QCD and collider physics IV: W/Z and high pt jet production

H. Jung (DESY)

- W & Z xsection
  - resume from last lecture
  - W/Z small pt: resummation
  - qt-resummed PDFs: latest news from DIS 2007
  - Applications for LHC
- Jet production
  - kinematics & cross sections
  - underlying events & multiparton scattering

http://www-h1.desy.de/~jung/qcd_collider_physics_sose_2007

W/Z production

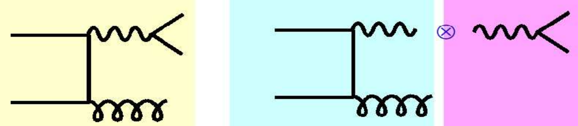
Factorizing x-section

Fred Olness, CTEQ
summerschool 2003

Side Note: From $pp\to\gamma/Z/W$, we can obtain $pp\to\gamma/Z/W\to l^+l^-$

Schematically:

$$d\sigma(q\bar{q}\to l^+ l^- g) = d\sigma(q\bar{q}\to\gamma^* g) \times d\sigma(\gamma^*\to l^+ l^-)$$



For example:

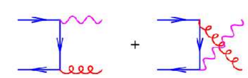
$$\frac{d\sigma}{dQ^2\, d\hat{t}}(q\bar{q}\to l^+ l^- g) = \frac{d\sigma}{d\hat{t}}(q\bar{q}\to\gamma^* g) \times \frac{\alpha}{3\pi Q^2}$$

➔ it works also for pQCD processes .....

QCD corrections for Drell-Yan

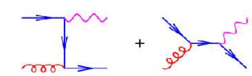
K. Ellis, LHC lecture,
http://theory.fnal.gov/people/ellis/Talks

- Calculate annihilation process
  $q+\bar{q}\to\gamma^*+g$



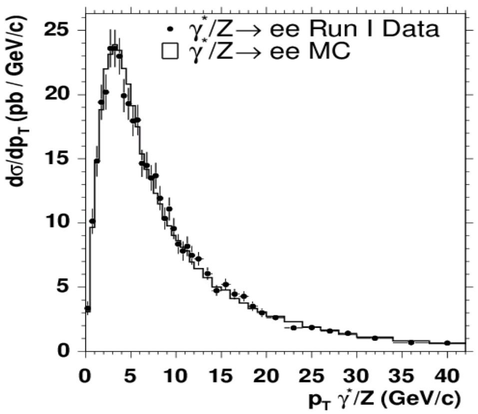
$$\begin{aligned}|M|^2 &= 16\pi^2\alpha_s\alpha\frac{8}{9}\left[\frac{\hat{u}}{\hat{t}}+\frac{\hat{t}}{\hat{u}}+\frac{2(M^2\hat{s})}{\hat{u}\hat{t}}\right]\\ &= 16\pi^2\alpha_s\alpha\frac{8}{9}\left[\left(\frac{1+z^2}{1-z}\right)\right.\\ &\qquad\left.\times\left(\frac{-s}{t}+\frac{-s}{u}-2\right)\right]\\ &= 16\pi^2\alpha_s\alpha\frac{8}{9}\left[P_{qq}(z)\right.\\ &\qquad\left.\times\left(\frac{-s}{t}+\frac{-s}{u}-2\right)\right]\end{aligned}$$

- Calculate QCDC process
  $q+g\to\gamma^*+q$



$$\begin{aligned}|M|^2 &= 16\pi^2\alpha_s\alpha\frac{1}{3}\left[-\frac{\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}-\frac{2(M^2\hat{u})}{\hat{s}\hat{t}}\right]\\ &= 16\pi^2\alpha_s\alpha\frac{1}{3}\left[(z^2+(1+z)^2)\times\cdots\right)\\ &= 16\pi^2\alpha_s\alpha\frac{1}{3}\left[P_{qg}(z)\times\cdots\right)\end{aligned}$$

Transverse Momentum of W/Z

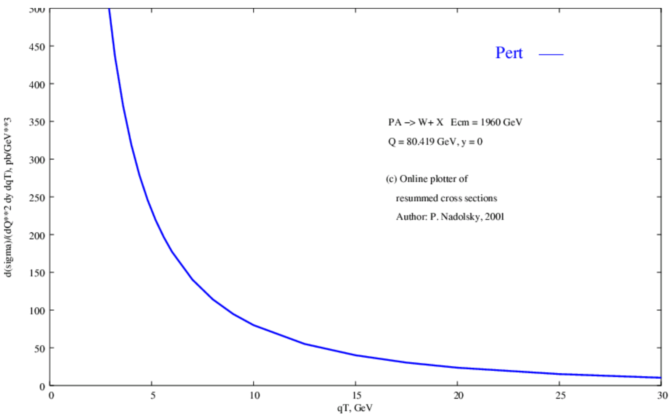


Measurements of Inclusive W and Z Cross Sections in p anti-p Collisions at s**(1/2) = 1.96 TeV
CDF Collaboration,Resubmitted to Phys. Rev. D July 3, 2006.

FIG. 12: Tuned PYTHIA 6.21 $d\sigma/dp_T$ in pb per GeV/c (on average) of $\gamma^*/Z \to ee$ pairs in the mass region 66 GeV/c^2 < M_{ee} < 116GeV/c^2 (histogram) versus the measurement made by CDF in Run I (points).

