Theory of W and Z boson production at the Tevatron and LHC

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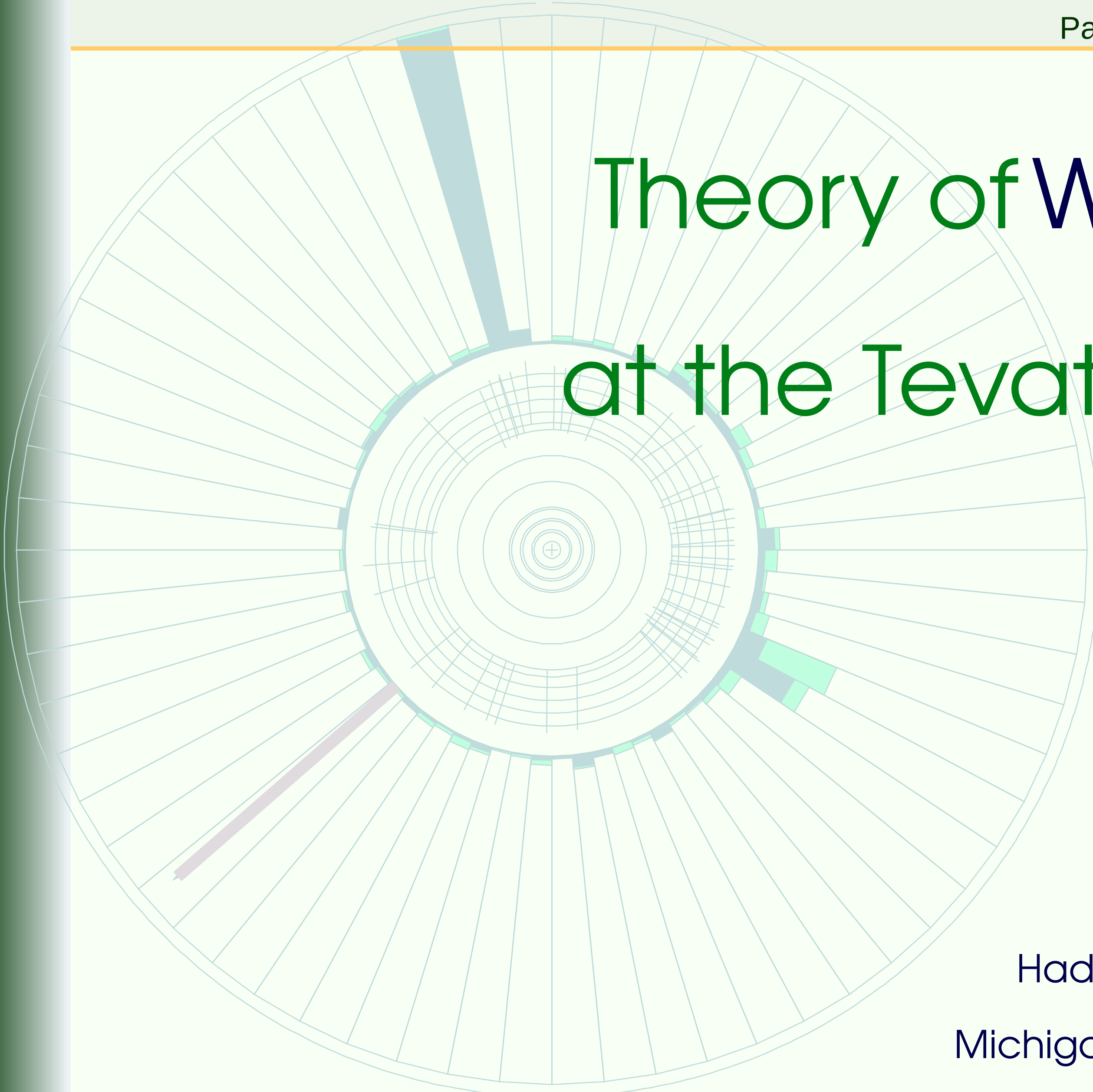


A W-boson event

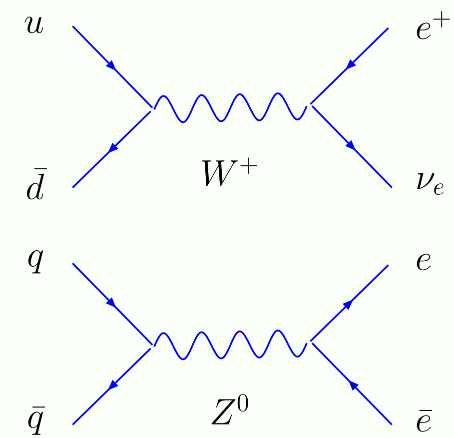
Hadron Collider Physics Conference

Michigan State University, June 15, 2004

"Theoretically clean" features of vector boson production

- Production from quark initial states

  $u\bar{d} \to W, u\bar{u} \to Z, d\bar{d} \to Z$



$\Rightarrow$ parton distribution functions (PDFs) known from deep inelastic scattering

- Decay into easily identifiable leptonic states

  $W \to e\nu, W \to \mu\nu, Z \to e^+e^-, Z \to \mu^+\mu^-$

- Relatively simple (but sizable) QCD radiative corrections

- Relatively small electroweak radiative corrections

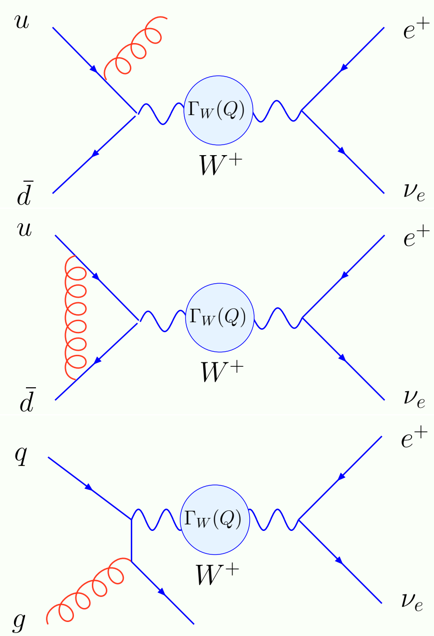
Tevatron and LHC are sensitive to

- initial-state gluons (up to -15% at the LHC)
- recoil from QCD and EW radiation
- Breit-Wigner line shape
- spin correlations between hadrons and leptons
- ...

The framework used in to describe these effects in the Tevatron Run-1 is $\mathcal{O}(\alpha_s)$ QCD with elements of $\mathcal{O}(\alpha)$ EW corrections

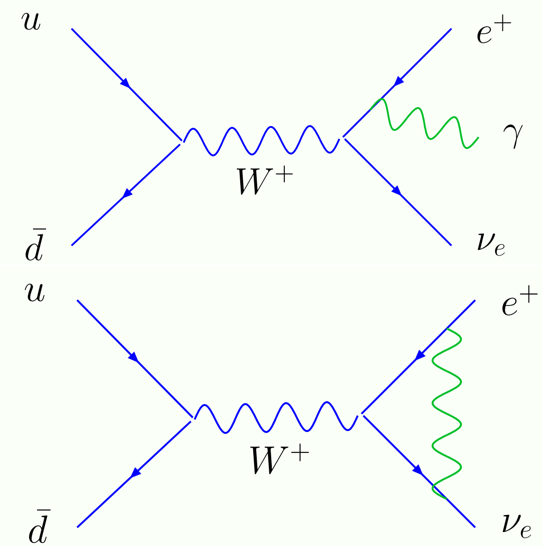
Base theory framework in the Tevatron Run-1

QCD corrections



- Full $\mathcal{O}(\alpha_s)$
- Breit-Wigner propagator with a running width $\Gamma_W(Q)$

Electroweak corrections



- $\mathcal{O}(\alpha)$ QED corrections (γ) to the final state *(Berends, Kleiss; Wagner)*

⇑ Calculated in independent computer programs ⇑

Adequate for comparison to the Run-1 data

Theory requirements for Tevatron Run-2

Experimental targets:

$\delta\sigma_{tot}/\sigma_{tot} \sim 2-3\%$
$\delta M_W \sim 30$ MeV

Many factors contribute at a percent level:

- $\mathcal{O}(\alpha_s^2)$ (NNLO-QCD) corrections
- $\mathcal{O}(\alpha)$ (NLO-EW) corrections
- uncertainties in parton distributions (PDFs)
- power corrections to resummed cross sections

The near-future challenge: consistent and efficient implementation of these effects

Total W and Z cross sections

- Monitors of the beam and parton luminosity at future colliders
  (Dittmar, Pauss, Zurcher; Khoze, Martin, Orava, Ryskin; Giele, Keller)

