Non Perturbative QCD effects in qT spectra of DY and Z-boson production

Ignazio Scimemi (UCM)

based on:
arXiv: JHEP1 1(2014)098 with U. D' Alesio (Cagliari), M.G. Echevarría (NIKHEF), S. Melis (Torino)

and also EIS (Echevarria, Idilbi, Scimemi) FORMALISM:
PRD90 (2014) 014003, PLB726(2013) 795, JHEP1207 (2012) 002
EIS+A. Schafer, EPJC 73(2013)2636

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Topics and outline

* At hadron colliders the peaks of transverse momentum spectra for boson production are located at small qT or pT: these regions are affected by non-perturbative QCD effects. We need a method to treat them.

* Transverse momentum distributions involve non-perturbative QCD effects which go beyond the usual PDF formalism. New factorization theorem are required. (Collins '11, Echevarría-Idilbi-S. '12)

* Other processes: Spin dependent observables and transverse momentum dependent observables need factorization theorems with TMD's

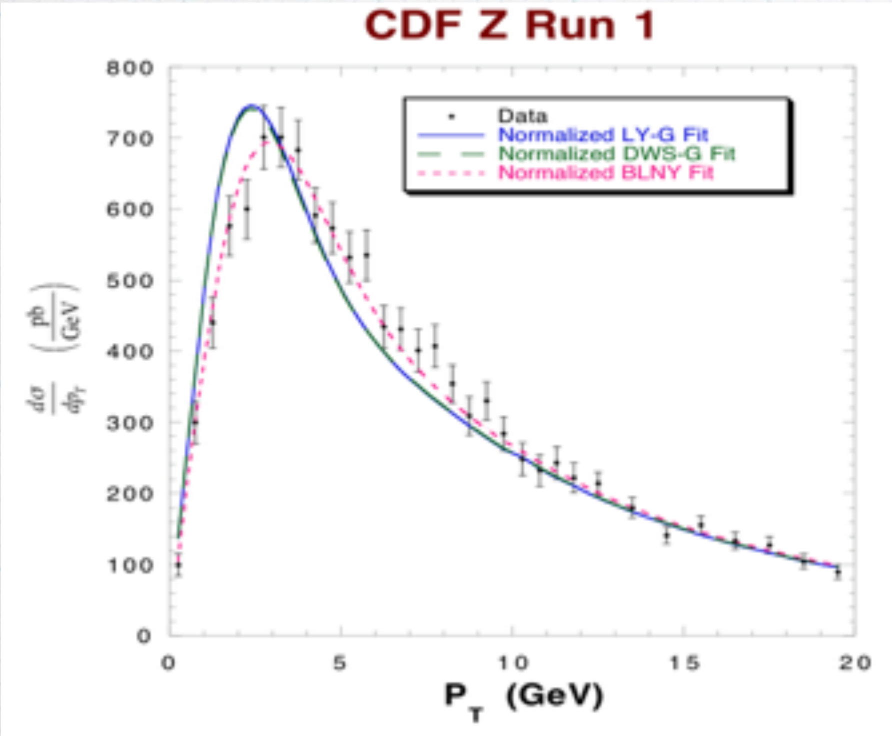
* We need to construct both perturbative and non-perturbative parts of TMD's compatibly with factorization theorems, maximizing the calculable information at our disposal.

* Properties of TMD's:
  1) The evolution of all TMD's is universal (alike PDF and FF it is process independent)
  2) The evolution of all TMD's is spin independent and it is the same for TMDPDF and TMDFF

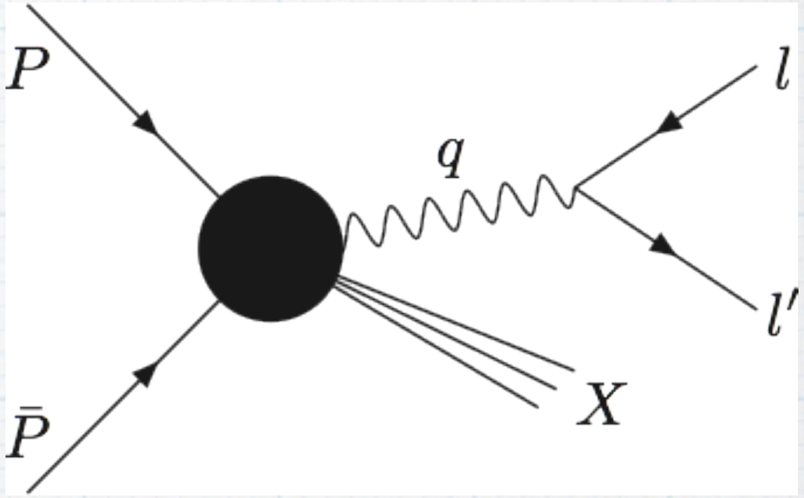
* We can map all these non-perturbative effects fitting DY, SIDIS, ee data at low M:

* Here results for DY fit and predictions for CMS

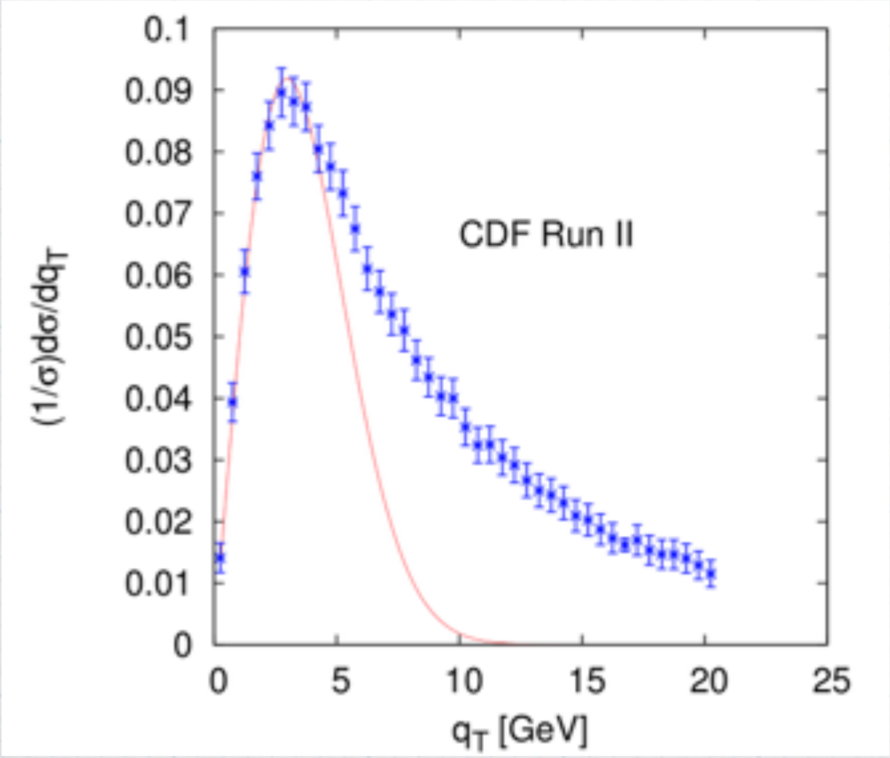
Example: Z case



Landry et al. Phys.Rev. D67 (2003) 073016

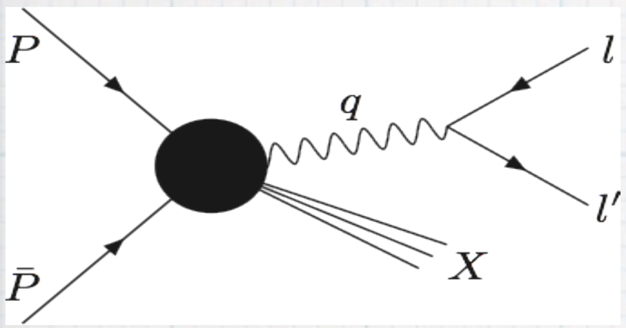


We want to describe several energy regimes



S. Melis, arXiv:1412.1719, Gaussian model

Energy scales: DY/Z



$$\boxed{q^2 = Q^2 \gg q_T^2}$$

Q=M=dilepton invariant mass

$$q_T^2 \sim \Lambda_{QCD}^2 \Longrightarrow \tilde{M} = H(Q^2/\mu^2)\, \tilde{F}_n(x_n, b; Q^2, \mu^2)\, \tilde{F}_{\bar{n}}(x_{\bar{n}}, b; Q^2, \mu^2)$$

$$q_T^2 \gg \Lambda_{QCD}^2 \Longrightarrow \tilde{M} = H(Q^2/\mu^2)\, \tilde{C}_n(b^2\mu^2, Q^2/\mu^2)\, \tilde{C}_{\bar{n}}(b^2\mu^2, Q^2/\mu^2)\, f_n(x_n;\mu^2)\, f_{\bar{n}}(x_{\bar{n}};\mu^2)$$

