Three- and FourJet Production in DIS and low-x_{Bj} Parton Dynamics at HERA

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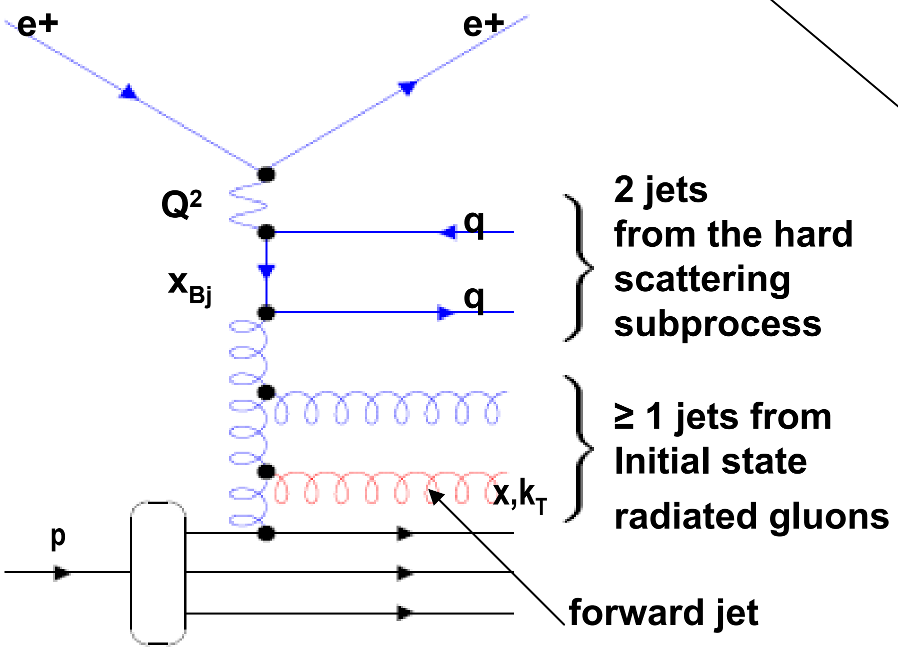
on behalf of the H1 Collaboration

- Motivation
- Event and Jet Selection
- Fixed Order QCD Calculations of ($O(\alpha_s^2)$) and ($O(\alpha_s^3)$) and LO MC Model Simulations
- Threejet Production
  - differential x-sections (N_{Jet}, x_{Bj}, η_{jet}, $p^*_{\perp,jet1}$*(in γ*p CMS), jet variables in 3-jet CMS*)
  - * inclusive sample
  - * 1 forward jet + 2 central jets
  - * 2 forward jets + 1 central jet
- Fourjet Production
  - differential x-sections ((η_1-η_4), $p^*_{\perp,jet1}$*(in γ*p CMS),jet variables in 4-jet CMS*)
- Summary

Three- and Fourjet Production - Motivation

Evolution terms ~$[\alpha_s \ln(Q^2)]^n$
$[\alpha_s \ln(1/x)]^n$
are both large at low $x \leq 10^{-3}$



How important is unordered gluon emission at low x ?

DGLAP: gluon radiation ordered in $k_\perp$
no ln(1/x) terms up to NLO
How does it look in higher order ?
NLOjet++ incl. ln(1/x) terms

resummed in BFKL evolution equation
ln(1/x) terms lead to unordered gluon radiation

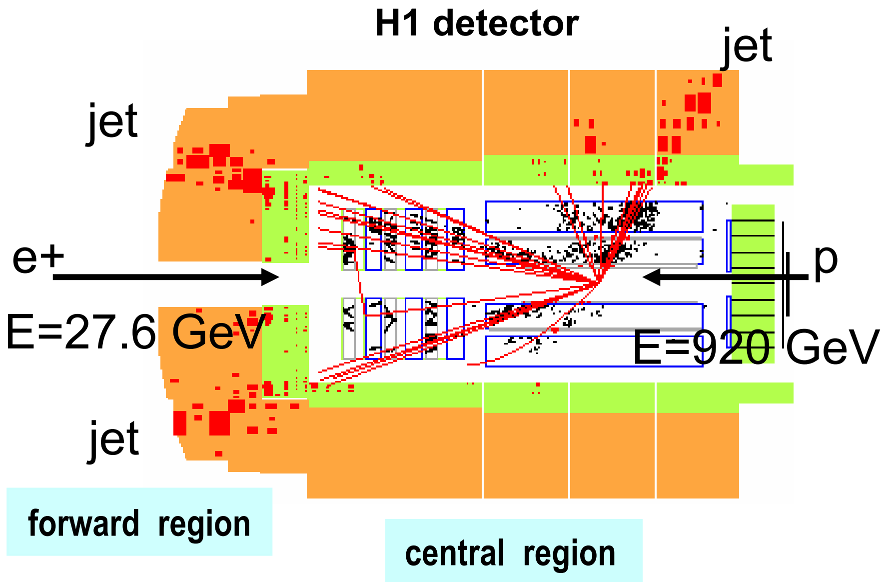
→ more hard gluons radiated away from the hard scattering subprocess

Look at **3- and 4-jet final states at low x**:
→ at least **1 (2) jets are gluon jets**

increase sensitivity to deviations from the DGLAP approach:
↓
a) events with 1 forward jet + 2 central jets
b) events with 2 forward jets + 1 central jet

select hard forward jets → effect of unordered gluon radiation should be the largest

Event and Jet Selection



Event selection

5 GeV^2< Q^2< 80 GeV^2
$10^{-4} < x_{Bj} < 10^{-2}$, $0.1 < y < 0.7$

Jet selection

Jets formed from the tracks and clusters (incl. $k_\perp$ algoritm in γ^*p CMS, dist. par.=1)

- **≥3 jets with $p^*_\perp$ > 4 GeV** (good correlation between jets@detector level and jets@hadron/parton level)
- **$p^*_{\perp 1} + p^*_{\perp 2}$ > 9 GeV** (to compare the data to the NLO($O(\alpha_s^3)$) calculat.)
- **$-1 < \eta_{jet} < 2.5$** in lab. frame
- **≥ 1 central jet with $-1 < \eta_{jet} < 1.3$**

*(quantities with * measured in γ^*p CMS)*

Data sample

1999/2000 e^+p data
38400 events with at least 3 jets
(6000 with more than 3 jets)