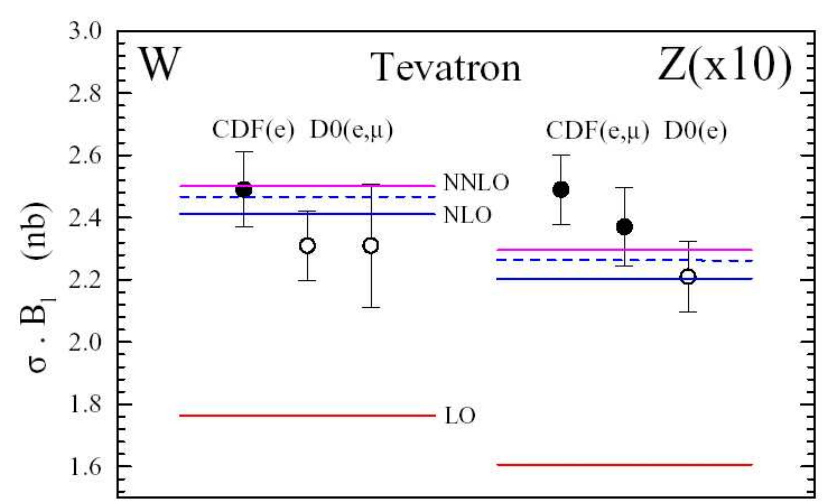
Total cross sections: NNLO QCD corrections

$$\sigma_{tot}(p\bar{p} \to V) = \sum_{partons} \int dx_1 dx_2 f_{a/p}(x_1) f_{b/\bar{p}}(x_2) \hat{\sigma}_{tot}(ab \to V)$$

- NNLO hard cross section $\hat{\sigma}_{tot}(ab \to V)$
  (Hamberg, van Neerven, Matsuura, 1991; Harlander and Kilgore, 2002)
- Partial NNLO results for parton distributions $f_{a/p}(x)$

☞ *Talks by W.-K. Tung and Eric Laenen*

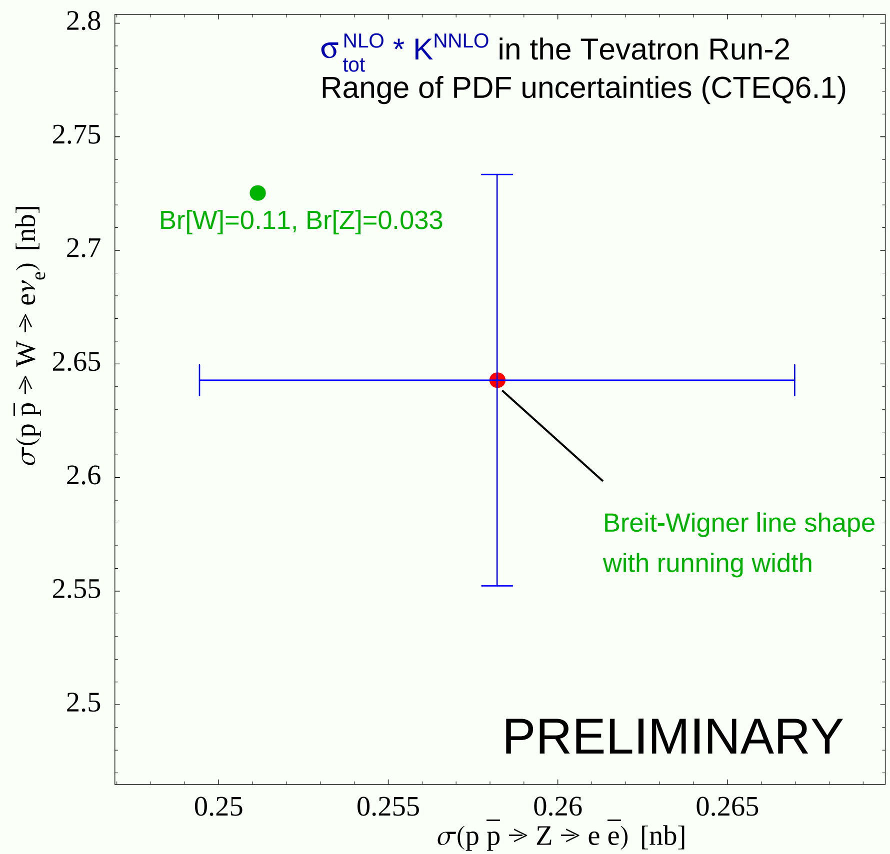
- Scale dependence of order 1%
- NNLO K-factor is about 1.04 at the Tevatron and 0.98 at the LHC *(MRST'03)*



Precision prediction for σ_{tot} depends on understanding of

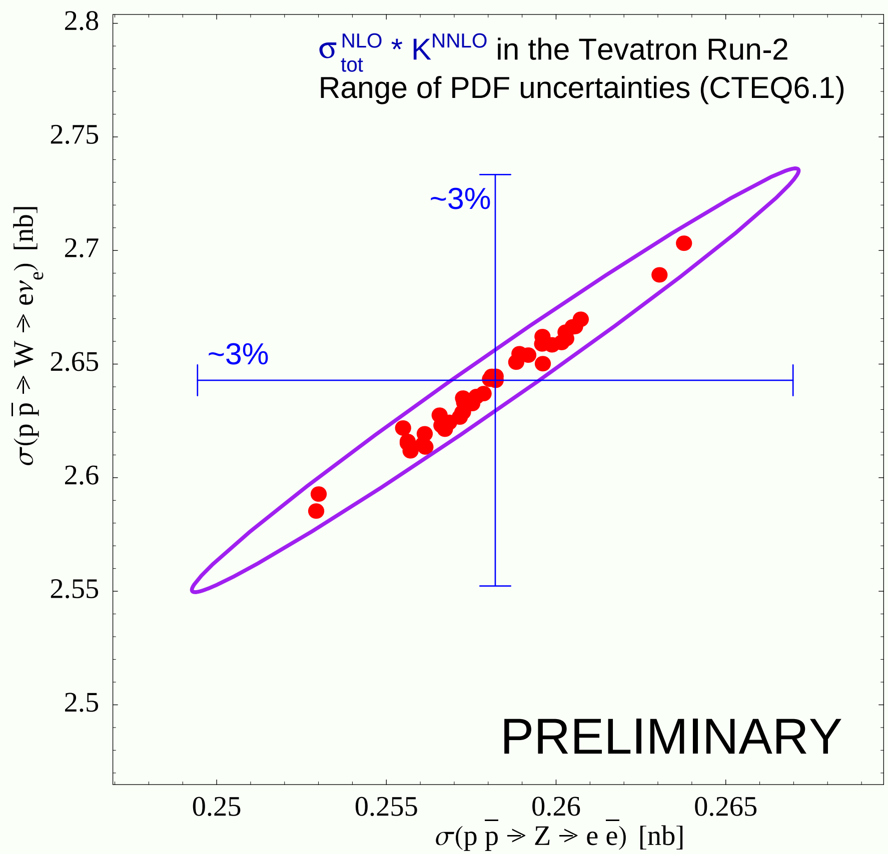
- ❑ uncertainties in PDF's
  ☞ *W.-K. Tung's talk*
- ❑ electroweak effects
  - ♦ tree-level approximaton insufficient!
    ☞ EW corrections, updated EW parameters
- ❑ acceptance

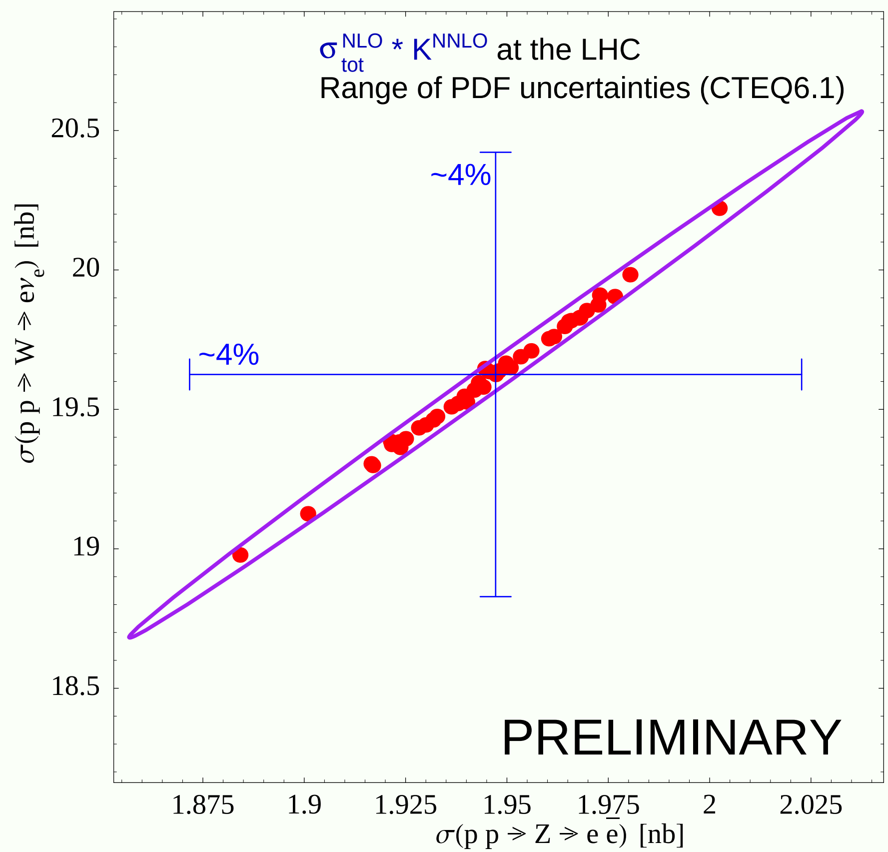
  (Frixione, Mangano, 2004)



Cancellation of PDF uncertainties in $\sigma_{tot}(Z)/\sigma_{tot}(W)$: new results from CTEQ

(Huston, P. N., Pumplin, Stump, Tung, Yuan, 2004)





- In spite of different quark flavors, a measurement of $\sigma(Z)$ will constrain $\sigma(W)$ (and possibly other quark-dominated cross sections)!

