Threshold Resummation for single-inclusive Hadron production

Daniel de Florian

FCEyN - UBA

Argentina

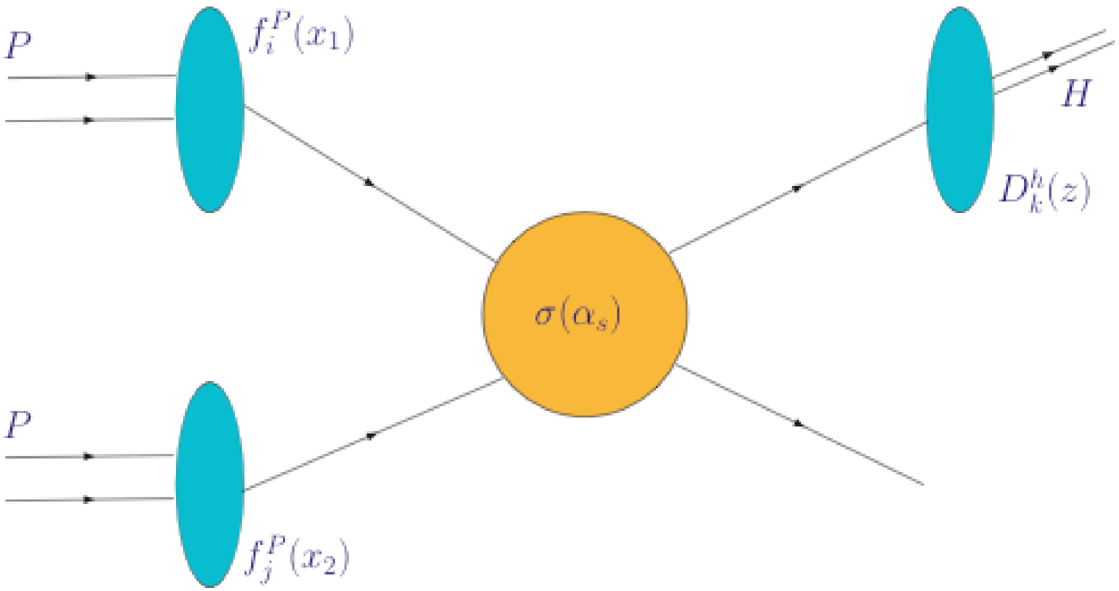
In collaboration with Werner Vogelsang

Phys. Rev.D71:114004,2005
Phys. Rev.D72:014014,2005
and hep-ph/**0704.1677**

Outline:

- Introduction
- Large Logarithms
- Resummation
- Hadron production
- Prompt photon production
- Jet production
- Conclusions

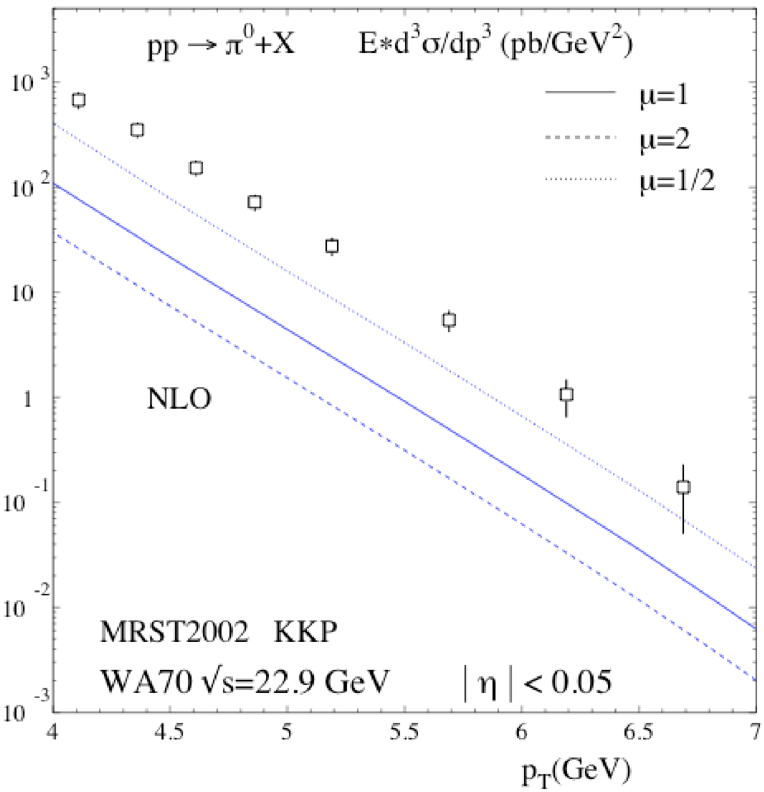
Relevance of hadron production in hadronic collisions

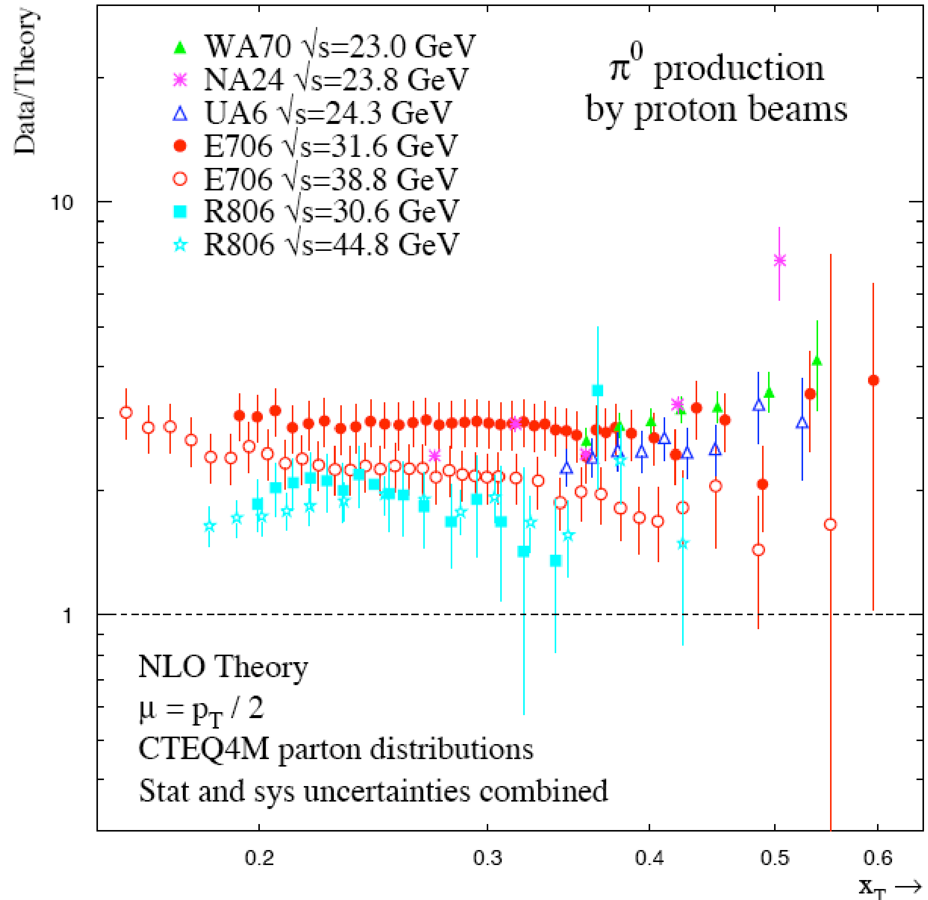


Involves almost all ingredients of QCD: coupling constant, hard cross-section, factorization, PDFs, FFs, non-pert. effects

$$d\sigma(pp \to h) = \sum_{i,j,k} \int_0^1 dx_1\, f_i^P(x_1, \mu_{FI}^2) \int_0^1 dx_2\, f_j^P(x_2, \mu_{FI}^2) \int_0^1 dz\, D_k^h(z, \mu_{FF}^2)\, d\hat{\sigma}(ij \to k)$$

Severe disagreement between data and pQCD (NLO) calculations for fixed target data





Very large F&R scale dependence

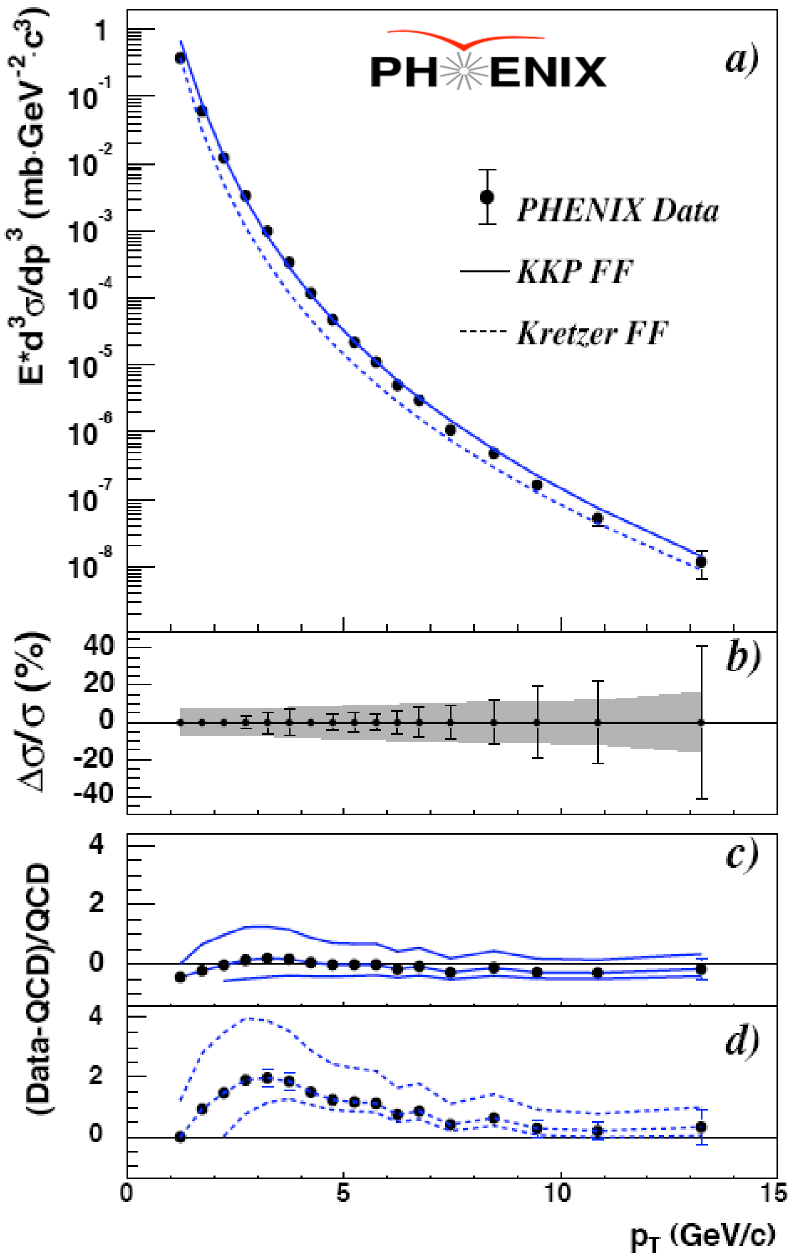
NLO already ~ 2.5 LO

Fixed order expansion valid?

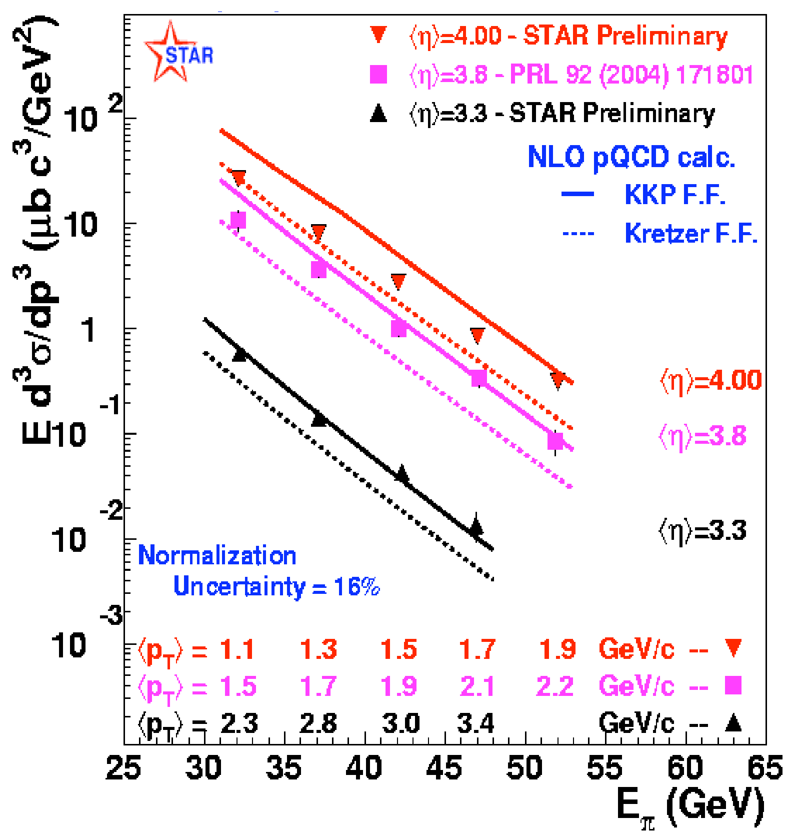
Apanasevich et al.

