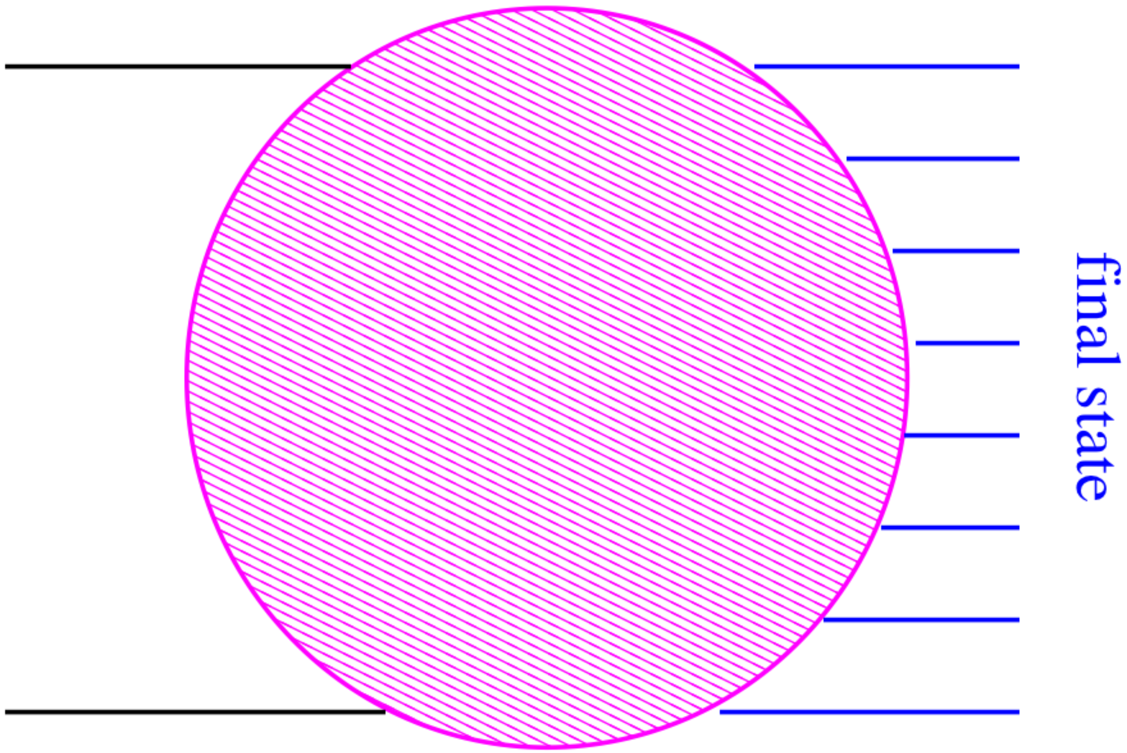
# Multiparton interactions and underlying events at HERA and the LHC

H. Jung (DESY, University Antwerp)

- Why are there multiparton interactions ?
- Experimental evidence for multiparton interactions
- Modeling of multiparton interactions
- Do we understand high density systems ?
- Prospects for LHC
- Outlook

# The general case

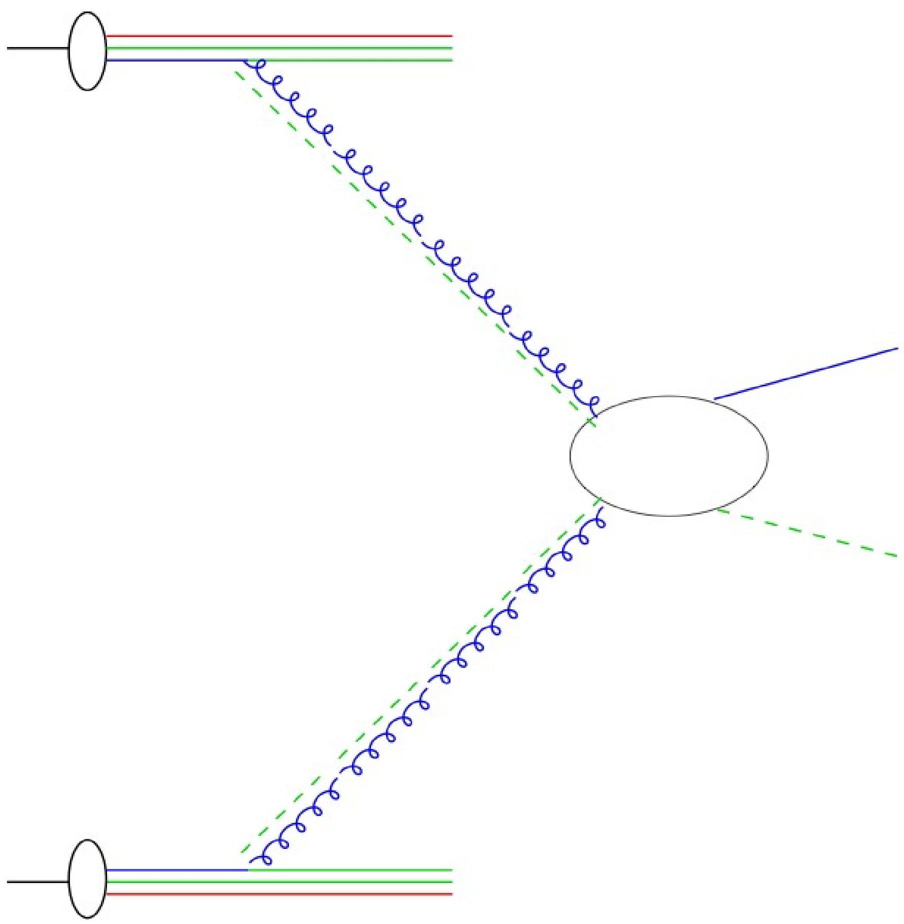
- Calculation of cross section of $A + B \rightarrow \text{anything}$




➔ Start with jet production ....

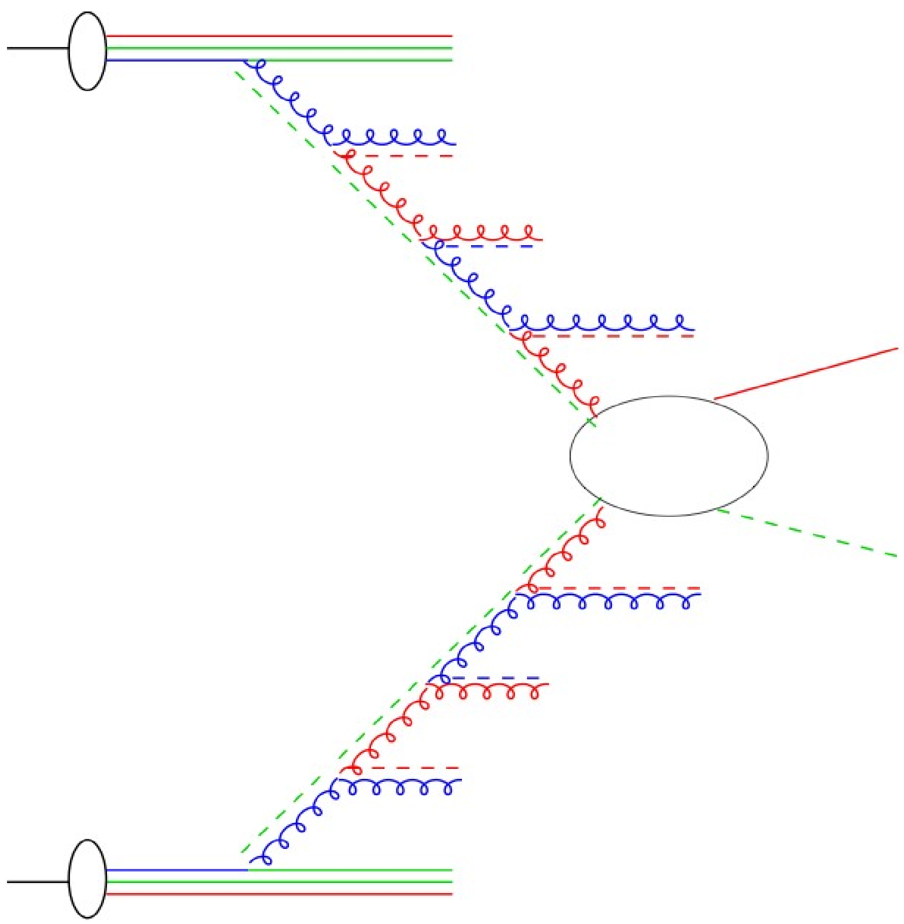
# Picture of jet production

- General approach to hard scattering processes



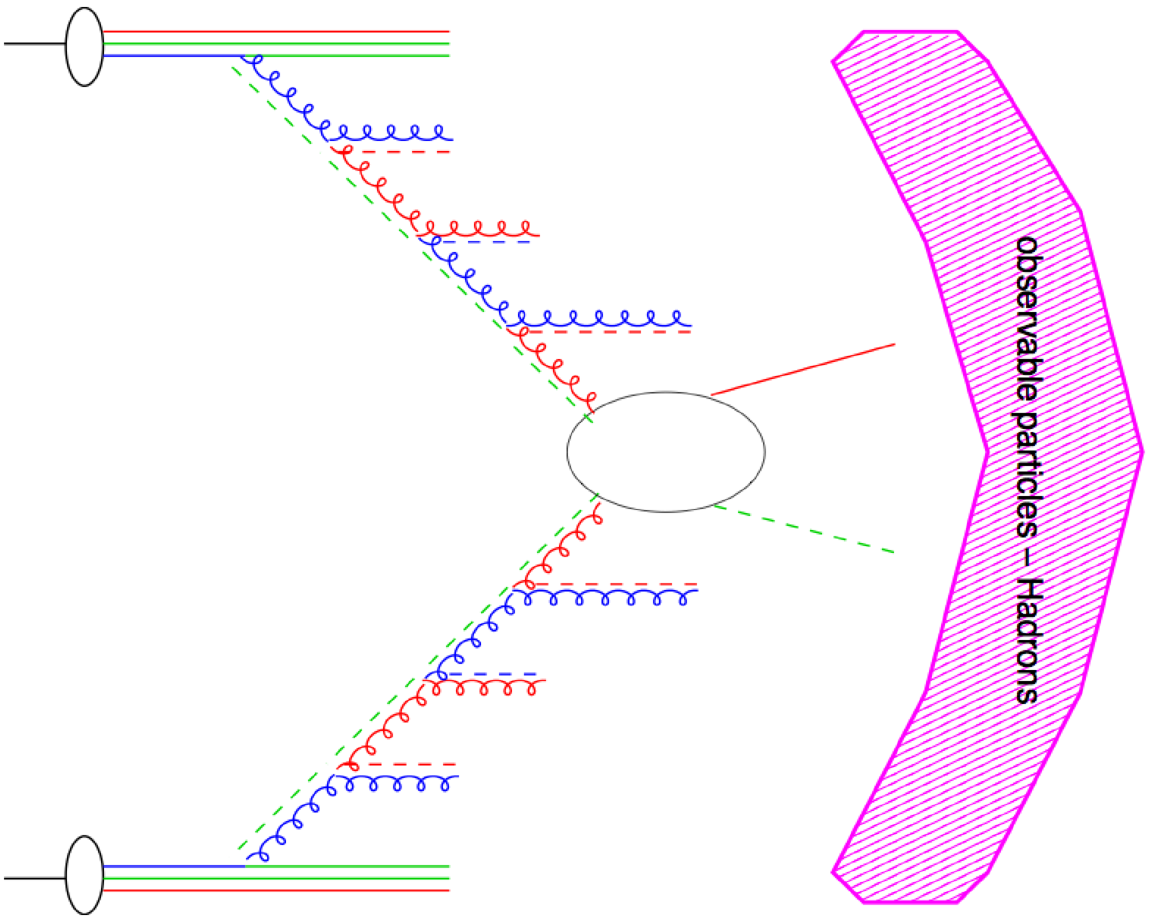
# Picture of jet production

- General approach to hard scattering processes
  - including higher order parton radiation



# Picture of jet production

- General approach to hard scattering processes
  - including higher order parton radiation
    - adding hadronization and fragmentation

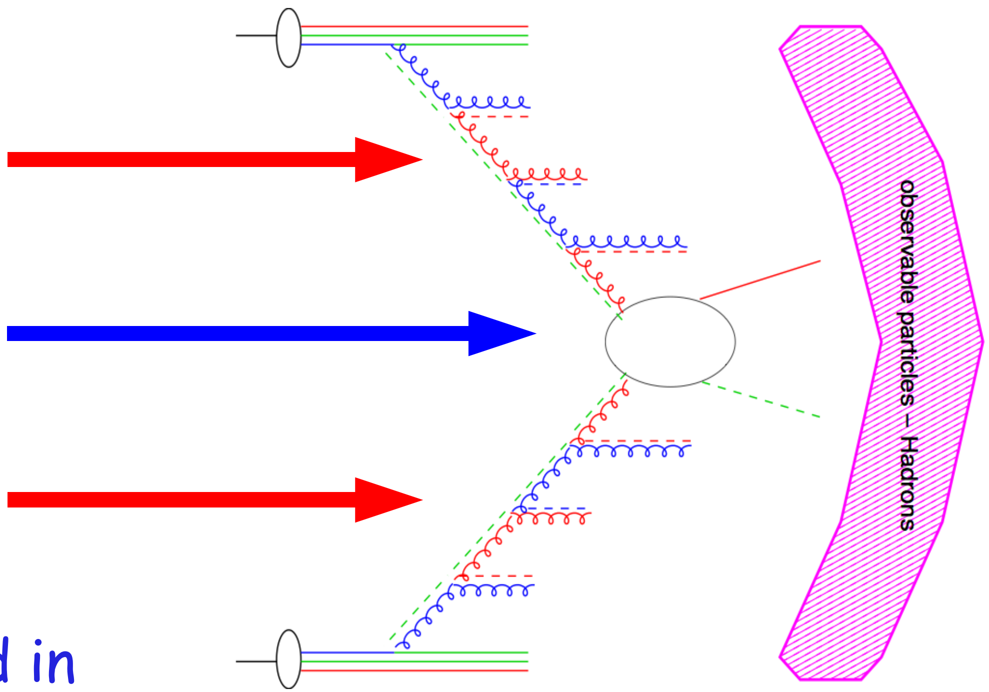


# Picture of jet production

- General approach to hard scattering processes
  - including higher order parton radiation
    - adding hadronization and fragmentation

➔ leads to the concept of factorization:

$$\sigma = f(x_1, \mu^2) \otimes \hat{\sigma}(x_1, x_2, \mu^2) \otimes f(x_2, \mu^2)$$




➔ factorization ansatz is used in

**any calculation (LO,NLO, MC event generators ...)**

# Where is factorization applicable ?

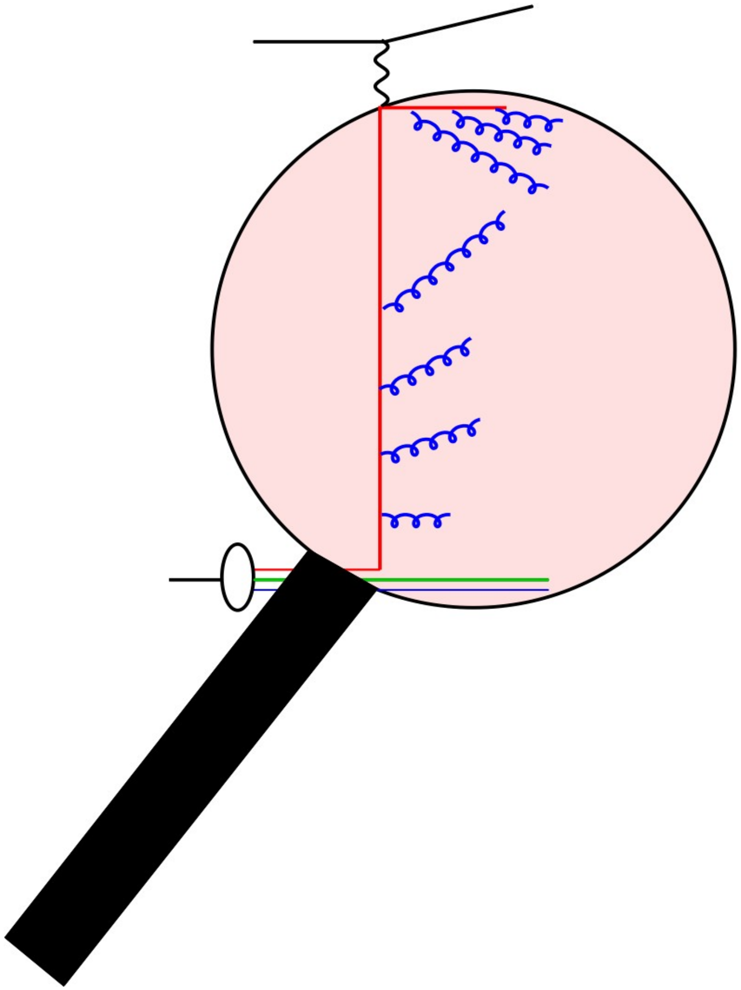
- **Factorization is only proven for a few processes !!!!!**
- Factorization Theorem in DIS (Collins, Soper, Sterman, (1989) in Pert. QCD, ed. A.H. Mueller, Wold Scientific, Singapore, p1.)
- explicit factorization theorems exist for:
  - diffractive DIS (... see above....)
  - Drell Yan (in hadron hadron collisions)
  - single particle inclusive cross sections (fragmentation functions)
- About factorization proofs (Wu-Ki Tung, pQCD and the parton structure of the nucleon, 2001, In *Shifman, M. (ed.): At the frontier of particle physics, vol. 2* 887-971)

tions $F_a^\lambda(x, \frac{Q}{m}, \alpha_s(\mu))$ ($a$ = all parton flavors). Although the underlying physical ideas are relatively simple, as emphasized in the last two sections, the mathematical proofs are technically very demanding.[7,15,19] For this reason, actual proofs of factorization only exist for a few hard processes; and certain proofs (e.g. that for the Drell-Yan process) stayed controversial for some time before a consensus were reached.[15] Because of the general character of the physical ideas and the mathematical methods involved, however, it is generally *assumed* that the attractive *quark-parton model does apply to all high energy interactions* with at least one large energy scale.

Factorization needs PDFs.

How to obtain PDFs
at highest energies ?

# DIS: the probe for high energy PDFs



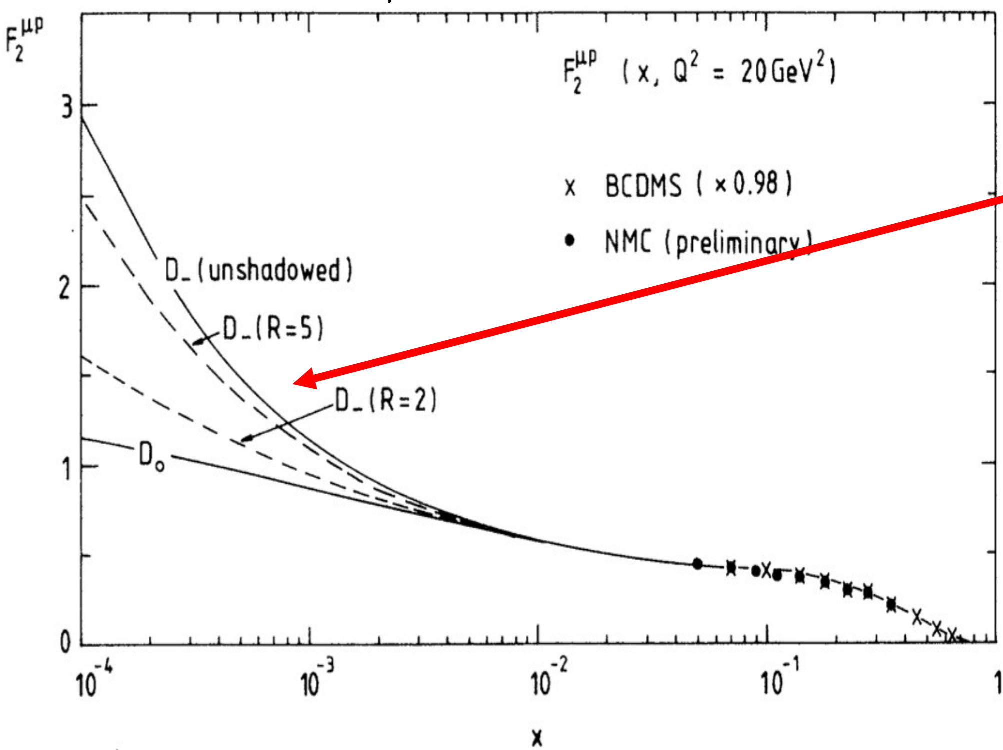
- Deep Inelastic Scattering is a incoherent sum of $e^+q \to e + q$
- only 50 % of p momentum carried by quarks
- need a large gluon component
- partonic part convoluted with parton density function $f_i(x)$
- BUT we know, PDF depends on resolution scale $Q^2$

$$\sigma(e^+p \to e^+X) = \sum_i f_i(x, Q^2)\sigma(e^+q_i \to e^+q_i)$$

# Remember the pre-HERA times

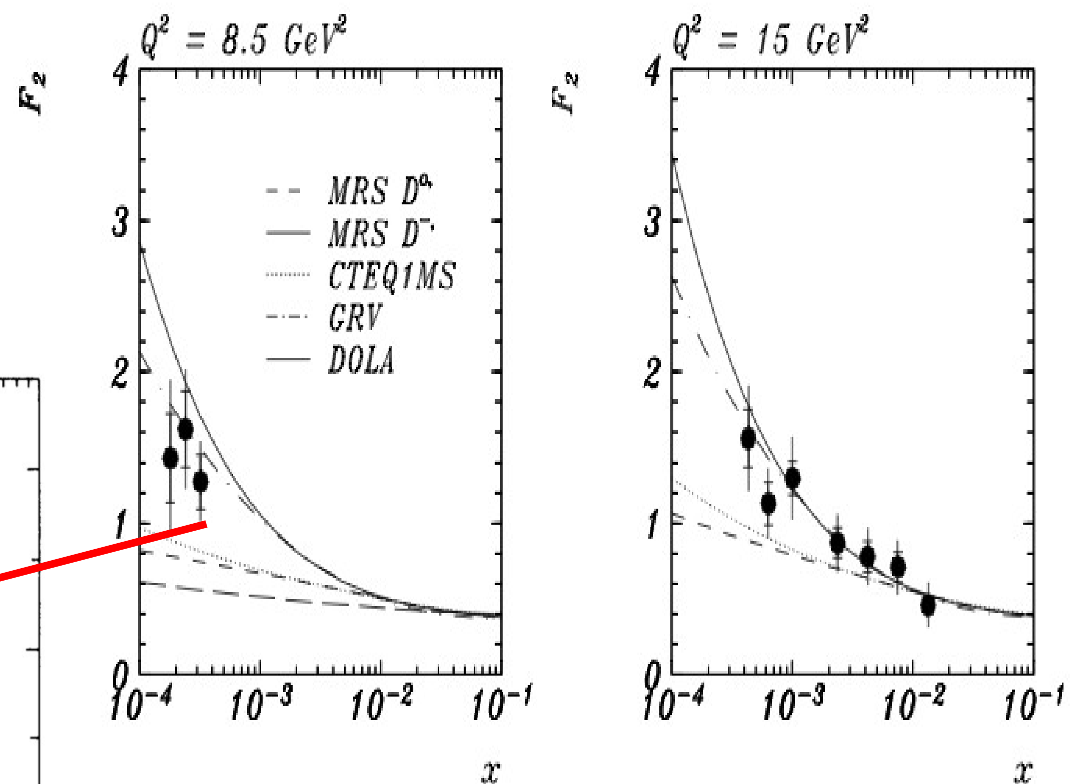
- Just before HERA started in 1992, new PDF fits (NLO DGLAP) were released, using all existing high precision data

Martin, Stirling, Roberts Apr 1992.
Phys.Rev.D47:867-882,1993.

