QCD and collider physics IV: LHC

Lectures by J. Bartels (Theory Uni HH) & H. Jung (H1/CMS, DESY)

- Announcements ...
- W & Z xsection
 - LO, NLO
 - W/Z + 1-jet
 - W-mass
 - W/Z small pt: resummation
 - qt-resummed PDFs: latest news from DIS 2007 (next lecture)
- Applications for LHC (next lecture)

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



- High energy physics school in Maria Laach runs in GERMAN (extracted from an email exchange in April 2007 with the organisers):
- ".... Meine Koorganisatoren sind so wie ich der Meinung, dass wir in Maria Laach bei Deutsch bleiben sollten. Neben den Standardargumenten wie z.B. "Deutsch als (Wissenschafts)sprache" spielt nach unserer Meinung auch eine Rolle, dass wir dort zu Gast im Kloster sind und unsere Gastgeber (d.h. die Moenche) in der Regel kein Englisch sprechen. Die Studenten haben regelmaessig den Kontakt mit einigen der Moenche gepflegt, was uns umgekehrt auch einen guten Ruf im Konvent verschafft hat. Wir denken, dass Maria Laach doch ein recht spezieller Platz ist und dass deshalb Englisch dort nicht angemessen ist. "
- Hm.... should we now switch here also to GERMAN ????

Literature and References

Literature:

- Applications of pQCD
- Basics of perturbative QCD
 Troyan Edition Frontiers 1991
- CMS physics design report
- Collider Physics
- Deep Inelastic Scattering.
- Handbook of pQCD

R.D. Field Addison-Wesley 1989

Yu. Dokshitzer, V. Khoze, A. Mueller, S.

V.D. Barger & R.J.N. Phillips Addison-Wesley 1987 R. Devenish & A. Cooper-Sarkar, Oxford 2 G. Sterman et al

- Hard interactions of quarks and gluons: a primer for LHC physics
- HERA and the LHC
- Quarks and Leptons,
- QCD and collider physics
 1996

J M Campbell et al 2007 Rep. Prog. Phys. 70 89-193 hep-ph/0601012, hep-ph/0601013 F. Halzen & A.D. Martin, J.Wiley 1984 R.K. Ellis & W.J. Stirling & B.R. Webber Cambridge

Structure & program

- Part I (H. Jung)
 .. until 11.6.07
- Phenomenology of hard processes at TeVatron and LHC
 - Transparencies
 - Calculations on blackboard
 - Exercises ...

- Part II (J. Bartels) starting on 18.6.07
- Theory of Higgs production & processes beyopnd the standard Model

- REQUEST to YOU
- → If things go wrong .. lecture is too easy... too trivial ... too complicated, too

chaotic or too boring ...

PLEASE complain immediately ! PLEASE ask questions any time !

Program of Lectures

9	30.4.	Intro & W/Z production	H. Jung					
٥	7.5.	Jets and prompt photons	H. Jung					
٥	14.5.	Heavy Quark production	H. Jung					
٥	21.5.	no lecture Blois 2007 workshop						
٥	28.5.	Pentecost – Whitsun Monday						
٥	4.6.	Calculation methods I: Monte Carlo generators, multiparton						
		final states	H. Jung					
٩	11.6.	Calculation methods II: NLO, MC@NLO, CKKW, etc	H. Jung					
٩	18.6.	Higgs production and decays	J. Bartels					
٩	25.6.	Higgs	J. Bartels					
9	2.7.	Beyond the Standard Model: SUSY	J. Bartels					
۹	9.7.	Beyond the Standard Model: Extra dimensions	J. Bartels					

W & Z cross sections

- Basic process: Drell Yan $q + \bar{q} \rightarrow \gamma^* \rightarrow l^+ + l^-$
- Factorise process:
 - $q + \bar{q} \to \gamma^*$
 - $q + \bar{q} \to Z_0$
 - $q + \bar{q'} \to W^{\pm}$



- Include decay of $\gamma^*
 ightarrow l^+ + l^-$
 - $Z_0 \to l^+ + l^-$
 - $W^{\pm} \rightarrow l + \nu$

Not considered further...

