# Jet Physics At HERA

Roman Kogler

Max-Planck-Institute for Physics
Munich

Hamburg Student Seminar

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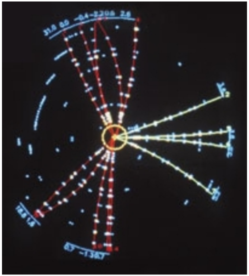
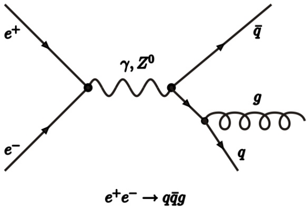
# Why Jets?



3-jet event at TASSO,
discovery of the gluon in 1979




a gluon-bremsstrahlung diagram
in $e^+e^-$ annihilation

**Detecor:** Jets are regions of high energy density

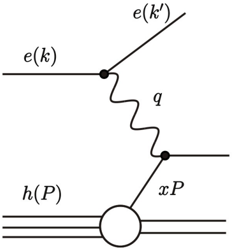
**Hadrons:** Jets are collimated sprays of hadrons

**Partons:** Jets are formations of close-by partons (jet $\neq$ parton)

*Find a mapping between these levels!*

# A Little Bit Of QCD

# DIS Kinematics




$q^\mu = k^\mu - k'^\mu$, momentum transfer

$Q^2 = -q^2$, virtuality

$x = \frac{Q^2}{2P \cdot q}$, Bjorken scaling variable

$y = \frac{P \cdot q}{P \cdot k}$, inelasticity

At HERA, $E_p = 920\,(820)$ GeV and $E_e = 27.6$ GeV
center-of-mass energy $\sqrt{s} \approx 320\,(300)$ GeV

Beyond the DIS Born diagram having some hard scale in the event, e.g. $Q^2 \gtrsim 3$ GeV$^2$, pQCD is applicable

Testing ground and precision measurements of QCD

# Factorization Theorem In DIS

$$d\sigma_{ep} = \sum_{i=q\bar{q}g} \int_0^1 dx\, f_i(x, \mu_F^2; \alpha_s)\, d\hat{\sigma}_i(xP, \alpha_s, \mu_R, \mu_F)$$

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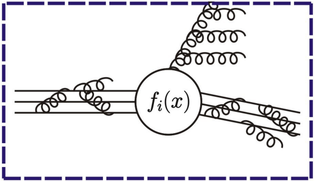


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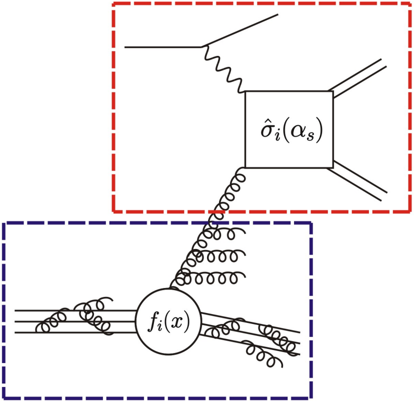
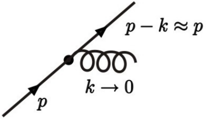



$d\hat{\sigma}_i(xP, \alpha_s, \mu_R, \mu_F)$ : partonic hard cross section, calculable in pQCD, IR safe quantity, independent of long-range effects, i.e. soft $(p_T < \mu_F)$ physics

$f_i(x, \mu_F^2; \alpha_s)$ : parton distribution function, not calculable in pQCD, contains long-range effects, independent of the hard cross section

# Calculation Of The Short Distance (Hard) Part

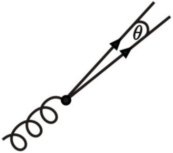
Already at one-loop $\mathcal{O}(\alpha_s)$ the hard **partonic** cross section is divergent:




divergent for $k \to 0$:

$$\int_0 \frac{dk}{k} \to \infty$$

IR divergency

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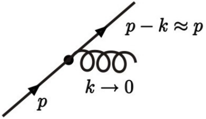


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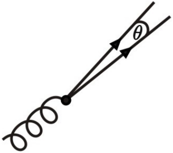


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**Solution**: define IR safe quantities which do not change under soft emissions or collinear splittings. Also ensures that the total cross section is finite.

