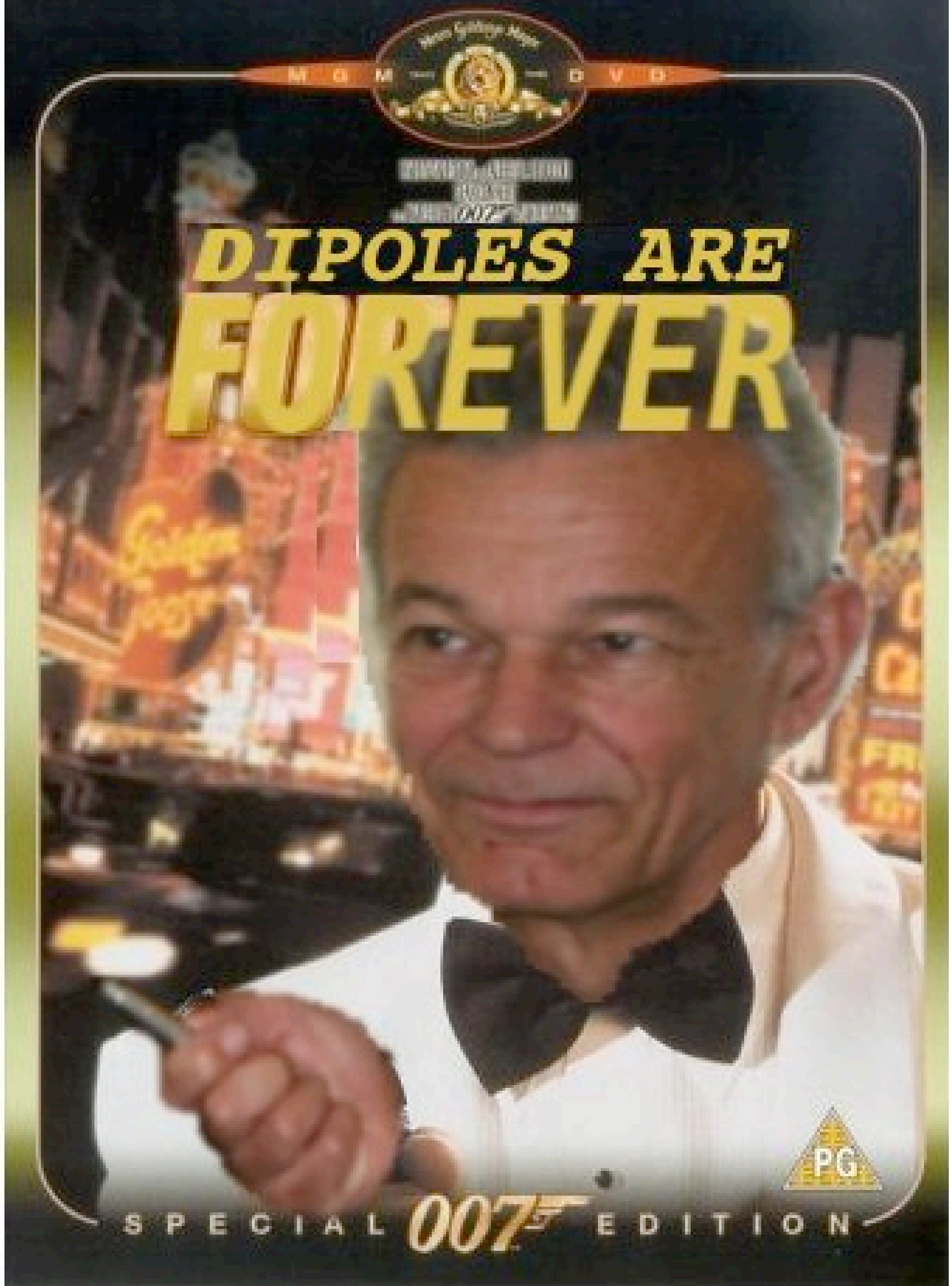
The DESY directorate sends the best wishes to Gösta Gustafson and the symposium to celebrate the long and successful career of Gösta Gustafson and his scientific work for a better and deeper understanding of non-perturbative and perturbative QCD.

The DESY directorate and DESY acknowledges very much the outstanding role Gösta had for the measurements and their interpretation at the DORIS and PETRA storage rings and later at HERA. Without his significant contributions the HERA results would have been not so much recognized and understood, worldwide.

The DESY directorate is very glad that Gösta now has the possibility to come to Hamburg as a Mercator Professor for one year, to actively continue his research projects also in connection with the physics at the LHC.

The DESY directorate wishes Gösta very much a long, healthy and interesting future.

A. Wagner, R.D. Heuer.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DIPOLES ARE
FOREVER
PG
SPECIAL 007 EDITION

The strings between experiment and theory

The strings between experiment and theory

Understanding QCD ...

The strings between experiment and theory

Understanding QCD ...

➔ the easy case: e^+e^-

The strings between experiment and theory

Understanding QCD ...

- ➔ the easy case: e^+e^-
- ➔ the next-to-easy case ep

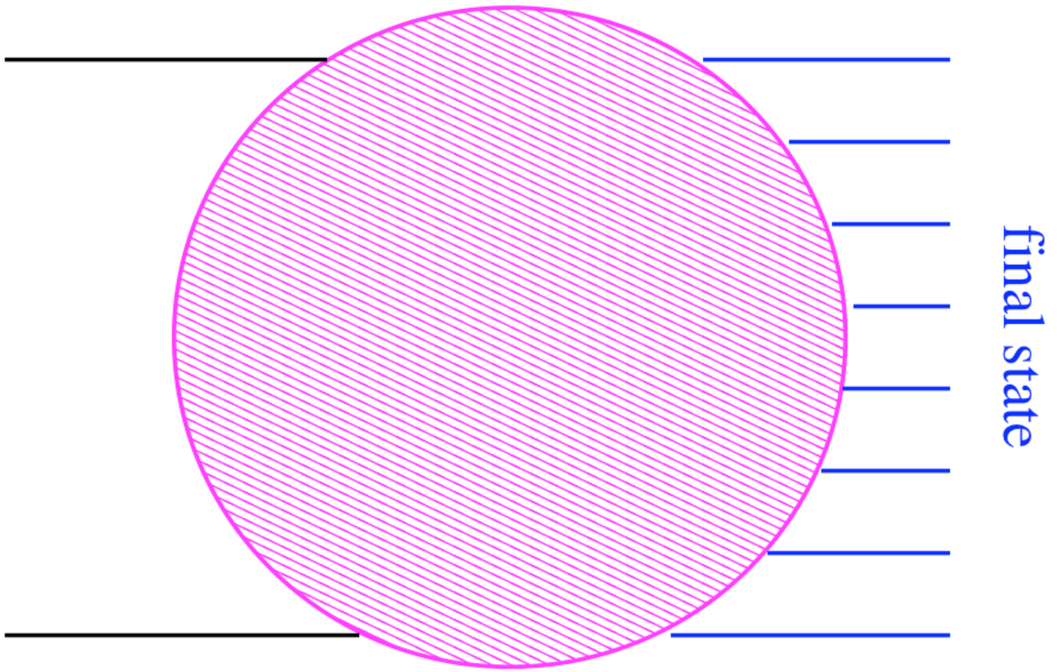
The strings between experiment and theory

Understanding QCD ...

- ➔ the easy case: e^+e^-
- ➔ the next-to-easy case ep
- ➔ the next-to-next-to-easy ... the complicated case pp

The general case

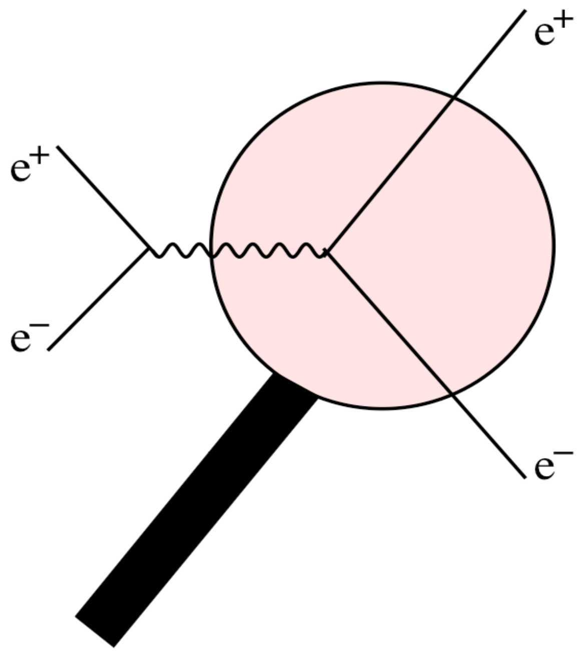
- Ambitious Aims....
- describe interaction of $A + B \rightarrow \text{anything}$

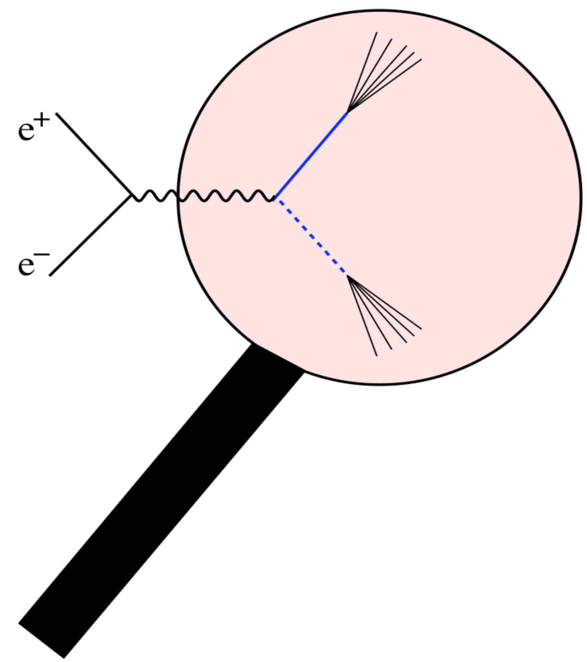


- where anything can be:
  - ➔ leptons
  - ➔ stable hadrons
  - ➔ new particles ....

The easy case: $e^+e^- \to X$

- use $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to q\bar{q} \to \text{hadrons}$





- cross sections can be calculated in QED: $\sigma(e^+e^- \to l^+l^-) = \frac{4\pi\alpha^2}{3s}$

- and for quarks $\sigma(e^+e^- \to q\bar{q}) = 3\frac{4\pi\alpha^2}{3s}e_q^2$

➔ but quarks carry color and fractional charge !!!!!

color charge

The easy case: $e^+e^- \to X$

- measure ratio of hadronic / leptonic cross section

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e- \to \mu^+\mu^-)}$$
$$= N_c \sum_i e_q^2 = 3 \sum_i e_q^2$$

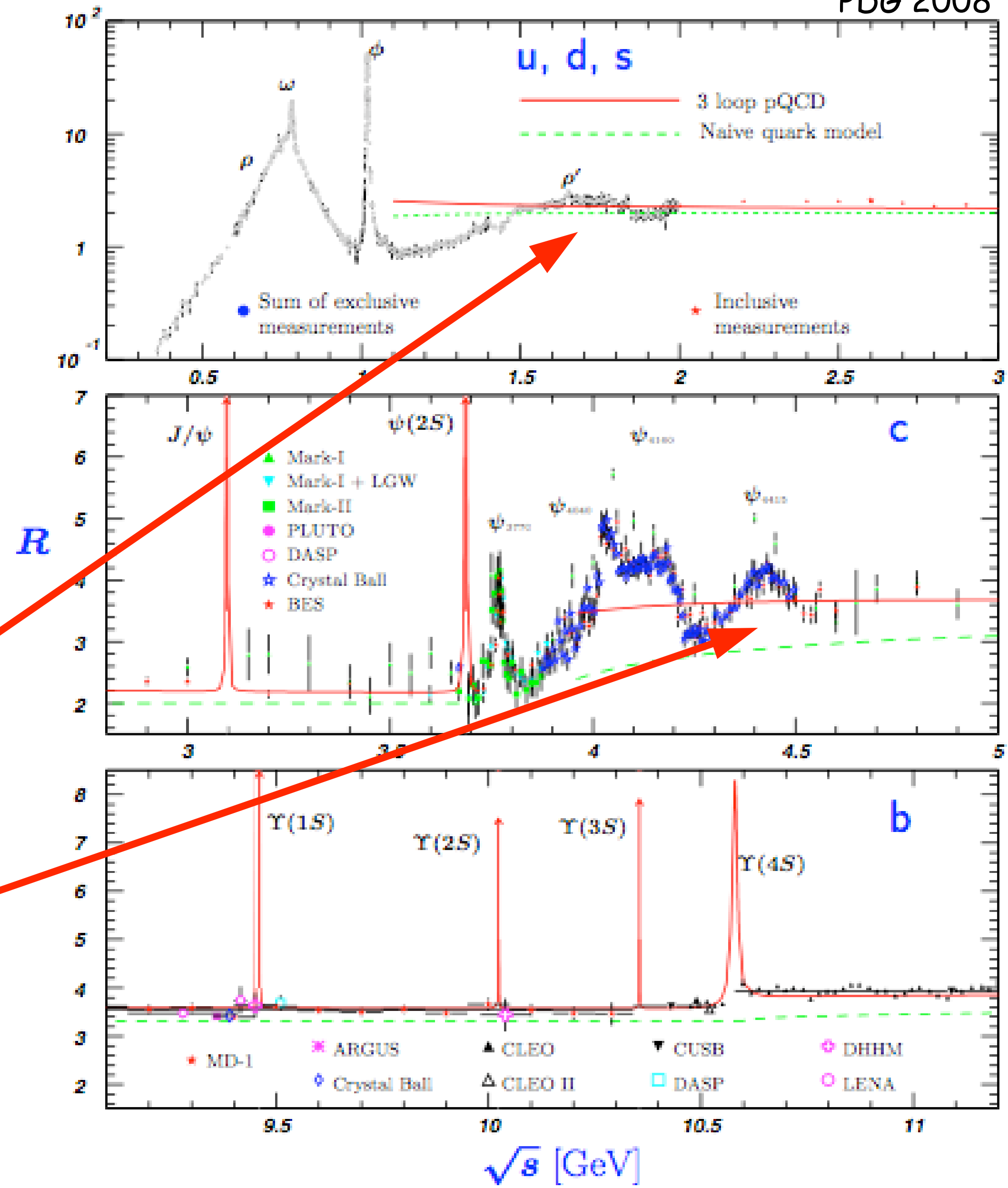
- for 3 quarks:

$$R = 3\left[\left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = 2$$

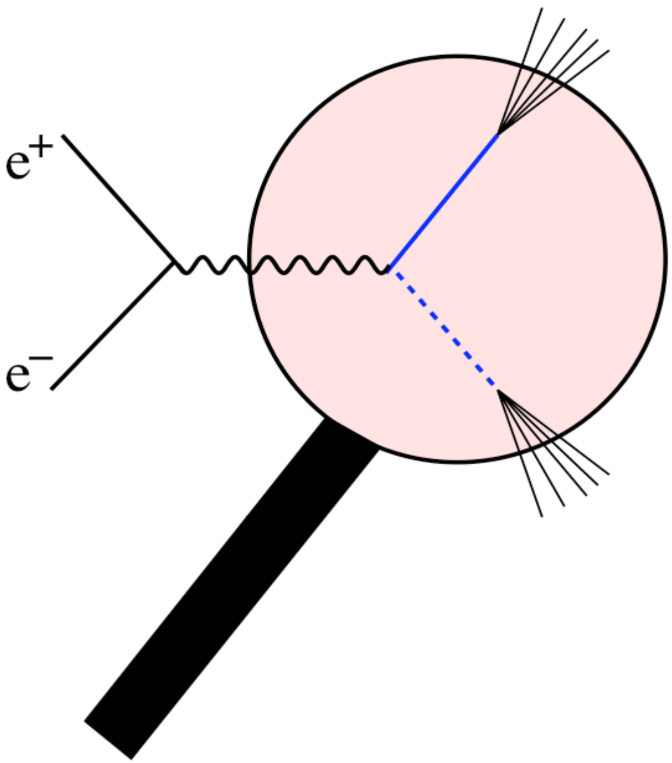
- including charm

$$R = 3\left[\frac{2}{3} + \left(\frac{2}{3}\right)^2\right] = 3.333$$

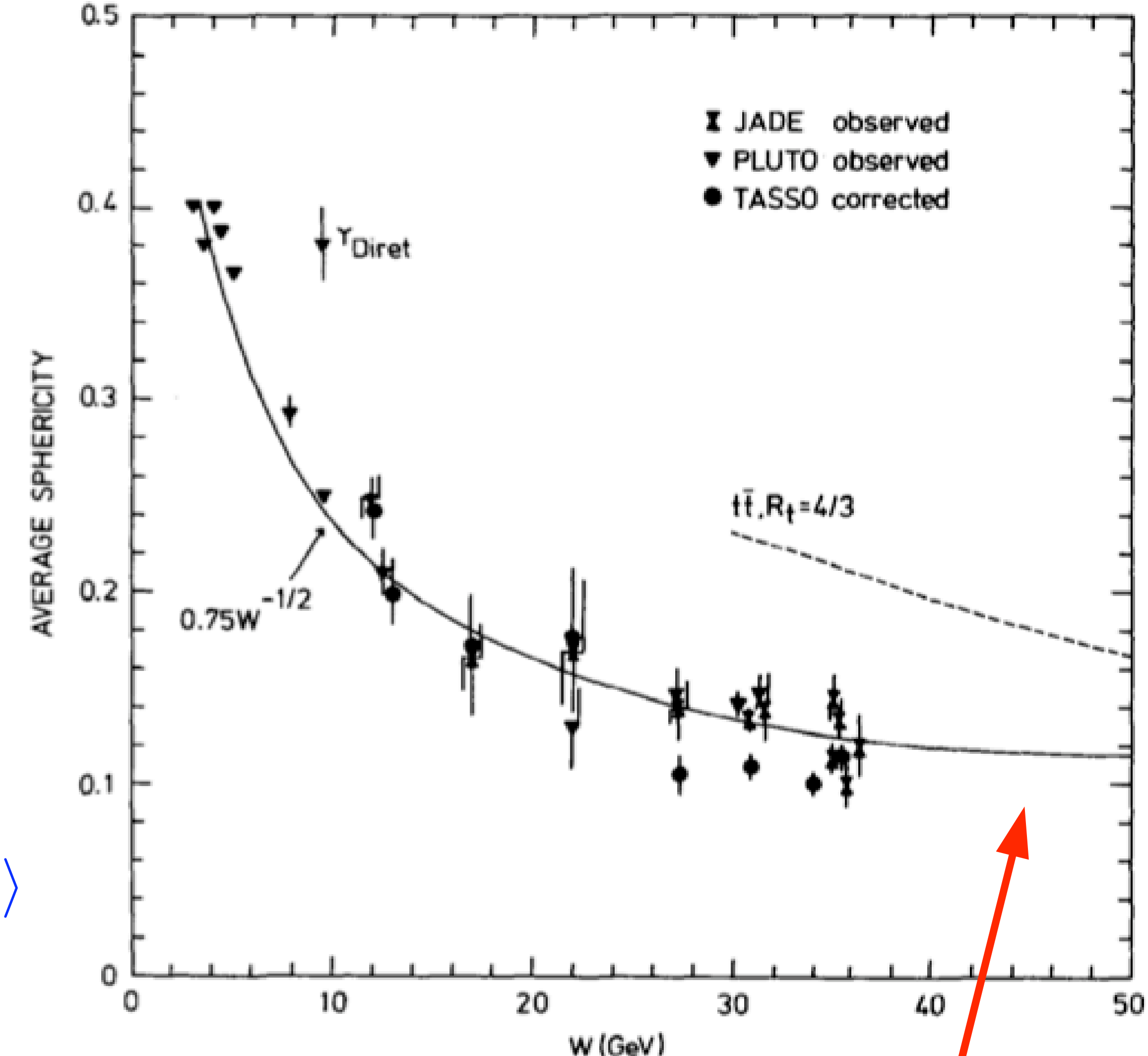
PDG 2008



The early steps: $e^+e^- \rightarrow$ hadrons



Soding,Wolf Experimental Evidence on QCD
Ann Rev Nucl Part Sci 1981, 31, 231



- sphericity: $S \sim 3/2\langle\delta^2\rangle$

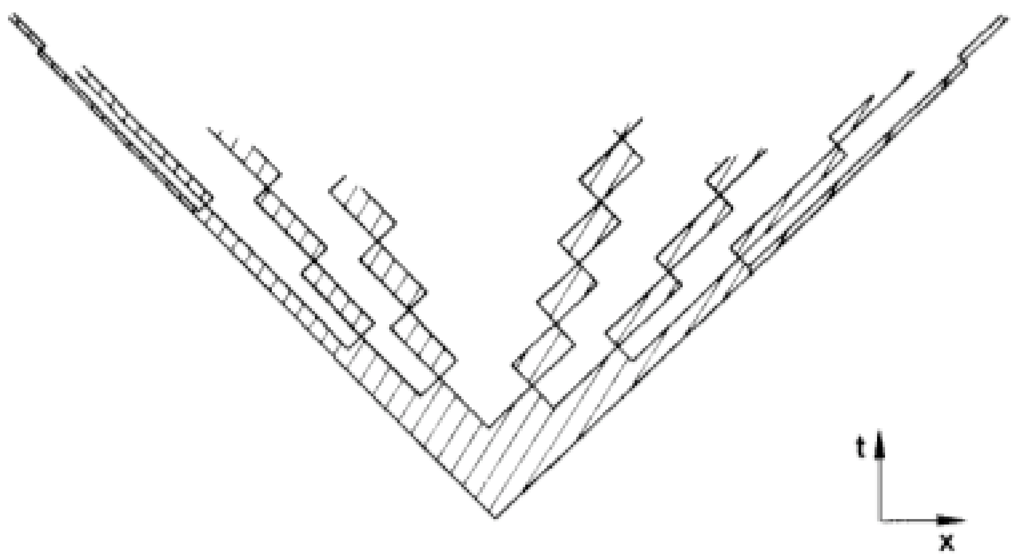
  jet opening angle $\langle\delta\rangle = \langle P_t/P_{\parallel}\rangle$
- S ~ 0 for extreme jets

  S → 1 for spherical events

➔ evidence for 2 -jet structure

Transition from Quarks to Hadrons

- Independent Fragmentation (Feynman & Field: Phys. Rev D15 (1977)2590, NPB 138 (1978) 1)
  - quarks fragment independently
  - gluon are split: $g \to q\bar{q}$
  - not Lorentz invariant
- Lund String Fragmentation (Andersson, Gustafson, Peterson ZPC 1, 105 (1979), Andersson, Gustafson, Ingelman, Sjostrand Phys. Rep 97 (1983) 33 (> 1800 citations))



from PhysRep 97 (1983) 33

Fig. 2.4. The final picture when q_0 and $\bar{q}_0$ move with large energies in opposite directions. The field has broken at many places by the production of $q\bar{q}$ pairs. Hatched areas indicate nonvanishing field.

Transition from Quarks to Hadrons

- Independent Fragmentation (Feynman & Field: Phys. Rev D15 (1977)2590, NPB 138 (1978) 1)
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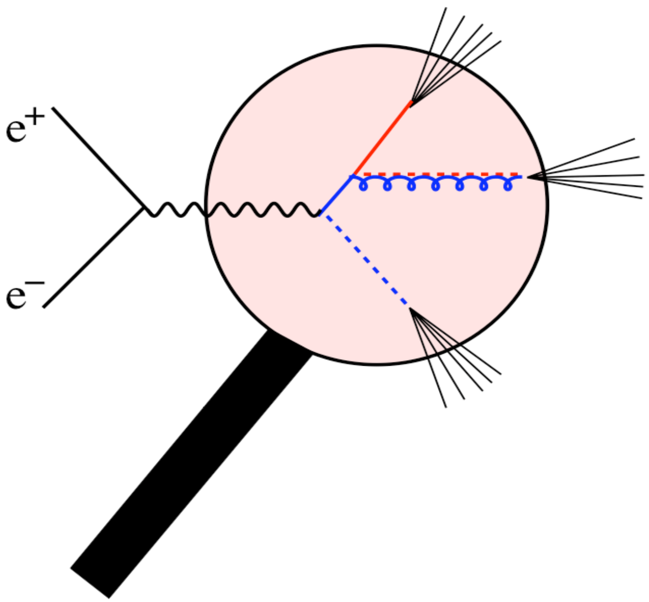
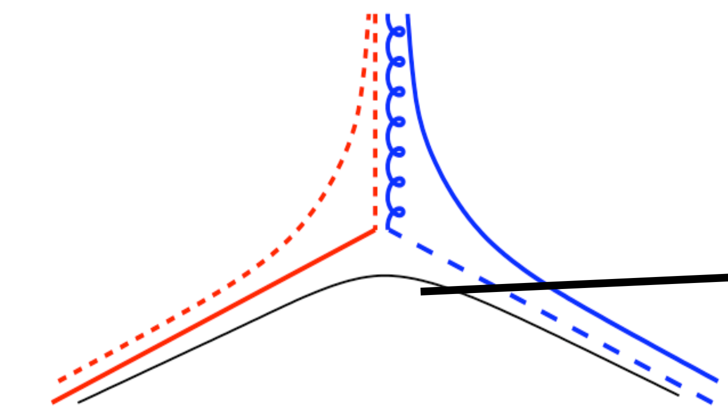
  - not Lorentz invariant
- Lund String Fragmentation (Andersson, Gustafson, Peterson ZPC 1, 105 (1979), Andersson, Gustafson, Ingelman, Sjostrand Phys. Rep 97 (1983) 33)
  - for $q\bar{q}$ is similar to independent fragmentation
  - ➔ BUT is covariant and has no leftover
  - ➔ constraints on fragmentation function: $q\bar{q}$ symmetric
  - ➔ transverse momentum distribution from tunneling effect
  - ➔ gluons act as kinks on the string: string effect
- Cluster Fragmentation (Webber NPB 238 (1984) 492)
  - pre-confinement of color
  - gluon split $g \to q\bar{q}$

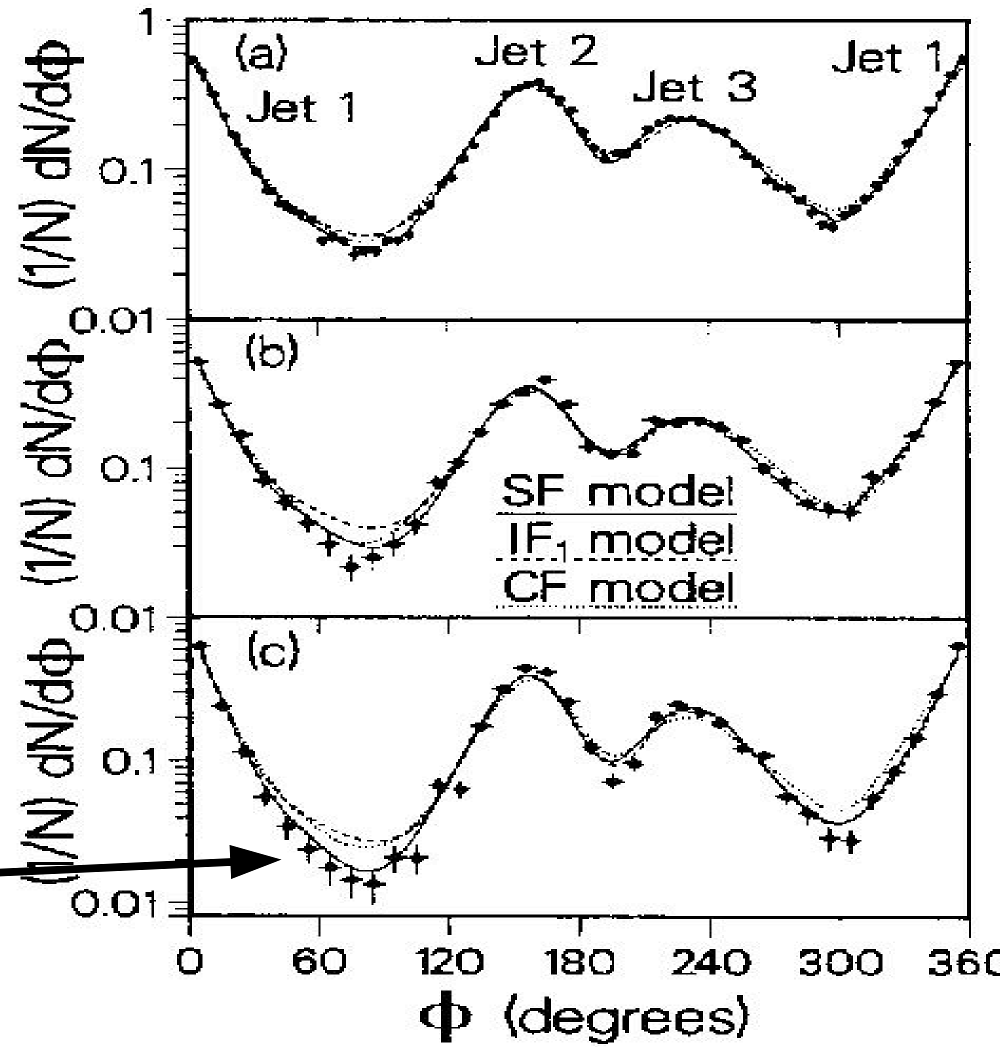
How to find gluon jets ?