Transverse Momentum of W/Z

Perturbative calculation $\mathcal{O}(\alpha_s)$, $\mathcal{O}(\alpha_s^2)$ diverges for small p_t

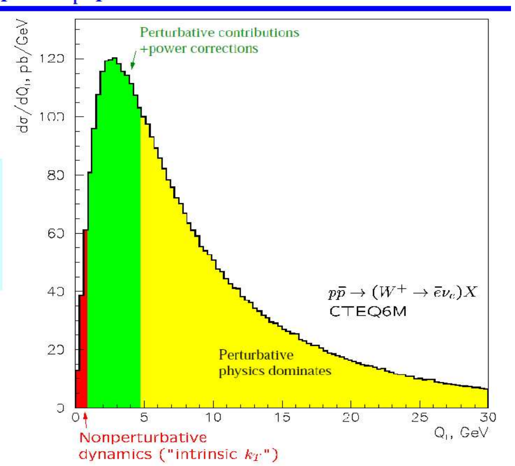


Transverse Momentum of W/Z

The complete P_T spectrum for the W boson

Fred Olness, CTEQ summerschool 2003

The full P_T spectrum for the W-boson showing the different theoretical regions



What happens at small p_t ?

- taking the limit of small p_t:

$$\begin{aligned}\frac{d\sigma}{dM^2 dy dp_t^2} &= \frac{8}{27}\frac{\alpha^2\alpha_s}{sM^2}\frac{1}{p_T^2}\int_{x_a^{min}}^1 dx_a H_q(x_a,x_b,M^2) \\ & \quad \frac{1}{x_a - x_1}\left(1+\frac{\tau^2}{(x_a x_b)^2} - \frac{x_T^2}{2x_a x_b}\right) \\ &\sim \frac{8}{27}\frac{\alpha^2\alpha_s}{sM^2}\frac{2}{p_T^2} H_q(x_a,x_b,M^2)\log\frac{s}{p_t^2} \\ &= \left(\frac{d\sigma}{dM^2 dy}\right)_{Born} \times \left(\frac{4\alpha_s}{3\pi}\frac{1}{p_t^2}\log\frac{s}{p_t^2}\right)\end{aligned}$$

- with $\left(\frac{d\sigma}{dM^2 dy}\right)_{Born} = \frac{4\pi\alpha^2}{9sM^2} H_q(x_a,x_b,M^2)$

➔ cross section diverges as for p_t-> 0: $\frac{\log\frac{s}{p_t^2}}{p_t^2}$

Small pt x-section

- x-section at small pt
$$\frac{d\sigma}{dM^2 dy dp_t^2} \sim \frac{8}{27}\frac{\alpha^2\alpha_s}{sM^2}\frac{2}{p_T^2}H_q(x_a,x_b,M^2)\log\frac{s}{p_t^2}$$
$$= \left(\frac{d\sigma}{dM^2 dy}\right)_{Born} \times \left(\frac{4\alpha_s}{3\pi}\frac{1}{p_t^2}\log\frac{s}{p_t^2}\right)$$
- with
$$\left(\frac{d\sigma}{dM^2 dy}\right)_{Born} = \frac{4\pi\alpha^2}{9sM^2}H_q(x_a,x_b,M^2)$$
- from previous we know, that integral over p_t^2 is finite:
$$\int_0^s \frac{d\sigma}{dM^2 dy dp_t^2} = \left(\frac{d\sigma}{dM^2 dy}\right) + \mathcal{O}(\alpha_s)$$

➔ which gives
$$\int_0^{p_t^2}\frac{d\sigma}{dM^2 dy dp_t^2} = \left(\frac{d\sigma}{dM^2 dy}\right)_{Born}\left[1 - \int_{p_t^2}^s \frac{4\alpha_s}{3\pi}\frac{\log s/p_t^2}{p_t^2}dp_t^2\right]$$
$$= \left(\frac{d\sigma}{dM^2 dy}\right)_{Born}\left[1 - \frac{2\alpha_s}{3\pi}\log^2 s/p_t^2\right]$$

All order resummation - kinematics

Ellis, Fleishon,Stirling, PRD 24,1386 (1981)

- impose kinematic constraints ... delta function for k_t
$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim \prod_{i=1}^{N}\left[\int d^2k_{ti}dx_i M^{(N)}\right]\delta\left(\sum \vec{k}_{ti} + \vec{p}_t\right)$$

with for soft gluons $M^{(N)} \sim \prod \frac{\alpha_s}{k_{ti}^2}$

$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim \prod_{i=1}^{N}\left[\int \frac{d^2k_{ti}}{k_{ti}^2}\log\frac{s}{k_{ti}^2}\right]\delta\left(\sum \vec{k}_{ti} + \vec{p}_t\right)$$

➔ in limit of strong ordering:

$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim p_t^2 \log\frac{s}{p_t^2}\int\frac{d^2k_{t,N-1}}{k_{t,N-1}^2}\log\frac{s}{k_{t,N-1}^2}\int\frac{d^2k_{t,N-2}}{k_{t,N-2}^2}\log\frac{s}{k_{t,N-2}^2}\cdots$$

