The Status of NNLO Tools for W/Z Production at Hadron Colliders

Frank Petriello

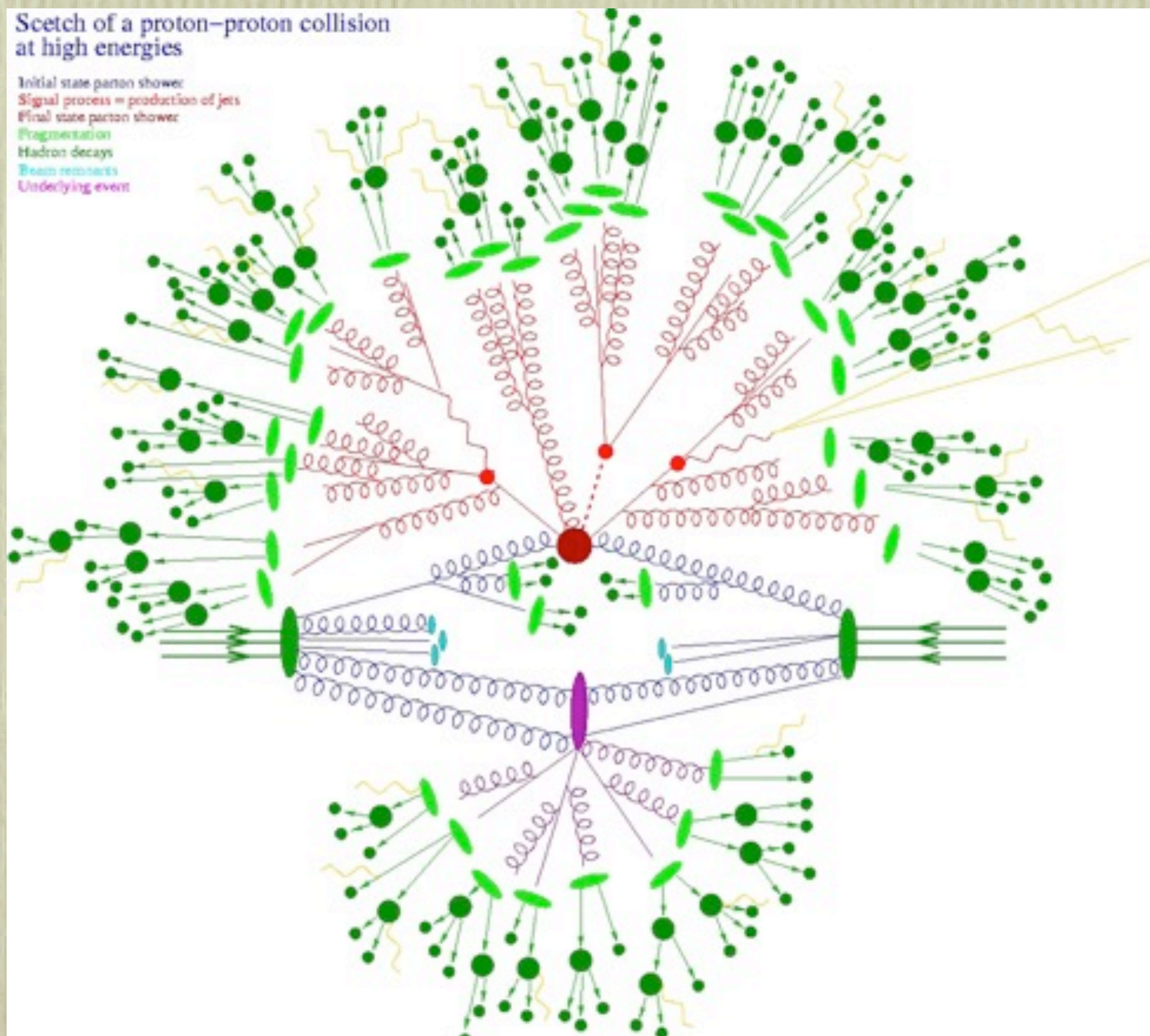
University of Wisconsin, Madison

The Physics of W and Z Bosons
June 25, 2010

Outline

- Intro: QCD at higher orders
- Physics with W, Z bosons at hadron colliders (focus on Tevatron, LHC)
- Importance of leptonic cuts
- Fully differential NNLO codes: ***FEWZ, DYNNLO***
- Tevatron results: W charge asymmetry, a question about the Z rapidity
- Combination of EW and QCD corrections

Collisions at the LHC



A lot going on...

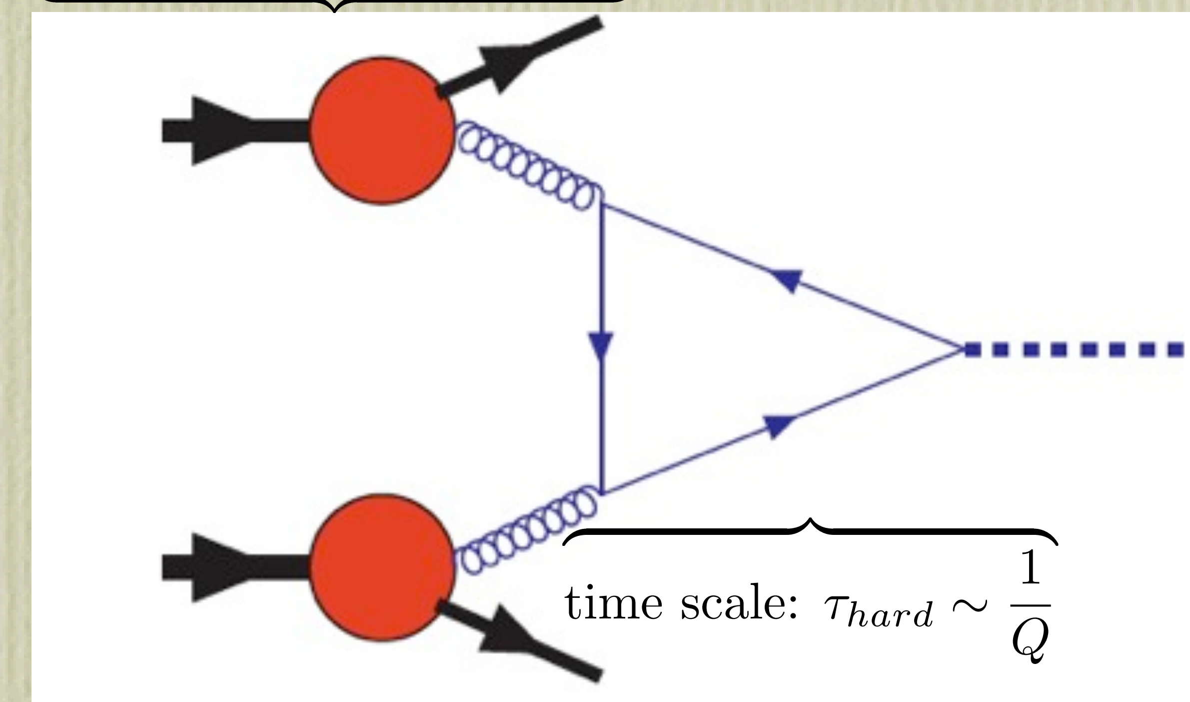
- New physics at hard scale; M for example
- Parton shower evolution from M to Λ_{QCD}
- Final state hadronization at Λ_{QCD}
- Parton distribution functions at Λ_{QCD}
- Multiple parton interactions, hadron decays, ...

How does one make a prediction for such an event?

Divide and conquer: PDFs

Make sense of this with *factorization*: separate hard and soft scales

$$\underbrace{\text{time scale: } \tau_{proton} \sim \frac{1}{\Lambda_{QCD}}}$$



$$\sigma_{h_1 h_2 \to X} = \int dx_1 dx_2 \underbrace{f_{h_1/i}(x_1; \overbrace{\mu_F^2}^{\text{factorization scale}}) f_{h_1/j}(x_2; \mu_F^2)}_{PDFs} \underbrace{\sigma_{ij \to X}(x_1, x_2, \mu_F^2, \{q_k\})}_{\text{partonic cross section}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{Q}\right)^n}_{\text{power corrections}}$$

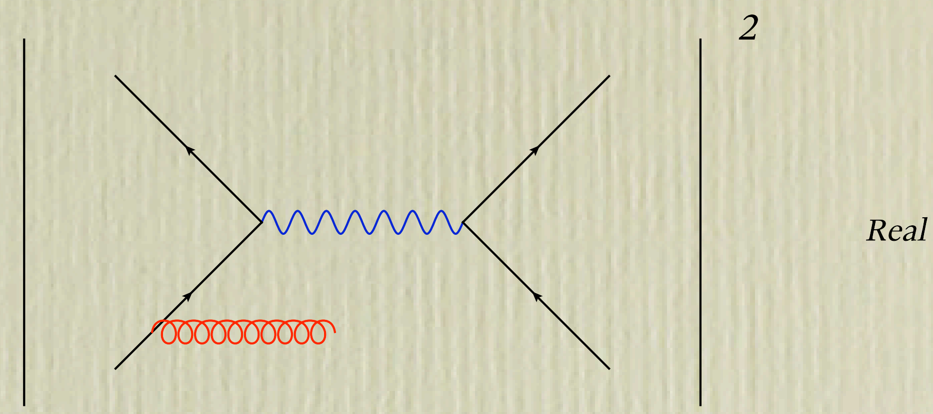
Non-perturbative but *universal*; measure in DIS, fixed-target, apply to Tevatron, LHC

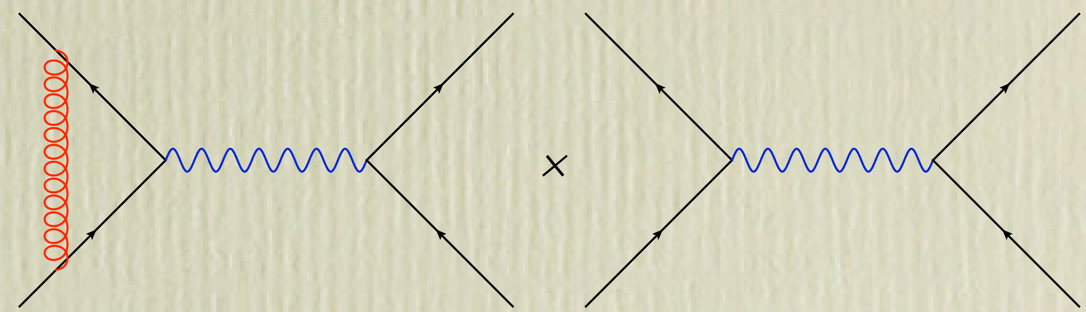
Process dependent but calculable in pQCD

Small for sufficiently inclusive observables

Computing σ: NLO

$$\sigma = \overbrace{\sigma_0}^{LO} + \overbrace{\frac{\alpha_s}{\pi}\sigma_1}^{NLO} + \overbrace{\left(\frac{\alpha_s}{\pi}\right)^2}^{NNLO}\sigma_2 + \ldots$$





Contributions separately singular

- Soft singularities: $E_g \rightarrow 0$
- Collinear singularities: $p_g \,||\, p_i$

Kinoshita-Lee-Nauenberg (KLN) theorem:

singularities cancel after summation over degenerate initial/final states

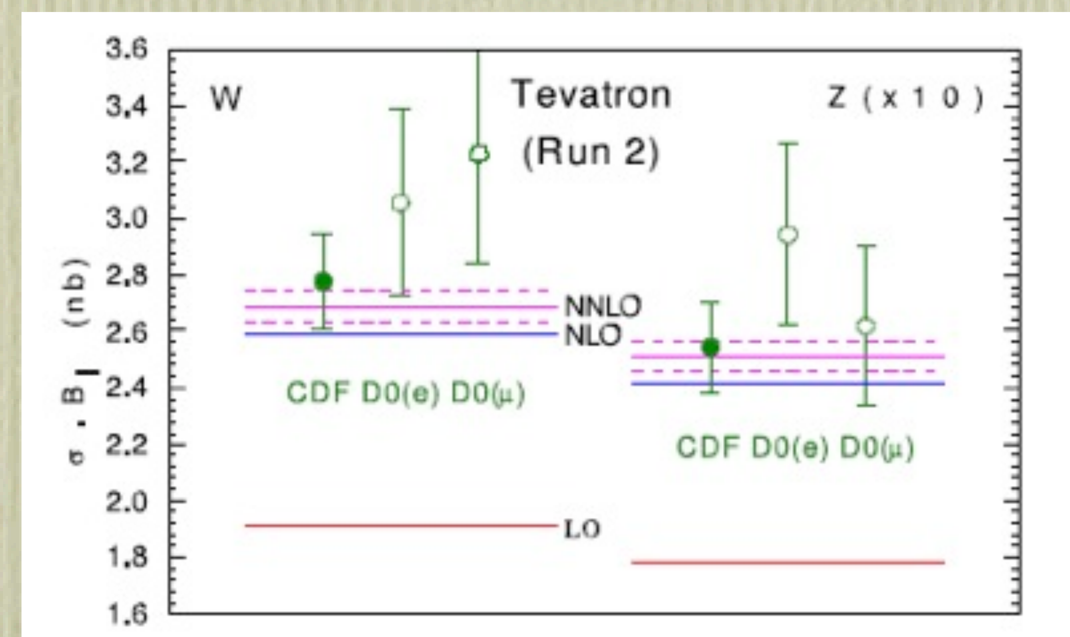
Cancellation occurs for *infrared-safe* observables: insensitive to soft/collinear radiation

