Hard Probes 2008

Illa de A Toxa, Spain, June 8-14, 2008

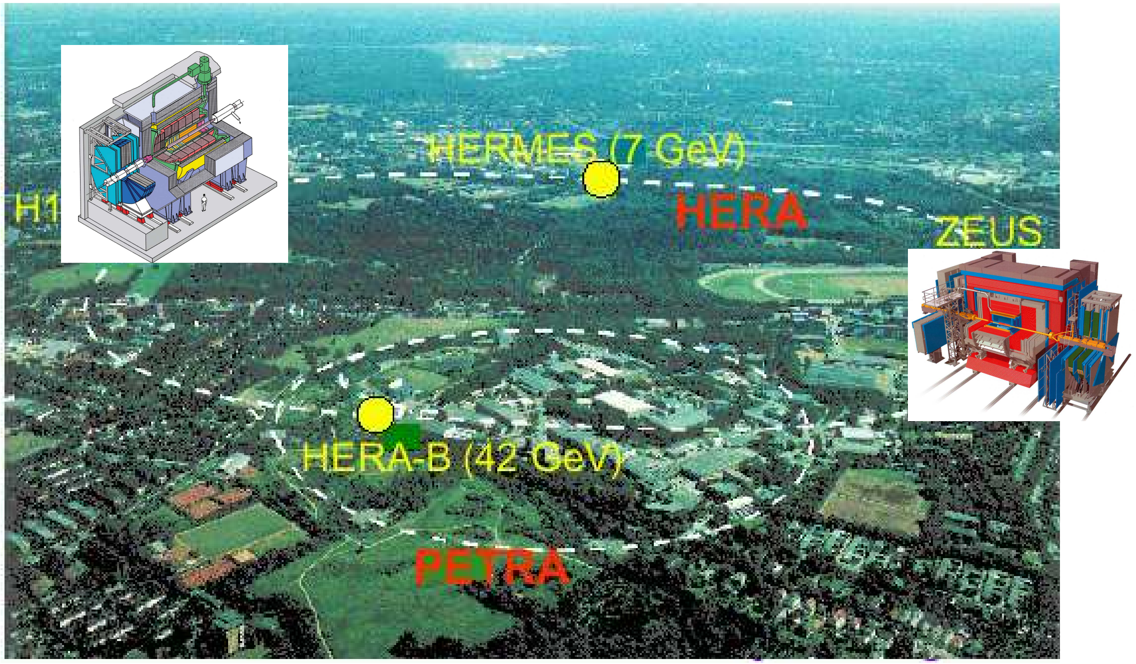
Jet production at low Bjorken-x from HERA

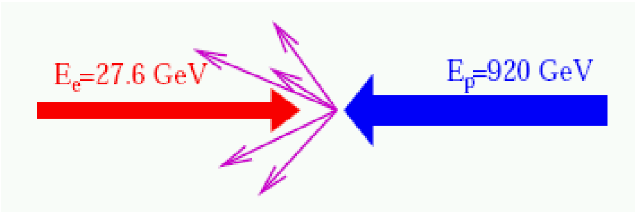
S. Levonian

- HERA and low x physics
- Inclusive Forward jets
- Forward jets in multijet configurations
- Azimuthal correlations in dijet system

Low $x \leq 5 \cdot 10^{-3}$

The HERA Collider

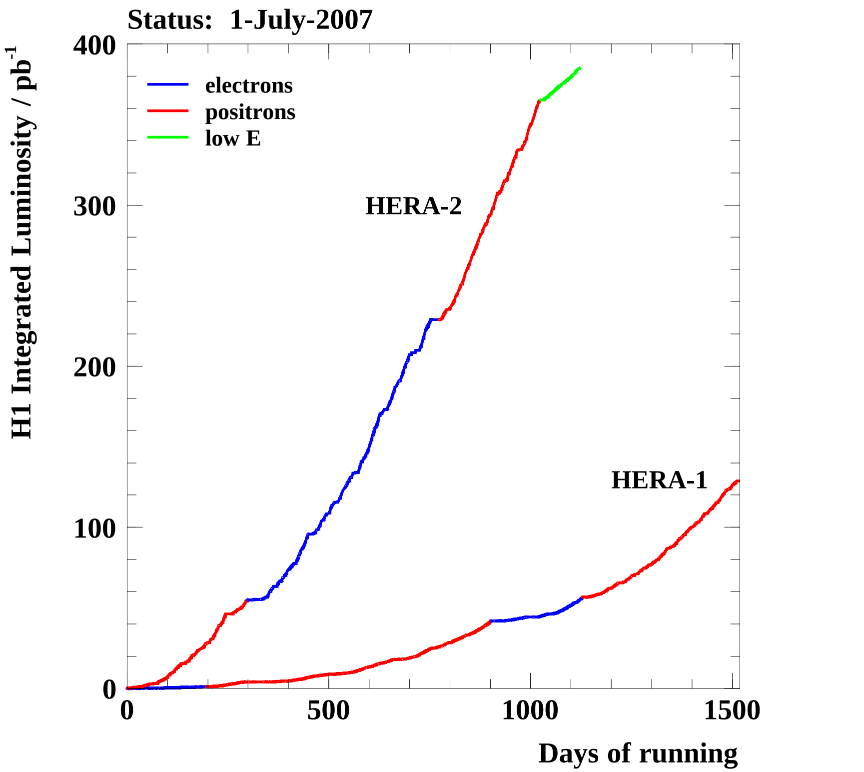




HERA-1 (1993-2000) $\simeq 120$ pb^{-1}

HERA-2 (2003-2007) $\simeq 380$ pb^{-1}

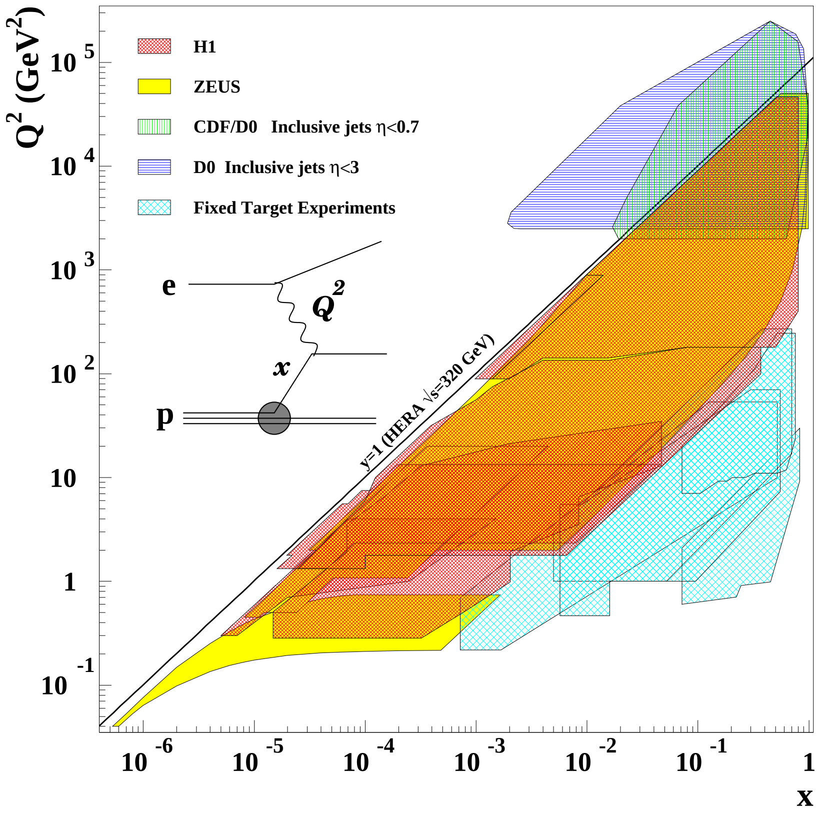
last 3 months - low E_p run to measure F_L^p
($E_p = 460;\ 575$ GeV, $\mathcal{L} = 20 pb^{-1}$)



- HERA upgrade: $\mathcal{L} \times 3$, Polarised e^+/e^-
  (Exp. improvements: silicon trackers, triggering, ...)

- Final Data samples H1+ZEUS: 2×0.5 fb^{-1}

Small x domain of HERA



- ep DIS: clean QCD laboratory with high resolving power $Q^2 \Rightarrow 0.001$fm
- Low $x \leq 10^{-3}$: new kinematic domain at HERA
  $\Rightarrow$ any sign of novel parton dynamics?

