Dilepton transverse momentum distribution variables at the Tevatron and the LHC

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in collaboration with
Banfi, Dasgupta and Tomlinson

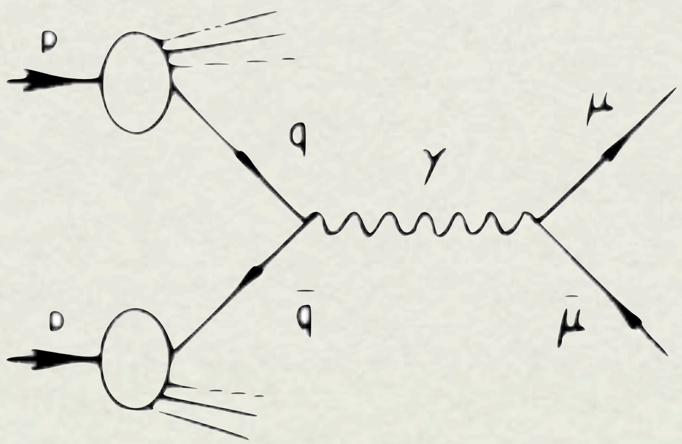
arXiv:1102.3594
arXiv:1110.4009
arXiv:12*xx.xxxx*

Outline

- Motivation for studying the EW boson transverse momentum
- Resumming large logarithms
- Novel variables
  - resummation to NNLL
  - matching to fixed order
- Comparison to data
- Conclusions and Outlook

The Drell-Yan Process

- The production of a lepton pair in hadron- hadron collisions is one of the most studied processes in particle phenomenology
  - Original paper: S. D. Drell and T. M. Yan, “Massive Lepton Pair Production In Hadron-Hadron Collisions At High-Energies,” Phys. Rev. Lett. 25 (1970) 316 [Erratum-ibid. 25 (1970) 902].
- Strictly speaking it is the *only* process for which factorisation has been proven in hadron – hadron collisions



- QCD corrections are known to $O(\alpha_s^2)$:
  Hamberg, van Neervan and Matsuura, Nucl.Phys.B359:343-405

Transverse Momentum

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

- 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 test of QCD dynamics
- This is a multi-scale problem
- The correct treatment of these effects goes beyond fixed order perturbation theory: we need resummation

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

Need For Accuracy

- Very precise measurements together with accurate theoretical calculations can set limits on the non-perturbative contribution (intrinsic transverse momentum of the initial state quarks)
- An accurate theoretical description of the transverse momentum of weak boson is important for the extraction of the W mass (and hence relevant to top and Higgs physics)
- Our aim to improve and validate the theoretical tools using Tevatron data to be able to do accurate phenomenology at the LHC

Leading Log Resummation

- Fixed order calculations work well at large Q_T but fail when Q_T is small

- Large logarithms appear and we need to resum them

$$\frac{1}{\sigma}\frac{d\sigma}{dQ_T^2} \simeq \frac{1}{Q_T^2}\left[A_1\alpha_s \ln\frac{M^2}{Q_T^2} + A_2\alpha_s^2 \ln^3\frac{M^2}{Q_T^2} + \ldots\right]$$

- At leading logarithmic accuracy (LL) this expression can be resummed to

$$\frac{1}{\sigma}\frac{d\sigma}{dQ_T^2} \simeq \frac{d}{dQ_T^2} e^{-\frac{\alpha_s}{2\pi}C_F \ln^2 \frac{M^2}{Q_T^2}}$$

- This exhibits a Sudakov peak

Resummation Beyond LL

- Resummation is based on factorisation properties
- In the eikonal (soft) limit it easy to see that matrix elements factorise
- Less trivial is to properly treat momentum conservation, essential to go beyond LL
- We can achieve full factorisation in impact parameter space

$$\delta^{(2)}\left(\sum_{i=1}^{n} \underline{k}_{Ti} + \underline{Q}_T\right) = \frac{1}{(2\pi)^2}\int d^2\underline{b}e^{i\underline{b}\cdot\underline{Q}_T}\prod_{i=1}^{n} e^{i\underline{b}\cdot\underline{k}_{Ti}}$$

- One of the problems with this approach is then the inversion back to momentum space (more later)
- New source of suppression: kinematic cancellation rather than Sudakov

Q_T Resummation

- In the usual transverse momentum resummation one is interested in the magnitude Q_T
- Hence one integrates over the angle between *b* and Q_T
- This results into a Bessel function J_0

$$\frac{d\sigma}{dQ_T^2} \simeq \int_0^\infty db\, b\, J_0(bQ_T) e^{-R(b)} \Sigma(x_1, x_2, \cos\theta^*, bM)$$

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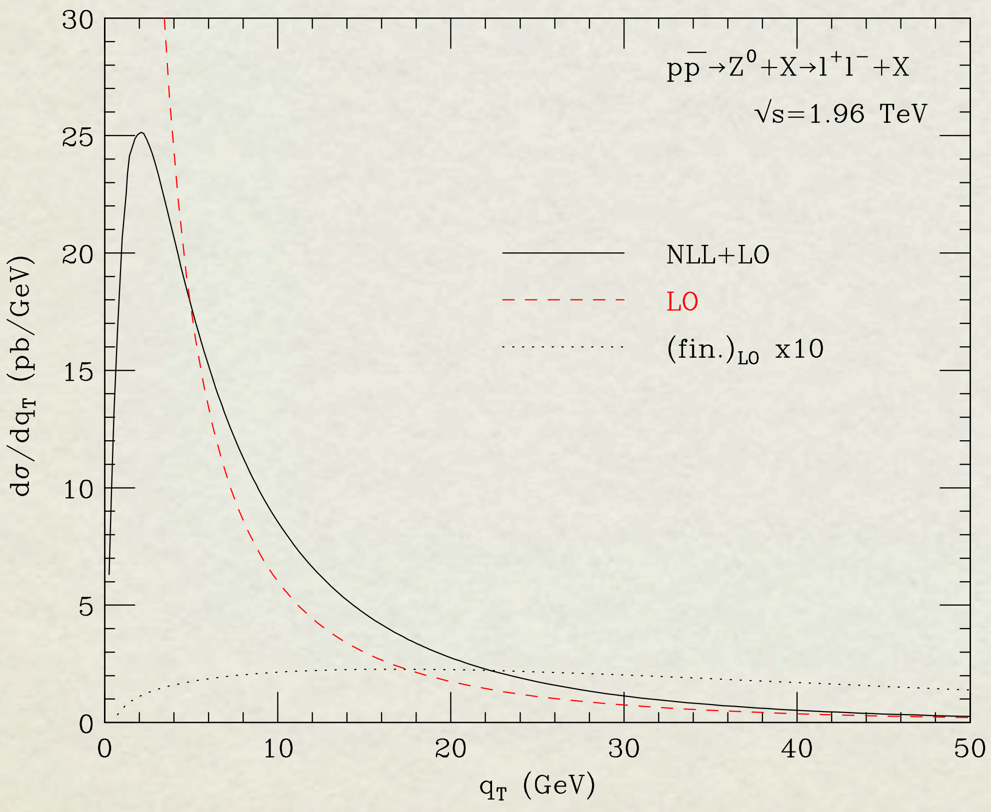
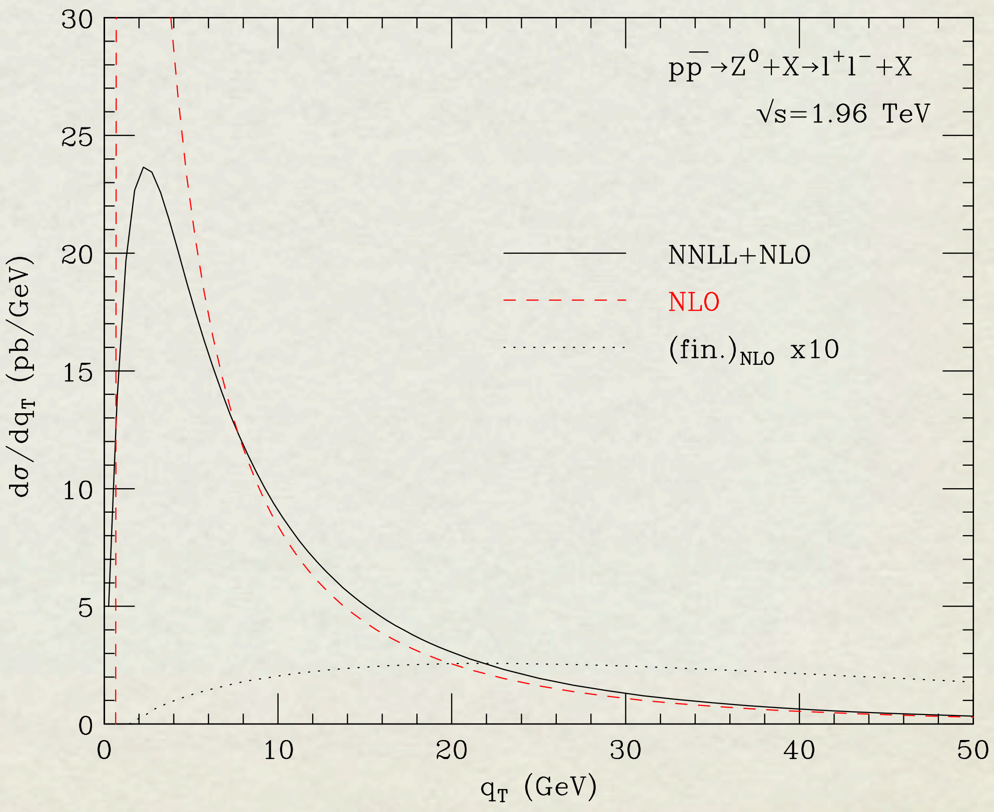
Σ contains the non-logarithmic terms convolved with the PDFs

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)





