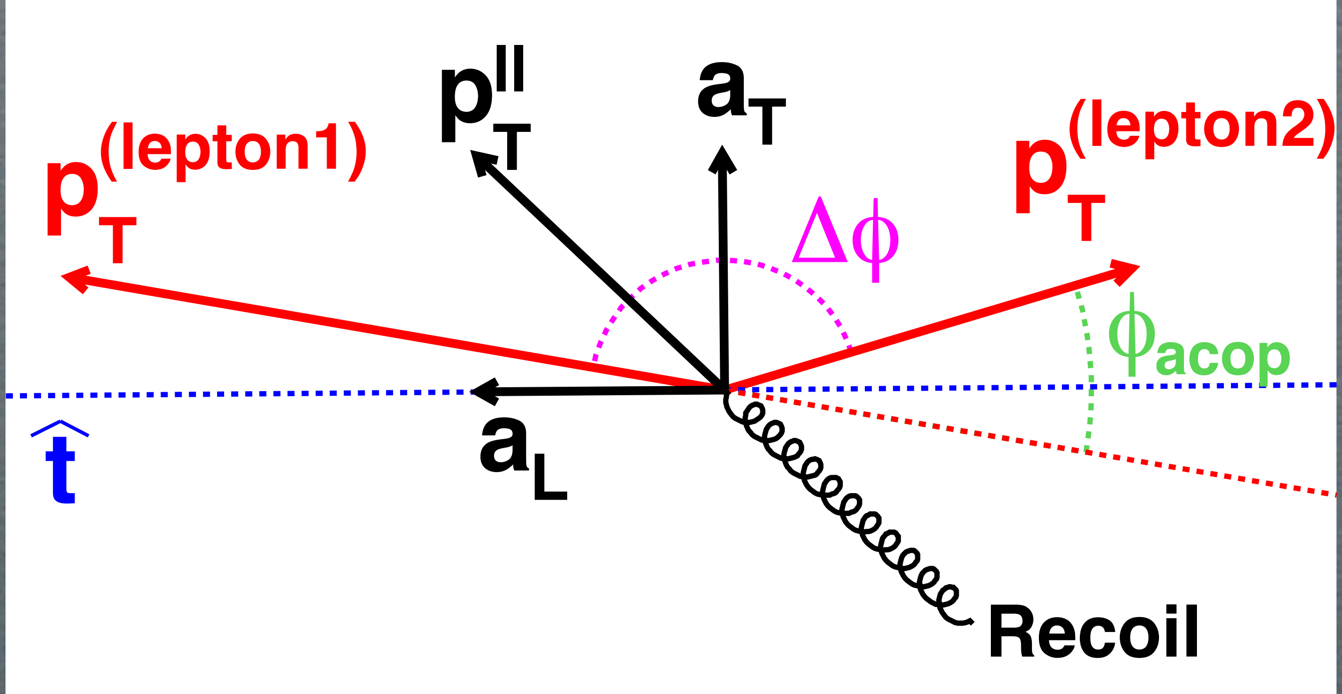
PREDICTIONS FOR DRELL-YAN ϕ^* AND Q_T OBSERVABLES AT THE LHC



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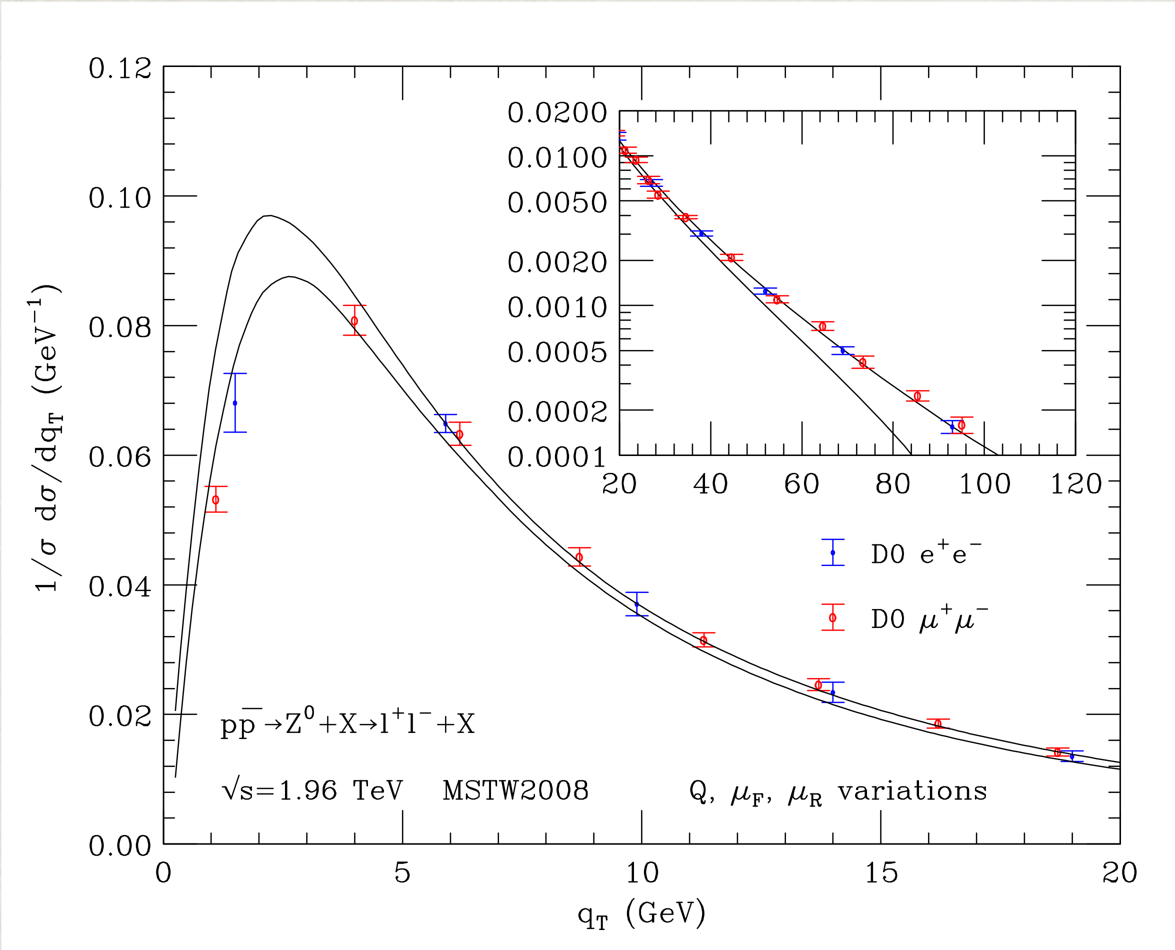
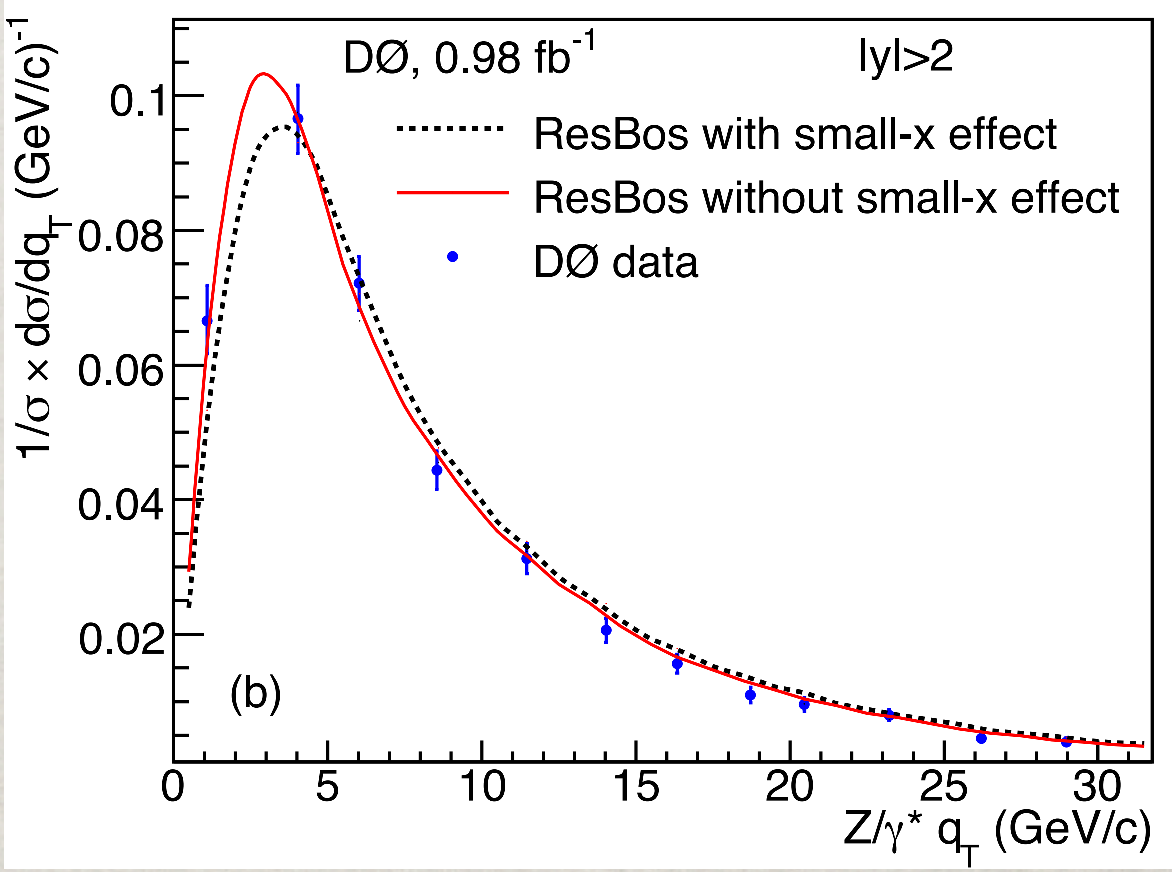
DRELL-YAN QT RESUMMATIONS

