

The Z boson a_T distribution

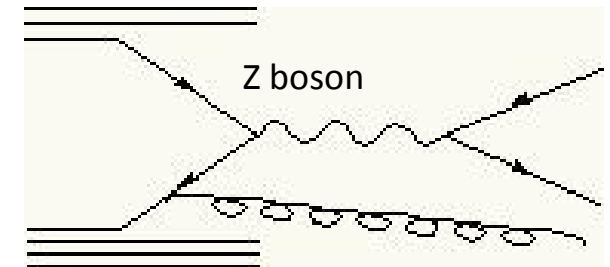
a_T : novel variable to study low transverse momentum vector boson production at hadron colliders.

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Weak boson production at hadron colliders

1

- Large production rate + clean signal → 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

2

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

□ Shortage

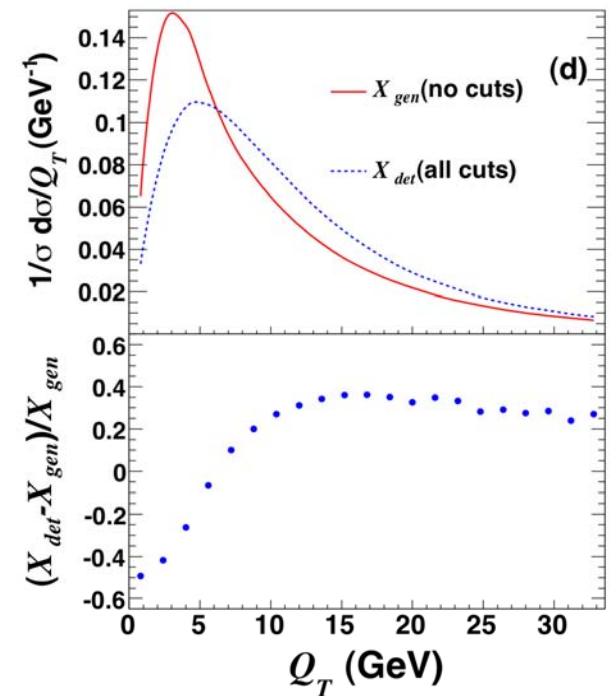
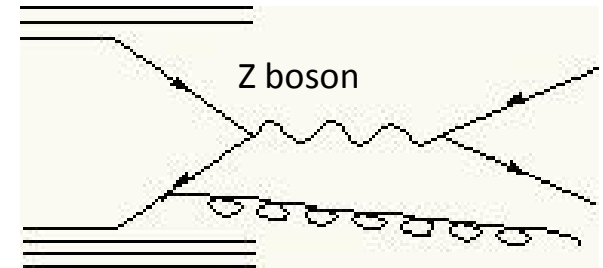
Q_T is highly sensitive to experimental systematics

- 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]



a_T definition

3

[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 :
component of Q_T perpendicular to the thrust axis