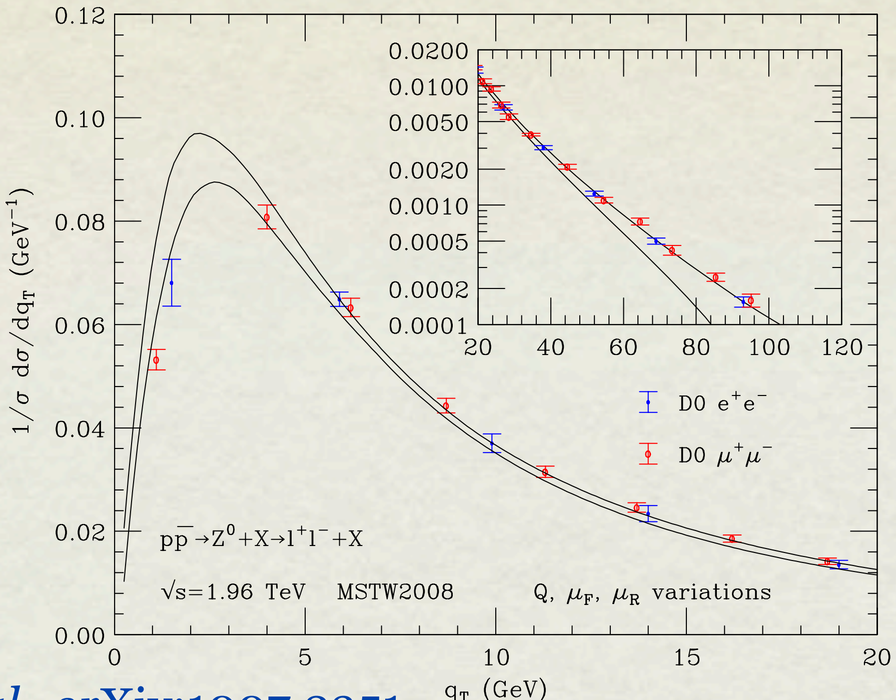
Catani *et al.* arXiv:1007.2351

- At the moment, most of the approaches are fully inclusive in the leptons' momenta

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
- This translates into a Gaussian smearing in *b* space
- 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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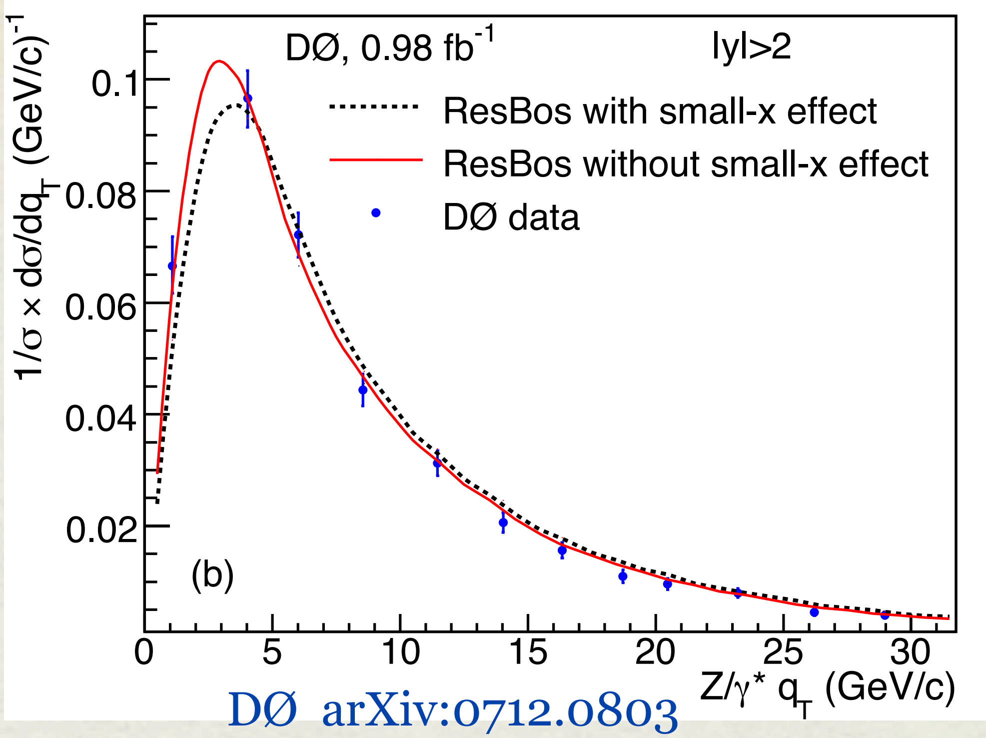
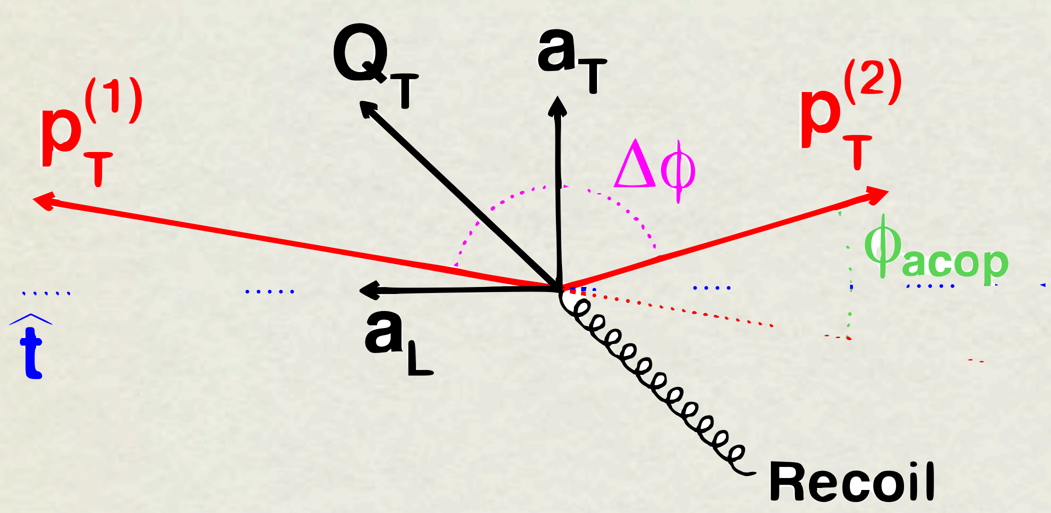


DØ arXiv:0712.0803

- 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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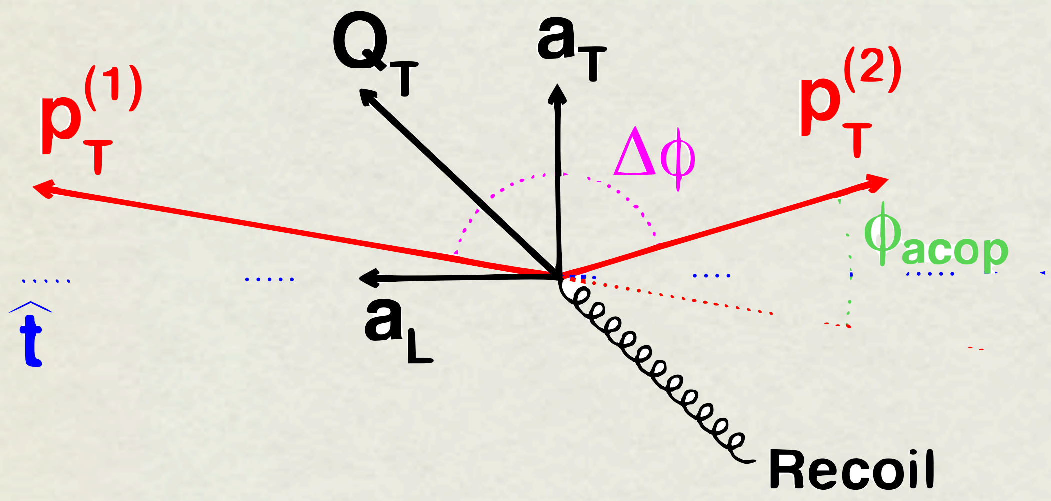

$$\phi^* = \tan\left(\phi_{\text{acop}}/2\right)\sin\theta^*$$

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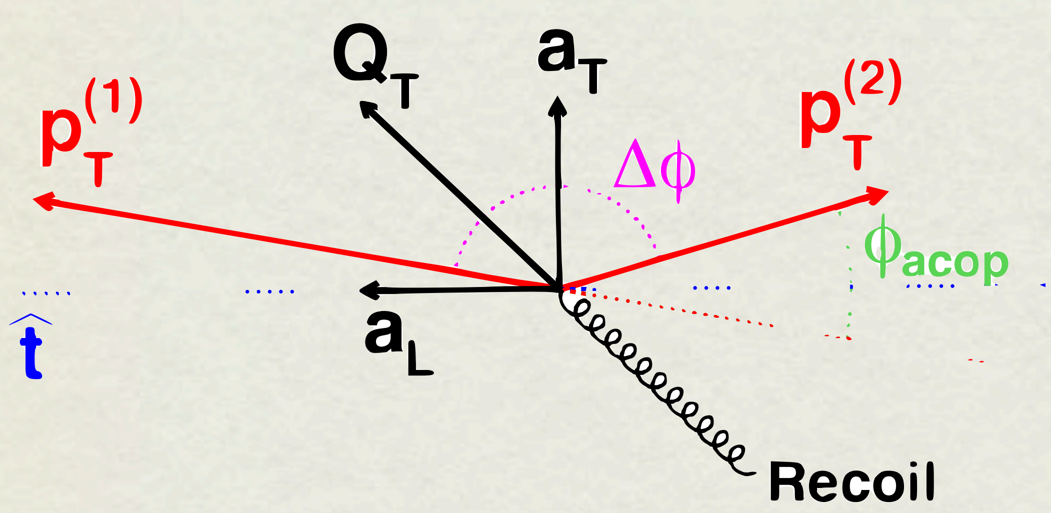