- Available resummations of large logarithms $\ln(Q_T/M_Z)$ in the Z-boson Q_T distribution follow two distinct philosophies





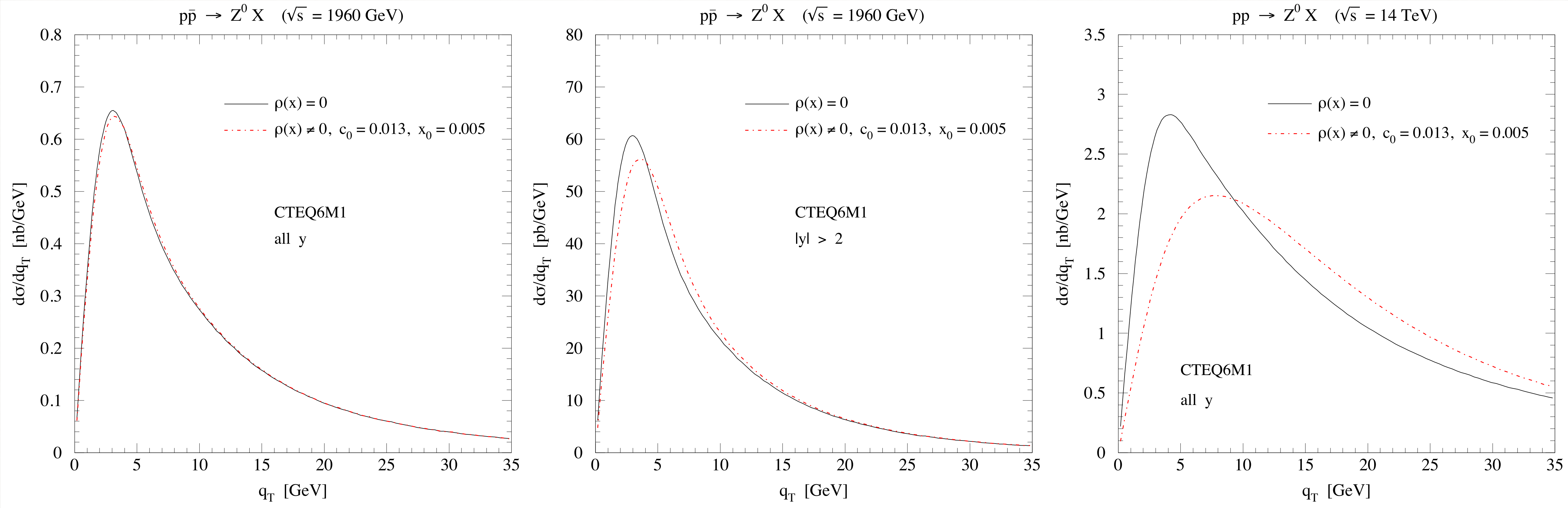
Catani et al: very accurate (NNLL+NNLO) resummation and no non-perturbative (NP) effects [Catani et al '10]

RESBOS: less accurate (NLL+NLO) resummation and intrinsic parton k_t modelled with a NP form factor

SMALL-X BROADENING

- RESBOS NP form factor predicts a significant broadening of the Z-boson Q_T spectrum at the LHC due to small-x effects

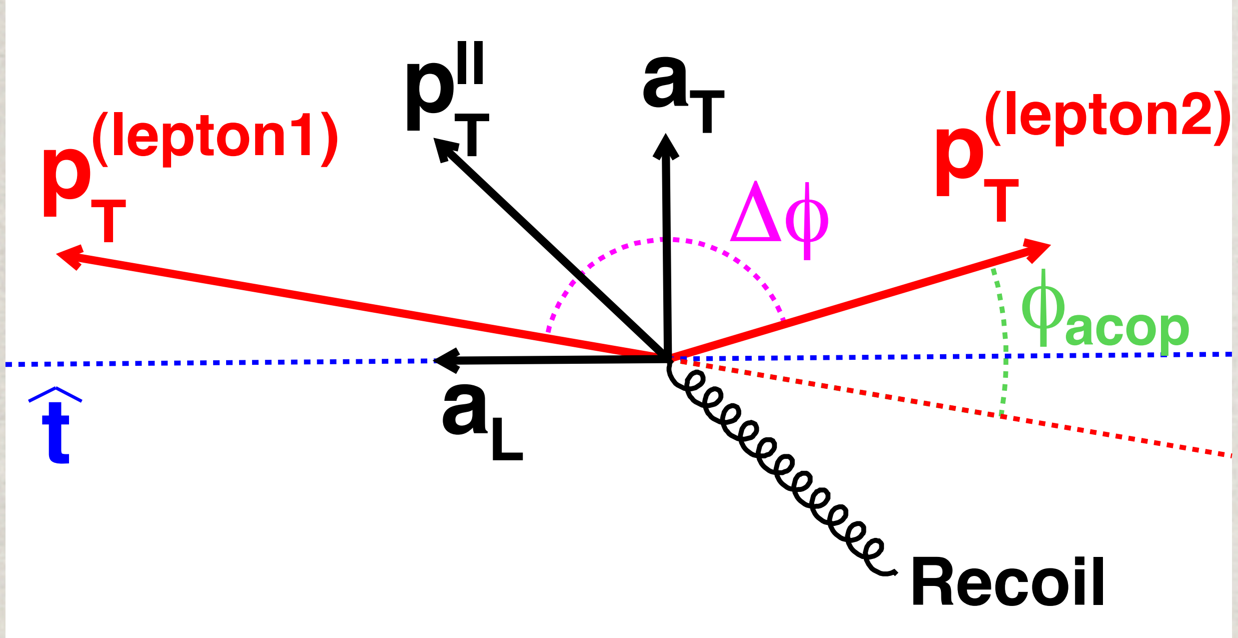
[Berge Nadolsky Olness Yuan ’04]



- The understanding of this small-x broadening needs a dedicated study with precision observables probing the low-Q_T domain

