From ResBos1 to ResBos2

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Outline

- Discussion of Status of ResBos1
- Angular functions
- Motivation for ResBos2
- CSS vs CFG Formalisms
- N^3LL Accuracy
- Non-Physics Improvements
- Future Goals

Angular function in Drell-Yan process

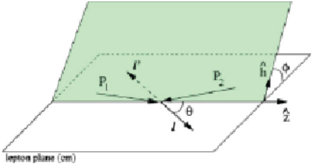
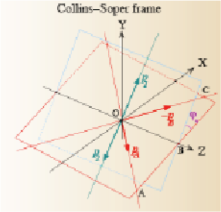


FIG. 1. Kinematics of the Drell-Yan process in the lepton center of mass frame.



Lam-Tung relation

PHYSICAL REVIEW D 16, 2219 (1977)

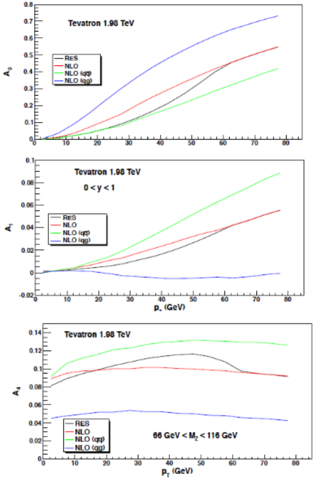
$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta + \left(\tfrac{1}{2} - \tfrac{3}{2}\cos^2\theta\right)A_0 + 2\cos\theta\sin\theta\cos\phi\, A_1 + \tfrac{1}{2}\sin^2\theta\cos 2\phi\, A_2\,,$$

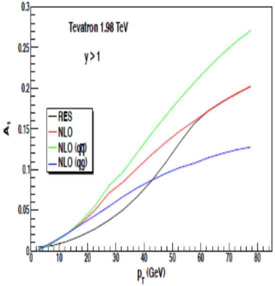
$$A_2 = A_0$$

PHYSICAL REVIEW D 73, 052001 (2006)

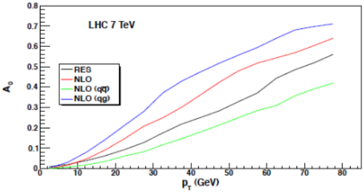
$$\frac{d\sigma}{dq_T^2\,dy\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d\sigma^u}{dq_T^2\,dy}\Big[(1+\cos^2\theta) + \tfrac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \tfrac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big], \quad (1)$$

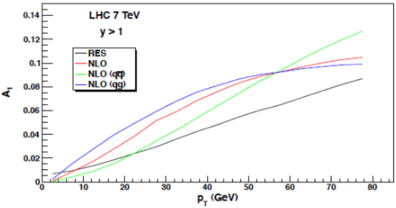
Angular Functions at Tevatron

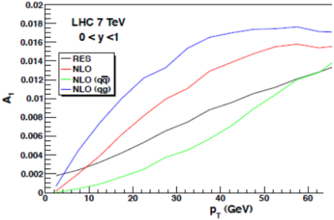




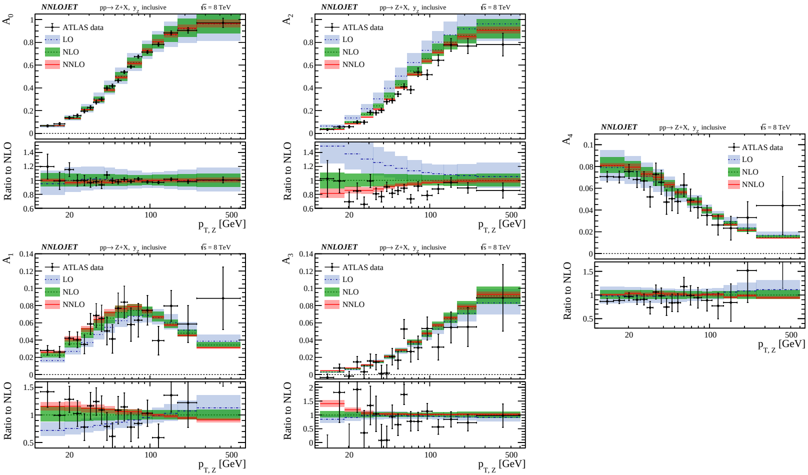
Angular Functions at LHC 7TeV







NNLO Z+j Angular K-Factors (1708.00008)

