

Quark and gluon fragmentation functions into hadrons and photons

Main sources of uncertainty

Monique Werlen (LAPTH)

Thanks to

Patrick Aurenche, Zouina Belghobsi,
Thomas Binoth, Luc Bourhis, Pierre Chiappetta,
Michel Fontannaz, Mario Greco,
Jean-Philippe Guillet,
Gudrun Heinrich, Bernd Kniehl,
Eric Pilon, Simona Rolli, ...

And of course, all mistakes,
due to a poor experimentalist's interpretation
even after years of collaboration, are mine!

Outline

- Terminology
- Major sources of **uncertainties** in inclusive **hadron** cross sections
- NLO Fragmentation functions **fits** on e^+e^- and **pp** data: methodology (**CGGRW**, **BFGW**)
- Theoretical and experimental sources of uncertainty in FF

The PHOX Family



- Inclusive **photon** cross sections
- Photon FF

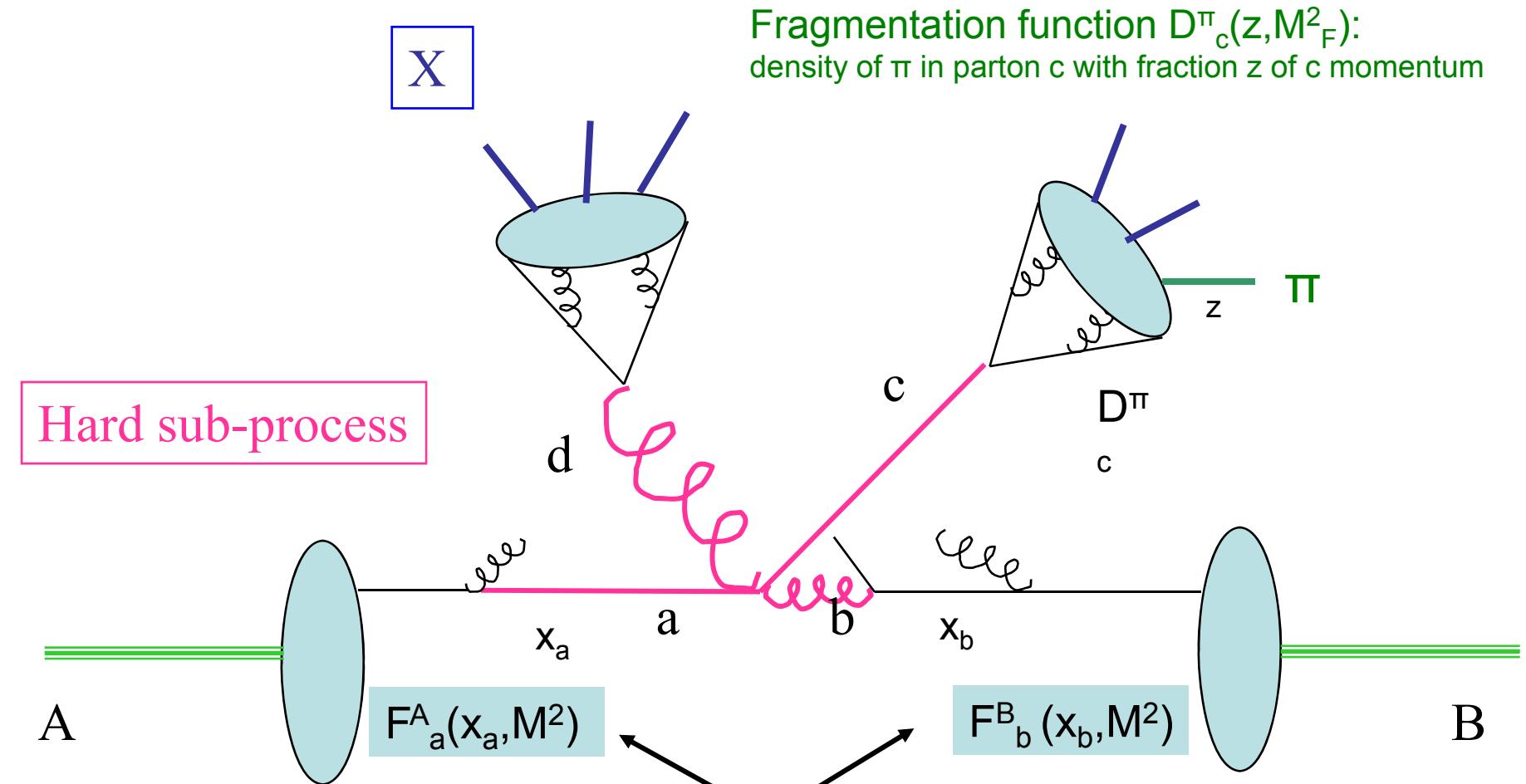
Fragmentation functions

$D_i^h(z, t)$ gives the distribution
of momentum fraction z
for hadrons of type h
in a jet initiated by a parton of type i ,
produced in a hard process at scale t .

Like for parton distributions in a hadron, $F_i^h(x, t)$, these are factorizable quantities, in which infrared divergences of PT can be factorized out and replaced by experimentally measured factor that contains all long-distance effects.

Hadro-production of pions

$$AB \rightarrow \pi X$$



PDF or structure function: density of parton a(b) in hadron A(B) with fraction $x_a(x_b)$ of A(B) momentum

Origin of fragmentation scale M_F^2

This scale separates

- short distance (calculated perturbatively)
- from
- long distance (experimental measurement)

similar to factorization scale M^2 for structure function

Theoretical and experimental sources of uncertainties

- **data:**
 - statistical error,
 - systematic,
 - normalization
 - z and Q^2 range, sensitivity to quark, gluon FF
- **theory:**
 - choice of functional form, z range of assumptions
 - choice of scales
 - order of theory (leading, NLO, resum)
 - further parameters (Structure Function, α_s)

PDF uncertainties: an old debate

See Joel Feltesse [introduction](#) to the technical session on PDF uncertainties at [PDF4LHC](#) meeting (Feb.22-23, 2008)

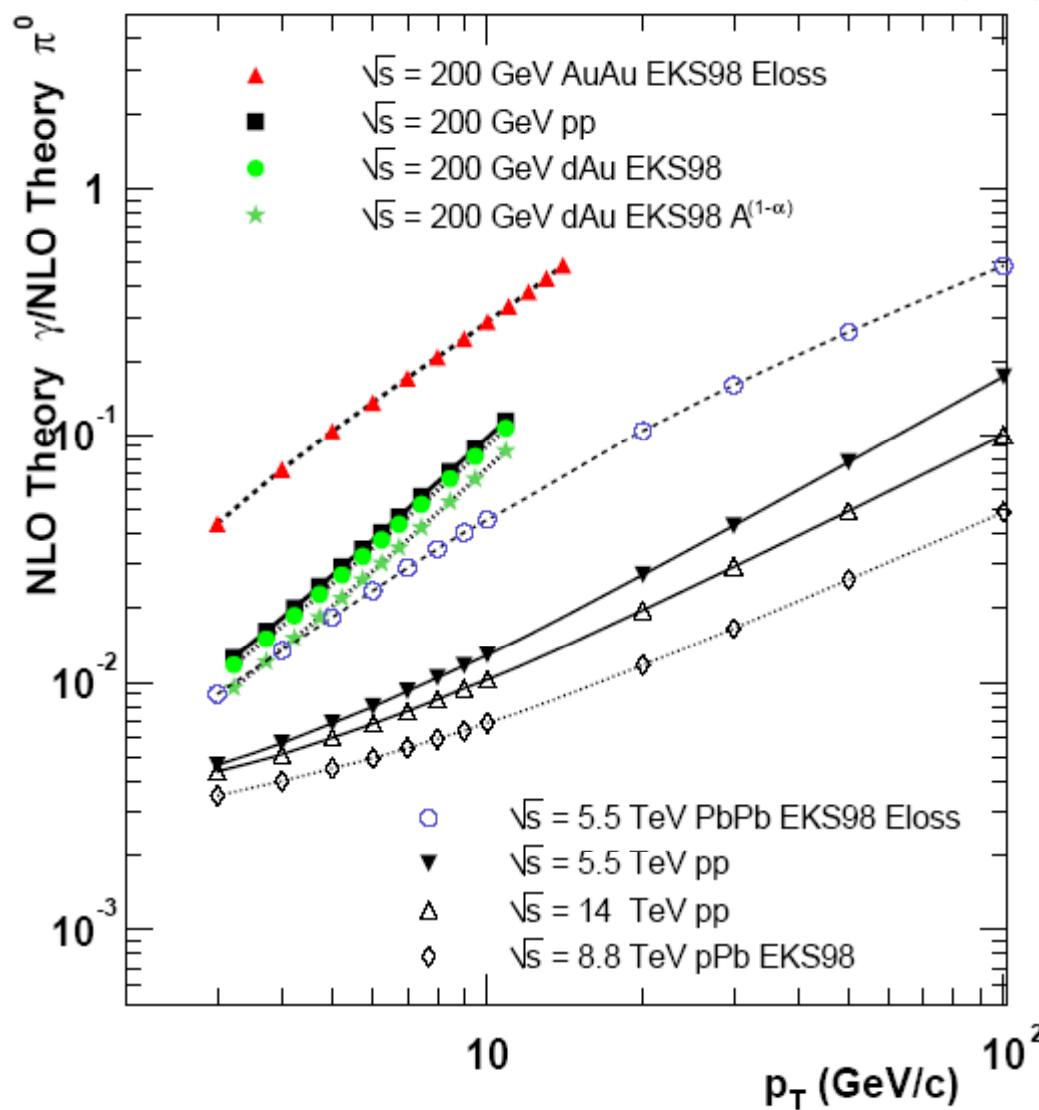
Many issues are similar (in particular the treatment of experimental systematic errors) but not yet so much debated for **FF uncertainties**

Importance of uncertainties on inclusive hadron cross sections

- Do we care about the uncertainty in fragmentation function?
- How does it compare to other uncertainties?

BFG: photon FF
 KKP: pion FF

$\text{pp, dAu, pPb, AuAu, PbPb} \rightarrow \gamma X$ CTEQ5M BFG set II $M = \mu = M_F = p_T$
 $\text{pp, dAu, pPb, AuAu, PbPb} \rightarrow \pi^0 X$ CTEQ5M KKP $M = \mu = M_F = p_T$

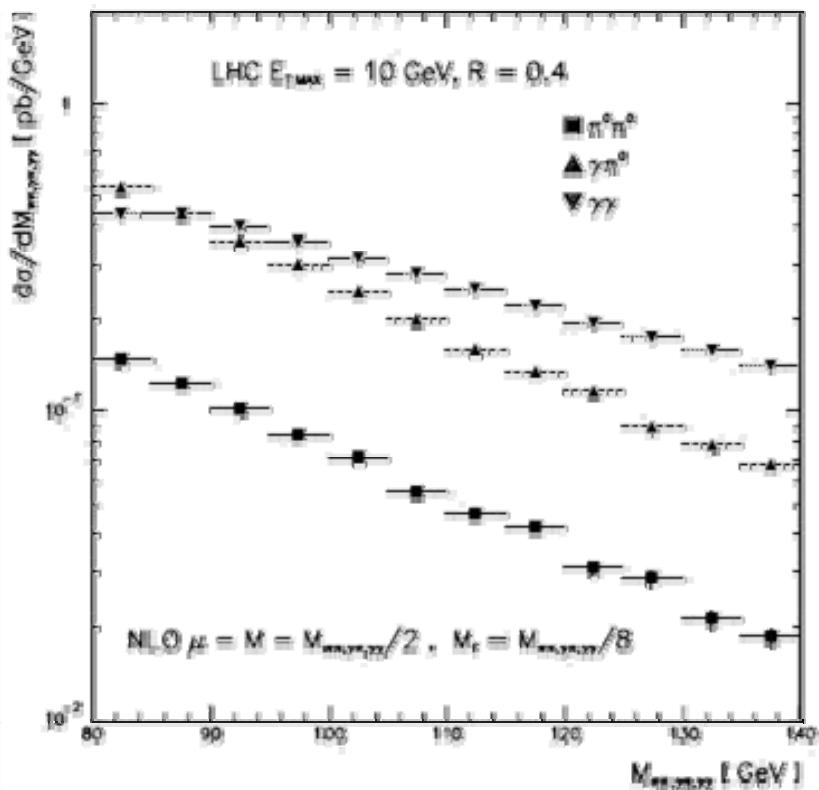
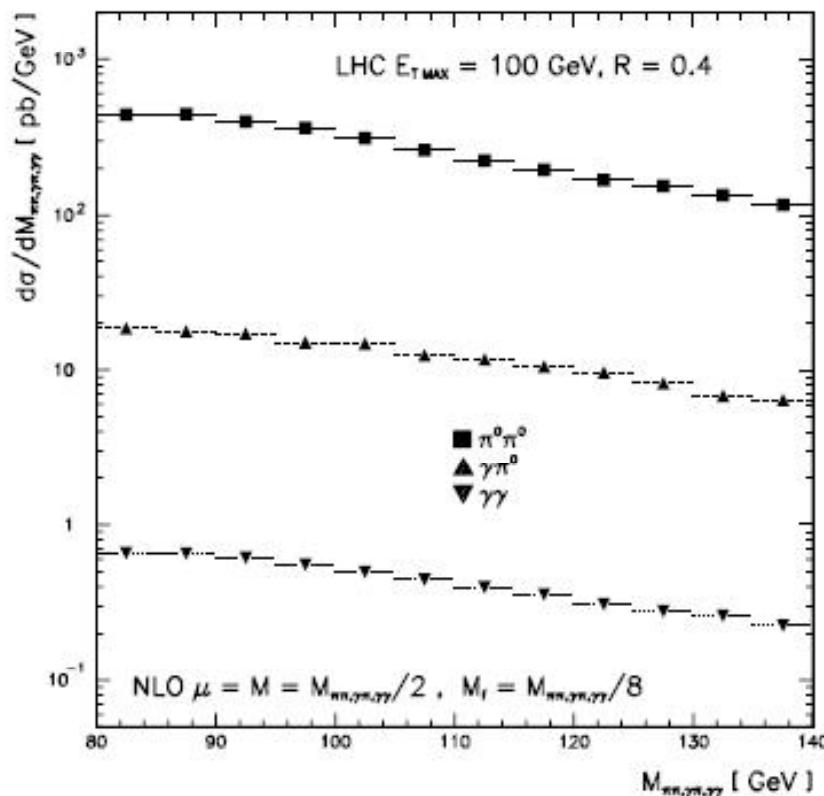


γ/π^0

[hep-ph/0311131](https://arxiv.org/abs/hep-ph/0311131)
 prepared for
 CERN YR-2004-009
**Hard probes in
 heavy-ion collisions
 at LHC**

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Reducible $\pi\pi$ and $\gamma\pi$ vs irreducible $\gamma\gamma$ backgrounds to $H \rightarrow \gamma\gamma$ search



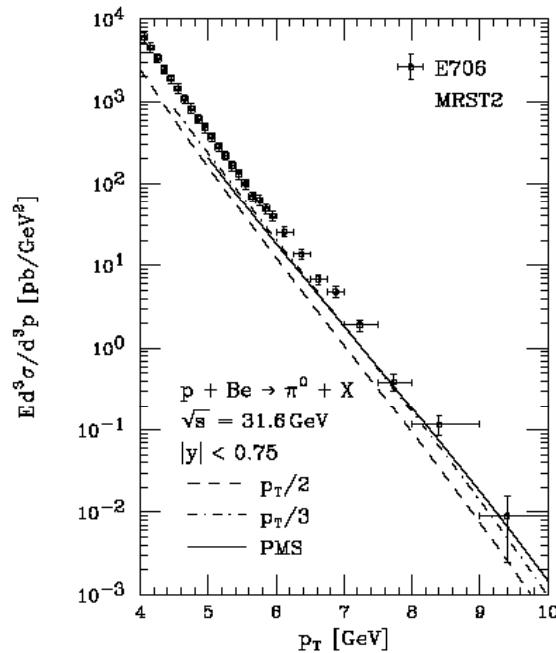
Explore with DIPHOX the strong isolation cuts,
uncertainties due to large z pion FF

[Eur. Phys. J. C4,7](#)
Bineth, Guillet,Pilon,
M.W.

π^0 phenomenology (hep-ph/9910252)

(Aurenche, Fontannaz, Guillet, Kniehl, M.W.)

EPJ C13,347



$$z = E_{\pi^0}/E_{\text{fragmenting parton}} \approx 0.8$$

BKK fragmentation (no constraining data for $z > 0.8$)

$\ln(1-z)$ resummation not available

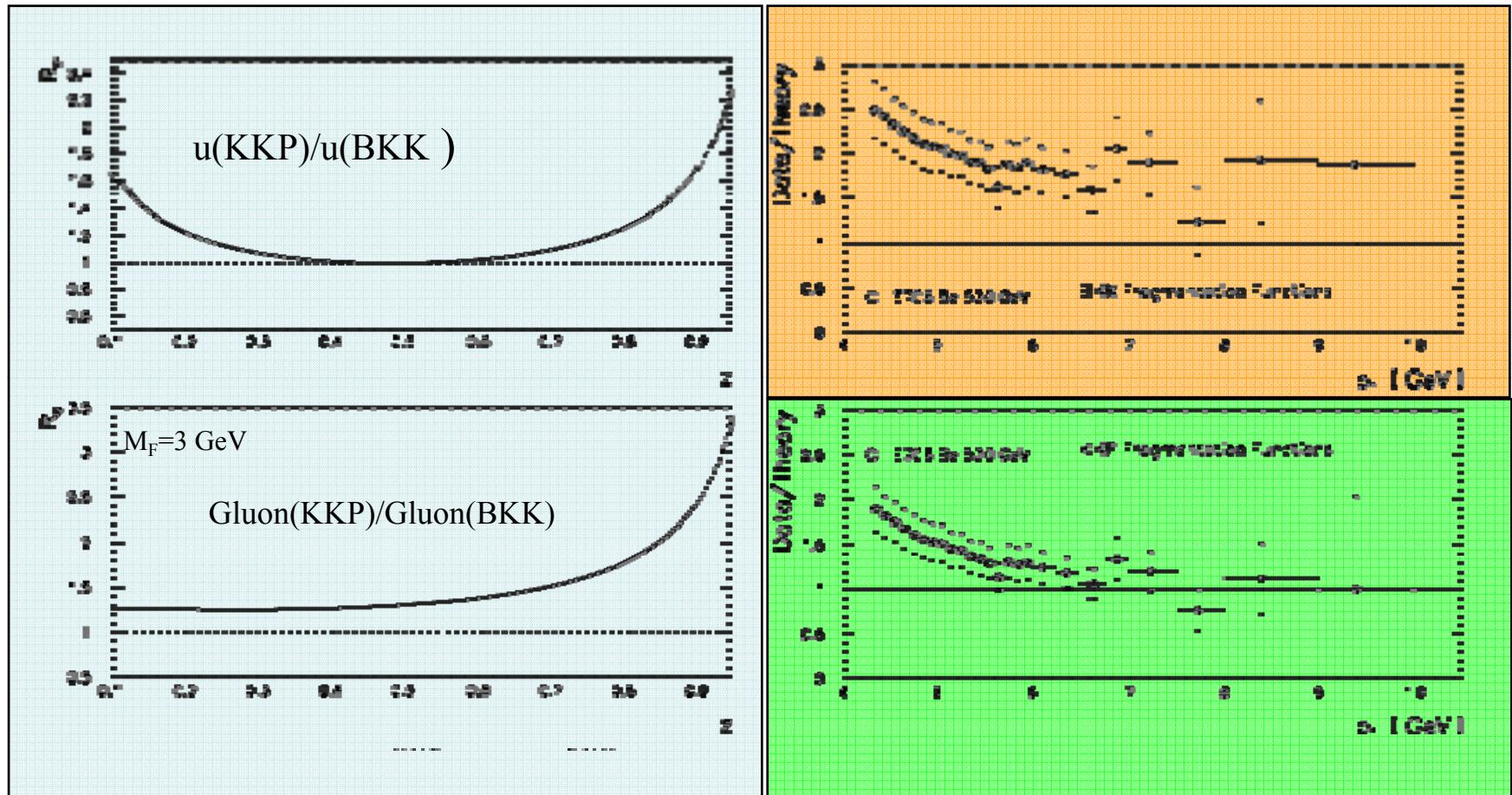
partly approximated with PMS scales

NLL $p_T/2 < \mu = M = M_F < p_T/3$ close to NLL PMS

with scales $p_T/3$: Data/theory ($x_T > 0.3$) ≈ 1.4 (UA6),
 ≈ 1.7 (WA70), ≈ 1.7 (E706/530), ≈ 1.2 (E706/800)

Data sets compatible.

