QCD

Sean Fleming
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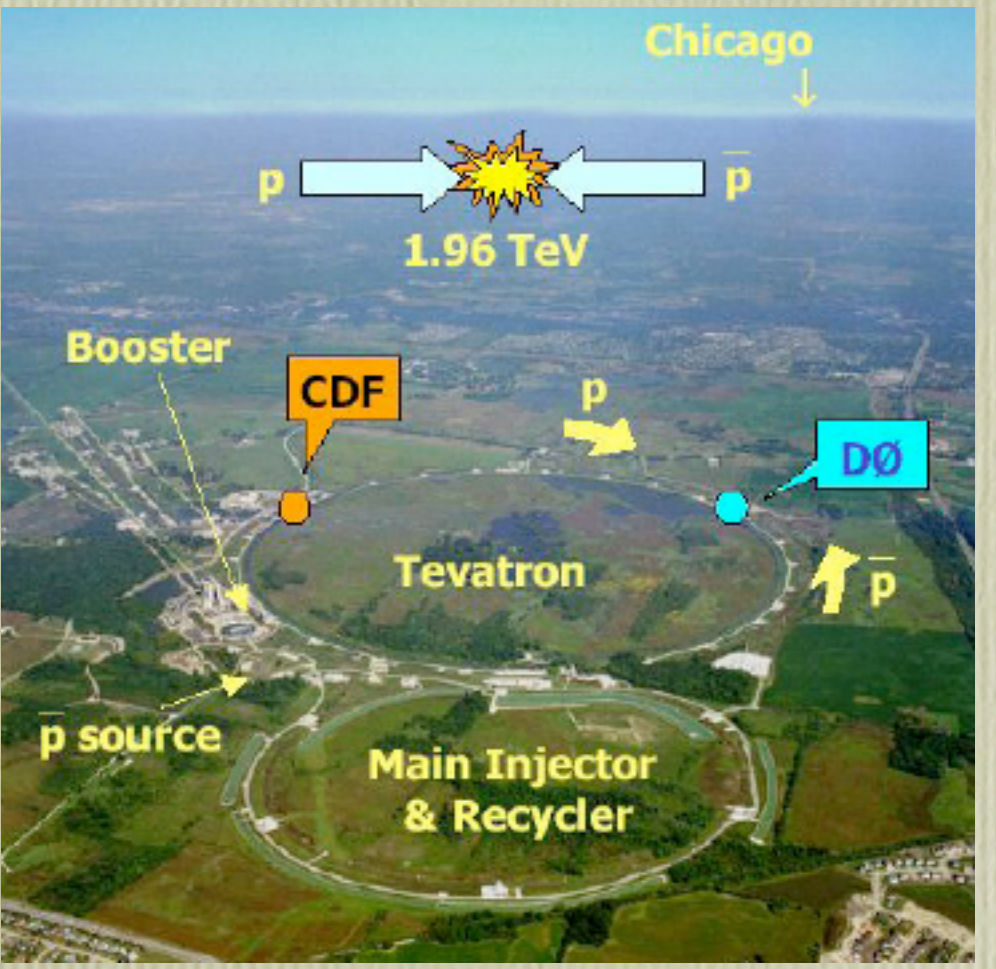
$$\mathcal{L} = -\frac{1}{4} F^A_{\mu\nu}(x) F^{\mu\nu}_A(x) + \bar{\psi}(x)(i\not{D} - m)\psi(x)$$

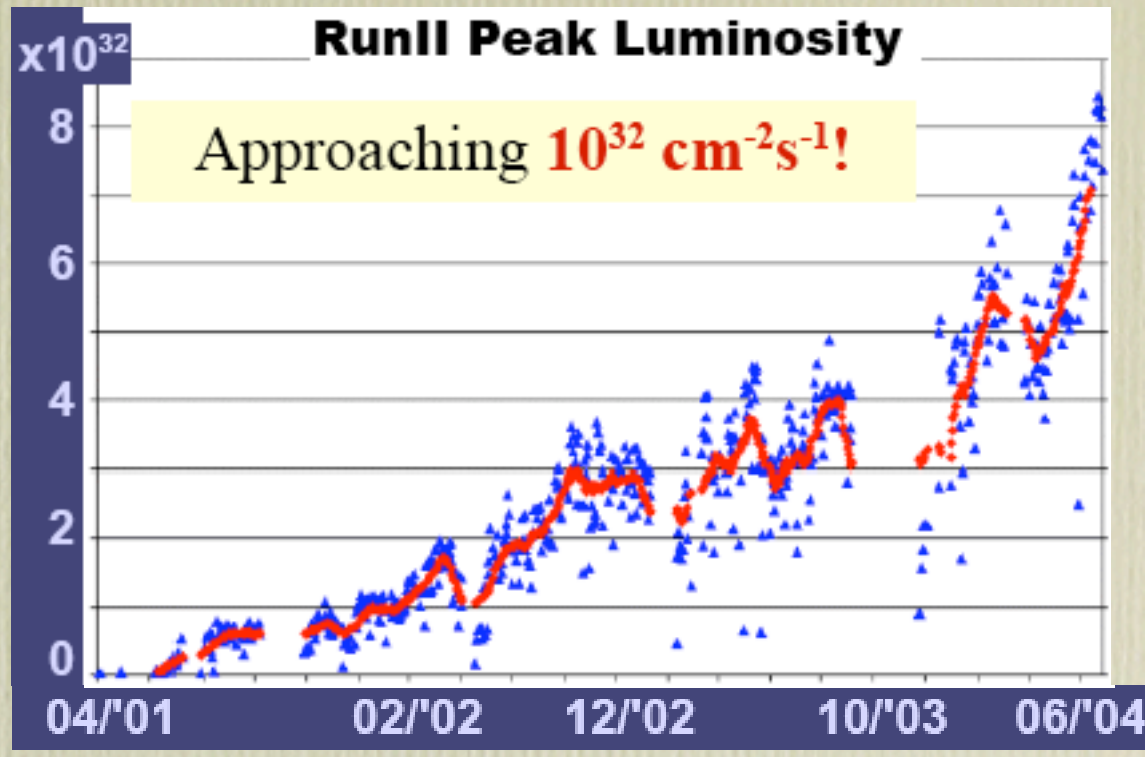
Meeting of the Division of Particles and Fields 2004
University of California, Riverside

Outline

- Experimental Review
  - Jets at the Tevatron
  - Inclusive b production at the Tevatron
  - $e^+e^- \to J/\psi + \eta_c$ as measured by Belle
- Theoretical Review
  - Quick review of NNLO QCD technique
  - Soft Collinear Effective Theory (SCET)

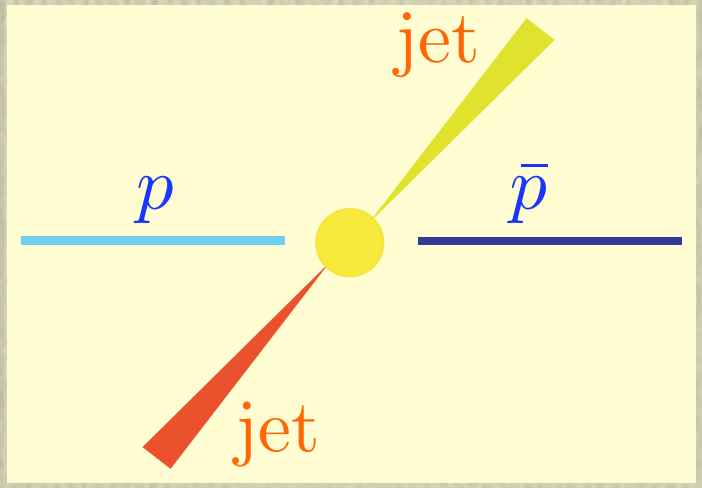
Tevatron: Run II

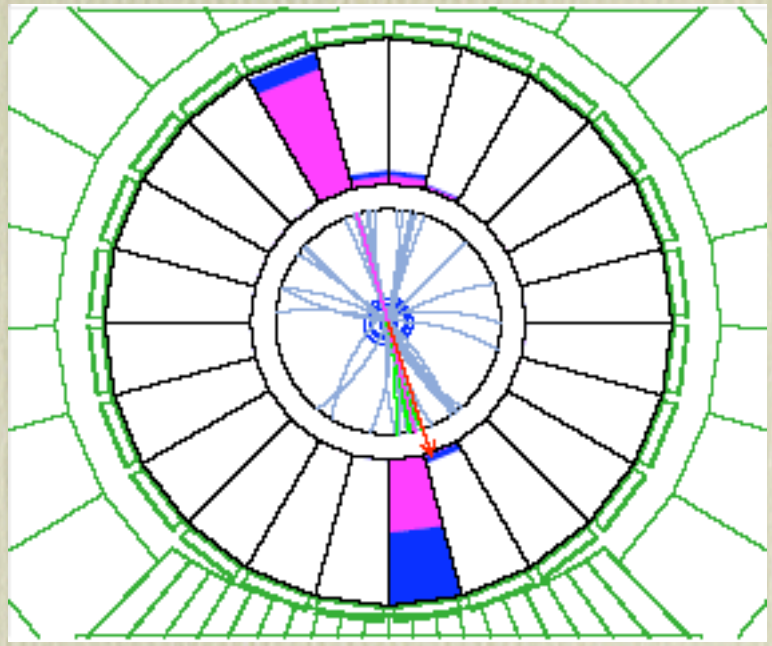




	$\int$ Luminosity	CME
Run I (1992-1995)	$\sim 0.1\,\mathrm{fb}^{-1}$	$\sqrt{s} = 1.8\,\mathrm{TeV}$
Run IIa (2001-2005)	$\sim 1\,\mathrm{fb}^{-1}$	$\sqrt{s} = 1.96\,\mathrm{TeV}$
Run IIb (2006-2009)	$\sim 4 - 8\,\mathrm{fb}^{-1}$	

Jets at the Tevatron

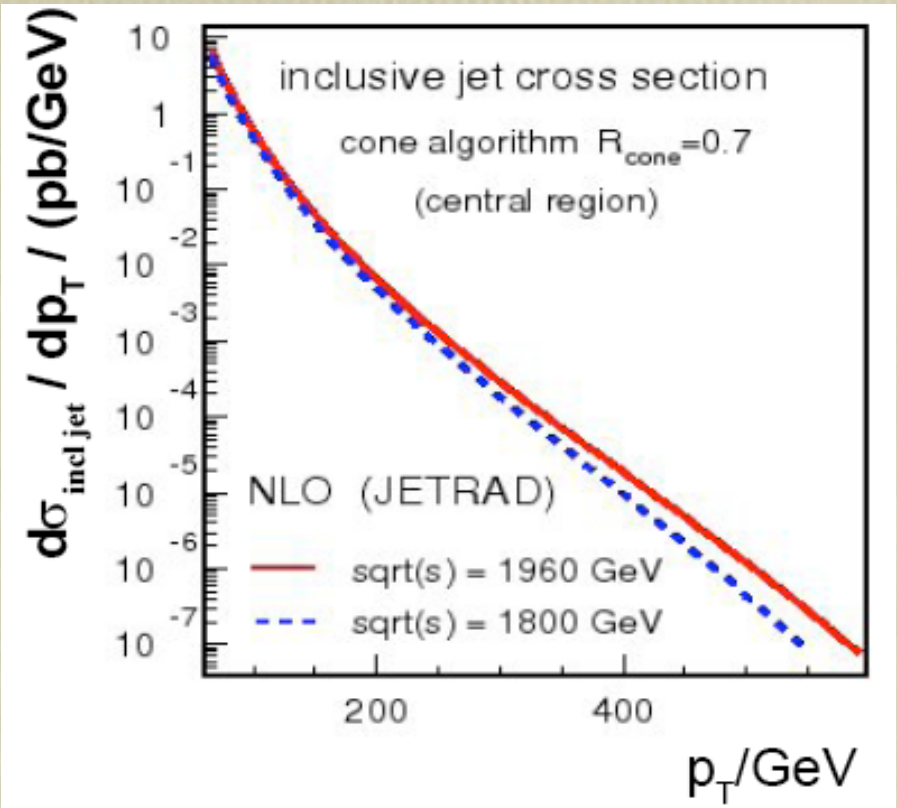


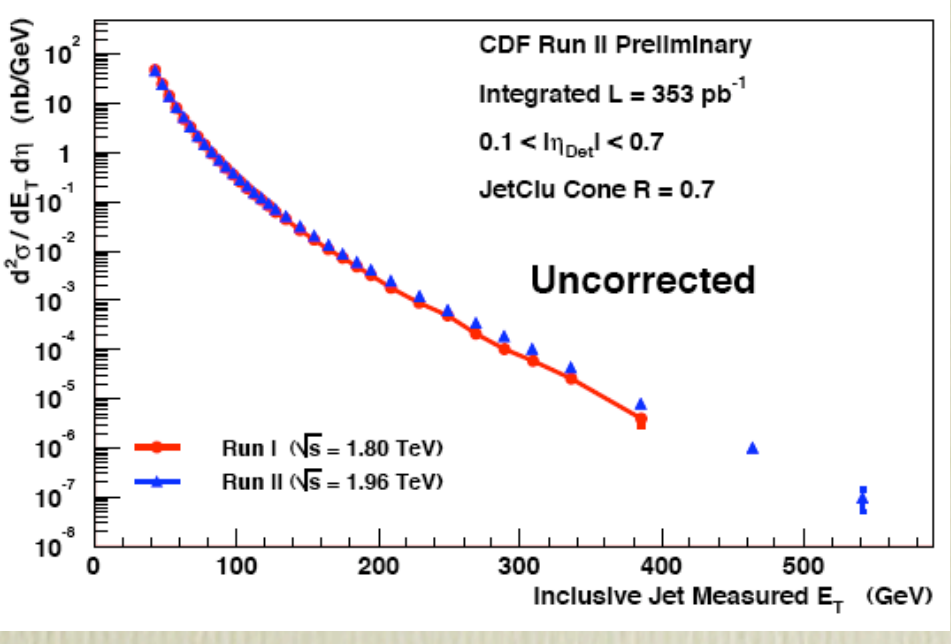


- Almost $500\,\mathrm{pb}^{-1}$ written to tape
- between about $350\,\mathrm{pb}^{-1}$ and $150\,\mathrm{pb}^{-1}$ analyzed

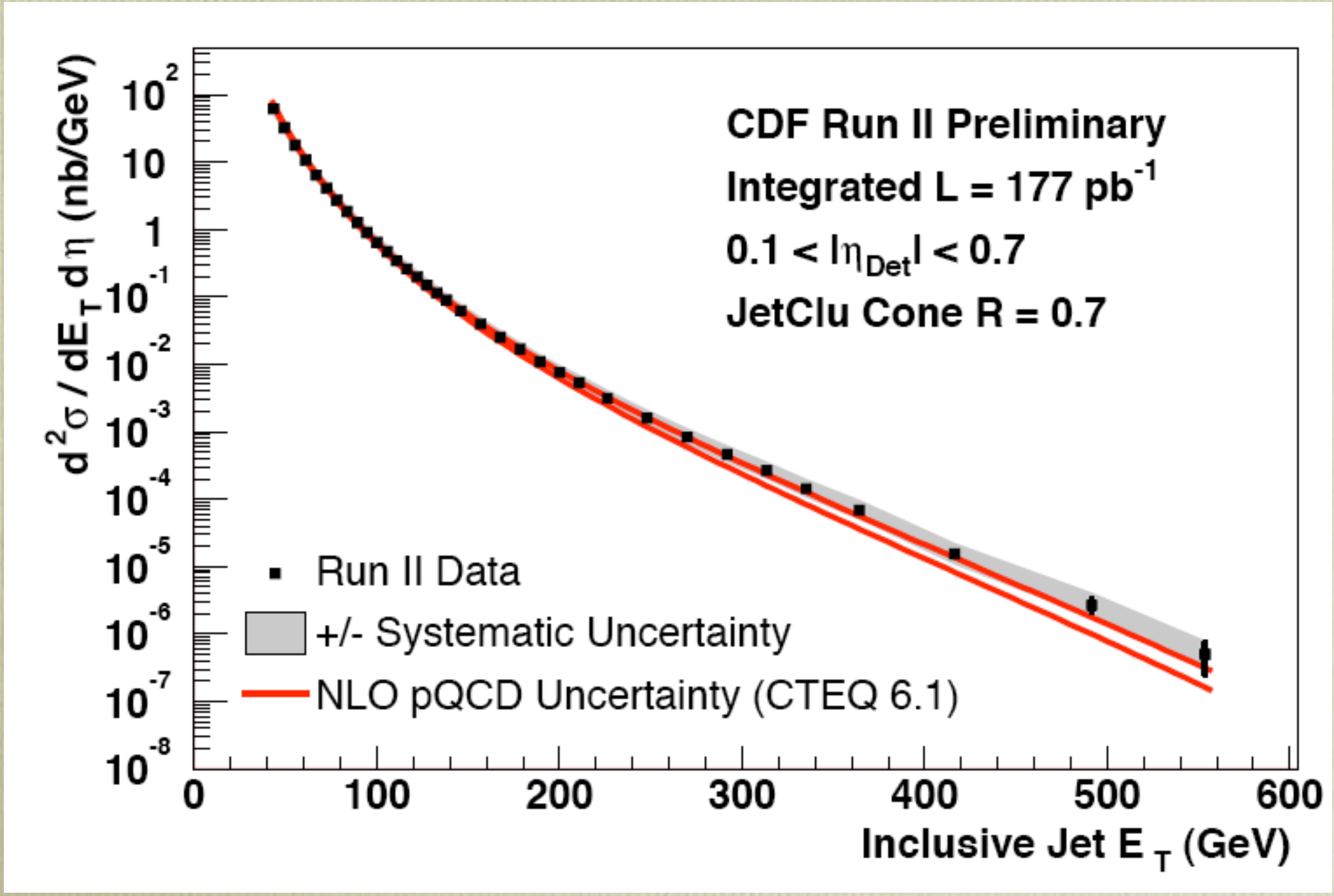
Jets at the Tevatron: what's new

- Detectors Upgraded
- Increase center-of-mass energy ($1.8 \rightarrow 1.96$ TeV)
  - Increased cross section $2\times$ at 400 GeV and $5\times$ at 600 GeV
  - Higher E_T
- New Jet cone algorithm
  - Infrared & Collinear safe

