Multijet Final States at HERA

Results from ZEUS

Tim Gosau
Hamburg University
for the ZEUS Collaboration

- Multijets at low-x in DIS
- Multijets in Photoproduction
- Three-Jet Angular Correlations in DIS

ICHEP 2006, Moscow

Multijets

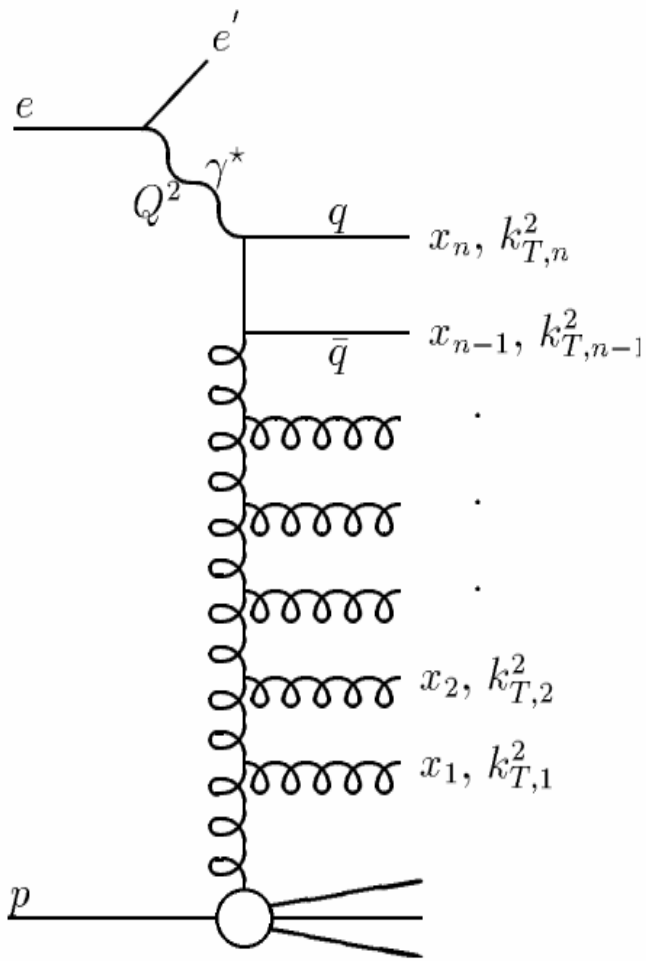
- Multijet events access parton dynamics at high order pQCD.
- Variables in Multijet systems test different fundamental QCD properties.

Analyses presented:

- Multijets at low-x in DIS
  - ➢DGLAP parton evolution at low-x_{Bj}
- Multijets in Photoproduction
  - ➢3-,4-Jets in PhP
  - ➢First analysis of four-jet events in photoproduction at HERA
  - ➢Test/tune MPI-models
- Three-Jet Angular Correlations in DIS
  - ➢Test underlying gauge symmetry

Multijets at low-x in DIS

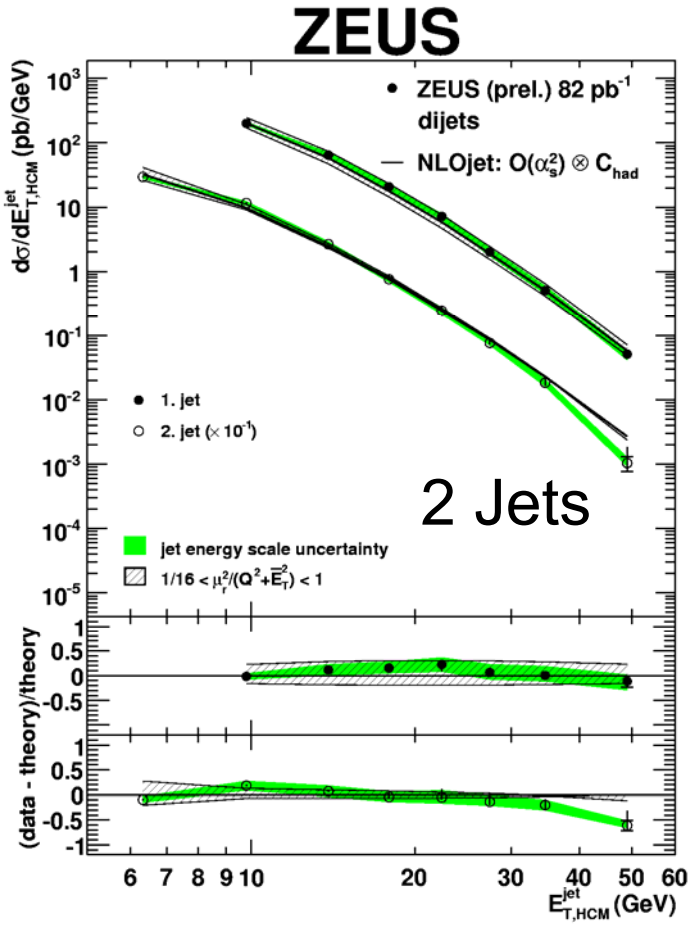
- DGLAP evolution sums over $\ln(Q^2)$ terms.
  - ➢predicts strong ordering of cascading partons in k_T and x
  - ➢well tested at medium to high Q^2.
- Examine QCD evolution at
  - ➢low-x_{Bj} ($10^{-4} < x_{Bj} < 10^{-2}$)
  - ➢low-Q^2 ($10\ GeV^2 < Q^2 < 100\ GeV^2$).
- Study angular correlations between two highest-E_T jets in hadronic-center-of-mass frame

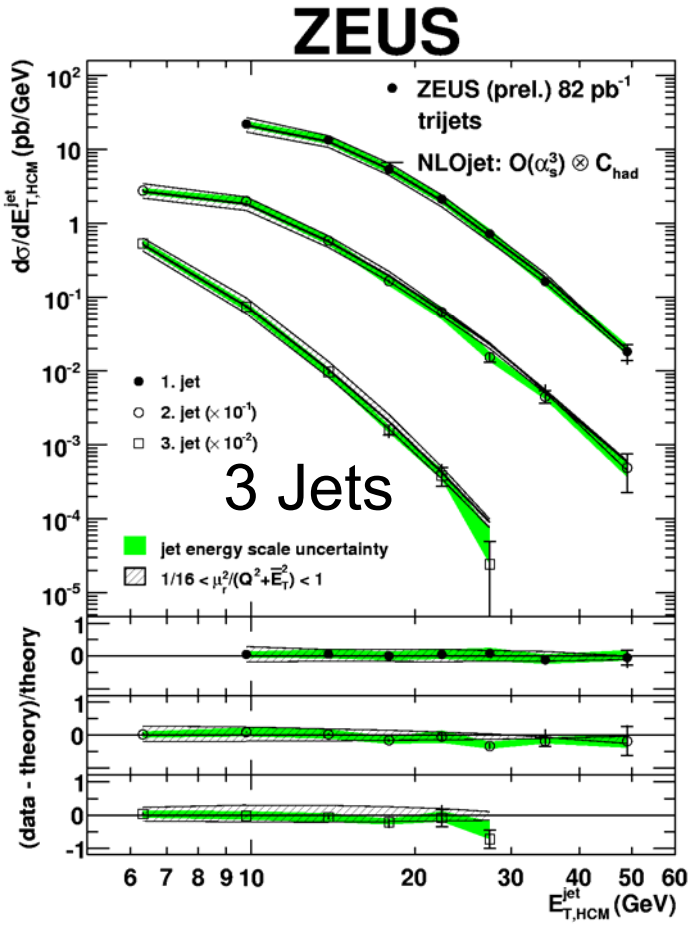


Jet selection:
2(3) jets in HCM frame
- E_T > 7/5/5 GeV
- $-1.0 < \eta_{jet,lab} < 2.5$

NLO Calculation:
- NLOjet
- $O(\alpha_s^2)$ for Dijets
- $O(\alpha_s^3)$ for Trijets
- $O(\alpha_s^3)$ for Dijets in a restricted phase space

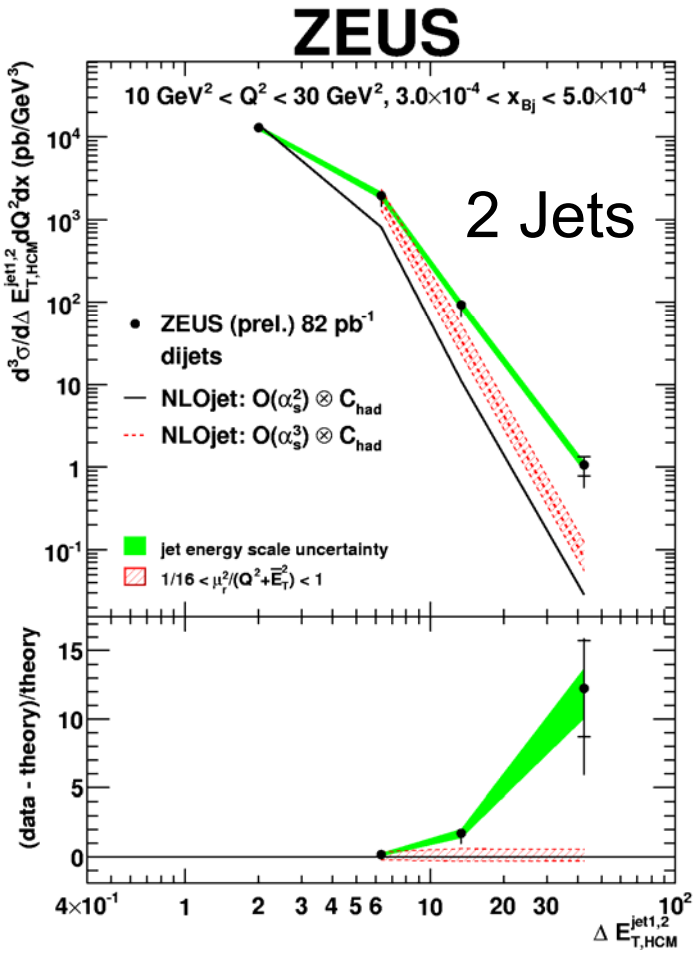
Di-,Trijet cross sections vs. Jet-E_T^{HCM}

