The Z boson a_T distribution

a_T: novel variable to study low transverse momentum vector boson production at hadron colliders

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In collaboration with

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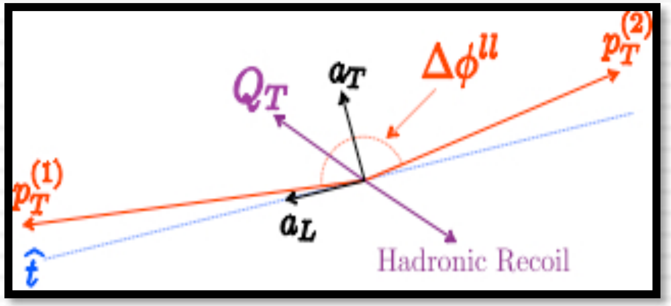
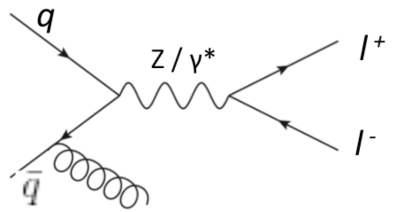


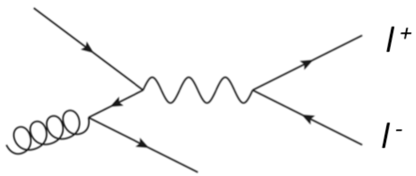
DIS09 Workshop, Madrid

Z boson production at hadron colliders

- Large production rate + clean signal →
  - Tevatron is now a 'Z factory'
    (~½m fully reconstructed Z→ee and Z→μμ events)
  - Proposed as luminosity monitor at the LHC



- Involved in searches for new physics
  (signal and background)

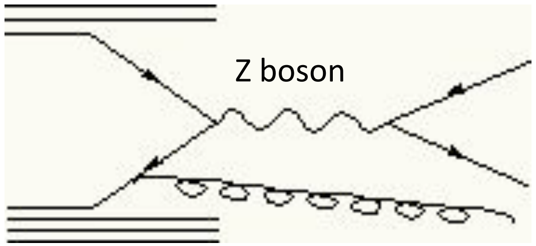


Theoretical predictions for total cross section

- QCD corrections up to NNLO in α_s :
  - R. Hamberg, W. L. van Neerven and T. Matsuura, Nucl. Phys. B 359 (1991)
  - R. V. Harlander and W. B. Kilgore, P [arXiv:hep-ph/0201206]
- Fully exclusive NNLO calculation, including leptonic decay:
  - S. Catani, L. Cieri, G. Ferrera, D. de Florian, M. Grazzini (12 Mar 2009) [arXiv:0903.2120]
  - K. Melnikov and F. Petriello [arXiv:hep-ph/0603182], [arXiv:hep-ph/0609070]
- Electroweak corrections up to $O(\alpha)$

Q_T spectrum

- Precise determinations of e.g. W & top quark masses
- Initial state radiation
- Used to constrain (universal) non-perturbative physics, like intrinsic k_T



Shortage

Q_T is highly sensitive to experimental systematics

- lepton p_T resolution
- event selection efficiency

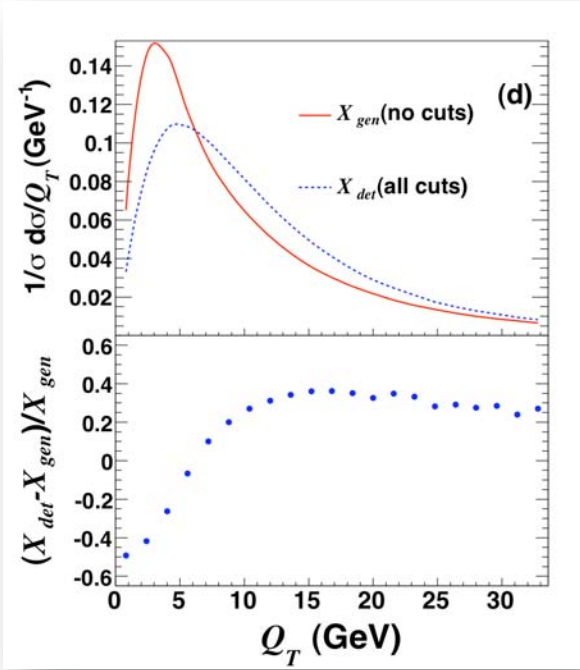


Figure (M.Vesterinen,T.R.Wyatt, [hep-ex:0807.4956]):
Gaussian smearing in $1/p_T$ and
selection cut applied to detector signal