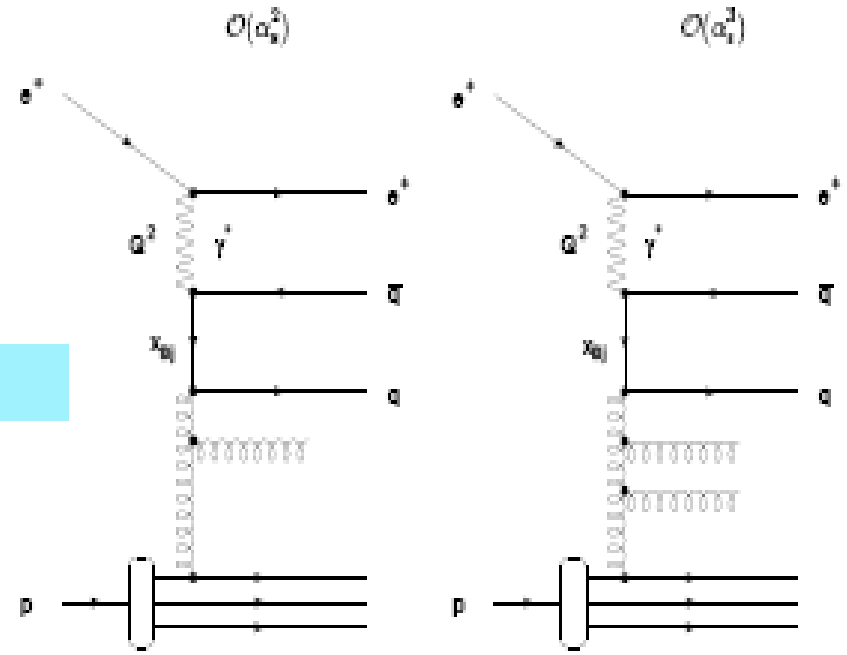
MC Simulations and Fixed Order QCD Predictions

LO Monte Carlo (MC) generators
+ higher order effects

to correct the data for detector inefficiencies and migrations

to compare with the measured x-sections

- **Color Dipol Model (CDM)**
  (Djangoh13, PDF:CTEQ5M)
  gluon radiation not ordered in $k_\perp$
- **DGLAP MC (RAPGAP)(RG d+r)**
  (PDF:CTEQ5L, SaS 2D)
  initial state radiation
  + resolved γ component,
  gluon emissions ordered in $k_\perp$



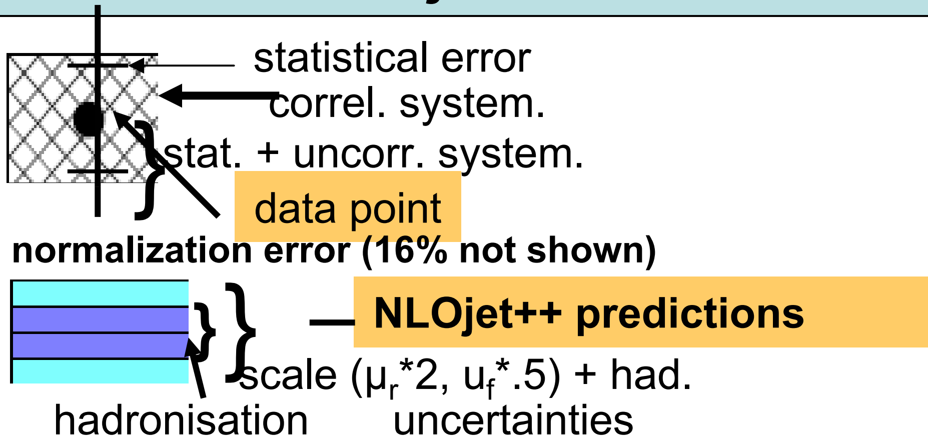
NLOjet++ program

3-jet x-sections LO($O(\alpha_s^2)$) and NLO($O(\alpha_s^3)$)
4-jet x-sections LO($O(\alpha_s^3)$)

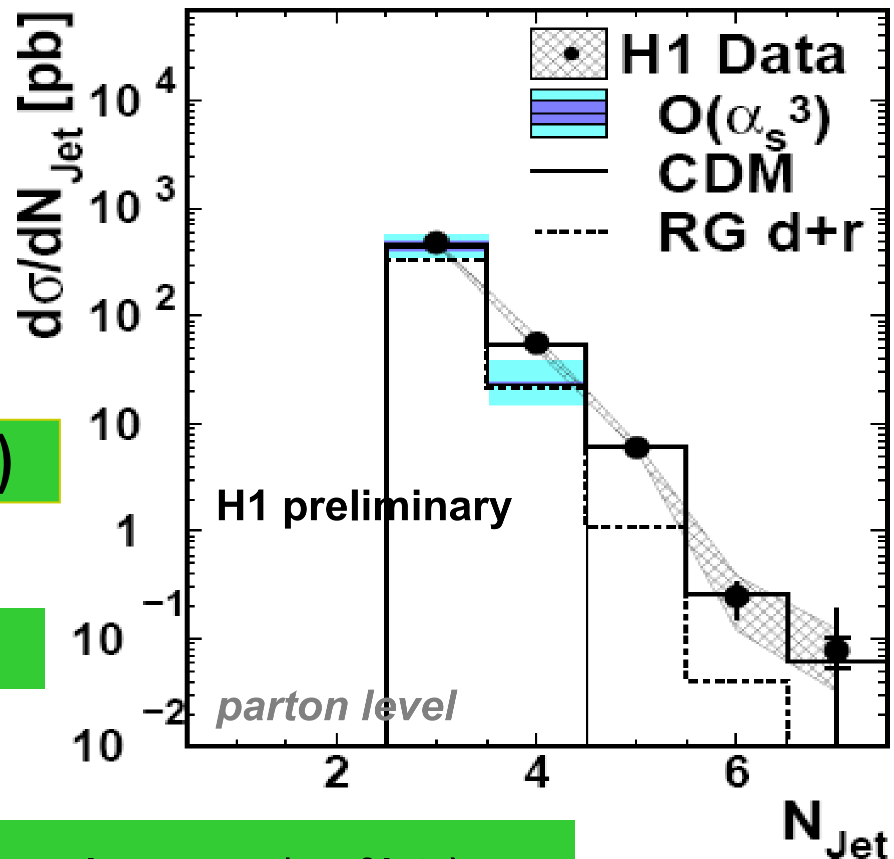
Comparison on hadron level

Comparison on parton level

Threejet Cross-sections - Inclusive Sample



dσ/dN_{Jet}



- **CDM (unordered emission)**

  describes N_{Jet}

- **RG d+r (ordered emission)**

  below data for all N_{Jet}

- **NLOjet++** (PDF:CTEQ6M, $\alpha_s(m_Z)$=0.118, scale: mean $p^*_\perp$ of jets)

$O(\alpha_s^3)$ agrees for N_{Jet}=3
misses 18% of events with $N_{Jet} \geq 4$ (no pred. for $N_{Jet} > 4$)