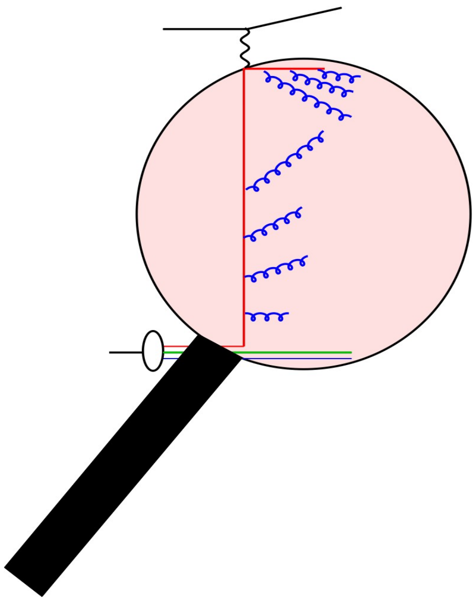



- 1st HERA data 1992

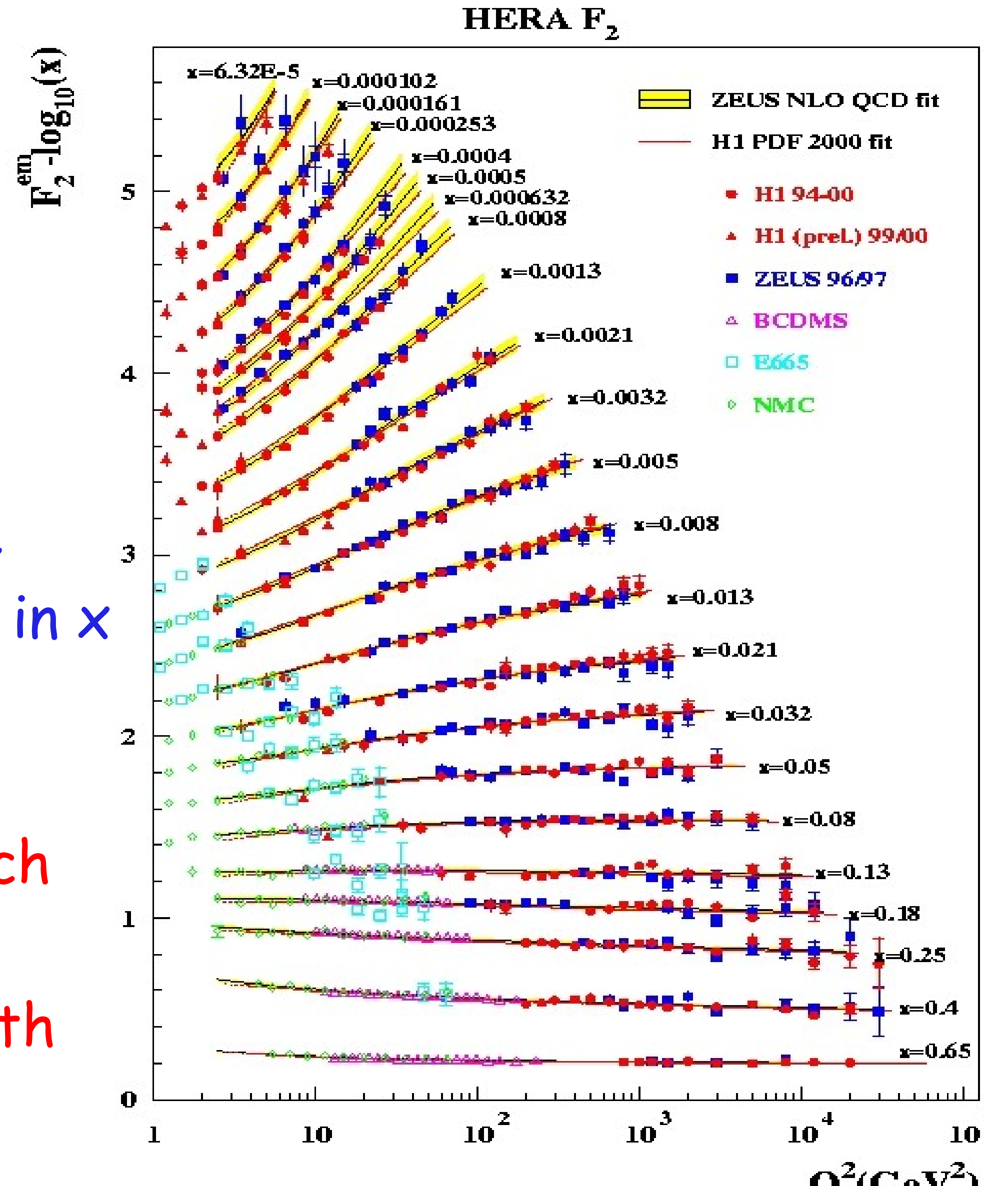
H1 Nucl. Phys. B407 (1993) 515



# DIS: obtain precise PDFs



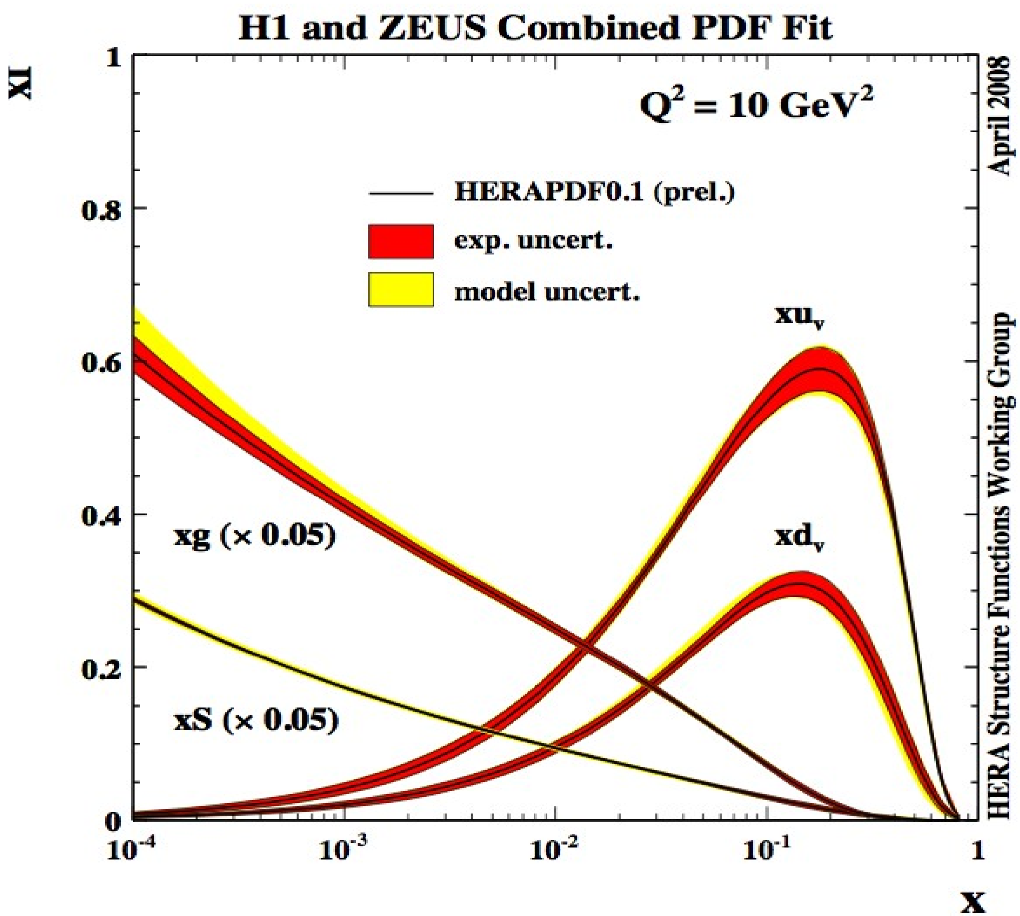
$$\sigma(e^+p \to e^+X) = \sum f_i(x, Q^2)\sigma(e^+q_i \to e^+q_i)$$

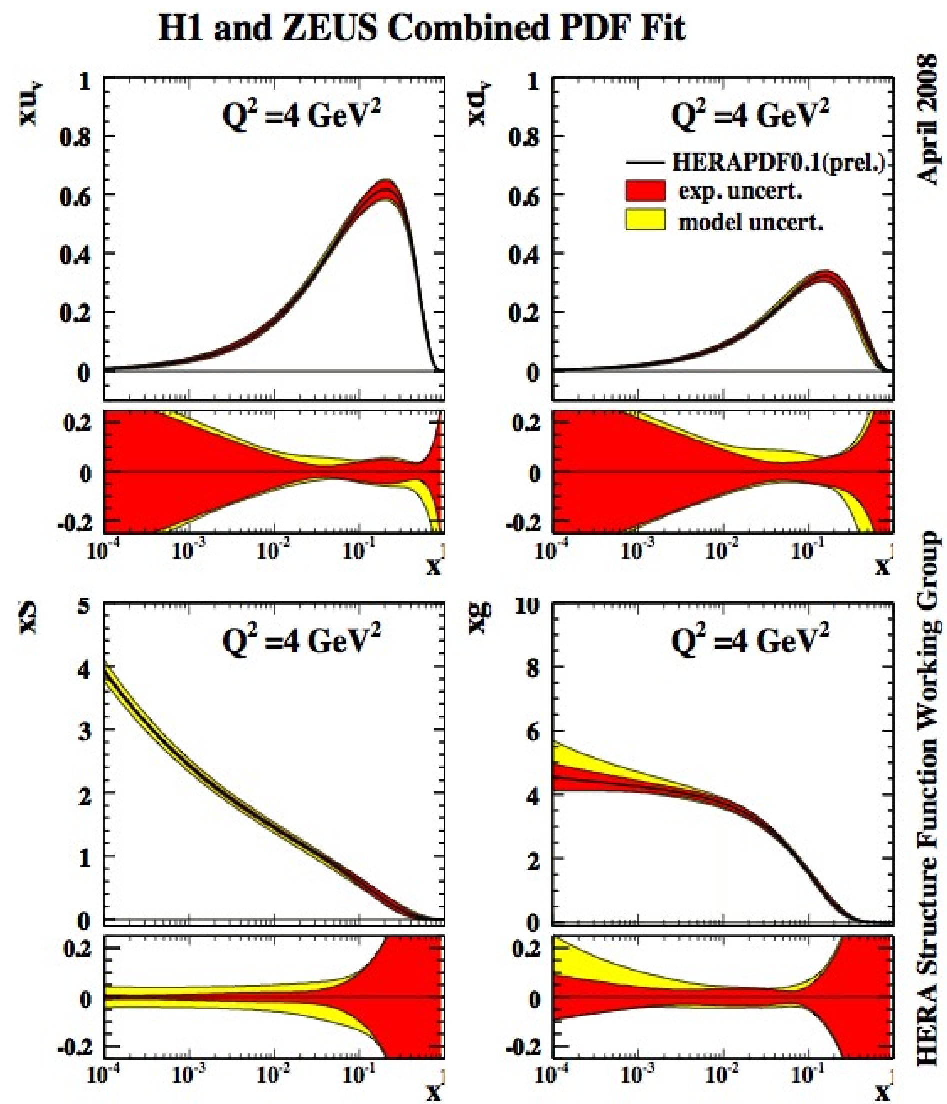



- perfect description of precise measurements of HUGE range in x and $Q^2$
- Theory works well.....
  - ➔ extract parton densities, which are universal ....
  - ➔ to be used for any process with protons in initial state

# The proton PDFs ...

- quark and gluon PDFs



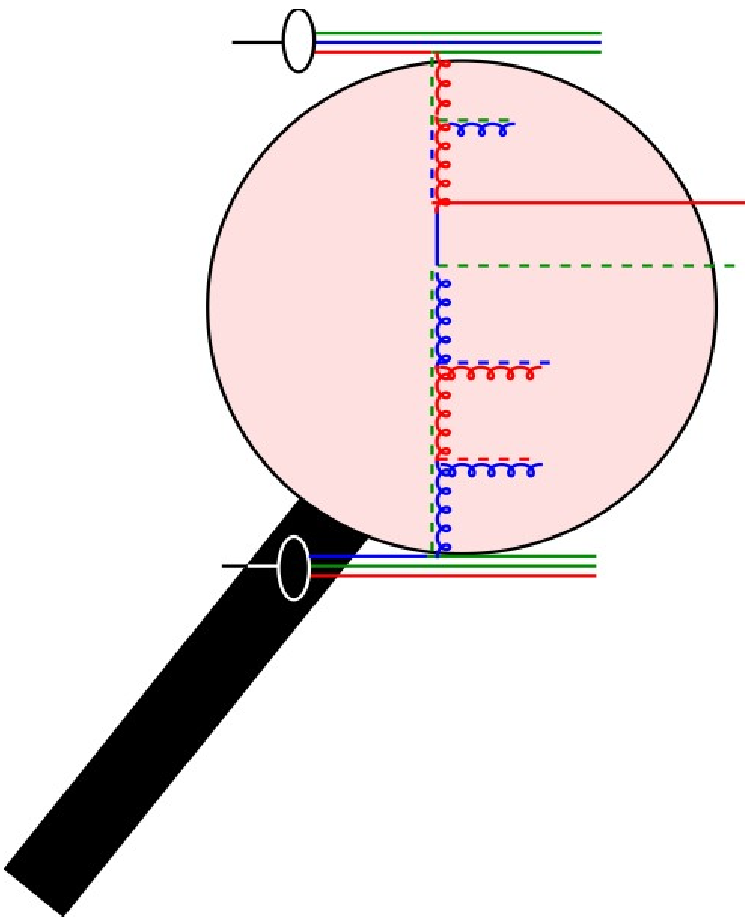




→ Very large gluon density, even at small resolution scales $Q^2$

# Partonic Cross sections

- Cross section

$$\sigma(p_1 + p_2 \to j_1 + j_2 + X) = f(x_1, \mu^2) \otimes \hat{\sigma}(x_1 p_1 + x_2 p_2 \to j_1 + j_2) \otimes f(x_2, \mu^2)$$



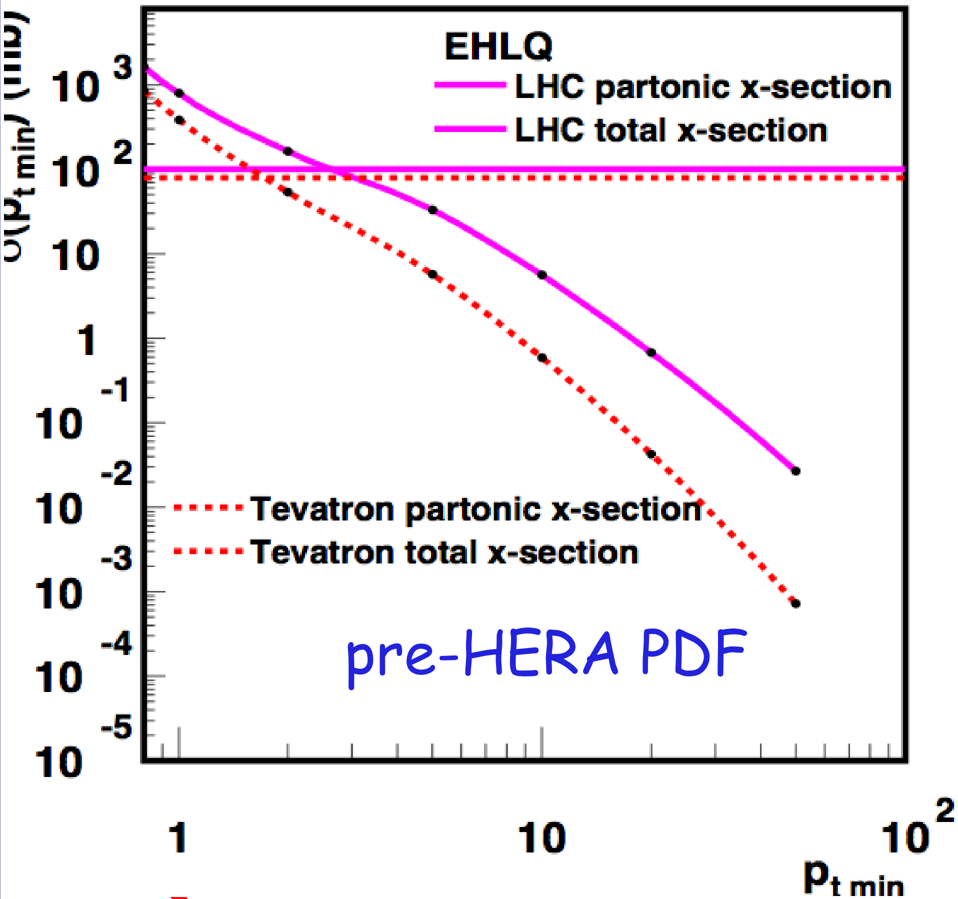
- partonic cross section diverges with $p_t$
- calculate x-section as function of $p_{tmin}$

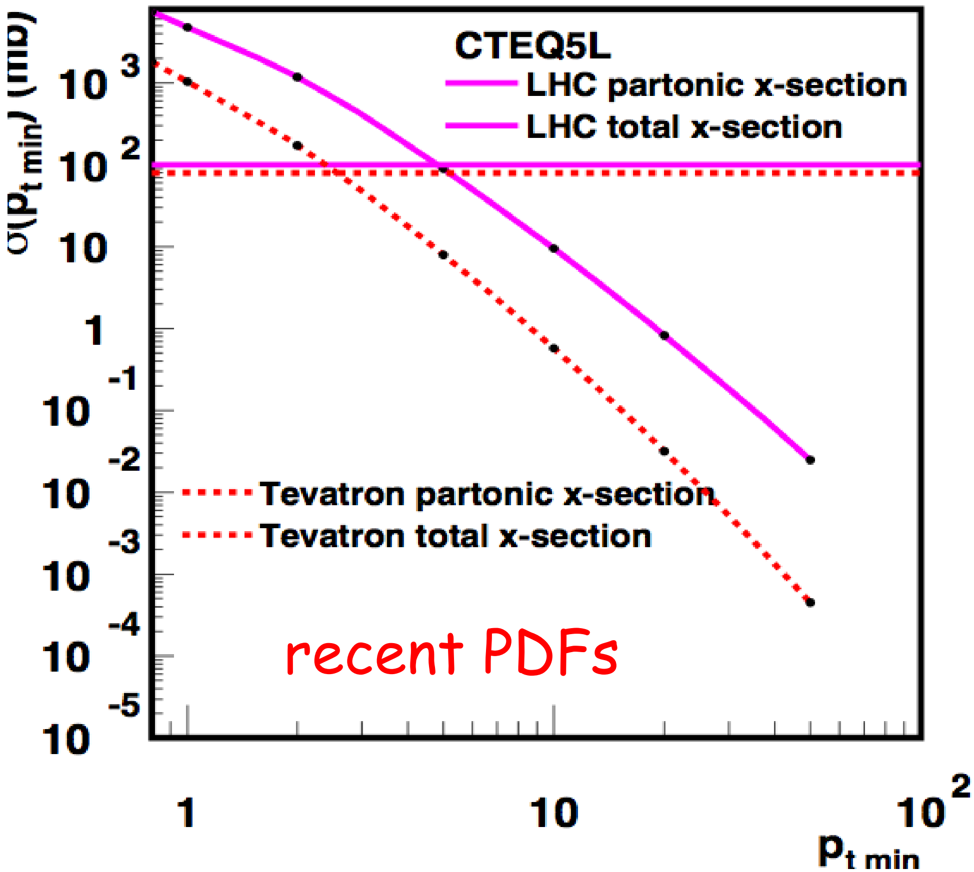
$$\sigma_{\mathrm{hard}}(p^2_{\perp \mathrm{min}}) = \int_{p^2_{\perp \mathrm{min}}} \frac{d\sigma_{\mathrm{hard}}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

# Partonic Cross sections

$$\sigma_{\mathrm{hard}}(p^2_{\perp\,\mathrm{min}}) = \int_{p^2_{\perp\,\mathrm{min}}} \frac{d\sigma_{\mathrm{hard}}(p^2_\perp)}{dp^2_\perp} dp^2_\perp$$

- Cross section at Tevatron/LHC



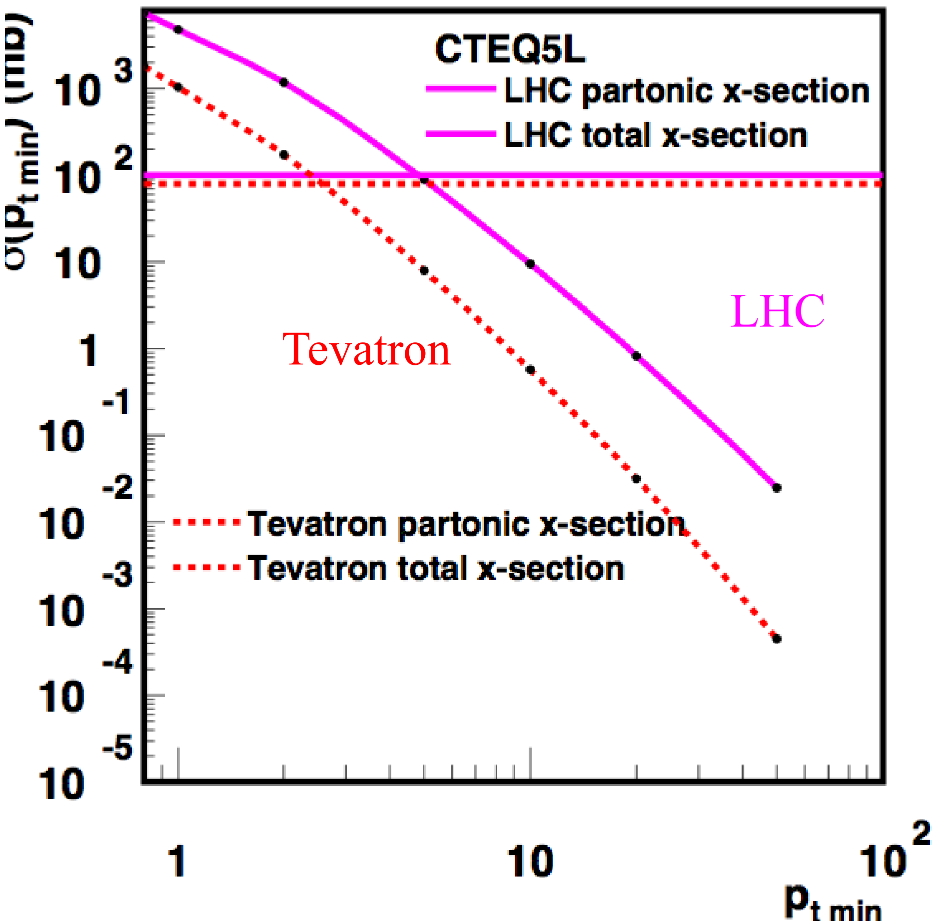

➔ Partonic x-section exceeds total x-section !!!

➔ with HERA PDFs .... at larger values of $p_{tmin}$ !!!!!

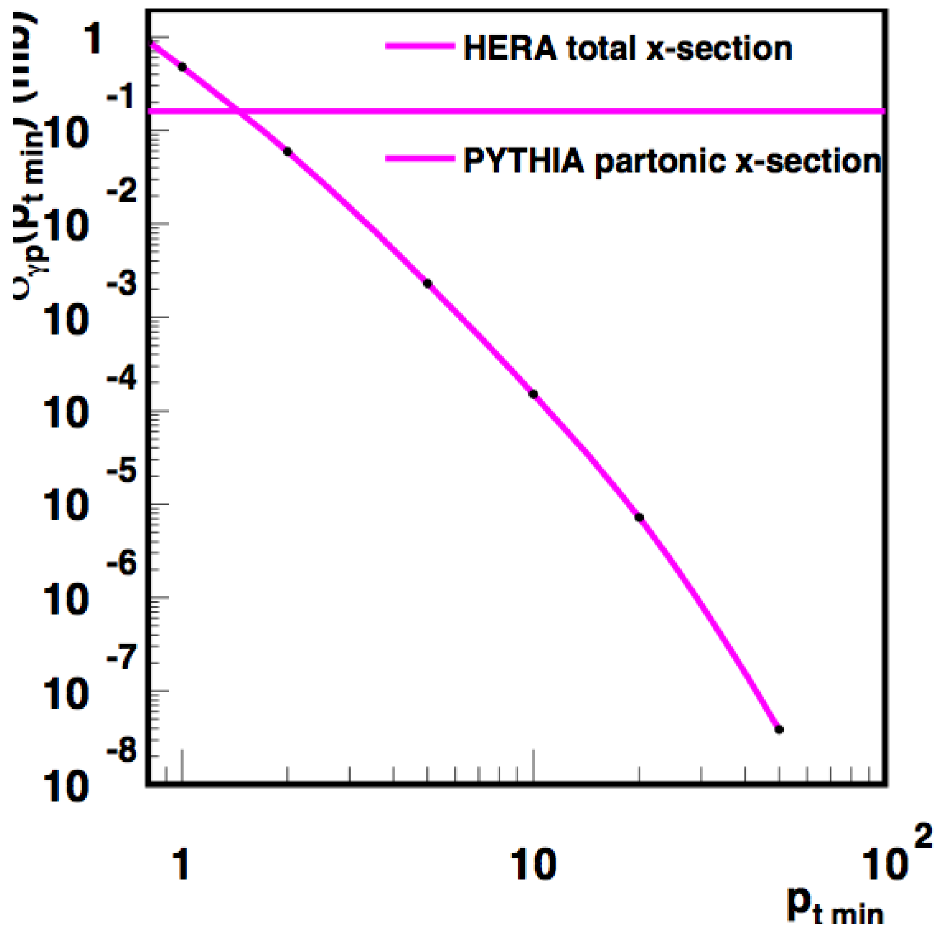
# Partonic Cross sections

$$\sigma_{\mathrm{hard}}(p'_{\perp\min}) = \int_{p'_{\perp\min}} \frac{d\sigma_{\mathrm{hard}}(p'_{\perp})}{dp'_{\perp}} dp'_{\perp}$$

- Cross section at Tevatron/LHC




- Cross section at HERA




➔ Partonic x-section exceeds total x-section !!!