# Jet Algorithms

# Requirements On A Jet Algorithm

From the theoretical considerations, a jet algorithm should exhibit

- infrared safety
- collinear safety
- factorizability - separation from the beam remnant(s)
- small renormalization scale dependence

These are required for meaningful (finite) fixed-order calculations (with small errors).

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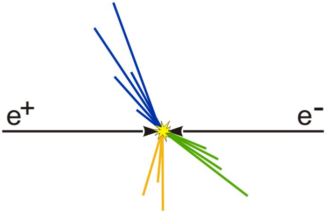
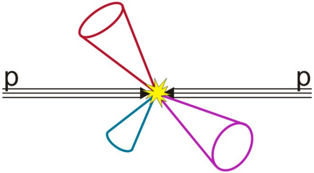
Some experimental/phenomenological aspects:

- approximate insensitivity to the soft underlying event, pileup
- fast running time
- close correspondance between final state partons and hadronic final state (small hadronization corrections)

These are required for the application of a jet algorithm in an analysis.

# Historical Development




Work with angles, angular 'distance' lead to successive recombination (clustering) algorithms

Work with coarse regions of high energy density, lead to cone-type algorithms

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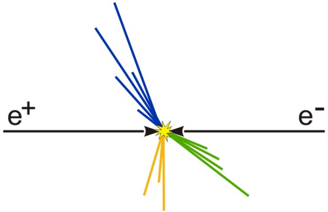


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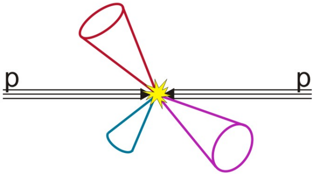


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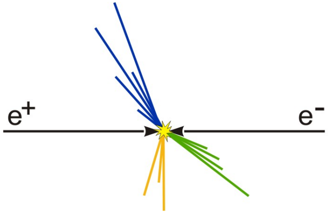


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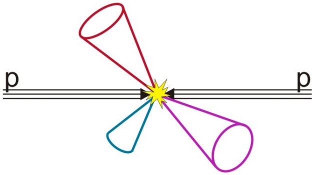
simplicity and modest hadronization corrections




Work with coarse regions of high energy density, lead to cone-type algorithms

They work because QCD modifies the energy flow on small scales

geometrical regularity and lower sensitivity to non-perturbative underlying event and pile-up

# A Modern Clustering Algorithm

**The longitudinally invariant $k_T$ algorithm**

distance between objects $i$ and $j$:

$$d_{ij} = \min(k_{T,i}, k_{T,j}) \cdot \sqrt{(\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2}/R_0$$

beam distance:

$$d_{iB} = k_{T,i}$$

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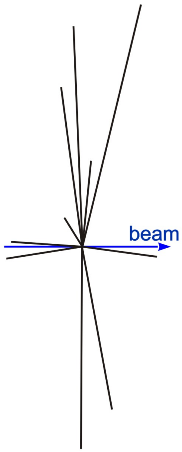

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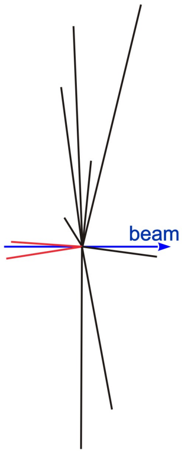

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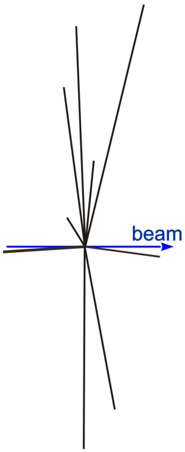

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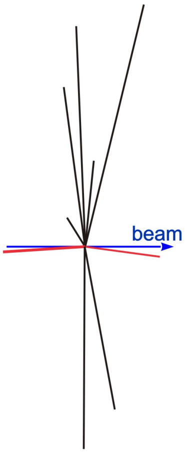

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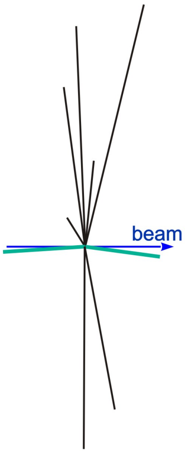

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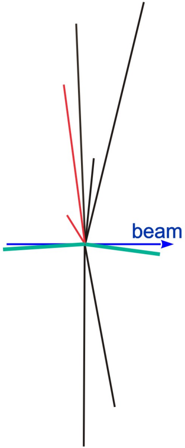