Threejet Cross-sections – Inclusive Sample

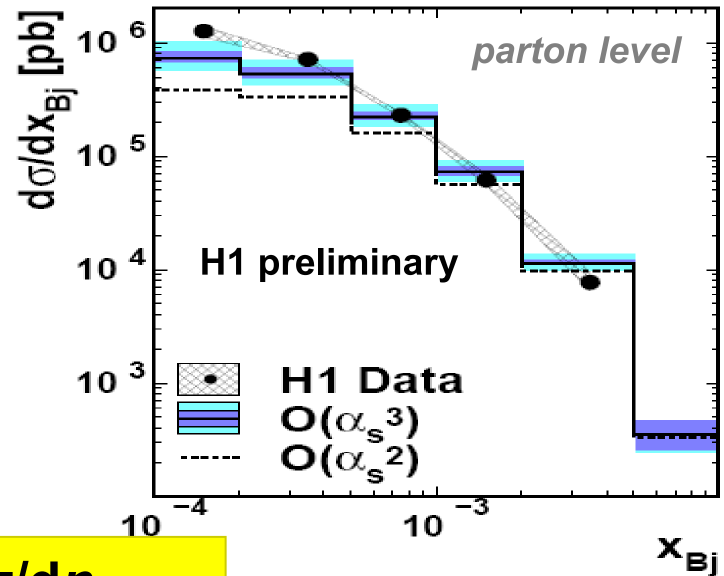
- **NLOjet++**

  $O(\alpha_s^2) \rightarrow O(\alpha_s^3)$

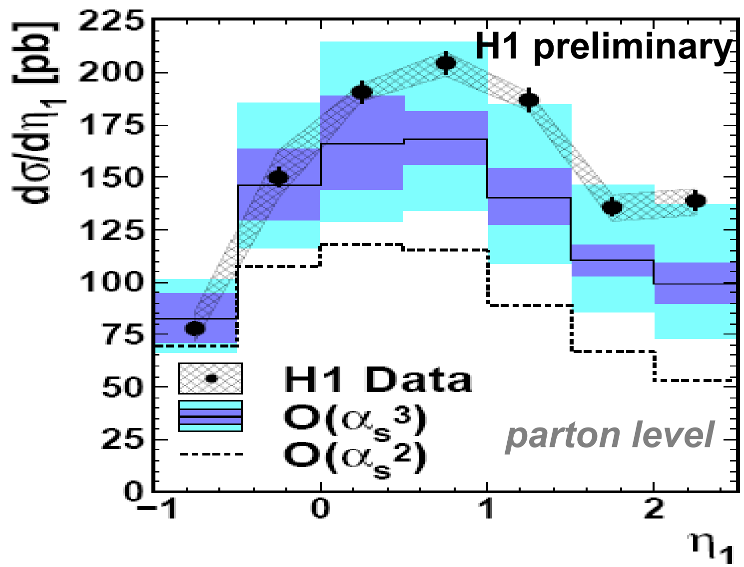
$O(\alpha_s^2)$ prediction too low

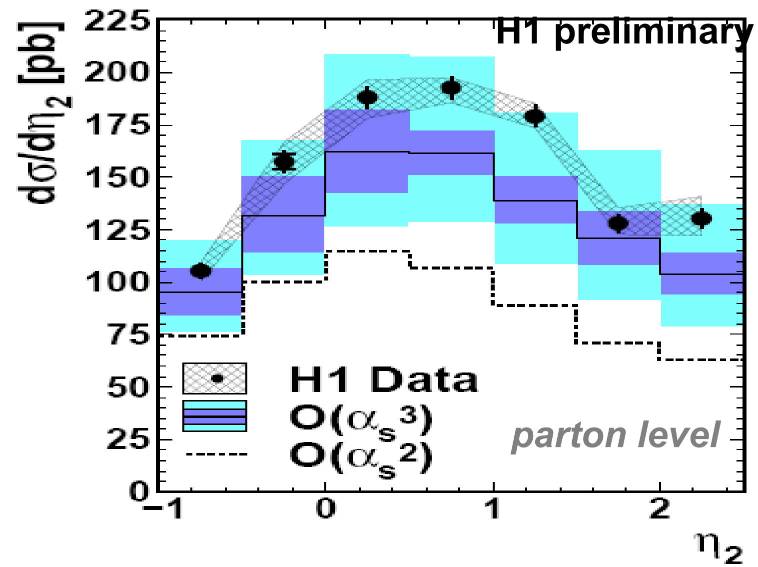
$O(\alpha_s^3)$ **<u>improvement</u> in all regions, particularly at low x_{Bj} and large η (forward region), but *still deficit* 18% below data**

