QCD Studies with

JETS AT HERA

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OUTLINE

Jet physics at HERA is a rather rich field. We will have time to cover only a few aspects (e.g. not heavy quarks, diffraction, …).

¶ Basics	Physics at HERA Jets at HERA, Tools HERA, H1 and ZEUS
¶ Measurements	High-Q^2 DIS (Q^2 > 125 GeV^2) Low-Q^2 DIS Photoproduction
¶ Extraction of QCD parameters	The strong coupling α_S Information on PDFs Color factors etc.
¶ Summary …	What we have seen What remains to be done … and what we would like to have …

PHYSICS AT HERA: BASICS

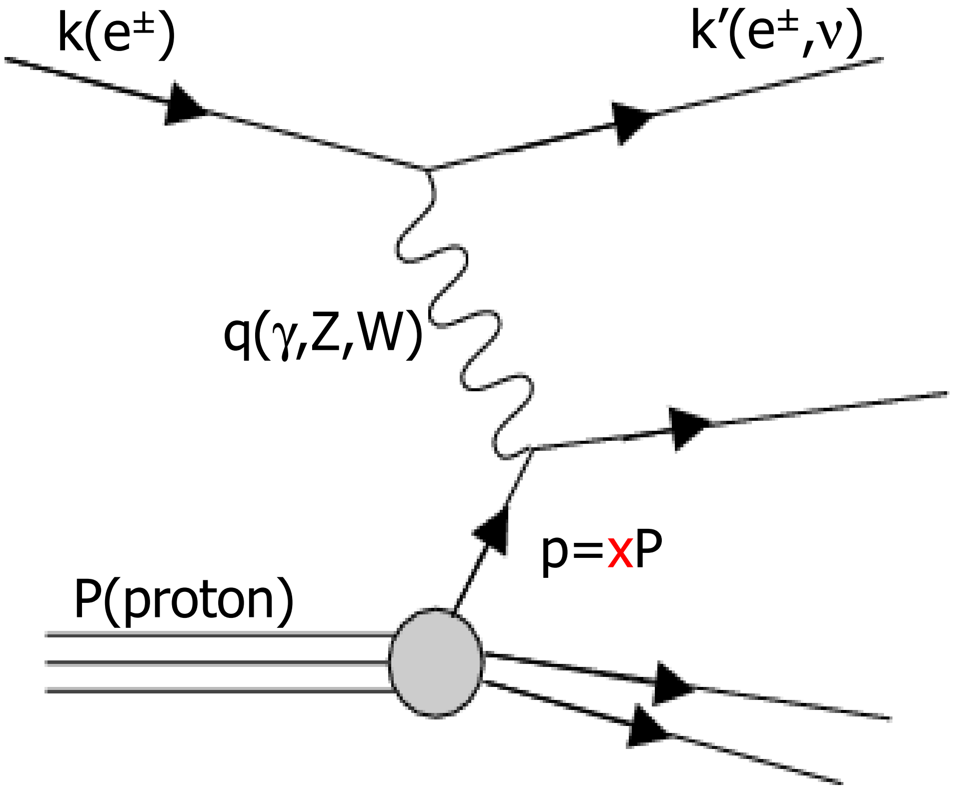
The electron as a probe for the proton structure:

Resolution power: $\lambda \sim 1/Q$ ➔ proton structures from ~1 fm to 0.001 fm resolvable!

E_e = 27.5 GeV

E_p = 920 GeV

$\sqrt{s}$ = 318 GeV



y=qp/kp: Inelasticity

$Q^2=-q^2=-(k-k')^2$ [Resolution $\lambda \sim 1/Q$]

$x=Q^2/2pq$: parton momentum fraction (in leading order)

$Q^2 = sxy$

Distinguish two kinematic regimes:

– Deep-inelastic scattering (DIS): $Q^2 > 1$ GeV^2.

– Photoproduction (PHP): $Q^2 \sim 0$ GeV^2.

PHYSICS AT HERA: INCLUSIVE σ

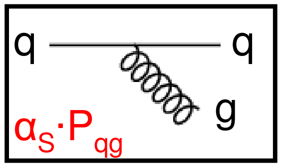
Electron/positron cross-section:

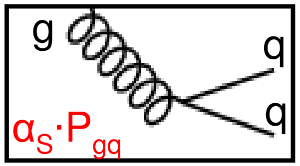
convolution of PDF f=q,g and hard scattering cross-section σ:

$$\frac{d^2\sigma^{\pm}}{dx dQ^2} \propto \hat{\sigma}(x,Q^2) \otimes q(x,Q^2)$$

Behaviour of quark density q(x,Q^2):

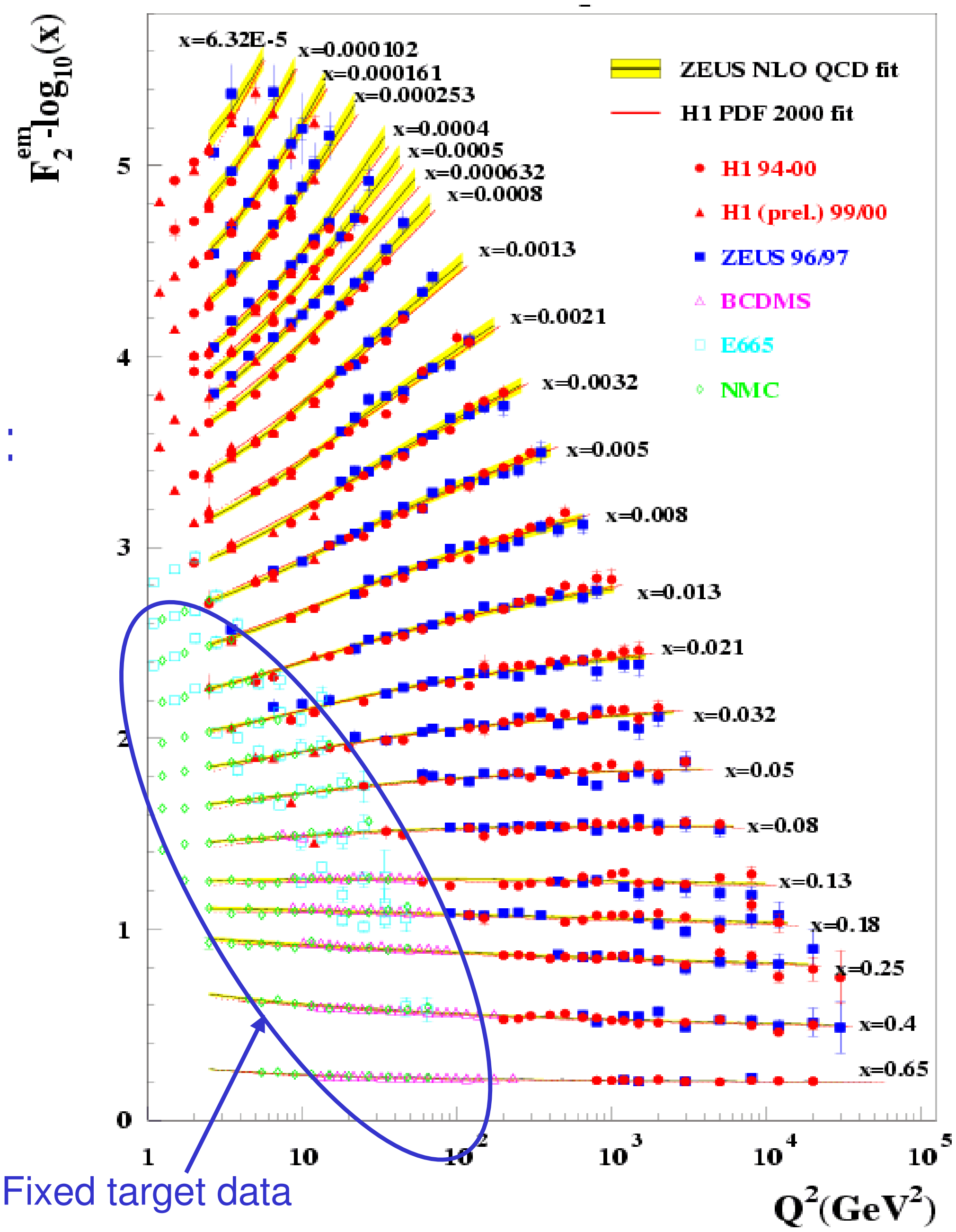
$$\frac{dq(x,Q^2)}{d\ln Q^2} \propto -\alpha_S \cdot P_{qg} \cdot q(x,Q^2) + \alpha_S \cdot P_{gq} \cdot g(x,Q^2)$$





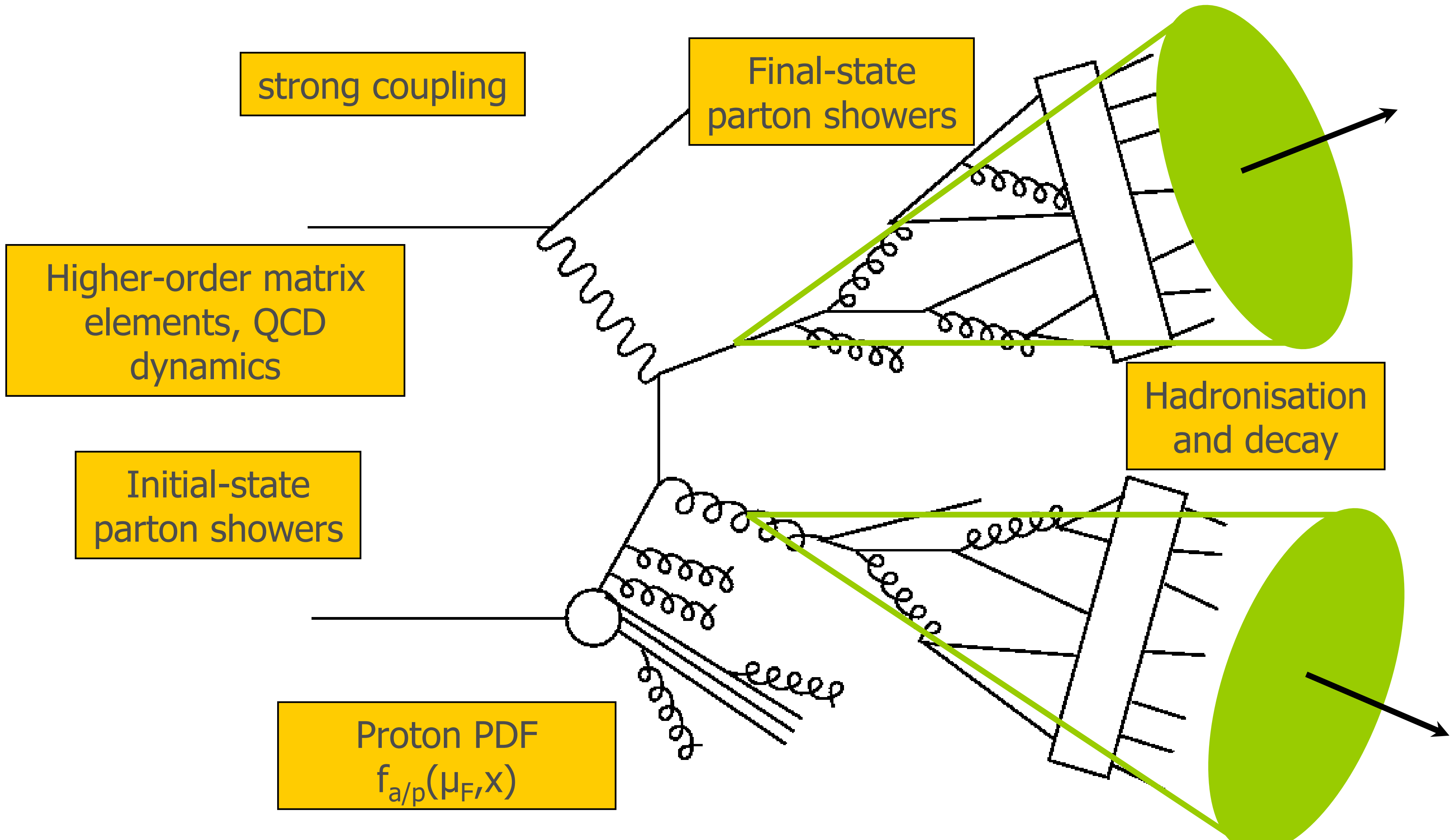
Experimental status:

– Data with ~2% precision.
– Accurate description by QCD.
– HERA: low x, high Q^2!
– α_S from scaling violations to ~4%!



JETS: WHY AND WHAT?

The ep collisions at HERA have more to offer: hadronic final state!



– pert. expansion
– factorisation

$$\sigma_{jet} = \sum_{n,a} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} = \sum_n \alpha_S^n\left(\mu_R^2\right) \cdot \sum_{a=q,\bar{q},g} \int dx f_{a/p}\left(x, \mu_F^2\right) \cdot \hat{\sigma}_{n,a}\left(\mu_R^2, \mu_F^2, \frac{x_{Bj}}{x}\right)$$

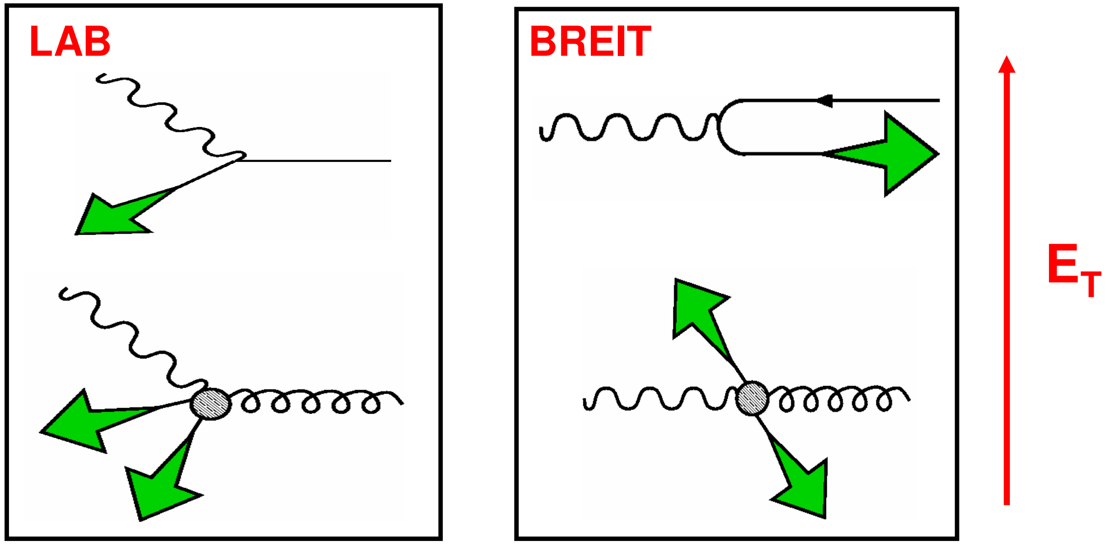
JET MEASUREMENTS: TOOLS

The "Breit" reference frame:

– "QPM" events: no QCD involved
  → want to discard these events!

– Go to frame where photon and parton are on z axis (Breit frame).

– Select interesting events based on transverse energy with respect to Breit z axis: $E_{T,Breit}$.



Jet algorithms: The standard is the k_T clustering algorithm

– Employed in the Breit frame for DIS analyses

– run on either calorimeter cells or energy-flow objects built from tracks and calorimeter cells (optimisation of resolution).