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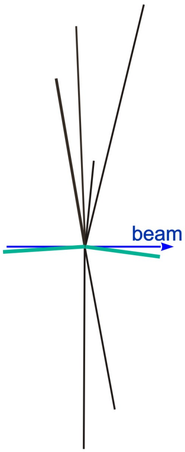

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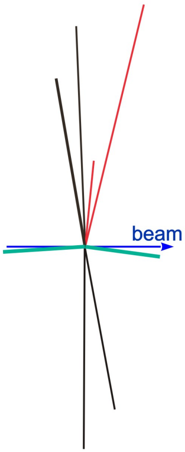

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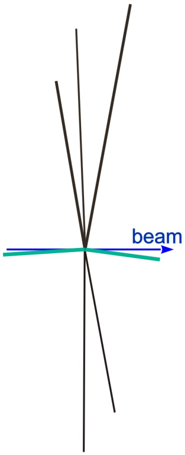

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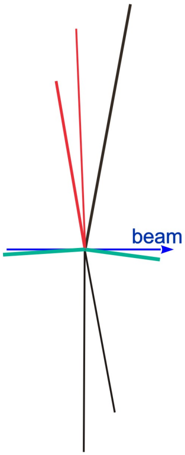

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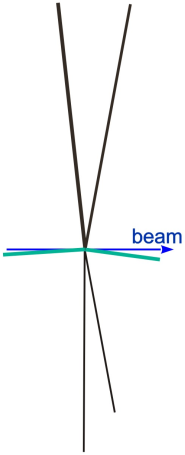

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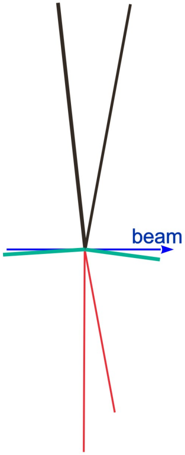

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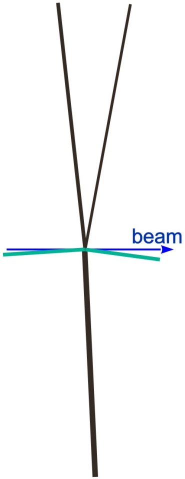

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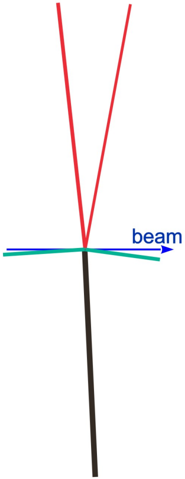

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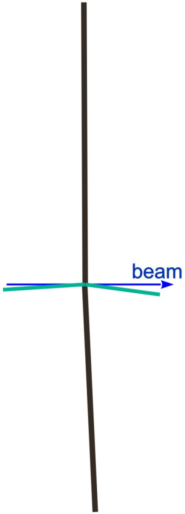

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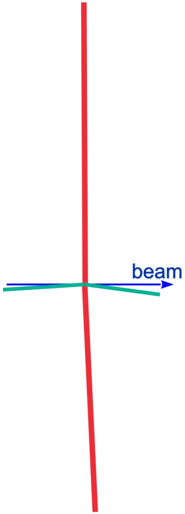

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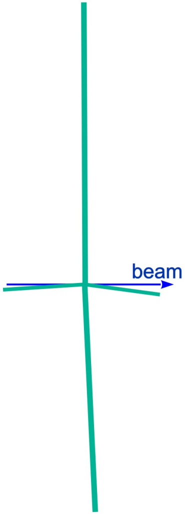

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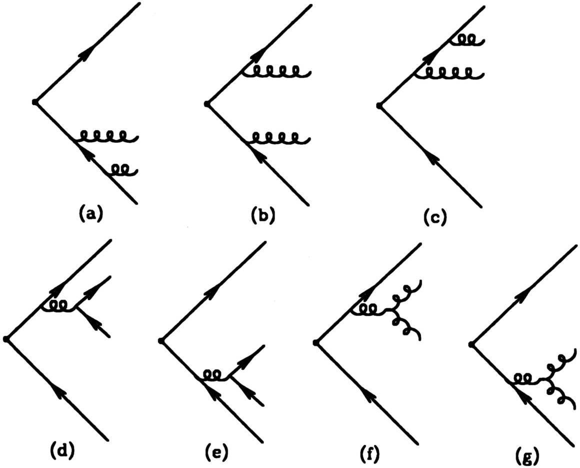
Two classes of tests:

1) Test jet-production cross sections in various regions of phase space.
2) More intimate testing: jet shapes, radius dependence, heavy flavour jets, . . .

