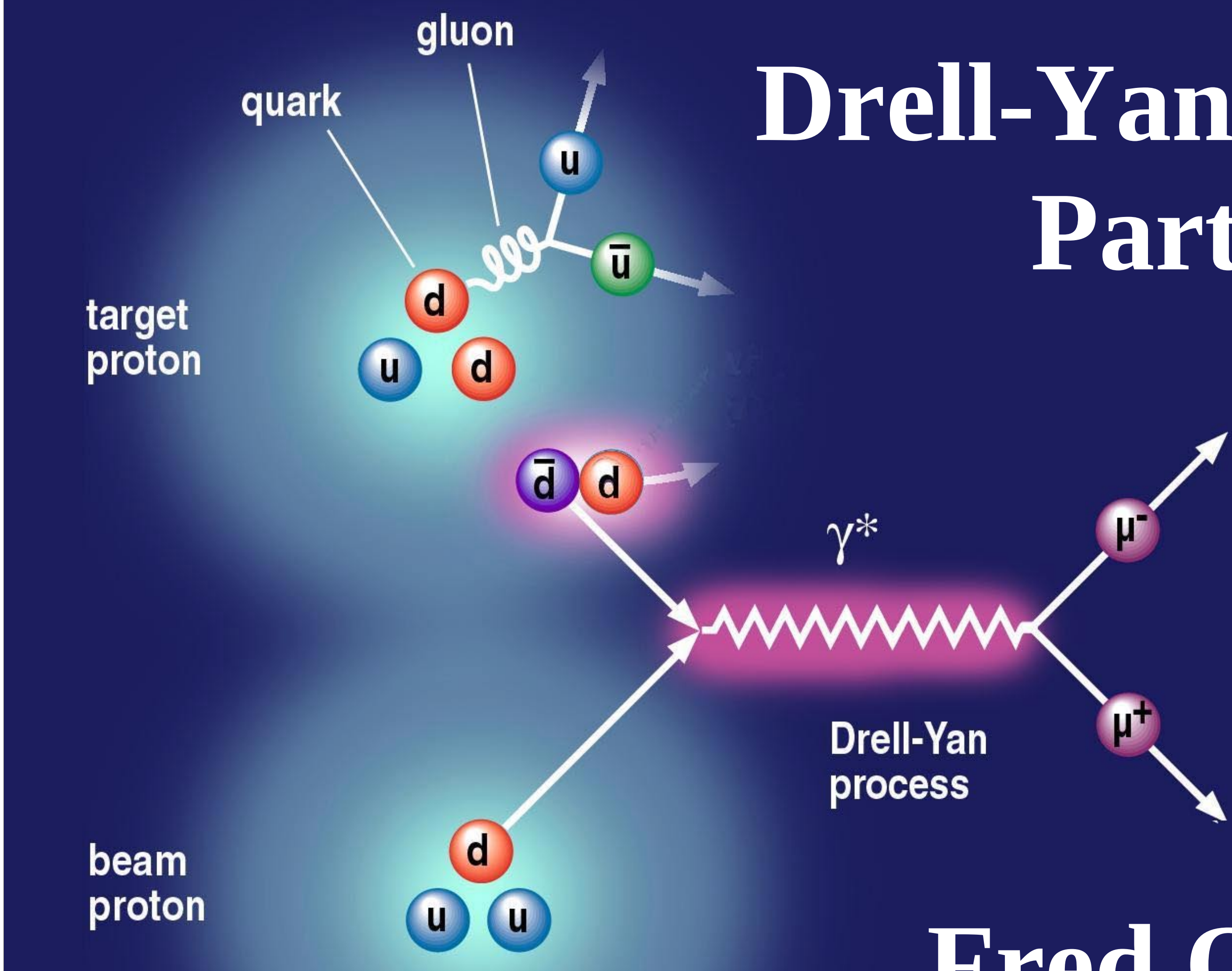
Drell-Yan Process: Part II



Fred Olness
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Part II: W Boson Production as an example

Finding the W Boson Mass:

The Jacobian Peak, and the W Boson P_T

Multiple Soft Gluon Emissions

Single Hard Gluon Emission

Road map of Resummation

Summing 2 logs per loop: multi-scale problem (Q, q_T)

Correlated Gluon Emission

Non-Perturbative physics at small q_T.

Transverse Mass Distribution:

Improvement over P_T distribution

What can we expect in future?

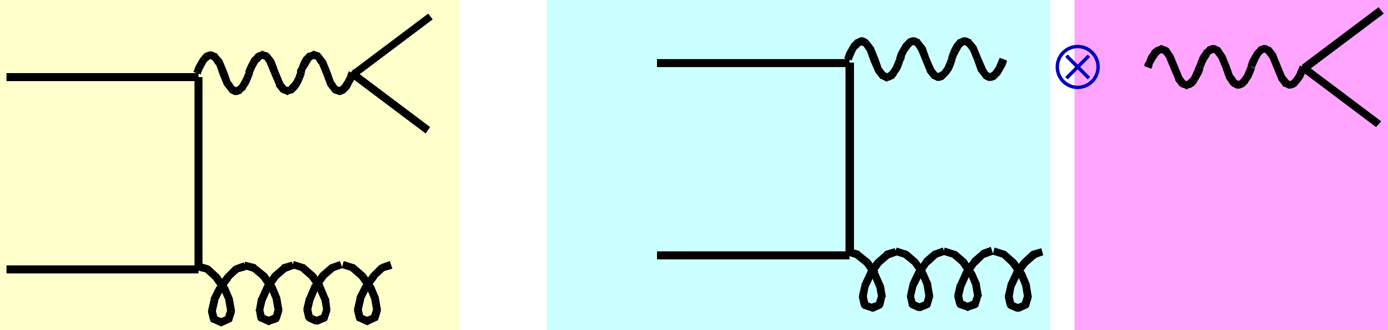
Tevatron Run II

LHC

Side Note: From *pp*→γ/Z/*W*, we can obtain *pp*→γ/Z/*W*→l^+l^-

Schematically:

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



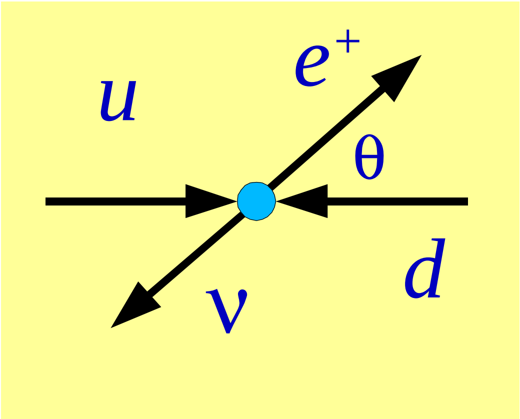
For example:

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

Part II: W Boson Production as an example

How do we measure the W-boson mass?

$$u + \overline{d} \rightarrow W^{+} \rightarrow e^{+} \nu$$

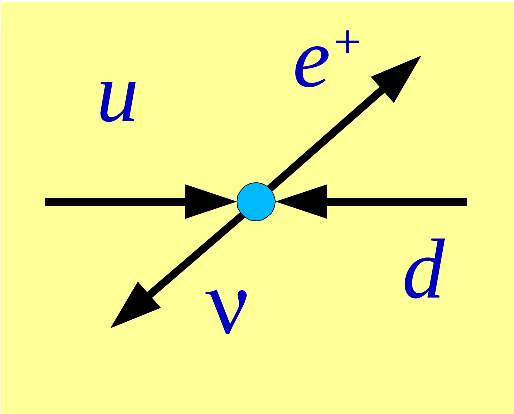


- Can't measure W directly
- Can't measure ν directly
- Can't measure longitudinal momentum

We can measure the P_T of the lepton

How can we use this to extract the W-Mass???

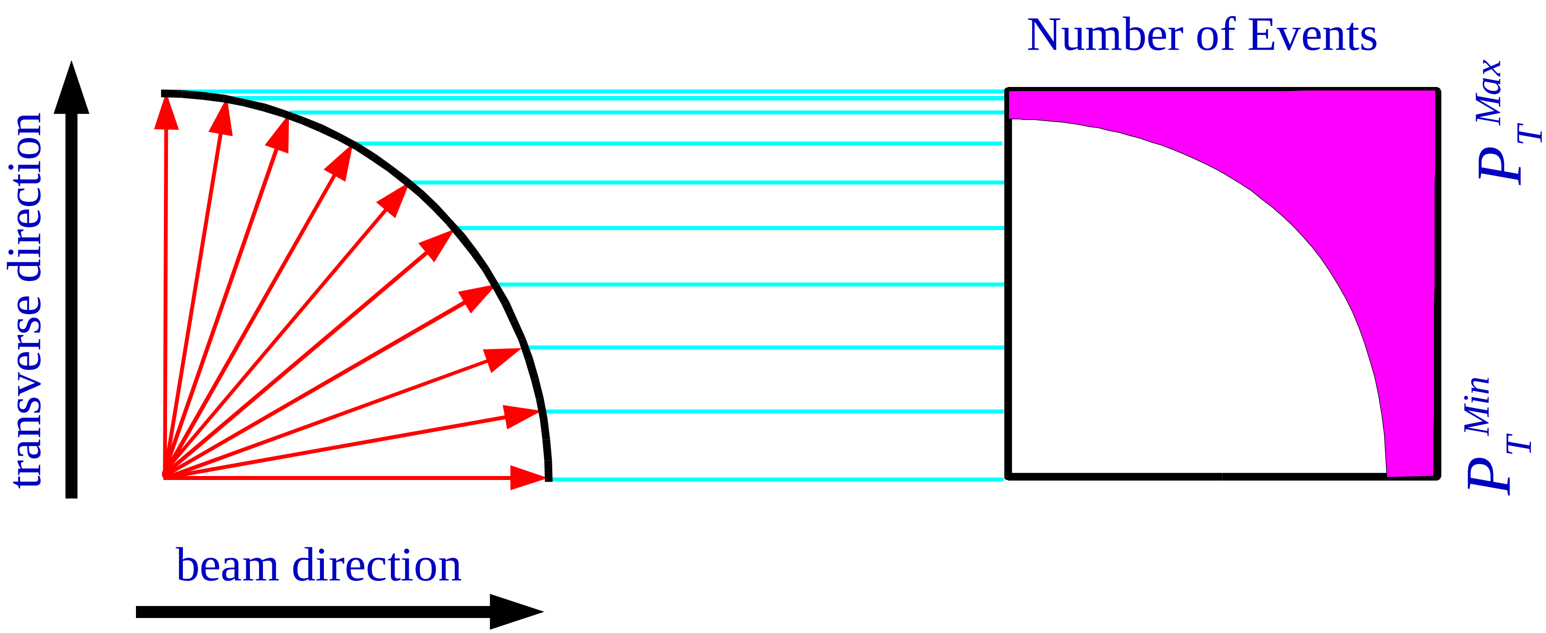
The Jacobian Peak



Suppose lepton distribution is uniform in θ

The dependence is actually $(1+\cos\theta)^2$, but we'll take care of that later

What is the distribution in P_T?



