New Frontiers in Physics
ICNFP 2015

Recent HERA results on hard QCD and heavy flavour production

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On behalf of the H1 and ZEUS Collaborations

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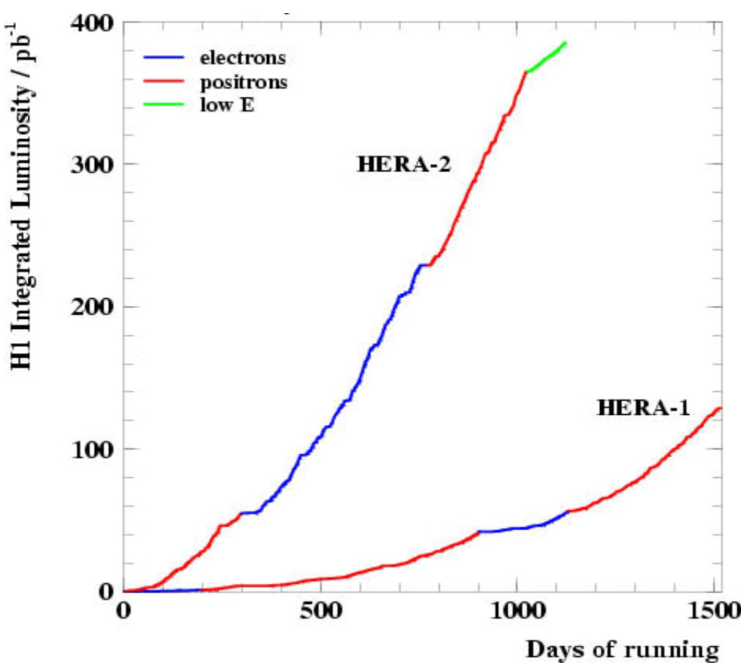
HERA

HERA: world's only $e^{\pm}p$ collider

Energies: $E_{e\pm}$ = 27.6 GeV E_p = 460-920 GeV
centre-of-mass energy: $\sqrt{s}$ = 225-319 GeV

Integrated luminosity: ~0.5 fb^{-1} (per experiment)



Two running periods:

1994-2000 : HERA I

2003-2007 : HERA II

Physics topics' outline

Multijets and determination of strong coupling constant

H1 ***EPJ C75 (2015) 2, 65***

Charm & beauty

- $D^{*+/-}$ measurements

- quark mass measurements

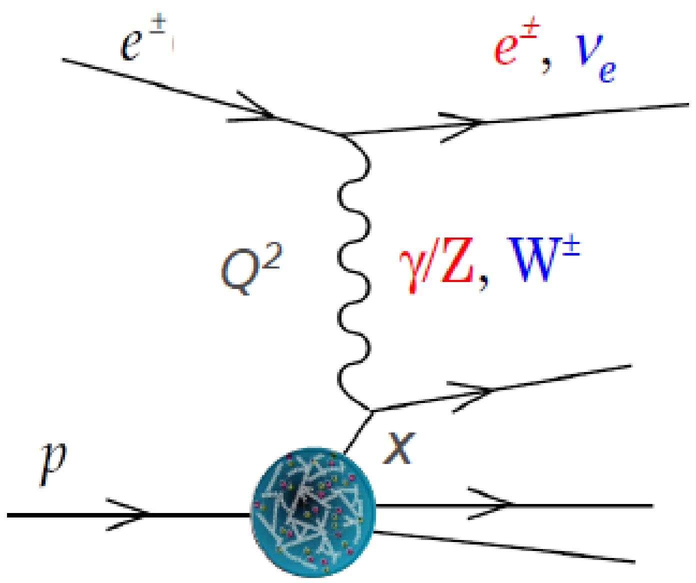
H1+ZEUS ***EPJ C73 (2013) 2311***
hep-ex 1503.06042

ZEUS ***JHEP 09 (2014) 127***
JHEP 10 (2014) 003

QCD Instantons

H1prelim-15-031

Introduction



Kinematics:

Q^2 - virtuality of exchanged boson

x – Bjorken scaling variable

y – inelasticity

$Q^2 = sxy$ ($\sqrt{s}$ centre-of-mass energy)

Neutral Current (NC): ep→eX **Charged Current (CC): ep→υX**

Photoproduction (PHP): $Q^2 \approx 0$ GeV^2

Deep Inelastic Scattering (DIS): $Q^2 > 1$ GeV^2

Multi-jets and strong coupling α_S determination

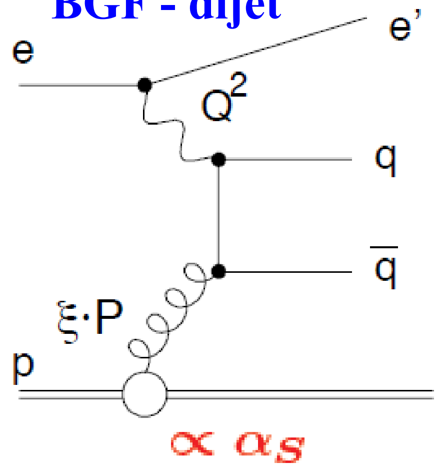
Jet production in NC DIS

k_T anti-k_T jet algorithms

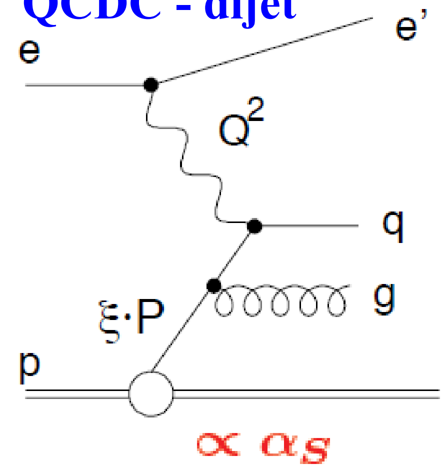
proton's longitudinal momentum fraction:

$\xi = x_{Bj}\,(1 + M_{jj(j)}^2/Q^2)$

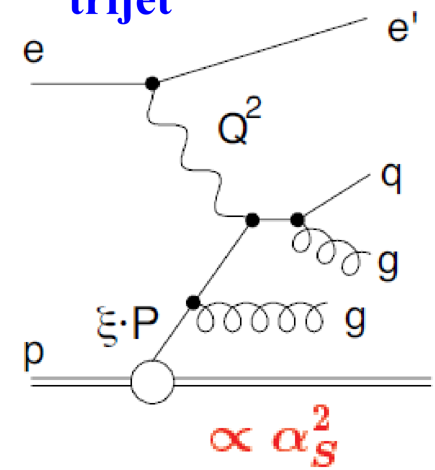
BGF - dijet



QCDC - dijet

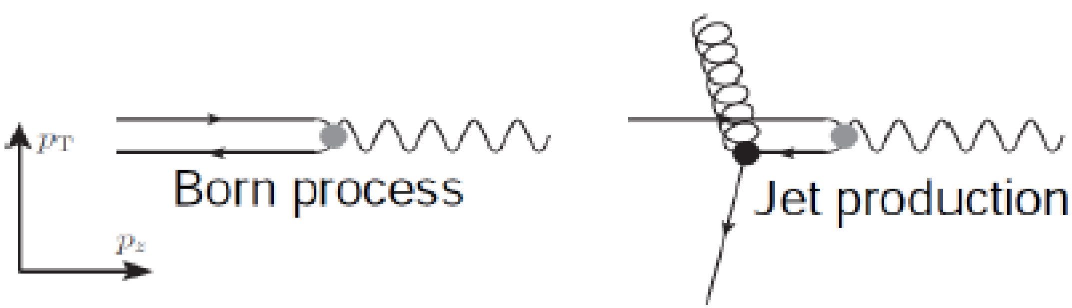


trijet



H1 measurements performed in *Breit frame: $2xP + q = 0$*

→ virtual boson collides head on with the parton from proton



Inclusive jets: **measure transverse jet's momentum**

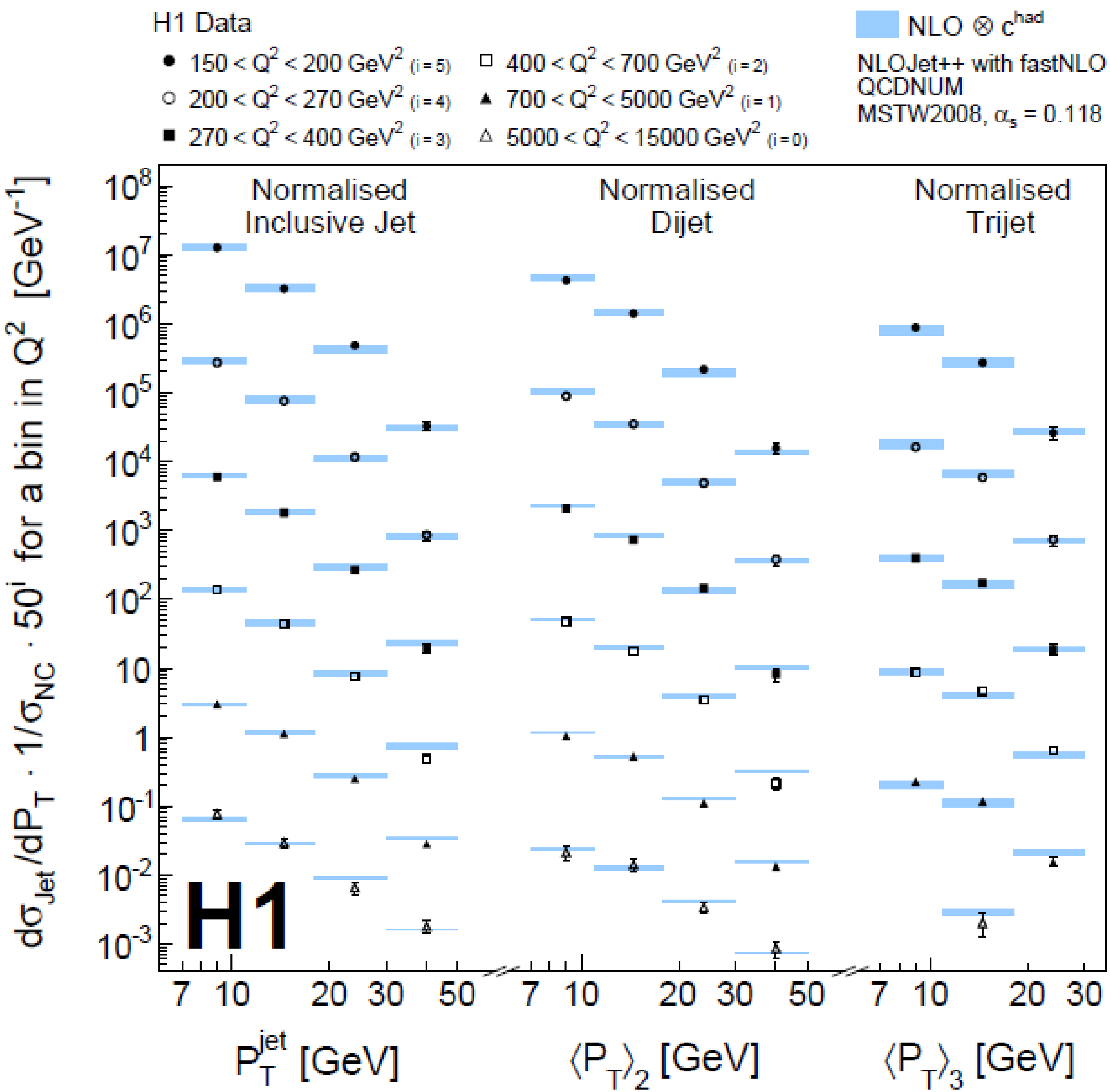
Dijets/trijets: **average P_T of two/three leading jets**