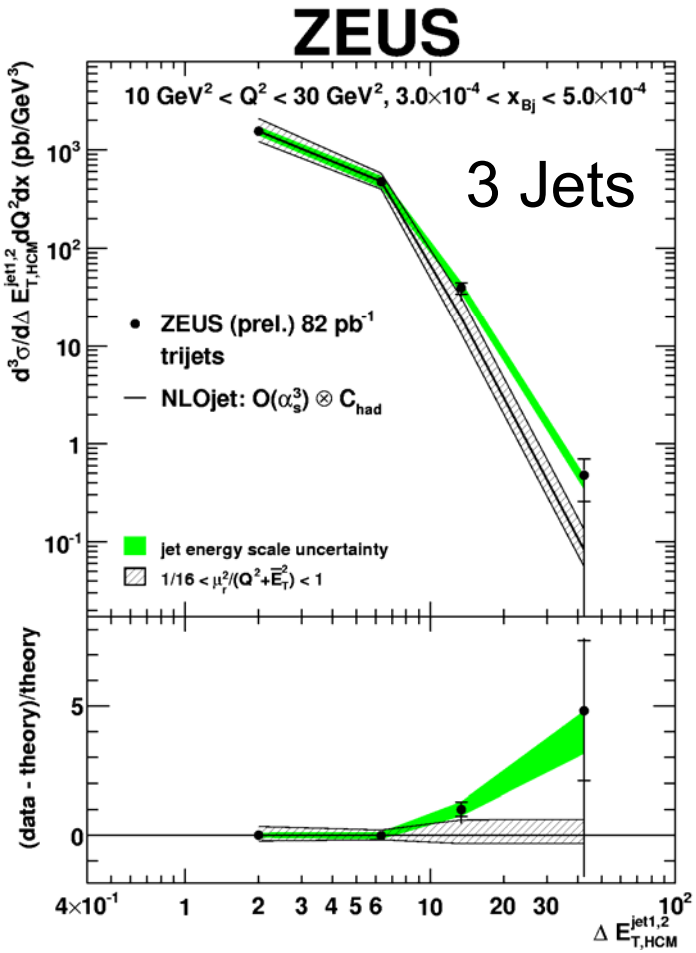




NLOjet describes data well, except at highest $E_{T,jet2(3)}$

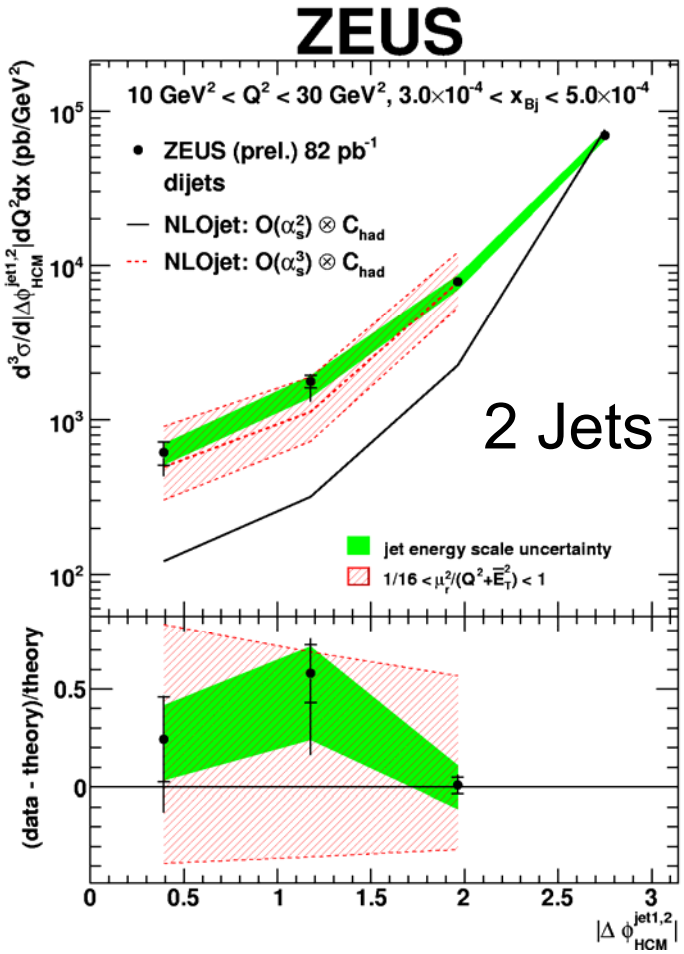
ΔE_T^{HCM} btw 2 highest-E_T Jets

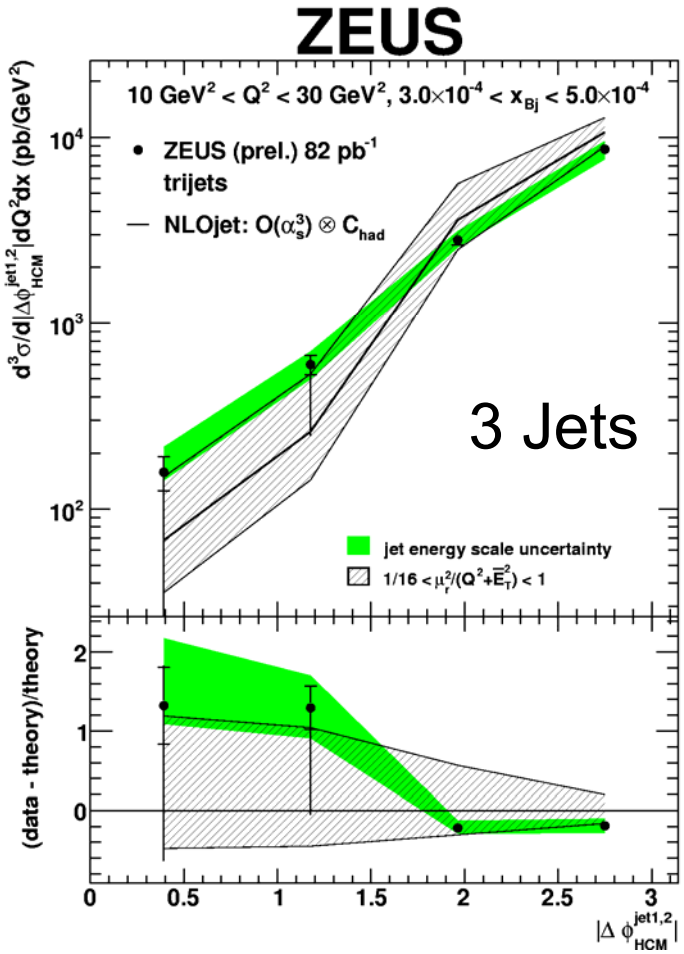




NLOjet at lowest order does not describe ΔE_T at high ΔE_T,
NLOjet $O(\alpha_s^3)$ gives slight improvement for dijets.

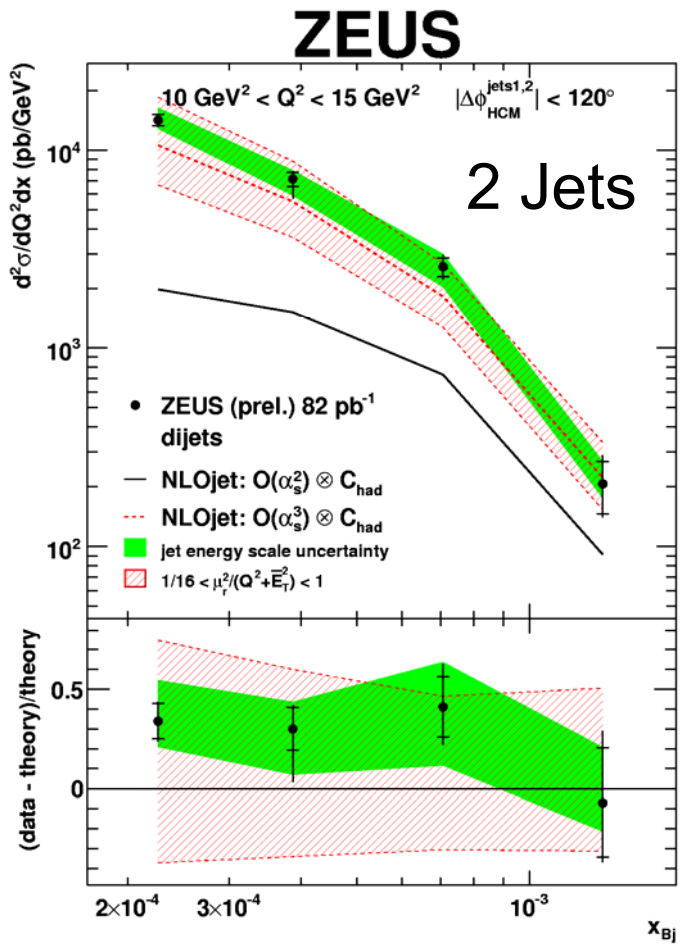
$|\Delta\Phi^{HCM}|$ btw 2 highest-E_T Jets

