Multi-jet topologies and multi-scale QCD

Experimental Introduction with emphasis on HERA

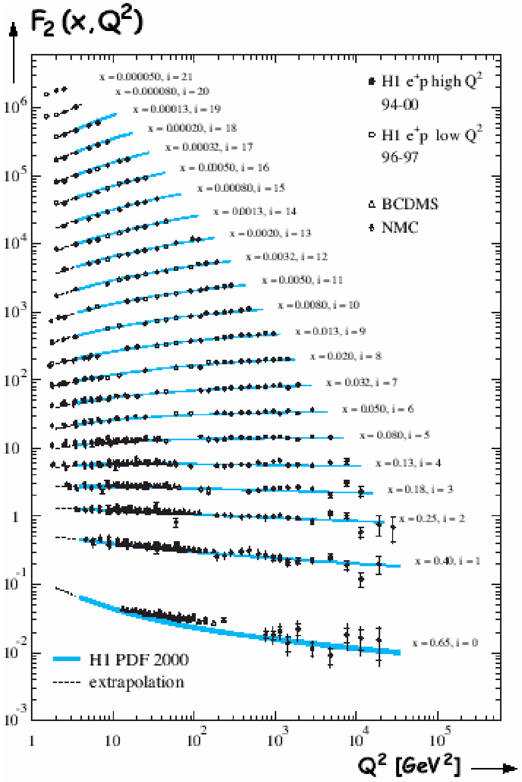
Goal: search for limits of applicability of the DGLAP approximation, find best method to describe the data beyond that limit

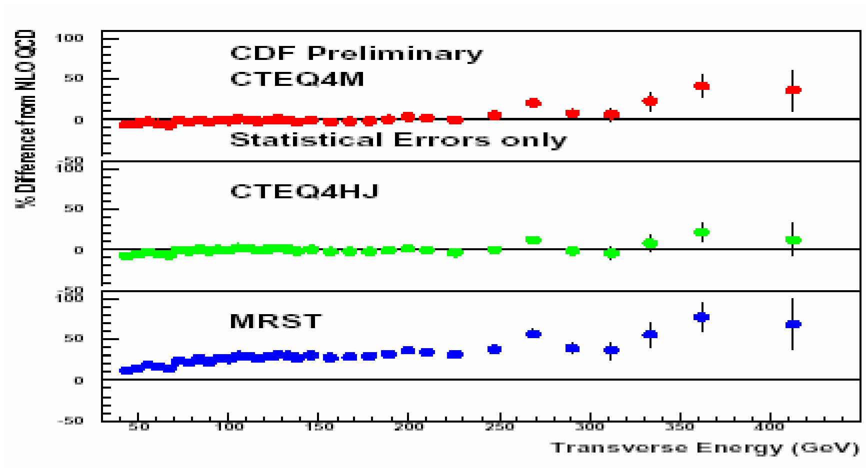
- Single- and multi-scale QCD processes
- QCD NLO calculations and event generators
- Where NLO DGLAP works: dijets nad 3-jets at high Q^2
- Where NLO DGLAP almost works :inclusive jets $Q^2 < 100$
- Closer look: azimutal correlations betweent jets
- Forward jets and particles
- Conclusions

Small x Phenomenenology: Summary and Status hep-ph/0312333 (→EPJC)

Typical single-scale processes

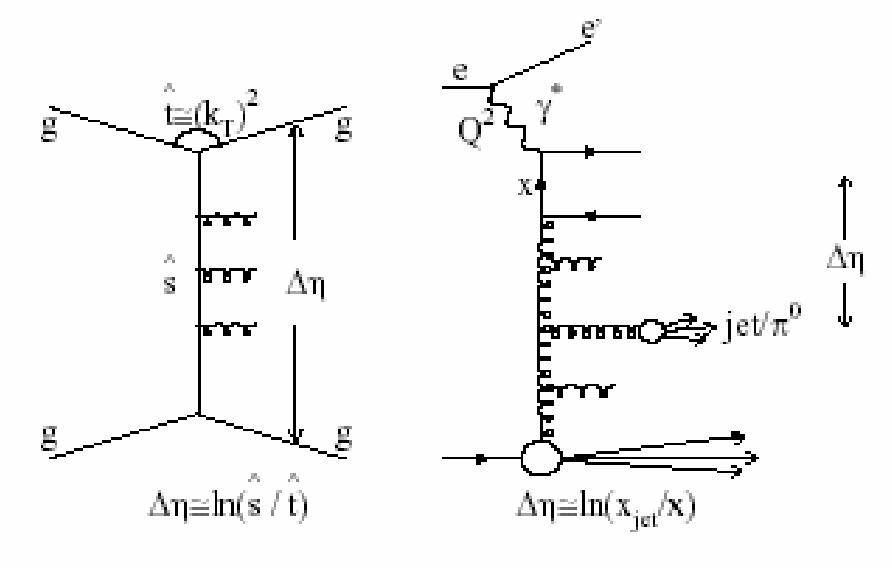
DGLAP approximation is extremly succesfull in describing inclusive processes characterized by single scale e.g. $F_2(x,Q^2)$, inclusive high E_T dijets Tevatron





Typical multiscale processes

When we go from inclusive to exclusive measurements in which second disparate scale is introduced, quality of DGLAP description deteriorates, depending on extent of „exclusivity". Disparate kinematical scales introduce large logarithms not included in DGLAP calculation



Large rapidity interval dijets at Tevatron

$$\bar{s} >> \bar{t}$$

Forward jets at HERA

$$x_{jet} >> x$$

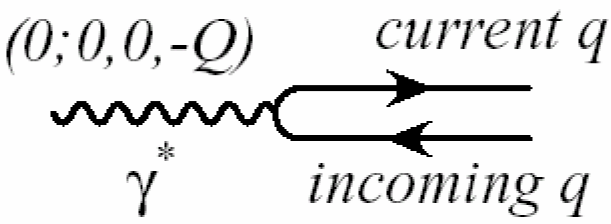
Typical multi-scale processes

- Dijet production at large values of E_T^2/Q^2
- Dijet production at large rapidity intervals $\bar{s} >> \bar{t}$
- Forward jet production in DIS $x_{jet} >> x$
- Charm & beauty production in DIS
- Large p_t particle production in DIS

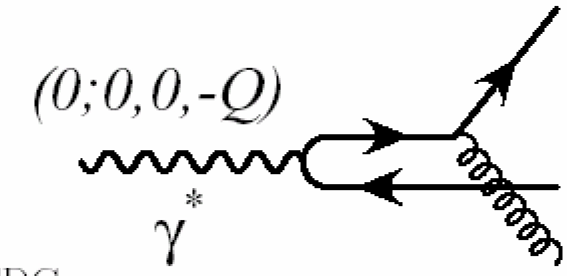
Multi -scale processes in DIS

	collinear factorization				$k_\perp$–factorization
	direct		resolved		
	LO+PS	higher order NLO (dijet)	LO+PS	higher order NLO (dijet)	LO+PS
HERA observables					
DIS D* production		ok [122,123]	?	?	ok [123,124]
photoprod. of D*	ok	ok [125,126]	ok [125]	no [125]	ok [6,127–129,124]
DIS B production (visible)	ok [130]	ok [130]	—	—	ok [130]
DIS B production (total)	no [131]	ok [131]	—	—	no [131]
photoprod. of B (visible)	ok [132,133]	?			ok [134,135]
photoprod. of B (total)	no [136,133]	no [136,133,126]	?	?	ok [134,135]
high Q^2 di-jets	?	ok [137,138]	?	?	?
low Q^2 di-jets (cross sec.)	?	ok [139]	?	no [137,138,140]	?
low Q^2 di-jets (azim.corr.)	no [139]	no [139] NLO 3-jet no [139]	ok [139]	?	ok [139]
photoprod. of di-jets	?	ok [141]	?	no [140,142] ok [141]	?
particle spectra	no [143,144]	—	ok [145]	—	ok [6]
energy flow	no [143,146,147]	—	ok [147,145]	—	?
HERA small-x observables					
DIS forward jet production	no [148–152]	no [151–153]	ok [149–152,154]	ok [152,153]	ok [6]
DIS forward π production	no [155,156]	?	ok [155,156]	?	1/2 [156]
DIS J/ψ prod.	?		?	?	ok [157,118]
photoprod. of J/ψ	no [158]	ok [159]		ok [160]	ok [161,162,118]
J/ψ polarization				low stat. [160]	low stat. [163,118]
Tevatron observables	direct		heavy quark excitation		
D meson prod.			no	?	ok [164,165]
J/ψ prod.	ok [100,102,103,166,167]				ok [113,114,168]
χ_c prod.	ok [102,103]				ok [116,168]
J/ψ polarization	low stat.[169]	no	no	no	ok [114,168]
high-$p_\perp$ B prod.	no [170]	ok [171]	ok [170]	?	ok [135,164,172–174]
$b\bar{b}$ (azim.corr.)		ok [171]			ok [174]
Υ prod.	ok [102,103]				ok [168]
high-$p_\perp$ jets at large $\Delta\eta^*$	no	?		?	?

Jet production in the Breit frame



Born



QCDC

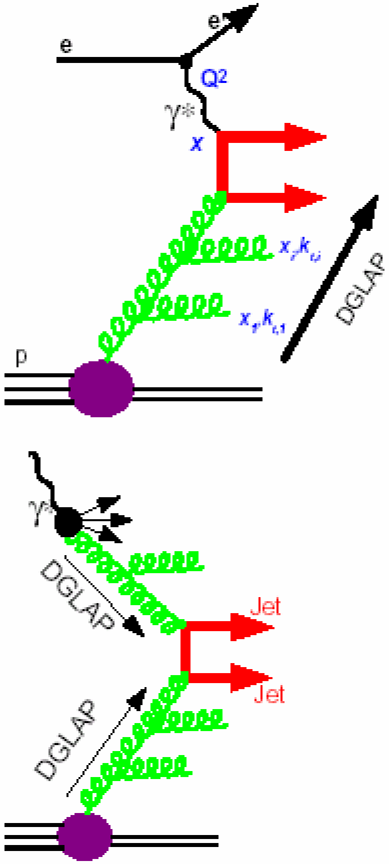
- Breit frame ➡ purely space-like photon.
- Inclusive jet production in LAB frame $\mathcal{O}(\alpha\alpha_s^0)$ at lowest order.
- Jets with high E_T in the Breit frame
  - ▷ Suppresses Born contribution (in Breit frame current quark has no E_T).
  - ▷ Lowest order contributions from $\gamma^* g \rightarrow q\bar{q}$ and $\gamma^* q \rightarrow qg$.

