Final State Properties. HERA-LHC Workshop

Gösta Gustafson. CERN Oct. 2004

I. pQCD: pdf from ep → transverse jets in pp

Can determine $E_\perp$ flow

II. But: Hadron multiplicity sensitive to nonpert. effects.

Large problems. Models differ by factors 3-4.

(cf talk by Arthur Moraes)

Important lesson to be learned from analyses by Rick Field and Sjöstrand-Skand

I. pQCD

Conventional collinear factorization

→ High $p_\perp$ jets

But: Minijet cross section diverges

$$\sigma_{jet} \sim \frac{1}{p_\perp^4}$$

Also total $E_\perp$ diverges

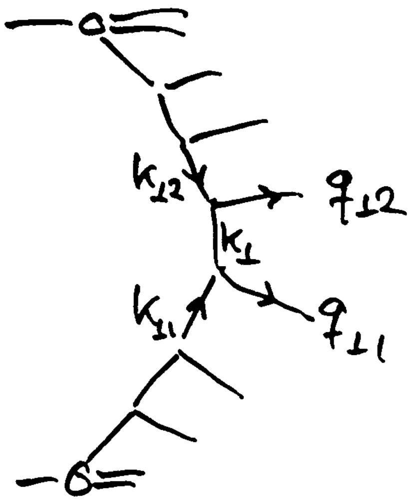
⇒ Cutoff needed

Can be determined by fit to data:

PYTHIA: $p_{\perp 0} \sim$ 2-3 GeV growing with energy!

No garantie for safe extrapolation to LHC energies

$k_\perp$-factorization



$k_\perp < k_{\perp 1}, k_{\perp 2} \Rightarrow$

Off shell ME does not blow up when $k_\perp \to 0$

$k_\perp$ does not determine jet $q_\perp$

$q_{\perp 1} \approx k_{\perp 1}$; $q_{\perp 2} \approx k_{\perp 2}$

Result determined by non-integrated str. fcn $\mathcal{F}(x, k_\perp^2)$ suppressed for small $k_\perp$.

Total $E_\perp$ finite

"Effective cutoff" $p_{\perp 0}$ increases with energy, but the increase is less steep for larger s.

(Leading log → $p_{\perp 0}$ saturates)

(GG-G.Miu -01)

Multiple hard subcollisions

At high energy $\sigma_{jet} > \sigma_{tot}$

⇒ Several hard collisions in each event

Exp. evidense for multiple collisions:
(cf Rick Field)

1) Multijet events
2) Forward-backward correlations
3) Pedestal effect
4) Associated particles in jet events.

Correlations important:

Exp. ⇒ Hard subcollisions <u>not independent</u>

Impact parameter dependense:

central coll.: many minijets
peripheral coll.: few —"—

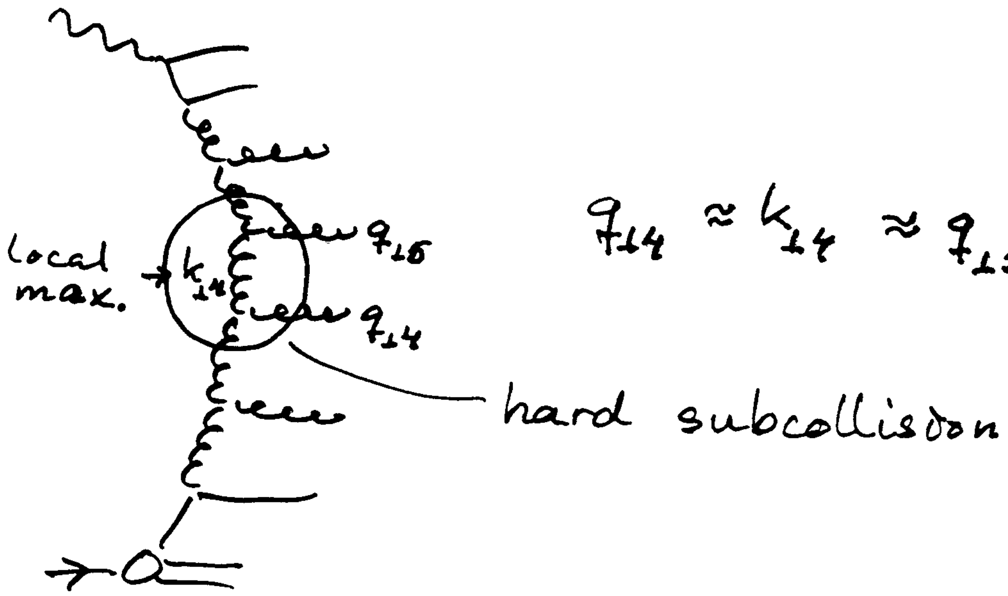
Double Gaussian distribution favoured
(T. Sjöstrand - M. v. Zijl)

→ Very close to geometric distribution in # coll., i.e. much wider than Poisson

Can the prob. for multiple coll. and the effective cutoff $p_{\perp 0}$ be determined by HERA DIS data?

Small x, low $k_\perp$: BFKL region

Non-$k_\perp$-ordered parton chains important



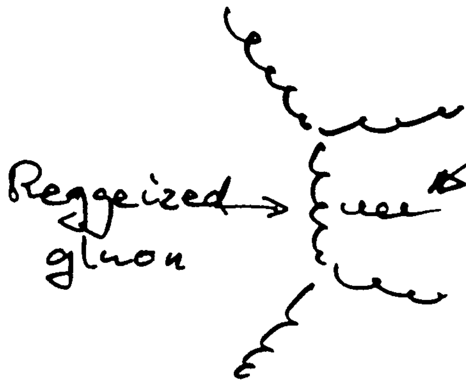
$q_{\perp 4} \approx k_{\perp 4} \approx q_{\perp 5}$

Single local max. → Resolved photon interacti

Several local maxima →

Correlated hard subcollisions

BFKL integral eq. only **inclusive**

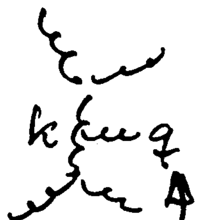


soft emissions compensated by virtual corrections

{ Do **not** contribute to parton distr. (i.e. total cross section)
{ **Do** contribute to final state properties

Added with Sudakov form factors.

CCFM-model interpolates between DGLAP & BFKL



Some soft emissions included in initial state radiation ⇒

⇒ Extra suppression from non-eikonal form factors

Linked Dipole Chain (LDC) model (Lund)

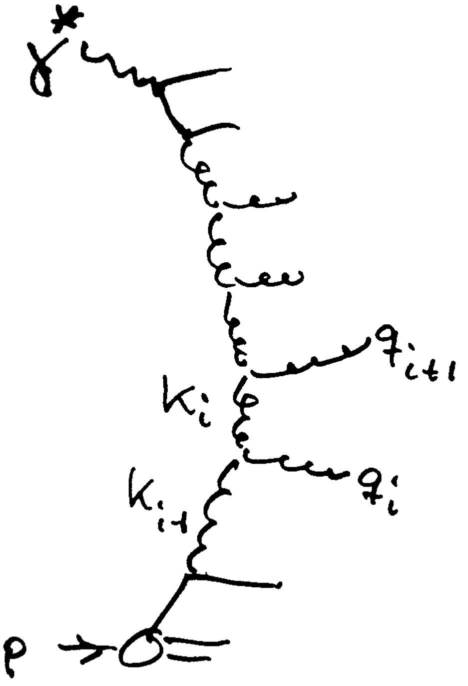
Reformulation and generalization of CCFM

Separation ISR–FSR more similar to BFKL formulation

q final state rad. if $q_\perp < k_\perp$

⇒ ISR chain in LDC is symmetric

photon end – proton end



Leading order in $\ln 1/x$:

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$$\times\, \Theta(q_{\perp i} - \min(k_{\perp i}, k_{\perp i-1}))$$

$$q_{\perp i}^2 \approx \max(k_{\perp i}^2, k_{\perp i-1}^2)$$

⇒ $\frac{dq_{\perp i}^2}{q_{\perp i}^2} \approx \frac{dk_{\perp i}^2}{k_{\perp i}^2}$ <u>except</u> local max or mi[n]

Local max. ⇒ $\frac{dk_{\perp i}^2}{k_{\perp i}^4}$ hard subcoll.

local min ⇒ $dk_{\perp i}^2$ no divergence

(fig)

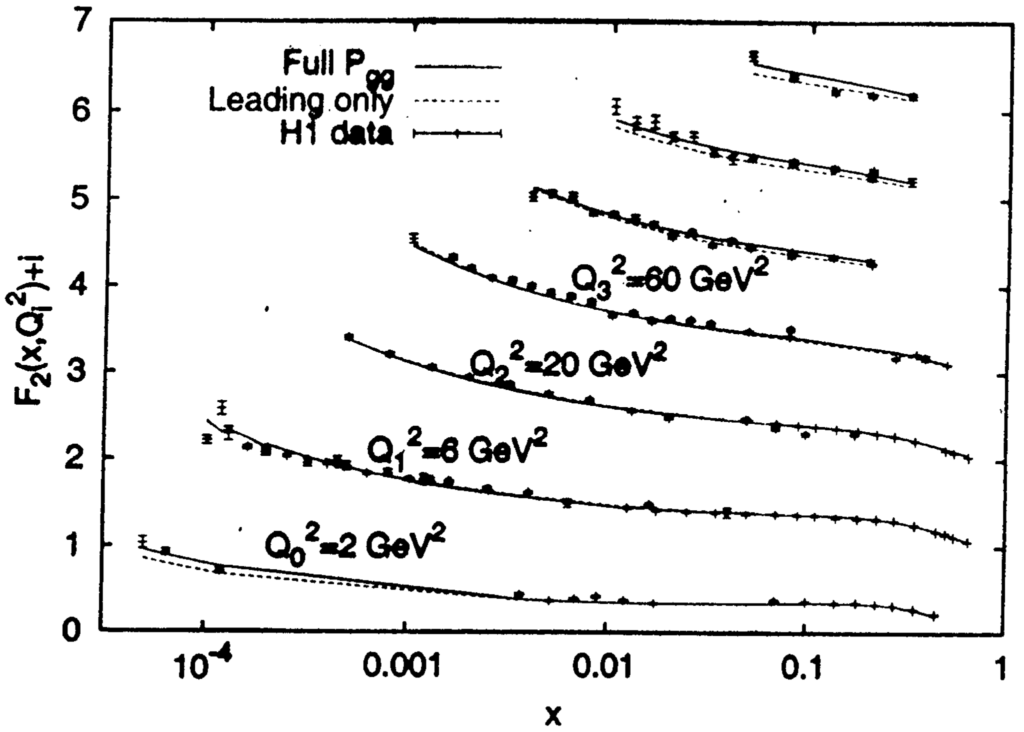
Symmetry ⇒ Also applicable to hh coll.

Fit to DIS ⇒ Cross section for a <u>chain</u> in pp coll.

(possibly more than one hard subcoll.)

F_2 Linked Dipole Chain MC

L. Lönnblad

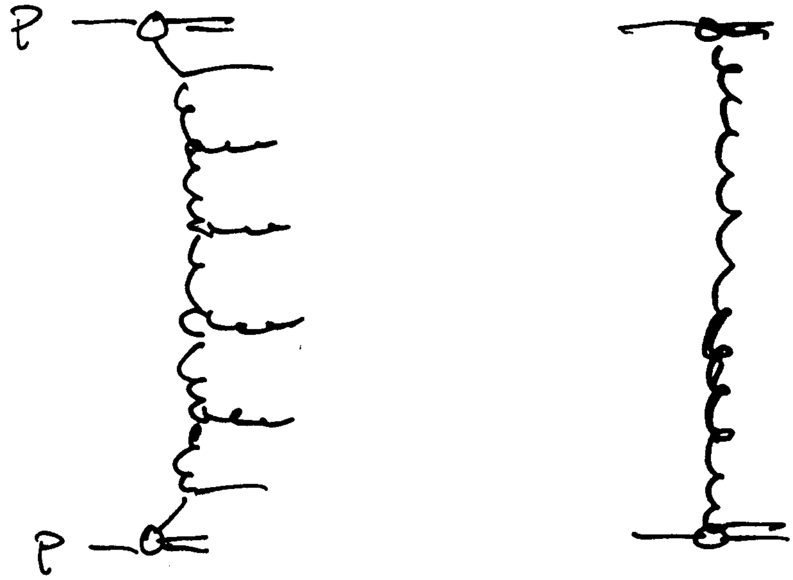


Potential problem

Fit to DIS: Running α_s $\Rightarrow$

$\Rightarrow$ Soft cutoff Q_0 needed

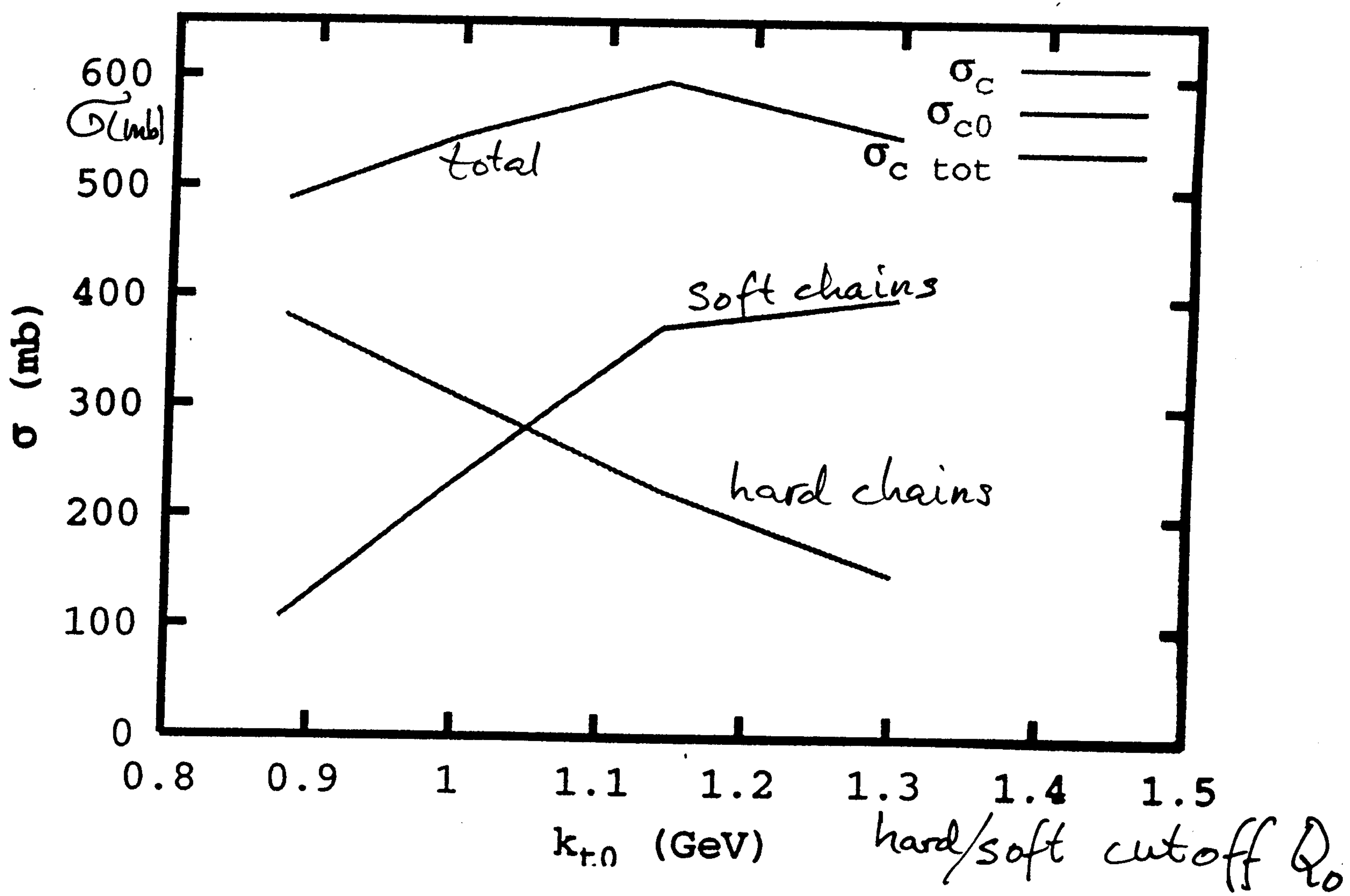
Good fits to DIS data possible with different cuts, if input distrib. $f_0(x, Q_0^2)$ is adjusted accordingly



