Three- and four-jet production at low-x at HERA

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  - Definition of variables
- Cross section measurements
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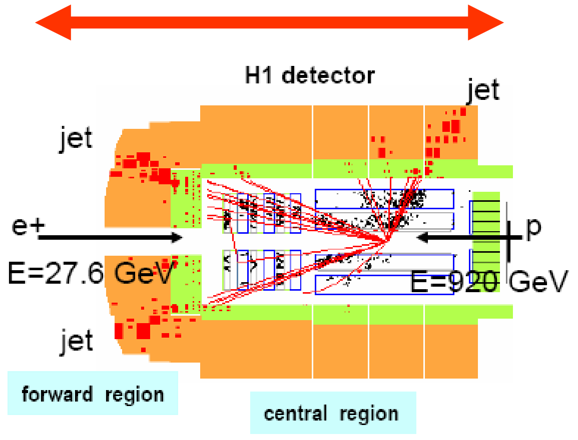
- Summary and conclusions

Multi-jet measurements at HERA

Three- and Four-jet Production at Low x at HERA.
By **H1** Collaboration **Eur.Phys.J.C54:389-409,2008**; **arXiv:0711.2606** [hep-ex]

$\Delta\eta\sim 4$

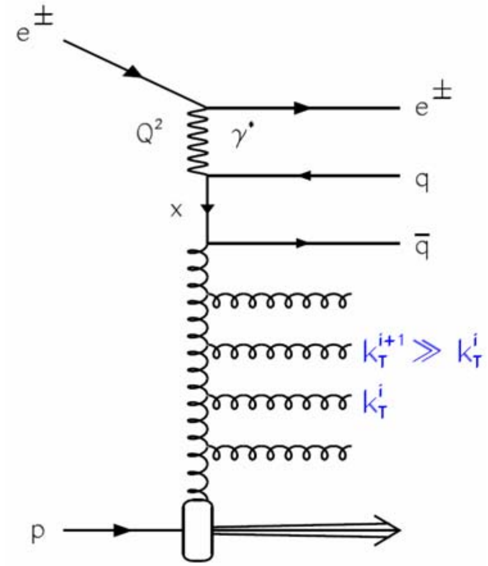


HERA jet measurement covers ~4 pseudorapidity units → we expect typically no more than 3-4 hard emissions

At HERA 3, 4 jets are at the limit of hard radiation phase space at small x

Physics motivation of this measurement

- **Check in detail** theory predictions of parton level calculations provided by **NLOJET++** (fixed order NLO for 3-jet inclusive sample)



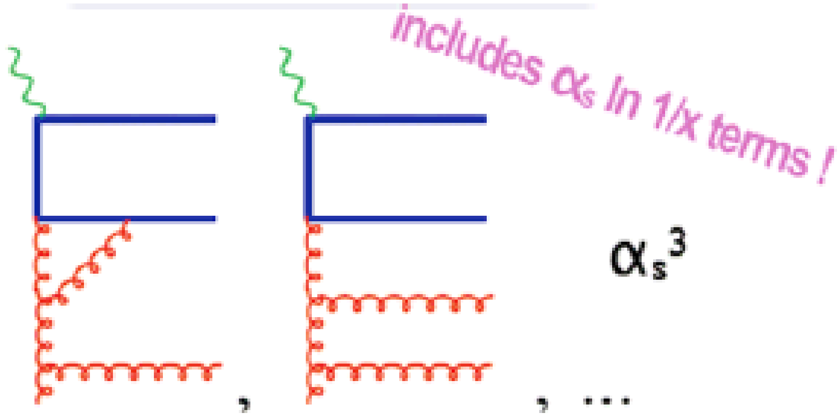
- NLOJET++ is theory based on DGLAP approximation, which assumes ordering of parton transverse momenta along cascade. QUESTION : **is DGLAP good enough in all available for 3-jet inclusive phase space at HERA ?**

- Check in detail predictions of LO+parton shower generators with k_T-ordered (RAPGAP) and unordered (Color Dipol Model) cascade

- In contrast to inclusive jets and di-jets three-jet final states require **at least one gluon radiation in addition to** $\gamma^* g \rightarrow q\bar{q}$ → 3-jet sample ideally suited to study gluon emissions and underlying parton dynamics

NLO parton level MC

NLOJET++ (Z.Nagi,Z.Trocsanyi)