➡ Directly sensitive to QCD subprocess at $\mathcal{O}(\alpha\alpha_s)$ and higher oders.

Monte Carlo Models and QCD Calculations

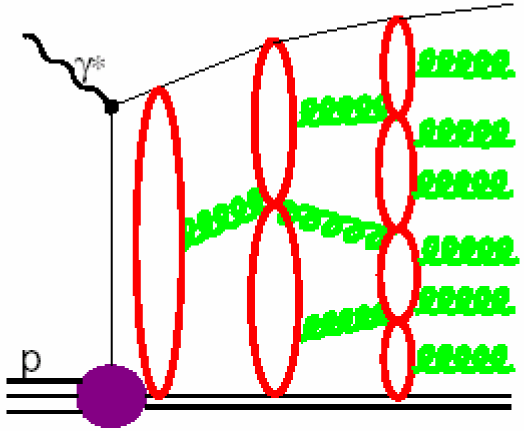
DGLAP Type

DISENT, RAPGAP



'BFKL'-Type

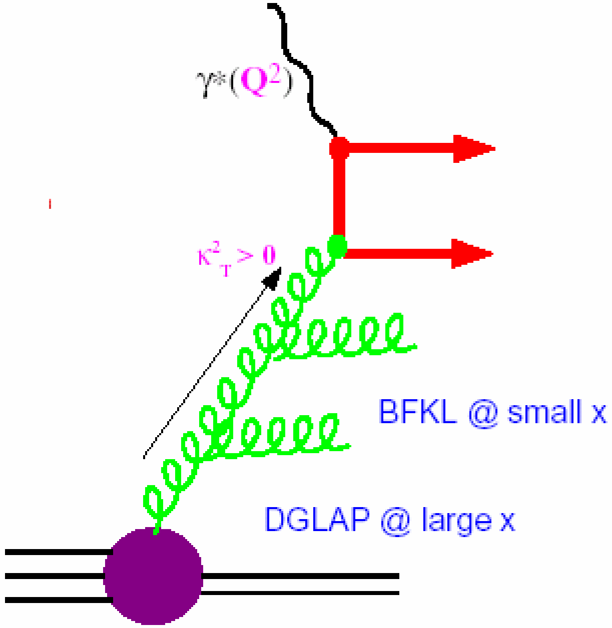
ARIADNE



Colour Dipole Model
Emission from independent dipoles produces
no k_t-ordering

CCFM

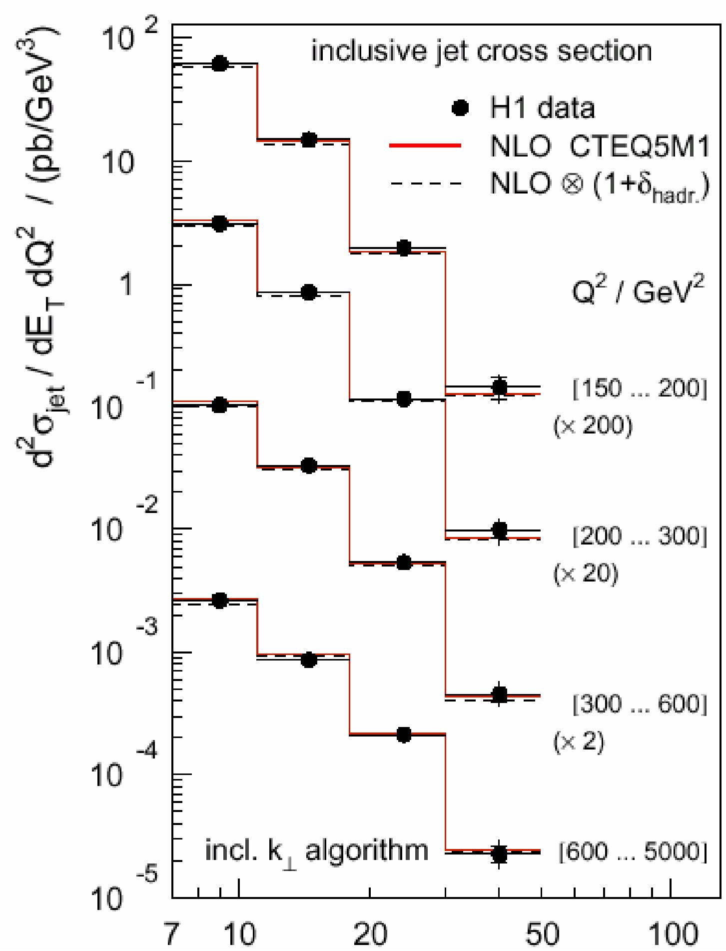
CASCADE

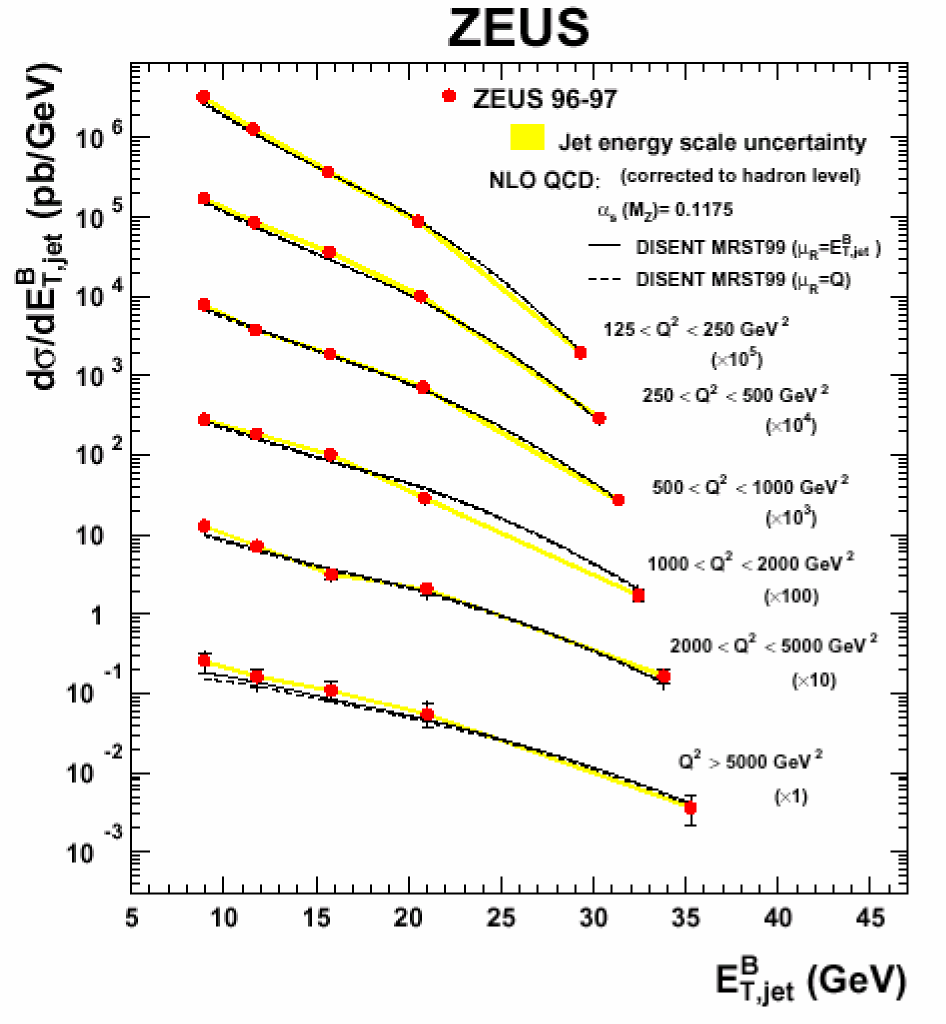


'k_t-factorisation'