NEW PRECISION OBSERVABLES IN DY

- In recent years new observables have been introduced that probe low p_t physics, but have better resolution than Z transverse momentum $\vec{Q}_T$



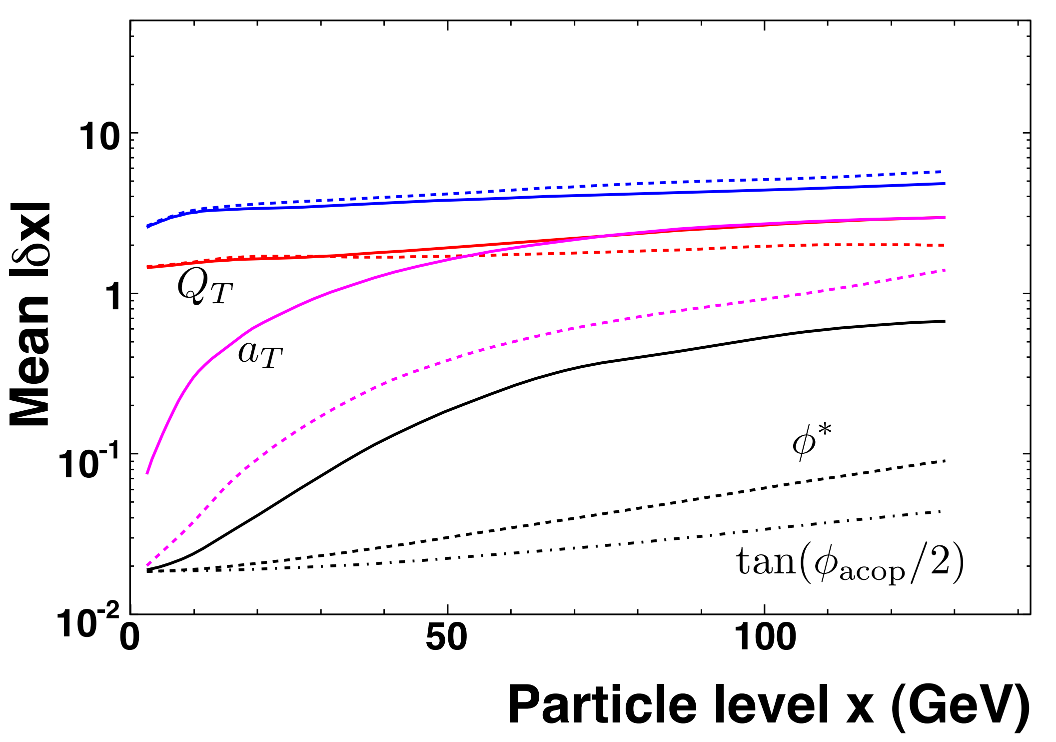
$$\vec{a}_T = \vec{Q}_T \times \frac{\vec{p}_{T1} - \vec{p}_{T2}}{|\vec{p}_{T1} - \vec{p}_{T2}|}$$

$$\phi^* = \tan(\phi_{\mathrm{acop}}/2)\sin\theta^* \simeq \frac{a_T}{M_Z}$$

[Vesterinen Wyatt '09, AB Redford Vesterinen Waller Wyatt '10]

- a_T performs much better than Q_T in the low Q_T region

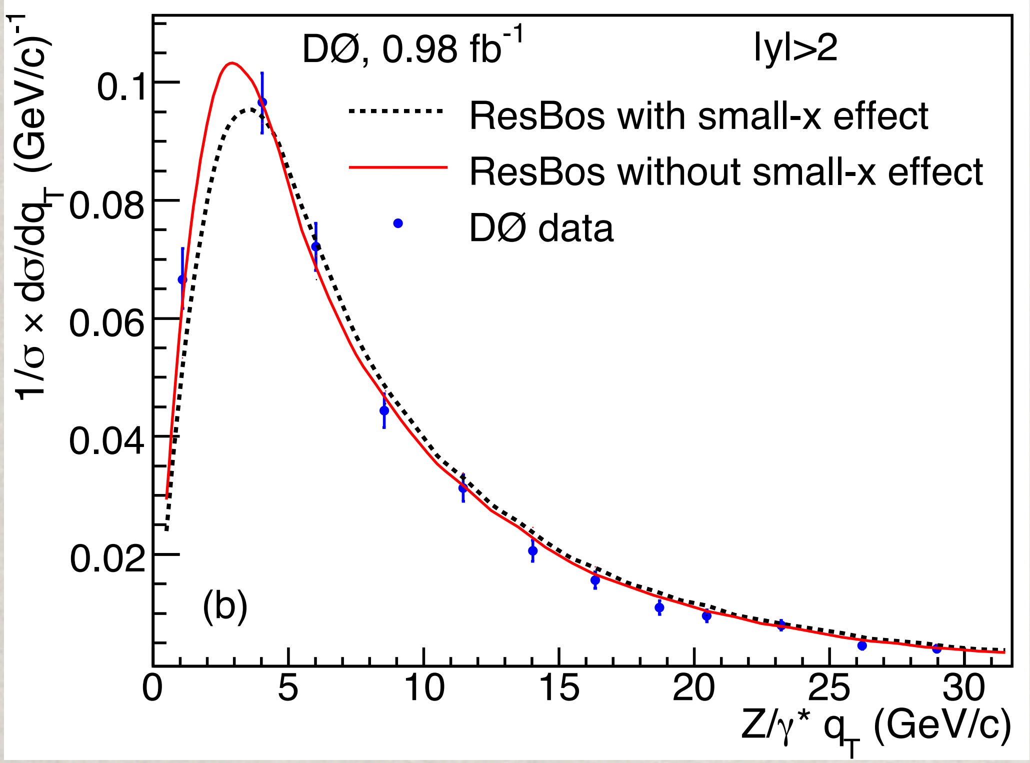
- Observables like ϕ^* or $\tan(\phi_{\mathrm{acop}}/2)$ are determined only by lepton directions and can be measured very precisely

