Z/γ^* transverse momentum distribution and implications on the W mass measurements.

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Main goals of this study

- Analysis of the Z/γ^* distribution in terms of ϕ_η^* at D0 Tevatron and LHC.
  D0 Coll. Phys.Rev.Lett. 106 (2011) 122001;
  ATLAS Coll. Phys.Lett. B705 (2011) 415-434.
- Comparison of recent data to a new improved version of ResBos NNLL/(NLO+K) using CTEQ NNLO PDFs.
- Discuss the main sources of systematic uncertainties emerging in this computation.
- Give an estimate of the size of non-perturbative effects in the small ϕ_η^* region (small Q_T).
- Discuss a new suitable parametrization of the NP func. relevant for precise measurements of M_W.

M_W measurements

- D0 Run II with 1 fb-1 of integrated luminosity, measured $M_W = 80.375 \pm 0.023 GeV$.
  arXiv:1203.0293 .

- CDF W-boson mass M_W using data corresponding to 2.2 fb-1 of integrated luminosity measured $M_W = 80387 \pm 12 stat \pm 15 syst = 80387 \pm 19 MeV/c^2$.
  arXiv:1203.0275.

  These are the most precise measurements of the W-boson mass to date.

$$\delta M_W \approx 20 MeV.$$

The bulk of this uncertainty is

"Theory uncertainty"

$$\delta M_W^{theory} \approx 15 MeV$$

Theory Uncertainty

PDF $\delta M_W \approx 10 MeV$

NP $\delta M_W \approx 4 - 5 MeV$

EW Corr.

Why is this important?

★ Accurate measurement of $M_W \Rightarrow$ very accurate knowledge of the kinematics of the charged leptons $l^{\pm}$ as decay products of $W^{\pm}$.

★ The bulk of the data is in the low Q_T region ($p_T^l \approx M_W/2$). To have accurate theory predictions $\Rightarrow$ initial state multiple emission of soft gluons must be resummed.

★ The model for the non-perturbative recoil is one of the major source of theoretical uncertainty in the extraction of M_W from the experimental data.

★ The current accuracy of experimental data allows to constrain our theory for the NP recoil of the heavy vector bosons on the QCD radiation.

Collins-Soper-Sterman formalism

It is well known for a long time that to have a good perturbative description of QCD observables like transverse momentum distributions, logarithmic contributions of the type $L = \ln(Q_T^2/Q^2)$ that have a singular behavior when $Q_T \to 0$, have to be resummed. An expression like

$$\frac{d\sigma}{dQ_T^2} \propto \frac{1}{Q_T^2}\left[\alpha_s(L+1) + \alpha_s^2(L^3 + \cdots + 1) + \alpha_s^3(L^5 + \cdots + 1) + \cdots\right] \quad (1)$$

must be reorganized as

$$\frac{d\sigma}{dQ_T^2} \propto \frac{1}{Q_T^2}\left[\alpha_s(L+1) + \alpha_s^2(L^3 + L^2) + \alpha_s^3(L^5 + L^4) + \right.$$
$$\left. \alpha_s^4(L^7 + L^6) + \cdots + \alpha_s^2(L+1) + \alpha_s^3(L^3 + L^2) + \alpha_s^4(L^5 + L^4) + \cdots\right] \quad (2)$$

CSS Formalism

This reorganization is achieved by the Collins Soper Sterman (CSS) formalism (Nucl.Phys.B250-199, 1985), according to which the Q_T distribution of hadronically produced lepton pairs $h_1 h_2 \to V(\to l_1 l_2)X$ is described by the following combination

$$\frac{d\sigma}{dQ_T} = \frac{d\sigma}{dQ_T}\Big|_{W-Resummed} + \frac{d\sigma}{dQ_T}\Big|_{F.O.} - \frac{d\sigma}{dQ_T}\Big|_{Asymptotic} \tag{3}$$

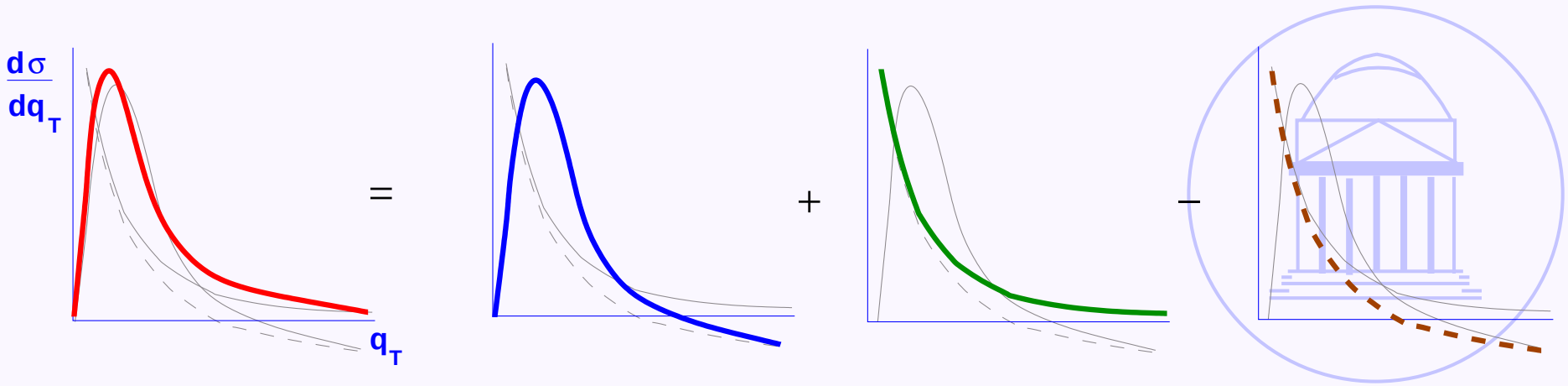
CSS Formalism

$$\frac{d\sigma}{dQT} = \text{RES} + \text{FO} - \text{SUBTRACTION}$$

Piece containing the Sudakov exponent

Calculate in perturbative QCD at order α_s^n

Calculate as an expansion of RES up to order α_s^n

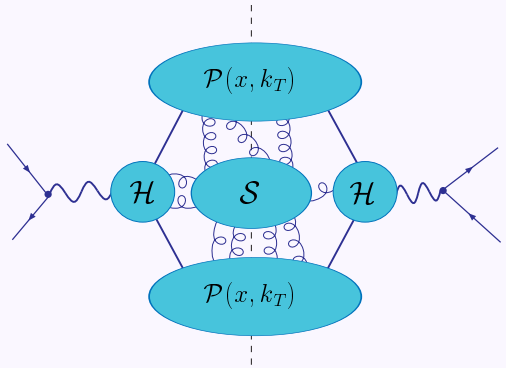


QCD factorization as a function of q_T

(according to Collins, Soper, and Sterman approach)

Small-q_T term

$\Lambda^2_{QCD} \ll q_T^2 \ll Q^2$



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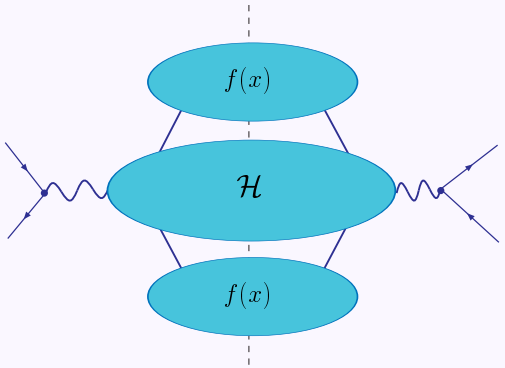
Large-q_T term

$\Lambda^2_{QCD} \ll q_T^2 \sim Q^2$



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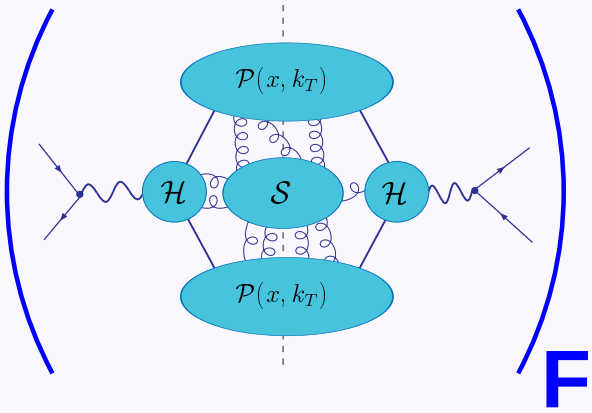
Overlap term



FO

- k_T-dependent PDFs $\mathcal{P}(x, \vec{k}_T)$
- Sudakov function $\mathcal{S}(x, \vec{k}_T)$

▷ actually, their impact parameter (b) space transforms

- Collinear PDFs $f_a(x, \mu)$
- hard matrix elements $\mathcal{H}$ of order N

- Truncated perturbative expansion

$$\sum_{k=0}^{N} \alpha_s^k \sum_{m=0}^{2k-1} c_{km} \ln^m \left(\frac{q_T^2}{Q^2} \right)$$

Factorization at $Q_T \ll Q$

$$\left.\frac{d\sigma_{AB\to VX}}{dQ^2 dy dQ_T^2}\right|_{Q_T^2 \ll Q^2} = \sum_{a,b=g,\overset{(-)}{u},\overset{(-)}{d},\ldots} \int \frac{d^2 b}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}} \widetilde{W}_{ab}(b,Q,x_A,x_B)$$

$$\widetilde{W}_{ab}(b,Q,x_A,x_B) = |\mathcal{H}_{ab}|^2 \; e^{-\mathcal{S}(b,Q)} \overline{\mathcal{P}}_a(x_A,b)\overline{\mathcal{P}}_b(x_B,b)$$

$\mathcal{H}_{ab}$ is the hard vertex, $\mathcal{S}$ is the soft (Sudakov) factor, $\overline{\mathcal{P}}_a(x,b)$ is the unintegrated PDF in the gauge $\eta\cdot\mathcal{A}=0$, $\eta^2<0$

$\overline{\mathcal{P}}_a(x,b) = \int d^{n-2}\vec{k}_T e^{i\vec{k}_T\cdot\vec{b}} \mathcal{P}_a(x,\vec{k}_T)$, with
$\mathcal{P}_a(x,\vec{k}_T) \sim \int \frac{dy^- d\vec{y}_T}{(2\pi)^3} e^{ixp_A^+ y^- - i\vec{y}_T\cdot\vec{k}_T} \langle p_A|\psi(y)\frac{\gamma^+}{2}\psi(0)|p_A\rangle$

When $b \ll 1$ GeV^{-1}, $\mathcal{S}(b,Q)$ and $\overline{\mathcal{P}}_a(x,b)$ are calculable in perturbative QCD;

$$\overline{\mathcal{P}}_{a/A}(x,b) = \left(\mathcal{C}_{ja}\otimes f_{a/A}\right)(x,b;\mu_F) + \mathcal{O}(b^2)$$

The differential cross section

The result for the differential cross section is given by

$$\frac{d\sigma\left(h_1 h_2 \to Z(\to l_1 \bar{l}_2)X\right)}{dQ^2 dy dq_T^2 d\Omega} = \frac{1}{48\pi S}\frac{Q^2}{(Q^2 - M_Z^2)^2 + Q^4\Gamma_Z^2/M_Z^2}$$
$$\times \frac{1}{(2\pi)^2}\left\{ \int d^2b e^{i\vec{q}_T\cdot\vec{b}} \sum_{j,k} \tilde{W}_{j\bar{k}}(b_*, Q, x_1, x_2, \Omega, C_1, C_2, C_3) * \right.$$
$$\left. \tilde{W}^{NP}_{j\bar{k}}(b, Q, x_1, x_2) + Y(q_T, Q, x_1, x_2, \Omega, C_4) \right\}, \tag{4}$$

where

$$\tilde{W}_{j\bar{k}}(b_*, Q, x_1, x_2, \Omega, C_1, C_2, C_3) \propto$$
$$e^{-S(b,Q,C_1,C_2)} \left(\mathcal{C}_{ja} \otimes f_{a/h_1}\right)(x_1) \left(\mathcal{C}_{\bar{k}a} \otimes f_{b/h_2}\right)(x_2). \tag{5}$$

The parameter b_* is the separation scale at which the perturbative $\tilde{W}$ factorizes from the non-perturbative $\tilde{W}^{NP}$.

Non-perturbative function

The non-perturbative $\tilde{W}^{NP}(b,Q)$ function as originally parametrized in CSS paper, is given by

$$\tilde{W}^{NP}_{j\bar{k}}(b,Q,Q_0,x_1,x_2) = \left[-F_1(b)\ln\left(\frac{Q^2}{Q_0^2}\right)\right.$$
$$\left.-F_{j/h_1}(x_1,b) - F_{\bar{k}/h_2}(x_2,b)\right] , \tag{6}$$

where functions $F_1(b)$, F_{j/h_1} and $F_{\bar{k}/h_2}$ have to be determined by fits to the experimental data.