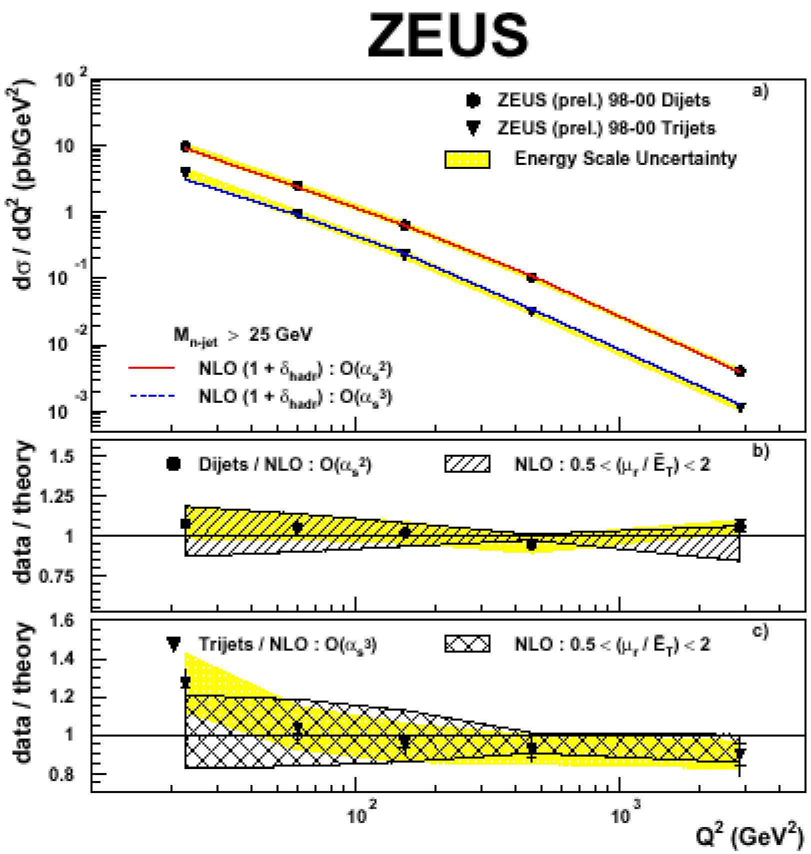
Where DGLAP works

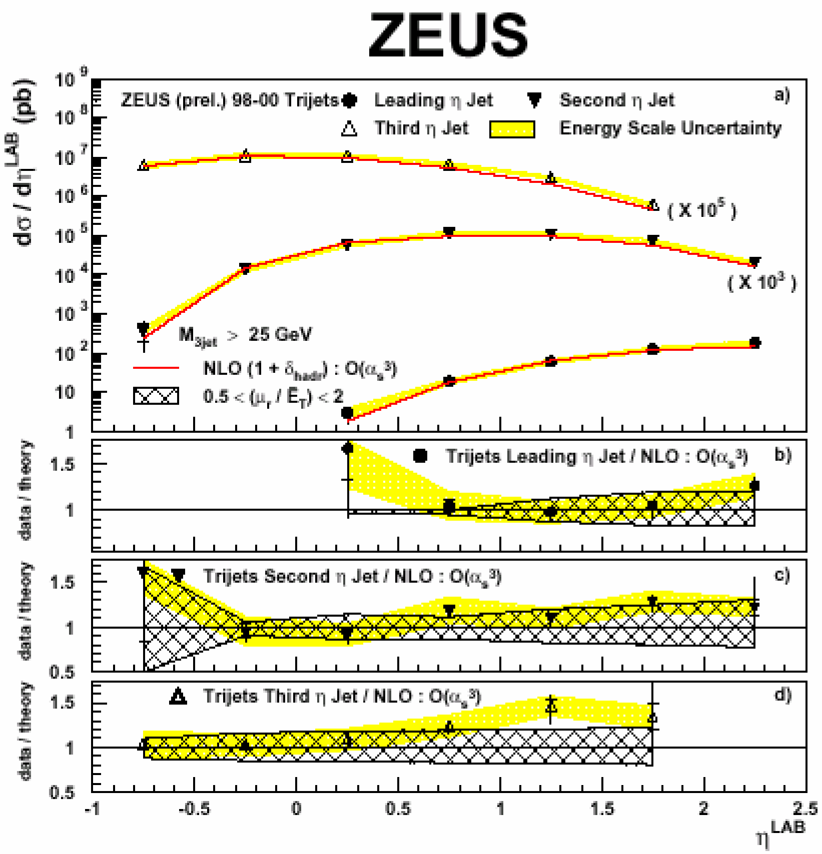
Single (Breit frame) inclusive jets at high Q^2





Multi-jets in DIS



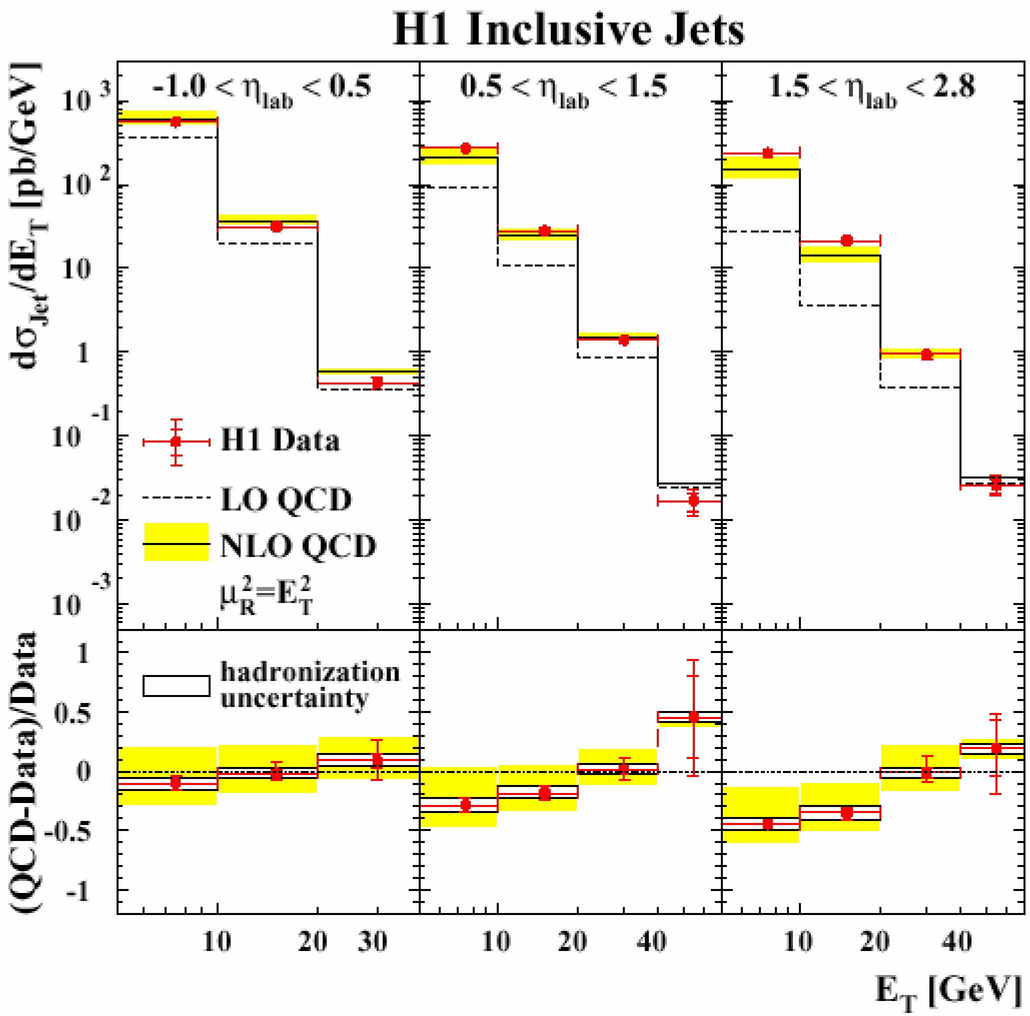


- Two and three-jet production in Breit frame,

$$10 < Q^2 < 5000 \text{ GeV}^2, \quad E_T^{\text{Breit}} > 5 \text{ GeV}, \quad -1 < \eta^{\text{LAB}} < 2.5, \quad M_{\text{jets}} > 25 \text{ GeV}$$

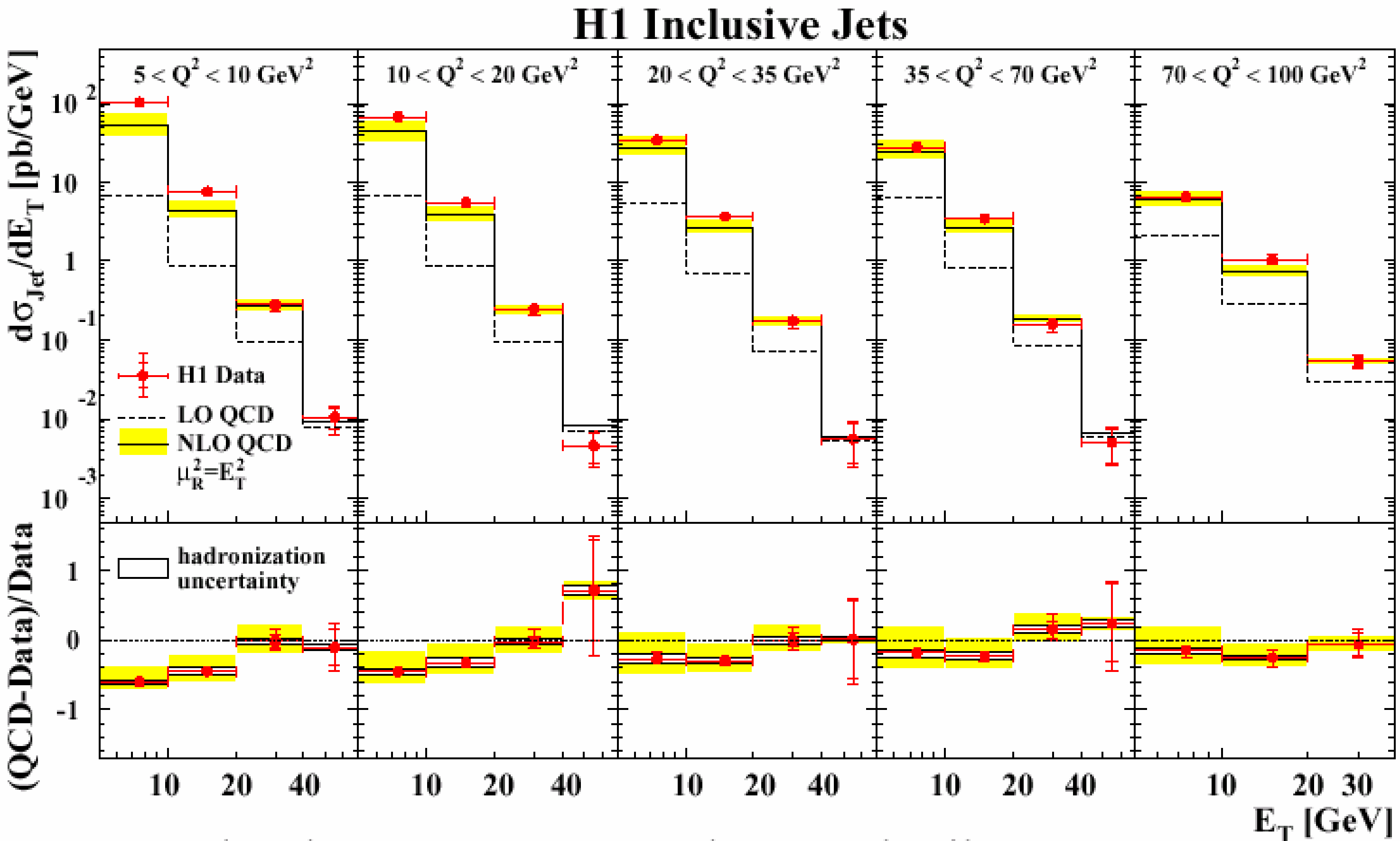
- Dynamics well described.

Where DGLAP (almost) works



- Low Q^2 region, $E_T^{\text{Breit}} > 5$ GeV, $5 < Q^2 < 100$ GeV^2, $0.2 < y < 0.6$
- NLO corrections large for low E_T and forward $\eta_{\text{lab}} > 1.5$
  ⇒ Theory lies below data.