$$x_T = \frac{4p_T^2}{S}$$

Situation is much better for collider experiments

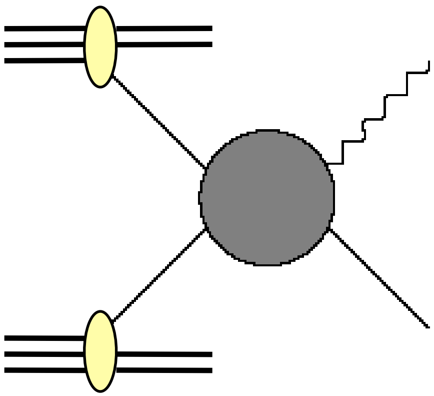


$pp \to \pi^0 X$ **at RHIC**

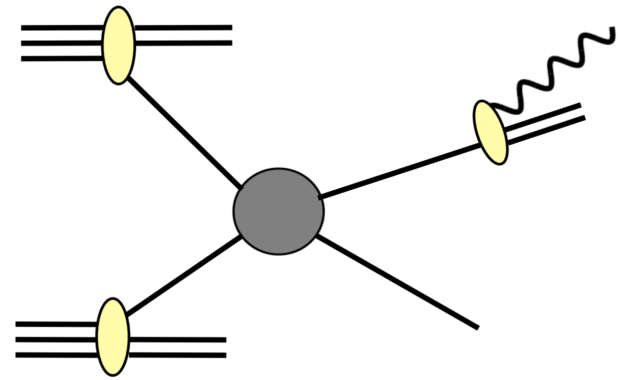


Hadron production relevant for prompt photons: $pp \to \gamma X$

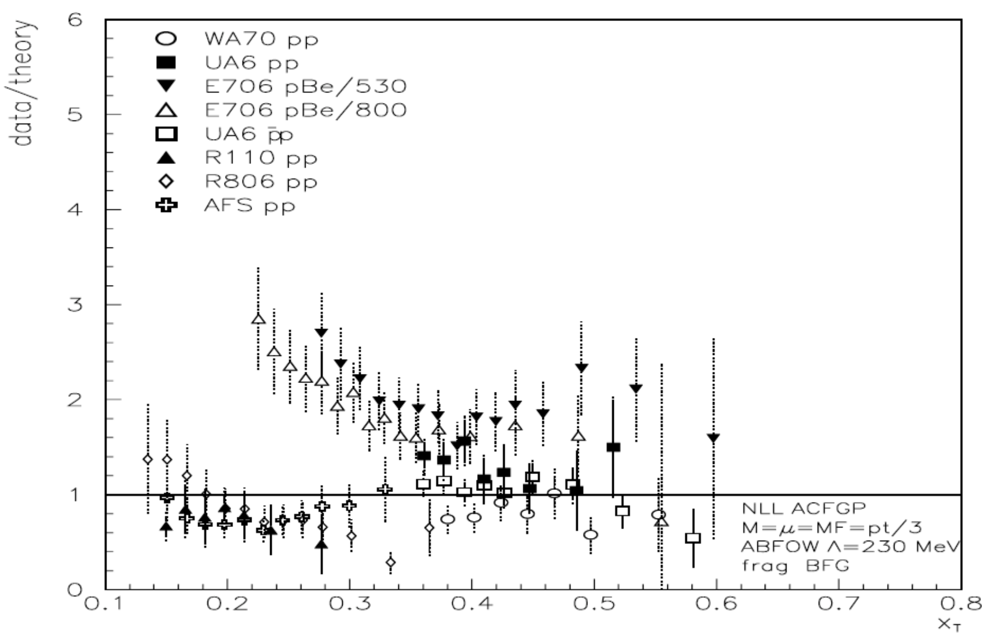
"direct" contribution



"fragmentation" contribution



like π^0 production, but different fragmentation function



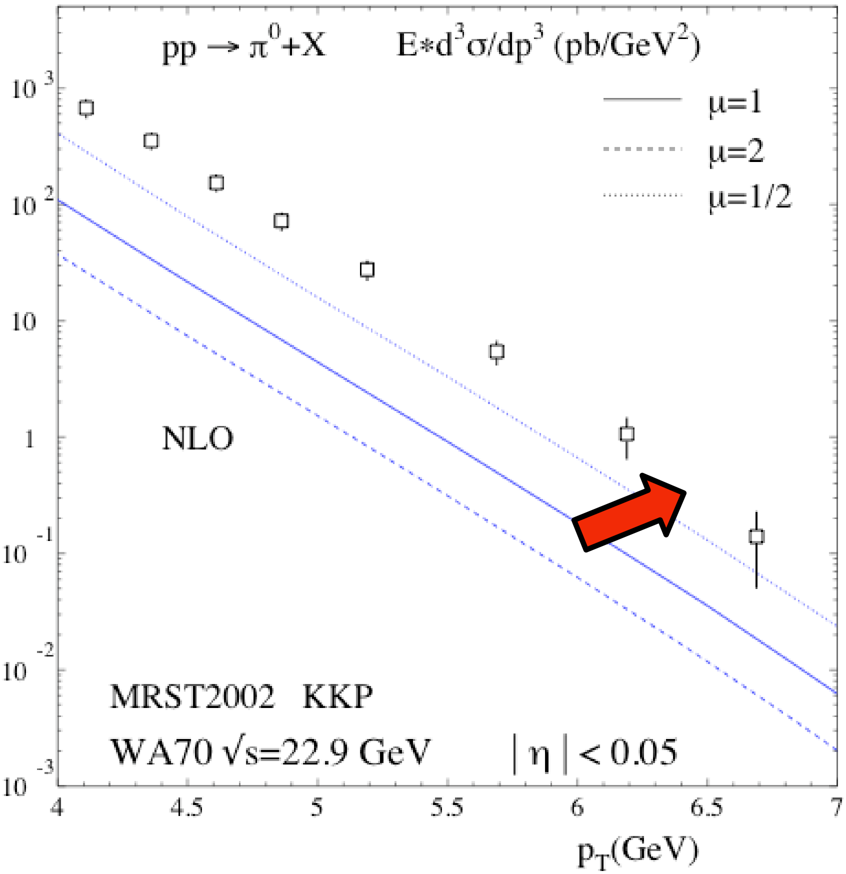
- Problems with some fixed target data sets.
- Also some "extreme" choices of scales needed $\mu_{F,R} = P_T/3$

Aurenche et al.

One phenomenological approach:

- Ad-hoc intrinsic k_T needed to cover the gap

$$f(x,Q^2) \to \int dk_T \; f(x,Q^2,k_T) \qquad f(x,Q^2,k_T) \sim f(x,Q^2) e^{-bk_T^2}$$



$k_T \sim \Lambda_{QCD}$ **reasonable but**

$k_T > 1\text{GeV}$ **Needed!**

Most of it could have more "perturbative" origin:

Go beyond fixed order !

This talk: multiple soft gluon emission affects these observables
Resummation needed

This talk: multiple soft gluon emission affects these observables
Resummation needed

- **Hadron production: corrections are large enough to bring agreement with fixed target data**

- **Photon production: resolved contribution increased. Reduction of Theoretical deficit at small transverse momentum**

This talk: multiple soft gluon emission affects these observables Resummation needed

- **Hadron production: corrections are large enough to bring agreement with fixed target data**

- **Photon production: resolved contribution increased. Reduction of Theoretical deficit at small transverse momentum**

Some phenomena usually explained by non-perturbative arguments can actually be (at least partially) understood in terms of (all orders) pQCD

This talk: multiple soft gluon emission affects these observables
Resummation needed

- Hadron production: corrections are large enough to bring agreement with fixed target data

- Photon production: resolved contribution increased. Reduction of Theoretical deficit at small transverse momentum

Some phenomena usually explained by non-perturbative arguments can actually be (at least partially) understood in terms of (all orders) pQCD

Why?

Large Logarithms in QCD

Any process involving two or more scales: Perturbative coefficients contain logs of scale ratios

Not a problem unless the scales are very different

Fixed order calculation $\sigma = C_0 + \alpha_s C_1 + \alpha_s^2 C_2 + \ldots$

Logs appear in the coefficients as $C_n \sim \log^{2n-1} \frac{E_1}{E_2}$

when $E_1 \sim E_2 \gg \Lambda_{QCD} \rightarrow \alpha_s \ll 1$ and $C_n \sim \mathcal{O}(1)$

Large Logarithms in QCD

Any process involving two or more scales: Perturbative coefficients contain logs of scale ratios

Not a problem unless the scales are very different

Fixed order calculation $\sigma = C_0 + \alpha_s C_1 + \alpha_s^2 C_2 + \ldots$

Logs appear in the coefficients as $C_n \sim \log^{2n-1} \frac{E_1}{E_2}$

when $E_1 \sim E_2 \gg \Lambda_{QCD} \rightarrow \alpha_s \ll 1$ and $C_n \sim \mathcal{O}(1)$

pQCD series converges well. Typically NLO calculations OK

Large Logarithms in QCD

Any process involving two or more scales: Perturbative coefficients contain logs of scale ratios

Not a problem unless the scales are very different

Fixed order calculation $\sigma = C_0 + \alpha_s C_1 + \alpha_s^2 C_2 + \ldots$

Logs appear in the coefficients as $C_n \sim \log^{2n-1} \frac{E_1}{E_2}$

when $E_1 \sim E_2 \gg \Lambda_{QCD} \to \alpha_s \ll 1$ and $C_n \sim \mathcal{O}(1)$

pQCD series converges well. Typically NLO calculations OK

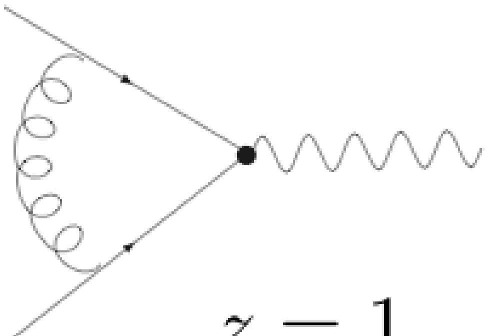
But if $E_1 \gg E_2$ **convergence is spoiled: even if coupling constant is small, power of Logs grows twice as fast!** $\log\left(1 - 4p_T^2/\hat{s}\right)$

Origin of the Logs

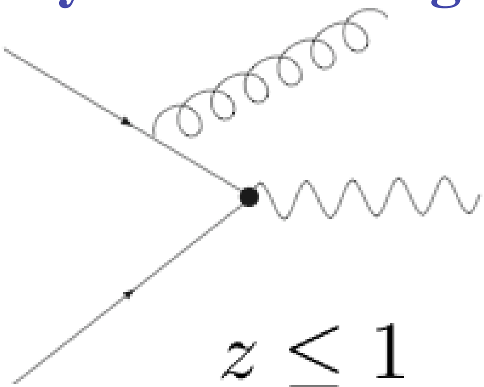
Unbalanced cancellation of real and virtual contributions at the boundaries of the phase space (soft gluon radiation)

Example: Drell-Yan $z = \frac{Q^2}{\hat{s}}$

(1-z) Momentum fraction carried by the emitted gluon



$z = 1$



$z \leq 1$

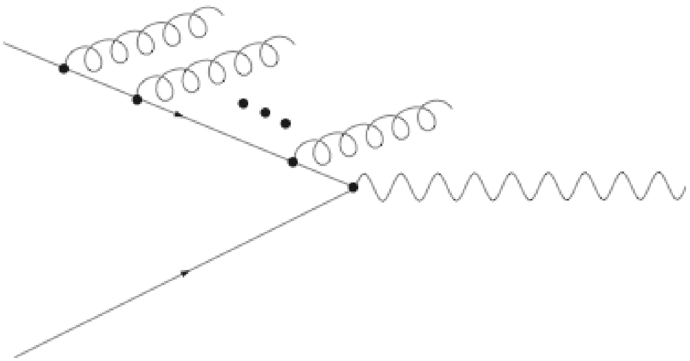
Both contributions infrared divergent: cancellation at z=1

Full after $\int_0^1 dz$ **(inclusive), otherwise some logs remain**

In the elastic limit (threshold) $\left(\frac{\log^m(1-z)}{1-z}\right)_+$ **can be very large**

Each gluon contributes with a double log (soft-collinear) at most

Typically one encounters corrections like $\alpha_s^n \log^{2n}$



- **Where relevant?**

$$\sigma(\tau) = \int_\tau^1 \frac{dz}{z} \sum_i \hat{\sigma}(z)\; q_i\left(\frac{\tau}{z}, Q^2\right) \bar{q}_i\left(\frac{\tau}{z}, Q^2\right)$$

For sure if $\tau = \frac{Q^2}{S_H}$ **close to 1 (hadronic threshold)**

- **But even for** $\tau \ll 1$ **parton distributions prefer z** $\longrightarrow$ **1**
- **Steeply falling densities leave partons with just enough energy for the process** $\longrightarrow$ **partonic threshold (often) reached**

Even more when fragmentation functions involved!

Therefore large logs can be dominant even at collider energies

In order to be able to perform a quantitative analysis of the data
Logs have to be resummed to all orders in the coupling constant

- **Restoration of perturbative series**
- **Precise predictions**
- **Structure of pQCD series at large orders**

Technicalities

$$\sigma(\tau) = \sum_{i,j} \int f_i(x_i) \otimes f_j(x_j) \otimes \hat{\sigma}_{ij}(z) \qquad \sigma(N) = \int_0^1 \tau^{N-1} \sigma(\tau)$$

Trade convolutions into products : Mellin

$$\sigma(N) = \sum_{i,j} f_i(N+1) \times f_j(N+1) \times \hat{\sigma}_{ij}(N)$$

$z \to 1 \; (\tau \to 1)$ **corresponds to** $N \to \infty$

$$\left(\frac{\log^m(1-z)}{1-z}\right)_+ \longrightarrow \log^{m+1} N$$

- **Resummation: reorganize perturbative structure**

$$\mathbf{L} \equiv \ln(\mathbf{N})$$

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure**

$$\mathbf{L} \equiv \ln(\mathbf{N})$$

Fixed order

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure**

$\mathbf{L \equiv \ln(N)}$

Fixed order

LO 1

$\alpha_s L \simeq 1$

- **Resummation: reorganize perturbative structure**

$$\mathbf{L} \equiv \ln(\mathbf{N})$$

Fixed order

LO	$\mathbf{1}$			
NLO	$\alpha_{\mathbf{s}}\,\mathbf{L}^{\mathbf{2}}$	$\alpha_{\mathbf{s}}\,\mathbf{L}$	$\alpha_{\mathbf{s}}$	$+\ \ldots$

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure** $\mathbf{L} \equiv \ln(\mathbf{N})$

Fixed order

LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s		$+ \ldots$
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$+ \ldots$

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure** $\mathbf{L \equiv \ln(N)}$

Fixed order →

LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s		$+\ \dots$
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$+\ \dots$
	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$+\ \dots$
	$\alpha_s^4 L^8$	$\alpha_s^4 L^7$	$\alpha_s^4 L^6$	$\alpha_s^4 L^5$	$+\ \dots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure** $\mathbf{L \equiv \ln(N)}$

Fixed order →

LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s		$+\dots$
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$+\dots$
	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$+\dots$
	$\alpha_s^4 L^8$	$\alpha_s^4 L^7$	$\alpha_s^4 L^6$	$\alpha_s^4 L^5$	$+\dots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
N^kLO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$+\dots$

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure** $\mathbf{L \equiv \ln(N)}$

Fixed order →

Resummation ↓

LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s		$+\dots$
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$+\dots$
	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$+\dots$
	$\alpha_s^4 L^8$	$\alpha_s^4 L^7$	$\alpha_s^4 L^6$	$\alpha_s^4 L^5$	$+\dots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
N^kLO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$+\dots$

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure**

$\mathbf{L} \equiv \ln(\mathbf{N})$

Fixed order

Resummation

LO	1				
NLO	$\alpha_s \mathbf{L}^2$	$\alpha_s \mathbf{L}$	α_s		$+ \dots$
NNLO	$\alpha_s^2 \mathbf{L}^4$	$\alpha_s^2 \mathbf{L}^3$	$\alpha_s^2 \mathbf{L}^2$	$\alpha_s^2 \mathbf{L}$	$+ \dots$
	$\alpha_s^3 \mathbf{L}^6$	$\alpha_s^3 \mathbf{L}^5$	$\alpha_s^3 \mathbf{L}^4$	$\alpha_s^3 \mathbf{L}^3$	$+ \dots$
	$\alpha_s^4 \mathbf{L}^8$	$\alpha_s^4 \mathbf{L}^7$	$\alpha_s^4 \mathbf{L}^6$	$\alpha_s^4 \mathbf{L}^5$	$+ \dots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
$\mathrm{N^kLO}$	$\alpha_s^k \mathbf{L}^{2k}$	$\alpha_s^k \mathbf{L}^{2k-1}$	$\alpha_s^k \mathbf{L}^{2k-2}$	$\alpha_s^k \mathbf{L}^{2k-3}$	$+ \dots$
	LL				

$\alpha_s L \simeq 1$

- **Resummation: reorganize perturbative structure** $\mathbf{L \equiv \ln(N)}$

Fixed order →

Resummation ↓

LO	1				
NLO	$\alpha_s \mathbf{L}^2$	$\alpha_s \mathbf{L}$	α_s		$+ \dots$
NNLO	$\alpha_s^2 \mathbf{L}^4$	$\alpha_s^2 \mathbf{L}^3$	$\alpha_s^2 \mathbf{L}^2$	$\alpha_s^2 \mathbf{L}$	$+ \dots$
	$\alpha_s^3 \mathbf{L}^6$	$\alpha_s^3 \mathbf{L}^5$	$\alpha_s^3 \mathbf{L}^4$	$\alpha_s^3 \mathbf{L}^3$	$+ \dots$
	$\alpha_s^4 \mathbf{L}^8$	$\alpha_s^4 \mathbf{L}^7$	$\alpha_s^4 \mathbf{L}^6$	$\alpha_s^4 \mathbf{L}^5$	$+ \dots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
N^{k}LO	$\alpha_s^k \mathbf{L}^{2k}$	$\alpha_s^k \mathbf{L}^{2k-1}$	$\alpha_s^k \mathbf{L}^{2k-2}$	$\alpha_s^k \mathbf{L}^{2k-3}$	$+ \dots$
	LL	**NLL**			

$$\alpha_s L \simeq 1$$

- **Resummation: reorganize perturbative structure** $\mathbf{L} \equiv \ln(\mathbf{N})$

Fixed order →

Resummation ↓

LO	1				
NLO	$\alpha_s L^2$	$\alpha_s L$	α_s		$+ \dots$
NNLO	$\alpha_s^2 L^4$	$\alpha_s^2 L^3$	$\alpha_s^2 L^2$	$\alpha_s^2 L$	$+ \dots$
	$\alpha_s^3 L^6$	$\alpha_s^3 L^5$	$\alpha_s^3 L^4$	$\alpha_s^3 L^3$	$+ \dots$
	$\alpha_s^4 L^8$	$\alpha_s^4 L^7$	$\alpha_s^4 L^6$	$\alpha_s^4 L^5$	$+ \dots$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	
N^kLO	$\alpha_s^k L^{2k}$	$\alpha_s^k L^{2k-1}$	$\alpha_s^k L^{2k-2}$	$\alpha_s^k L^{2k-3}$	$+ \dots$
	LL	**NLL**	**NNLL**		

