Three-Jet Angular Correlations in ep Collisions

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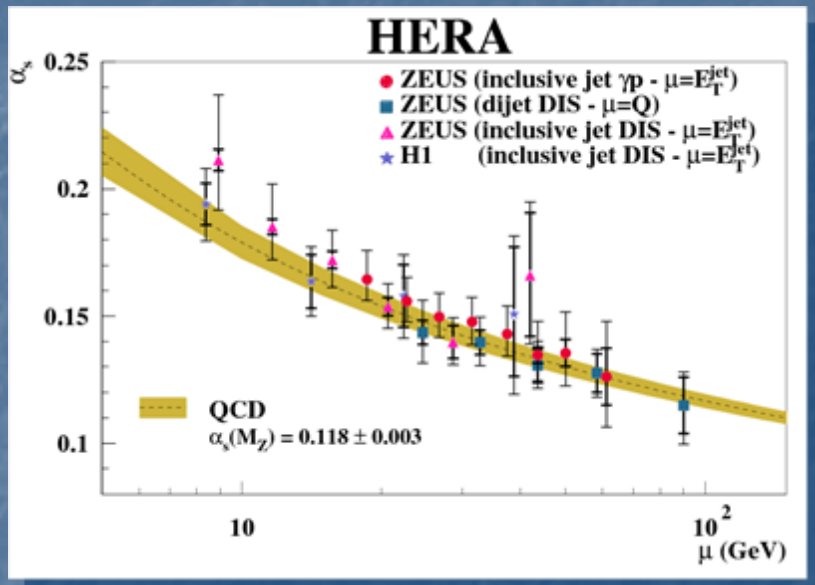
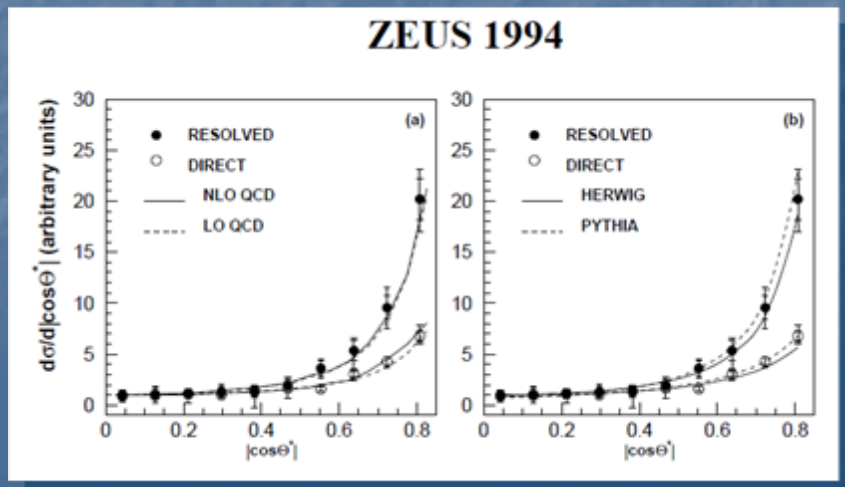
Tests of QCD at HERA

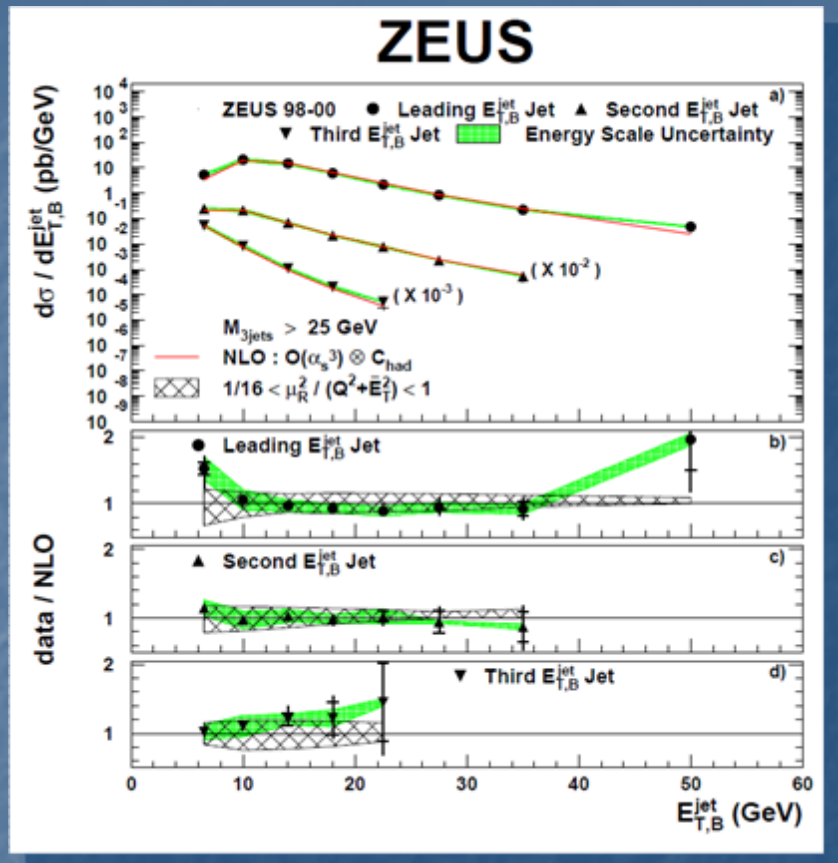
Strength of QCD interactions - α_s



Evidence for spin1 gluon propagator



Jet cross sections vs fixed-order QCD

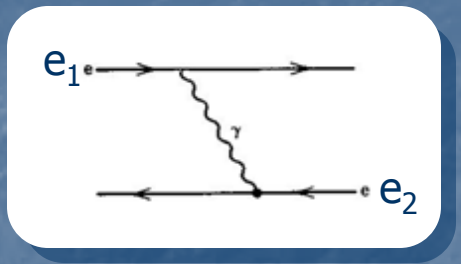


-> More fundamentals of QCD

- Color effects
- Gluon self-coupling
- Gauge group structure

Color Factors in QCD

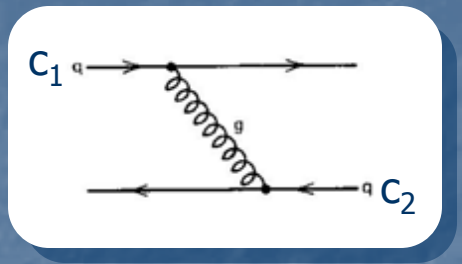
QED : γ coupling between 2 charged particles



-> $e_1 e_2 \alpha$

Abelian – photon carries no charge

QCD : gluon coupling between 2 colored quarks



-> $\frac{1}{2} c_1 c_2 \alpha_s$

Non-Abelian – gluon is colored

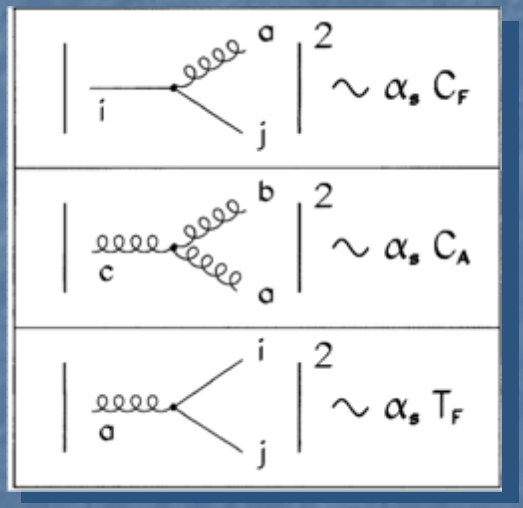
QCD Color Factors

gluon emission/absorption by a quark

gluon splitting into/forming from 2 gluons

Triple Gluon Vertex (TGV)

