Precise theoretical predictions for Drell-Yan processes at hadron colliders: lecture 1

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thanks to discussions and collaboration with

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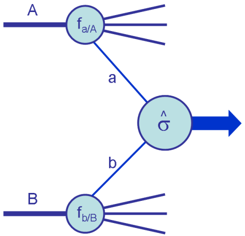
Outline

1. Introduction
   - Relevance of DY processes in precision studies at hadron colliders
   - different observables for different purposes
2. QCD corrections
   - fixed order calculations: NLO and NNLO accuracy
   - resummation
   - Parton Shower Monte Carlo event generators
   - matching NLO and Parton Shower Monte Carlo
   - available programs
3. EW corrections
   - generalities on NLO EW calculations
   - input schemes
   - treatment of unstable virtual W and Z
   - higher order contributions
     - QED corrections
     - Sudakov logarithms
   - available programs/calculations
4. Combination EW$\oplus/\otimes$QCD

Linking theory and experiment

$$\sigma^{\text{exp}} \equiv \frac{1}{\int \mathcal{L}dt} \frac{N^{obs}}{A\ \epsilon} = \sigma^{\text{theory}}$$

$$\sigma^{\text{theory}} \equiv \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times$$
$$\times \int_\Phi d\hat{\sigma}_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2) + \mathcal{O}\left(\frac{\Lambda^n_{QCD}}{Q^n}\right)$$



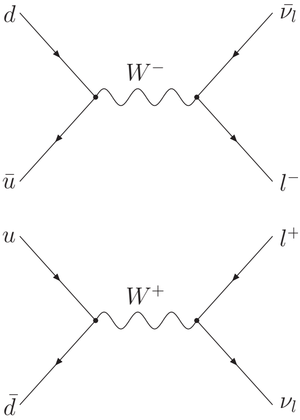
Campbell, Huston, Stirling, hep-ph/0611148

- PDF's fitted from data
- $\hat{\sigma}$ calculated perturbatively

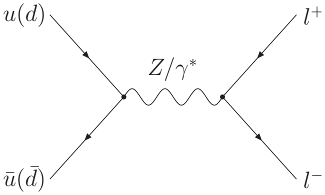
$$\sigma = \sigma_0(1 + \alpha_s \delta_1^{\text{QCD}} + \alpha_s^2 \delta_2^{\text{QCD}} + \alpha \delta_1^{\text{EWK}} + \ldots)$$

Drell-Yan kernel processes at LO

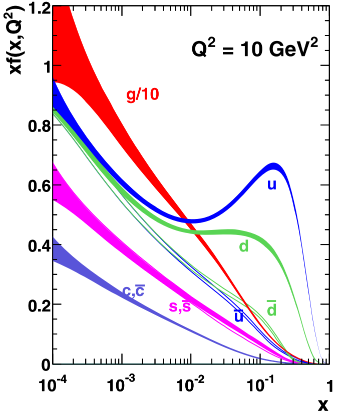
CC

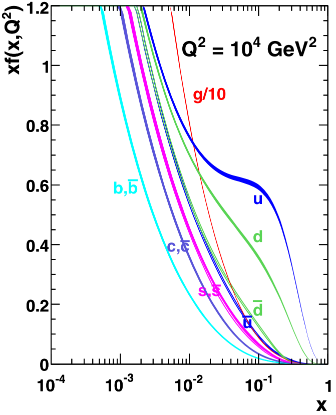


NC



to bear in mind: relative size of PDF's

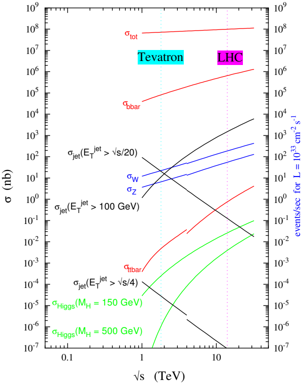


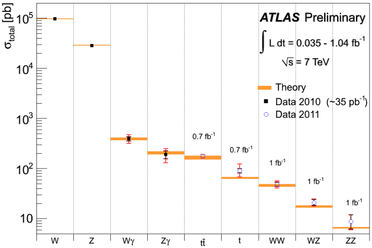


A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, arXiv:0901.0002[hep-ph]

