Spin effects of gluons and (quarks) before LHC

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EF05 Topical Group Meeting:
EECs and Spin Correlated Parton Evolution
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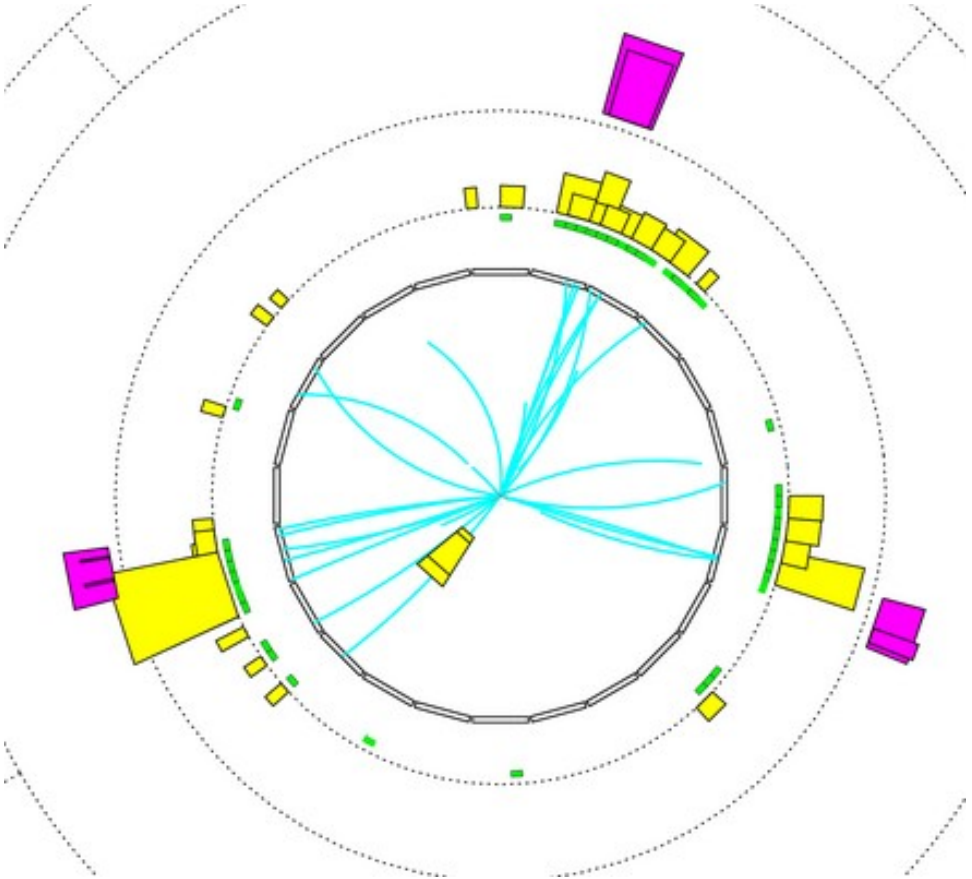
Friedrich Wilhelm IV., King of Prussia, visiting Aug 1845 the new observatory of Bonn University to its director F.W. Argelander:
“Na, Argelander, was gibt es Neues am Himmel?"
"Kennen Majestät schon das Alte?”

Gluon spin with 3-jet events



LEP at 91 GeV, select 3-jet events with JADE @ $y_{cut} = 0.01$

$x_i = 2E_{jet,i} / \sqrt{s}$

Energy ordering: $x_1 > x_2 > x_3$

Symmetrise XS to account for all maps $(x_1, x_2, x_3) \rightarrow (x_q, x_{\bar{q}}, x_g)$

[OPAL coll., G. Alexander et al., Z. Phys. C52 (1991) 543]

Gluon spin with e^+e^- → 3-jet events

XS (LO) for $e^+e^- \rightarrow q\bar{q}g$ for spin-1 (vector) or spin-0 (scalar) gluon

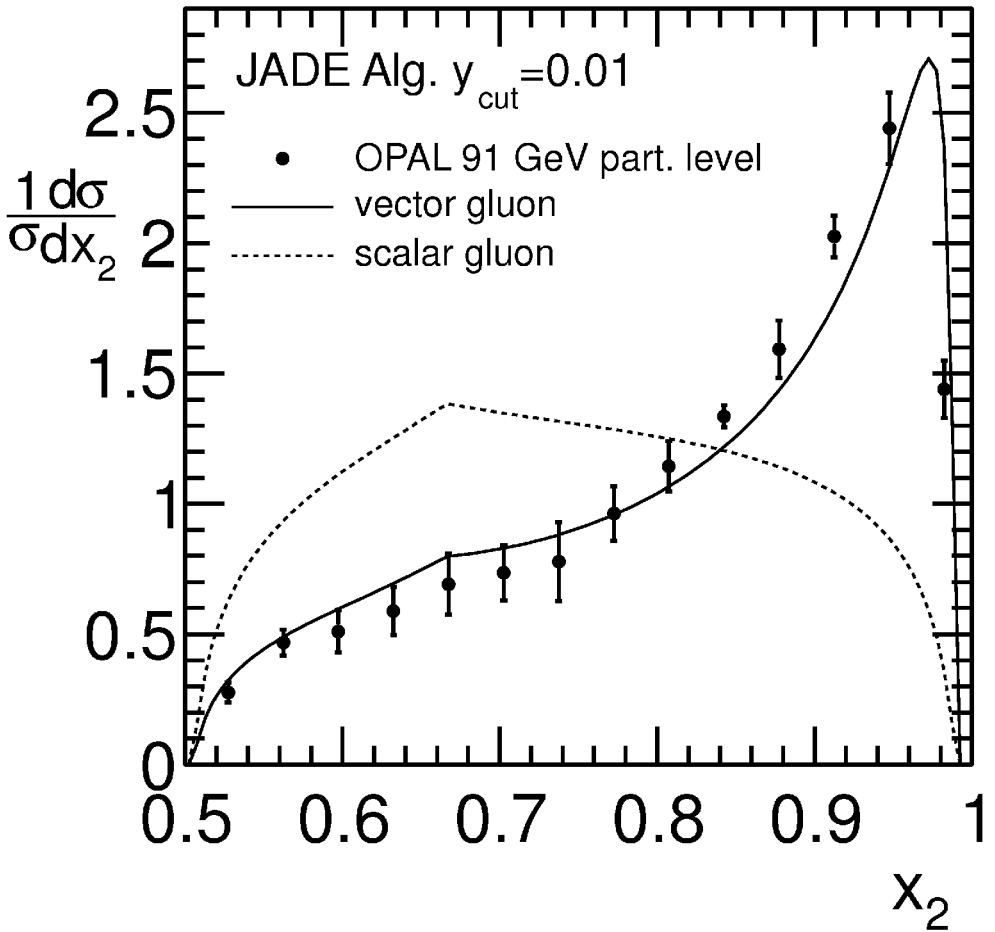
Vector: $d^2\sigma^{(v)}/(dx_1 dx_2) \sim (x_1^3+x_2^3+x_3^3) / ((1-x_1)(1-x_2)(1-x_3))$