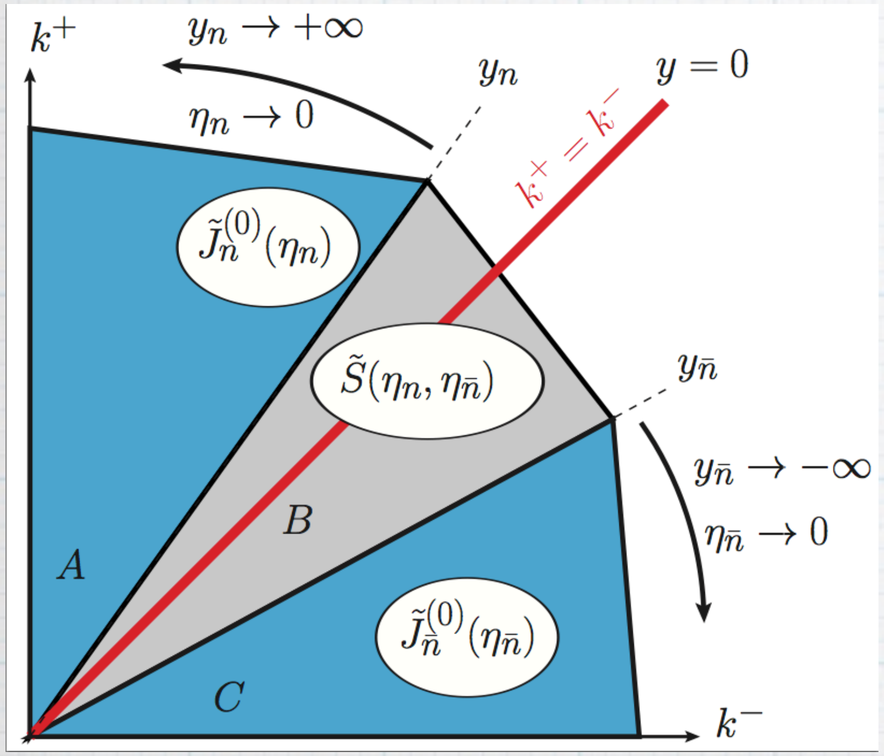
All coefficients are extracted matching effective field theories. During the matching the IR parts have to be regulated consistently above and below the matching scales

Processes with several energy scales are more easily treated with EFT

$$\text{QCD} \xrightarrow{q_T^2 \gg \Lambda_{QCD}^2} \text{SCET}_{q_T} \xrightarrow{q_T^2 \sim \Lambda_{QCD}^2} \text{SCET}_{\Lambda_{\text{QCD}}}$$

Modes in EFT

Using power counting we have collinear, anti-collinear, and soft sectors



$$H(Q^2)\, \tilde{J}_n^{(0)}(\eta_n)\, \tilde{S}(\eta_n, \eta_{\bar{n}})\, \tilde{J}_{\bar{n}}^{(0)}(\eta_{\bar{n}})$$

$$\tilde{F}_n = \tilde{J}_n^{(0)}(\eta_n)\sqrt{\tilde{S}(\eta_n, \eta_n)}$$

$$\tilde{F}_{\bar{n}} = \tilde{J}_{\bar{n}}^{(0)}(\eta_{\bar{n}})\sqrt{\tilde{S}(\eta_{\bar{n}}, \eta_{\bar{n}})}$$

(+,-,perp)

$$k_n \sim Q(1, \lambda^2, \lambda) \quad \to \quad y \gg 0$$
$$k_{\bar{n}} \sim Q(\lambda^2, 1, \lambda) \quad \to \quad y \ll 0$$
$$k_s \sim Q(\lambda, \lambda, \lambda) \quad \to \quad y \approx 0$$
$$\lambda \sim \frac{q_T}{Q}$$

- A well-defined TMDPDF should:

1. Be compatible with a factorization theorem.
2. Have no mixed UV/nUV divergencies, i.e., be renormalizable
3. Have a matching coefficient onto PDFs independent of nUV regulators.

Evolution kernel for TMD's

$$\frac{d}{d\ln\zeta_F}\ln\tilde{F}^{[\Gamma]}_{f/N}(x,\mathbf{b}_\perp,S;\zeta_F,\mu^2) = -D(b_T;\mu^2)\,,$$
$$\frac{d}{d\ln\zeta_D}\ln\tilde{D}^{[\Gamma]}_{h/f}(z,\mathbf{b}_\perp,S_h;\zeta_D,\mu^2) = -D(b_T;\mu^2)\,.$$

$$\frac{dD}{d\ln\mu} = \Gamma_{cusp}$$

$$\tilde{F}^{[\Gamma]}_{f/N}(x,\mathbf{b}_\perp,S;\zeta_{F,f},\mu_f^2) = \tilde{F}^{[\Gamma]}_{f/N}(x,\mathbf{b}_\perp,S;\zeta_{F,i},\mu_i^2)\,\tilde{R}\left(b_T;\zeta_{F,i},\mu_i^2,\zeta_{F,f},\mu_f^2\right)\,,$$
$$\tilde{D}^{[\Gamma]}_{h/f}(z,\mathbf{b}_\perp,S_h;\zeta_{D,f},\mu_f^2) = \tilde{D}^{[\Gamma]}_{h/f}(z,\mathbf{b}_\perp,S_h;\zeta_{D,i},\mu_i^2)\,\tilde{R}\left(b_T;\zeta_{D,i},\mu_i^2,\zeta_{D,f},\mu_f^2\right)\,,$$
$$\boxed{\tilde{R}(b;\zeta_i,\mu_i^2,\zeta_f,\mu_f^2) = \exp\left\{\int_{\mu_i}^{\mu_f}\frac{d\bar{\mu}}{\bar{\mu}}\,\gamma\left(\alpha_s(\bar{\mu}),\ln\frac{\zeta_f}{\bar{\mu}^2}\right)\right\}\left(\frac{\zeta_f}{\zeta_i}\right)^{-D(b_T;\mu_i)}}\,,$$

We evolve from one M to another

Consistently the A.D. of the TMD is the opposite of the one of the hard coefficient

$$\gamma_H = -\gamma_F\left(\alpha_s(\mu),\ln\frac{\zeta_F}{\mu^2}\right) - \gamma_D\left(\alpha_s(\mu),\ln\frac{\zeta_D}{\mu^2}\right)$$

$$\gamma_{F,D}\left(\alpha_s(\mu),\ln\frac{\zeta_{F,D}}{\mu^2}\right) = -\Gamma_{\rm cusp}(\alpha_s(\mu))\ln\frac{\zeta_{F,D}}{\mu^2} - \gamma^V(\alpha_s(\mu))$$

D-resummation

$$\frac{dD(b;\mu)}{d\ln\mu} = \Gamma_{cusp}(\alpha_s)$$

$$D(b;\mu) = \sum_{n=1}^{\infty} d_n(L_\perp)\left(\frac{\alpha_s}{4\pi}\right)^n$$

LL NLL NNLL

$$\begin{aligned}
d_1(L_\perp) &= d_1^{(1)}L_\perp + d_1^{(0)} \\
d_2(L_\perp) &= d_2^{(2)}L_\perp^2 + d_2^{(1)}L_\perp + d_2^{(0)} \\
d_3(L_\perp) &= d_3^{(3)}L_\perp^3 + d_3^{(2)}L_\perp^2 + d_3^{(1)}L_\perp + d_3^{(0)} \\
d_4(L_\perp) &= d_4^{(4)}L_\perp^4 + d_4^{(3)}L_\perp^3 + d_4^{(2)}L_\perp^2 + d_4^{(1)}L_\perp + d_4^{(0)} \\
d_5(L_\perp) &= \ldots
\end{aligned}$$

$$D\left(b;Q_i\right) = D\left(b;\mu_b\right) + \int_{\mu_b}^{Q_i}\frac{d\bar\mu}{\bar\mu}\Gamma_{\text{cusp}}; \qquad \mu_b = 2e^{-\gamma_E}/b$$

$$D(b;Q_i) = -\frac{\Gamma_0}{2\beta_0}\ln\frac{\alpha_s(Q_i)}{\alpha_s(\mu_b)} \longrightarrow D(b;Q_i) = -\frac{\Gamma_0}{2\beta_0}\ln(1-X)$$

