# Fisica con $W$ e $Z$, Pdf's

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V Workshop italiano sulla Fisica $p$-$p$ a LHC
Perugia, 30/1 - 2/2, 2008

# Sommario

- C.M. Carloni Calame: "The theory side of $W/Z$ Physics and PDFs"
  - ⋆ Introduzione e motivazioni
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- S. Diglio: "Parton Density Functions after HERA, prospect of measurement at LHC"
  - ⋆ Stato delle PDF dopo HERA
  - ⋆ Incertezze sulle PDF e misure di $W/Z$
  - ⋆ Input di LHC per le PDF
- M. Malberti: "Commissioning della fisica con $W/Z$"
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- Tutti: discussione

# The theory side of $W/Z$ Physics and PDFs

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# Outline

- Relevance of DY processes for LHC Physics
- PDF and hard scattering cross section
- Tools and calculations for DY physics
  - ⋆ QCD corrections
  - ⋆ EW corrections
  - ⋆ implementation in Monte Carlo EG
- PDF, a non-expert point of view
  - ⋆ PDFs errors
  - ⋆ Theoretical uncertainties
- Conclusions

# Drell-Yan processes at hadron colliders

- easy detection: high $p_\perp$ leptons pair or lepton+missing $p_\perp$ (tipically look for $p_\perp > 25$ GeV in the central detector region)
- large cross sections. At LHC:
  - $\sigma(W) = 30\ nb$ , i.e. $3 \times 10^8$ events with $\mathcal{L} = 10\ fb^{-1}$
  - $\sigma(Z) = 3.5\ nb$ , i.e. $3.5 \times 10^7$ events with $\mathcal{L} = 10\ fb^{-1}$
  - no statistics limitations for precision physics
- main physics motivations (DY processes are considered “standard candles”)
  - ⋆ detectors calibration
  - ⋆ PDF validation and constraint
  - ⋆ $W$ mass and $\Gamma$ measurement
  - ⋆ collider luminosity monitoring (as done at LEP with Bhabha)
  - ⋆ background to New Physics searches
- Precise theoretical prediction are strongly required

# Theoretical cross section at hadron colliders

$$\sigma^{\text{theory}} = \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times \\ \times \int_\Phi d\sigma^h_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2)$$

- it relies on *factorization theorems*
- $f_{c,H}$ $(c = u, \bar{u}, d, \cdots, g, \cdots)$ are the PDFs of hadron $H$.
- $d\sigma^h_{a,b}$ describes the hard parton-parton process, improved by adding higher-order radiative corrections
  - ⋆ $\mathcal{O}(\alpha_S)$ (QCD NLO), $\mathcal{O}(\alpha_S^2)$ (QCD NNLO)
  - ⋆ $\mathcal{O}(\alpha)$ (EW NLO)
  - ⋆ combination EW⊗QCD
  - ⋆ Parton Shower

⋆ complex interplay of different sources of (theoretical and experimental) errors

# Linking theory and experiment

$$\sigma^{\text{exp}} \equiv \frac{1}{\int \mathcal{L} dt} \frac{N^{obs} - N^{bkg}}{A\ \epsilon} = \sigma^{\text{theory}} \equiv \sum_{a,b} \mathcal{P}_{ab} \sigma^h_{a,b}$$

With DY processes, we can

- monitor the collider luminosity, the parton luminosities, measure the PDFs
  - ⋆ relevant observables: total cross section, $W$ and $Z$ rapidity distribution, lepton(s) rapidity distribution
  - ⋆ an accuracy of $\mathcal{O}(1\%)$ is required/achievable

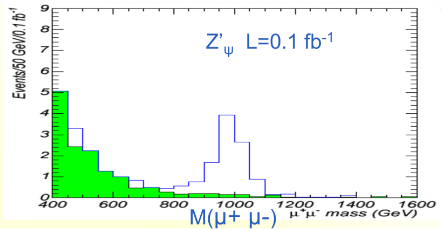
Frixione & Mangano '04 and refs. therein

- measure the $W$ mass and width from $M_T^W$ distribution
- discover deviations from SM physics in the distribution tails

# Background to New Physics

## DY as background to the searches of new heavy gauge bosons

from Menici's talk at IFAE 2006




- new heavy gauge bosons decay into lepton pairs
- if existing → clear signal even at low luminosity
- if not detected, SM-DY represents the main background whose precise estimate allows to put the correct lower bounds
  → need to control the background at per cent level

Is the SM prediction at large invariant masses under control ?