- measured by means of fits to fixed target data, DIS and Tevatron data on jets

Cross sections at hadron colliders

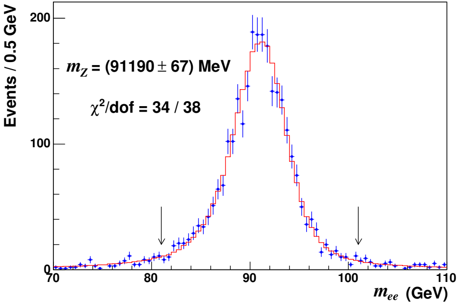




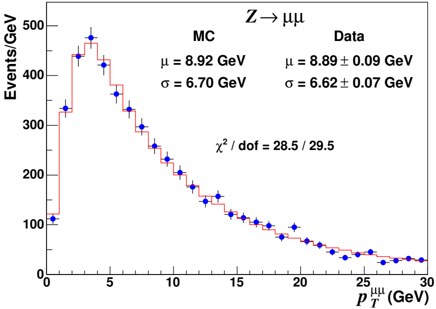
Drell-Yan processes at hadron colliders

- 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. 3×10^8 events with $\mathcal{L} = 10\ fb^{-1}$
  - $\sigma(Z) = 3.5\ nb$, i.e. 3.5×10^7 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, Γ_W and possibily $\sin^2\vartheta^l_{\rm eff}$ measurements
  - ⋆ background to New Physics searches

- detector calibration
  - $p_\perp^l$ from NC DY
  - invariant mass shape $M(l^+l^-)$ from NC DY
  - $p_\perp^{l^+l^-}$ from NC DY



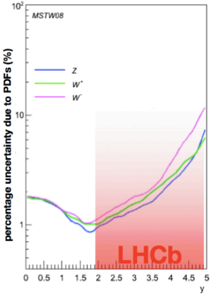
CDF, PRD77, 112001 (2008)



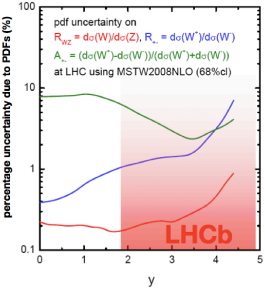
CDF, PRD77, 112001 (2008)

Interesting observables (II)

- PDF determination
  - W and Z total cross section
  - W and Z rapidities ($y = \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$)
  - $R_W = \sigma(W^+ \to l^+\nu)/\sigma(W^- \to l^-\nu)$
  - lept. charge asymm. ($A(\eta) = \frac{d\sigma(W^+)-d\sigma(W^-)}{d\sigma(W^+)+d\sigma(W^-)}$) for different $p_\perp^l$ thresholds

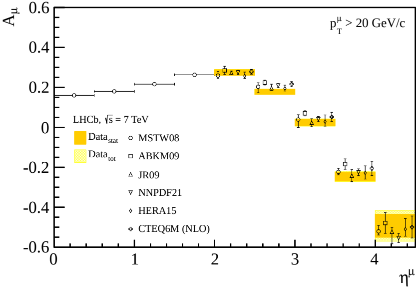


LHCb, arXiv:1202.0654[hep-ex]

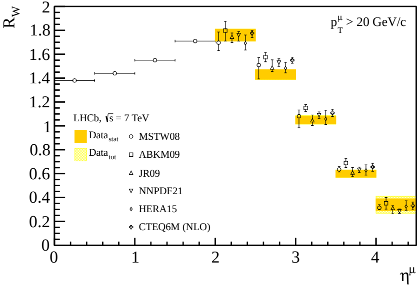


LHCb, arXiv:1202.0654[hep-ex]

Interesting observables (III)

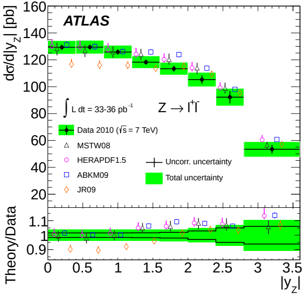


LHCb, arXiv:1202.0654[hep-ex]

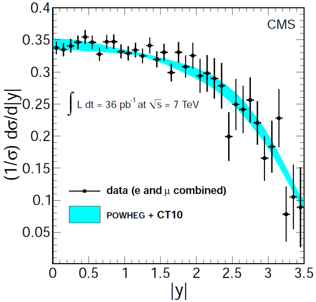


LHCb, arXiv:1202.0654[hep-ex]

- error bands include the estimate error from PDF’s in quadrature with the theoretical uncertainty see later