The Sudakov exponent

The Sudakov exponent is given by

$$S(b,Q,C_1,C_2) = \int_{C_1^2/b^2}^{C_2^2 Q^2} \frac{d\bar{\mu}^2}{\mu^2} \left[A(\alpha_s(\bar{\mu}),C_1) \ln\left(\frac{C_2^2 Q^2}{\bar{\mu}^2}\right) + B(\alpha_s(\bar{\mu}),C_1,C_2) \right], \quad (7$$

$$A(\alpha_s(\bar{\mu}),C_1) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s(\bar{\mu})}{\pi}\right)^n A^{(n)}(C_1)\,,$$

$$B(\alpha_s(\bar{\mu}),C_1,C_2) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s(\bar{\mu})}{\pi}\right)^n B^{(n)}(C_1,C_2)\,, \quad (8)$$

where coefficients $A^{(n)}(C_1)$ and $B^{(n)}(C_1,C_2)$ are known from the literature, while parton convolutions are defined as

$$\left(\mathcal{C}_{ja} \otimes f_{a/h_1}\right)(x_1) = \int_{x_1}^{1} \frac{d\xi_1}{\xi_1} \mathcal{C}_{ja}\left(\frac{x_1}{\xi_1}, b, \mu = \frac{C_3}{b}, C_1, C_2\right) f_{a/h_1}(\xi_1, \mu = \frac{C_3}{b}). \quad (9)$$

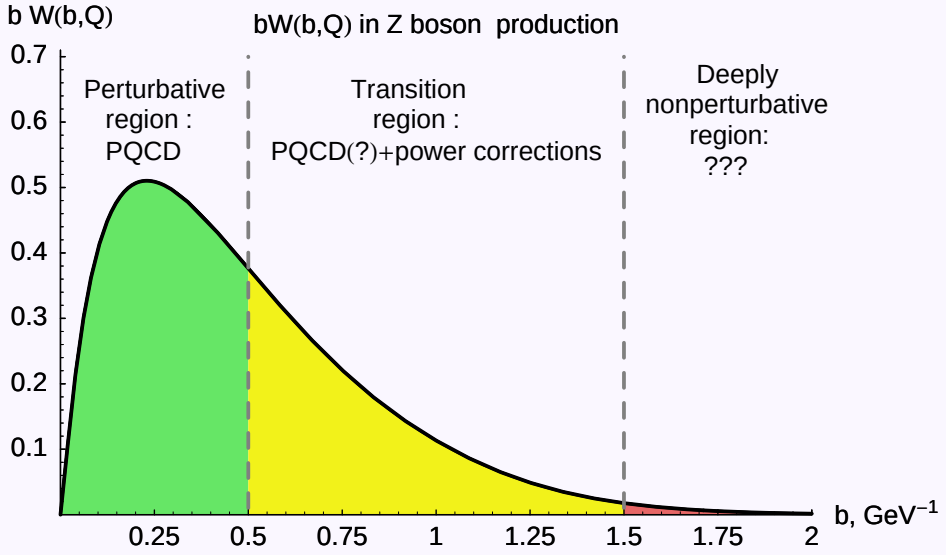
The Y contribution

The Y term which is defined as the difference between the fixed order perturbative contribution and those obtained by expanding the perturbative part of $\tilde{W}_{j\bar{k}}$ is given by

$$Y(Q_T, Q, x_1, x_2, \theta, \phi, C_4) = \int_{x_1}^{1} \frac{d\xi_1}{\xi_1} \int_{x_2}^{1} \frac{d\xi_2}{\xi_2} \sum_{n=1}^{\infty} \left[\frac{\alpha_s(C_4 Q)}{\pi} \right]^n$$
$$f_{a/h_1}(\xi_1, C_4 Q) R_{ab}^{(n)} \left(Q_T, Q, \frac{x_1}{\xi_1}, \frac{x_2}{\xi_2}, \theta, \phi \right) f_{b/h_2}(\xi_2, C_4 Q), \quad (10)$$

where $R_{ab}^{(n)}$ are less singular than Q_T^{-2} or $Q_T^{-2}\left(Q_T^2/Q^2\right)$ when $Q_T \to 0$.

$b\widetilde{W}(b,Q)$ in Z boson production

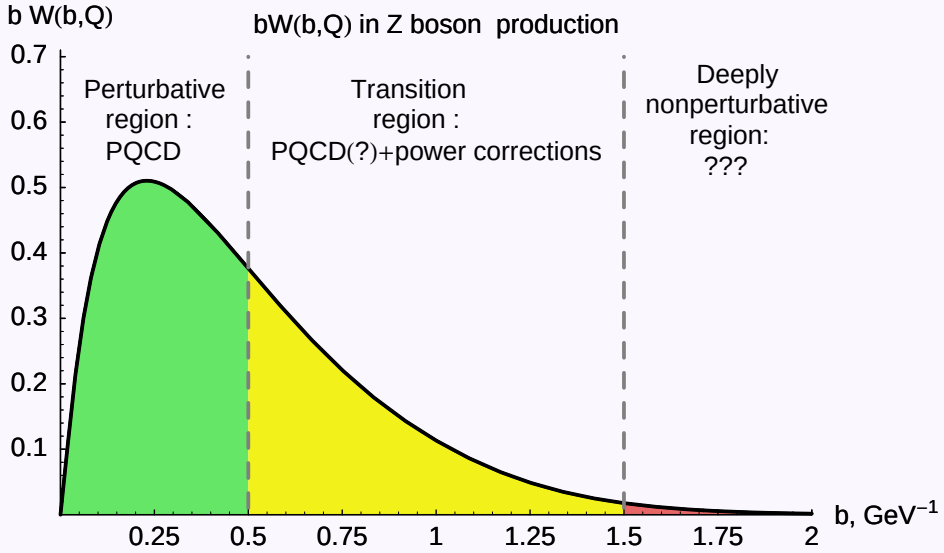


- $b \lesssim 0.5$ GeV^{-1} ($\mu_b \sim 1/b > 2$ GeV)

- dominated by the leading-power (logarithmic) term, calculable in PQCD: $\widetilde{W}(b,Q) \approx \widetilde{W}_{LP}(b,Q)$

- contributes most of the rate at large Q

$b\widetilde{W}(b,Q)$ in Z boson production

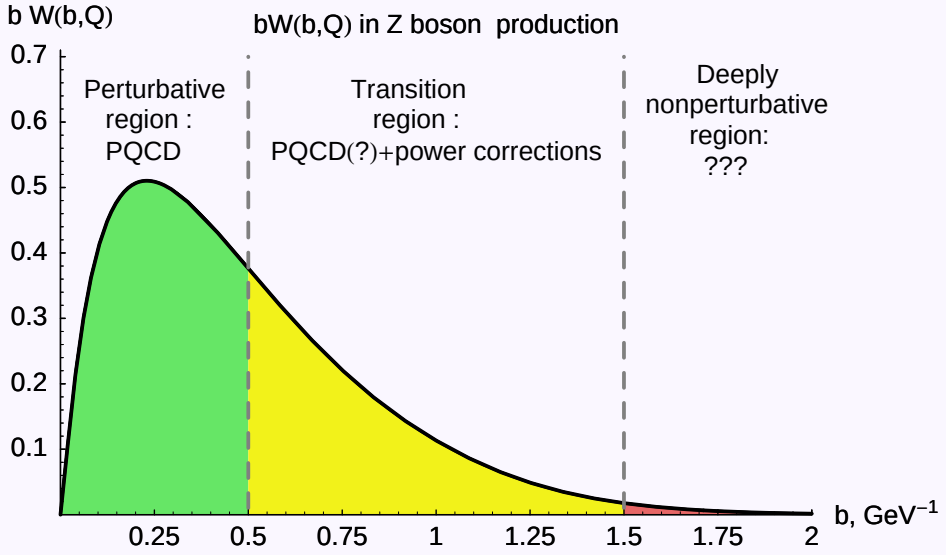


- $0.5 \lesssim b \lesssim 1.5 - 2$ GeV^{-1} ($0.5 - 0.7 \lesssim \mu_b \lesssim 2$ GeV)

- higher-order terms in α_s and b^p modify $d\sigma/dQ_T$ at $Q_T \lesssim 10$ GeV

- Can be large compared to $\delta M_W \sim 20 - 30$ MeV; constrained within a global Q_T fit (similar to PDF's), especially by the Drell-Yan process at $Q = 3 - 10$ GeV

$b\widetilde{W}(b,Q)$ in Z boson production



- $b \gtrsim 1.5 - 2$ GeV^{-1}

- terra incognita; tiny contributions
- negligible effect on the analyzed data

Theoretical developments

A lot of work in progress on the TMD, PDFs and FFs side!

- Aybat and Rogers PRD 2011
- J. C. Collins and F. Hautmann, PLB 472, 129 (2000); J. C. Collins and F. Hautmann, JHEP0103, 016 (2001).
- A. A. Henneman, D. Boer and P. J. Mulders, NPB 620, 331 (2002).
- A. V. Belitsky, X. Ji and F. Yuan, NPB 656, 165 (2003).
- D. Boer, P. J. Mulders and F. Pijlman, NPB667, 201 (2003).
- J.C. Collins, Acta Phys. Polon. B 34, 3103 (2003).
- F. Hautmann and D. E. Soper, PRD 75, 074020 (2007).
- J. C. Collins, T. C. Rogers and A. M. Stasto, PRD 77, 085009 (2008).
- I. O. Cherednikov and N. G. Stefanis, Phys. Rev. D 77, 094001 (2008); I. O. Cherednikov, A. I. Karanikas and N. G. Stefanis, NPB 840, 379 (2010).

Theoretical developments

★ In very high energy (small-x) resummation physics, where there is a lack of k_T-ordering, the TMD gluon distribution is especially important.

★ TMD functions are useful tools in the construction of Monte Carlo event generators, where the details of final state kinematics are important.

★ We will benefit by clarifying the relationship between the parton model description of TMD-factorization and the CSS formalism.

Various theory computations

★ $ResBos$ by Balazs, Yuan (1997); Balazs Qiu and Yuan (1995); Brock, Landry, Nadolsky, Yuan (2002)

★ Fully differential NNLO computations

- $FEWZ$ by K. Melnikov and F. Petriello PRD 74 (2006) 114017
- $DYNNLO$ by G.Bozzi, S.Catani, M.Grazzini, D. De Florian, NPB 737 (2006) 73

★ Resummed NNLL/NNLO computation

- Ferrera, Grazzini et al. Forthcoming

★ Resummed NNLL/NLO computation - ϕ_η^* distr.

- A.Banfi, M.Dasgupta, S.Marzani, L.Tomlinson JHEP 1201 (2012) 044

Current version of ResBos

★ Approximated Resummed NNLL/NNLO computations

- ResBos + CANDIA (← M.G., A. Cafarella, C. Corianò 2006)
  -Approximate NNLO ($\mathcal{C}^{(2)}$ found numerically)
  - NNLL resummation $A^{(3)}, B^{(2)}$

♠ For purposes of M_W measurements the current accuracy of $ResBos$ is competitive with full NNLL/NNLO resummed computations.

♠ It's fast and includes all the dominant components of the full NNLO calculation.

$O(\alpha_s^2)$ corrections in ResBos NNLL/(NLO+K): current setup

- the FO contribution, is computed up to $O(\alpha_s^2)$ for the leading structure functions.
- The $Y = Y_{NLO} K_{NNLO}$ piece is computed up to $O(\alpha_s^2)$ by using the K-factors as in Arnold and Reno Nucl.Phys. B319 (1989); Arnold and Kauffman Nucl.Phys. B349 (1991), for the dominant F_{-1} only.
- The W piece is computed up to NNLL approximation in the Sudakov exponent, while the finite part of the coefficient functions $\mathcal{C}^{(n)}(\xi, b, \mu, C_1, C_2)$ is computed up to $O(\alpha_s^2)$ by using K-factors obtained by $CANDIA$ (Cafarella, Corianò, M.G., JHEP 0708 (2007); CPC 179 (2008)).
- In $\mathcal{C}^{(2)}(\xi, b, \mu, C_1, C_2)$ included is also the logarithmic dependence on the coefficients C_1, C_2 up to $O(\alpha_s^2)$.

Z/γ^* boson transverse momentum distribution in terms of ϕ^*_η: Recent data! 1010.0262(hep-ex)

A new variable ϕ^*_η has been proposed by Banfi et al. EPJC 2011, PLB701 2011 to describe final state electron and muon angular distributions in hadronic collisions.

$$\phi^*_\eta = \tan\left(\phi_{acop}/2\right)\sin\theta^*_\eta, \qquad \cos\theta^*_\eta = \tanh\left(\frac{\eta^- - \eta^+}{2}\right), \tag{11}$$

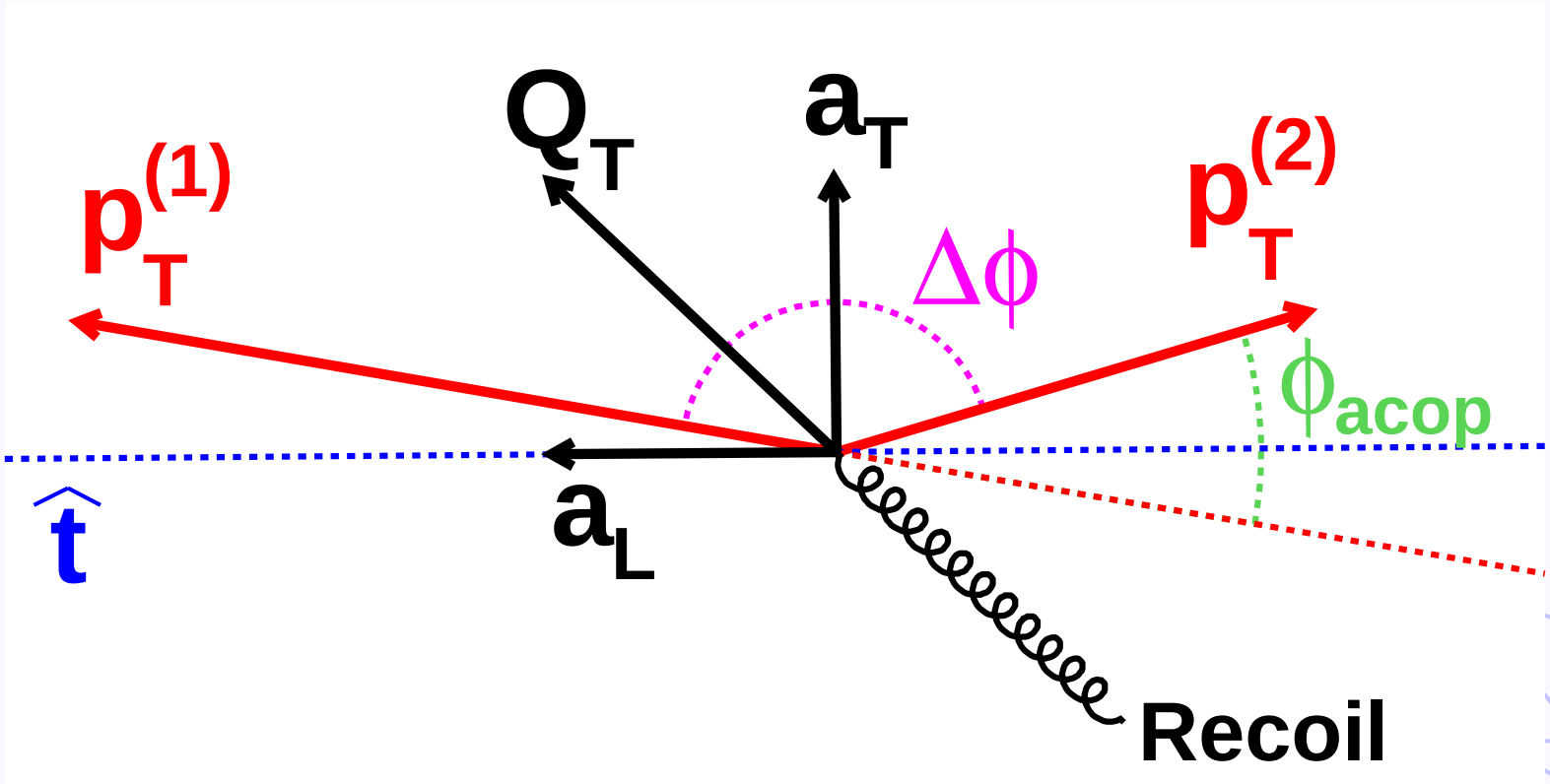
where $\phi_{acop} = \pi - \Delta\varphi$ and $\Delta\varphi$ denote the difference in azimuthal angle φ between the lepton. In the $Q_T \to 0$ limit one has

$$\phi^*_\eta \approx a_T/M \qquad \cos\theta^*_\eta \approx \cos\theta_{css}, \tag{12}$$

where M is the dilepton invariant mass.

