The low-Q_T domain of the Z boson

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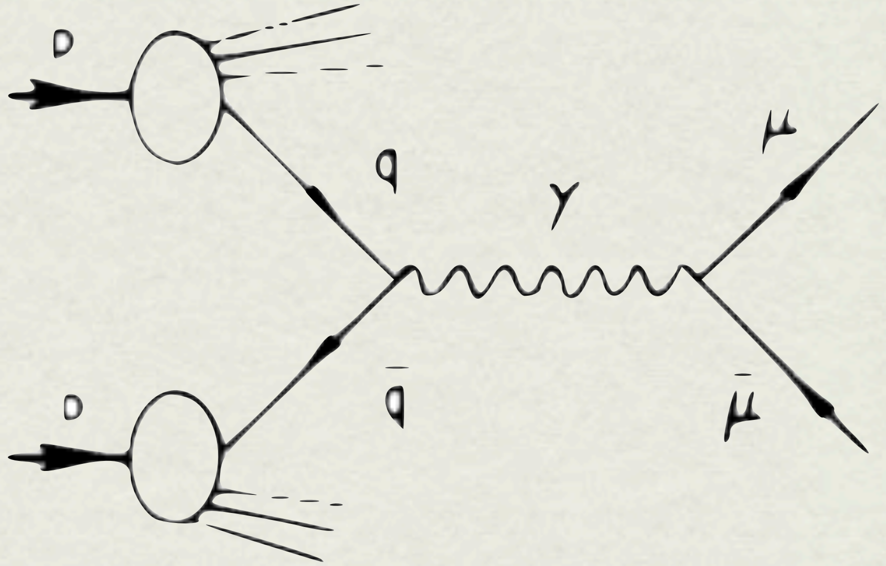
in collaboration with
Banfi, Dasgupta and Tomlinson

arXiv:1102.3594
arXiv:1110.4009
arXiv:12*xx.xxxx*

The Drell-Yan Process

- The production of a lepton pair in hadron- hadron collisions is one of the most studied processes in particle phenomenology

- Strictly speaking it is the *only* process for which factorisation has been proven in hadron – hadron collisions



- QCD corrections are known to O(α_s^2)

  Hamberg, van Neervan and Matsuura, NP B359:343-405

- We want to study the transverse momentum distribution of the lepton pair (or of the gauge boson)

- It is sensitive to multi-gluon emission from the initial state partons, so it provides a clean test of QCD dynamics

Different Scales

- Let us call
  - Q_T: transverse momentum of the Z boson
  - M: invariant mass of the lepton pair (close to the Z mass)
- In principle we have to consider three different regimes

$$Q_T \quad \sim \quad M$$

Fixed-order PT works:

F.O. programs like MCFM, FEWZ, DYNNLO

$$\Lambda_{QCD} \ll Q_T \ll M$$

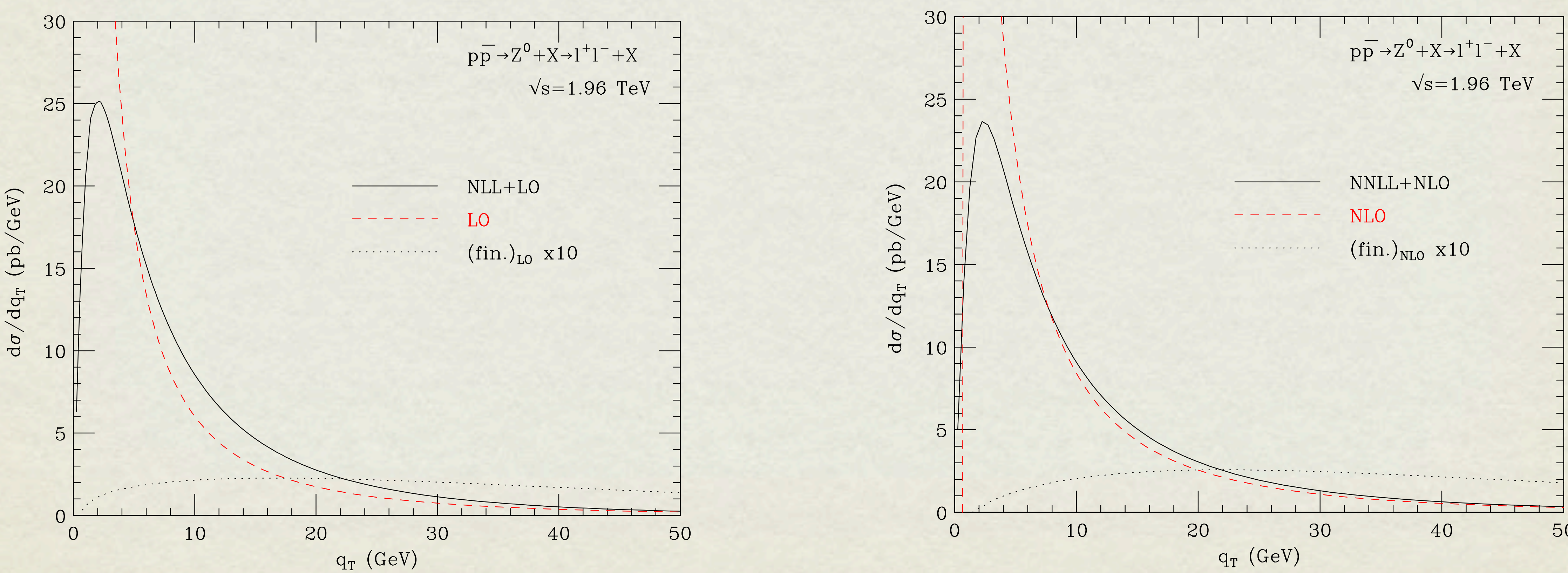
PT works but large logs in M/Q_T: need for resummation

$$Q_T \quad \sim \quad \Lambda_{\rm QCD}$$

Non-perturbative domain

State Of The Art For Q_T

- The resummation of the Q_T spectrum has been widely studied
- Different groups, different formalisms (e.g. Collins Soper Sterman, Catani *et al.*, SCET)
- It is known to NNLL accuracy (with $A^{(3)}$ recently computed by Becher & Neubert)

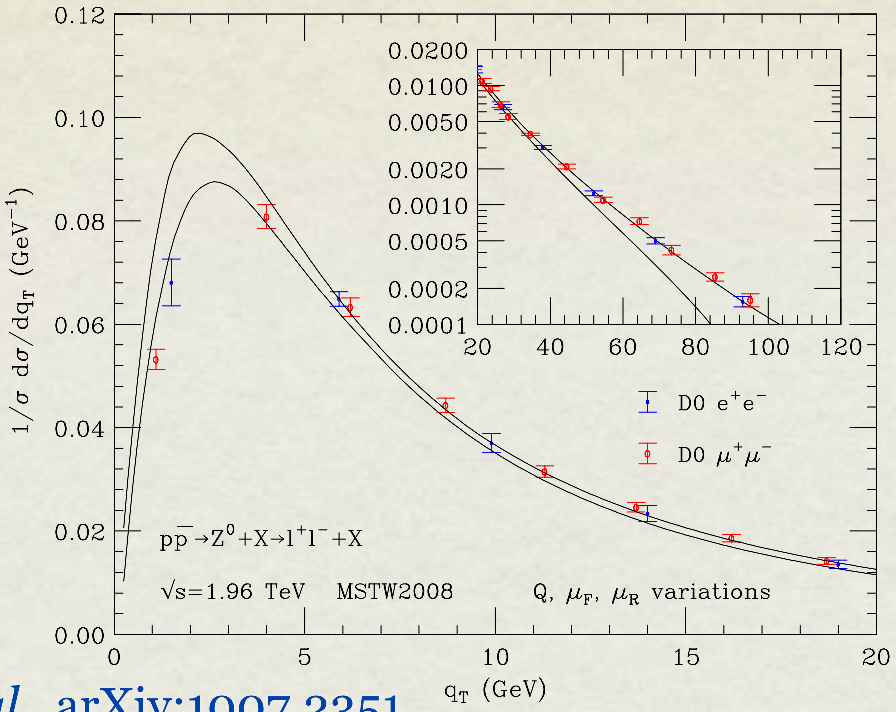


Catani *et al.* arXiv:1007.2351

Non-perturbative Effects

- In principle important as Q_T approaches Λ_{QCD}
- At this scale the factorisation the resummation is based on breaks down
- But, how big are they in practice ?
- Common models assume that incoming partons have an intrinsic primordial k_T with Gaussian distribution
- In principle we can compare perturbative results with data and constrain NP effects
- However no clear conclusions reached to date

