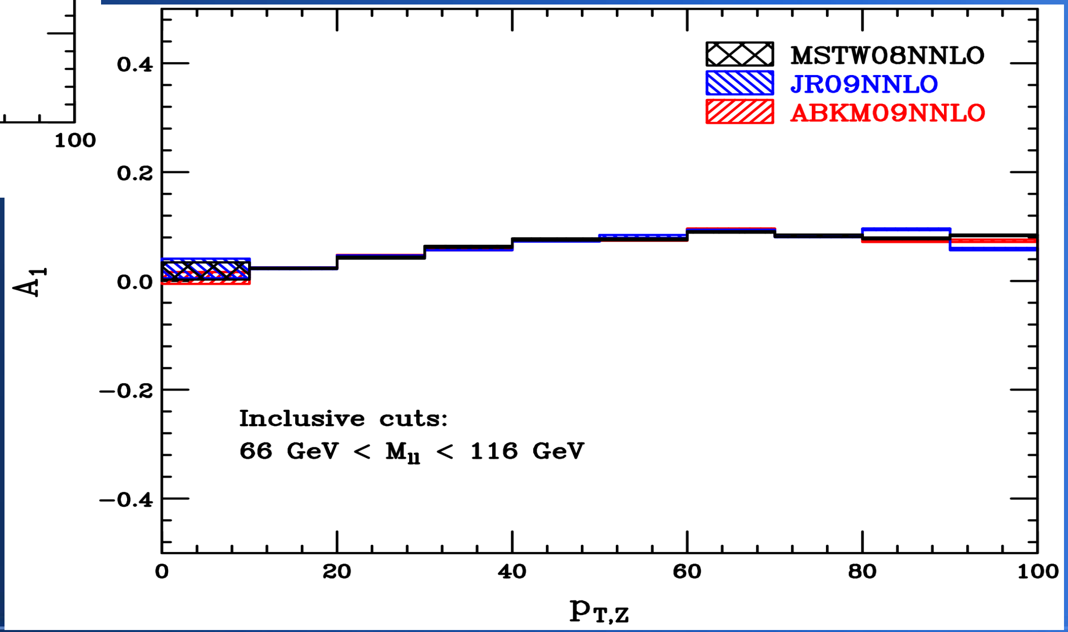
- Code can also calculate coefficients of Collins-Soper expansion

$$\frac{d\sigma}{d\,p_T^2\,d\,Y\,d\cos\theta\,d\,\phi} \sim 1+\cos^2\theta+\frac{1}{2}A_0\left(1-3\cos^2\theta\right)$$
$$+A_1\sin 2\theta\cos\phi+\frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+A_3\sin\theta\cos\phi+A_4\cos\theta$$

