QCD transverse-momentum resummation for Higgs and Vector Boson production at the LHC

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Outline

Motivations I

- The discovery of the Higgs boson and the study of its properties depends, in various way, by theoretical predictions for Higgs boson cross sections.
- The study of Drell-Yan lepton pair production is well motivated.
  Large production rates and clean experimental signatures:
  Important for detector calibration.
  Possible use as luminosity monitor.

Motivations II

Transverse-momentum distributions needed for:

- Precise prediction for M_W.
- Beyond the Standard Model analysis (Z' non SUSY Higgs).
- Test of perturbative QCD predictions.
- Constrain for fits of PDFs.

To fully exploit the information contained in the experimental data from hadron colliders, precise theoretical predictions are needed

$\Longrightarrow$ computation of higher-order QCD corrections.

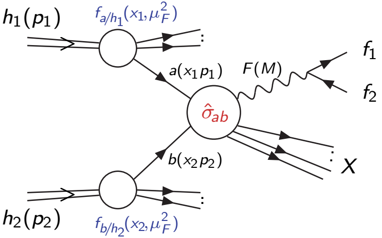
State of the art: fixed order calculations for DY

- QCD corrections:
  - Total cross section known up to NNLO [Hamberg,Van Neerven,Matsuura('91)], [Harlander,Kilgore('02)]
  - Rapidity distribution known up to NNLO [Anastasiou,Dixon,Melnikov,Petriello('03)]
  - Fully exclusive NNLO calculation completed [Melnikov,Petriello('06)], [Catani,Cieri,de Florian,G.F.,Grazzini('09)]
  - Vector boson transverse-momentum distribution known up to NLO [Ellis,Martinelli,Petronzio('83)],[Arnold,Reno('89)], [Gonsalves,Pawlowski,Wai('89)]
- Electroweak correction are know at $\mathcal{O}(\alpha)$ [Dittmaier et al.('02)],[Baur et al.('02)], [Carloni Calame, Montagna,Nicrosini,Vicini('06)]

State of the art: fixed order calculations for $gg \to H$

- QCD corrections:
  - Total cross section known up to NNLO QCD corrections in the large-m_t approx. [Harlander,Kilgore('02)], [Anastasiou,Melnikov,Petriello('04)] [Ravindran,Smith,Van Neerven('03)].
  - NNLO QCD corrections beyond large-m_t approx. [Marzani,Ball,Del Duca,Forte,Vicini('08)] [Harlander,Mantler,Marzani,Ozeren('09)],[Pag,Rogal,Steinhauser('09)]. Accuracy of large-m_t approximation better than 1% for $100 \leq m_H \leq 300$ GeV.
  - Large QCD corrections: $\sim +100\%$ at NLO, $\sim +25\%$ at NNLO. The bulk due to threshold ($\hat{s} \to m_H^2$) soft/collinear emissions: NNLL resummation gives a further $\sim +10\%$ correction [Catani,de Florian,Grazzini,Nason('03)].
  - Fully exclusive NNLO QCD calculation available [Anastasiou,Melnikov,Petriello('04)], [Catani,Grazzini('07)]
  - Transverse-momentum distribution known up to NLO [de Florian,Grazzini,Kunszt,('99)],[Ravindran,Smith,Van Neerven('02)], [Glosser,Schmidt('02)]
- NLO EW corrections $\sim +5\%$ [Aglietti,Bonciani,Degrassi,Vicini('04)], [Actis,Passarino,Sturm,Uccirati('08)].

Transverse-momentum distribution



$$h_1(p_1) + h_2(p_2) \;\rightarrow\; F(M, q_T) + X \;\rightarrow\; f_1 + f_2 + X$$

$$\text{where} \quad F = \gamma^*/Z^0, W^{\pm}, H \quad \text{and} \quad f_1 f_2 = \ell^+\ell^-, \ell\nu_\ell, \gamma\gamma$$

Theoretical framework: QCD factorization formula

$$\frac{d\sigma}{dq_T^2}(q_T,M,s) = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1,\mu_F^2)\, f_{b/h_2}(x_2,\mu_F^2)\, \frac{d\hat{\sigma}_{ab}}{dq_T^2}(q_T,M,\hat{s};\alpha_S,\mu_R^2,\mu_F^2).$$

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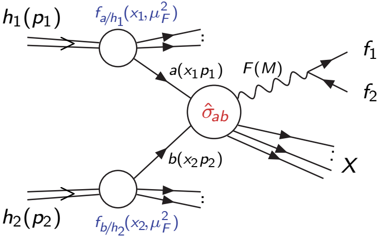

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Transverse-momentum distribution

The standard fixed-order QCD perturbative expansions gives:

$$\int_{Q_T^2}^{\infty} dq_T \frac{d\hat{\sigma}_{q\bar{q}}}{dq_T^2} \sim \alpha_S \left[c_{12} \log^2(M^2/Q_T^2) + c_{11} \log(M^2/Q_T^2) + c_{10}(Q_T) \right]$$

$$+\alpha_S^2 \left[c_{24} \log^4(M^2/Q_T^2) + \cdots + c_{21} \log(M^2/Q_T^2) + c_{20}(Q_T) \right] + \mathcal{O}(\alpha_S^3)$$

The logarithmic corrections are the residue of the cancellantion of the real-virtual infrared singularities:

$$\frac{\alpha_S}{2\pi} \int \frac{dk_T^2}{k_T^2} \int_{k_T/M}^{1} \frac{d\omega}{\omega} C_F (2 - 2\omega + \omega^2) \left[\delta^2(\vec{q}_T - \vec{k}_T) - \delta^2(\vec{q}_T) \right]$$

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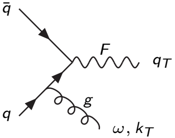

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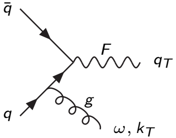

$$\frac{\alpha_S}{2\pi} \int \frac{dk_T^2}{k_T^2} \int_{k_T/M}^{1} d\omega \;\; P_{qq}(\omega) \;\; \left[\delta^2(\vec{q}_T - \vec{k}_T) - \delta^2(\vec{q}_T) \right]$$

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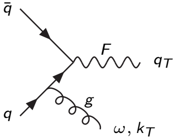

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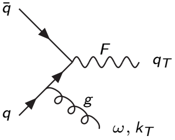

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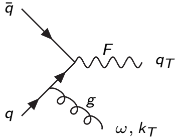