– Distance measure for object combination: $d_{ij} = \min\left(E_{T,i}^2, E_{T,j}^2\right) \cdot \left(\left(\eta_i - \eta_j\right)^2 + \left(\varphi_i - \varphi_j\right)^2\right)$

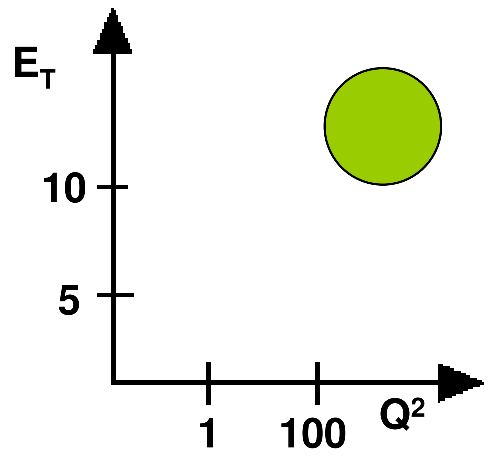
– Theoretically preferable to cone algorithms (full infrared and collinear safety)

– Smaller hadronisation corrections than other algorithms!

JET MEASUREMENTS: OVERVIEW

Kinematic regimes:

- High-Q^2 DIS (> 125 GeV^2): Smaller statistics; reliable theoretical predictions with small errors - $\alpha_S=\alpha_S(Q^2)$!
- Low-Q^2 (5 - 100 GeV^2): Large statistics, low scales (Q^2).
- Photoproduction: large statistics, but effects of photon PDF and underlying event (hadron-hadron like!)
- High/low E_T: E_T as hard scale – $\alpha_S=\alpha_S(E_T)$?

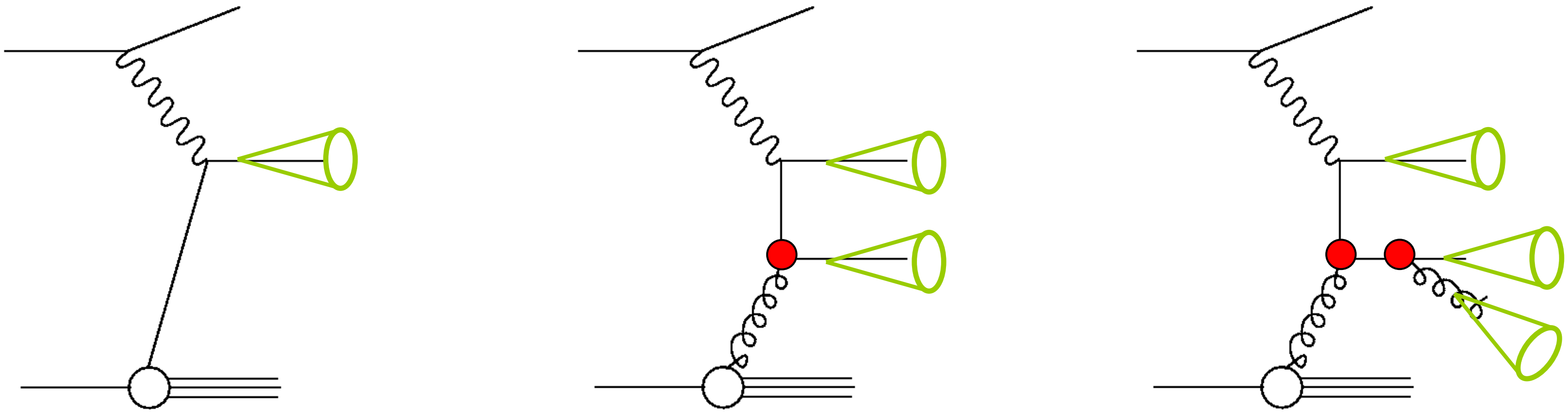


Jet Multiplicity:

“Inclusive jets”: count single jets → large statistics, precise α_S and PDF determinations.

Dijets: full access to matrix elements, QCD dynamics. Statistics?

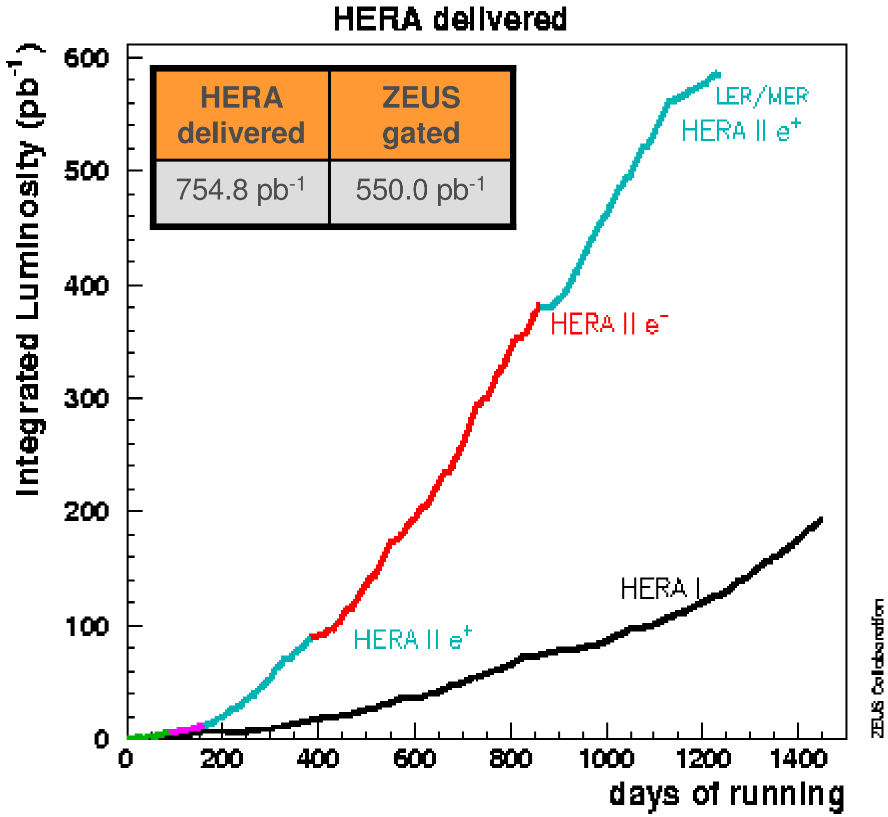
Threejets: More QCD degrees-of-freedom. Already in LO ~ α_S^2!

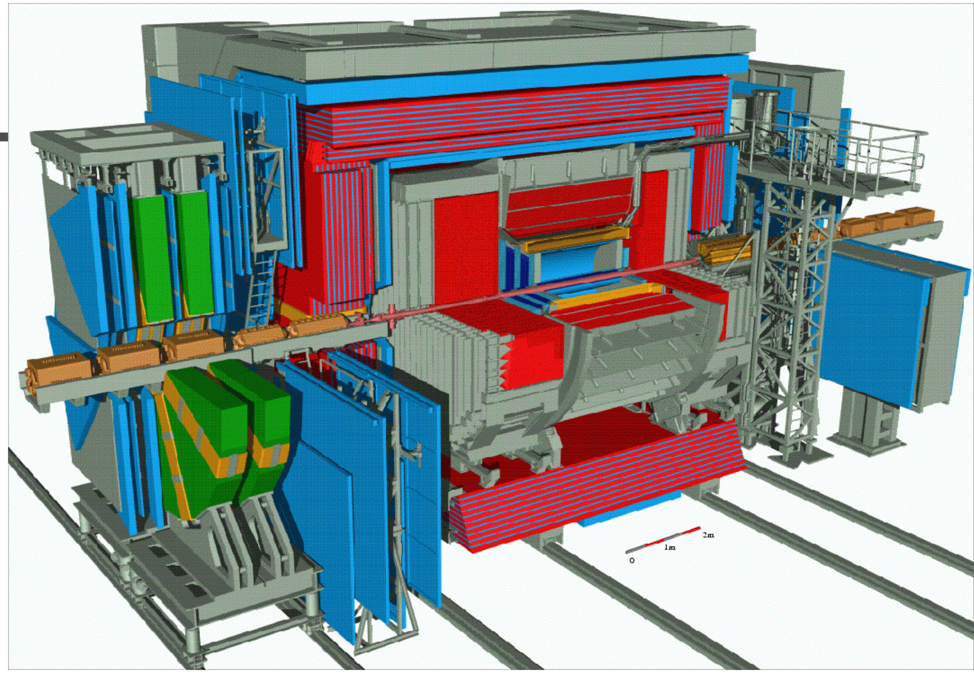


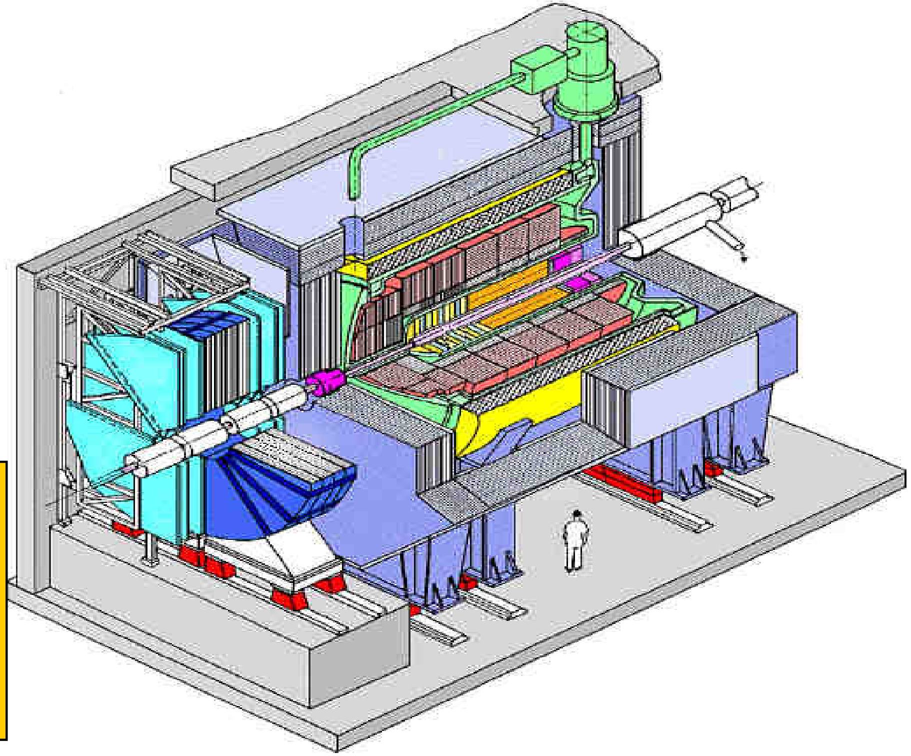
HERA, H1, ZEUS

HERA: lumi from 1992 to 2007.

No challenge for these data in sight!



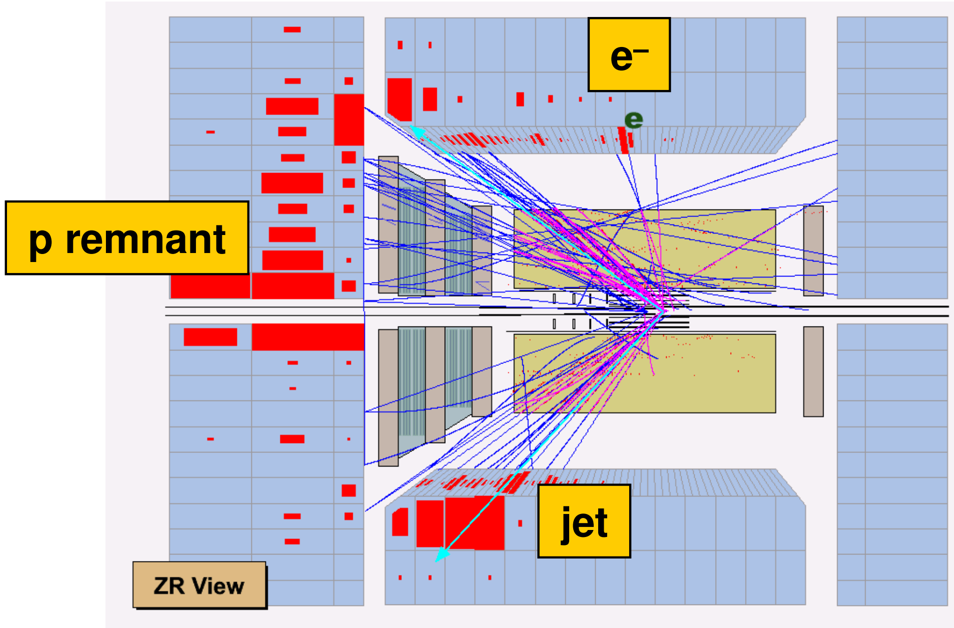




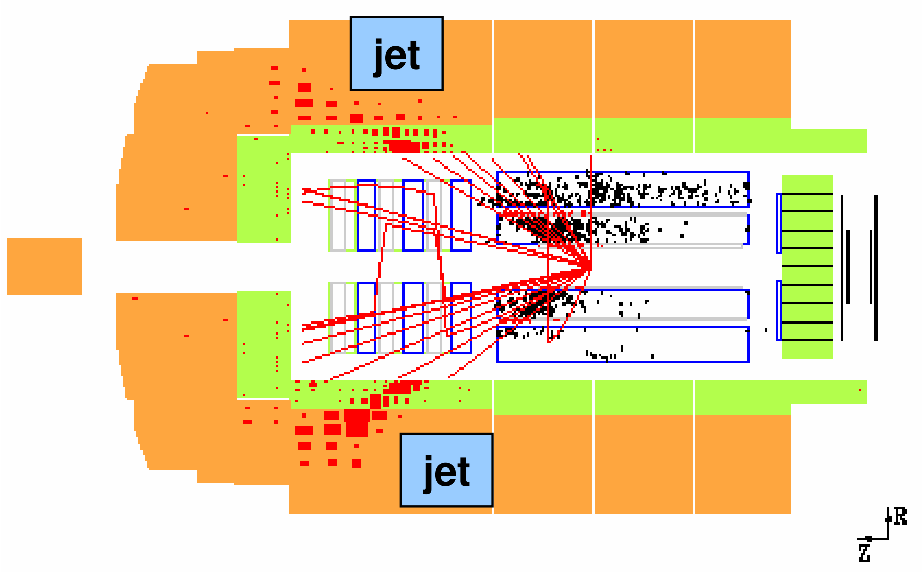
- LAr (H1) or U/scint. calorimeter (ZEUS)
- 45000 / 12000 cells (H1 / ZEUS).
- e±: $\sigma/E = 12\%/\sqrt{E[GeV]}$ (H1, ZEUS 18%)
- π,p: $\sigma/E = 50\%/\sqrt{E[GeV]}$ (H1, ZEUS 35%)