\+ Lepton from Z decay η distribution

\- Number of partons in event

Benefits of NLO

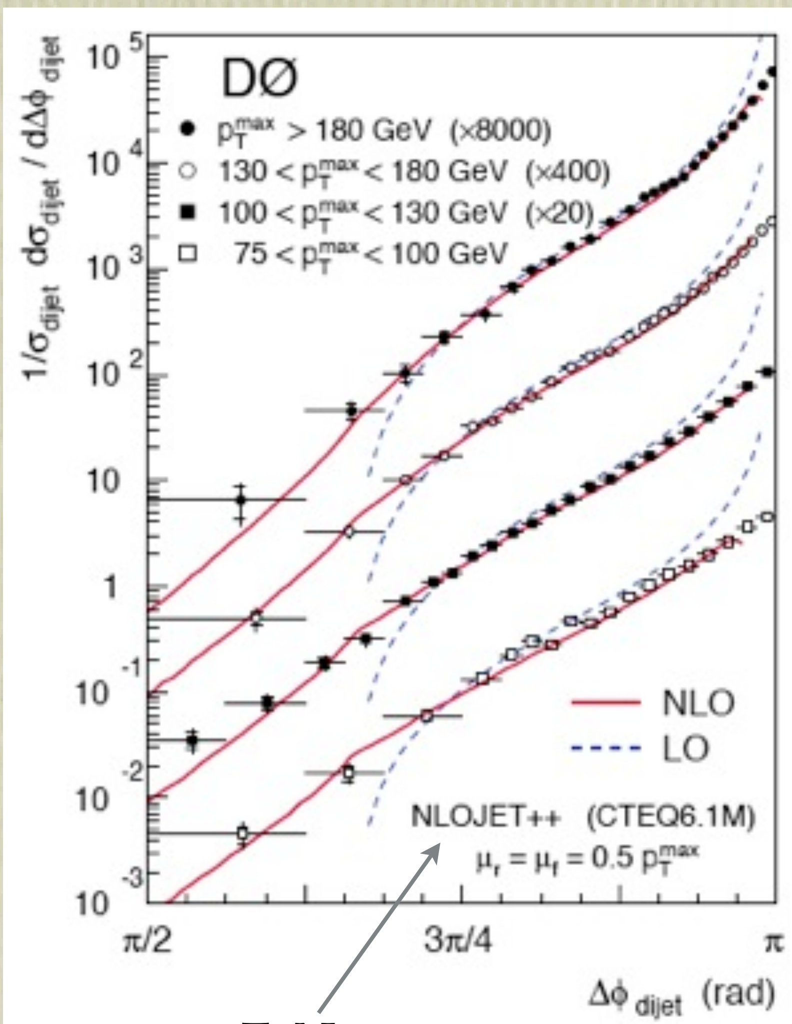
- ☑ Improved normalization and smaller residual uncertainty
- ☑ Better description of distribution shapes
- ☑ First serious quantitative prediction only at NLO



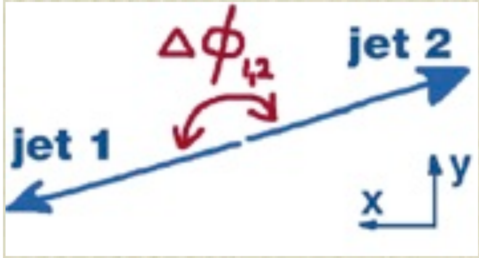
W+jets

number of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

BLACKHAT: Berger et al., 0907.1984



Z. Nagy

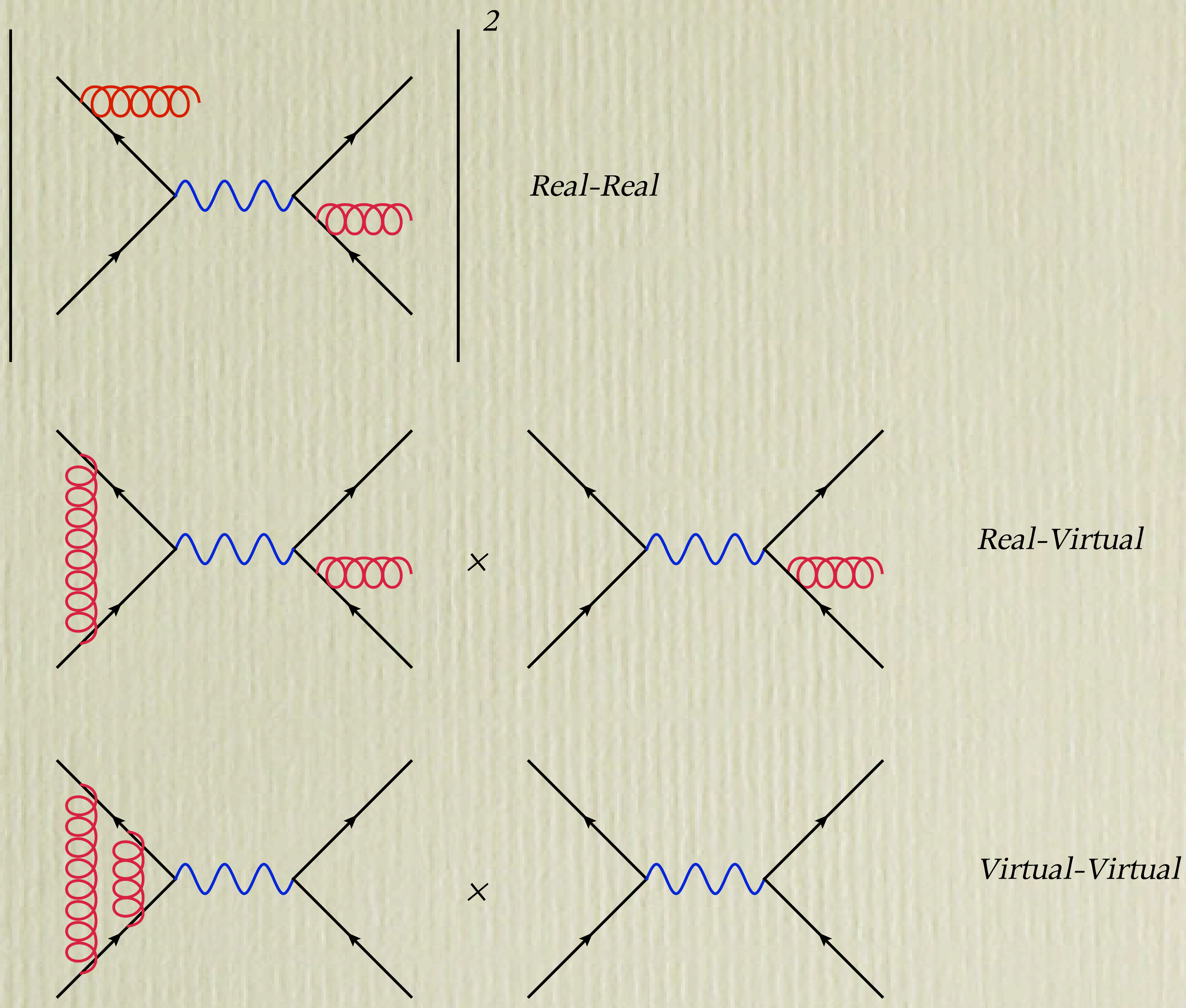


Computing σ: NNLO

$$\sigma = \overbrace{\sigma_0}^{LO} + \overbrace{\frac{\alpha_s}{\pi}\sigma_1}^{NLO} + \overbrace{\left(\frac{\alpha_s}{\pi}\right)^2 \sigma_2}^{NNLO} + \ldots$$

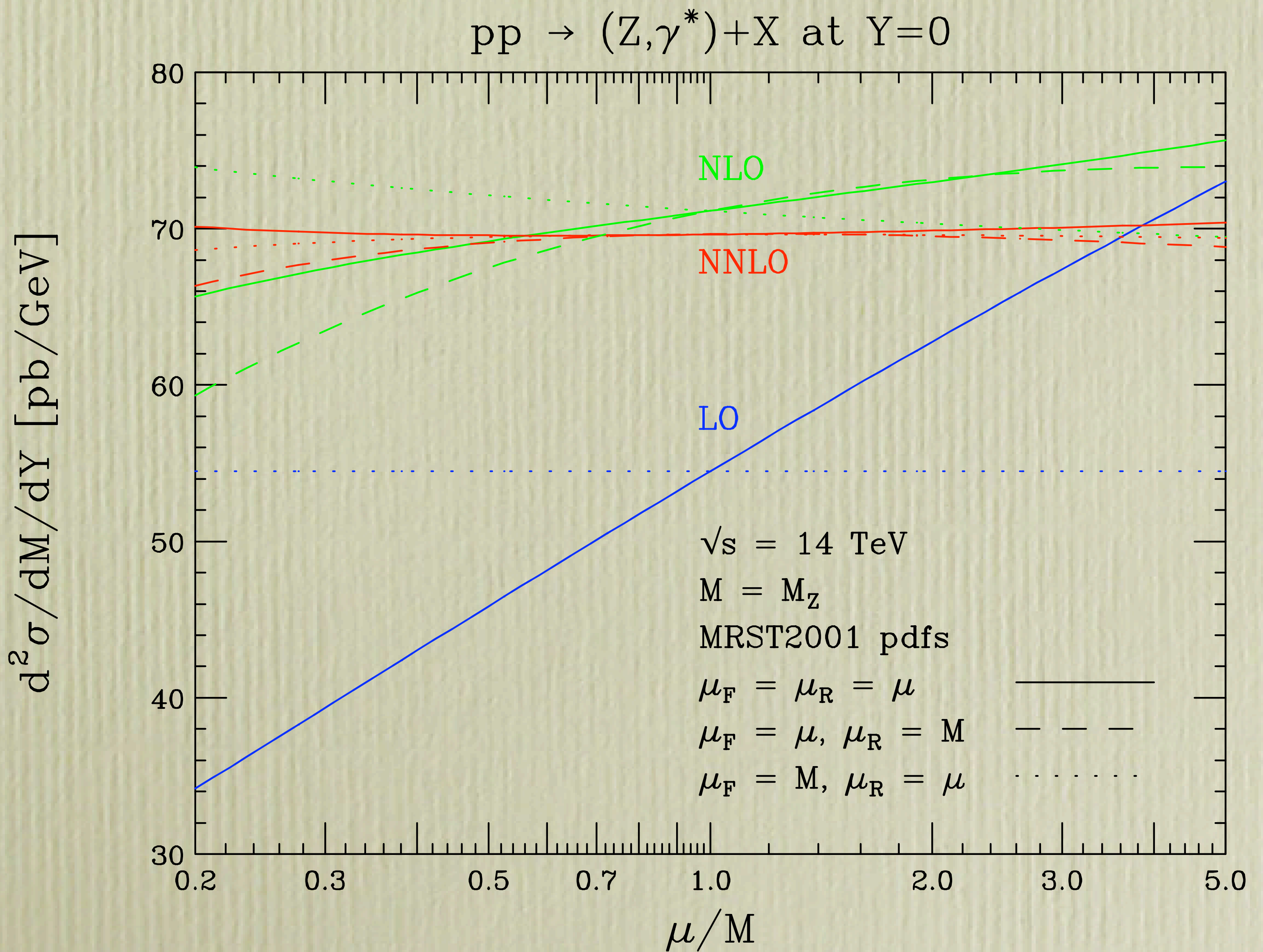
When is NNLO necessary?

- ☑ When NLO corrections are large, and NNLO is needed to check expansion (gg→H)
- ☑ For benchmark processes where high precision is needed (DIS, Drell-Yan for PDFs, $e^+e^- \rightarrow 3$ jets for α_s)



Standard Candles

$$\sigma(\mu_R,\mu_F) = \sigma^{(0)}(\mu_F) + \frac{\alpha_s(\mu_R)}{\pi}\sigma^{(1)}(\mu_R,\mu_F) + \left(\frac{\alpha_s(\mu_R)}{\pi}\right)^2 \sigma^{(2)}(\mu_R,\mu_F)$$