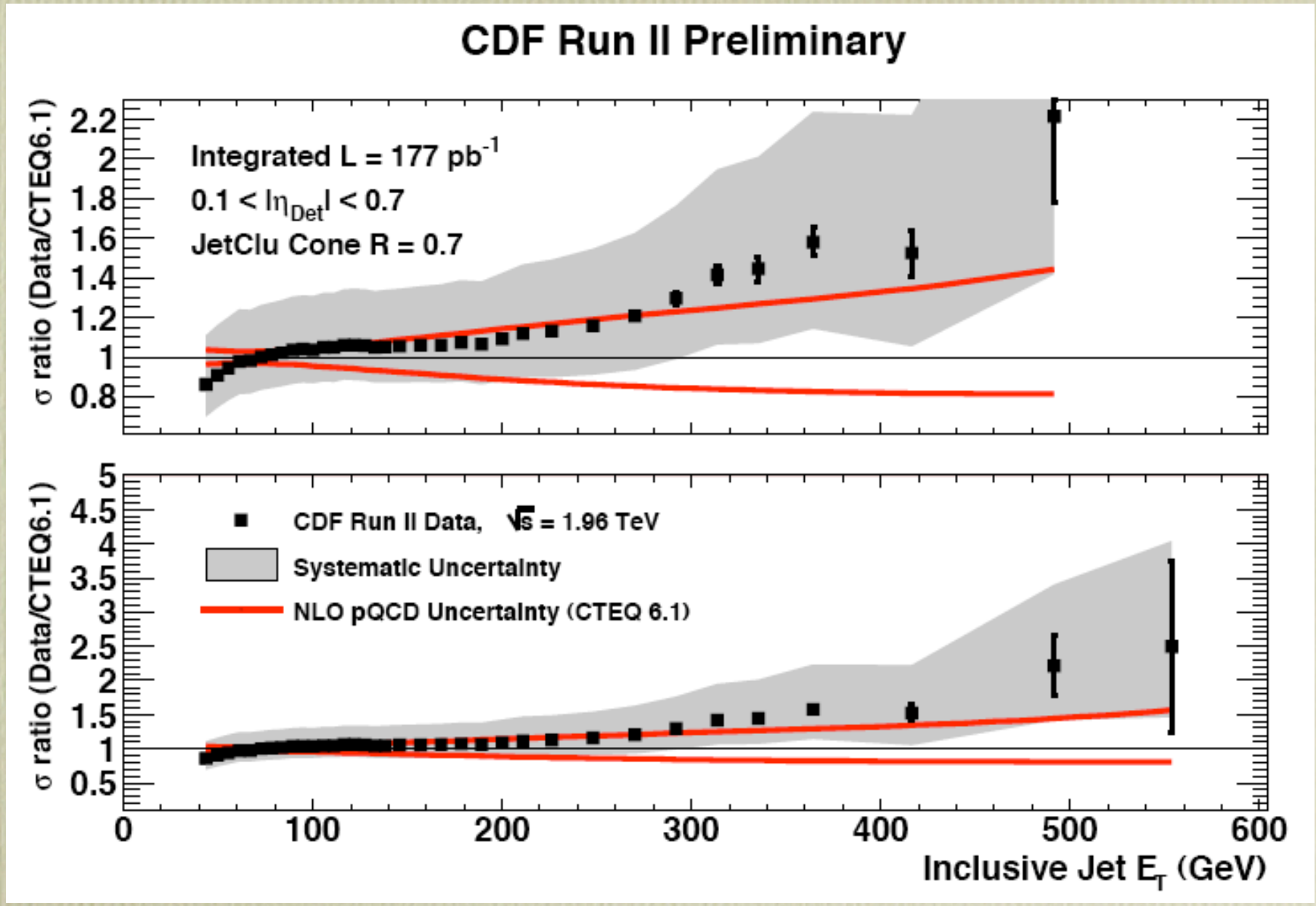




CDF Run II

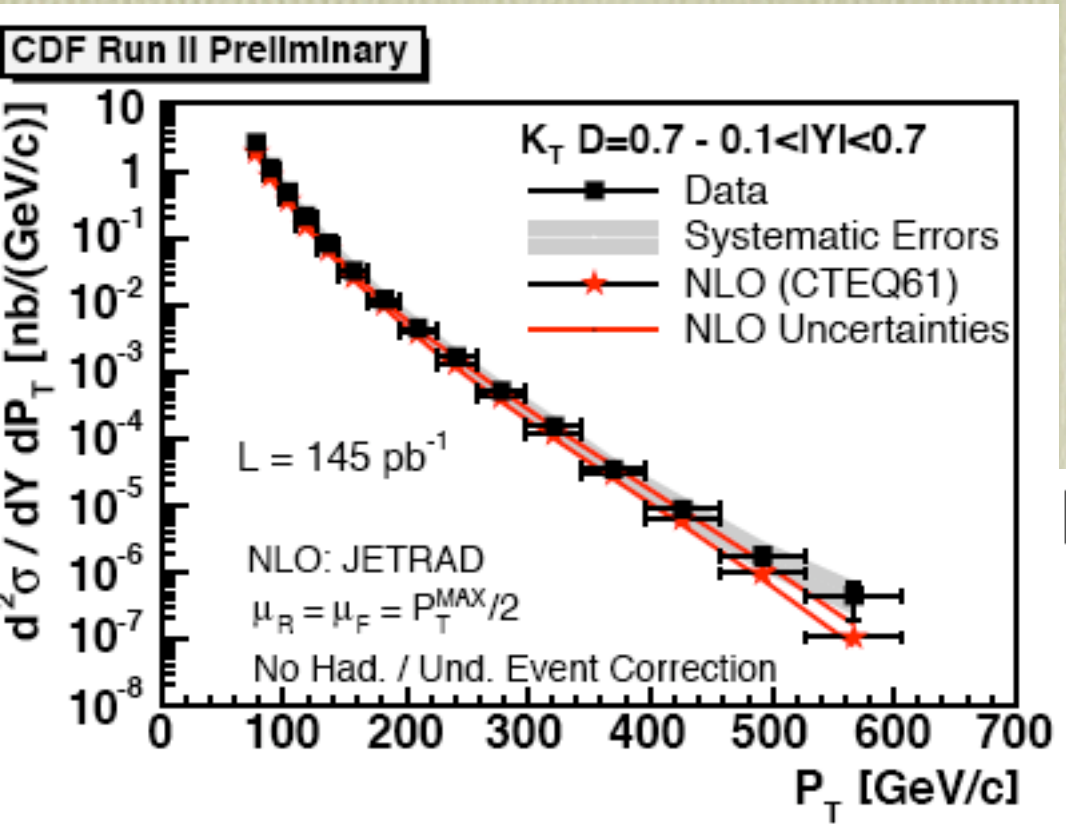

CDF Run II Preliminary
Integrated L = 177 pb^{-1}
0.1 < |η_{Det}| < 0.7
JetClu Cone R = 0.7
Run II Data
+/- Systematic Uncertainty
NLO pQCD Uncertainty (CTEQ 6.1)
$d^2\sigma / dE_T d\eta$ (nb/GeV)
Inclusive Jet E_T (GeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
100
200
300
400
500
600

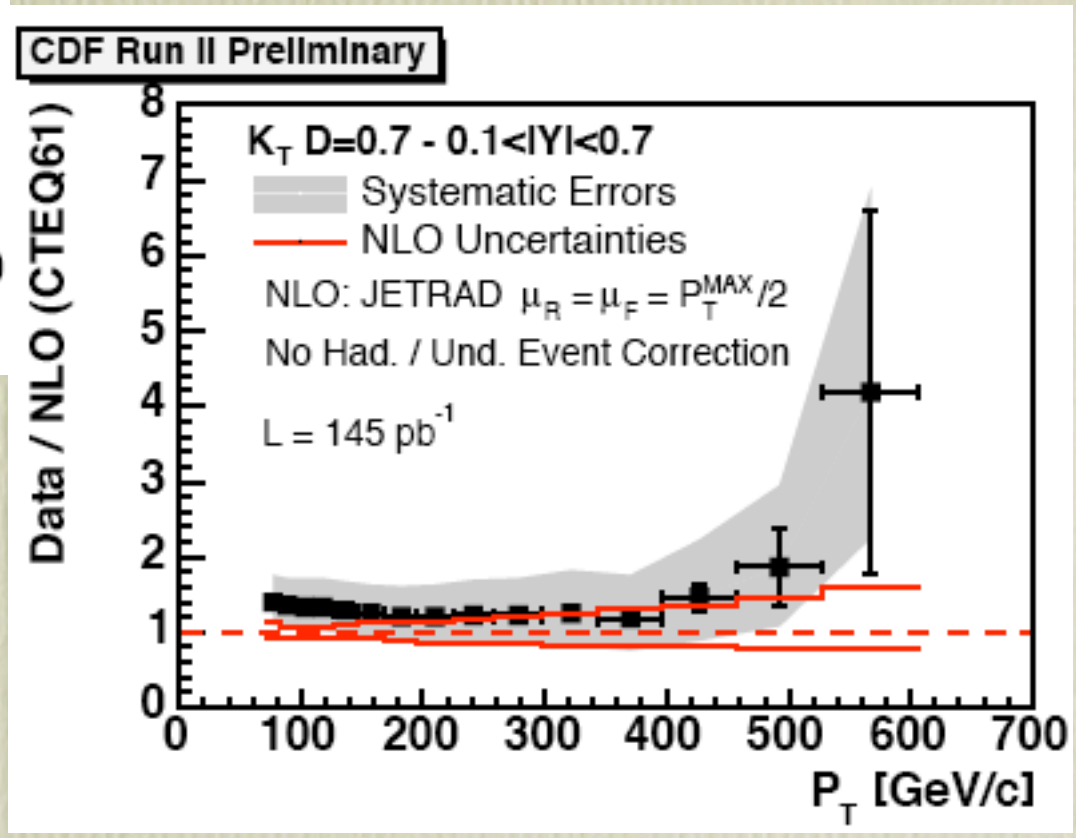
CDF Run II



Run I data exhibited an excess at large E_T which could be explained by an enhanced gluon density at high x: fit by CTEQ6.1

kT clustering algorithm

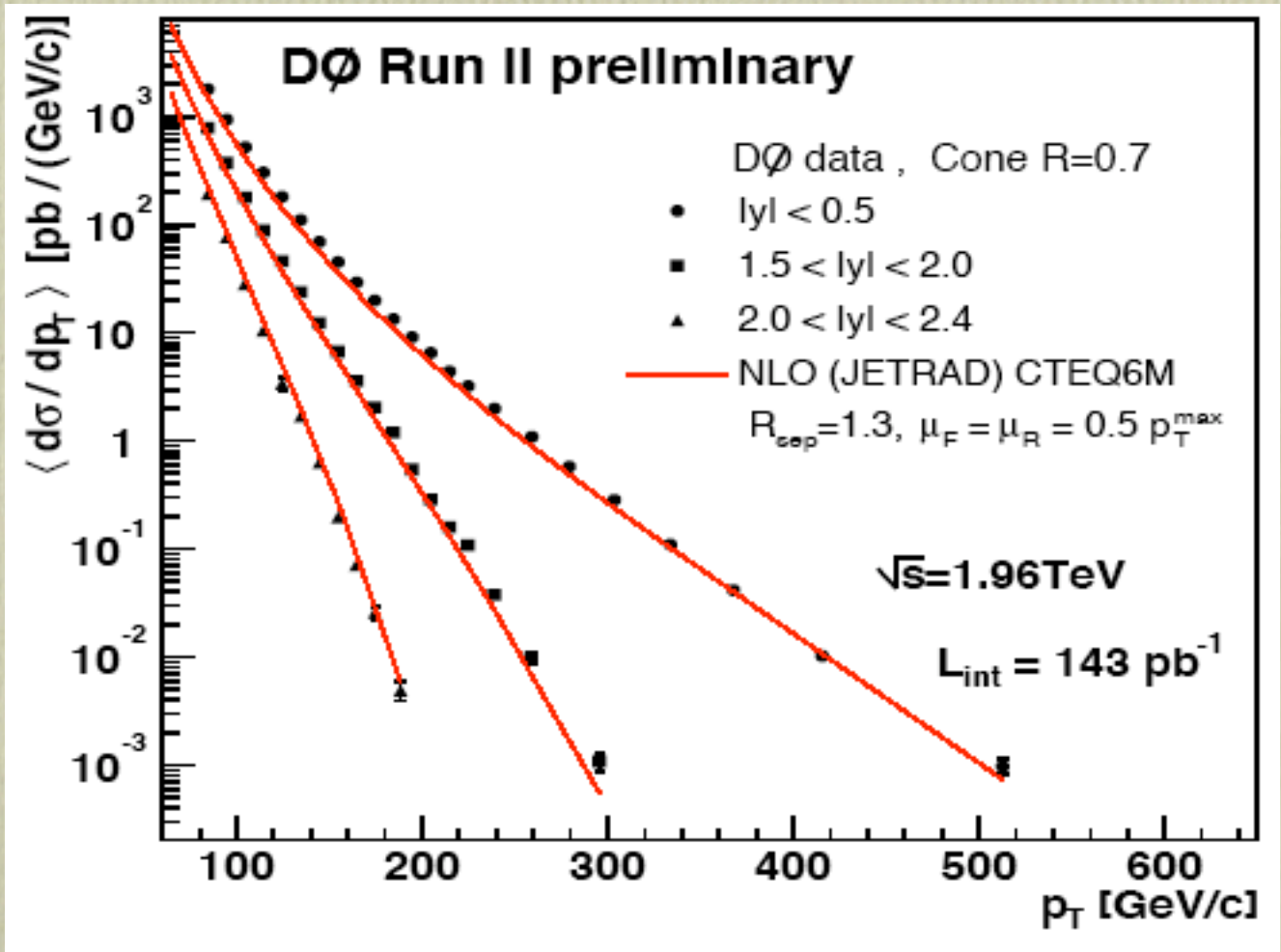




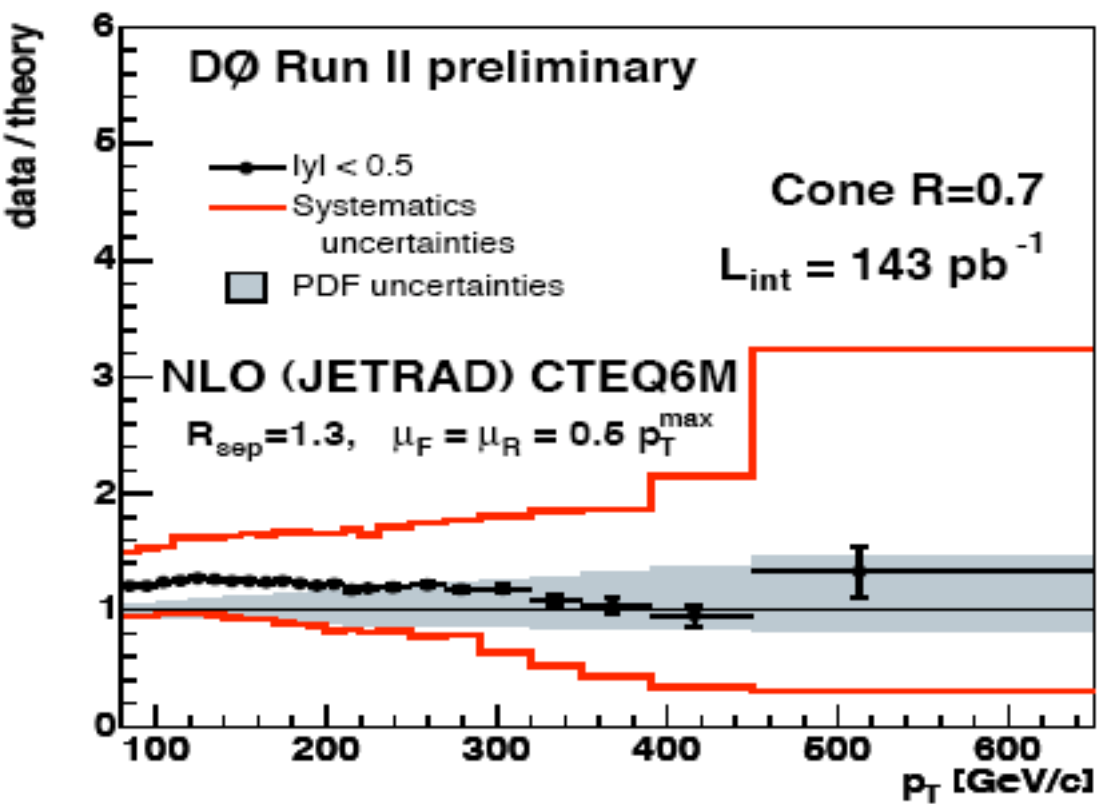
DØ Data

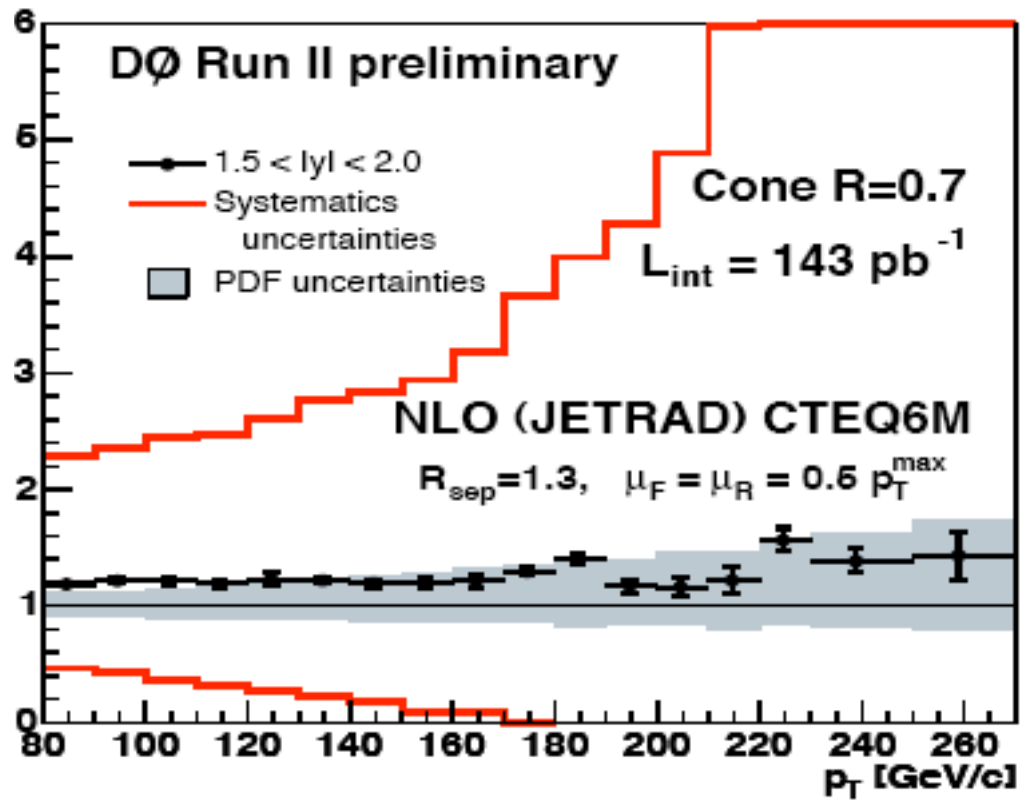
Talk by B. Hirosky

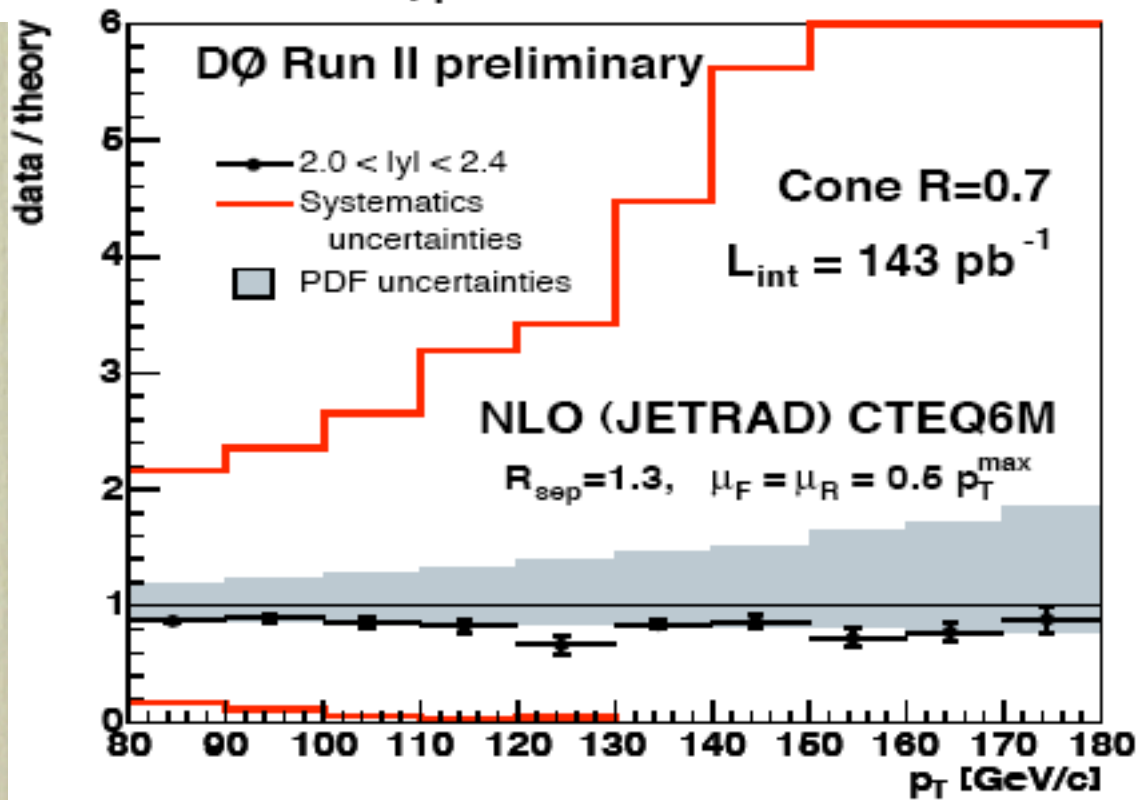
Inclusive Jet Cross Section in Different Rapidity Bins