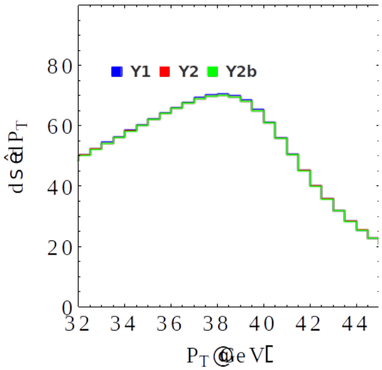


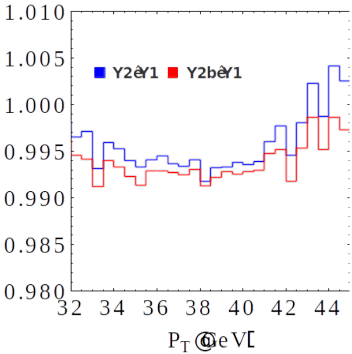
W Mass Study: Cuts

Cuts at LHC 8 TeV:

- $p_T(e) > 25$ GeV
- $|y_e| < 2.5$
- $M_T > 50$ GeV
- $\not{E}_T > 25$ GeV

W Mass Study: Results





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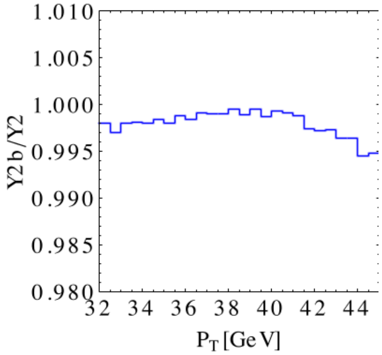

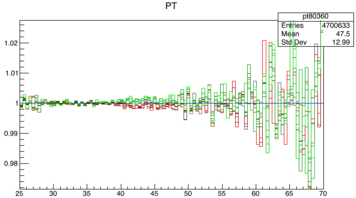

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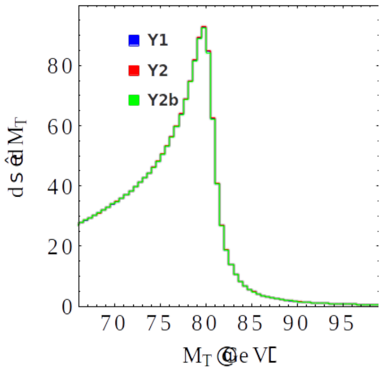

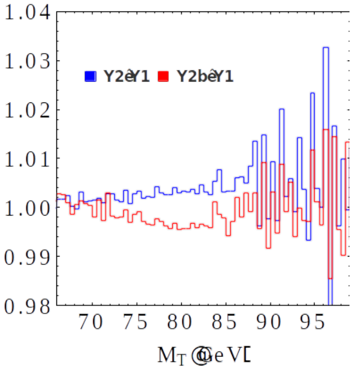

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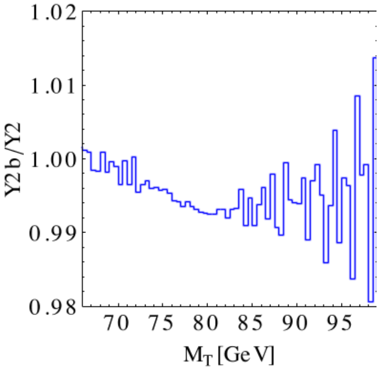
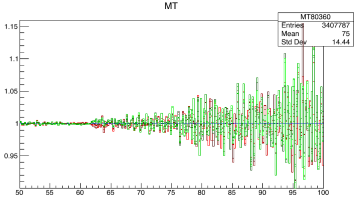
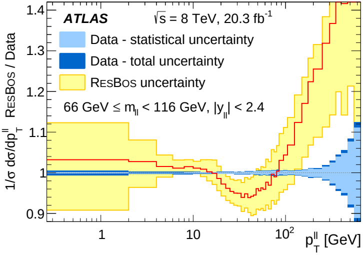