Rapidity distributions
and
W charge asymmetry

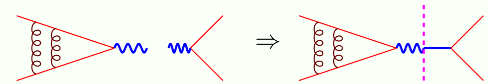
Rapidity distributions at $\mathcal{O}(\alpha_s^2)$

(Anastasiou, Dixon, Melnikov, Petriello, 2004)

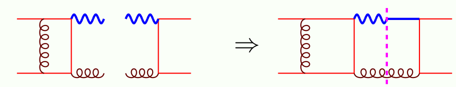
New method for calculation of two-loop cut diagrams

- Transformation of phase space constraints into propagators via unitarity relations
- Recursive reduction to known integrals *(Tkachov; Chetyrkin, Tkachov; Laporta; Gehrmann, Remiddi)*
  - using Lorentz invariance
  - integration by parts

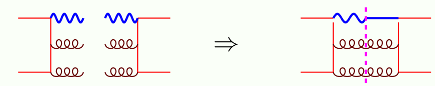
- Virtual-Virtual;



- Real-Virtual;

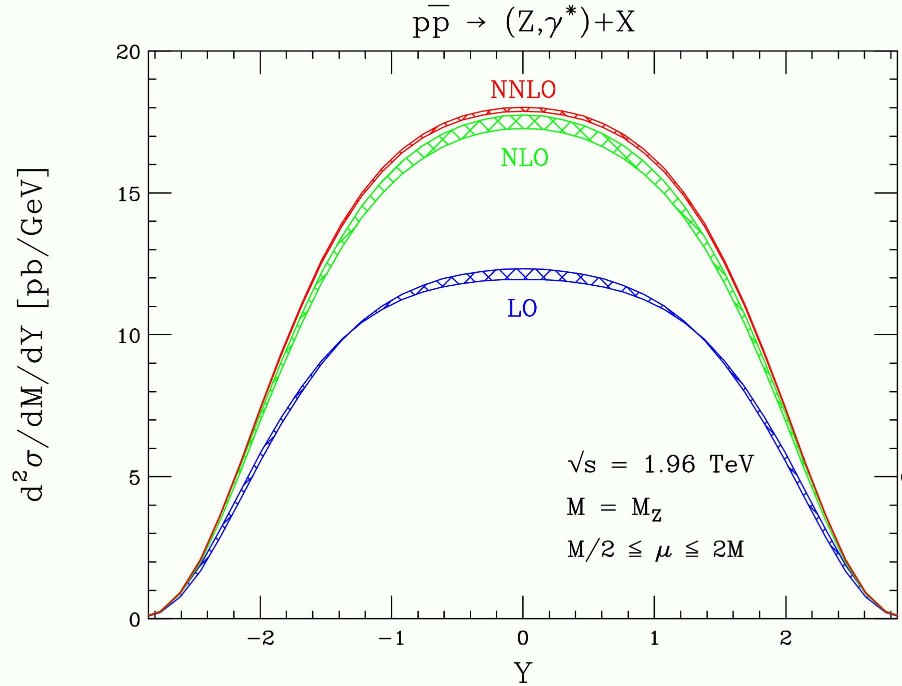


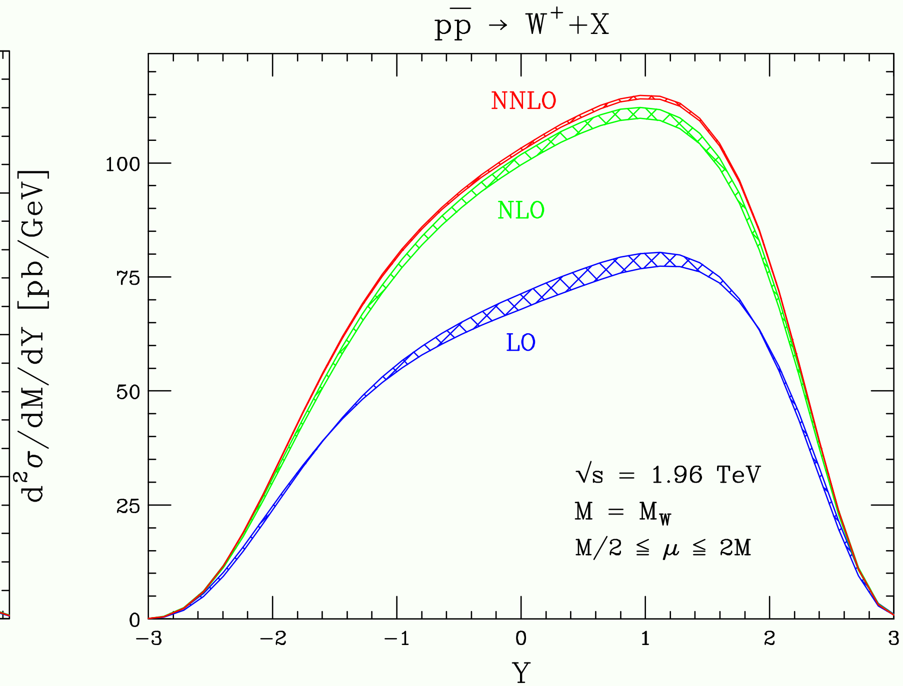
- Real-Real.



- Solution of master integrals with the help of
  - differential equations *(Kotikov; Gehrmann, Remiddi; Bern, Dixon, Kosower)*
  - Mellin-Barnes method *(Smirnov; Tausk)*

NNLO rapidity distributions at the Tevatron





- Tiny scale dependence $(< 1\%)$
- For $|y| < 2$, NNLO leads to a uniform enhancement

$$\sigma_{NNLO} \approx K \cdot \sigma_{NLO}$$

$K(Z) \sim 3 - 5\%$, $K(W) \sim 2.5 - 4\%$

- Larger corrections in forward regions

Charge lepton asymmetry

$$A_{ch}(y_e) \equiv \frac{\frac{d\sigma^{W^+}}{dy_e} - \frac{d\sigma^{W^-}}{dy_e}}{\frac{d\sigma^{W^+}}{dy_e} + \frac{d\sigma^{W^-}}{dy_e}}$$

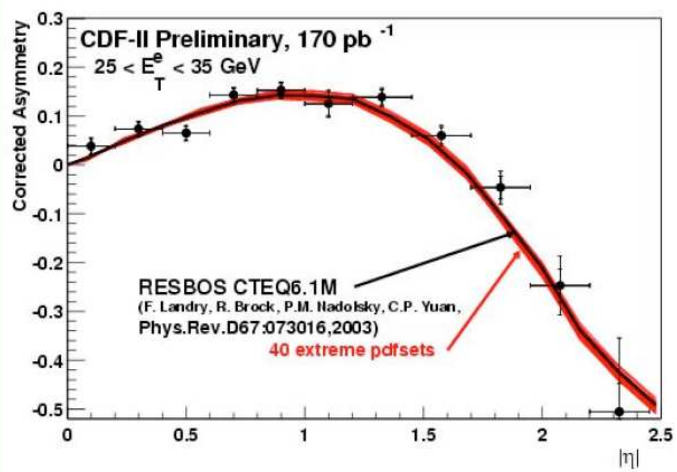
- related to the boson Born-level asymmetry (y_W=rapidity of W)

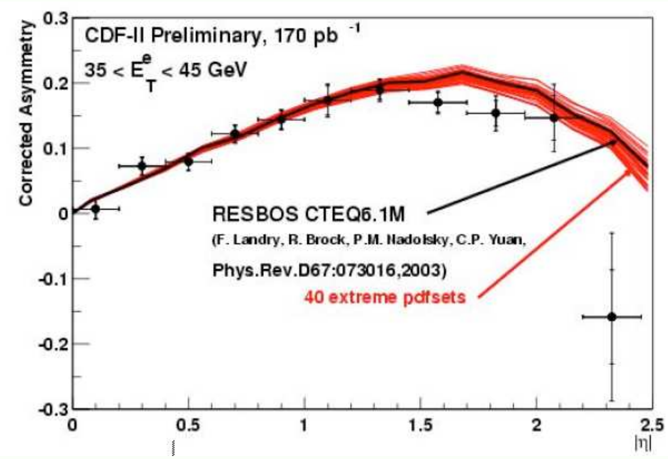
$$A_{ch}(y_W) \stackrel{y_W \to y_{max}}{\longrightarrow} \frac{r(x_b) - r(x_a)}{r(x_b) + r(x_a)}, \; r(x) \equiv \frac{d(x, M_W)}{u(x, M_W)}$$