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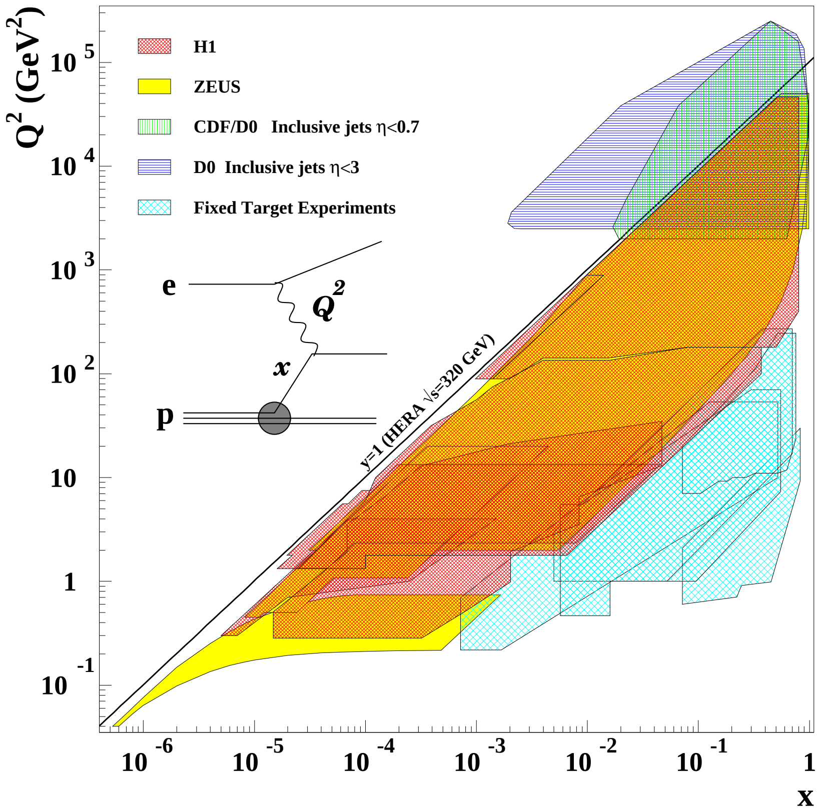

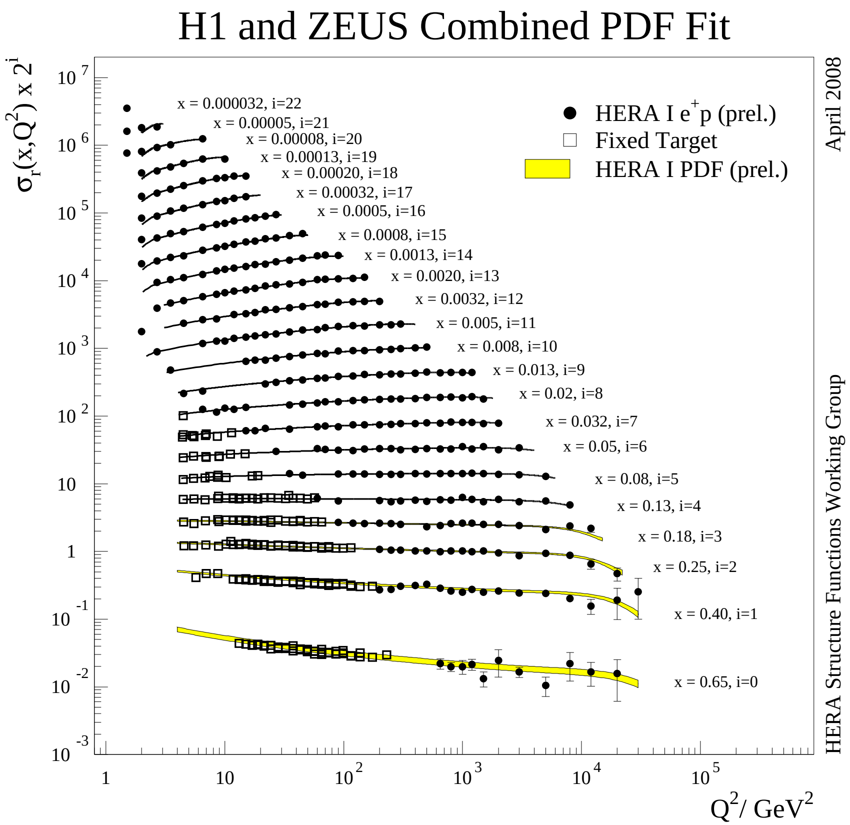

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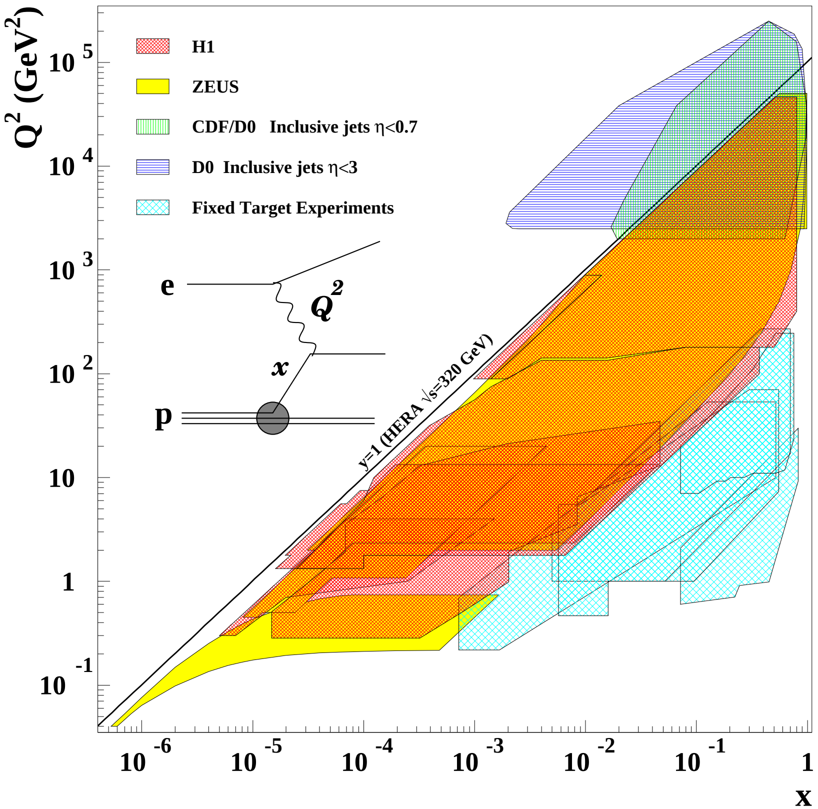

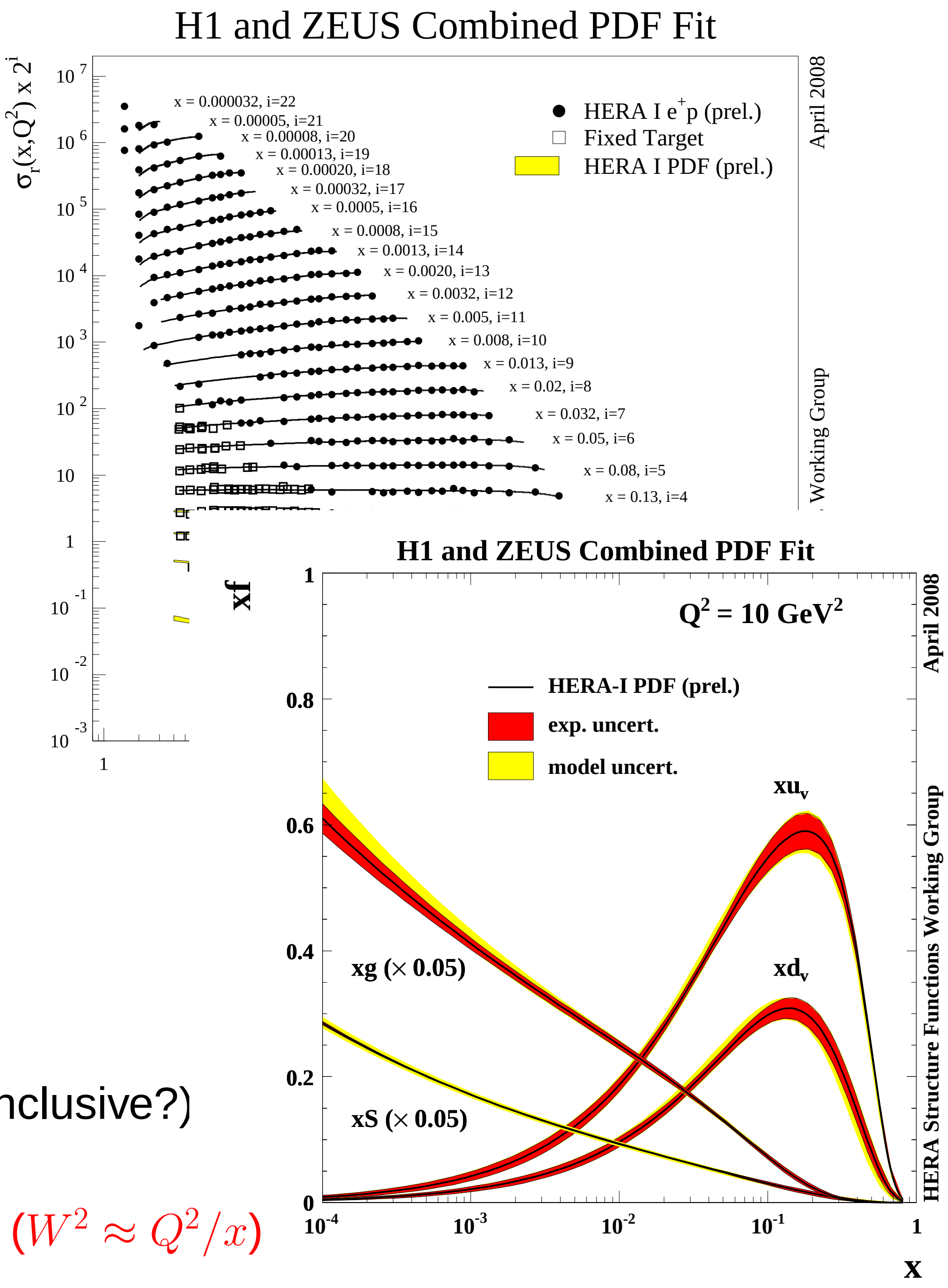

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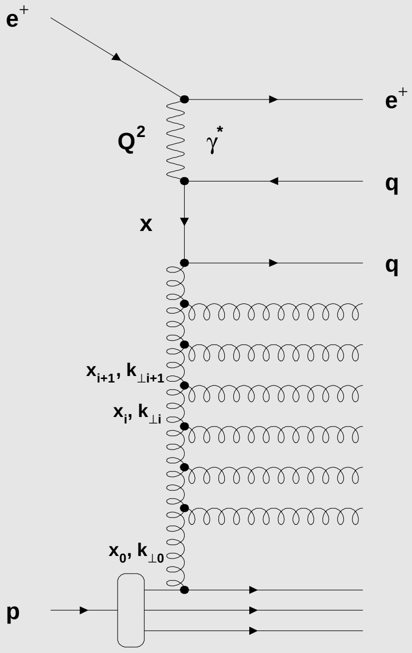
- NLO DGLAP is still perfectly OK for F_2^p (too inclusive?)
- There is a lot of glue in proton at low x!
  $\Rightarrow$ gluodynamics in high energy limit of QCD ($W^2 \approx Q^2/x$)