$\alpha_s L \simeq 1$

Resummation achieved by exponentiation of logarithmic terms:
Sudakov form factor not trivial in QCD: color correlations

$$\sigma^{\rm res}_{ij\to kl} \sim \sum_c e^{S_c}\, \sigma^c_{ij\to kl}$$

Catani, Trentadue
Sterman
Bonciani, Catani, Mangano, Nason

After rapidity integration

$$\int d\eta\; \sigma(\eta) \;\sim \sigma(\eta=0) + \mathcal{O}(1/N)$$

$$\sigma^c_{ij\to kl} \;\to\; G^c\, \sigma^{\rm Born}_{ij\to kl}$$

- **How does resummed formula look ?**

usually,

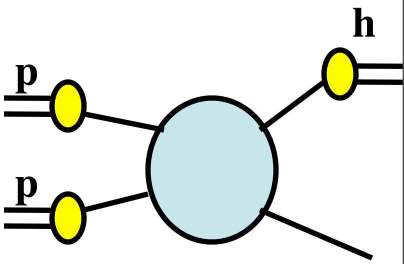
$$\exp\left[\; \underbrace{\mathbf{L\, h_1(\alpha_s L)}}_{\alpha_s^k\, L^{k+1}} \;+\; \underbrace{\mathbf{h_2(\alpha_s L)}}_{\alpha_s^k\, L^k} \;+\; \frac{\mathbf{1}}{\mathbf{L}}\mathbf{h_3(\alpha_s L)} \;+\; \ldots \right]$$

LL **NLL**

As a result of exponentiation: "simple" set of rules for each parton participating (in many cases universal):radiative factors

Initial state (pdf): **soft gluon radiation collinear to parton**

$$\Delta_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\int_{\mu_{FI}^2}^{(1-z)^2Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2))\right\}$$



Final state identified parton: **same as initial state pdf ⟷ ff**

Final state not-identified parton (jet): **collinear (soft or hard)**

$$J_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\left[\int_{(1-z)^2Q^2}^{(1-z)Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2))+\frac{1}{2}B_a(\alpha_s((1-z)Q^2))\right]\right\}$$

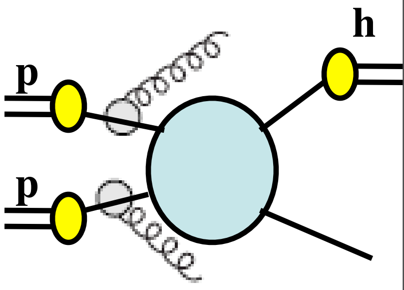
Large angle soft gluons: **process dependent (color interference)**

$$\Delta_{I\,N}^{int\ ab\rightarrow cd} = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}D_{I\,ab\rightarrow cd}(\alpha_s((1-z)Q^2))\right\}$$

As a result of exponentiation: “simple” set of rules for each parton participating (in many cases universal):radiative factors

Initial state (pdf): soft gluon radiation collinear to parton

$$\Delta_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\int_{\mu_{FI}^2}^{(1-z)^2Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2))\right\}$$



Final state identified parton: same as initial state pdf $\longleftrightarrow$ ff

Final state not-identified parton (jet): collinear (soft or hard)

$$J_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\left[\int_{(1-z)^2Q^2}^{(1-z)Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2)) + \frac{1}{2}B_a(\alpha_s((1-z)Q^2))\right]\right\}$$

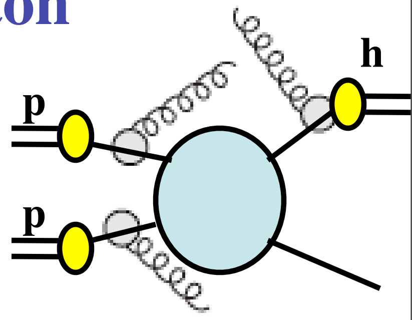
Large angle soft gluons: process dependent (color interference)

$$\Delta_{I\,N}^{int\;ab\to cd} = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}D_{I\,ab\to cd}(\alpha_s((1-z)Q^2))\right\}$$

As a result of exponentiation: "simple" set of rules for each parton participating (in many cases universal):radiative factors

Initial state (pdf): soft gluon radiation collinear to parton

$$\Delta_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\int_{\mu_{FI}^2}^{(1-z)^2Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2))\right\}$$



Final state identified parton: same as initial state pdf ⟷ ff

Final state not-identified parton (jet): collinear (soft or hard)

$$J_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\left[\int_{(1-z)^2Q^2}^{(1-z)Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2)) + \frac{1}{2}B_a(\alpha_s((1-z)Q^2))\right]\right\}$$

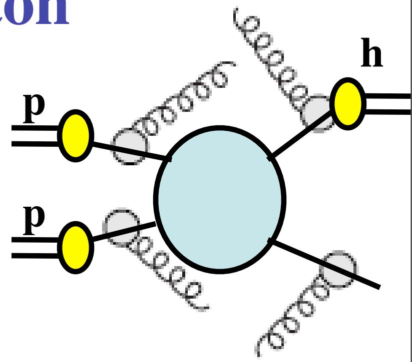
Large angle soft gluons: process dependent (color interference)

$$\Delta_{I\,N}^{int\ ab\to cd} = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}D_{I\,ab\to cd}(\alpha_s((1-z)Q^2))\right\}$$

As a result of exponentiation: “simple” set of rules for each parton participating (in many cases universal):radiative factors

Initial state (pdf): soft gluon radiation collinear to parton

$$\Delta_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\int_{\mu_{FI}^2}^{(1-z)^2Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2))\right\}$$



Final state identified parton: same as initial state pdf ⟷ ff

Final state not-identified parton (jet): collinear (soft or hard)

$$J_N^a = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}\left[\int_{(1-z)^2Q^2}^{(1-z)Q^2}\frac{dq^2}{q^2}A_a(\alpha_s(q^2))+\frac{1}{2}B_a(\alpha_s((1-z)Q^2))\right]\right\}$$

Large angle soft gluons: process dependent (color interference)

$$\Delta_{I\,N}^{int\ ab\to cd} = \exp\left\{\int_0^1 \frac{z^{N-1}-1}{1-z}D_{I\,ab\to cd}(\alpha_s((1-z)Q^2))\right\}$$

Coefficients have a perturbative expansion (free of logs)

$$\mathbf{A}(\alpha_s) = \frac{\alpha_s}{\pi}\mathbf{A}^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \mathbf{A}^{(2)} + \ldots$$

$$A_q^{(1)} = C_F \quad A_g^{(1)} = C_A \quad B_q^{(1)} = -\frac{3}{2}C_F \quad B_g^{(1)} = -\beta_0$$

At leading log, exponents behave like (color interf. NLL)

$$\Delta_N^a = \exp\left[\frac{\alpha_s}{\pi}A_a^{(1)}\ln^2 N\right] \qquad J_N^a = \exp\left[-\frac{\alpha_s}{2\pi}A_a^{(1)}\ln^2 N\right]$$

Sudakov enhancement

(PDF or FF already much supression in factorization)

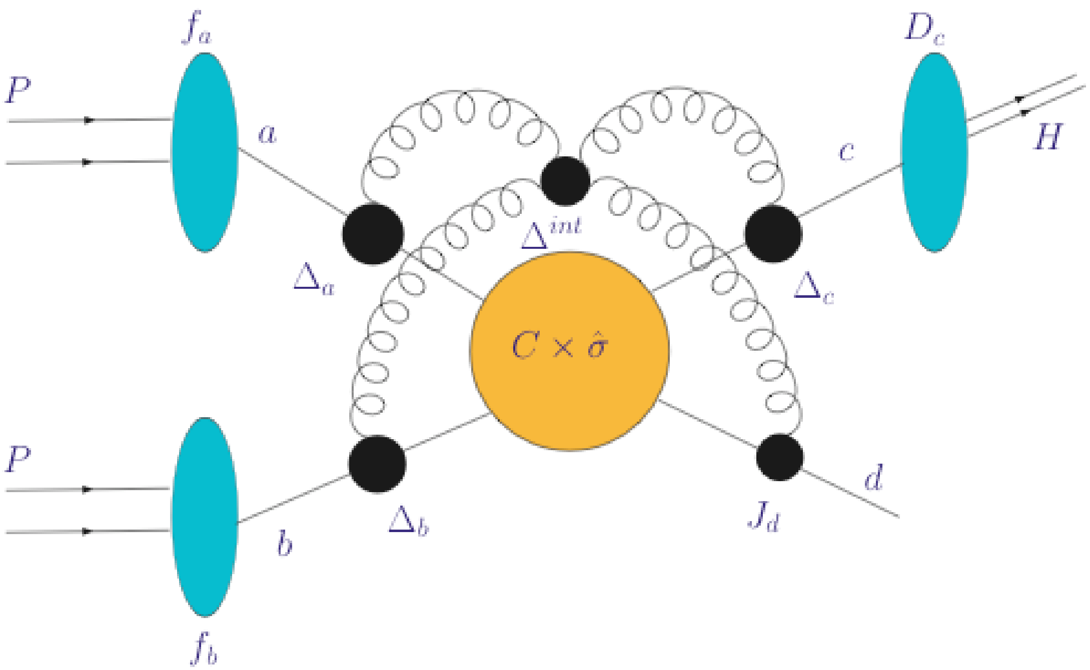
Sudakov supression

(final state not ID)

Important: the effect is amplified if hard gluons present $\frac{C_A}{C_F} = 2.25$

Pion production in pp collisions

$\log(1 - x_T)$ $\quad x_T = \frac{2p_T}{\sqrt{S}}$



After integration over rapidity

$$\sigma(N) = \sum_{a,b,c} f_{a/H_1}(N+1, \mu_{FI}^2)\, f_{b/H_2}(N+1, \mu_{FI}^2)\, D_{h/c}(2N+3, \mu_{FF}^2)\, \hat{\sigma}_{ab\to cd}(N)$$

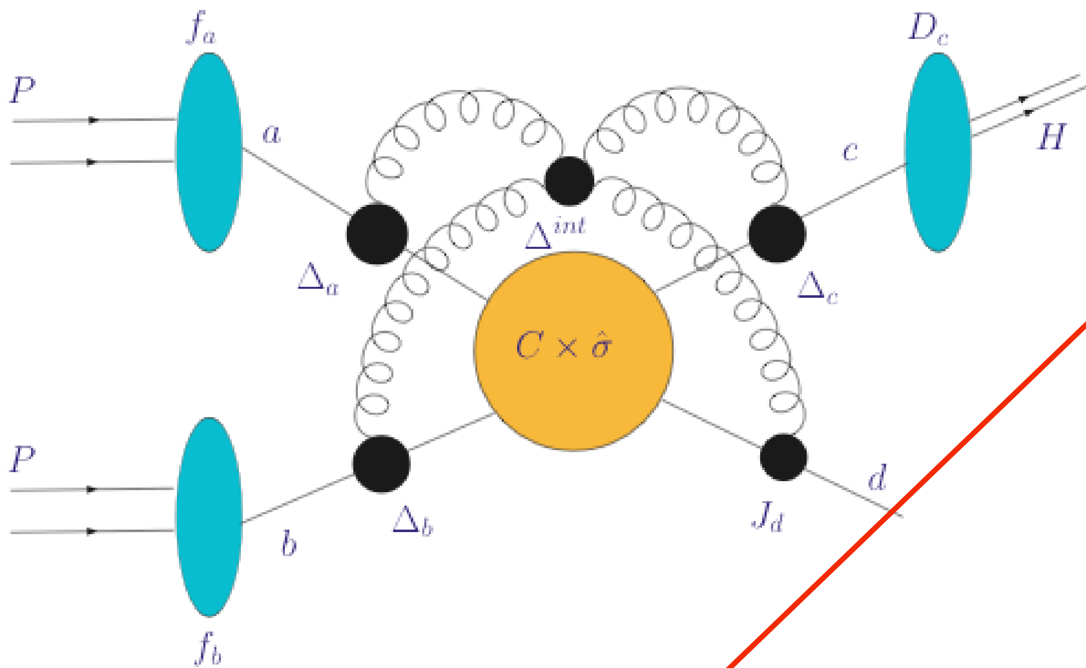
$$\hat{\sigma}^{(\mathrm{res})}_{ab\to cd}(N) = C_{ab\to cd}\, \underbrace{\Delta_N^a\, \Delta_N^b\, \Delta_N^c\, J_N^d}_{\text{Hard partons}} \left[\sum_I \underbrace{G^I_{ab\to cd}\, \Delta_{I\,N}^{(\mathrm{int})ab\to cd}}_{\text{Color interferences}} \right] \hat{\sigma}^{(\mathrm{Born})}_{ab\to cd}(N)$$

Hard partons **Color interferences**

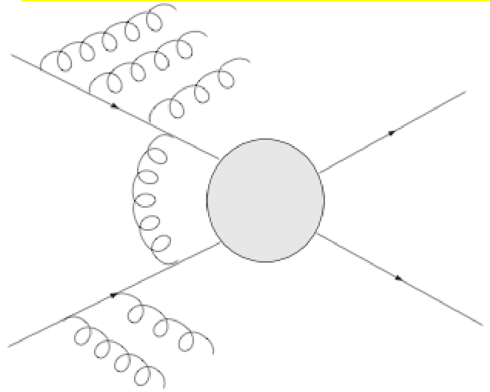
Kidonakis, Oderda, Sterman

Pion production in pp collisions

$\log(1 - x_T)$ $\quad x_T = \frac{2p_T}{\sqrt{S}}$



C contains virtual corrections



After integration over rapidity

$$\sigma(N) = \sum_{a,b,c} f_{a/H_1}(N+1, \mu_{FI}^2)\, f_{b/H_2}(N+1, \mu_{FI}^2)\, D_{h/c}(2N+3, \mu_{FF}^2)\, \hat{\sigma}_{ab\to cd}(N)$$

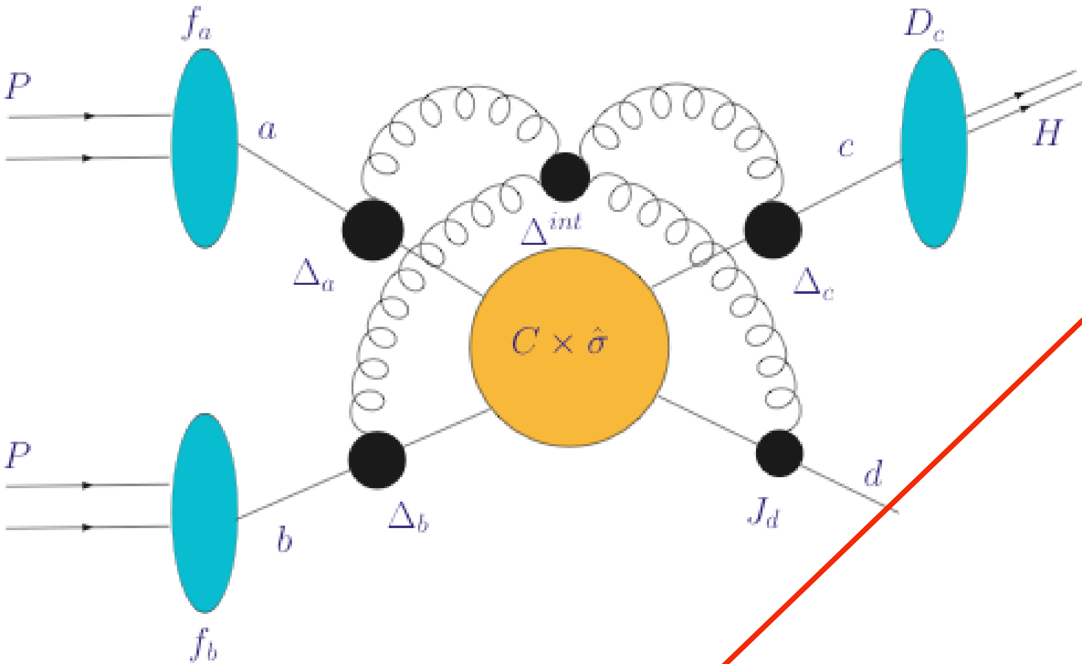
$$\hat{\sigma}^{(\mathrm{res})}_{ab\to cd}(N) = C_{ab\to cd}\, \underbrace{\Delta^a_N\, \Delta^b_N\, \Delta^c_N\, J^d_N}_{\text{Hard partons}} \left[\sum_I \underbrace{G^I_{ab\to cd}\, \Delta^{(\mathrm{int})ab\to cd}_{I\,N}}_{\text{Color interferences}} \right] \hat{\sigma}^{(\mathrm{Born})}_{ab\to cd}(N)$$