How to find the gluon jets, Andersson, Gustafson, Sjostrand, PLB 94,211 (1980)

TPC (PEP) H. Aihara, ZPC 28, 31 (1985)



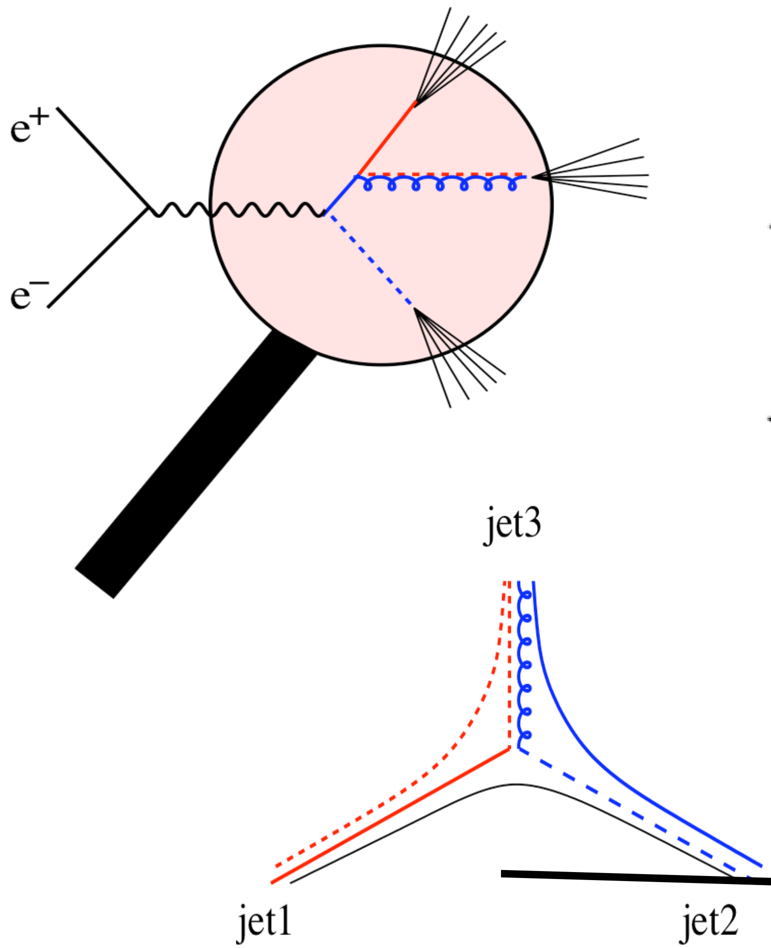




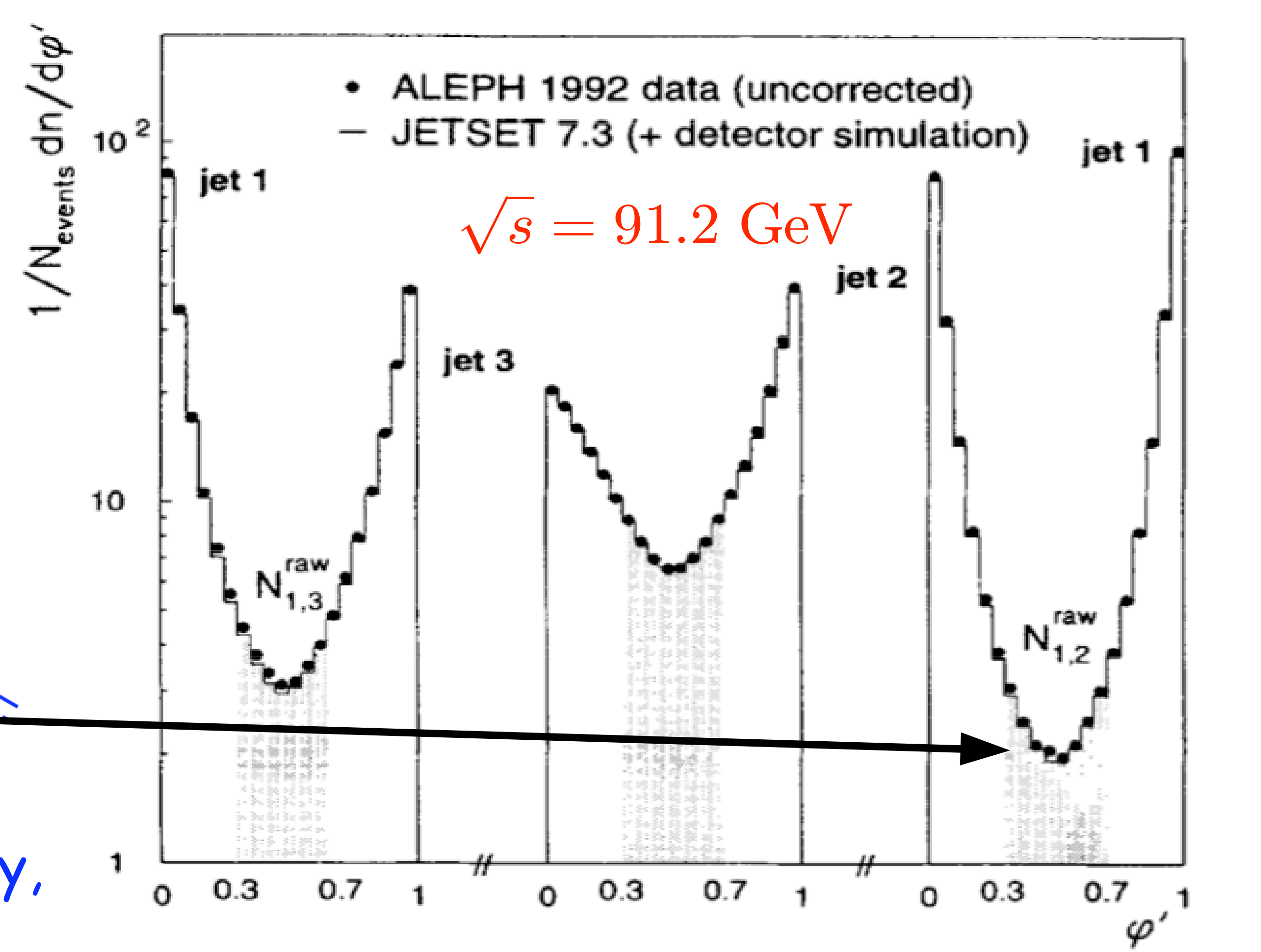
➔ gluons act as kinks on strings

How to find gluon jets ?

How to find the gluon jets, Andersson, Gustafson, Sjostrand, PLB 94,211 (1980)

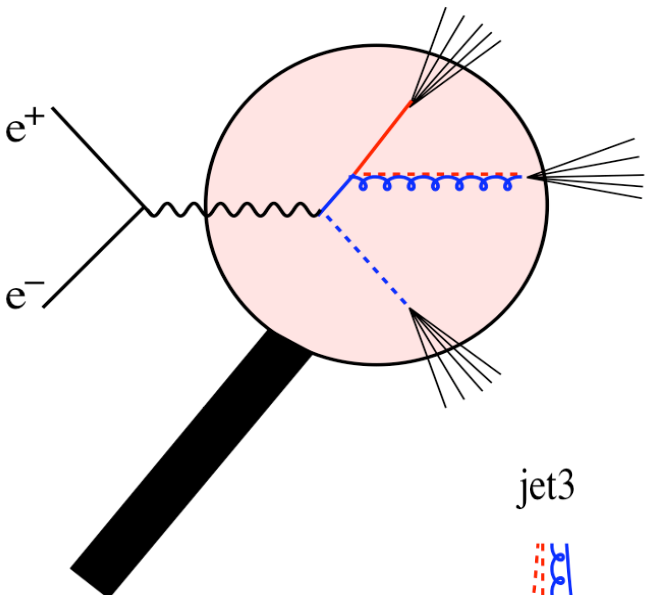


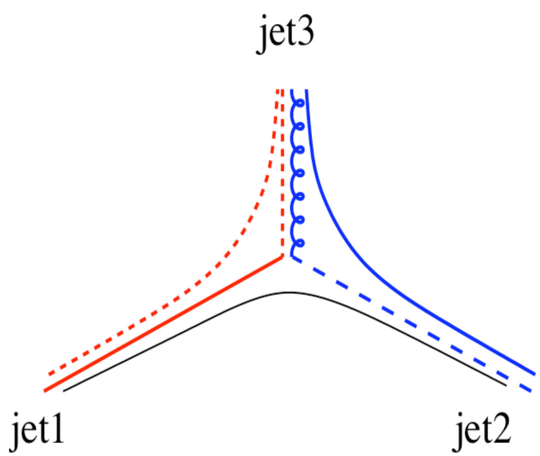
ALEPH Collaboration / Physics Reports 294 (1998) 1–165



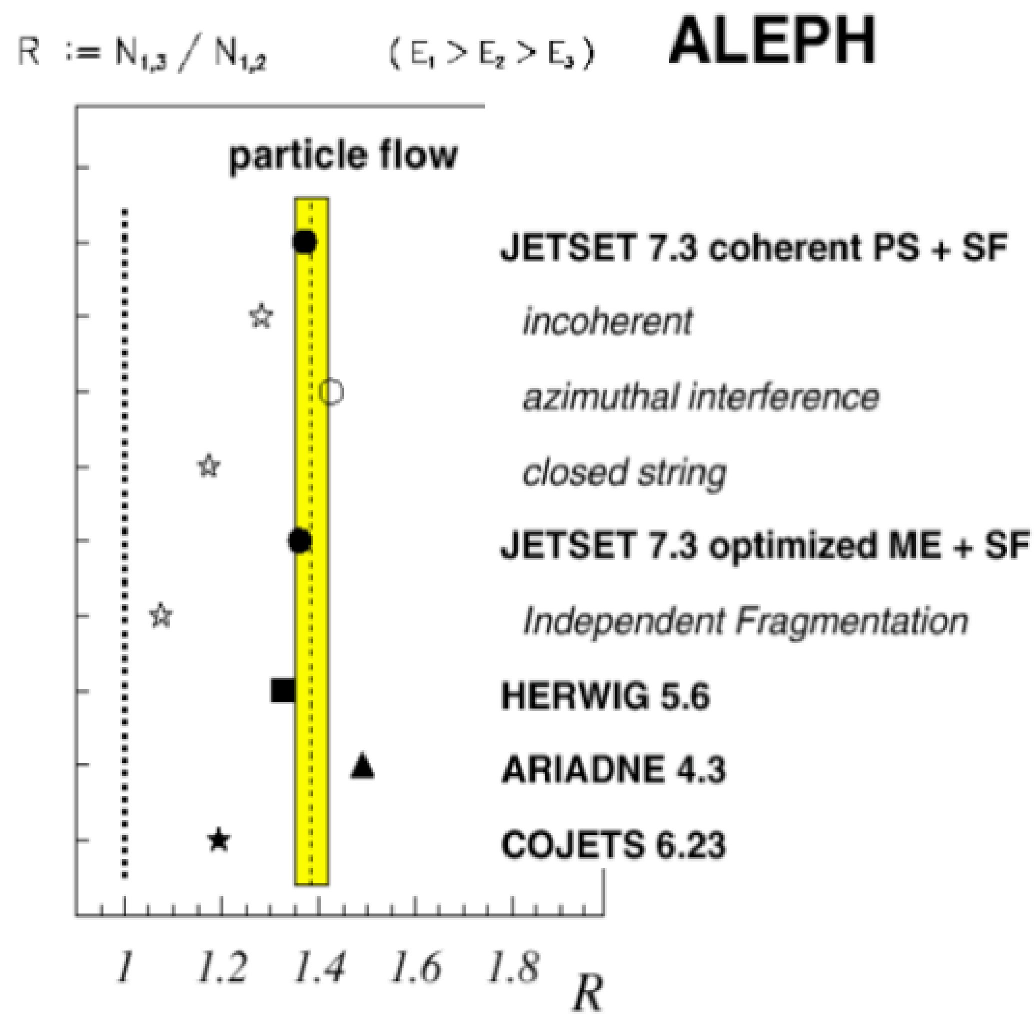
- jets ordered by energy,
  highest is quark (~94 %) ,
  lowest is gluon (~70%)

How to find gluon jets ?





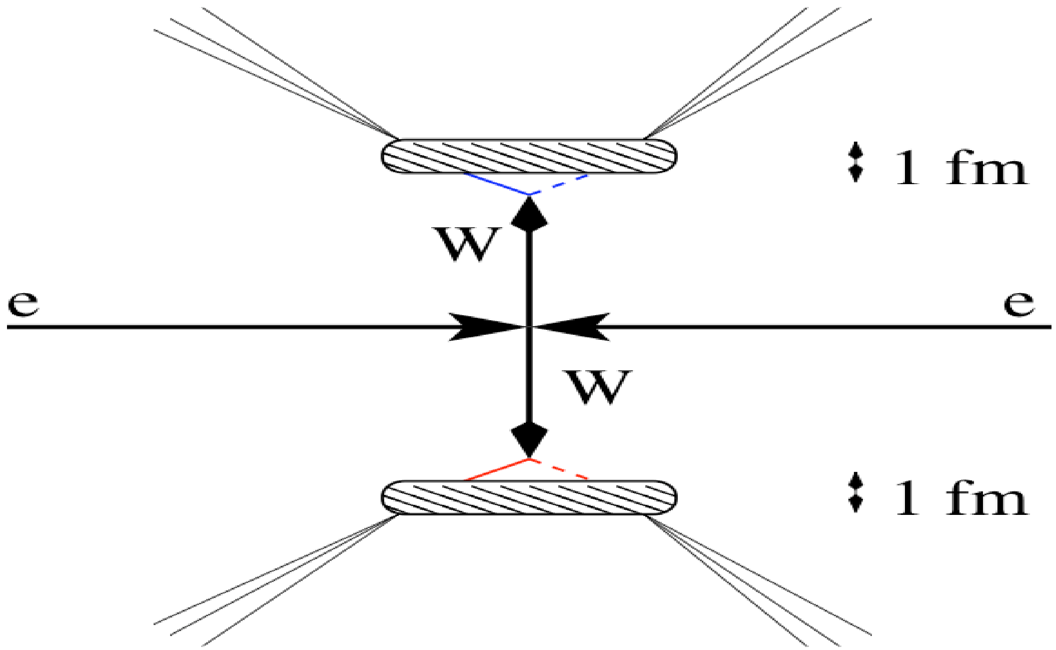
How to find the gluon jets, Andersson, Gustafson, Sjostrand, PLB 94,211 (1980)



- jets ordered by energy,
  highest is quark (~94 %) ,
  lowest is gluon (~70%)

➔ clear evidence for string effect & color coherence

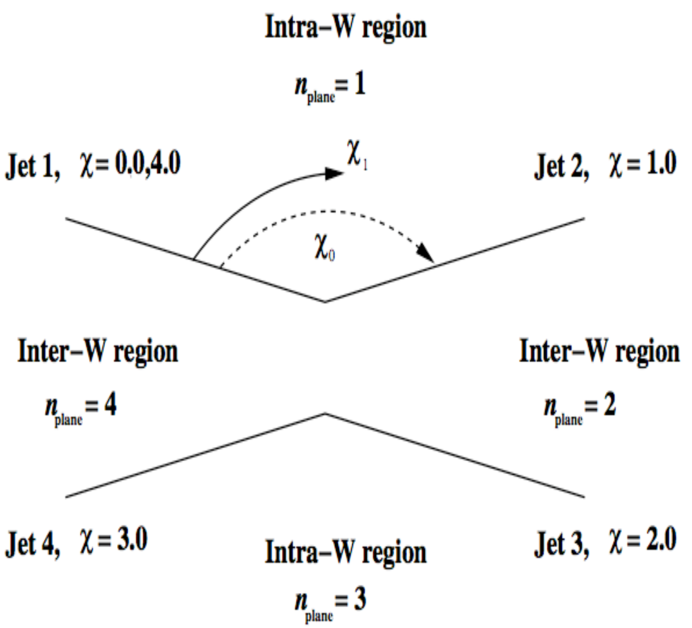
String effect in W⁺W⁻ production

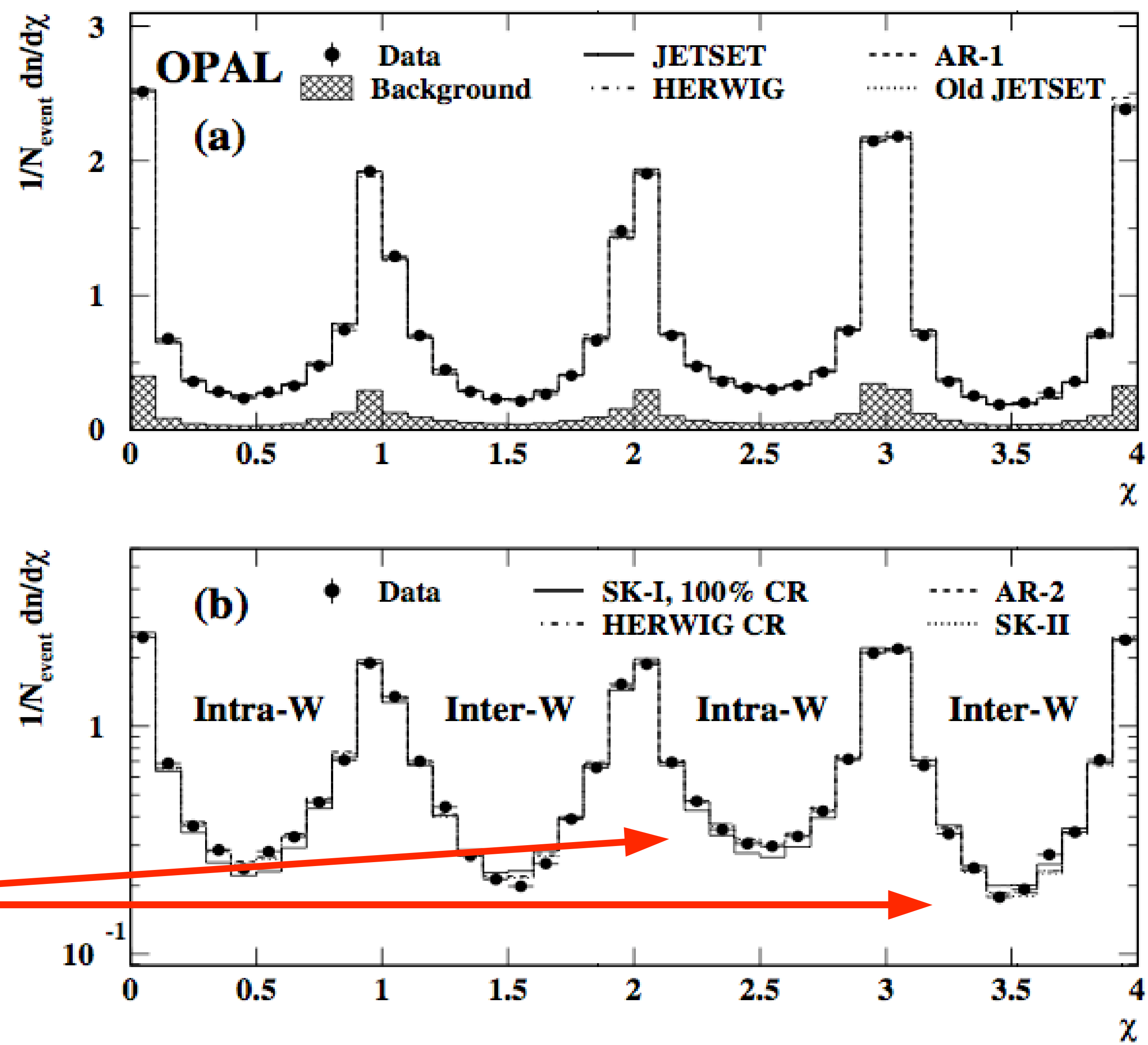


Jet final states in WW pair prod,
Gustafson, Pettersson, Zerwas, PLB 209,90, 1988
On Color rearrangement in hadronic W+ W- events
Sjostrand, Khoze Z.Phys.C62:281,1994.

- depending on string size and flight time strings could overlap and exchange soft gluons
- similar situation in $b \to cW^- \to ccs \to J/\psi X$
- generalise idea from $e^+e^- \to q\bar{q}g$ to $e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$
- can also happen in $t\bar{t} \to W^+bW^-\bar{b}$

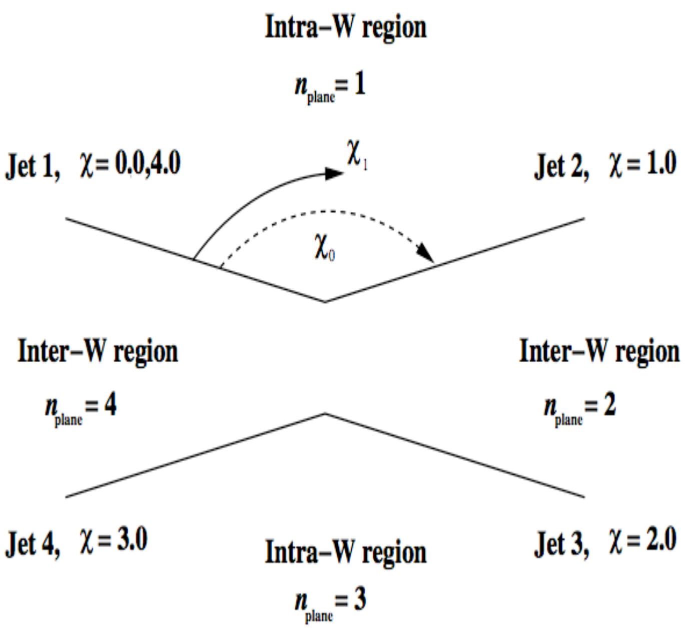
String effect in W^+W^- production

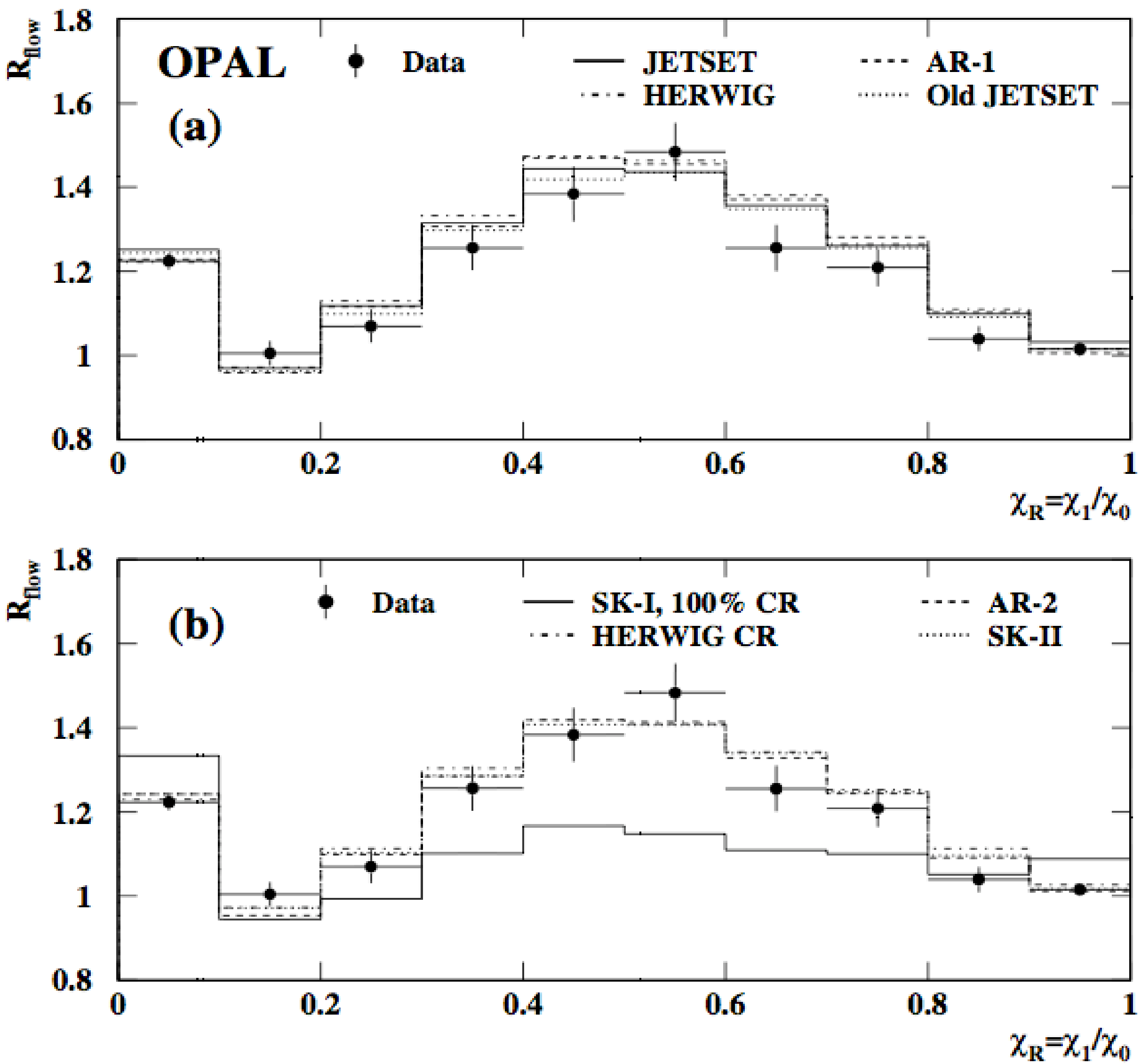




- measurement of E-flow between jets
- observe clear string effect ...

String effect in W^+W^- production



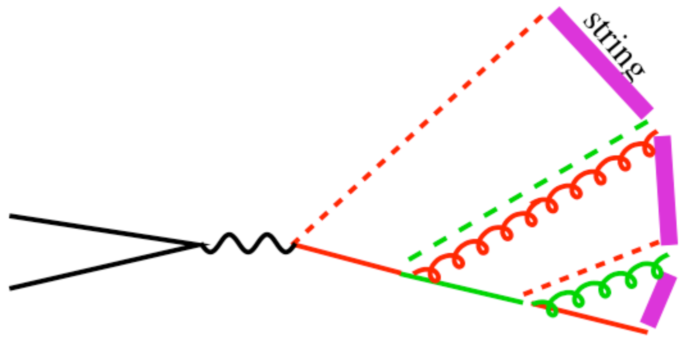


- define:

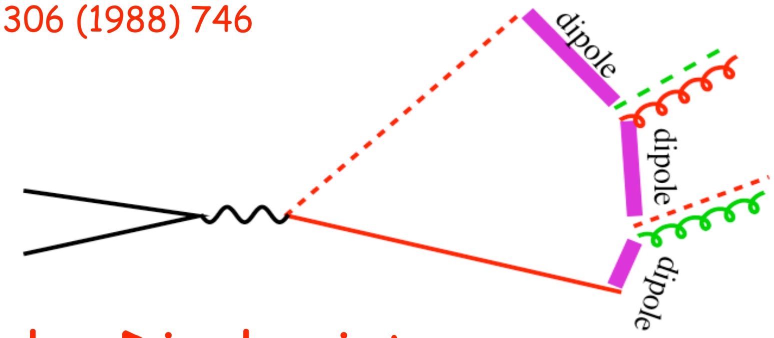
$$R_{flow} = \frac{\frac{dn}{d\chi_R}(\text{intra-W})}{\frac{dn}{d\chi_R}(\text{inter-W})}$$

- Observe clearly string effect
- small color reconnection, extreme model with fat strings excluded ...