Scale

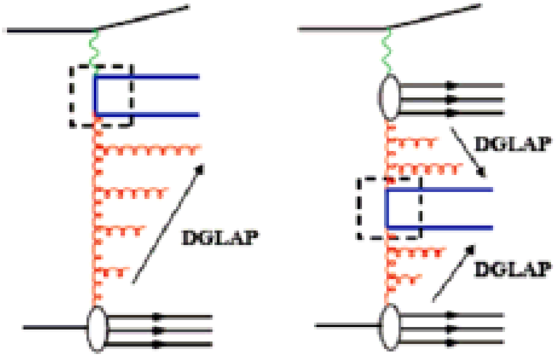
$$\mu_r = \mu_f = \frac{1}{m} \sum p_{Ti}^*$$

uncertainty

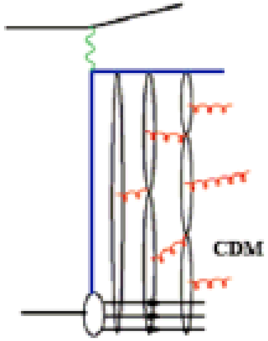
μ_f and μ_r varied by common factor of 2 or 0.5

- NNLO calculation for dijets
- NLO calculation for trijets
- LO calculation for four-jets
- Trijet calculation contains α_s ln(1/x) term

QCD models based on DGLAP and Color Dipole Model (CDM)

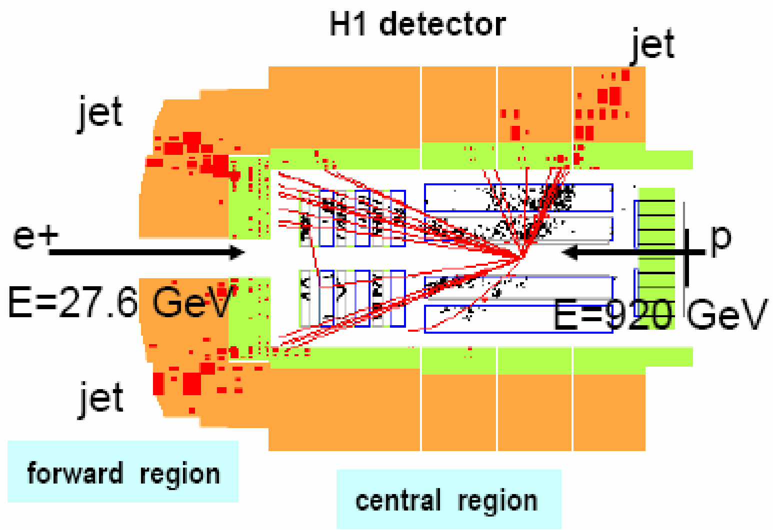


- RAPGAP : implements DGLAP evolution with k_t ordering
- RAPGAP RESOLVED: also evolution from „hadronic photon" side, in a sense breaks ordering, but within DGLAP scheme



- ARIADNE: implements Color Dipoles Model:
- Quasi-classical color dipoles radiate independently
- No k_t ordering

Event and jet selection



Data sample

Integrated lumi 44.2 pb^{-1}

384000 events ≥ 3 jets

6000 events ≥ 4 jets

Event selection

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

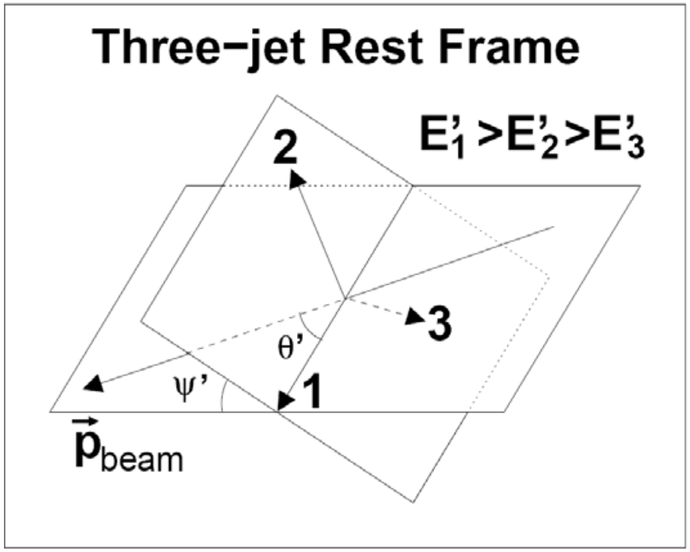
Jet selection

Jets formed from the tracks and clusters (incl. $k_\perp$ algoritm in $\gamma^* p$ 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 $-1 < \eta_{jet} < 1.3$**