Scalar: $d^2\sigma^{(s)}/(dx_1 dx_2) \sim (x_1^2(1-x_1)+x_2^2(1-x_2)+ x_3^2(1-x_3)) / ((1-x_1)(1-x_2)(1-x_3)) + 7.45$

2nd term "7.45" for scalar gluon due to axial vector couplings of Z

x_2-distribution: $1/\sigma d\sigma^{(s,v)}/dx_2 \sim \int_{x1,min}^{x1,max} d^2\sigma^{(s,v)}/(dx_1 dx_2)\, dx_1$

Gluon spin with e^+e^- → 3-jet events

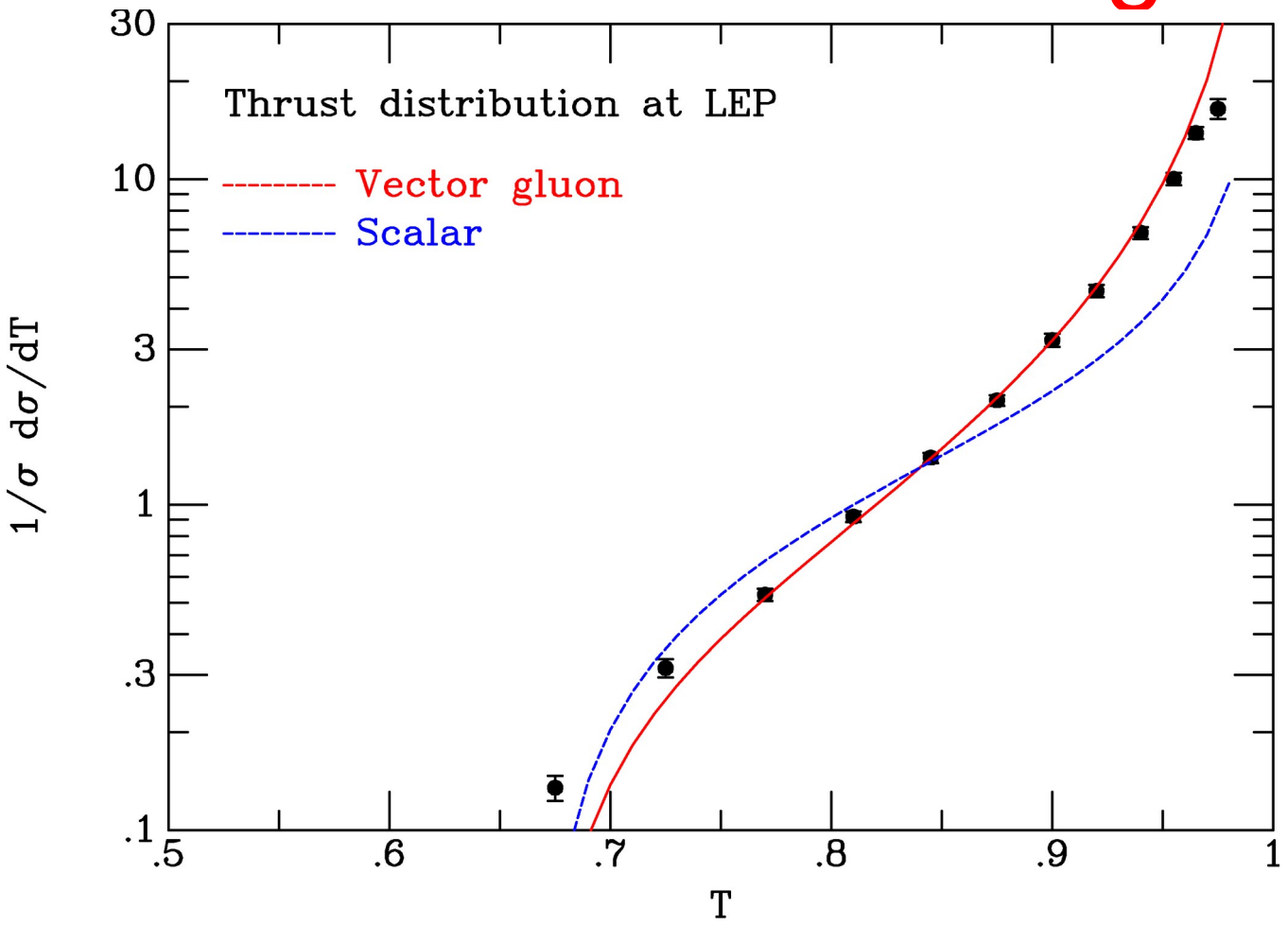


Data points at parton level

Curves are LO QCD, normalised to integral of data
Edges at $x_2 = 2/3$ due to phase space borders

Analysis with NLLO and improved MCs for had. corrections? Set limit on “scalar gluon” contributions?