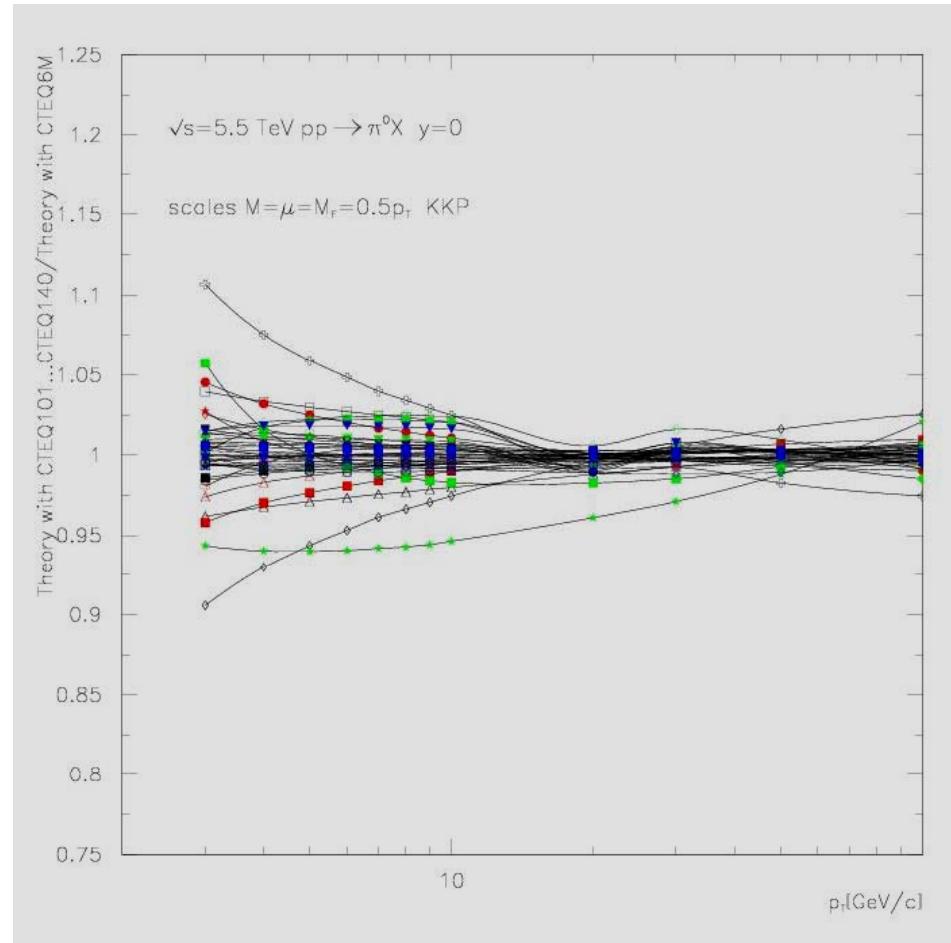
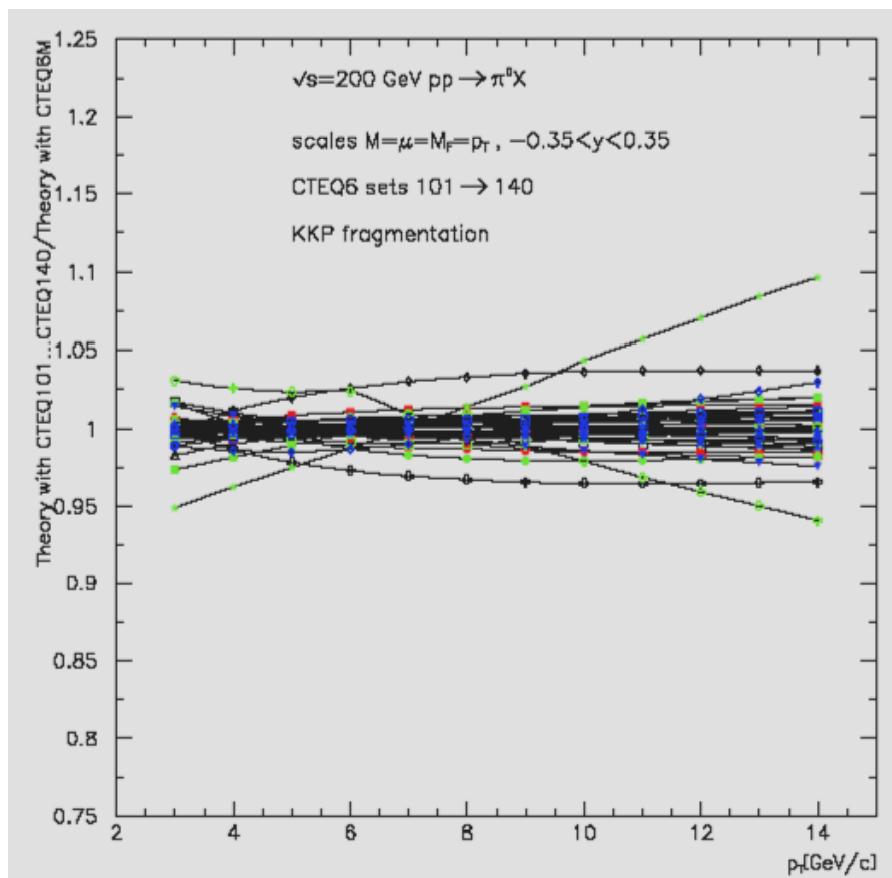
Production of π^0 , E706 data vs NLO theory



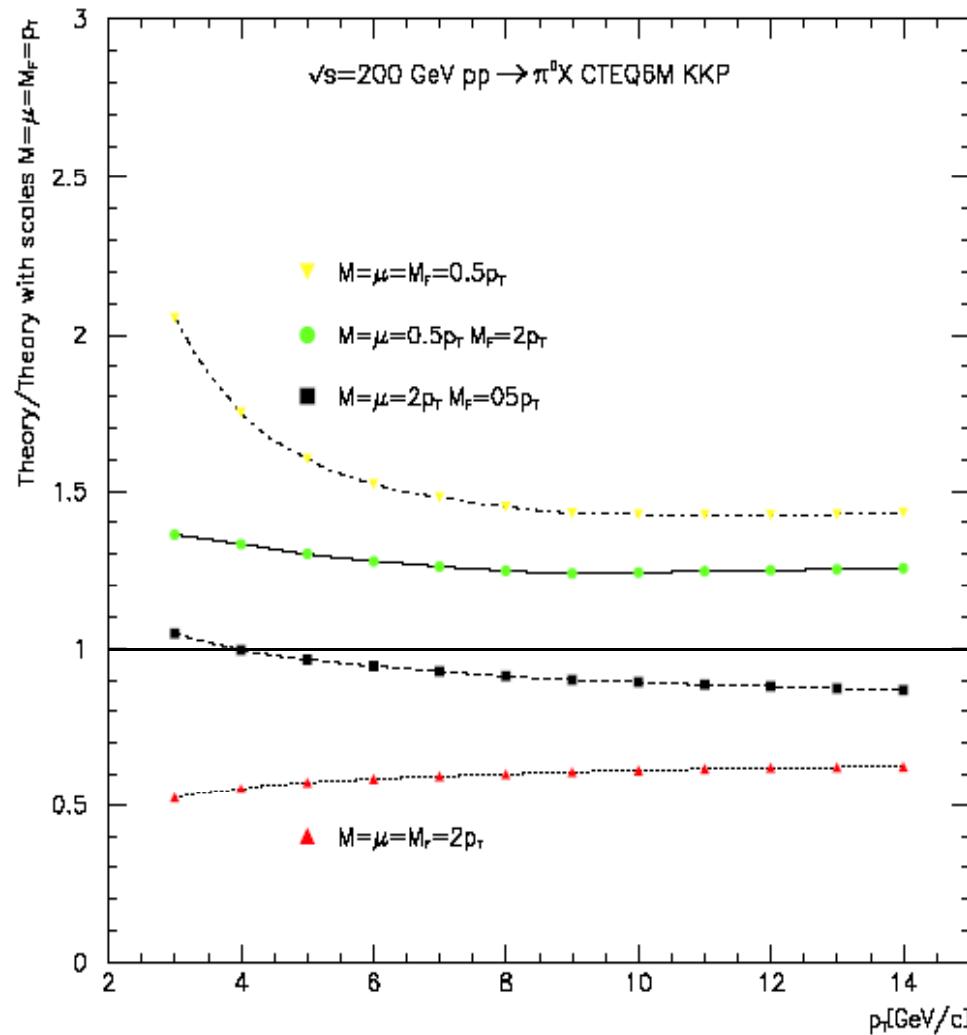
Better fit with fragmentation functions KKP than BKK

$M=M_F=\mu=p_T/3$ $\langle z \rangle \quad 0.75-0.9$
Binotto, Guillet, Pilon, M.W. [EPJC24,245](#)

Typical SF uncertainties in π^0 production?



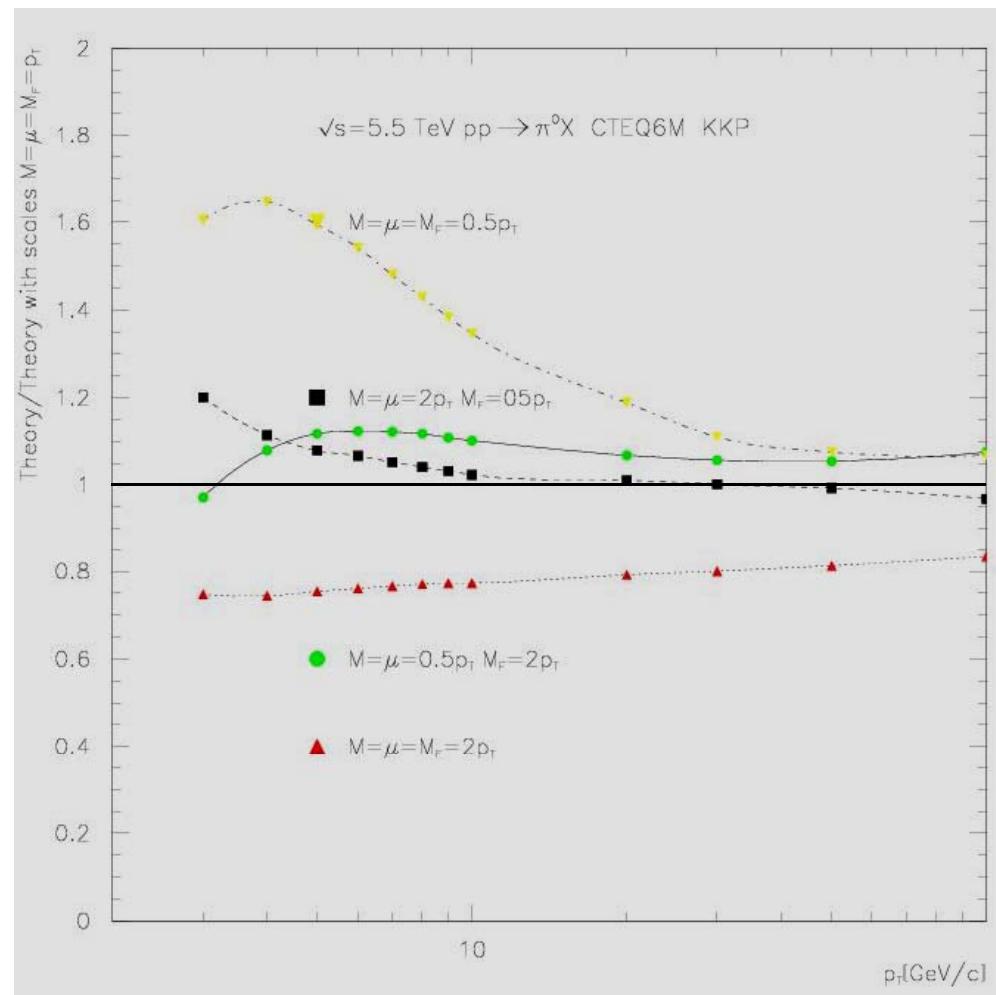
Uncertainties at RHIC energy due to fragmentation, factorization and renormalization scales



Improved with $\ln(1-z)$ resummation of soft gluons ?

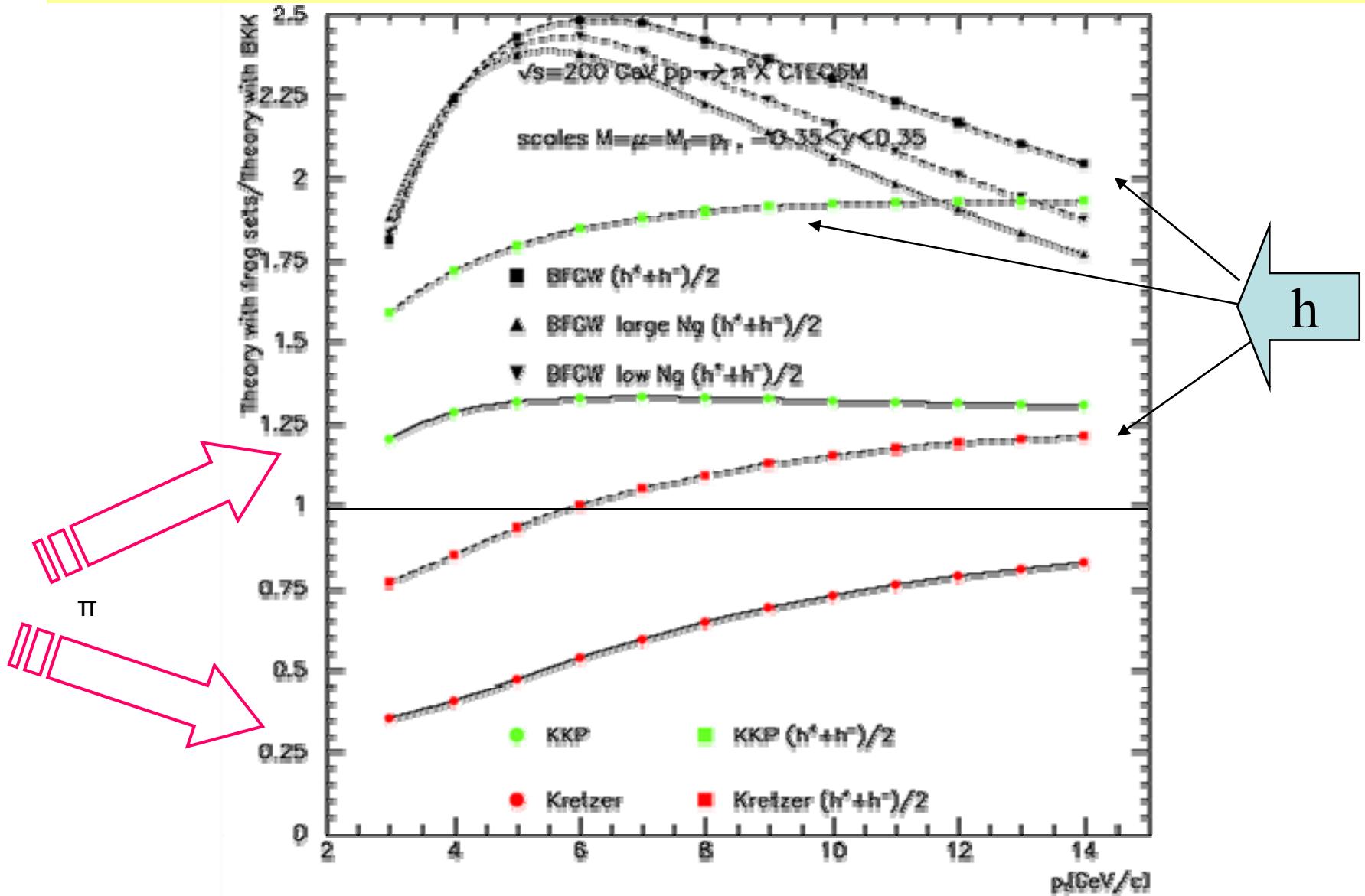
15

Uncertainties at LHC energy due to fragmentation, factorization and renormalization scales

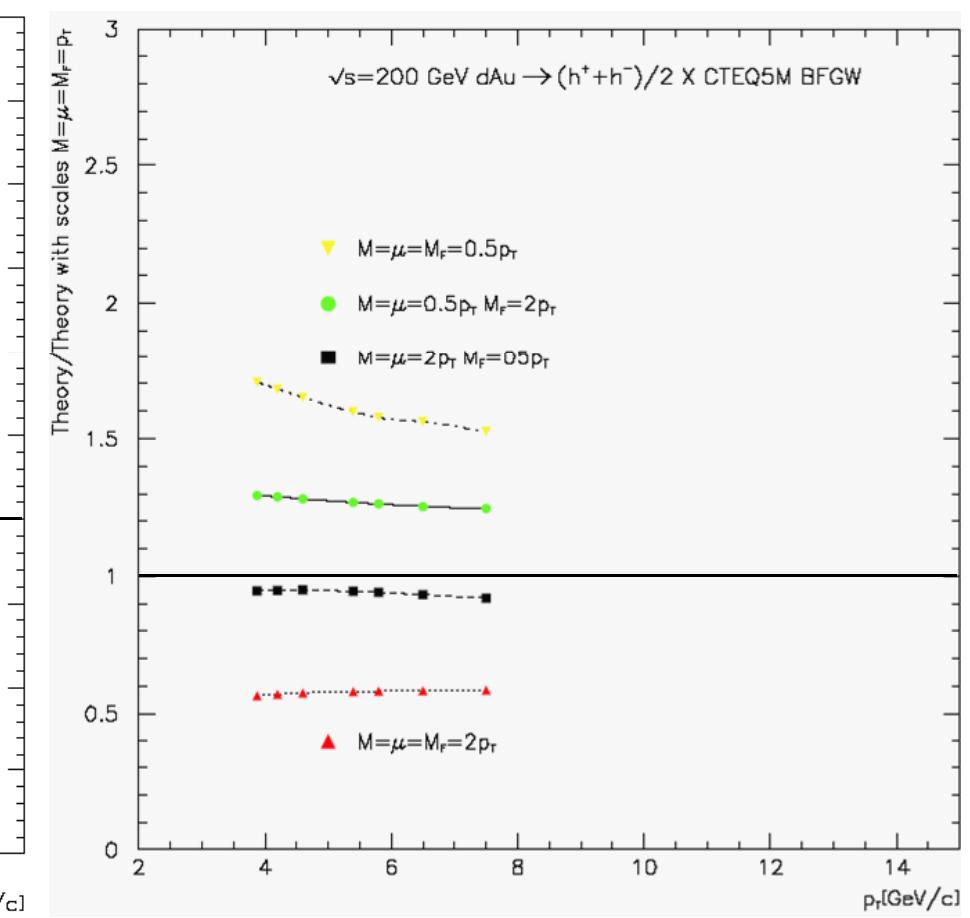
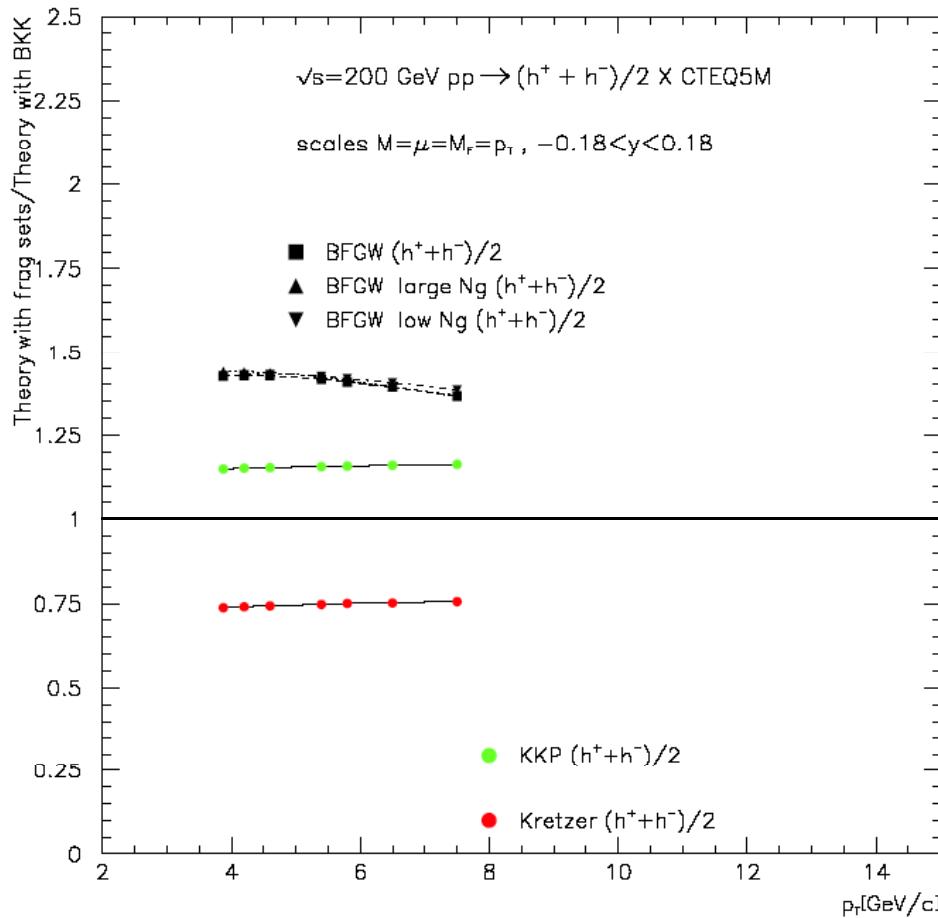


Rem. scales frozen below $M_0=2\text{GeV}$, $M_{f0}=\sqrt{2}\text{ GeV}$

Uncertainties due to fragmentation functions (RHIC)?