Comparison To Data



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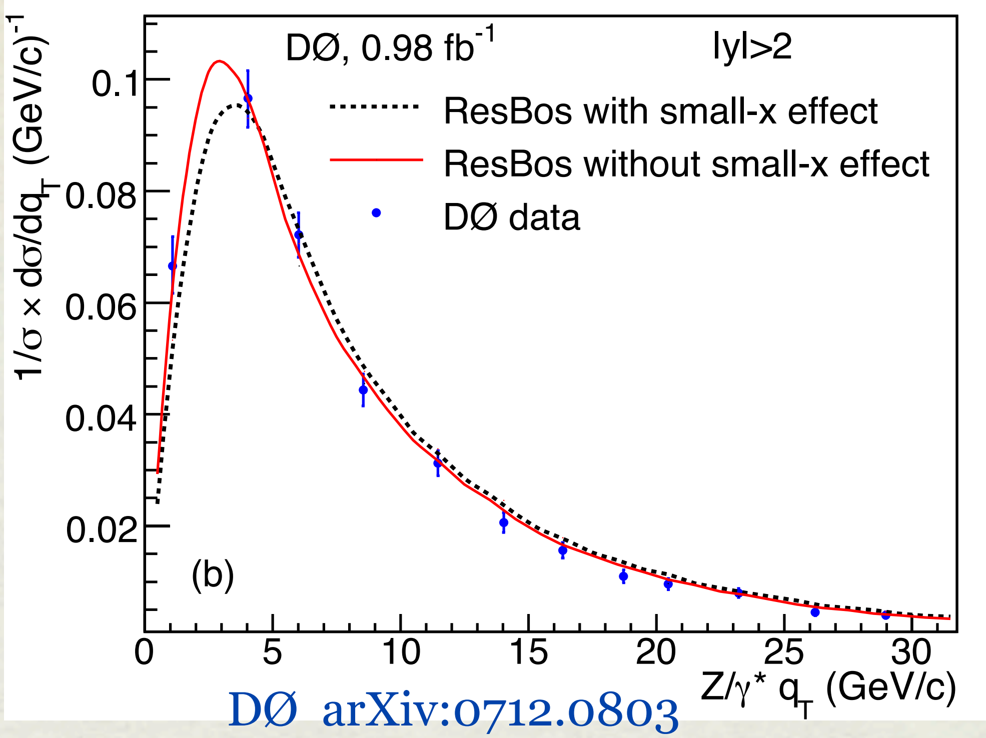
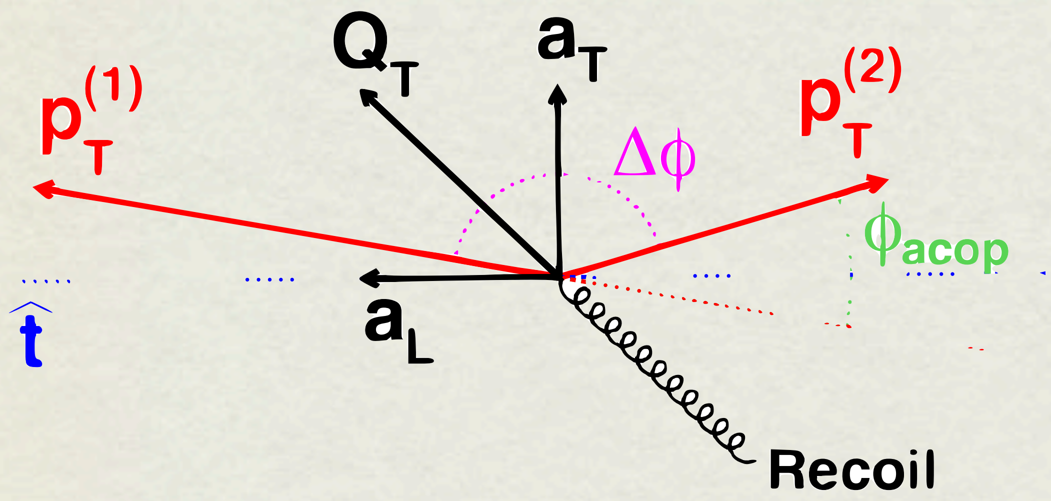


DØ arXiv:0712.0803

- ResBos: resummation of the relevant logs at (N?)NLL (CSS formalism) matched to NLO
- NP effects are *x* dependent (small-*x* broadening fitted to semi-inclusive DIS data)
- NP effects of the same size as the perturbative uncertainty
- Data are not precise enough to separate different NP models

New Variables

- New variables introduced by the DØ collaboration for studying the transverse momentum of the Z boson
- Experimental viewpoint: one wants to measure angles rather than momenta



$$\underline{a}_T = \frac{\underline{Q}_T \times (\underline{p}_T{}^{(1)} - \underline{p}_T{}^{(2)})}{|\underline{p}_T{}^{(1)} - \underline{p}_T{}^{(2)}|}$$

transverse component of Q_T wrt leptons' thrust axis

Vesterinen and Wyatt (*et al.*)
arXiv:0807.4956 [hep-ex]
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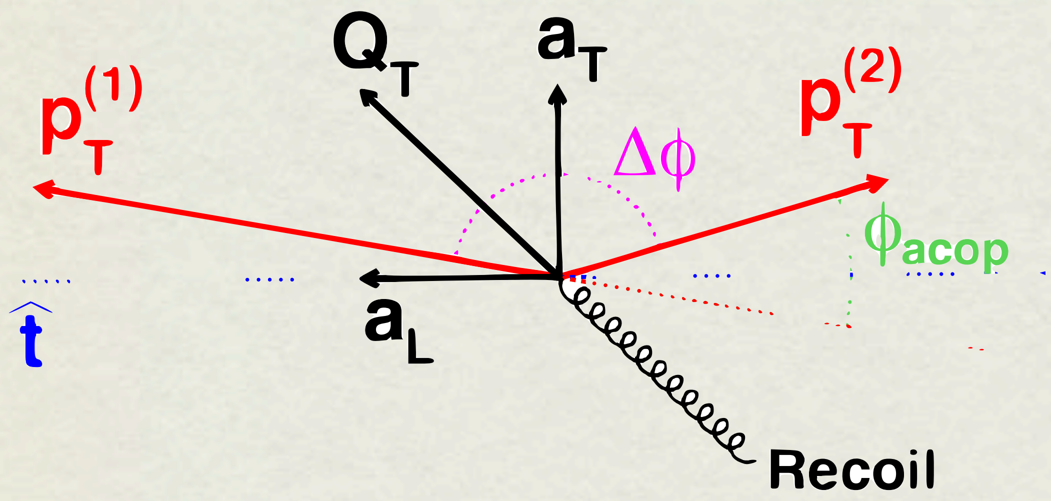

$$\phi^* = \tan(\phi_{\rm acop}/2)\sin\theta^*$$

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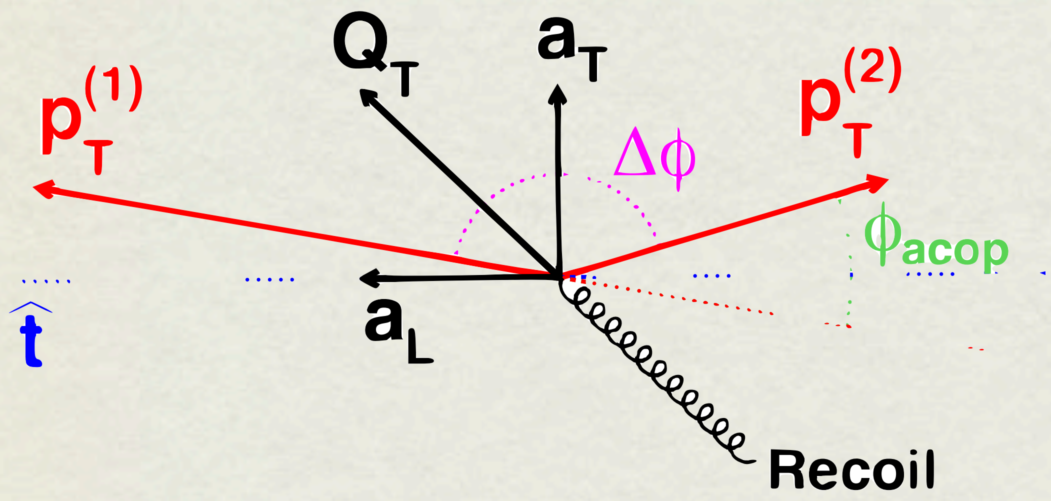

$$\phi^* = \tan\left(\phi_{\rm acop}/2\right)\sin\theta^*$$

θ^* : scattering angle in the frame where the leptons are aligned; it only depends on their pseudorapidities

