Measurement of Event Shapes in Deep Inelastic Scattering with ZEUS at HERA

UNIVERSITY OF
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MADISON

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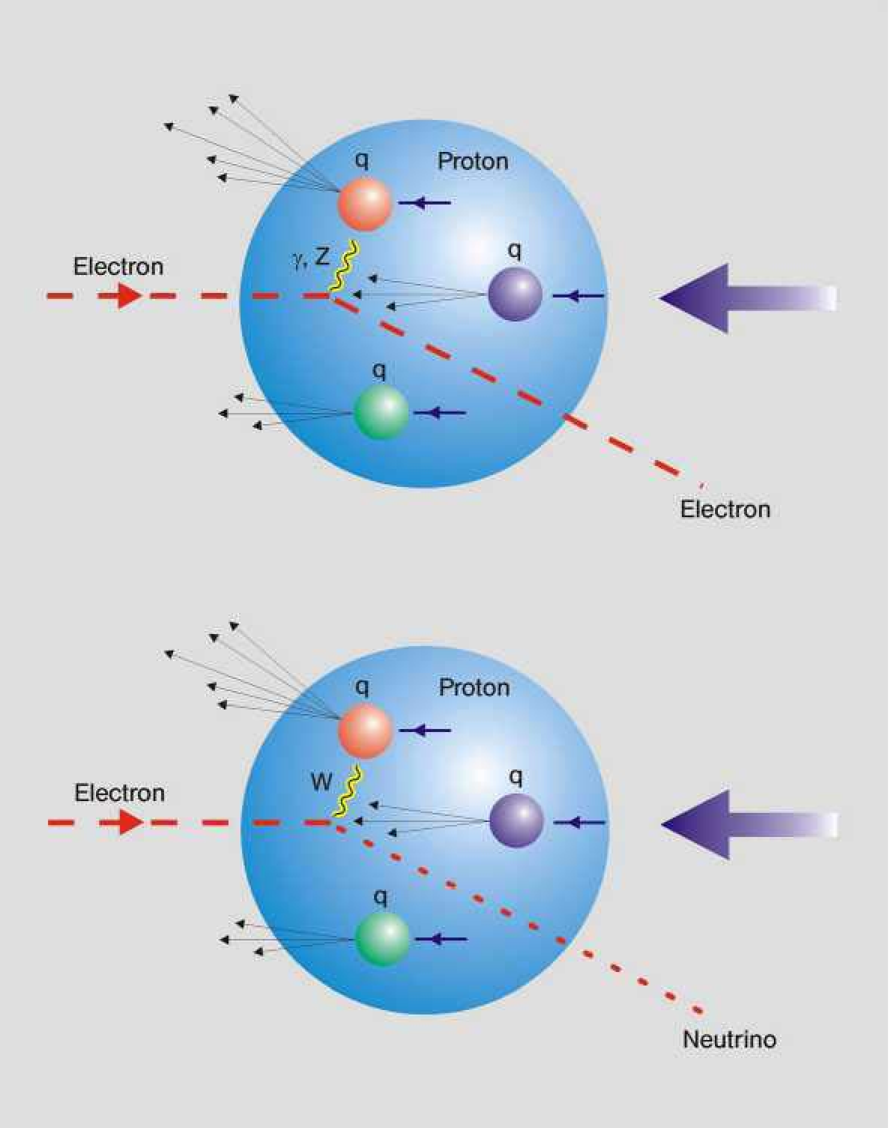
Study of Partons



Particle Scattering

- **Study charge & magnetic moment distributions**
- **Scattering via probe exchange**
    - Wavelength $\lambda = \frac{\hbar}{Q}$

h : Plank’s Constant

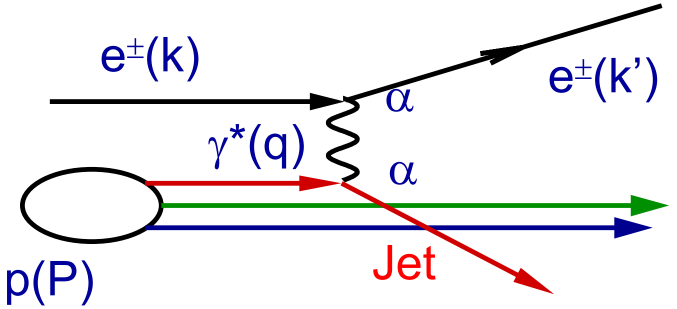
Q: related to momentum of photon

- **Special Case : Deep Inelastic Scattering**
    - High energy lepton transfers momentum to a nucleon via probe

Naïve Quark Parton Model

Scattering on proton is sum of elastic scattering on all of the proton's constituents (partons)

Point-like Partons



Structure Functions: quantify distribution of partons and their momentum

$$F_2 = \sum_i e_i^2 x f_i(x) \qquad F_i \rightarrow F_i(x)$$

Bjorken Scaling: Only x dependence

x related to fraction of momentum carried by quark

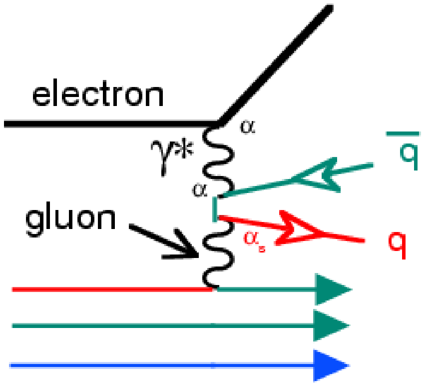
Parton Distribution Functions (PDF)

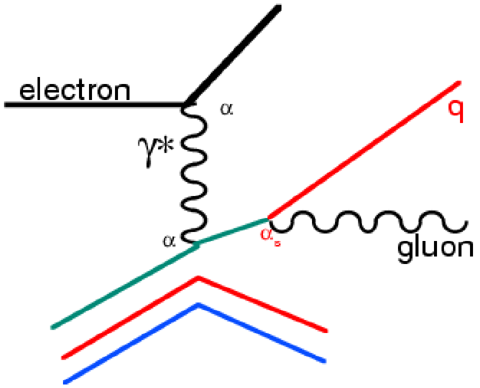
- **Must be derived from experiment**

QCD Theory

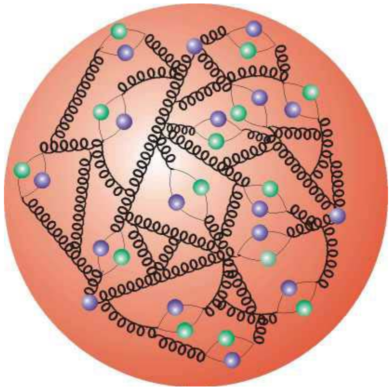
Gluons: vector colored bosons carry strong force

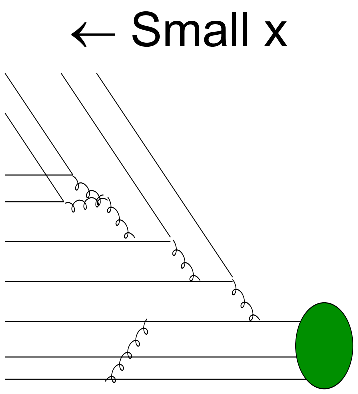
- **Gluons produce quark and gluon pairs**
- **Quarks gain transverse momentum**



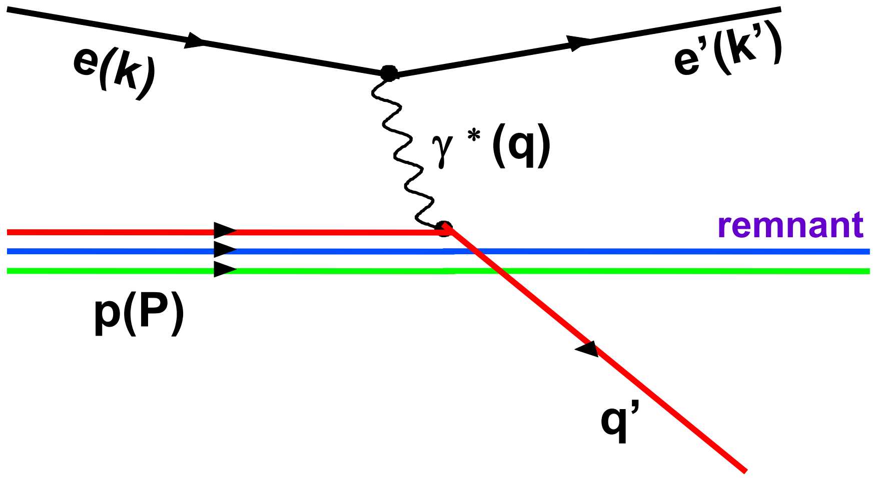


- **Gluon-driven increase in F_2**
  - ⇒Bjorken Scaling Violation:
    $F_i(x) \rightarrow F_i(x,Q^2)$
    - **⇒Observation of QCD effects**





Deep Inelastic Scattering



Center of Mass Energy of ep system squared:

- $s = (p+k)^2 \sim 4E_pE_e$

Photon Virtuality (4-momentum transfer squared at electron vertex):

- $q^2 = -Q^2 = (k-k')^2$

Fraction of Proton's Momentum carried by struck quark:

- $x_{Bjorken} = Q^2/(2p \cdot q)$

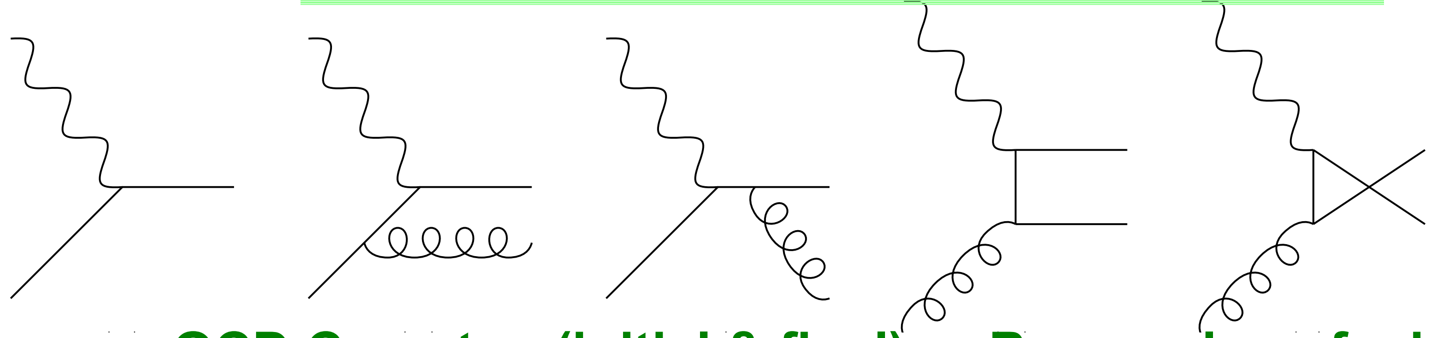
Fraction of e's energy transferred to Proton in Proton's rest frame:

- $y = (p \cdot q)/(p \cdot k)$

Perturbative and Non-Perturbative QCD

Leading Order (LO)

Lowest Order no α_s vertex



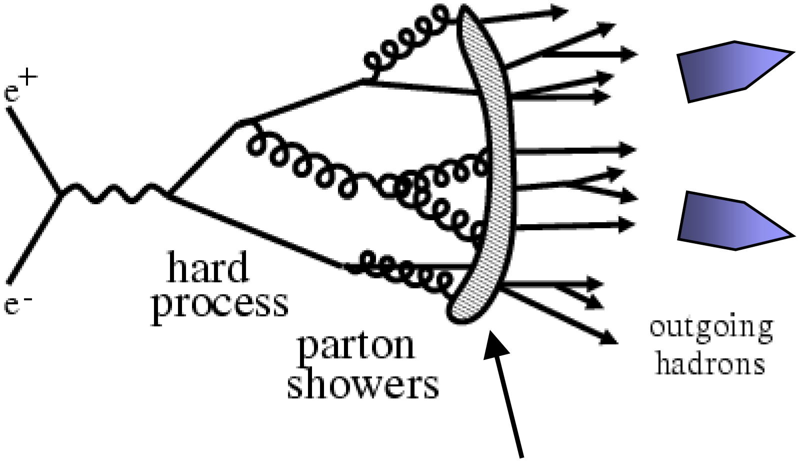
QPM **QCD Compton (initial & final)** **Boson gluon fusion**