# Parton Shower Event Generators

- widely popular EG are **HERWIG**, **PYTHIA**, **ISAJET** and **ARIADNE**

G. Corcella et al., JHEP 0101 (2001) 010

T. Sjostrand et al., hep-ph/0308153

F.E. Paige et al., hep-ph/9810440

L. Lonnblad, CPC 71 (1992) 15

- based typically on LO ME for $2 \to 1$ or $2 \to 2$
- they provide a complete (exclusive) description of the final state
  - including hadronization
- QCD dynamics is approximate
  - Parton Shower algorithms are used to solve DGLAP equations, with various improvements
  - resummation of soft and collinear radiation is natural
  - "exclusive" observables are tipically not well described
- the bulk of the kinematics and QCD dynamic effects are catched, but the accuracy remains at LO
- being the PS & hadronization effects "factorized", they can be applied to dress events produced by any EG (LHA)

# QCD perturbative calculations

A complementary approach is the calculation of exact corrections order by order in $\alpha_s$

- NLO/NNLO corrections to $W/Z$ total production rate

G. Altarelli, R.K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12

R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343

W.L. van Neerven and E.B. Zijlstra, Nucl. Phys. **B382** (1992) 11

- fully exclusive NLO corrections to $W/Z$ production (and to $W/Z$ + 1 jet, $W/Z$ + 2 jets) (**MCFM**)

J. M. Campbell and R.K. Ellis, Phys. Rev. **D65** 113007

- fully exclusive NNLO corrections to $W/Z$ production (**FEWZ**)

C. Anastasiou et al., Phys. Rev. **D69** (2004) 094008

K. Melnikov and F. Petriello, Phys. Rev. Lett. **96** (2006) 231803

# Parton Level and "matched" event generators

- EG implementing exact LO matrix elements, tipically designed for multi-jet final states
  - ⋆ for instance **ALPGEN**, **MADEVENT**, **SHERPA**

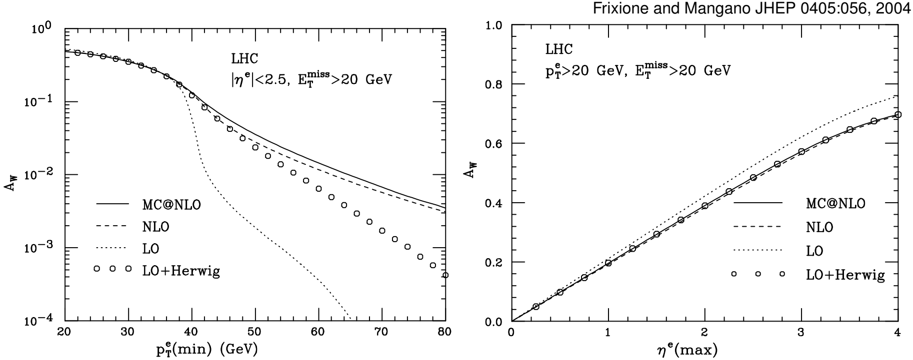
M.L. Mangano et al., Maltoni and Steltzer, Gleisberg et al.

- exclusive multi-jet events can be combined with PS into inclusive samples
  - ⋆ better description of radiation events
  - ⋆ the double counting between ME and PS has to be resolved (CKKW, MLM prescription)

Catani Krauss Kuhn Webber

  - ⋆ the accuracy is still at LO
- exact matching of NLO calculation with PS, avoiding double counting and exploiting the complete NLO information (NLO accuracy) and PS advantages (resummation of soft and collinear corrections)
  - ⋆ **MC@NLO** (Frixione Webber)
  - ⋆ **POWHEG** (Frixione Nason Ridolfi Oleari)