QCD at low x

Lots of glue in the proton $\Rightarrow$ long gluon cascade at low x. Perturbative expansion of evolution equations $\sim \sum_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$ hard to calculate explicitely

$\Rightarrow$ approximations needed



DGLAP: resums $\ln(Q^2)^n$ terms, neglecting $\ln(1/x)^n$ terms
strong k_T ordering in partonic cascade

BFKL: resums $\ln(1/x)^n$ terms
no k_T ordering in partonic cascade $\Rightarrow$ more hard gluons are radiated far from the hard interaction vertex

CCFM: angular ordered parton emission $\Rightarrow$
reproduces DGLAP at large x and BFKL at $x \rightarrow 0$

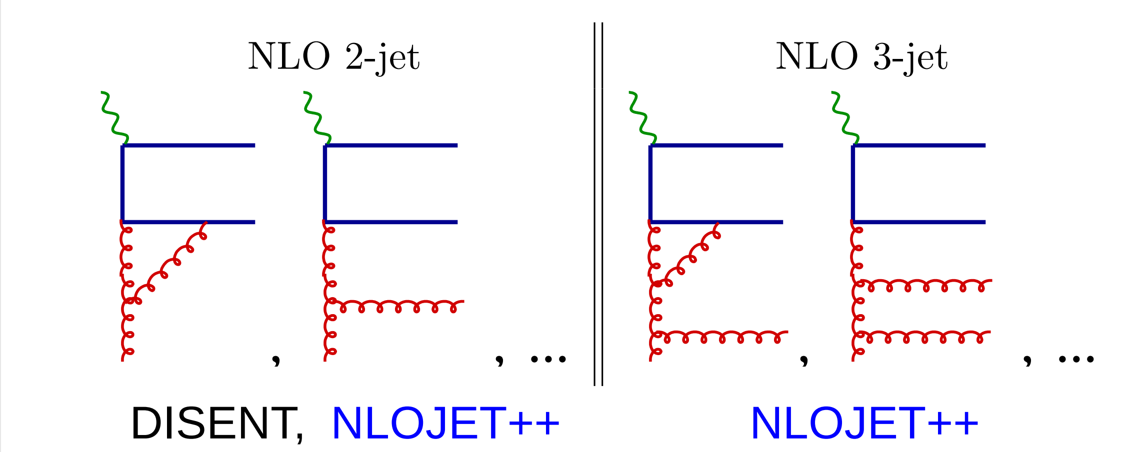
- How long is partonic cascade at HERA, at small x?
- Do the $\ln(1/x)^n$ terms play a major role in parton dynamics as suggested by BFKL?

$\Rightarrow$ Look at (multi)jet final states at low x in different configurations

Low x phenomenology

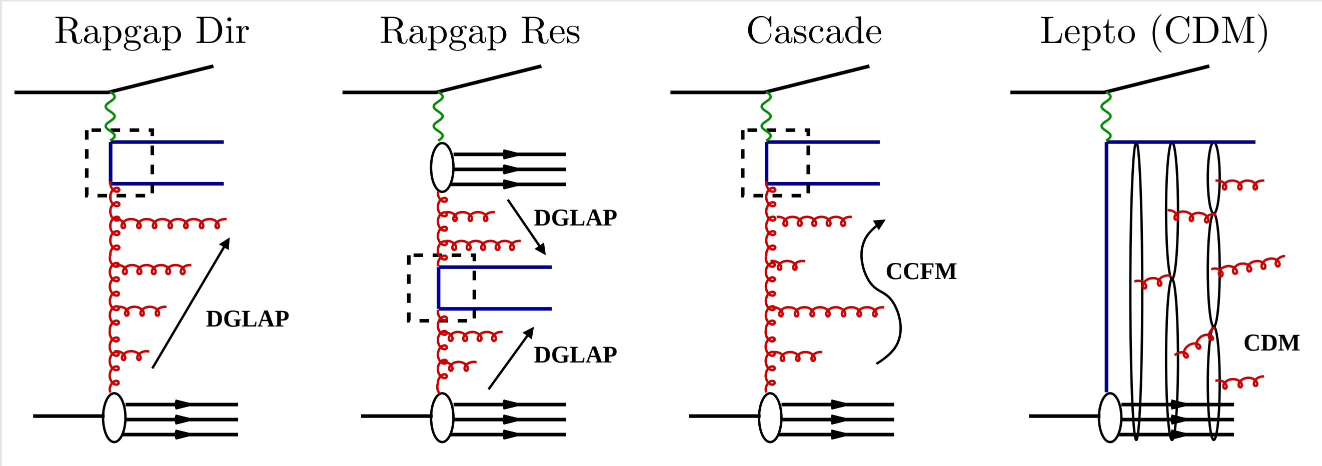
Fixed order

QCD calculations



LO ME + PS

MC models

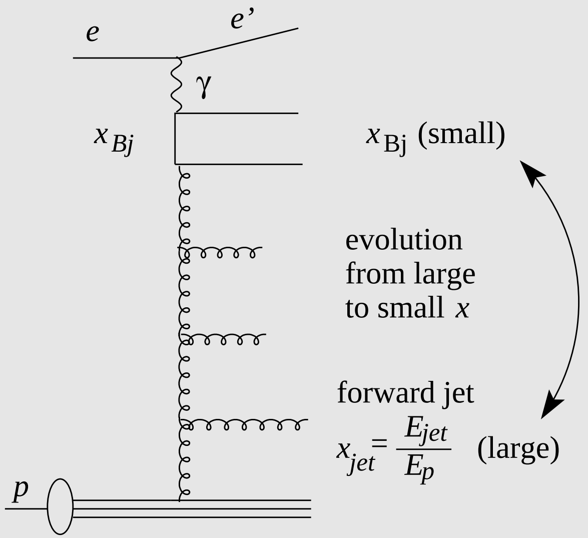


k_t-ordered gluon radiation (DGLAP)

angular ordering (DGLAP $\Longleftrightarrow$ BFKL)

random walk in k_t (BFKL like)