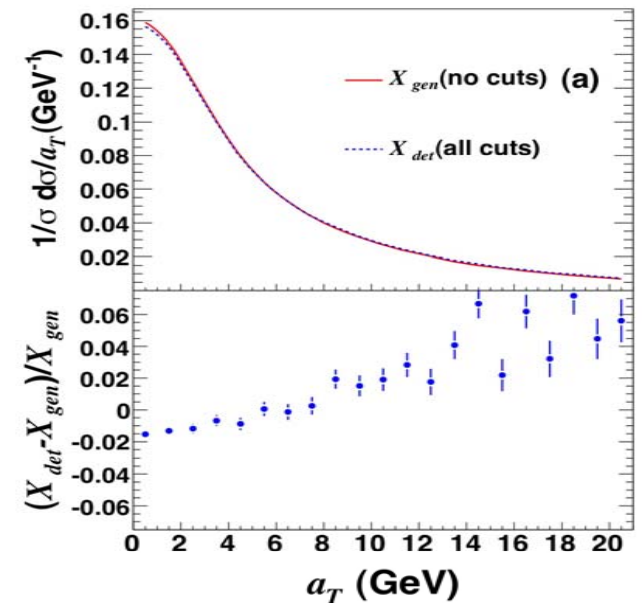
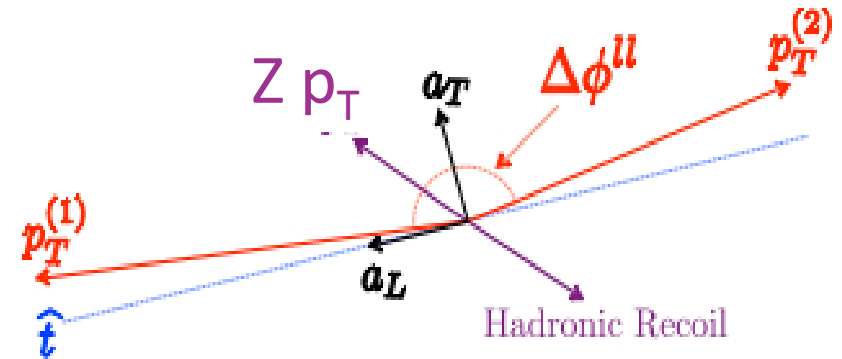
$$\hat{t} = \frac{\vec{p}_T^{(1)} - \vec{p}_T^{(2)}}{|\vec{p}_T^{(1)} - \vec{p}_T^{(2)}|}$$

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

$$= p_T^{(1)} p_T^{(2)} \sin(\pi - \delta) = p_T^{(1)} p_T^{(2)} \sin \delta$$

a_T is substantially less sensitive to experimental systematics than $Q_T \rightarrow$

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



Soft gluon resummation

4

Region where $Q_T \sim m_V$, m_V being the mass of the vector boson:
fixed-order calculations are theoretically justified

When $Q_T \ll m_V$:

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*: $\frac{d\sigma}{dp_T} \propto \alpha_s \left[A \cdot \frac{\log M_Z^2/p_T^2}{p_T^2} + B \cdot \frac{1}{p_T^2} + C(p_T^2) \right]$

Does this mean that $\lim_{p_T \rightarrow 0} \frac{d\sigma}{dp_T} = \infty$?

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

$$\frac{d\sigma}{dp_T^2} \approx \frac{\sigma}{p_T^2} \left[A_1 \alpha_s \log \frac{M_Z^2}{p_T^2} + A_2 \alpha_s^2 \log^3 \frac{M_Z^2}{p_T^2} + \dots + A_n \alpha_s^n \log^{2n-1} \frac{M_Z^2}{p_T^2} + \dots \right] \approx \sigma \frac{d}{dp_T^2} \exp \left(-\frac{\alpha_s}{2\pi} C_F \log^2 \frac{M_Z^2}{p_T^2} \right)$$

Theoretical study of the a_T distribution

5

- integrated cross-section

$$\Sigma_N(a_T) = \int_0^{a_T} da'_T \frac{d^2\sigma}{da'_T dQ^2 d\phi} \tau^N d\tau$$

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

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

Fourier representation of the step function:

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

Theoretical study of the a_T distribution

6

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 integrations):

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

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

Additional single-logarithmic contribution not present in the Q_T resummation

Theoretical study of the a_T distribution

7

- Resummation results (with running coupling, MS scheme)