$d\sigma/dx_{Bj}$



$d\sigma/d\eta_1$, $d\sigma/d\eta_2$





Threejet Cross-sections – Inclusive Sample

Variables describing
the topology of 3-jet events
in 3-jet CMS

$d\sigma/dX'_i$

$X'_i \equiv$ scaled energies

$X'_i = E'_i/(E'_1+E'_2+E'_3)$ i=1,2,3

$E'_1>E'_2>E'_3$

$d\sigma/d\cos\theta'$, $d\sigma/d\cos\psi'$

$\cos\theta'$ **(between leading jet and pbeam)**

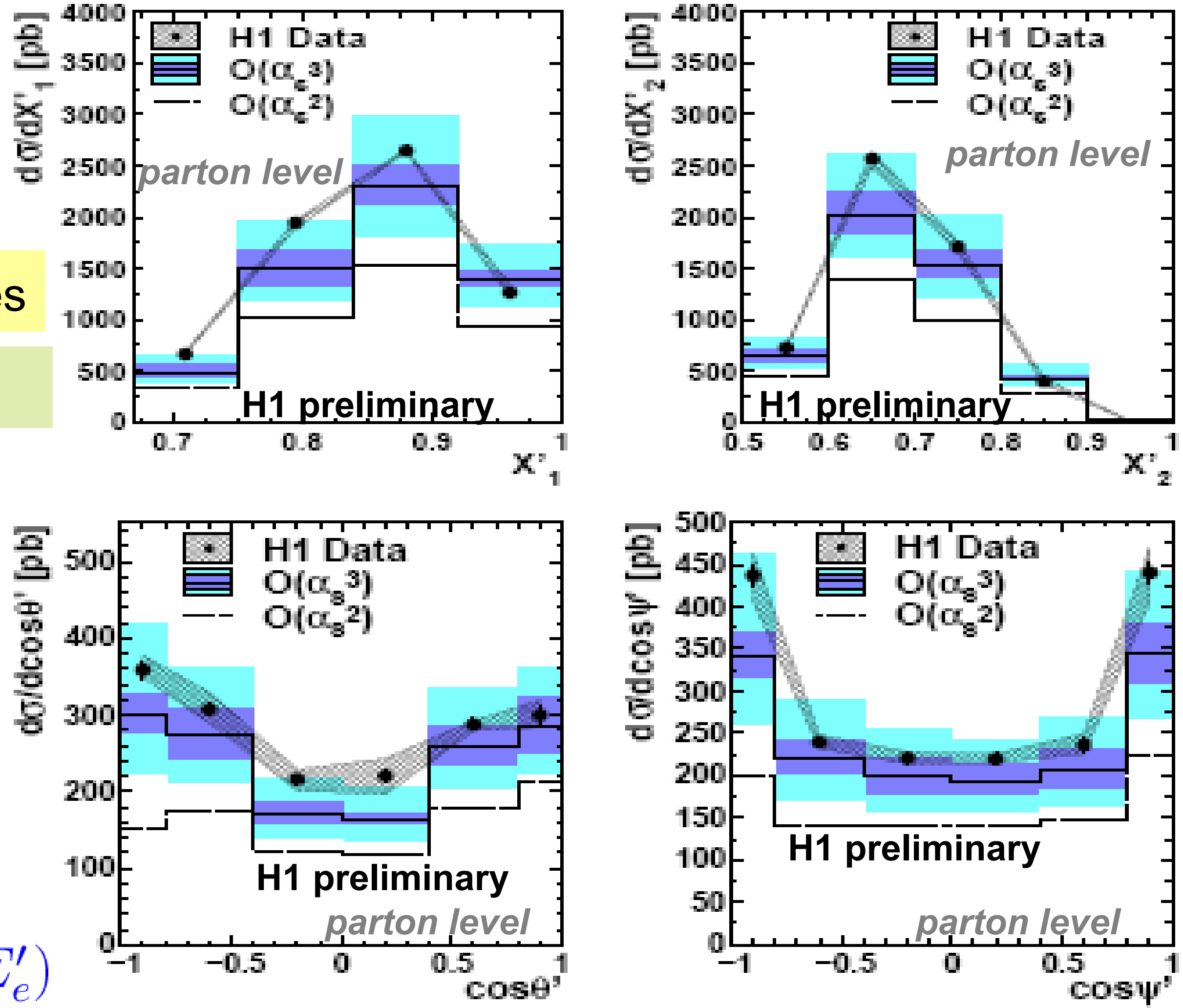
$\cos\psi'$ **(between plane (lead. jet, pbeam) and threejet plane)**

$$\vec{p}_{\mathrm{beam}} = \pm(x_{\mathrm{gluon}}\,\vec{p}_p - y\,\vec{p}_e)$$

$$(+\ \mathrm{sign} \Leftrightarrow x_{\mathrm{gluon}}\,E'_p > y\,E'_e)$$

$E'_p, E'_e, \vec{p}_p, \vec{p}_e$

energy and momentum of incoming particles



shape well described by the NLO($O(\alpha_s^3)$) predictions
normalization about 18% below data

Threejet Cross-section – Forward Jet Selection

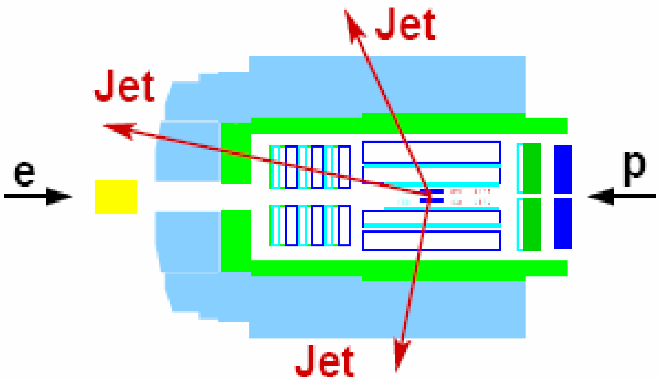
largest disagreement at low *x* and large *η*

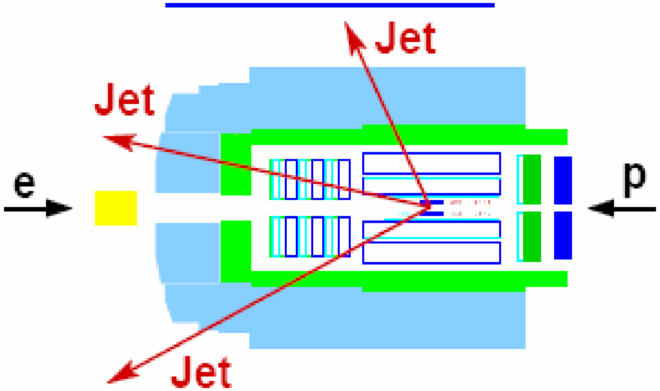
$d\sigma/dx_{Bj}$

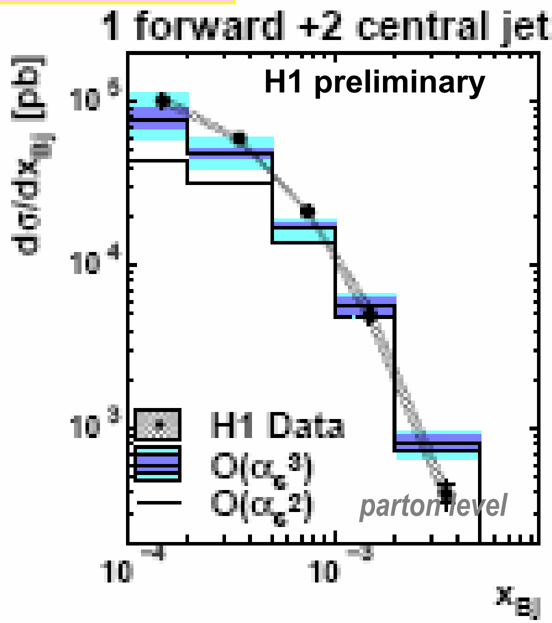
subsample with forward jet:

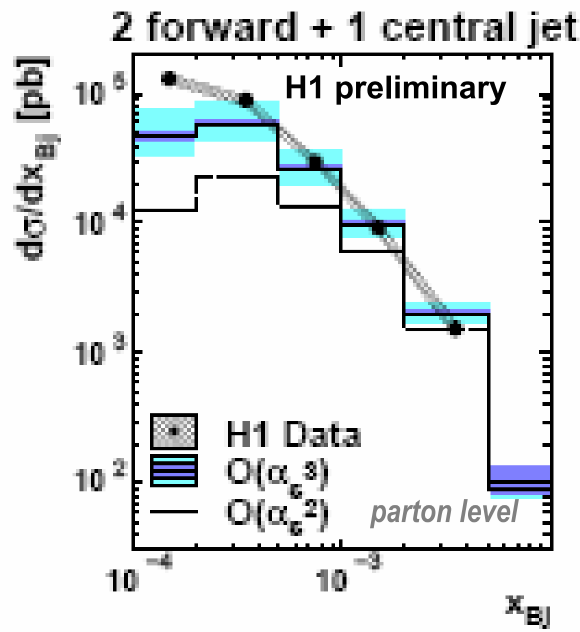
$\eta_{jet} > 1.73$,

$x_{jet} = E^*_{jet}/E_{p,beam} > 0.035$









LO $O(\alpha_s^2)$ (1 gluon rad.) ⟶ NLO $O(\alpha_s^3)$ (2 gluons rad.)