Models for jet evolution



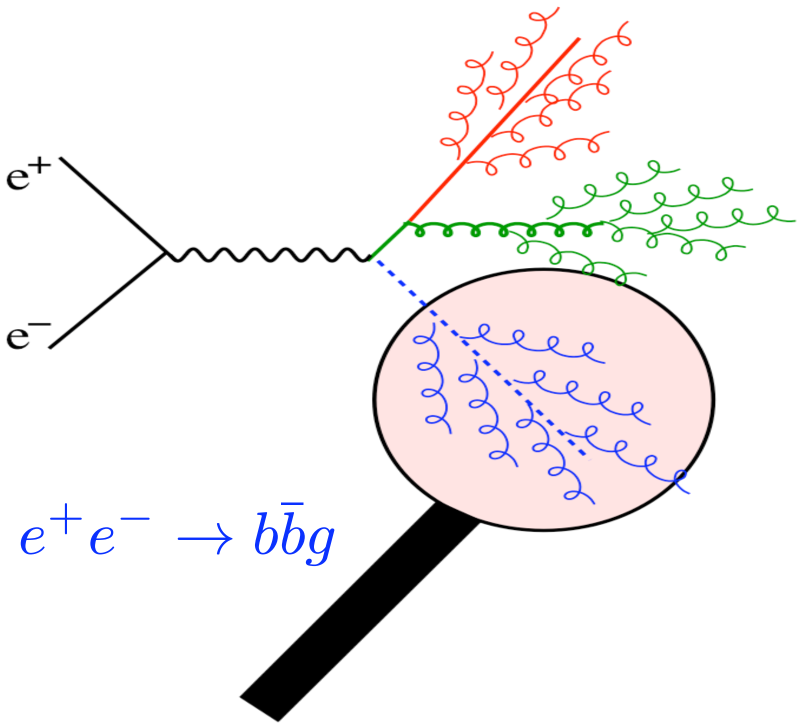
Gustafson,Pettersson, Dipole formulation of QCD Cascades
NPB 306 (1988) 746



- Parton Showering
- Color field of Lund string interpreted in terms of gluons
- successive parton radiation, with DGLAP splitting function
- ordering introduced explicitly:
  - virtuality, pt or angular ordered
- need to take care of recoil
- impelmented in JETSET/PYTHIA/HERWIG

- Color Dipole picture
- Color field of Lund string interpreted in terms of dipoles
- radiation from dipole, including soft gluon interference
- automatically satisfies color coherence (angular ordering)
- in limits, DGLAP reproduced
- implemented in ARIADNE

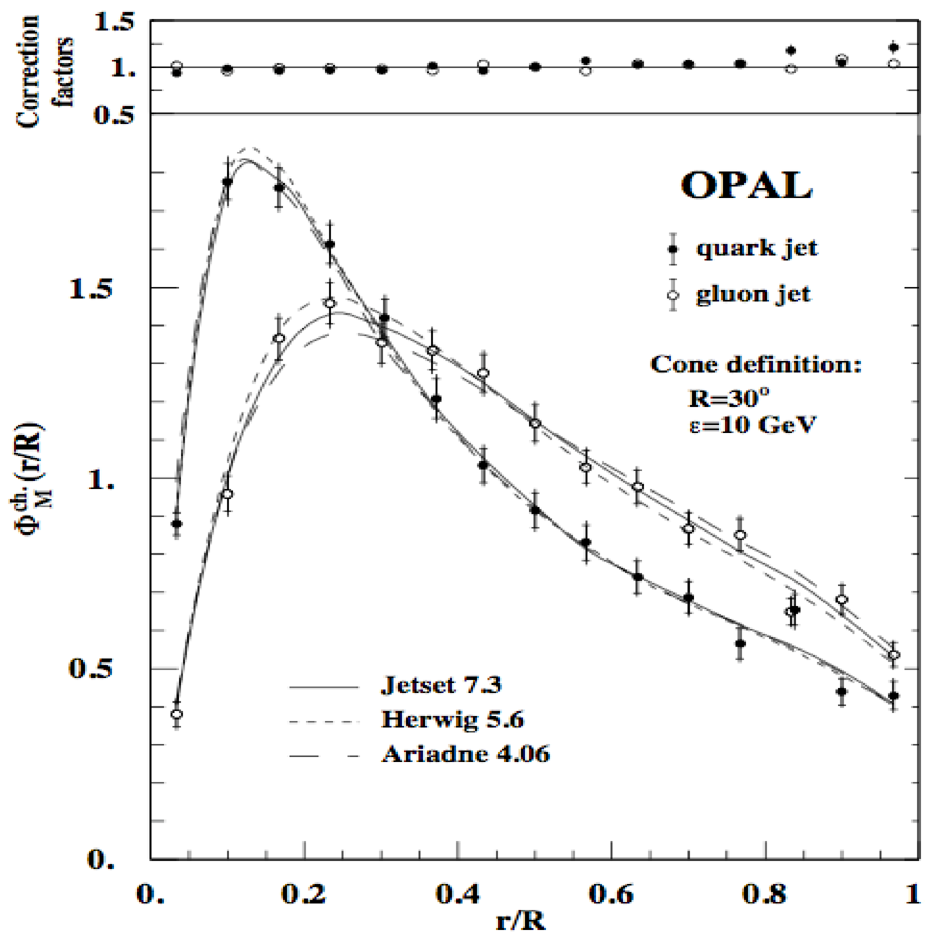
Jet evolution: q and g jets



$e^+e^- \to b\bar{b}g$

- select 3 jets, highest E-jet with secondary vertex (b-jet)
- 2 lower E jets are enriched gluon-jets
- use MC for corrections to true gluon

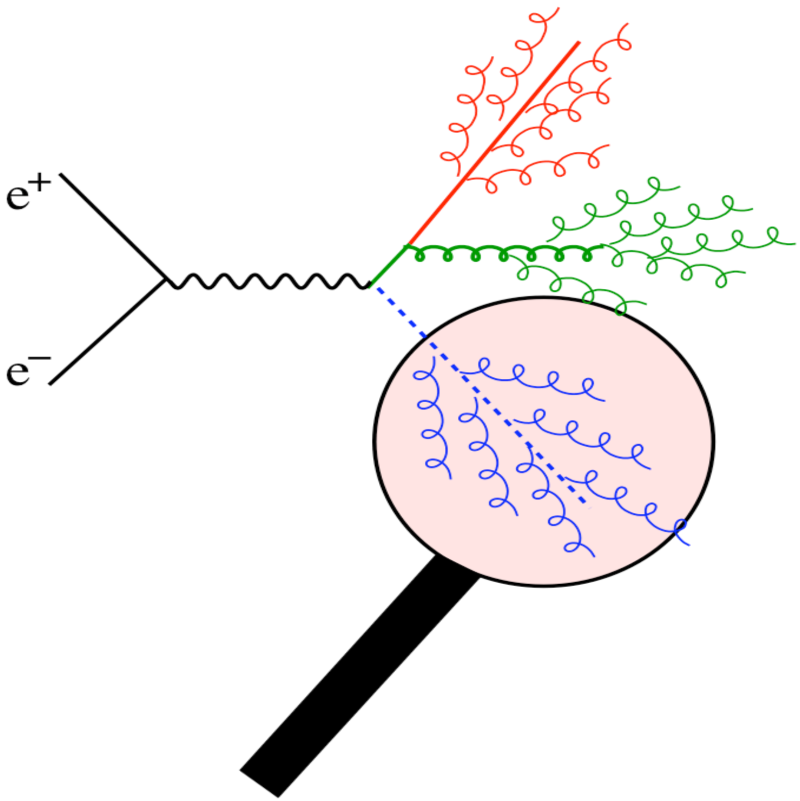
OPAL Collaboration Z.Phys.C68:179-202,1995.



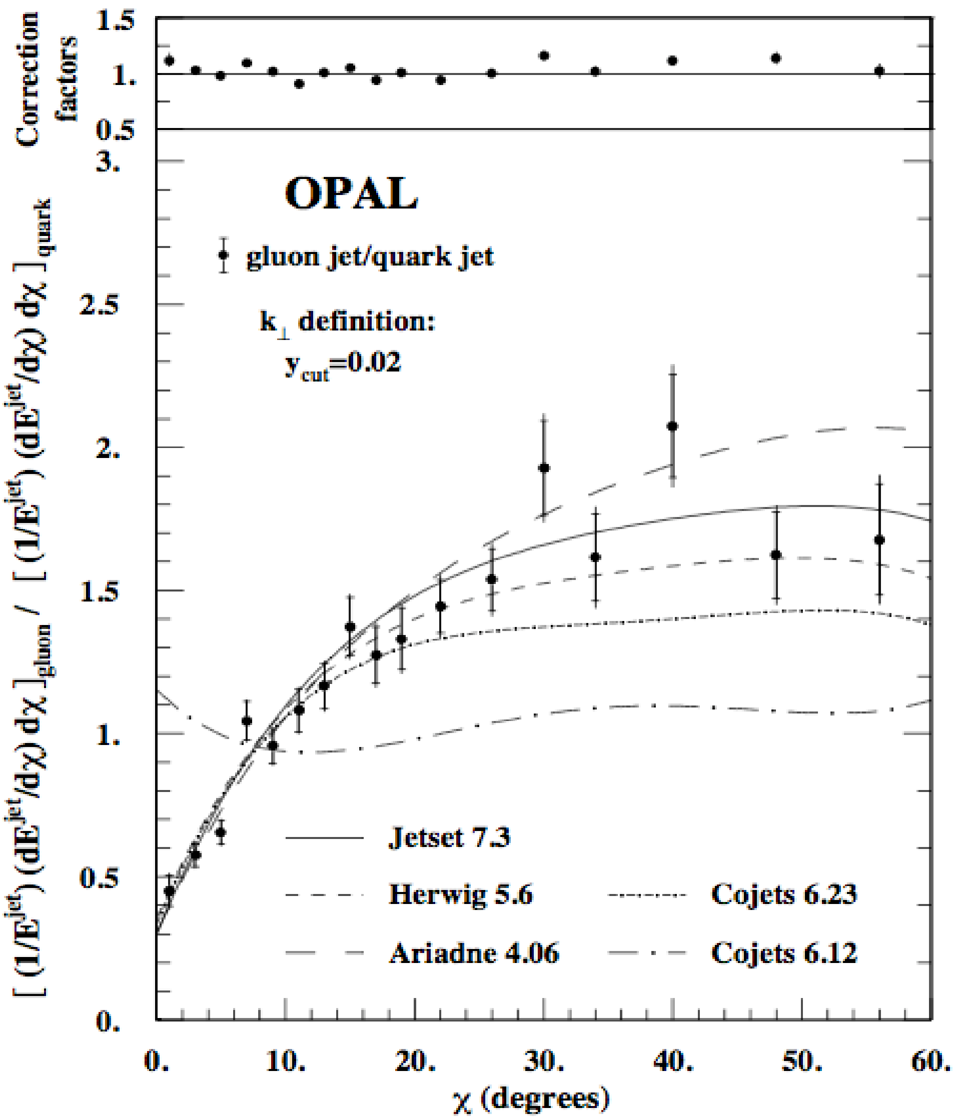
➔ gluon jets are wider ...

➔ MC's with parton shower and CDM describe jet shapes

Jet evolution: q and g jets



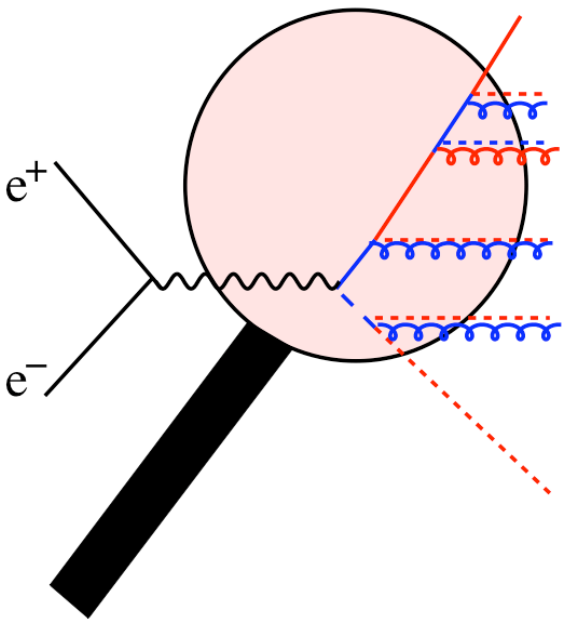
OPAL Collaboration Z.Phys.C68:179-202,1995.



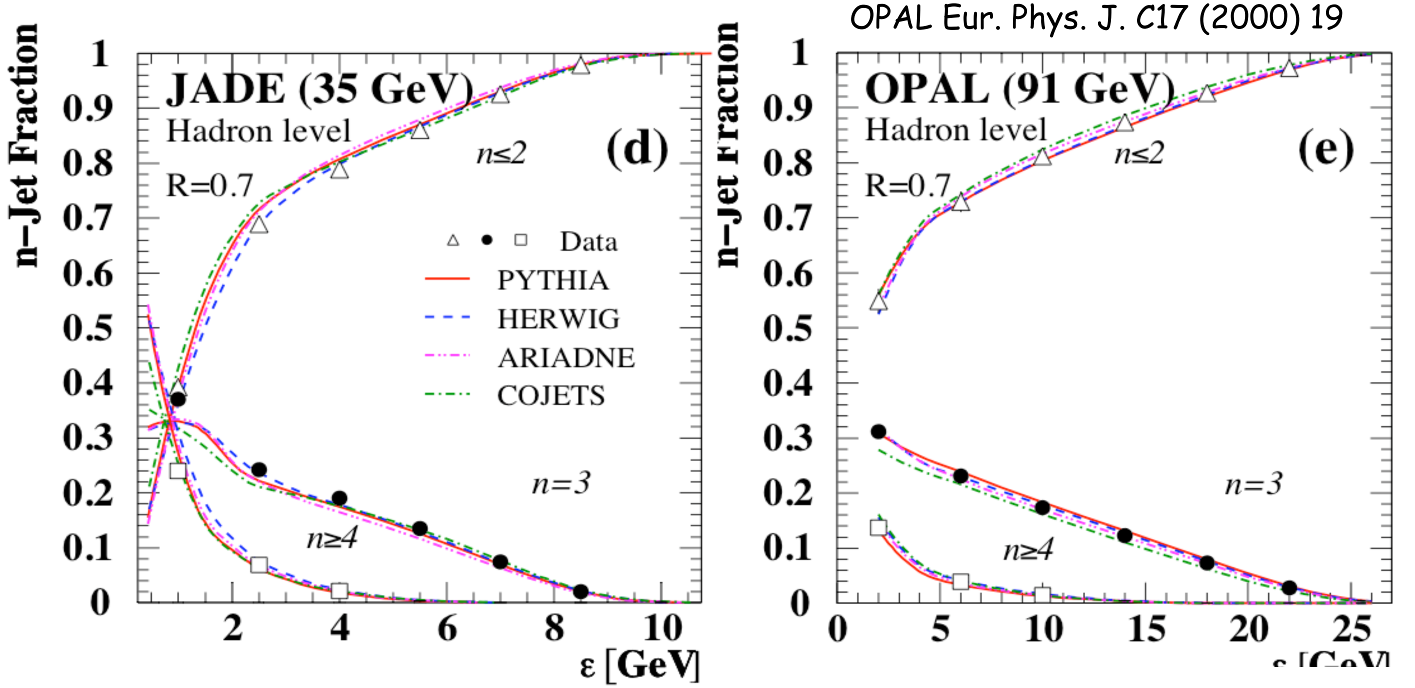
- small differences of parton radiation as function of jet opening angle χ

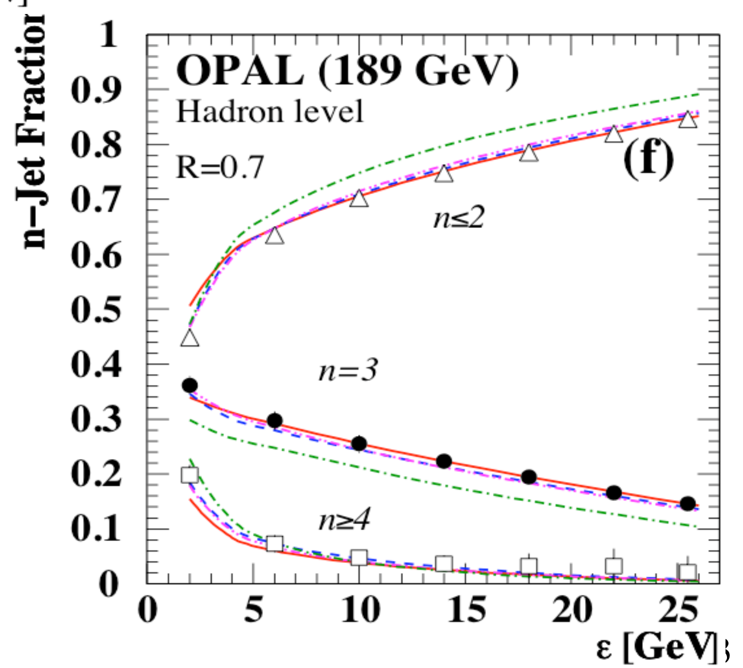
➔ overall well description by shower MCs and CDM

Multijet production



OPAL Eur. Phys. J. C17 (2000) 19





- using cone jet algorithm
- shower MCs and ARIADNE are able to reproduce multi jets rates from low to highest CM energy

Lessons from e^+e^-

- pQCD describes total rates if color and fractional charge is included
- 3-jet and multijet event require color coherence:
  - string effect and angular ordering
  - color field can be specified in terms of gluons or dipoles
- q- and g- jet evolution well described by parton shower (ala DGLAP) approaches and CDM
- Multijet rates (up to n > 4 jets) still well described by shower MCs and CDM

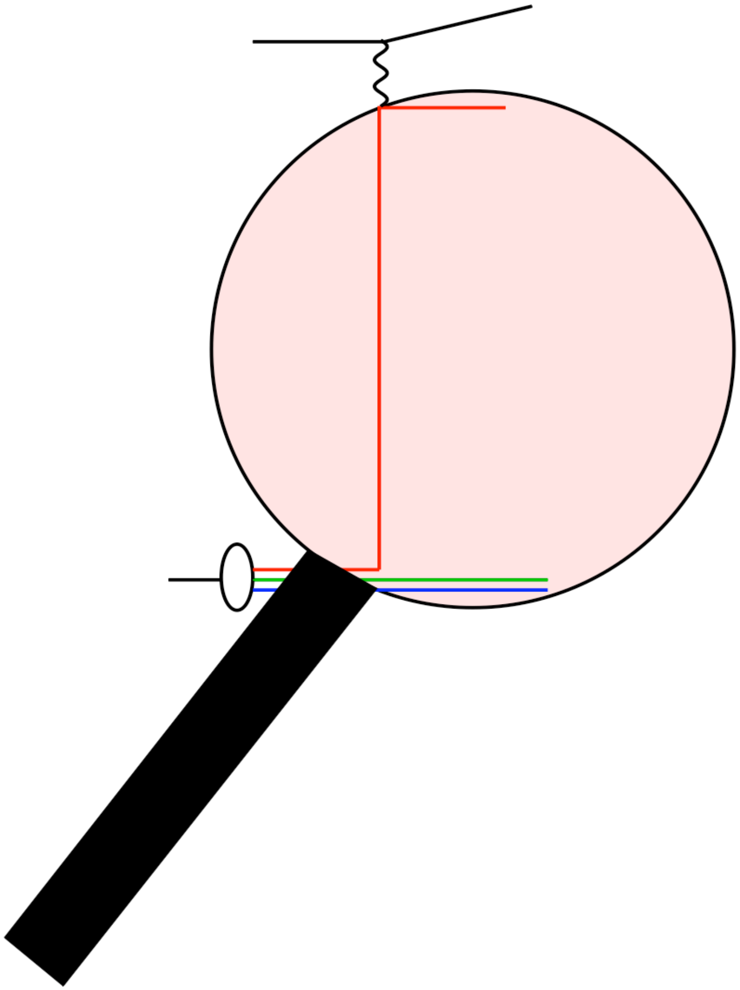
➔ pQCD and soft QCD (hadronization) are understood .... really ?

Is that all in QCD ???

Adding one more complication ....

the proton in the initial state

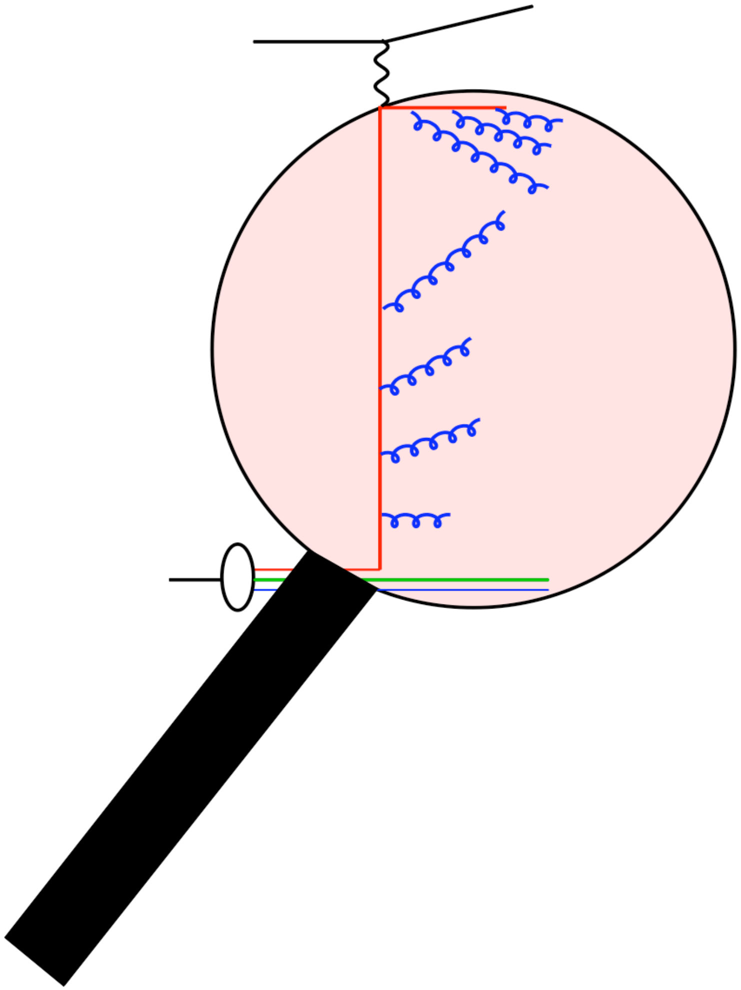
The fun with ep scattering



- 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 $f_i(x)$

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

The fun with ep scattering

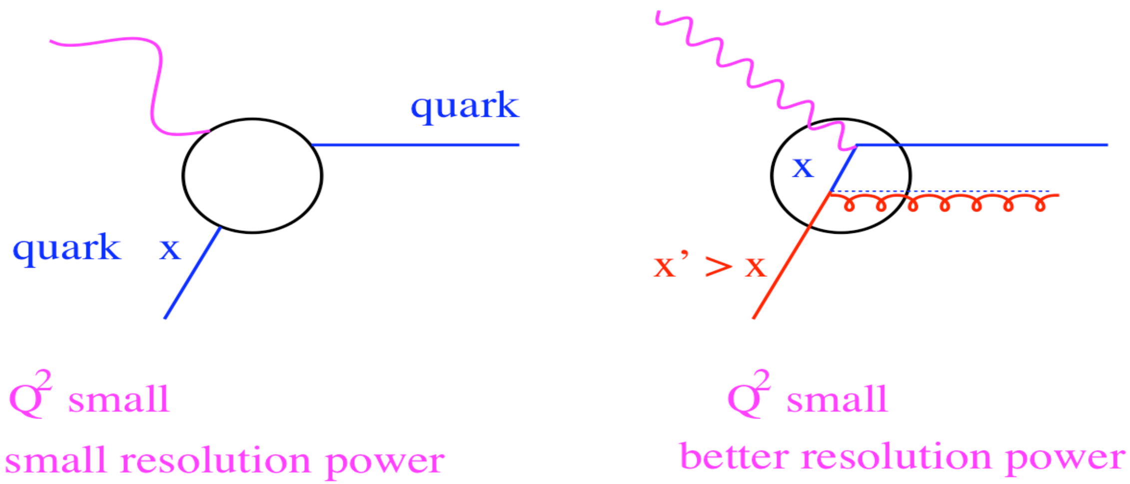


- Deep Inelastic Scattering is a incoherent sum of $e^+ q \to e + q$
- only 50 % of p momentum carried by quarks
- need a large gluon component
- partonic part convoluted with parton density function $f_i(x)$
- BUT we know, PDF depends on resolution scale Q^2

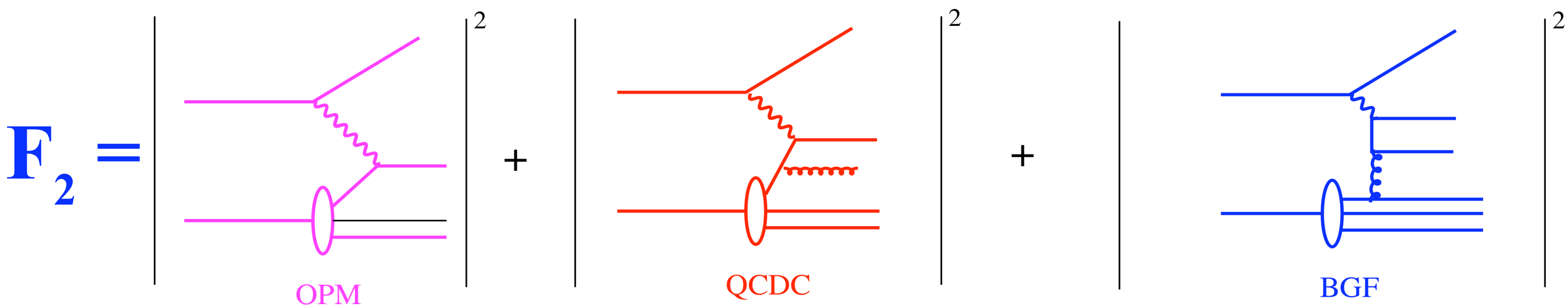
$$\sigma(e^+ p \to e^+ X) = \sum_i f_i(x, Q^2) \sigma(e^+ q_i \to e^+ q_i)$$

The fun with ep scattering: DGLAP

- QPM: F_2 is independent of Q^2
- Q^2 dependence of structure function: **D**okshitzer **G**ribov **L**ipatov **A**ltarelli **P**arisi



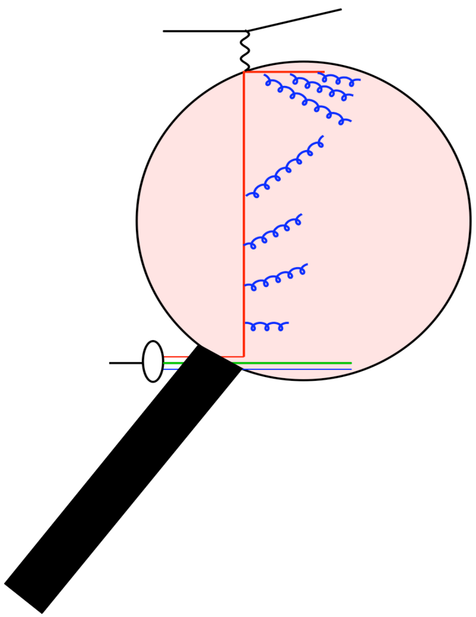
➔ Probability to find parton at small x increases with Q^2

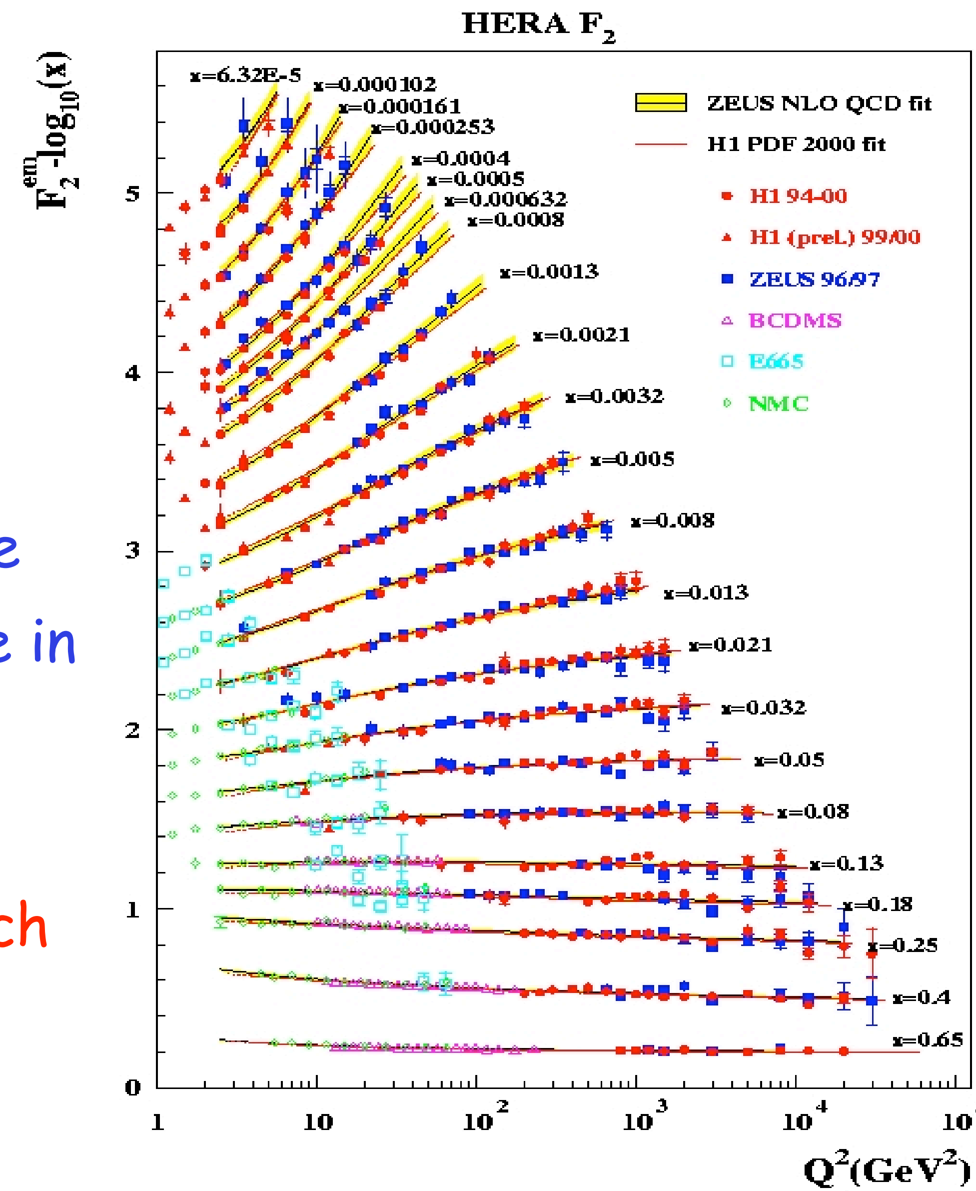


➔ **Test of theory: Q^2 evolution of $F_2(x,Q^2)$!!!!!**

The fun with ep scattering

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





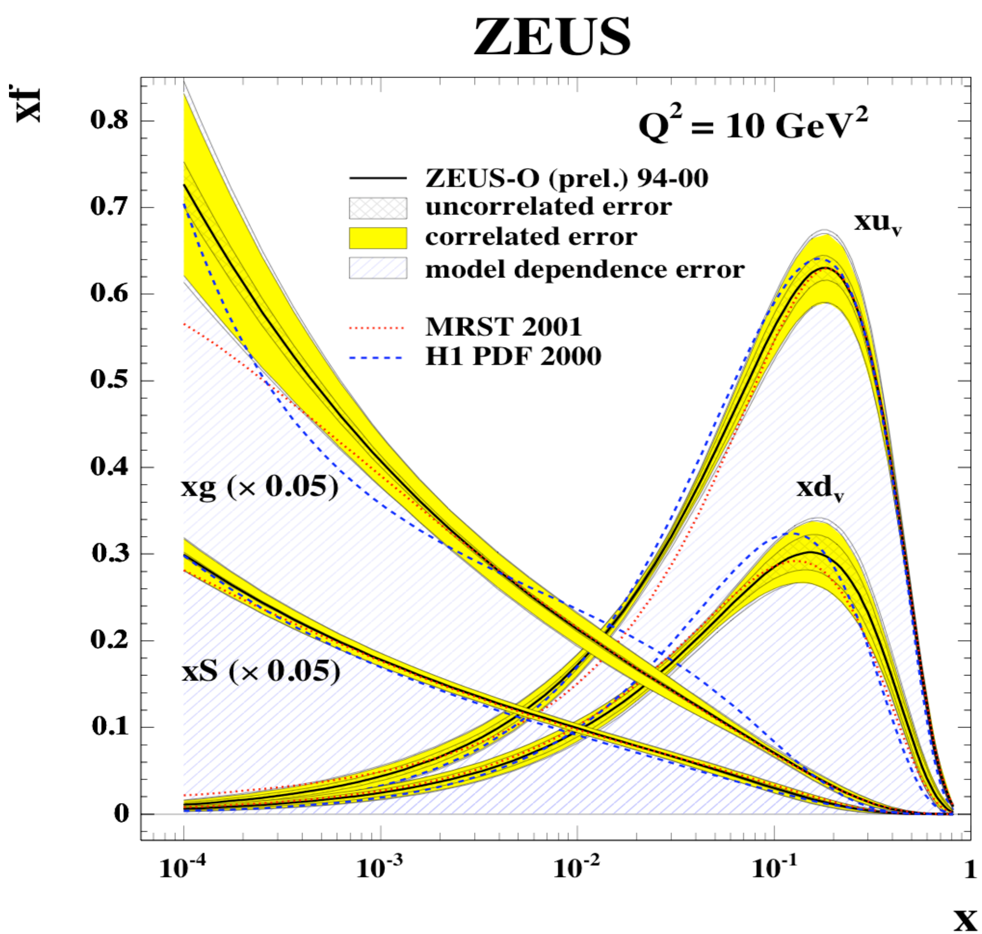
- perfect description of precise measurements of HUGE range in x and Q^2
- Theory works well.....