➔ at HERA at small values of $p_{tmin}$ !!!

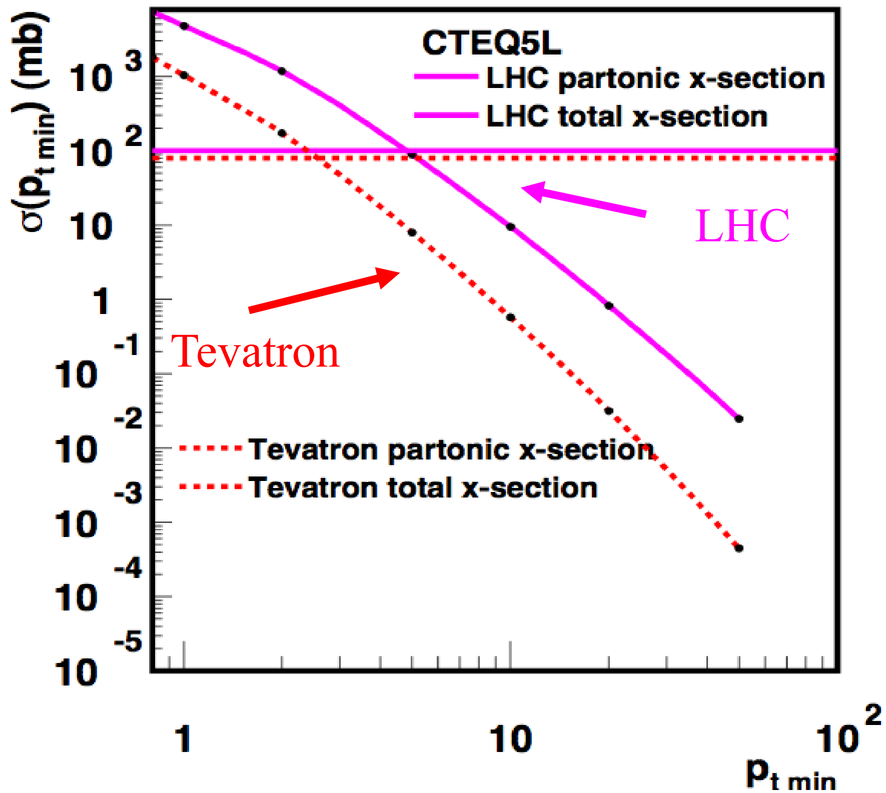
# Underlying event - Multiple Interaction

- Basic partonic perturbative cross section

$$\sigma_{\mathrm{hard}}(p_{\perp\min}) = \int_{p_{\perp\min}} \frac{d\sigma_{\mathrm{hard}}(p_\perp)}{dp_\perp} dp_\perp$$

➔ diverges faster than $1/p^2_{\perp\min}$ as $p_{\perp\min} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section

- Interaction x-section exceeds total xsection
- happens well above $\lambda_{QCD}$
- in perturbative region



# Underlying event - Multiple Interaction

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➔ diverges faster than $1/p^2_{\perp\text{min}}$ as $p_{\perp\text{min}} \to 0$ and exceeds eventually total inelastic (non-diffractive) cross section

HELP ....

HOW to solve this ?

# Underlying event – Multiple Interaction

- Basic partonic perturbative cross section

$$\sigma_{\text{hard}}(p^2_{\perp\text{min}}) = \int_{p^2_{\perp\text{min}}} \frac{d\sigma_{\text{hard}}(p^2_{\perp})}{dp^2_{\perp}} dp^2_{\perp}$$

➔ diverges faster than $1/p^2_{\perp\text{min}}$ as $p_{\perp\text{min}} \to \cdot$ and exceeds eventually total inelastic (non-diffractive) cross section, resulting in more than 1 interaction per event (multiple interactions, MI).

- Average number of interactions per event is given by:

$$\langle n \rangle = \frac{\sigma_{\text{hard}}(p_{\perp\text{min}})}{\sigma_{nd}}$$

- It depends on how soft interactions are treated, ***BUT*** also on the **parton densities** and **factorization scheme**, **parton evolution (DGLAP/BFKL)** !!!!!!!!

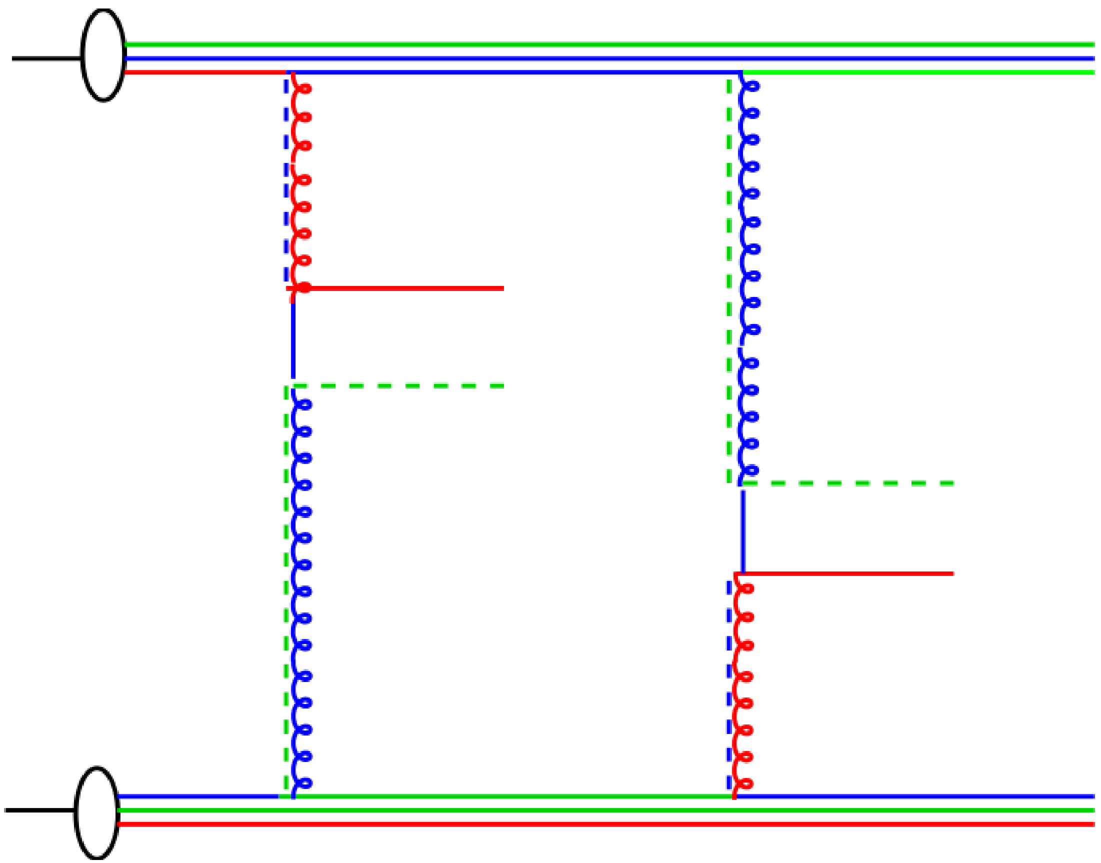
# Models for Multi-Parton Interaction

- The very simple model
  - ➔ add secondary interactions
  - ➔ first model by: T. Sjostrand, M. Zijl PRD 36 (1987) 2019
- order scatterings in $p_t$
  - ➔ use of sudakov form factor
  - ➔ result in Poisson distribution of number of scatterings:

$$p_r = \frac{\mu^r}{r!} \exp\left(-\mu\right)$$

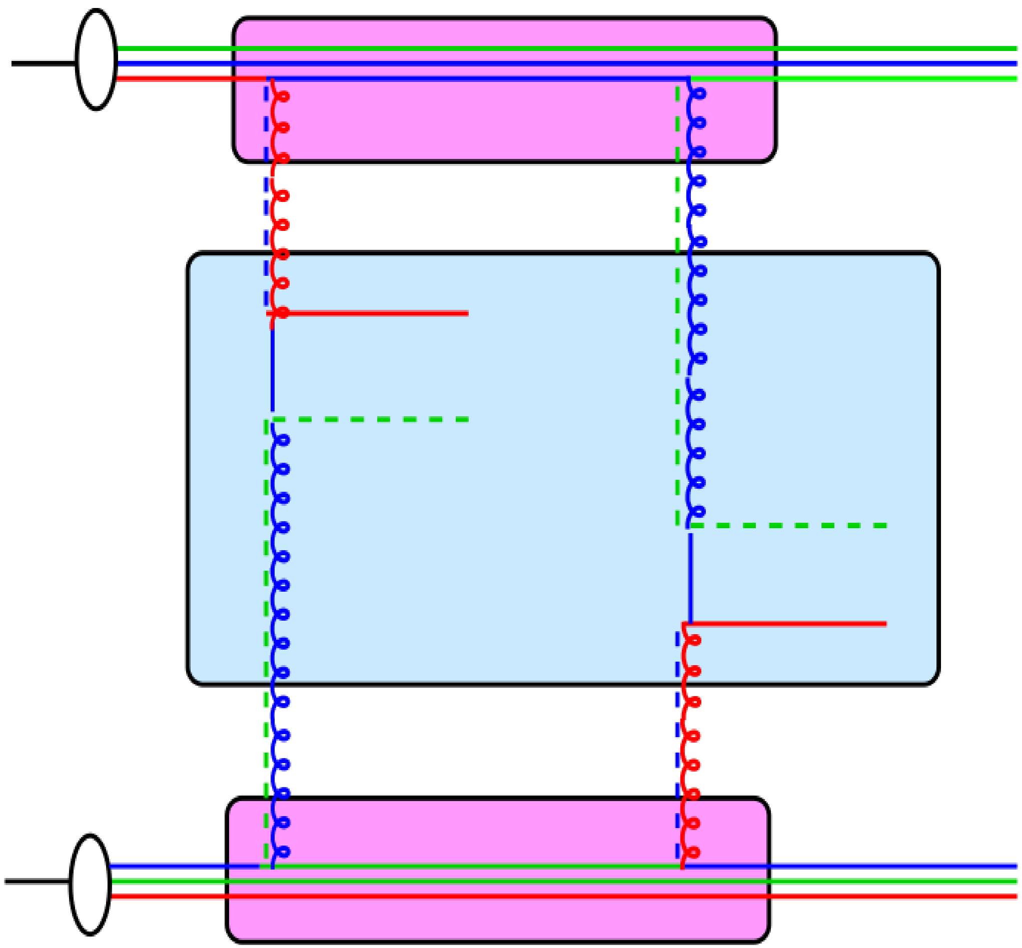
with

$$\mu = \langle n \rangle = \frac{1}{\sigma_{nd}} \int_{p_{\perp\min}}^{p_{\perp;\max}} \frac{d\sigma_{\text{hard}}}{dp'_\perp} dp'_\perp$$



# Questions ...

- Does this approach still satisfy the basic factorization theorem ?
- Is inclusive dijet cross section changed by including MPI ?



# Factorization

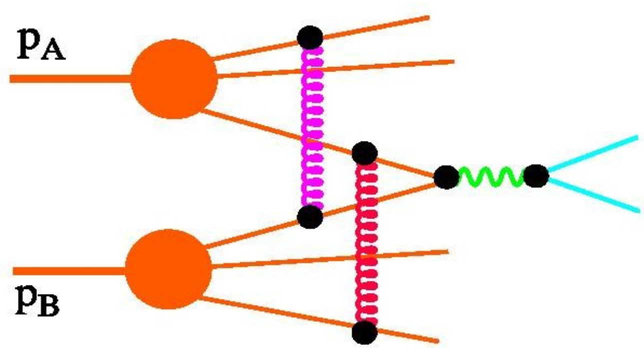
- factorization means:

$$\frac{d\sigma}{dy} = \sum_{a,b} \int_{x_A}^{1} d\xi_A \int_{x_B}^{1} d\xi_B f_A^a(\xi_A,\mu) f_B^b(\xi_B,\mu) \frac{d\hat{\sigma}_{ab}(\mu)}{dy} + \mathcal{O}\left(\left(\frac{m}{P}\right)^p\right)$$

- MPI approach reproduces inclusive jet x-section with

$$\langle n \rangle = \frac{\sigma_{\text{hard}}(p_{\perp\text{min}})}{\sigma_{nd}}$$

- Similar in Drell-Yan with initial state interactions...
- factorization here does not hold graph-by-graph but only for all ....



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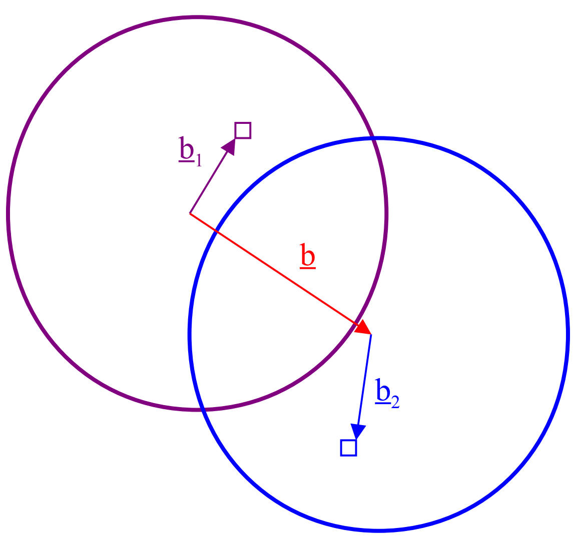
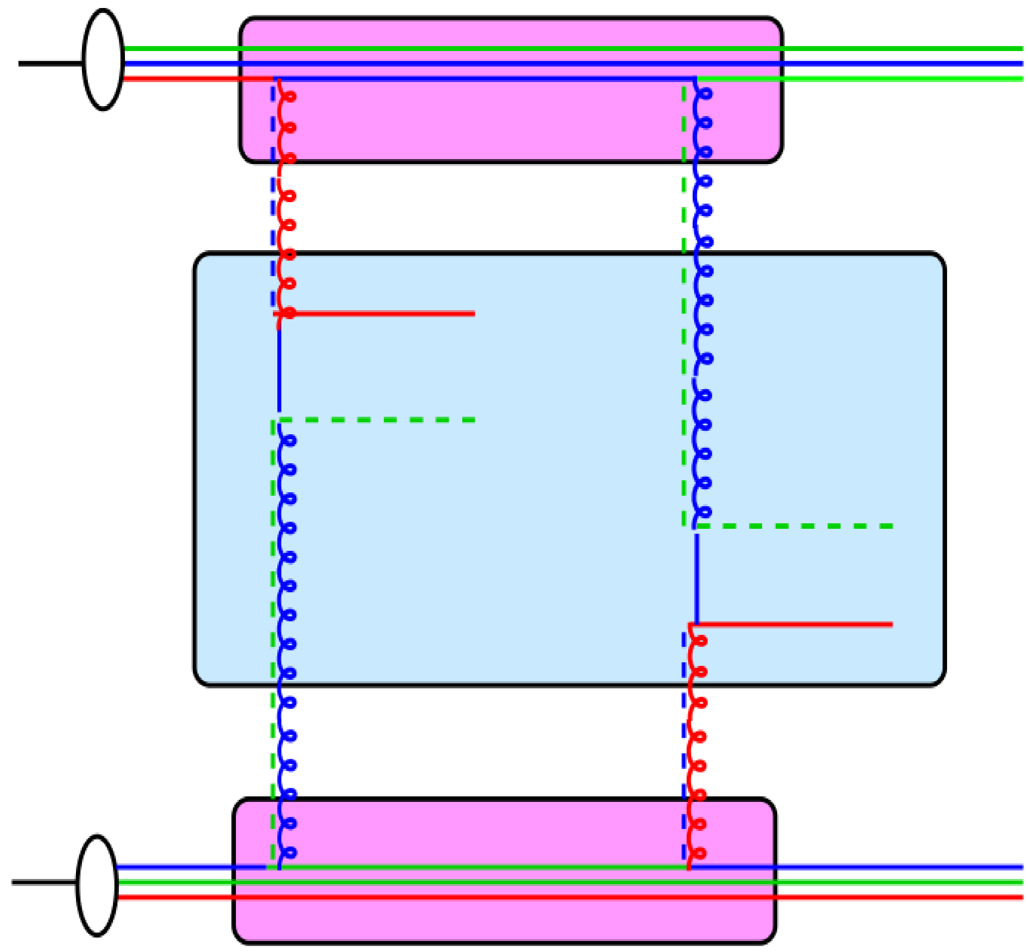
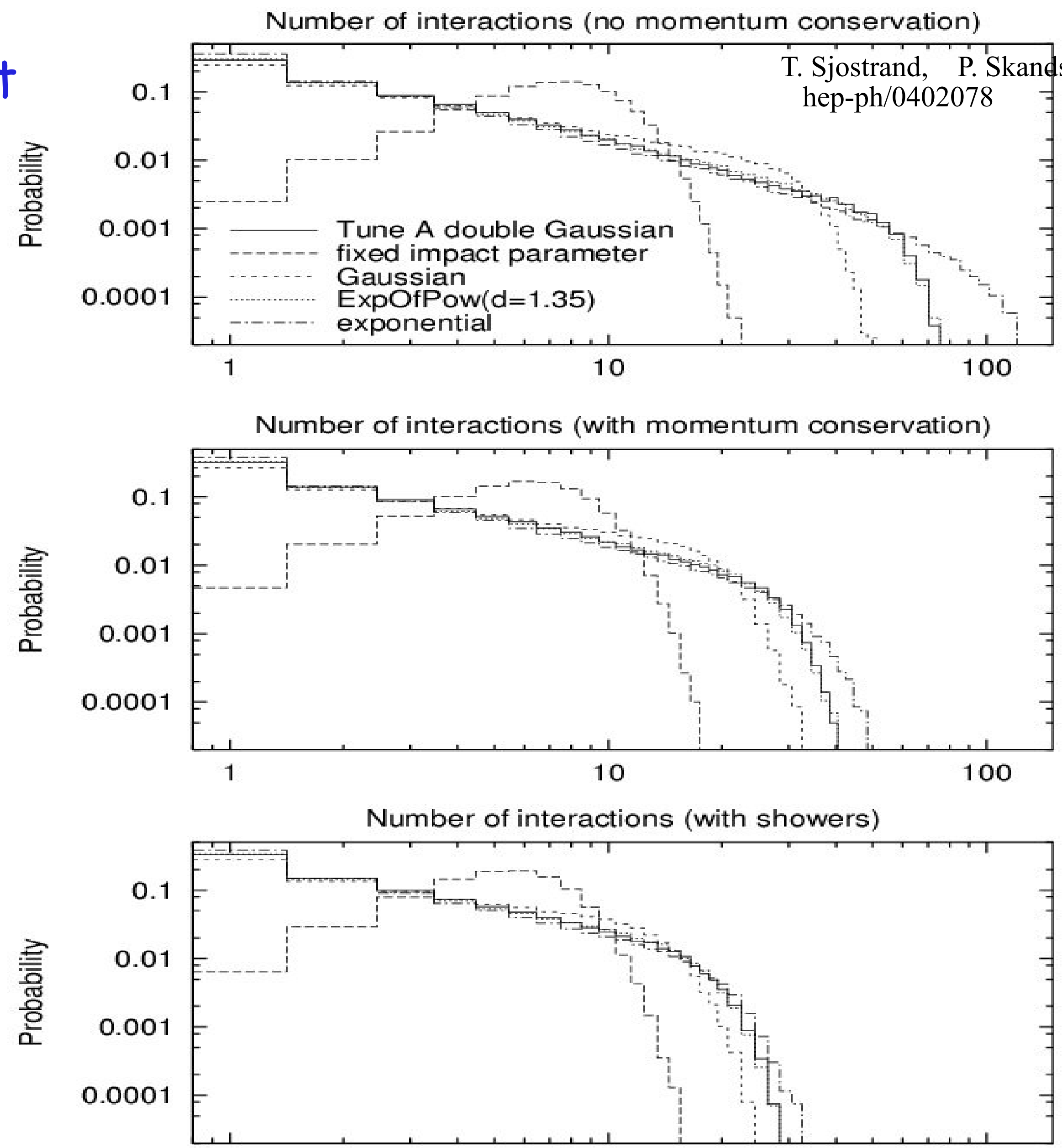
- what about kinematics ?
- what about impact parameter dependence ?



# Nr of Multiparton Interactions

- Nr of interactions in $p\bar{p}$ at $\sqrt{s} = 1.8$ TeV
- different choices for overlap function:
  - ➔ single Gauss
  - ➔ exponential
  - ➔ double Gauss
  - ➔ exp(-$b^d$)
- significant effects from energy momentum conservation
- Nr of interactions depends on $p_{tmin}$ cutoff...