1 forward + 2 central jets: good agreement

at low *x* description improves by a factor of 2;

missing only 30% of events

2 forward + 1 central jets: large deficit

discrepancy at low *x* reduced: 10 → 3.5

but with still a large discrepancy remaining

Threejet Cross-sections Forward Jet Selection

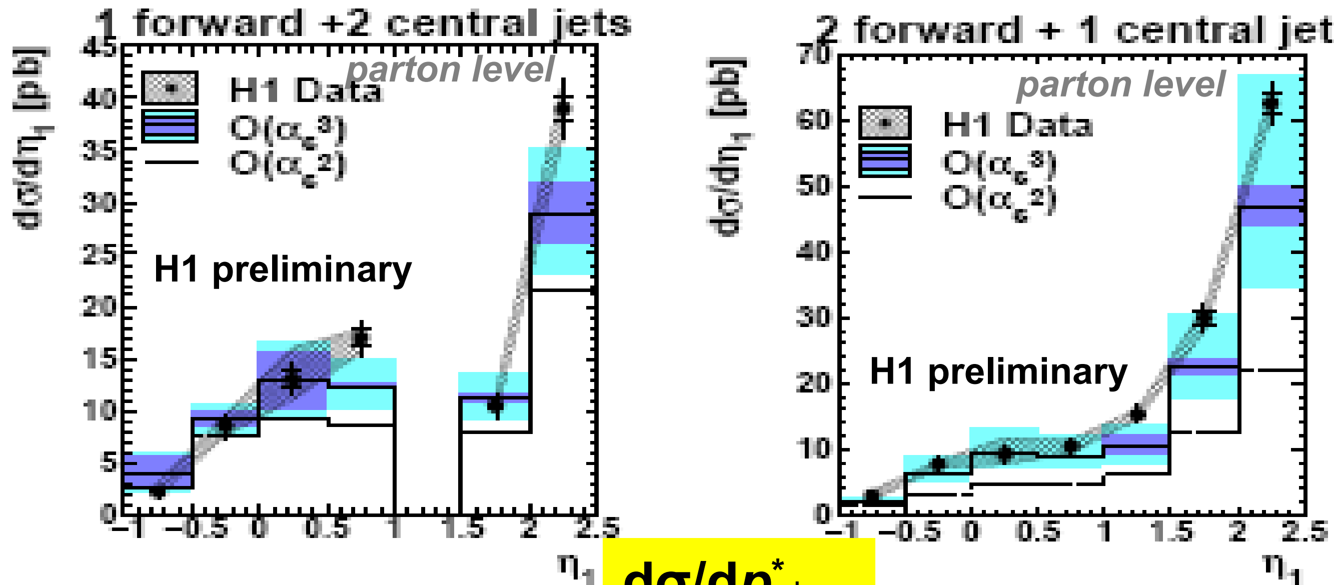
dσ/dη_1

large improvement going from α_s^2 to α_s^3

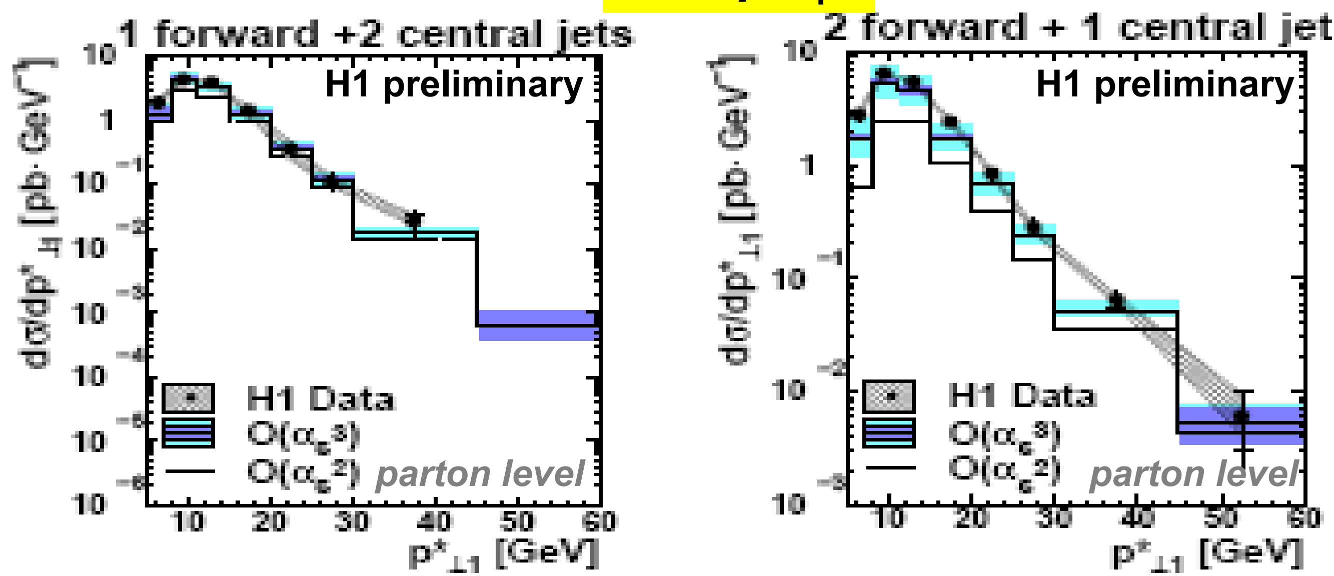
good agreement for 2 central jet top.

still deficit for 2 forward jet top.