$$\alpha_s(\mu_b) = \alpha_s(Q)/(1-X)$$

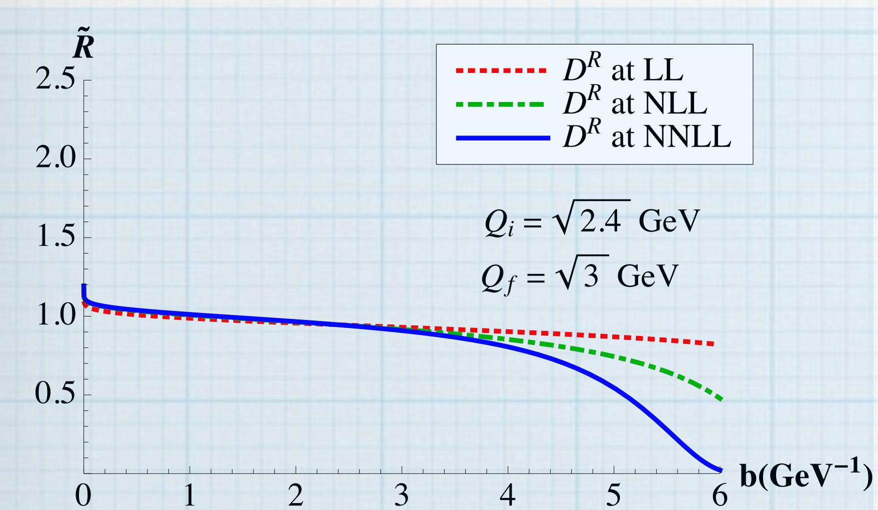
Landau pole

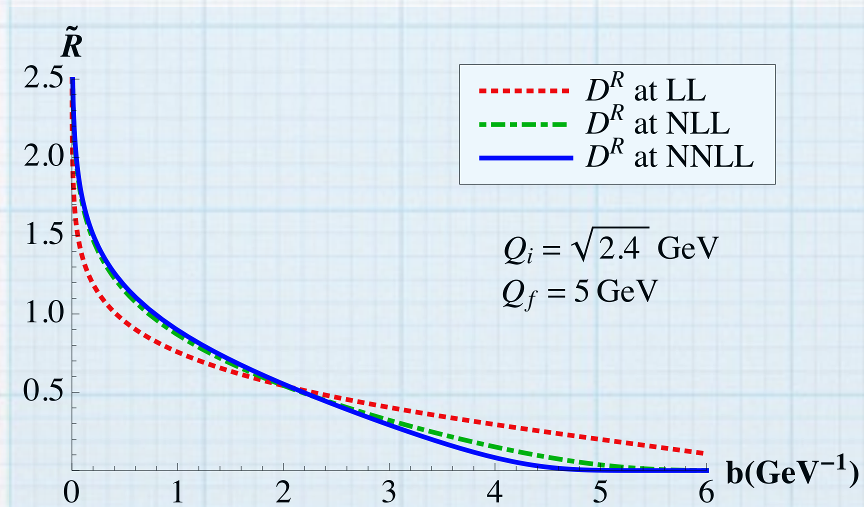
The perturbative expansion of the D is valid in limited (but large, using **resummation**) portion of Impact Parameter Space.

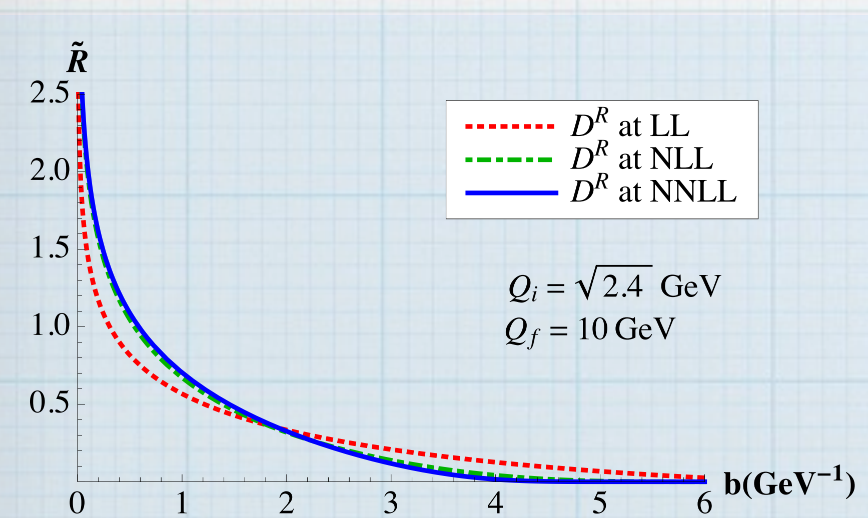
Is the bulk of the evolution kernel given by the Landau pole region?

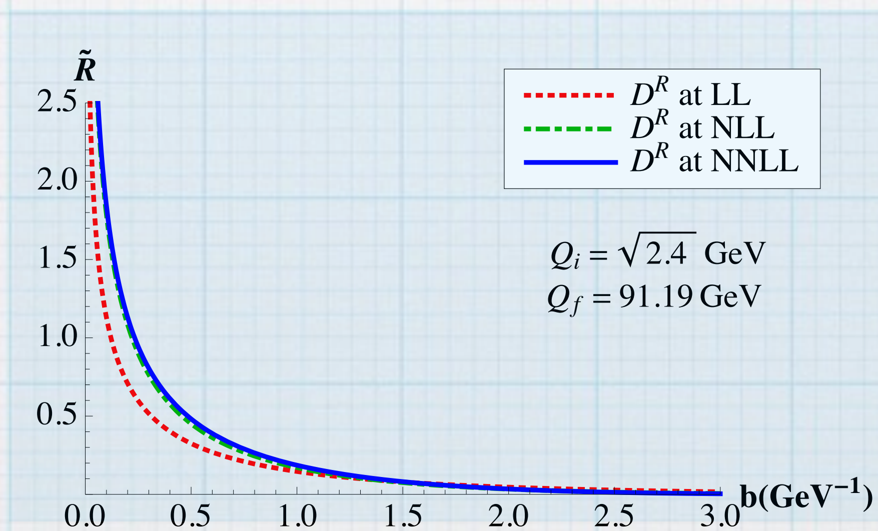
If the answer is yes we are almost lost ..

Plots for resummed evolution kernel









- Very good convergence up to b=4-5/GeV in all cases
- The region sensitive to the Landau pole is strongly suppressed b>5/GeV
- For Q_f=M_Z we are sensitive only to b<1.5/GeV region
- For Q_f=3-5 GeV we are sensitive only to b<4/GeV region
- For Q_f <2 GeV we can be sensitive to the Landau pole region

- Studying processes at different energies one explores different regions in IPS
- The Landau pole problems appear there where also the Factorization Hyp. fails

Unpolarized TMDPF: construction and fits

* Basic test, preliminary to all spin dependent analysis, many ingredients as in standard perturbative QCD.

* More or less standard recipe for TMD construction (CSS, ...):
  - take the asymptotic limit of the TMDPDF

Common to all analysis:
Florence (Catani et al.), Zurich (Gehrmann. et al)

$$\tilde{F}_{q/N}(x,\vec{b},Q_i,\mu) = \left(\frac{Q_i^2 b^2}{4e^{2\gamma_E}}\right)^{-D_R(b,\mu)} \sum_j \tilde{C}_{q\leftarrow j}(x,\vec{b}_\perp,\mu) \otimes f_{j/N}(x;\mu) \otimes M_q(x,\vec{b},Q_i)$$

OPE to PDF, valid for qT>> Λ_{QCD}

PDF

Process independent
Non-perturbative correction

  - Exponentiation of part of the coefficient and complete resummation of the logs in the exponent
(Kodaira, Trentadue 1982, Becher, Neubert Wilhelm 2011)

$$\tilde{C}_{q\leftarrow j}(x,\vec{b}_\perp,\mu) \equiv \exp(h_\Gamma - h_\gamma)\hat{C}_{q\leftarrow j}(x,\vec{b}_\perp,\mu)$$

$$\frac{dh_\Gamma}{d\ln\mu} = \Gamma_{cusp} L_\perp$$

Same resummation as for the D

$$\frac{dh_\gamma}{d\ln\mu} = \gamma^V$$

$$h_\Gamma^R(b,\mu) = \int_{\alpha_s(1/\hat{b})}^{\alpha_s(\mu)} d\alpha' \frac{\Gamma_{cusp}^F(\alpha')}{\beta(\alpha')} \int_{\alpha_s(1/\hat{b})}^{\alpha'} \frac{d\alpha}{\beta(\alpha)} .$$

finally write a(1/b) in terms of a(mu) and fix mu=Qi.

Logs are minimized with the choice Qi=Q0+qT

Experimental Data

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
points	32	16	41	9
$\sqrt{s}$	1.8 TeV	1.8 TeV	1.96 TeV	1.96 TeV
σ	248 ± 11 pb	221 ± 11.2 pb	256 ± 15.2 pb	255.8 ± 16.7 pb

Z, run I: Becher, Neubert, Wilhelm 2011
Catani et al. 2009:
ad-hoc assumptions just for these data

	E288 200	E288 300	E288 400	R209
points	35	35	49	6
$\sqrt{s}$	19.4 GeV	23.8 GeV	27.4 GeV	62 GeV
E_{beam}	200 GeV	300 GeV	400 GeV	-
Beam/Target	p Cu	p Cu	p Cu	p p
M range used	4-9 GeV	4-9 GeV	5-9 and 10.5-14 GeV	5-8 and 11-25 GeV
Other kin. var	y=0.4	y=0.21	y=0.03	
Observable	$Ed^3\sigma/d^3\mathbf{p}$	$Ed^3\sigma/d^3\mathbf{p}$	$Ed^3\sigma/d^3\mathbf{p}$	$d\sigma/dq_T^2$