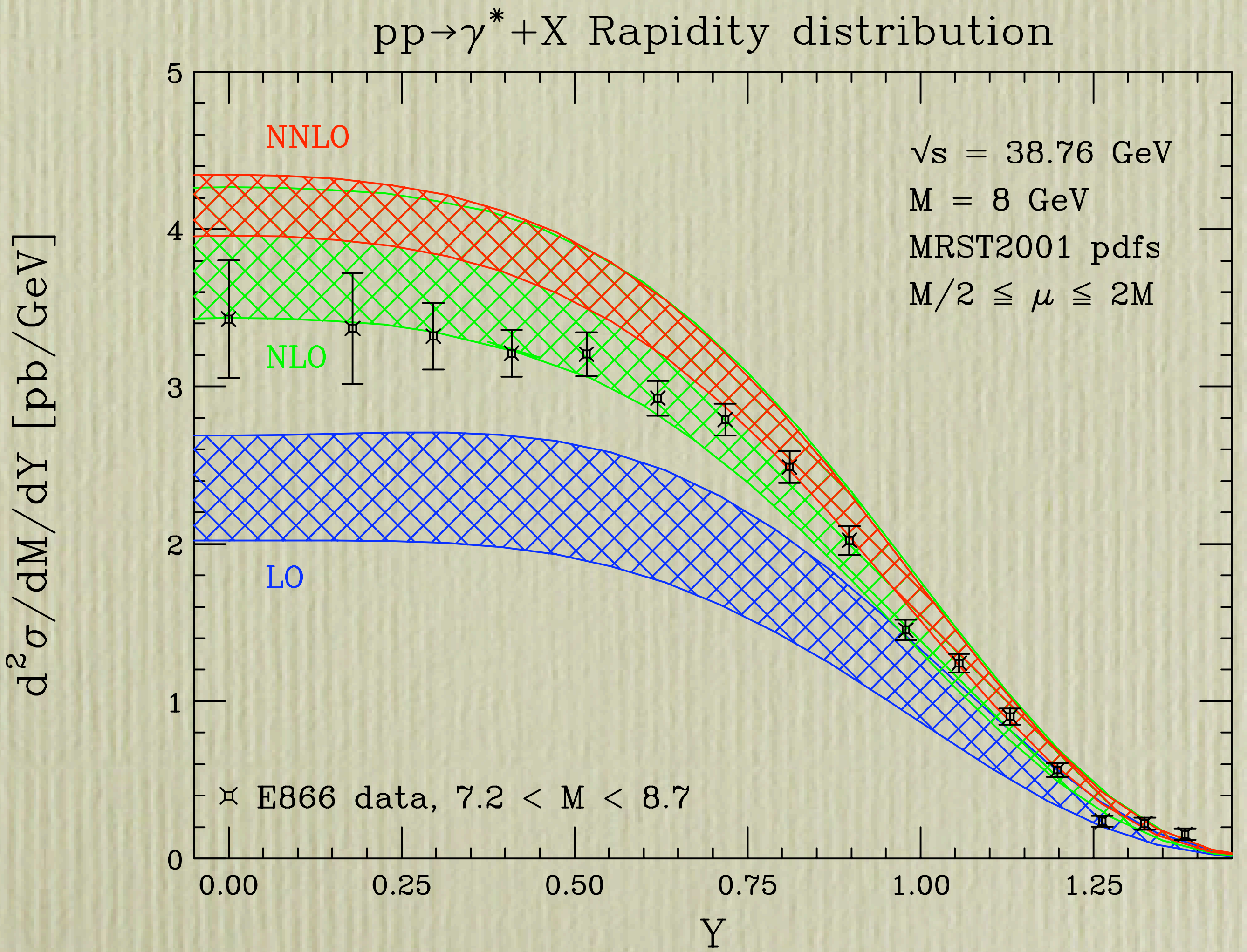


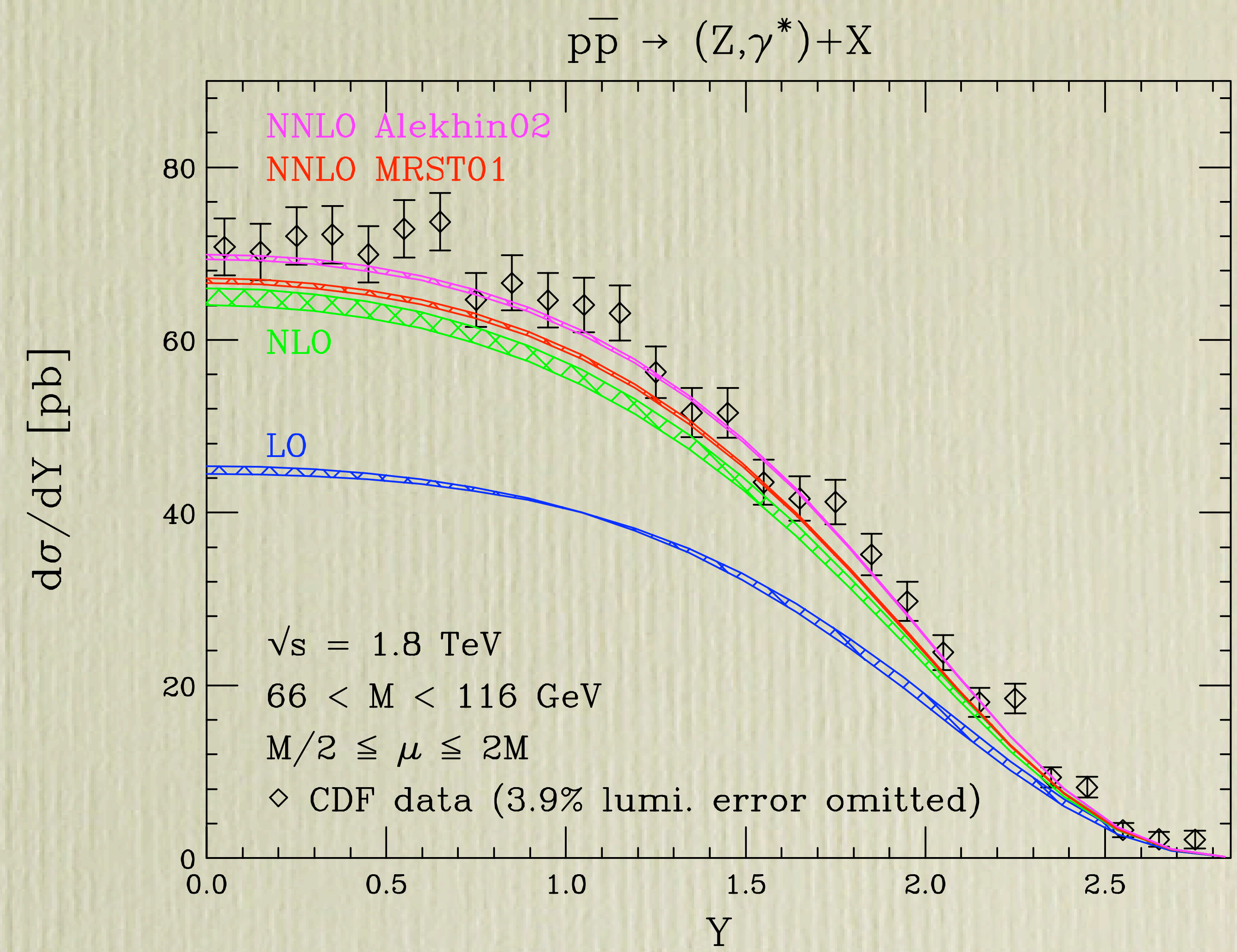
Anastasiou, Dixon, Melnikov, FP (ADMP) hep-ph/0312266

- W,Z production known through NNLO in pQCD
- Residual theoretical uncertainties from scale variations <1% on inclusive quantities
- "Gold-plated" observables suited to high-precision measurements

γ^*/Z rapidity distributions

ADMP hep-ph/0306192



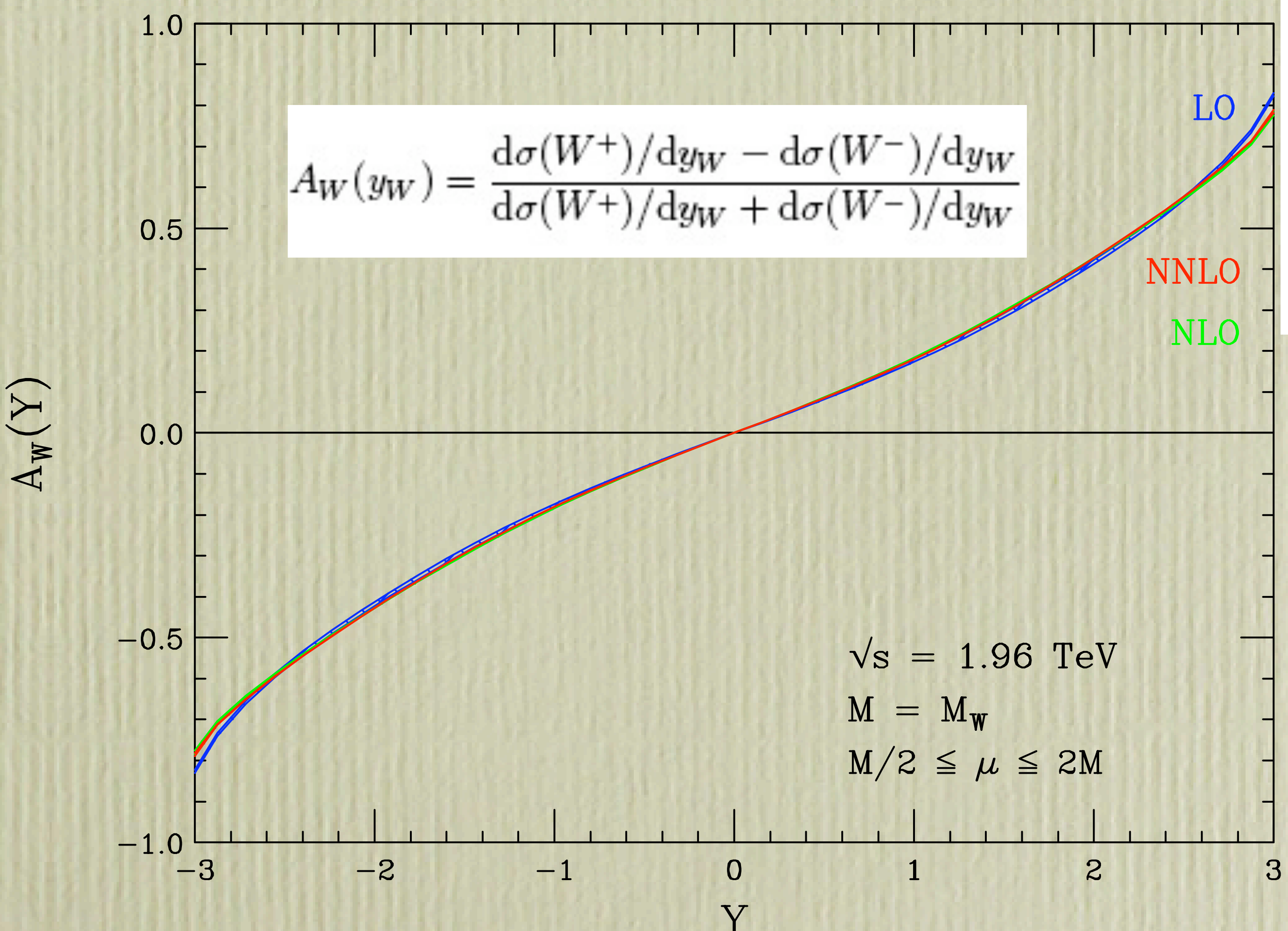


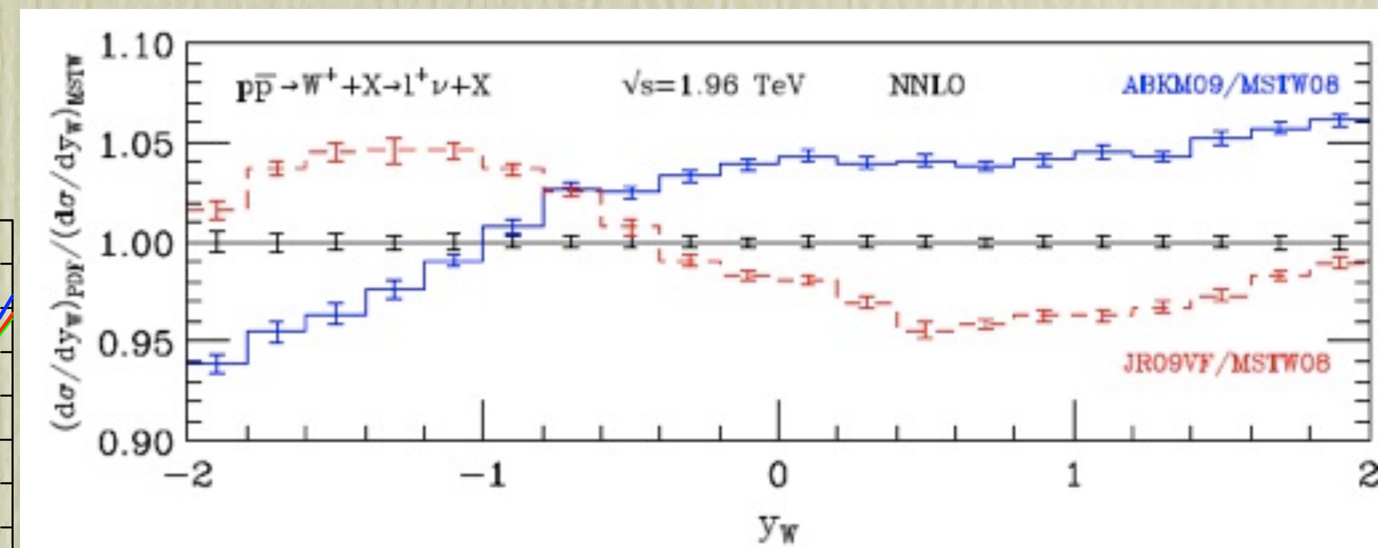
- Significant impact on fixed-target data, quark distributions
  MSTW 0706.0459, 0901.0002
- Generally good agreement with CDF/D0 data

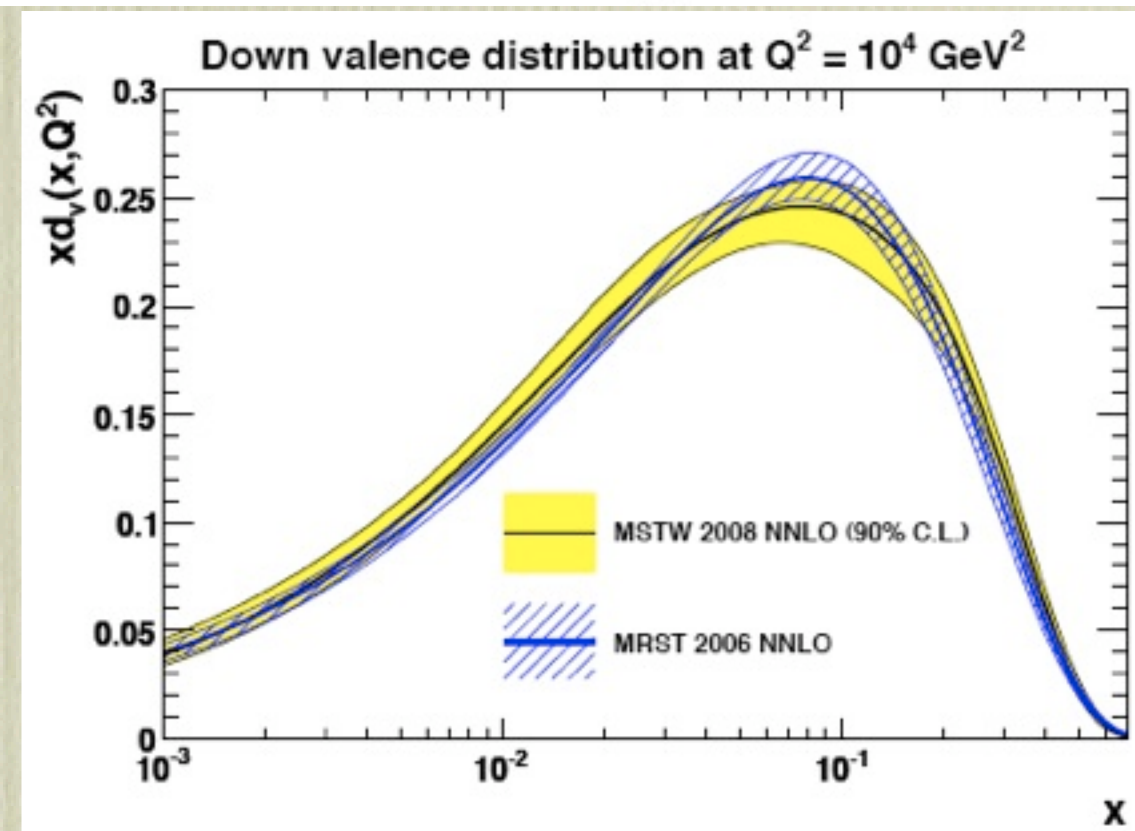
from ***VRAP***: NNLO γ^*+Z,W rapidity distributions