Hard partons **Color interferences**

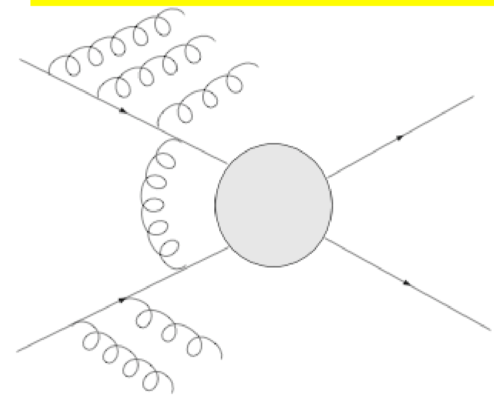
Kidonakis, Oderda, Sterman

Pion production in pp collisions

$\log(1 - x_T)$ $\qquad x_T = \dfrac{2p_T}{\sqrt{S}}$



C contains virtual corrections



After integration over rapidity

$$\sigma(N) = \sum_{a,b,c} f_{a/H_1}(N+1, \mu_{FI}^2)\, f_{b/H_2}(N+1, \mu_{FI}^2)\, D_{h/c}(2N+3, \mu_{FF}^2)\, \hat{\sigma}_{ab\to cd}(N)$$

$$\hat{\sigma}^{(\text{res})}_{ab\to cd}(N) = C_{ab\to cd}\, \Delta^a_N\, \Delta^b_N\, \Delta^c_N\, J^d_N \left[\sum_I G^I_{ab\to cd}\, \Delta^{(\text{int})ab\to cd}_{I\,N} \right] \hat{\sigma}^{(\text{Born})}_{ab\to cd}(N)$$

Enhancement

Hard partons $\qquad$ **Color interferences**

Kidonakis, Oderda, Sterman

Several subprocesses, largest enhancement from

$gg \to gg$ $\quad \exp\left[\underbrace{\left(C_A + C_A + C_A - \frac{1}{2} C_A \right)}_{\frac{15}{2}} \frac{\alpha_s}{\pi} \ln^2(N) \right]$

$q\bar{q} \to g$

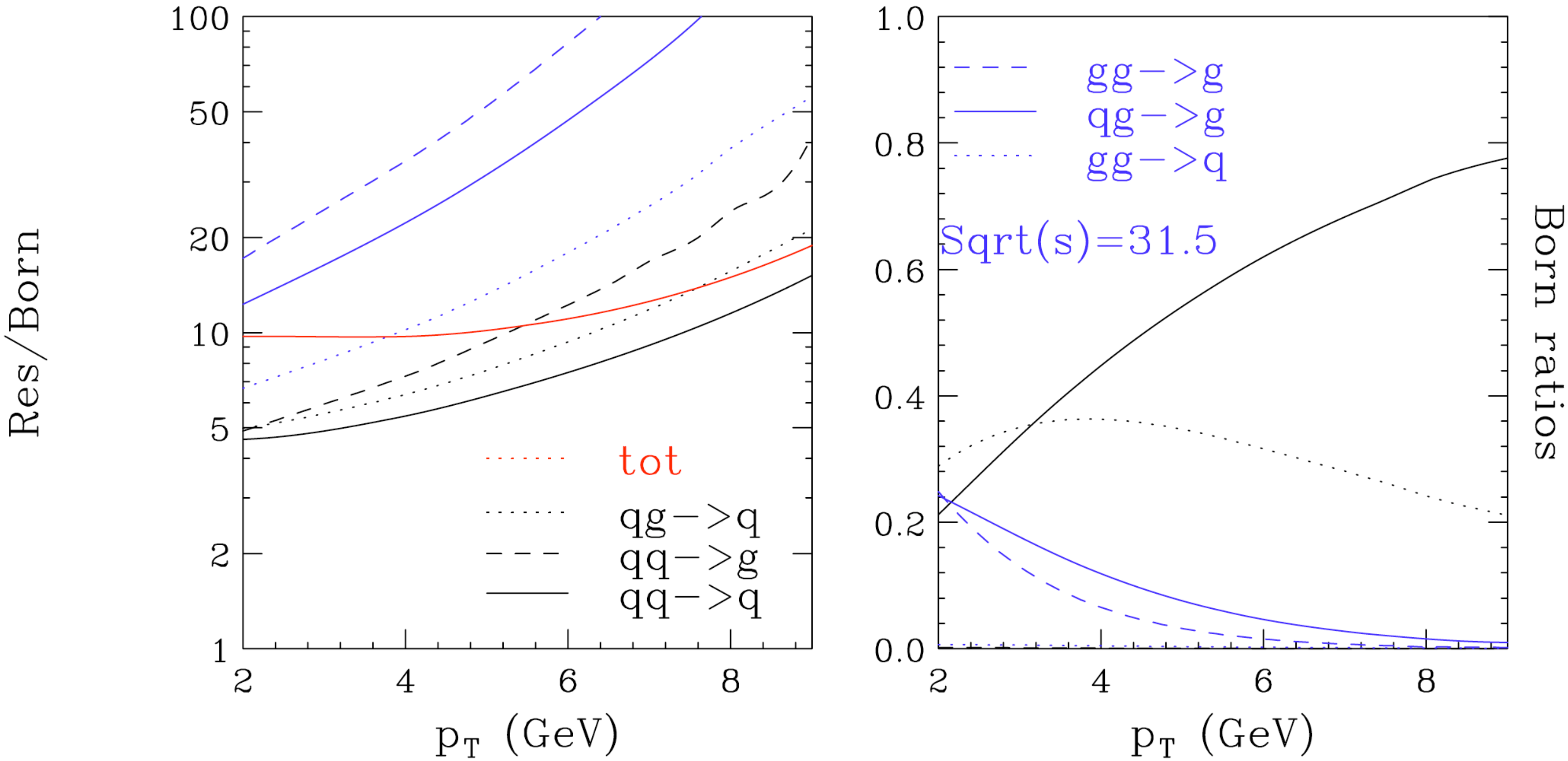
$qq \to q$

$qg \to g$

$qg \to q$

$gg \to q$

$gg \to g$



NLL included D.de F. & W. Vogelsang

Amplified by fragmentation $p_T^{\rm parton} = \frac{p_T^h}{z}$

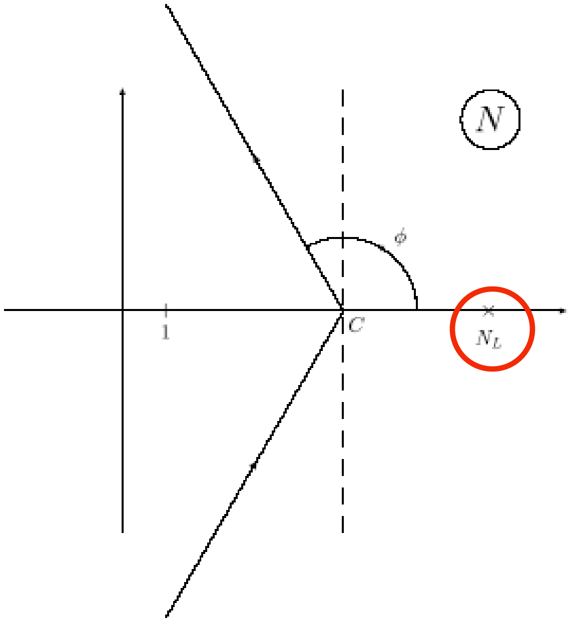
- always want to keep benefits of full fixed-order calculation:

  → "matching":

$$\sigma^{\mathrm{matched}} = \sigma^{\mathrm{res.}} - \sigma^{\mathrm{res.}}\Big|_{\mathcal{O}(\alpha_s^n)} + \sigma^{\mathrm{f.o.}}\Big|_{\mathcal{O}(\alpha_s^n)}$$

  in phenomenological applications

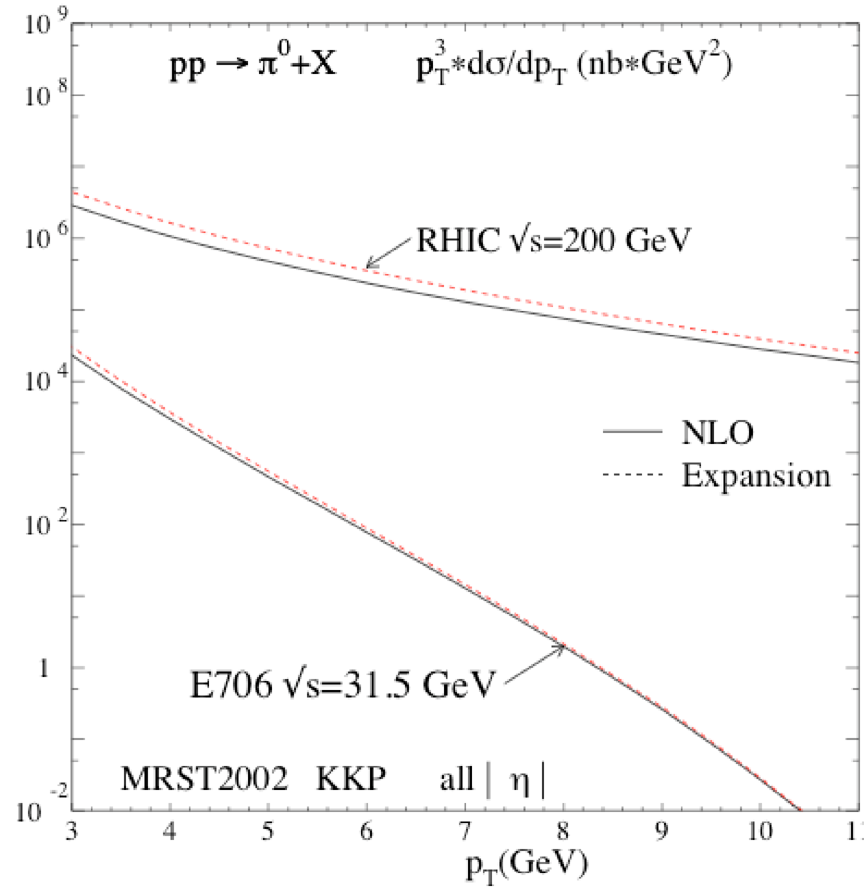
- Avoid Landau Pole: Mellin contour as



Minimal prescription

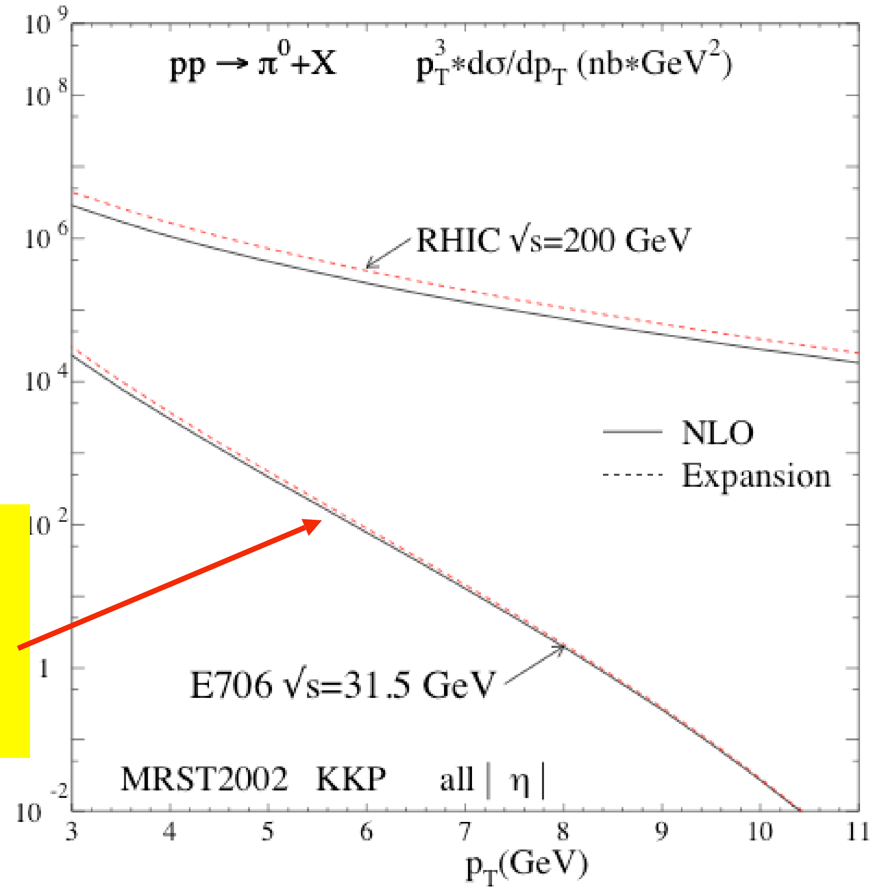
(Catani, Mangano, Nason, Trentadue)

•**Validity of resummation (kinematical range) :**
Compare full NLO to soft approximation (expansion of resummed)



•Validity of resummation (kinematical range) :
Compare full NLO to soft approximation (expansion of resummed)

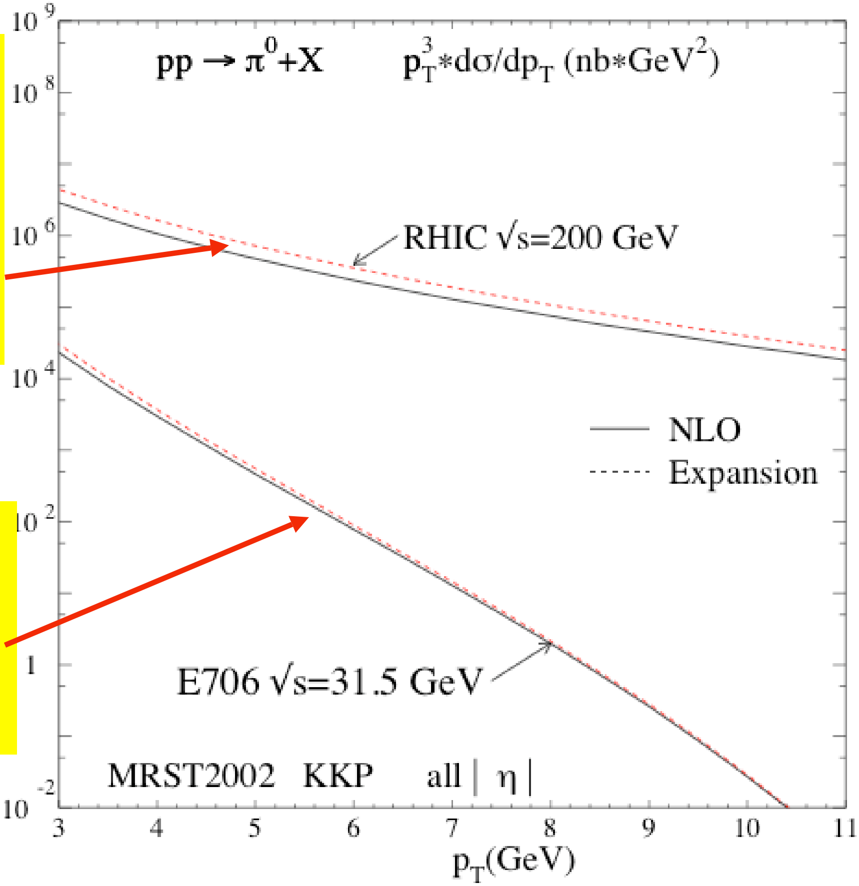
At "lower" energies very good agreement: dominance of soft contributions ✓



•Validity of resummation (kinematical range) :
Compare full NLO to soft approximation (expansion of resummed)

At collider energies soft app. overestimates NLO: hard corrections and subleading terms more important