Large rapidity put constraints on gluon content of the proton at high x values

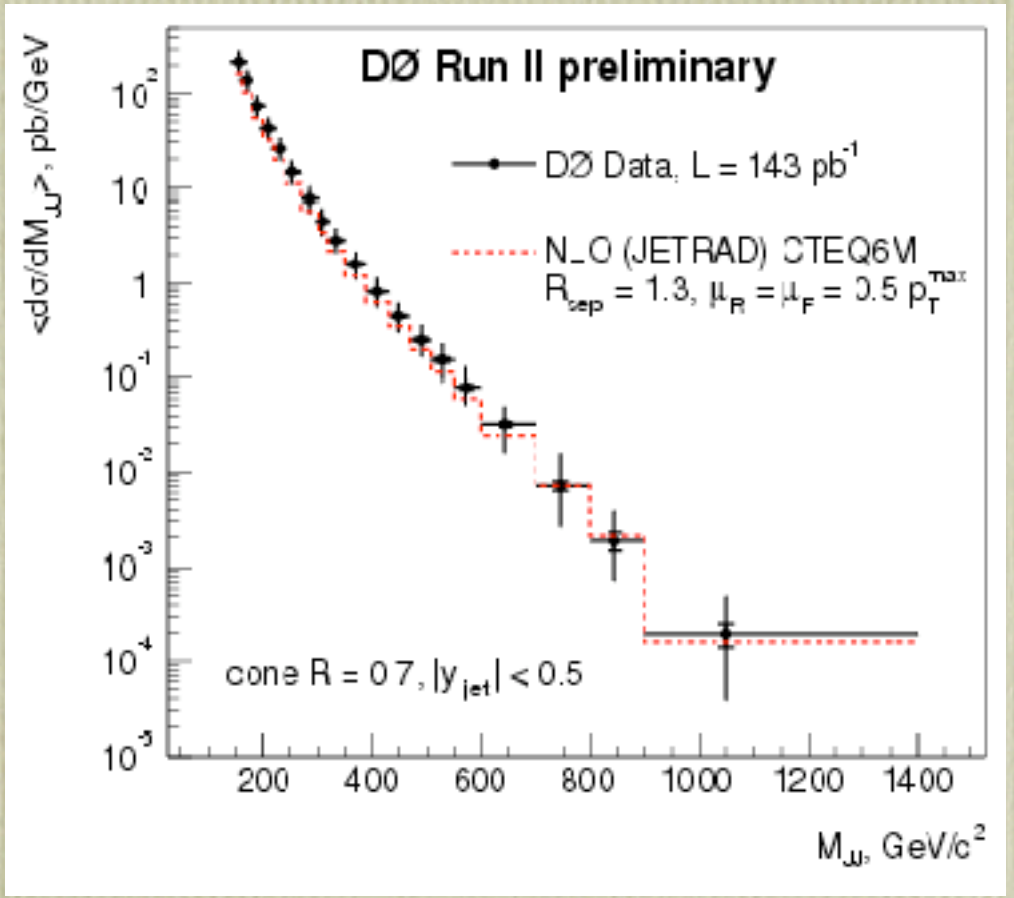

DØ Run II preliminary
|y| < 0.5
Systematics uncertainties
PDF uncertainties
Cone R=0.7
L_{int} = 143 pb^{-1}
NLO (JETRAD) CTEQ6M
R_{sep}=1.3, $\mu_F = \mu_R = 0.5\ p_T^{max}$
data / theory
p_T [GeV/c]

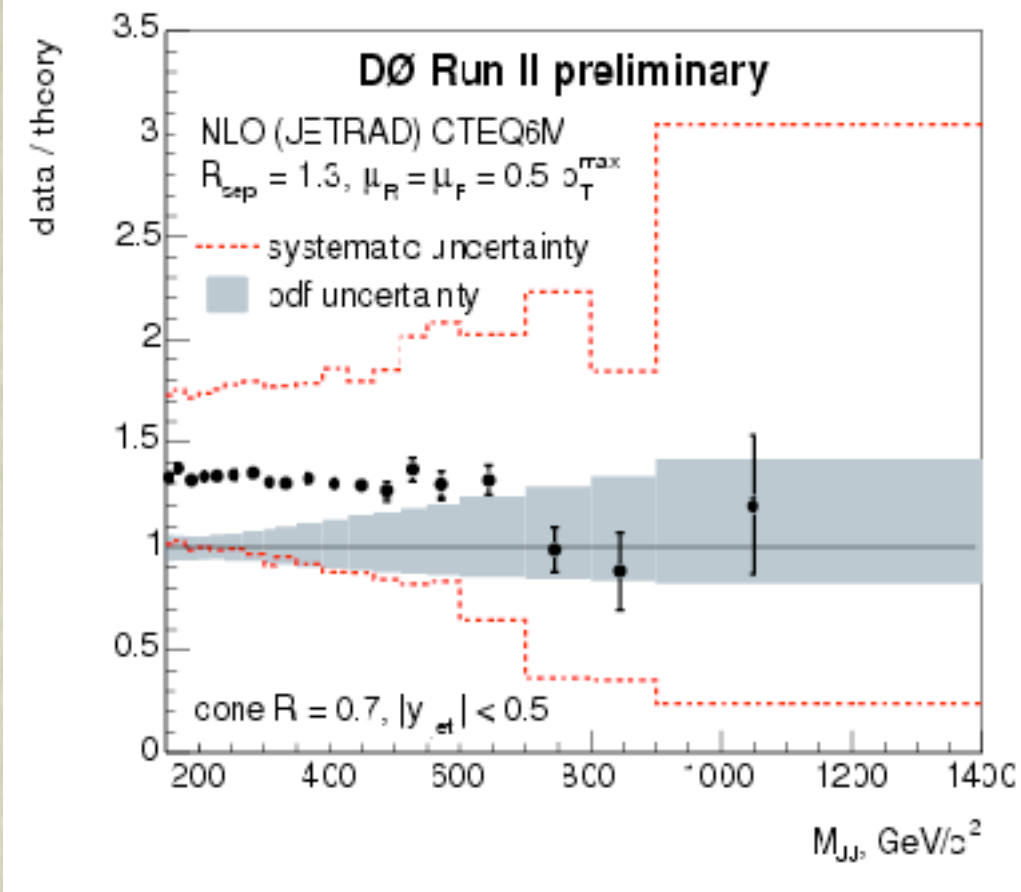

DØ Run II preliminary
1.5 < |y| < 2.0
Systematics uncertainties
PDF uncertainties
Cone R=0.7
L_{int} = 143 pb^{-1}
NLO (JETRAD) CTEQ6M
R_{sep}=1.3, $\mu_F = \mu_R = 0.5\ p_T^{max}$
p_T [GeV/c]


DØ Run II preliminary
2.0 < |y| < 2.4
Systematics uncertainties
PDF uncertainties
Cone R=0.7
L_{int} = 143 pb^{-1}
NLO (JETRAD) CTEQ6M
R_{sep}=1.3, $\mu_F = \mu_R = 0.5\ p_T^{max}$
data / theory
p_T [GeV/c]

Di-Jet Mass Spectrum

Greater sensitivity to new phenomena





- Central region $|y_{\rm jet}| < 0.5$, data sample $\sim 143\,{\rm pb}^{-1}$
- Run II midpoint algorithm
- Agreement within uncertainties with NLO/CTEQ6M
- Jet Energy Scale ($< 7\%$) dominant error on measurement

Jets at the Tevatron

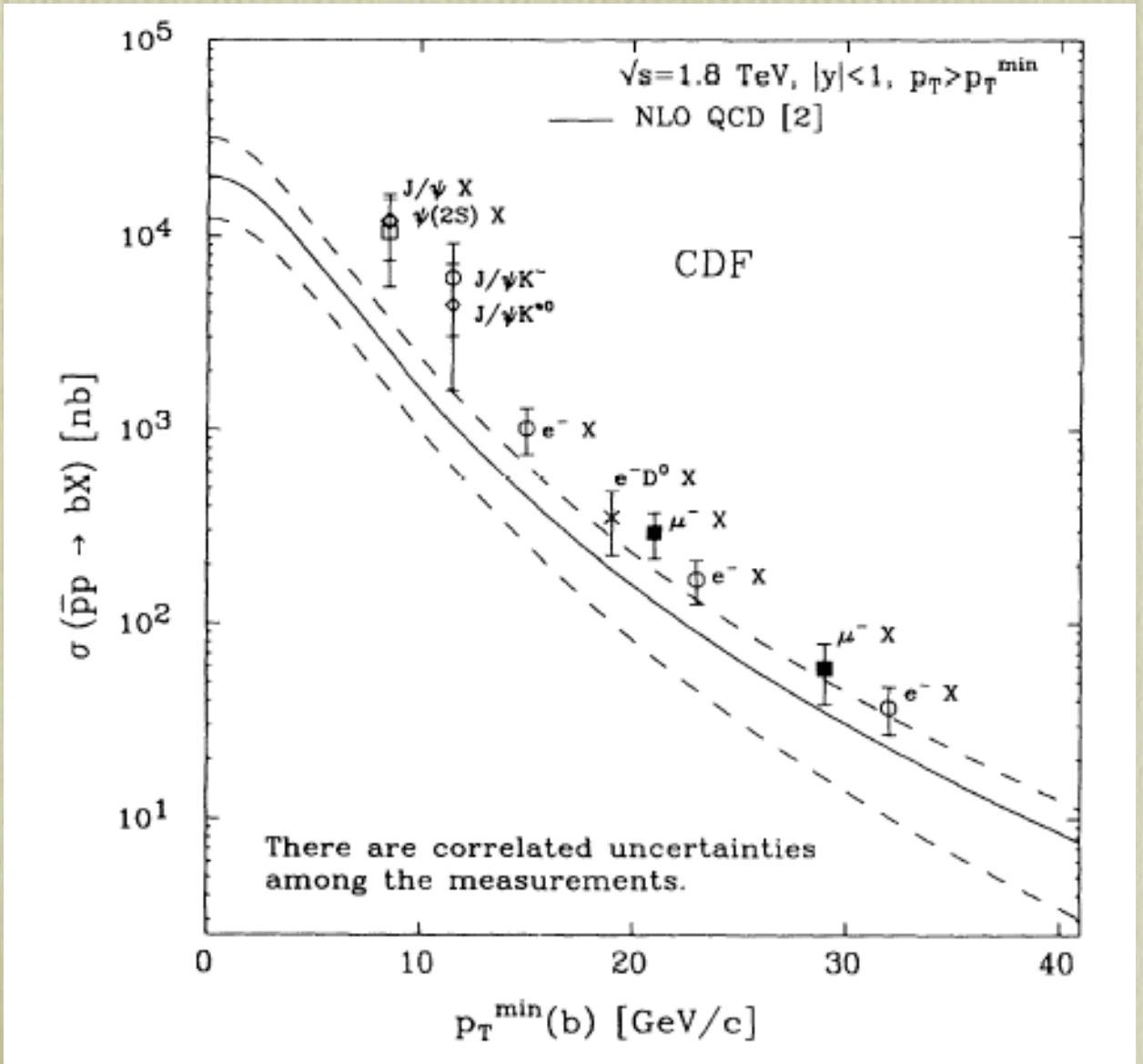
- First results: good agreement between theory and data
- Explore high P_T and M_{jj} regions over wide range of rapidities
  - Constrain high-x gluon contributions
  - Direct searches for new physics
- Measurements will become increasingly precise
- Tevatron is essential for
  - Precision measurements & searches for new physics
  - Expectations for LHC

b-production at the Tevatron

b-quark production at the Tevatron 1993

Measured by CDF (Phys. Rev. Lett. 71, 2396 (1993))

Compared to NLO QCD (P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B **303**, 607 (1988))

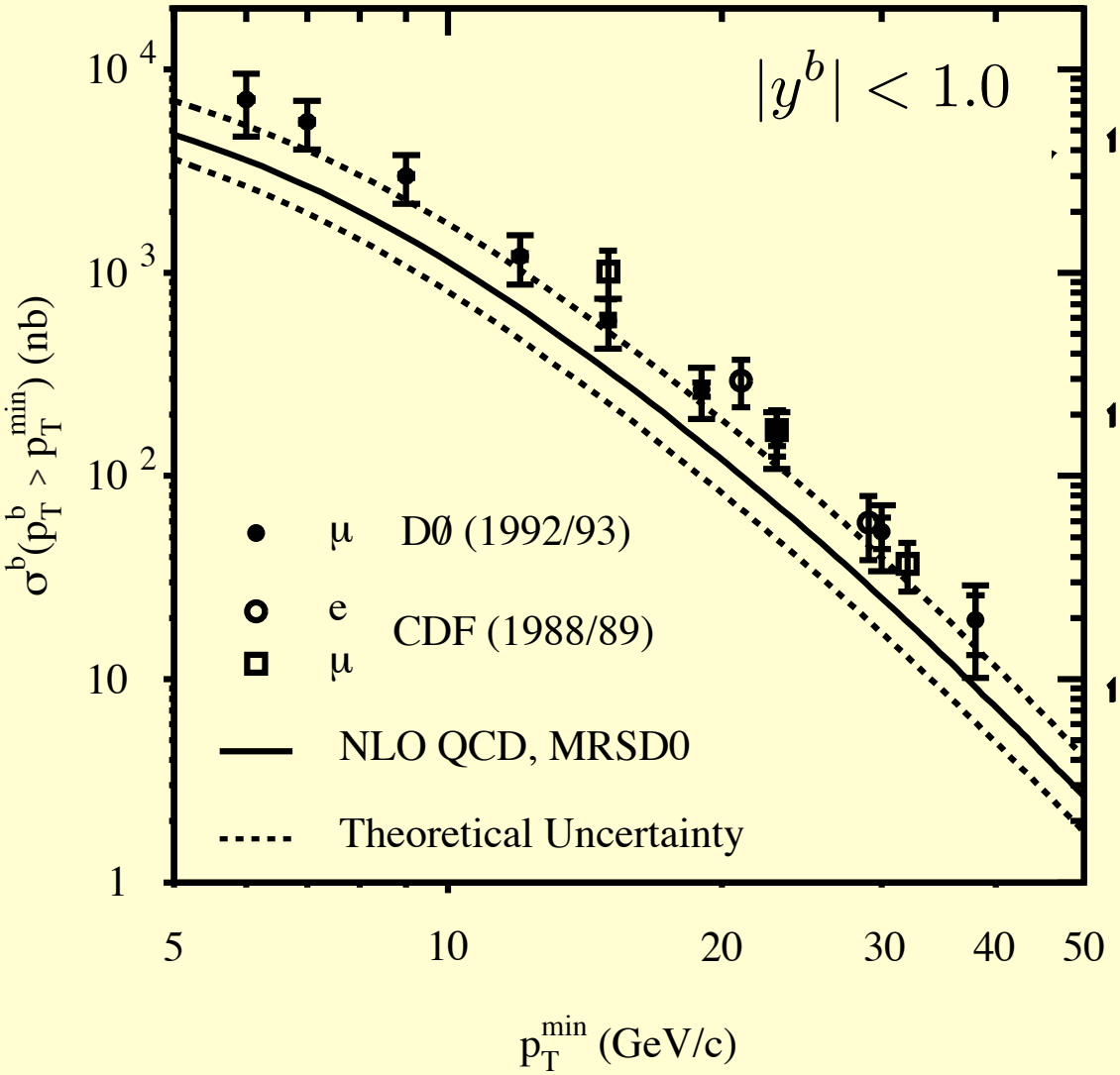


"...the next-to-leading QCD calculation tends to underestimate the inclusive b-quark cross section."

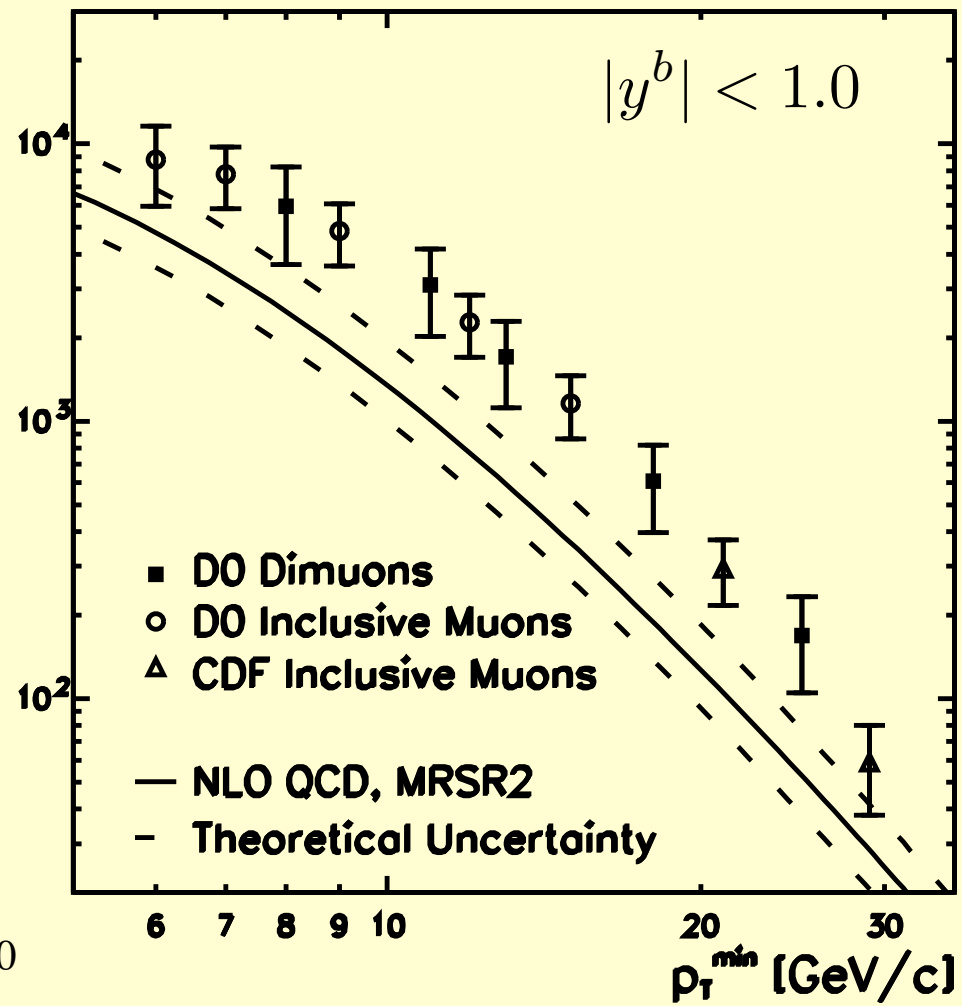
DØ weighs in...

By 2000 excess is established

Phys. Rev. Lett. 74, 3548 (1995)



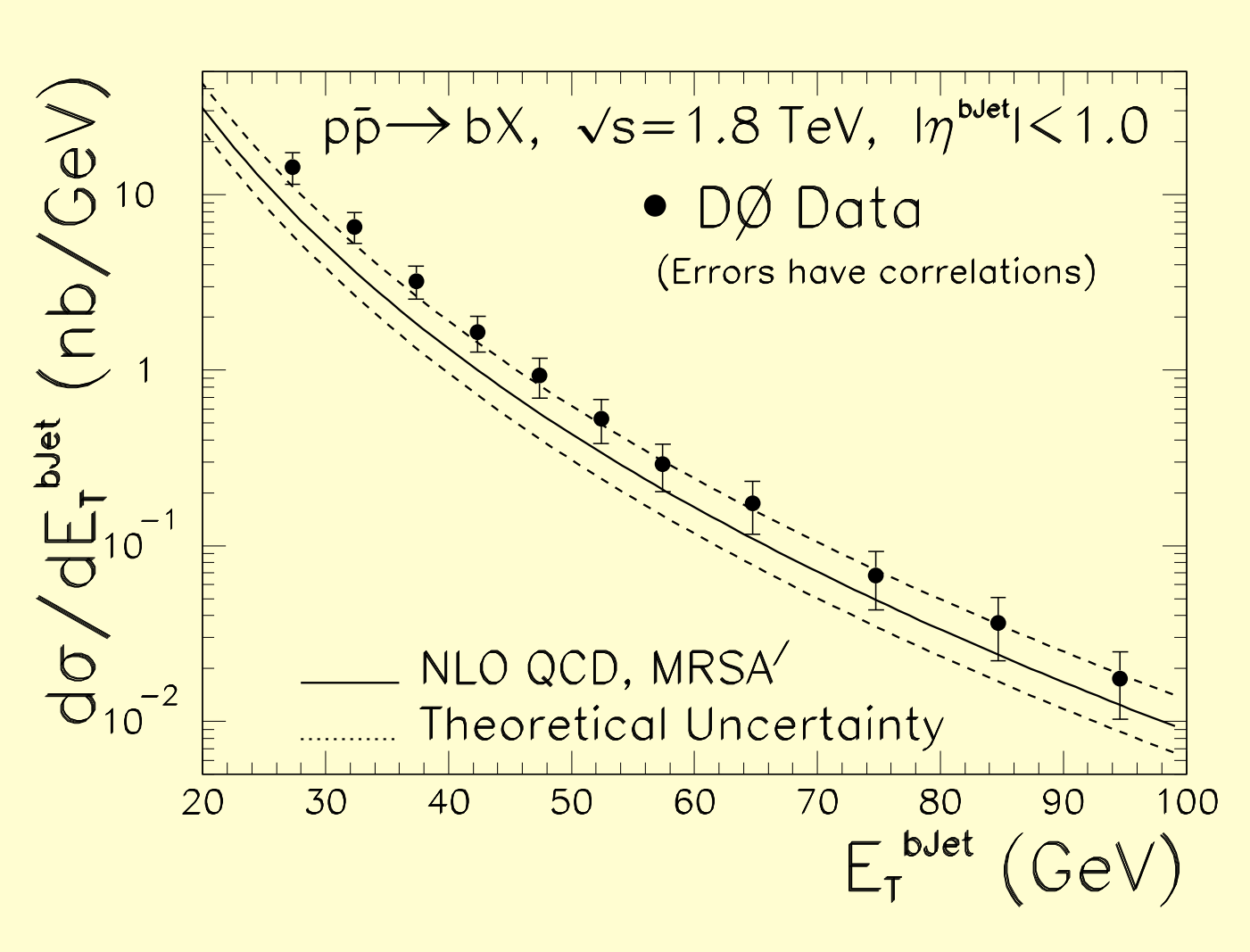
Phys. Lett. B487, 264 (2000)



DØ weighs in..