Vector vs scalar gluon ESW

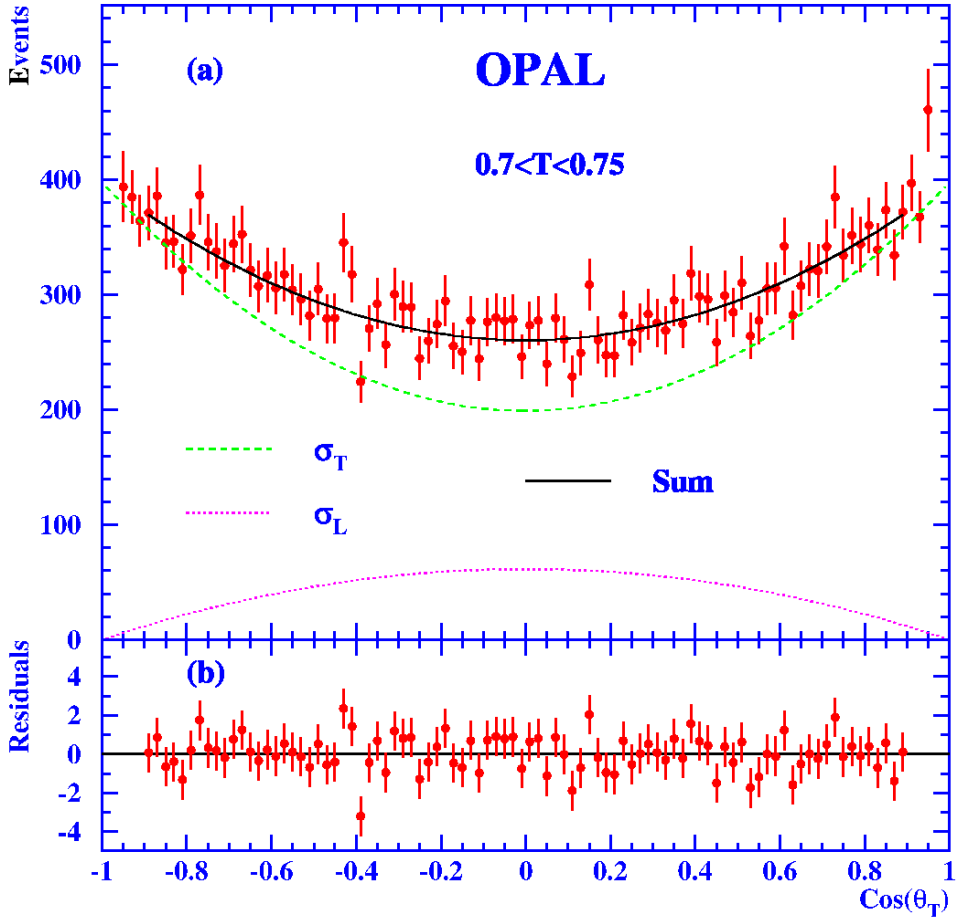


Same argument for Thrust

DELPHI LEP 1 data

[R. K. Ellis, W. J. Stirling, B. R. Webber, QCD and collider physics, Cambridge University Press, 1996]

Quark spin at LEP



Thrust $T = \max_{\mathbf{u}}(\Sigma_i |\mathbf{p}_i \cdot \mathbf{u}|) / (\Sigma_i |\mathbf{p}_i|)$