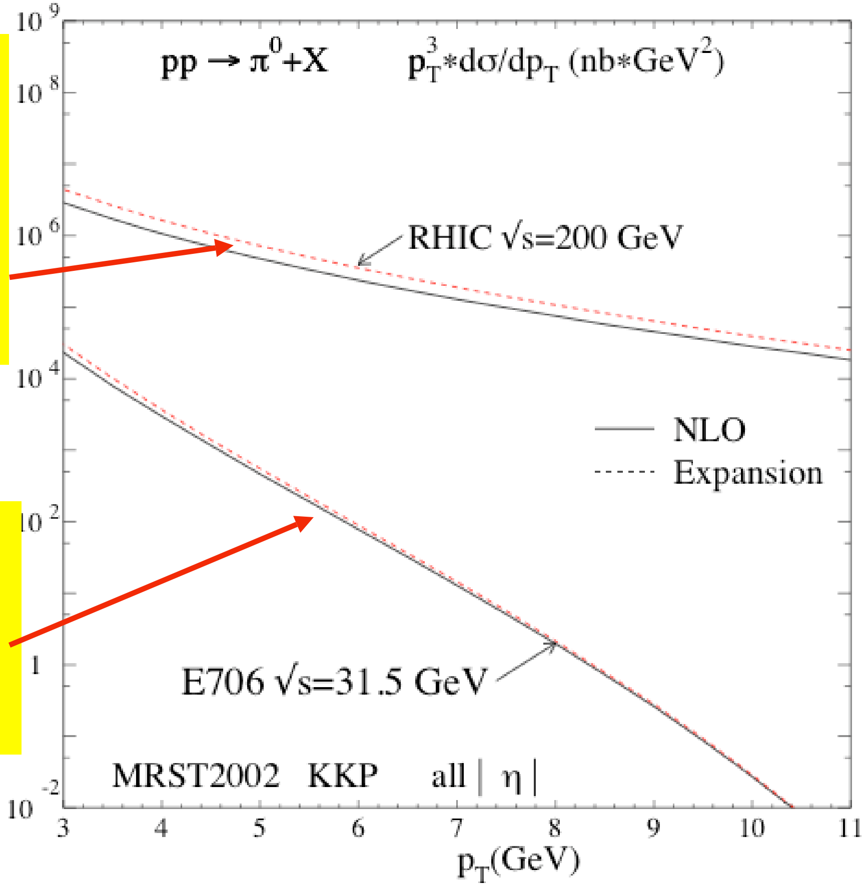
At "lower" energies very good agreement: dominance of soft contributions



•Validity of resummation (kinematical range) :
Compare full NLO to soft approximation (expansion of resummed)

At collider energies soft app. overestimates NLO: hard corrections and subleading terms more important

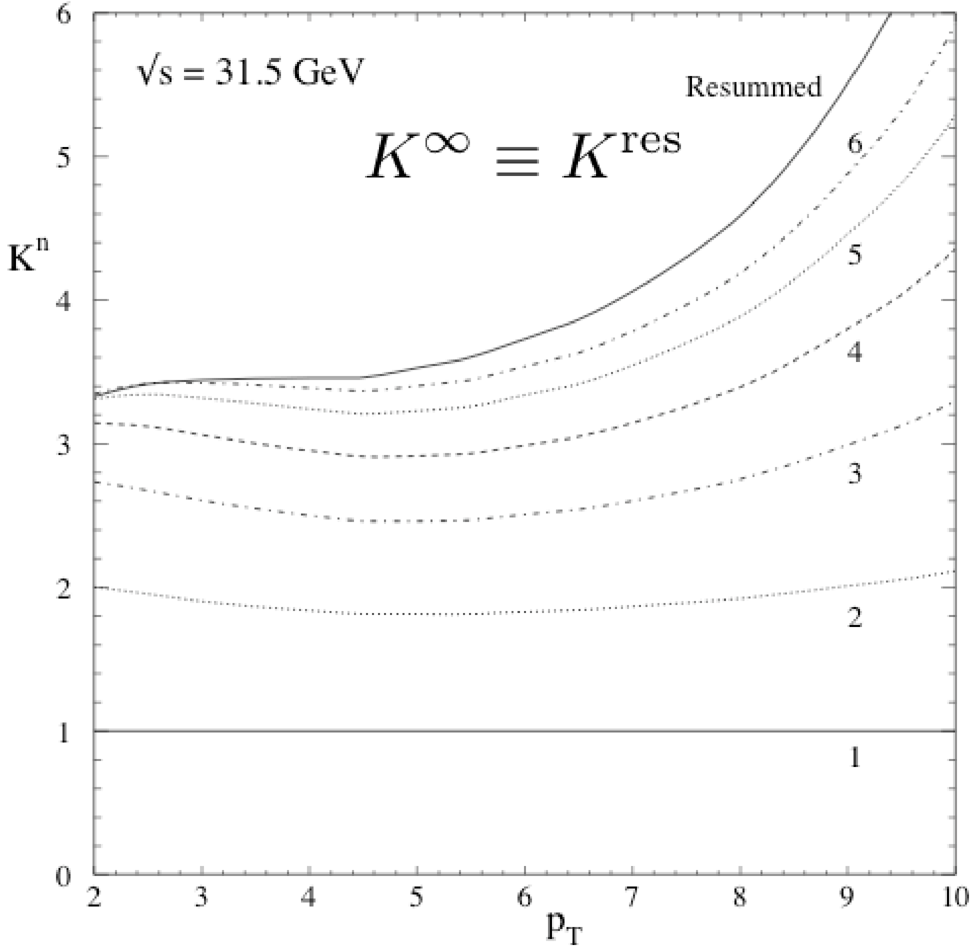
At "lower" energies very good agreement: dominance of soft contributions



Faliure at RHIC not a surprise: x_T much smaller at colliders
•Far away from threshold

•K-factors and convergence of resummed expression

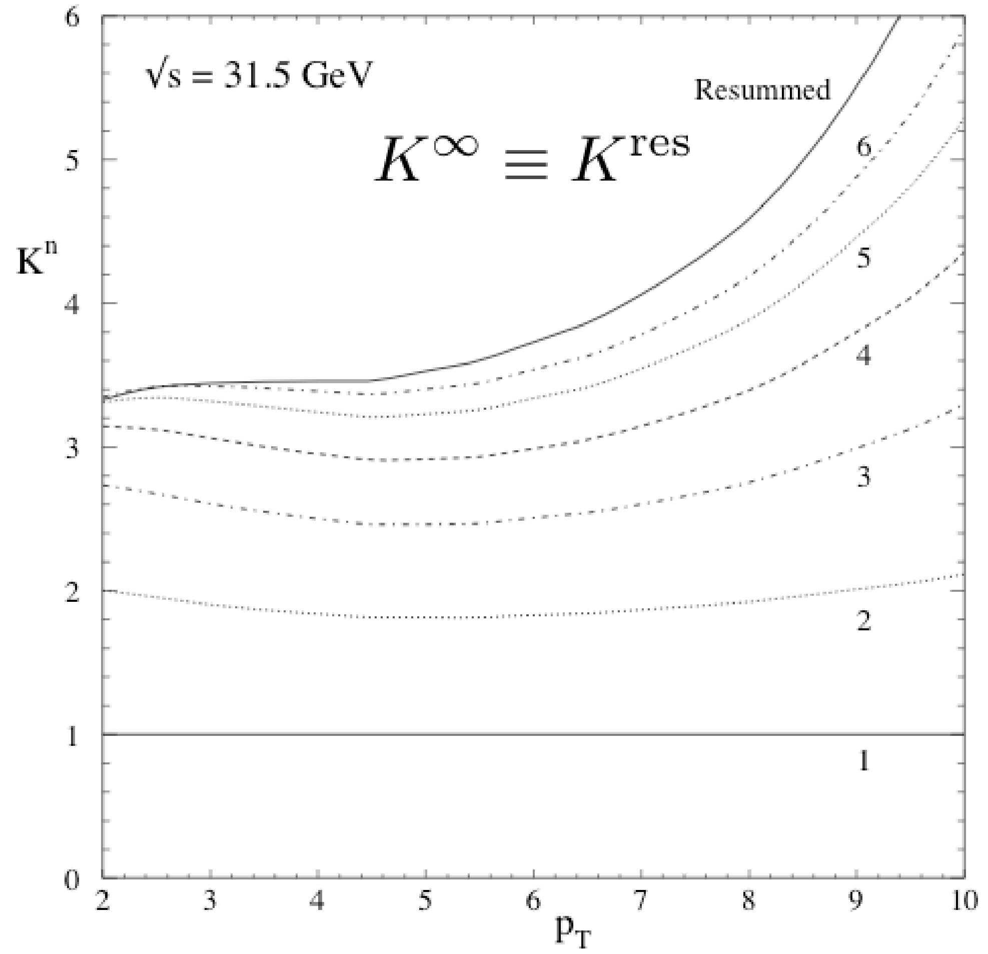
$$K^n = \frac{d\sigma^{(\mathrm{match})}/dp_T\big|_{\mathcal{O}(\alpha_s^{2+n})}}{d\sigma^{(NLO)}/dp_T}$$



Very slow convergence even for fixed target and low transverse momentum: all orders needed!

•K-factors and convergence of resummed expression

$$K^n = \frac{d\sigma^{(\mathrm{match})}/dp_T\big|_{\mathcal{O}(\alpha_s^{2+n})}}{d\sigma^{(NLO)}/dp_T}$$



Very slow convergence even for fixed target and low transverse momentum: all orders needed!

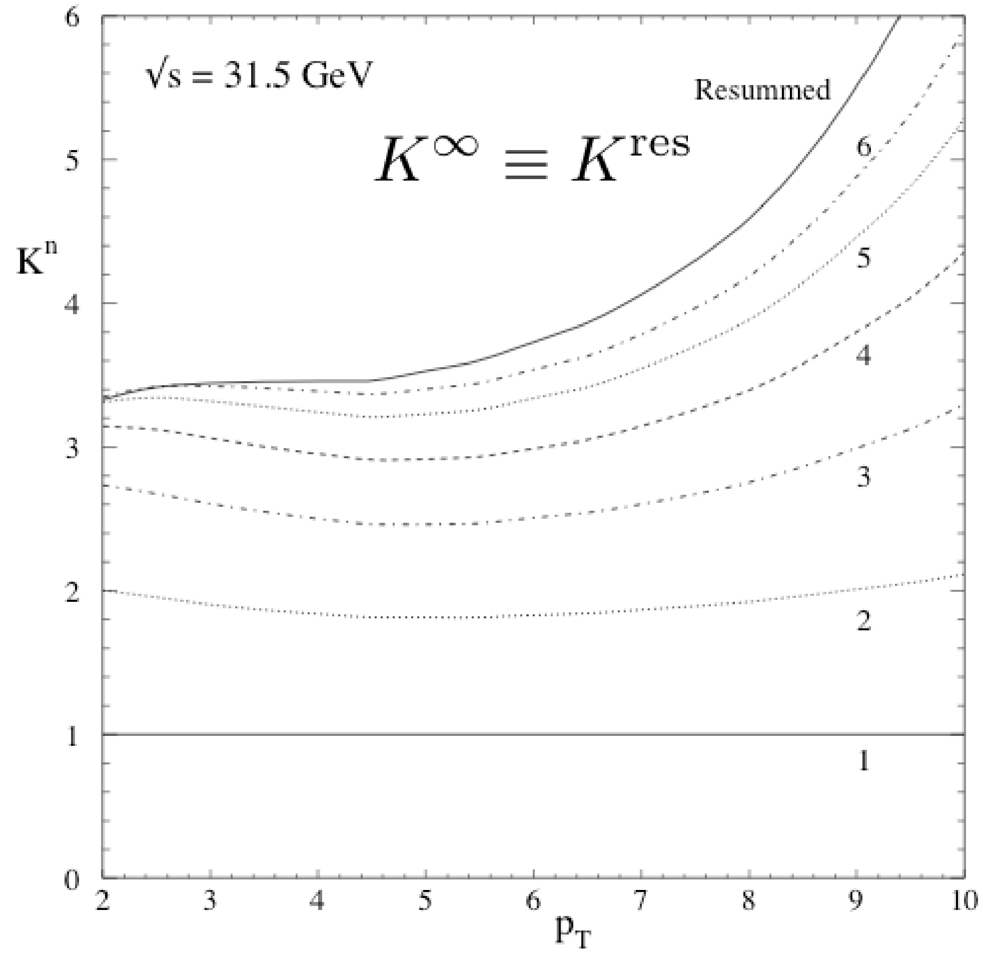
Comparison to data only approximation: rapidity

$$\frac{p_T^3\, d\sigma^{(\mathrm{match})}}{dp_T}(\eta \,\mathrm{in\, exp.\, range}) = K^{(\mathrm{res})}\,\frac{p_T^3\, d\sigma^{(\mathrm{NLO})}}{dp_T}(\eta\,\mathrm{in\,exp.\,range})$$

η integrated

•K-factors and convergence of resummed expression

$$K^n = \frac{d\sigma^{(\mathrm{match})}/dp_T\big|_{\mathcal{O}(\alpha_s^{2+n})}}{d\sigma^{(NLO)}/dp_T}$$



Very slow convergence even for fixed target and low transverse momentum: all orders needed!

Comparison to data only approximation: rapidity

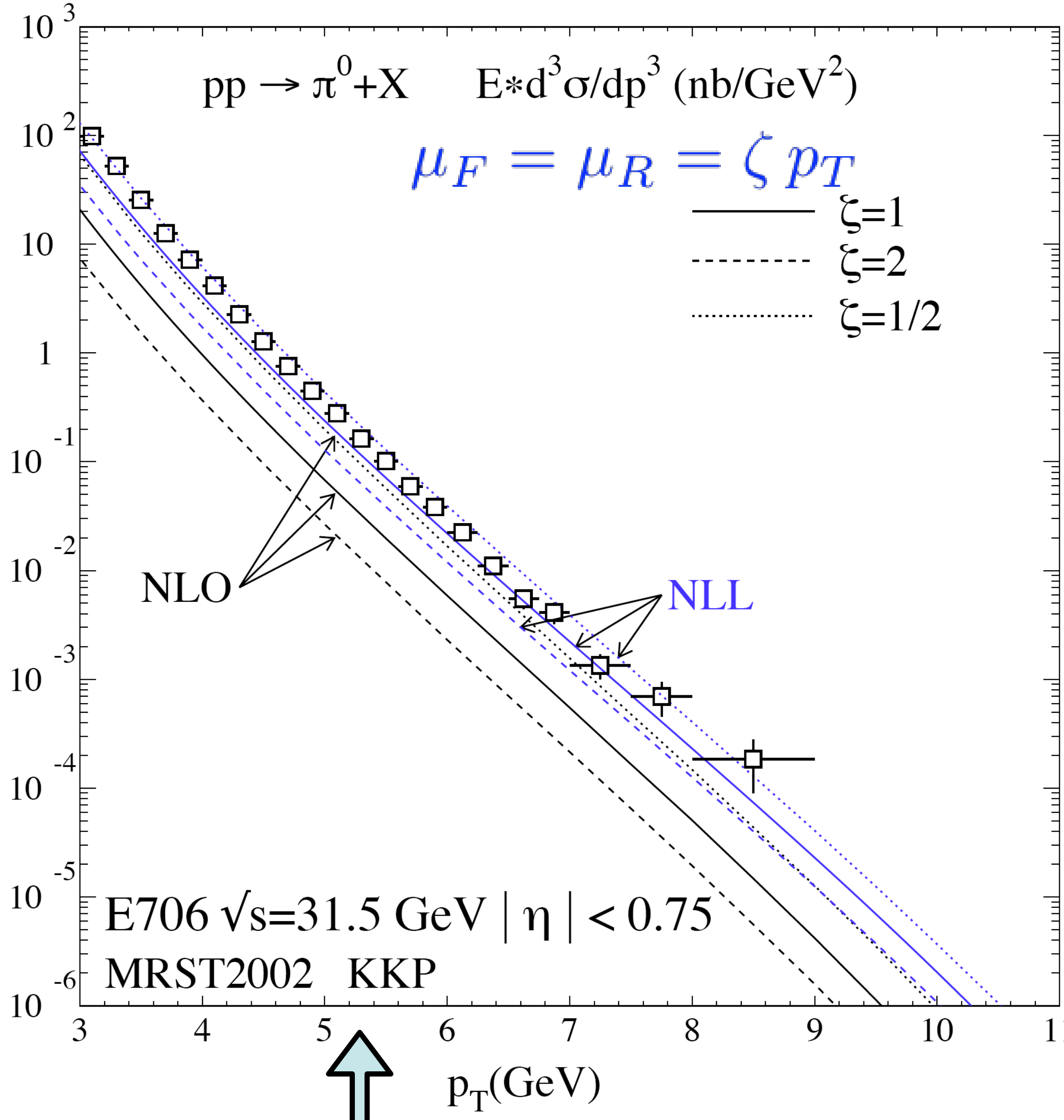
$$\frac{p_T^3\, d\sigma^{(\mathrm{match})}}{dp_T}(\eta \text{ in exp. range}) = K^{(\mathrm{res})}\, \frac{p_T^3\, d\sigma^{(\mathrm{NLO})}}{dp_T}(\eta \text{ in exp. range})$$

η integrated

OK for prompt photons!