...and a Mystery

Phys. Rev. Lett. 85, 5068 (2000)

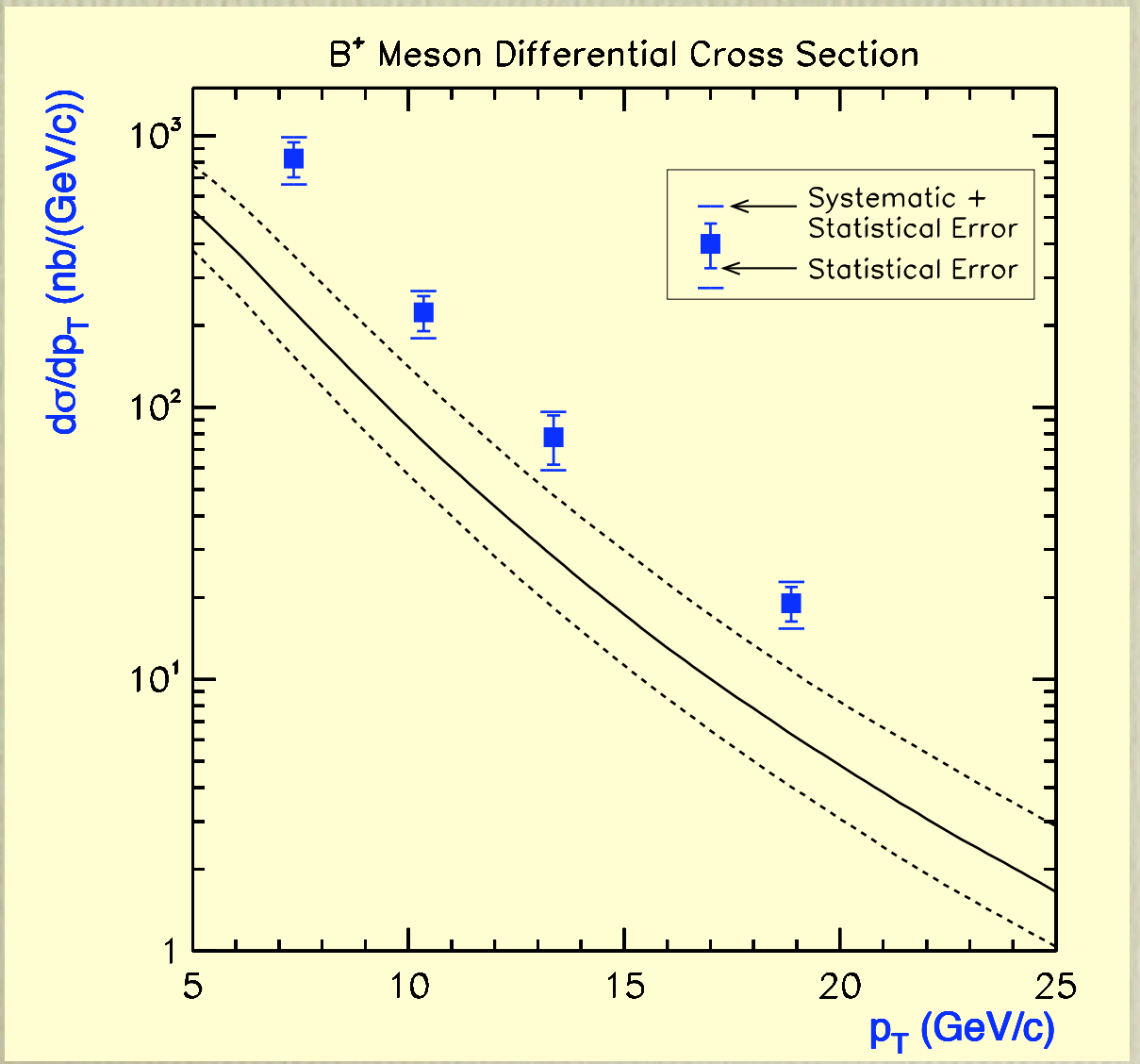


- b-jets: hadronic jets carrying b flavor
- Directly observable
  - Reduces model dependency

Get to this in a moment

More CDF Results

CDF (Phys. Rev. D65, 052005 (2002))



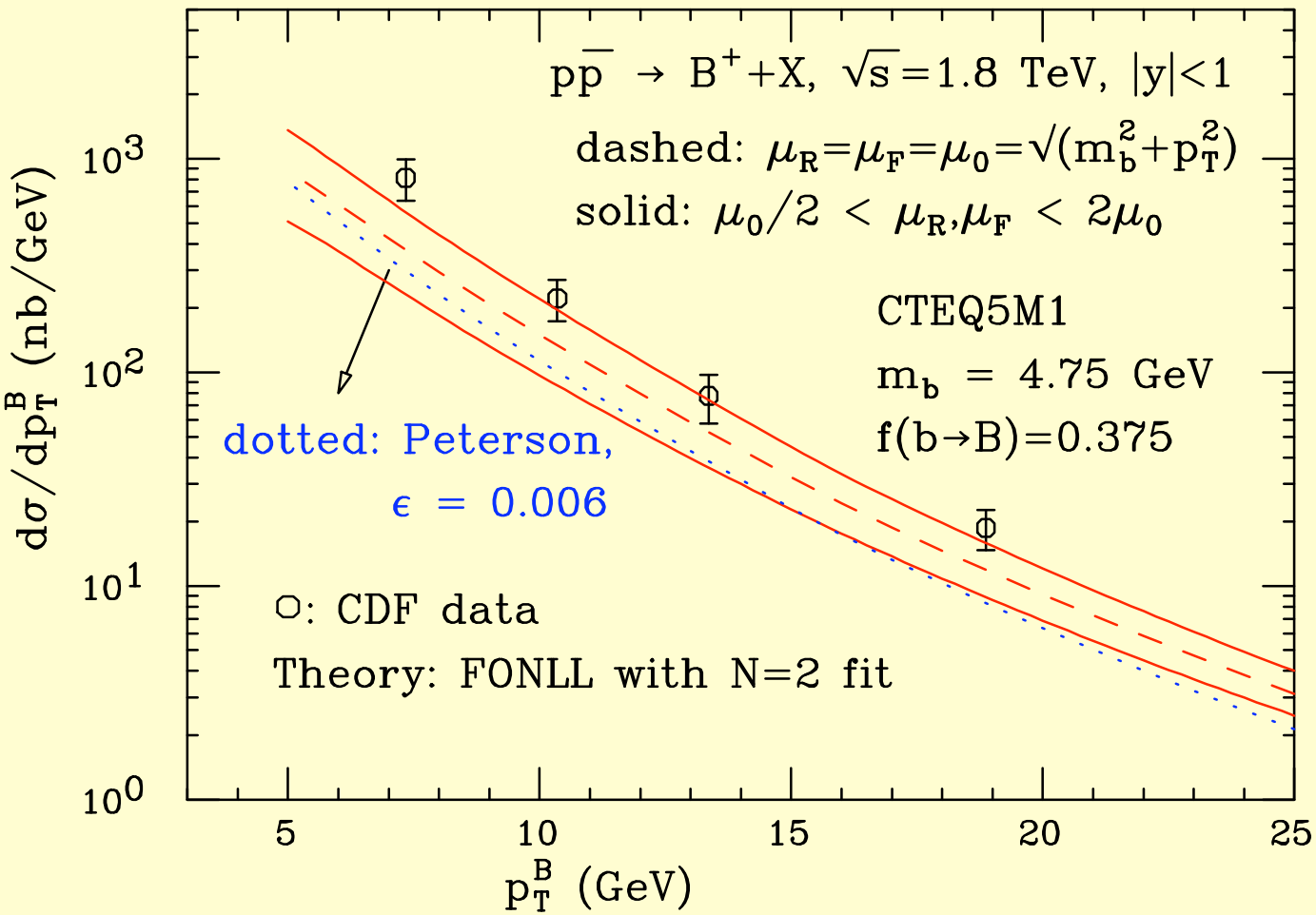
- data/theory

$$2.9 \pm 0.2(\mathrm{stat} \oplus \mathrm{syst}_{p_T}) \pm 0.4(\mathrm{syst}_{\mathrm{fc}})$$

  - does not include theory uncertainty
- Model dependence
  - Non-pert. Peterson fragmentation func.
  - Information on hadronization $b \to B$

New Theory Analysis

M. Cacciari and P. Nason, Phys. Rev. Lett. **89** (2002) 122003



- data/theory

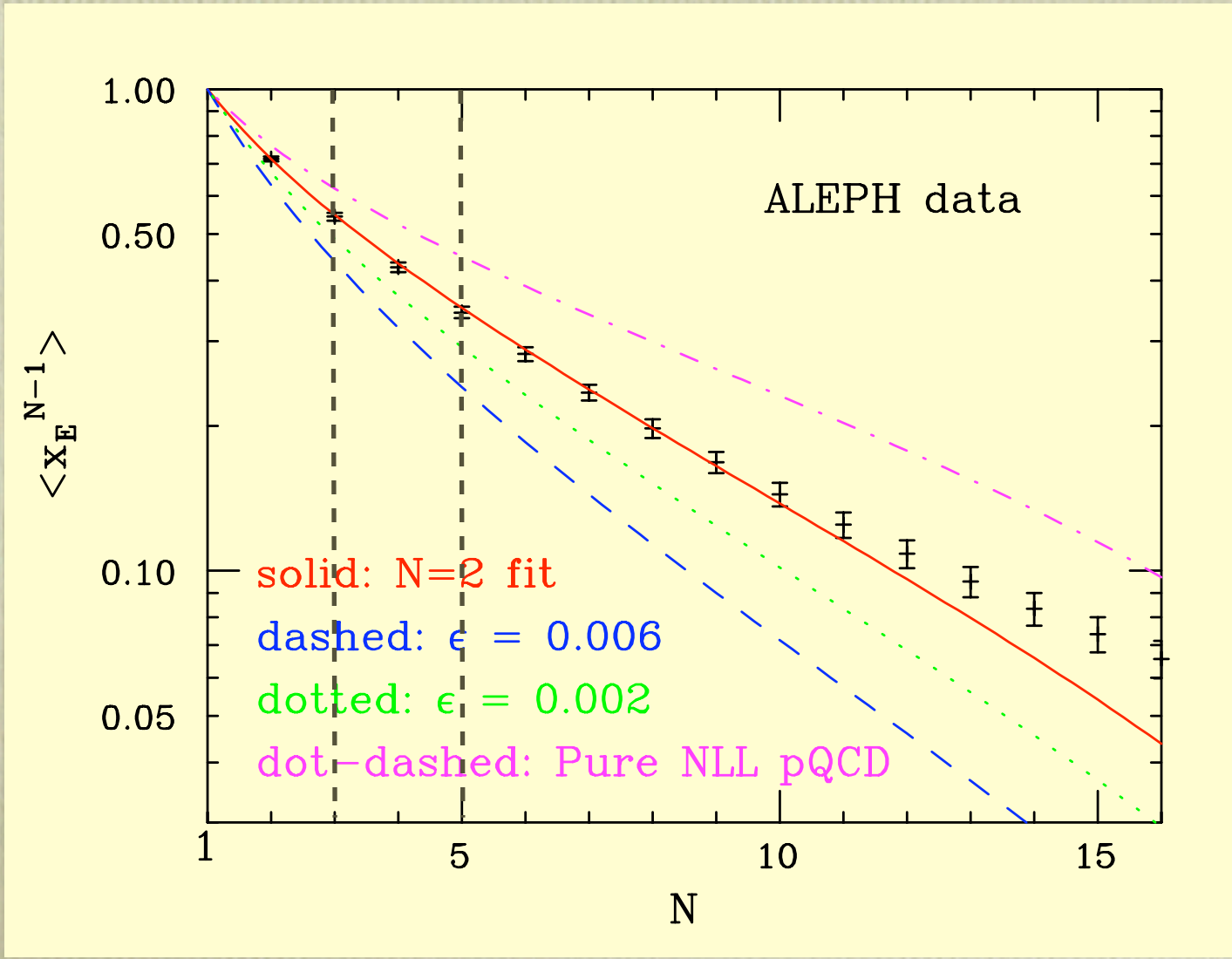
$1.7 \pm 0.5(\text{expt}) \pm 0.5(\text{th})$

  - does include theory uncertainty

- Change due to fragmentation function!

Fragmentation Function

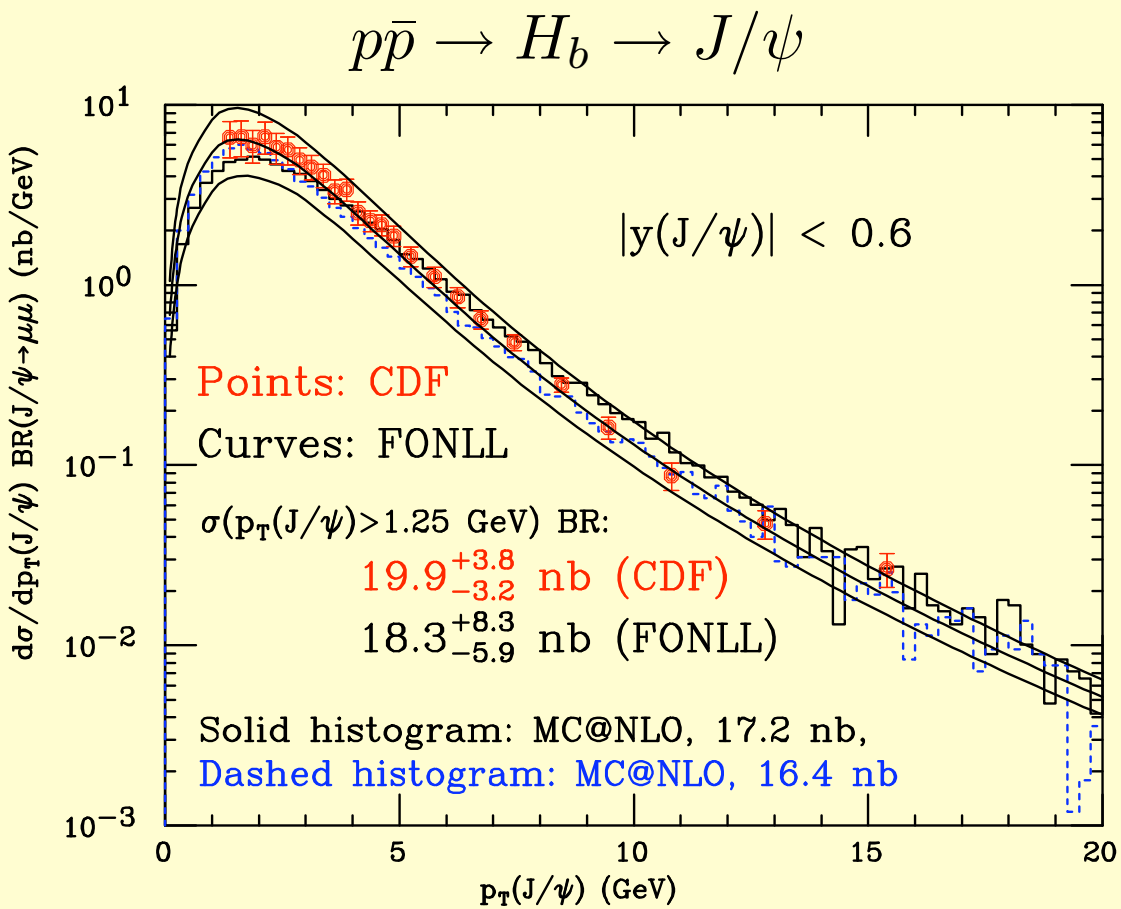
Fit fragmentation function to LEP data



- Use the same theory ingredients as in b-production
  - including NLO and NLL
- b-production is most sensitive to the N=3,4,5 moments

CDF Run II Preliminary Data

$\sqrt{s} = 1.96\,\mathrm{TeV}$



M. Cacciari *et al* Phys. Rev. Lett. 89, 122003 (2002)

$$\sigma(p\bar{p} \to H_b \to J/\psi; P_{\perp\psi} > 1.25, |y| < 0.6)$$

$$\sigma^{\mathrm{CDF}}_{J/\psi} = 19.9^{+3.8}_{-3.2(\mathrm{stat\,+\,syst})}\mathrm{nb}$$

$$\sigma^{\mathrm{FONLL}}_{J/\psi} = 19.0^{+8.4}_{-6.0}\mathrm{nb}$$

$$\sigma(p\bar{p} \to H_b X; P_\perp > 0, |y| < 0.6) \times B(H_b \to J/\psi)$$

$$\sigma^{\mathrm{CDF}}_{H_b} = 24.5^{+4.7}_{-3.9(\mathrm{stat\,+\,syst})}\mathrm{nb}$$

$$\sigma^{\mathrm{FONLL}}_{H_b} = 22.9^{+9.5}_{-6.8}\mathrm{nb}$$

$$\sigma(p\bar{p} \to bX; P_\perp > 0, |y| < 1.0)$$

$$\sigma^{\mathrm{CDF}}_{b}(|y| < 1) = 29.4^{+6.2}_{-5.4(\mathrm{stat\,+\,syst})}\mu\mathrm{b}$$

$$\sigma^{\mathrm{FONLL}}_{b}(|y| < 1) = 23.6^{+11.9}_{-7.6}\mu\mathrm{b}$$

Excellent Agreement!

Why is agreement so good?

- Improved determination of fragmentation function from LEP data
- New pdf determinations from data increase theory cross section
- Run II CDF data is about 30% lower than Run I data

Phenomenological input extremely important

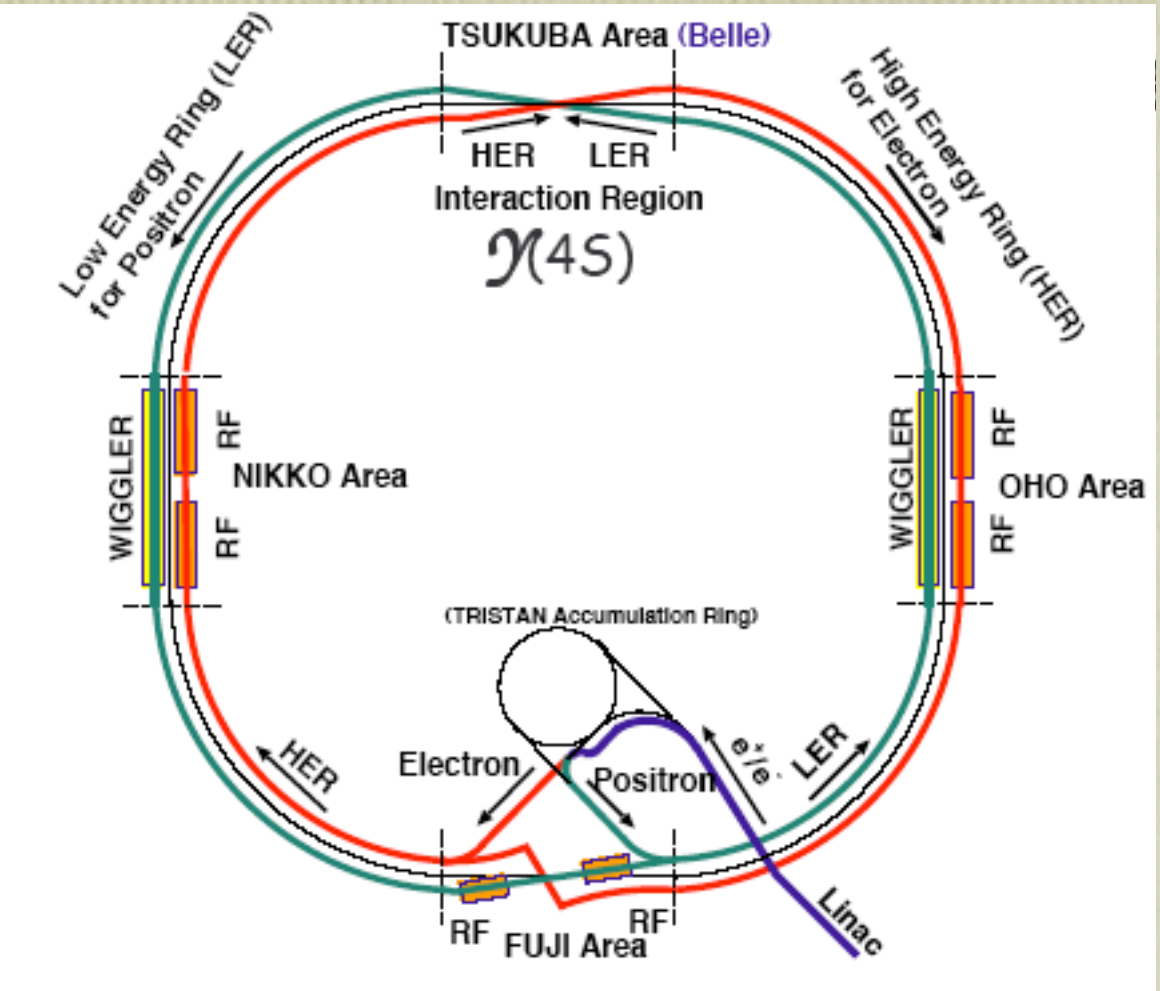
Run II analysis in progress

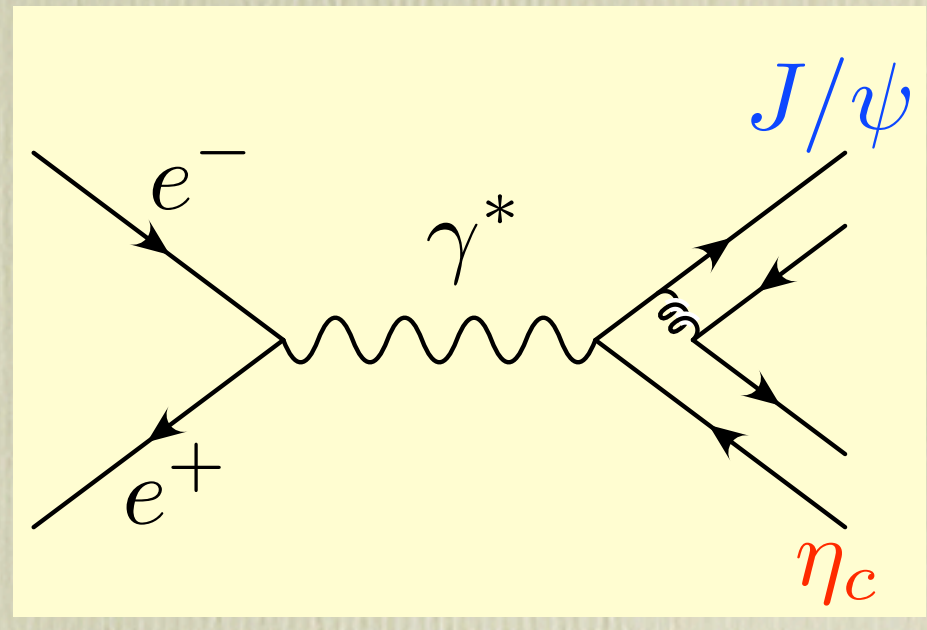
- Both CDF and DO have b-jet analysis in progress
- CDF and DO also looking at di-jet production with b-tagging
  - study b-jet production mechanism and di-jet mass
- A lot more data coming: $400\,\mathrm{pb}^{-1}$ collected and by summer 2006 expect $1.5\,\mathrm{fb}^{-1}$

Can theory keep up?!?!