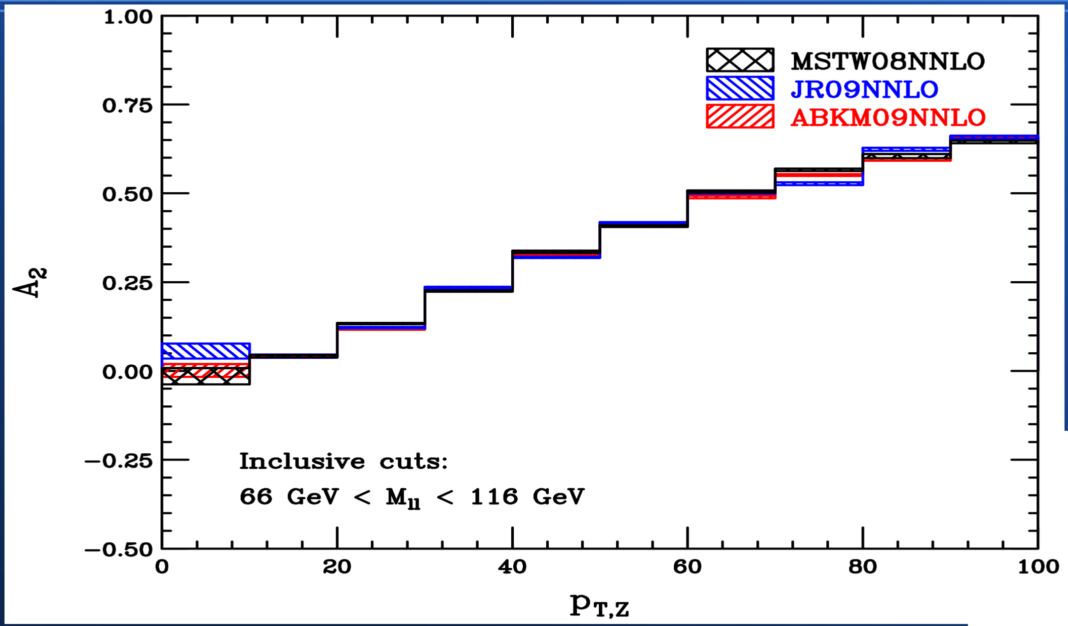
  - Only A_4 nonzero at LO

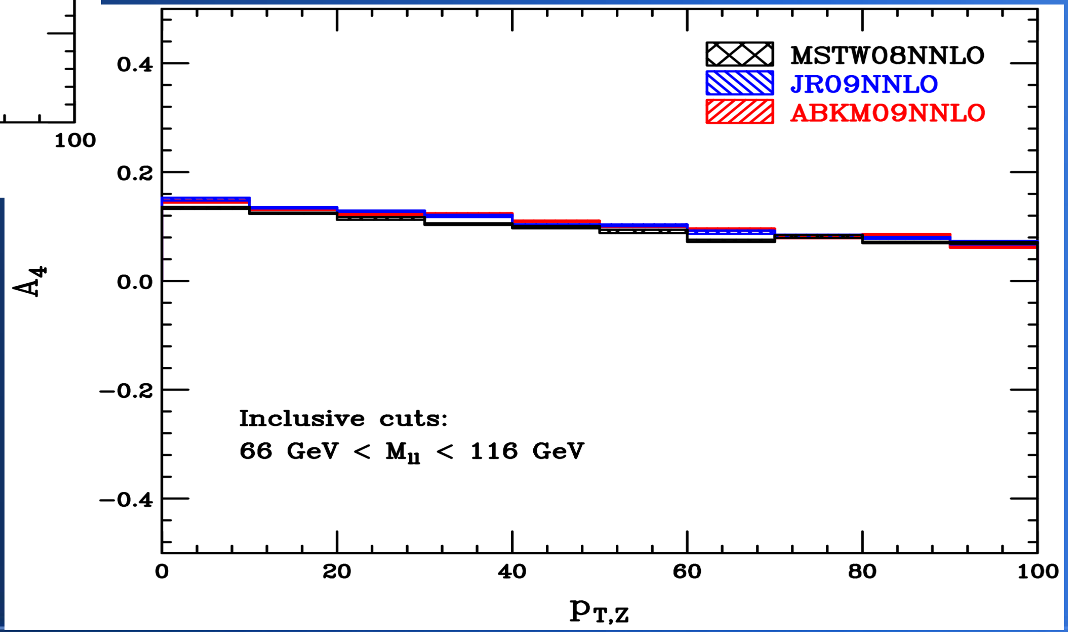
Collins-Soper angles