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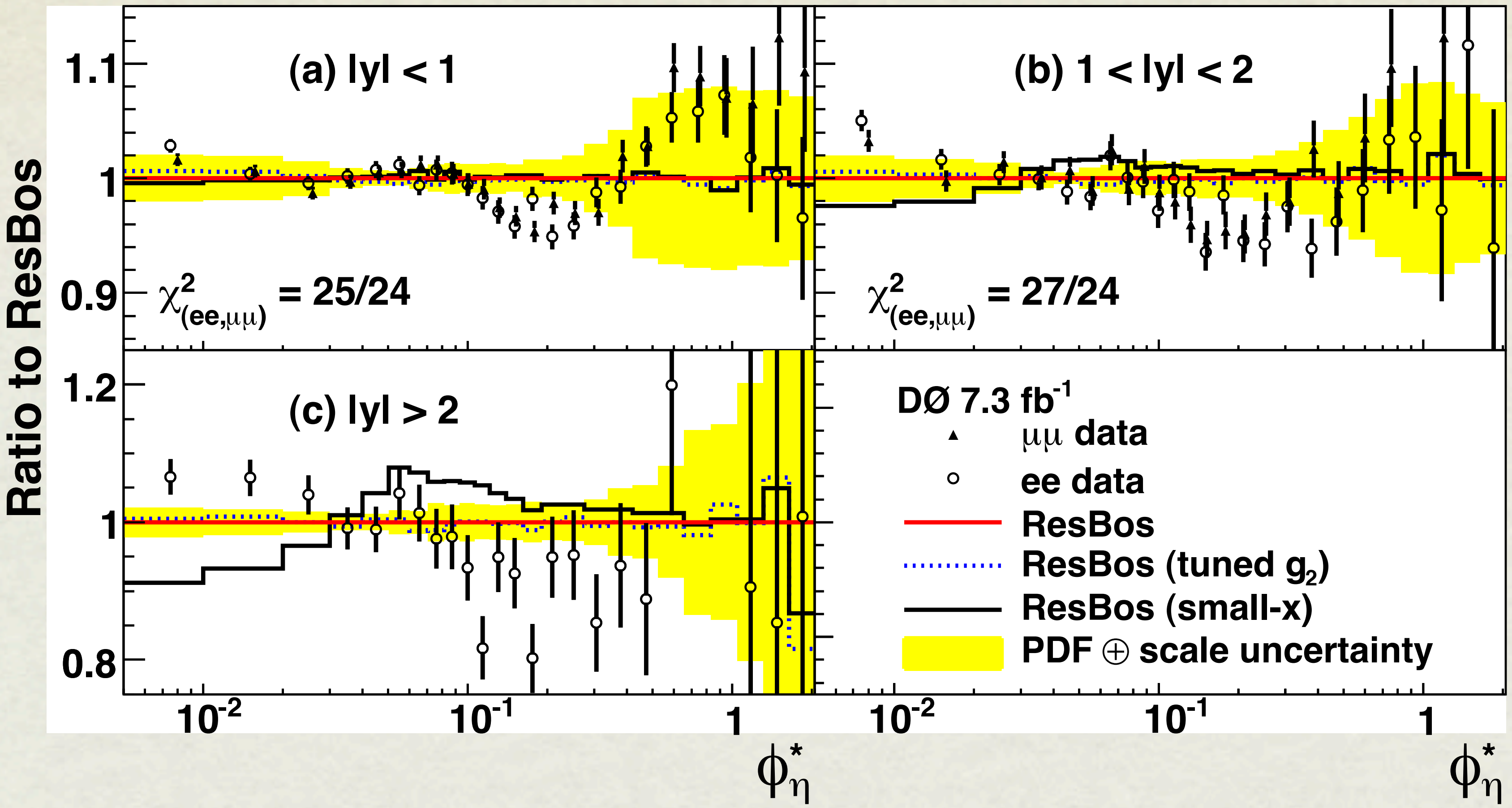
DØ Results

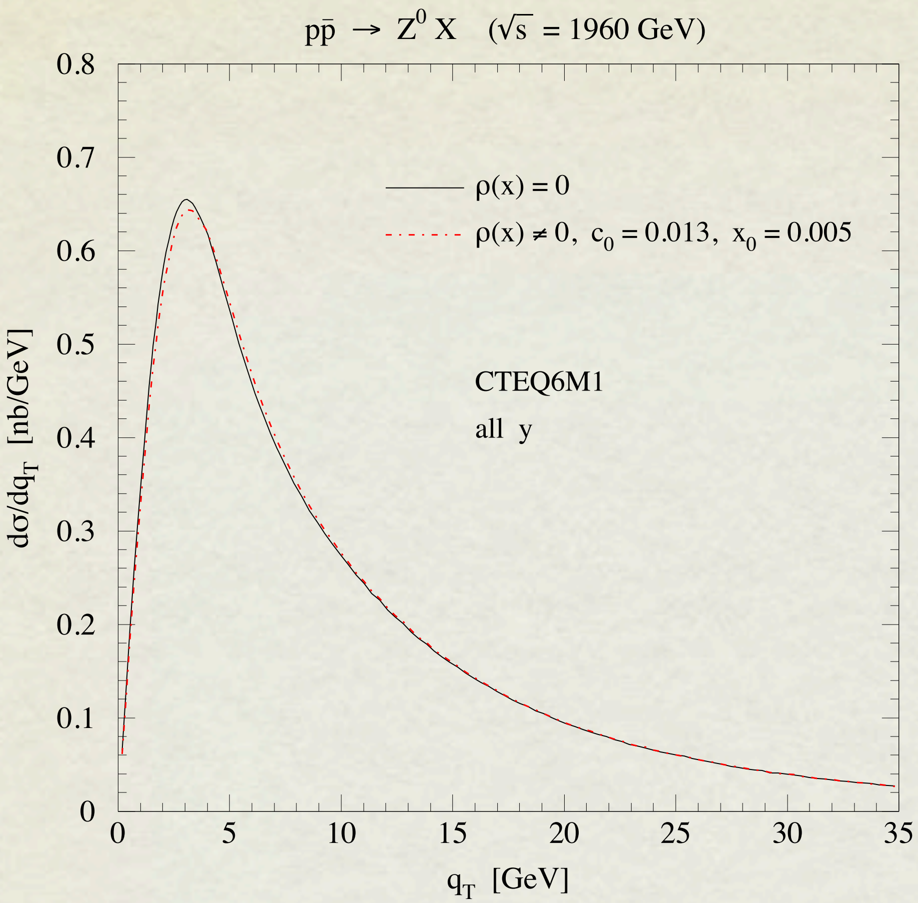


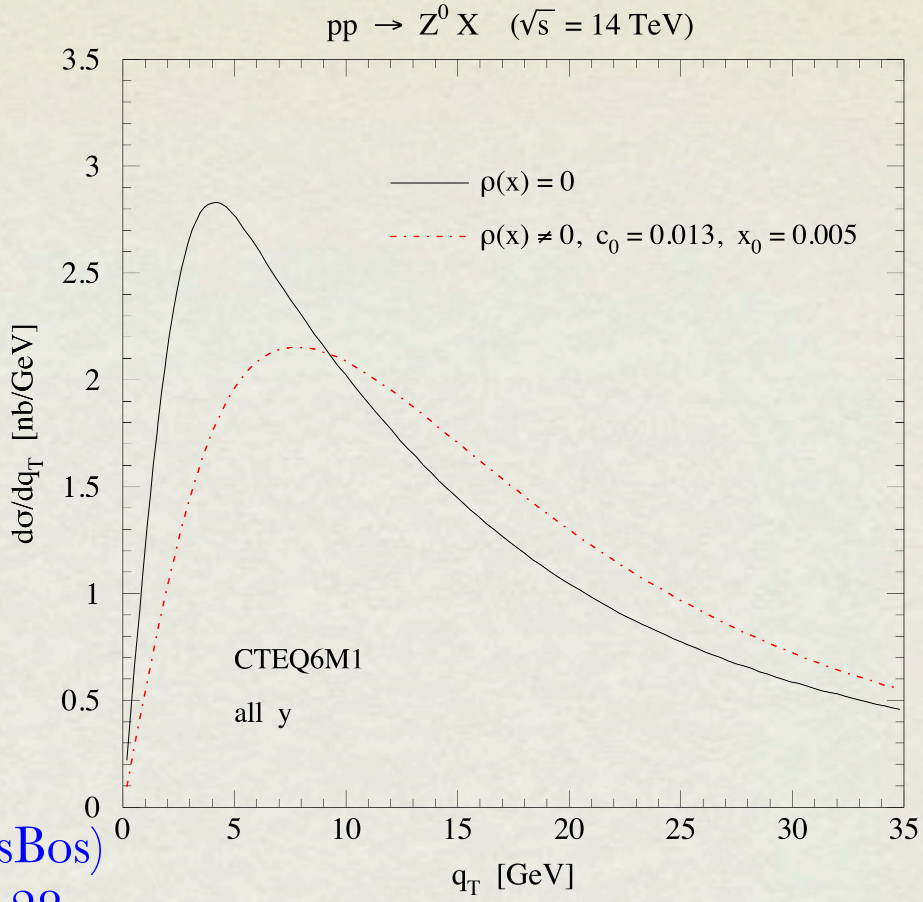
DØ collaboration

arXiv:1010.0262

- DØ compared their results to ResBos predictions
- Matching to NLO for Q_T only ?
- Small-*x* broadening is disfavoured by data
- Small-*x* broadening has consequences for LHC phenomenology (wider rapidity span)

Small-x Effects @ LHC





Berge *et al* (ResBos)
hep-ph/0401128

- Small-x broadening is supposed to be quite significant at the LHC
- The theoretical understanding is not satisfactory: need for a dedicated study

Theory Viewpoint

- From theory point of view: can we use the very well established Q_T resummation to study these new variables ?