W charge asymmetry

Catani, Ferrera, Grazzini 1002.3115

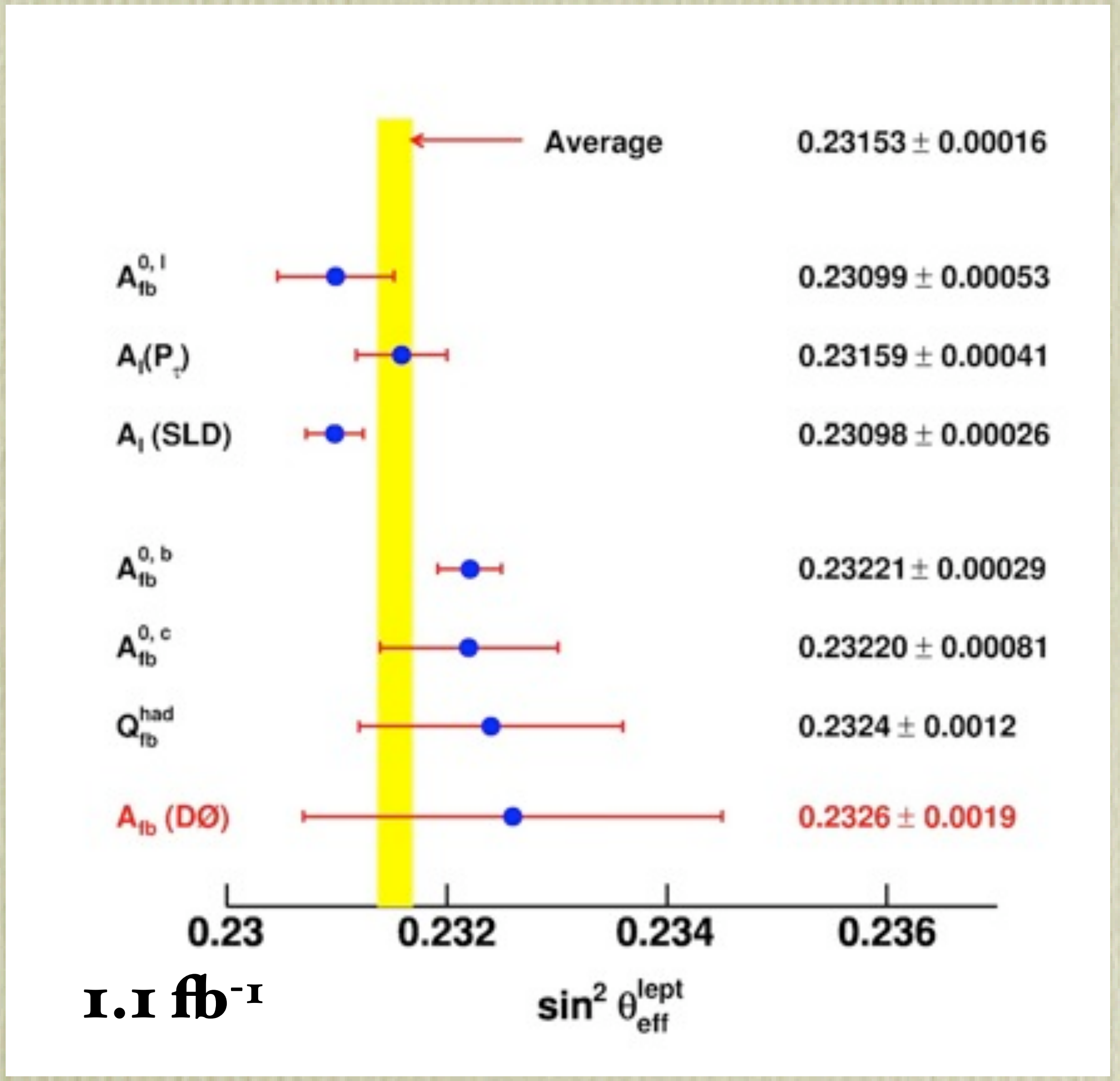






- Remarkable stability under perturbative corrections
- Together with Z rapidity, constraint quark PDFs

A_{FB} and $\sin^2\theta$

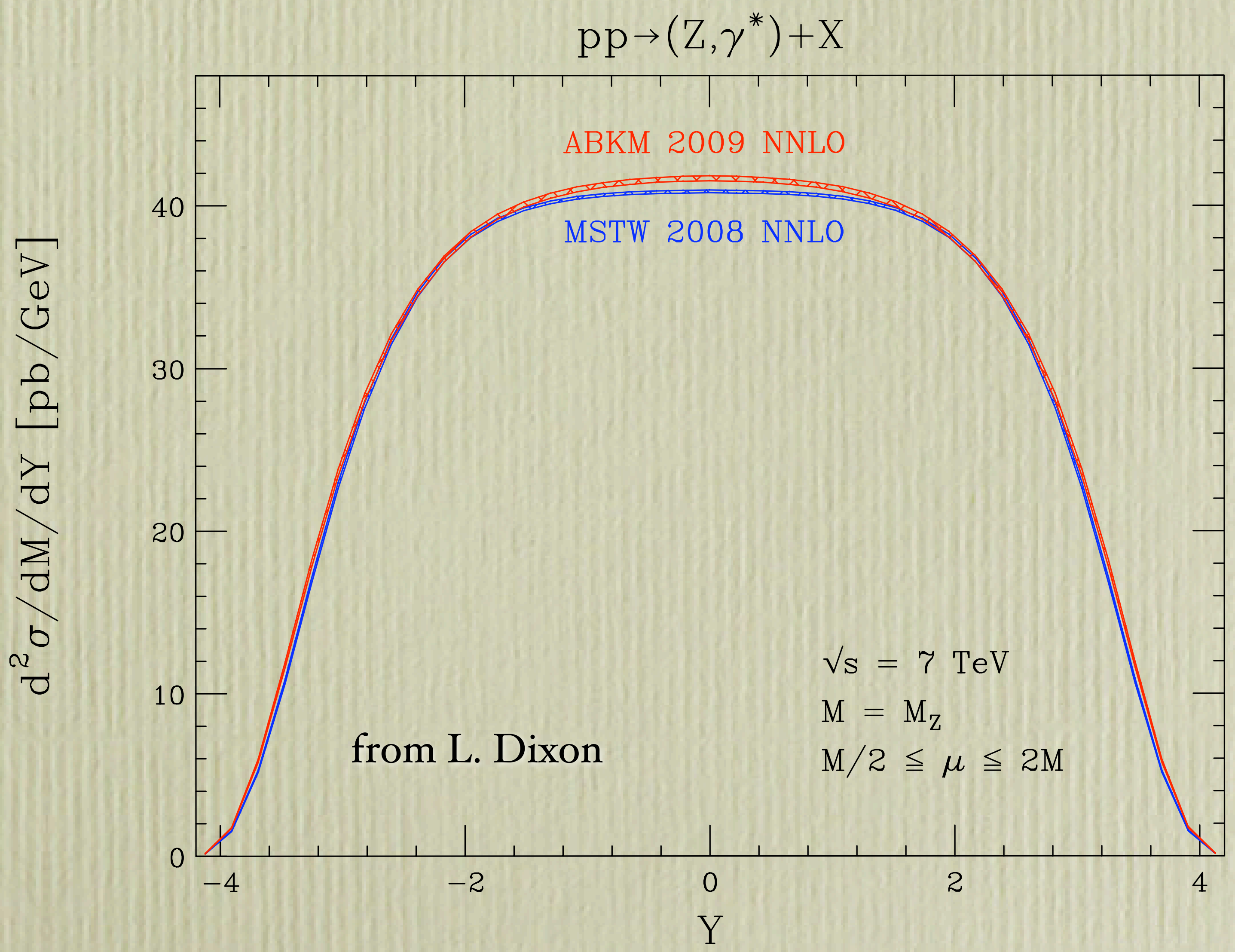


M_{ee} range (GeV)	$\langle M_{ee}\rangle$ (GeV)	Predicted A_{FB} PYTHIA	Predicted A_{FB} ZGRAD2	Unfolded A_{FB}
50 – 60	54.5	−0.293	−0.307	$-0.262 \pm 0.066 \pm 0.072$
60 – 70	64.9	−0.426	−0.431	$-0.434 \pm 0.039 \pm 0.040$
70 – 75	72.6	−0.449	−0.452	$-0.386 \pm 0.032 \pm 0.031$
75 – 81	78.3	−0.354	−0.354	$-0.342 \pm 0.022 \pm 0.022$
81 – 86.5	84.4	−0.174	−0.166	$-0.176 \pm 0.012 \pm 0.014$
86.5 – 89.5	88.4	−0.033	−0.031	$-0.034 \pm 0.007 \pm 0.008$
89.5 – 92	90.9	0.051	0.052	$0.048 \pm 0.006 \pm 0.005$
92 – 97	93.4	0.127	0.129	$0.122 \pm 0.006 \pm 0.007$
97 – 105	99.9	0.289	0.296	$0.301 \pm 0.013 \pm 0.015$
105 – 115	109.1	0.427	0.429	$0.416 \pm 0.030 \pm 0.022$
115 – 130	121.3	0.526	0.530	$0.543 \pm 0.039 \pm 0.028$
130 – 180	147.9	0.593	0.603	$0.617 \pm 0.046 \pm 0.013$
180 – 250	206.4	0.613	0.600	$0.594 \pm 0.085 \pm 0.016$
250 – 500	310.5	0.616	0.615	$0.320 \pm 0.150 \pm 0.018$

Statistics **Systematics**

- Recent CDF measurement with 4.1 fb⁻¹, prospects for improved determination of $\sin^2\theta$

LHC W/Z errors



W→μν

Source	Uncertainty (%)
Tracker efficiency	0.5
Muon efficiency	1
Magnetic field knowledge	0.05
Tracker alignment	0.84
Trigger efficiency	1.0
Transverse missing energy	1.33
Pile-up effects	0.32
Underlying event	0.24
Total exp.	2.2

From G. Dissertori, HP² 2006

- Large samples, small theory and experimental systematic errors
- $\delta(\sin^2\theta) \approx 2\times10^{-4}$ with 100 fb^{-1} at 14 TeV

LHC physics with W/Z

- Luminosity monitoring: normalize to W/Z production

$$N_{pp\to WW} = N_{pp\to Z} \cdot \frac{\sigma_{q,\bar{q}\to WW}}{\sigma_{q,\bar{q}\to Z}} \cdot \frac{PDF(x_1',x_2',Q'^2)}{PDF(x_1,x_2,Q^2)}$$

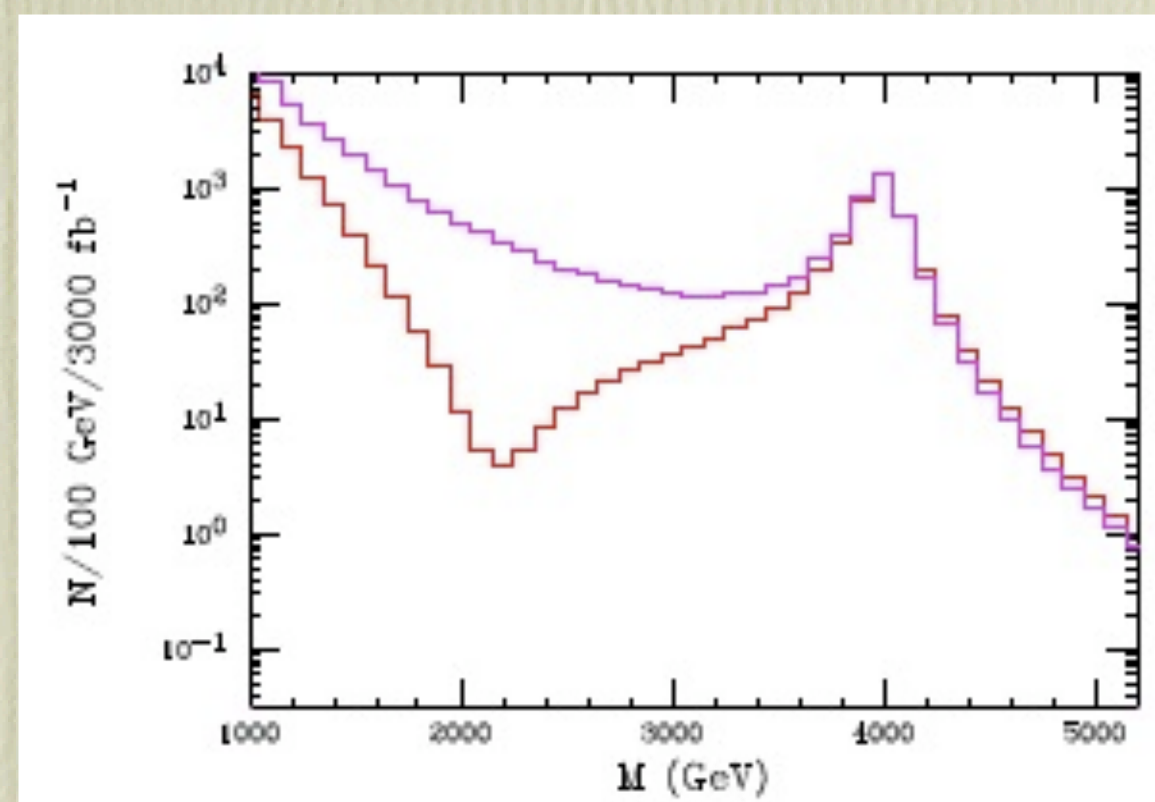
$\Delta L_{pp} = 0!$

Normalization process

Calculable with small theory error

Dittmar, Pauss, Zurcher hep-ex/9705004

- KK/Z' differentiation via SM interference



T. Rizzo hep-ph/0305077

Spin correlations

$$\sigma = \frac{N}{\epsilon \times \mathcal{L} \times A}$$

→ Measure leptons, not W/Z, with cuts imposed ⇒spin correlations between production, decay

- **Cut 1 :** $p_T^e > 20$ GeV , $|\eta^e| < 2.5$, $\not{E}_T > 20$ GeV ;
- **Cut 2 :** $p_T^e > 40$ GeV , $|\eta^e| < 2.5$, $\not{E}_T > 20$ GeV .