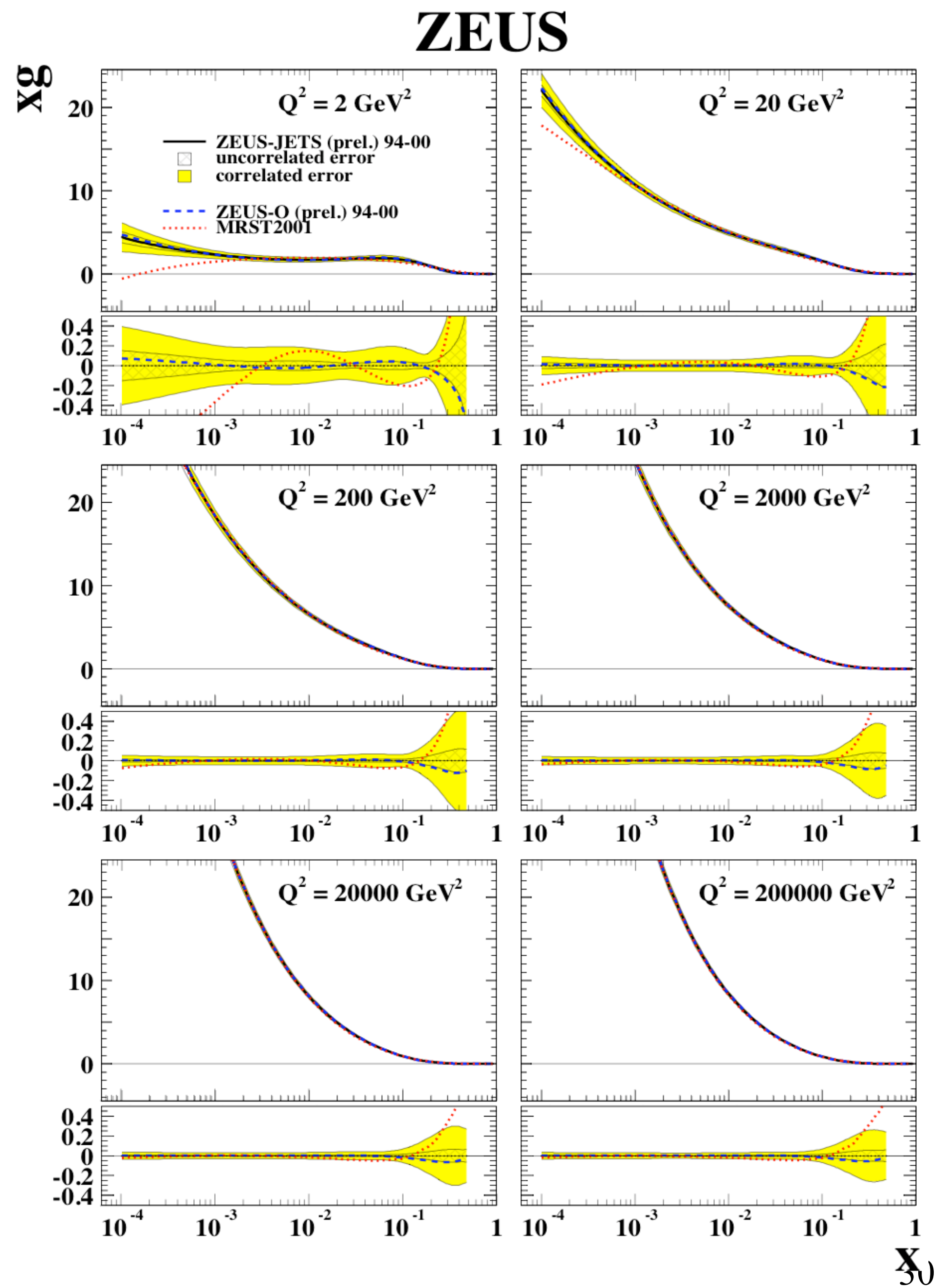
➔ extract parton densities, which are universal

➔ to be used at LHC.....

The proton PDFs ...

- quark and gluon PDFs



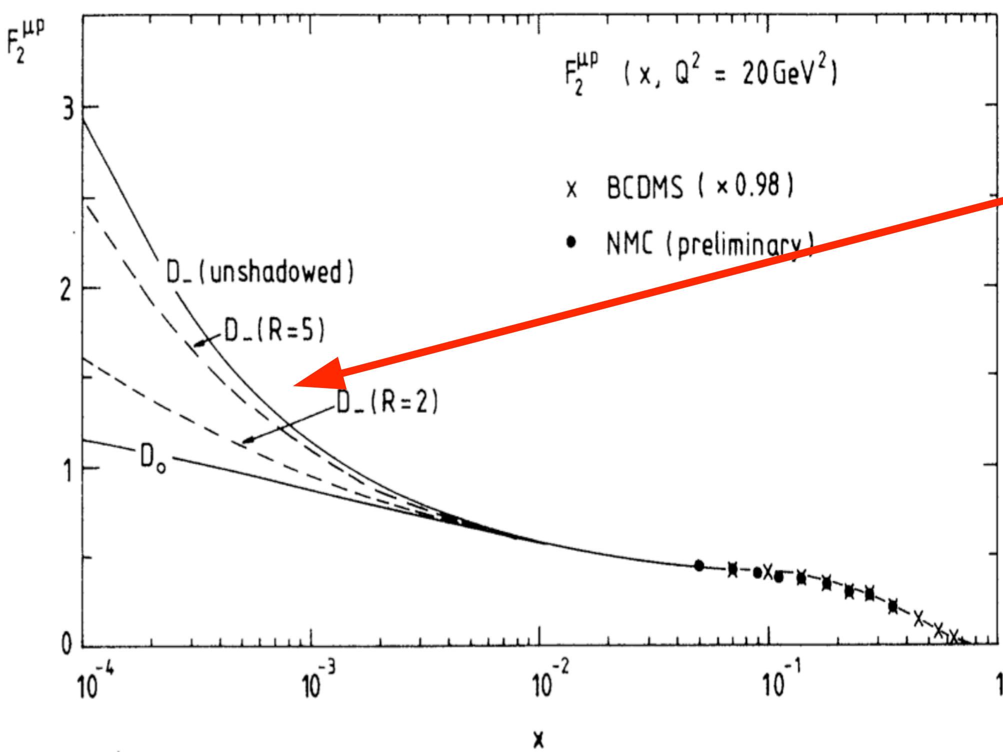


→ Very large gluon density, even at small resolution scales Q^2

Remember the pre-HERA times

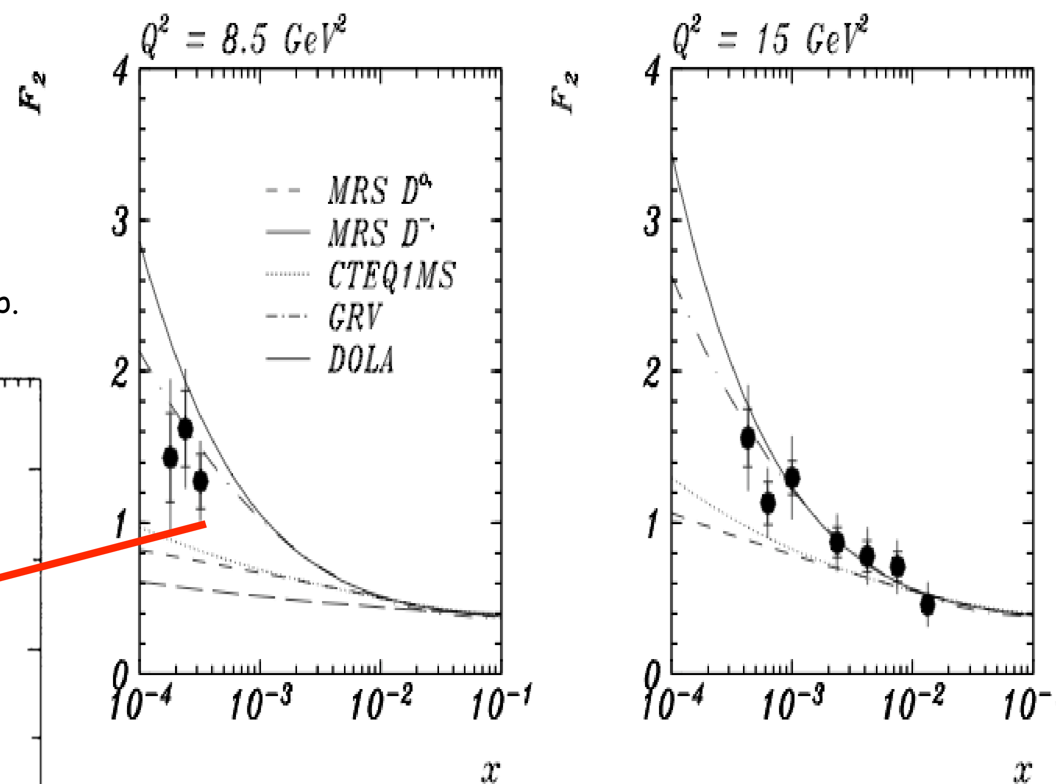
- Just before HERA started in 1992, new PDF fits (NLO DGLAP) were released, using all existing high precision data

Martin, Stirling, Roberts Apr 1992. 49pp.
Phys.Rev.D47:867-882,1993.



- 1^{st} HERA data 1992

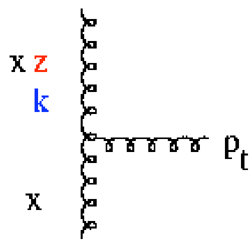
H1 Nucl. Phys. B407 (1993) 515

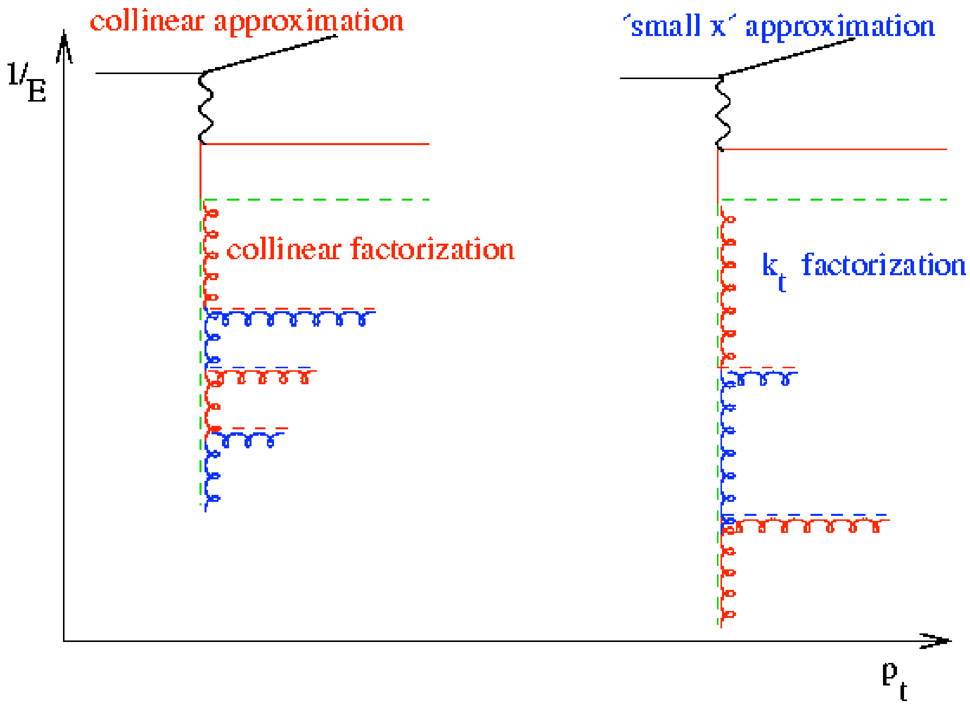


Theory recap: what are we doing ?

gluon bremsstrahlung

$$\sim \frac{1}{k^2}\left(\frac{1}{z} + \cdots\right)$$





Dokshitzer **G**ribov **L**ipatov **A**ltarelli **P**arisi

- collinear singularities factorized in pdf
- evolution in $Q^2 \sim k^2$, or k_t^2 or ?
- $$\sigma = \sigma_0 \int \frac{dz}{z} C^a\left(\frac{x}{z}\right) f_a(z, Q^2)$$

Balitski **F**adin **K**uraev **L**ipatov

- k_t dependent pdf → unintegrated pdf
- evolution in x
- $$\sigma = \int \frac{dz}{z} d^2k_t \hat{\sigma}\left(\frac{x}{z}, k_t\right) \mathcal{F}(z, k_t)$$

Questions from this ...

- Strong rise of structure function at small x:
  - ➔ where is it coming from ?
    - ➔ typical BFKL behavior ?
    - ➔ or
    - ➔ steep starting distribution at which scale ?
    - ➔ or
    - ➔ generated dynamically from a small scale (GRV ansatz) ?
- if high parton density at small x, do we also observe saturation and parton recombination
- How is initial state parton cascade generated ?

How many gluons are there ?

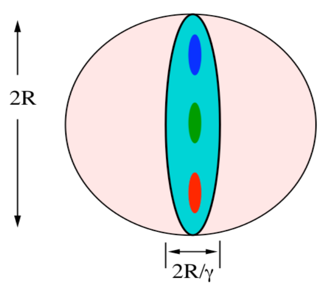
- number of gluons in long. phase space dx/x:

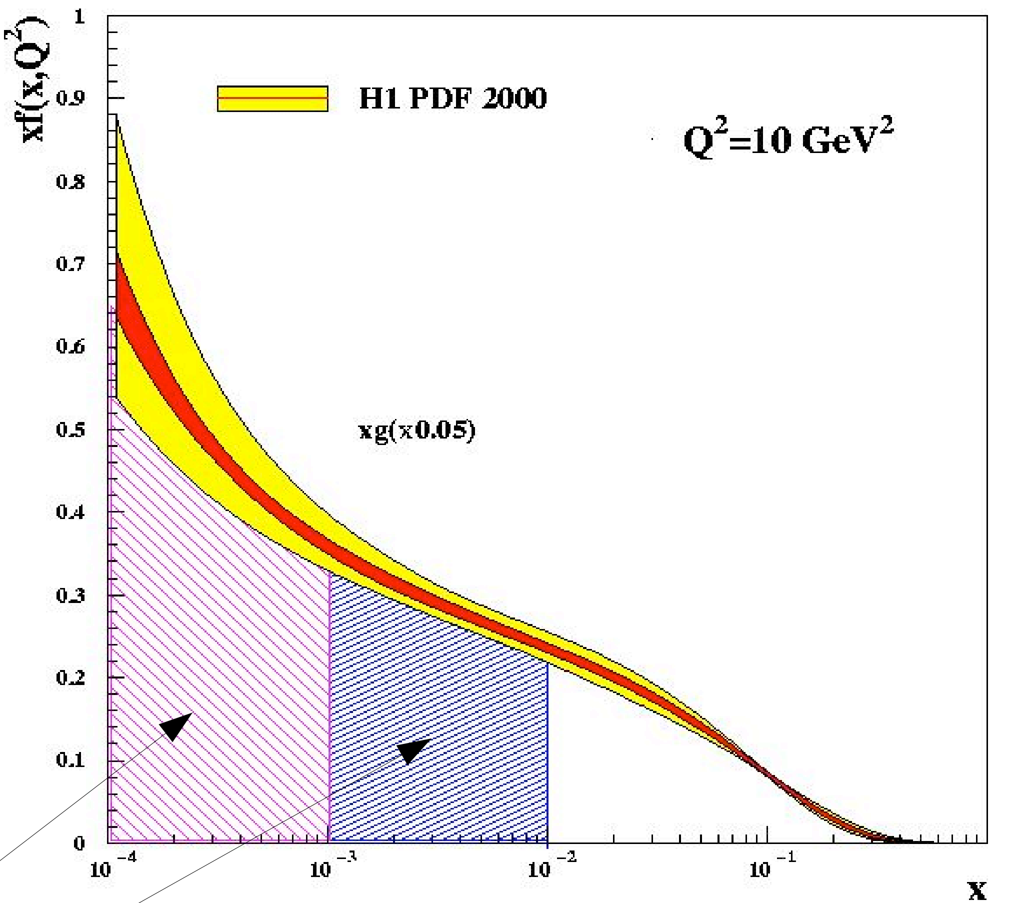
  $xg(x,\mu^2)dx/x$

- occupation area:

  nr of gluons x (trans size)²

  $$g(x,\mu^2)\frac{1}{\mu^2}$$



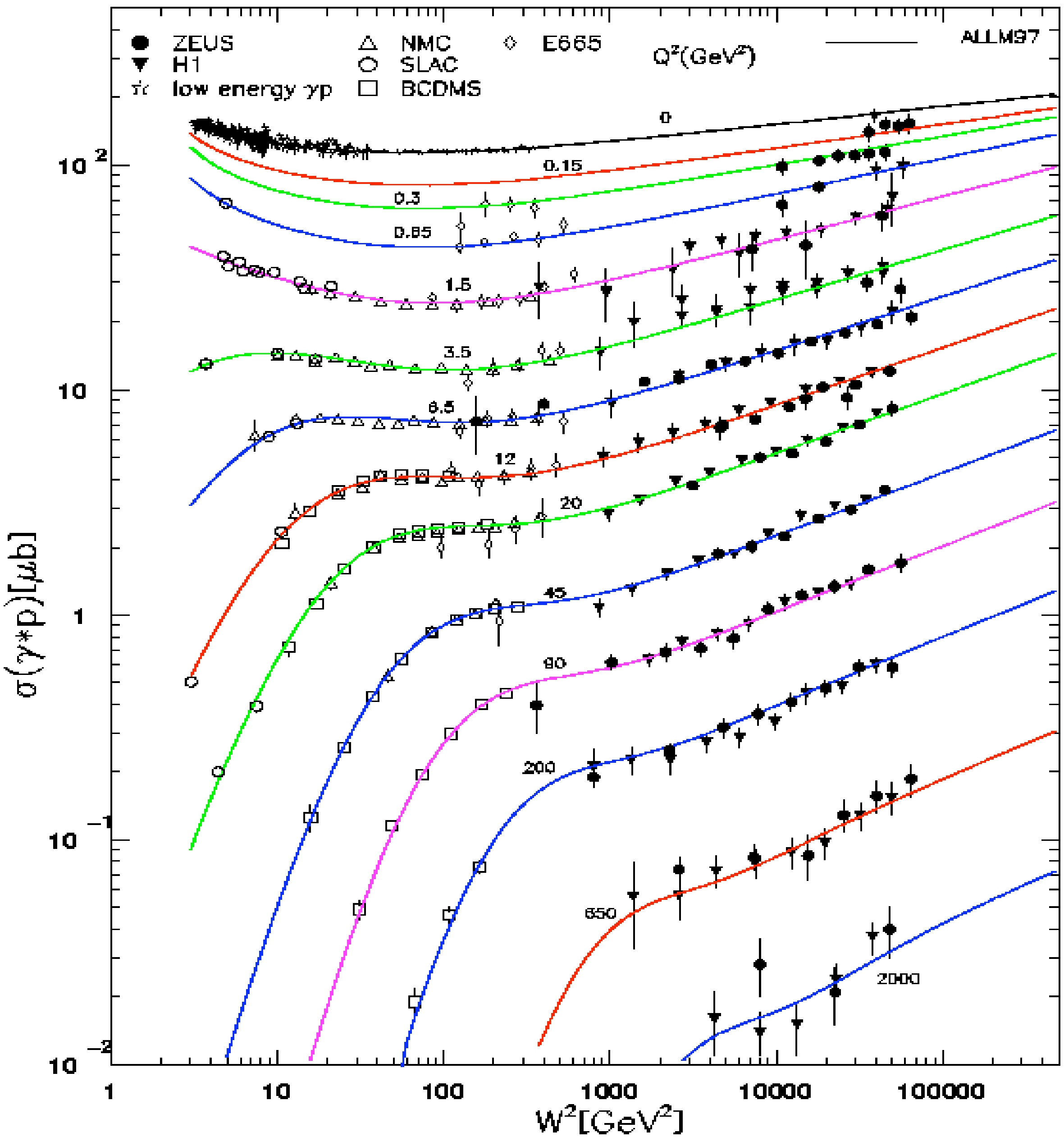


- saturation starts when:

  $$\frac{\alpha_s(\mu^2)}{\mu^2}xg(x,\mu^2)\frac{dx}{x} \geq \pi R^2$$

- gluon density is very large:~ 90 or 45 Gluons !!!!!
- with R ~ 1 GeV⁻¹ we obtain: $\frac{0.2}{10GeV^2}100 \sim \pi R^2 \sim \pi$! ! ! ! !

High energy behavior of x section



$$\sigma(\gamma^* p) = \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2)$$

$$= \frac{4\pi^2\alpha}{Q^2} \sum e_q^2 x q(x, Q^2)$$

$$x = \frac{Q^2}{W^2 + Q^2}$$

- rising x-section with W^2
- at large energies can become larger than σ_{tot}
- mechanism needed which tames rise at large energies

➔ saturation !!!

Saturation and geometric scaling

- Saturation scale:

$$Q_s^2(x) \sim \frac{\alpha_s(Q_s^2)g(x,Q_s^2)}{\pi R^2}$$

- Define new variable:

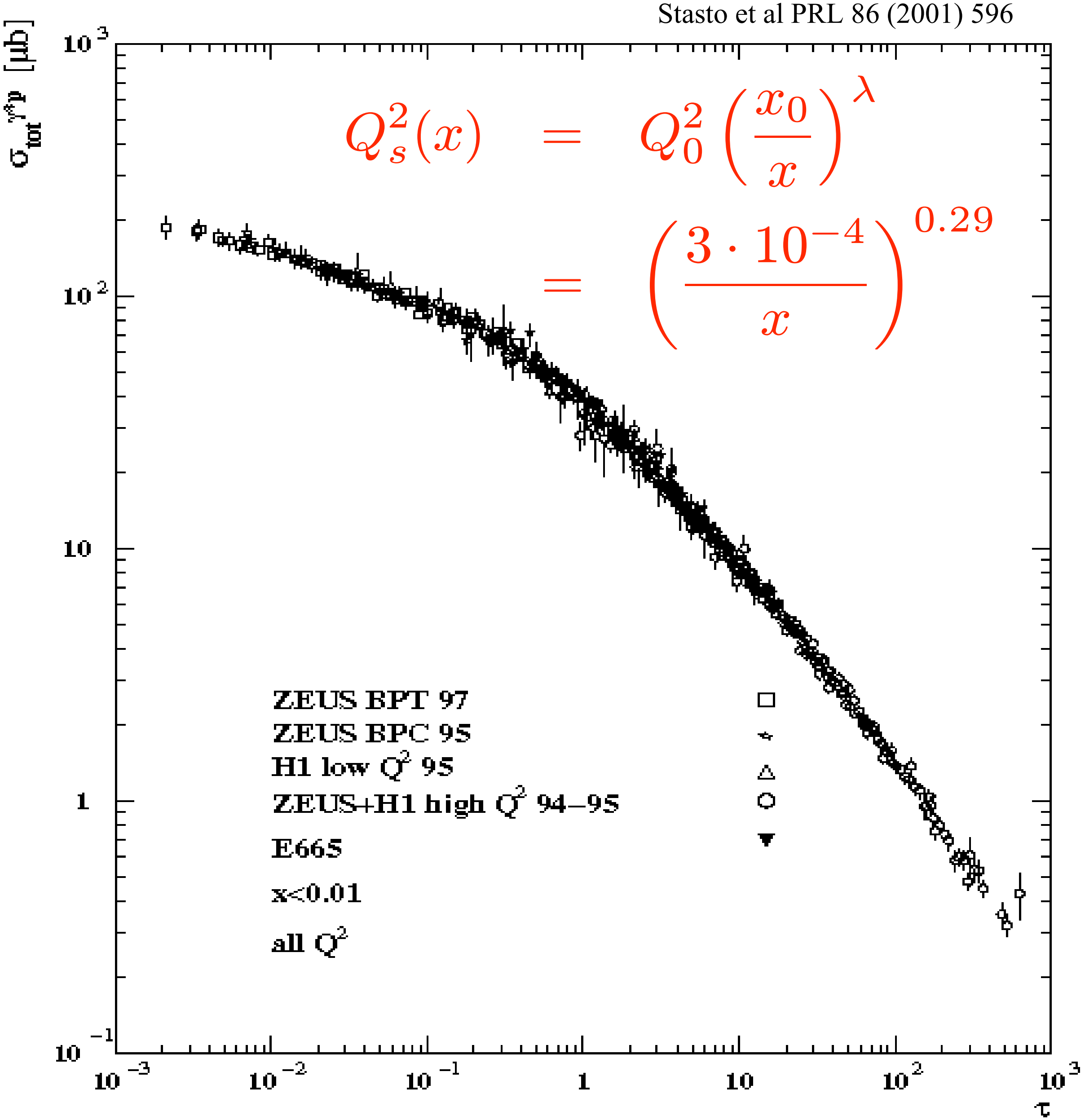
$$\tau(x) = \frac{Q^2}{Q_s^2(x)}$$

- scaling observed from small x<0.01

➔ all $F_2(x,Q^2)$ points depend on only one variable: τ

➔ Is this really saturation ???