hard chain $q_\perp > Q_0$ soft chain $q_\perp < Q_0$

$Q_0^2 \nearrow \Rightarrow$ $\searrow$ $\nearrow$

G.G. - L. Lönnblad - G. Miu, 2002

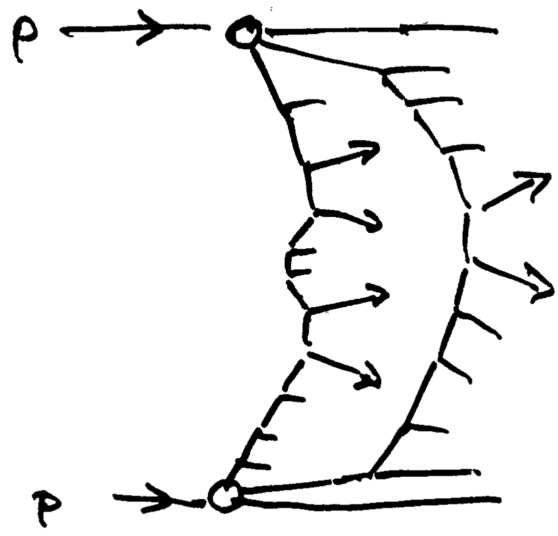


Total cross section for a chain
<u>independent</u> of the soft cutoff!

$\sigma_{chain} = \sigma_{hard\ chain} + \sigma_{soft\ chain}$
is fixed from DIS

Relevanse for AGK cutting rules?
Does this reflect the number of exchanged $\mathbb{P}$?

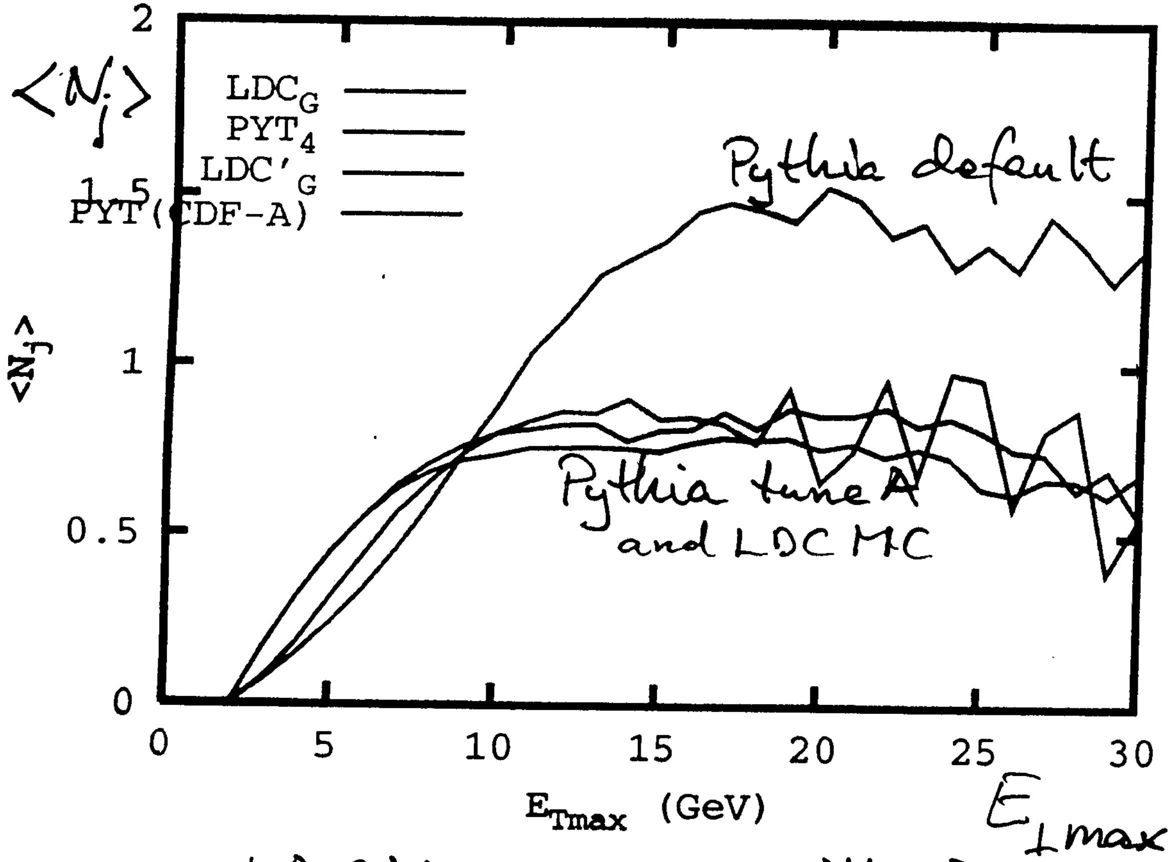
<u>Multiple interactions</u> from 2 hard scatt.
in the same chain <u>and</u> from more
than one chain in a single event.



Pythia: b-dep. double Gaussian → Geometric distr
with tail reduced by energy cons.

Pedestal effect; # jets in min. azimuth

1.8 TeV $|\eta| < 2.5$



LDCMC $k_{\perp 0}$:

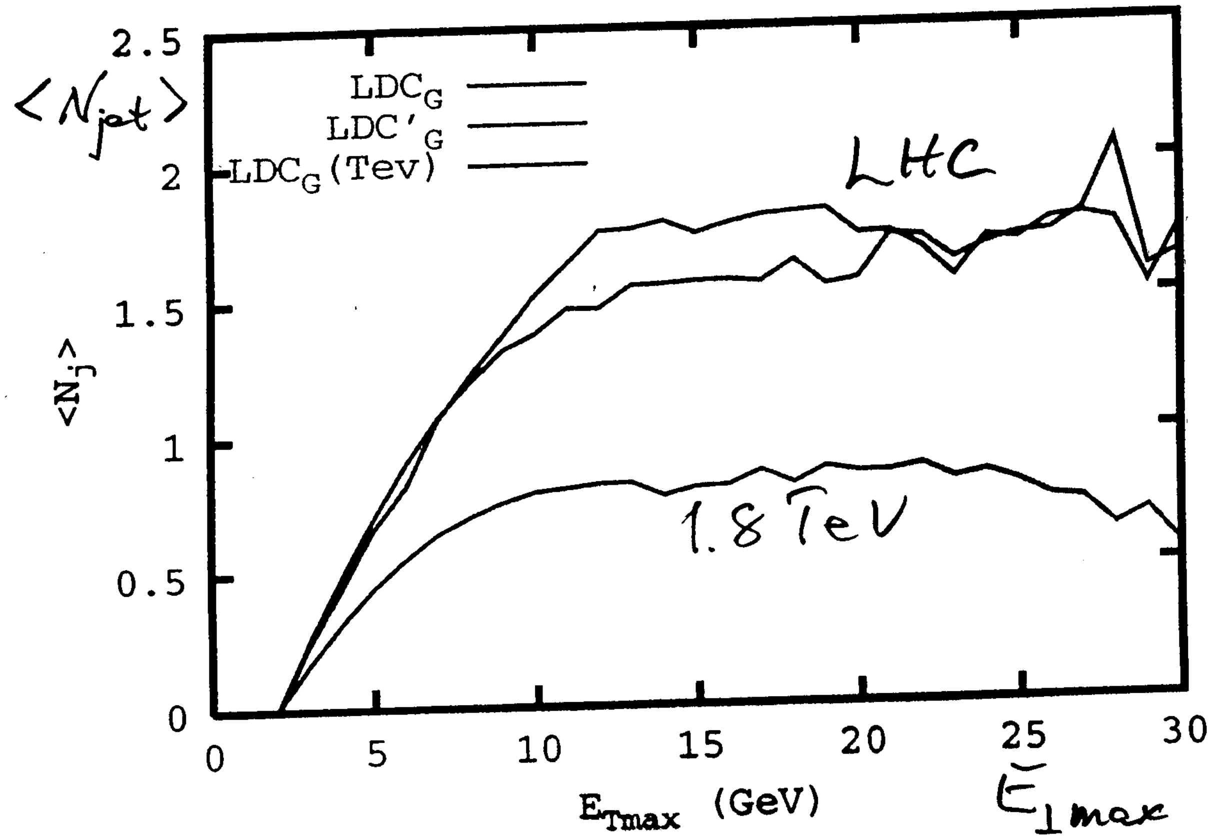
0.99 GeV → 1.3 GeV

PYTHIA:

Default → CDF-A

LDCMC agrees with Pythia tune A independent of cut off

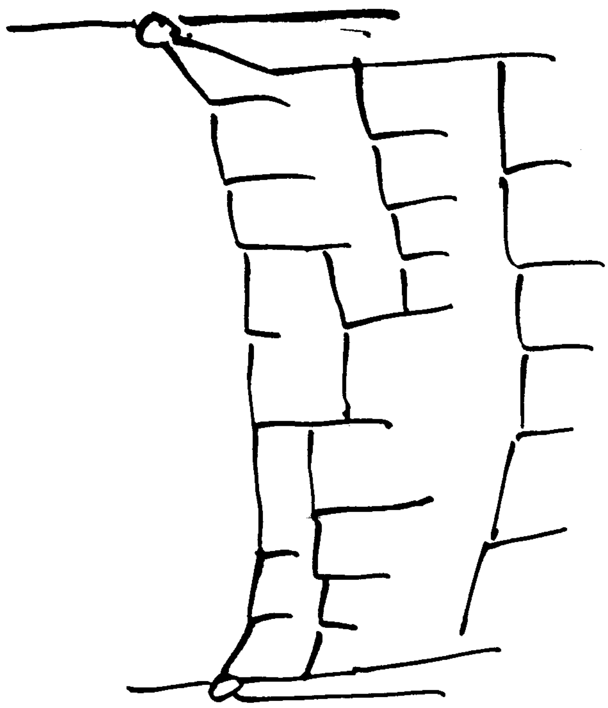
LHC ?



LDCMC $k_{\perp 0}$:

$0.99 \rightarrow 1.3$ GeV

Saturation



The chains join at one end at the same rate as they multiply at the other

Work on saturation in progress

Combine the LDC model with Mueller's dipole formulation in transverse coordinate space (relations to the Balitsky-Kovchegov eq.)

(Avsar - G.G. - Lönnblad)

II. Hadron multiplicities

Depends on colour connections between produced partons.

Non-pert. soft physics

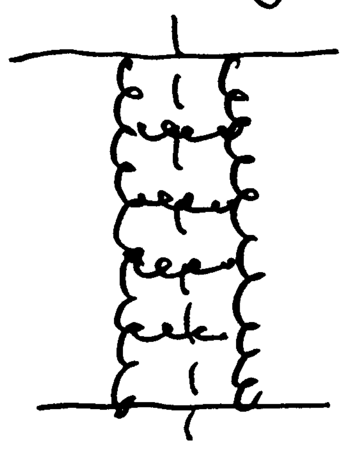
Multiple interactions – multi $I\!P$ exchange

Abramovskii - Gribov - Kancheli

Multiperipheral model: Similar to gluon chain

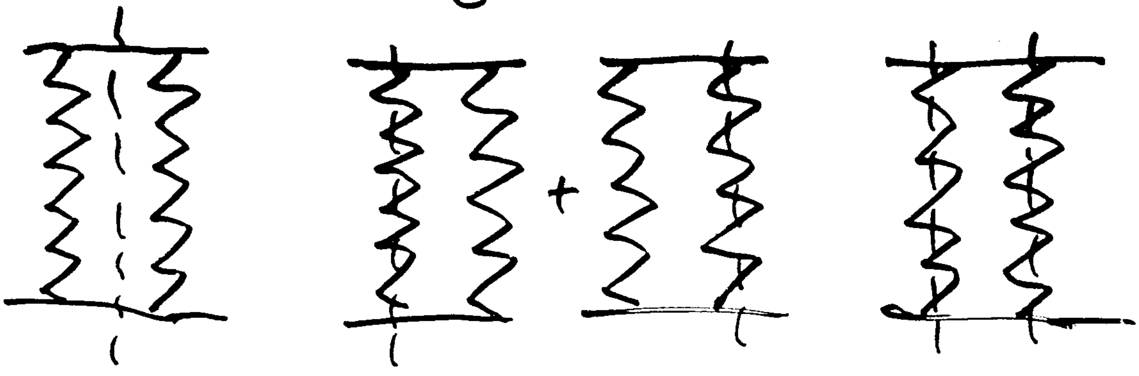
Small momentum exchange at each vertex

$I\!P$ = 2 gluon exchange



Multiple chains: Multi-$\mathbb{P}$ exchange

AGK cutting rules

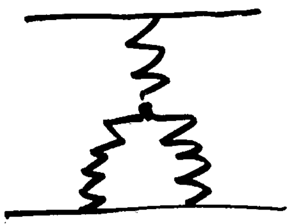


Rel. weight 1 −4 2

Contributes to multiplicity fluctuations
No effect on the # produced particles =

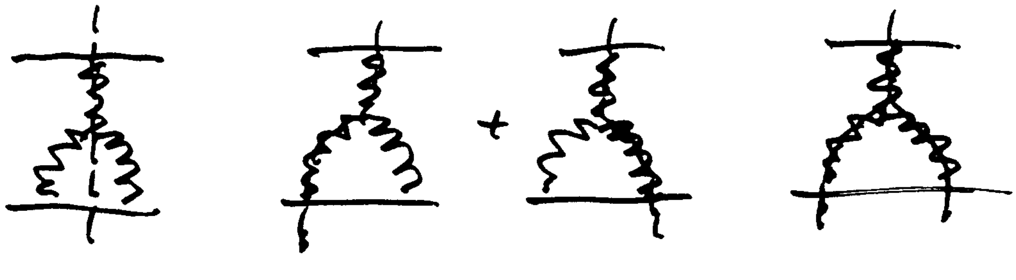
$= \sum n \sigma_n$

3$\mathbb{P}$ coupling



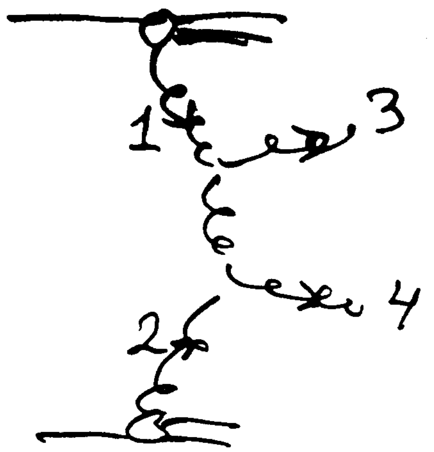
J Bartels et al.