Double Charmonium Production in e^+e^- collisions measured by Belle

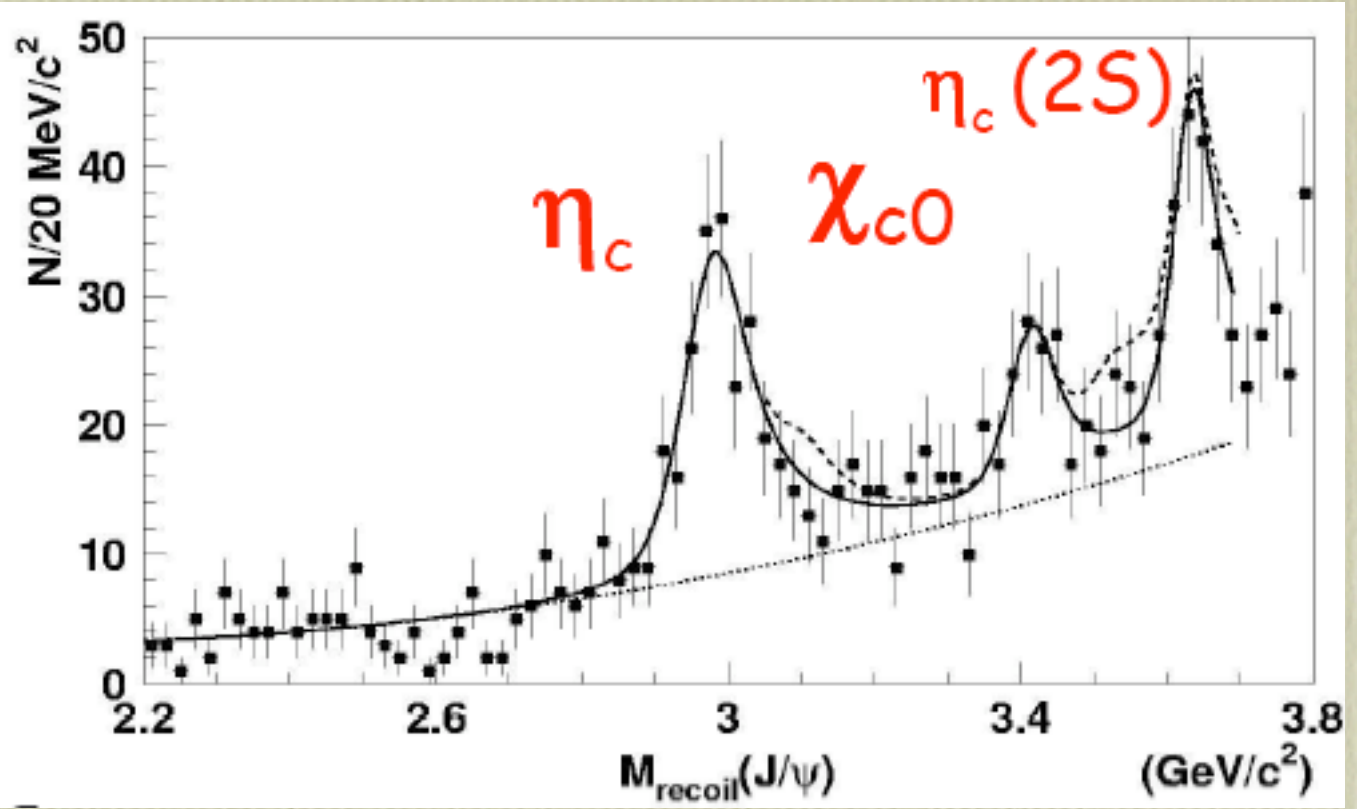
Talk by T. Ziegler





- $140\,\mathrm{fb}^{-1}$ on-resonance
- $15\,\mathrm{fb}^{-1}$ off-resonance

$155\,\mathrm{fb}^{-1}$ total



—— set * to

- - - - - set * to 90% C.L. upper limits

State	M_{recoil}	N_{evt}	σ
η_c	2.972 ± 0.007	235 ± 26	10.7
J/Ψ	Fixed @ PDG	-14 ± 20	*
χ_{c0}	3.407 ± 0.011	89 ± 24	3.8
$\chi_{c1} + \chi_{c2}$	Fixed @ PDG	10 ± 27	*
$\eta_c(2S)$	3.630 ± 0.008	164 ± 30	6.0
$\Psi(2S)$	Fixed @ PDG	-26 ± 29	*

* Masses fixed at PDG value

Comparison to Theory

E. Braaten & J. Lee, Phys. Rev. D67, 054007 (2003)

$H_2 \setminus H_1$	J/ψ	$\psi(2S)$	$h_c(1P)$	$\psi_1(1D)$	$\psi_2(1D)$
η_c	2.31 ± 1.09	0.96 ± 0.45	0	0.052 ± 0.021	1.04 ± 0.23
$\eta_c(2S)$	0.96 ± 0.45	0.40 ± 0.19	0	0.022 ± 0.009	0.43 ± 0.09
$\chi_{c0}(1P)$	2.28 ± 1.03	0.95 ± 0.43	0.053 ± 0.019		
$\chi_{c1}(1P)$	0.47 ± 0.16	0.19 ± 0.07	0.258 ± 0.064		
$\chi_{c2}(1P)$	0.59 ± 0.13	0.25 ± 0.05	0.017 ± 0.002		
$\eta_{c2}(1D)$	0.27 ± 0.05	0.11 ± 0.02			

Belle Data

$(c\bar{c})_{\rm res}$	$\sigma_{\rm Born} \times \mathcal{B}(c\bar{c})_{\rm res} \to > 2$ charged [fb]	
	J/ψ	$\psi(2s)$
η_c	$25.6 \pm 2.8 \pm 3.4$	$16.3 \pm 4.6 \pm 3.9$
J/Ψ	< 9.1	< 16.9
χ_{c0}	$6.4 \pm 1.7 \pm 1.0$	$12.5 \pm 3.8 \pm 3.1$
$\chi_{c1} + \chi_{c2}$	< 5.3	< 8.6
$\eta_c(2S)$	$16.5 \pm 1.7 \pm 0.4$	$16.3 \pm 4.6 \pm 3.9$
$\Psi(2S)$	< 9.1	$< 16.$

- Factor of 10 discrepancy!!
- Extra th. errors $\sim 60\%$
- Relativistic corrections not under control

Double Charmonium Production

- Exclusive double charmonium exhibits a remarkable factor of 10 discrepancy between Belle data and theory
- Data is quality is very good with errors on $e^+e^- \to J/\psi + \eta_c$ at $\sim 15\%$
- Theoretical errors need to be brought under control
  - Understand relativistic corrections
- Belle has more data
  - Angular analysis
  - Inclusive data: $e^+e^- \to J/\psi + c\bar{c}$

Theory Overview

- New Techniques For higher order QCD calculations
- Soft Collinear Effective Theory

$$\mathcal{L} = -\frac{1}{4} F^A_{\mu\nu}(x) F^{\mu\nu}_A(x) + \bar{\psi}(x)(i\not{D} - m)\psi(x)$$

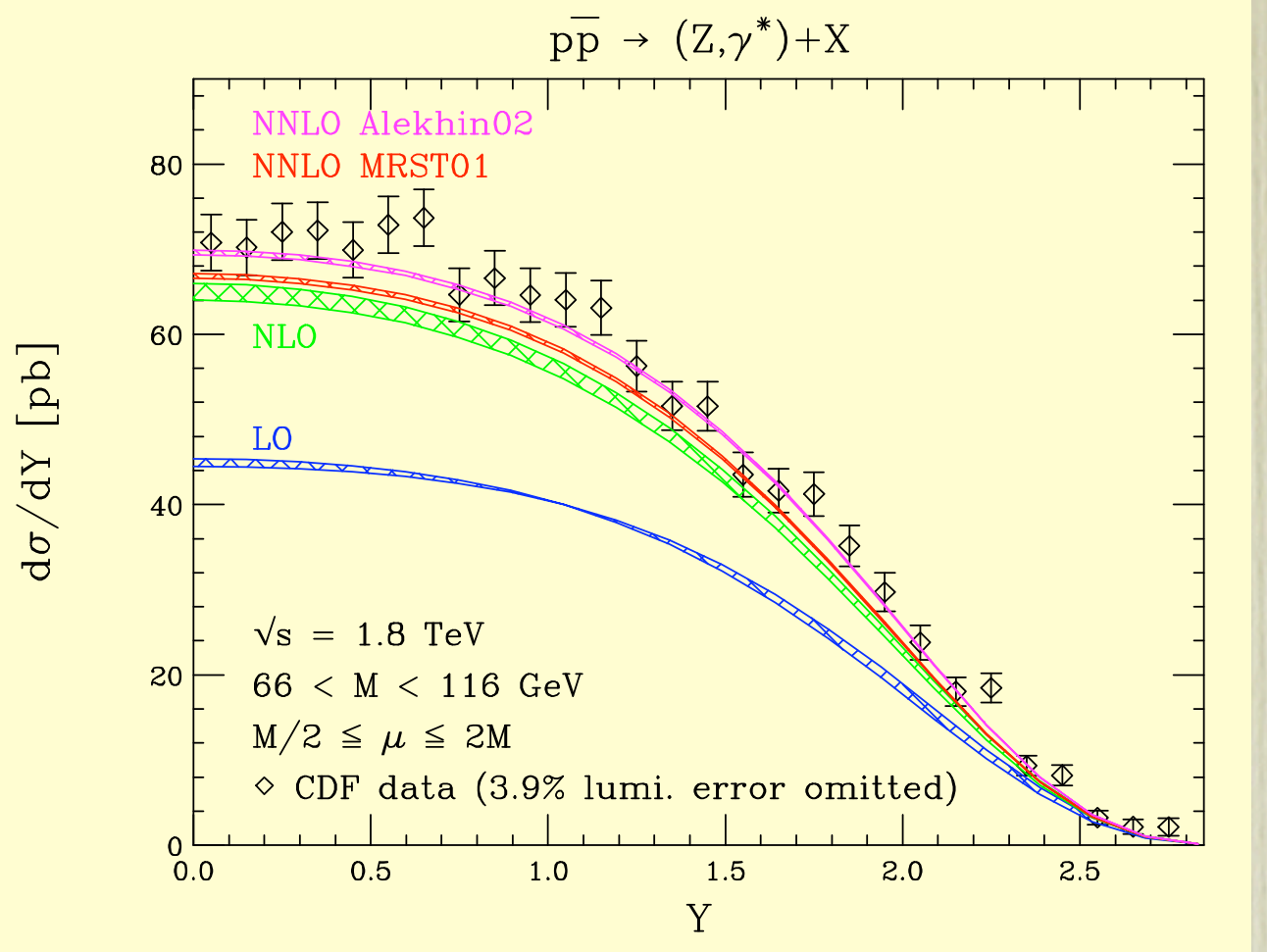
QCD at NNLO

C. Anastasiou *et al* Phys. Rev. D69, 094008 (2004)

"...the Tevatron and LHC physics programs require NNLO calculations for differential distributions in kinematic variables; knowledge of inclusive rates is insufficient."

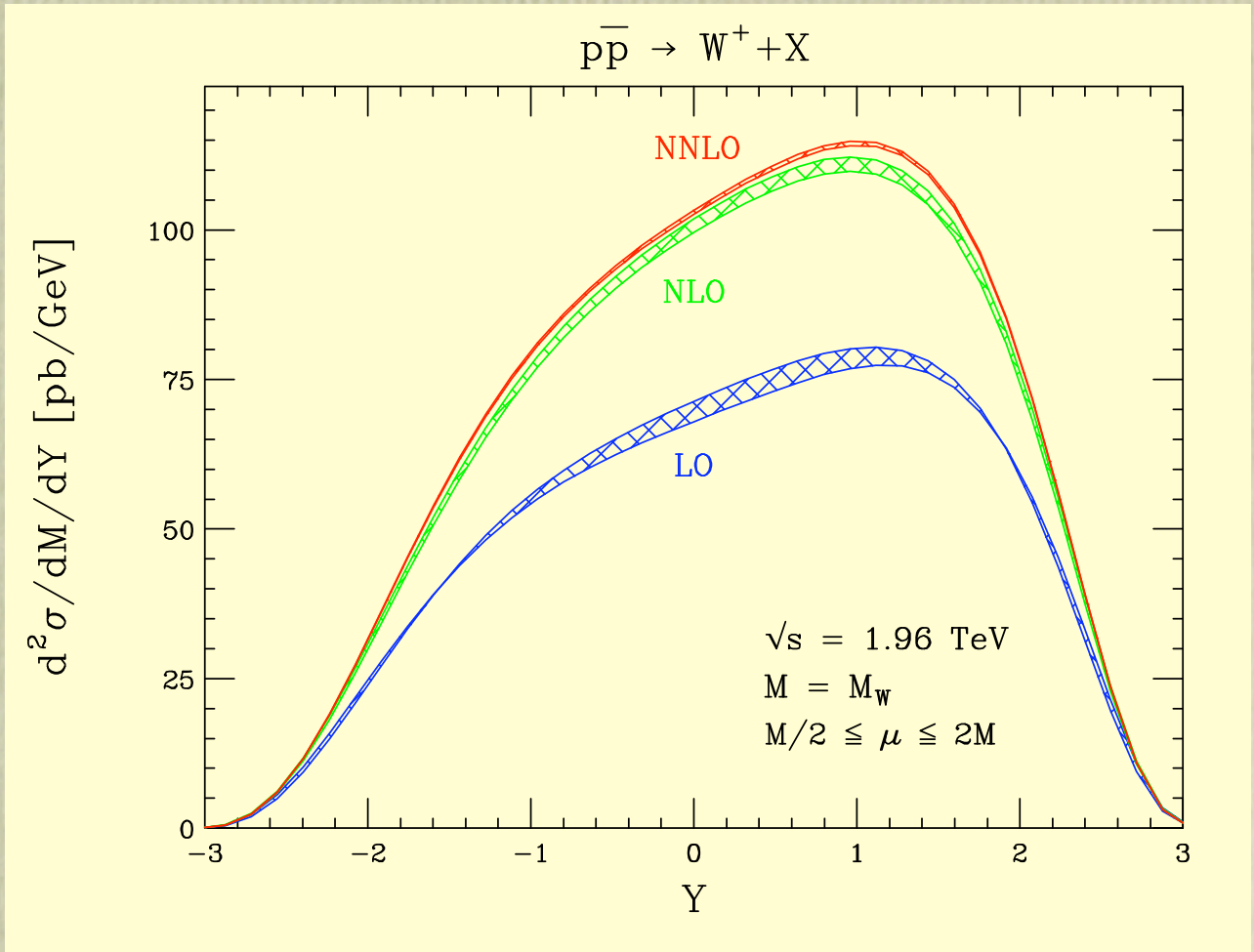
- Process considered: $h_1 + h_2 \to V + X$
  - V: vector boson (W, Z, γ^*)
  - X: any number of additional hadrons
- Differential CS $\frac{d\sigma^V}{dY} = \sum_{ab} \int_{\sqrt{\tau}e^Y}^1 \int_{\sqrt{\tau}e^{-Y}}^1 dx_1 dx_2\, f_a^{(h_1)}(x_1) f_b^{(h_2)}(x_2) \frac{d\sigma_{ab}^V}{dY}(x_1, x_2)$
  - Calculated to NNLO: $\frac{d\sigma_{ab}^V}{dY} = \frac{1}{2s} \int d\Pi_f\, \overline{||\mathcal{M}_{ab\to V+X}||^2}\, \delta\left(\frac{p_V \cdot p_1}{p_V \cdot p_2} - u\right)$
- Requires a new calculation technique

Run I Result



- Comparison to Run I CDF data
  - 3.9% normalization error to data
- 4 – 5% difference between different PDFs
- Approximate NNLO running of PDFs

Run II prediction



- Scale uncertainty at NNLO $\approx 0.3 - 0.7\%$!!!!
- Approximate NNLO running of PDFs
  - Full NNLO running now available

S. Moch, Vermaseren & A. Vogt, hep-ph/0407321

QCD at higher orders

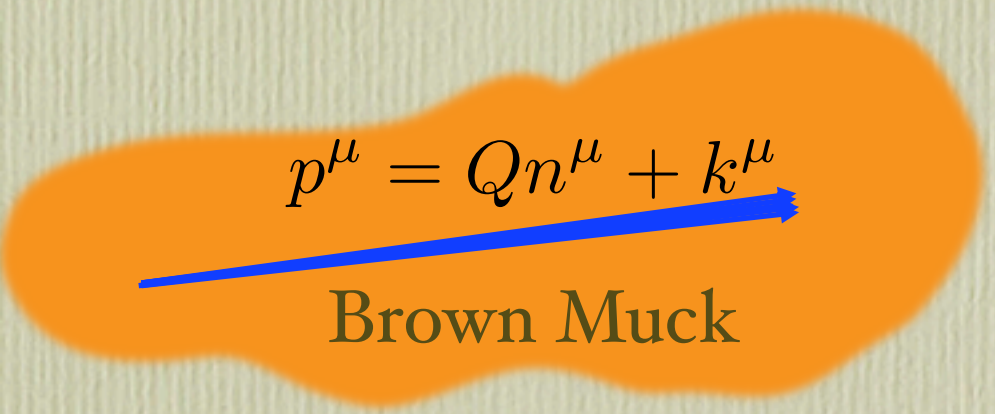
- New Technique allows for the calculation of NNLO differential distributions in hadronic collisions: Unprecedented!
  - Precision calculations with errors $O(1\%)$
  - Compare to precision data from Tevatron Run II and LHC
- Interest from string theory community: *Perturbative gauge theory as a string theory in twistor space,* E. Witten hep-th/0312171

Soft Collinear Effective Theory

Soft-Collinear Effective Theory: An Overview

Bauer, Fleming, Luke, Pirjol, Stewart

- SCET is: Effective theory of a highly energetic, approximately massless particle interacting with a soft background