u is thrust axis, θ_T is polar angle of **u**

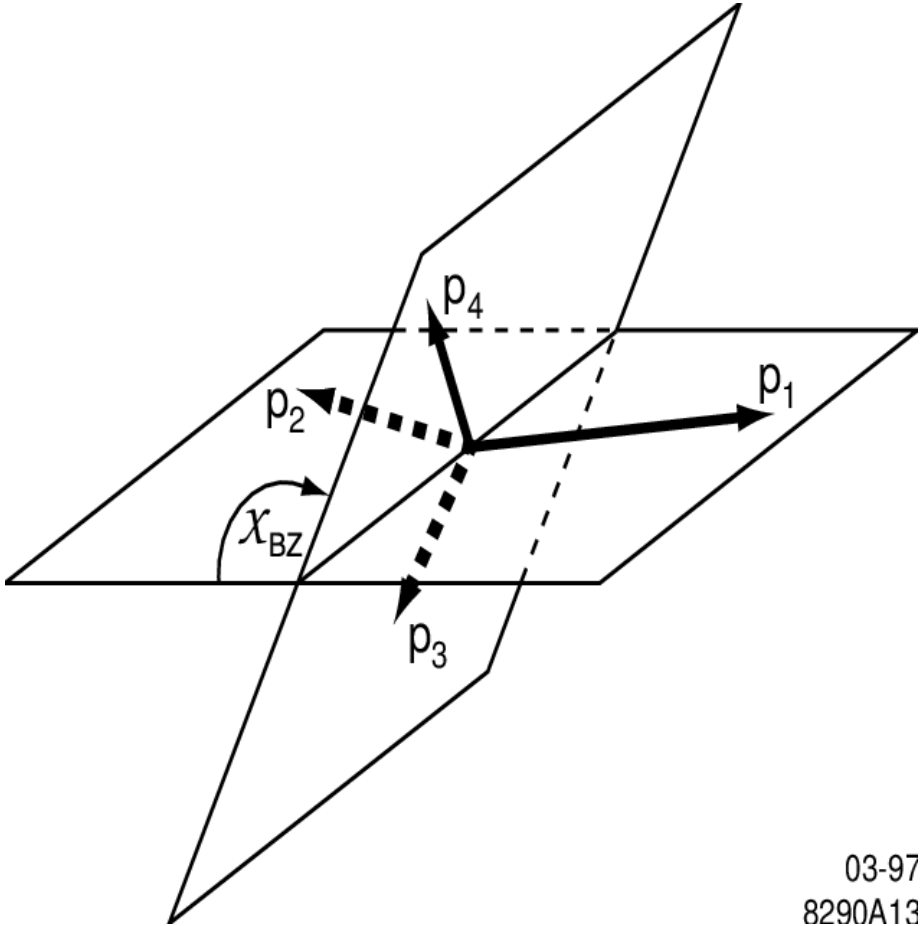
Expectation for $e^+e^- \rightarrow q\bar{q}$ with spin-1/2 quarks:

$$d\sigma/d\cos(\theta_T) \sim 1 + \cos^2(\theta_T)\ \sigma_T$$
$$\sim 1 - \cos^2(\theta_T)\ \sigma_L$$

Fit (σ_T) is $\sim 1 + \cos^2(\theta_T)$

[OPAL coll., R. Akers at al., Z. Phys. C68 (1995) 203]

e^+e^- → 4-jet final states at 91 GeV



Four Durham jets at $y_{cut} = 0.008$
Energy ordering: $E_1 > E_2 > E_3 > E_4$

Bengtsson-Zerwas angle:

$$\chi_{BZ} = \angle(p_1 \times p_2, p_3 \times p_4)$$

Körner-Schierholtz-Willrodt angle:

$$\Phi_{KSW} = 1/2(\angle(p_1 \times p_4, p_2 \times p_3) + \angle(p_1 \times p_3, p_2 \times p_4))$$

Modified Nachtmann-Reiter angle:

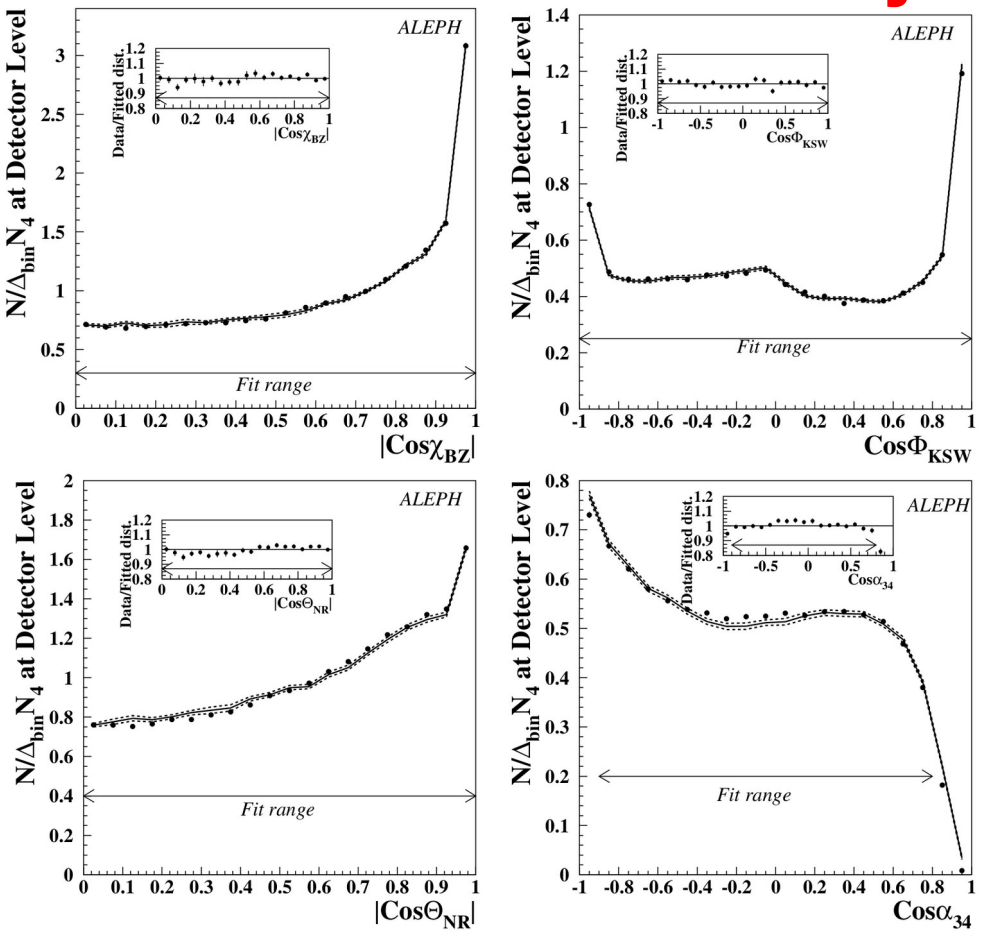
$$\Theta_{NR} = \angle(p_1 - p_2, p_3 - p_4)$$