Similar AGK cutting relations

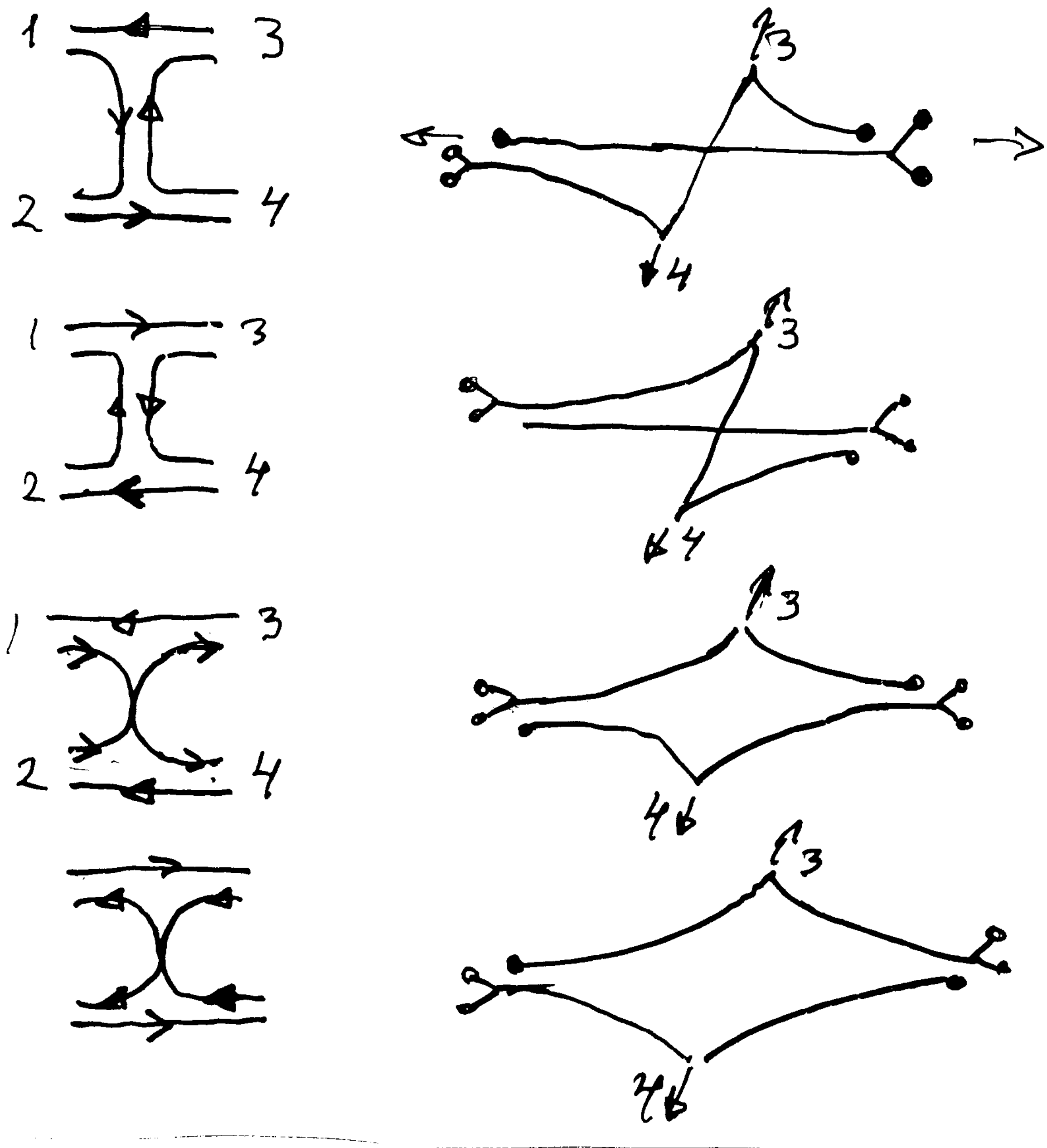


Expected to give smaller contributions ?

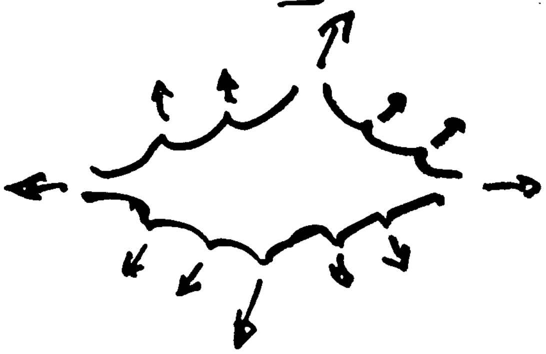
Hard subcollision $gg \to gg$

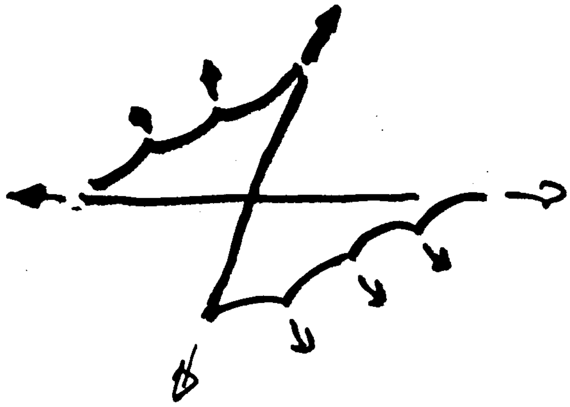


Possible colour connections:

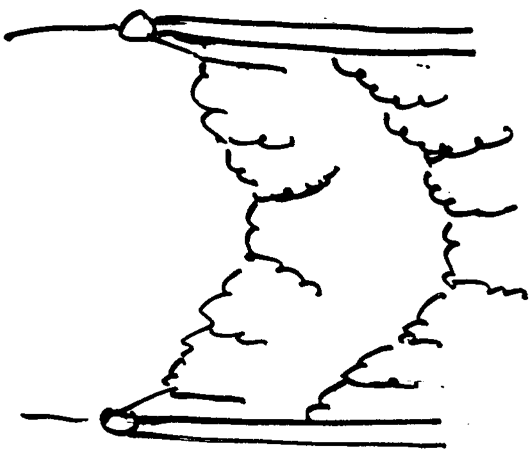


Including <u>initial state radiation</u>

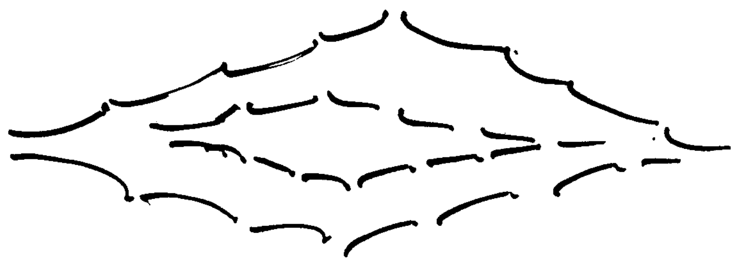




<u>Multiple coll.</u>



Expect



~ double multiplicity à la AGK

<u>CDF data</u> ⇒ <u>Far</u> from reality

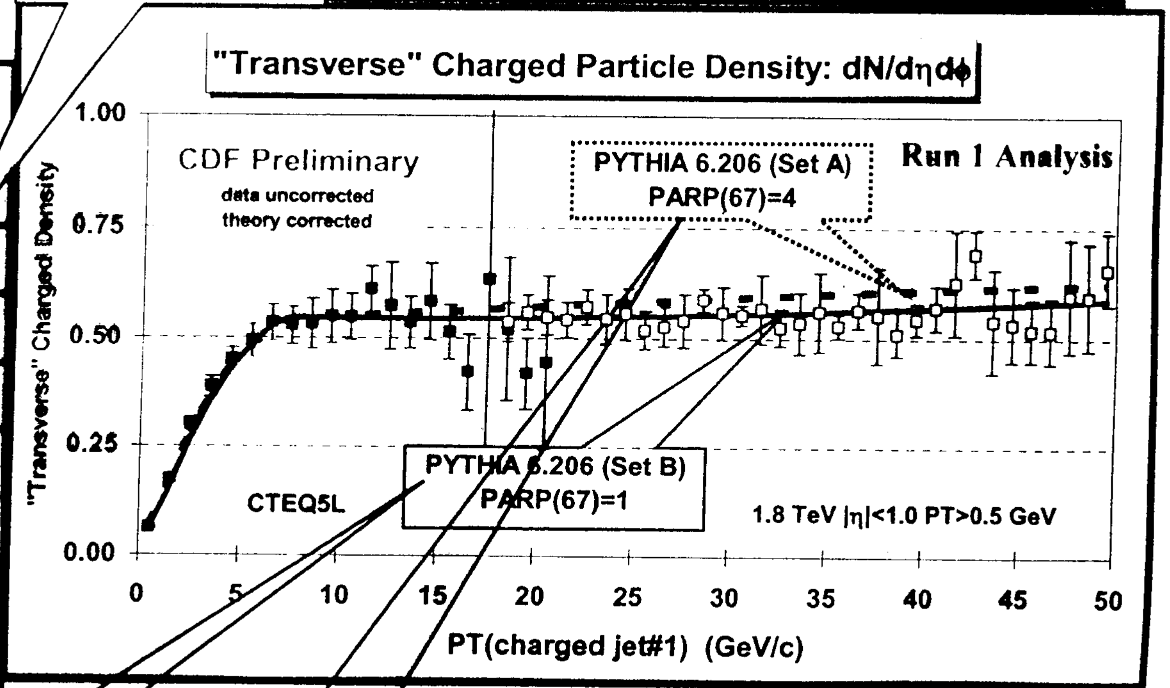
Rick Field

Tuned PYTHIA 6.206

Double Gaussian

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	**1**
MSTP(82)	4	**4**
PARP(82)	1.9 GeV	**2.0 GeV**
PARP(83)	0.5	**0.5**
PARP(84)	0.4	**0.4**
PARP(85)	1.0	**0.9**
PARP(86)	1.0	**0.95**
PARP(89)	1.8 TeV	**1.8 TeV**
PARP(90)	0.25	**0.25**
PARP(67)	1.0	**4.0**

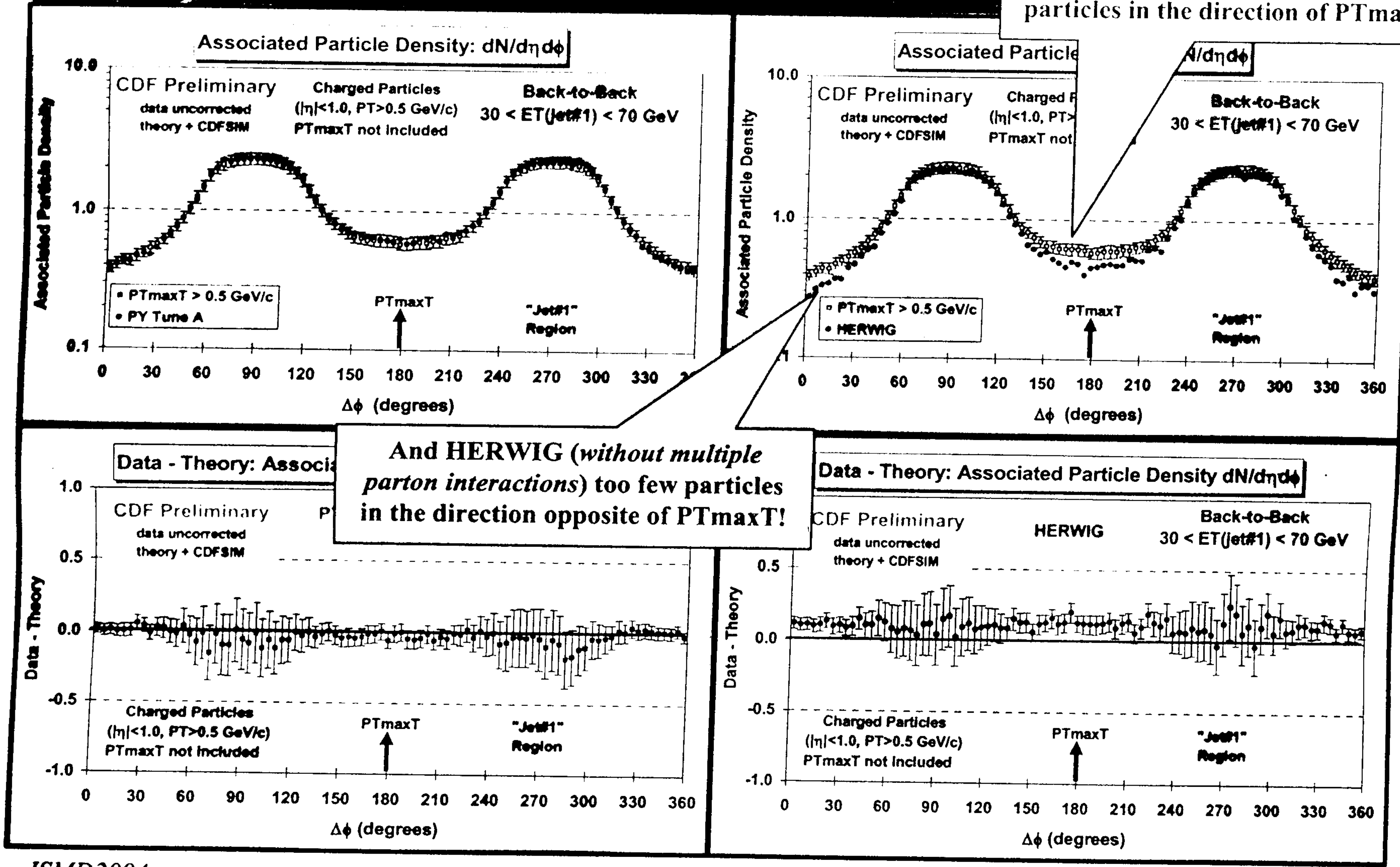


- **Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).**

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

"Associated" Charge Density PYTHIA Tune A vs HERWIG

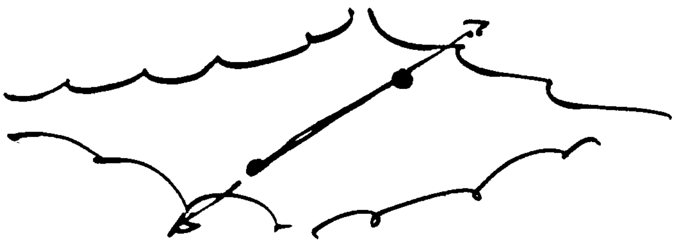


Rick Field's successful tune A is a fit using an early Pythia version

Second hard scatt. has 3 possibilities

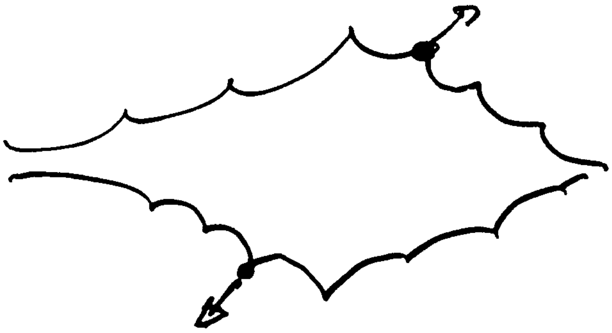
1) Extra closed string between gluons

2) Single string in $q\bar{q}$ pair



lower multipl. increase

3) New gluons give extra kinks on initial strings with minimal extra string length