Energetic: $Q \gg \Lambda_{\rm QCD}$

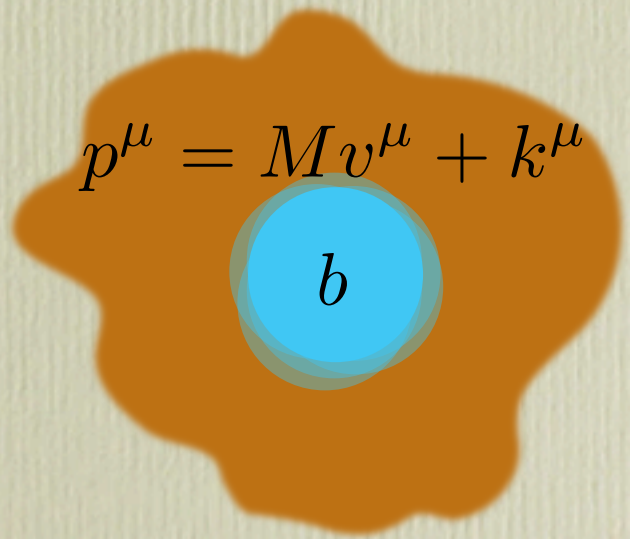
Light-like: $n^\mu = (1, 0, 0, 1)$

Residual Momentum: $k \sim \Lambda_{\rm QCD}$

- Expansion in a small parameter $\lambda \sim \dfrac{\Lambda_{\rm QCD}}{Q}$

Make an Analogy with HQET

Expansion in: $\dfrac{\Lambda_{\rm QCD}}{M}$



Heavy: $M \gg \Lambda_{\rm QCD}$

Static: $v^\mu = (1, 0, 0, 0)$

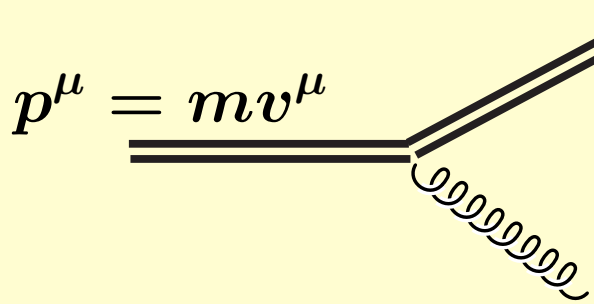
Residual Momentum: $k \sim \Lambda_{\rm QCD}$

Soft-Collinear Effective Theory

- Analogy with HQET breaks down:

HQET

Not Allowed!!!



$$p'^\mu = mzv^\mu$$

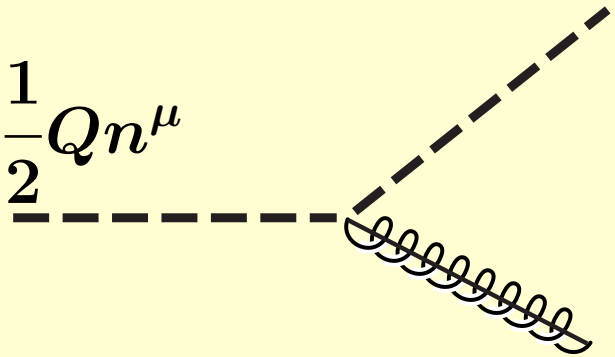
$$p^\mu = mv^\mu$$

$$q^\mu = m(1-z)v^\mu$$

$$q^2 = m^2(1-z)^2$$

SCET

O.K.

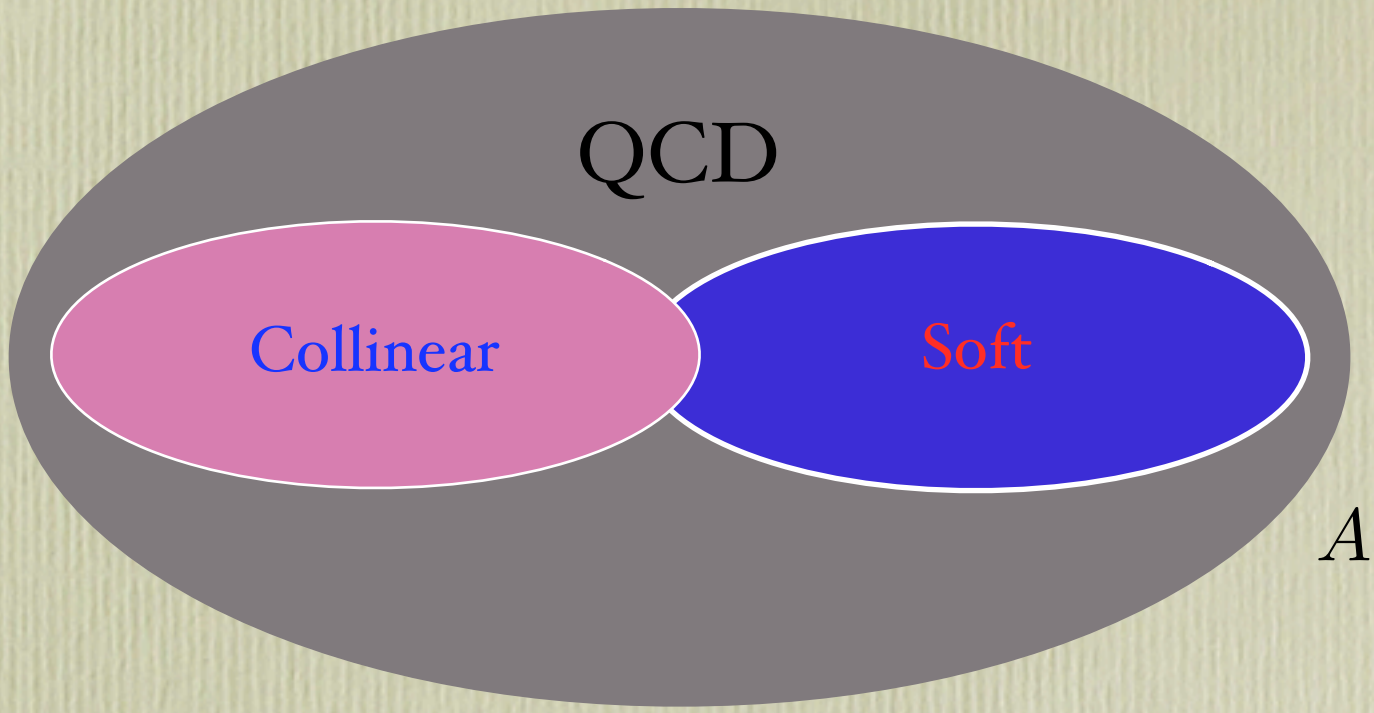


$$p^\mu = \frac{1}{2}Qn^\mu$$

$$p'^\mu = \frac{1}{2}zQn^\mu$$

$$q^\mu = \frac{1}{2}(1-z)Qn^\mu \qquad q^2 = 0$$

SCET Lagrangian



$$\psi(x) \to \psi_s(x) + \xi_n(x)$$

$$A^\mu(x) \to A_s^\mu(x) + A_n^\mu(x)$$

$$\mathcal{L}_c = \bar{\xi}_n \left\{ in \cdot D_c + i\not{D}_c^\perp \frac{1}{i\bar{n} \cdot D_c} i\not{D}_c^\perp + gn \cdot A_s \right\} \frac{\not{\bar{n}}}{2} \xi_n$$

$$\mathcal{L}_s = \bar{\psi}_s \, i\not{D}_s \psi_s$$

- Collinear sector: QCD in boosted frame
- Soft sector: QCD
- Coupled through a single term

Symmetries

- Separate collinear and soft gauge symmetries
  - Powerful restriction on the form of operators allowed
  - Soft fields act as a background field to collinear fields
  - Any gauge symmetry connecting soft to collinear introduces a large scale
- Global $U(1)$ helicity spin symmetry
- Reparameterization invariance which is a consequence of Lorentz invariance of QCD
  - Relates operators

Currents

Two important points:

1. Introduce a collinear Wilson line: $W = \mathrm{P}\exp\left(ig\int_{-\infty}^{x} ds\, \bar{n}\cdot A_n(s\bar{n})\right)$

$$W^\dagger \xi_n(x) \to W^\dagger \xi_n(x)$$ under collinear gauge transformations

2. Wilson coefficients are a function of the large light-cone component of the collinear momentum

$$C(\bar{n}\cdot P)$$ Hard-Collinear Factorization in SCET

- Example: Energetic up quark produced in $b \to u\ell\nu$ decays (leading order in λ)

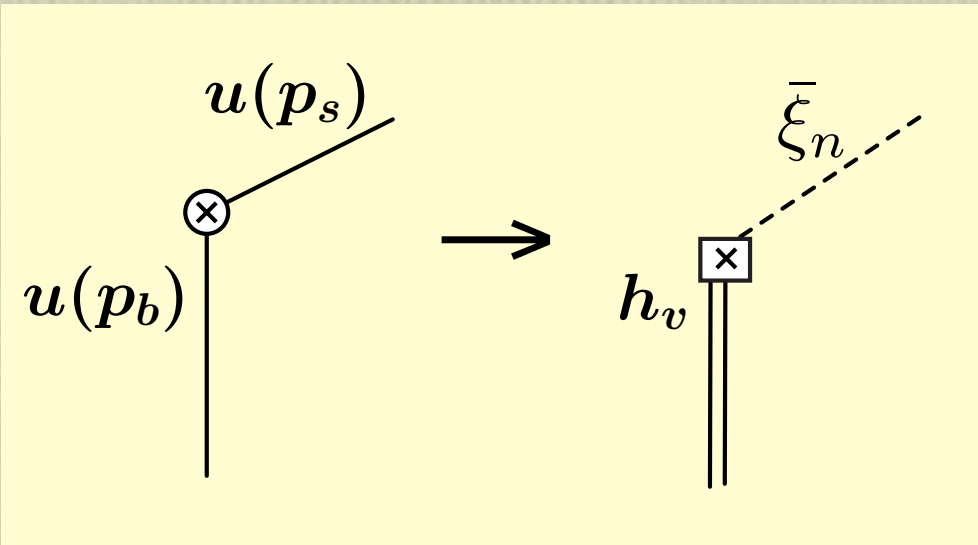
$$\cancel{\bar{u}(p_u)\Gamma u(p_b) \to \sum_i C_i(M)\bar{\xi}_{n,p}\Gamma_i h_v}$$

$$\bar{u}(p_u)\Gamma u(p_b) \to \sum_i \bar{\xi}_{n,p} W^\dagger C_i(\bar{n}\cdot \overleftarrow{P}_{\mathrm{op}})\Gamma_i h_v$$

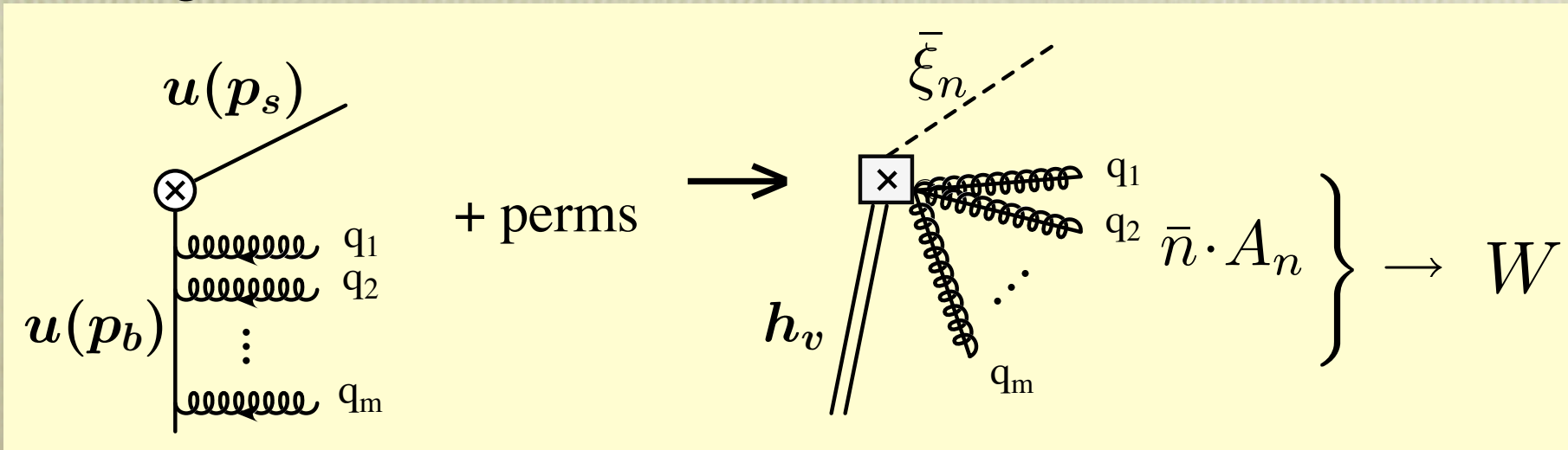
Heavy-Light Current: $b \to u$

Origin of the collinear Wilson line

- Leading order in α_s



- Higher orders



Decoupling Collinear & Soft

- Decouple Soft from Collinear in the Lagrangian

1) Soft Wilson Line $$Y(x) = \mathrm{Pexp}\left(ig \int_{-\infty}^{x} ds\, n \cdot A_s(ns) \right)$$

2) Field Redefinition $$\xi_n(x) = Y(x)\xi_n^{(0)}(x)$$

eikonal phase

$$\mathcal{L}_c \to \bar{\xi}_n \left\{ in \cdot D_c + i\not{D}_c^{\perp} \frac{1}{i\bar{n} \cdot D_c} i\not{D}_c^{\perp} \right\} \frac{\not{\bar{n}}}{2} \xi_n$$

- Complicates vertex: For our Heavy-Light example

$$\bar{\xi}_n W \Gamma h_v \to \bar{\xi}_n^{(0)} W^{(0)} \Gamma Y^{\dagger} h_v$$

Origin of Soft-Collinear Factorization in SCET

Soft-Collinear Effective Theory:

What have we learned:

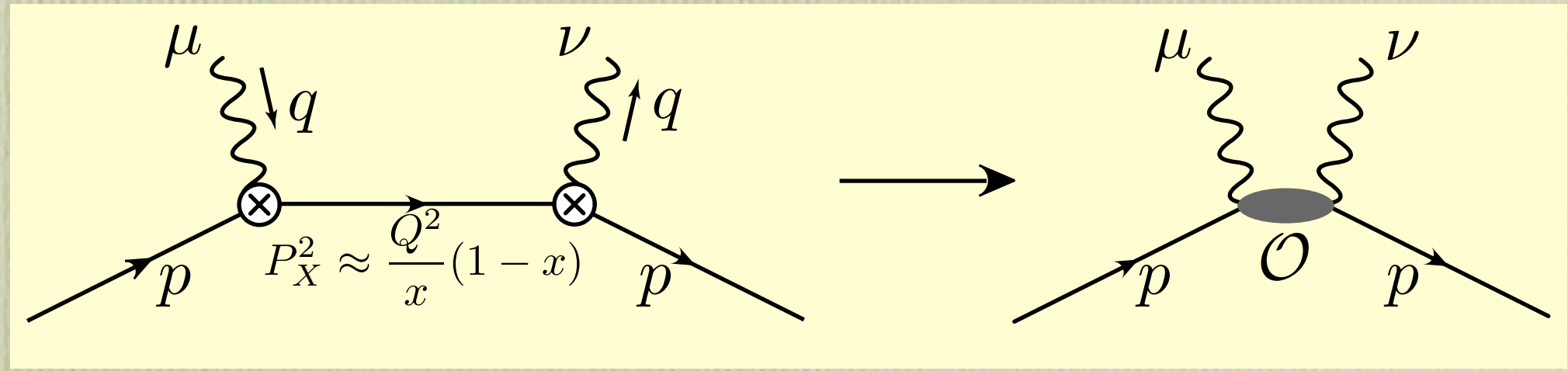
- SCET: EFT of collinear d.o.f. coupled to soft d.o.f.
  - Powerful gauge symmetries constrain operators
  - Decoupling via field redefinition

What is it good for?

- SCET is useful for understanding:
  - Factorization: Obtained from field redefinition and simple algebraic manipulations
  - Summation of Logarithms at the edges of phase space: Obtained from Renormalization Group Equations (RGEs)
  - Systematic Power Corrections in λ : Turn the crank

An Example: Factorization in DIS

- OPE: integrate out final state below the scale Q^2 by matching onto SCET



- Match onto SCET operators $\mathcal{O}(\omega_1, \omega_2) = \left[\bar{\chi}_{n,\omega_1} \frac{\bar{\not{n}}}{2} \chi_{n,\omega_2}\right]$

$$\chi_{n,\omega} = [\delta(\bar{n}\cdot P_{\rm op} - \omega) W^\dagger \xi_n]$$

Wilson coefficient depends on large light-cone momentum in hard scattering: Standard Convolution form of cross section

$$T_{\mu\nu}^{\rm eff} \sim \int d\omega_1\, d\omega_2\, C_{\mu\nu}(\omega_1, \omega_2)\, \mathcal{O}(\omega_1, \omega_2)$$

- Fix $C_{\mu\nu}(\omega_1, \omega_2)$ by forcing $T_{\mu\nu} = T_{\mu\nu}^{\rm eff}$

Factorization in DIS

- Decouple soft from Collinear $\chi_{n,\omega} \to Y \chi^{(0)}_{n,\omega}$

$$[\bar{\chi}_{n,\omega_1} \frac{\not{\bar{n}}}{2} \chi_{n,\omega_2}] \to [\bar{\chi}^{(0)}_{n,\omega_1} \frac{\not{\bar{n}}}{2} \underbrace{Y^\dagger Y}_{\to 1} \chi^{(0)}_{n,\omega_2}]$$

KLN Theorem

- Parton distributions in SCET

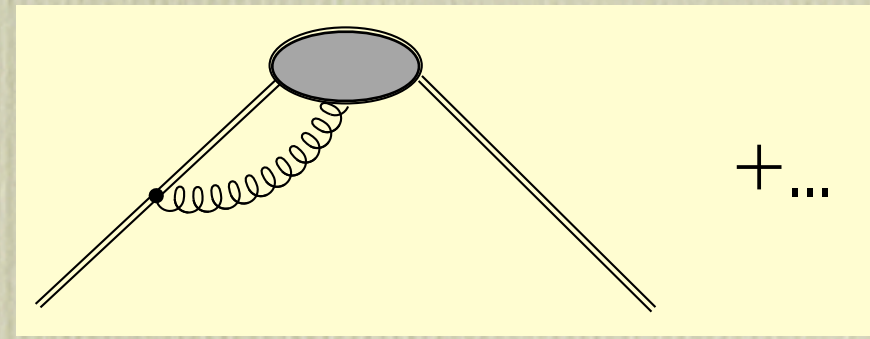
$$\frac{1}{4} \sum_{\text{spin}} \langle p_n | \bar{\chi}_{n,\omega} \not{\bar{n}} \chi_{n,\omega'} | p_n \rangle = \int_0^1 d\xi \, \delta(\omega_-) \delta\left(\frac{\omega_+}{2\bar{n}\cdot p} - \xi \right) f_{i/p}(\xi)$$

- Factored form

$$d\sigma \sim \int \frac{d\xi}{\xi} H\left(\frac{\xi}{x}; \mu \right) f_{i/p}(\xi; \mu)$$

Operator Evolution Equations

- Operator running



$$\longrightarrow \gamma$$

RGE $$\mu \frac{d}{d\mu} \mathcal{O}(\omega_1, \omega_2; \mu) = \int dx dy \, \gamma(\omega_1, \omega_2, x, y; \mu) \mathcal{O}(x, y; \mu)$$

Different momentum constraints give different running:

$$\omega_1 = \omega_2 \rightarrow \text{DGLAP or } \omega_1 + \omega_2 = \text{Const.} \rightarrow \text{BL}$$

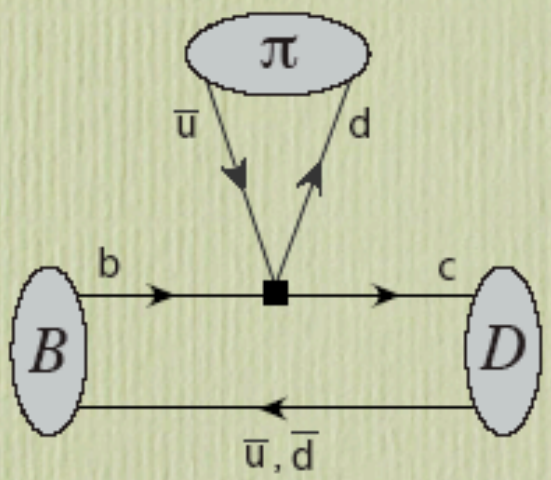
Some More Applications

- Color Suppressed $B \to D\pi$ Decays
- J/ψ Production at Belle & Babar

$B \to D\pi$

Mantry, Pirjol, Stewart

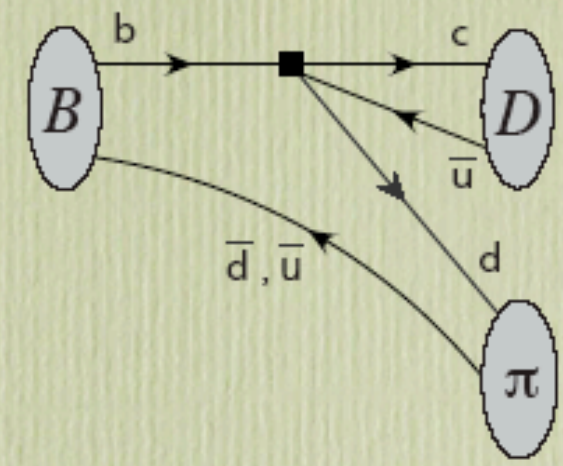
"Tree"