All order resummation

- Iterative procedure:

$$\frac{d\sigma^{(1)}}{dp_t^2} \simeq \frac{1}{p_t^2}\log\frac{s}{p_t^2} = A$$

$$\frac{d\sigma^{(2)}}{dp_t^2} \simeq A\int\frac{d^2k_t}{k_t^2}\log\frac{s}{k_t^2} = A\frac{1}{2}\log^2\frac{s}{k_t^2}$$

$$\frac{d\sigma^{(3)}}{dp_t^2} \simeq \int\frac{d^2k_t}{k_t^2}\log\frac{s}{k_t^2}\frac{d\sigma^{(2)}}{dp_t^2} = A\frac{1}{2}\int\frac{d^2k_t}{k_t^2}\log^3\frac{s}{k_t^2} = A\frac{1}{2}\left(\frac{1}{2}\log^2\frac{s}{k_t^2}\right)^2$$

$$\frac{d\sigma^{(4)}}{dp_t^2} \simeq \int\frac{d^2k_t}{k_t^2}\log\frac{s}{k_t^2}\frac{d\sigma^{(3)}}{dp_t^2} = A\frac{1}{2}\frac{1}{4}\int\frac{d^2k_t}{k_t^2}\log^5\frac{s}{k_t^2} = A\frac{1}{2}\frac{1}{3}\left(\frac{1}{2}\log^2\frac{s}{k_t^2}\right)^3$$

$$\frac{d\sigma^{(N)}}{dp_t^2} \simeq A\frac{1}{(N-1)!}\left(\frac{1}{2}\log^2\frac{s}{k_t^2}\right)^{N-1}$$

- x-section for up to N gluons:

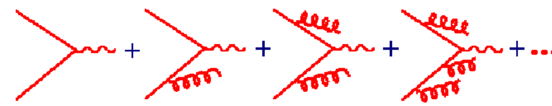
$$\frac{d\sigma}{dp_t^2} = \sum_i\frac{d\sigma^{(i)}}{dp_t^2} \simeq A\sum_i\frac{1}{(i-1)!}\left(\frac{1}{2}\log^2\frac{s}{p_t^2}\right)^{i-1}$$

$$\simeq A\exp\left[\frac{1}{2}\log^2\frac{s}{p_t^2}\right]$$

Resummation

C-P Yuan, CTEQ summerschool 2002

Diagramatically, Resummation is doing



➡ Resum large $\alpha_s^n \ln^m\left(\frac{Q^2}{q_T^2}\right)$ terms

$$\left.\frac{d\sigma}{dq_T^2 dy}\right|_{q_T\to 0} \sim \frac{1}{q_T^2}\sum_{n=1}^{\infty}\sum_{m=0}^{2n-1}\alpha_s^n \ln^m\left(\frac{Q^2}{q_T^2}\right)\cdot C_m^n$$

Monte-Carlo programs ISAJET, PYTHIA, HERWIG contain these physics.

small pt-resummation to all orders

- Result suggest series of logs...: $1 + a + \frac{a^2}{2!} + \frac{a^3}{3!} ... = \exp(a)$

$$\int_0^{p_t^2} \frac{d\sigma}{dM^2 dy dp_t^2} = \left(\frac{d\sigma}{dM^2 dy}\right)_{Born} \exp\left(-\frac{2\alpha_s}{3\pi} \log^2 s/p_t^2\right)$$

➔ differentiate wrt p_t^2:

$$\frac{d\sigma}{dM^2 dy dp_t^2} = \left(\frac{d\sigma}{dM^2 dy}\right)_{Born} \left(\frac{1}{p_t^2} \frac{4\alpha_s}{3\pi} \log s/p_t^2\right) \exp\left(-\frac{2\alpha_s}{3\pi} \log^2 s/p_t^2\right)$$

➔ Sudakov form factor appears

➔ expresses resummation of leading double logs

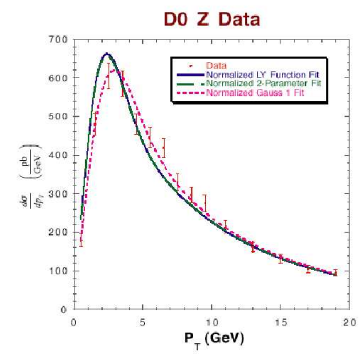
➔ exponential cancels singularity at pt -> 0

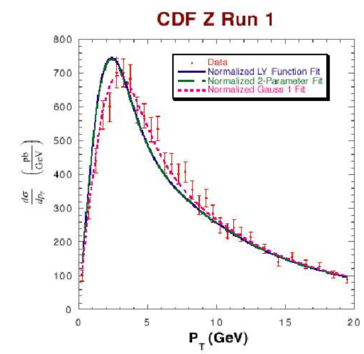
➔ **Probability to produce massive lepton pair (or Z_0, W etc) without additional soft gluon radiation is ZERO**

Transverse Momentum of W/Z

Fred Olness, CTEQ summerschool 2003

We'll look at Z data where we can measure both leptons for $Z \to e^+e^-$



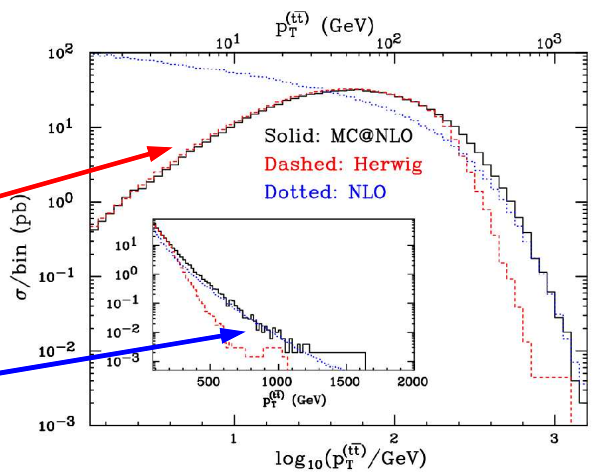


different $S_{NP}(b,Q)$ functions yield difference at small q_T.