	Tevatron			LHC		
	LO	NLO	MC@NLO	LO	NLO	MC@NLO
Cut 1	0.409	0.385	0.383	0.524	0.477	0.485
Cut 1, no spin	0.413	0.394	0.394	0.553	0.510	0.515
Cut 2	0.356	0.340	0.336	0.058	0.129	0.133
Cut 2, no spin	0.389	0.374	0.370	0.075	0.150	0.157

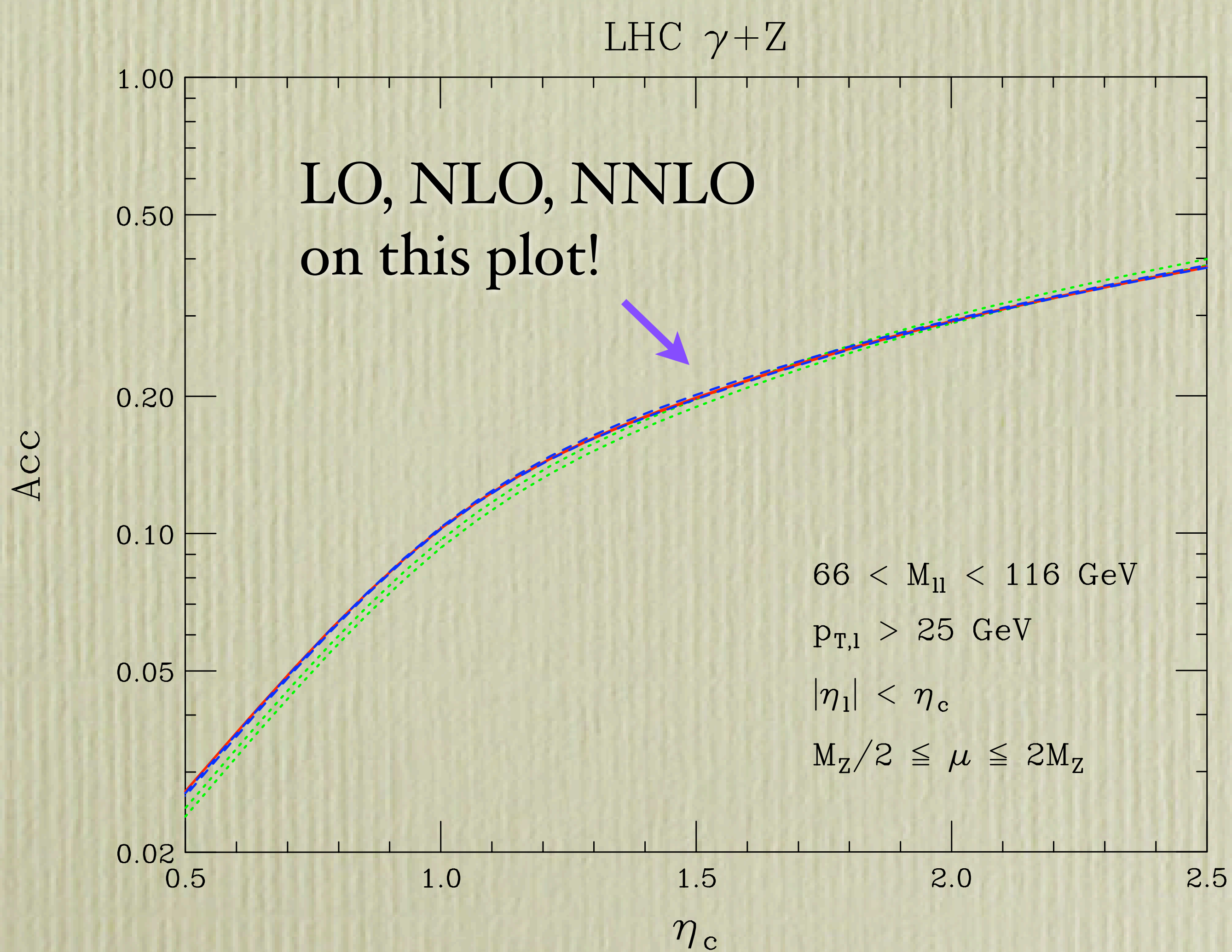
Frixione, Mangano hep-ph/0405130

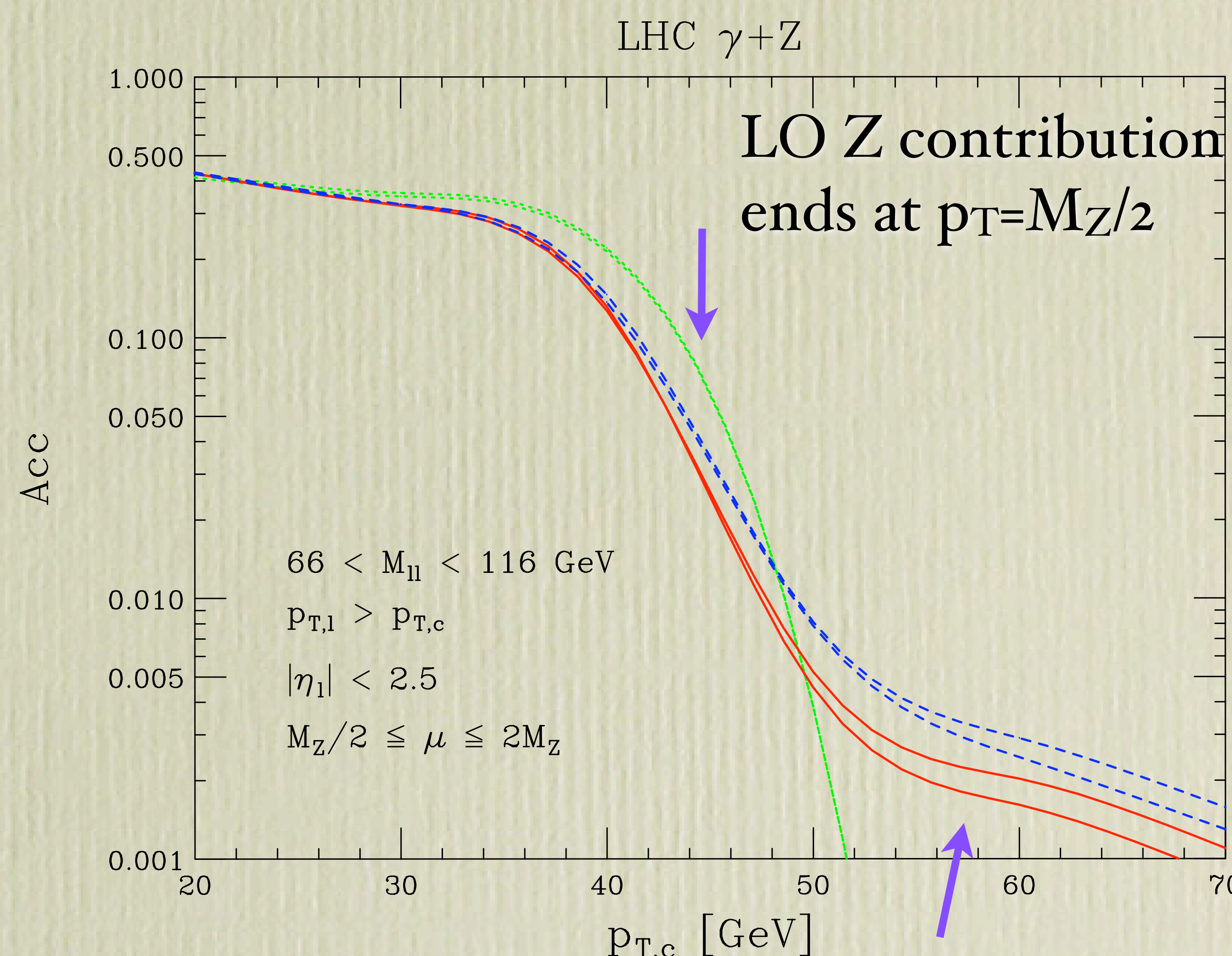
Essential: fully differential NNLO with spin correlations, γ/Z interference

FEWZ

- ***FEWZ***: Fully exclusive W, Z production

Melnikov, FP hep-ph/0603182, 0609070





- ☑ Generally, percent-level predictions for acceptances

Need V+jet at NNLO for this region Boughezal, Gehrmann-de Ridder, Ritzmann 1001.2396

Forward electrons from W

- CDF: forward electrons from W decay hep-ex/0702037

- Forward: $1.2 < |\eta| < 2.8$, $E_T > 20$ GeV, $\not{E}_T > 25$ GeV
- Central: $|\eta| < 1.1$, $E_T > 25$ GeV, $\not{E}_T > 25$ GeV.

FEWZ:

	NLO	NNLO
A_{for}	0.2616(2)	0.2614(2)
A_{cen}	0.2458(28)	0.2422(5)
$R_{c/f}$	0.940(12)	0.9266(19)

☑ CDF result: 0.925±0.033

Acceptances very well predicted by NNLO calculations

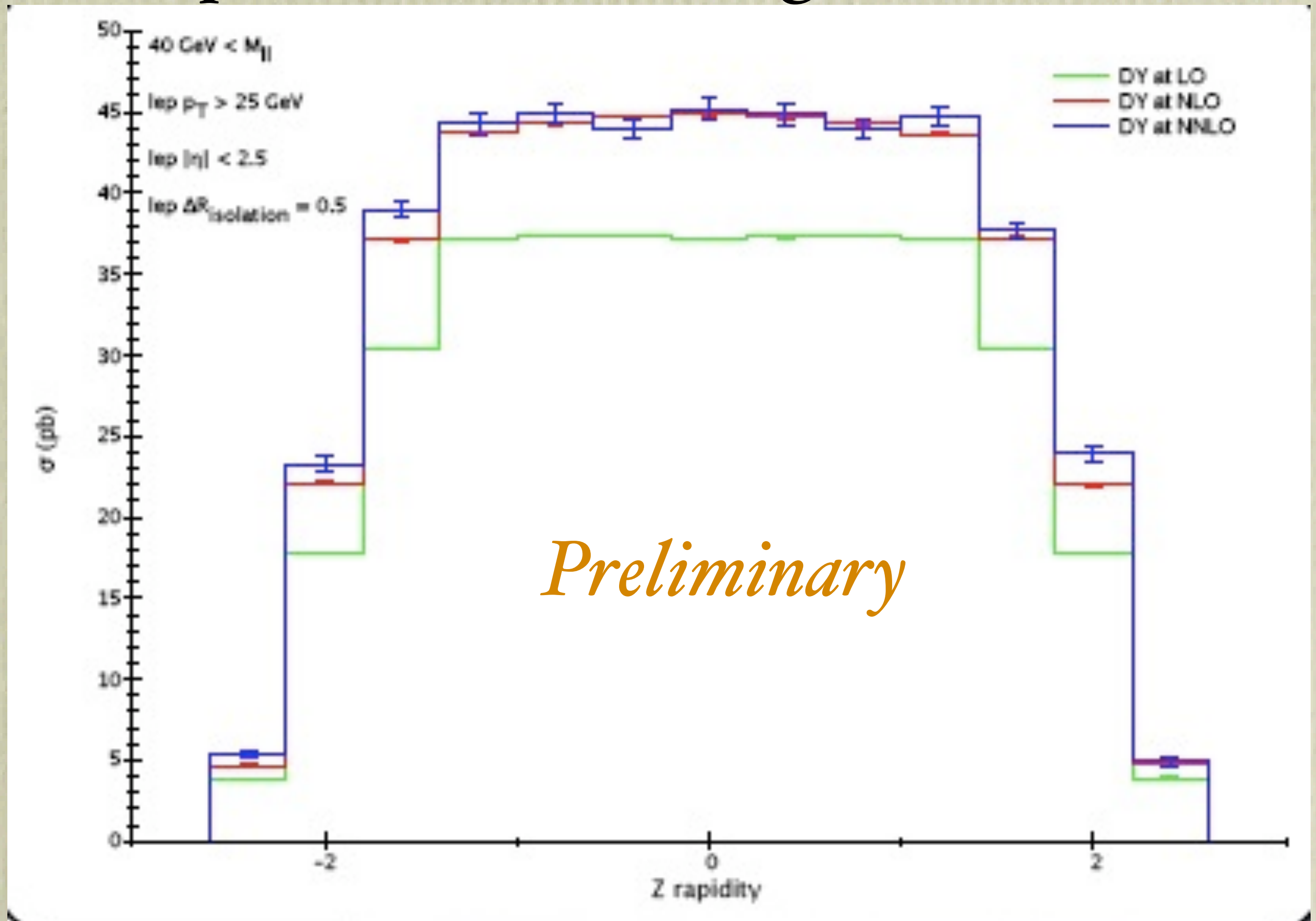
New and improved FEWZ

Previous version:

- Multiple code runs required for single histogram
- Difficulty in sub-% precision for stringent cuts Adam, Halyo, Yost 0802.3251, 0808.0758

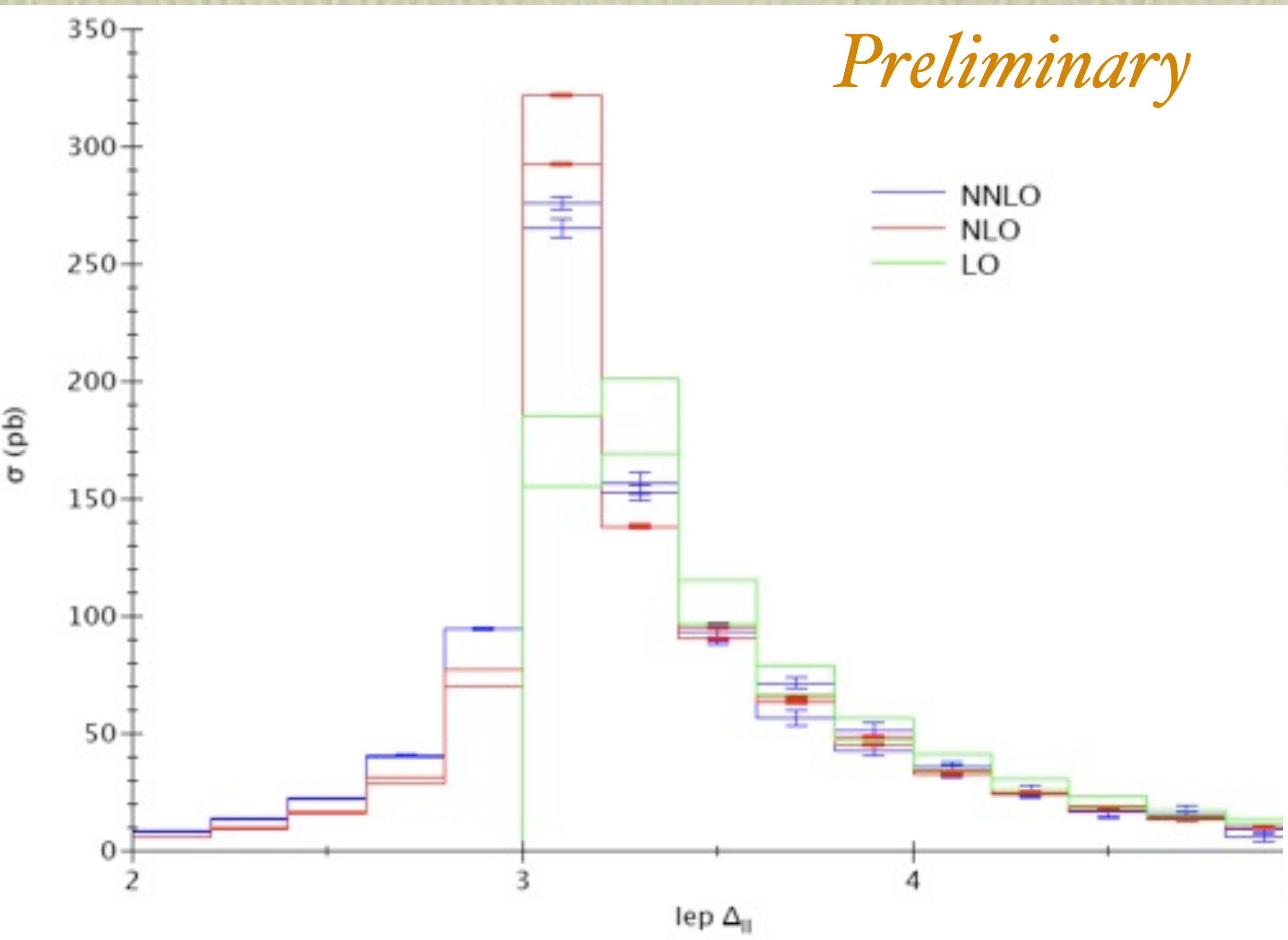
New! Gavin, Li, FP, Quackenbush, in progress