gluon splitting into/forming from 2 quarks

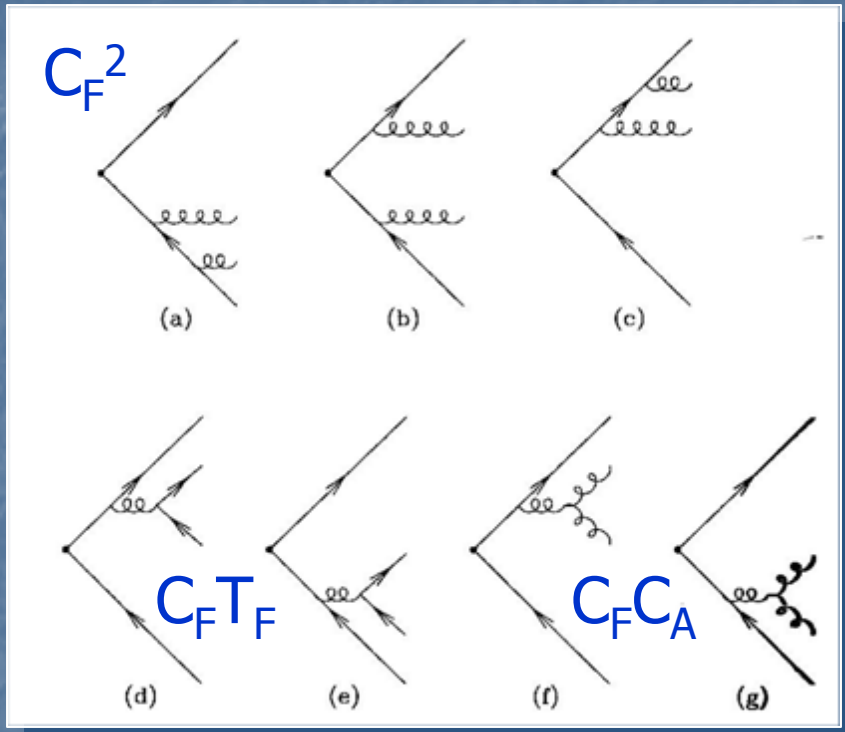


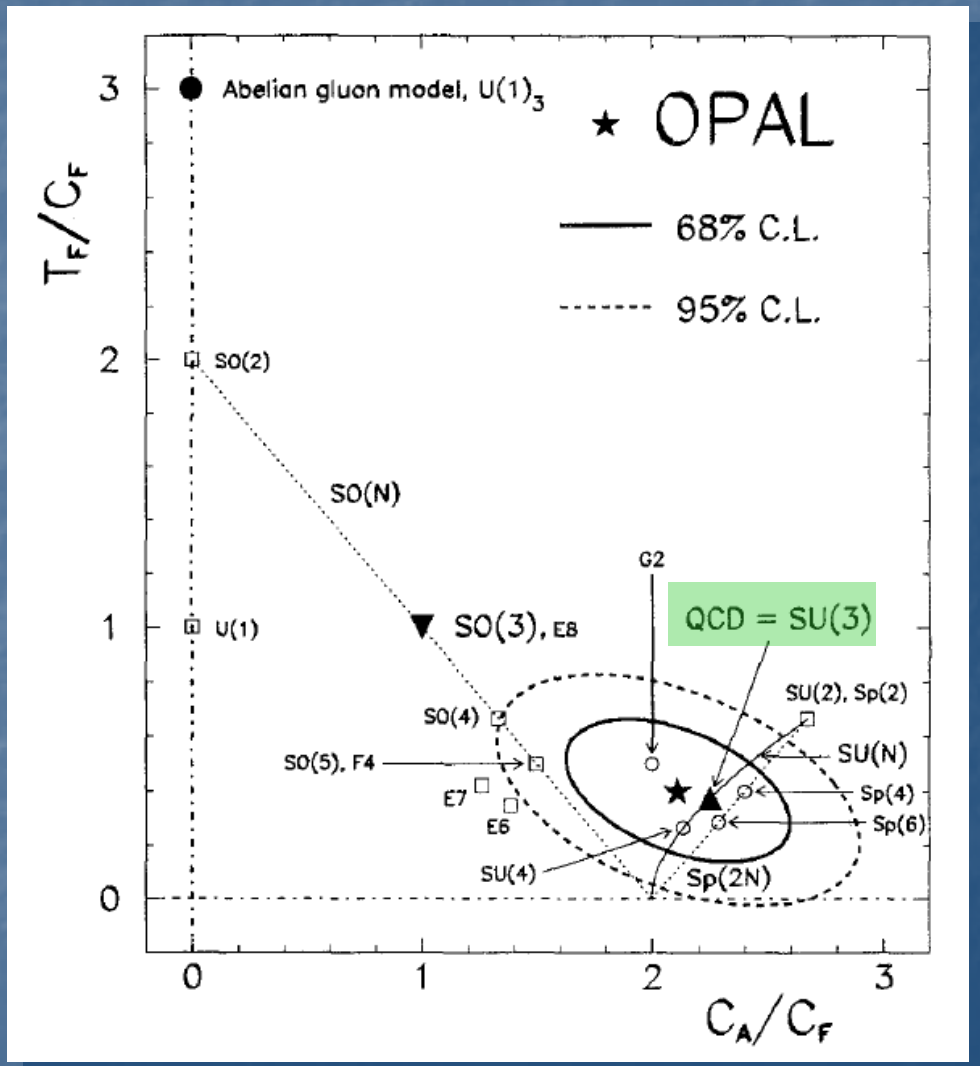
Color factors for some selected gauge groups

	Type	C_F	C_A/C_F	T_F/C_F
SU(N)	Non-Abelian	$(N^2-1)/2N$	$2N^2/(N^2-1)$	$N/(N^2-1)$
SU(3) QCD	Non-Abelian	4/3	9/4	3/8
$U(1)^3$	Abelian	1	0	3
SO(3)	Non-Abelian	1/3	1	1

Color Factors in 4-Jet Events at LEP

4-jet processes in e^+e^- events at LEP





Color Factor ratio results :

$$C_A/C_F = 2.11 \pm 0.16\,(\text{stat.}) \pm 0.28\,(\text{syst.})$$
$$T_R/C_F = 2.01 \pm 0.54\,(\text{stat.}) \pm 0.68\,(\text{syst.})$$

$$T_F/C_F = 0.40 \pm 0.17$$

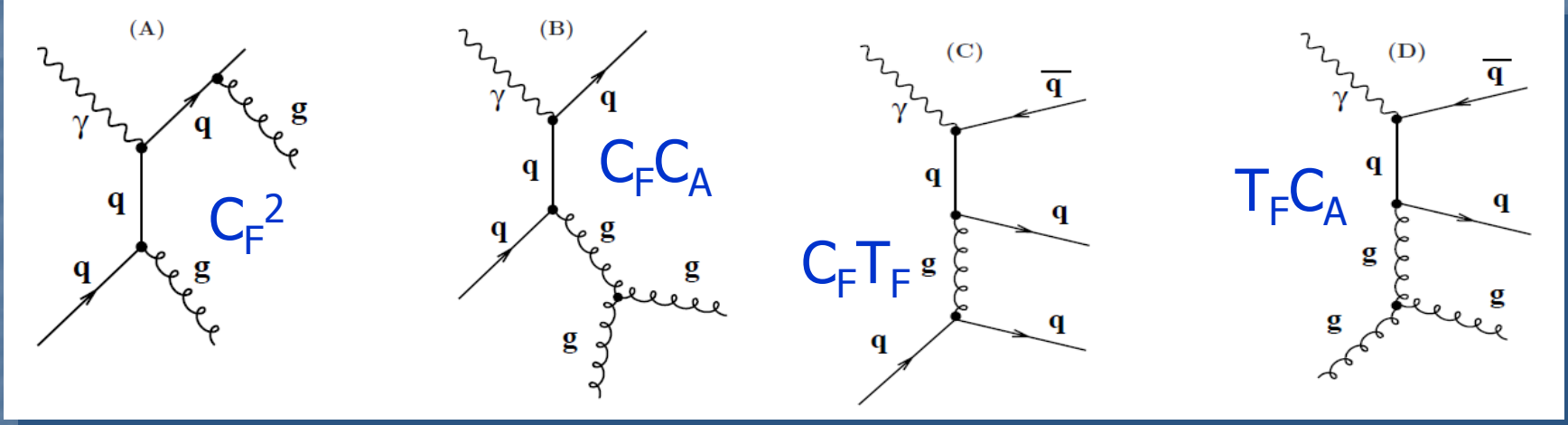
~22K 4-jet events

Color Factors in 3-Jet Events at HERA

3-Jet events from Direct γp^* and DIS can be used to test the properties of the underlying gauge group, e.g. QCD as SU(3), determined by combinations of the appropriate color factors.