Stasto et al PRL 86 (2001) 596



Saturation and geometric scaling

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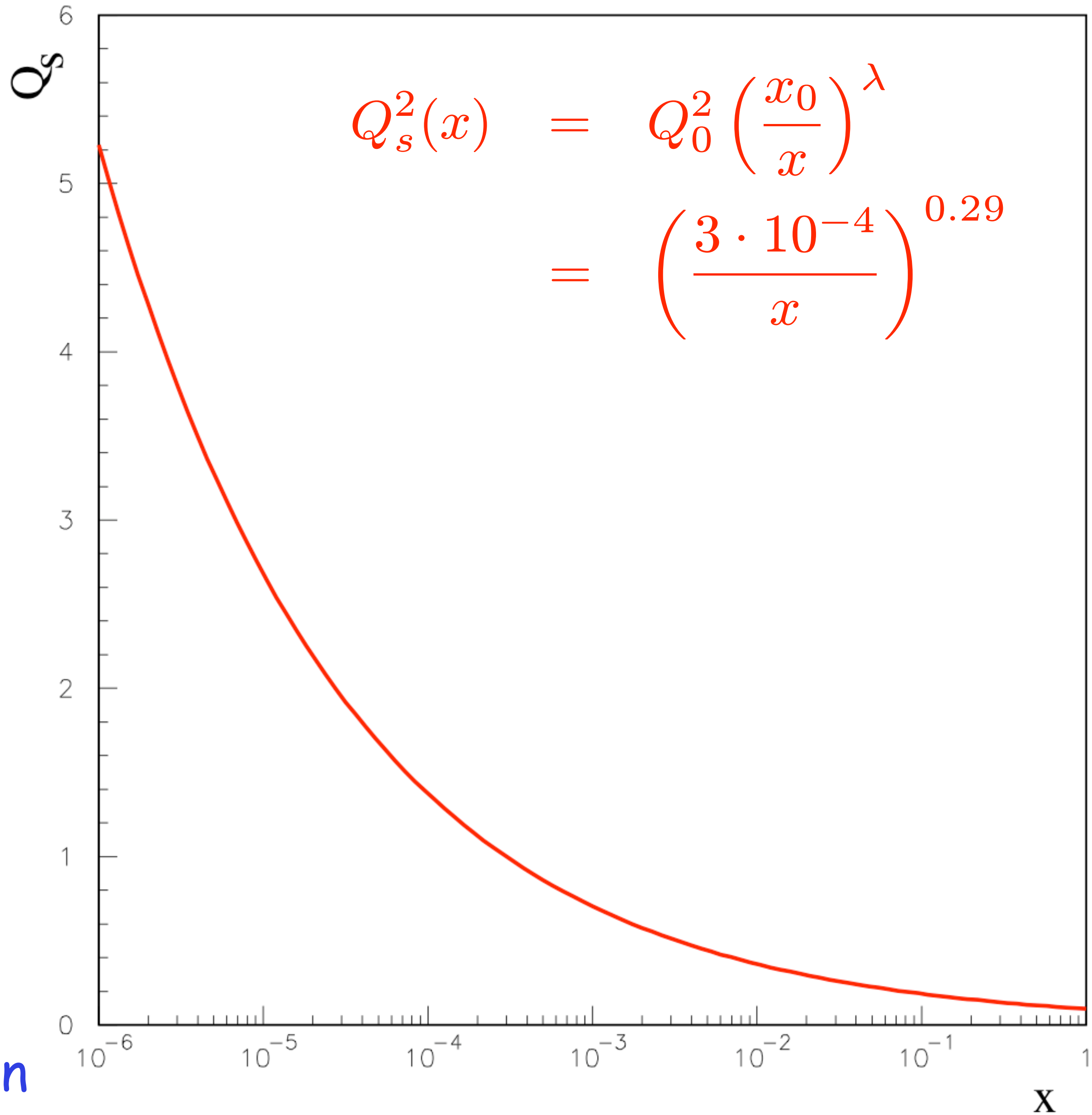
- Define new variable:

$$\tau(x) = \frac{Q^2}{Q_s^2(x)}$$

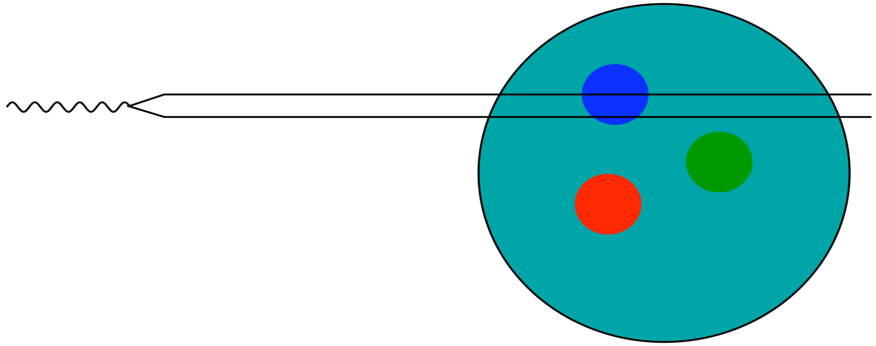
- scaling observed form small x<0.01

➔ BUT, saturation scale is very small, only at $x \sim 10^{-4}$ $Q_s \sim 1$ GeV

➔ BUT, also depends on gluon



The dipoles sneak in again ...



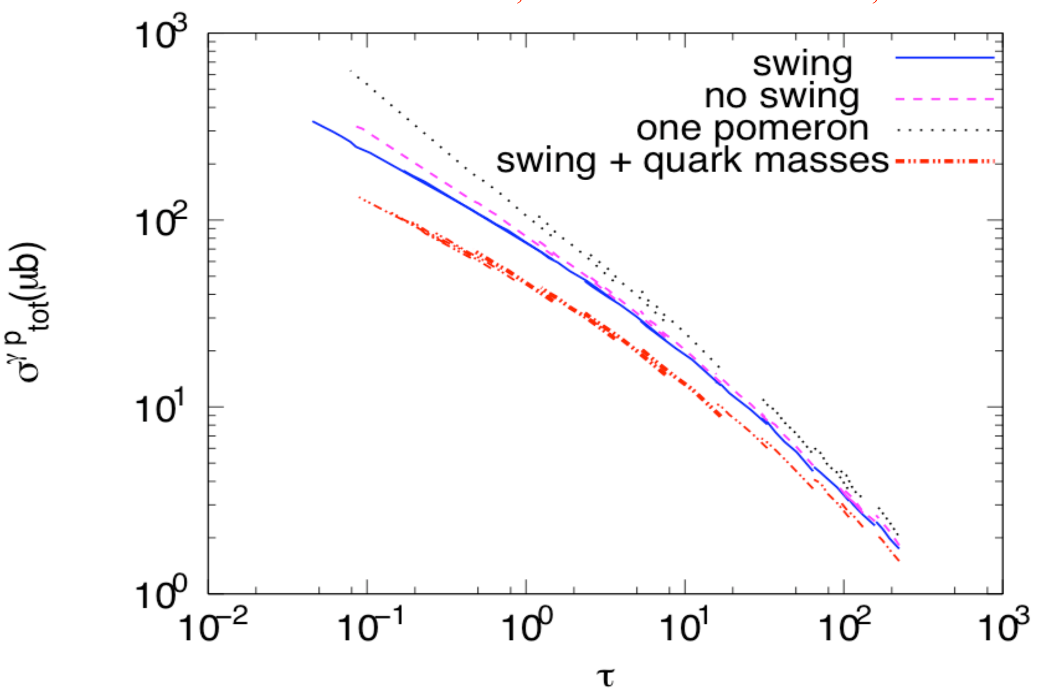
$$\sigma^{tot}_{\gamma^* p} = \int d^2\mathrm{r} \int_0^1 dz \, (|\psi_L(z,r)|^2 + |\psi_T(z,r)|^2) \, \sigma_{dp}(z,\mathrm{r})$$

- geometric scaling found with dipole model

➔ implement energy momentum conservation to dipole model

(Avsar, Gustafson, Lonnblad JHEP 07 (2005) 062)

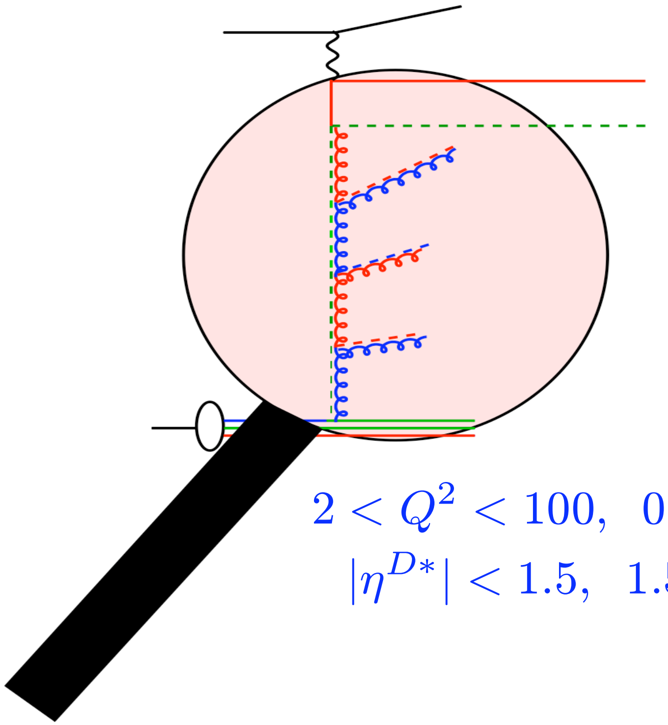
Avsar, Gustafson JHEP 0704:067,2007.



- largest effect from q masses and energy-mom conservation
- only small effect from saturation.....
- Ahh, yes, also DGLAP did describe the data

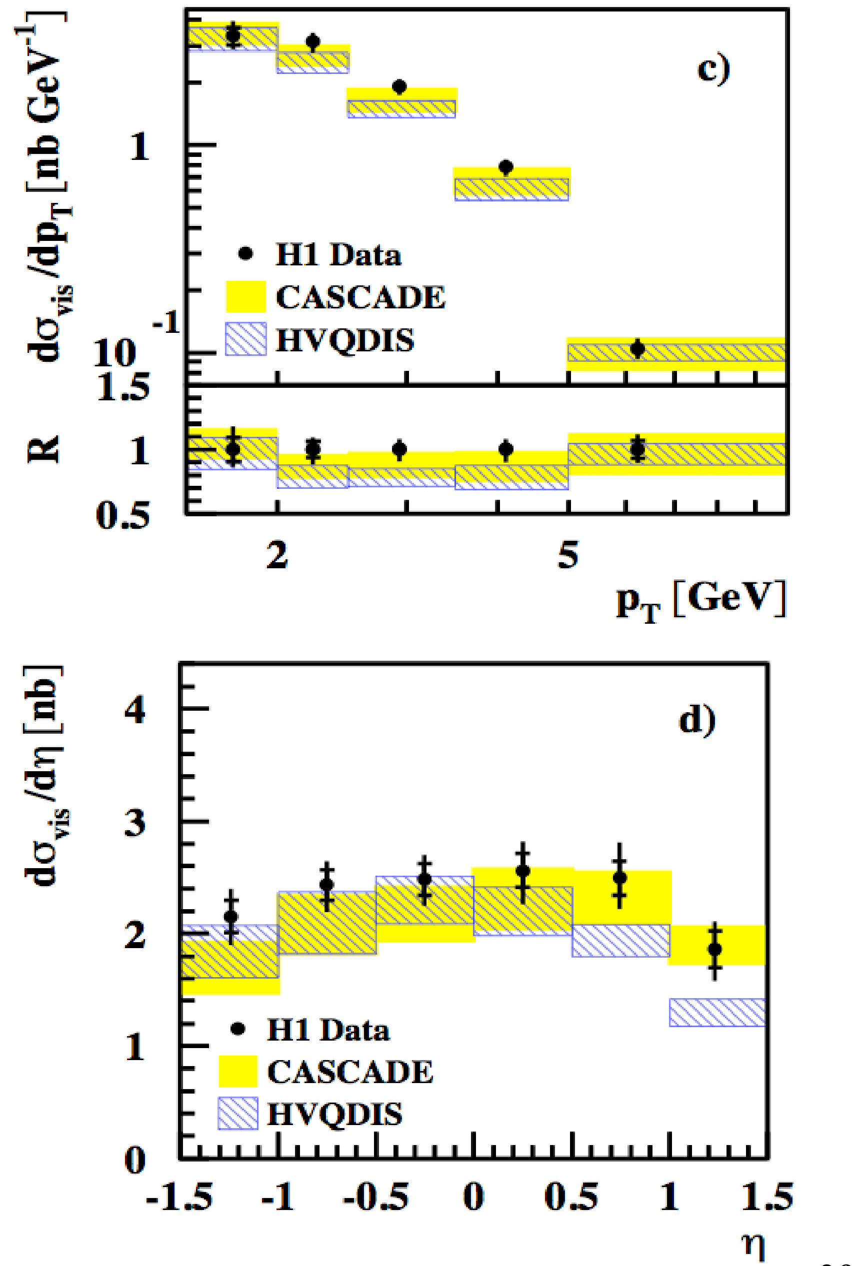
Walking down the ladder ...

- D* production in DIS



$2 < Q^2 < 100, \ \ 0.05 < y < 0.7$
$|\eta^{D*}| < 1.5, \ \ 1.5 < p_T^{D*} < 15$

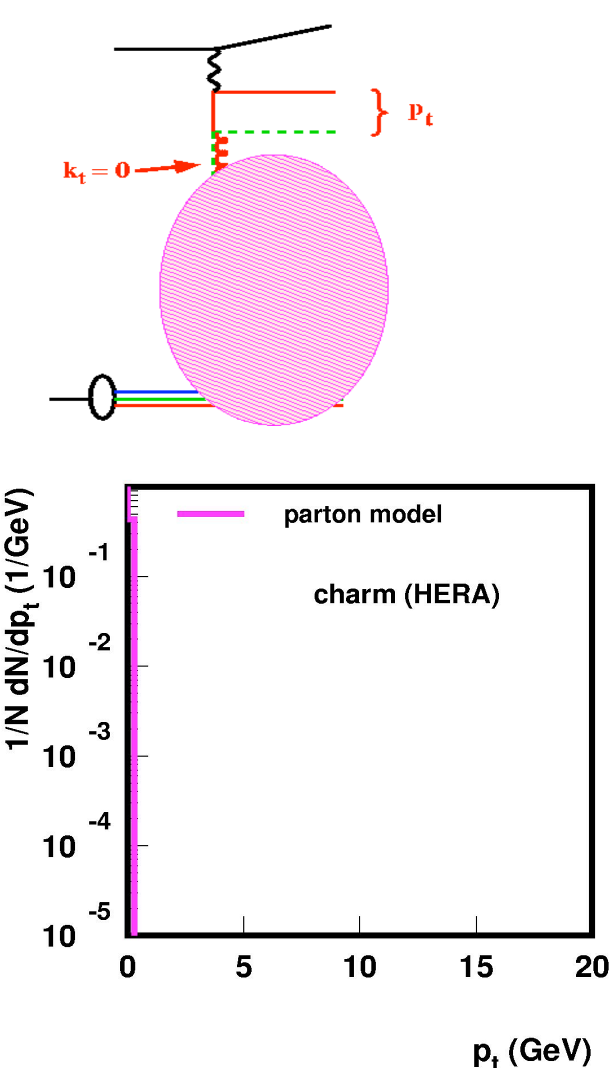
- good description of inclusive D* production by NLO (HVQDIS) but also using kt-factorization and uPDFs (CASCADE) .....



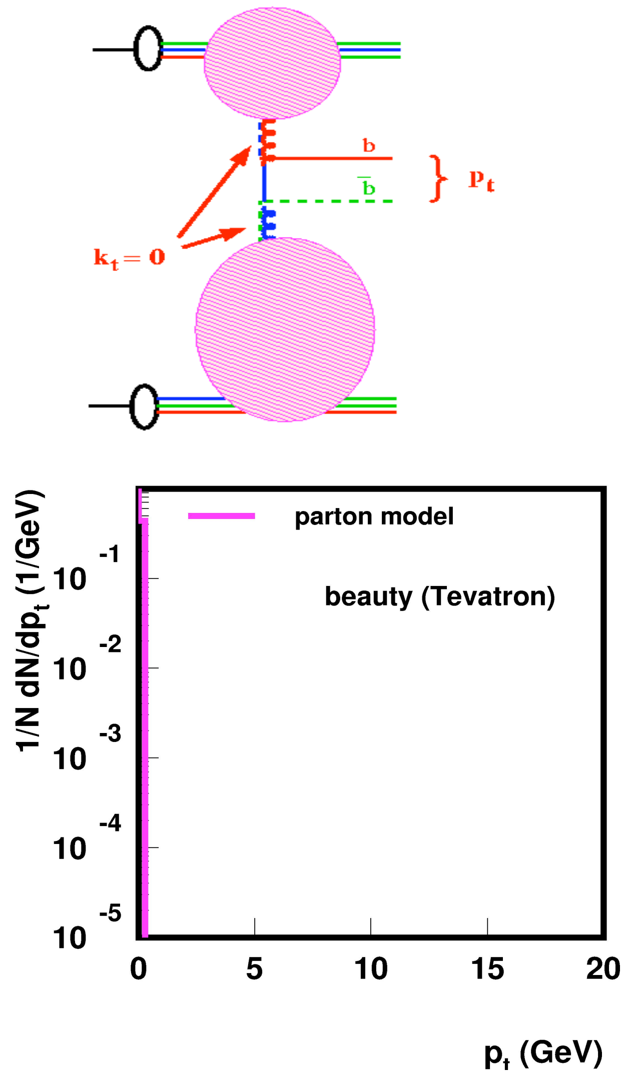
Problems in Collinear Approximation

J. Collins, H. Jung hep-ph/0508280

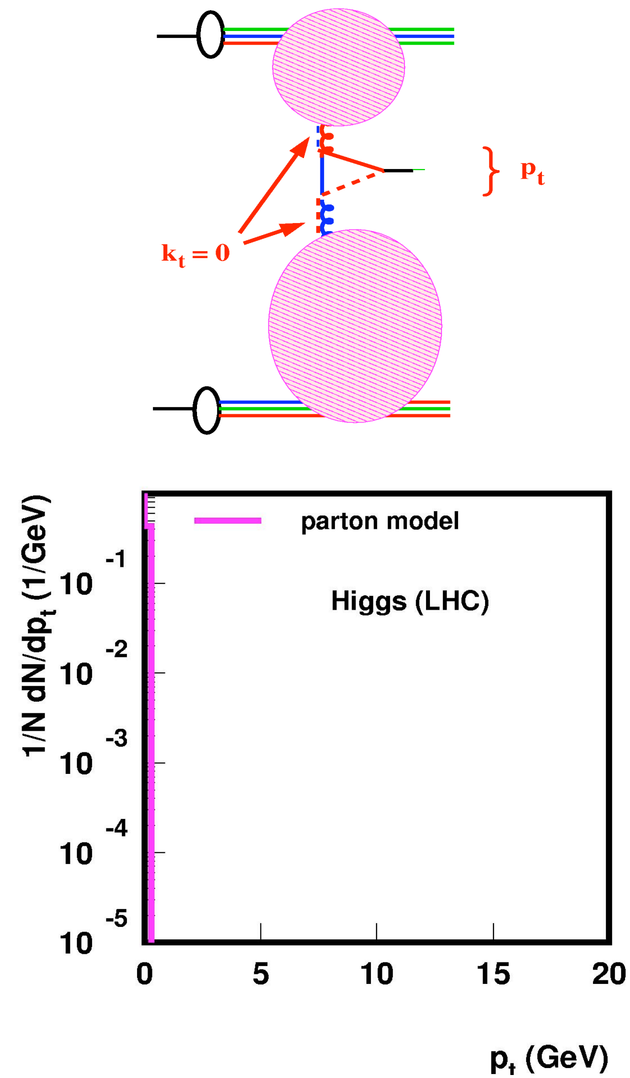
heavy quarks at HERA



heavy quarks in



Higgs in pp

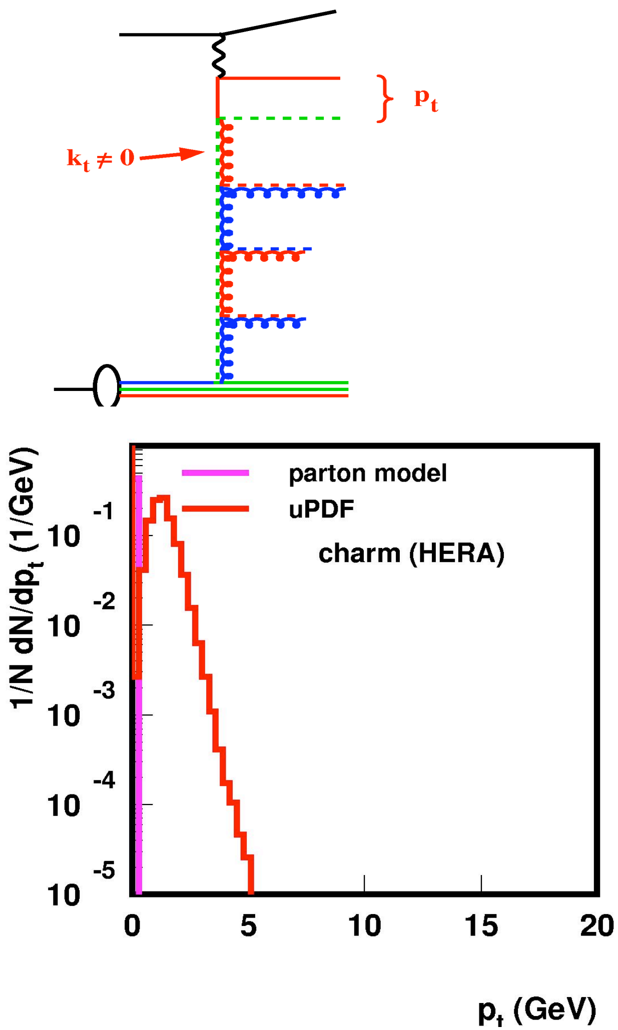


➔ NLO corrections will be very large for these LO processes .....

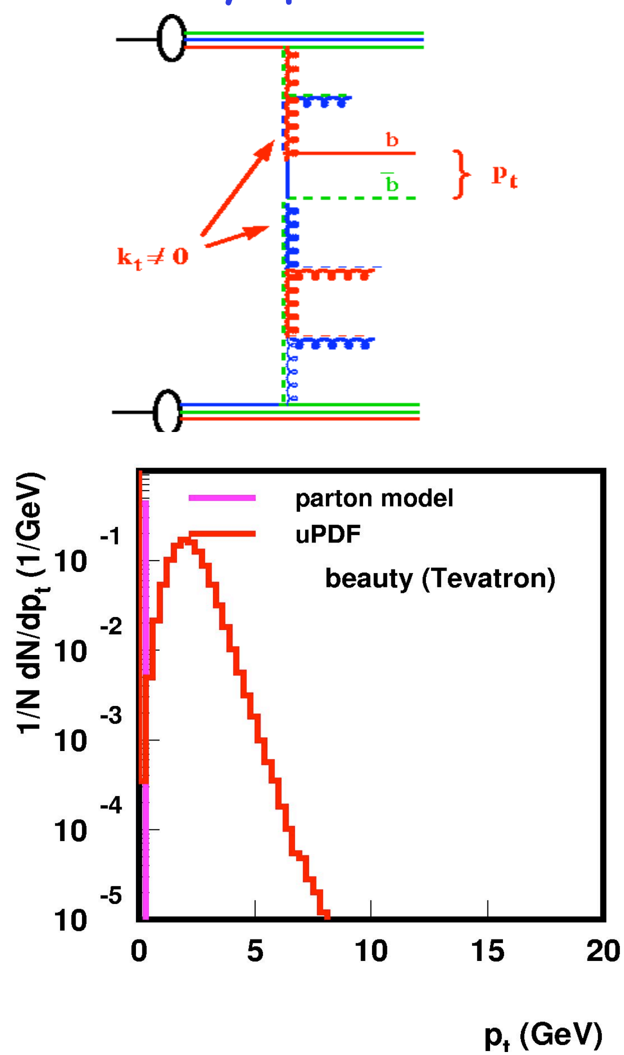
Doing much better with uPDFs ...

J. Collins, H. Jung hep-ph/0508280

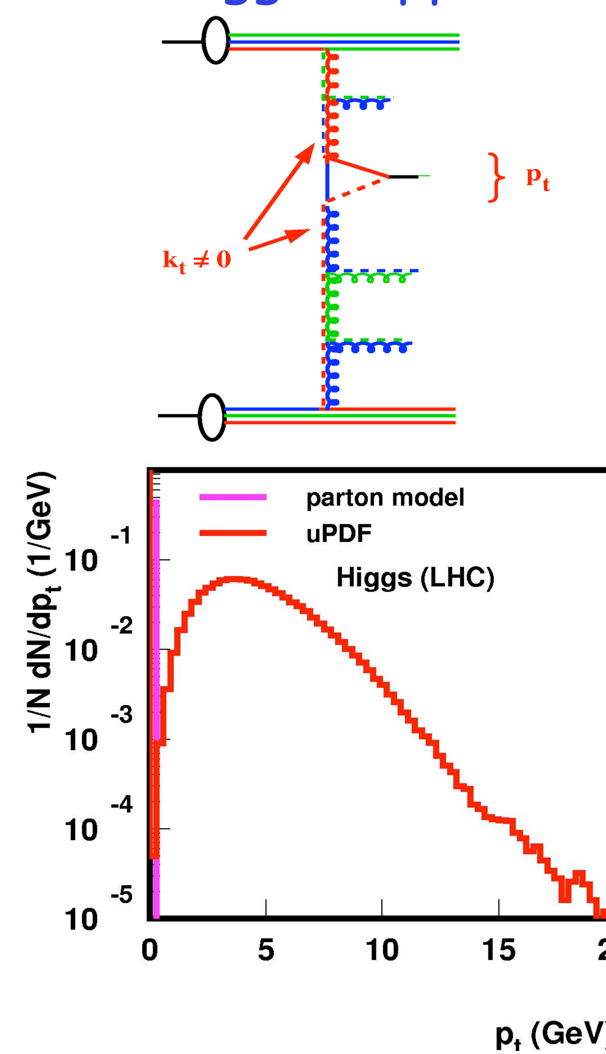
heavy quarks at HERA



heavy quarks in

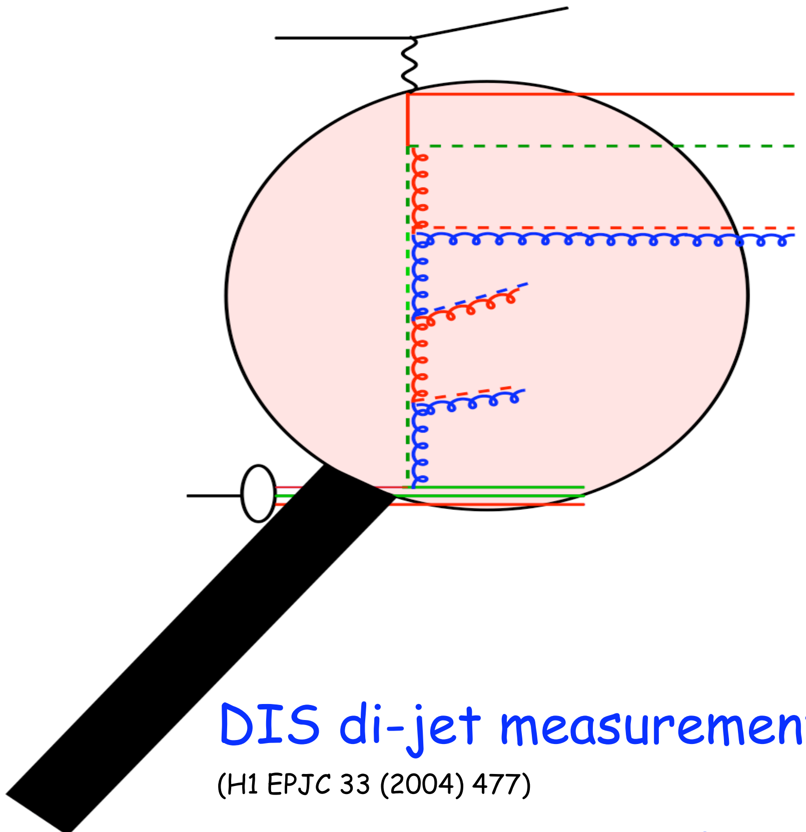


Higgs in pp



➔ doing kinematics correct at LO, reduces NLO corrs,.... NEED uPDFs !!!!