$$\phi^* = \tan(\phi_{\mathrm{acop}}/2)\sin\theta^*$$

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

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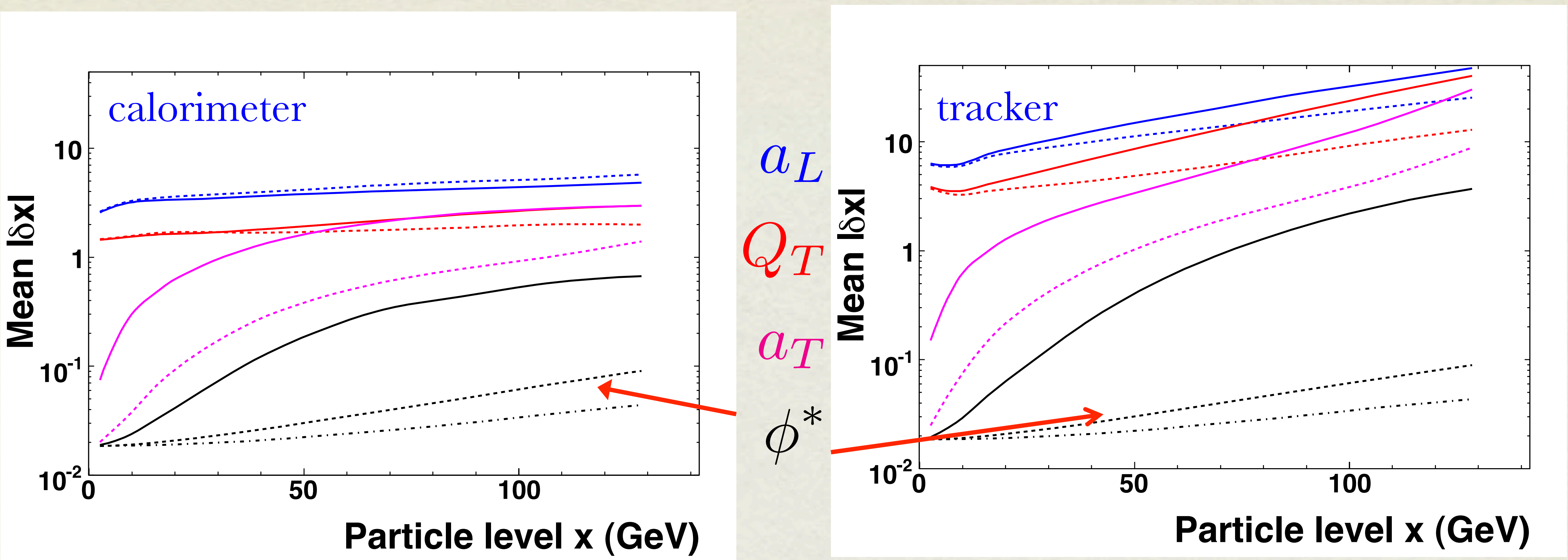
Better Experimental Resolution

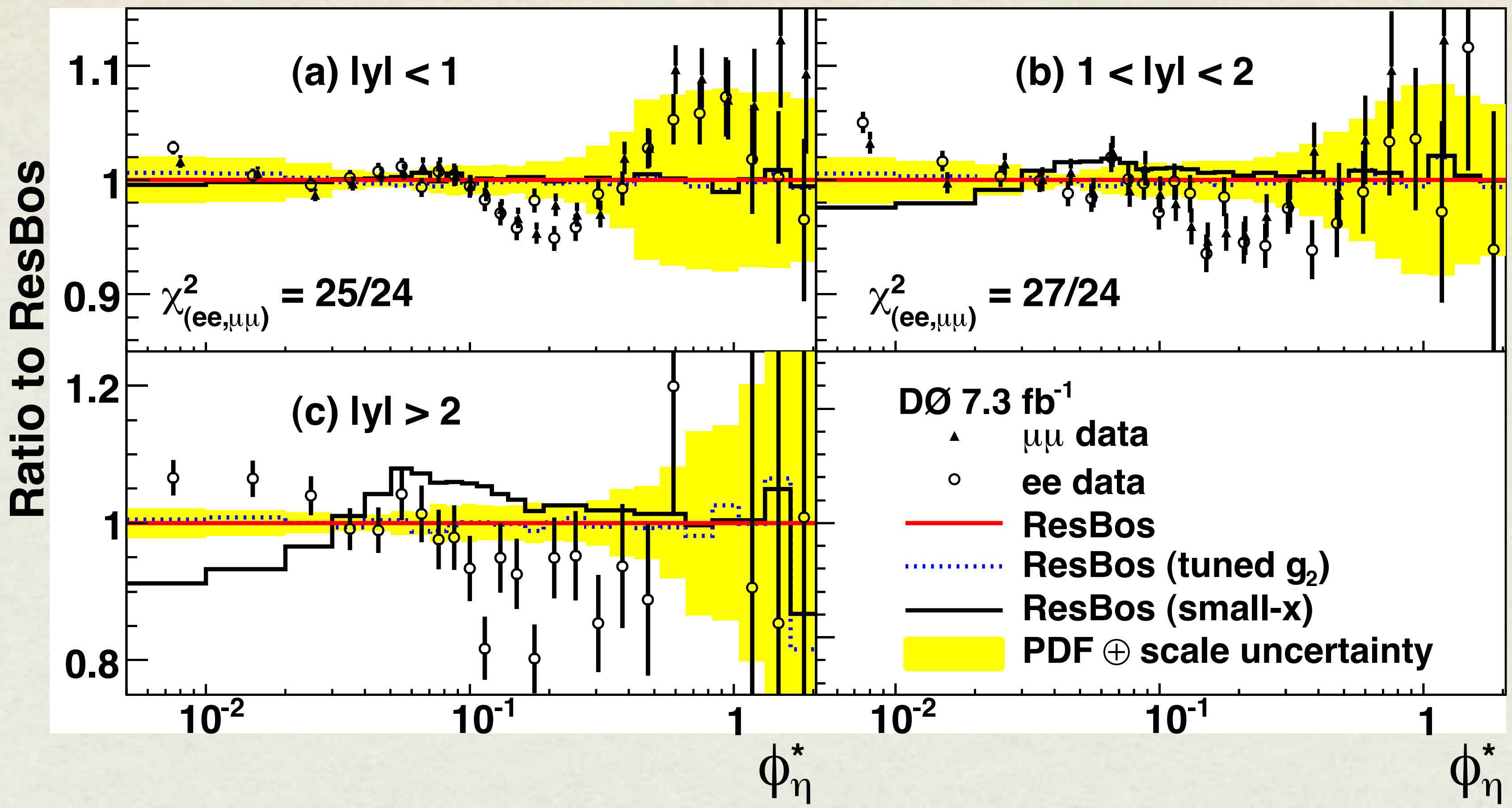


- Study of the experimental resolution for different variables (times some rescaling factor)
- Dashed lines represent ratios of a given variable to the dilepton invariant mass

Banfi et *al.*

arXiv:1009.1580 [hep-ex]