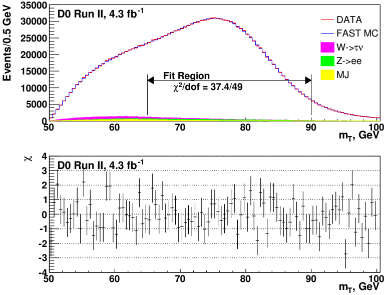
ATLAS and CMS, arXiv:1202.0149[hep-ex]



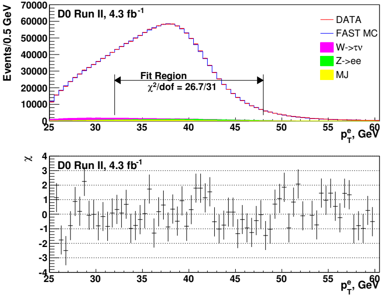
ATLAS and CMS, arXiv:1202.0149[hep-ex]

Interesting observables (V)

- W (and also width Γ_W) measurement
  - $p_\perp^{(e,\mu)}$
  - $M_\perp = \sqrt{p_\perp^l \not{p}_\perp (1 - \cos \Delta\phi_{l\not{p}_\perp})}$

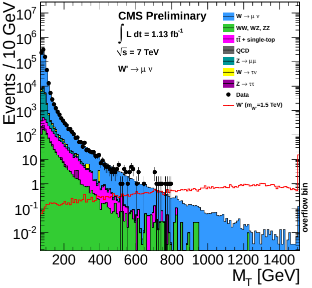


CDF and D0, arXiv:1204.3260[hep-ex]

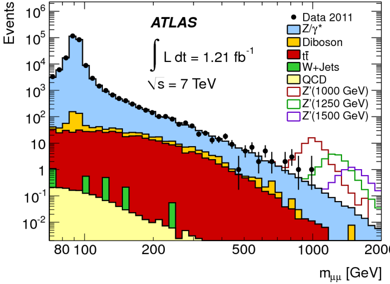


CDF and D0, arXiv:1204.3260[hep-ex]

- New Physics searches $(W'$ and/or $Z')$: $M_\perp$ and $M(l^+l^-)$

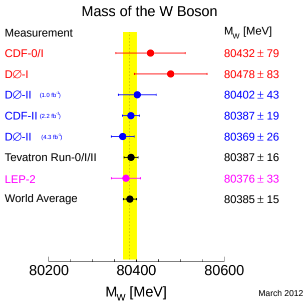


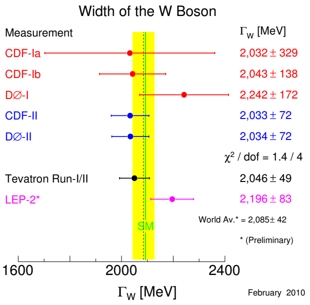
CMS-PAS-EXO-11-024



ATLAS: arXiv:1108.1582[hep-ex]

Summary of direct measurements

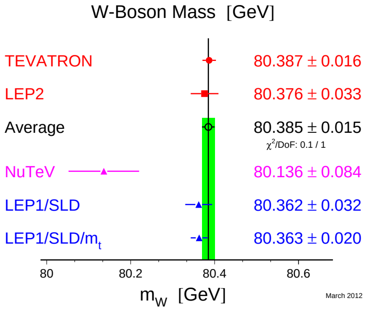




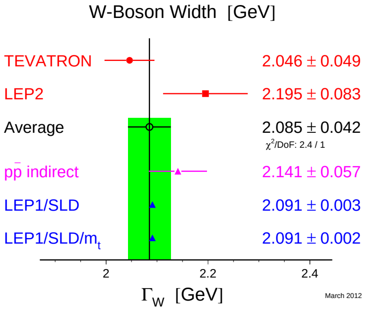
TEVEWWG: arXiv:1204.0042[hep-ex]

TEVEWWG: arXiv:1003.2826[hep-ex]

SM consistency checks (I)



LEPEWWG homepage



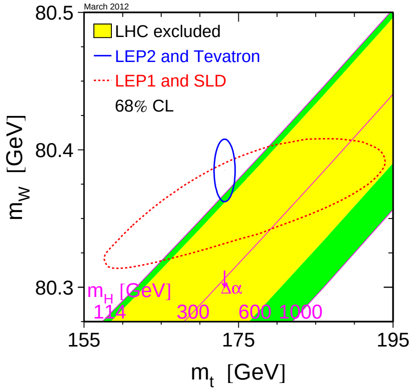
LEPEWWG homepage

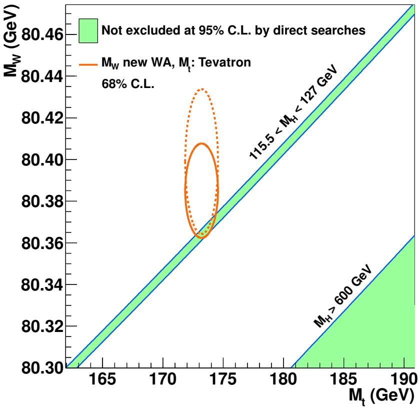
LEP1/SLD values results from theory: highly non trivial test!