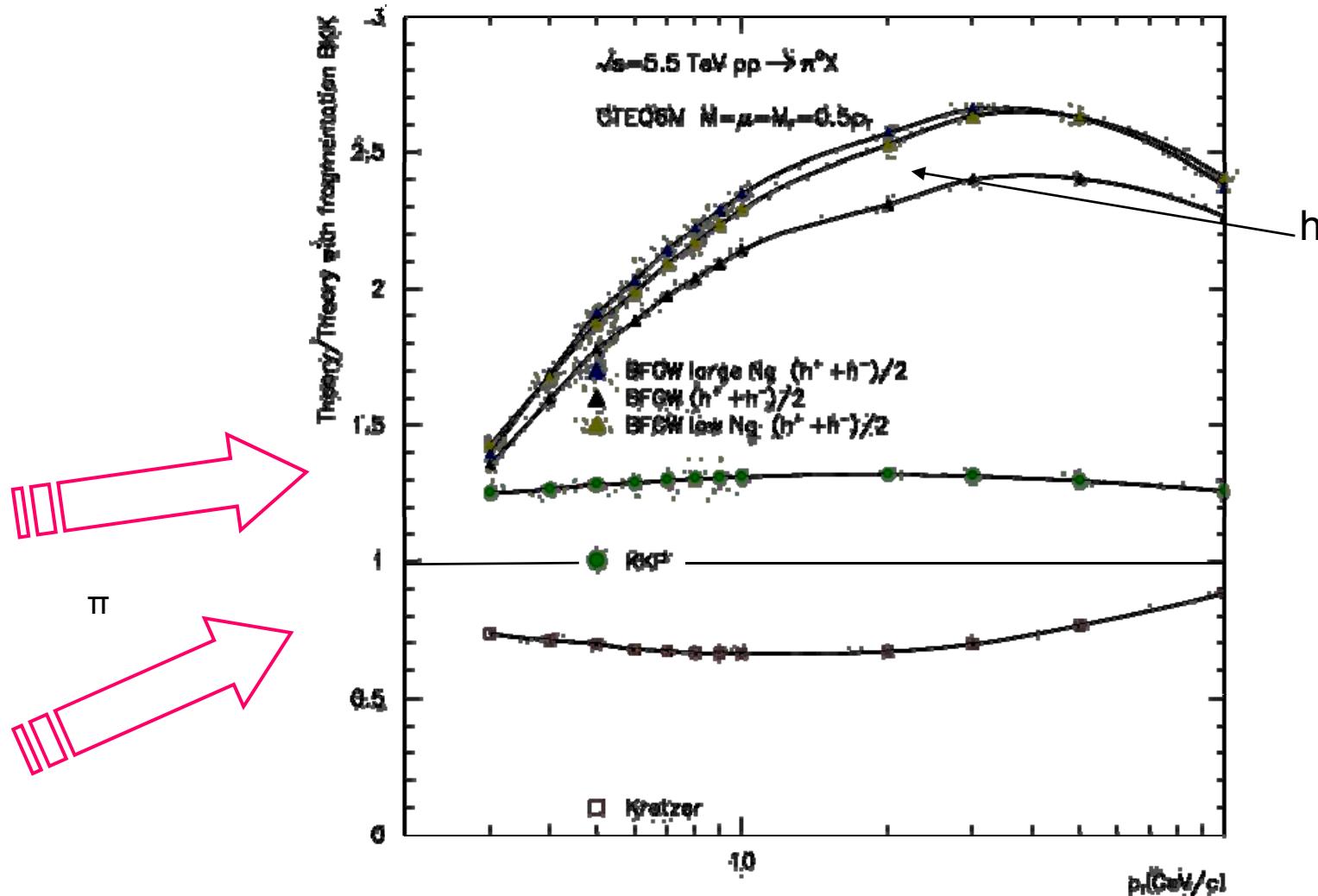


Typical fragmentation function and scale uncertainties in charged hadron production at RHIC energy



uncertainties from scale > uncertainties from FF

Uncertainties due to fragmentation functions (LHC)?



Importance of uncertainties on inclusive hadron cross sections

- Do we care about the uncertainty in hadron fragmentation function?
- How does it compare to other uncertainties?

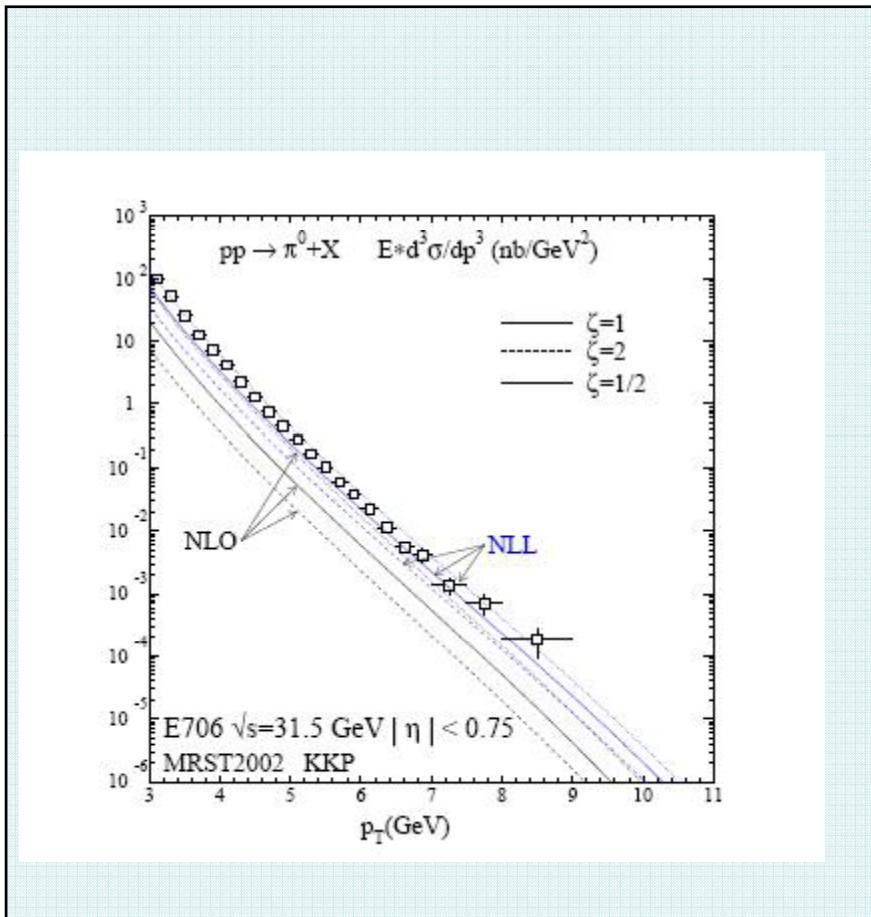
At RHIC energy, uncertainties from:

- scales are important: $\pm 50\%$ at $p_t = 8 \text{ GeV}/c$
as well as from
- different FF sets
(Kretzer set reduces sizably the cross section compared to KKP and BFGW sets)

At LHC energy, uncertainties from

- scales are of order of: $\pm 20\%$ for $p_t > 10 \text{ GeV}/c$
while
- differences from FF sets are dominant

Production of π^0 , E706 data vs NLO and NLL theory



Vogelsang + de Florian
[PR D71 \(2005\) 114004](#)

much reduced scale dependence
with threshold resummation (NLL)

(rem: NLO with small scale pt/3 to pt/2
rough approximation)

Fragmentation functions: methodology

- Parametrize FF z dependence at a given scale (MF=2GeV)
- Fit inclusive cross section data (pp and/or e+e-) with NLO theory
- Further uncertainties from:
 - structure functions,
 - factorization scale M (evol. SF)
 - fragmentation scale MF (evol. FF)
 - renormalization scale μ (evol. α_s)
 - running coupling constant α_s

Complementarities pp and e+e-:

- pp data more sensitive to gluon FF
- e+e- data more sensitive to quark FF
- z range : LEP most statistics $z < 0.7$

Neutral pions:

Chiappetta, Greco, Guillet,
Rolli, M.W.
Nucl. Phys. [B412,3](#) (1994)

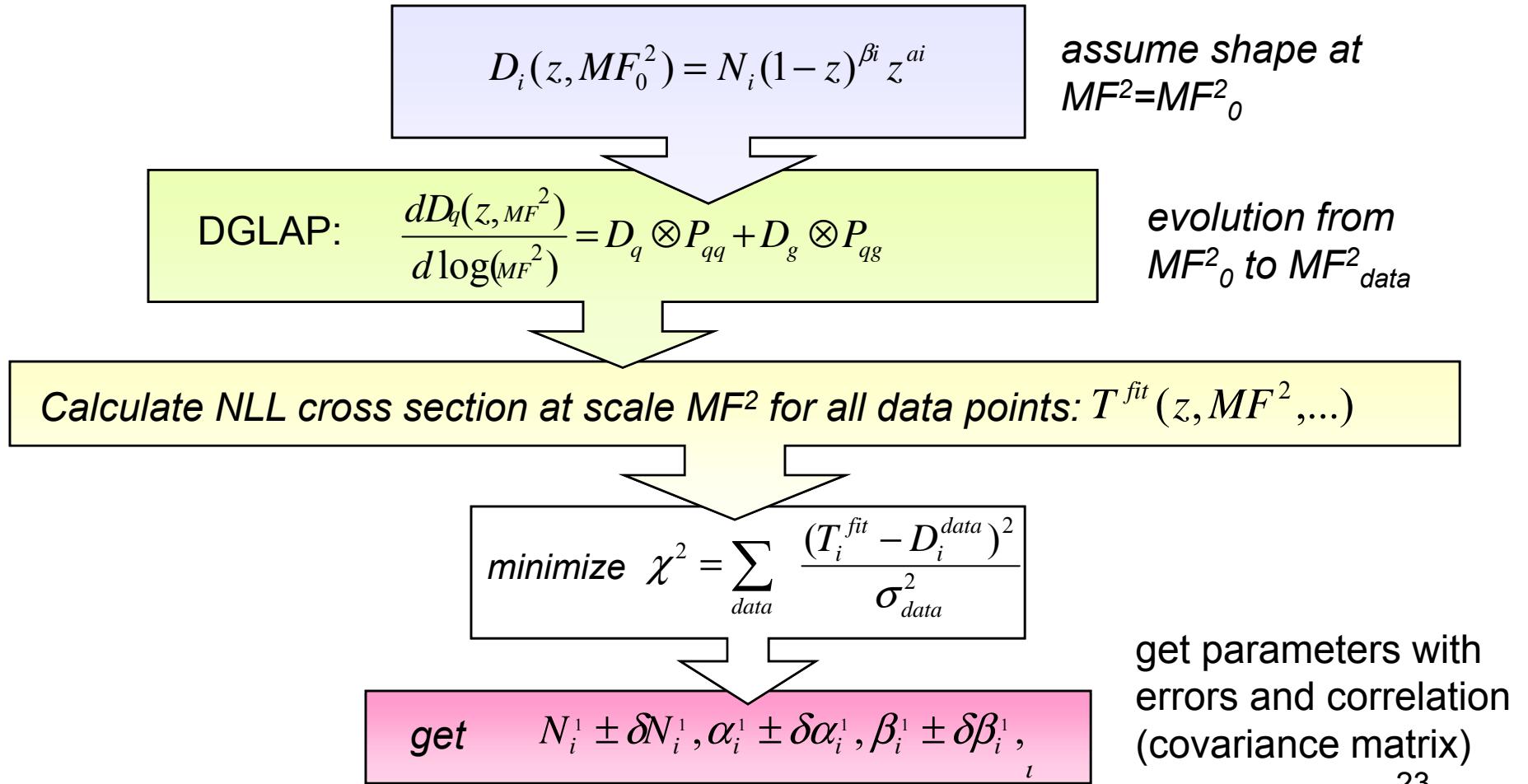
(first attempt to get
NLL π^0 FF)

Charged hadrons:

Bourhis, Fontannaz,
Guillet, M.W.
Eur. Phys. [C19,89](#) (2001)

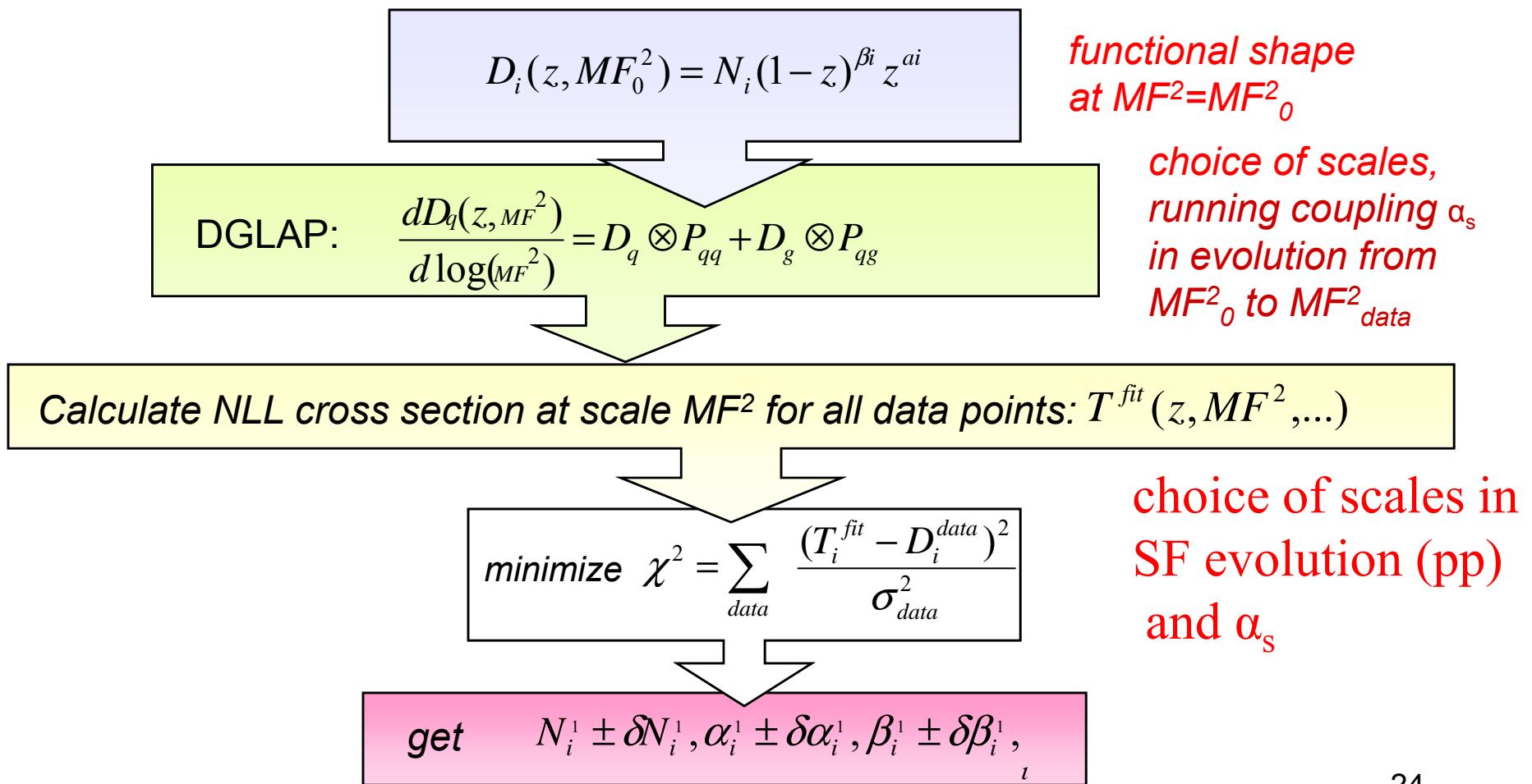
NLO QCD fits for fragmentation

Get the parton i to hadron h fragmentation function $D_i(z, MF^2)$ by fitting the inclusive cross section data in $e^+e^- \rightarrow h X$ and $pp \rightarrow h X$ with NLO QCD theory



NLO QCD fits for fragmentation

“theoretical” systematic uncertainties from



Inclusive π^0 production in NLO approximation

AB = pp or e^+e^-

$$E_{\pi^0} \frac{d^3\sigma_{AB \rightarrow \pi^0}}{d^3\vec{p}_{\pi^0}} = \sum_i \int_x^1 \frac{dz}{z^2} D_i^{\pi^0}(z, M_f^2) \times E_i \frac{d^3\sigma_{AB \rightarrow i}}{d^3\vec{p}_i} \left(\frac{x}{z}, \theta, \alpha_s(\mu^2), M_f^2, \dots \right)$$

$$E_i \frac{d^3\sigma_{AB \rightarrow i}}{d^3\vec{p}_i} = \sigma_{AB \rightarrow i}^0 \left(\frac{x}{z}, \theta \right) + \frac{\alpha_s(\mu^2)}{2\pi} \sigma_{AB \rightarrow i}^1 \left(\frac{x}{z}, \theta, M_f^2 \right) + \dots$$

LL approximation : σ^0

NLL approximation : σ^0, σ^1

Fragmentation function: evolution

$D_i^{\pi^0}(z, M_f^2)$ density of π^0

inside the parton i carrying
a fraction z of the parton impulsion
at fragmentation scale M_f

$$\frac{dD_q^{\pi}(z, M_f^2)}{d \log(M_f^2)} = \frac{\alpha_s(M_f^2)}{2\pi} \int_z^1 \frac{dy}{y} (P_{qq}^T(\frac{z}{y}, \alpha_s(M_f^2)) D_q^{\pi}(y, M_f^2) + P_{gq}^T(\frac{z}{y}, \alpha_s(M_f^2)) D_g^{\pi}(y, M_f^2))$$

$$\frac{dD_g^{\pi}(z, M_f^2)}{d \log(M_f^2)} = \frac{\alpha_s(M_f^2)}{2\pi} \int_z^1 \frac{dy}{y} (P_{qg}^T(\frac{z}{y}, \alpha_s(M_f^2)) D_q^{\pi}(y, M_f^2) + P_{gg}^T(\frac{z}{y}, \alpha_s(M_f^2)) D_g^{\pi}(y, M_f^2))$$

$$P_{ij}^T(x, \alpha_s(M_f^2)) = P_i j^0(x) + \frac{\alpha_s(M_f^2)}{2\pi} P_{ij}^{T1}(x) + \dots$$

Petronzio, Furmansky Phys. Lett. [B97,437](#) (1980)
code from P.NASON

$$\frac{dD_q(z, M_f^2)}{d \log(M_f^2)} = D_q \otimes P_{qq} + D_g \otimes P_{gq}$$

$$\frac{dD_g(z, M_f^2)}{d \log(M_f^2)} = D_q \otimes P_{qg} + D_g \otimes P_{gg}$$

LL approximation : P^0

NLL approximation : P^0, P^1

Fragmentation function: parameterization

9 parameters

For valence quark, sea quark ,
and gluon fragmentation

$$D_v(z) = N_v (1-z)^{\beta v} z^{\alpha v}$$

$$D_s(z) = N_s (1-z)^{\beta s} z^{\alpha s}$$

$$D_g(z) = N_g (1-z)^{\beta g} z^{\alpha g}$$

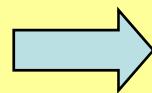
set I fix $\alpha v = \alpha s = \alpha g = 0$

Parametrisation of $D_i^{\pi^0}(y, M_{f0}^2)$
at $M_{f0}^2 = 2 \text{ GeV}^2$

$$D_u^{\pi^0}(y, M_{f0}^2) = D_{\bar{u}}^{\pi^0}(y, M_{f0}^2) = \\ D_d^{\pi^0}(y, M_{f0}^2) = D_{\bar{d}}^{\pi^0}(y, M_{f0}^2) = \\ D_v(z) + D_s(z)$$

$$D_s^{\pi^0}(y, M_{f0}^2) = D_{\bar{s}}^{\pi^0}(y, M_{f0}^2) = \\ D_c^{\pi^0}(y, M_{f0}^2) = D_{\bar{c}}^{\pi^0}(y, M_{f0}^2) = \\ D_g(z)$$

$$D_g^{\pi^0}(y, M_{f0}^2) = D_g(z)$$



NLO fits to e^+e^- data quark fragmentation

NLO theory

Altarelli, Ellis, Martinelli, Pi

Nucl. Phys. [B160,301](#) (1979)

Data from PETRA, PEP

- CELLO: Z. Phys. C20 (1983) 207 and C47 (1990) 1.
- TPC: Z. Phys. C27 (1985) 187.
- TASSO: Z. Phys. C33 (1986) 13.
 $E_\pi > 2 \text{ GeV}$

$$\mu^2 = M_F^2 = Q^2$$

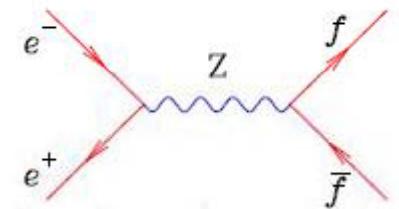
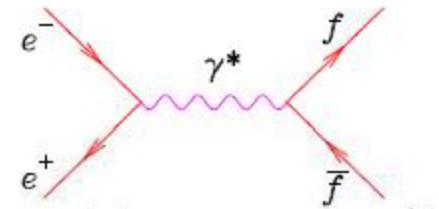
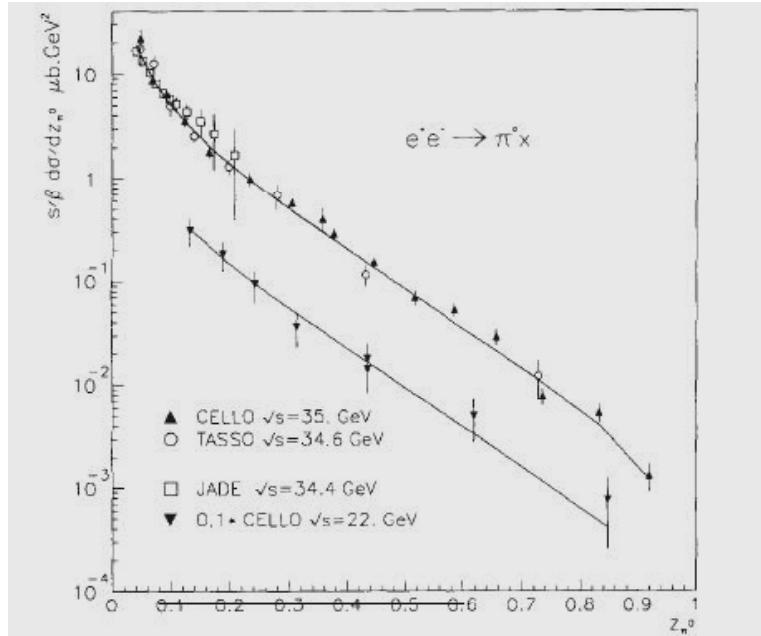
$\rightarrow N_v, \beta_v$ well constrained

$\rightarrow N_v = 0.185$ WHEN $\beta_v = 1$.

but not N_s, N_g, β_g

Then check with DORIS and LEP data

- ARGUS: Z. Phys. C46 (1990) 15.
- L3: Phys. Lett. B259 (1991) 199.