Walking further down the ladder

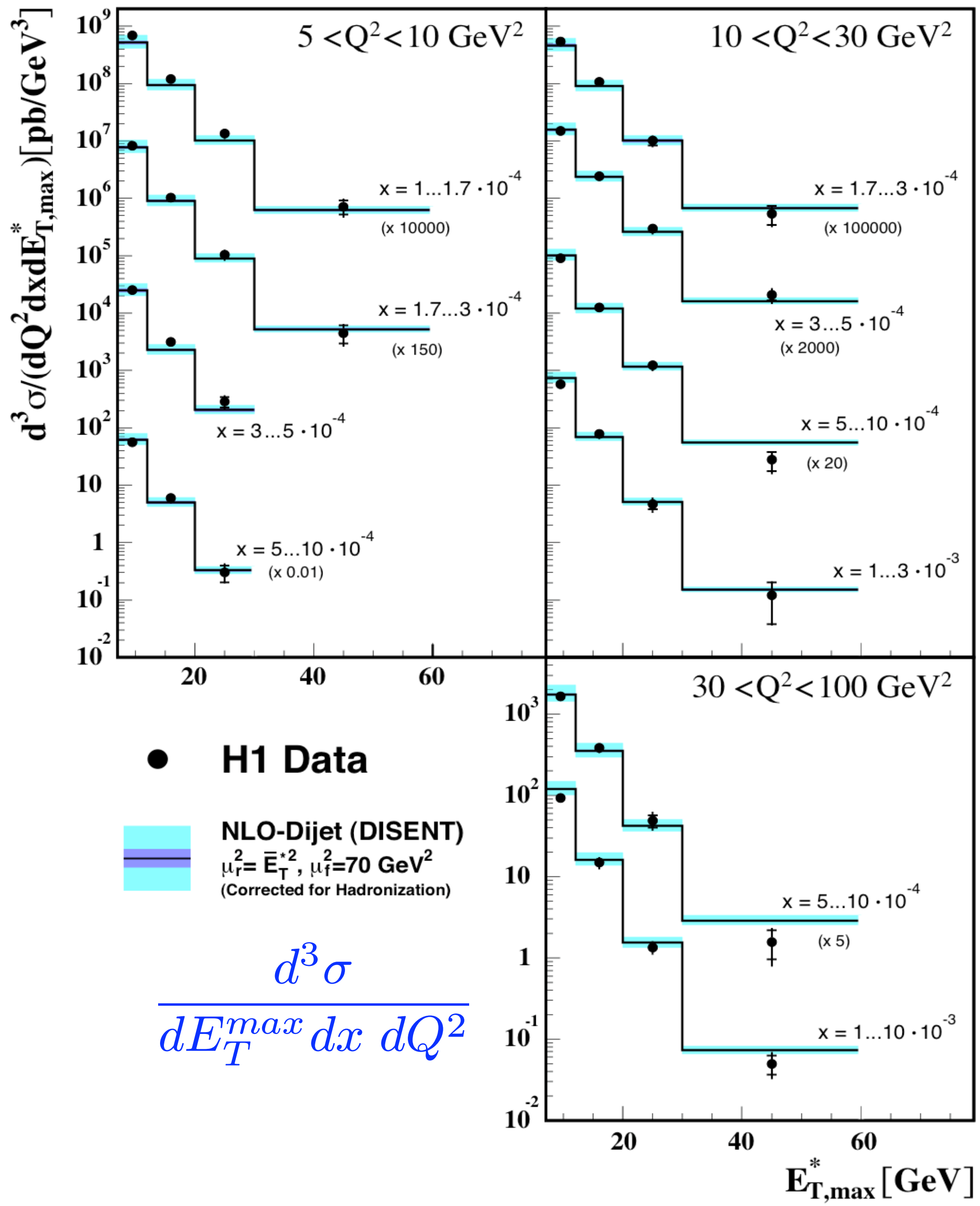


DIS di-jet measurements

(H1 EPJC 33 (2004) 477)

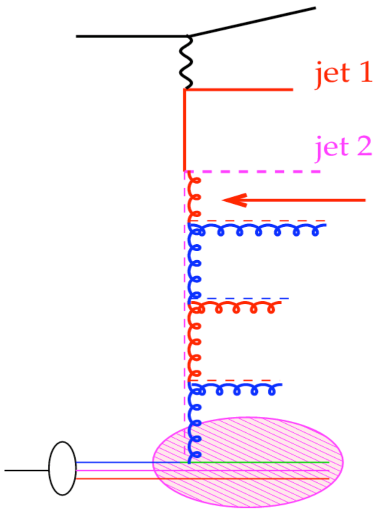
$$5 < Q^2 < 100 \text{ GeV}^2$$
$$-1 < \eta < 2.5$$
$$E_T > 5 \text{ GeV}$$

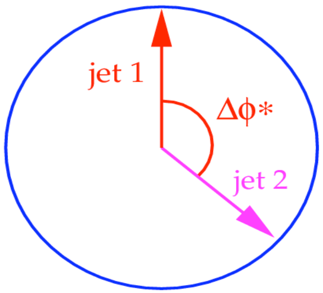
➔ calculation with at least 3 hard partons essential ...



$$\frac{d^3\sigma}{dE_T^{max}\, dx\, dQ^2}$$

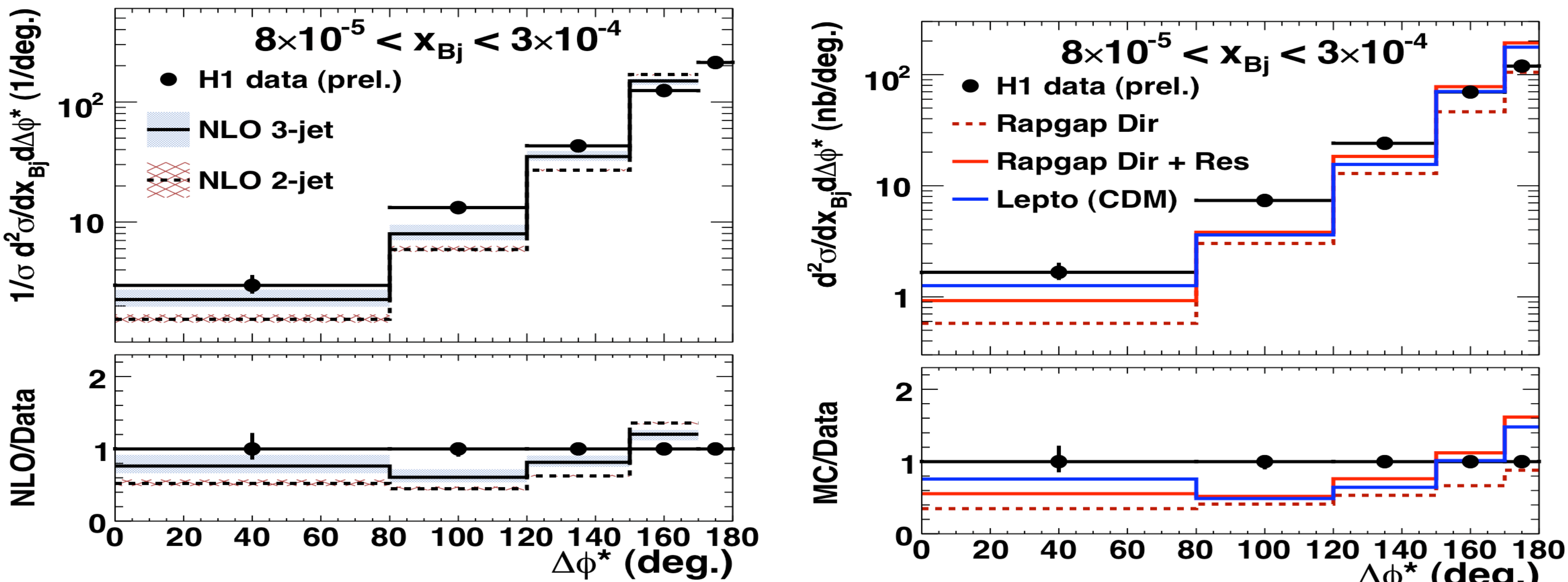
More on the ladder ...





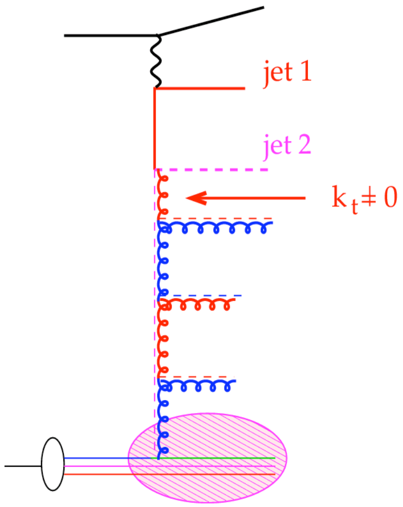
- H1 prel data $5 < Q^2 < 100$ GeV^2
  $-1 < \eta < 2.5$
  $E_T > 5$ GeV

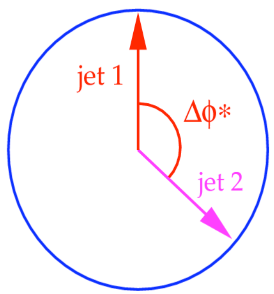
➔ None of the calculations can describe measurements !!!

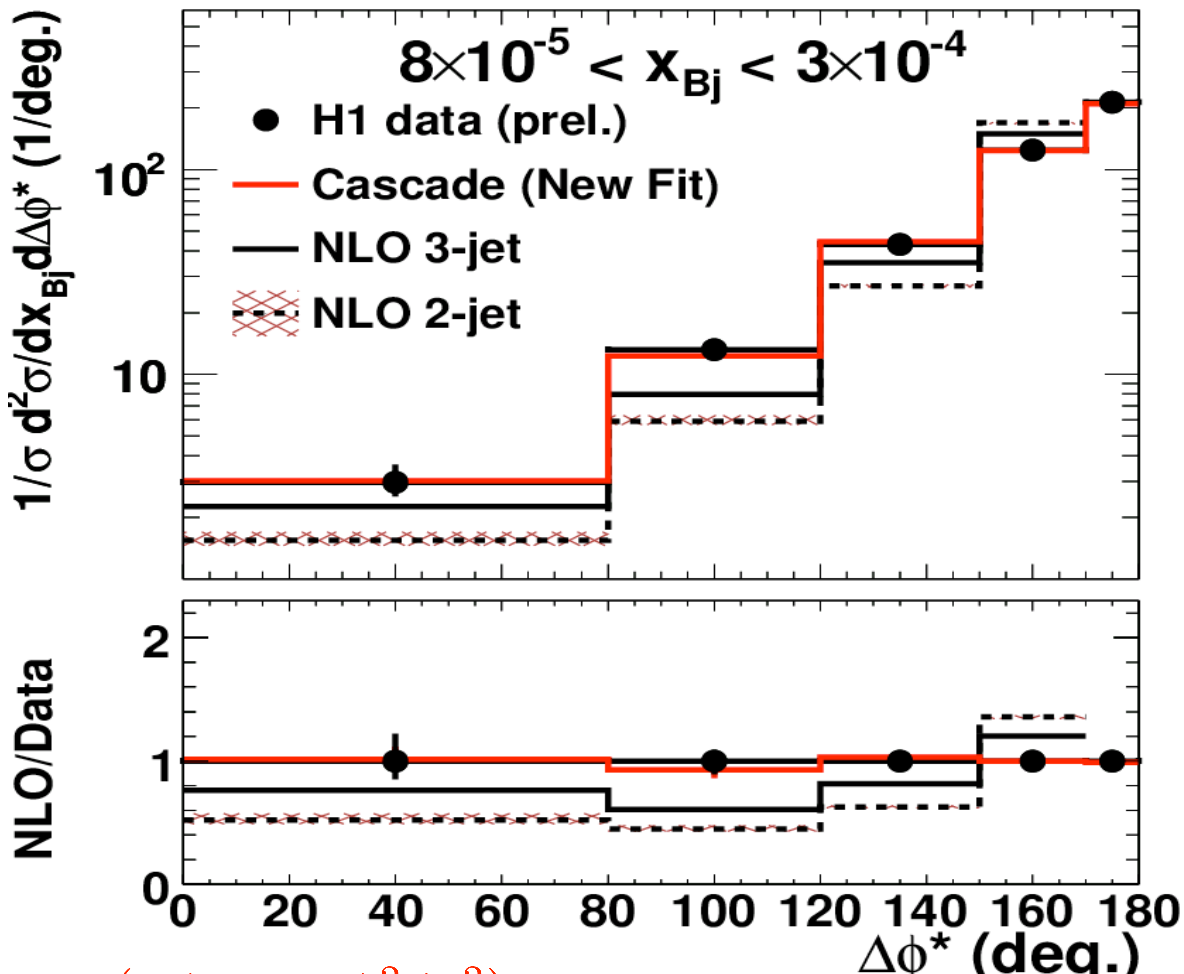


uPDFs from di-jets: k_t-dependence

Hansson, Jung arXiv:0707.4276







- H1 prel data

  $5 < Q^2 < 100\ \mathrm{GeV}^2$

  $-1 < \eta < 2.5$

  $E_T > 5\ \mathrm{GeV}$

- determine small k_t region with

$$x\mathcal{A}(x,\mu_0^2) = Nx^{-B_g}\cdot(1-x)^4\cdot\exp\left(-(k_{t0}-\mu)^2/\sigma^2\right)$$

- large k_t from evolution

➔ perfect description of shape and rate

Evolution of uPDFs and x-section

- unintegrated PDFs (**uPDFs**): keep full k_t dependence during perturbative evolution
  - ➔ using **D**okshitzer **G**ribov **L**ipatov **A**ltarelli **P**arisi, **B**alitski **F**adin **K**uraev **L**ipatov or **C**iafaloni **C**atani **F**iorani **M**archesini /**L**iinked **D**ipole **C**hain evolution equations
  - ➔ CCFM/LDC treats explicitly real gluon emissions
    - ➔ according to color coherence ... angular ordering
    - ➔ angular ordering includes **DGLAP** and **BFKL** as limits...
- cross section (in k_t factorization) :

$$\frac{d\sigma^{jets}}{dE_T d\eta} = \sum \int \int \int dx_g \, dQ^2 d \ldots \left[dk_\perp^2 x_g \mathcal{A}_i(x_g, k_\perp^2, \bar{q}) \right] \hat{\sigma}_i(x_g, k_\perp^2)$$

➔ can be reduced to the collinear limit:

$$\frac{d\sigma^{jets}}{dE_T d\eta} = \sum \int \int \int dx \, dQ^2 d \ldots x f_i(x, Q^2) \hat{\sigma}_i(x, Q^2, \ldots.)$$

uPDFs from di-jets: intrinsic k_t

$$xA(x, k_\perp, \bar{q}) = \int dx_0 A_0(x_0, \mu_0) \times \frac{x}{x_0} \tilde{A}\left(\frac{x}{x_0}, k_\perp, \bar{q}\right)$$

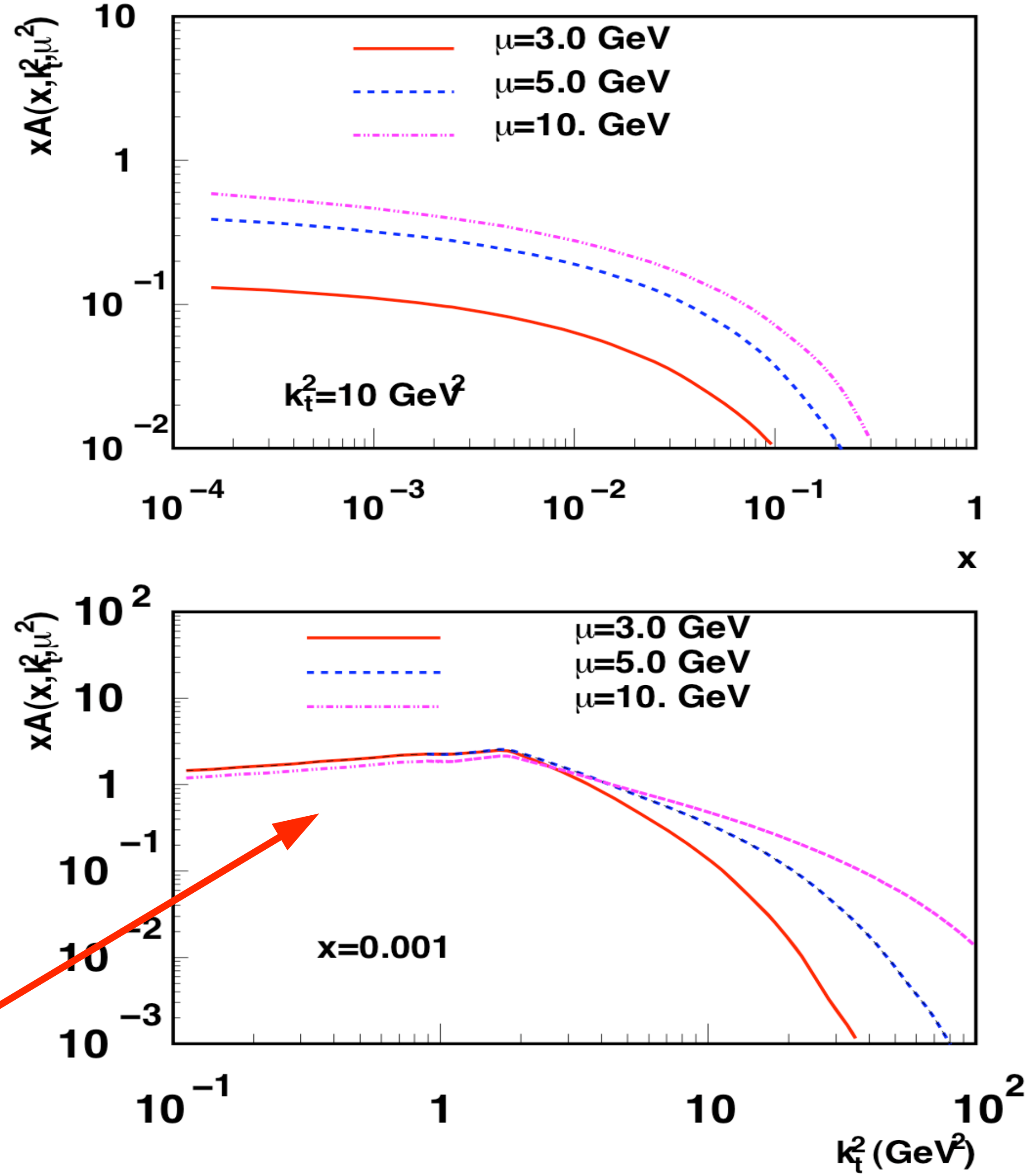
- different intrinsic k_t-distributions only accessible in uPDFs
- sensitive to the mix of small and large k_t

➔ small k_t determines total x-section

➔ large k_t influences perturbative tails ...

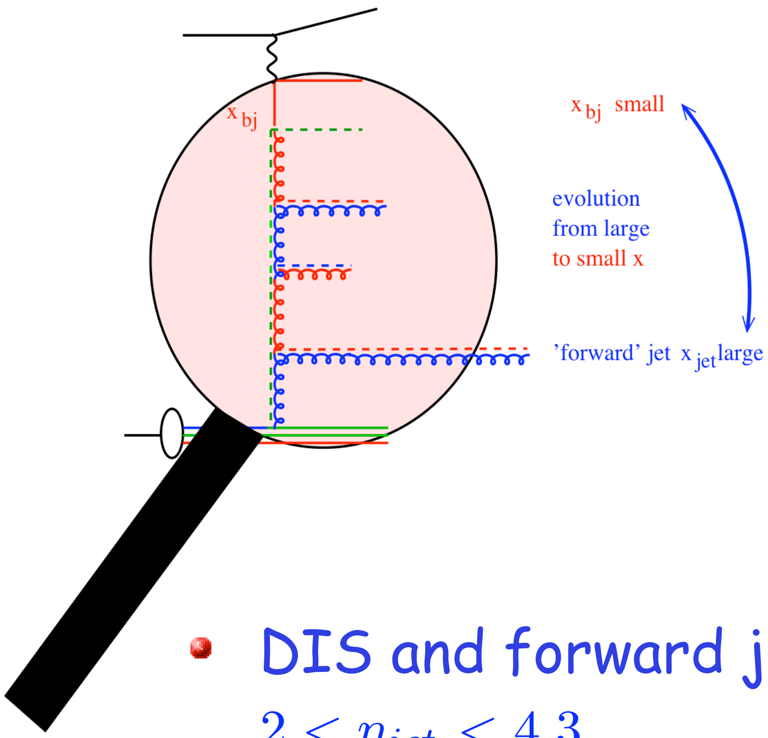
BUT .....

Hautmann, Jung arXiv:0712.0568 [hep-ph]

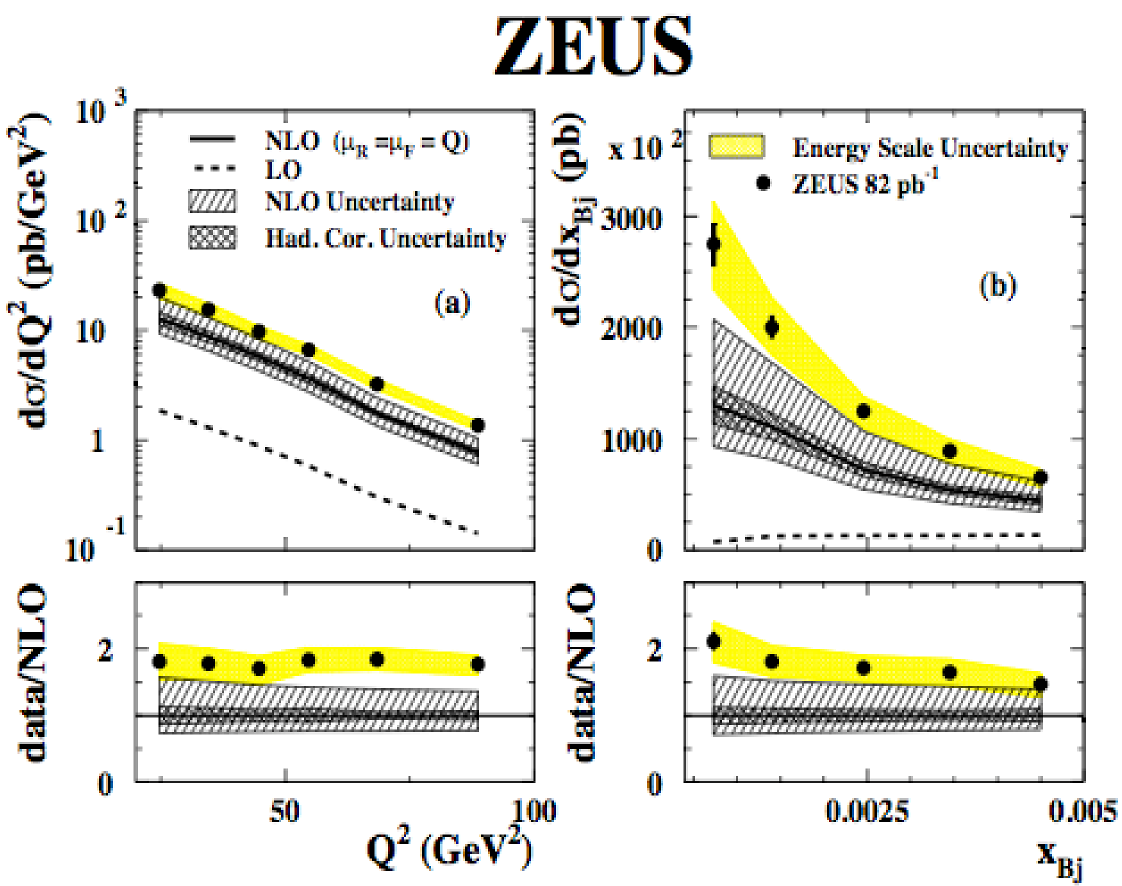


H. Jung, DESY

Looking forward ...



ZEUS, EPJ C 52 (2007) 515-530



- DIS and forward jet:

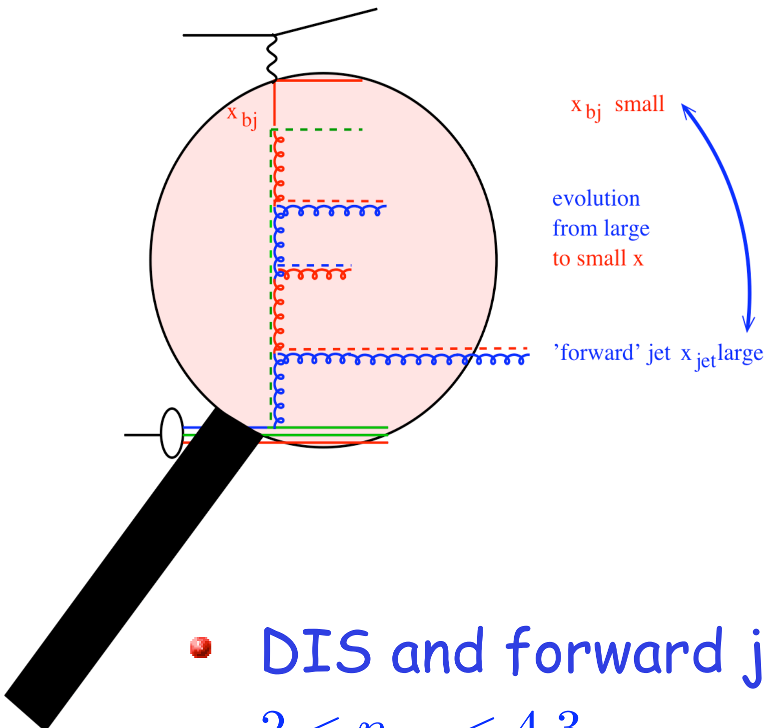
$$2 < \eta_{jet} < 4.3$$

$$x_{jet} > 0.036$$

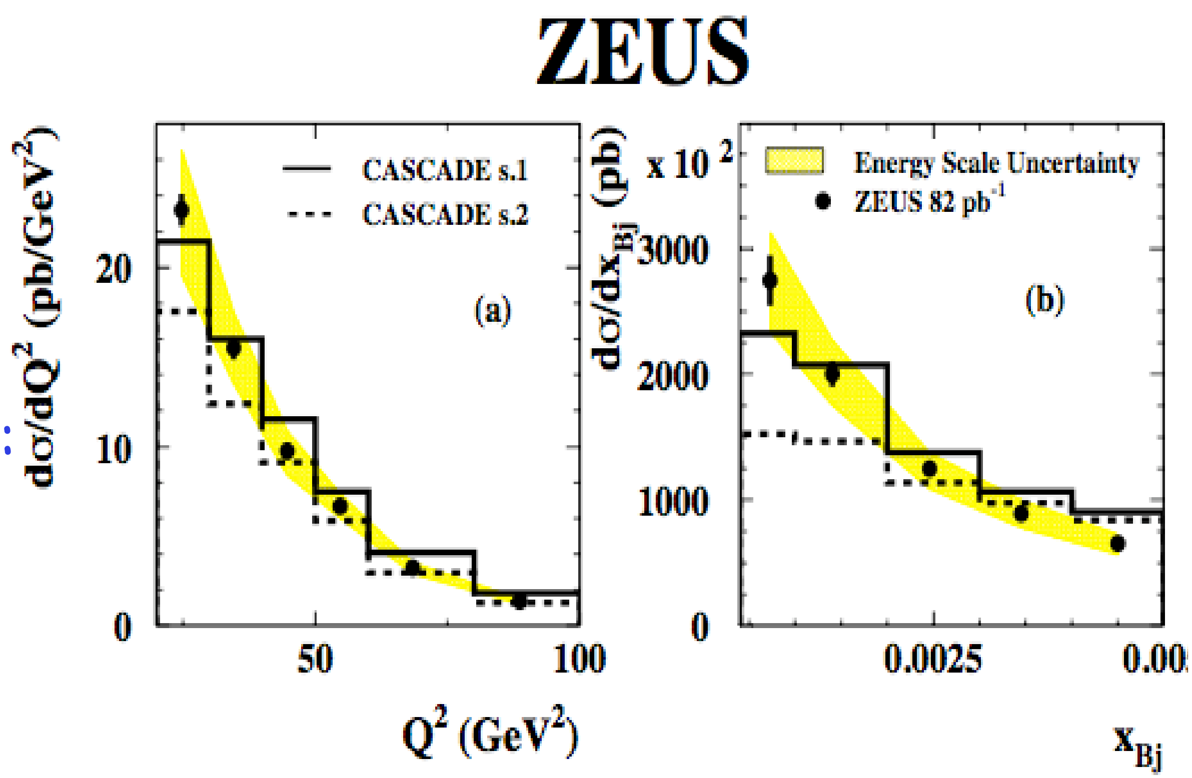
$$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$$

➔ NLO factor 2 toooo low

Looking forward ...