Inclusive jet production – foward region



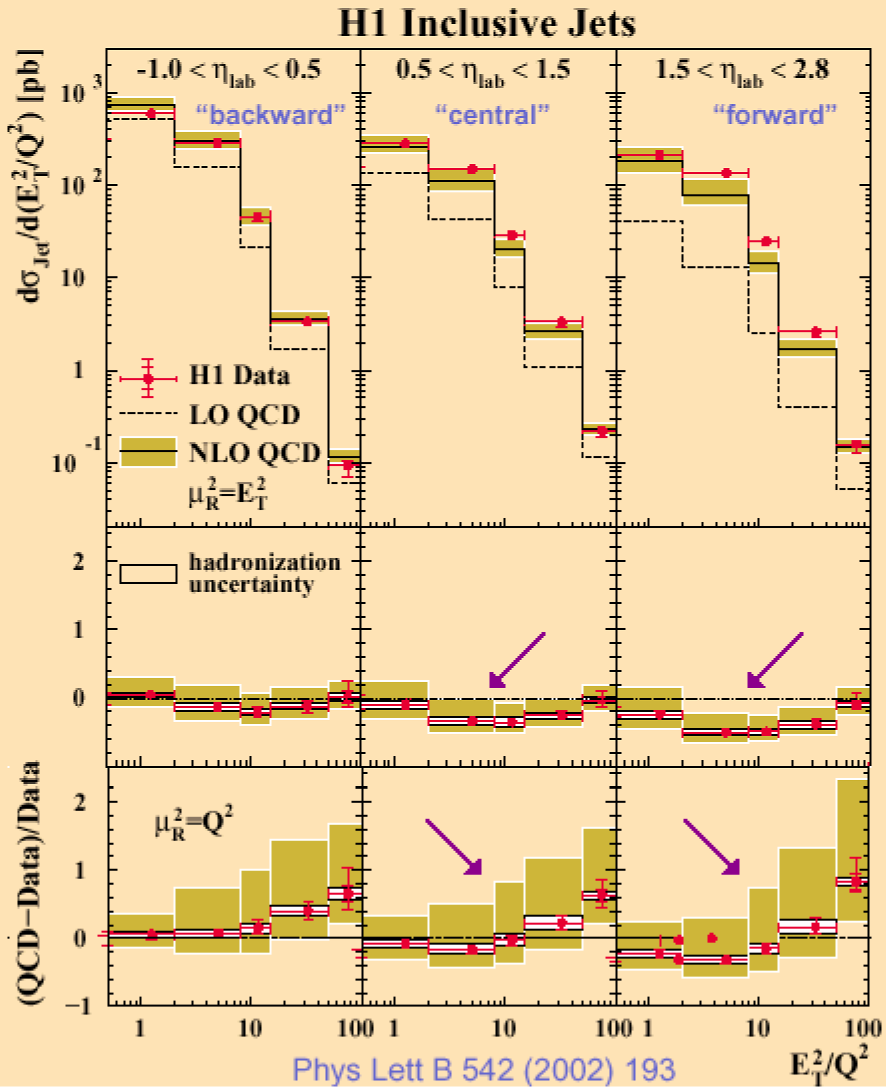
- Forward region, $1.5 < \eta_{lab} < 2.8$ in more detail.
- Discrepancy between data and NLO large at low Q^2 and low E_T.

  ➡ Improved calculations are needed; Contributions proton PDF's? virtual photon structure? alternative evolution schemes (CCFM, BFKL)?

$d\sigma/d(E_{T,\mathrm{B}}^{\mathrm{jet}}/Q)^2$: interplay of the two hard scales

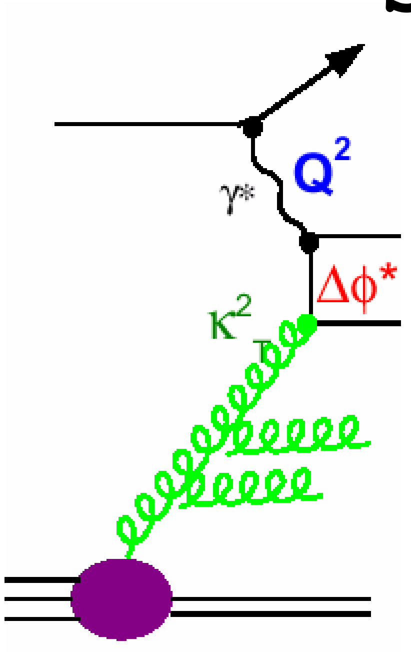
- "Backward" region well described by NLO
- NLO predictions lower than the data in "central" and "forward" regions for $2 < (E_{T,\mathrm{B}}^{\mathrm{jet}}/Q)^2 < 50$
  $\longrightarrow$ regions dominated by small values of $(E_{T,\mathrm{B}}^{\mathrm{jet}})^2$ and Q^2
- NLO calculations with $\mu_R = Q$
  $\longrightarrow$ disagreement for large $(E_{T,\mathrm{B}}^{\mathrm{jet}}/Q)^2$ (small Q^2)

$\longrightarrow$ Improved calculations are needed to understand jet production at low Q^2



Phys Lett B 542 (2002) 193

Study of Azimutal Correlations beteen two hardest jets

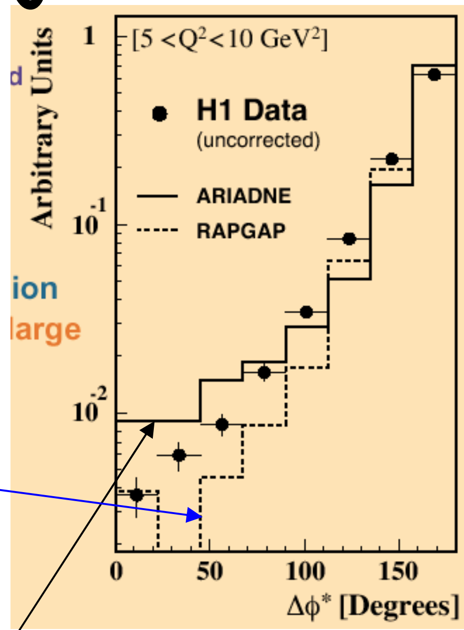


DGLAP: $g(x, \kappa_T^2, Q^2) \rightarrow g(x, Q^2)$

$\rightarrow \kappa_t^2 \approx 0$

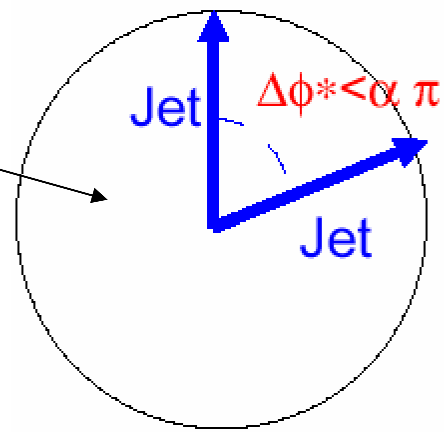
LO: $\Delta\phi^* = \pi$

HE (e.g. PS): $\Delta\phi^* \neq \pi$

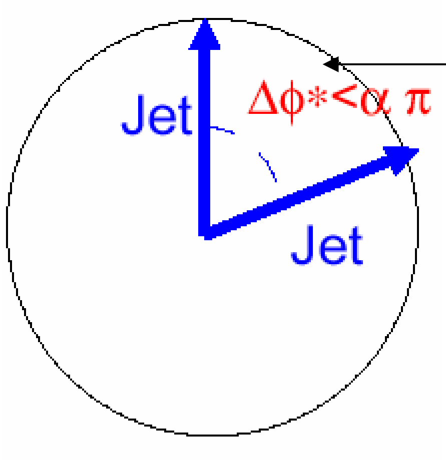


NON-DGLAP e.g. ARIADNE

$\kappa_t^2 \neq 0 \rightarrow \Delta\phi^* \neq \pi$



Azimutal correlations beteen two hardest jets



$$S = \frac{\#\ \text{Events with}\ \Delta\phi^* < 120^o}{\text{All Dijet Events}}$$

Rate of dijet events separated by an azimuthal angle (much) smaller than π

(proposed by A.Szczurek et al. hep-ph/0011281)

Better stability against migrations then $\Delta\phi^*$

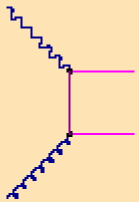
x and Q^2 dependence of S

- Measurement of the S distribution as a function of x in bins of Q^2
- The data rise towards low x, especially at low Q^2

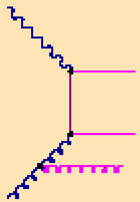
Contributed paper to EPS03

- Comparison to NLO-dijet predictions (DISENT):
  - $\longrightarrow$ the calculations are several standard deviations below the data and show no rise towards low x

DISENT:

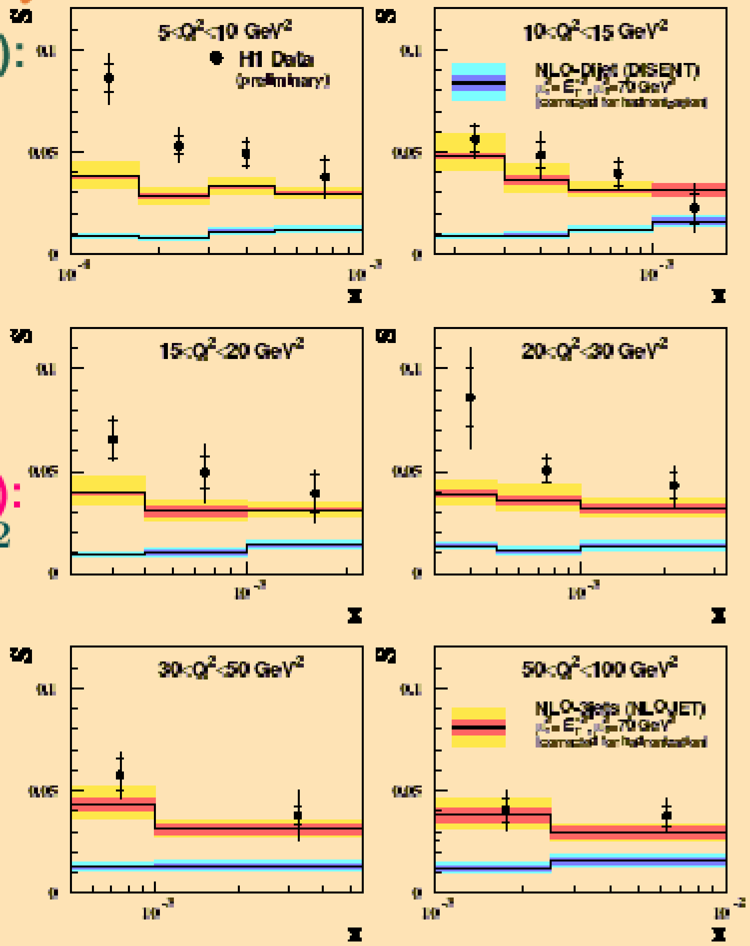


no k_T

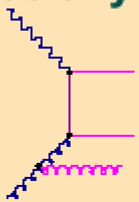


k_T

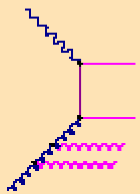
- Comparison to NLO-3jet predictions (NLOJET):
  - $\longrightarrow$ accurate description of the data at large Q^2 and large x
  - $\longrightarrow$ fail to describe the increase towards low x, especially at low Q^2