Low Q_T region not much better measured in
1 fb^{-1} Run II than in 100 pb^{-1} Run I analysis at DØ.
Comparable uncertainties for non-perturbative parameters
[DØ Collaboration, Phys. Rev. L. 100, 102002 (2008)]

Intrinsic k_T

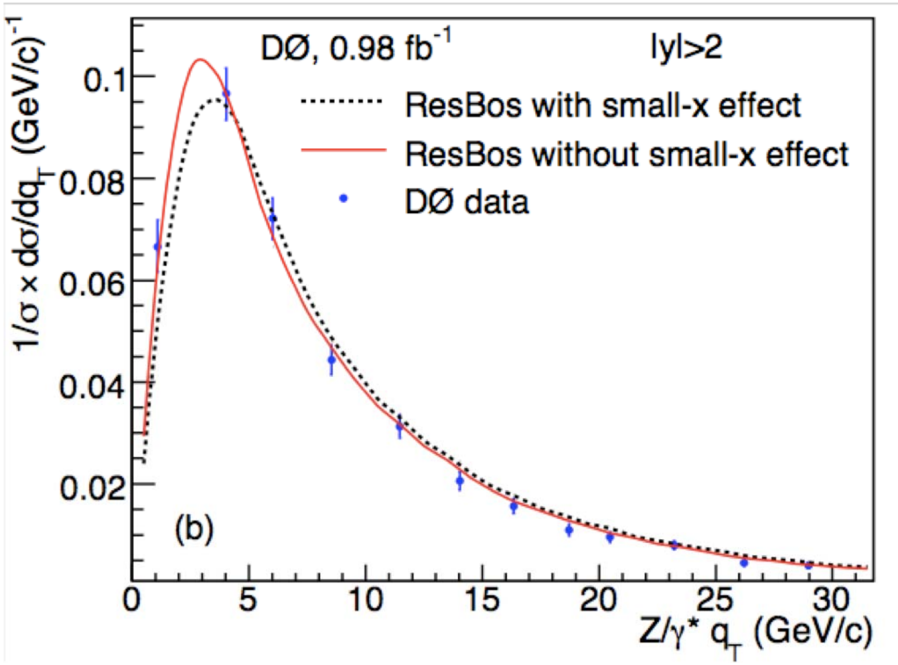
Parametrized with BLNY form factor [Brock, Landry, Nadolsky and Yuan, Phys. Rev. D 67, 073016]

Small-x broadening:

- DIS: Q_T broadening observed at HERA in the small x region: x = 10^{-4} – 10^{-2}
- Parametrized with extra factor

$$\rho(x) = c_0 \left(\sqrt{1/x^2 + 1/x_0^2} - 1/x_0 \right)$$

- If present in weak boson production: Q_T spectrum (& measurements of W mass and width) strongly affected [Berge et al. arXiv:hep-ph/0508215]