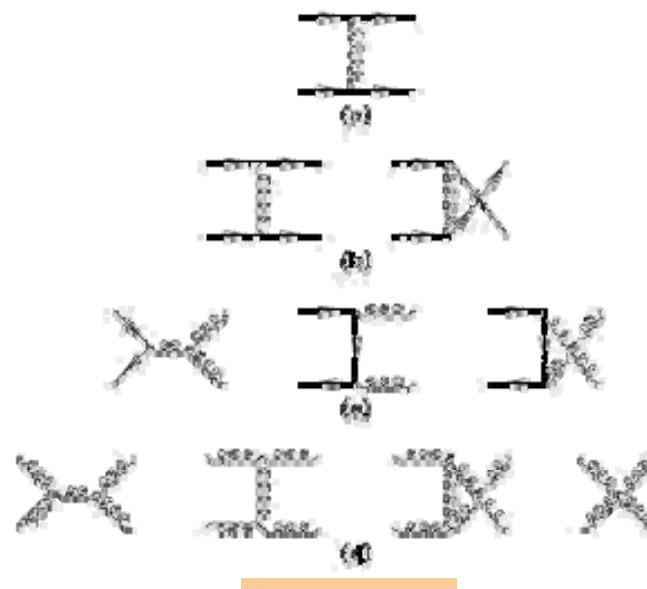


NLO fits to pp data gluon fragmentation

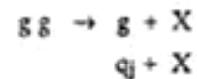
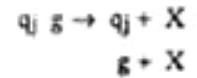
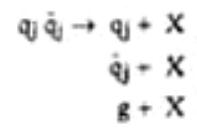
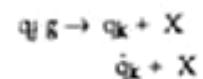
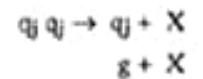
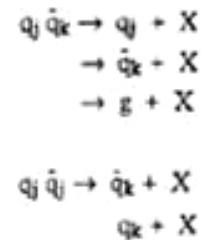
NLO theory

Ellis, Sexton: matrix elements
Nucl. Phys. [B269,445](#) (1986)

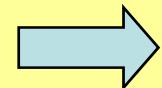
Aversa,Chiappetta,Greco,Guillet
Nucl. Phys. [B327,105](#) (1989)



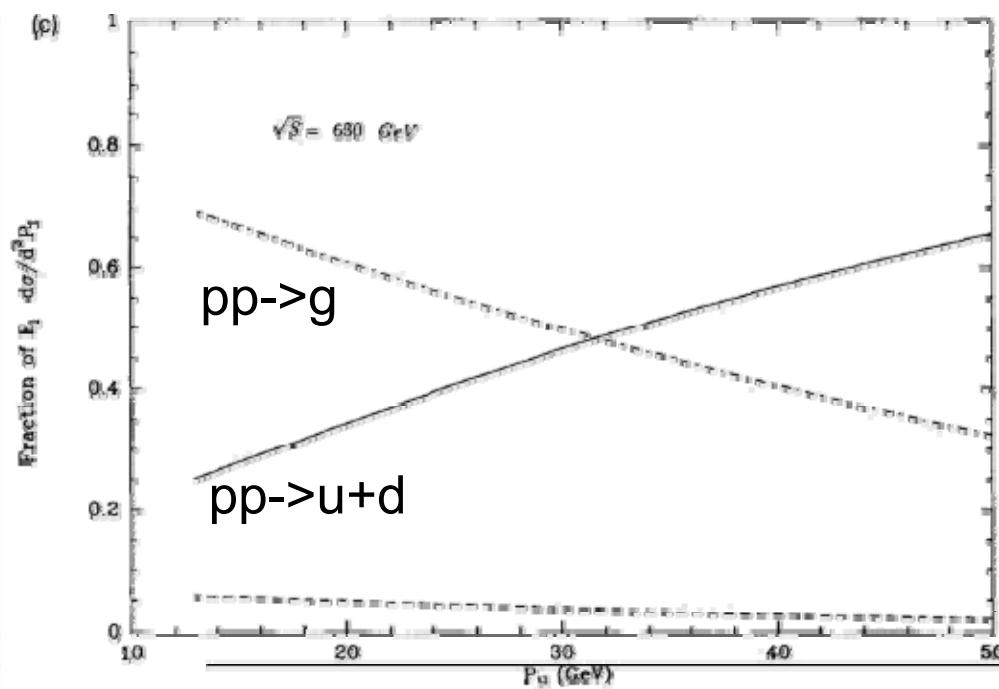
$$E_i \frac{d^3\sigma_{pp \rightarrow i}}{d^3\vec{p}_i} = \sum_{i,j} \int dx_1 \int dx_2 (F_i^p(x_1, M^2) F_j^p(x_2, M^2) \times (\alpha_s(\mu^2) H_{ij}^0(x_1, x_2, \vec{p}_i) + \alpha_s^3(\mu^2) H_{ij}^1(x_1, x_2, \vec{p}_1; \mu^2, M^2, M_f^2)))$$



Order α_s^3



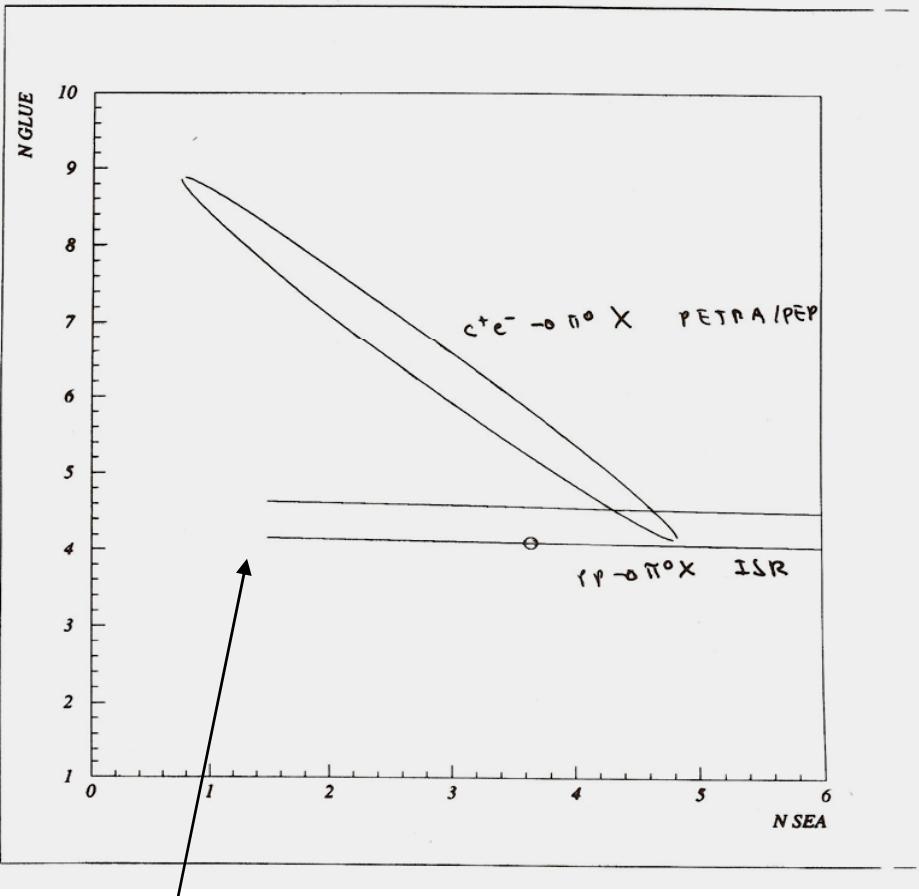
NLO fits to pp data gluon fragmentation



Data at $\sqrt{s}=23,31,63,540,630$ GeV

- WA70 Z.Phys. [C38,371](#) (1988)
- E706 Phys. [Rev.D45,3899](#) (1992)
- R806 Z.Phys. [C5,104](#) (1980)
- UA2 Z. Phys [C27,329](#) (1985)
Phys. Lett. [B176,239](#) (1986)

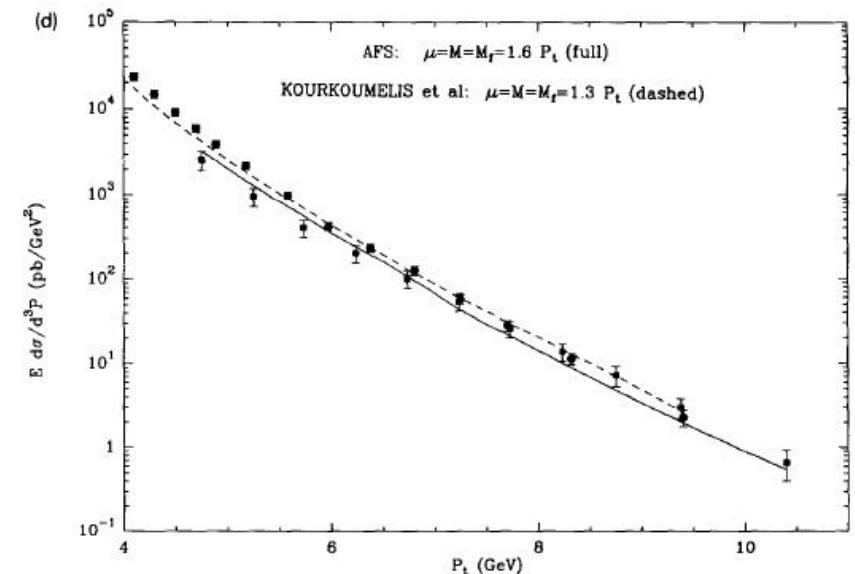
Correlation $N_{\text{glue}} - N$



illustrative only

Complementarities of e^+e^- and pp data for the N_g and N_s determination

ISR pp data very sensitive to N_g
... but have a scale dependence



Theoretical and experimental sources of uncertainties

- **data:**
 - statistical error,
 - systematic,
 - normalization
 - z and Q^2 range, sensitivity to quark, gluon FF
- matching **theory** and **data** (binning, cuts, defs,...)
- **theory:**
 - choice of functional form, z range of assumptions
 - choice of scales
 - order of theory (leading, NLO,...)
 - further parameters (Structure Function, α_s)

Systematic uncertainties from data Normalization

free parameter allowed to vary within 3σ of
normalization uncertainty quoted by expt

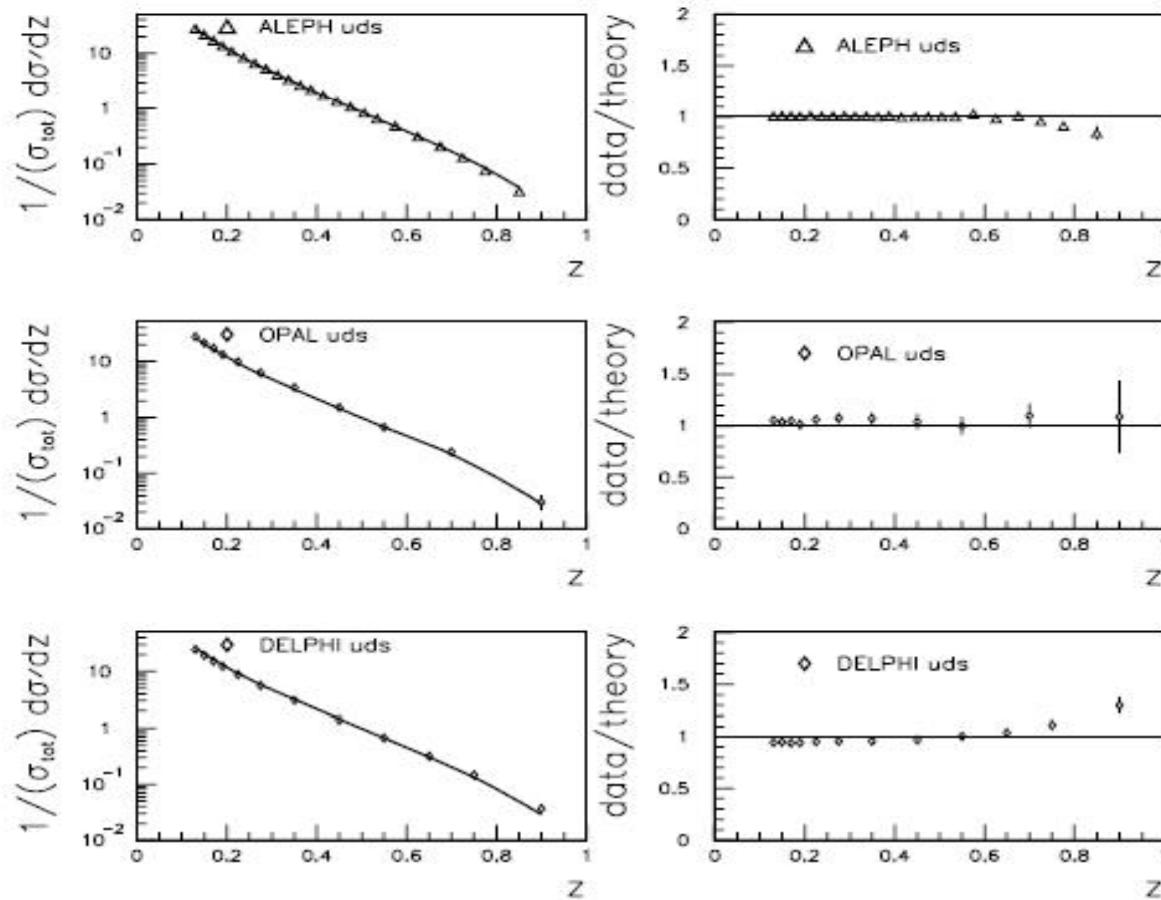
$$\chi^2 = \sum_{i=1}^{n^{\text{exp}}} \left[\sum_{j=1}^{n^{\text{data}}} \frac{(N_i D_j^{\text{data}} - T_j^{\text{theor}})^2}{(N_i \Delta D_j^{\text{data}})^2} \right]$$

Fitted normalization

Point to point independent systematics
sometime added in quadrature to statistical uncertainties

Typical z range of LEP data sets (for BFGW fits)

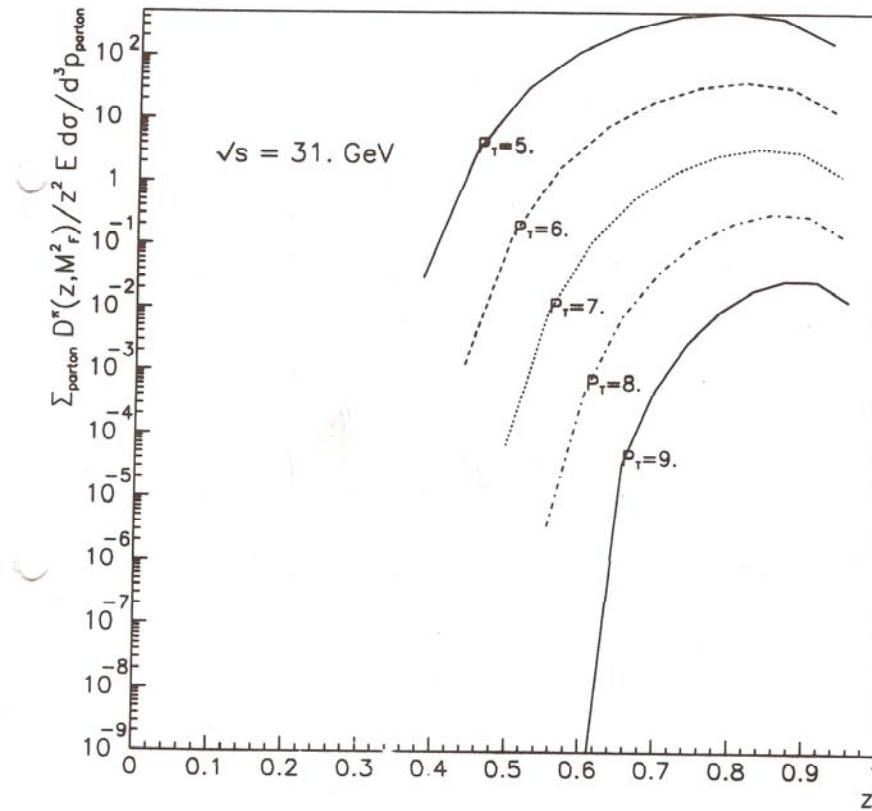
L. Bourhis et al.: Next-to-leading order d



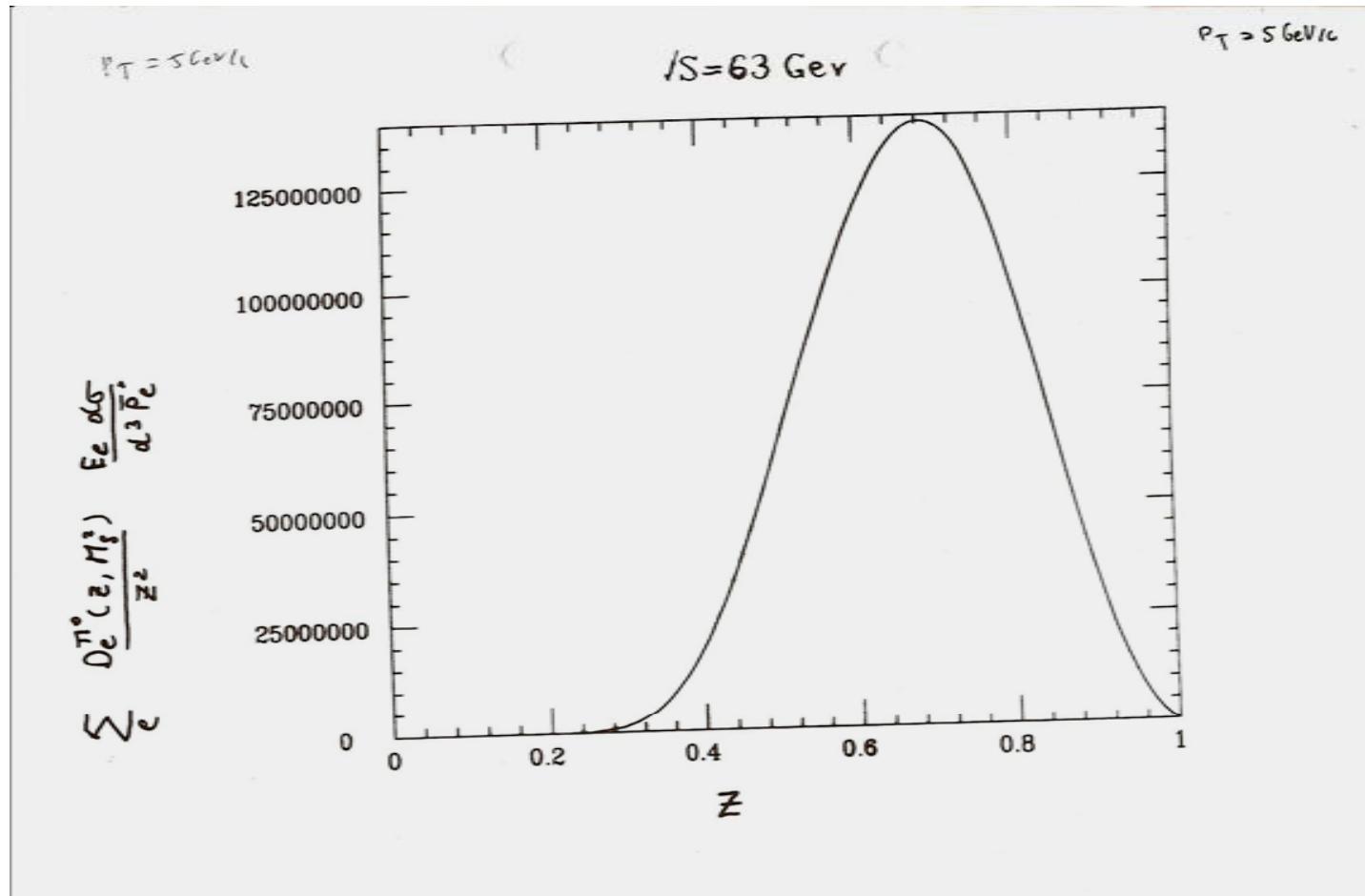
z range of $pp \rightarrow \pi^0 X$ at 31 GeV (E706, ISR)