- The a_T variable and its connection to Q_T already studied

Banfi, Duran and Dasgupta, arXiv:0909.5327

- The resummation for a_T is closely related to the one for Q_T

- Moreover, in the soft limit

$$\phi^* \simeq \frac{a_T}{M} = \left| \sum_i \frac{k_{Ti}}{M} \sin\phi_i \right| + \mathcal{O}\left(\frac{k_{Ti}^2}{M^2}\right)$$

- So we can adapt the Q_T formalism to study φ^* as well

Resummation For φ*

- In the case of these new variables we are interested in one of the components of Q_T rather than its magnitude

- In the *b*-space formalism this produces a cosine function rather than a Bessel function

$$\frac{d\sigma}{d\phi^*} = \frac{\pi\alpha^2}{sN_c} \int_0^\infty d(bM) \cos(bM\phi^*) e^{-R(b)} \\ \times \Sigma(x_1, x_2, \cos\theta^*, bM)$$

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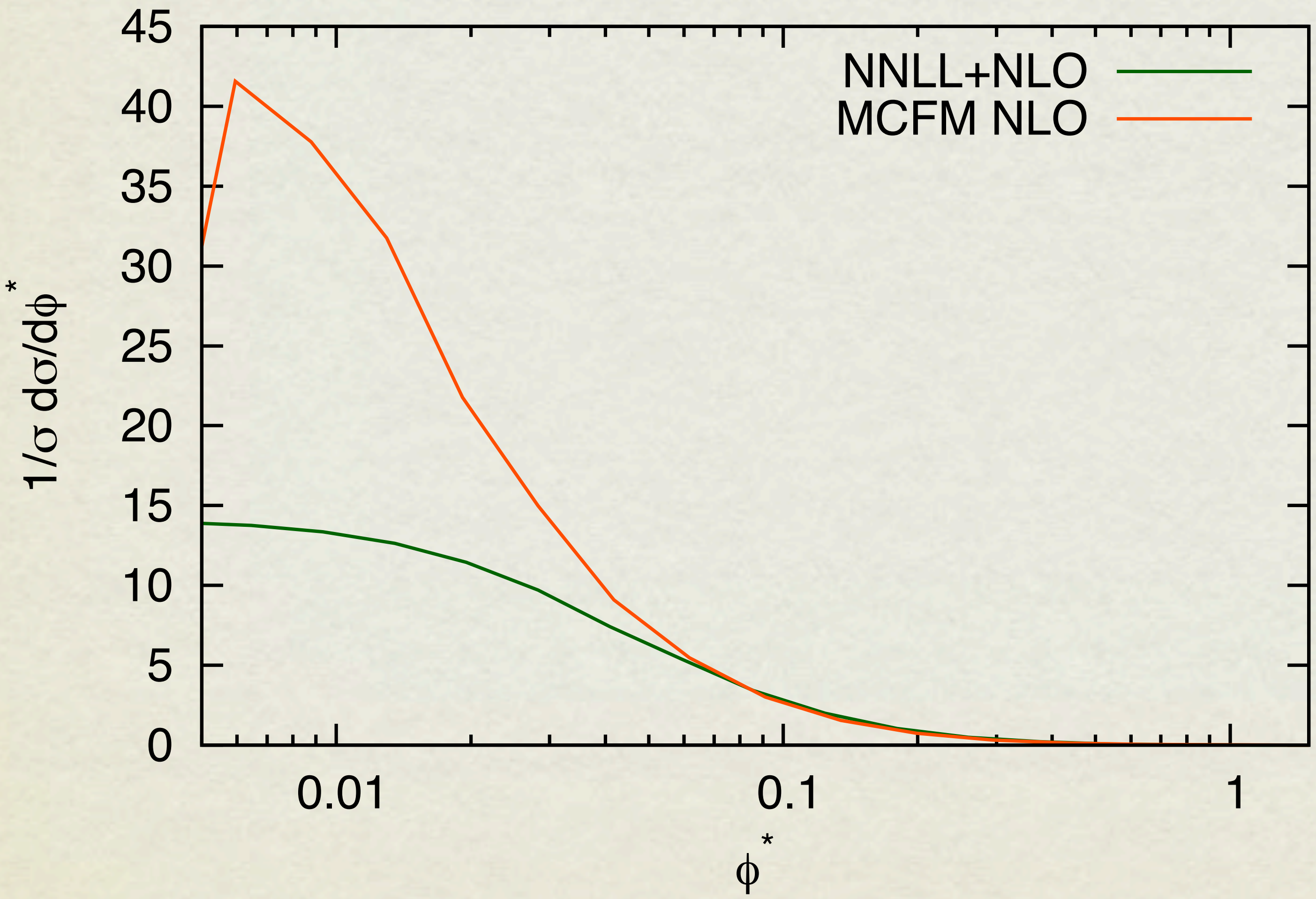
- Important phenomenological consequences

- In the case of these new variables the kinematical cancellation is the dominant suppression mechanism and it prevents the formation of a Sudakov peak