Expected to be insensitive to Landau pole region
Factorization hypothesis hold

Theoretical settings

* Matching scale of TMDPDF to PDF at Qi=2 GeV+qT
* Hard coefficient with π^2 resummation (Ahrens, Becher, Lin Yang, Neubert '08)
* Checked both NLL and NNLL
* Several sets of PDF checked (MSTW, CTEQ)
* Checked several form of non-perturbative models: gaussian, exponential, Q-dependence, ...
* Non-perturbative input

$$M_q(x,\vec{b},Q_i)=\exp[-\lambda_1 b](1+b^2\lambda_2+\dots)$$

Order	γ	Γcusp	C	D
LL	-	α	tree	-
NLL	α	α^2	tree	α
NNLL	α^2	α^3	α	α^2
NNNLL	α^3	α^4	α^2	α^3

$$\alpha_s L_\perp \sim 1$$

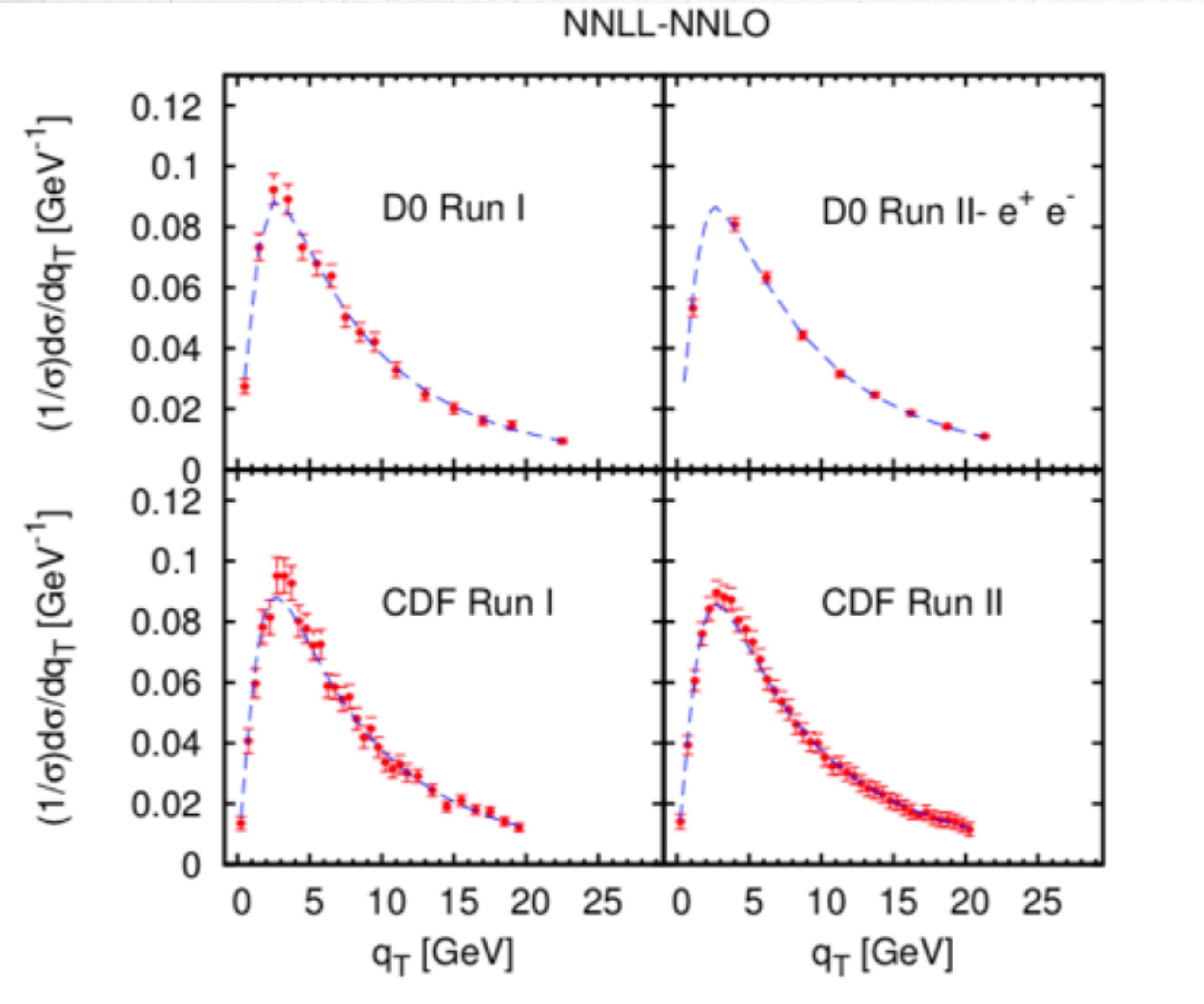
Naive attempts

Aybat, Collins , Qiu, Rogers; Aybat, Rogers; Anselmino, Boglione,Melis

EIS

Known pieces: C for unpolarized TMD from Catani et al. '12, Gehrmann, Luebbert. Lin Yang '12, '14

Results at NNLL: Z production



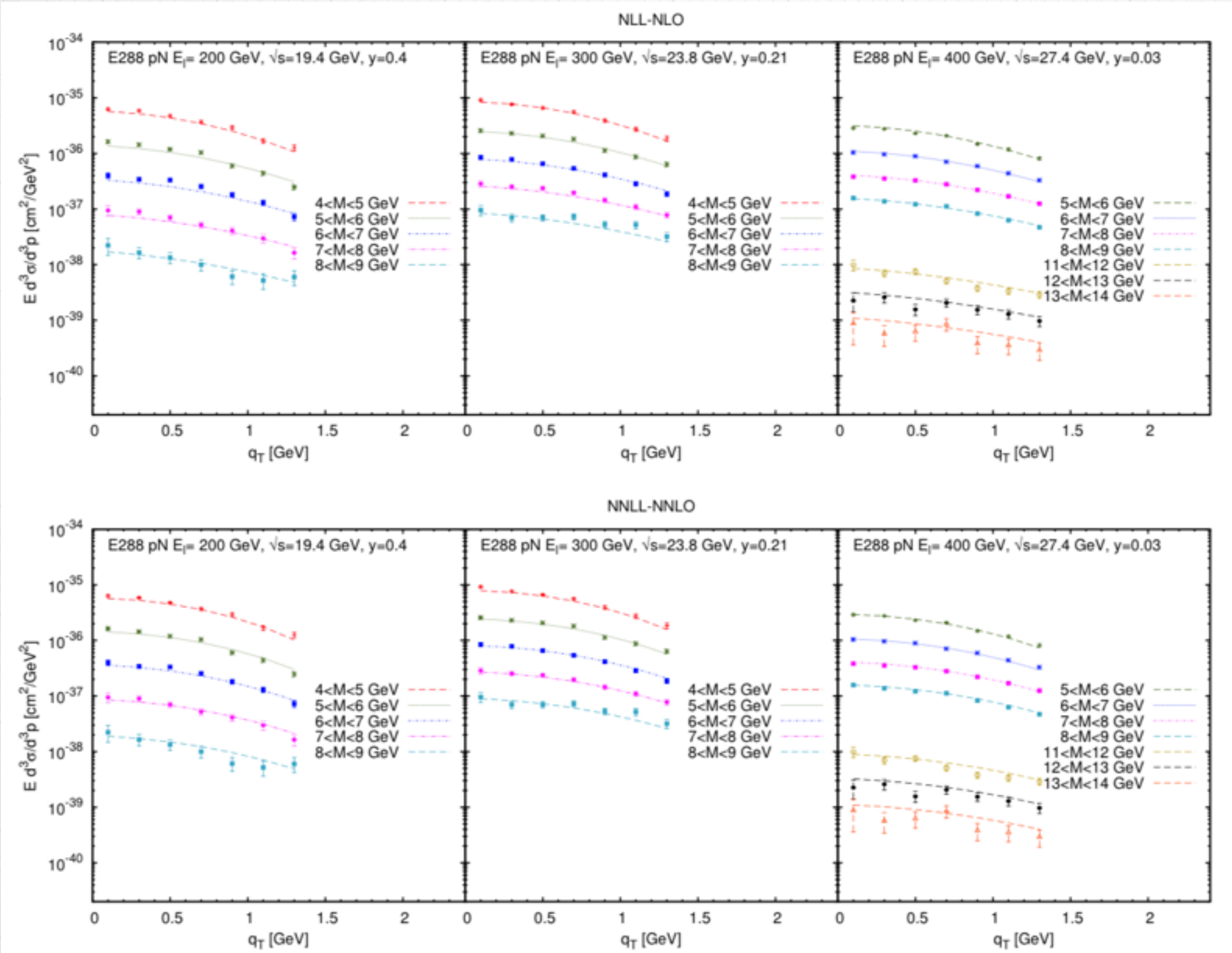
Z-boson data are (fairly) sensitive to functional non-perturbative form (gaussian vs exponential) and (poorly) sensitive just to λ_1.
In order to fix it we need the global fit

Data: $$\frac{1}{\sigma_{exp}}\left(\frac{d\sigma}{dq_T}\right)_{exp}$$

Theory: $$\frac{1}{\sigma_{th}}\left(\frac{d\sigma}{dq_T}\right)_{th}$$

DYNNLO: Catani, Grazzini '07, Catani, Cieri, Ferrera, de Florian, Grazzini '09

Results at NNLL



Exp. Normalization
NE288, NR209
deduced from the fit.