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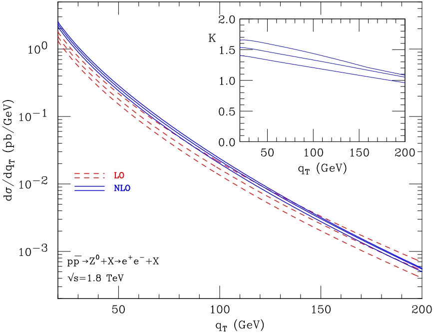
Fixed order results: q_T spectrum of Z boson at the Tevatron

For $q_T \sim M_F$ fixed order perturbative expansion feasible: Ellis, Martinelli, Petronzio ('83); Arnold, Reno ('89); Gonsalves, Pawlowski, Wai('89)



- LO: pdf=MRST02 LO, 1-loop α_S
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- Factorization and renormalization scale variations:
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  $q_T \sim m_Z$: $LO \pm 25\%$, $NLO \pm 8\%$
  $q_T \sim 20\ GeV$: $LO \pm 20\%$, $NLO \pm 7\%$
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$$K(q_T) = \frac{d\sigma/dq_{T\,NLO}(\mu_F, \mu_R)}{d\sigma/dq_{T\,LO}(\mu_F = \mu_R = m_Z)}$$

$K \sim 1.1$ at $q_T \sim 200\ GeV$ up to
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LO and NLO scale variations bands overlap only for $q_T > 70\ GeV$

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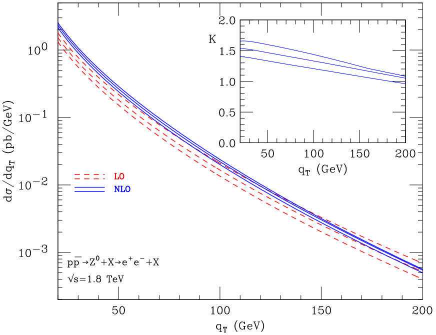

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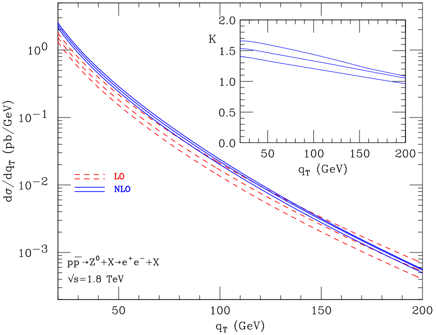

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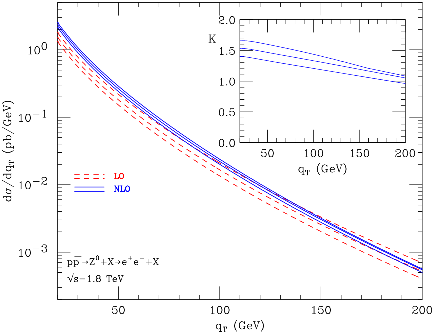

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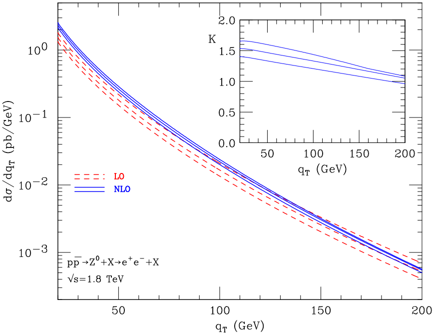

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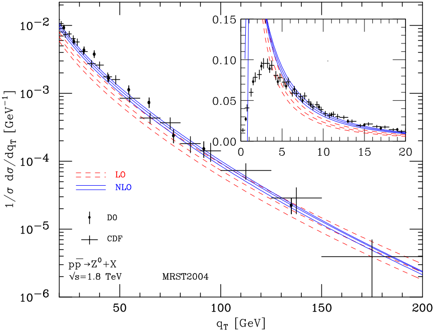

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  D0 data: $75\ Gev < M^2 < 105\ GeV$, $\sigma_{tot} = 221 \pm 11\ pb$ [D0 Collaboration ('00)]
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- In the small q_T region ($q_T \lesssim 20\ GeV$) LO and NLO result diverges to $+\infty$ and $-\infty$ (accidental partial agreement at $q_T \sim 5-7\ GeV$): need for resummation.

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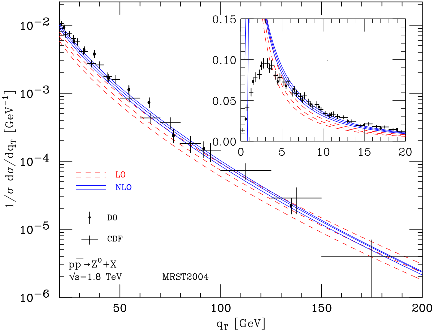

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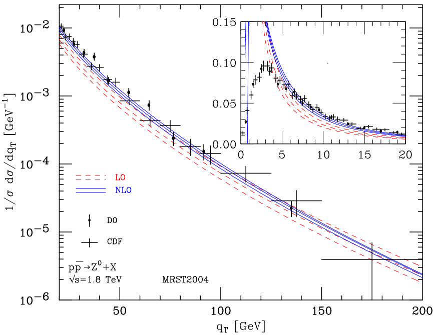

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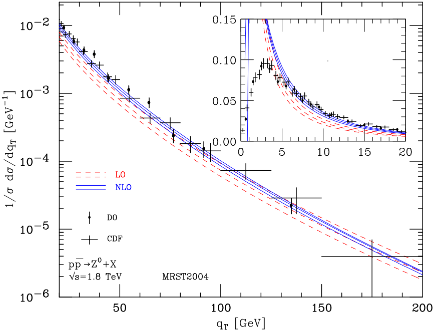
Fixed order results: q_T spectrum of Z boson at the Tevatron



- CDF data: $66\ Gev < M^2 < 116\ Gev$, $\sigma_{tot} = 248 \pm 11\ pb$ [CDF Collaboration ('00)]
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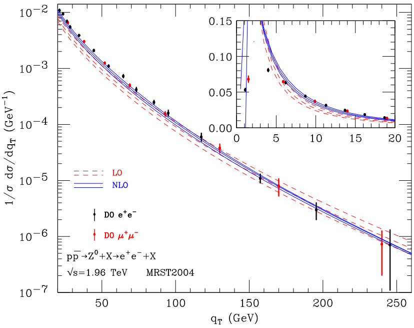

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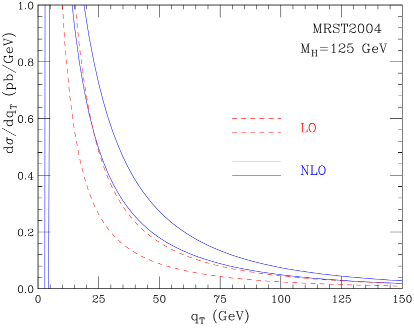

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Idea of large logs (Sudakov) resummation: reorganize the perturbative expansion by all-order summation ($L = \log(M^2/q_T^2)$).