Resummation in heavy quark prod.

Frixione et al, hep-ph/035252

- Compare fixed NLO calculation of top production with resummed calculation from Monte Carlo
- Similar effects at small pt are observed: Supression of xsection at small pt
- At large pt resummation is too small, NLO is better



All order resummation - kinematics

Ellis, Fleishon,Stirling, PRD 24,1386 (1981)

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$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim \prod_{i=1}^{N}\left[\int d^2k_{ti}dx_i M^{(N)}\right]\delta\left(\sum \vec{k}_{ti} + \vec{p}_t\right)$$

with for soft gluons $M^{(N)} \sim \prod \frac{\alpha_s}{k_{ti}^2}$

$$\frac{1}{\sigma}\frac{d\sigma^{(N)}}{dp_t^2} \sim \prod_{i=1}^{N}\int \frac{d^2k_{ti}}{k_{ti}^2}\log\frac{s}{k_{ti}^2}\delta\left(\sum k_{ti} + p_t\right)$$

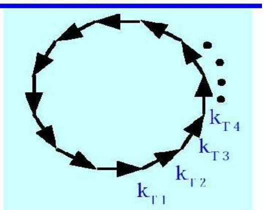
- relaxing strong ordering constraint -> keep delta function...
  - instead of nested integrals... integrals are coupled
- ➔ Collins Soper Sterman (CSS) formalism
  - ➔ implement energy momentum conservation by Fourier transform to b-space
  - ➔ obtain subleading corrections from energy-momentum conservation !

Kinematic constraints

Fred Olness, CTEQ
summerschool 2003

3) We assumed gluon emission was uncorrelated

$$\frac{d\sigma}{d\tau\, dy\, dp_T^2} \approx \frac{\ln s/p_T^2}{p_T^2} \times \exp\left\{ -\frac{2\alpha_s}{3\pi} \ln^2 \frac{s}{p_T^2} \right\}$$



This leads to too strong a suppression at $P_T=0$.
Need to impose momentum conservation for P_T.

A particle can receive finite k_T kicks, yet still have $P_T=0$

A convenient way to impose transverse momentum conservation is in impact parameter space (b-space) via the following relation:

$$\delta^{(2)}(\sum \vec{k}_{ti} - \vec{p}_t) = \frac{1}{(2\pi)^2} \int d^2 b \exp(-i\vec{b}\vec{p}_t) \prod \exp(i\vec{b}\vec{k}_{ti})$$

Resummation

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A Brief *(but incomplete)* History of Non-Perturbative Corrections

Original CSS: $S_{NP}^{CSS}(b) = h_1(b,\xi_a) + h_2(b,\xi_b) + h_3(b)\ln Q^2$

J. Collins and D. Soper, *Nucl.Phys.* **B193** 381 (1981);
erratum: **B213** 545 (1983); J. Collins, D. Soper, and G. Sterman, *Nucl. Phys.* **B250** 199 (1985).

Davies, Webber, and Stirling (DWS): $S_{NP}^{DWS}(b) = b^2[g_1 + g_2 \ln(b_{max} Q^2)]$

C. Davies and W.J. Stirling, Nucl. Phys. B244 337 (1984);
C. Davies, B. Webber, and W.J. Stirling, Nucl. Phys. B256 413 (1985).

Ladinsky and Yuan (LY): $S_{NP}^{LY}(b) = g_1 b\,[b + g_3 \ln(100\xi_a \xi_b)] + g_2 b^2 \ln(b_{max} Q)$

G.A. Ladinsky and C.P. Yuan, Phys. Rev. D50 4239 (1994);
F. Landry, R. Brock, G.A. Ladinsky, and C.P.Yuan, Phys. Rev. D63 013004 (2001).

"BLNY": $S_{NP}^{BLNY}(b) = b^2[g_1 + g_1 g_3 \ln(100\xi_a \xi_b) + g_2 \ln(b_{max} Q)]$

F. Landry, "Inclusion of Tevatron Z Data into Global Non-Perturbative QCD Fitting", Ph.D. Thesis, Michigan State University, 2001.
F. Landry, R. Brock, P. Nadolsky, and C.P.Yuan, PRD67, 073016 (2003)

"q_T resummation": $\mathcal{F}^{NP}(q_T) = 1 - e^{-a q_T^2}$ *(not in b-space)*

R.K. Ellis, Sinisa Veseli, Nucl.Phys. B511 (1998) 649-669
R.K. Ellis, D.A. Ross, S. Veseli, Nucl.Phys. B503 (1997) 309-338

Functional Extrapolation:

J. Qui, X. Zhang, PRD63, 114011 (2001); E. Berger, J. Qiu, PRD67, 034023 (2003)

Analytical Continuation:

A. Kulesza, G. Sterman, W. Vogelsang, PRD66, 014011 (2002)

Q_t - Resummation

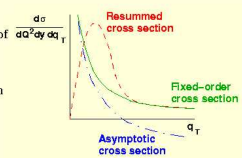
RESUMMED TRANSVERSE MOMENTUM DISTRIBUTIONS

go directly to the plotter

On this website, you can plot transverse momentum distributions for cross sections of several particle reactions. Currently, the following processes are implemented (p corresponds both to protons and antiprotons):

- Massive vector boson production: $pp \to W^{\pm}X$, $pp \to Z^0X$
- Photon pair production: $pp \to \gamma\gamma X$
- Z-boson pair production: $pp \to Z^0Z^0X$
- SM Higgs boson production $pp \to H^0X$

The output figure shows distributions $d\sigma/dQ^2dydq_T$ for the production of *on-shell* particles (or pairs of *on-shell* particles in the case of the $\gamma\gamma$ and ZZ production) with specified invariant mass Q, rapidity y and transverse momentum q_T in the lab frame (the center-of-mass frame of the hadron beams). You can plot resummed, fixed-order and asymptotic cross sections. For a short explanation of these quantities, visit **this page** (for a detailed explanation see, for instance, a paper by J.C. Collins, D.E. Soper and G. Sterman in Nucl. *Phys. B250, 199 (1985)).*



http://hep.pa.msu.edu/wwwlegacy/

All order resummation – kinematics II

Ellis, Fleishon,Stirling, PRD 24,1386 (1981)

- relaxing strong ordering constraint -> keep delta function...
  - instead of nested integrals... integrals are coupled
- ➔ Collins Soper Sterman (CSS) formalism
  - ➔ implement energy momentum conservation by Fourier transform to b-space .... obtain subleading corrections
- ➔ or alternative formalism in k_t space (Ellis, Veseli NPB511, 649 (1998))

$$\frac{d\sigma}{dM^2dydp_t^2} = \sum_q \sigma_0^{qq}\frac{d}{dp_t^2}\left([q(x_a,p_t)q(x_b,p_t)+a\leftrightarrow b]\right.$$
$$\left.\times\exp\left(-\int_{p_t^2}^{M^2}\frac{d\mu^2}{\mu^2}\left[A\log\left(M^2/\mu^2\right)+B\right]\right)\right)$$

- ➔ with coefficients from energy momentum conservation as in CSS: $A(\alpha_s), B(\alpha_s)$
- ➔ Now PDF are included, derivative of PDFs...
- ➔ $\frac{d}{dk_t^2}q(x,k_t) = uPDF$

Defining uPDFs

- start from integral equation of usual PDF (last semesters...):

$$f(x,q) = f(x,Q_0)\Delta_s(q) + \int \frac{dz}{z} \int \frac{d^2q'}{\pi q'^2} \cdot \frac{\Delta_s(q)}{\Delta_s(q')} \tilde{P}(z) f\left(\frac{x}{z}, q'\right)$$

- introduce unintegrated pdfs: $\mathcal{A}(x,k,q)$

$$x\mathcal{A}(x,k_t,q) = x\mathcal{A}_0(x,k_t)\Delta_s(q) + \int dz \int \frac{d^2q'}{\pi q'^2} \cdot \Delta_s(q, f(q')) \tilde{P}(z,q',k_t) \Theta(\mathcal{O}) \frac{x}{z} \mathcal{A}\left(\frac{x}{z}, k_t', q'\right)$$

define uPDF:

$$xg(x,Q) = \int \frac{d^2k_t}{\pi} x\mathcal{A}(x,k_t,Q)\Theta(Q-k_t)$$

- similar to integrated PDF ... but included explicitly dependence on transverse momentum k_t in addition to evolution scale q
- details are in the ordering constraints $f(q')$, $\Theta(\mathcal{O})$ and the splitting function ...

PDF fits including qt resummation I

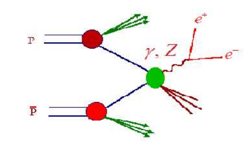
CP. Yuan, DIS2007

New from DIS07

New Task of Global Analysis

Include Transverse Momentum p_T distributions

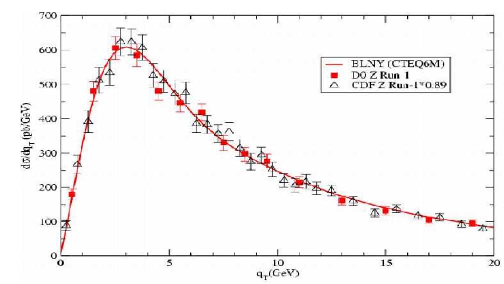
- New Data: include not only rapidity (y) but also p_T of Drell-Yan pairs and Z bosons



QCD P_T Resummation Global Analysis

hep-ph/0212159

Brock, Landry, Nadolsky, CPY



PDF fits including qt resummation II

New from DIS07

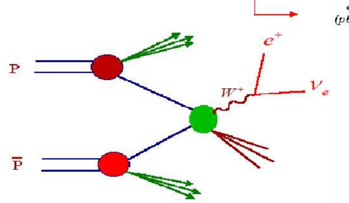
CP. Yuan, DIS2007

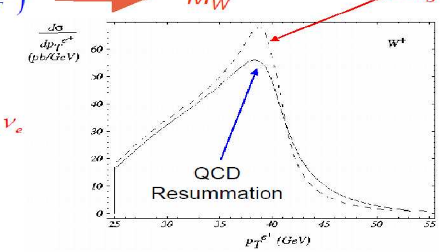
New Task of Global Analysis:

Include Transverse Momentum p_T distributions

- Better determine PDFs
- Better determine, for example, the mass of W boson M_W

Measuring $(y_e, p_T^e, m_T^{e\nu})$ → M_W





PDF fits including qt resummation III

New from DIS07

CP. Yuan, DIS2007

The need for combined PDF + P_T Fit

Example:

To precisely predict the rapidity distribution of the lepton from the W-boson decay,

ResBos prediction is needed.