We find a peak at $P_T^{max} \approx M_W/2$

The Jacobian Peak

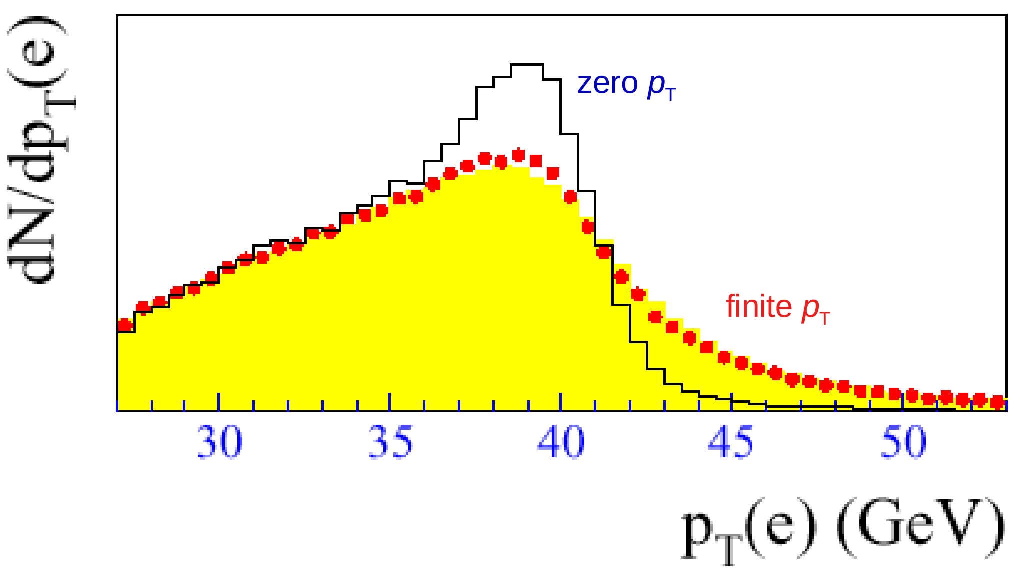
Now that we've got the picture, here's the math ... *(in the W CMS frame)*

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

So we discover the P_T distribution has a singularity at cosθ=0, or θ=π/2

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

singularity!!!



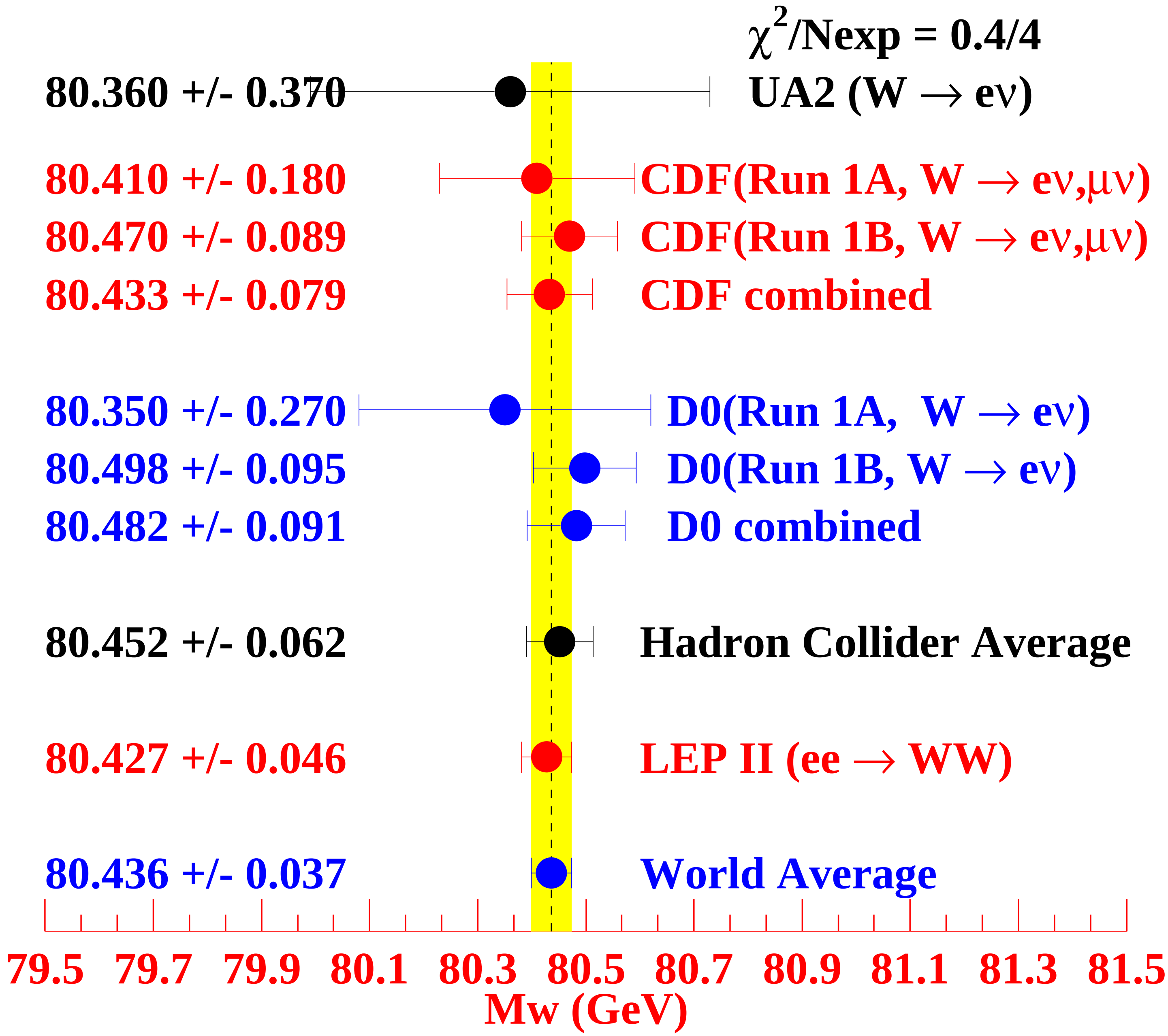
BUT !!!

Measuring the Jacobian peak is complicated if the W boson has finite P_T.

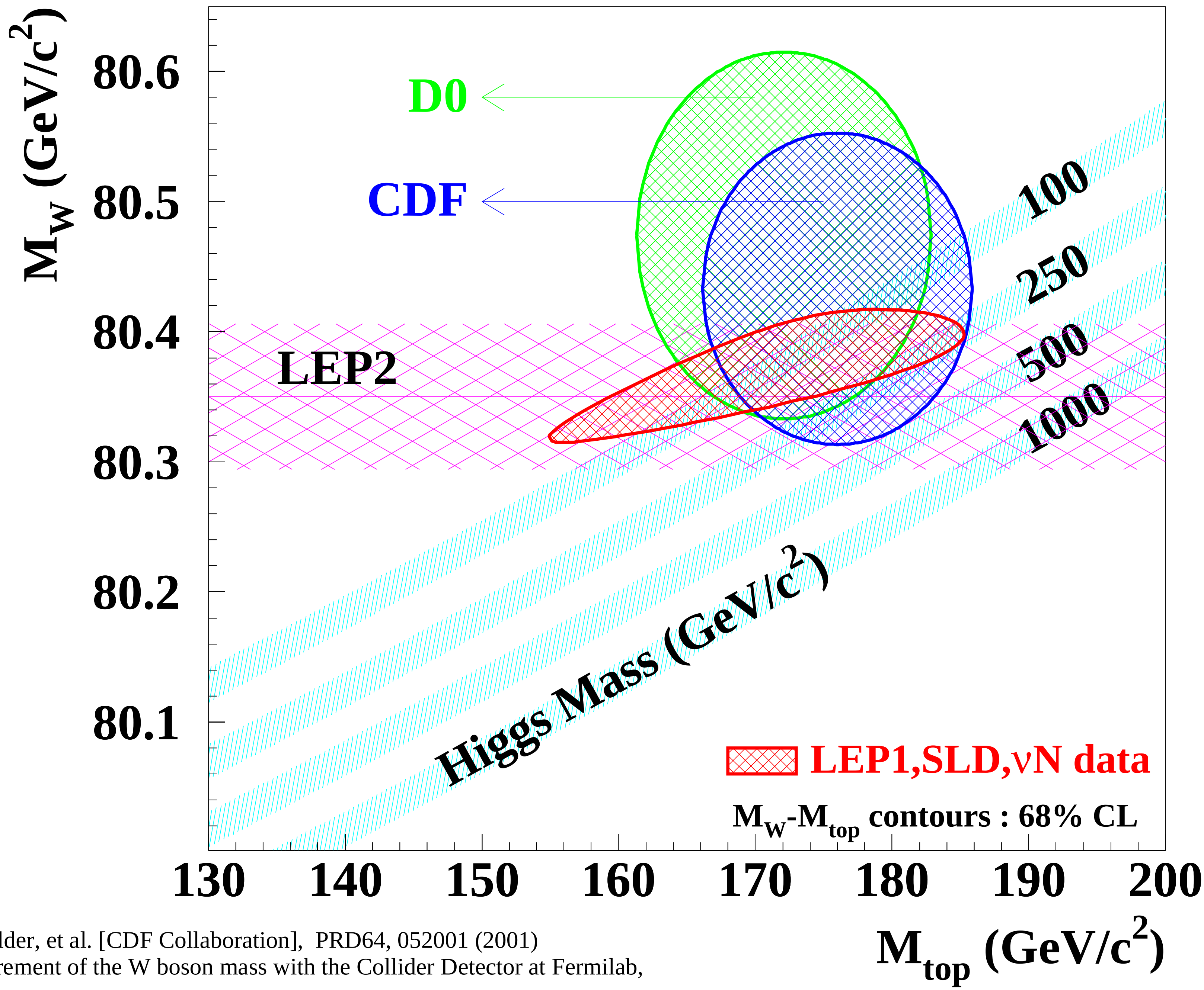
1) The W-mass is important fundamental quantity of the Standard Model

2) P_T Distribution is important for measuring the W-mass

The W-Mass is an important fundamental quantity



The W-Mass is an important fundamental quantity



T.Affolder, et al. [CDF Collaboration], PRD64, 052001 (2001)
Measurement of the W boson mass with the Collider Detector at Fermilab,

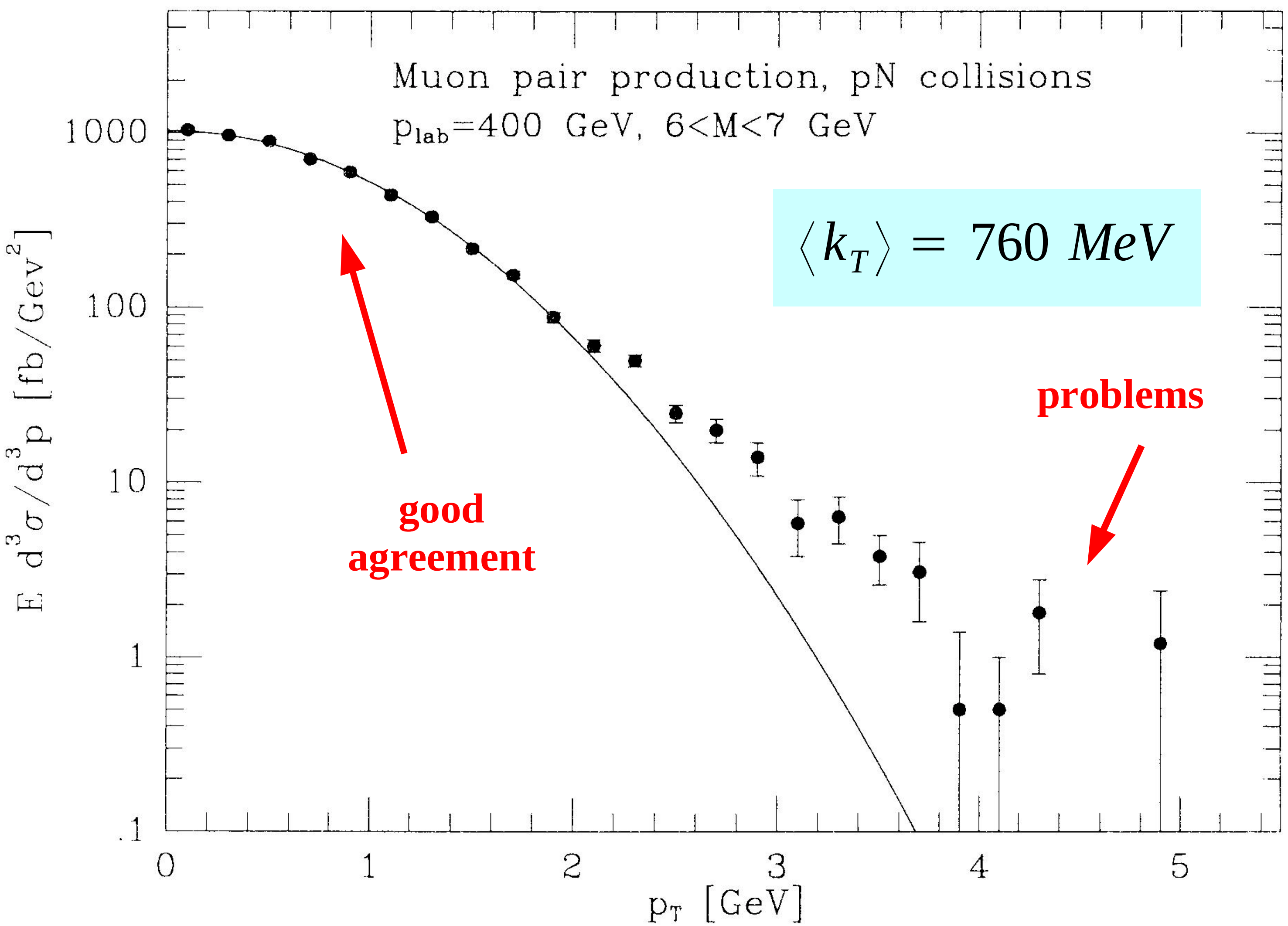
What gives the W

P_T ???