- less sensitivity to experimental resolution on lepton momenta.
- ϕ^*_η is accessed by a direct experimental measurement of track directions $\to$ very precise!

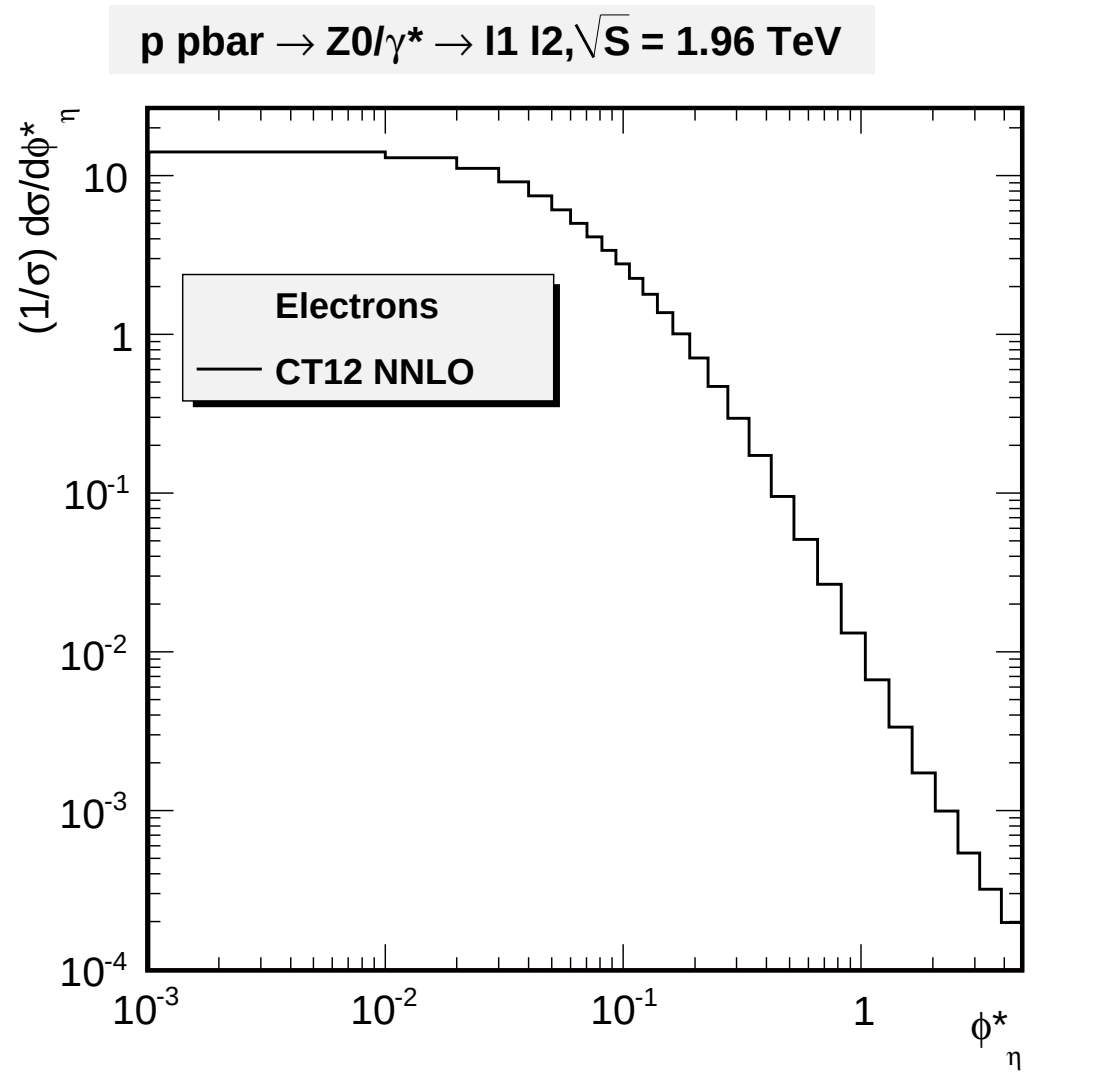
Graphical illustration



taken from EPJC (2011) 71 1600; PRL 106 (2011) 122001, arXiv:1010.0262 (hep-ex)

$(1/\sigma)d\sigma/d\phi^*_\eta$ shape integrated overall rapidity y_Z

-PRELIMINARY-



Main corrections in our computation

- EM corrections $\approx$ 2% at small ϕ_η^* (See backup slides),
- NNLO corrections,
- Kinematic corrections $\rightarrow$ dependence on the matching

Main source of systematic uncertainties

- Scale dependence,
- Non-perturbative function,
- PDF uncertainty.

$O(\alpha_s^2)$ corrections in ResBos NNLL/(NLO+K)

$$\mathcal{C}(z,b,\mu=C_3/b,C_1,C_2)=\sum_{n=0}^{\infty}\left(\frac{\alpha_s(\mu)}{\pi}\right)^n\mathcal{C}^{(n)}(z,b,\mu,C_1/C_2) \tag{13}$$

$$\mathcal{C}^{(n)}=\hat{\mathcal{C}}^{(n)}(z,\mu/Q)+\delta(1-z)\left[1+\delta\mathcal{C}_1(\mu b,b_0,C_1,C_2)\frac{\alpha_s}{\pi}+\delta\mathcal{C}_2(\mu b,b_0,C_1,C_2)\frac{\alpha_s^2}{\pi^2}+\cdots\right]$$

$\mathcal{C}^{(0)}$, $\mathcal{C}^{(1)}$ (and $\delta\mathcal{C}_1$) are known analitically, while at α_s^2 we can write

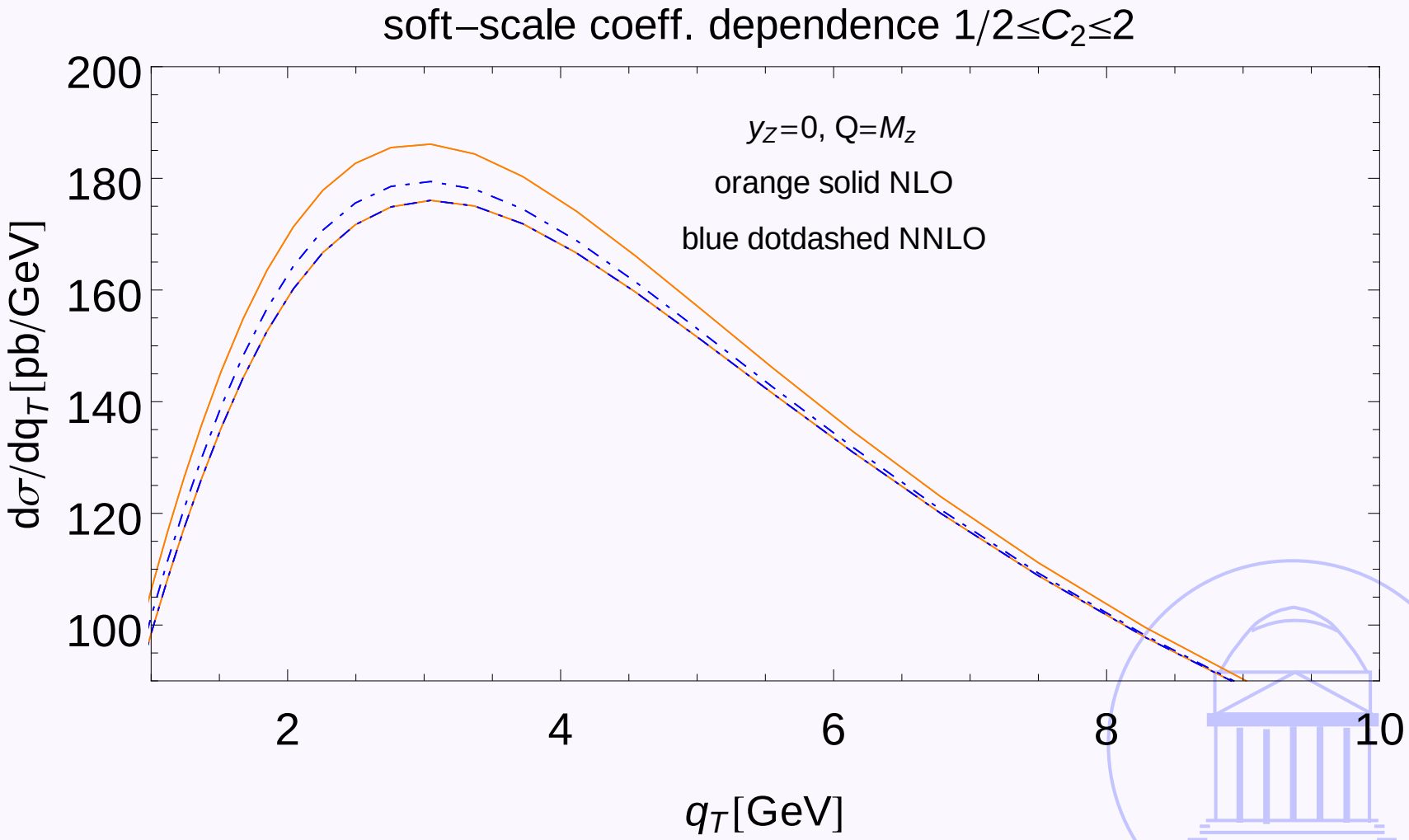
$$\mathcal{C}^{(2)}(z,\mu b,C_1,C_2)\approx\hat{\mathcal{C}}^{(2)}(z,\mu/Q)+\delta(1-z)\left[1+\delta\mathcal{C}_1\alpha_s^1+\delta\mathcal{C}_2\alpha_s^2+\cdots\right]+O(\alpha_s^3)$$

$$\hat{\mathcal{C}}^{(n)}(z,\mu/Q)\approx \qquad \mu\approx M_Z,\Rightarrow K-factors\ from\ the\ total\ rate. \tag{15}$$

The coefficient $\delta\mathcal{C}_2\propto$ power of logarithms of the type $\ln\left(\frac{b_0^2C_2^2}{C_1^2}\right)$ and it simplifies to zero if $C_1=b_0$ and $C_2=1$.

$\delta\mathcal{C}_2$ is included in our computation when $C_1\neq b_0$ and $C_2\neq 1$

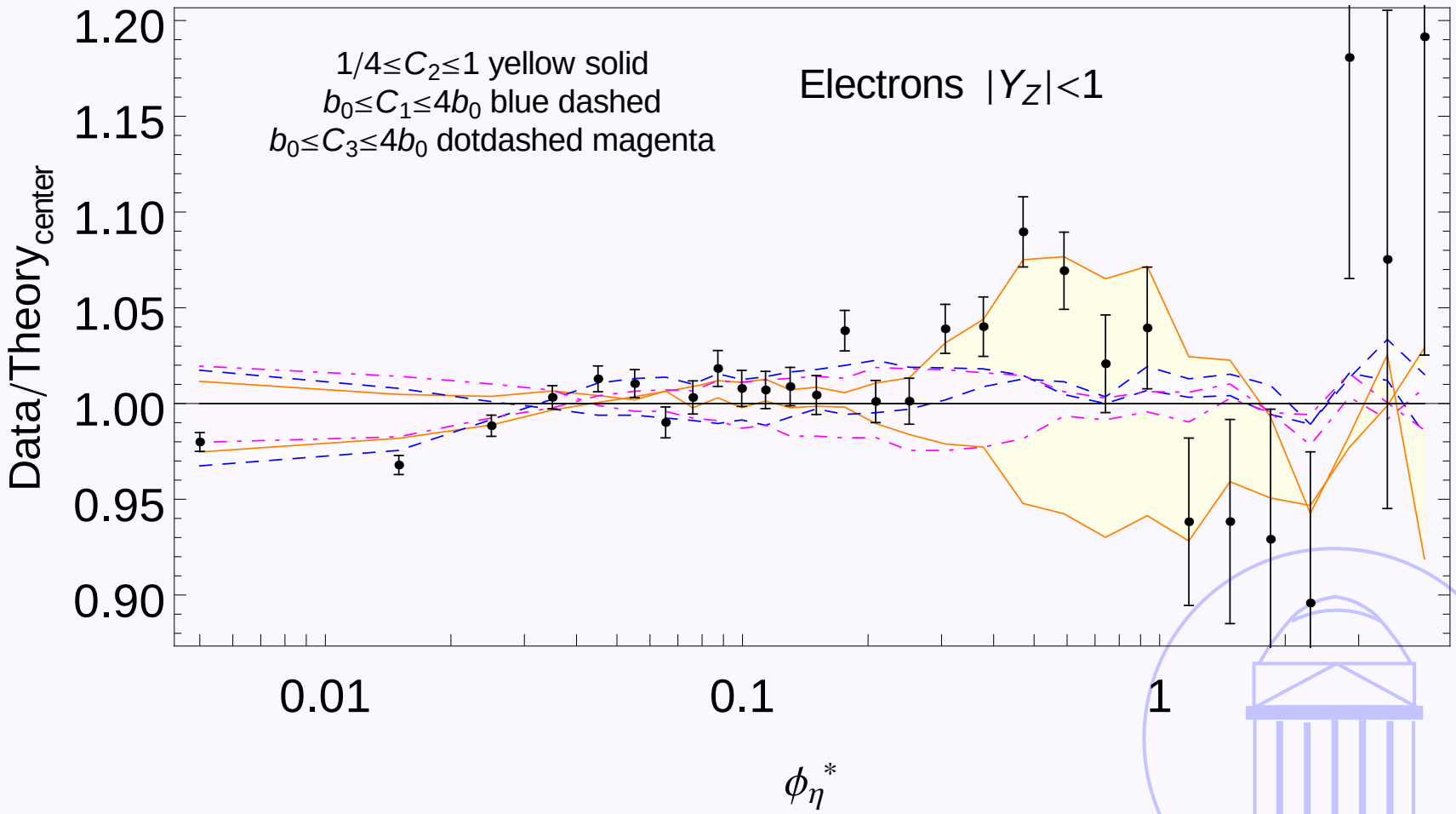
Reduction on C_2-sensitivity



Renormalization constant C_2 dependence: (NLO+K) vs NLO.