Total: 4 parameters

Results: PDF choice

Overall chi^2 good!

MSTW08

		NNLL, NNLO	NLL, NLO
	points	χ^2/points	χ^2/points
	223	1.10	1.48
E288 200	35	1.53	2.60
E288 300	35	1.50	1.12
E288 400	49	2.07	1.79
R209	6	0.16	0.25
CDF Run I	32	0.74	1.31
D0 Run I	16	0.43	1.44
CDF Run II	41	0.30	0.62
D0 Run II	9	0.61	2.40

NLL	223 points	χ^2/d.o.f. $= 1.51$
	$\lambda_1 = 0.26^{+0.05_{\rm th}}_{-0.02_{\rm th}} \pm 0.05_{\rm stat}$ GeV	$\lambda_2 = 0.13 \pm 0.01_{\rm th} \pm 0.03_{\rm stat}$ GeV^2
	$N_{\rm E288} = 0.9^{+0.2_{\rm th}}_{-0.1_{\rm th}} \pm 0.04_{\rm stat}$	$N_{\rm R209} = 1.3 \pm 0.01_{\rm th} \pm 0.2_{\rm stat}$
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	$N_{\rm E288} = 0.85 \pm 0.01_{\rm th} \pm 0.04_{\rm stat}$	$N_{\rm R209} = 1.5 \pm 0.01_{\rm th} \pm 0.2_{\rm stat}$

CTEQ10

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NLL	223 points	$\chi^2/\mathrm{dof} = 1.79$
	$\lambda_1 = 0.28 \pm 0.05_{\rm stat}$ GeV	$\lambda_2 = 0.14 \pm 0.04_{\rm stat}$ GeV^2
	$N_{\rm E288} = 1.02 \pm 0.04_{\rm stat}$	$N_{\rm R209} = 1.4 \pm 0.2_{\rm stat}$
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Results: PDF choice

Improvement NLL->NNLL

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Results: PDF choice

Values for fit parameters

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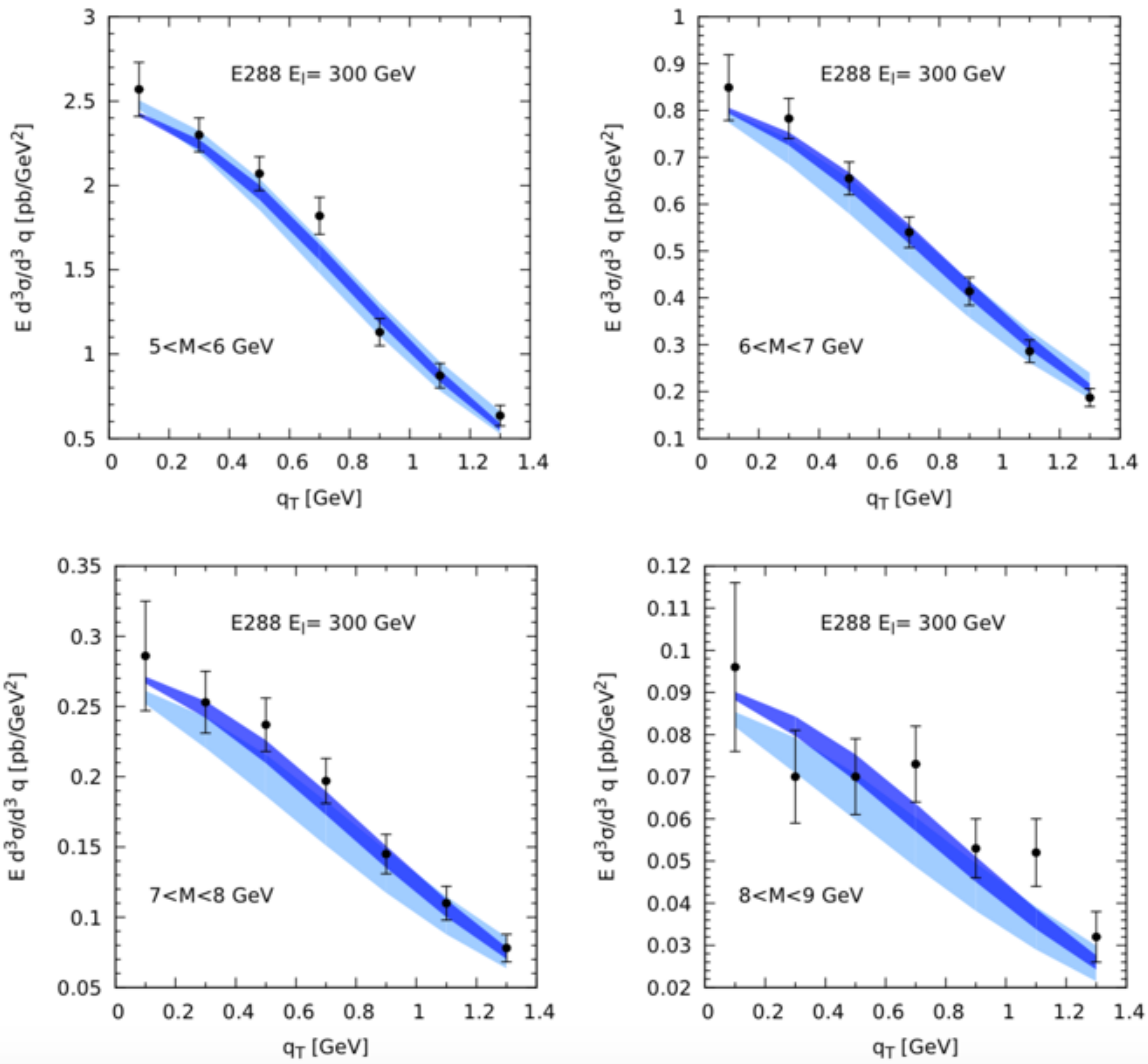
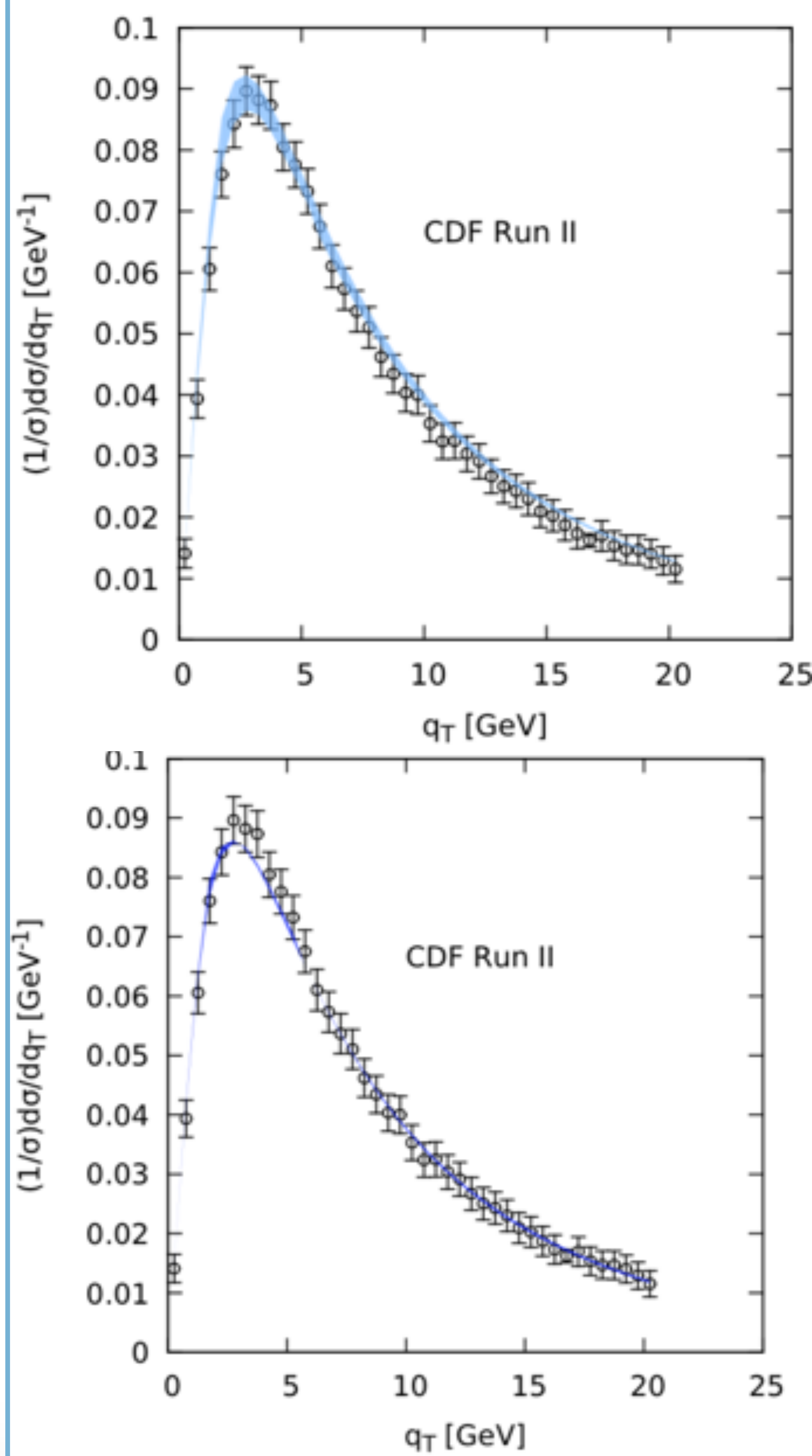
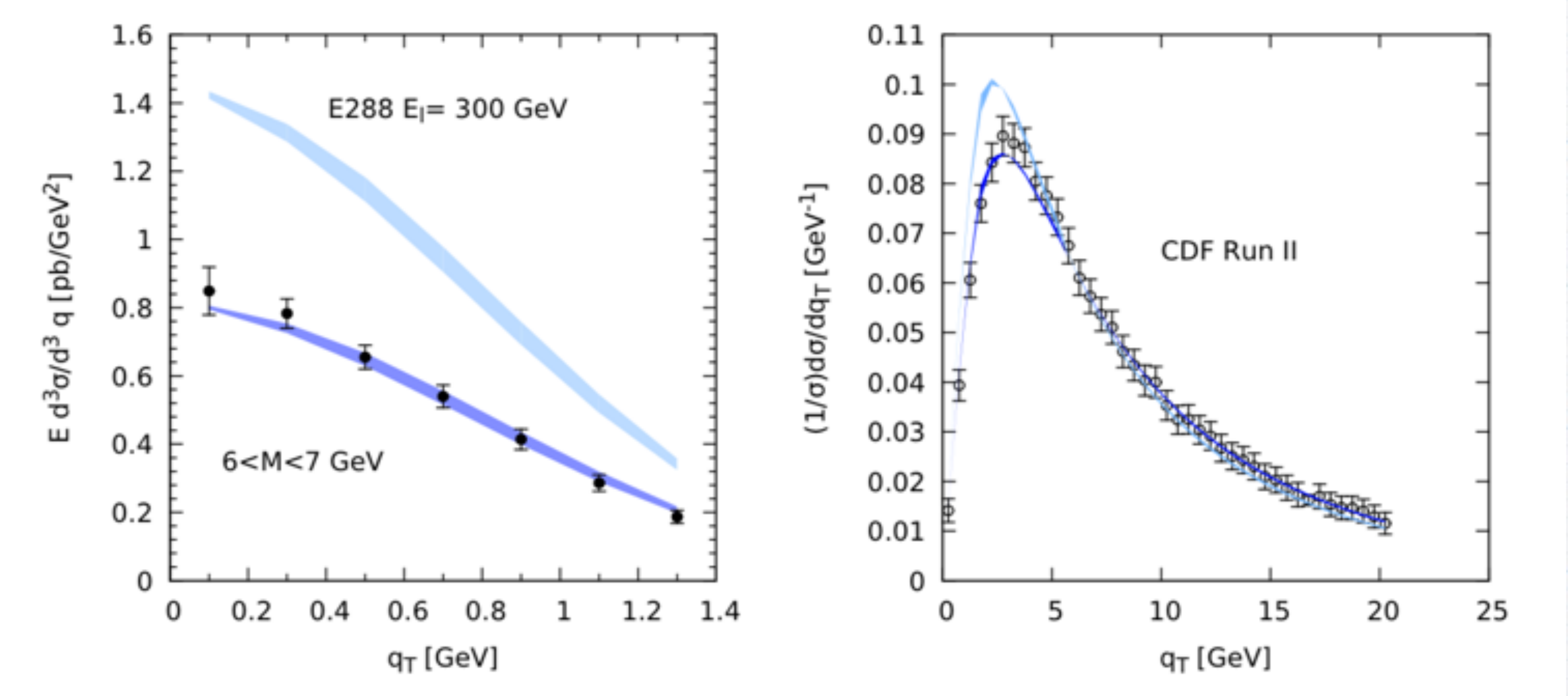
Scale dependence





