Diffraction 2014

Primošten, Croatia
10-16 September 2014

QCD and Hadronic Final States

Jan Olsson, DESY
for the H1 and ZEUS
Collaborations

Topics: Recent H1 and ZEUS results on the Hadronic Final State at HERA

Measurement of Multijet Production in *ep* Collisions at High Q^2 and Determination of the Strong Coupling α_s

DESY 14-089, arXiv:1406.4709

Trijet Production in Deep Inelastic Scattering at HERA

ZEUS-prel-14-008

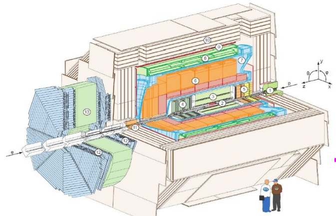
ZEUS results on Photoproduction of Isolated Photons: see following talk by Oleg Kuprash

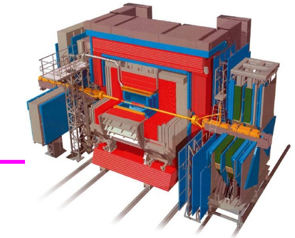
Search for QCD Instanton-Induced Processes in DIS at HERA

H1-Prelim-14-031

Measurement of Charged Particle Spectra in *ep* DIS at HERA

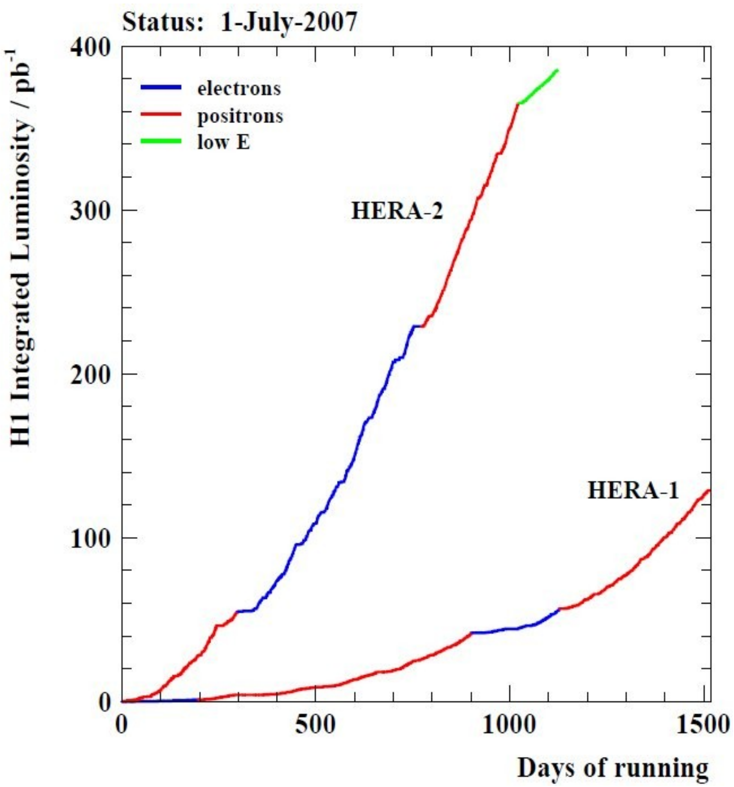
DESY 13-012, arXiv:1302.1321





$E_e = \quad 27$ GeV
$E_p = 920$ GeV
$\sqrt{s} = 319$ GeV
$\sim 0.5\ \text{fb}^{-1}$/exp.

HERA operation 1992-2007

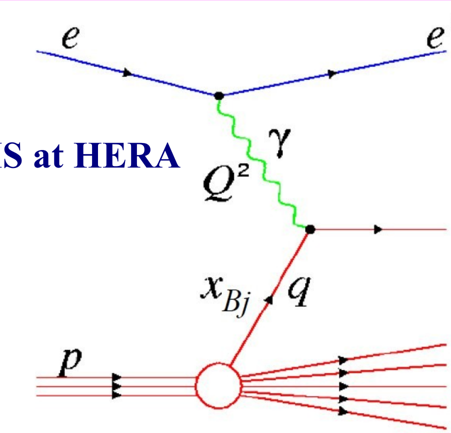


H1 and ZEUS:

High statistics data samples from HERA II, matched by highly improved control of Experimental Uncertainties in Event and Jet Reconstruction

- Hadronic Final State
  - Kinematically overconstrained system in DIS:
  - In situ calibration of HFS Energy Scale
  - Charged tracks, Calorimeter clusters
  - Energy Flow algorithms, avoid Double Counting
  - Separate Jet Energy calibration
- Jet Energy Scale uncertainty ~1%
- Electron Energy Scale uncertainty: ~0.5 - 1%
- Trigger and Acceptance uncertainties: 1 - 2%
- Integrated Luminosity uncertainty: 1.8 – 2.5%

NC DIS at HERA



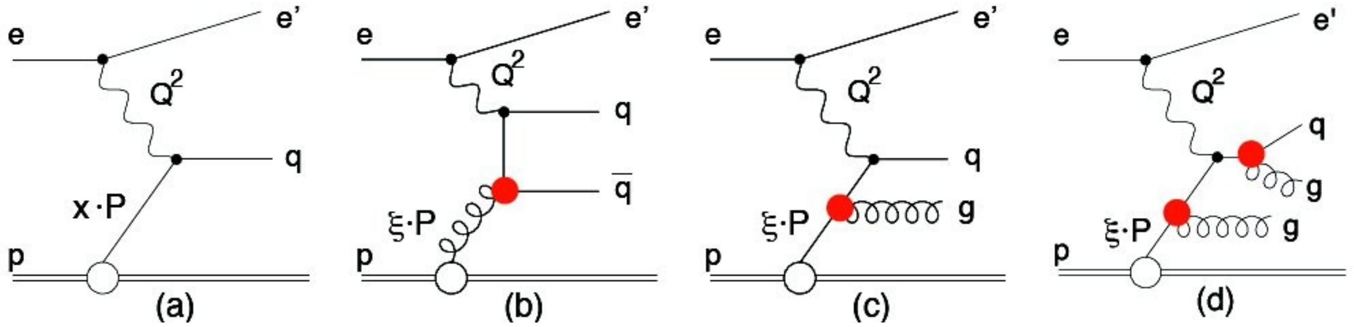
Q^2 Virtuality of exchanged boson
x_{Bj} Bjorken scaling variable
y Inelasticity $(y = Q^2/sx_{Bj})$

Measurement of Multijet Production in ep Collisions at High Q^2 and Determination of the Strong Coupling α_s

DESY 14-089, arXiv:1406.4709
Subm. to EPJ C

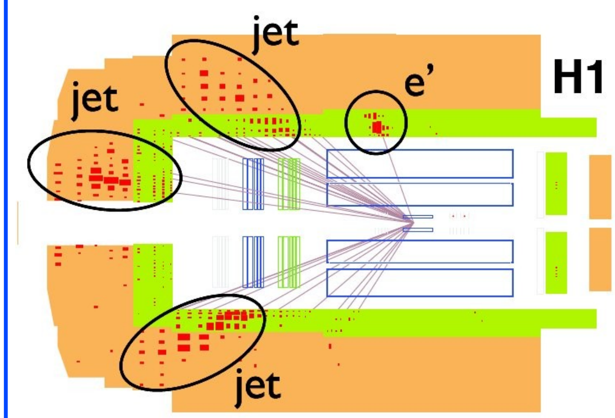
H1 Multijets

Jet Production in NC Dis: Inclusive, Dijets, Trijets



Born | **BGF** $\sim \alpha_s$ | **QCDC** $\sim \alpha_s$ | **3-jet** $\sim \alpha_s^2$

$$\xi = x_{Bj}(1 + M^2_{jj,jjj}/Q^2)$$



Jet Finding performed in Breit Frame $2xP + q = 0$

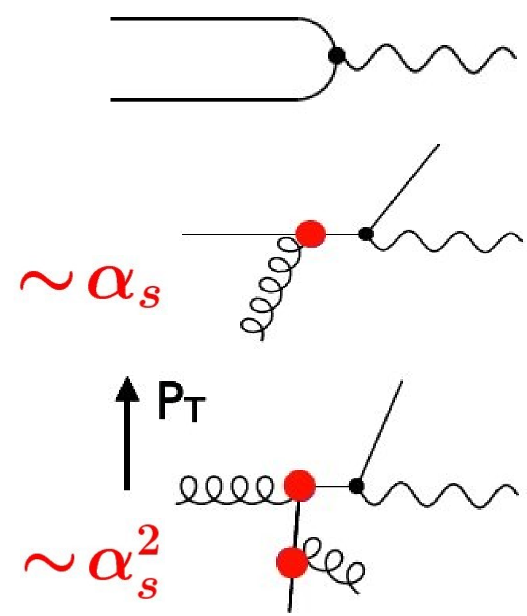
- **Only hard sub-processes generate large p_T**

  Sensitivity to α_s and gluon density

- **Inclusive k_T algorithm used for jet finding**

  (anti-k_T algorithm similar results)

- **Minimum Jet P_T required: $P_T^{jet} > 3$ GeV**



NC DIS Data Sample

HERA II data, 351 pb^{-1}

Jet Samples

Inclusive jets:
Each jet contributes to cross-section

2-jets (3-jets):
All events with at least 2 (3) jets contribute to cross-sections
Trijet sample is a subsample of Dijets

Measurement phase space for jet cross sections
$150 < Q^2 < 15\,000\ \mathrm{GeV}^2$ $0.2 < y < 0.7$
$-1.0 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.5$
$7 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\ \mathrm{GeV}$
$5 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\ \mathrm{GeV}$ $M_{12} > 16\ \mathrm{GeV}$

Extended Phase Space:
- Needed to handle migrations at boundaries of the Measurement p.s.
- Improves precision of Jet Measurements

Extended analysis phase space
$100 < Q^2 < 40\,000\ \mathrm{GeV}^2$ $0.08 < y < 0.7$
$-1.5 < \eta^{\mathrm{jet}}_{\mathrm{lab}} < 2.75$
$P_{\mathrm{T}}^{\mathrm{jet}} > 3\ \mathrm{GeV}$
$3 < P_{\mathrm{T}}^{\mathrm{jet}} < 50\ \mathrm{GeV}$

Regularised Unfolding*

- **Multidimensional Unfolding in Q2, y, P_T**
- **4-fold Simultaneous Cross Section measurements of**
  NC DIS, Inclusive Jets, Dijets and Trijets
- **Statistical and systematic correlations taken into account**
- **Extended Phase Space**
  handles migrations at boundaries, improves precision