DØ Results

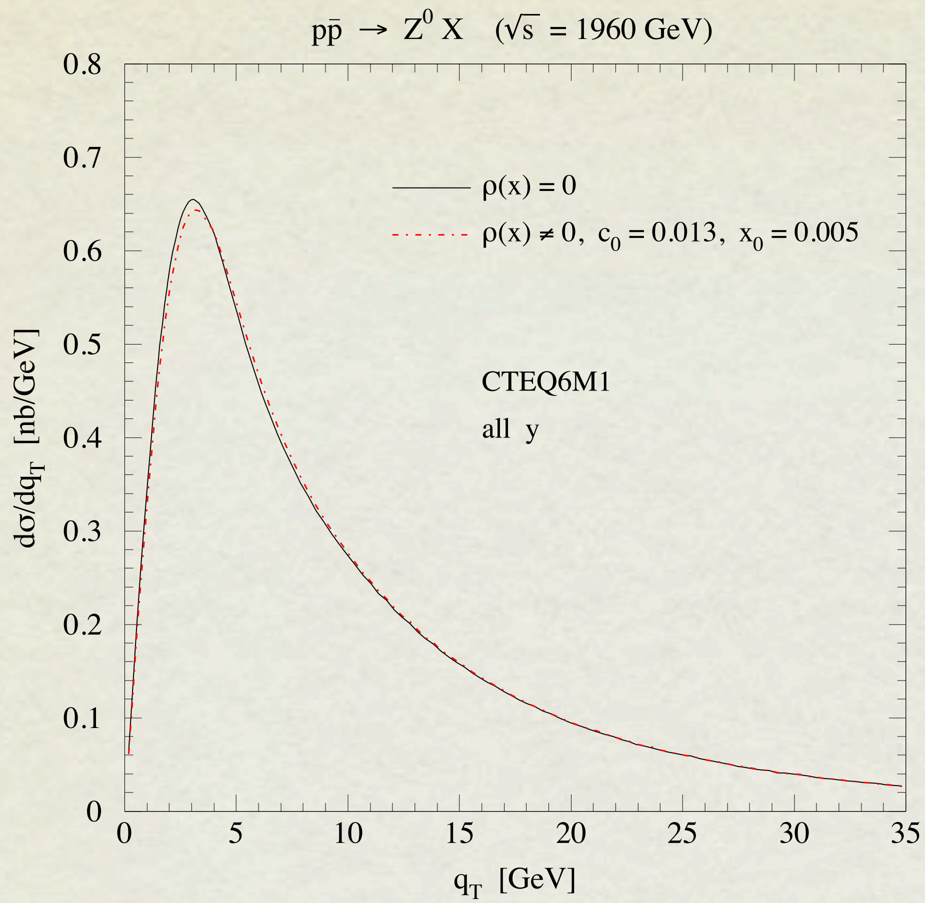


DØ collaboration

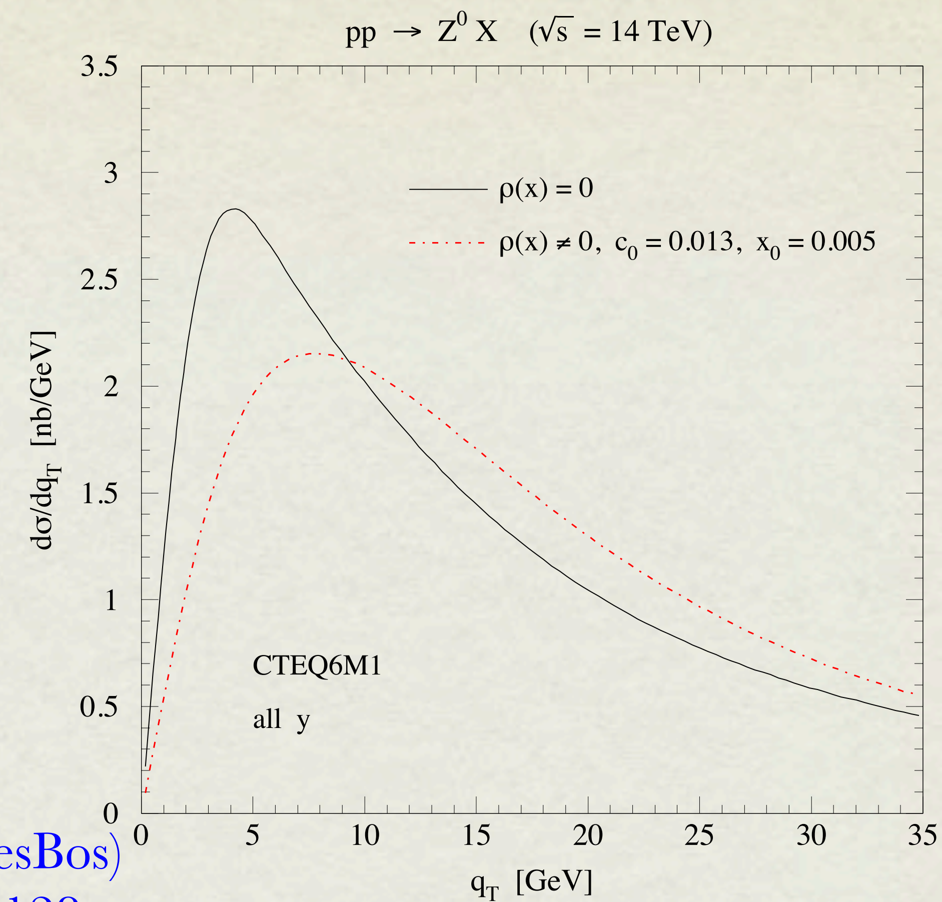
arXiv:1010.0262

- 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 the Bessel function J_0 we have encountered before

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

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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 Radiator

- Let's have a closer look at the radiator

$$R(b) = Lg^{(1)}(\alpha_s L) + g^{(2)}(\alpha_s L) + \frac{\alpha_s}{\pi} g^{(3)}(\alpha_s L) + \cdots$$

$$L = \ln\left(\bar{b}^2 M^2\right)$$

- The NNLL contribution known for some times

Catani *et al.*

- The NNLL coefficient $A^{(3)}$ was taken from threshold resummation

- A recent calculation in SCET showed that $A^{(3)}$ is different for Q_T resummation

Becher & Neubert

- We include this new contribution (although the effect is not big)

Issues With The b-integral

- In order to obtain the final result we have to invert the Fourier integral
- It is well known that this integral is ill-defined both at small- and large- b
- Small-b: spurious singularity outside the resummation region
  - we switch off the resummation below $b_{\rm min}$ such that $R(b_{\rm min})=0$
- Large-b: non perturbative region, Landau pole

$$g^{(1)} = -\frac{A^{(1)}}{\pi\beta_0}\left[1+\frac{\ln(1-\alpha_s\beta_0 L)}{\alpha_s\beta_0 L}\right]$$

  - we cut off the integration above a given b_{max}
- Increasing $b_{\rm max}$ beyond $(3\,\Lambda_{\rm QCD})^{-1}$ doesn't affect our results

Checking The Logs

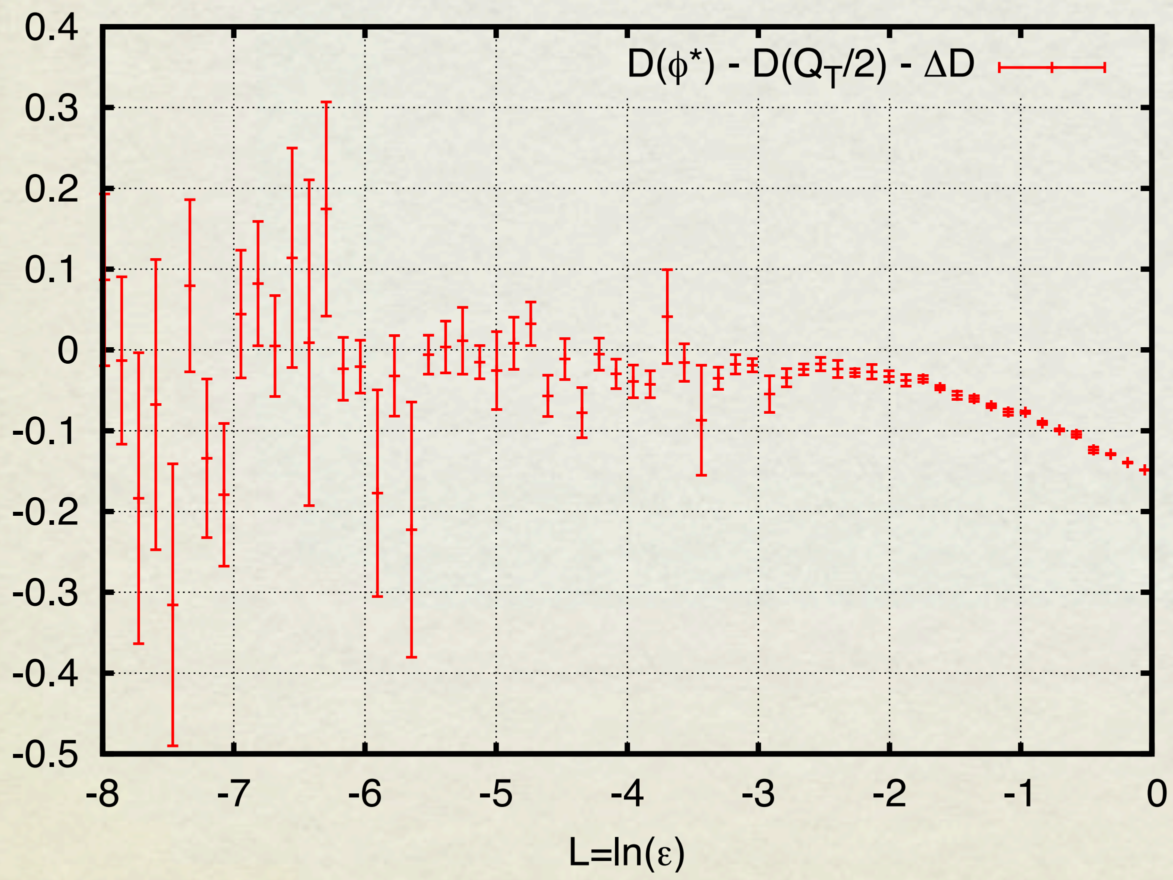
- Before presenting our final result for the resummed and matched distributions we have to check the logs
- We expand our resummation to second order and compare it to the fixed order result
- We use the fixed-order program MCFM Campbell & Ellis
- Because the resummation is NNLL we expect full control of all logarithms at $O(\alpha_s^2)$
- This will noticeably ease our matching procedure
- To test our understanding of the relation between φ^* and Q_T, we plot the difference of these distributions

Q_T vs φ^*

$$\Delta D(\epsilon) = \frac{1}{\tilde{\sigma}_0}\frac{\mathrm{d}}{\mathrm{d}\ln\epsilon}\left[\tilde{\sigma}\left(N_1,N_2,\phi^*\right)\big|_{\phi^*=\epsilon} - \tilde{\sigma}\left(N_1,N_2,Q_T/2\right)\big|_{Q_T/2=\epsilon}\right] =$$

$$\left(\frac{\alpha_s}{2\pi}\right)^2\frac{\mathrm{d}}{\mathrm{d}\ln\epsilon}\left[\pi^2 C_F^2\ln^2\frac{1}{\epsilon^2} + \left(-24C_F^2\zeta(3) - 3\pi^2 C_F^2 - \frac{4}{3}\pi^3 C_F\beta_0\right.\right.$$