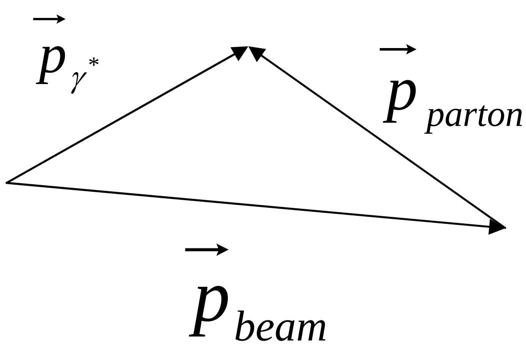
*(quantities with * measured in $\gamma^* p$ CMS)*

Observables describing 3-jet system



Scaled energies
$$X_i^{'} = \frac{E_i^{'}}{E_1^{'} + E_2^{'} + E_2^{'}}$$

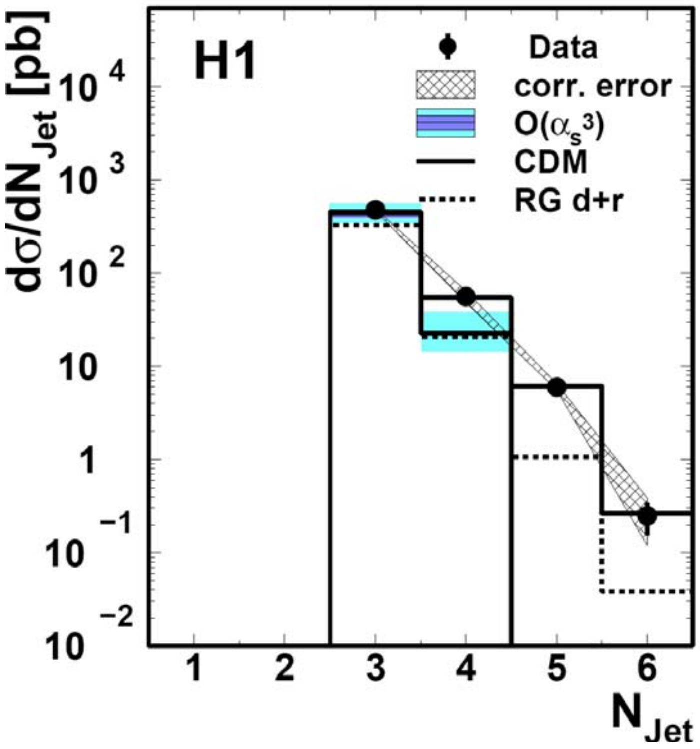
Two angles θ' and ψ' orientation of 3-jet system with respect to colliding boson-parton system



Jet transverse momenta $p_{T1}^{*} > p_{T2}^{*} > p_{T3}^{*}$ in $\gamma^{*}p$ system

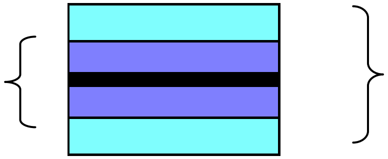
Jet pseudorapidities η_1 η_2 η_3 in laboratory system