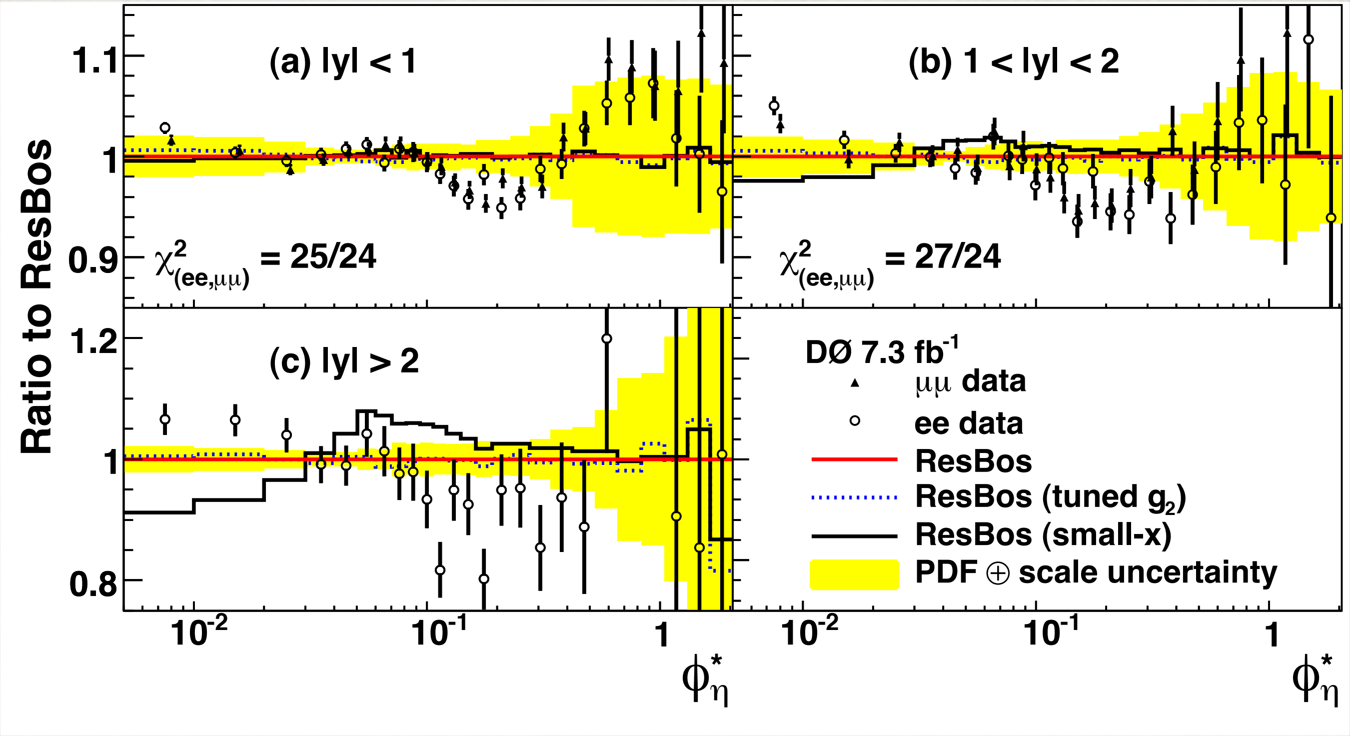


RESBOS VS TEVATRON DATA

- Comparison of ϕ^* distribution for large Z rapidity ($|y| > 2$) with RESBOS raised issues with small-x broadening

[D0 collaboration '10]





- However, agreement between Tevatron data and RESBOS seems to be restored in the new version of RESBOS

[Guzzi Nadolsky '12]

- We have decided to perform a dedicated theoretical study of the ϕ^* distribution using theoretical tools from perturbative QCD only, to see to what extent one really needs NP effects

PROBING LOW QT WITH PHISTAR

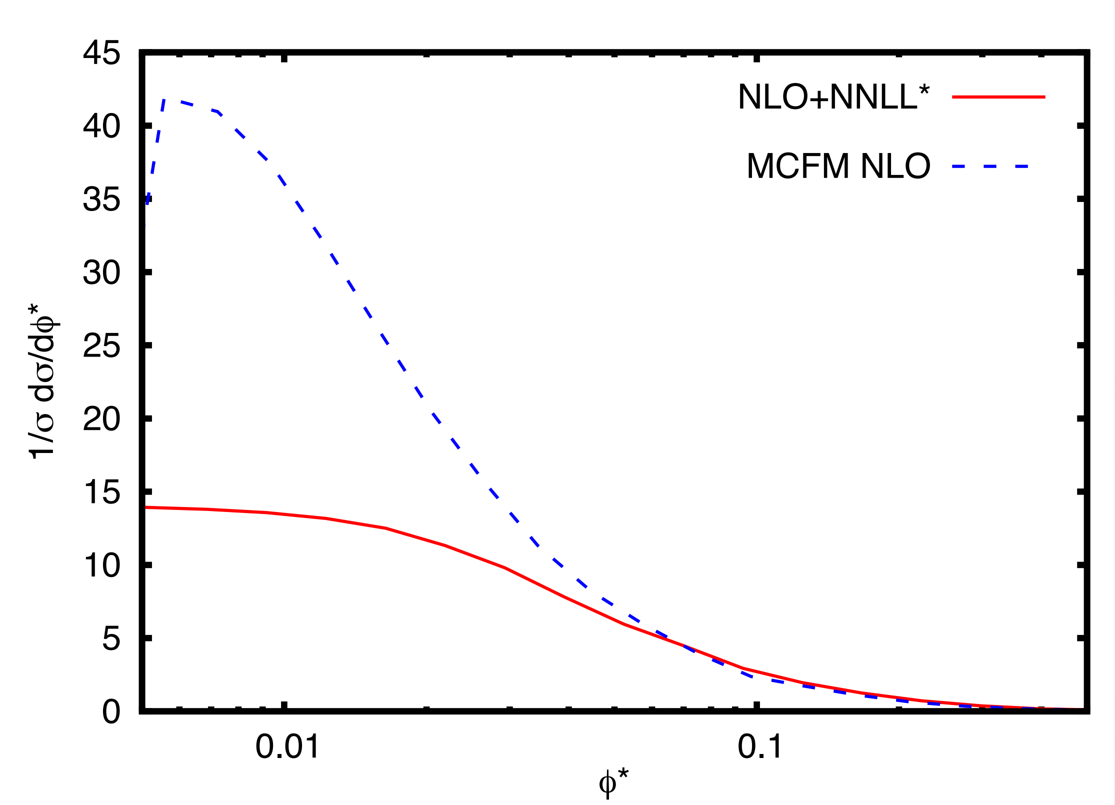
- At small ϕ^* the perturbative series does not converge because of the appearance of large logarithms up to $\alpha_s^n [\ln^{2n-1}\phi^*/\phi^*]_+$

$$\frac{1}{\sigma}\frac{d\sigma}{dM^2 d\phi^*} = \alpha_s \left[\frac{\ln(1/\phi^*)}{\phi^*}\right]_+ + \dots$$

- These logarithms can be resummed at all orders

$$\frac{d\sigma}{dM^2 d\phi^*} = \int_0^\infty dbM \cos(bM\phi^*)\, \mathcal{L}(\bar{b}^{-1})\, e^{-R(\bar{b}M)} \qquad \bar{b} = \frac{b e^{\gamma_E}}{2}$$

- $R(\bar{b}M)$ is the same Sudakov exponent as for boson Q_T
- $\mathcal{L}(1/\bar{b})$ is a process-dependent term, containing the parton luminosities at the scale $1/\bar{b}$



DETAILS OF OUR PREDICTION

- Our predictions are NNLL accurate, i.e. $\alpha_s^n \ln^{n-1}(\bar{b}M)$, and their ingredients $R(\bar{b}M)$ and $\mathcal{L}(1/\bar{b})$ are all known from Q_T resummation

[AB Marzani Dasgupta '11]

$$\frac{d\sigma}{dM^2 d\phi^*} = \int_0^\infty dbM \cos(bM\phi^*)\, \mathcal{L}(\bar{b}^{-1})\, e^{-R(\bar{b}M)} \qquad \bar{b} = \frac{b e^{\gamma_E}}{2}$$

- The "parton luminosity" $\mathcal{L}(1/\bar{b})$ contains all process-dependent terms

$$\mathcal{L}(\bar{b}^{-1}) = \int_{\text{lepton cuts}} [dk_1][dk_2] \int_0^1 dx_1 dx_2\, \delta(x_1 x_2 s - M^2) \sum_{i,j} \Big\{ f_i(x_1, \bar{b}^{-1}) f_j(x_2, \bar{b}^{-1}) \\ + \frac{\alpha_s(\bar{b}^{-1})}{2\pi} \left[\sum_k \int_{x_1}^1 \frac{dz}{z}\, C_{ik}^{(1)}(z)\, f_k\left(\frac{x_1}{z}, \bar{b}^{-1}\right) f_j(x_2, \bar{b}^{-1}) + \{i \leftrightarrow j, x_1 \leftrightarrow x_2\} \right] \Big\}\, M^2(x_1 p_1, x_2 p_2, k_1, k_2)$$

- The Born matrix element $M^2(x_1 p_1, x_2 p_2, k_1, k_2)$ for hadronic dilepton production is taken directly from MCFM: we are then fully differential in the lepton momenta by construction

- All convolutions are perform directly in x space (i.e. no Mellin transform) using the HOPPET package by Salam and Rojo

INTEGRATION OVER IMPACT PARAMETER

- We integrate numerically over the impact parameter b: this requires prescriptions both at large and at small b

$$\frac{d\sigma}{dM^2 d\phi^*} = \int_0^\infty dbM \cos(bM\phi^*)\,\mathcal{L}(\bar{b}^{-1})\,e^{-R(\bar{b}M)}$$