Tune A ~ 90%

Gives minimal extra multiplicity

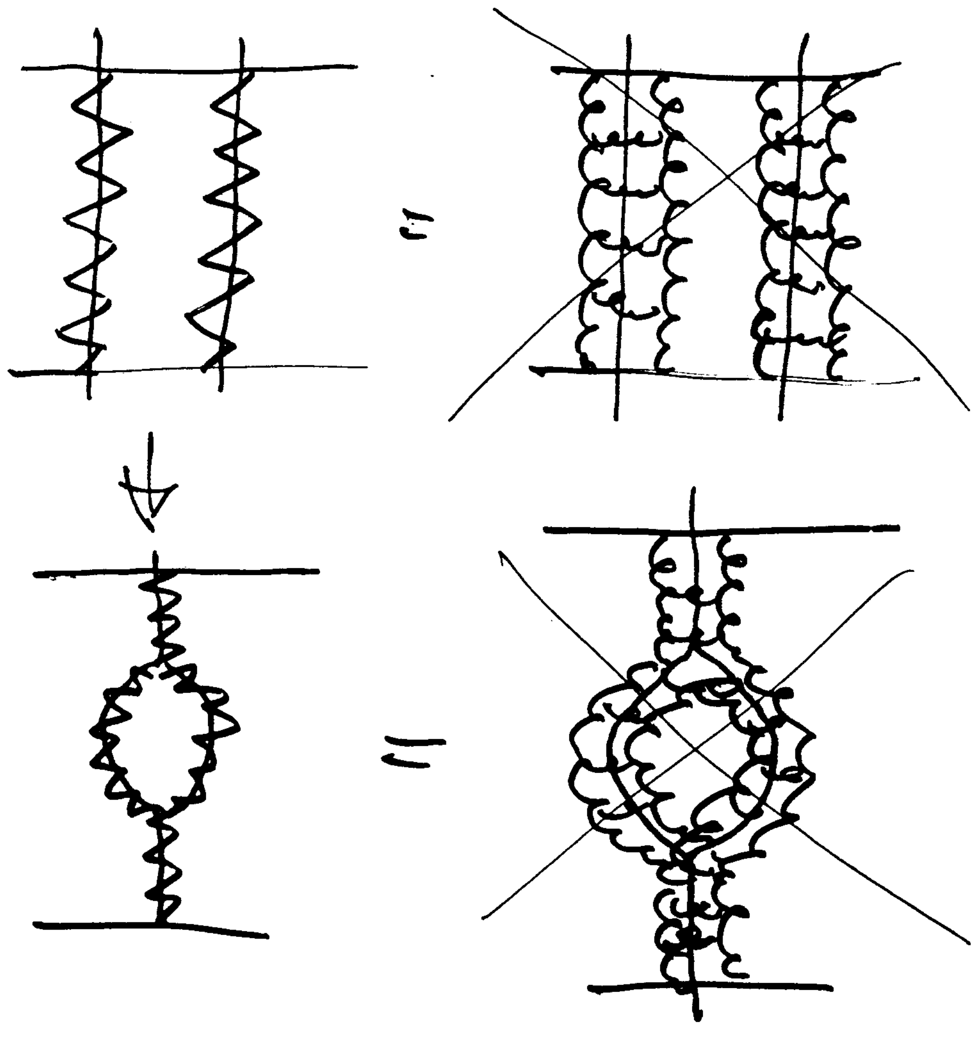
Note: No connection to forward and backward ends of the system.

Default Pythia: Equal shares

New more advanced Pythia version
by Sjöstrand - Skands (Pythia 6.3)

Does not work as well as tune A (fig)

CDF: Multiple interactions definitely needed.
Data fitted if colours rearranged so that
secondary hard scatterings give
minimum extra string length,
i.e. — " — multiplicity



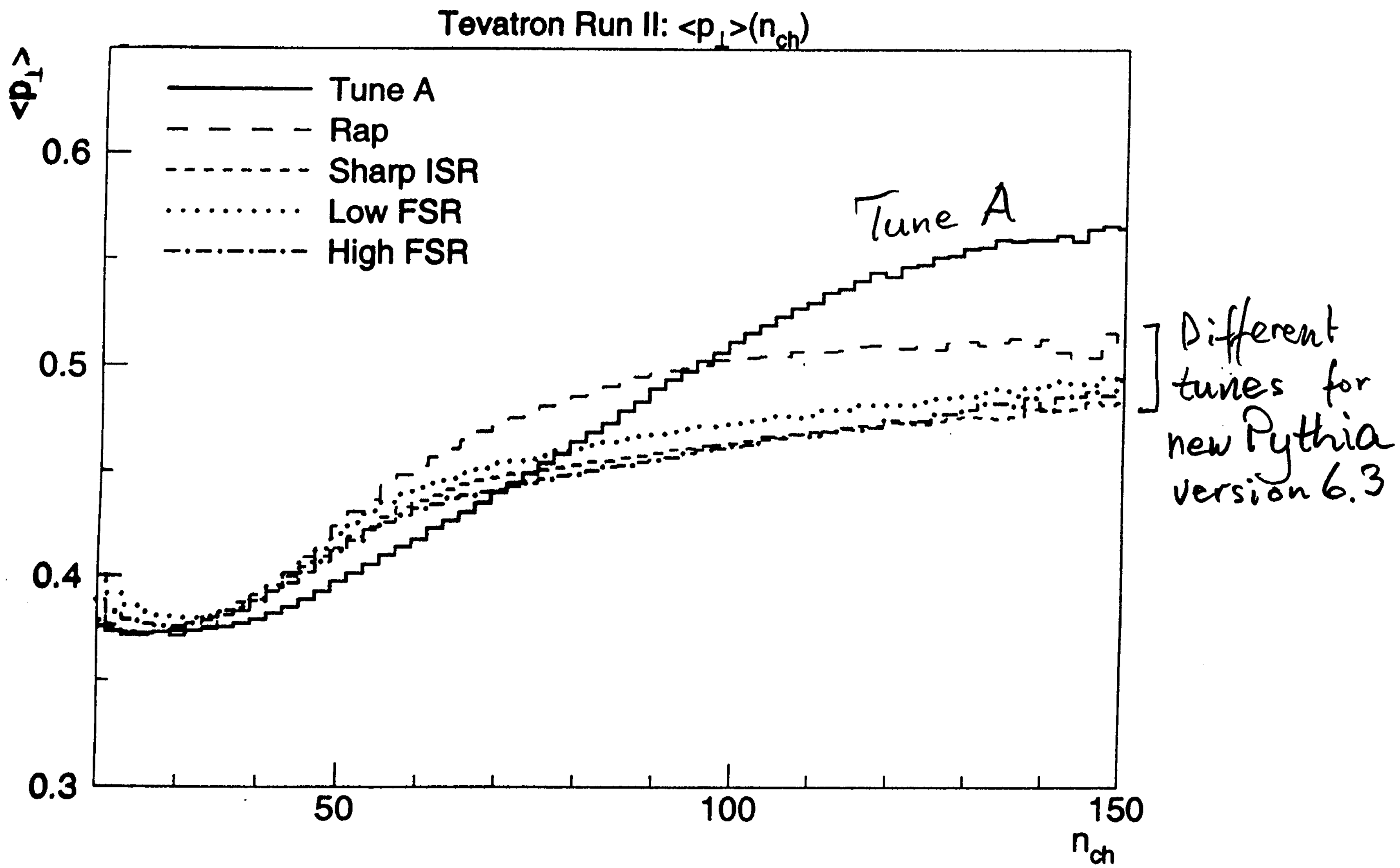
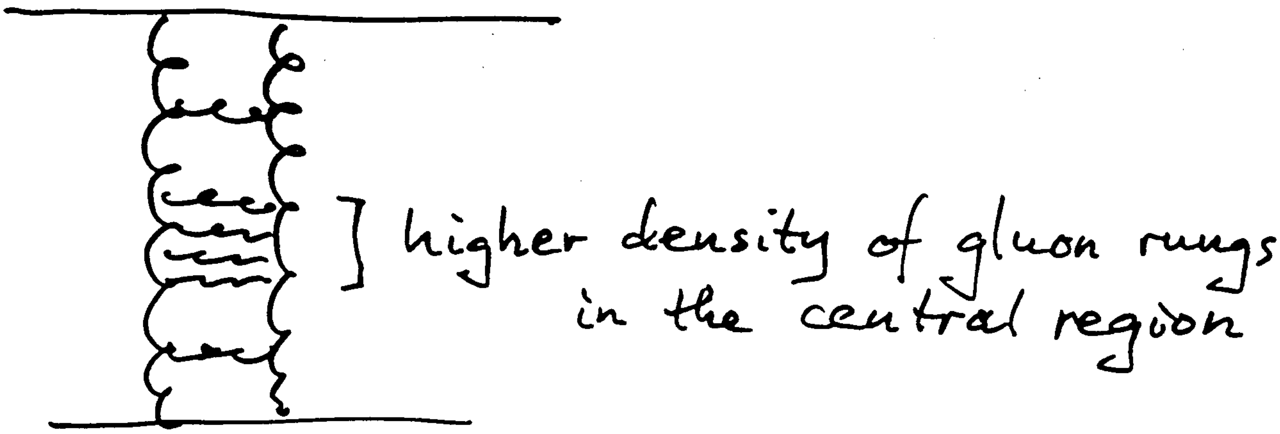


Figure 6: Average $p_\perp$ as a function of charged multiplicity, $\langle p_\perp \rangle (n_{\mathrm{ch}})$, for 1.96 TeV $\mathrm{p\overline{p}}$ minimum-bias events. Note that the origo of the plot is *not* at (0,0).

Looks like a single ladder



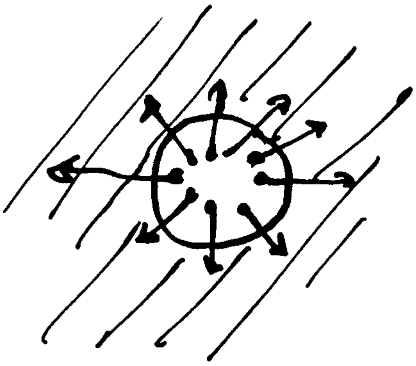
How can this be understood?

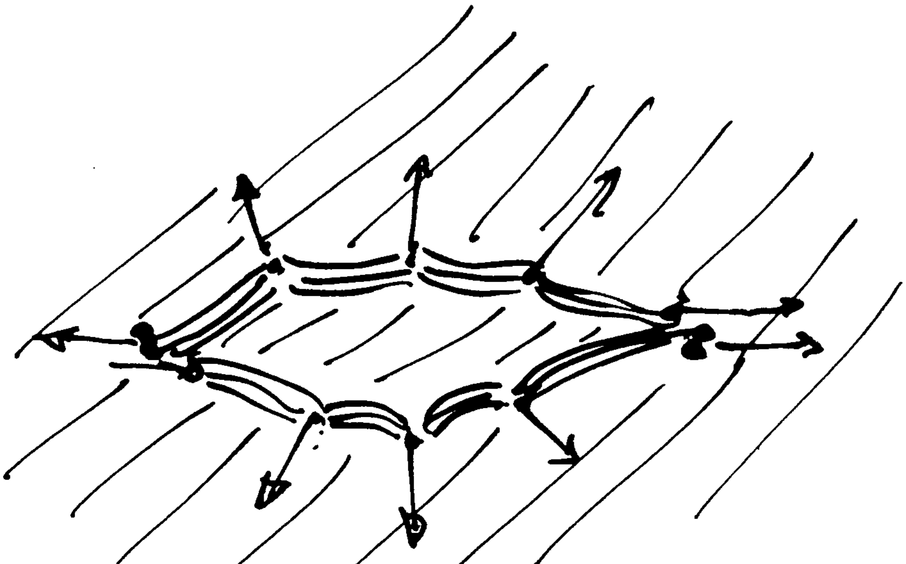
What does it imply for AGK and diffraction

Survival probability?

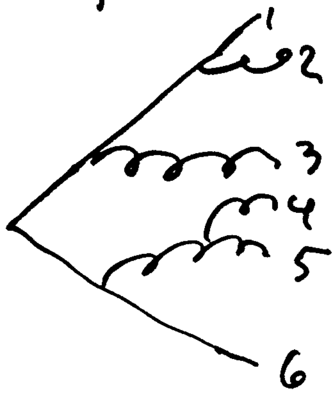
Does rescattering and unitarity constraints (and AGK) work in initial pert. phase?

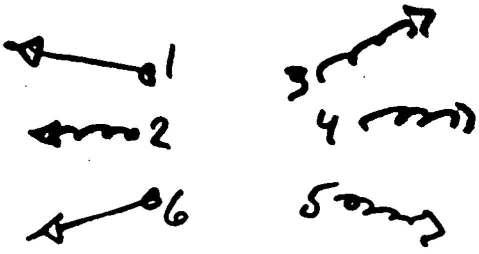
⇒ { Initial coll. inside a confining bag
Final state partons colour connected in a later non-pert. phase



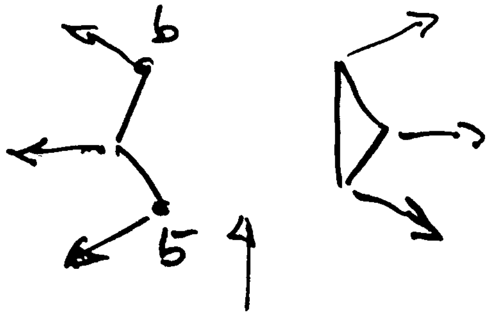


Cf. e^+e^--ann.