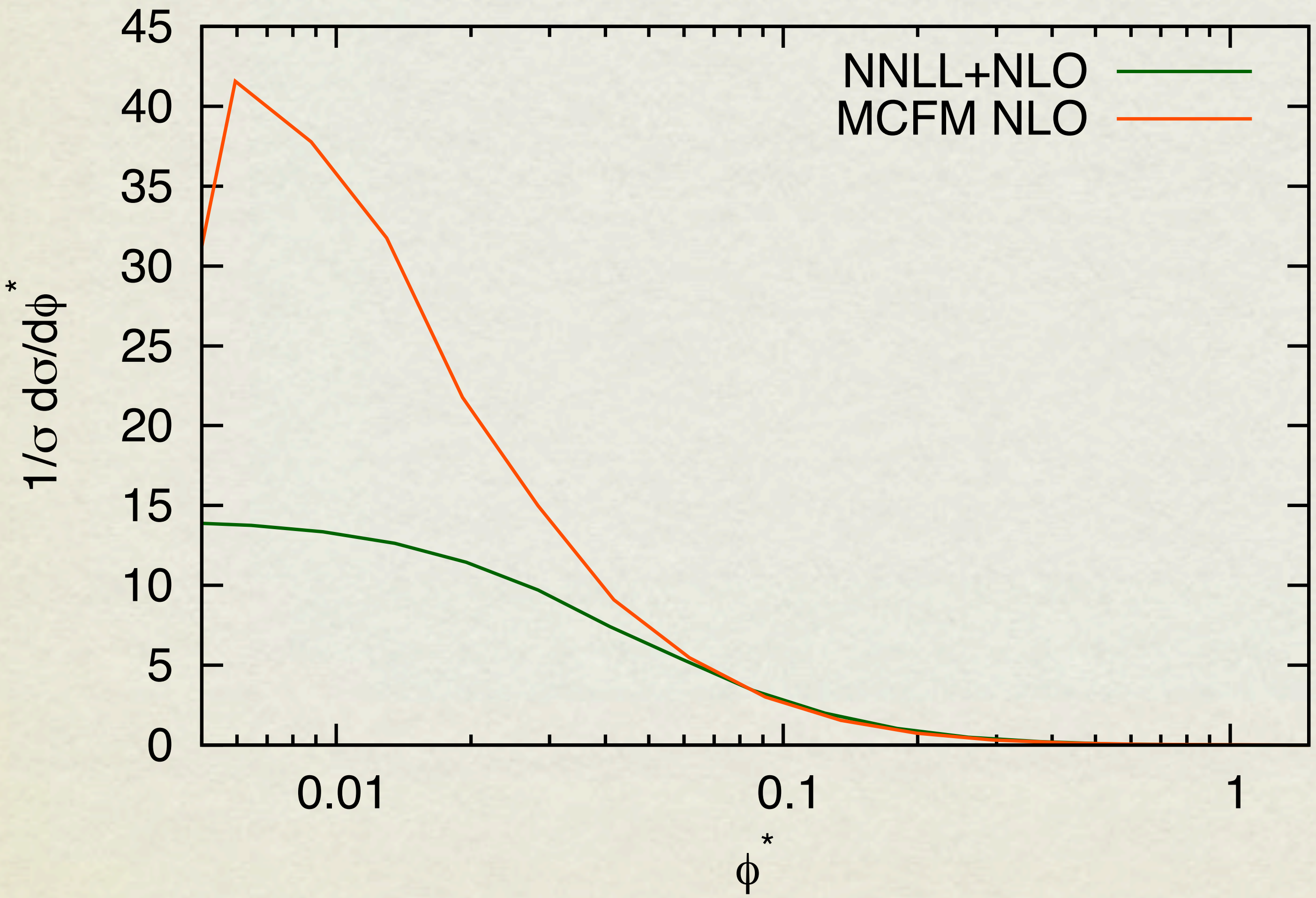
$$\left.\left. + \pi^2 C_F\frac{\left[\mathbf{\Gamma_0}(N_1)\tilde{\mathbf{f}}_{\mathbf{1}}(N_1)\right]_q \mathbf{f}_{\mathbf{2}\bar{q}}(N_2) + 1\leftrightarrow 2}{\mathbf{f}_{\mathbf{1}q}(N_1)\mathbf{f}_{\mathbf{2}\bar{q}}(N_2) + 1\leftrightarrow 2}\right)\ln\frac{1}{\epsilon}\right]$$



- The difference between the expansion of the resummation and the NLO curve vanishes at large |L|
- We have full control of next-to next-to leading logarithms at this order !

The Matched Result

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



- 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)

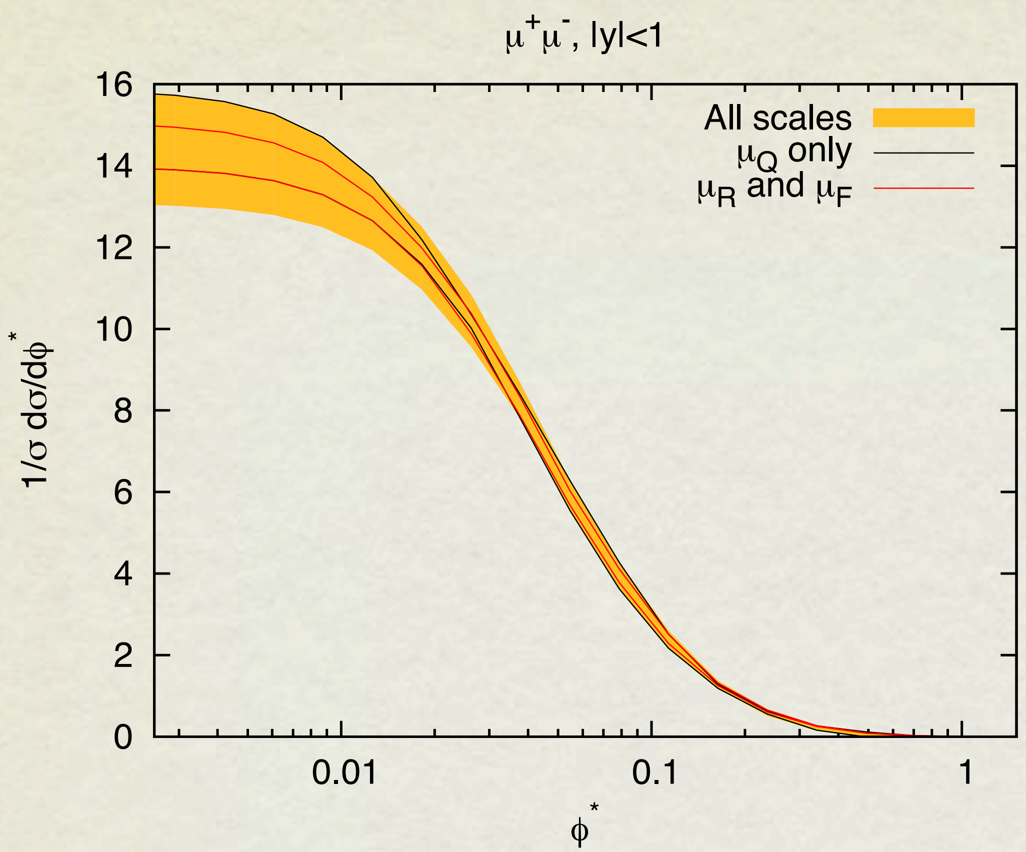
Theoretical Uncertainty

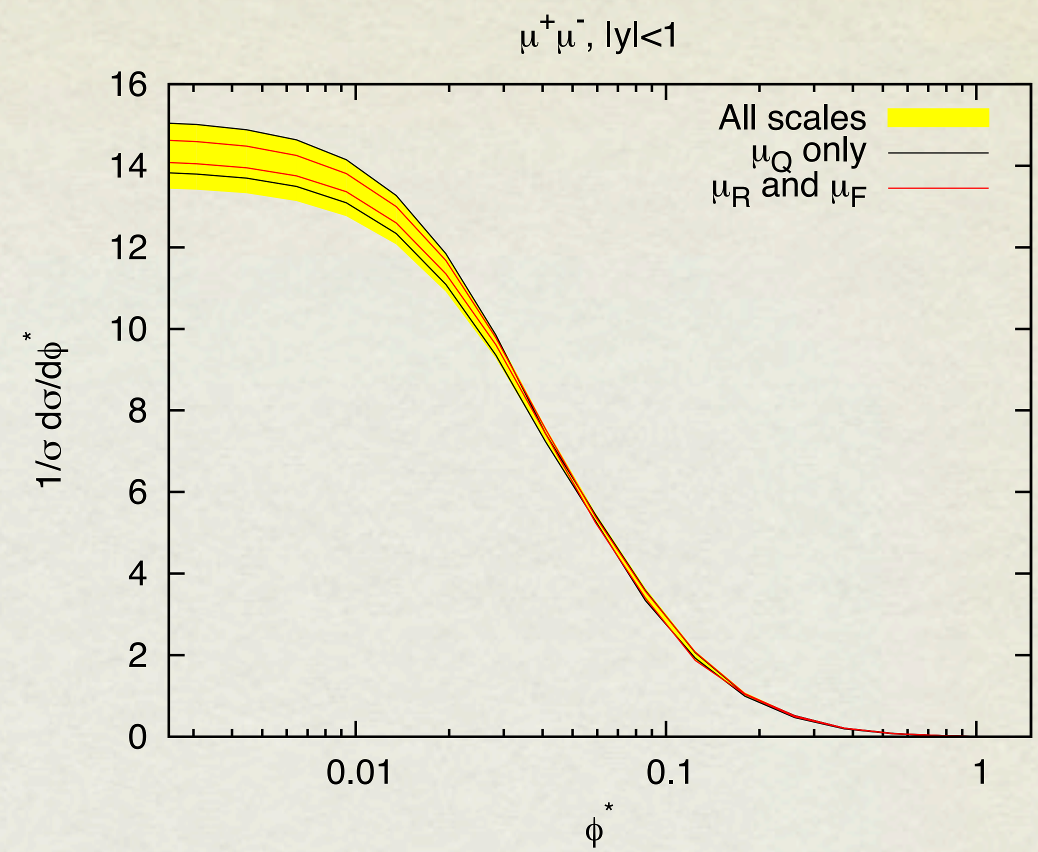
- We have now a resummed and matched theoretical prediction
- Before comparing to data we have to assess the uncertainties of our calculation
- Previously we had set all the perturbative scales to the dilepton mass
- As usual we have renormalisation (μ_R) and factorisation (μ_F) scales but also resummation scale (μ_Q)