In Breit frame only hard QCD process can generate significant P_T

Direct sensitivity to α_s and gluon PDF

Eur. Phys. J. C75 (2015) 2, 65

H1 high Q^2 Multi-Jets Results



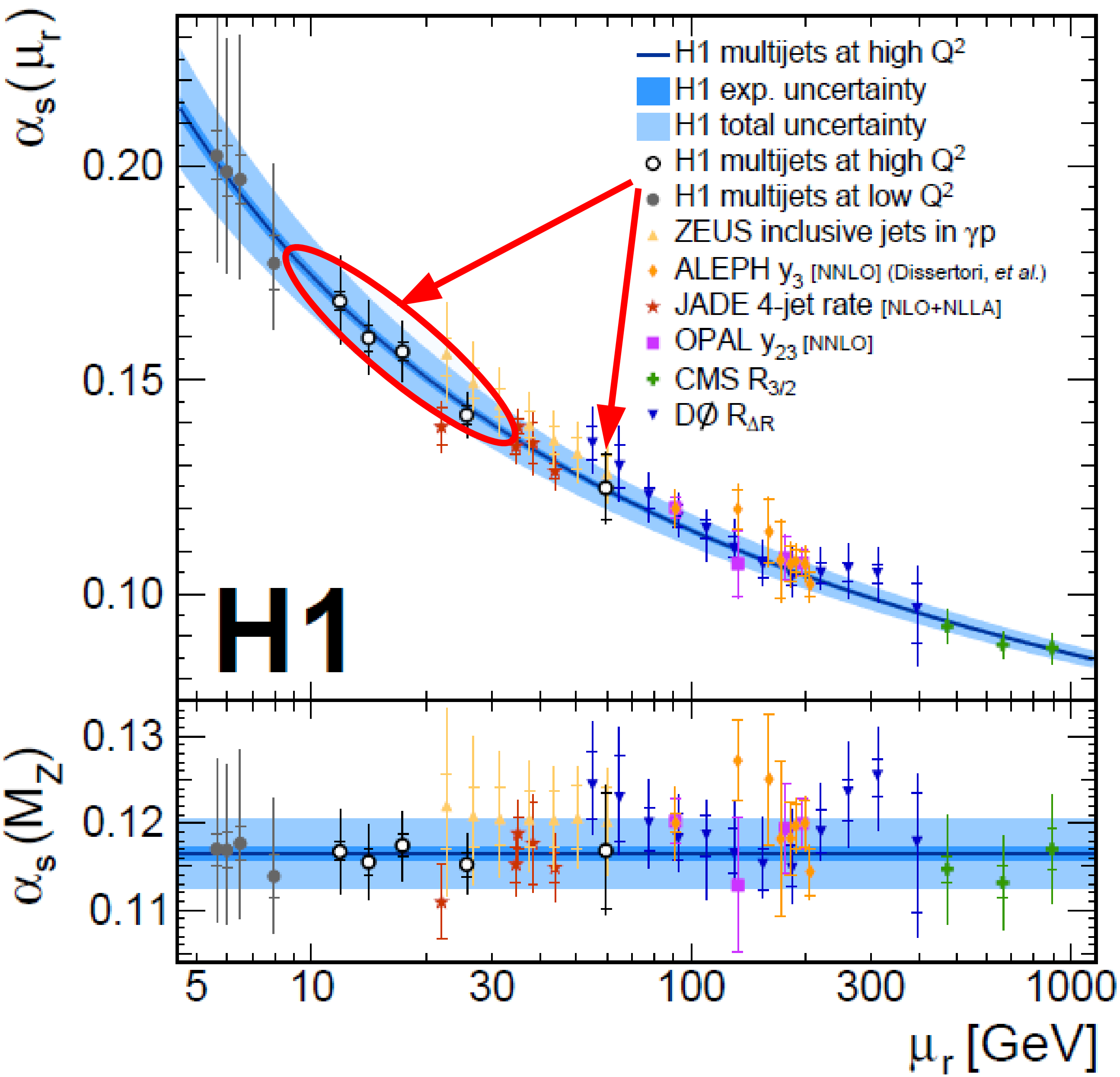
Experimental measurement:

- inclusive, dijet and trijet cross sections

- normalised inclusive, dijet and trijet cross sections (w.r.t. inclusive NC DIS)
Partial cancellation of experimntal uncertainties

NLO QCD predictions, corrected for hadronisation and electroweak effects, in good agreement with data within uncertainties

The determination and running of α_S



From normalised multijet:

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

The most precise measurement from jet cross sections so far

Running of strong coupling:

Consistent with other jet data

Agreement with theory prediction for more than two orders of magnitude

Better than CMS results on inclusive jet measurements

arXiv:1410.6765

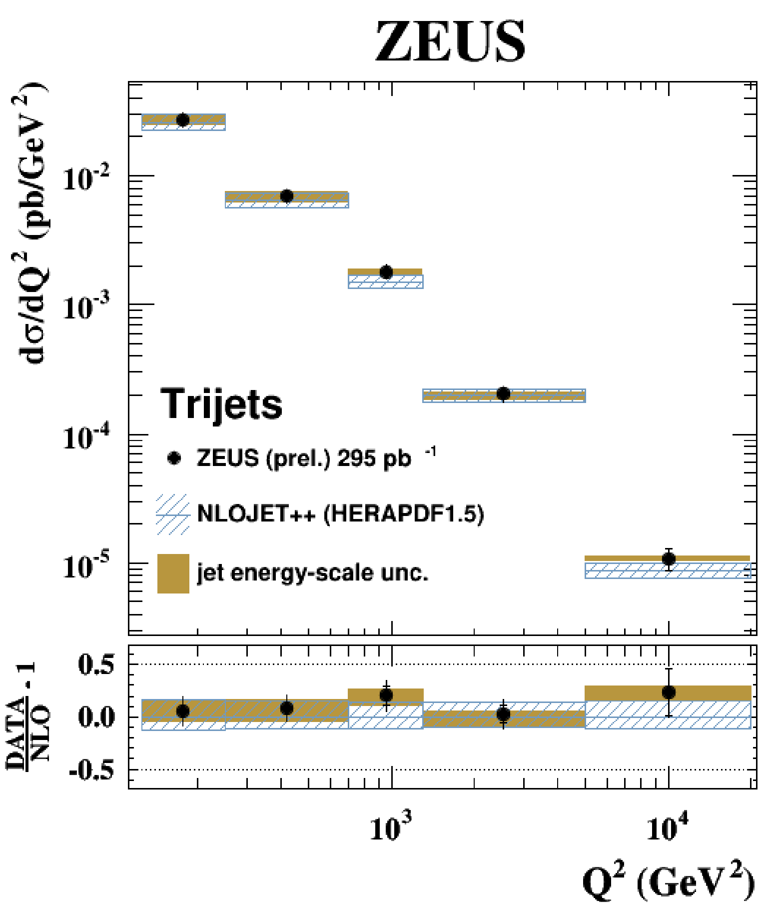
ZEUS trijet measurements

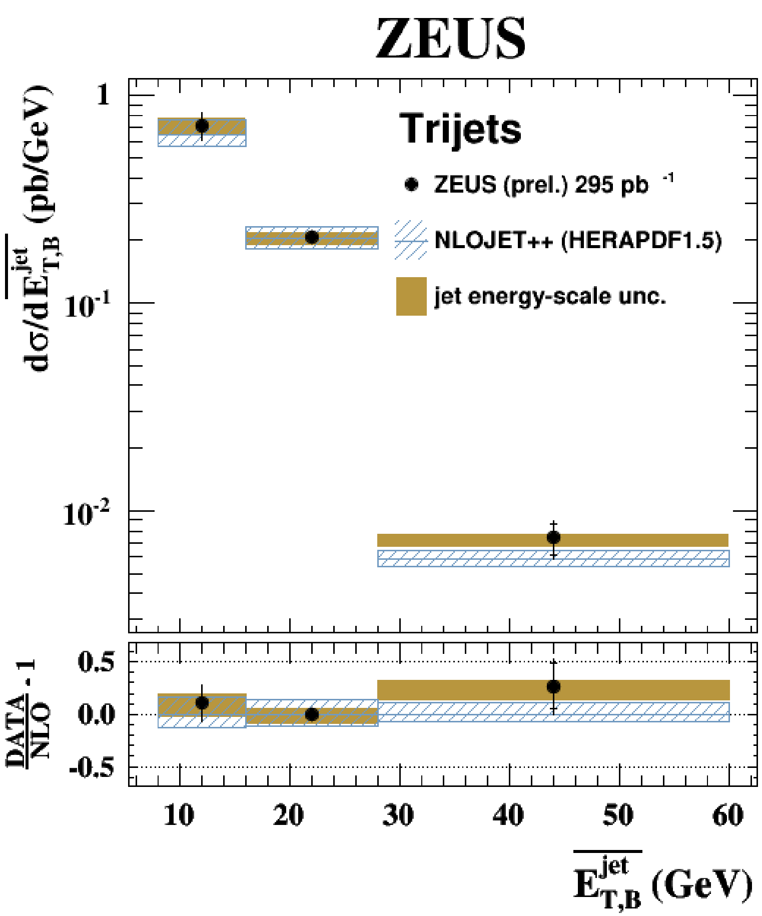
Phase space: $125 < Q^2 < 20000$ GeV^2
$0.2 < y < 0.6$

- At least three jets with $E_{T,B}^{jet} > 8$ GeV and $-1 < \eta_{LAB}^{jet} < 2.5$
- $M_{jj} > 20$ GeV

Prediction: NLOJet++

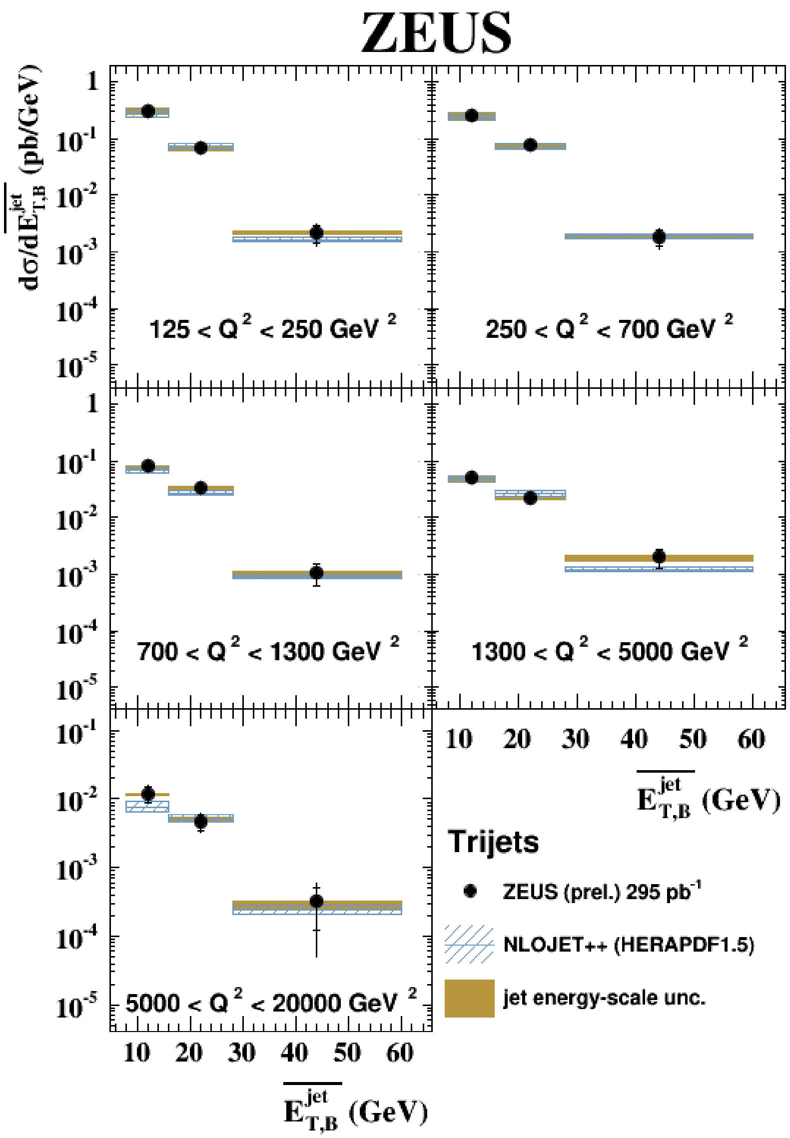
- pPDF: HERAPDF1.5
- $\mu_R^2 = Q^2 + \langle E_t^{jet} \rangle^2$
- $\mu_f^2 = Q^2$