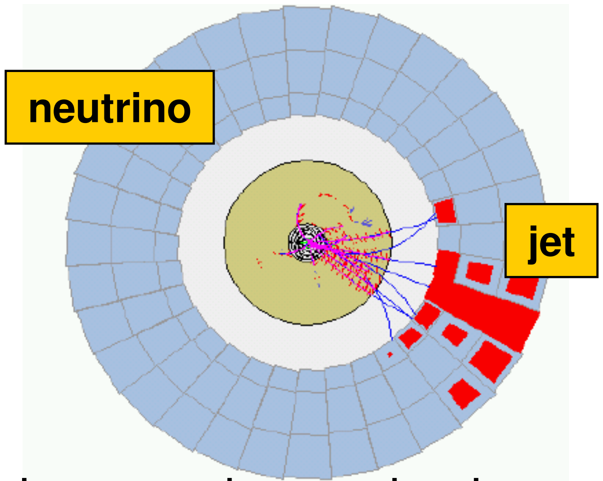
JET EVENTS IN H1 AND ZEUS

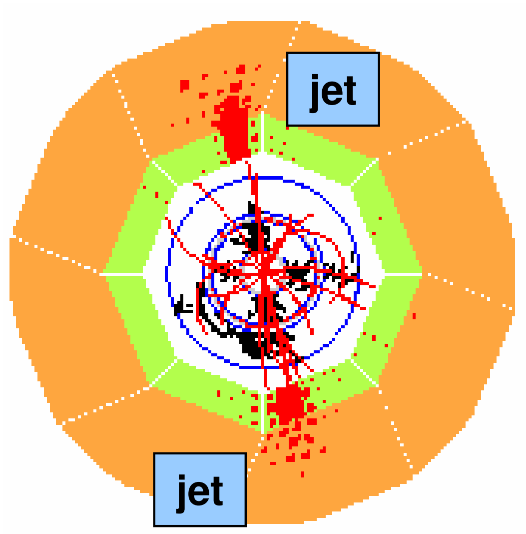
Neutral current jet production in DIS



Photoproduction of jets





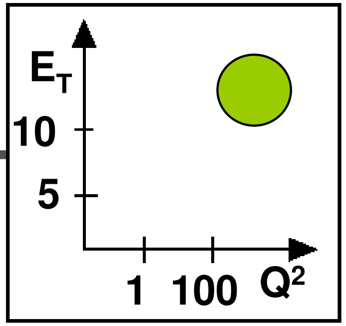


Charged current jet production

OUTLINE

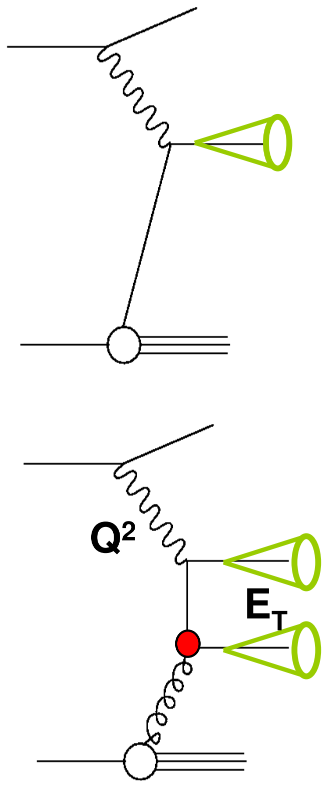
- ¶ Basics
  - Physics at HERA
  - Jets at HERA, Tools
  - HERA, H1 and ZEUS
- ¶ Measurements
  - High-Q^2 DIS ($Q^2 > 125$ GeV^2)
  - Low-Q^2 DIS
  - Photoproduction
- ¶ Extraction of QCD parameters
  - The strong coupling α_S
  - Information on PDFs
  - Color factors etc.
- ¶ Summary …
  - What we have seen
  - What remains to be done
  - … and what we would like to have …

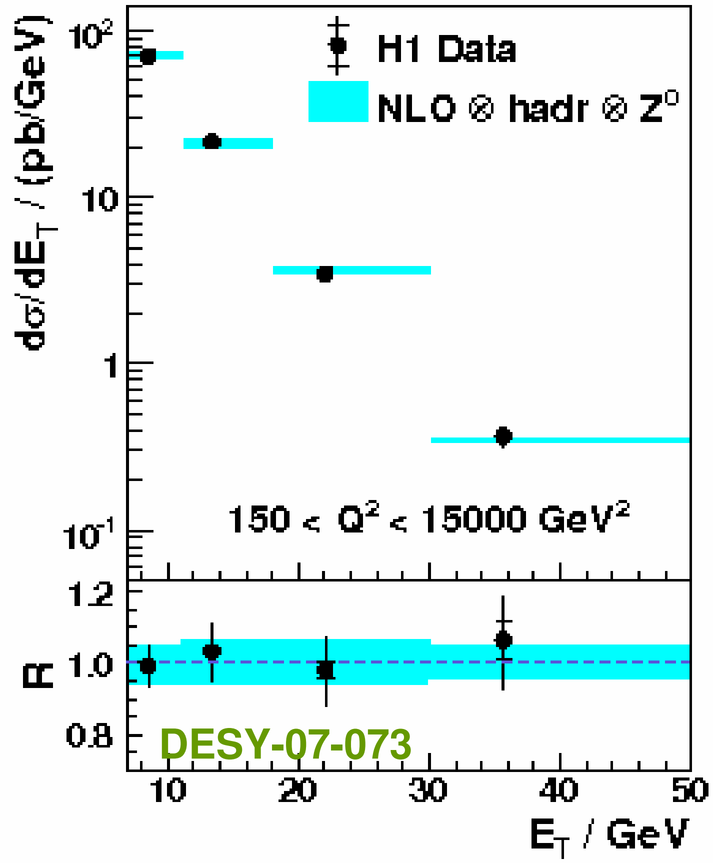
HIGH-Q^2: INCLUSIVE JETS

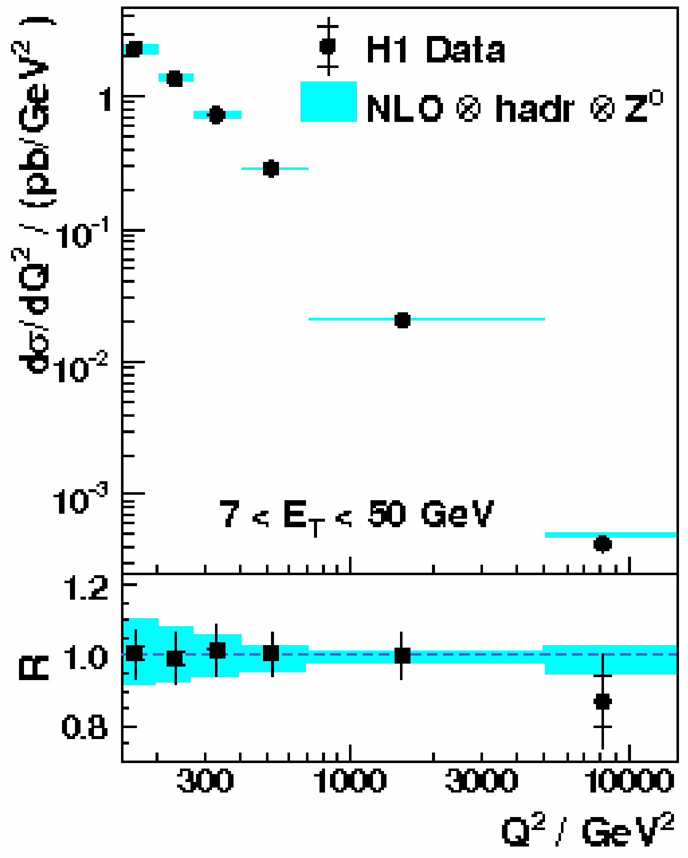


Typical hard-scale selection

$Q^2 > 150$ GeV^2 $E_{T,Breit} > 8$ GeV $-1 < \eta_{lab} < 2.5$

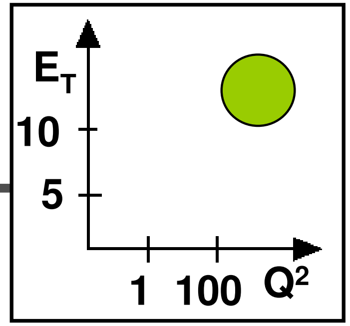






– NLO QCD describes data on the level of few percent!
– Statistical error between 1 and 10%, experimental error (scale, model) ~5%!
– Theory dominated by renormalisation scale (and PDF) errors (~±5%).
– Similar for double-diff. cross-section $d^2\sigma/dE_TdQ^2$.

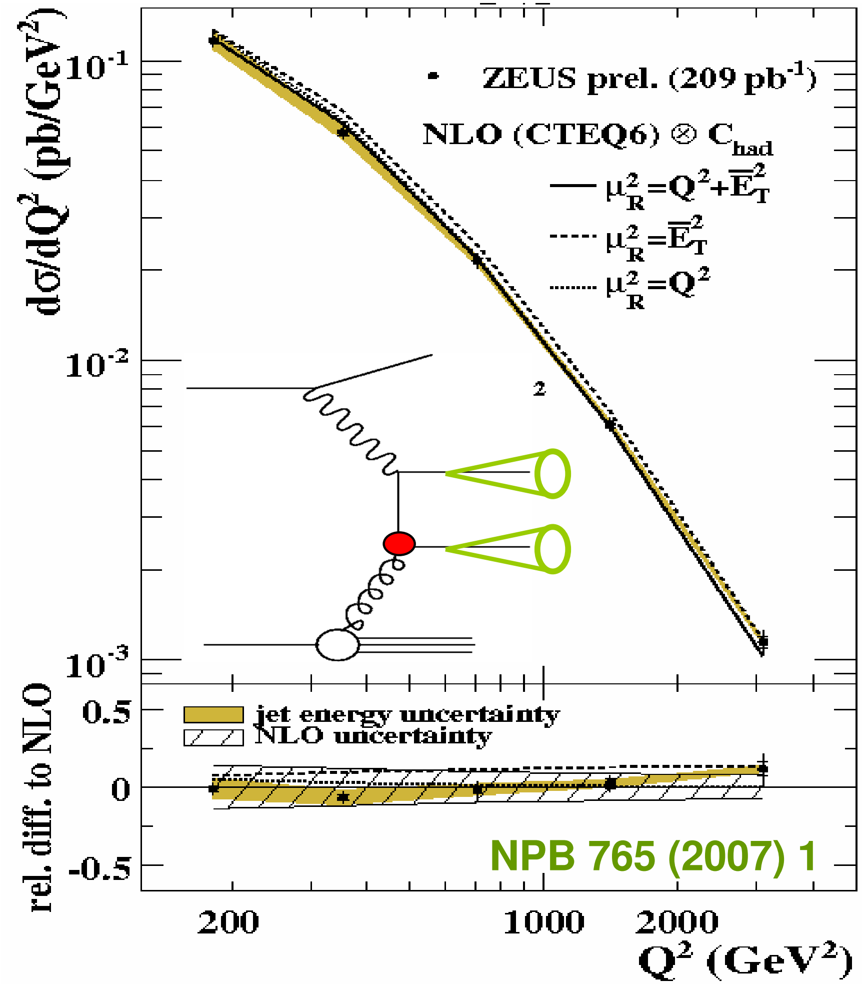
HIGH Q^2 DI/TRIJETS

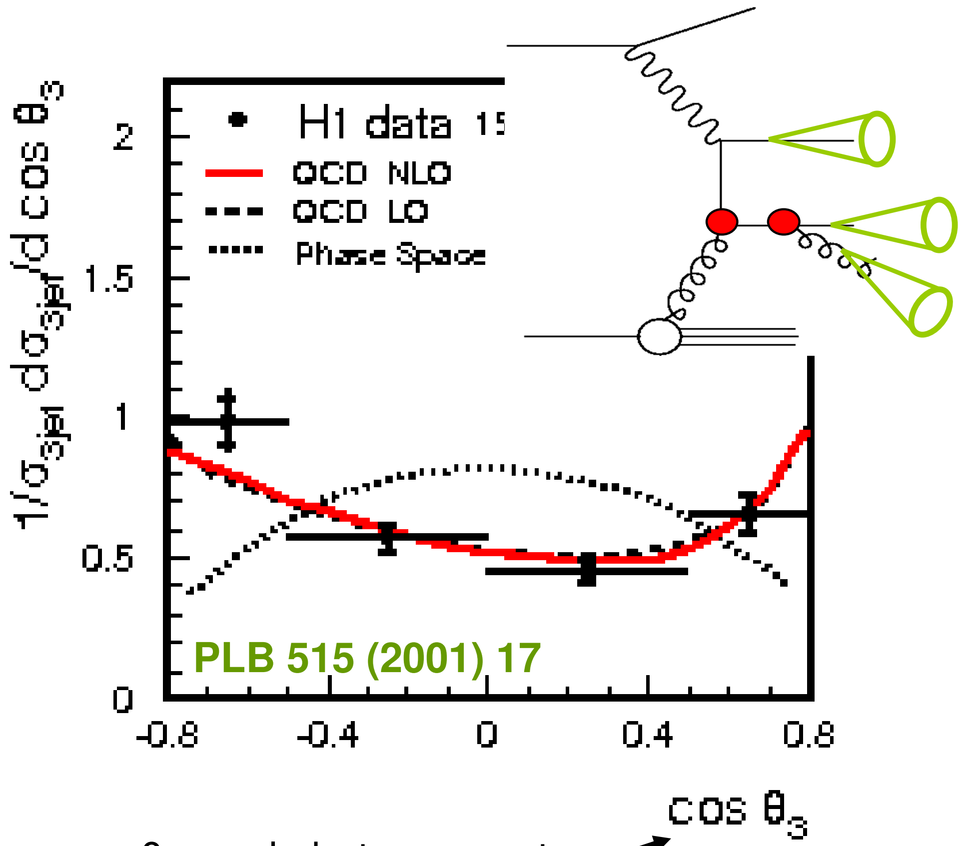


Detailed tests of factorisation:

Interplay of coupling, PDF, matrix element.

$$\sigma_{jet} = \sum_{n,a} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a}$$

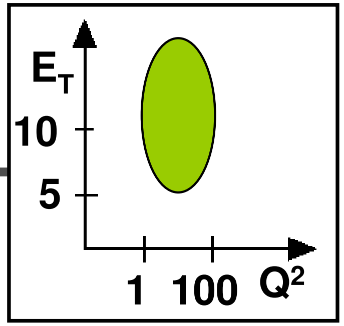




$\cos\theta_3$: angle between proton beam and highest-energy jet!

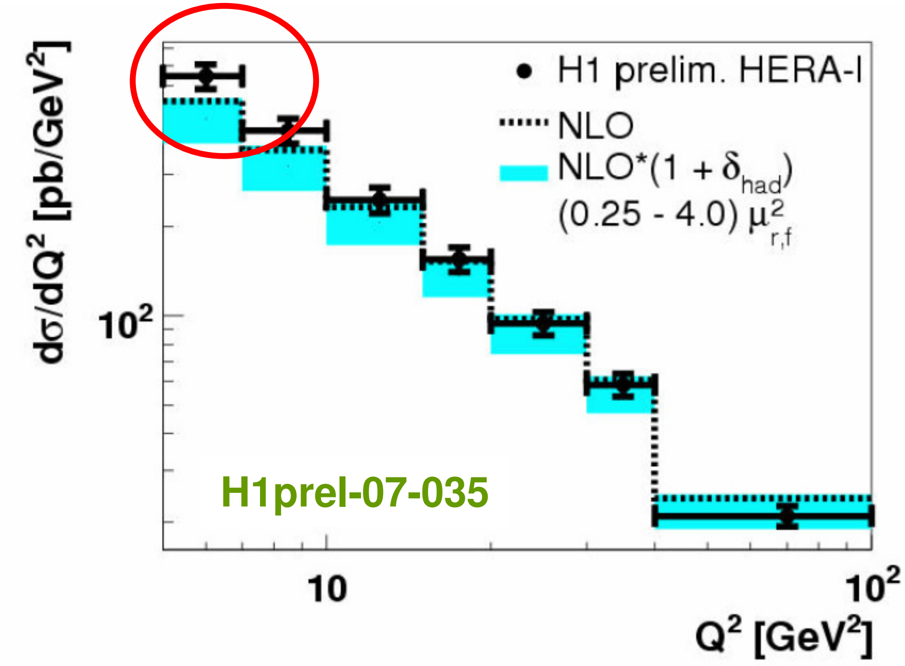
Normalisation and shapes described → higher-order QCD works excellently!
Fundamental test of $O(\alpha_S^2)$ and $O(\alpha_S^3)$ matrix elements.