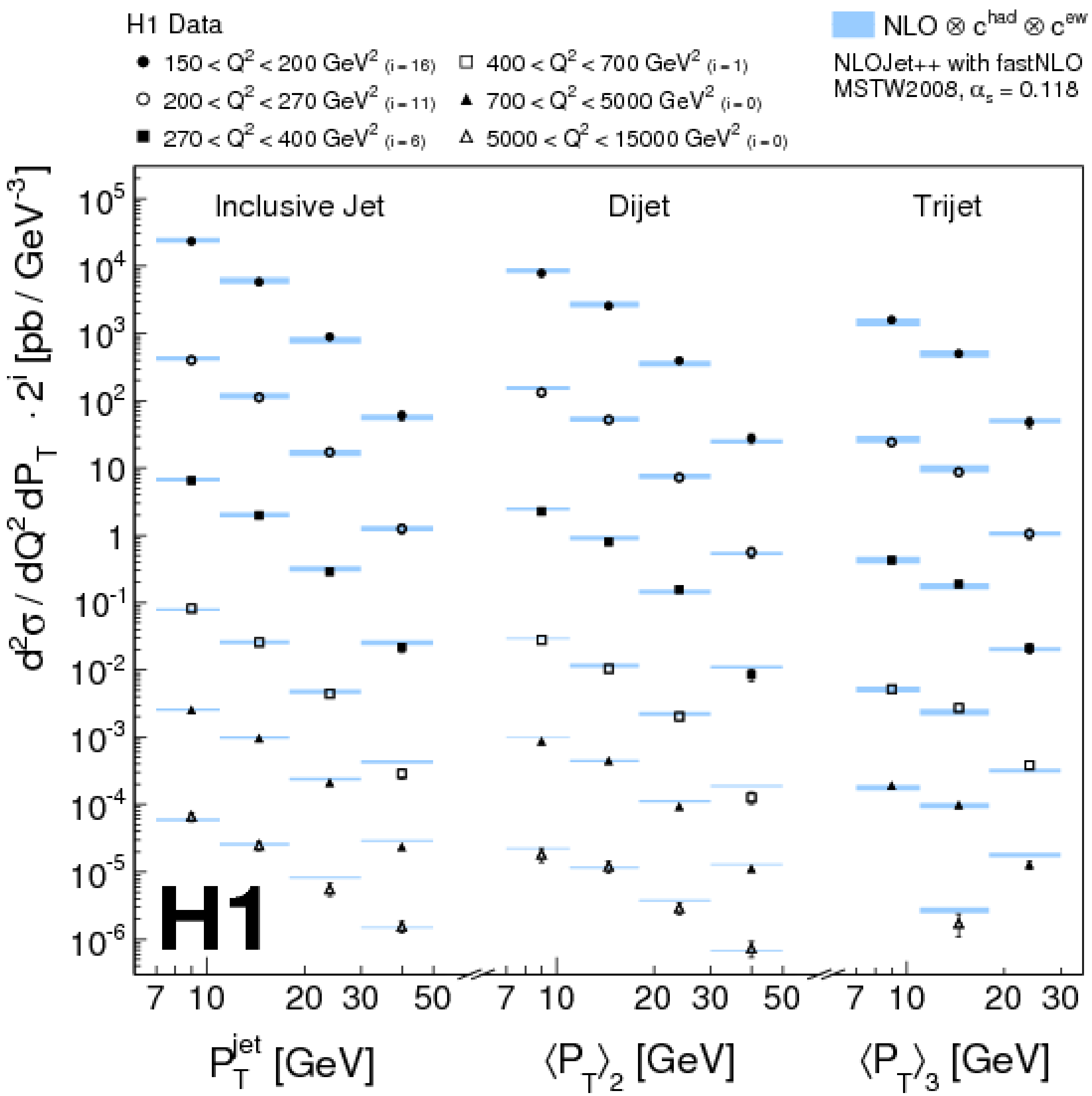
- **Absolute Jet Cross Sections, as well as**
  Jet Cross Sections Normalised to σ_{NCDIS}
  - **Large part of experimental uncertainties cancel**
  - **Note: PDF uncertainties do not cancel**

- **Final Differential Cross Sections in 64 bins**

*** TUnfold: S.Schmitt, arXiv:1205.6201**

Jet Cross Sections, double differential in Q^2 and P_T^{jet}

H1 Multijets



$$\langle P_T\rangle_2 = (P_T^{jet1} + P_T^{jet2})/2$$

$$\langle P_T\rangle_3 = (P_T^{jet1} + P_T^{jet2} + P_T^{jet3})/3$$

NLO pQCD Calculations:

- FastNLO, NLOJET++ QCDNUM
- MSTW2008 PDF
  Other PDFs only small diff.
- $\alpha_s(M_Z) = 0.118$
- Scales

$$\mu_r^2 = (Q^2 + P_T^2)/2 \quad \mu_f^2 = Q^2$$

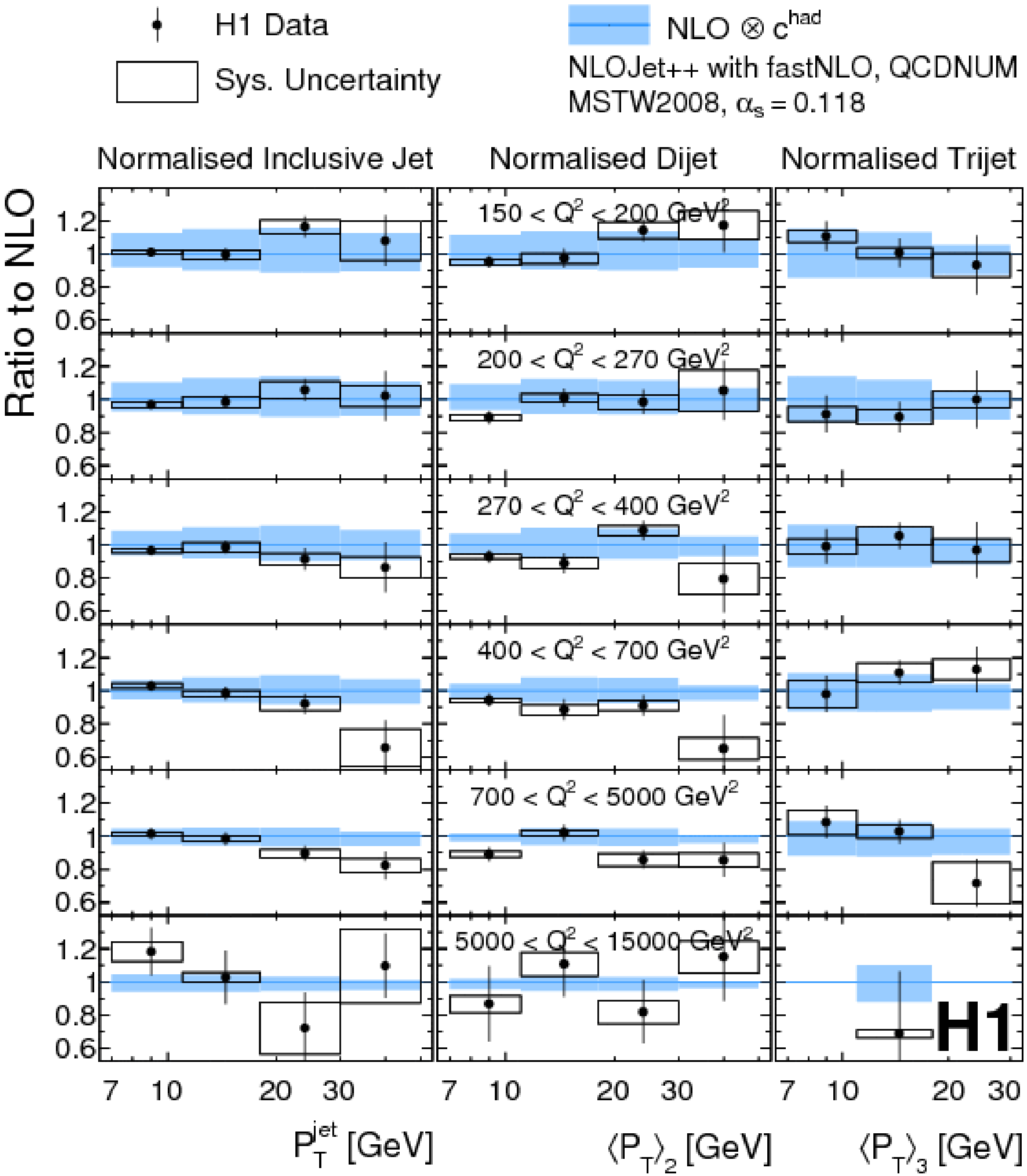
$$\mu_r^2 = \mu_f^2 = Q^2 \quad \text{(NC DIS)}$$

- Hadronisation & EW Corrections
- Theory uncertainty:
  Scale variations x 2 / x 0.5

NLO calculations describe well Inclusive Jet, Dijet & Trijet differential Cross Sections

Ratios of Normalised Jet Cross Sections to NLO

H1 Multijets



Experimental precision

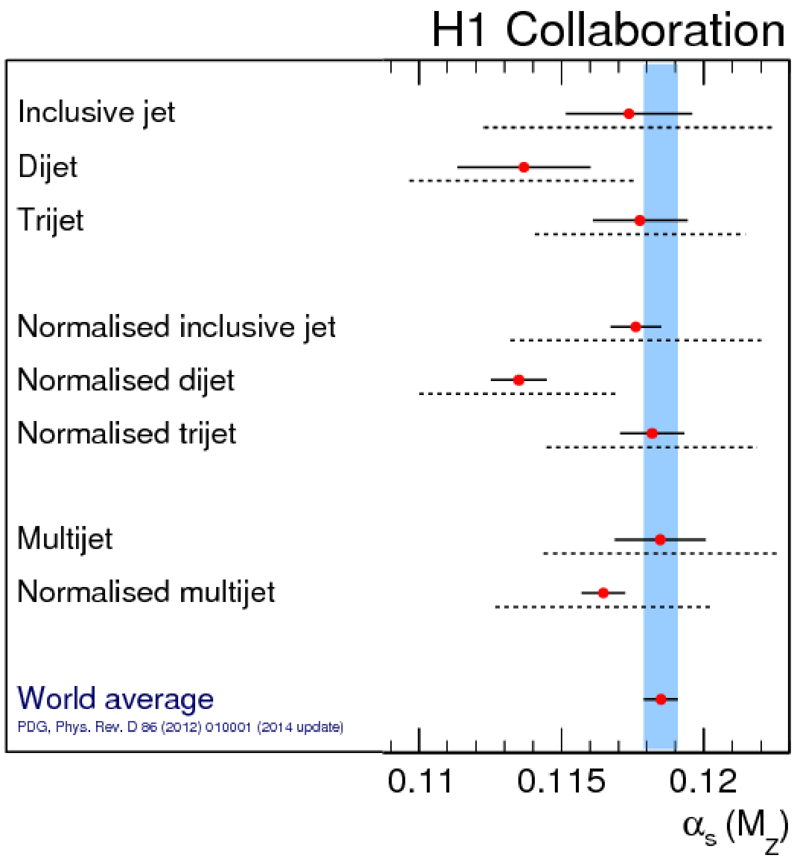
- **Better than Theory uncertainties**
- **Dominated by**
  - **Statistics,**
  - **Jet Energy Scale Uncertainty**
  - **MC Model uncertainty**

Normalised Dijet Cross sections:
Do lie below the NLO prediction in many places

Extraction of $\alpha_s(M_Z)$

H1 Multijets

- Jet Cross section measurements fitted with NLO theory
  Fit both absolute and normalised Jet Cross sections
  Fit Jet Cross sections both individually and simultaneously
- Iterative χ^2 minimisation, using Tminuit
- $\alpha_s(M_Z)$ free parameter
- Systematic errors handled as nuisance parameters in the fits



- Results consistent within total uncertainties
- Results consistent with world average
- Highest precision using
  Normalised Multijets measurements:

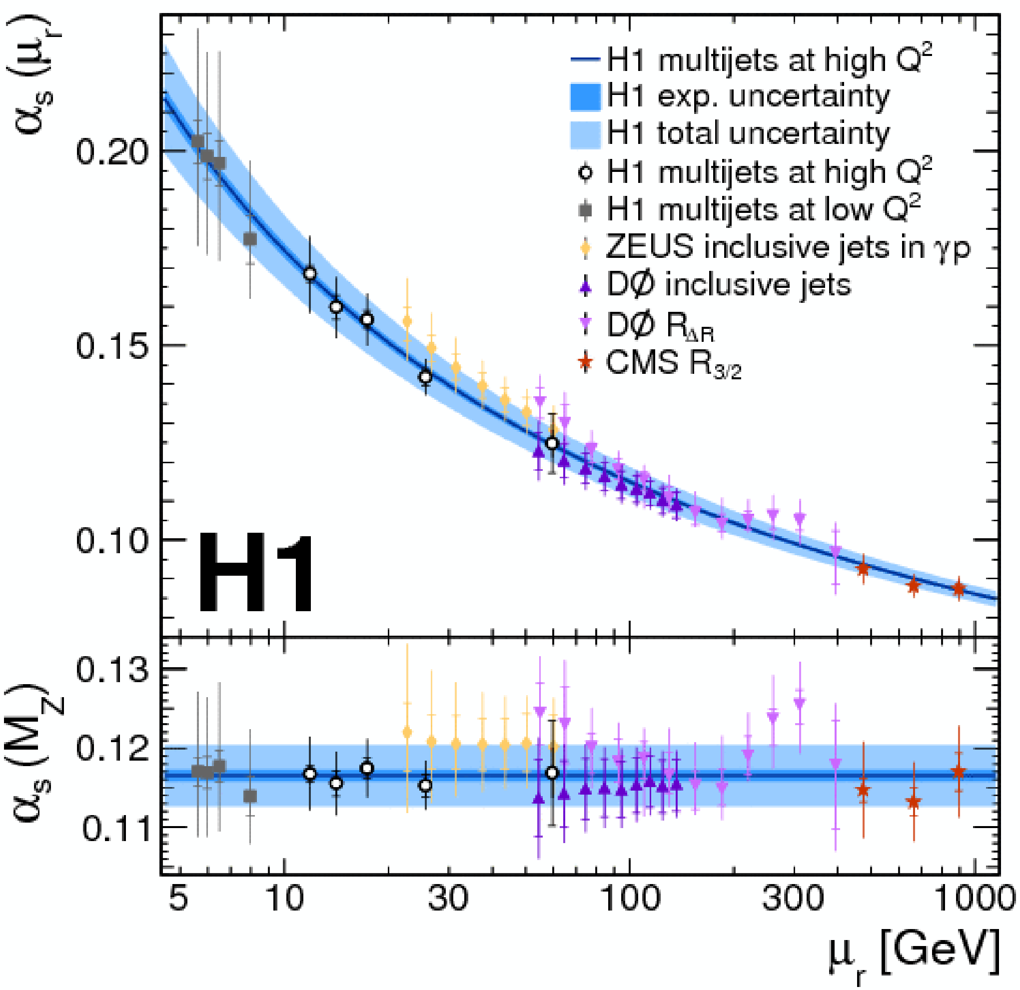
$$\alpha_s(M_Z) = 0.1165\,(8)_{exp}\,(38)_{pdf,theo.}$$

- Dijet results have lower values,
  but within total uncertainties
- Trijet values have smallest errors ($\sim \alpha_s^2$)

NLO theory precision
worse than experimental precision
==> NNLO calculations needed for jets!

Determination of α_s at various values of scale μ_r

H1 Multijets



H1:

5 fits, using Normalised Multijets
Each fit based on cross section set with comparable values of μ_r

α_s values with excellent precision from H1 Normalised Multijets

Prediction:

- RGE using $\alpha_s(M_Z)$ value from H1 Normalised Multijets
- Predicted Running of α_s agrees well with other Jet Data over >2 orders of magnitude

$$\alpha_s(M_Z) = 0.1165\,(8)_{exp}\,(38)_{pdf,theo.}$$

Most precise value derived so far from Jet Data, at NLO, in one single experiment

H1 in good agreement with other Jet Data

Trijet Production in Deep Inelastic Scattering at HERA

ZEUS-prel-14-008

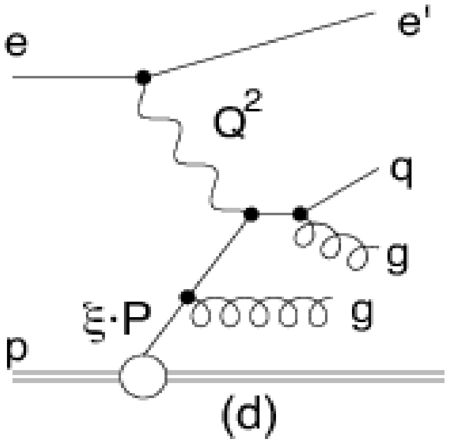
Trijet Production in DIS at HERA

ZEUS Trijets

ZEUS-prel-14-008

HERA II data,
Integrated Luminosity 295 pb^{-1}
Phase Space:

$$125 < Q^2 < 20000 \text{ GeV}^2$$
$$0.2 < y < 0.6$$



$$\xi = x_{Bj}(1 + M^2_{jjj}/Q^2)$$

Jet finding in Breit frame

- Inclusive k_T algorithm
- Select events with at least 3 Jets:

$$E^{jet}_{T,B} > 8 \text{ GeV} \qquad -1 < \eta^{jet}_{lab} < 2.5$$
$$M_{jj} > 20 \text{ GeV}$$

- 2199 events selected

NLO QCD Calculations:
- NLOJET++, HERAPDF1.5
- $\alpha_S(MZ) = 0.1176$
- Scales $\mu_r^2 = Q^2 + \langle E_T^{jet}\rangle^2 \quad \mu_f^2 = Q^2$

  $\langle E_T^{jet}\rangle$ Average E_T of 3 leading jets

- Theory uncertainty:
  By varying scales x 2 / x 0.5
  $\alpha_S(M_Z)$ +/- 0.002

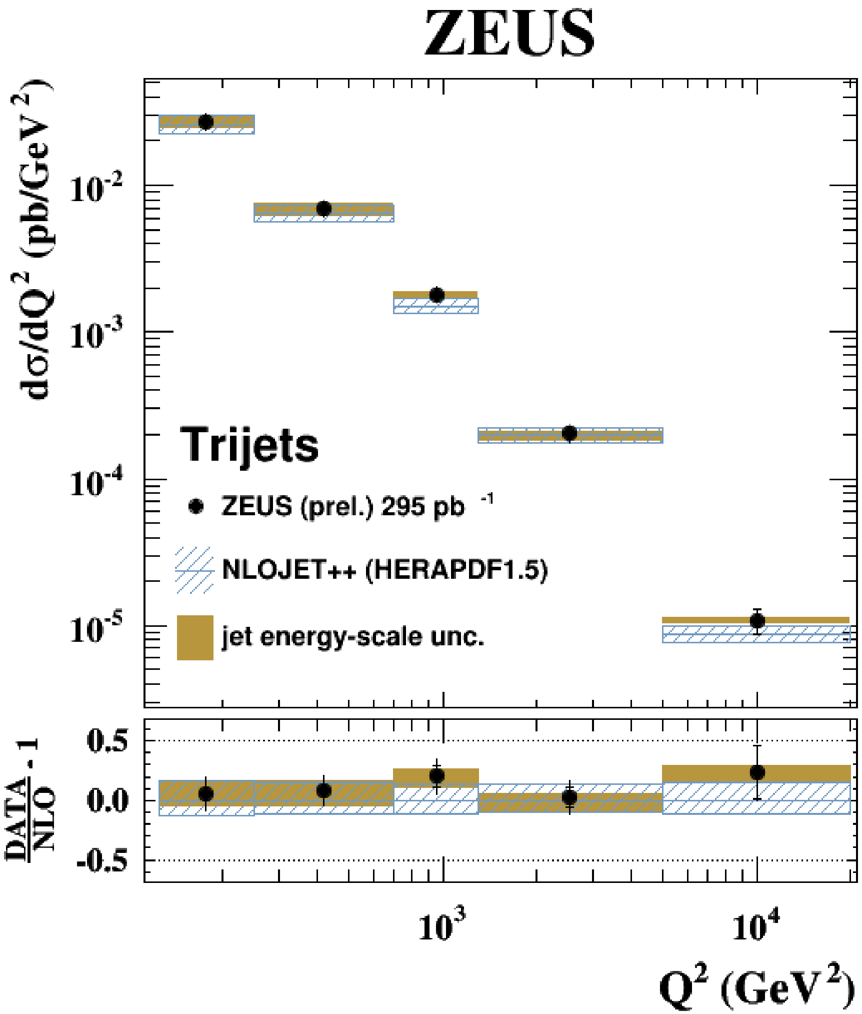
Bin averaged Cross Sections differential in

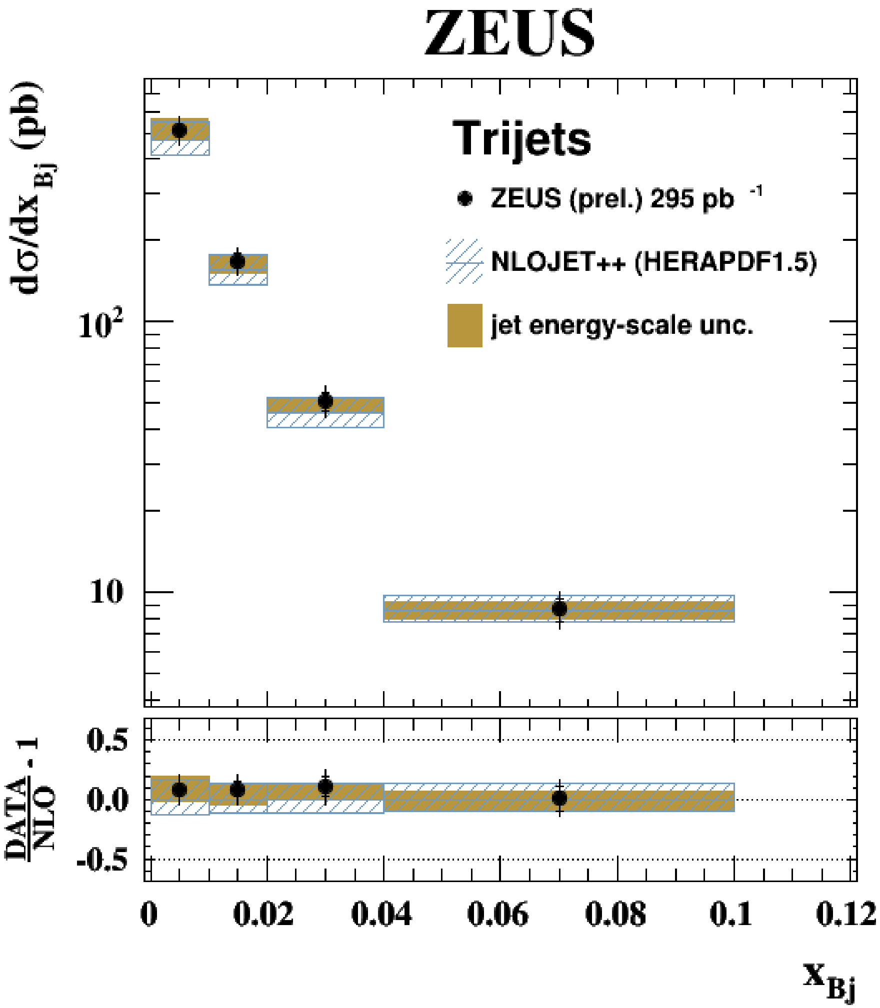
$$Q^2,\ x_{Bj},\ \xi \text{ and } \overline{E^{jet}_{T,B}}$$

$$\left(\overline{E^{jet}_{T,B}} = (E^{jet1}_{T,B} + E^{jet2}_{T,B} + E^{jet3}_{T,B})/3 \right)$$

Trijet Single differential Cross Sections

ZEUS Trijets





Jet Energy Scale Uncertainty:

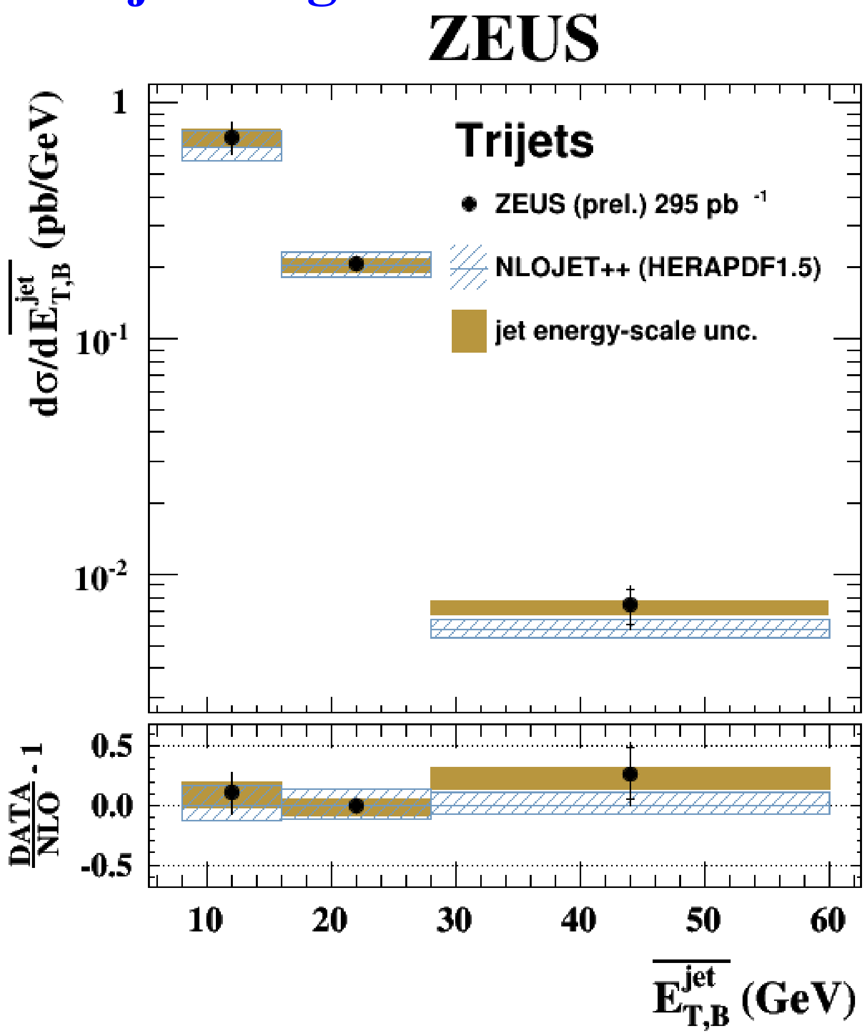
1% for $E_{T,Lab}^{jet} > 10$ GeV

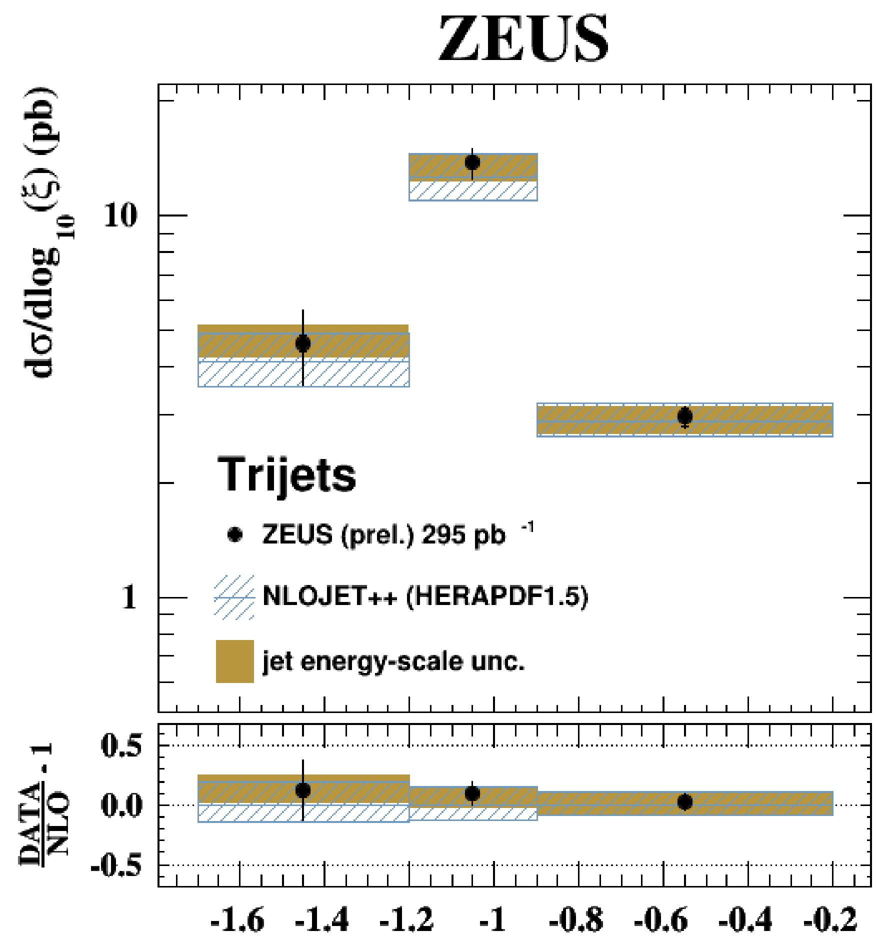
3% for $E_{T,Lab}^{jet} < 10$ GeV

Good agreement of NLO calc. with data, in shape and in normalisation

Trijet Single differential Cross Sections

ZEUS Trijets





Large E_T^{jet}:

Test of Matrix Element in pQCD

High ξ values suppression:

Due to decreasing quark /gluon densities

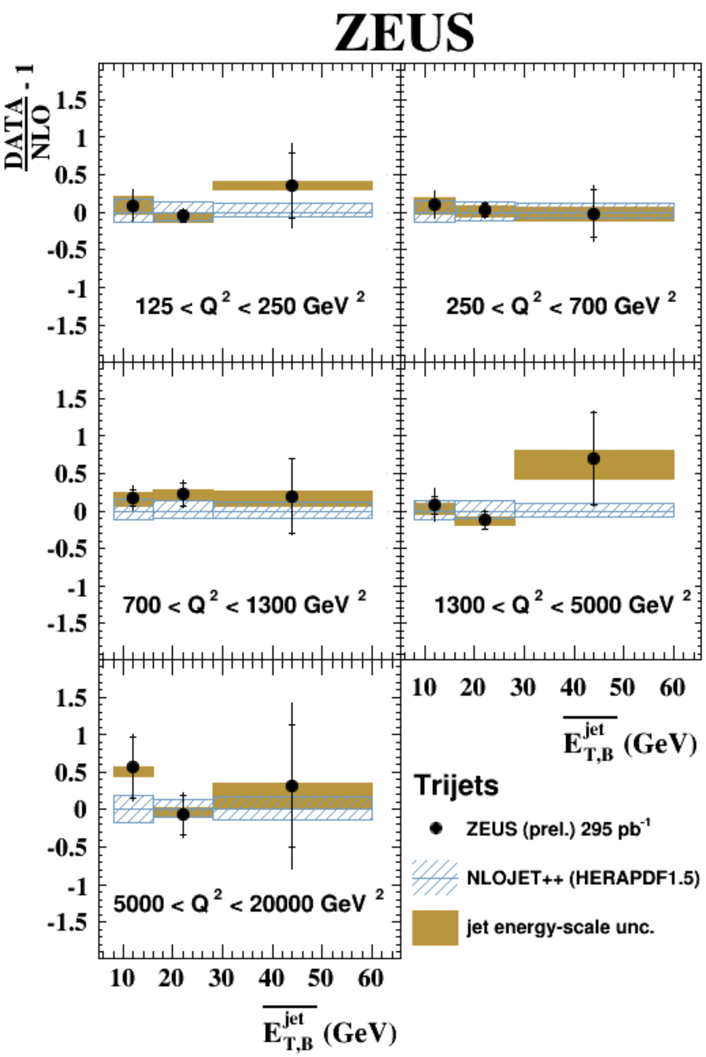
Low ξ values suppression:

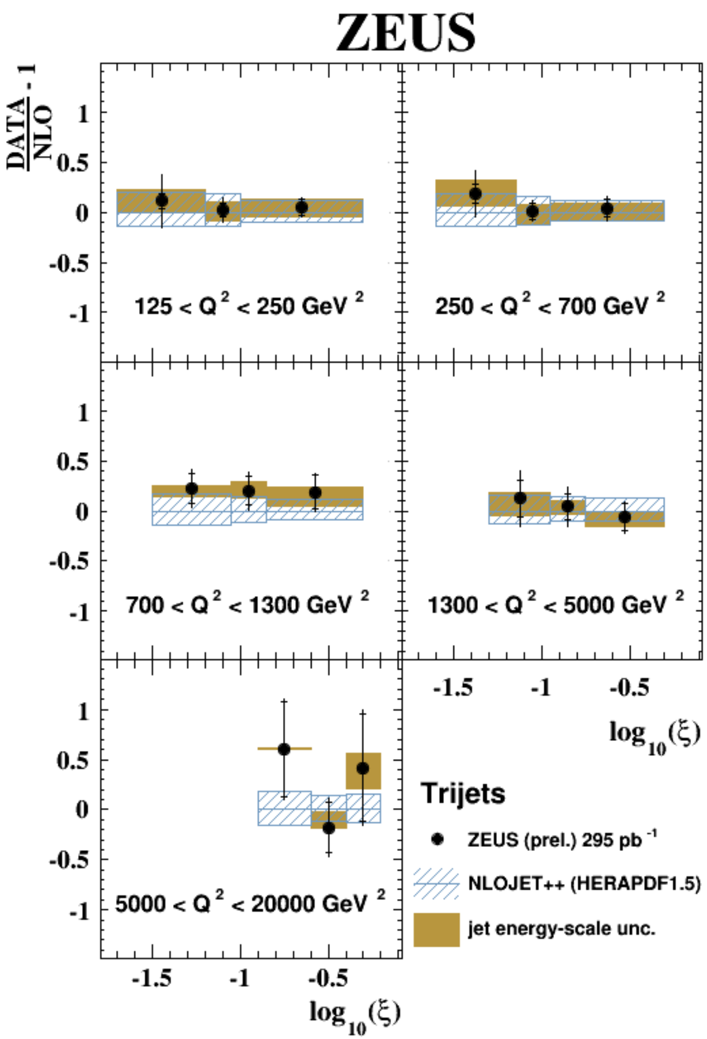
Due to E_T^{jet} selection cuts

NLO calculation agrees well with data, in shape and in normalisation

Trijet Double Differential Cross Sections, Ratios Data/NLO -1

ZEUS Trijets





Data sensitive to strong interaction dynamics and proton structure
Use for α_s extraction and for PDF constraints

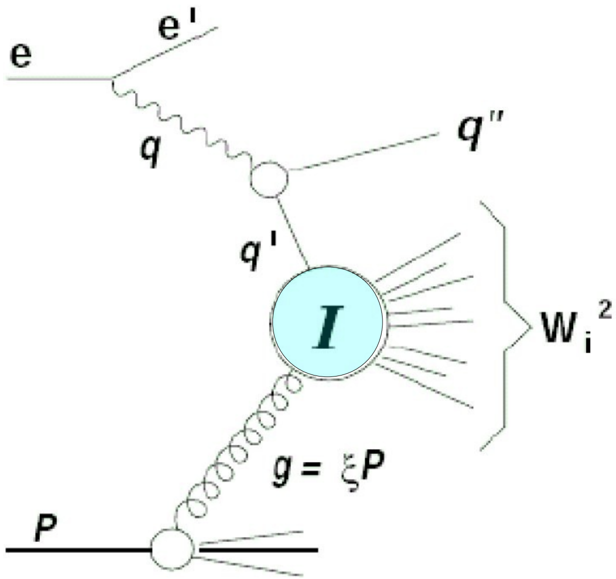
Search for QCD Instanton-Induced Processes in DIS at HERA

H1-Prelim-14-031

H1 QCD Instantons

Instantons

- Induce anomalous processes in Standard Model
- Non-perturbative fluctuations of Gluon field, tunneling between QCD vacua
- Their observation would be an important confirmation of the Non-perturbative QCD part of SM
- Can they be observed at HERA, in quark gluon fusion events ?



Theory says Yes:

- Sizeable cross section predicted, 10-100 pb
- Theory and Phenomenology A.Ringwald, F.Schrempp a.o:

hep-ph/9411217, hep-ph/9609445, hep-ph/9806528, hep-ph/9903039, hep-ph/9909338, hep-ph/9911516, Hep-ph/0012241, hep-ph/0109032

H1 and ZEUS searches:

- early HERA I data
- No signal seen
- Upper limits
- Compatible with Theory predictions

H1:
DESY 02-062, hep-ex/0205078
ZEUS :
DESY 03-201, hep-ex/0312048

Predicted Cross Section:
- Much smaller than Standard DIS cross section
- Key Issue of Search: Suppress Standard DIS Background!
  ==> Use Topology differences

Predictions for Topology:
- Hard "current" jet
- Instanton-band
  - High Multiplicity
  - Isotropy in I rest frame
  - Parton "democracy" u,d,s (strange particles !)