3-jet cross section and jet multiplicity distribution



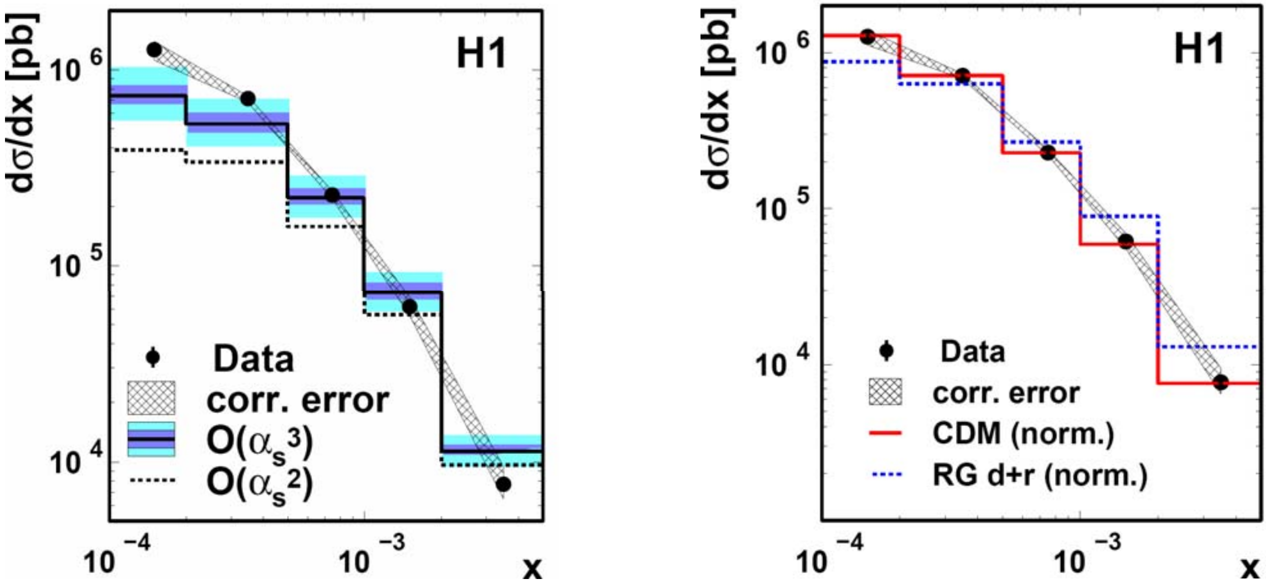
- 3-jet cross section well described by NLO(α_s^3)
- NLO(α_s^3) underestimates 4-jet rate by factor 2.6
- CDM (unordered radiation) provides excellent description of jet multiplicity distribution up to N_{jet} = 6
- RAPGAP (ordered parton shower) fails to describe jet multiplicity distribution, underestimates 4-jet rate by factor 2.9

Hadronisation corrections uncertainty (model dependence)



Scale + hadronisation uncertainty in quadrature

Bjorken-x distribution



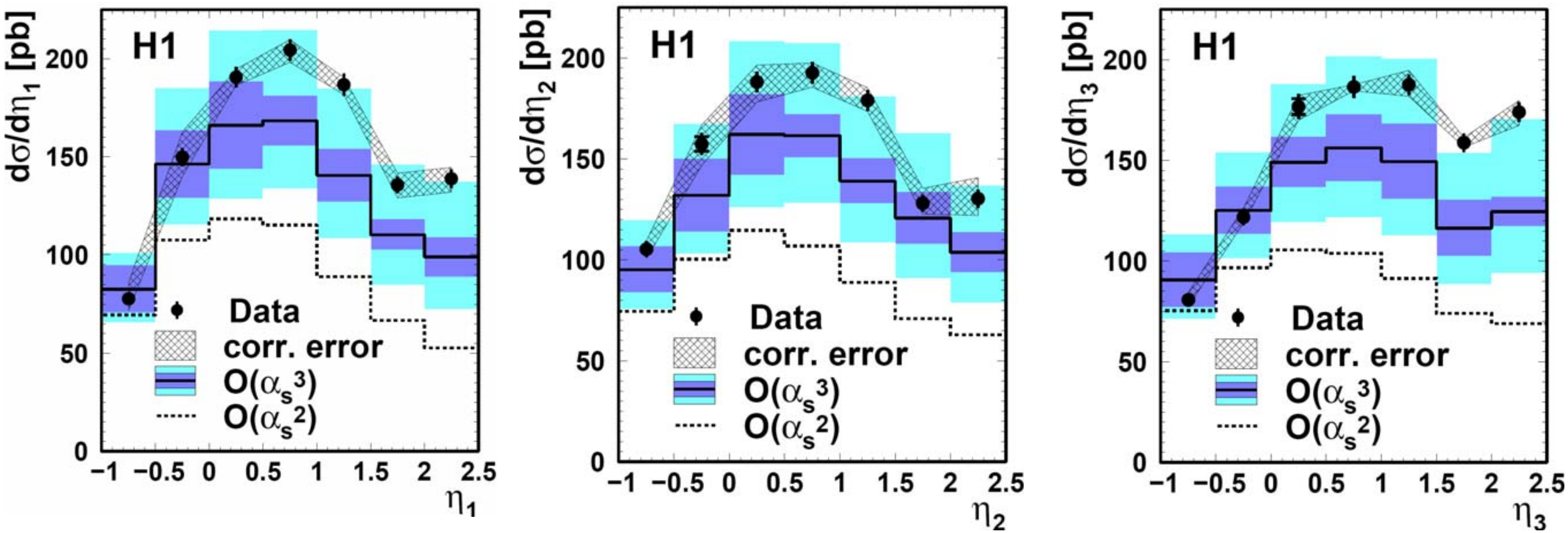
•Here and in all the other plots NLO(α_s^3) is **significant improvement** w.r.t. NLO(α_s^2)