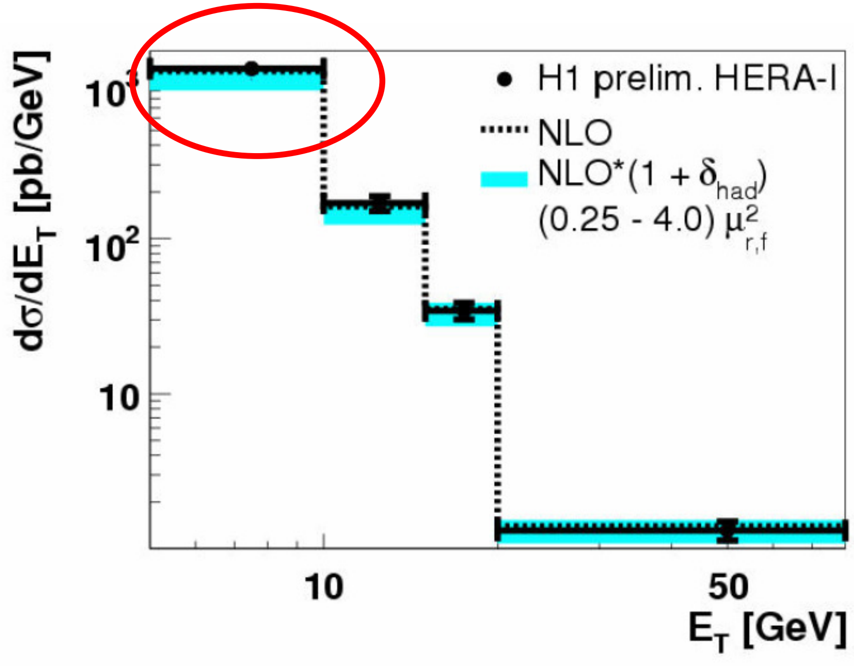
JETS AT LOW Q^2: INCLUSIVE

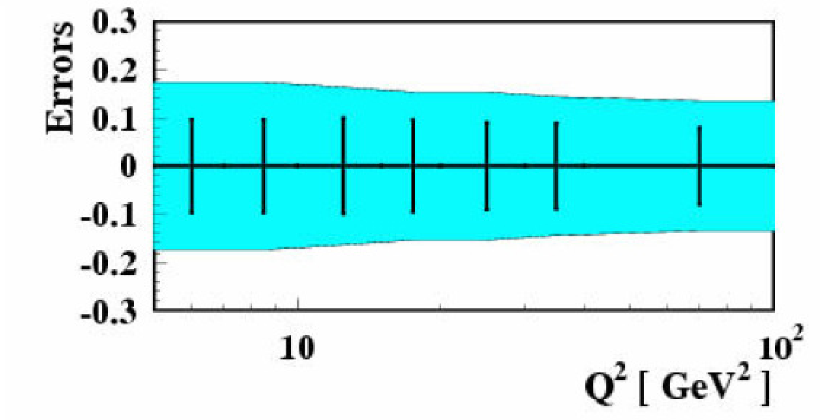


Typical low Q^2 selection:

- $5 < Q^2 < 100$ GeV^2.
- Jets in Breit, $E_T > 5$ GeV.

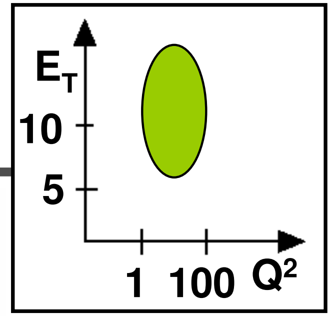






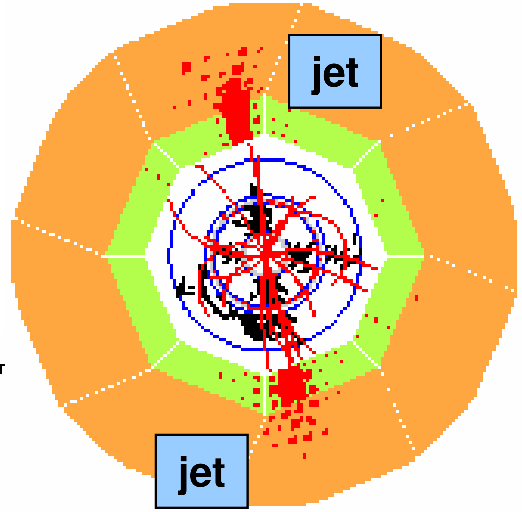
- Small statistical and exp. uncertainties!
- Also di/trijets at low Q^2 well described.
- Large theory uncertainty up to ±20%
  → problem of missing hard scale (Q^2, E_T)?
- Large discrepancies for Q^2, E_T < 10 GeV[(2)].
- Earlier studies: Problems located “forward”.

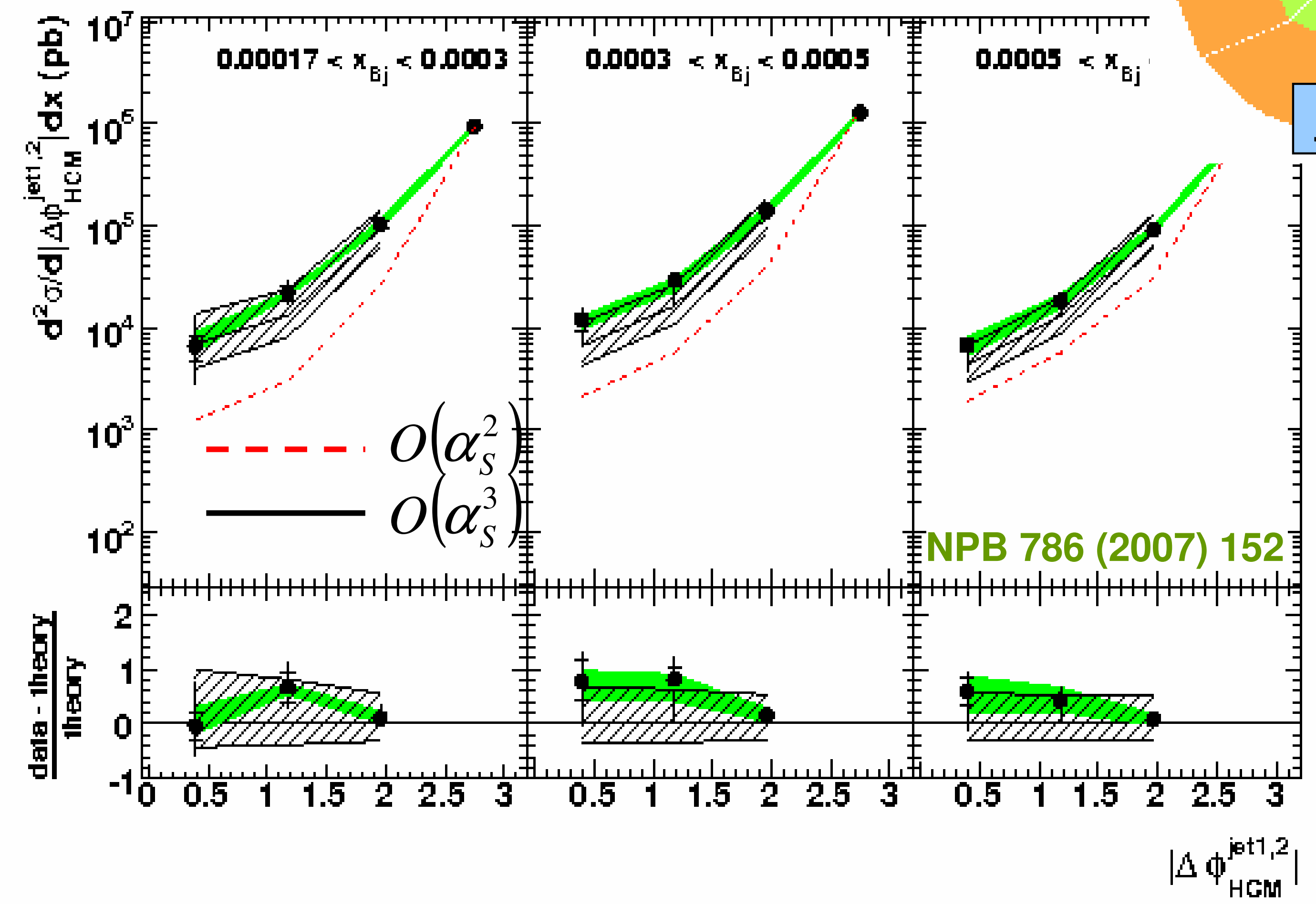
LOW Q^2 JETS: $\Delta\phi$



What about more difficult observables?

– difference in azimuthal angle of two jets.
– LO dijet expectation: two jets back-to-back!
– Compare NLO dijet and trijet QCD to data …





Additional radiation from $O(\alpha_S^3)$ needed – $O(\alpha_S^2)$ is effectively LO!

Detailed test of high-order terms!

Discrepancies more pronounced at low x_{Bj}: Connection to parton dynamics?

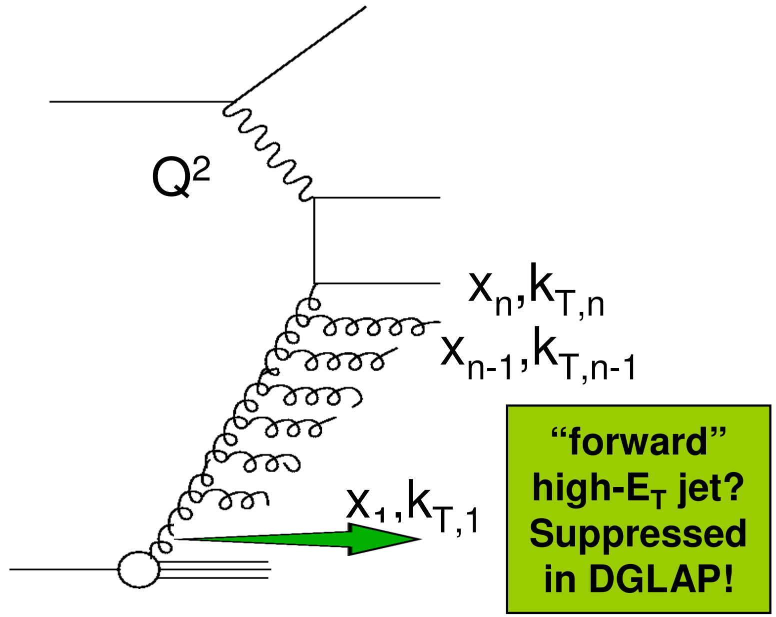
FORWARD JETS, PARTON DYNAMICS

¶ Basics: DGLAP evolution

Relevant evolution parameter $\ln Q^2$,
effect. resummation of terms $(\alpha_S \ln Q^2)^n$.

➔ Strong ordering of radiated transverse momenta

$$Q^2 \approx k_{T,n}^2 >> k_{T,n-1}^2 >> \ldots >> k_{T,1}^2$$



But at low x, terms $(\alpha_S \ln 1/x)^n$ might be large
→ taken into account in BFKL approximation.
→ ordering in x:

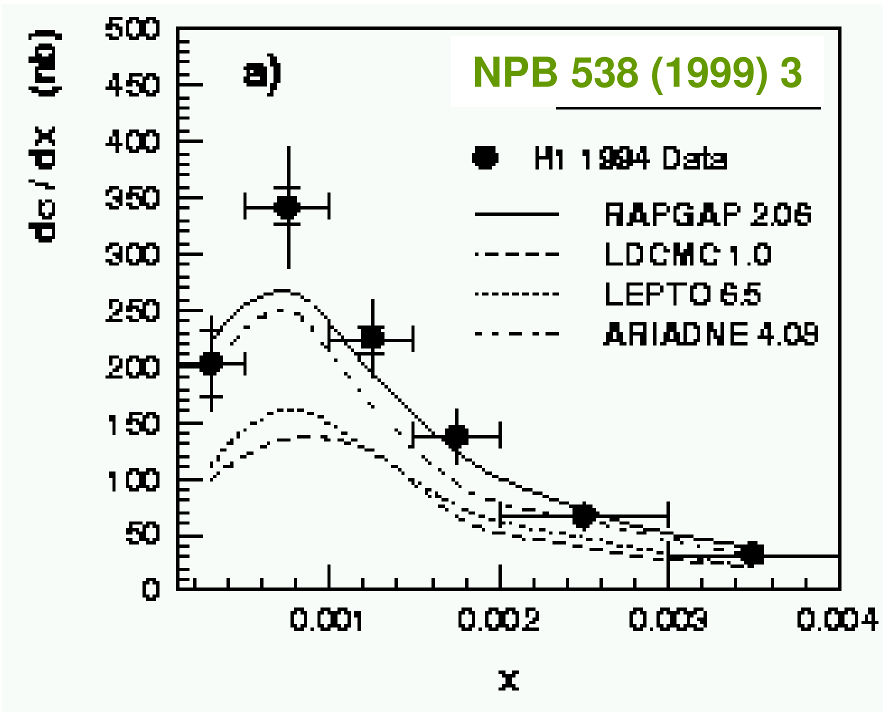
$$x_n << x_{n-1} << \ldots << x_1$$

Status in 2001: "forward jets"

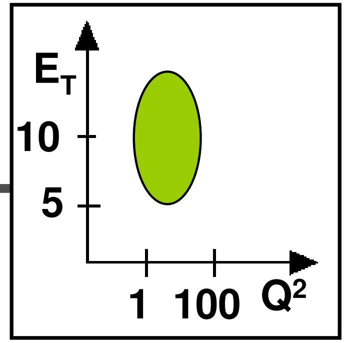
– DGLAP calculations / models fail at low x!
– Models with conceptual similarities to BFKL do a better job (color-dipole model).

– But also inclusion of resolved photon helps.
– … is it only missing higher orders?

– Similar observations with "forward pions".