A.Ringwald, F.Schrempp:
- QCDINS hep-ph/9911516
  - MC Event generator
  - Full Event topology
  - Suggested Phase Space

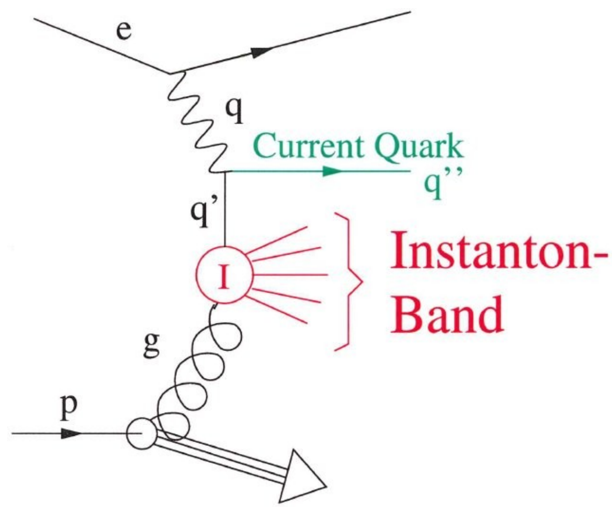
$x_{Bj} > 0.001 \quad 0.1 < y < 0.9$

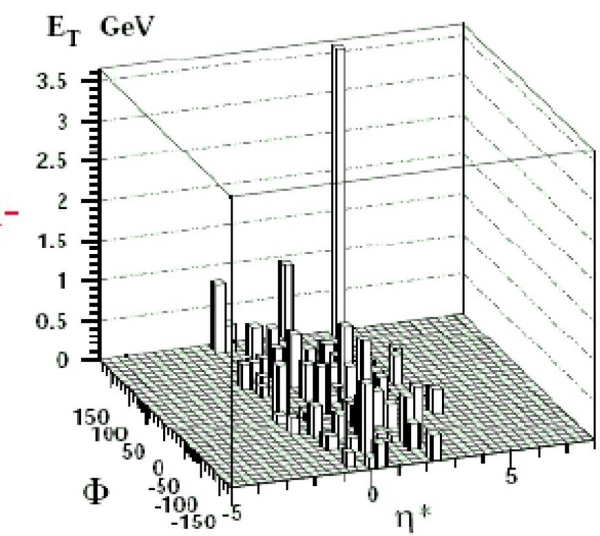
$Q^2 > Q'^2_{min} \approx 113\ \text{GeV}^2 \quad x' > 0.35$

Variables of I-Subprocess

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

$$x' = Q'^2/(2g \cdot q')$$



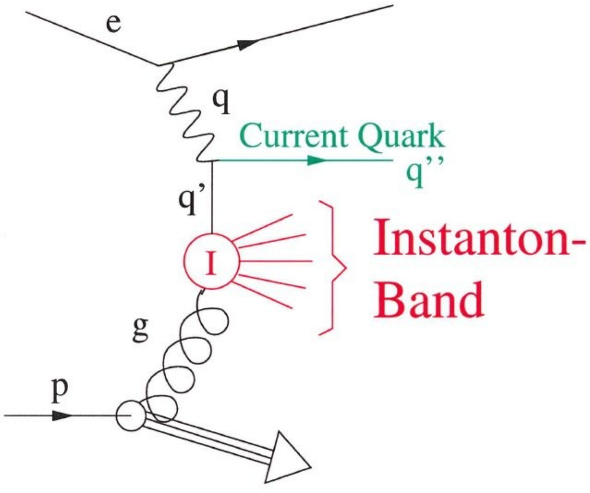


HERA II data:

$358\ pb^{-1}$ (17x larger than in previous search)

DIS Selection:

$$150 < Q^2 < 15000\ \mathrm{GeV}^2; \quad 0.2 < y < 0.7$$



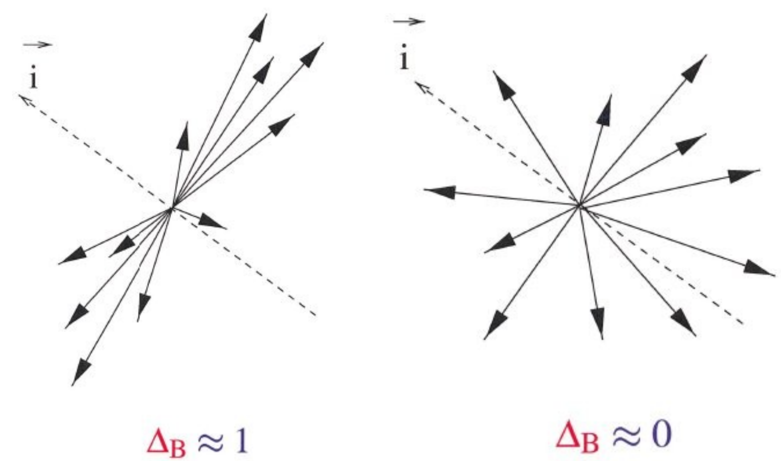
QCD Instanton search strategy

- Find hardest jet ("Current Jet")
  (k_T algorithm in Hadronic CMS)
- Remove Current jet from HFS objects
- Boost remaining objects to I-band CMS
  - Charged Multiplicity n_B
  - Transverse Energy of "band" $E_{T,B}$
- Topological variables
  - E_{IN}, E_{OUT}, $E_{T,Jet}$
  - Isotropy Δ_B
  - Sphericity,
    Fox-Wolfram moments

$$\Delta_B = (E_{IN} - E_{OUT})/E_{IN}$$

$$E_{IN} = \sum_h |\vec{p}_h \cdot \vec{i}_{max}|$$

$$E_{OUT} = \sum_h |\vec{p}_h \cdot \vec{i}_{min}|$$



MultiVariate Analysis

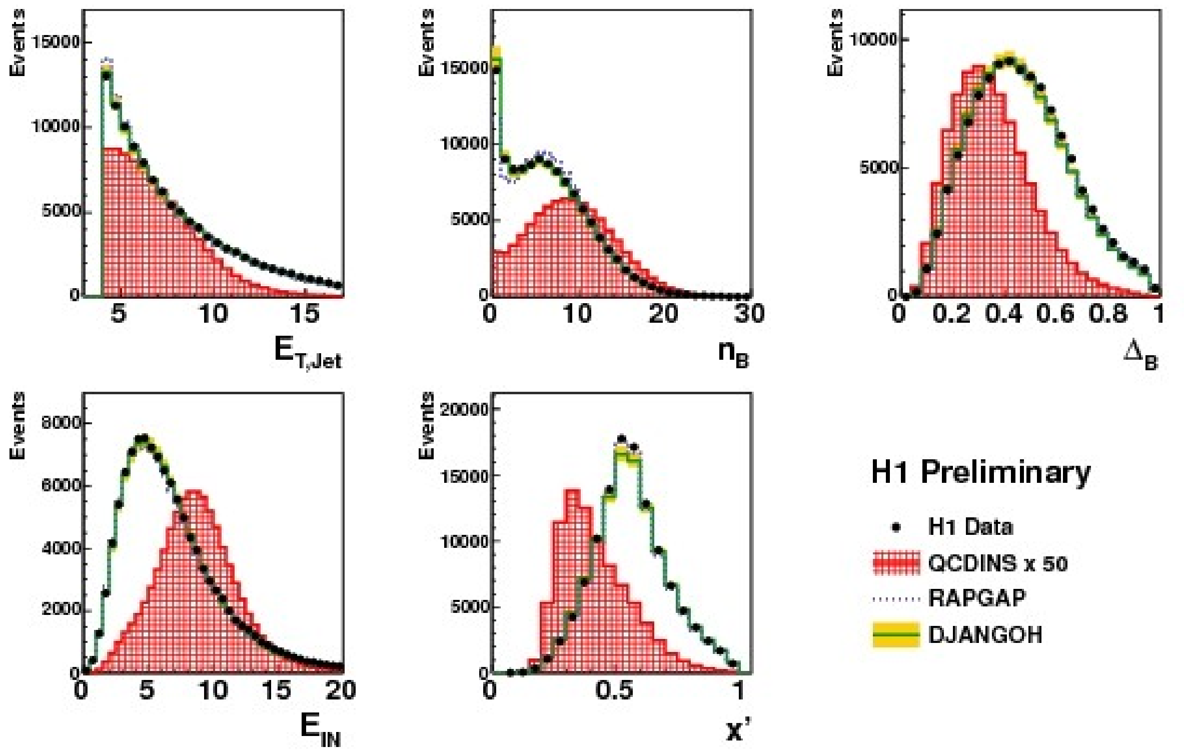
Use PDERS method and TMVA
(Probability Density Estimator with Range Search)

Select 5 observables

- with good S/B separation
- with reasonable background description

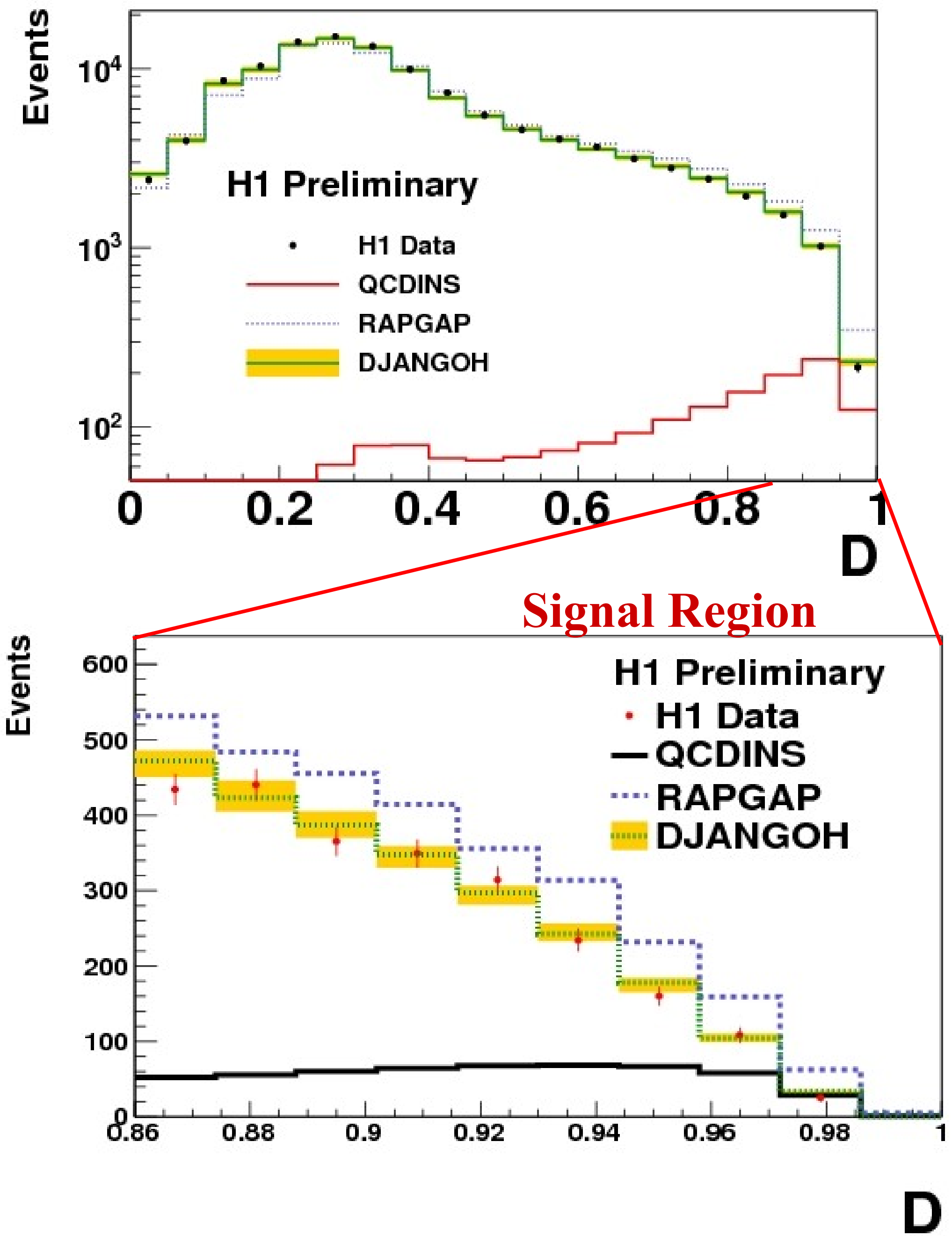
Training with

QCDINS (Signal)
DJANGOH / RAPGAP (Bkgr)
(In the further analysis, only DJANGOH used)