Drell - Yan in lowest order

Study Of Scaling In Hadronic Production Of Dimuons. J.K.Yoh et al. Phys.Rev.Lett.41:684,1978, Erratum-ibid.41:1083,1978.



$$\tau = z = \frac{M^2}{s}, M^2 = m_{l^+l^-}^2$$

FIG. 3. (a) $s d^2\sigma/d\sqrt{\tau}dy|_{y=0.2}$ vs $\sqrt{\tau}$. Circles, triangles, and squares correspond to 400-, 300-, and 200-GeV beam energy, respectively. (b) Above data divided by the overall fit $Ae^{-b\sqrt{\tau}}$.

H. Jung, QCD & Collider Physics IV, Lecture 1 SoSe 07

Rapidities and all that ...



x-section, phase space, ME ...

- cross section definition: $d\sigma = rac{1}{F} d {
 m Lips} \left| ME
 ight|^2$
- with initial flux $F=4\sqrt{(p_1p_2)^2-m_1^2m_2^2}$
- and Lorentz invariant phase space

$$dLips = (2\pi)^4 \delta^4 (-p_1 - p_2 + \sum_i p_i) \sum_i \frac{d^4 p_i}{(2\pi)^3} \delta(p_i^2 - m_i^2)$$
$$dLips = (2\pi)^4 \delta^4 (-p_1 - p_2 + \sum_i p_i) \sum_i \frac{d^3 p_i}{(2\pi)^3 2E_i}$$
$$dLips = (2\pi)^4 \delta^4 (-p_1 - p_2 + \sum_i p_i) \sum_i \frac{1}{(2\pi)^3} \frac{dp_i^+}{p_i^+} d^2 p_{t\,i}$$

Drell - Yan at high energies: Z, W

$$\sigma(q\bar{q} \rightarrow l^{+}l^{-}) = \frac{4\pi\alpha^{2}}{3s} \frac{1}{N} \left(e_{q}^{2} - 2e_{q}V_{l}V_{q}\chi_{1}(s)\right) \xrightarrow{\text{Measurement of 20 and Drel+ Yan productor cross-section using dimons in ani-p collisions at S*(l2) = 1.8 + EV. CDF Collaboration F. Abe et al. Phys.Rev.D59:052002,1999. + (A_{l}^{2} + V_{l}^{2})(A_{q}^{2} + V_{q}^{2})\chi_{2}(s))$$

$$\sigma(q\bar{q} \rightarrow \gamma^{*} \rightarrow l^{+}l^{-}) = \frac{4\pi\alpha^{2}}{3s} \frac{1}{N}e_{q}^{2}$$

$$\chi_{1}(s) = \xi \frac{s(s - M_{Z}^{2})}{(s - M_{Z}^{2})^{2} + \Gamma_{Z}^{2}M_{Z}^{2}}$$

$$\chi_{2}(s) = \xi^{2} \frac{s(s - M_{Z}^{2})}{(s - M_{Z}^{2})^{2} + \Gamma_{Z}^{2}M_{Z}^{2}}$$

$$\xi = \frac{\sqrt{2}G_{F}M_{Z}^{2}}{16\pi\alpha}$$

$$\xi = \frac{\sqrt{2}G_{F}M_{Z}^{2}}{16\pi\alpha}$$

$$V/Z \text{ exchange, visible !!!}$$

$$\int_{\text{H-Jung QOD Chemer Provise (Letter) to Sector}} \frac{10^{-4}}{10^{-4}}$$

$$\int_{\text{H-Jung ADD Chemer Provise (Letter) to Sector}} \frac{10^{-4}}{10^{-4}}$$

$$\int_{\text{H-Jung ADD Chemer Provise (Letter) to Sector}} \frac{10^{-4}}{10^{-4}}$$