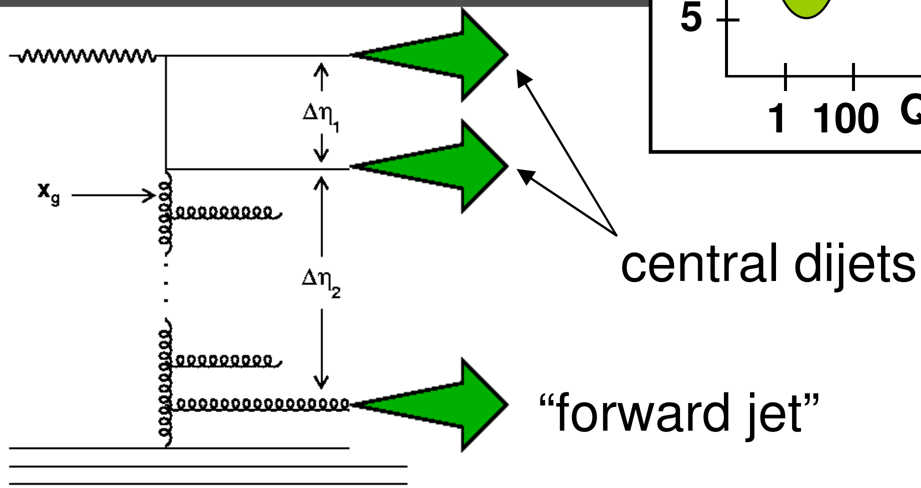


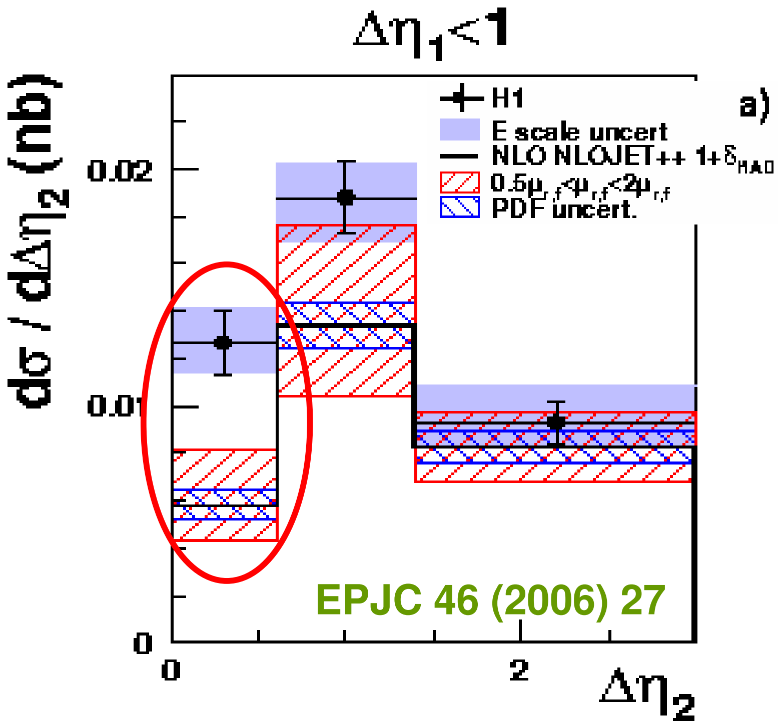
FORWARD JETS: NEWS

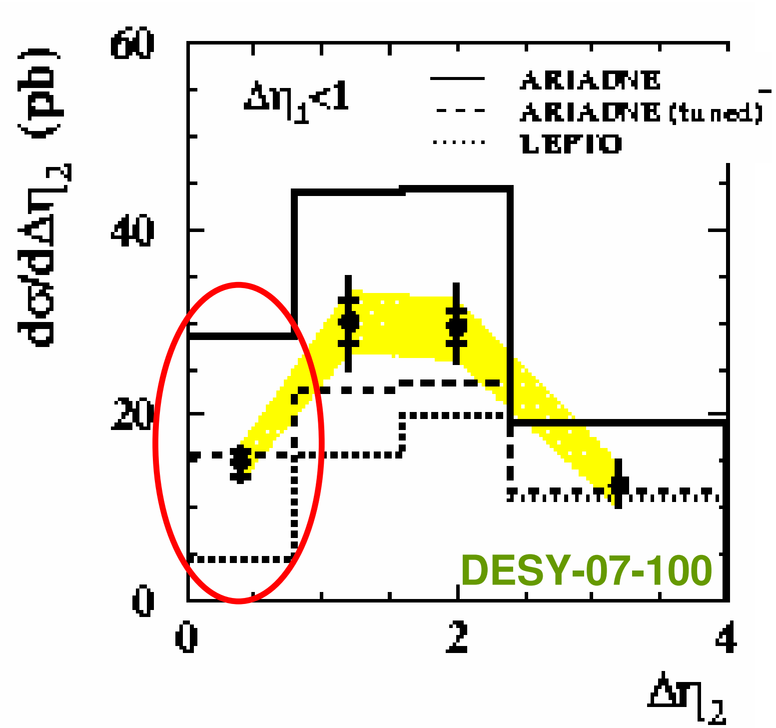


- Today, the phenomenon is reproduced in much larger data samples.
- Go for more exclusive final states: Require forward jet + central dijets.

→ - 3-jet NLO describes (only) large $\Delta\eta_2$.
- (Tuned) ARIADNE is pretty good.

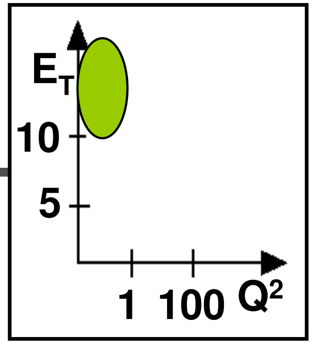






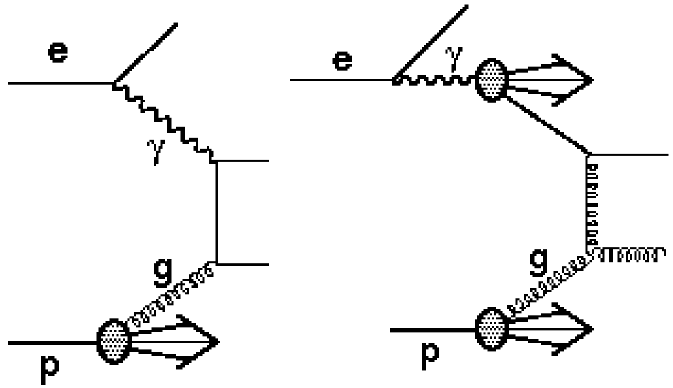
Problem not fully solved. More theory input needed (BFKL program?)

JETS IN PHOTOPRODUCTION



Remember: direct and resolved events

Direct: photon couples directly to hard scattering



Resolved: photon as source of hadrons

Experimentally observable $x_{\gamma,obs}$:

$$x_\gamma = \frac{E_{T,1}e^{-\eta_1} + E_{T,2}e^{-\eta_2}}{2yE_e}$$

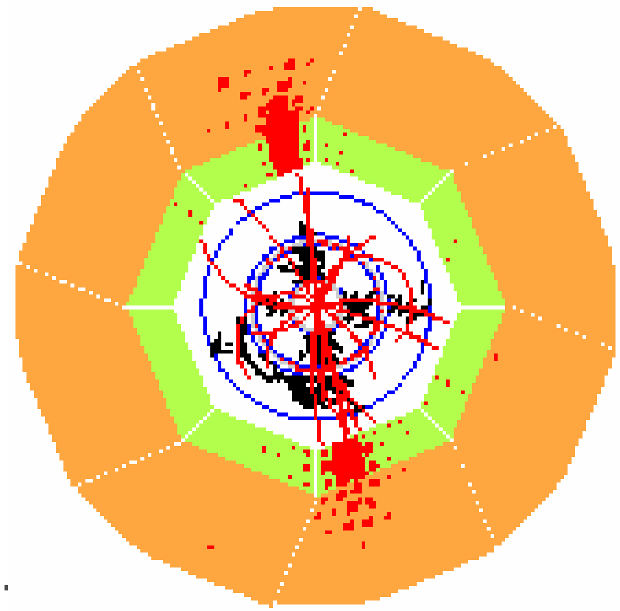
$x_{\gamma,obs} > 0.75 \rightarrow$ direct
$x_{\gamma,obs} < 0.75 \rightarrow$ resolved

Various additional challenges:

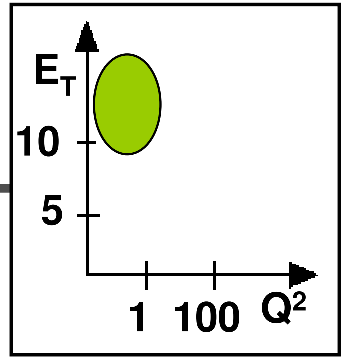
– Photon PDF relatively poorly known:

$$\sigma_{jet} = \sum_{n,a,b} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} \otimes f_{b/\gamma}$$

– Effects of underlying event, multi-parton interactions ?
– but no electron, large statistics, nicely balanced events, .



JETS IN PHOTOPRODUCTION



High-E_T dijets: Tests of cross-section shapes + normalisation!

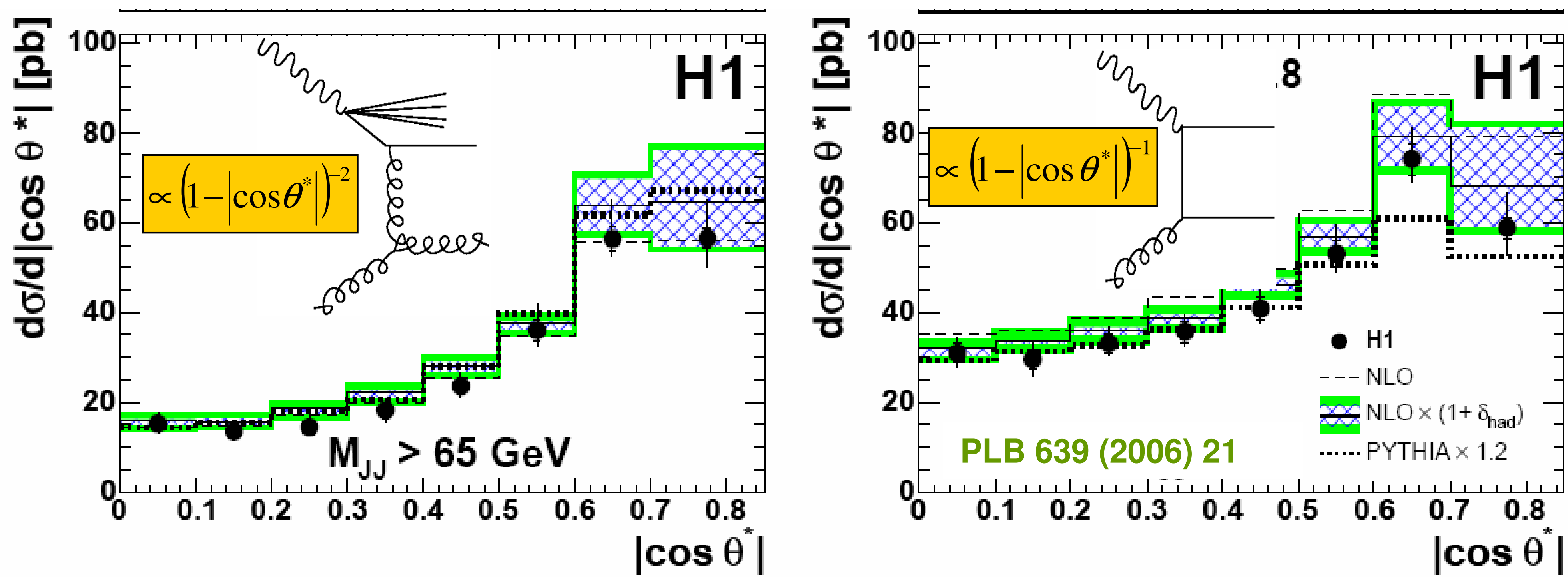
$$\sigma_{jet} = \sum_{n,a,b} \alpha_S^n \cdot f_{a/p} \otimes \hat{\sigma}_{n,a} \otimes f_{b/\gamma}$$

Example: cos(θ*) – CMS scattering angle:

$$\cos\theta^* = \tanh\left(\frac{\eta^{(1)} - \eta^{(2)}}{2}\right)$$

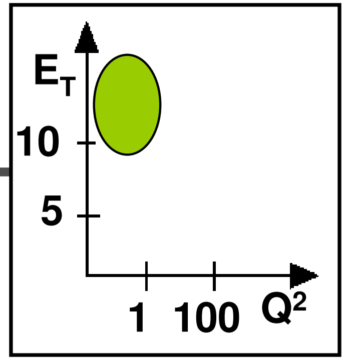
Expectation from QCD:

Resolved should rise more rapidly due to different nature of propagator:



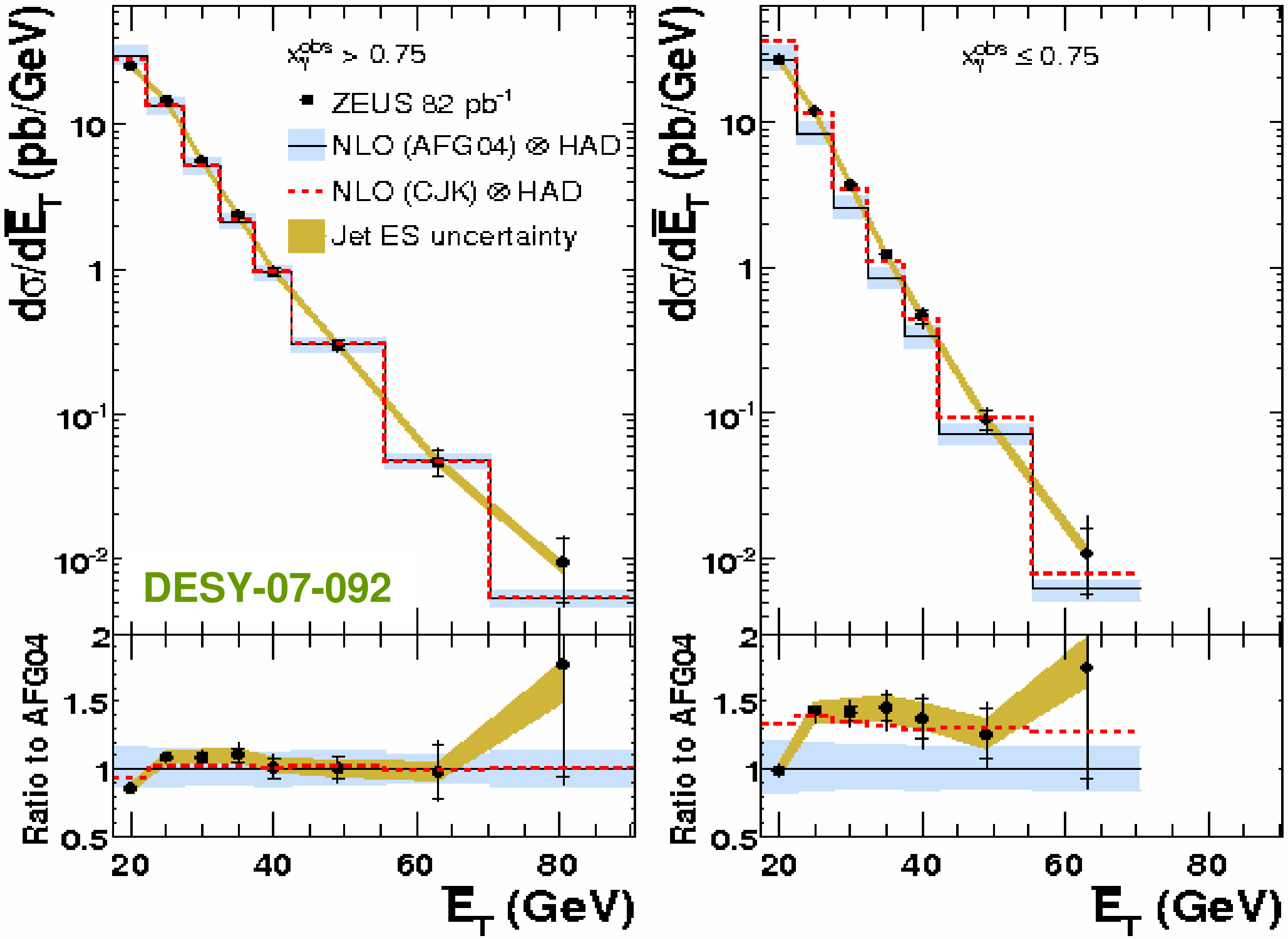
– NLO works very well also in photoproduction (data / theory ±10%).
– Beautiful confirmation of “resolved” concept in photoproduction.