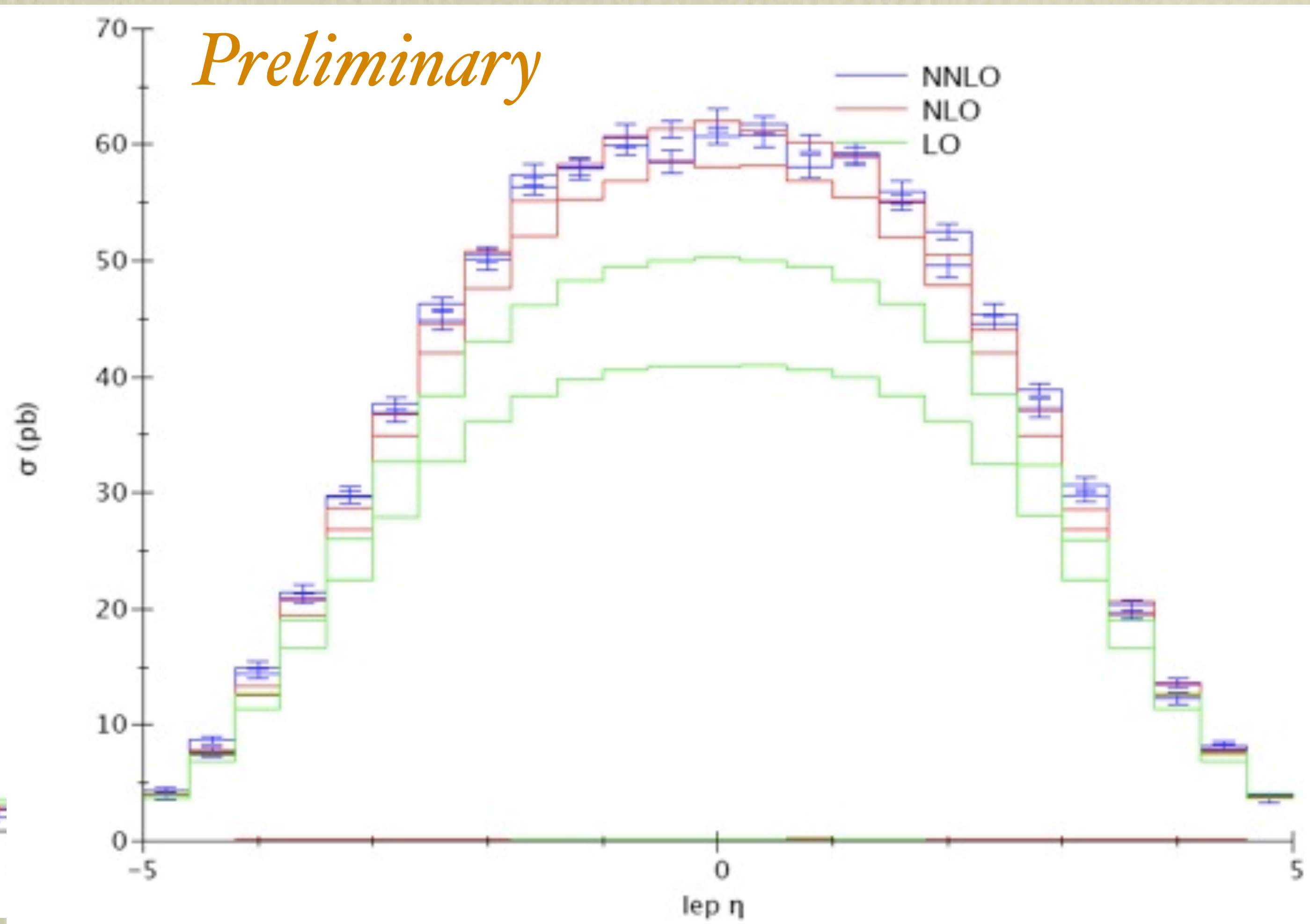
- Multiple, arbitrary histograms filled in one run
- Sector-by-sector, parallelizable integration routine



Lepton distributions

Z @ LHC @ 7 TeV

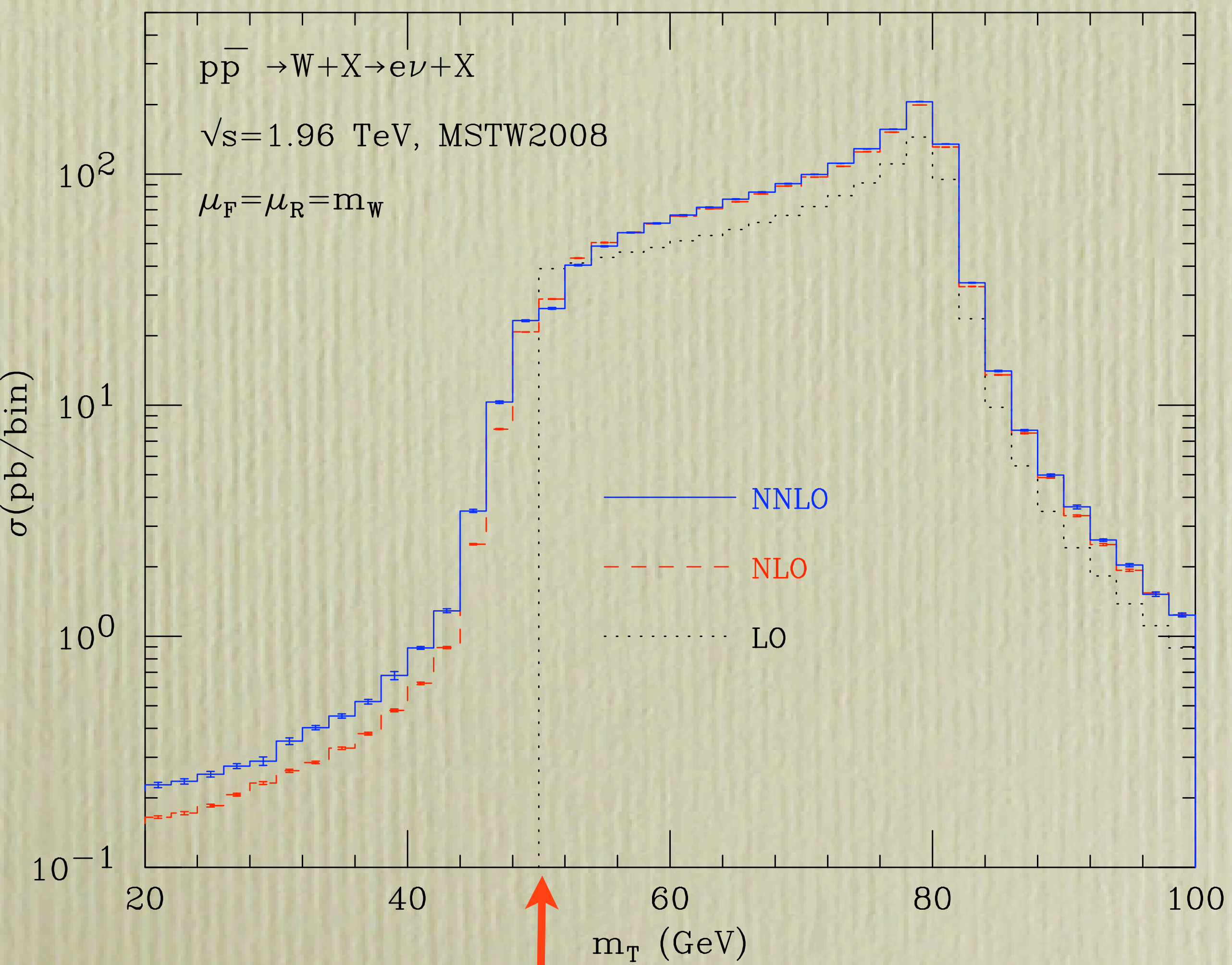




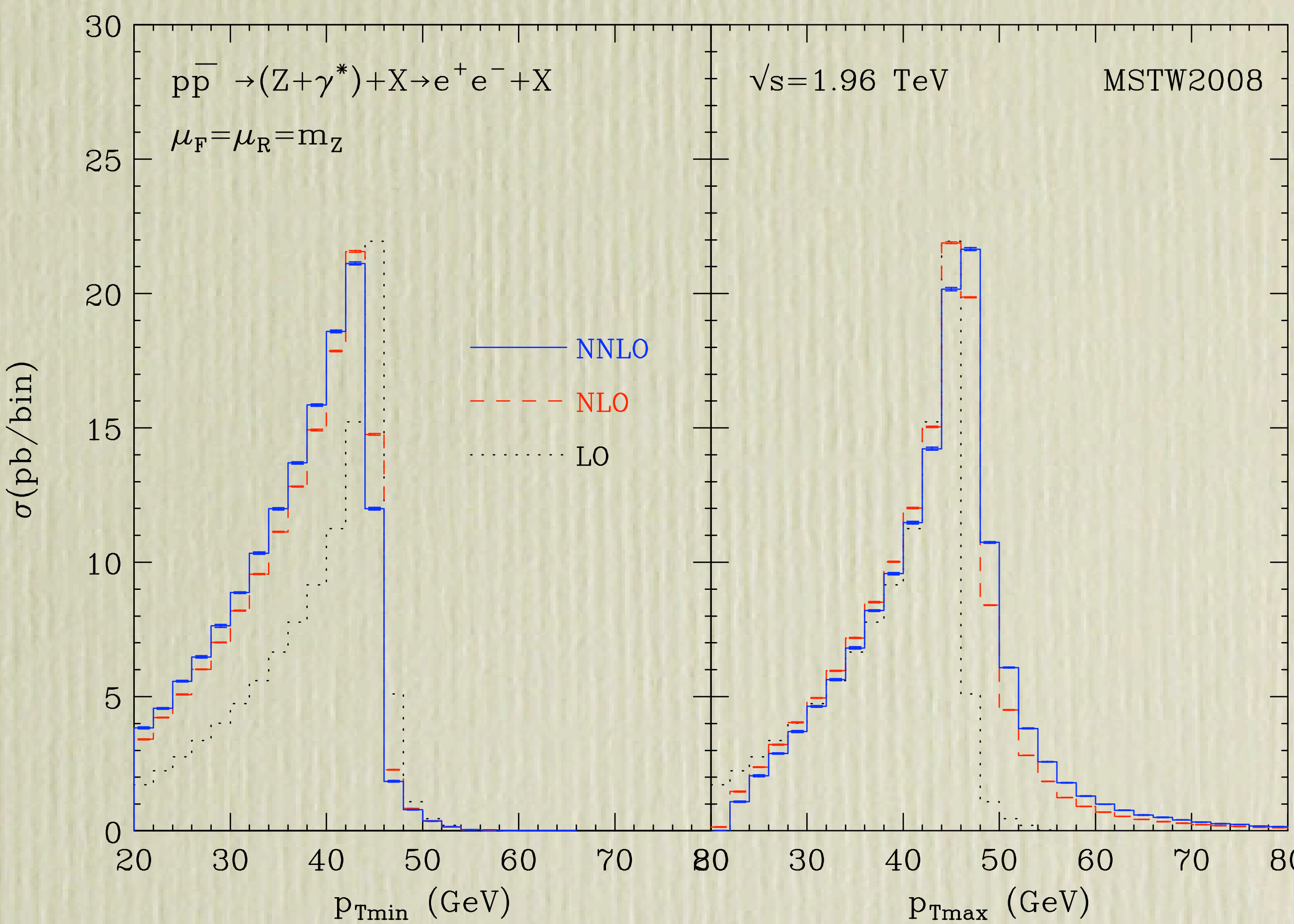
LO boundary: leptons back-to-back in transverse plane

DYNNLO

- Alternative subtraction approach to handling IR singularities at NNLO Catani,Cieri, Ferrera, de Florian, Grazzini 0903.2120