NLOJET:



k_T



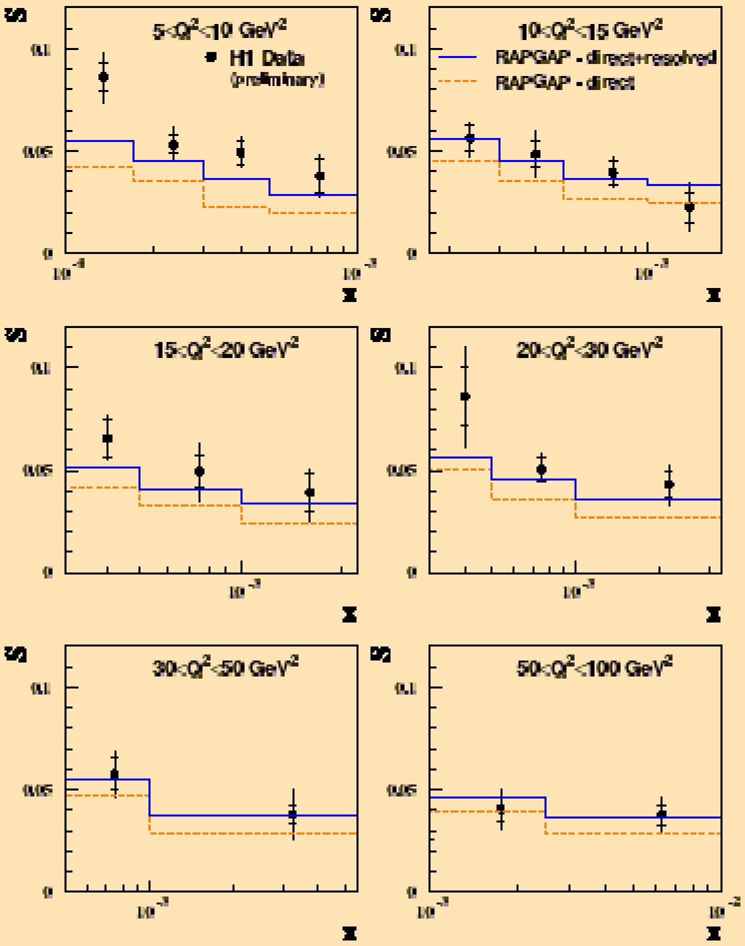
k_T

x and Q^2 dependence of S

- **Measurement of the S distribution as a function of x in bins of Q^2**

Contributed paper to EPS03

→ A useful comparison is only provided by models which incorporate higher order effects beyond NLO



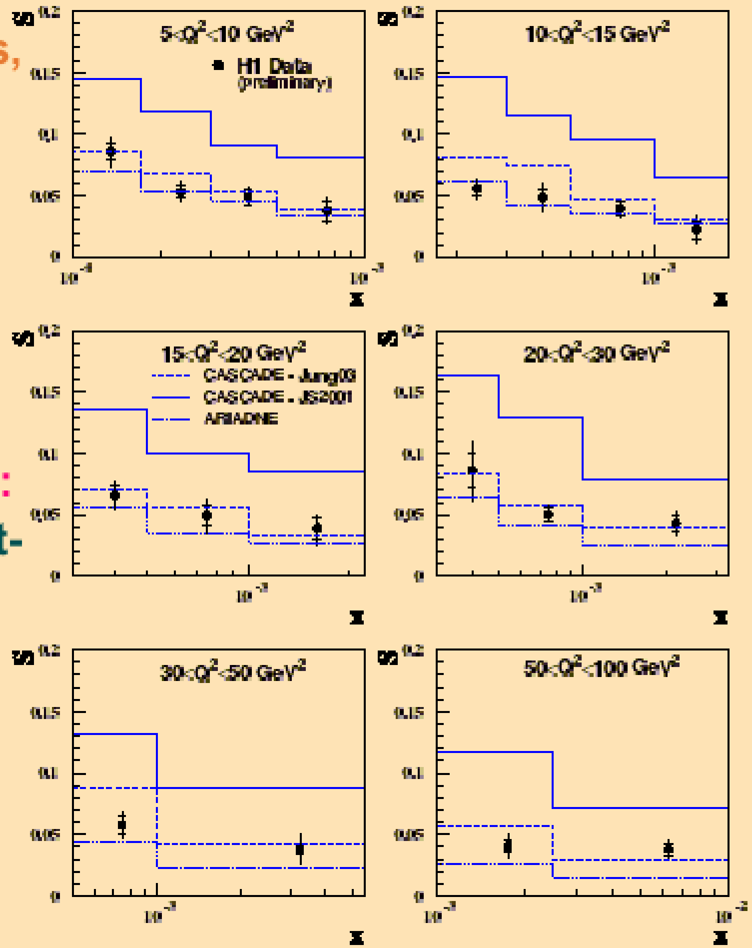
- Comparison to RAPGAP predictions (DGLAP approach):
  - → good description of data at large Q^2 and large x
  - → fail to describe the increase towards low x, especially at low Q^2
  - → improved description of data when incorporating resolved photons, but still prediction too low at low x

x and Q^2 dependence of S

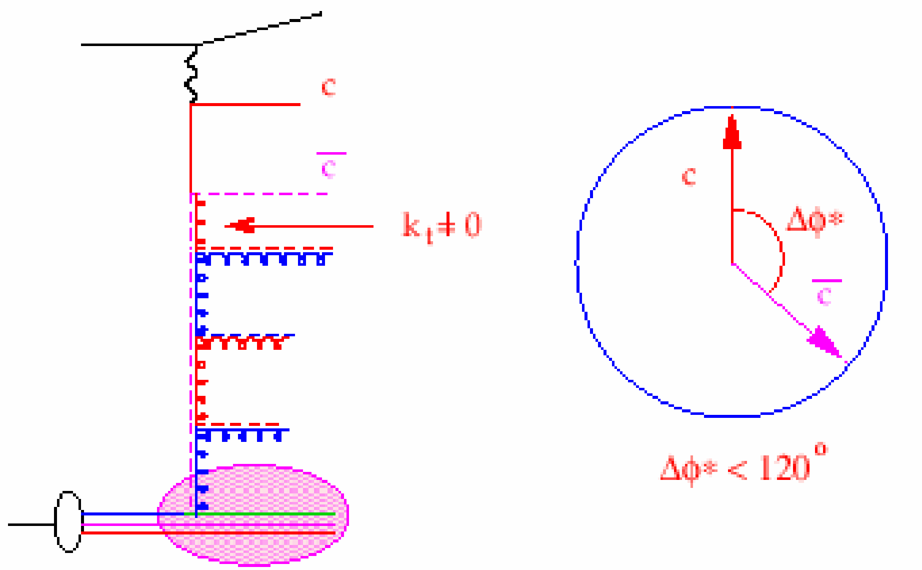
- Measurement of the S distribution as a function of x in bins of Q^2
- If the observed discrepancies are due to the influence of non-k_T-ordered parton emissions, models based on the color dipole model or the CCFM evolution equations, may provide a much better description of the ratio S
- Comparison to CDM predictions (ARIADNE):
  - $\longrightarrow$ good description of data at low x and Q^2
  - $\longrightarrow$ fail to describe the data at high Q^2
- Comparison to CCFM predictions (CASCADE):
  - $\longrightarrow$ the prediction using JS2001 lies significantly above the data
  - $\longrightarrow$ the prediction using the set 2 of Jung2003 closer to the data

$\longrightarrow$ The measurement of the ratio S is sensitive to the details of the unintegrated gluon distribution

Contributed paper to EPS03



Aizmutal correlations with double charm ?