Angle between lowest energy jets:

$$\alpha_{34} = \angle(p_3, p_4)$$

[ALEPH coll. A. Heister et al., Eur. Phys. J. C27 (2003) 1;
OPAL coll. G. Abbiendi et al., Eur. Phys. J. C20 (2001) 601]

$e^+e^- \rightarrow$ 4-jet final states



[ALEPH coll. A. Heister et al., Eur. Phys. J. C27 (2003) 1]

NLO QCD prediction:

$d\sigma/dy \sim \alpha_S^2 B(y) + \alpha_S^3 C(y)$

$B(y) = C_F B_1 + C_A B_2 + T_R B_3$

$C(y) \approx C_F^2 C_1 + C_F C_A C_2 + C_F T_R C_3 + C_A^2 C_4 + C_A T_R C_5 + T_R^2 C_6$

$\Rightarrow$ fit "colour factors" and $\alpha_S(m_Z)$

ALEPH: $C_A = 2.93 \pm 1.06$

$C_F = 1.35 \pm 0.46$

OPAL: $C_A = 3.02 \pm 1.07$

$C_F = 1.34 \pm 0.47$

Conservative uncertainties from SK, Rept. Prog. Phys. 69 (2006) 1771

Confirmation of spin-1 gluon

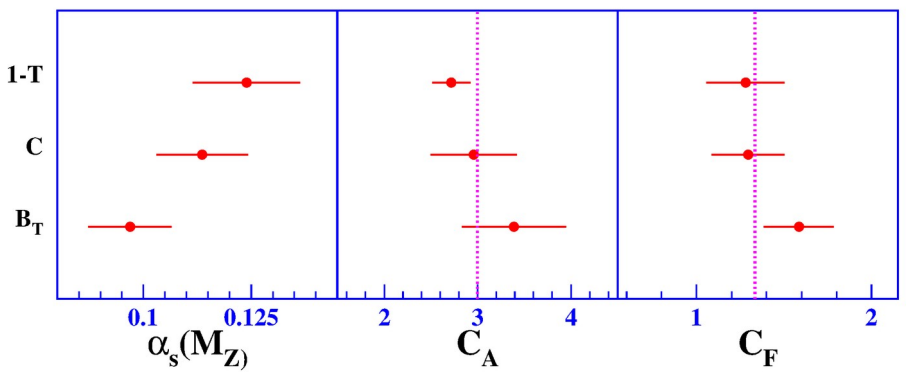
Event shapes in e^+e^- → hadrons

Data from JADE / OPAL 14-189 GeV

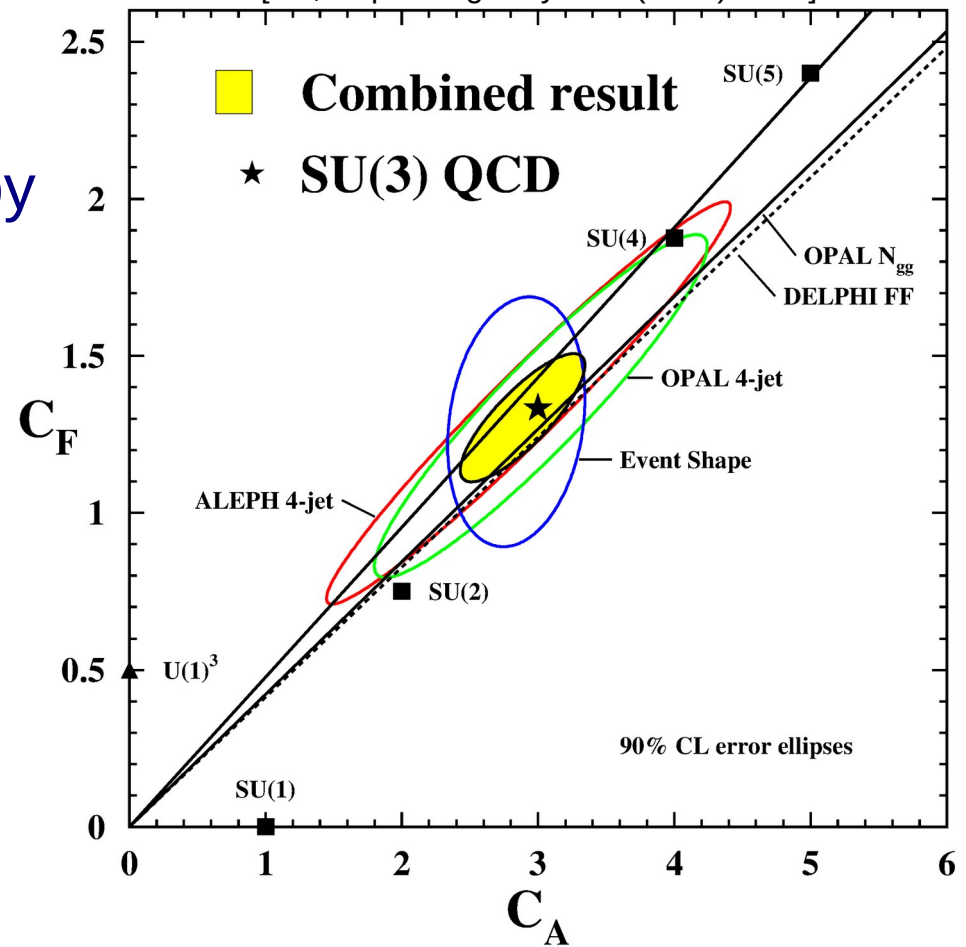
NLO+NLLA+pc QCD, decomposed by colour factors