* Resolved γp with 2 jets has the TGV contribution, but it is difficult to distinguish these from 2-jet events with no TGV

Process diagram classes for DIS and Direct γp :



3-Jet cross section at leading order (α_s^2) :

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

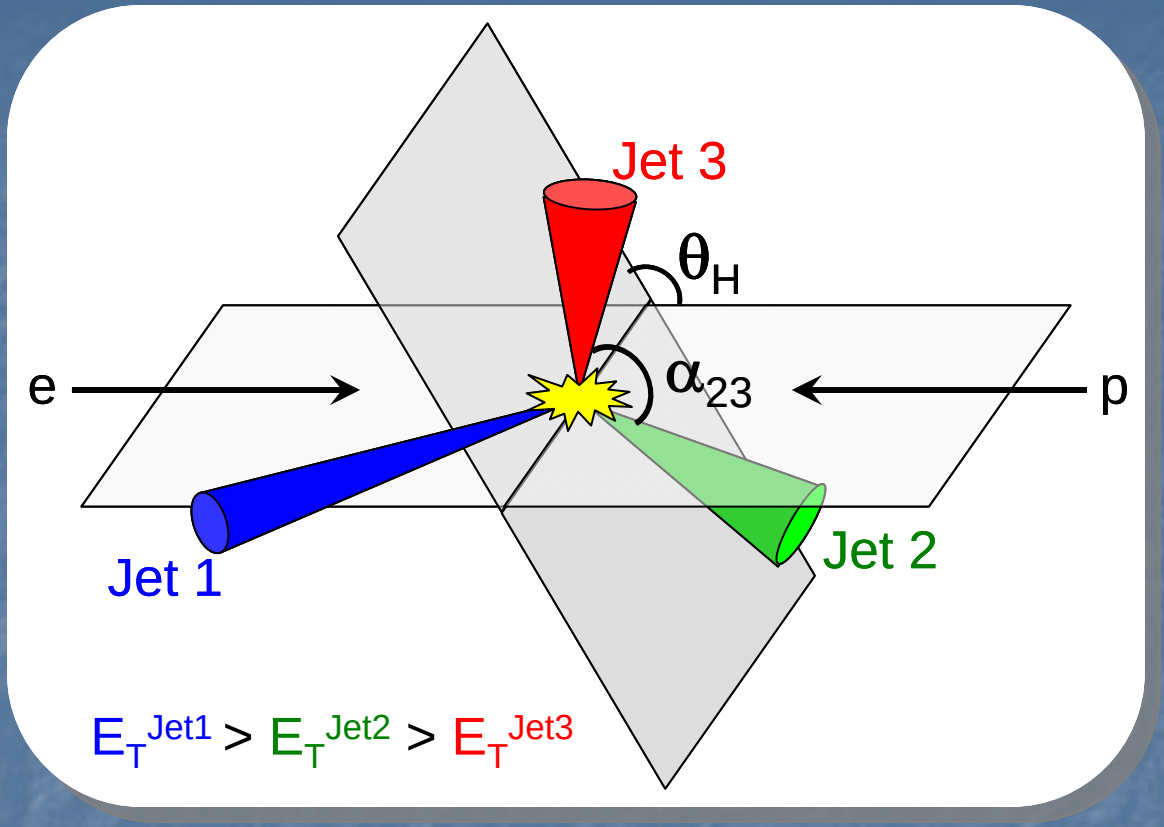
-> Angular variables can be defined which highlight the correlated jet structure of the events and provide sensitivity to the various color configurations.

Definition of Angular Variables

θ_H :
angle between plane of highest E_T jet and beam and plane of 2 lowest E_T jets
-> sensitive to TGV in $C_F C_A$ process

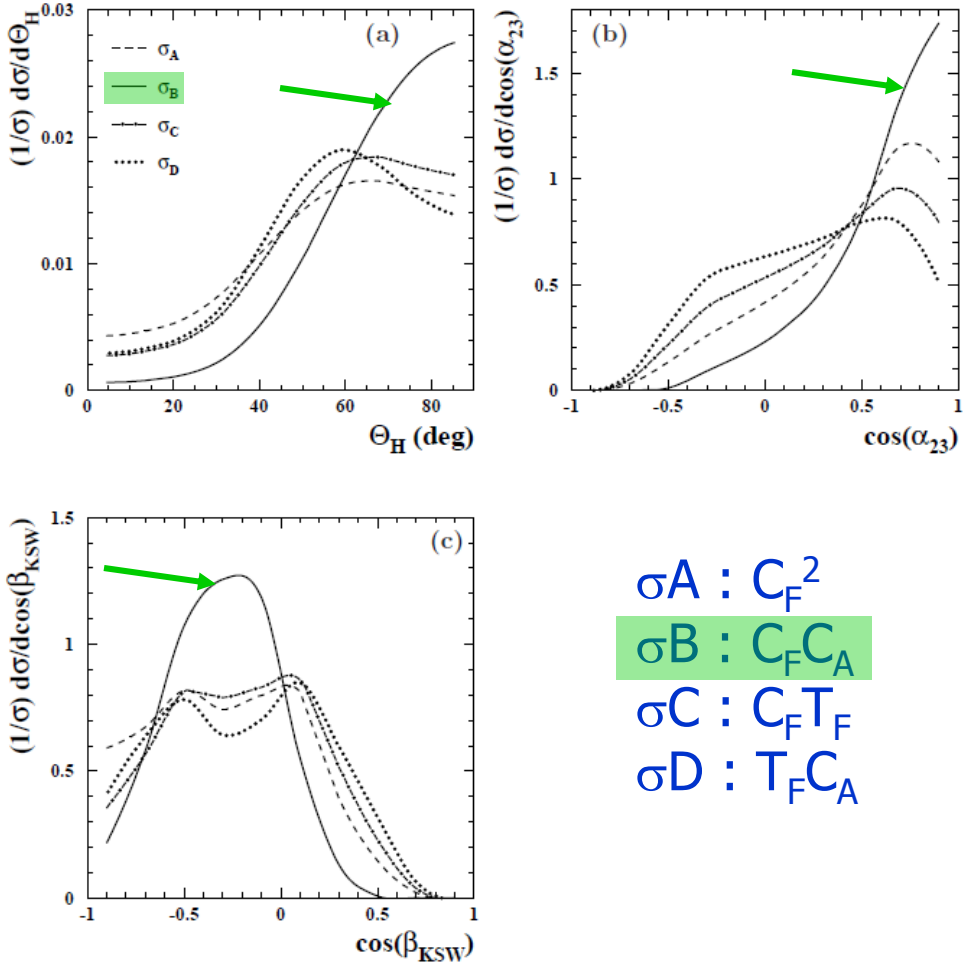
η^{jet}_{max} :
pseudorapidity of most forward jet

α_{23} :
angle between 2 lowest E_T jets, based on α_{34} defined for e^+e^- -> 4 jets
-> distinguishes between double-bremsstrahlung diagrams (C_F^2) and those with a TGV ($C_F C_A$, $T_F C_A$)



β_{KSW} :
angle defined by $\cos(\beta_{KSW}) = \cos[\frac{1}{2}(\angle[(\mathbf{p}_1\times\mathbf{p}_3),(\mathbf{p}_2\times\mathbf{p}_B)]+\angle[(\mathbf{p}_1\times\mathbf{p}_B),(\mathbf{p}_2\times\mathbf{p}_3)])]$, based on the Körner-Schierholz-Willrodt angle Φ_{KSW} for e^+e^- -> 4 jets
-> sensitive to differences in $C_F C_A$ and $C_F T_F$ processes