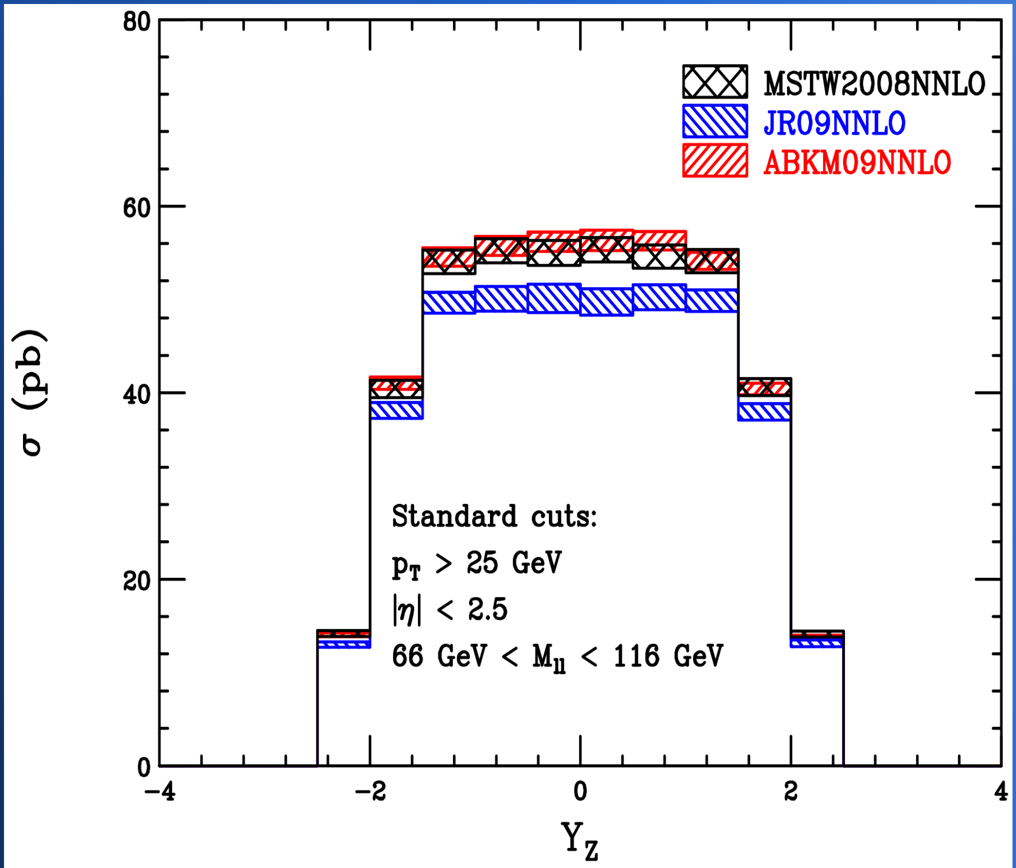
Collins-Soper angles



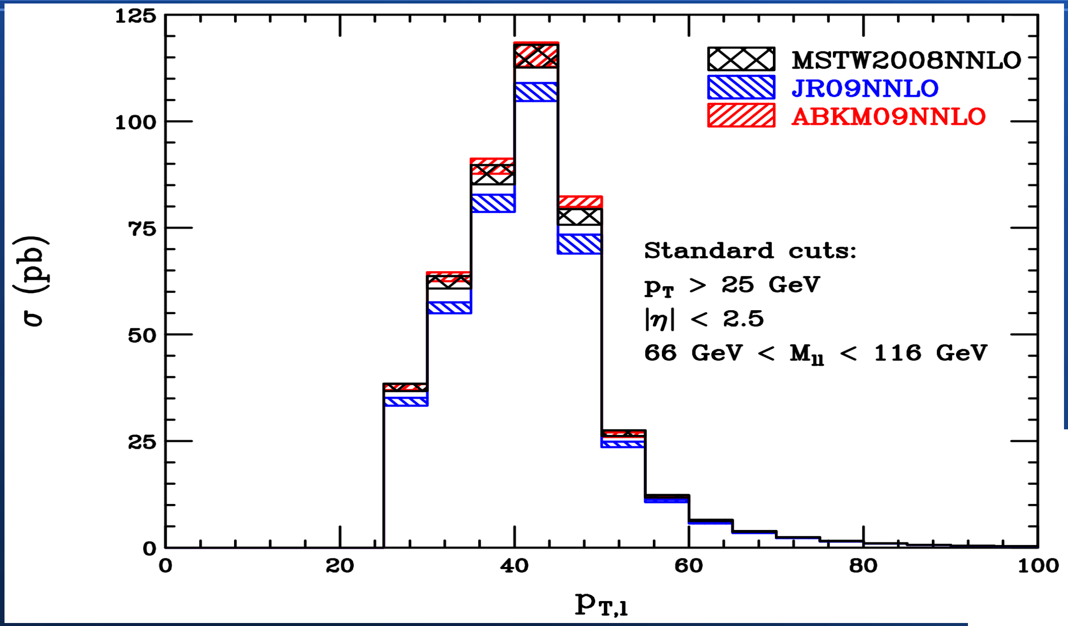


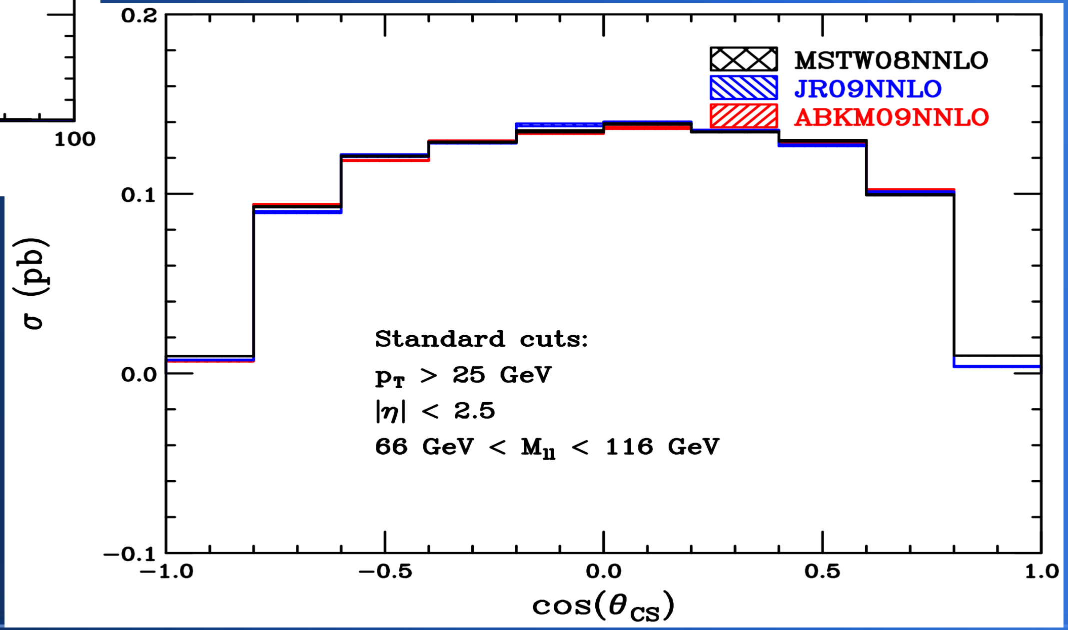
Distributions with cuts

- Realistic acceptance cuts real test of FEWZ
- Experiments should not use flat K-factor, should reweight with distribution