- Large b: avoid Landau pole in $R(\bar{b}M)$ as well as factorisation scale $1/\bar{b}$ become less than $Q_0 \lesssim 1\mathrm{GeV} \Rightarrow$ sharp cutoff $b_{\max} \geq 1/Q_0$ and freeze the pdfs for $b \geq 1/Q_0$

- Small b: freeze $R(\bar{b}M)$ and $\mathcal{L}(\bar{b}^{-1})$ at their value for $\bar{b}M \leq 1 \Rightarrow$ the ϕ^* distribution is normalised to the total cross section

- A PT resummation with such prescriptions to perform the b integral is what we mean by PT prediction

- By NP effects we mean either a gaussian smearing $\exp[-g_{\mathrm{NP}} b^2]$ or even introducing k_t dependent parton densities

PERTURBATIVE UNCERTAINTIES

- We vary renormalisation, factorisation and resummation scales μ_R, μ_F and μ_Q in the range $[M/2, 2M]$ with $1/2 \leq \mu_i/\mu_j \leq 2$

$$\frac{d\sigma}{dM^2 d\phi^*} = \int_0^\infty dbM \cos(bM\phi^*) \left[C\left(\frac{\mu_F}{\mu_Q}\right) \otimes \mathcal{L}\left(\alpha_s(\mu_R), \frac{\mu_R}{M}, \frac{\mu_F}{\bar{b}\mu_Q}\right)\right] e^{-R\left[\alpha_s(\mu_R), \frac{\mu_R}{M}, \frac{\mu_Q}{M}, \bar{b}\mu_Q\right]}$$

- We match our results to Z+1jet@NLO, obtained with MCFM

$$\left(\frac{d\sigma}{d\phi^*}\right)_{\text{matched}} = \left(\frac{d\sigma}{d\phi^*}\right)_{\text{resummed}} + \left(\frac{d\sigma}{d\phi^*}\right)_{\text{fixed order}} - \left(\frac{d\sigma}{d\phi^*}\right)_{\text{expanded}}$$

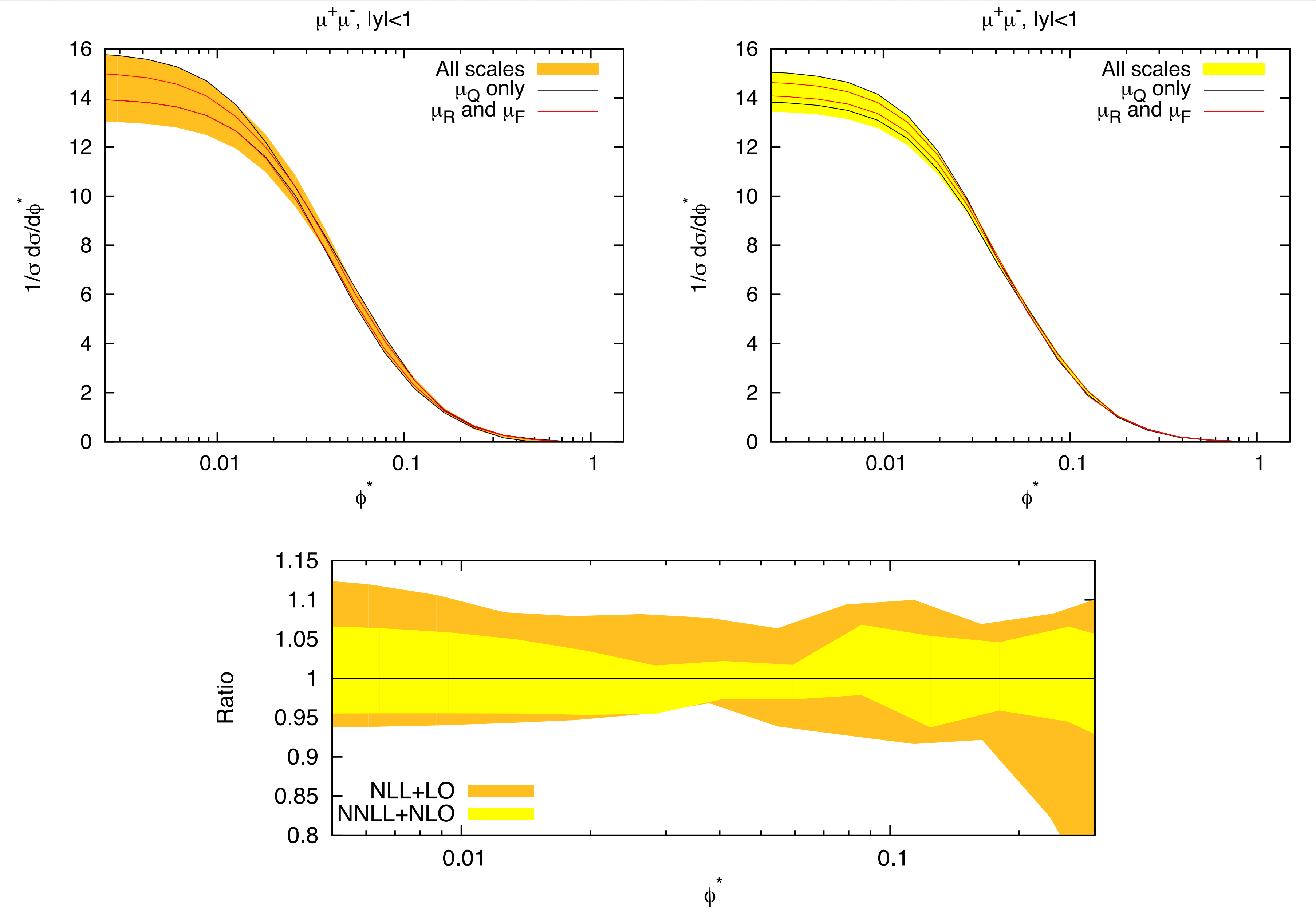
- We compute $1/\sigma d\sigma/d\phi^*$ by dividing $d\sigma/d\phi^*$ by its area: dividing by the NLO total cross section gives 1% difference

- We validate our predictions by comparing $1/\sigma d\sigma/d\phi^*$ to Tevatron data for electrons and muons, in different bins of Z-boson rapidity

[AB Marzani Tomlinson Dasgupta '11]