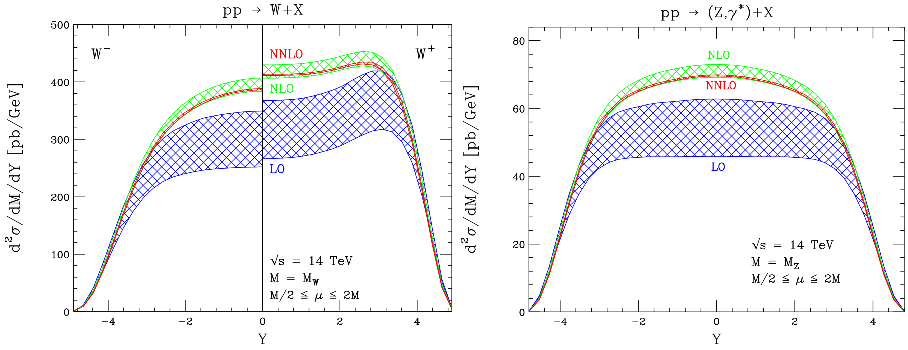
# Herwig vs MC@NLO on $W$ acceptances




- acceptances at LHC: matching NLO corrections with PS ensures a (QCD) theoretical accuracy at $\sim 2\%$, for $p_T^\ell > 20$ GeV

# High-precision QCD: $W/Z$ rapidity @ NNLO

C. Anastasiou et al., Phys. Rev. **D69** (2004) 094008




- First calculation of a differential distribution at NNLO in $\alpha_s$. Residual scale dependence below 1%.
- $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \rightarrow$ need to worry about electroweak corrections!

# EW calculations for W & tools

- $\mathcal{O}(\alpha)$ electroweak corrections to $W$ production
  - ⋆ Pole approximation ($\sqrt{\hat{s}} = M_W$)
    - → D. Wackeroth and W. Hollik, PRD **55** (1997) 6788
    - → U. Baur et al., PRD **59** (1999) 013002
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → V.A. Zykunov et al., EPJC **3** 9 (2001)
    - → S. Dittmaier and M. Krämer, PRD **65** (2002) 073007 **DK**
    - → U. Baur and D. Wackeroth, PRD **70** (2004) 073015 **WGRAD2**
    - → A. Arbuzov, et al., EPJC **46**, 407 (2006) **SANC**
    - → C.M.C.C. et al., JHEP 0612:016 (2006) **HORACE**
- Multi-photon radiation
  - → C.M.C.C. et al., PRD **69**, 037301 (2004); JHEP 0612:016 (2006) **HORACE**
  - → S. Jadach, W. Płaczek, EPJC **29** 325 (2003) **WINHAC**

# EW calculations for Z (& tools)

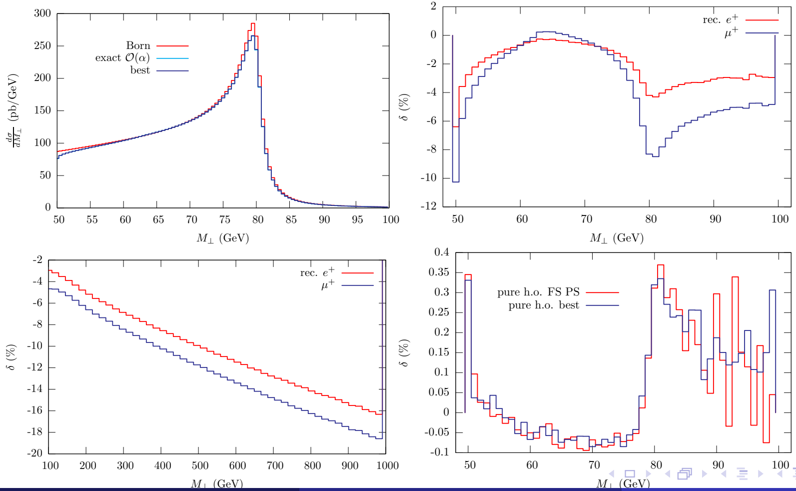
- $\mathcal{O}(\alpha)$ electroweak corrections to $Z$ production
  - ⋆ QED corrections
    - → U. Baur, *et al.*, Phys. Rev. **D57** (1998) 199 (**ZGRAD**)
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → U. Baur, *et al.*, Phys. Rev. **D65** (2002) 033007 (**ZGRAD2**)
    - → C.M.C.C. et al, JHEP 0710:109 (2007) (**HORACE**)
    - → Bardin et al., **arXiv:0711.0625 [hep-ph]** (**SANC**)
- Multi-photon radiation
  - → C.M.C.C. et al., JHEP 0505:019 (2005) + JHEP 0710:109 (2007) (**HORACE**)
  - → W. Płaczek et al., in preparation (**ZINHAC**)

⋆ all these codes have been carefully (and successfully) compared during Les Houches 2005, TeV4LHC and Les Houces 2007 workshops