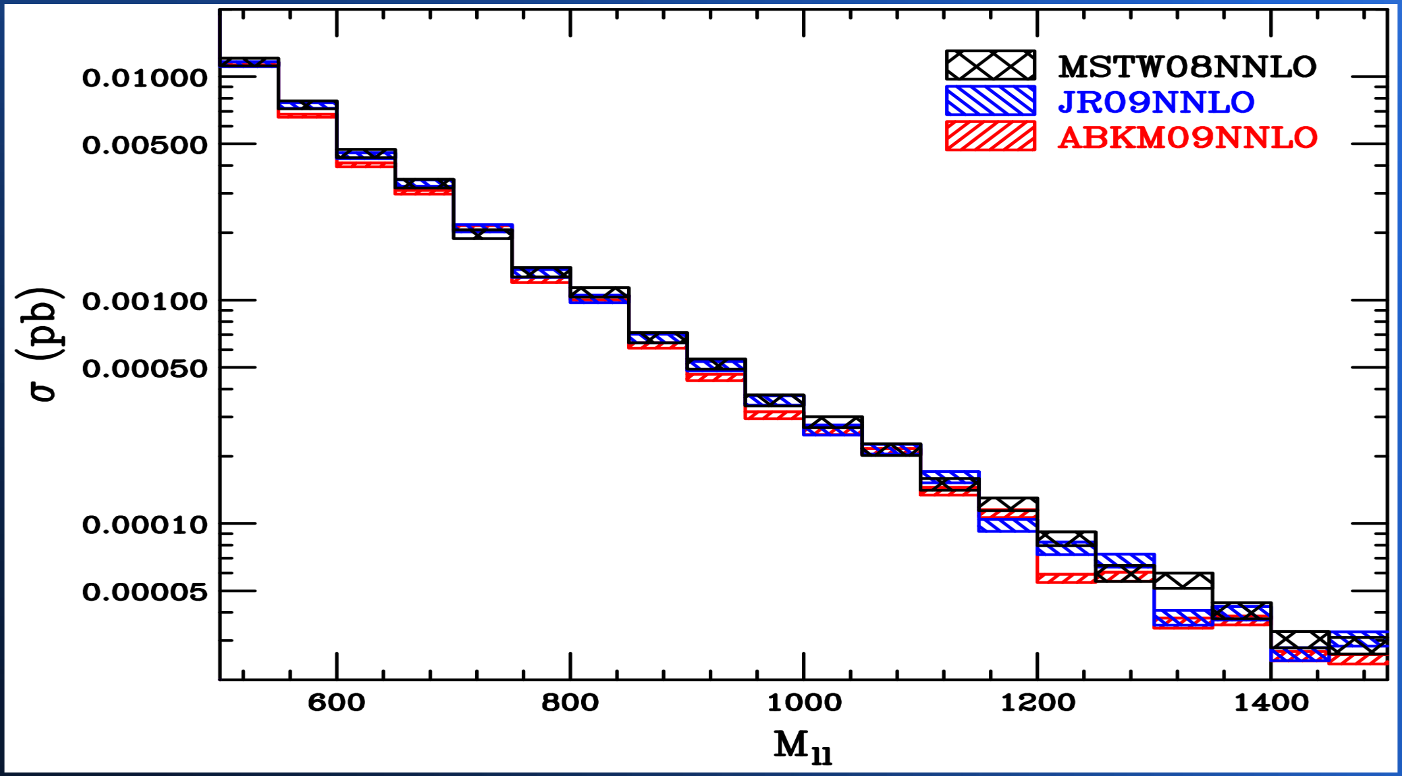


Distributions with cuts





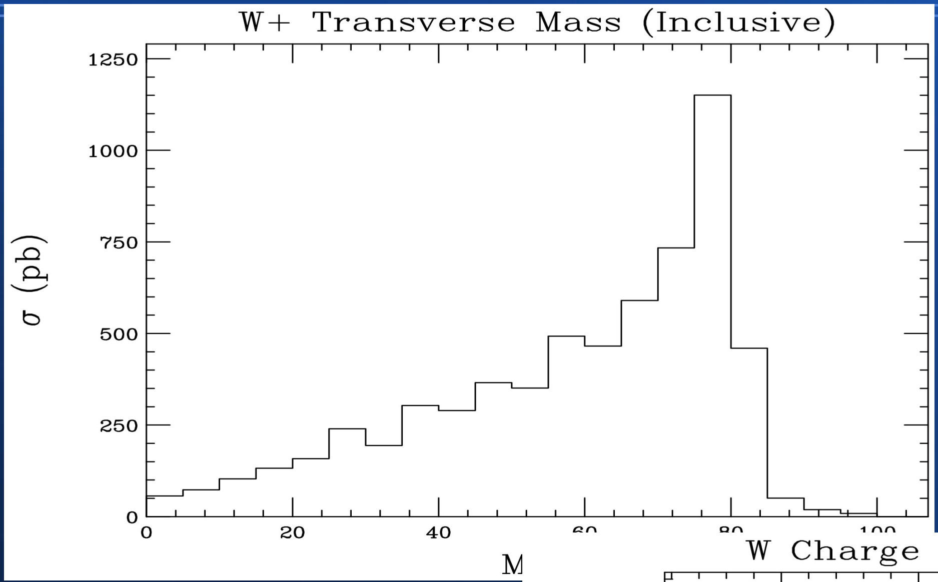
Relevance for new physics

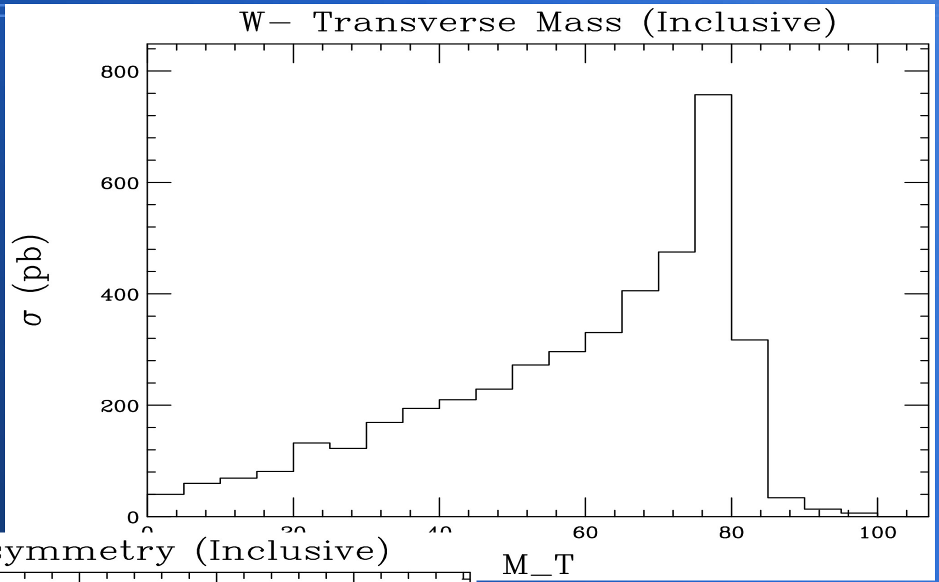


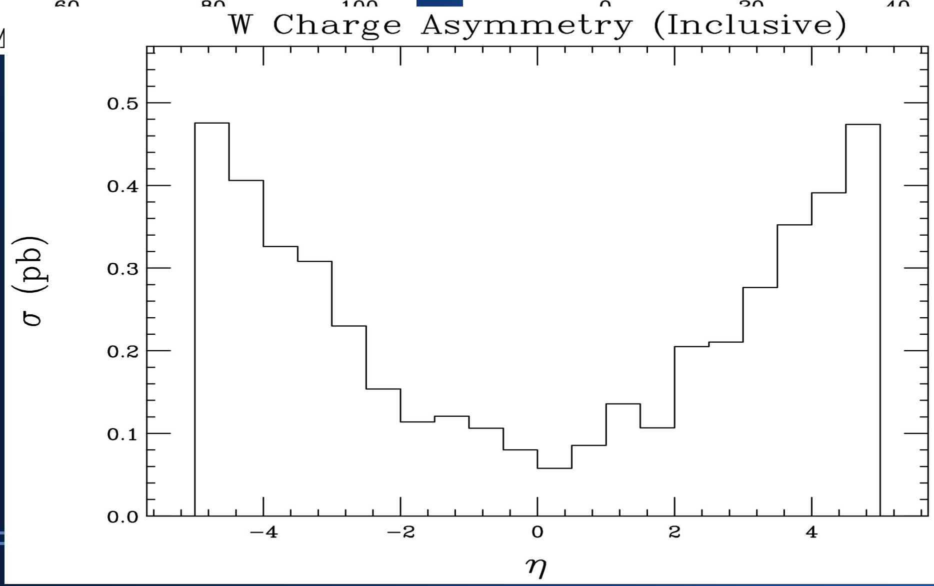
Return of the W

- FEWZ 2.0 updates Z code–2.1 will feature W
  - Most of calculation is the same, large amounts of overlapping code
  - Similar changes: sector splits/parallelization, histogramming, PDF errors
- Basic structure is done, now optimizing sector splitting
- Combination scripts can do charge asymmetry, W/Z ratio

Preliminary W plots







Summary

- Understanding basic processes is understanding unknown processes
- Precision is key
- FEWZ is a tool that gives as much theoretical precision as possible
- Updates make it user-friendly and powerful
- Try FEWZ! http://gate.hep.anl.gov/fpetriello/FEWZ.html

The future

- Finish up that W! Hope to have public code in O(1 month)
- Electroweak corrections comparable to $O(\alpha_s^2)$, important especially for FSR observables, known
  - Incorporation into FEWZ in progress

Perturbative stability