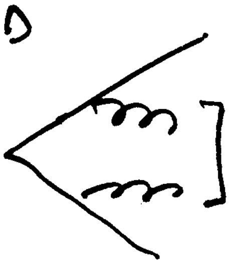




Shortest strings



Pert. QCD



colour singlet with prob. $\sim \frac{1}{N_c^2}$

Not even this small fraction is clearly seen

Why do the strings make the shortest connections in ~100% in pp, and almost never in e^+e^-?

How do multiplicity fluctuations and the relation diffraction <-> high mult. events reflect features of AGK in ep, γp and pp?

Summary

Pythia tune A fits many (all?) data at the Tevatron

Jets and E_t-flow: pQCD works OK

Important features can be related to Hera data on DIS.

Although non-integrated str. fcns not yet well determined

Multipl. distrib.: Non-pert. effects important

Colours seem to combine to give short strings

Very different from e^+e^--ann.

Do unitarity effects and AGK cutting rules work as expected in initial pert. phase?

How could this be tested at Hera or the Tevatron?

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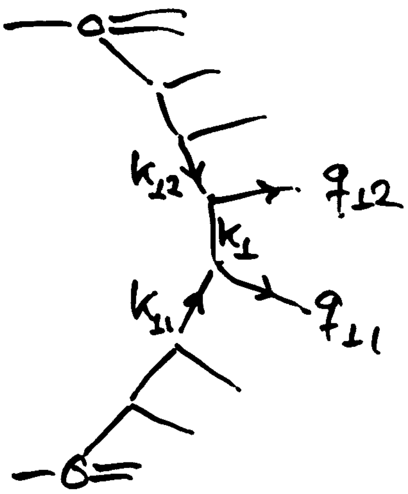

$k_\perp < k_{\perp 1}, k_{\perp 2}$ =>

Off shell ME does not blow up when $k_\perp \to 0$

$k_\perp$ does not determine jet $q_\perp$

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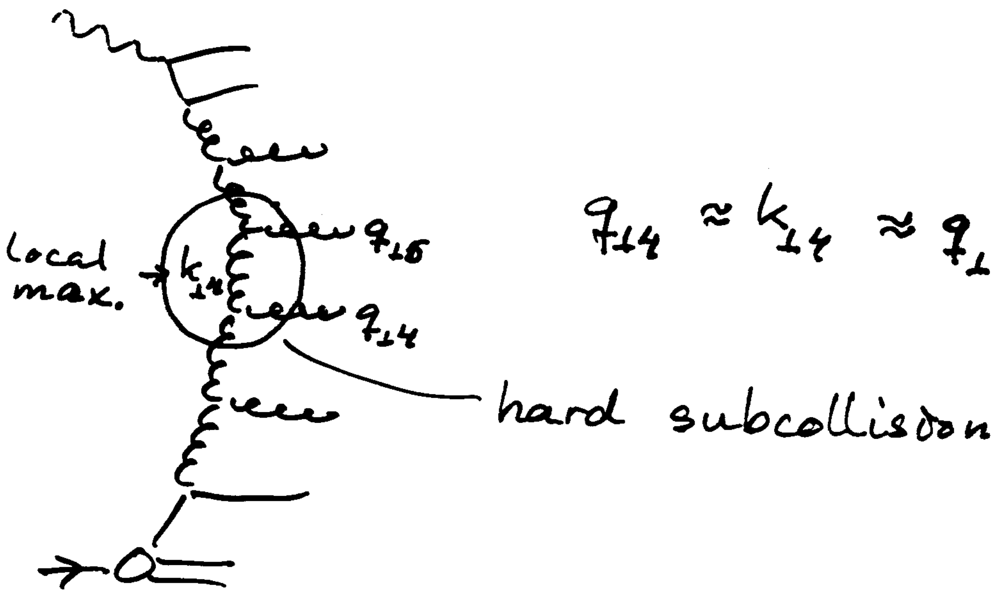
Small x, low $k_\perp$: BFKL region

Non-$k_\perp$-ordered parton chains important



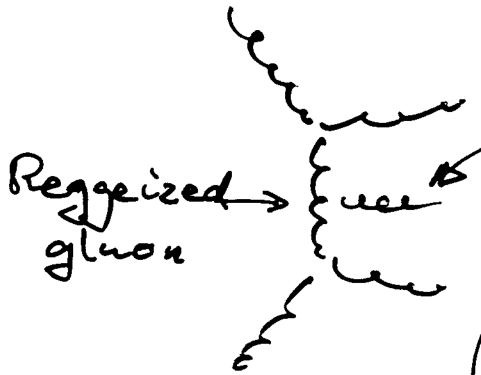
$q_{\perp 4} \approx k_{\perp 4} \approx q_{\perp 5}$

Single local max. → Resolved photon interaction

Several local maxima →

Correlated hard subcollisions

BFKL integral eq. only inclusive



soft emissions compensated by virtual corrections

- Do not contribute to parton distrib. (i.e. total cross sections)
- Do contribute to final state properties

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Some soft emissions included in initial state radiation ⇒

⇒ Extra suppression from non-eikonal form factors

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q final state rad. if $q_\perp < k_\perp$

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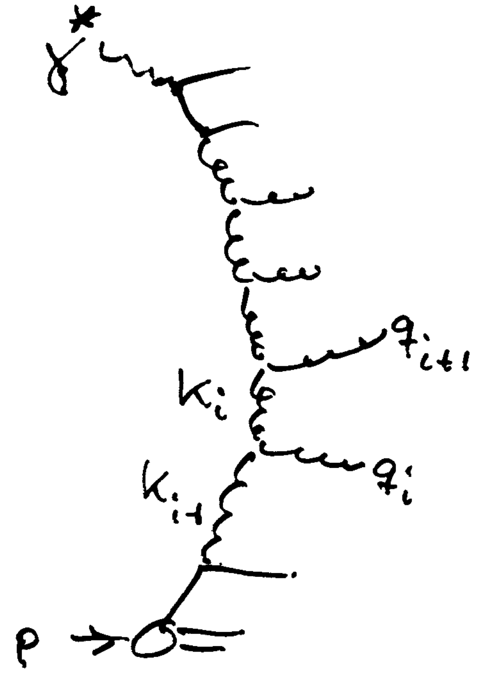
photon end – proton end



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$$\times\, \Theta(q_{\perp i} - \min(k_{\perp i}, k_{\perp i-1}))]$$

$$q_{\perp i}^2 \approx \max(k_{\perp i}^2, k_{\perp i-1}^2)$$

⇒ $\frac{d q_{\perp i}^2}{q_{\perp i}^2} \approx \frac{d k_{\perp i}^2}{k_{\perp i}^2}$ <u>except</u> local max or min.

Local max. ⇒ $\frac{d k_{\perp i}^2}{k_{\perp i}^4}$ hard subcoll.

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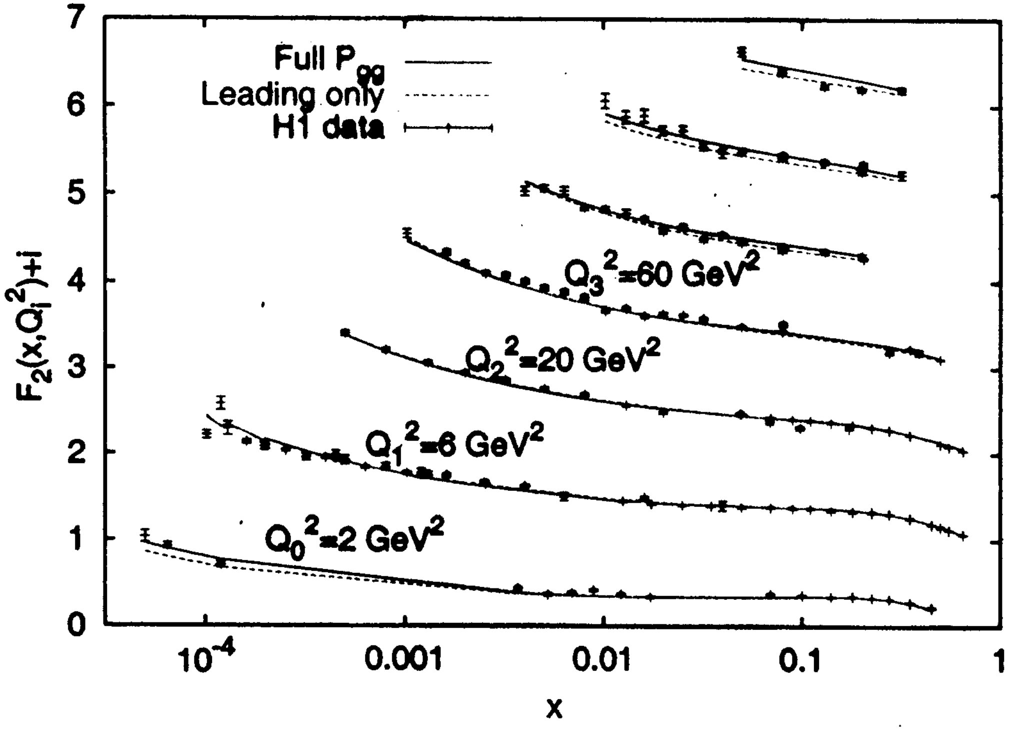
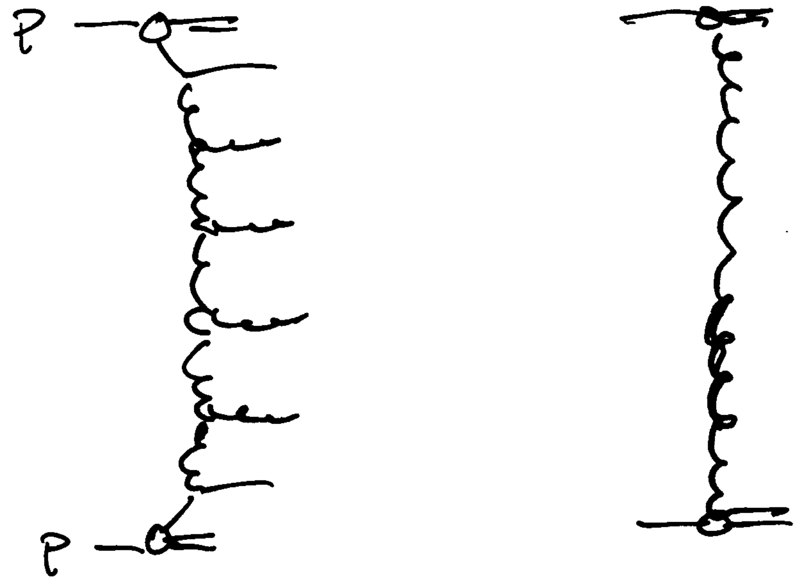


Potential problem

Fit to DIS: Running $\alpha_s \Rightarrow$

$\Rightarrow$ Soft cutoff Q_0 needed

Good fits to DIS data possible with different cuts, if input distrib. $f_0(x, Q_0^2)$ is adjusted accordingly

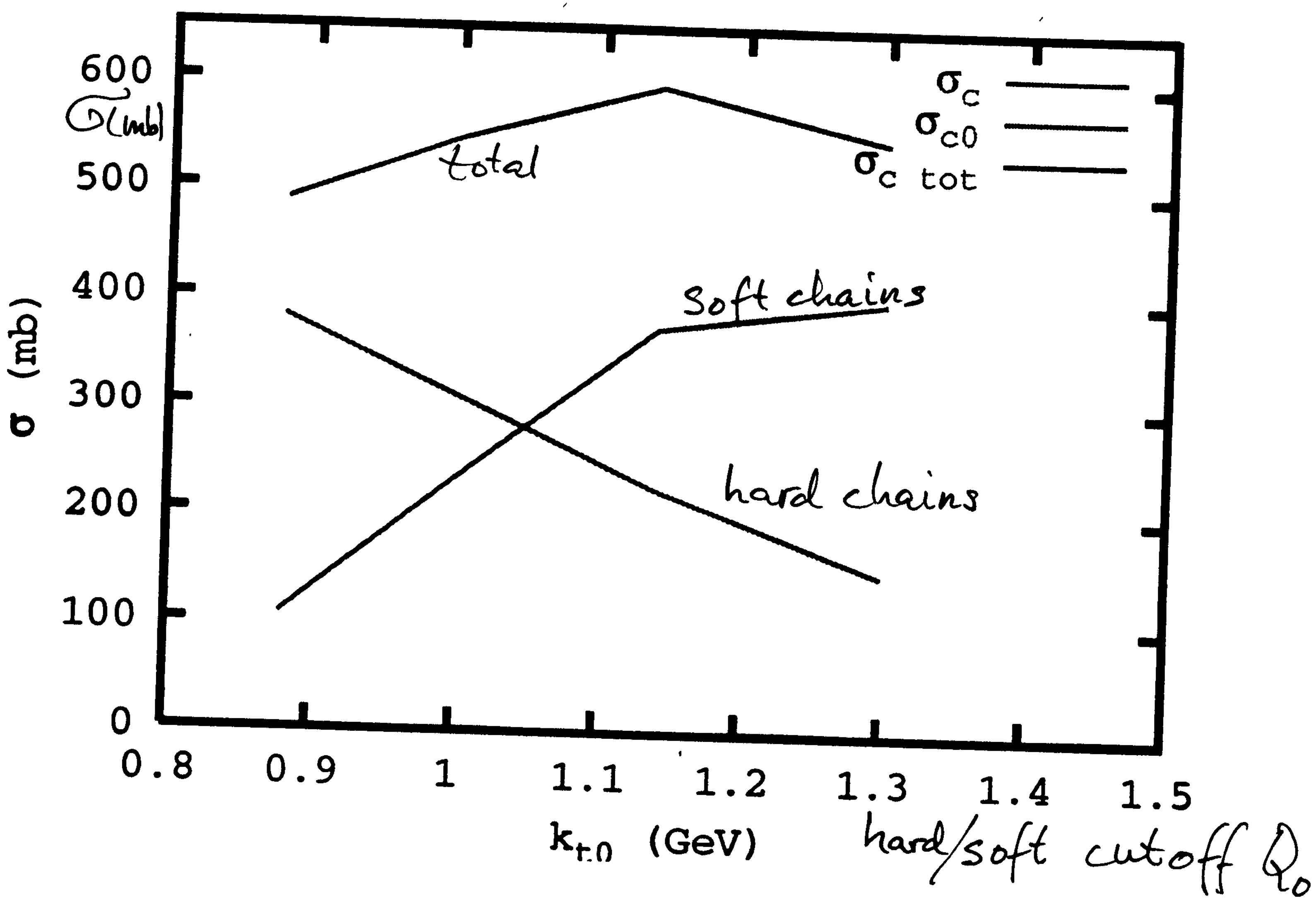


hard chain — $q_\perp > Q_0$

soft chain — $q_\perp < Q_0$

$Q_0^2 \nearrow \Rightarrow$ hard chain $\searrow$, soft chain $\nearrow$

G.G. - L. Lönnblad - G. Miu, 2002



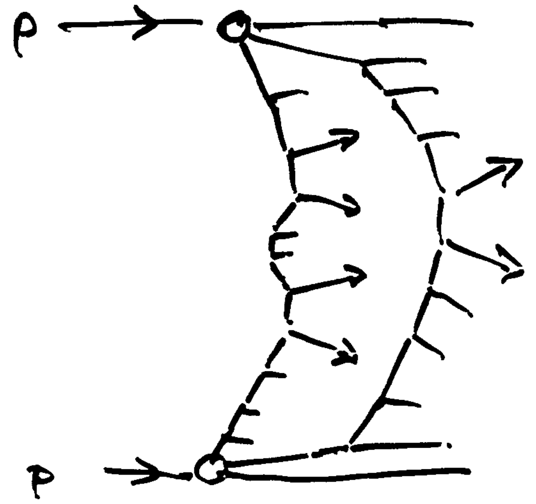
Total cross section for a chain
<u>independent</u> of the soft cutoff!