JETS IN PHOTOPRODUCTION



High-E_T dijets: Cross-sections as functions of E_T.

– Also 3,4 jet events described (by LO MC) if hard scale (E_T, M)!

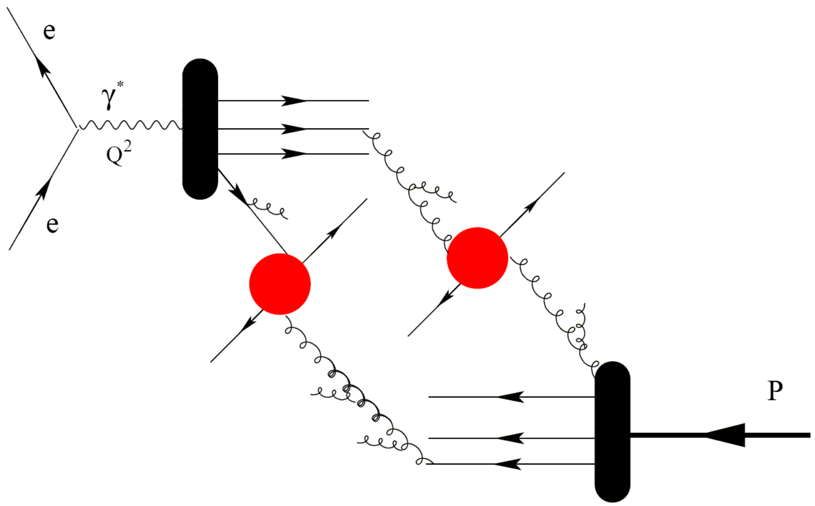


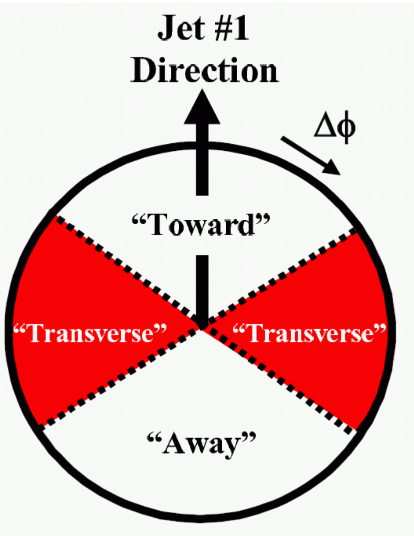
– NLO QCD describes (direct) data very well! 15-20% NLO uncertainty.

– Resolved: choice of photon PDF has large influence (50%!) → constrain it?

THE UNDERLYING EVENT

Resolved PHP: hadron-hadron-like
→ phenomenon of underlying event!
– (soft) beam remnant interactions
– additional (semi)hard constituent scatterings (multi-parton interactions, MPI)
– initial and final state radiation etc.



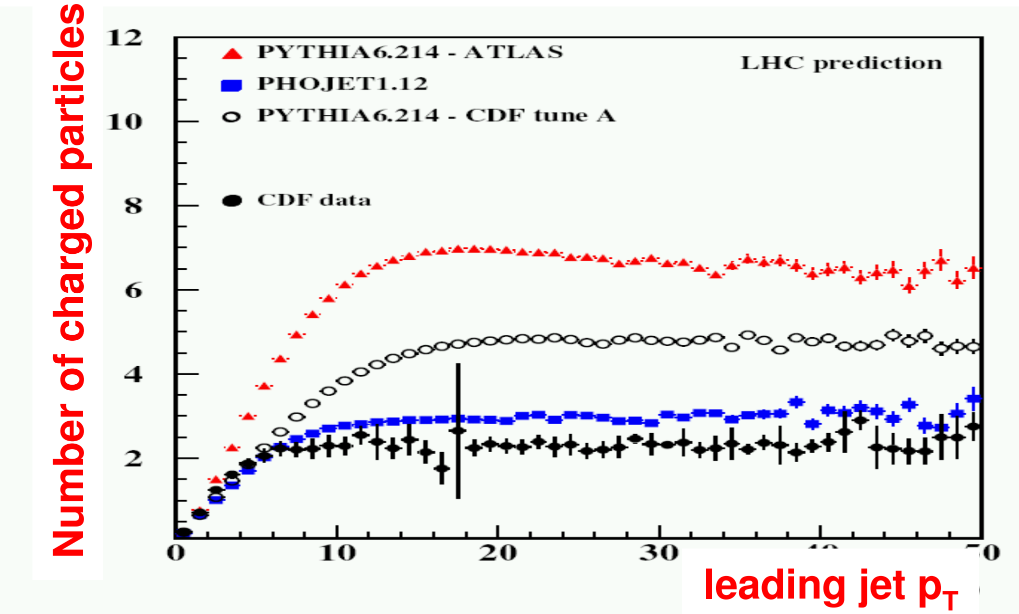


Quantify: "Activity in transverse regions"
Regions away from hard scattering products (jets) should be most sensitive to UE effects.

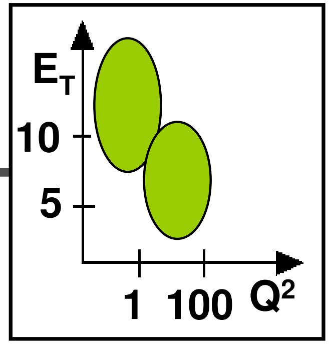
CDF experience:

– MPI models can be tuned to CDF data!
– But extrapolation to LHC not meaningful!

→ Important + theoretically challenging!

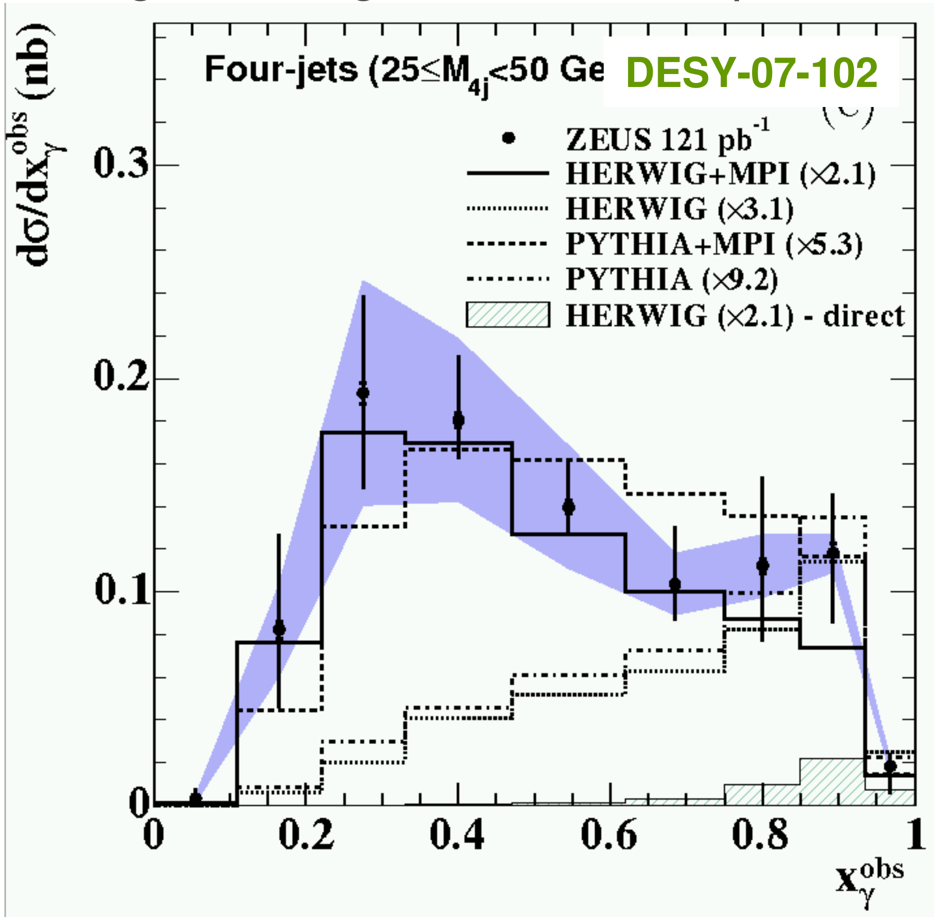


UNDERLYING EVENT AT HERA



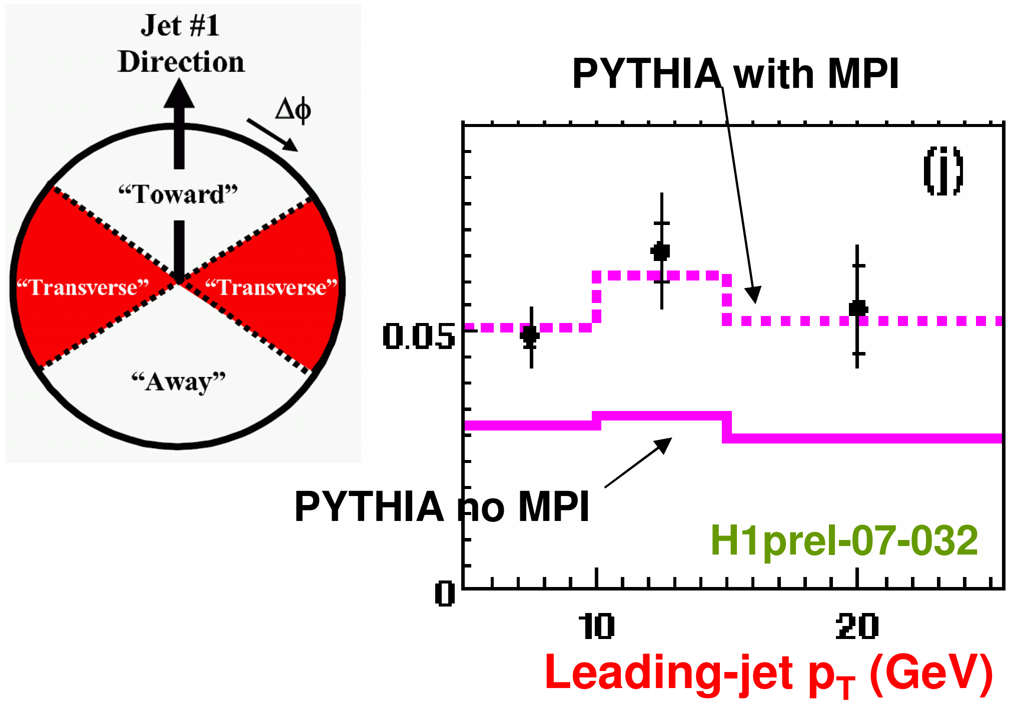
¶ ZEUS 3+4 jets in PHP:

At low $x_{\gamma obs}$ direct+resolved MC not enough! Adding MPI model helps!



¶ H1 "minijets", low Q^2:

– Study average number of very soft "minijets" (E_T > 3 GeV) in different azimuthal regions.



Measurements clearly indicate need for MPI models.

Need more data to allow fixing of underlying mechanism. HERA ideal place!

OUTLINE

¶ Basics

Physics at HERA
Jets at HERA, Tools
HERA, H1 and ZEUS

¶ Measurements

High-Q^2 DIS (Q^2 > 125 GeV^2)
Low-Q^2 DIS
Photoproduction

¶ Extraction of QCD parameters

The strong coupling α_S
Information on PDFs
Color factors etc.

¶ Summary …

What we have seen
What remains to be done
… and what we would like to have …

STRONG COUPLING

Strong coupling α_S: fundamental QCD parameter

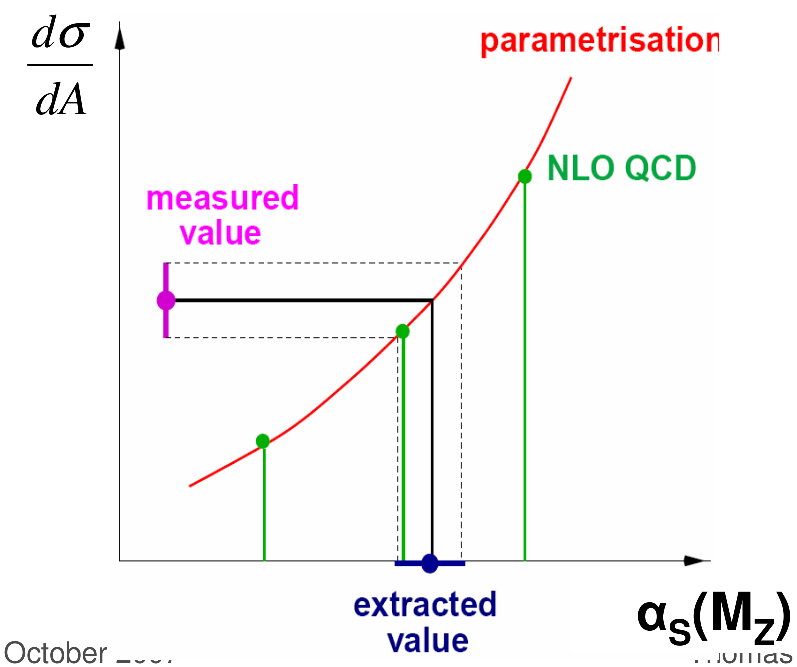
– Success of QCD relies on precise determinations in different processes/scales.
→ disentangle factorisation of α_S, PDF, σ.

$$\alpha_S^{(1loop)}\left(Q^2\right)=\frac{\alpha_S\left(M_Z^2\right)}{1+\frac{\left(33-2n_f\right)}{\left(12\pi\right)}\alpha_S\left(M_Z^2\right)\ln\frac{Q^2}{M_Z^2}}$$

Method of extraction:

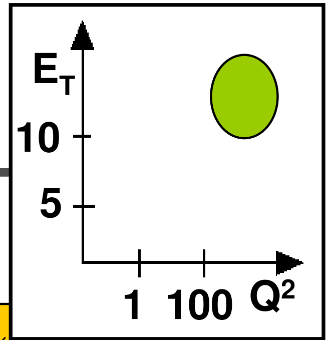
– Parametrise dependence of NLO on $\alpha_S(M_Z)$ using PDFs with different input $\alpha_S(M_Z)$.
– Map measured cross-section dσ/dA onto $\alpha_S(M_Z)$.
– Do this for many different data points (Q^2, E_T, …) and combine …

$$\left.\frac{d\sigma(\alpha_S(M_Z))}{dA}\right|_{NLO}=C_1\alpha_S(M_Z)+C_2\alpha_S^2(M_Z)$$



Measurements used:
– Inclusive jets at high Q^2.
– Inclusive jets in PHP.
– Dijets in PHP.
– $R_{3/2}(Q^2)$.
– Jet substructure and shape.
– Jet radius dependence.