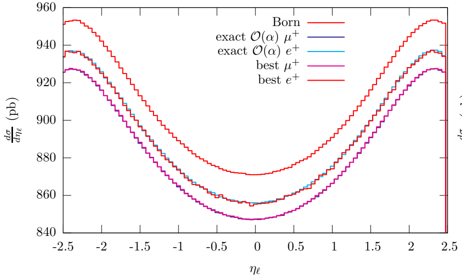
# EW effects for $W$

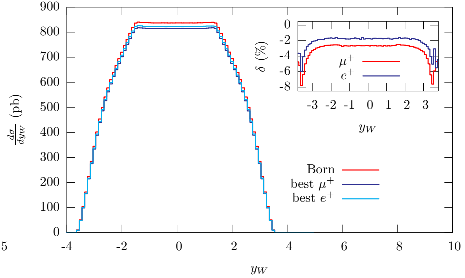
C.M.C.C. et al., JHEP 0612:016 (2006)

- $M_T^W$ distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, multiple-photon effects at peak



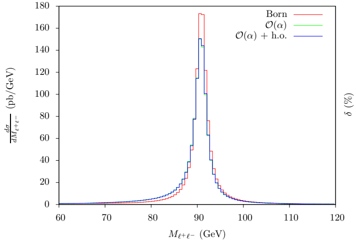
- lepton and $W$ rapidity

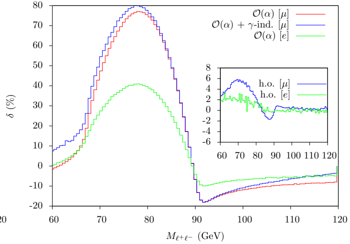


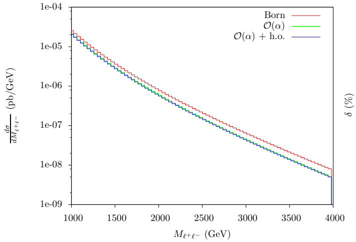



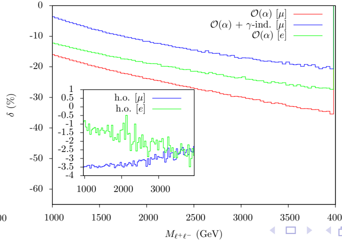
C.M.C.C. et al., JHEP 0710:109 (2007)

- $M_{\ell^+\ell^-}$ distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, h.o. QED effects at peak



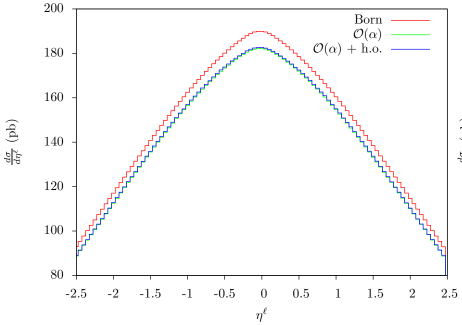



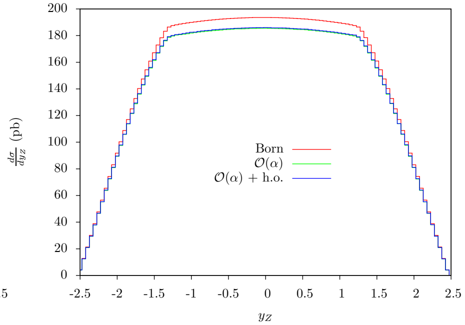



# EW effects for $Z$

- lepton and $Z$ rapidity



# Combining EW and QCD corrections

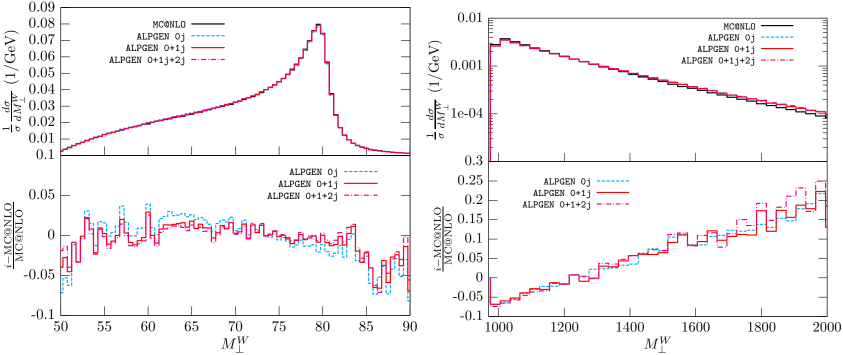
work in progress: Balossini, CMCC, Montagna, M. Moretti, Nicrosini, Piccinini, Treccani, Vicini