# Is QCD Non-Abelian?




All LO diagrams for $e^+e^- \rightarrow q\bar{q}q\bar{q},\ q\bar{q}gg$ contribution to 4-jet production in $e^+e^-$ annihilation

Non-abelian QCD, SU(3), includes the selfcoupling of the gluon (f) and (g)

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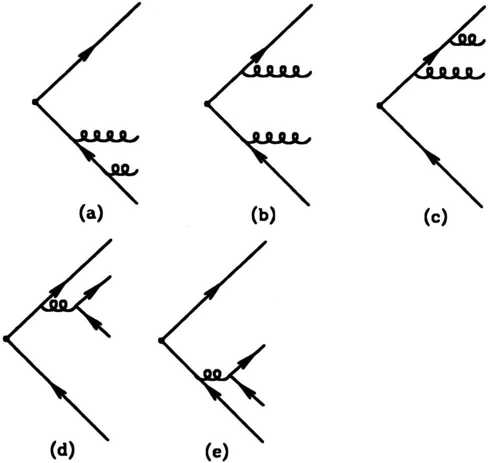


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Abelian QCD', $[\mathrm{U}(1)]^3$ has less $q\bar{q}gg$ contributions to the 4-jet cross section

# Is QCD Non-Abelian?

A. Ali et al., Phys. Lett. B82 (1979) 285:

$$d\sigma^{4jet} = \left(\frac{\alpha_s}{4\pi}\right)^2 [C_F T_F n_f \mathscr{A} + C_F^2 \mathscr{B} + C_F C_A \mathscr{C}]$$

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**Strategy:**

Fix $\alpha_s$ by 3-jet rate and calculate $d\sigma^{4jet}$ for both theories
Experimental test is difficult because the absolute normalization changes only slightly

Find different observables!

# Is QCD Non-Abelian?

L3 collaboration (LEP): Phys. Lett. B 248 (1990), 227:
Measure the relative orientation of the planes containing the primary $q\bar{q}$ jets and the secondary $q\bar{q}$ or $gg$ jets

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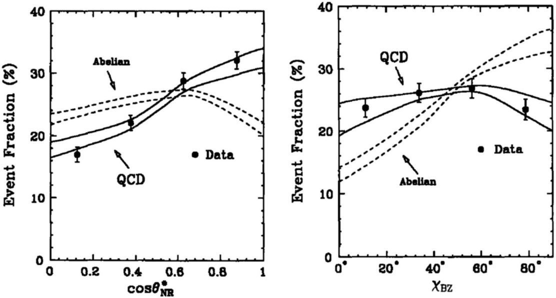


SU(3) is clearly favored compared to $[U(1)]^3$

Nachtmann-Reiter angle $\theta^*_{NR}$ is the angle between the momentum vector differences of the primary and secondary jets
Bengtsson-Zerwas angle $\chi_{BZ}$ is the angle between the planes of the primary and secondary jets

# Inclusive Jets At HERA

$$d\sigma_{ep}^{jet} = \sum_{i=q\bar{q}g} \int_0^1 dx\, f_i(x, \mu_F^2; \alpha_s)\, d\hat{\sigma}_i^{jet}(xP, \alpha_s, \mu_R, \mu_F) \cdot C_{had}$$

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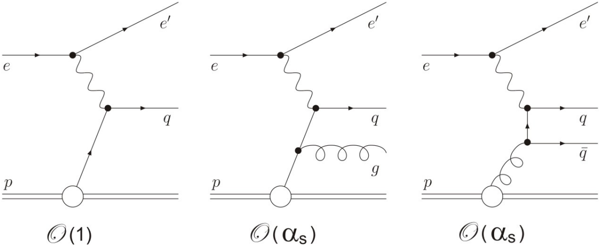