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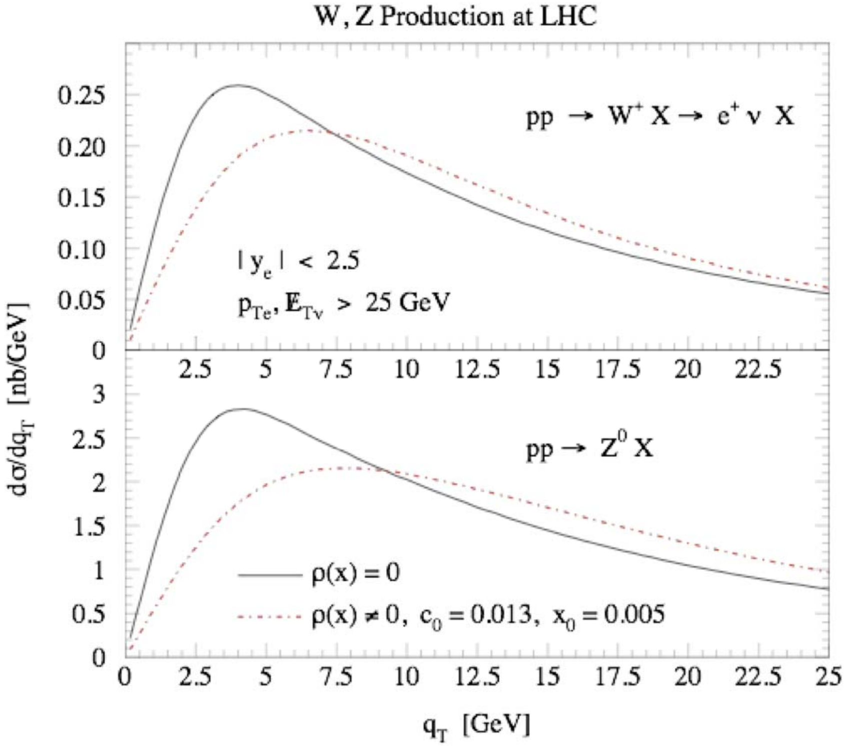

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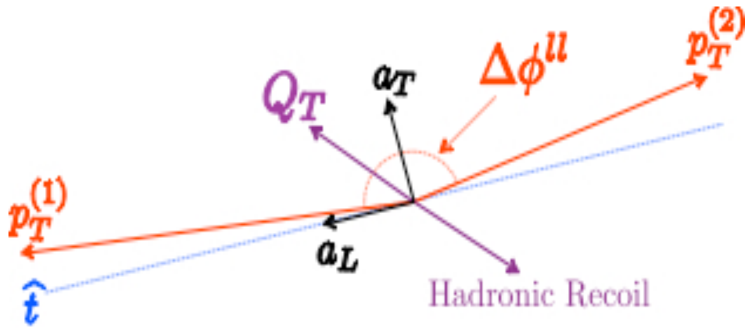
a_T definition

[M. Vesterinen, T.R. Wyatt, hep-ex: 0807.4956]



Keep in mind that collider detectors generally have far better angular resolution than p_T resolution

a_T :

$$a_T = |\vec{Q}_T \times \hat{t}|$$

component of Q_T perpendicular to the thrust axis

$$\hat{t} = \frac{\vec{p}_T^{\,(1)} - \vec{p}_T^{\,(2)}}{|\vec{p}_T^{\,(1)} - \vec{p}_T^{\,(2)}|}$$

$$a_T \propto p_T^{(1)} p_T^{(2)} \sin \Delta\phi^{ll}$$
$$= p_T^{(1)} p_T^{(2)} \sin(\pi - \delta) = p_T^{(1)} p_T^{(2)} \sin \delta$$

$a_T \propto (\pi - \Delta\phi_{ll})$: related to azimuthal correlation

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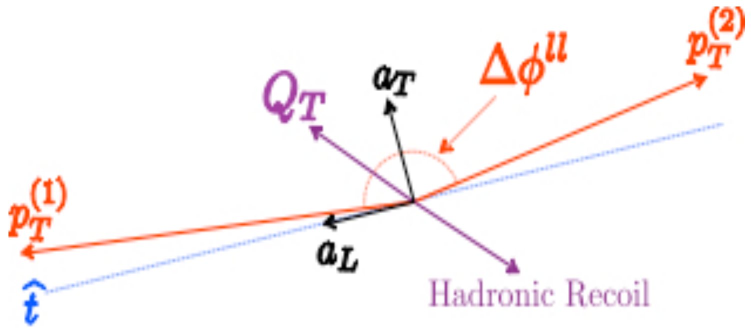