Confirms spin-1 gluon

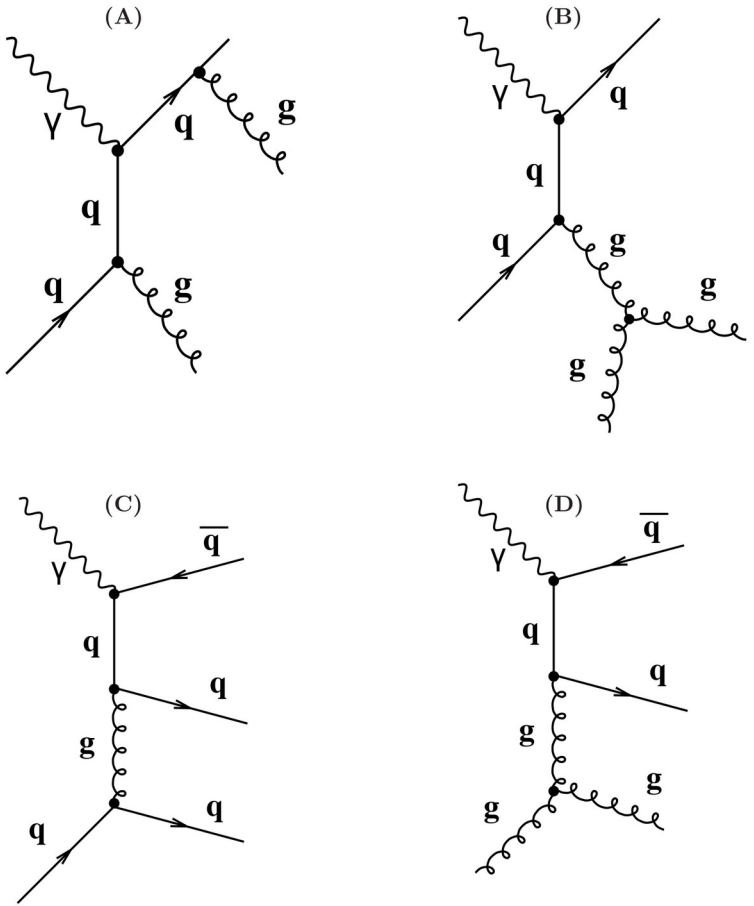
[SK et al., Eur. Phys. J. C21 (2001) 199]



[SK, Rept. Prog. Phys. 69 (2006) 1771]



3-jets in γp or NC DIS (ZEUS)



[ZEUS coll., S. Chekanov et al., Phys. Rev. D85 (2012) 052008]

3-jets in ep scattering γp: $Q^2 < 1$ GeV^2,
NC DIS: $Q^2 > 125$ GeV^2 or
$500 < Q^2 < 5000$ GeV^2
Long. inv. k_t algorithm

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

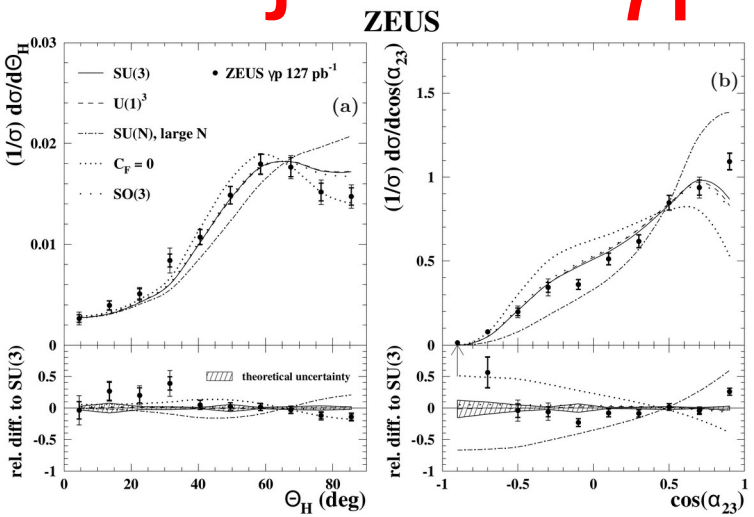
Θ_H: $\angle(p_{Et,1} \times p_b, p_{Et,2} \times p_{Et,3})$

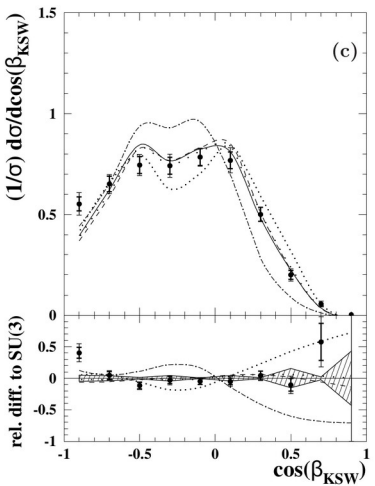
α_{23}: $\angle(p_{Et,2}, p_{Et,3})$

β_{KSW}: $1/2(\angle(p_{Et,1} \times p_{Et,3}, p_{Et,2} \times p_b) + \angle(p_1 \times p_b, p_{Et,2} \times p_{Et,4}))$