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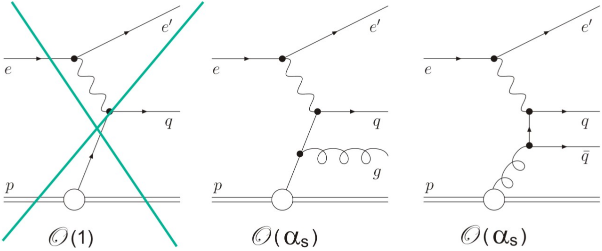
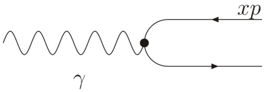
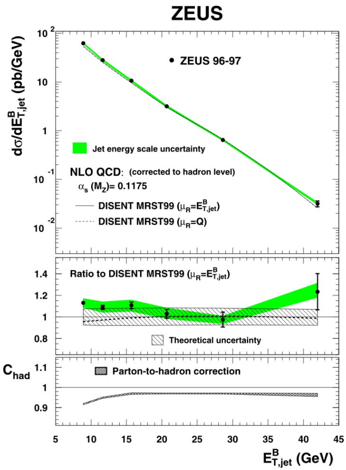



To exclude QPM $\mathcal{O}(\alpha_s^0)$ diagrams,
boost to the Breit frame and cut on $P_T^{jet}$



# Inclusive Jets At HERA

ZEUS, Physics Letters B 547 (2002) 164-180:




PDF was determined from global fits without any HERA jet-data - independent test of its validity

calculation was corrected to hadron level ($C_{had}$) and for $Z^0$ exchange

fixed-order calculation $\mathcal{O}(\alpha_s^2)$ describes the data very well over more than 3 orders of magnitude

# Azimuthal Jet Asymmetry At HERA

ZEUS, Physics Letters B 551 (2003) 226-240:

$$\frac{d\sigma}{d\phi_{jet}^{BF}} = A + B\cos(\phi_{jet}^{BF}) + C\cos(2\phi_{jet}^{BF})$$

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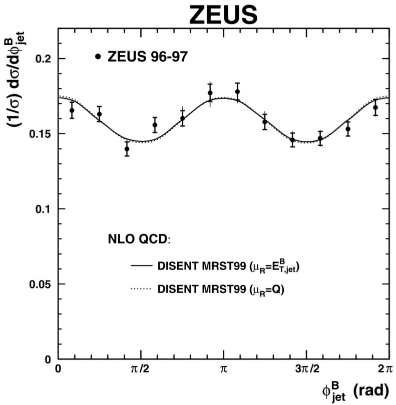
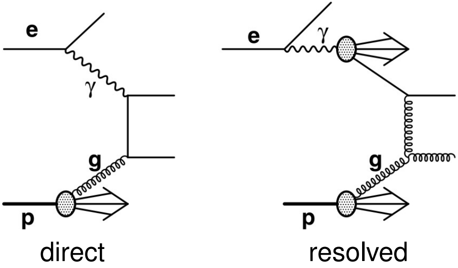


# Dijets In Photoproduction

$$d\sigma_{\gamma p}^{jet} = \sum_{i,j=q\bar{q}g} \int_0^1 \int_0^1 dx_p dx_\gamma \, f_i(x_p, \mu^2) f_j(x_\gamma, \mu^2) \, d\hat{\sigma}_{ij}^{jet}(x_p, x_\gamma, \alpha_s, \mu)$$



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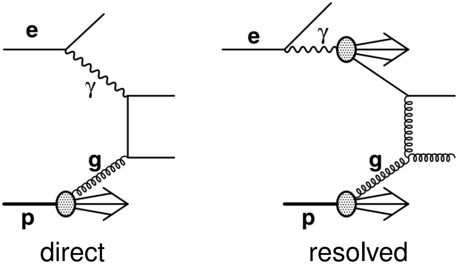


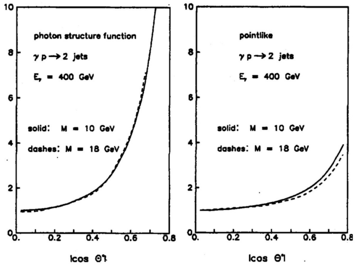

define $\theta^*$ as the dijet scattering angle in the parton-parton centre-of-mass frame, $\cos\theta^* = \tanh\left(\frac{\eta_1 - \eta_2}{2}\right)$