- Lepton rapidity asymmetry is sensitive to quark PDFs
- Transverse momentum distributions in all P_T range can only be reliably predicted by resummation calcaultion.

→ Combined fit can further constrain the PDFs

PDF fits including qt resummation IV

CP. Yuan, DIS2007

New from DIS07

Potential of Combined
P_T resummation and PDF global QCD analysis

- New constraints on PDFs,
- Better predictions for precision
  W, Z, Top, and Higgs physics at the Tevatron and LHC.

We have recently succeeded in performing the combined PDF+P_T fits

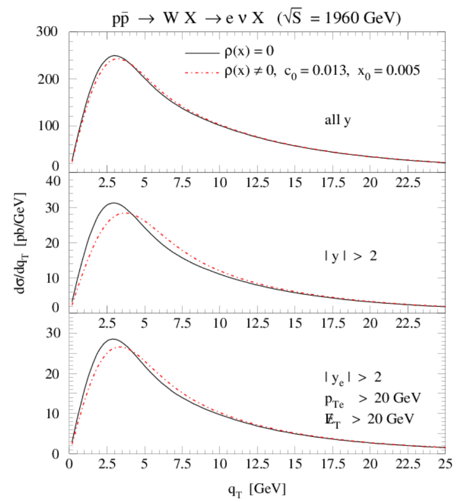
(Overcome the problem of speed and precision of calculations.)

In collaboration with
Lai, Nadolsky, Pumplin, Tung
(Argonne, Michigan State, U Washington)

Qt spectrum: small x improved ...

Berge, Nadolsky, Olness, Yuan
hep-ph/0410375

- in standard p_t resummation, no small x effects are included.
- at large energies (small x) BFKL effects might play a role... diffusion of transverse momenta, qt broadening...
- obtain effective pt-broadening by HERA data on transverse energy flow... include that for qt spectra of W/Z (Berge, Nadolsky, Olness, Yuan hep-ph/0410375)



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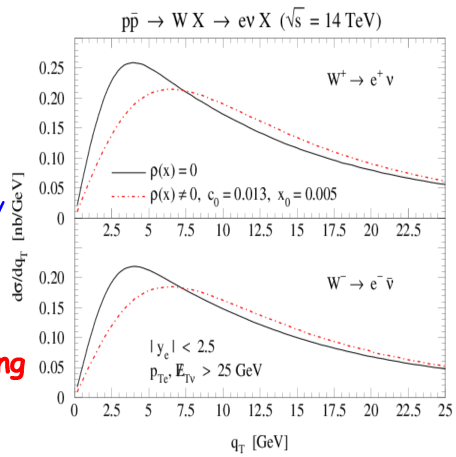
hep-ph/0410375

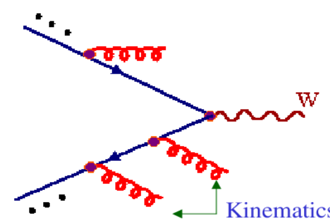
- in standard p_t resummation, no small x effects are included.
- at large energies (small x) BFKL effects might play a role... diffusion of transverse momenta, qt broadening...
- obtain effective pt-broadening by HERA data on transverse energy flow... include that for qt spectra of W/Z (Berge, Nadolsky, Olness, Yuan hep-ph/0410375)

➔ **Interesting physics coming with hard QCD processes !!!!**



Monte Carlo approach

C-P Yuan, CTEQ
summerschool 2002



Backward Radiation
(Initial State Rad.)

Kinematics of the radiated gluon, controlled by Sudakov form factor with some arbitrary cut-off. (In contrast to perform integration in impact parameter space, i.e., b space.)

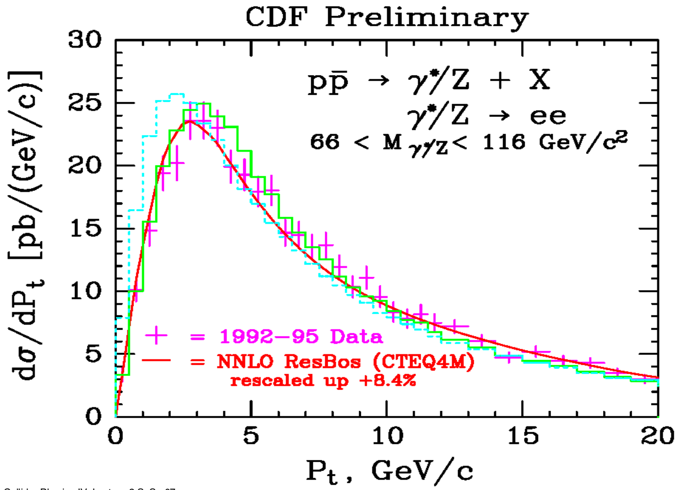
➔ The shape of q_T (w) is generated. But, the integrated rate remains the same as at Born level (finite virtual correction is not included).