Forward jets



Strategy

$(E_t^{jet})^2 \approx Q^2 \Rightarrow$ suppress phase space for DGLAP evolution

large $x_{jet} >> x_{Bj} \Rightarrow$ enhance BFKL evolution

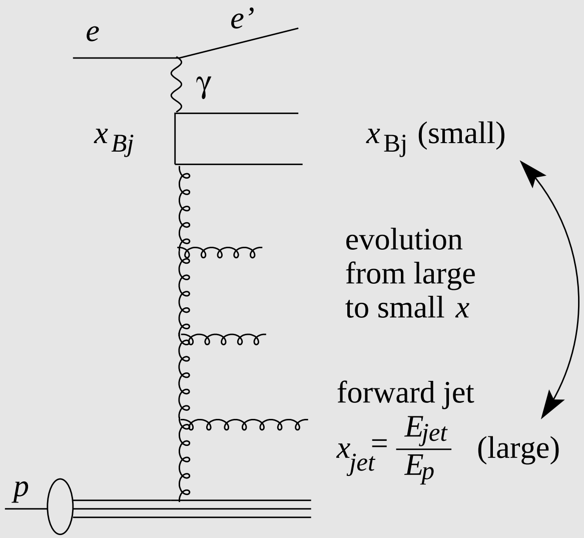
Event selection

$10^{-4} < x < 4 \cdot 10^{-3}$ $\quad 5 < Q^2 < 85\text{GeV}^2$

$E_t^{jet} > 3.5\text{GeV}$ $\quad 7^o < \theta_{jet} < 20^o$

$x_{jet} > 0.035$ $\quad 0.5 < (E_t^{jet})^2/Q^2 < 2$

Forward jets



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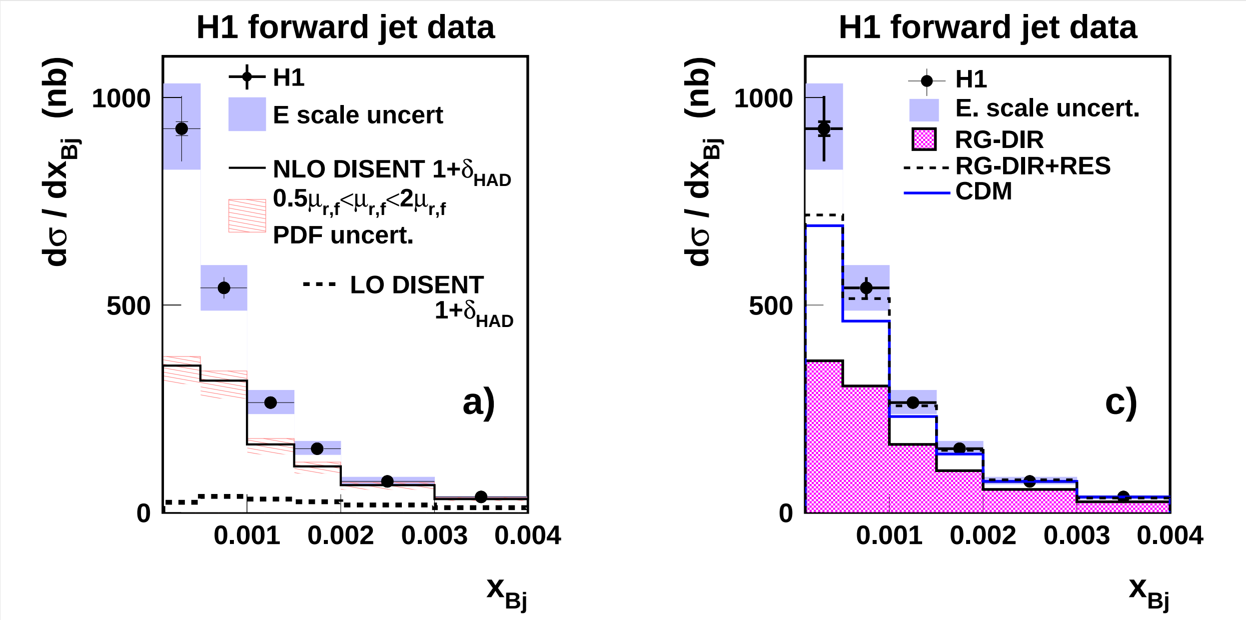
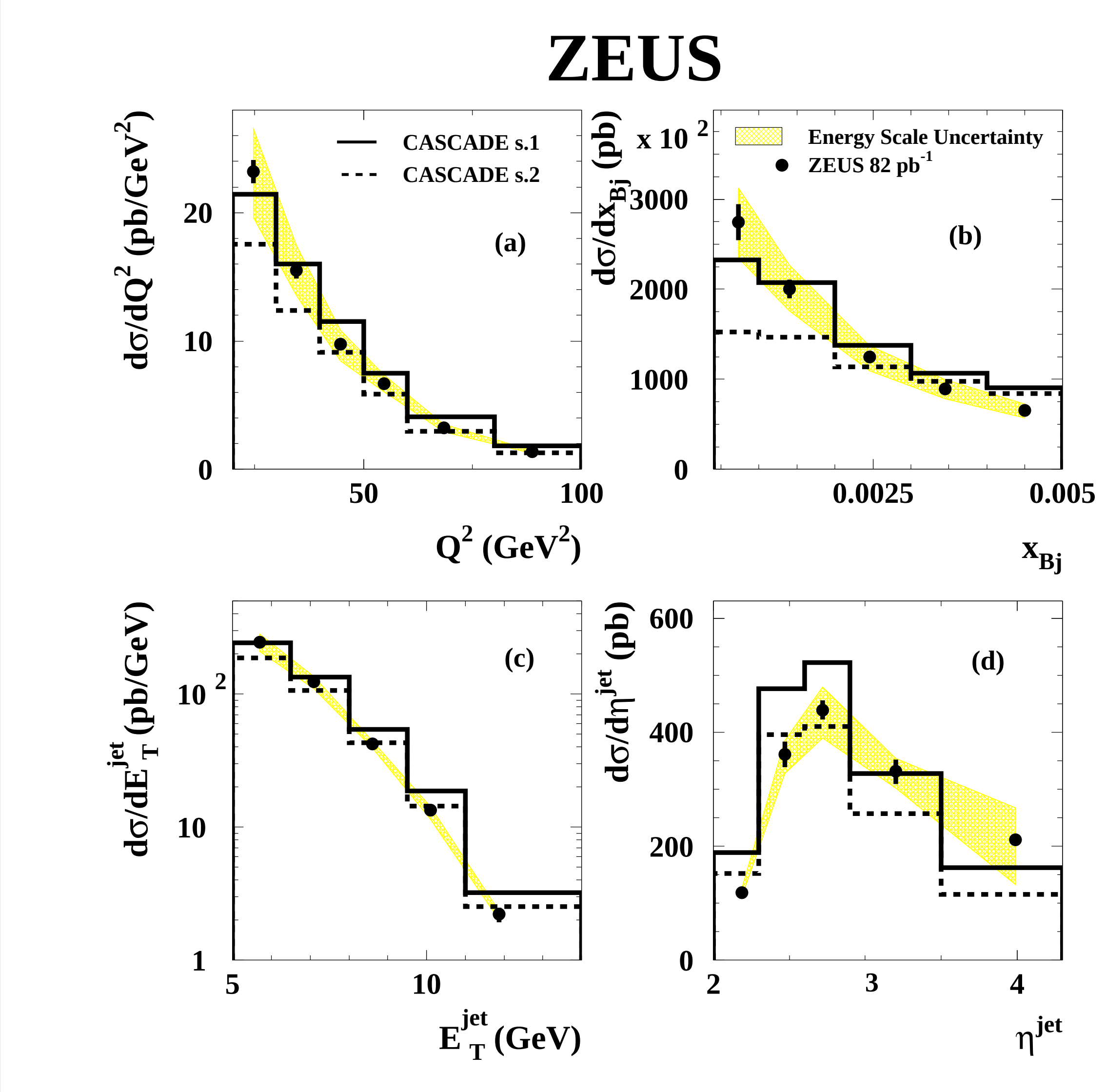


- Huge improvement from LO to NLO, but still insufficient at low x
- Resolved γ component in DGLAP MC helps ("breaks" k_t ordering)
- CDM and RG(d+r) provide similar description $\Rightarrow$ inconclusive

Forward jets against CCFM Monte Carlo



- extended forward range
  $2 < \eta^{jet} < 4.3$
  $E_t^{jet} > 5\text{GeV}, x_{jet} > 0.036$