$\alpha_S L^2$	$\alpha_S L$	$\cdots$	$\cdots$	$\cdots$	$\mathcal{O}(\alpha_S)$
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$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\alpha_S^n L^{2n}$	$\alpha_S^n L^{2n-1}$	$\alpha_S^n L^{2n-2}$	$\cdots$	$\cdots$	$\mathcal{O}(\alpha_S^n)$
dominant logs	next-to-dominant logs	$\cdots$	$\cdots$	$\cdots$	$\cdots$

- Ratio of two successive rows $\mathcal{O}(\alpha_S L^2)$: fixed order expansion valid when $\alpha_S L^2 \ll 1$.
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State of the art: transverse-momentum resummation

- The method to perform the resummation of the large logarithms of q_T is known [Parisi,Petronzio.('79)], [Kodaira,Trentadue('82)],[Altarelli, Ellis, Greco, Martinelli('84)], [Collins,Soper,Sterman('85)], [Catani,de Florian,Grazzini('01)]
- Various phenomenological studies of the vector boson transverse momentum distribution exist [Balasz,Qiu,Yuan('95)],[Balasz,Yuan('97)],[Ellis et al.('97)], [Kulesza et al.('02)]
- In this study we apply the transverse-momentum distribution the resummation formalism developed by [Catani,de Florian, Grazzini('01)] .
- Recently various results for transverse-momentum resummation in the framework of Effective Theories appeared [Gao,Li,Liu('05)],[Idilbi,Ji,Yuan('05)], [Mantry,Petriello('10)],-[Becher,Neubert('10)],[García,Idibli,Scimemi('11)].

Transverse-momentum resummation in pQCD

$$\frac{d\hat\sigma}{dq_T^2} = \frac{d\hat\sigma^{(res)}}{dq_T^2} + \frac{d\hat\sigma^{(fin)}}{dq_T^2}; \qquad \begin{array}{l} \int_0^{Q_T^2} dq_T^2 \left[\frac{d\hat\sigma^{(res)}}{dq_T^2}\right]_{f.o.} \overset{Q_T\to 0}{\sim} 1 + \sum_n \sum_{m=1}^{2n} c_{nm}\,\alpha_S^n \log^m \frac{M^2}{Q_T^2} \\ \int_0^{Q_T^2} dq_T^2 \left[\frac{d\hat\sigma^{(fin)}}{dq_T^2}\right]_{f.o.} \overset{Q_T\to 0}{=} 0 \end{array}$$

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- Resummation performed at partonic cross section level: PDF evaluated at $\mu_F \sim M$: no PDF extrapolation in the non perturbative region, study of μ_R and μ_F dependence as in fixed-order calculations.
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- We have performed the resummation up to NNLL+NLO. It means that our complete formula includes:
  - NNLL logarithmic contributions to all orders;
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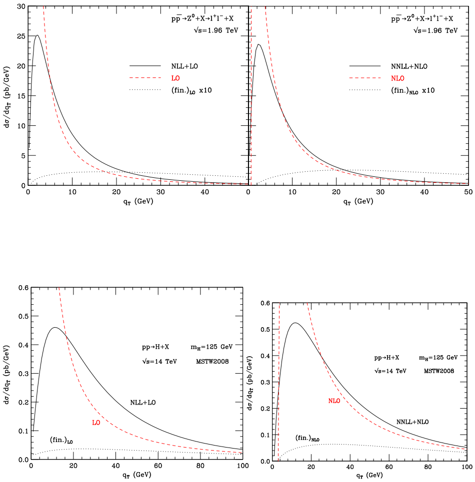

- Left side: NLL+LO result compared with fixed LO result.
  Resummation cure the fixed order divergence at $q_T \to 0$.
- Right side: NNLL+NLO result compared with fixed NLO result.
- The q_T spectrum of Z boson is slightly harder at NNLL+NLO accuracy than at NLL+LO accuracy.
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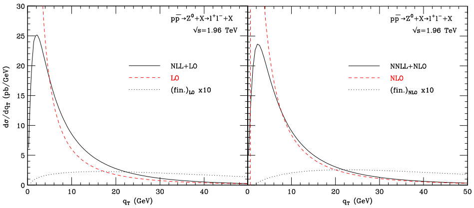

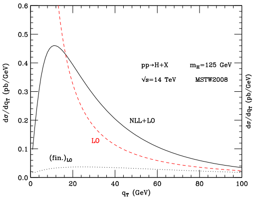

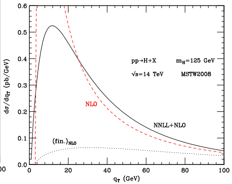

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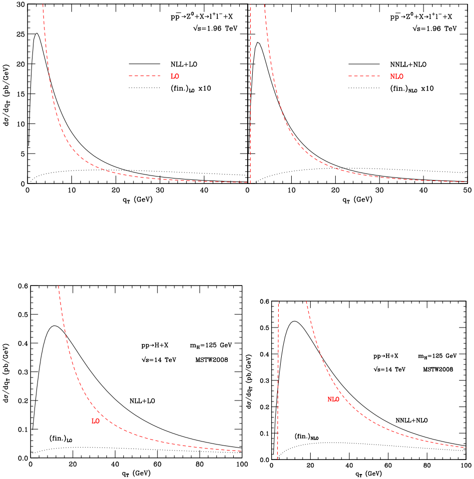

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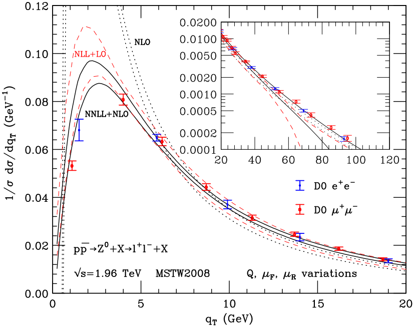
Resummed results: q_T spectrum of Z boson at the Tevatron



D0 data for the Z q_T spectrum compared with perturbative results.