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Trying to do things easier

Fred Olness, CTEQ summerschool 2003

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



For example:

$$\frac{d\sigma(q\bar{q}\to l^+l^-)}{dM^2} = \frac{d\sigma(q\bar{q}\to\gamma^*)}{dM^2} \times \frac{\alpha}{3\pi M^2}$$

W production in LO

- W production $q(p_1) + \overline{q'}(p_2) \to W^{\pm}(p)$
- Matrix element:

$$\begin{split} M &= -iV_{qq'}\frac{g}{\sqrt{2}}\epsilon\bar{v}(p_2)\gamma^{\mu}\frac{1}{2}(1-\gamma_5)u(p_1)\\ |M|^2 &= |V_{qq'}|^2\frac{G_F M_W^4}{\sqrt{2}}\frac{2}{3} \qquad \text{with} \qquad g^2 = \frac{8G_F M_W^2}{\sqrt{2}} \end{split}$$

• partonic x-section:

$$d\sigma = \frac{1}{F} d\text{Lips} |ME|^2$$

with $d\text{Lips} = (2\pi)^4 \delta^4 (-p_1 - p_2 + \sum_i p_i) \sum_i \frac{d^4 p_i}{(2\pi)^3} \delta(p_i^2 - m_i^2)$
gives:

$$\hat{\sigma} = \frac{1}{2s} 2\pi \delta(p^2 - M_W^2) |M|^2$$
$$= \frac{2\pi}{3} \frac{G_F M_W^2}{\sqrt{2}} |V_{qq'}|^2 \delta(\hat{s} - M_W^2)$$

H. Jung, QCD & Collider Physics IV, Lecture 1 SoSe 07

Z/y* production in LO

 γ^{\star}

- Z_0/γ^* production $q(p_1) + \bar{q}(p_2) \rightarrow Z^0(p)(\gamma^*(p))$
- Matrix element: Z₀

 $M = -ig\epsilon_{\mu}\bar{v}(p_2)\gamma^{\mu}(g_v - g_a\gamma_5)u(p_1) \qquad \text{or} \qquad M = -ig\epsilon_{\mu}\bar{v}(p_2)\gamma^{\mu}u(p_1)$

$$\begin{split} |M|^2 &= \frac{8}{3} \frac{G_F M_Z^4}{\sqrt{2}} (g_a^2 + g_v^2) \qquad \qquad \text{or} \qquad |M|^2 = \frac{4\pi\alpha}{3} e_q^2 M_\gamma^2 \\ \text{with} \quad g_a^2 + g_v^2 &= \frac{1}{8} (1 - 4|e_q| \sin^2 \Theta_W + 8e_q^2 \sin^4 \Theta_W) \end{split}$$

partonic x-section:

$$d\sigma = \frac{1}{F} d\text{Lips} |ME|^2$$
with $d\text{Lips} = (2\pi)^4 \delta^4 (-p_1 - p_2 + \sum_i p_i) \sum_i \frac{d^4 p_i}{(2\pi)^3} \delta(p_i^2 - m_i^2)$
gives:
$$\hat{\sigma}(Z^0) = \frac{8\pi}{3} \frac{G_F M_Z^2}{\sqrt{2}} (g_a^2 + g_v^2) \delta(\hat{s} - M_Z^2)$$

$$\hat{\sigma}(\gamma^*) = \frac{4\pi^2 \alpha}{3} e_q^2 \delta(\hat{s} - M_\gamma^2)$$

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Drell-Yan: comparison with experiment

Measurement Of Continuum Dimuon Production In 800-GeV/C Proton-Nucleon Collisions Jason C. Webb, hep-ex/0301031

Table 1.2:Experimental K-factors.