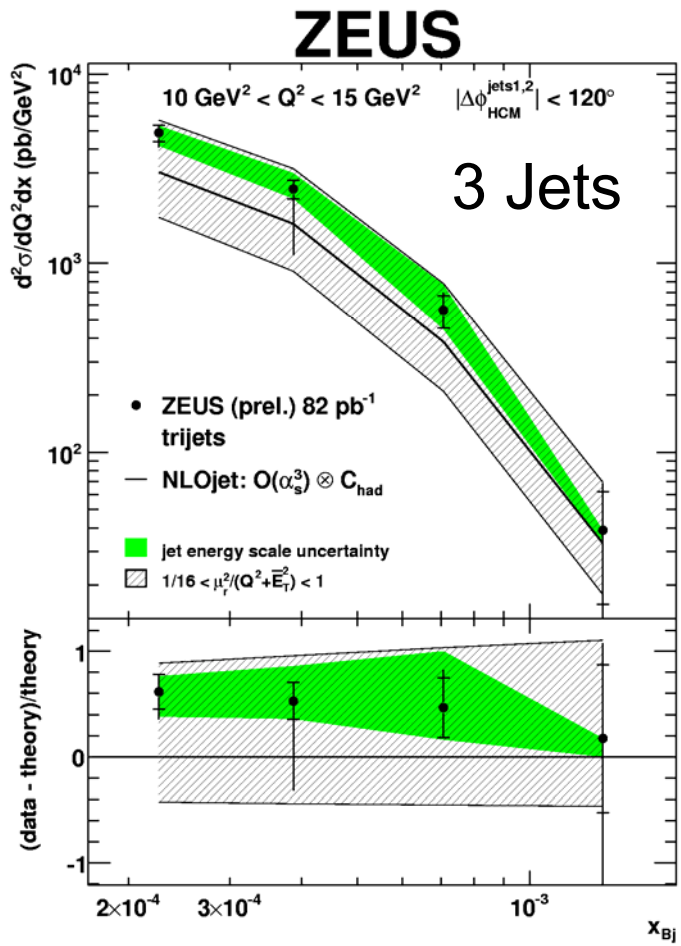




NLOjet at $O(\alpha_s^3)$ describes data

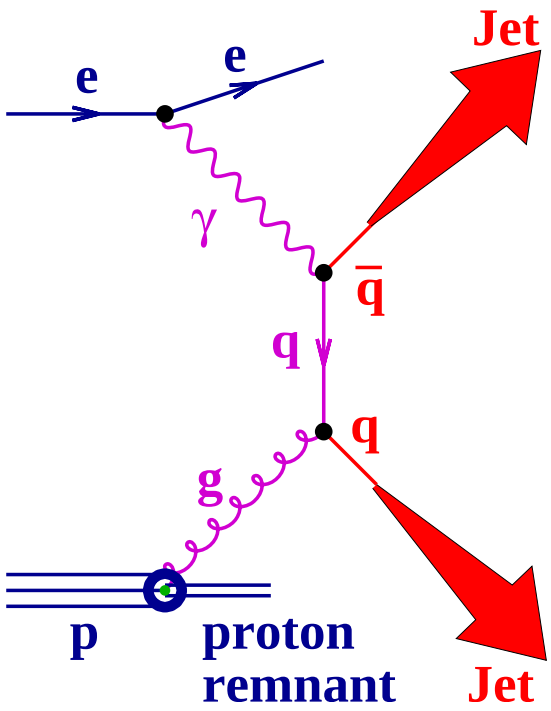
Di-,Trijets for $|\Delta\Phi^{HCM}| < 120°$





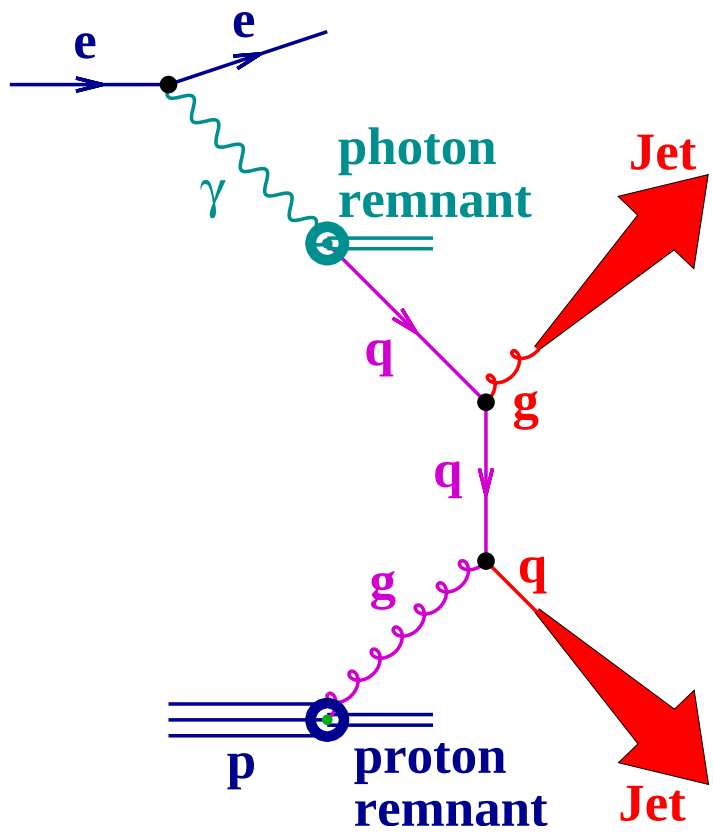
NLOjet at $O(\alpha_s^3)$ describes data