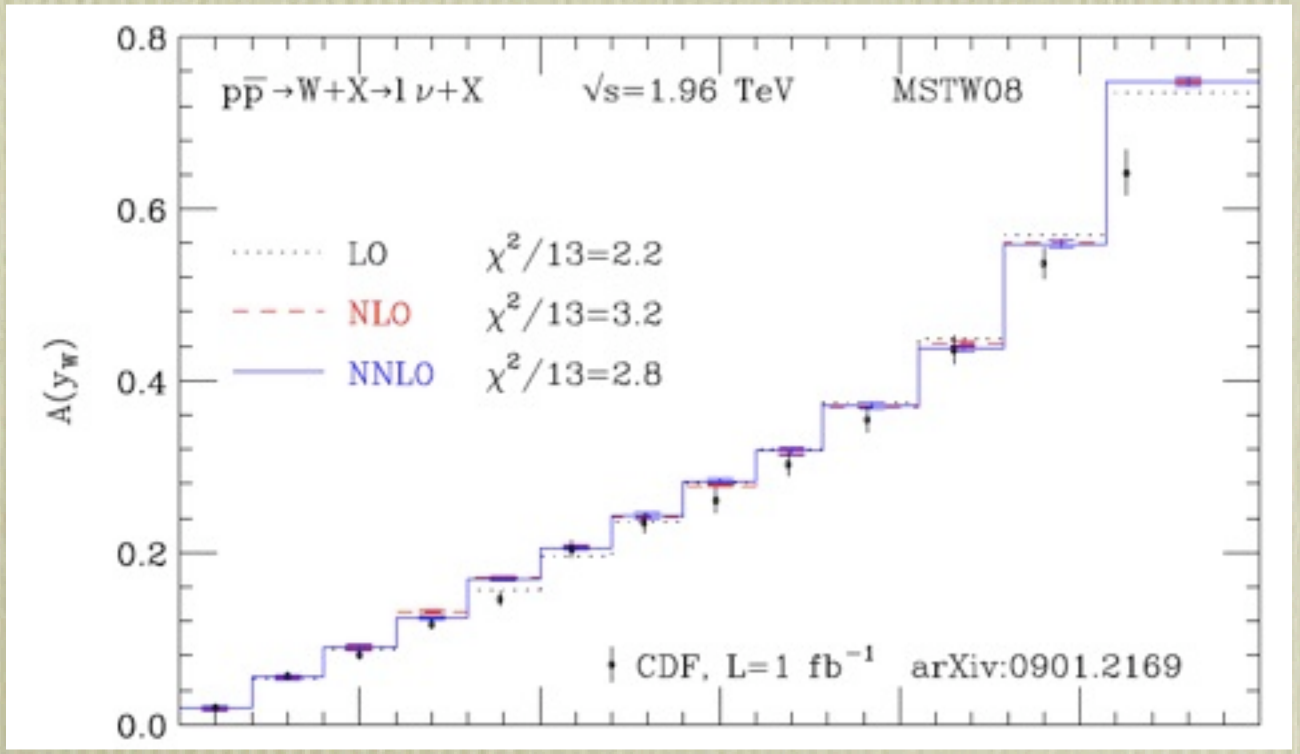
LO boundary created by p_T^{miss} >25 GeV

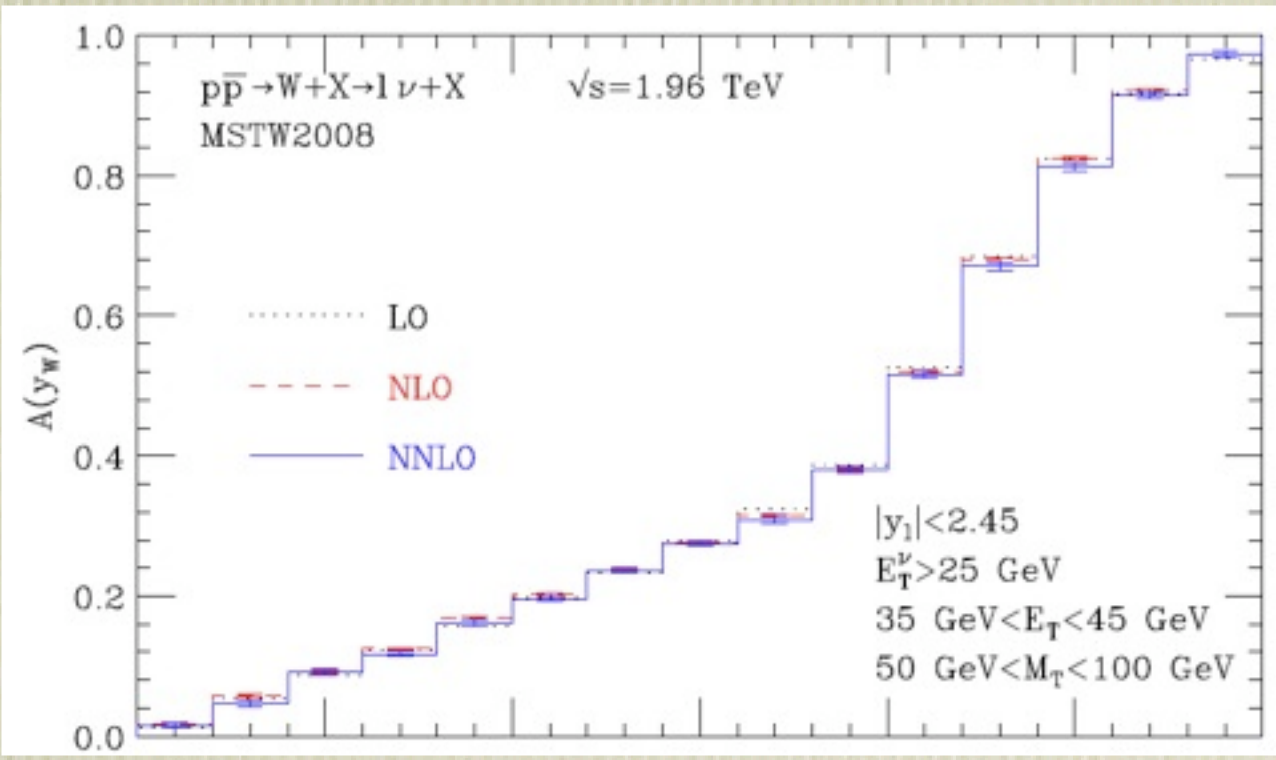


Realistic W charge asymmetry

- Cuts on leptons qualitatively impact measurement
  (from Catani et al. 1002.3115)
  - W^+ follows u in $u\bar{d} \rightarrow W^+$
  - However, lepton follows $\bar{d}$ ⇒changes measured $A(y_W)$

$$\frac{d\sigma_{u\bar{d}}}{d\cos\theta_{ld}} \sim (1 + \cos\theta_{ld})^2$$





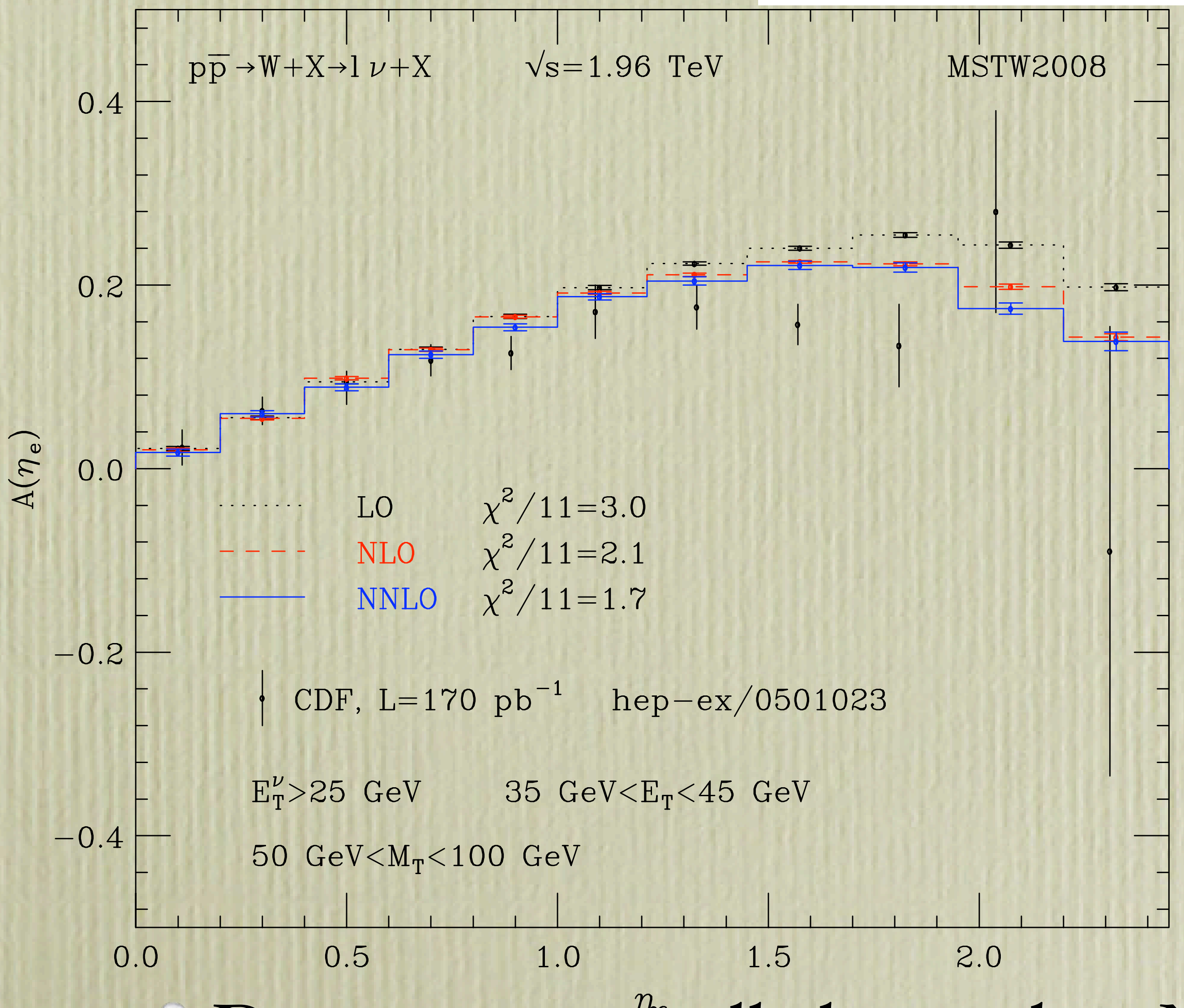
DYNNLO

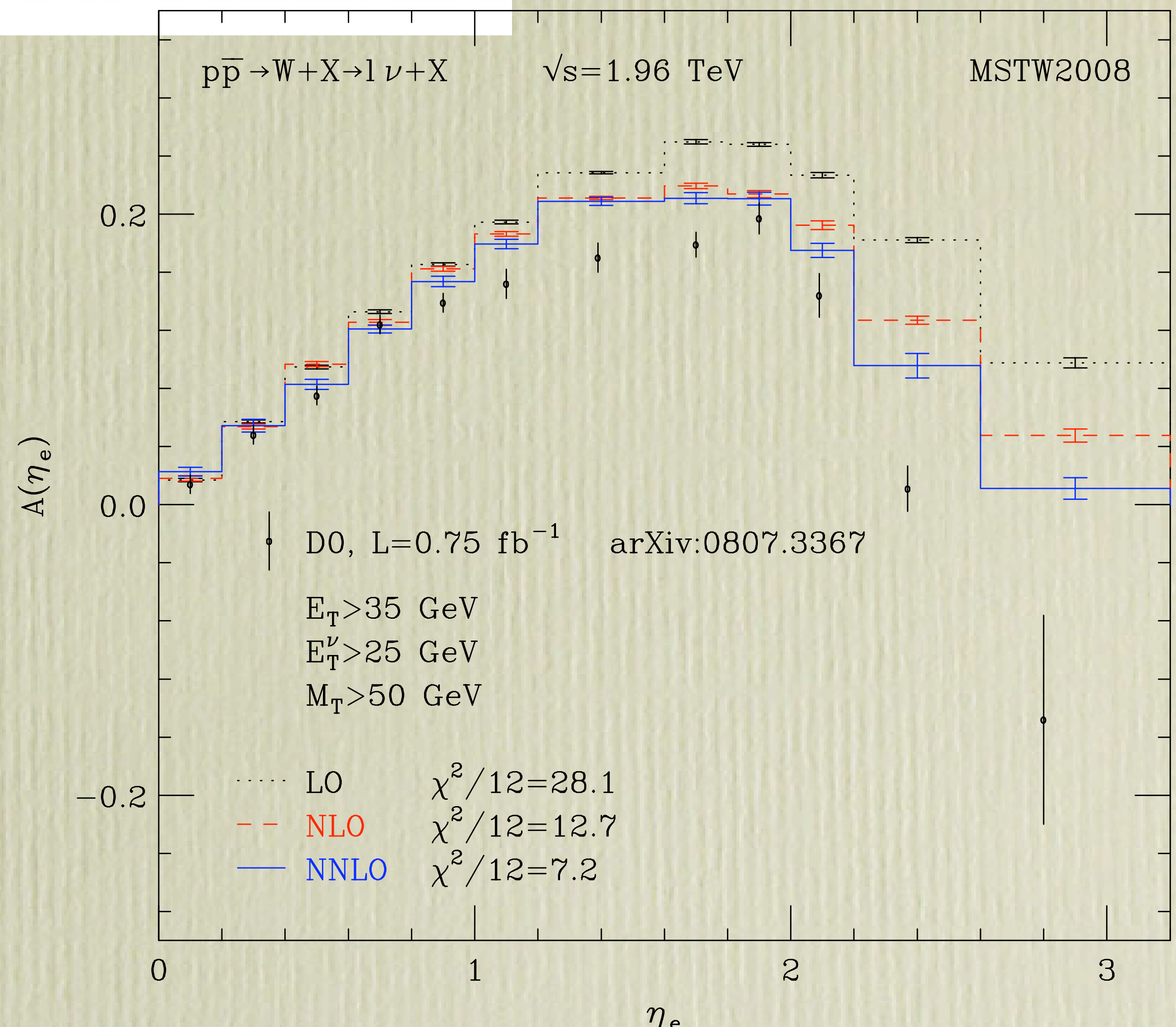
- High y_W: get W^+, not W^-; l^+ pulled back into acceptance, not l^-

Lepton asymmetry at high E_T

$$A_{h_1h_2}(y_l) = \frac{d\sigma_{h_1h_2}(l^+)/dy_l - d\sigma_{h_1h_2}(l^-)/dy_l}{d\sigma_{h_1h_2}(l^+)/dy_l + d\sigma_{h_1h_2}(l^-)/dy_l}$$