$$M_W^2 = \frac{4\sqrt{2}\pi\alpha}{8G_\mu \sin^2\vartheta}\,(1+\Delta r)$$

input parameters: α, G_μ, M_Z, $m_{\rm top}$, m_H, $\alpha_s(M_Z^2)$

SM consistency checks (II)





LEPEWWG homepage

Theoretical predictions

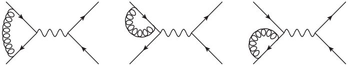
- First calculations of radiative corrections to W/Z total production rates date back to more than twenty years ago!

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

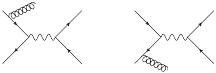
- The experimental accuracy reached at Tevatron run-II and even more at the LHC requires complete theoretical control of the exclusive leptonic final states $\Longrightarrow$ every theoretical calculation for DY observables needs to be implemented in a (quite complicated) computer program
- Four main classes of computer programs
  - fixed order parton-level Monte Carlo programs
  - programs which give predictions with resummation of potentially large logarithms, limited to specific observables
  - general purpose Monte Carlo event generators, which can simulate in a completely exclusive way (even if with some approximations) the complete evolution of a hadron-hadron collision
  - matched fixed-order with parton shower event generators

$$\sigma_{\rm NLO} = \int d\sigma_0 + \int d\sigma_V + \int d\sigma_R$$
$$= \int d\Phi_2 \, |M_0^2| + \int d\Phi_2 \, 2\mathcal{R}e \left(M_0^\dagger M_{\rm virtual} \right) + \int d\Phi_3 \, |M_{\rm real}|^2$$

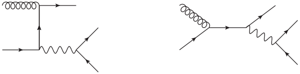
- virtual corrections



- real corrections
    - initial state radiation

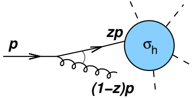


    - new process: gluon in the initial state

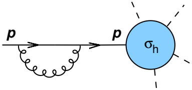


NLO QCD corrections (II)

- After removal of the UV divergences of the virtual amplitude through coupling constant renormalization, both virtual and real contribution are still divergent because $m_g = 0$ (soft IR div.)
- Assuming $m_q = 0$ also collinear divergences
- This is a general feature of higher order QCD corrections for any process with radiation from external legs



$$\sigma_{g+h}(p) \simeq \sigma_h(zp)\frac{\alpha_s C_F}{\pi}\frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$



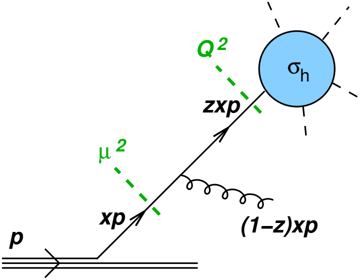
$$\sigma_{g+h}(p) \simeq -\sigma_h(p)\frac{\alpha_s C_F}{\pi}\frac{dz}{1-z}\frac{dk_t^2}{k_t^2}$$

$$\sigma_{g+h} + \sigma_{V+h} \simeq \frac{\alpha_s C_F}{\pi}\underbrace{\int_0^{Q^2}\frac{dk_t^2}{k_t^2}}_{\text{infinite}}\underbrace{\int_0^1\frac{dz}{1-z}[\sigma_h(zp) - \sigma_h(p)]}_{\text{finite}}$$

G. Salam, arXiv:1011.5131[hep-ph]

NLO QCD corrections (III)

- in QCD usual regularization is dim. reg. (both for UV and IR) in $\overline{\mathrm{MS}}$ scheme
- IR soft divergences, $\frac{1}{\varepsilon^2}$ and $\frac{1}{\varepsilon}$ poles, cancel between virtual and real
- $\frac{1}{\varepsilon}$ terms of collinear origin survive: they get reabsorbed in the PDF