z range of $pp \rightarrow \pi^0 X$

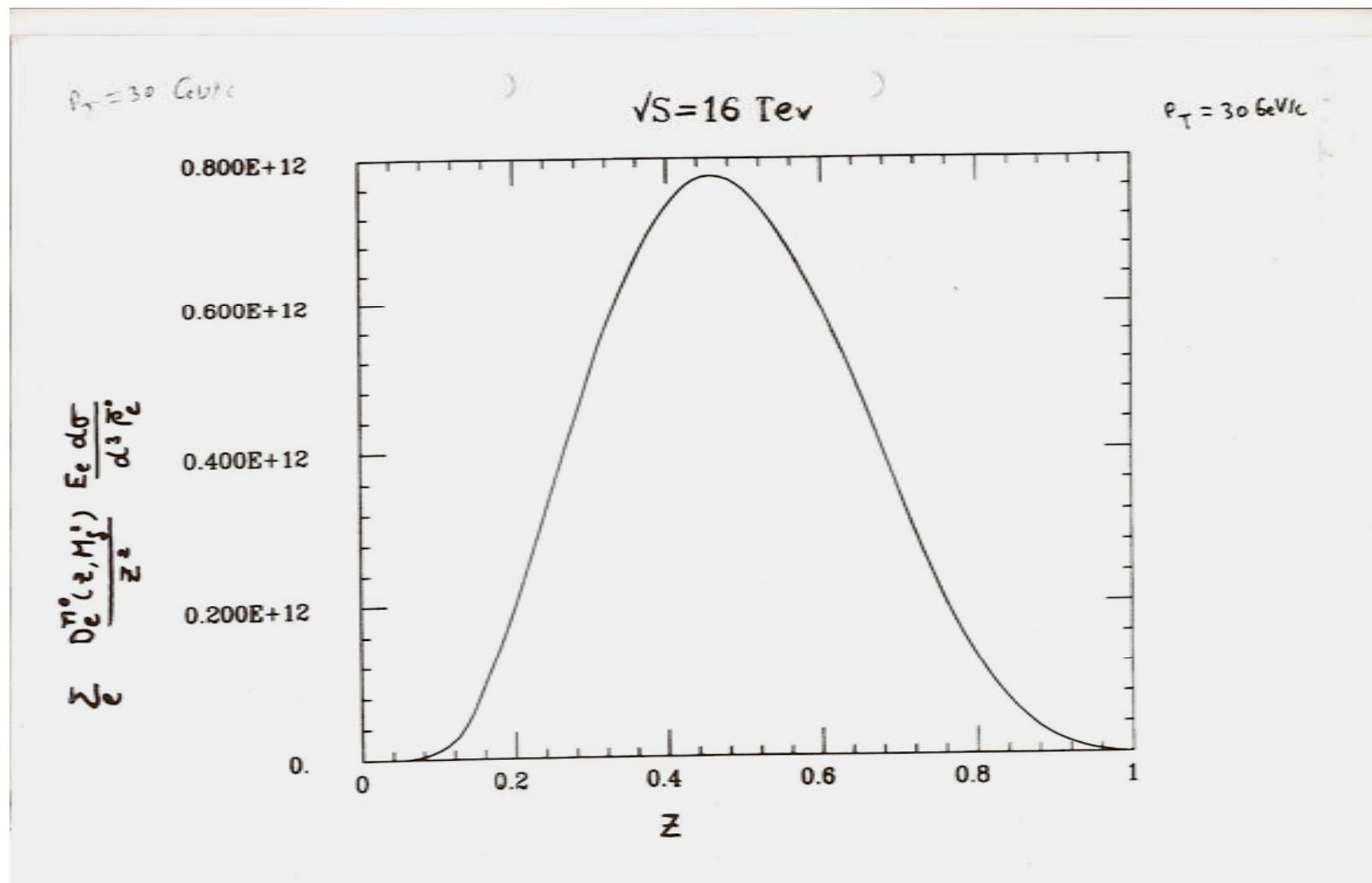
E706, ISR



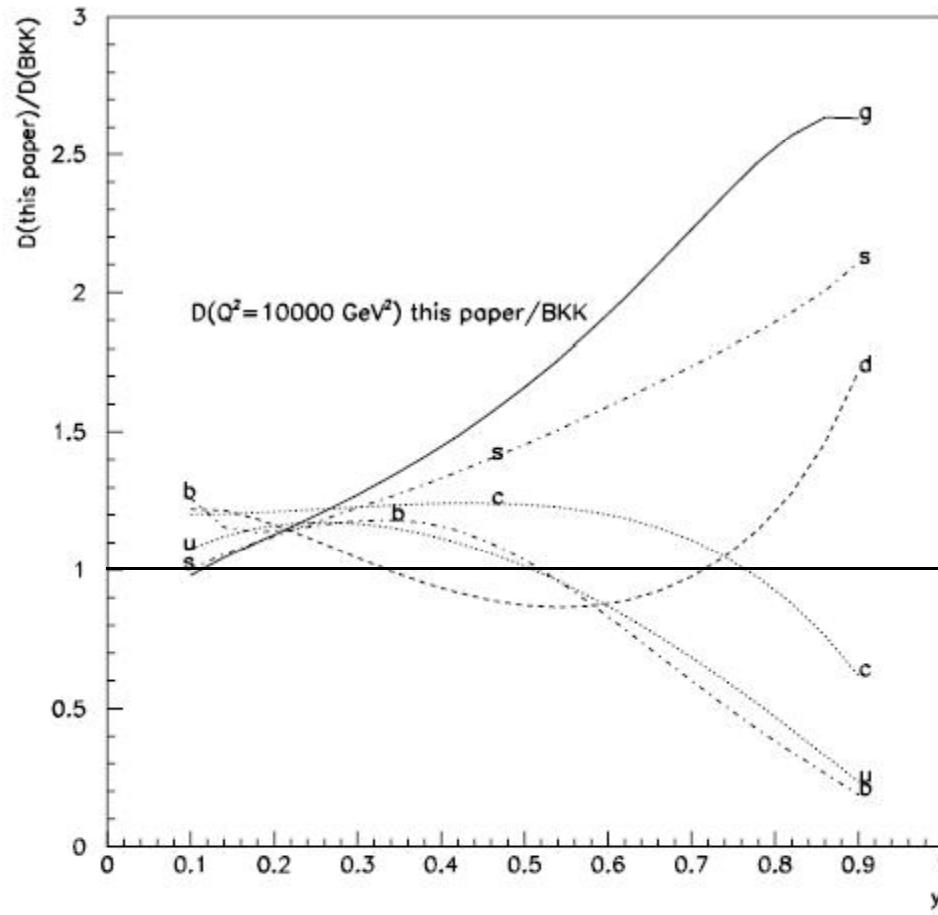
z range at ISR (63 GeV)



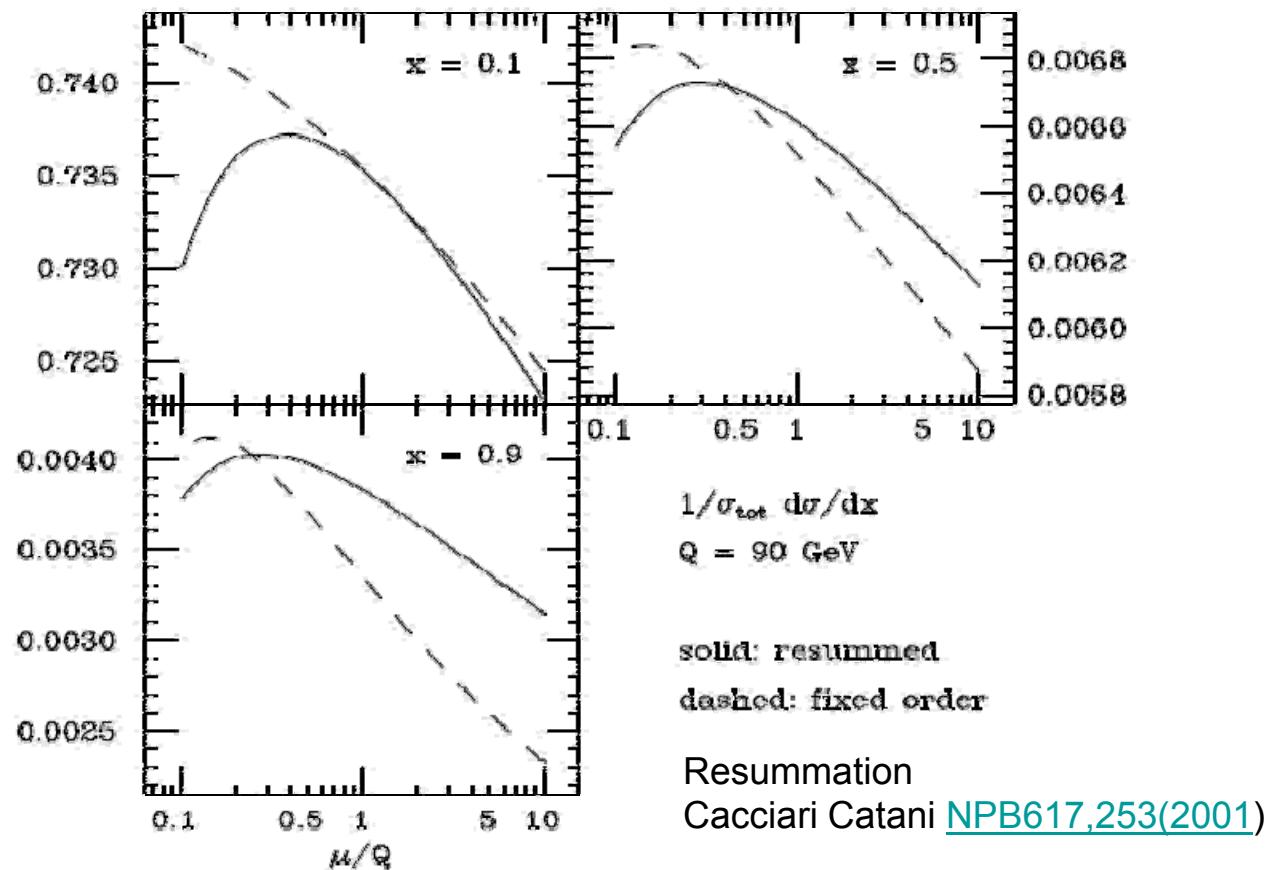
z range at LHC (version 16 TeV)



FF BFGW/BKK



$\ln(1-z)$ resummation of soft gluons in FF



- Resummation reduces dependence on renormalization and fragmentation scale for e^+e^-
- “optimized scales” in BFGW fit to e^+e^- ($\mu/Q \approx 0.2$ at large x) was a rough approximation
(for a new approach, see [AKK](#), arXiv 0711.1086)

Uncertainties on gluon fragmentation BFGW low and high Ng/BFGW

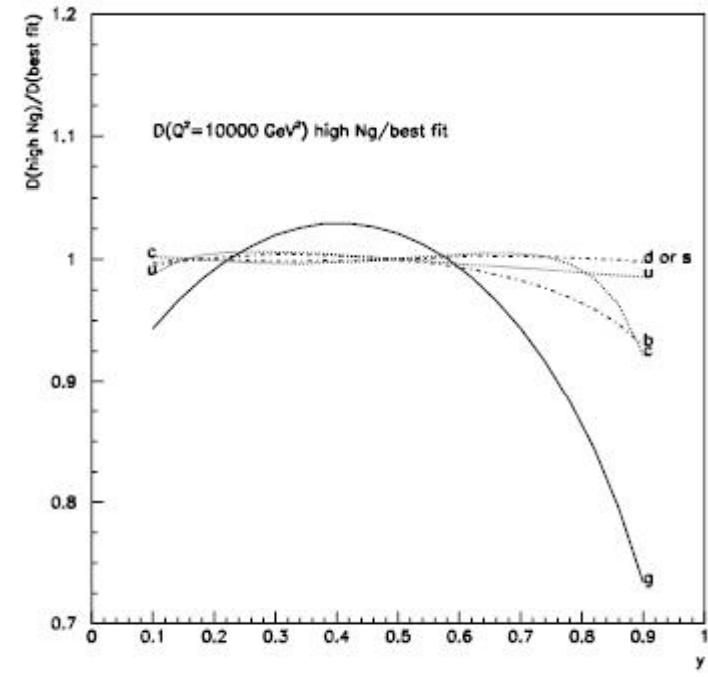
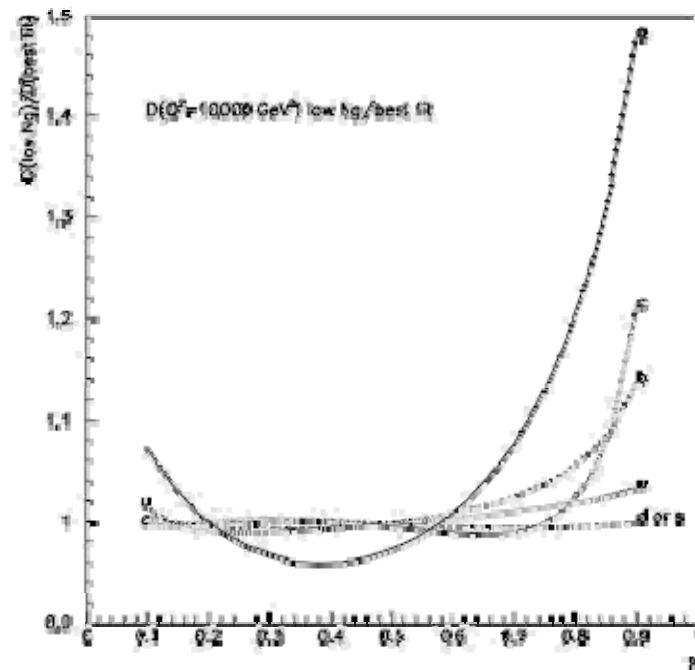
$$D_g(y, Q_0^2) = N_g(1-y)^{\beta_g} y^{\alpha_g}$$

$$D_u(y, Q_0^2) = \left(N_u(1-y)^{\beta_u} + \bar{N}_u(1-y)^{\bar{\beta}_u}\right) y^{\alpha_u}$$

$$D_{d+s}(y, Q_0^2) = \left(N_{d+s}(1-y)^{\beta_{d+s}} + \bar{N}_{d+s}(1-y)^{\bar{\beta}_{d+s}}\right) y^{\alpha_u}$$

$$D_c(y, Q_0^2) = N_c(1-y)^{\beta_c} y^{\alpha_c}$$

$$D_b(y, m_b^2) = N_b(1-y)^{\beta_b} y^{\alpha_b}$$



Fragmentation to charged hadron

	#param	data used	$\chi^2 / \#points$	rem.
<u>KKP</u> (2000)	3*5*3	$e^+e^- \rightarrow \pi, k, p$ TPC, LEP, SLD	$0.2 < \chi^2 / DF < 1.28$	no error for parameters
<u>Kretzer</u> (2000)	30	$e^+e^- \rightarrow \pi, k$ SLD $e^+e^- \rightarrow h$ ALEPH	not given not given	flavor tag sum rule
<u>BFGW</u> (2001)	13	$e^+e^- \rightarrow h$ LEP, PETRA $p\bar{p} \rightarrow h$ UA1	201/217 ~ok	error analysis Nason code PMS scales
<u>AKK</u> (2005)	3*6*3	$e^+e^- \rightarrow \pi, k, p$ $p\bar{p}$ RHIC	$\chi^2 / DF = 1.15$ ok	
<u>DSS</u> (2007)	5*8(p) 5*5	e^+e^- , pp, SIDIS res. h	171.9/159 1227/661	flexible shape πk <u>DSS1</u>

Parton to hadron fragmentation

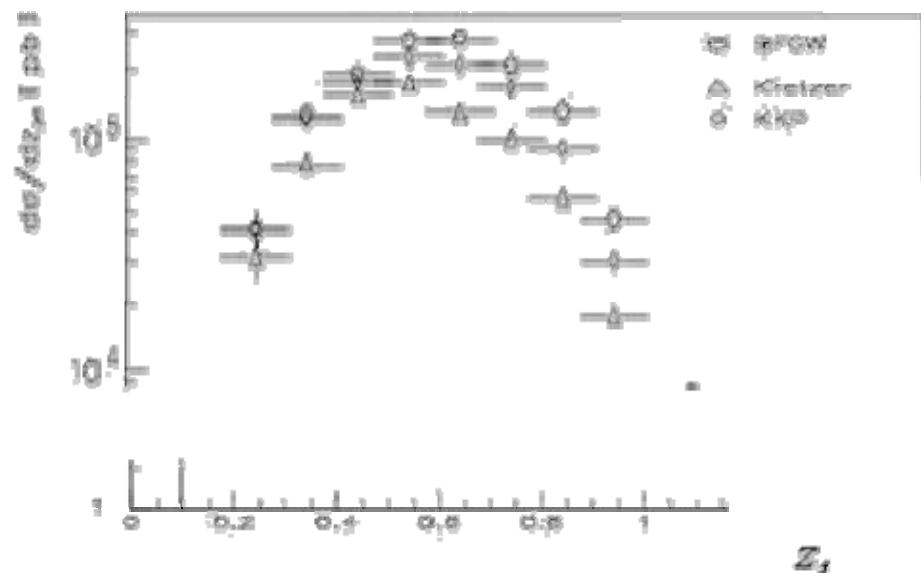
p_t balance between hadron and jet
at RHIC energy using
[JETPHOX](#)

direct access to fragmentation
function

may help discriminate sets
at large z

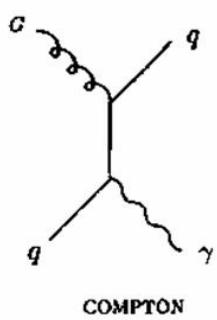
with Belghobsi, Fontannaz, Guillet, Heinrich, Pilon
preliminary

$$Z_h = \frac{P_{Tj}}{P_{Th}} \sim \frac{1}{z} \quad \text{at LO}$$
$$Z_j = \frac{P_{Th}}{P_{Tj}} \sim z$$

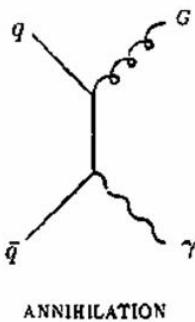


CTEQ6M, $M=M_f=\mu=p_t(h)/2$
 $p_t(h)>25\text{GeV}$ $p_t(\text{jet})>30\text{GeV}$