- Uncertainty bands obtained varying μ_R, μ_F, Q independently:
  $$1/2 \leq \{\mu_F/m_Z, \mu_R/m_Z, 2Q/m_Z, \mu_F/\mu_R, Q/\mu_R\} \leq 2$$
  to avoid large logarithmic contributions ($\sim \ln(\mu_F^2/\mu_R^2)$, $\ln(Q^2/\mu_R^2)$) in the evolution of the parton densities and in the the resummed form factor.
- Significant reduction of scale dependence from NLL+LO to NNLL+NLO for all q_T.
- Good convergence of resummed results: NNLL+NLO and NLL+LO bands overlap (contrary to the fixed-order case).
- Good agreement between data and resummed predictions (without any model for non-perturbative effects).
  The perturbative uncertainty of the NNLL+NLO results is comparable with the experimental errors.

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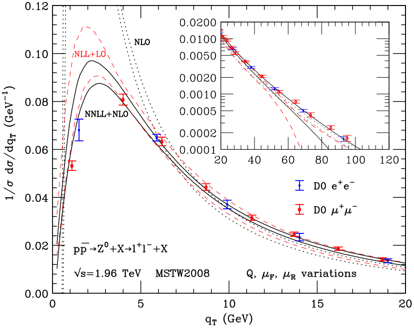

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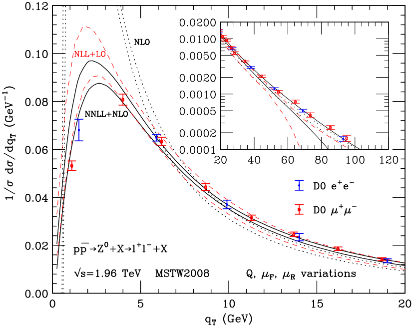

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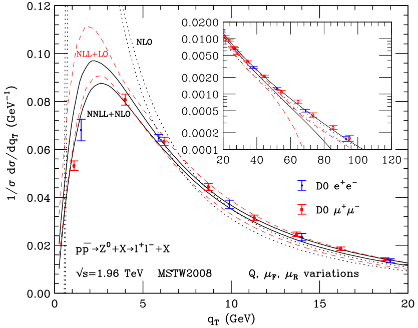

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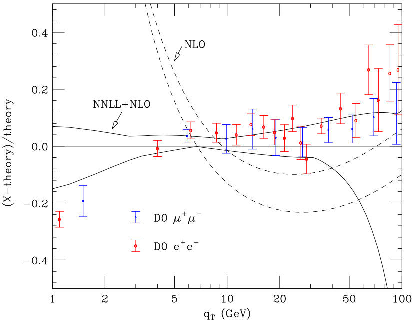

D0 data for the Z q_T spectrum: Fractional difference with respect to the reference result: NNLL+NLO, $\mu_R = \mu_F = 2Q = m_Z$.

- NNLL+NLO scale dependence is $\pm 6\%$ at the peak, $\pm 5\%$ at $q_T = 10\,GeV$ and $\pm 12\%$ at $q_T = 50\,GeV$. For $q_T \geq 60\,GeV$ the resummed result looses predictivity.
- At large values of q_T, the NLO and NNLL+NLO bands overlap.
  At intermediate values of transverse momenta the scale variation bands do not overlap.
- The resummation improves the agreement of the NLO results with the data.
  In the small-q_T region, the NLO result is theoretically unreliable and the NLO band deviates from the NNLL+NLO band.

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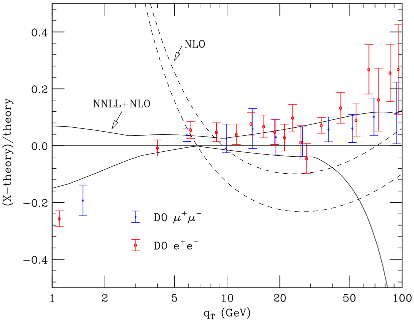

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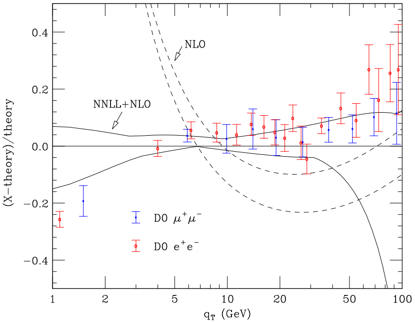

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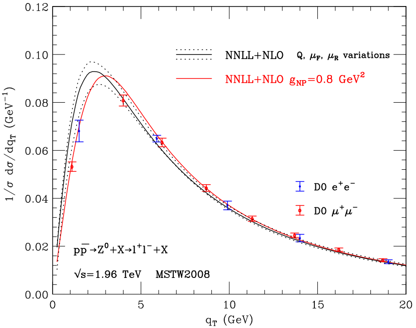
Non perturbative effects: q_T spectrum of Z boson at the Tevatron



D0 data for the Z q_T spectrum.

- Up to now result in a complete perturbative framework.
- Non perturbative effects parametrized by a NP form factor $S_{NP} = \exp\{-g_{NP} b^2\}$:

$$\exp\{\mathcal{G}_N(\alpha_S, \widetilde{L})\} \rightarrow \exp\{\mathcal{G}_N(\alpha_S, \widetilde{L})\}\, S_{NP}$$

$$g_{NP} = 0.8\, GeV^2 \quad \text{[Kulesza et al.('02)]}$$

- With NP effects the q_T spectrum is harder.
  Quantitative impact of such NP effects is comparable with perturbative uncertainties.