PHISTAR AT THE TEVATRON

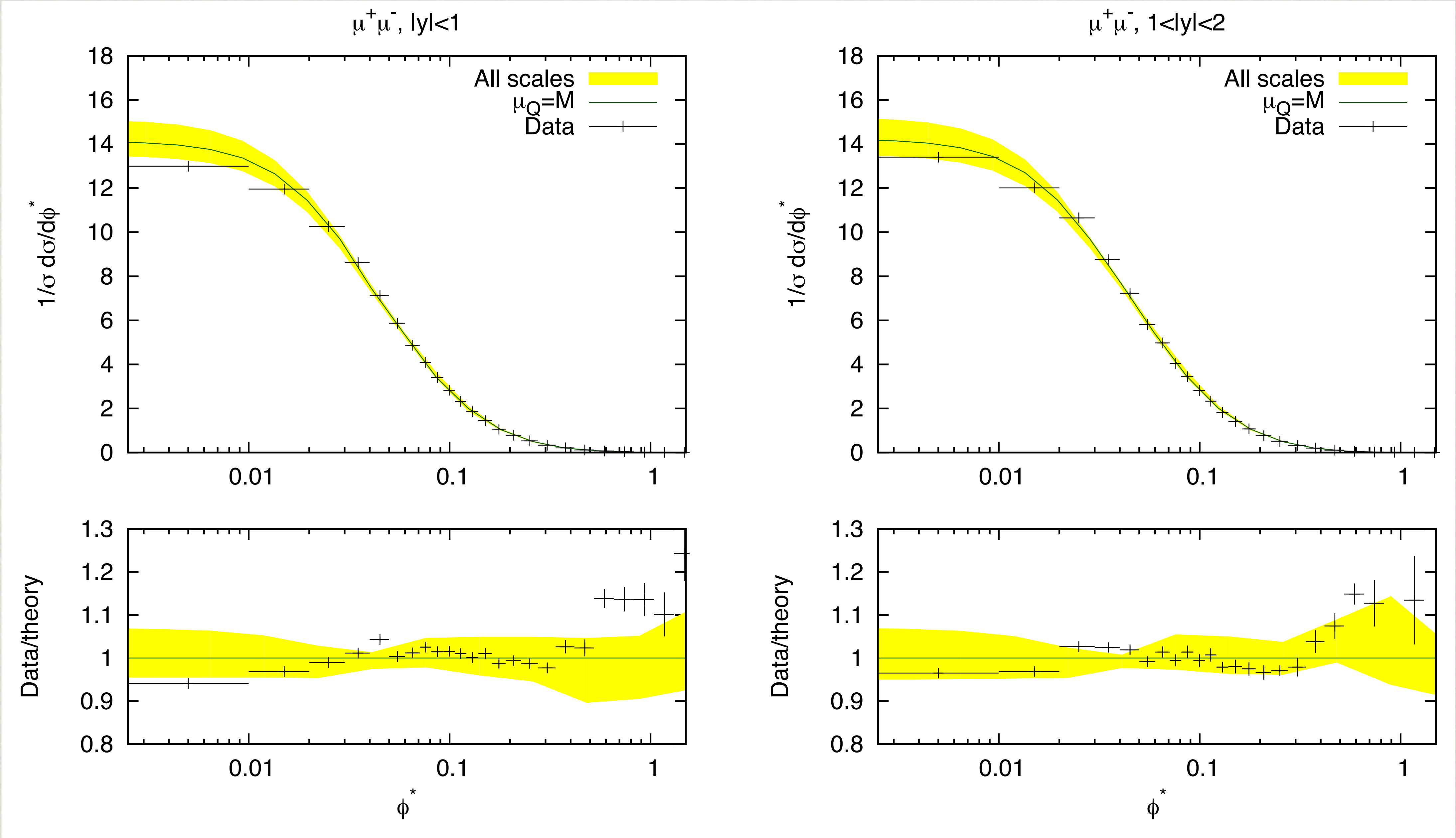
- Going from NLL to NNLL resummation reduces the theoretical uncertainty from 10% to 5-6%



- Different prescriptions to evaluate the b integral (e.g. changing the freezing point of the pdfs Q_0 by a factor of two) give curves within our uncertainty band

VALIDATION AGAINST TEVATRON DATA (I)

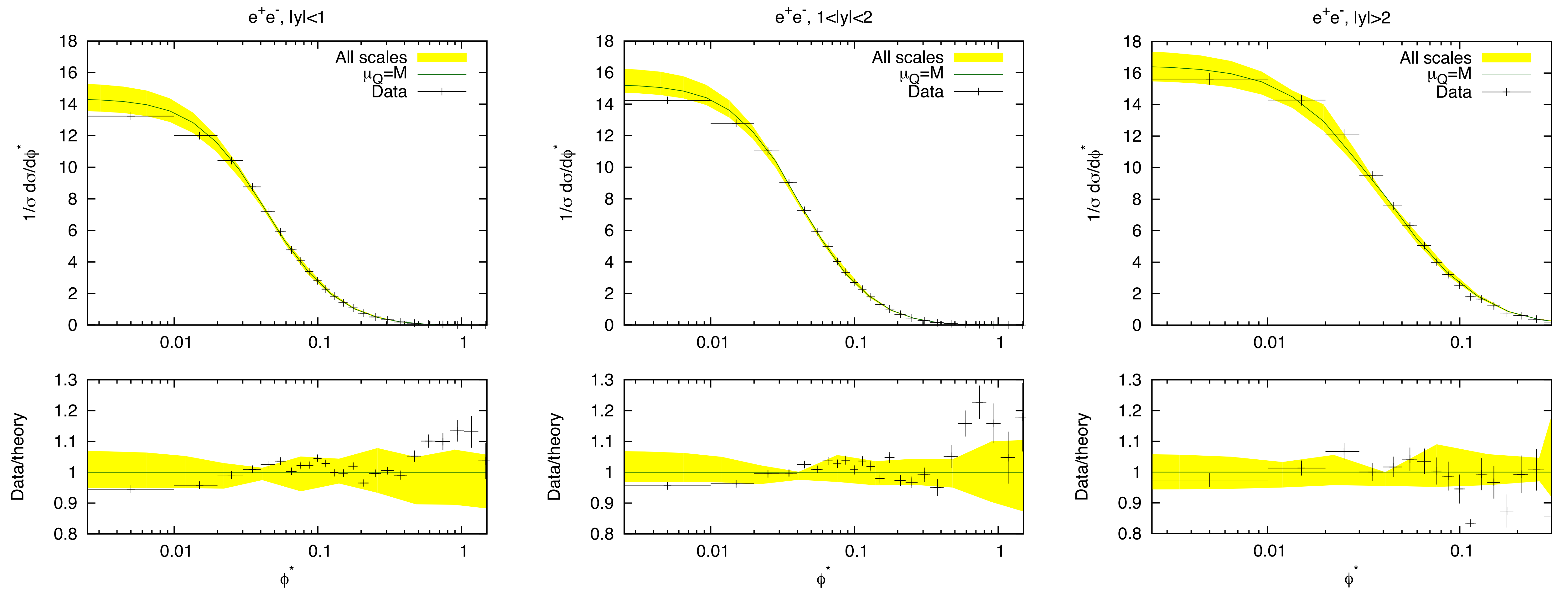
- $Z \to \mu^+\mu^-$ with two different bins in Z-boson rapidity



- Good agreement with Tevatron data even at very low values of ϕ^* without any NP effects

VALIDATION AGAINST TEVATRON DATA (II)