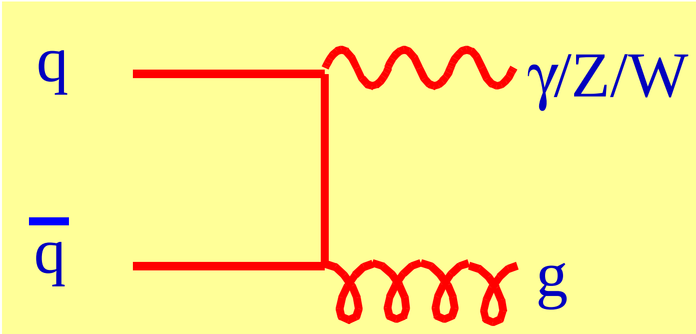
What about the intrinsic k_T of the partons?

Assume a Gaussian form:

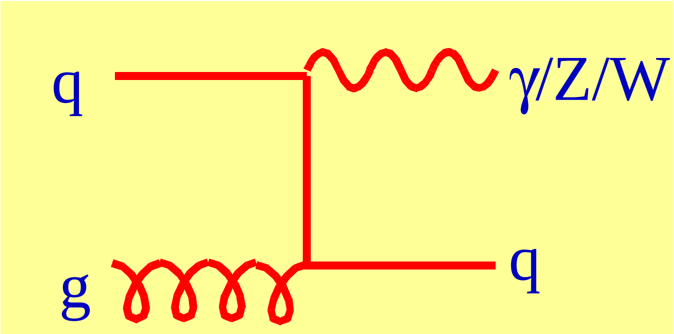
$$\frac{d^2\sigma}{d^2 p_T} \approx \sigma_0 \, e^{-p_T^2}$$



For high P_T, we need a hard parton emission



annihilation



Compton

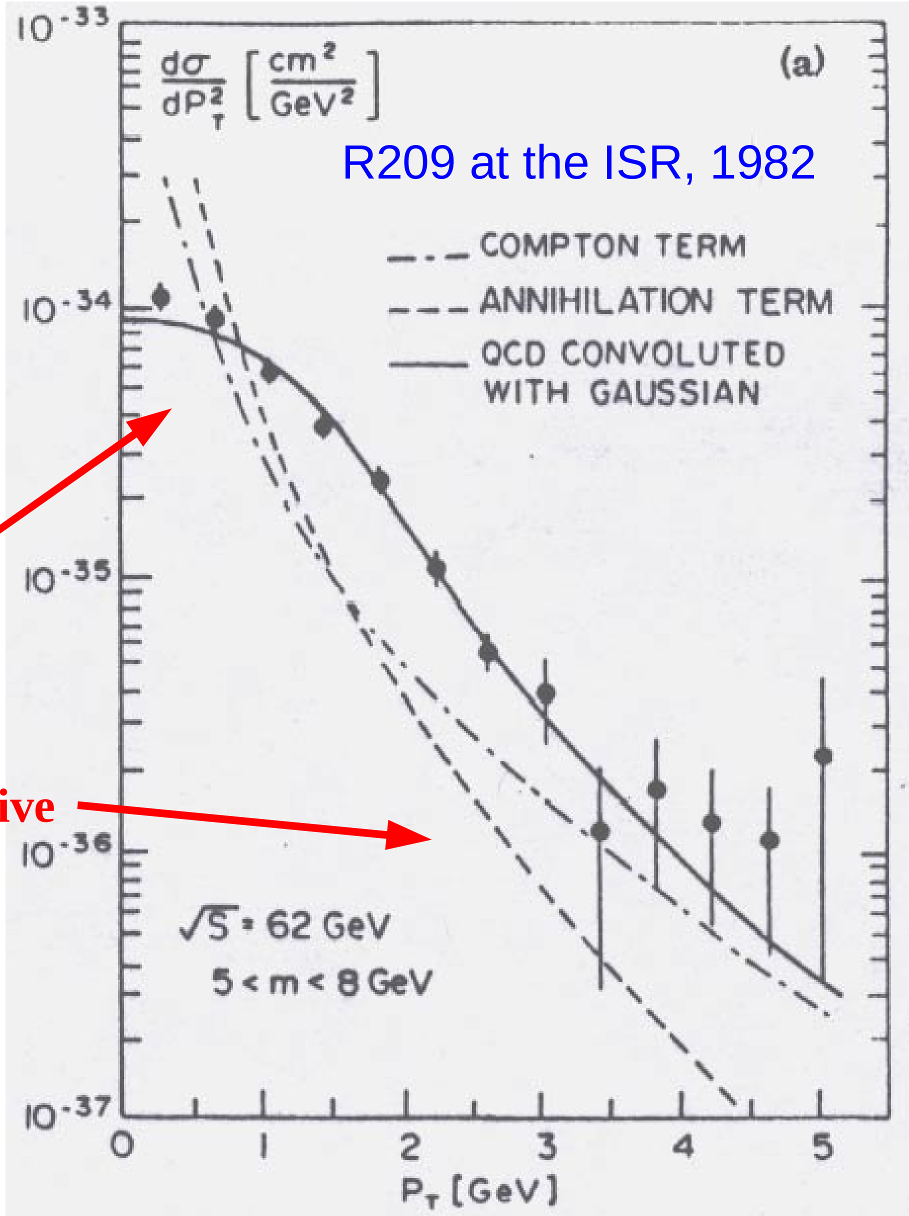
Combination of Gaussian & QCD corrections

Gaussian

$$e^{-p_T^2}$$

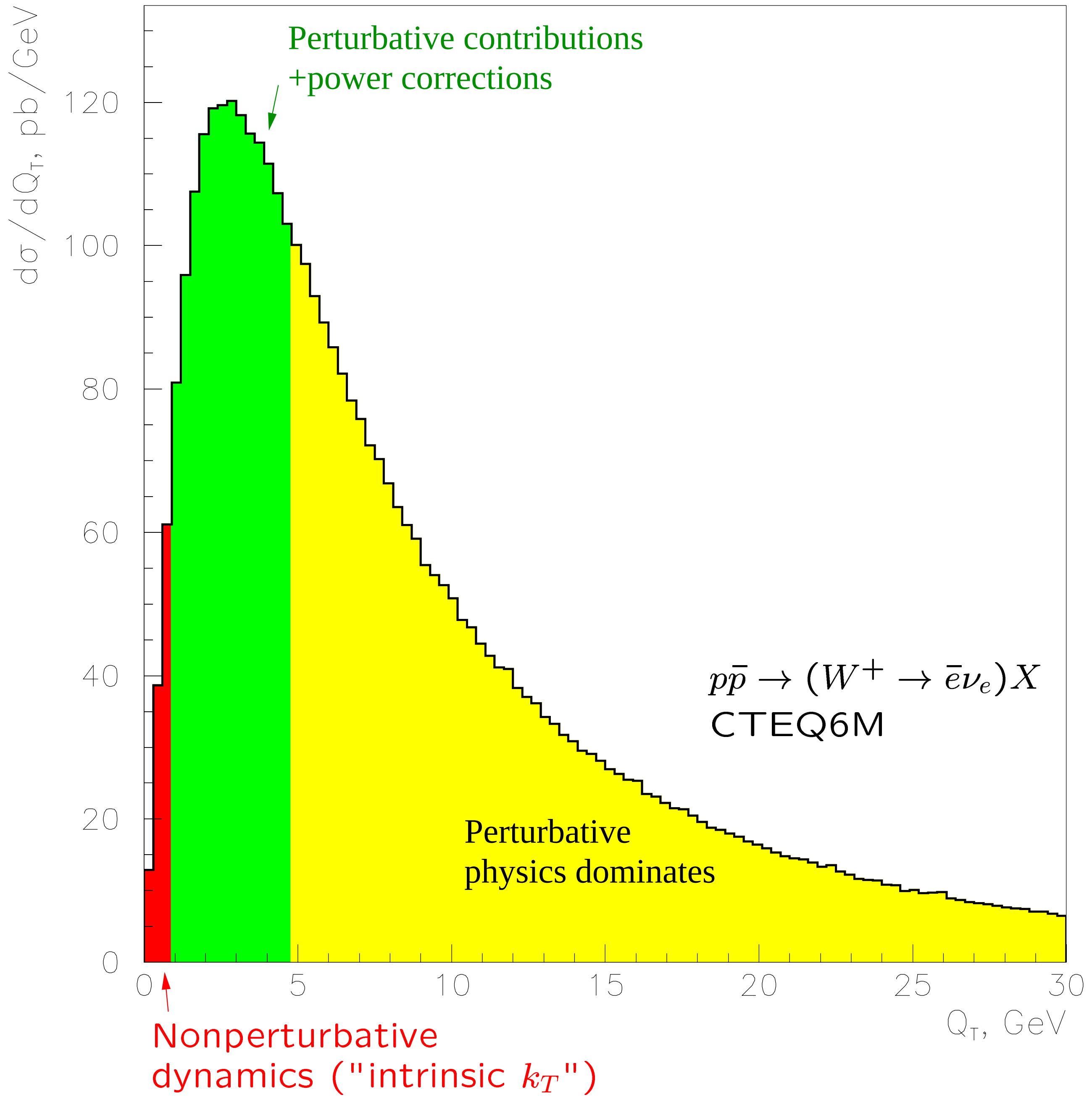
Perturbative

$$\frac{1}{p_T^2}$$



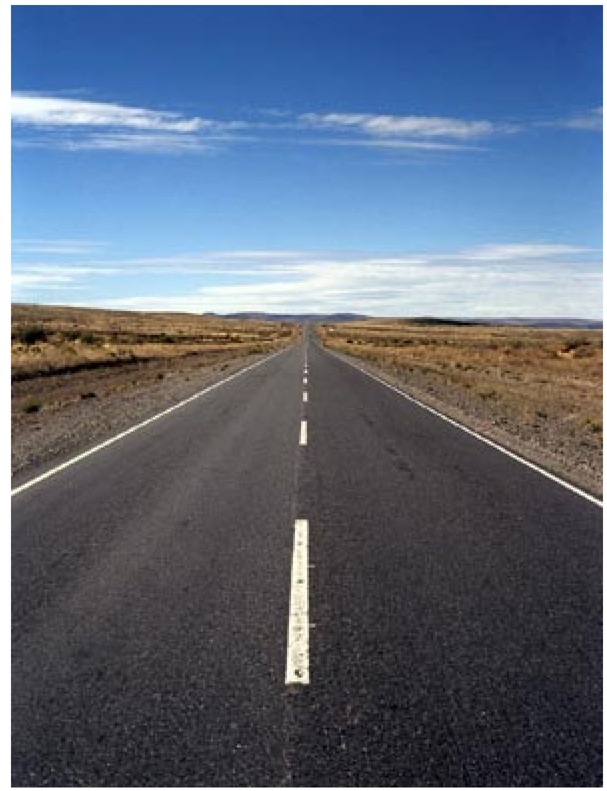
The complete P_T spectrum for the W boson