ZEUS, EPJ C 52 (2007) 515-530



- DIS and forward jet:

$$2 < \eta_{jet} < 4.3$$

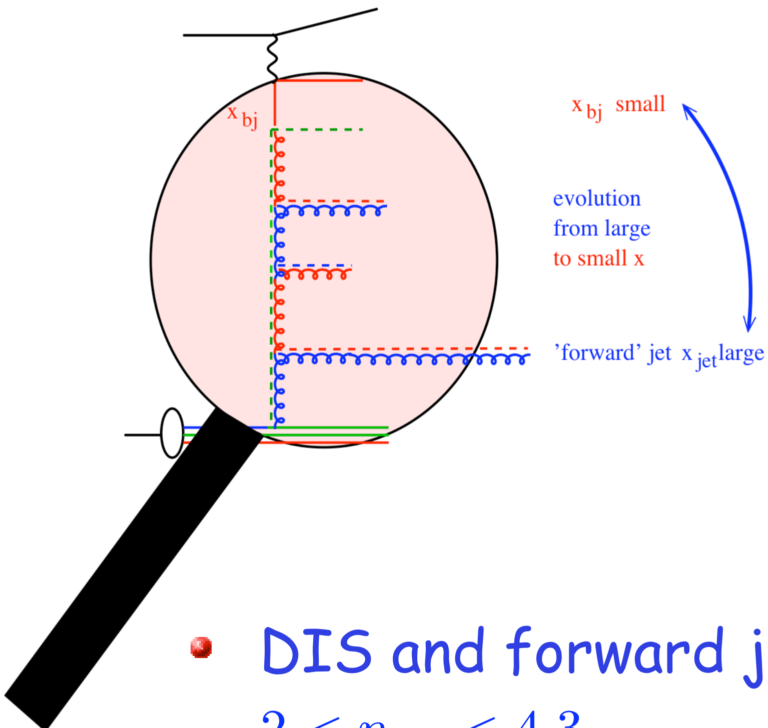
$$x_{jet} > 0.036$$

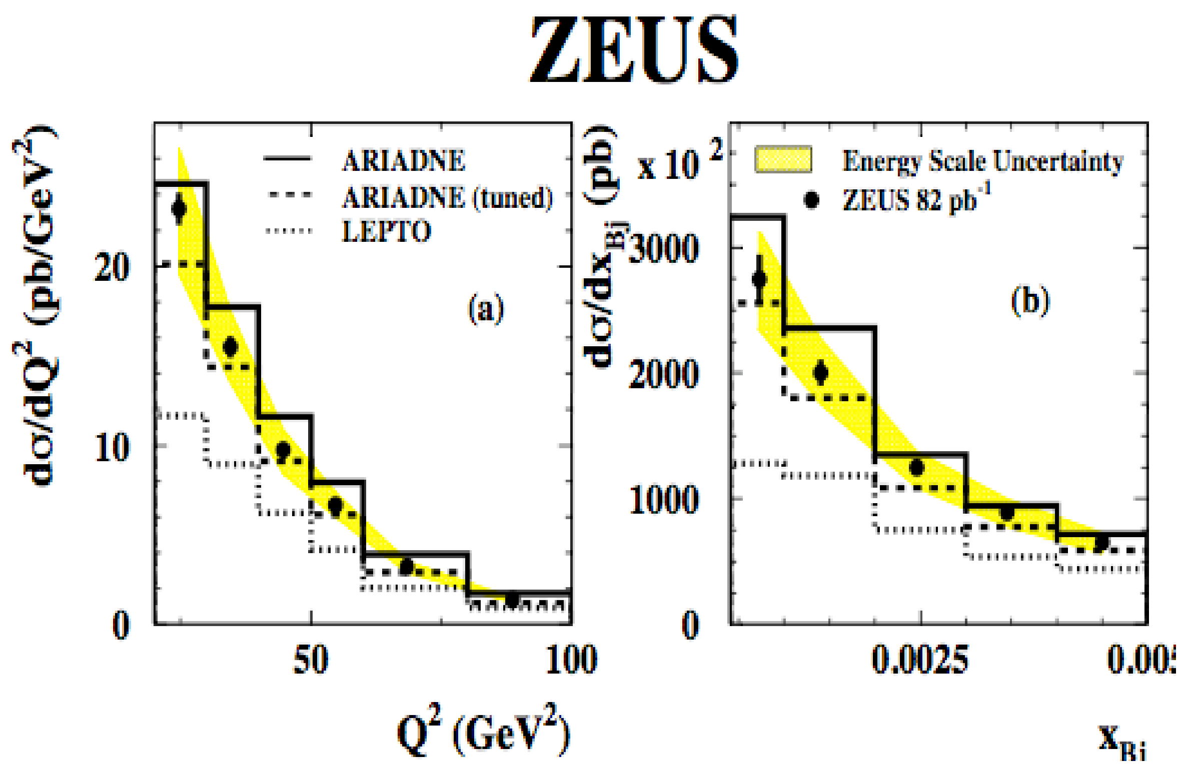
$$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$$

➔ Hm...... not too bad.... BUT

Looking forward ...

ZEUS, EPJ C 52 (2007) 515-530





- DIS and forward jet:

$$2 < \eta_{jet} < 4.3$$
$$x_{jet} > 0.036$$
$$0.5 < \frac{p_{t\ jet}^2}{Q^2} < 2$$

➔ CDM (ARIADNE) best ...

what did we learn ...

- inclusive DIS x-section well described by NLO DGLAP
  - x-section rises strongly for small x
  - large gluon/sea quark densities
  - ➔ is linear evolution enough ?
  - ➔ saturation effects ?
- understanding parton evolution at high energies still challenging:
  - hadronic final state not really well understood
  - k_t distribution, $\Delta\phi$ needs further investigations ....
  - forward jet production ....

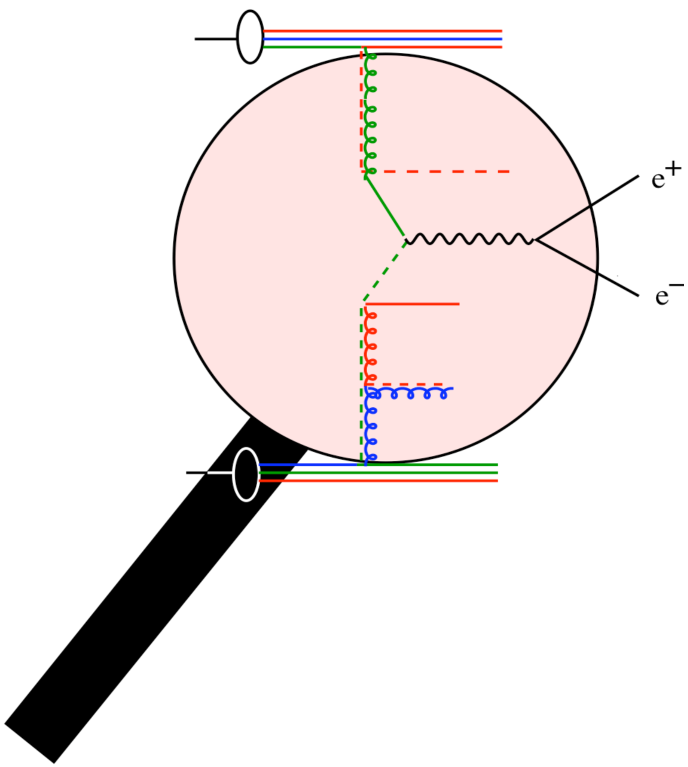
➔ best description still by CDM (ARIADNE) although effects from extended dipoles...

➔ best theory .. CCFM/LDC ....
still does not provide a very good description.....

Adding another complication ....

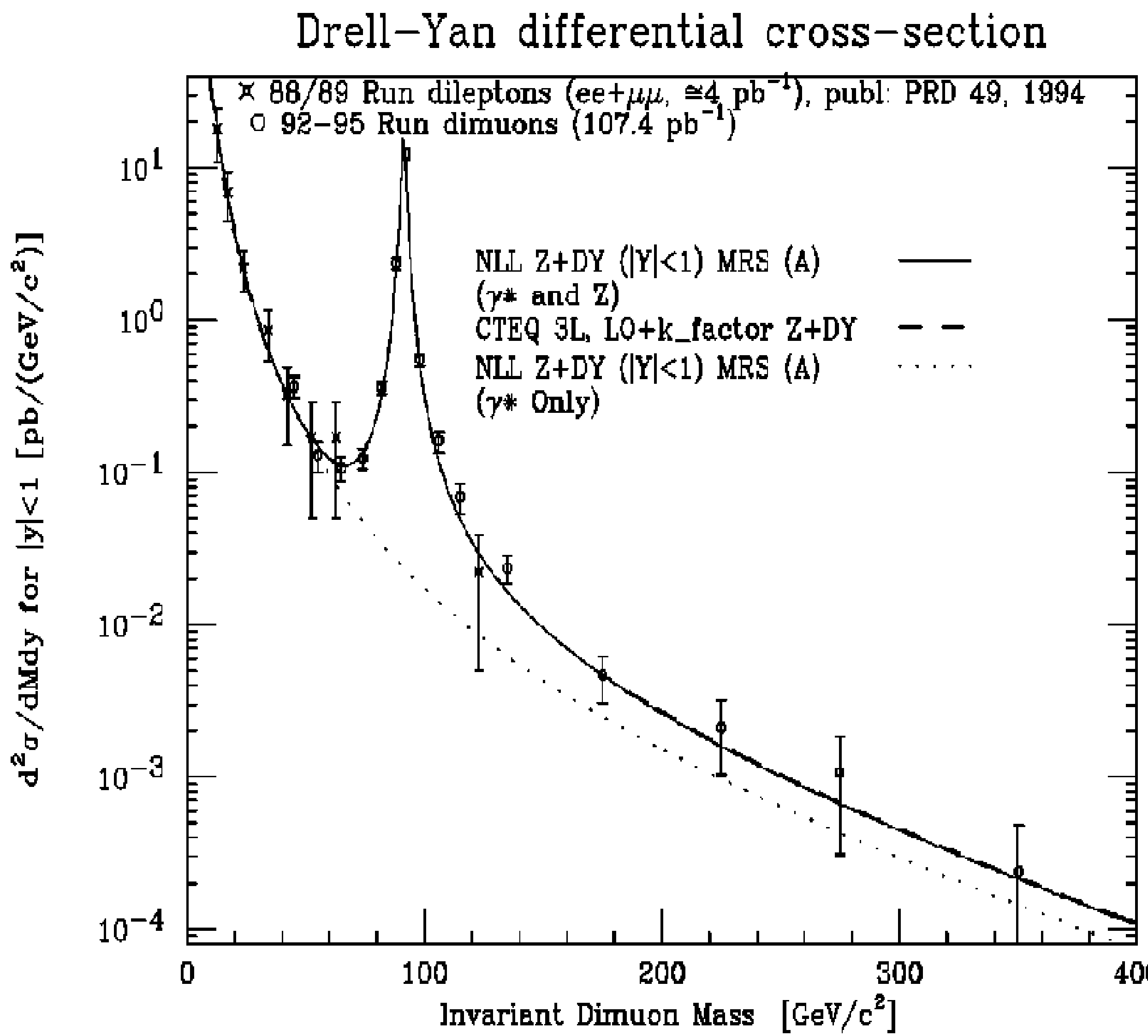
two protons in the initial state

The easy case in pp ....



$$\sigma(q\bar{q} \rightarrow l^+ l^-) = \frac{4\pi\alpha^2}{3\times 3s} e_q^2$$

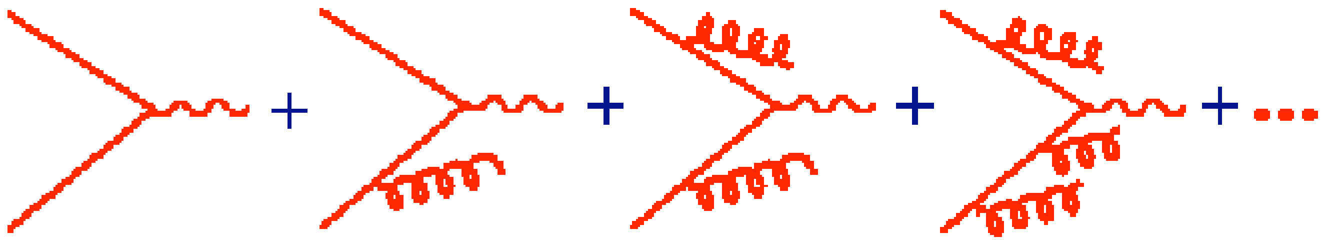
Measurement of Z0 and Drell-Yan production cross-section using dimuons in anti-p p collisions at S**(1/2) = 1.8-TeV.
CDF Collaboration F. Abe et al. Phys.Rev.D59:052002,1999.



Resummation

C-P Yuan, CTEQ
summerschool 2002

Diagramatically, Resummation is doing



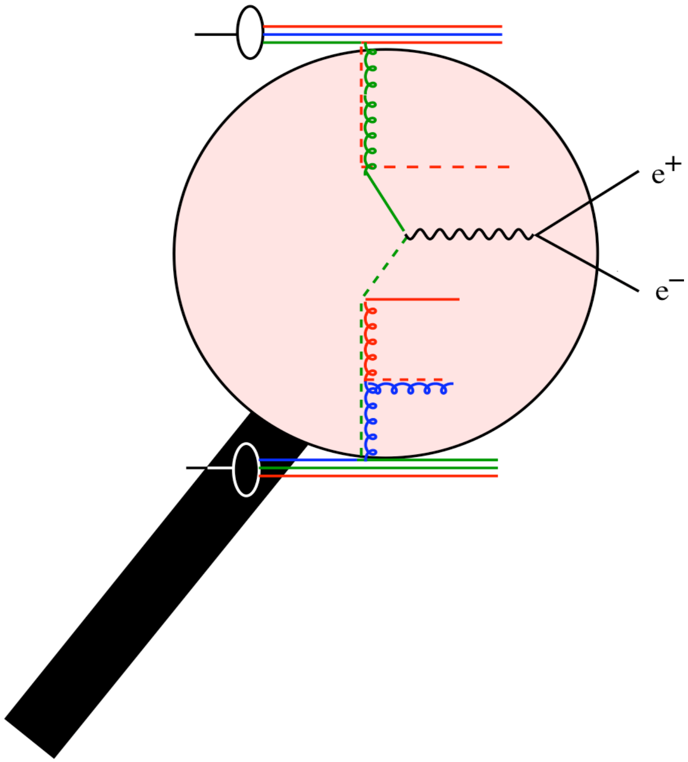
→ Resum large $\alpha_S^n \ln^m\left(\frac{Q^2}{q_T^2}\right)$ terms

$$\left.\frac{d\sigma}{dq_T^2 dy}\right|_{q_T \to 0} \sim \frac{1}{q_T^2}\sum_{n=1}^{\infty}\sum_{m=0}^{2n-1}\alpha_S^n \ln^m\left(\frac{Q^2}{q_T^2}\right)\cdot C_m^n$$

Monte-Carlo programs ISAJET, PYTHIA, HERWIG contain these physics.

Transverse Momentum of W/Z

Measurements of Inclusive W and Z Cross Sections in p anti-p Collisions at s**(1/2) = 1.96 TeV CDF Collaboration,Resubmitted to Phys. Rev. D July 3, 2006.



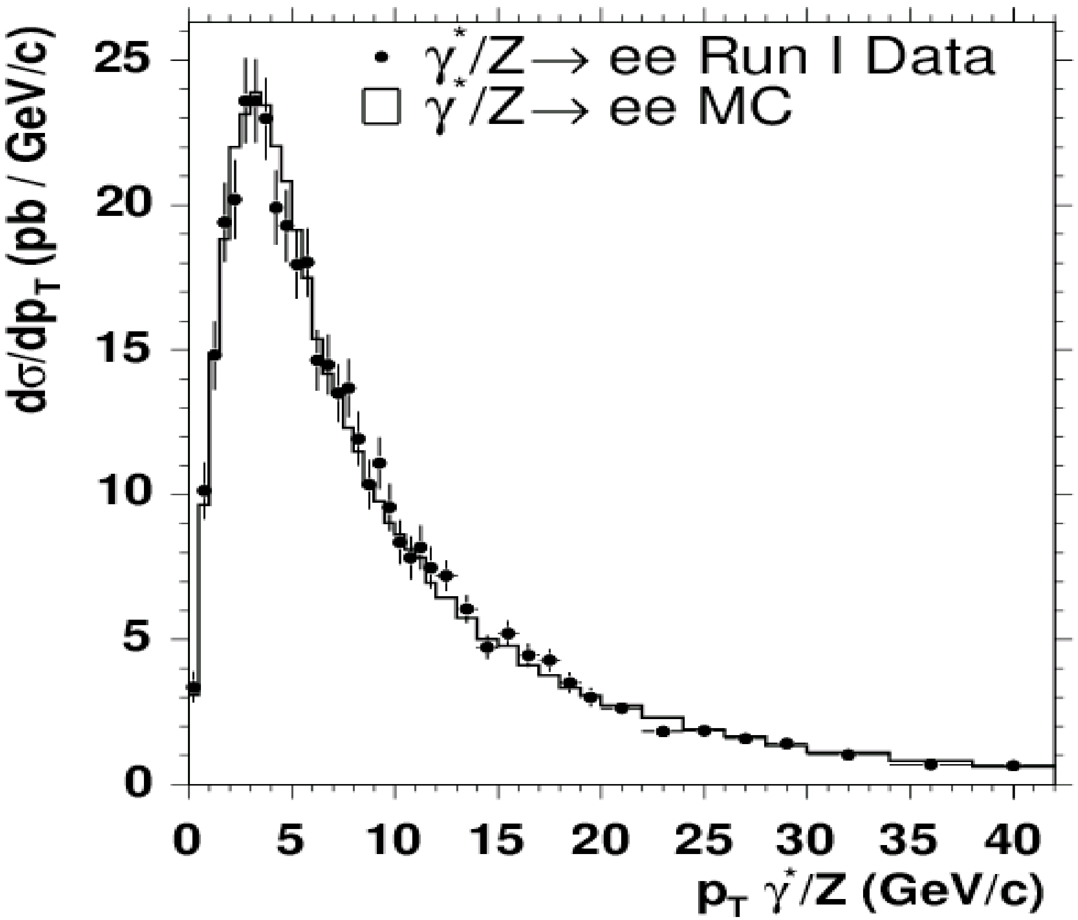


FIG. 12: Tuned PYTHIA 6.21 $d\sigma/dp_T$ in pb per GeV/c (on average) of $\gamma^*/Z \rightarrow ee$ pairs in the mass region 66 GeV/c^2 < M_{ee} < 116GeV/c^2 (histogram) versus the measurement made by CDF in Run I (points).

PDF fits including q_t resummation

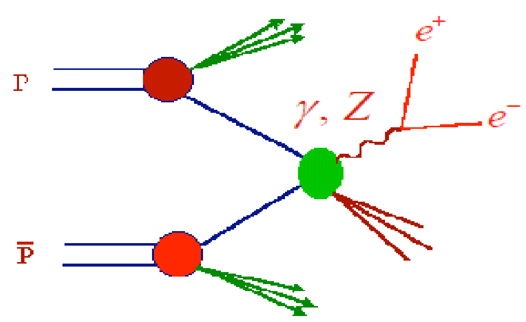
CP. Yuan, DIS2007

New from DIS07

New Task of Global Analysis

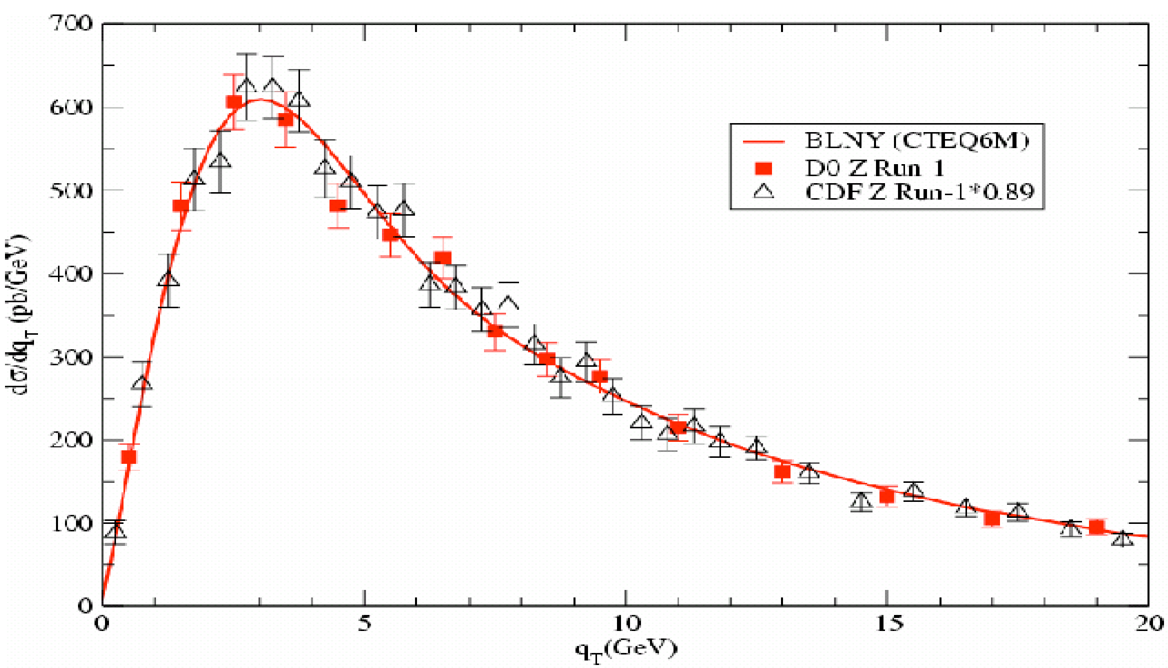
Include Transverse Momentum p_T distributions

- New Data: include not only rapidity (y) but also p_T of Drell-Yan pairs and Z bosons



QCD P_T Resummation
Global Analysis

hep-ph/0212159
Brock, Landry, Nadolsky, CPY

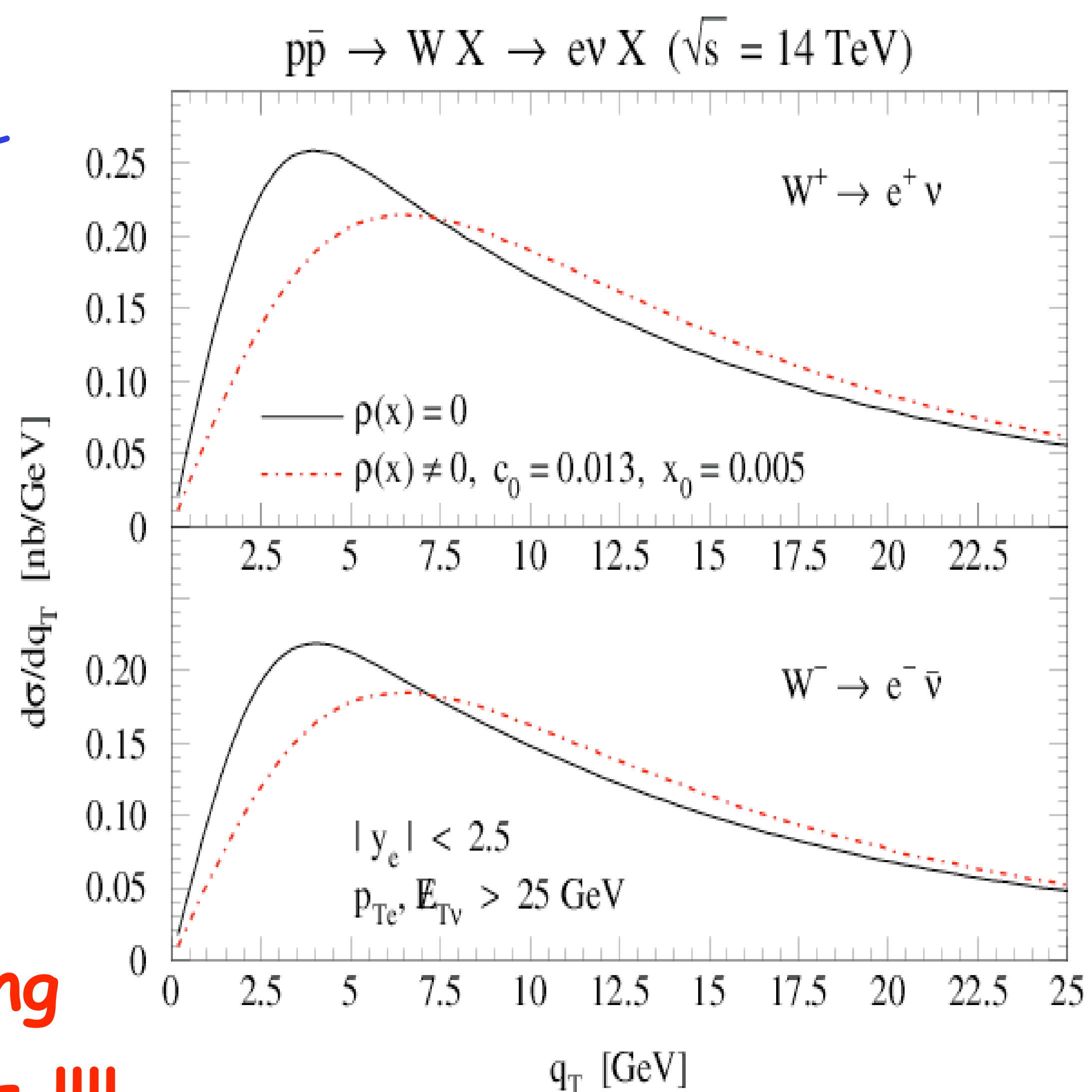


Q_t spectrum: small x improved ...

- in standard p_t resummation, no small x effects are included.
- at large energies (small x) BFKL effects might play a role... diffusion of transverse momenta, qt broadening...
- obtain effective p_t-broadening by HERA data on transverse energy flow... include that for q_t spectra of W/Z (Berge, Nadolsky, Olness, Yuan hep-ph/0410375)

➔ **Interesting physics coming with hard QCD processes !!!!**

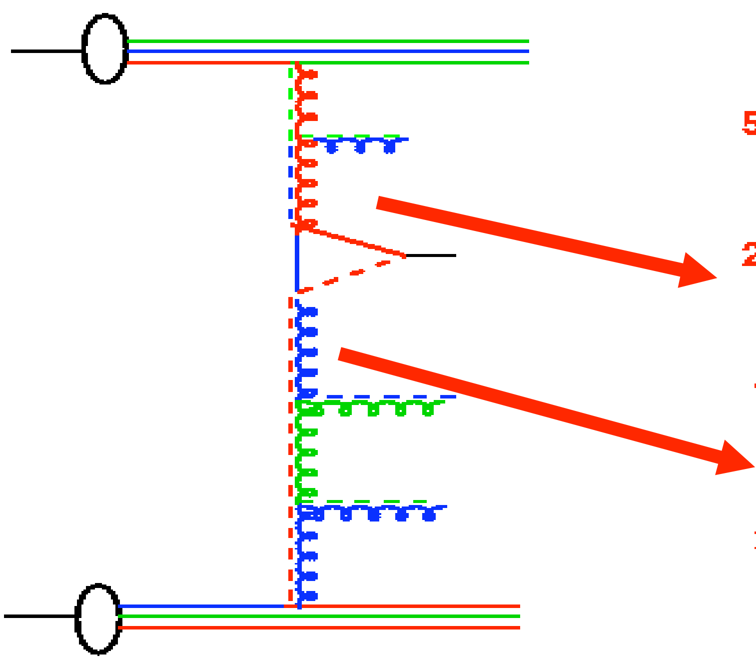
Berge, Nadolsky, Olness, Yuan
hep-ph/0410375

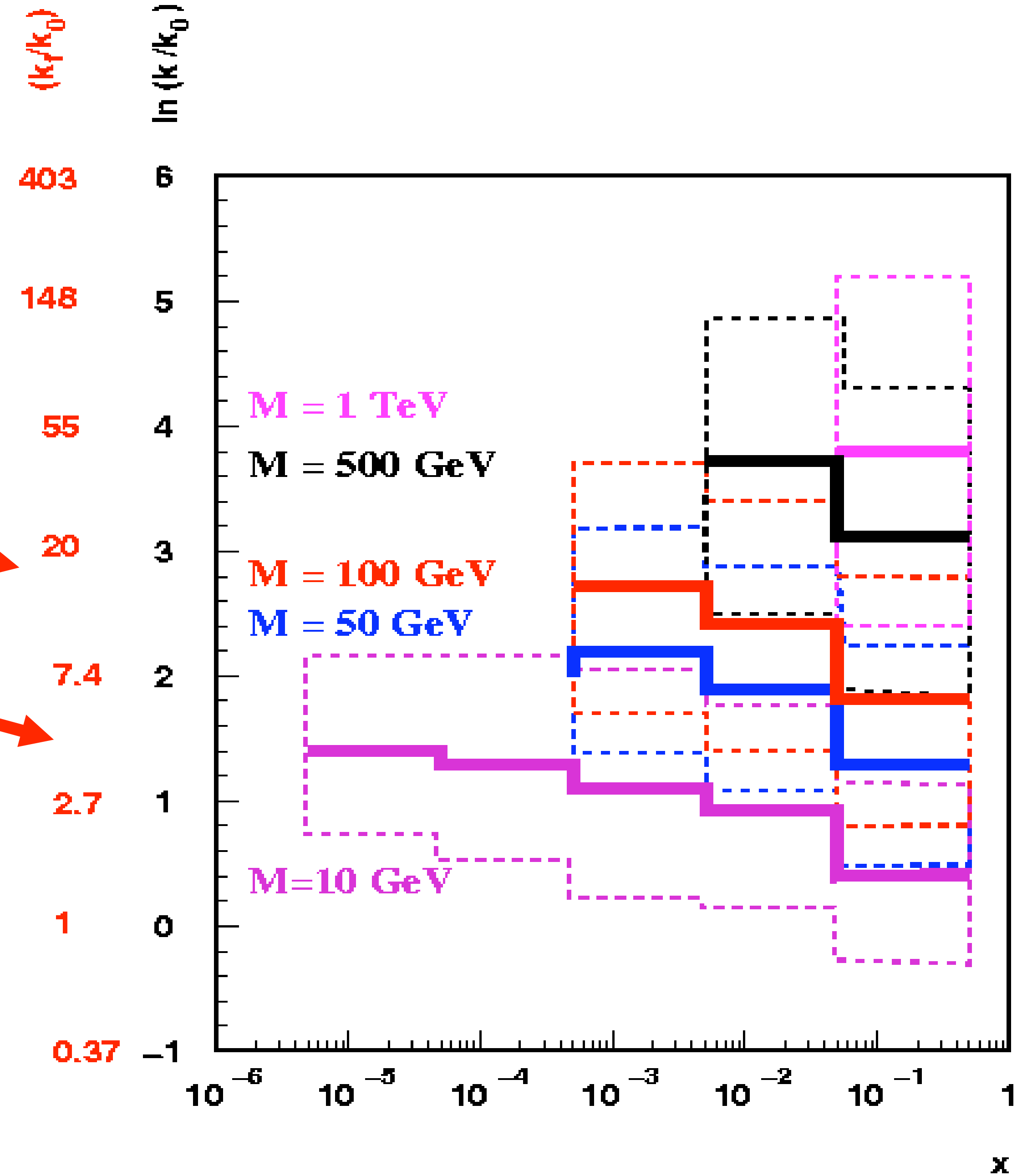


uPDFs calling ...., again ...