→ kinematic region where *unordered gluon radiation* is expected to make large contribution



dσ/d$p^*_{\perp 1}$



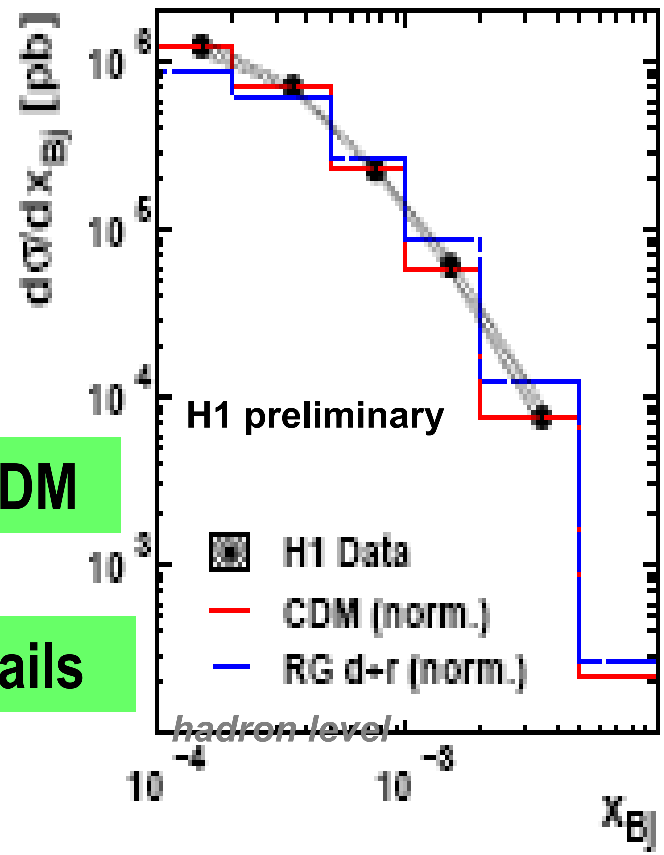
Threejet Cross-sections – Comparison to LO MCs

x_{Bj} and $(\eta_1 - \eta_2)$ (difference of pseudorapidities of the two leading $p^*_\perp$ jets)

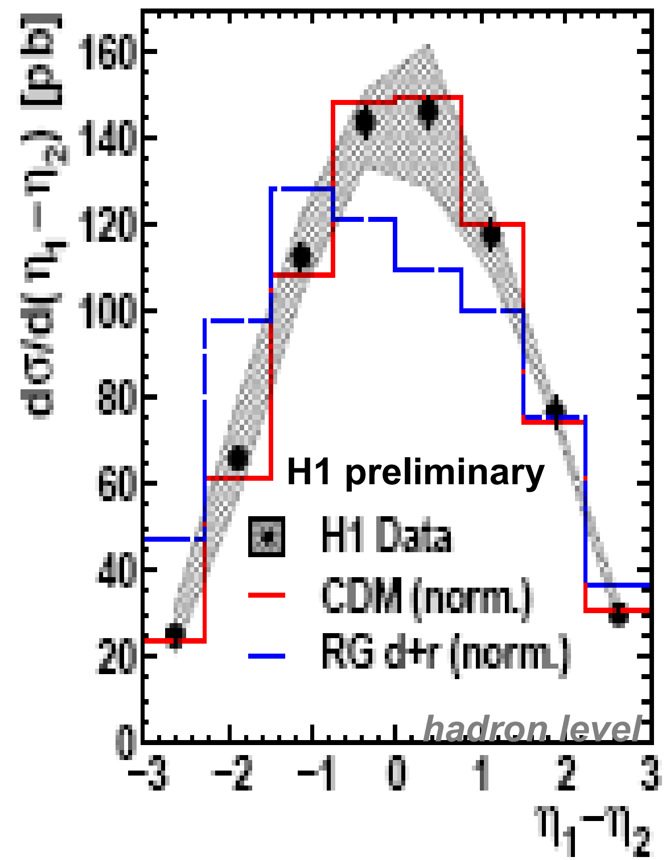
well described by CDM

RG d+r prediction fails

$d\sigma/dx_{Bj}$



$d\sigma/d(\eta_1 - \eta_2)$



cross sections are shape normalized to the data (CDM + 5%, RAPGAP +51%)