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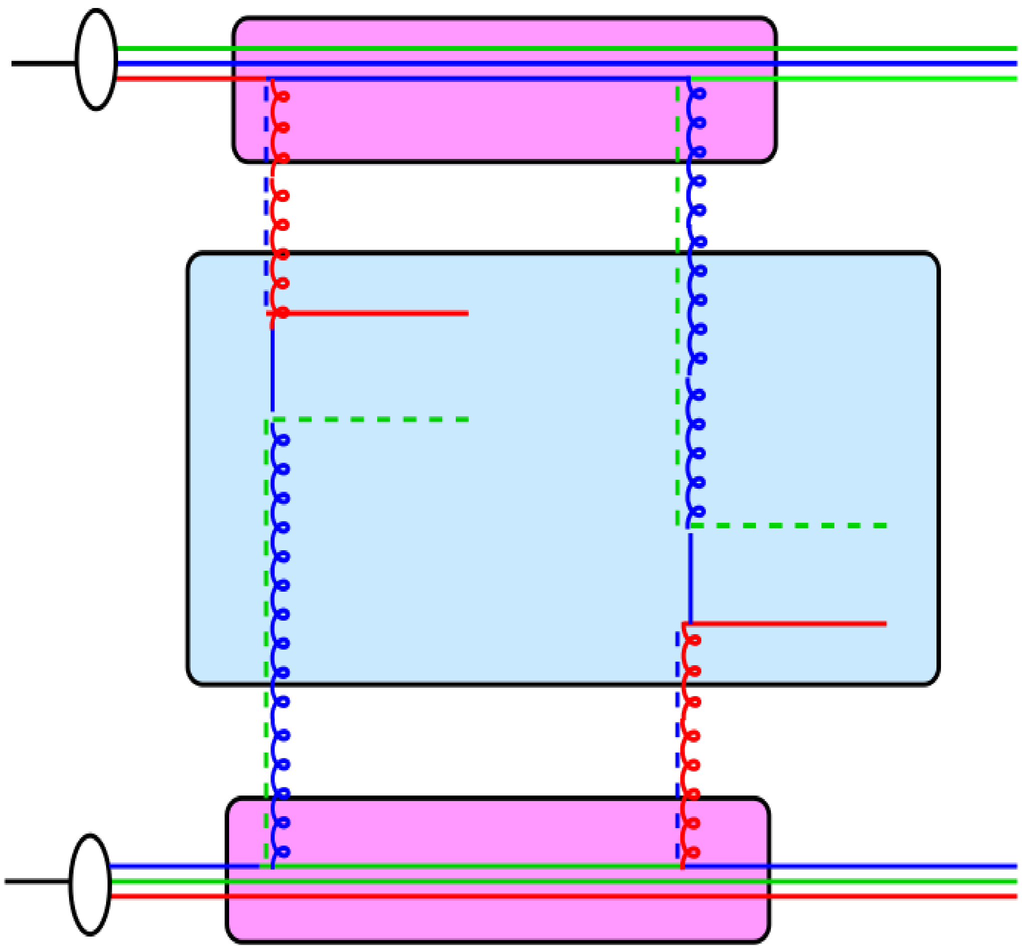
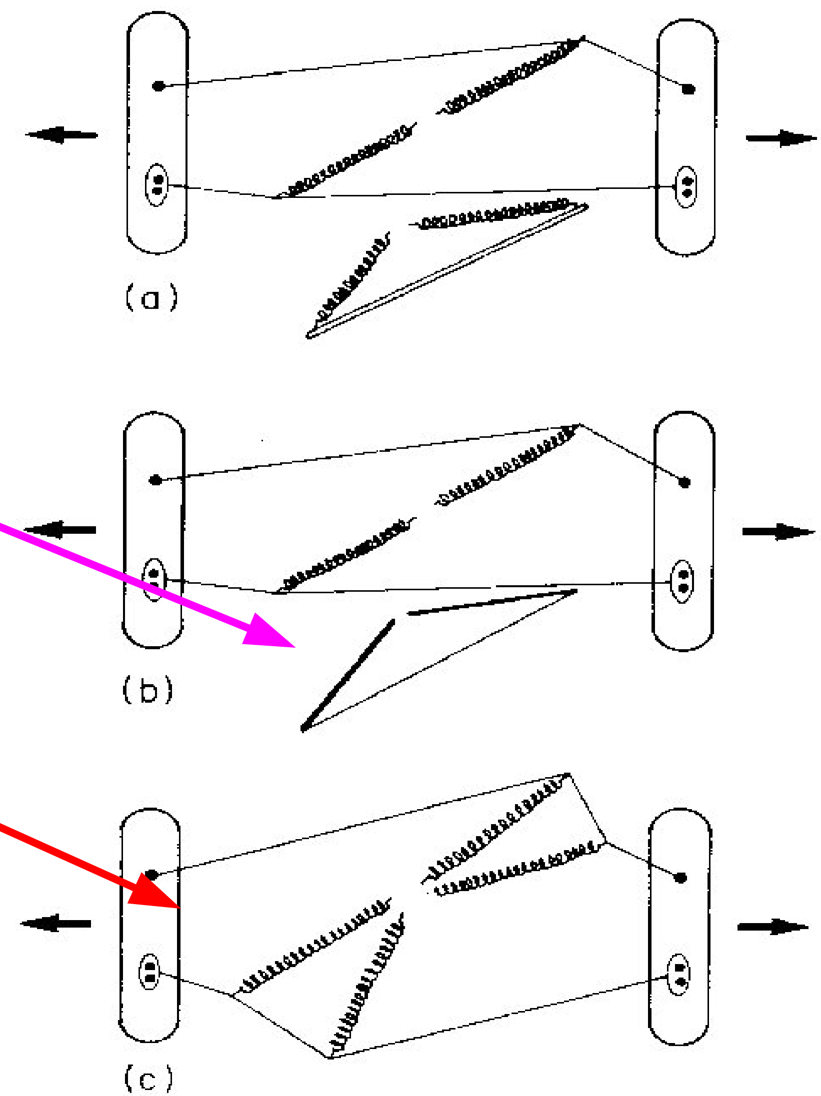


# Color flow in a simple model

- possible scenarios for color string connection in multiparton events
- 33% quarks
  66% gluons
  out of which 33 %
  are

T. Sjostrand, M. Zijl
PRD 36 (1987) 2019



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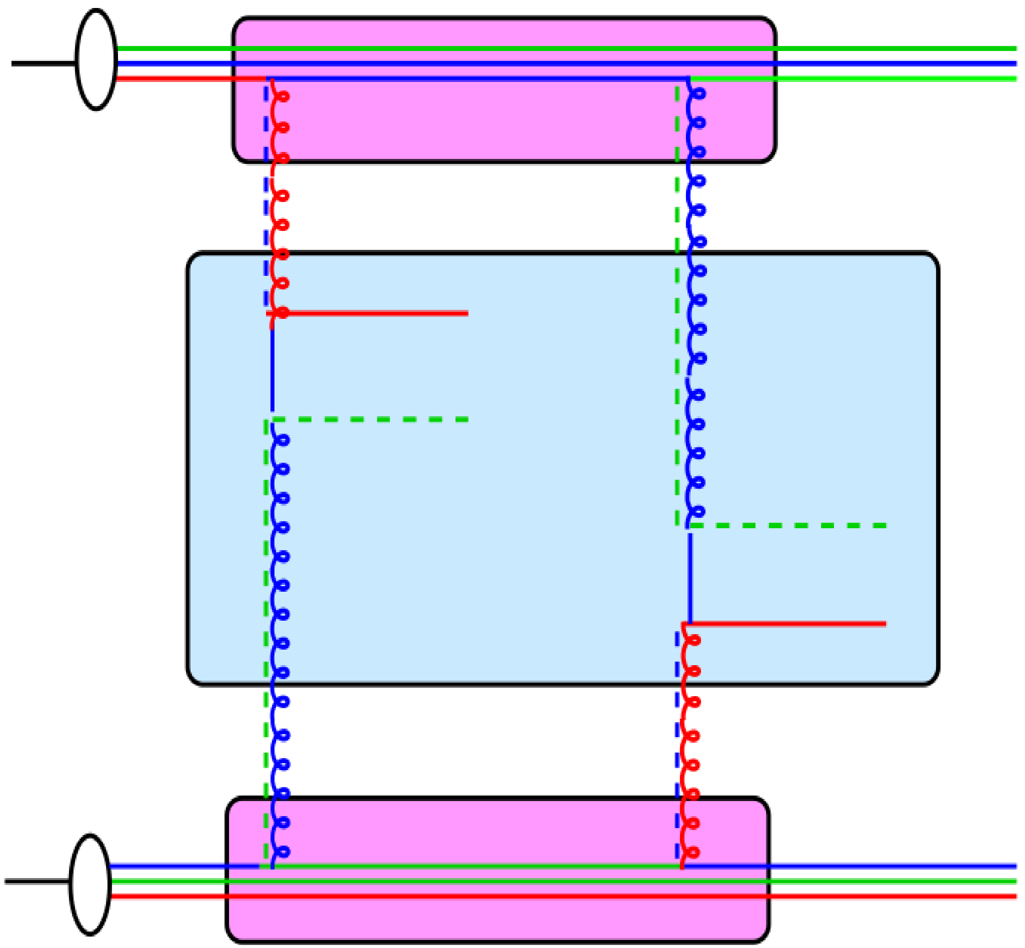
- what about parton showering ?

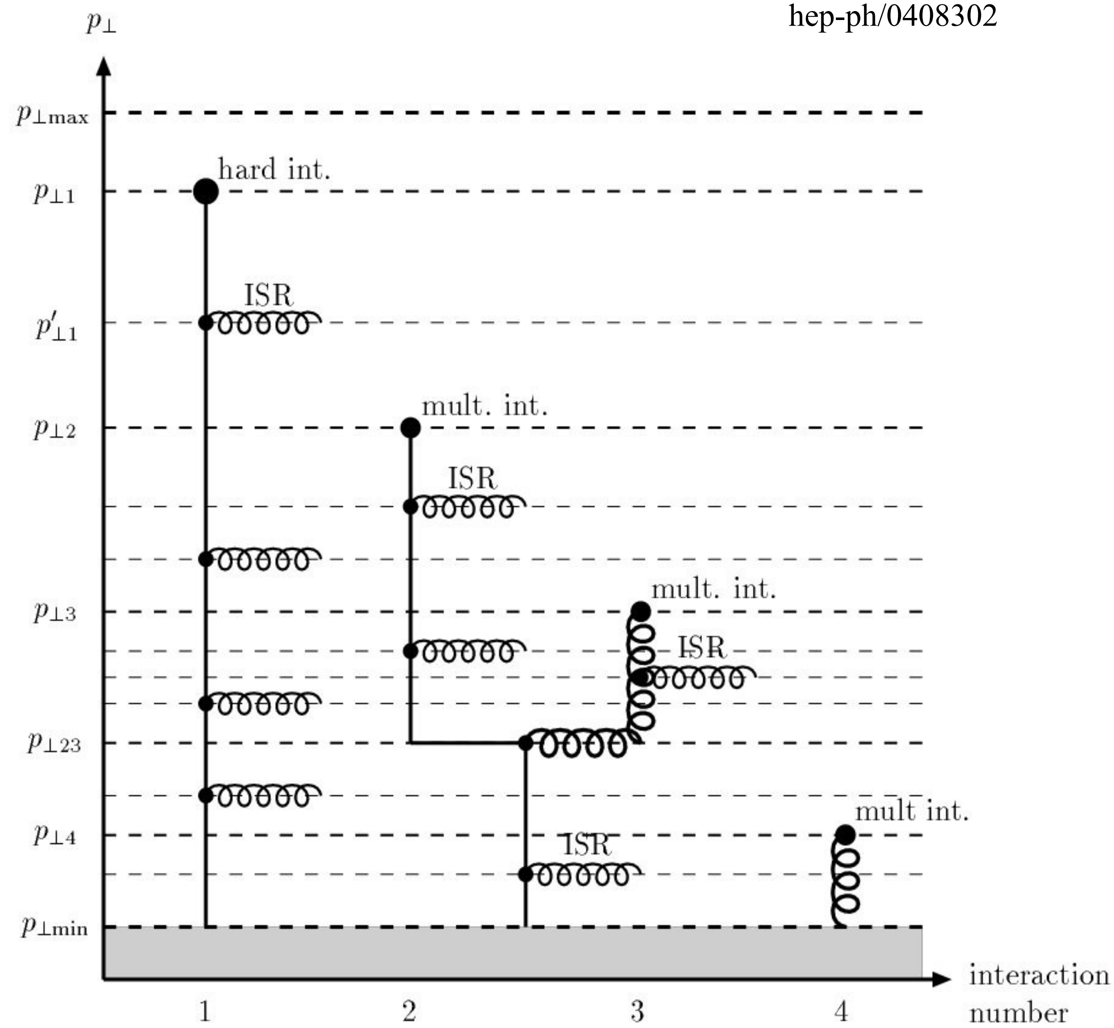


# Improvements: interleaved PS & MPI

T. Sjostrand, P. Skands
hep-ph/0408302

- until ~2004, PS only for hardest interaction...
  - ➔ new approach which treats initial state PS and MPI at the same time

$$\frac{dP}{dp_t} = \left(\frac{dP_{MI}}{dp_t} + \sum \frac{dP_{IPS}}{dp_t}\right)$$
$$\otimes \quad \exp\left(\frac{dP_{MI}}{dp_t} + \sum \frac{dP_{IPS}}{dp_t}\right)$$



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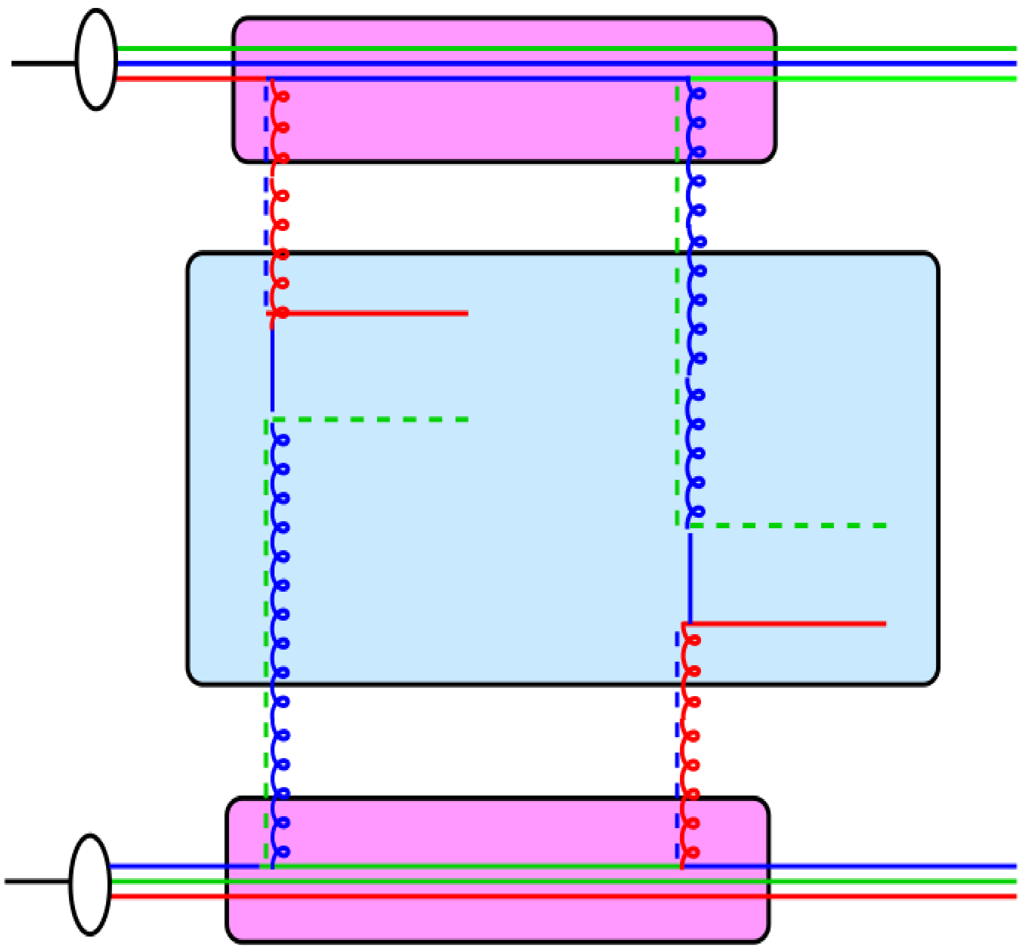
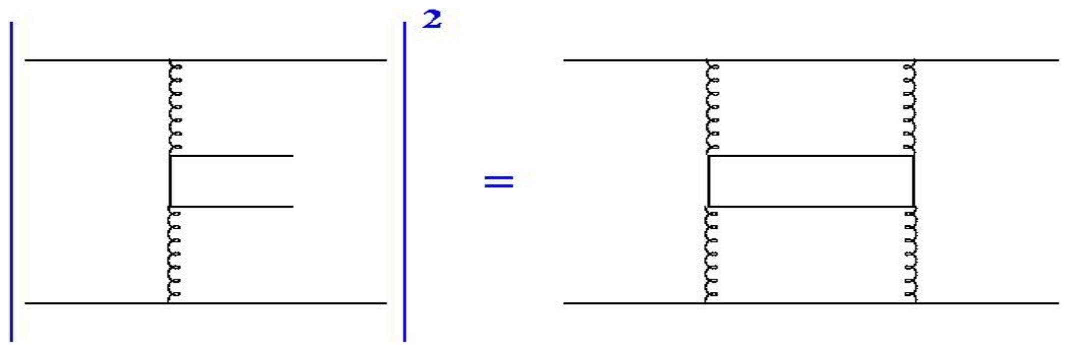
- what about connection to saturation and diffraction ?

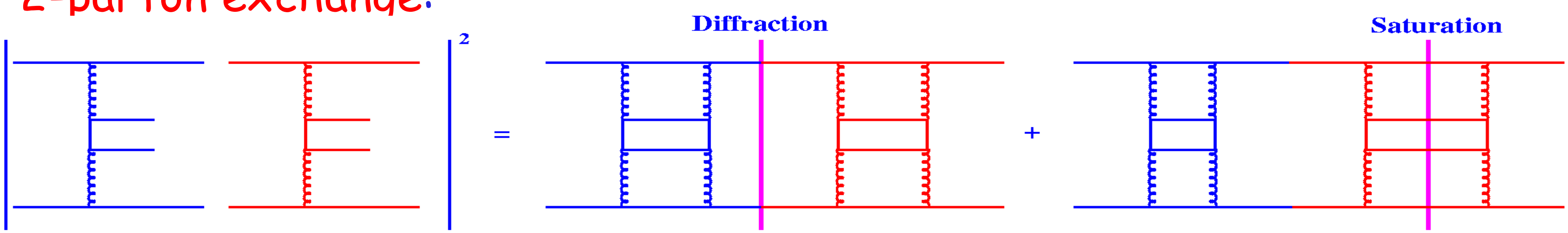


# Toy Model for AGK

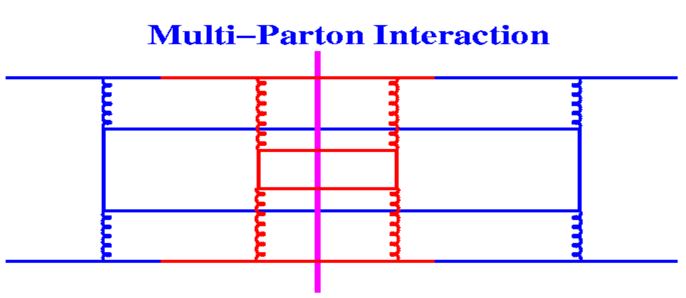
- where is relation of diffraction - multiple scatterings - saturation coming from ?
- single parton exchange:




- 2-parton exchange:




✗ **BUT......** this is not yet realized in any Monte Carlo model



# Questions ...

- Does this approach still satisfy the basic factorization theorem ?
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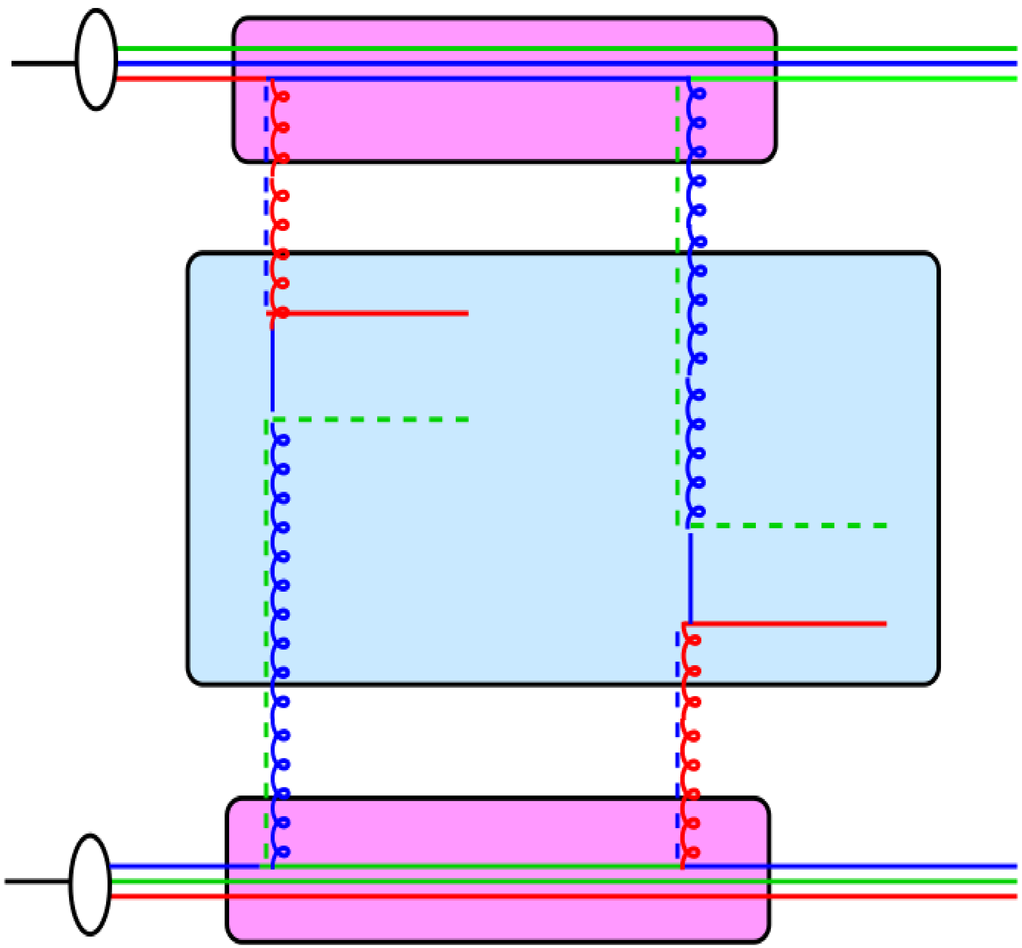
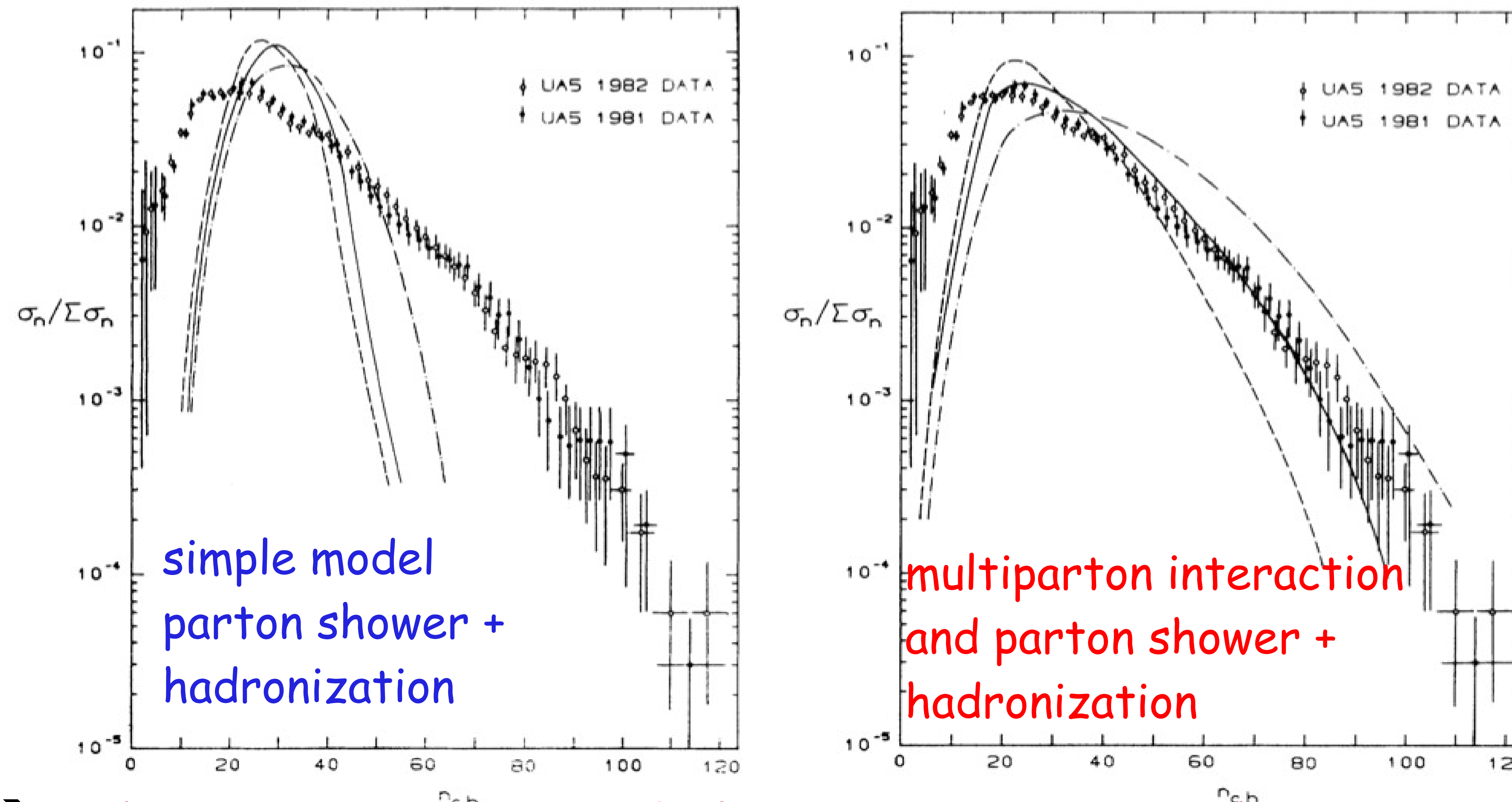
- what about parton densities ?
- what about kinematics ?
- what about impact parameter dependence ?
- what about color-flow and hadronization ?
- what about parton showering ?
- what about connection to saturation and diffraction ?
- why all this ?