- uPDFs (single and double unintegrated)

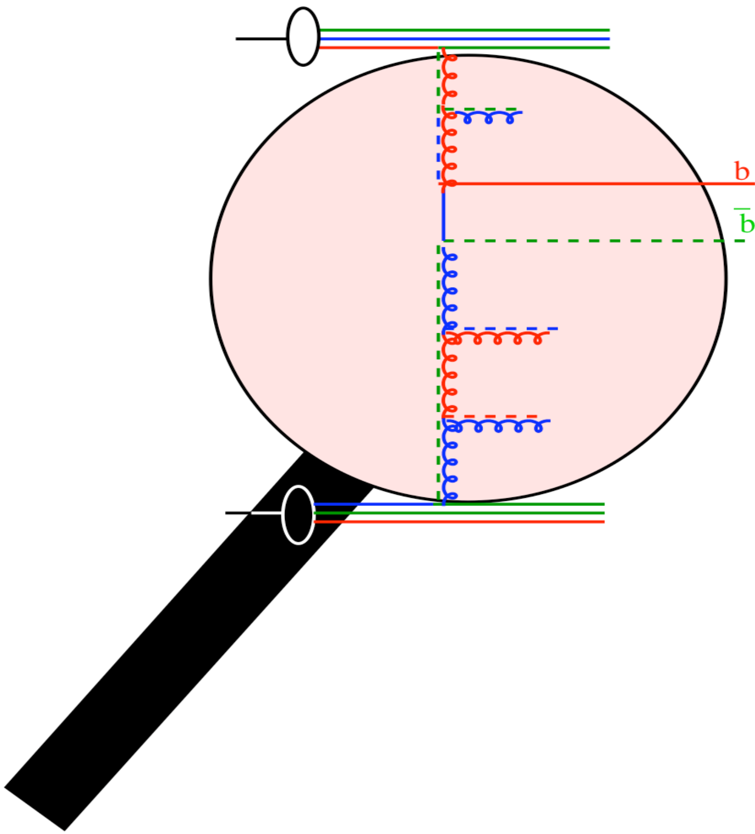
Higgs production et al



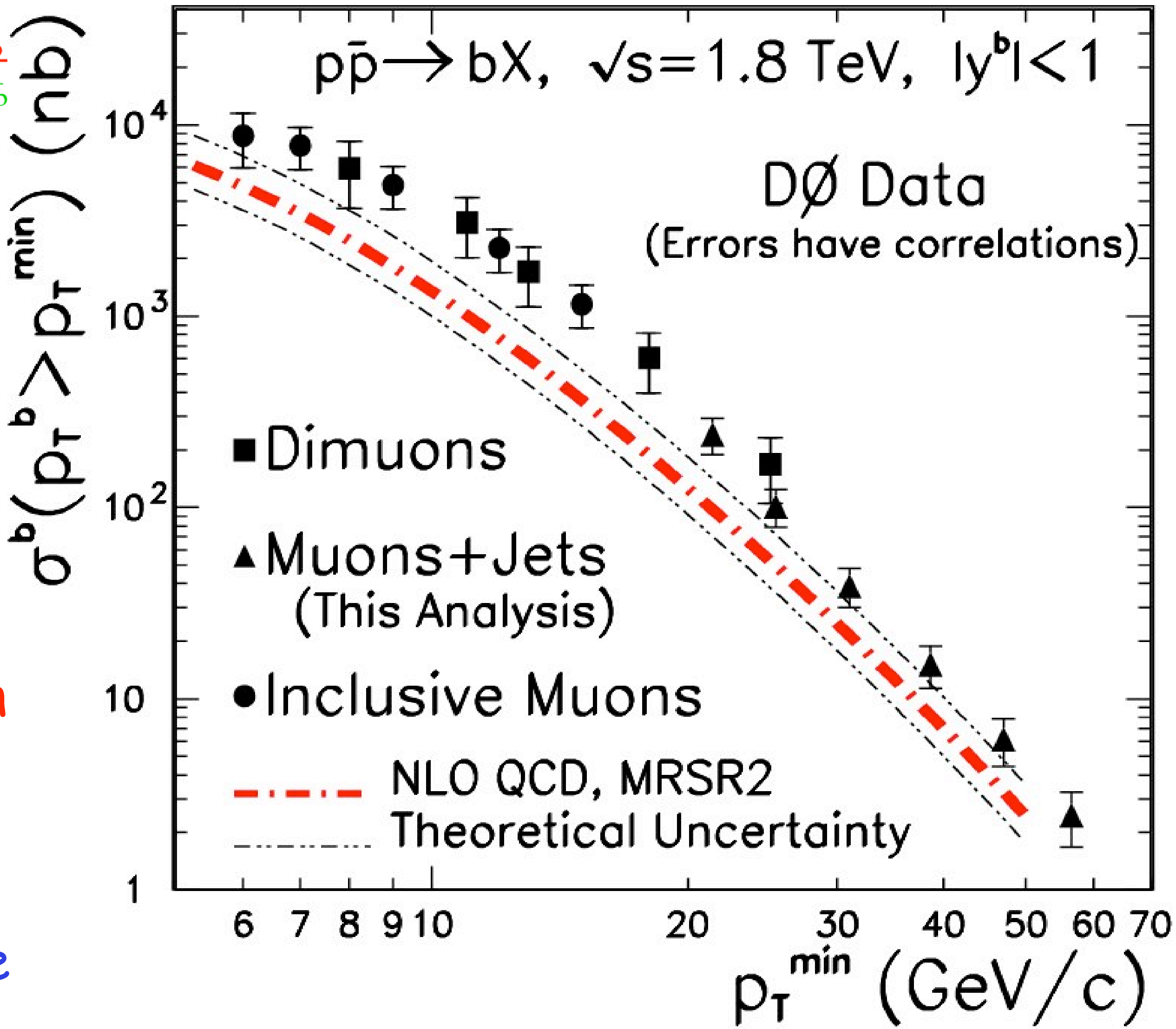


- can have sizable k_t
- respect kinematics .....

The fun with beauty in pp (<2002)



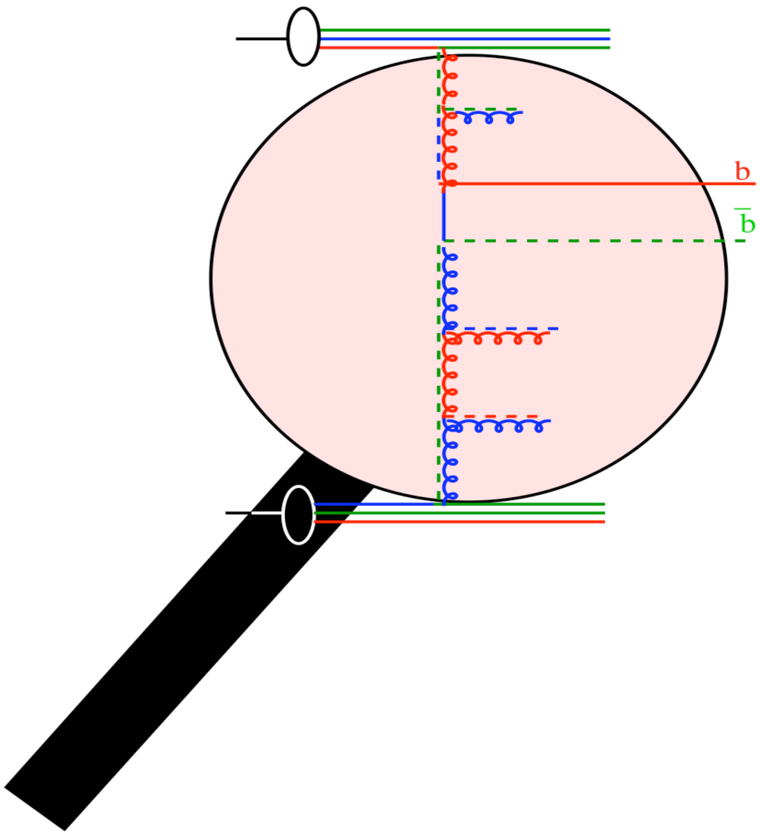
D0 Collaboration; B. Abbott~et al., PRL 84 (2000) 5478.



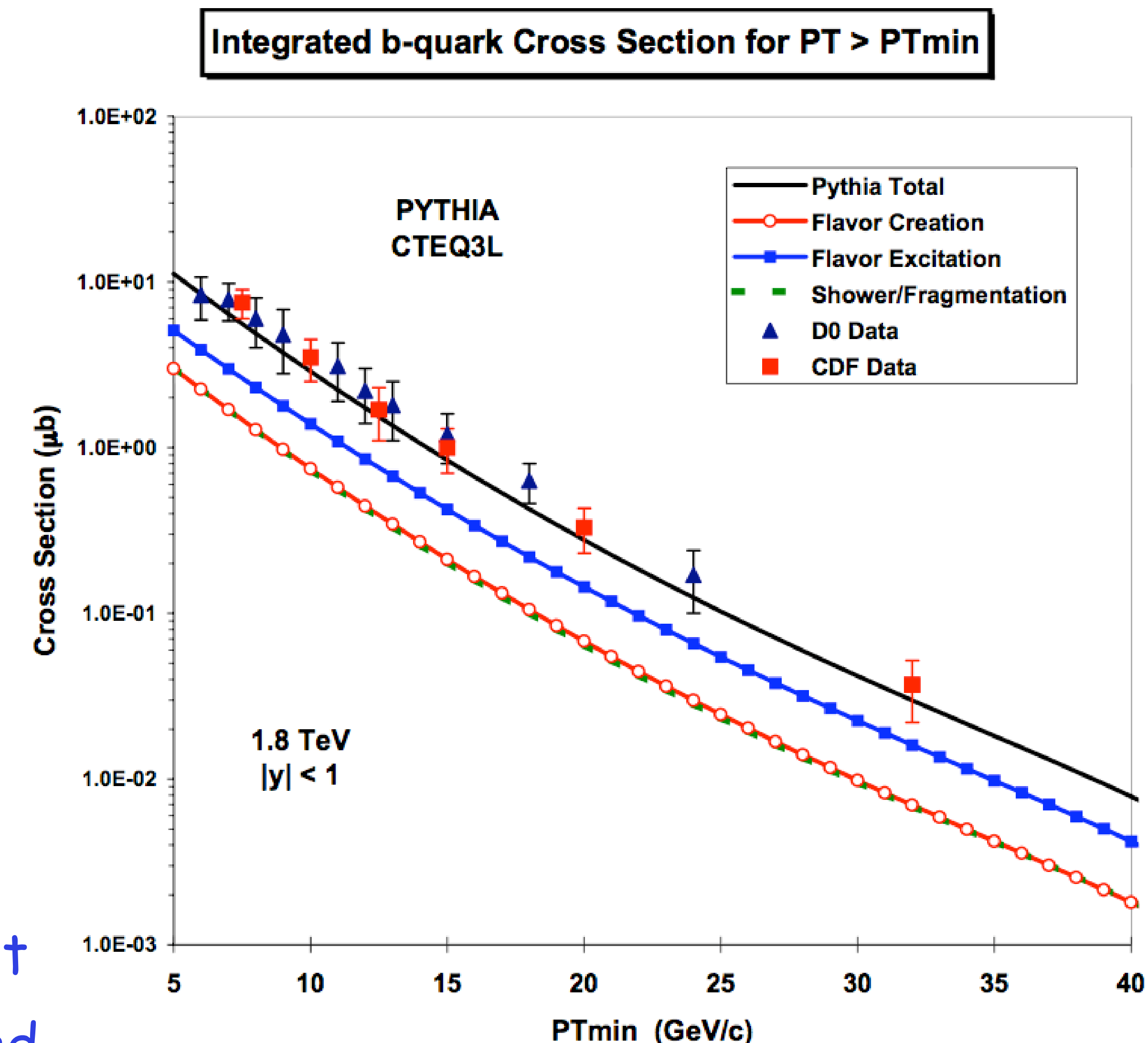
- data are ~ 2 larger than prediction at NLO
- at this time ...

➔ speculations on possible SUSY contributions etc ..

The fun with beauty in pp



Field Phys.Rev.D65:094006,2002.



- b-X-section described by

➔ PYTHIA

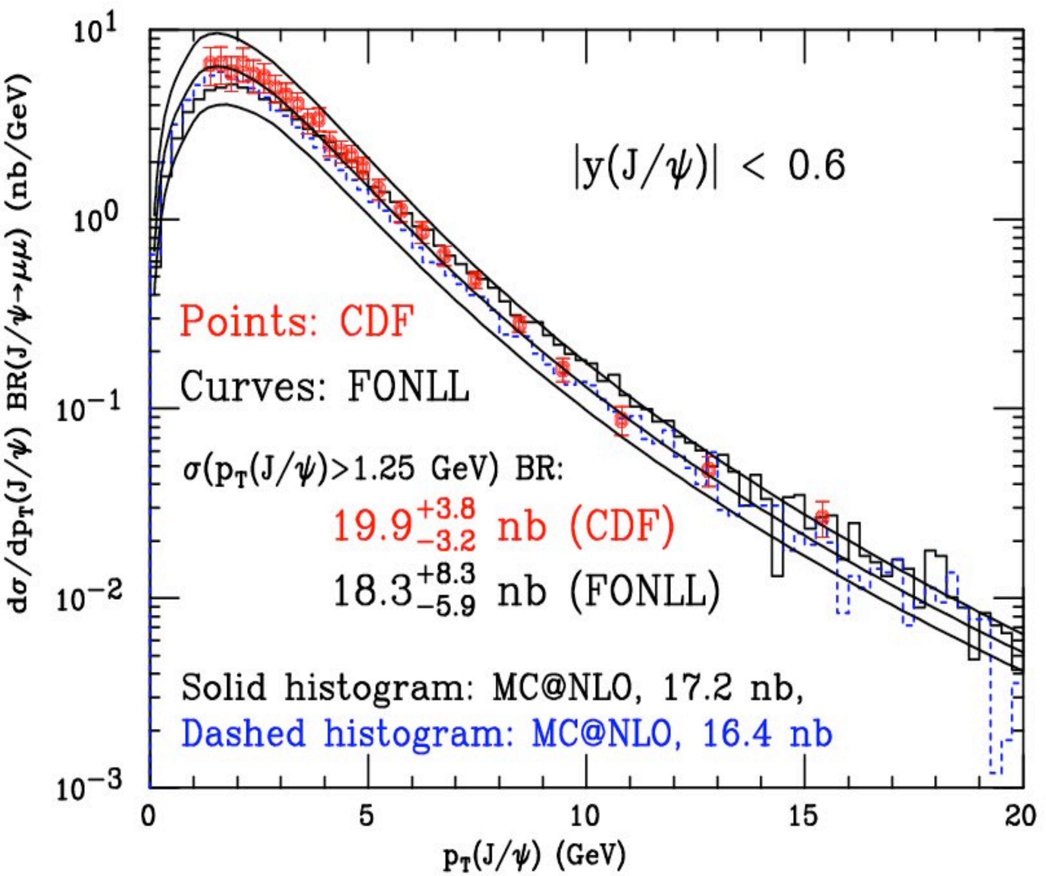
➔ NLO if proper PDF,frag.fct and resummation is included

➔ CASCADE/LDCMC with uPDFs

bbar at TeVatron (NLO catches up)

- Improvements:
  - ➔ consistent treatment and determination of fragmentation function (consistent at NLO...)
  - ➔ improved PDFs (mainly from HERA)
  - ➔ inclusion of resummation effects (either analytically or via parton showers, as in MC@NLO)

M. Cacciari et al
hep-ph/0312132



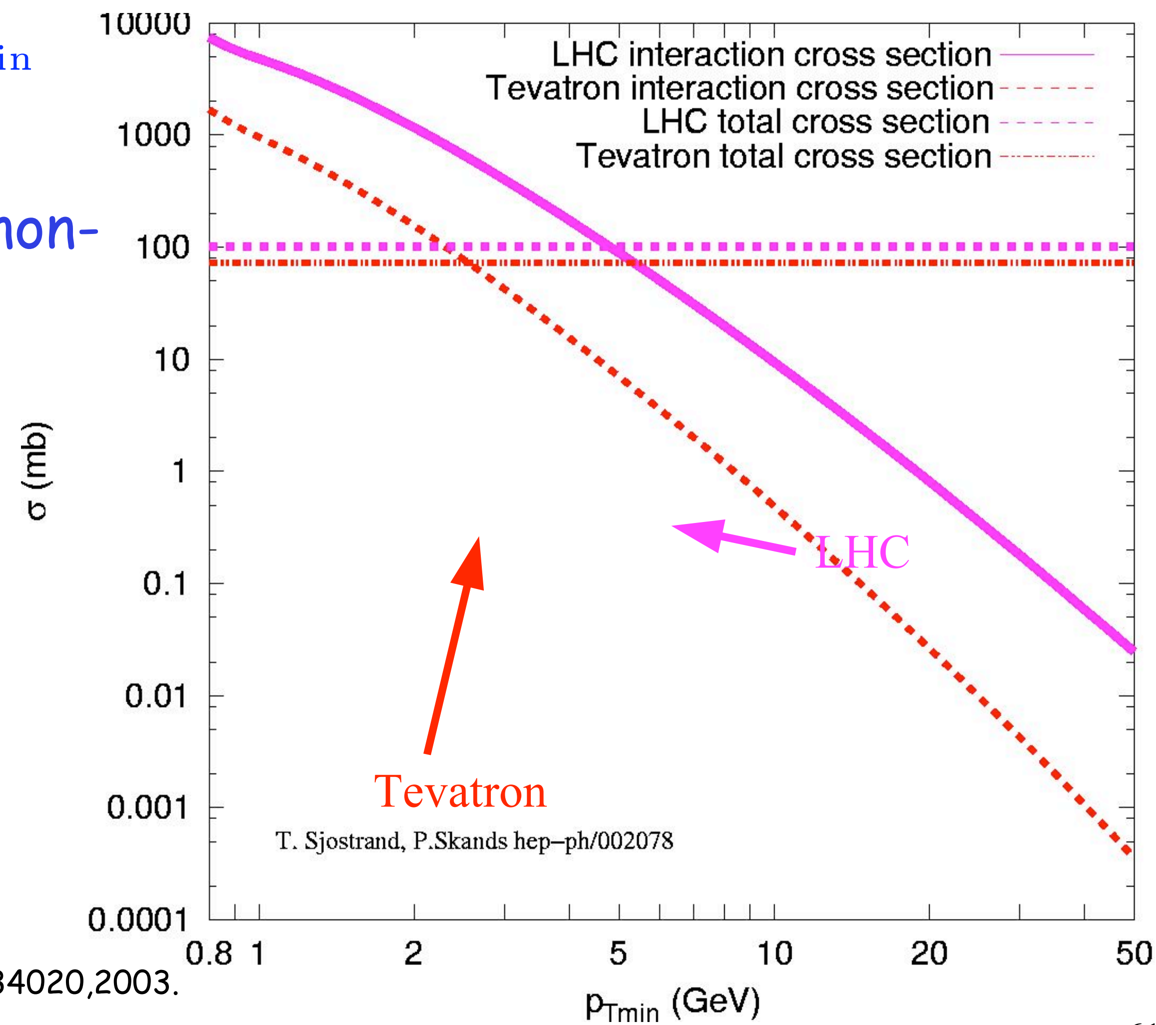
Underlying event – Multiple Interaction

- Basic partonic perturbative cross section

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

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

- Interaction x-section exceeds total x-section
- happens well above λ_{QCD}
- still in perturbative region



New ansaetze:

Small-x dipole evolution beyond the large-N(c) limit.
Avsar,Gustafson,Lonnblad, JHEP 0701:012,2007.
Hadronic collisions in the linked dipole chain model.
Gustafson, Lonnblad, Miu (Lund U.) . Phys.Rev.D67:034020,2003.

Double-Parton Interactions at LHC

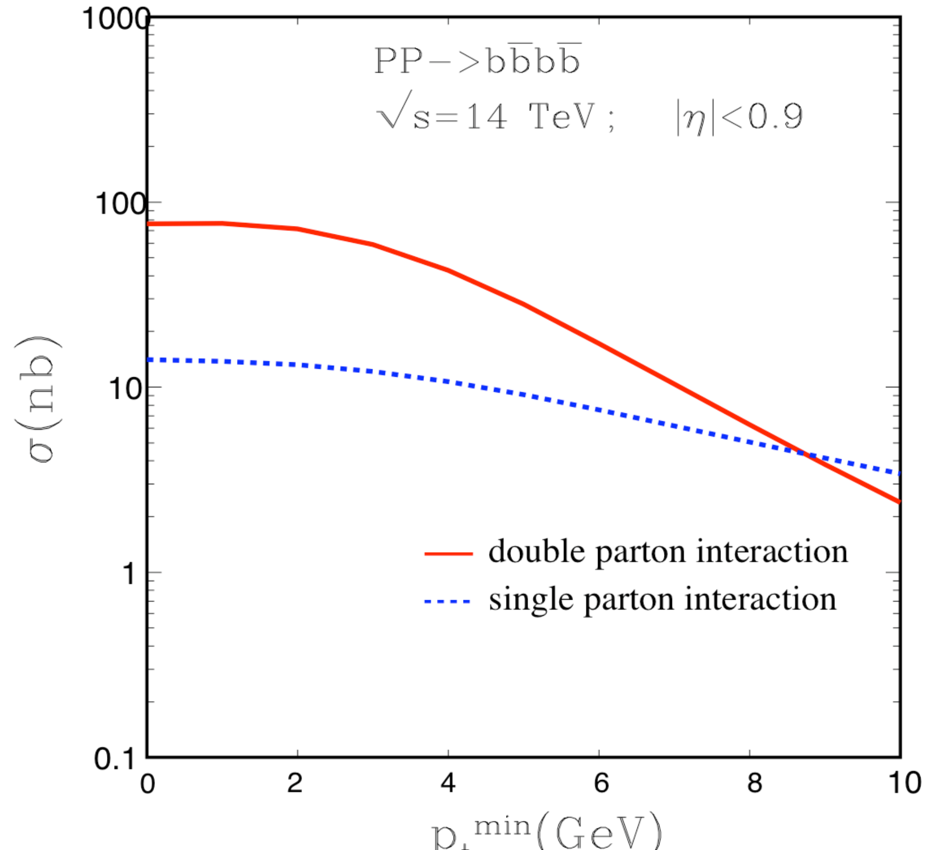
- x-section for $p + p \to b\bar{b}b\bar{b}$

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

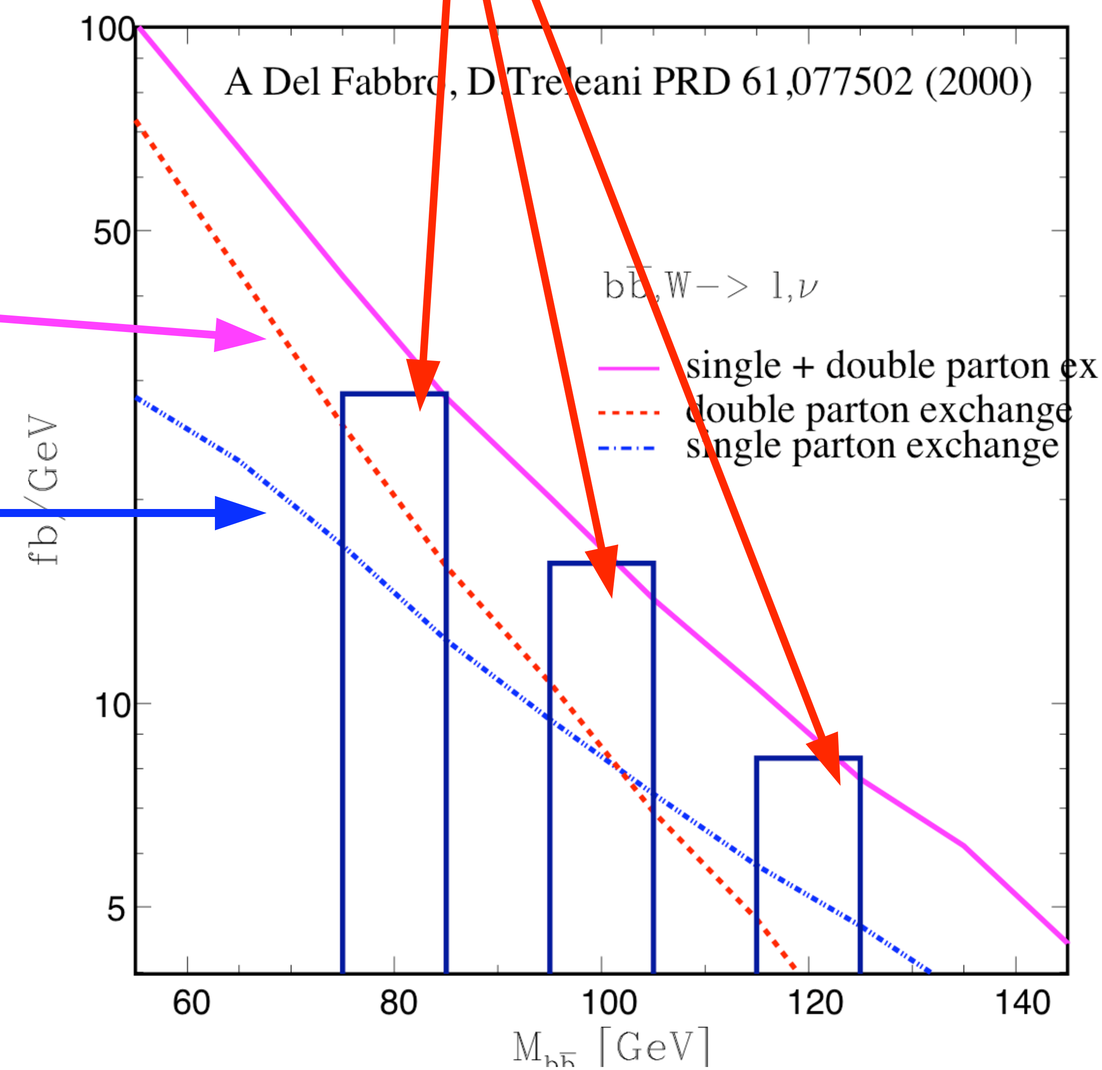
- Double parton scattering:

➔ $p+p \to b\bar{b}X$

$p+p \to W + X$

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

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



what did we learn from pp ?

- soft gluon resummation/parton showering is important ...
  - pt spectrum of W/Z ... but also for heavy quarks ....
    - kt of incoming partons can be large ...
  - important to treat kinematics properly....
    - and include it in PDF fits
    - ➔ calling for uPDFs
- high parton densities
  - ➔ multiparton interactions are significant ..
    - ➔ BUT ...

      collinear factorization is not appropriate for high density systems
    - ➔ calling for better treatment applying small x machinery ....
  - ➔ multiparton interactions can contribute significantly to high pt discovery channels .... like $pp \to W + H + X \to W + b\bar{b} + X$

The strings between experiment and theory

Investigations in QCD call for

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➔ multipurpose physics and physicists

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➔ physicists in-between the chairs ...

The strings between experiment and theory

Investigations in QCD call for

- ➔ multipurpose physics and physicists
- ➔ physicists in-between the chairs ...
- ➔ or just for people like you

  here in Lund

  and in the MCnet
- ➔ people having knowledge of both experiment and theory

and now ?

Detailed understanding of QCD
is still challenging,
but there is a bright future
at the next QCD colliders,
and never forget ...

Dipoles are forever,
They are all I need to please me,
They can stimulate and tease me, ...