Normalized Differential 3-Jet X-Sections in γp



$\sigma A : C_F^2$

$\sigma B : C_F C_A$

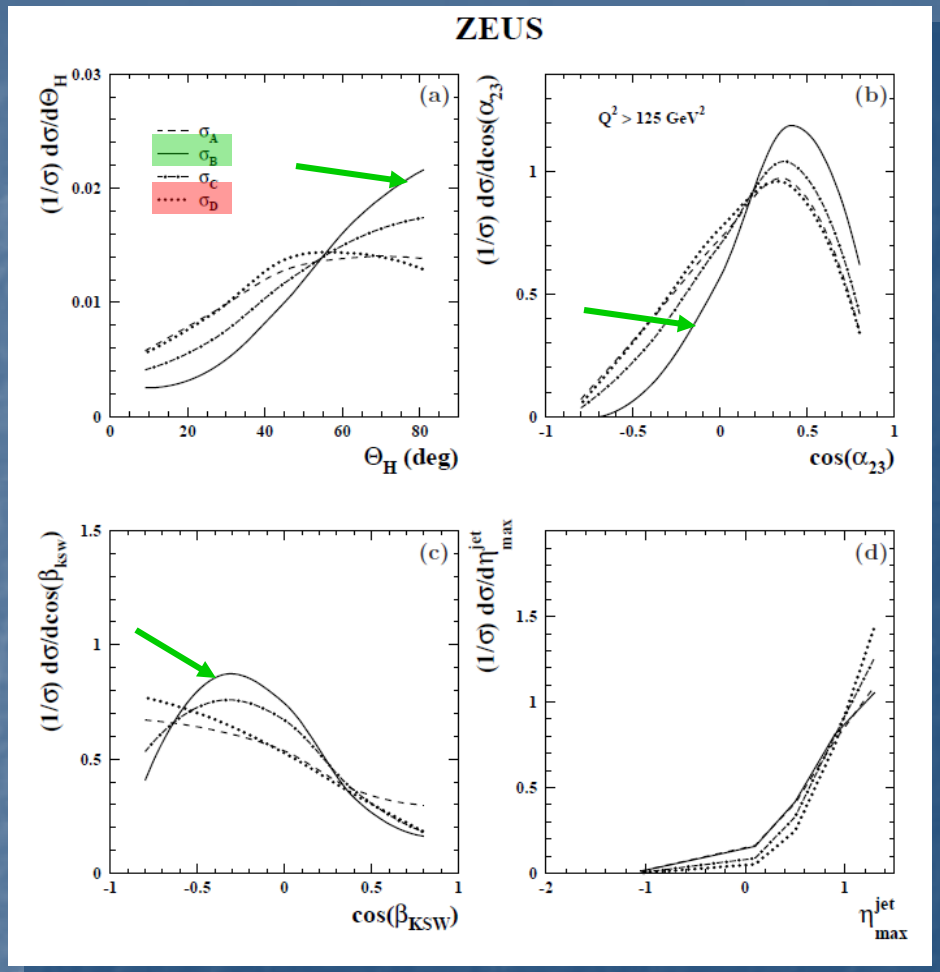
$\sigma C : C_F T_F$

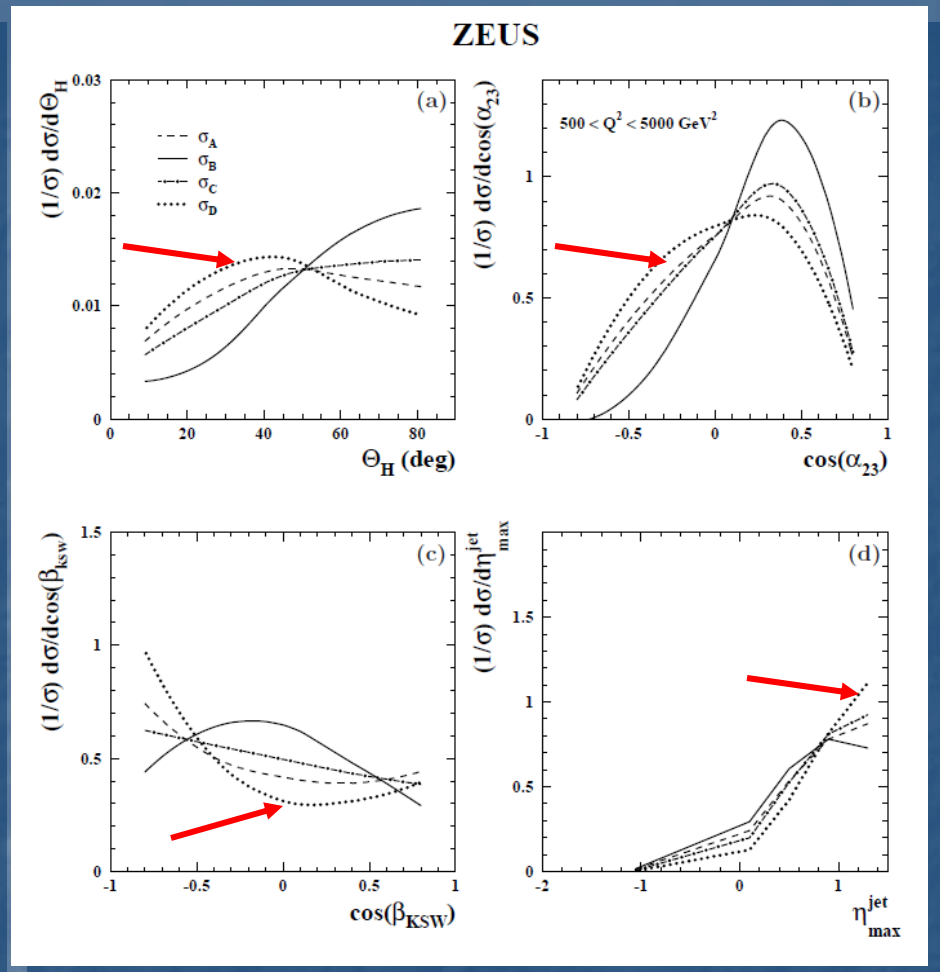
$\sigma D : T_F C_A$

σ_B, the quark-induced process containing a TGV ($C_F C_A$), has a different shape than others in all angular variables

Best separation of all processes is in the variable $\cos(\alpha_{23})$ for γp interactions

Normalized Differential 3-Jet X-Sections in DIS





$\sigma A : C_F^2$

$\sigma B : C_F C_A$

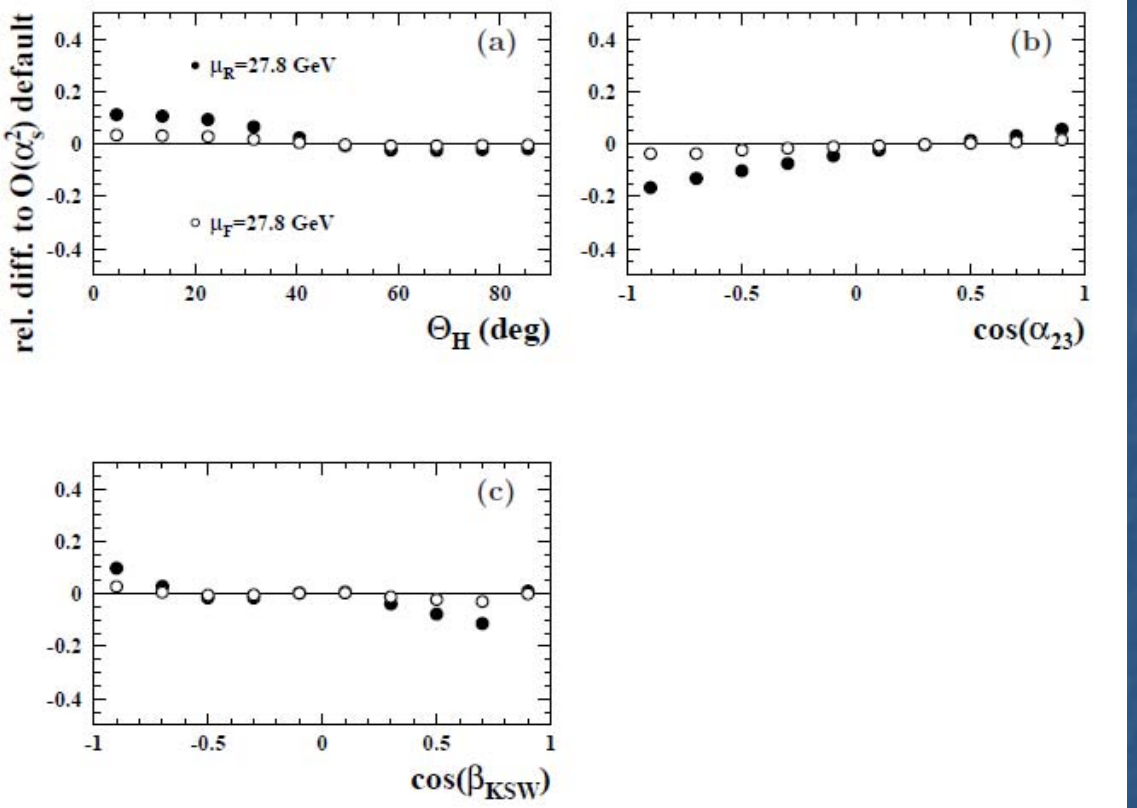
$\sigma C : C_F T_F$

$\sigma D : T_F C_A$

Again, σ_B, the quark-induced process with a TGV ($C_F C_A$), has a different shape than the others in most angular variables

σ_D, the gluon-induced process with a TGV ($T_F C_A$), seems to stand out in the high Q^2 DIS data

Fixed Order Calculations of Direct γp Processes



Fixed order calculation : Order (α_s^2), # q flavors = 5, ZEUS-S proton pdfs, α_s @ 2 loops using $\Lambda_{MS}^{(5)}$=226 MeV -> $\alpha_s(M_Z)$=0.118

$\mu_R = \mu_F = E_T^{max}$ (E_T^{jet1})