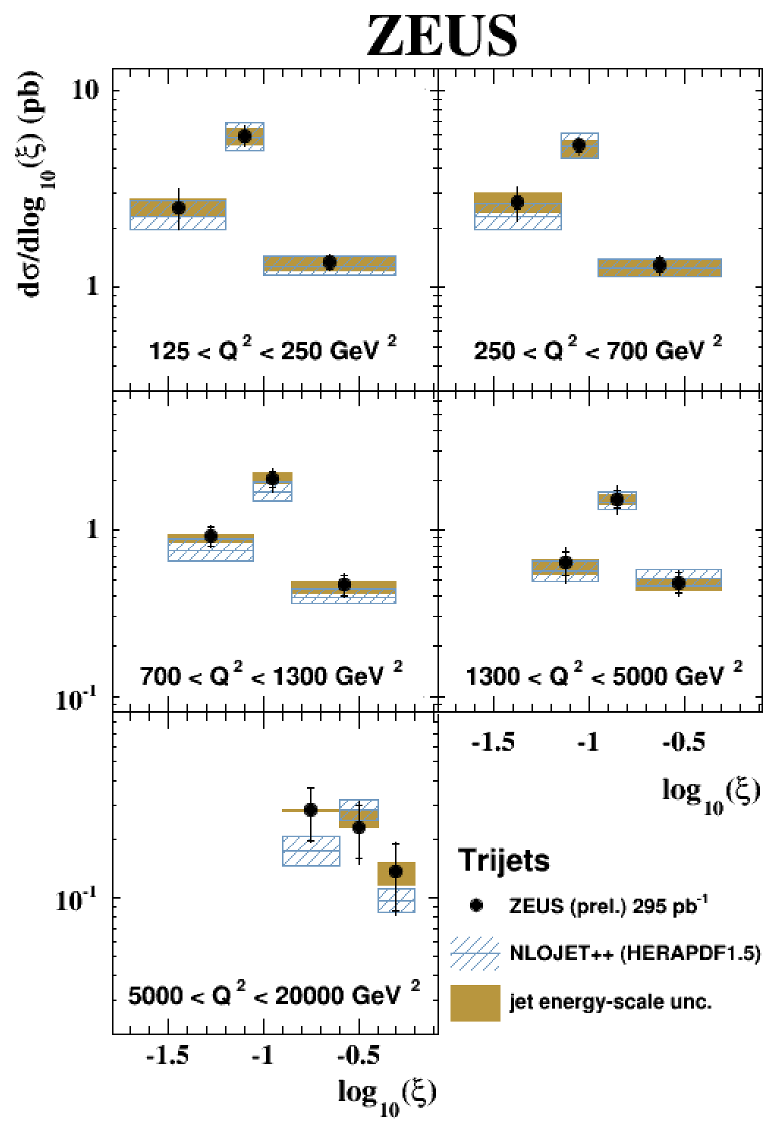




ZEUS trijet measurements

Double differential cross sections





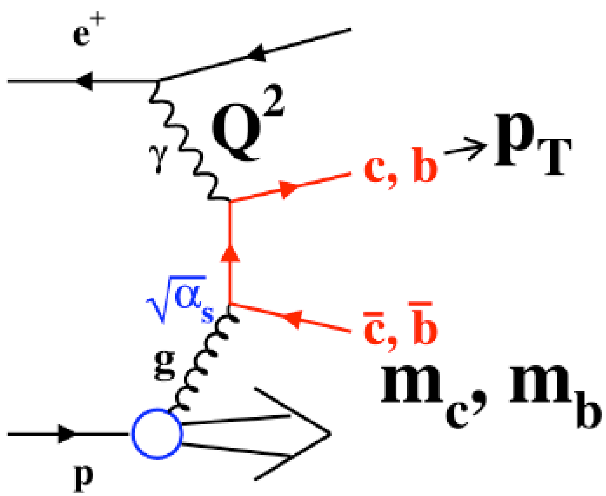
Good agreement between data and NLO calculations

Charm & beauty

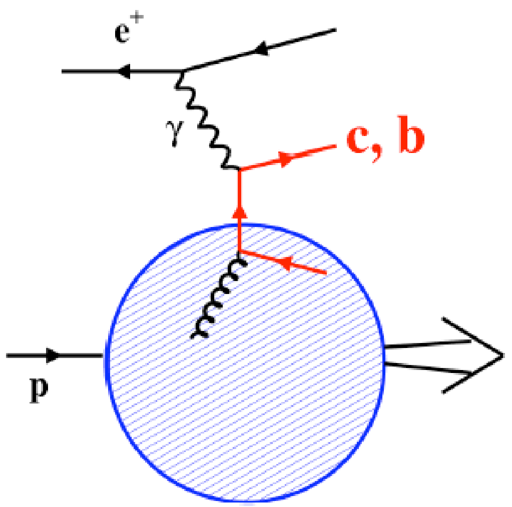
$D^{*+/-}$ PHP/DIS and charm mass measurements