Motivations for ResBos2

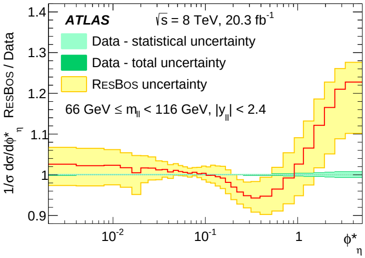
- Understand errors introduced by q_T resummation scheme choice
- Improve agreement with Drell-Yan data



ATLAS, 1512.02192v2

Motivation (Cont.)

$$\phi_\eta^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sqrt{1 - \tanh\left(\frac{\eta_1 - \eta_2}{2}\right)} \approx \frac{Q_T}{Q}\sin\phi_{CS}$$



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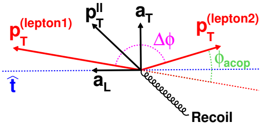


Vesterinen and Wyatt et al., arXiv:1010.0262

CSS vs. CFG Formalism

Resummation

$$\frac{d\sigma}{dQ^2 dq_T^2 dy d\Omega} = \sigma \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}} \tilde{W} + Y,$$

$$\tilde{W} = e^{-S(b)} e^{-S_{NP}(b)} C(C_3) \otimes f(x_A) C(C_3) \otimes f(x_B)$$

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

Collins-Soper-Sterman Formalism:

- Resummation process dependent (B and C Coefficients)

Catani-de Florian-Grazzini Formalism:

- Resummation process independent (B and C Coefficients)
- More in line with Transverse

CSS vs. CFG Formalism

Hard Factor:

- CSS: $\sigma = \sigma_0 \times (1)$
- CFG: $\sigma = \sigma_0 \times \left(1 + \frac{\alpha_s}{\pi} H^{(1)} + ...\right)$

Theoretical Scales:

- Canonical Scale: $C_1 = b_0$, $C_2 = 1$, $C_3 = b_0$
- Factorization Scale (PDFs): μ_F
- Renormalization Scale (Couplings): μ_R

CSS vs. CFG (Cont.)

All Orders Conversion

$$A^{CSS} = A^{CFG}$$

$$B^{CSS} = B^{CFG} - \beta\left(\alpha_s\right)\frac{d\ln H\left(\alpha_s\right)}{d\ln\alpha_s}$$

$$C^{CSS} = \left[H\left(\alpha_s\right)\right]^{1/2} C^{CFG}$$

CSS vs. CFG (Cont.)

Conversion between CSS and CFG (Hard Factors):

Conversion

$$C_{ab}^{(1)CSS}(z) = C_{ab}^{(1)CFG}(z) + \delta_{ab}\delta(1-z)\frac{1}{2}H_a^{(1)}$$

$$C_{ab}^{(2)CSS}(z) = C_{ab}^{(2)CFG}(z) + \frac{1}{2}H_a^{(1)}C_{ab}^{(1)CFG}(z) + \delta_{ab}\delta(1-z)\frac{1}{2}\left(H_a^{(2)} - \frac{1}{4}\left(H_a^{(1)}\right)^2\right)$$

CSS vs. CFG (Cont.)

Conversion between CSS and CFG (Sudakov Factors):

Conversion

$$B^{(1)CSS} = B^{(1)CFG}$$

$$B^{(2)CSS} = B^{(2)CFG} + \beta_0 H^{(1)}$$

$$B^{(3)CSS} = B^{(3)CFG} + \beta_1 H^{(1)} + 2\beta_0 \left(H_a^{(2)} - \frac{1}{2} \left(H_a^{(1)} \right)^2 \right)$$