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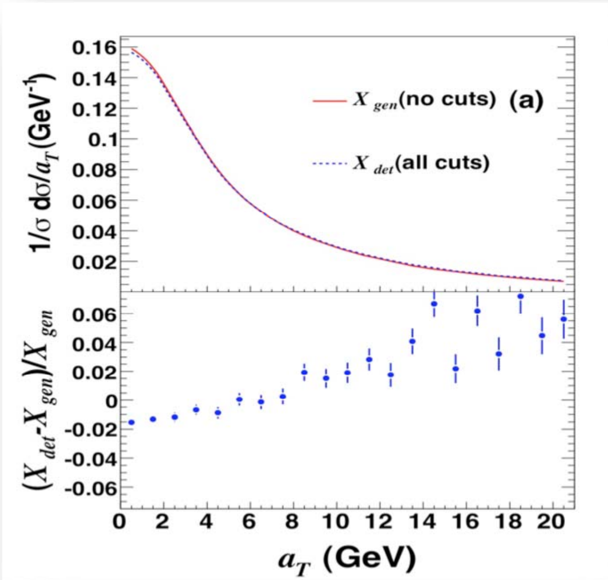
a_T is substantially less sensitive to experimental systematics than Q_T →

- will help us better constrain non-perturbative effects
- interesting variable for the tuning of MC event generators



Theoretical study of the a_T distribution

Aim:

NLL resummation in $L(a_T/Q)$ + NLO prediction

Soft gluon resummation

Region where $Q_T^2 \sim Q^2$, Q^2 being the invariant mass of the leptons:

fixed-order calculations are theoretically justified

When $Q_T^2 \ll Q^2$:

convergence of the QCD perturbative series is spoiled.

Large logarithms terms appeared in the Q_T distribution

To obtain reliable predictions, these terms have to be resummed to all orders in α_s

$$\frac{\alpha_s^n}{Q_T^2} \ln^m \left(\frac{Q^2}{Q_T^2} \right)$$

E.g. *Drell-Yan LO QCD corrections:* $$\frac{d\sigma}{dQ_T} \propto \alpha_s \left[A \cdot \frac{\log Q^2/Q_T^2}{Q_T^2} + B \cdot \frac{1}{Q_T^2} + C(Q_T^2) \right]$$

Does this mean that $\lim_{Q_T \to 0} \frac{d\sigma}{dQ_T} = \infty$?

Wrong. Higher order terms are needed. The leading contributions ‘resum’ to

$$\frac{d\sigma}{dQ_T^2} \approx \frac{\sigma}{Q_T^2} \left[A_1 \alpha_s \log \frac{Q^2}{Q_T^2} + A_2 \alpha_s^2 \log^3 \frac{Q^2}{Q_T^2} + ... + A_n \alpha_s^n \log^{2n-1} \frac{Q^2}{Q_T^2} + ... \right] \approx \sigma \frac{d}{dQ_T^2} \exp \left(-\frac{\alpha_s}{2\pi} C_F \log^2 \frac{Q^2}{Q_T^2} \right)$$

Theoretical study of the a_T distribution

- Integrated cross-section

$$\Sigma_N(a_T) = \int \tau^N d\tau \int_0^{a_T} da'_T \frac{d\sigma}{da'_T}$$

Independent emission approximation, valid to NLL accuracy (probability of emission of soft gluons is merely the product of single gluon emission probabilities):

$$\Sigma_N(a_T) = \Sigma_0(N) \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int_0^{1-k_t/Q} dz\ 2C_F \frac{\alpha_s(k_{ti}^2)}{2\pi} \left(\frac{1+z_i^2}{1-z_i}\right) \frac{dk_{t_i}^2}{k_{ti}^2} \frac{d\phi_i}{2\pi} \times$$
$$\times \left[z_i^{N-1} \Theta\left(|a_T| - \left| \sum_i k_{ti} \sin\phi_i \right| \right) - 1 \right]$$