Beauty production in DIS

Heavy quarks production and masses



Massive scheme (FFNS)



Massless scheme (ZM-VFNS)

FFNS: Fixed Flavour number scheme
Expected to be valid for $Q^2 \approx m_{c/b}^2$
Three active flavours in proton
One can calculate differential cross sections (i.e. HVQDIS)

Zero-mass variable flav. number scheme
Expected to be valid for $Q^2 >> m_{c/b}^2$
c or b treated as massless parton
Resummation of large logarithms of Q^2/m_q^2

Mixed scheme (GM-VFNS)

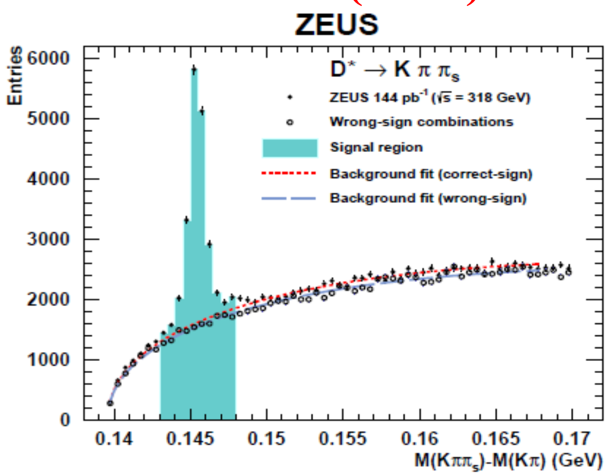
Employ both FFNS and ZM-VFNS
Interpolation in between (various schemes)
Used in PDF fits – useful at LHC

D* PHP cross sections

JHEP 10 (2014) 003

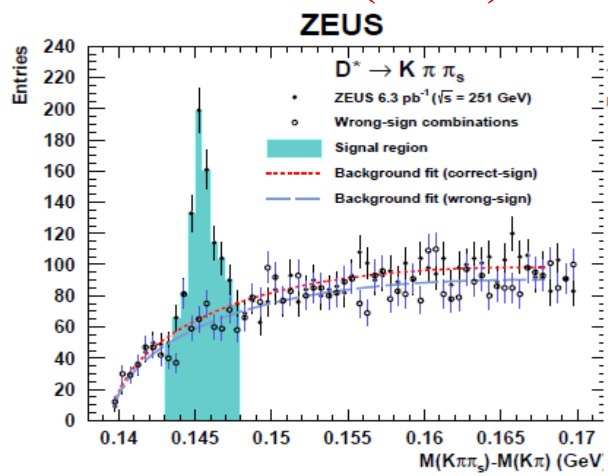
Clear $D^{*+/-}$ signals seen in $M(K^-\pi^+\pi_s^+)$ - $M(K^-\pi^+)$ distributions at 3 different CM energies:

$\sqrt{s}$ = 318 (HER)



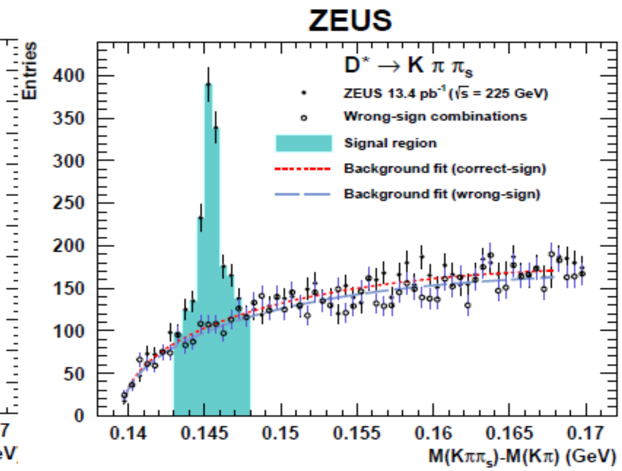
HER: $\mathcal{L} = 144\ \text{pb}^{-1}$

$\sqrt{s}$ = 251 (MER)



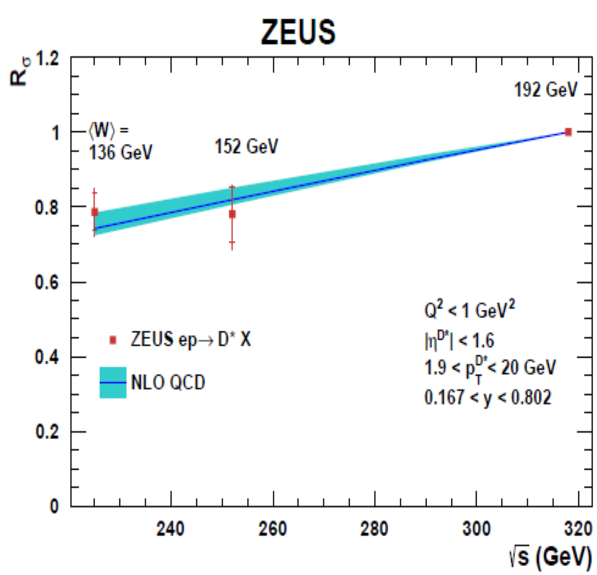
MER: $\mathcal{L} = 6.3\ \text{pb}^{-1}$

$\sqrt{s}$ = 225 (LER)



LER: $\mathcal{L} = 13.4\ \text{pb}^{-1}$

$R_\sigma = \sigma_i / \sigma_{HER}$



kin. region: $1.9 < p_T^{D^*} < 20$ GeV ; $|\eta^{D^*}| < 1.6$; $0.167 < y < 0.802$