Threejet Cross-sections – Comparison to LO MCs

$d\sigma/dp^*_{\perp 1}$

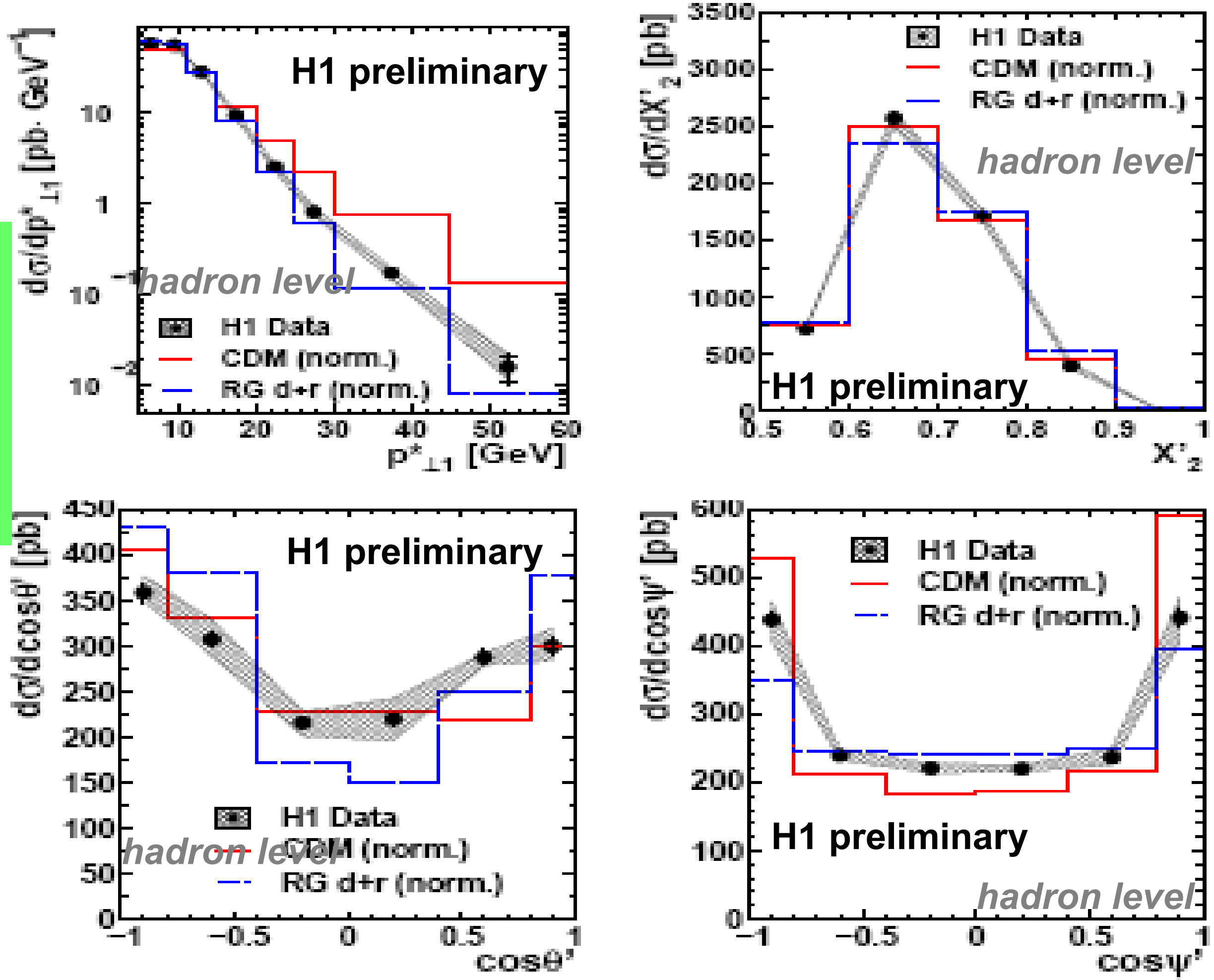
well described by RG d+r

CDM
does not describe $p^*_{\perp}$,
too many jets with
$p^*_{\perp 1} > 15$ GeV

$d\sigma/dX'_2$

$d\sigma/d\cos\theta'$, $d\sigma/d\cos\psi'$

CDM slightly better

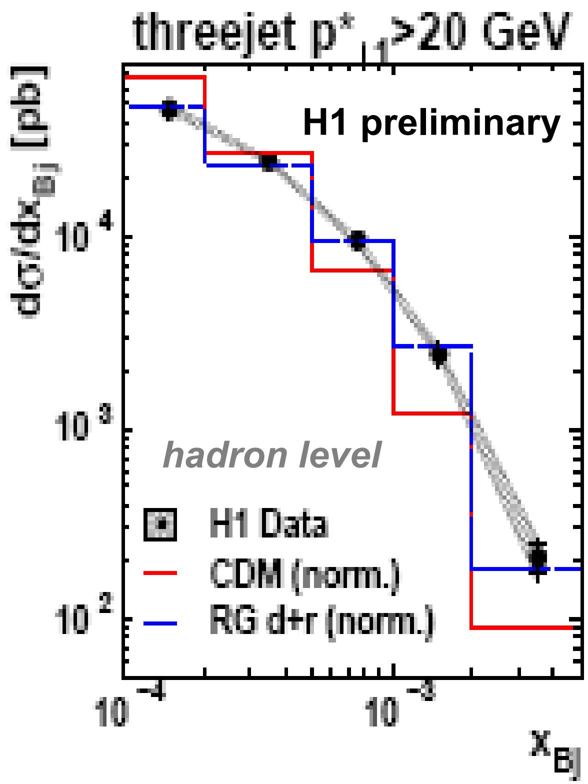


cross sections are shape normalized to the data (CDM + 5%, RAPGAP +51%)

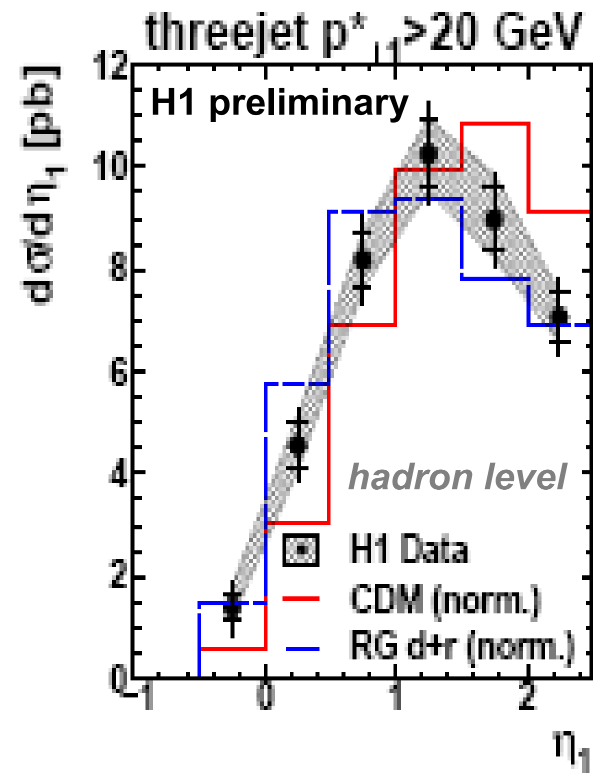
Three-Jet Cross-sections – Comparison to LO MCs

events with $p^*_{\perp 1}$ > 20 GeV

$d\sigma/dx_{Bj}$



$d\sigma/d\eta_1$



deviations between data and CDM predictions

RG d+r follows data

cross sections are shape normalized to the data (CDM -59%, RAPGAP +86 %)