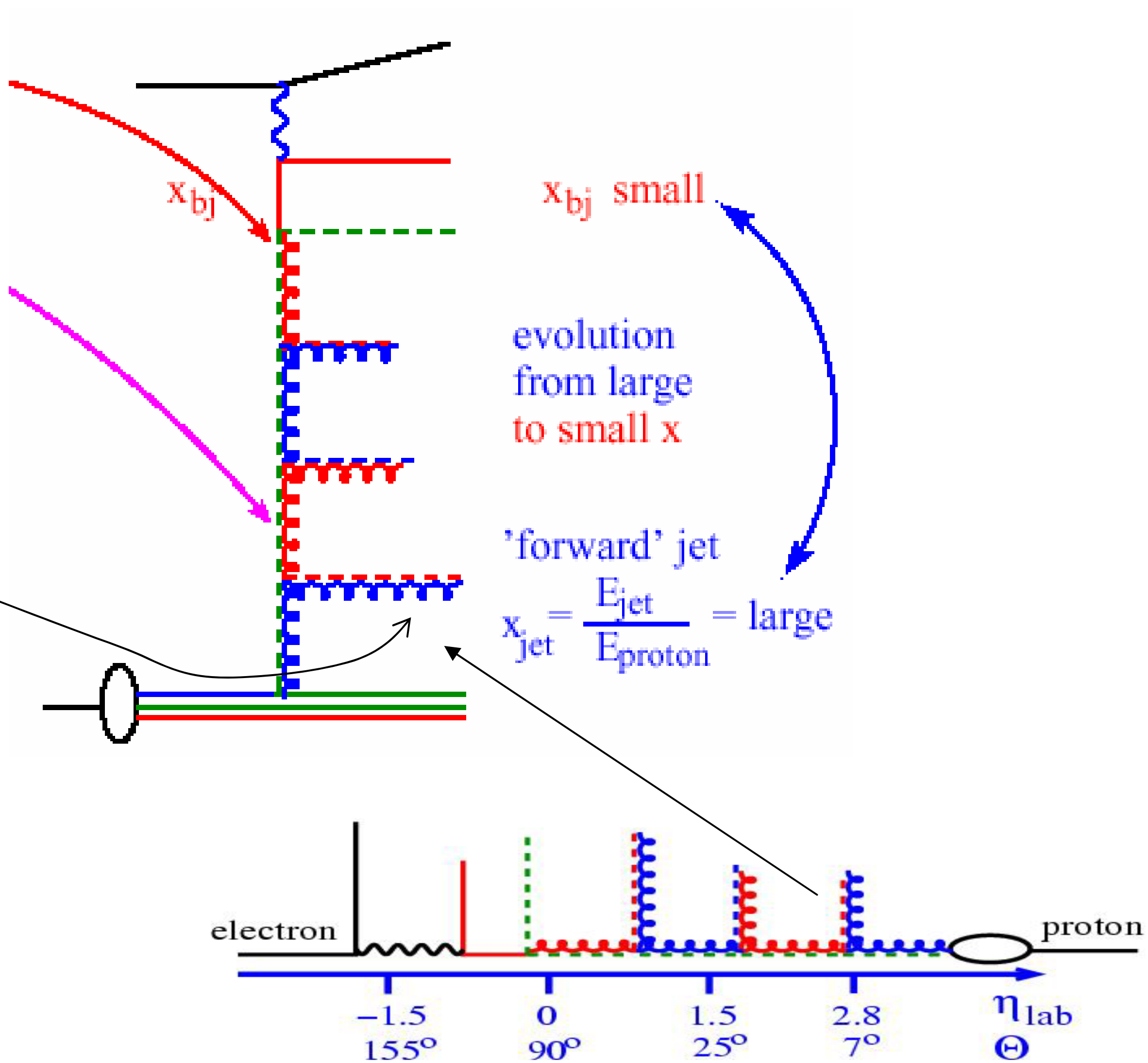
- reconstruct

$$S(x, Q^2, \Delta\Phi) = \frac{\int_0^{120^\circ} d\sigma\, d\Phi}{\int_0^{180^\circ} d\sigma\, d\Phi}$$

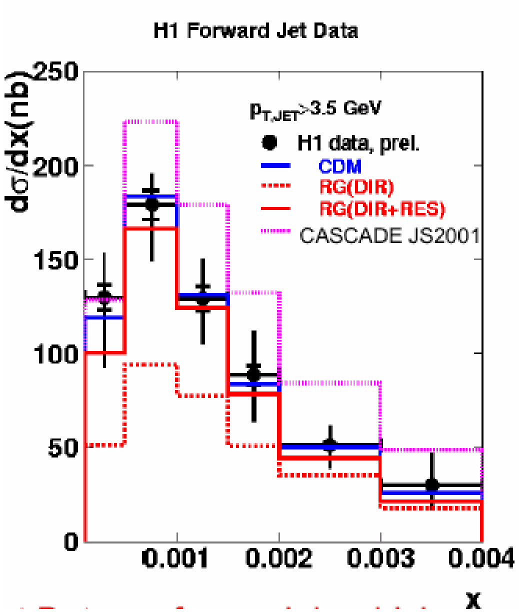
Where DGLAP does not work (by construction)

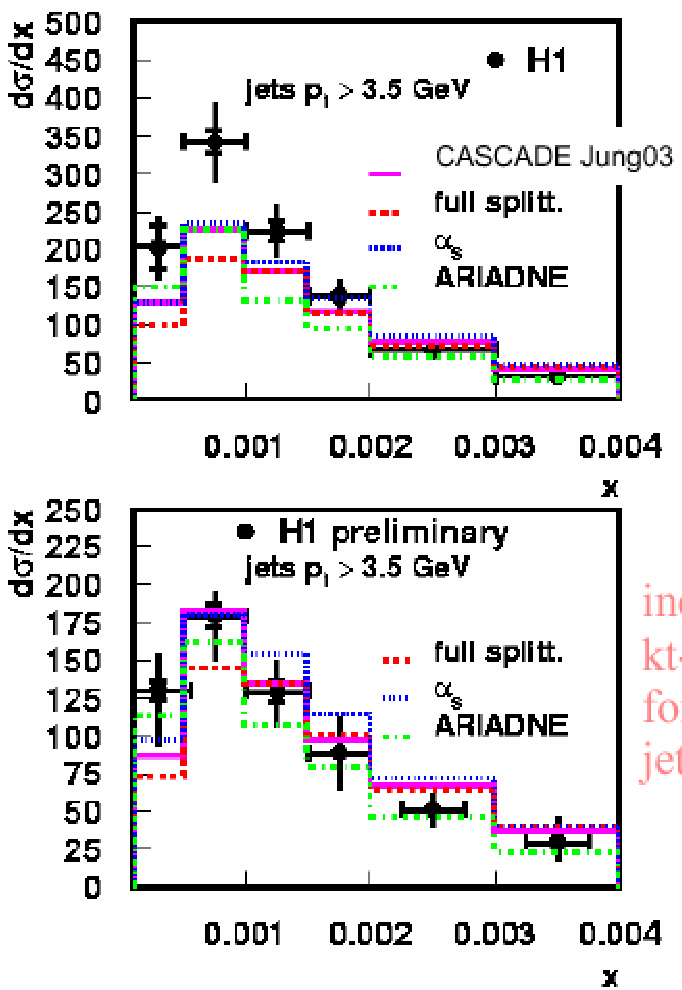
Large x_{jet}/x_{bj} to enhence phase space for BFKL evolution

$p_{tjet}^{\ 2} \approx Q^2$ to supress DGLAP evolution



Forward jet data



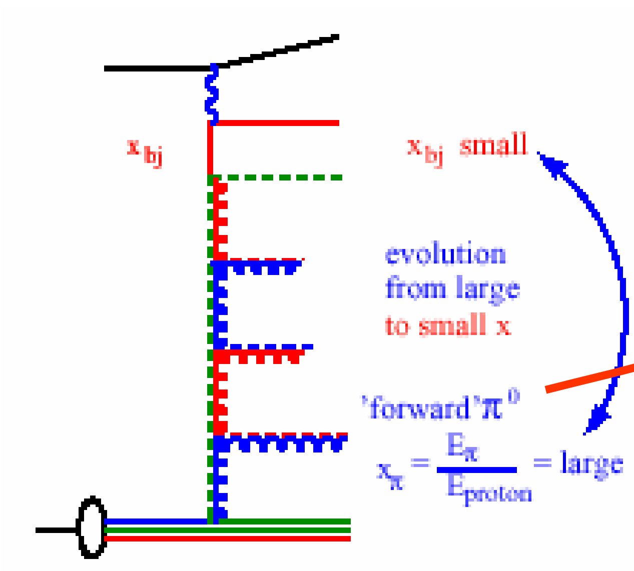


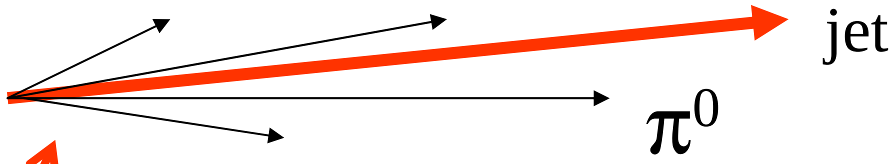
Cone Algo. For jets

inclusive kt-Algo. for jets

- Forward jet data prefer models which do not impose k_t-ordering
- Cascade prediction sensitive to input pdf
- Different conclusions for different jet-finding

Forward jets ⇔forward particles (π^0)

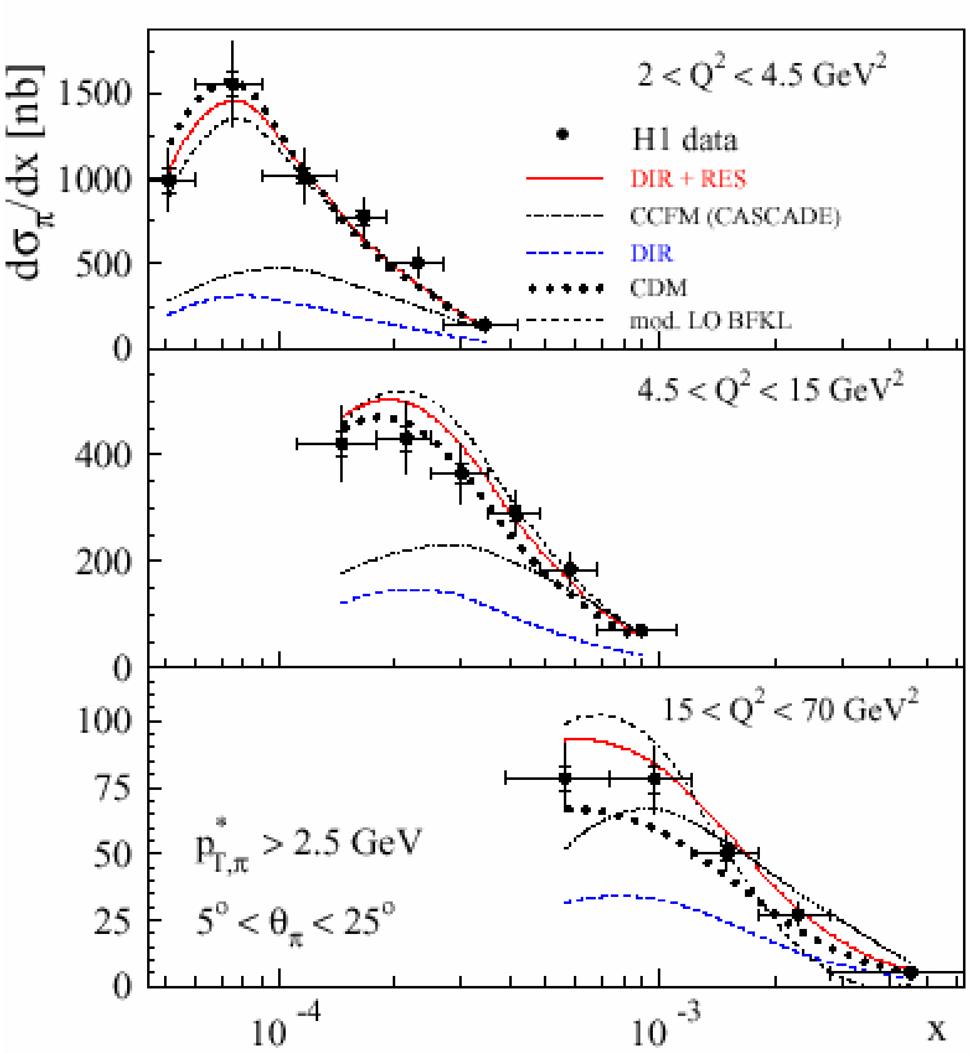




$$\sigma(\pi^0) = \begin{pmatrix} \text{FF} \\ \text{JETSET} \\ \text{PYTHIA} \end{pmatrix} \otimes \sigma(jet)$$