$\sigma_{chain} = \sigma_{hard\ chain} + \sigma_{soft\ chain}$

is <u>fixed from DIS</u>

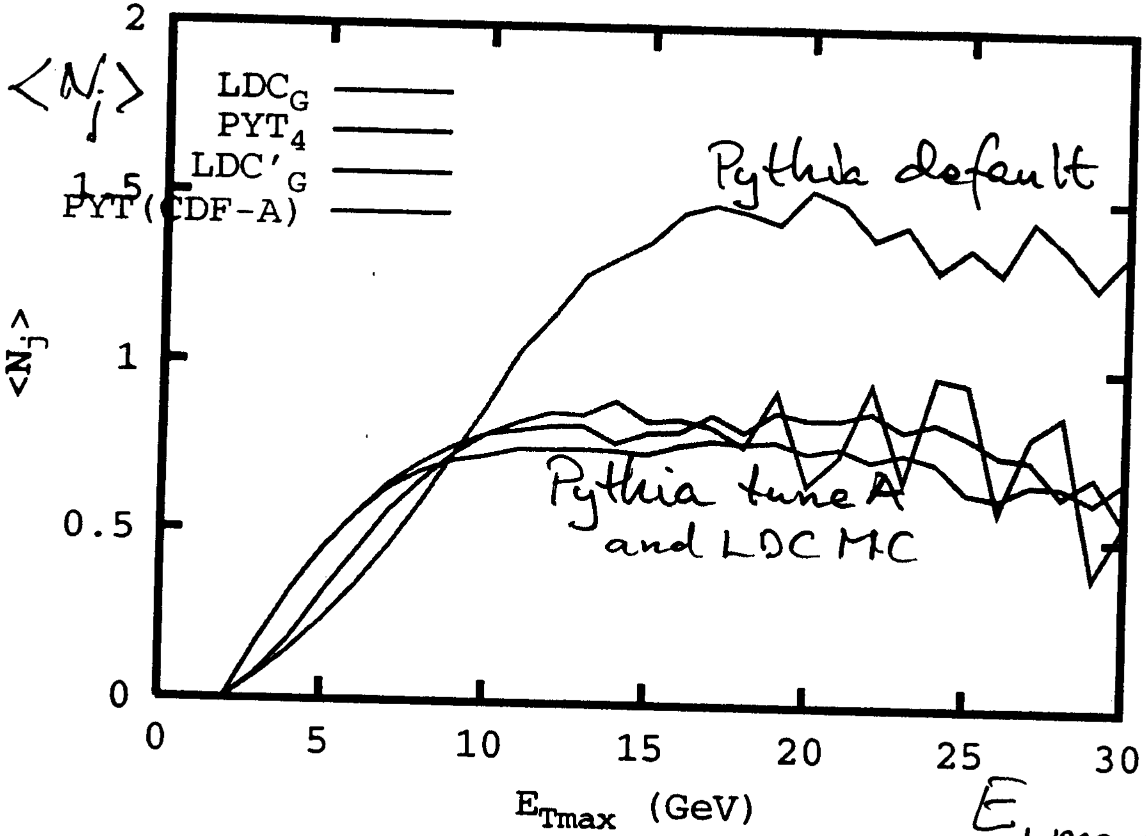
Relevanse for AGK cutting rules?
Does this reflect the number of exchanged $I\!P$?

<u>Multiple interactions</u> from 2 hard scatt.
in the same chain <u>and</u> from more than one chain in a single event.



Pythia: b-dep. double Gaussian → Geometric distr.
with tail reduced by energy cons.

Pedestal effect; # jets in min. azimuth
1.8 TeV $|\eta|<2.5$



LDCMC $k_{\perp 0}$:

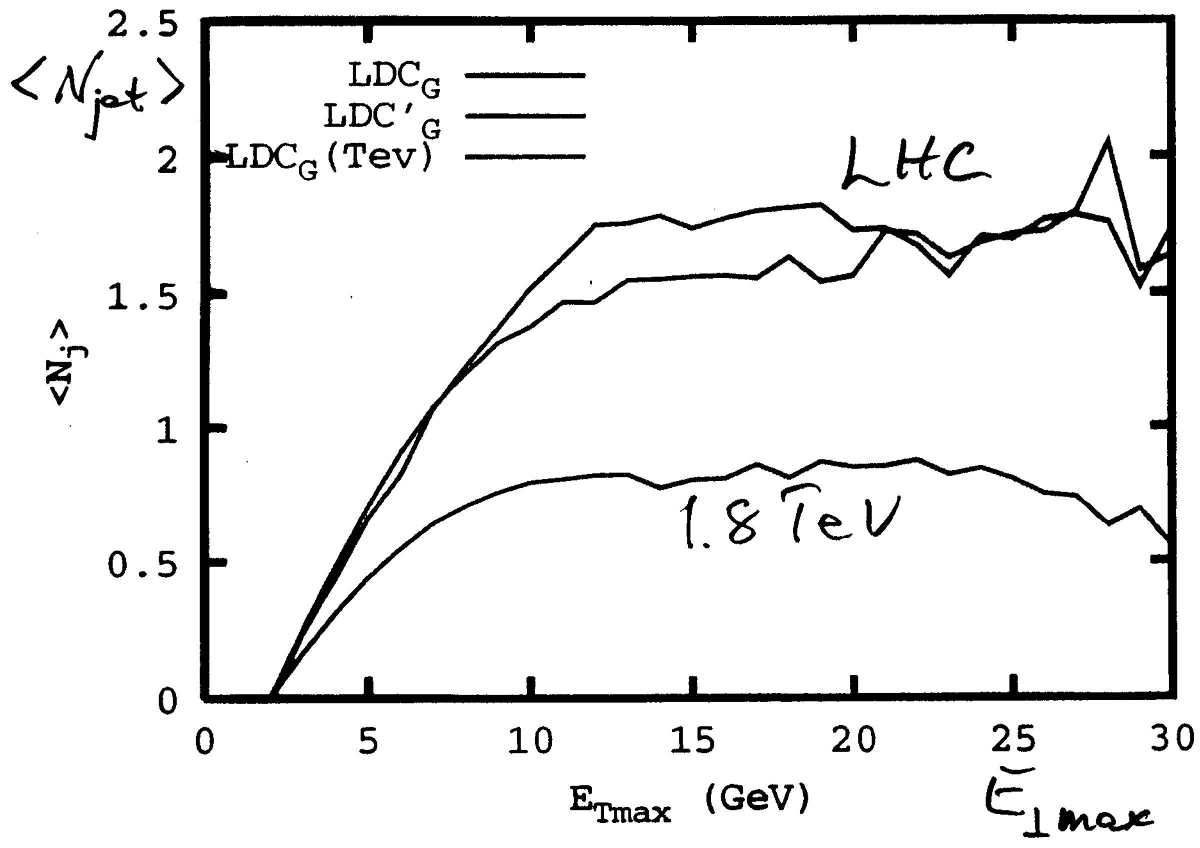
0.99 GeV→ 1.3 GeV

PYTHIA:

Default→CDF-A

LDCMC agrees with Pythia tune A
independent of cutoff

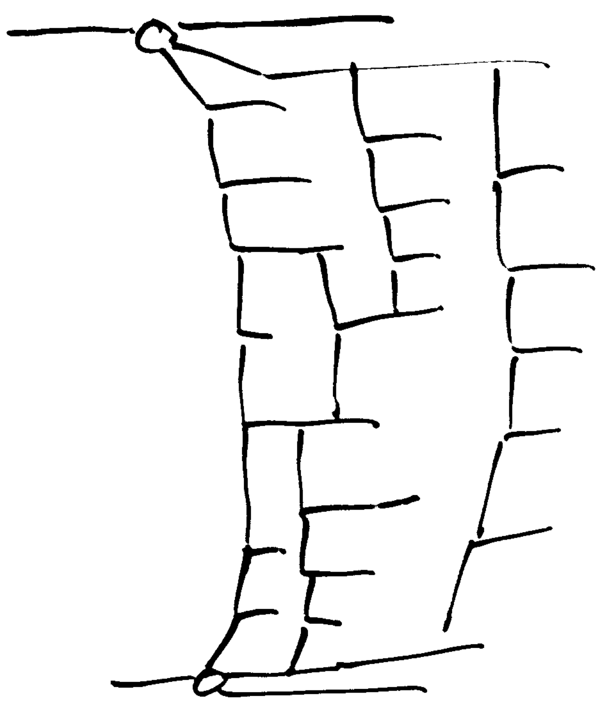
LHC ?



LDCMC $k_{\perp 0}$:

$0.99 \rightarrow 1.3$ GeV

Saturation



The chains join at one end at the same rate as they multiply at the other

Work on saturation in progress

Combine the LDC model with Mueller's dipole formulation in transverse coordinate space (relations to the Balitsky-Kovchegov eq.)

(Avsar - G.G. - Lönnblad)

II. Hadron multiplicities

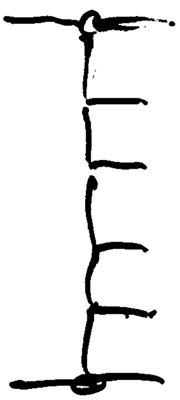
Depends on colour connections between produced partons.

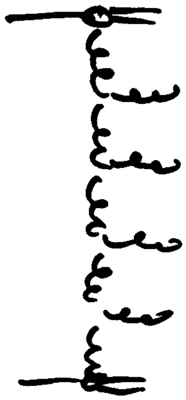
Non-pert. soft physics

Multiple interactions – multi $\mathbb{P}$ exchange

Abramovskiĭ - Gribov - Kancheli

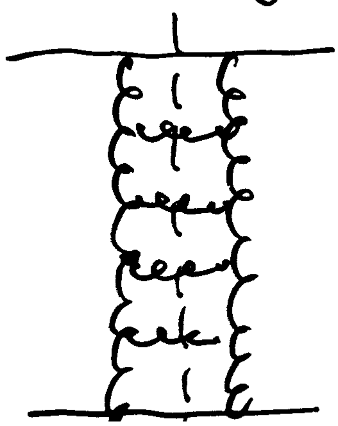
Multiperipheral model: Similar to gluon chain





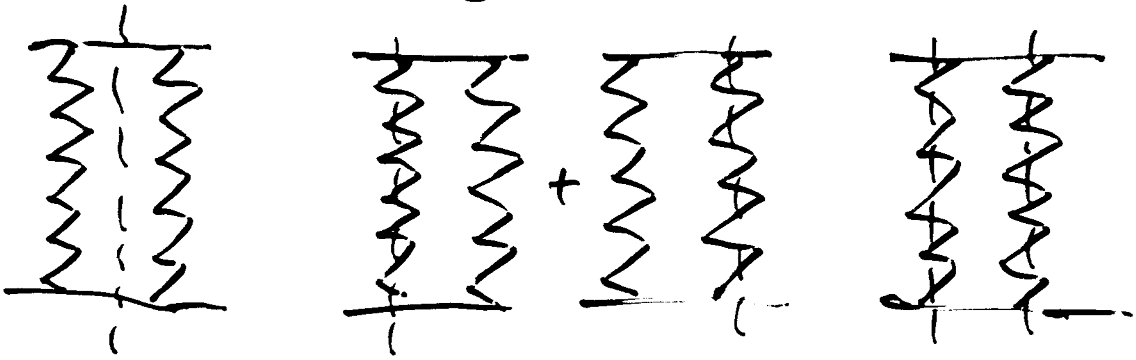
Small momentum exchange at each vertex

$\mathbb{P}$ = 2 gluon exchange



Multiple chains: Multi-IP exchange

AGK cutting rules



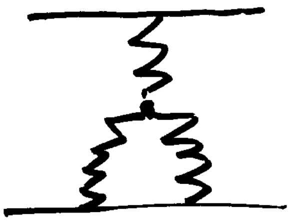
Rel. weight	1	−4	2

Contributes to multiplicity <u>fluctuations</u>

No effect on the # produced particles =

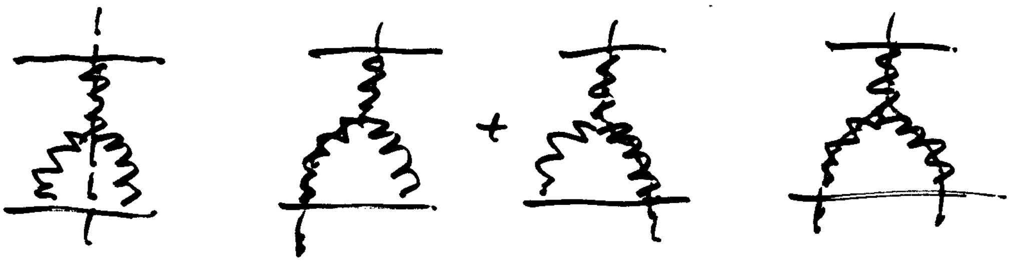
$= \sum n \sigma_n$

<u>3 IP coupling</u>



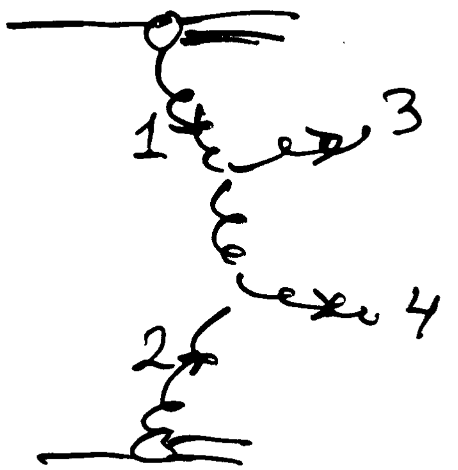
J Bartels et al.