From these 5 observables, form the Discriminator

PDERS Discriminator distribution



Good Discriminator Description in background region
==> Signal region D > 0.86
(Gives smallest statistical error for a hypothetical Instanton signal)

Good description of Data by DJANGOH in both regions

The expected Instanton signal, > 500 events, is not seen

Theory prediction:

$$\sigma_{QCDINS} = 10 \pm 2 \text{ pb}$$

Thus:
no Signal, get Upper Limit

Upper Limit calculation, CLs method

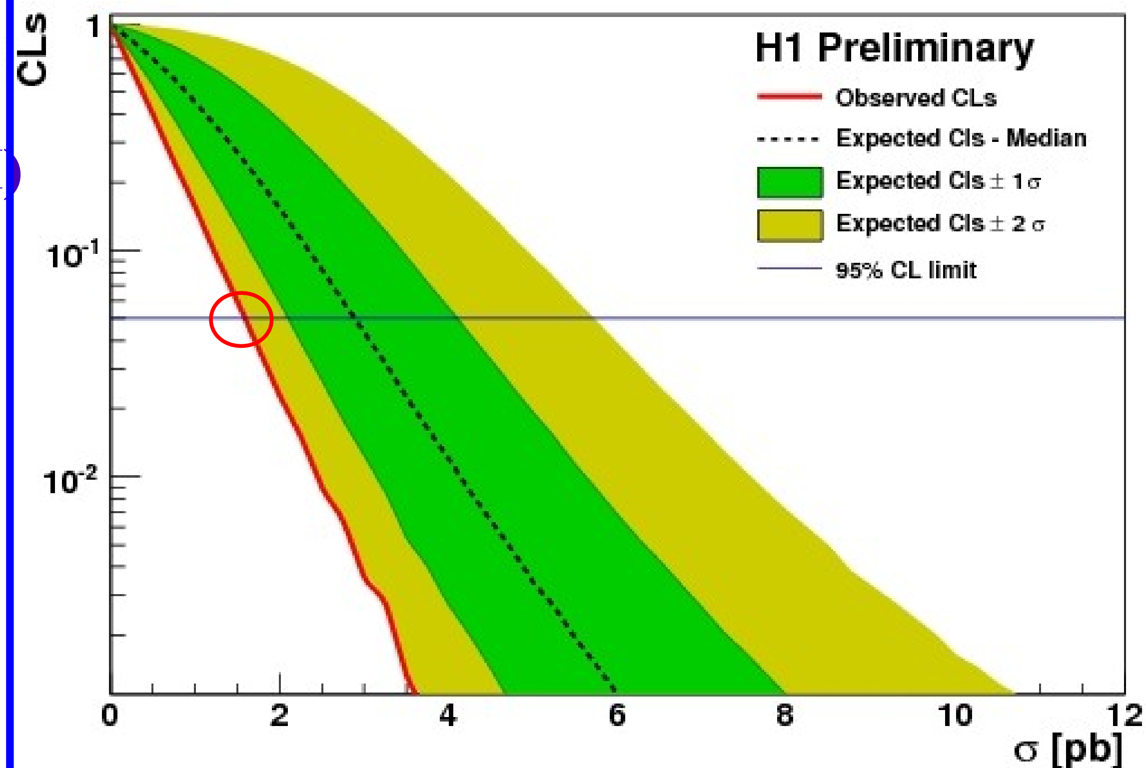
- CLs vs. Signal cross section: from toy MC experiments
  - Background only (DJANGOH)
  - Signal + Background

- Upper Limit Conf. Level given by 1 - CLs

- Expected CLs-Median Limit: (Background Only hypothesis)

$$2.9^{+1.2,+2.8}_{-0.8,-1.3}\ \text{pb} \text{ at 95\% C.L.}$$

- Observed Upper Limit **1.6 pb** at 95% C.L.
  (lower than Median Expectation, due to downward fluctuation in data)



The Ringwald / Schrempp Prediction for this Phase Space:

$$\sigma_{QCDINS} = 10 \pm 2\,\text{pb}$$

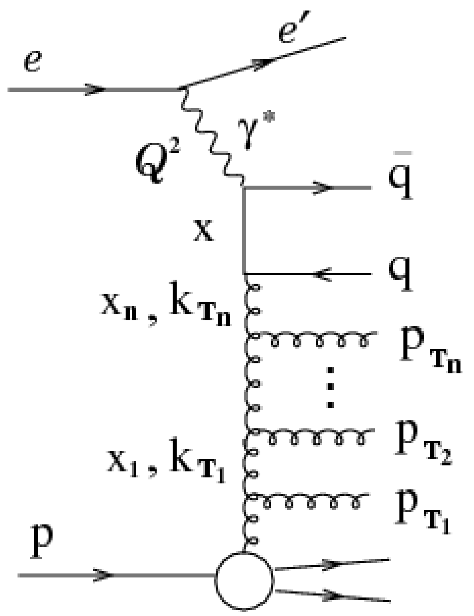
Seems to be excluded

Measurement of Charged Particle Spectra in *ep* DIS at HERA

DESY 13-012, arXiv:1302.1321
EPJ C73 (2013) 2406

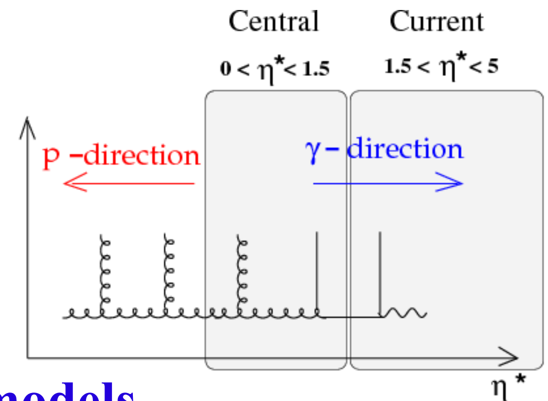
Charged Particle Spectra in DIS at HERA

Hadron production in DIS:
- Transverse Momentum
  - At Low p_T
    Constraints on Hadronisation parameters
  - At High p_T
    Sensitive to dynamics of Parton Evolution
    (since high p_T disfavored by strong p_T ordering)



Hadronic CMS:
Look at 2 regions*
in the γ-hemisphere $\eta^* > 0$
- Central region
  $0 < \eta^* < 1.5$
  Sensitivity to Parton Shower models
- Current region
  $1.5 < \eta^* < 5$
  Sensitivity to hard scatter

*Target region (p-remnant), i.e. $\eta^* < 0$ is not accessible in this analysis



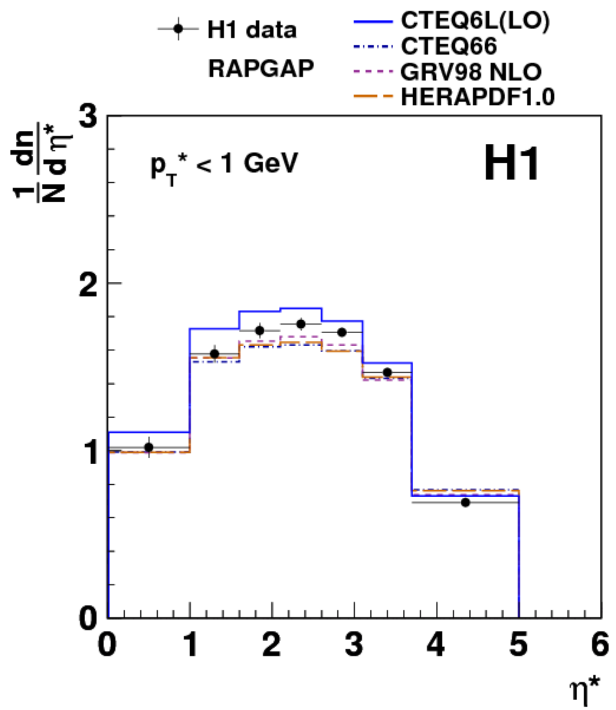
$-2 < \eta < 2.5$ $p_T > 150$ MeV	LAB
$0 < \eta^* < 5$ $0 < p_T^* < 10$ GeV	HCMS

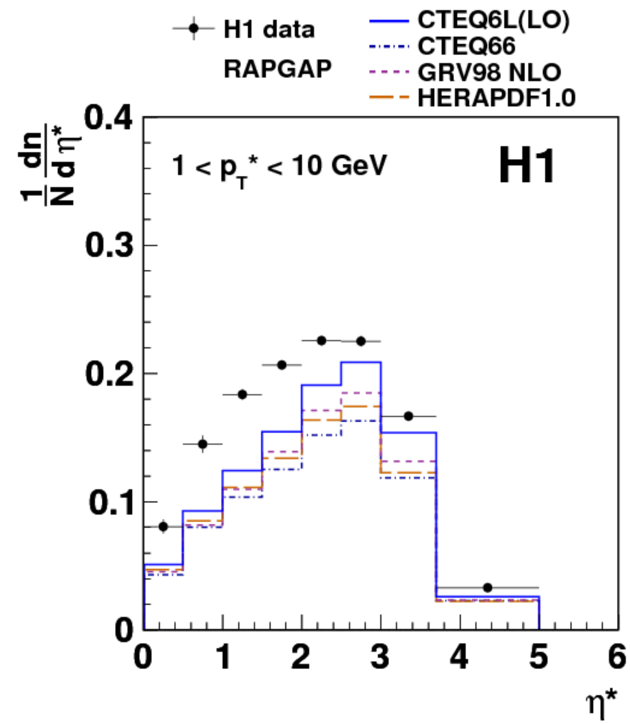
H1 at HERA II
$88.6\ \mathrm{pb}^{-1}$ (2006 data)
$5 < Q^2 < 100\ \mathrm{GeV}^2$
$0.05 < y < 0.6$

Charged Particle Densities as functions of η^* and p_T^* differential in Q^2 and x_{Bj}

η* dependence in Low and High p_T* regions

H1 Charged Particle Spectra





Low p_T* region:

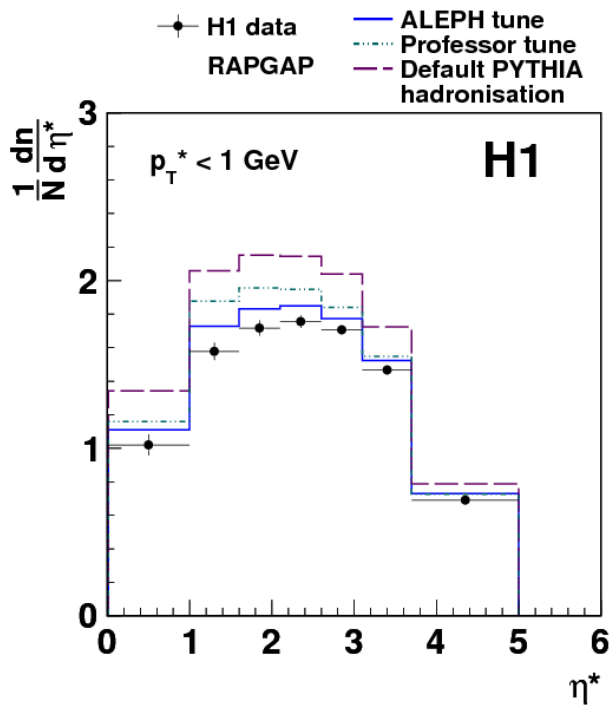
- Flat plateau in η*
  Decrease at low values due to acceptance
- RAPGAP (DGLAP-like) describes data well
- Different PDFs
  Only small differences