Jet measurements	**forward particle detection π^0**
+ better parton correlation	— fragmetation effects more significant
+ higher rates	— smaller rate
— ambiguities of jet algoriths	+ identification possible in more forward region
— exp. difficult in very forward (p) region	

Forward π^0



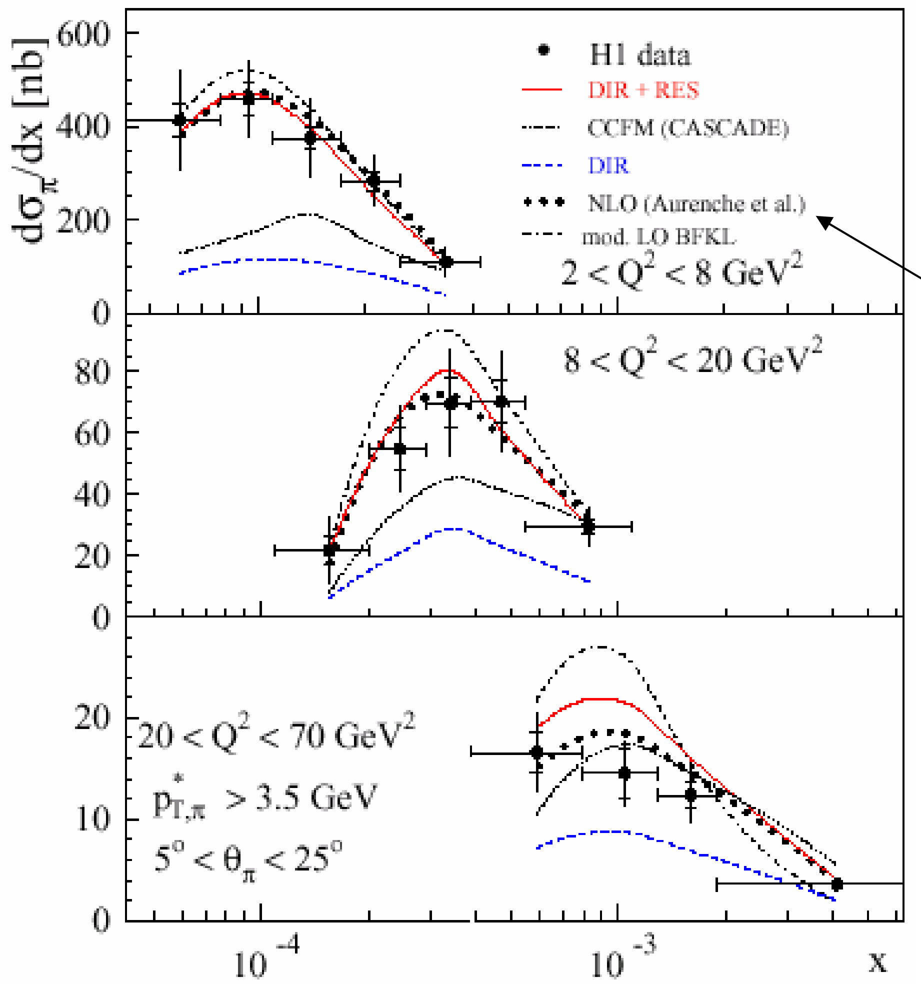
Best description:

direct + resolved at scale $\mu^2 = Q^2 + 4p_T^2$

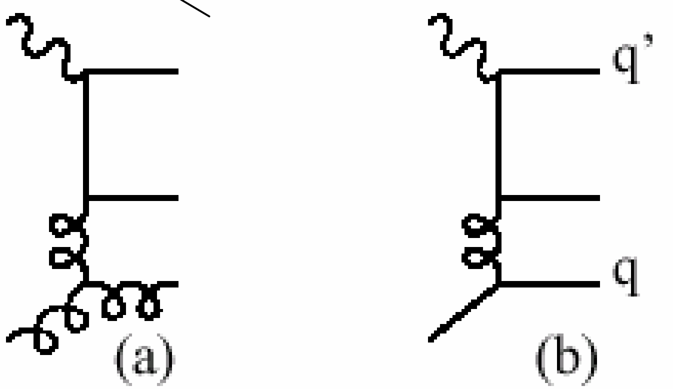
DGLAP direct: too low

CCFM comes too low !

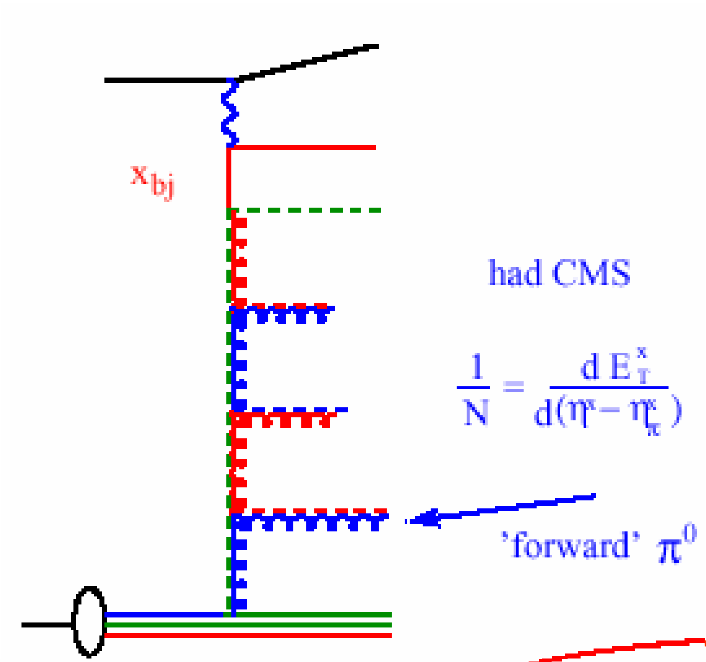
Forward π^0

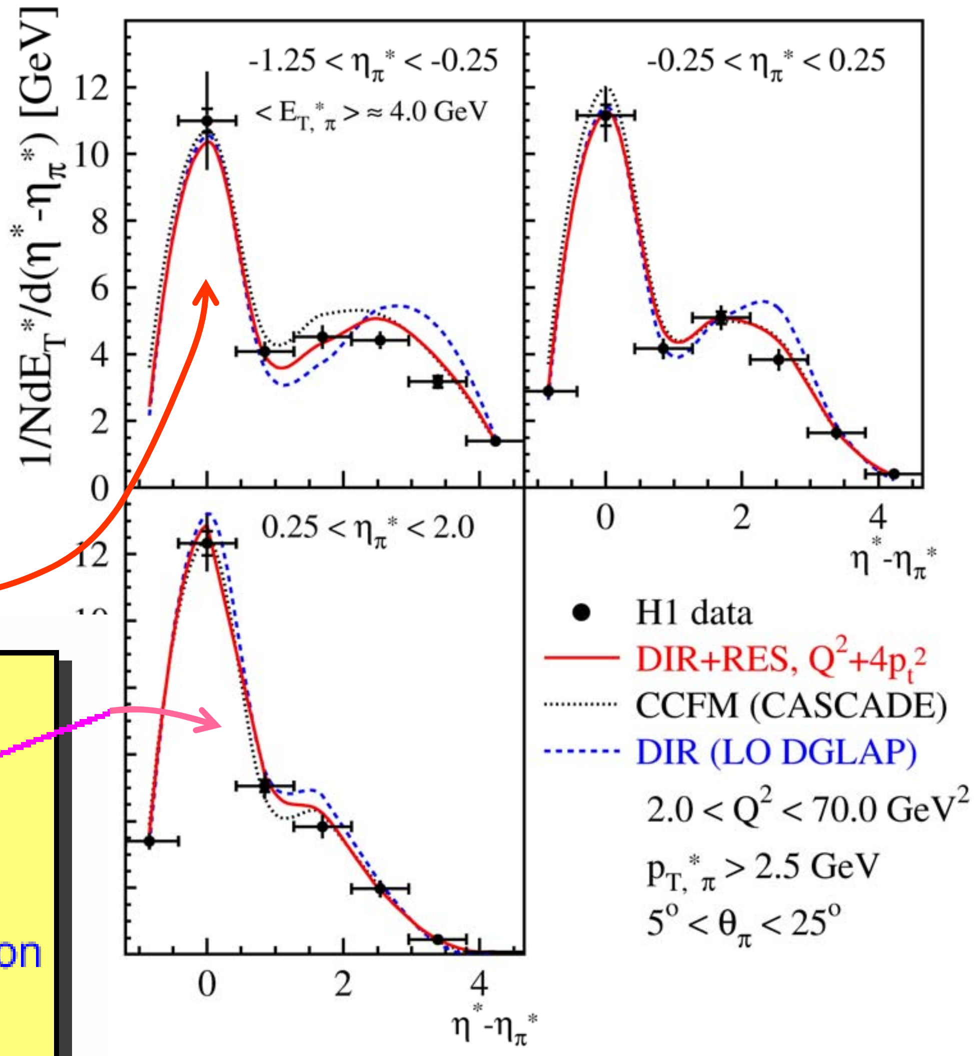


BFKL-like diagrams initiated by gluons and quarks (!), not present in CASCADE



Transverse energy flow associated with forward π^0





in hadronic CMS

- π^0 close to proton
- π^0 towards photon
- E_T-flow around π: transverse momentum compensation along ladder