Similar AGK cutting relations

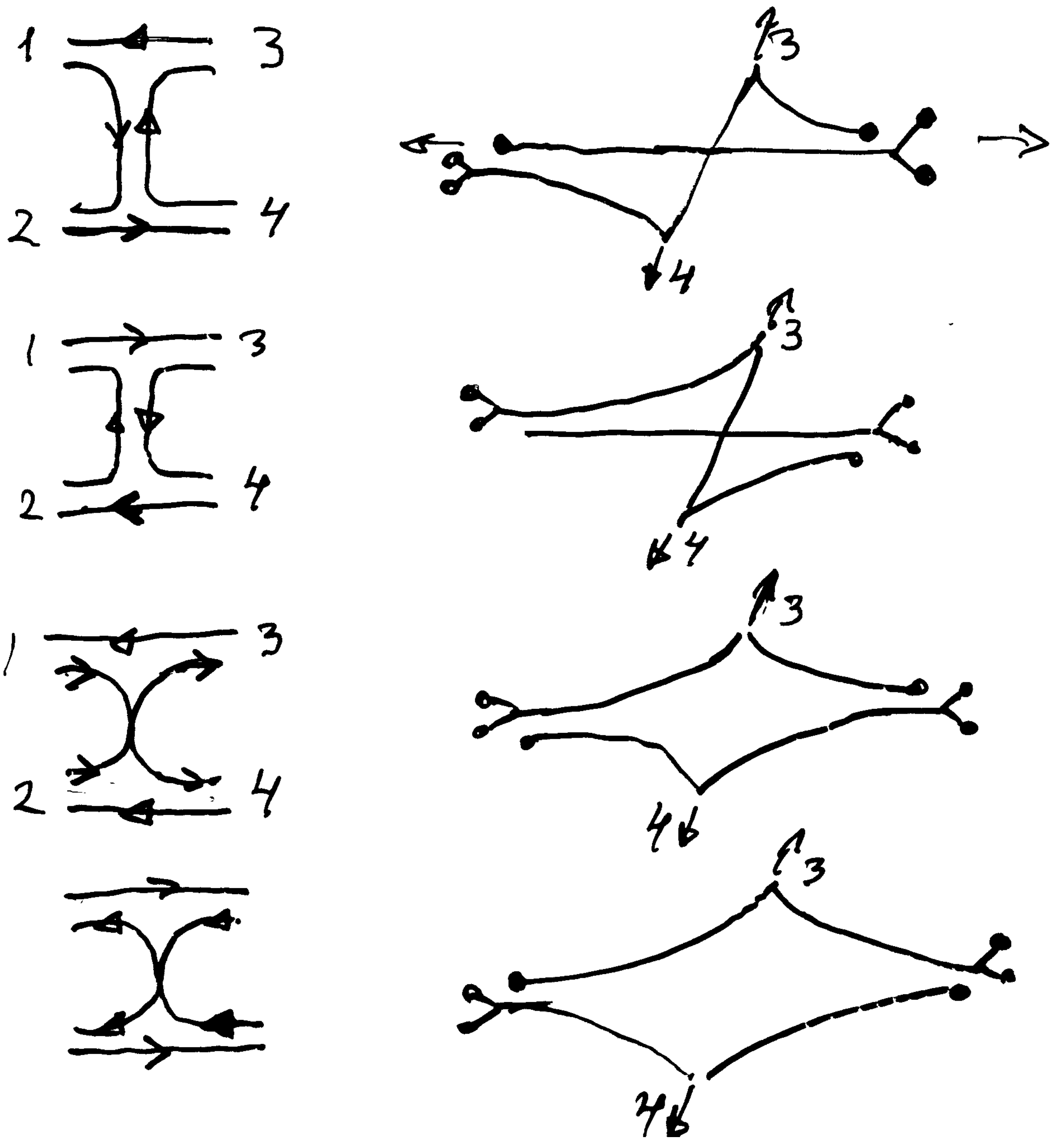


Expected to give smaller contributions ?

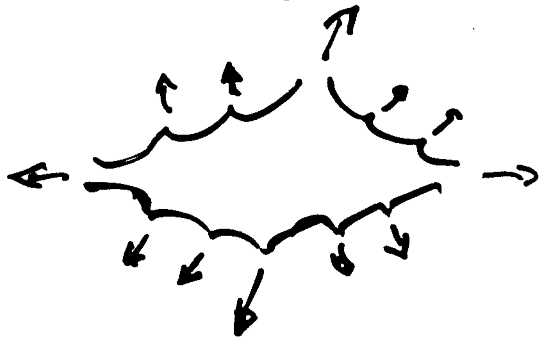
<u>Hard subcollision</u> $gg \to gg$

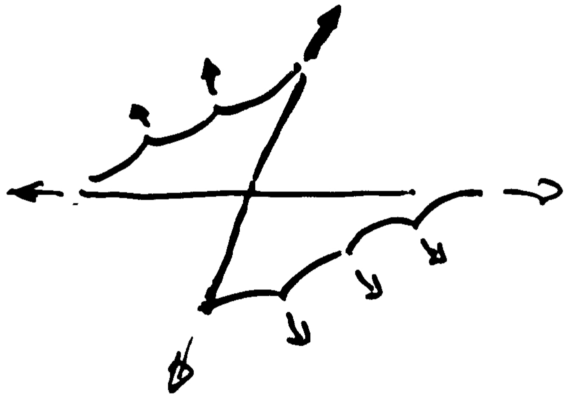


Possible colour connections:

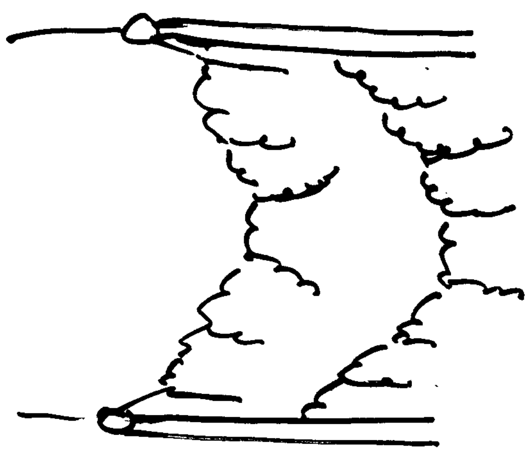


Including initial state radiation

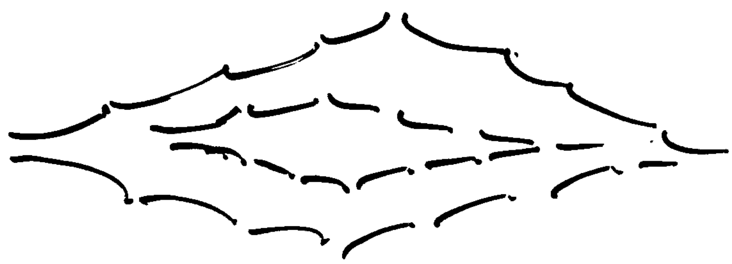




Multiple coll.



Expect



~ double multiplicity à la AGK

CDF data ⇒ Far from reality

Rick Field

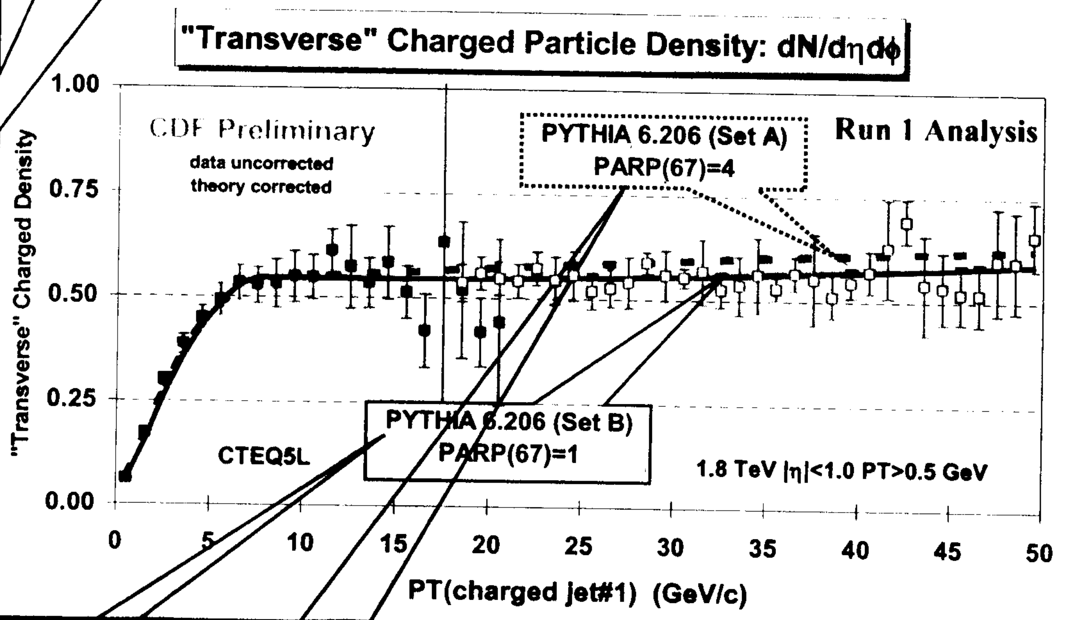
19

Tuned PYTHIA 6.206

Double Gaussian

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0



➡ Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

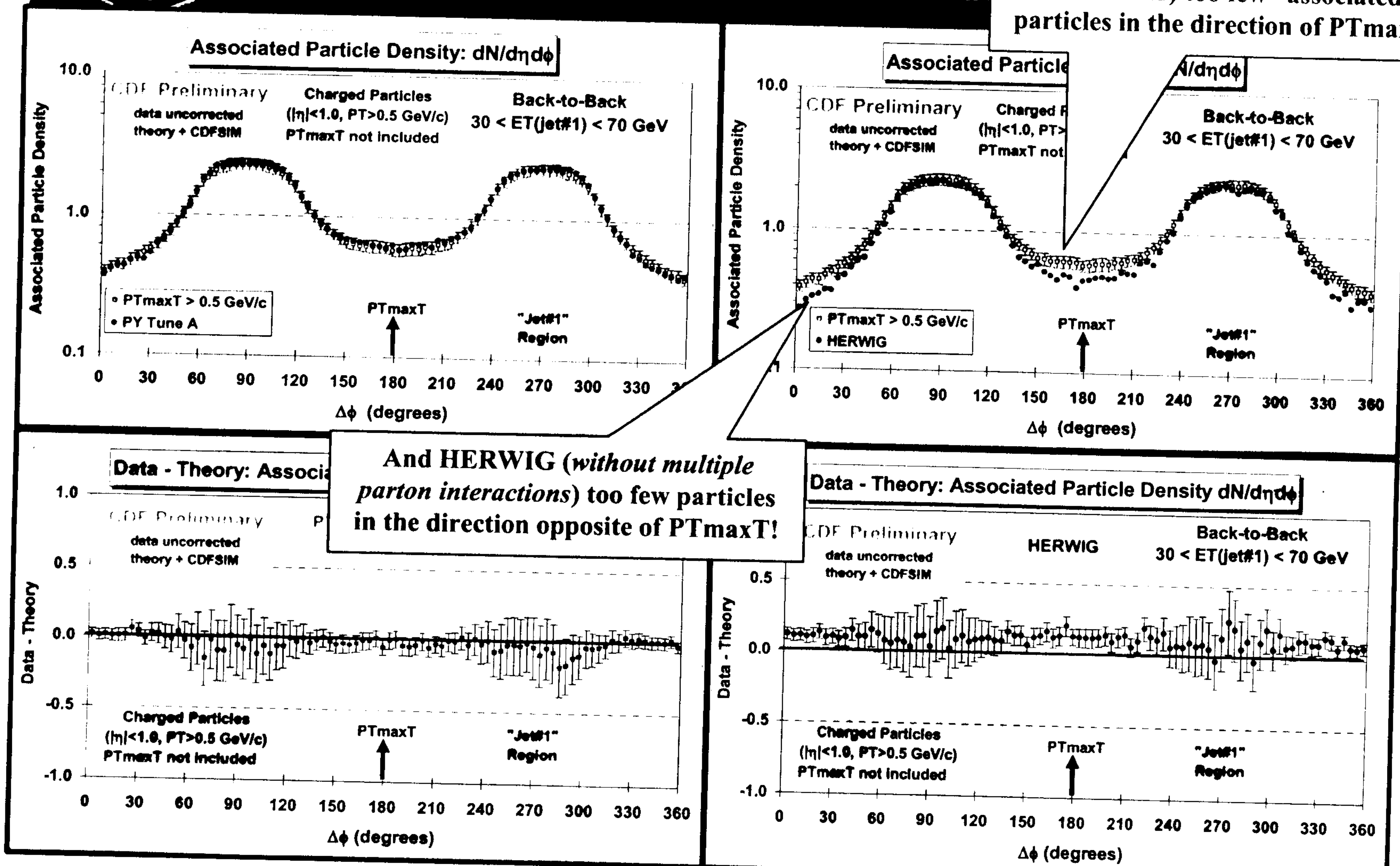
New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

Rick Field

"Associated" Charge Density PYTHIA Tune A vs HE[RWIG]

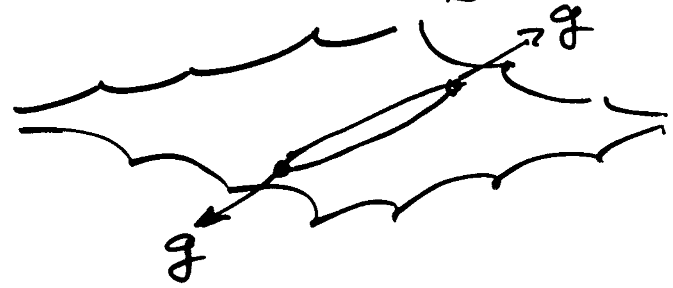
HERWIG (*without multiple parton interactions*) too few "associated" particles in the direction of PTmaxT!



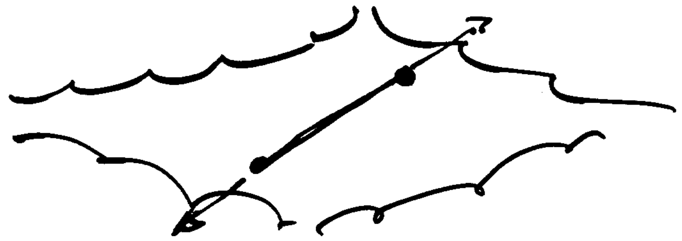
And HERWIG (*without multiple parton interactions*) too few particles in the direction opposite of PTmaxT!

Rick Field's successful tune A is a fit using an early Pythia version
Second hard scatt. has 3 possibilities

1) Extra closed string between gluons

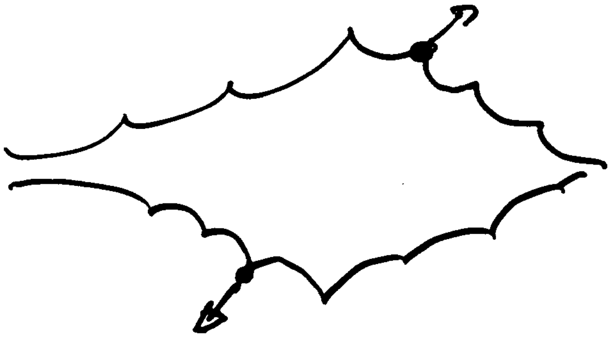


2) Single string in $q\bar{q}$ pair



lower multipl. increase

3) New gluons give extra kinks on initial strings with <u>minimal</u> extra string length



Tune A ~ 90%

Gives minimal extra multiplicity

<u>Note</u>: No connection to forward and backward ends of the system.