Fourier representation of the step function:

$$\Theta\left(|a_T| - |\sum_i v(k_i)| \right) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{db}{b} \sin(b a_T) \prod_i e^{ibv(k_i)}$$

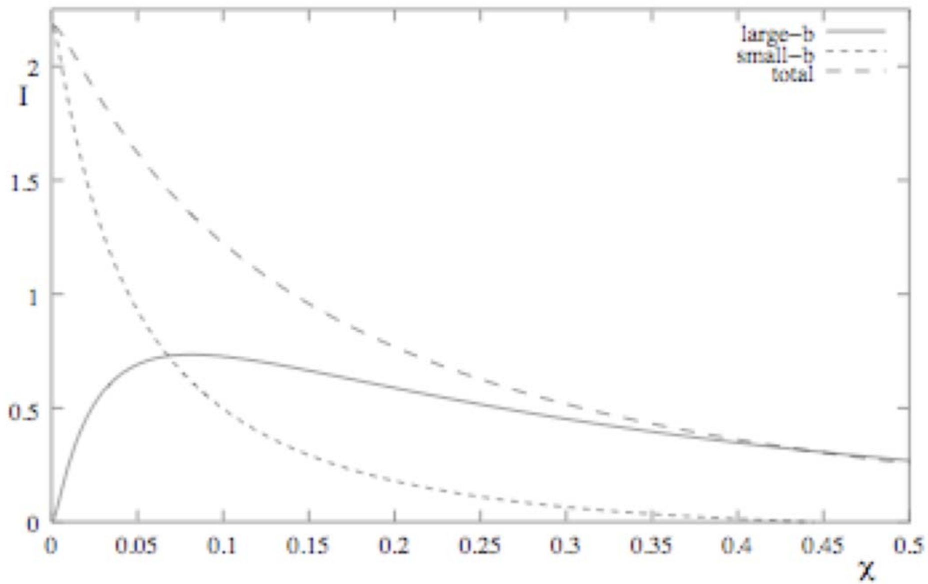
Theoretical study of the a_T distribution

- Resummation results

$$\Sigma_N(a_T) = \Sigma_0 \frac{2}{\pi} \int_0^\infty \frac{db}{b} \sin(b a_T) e^{-R(b)}$$

→ *no Sudakov peak*

← Different to Q_T



[Banfi and Smye, arXiv:hep-ph/0203150]

Theoretical study of the a_T distribution

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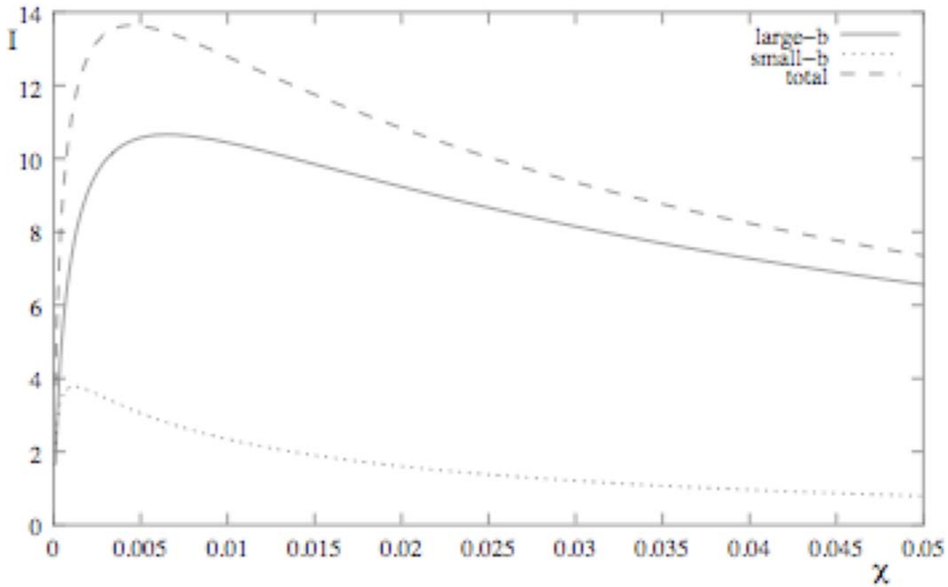