- Jet rate is OK, but shapes of the distributions are not described

- Clear sensitivity to uPDF

Jet multiplicity

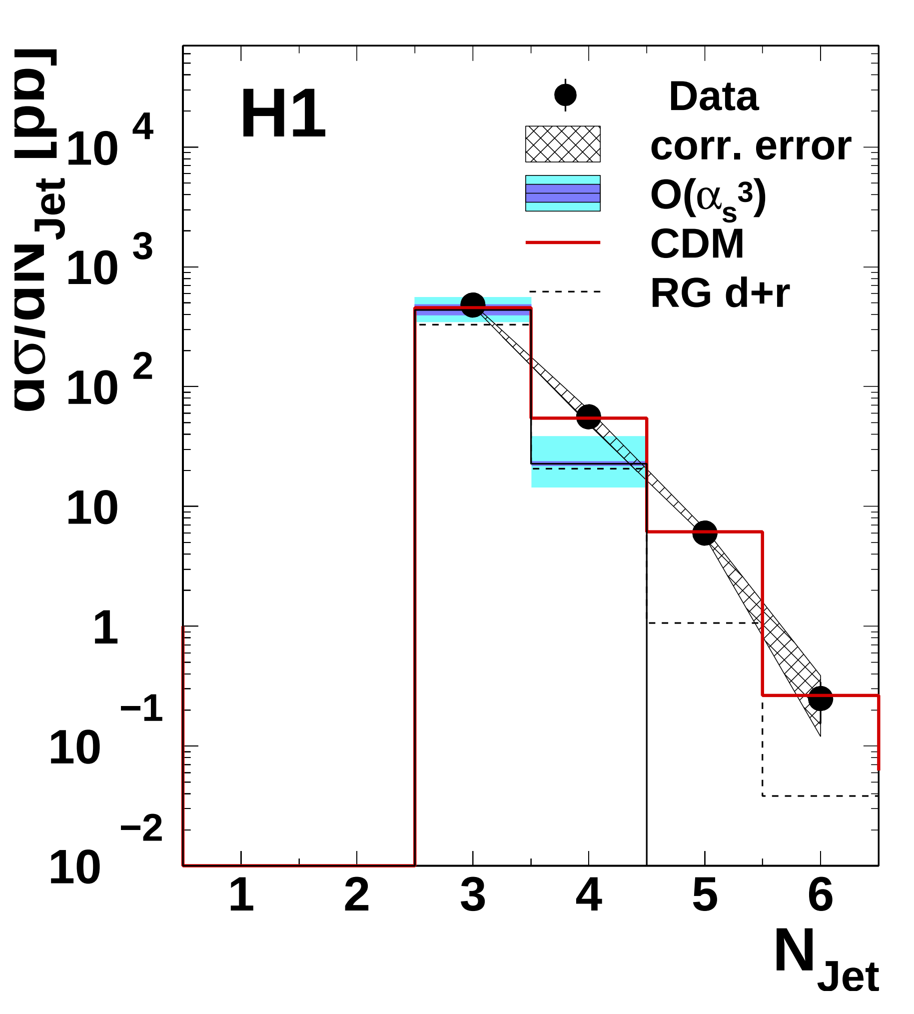
$5 < Q^2 < 80\ \mathrm{GeV}^2$

$10^{-4} < x < 10^{-2}$

Jets: $E^*_{t,jet} > 4$ GeV

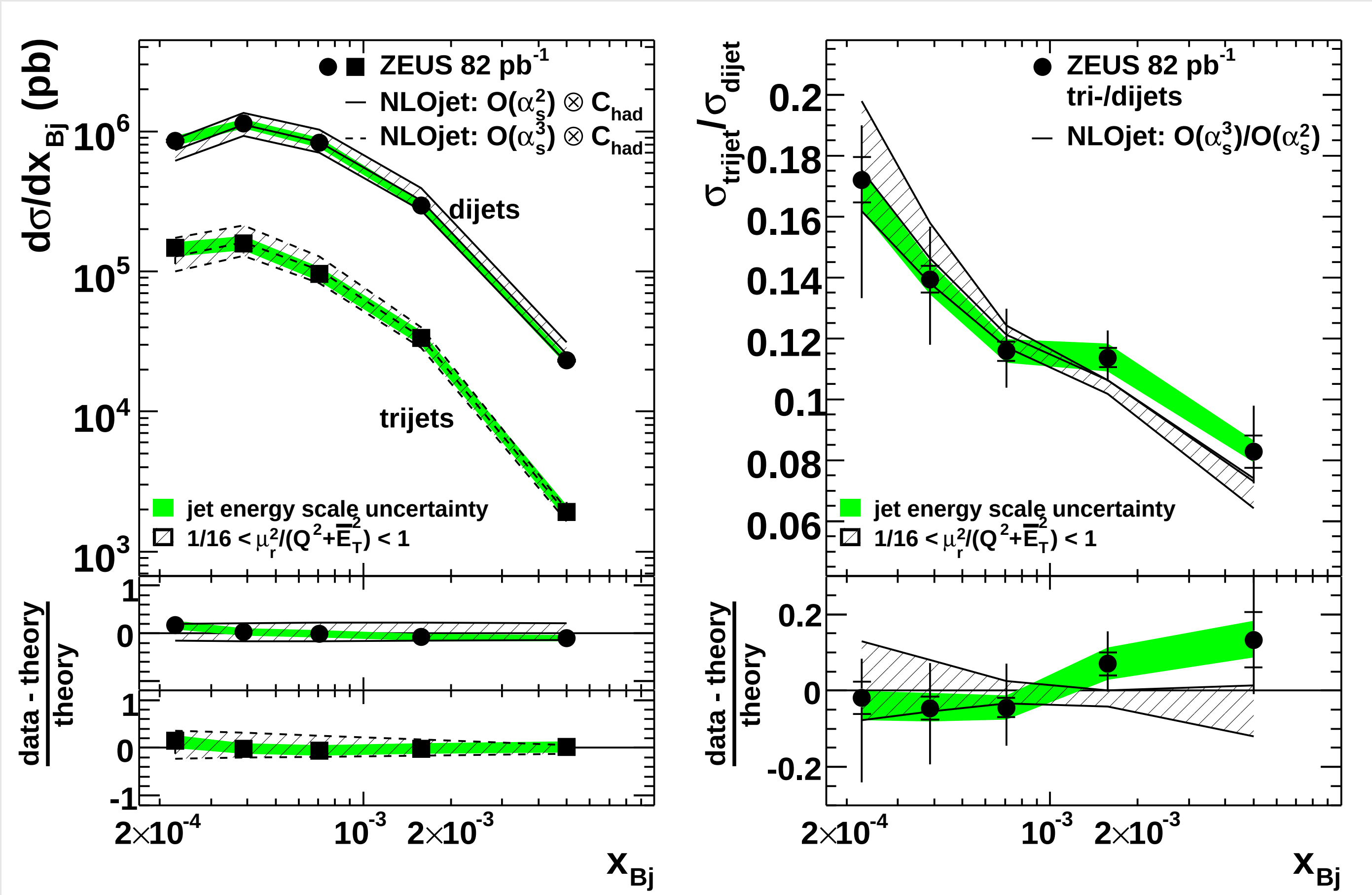
$-1 < \eta < 2.5$

$N_{jet} \geq 3$



- Gluon radiation is frequent at low x
- $\mathcal{O}(\alpha_s^3)$ QCD can only predict up to 4 jets
- RG d+r (DGLAP type of MC) underestimates high jet multiplicities
- CDM (BFKL like MC) is just perfect!

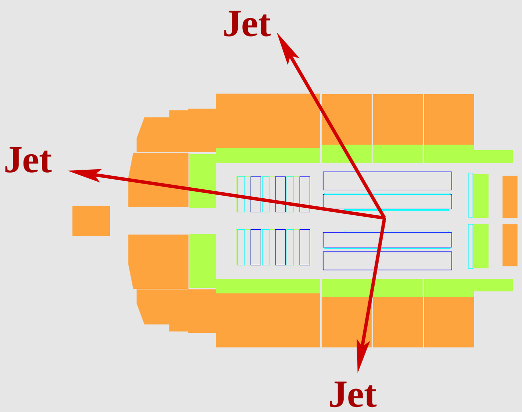
Two and Three Jet production vs NLO QCD



- NLO QCD is OK in this domain ($x > 2\cdot10^{-4},\ E_t^{j1} > 7\mathrm{GeV},\ E_t^{j2(3)} > 5\mathrm{GeV}$)

  $\Rightarrow$ Try even higher jet multiplicities and look for specific jet topologies

3-jet samples with different topologies



Central jets:

$-1 < \eta_{jet} < 1$

Forward jets:

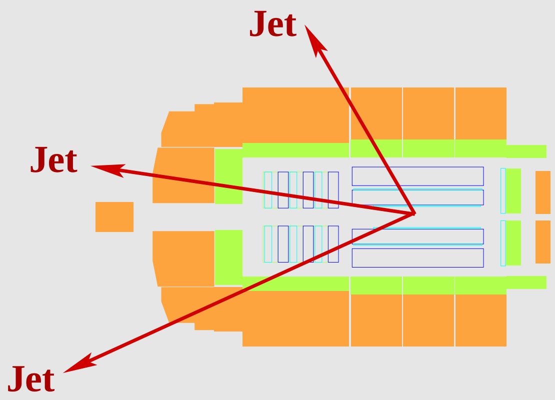
$\eta_{fj1} > 1.73$

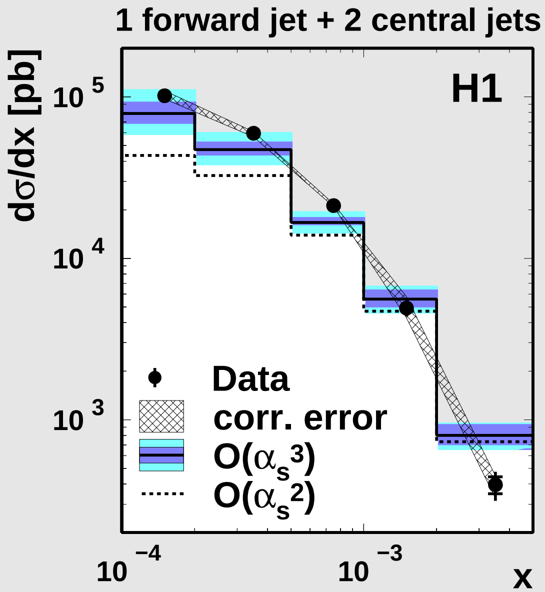
$x_{fj1} > 0.035$

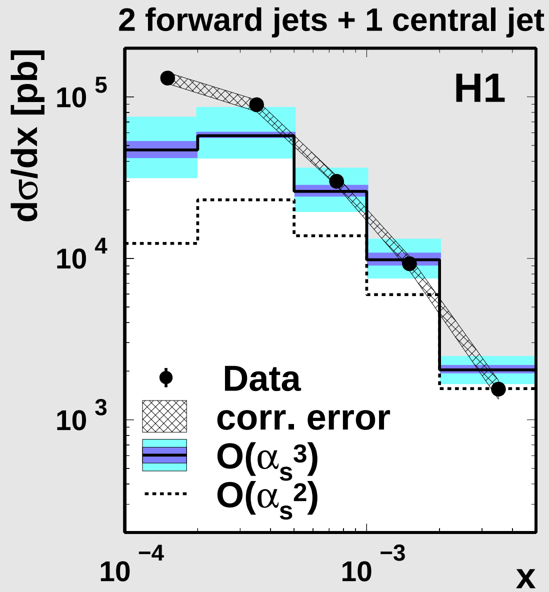
$\eta_{fj2} > 1$

All jets:

$E^{*}_{t,jet} > 4$ GeV





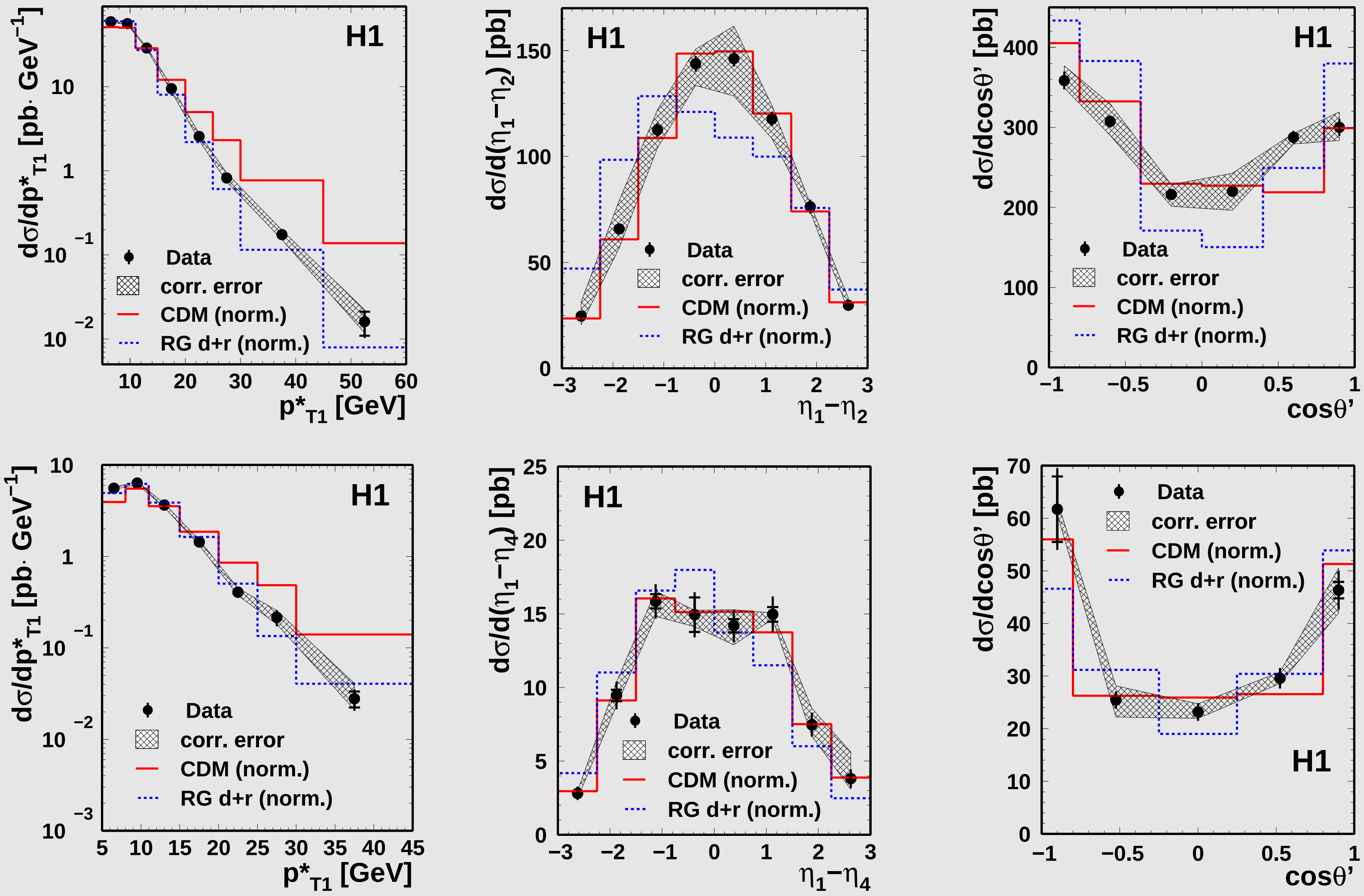


- **Large deficit at small x for 2-forward jet topology! There $\mathcal{O}(\alpha_s^3)$ calculation is insufficient**

3- and 4-jet distributions vs LO+PS Monte Carlo

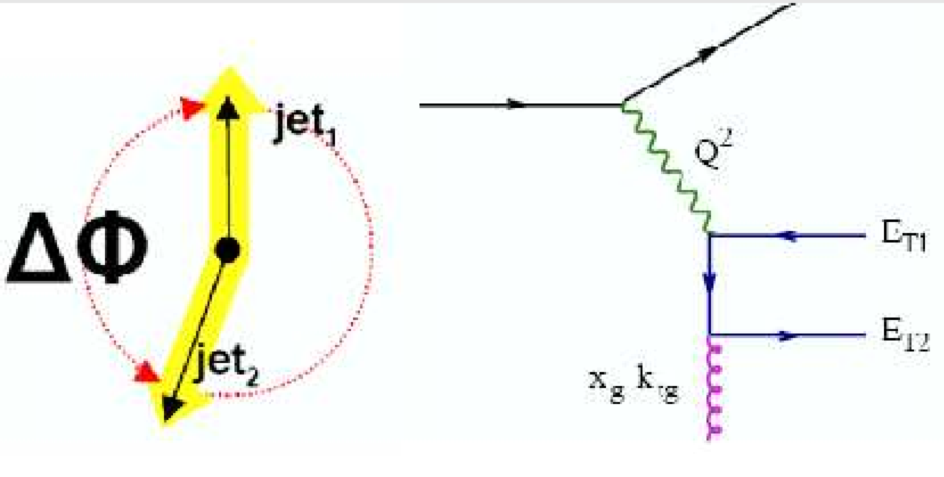
3-jet

4-jet



- CDM describes well all distributions except high p_T tail where it is too hard
- DGLAP MC (RG dir+res) fails both in shapes and normalization (3j$\times 1.55$, 4j$\times 2.9$)

Azimuthal correlations in di-jet system



Collinear factorisation scheme:

jets are back-to-back at LO, hence

$\Delta\Phi^* < 180^o$ are only possible at higher orders

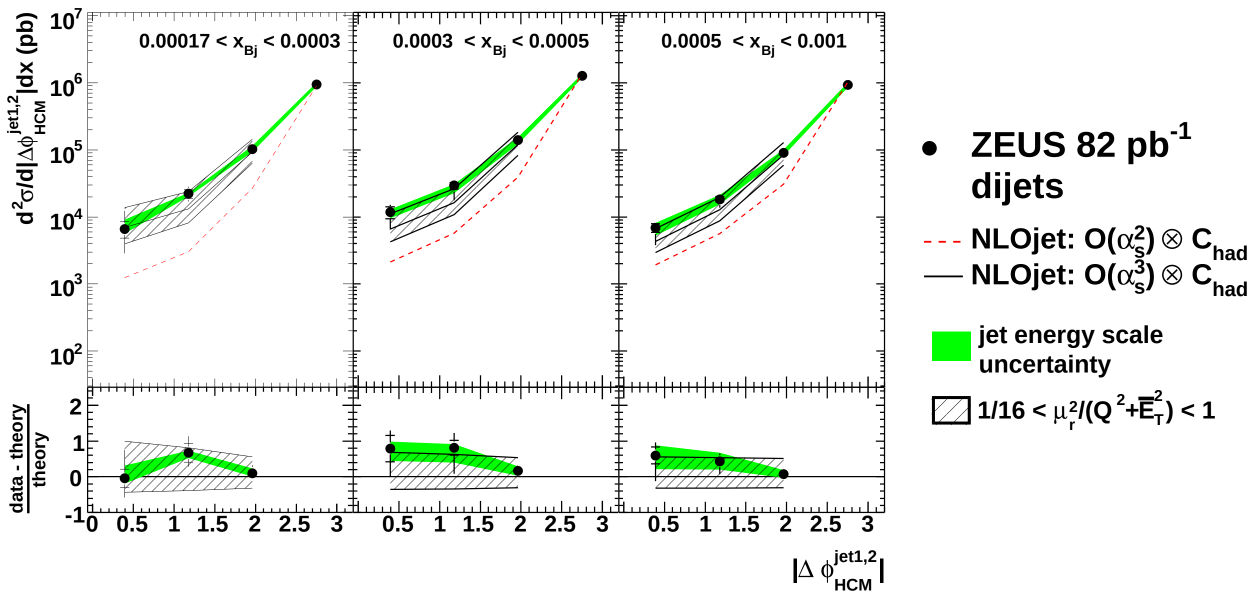
k_t factorisation scheme:

$\Delta\Phi^* < 180^o$ already at LO

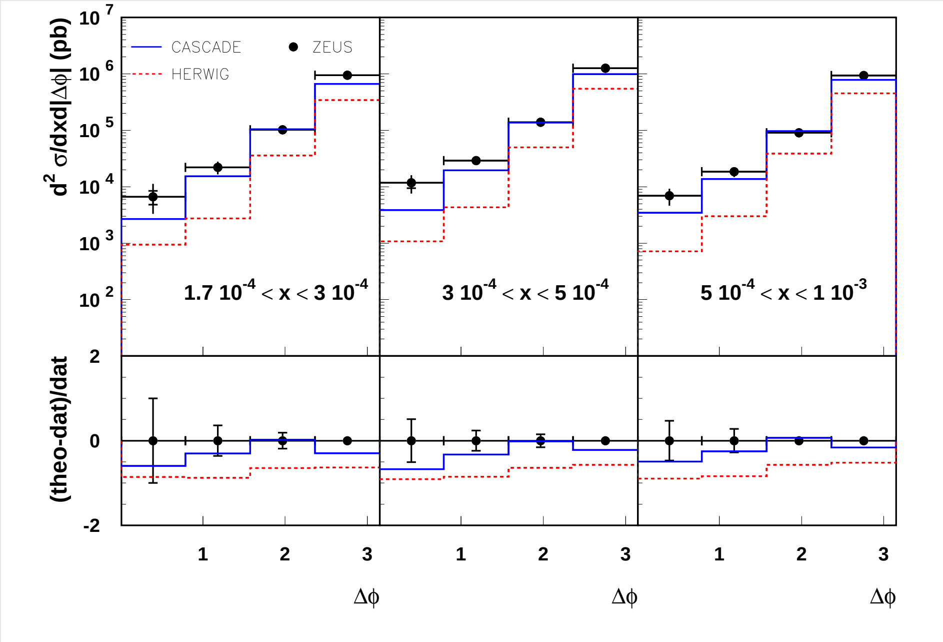
Sensitive to details of parton dynamics

ZEUS vs NLO DGLAP

$\mathcal{O}(\alpha_s^3)$ calculations describes the data reasonably well (although with still large scale uncertainty)