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

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

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

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

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

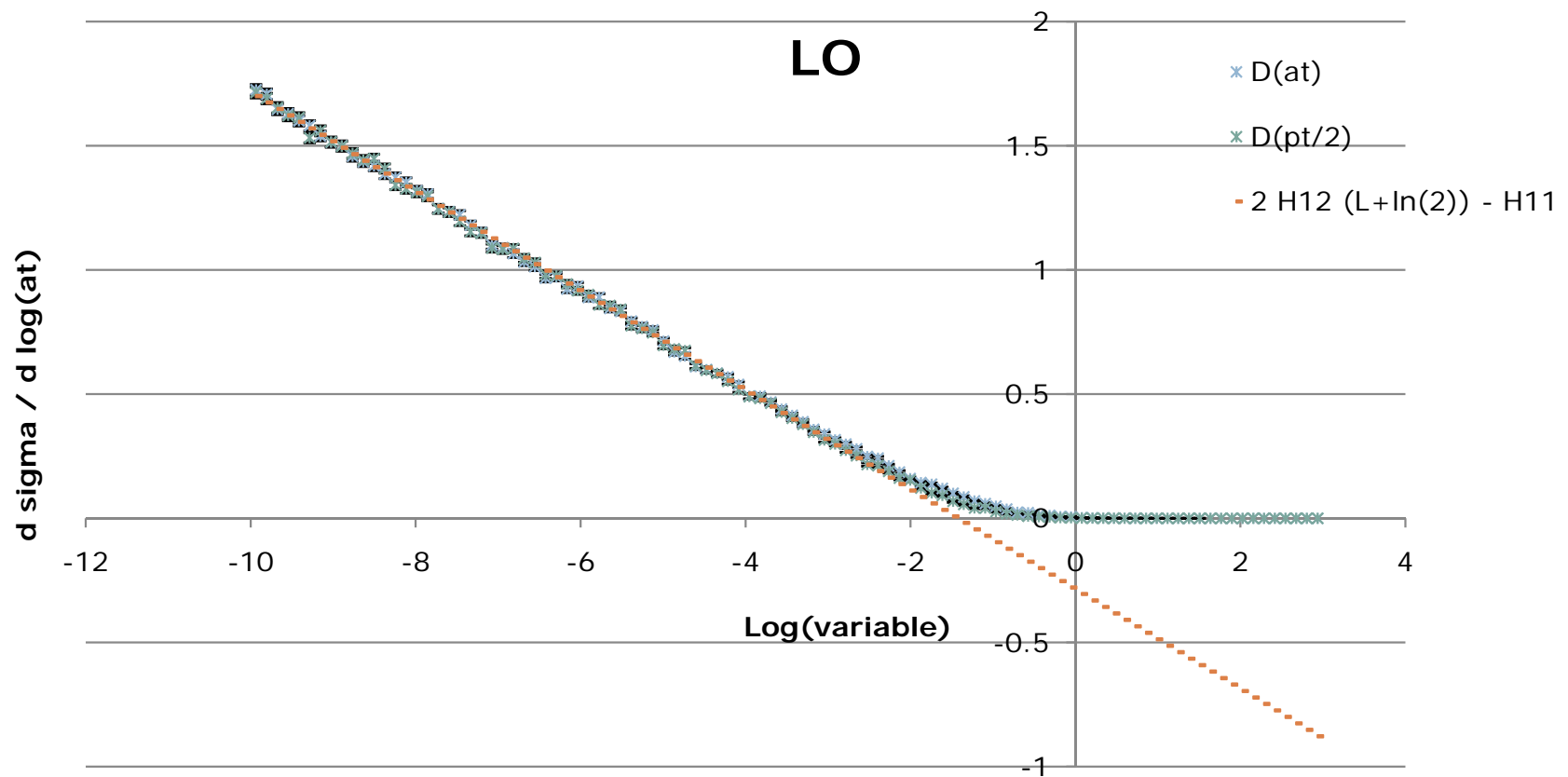


additional single-logarithmic term in g_2

Simulated LO differential a_T distribution

8

- Resummation expanded to fixed order, compared with MCFM



Simulated LO integrated a_T distribution

9

- 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 $L(Q_T/Q)$.