- our attempt (preliminary results) is based on the following formula

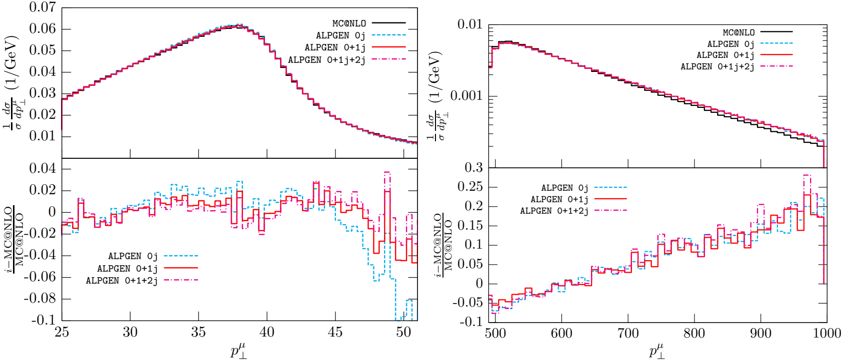
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\oplus\text{EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\text{best QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{best EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{Born}}\right\}_{\texttt{HERWIG}\ \text{PS}}$$

- best QCD $\Rightarrow$ **MC@NLO**, **ALPGEN** (with CKKW PS matching according to MLM prescription, `0+1 jet`, `0+1+2 jets`)
- EW part (**HORACE**) is interfaced to **HERWIG** PS (EW $\otimes$ QCD LL)
  - ⋆ NLO EW is convoluted with QCD LL parton shower $\Rightarrow$ $\mathcal{O}(\alpha\alpha_s)$ corrections not reliable where hard non log QCD corrections are important (e.g. high $p_\perp$ lepton distribution without cut on the $W$ invariant mass). In this case a two-loop calculation needed for a sound estimate of $\mathcal{O}(\alpha\alpha_s)$ effects

⋆ not suited for true event generation. . .

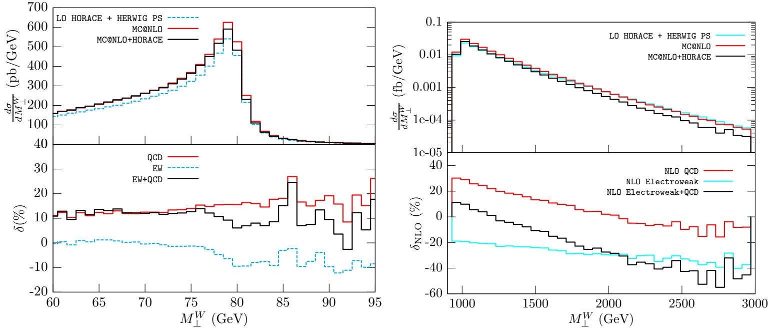



- each distribution normalized to its cross section (shape differences)



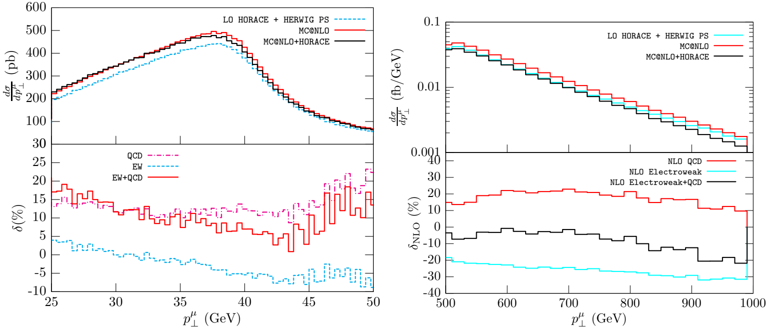

- each distribution normalized to its cross section

# QCD ⊕ EW @ LHC




- absolute distributions

# QCD ⊕ EW @ LHC




- absolute distributions

# PDFs

- they describe the parton content of the proton
- the $\mu^2$ evolution is driven by the DGLAP equations. At lowest-order