Jets in Photoproduction



direct

$x_\gamma^{obs} \approx 1$

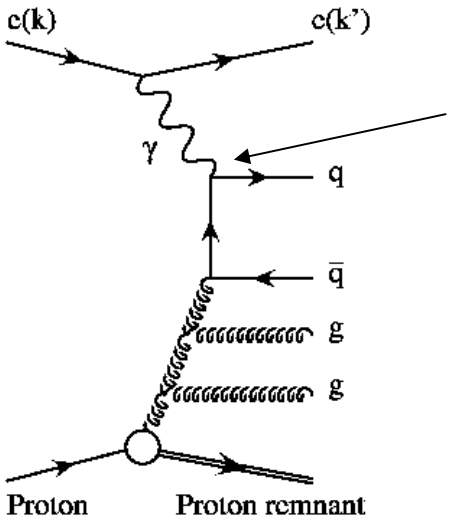


resolved

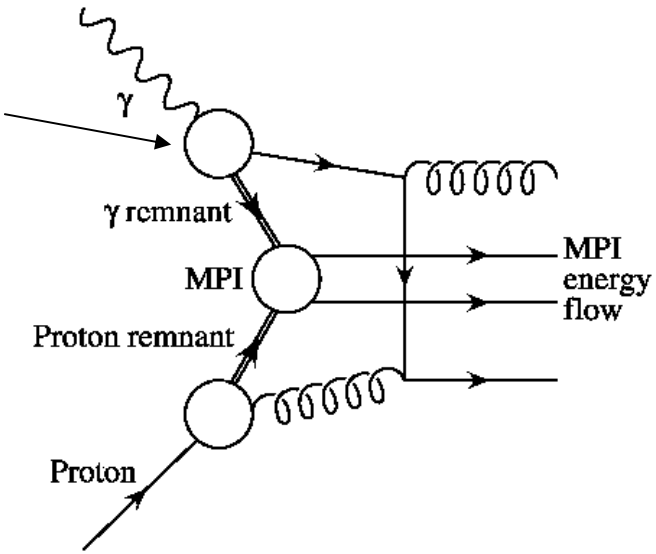
$x_\gamma^{obs} < 1$

Multijets in Photoproduction 3-,4-Jet production

First Measurement of 4-Jet Events in PHP
at HERA examines higher order QCD



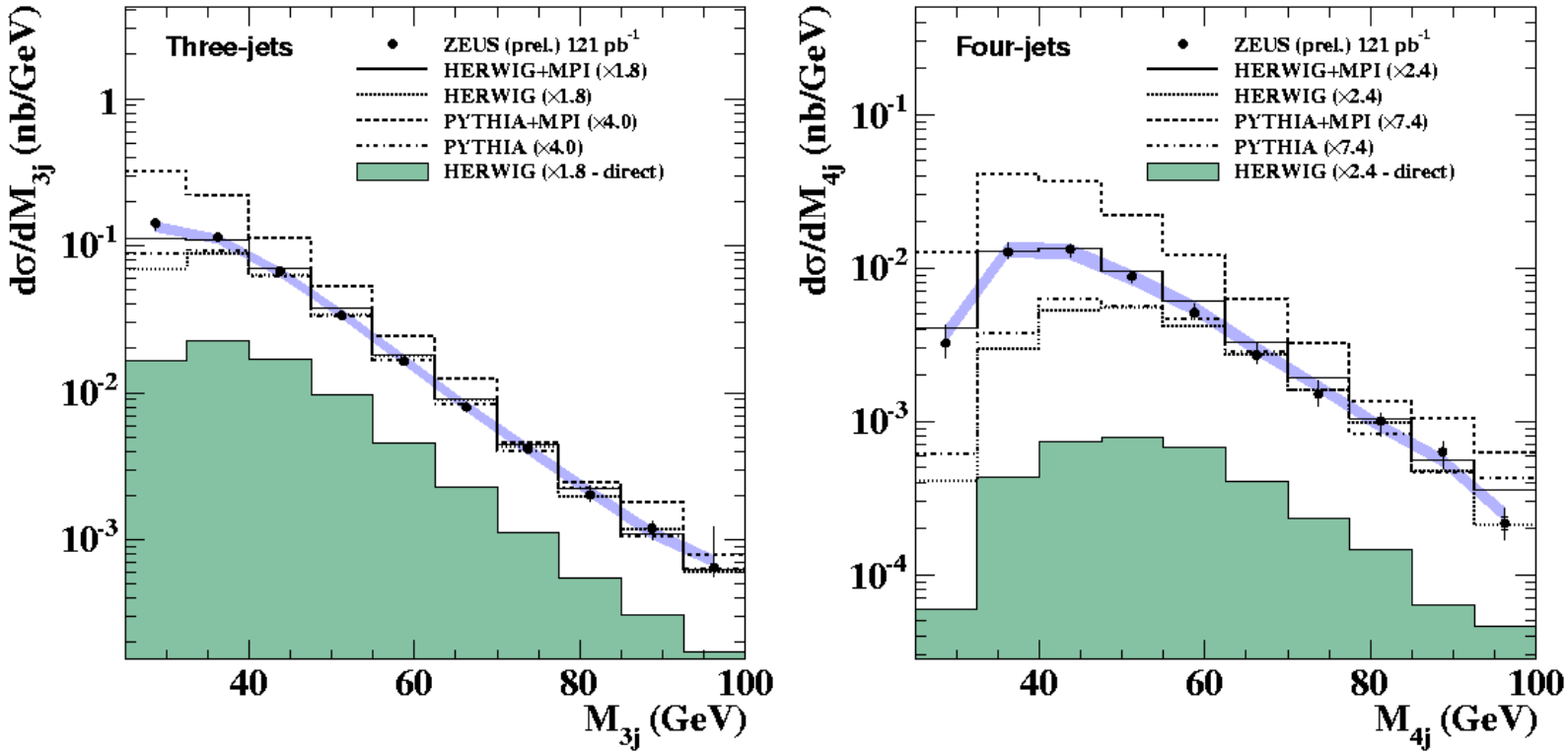
direct resolved
Photoproduction



lowest order to 4-Jet process
- access higher orders

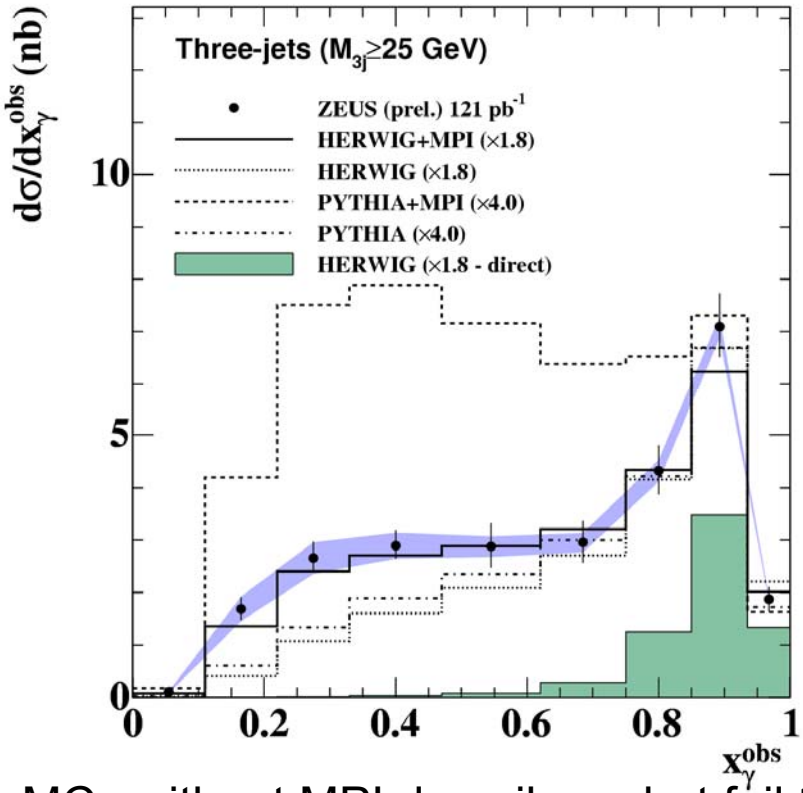
MPI contribution to 4-Jet events
- test of MPI in „clean“ hadronic - induced reaction

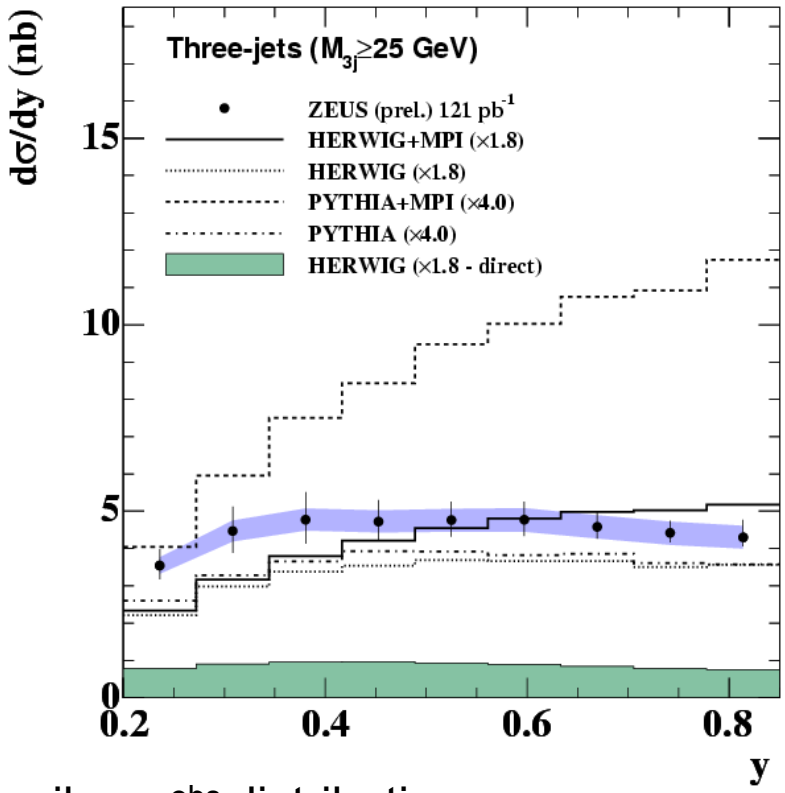
Multijets in PHP
3,4-Jet cross section vs. M_{nj}



- For $M_{3j(4j)}$ > 50(70) GeV MCs describe data without MPI
- MC without MPI normalized to data for M_{nj} > 70 GeV
- HERWIG with tuned MPI describes data well
- PYTHIA with MPI overestimates cross section

Multijets in PHP
MC and MPI



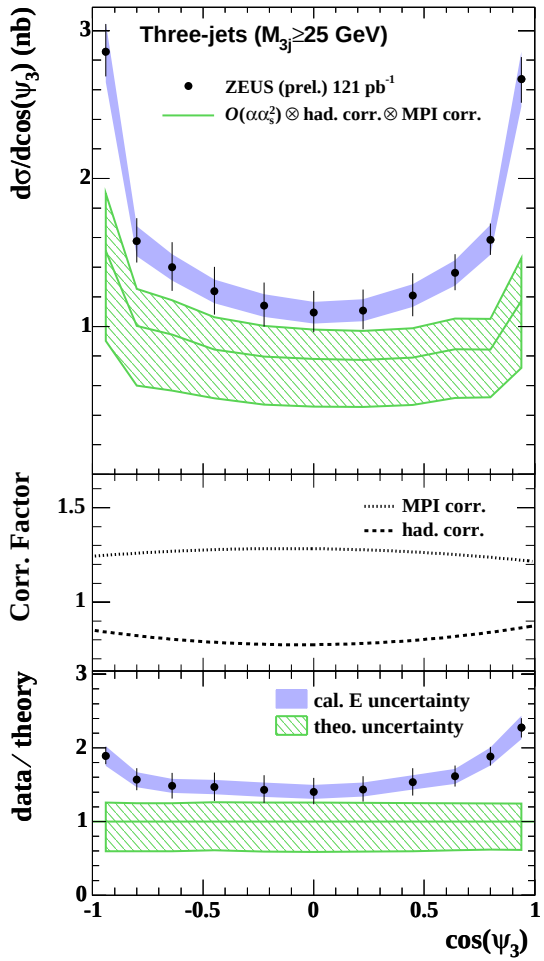


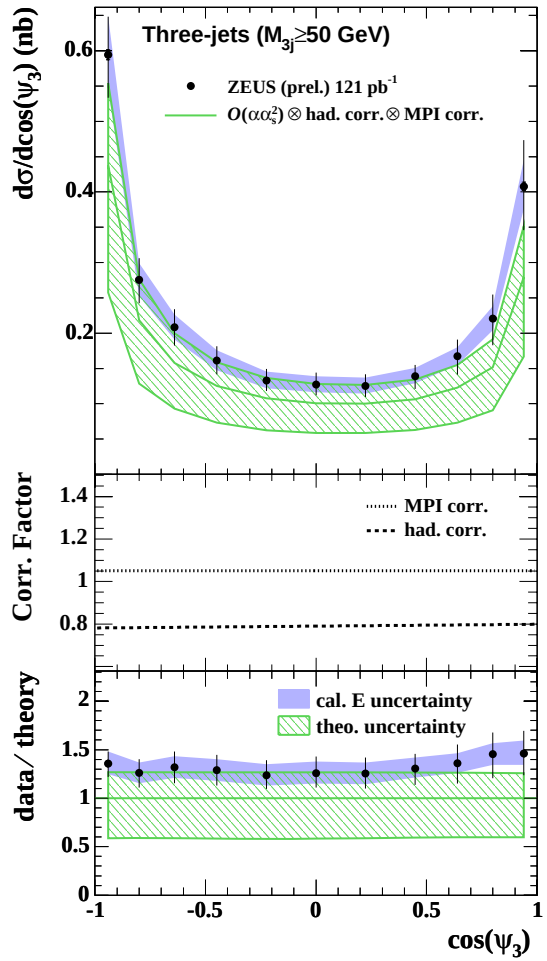
- MCs without MPI describe y, but fail to describe x_γ^{obs} distribution
- PYTHIA: MPI tuned to generic collider data, HERWIG: MPI tuned to describe x_γ^{obs}
- HERWIG+MPI describes x_γ^{obs}, y not described anymore
- PYTHIA+MPI does not describe data
- x_γ^{obs} and y distribution: ideal ground for tuning and testing MPI models