Leading Order (LO) **Next to Leading Order (NLO)**

$$A = A_0 + A_1\alpha_s + A_2\alpha_s^2 + \ldots$$

Perturbative: Q^2 large	Nonperturbative: Q^2 small
Small α_s (hard scale)	Large α_s (soft scale)
Can expand with α_s	Can't expand in α_s
High energy scale	Low energy scales
$\Rightarrow$Small distances	$\Rightarrow$ Large distances

From Partons to Hadrons



"Jets" of particles

Distribution of Particle Energy:
"Energy Flow"

We seek to penetrate this fog

hard scattering ⊗ parton showers ⊗ hadronization

- Hard scattering: hard scale (short distance) perturbative process
- Parton showers: initial QCD radiation of partons from initial partons
- Hadronization: colorless hadrons produced from colored partons
  soft process (large distance) - not perturbatively calculable
  phenomenological models and experimental input
- Jets: colored partons evolve into ~collinear "spray" of colorless hadrons

Energy Flow

- The hard scattering process determines the initial distribution of partons
- Parton Shower + Hadronization determine the final energy flow of the event
  - Event shape is energy flow carried by hadrons
- Universality of the hadronization process tested by comparison of measurements of energy flow dependence in reactions with different initial states
  - ep, e^+e^-
- Power Corrections (see next slide) offer an opportunity to analytically study hadronization
- Use Event Shapes to check the validity of Power Corrections

Approach to Non-perturbative Calculations

pQCD prediction→phenomenology→measured distribution

- **Correction factors for non-perturbative (soft) QCD effects**

Proposed theory*: Use power corrections to correct for non-perturbative effects in infrared and collinear safe event shape variable, F:

Used to determine the hadronization corrections (α_S: not an input)

$$\langle F \rangle = \langle F \rangle_{perturbative} + \langle F \rangle_{power\ correction}$$

$$\langle F \rangle_{pow} = a_V \frac{3MA_1(\alpha_s, \overline{\alpha}_0)}{\pi Q}$$

Valid for event shape means and differential distributions

Power correction (PC)

- **Independent of any fragmentation assumptions**

$\overline{\alpha}_0 =$ **Universal "non-perturbative parameter"**

*** – (Dokshitzer, Webber, phys. Lett. B 352(1995)451)**

HERA Description

DESY Hamburg, Germany

- 920 GeV p^+
- 27.5 GeV e^- or e^+
- 318 GeV cms
- Equivalent to 50 TeV Fixed Target

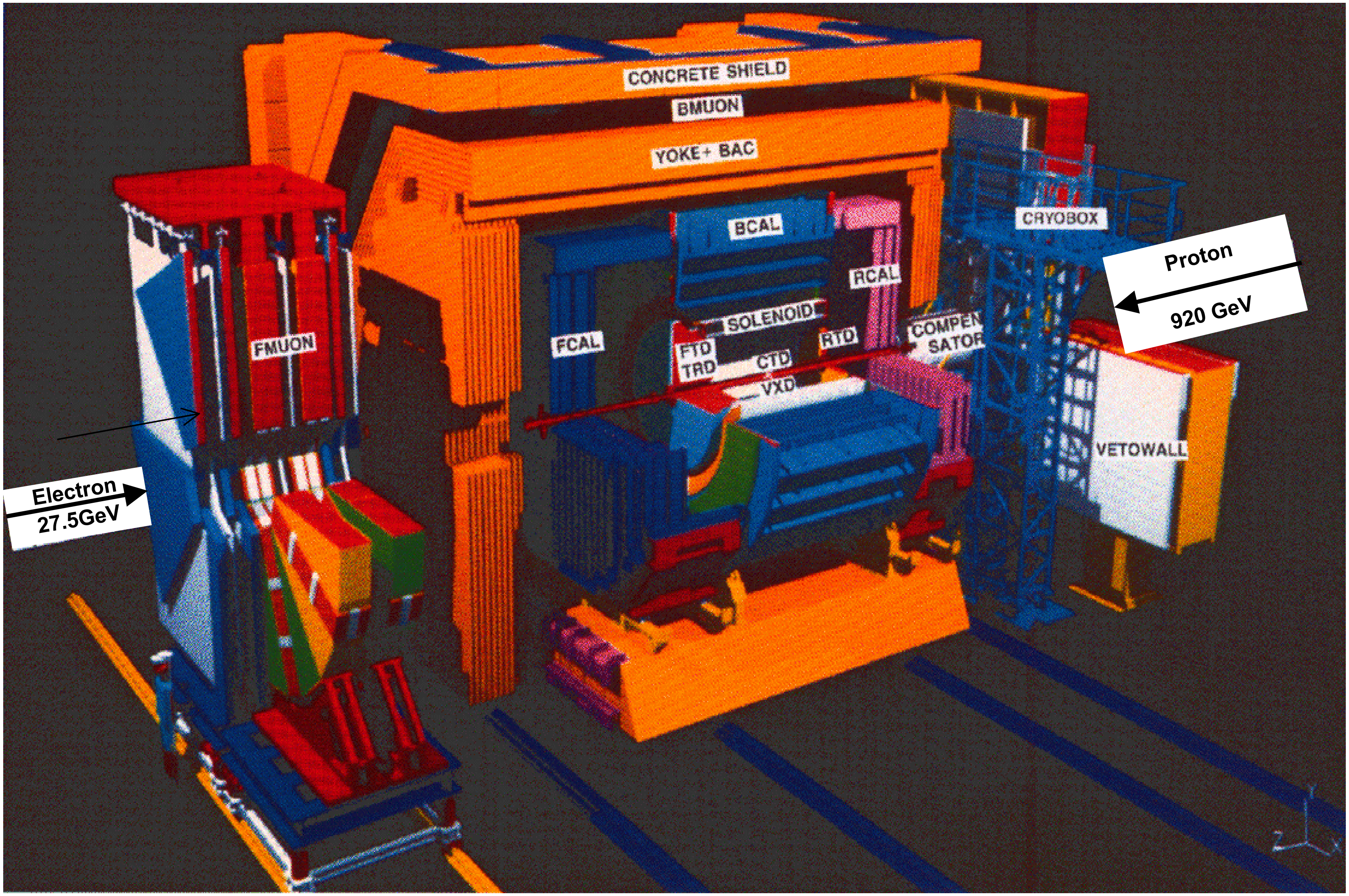
Instantaneous luminosity max: 1.8×10^{31} $cm^{-2}s^{-1}$

- 220 bunches
- 96 ns crossing time

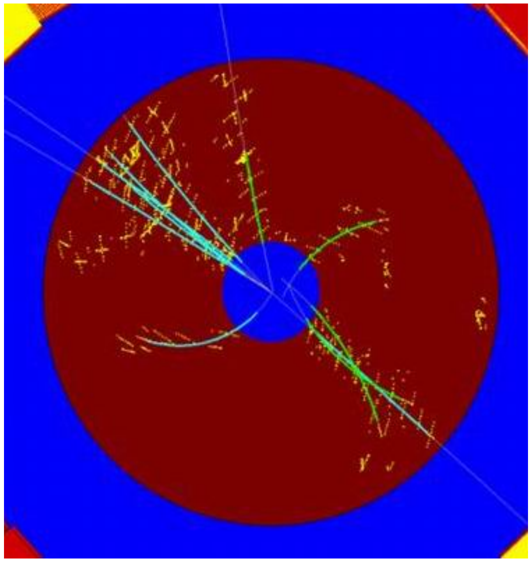
I_P~90mA p

I_e~40mA e^+

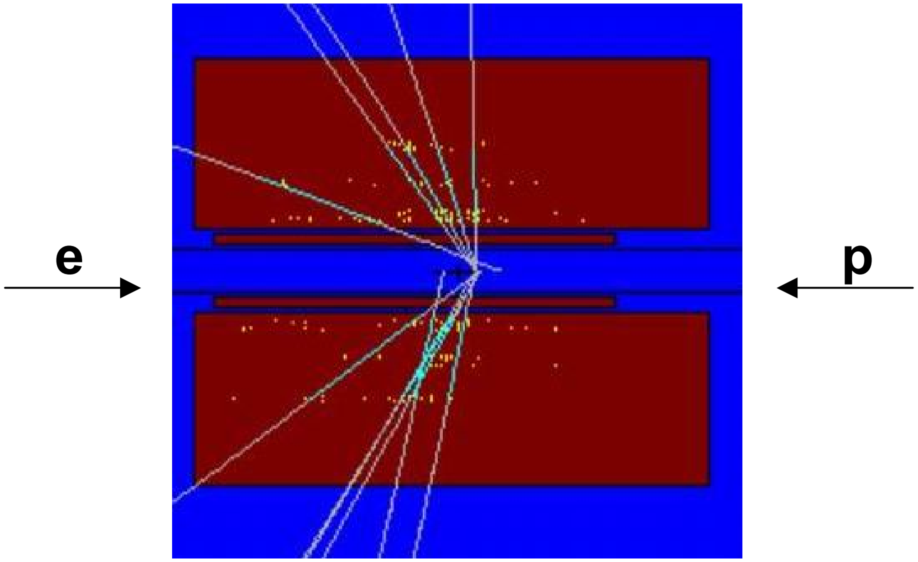
ZEUS Detector



Central Tracking Detector



View Along Beam Pipe

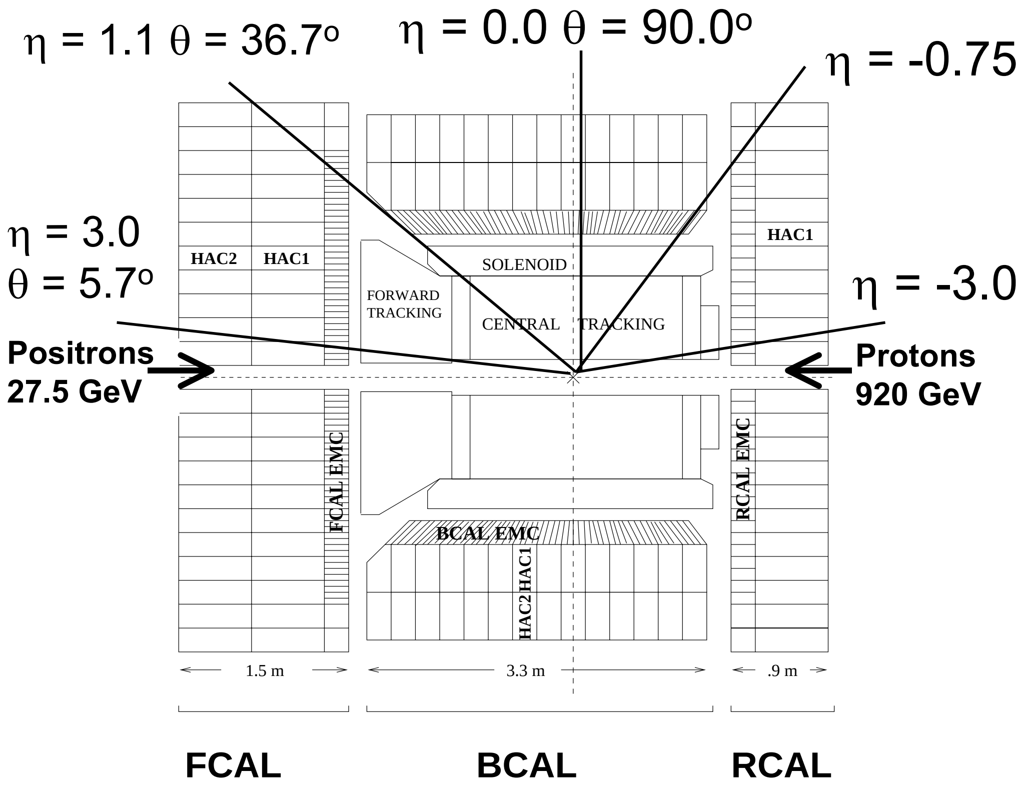


Side View

Drift Chamber inside 1.43 T Solenoid
Can resolve up to 500 charged tracks
Average event has ~20-40 charged tracks
Determine interaction vertex of the event
Measure number of charged particles (tracks)
Region of good acceptance: $-1.75 < \eta < 1.75$