Compare to μ_R, μ_F fixed

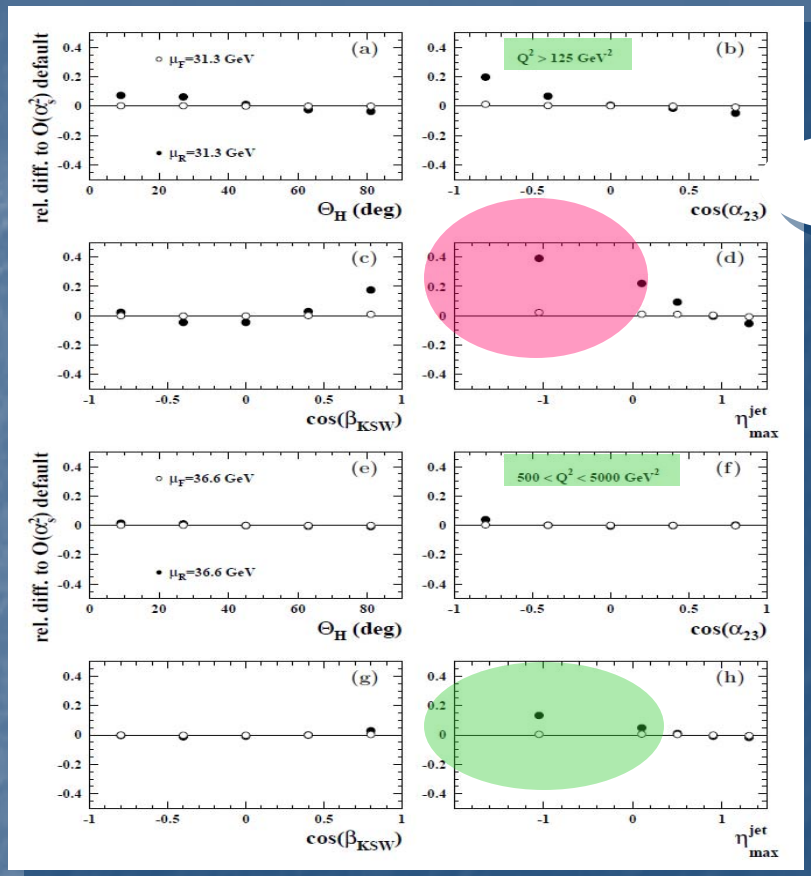
Order (α_s^3) not yet available

Evolution of pdfs and running of α_s introduces additional dependencies on the color factors – using normalized cross section suppresses the pdf dependence.

μ_F variation (open dots) -> very small differences

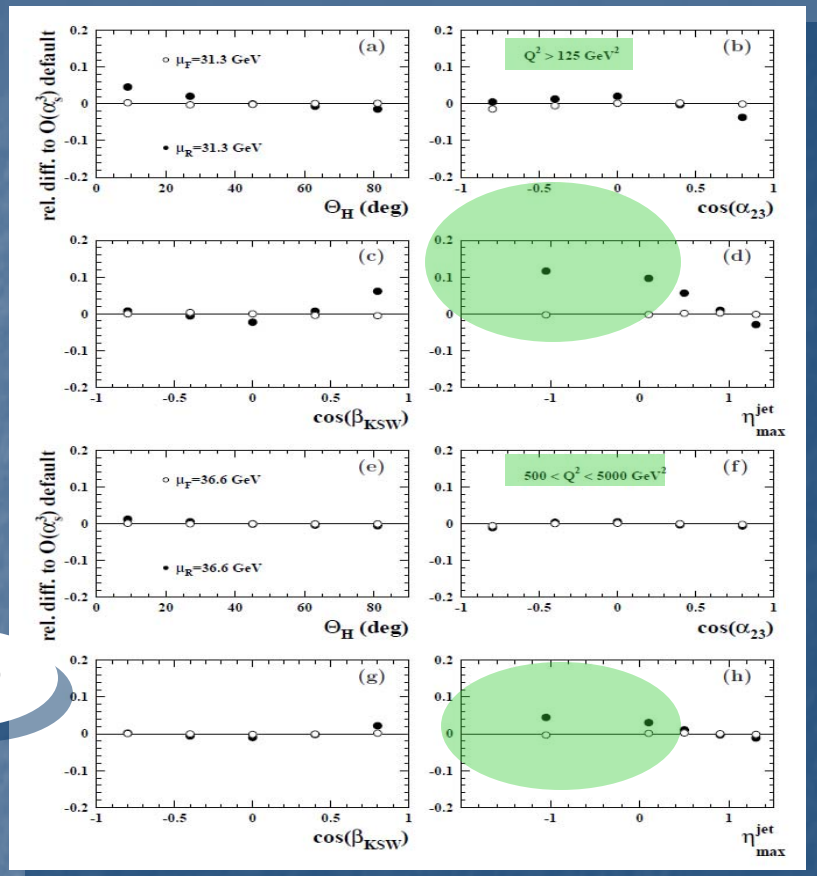
μ_R variation (solid dots) -> sometimes large variations (especially DIS ->)

Fixed Order Calculations of DIS Processes



α_s^2

α_s^3



Fixed order calculations as in γp :

$\mu_R = \mu_F = Q$, compare to μ_R, μ_F fixed

μ_F variation (open dots) -> again, very small differences

μ_R variation (solid dots) -> large variations, especially in η_{max}^{jet}, $\langle Q^2 \rangle \Uparrow$ as $\eta_{max}^{jet} \Downarrow$

-> Reduced effect at high Q^2 at α_s^2 (running α_s)

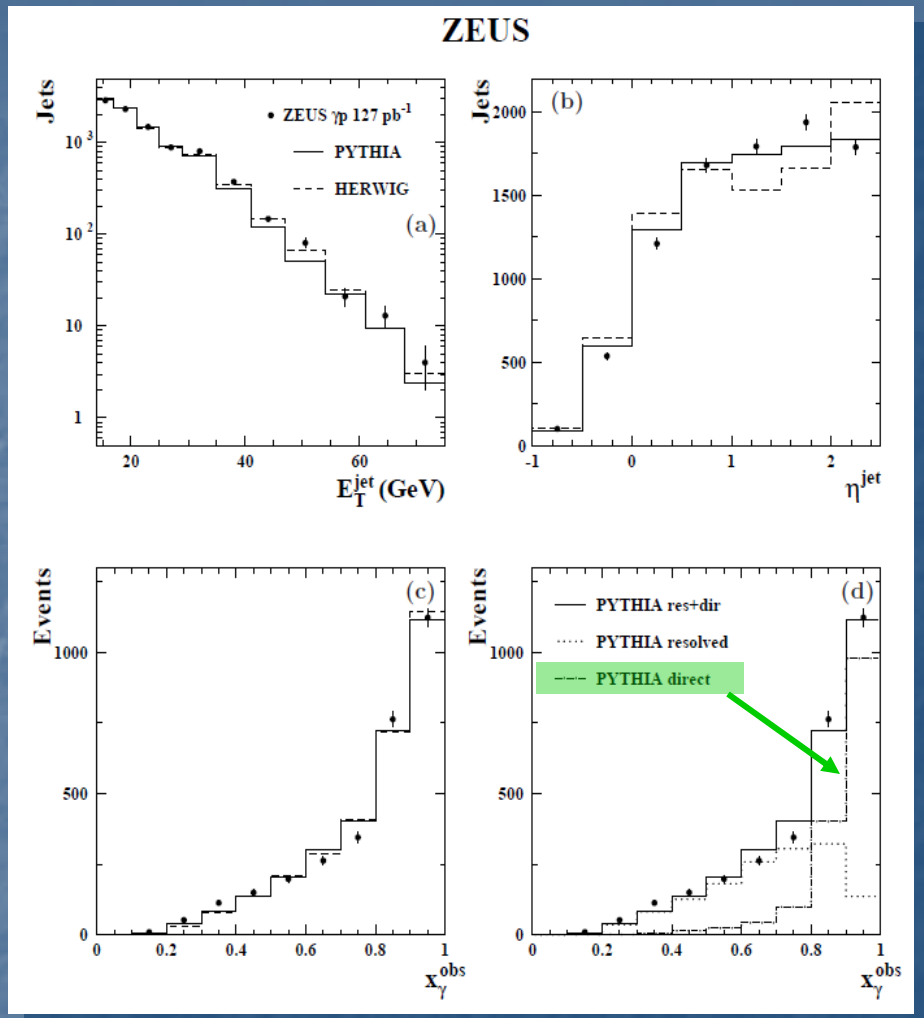
-> Reduced effect at α_s^3 -> can extract color factors in entire region

Event Selection and Jet Definition in γp

Lumi, ep parameters
~45 pb^{-1} e$^+$p 1995-1997
E_p=820 GeV, E_e=27.5 GeV,
$\sqrt{s}$=300 GeV

~65 pb^{-1} e$^+$p 1999-2000
~17 pb^{-1} e-p 1998-1999
E_p=920 GeV, E_e=27.5 GeV,
$\sqrt{s}$=318 GeV

Q^2<1 GeV^2 (median $Q^2 \approx 10^{-3}$ GeV^2)
0.2<y<0.85



Jet Selection :
k_T cluster algorithm in longitudinally invariant inclusive mode from CAL cells