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



Road map for Resummation

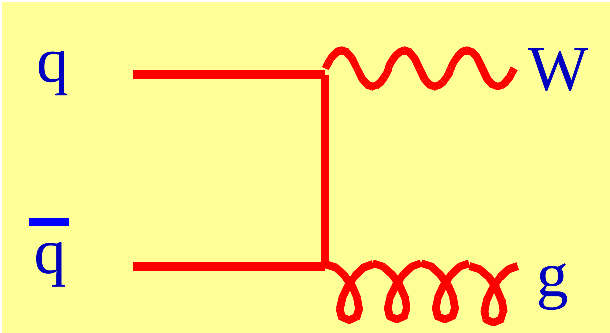
$\Rightarrow$



BEFORE

AFTER

NLO P_T distribution for the W boson



In the limit $P_T \rightarrow 0$

$$\frac{d\sigma}{d\tau\, dy\, dp_T^2} \approx \left(\frac{d\sigma}{d\tau\, dy}\right)_{Born} \times \frac{4\alpha_s}{3\pi} \frac{\ln s/p_T^2}{p_T^2}$$

singular

$$\int_0^s \frac{d\sigma}{d\tau\, dy\, dp_T^2}\, dp_T^2 = \left(\frac{d\sigma}{d\tau\, dy}\right)_{Born} + O(\alpha_s)$$

finite

$$\int_0^{p_T^2} \frac{d\sigma}{d\tau\, dy\, dp_T^2}\, dp_T^2 = \left(\frac{d\sigma}{d\tau\, dy}\right)_{Born} \times \left\{1 - \int_{p_T^2}^{s} \frac{4\alpha_s}{3\pi} \frac{\ln s/p_T^2}{p_T^2}\, d\,p_T^2\right\}$$

$$= \left(\frac{d\sigma}{d\tau\, dy}\right)_{Born} \times \left\{1 - \frac{2\alpha_s}{3\pi} \ln^2 \frac{s}{p_T^2}\right\}$$

effect of gluon emission

$$= \left(\frac{d\sigma}{d\tau\, dy}\right)_{Born} \times \exp\left\{\frac{2\alpha_s}{3\pi} \ln^2 \frac{s}{p_T^2}\right\}$$

assume this exponentiates

Parisi & Petronzio, NP B154, 427 (1979)
Dokshitzer, D'yakanov, Troyan, Phy. Rep. 58, 271 (1980)

Resummation of soft gluons: Step #1

Sudakov Form Factor

Differentiating the previous expression for $d^2\sigma/d\tau\, dy$

$$\frac{d\sigma}{d\tau\, dy\, dp_T^2} \approx \left(\frac{d\sigma}{d\tau\, dy}\right)_{Born} \times \frac{4\alpha_s}{3\pi} \frac{\ln s/p_T^2}{p_T^2} \times \exp\left\{-\frac{2\alpha_s}{3\pi}\ln^2\frac{s}{p_T^2}\right\}$$

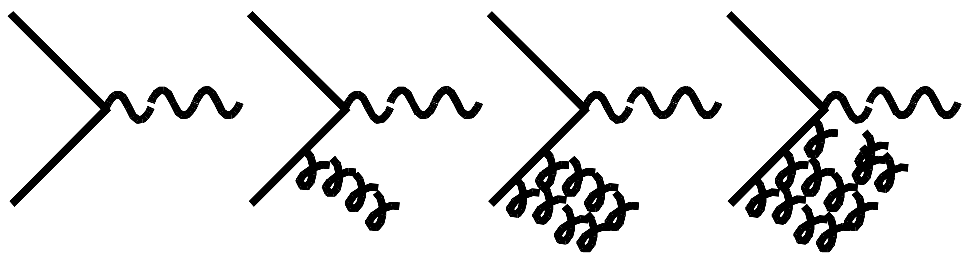
finite at p_T=0

We just resummed (exponentiated) an infinite series of soft gluon emissions

$$e^{-\alpha_s L^2} \approx 1 - \alpha_s L^2 + \frac{(\alpha_s L^2)^2}{2!} - \frac{(\alpha_s L^2)^3}{3!} + \ \ldots$$

$$L = \ln\frac{s}{p_T^2}$$

Soft gluon emissions treated as uncorrelated



I've skipped over some details ..

Parisi & Petronzio, NP B154, 427 (1979)
Dokshitzer, D'yakanov, Troyan, Phy. Rep. 58, 271 (1980)

Curci, Greco, Srivastava, PRL 43, 834 (1979); NP B159, 451 (1979)
Jeff Owens, 2000 CTEQ Summer School Lectures

We skipped over a few details ...

1) We summed only the leading logarithmic singularity, $\alpha_s L^2$.

We'll need to do better to ensure convergence of perturbation series

2) We assumed exponentiation; proof of this is non-trivial.

The existence of two scales $(Q,p_T) \equiv (Q,q_T)$ yields 2 logs per loop

3) Gluon emission was assumed to be uncorrelated.

This leads to too strong a suppression at $P_T=0$.

Will need to impose momentum conservation for P_T.

4) In the limit $P_T \to 0$, terms of order $\alpha_S(\mu=P_T) \to \infty$;

Must handle this Non-Perturbative region.

1) We summed only the leading logarithmic singularity

we resum these terms

we miss these terms

$$\frac{d\sigma}{dq_T^2} \sim \frac{\alpha_s L}{q_T^2}\left\{1 + \alpha_s^1 L^2 + \alpha_s^2 L^4 + \ldots\right\}$$

$$\frac{\alpha_s L}{q_T^2}\left\{ \quad + \alpha_s^1 L^1 + \alpha_s^2 L^3 + \alpha_s^3 L^5 + \ldots\right\}$$

$$L = \ln \frac{s}{p_T^2}$$

The terms we are missing are suppressed by $\alpha_s L$, not α_s!

If (somehow) we could sum the sub-leading log ...

$$\frac{d\sigma}{dq_T^2} \sim \frac{\alpha_s L}{q_T^2}\, e^{\alpha_s (L^2 + L)}$$

we resum these terms

we miss these terms

$$\frac{d\sigma}{dq_T^2} \sim \frac{1}{q_T^2}\left\{\alpha_s^1 (L^1 + 1) + \alpha_s^2 (L^3 + L^2) + \alpha_s^3 (L^5 + L^4) + \ldots\right\}$$

$$\frac{1}{q_T^2}\left\{ \quad + \alpha_s^2 (L^1 + 1) + \alpha_s^3 (L^3 + L^2) + \alpha_s^4 (L^5 + L^4) + \ldots\right\}$$

Now, the terms we are missing are suppressed only by α_s!

2) We assumed exponentiation; proof is non-trivial

Review where the logs come from

Review one-scale problem *(Q)*

resummation via RGE

Review two-scale problem (Q,q_T)

resummation via RGE+ Gauge Invariance

Where do the

Logs come from?

Total Cross Section: $\sigma(e^+e^-)$ at 3 Loops

$$\sigma(Q^2)=\sigma_0\Bigg\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left(\frac{3}{2}\right)+C_FC_A\left(\frac{123}{2}-44\zeta(3)\right)-C_FTn_f(-22+16\zeta(3))\right]$$

$$+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^3\Bigg[C_F^3\left(-\frac{69}{2}\right)+C_F^2C_A(-127-572\zeta(3)+880\zeta(5))$$

$$+C_FC_A^2\left(\frac{90445}{54}-\frac{10948}{9}\zeta(3)+\frac{440}{3}\zeta(5)\right)$$

$$+C_F^2Tn_f(-29+304\zeta(3)-320\zeta(5))+C_FC_ATn_f\left(-\frac{31040}{27}+\frac{7168}{9}\zeta(3)+\frac{160}{3}\zeta(5)\right)$$

$$+C_FT^2n_f^2\left(\frac{4832}{27}-\frac{1216}{9}\zeta(3)\right)-C_F\pi^2\left(\frac{11}{3}C_A-\frac{4}{3}Tn_f\right)^2+\frac{\left(\sum_f Q_f\right)^2}{\left(N\sum_f Q_f^2\right)}\frac{D}{16}\left(\frac{176}{3}-128\zeta(3)\right)\Bigg]\Bigg\}. \quad (5.1)$$

Rev. Mod. Phys., Vol. 67, No. 1, January 1995

One mass scale: Q^2. No logarithms!!!

Drelly-Yan at 2 Loops:

$$
\begin{aligned}
H^{(2),S+V}_{q\bar q}(z) = \left[\frac{\alpha_s}{4\pi}\right]^2 \delta(1-z) \Bigg\{ C_A C_F \Bigg[& \left[\tfrac{193}{3} - 24\zeta(3)\right] \ln\left[\frac{Q^2}{M^2}\right] - 11 \ln^2\left[\frac{Q^2}{M^2}\right] - \tfrac{12}{5}\zeta(2)^2 + \tfrac{592}{9}\zeta(2) + 28\zeta(3) - \tfrac{1535}{12} \Bigg] \\
& + C_F^2 \Bigg[[18 - 32\zeta(2)] \ln^2\left[\frac{Q^2}{M^2}\right] + [24\zeta(2) - 176\zeta(3) - 93] \ln\left[\frac{Q^2}{M^2}\right] \\
& \quad + \tfrac{8}{5}\zeta(2)^2 - 70\zeta(2) - 60\zeta(3) + \tfrac{511}{4} \Bigg] \\
& + n_f C_F \Bigg[2 \ln^2\left[\frac{Q^2}{M^2}\right] - \tfrac{34}{3} \ln\left[\frac{Q^2}{M^2}\right] + 8\zeta(3) - \tfrac{112}{9}\zeta(2) + \tfrac{127}{6} \Bigg] \Bigg\} \\
+ C_A C_F \Bigg[& -\tfrac{44}{3}\mathcal{D}_0(z) \ln^2\left[\frac{Q^2}{M^2}\right] + \left\{ \left[\tfrac{536}{9} - 16\zeta(2)\right]\mathcal{D}_0(z) - \tfrac{176}{3}\mathcal{D}_1(z) \right\} \ln\left[\frac{Q^2}{M^2}\right] \\
& - \tfrac{176}{3}\mathcal{D}_2(z) + \left[\tfrac{1072}{9} - 32\zeta(2)\right]\mathcal{D}_1(z) + \left[56\zeta(3) + \tfrac{176}{3}\zeta(2) - \tfrac{1616}{27}\right]\mathcal{D}_0(z) \Bigg] \\
+ C_F^2 \Bigg[& [64\mathcal{D}_1(z) + 48\mathcal{D}_0(z)] \ln^2\left[\frac{Q^2}{M^2}\right] + \{192\mathcal{D}_2(z) - 96\mathcal{D}_1(z) - [128 + 64\zeta(2)]\mathcal{D}_0(z)\} \ln\left[\frac{Q^2}{M^2}\right] \\
& + 128\mathcal{D}_3(z) - (128\zeta(2) + 256)\mathcal{D}_1(z) + 256\zeta(3)\mathcal{D}_0(z) \Bigg] \\
+ n_f C_F \Bigg[& \tfrac{8}{3}\mathcal{D}_0(z) \ln^2\left[\frac{Q^2}{M^2}\right] + \left[\tfrac{32}{3}\mathcal{D}_1(z) - \tfrac{80}{9}\mathcal{D}_0(z)\right] \ln\left[\frac{Q^2}{M^2}\right] + \tfrac{32}{3}\mathcal{D}_2(z) - \tfrac{160}{9}\mathcal{D}_1(z) - \left[\tfrac{224}{27} - \tfrac{32}{3}\zeta(2)\right]\mathcal{D}_0(z) \Bigg] .
\end{aligned}
\tag{7.14}
$$

Two mass scales: $\{Q^2, M^2\}$. Logarithms!!!