# Experimental evidence

# Once upon a time ...

- UA5 measurement of charged particle multiplicities (~1982) T. Sjostrand, M. Zijl PRD 36 (1987) 2019

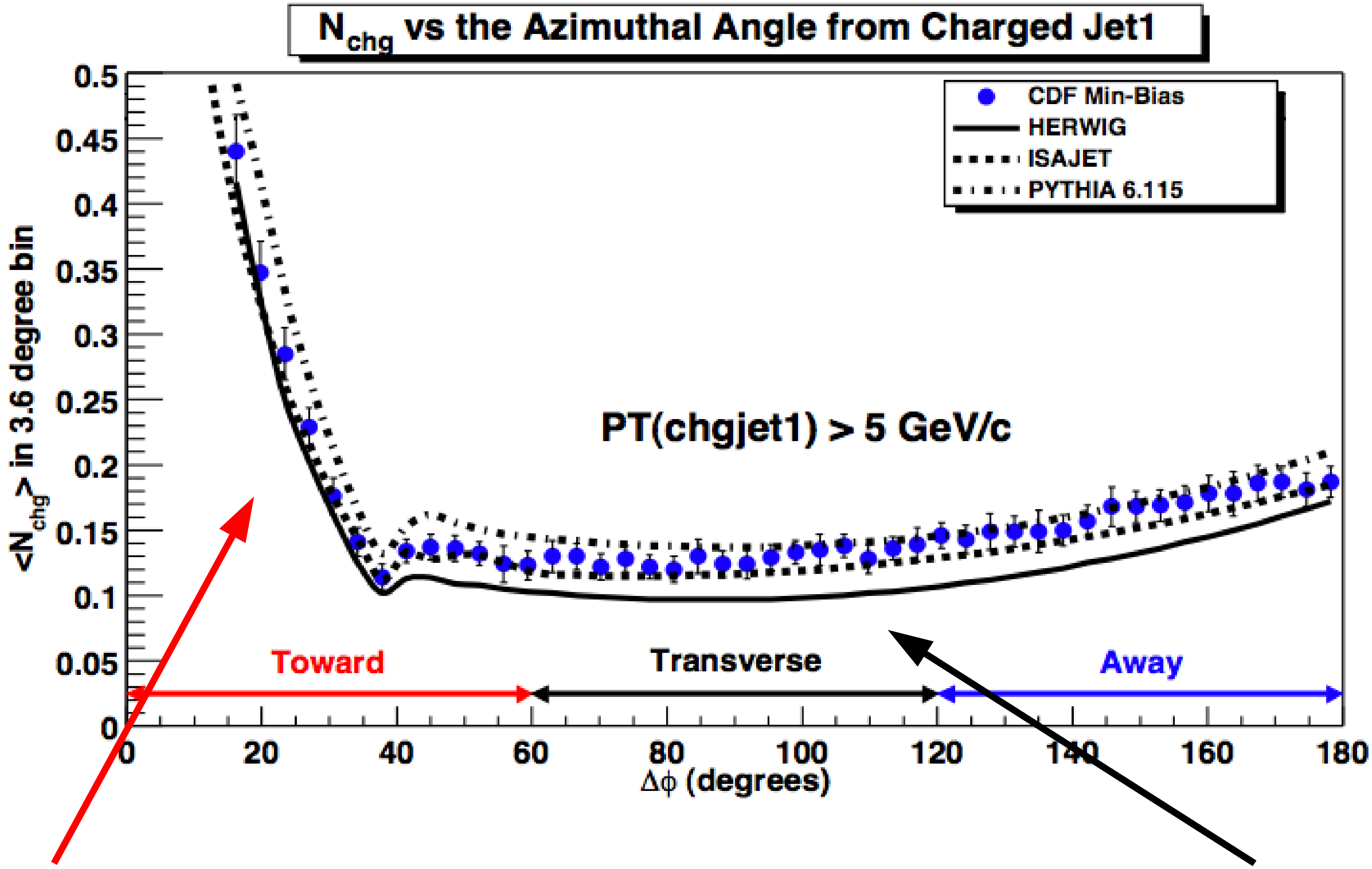



➔ Multiparton interaction help to describe particle multiplicities in minimum bias events ....

# and we have the jet pedestals ...

- charged particle ( $p_t > 5\text{GeV}, |\eta| < 1$ ) distribution around jets $p_t > 5\text{GeV}$

Affolder et al (CDF)
Phys. Rev. 2002 D65 092002




➔ Jet region reasonably well described, deficits in transverse region

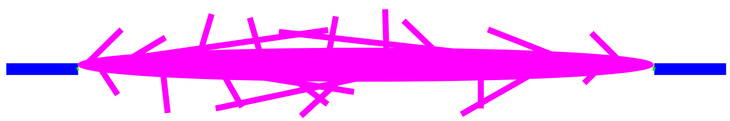
BUT is this is only
soft physics ...

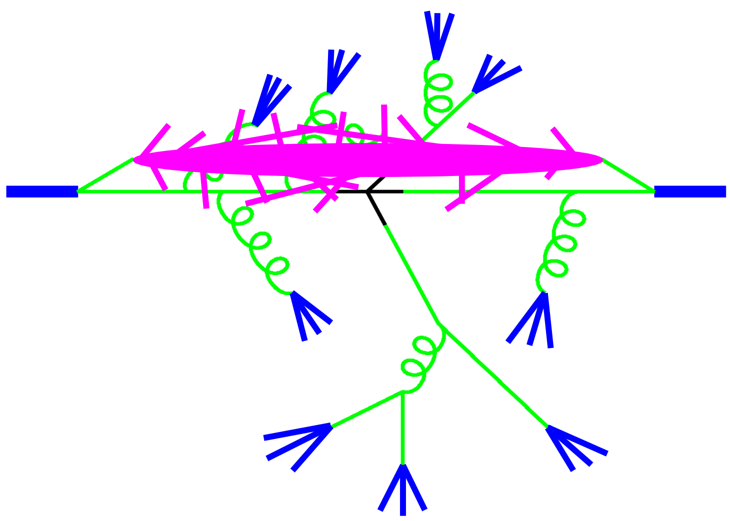
and can also be described
by parametrization

# The old soft underlying event model...

G.Marchesini & B.R.Webber, PRD38(1988)3419
M. Seymour, talk at TEV4LHC, Sept 2004

- Uncorrelated soft scatters – UA5 model (and old HERWIG)
  - parametrization of data
  - broad multiplicity distributions
  - large fluctuations
  - long range correlations
- BUT
  - energy dependence ?
  - hard component ?
  - hard/soft correlation ?





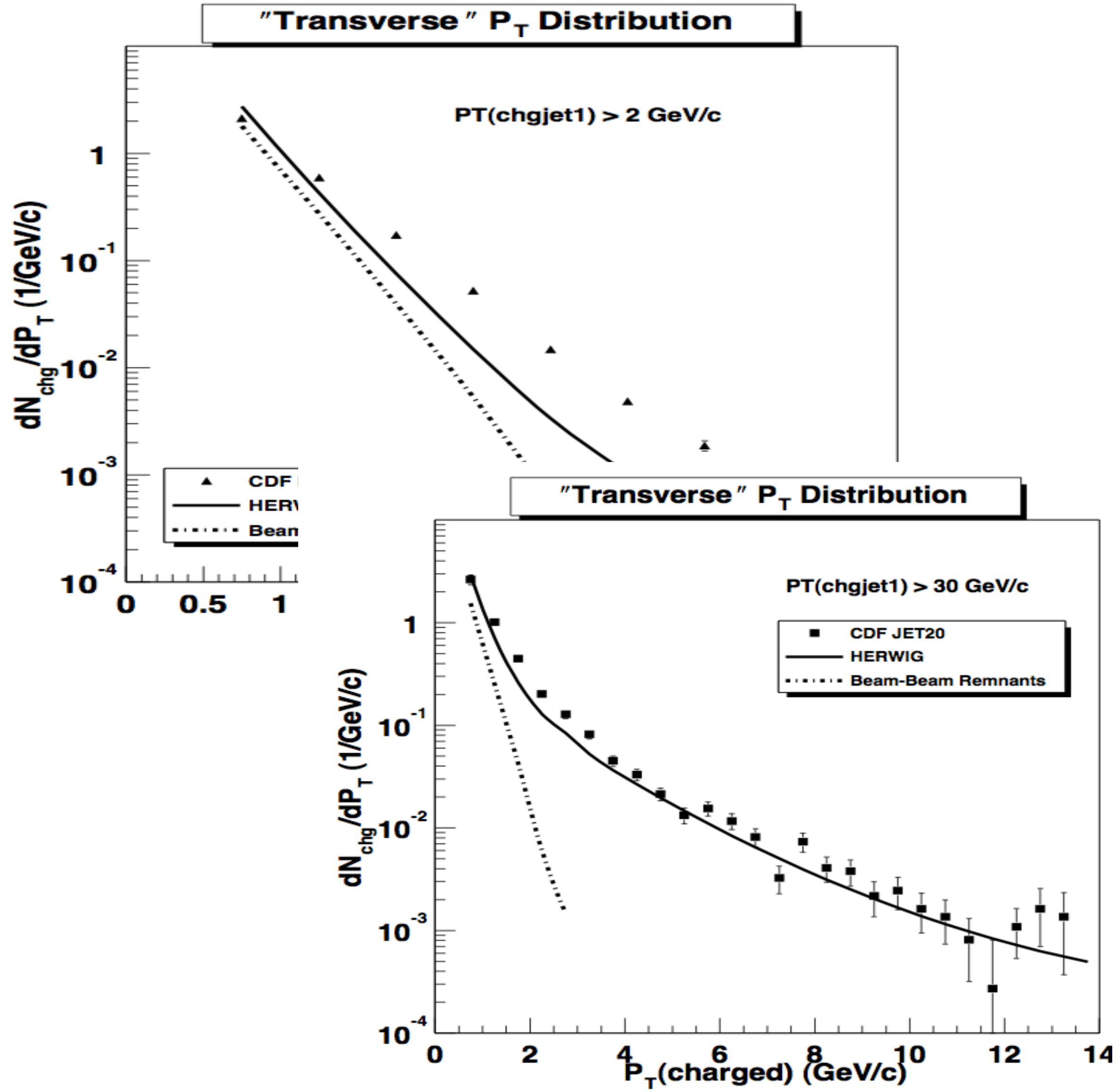
➔ THIS approach obviously satisfies factorization on a event by event basis ...

**BUT** ...

# The soft underlying event model

- Apply the soft underlying event model
- transverse momentum generated is not enough at small $p_t$
- at large $p_t$ description is ok

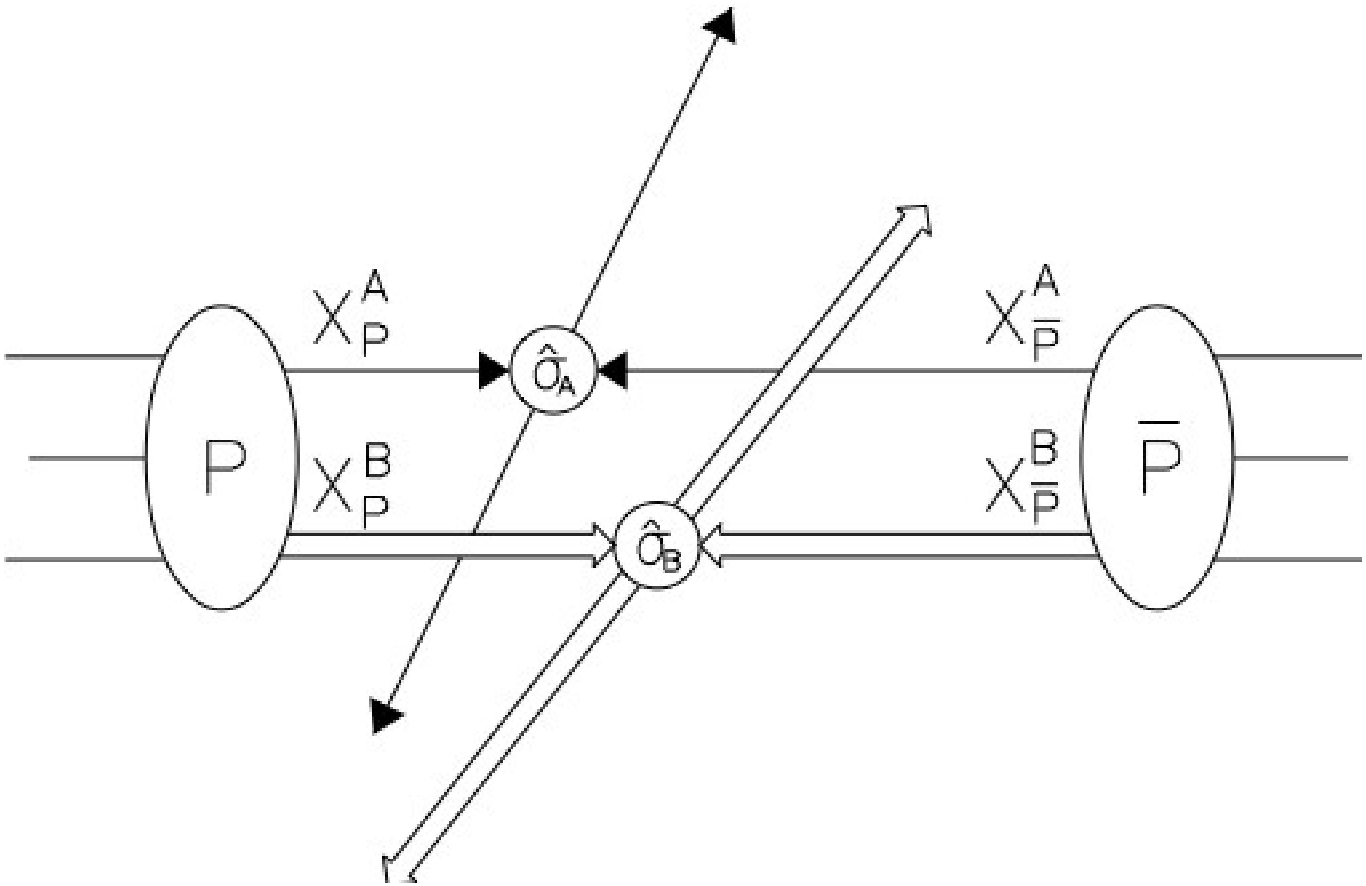
➔ **semi soft component is the challenge**



# Evidence for hard multiple interactions

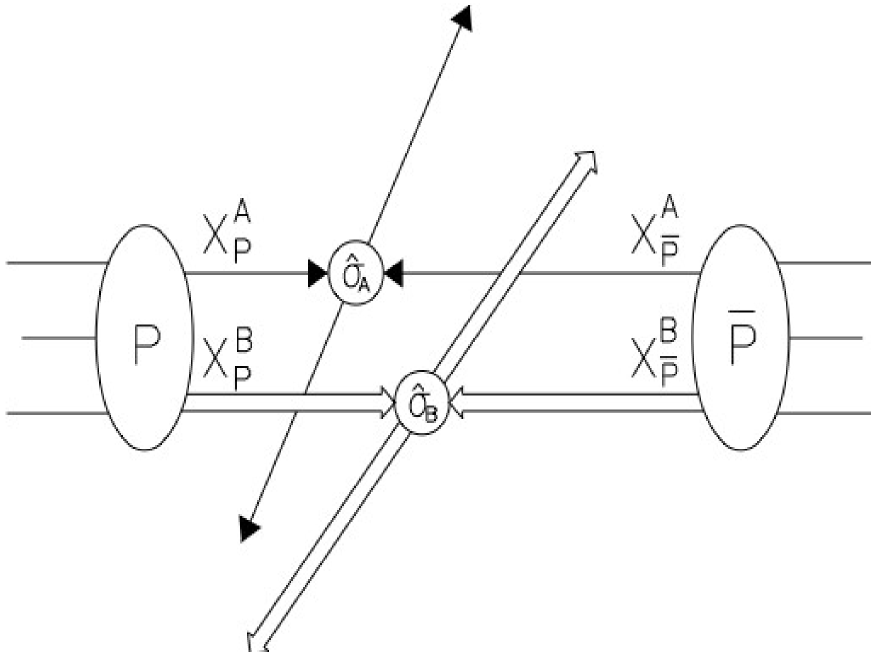
# Evidence for hard multiple interaction

- observation of 4 jet final states

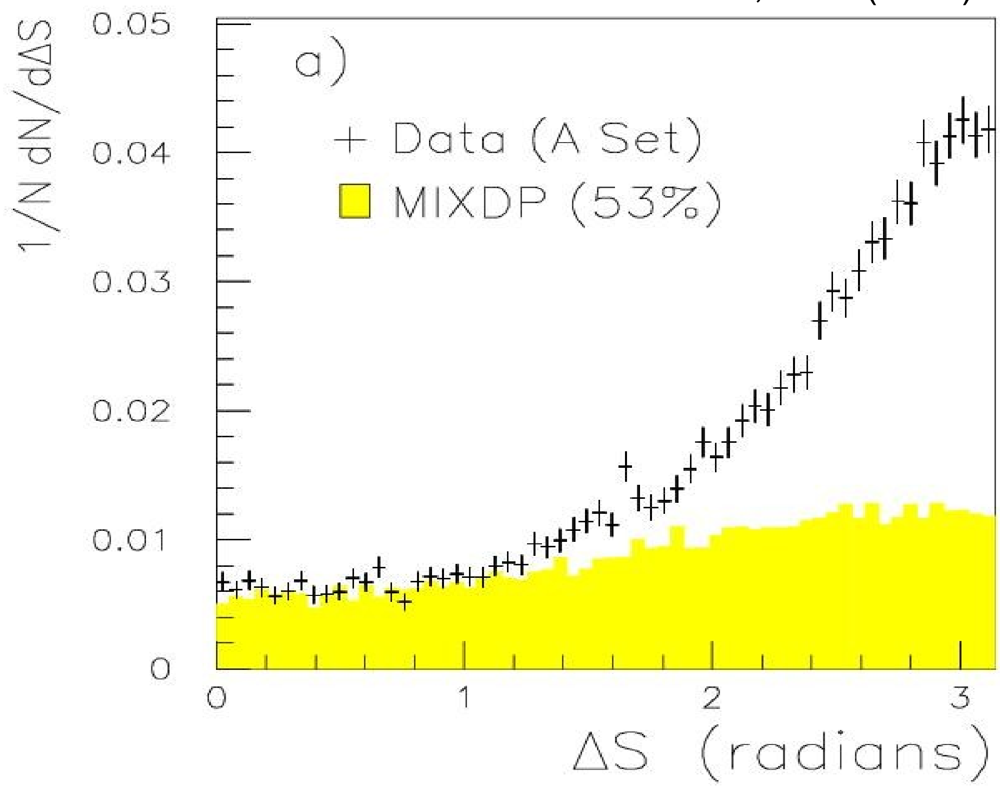



- Measure cross section and azimuthal correlations
- Difficulty: tell the difference from $2 \rightarrow 4$ process !

# Evidence for Multi-Parton Interactions




CDF coll. PRD 56, 3811 (1997)




- look at $\gamma + 3$ Jets with

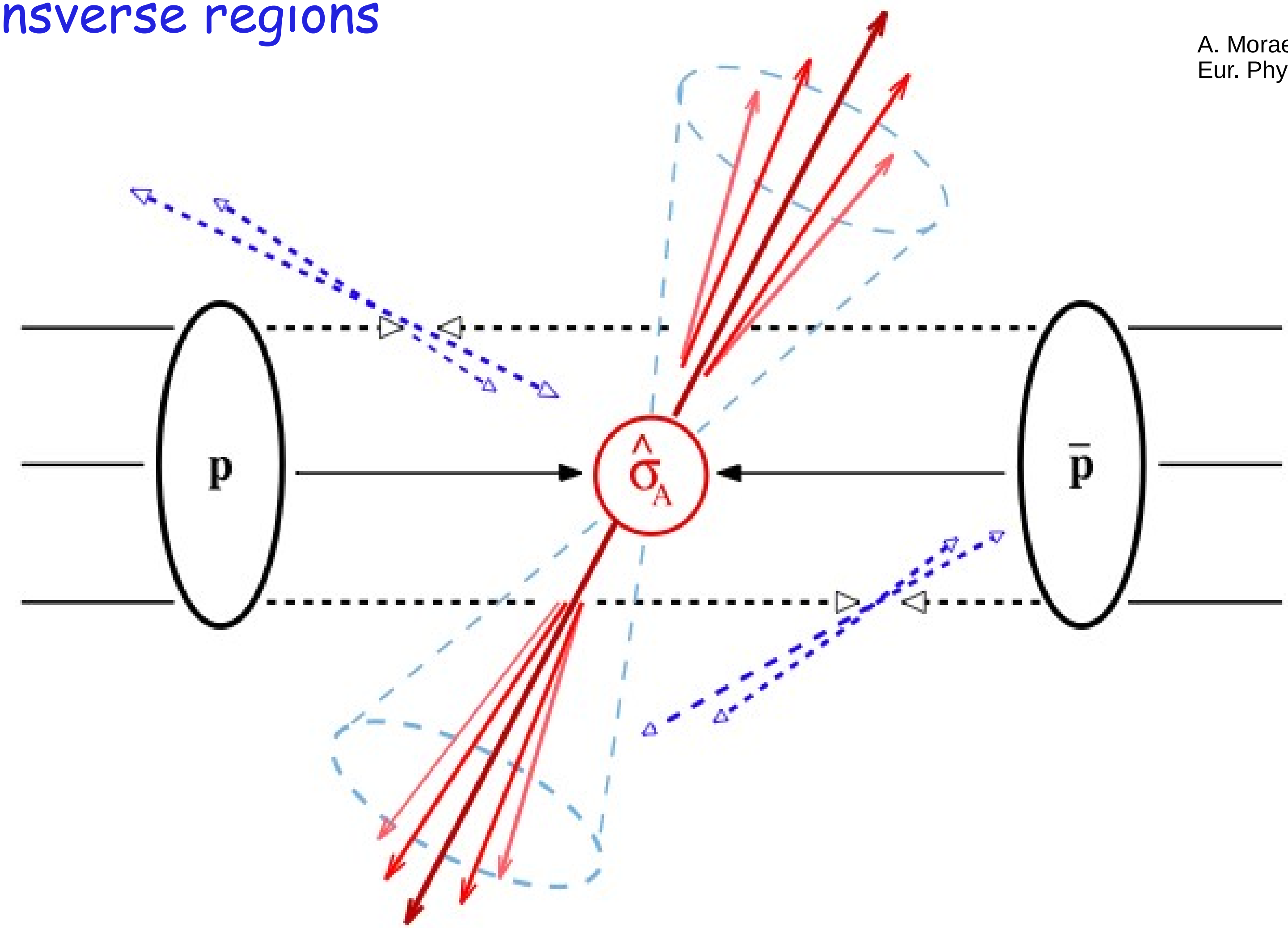
$$E_T^\gamma > 16 GeV$$
$$E_T^{Jets} > 5 GeV$$

- angular correlation of jet/photon pairs $\Delta S$
- compare to $\gamma + 3$ Jets calculation
- **Need > 50 % double parton interaction to describe data**

# Evidence for Multi Parton Interaction

- Study of the underlying event structure:
- trigger on high $p_t$ jets, observe additional hadron activity in the transverse regions

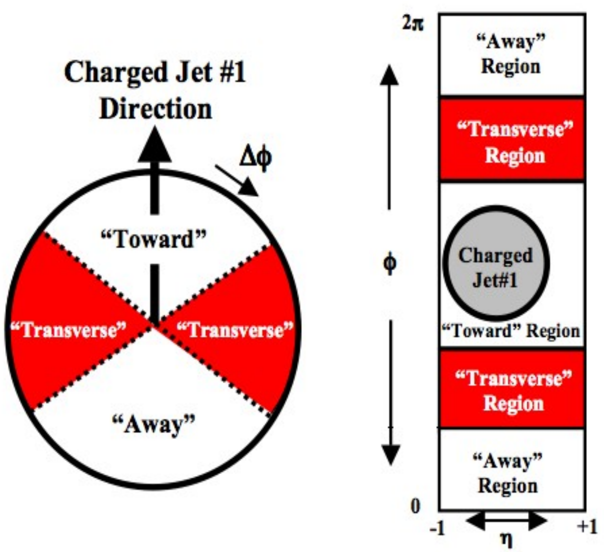
A. Moraes, C. Buttar, and I. Dawson. Eur. Phys. J., C50:435–466, 2007.