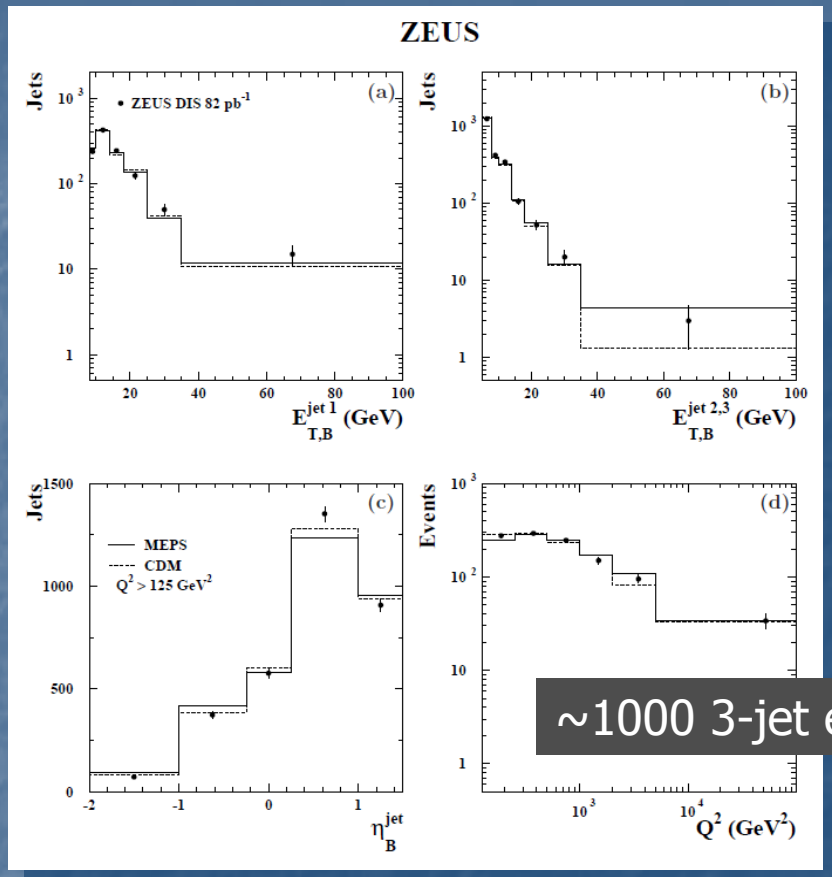
Jet search in η-φ plane of lab frame

Jets corrected in $E_T(\eta, E_T)$, at least 3 jets with E_T^{jet}>14 GeV and -1<η^{jet}<2.5

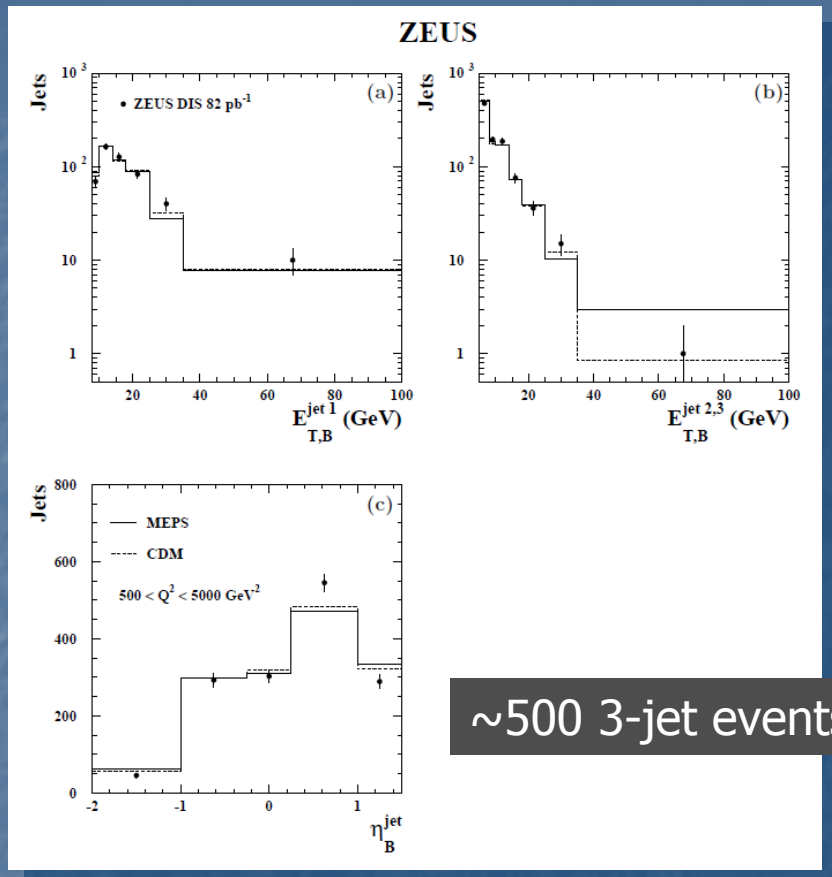
Direct γp events chosen with x_γ^{obs}>0.8 - from MC, direct process dominates

1888 3-jet events

Event Selection and Jet Definition in DIS



~1000 3-jet events



~500 3-jet events

Lumi, ep parameters
~65 pb^{-1} e$^+$p 1999-2000
~17 pb^{-1} e$^-$p 1998-1999
E_p=920 GeV, E_e=27.5 GeV, $\sqrt{s}$=318 GeV

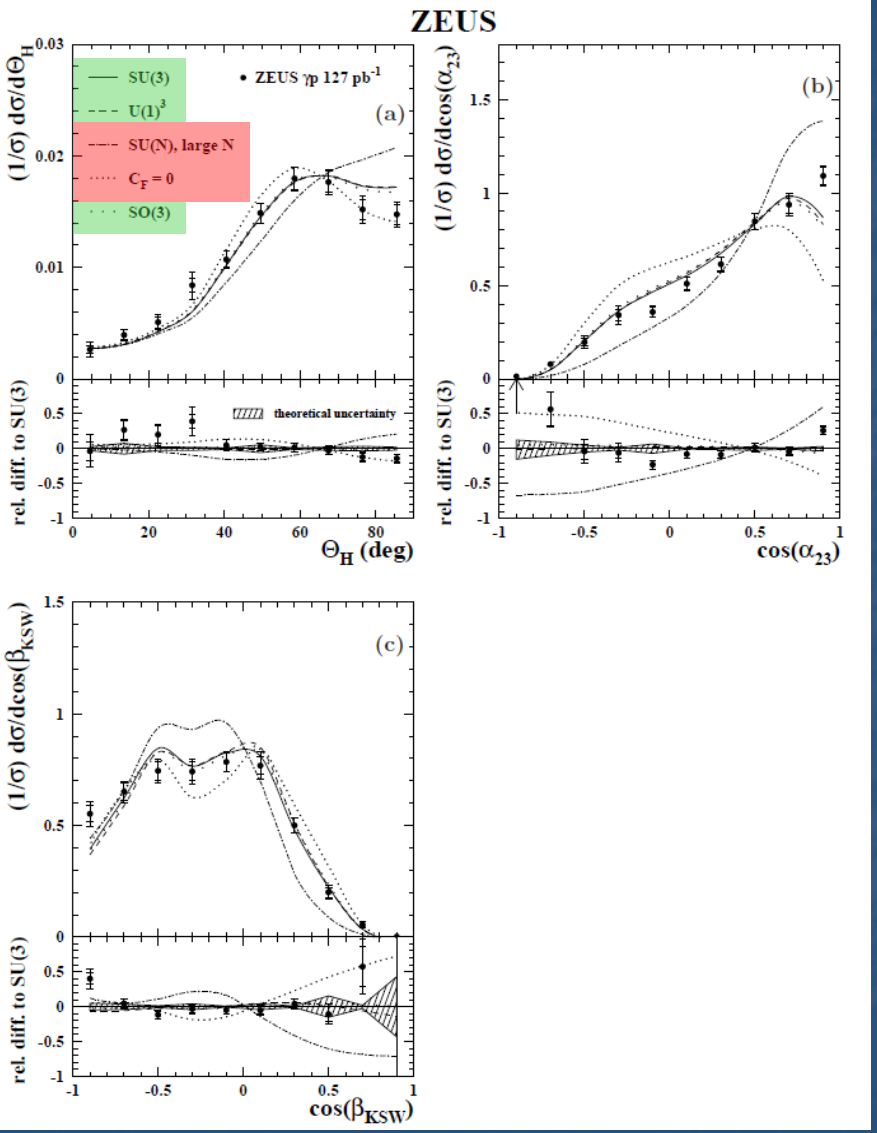
$|\cos \gamma h|<0.65$ (QPM struck quark angle)

Jet Selection :
k_T algorithm on CAL cells excluding scattered electron in Breit frame

Jets corrected in E_T

$E_{T,B}^{jet1}>8$ GeV, $E_{T,B}^{jet2,3}>5$ GeV
$-2<\eta_B^{jet}<1.5$

Gauge Group Comparison with Direct γp Data



SU(3) : $C_A/C_F=9/4$, $T_F/C_F=3/8$
$U(1)^3$: $C_A/C_F=0$, $T_F/C_F=3$
SU(N) large N : $C_A/C_F=2$, $T_F/C_F=0$
SO(3) : $C_A/C_F=1$, $T_F/C_F=1$