STRONG COUPLING: INCLUSIVE JETS



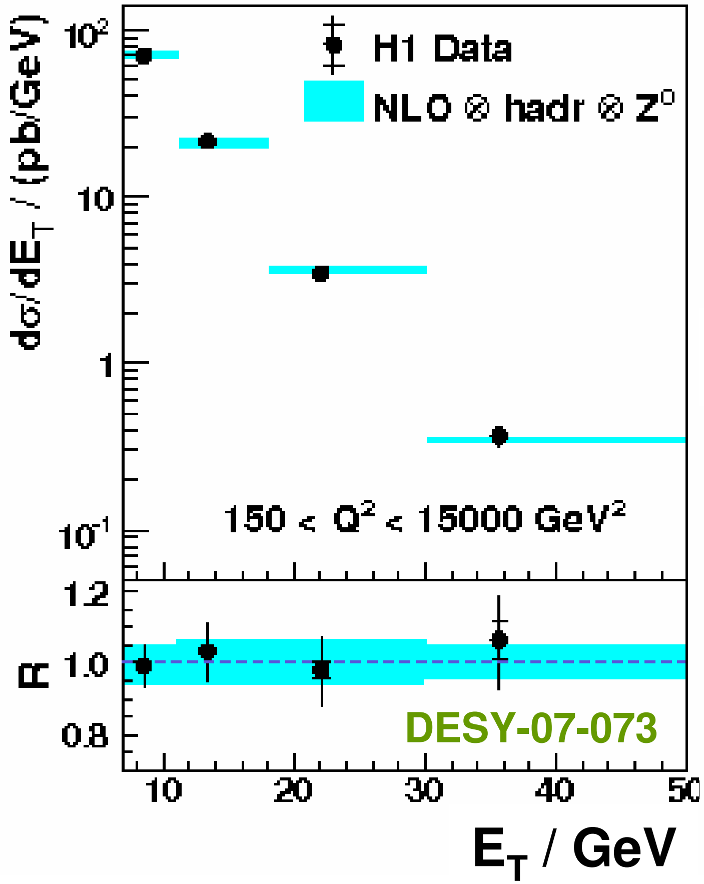
Advantage of jets over inclusive measurements:

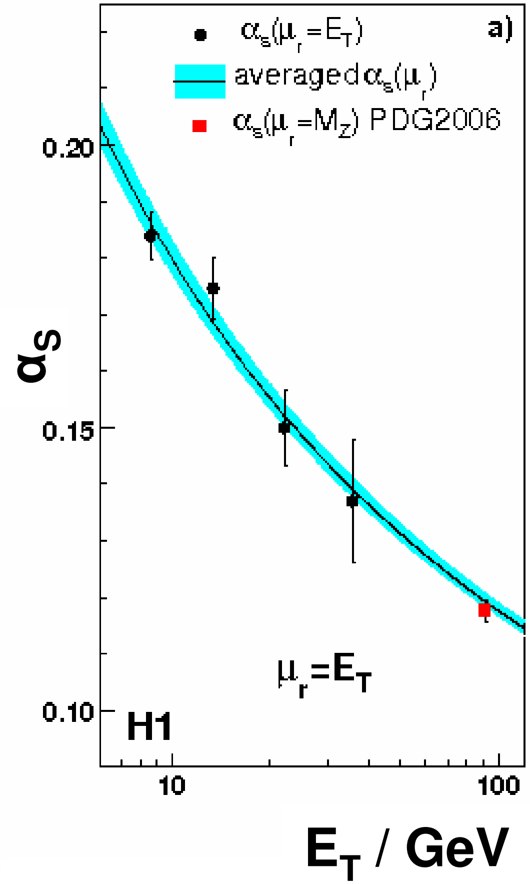
– All inclusive cross-section points give ONE α_S value through scaling violations in parton densities.

$$\frac{dq(x,Q^2)}{d\ln Q^2} \propto -\alpha_S \cdot P_{qg} \cdot q(x,Q^2) + \alpha_S \cdot P_{gq} \cdot g(x,Q^2)$$

– But each single jet data point gives ONE α_S value at relevant scale (Q_2 or E_T).

→Inherent test of running of strong coupling and of compatibility of various extractions of α_S!



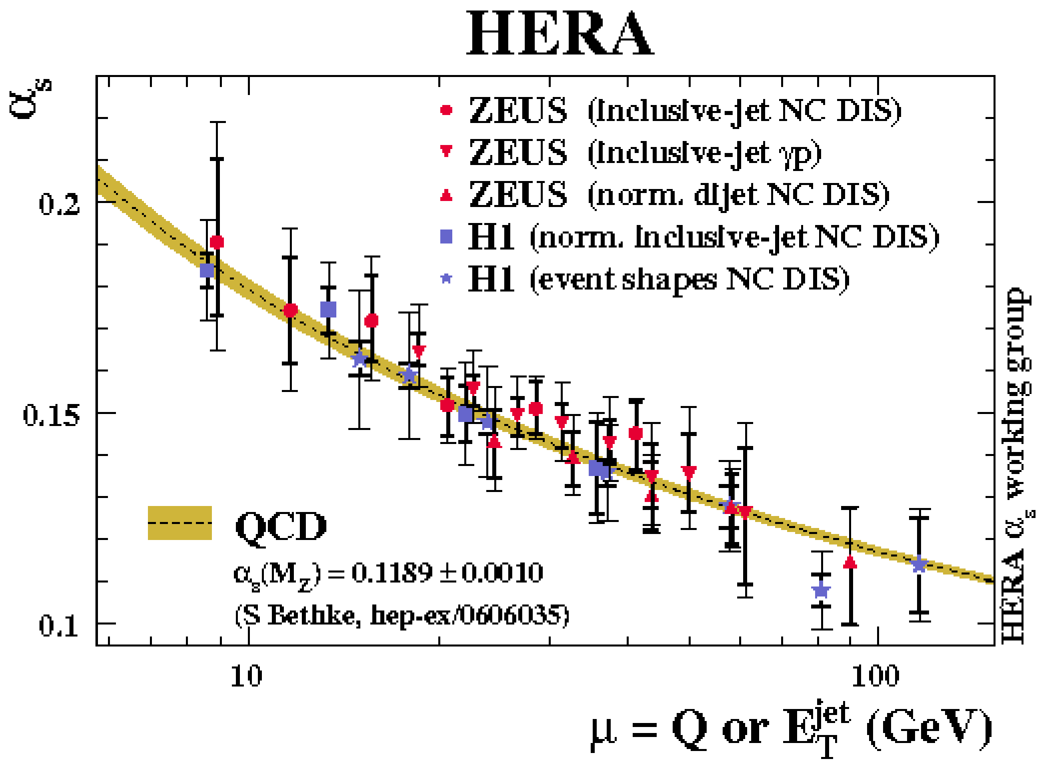


Either combination of single values or combined fit to all data points.

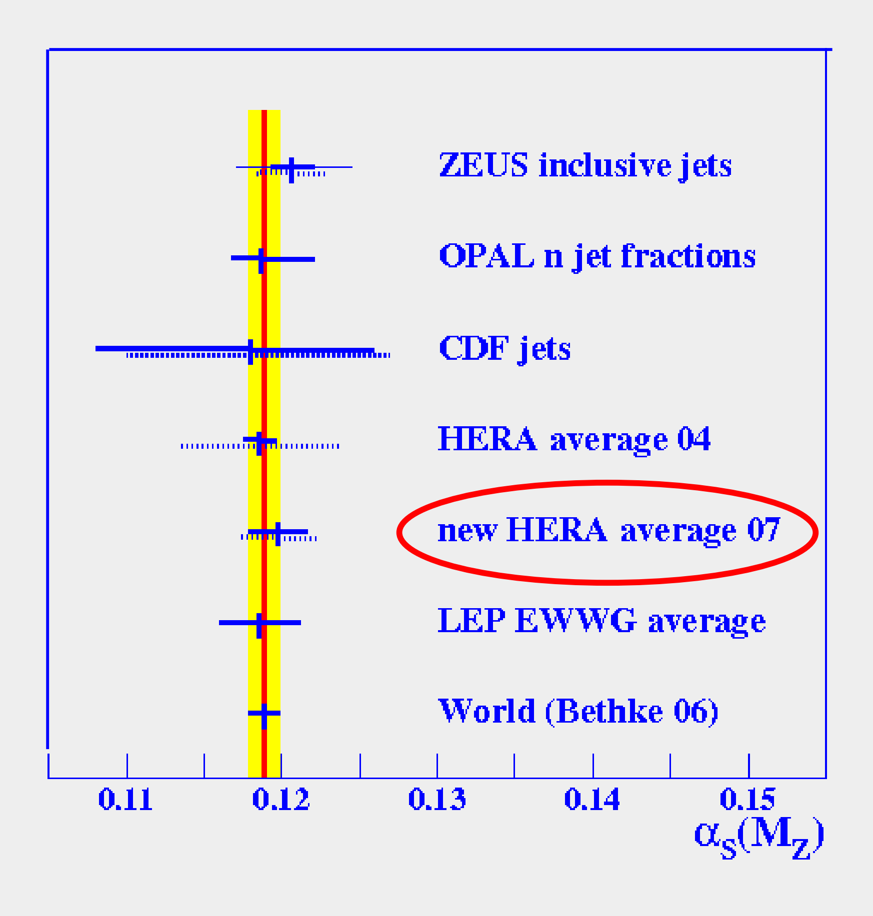
Latest H1+ZEUS combined fit (total error of 2.7%!):

$$\alpha_S(M_Z) = 0.1198 \pm 0.0019(\text{exp.}) \pm 0.0026(th.)$$

STRONG COUPLING



Nice demonstration of running of strong coupling from HERA jet data!



All measurements consistent with each other and world average!

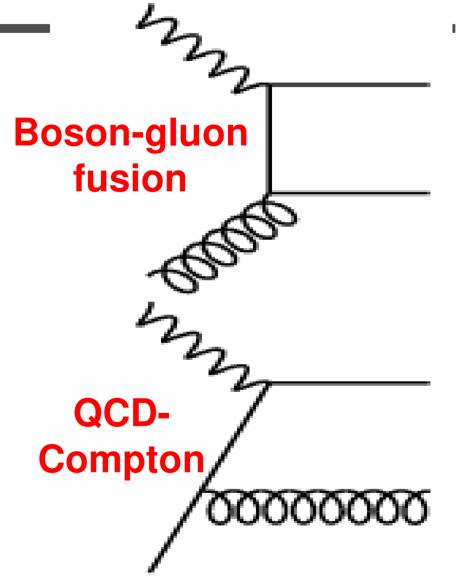
HERA measurements very competitive!

JETS AND PDFs

ZEUS effort: Use DIS and PHP jet cross-sections:

… in addition to inclusive (F_2) measurements.
→ increased sensitivity to high-x gluon density, and
partial decoupling of α_S and gluon density:

→Use inclusive jets at high Q^2 double-differential in Q^2 and E_T
and photoproduction dijets at high transverse energies E_T.



Technically challenging:

– PDF fits require many evalutions of NLO jet cross-sections (O(1000)) – but ONE calculation takes typically 24 h (100M events) → not feasible!

$$\sigma_{jet} = \sum_{n,a} \alpha_S^n \cdot \int dx f_{a/p}\left(x, \mu_F^2\right) \cdot \hat{\sigma}_{n,a}\left(\mu_F^2, x\right)$$

– Idea: Divide phase-space in small x-Q^2 intervals and transform phase-space integral in sum over these small intervals in which PDFs are assumed constant:

$$\sigma_{jet} \approx \sum_{n,a} \alpha_S^n \cdot \sum_{x,Q^2} f_{a/p}\left(x, \mu_F^2\right) \cdot \int dx \cdot \hat{\sigma}_{n,a}\left(\mu_F^2, x\right)$$

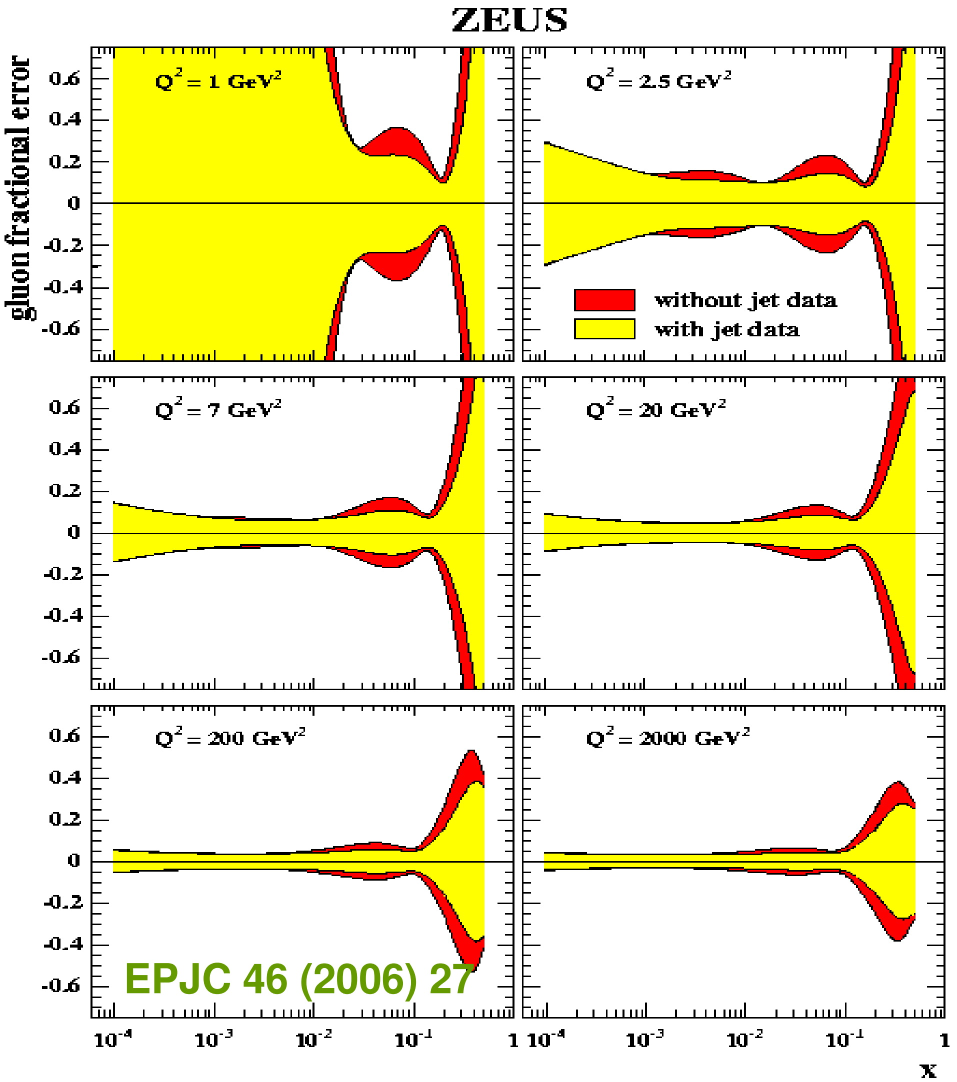
Independent of PDF!
Calculate once and store!