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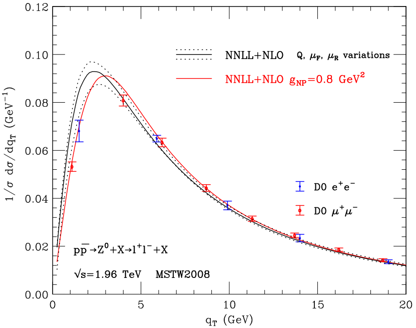

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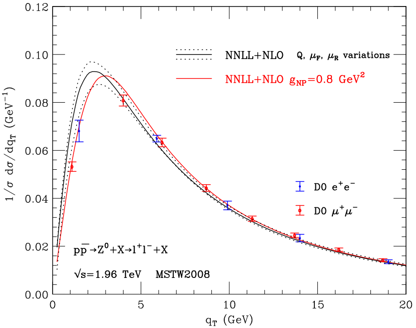

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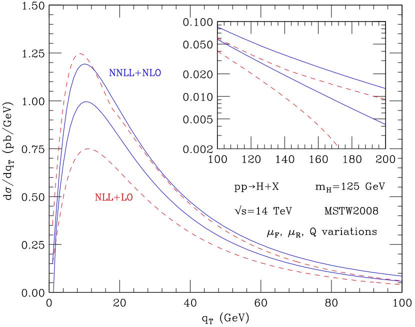
Resummed results: q_T spectrum of H boson at the LHC $\sqrt{s} = 14\ TeV$



Higgs q_T spectrum for $m_H = 125\ GeV$ at LHC.

- Uncertainty bands obtained as before: $1/2 \leq \{\mu_F/m_Z, \mu_R/m_Z, 2Q/m_Z, \mu_F/\mu_R, Q/\mu_R\} \leq 2$
- Significant reduction of scale dependence from NLL+LO to NNLL+NLO for all q_T.
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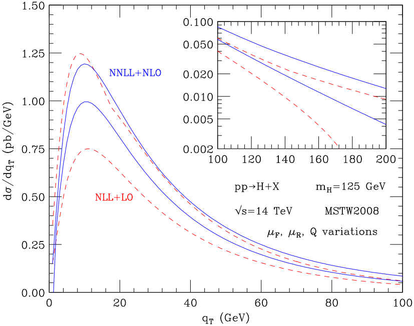

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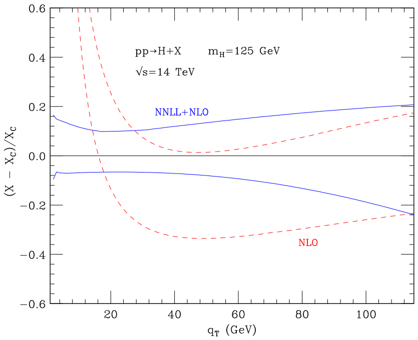

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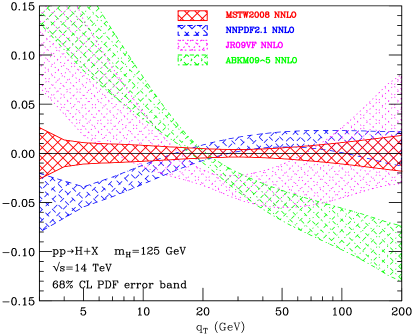

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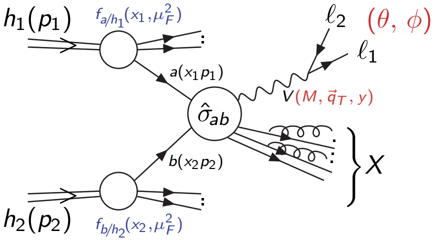
q_T-resummation with decay variables dependence



- Experiments have finite acceptance: important to provide exclusive theoretical predictions.
- Analytic resummation formalism inclusive over soft-gluon emission: not possible to apply selection cuts on final state partons.
- We have included the full dependence on the decay variables: possible to apply cuts on vector/Higgs boson and decay products.
- To construct the "finite" part we rely on the fully-differential NNLO result from the codes HNNLO/DYNNLO [Catani,Cieri,de Florian,Ferrera,Grazzini('09)], [Catani,Grazzini('09)].
- Calculation implemented in numerical codes (HRes/DYRes) which include spin correlations, finite-width effects and compute distributions in form of bin histograms.

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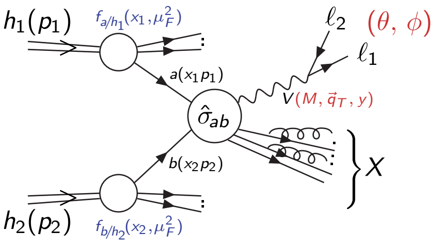

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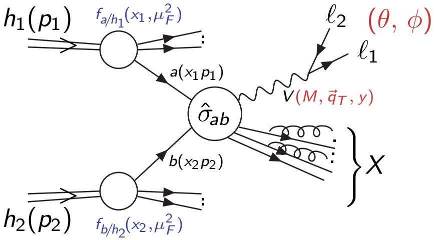

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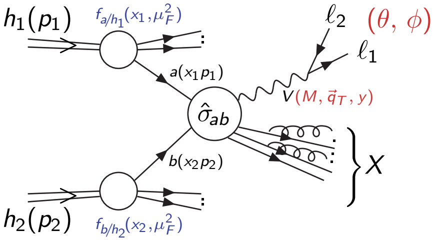

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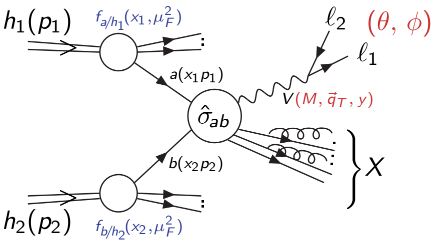

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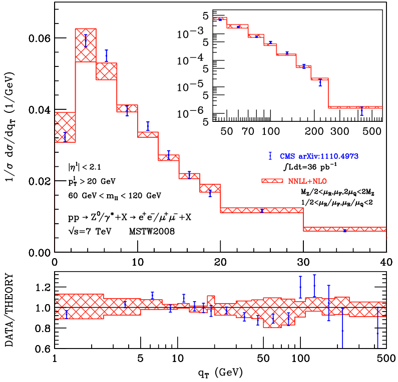
DY q_T-resummation with V boson decay



CMS data for the Z q_T spectrum compared with NNLL+NLO result. Scale variation:

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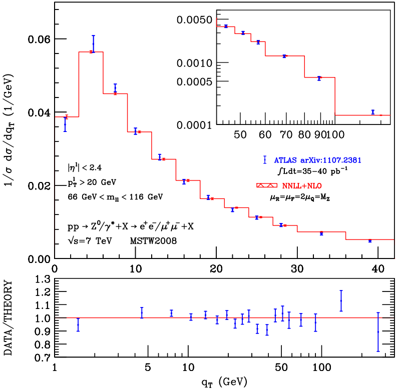
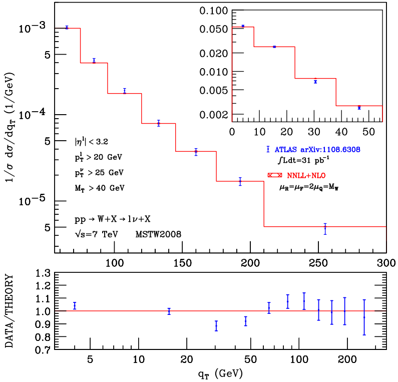
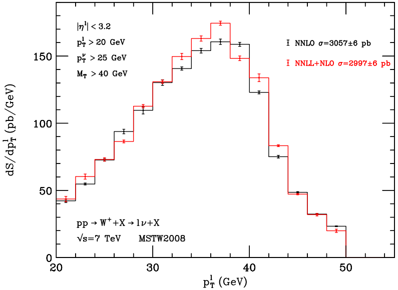


ATLAS data for the Z q_T spectrum compared with NNLL+NLO result.