* Recently, there are efforts to include part of higher order effect in the event generator.

Monte Carlo vrs ResBos

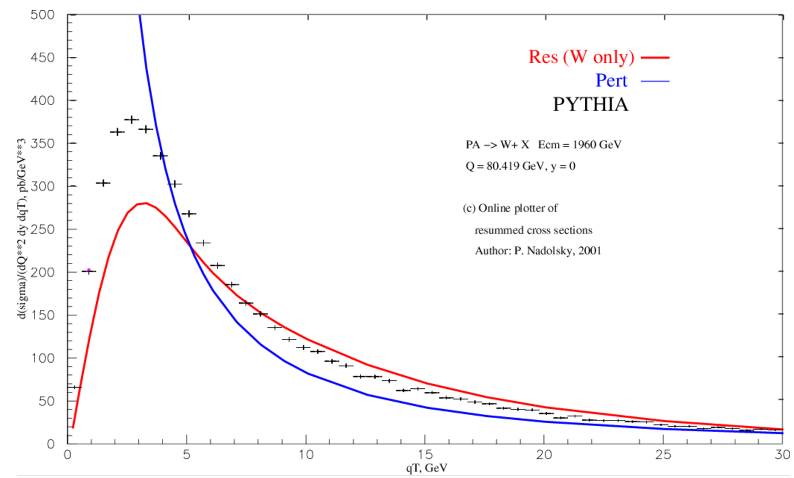
- Comparison of pt spectrum from ResBos and PYTHIA

Campbell, Huston Stirling
Rep.Prog.Phys 70 (2007) 89



Monte Carlo vrs ResBos

- Comparison of pt spectrum from ResBos and PYTHIA



Angular x-section of W+jet and dijets

- check on propagator:

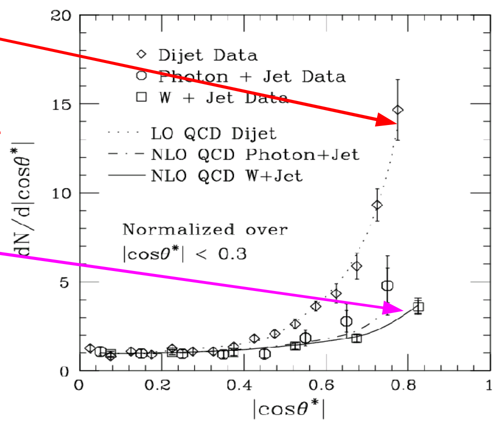
CDF Collaboration (F. Abe et al.). Phys.Rev.Lett.73:2296-2300,1994.

$qq \to qq$

$$|M|^2 \sim \frac{s^2+u^2}{t^2} \sim \frac{1}{t^2} \sim \frac{1}{(1-cos\theta^*)^2}$$

$qq \to W+g$:

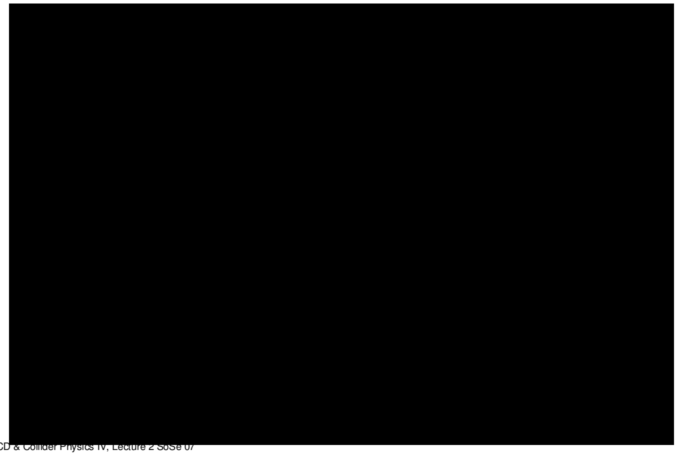
$$|M|^2 \sim \frac{1}{t} \sim \frac{1}{(1-cos\theta^*)}$$



From W/Z + 1 jet
to
W/Z + n jets

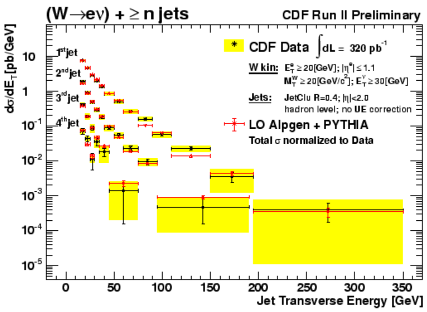
W + n jets

- tree level calculations available for W/Z + 4 jets
- NLO calculations for W/Z + 2 jets (Arnold, Hall Reno, NPB 319 (1989) 37)

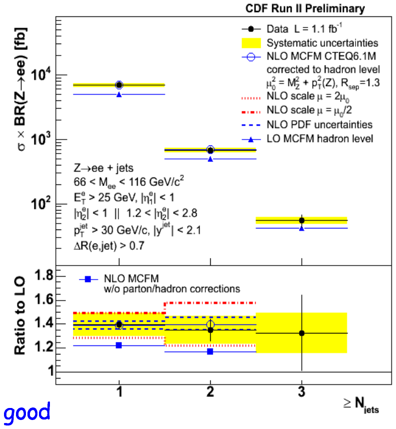


W/Z + n-jet xsections

- W + n-jets: using tree level calculation with MC for parton showering and hadronization (PYTHIA)