-PRELIMINARY- Center is ResBos with $\{C_2 = 1/2, C_1 = C_3 = 2b_0\}$

Data in Phys.Rev.Lett. 106 (2011) 122001 arXiv:1010.0262 (hep-ex)



Theoretical uncertainties due to renormalization constants C_2, C_1, C_3. All the other bins of rapidity are in the backup slides

Dependence on the Matching: Kinematic Corrections

Delicate interplay between FO and asymp. contributions

- they cancel each other as $q_T \to 0 \Rightarrow$ final regular W
- when q_T is large, cancellations occur between W and ASY, and these are sensitive to the way kinematic constraints from energy momentum conservation are implemented in the computation.

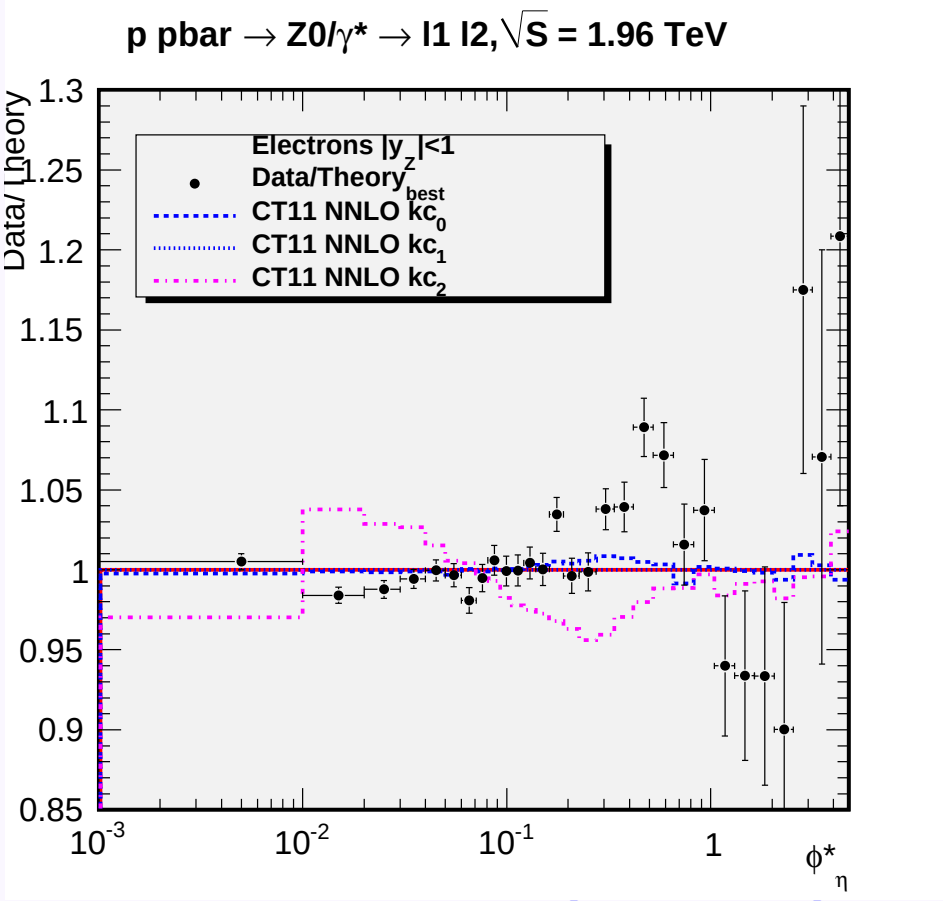
This is related to the treatment of phase-space for real emissions

$$\frac{d\sigma}{dQ^2 dy dq_T^2} = \int_{\xi_{1,min}}^{1} d\xi_1 \int_{\xi_{2,min}}^{1} d\xi_2 h(\xi_1, \xi_2)\, \delta\left[\left(\frac{\xi_1}{x_1} - 1\right)\left(\frac{\xi_2}{x_1} - 1\right) - \frac{q_T^2}{M_T^2}\right], \quad (16)$$

Dependence on the Matching

-PRELIMINARY-

kc0 and kc1 give a good description of data. kc2 turns out to be an extreme choice.



Main sources of systematic uncertainties

- Non-perturbative function,
- PDF uncertainty.

These are the major sources of uncertainty in the M_W mass measurement.

An optimized NP-form for W and Z production

We used an optimized form of the Sudakov exponent, suitable for both W and Z production.
In the case of Z production

$$\tilde{W}^{NP}_{j\bar{k}}(b,Q) = e^{-\tilde{S}^{NP}(b,Q)} = e^{-b^2\left[a_1 + a_2 \ln\left(\frac{Q}{M_Z}\right) + a_3 \ln\left(\frac{x_1 x_2}{0.01}\right)\right]} . \qquad (17)$$

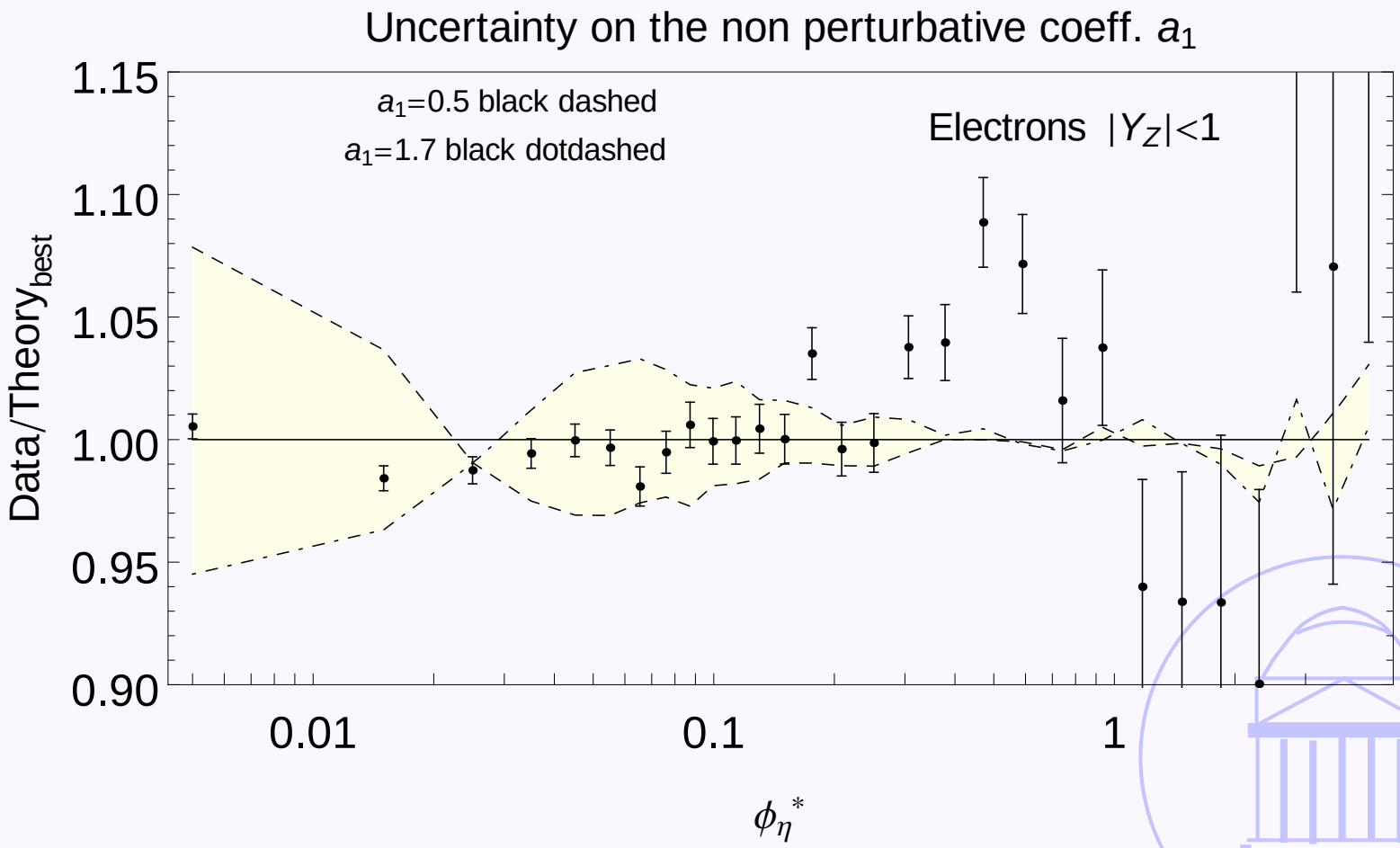
For $Q \approx M_Z$ we have that $x_1 x_2 \approx 0.01$, therefore

$$\tilde{S}^{NP}(b, Q = M_Z) = -b^2 a_1; \qquad a_1 \approx 1\ GeV^{-2} , \qquad (18)$$

which is obtained (together with its uncertainty) by a fit to the ϕ^*_η distribution of Z/γ^* at D0.

Very simple, you only need a_1

a_1 matters! -PRELIMINARY-



Gaussian smearing in global p_T fits

$a_{1,2,3}$ found from the fit are correlated with the assumed form of $\widetilde{W}_{NP}$ (value of b_{max})

Landry, Brock, Nadolsky, Yuan, 2002 **($b_{max} = 0.5$ GeV^{-1}):**

$$a(Q) = \underbrace{0.21}_{a_1} + \underbrace{0.68}_{a_2} \ln \frac{Q}{3.2} - \underbrace{0.13}_{a_3} \ln(100 x_A x_B)$$

- a_3 is comparable to a_1, a_2
- For $\sqrt{s} = 1.96$ TeV, $a(M_Z) \approx 2.7$ GeV^2 (surprisingly large)

Konychev-Nadolsky, 2006 **($b_{max} = 1.5$ GeV^{-1}):**

$$a(Q) = 0.20 + 0.19 \ln \frac{Q}{3.2} - 0.03 \ln(100 x_A x_B)$$

- $a_2 \sim 0.19$ GeV^2
- $a_3 \ll a_1, a_2$; in Z production, $a(M_Z) \approx 0.9$ GeV^2
- reduced $\chi^2/d.o.f.$ in the fit

An optimized NP-form for W and Z production

In the case of $Q \approx M_W$ we have a small correction

$$\tilde{S}^{NP}(b, Q = M_W) = -b^2(a_1' + \underbrace{a_2' \ln \frac{M_W}{M_Z} + a_3' \ln\left(\frac{x_1 x_2}{0.01}\right)})$$

$$a_1' = a_{1,KN} + a_{2,KN} \ln\left(\frac{Q}{M_Z}\right) + a_{3,KN} \ln\left(\frac{x_1 x_2}{0.01}\right)$$
$$a_2' = a_{2,KN}, \qquad a_3' = a_{3,KN} \tag{19}$$

Even including this small correction, we show that the value of a_1' computed in the case of M_W is compatible with the error band of a_1 computed from the analysis of the Z/γ^* ϕ_η^* distribution.

Z and W production: a_1 from fit to the data.

We will determine the value of a_1 from a fit to the D0 ϕ^*_η distribution data using two methods.

★ Method I: we computed the χ^2 without including the shifts due to variations of C_1, C_2, C_3.

★ Method II: we computed the χ^2 including the covariance matrix due to these shifts.