B^3 for Drell-Yan

CSS

$$B^{(3)} = 114.982 - 11.2737 n_f + 0.321798 n_f^2$$

$$B^{(1)}_{n_f=5} = -2 \quad B^{(2)}_{n_f=5} = 1.9 \quad B^{(3)}_{n_f=5} = 66.66$$

$$\frac{B^{(3)} \frac{\alpha_s}{\pi}}{B^{(2)}} = 1.32$$

CFG

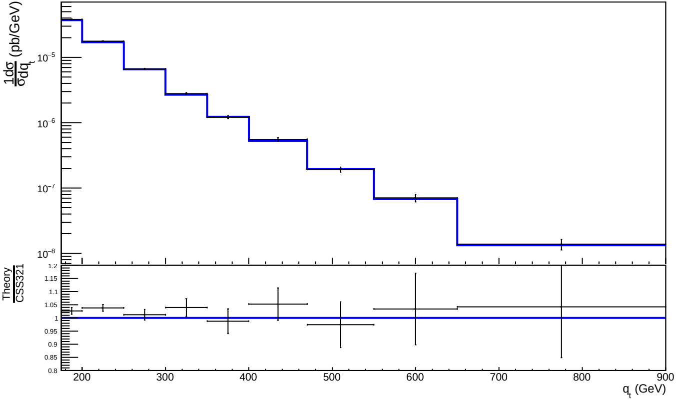
$$B^{(3)} = -16.185 - 0.011592 n_f + 0.11379 n_f^2$$

$$B^{(1)}_{n_f=5} = -2 \quad B^{(2)}_{n_f=5} = -0.488 \quad B^{(3)}_{n_f=5} = -13.38$$

$$\frac{B^{(3)} \frac{\alpha_s}{\pi}}{B^{(2)}} = 1.03$$

HuaXing Zhu, et al. arXiv:1604.01404

High q_T Scale Choice



Theory vs. Data at high q_T with scale choice of

$$\mu = M_T = \sqrt{M_Z^2 + q_T^2}$$

Asymptotic Expansion

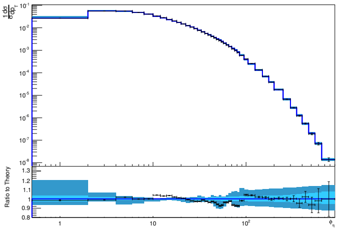
$$\frac{d\sigma}{dq_t^2}_A = \sigma \sum_{i,j} \sum_{n,m} \left(\frac{\alpha_s\left(\mu\right)}{\pi} \right)^n \ {}_nC_m^{(ij)} \ln^m \left(\frac{Q^2}{q_T^2} \right)$$

First term that is different between the CSS and CFG Formalism in the asymptotic expansion is:

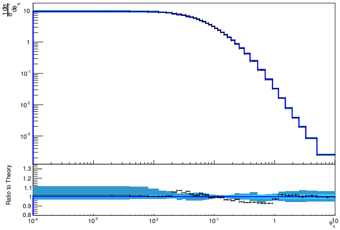
$$\frac{d\sigma}{dq_t^2}_A \subset \alpha_s^4 \ln\left(\frac{Q^2}{Q_T^2}\right) \left[A^{(4)} f_i f_j + \left(A^{(1)}\left(C^{(3)} \otimes f_i\right) f_j + A^{(1)} \left(C^{(3)} \otimes f_j\right) f_i\right)\right]$$

CSS P_T and ϕ_η^* Distributions

Transverse Momentum

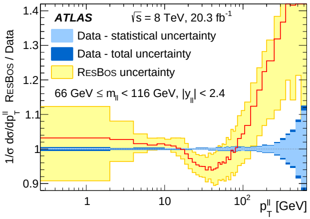


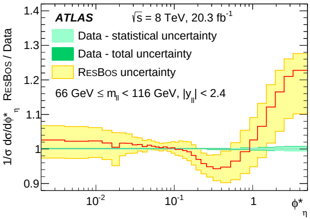
ϕ_η^*

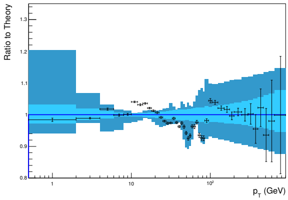


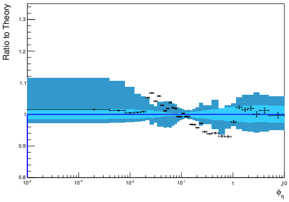
Light blue is PDF Uncertainty. Dark blue is scale uncertainty plus PDF uncertainty. Scale uncertainty is given by: $C_1 = 0.5(2)b_0$, $C_2 = 2(0.5)$, $C_3 = 0.5(2)b_0$, $\mu_F = 0.5(2)\mu_0$, $\mu_R = 0.5(2)\mu_0$. A total of 7 scale variations are used.