3-jet x-sections, Frwd Jet Selection, Comparison

$d\sigma/d\cos\theta'$, $d\sigma/d\cos\psi'$

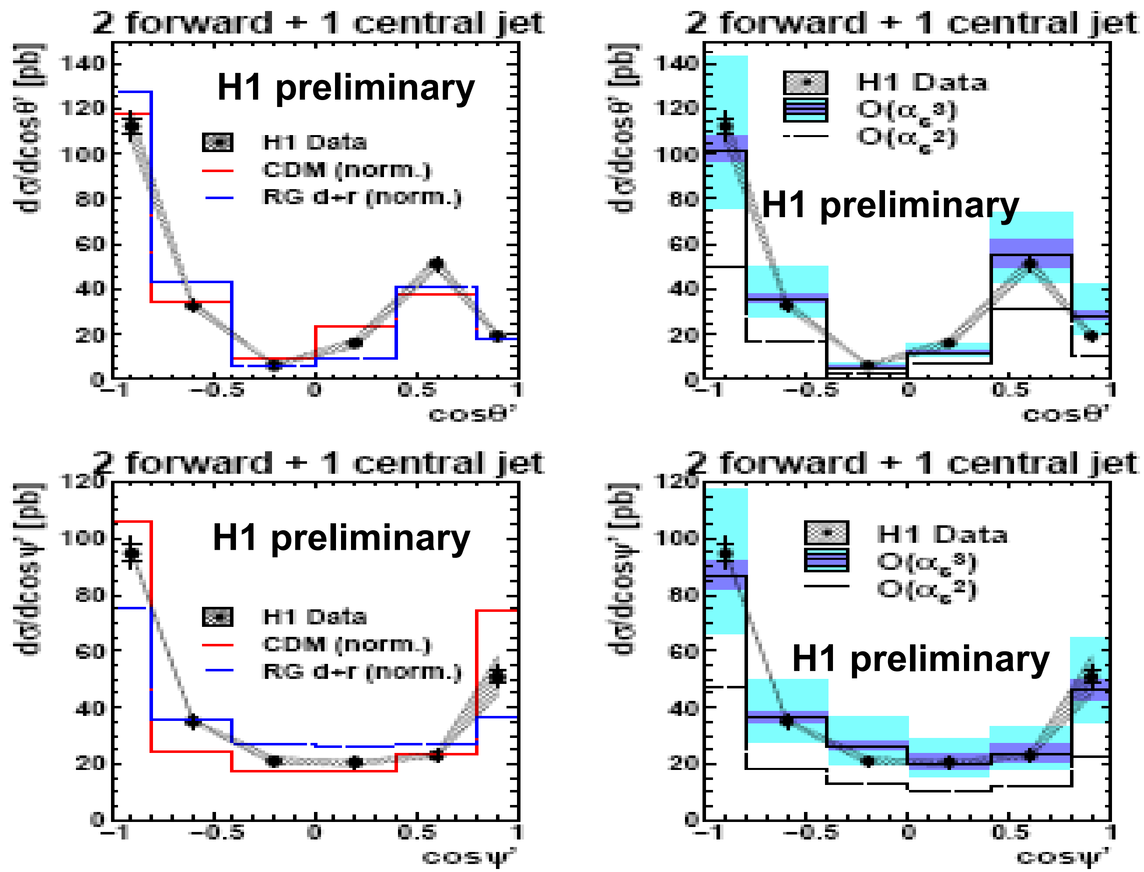
angular topology for

2 forward jet sample

here:

NLOjet++ better than CDM

CDM better than RG d+r



CDM, RAPGAP (hadron level) **NLOjet++ (parton level)**

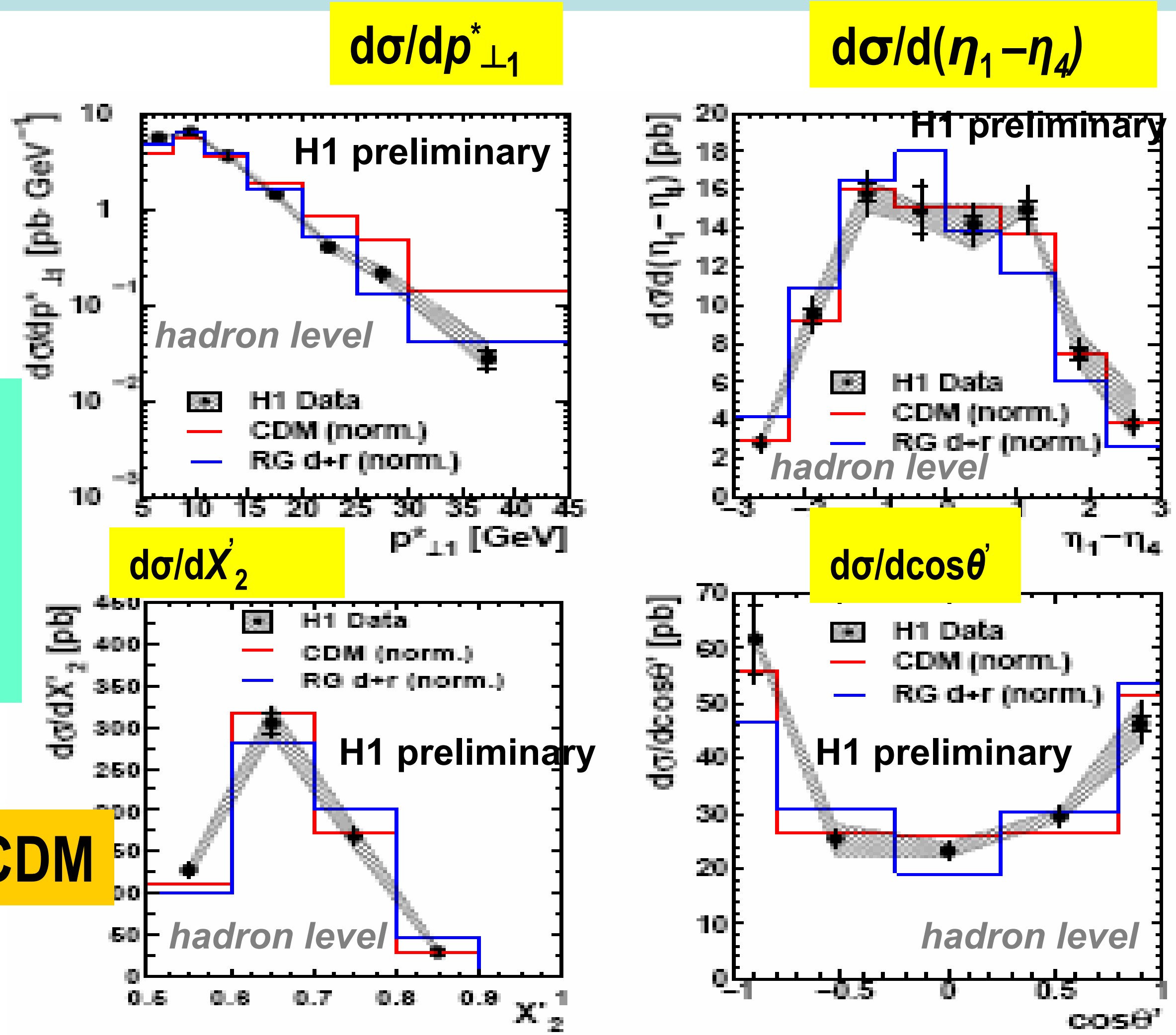
cross sections are shape normalized to the data (NLOjet++ +32%, CDM -9%, RAPGAP +63 %)

Fourjet Cross-sections Comparison to LO MCs

CDM gives nearly perfect description (for $p^*_{\perp 1}$ < 15 GeV)

LO+initial state radiation + resolved photon (RG d+r) does not describe data, except for $p^*_{\perp 1}$ distribution

multijet events in favour of CDM



cross sections are shape normalized to the data (CDM +1%, RAPGAP x 2.82)

Summary

Three- and fourjet events well suited to study gluon radiation at low x:
many hard gluons radiated forward

Fixed order QCD DGLAP prediction in $O(\alpha_s^3)$:
- **huge improvement w.r.t. $O(\alpha_s^2)$**
- **especially good for 2 central jest sample**
- **and in describing the threejet topology (better than CDM)**

but
- **still deficit w.r.t. data at large rapidities and small x for 2 forward jet sample (phase space most sensitive to gluon radiation)**

MC models for gluon radation:
- **CDM (additional gluon radiation not ordered in $k_\perp$)**
  - **gives a good description of multijet events (except at $p^*_\perp > 15$ GeV)**
- **RG d+r (gluon radiation via ordered initial state radation + a resolved photon contribution) does not describe data in forward region at low x**

Unordered in $k_\perp$ gluon emission at low x plays a significant role as expected from ln(1/x) contributions in the evolution equations.