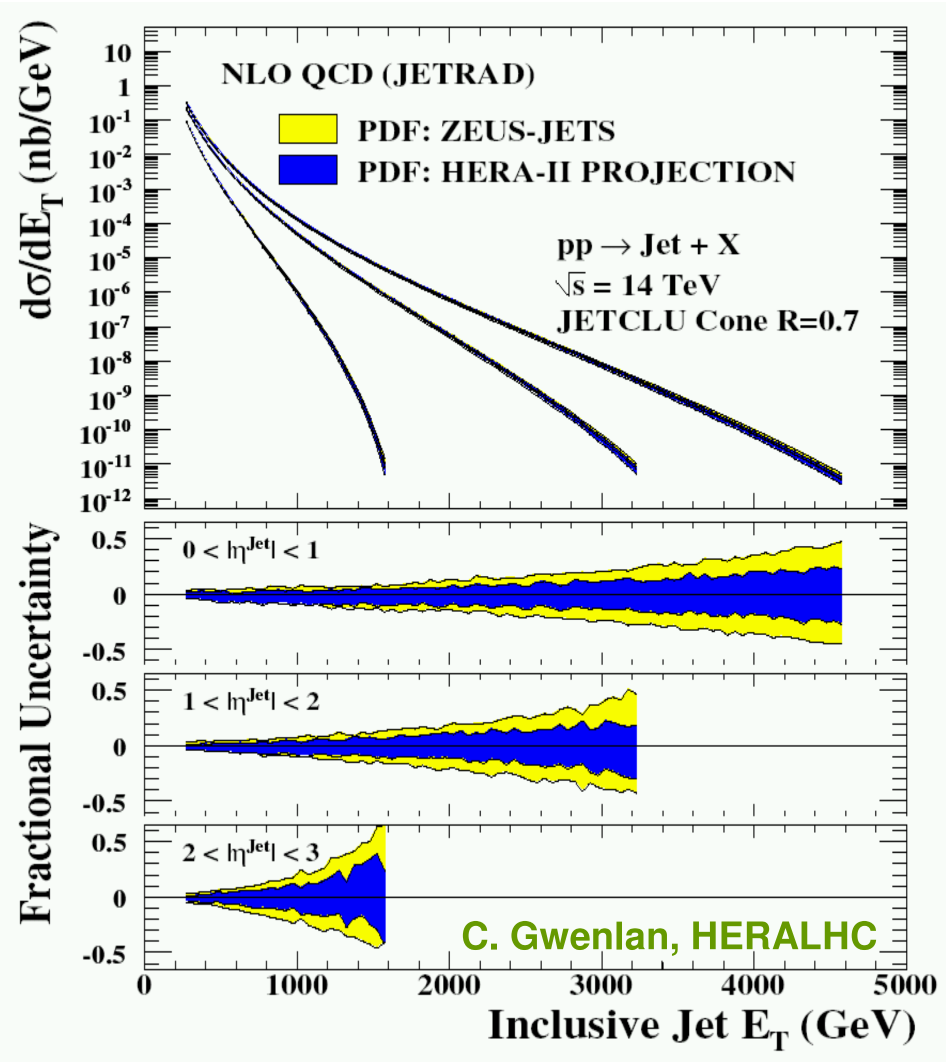
Need evalutation of integral over hard matrix elements once and for all, then can quickly combine with any PDF $f_{a/p}$ → fraction of seconds!

JETS AND PDFs: ZEUS/LHC

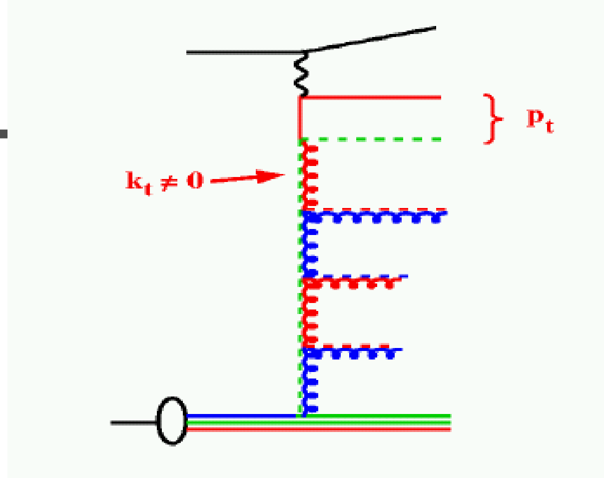
As expected jets improve gluon density at medium/high x (0.01-0.5):

… by up to 50% or so …. Further improvement with more HERA-II data might also have massive impact on QCD predictions for LHC (searches background)!





UNINTEGRATED PDFs



Typically for jets: collinear factorisation

→ parton entering hard scattering: zero p_T!
But evidence that this is not good approximation (production of high masses, heavy flavours, Higgs, …).

→ Unintegrated PDFs (uPDFs) to keep full k_T dependence during parton evolution. Cross sections then with unintegrated PDF A_i:

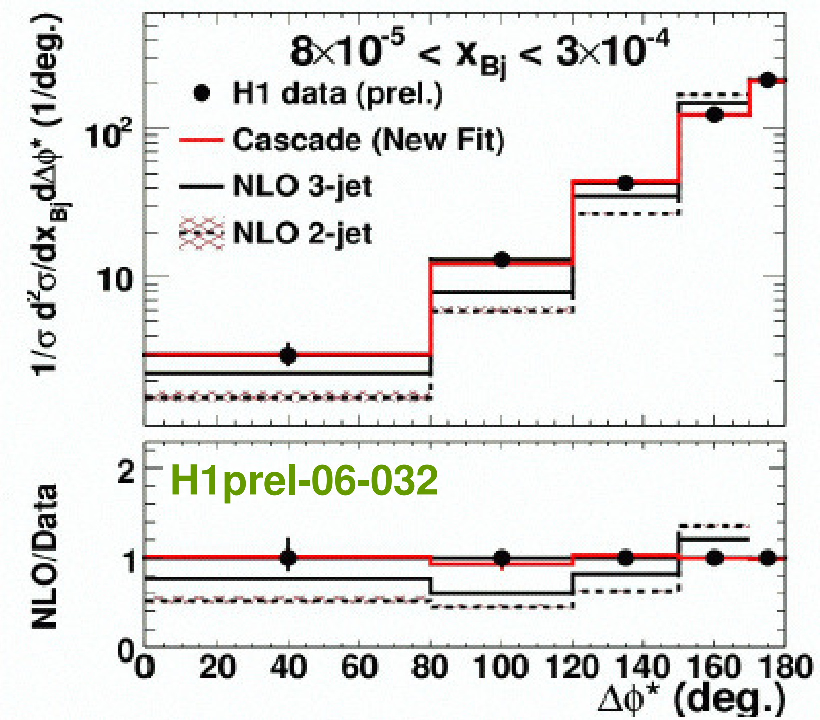
$$\sigma_{jet} = \sum \int dx dQ^2 d\ldots \left[dk_\perp^2 x A_i\left(x, k_\perp^2, q\right)\right] \hat{\sigma} = \sum \int dx dQ^2 d\ldots x f_i\left(x, Q^2\right) \hat{\sigma}$$

Starting distribution for A (to be evolved):

$$xA(x, \mu_0) \propto (1-x)^4 \exp\left(-\left(k_{T0} - \mu\right)^2 / \sigma^2\right)$$

Fit to low-Q² dijet data (H1) and extract μ and σ of initial gaussian k_T distribution:

μ ~ 1.5 GeV
σ ~ 1.5 GeV



Data described by CASCADE MC with uPDF!
First HERA extraction of initial k_T in proton!

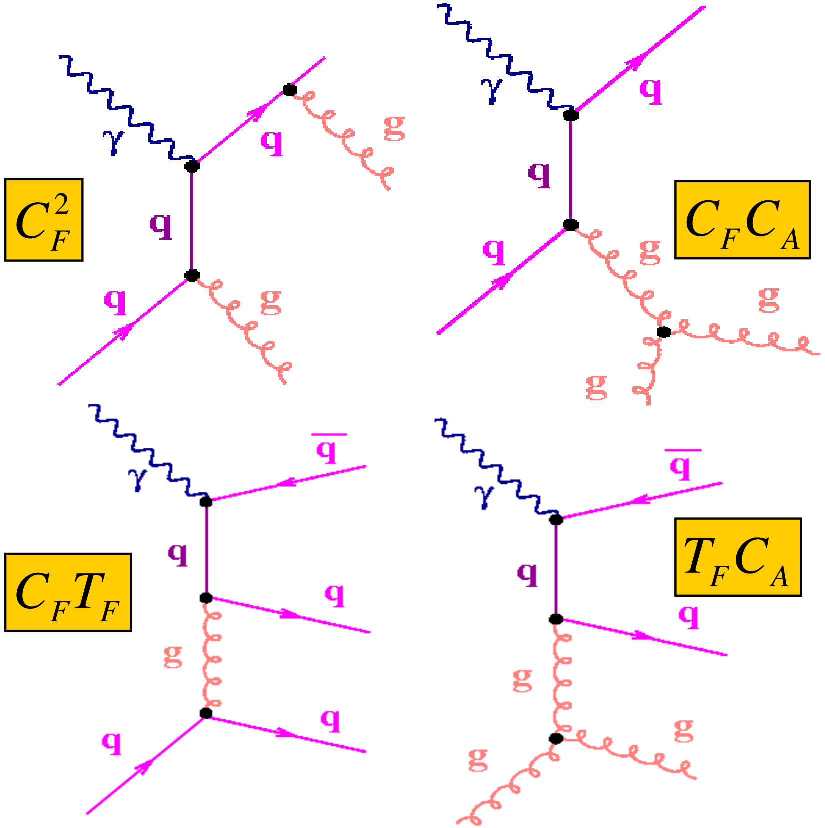
QCD GAUGE GROUP: COLOR FACTORS

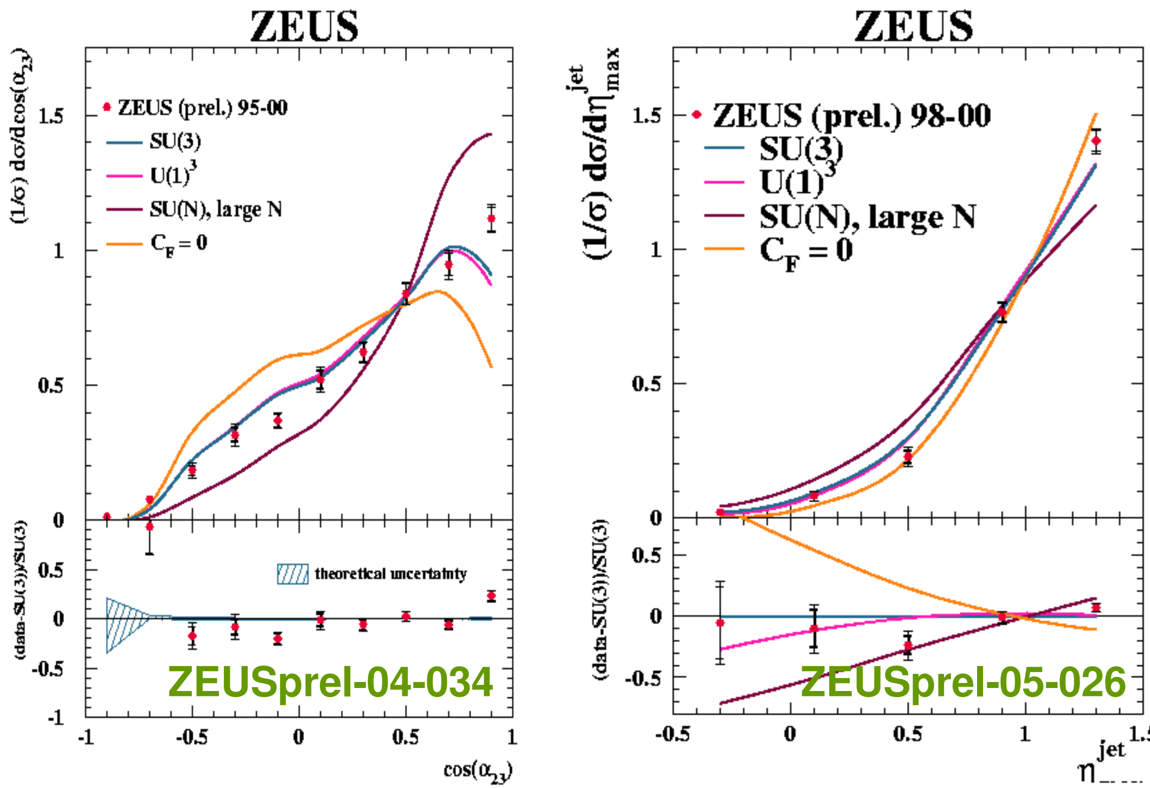
Further QCD parameters: color factors of SU(3)$_C$ gauge group:

→ relative strength of different QCD vertices, determination of group dynamics.

HERA 3-jets: various contributions sensitive to different color factors:

$$\sigma = C_F^2 \cdot \sigma_A + C_F C_A \cdot \sigma_B + C_F T_F \cdot \sigma_C + T_F C_A \cdot \sigma_D$$





– Higher-dim. gauge groups and SU(3)$_C$ with C_F=0 ruled out.
– HERA jet data do not allow distinction of SU(3)$_C$ versus abelian U(1)^3 (no ggg vertex)

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WE HAVE SEEN …

(not seen: jets and heavy flavour, jets in charged current, jet substructure, jet shapes, more cross-sections, more α_S determinations, discussion of uncertainties, …)

¶ Jets at high Q^2 values above 125 GeV^2:

- Inclusive jets: experimental precision better than 5% → α_S, PDFs.
- Dijets and trijets: More detailed tests of QCD dynamics and of factorisation.
- NLO QCD (even for three-jets) describes both normalisation and shape of data.

¶ Jets at low Q^2 between 5 and 100 GeV^2:

- Well described by NLO QCD if either E_T or Q^2 > 10 $GeV^{(2)}$ (hard scale).
- But larger theoretical uncertainties (scale choice, up to 20,30,40%).
- Detailed checks of specific observables →need for ever higher orders.
- Question of parton dynamics DGLAP/BFKL to be better understood.

¶ Jets in Photoproduction:

- Precise NLO tests and input to PDF fits (direct).
- But complication due to photon PDF and underlying event effects.

¶ α_S, PDF and color factors

- from inclusive jets $\alpha_S(M_Z) = 0.1198 \pm 0.0019(\text{exp}) \pm 0.0026(\text{theo})$ (2.7%!)
- Reduction of gluon uncertainty by up to 50% when using jet data.

Jet physics and QCD at HERA is a mature and very precise field of research.
Large progress in the past 10 years due to theoretical and experimental efforts.

NEXT ON THE AGENDA

… a loose collection of things to be done with jets at HERA:

– Finalise the main cross-section measurements with combined HERA-I+II data sets (mainly high-Q^2 and high-E_T photoproduction).

– Extract the final HERA α_S from jet data.

– Provide more data sets as inputs to PDF fits (heavy flavours, specially designed observables, normalised cross-sections, low-Q^2 data sets, …).

– Provide more measurements of the underlying event and of multi-parton interactions (help understand the energy dependence of MPI).

– Design yet more specific analyses to understand parton dynamics at low Q^2.

– Dare to go for combined proton and photon PDF fits from phoproduction data?

– …

JET PHYSICIST'S WISHLIST

In general we have great support from theorist's (imagine we have three-jet NLO calculations!)!

Nevertheless, there are a few things we would like to have …

- ¶ Higher-order calculations for jet processes in ep:
  - So far limited to NLO for di/trijets in DIS and dijets in PHP.
  - For some observables effectively LO.
  - In many cases missing higher orders limiting factor of measurements.
  - Inclusion of W,Z in existing NLO programs.
- ¶ Combination of NLO calculations and parton showers:
  - … commonly known as MC@NLO.
  - Would remedy some unsatisfactory inconsistencies in data treatment; should reduce uncertainties.
- ¶ Maybe a BFKL NLO program for experimentalists?
- ¶ Resummed calculations for jet quantities like $\Delta\varphi$ etc …

  … should be on the way …

… and I am sure that I can think of more …