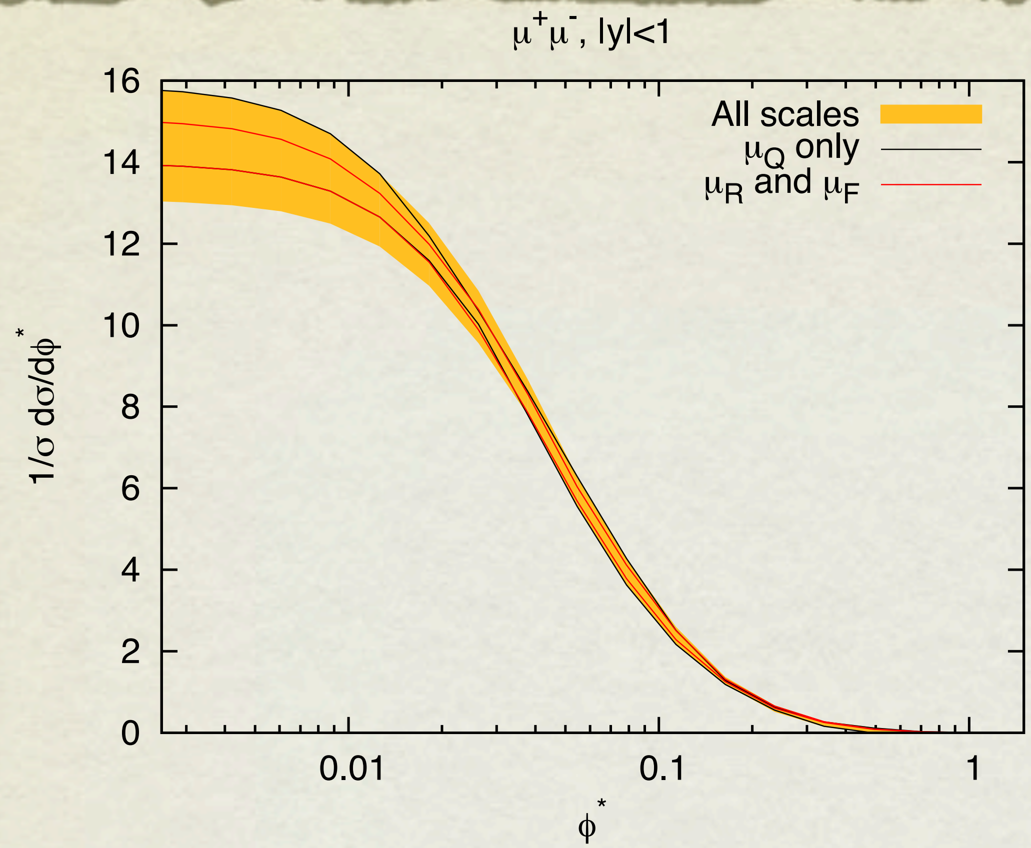
The Matched Result

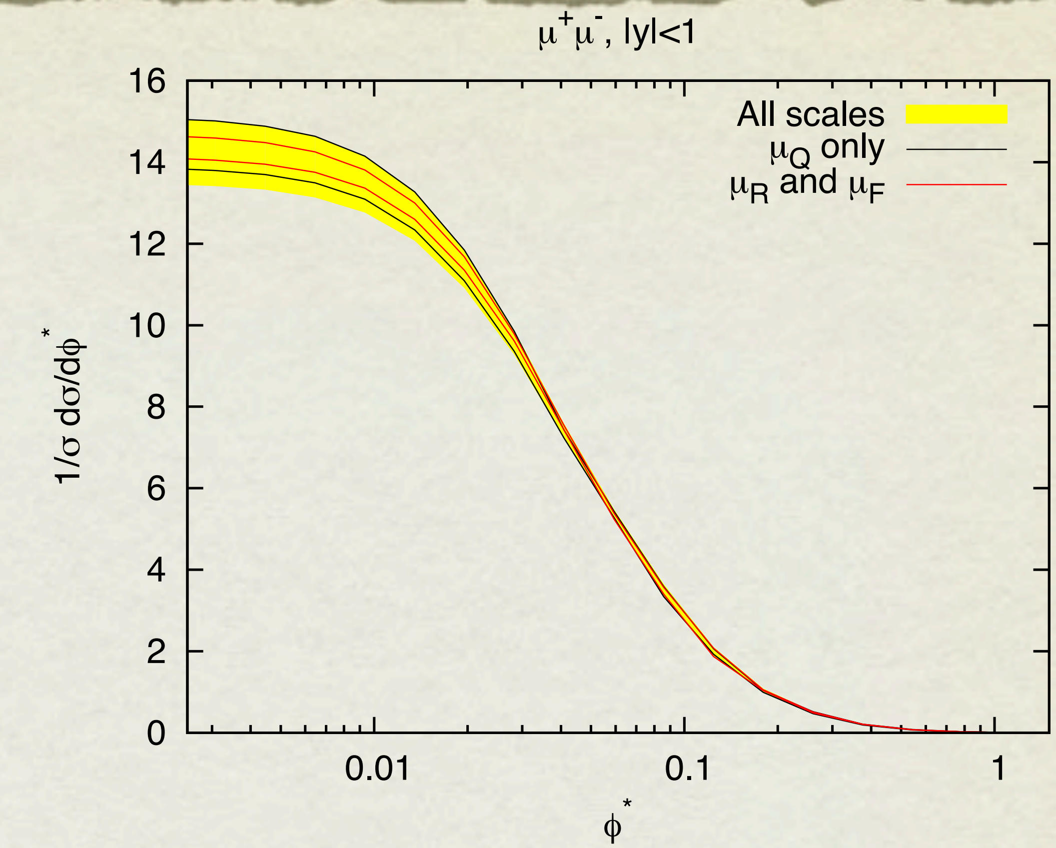
$$\left(\frac{d\sigma}{d\phi^*}\right)_{\text{matched}} = \left(\frac{d\sigma}{d\phi^*}\right)_{\text{resummed}} + \left(\frac{d\sigma}{d\phi^*}\right)_{\text{fixed order}} - \left(\frac{d\sigma}{d\phi^*}\right)_{\text{expanded}},$$

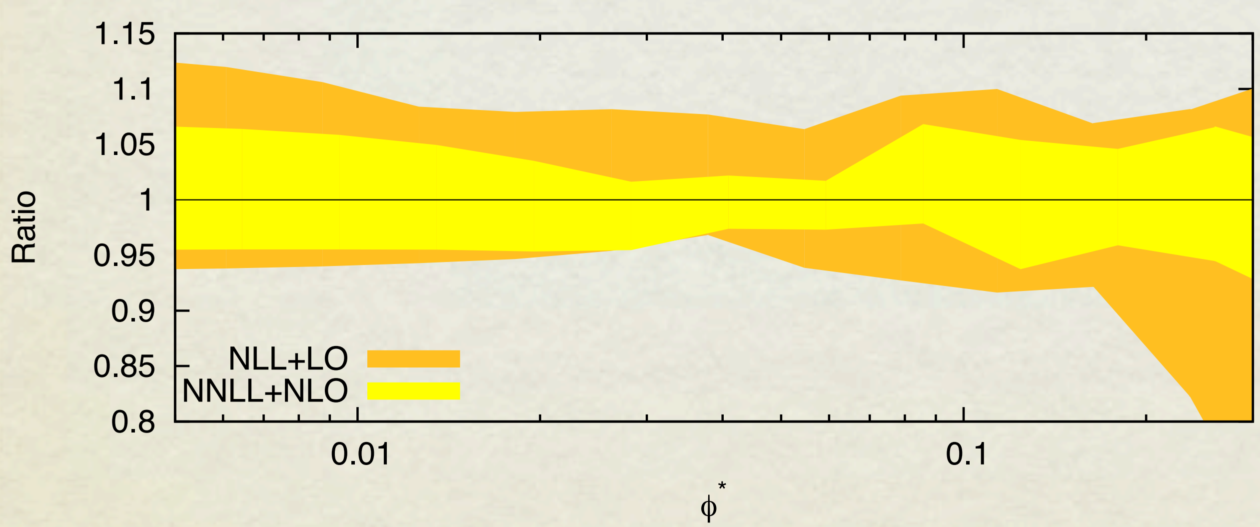


- Smooth matched result
- The matched curve and fixed order agree at large φ*
- But they very much differ in a large region
- As anticipated the φ* distribution does not exhibits a peak (in contrast with the Q_T case)