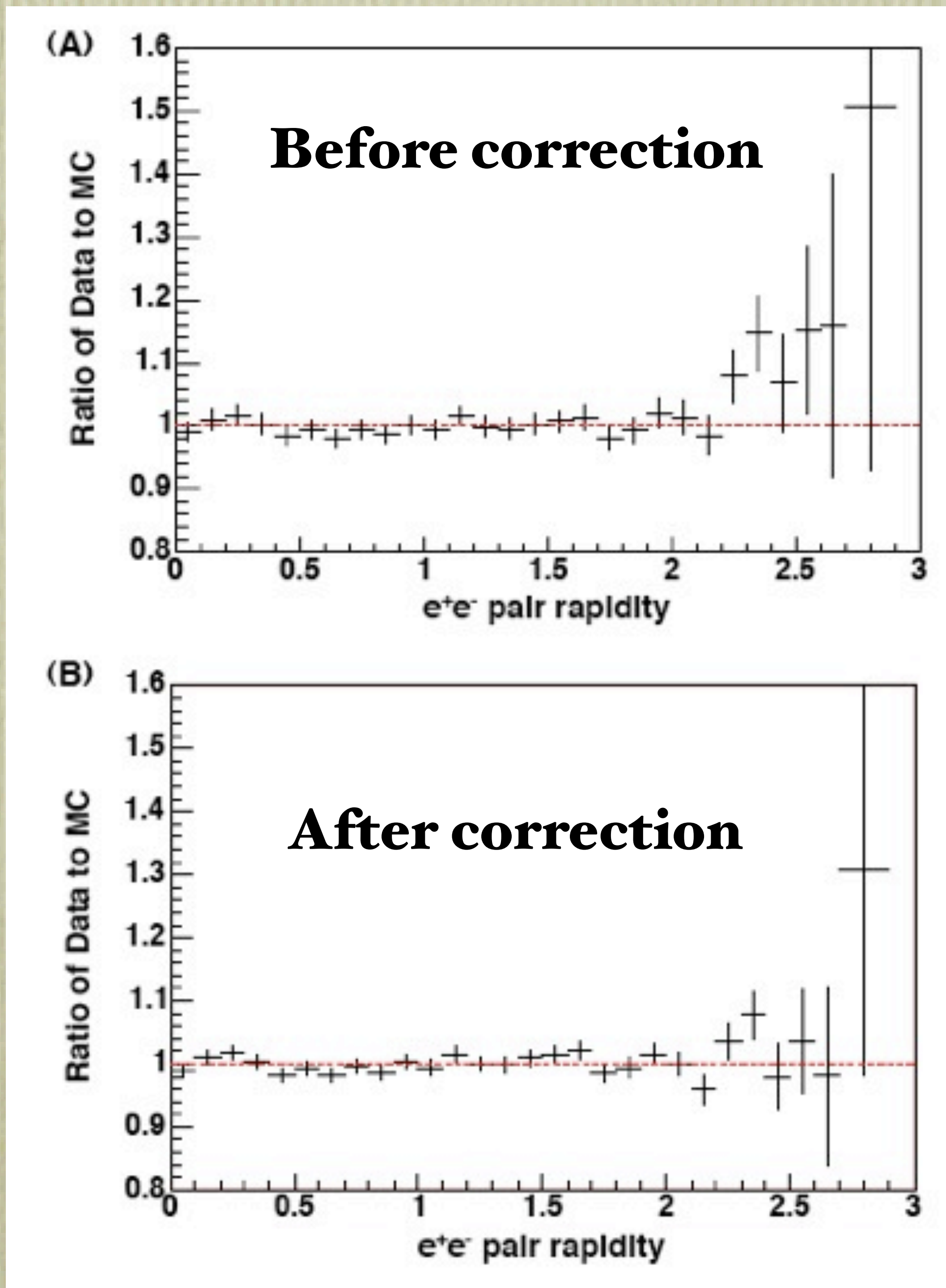
Catani et al. 1002.3115





- Data systematically lower than NNLO; D0 data not included in MSTW fit due to tension with DIS/low energy DY data sets

CDF rapidity distribution



CDF, 0908.3914

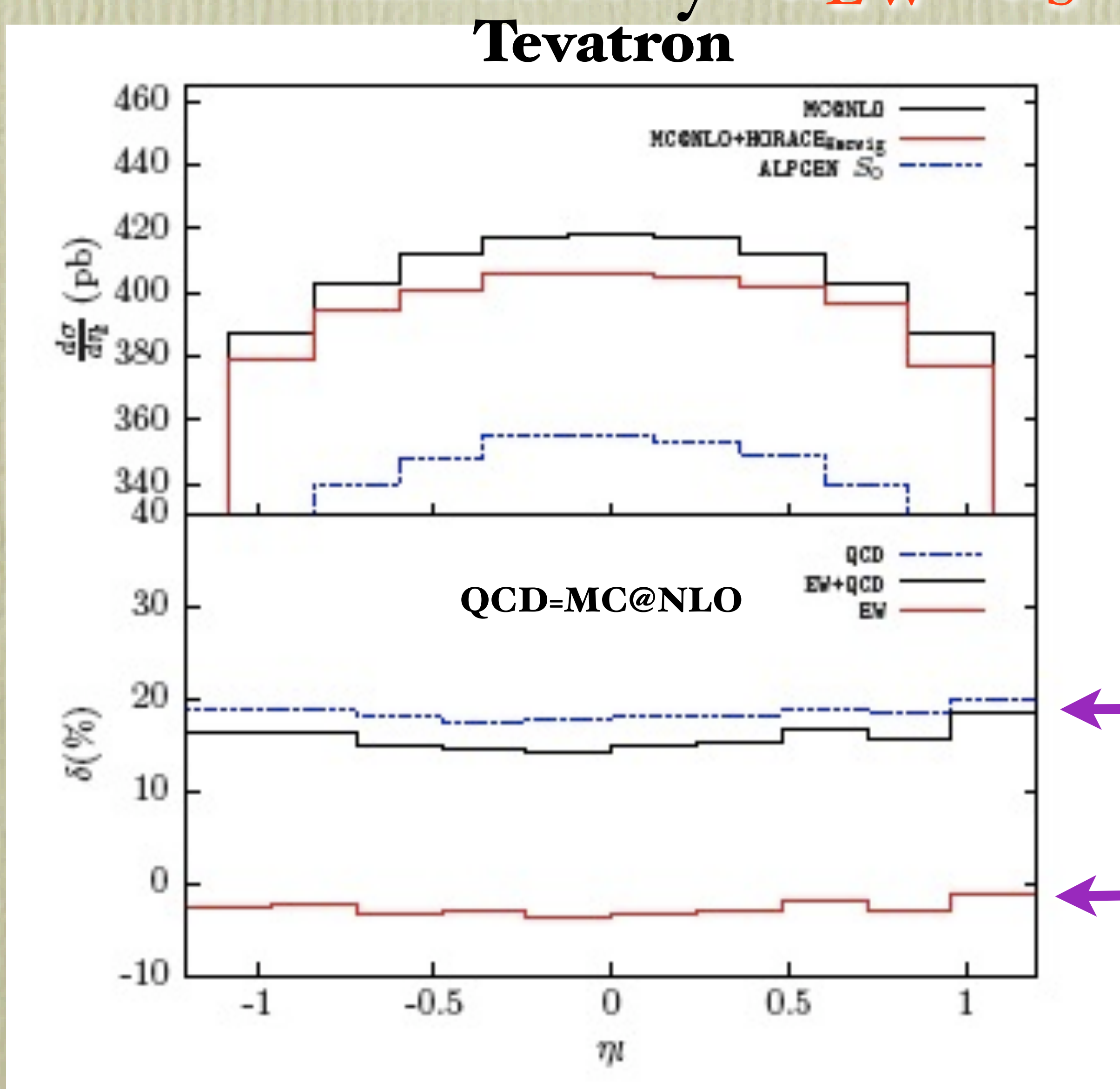
Because the acceptance depends on modeling of the Z boson rapidity, transverse momentum and angular distributions of the electron pairs, it is important to correct for possible model dependences arising from the choice of the event generator or a particular PDF set. The uncorrected acceptance is calculated using the CTEQ5L [9] LO PDFs, and we compare relevant kinematic distributions in the MC simulation to those observed in the data to correct the acceptance for possible observed discrepancies.

While the generated rapidity spectrum is in good agreement with the data for $y < 2$, the data and simulation do not agree at larger values of y. To correct for this discrepancy, we modify the MC generated event spectrum (dN/dy) so that the final accepted MC spectrum matches the spectrum in data, as shown in Fig. 2. A comparison of the reconstructed transverse momentum spectra of the e^+e^- pairs in the data and the MC simulation reveals good agreement as shown in Fig. 3.

- Acceptance computable with NLO/NNLO, as shown before
- Compare rapidity distribution with lepton cuts directly with NNLO simulation code; get acceptance with NNLO code and consistently use same code+PDFs to get inclusive result

EW+QCD corrections

- At %-level, inclusion of EW corrections mandatory: $\alpha_{EW} \sim \alpha_S^2$



Balossini, Carloni Calame, Montagna, Moretti, Nicrosini, Piccinini, Treccani, Vicini, 0907.0276

EW Sudakovs; NB, ameliorated if selection includes EW emissions U. Baur, hep-ph/0611241

$\delta(\%)$	NLO QCD	NLL QCD	NLO EW	Shower QCD	$O(\alpha\alpha_s)$
Tevatron	8	16.8	-2.6	-1.3	~ 0.5
LHC a	-2	12.4	-2.6	1.4	~ 0.5
LHC b	21.8	20.9	-21.9	-0.6	~ 5

LHC
a. $p_\perp^l \geq 25$ GeV $\not{E}_T \geq 25$ GeV and $\lvert\eta_l\rvert < 2.5$
b. the cuts as above $\oplus$ $M_\perp^W \geq 1$ TeV

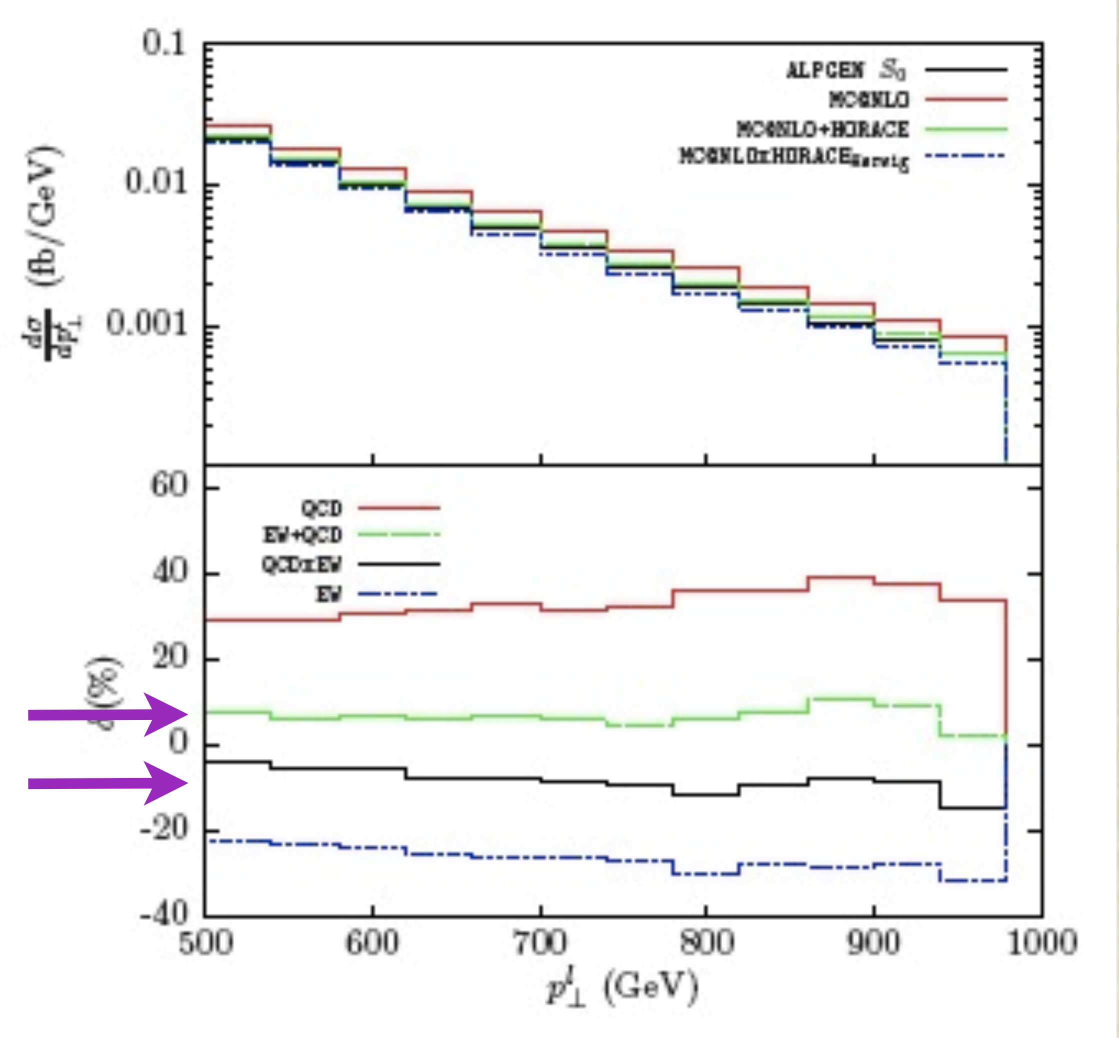
- Tendency for EW corrections to cancel a few percent of QCD correction
- Can be severe for certain cuts

Mixed QCD-EW

- Without exact $O(\alpha\alpha_S)$ corrections, only estimates of their effect

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD\&EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\text{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{LO}}\right\}_{\text{HERWIG PS}}$$

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{[d\sigma/d\mathcal{O}]_{\text{MC@NLO}} - [d\sigma/d\mathcal{O}]_{\text{HERWIG PS}}}{[d\sigma/d\mathcal{O}]_{\text{LO/NLO}}}\right) \times \left\{\frac{d\sigma}{d\mathcal{O}_{\text{EW}}}\right\}_{\text{HERWIG PS}},$$



- Differences in prescription can reach 5% in certain phase-space regions ⇒ calculation would be helpful

Balossini et al., 0907.0276

Conclusions

- Percent-level predictions for inclusive quantities in W, Z production at LHC, Tevatron: **FEWZ, DYNNLO**
- Crucial to include effects of leptonics cuts
- Acceptances accurately predicted at NNLO
- Host of interesting physics measurements: W charge asymmetry, Z rapdity to give $\sin^2\theta$, PDFs
- Still needed: combination of EW, QCD