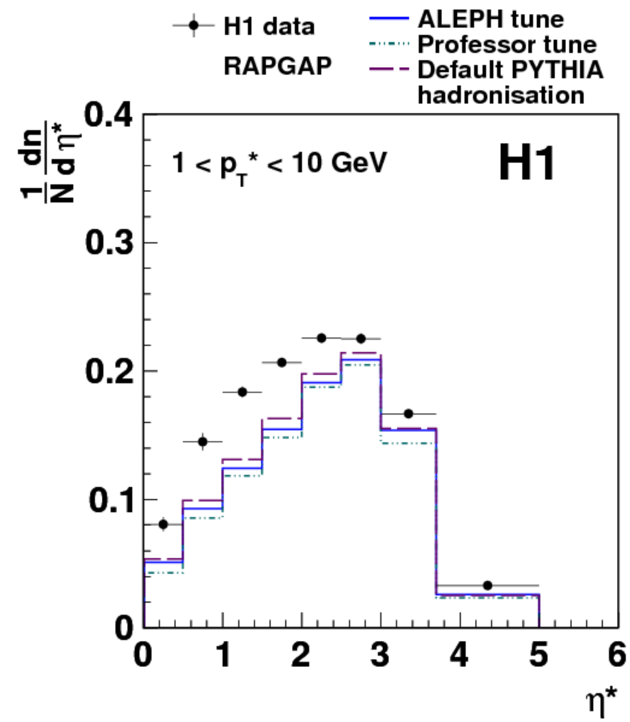
High p_T* region:

- Density increase towards photon direction, as expected from strong p_T ordering
- RAPGAP below data
- Differences larger among PDFs

η* dependence in Low and High p_T* regions

RAPGAP with 3 different sets of hadronisation parameters





Low p_T* region:

- Considerable differences between different parameter sets
- The LEP tuning (ALEPH) describes the data best

High p_T* region:

- Only small differences between different parameter sets
- No set is able to describe data

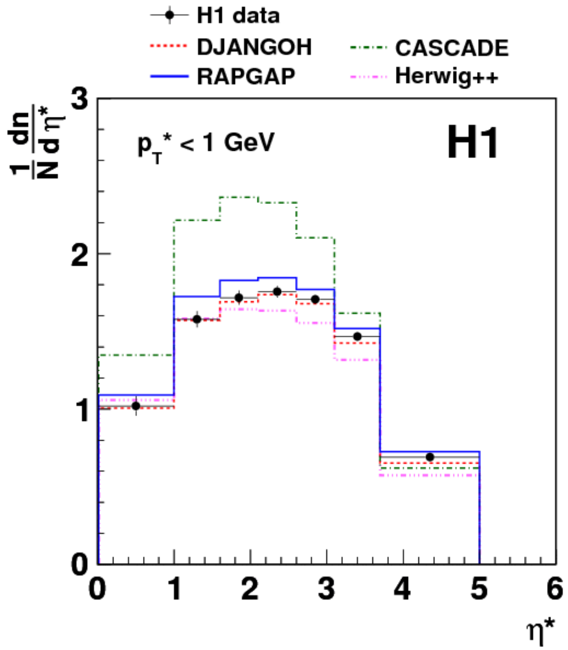
Parton Shower Model Dependence

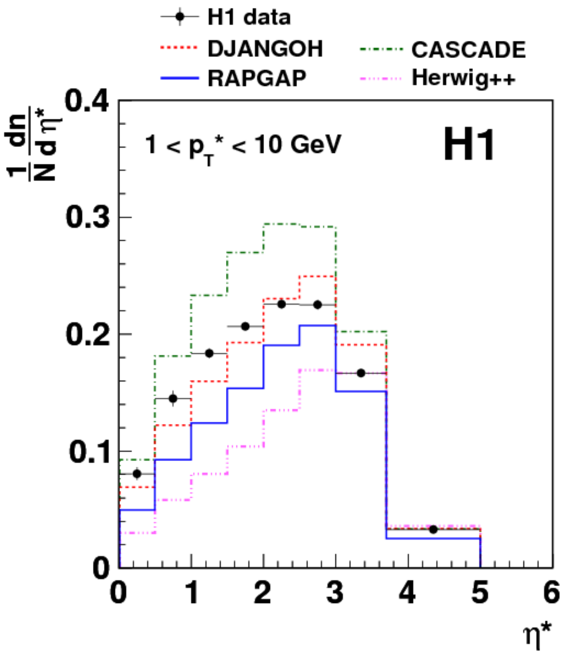
DJANGOH: PS from CDM (ARIADNE)

RAPGAP: Collinear PS, virtuality ordered

CASCADE: angularly ordered, CCFM PS

HERWIG++: Collinear PS, angularly ordered





Low p_T^* region:

- CASCADE fails description
- Other models describe data

High p_T^* region:

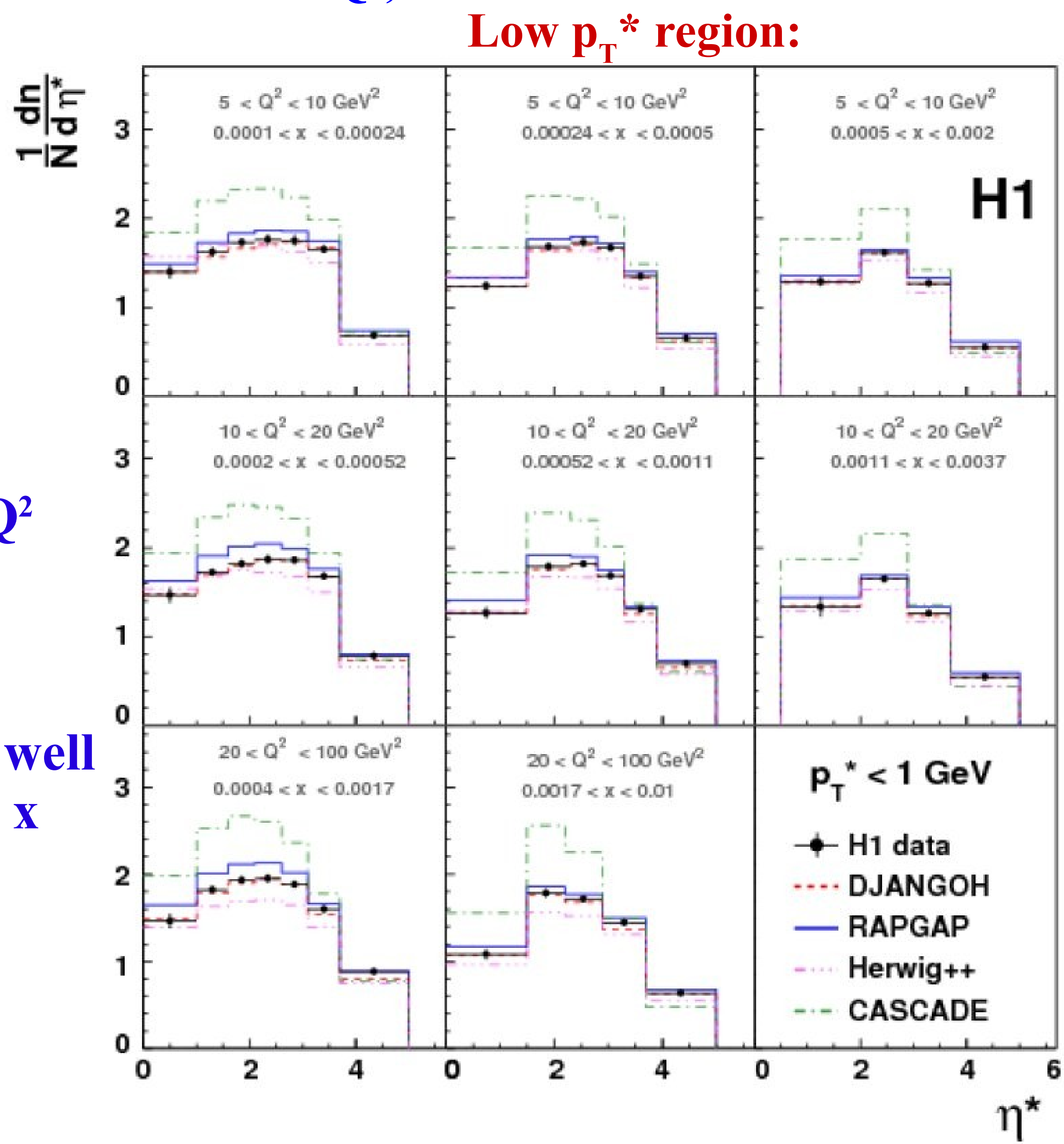
- CDM (DJANGOH) Best description

RAPGAP, HERWIG++ Below data

CCFM (CASCADE) above data

Low p_T* region: η* dependence in bins of Q^2, x

H1 Charged Particle Spectra



- Plateau at 1.6 < η* < 4.0
  Shrinks with increasing Q^2

- All models,
  except CASCADE,
  describe data reasonably well
  over full range of Q^2 and x

High p_T* region: η* dependence in bins of Q^2, x

H1 Charged Particle Spectra

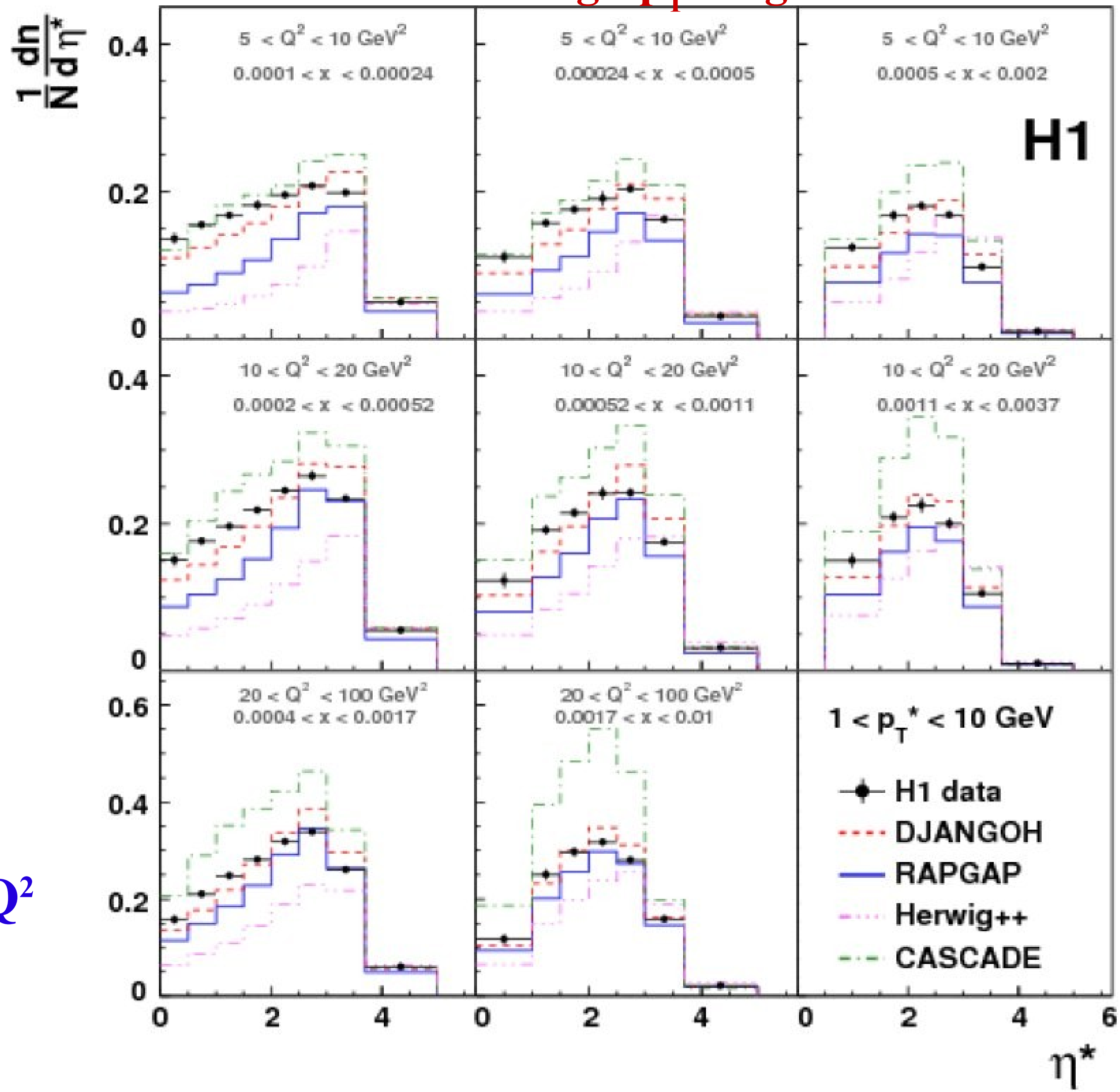
High p_T* region:

- No model with good description in full range

- CDM (DJANGOH) Best description

- RAPGAP, HERWIG (collinear PS models) Fail at low Q^2, get better at higher Q^2

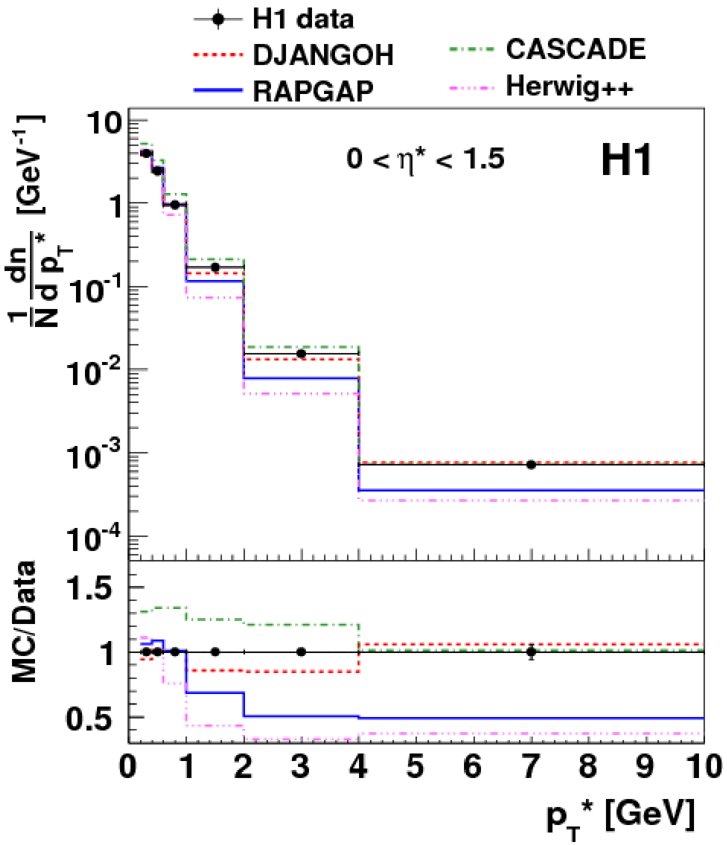
- CCFM (CASCADE) OK at low x and low Q^2 Fails at large Q^2

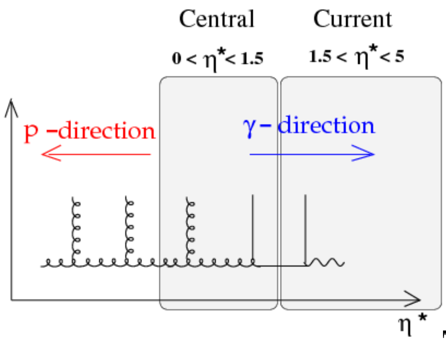


p_T* dependence in Central and Current regions

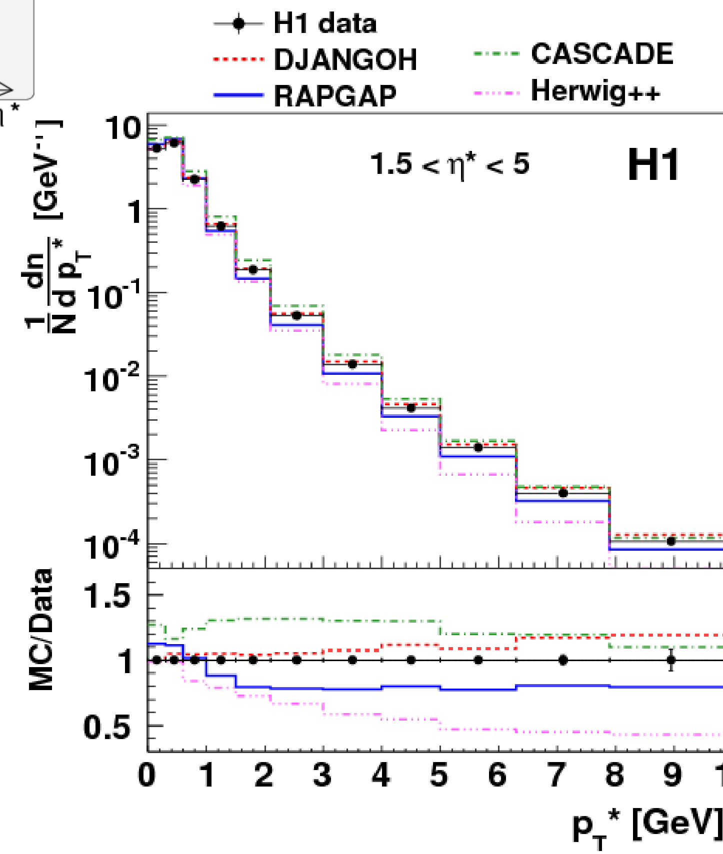
H1 Charged Particle Spectra

Central region
$0 < \eta^* < 1.5$





Current region
$1.5 < \eta^* < 5$



Sensitivity to higher order radiation

Sensitivity to hard scattering

Collinear PS models (RAPGAP, HERWIG++) fail, particularly at high p_T*

SUMMARY

- The Hadronic Final State, in NC DIS at HERA:
  New Results from H1 and ZEUS, using high statistics HERA II data

Multijet Cross Section Measurements from H1 and ZEUS

- Double Differential Jet Cross Sections, in Q^2, P_T^{jet} and ξ

  H1: Inclusive Jets, Dijets and Trijets, ZEUS: Trijets

- Good description of data by NLO pQCD calculations
- Experimental Precision of Jet measurements better than NLO Precision

  NNLO calculations for Jets needed !

- H1: Most precise $\alpha_S(M_Z)$ extraction (so far) from Jet measurements,

$$\alpha_s(M_Z) = 0.1165\,(8)_{exp}\,(38)_{pdf,theo.}$$

- α_S runs, in agreement with RGE and with other Jet Data results

H1: Search for QCD-Instanton Induced Processes

- No signal found, Upper Limit $\sigma_{\text{Instanton}} < 1.6$ pb, 95% C.L.
- Ringwald / Schrempp prediction: 10 +/- 2 pb Seems to be excluded

H1: Charged particle Spectra Measurements

- Particle Densities as function of p_T^* and η^*, differential in Q2, x
- Enable extensive tests of Hadronisation and Parton Shower Models

Backup

Upper Limit calculation, CLs method

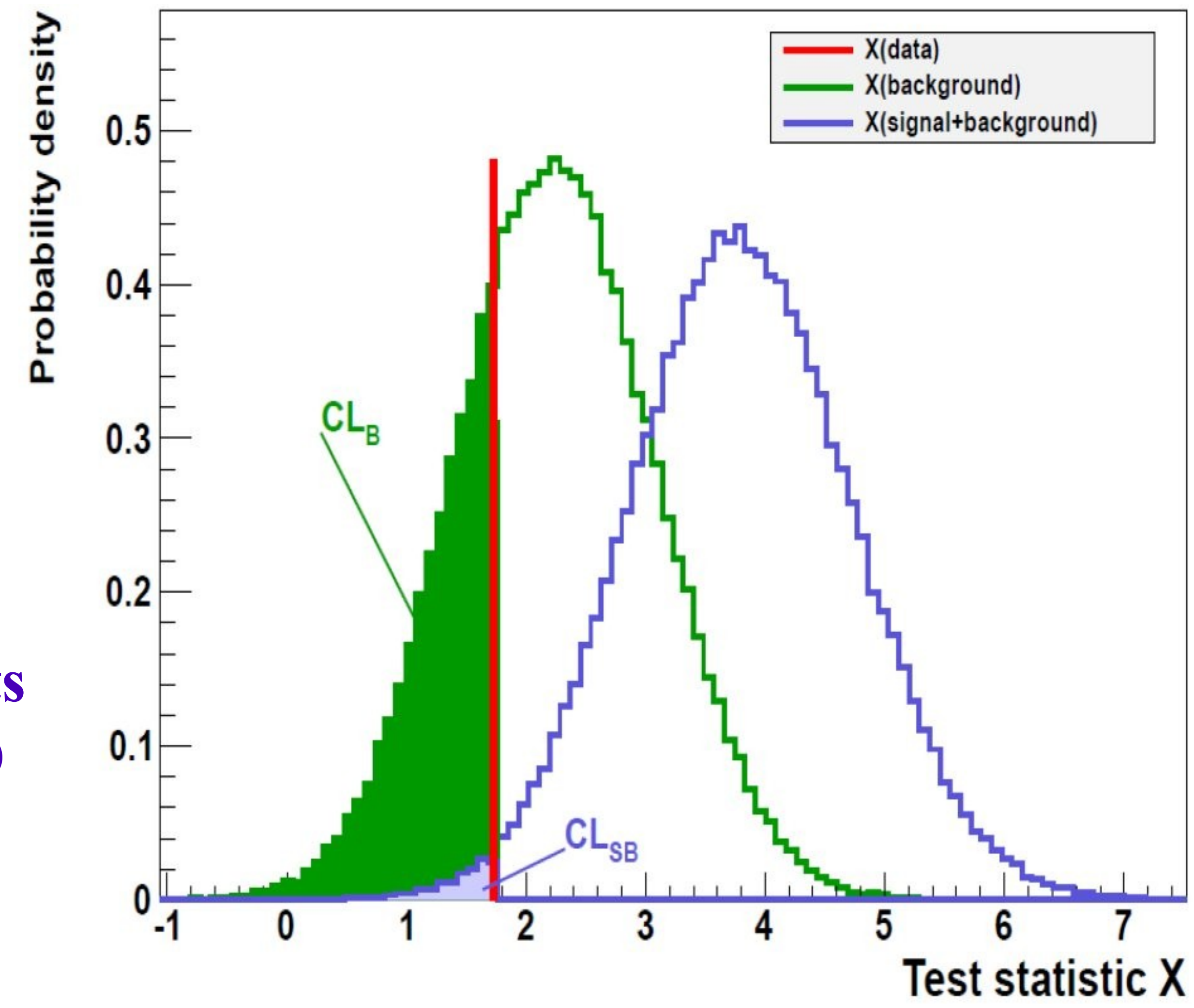
- Test Statistics

$$X = \sum_{i=1}^{N_{bin}} w_i n_i$$

Sum over all bins in D

- For better sensitivity, use full D range (0 - 1)

- Perform toy MC experiments
  - Background only (DJANGOH)
  - Signal + Background



$$CL_S = CL_{SB}/CL_B$$

Upper Limit Confidence Level: $1 - CL_S$