Comparison between DISENT,RAPGAP and CASCADE in terms of χ^2/n.d.f

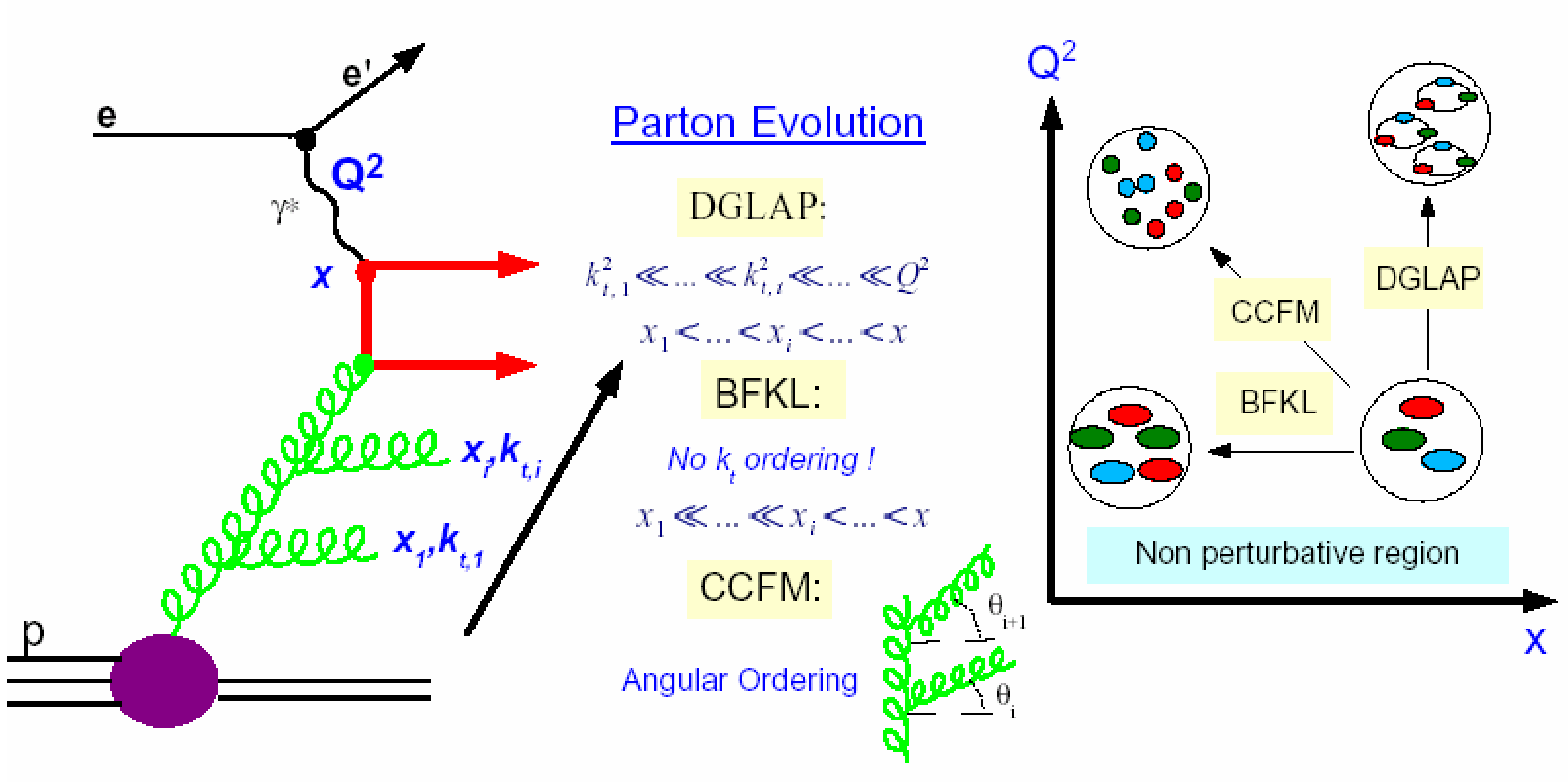
	NLO-dijet		CASCADE J2003		RAPGAP		
					dir	dir + res	
parton density	CTEQ6M	CTEQ6M	set 1	set2	CTEQ6M	CTEQ6M + SaS	
factorization scale μ_f^2	70 GeV^2	Q^2				$Q^2 + p_\perp^2$	$Q^2 + 4p_\perp^2$
$d\sigma/dE_t$ (in bins of η) (cf. Fig. 19)	12.8	13.2	25.5	4.0	23.7	1.3	8.6
$d\sigma/dE_t$ (in bins of Q^2 for $1.5 < \eta < 2.8$) (cf. Fig. 20)	3.9	13.6	17.3	6.0	13.2	2.1	13.2
$d\sigma/d\Delta\eta$ (cf. Fig. 23)	40.1	40.9	116.8	37.7	66.9	22.6	46.7
$S = \frac{\int^{\alpha} N_{2-jet}(\Delta\phi^*, x, Q^2) d\Delta\phi^*}{\int N_{2-jet}(\Delta\phi^*, x, Q^2) d\Delta\phi^*}$ (cf. Fig. 24)	17.8	15.7	23.2	3.9	3.3	2.6	1.7
forward jets H1 $p_\perp > 3.5$ GeV (cf. Fig. 25(a))	8.9	17.0	2.7	4.7	10.8	4.4	0.3
forward jets H1 $p_\perp > 5$ GeV (cf. Fig. 25(b))	5.7	11.2	1.9	2.3	6.7	2.6	0.7
forward jets H1 prel $p_\perp > 3.5$ GeV (cf. Fig. 26)	1.7	6.4	1.3	1.1	4.4	0.9	1.7
forward jets ZEUS $p_\perp > 5$ GeV (cf. Fig. 27)	28.9	38.4	19.2	9.5	27.1	20.1	16.8

Table 2. *Comparison of χ^2/ndf obtained from comparing different predictions to the data. For the NLO-dijet calculation with the DISENT program the renormalization scale was set to $\mu_r = \sum k_\perp$, the CTEQ6M [185] and SaS [197] parton distribution functions of the proton and photon, respectively, are used.*

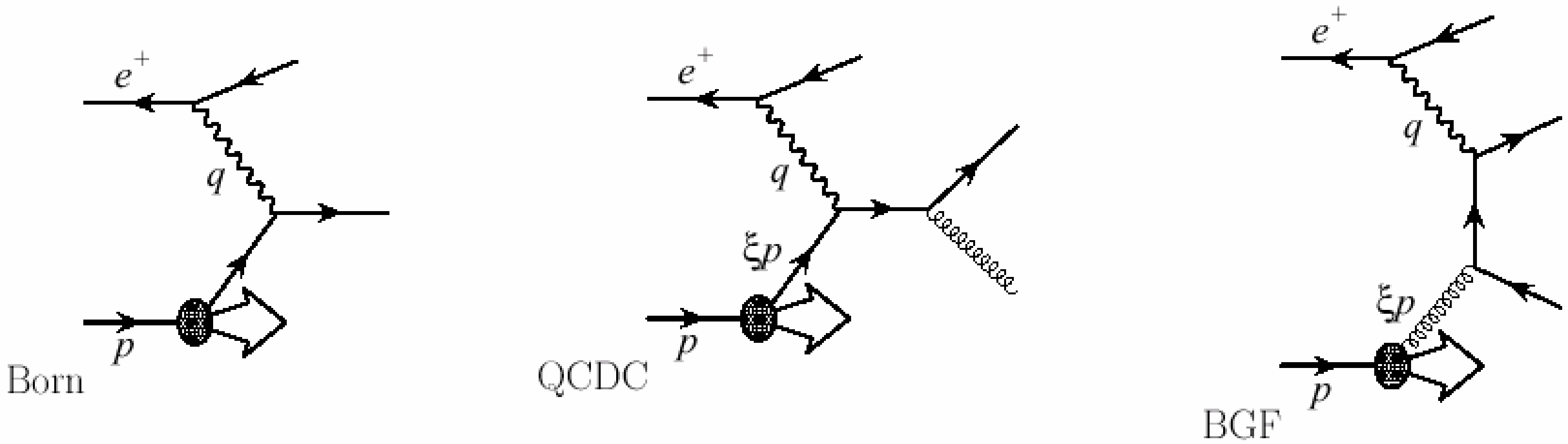
Conclusions and outlook

- DGLAP evolution provides very good description of single-scale QCD processes at HERA and TEVATRON
- At HERA for large values of $Q^2 > 100$ GeV^2 DGLAP is good approximation even if two scales are involved
- For $Q^2 < 100$ GeV^2 DGLAP NLO description deteriorates for some kinematical regions (central and forward jets)
- Azimutal correlations between two hardest jets seem to be very powerful tool for observation of parton dynamics and determination of unintegrated gluon structure function . Double charm measurements at HERA II may appear very intersting in context of small x dynamics
- Forward jets at HERA are sensitive to parton dynamics, further measurements needed
- Measurement of the forward particles at HERA (π^0) seems to reveal some additional aspects of the parton dynamics
- In most cases when DGLAP description fails model without p_t ordering provide reasonable description

DIS and Parton Dynamics



Jets in deep inelastic scattering



- Factorise jet cross-section into a convolution of PDF's in the proton, f_a, with short distance subprocess, $\mathrm{d}\hat{\sigma}_a$....

$$d\sigma_{\mathrm{jet}} = \sum_{a=q,\bar{q},g} \int \mathrm{d}x\ f_a(x,\mu_F^2)\ \mathrm{d}\hat{\sigma}_a(x,\alpha_s(\mu_R^2),\mu_R^2,\mu_F^2) \times (1+\delta_{\mathrm{had}})$$

- Longitudinally invariant k_T algorithm (Catani et al).
  ➡ At high E_T hadronisation effects are small ➡ more reliable QCD predictions.
- Large scale variation possible in both Q^2 and E_T ➡ what is the appropriate scale?

NLO QCD calculations of jet production in DIS

- Several calculations available, virtual and collinear singluarities cancelled using subtraction or phase space slicing methods,
  - ▷ Dijet production
    DISENT (Catani and Seymour) – subtraction method.
    DISASTER++ (Graudenz) – subtraction method.
    MEPJET (Mikes and Zepenfeld) – phase space slicing method.
  - ▷ Two and Three jet productuion
    NLOJET (Nagy and Trocsanyi) – subtraction method.
- Two “natural” scales in jet production, Q and $E_T^{\rm jet}$, renormalisation and factorisation scales, μ_R, $\mu_F = Q$ or $E_T^{\rm jet}$.
- Calculations at parton level ➡ correct calculations for hadronisation effects.
- Theoretical uncertainties...
  - ▷ Terms beyond NLO, usually estimated by varying scale, μ_R by factor of 2.
  - ▷ Uncertainty on α_s and the proton parton distribution functions.