Total systematic uncertainty: **≈5% in data**
few % in theory

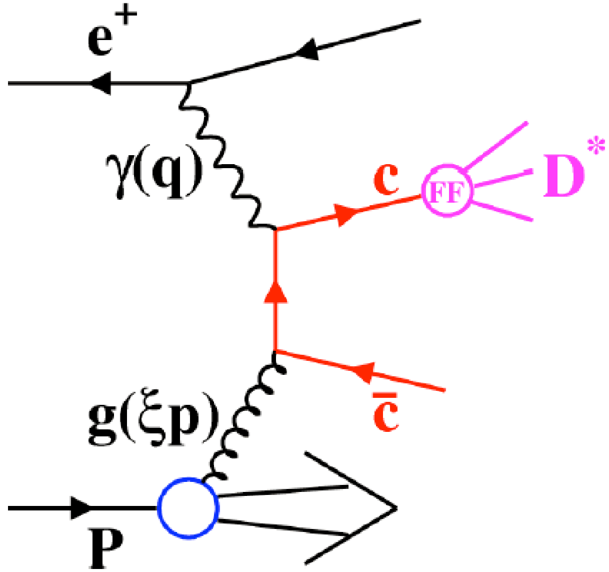
Cross sections increase with increase of s

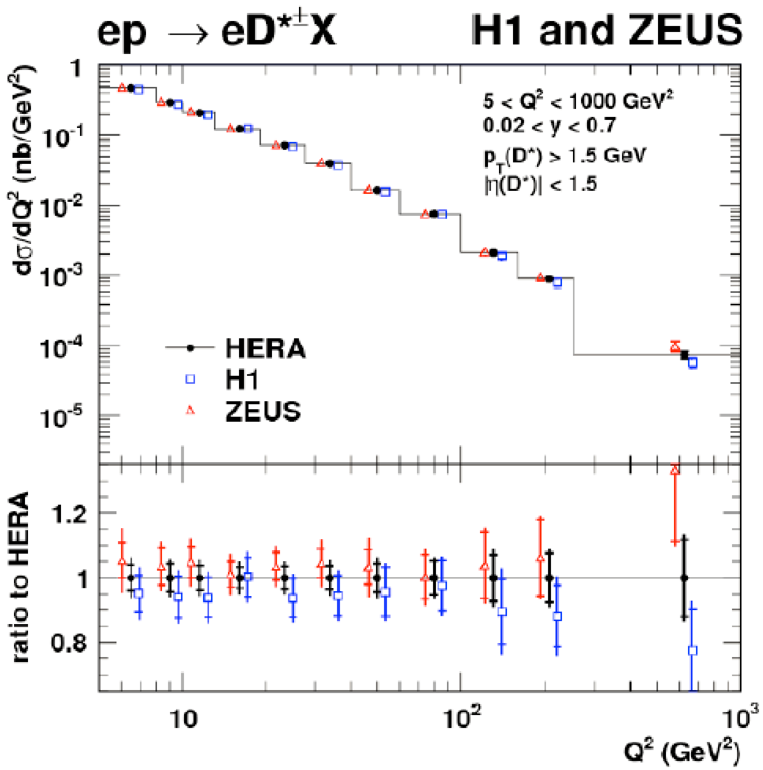
Good description by FFNS NLO

Charm production

D* differential cross sections in DIS

hep-ex 1503.06042 submt. to JHEP





Combined:

EPJ C71 (2011) 1769 H1 med Q^2
PL B686 (2010) 91 H1 high Q^2
JHEP 05 (2013) 097 ZEUS all Q^2