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

Uranium-Scintillator Calorimeter (CAL)



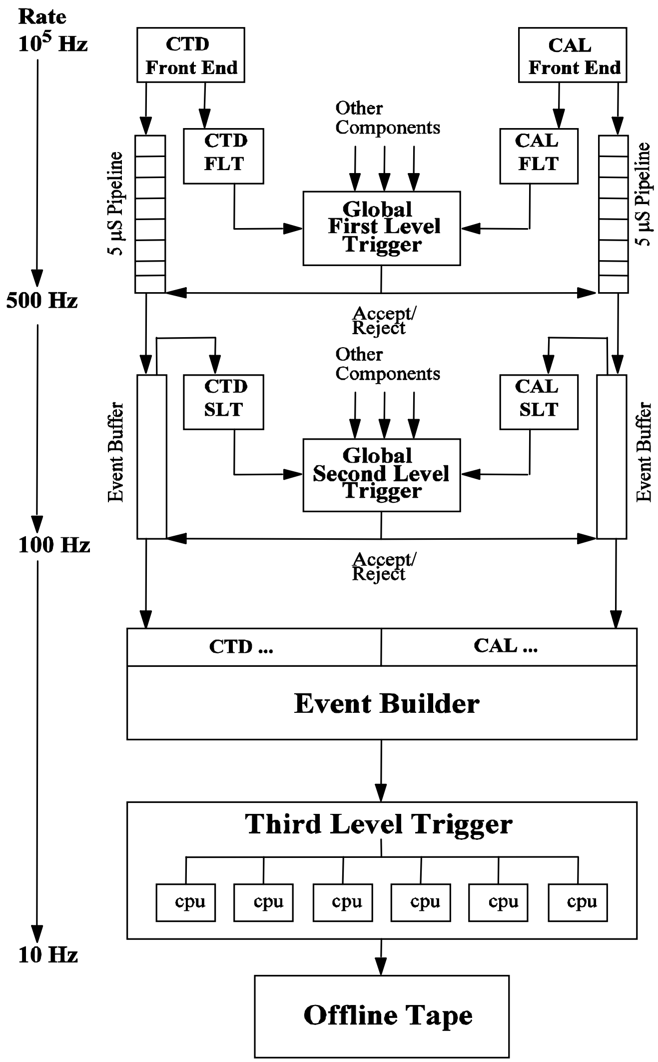
- alternating uranium and scintillator plates (sandwich calorimeter)
- compensating - equal signal from hadrons and γ / $e^{\pm}$ particles of same energy - e/h = 1
- energy resolution $\sigma_e/E_e = 18\% / \sqrt{E}$ $\sigma_h/E_h = 35\% / \sqrt{E}$, E in GeV
- covers 99.6% of the solid angle in the lab frame

$$\eta = -\ln(\tan(\frac{\theta}{2}))$$

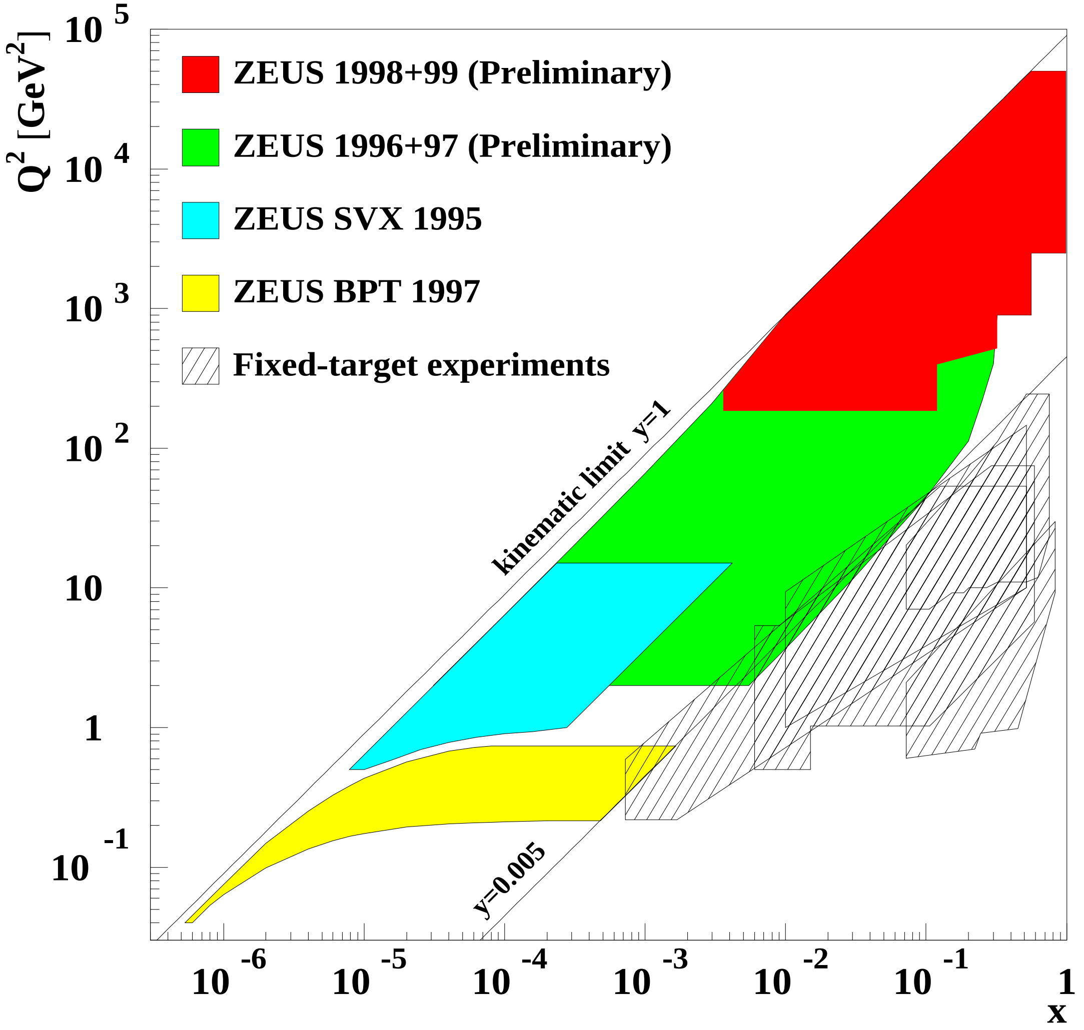
ZEUS Trigger

10^7 Hz Crossing Rate,10^5 Hz Background Rate, 10 Hz Physics Rate

- First Level
  - Dedicated custom hardware
  - Pipelined without deadtime
  - Global and regional energy sums
  - Isolated μ and e^+ recognition
  - Track quality information
- Second Level
  - “Commodity” Transputers
  - Calorimeter timing cuts
  - E - p_z cuts
  - Vertex information
  - Simple physics filters
- Third Level
  - Commodity processor farm
  - Full event info available
  - Refined Jet and electron finding
  - Advanced physics filters



HERA Kinematic Range

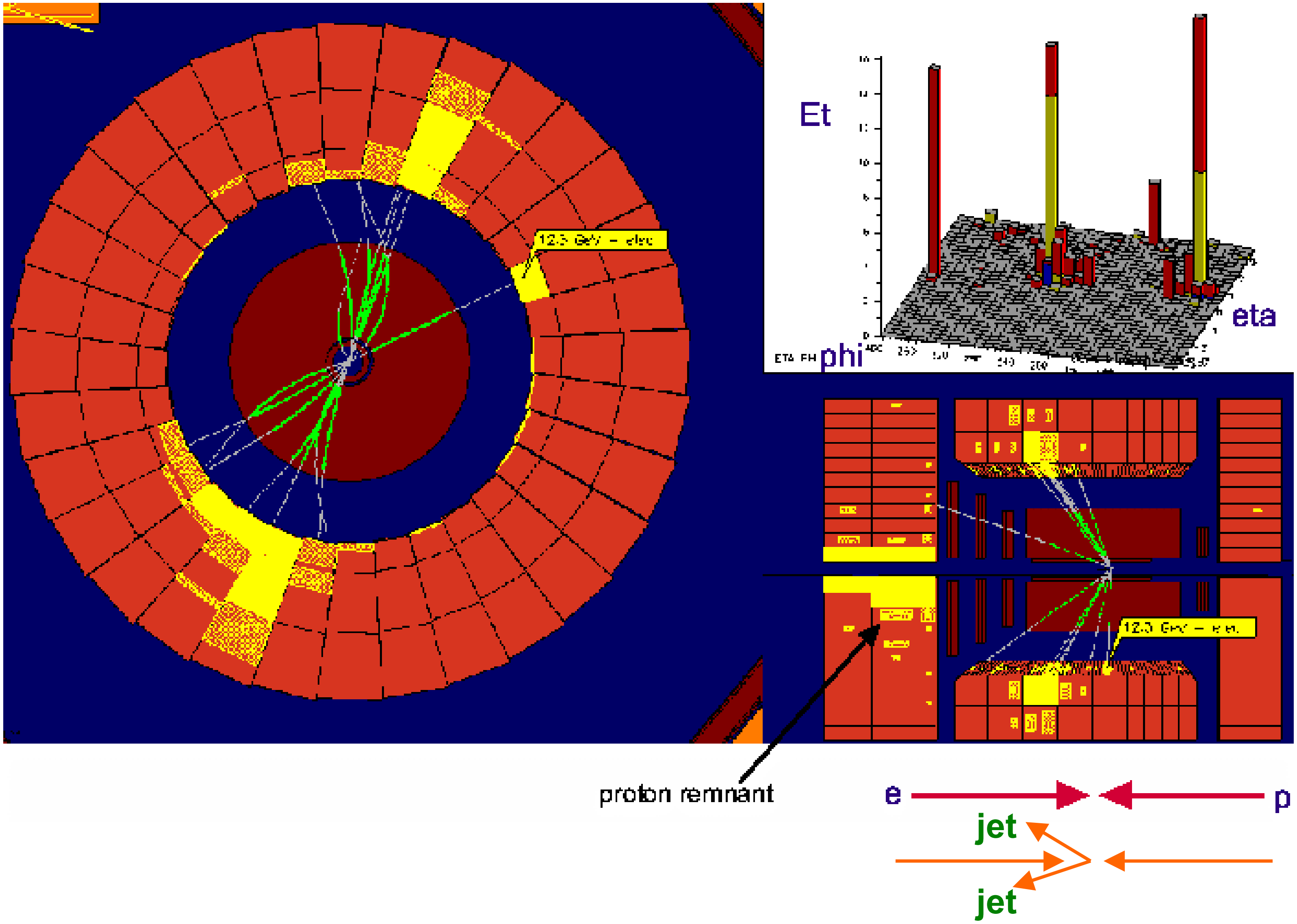


$$Q^2 = sxy$$

$$0.1 < Q^2 < 20000\ \text{GeV}^2$$

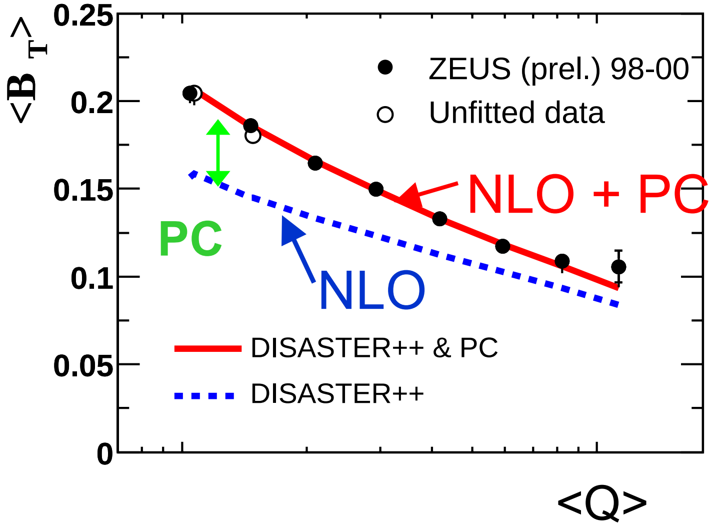
$$10^{-6} < x < 0.9$$

Dijet Event


12.3 GeV – elec
Et
eta
phi
ETA FH
12.3 GeV – elec
proton remnant
e
p
jet
jet

Extraction of α_0 and α_S

Two separate (but related) analyses:



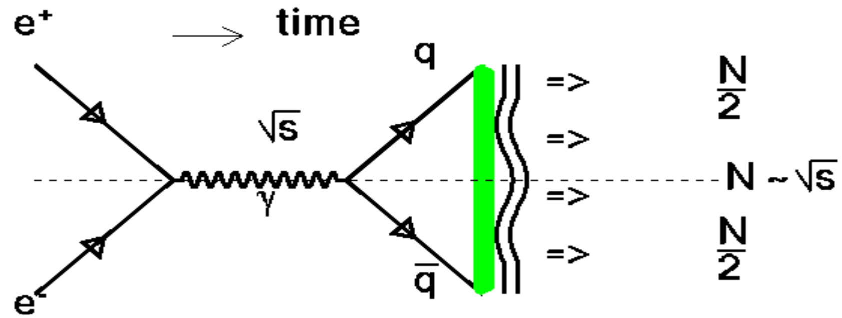
Apply Power Corrections to Event Shape Means vs. Q^2

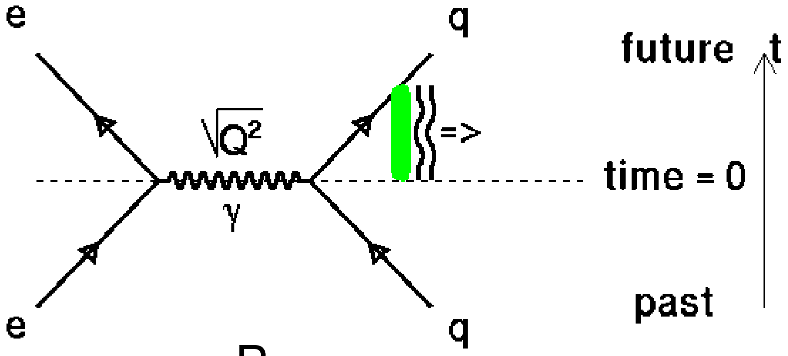
- **Measure <F> and compare to pQCD calulcation (NLO) plus power correction (PC)**
- **Extract α_0 and α_S from fits to means**
  - Check consistency to test PC model

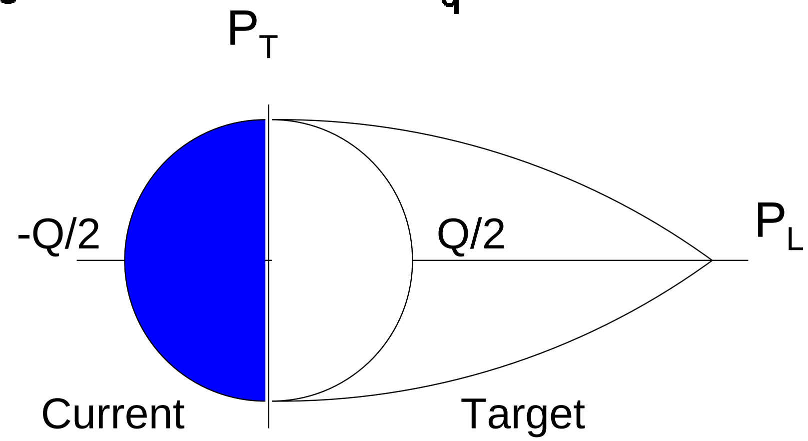
Apply Power Corrections to Event Shape Distributions

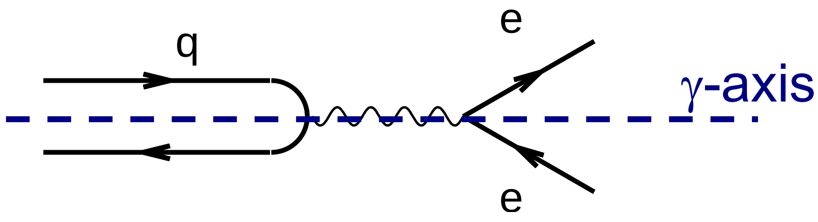
- **Measure F and compare to theoretical calculation plus power correction**
- **Extract α_0 and α_S from fits to distributions**
  - Check consistency to test PC model

Current Hemisphere of the Breit Frame









$$2xP + q = 0$$

Current region of Breit frame

- **equiv. to single hemisphere e^+e^-**
- **e^+e^-: quarks produced back to back with E=√s/2**
- **DIS: struck quark with E=Q/2**
- **quark's hadronization products in current hemisphere**
- **Breit frame great for identifying jets of particles**

Particle and Energy Flow

Three classes of event shapes studied in this analysis

- **Axis independent**
    - **Analysis done in current region of Breit frame**
  - Invariant jet mass: M^2
  - C-Parameter: C
- **Axis dependent**
    - **Analysis done in current region of Breit frame**
  - Thrust: T_T, T_γ
  - Broadening: B_T, B_γ
- **Multi-jet**
    - **Analysis done in full Breit frame**
  - Out-of-plane Momentum: K_{out}
  - Jet transition parameter: y_n

Axis Independent Shapes

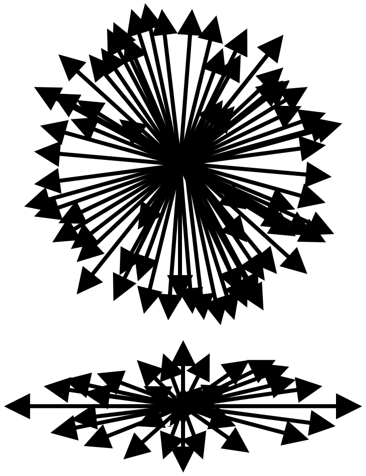
Sphericity: describes isotropy of energy flow

- **Theoretical issue: *NOT* collinear and infrared safe**
  - Unusable in DIS

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

$$0 \le S \le 1$$



C-Parameter:

- **collinear and infrared safe combination of the sphericity eigenvalues**

C Parameter

$$C = \frac{3\sum_{ij}|\vec{p}_i||\vec{p}_j|\sin^2(\theta_{ij})}{2\left(\sum_i |\vec{p}_i|\right)^2}$$

Invariant Jet Mass

Jet Mass

$$M^2 = \frac{\left(\sum_i p_i^\mu\right)^2}{\left(2\sum_i E_i\right)^2}$$

Thrust in DIS

Linear collimation of hadronic system along a specified (“thrust”) axis

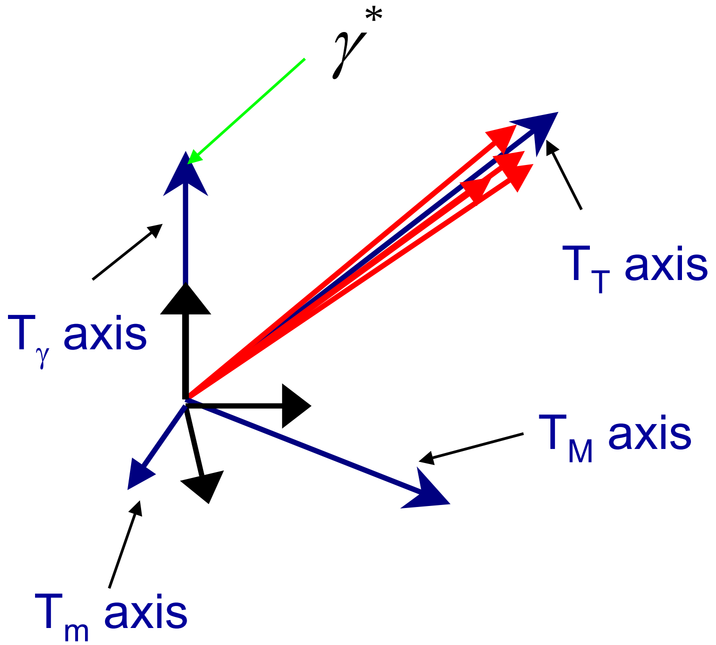
T interpretation depends on choice of axis:

- **Four Thrusts in DIS: T_γ, T_M, T_m, T_T**

$$T = \max_{\hat{n}_k} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$

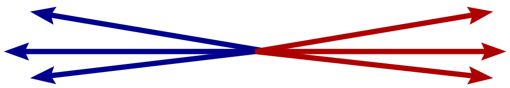
$$\tfrac{1}{2} \le T_T \le 1$$

$$0 \le T_\gamma \le 1$$

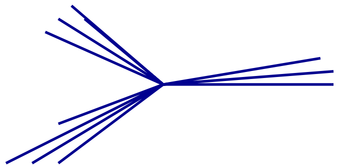


Thrust and Sphericity

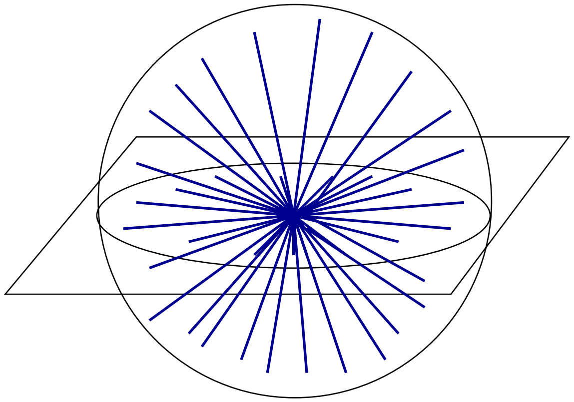
Collimated



Planar



Isotropic



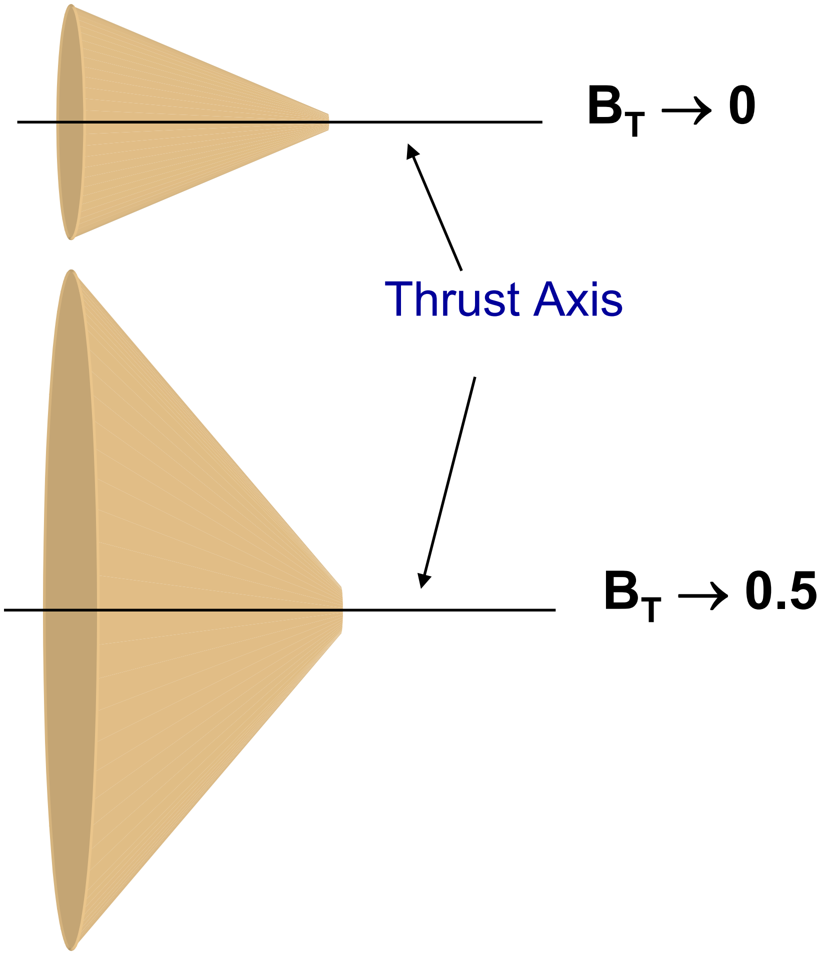
$T_T=1$	← Increase	$T_T=3/4$	← Increase	$T_T=1/2$
S=0	Increase →	S=1/2	Increase →	S=1