- constrains the PDF ratio $d(x, M_W)/u(x, M_W)$ at $x \to 1$
- In experimental analyses, a selection cut $p_{Te} > p_{Te}^{min}$ is imposed

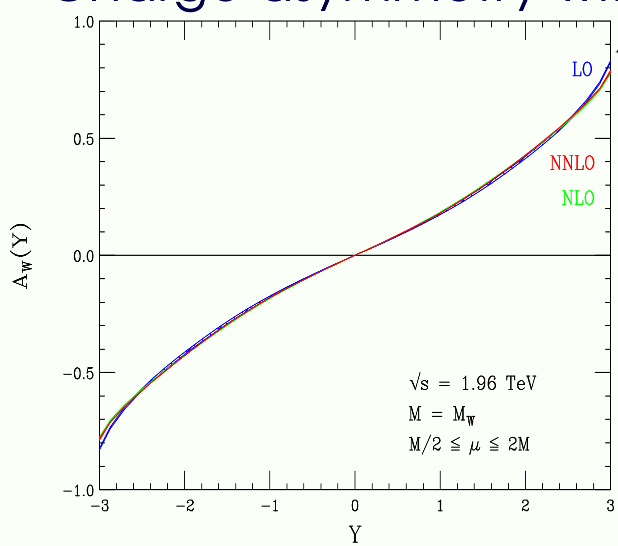
Charge asymmetry: CDF Run-2 vs. CTEQ6.1 and ResBos

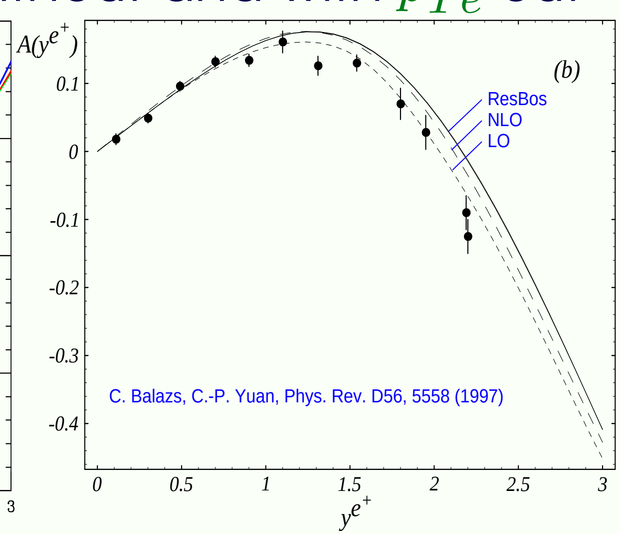
(Stump et al; Balazs, Yuan; Brock, Landry, P. N., Yuan)





Charge asymmetry without and with p_{Te} cut





- p_{Te} cut introduces dependence of $A_{ch}(y_e)$ on QCD corrections

Measurement of W boson mass M_W and width Γ_W

- Test of the standard model (SM)

Standard model relates M_W, top mass m_t, and Higgs boson mass M_H:

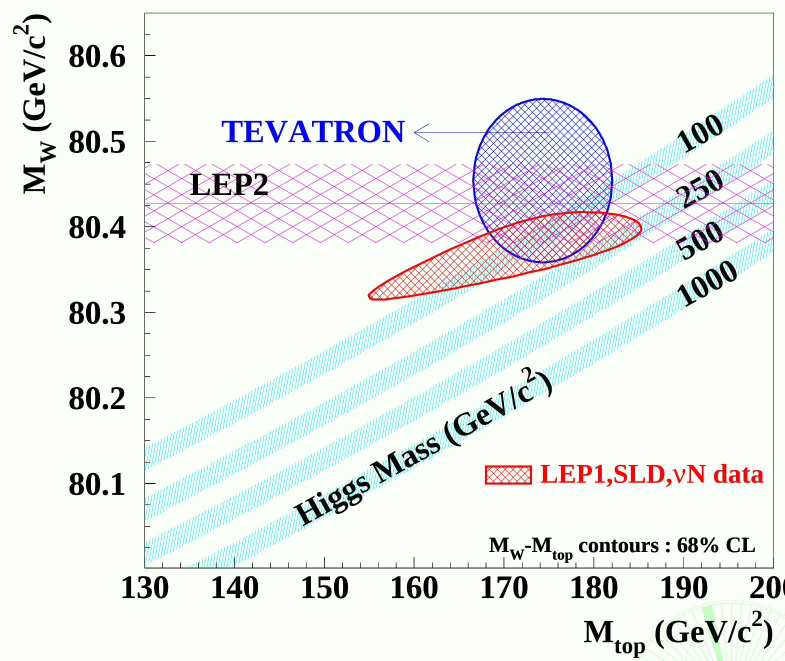
☞ S. Dawson's talk

$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\text{ GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\text{ GeV}}\right)$$
$$+0.543\left(\left(\frac{m_t}{175\text{ GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha_{had}^{(5)}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$

- Measurement of M_W and m_t constrains $\log M_H$ in SM

$$\left.\begin{array}{c}\delta M_W \sim 30\text{ MeV}\\ \delta m_t \sim 2\text{ GeV}\end{array}\right\} \Rightarrow \frac{\delta M_H}{M_H} \sim 35\%$$

- Measurement of M_W, m_t and M_H tests consistency of SM



Observables sensitive to M_W

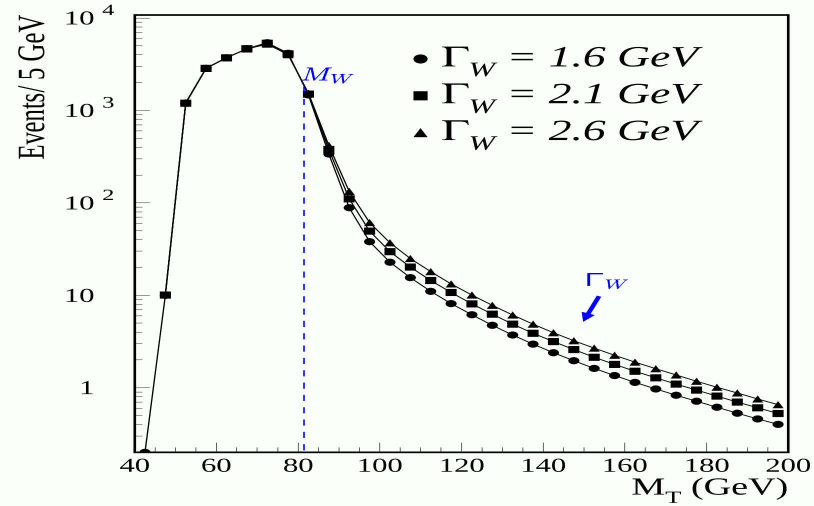
1. Leptonic transverse mass

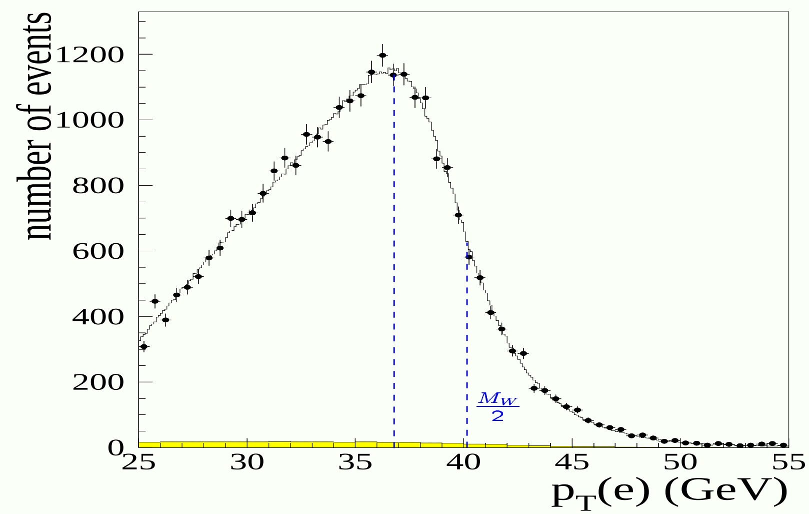
   (Smith, van Neerven, Vermaseren, 1983)

   $$M_T^{\ell\nu} \equiv 2\,|\vec{p}_{Te}|\,|\vec{p}_{T\nu}| - 2\,(\vec{p}_{T\ell} \cdot \vec{p}_{T\nu})$$

   Sensitivity region

   - M_W: $M_T^{\ell\nu} \sim 60 - 100$ GeV
   - Γ_W: $M_T^{\ell\nu} > 100$ GeV





2. Transverse momentum of the charged lepton ($p_{T\ell}$)
   - M_W : $p_{T\ell} \sim 35 - 45$ GeV

3. p_T of the neutrino ($\not{E}_T$)