E706

- Large enhancement
- Reduction of scale dep.
- Nice agreement with data!
- No need of intrinsic k_T

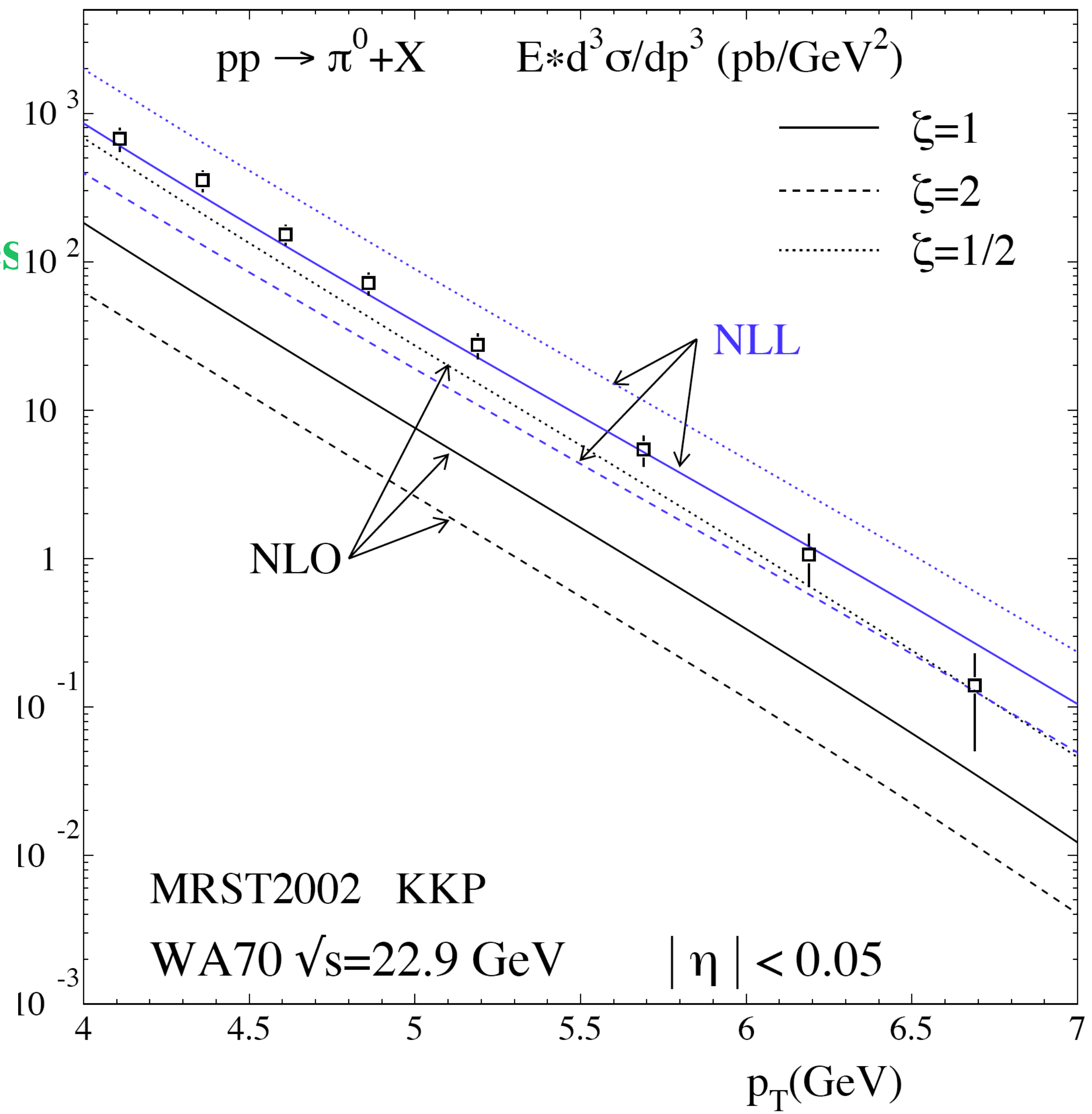


Kniehl, Kramer and Potter

Same for WA70

No need of exotic scales

$\mu = p_T$ **is enough**

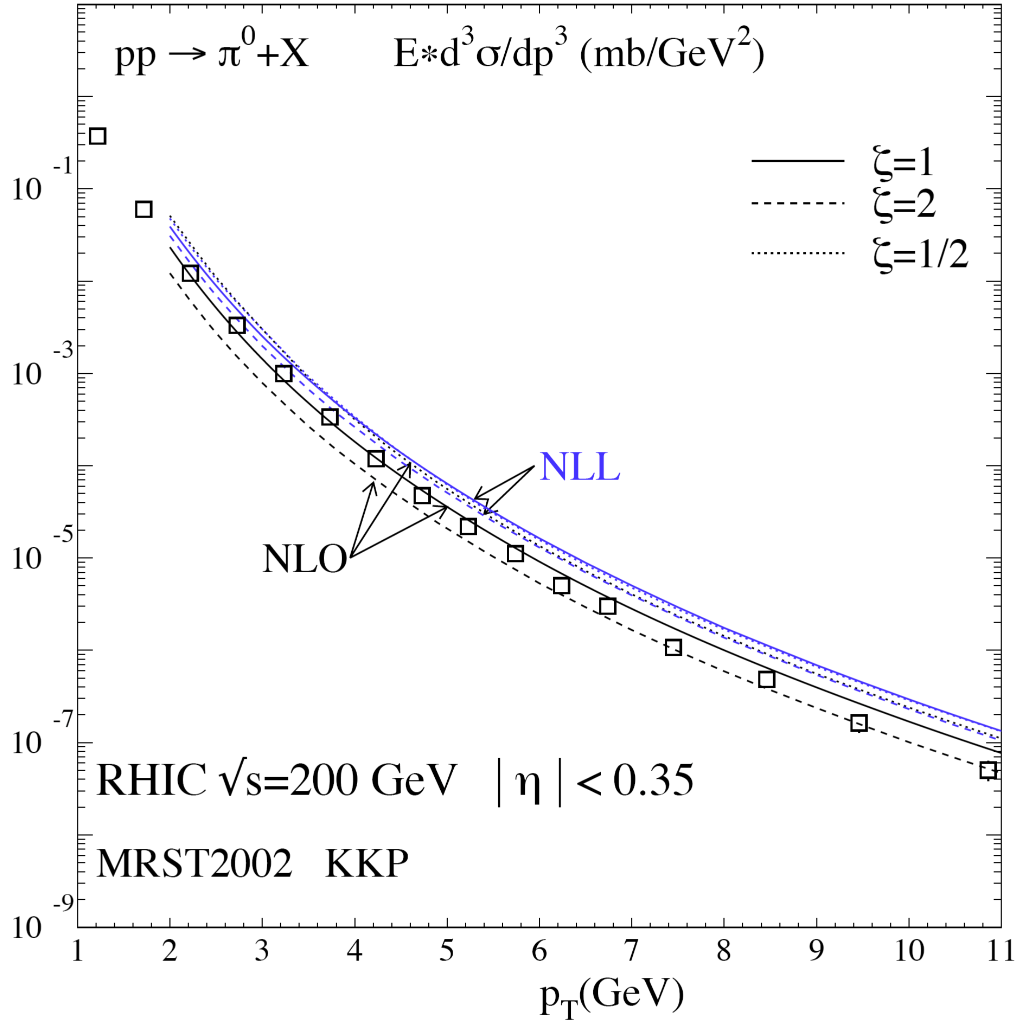


At RHIC energies resummed cross section overestimates data

Hard effects dominate over soft, not expected to work

$$x_T \ll 1$$

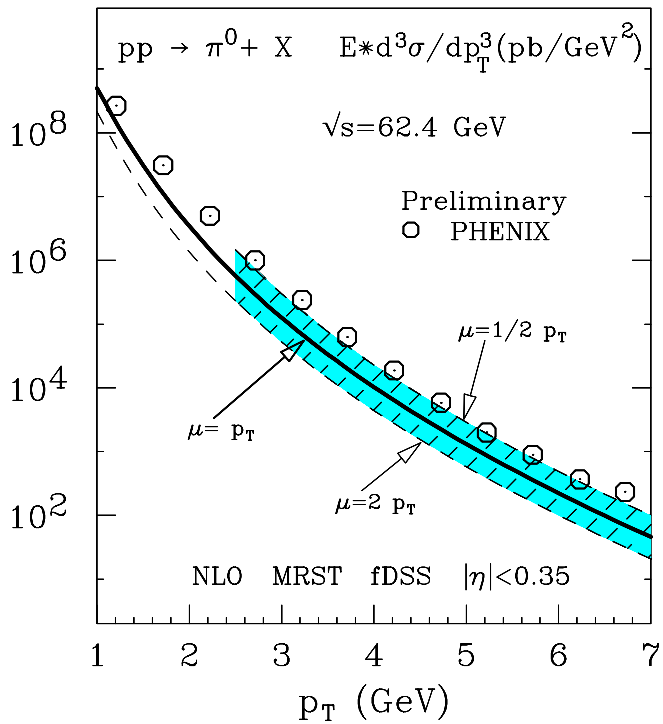
$$\sqrt{S} = 200\,\mathrm{GeV}$$



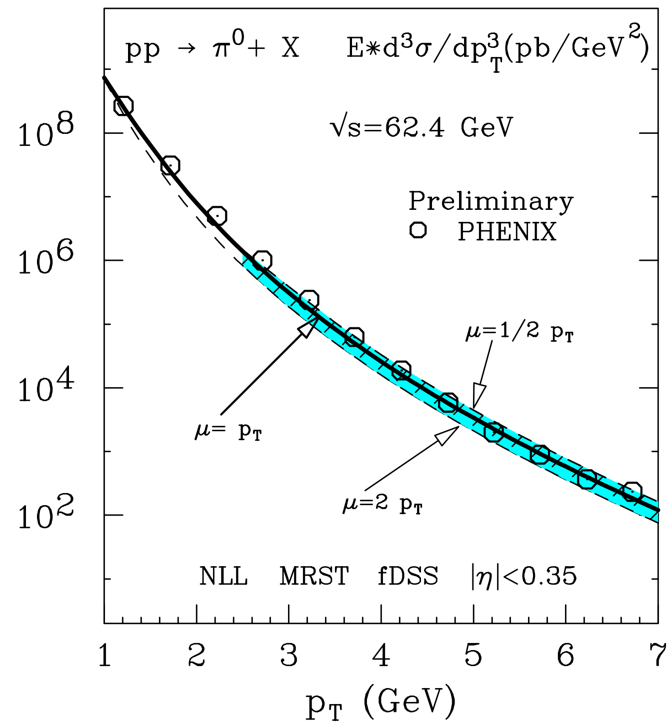
But at lower energies the situation is much better even at RHIC

$$\sqrt{S} = 62.4\,\mathrm{GeV}$$

NLO



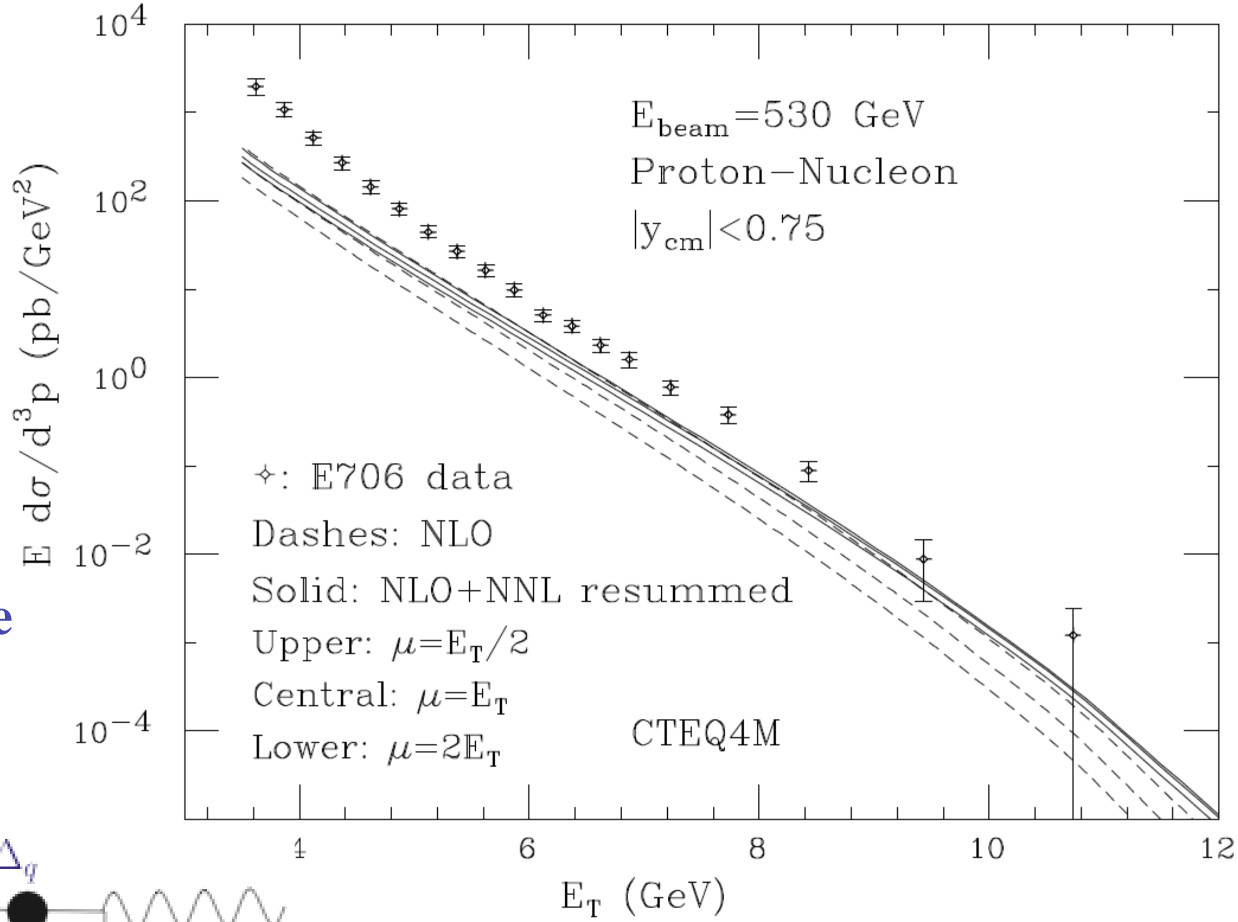
NLL



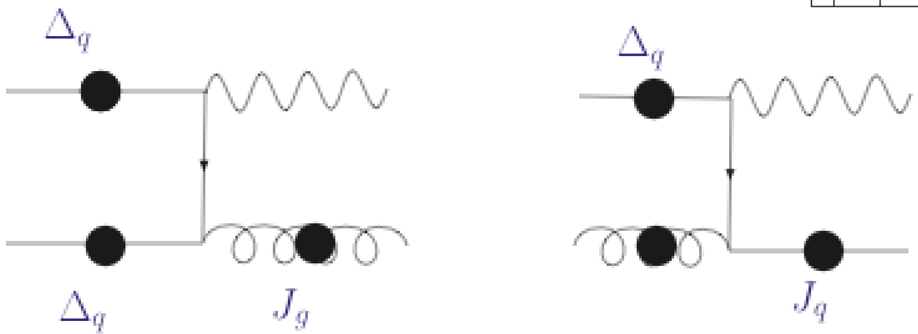
At 62.4 GeV (half way between fixed target and “colliders”) soft logs still dominate