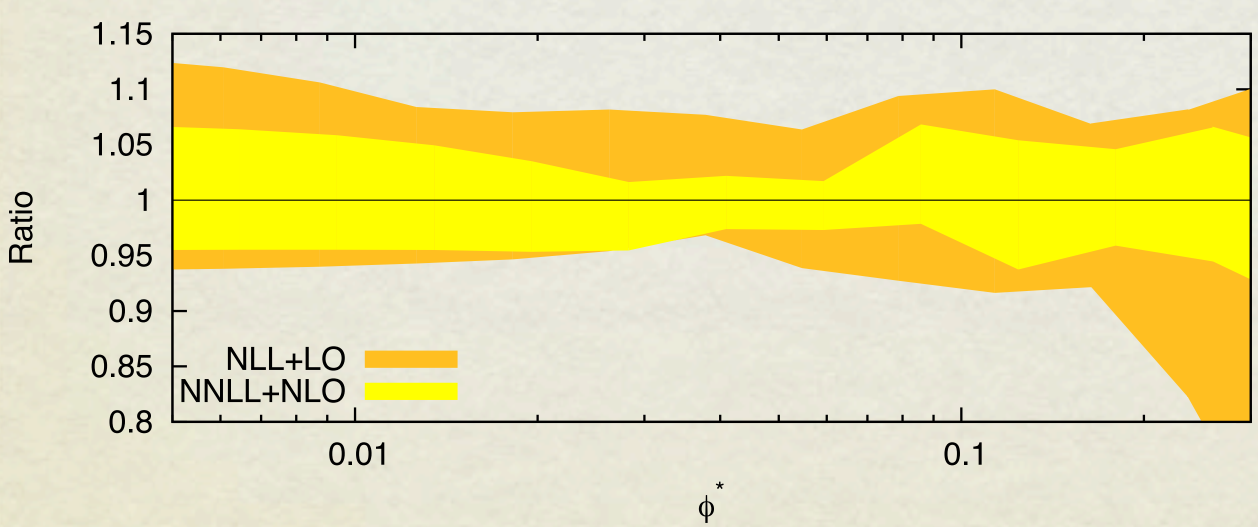
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\phi^*}(\phi^*, M, \cos\theta^*, y) = \frac{\pi\alpha^2}{sN_c}\int_0^\infty \mathrm{d}b\, M\ \cos(bM\phi^*)\, e^{-R(\bar{b}, M, \mu_Q, \mu_R)} \times \Sigma(x_1, x_2, \cos\theta^*, b, M, \mu_Q, \mu_R, \mu_F)$$

- The NLO part of the calculation also depends on μ_R and μ_F
- Varying these scales around the pair mass gives us information about terms beyond our accuracy (i.e. at least N^3LL and NNLO)

NLL+LO vs NNLL+NLO

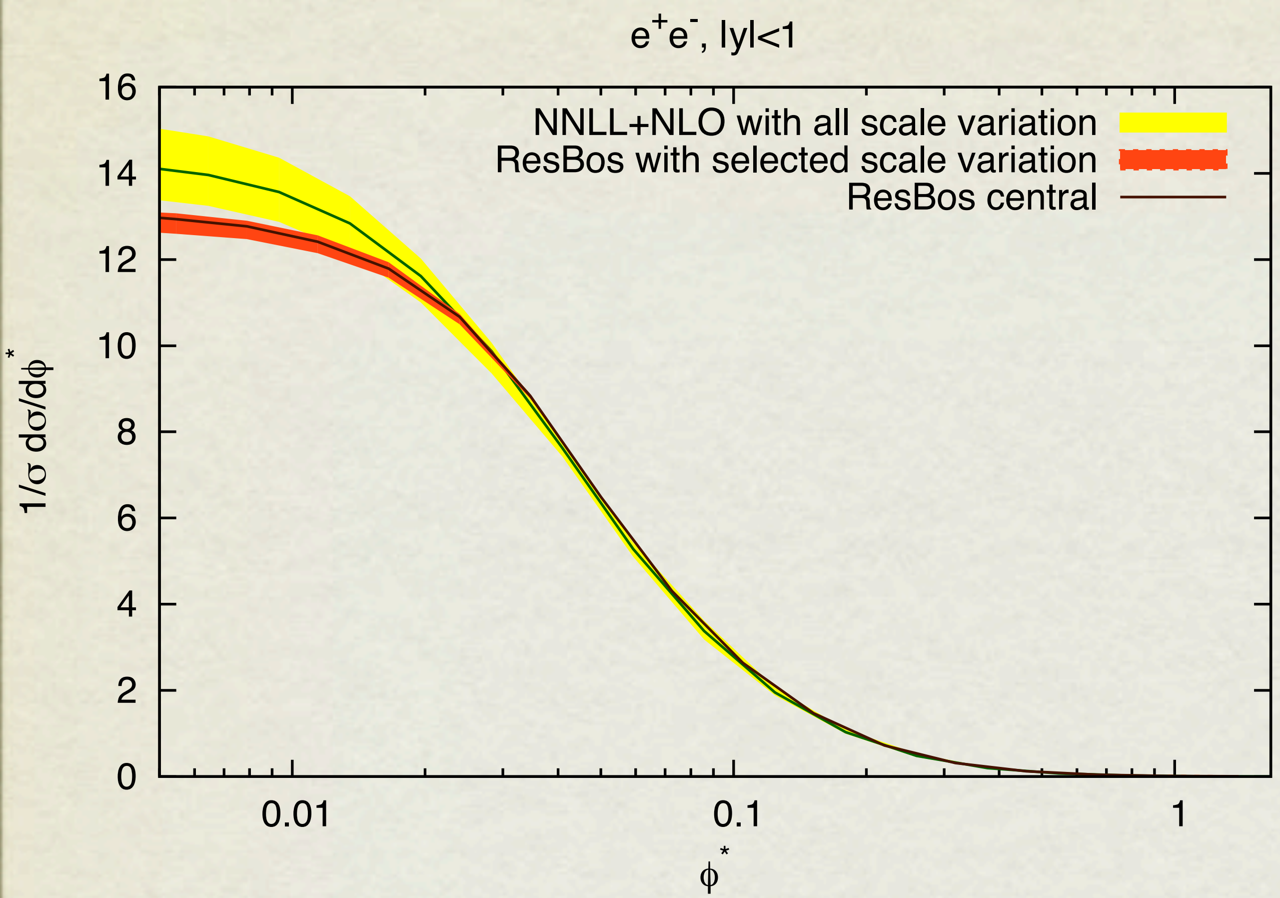


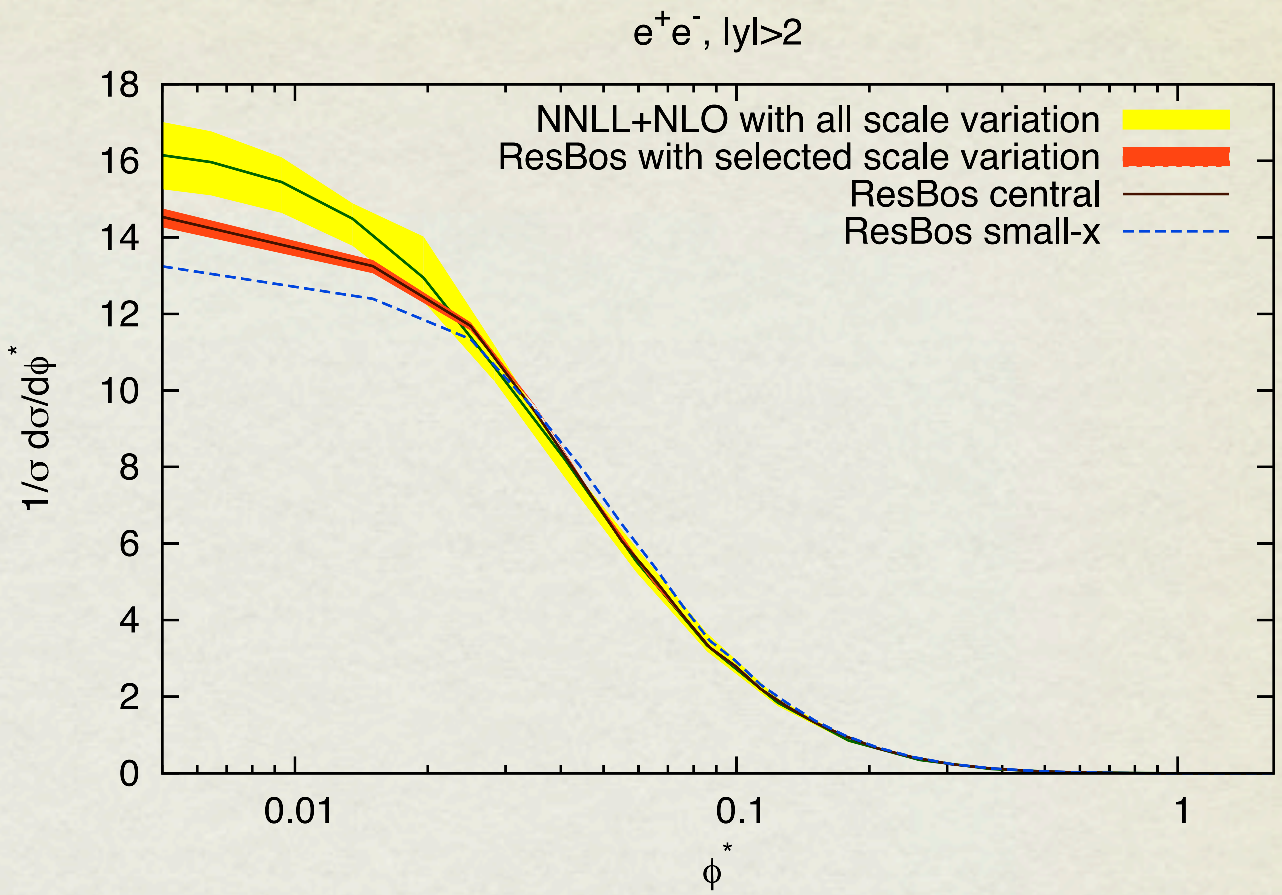




- All scales are varied independently
- Biggest contribution as small φ^* from μ_Q
- Band almost halved (20% to 10%)
- PDFs uncertainties mostly cancel in the ratio
- They are at the percent level