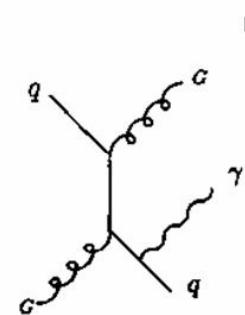
Photons: Direct and Fragmentation



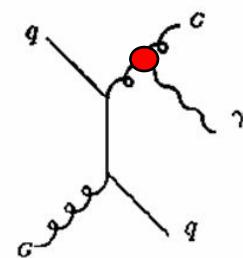
COMPTON



ANNIHILATION

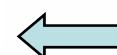


EXAMPLES OF BREMSSTRAHLUNG DIAGRAMS

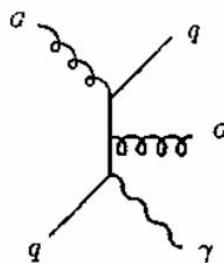


$$\mathcal{O}(\alpha\alpha_s)$$

$$\mathcal{O}(\alpha_s^2 \alpha(1/\alpha_s + g))$$



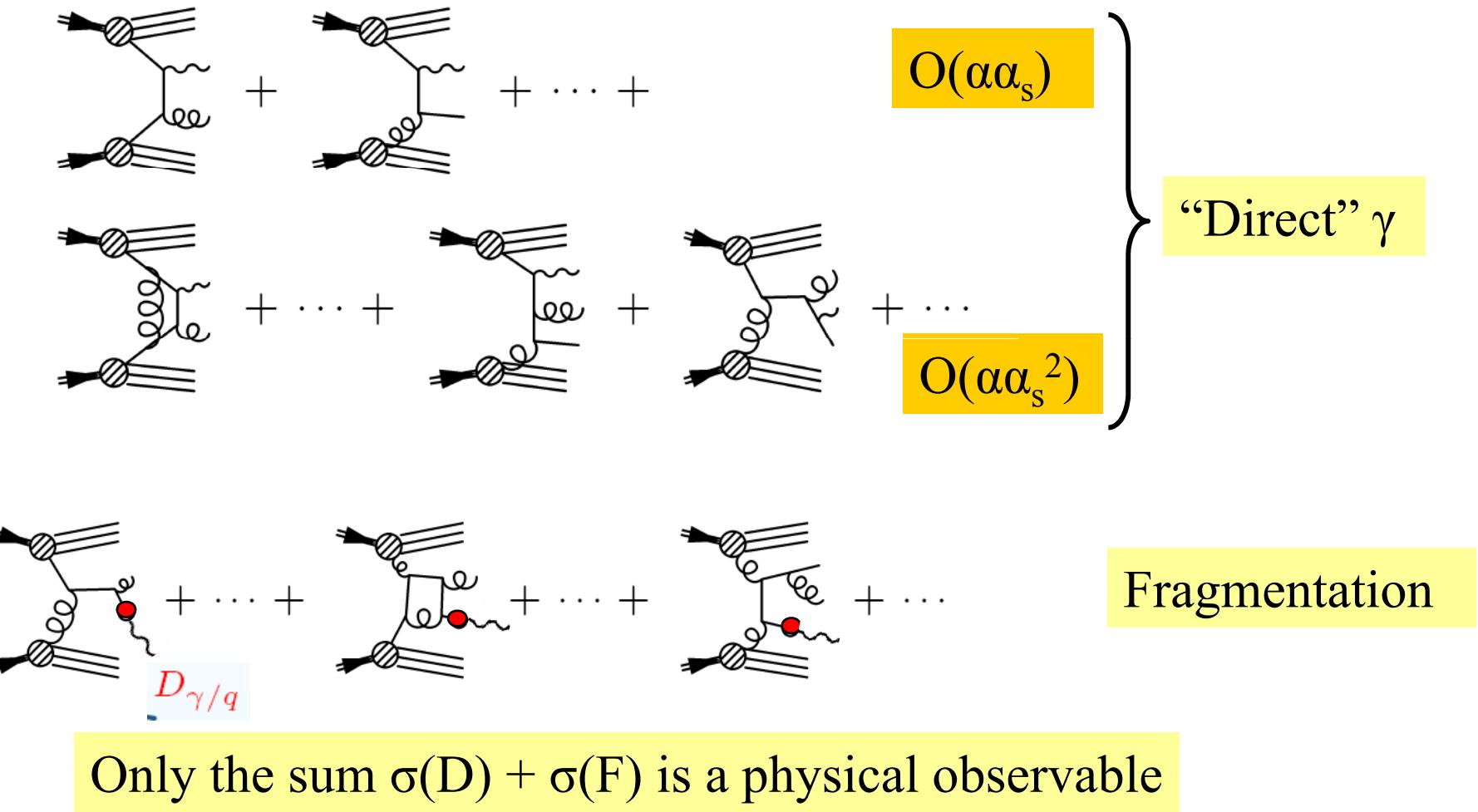
Important at high \sqrt{s} and low p_t
(NLO ACFGP NPB399,34)



EXAMPLES OF HIGHER ORDER DIAGRAMS

$$\mathcal{O}(\alpha\alpha_s^2)$$

Direct photon production



Direct photon production

NLO codes

	type of code	Direct	Fragmentation
INCNLO (*)	I/FO	NLO	NLO
Vogelsang, Gordon (*)	I/FO	NLO	NLO
Owens et al. (*)	G/FO	NLO	LO
Frixione, Vogelsang	G/FO	NLO	LO
JETPHOX (*)	G/FO	NLO	NLO

I : Inclusive
G : Generator
FO : Fixed Order

(*) http://wwwlapp.in2p3.fr/lapth/PHOX_FAMILY/main.html

Threshold resummation:(*) Catani et al.

(*) Kidonakis, Owens

Guillet, DIS04

The PHOX Family

NLO event generators (parton level)
for large p_t **PHOton** (hadron or jet) **X**-sections

http://www.lapp.in2p3.fr/lapth/PHOX_FAMILY/main.html

P.Aurenche, T.Binot, M.Fontannaz, J.Ph.GUILLET, G.Heindrich, E.Pilon, M.W.

DIPHOX:

$$\begin{aligned} h_1 h_2 &\rightarrow \gamma \gamma + X \\ h_1 h_2 &\rightarrow \gamma h_3 + X \\ h_1 h_2 &\rightarrow h_3 h_4 + X \end{aligned}$$



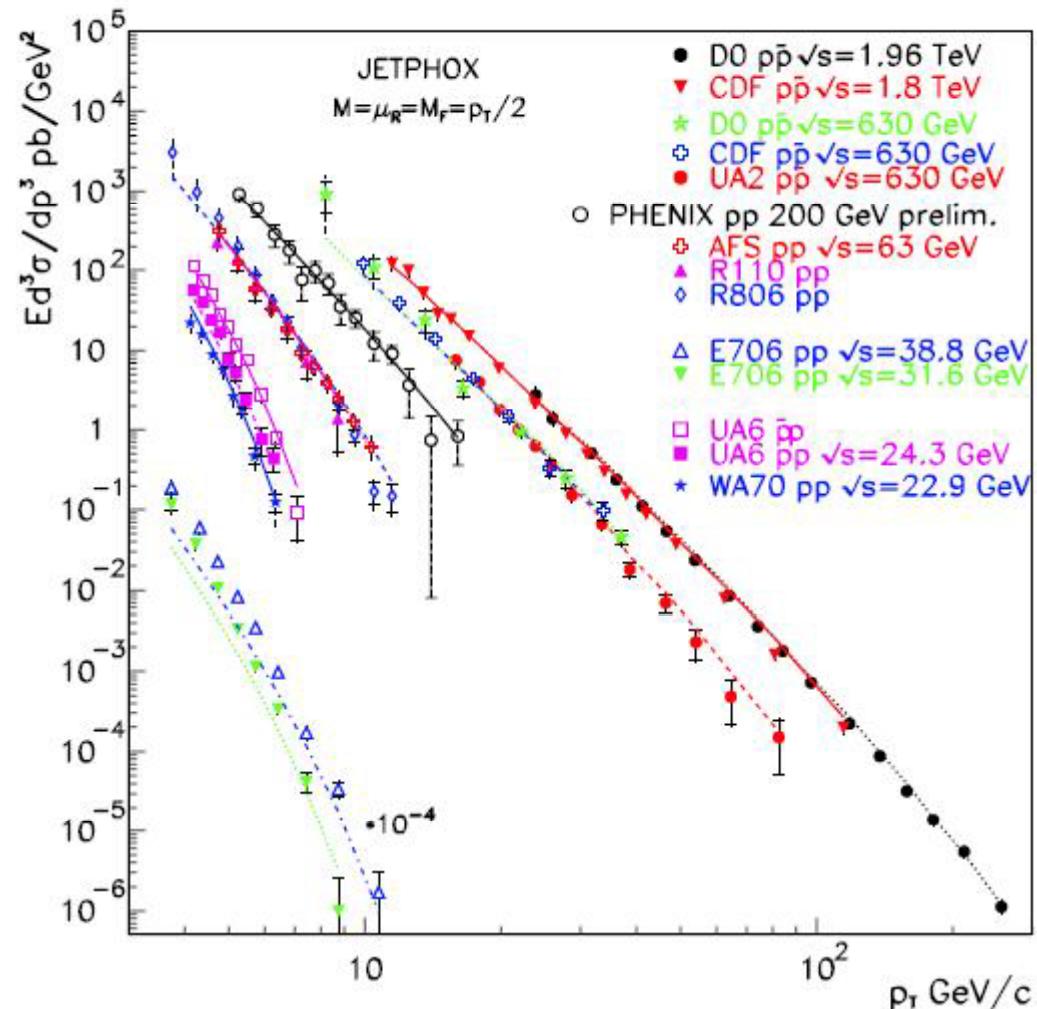
JETPHOX:

$$\begin{aligned} h_1 h_2 &\rightarrow \gamma + X \\ h_1 h_2 &\rightarrow h_3 + X \end{aligned}$$

Data vs NLO QCD

$23 \text{ GeV} \leq \sqrt{s} \leq 1.96 \text{ TeV}$

$pp, \bar{p}\bar{p} \rightarrow \gamma X$

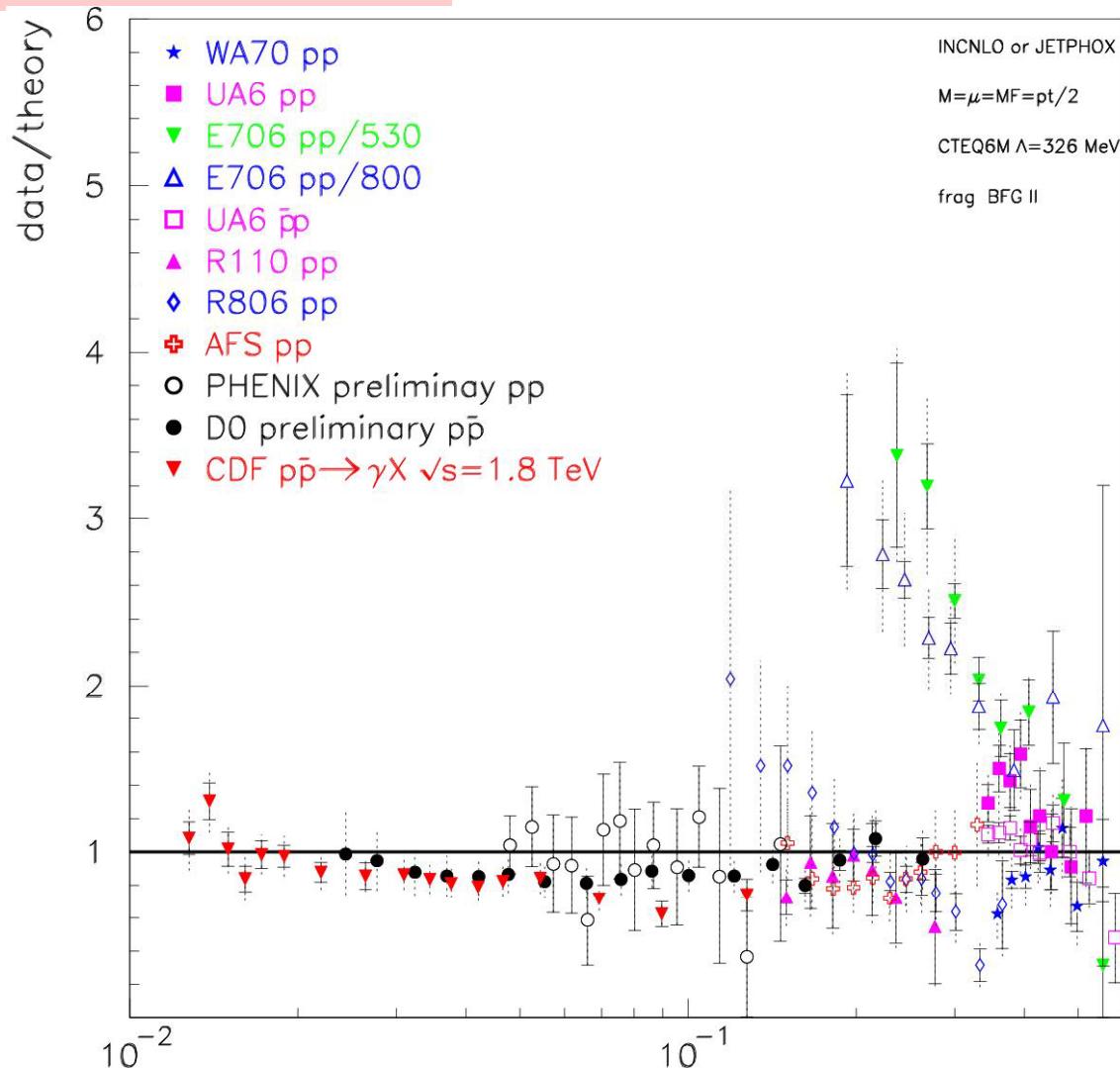


Aurenche, Fontannaz, Guillet, Pilon, M.W.
Phys. Rev. D73, 094007 (2006)

Data vs NLO QCD

$23 \text{ GeV} \leq \sqrt{s} \leq 1.96 \text{ TeV}$

$p p, \bar{p} \bar{p} \rightarrow \gamma X$

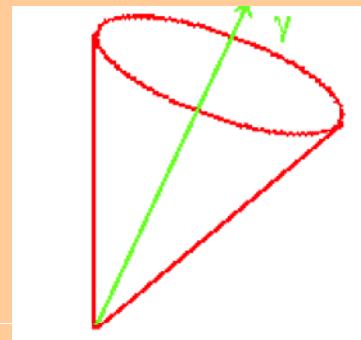


Aurenche, Fontannaz, Guillet, Pilon, M.W.
Phys. Rev. **D73**, 094007 (2006)

Phenix and D0 data clarify the data/theory puzzle

Importance of uncertainties on inclusive photon cross sections

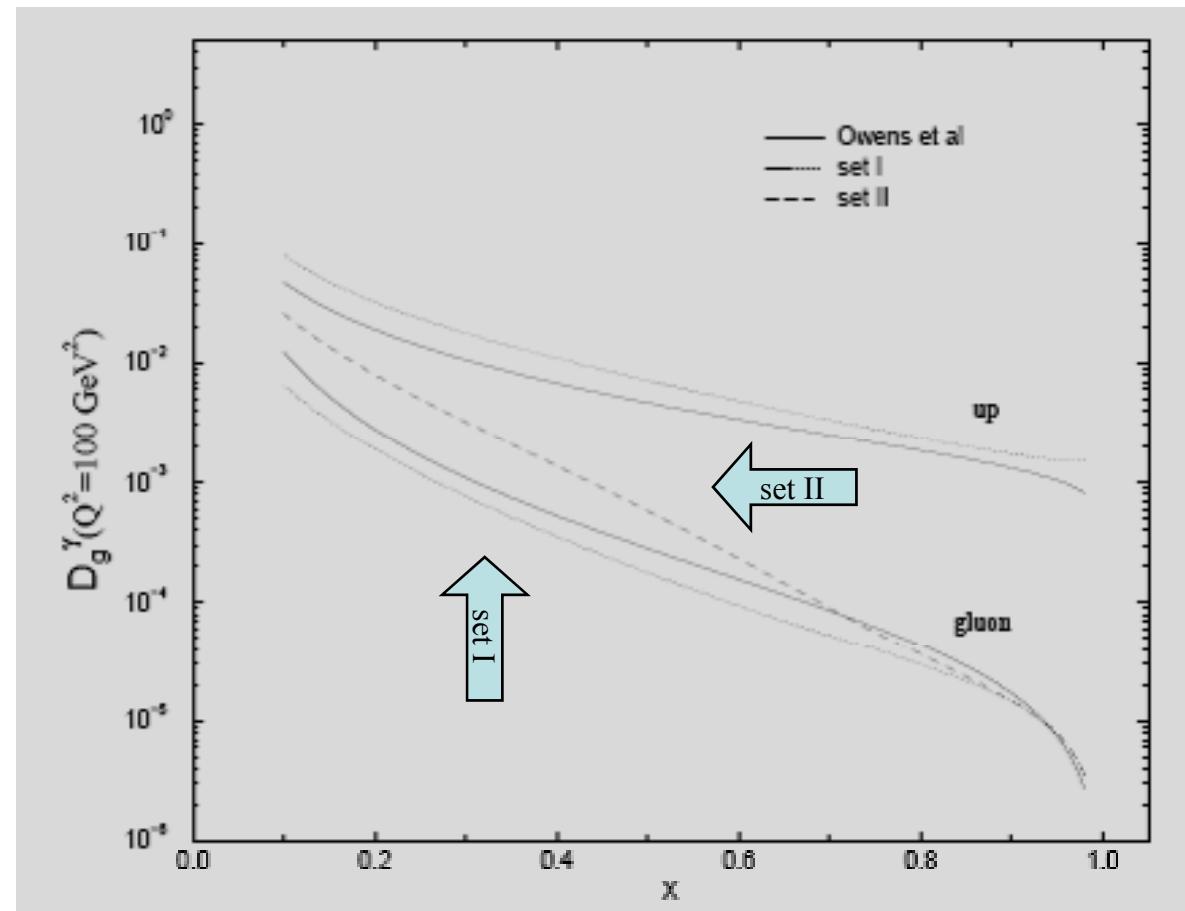
- Do we care about the uncertainty in **photon fragmentation function**?
- Most of collider data obtained with **isolation cuts**
- How does it compare to other uncertainties?



Parton to Photon fragmentation

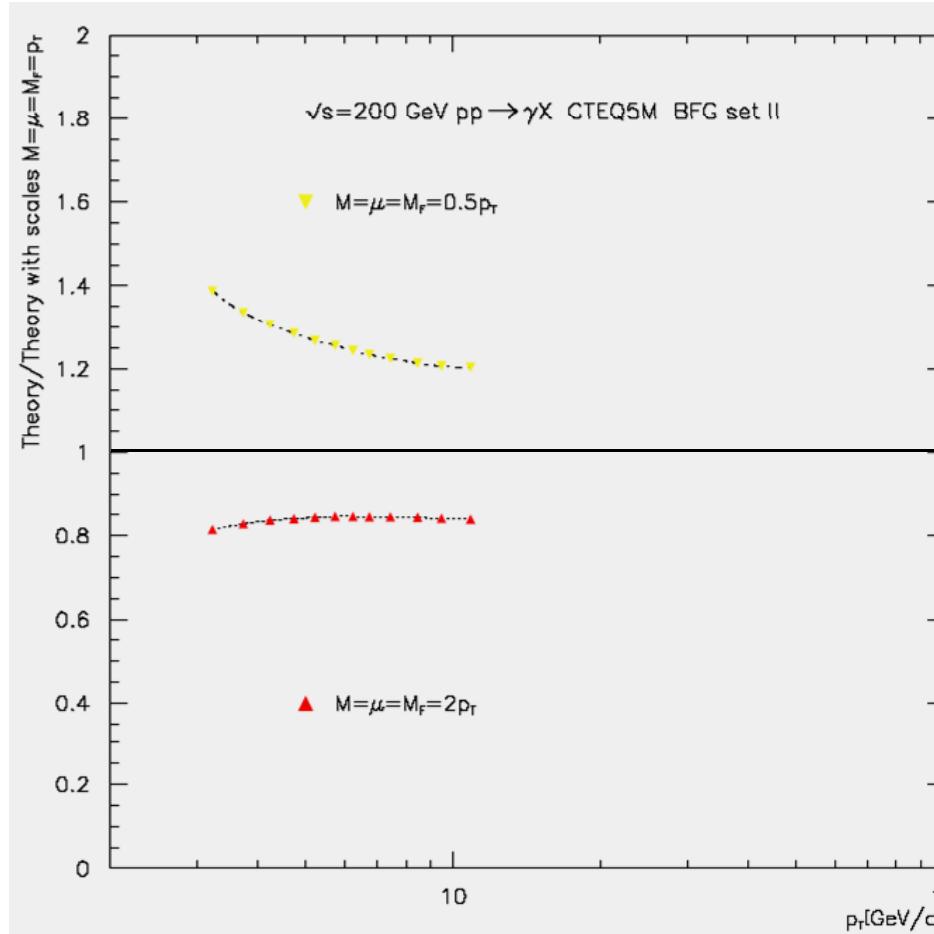
Bourhis, Fontannaz, Guillet
Eur. Phys. C2,529 (1998)