Prompt Photons: direct contribution resummed some time ago

Some enhancement, not enough for E706
resolved contribution only at fixed order



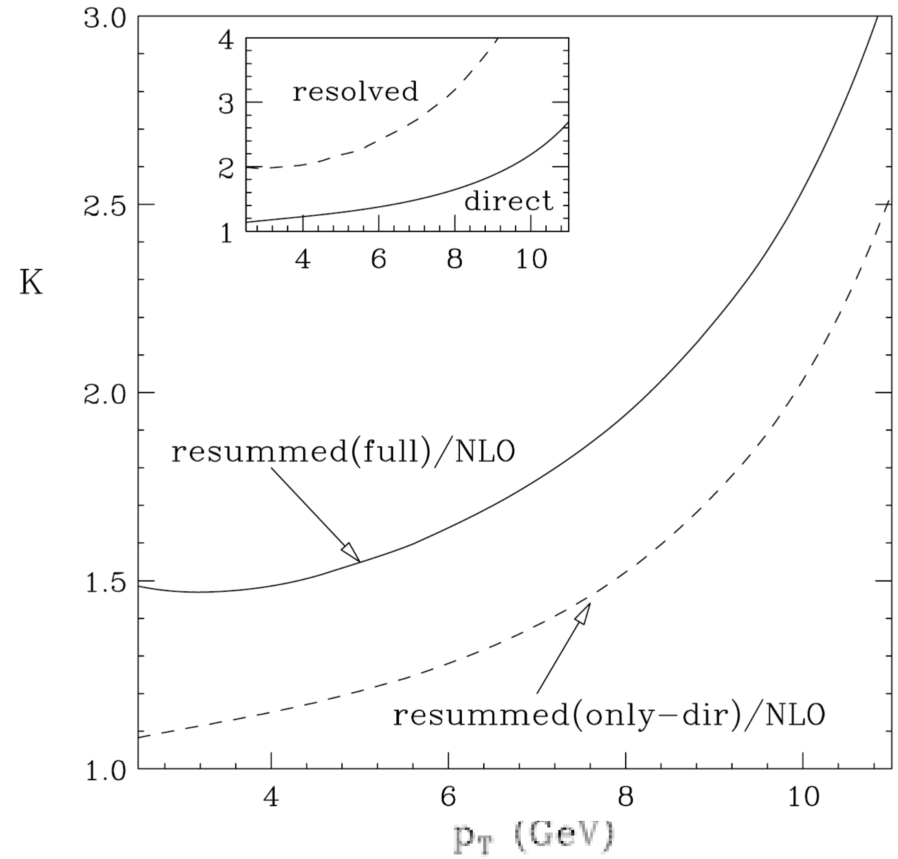
Soft emission less important for direct contribution: more quarks and no identified final state parton



Catani, Mangano, Nason, Oleari, Vogelsang

Resolved component similar to pion production: just use photon fragmentation functions (GRV)

$\sim 40\%$ increase at low p_T
K-Resolved not as big as for pions
Less gluon to photon fragmentation

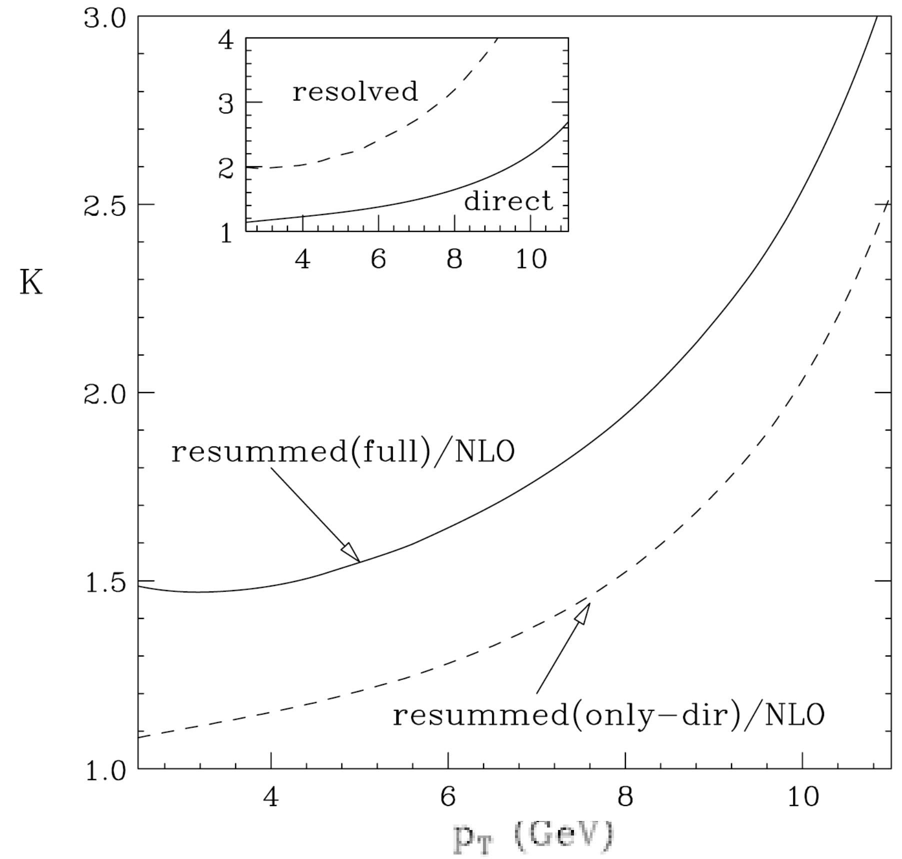


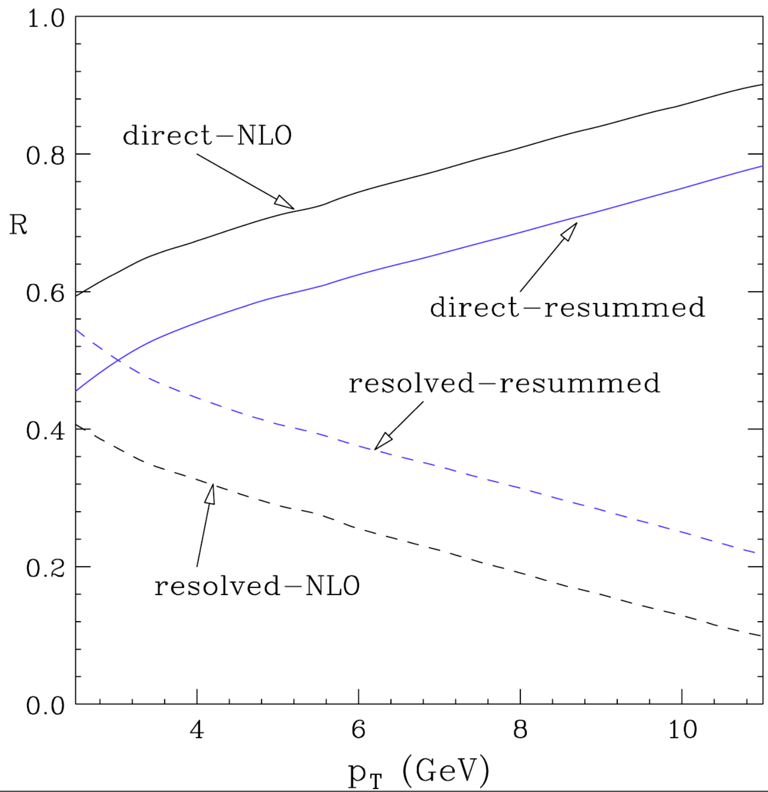
Resolved component similar to pion production: just use photon fragmentation functions (GRV)

$\sim 40\%$ increase at low p_T

K-Resolved not as big as for pions

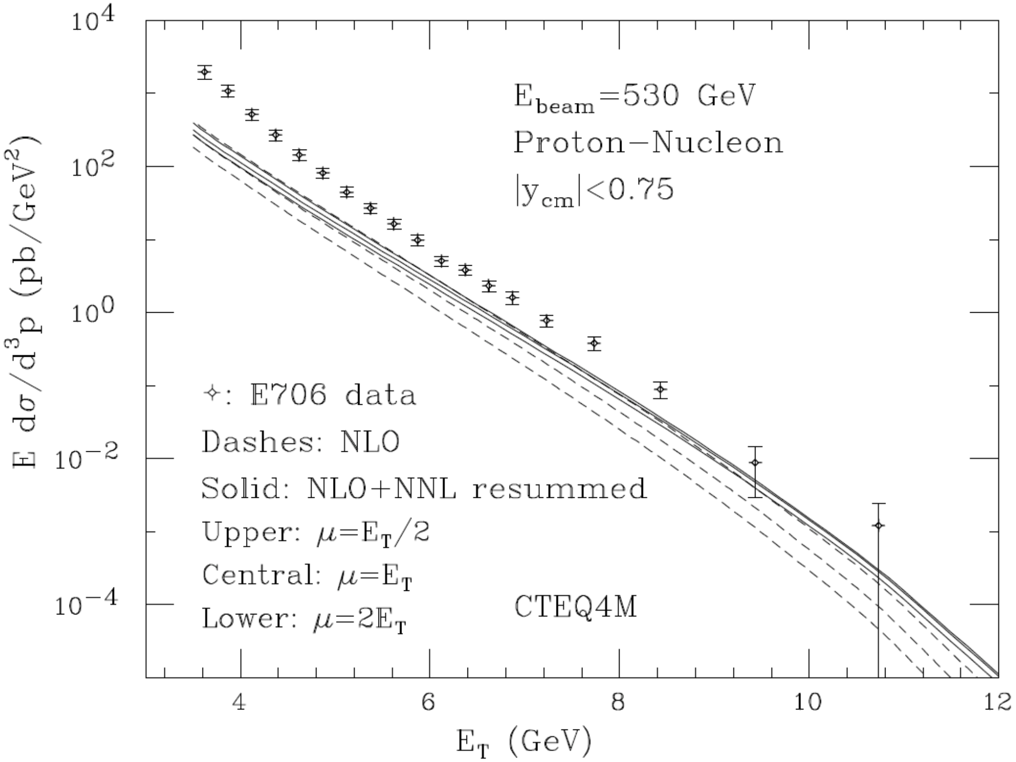
Less gluon to photon fragmentation



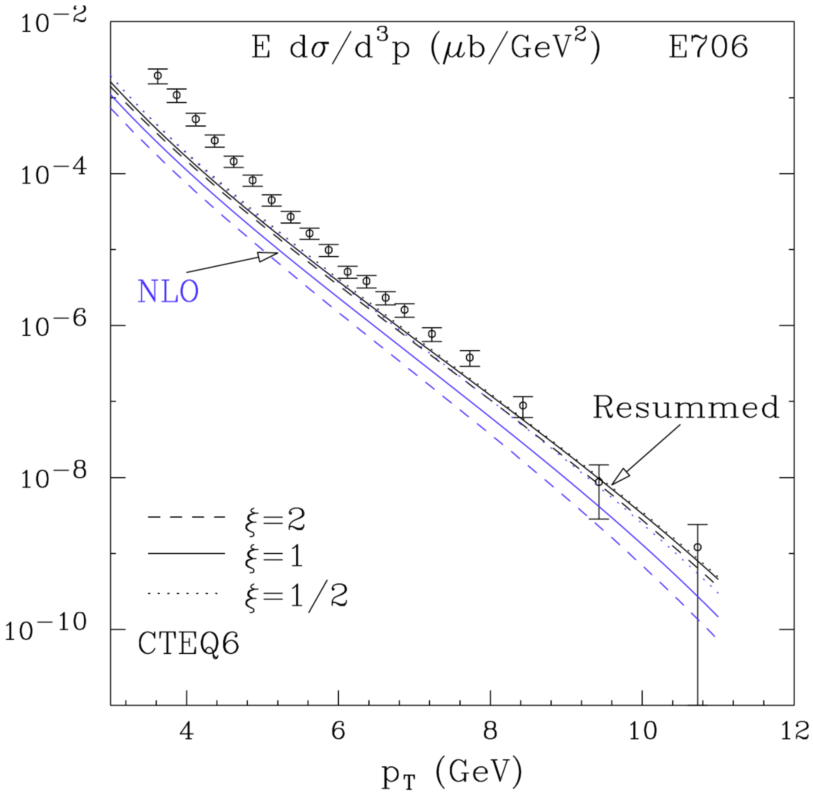


Resolved contribution becomes more important (see ratios)

Increase not enough, but helps at large transverse momentum

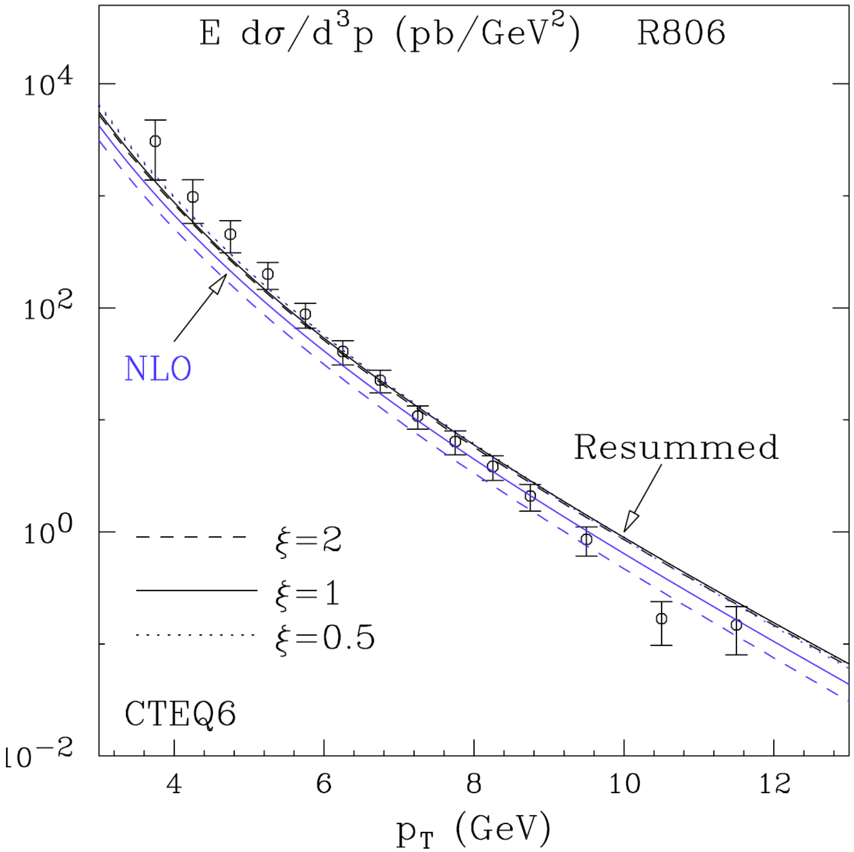


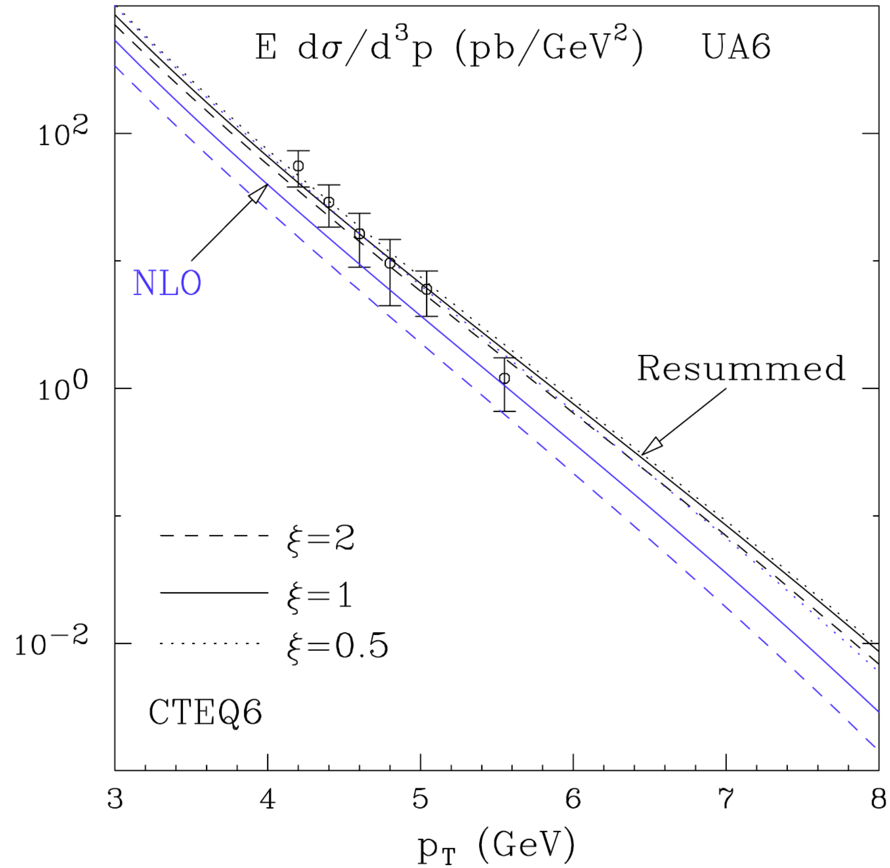
Only direct resummed



Direct+resolved resummed

Nice improvements for R806 and UA6



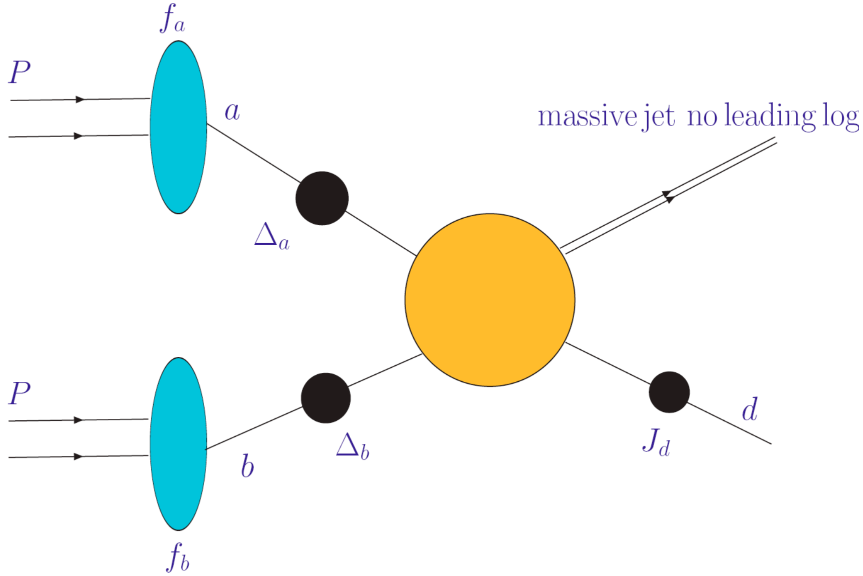


Threshold resummation can not "solve" prompt photons but certainly helps to improve agreement, besides providing more reliable predictions