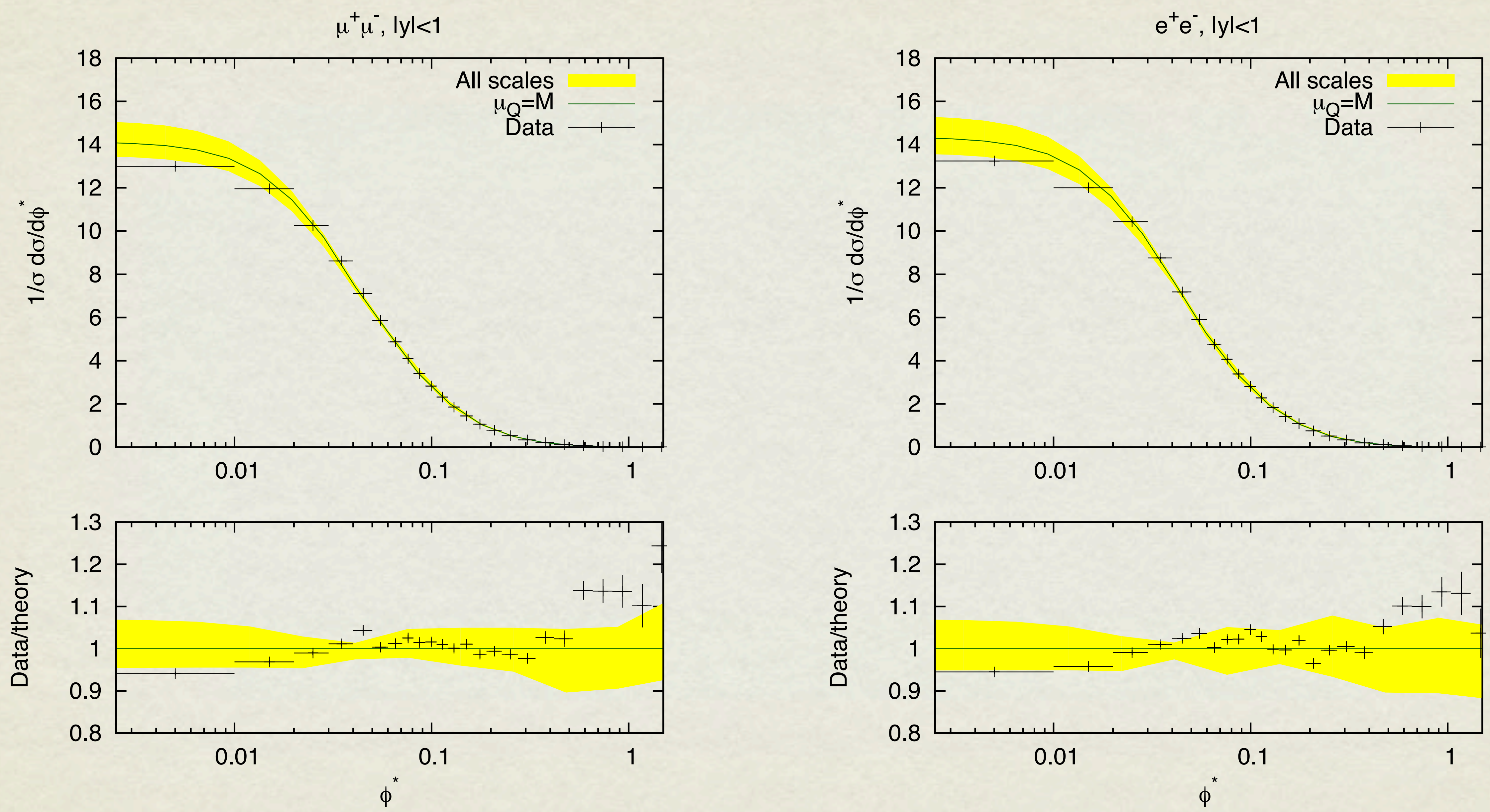
Comparison To ResBos





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

Comparison To Data



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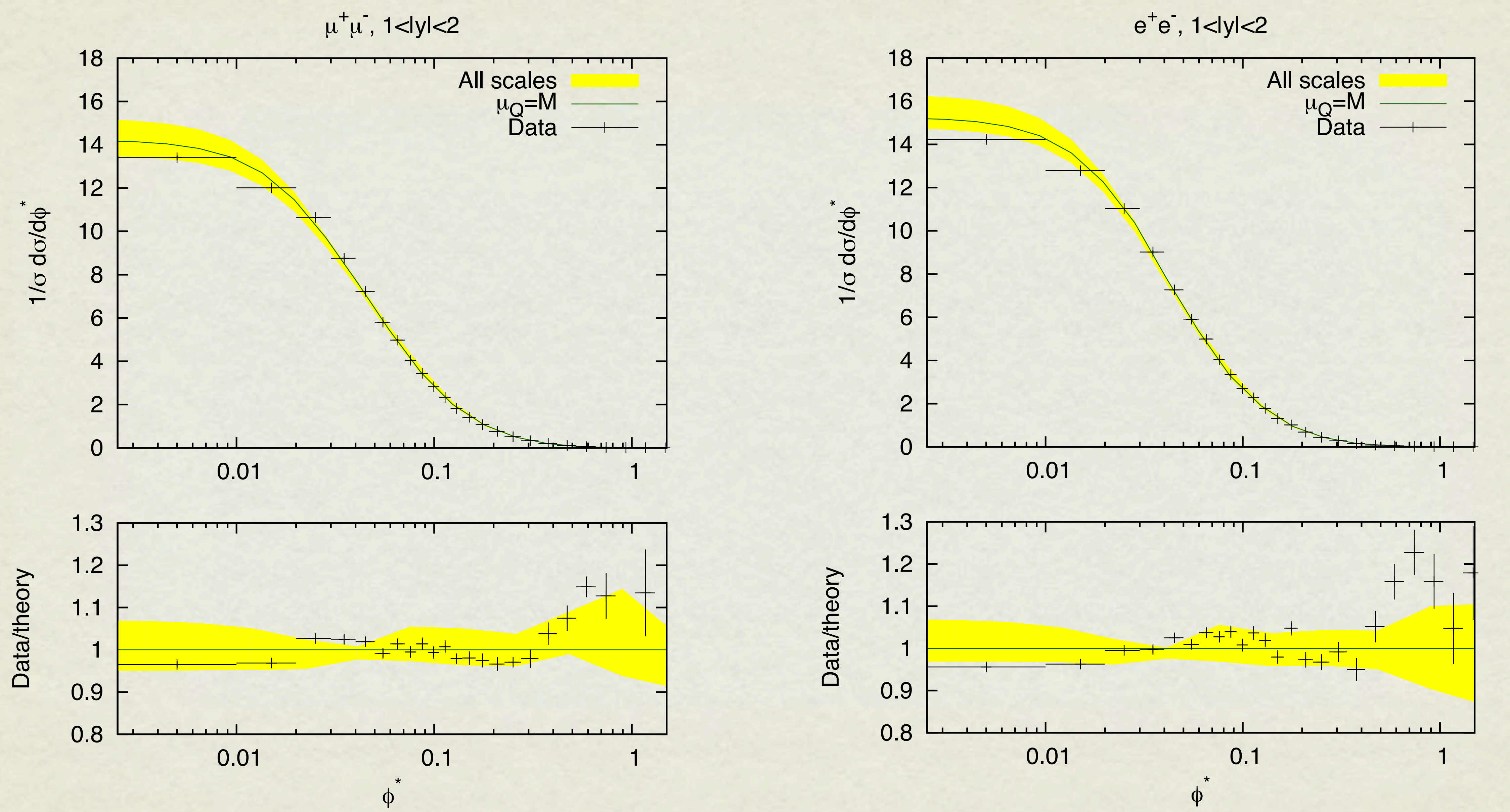