Broadening

Broadening of particles in transverse momentum wrt. thrust axis

$$B = \frac{\sum_i |\vec{p}_i \times \vec{n}|}{\sum_i |\vec{p}_i|}$$

$$0 \le B \le \tfrac{1}{2}$$



$B_T \to 0$

Thrust Axis

$B_T \to 0.5$

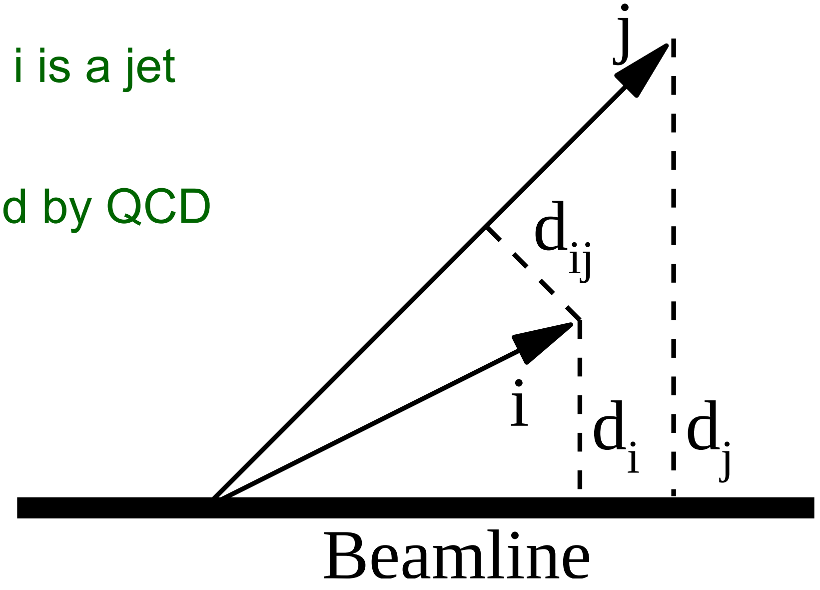
Jet Finding: Longitudinally Invariant k_T Algorithm$\rightarrow y_2$

In ep: k_T is transverse momentum with respect to beamline

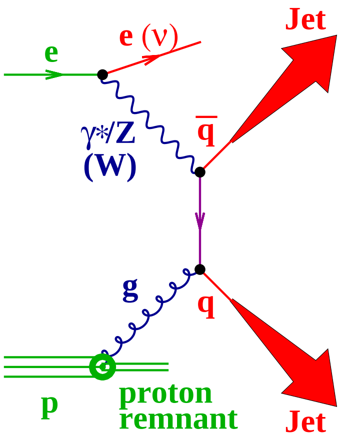
- **Algorithm**
  - For every object i and every pair of objects i, j compute
  - $d_i = E^2_{T,i}$ (distance to beamline in momentum space)
  - $d_{ij} = \min\{E^2_{T,i}, E_{2T,j}\}[D_h^2 + D_f^2]$ (distance between objects)
  - Calculate min{ d_i , d_{ij} } for all objects
  - If (d_{ij}/R^2) is the smallest, combine objects i and j into a new object
    - **R is radius in η - ϕ space**
  - If d_i is the smallest, then object i is a jet
- **Advantages:**
  - k_T distributions can be predicted by QCD

Jet Rate

$$y_n \equiv \min\{d_i, d_j, d_{ij}\}$$

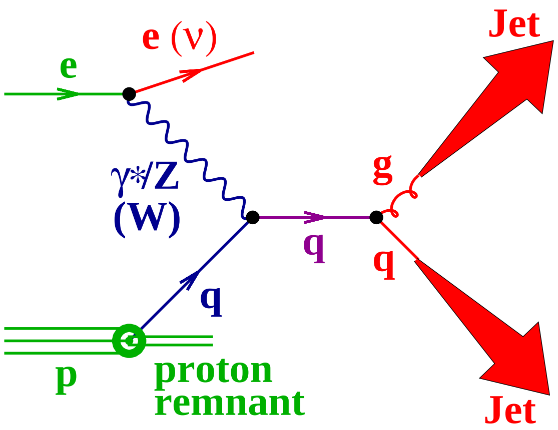


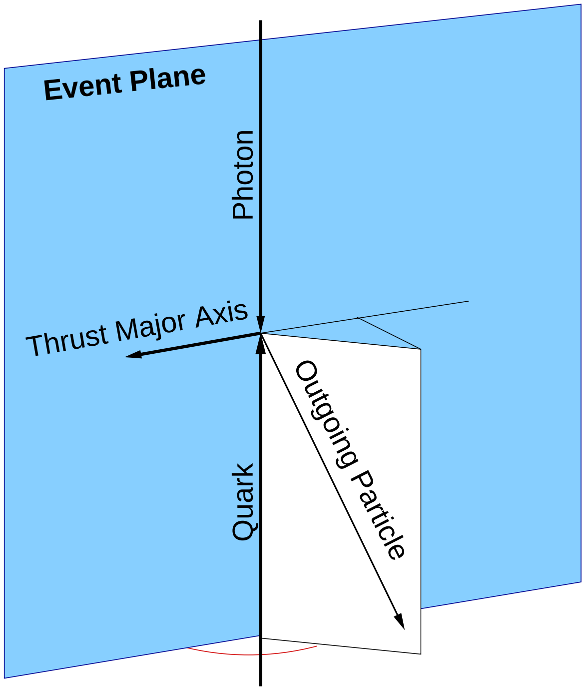
Event Shapes With Jets: K_{out}



$$O(\alpha^1 \alpha_S^2)$$

2 jets





Momentum out of plane

$$K_{out} = \sum_i \left| \vec{p}_i \right|$$

Energy flow out of event plane defined by proton direction and thrust major axis

- **Sensitive to perturbative & non-perturbative contributions**
- **Dijet event:**
  - LO dijet pQCD calculation gives $K_{out} = 0$
  - First contribution to K_{out} is from non-perturbative part or from NLO dijet pQCD calculation

Modeling DIS with Monte Carlo

Event generators use algorithms based on QCD and phenomenological models to simulate DIS events

- Hard subprocess: pQCD
- Parton Cascade
- Hadronization
- Detector Simulation
  - correct for detector effects: finite efficiency, resolutions & acceptances

Hadronization Models

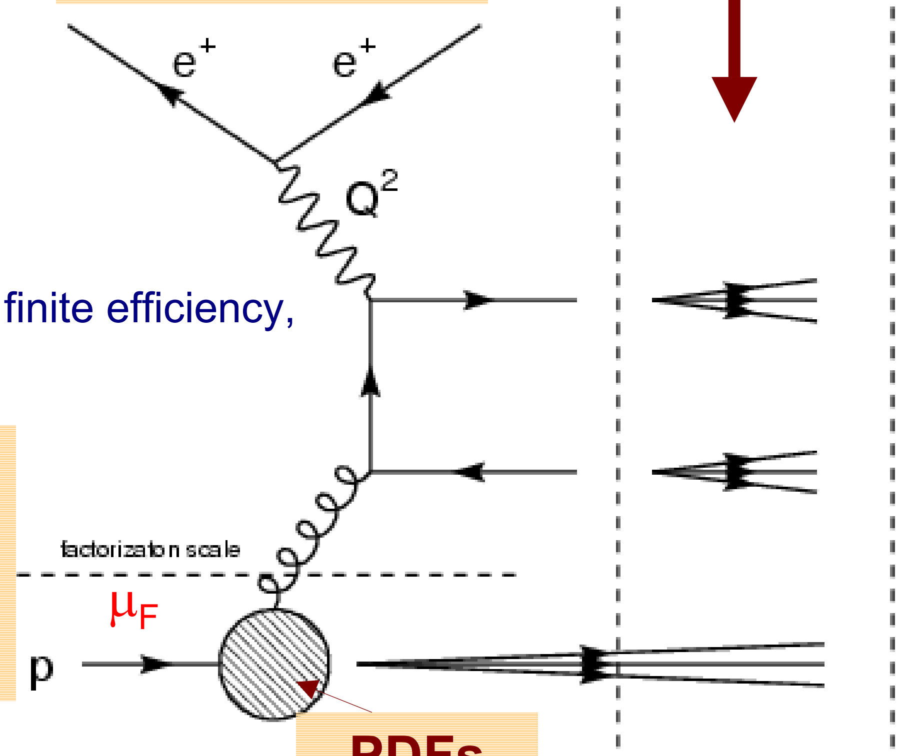
- **String Fragmentation (Lund)**
- **Cluster Model**

Next slide

NLO calculations stop here: μ_R

Parton Level

Hadron Level



Detector Simulation

Parton Cascades

- **LO Matrix Element + Parton Showers (MEPS)**
- **Color Dipole Model (CDM)**

Next slide

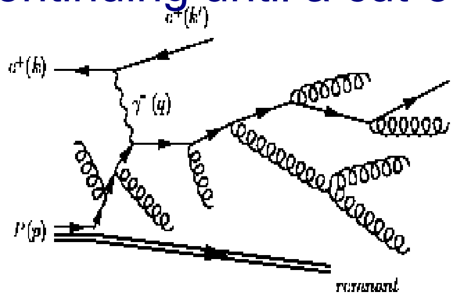
PDFs

Monte Carlo models: parton cascades and hadronization

Models for parton cascades:

Parton Shower Model:

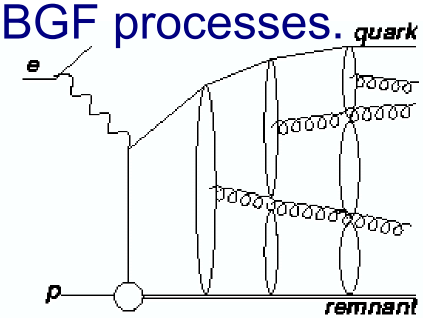
- cascade of partons with decreasing virtuality continuing until a cut-off



LEPTO
HERWIG

Color Dipole Model:

- Gluons are emitted from the color field between quark-antiquark pairs, supplemented with BGF processes.

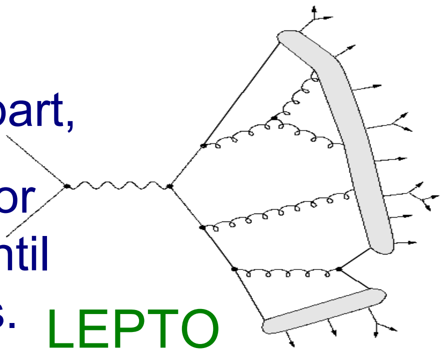


ARIADNE

Hadronization models:

Lund String Model:

- color "string" stretched between q and q moving apart,
- string breaks to form 2 color singlet strings, and so on until only on-mass-shell hadrons.