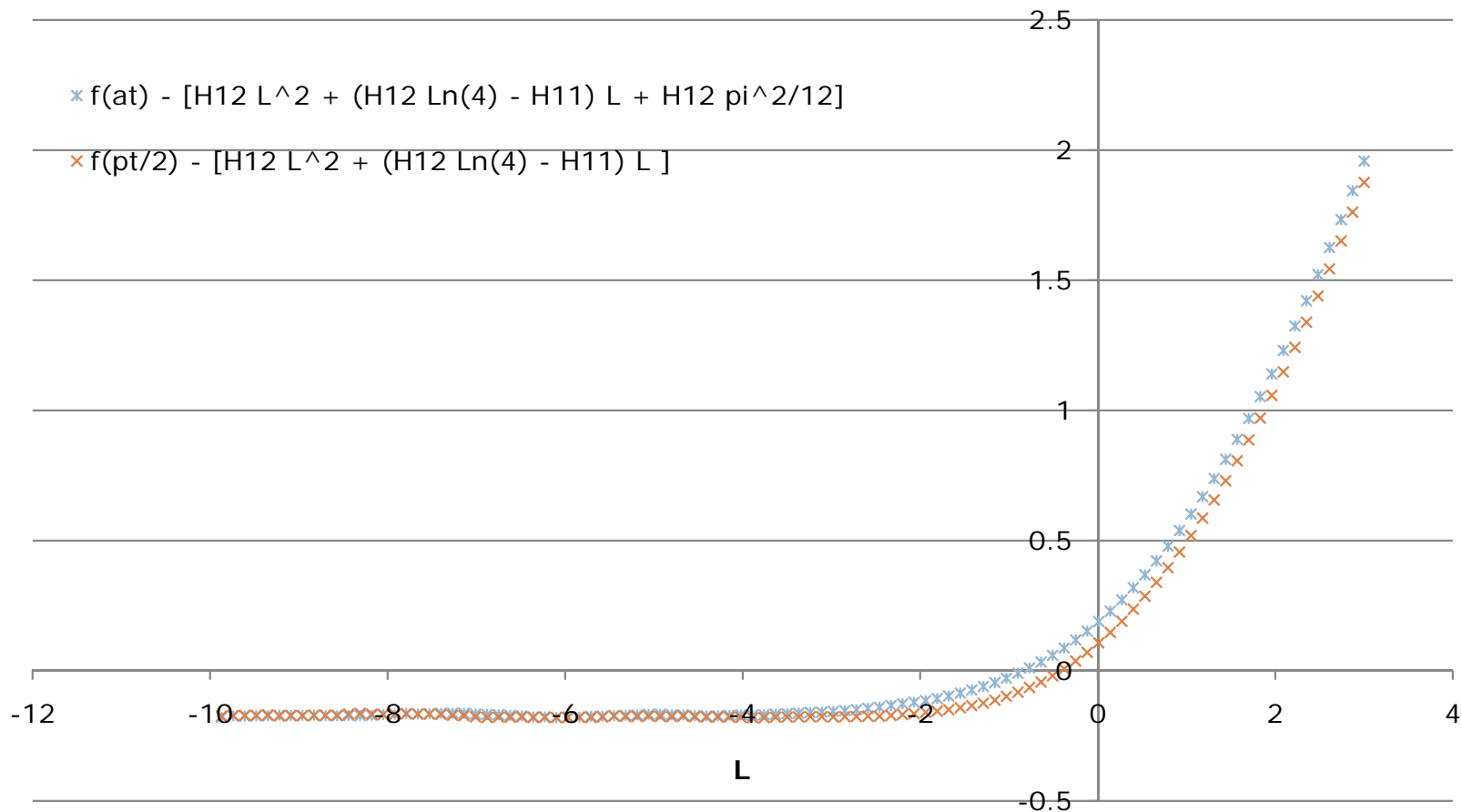
Integrated distribution to first approximation:

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

Simulated LO integrated a_T distribution

10

- LO integrated distribution – (integrated) expansion of resummation



Conclusions

11

- 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*)
- Interesting variable also for the tuning of Monte Carlo event generators

- 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