Expe	eriment	Interaction	Beam Momentum	$K = \sigma_{\rm meas.} / \sigma_{\rm DY}$		
E288	[Kap 78]	p Pt	$300/400~{\rm GeV}$	~ 1.7		
WA39	[Cor 80]	$\pi^{\pm} W$	$39.5~{ m GeV}$	~ 2.5		
E439	[Smi 81]	p W	$400~{\rm GeV}$	1.6 ± 0.3		
		$(\bar{p} - p)Pt$	$150~{ m GeV}$	2.3 ± 0.4		
		p Pt	$400~{\rm GeV}$	$3.1\pm0.5\pm0.3$		
NA3	[Bad 83]	$\pi^{\pm} Pt$	$200~{\rm GeV}$	2.3 ± 0.5		
		$\pi^- Pt$	$150~{ m GeV}$	2.49 ± 0.37		
		$\pi^- Pt$	$280~{ m GeV}$	2.22 ± 0.33		
NA10	[Bet 85]	$\pi^- W$	$194~{ m GeV}$	$\sim 2.77 \pm 0.12$		
E326	[Gre 85]	$\pi^- W$	$225~{\rm GeV}$	$2.70 \pm 0.08 \pm 0.40$		
E537	[Ana 88]	$\bar{p} W$	$125 \mathrm{GeV}$	$2.45 \pm 0.12 \pm 0.20$		
E615	[Con 89]	$\pi^- W$	$252~{ m GeV}$	1.78 ± 0.06		

• K - factors at low energies

 $K = \frac{\sigma^{measur\,ed}}{\sigma^{calc}(LO)}$

Need for higher order calculations.....

Doing things easier ...

Fred Olness, CTEQ summerschool 2003

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



For example:

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

it works also for pQCD processes

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QCD corrections for Drell-Yan

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• Calculate annihilation process $q+ar{q}
ightarrow \gamma^*+g$



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

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

Calculate QCDC process $q+g
ightarrow \gamma^* + q$



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

W (or D-Y) + 1-jet production

Hard interactions of quarks and gluons: a primer for LHC physics J M Campbell et al 2007 Rep. Prog. Phys. 70 89-193

Suggestive for initial state

Suggestive for a hard 2 -> 2 process



Figure 9. The rapidity distribution of the final-state parton found in a lowest-order calculation of the W + 1 jet cross section at the LHC. The parton is required to have a p_T larger than 2 GeV (left) or 50 GeV(right). Contributions from $q\bar{q}$ annihilation (solid red line) and the qg process (dashed blue line) are shown separately.

D-Y + 1-jet production

R. Field, Appl. of pQCD, p195 ff



D-Y + 1-jet production

R. Field, Appl. of pQCD, p195 ff

 $\frac{d\sigma}{dM^2 dy dp_t^2}$

- → annihilation term gives a p_t⁻² tail to the p_t distribution (this falls off more slowly than a gaussian)
- Compton contribution is a bit more complicated
- Tail of pt distribution ______
 can be calculated in QCD



What happens at small p,?

taking the limit of small p₁:

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

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

• cross section diverges as for $p_t \rightarrow 0$: $\frac{\log \frac{s}{p_t^2}}{p_t^2}$

NLO needs virtual corrections



amplitudes must be added:

 $|A_0 + A_v + B_v + C_v|^2 = |A_0|^2 + 2Re(A_0A_v^* + A_0A_v^* + A_0C_v^*) + |A_v + B_v + C_v|^2$

- enter loop integrals which are divergent for $\,k
 ightarrow\infty$ and $\,k
 ightarrow0$
- Adding vertex + self-energy diagrams
 - → UV divergencies cancel (similar to that in calc of α_{em})
 - > only IR divergencies stay.... and can cancel real emissions

QCD Corrections to Drell Yan

• Virtual emissions, integrated over z (R. Field, App. pQCD, p179ff): $q\bar{q}
ightarrow \gamma^* g$

$$\begin{split} \hat{\sigma}_{MG}(virtual)_{DY} &= \frac{2\alpha_{\rm s}}{3\pi} \hat{\sigma}_0 \left[-\log^2(\beta) - 3\log(\beta) - \frac{7}{2} - \frac{2\pi^2}{3} + \pi^2 \right] \\ \text{with} \quad \beta &= \frac{m_g^2}{M^2} \\ (\hat{\sigma}_{MG}(real) + \hat{\sigma}_{MG}(virtual))_{DY} &= \frac{2\alpha_{\rm s}}{3\pi} \hat{\sigma}_0 \left[\frac{4\pi^2}{3} - \frac{7}{2} \right] \end{split}$$