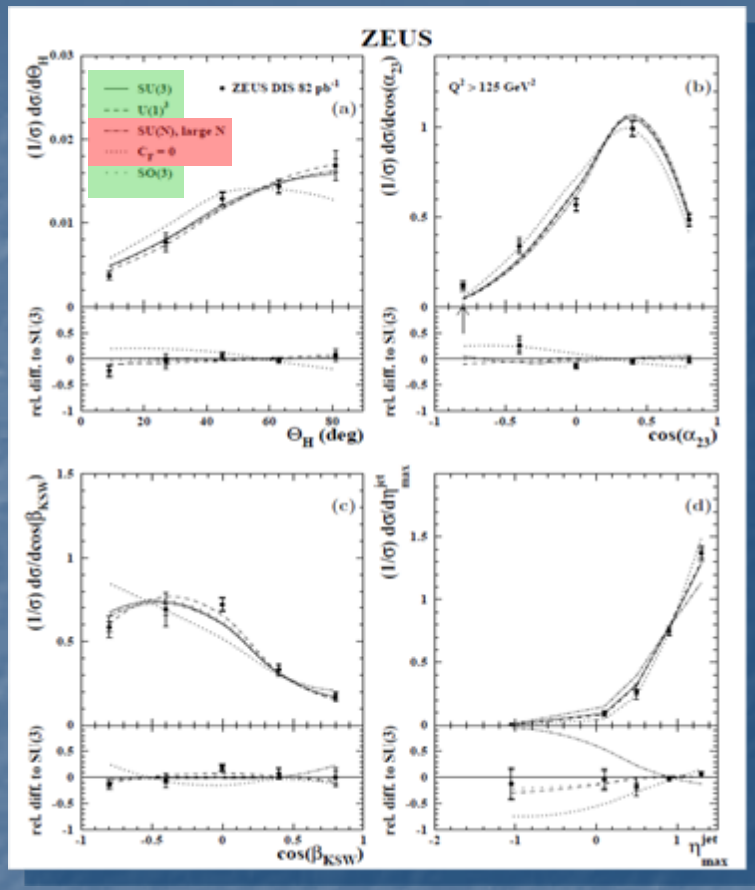
Predictions based on the non-Abelian gauge group SU(3) describe the data for all angular variables

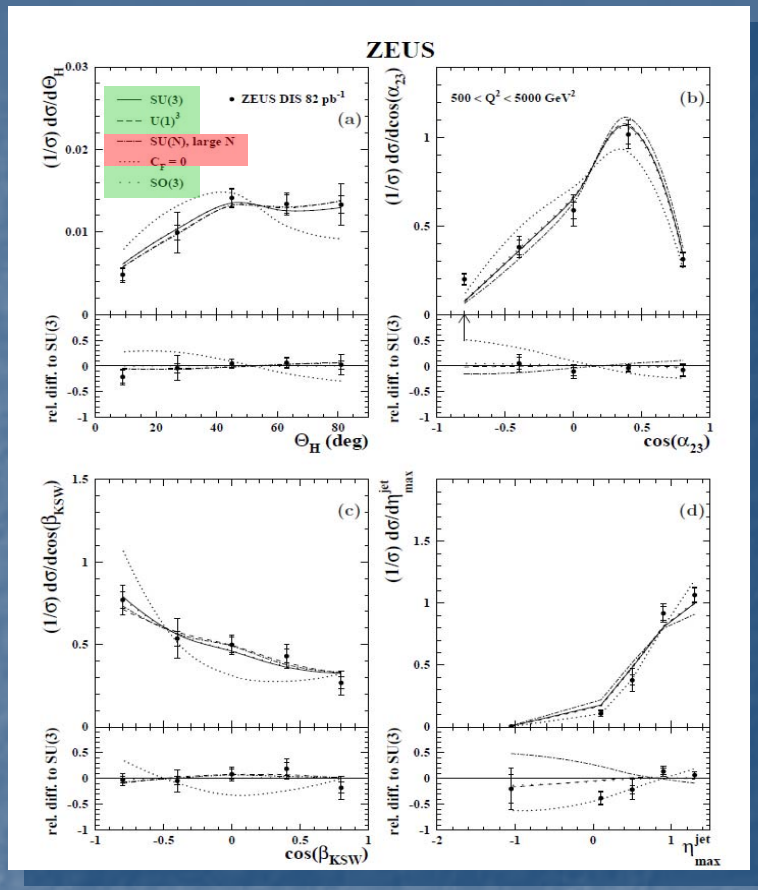
The Abelian group $U(1)^3$ is also consistent with the γp data