Multijets in PHP

$\cos(\psi_3)$ reflects orientation of lowest energy jet

- directly sensitive to $O(\alpha_s^2)$





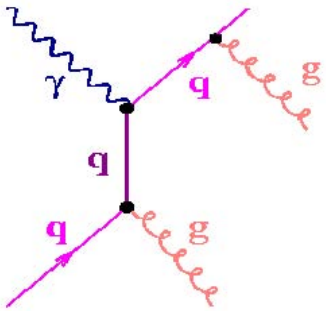
$O(\alpha\alpha_s^2)$ pQCD (corrected for hadronization and MPIs) describes high mass region.

Angular Correlations of 3-Jets in DIS

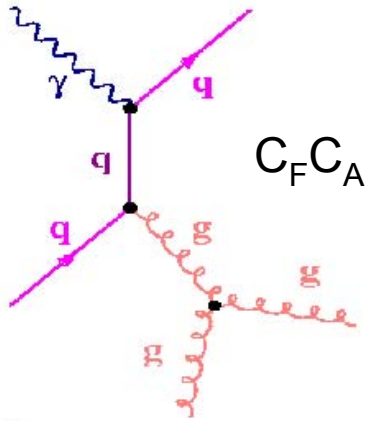
At $O(\alpha\alpha_s^2)$ calculations of three-jet cross sections the color factors control the rates of these processes:

$$\sigma_{ep\to 3jets} = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$

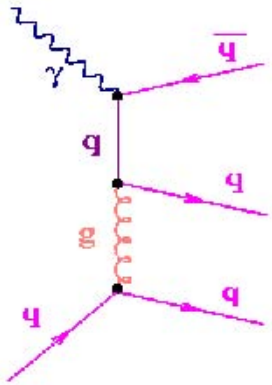
A) C_F^2



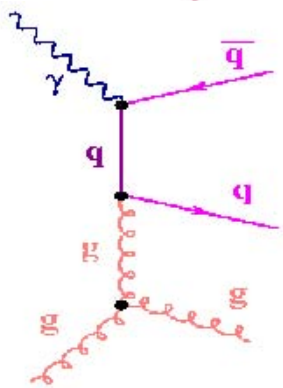
B) $C_F C_A$



C) $C_F T_F$



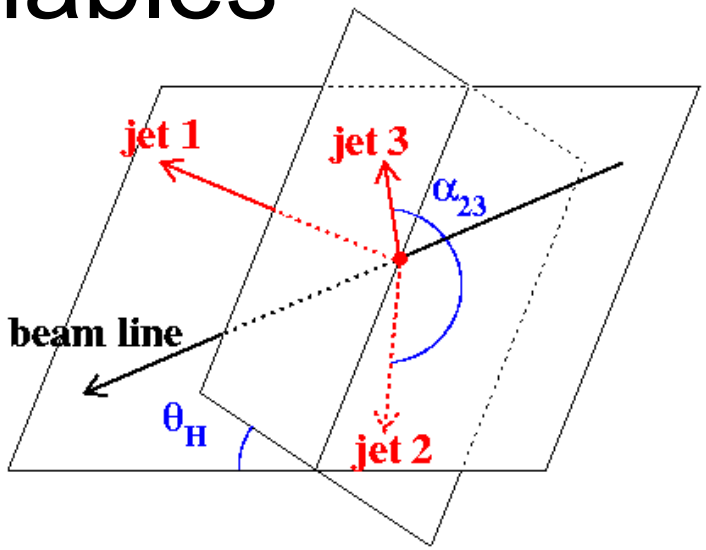
D) $T_F C_A$



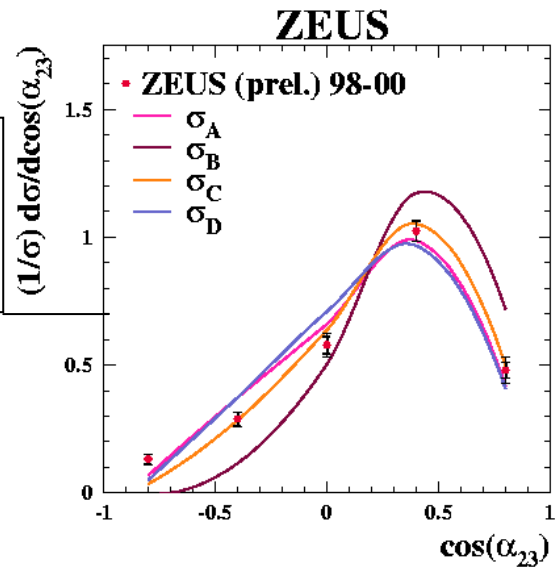
- SU(3) (QCD):
  $C_A/C_F = 9/4$, $T_F/C_F = 3/8$
- Abelian gluon model based on $U(1)^3$ (no gluon self-coupling):
  $C_A/C_F = 0$, $T_F/C_F = 3$
- SO(3):
  $C_A/C_F = 1$, $T_F/C_F = 1$
- SU(N):
  $C_A = N_C$, $C_F = \frac{N_C^2 - 1}{2N_C}$, $T_F = 1/2$

Angular Correlations Definition of Variables

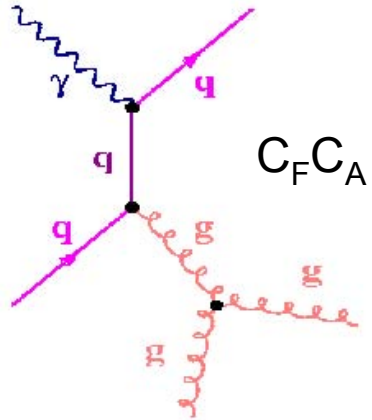
- Θ_H: angle between the plane determined by the highest-E_T jet and the beam, and the plane of the two lowest-E_T jets
- α_{23}: angle between the lowest-E_T jets
- $\cos(\beta_{KSM})$: $\cos\left[\frac{1}{2}\left(\angle[(\vec{p}_1\times\vec{p}_3),(\vec{p}_2\times\vec{p}_B)]+\angle[(\vec{p}_1\times\vec{p}_B),(\vec{p}_2\times\vec{p}_3)]\right)\right]$
- η^{jet}_{max}: η of the most forward jet of the three-jet system in the Breit frame



Shapes of different processes contributing to $\cos(\alpha_{23})$ cross section



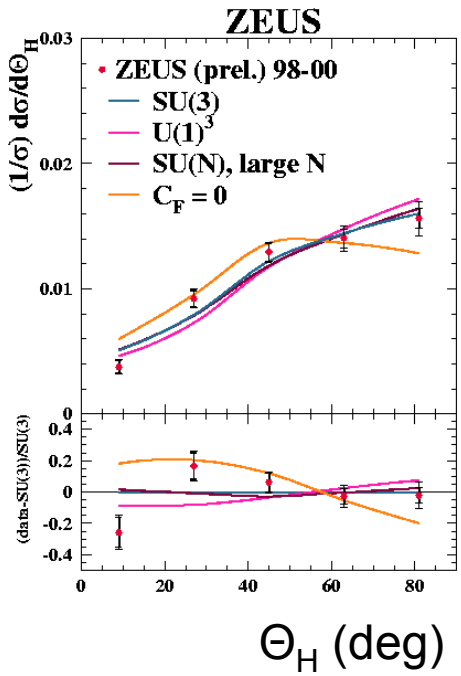
B)



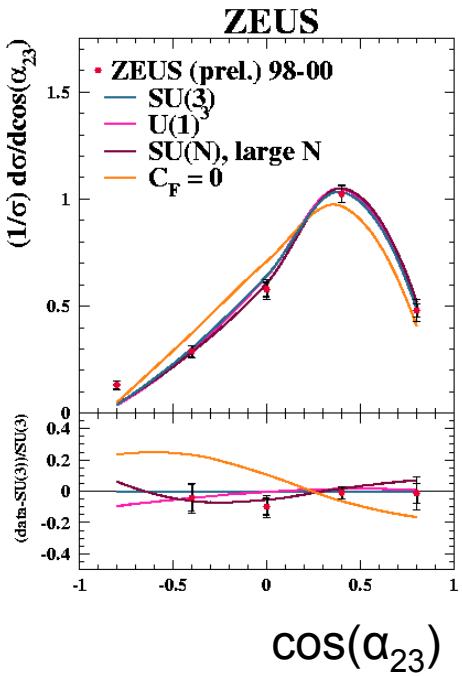
$C_F C_A$

Data: 81.7pb^{-1}
$Q^2 > 125$ GeV^2, $|\cos(\gamma_h)| < 0.65$
3 Jets in Breit frame with
$E_T > 8/5/5$ GeV, $-2 < \eta < 1.5$