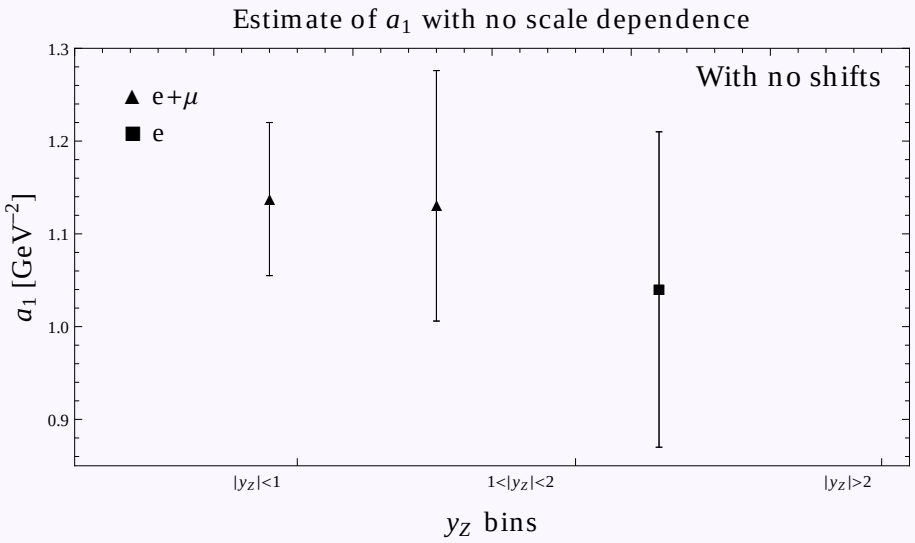
Results

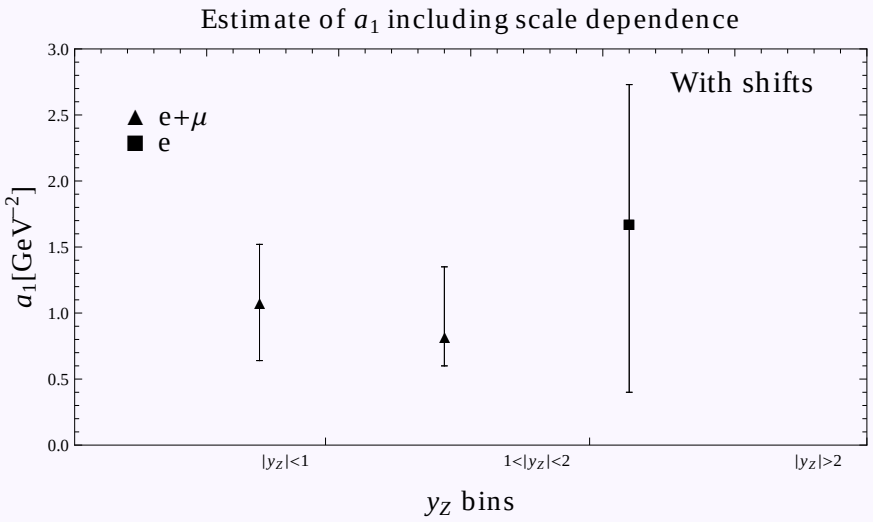
We evaluate χ^2 in the $\phi_\eta^* \leq 0.1$ region, as a function of a_1 that varies in $[0.1, 3.5]$ GeV^{-2}.

- when shifts are not included, the uncertainty on a_1 is pretty much symmetric.
- when shifts are included, the uncertainty on a_1 is larger and it starts to be asymmetric.

Results for a_1

-PRELIMINARY-





Results for a_1

- We give a new parametrization suitable for M_Z and M_W mass measurements.
- It is very simple: the uncertainty on $\tilde{W}_{NP}$ is driven by a_1.
- The estimate of a_1 can be obtained by a combination of the two methods. The results seem to indicate that $a_1 \approx 1$ GeV^{-2}, and therefore not $= 0$.
  This result is provided by the constraining power of D0 data.

PDF uncertainties

- New ResBos NNLL/(NLO+K) grids with $CTEQ$ NNLO, optimized for M_W measurements, and including error sets, are going to be available.
- CTEQ PDFs at NNLO are going to be released in the next couple of weeks. W-asymmetry results will be included in these new fits.
- Determination of the impact of the PDF errors is going to be extremely important for W and Z mass extraction from novel forthcoming data by hadron colliders.

Concluding remarks

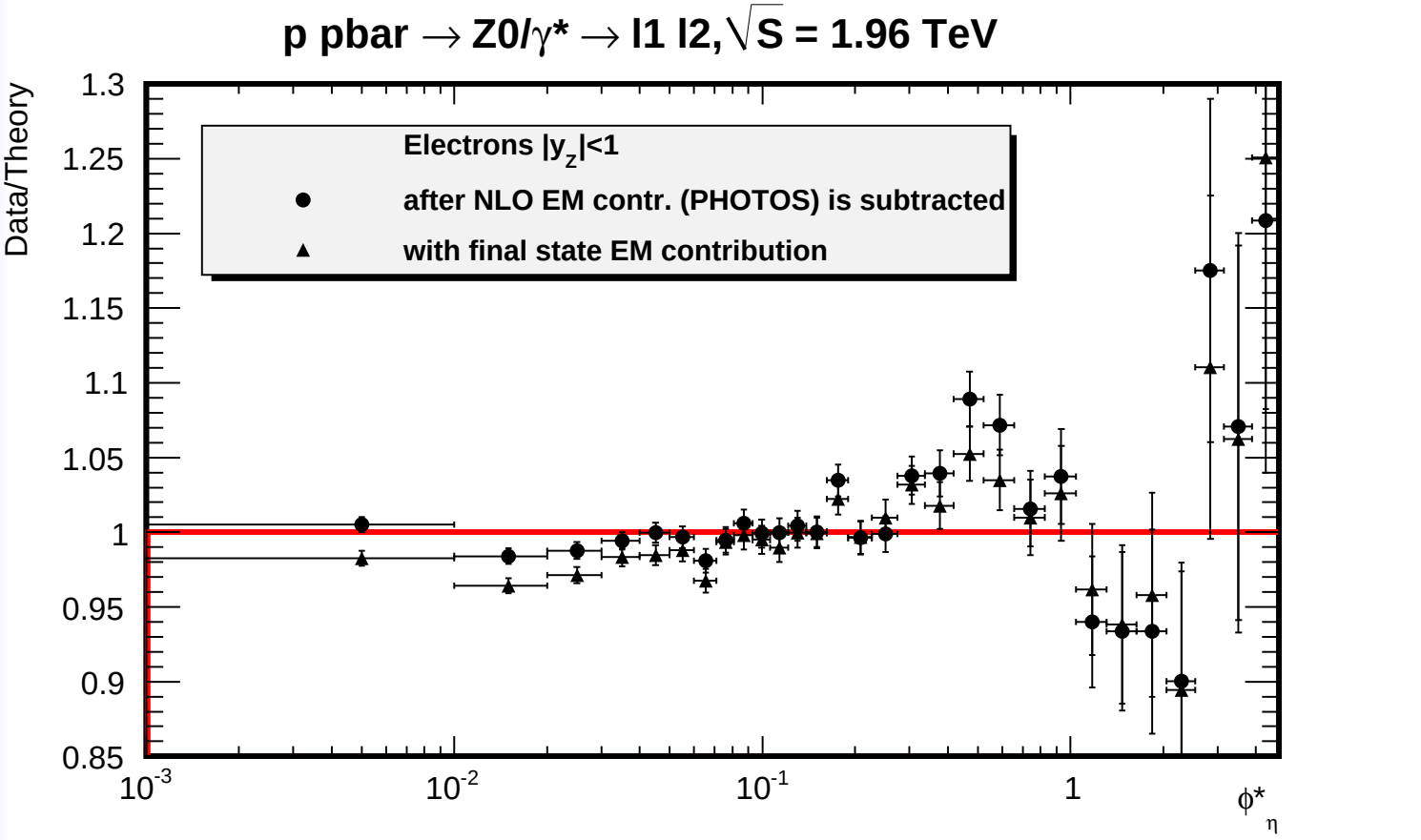
- We tried to address the main sources of uncertainty in comparisons of Th vs Data.
- New ResBos NNLL/(NLO+K) $\Rightarrow$ we have good control on $O(\alpha_s^2)$ soft-scale dependence.
- A new set of CTEQ NNLO PDFs is used in our comparisons.
- We used the constraining power of D0 data to get gahter information on the non-perturbative function.
- We provide a new simple parametrization which depends only upon one number and it is also optimized for M_W measurements.
- Still work in progress on evaluation of PDFs uncertainty on these observables.
- It will be great to learn more from the interplay between TMD and CSS formalism in this kind of analysis.

BACK-UP SLIDES

Size of electromagnetic corrections

Final state EM radiation is accounted for by using PHOTOS (Barberio and Was CPC79 1994). Here Theory is ResBos NNLL/(NLO+K).

-PRELIMINARY-



These are around 2% at small ϕ^*_η

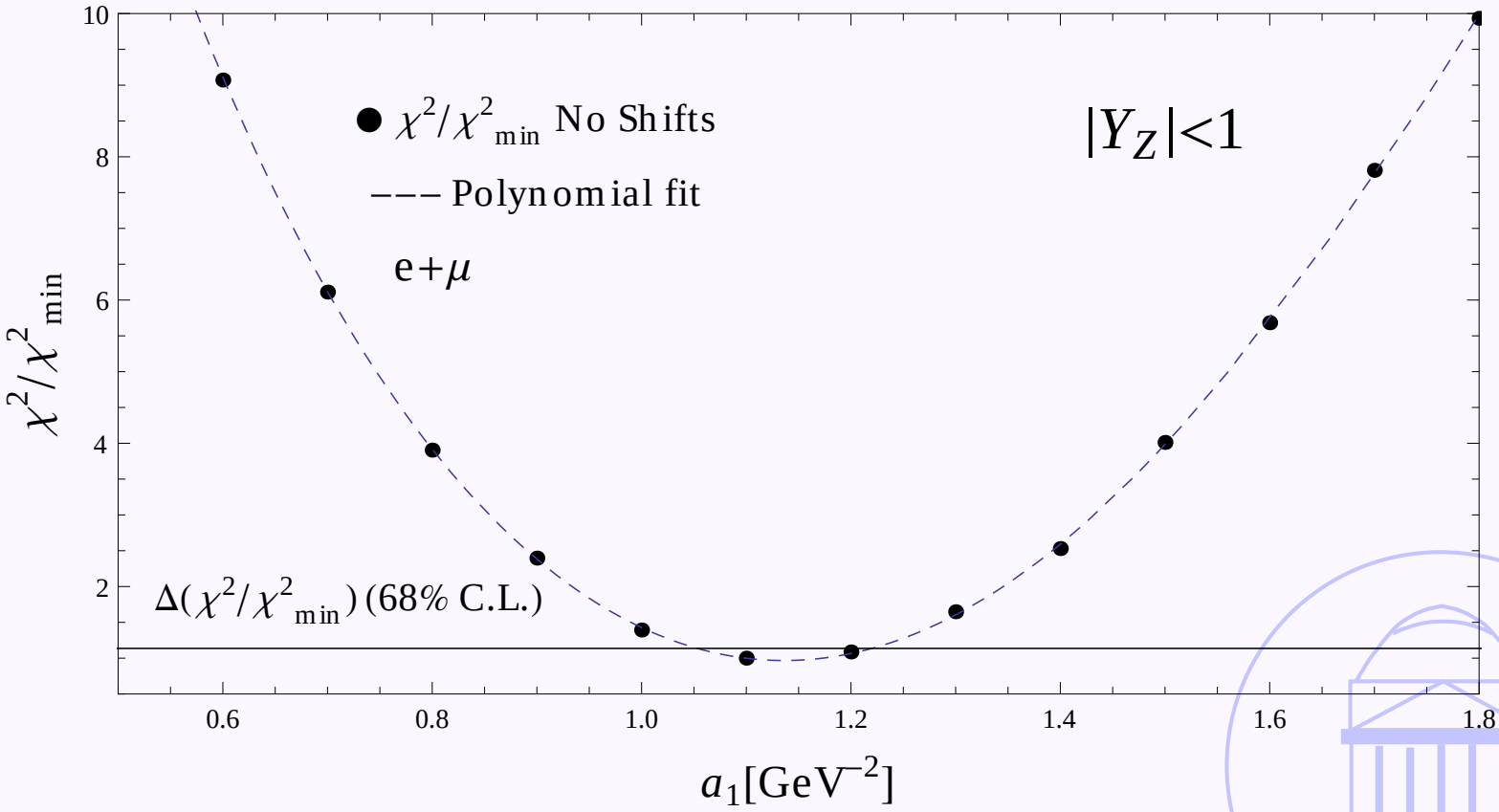
Various theory computations

★ NLO EW Corrections

- $ZGRAD$ by U. Baur, S.Keller, W.K. Sukamoto, PRD57 (1998) 199-215
- $WGRAD$ by U. Baur, O. Brein, W. Hollik, C. Schappacher, D. Wackeroth PRD65 (2002) 033007
- $PHOTOS$ by E.Barberio and Z.Was CPC79 291 (1994)
- $HORACE$ by C. M. Carloni-Calame, G.Montagna G, O.Nicrosini, A. Vicini, JHEP016(2007)12
- $SANC$ by A. Andonov, D. Bardin et al., CPC 174 (2006) 481-517; CPC 177 (2007) 738
- $ResBos - A$ by Q.H.Cao, C.P. Yuan, PRL93:042001,2004