η_{max}^{jet}: $\max(\eta_1, \eta_2 \eta_3)$

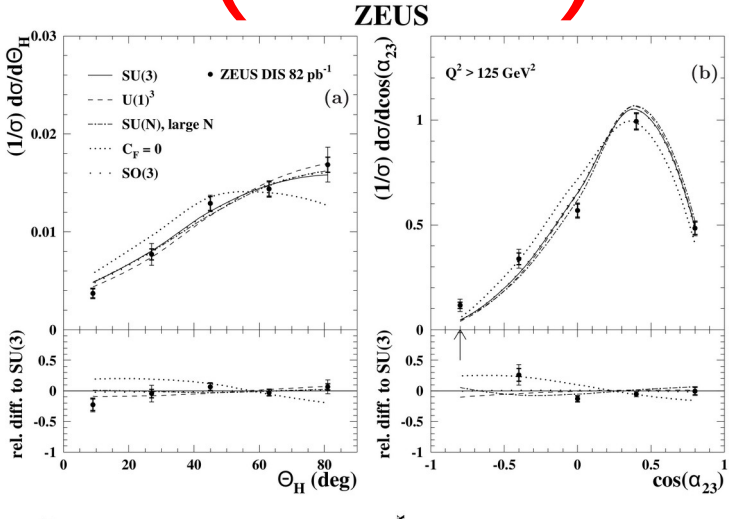
3-jets in γp or NC DIS (ZEUS)