CSS P_T and ϕ^*_η Distributions

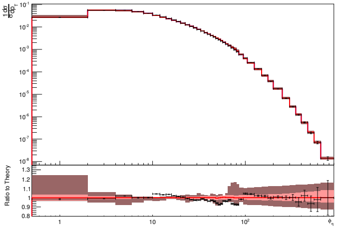


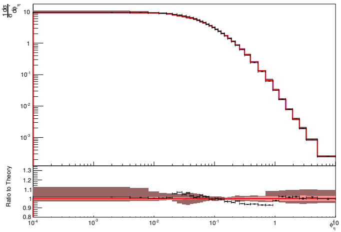






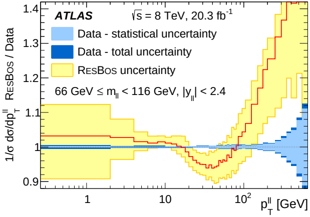
CFG P_T and ϕ_η^* Distributions

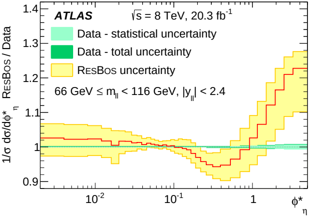


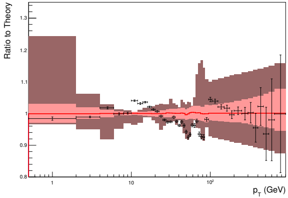


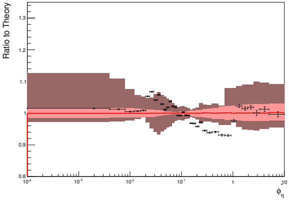
Light red is PDF Uncertainty. Dark red is scale uncertainty plus PDF uncertainty. Scale uncertainty is given by: $C_1 = 0.5(2)b_0$, $C_2 = 2(0.5)$, $C_3 = 0.5(2)b_0$, $\mu_F = 0.5(2)\mu_0$, $\mu_R = 0.5(2)\mu_0$. A total of 7 scale variations are used.

CFG P_T and ϕ_η^* Distributions



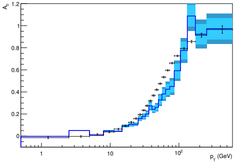




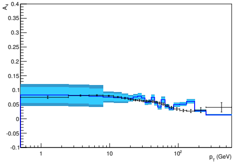


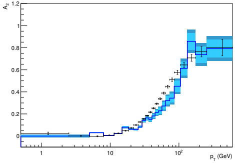
Comparison to Data for Angular Functions

A_0

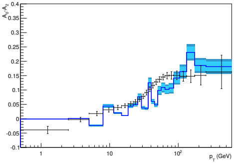


A_4





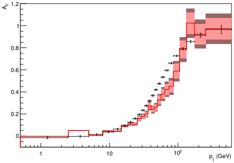
A_2



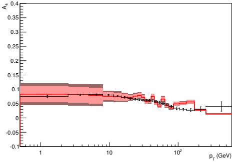
Lam-Tung Relationship

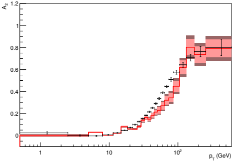
Comparison to Data for Angular Functions

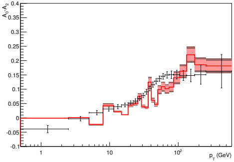
A_0



A_4







A_2

Lam-Tung Relationship

ResBos2: Program Improvements

- The user has complete control over grid generation
- Implement multi-threading to improve grid generation speed
- Interface to LHAPDF to allow any PDF to be used for the calculation

Conclusion

- Resolve predictions for both p_T and ϕ_η^* for the ResBos predictions
- Properly include the Lam-Tung relations breaking
- Study uncertainty induced by scheme choice
- ResBos2 merges old ResBos code with Legacy code (no need for privately made grid files)

Future Steps

- Matching to NNLO $Z + j$
- New Non-pert fit for each scale choice
- Detailed study of relationship between uncertainties for Drell-Yan and $W^{\pm}$
- Make the ResBos2 Code public