Model dependence



Non-perturbative inputs necessary for the peak region in Z-production

Theoretical arguments suggest also a non-perturbative Q-dependence of the evolution kernel (check RESBOS).
We test

$$M_q(x,b,Q) = \exp[-\lambda_1 b]\,(1+\lambda_2 b^2+\ldots)\left(\frac{Q^2}{Q_0^2}\right)^{-\lambda_3 b^2/2}$$

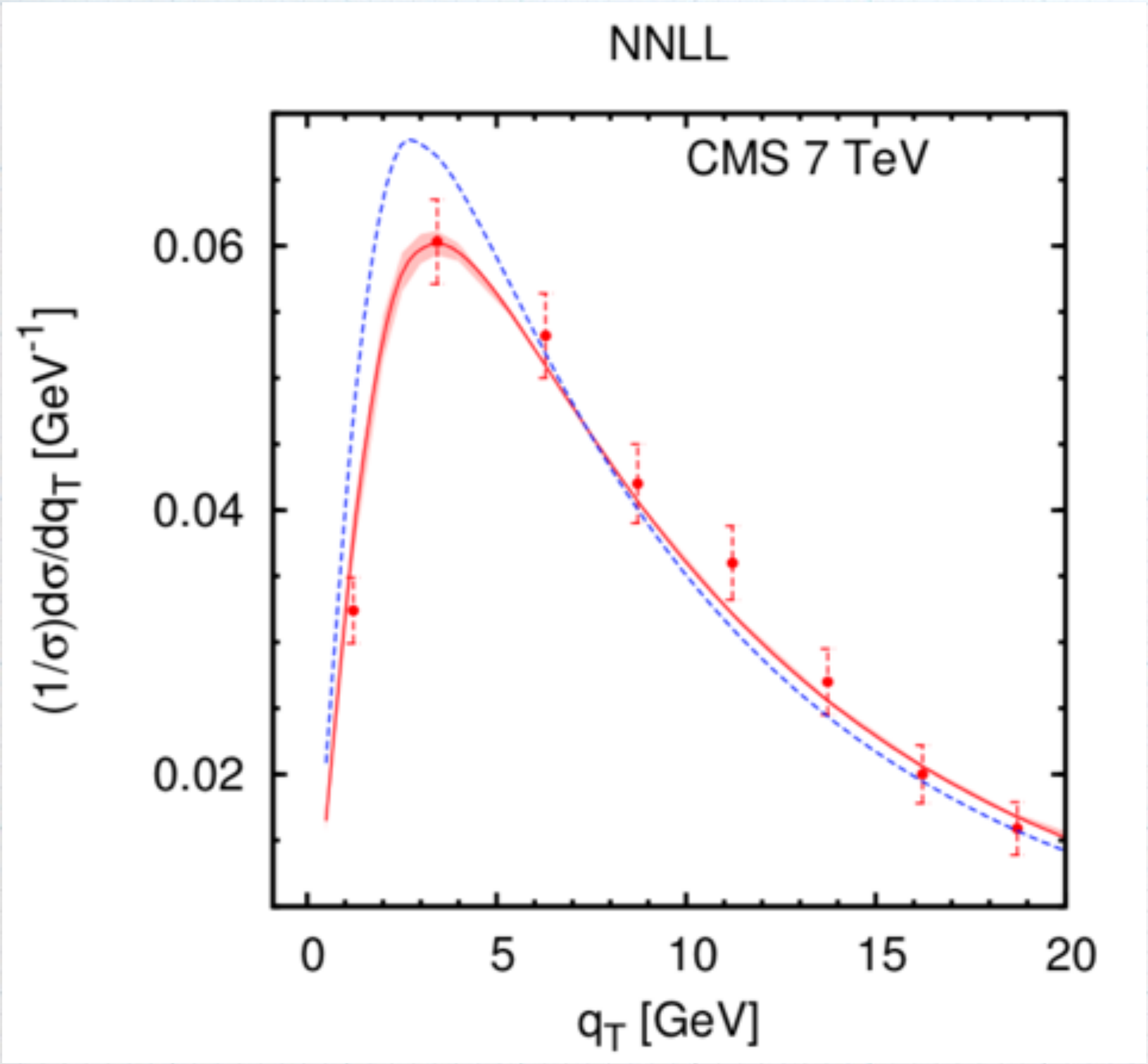
Model dependence

$Q_0 = 2.0$ GeV $+ q_T$		NNLL	NLL
λ_1		$0.29 \pm 0.04_{\rm stat}$ GeV	$0.27 \pm 0.06_{\rm stat}$ GeV
λ_2		$0.170 \pm 0.003_{\rm stat}$ GeV^2	$0.19 \pm 0.06_{\rm stat}$ GeV^2
λ_3		$0.030 \pm 0.01_{\rm stat}$ GeV^2	$0.02 \pm 0.01_{\rm stat}$ GeV^2
N_{E288}		$0.93 \pm 0.01_{\rm stat}$	$0.98 \pm 0.06_{\rm stat}$
N_{R209}		$1.5 \pm 0.1_{\rm stat}$	$1.3 \pm 0.2_{\rm stat}$
χ^2		180.1	375.2
	points	χ^2/points	χ^2/points
	223	0.81	1.68
	points	χ^2/dof	χ^2/dof
	223	0.83	1.72
E288 200	35	1.35	2.28
E288 300	35	0.98	1.22
E288 400	49	1.05	2.33
R209	6	0.27	0.40
CDF Run I	32	0.70	1.50
D0 Run I	16	0.41	1.77
CDF Run II	41	0.25	0.76
D0 Run II	9	0.82	3.2