$\bar{B}^0 \to D^+\pi^-$
$B^- \to D^0\pi^-$

N_c^0

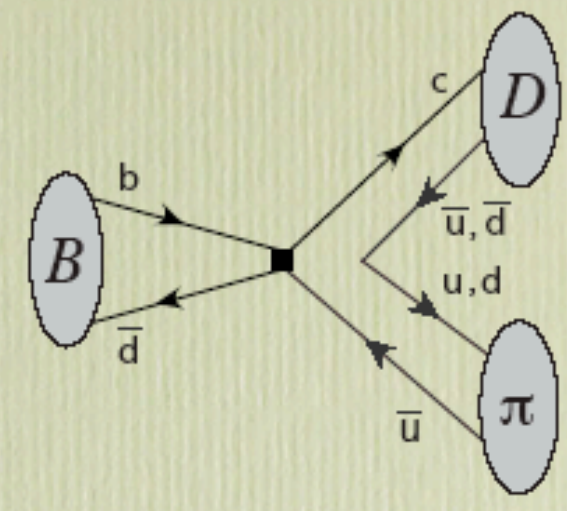
"Color suppressed"



$B^- \to D^0\pi^-$
$\bar{B}^0 \to D^0\pi^0$

$\frac{1}{N_c}$

"Exchange"



$\bar{B}^0 \to D^+\pi^-$
$\bar{B}^0 \to D^0\pi^0$

Observed 2001

$\frac{1}{N_c}$

Data

(Cleo, Belle, Babar)

Type	Decay	Br(10^{-3})	Decay	Br(10^{-3})
I	$\bar{B}^0 \to D^+\pi^-$	2.68 ± 0.29	$\bar{B}^0 \to D^{*+}\pi^-$	2.76 ± 0.21
III	$B^- \to D^0\pi^-$	4.97 ± 0.38	$B^- \to D^{*0}\pi^-$	4.6 ± 0.4
II	$\bar{B}^0 \to D^0\pi^0$	0.29 ± 0.03	$\bar{B}^0 \to D^{*0}\pi^0$	0.26 ± 0.05
I	$\bar{B}^0 \to D^+\rho^-$	7.8 ± 1.4	$\bar{B}^0 \to D^{*+}\rho^-$	6.8 ± 1.0
III	$B^- \to D^0\rho^-$	13.4 ± 1.8	$B^- \to D^{*0}\rho^-$	9.8 ± 1.8
II	$\bar{B}^0 \to D^0\rho^0$	0.29 ± 0.11	$\bar{B}^0 \to D^{*0}\rho^0$	< 0.56

- Color- Suppressed decays are indeed suppressed

But

Large is N_c not very predictive

- How about using SCET & HQET?

Color Suppressed Decays in SCET

- Possible to derive a factorization formula in SCET

Complicated because SCET operators are suppressed

$$\lambda \sim \frac{\Lambda_{\rm QCD}}{E_\pi} \sim 0.2$$

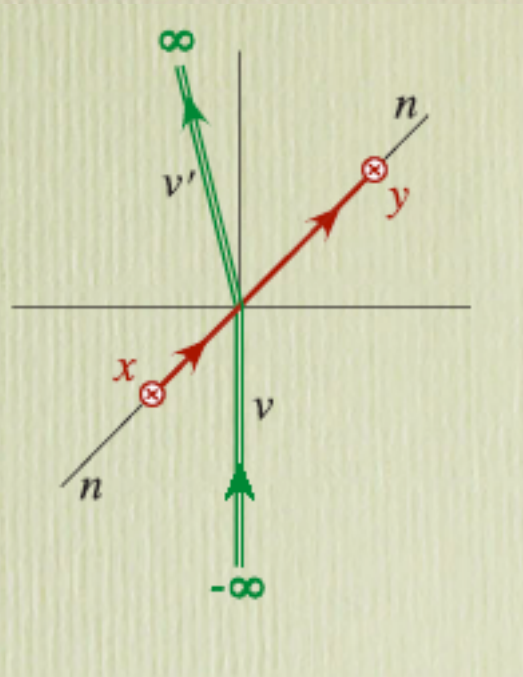
$$A_{00}^{D^{(*)}} = N_0^{(*)} \int dx\, dz\, dk_1^+ dk_2^+ \underbrace{T^{(i)}(z)}_{Q^2} \underbrace{J^{(i)}(z, x, k_1^+, k_2^+)}_{Q\Lambda} \underbrace{S^{(i)}(k_1^+, k_2^+)\, \phi_M(x)}_{\Lambda^2}$$

$$+ A_{\rm long}^{D^{(*)}M}$$

$$Q^2 \gg Q\Lambda \gg \Lambda^2$$

- New non-perturbative function: $S^{(i)}(k_1^+, k_2^+)$

Color Suppressed Decays in SCET



- $S^{(i)}(k_1^+, k_2^+) = \langle D^{(*)}|O_s|B\rangle$ is the lightcone distribution function for the spectator quarks in the B and D
- It is universal for a particular set of directions $\{v, v', n\}$
  - Will be the same for D and D^*
- It is a complex function: large strong phases are natural

Comparison to Date

- Universality for D and D^*
  - Branching ratio
    $$Br(D^0\pi^0) = (0.29 \pm 0.03) \times 10^{-3}$$
    $$Br(D^{*0}\pi^0) = (0.26 \pm 0.05) \times 10^{-3}$$
  - Strong Phase
    $$\delta(D\pi) = 30.4 \pm 4.8^\circ$$
    $$\delta(D^*\pi) = 31.0 \pm 5.0^\circ$$
- Predict $r^\rho_{00} = \dfrac{A(\bar{B}^0 \to D^{*0}\rho^0)}{A(\bar{B}^0 \to D^0\rho^0)} = 1$
- Explain naturally

$$|r^{D\pi}| = \frac{|A(\bar{B}^0 \to D^+\pi^-)|}{|A(B^- \to D^0\pi^-)|} = 0.77 \pm 0.05\,, \qquad |r^{D\rho}| = 0.80 \pm 0.09$$

SCET Predicts $$r^{DM} = 1 - \frac{16\pi\alpha_s m_D}{9(m_B + m_D)} \frac{\langle x^{-1}\rangle_M}{\xi(w_{max})} \frac{s_{\rm eff}}{E_M}$$

Natural sized parameter fits the data: $s_{\rm eff} \simeq (430\,{\rm MeV})e^{i\,44^\circ}$

One More Application

- J/ψ Production at Belle & Babar

J/ψ Production at Belle & Babar

Fleming, Leibovich, Mehen

$$e^+e^- \to J/\psi + X \; (\sqrt{s} = 10.6\,\mathrm{GeV})$$

Angular distribution

$$\frac{d\sigma}{dp\; dcos\theta} = S(p)(1 + A(p)cos^2\theta)$$

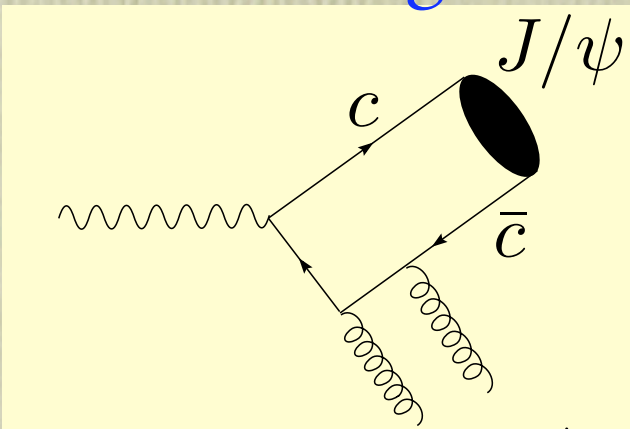
$$A(p)$$

	σ_{tot}(pb)	$p \lesssim 3.5$ GeV	$p \gtrsim 3.5$ GeV
Babar	$2.52 \pm 0.21 \pm 0.21$	0.05 ± 0.22	1.5 ± 0.6
Belle	$1.47 \pm 0.10 \pm 0.13$	0.7 ± 0.3	$1.1^{+0.4}_{-0.3}$

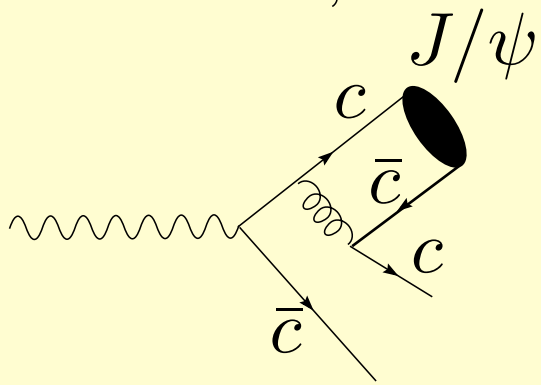
Belle $$\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12$$

NRQCD

Color Singlet

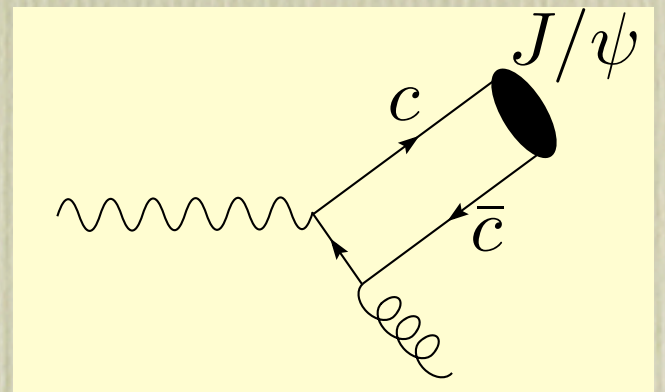


$\sigma = 0.73$ pb

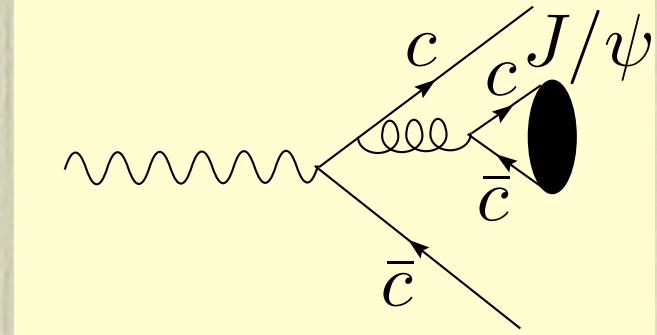


$\sigma = 0.20$ pb

Color Octet



$\sigma = 0.79$ pb

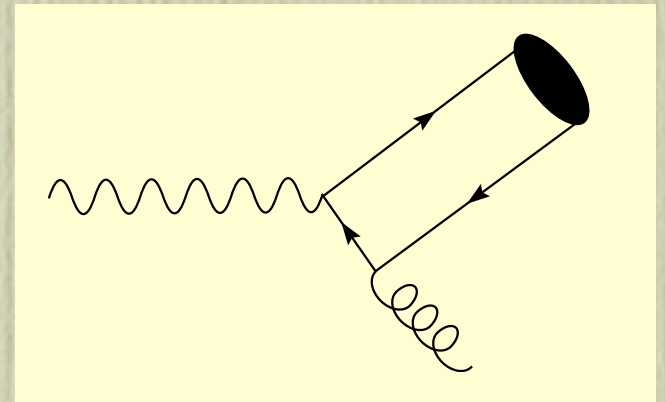


$\sigma = 0.08$ pb

$$\sigma_{\rm tot}^{(1)} = 0.93 \text{ pb} + \sigma_{\rm tot}^{(8)} = 0.87 \text{ pb} \rightarrow \sigma_{\rm tot} = 1.8 \text{ pb}$$

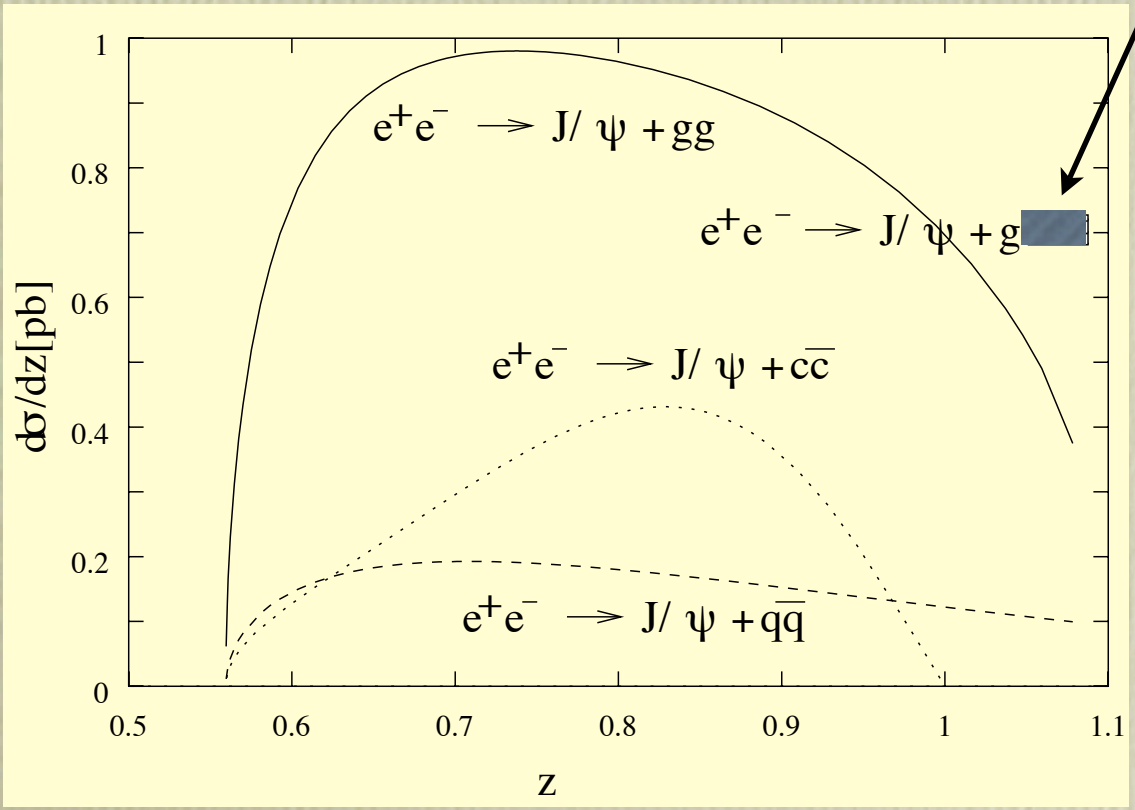
$$\frac{\sigma(e^+e^- \rightarrow J/\psi\ c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi\ X)} = 0.1$$

Differential Distribution

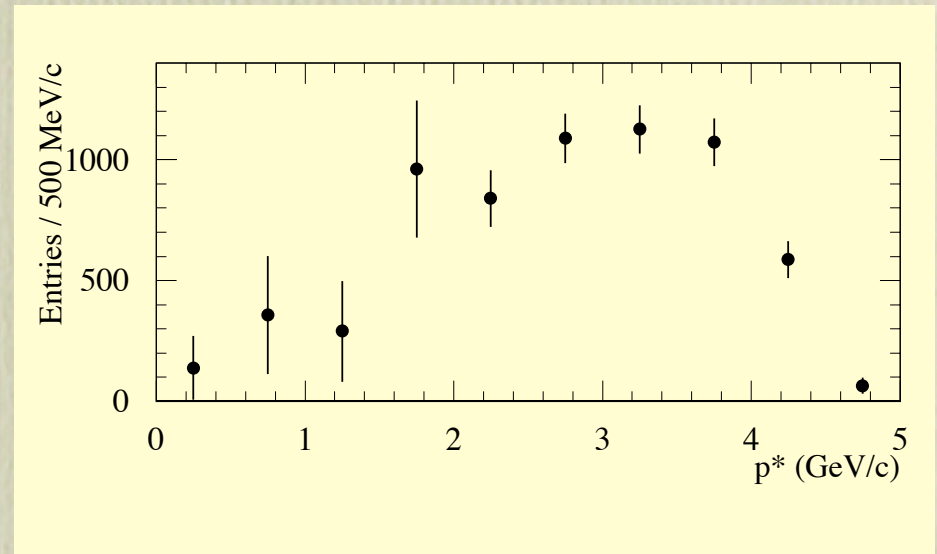


$$\rightarrow d\sigma \propto \delta(1 - z_p) \qquad z_p = p/p_{\max}$$

Theory

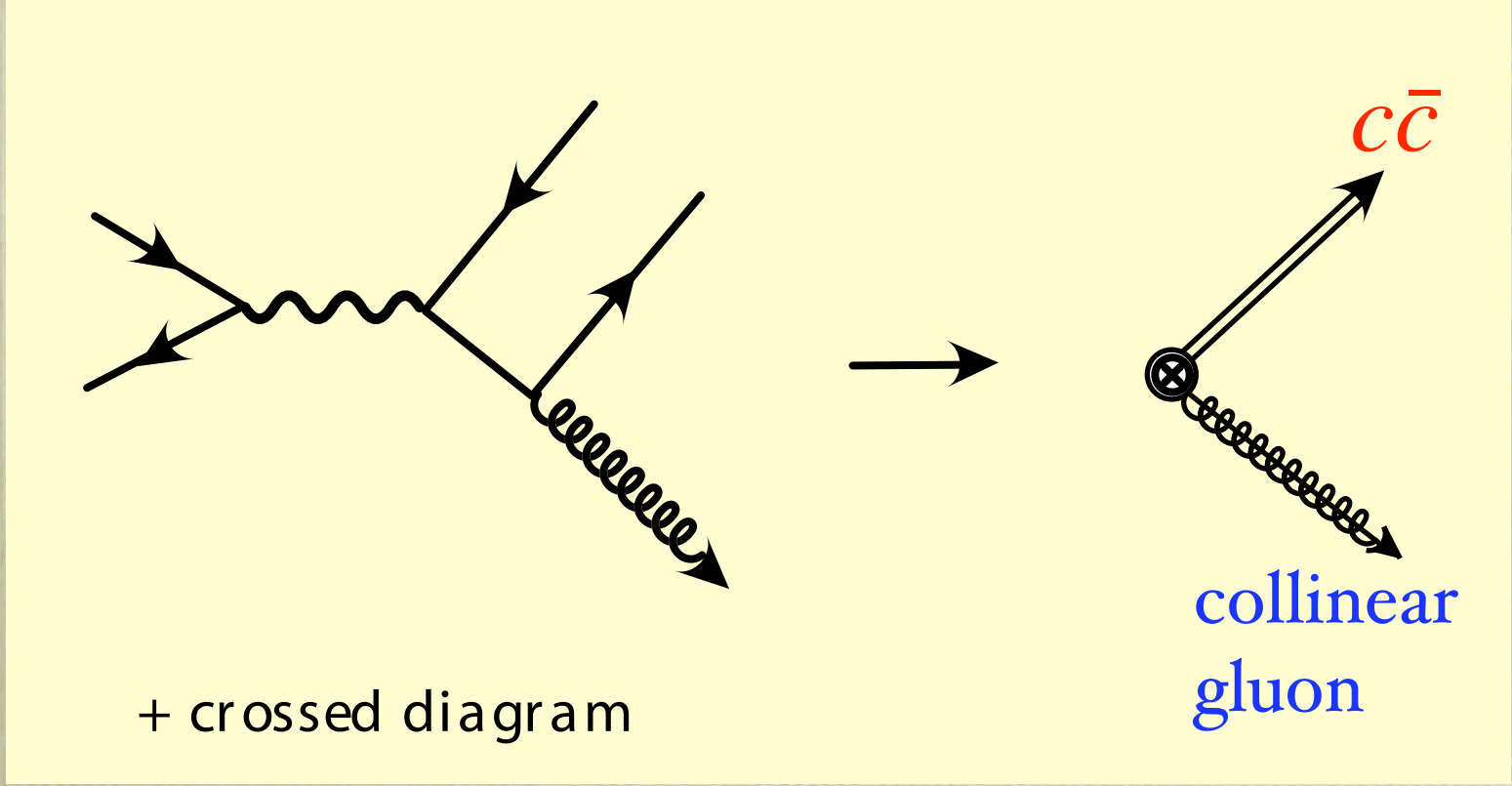


Babar



SCET & NRQCD

- In the Endpoint region:
  - use SCET for the fast & soft d.o.f.
  - use NRQCD for the heavy quark-antiquark