Analysis in each bin without shifts on C_i

-PRELIMINARY-



Electrons and Muons combined $|y_Z| \leq 1$

$|y_Z| \leq 1$ bin with C_i shifts

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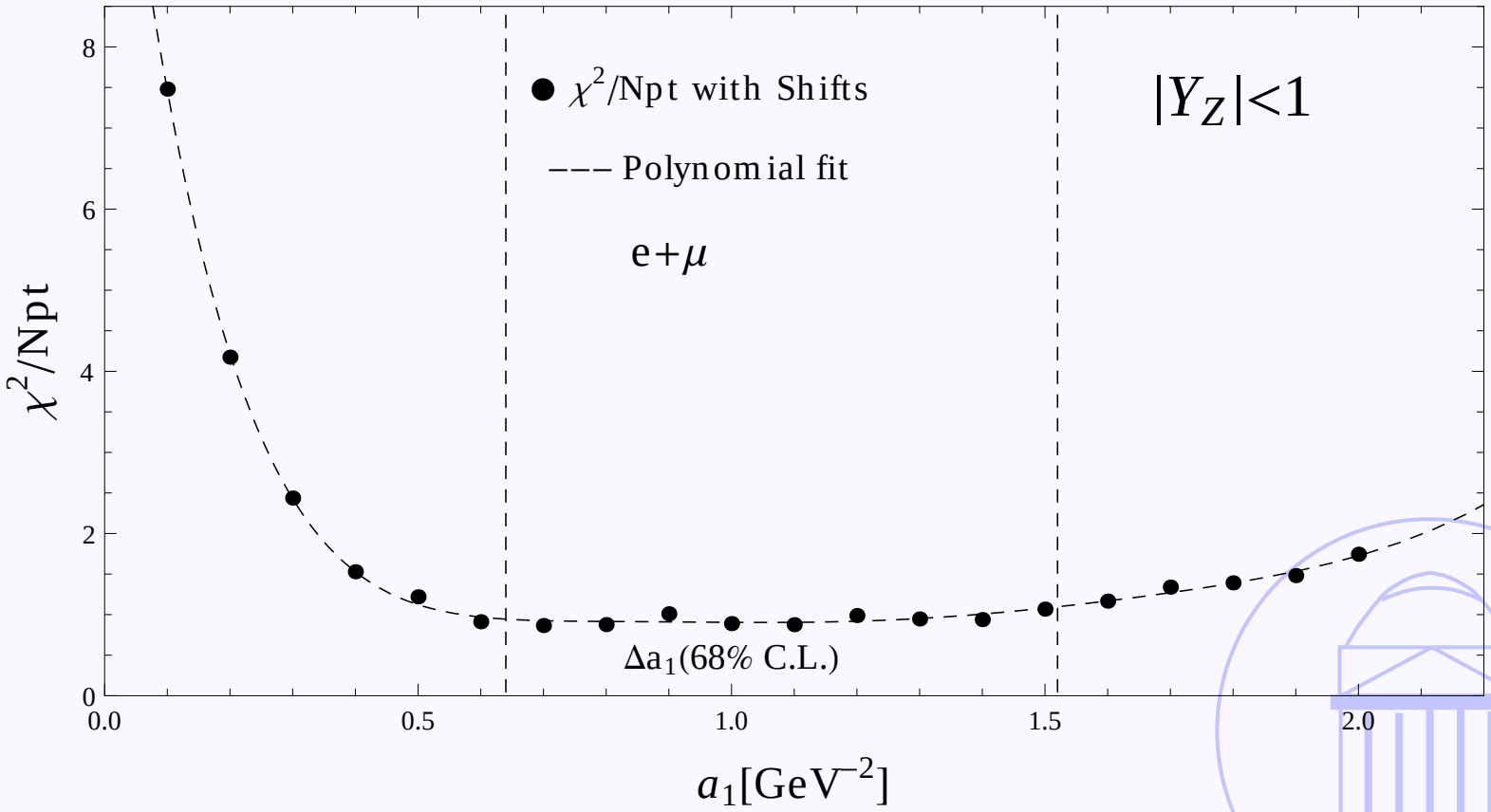
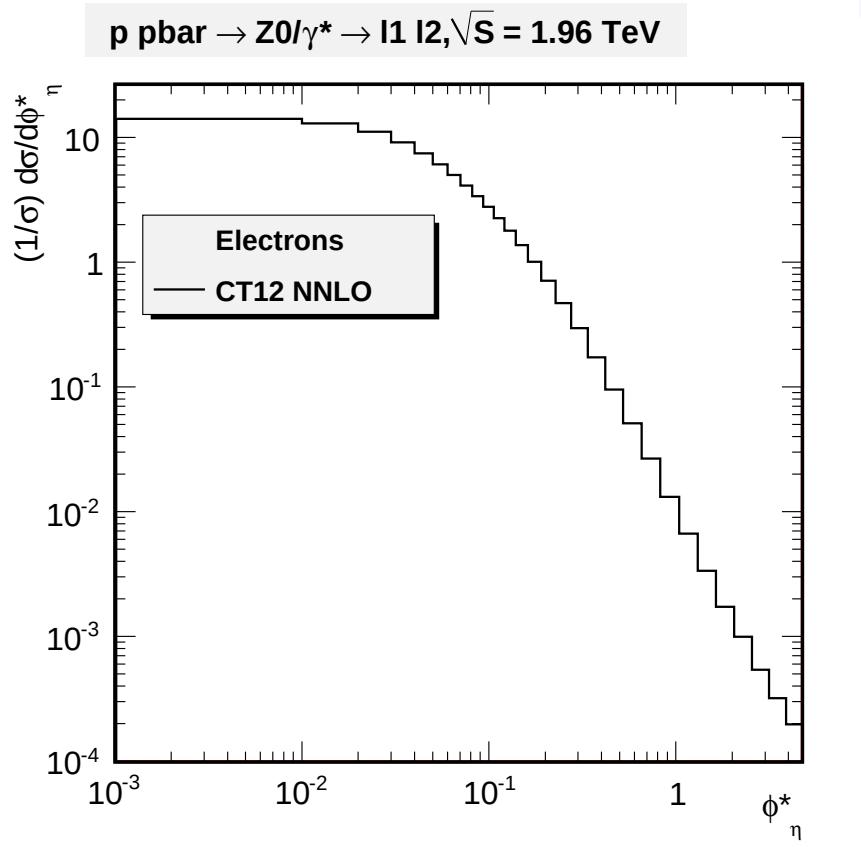
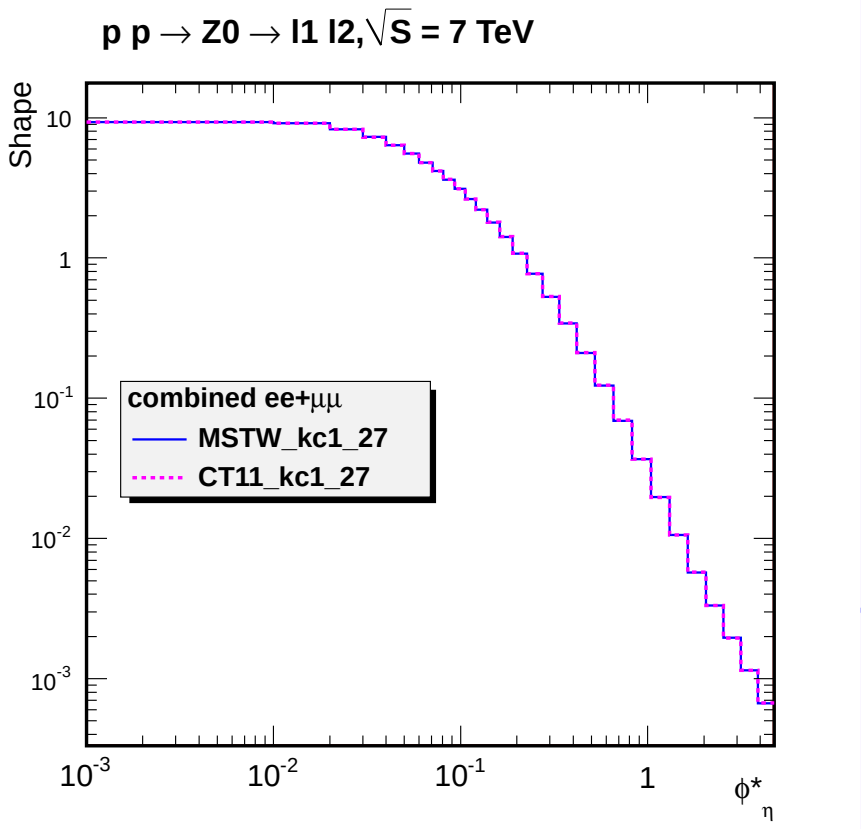


$d\sigma/d\phi^*_\eta$ shape integrated overall rapidity y_Z

-PRELIMINARY-





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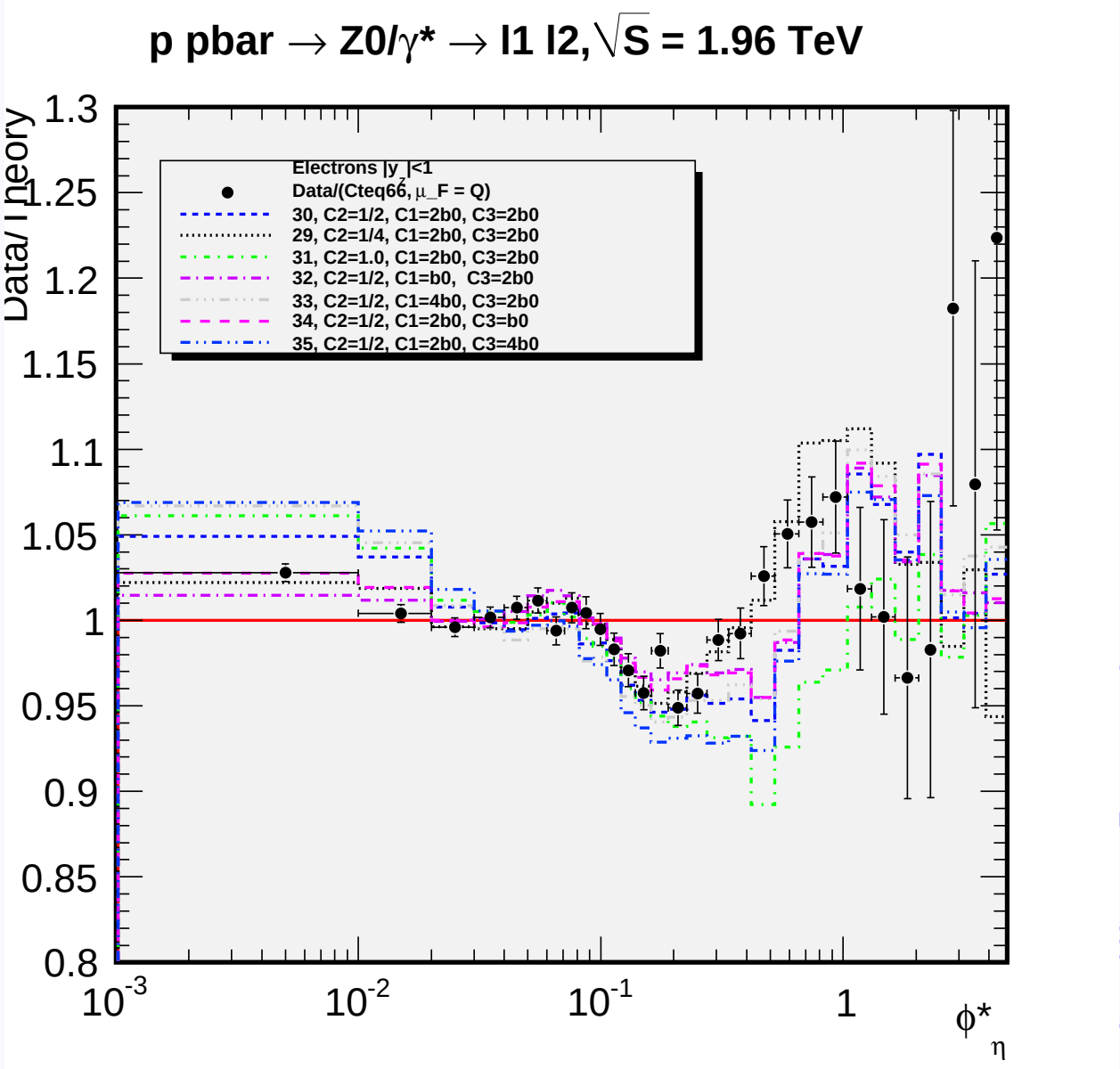

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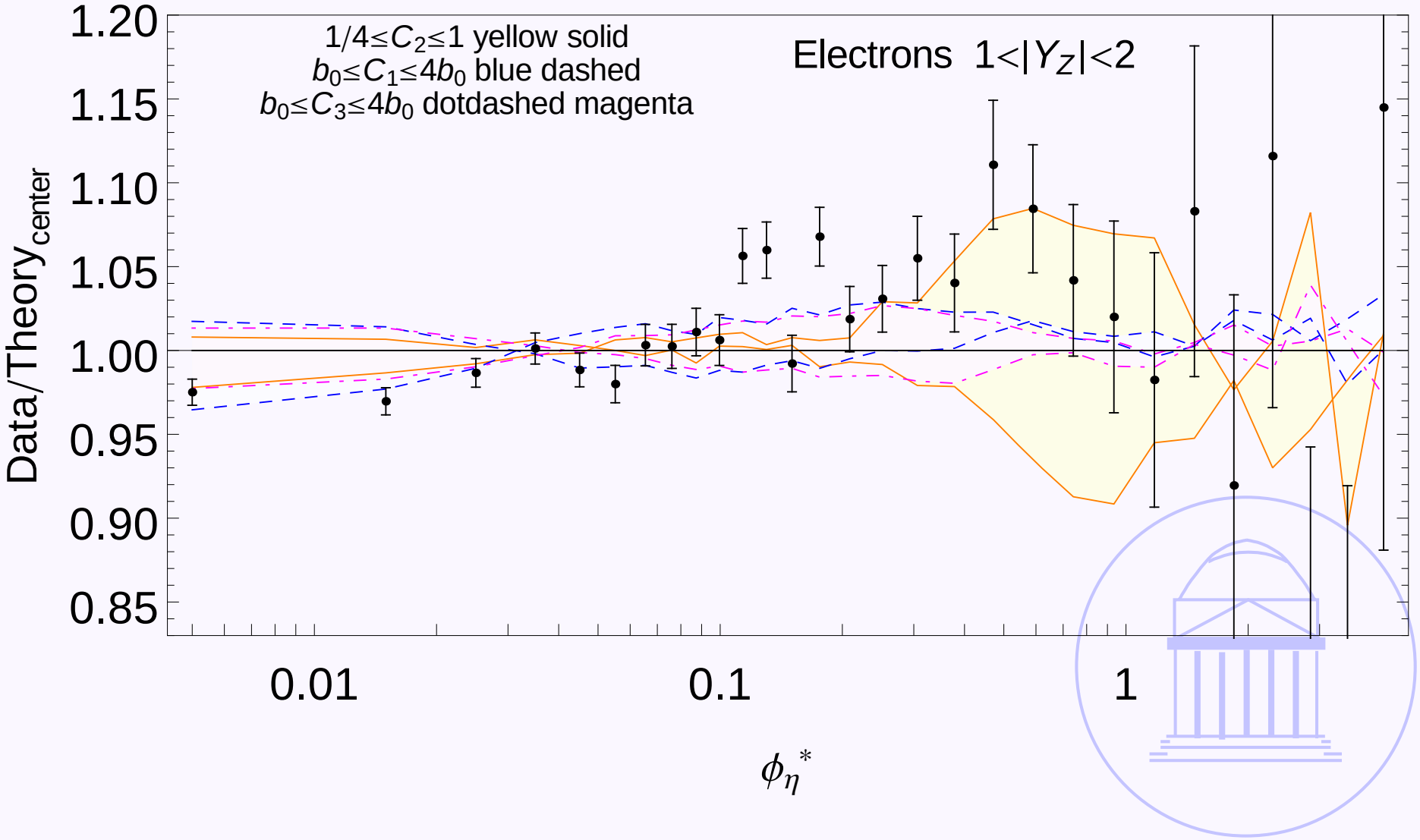