G. Salam, arXiv:1011.5131[hep-ph]

NLO QCD: handling divergences in practice

- $\int d\sigma_R$ worked out according to one of the following schemes:
  - slicing (using mass regularization)
  - subtraction (the most popular) in its different realizations
    - dipole formalism (Catani-Seymour)
    - antenna formalism (Kosower)
    - FKS formalism (Frixione-Kunzt-Signer)
  - all methods use the property of factorization of IR soft/collinear singularities

$$\begin{aligned}\langle O\rangle &= \int \mathrm{d}\Phi_{\mathrm{B}}(B(\Phi_{\mathrm{B}})+\hat{V}(\Phi_{\mathrm{B}}))O(\Phi_{\mathrm{B}})+\int \mathrm{d}\Phi_{\mathrm{R}}\, R(\Phi_{\mathrm{R}})O(\Phi_{\mathrm{R}}) \\ &= \int \mathrm{d}\Phi_{\mathrm{B}}\,[B(\Phi_{\mathrm{B}})+V(\Phi_{\mathrm{B}})]\,O(\Phi_{\mathrm{B}}) \\ &+ \int \mathrm{d}\Phi_{\mathrm{R}}\,\,[R(\Phi_{\mathrm{R}})O(\Phi_{\mathrm{R}})-C(\Phi_{\mathrm{R}})O(\Phi_{\mathrm{B}})]\end{aligned}$$

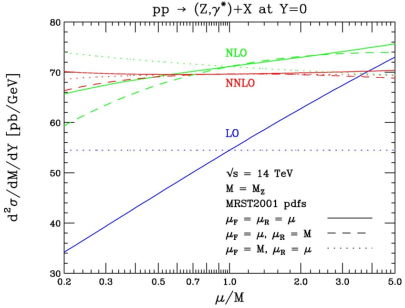
$$V(\Phi_{\mathrm{B}})=\hat{V}(\Phi_{\mathrm{B}})+\int \mathrm{d}\Phi_{\mathrm{rad}}\,C(\Phi_{\mathrm{R}}(\Phi_{\mathrm{B}},\Phi_{\mathrm{rad}}))$$

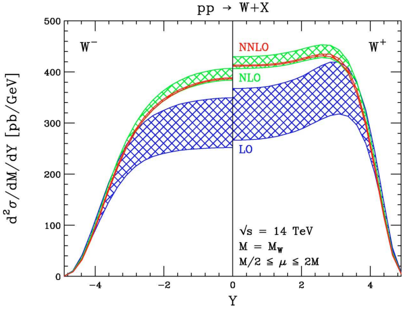
P. Nason and B. Webber, arXiv:1202.1251[hep-ph]

- with ISR two additional counterterms with Born kine and an additional integration on z

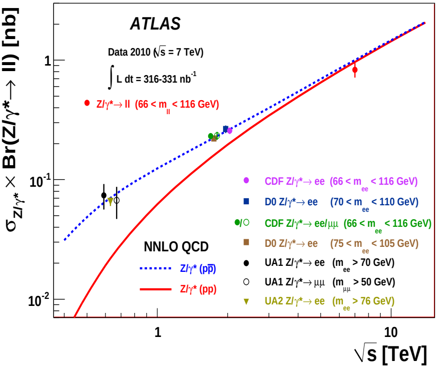
NNLO QCD corrections

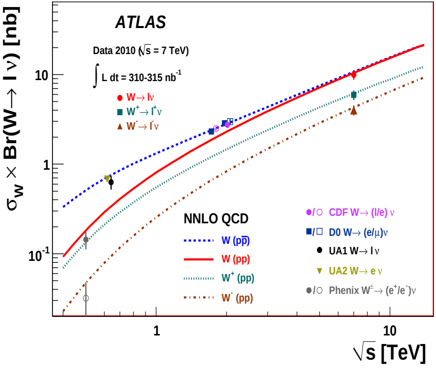
- In recent years the complete two-loop QCD correction, completely exclusive on lepton momenta, for DY has been calculated (independently by two groups)
- building blocks:
    - two-loop virtual correction
    - one-loop virtual correction to radiative DY
    - double radiative real contribution





Comparison between NNLO QCD and data





fixed order MC programs

- positive features
  - ideal for accurate predictions on IR safe observables
  - they allow to test the convergence of the perturbative series
  - stabilization of the predictions w.r.t. renormalization/factorization scale variations
  - any cut on the leptons inclusive on extra radiation can be imposed
- problems
  - only parton level events described
  - event generation not possible
  - observables exclusive on radiation