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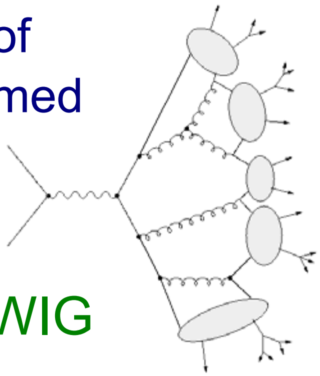
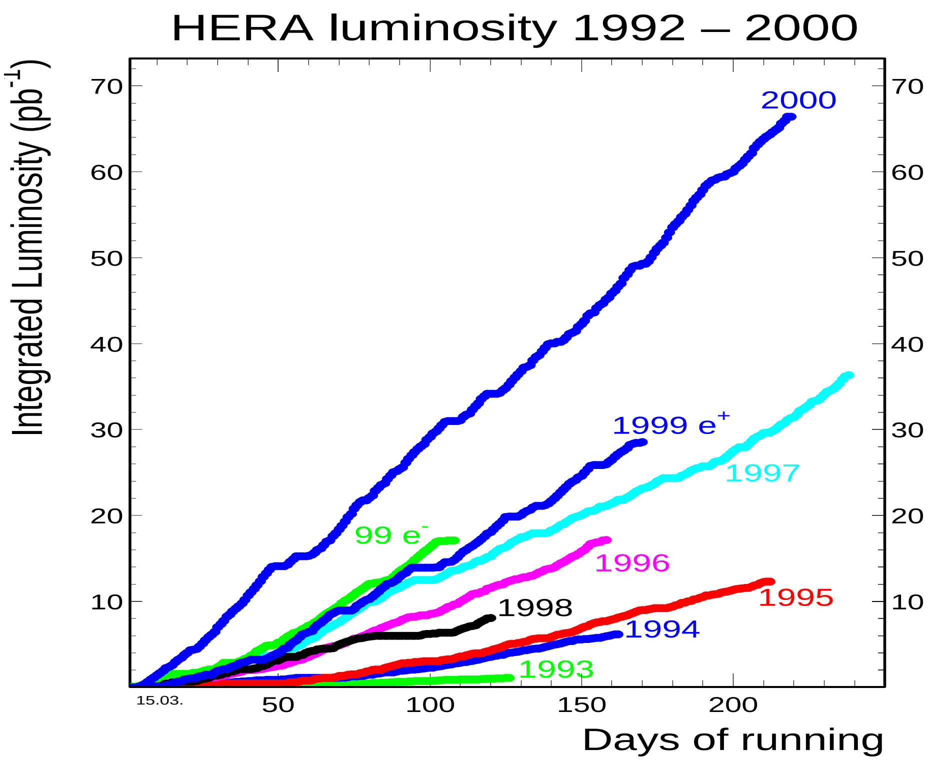
Cluster Fragmentation Model:

- color-singlet clusters of neighboring partons formed
- Clusters decay into hadrons



HERWIG

ZEUS Event Shape Analysis: HERA I Data



Used well studied NC DIS sample of events taken in 1998-00 ~ 82.2 pb^{-1}

Luminosity upgrade in 2003/2004: HERA II

- 5x increase in Luminosity

ZEUS Luminosities (pb^{-1})			# events (10^6)
Year	**HERA**	**ZEUS on-tape**	**Physics**
e$^-$: *93-94, 98-99*	27.37	18.77	32.01
e$^+$: *94-97, 99-00*	165.87	124.54	147.55

Inclusive Event Selection

ZEUS 98-00 (82.2 pb^{-1})

General DIS cuts

- $Q^2_{DA} \geq 80$ (100) GeV^2
- $y_{JB} > 0.04$
- $y_{el} < 0.9$
- Vertex with $|z| < 40$ cm
- $38 < E\text{-}p_Z < 60$ GeV
- Good positron
  - electron probability > 0.9
  - $E_{e'} > 10$ GeV

Additional Requirements

- **Global Shapes**
  - $|\eta_{lab}| < 1.75$
  - $p_t > 0.15$ GeV
    - Use the full tracking acceptance
  - Current region multiplicity > 1
  - $E_C/Q > 0.25$
- **K_{out}**
  - $|\eta_{lab}| < 2.2$
  - $p_t > 0.15$ GeV
  - $\eta_{Breit} < 3$
    - Select current region
  - At least 2 jets in the Breit Frame
  - $y_2 > 0.1$
- **y_2**
  - At least 1 particle in Breit frame
  - $p_t > 0.15$ GeV

Event Shape Means

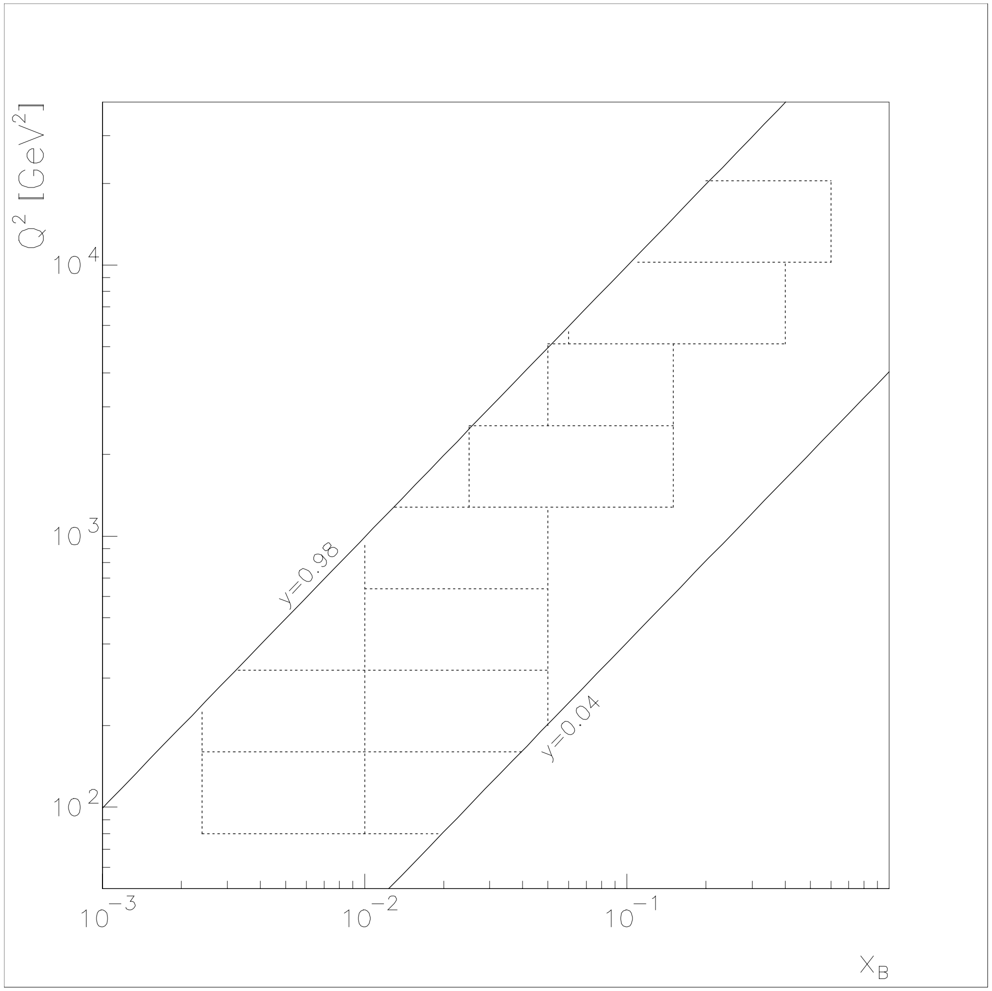
Apply Power Corrections to Event Shape Means vs. Q^2

- **Measure <F> and compare to pQCD calculcation (NLO) plus power correction (PC)**
  - NLO calculated with DISENT (Seymour and Catani) and DISASTER++ (Graudenz)
- **Extract α_0 and α_s from fits to means**
  - Check consistency to test PC model

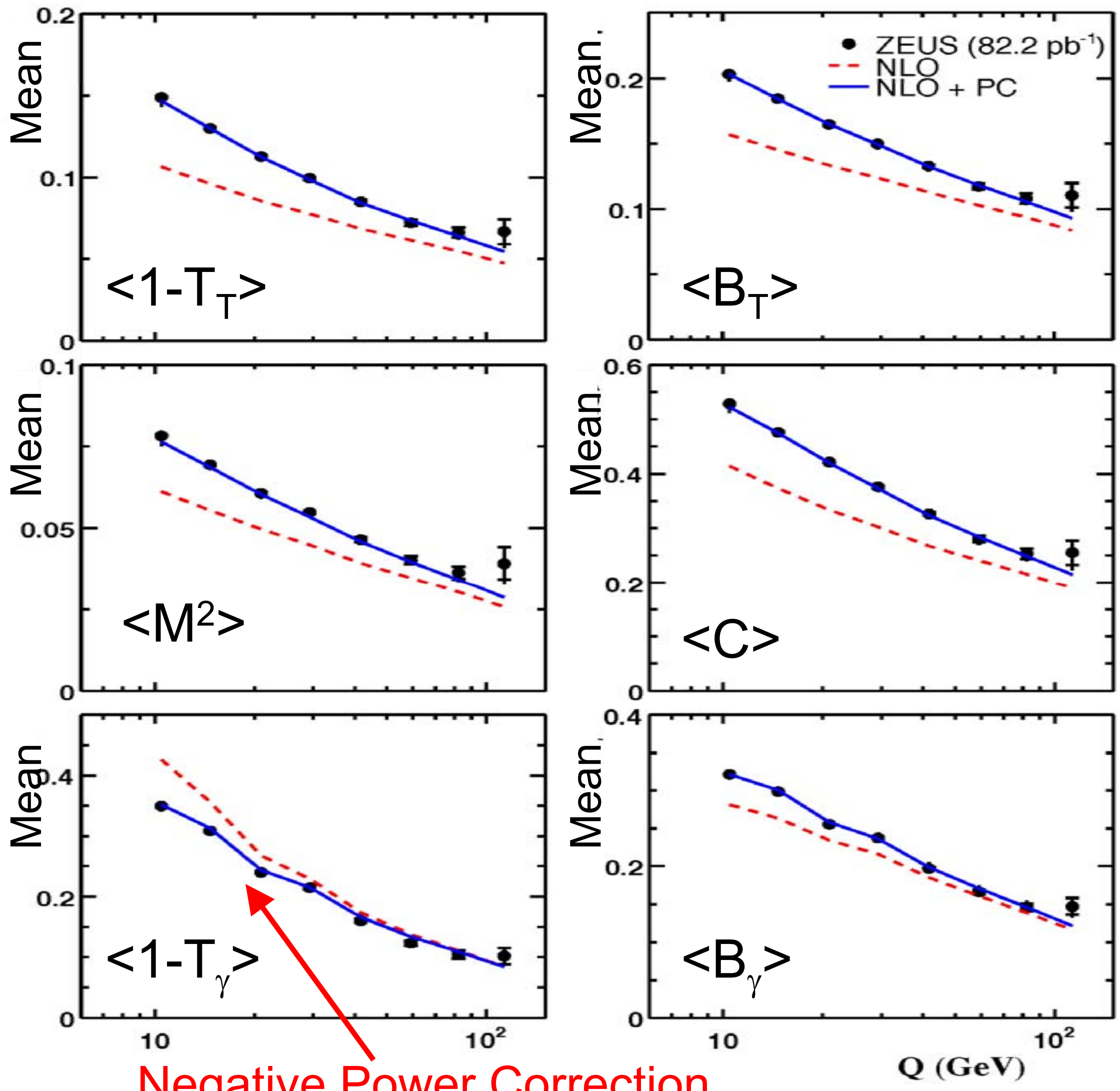
Kinematic Bins

- Analysis conducted in 8 bins of Q^2
- Lowest two Q^2 bins are divided into two bins of x
- Two studies:
  - Means of each variable in each bin
  - Differential distributions of each variable in each bin