•**At very small x < 2•10^{-4} NLO(α_s^3) undershoots the data** (upper edge of theoretical error band). Not observed or less accentuated in previous analyses with restricted phase space (M_{3jet} >25 GeV or higher E_T – jet cut)

•RAPGAP fails to describe both shape and normalization (plot normalized by 1.55)

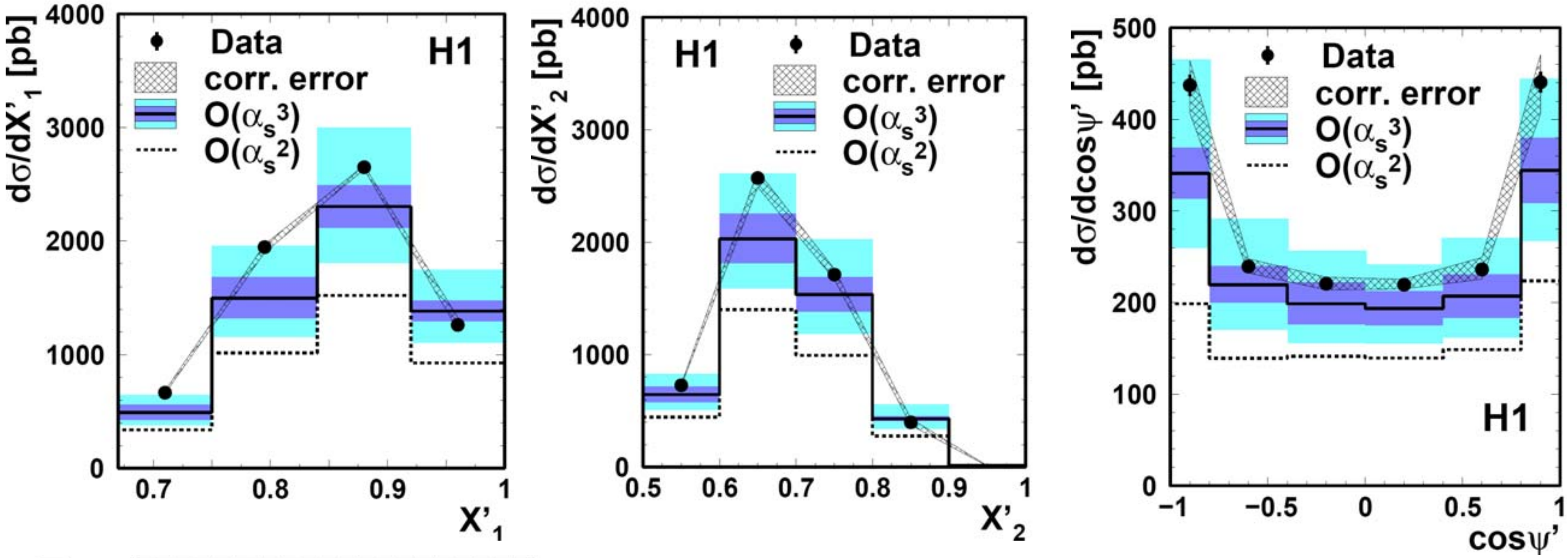
•**CDM provides excellent description** in shape and fair in normalization (here 1.05)

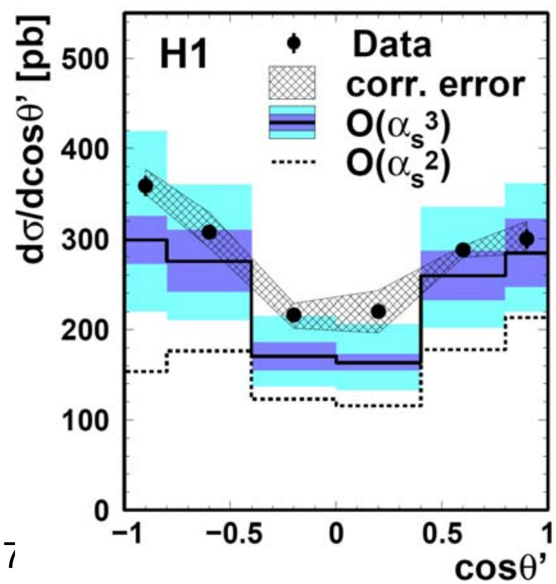
3-jet inclusive sample : pseudorapidities in laboratory