# Dijets In Photoproduction

in direct events the dominant boson-gluon fusion processes $\gamma^* g \to q\bar{q}$ have a quark propagator $\propto \frac{1}{1 - |\cos\theta^*|}$

in resolved events, the gluon propagator is more prominent, $qg \to qg$ and $gg \to gg$ $\propto \frac{1}{(1 - |\cos\theta^*|)^2}$

H. Baer et al., Phys. Rev. D 40 (1989) 2844:



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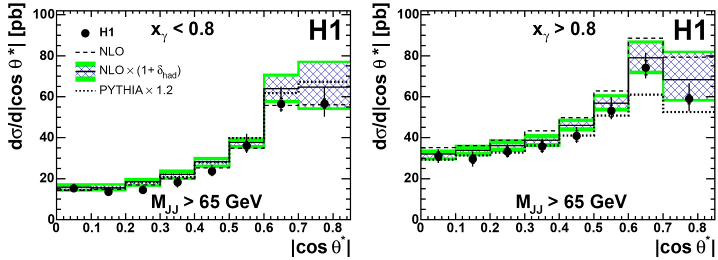
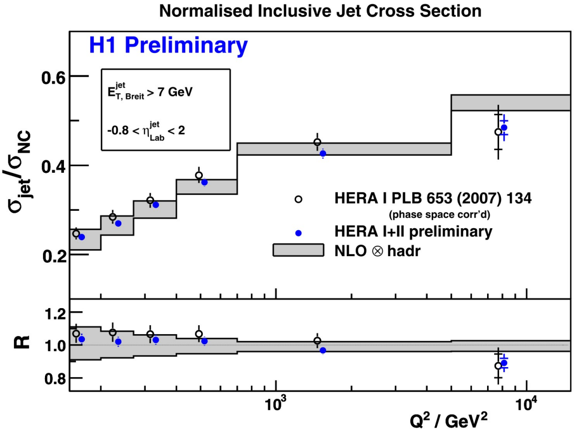
H1 collaboration, Phys. Lett. B 639 (2006) 21:



# Precision Physics With Jets

# Determination Of The Strong Coupling

With the full HERA dataset, so-far unachieved precision measurements are possible



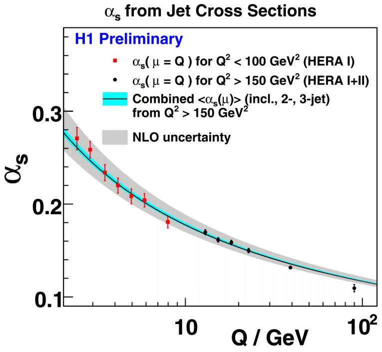

tiny experimental errors, partly due to cancellations

data very well described by fixed-order calculation

theoretical errors dominate in most regions

# Determination Of The Strong Coupling

Results from H1prelim-08-31 (black) and H1prelim-08-32 (red)




solid line is $\alpha_s$ evolved from high $Q^2$ fits, via two-loop solution of the renormalization group equation

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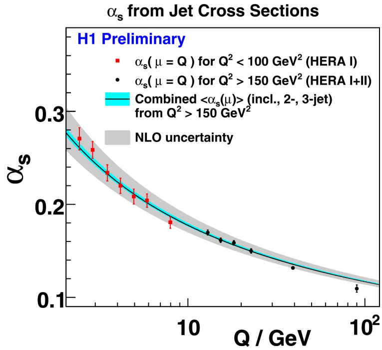
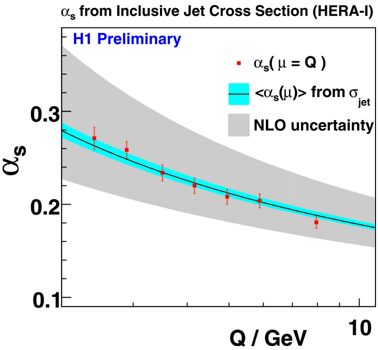
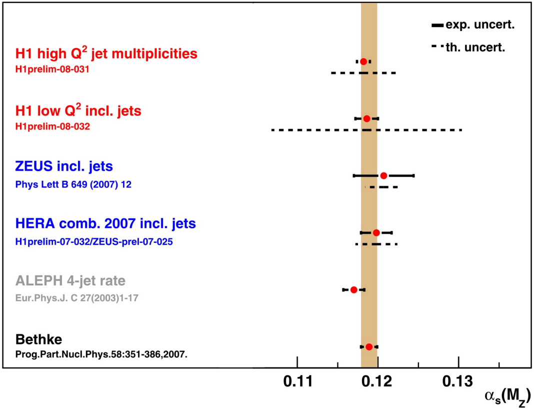



solid line is $\alpha_s$ evolved from high Q$^2$ fits, via two-loop solution of the renormalization group equation

fitting $\alpha_s$ to low Q$^2$ data gives huge theoretical errors

# Determination Of The Strong Coupling




experimental errors from HERA jets are competitive with LEP and world average

theoretical errors are dominant because of missing higher orders in NLO calculations