BFG set I and II
gluon fragmentation

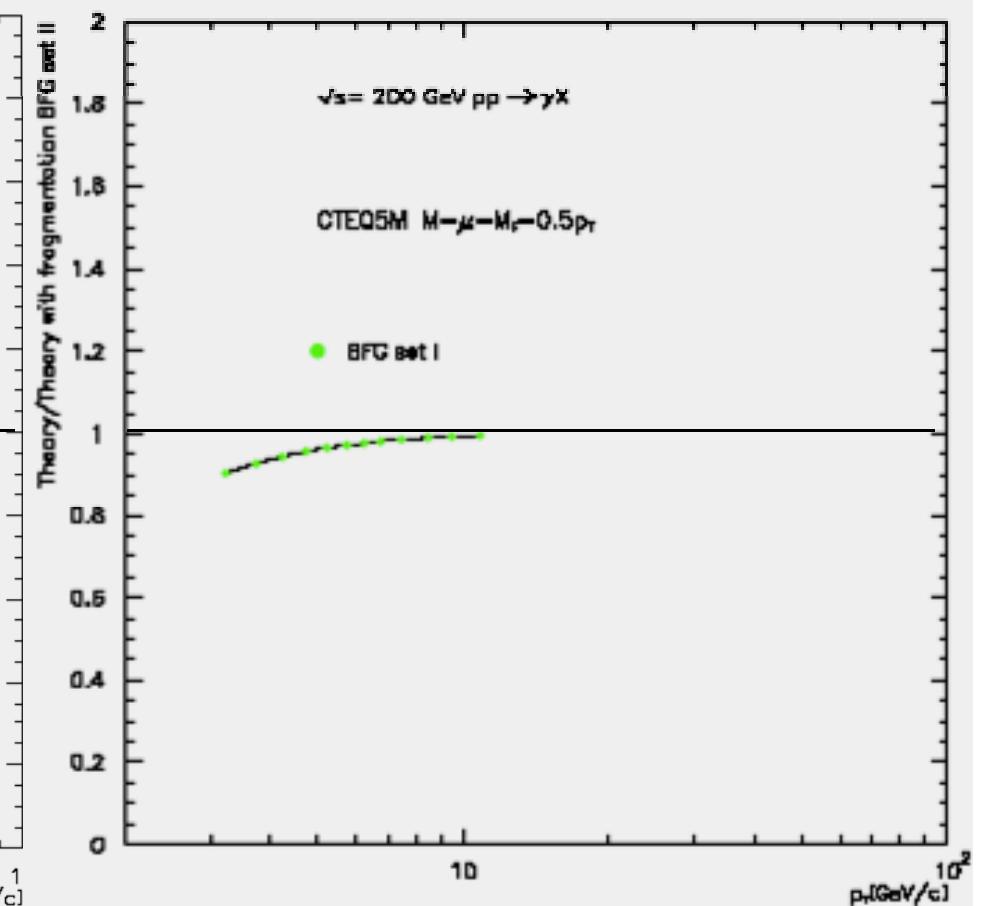


Theoretical uncertainties at RHIC energy

Scales uncertainty



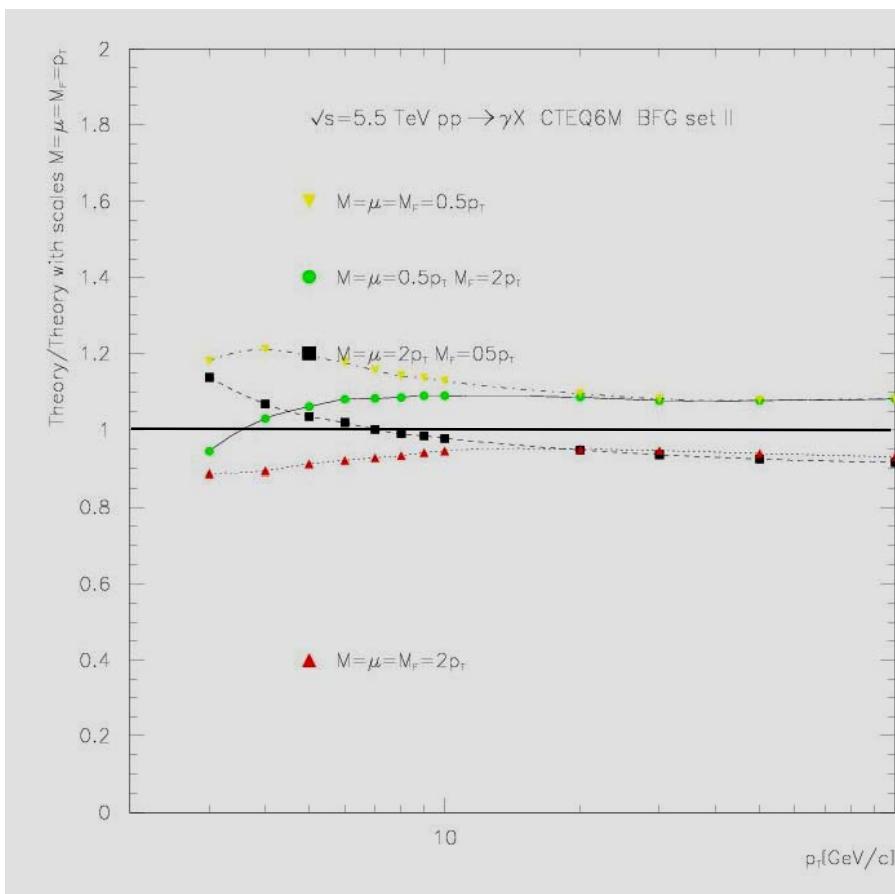
Fragmentation BFGI/BFGII



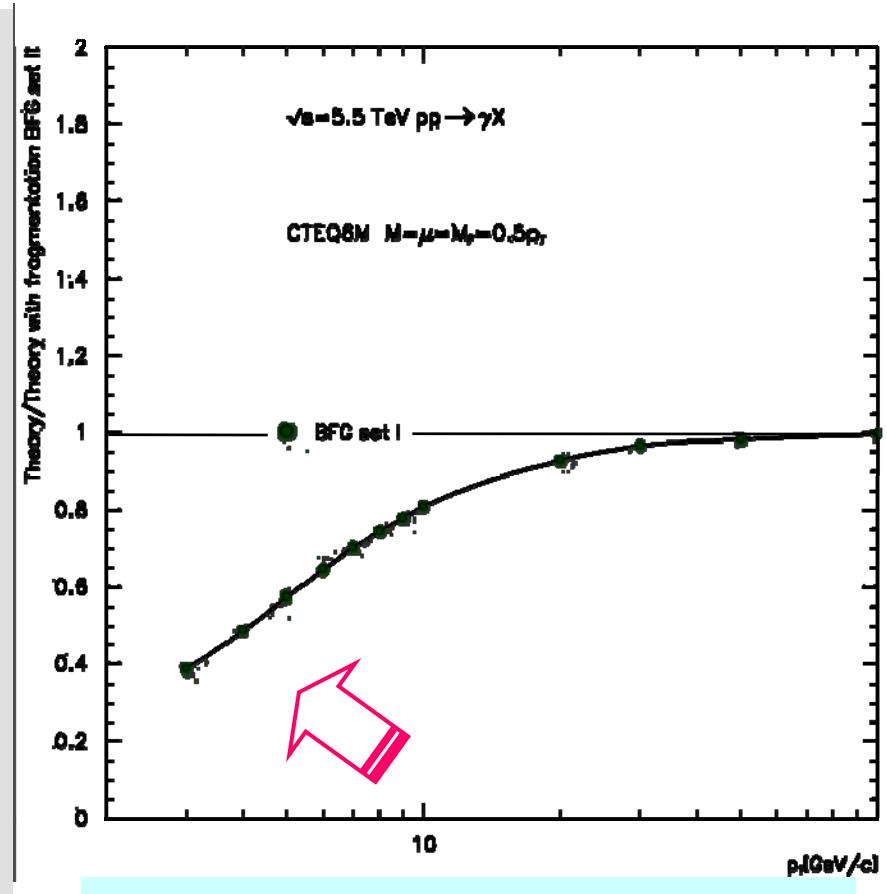
Uncertainties from scales > from fragmentation

Theoretical uncertainties at LHC energy

Scales uncertainty



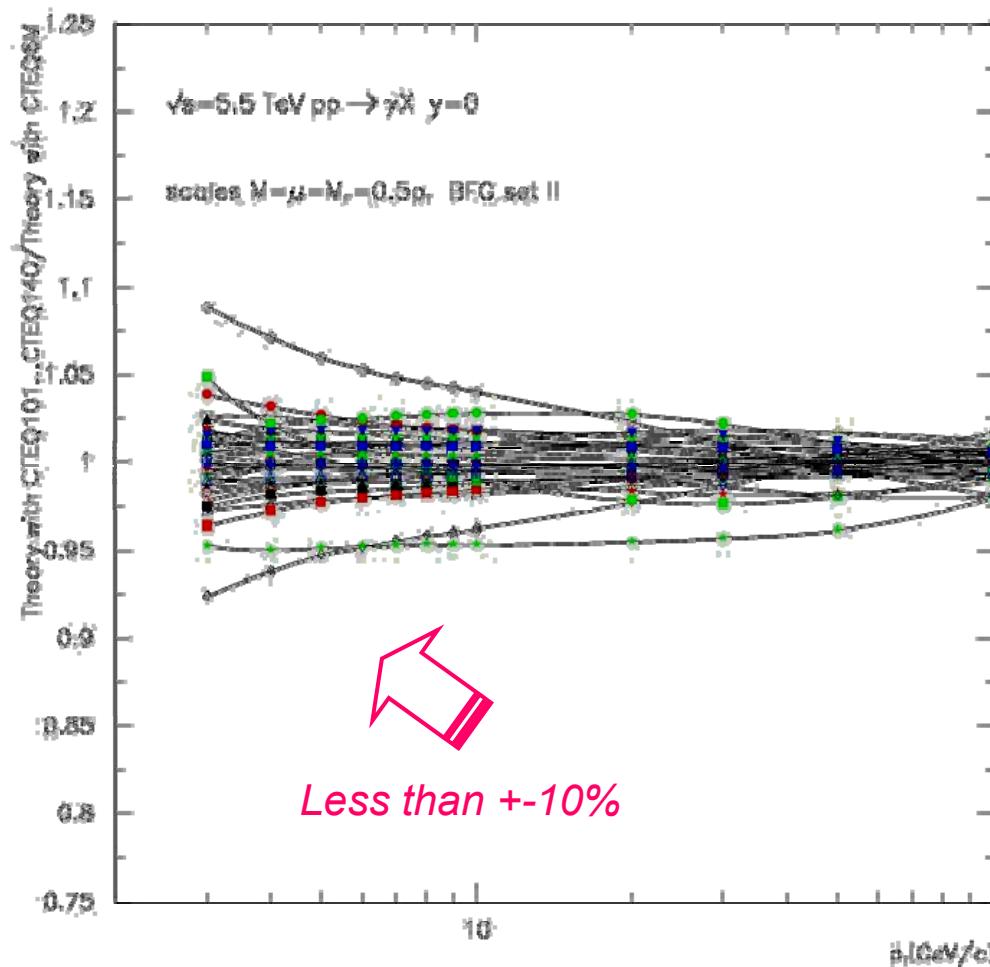
Fragmentation BFGI/BFGII



*Uncertainties from gluon fragmentation
into photon dominates at low pt*

Theoretical uncertainties from structure functions

Theory with 40 CTEQ6 sets/ theory with CTEQ6M



Importance of uncertainties on inclusive photon cross sections

- Do we care about the uncertainty in photon fragmentation function?
- How does it compare to other uncertainties?

At RHIC energy, small effect

At LHC, the gluon fragmentation uncertainty is dominant for low p_t photon production

BFG I reduces cross section by up to 2.5 at $p_t=3 \text{ GeV}/c$ compared to BFGII

Parton to Photon fragmentation

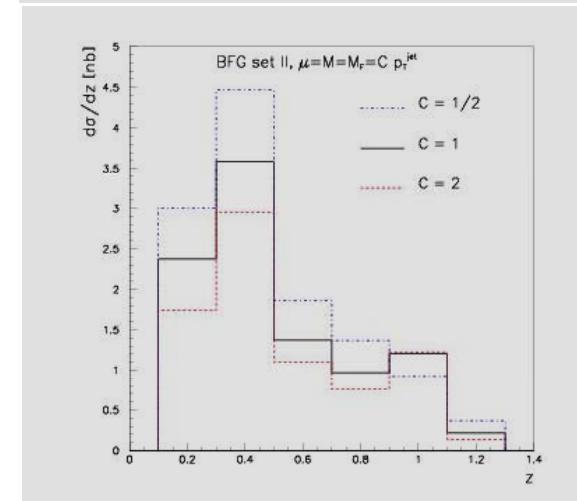
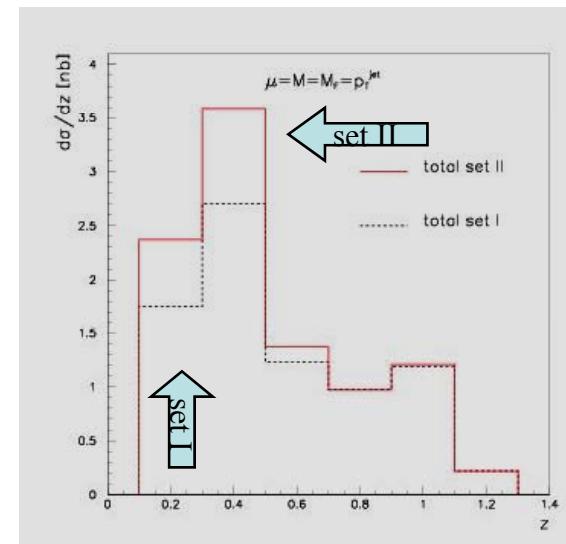
Photon+jet correlation at RHIC energy
with non isolated photon
 p_t (jet) fixed p_t (photon) 3-16 GeV/c
using JETPHOX

May discriminate BFG sets I and II at low z

see however uncertainty from fragmentation scale

Belghobsi, Fontannaz, Guillet, Heinrich, Pilon, M.W.,
preliminary

$$z_\gamma = -\frac{\vec{p}_T^\gamma \cdot \vec{p}_T^{\text{jet}}}{|\vec{p}_T^{\text{jet}}|^2}$$



Summary I

Inclusive hadron Production

- In $p\bar{p}$ collisions, **scale** and **fragmentation** uncertainties are comparable at RHIC energy.
Scales uncertainties are reduced by threshold resummation.
- The **FF sets** difference is dominated by the extrapolation to **high z** where e^+e^- statistics is poor
- The $\ln(1-z)$ **soft gluon resummation** reduces scale dependence.
- High z hadron fragmentation may be measured with **hadron-jet correlations** at RHIC energy

Summary II

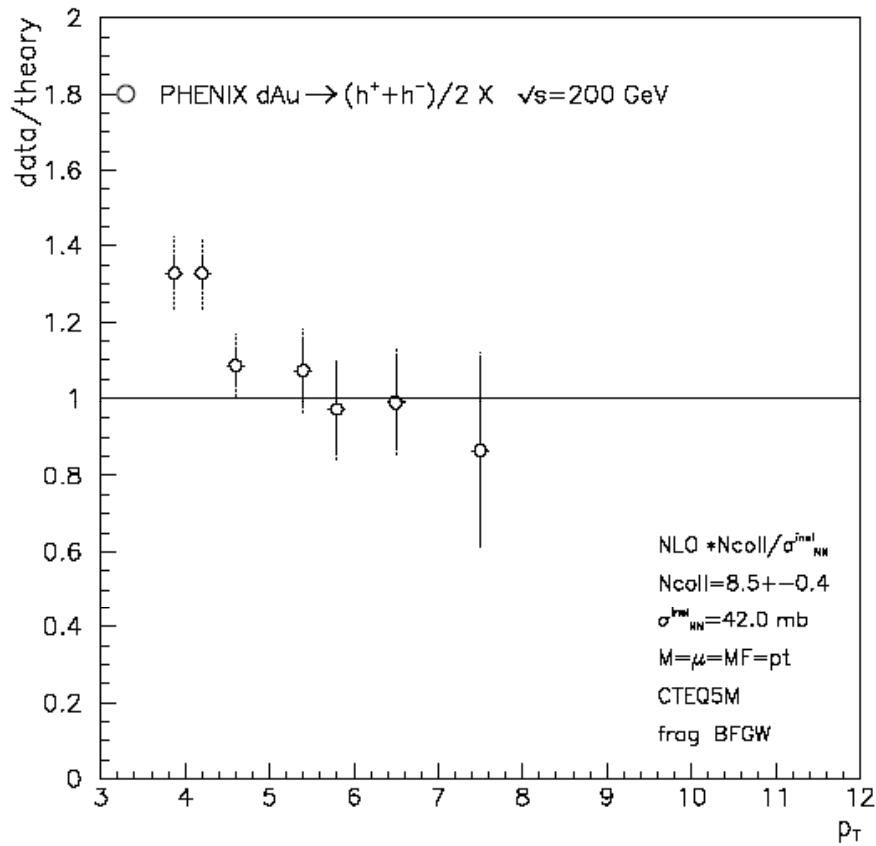
Direct photon production

- PHENIX and D0 data **favor** the NLO QCD theory
(like most of ISR and fixed target data)
- Photon fragmentation function at **low z** may be measured in photon-jet correlations at RHIC,
a region not constrained by e^+e^- data

extra slides:
Charged hadrons at RHIC energies

Fragmentation function BFGW

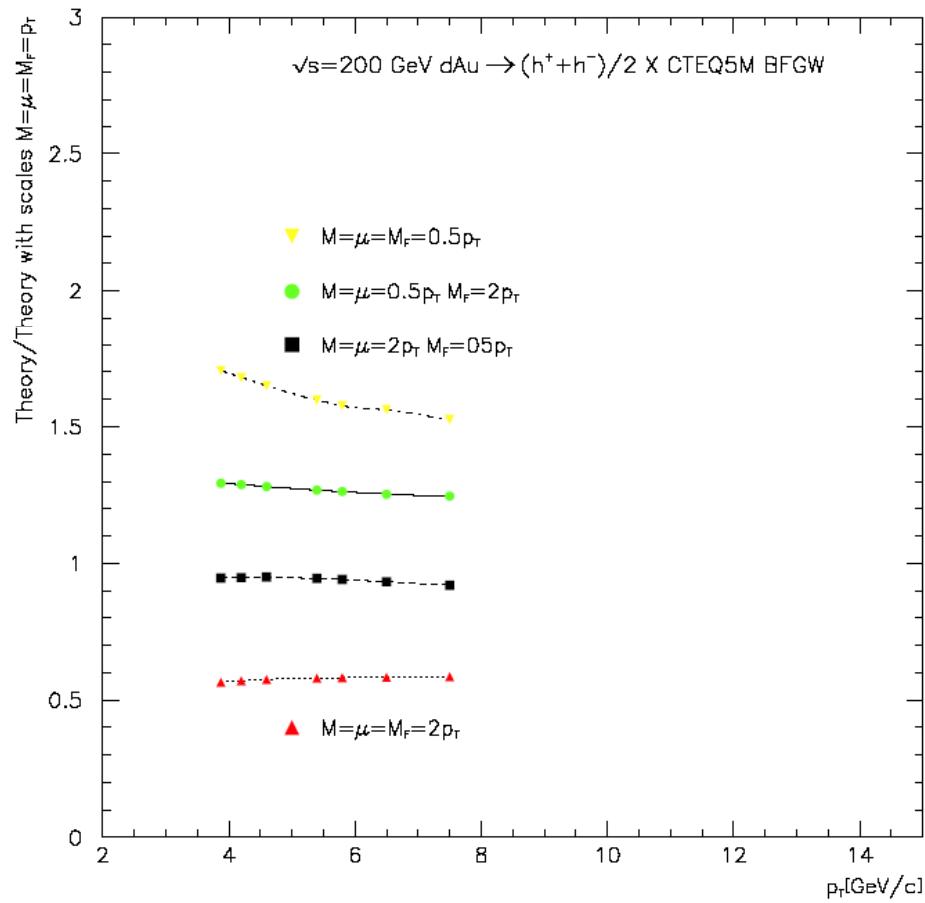
Eur. Phys. J. C 19, 89–98 (2001)



PHENIX:PRL 91,072303

60

Typical scales uncertainties in charged hadron production



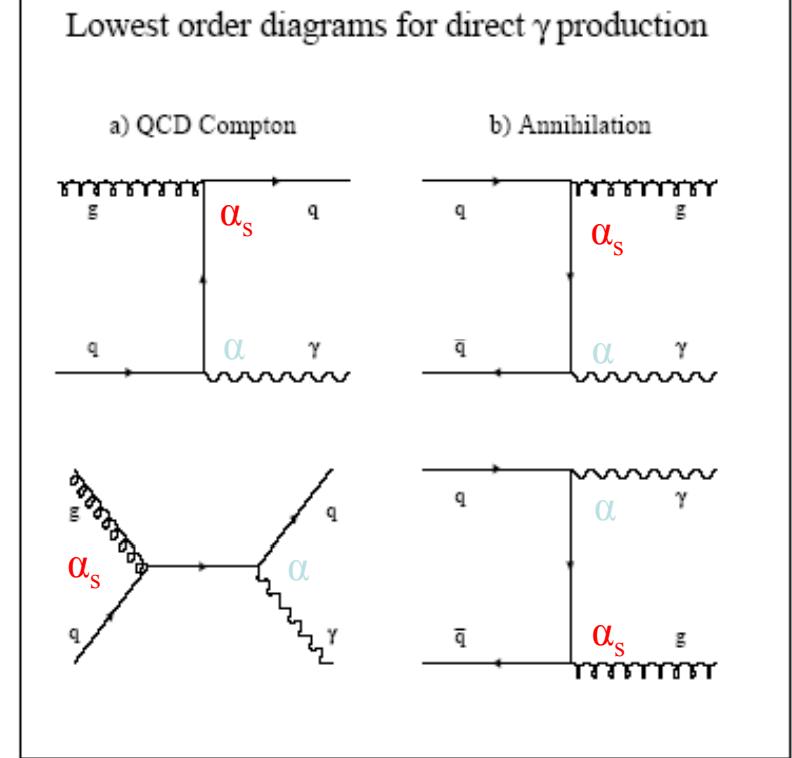
Extra slide on photon production

Why are direct photons interesting?