Renormalization Group Equation

More Differential Quantities ⇒ More Mass Scales ⇒ More Logs!!!

$$\frac{d\sigma}{dQ^2} \sim \ln\left(\frac{Q^2}{\mu^2}\right)$$

$$\frac{d\sigma}{dQ^2} \sim \ln\left(\frac{Q^2}{\mu^2}\right) \quad and \quad \ln\left(\frac{q_T^2}{\mu^2}\right)$$

How do we resum logs? Use the Renormalization Group Equation

For a physical observable R:

$$\mu \frac{dR}{d\mu} = 0$$

Using the chain rule:

$$\left\{\mu^2 \frac{\partial}{\partial \mu^2} + \left[\mu^2 \frac{\partial \alpha_s(\mu^2)}{\partial \mu^2}\right] \frac{\partial}{\partial \alpha_s(\mu^2)}\right\} R(\mu^2, \alpha_s(\mu^2)) = 0$$

$$\beta\left(\alpha_s(\mu)\right)$$

Solution⇒ $\ln\left(\frac{Q^2}{\mu^2}\right) = \int_{\alpha_s(\mu^2)}^{\alpha_s(Q^2)} \frac{dx}{\beta(x)}$

Renormalization Group Equation: *OVER SIMPLIFIED!*

$$\left\{ \mu^2 \frac{\partial}{\partial \mu^2} + \beta\left(\alpha_s(\mu)\right) \frac{\partial}{\partial \alpha_s(\mu^2)} \right\} R(\mu^2, \alpha_s(\mu^2)) \;=\; 0$$

If we expand R in powers of α_s, and we know β, we then know μ dependence of R.

$$R(\mu, Q, \alpha_s(\mu^2)) \;=\; R_0 + \alpha_s(\mu^2)\, R_1\left[\ln\left(Q^2/\mu^2\right) + c_1\right] + \alpha_s^2(\mu^2)\, R_2\left[\ln^2\left(Q^2/\mu^2\right) + \ln\left(Q^2/\mu^2\right) + c_2\right] + O(\alpha_s^3(\mu^2))$$

Since μ is arbitrary, choose μ=Q.

$$R(Q, Q, \alpha_s(Q^2)) \;=\; R_0 + \alpha_s(Q^2)\, R_1\left[0 + c_1\right] + \alpha_s^2(Q^2)\, R_2\left[0 + 0 + c_2\right] + \ldots$$

We just summed the logs

Two-Scale Problems

For $R(\mu,Q,\alpha_s)$, we could resum $\ln(Q^2/\mu^2)$ by taking $Q=\mu$.

What about $R(\mu,Q,q_T,\alpha_s)$; how do we resum $\ln(Q^2/\mu^2)$ and $\ln(q_T^2/\mu^2)$.

Are we stuck? Can't have $\mu^2=Q^2$ and $\mu^2=q_T^2$ at the same time!

Solution: Use Gauge Invariance; cast in similar form to RGE

Use axial-gauge with axial vector ξ.

This enters the cross section in the form: $(\xi \bullet p)$.

$$\sigma\left(x, \frac{Q^2}{\mu^2}, \frac{(p\cdot\xi)^2}{\mu^2}, \ldots \right)$$

$$\frac{d\sigma}{d\mu^2}=0$$

RGE allows us to vary μ to resum logs

$$\frac{d\sigma}{d\,(p\cdot\xi)^2}=0$$

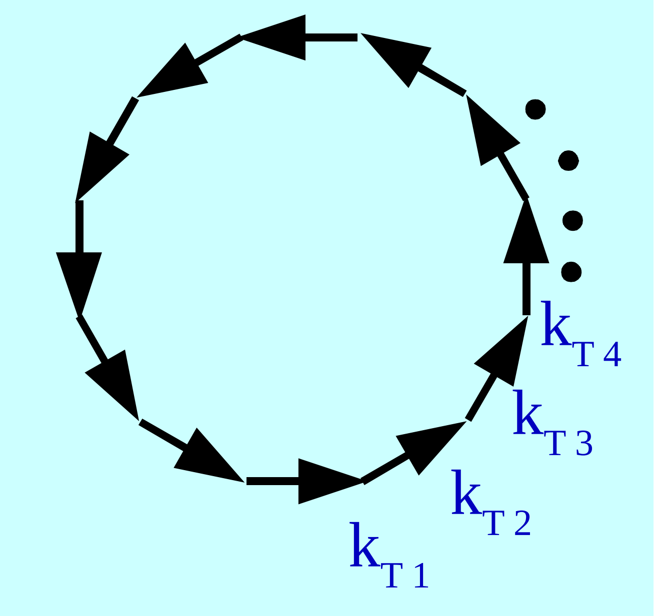
Gauge invariance allows us to vary $(\xi \bullet p)$ to resum logs

It is covenient to transform to impact parameter space (b-space) to implement this mechanism

The details will fill multiple lectures:
See Sterman TASI 1995; Soper CTEQ 1995

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:

$$\delta^{(2)}\left(\sum_{i=1}^{n} \vec{k}_{i\,T} - \vec{p}_T \right) = \frac{1}{(2\pi)^2} \int d^2 b\, e^{-i\vec{b}\cdot\vec{p}_T} \prod_{i=1}^{n} e^{-i\vec{b}\cdot\vec{k}_{i\,T}}$$

4) We encounter Non-Perturbative Physics

$$S(b,Q) = \int_{\sim 1/b^2}^{\sim Q^2} \frac{d\mu^2}{\mu^2} \left\{ A(\alpha_s(\mu^2)) \ln\left(\frac{Q^2}{\mu^2}\right) + B(\alpha_s(\mu^2)) \right\}$$

as b $\to \infty$, $\alpha_S(\sim 1/b) \to \infty$. **PROBLEM!!!**

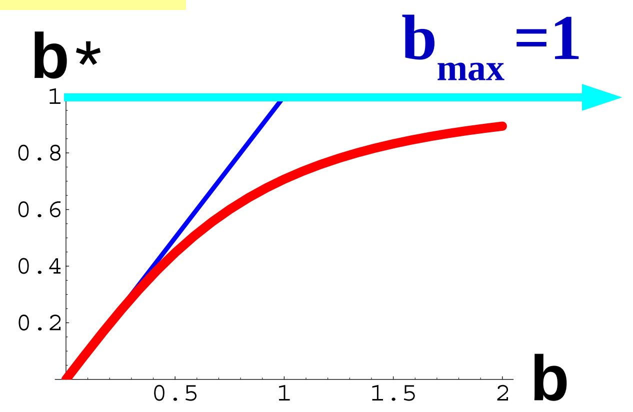
Solution: Use a Non-Perturbative Sudakov form factor (S_{NP}) in the region of large b (small q_T)

$$\tilde{\sigma}(b) \sim e^{S(b)} \to e^{S(b_*)} * e^{S_{NP}(b)}$$

with

$$b_* = \frac{b}{\sqrt{1 + b^2/b_{max}^2}}$$

Note, as b $\to \infty$, $b_* \to b_{max}$.



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): $S_{NP}^{DWS}(b) = b^2\left[g_1 + g_2 \ln(b_{max} Q^2)\right]$

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

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

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": $\widetilde{F}^{NP}(q_T) = 1 - e^{-\tilde{a}\, q_T^2}$ *(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)

Recap: Where have we been???

1) We now summed the two leading logarithmic singularities, $\alpha_s(L^2+L)$.

2) We still assumed exponentiation; but sketched ingredients of proof.

The existence of two scales $(Q,p_T)\equiv(Q,q_T)$ yields 2 logs per loop

Use Renormalization Group + Gauge Invariance

Transformation to b-space

3) Gluon emission was assumed to be uncorrelated.

Impose momentum conservation for P_T. *(In b-space)*

4) Introduced Non-Perturbative function for small q_T (large b) region.

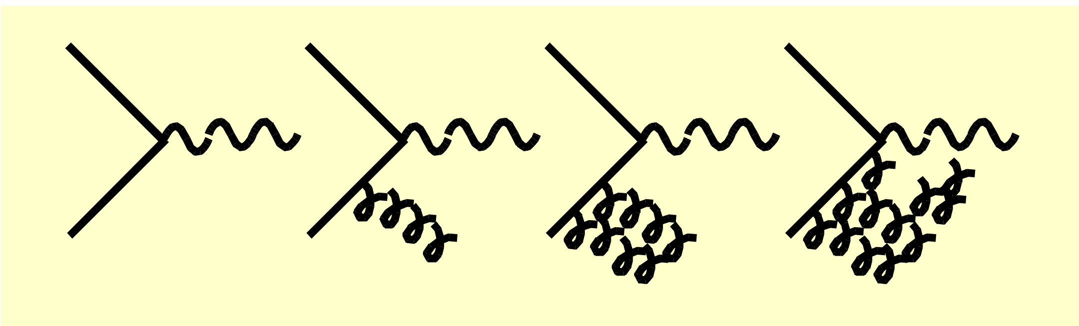
What do we get for the cross section

$$\frac{d\sigma}{dy\,dQ^2\,dq_T^2} = \frac{1}{(2\pi)^2}\int_0^\infty d^2b\; e^{i b\cdot q_T}\,\widetilde{W}(b,Q)\; e^{-S(b_*,Q)+S_{NP}(b,Q)}$$

with

$$-S(b,Q) = -\int_{\sim 1/b^2}^{\sim Q^2} \frac{d\mu^2}{\mu^2}\left\{ A\ln\left(\frac{Q^2}{\mu^2}\right) + B \right\}$$

where we have resummed the soft gluon contributions



I've left out A LOT of material

Putting it all together: $\sigma_{TOT} = \sigma_{RESUM} + \sigma_{PERT} - \sigma_{ASYM}$

Let's expand out the resummed expression:

$$\frac{d\sigma}{dq_T^2} \sim \frac{\alpha_s L}{q_T^2}\, e^{\alpha_s (L^2+L)} \sim \frac{1}{q_T^2}\left\{\alpha_s L \;+\; \alpha_s^2 (L^3 + L^2) + \ldots\right\}$$

Compare the above with the perturbative and asymptotic results:

$$d\sigma_{resum} \sim \left\{\alpha_s L \;+\; \alpha_s^2 (L^3 + L^2 + \;0 + 0) \;+\; \alpha_s^3 (L^5 + L^4) + \ldots\right\}$$

$$d\sigma_{pert} \sim \left\{\alpha_s L \;+\; \alpha_s^2 (L^3 + L^2 + L^1 + 1) \;+\; \alpha_s^3 (0 + 0)\right\}$$

$$d\sigma_{asym} \sim \left\{\alpha_s L \;+\; \alpha_s^2 (L^3 + L^2 + \;0 + 0) \;+\; \alpha_s^3 (0 + 0)\right\}$$

Note that σ_{ASYM} removes overlap between σ_{RESUM} and σ_{PERT}.