- Data described within large theoretical uncertainties, **but tendency to underestimate cross section at large positive pseudorapidities** (forward jets)
- Improvement of $O(\alpha_s^3)$ w.r.t. $O(\alpha^2)$ increases with pseudorapidity

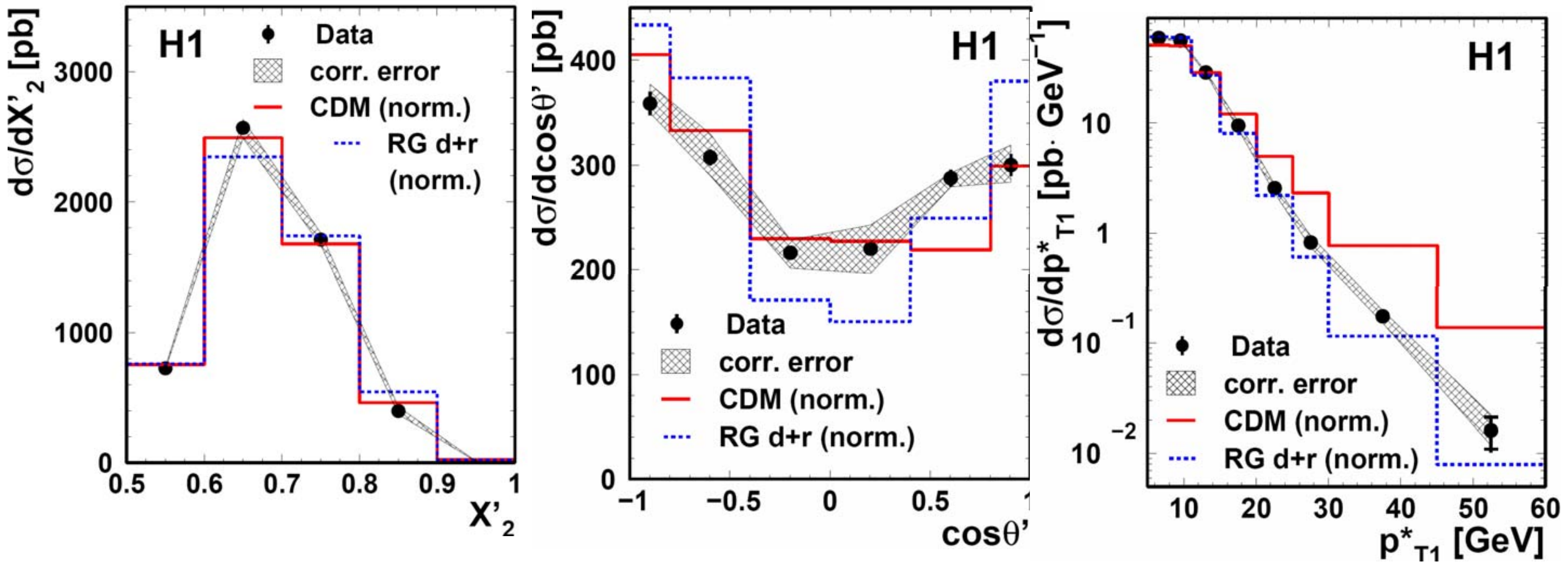
3-jet system variables $X_1{}',X_2{}',\psi', \theta'$ in NLO($\alpha_s{}^{2,3}$)





•Good description apart from slight deficit in normalisation, seen in previous plots at large pseudorapidities

3-jet system variables X_2', cos θ' and p_{T1}^* in MC



•CDM provides in general good description of 3-jet system except except transverse momentum of the leading jet

•RAPGAP in most cases fails to descibe shapes of the distributions

3-jet sample subsamples

Central jets:

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

Forward jets:

$\eta_{fj1} > 1.73$

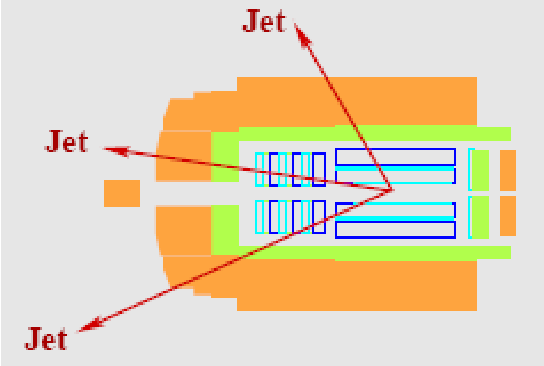
$x_{fj1} > 0.035$

$\eta_{fj2} > 1$

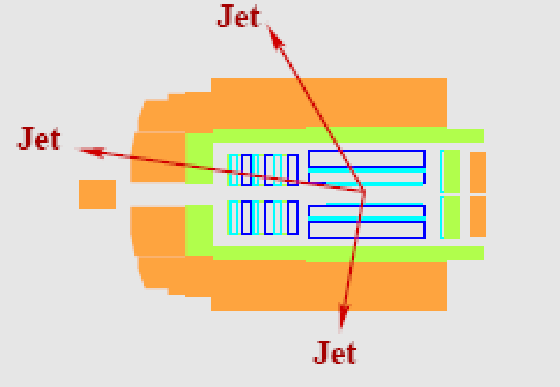
All jets:

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

2 forward + 1 central

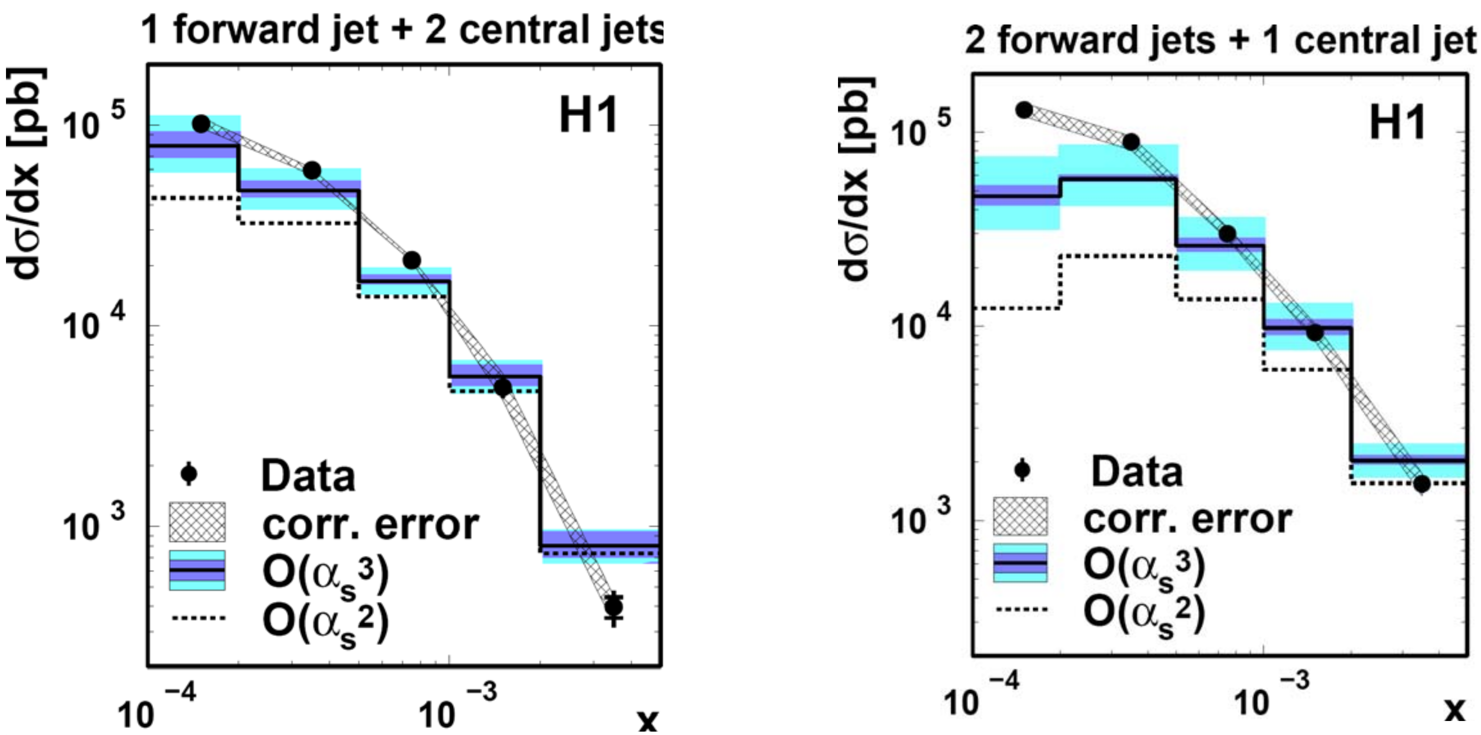


1 forward + 2 central



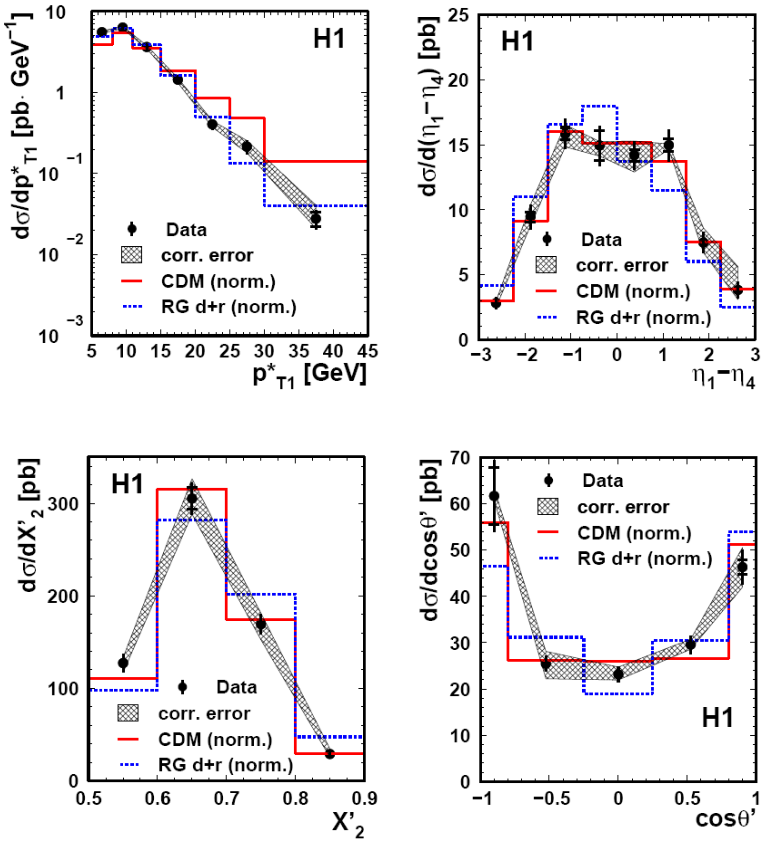
- The fraction of jets due to gluon radiation is expected (MC) to be larger for forward jets than for central jets
- **f+2c** sample will have many events with a single radiatied gluon (3-jet)
- **2f+1c** sample has a larger fraction with 2 radiated gluons (4-jet→LO)

Bjorken-x distribution of forward jet subsamples



- NLO(α_s^3) provides rather good description of 1f+2c sample
- For 2f+1c subsample dramatic improvement from O(α_s^2) to O(α_s^3). The large remaining deficiency for $x < 2 \bullet 10^{-4}$ is significant
- 2f+1c sample in large part is process with 2 radiated gluons → O(α_s^3) is effectively LO calculation

Four-jet sample: comparison with MC



- CDM (LO+ k_T-unordered parton shower) provides almost perfect description of the N_{jet} >3 data sample, except p_T^* > 15 GeV
- RAPGAP(LO+ k_T-ordered parton shower) fails to describe tha data (normalization factor 2.9)

Summary and conclusions

- **Remarkable success of NLO(α_s^3) calculation by NLOJET++**
- Huge improvement w.r.t. to O(α_s^2) theory especially for large positive rapidities and small x
- There are regions of phase space where fixed order NLO DGLAP calculation O(α_s^3) cannot describe the HERA data
- LO+ p_T- unordered parton shower (Color Dipol Model) describes the data surprisingly well (except $p_T^* > 15$ GeV)
- LO+ p_T-ordered parton shower (RAPGAP) fails to describe the data