The non-Abelian group SO(3) is also consistent with the data

Clearly disfavored are groups SU(N) where N is large and any group with $C_F=0$

Gauge Group Comparison with DIS Data



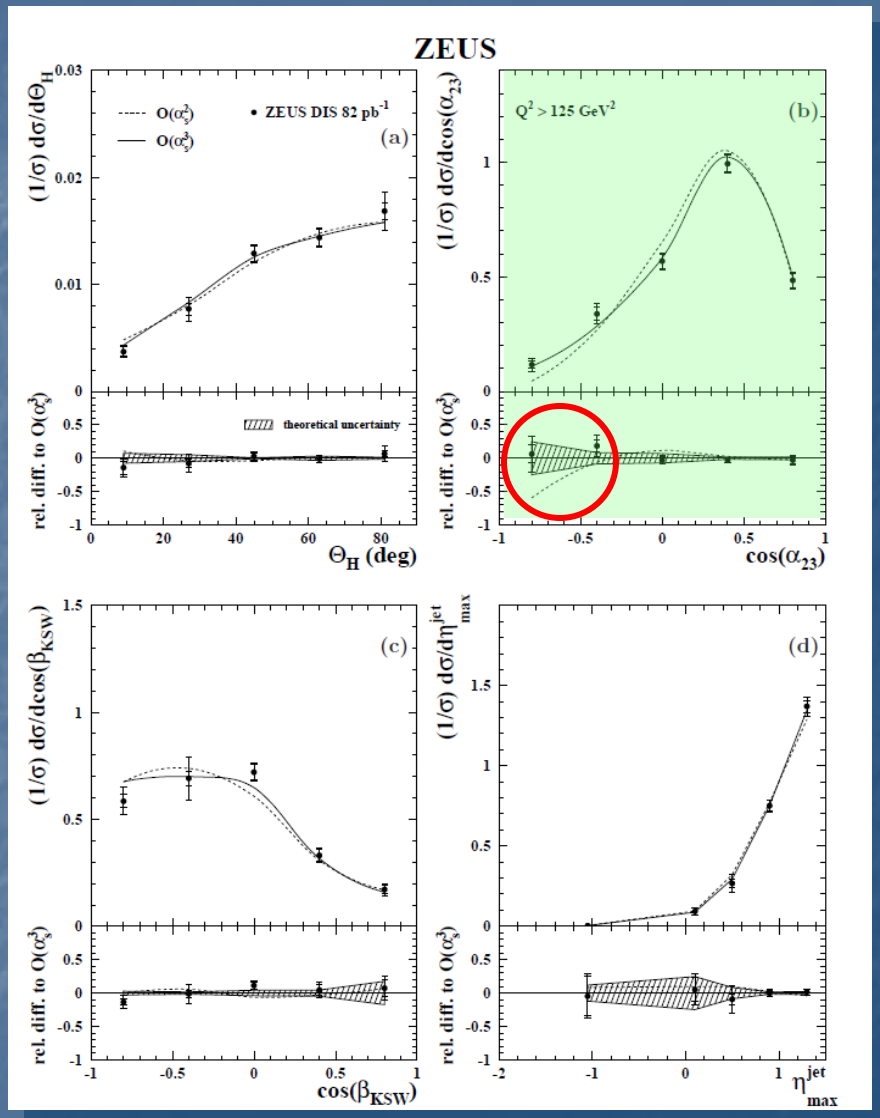


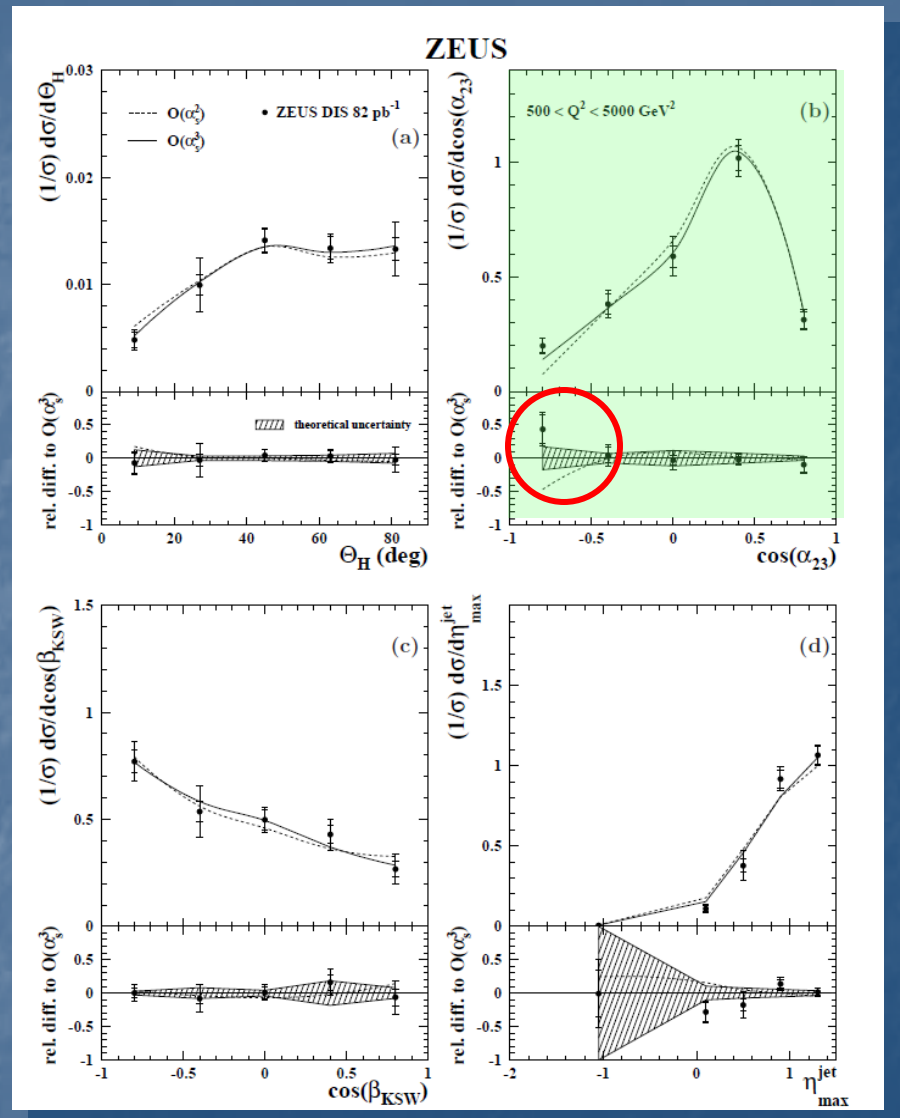
Again, predictions based on the non-Abelian gauge group SU(3) describe the data for all angular variables, as does the non-Abelian group SO(3) and the Abelian group $U(1)^3$

-> However, in DIS, the $U(1)^3$ group shows differences of ~10% with respect to SU(3) (of the same order as the statistical uncertainties)

Clearly disfavored are groups SU(N) where N is large and any group with $C_F=0$

Fixed Order (α_s^n) Comparison with DIS Data





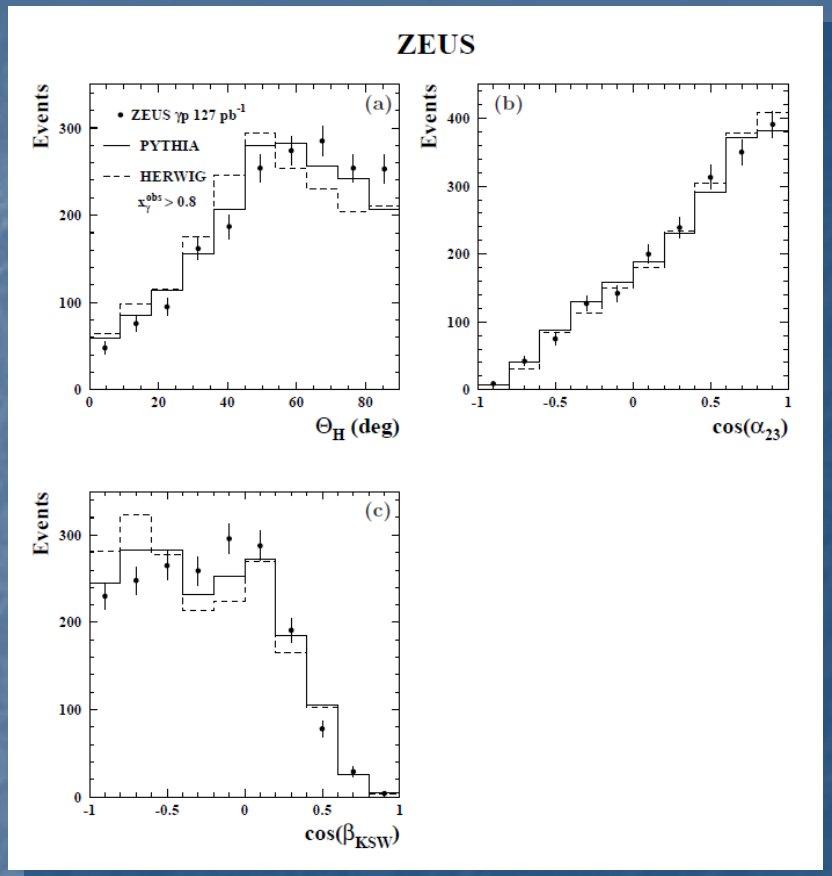
Very good α_s^3 description of data – improvement over α_s^2

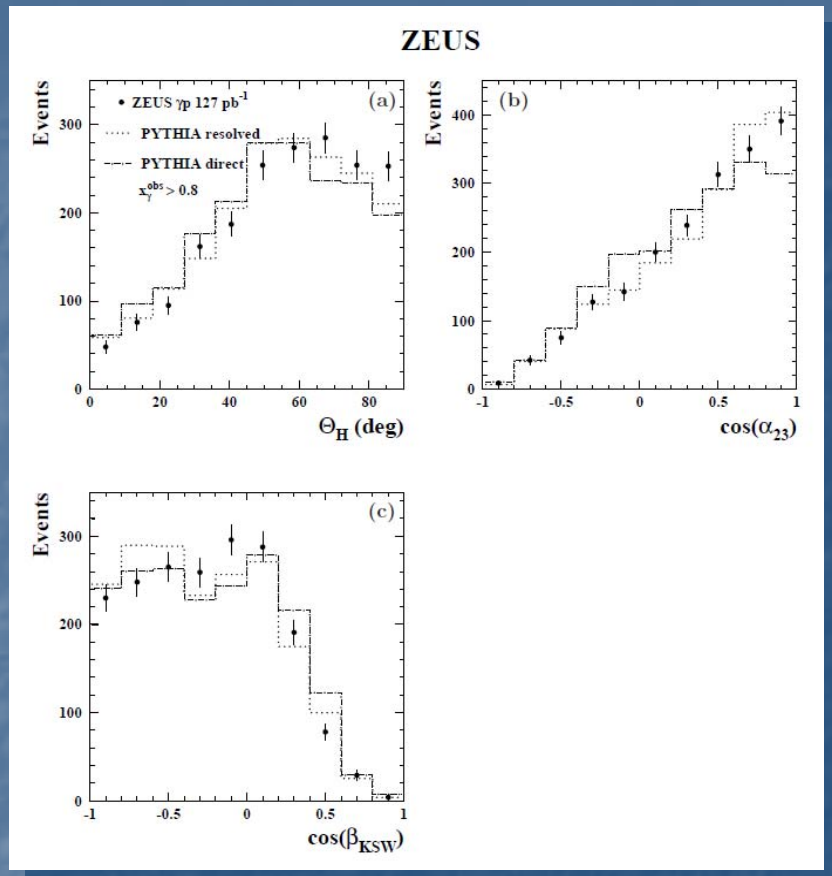
Summary

- Measurements of 3-jet angular correlations in γp and NC DIS were done with the ZEUS detector on 127 pb^{-1} of ep scattering data.
- Differential 3-jet cross sections were measured as functions of θ_H, α_{23}, β_{KSW}, and η_{max}^{jet}, variables motivated by angles defined for 4-jet events in e^+e^- scattering at LEP.
- Fixed-order (α_s^2) calculations were separated according to color configurations and used to study the sensitivity of the angular correlations to underlying gauge group structures.
- The data clearly disfavor SU(N) in the limit of large N or any theory where $C_F=0$.
- Predictions based on SU(3) describe the data for all of the angular variables, while the predicted differences between SU(3) and $U(1)^3$ of ~10% are smaller than the current statistical uncertainties on the data.
- With complete α_s^3 calculations, extraction of individual color factors may be possible with the full set of HERA data (~500 pb^{-1}).

Backup Slides

Data/MC Comparisons for γp 3-Jet Events





Data/MC Comparisons for DIS 3-Jet Events