NOTE: multiple x bins at low Q^2



Fitted Mean Event Shapes to NLO + Power Correction



Negative Power Correction

Add Power Correction to NLO in order to agree with data

2-parameter NLO + PC fit

- Simultaneous fit for α_s and α_0
- Each shape fit separately

Fits use Hessian method for statistical and systematic errors

- **Complete error matrix with error correlations**

NLO calculation using DISASTER++

T_γ illustrates PC limitations: x

Systematic Studies

Studies systematic effect of cuts and analysis method on the event shape measurement

$$\delta_{<F>} = \frac{<F>_{systematic} - <F>_{central}}{<F>_{central}}$$

Largest systematic uncertainties:

- Corrected particle energies (1-2%)
- Loosen the particle cuts (2-10%)
- Correct data with HERWIG (LEPTO) (2-10%)

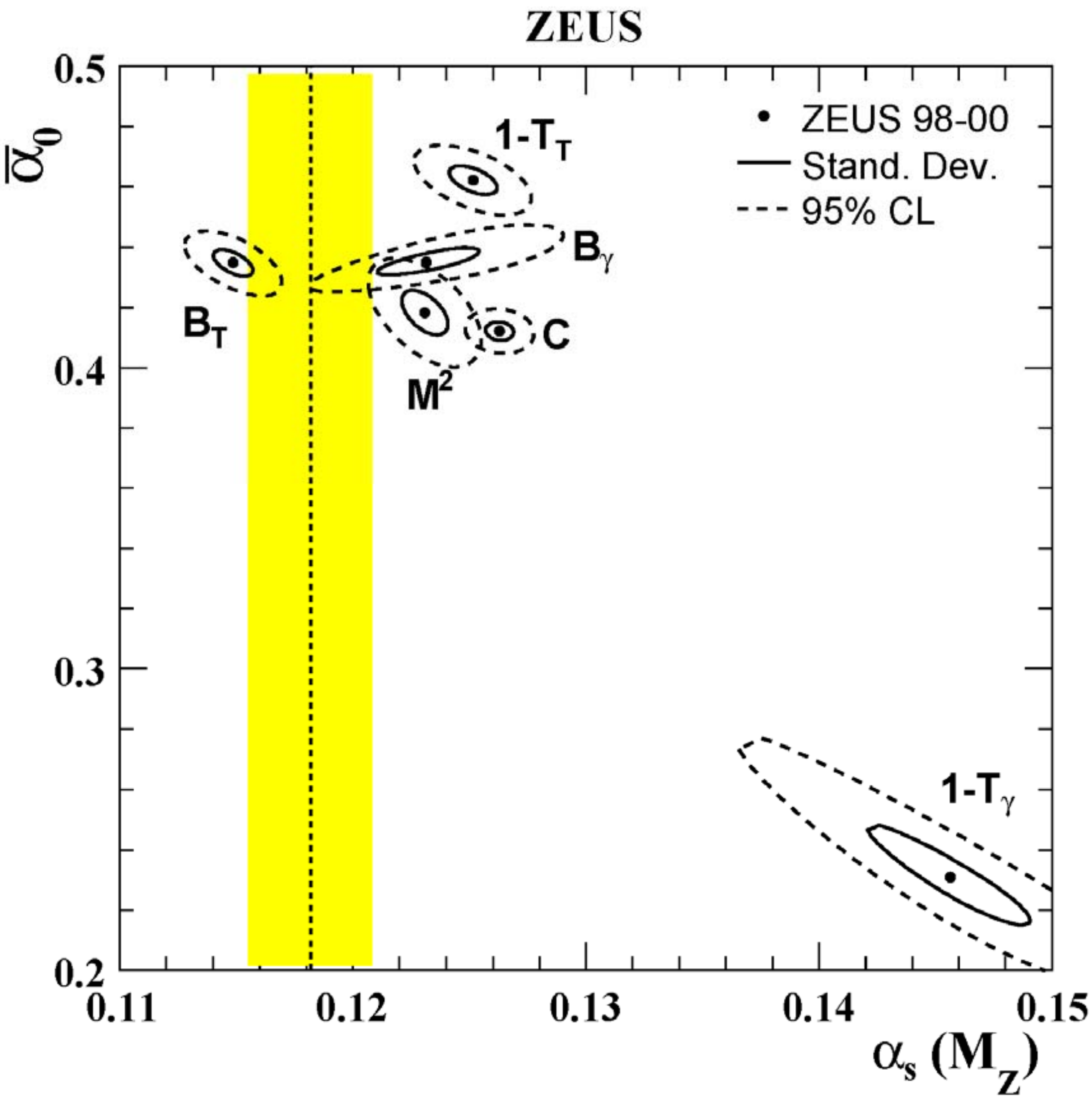
Other systematic uncertainties smaller than the statistical uncertainties.

Extraction of α_0 and α_S from Mean Event Shapes

Extracted free parameters for each shape

- **Fitted α_s values consistent**
  - (excluding B_T,T_γ)
- **Fitted α_0 consistent to ~10%**
  - (excluding $T\gamma$)

Theory errors dominate, except for γ axis shapes

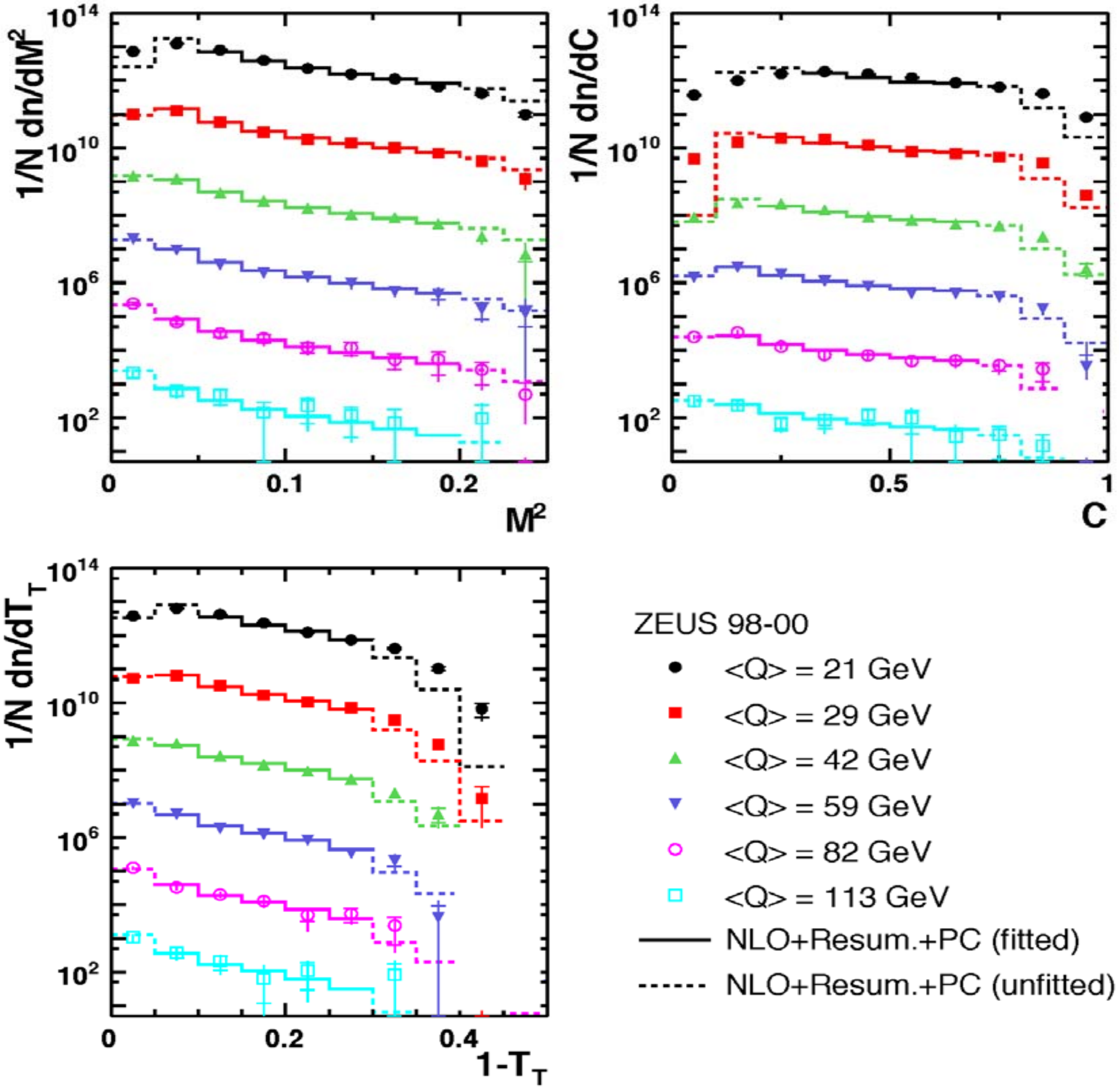


Differential Distributions: Resummation and Matching

Apply Power Corrections to Event Shape Distributions

- **Fit theory prediction to measured F**
  - Resummation of next-to-leading log (NLL) corrections for small F
    - **Because perturbative radiation is suppressed**
  - Match NLL to fixed-order results that are valid at large F
    - **Six choices for matching method:**
      - M, M2, logR, Mmod, M2mod, logRmod
  - Fit sub-range where calculation is expected to be correct
    - **Means were fitted to full range**
  - Resummation, Matching, and PC calculated with DISRESUM
- **Extract α_0 and α_s from fits to distributions**
  - Check consistency to test PC technique

Fit to M^2, C, T_T Differential Distributions

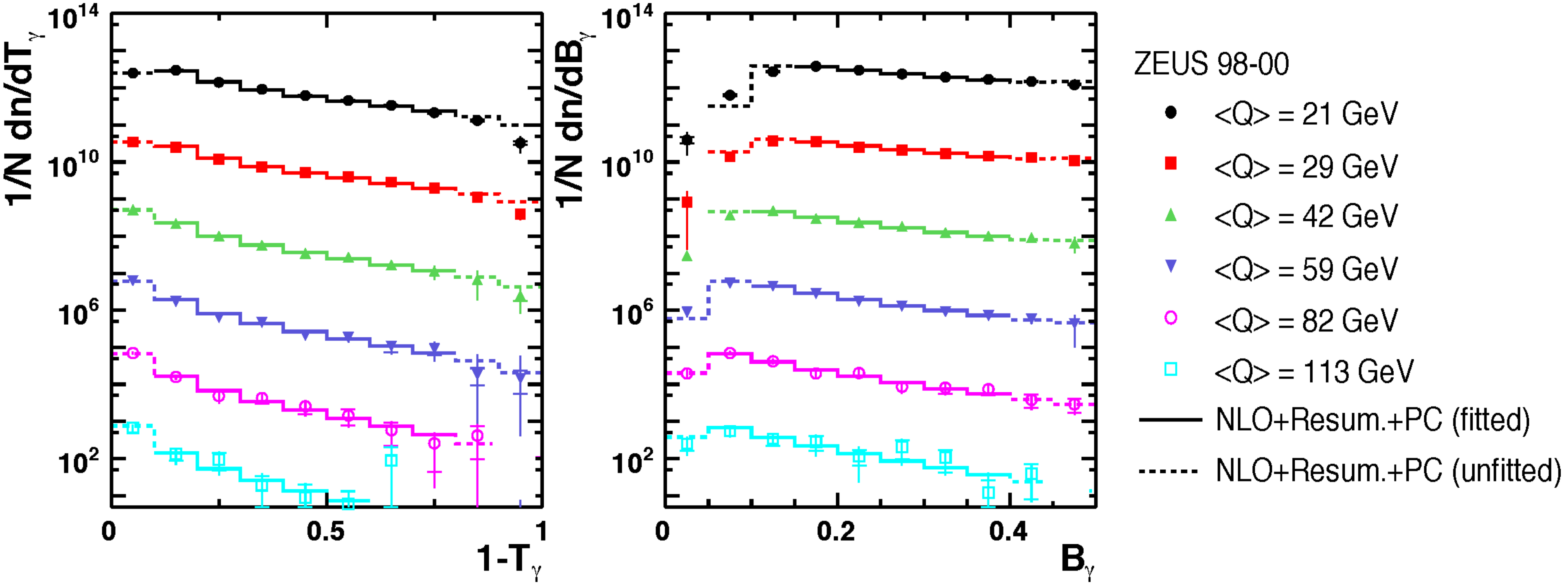


Fit of ZEUS 98-00 differential distribution to NLO+NLL+PC

- NLO Calculated with DISPATCH
- Resummation is applied with DISRESUM
- Bins for which theoretical calculations are expected to be questionable are omitted from fit