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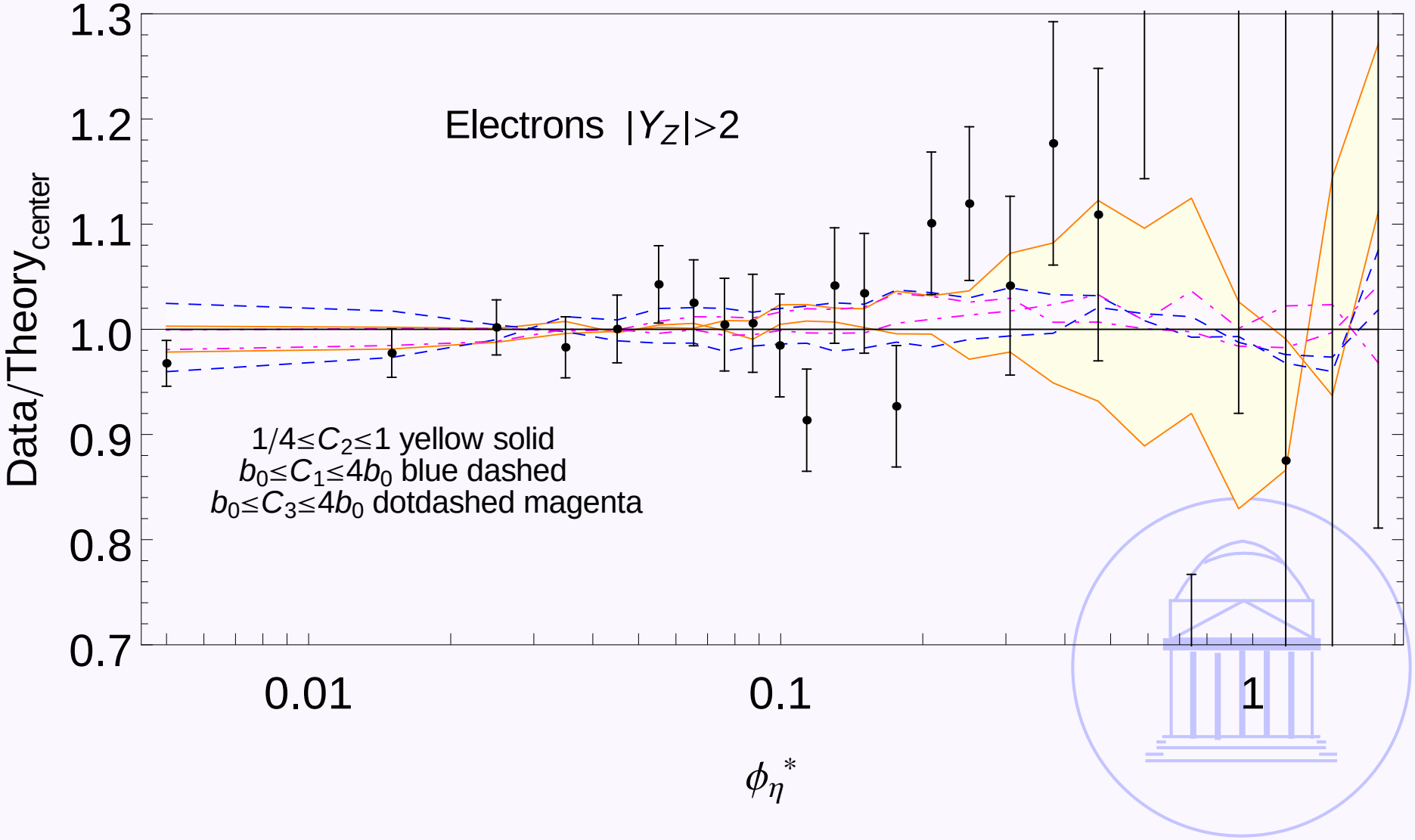

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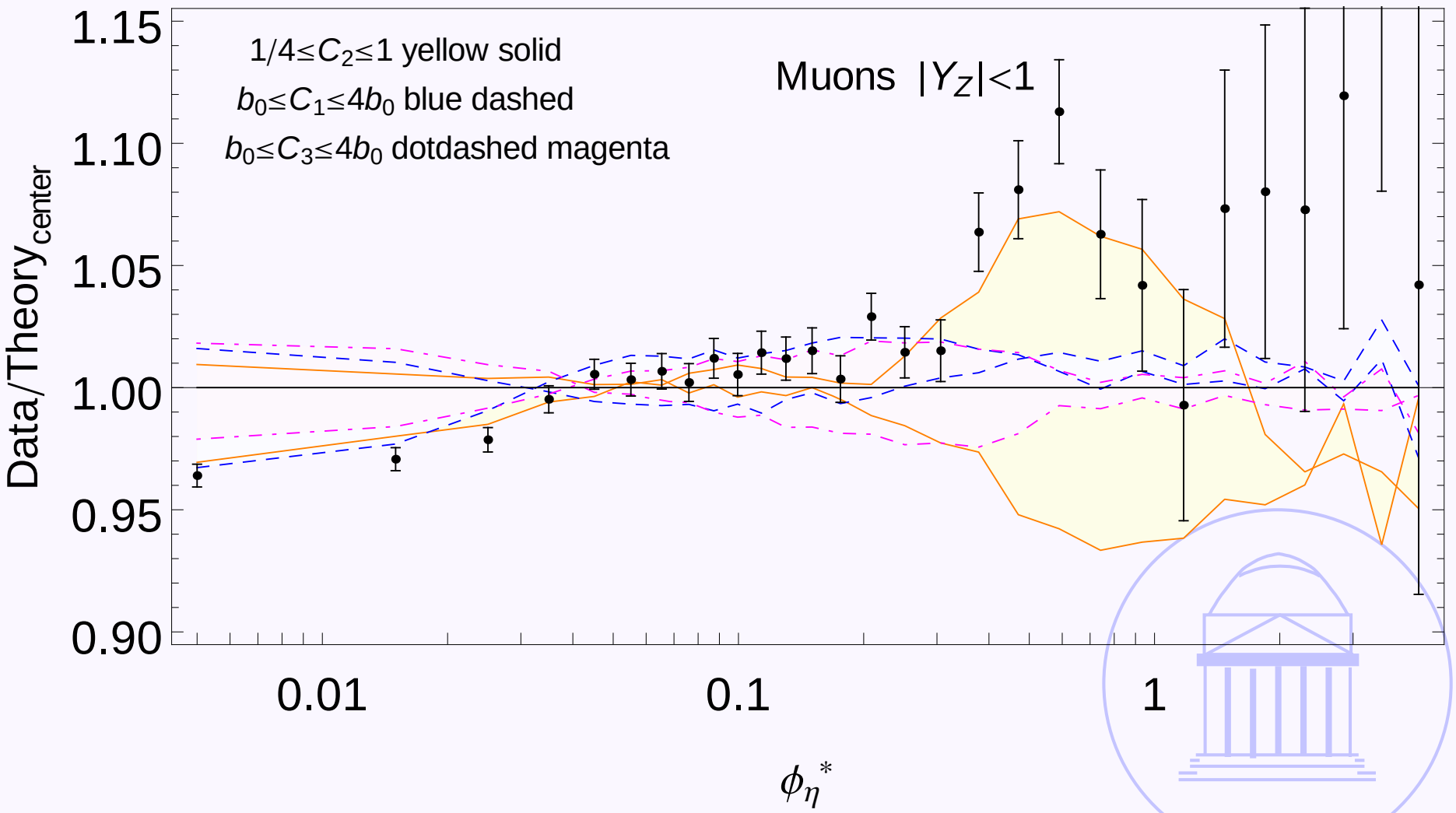

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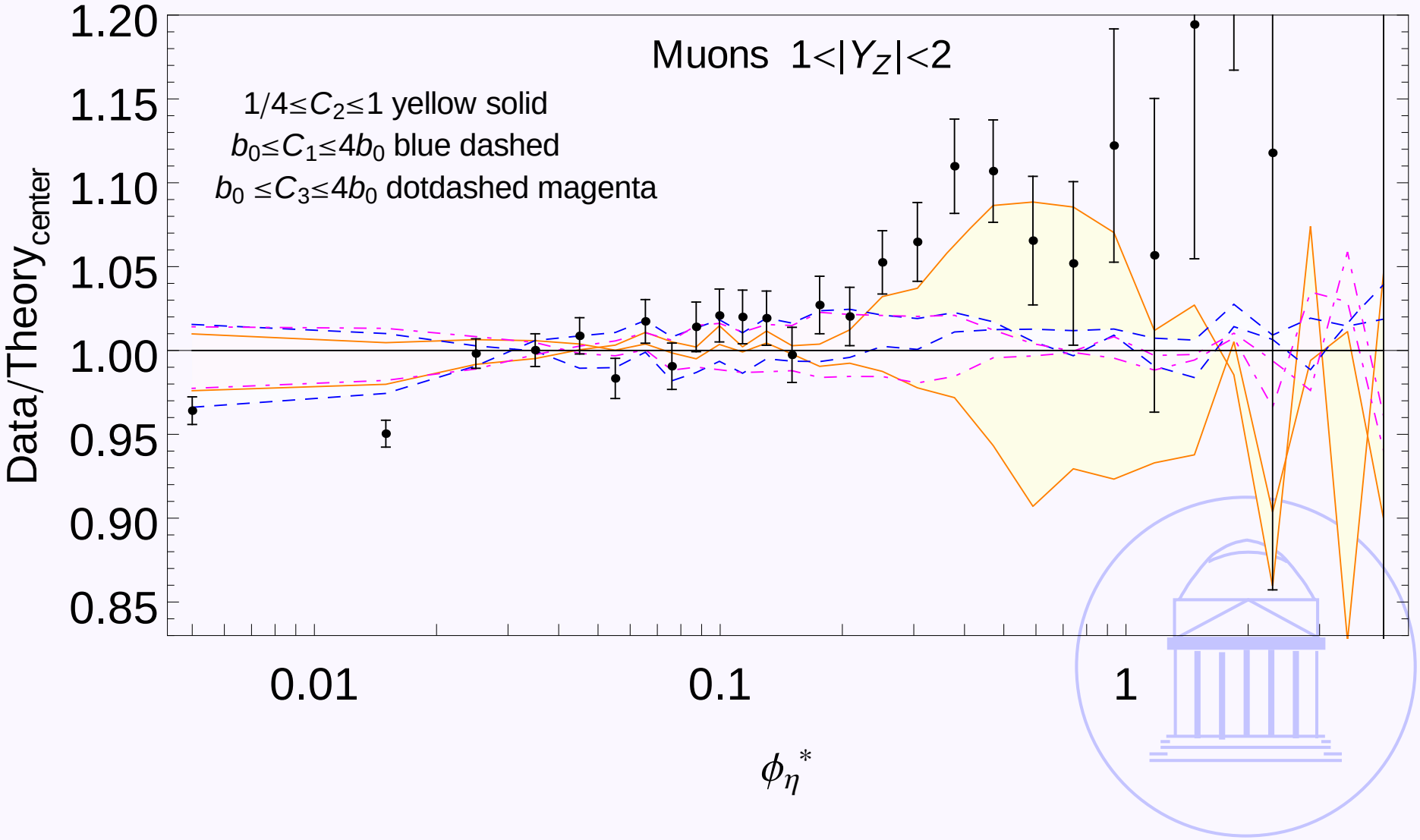
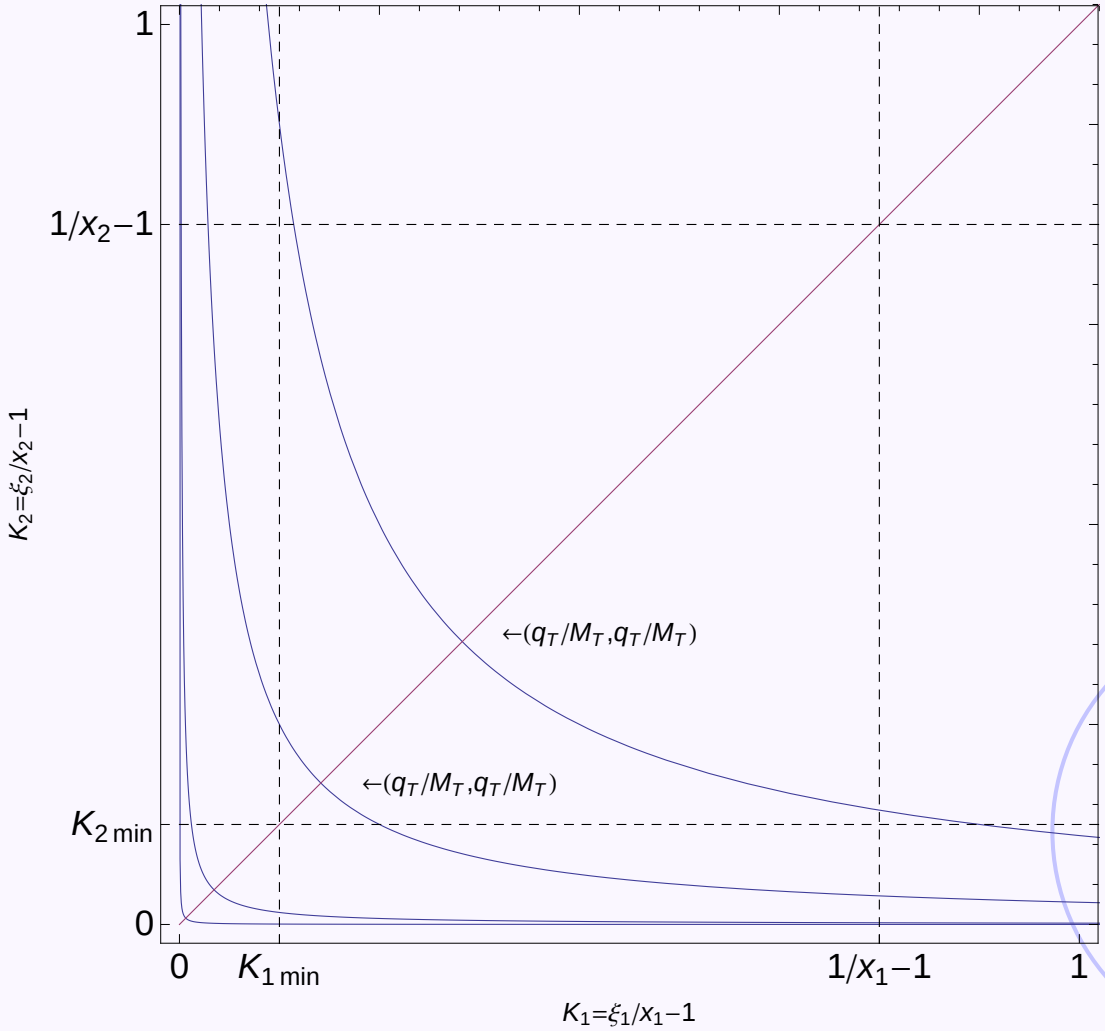


Dependence on the Matching: Kinematic Corrections



Kinematic Corrections

We explored this issue with ResBos using different definitions of light-cone variables $x_{1,2}$

$$x_{1,2}^{(0)} = \frac{Q}{\sqrt{S}} e^{\pm y} \qquad \Longrightarrow \xi_{1,2}^{min} = x_{1,2} + \frac{Q^2}{S} \frac{q_T^2}{M_T^2} \frac{1}{(1 - x_{2,1})}$$

$$x_{1,2} = \frac{M_T}{\sqrt{S}} e^{\pm y} \qquad \Longrightarrow \xi_{1,2}^{min} = x_{1,2} + \frac{q_T^2}{S} \frac{1}{(1 - x_{2,1})}$$

$$\xi_{1,2c} \leq \xi_{1,2}^{min} \leq \xi_{1,2} \leq 1. \tag{20}$$

such definitions are coincident in the $q_T \to 0$ limit.