- $Z \to e^+e^-$ with three different bins in Z rapidity

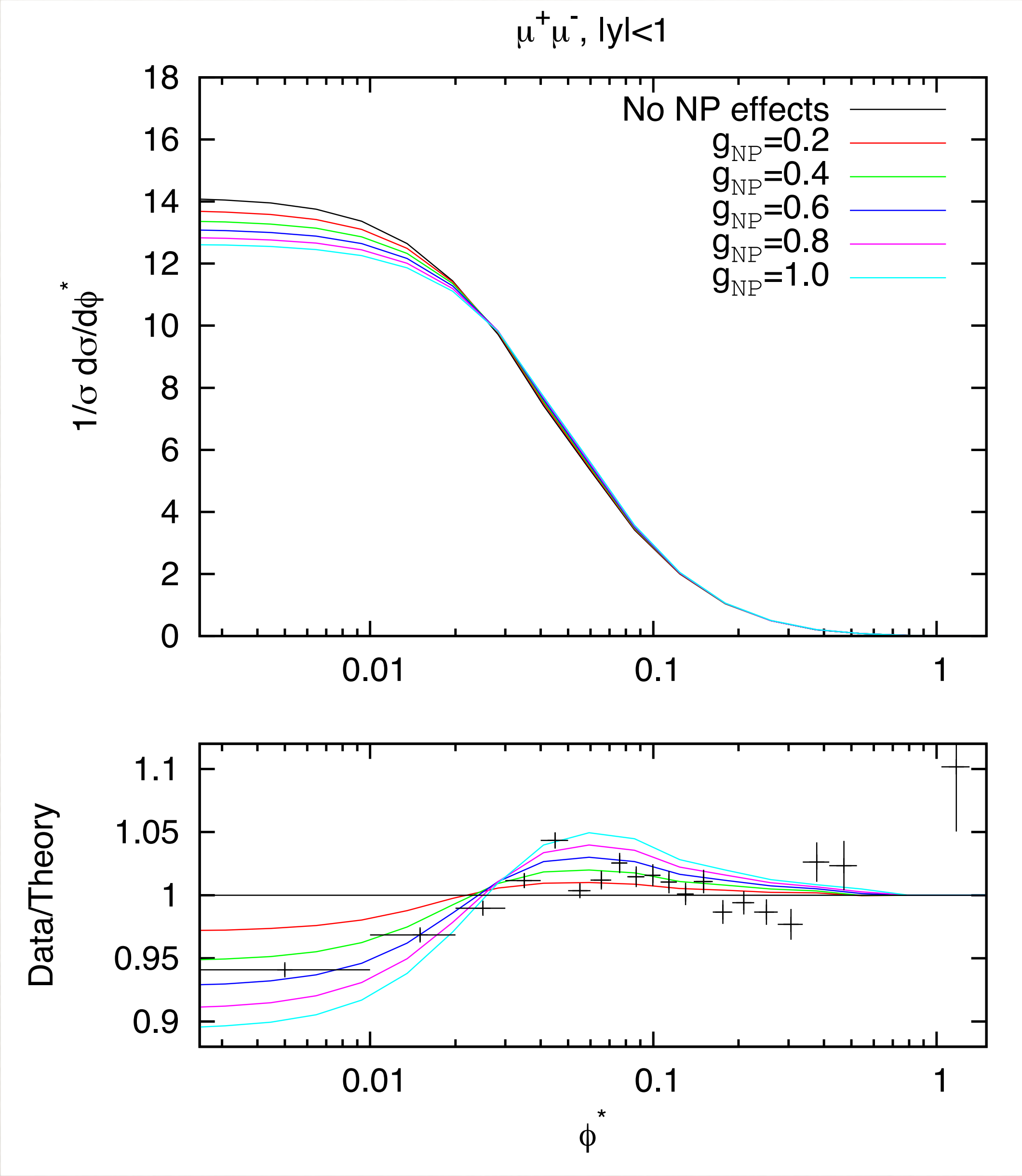


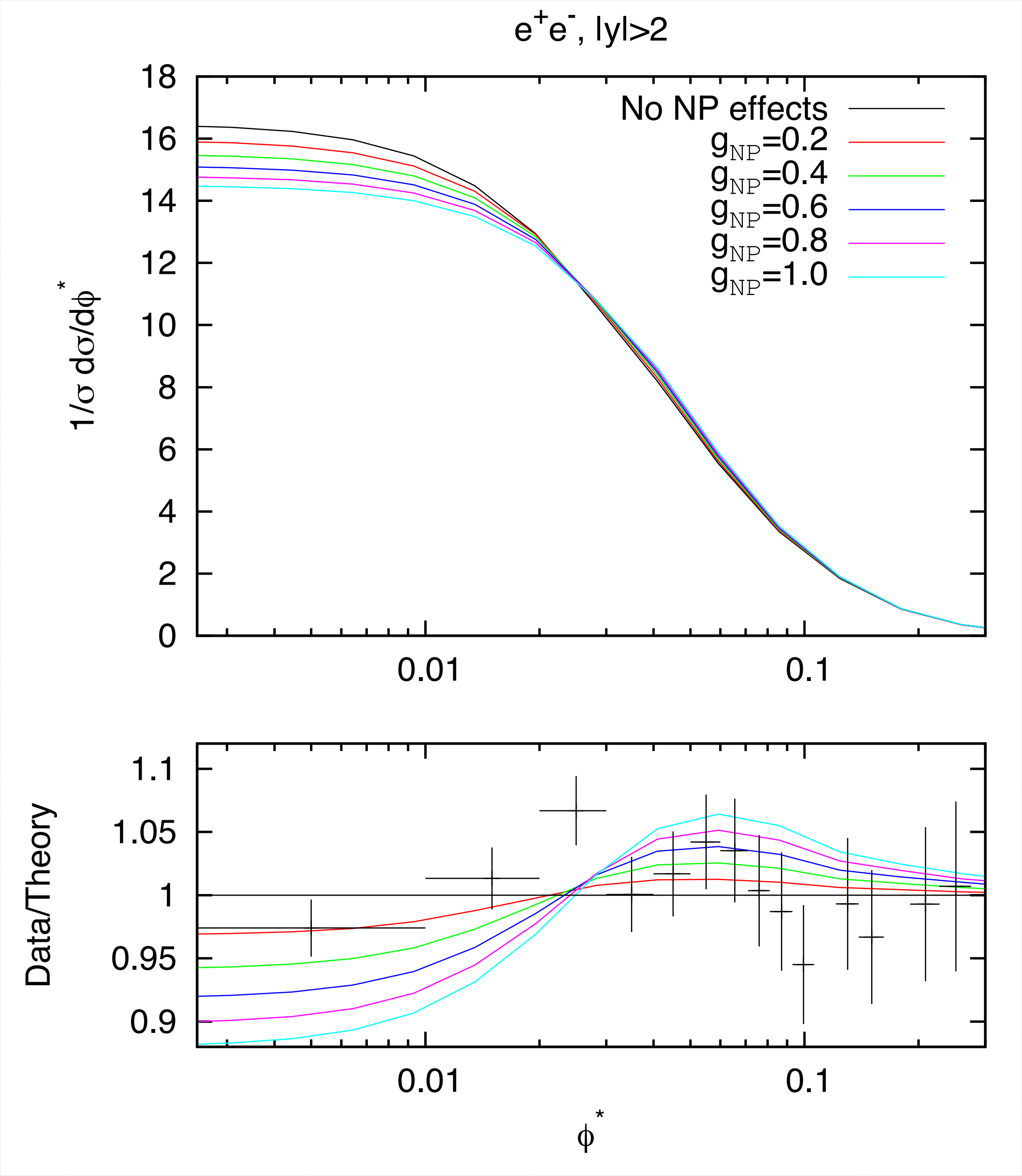
- Agreement of our predictions with data persists even in the small-x region $|y| > 2$ $\Rightarrow$ No need for small-x broadening

- Slight disagreement in the large ϕ^* region where multi-jet configurations become important $\Rightarrow$ case for Z+1jet@NNLO

IMPACT OF NON-PERTURBATIVE EFFECTS

- We take the curve with $\mu_R = \mu_F = \mu_Q = M_Z$ and add to the resummation a gaussian smearing $\exp[-g_{\rm NP} b^2]$





- Inclusion of NP corrections gives an effect that is comparable to the variation of perturbative scales ⇒ N^{3}LL resummation needed?

ISSUES WITH QT RESUMMATION AT LHC

- Our resummation can be applied to the Q_T distribution ⇒ validation of our predictions against LHC data!

$$\frac{d\sigma}{dM^2 dQ_T} = Q_T \int_0^\infty db\, b\, J_0(bQ_T)\, \mathcal{L}(1/\bar{b})\, e^{-R(\bar{b}M)}$$