•Jet production

Same partonic subprocesses but different logarithmic structure: final state is an observed jet, not an "isolated" hadron

f.s. singularities regularized by jet mass/cone size



Some issues about jet definition might even be

Only slight enhancement expected

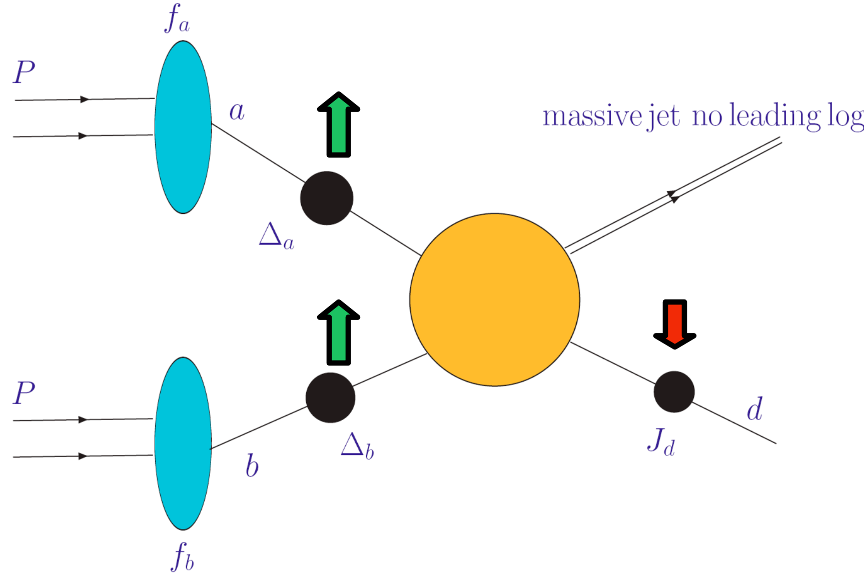
Calculation within the small cone approximation **D. de F & W.Vogelsang**

Full NLL with matching to NLO

•Jet production

Same partonic subprocesses but different logarithmic structure: final state is an observed jet, not an "isolated" hadron

f.s. singularities regularized by jet mass/cone size



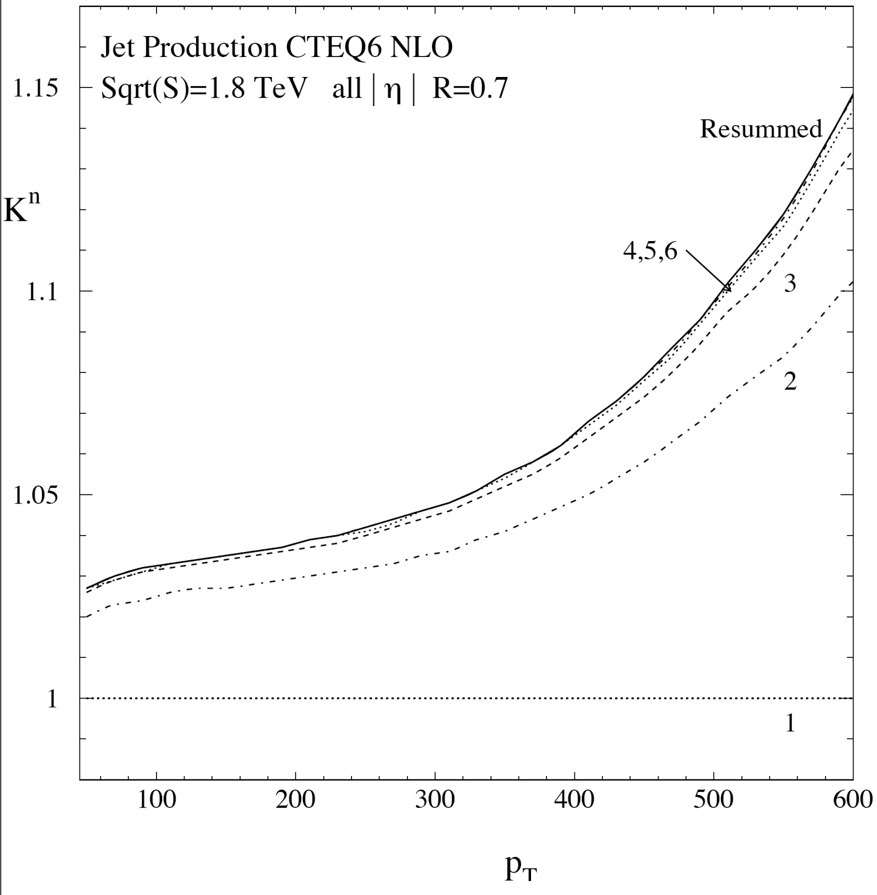
Some issues about jet definition might even be ⇩

Only slight enhancement expected

Calculation within the small cone approximation D. de F & W.Vogelsang

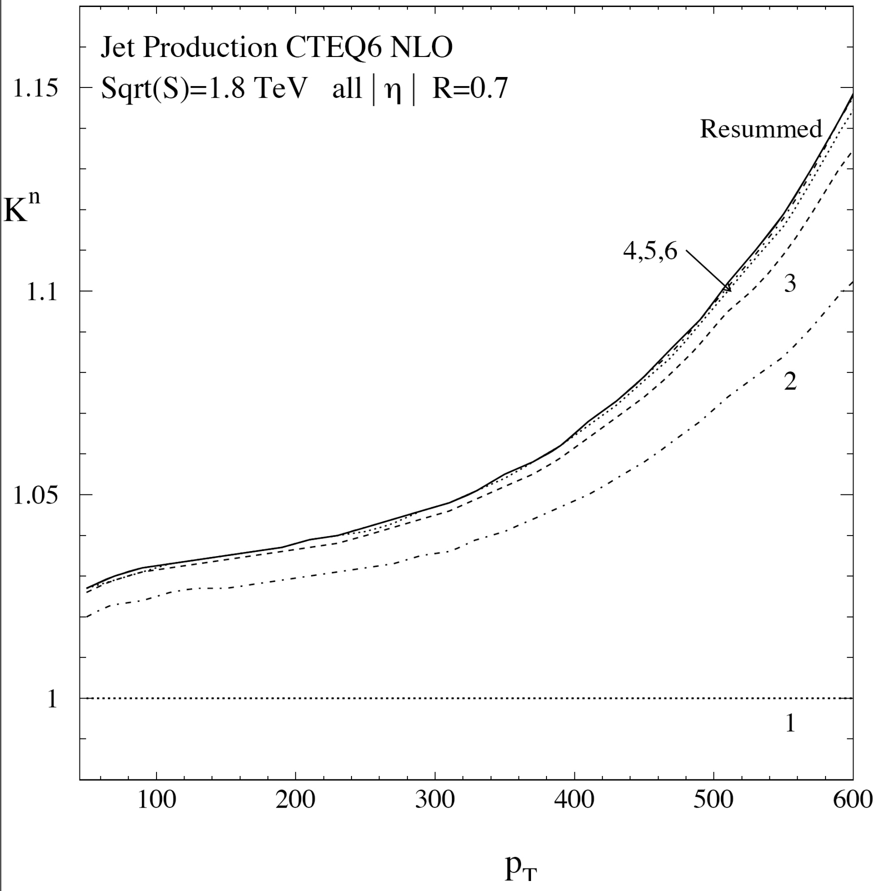
Full NLL with matching to NLO

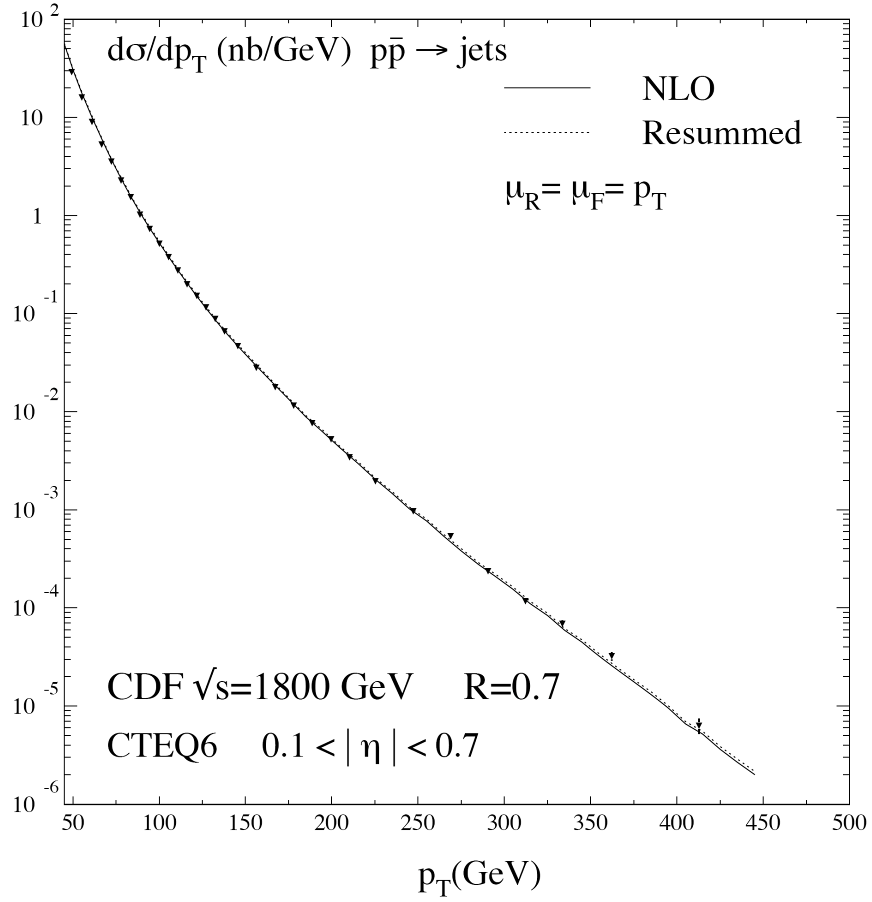
Effect rather small, < 10% at largest transverse momentum CDF 1.8 TeV



Very good convergence already at 3rd order

Effect rather small, < 10% at largest transverse momentum CDF 1.8 TeV

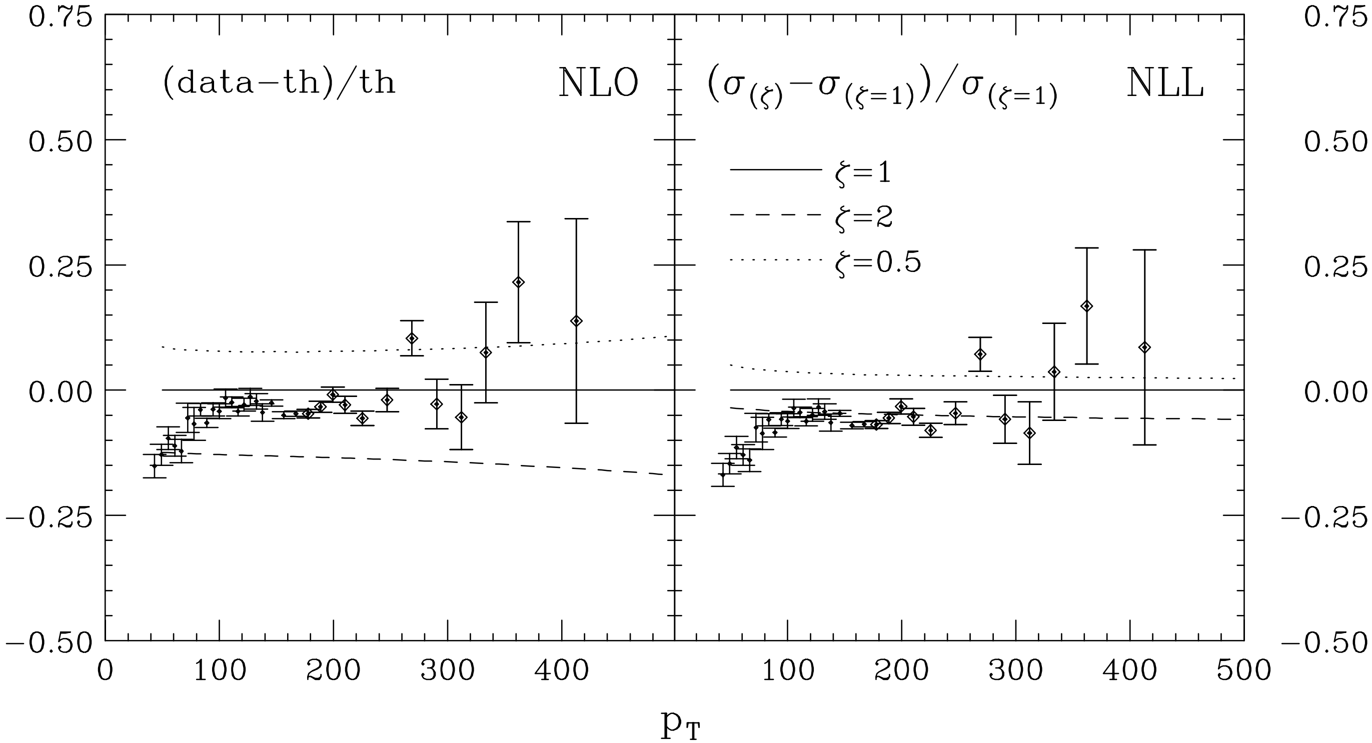




Very good convergence already at 3rd order

Hardly noticeable in Log plot

(data-th)/th



Small improvement at large transverse momentum

Conclusions

Conclusions

•Hadron production: corrections are large enough to bring agreement with fixed target data

• Photon production: resolved contribution increased.
Not enough to solve all problems but reduction of theoretical deficit at small transverse momentum

•Jet production: 10% increase at very large transverse momentum

Conclusions

•Hadron production: corrections are large enough to bring agreement with fixed target data

• Photon production: resolved contribution increased.
Not enough to solve all problems but reduction of theoretical deficit at small transverse momentum

•Jet production: 10% increase at very large transverse momentum

Some phenomena usually explained by non-perturbative arguments (intrinsic k_T for hadrons and photons, gluon distribution for jets) can actually be (at least partially) understood in terms of (all orders) pQCD: take care!

RHIC
E706 Tevatron
WA70 CERN
UA6
R806
NA 24