Azimuthal correlations vs CCFM

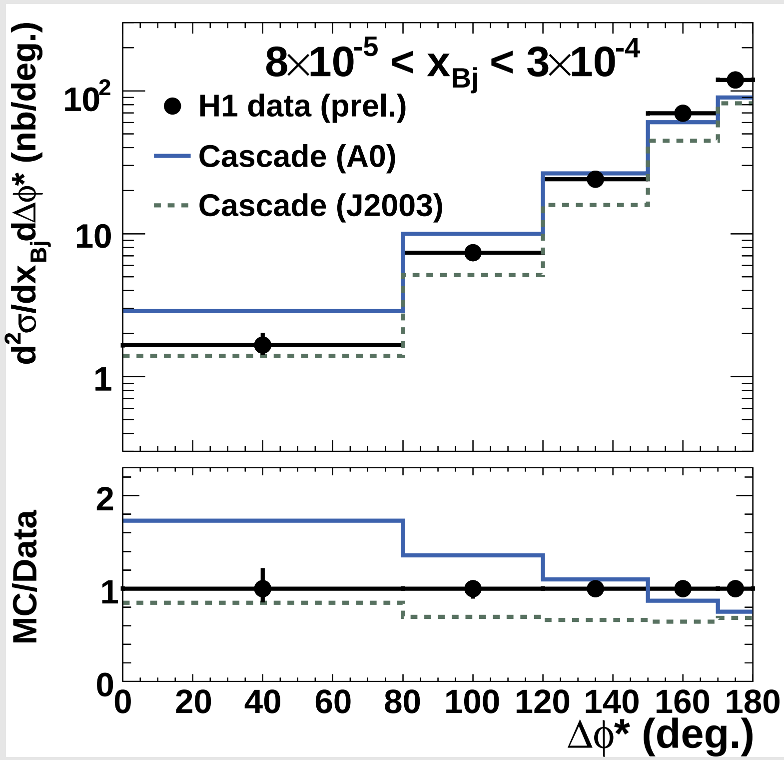


ZEUS data vs CCFM based MC

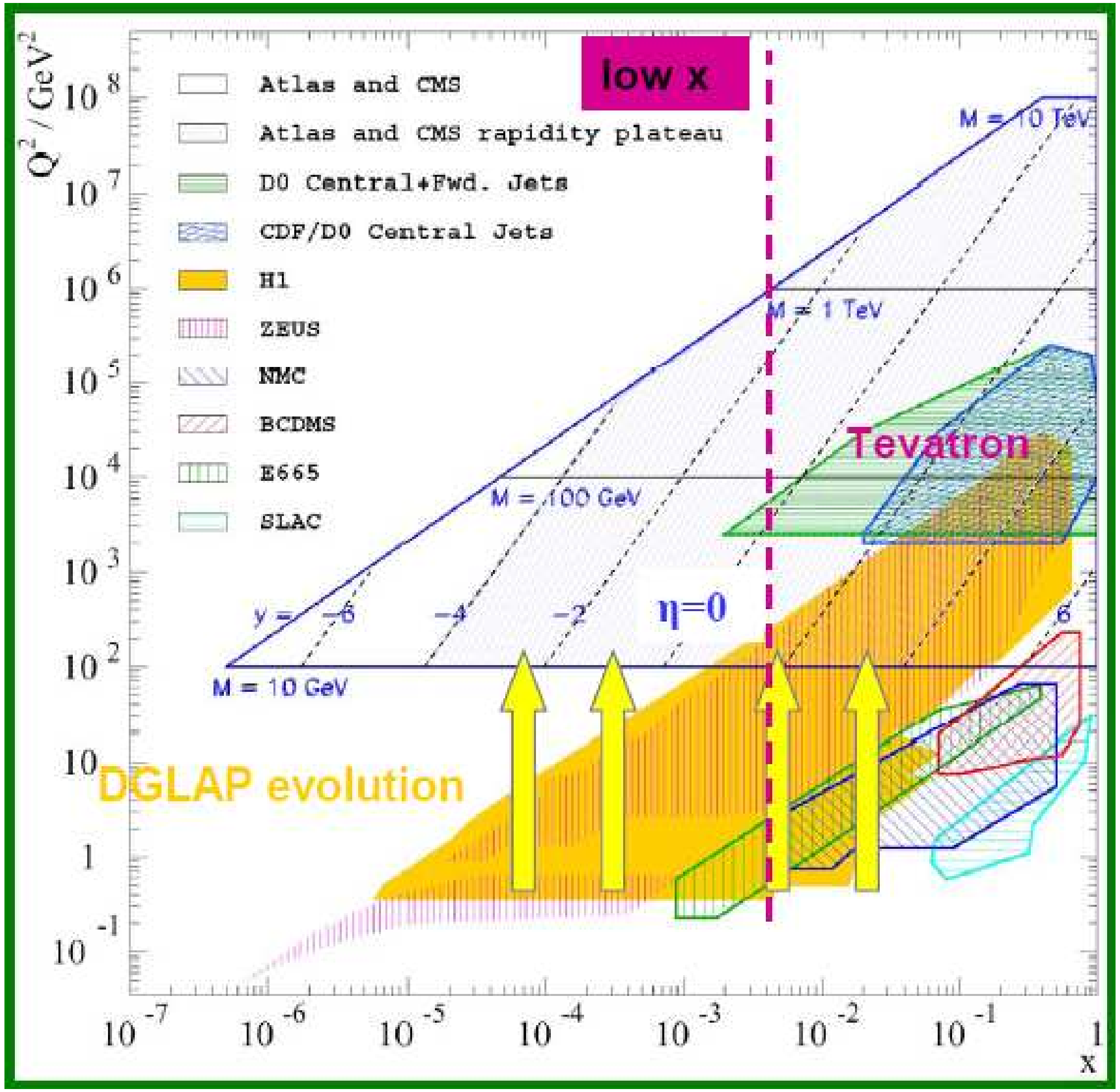
- "collinear approach" (HERWIG) fails
- Cascade based on k_t factorisation describes data much better

H1 data vs CCFM based MC

- Although Cascade fail to describe the shape of $\Delta\Phi^*$, 2 sets of uPDF (both describing HERA F_2) essentially cover the data
- large sensitivity to uPDF



Implications for LHC predictions



- Large part of LHC phase space is at low x
- Tevatron is at large x

$\Rightarrow$ SM predictions based on fixed order calculations and on DGLAP MC may not work even if tuned to Tevatron data

- Low x dynamics has to be implemented
- CDM and Cascade MC after additional tuning are promissing tools for LHC

Summary

- There is **a lot of gluon radiation at small x**.
Hard gluons are often radiated forward, with large rapidity separation from hard interaction vertex. This has **an important implications for LHC!**