• Define K -factor (1st order): $\hat{\sigma}_{tot}^{DY} = \hat{\sigma}_0 \times (1 + \cdots) = \hat{\sigma}_0 \times K$

$$K^{DY}(1 \text{st order}) = 1 + \frac{\alpha_{s}}{\pi} \left[\frac{8\pi^{2}}{9} - \frac{7}{3} \right] = 1 + 2.05\alpha_{s} \sim 2$$

• compare to DIS $K^{DIS}(1st \text{ order}) = 1 - \frac{\alpha_s}{\pi}$

$\mathcal{O}(\alpha_{\rm s})$ corrections to Drell-Yan

Barger, Phillips, p231

• Real and virtual corrections up to $\mathcal{O}(\alpha_s)$ in dim. regularization:

$$\frac{d\sigma^{DY}}{dM^{2}}(AB \to l\bar{l}X) = \sum_{q} e_{q}^{2} \int_{0}^{1} dx_{a} \int_{0}^{1} dx_{b} \frac{4\pi\alpha^{2}}{9s^{2}} \left(\left[q^{A}(x_{a})\bar{q}^{B}(x_{b}) + A \leftrightarrow B \right] \right]$$

$$\left[\delta(1-z) + \theta(1-z) \frac{\alpha_{s}}{2\pi} 2P_{qq}(z) \left(-\frac{1}{\epsilon} + \ln \frac{M^{2}}{\mu^{2}} \right) + \alpha_{s} f_{q}^{DY}(z) \right] + \left[(q^{A}(x_{a}) + \bar{q}^{A}(x_{a}))g^{B}(x_{b}) + A \leftrightarrow B \right]$$

$$+ \left[(q^{A}(x_{a}) + \bar{q}^{A}(x_{a}))g^{B}(x_{b}) + A \leftrightarrow B \right]$$

$$\theta(1-z) \frac{\alpha_{s}}{2\pi} P_{qg}(z) \left(-\frac{1}{\epsilon} + \ln \frac{M^{2}}{\mu^{2}} + \alpha_{s} f_{g}^{DY}(z) \right) \right]$$

- Splitting $P_{qq}(z), P_{qg}(z)$ functions are the same as in $F_{2'}$, but non-leading terms f_q^{DY}, f_g^{DY} are different !!!
- absorb $1/\epsilon$ and $\ln(M^2/\mu^2)$ into PDFs

CO

 $\mathcal{O}(\alpha_{s})$ result for annihilation

• annihilation result in MSbar scheme

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{9M^2s} \sum_q \int \frac{dx_a}{x_a} \int \frac{dx_b}{x_b} \times \left[H_q(x_a, x_b, M^2) \left(\delta(1-z) + \frac{\alpha_s(M^2)}{2\pi} D_q(z) \right) + \left[(f_q(x_a, M^2) + f_{\bar{q}}(x_a, M^2)) f_g(x_b, M^2) + (a \leftrightarrow b) \right] \times \frac{\alpha_s(M^2)}{2\pi} D_g(z) \right]$$

- with $f_q(x,Q^2), f_g(x,Q^2)$ being the MSbar scale dependent PDFs
- and $D_q(x,Q^2), D_g(x,Q^2)$ giving the finite $\mathcal{O}(\alpha_{\rm s})$ corrections
- note presence of scale dependent PDF and running coupling

QCD corrections for Drell - Yan



(0)

- (1)soft divergencies canceled by real and virtual emissions
- factorize collinear (2)divergency into renormalized parton density

 $H_{ij}^{(0)} = \sigma_{ij}^{(0)} =$ "Born"

suppress "^" from now on

scheme dependent)

$$H_{ij}^{(1)} = \sigma_{ij}^{(1)} - \left[\sigma_{il}^{(0)} \phi_{l/j}^{(1)} + \phi_{k/i}^{(1)} \sigma_{kj}^{(0)} \right]$$