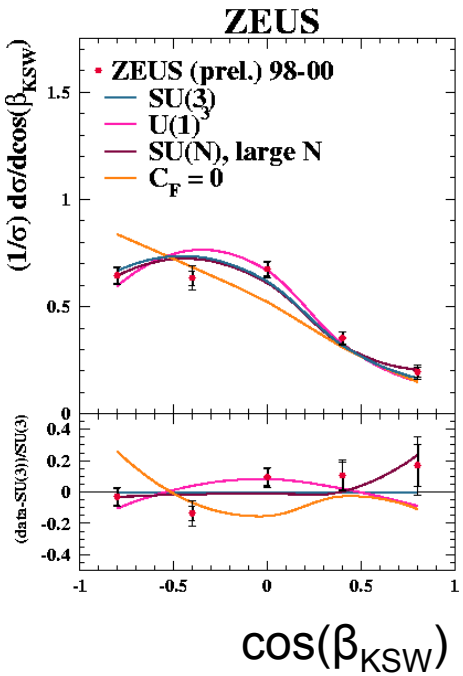
Angular Correlations Comparison to theory



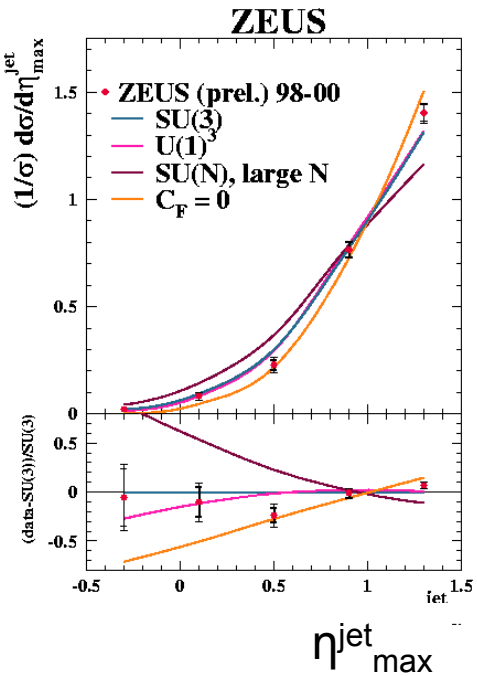
Θ_H (deg)



$\cos(\alpha_{23})$



$\cos(\beta_{KSW})$



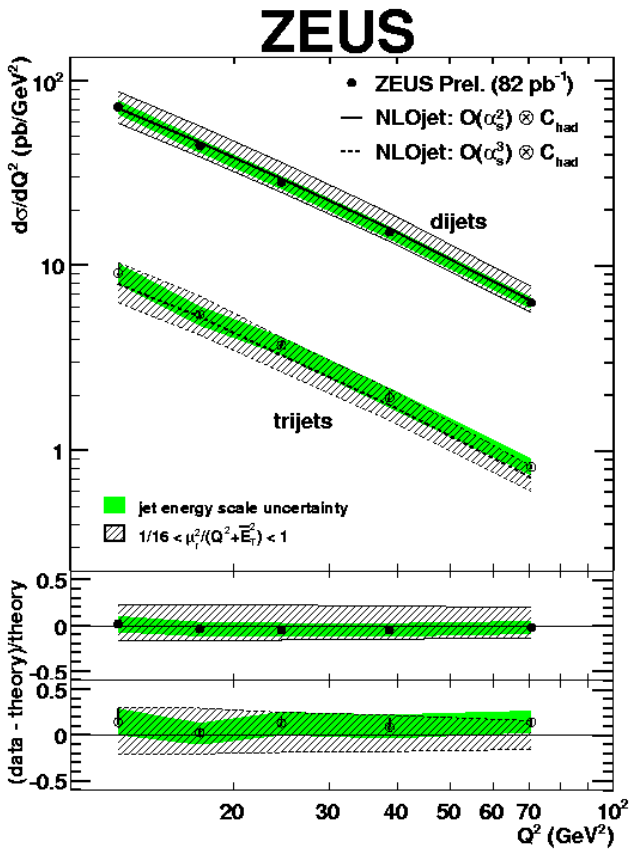
η^{jet}_{max}

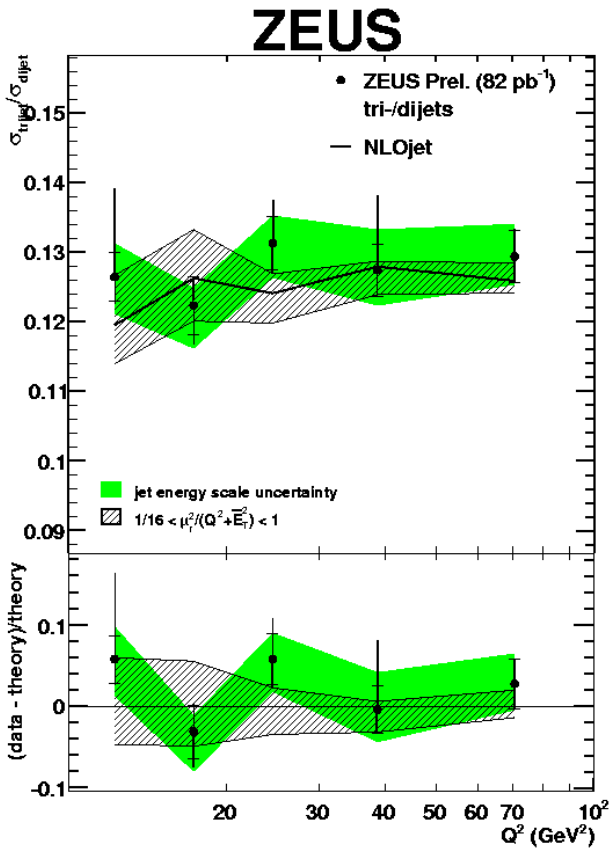
- Data reasonably described by SU(3)
- Differences to $U(1)^3$ are of the order of the statistical error
- Prediction with $C_F = 0$ doesn't describe shape of data
- SU(N) in large-N limit ($\rightarrow T_F/C_F \approx 0$) fails to describe η^{jet}_{max} distribution

Summary – ZEUS Multijets

- Multijets at low-x in DIS
  - NLOjet (DGLAP based pQCD) at $O(\alpha_s^2)$ does not describe dijet cross section with low azimuthal separation
  - Including another order of α_s improves NLOjet agreement for dijets
  - High-$\Delta E_{T,jets}$ tail of the data is not described for di-, trijets
    - improvement shown with higher order for dijets
- Multijets in Photoproduction
  - First measurement of 4-jets in photoproduction
  - HERWIG+MPIs describes data well
  - $O(\alpha\alpha_s^2)$ pQCD describes three-jets for $M_{3j} > 50$ GeV
- Three-Jet Angular Correlations in DIS
  - Sensitivity to different color components allows access to underlying gauge group
  - SU(3) gives a reasonable description of data
  - Calculations with $T_F/C_F \approx 0$ or $C_F = 0$ disfavored