Fit over this range gives a good χ^2/dof

Fit to T_γ, B_γ Differential Distributions

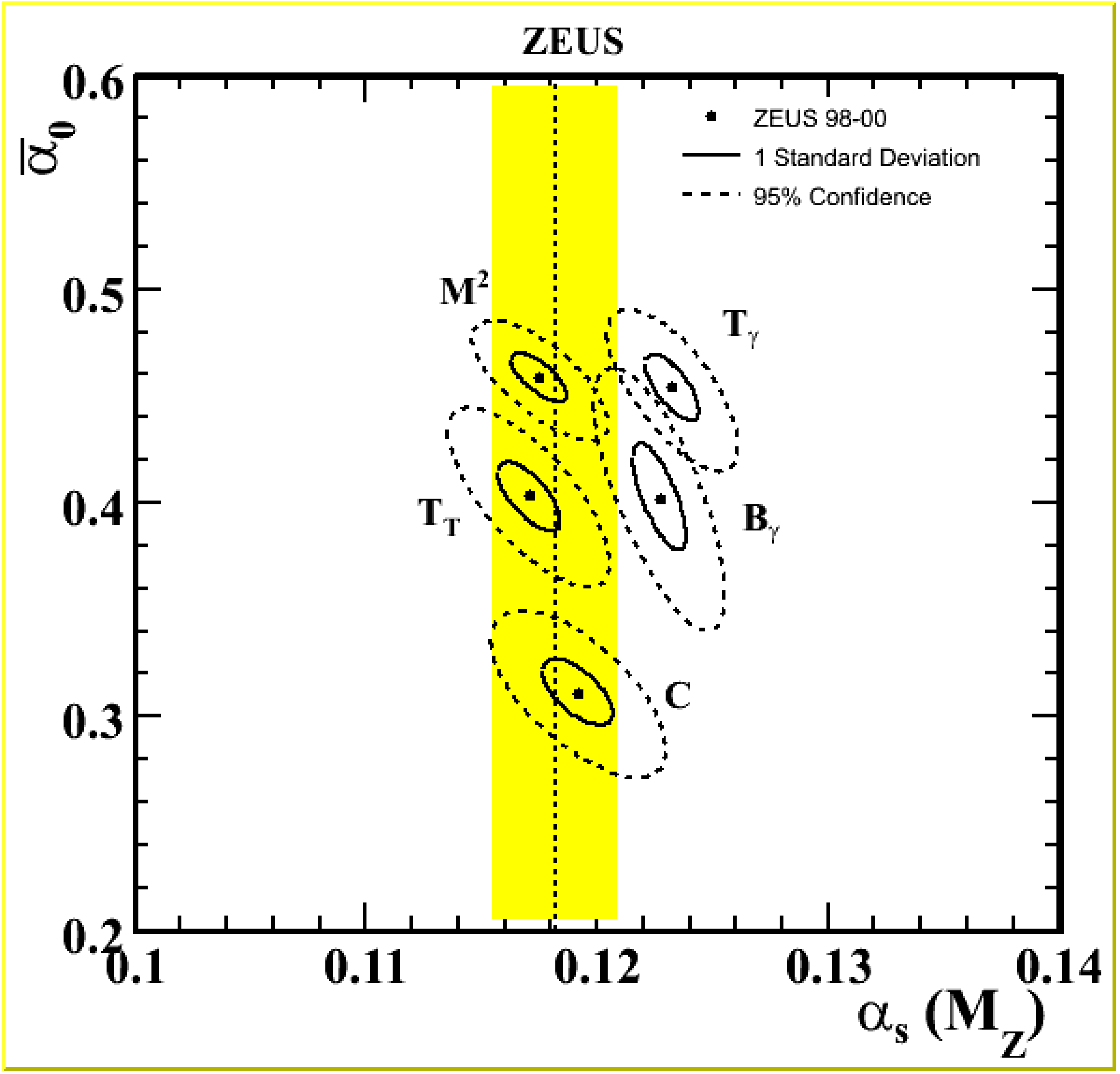


Fit of ZEUS 98-00 differential distribution to NLO+NLL+PC

- **NLO Calculated with DISPATCH**
- **Resummation is applied with DISRESUM**
- **Bins for which theoretical calculations are expected to be questionable are omitted from fit**

Fit over this range gives a good χ^2/dof

Differential α_0 and α_s Extraction

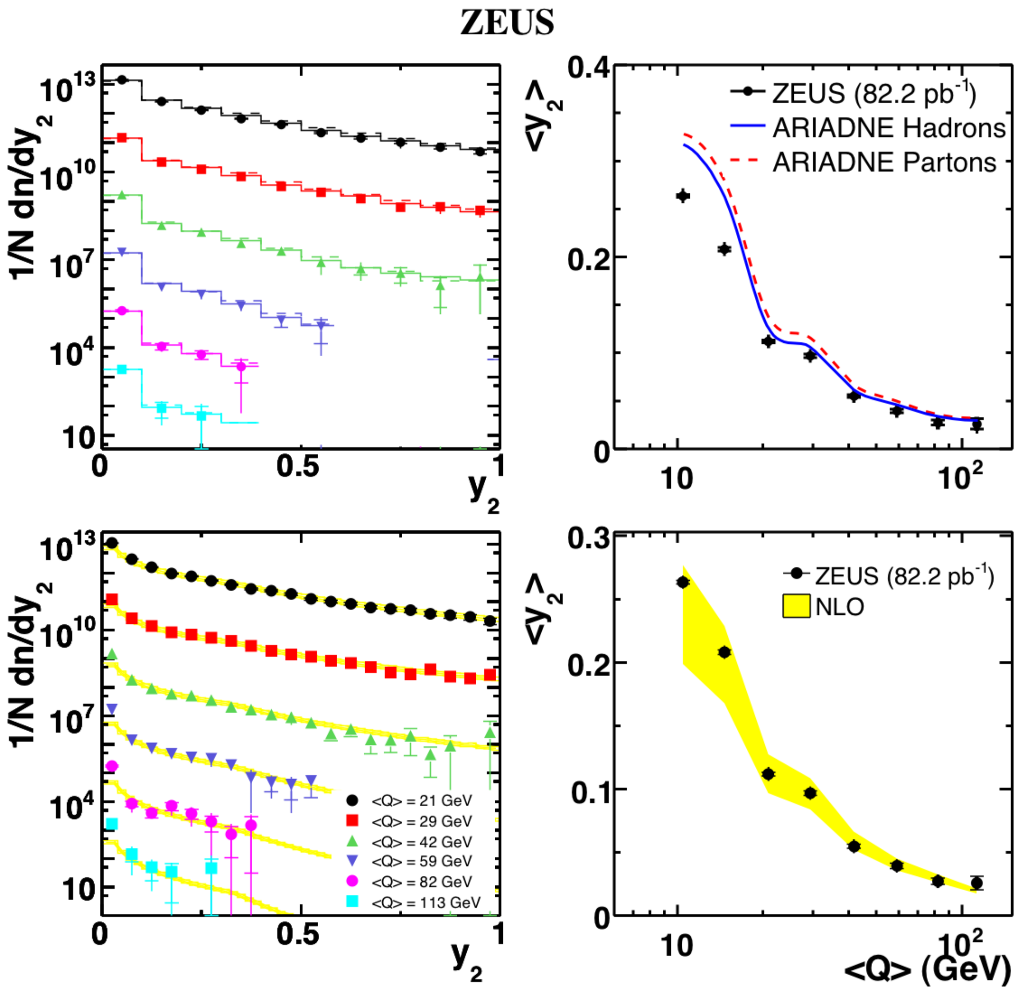


Extracted free parameters for each shape

- **Fitted α_s values consistent**
- **Fitted α_0 consistent**
  - (excluding C)

M2mod matching

Measured Distributions and Means of y_2



event shape: y_2

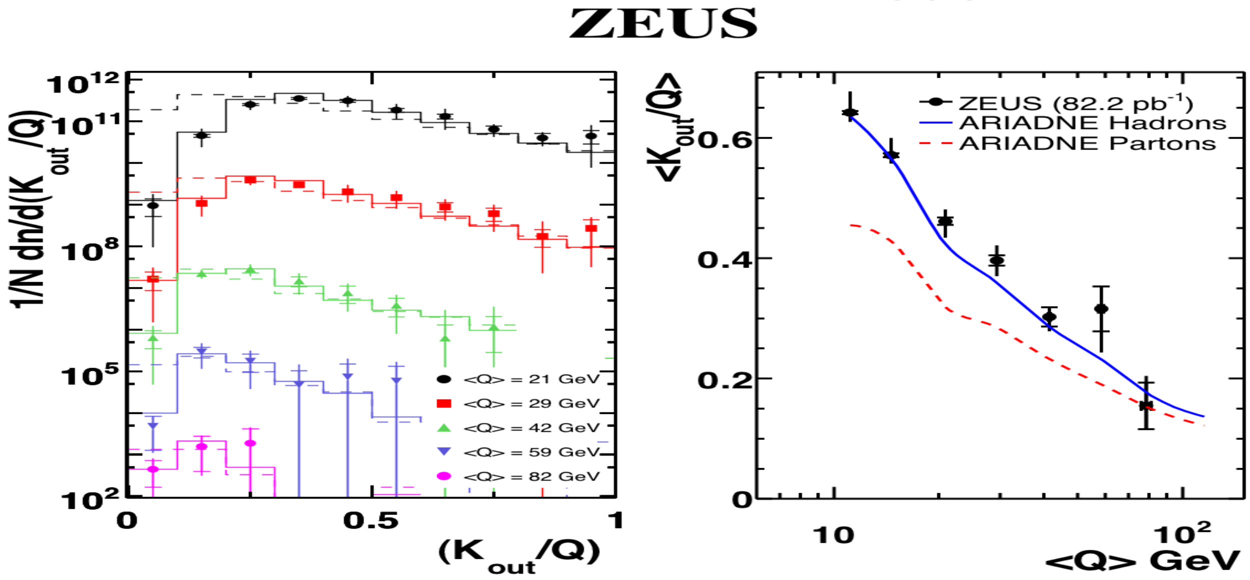
- Distributions and means measured in bins of (x,Q^2)

Compared to NLO (without PC) calculated by DISENT

- Theoretical mechanism for applying Power Correction not yet available

Conclusion: hadronization for y_2 is very small

Measured Distributions and Means of K_{out}



New event shape variable: K_{out}

- Distribution and means measured in bins of (x,Q^2)

Compared to ARIADNE (LO): parton and hadron level

- Theoretical mechanism for applying Power Correction not yet available

Conclusion:

- Hadron level describes data well
- Hadronization effects are significant for K_{out}

Summary

Precise measurement of event shapes in DIS has been done

- Means
  - α_0 and α_s still do not give a self-consistent results for all shapes
- Differential distributions
  - α_0 are consistent within 10% (exclude C) in range 0.4-0.5
  - α_s are in good agreement with the world average
- y_2 and K_{out} await theoretical input

PC technique

- Generally successful
- Suggests importance of higher-order processes

Event Shapes Beyond HERA

Universality of Power Corrections

- **Higher energies**
- **Different kinematic regions**
- **Test validity in pp collisions**