NLL+LO vs NNLL+NLO

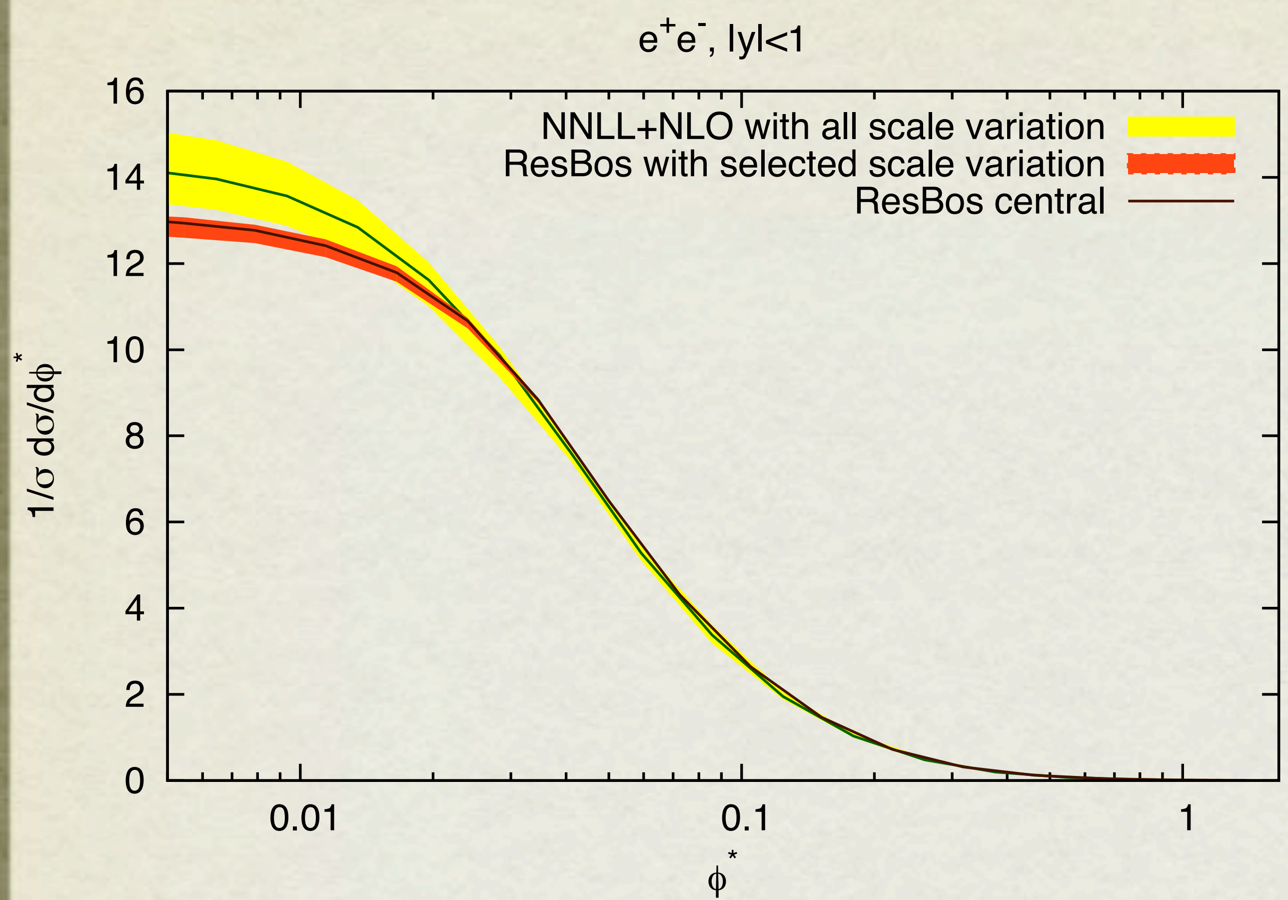


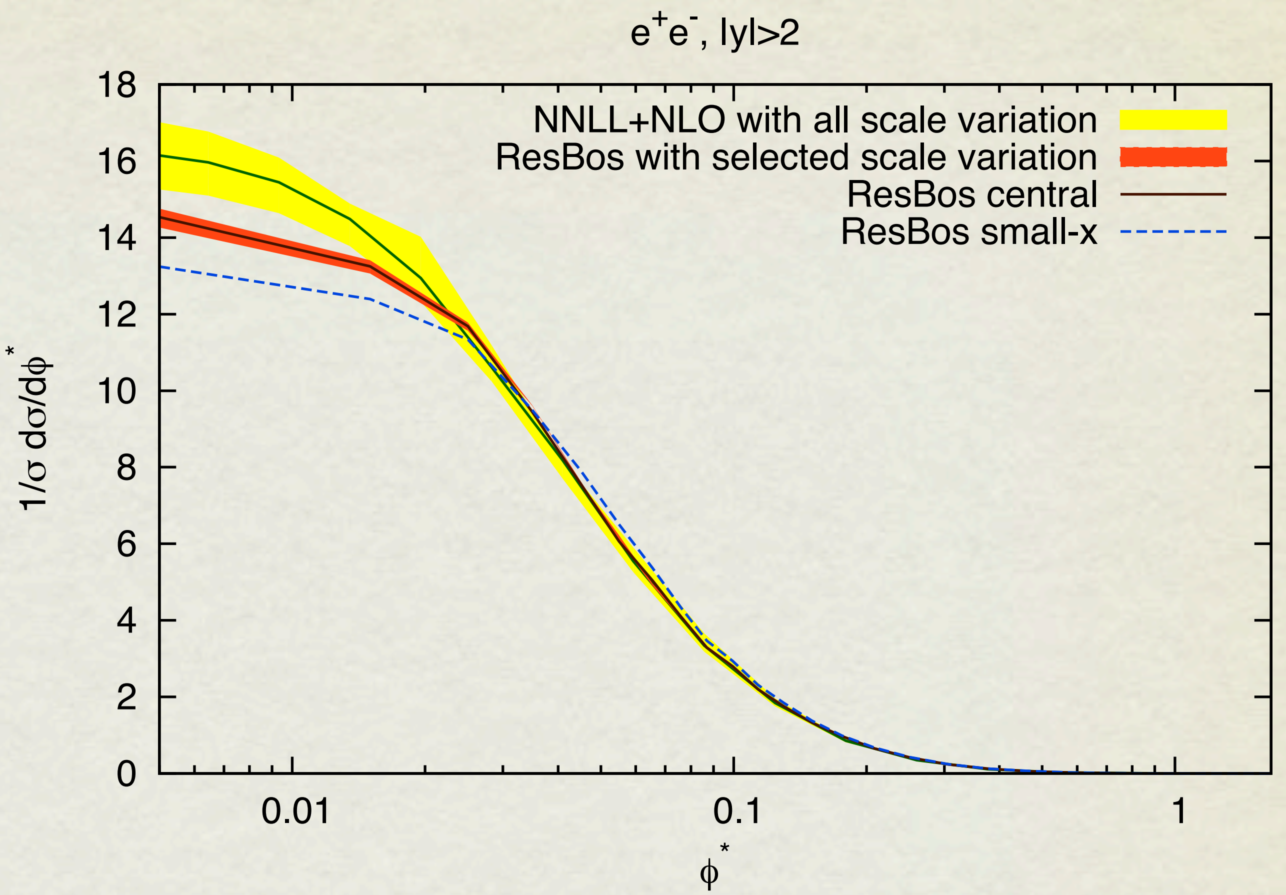




- Usual renormalisation (μ_R) factorisation (μ_F) scales but also resummation scale (μ_Q)
- All scales are varied independently
- Biggest contribution as small φ^* from μ_Q
- Band almost halved (20% to 10%)
- PDFs uncertainties mostly cancel in the ratio
- They are at the percent level