No significative improvement:
1- Resummation in the evolution kernel greatly reduce TMD model dependence
2- The bulk of non-perturbative QCD corrections is scale independent

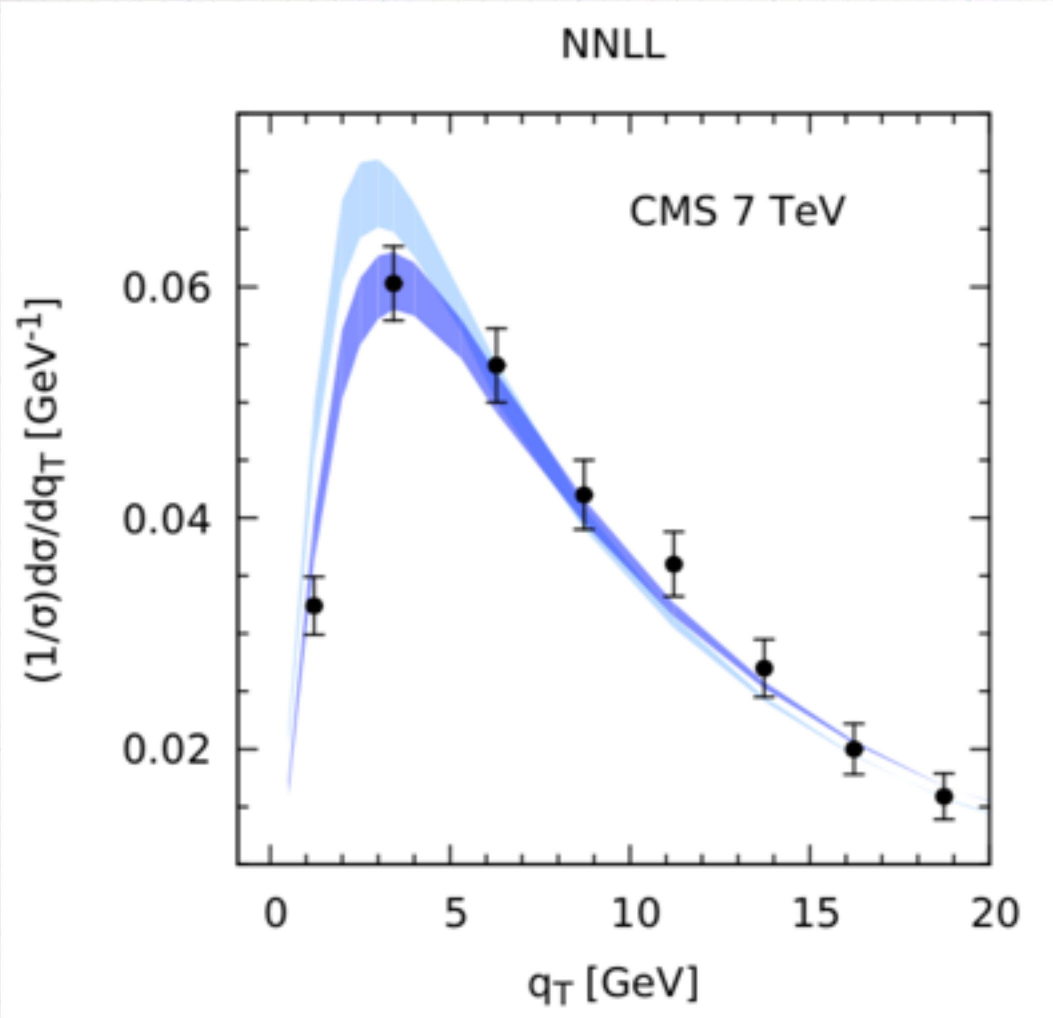
CTEQ10

Predictions for CMS



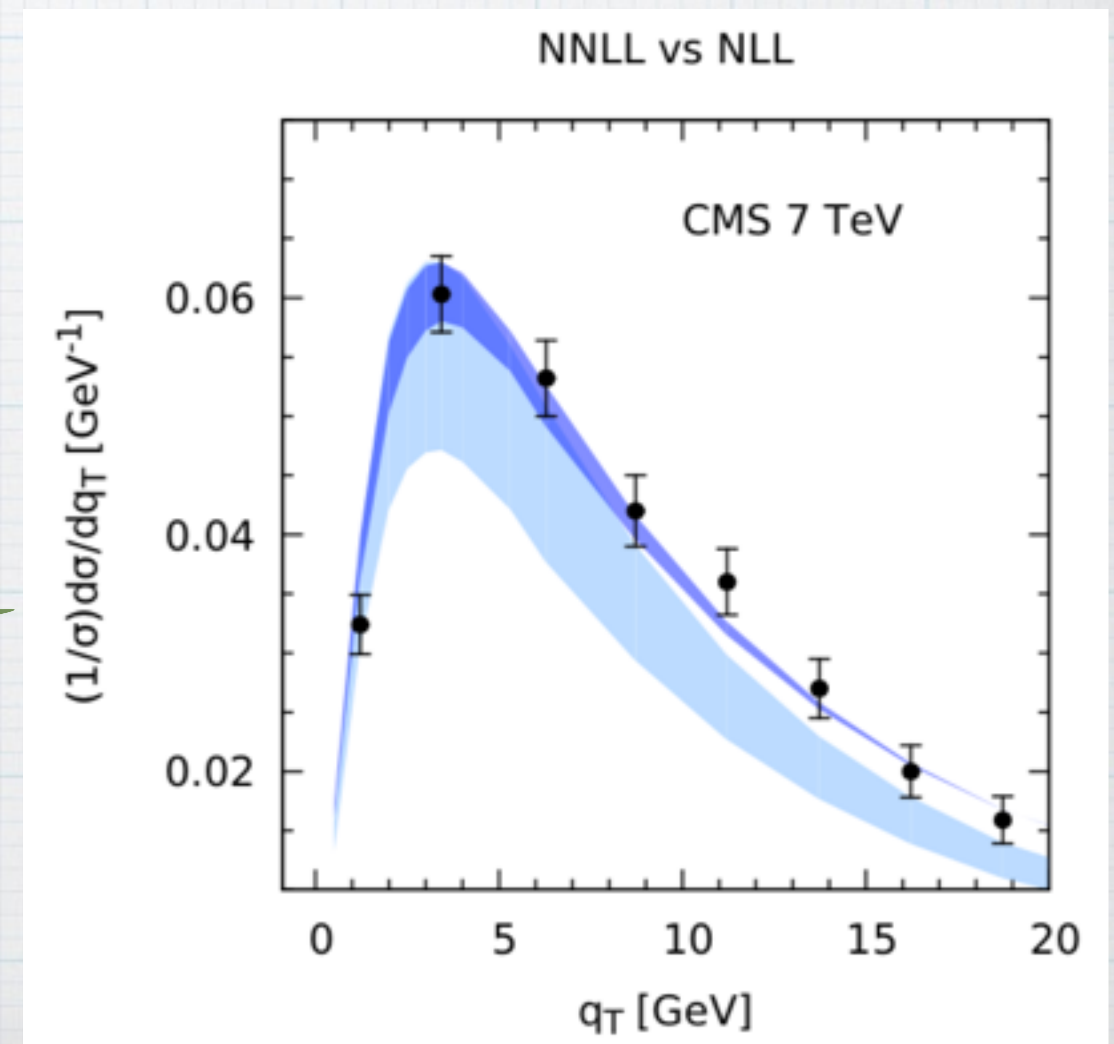
Band from parameter statistical error.
Very large bins:
results mediated over a bin