$$
\begin{aligned}
\frac{\partial q_i(x,\mu_F^2)}{\partial \log \mu_F^2} &= \frac{\alpha_S(\mu_R)}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{qq}(y)\, q_i(\frac{x}{y},\mu_F^2) + P_{qg}(y)\, g(\frac{x}{y},\mu_F^2) \right\} \\
\frac{\partial g(x,\mu_F^2)}{\partial \log \mu_F^2} &= \frac{\alpha_S(\mu_R)}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{gq}(y) \sum_j q_j(\frac{x}{y},\mu_F^2) + P_{gg}(y)\, g(\frac{x}{y},\mu_F^2) \right\}
\end{aligned}
$$

- splitting functions $P_{ij}(x)$ are now known up to NNLO (3-loops)

Moch, Vermaseren, Vogt

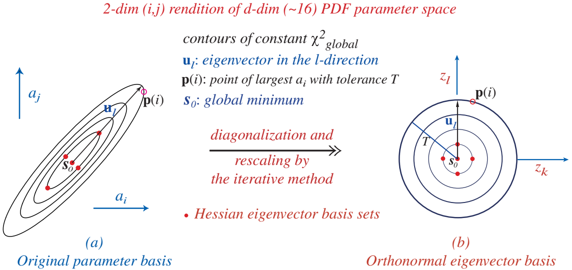
- an initial condition is needed at $\mu_0$ to solve the DGLAP eq.
  - ⋆ e.g.: $q_u(x), q_d(x), g(x) = a_0 x^{a_1}(1-x)^{a_2} e^{a_3 x + a_4 x^2}$
  - ⋆ the parameters are fitted from a huge amount of data
  - ⋆ many groups/collaborations make the job (MRST, CTEQ, ZEUS, Alekhin,. . . )

# Errors on PDF

- different sources of error play in the game
- experimental errors (they reflect on fitted parameters)
- theoretical issues
  - ⋆ heavy quarks mass effect
  - ⋆ Low-$x$ behaviour and effects (LHC is a low-$x$ machine!)
  - ⋆ (biased) assumptions in the choice of the functional form at $Q = Q_0$

# PDF experimental errors

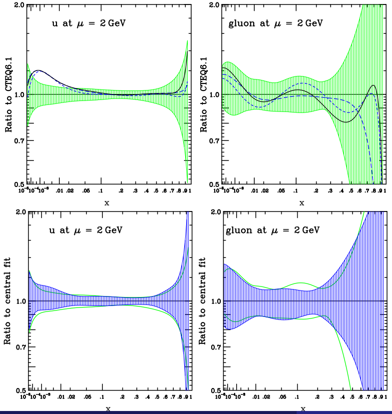
- the error on PDFs is usually estimated by means of the Hessian method (the "effective" $\Delta\chi^2$ is expanded around the global minimum in the parameter space)

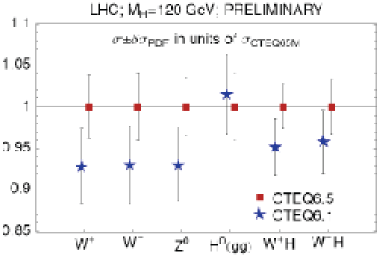



- a set of PDF are given, corresponding to $\Delta\chi^2 < T$. This does not have a clear statistical meaning
- a more refined procedure considers the Lagrange multiplier method which can assess more reliably the error induced by data on a given observable (e.g. $\sigma_W$). Generally, Hessian and LMM errors are comparable

# Heavy quark mass effects (CTEQ)

- they have to be carefully accounted for
- different ambiguities have to be resolved (FFNS vs VFNS, threashold treatment, scales matching in VFNS, phase-space boundaries)
- e.g., CTEQ6.1 → CTEQ6.5



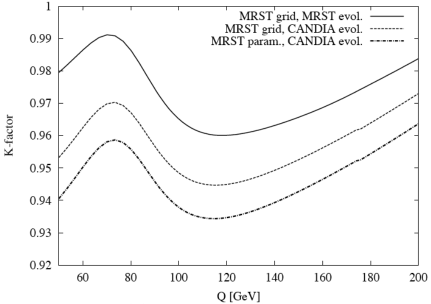

- $\delta\sigma^{6.1}{}_W = ^{+5.2\%}_{-5.9\%}$, $\delta\sigma^{6.5}{}_W = ^{+4.9\%}_{-4.1\%}$
- better agreement with MRST PDF (which include mass effects) at $x \simeq 10^{-3}$