4. $M_T^{e\nu}(W)/M_T^{\ell\bar{\ell}}(Z)$ *(Rajagopolan, Rijssenbeek; Giele, Keller; Shpakov)*

5. $\sigma_{tot}(W)/\sigma_{tot}(Z)$ *(R. Brock et al., 2001)*

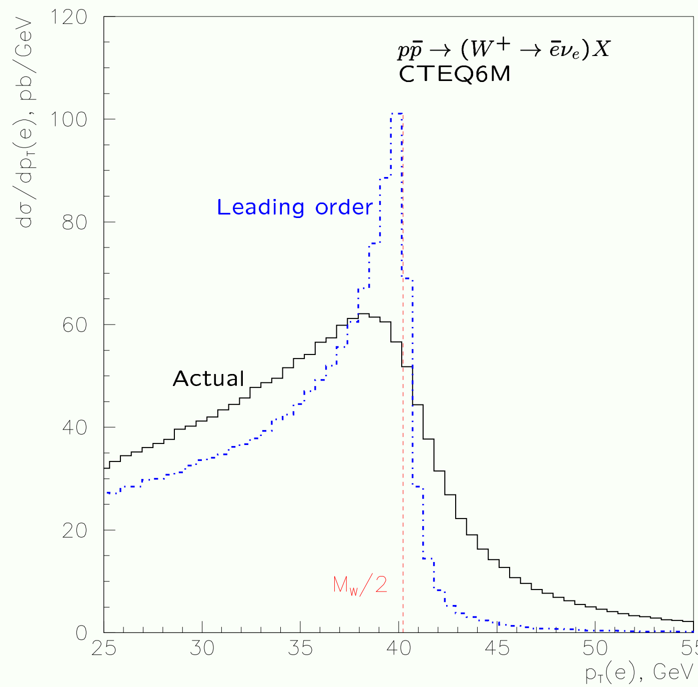
Determination of M_W from distributions of transverse momenta

Kinematical (Jacobian) peaks...
...located exactly at M_W ($M_W/2$)
at Born level

...smeared by EW and QCD radiation

...sensitive to

- EW radiative corrections
- PDF parametrizations
- the shape of q_T distributions

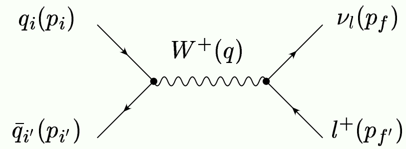


⇑ Sources of the largest theory uncertainties on M_W (tens of MeV) in Run-1

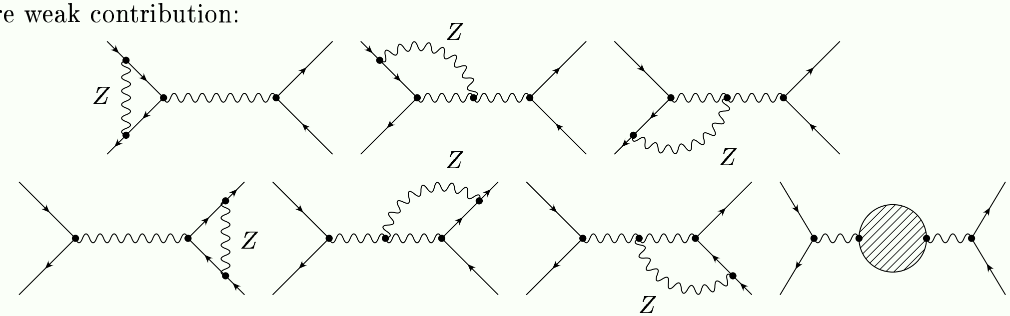
NLO electroweak corrections to W boson production

(S. Dittmaier, M. Krämer, 2002; U. Baur, D. Wakeroth, 2004)

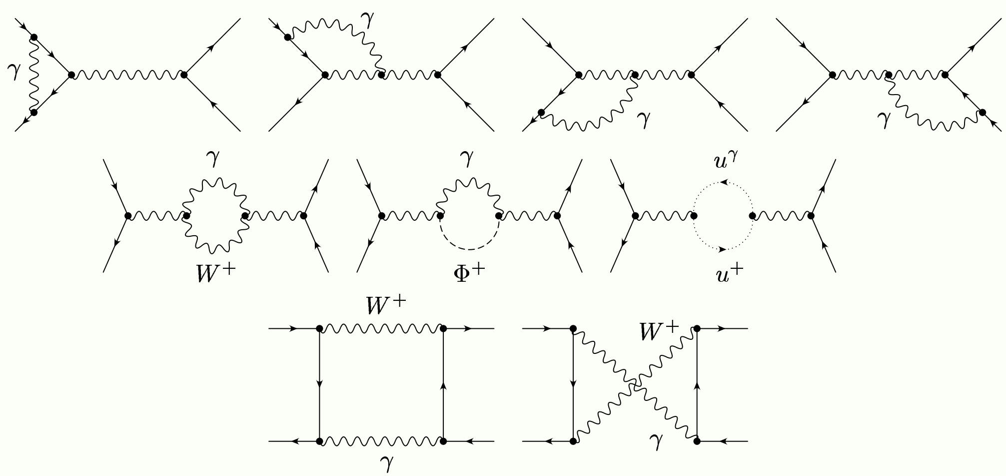
Born-diagram:



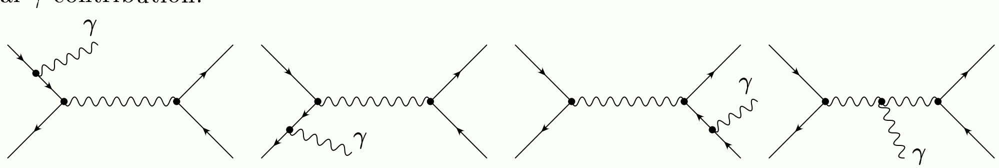
pure weak contribution:



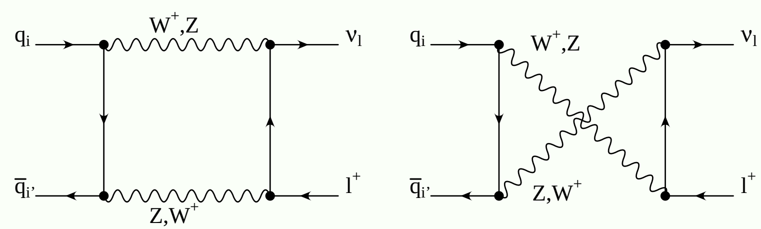
virtual γ contribution:



real γ contribution:

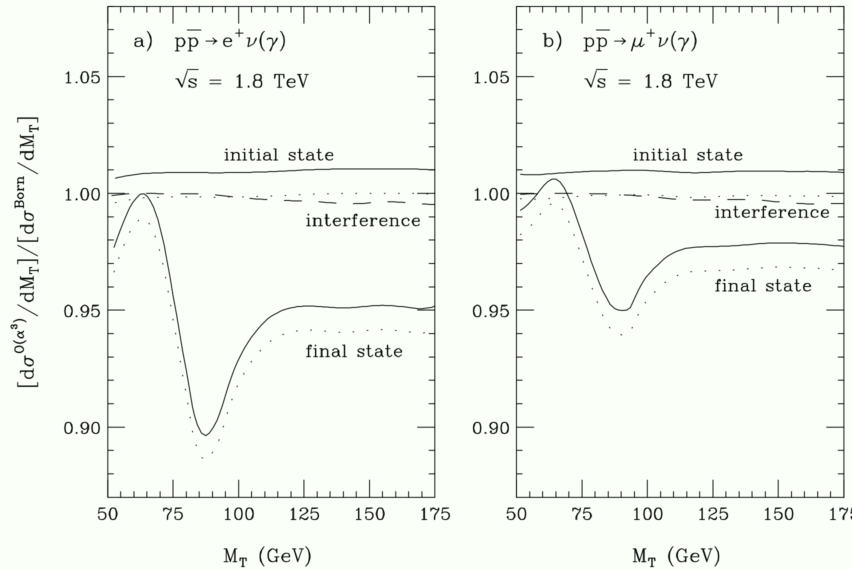


W & Z box diagrams

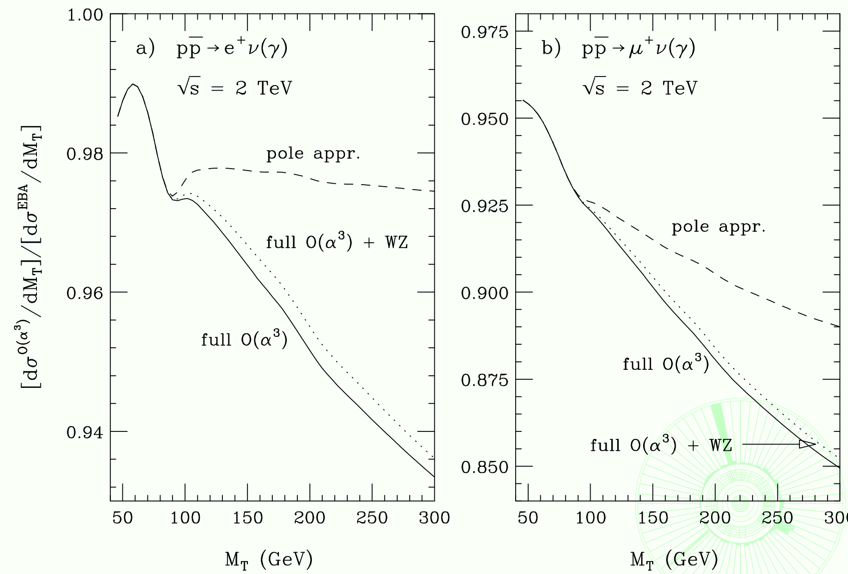


Hierarchy of electroweak radiative corrections

- ❑ Effective Born approximation (EBA)
  - ♦ used in QCD programs in Run-1
- ❑ NLO corrections in the pole approximation
  - ♦ large effect at $Q \sim M_V$
  - ♦ Can be classified into initial-state, final-state, and interference terms
  - ♦ Final-state QED radiation dominates *(Baur, Keller, Wakeroth, 1998)*
- ❑ Full NLO (including non-resonant terms)
  - ♦ required at $Q \gg M_V$
- ❑ Radiation of two *(Baur, Stelzer, 2000)* and many photons *(Placzek, Jadach, 2003; Carlone Calame et al., 2003)*



$\delta M_W^{EW} = -65 \pm 20$ MeV and -168 ± 10 MeV in the electron and muon channels



Factorization at small q_T (resummation)

☞ E. Laenen's talk

Relevant momentum scales:

$$Q^2 \gg 1\ \text{GeV}^2,\ q_T \ll Q,\ x \sim 1$$

Trouble:

The series $\frac{1}{q_T^2}\alpha_S^n \ln^m \frac{q_T^2}{Q^2}$, $m = 0, ..., 2n-1$ lose convergence

Solution: summation of logarithms through all orders of α_S

q_T resummation: mainstream approaches

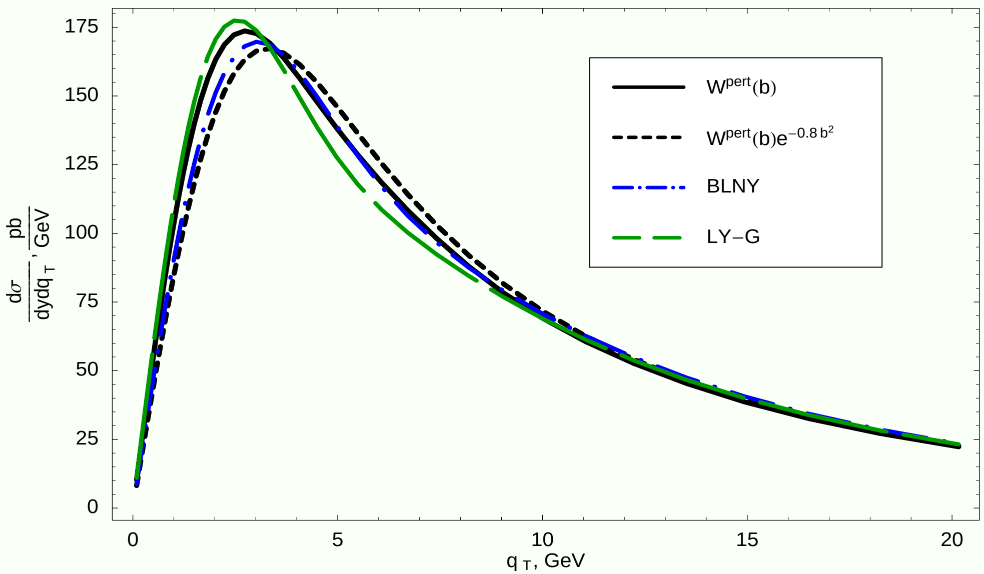
- Formalism in impact parameter (b) space *(Collins, Soper, Sterman)*
  - theory symmetries preserved automatically
  - conservation of momentum
  - fast and accurate evaluation of Fourier-Bessel transform possible *(ResBos, Balazs, P. N., Yuan)*
- Formalism in q_T space *(Altarelli, Ellis, Greco, Martinelli; Ellis, Ross, Veseli)*
  - straightforward identification of logs for matching with the fixed-order result

Recent developments

- Hybrid methods:
  - analytical evaluation of Fourier-Bessel transform *(Kulesza, Stirling)*
  - threshold-q_T resummation *(Kulesza, Sterman, Vogelsang)*
  - q_T resummation for c, b quarks in a variable-flavor number (ACOT) scheme *(Berge, P. N., Olness)*
    - flavor dependence of W and Z cross sections
  - q_T resummation with small-x effects *(Berge, P. N., Olness, Yuan)*
    - broadening of $d\sigma/dq_T$ at the LHC
- Structure of the resummed form factor
  (Collins, Soper; CSS; Catani, de Florian, Grazzini)
- Application to polarized W and Z production at RHIC
  (Weber; P. N., Yuan)

Sensitivity of q_T cross sections to nonperturbative contributions

Resummed $d\sigma/dq_T^2$ is expected to include a universal nonperturbative function $S_{NP}(b,Q)$ (analogous to universal PDF's)



Comparison of models for nonpert. terms (b_* and extrapolation)

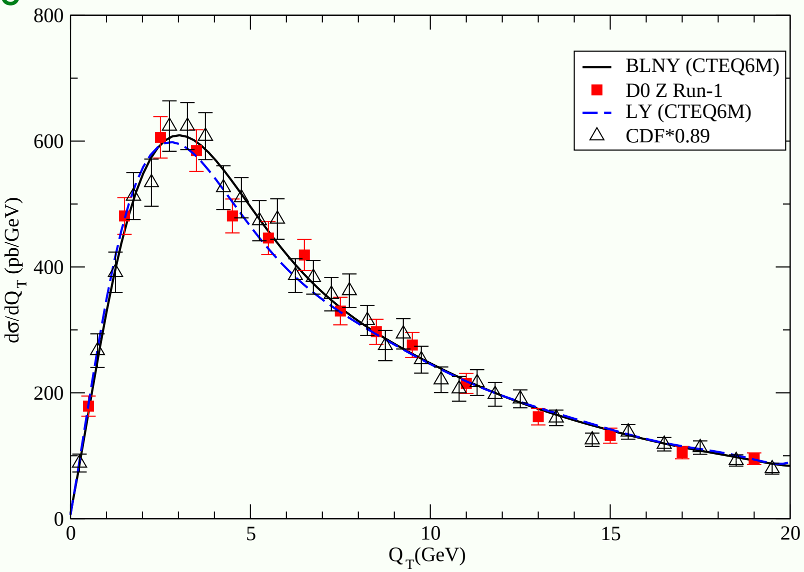
$S_{NP}(b,Q)$ is non-negligible in any non-pert. model at $q_T < 10$ GeV

Variation of non-pert. terms moves the peak of $d\sigma/dq_T$ by 200-500 MeV

- Valid models for $S^{NP}(b,Q)$ must provide accuracy comparable to $\delta M_W \sim 30$ MeV

Models for nonperturbative contributions

- b_* anzatz *(CSS, 1985)*
  - simultaneous agreement with all fixed-target Drell-Yan and Z^0 boson data *(Landry, Brock, P. N., Yuan, 2002)*
  - strong evidence for universality of $S_{NP}(b, Q)$



BLNY result vs. Run-1 Z data

- freezing $\alpha_s(\mu)$ at $\mu \sim \Lambda_{QCD}$
- renormalon analysis *(Korchemsky, Sterman, 1995)*
- extrapolation of leading power terms *(Qiu, Zhang, 2000)*
- principal value resummation *(Sterman; Kulezsa, Sterman, Vogelsang, 2002)*
- dispersive equations *(Guifanti, Smye, 2000)*
- k_T-dependent factorization *(X. Ji, J. Ma, F. Yuan, 2004)*

In all models, incalculable power correction terms are required for agreement with data ($\sim$ exp$\{-gb^2\}$, with $g \sim$ 0.8 (2.7) in extrapolation (b_*) model)