Default Pythia: Equal shares

<u>New</u> more advanced Pythia version
by Sjöstrand - Skands (Pythia 6.3)

Does <u>not</u> work as well as tune A (fig)

<u>CDF</u>: <u>Multiple interactions</u> definitely needed.
Data fitted if <u>colours rearranged</u> so that
secondary hard scatterings give
<u>minimum extra string length</u>.
i.e. — " — multiplicity

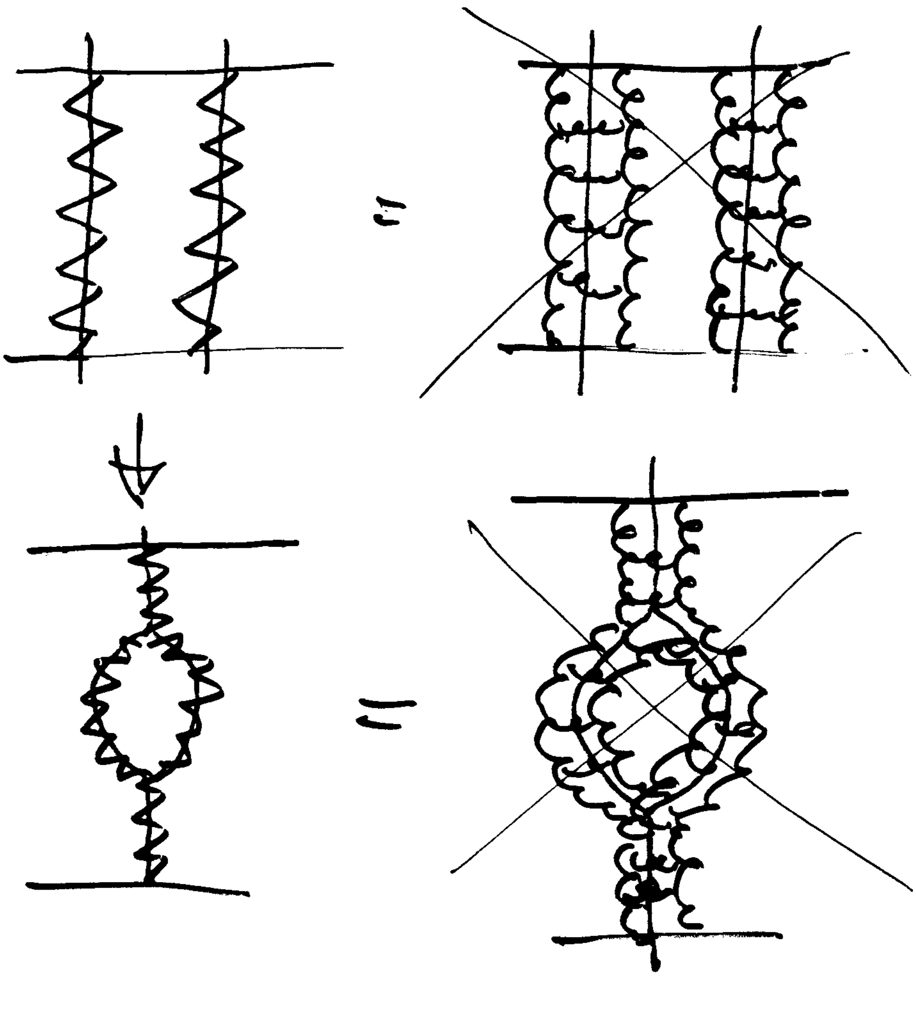


Figure 5: Charged multiplicity distributions, for 1.96 TeV $p\bar{p}$ minimum-bias events.

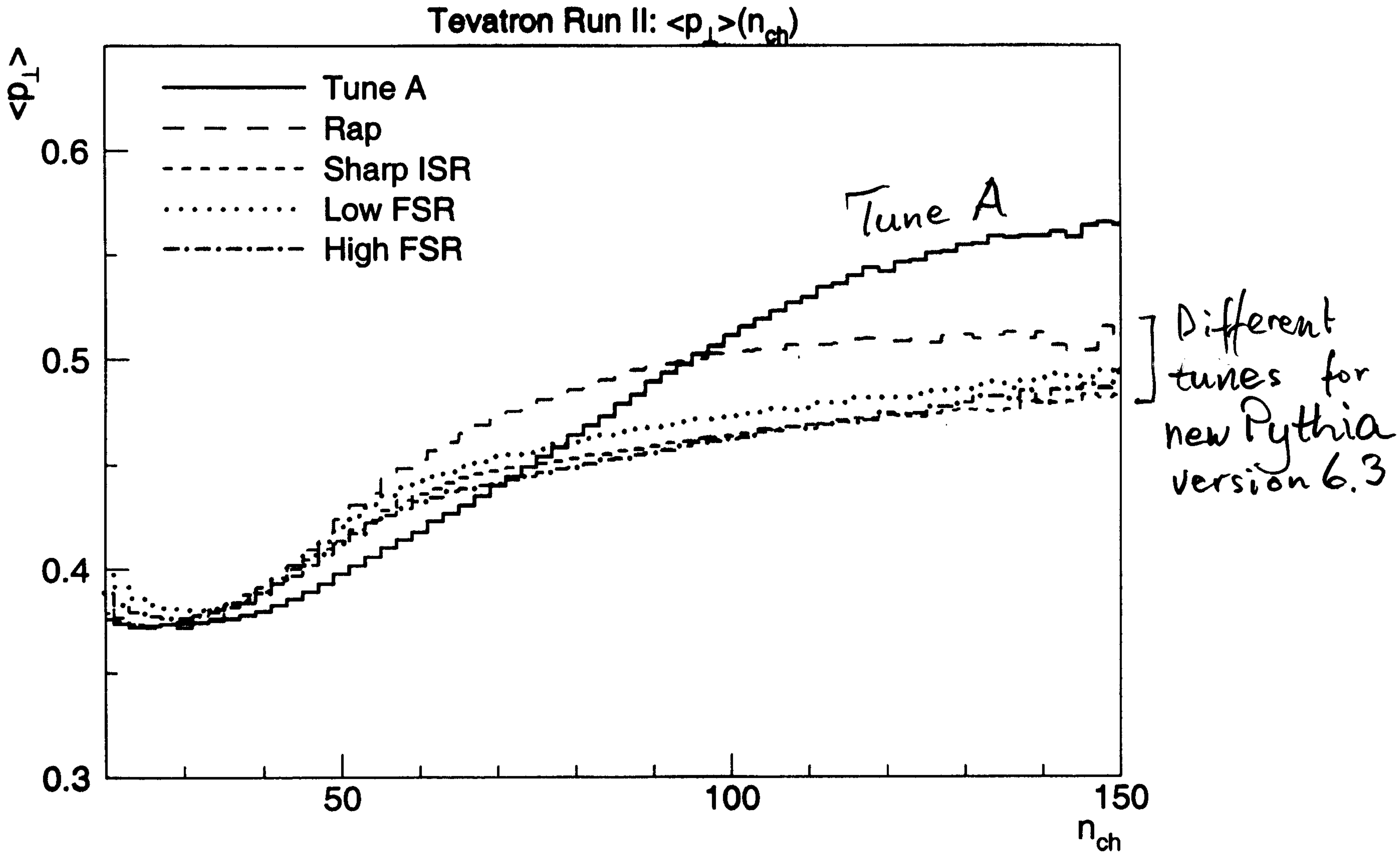
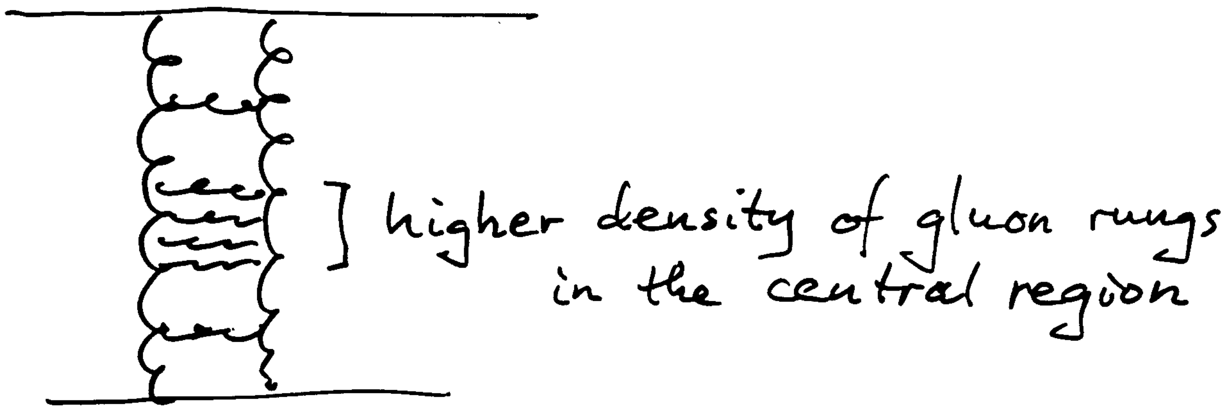


Figure 6: Average $p_\perp$ as a function of charged multiplicity, $\langle p_\perp \rangle (n_{\mathrm{ch}})$, for 1.96 TeV $p\bar{p}$ minimum-bias events. Note that the origo of the plot is *not* at (0,0).

Looks like a single ladder

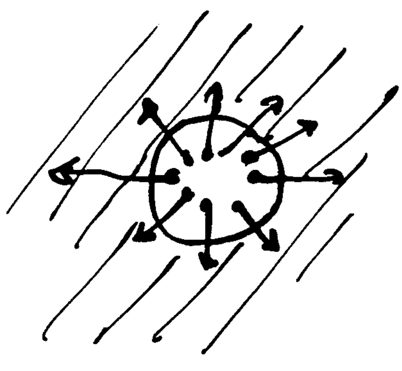


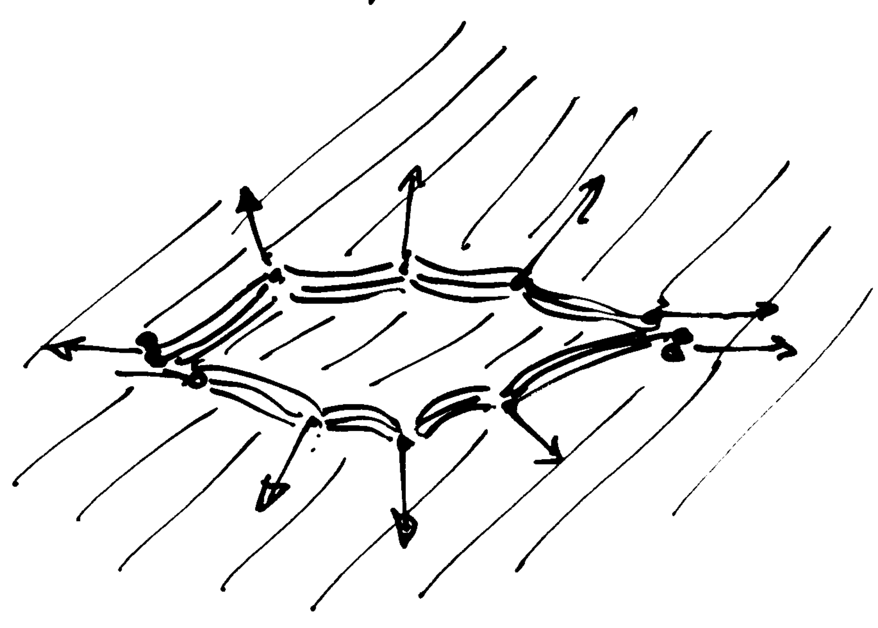
How can this be understood?

What does it imply for AGK and diffraction?
Survival probability?

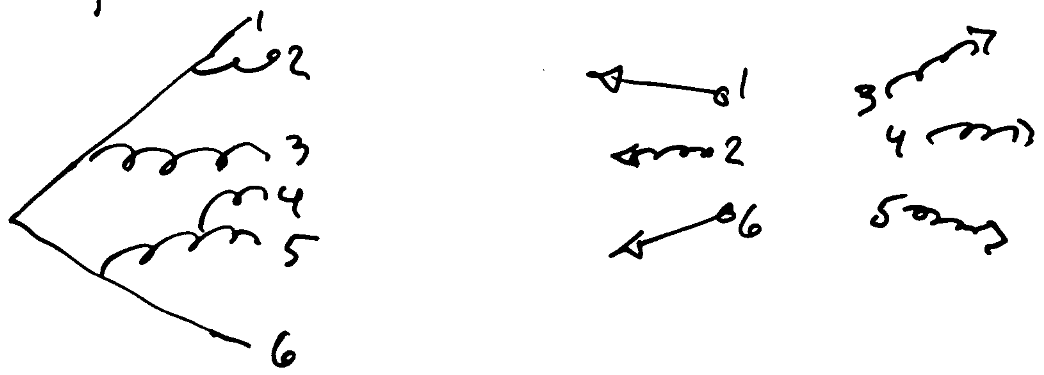
Does rescattering and unitarity constraints (and AGK) work in initial pert. phase?

⇒ Initial coll. inside a confining bag
Final state partons colour connected in a later non-pert. phase

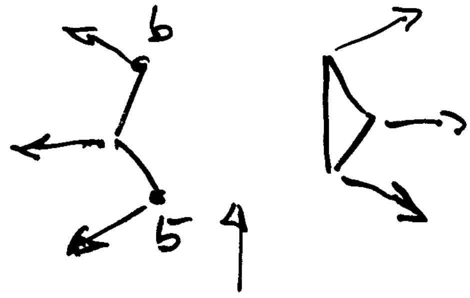




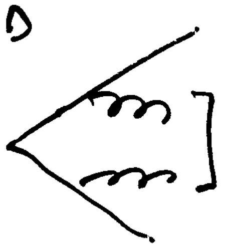
Cf. e^+e^--ann.



Shortest strings



Pert. QCD



] colour singlet with prob. $\sim \frac{1}{N_c^2}$

Not even this small fraction is clearly seen

Why do the strings make the shortest connections in ~100% in pp, and almost never in e^+e^-?

How do multiplicity fluctuations and the relation diffraction <-> high mult. events reflect features of AGK in ep, γp and pp?

Summary

Pythia tune A fits many (all?) data at the Tevatron

Jets and E_T-flow: pQCD works OK

Important features can be related to Hera data on DIS.

Although non-integrated str. fcns not yet well determined.

Multipl distrib.: Non-pert. effects important

Colours seem to combine to give short strings

Very different from e^+e^--ann.

Do unitarity effects and AGK cutting rules work as expected in initial pert. phase?

How could this be tested at Hera or the Tevatron?