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Theoretical study of the a_T distribution

- Resummation results

$$\Sigma_N(a_T) = \Sigma_0 \frac{2}{\pi} \int_0^\infty \frac{db}{b} \sin(ba_T) e^{-R(b)}$$

where the ‘radiator’:

$$-R(b) = \int_0^{1-k_t/Q} dz\ 2C_F \frac{\alpha_s(k_t^2)}{2\pi} \left(\frac{1+z^2}{1-z}\right) \frac{dk_t^2}{k_t^2} \frac{d\phi}{2\pi} \left(z^{N-1} e^{ib(k_t \sin\phi)} - 1\right)$$

Radiator up to single-logarithmic accuracy, following the customary procedure (introducing anomalous dimension matrix and performing the z integration):

$$R(\bar{b}) = 2C_F \int_0^{2\pi} \frac{d\phi}{2\pi} \int_0^{M^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s(k_t^2)}{2\pi} \theta\left(k_t|\sin\phi| - \frac{1}{\bar{b}}\right) \left(2\ln\frac{M}{k_t} - \frac{3}{2} + \frac{\gamma_{qq}(N)}{C_F}\right) + \mathcal{O}\left(\frac{k_t}{Q}\right)$$

with $\bar{b} = be^{\gamma_E}$

Additional single-logarithmic contribution not present in the Q_T resummation

Theoretical study of the a_T distribution

- **Resummation results** (with running coupling, MS scheme)

$$R(\bar{b}) = Lg_1(\alpha_s L) + g_2'(\alpha_s L) \qquad L \equiv \ln\left(\bar{b}^2 Q^2\right)$$

$$g_1(\lambda) = \frac{C_F}{\pi \beta_0 \lambda}\left[-\lambda - \ln\left(1-\lambda\right)\right] \qquad \lambda = \beta_0 \alpha_s(Q^2) L$$

In order to deal with the Φ dependence to NLL accuracy we expand the radiator:

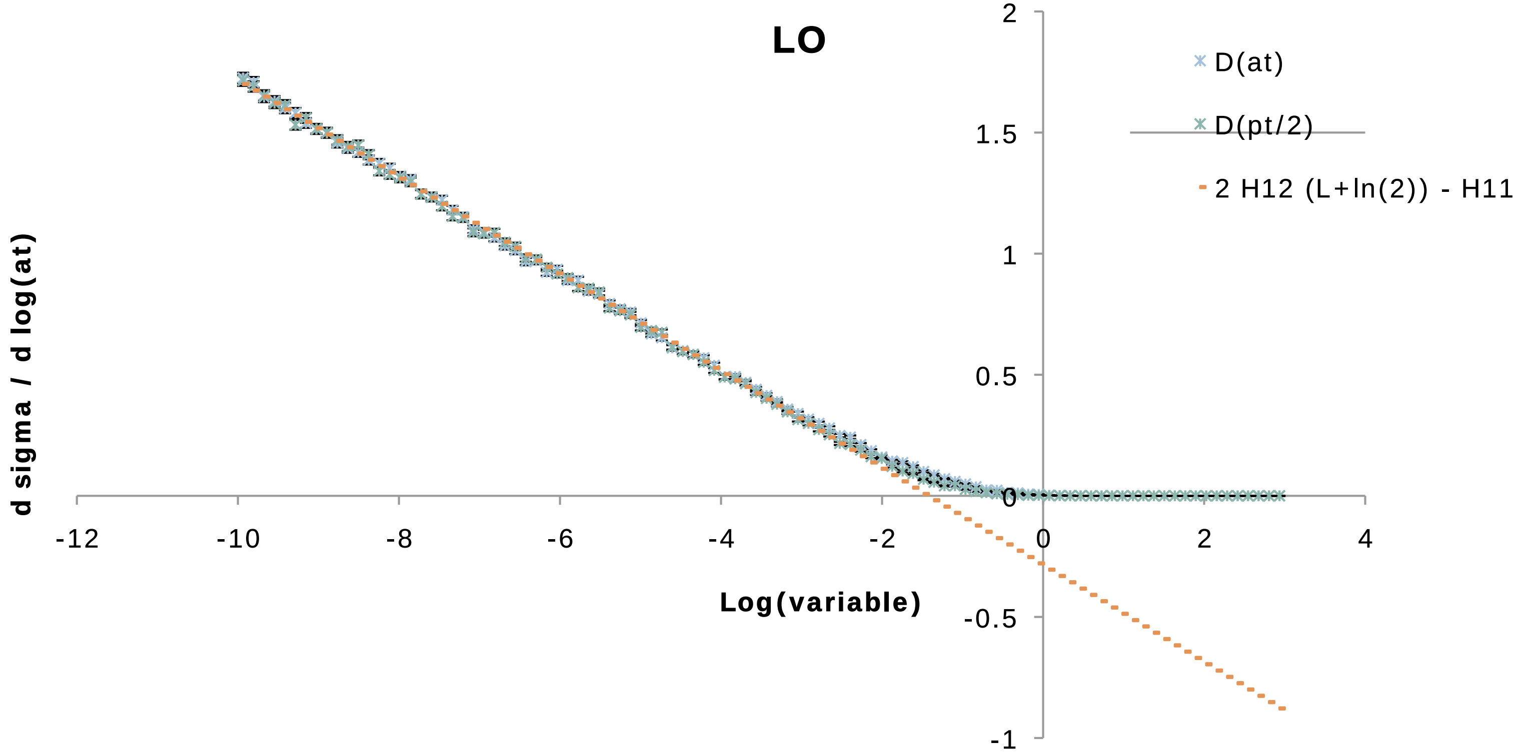
$$R(\bar{b}) = R(\bar{b})_{Q_T} + \frac{\partial R(\bar{b})}{\partial \ln \bar{b} Q} \int_0^{2\pi} \frac{d\phi}{2\pi} \ln|\sin\phi| + \cdots$$

$$R(\bar{b}) \approx R(\bar{b})_{Q_T} - \frac{2C_F}{\pi\beta_0}\frac{\lambda}{1-\lambda}\ln 2 \approx R(\bar{b}/2)_{Q_T}$$

additional single-logarithmic term in g_2

Simulated LO differential a_T distribution

- Resummation expanded to fixed order, compared with MCFM



Simulated LO integrated a_T distribution

- Relationship between $C_1(a_T)$ and $C_1(Q_T)$:

Extra constant term coming from resummation in $L(a_T/Q)$ wrt resummation in $L(Q_T/Q)$.