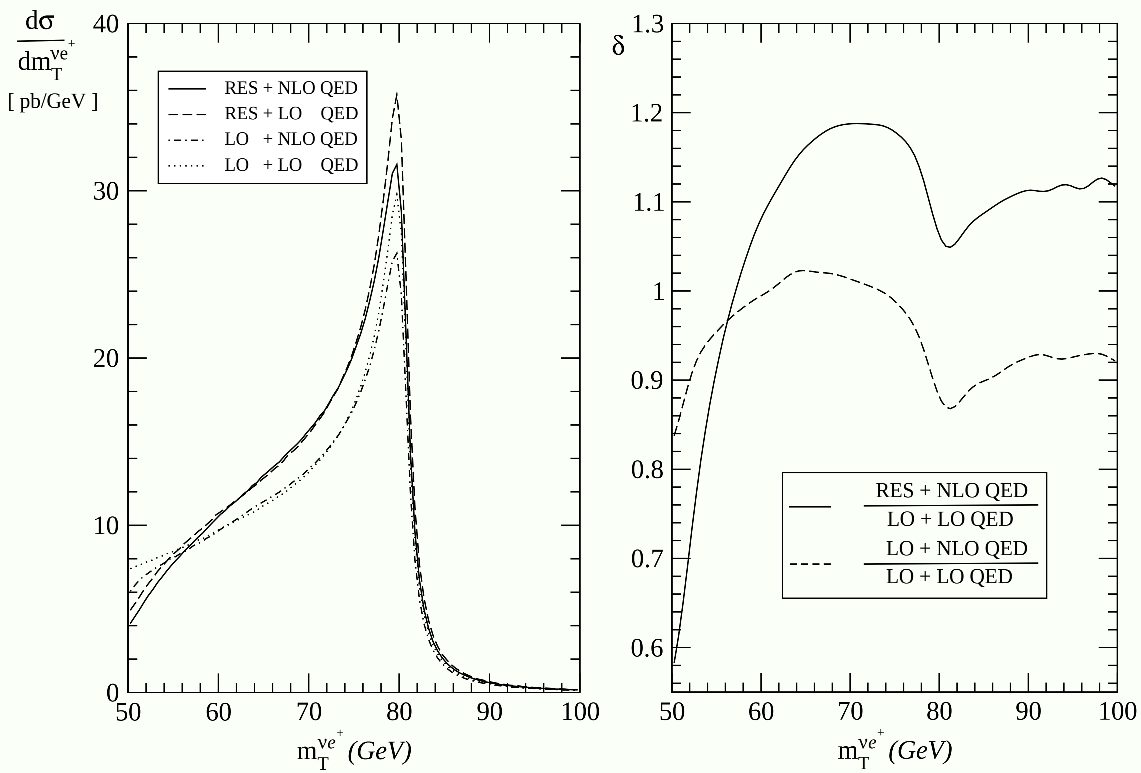
Combined effects of electroweak corrections, resummation, and PDF uncertainties

(Active ongoing work)

QCD resummation + final-state QED radiation

(Q. Cao, C.-P. Yuan, 2004)

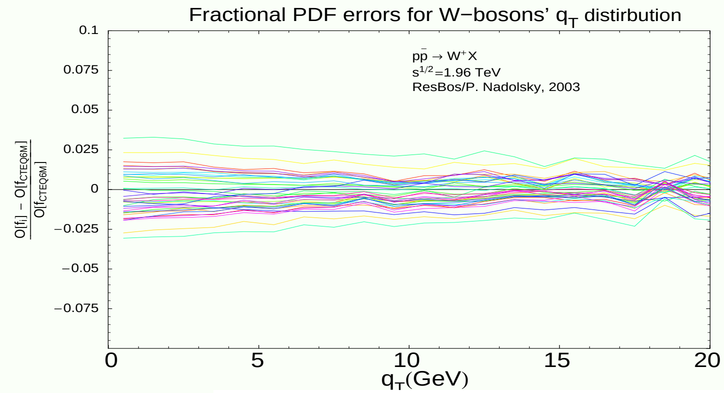
- New version of the resummation program ResBos (ResBos-A)
- Includes the dominant EW contribution from final-state QED radiation
- Without detector smearing, QCD and QED corrections to M_T are of similar magnitude and opposite sign



Detector smearing reduces QED correction without strong effect on QCD corrections

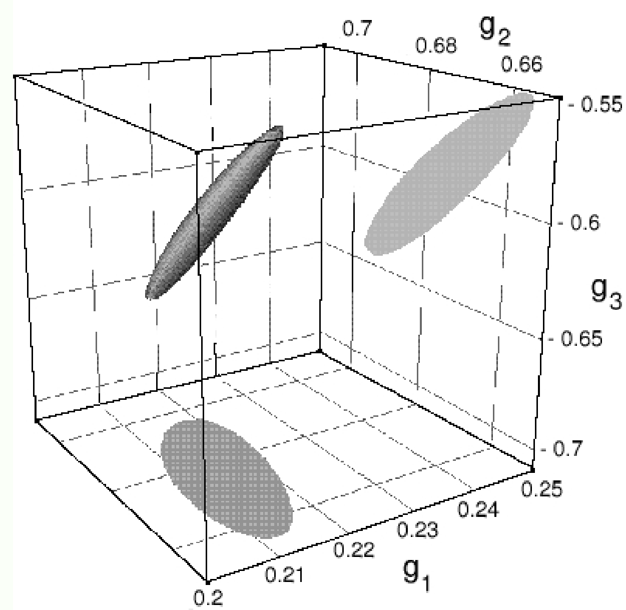
CTEQ error analysis for W and Z observables

(Huston, P. N., Pumplin, Stump, Tung, Yuan, in progress)



1. Effect of PDF uncertainties on W and Z distributions

2. Nonperturbative corrections to q_T distributions
   - explore form and universality of $S_{NP}(b, Q)$
   - determine "tolerance range" for $S_{NP}(b, Q)$ and uncertainties in $d\sigma/dq_T$, etc.



3. Simultaneous global analysis of PDF's and q_T distributions
   - correlated errors for the PDF's and $d\sigma/dq_T$

Vector boson production as the background for new physics

- Searches for contact interactions, W' and Z', extra dimensions...

- WW and ZZ production
  - background for heavy Higgs production ($M_H > 160$ GeV)

- $\gamma\gamma$ production:
  - background for light Higgs production ($M_H \sim 120 - 140$ GeV)
  - soft gluon radiation in gg channel
  - photon fragmentation contributions

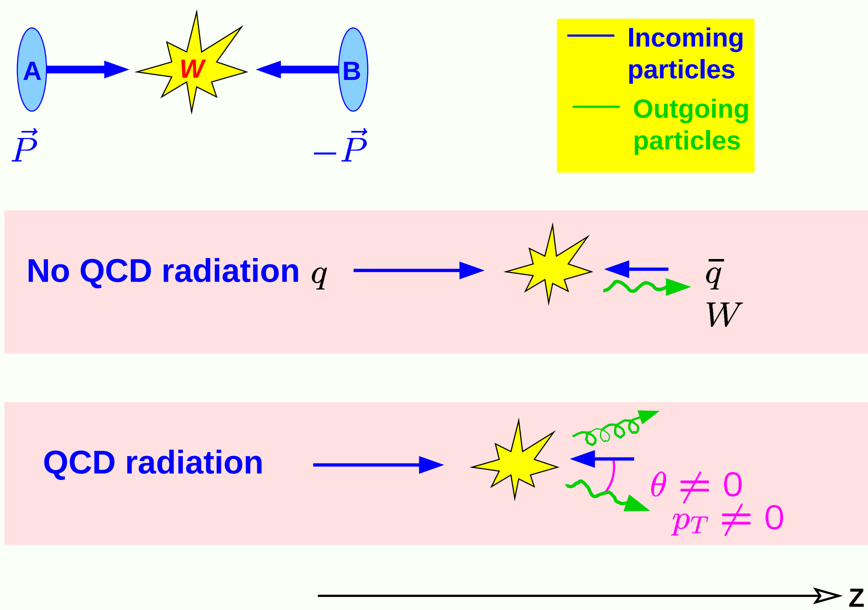
Conclusions

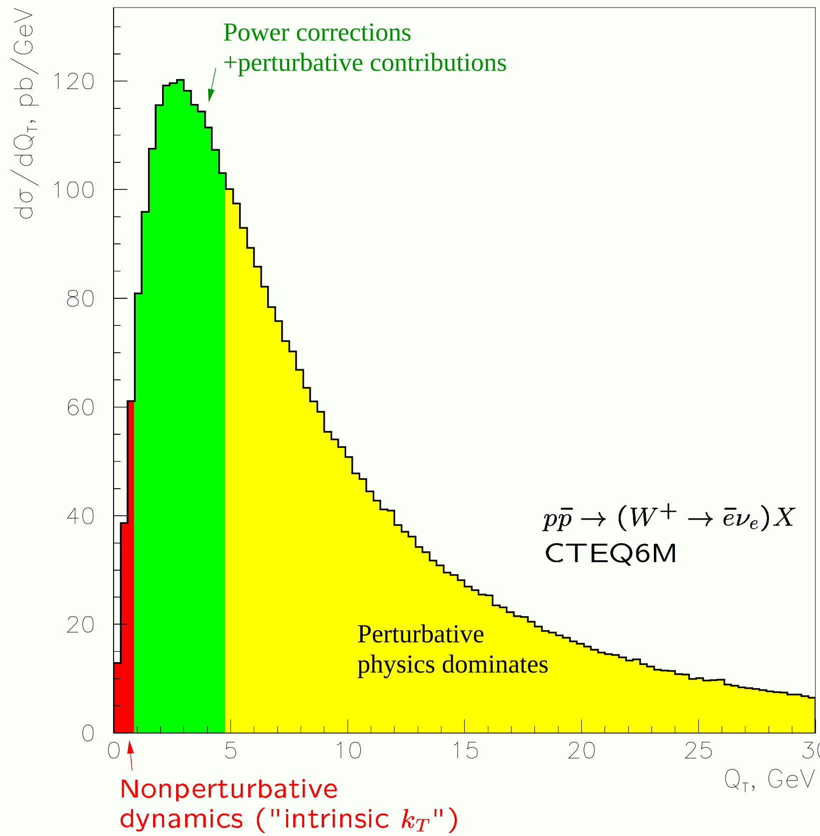
1. NNLO for σ_{tot} & rapidity distributions
   - ❑ global effect: rescaling of σ_{NLO} by $K \sim 2.5 - 5\%$
   - ❑ full NNLO is needed to describe details (forward rapidity, high p_T, angular distributions (?))
2. Requirements for the Tevatron Run-2 and LHC ($\delta \sim 1\%$)
   - ❑ Simultaneous implementation of leading NNLO-QCD and NLO-EW effects
   - ❑ Reduction of uncertainties in nonperturbative inputs (PDF's, p_T power corrections)
   - ❑ Correlated theory uncertainties (PDF's vs. p_T)
   - ❑ Attention to minor details: old electroweak parameters or low computer accuracy can now make big difference!