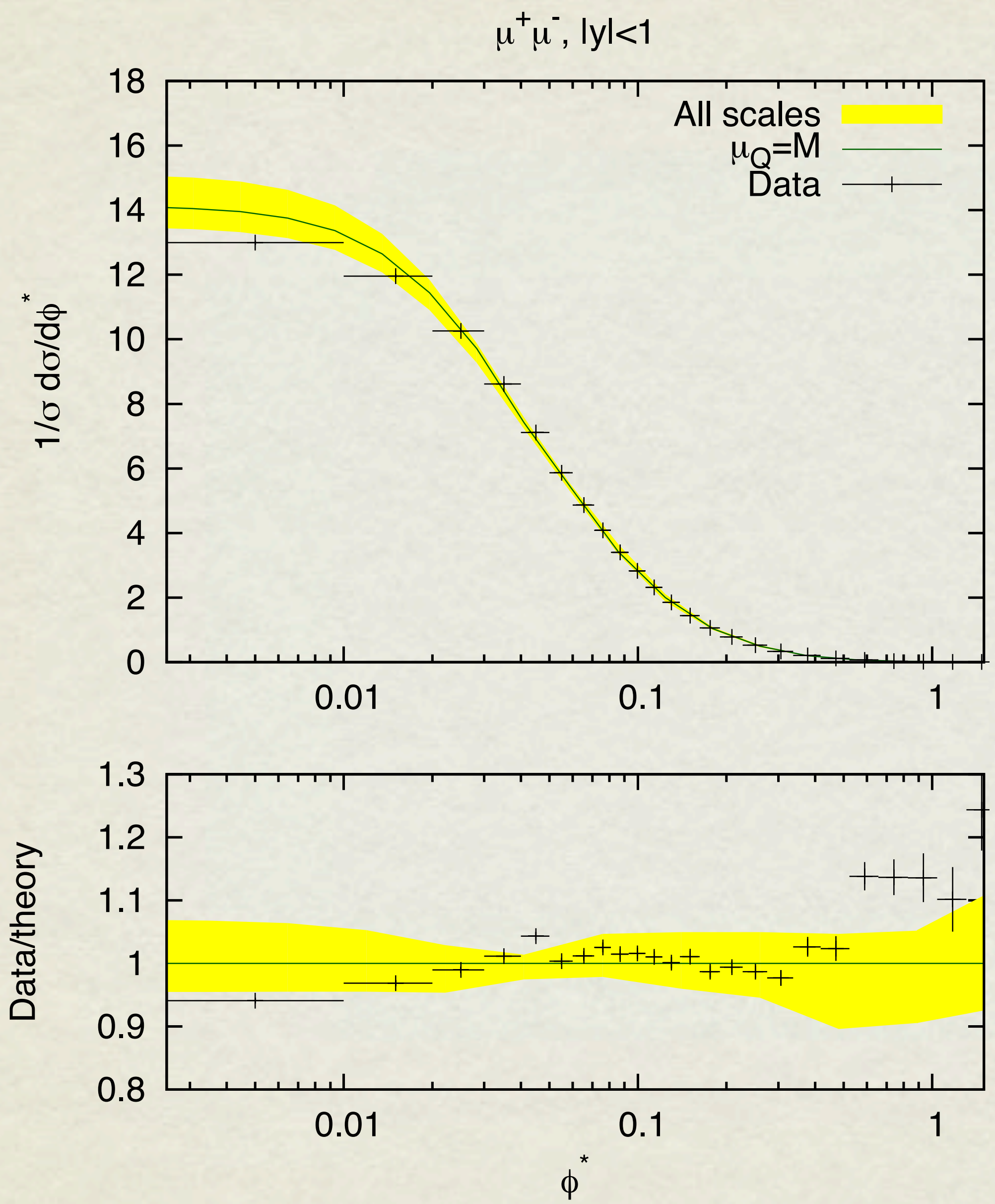
Comparison To ResBos

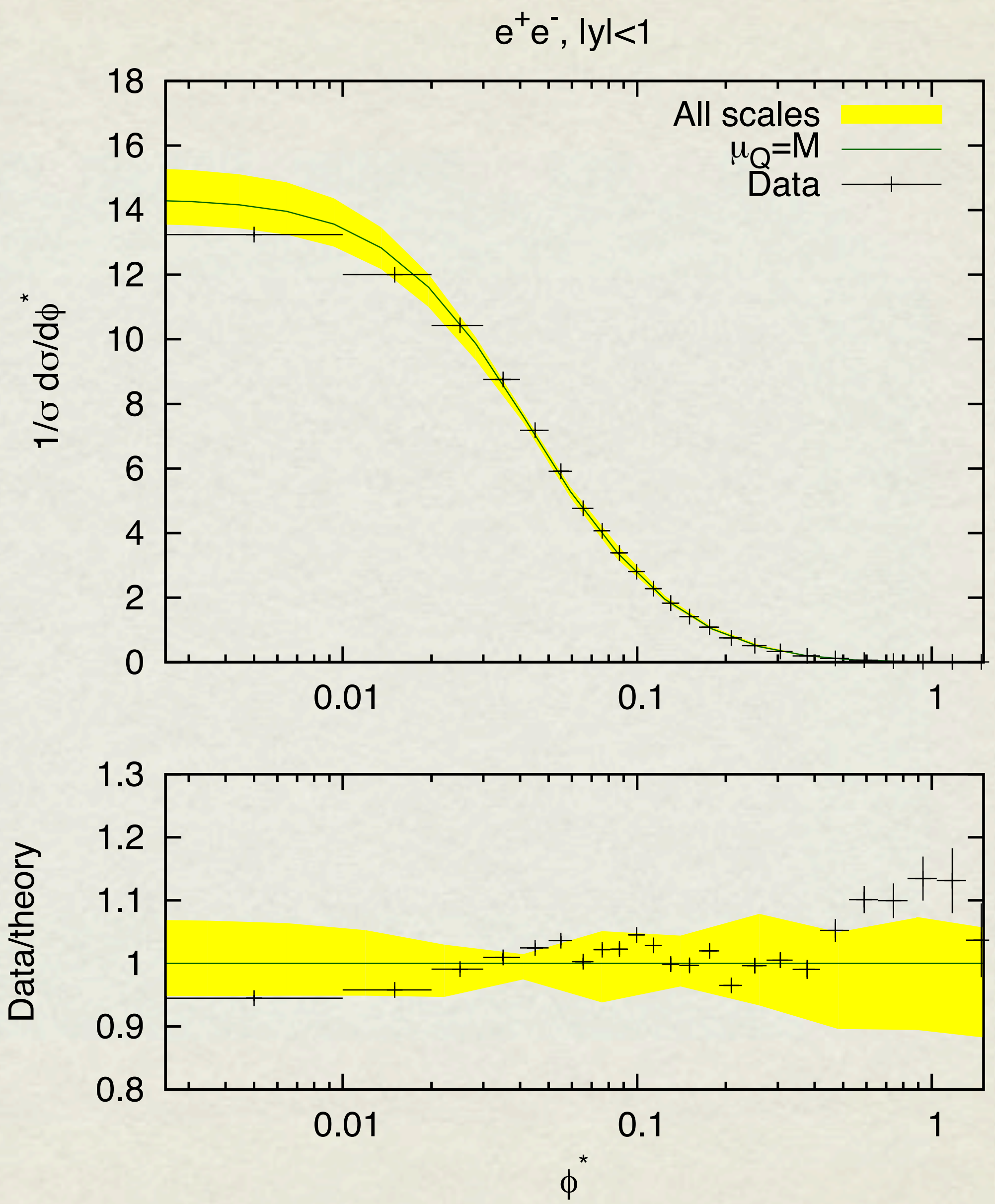




- Comparison of perturbative uncertainties
- ResBos tends to underestimate them
- Differences in the central values are due to NP contributions

Comparison To DØ Data





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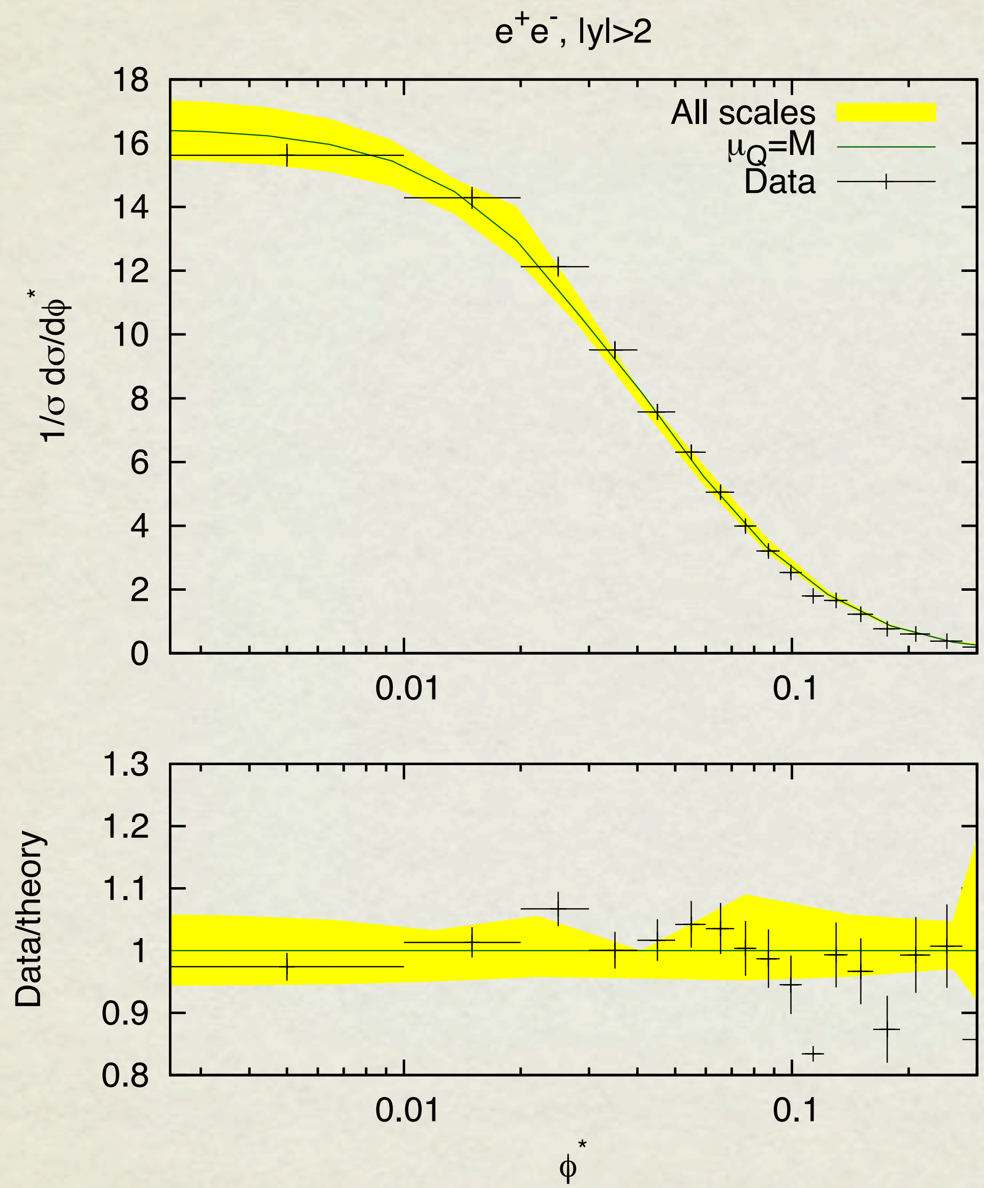
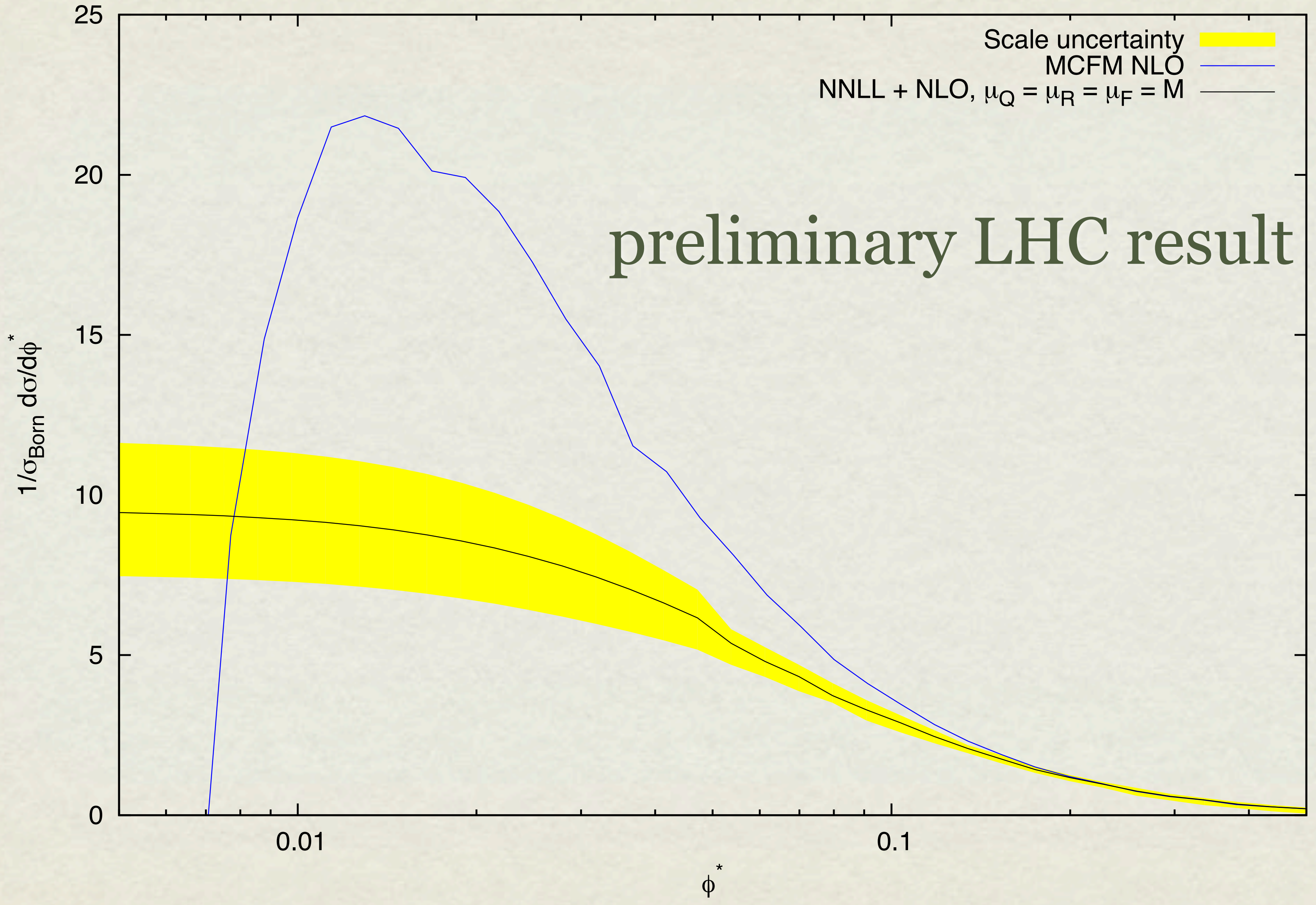