DY q_T-resummation with V boson decay



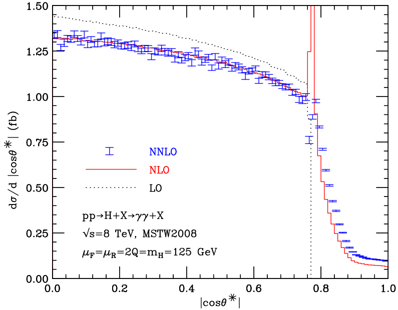
ATLAS data for the W q_T spectrum compared with NNLL+NLO result.

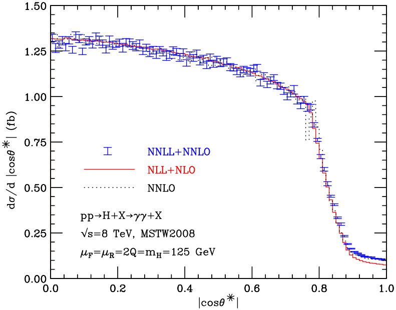


Lepton p_T spectrum from W^+ decay. NNLL+NLO result compared with the NNLO result.

Important spectrum for the measurement of M_W at the LHC.

$gg \to H$ q_T-resummation with H boson decay





Fixed order results for $|\cos\theta^*| = \sqrt{1 - 4p^2_{T,\gamma}/m^2_H}$ distribution at the LHC.

Resummed results for $|\cos\theta^*| = \sqrt{1 - 4p^2_{T,\gamma}/m^2_H}$ distribution at the LHC. Important spectrum for the measurement of M_W at the LHC.

Conclusions

- NNLL+NLO q_T-resummation for Drell-Yan and Higgs production in gluon fusion.

  Reduction of scale uncertainties from NLL+LO to NNLL+NLO accuracy. The NNLL+NLO results for Drell-Yan consistent with the experimental data in a wide region of q_T.
- Added full kinematical dependence on the vector/Higgs boson and on the final state leptons/photons.
- Preliminary comparison with LHC data (implementing experimental cuts): good agreement between data and NNLL+NLO results without any model for Non Perturbative effects.
- Public version of the numerical codes HqT/DYqT and HRes/DYRes available.

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Back up slides

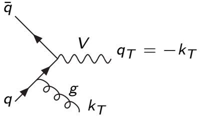
Fully-Exclusive Cross Sections at NNLO in hadron-collisions

- Experiments have finite acceptance, in particular *VH* experimental analyses performed in extreme kinematical regimes (e.g. boosted analysis with jet veto): important to provide exclusive theoretical predictions.
- At NLO general algorithms (e.g. Dipole formalism [Catani,Seymour('98)]) allow (relative) straightforward fully-exclusive calculations.
- At NNLO in hadronic collisions only few fully exclusive calculations exist:
    - Sector decomposition: [Binoth,Heinrich('00)]
      $gg \to H$ [Anastasiou,Melnikov,Petriello('04)]→FEHIP
      Drell-Yan [Melnikov,Petriello('06)]→FEWZ
    - q_T-subtraction:
      $gg \to H$ [Catani,Grazzini('07)]→HNNLO
      Drell-Yan [Catani,Cieri,de Florian,G.F.,Grazzini('09)]→DYNNLO
      Associated *WH* production [G.F.,Grazzini,Tramontano('11)]→ WNNLO
      Diphoton prod. [Catani,Cieri,de Florian,G.F.,Grazzini('11)]→2γNNLO

The q_T-subtraction formalism at NNLO

$$h_1(p_1) + h_2(p_2) \;\rightarrow\; V(M, q_T) + X$$

V is one or more colourless particles (vector bosons, leptons, photons, Higgs bosons,...) [Catani,Grazzini('07)].



- Key point I: at LO the q_T of the V is exactly zero.

$$d\sigma^{V}_{(N)NLO}|_{q_T \neq 0} = d\sigma^{V+\text{jets}}_{(N)LO} \quad ,$$

for $q_T \neq 0$ the NNLO IR divergences cancelled with the NLO subtraction method.

- The only remaining NNLO singularities are associated with the $q_T \rightarrow 0$ limit.
- Key point II: treat the NNLO singularities at $q_T = 0$ by an additional subtraction using the universality of logarithmically-enhanced contributions from q_T resummation formalism [Catani,de Florian,Grazzini('00)].

$$d\sigma^{V}_{N^nLO} \xrightarrow{q_T \rightarrow 0} d\sigma^{V}_{LO} \otimes \Sigma(q_T/M) dq_T^2 = d\sigma^{V}_{LO} \otimes \sum_{n=1}^{\infty} \sum_{k=1}^{2n} \left(\frac{\alpha_S}{\pi}\right)^n \Sigma^{(n,k)} \frac{M^2}{q_T^2} \ln^{k-1} \frac{M^2}{q_T^2} \, d^2 q_T$$

$$d\sigma^{CT} \xrightarrow{q_T \rightarrow 0} d\sigma^{V}_{LO} \otimes \Sigma(q_T/M) dq_T^2$$

The final result valid also for $q_T = 0$ is:

$$d\sigma^V_{(N)NLO} = \mathcal{H}^V_{(N)NLO} \otimes d\sigma^V_{LO} + \left[d\sigma^{V+\text{jets}}_{(N)LO} - d\sigma^{CT}_{(N)LO} \right] ,$$

$$\textit{where} \quad \mathcal{H}^V_{NNLO} = \left[1 + \frac{\alpha_S}{\pi} \mathcal{H}^{V(1)} + \left(\frac{\alpha_S}{\pi} \right)^2 \mathcal{H}^{V(2)} \right]$$