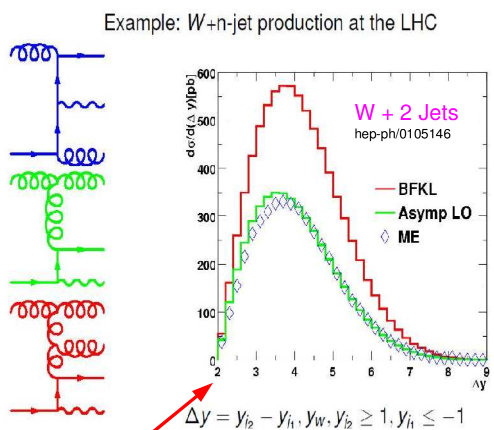
- Z0 + n-jets using NLO calculation



- Agreement with data at TeVatron is good
- Is that ok also for LHC ?

W + n-Jets

J. Andersen HERALHC CERN 2006



rapidity difference of 2 jets

W+n jets complicated: in fixed order: W+5 jets in MadGraph is the limit..., W+1 (2) jets in NLO
for n>5 jets only BFKL calculation available
work started to extend LO BFKL calc to NLL (quark contribution is ready...)
Program for analysis of W+n-jet is available:
http://www.hep.phy.cam.ac.uk/~andersen/BFKL

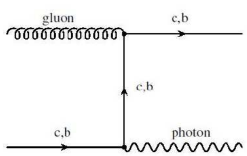
Prospects for LHC

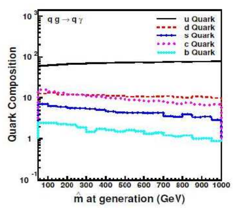
- $W \to l\nu$ and $Z \to l^+l^-$ have large x-section 10 nb (1nb) in fiducial region of detectors
- ➔ use them as luminosity monitor, detector calibration and physics...

PDF determination at LHC

K. Mazumdar et al
at HERA-LHC CERN 2006

- charm quark PDF



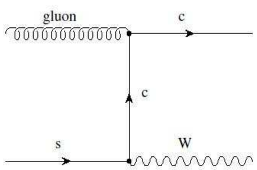


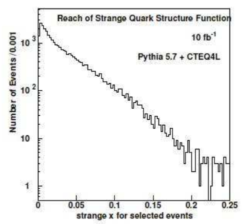
➔ ~ 10^5 c+b events in 10 fb^{-1} with p_t^{muon} >10 GeV

➔ x_c,x_b probed in $0.05<x_c,x_b<0.1$ with 10% stat.accuracy

- ~ 20% of these γ+jet events are from $gc/b \to \gamma c/b$.
- Select semileptonic decays of heavy mesons in γ+jet events

- strange quark PDF





➔ x_s ~0.1 for 10 fb^{-1} with 10% stat. accuracy

- need u,d uncertainties
- simulation of final state including

Wishlist for processes

Campbell, Huston Stirling
Rep.Prog.Phys 70 (2007) 89

Hard interactions of quarks and gluons: a primer for LHC physics 171

Table 2. The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

Process ($V \in \{Z, W, \gamma\}$)	Relevant for
1. $pp \to V\,V$+jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF→ $H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2$ jets	VBF→ $H \to VV$
7. $pp \to V + 3$ jets	Various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton searches

➔ There is still plenty of things to do for you ....

Jet production

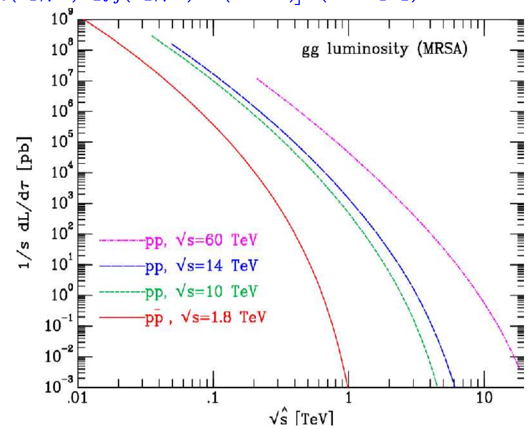
Jets: parton lumi and x-section

- parton luminosity:

$$\tau \frac{dL_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int dx_1 dx_2 \left[(x_1 f_i(x_1,\mu^2) x_2 f_j(x_2,\mu^2) + (1 \leftrightarrow 2) \right] \delta(\tau - x_1 x_2)$$

- cross section:

$$\sigma(s) = \sum_{ij} \int \frac{d\tau}{\tau} \left[\frac{1}{s} \frac{dL_{ij}}{d\tau} \right] [\hat{s}\hat{\sigma}_{ij}]$$



Jets: kinematics

- use varibales which transform simple under longitudinal boosts

$$p^\mu = (p_x, p_y, p_z, E)$$
$$= (p_T \sin\phi, p_T \cos\phi, m_T \sinh y, m_T \cosh y)$$

with $y = \frac{1}{2} \log\left(\frac{E + p_z}{E - p_z}\right)$

and $m_T = \sqrt{p_T^2 + m^2}$

- in practice often used:

pseudorapidity: $\eta = -\log\tan\left(\frac{\theta}{2}\right)$

transverse energy: $E_T = E \sin\theta$