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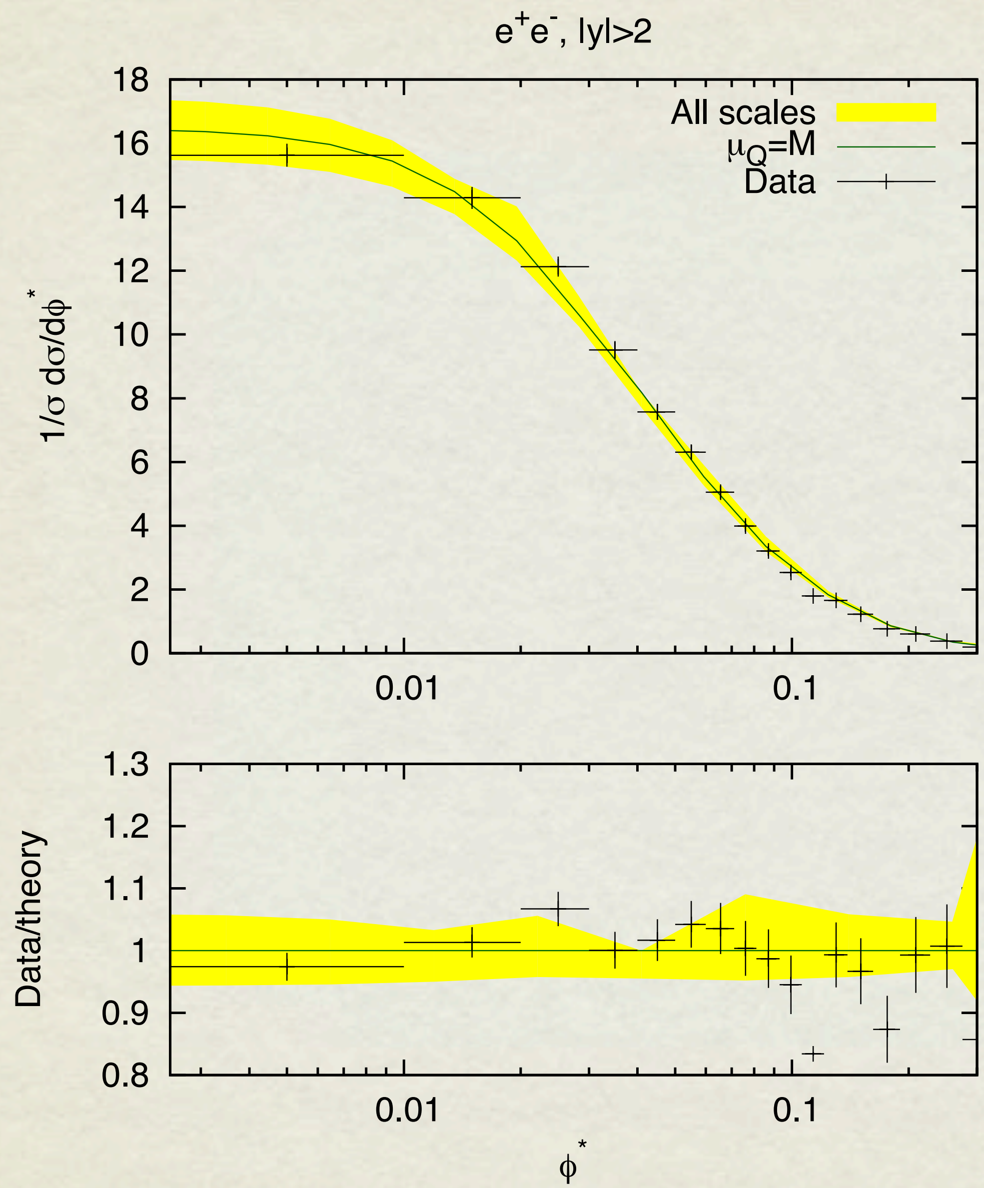
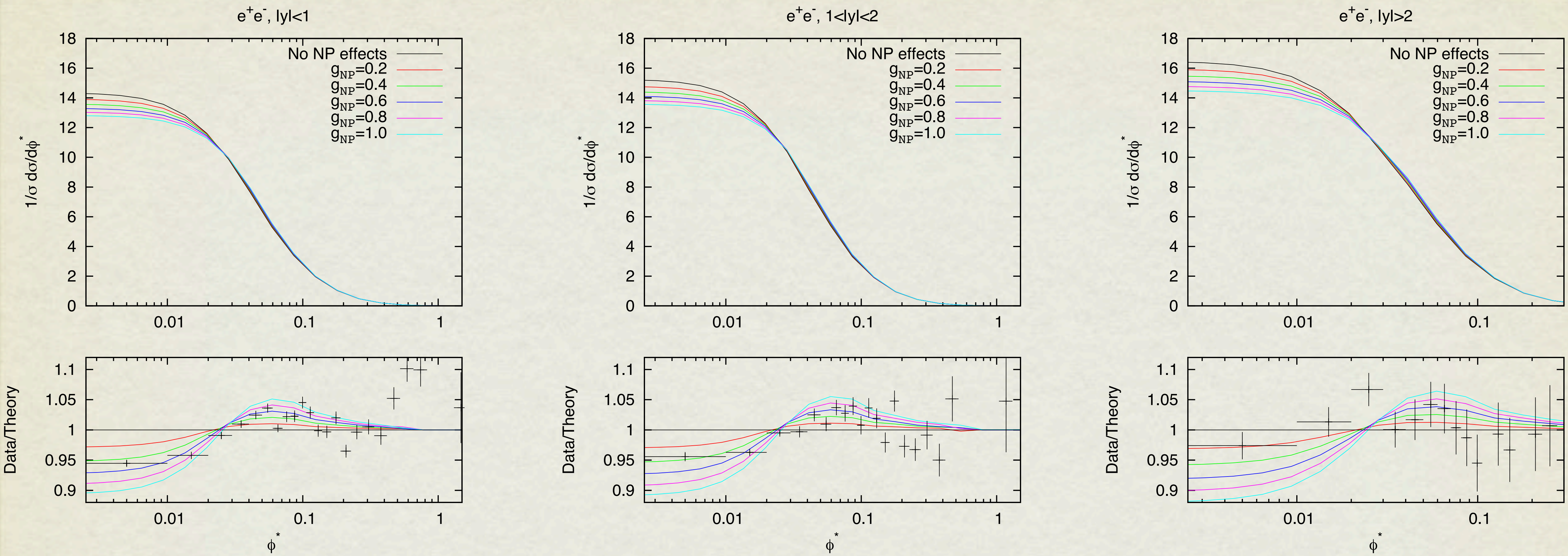


- Good agreement, within uncertainties, for all rapidity bins
- NP form factors are not required to describe the data at low φ^*
- We could in principle take our central value and correct with NP effects

NP Gaussian Smearing

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

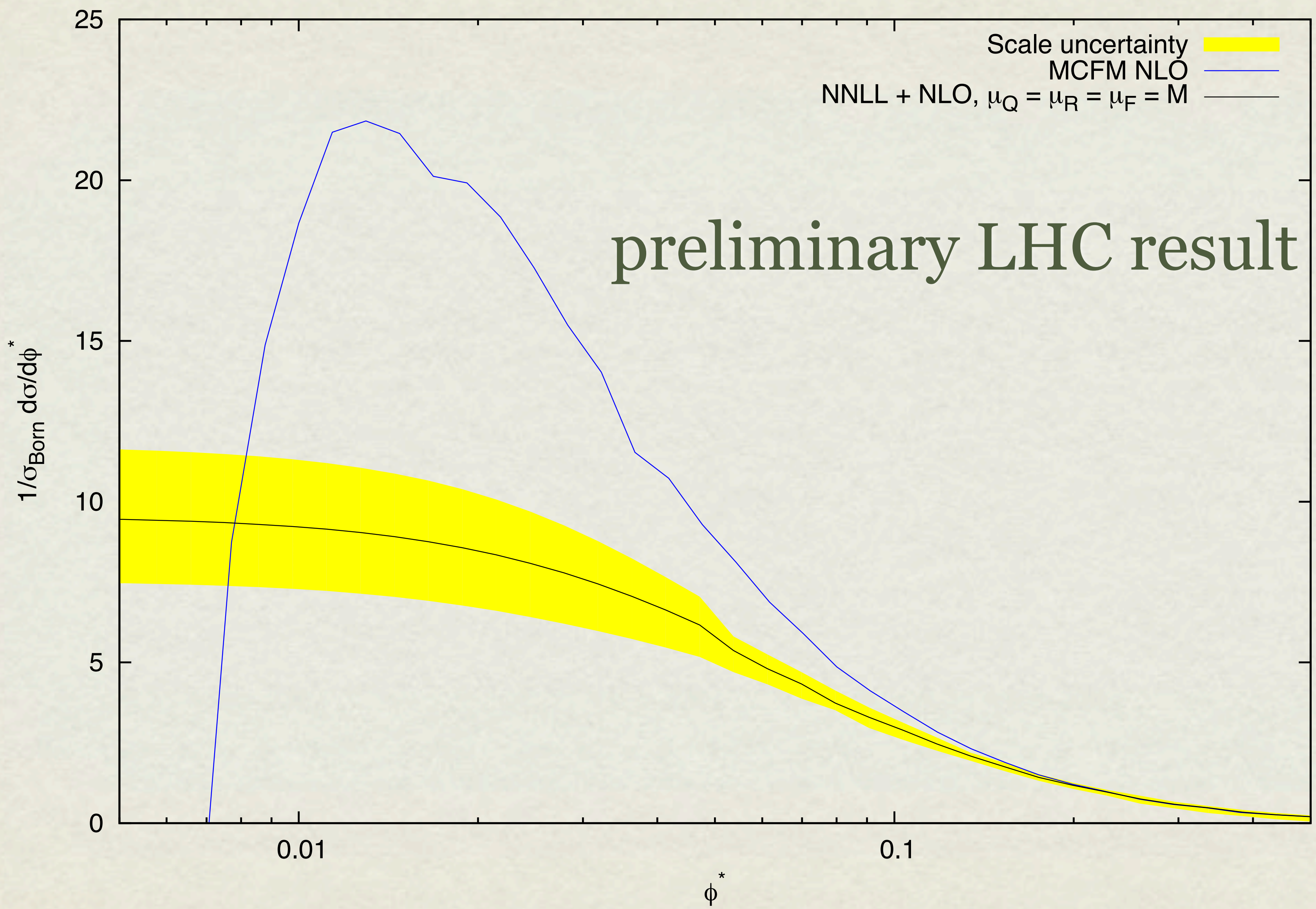


- Spread similar to the perturbative band
- This is misleading: we are ascribing pert. uncertainties to a universal NP parameter
- Consequences for related studies if we use were to use the fitted NP parameter

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



preliminary LHC result

A few words on the method

- Q_T resummation formalism established since 1980's
- Steadily progress has been achieved by several groups in the accuracy of the resummation. So why bother?
- The key point is the relation between Q_T and the other angular variables
- Technical viewpoint: very general set-up for the resummation:
    - Born configurations are taken from a FO program and re-weighted
    - This enables us to be fully differential in the final state's kinematics
    - Different (colour-singlet) final states: just change the Born

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 improves theoretical understanding (resummation, factorisation)
  - extension to di-bosons final states and Z H as well

Thank you very much

for your attention