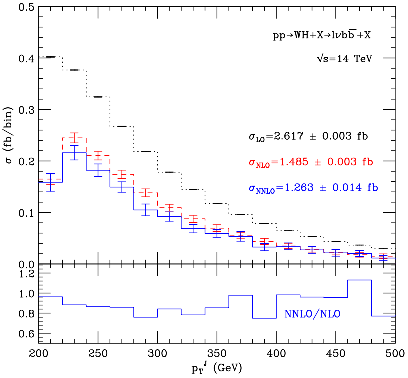
- The choice of the counter-term has some arbitrariness but it must behave $d\sigma^{CT} \stackrel{q_T \to 0}{\longrightarrow} d\sigma^V_{LO} \otimes \Sigma(q_T/M) dq_T^2$ where $\Sigma(q_T/M)$ is universal.
- $d\sigma^{CT}$ regularizes the $q_T = 0$ singularity of $d\sigma^{V+\text{jets}}$: *double real* and *real-virtual* NNLO contributions, while (the finite part of) *two-loops virtual* corrections are contained in $\mathcal{H}^V_{NNLO}$.
- Final state partons only appear in $d\sigma^{V+\text{jets}}$ so that NNLO IR-safe cuts are included in the NLO computation: observable-independent NNLO extension of the subtraction formalism.

Associated *WH* production in NNLO QCD

G.F.,Grazzini,Tramontano arXiv:1107.1164

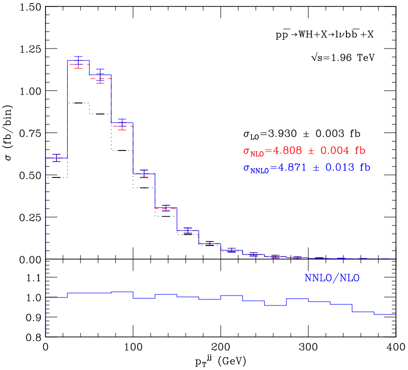
- A NLO calculation for $h_1 h_2 \to V + X$ requires:
  - $d\sigma_{LO}^{V+\text{jets}}$ (and $d\sigma_{LO}^{V}$).
  - $\mathcal{H}^{V(1)}$ [de Florian, Grazzini('01)]: contains the finite-part of the one-loop amplitude $c\bar{c} \to V$.
  - $d\sigma_{LO}^{CT}$: depends by the (universal) q_T-resummation coeff. A_1 and B_1.
- A NNLO calculation for $h_1 h_2 \to V + X$ requires also:
  - $d\sigma_{NLO}^{V+\text{jets}}$.
  - $\mathcal{H}^{V(2)}$: contains the finite-part of the two-loops amplitude $c\bar{c} \to V$.
  - $d\sigma_{NLO}^{CT}$: depends by the (universal) q_T-resummation coeff. A_2 and B_2.
- *WH* production at NNLO within q_T-subtraction:
  - $d\sigma_{NLO}^{WH+\text{jets}}$.
  - $\mathcal{H}^{DY(2)}$ [Catani,Cieri,de Florian,G.F.,Grazzini('12)].

Fully-exclusive NNLO calculation, implemented in the parton-level Monte Carlo code: [G.F.,Grazzini,Tramontano('11)]



$pp \to WH(\to l\nu\, b\bar{b})$
p_T spectra of the fat jet at the LHC@14TeV for $m_H = 120 GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

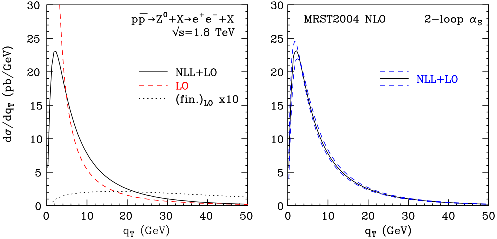
- Selection strategy of [Butterworth et al.('08)]: search a large-p_T Higgs boson thorough a collimated $b\bar{b}$ pair decay.
  Cuts:
  Leptons: $p_T^l > 30 GeV$, $|\eta^l| < 2.5$,
  $p_T^{miss} > 30 GeV$, $p_T^W > 200 GeV$.
  Jets: Cambridge/Aachen algorithm with R=1.2.
  Fat jet (contain the $b\bar{b}$) $p_T^J > 200 GeV$, $|\eta^J| < 2.5$
  Jet veto: No other jets with $p_T > 20 GeV$ and $|\eta| < 5$.
- Large negative higher-order corrections: NLO (NNLO) effects -52%/-36% (-6%/-19%), depending on the scale choice (factor two around $\mu_F = \mu_R = m_W + m_H$).
- Jet veto strongly affect the higher order corrections ⇒ stability of fixed order calculation challenged.



$p\bar{p} \to WH(\to l\nu\, b\bar{b})$
p_T spectra of the dijet system at the Tevatron for $m_H = 120GeV$ at LO (dots), NLO (dashes) and NNLO (solid).

- Cuts:
  Leptons: $p_T^l > 20GeV$, $|\eta^l| < 2$, $p_T^{miss} > 20GeV$.
  Jets: k_T algorithm with R=0.4.
  Exactly two jets (with $p_T > 20GeV$ and $|\eta| < 2$) at least one of them has to be a b jet (with $|\eta| < 1$).
- Higher-order corrections: NLO (NNLO) effects from $+13\%$ to $+30\%$ (from -1% to $+4\%$) depending on the scale choice (factor two around $\mu_F = \mu_R = m_W + m_H$). The scale dependence is at the level of about $\pm 1\%$ both at NLO and NNLO.
- The shape of the distribution is stable against perturbative corrections. Perturbative expansion under good control.

Resummed results: q_T spectrum of Drell-Yan e^+e^- pairs at $\sqrt{s} = 1.8\ TeV$



- Left side: NLL+LO result compared with fixed LO result. Resummation cure the fixed order divergence at $q_T \to 0$.
- Right side: variation of factorization and renormalization scales as in customary fixed-order calculations: $\sim 5\%$ at low q_T, $\sim 9\%$ at $q_T \sim 50\ GeV$.
- Finite LO component contribution is: $\lesssim 1\%$ near the peak, $\sim 8\%$ at $q_T \sim 20\ GeV$, $\sim 60\%$ at $q_T \sim 50\ GeV$.
- Integral of the NLL+LO curve reproduce the total NLO cross section to better 1% (check of the code).