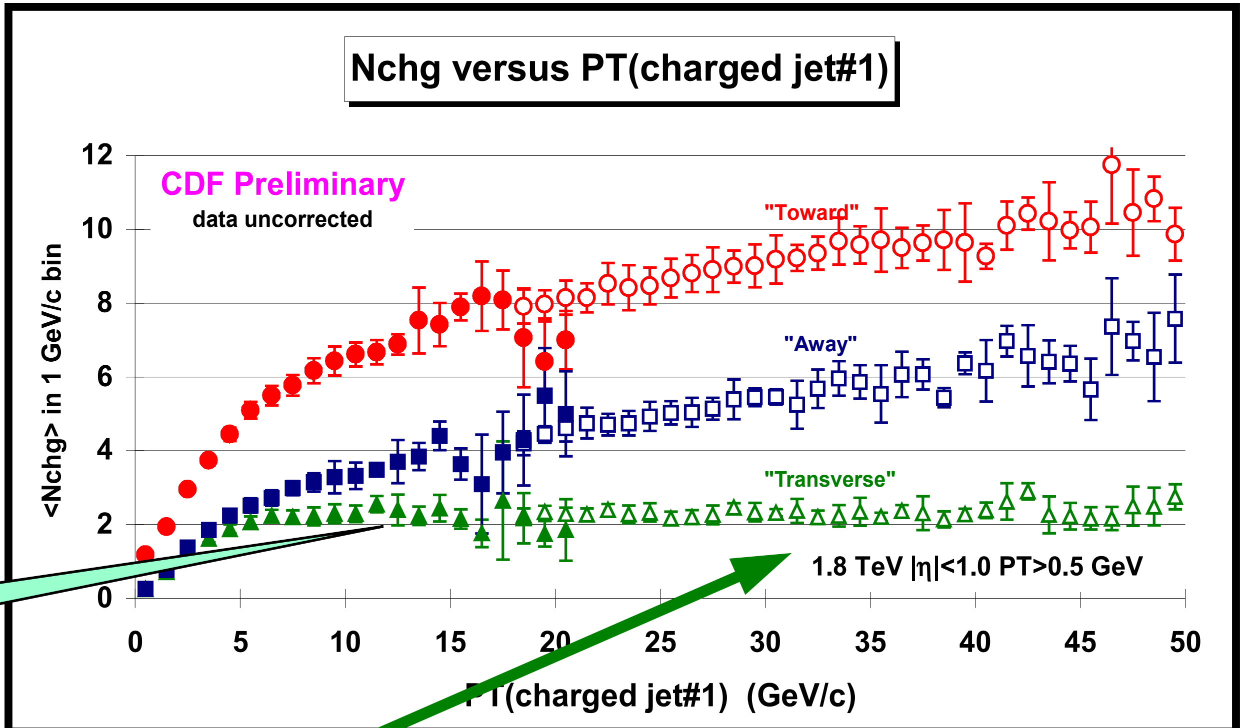
# Evidence for Multi Parton Interaction

- charged particle multiplicities

R. Field, talk D0 meeting sept 6, 2002

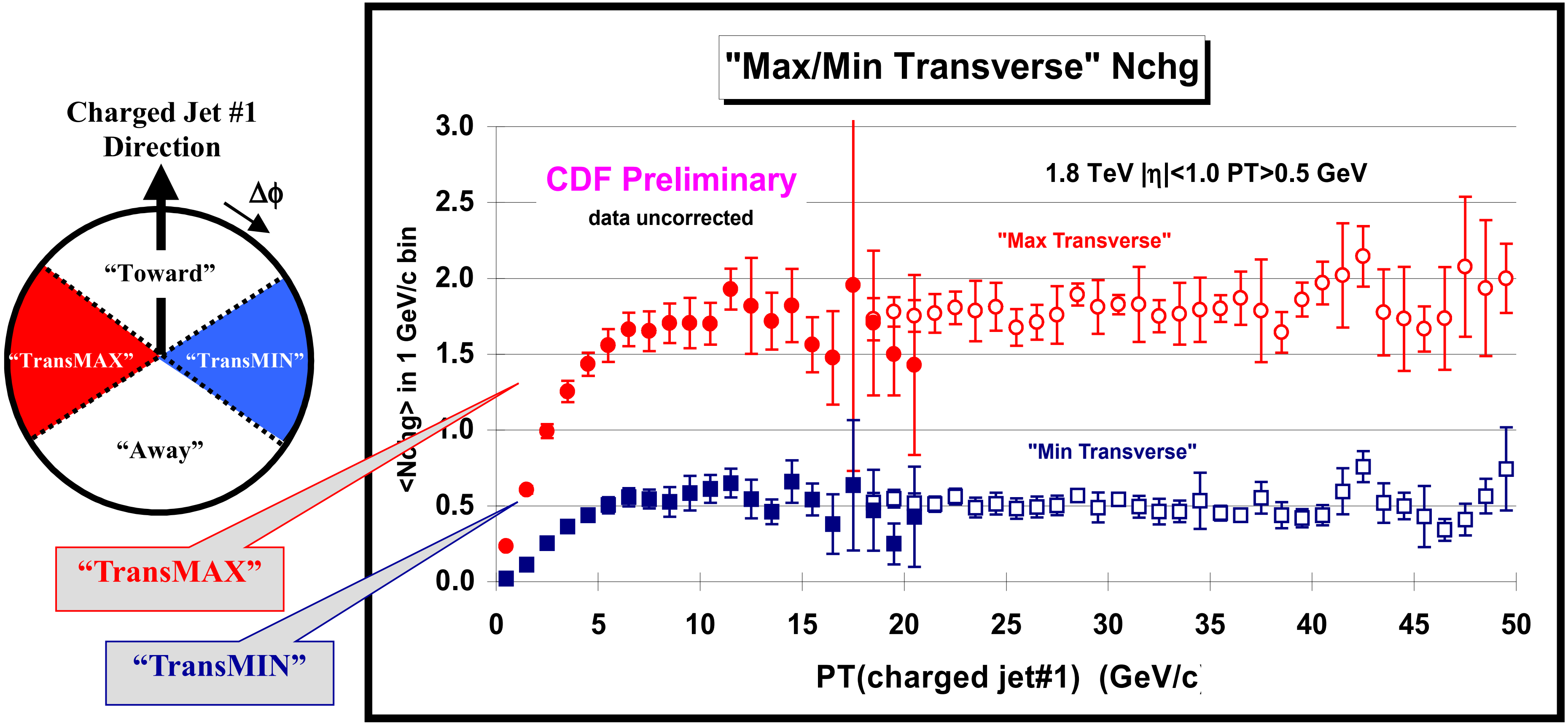



Underlying Event "plateau"




- Factor ~ 2 more activity in the transverse region than on average min-bias events

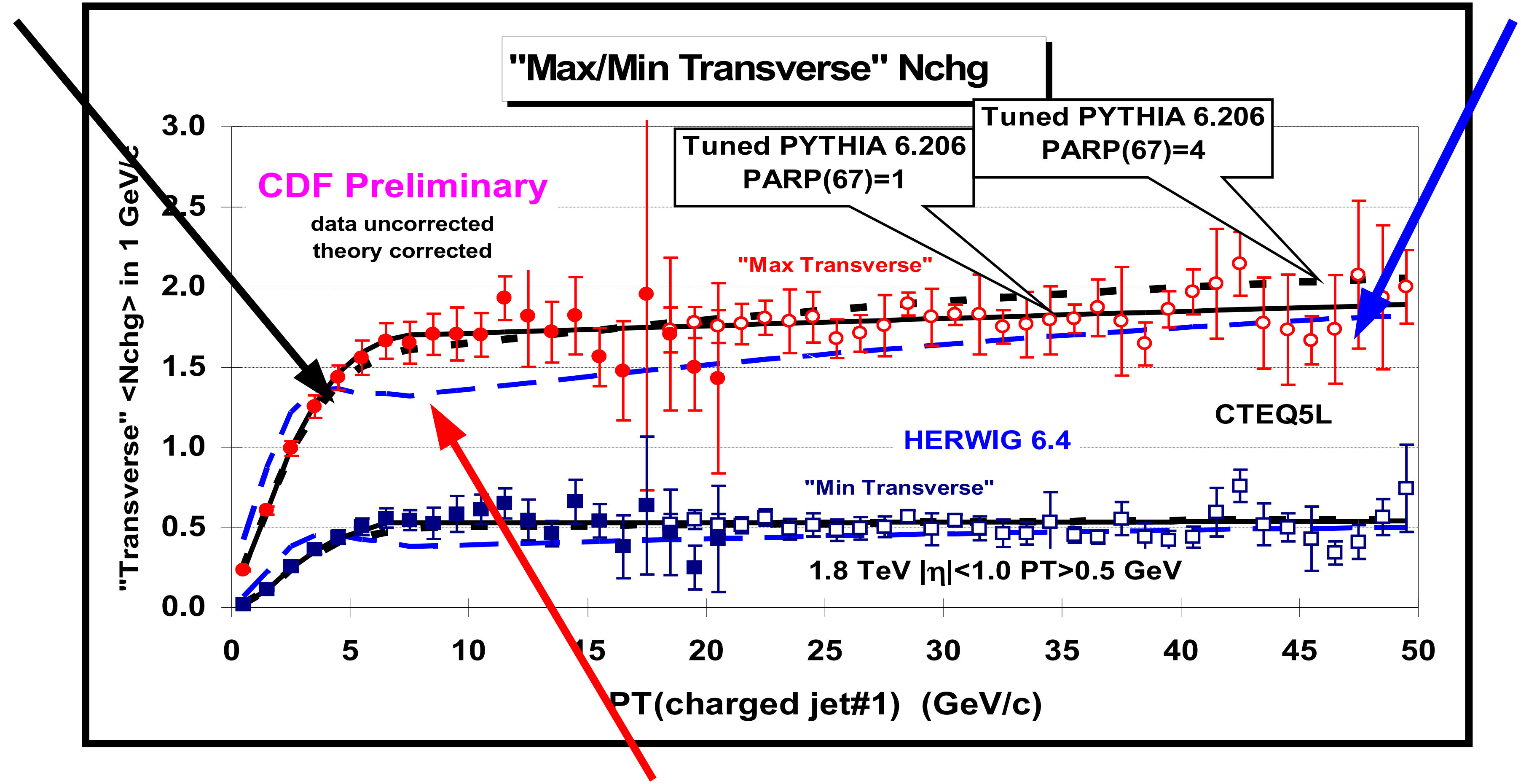
# More on Underlying events




- TransMAX region: Sensitive to hard component: higher order radiation/parton showers
- TransMIN region: sensitive to beam remnant interactions

# Modeling underlying events

- PYTHIA:
  multiparton interactions
- HERWIG uses here
  soft underlying event model from UA5




➔ soft underlying event model cannot account for activity

➔ Multiparton Interaction model can describe measurement !!!

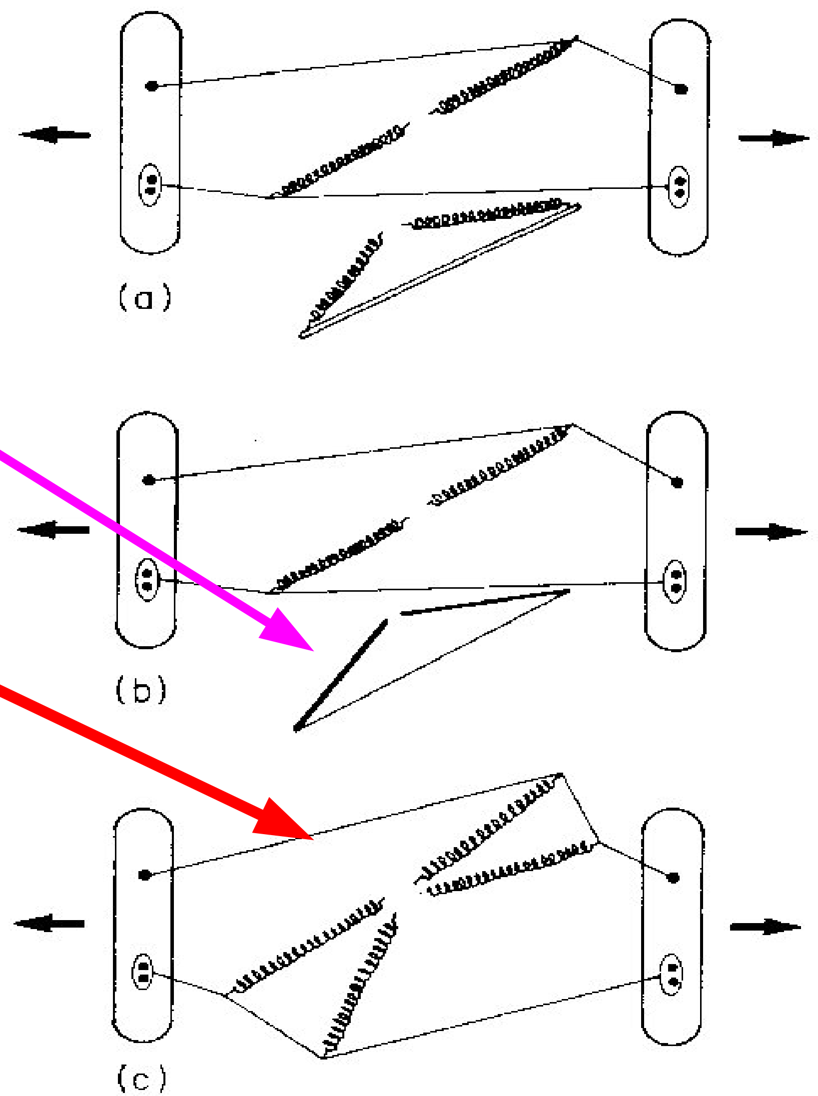
# Tuning to CDF data... Color flow in MPI

- possible scenarios for color string connection in multiparton events
- to describe underlying events.... need (CDF Tune A)
  - 5 % quarks (default 33 %)
  - 95 % gluons (default: 66%)
  - out of which 90 % (default 33 %) are

➔ smaller multiplicity with large transverse energy

- Are there good physics reasons for this mix ???
- **Highly nontrivial to describe multiplicity AND transverse energy distributions ...**

T. Sjostrand, M. Zijl
PRD 36 (1987) 2019



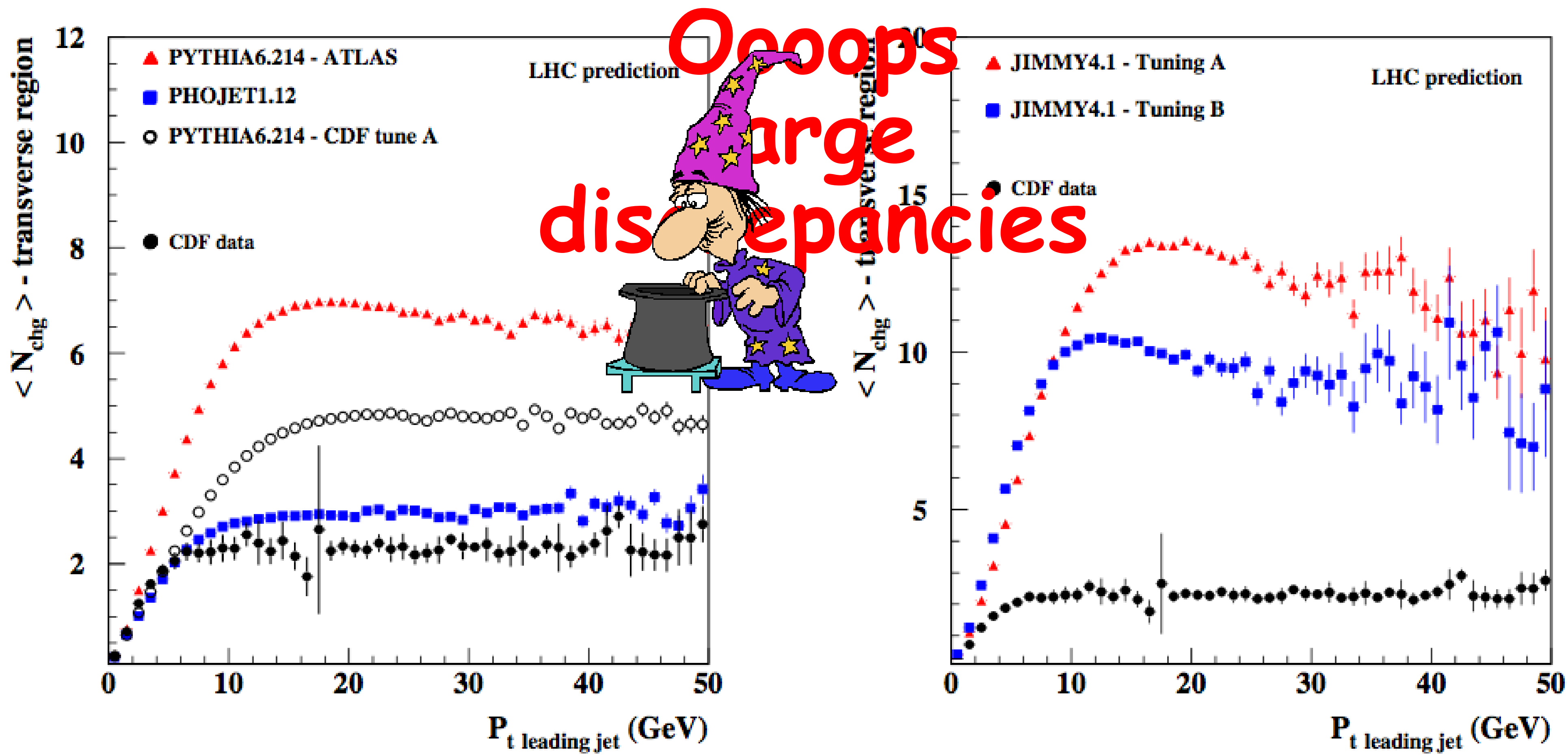
# Resumee ... so far

- in hadron-hadron collisions additional hadron activity is observed
  - ➔ for charged particle multiplicity in min-bias events
  - ➔ for jet pedestal
  - ➔ in transverse region in high pt jet/dijet events
- models: soft underlying event or multiparton interaction ?
  - ➔ soft underlying event model can be tuned to describe
    - ➔ multiplicity in minimum bias events
    - ➔ jet pedestal
    - ➔ **BUT** fails for transverse region in high pt jet/dijet events
  - ➔ multiparton interaction model can be tuned to describe all studied distributions .....
  - ➔ **requires highly non-trivial color connections**
- 4-jet/3-jet+photon angular de-correlation
  - ➔ only described by multiparton interaction model

# Prospects for LHC

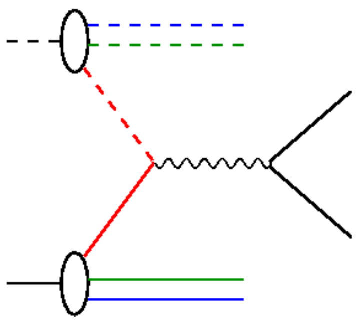
- use TeVatron data to determine model parameters
- predict underlying events at LHC ....

C. Buttar et al in HERA – LHC workshop proceedings hep-ph/0601012



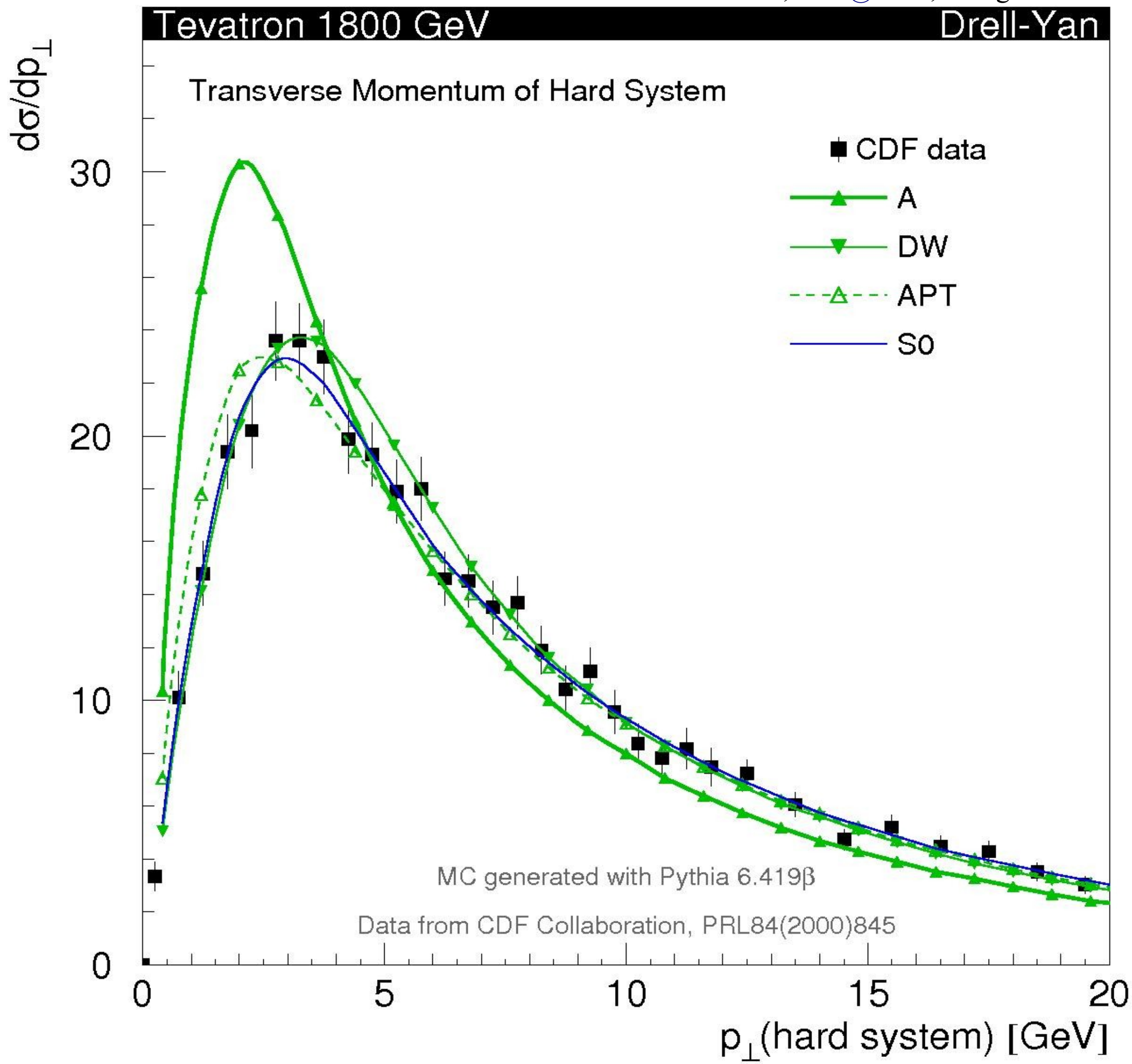
# Does it matter for high pt physics ?

# Drell Yan process is affected ...



- $P_t$ of Drell Yan is affected by parton shower BUT also by the underlying events ....
- significant effects
- how to tune the truth ?

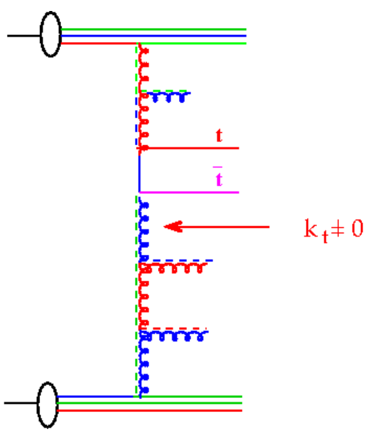
P. Skands, MPI@LHC, Perugia 2008

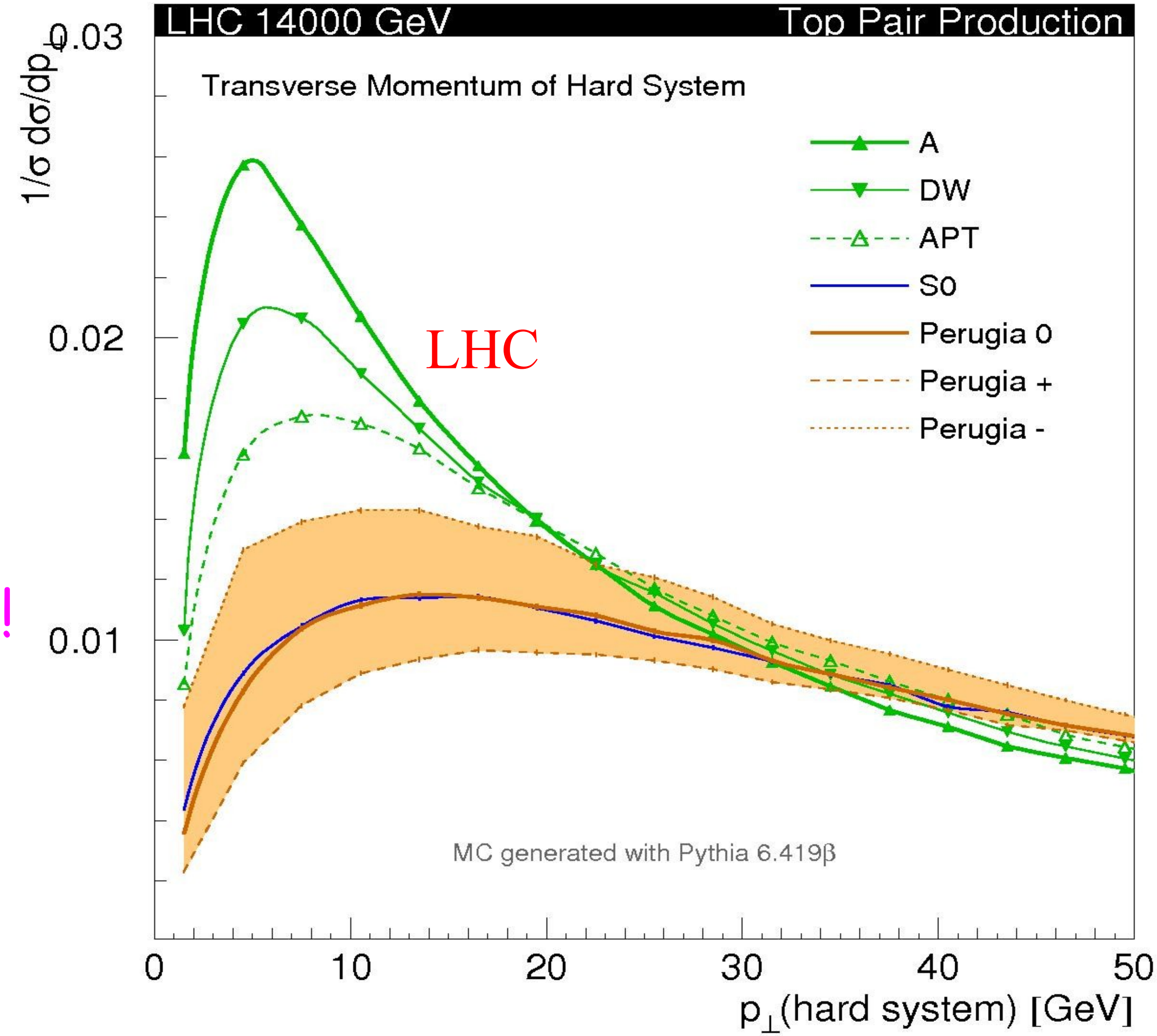


# ttbar is also affected ...

P. Skands, MPI@LHC, Perugia 2008

- $P_t$ of $t\bar{t}$ is affected by parton shower BUT also by the underlying events ....