We have found that kc0 and kc1 well describe the data, while kc2 is extreme.

Gaussian smearing in Z boson production

The large-b behavior of $\widetilde{W}(b,Q)$ is often approximated as

$$\widetilde{W}(b,Q,x_A,x_B)\Big|_{all\ b} \approx \widetilde{W}'_{LP}(b,Q,x_A,x_B)e^{-a(Q,x_A,x_B)b^2},$$

where $\widetilde{W}'_{LP}(b,Q,x_A,x_B)$ is a continuation of the perturbative (leading-power) contribution to $b \gtrsim b_{max} \sim 1$ GeV^{-1}

For example, in the "b$_*$" model *(CSS, 1985)*:

$$\widetilde{W}'_{LP}(b) \equiv \widetilde{W}_{pert}(b_*) \rightarrow \begin{cases} \widetilde{W}_{pert}(b), & b \ll b_{max} \\ \widetilde{W}_{pert}(b_{max}), & b \gg b_{max} \end{cases}$$

$$b_* \equiv \frac{b}{\sqrt{1+b^2/b_{max}^2}}$$

Gaussian smearing in Z boson production II

The large-b behavior of $\widetilde{W}(b,Q)$ is often approximated as

$$\widetilde{W}(b,Q,x_A,x_B)\Big|_{all\ b} \approx \widetilde{W}'_{LP}(b,Q,x_A,x_B)e^{-a(Q,x_A,x_B)b^2}$$

$a(Q,x_A,x_B)$ is the non-perturbative "Gaussian smearing";

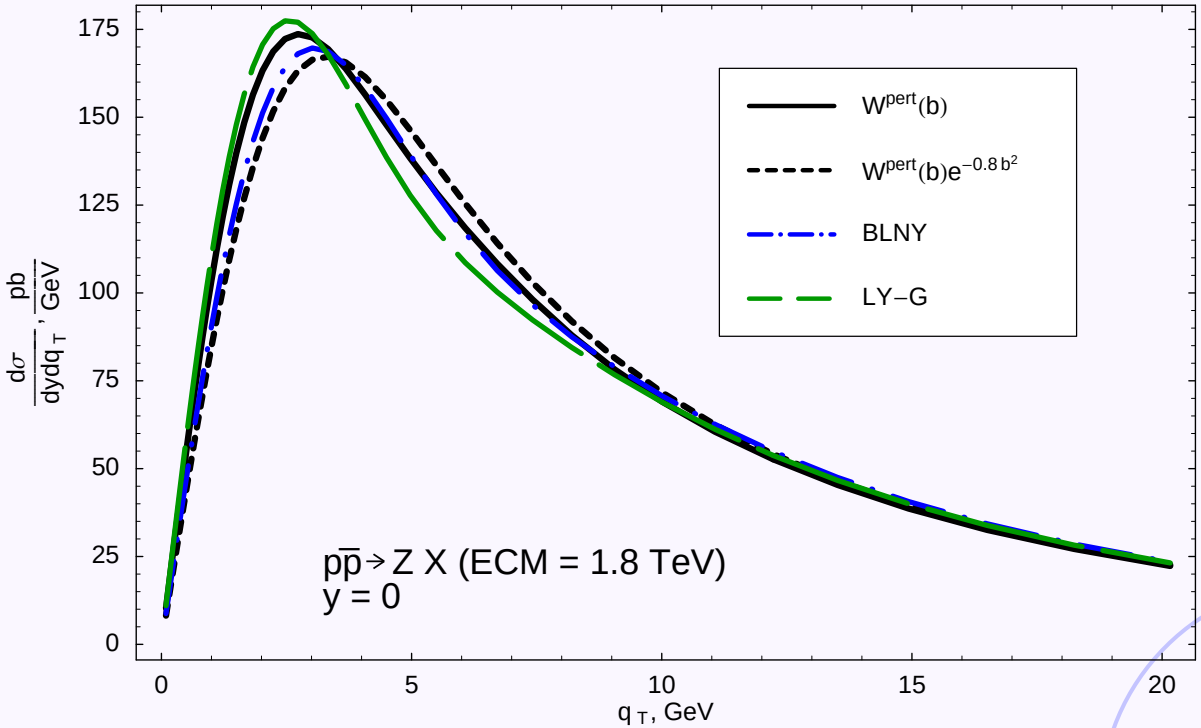
- dominates NP terms at $b \lesssim 2$ GeV^{-1}
- is universal in Drell-Yan-like processes and SIDIS;
- can be found from a fit to p_T data (currently 3 low-Q Drell-Yan pair and 2 Run-1 Z production data sets)
- RG invariance + factorization properties of $\widetilde{W}(b,Q)$:

$$a(Q,x_A,x_B) \approx a_1 + a_2 \ln\frac{Q}{Q_0} + a_3\left[\phi(x_A)+\phi(x_B)\right]$$

Renormalon analysis+lattice QCD: $a_2 = 0.19^{+0.12}_{-0.09}$ GeV^2 *(Tafat)*

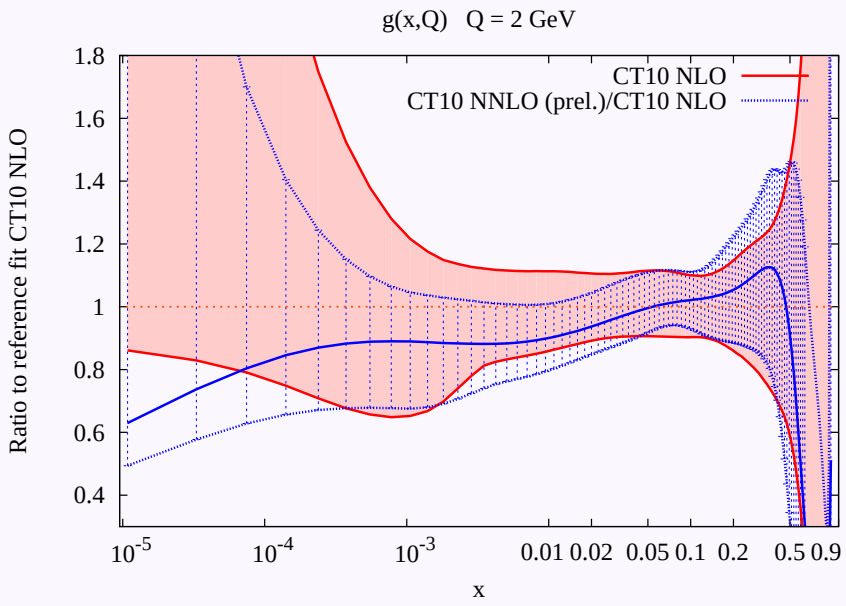
Several models for the form factor $W(b)$

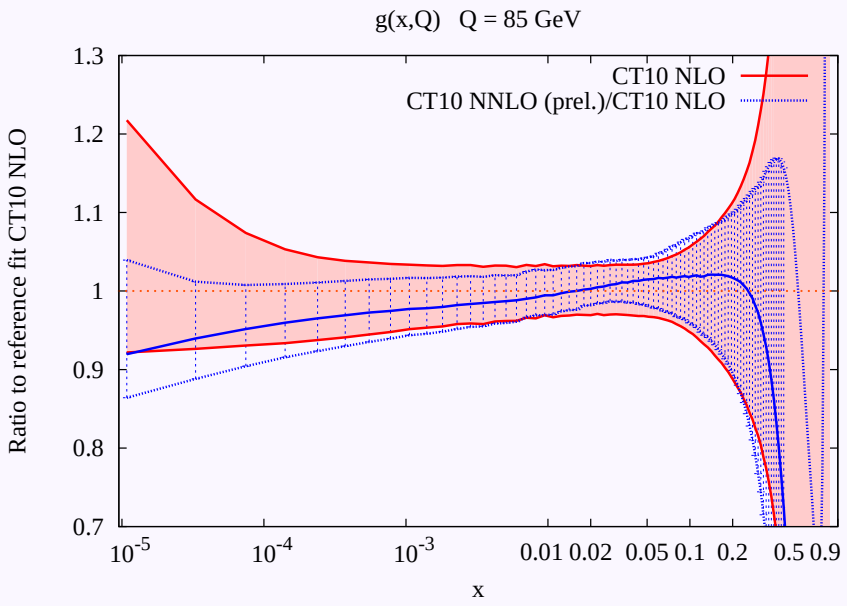
From P. Nadolsky hep-ph/0412146

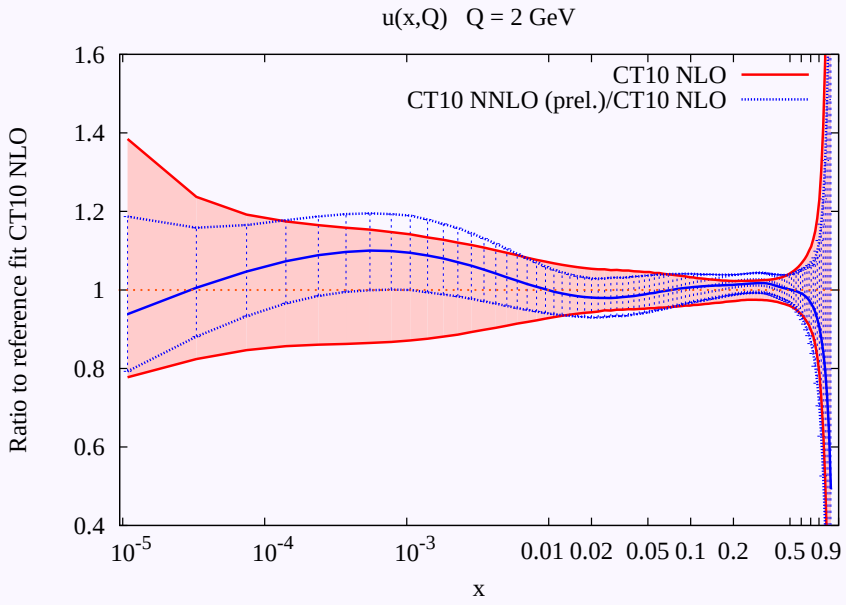


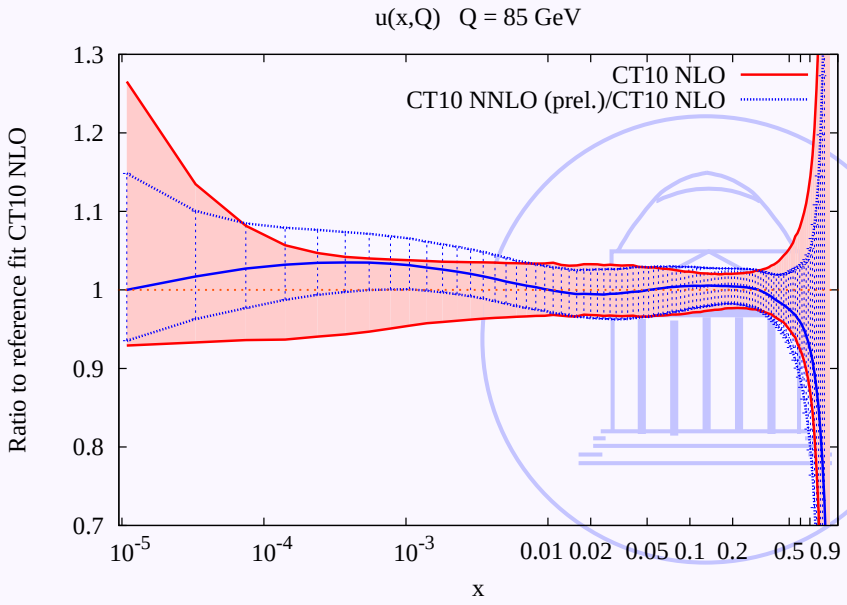
The CSS resummed cross sections in Z boson production at the Tevatron. Several models for the CSS form factor $W(b)$ at large impact parameters ($b > 1$ GeV^{-1}).

PDF uncertainties CTEQ NNLO









More on ϕ^*_η

In the limit $Q_T \to 0$

$$\sin^2\theta^* = 4l_T^2/M^2 \tag{21}$$

$$a_T = Q_T \sin\alpha \tag{22}$$

α is the angle between $\vec{Q}_T$ and the lepton axis in the transverse plane.

$$\tan\frac{\phi_{acop}}{2} \approx \frac{Q_T \sin\alpha}{2l_T} \tag{23}$$

(For more details see Banfi et al. PLB 701 2011)