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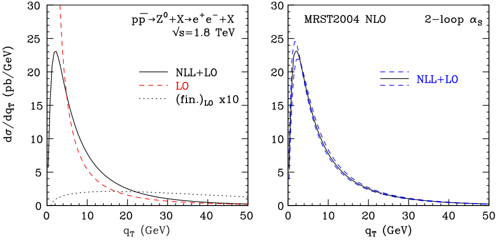

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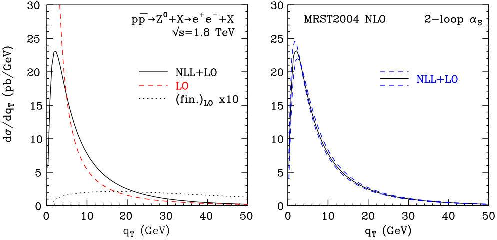

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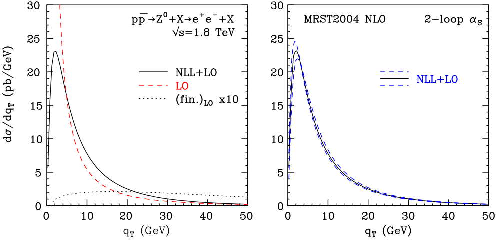

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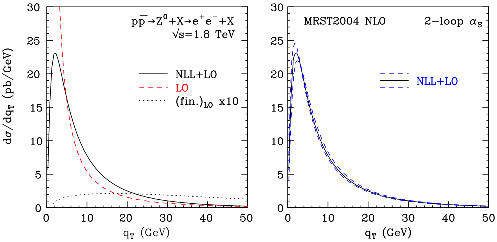

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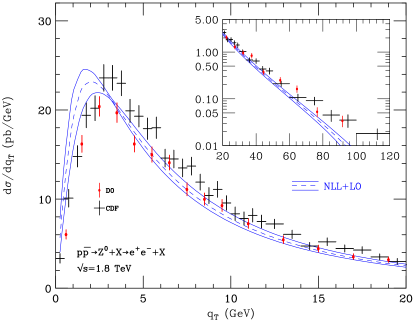

- CDF data: $66\ GeV < M^2 < 116\ GeV$, $\sigma_{tot} = 248 \pm 11\ pb$ [CDF Collaboration ('00)]
  D0 data: $75\ GeV < M^2 < 105\ GeV$, $\sigma_{tot} = 221 \pm 11\ pb$ [D0 Collaboration ('00)]
- Our calculation implements $\gamma^* Z$ interference and finite-width effects. Here we use the narrow width approximation (differences within 1% level).
- NLL+LO resummed result fits reasonably well also in the $q_T \lesssim 20\ GeV$ (without a model for non-perturbative effects).
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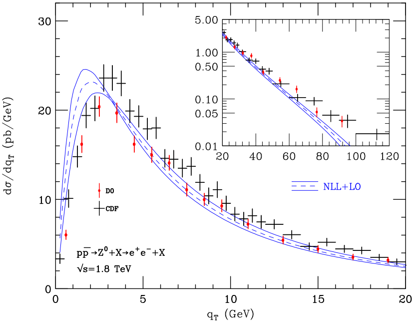

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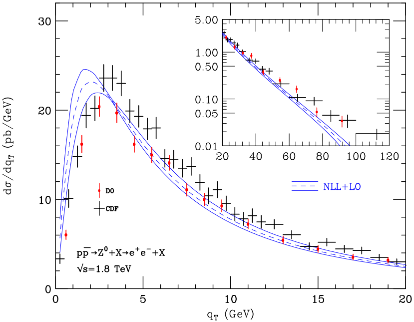

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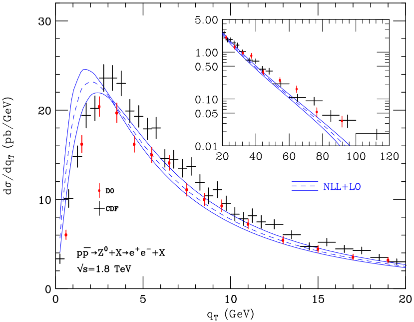

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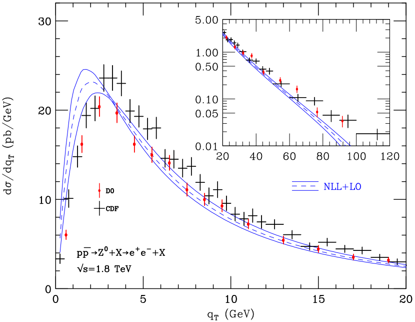

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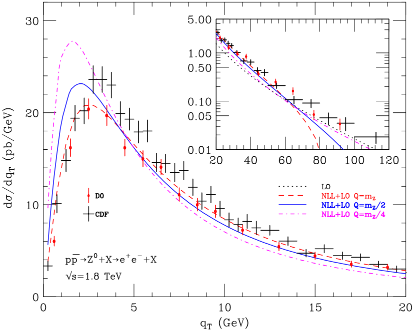

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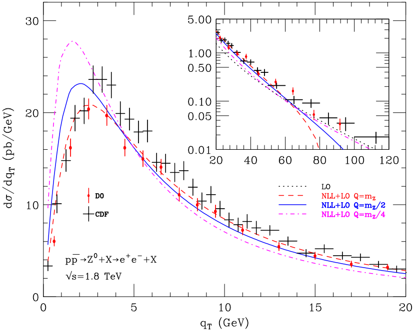

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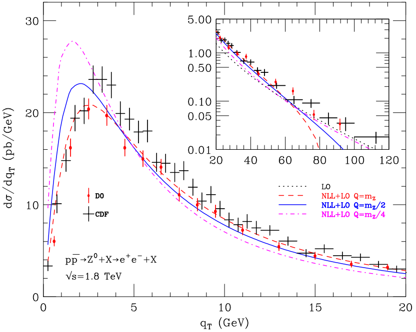

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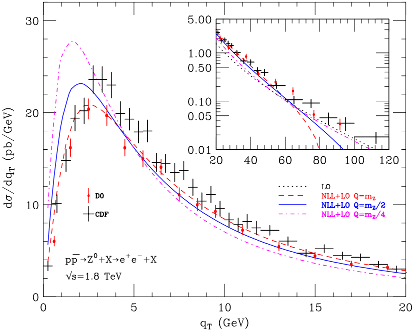

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