We expect:

σ_{RESUM} is a good representation for $q_T \sim 0$

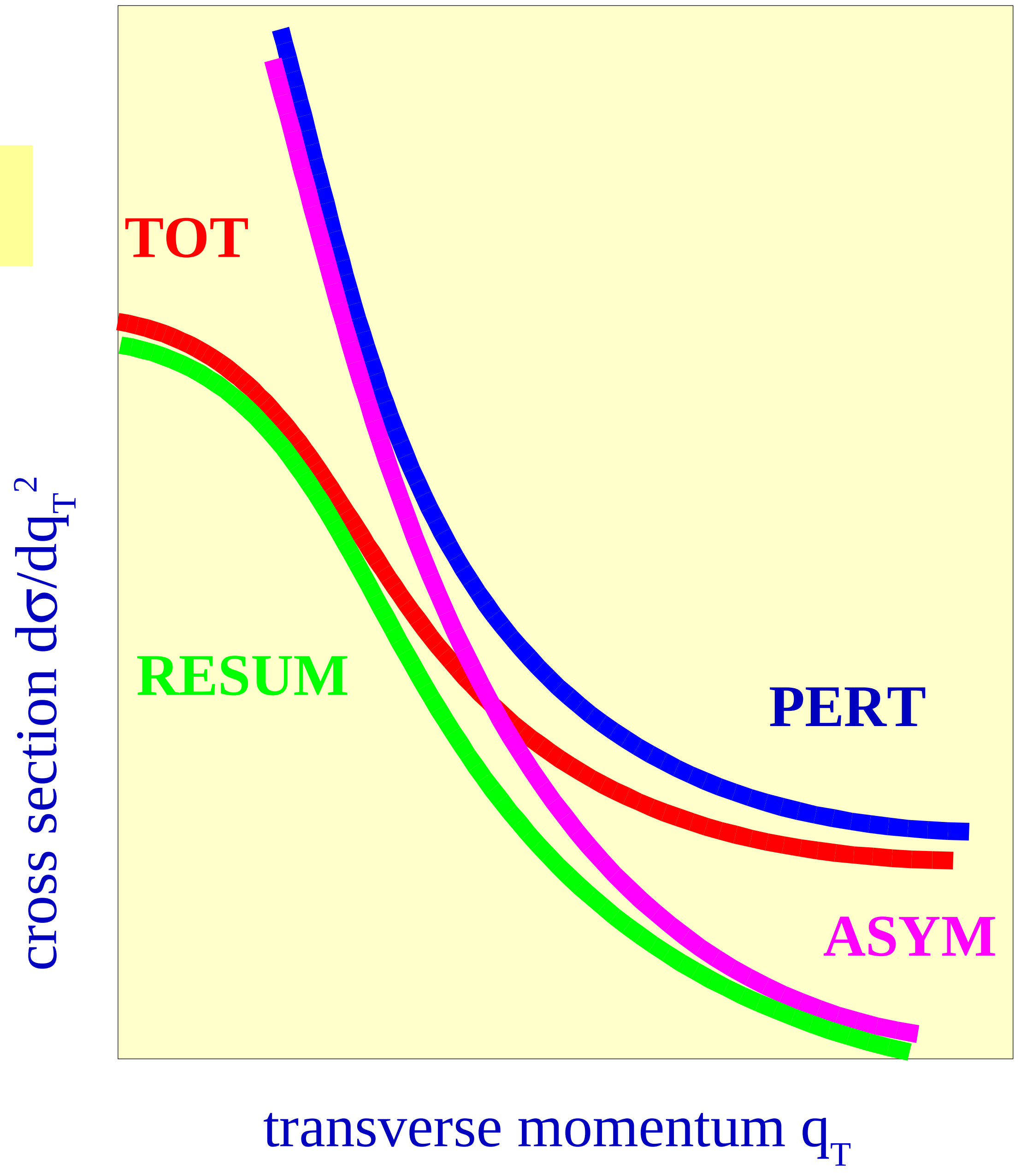
σ_{PERT} is a good representation for $q_T \sim M_W$

Putting it all together: $\sigma_{TOT} = \sigma_{RESUM} + \sigma_{PERT} - \sigma_{ASYM}$

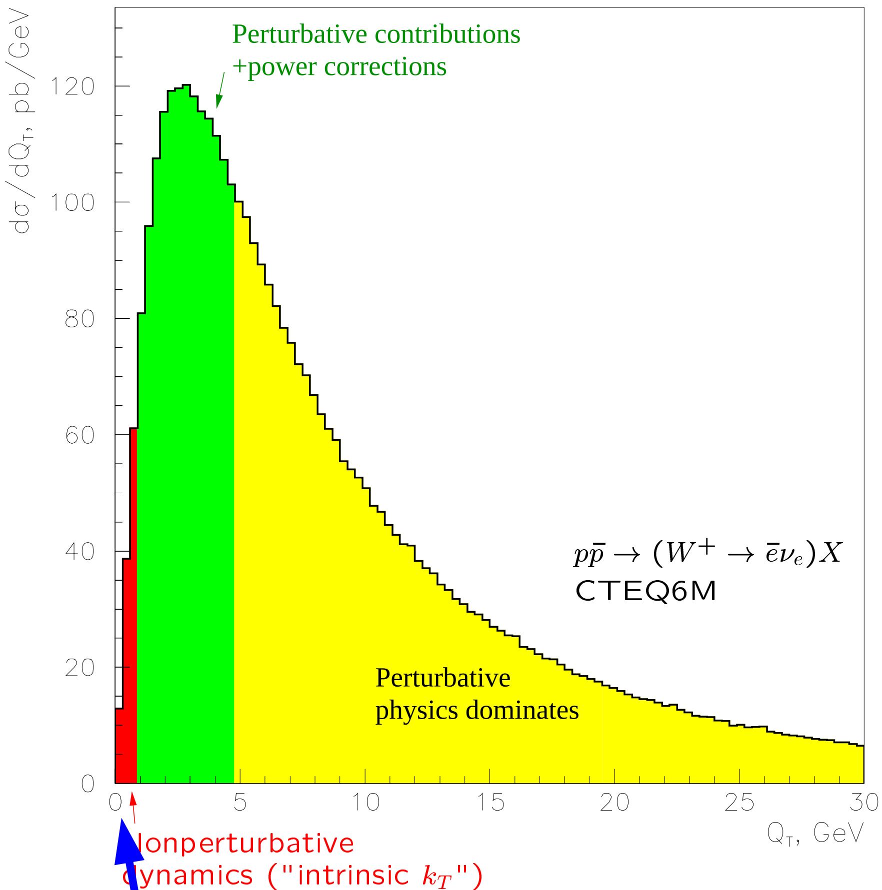
$\sigma_{TOT} = \sigma_{RESUM} + \sigma_{PERT} - \sigma_{ASYM}$

σ_{RESUM} for $q_T \sim 0$

σ_{PERT} for $q_T \sim M_W$

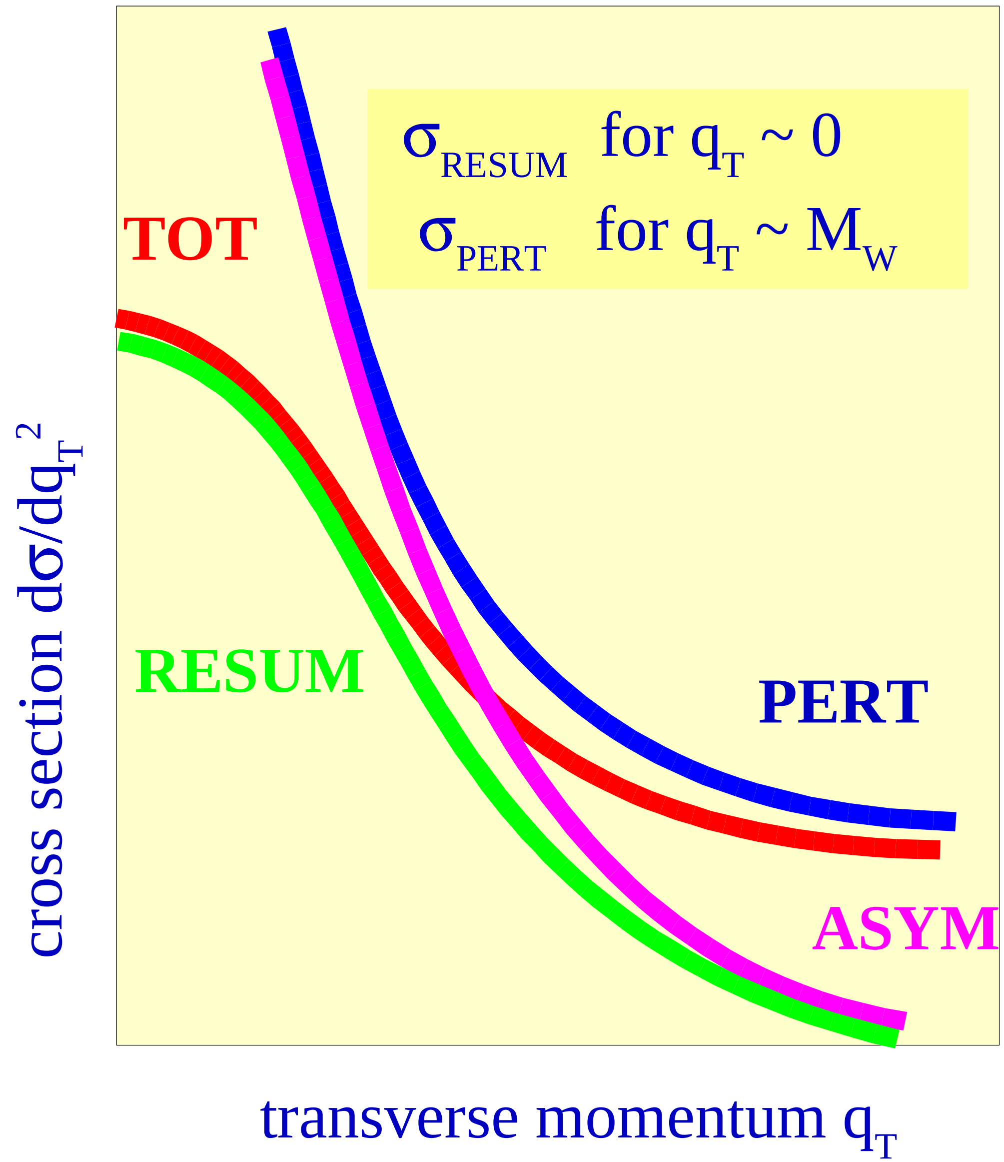


Putting it all together: $\sigma_{TOT} = \sigma_{RESUM} + \sigma_{PERT} - \sigma_{ASYM}$