Predictions for CMS



Pure-perturbative vs complete TMDs at NNLL

NLL vs NNLL for complete TMDs: scale dependence



CMS goes at smaller values of Bjorken x than TeVatron: broader bands

Conclusions

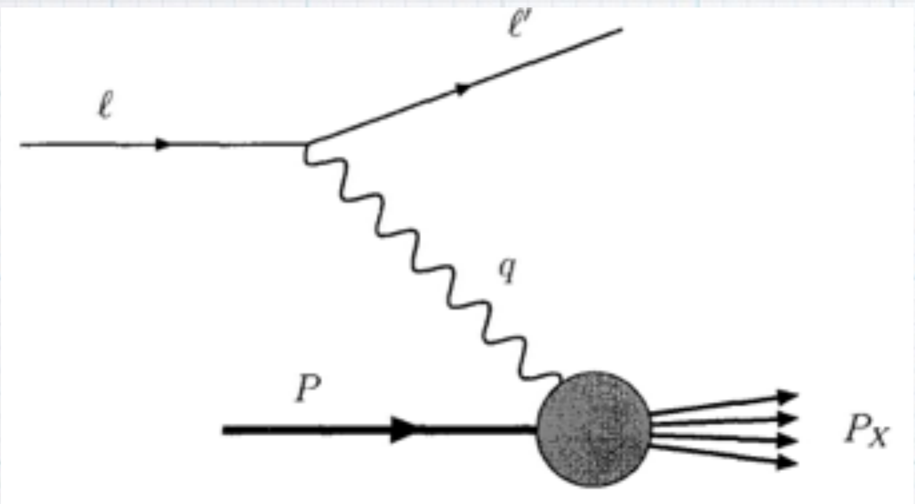
- The correct measurement of non-perturbative effects in transverse momentum dependent observables requires the use of TMDs (We want to use TMDPDF in the same way as PDF).
- First fits for unpolarized TMDPDF in DY. Data with 4<Q/GeV<10 can fix non-perturbative parameters, which have some impact on vector boson production and DY processes in LHC. More data required. SIDIS and ee-> 2j analysis to be done.
- The evolution of TMD's should be used at highest available order (here NNLL, expandable at N^3LL)
- We find that the bulk of non-perturbative QCD corrections are independent of M. Still true in SIDIS?
- TMD's are universal (the same for SIDIS, DY, ee-> 2 j) . Can we check this on data?
- The evolution of TMDPDF and TMDFF is the same and spin independent.
- TMD non-perturbative QCD effects should be included in high precision LHC observables: Frontier of QCD precision
- Analysis of spin dependent observables including evolution is starting now. Data from Belle, Compass, JLab, LHC..

Thanks!!.. and enjoy the workshop!

Back up

M.G. Echevarría, A. Idilbi, IS, 2011-2014, J. Collins, 2011

Outline of Factorization theorem



SIDIS as a study case: both PDF and FF

$$q^2 \gg q_T^2$$

$$l(k) + N(P) \to l'(k') + h(P_h) + X(P_X)$$

Fact. scale

$$W^{\mu\nu} = H(Q^2/\mu^2)\frac{2}{N_c}\sum_q e_q \int d^2k_{n\perp} d^2k_{\bar{n}\perp}\delta^{(2)}(\mathbf{q}_\perp + \mathbf{k}_{\mathbf{n}\perp} - \mathbf{k}_{\bar{\mathbf{n}}\perp})$$

$$\times \mathrm{Tr}\left[F(x, \mathbf{k}_{\mathbf{n}\perp}, S; Q^2/\alpha, \mu^2)\,\gamma^\mu D(z, \hat{P}_{h\perp}, S_h; Q^2\alpha, \mu^2)\gamma^\nu\right]$$

Hard coeff.

$$\mathbf{k}_{\bar{\mathbf{n}}\perp} = -\hat{\mathbf{P}}_{\mathbf{h}\perp}/z$$

TMDPDF

TMDFF

$$\zeta_F = Q^2/\alpha$$

$$\zeta_D = \alpha\, Q^2$$

Soft splitting number

Definition of TMD's

Positive and negative rapidity quanta can be collected into 2 different TMDs because of the splitting of the soft function: we can consistently split the soft radiation in the two sectors

$$\tilde{S}(b_T; \frac{Q^2\mu^2}{\Delta^+\Delta^-}, \mu^2) = \tilde{S}_-\left(b_T; \zeta_F, \mu^2; \Delta^-\right) \tilde{S}_+\left(b_T; \zeta_D, \mu^2; \Delta^+\right)$$

$$\tilde{S}_-\left(b_T; \zeta_F, \mu^2; \Delta^-\right) = \sqrt{\tilde{S}\left(\frac{\Delta^-}{p^+}, \alpha\frac{\Delta^-}{\bar{p}^-}\right)}$$

$$\tilde{S}_+\left(b_T; \zeta_D, \mu^2; \Delta^+\right) = \sqrt{\tilde{S}\left(\frac{1}{\alpha}\frac{\Delta^+}{p^+}, \frac{\Delta^+}{\bar{p}^-}\right)}$$

$$\zeta_F = Q^2/\alpha$$

$$\zeta_D = \alpha\ Q^2$$

Pure collinear

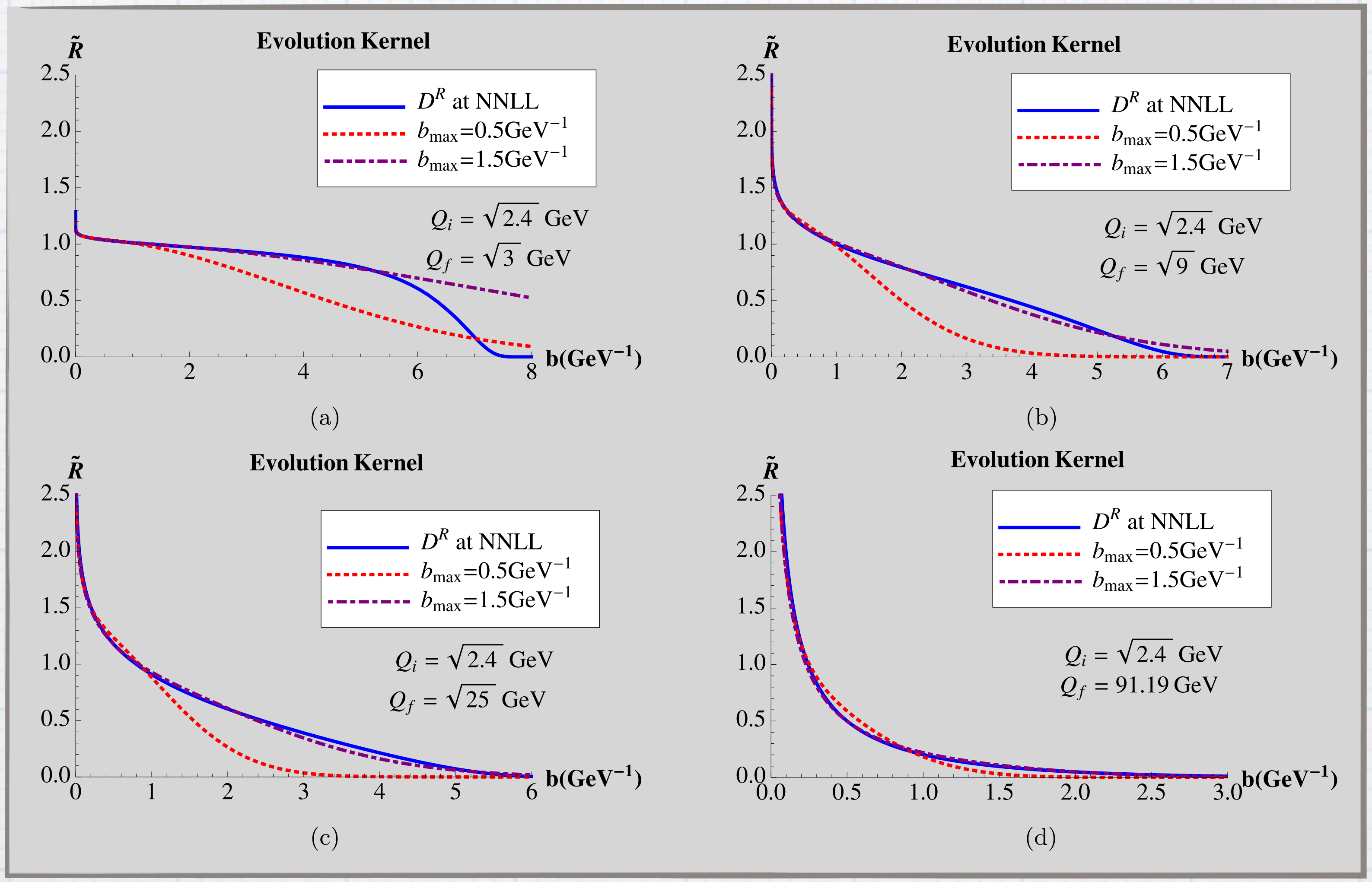
TMDPDF

$$\ln F_{ij}(x, \mathbf{b}_\perp, S; \zeta_F, \mu^2; \Delta^-) = \ln \tilde{\Phi}^{(0)}_{ij}(x, \mathbf{b}, S; \mu^2; \Delta^-) + \ln \tilde{S}_-(b_T; \zeta_F, \mu^2; \Delta^-)$$

TMDFF

$$\ln D_{ij}(x, \mathbf{b}_\perp, S_h; \zeta_D, \mu^2; \Delta^+) = \ln \tilde{\Delta}^{(0)}_{ij}(x, \mathbf{b}, S_h; \mu^2; \Delta^+) + \ln \tilde{S}_+(b_T; \zeta_D, \mu^2; \Delta^-)$$

EISS vs CSS



CSS: The evolution is modeled with a bmax and a gaussian. In this way it is defined also BEYOND the Landau pole