Backup slides

q_T resummation for vector boson production

Resummation: W boson production at the Tevatron





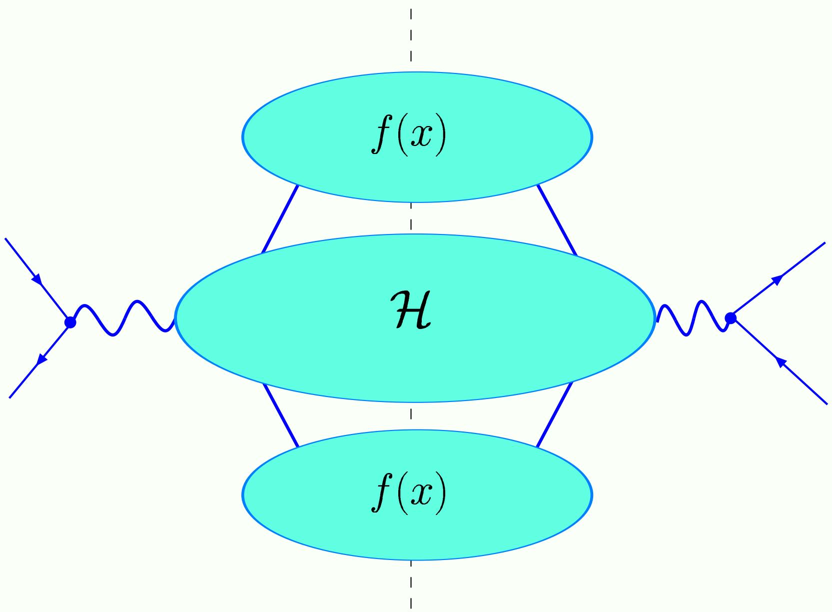
Needed to precisely measure W-boson mass

Resummation describes all q_T range in one unified framework

QCD factorization in hard and soft regions (CSS)

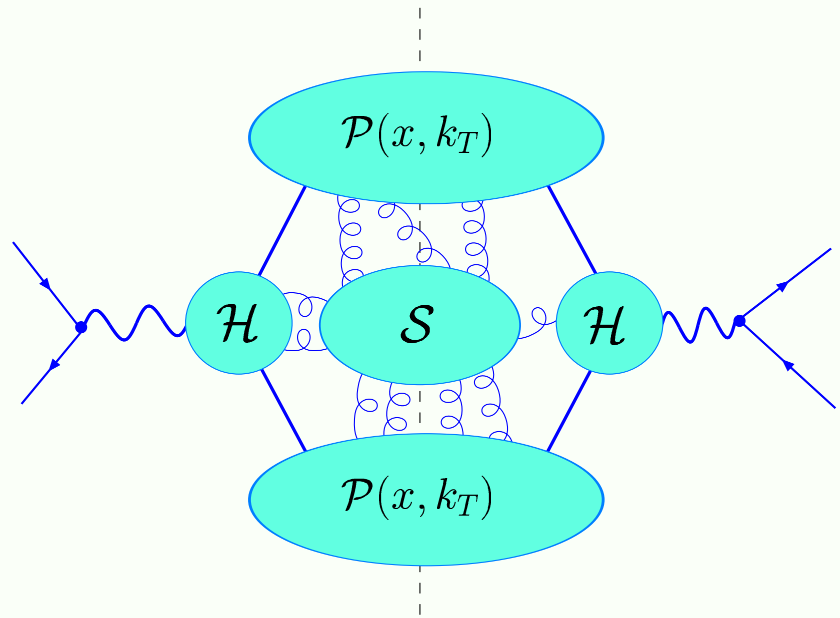
Finite-order (FO) factorization

$\Lambda^2_{QCD} \ll q_T^2 \sim Q^2$

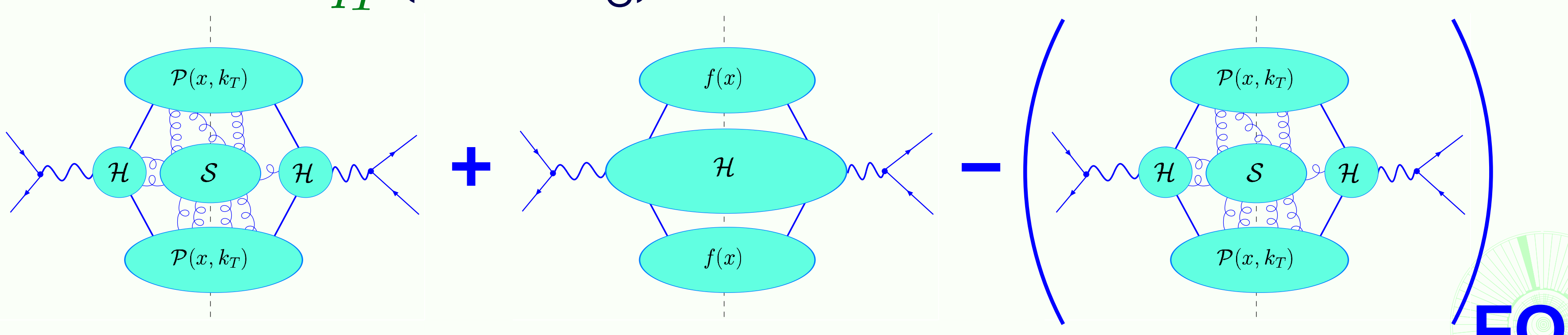


Small-q_T factorization

$\Lambda^2_{QCD} \ll q_T^2 \ll Q^2$



Solution for all q_T (matching):



Factorization at $q_T \ll Q$

Realized in the space of the impact parameter b (conjugate to q_T)

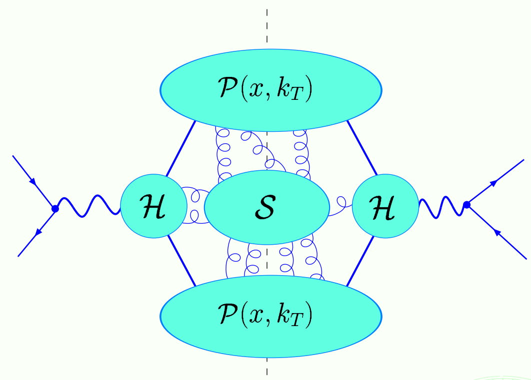
$$\left.\frac{d\sigma_{AB\to VX}}{dQ^2 dy dq_T^2}\right|_{q_T^2 \ll Q^2} = \sum_{a,b=g,\overset{(-)}{u},\overset{(-)}{d},\ldots} \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} \widetilde{W}_{ab}(b, Q, x_A, x_B)$$

In the perturbative region ($b \ll 1$ GeV^{-1}):

$$\widetilde{W}_{ab}(b, Q, x_A, x_B) = \sum_j \left|\mathcal{H}_j\right|^2 e^{-\mathcal{S}(b,Q)} \overline{\mathcal{P}}_a(x_A, b)\overline{\mathcal{P}}_b(x_B, b)$$

$\mathcal{H}_j$ is the hard vertex, $\mathcal{S}$ is the soft (Sudakov factor),
$\overline{P}_a(x,b)$ is the unintegrated PDF,

$$\overline{\mathcal{P}}_a(x,b) = \int d^{n-2}\vec{k}_T e^{-i\vec{k}_T\cdot\vec{b}} \mathcal{P}_a(x, \vec{k}_T)$$



$\overline{P}_a(x,b)$ factorizes as

$$\overline{\mathcal{P}}_a(x,b) \equiv \sum_{i=g,u,d\ldots} \left[\mathcal{C}_{ai} \otimes f_i\right](x_A, \mu_F, b)$$

$S(b,Q)$, $\overline{\mathcal{P}}_a(x,b)$, and $\mathcal{C}_{ai}(x_A, \mu_F b)$ are calculable in perturbative QCD