Computed from
Feynman diagrams
(process dependent)
Computed from
the definition of
perturbative parton
distribution function
(process independent,

$$\sigma_{kl}^{(0)} = H_{kl}^{(0)} \Rightarrow H_{kl}^{(0)} = \sigma_{kl}^{(0)}$$

$$\sigma_{kl}^{(1)} = H_{kl}^{(0)} + H_{k$$

-(0)



LO/NLO K-factors

Hard interactions of quarks and gluons: a primer for LHC physics J M Campbell et al 2007 Rep. Prog. Phys. 70 89-193

• K-factor:
$$K = \frac{\sigma(LO)}{\sigma(NLO)}$$

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

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Table 1. *K*-factors for various processes at the Tevatron and the LHC calculated using a selection of input parameters. In all cases, the CTEQ6M pdf set is used at NLO. \mathcal{K} uses the CTEQ6L1 set at leading order, whilst \mathcal{K}' uses the same set, CTEQ6M, as at NLO. Jets satisfy the requirements $p_T > 15 \text{ GeV}$ and $|\eta| < 2.5$ (5.0) at the Tevatron (LHC). In the W + 2 jet process the jets are separated by $\Delta R > 0.52$, whilst the weak boson fusion (WBF) calculations are performed for a Higgs boson of mass 120 GeV. Both renormalization and factorization scales are equal to the scale indicated.

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
W + 1 jet	m_W	$\langle p_T^{\rm jet} \rangle$	1.42	1.20	1.43	1.21	1.32	1.42
W + 2 jets	m_W	$\langle p_T^{\rm jet} \rangle$	1.16	0.91	1.29	0.89	0.88	1.10
tī	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet} \rangle$	1.07	0.97	1.07	1.23	1.34	1.09



Fig. 4. The two-loop corrections to the process $q + \overline{q} \rightarrow V$.



Fig. 5. The one-loop corrections to the process $q + \overline{q} \rightarrow V + g$. The diagrams corresponding to the one-loop correction to the subprocess $q(\overline{q}) + g \rightarrow V + q(\overline{q})$ can be obtained via crossing.



Fig. 6. Diagrams contributing to the subprocess $q + \overline{q} \rightarrow V + g + g$. The graphs corresponding to the subprocess $q(\overline{q}) + g \rightarrow V + q(\overline{q}) + g$ can be obtained from those presented in this figure via crossing. By crossing two pairs of lines one can obtain the diagrams corresponding to the subprocess $g + g \rightarrow V + q + \overline{q}$.



Fig. 16. Mass factorization scale (*M*) dependence of $\sigma_{W^+W^-}$ for LHC, $\sqrt{S} = 16$ TeV. Solid line: Born, DIS scheme. Long-dashed line: $O(\alpha_s)$, DIS scheme. Dash-dot line: $O(\alpha_s^2)$, DIS scheme. Dotted line: $O(\alpha_s^2)$, \overline{MS} scheme.

W/Z cross section at NNLO

Intest calculations and latest results from CDF (TeVatron):



perfect description of measurements ... for total x-section

Measurement of W - mass

The Jacobian Peak

Fred Olness, CTEQ summerschool 2003

Now that we've got the picture, here's the math ... *(in the W CMS frame)*

$$p_T^2 = \frac{\mathbf{\hat{s}}}{4} \sin^2 \theta \qquad \cos \theta = \sqrt{1 - \frac{4 p_T^2}{\mathbf{\hat{s}}}} \qquad \frac{d \cos \theta}{d p_T^2} = \frac{2}{\mathbf{\hat{s}}} \frac{1}{\cos \theta}$$

So we discover the P_{T} distribution has a singularity at $\cos\theta=0$, or $\theta=\pi/2$

$$\frac{d\boldsymbol{\sigma}}{dp_T^2} = \frac{d\boldsymbol{\sigma}}{d\cos\boldsymbol{\theta}} \times \frac{d\cos\boldsymbol{\theta}}{dp_T^2} \approx \frac{d\boldsymbol{\sigma}}{d\cos\boldsymbol{\theta}} \times \frac{1}{\cos\boldsymbol{\theta}}$$



BUT !!!