- Good agreement, within uncertainties, for all rapidity bins
- NP form factors are not required to describe the data at low φ^*

Moving To The LHC

- ATLAS and CMS experiments published measurements of the Q_T spectrum of the Z boson
- Our resummation is fully differential in the leptons' momenta so we can take into account all the cuts
- We will be able to make comparison with the data in the fiducial region with no need of extrapolation
- We also encourage the measurement of the φ^* distribution for precise study of EW / QCD physics at the LHC

φ* At The LHC



Scale uncertainty
MCFM NLO
NNLL + NLO, μQ = μR = μF = M
preliminary LHC result
25
20
15
10
5
0
0.01
0.1
1/σBorn dσ/dφ*
φ*

Conclusions

- The DØ collaboration introduced new variables to probe the Q_T spectrum of the Z boson
- The data are very accurate and disfavour non-perturbative models currently on the market (e.g. small-*x* broadening)
- We have performed a dedicated study of the φ^* variable
- We have computed a state-of-the-art perturbative prediction NNLL+NLO, with a faithful estimate of the theoretical uncertainties
- We have a good description of DØ, in all rapidity bins with no need of NP form factors, once the perturbative uncertainties are properly taken into account
- We are almost ready to compare our theoretical predictions to first LHC data for the Q_T spectrum

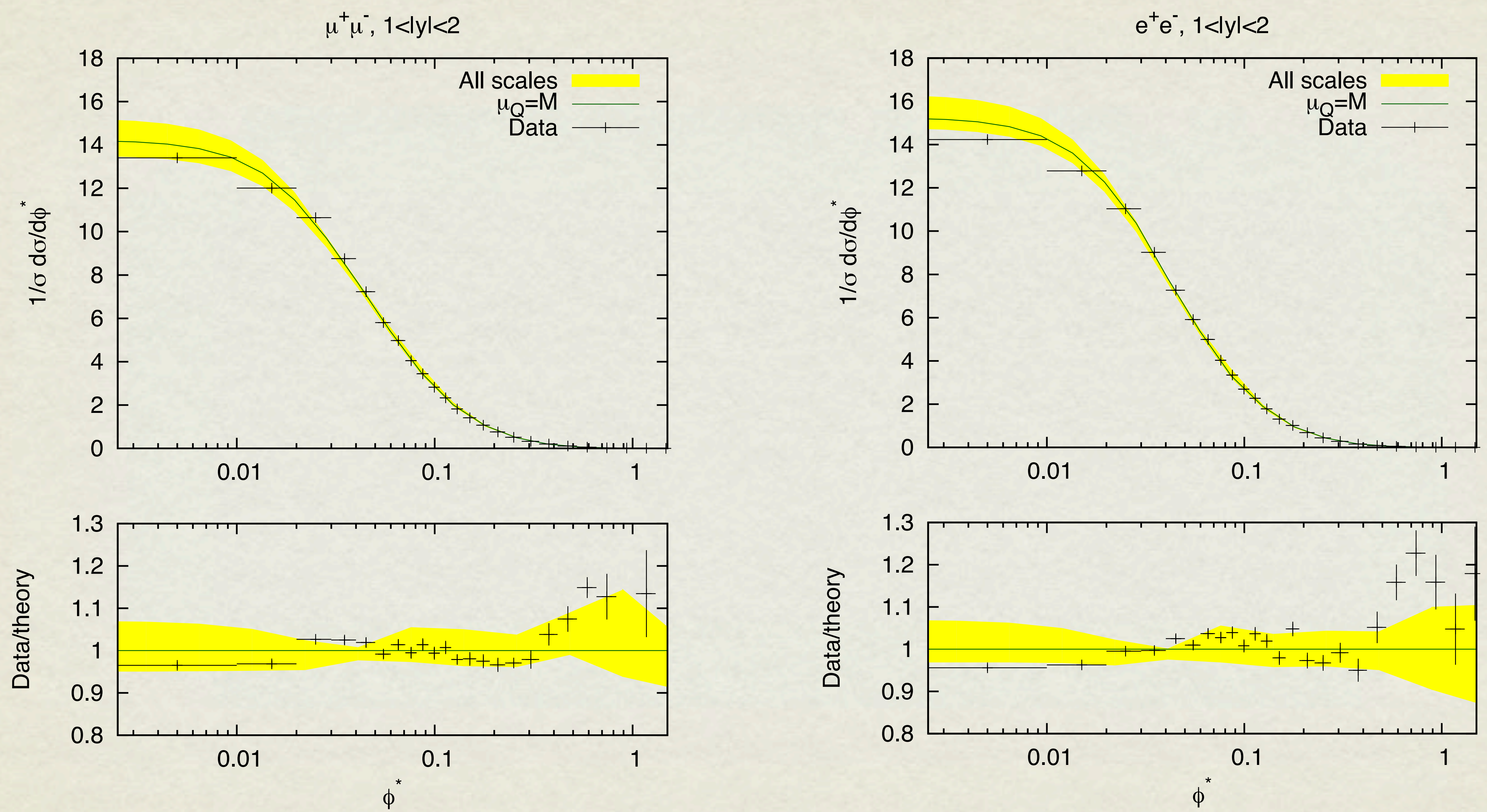
Outlook

- ATLAS and CMS have already measured the Q_T spectrum
- We encourage LHC measurements for these new variables as well
- Plans for a big theoretical / experimental project to study EW/QCD physics at the LHC:
  - data from ATLAS and LHCb (sensitive to different kinematics)
  - efforts to improve theoretical understanding (resummation, factorisation)
  - extension to di-boson final states and Z H as well

Thank you very much

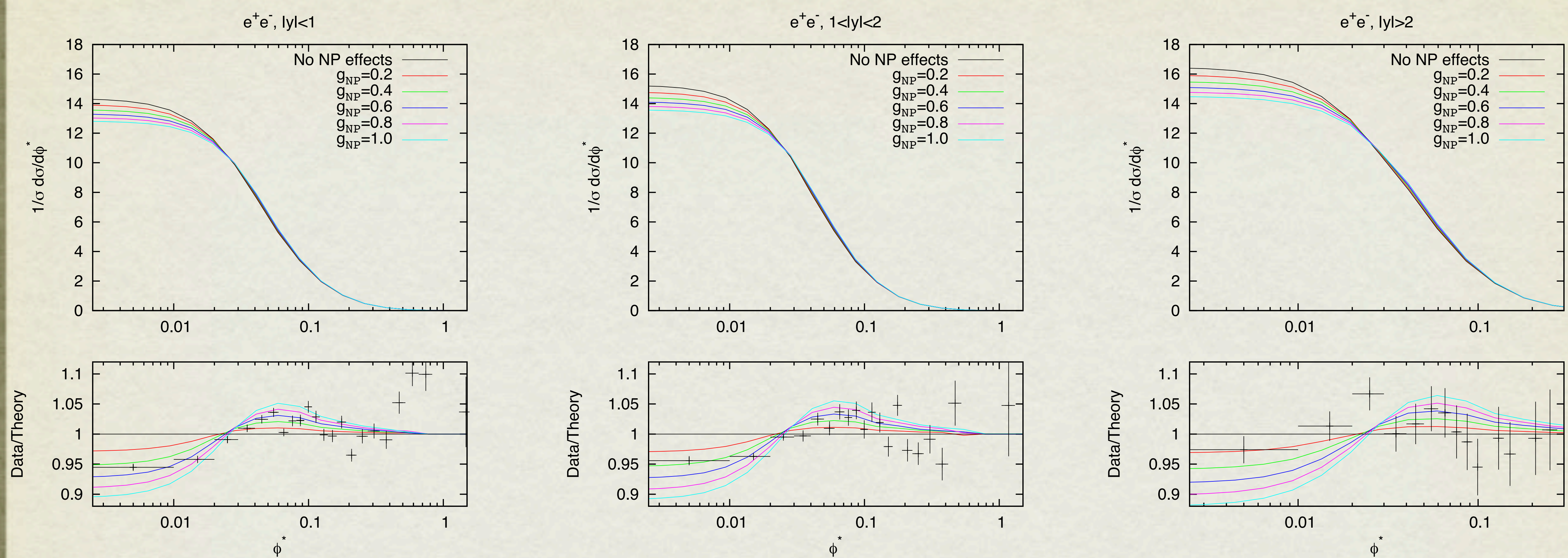
for your attention

Comparison To DØ Data



NP Gaussian Smearing

$$R_{\rm NP} = R + g_{\rm NP} b^2$$



- Spread similar to the perturbative band
- This is misleading: we are ascribing pert. uncertainties to a universal NP parameter
- Consequences for related studies if we use were to use the fitted NP parameter