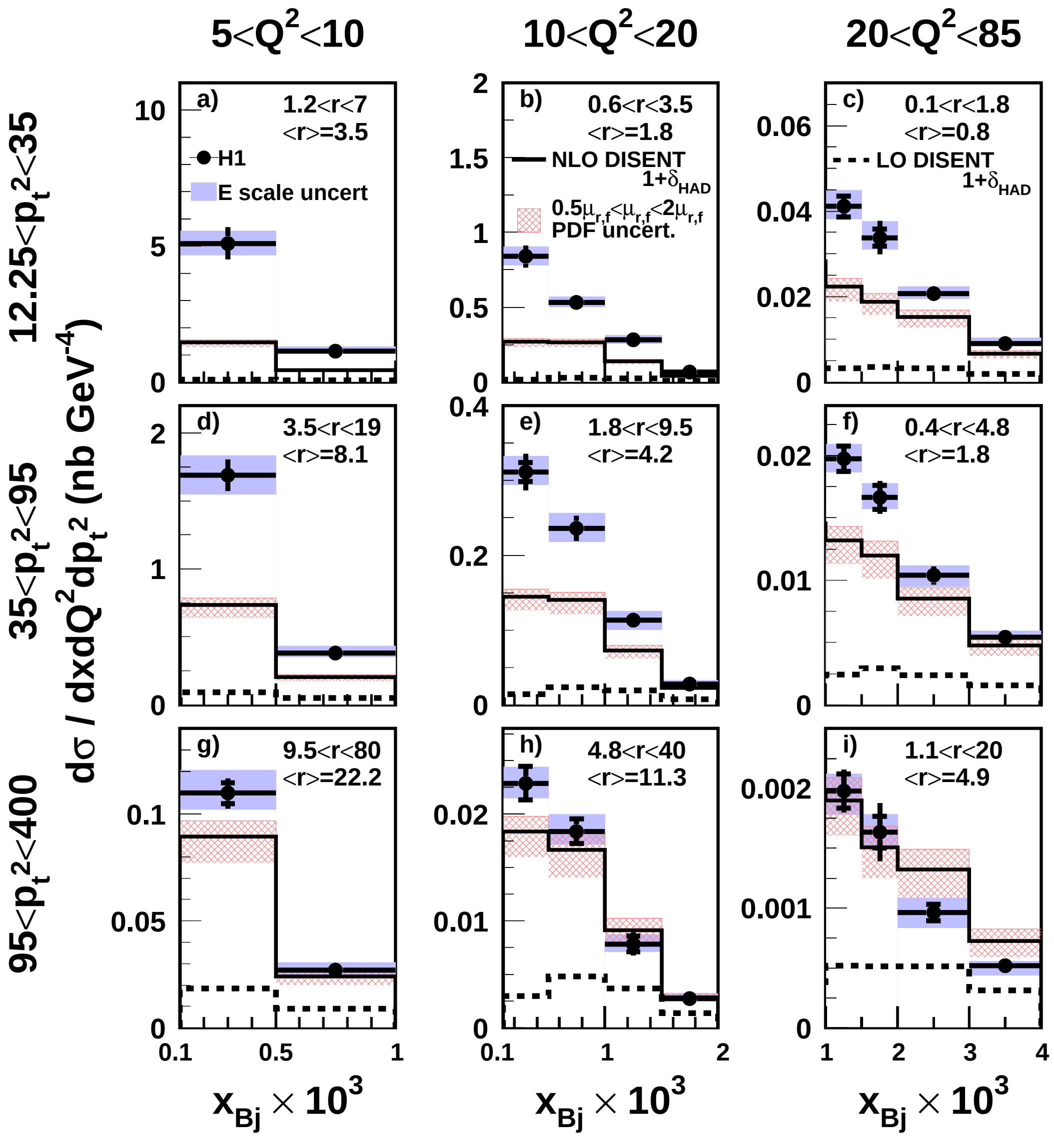
- **Fixed order QCD predictions based on DGLAP approach** give large improvement with every order in α_s. Presently available calculations describe basic properties of multijet production in DIS, however it still fails at lowest x and for specific configurations with very forward jets.

- **Color Dipole Model** gives best description of jet production at HERA down to lowest x while models with k_t-ordered gluon radiation fail completely. This provides a substantial indication for unordered gluon radiation at small x as expected from $\ln(1/x)$ terms in evolution equations.

- Forward jet data and azimuthal correlations in dijet system show **sensitivity to unintegrated PDFs** and therefore can be used for their extraction.

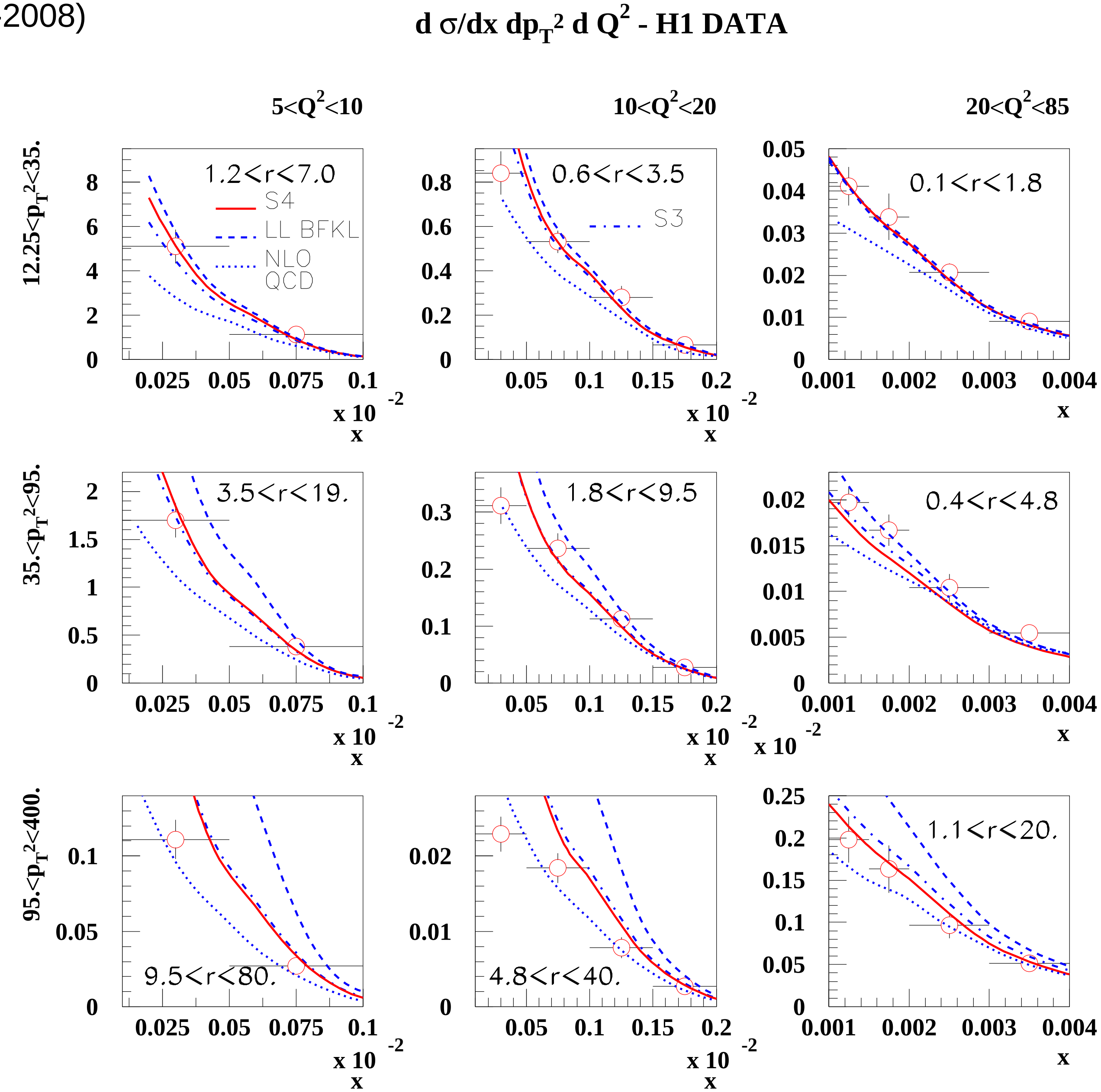
BACKUP SLIDES...

H1 Forward jets: triple differential cross sections

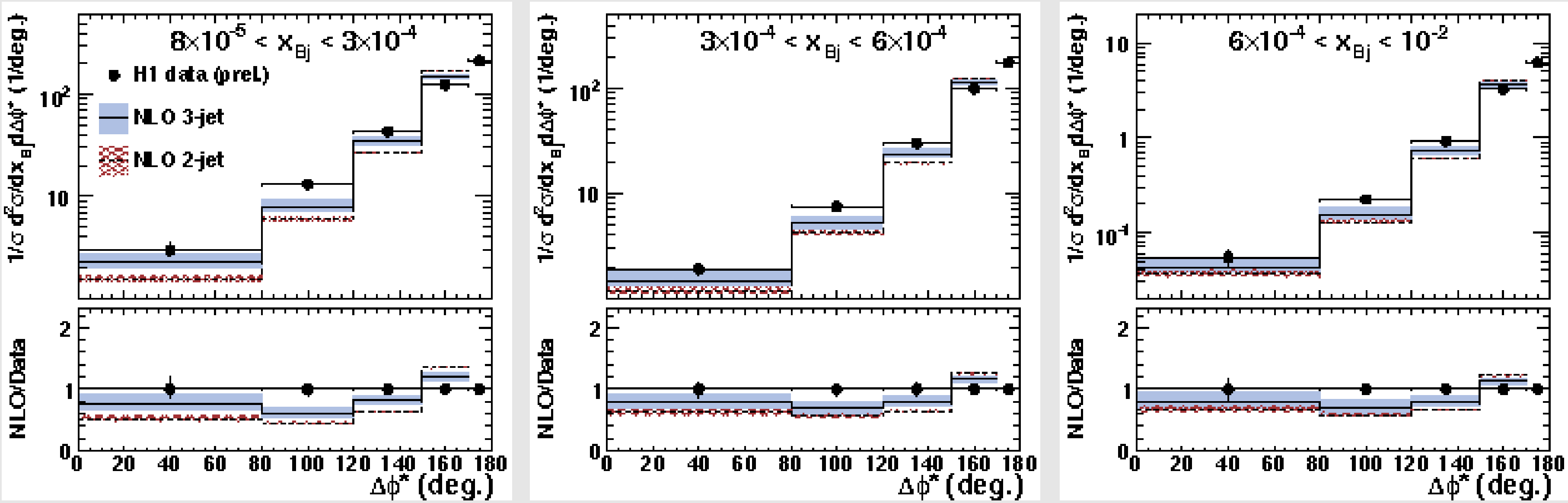


H1 Forward jets vs NLL BFKL

(C.Royon, DIS-2008)



Azimuthal correlations: Data vs NLOJET++



- NLO 3-jet is not in agreement with H1 data