# PDF Determination Including Jets

Parton distribution functions (PDFs) are often determined from inclusive cross sections in global fits within the DGLAP formalism.
What about jet data? Reminder:

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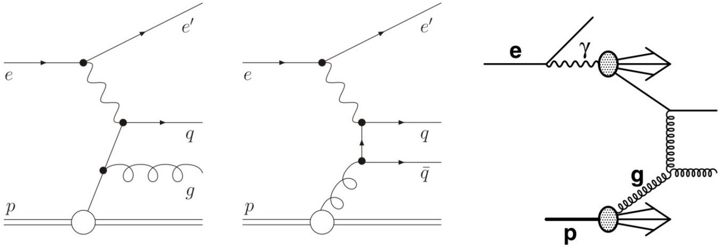
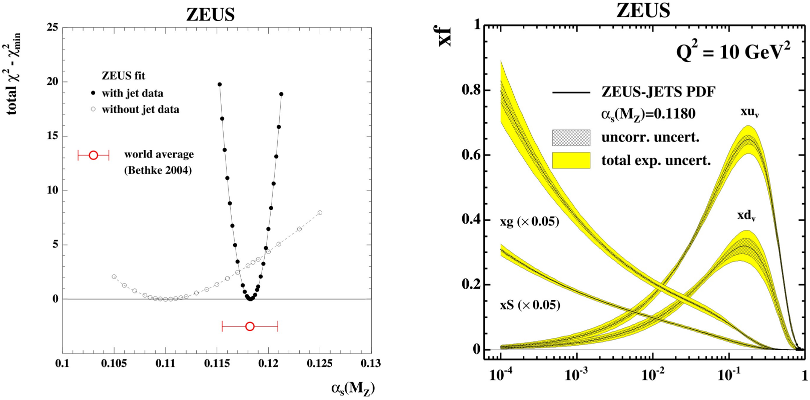



Jet data are directly sensitive to $\alpha_s$ and the gluon PDF.
Instead of using fixed target DIS data for the medium to high $x$ region, use jet data in the PDF determination.

# PDF Determination Including Jets

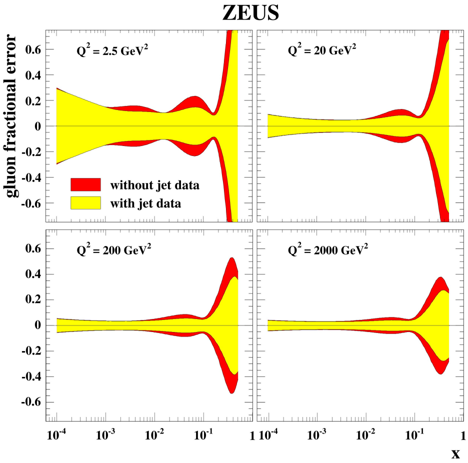
ZEUS collaboration, European Physical Journal C 42 (2005) 1:




Consistent fit without heavy-nuclei corrections, higher-twist contributions or isospin-symmetry assumptions.

# PDF Determination Including Jets

The fitted $\alpha_s(M_Z)$ is consistent with the world average. The errors on the gluon could be reduced.




The ZEUS-JETS pdf was determined from HERA I data. Dominant errors in global fits are systematic ones, here statistical uncertainties were dominant. Expect improvement for HERA II.

# Summary And Outlook

Jets helped to test and establish QCD.

This talk: jet measurements in the main HERA phase space, where perturbative QCD works very well.

Many topics were not covered,

+ forward jets (small x, DGLAP?)
+ minijets and multiple interactions
+ jet substructure
+ heavy flavour jets
+ diffraction (factorization?)
+ ...

Wherever pQCD calculations describe data, physical quantities can be extracted. Expect high precision measurements with the full HERA II dataset.