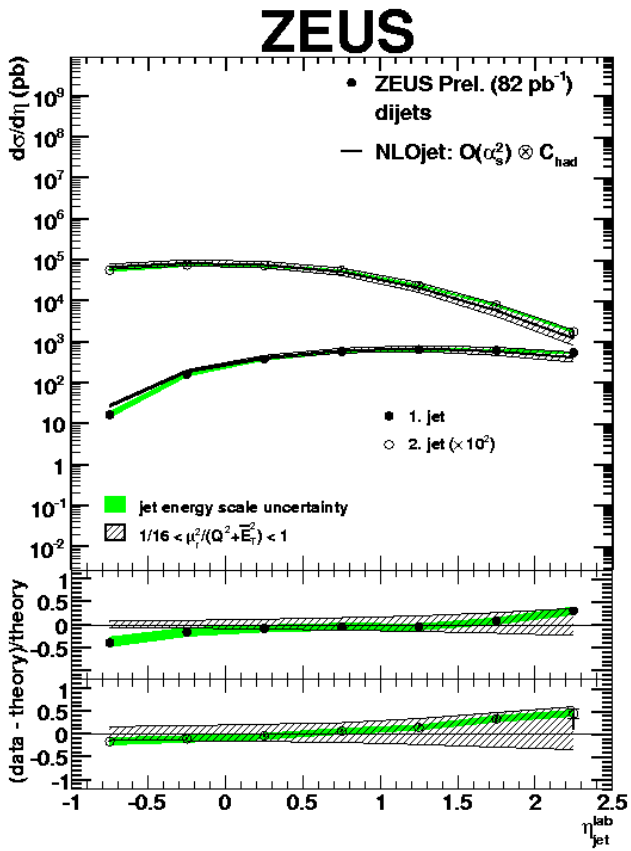
Di-,Trijet cross sections vs. Q^2

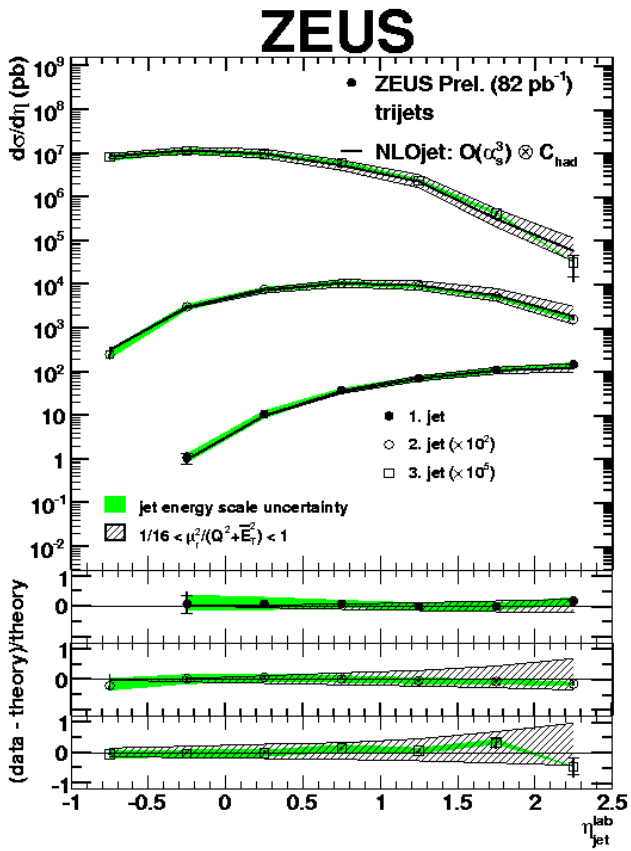




Dijet and Trijet cross sections described by NLOjet within uncertainties.

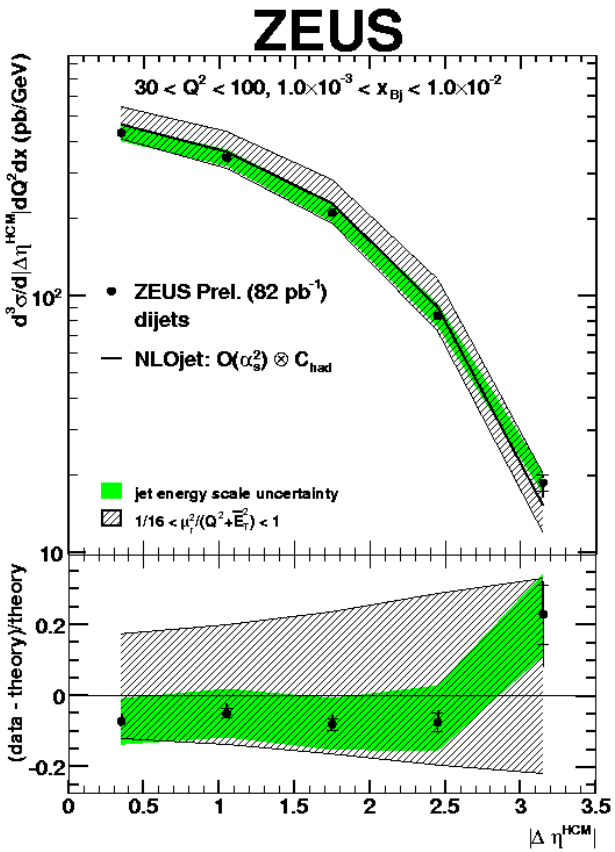
Di-,Trijet cross sections vs. Jet-η

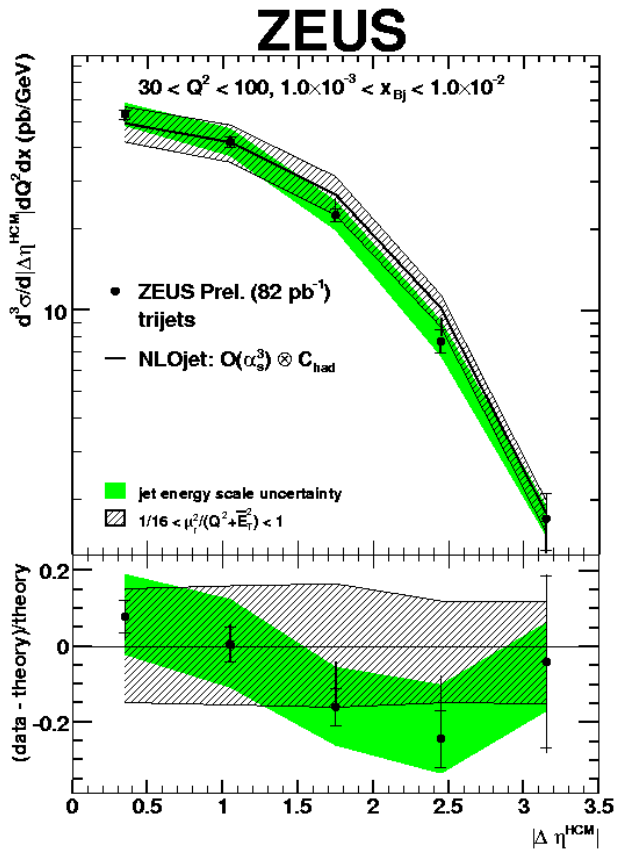




Jet-η well described within uncertainties

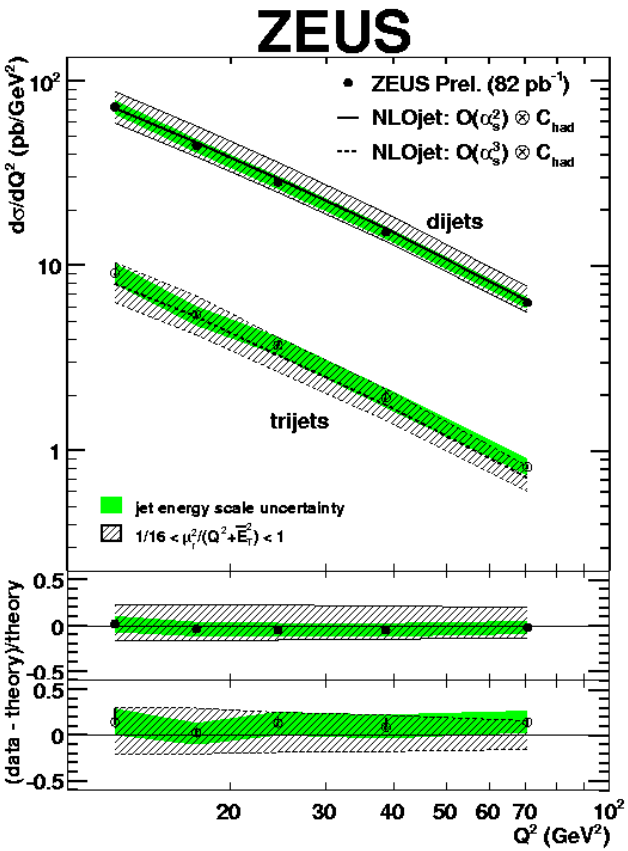
$\Delta\eta^{HCM}$ btw 2 highest-E_T Jets