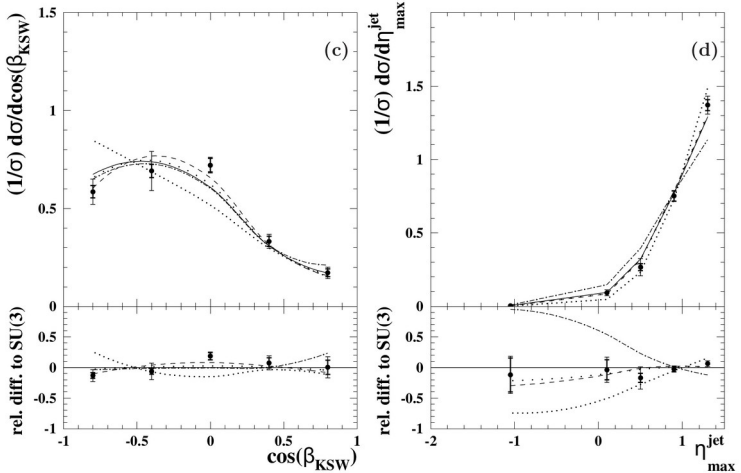




Sensitivity limited

Confirms spin-1 gluon for SU(3) QCD

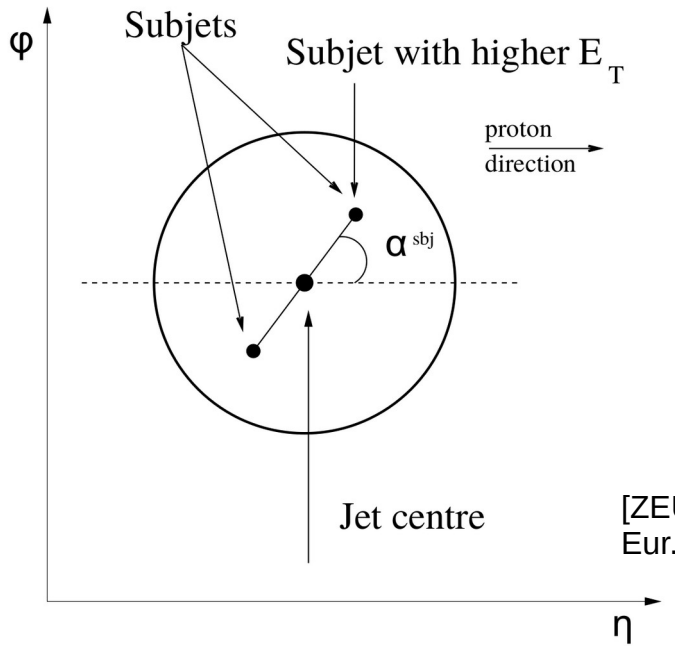




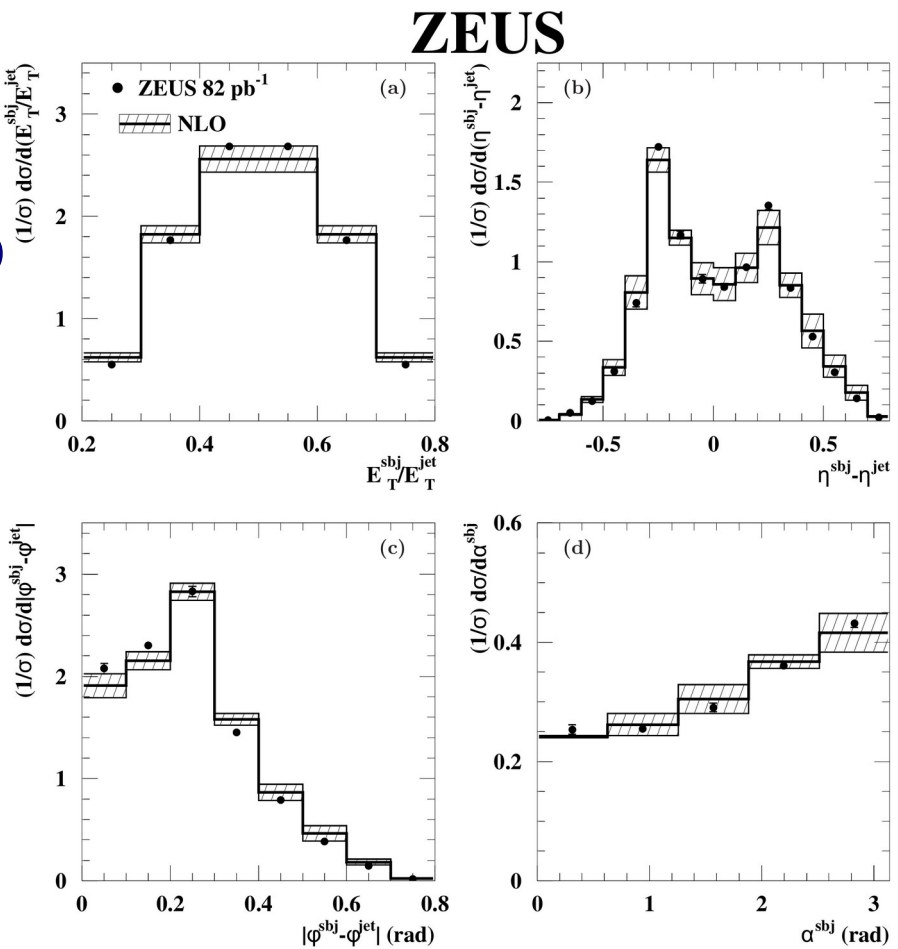
ZEUS NC DIS subjets distributions

$Q^2 > 125$ GeV^2, k_t jets $E_{t,jet} > 14$ GeV,
$-1 < \eta_{jet} < 2.5$, 2 subjets $y_{cut} = 0.05$

Confirms spin-1 gluon in SU(3) NLO QCD



[ZEUS coll., S. Chekanov et al., Eur. Phys. J. C63 (2009) 527]



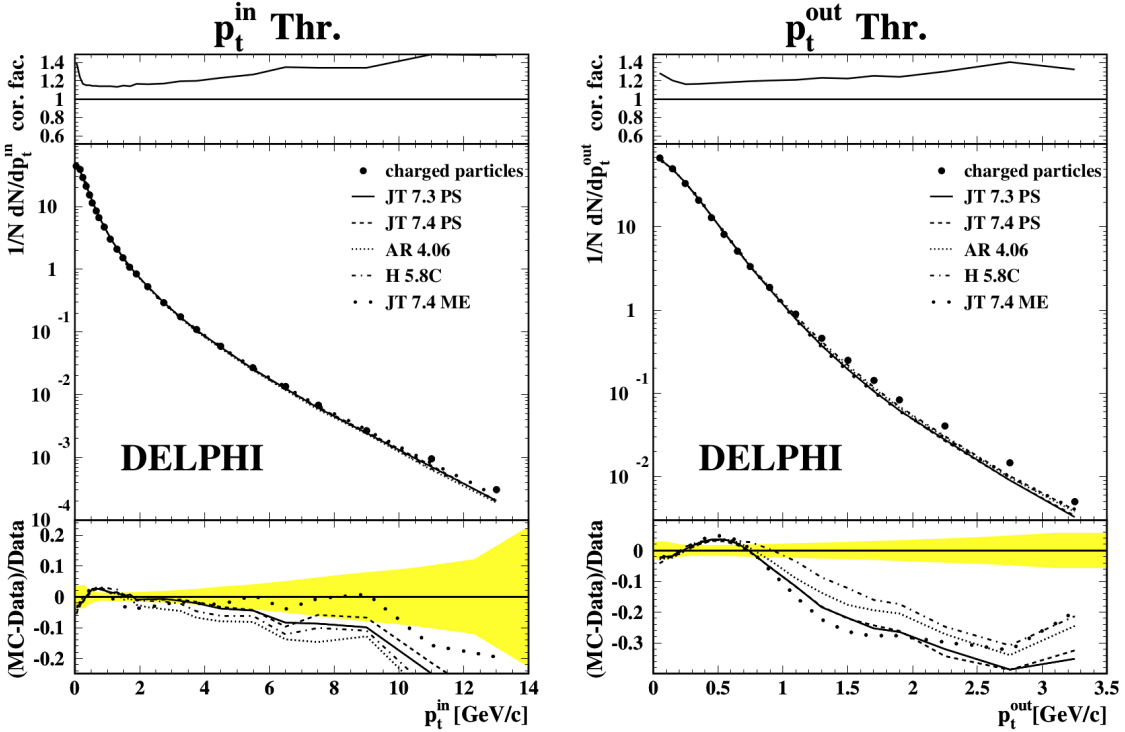
Other analyses

- Properties of quark and gluon initiated jets
  - Multiplicity, energy profile, etc
  - Gluon spin dependence from subjets?
- Final state particles correlations
  - E.g. Bose-Einstein: hadronisation ⇒ “too late” (?)
- EEC like observables
  - QCD prediction as for x_2 or event shapes
  - Many measurements $\sqrt{s} \leq m_Z$ exist

New observables?

- Lund plane: never studied at LEP
  - But should be
- "Jet pull"
  - Transverse momenta w.r.t. thrust axes p_t^{in} and p_t^{out}
  - ≤ 3-jet events planar
- Others?
  - O(10^6) events / LEP expt
  - 91 to 209 GeV (14 GeV incl JADE)

$p_t^{in} = \mathbf{p}\cdot\mathbf{u}_{major}$ $p_t^{out} = \mathbf{p}\cdot\mathbf{u}_{minor}$



[DELPHI coll., P. Abreu et al, Z. Phys. C73 (1996) 11]

Summary

- Few direct studies of gluon / quark spin
  - x_2 distribution fits, pol. angle dist'n of thrust axis
- Colour factor analyses
  - 4-jet angular correlations or event shapes
  - Reinterpret to suggest sensitivity to gluon spin
- EECs?
  - Well studied at LEP 1 and before (but not LEP 2)
  - Analytic NLO QCD, NNLO, NNLL resummation