- Photons produced in the partonic interaction probe QCD dynamic without hadronic complications
- γ – quark: coupling precisely known (QED)

Two processes at lowest order:

- QCD Compton : sensitive to gluon distribution in the hadron and tag for quark fragmentation
- Annihilation: sensitive to the QCD running coupling constant α_s and tag for gluon fragmentation



World Data vs NLO QCD

INCNLO

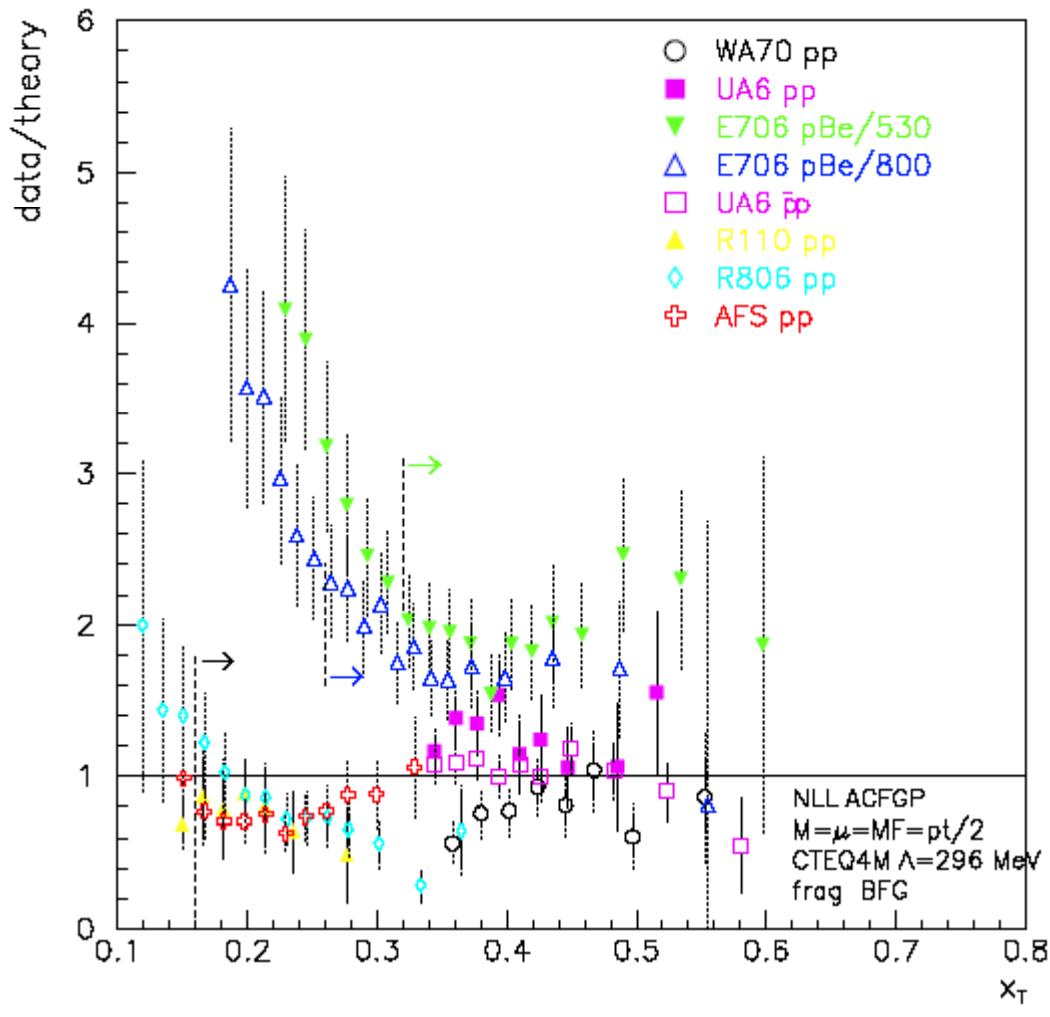
$pp, \bar{p}p \rightarrow \gamma X$

$23 \text{ GeV} \leq \sqrt{s} \leq 63 \text{ GeV}$

Aurenche, Fontannaz, Guillet, Kniehl,
Pilon, M.W. Eur. Phys. JC9, 107 (1999)

Possible experimental problems?

Or theory misses the \sqrt{s} dependence?

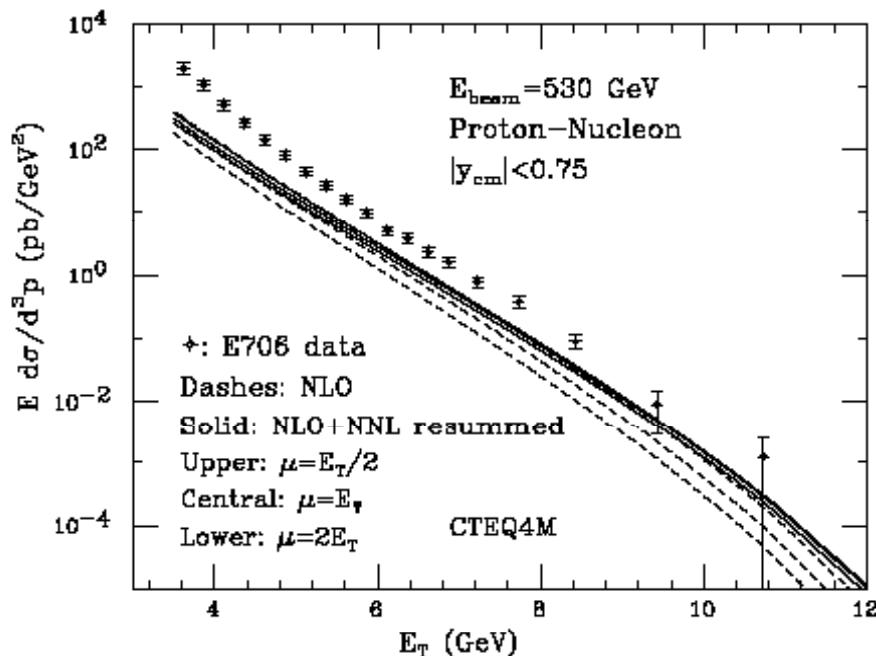


Soft gluons resummation and E706

(hep-ph/9903436)

Catani, Mangano, Nason, Oleari, Vogelsang

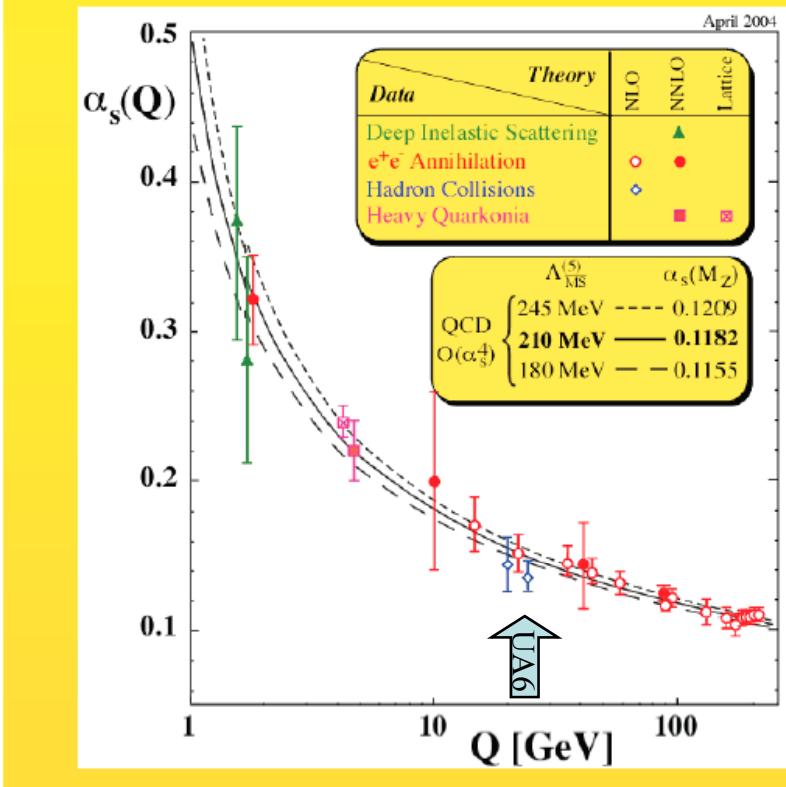
Additional contributions
to solve the Pb? NNL_{res}



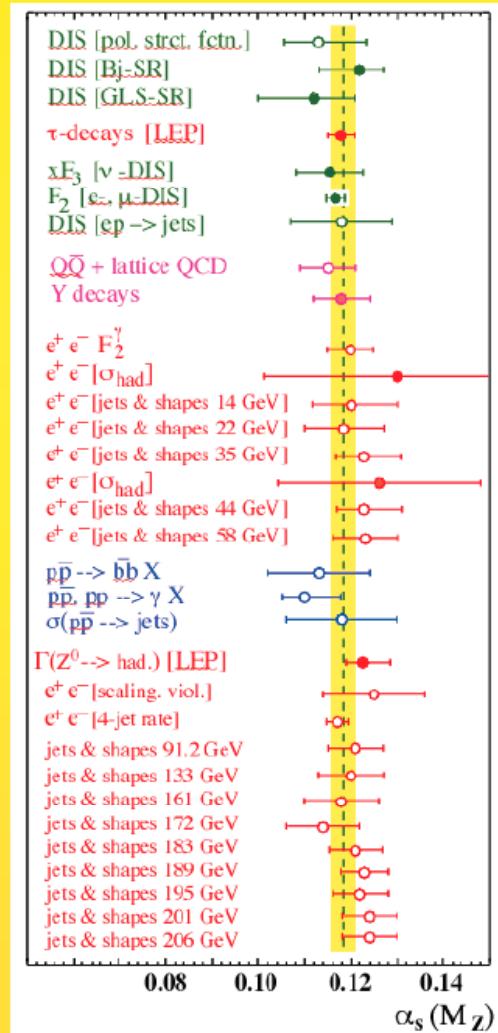
- Takes into account soft gluons at large x_T
- Reduces scale dependence
- Small corrections for scales set to $p_T/2$

Main corrections at large x_T (decreasing with scale)
does not help data/theory at small x_T
i.e. does not solve the " k_T problem"

**THE DISCOVERY, EXPLORATION,
VERIFICATION AND UNDERSTANDING
OF QCD IS DUE TO THE REMARKABLE
WORK OF MANY EXPERIMENTERS
AND THEORISTS OVER 40 YEARS !**

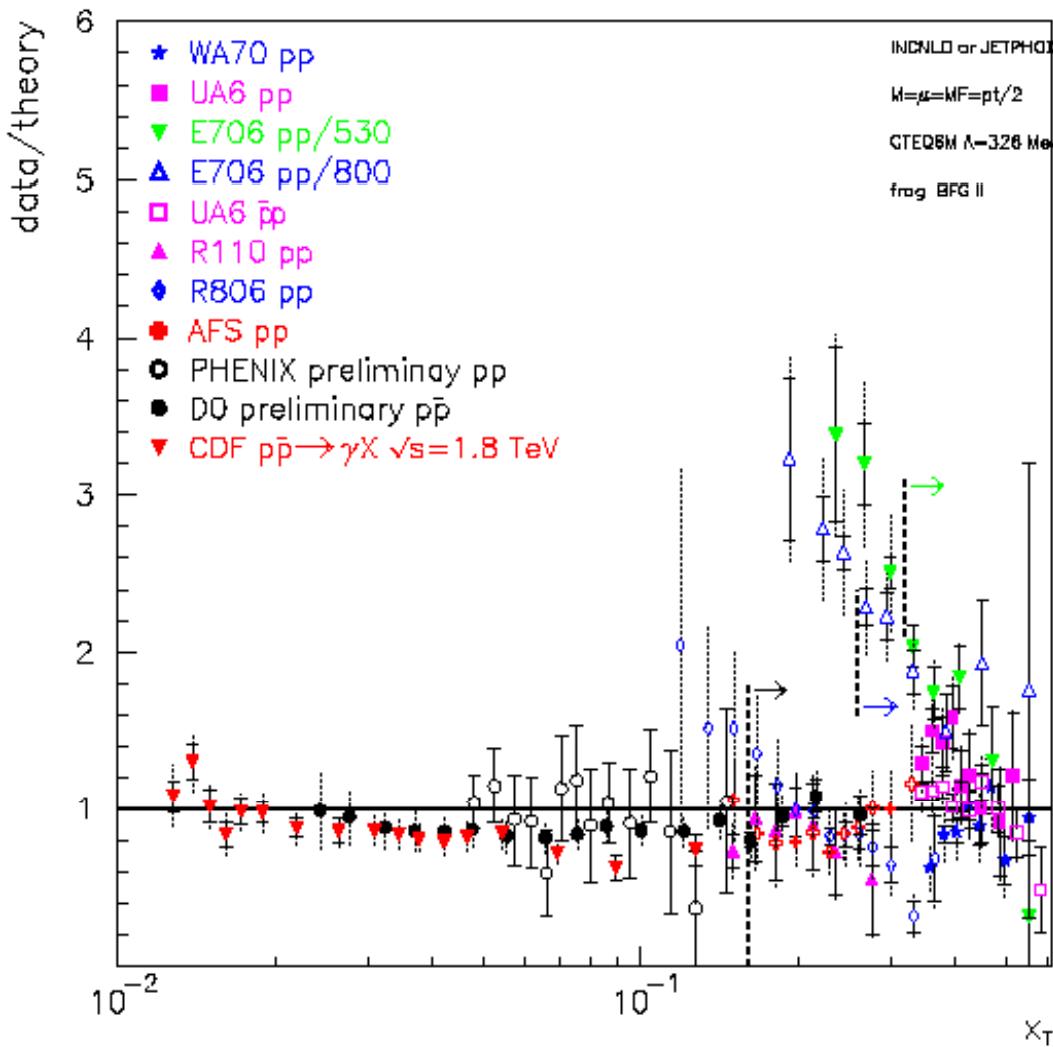


World summary of $\alpha_s(M_Z)$



Data vs NLO QCD

INCNLO or JETPHOX



$$pp, \bar{p}p \rightarrow \gamma X$$

$$23 \text{ GeV} \leq \sqrt{s} \leq 1.96 \text{ TeV}$$

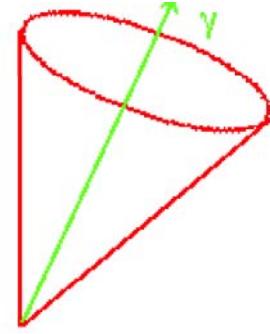
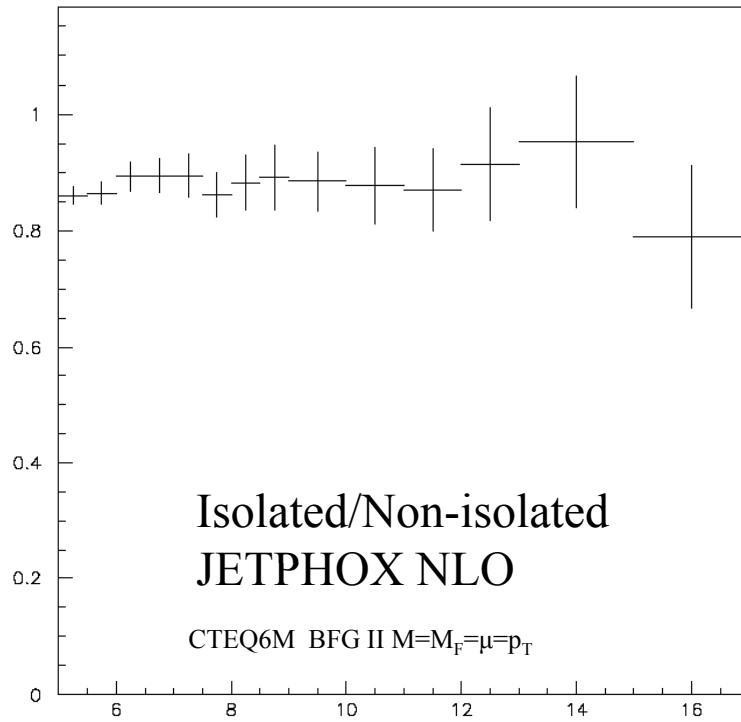
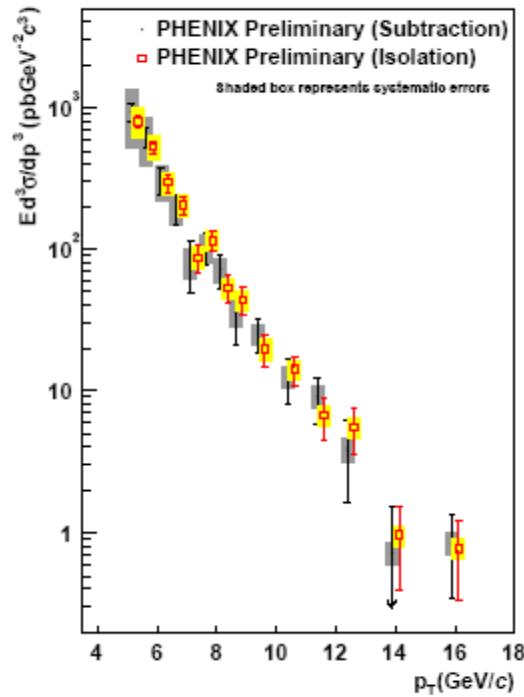
Aurenche, Fontannaz, Guillet, Pilon,
M.W. Phys. Rev. [D73](#), 094007 (2006)

Possible experimental problems?
Or theory misses the \sqrt{s} dependence?

Phenix and D0 data clarify
the data/theory puzzle

Arrows: perturbative predictions "STABLES" vs scale

Photon Isolation



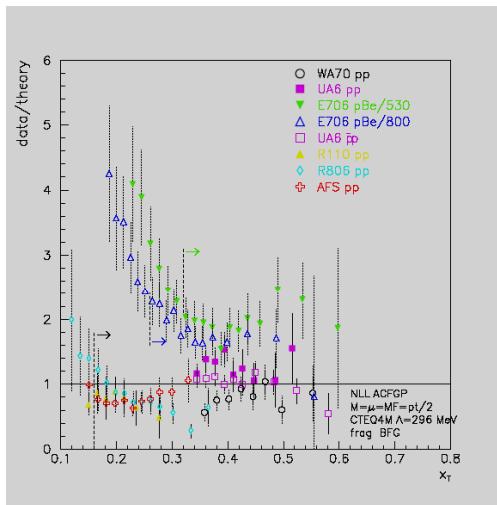
in a cone around photon with:

$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$$

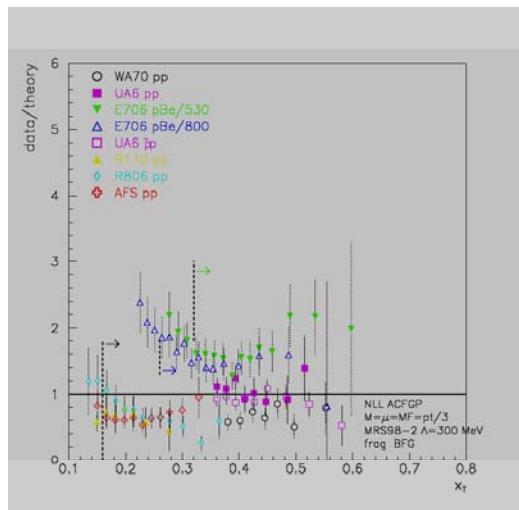
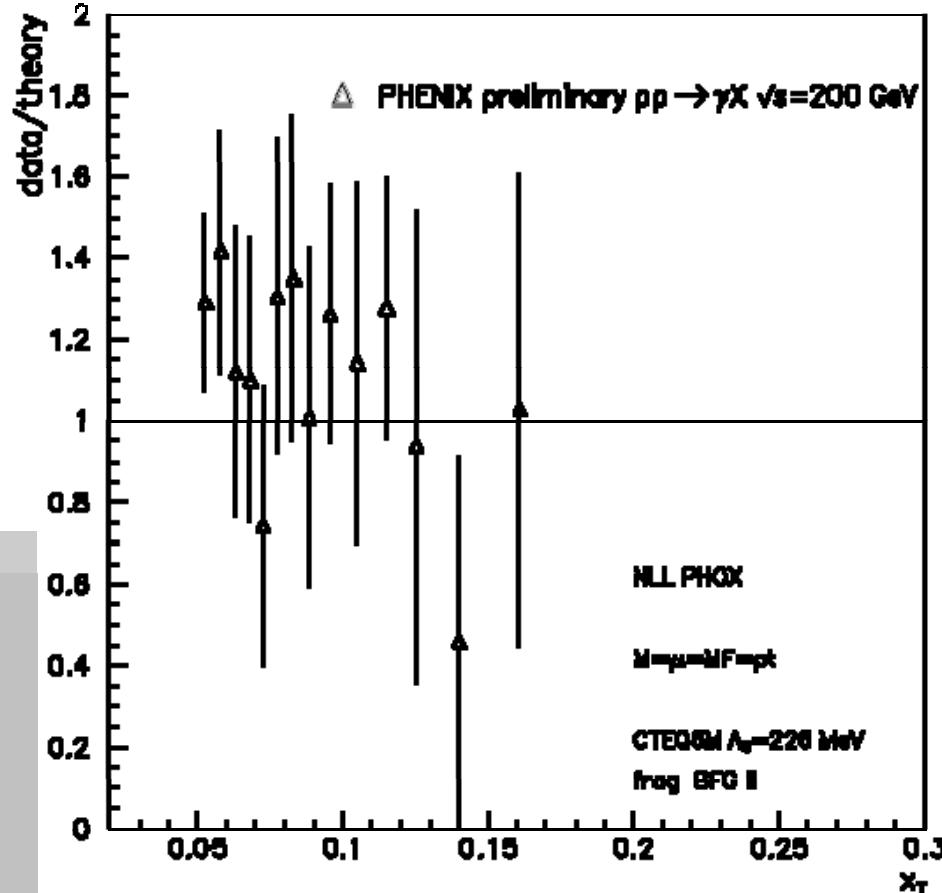
E_T (parton) $\leq E_T$ max $= 0.1E_\gamma$

Isolated vs non-isolated: not much difference in data and in theory

CTEQ4M



MRS-98-2



Monique Werlen, Feb.25,2008

Parton fragmentation workshop, ECT