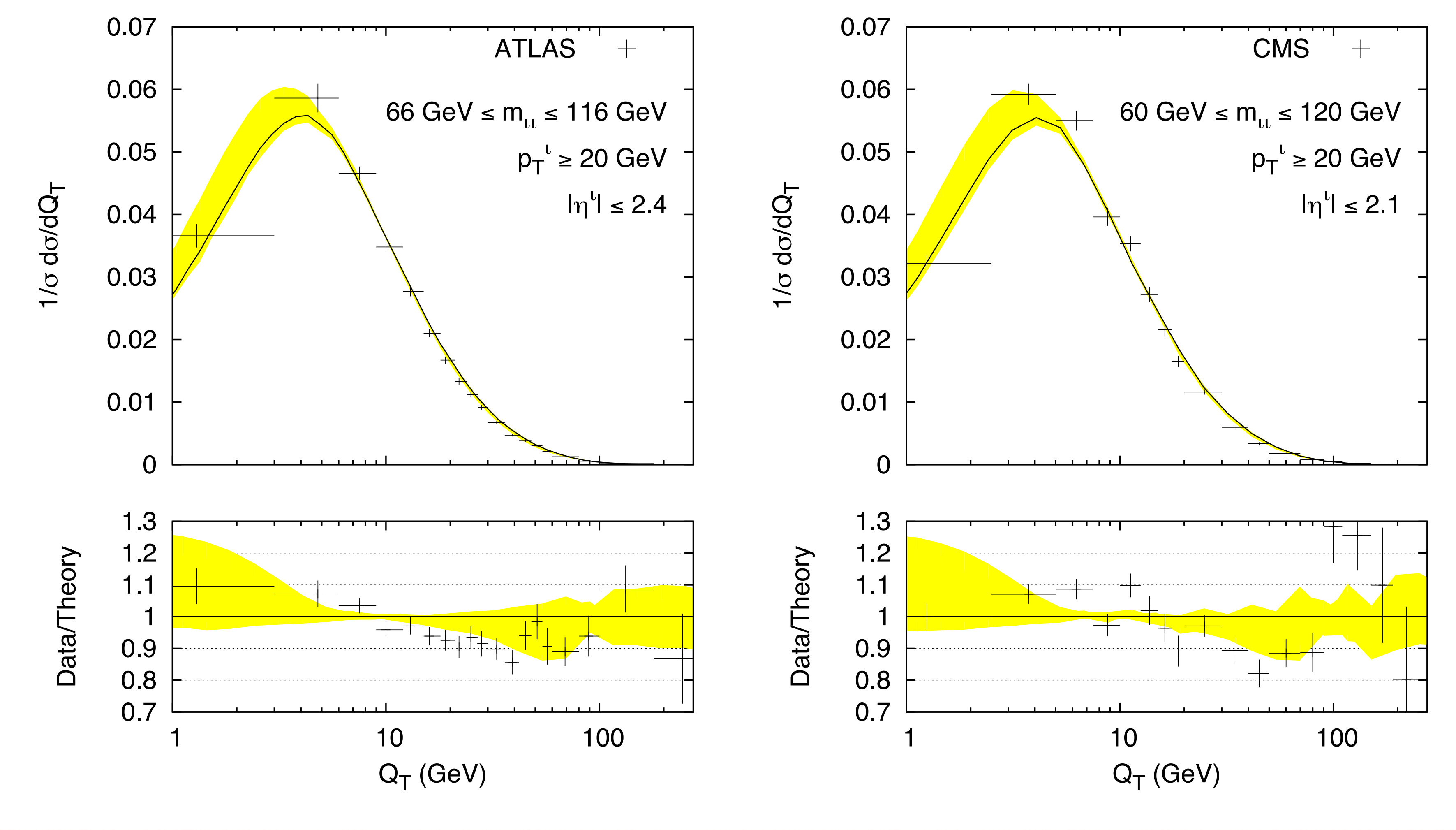
- Freezing of the pdfs below $Q_0 = 1\text{GeV}$ leads to an unphysical oscillatory behaviour at large $Q_T \Rightarrow$ extrapolate the pdfs for $b \geq 1/Q_0$

- All curves with $\mu_F/\mu_Q = 1/2$ are very sensitive to variation of Q_0 by a factor 2 around $1\text{GeV} \Rightarrow$ sensitivity to Physics beyond collinear factorisation?

- We have decided therefore to evaluate our perturbative uncertainties by varying all scales in the range $\mu_F/\mu_Q \geq 1$ only

PREDICTIONS FOR QT AT THE LHC

- We can provide predictions for the Q_T distribution with the fiducial cuts employed by ATLAS and CMS

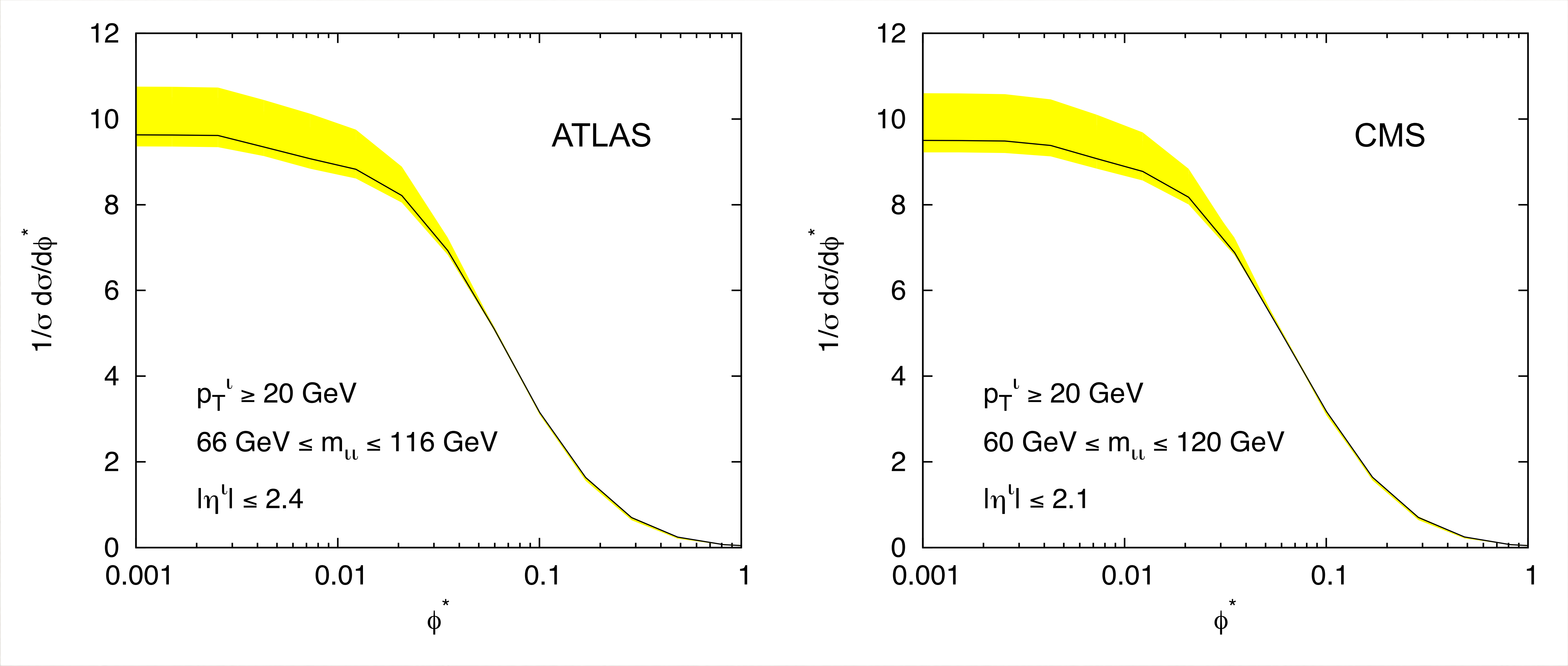


- Also at the LHC data lie within our PT uncertainty band

- The inclusion of a NP term $\exp[-0.5\mathrm{GeV}^2 b^2]$ gives a distribution compatible with our theoretical uncertainty

PREDICTIONS FOR PHISTAR AT THE LHC

- Having validated our resummation with the Q_T distribution, we can confidently provide predictions for ϕ^* at the LHC



[AB Marzani Tomlinson Dasgupta ’12]

CONCLUSIONS AND OPEN ISSUES

- The novel observable ϕ^* can be measured very precisely and provides an accurate probe of $\vec{Q}_T$ physics over a wide range of scales
- We have a code that can produce perturbative resummed predictions for ϕ^* and Q_T distributions in the Drell-Yan process with arbitrary cuts on lepton momenta
- Our code is easily generalisable to other $\vec{Q}_T$-type resummations in other processes (e.g. $\vec{p}_{T,t\bar{t}}$ in top production), since it is just a reweighting of MCFM
- Tevatron data call for more precise theoretical predictions both at low (N^3LL resummation) and at high ϕ^* (Z+1jet@NNLO)
- Our theoretical predictions at the LHC are sensitive to behaviour of pdfs below 1GeV: this calls for a better theoretical understanding of the breaking of collinear factorisation (need for k_t dependent pdfs?) $\Rightarrow$ comparisons with other resummation codes would be valuable