- note: pt of the pair is plotted !!
- **HUGE effects**

# Double-Parton Interactions at LHC

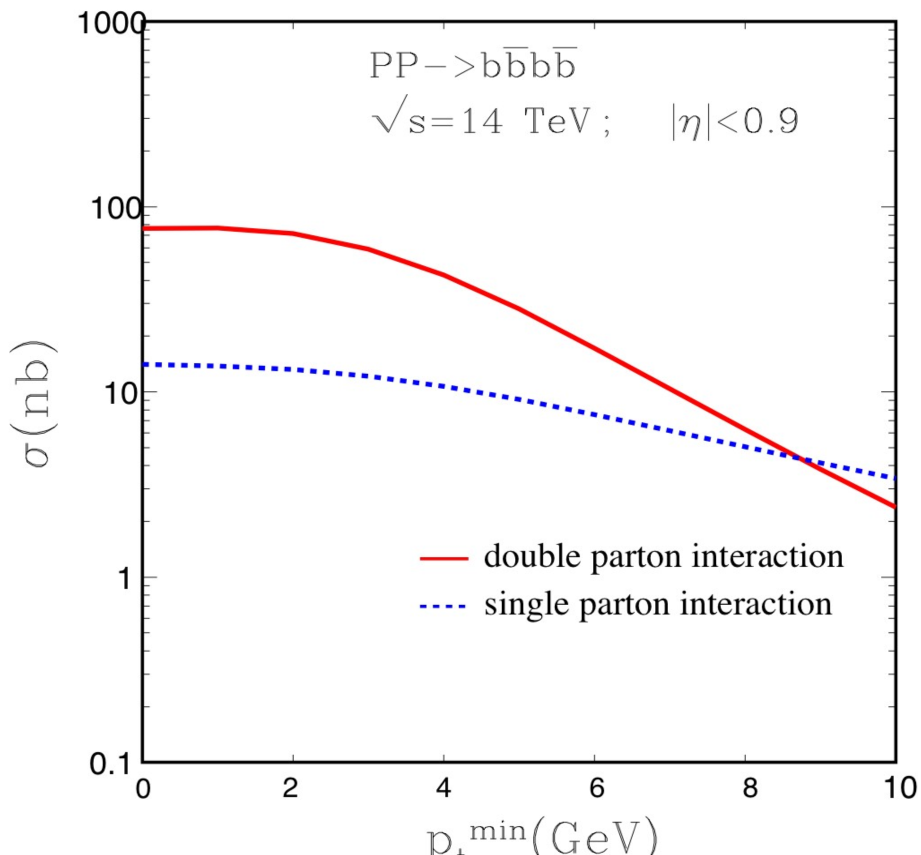
- xsection for $p+p \to b\bar{b}b\bar{b}$

single parton exchange (SP)

$$\sigma^{SP} \sim f^2 \hat{\sigma}(2 \to 4)$$

double parton exchange (DP)

$$\sigma^{DP} \sim f^4 \hat{\sigma}^2(2 \to 2)$$




- PYTHIA predictions:

$$\sigma^{DP} = 0.8 \cdots 11.1 \;\; \mu b$$

➔ Depending on model for underlying event/multi-parton interactions...

# Multi-Parton Interactions at LHC

- Higgs: $p+p \to W+H+X$

with $W \to l\nu, \quad H \to b\bar{b}$

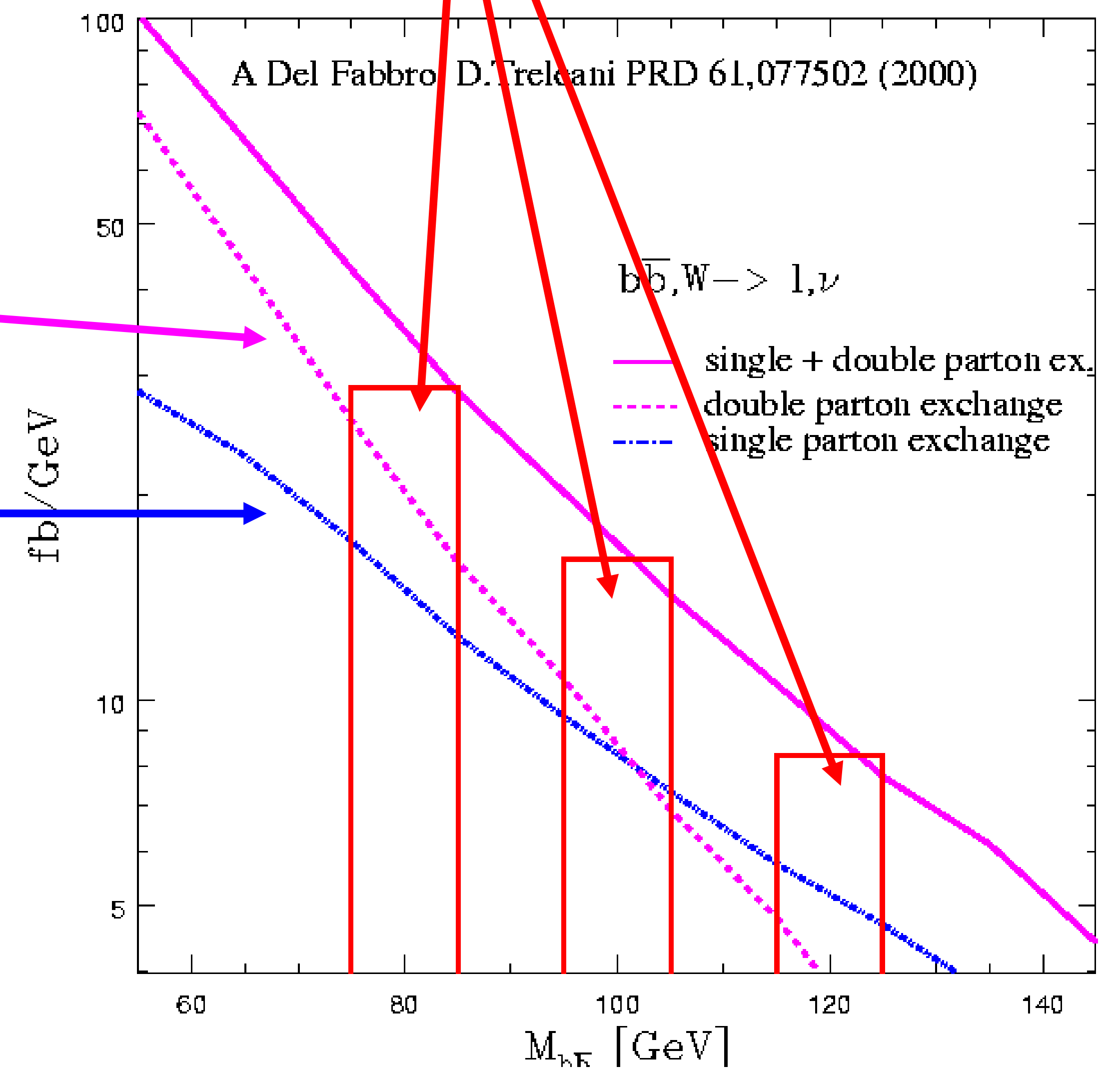
- Double parton scattering:

  $p+p \to b\bar{b}X$

  $p+p \to W+X$

  $p+p \to W+b\bar{b}+X$

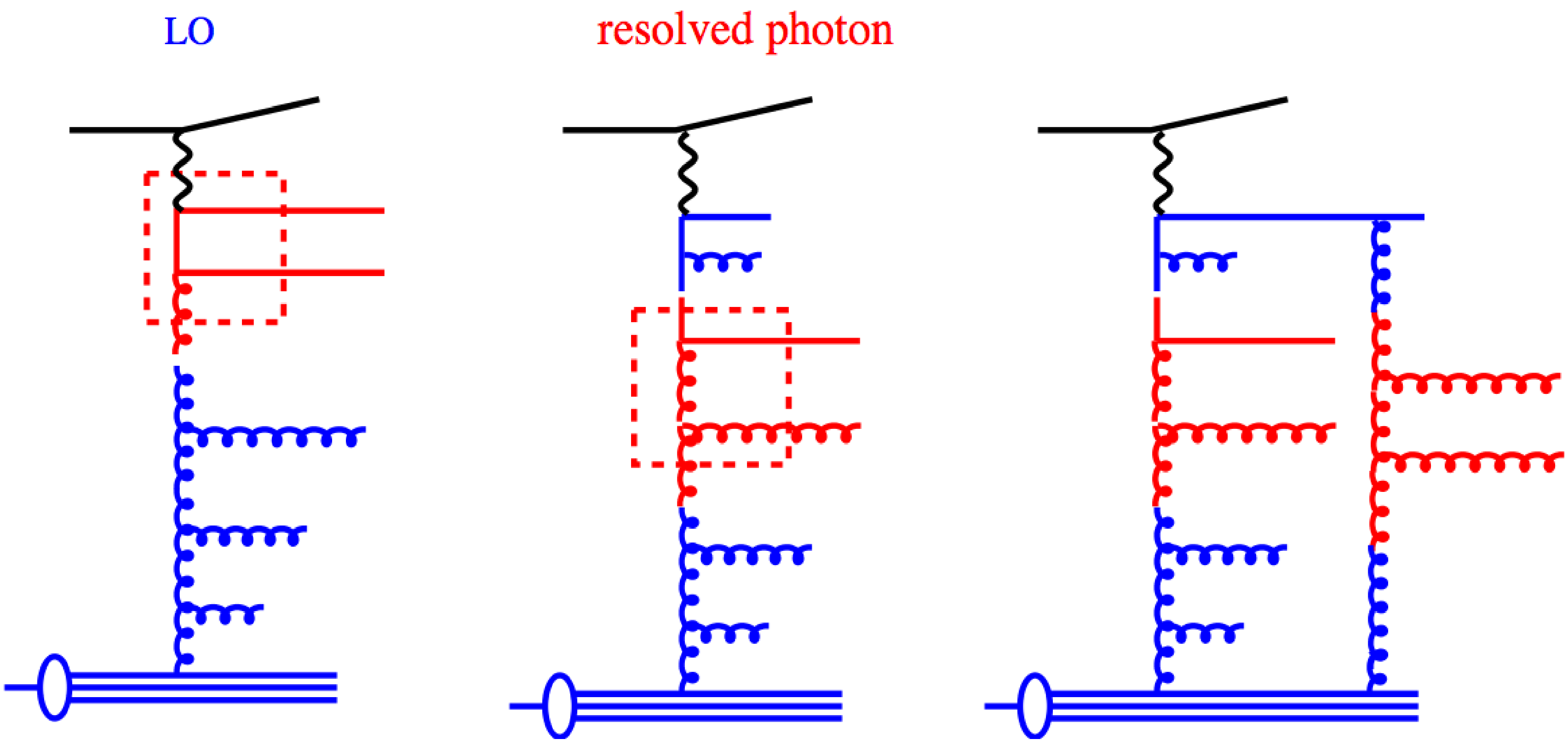
$p+p \to W+H+X$



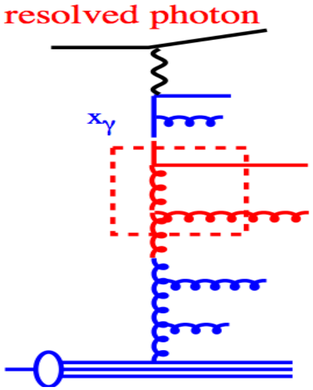
Do we really understand, what we are doing ???

# Go back to clean environment ...

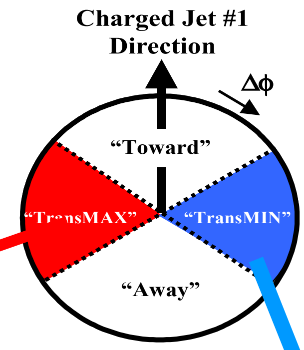
- Study of jet production and underlying event structures in ep:
  - photoproduction:
    - ➔ smooth transition from pointlike to hadronlike interaction
  - DIS:
    - ➔ pointlike interaction, important as benchmark checks