# PDF evolution “uncertainties”

DGLAP equations can be solved (at LO, NLO, NNLO) by

1. numerical brute force
2. Mellin moments + inversion
3. Logarithmic expansion

- in 2. and 3. assumptions/approximations (e.g. truncation) are used
- all these “uncertainties” have been studied with **CANDIA** (www.le.infn.it/candia)




(a) $K = \sigma_{NNLO}/\sigma_{NLO}$

Cafarella, Corianò, Guzzi

# QCD at low-$x$

- at HERA and LHC the low-$x$ region is explored
- big logs $(\alpha_s \log 1/x)^n$ can not be neglected in the singlet splitting function
- the low-$x$ logs are resummed by the BFKL equation.
- the low-$x$ (BFKL) and high-$x$ regime (DGLAP) formalisms have to be combined for successful and predictive phenomenology
- The LO BFKL equation must be improved with NLO and $\alpha_s$ running to produce reliable results
- huge amount of work done in this field: see Altarelli-Ball-Forte, Ciafaloni-Colferai-Salam-Stasto, Thorne-White

from G. Altarelli, RadCor07

## Summary and Conclusion

- The matching of perturbative QCD evolution at large x and of BFKL at small x is now understood.
- Duality, momentum conserv., symm. under gluon exchange of the BFKL kernel and running coupling effects are essential
- The resulting asymptotic small x behaviour is much softened with respect to the naive BFKL, in agreement with the data.
- We have constructed splitting functions and coefficients that reduce to the pert. results at large x and incorporate BFKL with running coupling effects at small x.
- We have results expressed in the commonly used $MS^{bar}$ scheme, but can give them in any scheme.
- All formalism is ready for systematic phenomenology (e.g. at the LHC)

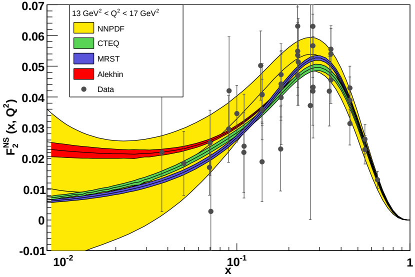
# Neural Network approach to PDF fit

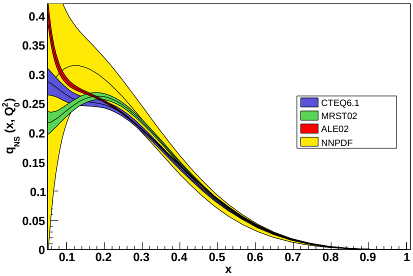
NNPDF Collaboration: L. Del Debbio, S. Forte, J.I. Latorre, A. Piccione, J. Rojo

- fixing a functional form to parametrize PDFs introduces a bias (which is the uncertainty?)
- The Neural Network approach can naturally provide an unbiased interpolation of data points
- Neural networks can provide an unbiased PDF parametrization with a "faithful" estimate of the uncertainties (the only assumption is *smoothness*)
- the basic idea is to generate MC replica of the data and train a Neural Network set on the MC replica
  - each data replica gives a PDF
  - the PDF error on $\mathcal{O}$ is then

$$\Delta(\mathcal{O}) = \sqrt{< \mathcal{O}^2 >_{\text{NNpdf set}} - < \mathcal{O} >^2_{\text{NNpdf set}}}$$

# Neural Network approach to PDF fit




- NNPDF produces larger errors
- NNPDF error band includes “standard” PDF sets where they disagree

# Conclusions

- Drell-Yan processes are key processes for LHC
  - ⋆ detector calibration
  - ⋆ luminosity monitoring
  - ⋆ precise $M_W$ measurement
  - ⋆ PDF constraint and measurement
  - ⋆ background to BSM
- Perturbative calculations are accurate at a few 1% level
  - ⋆ NLO QCD + PS, NNLO QCD, EW
- PDF are an ubiquitous ingredient. From a theoretical point of view
  - ⋆ mass effects have a big impact
  - ⋆ ambiguities/prescriptions for DGLAP evolution do matter
  - ⋆ BFKL region must be included in fit and evolution, important for phenomenology
  - ⋆ an unbiased fit to data is provided by the neural network approach