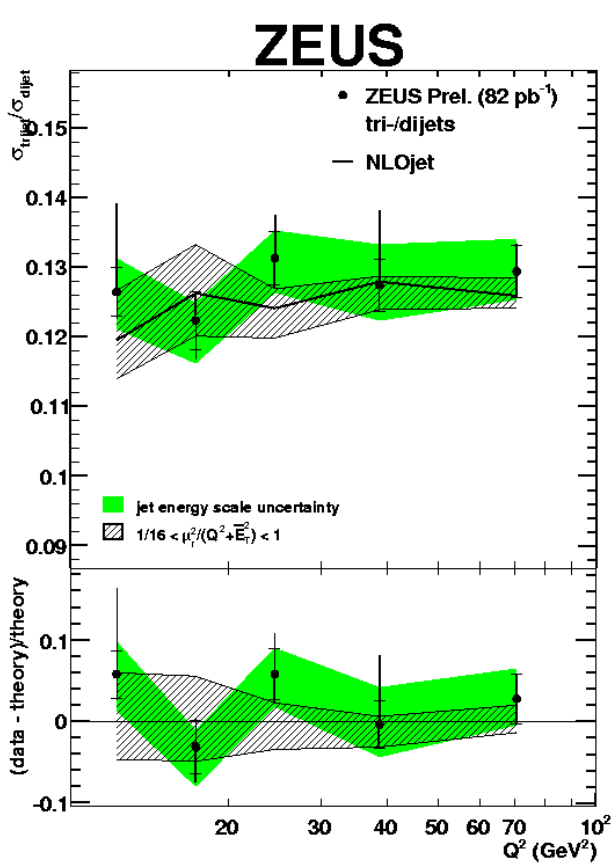


NLOjet consistent within large uncertainties

Di-,Trijet cross sections vs. Q^2

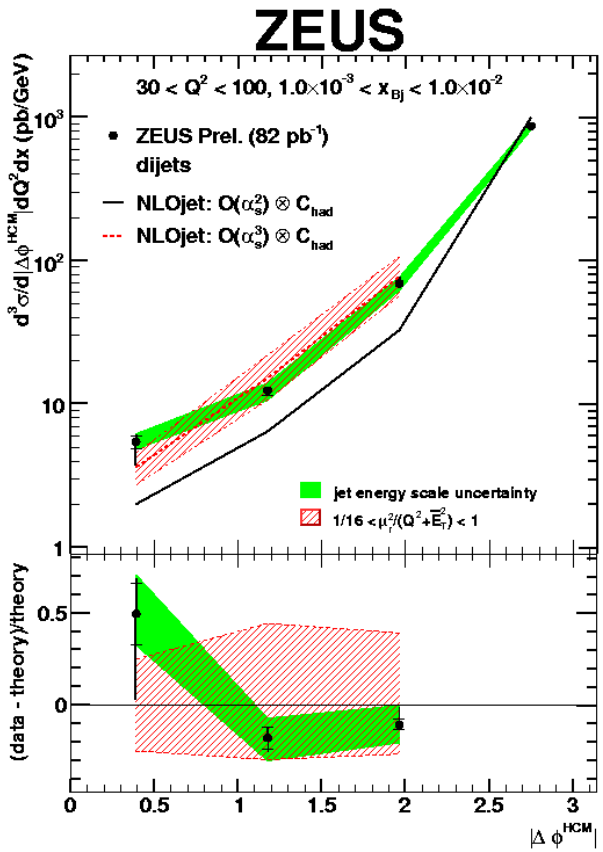


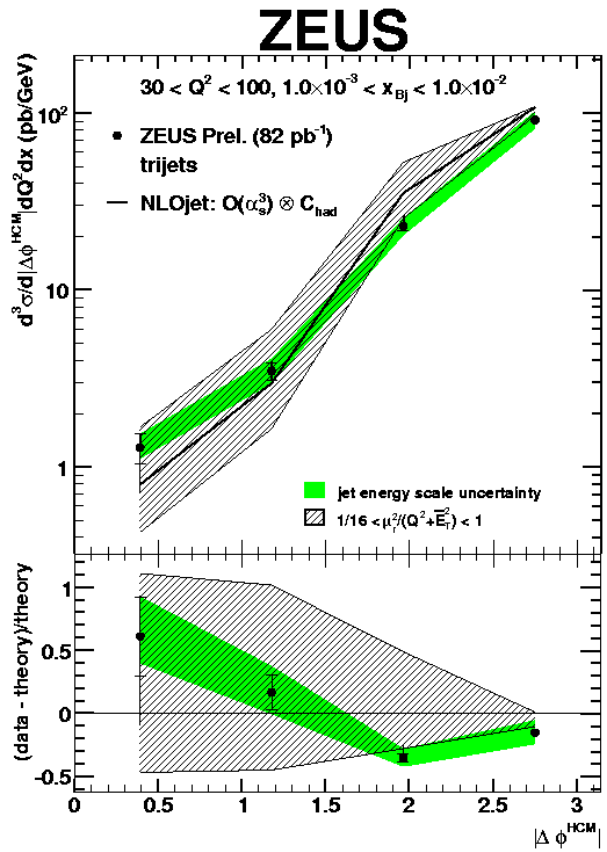
$$\frac{\text{data} - \text{theory}}{\text{theory}}$$



Dijet and Trijet cross sections described by NLOjet within uncertainties.

$|\Delta\Phi^{HCM}|$ btw 2 highest-E_T Jets





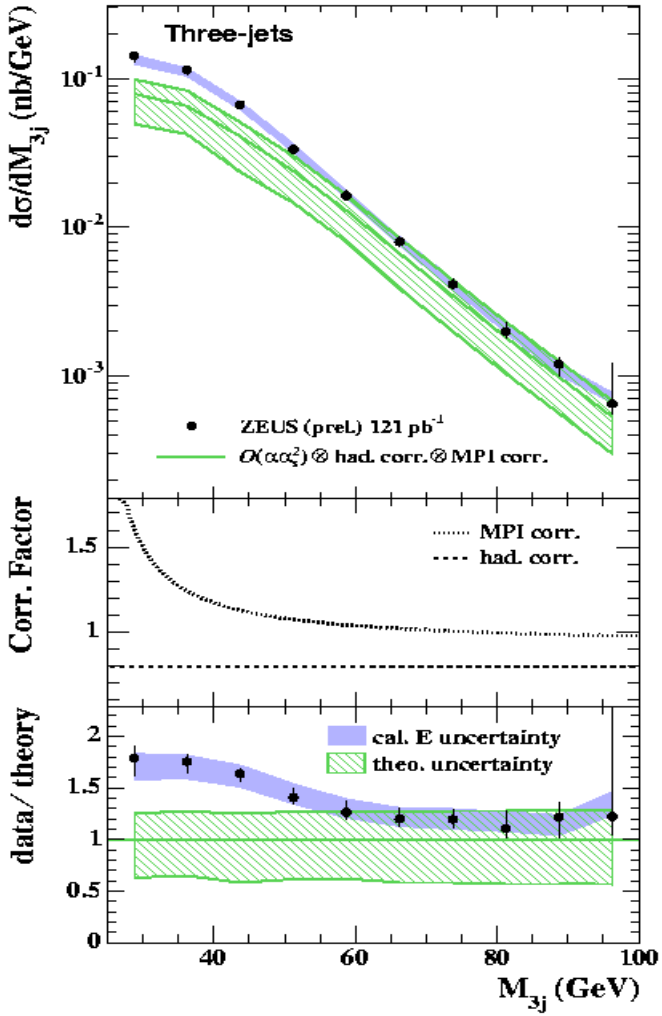
NLOjet agreement for dijets using a higher order calculation, description for trijets inside the large uncertainties

Multijets in PHP comparison to pQCD

$O(\alpha\alpha_s^2)$ pQCD (Klasen, Kleinwort, Kramer) with MPI correction from HERWIG compared to the data.

There is no calculation to compare to four-jets in PHP yet.

The calculation mostly describes data at high $M_{3j} > 50$ GeV. For lower M_{3j} the data get described worse. Reasons: missing orders or MPI?

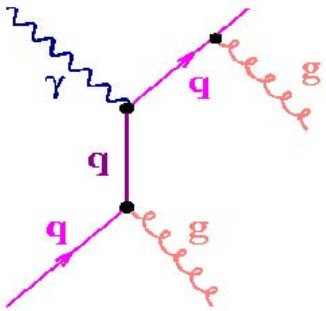


Angular Correlations of 3-Jets in DIS

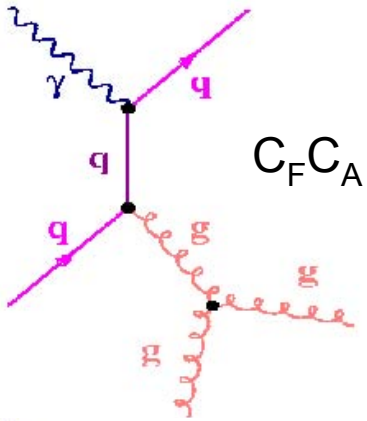
In $O(\alpha\alpha_s^2)$ calculations of three-jet cross sections the color factors control the contributions of these processes:

$$\sigma_{ep\to 3jets} = C_F^2\cdot\sigma_A + C_F C_A\cdot\sigma_B + C_F T_F\cdot\sigma_C + T_F C_A\cdot\sigma_D$$

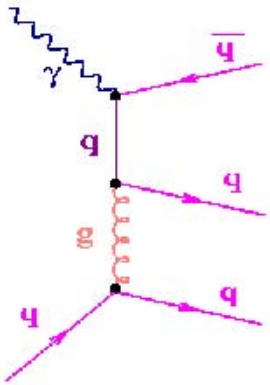
A) C_F^2



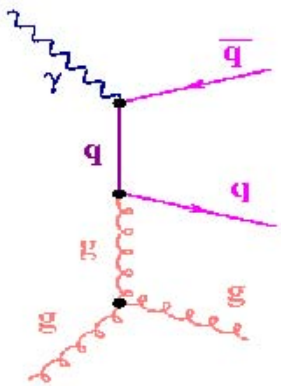
B) $C_F C_A$

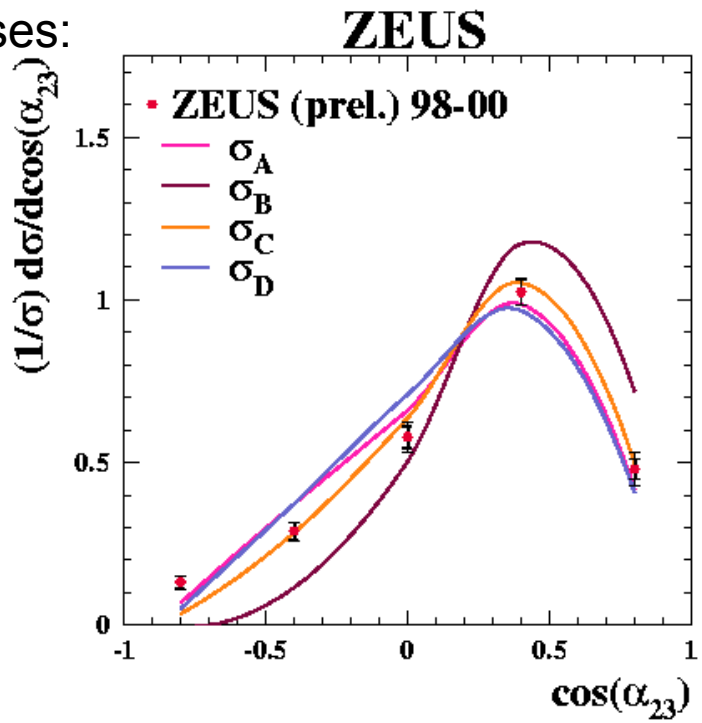


C) $C_F T_F$



D) $T_F C_A$





Data: 81.7pb^{-1}
$Q^2 > 125$ GeV^2, $|\cos(\gamma_h)| < 0.65$
3 Jets in Breit frame with
$E_T > 8/5/5$ GeV, $-2 < \eta < 1.5$