Factorization

- New factorization formula in the endpoint region:
  (Similar to $B \to X_s \gamma$)

Nonperturbative shape function

$$\frac{d\sigma}{dz} \propto \int_z^1 d\xi \, S(\xi;\mu) J(\xi - z;\mu)$$

Jet function

Jet function: perturbatively calculable in $\alpha_s\left(\sqrt{\frac{s}{m_c}\Lambda_{QCD}}\right)$

Shape function is universal

Used a simple model with 2 parameters: require moments to scale appropriately

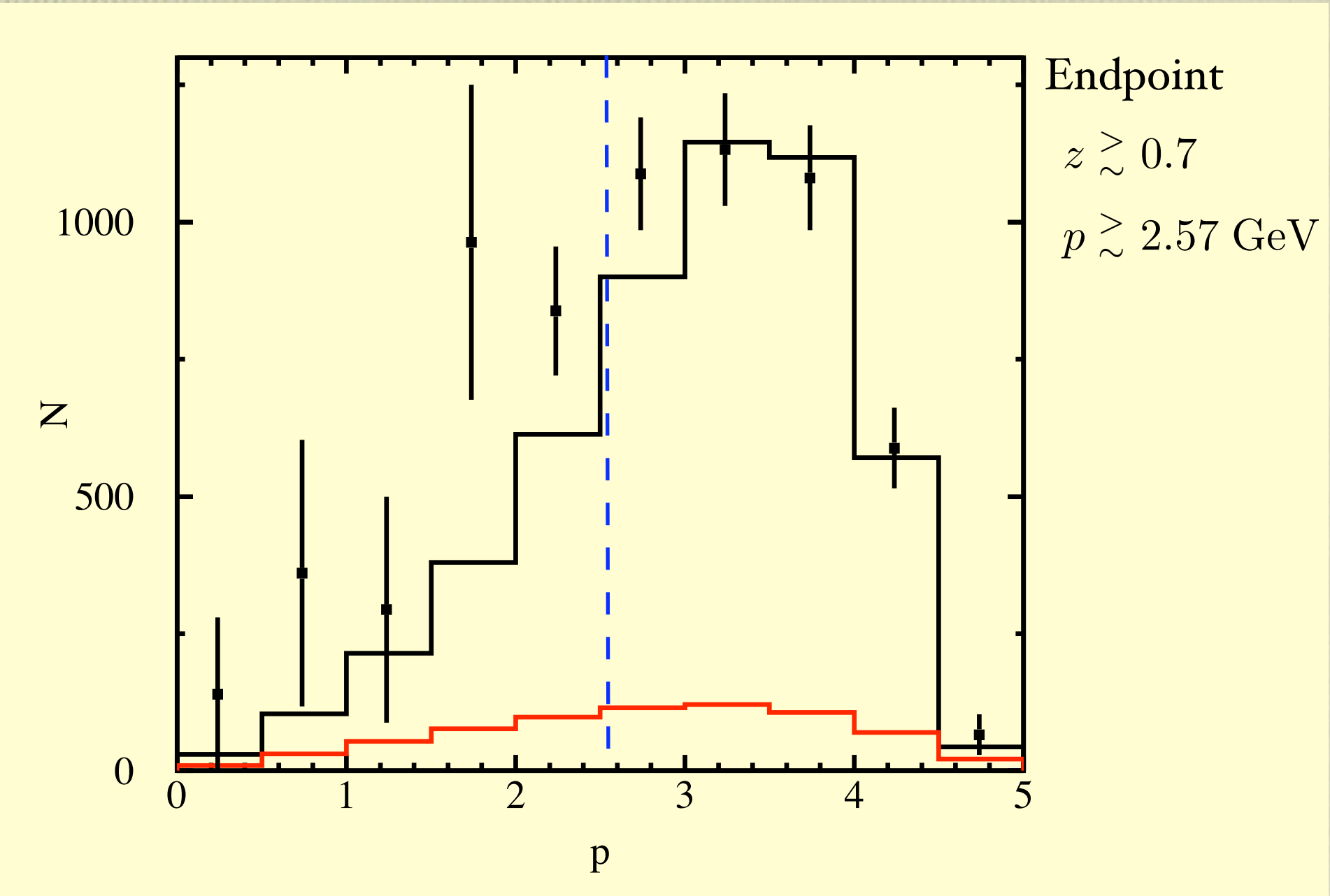
Overall normalization includes color-octet matrix element

Not well determined

Sum logs using RGEs

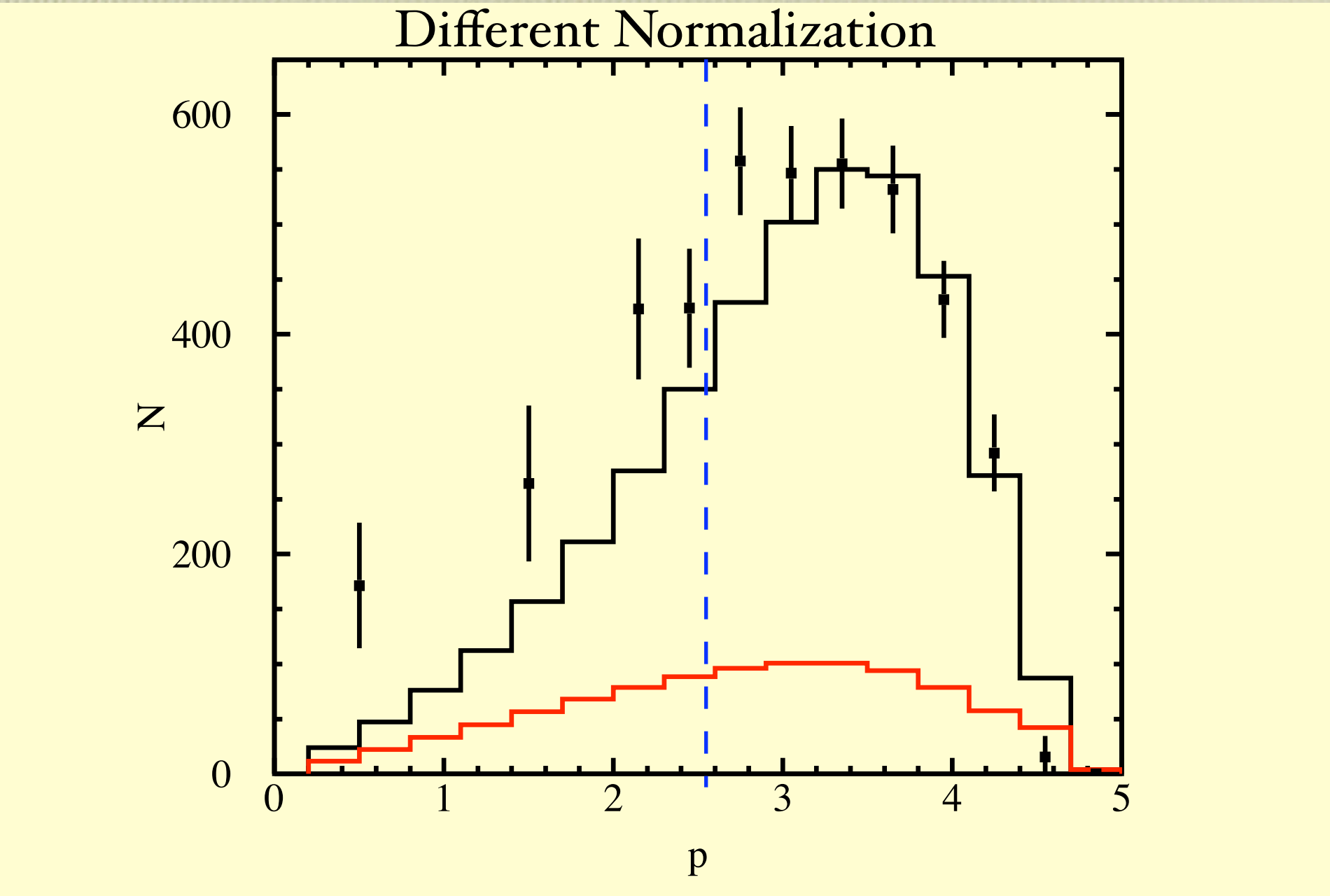
Comparison to Babar Data

B. Aubert *et al.* Phys. Rev. Lett. 87: 162002 (2001)

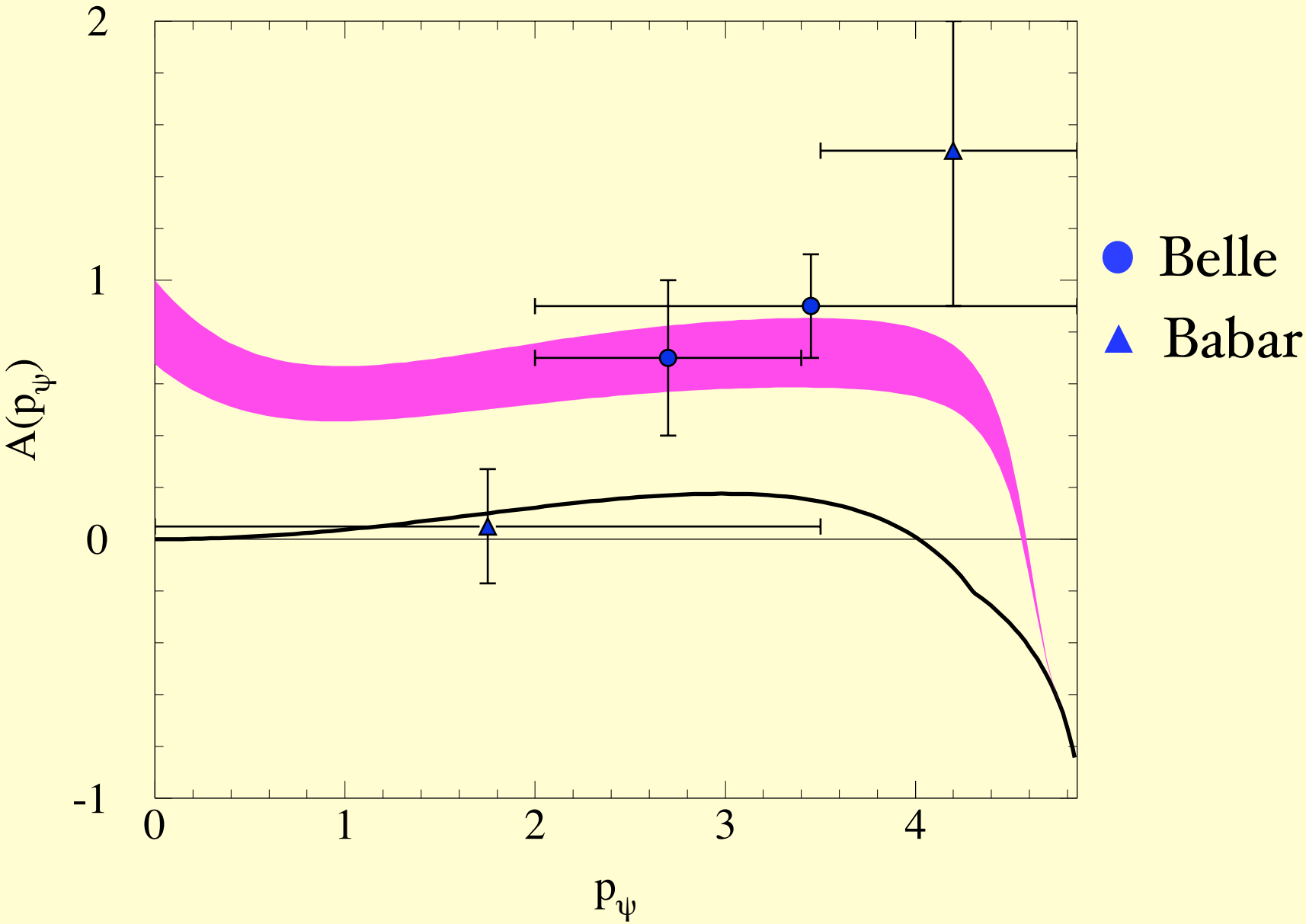


Comparison to Belle Data

K. Abe *et al.* Phys. Rev. Lett. 88: 052001 (2002)



Angular Distribution



SCET Summary

- Flavor of Soft Collinear Effective Theory
  - Theory of light-like particles interacting with a soft background
  - Derive factorization
  - Sum logarithms
  - Systematically treat power corrections
- Scope of applications is large
  - B decays, sub-leading pion form factor, event shapes, Quarkonium production and decay
- A very active field: more to come...
  - Watch for collider physics applications

Summary

- Experiment
  - Jets at the Tevatron: Precision Physics
  - Tevatron b-production: resolved
  - Double charmonium at Belle????
- Theory
  - New methods for high order QCD perturbation theory
  - Soft Collinear Effective Theory

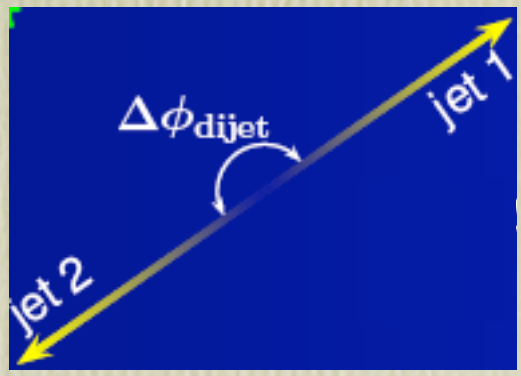
Di-Jet Azimuthal Decorrelations

Talk by M. Begel

Sensitive to higher-order QCD radiation without explicitly measuring 3rd and 4th jets

- Di-Jets produced at LO in perturbation theory

$$\Delta\phi_{\rm dijet} = \pi$$

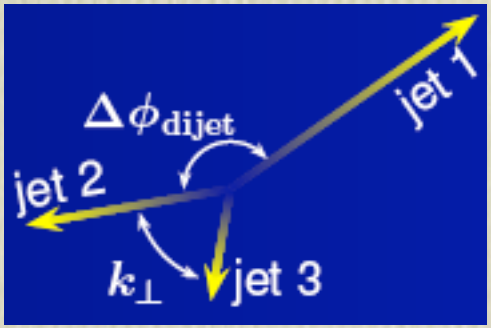


- Soft radiations results in small decorrelations

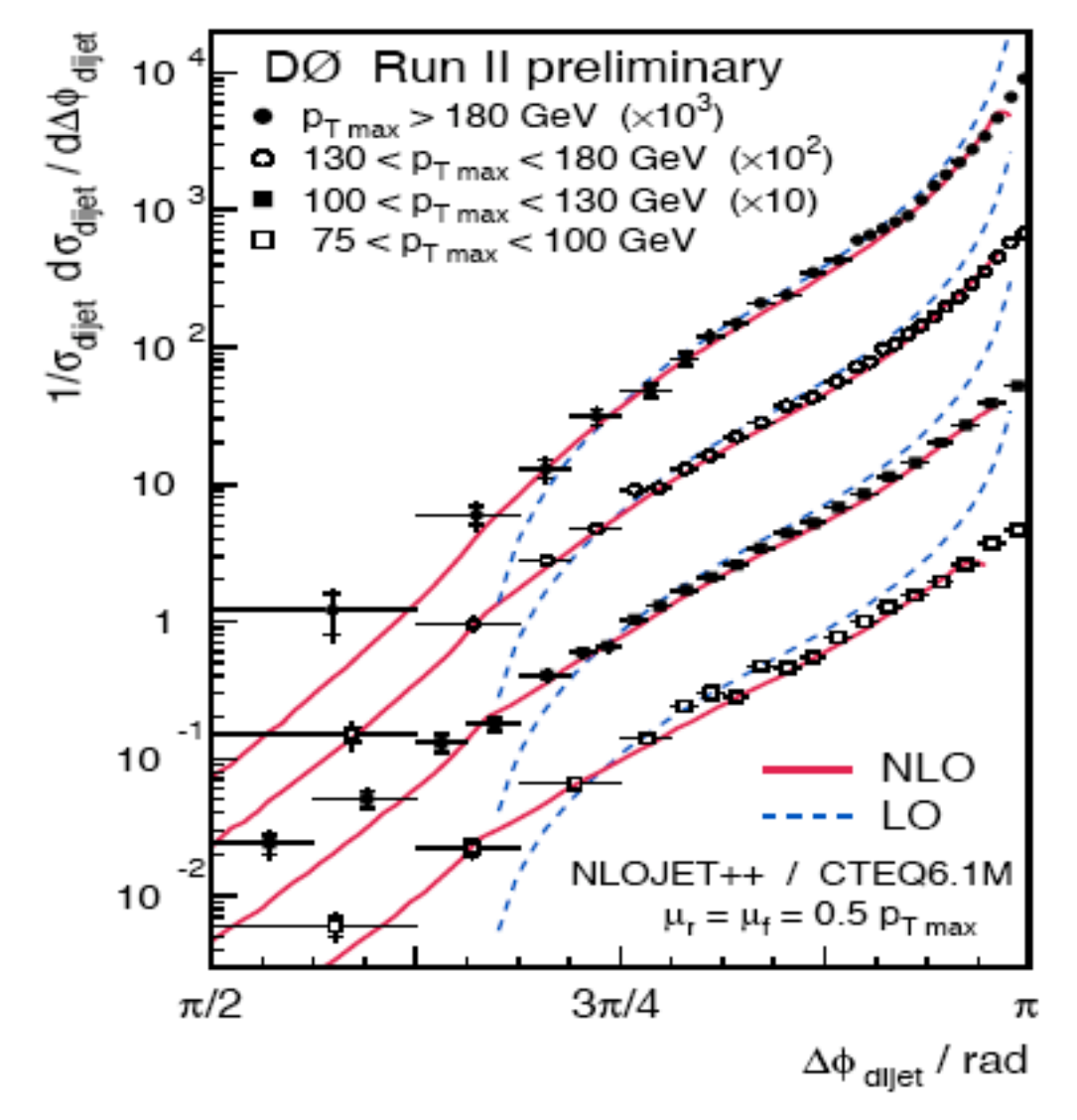
$$\Delta\phi_{\rm dijet} \sim \pi$$

- Hard radiation ($k_\perp$ large) leads to large decorrelations

$$\frac{2\pi}{3} \leq \Delta\phi_{\rm dijet} < \pi$$

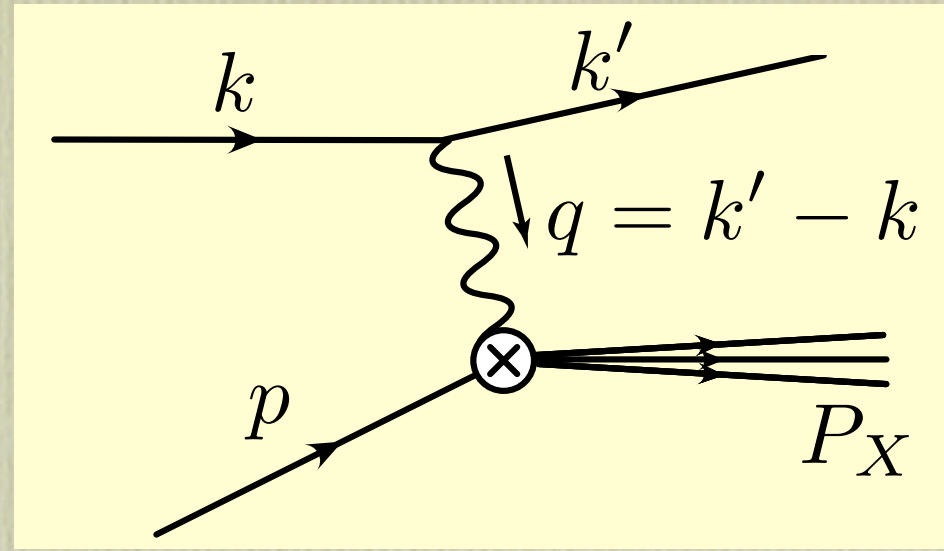


Di-Jet Azimuthal Decorrelations



- LO: QCD calculation of three jet production $O(\alpha_s^3)$
- NLO: QCD calculation of four jet production $O(\alpha_s^4)$

An Example: Factorization in DIS



- Kinematics: Breit frame

$$q^\mu = Q(\bar{n}^\mu - n^\mu)/2 \quad \text{with} \quad q^2 = -\frac{\bar{n}\cdot n}{2}Q^2 = -Q^2$$

$$x = \frac{Q^2}{2p\cdot q}$$

$$p^\mu = n^\mu \frac{Q}{2x} + \bar{n}^\mu x \frac{m_p^2}{2Q} + \mathcal{O}\left(\frac{m_p^2}{Q^2}\right)$$

$$P_X^\mu = p^\mu + q^\mu \quad \text{with} \quad \boxed{P_X^2 = \frac{Q^2}{x}(1-x) + m_p^2}$$