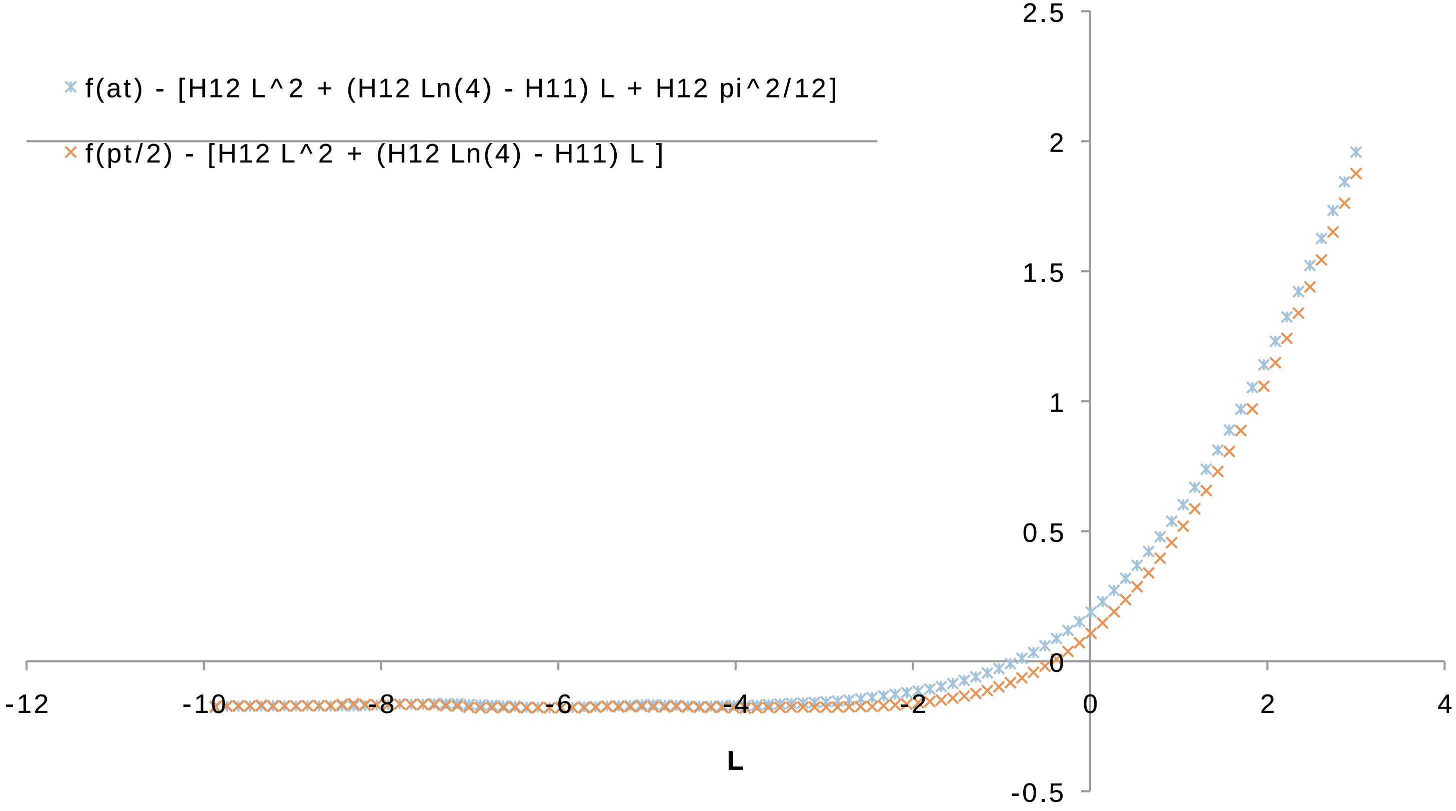
Integrated distribution to first approximation:

$$\Sigma(a_T) \approx -R(a_T) - \frac{\partial R(a_T)}{\partial \ln a_T Q} \int_0^{2\pi} \frac{d\phi}{2\pi} \ln|\sin\phi| - \frac{1}{2}\frac{\partial^2 R(a_T)}{\partial(\ln a_T Q)^2} \int_0^{2\pi} \frac{d\phi}{2\pi} (\ln|\sin\phi|)^2$$

$$-\frac{1}{2}\frac{\partial^2 R(a_T)}{\partial(\ln a_T Q)^2} \int_0^{2\pi} \frac{d\phi}{2\pi} (\ln|\sin\phi|)^2 = -4C_F\frac{\alpha_s}{2\pi}\left(\frac{\pi^2}{12} + (\ln 2)^2\right)$$

Simulated LO integrated a_T distribution

- LO integrated distribution – (integrated) expansion of resummation



Conclusions

- Novel variable a_T (component of Q_T transverse to the di-lepton thrust axis) is substantially less sensitive than Q_T to the dominant experimental systematics
- This improved experimental accuracy will help us to better constrain non-perturbative effects like intrinsic k_T (and to answer questions about the potential x dependence of the intrinsic k_T, *small-x broadening*)

- We have performed a NLL resummation in $L(a_T/Q)$ and checked its expansion to fixed order predictions

- Matching to NLO MCFM is work in progress
- Future work will involve applying models for the intrinsic k_T and comparing directly to Tevatron data