Measuring the Jacobian peak is complicated if the W boson has finite P_{T} .

Measurement of m_w

Fred Olness, CTEQ summerschool 2003

We can measure $d\sigma/dp_T$ and look for the Jacobian peak. However, there is another variable that is relatively insensitive to $p_T(W)$.

Transverse Mass
$$M_T^2(e, \mathbf{v}) = \left(|\vec{p}_{eT}| + |\vec{p}_{\mathbf{v}T}|\right)^2 - \left(\vec{p}_{eT} + \vec{p}_{\mathbf{v}T}\right)^2$$
Invariant Mass $M^2(e, \mathbf{v}) = \left(|\vec{p}_e| + |\vec{p}_v|\right)^2 - \left(\vec{p}_e + \vec{p}_v\right)^2$

In the limit of vanishing longitudinal momentum, $M_{_T} \sim M.$ $M_{_T}$ is invariant under longitudinal boosts.

M_T can also be expressed as: $M_T^2(e, \mathbf{v}) = 2|\vec{p}_{eT}||\vec{p}_{\mathbf{v}T}|(1 - \cos \Delta \phi_{e\mathbf{v}})$

Transverse Mass Distribution & M_w measurement

Transverse Mass distribution



Combined world measurements of M_w



Prospects for m_{w} at LHC

- using transverse mass
 - missing transverse energy (from neutrino) determined by (for example CMS):
 - vector sum from all clusters in calorimeter
 - vector sum of "hard objects": jets with p₊ > 20 GeV, |η| < 2.4



Transverse Momentum of W/Z

The complete $\boldsymbol{P}_{_{\rm T}}$ spectrum for the W boson summerschool 2003 dơ∕dQ_r, pb∕GeV Perturbative contributions +power corrections 120 100 80 The full P_{T} spectrum for the W-boson showing the different 60 theoretical regions $p\bar{p} \to (W^+ \to \bar{e}\nu_e)X$ 40 CTEQ6M 20 Perturbative physics dominates 0 5 10 15 20 25 30 O 🌢 Q_T, GeV Nonperturbative

Fred Olness, CTEQ

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

• from previous we know, that integral over p_t^2 is finite: $\int_0^s \frac{d\sigma}{dM^2 dy dp_t^2} = \left(\frac{d\sigma}{dM^2 dy}\right) + \mathcal{O}(\alpha_s)$

 $\Rightarrow \text{ which gives}$ $\int_{0}^{p_{t}^{2}} \frac{d\sigma}{dM^{2}dydp_{t}^{2}} = \left(\frac{d\sigma}{dM^{2}dy}\right)_{Born} \left[1 - \int_{p_{t}^{2}}^{s} \frac{4\alpha_{s}}{3\pi} \frac{\log s/p_{t}^{2}}{p_{t}^{2}}dp_{t}^{2}\right]$ $= \left(\frac{d\sigma}{dM^{2}dy}\right)_{Born} \left[1 - \frac{2\alpha_{s}}{3\pi} \log^{2} s/p_{t}^{2}\right]$

H. Jung, QCD & Collider Physics IV, Lecture 1 SoSe 07

small pt-resummation to all orders

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

$$\int_{0}^{p_{t}^{2}} \frac{d\sigma}{dM^{2}dydp_{t}^{2}} = \left(\frac{d\sigma}{dM^{2}dy}\right)_{Born} \exp\left(-\frac{2\alpha_{s}}{3\pi}\log^{2}s/p_{t}^{2}\right)$$

→ differentiate wrt p_1^2 :

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

- Sudakov form factor appears
- expresses resummation of leading double logs
- exponential cancels singularity at pt -> 0
- → Probability to produce massive lepton pair (or Z₀, 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 $Z \rightarrow e^+e^-$



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