Extra power of q_T

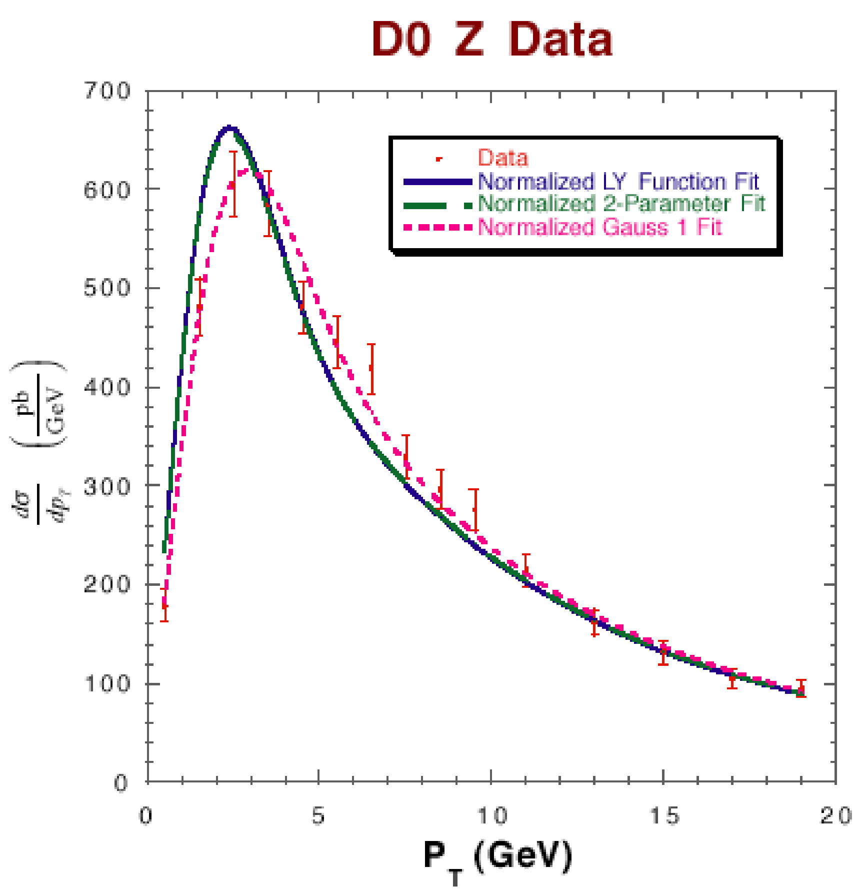
$d\sigma/dq_T^{\,1}$

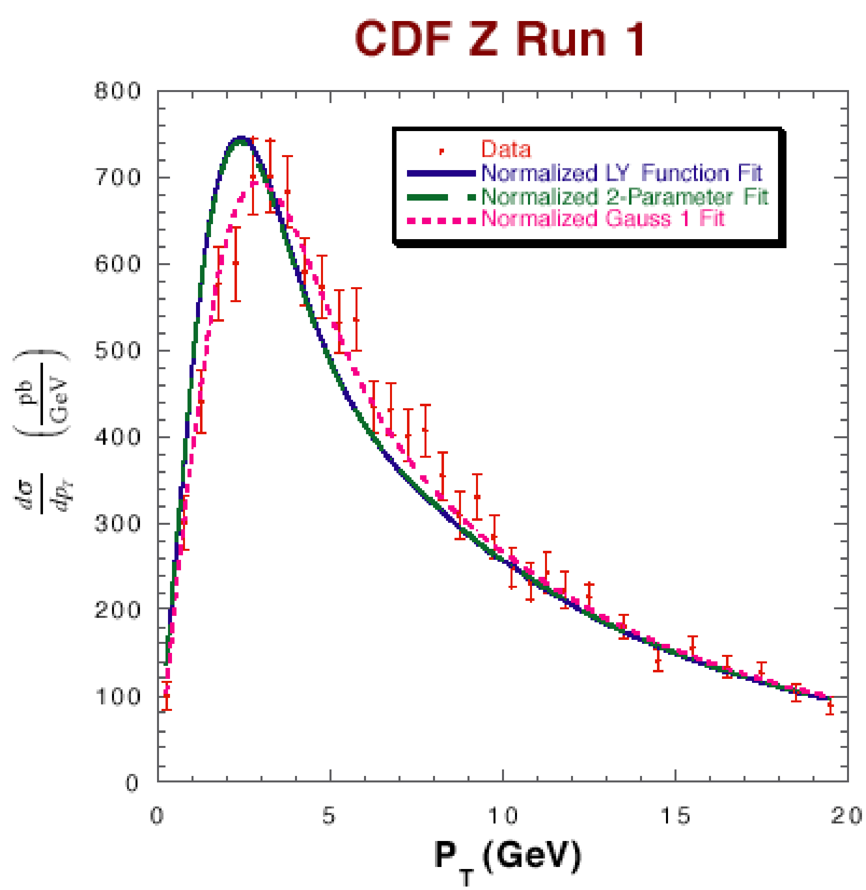


$\sigma_{TOT} = \sigma_{RESUM} + \sigma_{PERT} - \sigma_{ASYM}$

Let's compare with some real results

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.

Let's return

to the

measurement

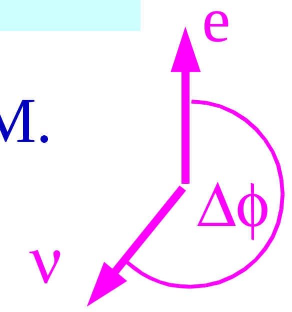
of M_W

Transverse Mass Distribution

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 $$M_T^2(e,\nu) = \left(|\vec{p}_{eT}|+|\vec{p}_{\nu T}|\right)^2 - \left(\vec{p}_{eT}+\vec{p}_{\nu T}\right)^2$$

Invariant Mass $$M^2(e,\nu) = \left(|\vec{p}_{e}|+|\vec{p}_{\nu}|\right)^2 - \left(\vec{p}_{e}+\vec{p}_{\nu}\right)^2$$



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: $$M_T^2(e,\nu) = 2|\vec{p}_{eT}||\vec{p}_{\nu T}|\left(1-\cos\Delta\phi_{e\nu}\right)$$

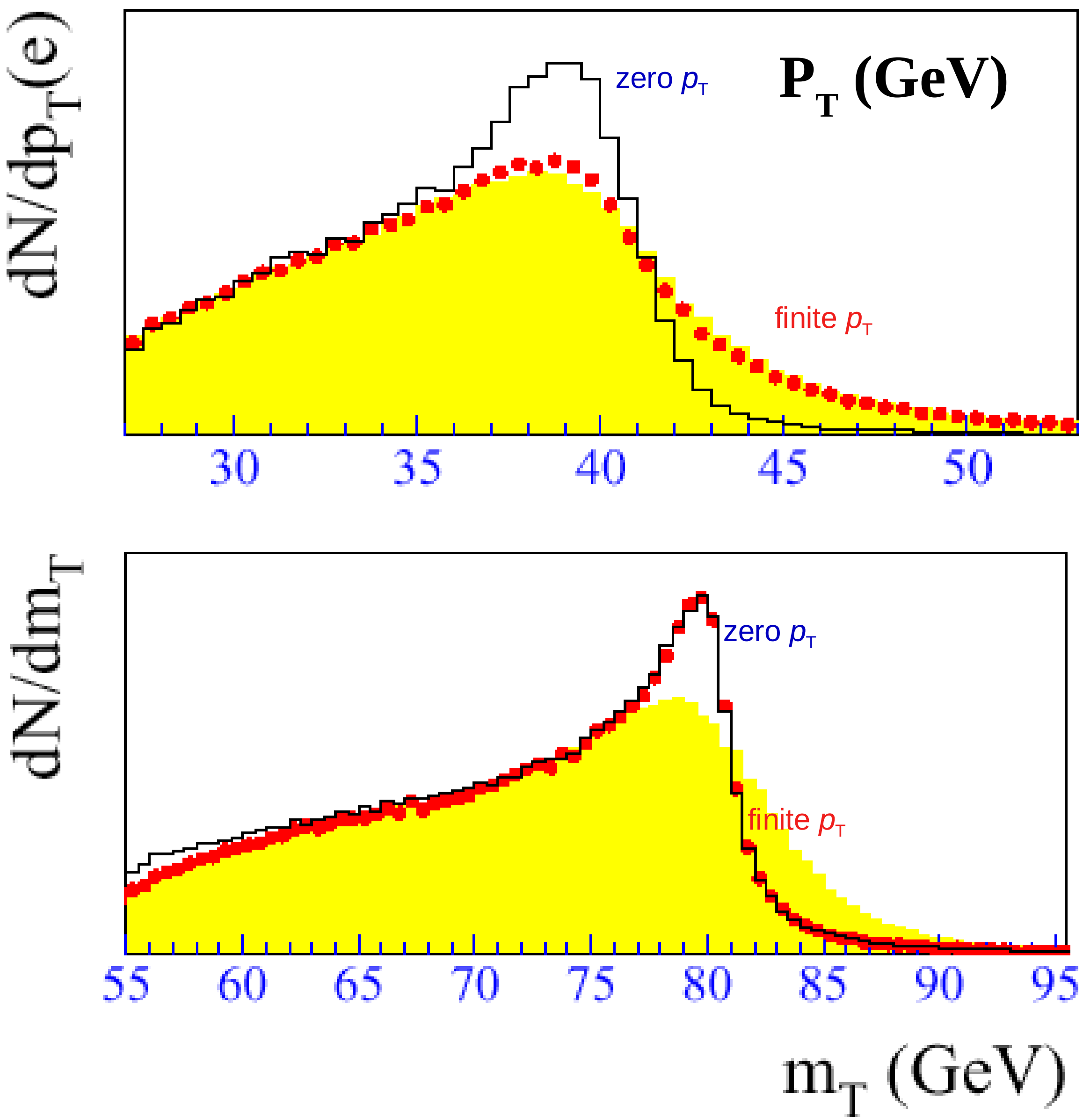
For small values of P_T^W, M_T is invariant to leading order.

Exercise:

a) Verify the above definitions of M_T are ≡.

b) For $p_{Te} = +p^* + p_T^W/2$ and $p_{T\nu} = -p^* + p_T^W/2$; verify M_T is invariant to leading order in p_T^W.

Compare P_T and Transverse Mass Distribution



M_T distribution is much less sensitive to P_T of W

Still, we need P_T distribution of W to extract mass and width with precision

PDF and p_T(W) uncertainties will need to be controlled: currently uncertainty: ~10-15 & 5-10 MeV/c^2

Statistical precision in Run II will be miniscule…placing an enormous burden on control of modeling uncertainties.

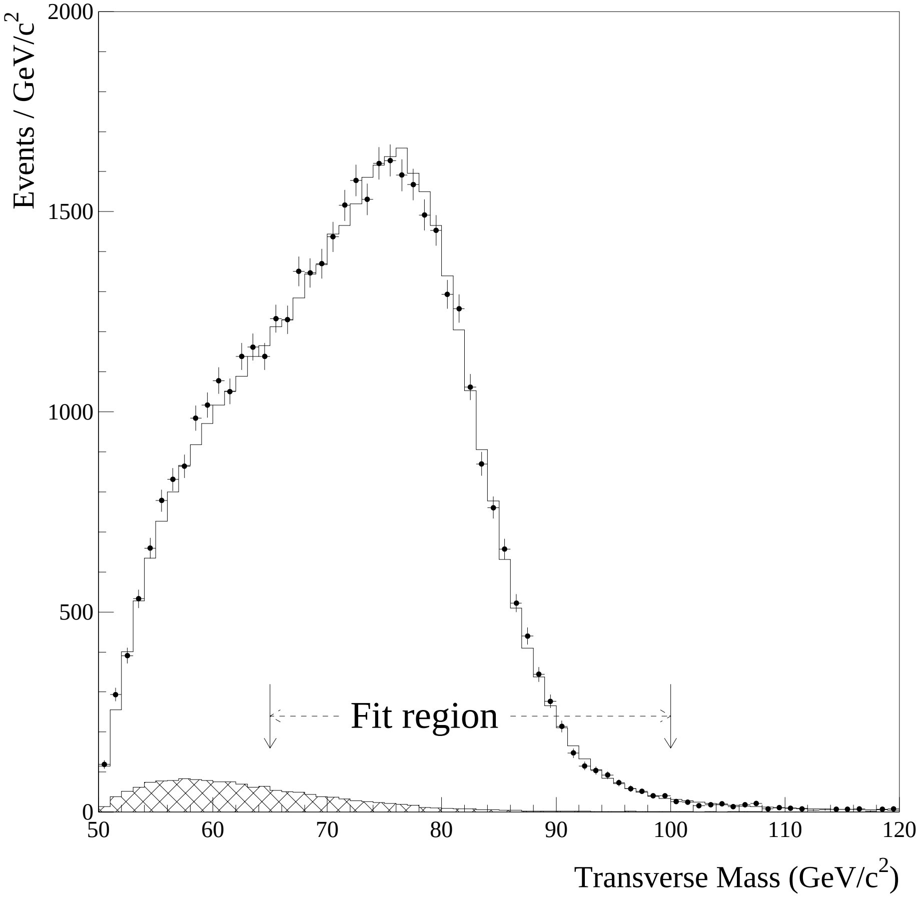
The Future:

Tevatron Run II ... *happening now*

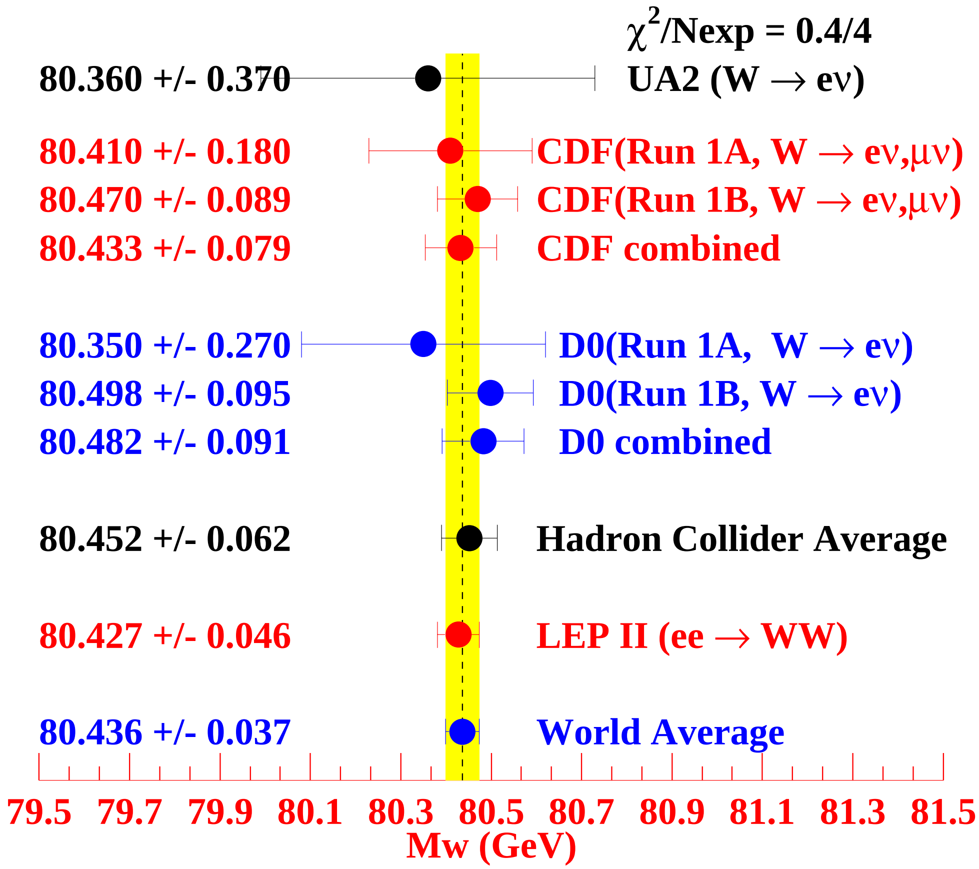
LHC ... *happening soon*

Transverse Mass Distribution and M_W Measurement

Transverse Mass Distribution from CDF



Combined World Measurements of M_W



T.Affolder, et al. [CDF Collaboration], PRD64, 052001 (2001)
Measurement of the W boson mass with the Collider Detector at Fermilab,

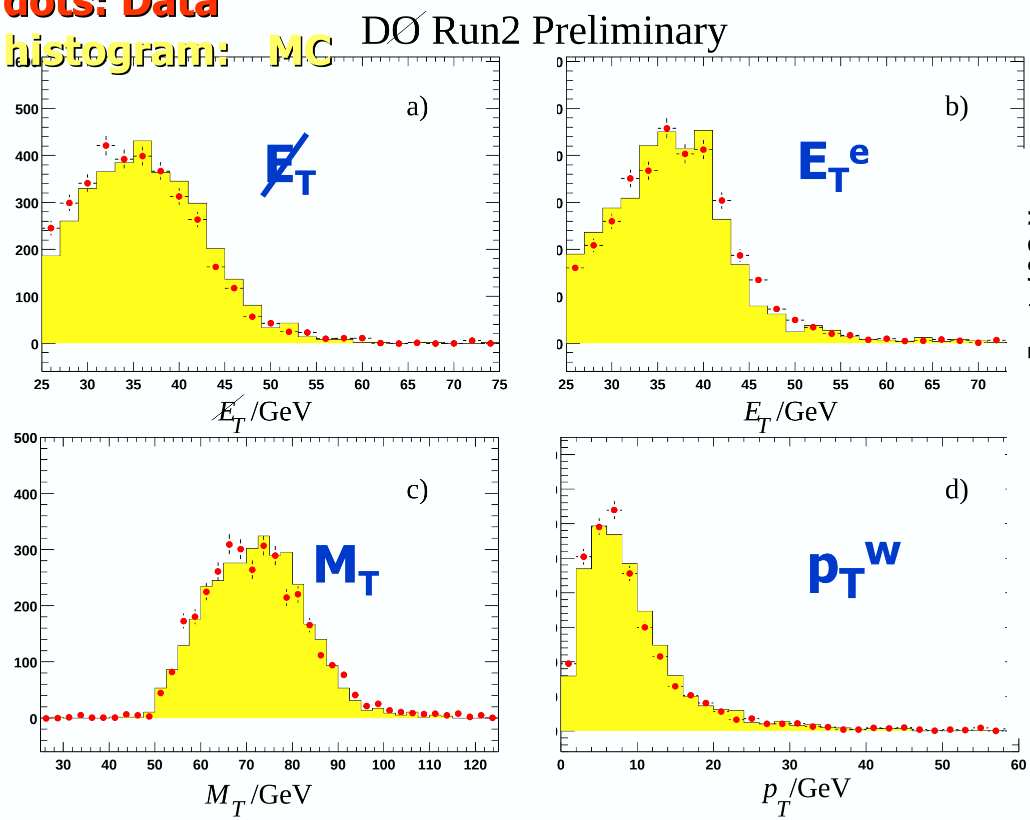
Preliminary
Run II
measurements

Electroweak Physics

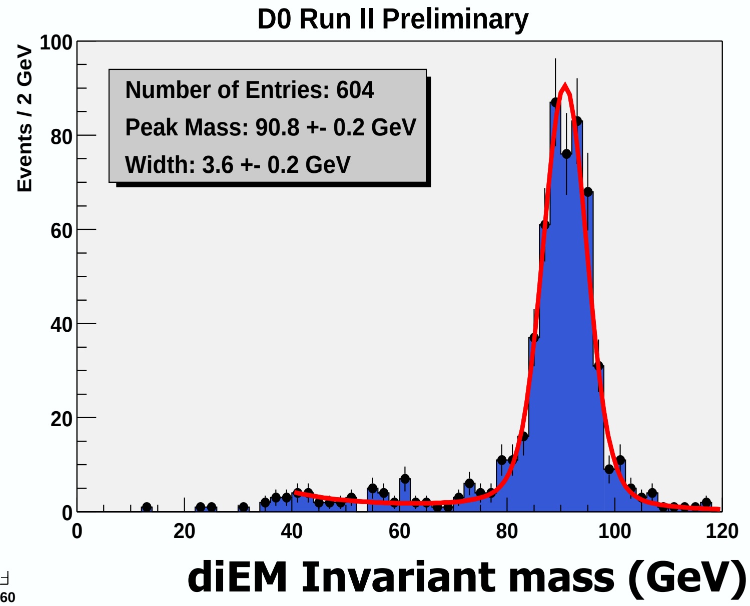
High priority measurements

- W→eν cross-section

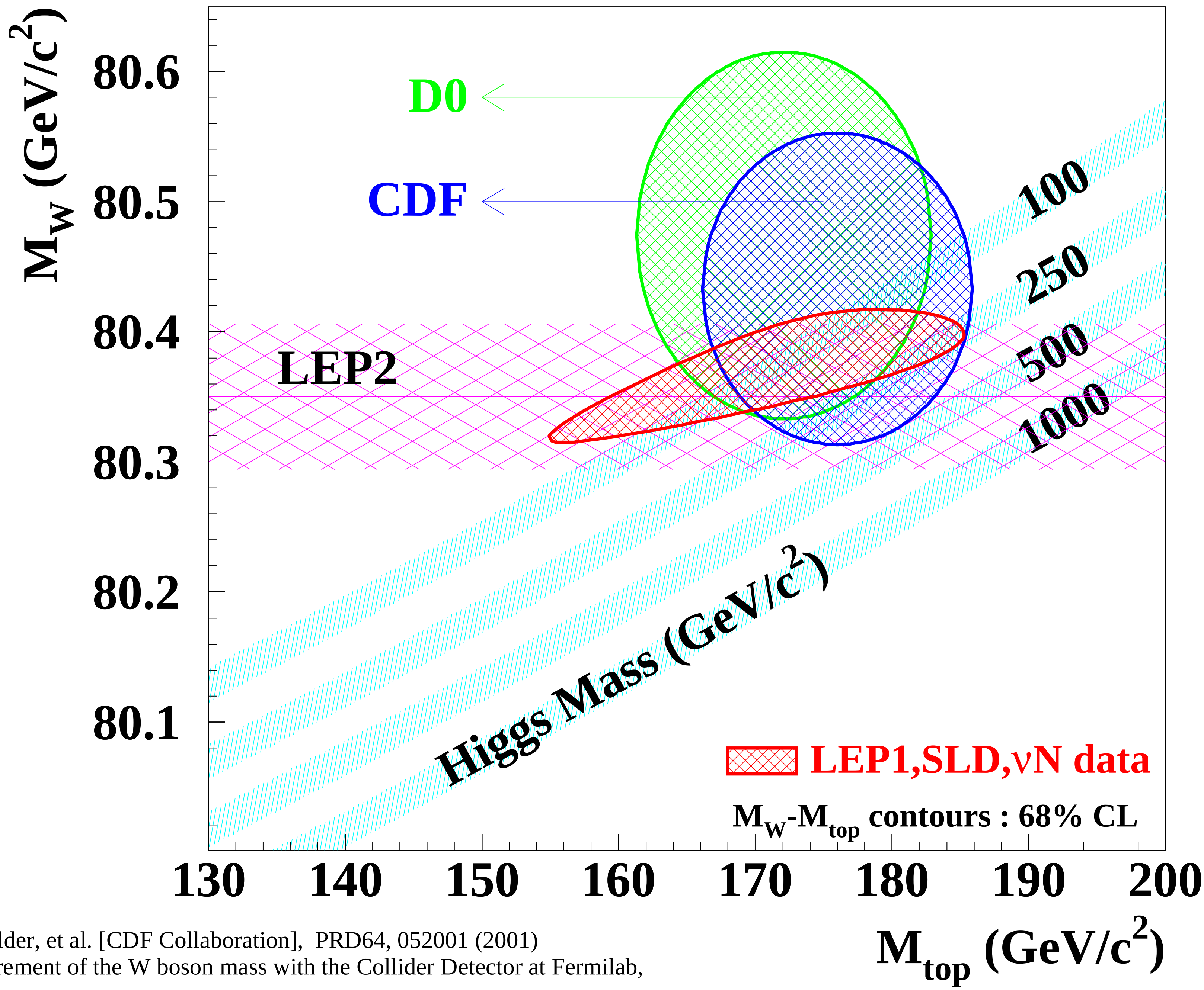
dots: Data
histogram: MC



- Z→e⁺e⁻ cross-section



The W-Mass is an important fundamental quantity



T.Affolder, et al. [CDF Collaboration], PRD64, 052001 (2001)
Measurement of the W boson mass with the Collider Detector at Fermilab,

Part II: Drell-Yan Process: Where have we been???

Finding the W Boson Mass:

- The Jacobian Peak, and the W Boson P_T
- Multiple Soft Gluon Emissions
- Single Hard Gluon Emission

Road map of Resummation

- Summing 2 logs per loop: multi-scale problem (Q,q_T)
- Correlated Gluon Emission
- Non-Perturbative physics at small q_T.

Transverse Mass Distribution:

- Improvement over P_T distribution

What can we expect in future?

- Tevatron Run II
- LHC

Thanks to ...

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Dave Soper

and my other CTEQ colleagues

and the many web pages where I borrowed my figures ...

References:

Ellis, Webber, Stirling

Barger & Phillips, 2nd Edition

Rick Field; Perturbative QCD

CTEQ Handbook
CTEQ Pedagogical Page:

CTEQ Lectures:
C.P. Yuan, 2002
Chip Brock, 2001
Jeff Owens, 2000

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calculate

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