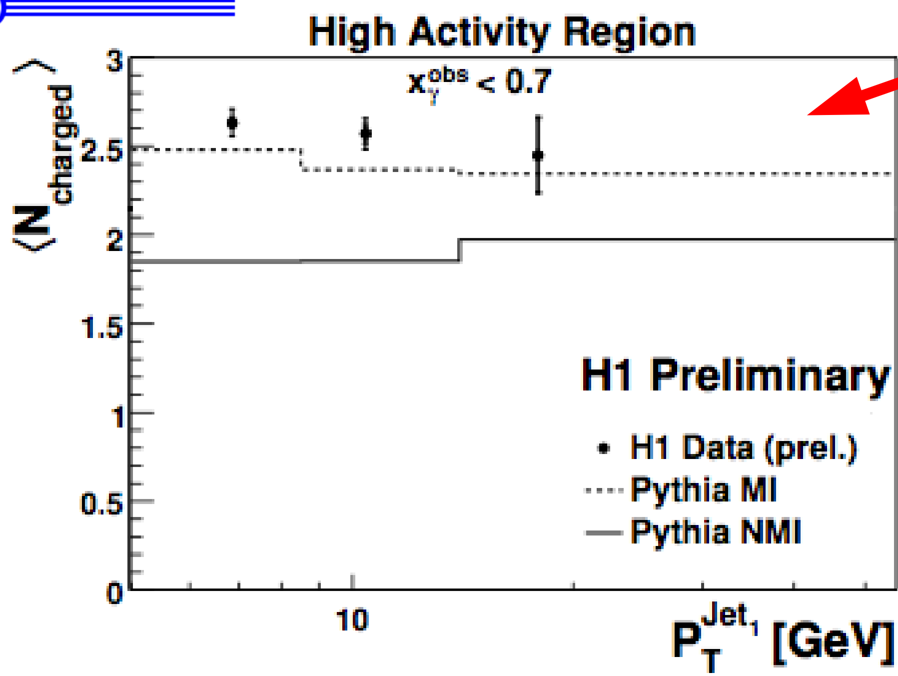


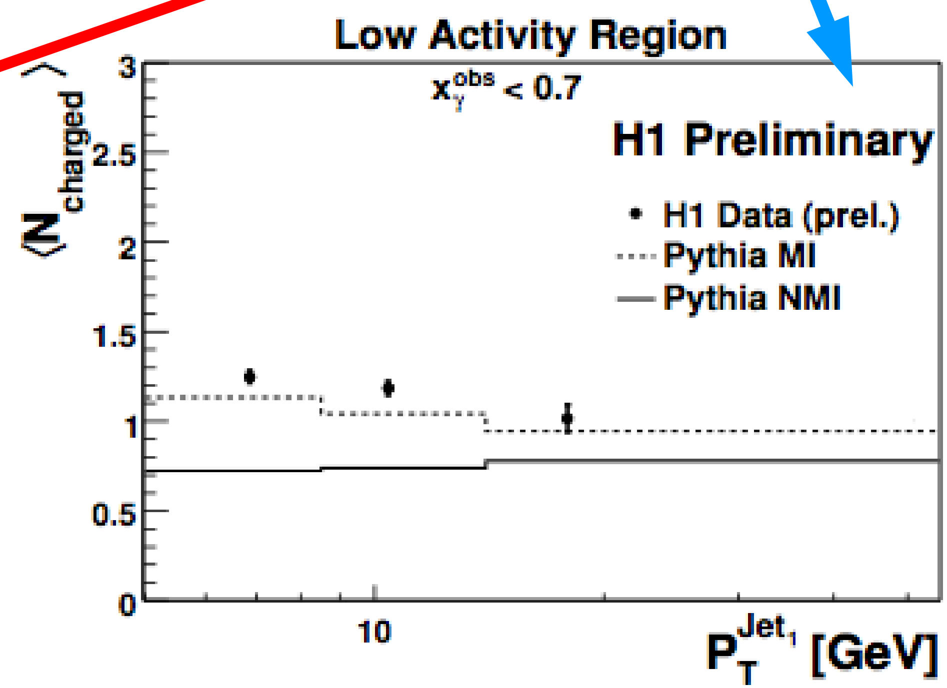
# Studies at HERA: photoproduction




- Underlying events in photoproduction: charged particle spectra

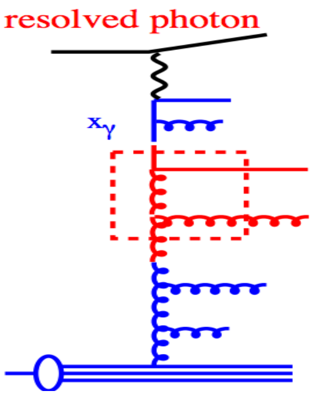


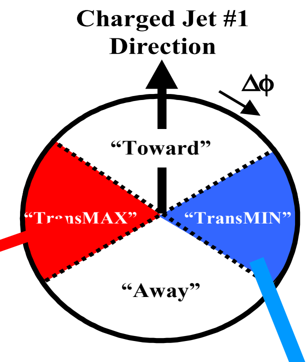



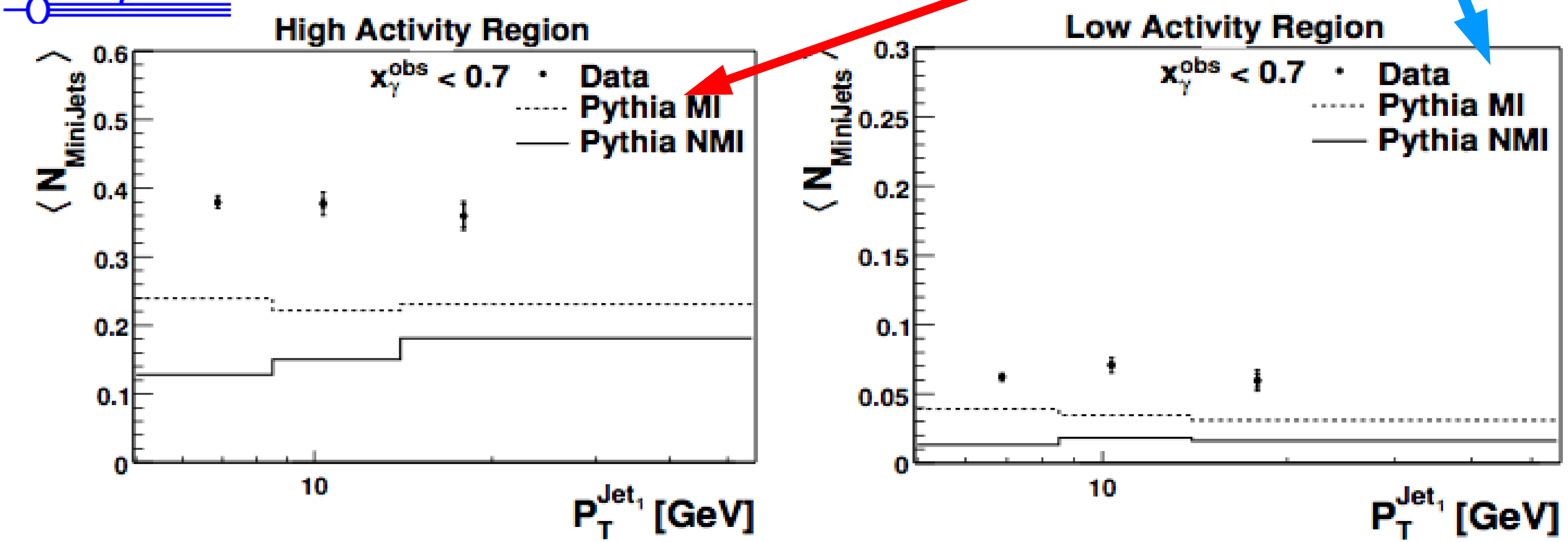

➔ **charged particle multiplicities are described !**

# Studies at HERA: photoproduction



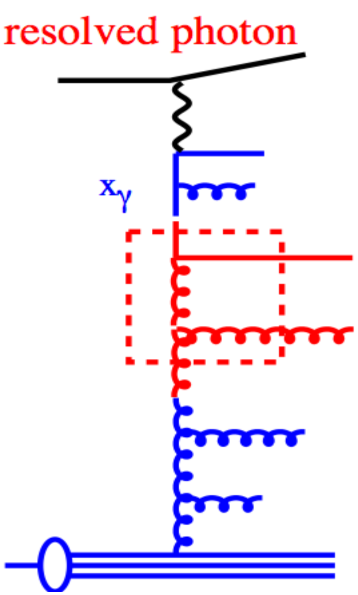

- Underlying events in photoproduction: minijets $p_t > 3.5$ GeV



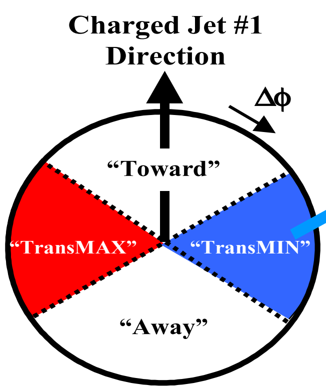



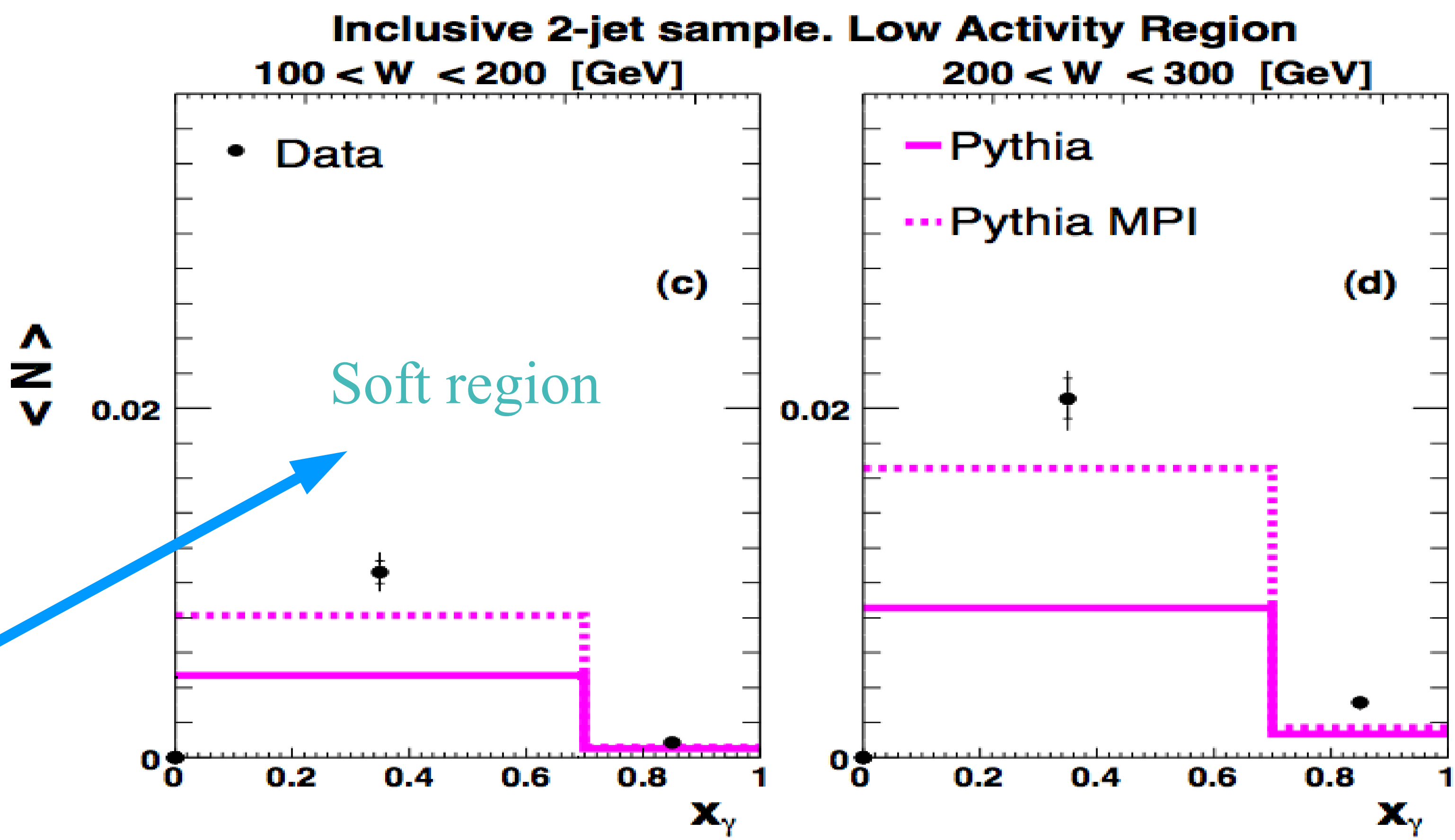

➔ **Minjet multiplicities are not at all described !**

# Studies at HERA: DIS




- Underlying events in DIS ($Q^2 > 5$ GeV$^2$): minijets $p_t > 3.5$ GeV

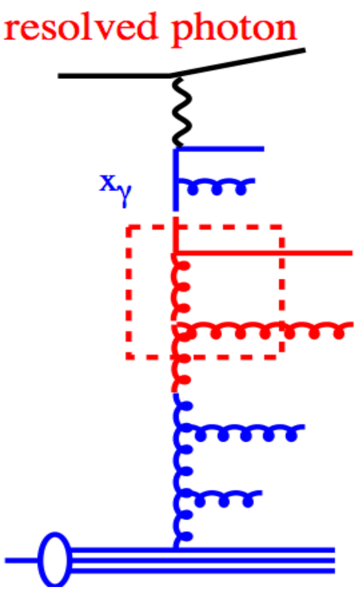


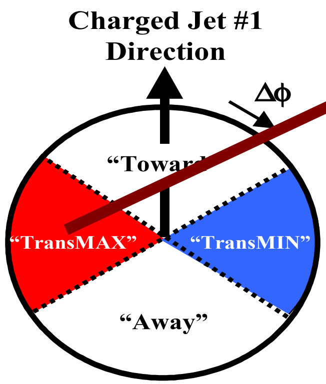



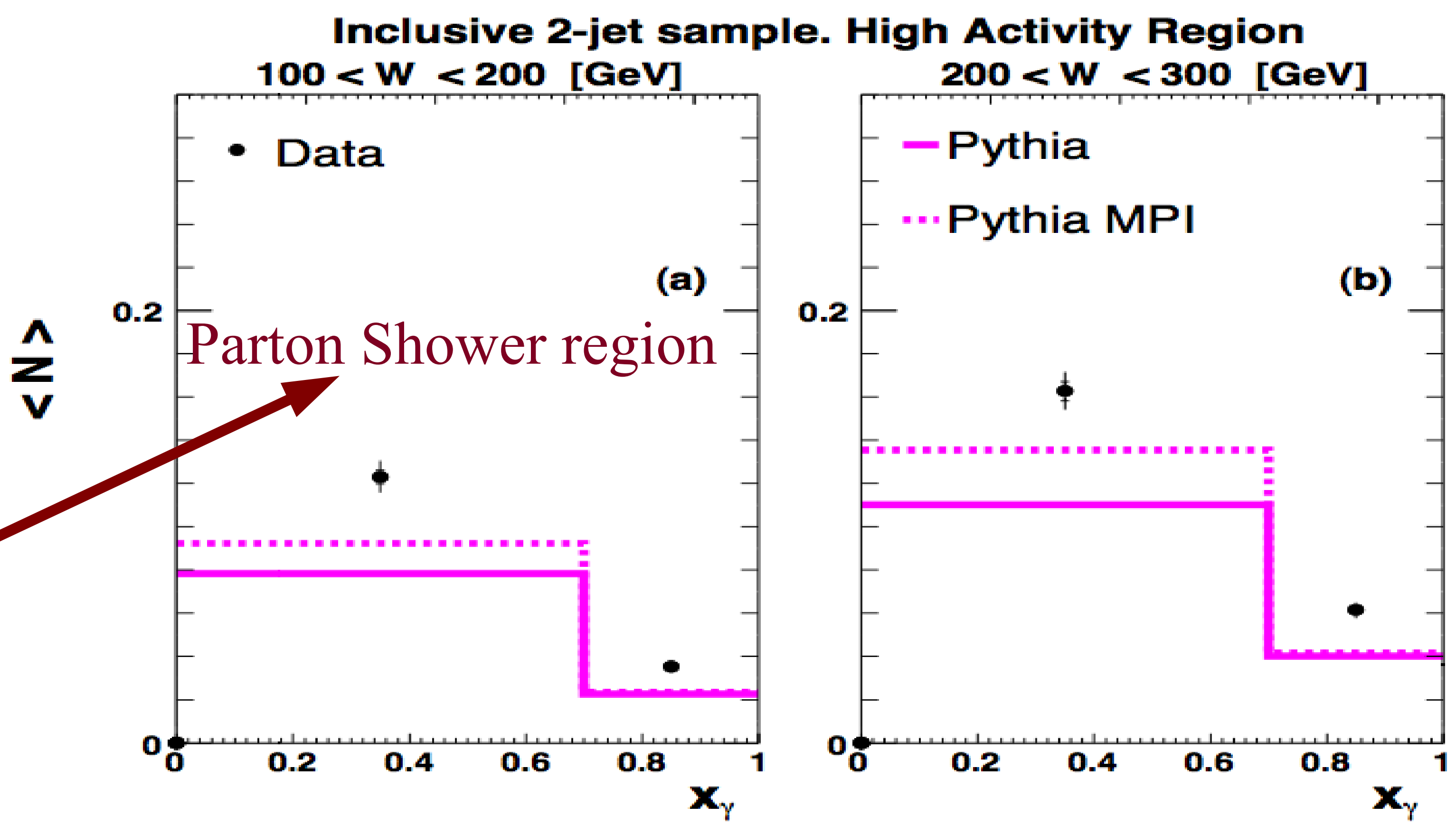

➔ **Minjet multiplicities are not at all described !**

# Studies at HERA: DIS

- Underlying events in DIS (Q2 > 5 GeV2): minijets pt > 3.5 GeV



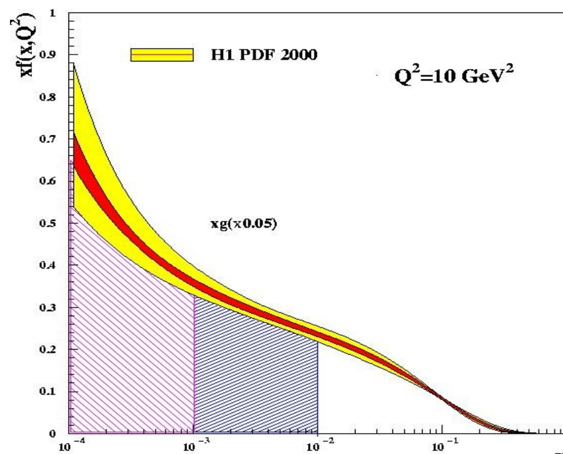

➔ **Minjet multiplicities are not at all described !**

Even in lepton-proton scattering, minjet multiplicities are not well described.

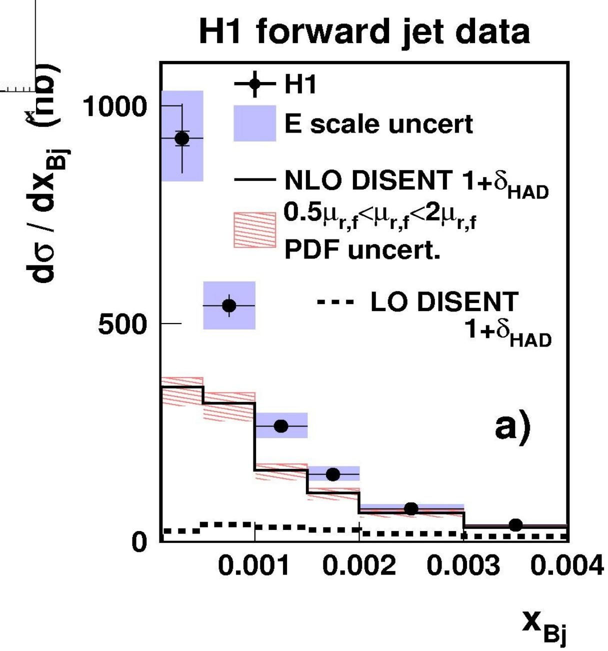
Why ?

# What happens at high energies ?

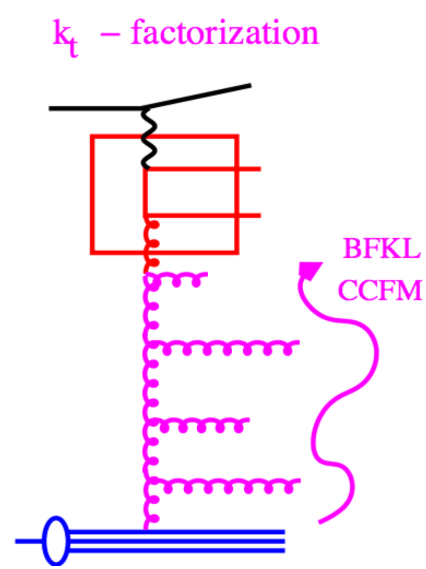
- parton densities are large at small x



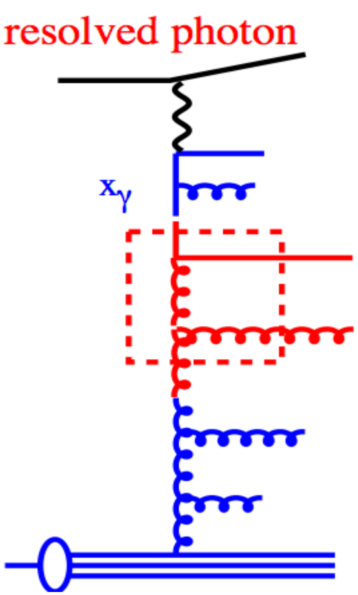

- DGLAP evolution cannot describe all final states




- need BFKL/CCFM evolution to account for increased phase space



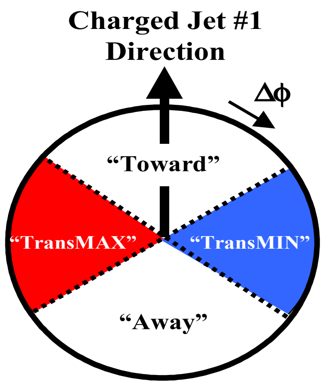
# What if using CCFM in DIS ?

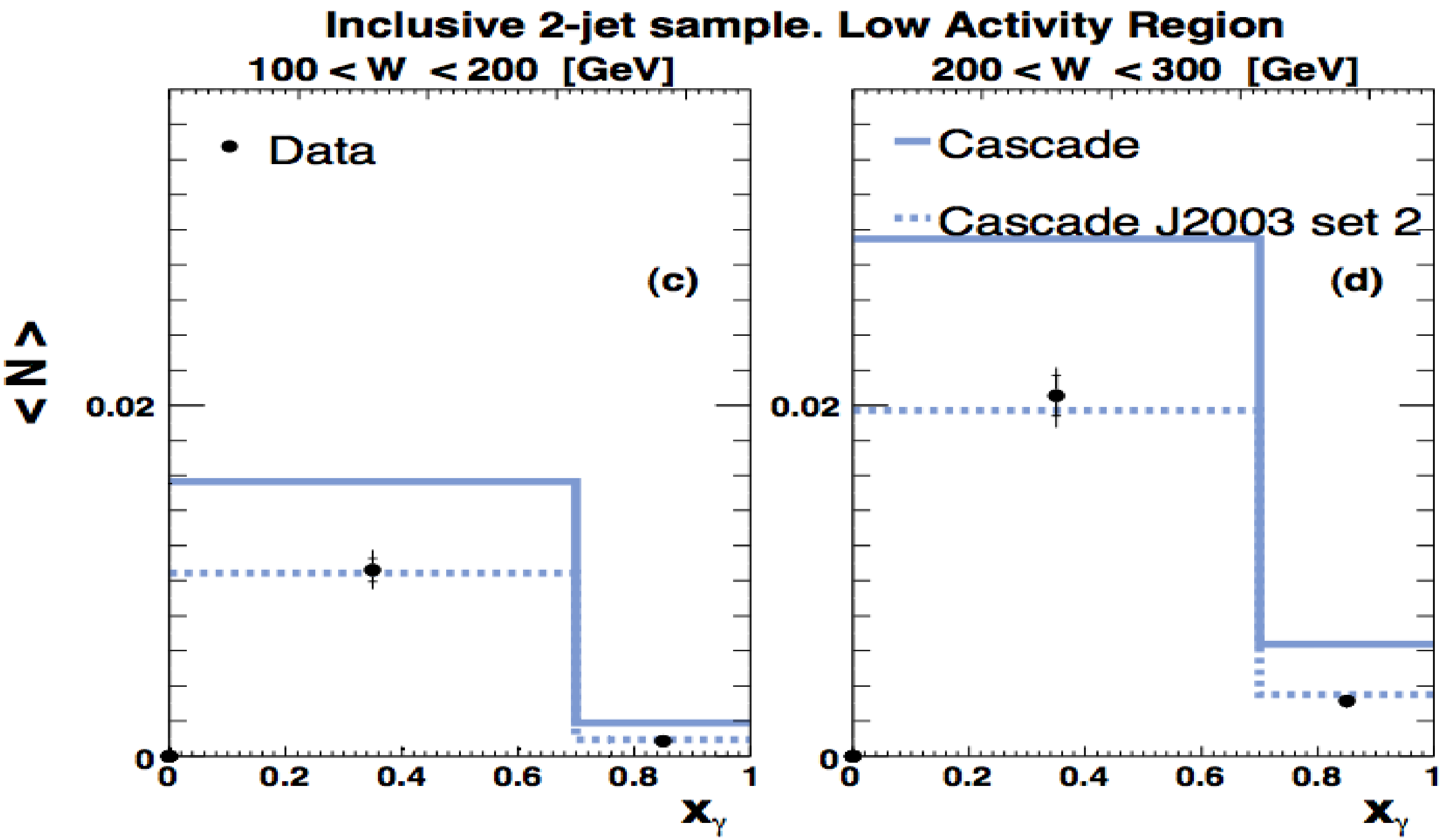



- Underlying events in DIS (Q2 > 5 GeV2): minijets pt > 3.5 GeV

S. Osman, H1 PhD thesis, Lund 2008,h1th-499

- CASCADE has no multi-parton interaction

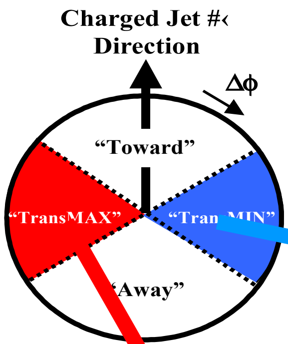


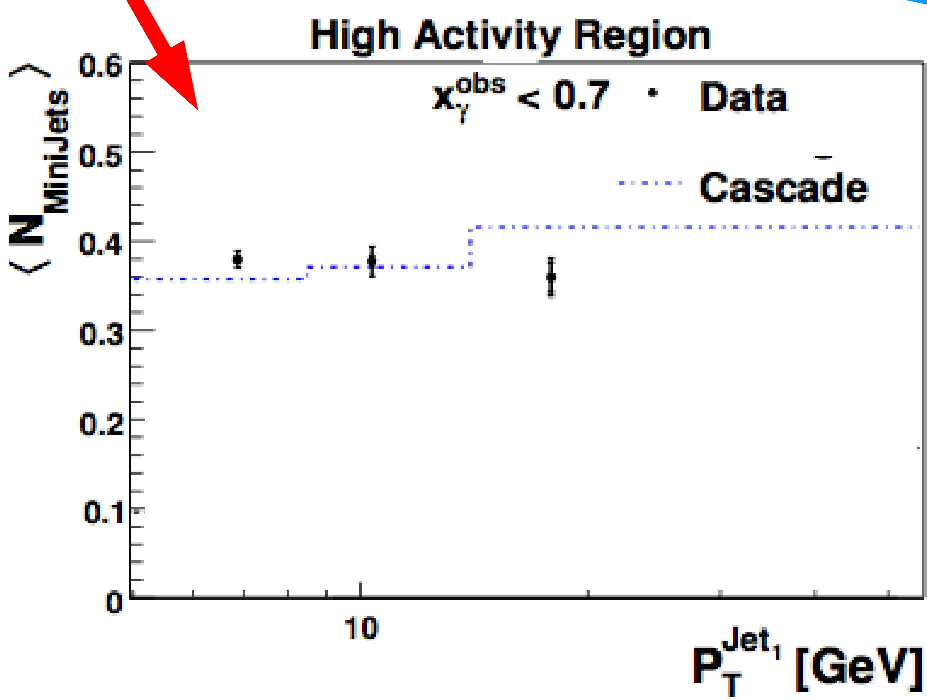

➔ **Minjet multiplicities are well described !**

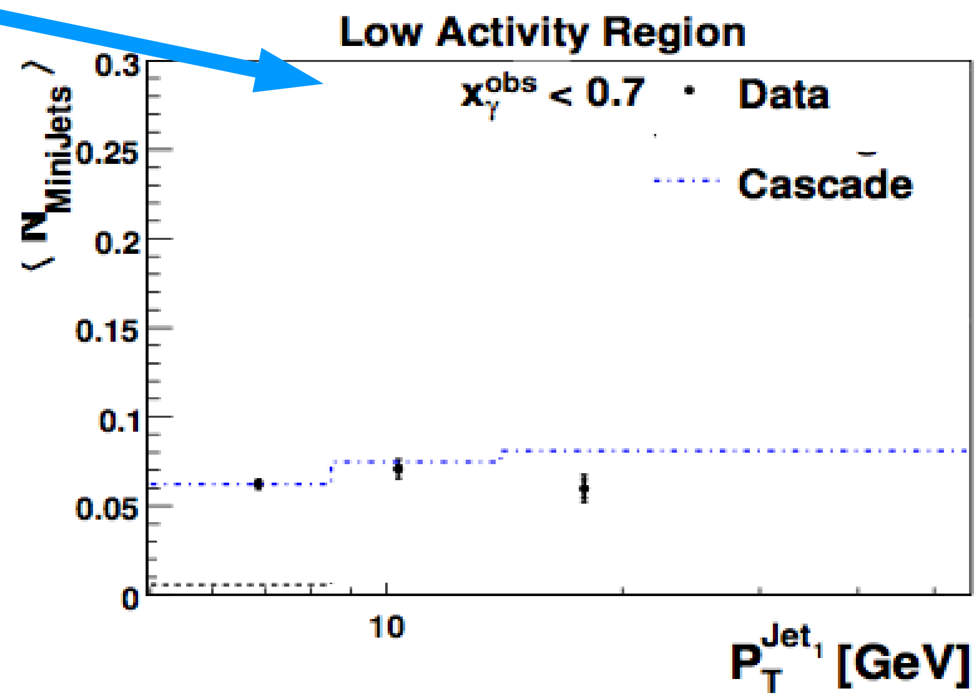
# What if using CCFM in $\gamma$-p ?

Ll. Marti, H1 PhD thesis, DESY 2009, h1th-507




- Underlying events in photoproduction: minijets pt > 3.5 GeV
- CASCADE has no multi-parton interaction

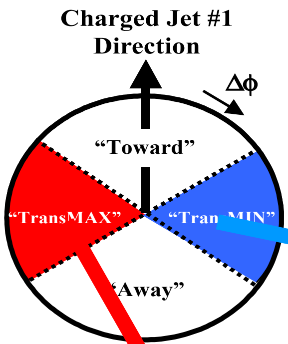


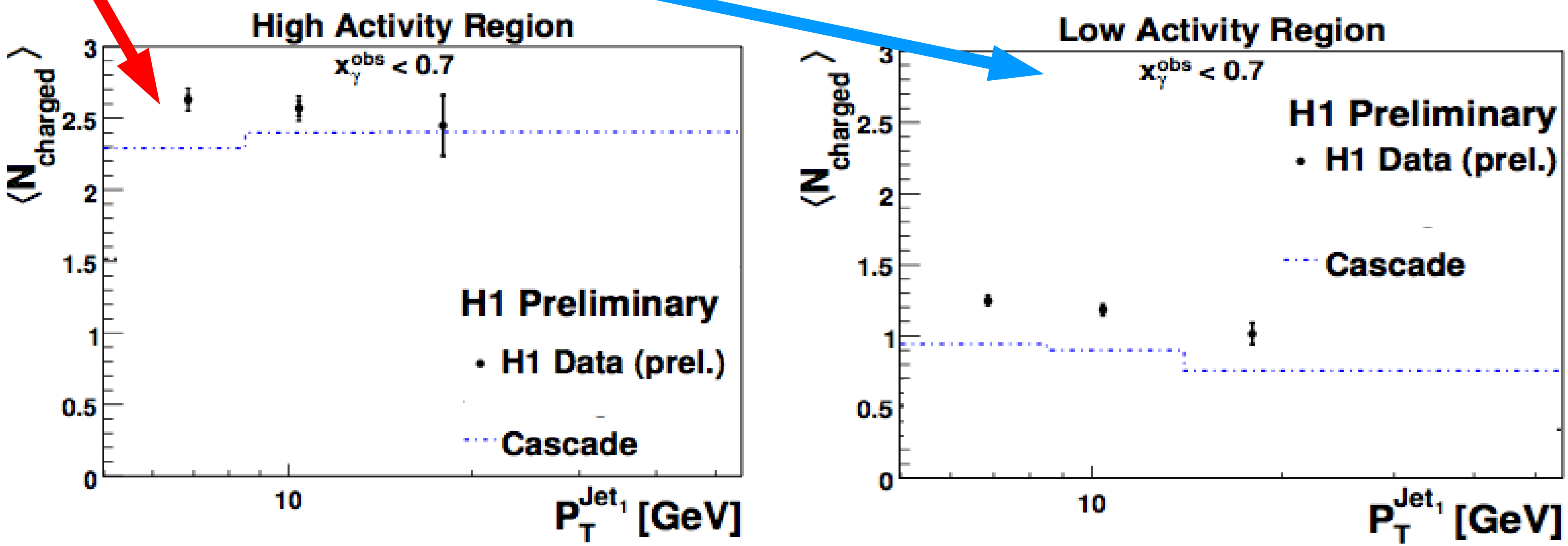

→ **Minjet multiplicities are described !**

# Studies at HERA: photoproduction

Ll. Marti, H1 PhD thesis, DESY 2009, h1th-507




- Underlying events in photoproduction: charged particle spectra
- CASCADE has no multi-parton interaction




→ **high activity region (parton shower) is ~ ok**

→ **low activity region too low !**

# What do we learn from this ?

- Proper treatment of parton radiation at highest energies is needed
  - DGLAP parton showers are never sufficient
  - BFKL/CCFM parton showers able to describe regions where expected
  - ➔ high activity transverse regions
- The amount of additional activity in transverse regions depends crucially on treatment of Parton Showers/higher order radiation
- Using DGLAP evolved parton densities in a region of high parton density can lead to wrong results..

➔ Multi Parton Interaction is **entirely a small x effect**

➔ need proper treatment of **small x parton dynamics**

# Outlook and prospects

- Systematic investigation of parton shower and parton densities is essential
- activities started within Terascale Alliance (Monte Carlo group) ( http://www.terascale.de/)
  - PDF4MC project
  - parton shower institute in May at DESY
  - regular pheno-weeks for discussion
- many of these studies are done also in the frame of the workshop
  HERA and the LHC
  proceedings 2006-2008
  0903.3861 and http://www.desy.de/~heralhc

# Conclusions

- Multiparton interaction
  - ➔ affect all measurements in hadronic collisions
    - ➔ need to be well understood
  - ➔ directly related to small x, high density systems, saturation
    - ➔ without proper small x simulation (BFKL/CCFM), no realistic description possible.
  - ➔ systematic model tuning is necessary
    - ➔ including HERA measurements

**Challenge to describe small x, saturation, multiparton interaction, diffraction and high density QCD**