Precision of combined data: ≈5%

Similar results and precision obtained for $d\sigma/dQ^2$ and $d\sigma/dy$

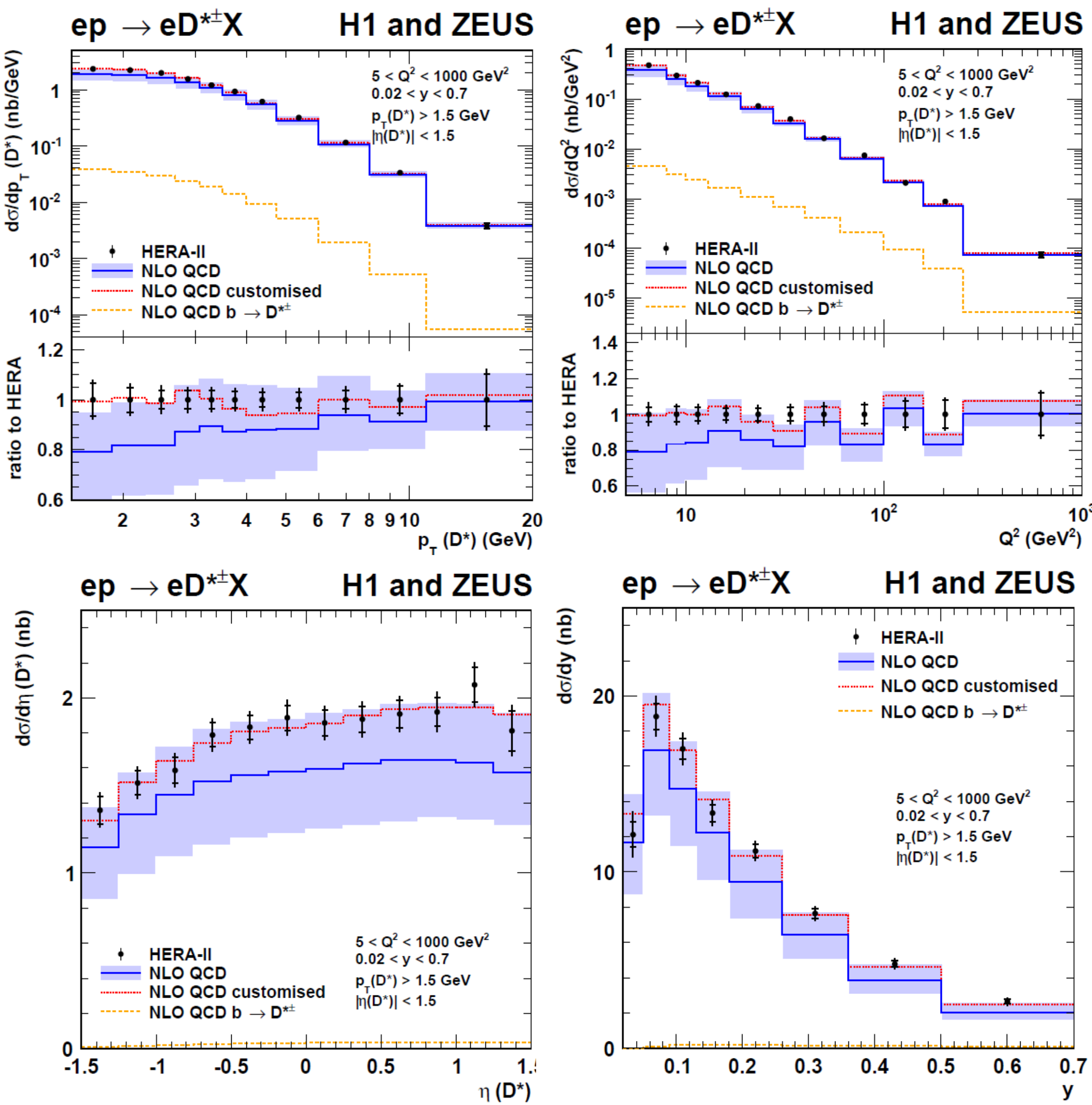
Charm mass measurement

EPJ C73 (2013) 2311

The value of m_c^{pole}=1.4 GeV was found to describe data better in a study of reduced $c\bar{c}$ cross sections (m_c^{pole} effective (not physical) mass parameter). Using the running mass definition in $\overline{MS}$ scheme, instead of pole mass, measured mass yields:

$$m_C(m_C) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{param} \pm 0.02_{alpha\text{-}S}\ \text{GeV}$$

D* differential cross sections in DIS



Combination procedure does not introduce theoretical ucertainties to data points

Precision of combined data: ≈5%

NLO scale uncertainties: O(10-30%)

Customised NLO describe data well (although it is NOT a prediction) with two (arbitrary) parameters:

$$\mu_r^2 = 0.25\,(Q^2+4m_C^2)\ ;\ m_C^{pole}=1.4\text{ GeV}$$

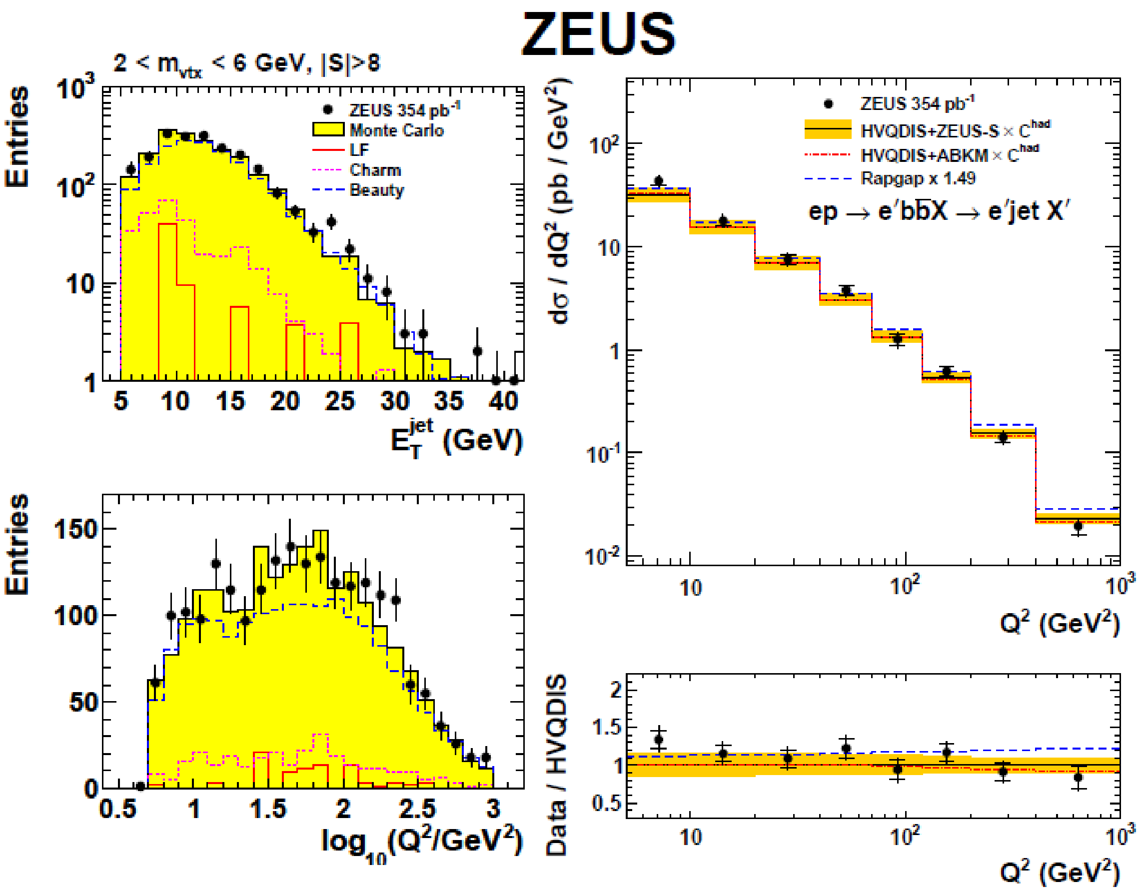
"NLO QCD customised"

NNLO calculation and improved fragmentation models might help

Similar conclusion for D* double-differential cross section in Q^2 and y

JHEP 09 (2014) 127

Beauty production in DIS



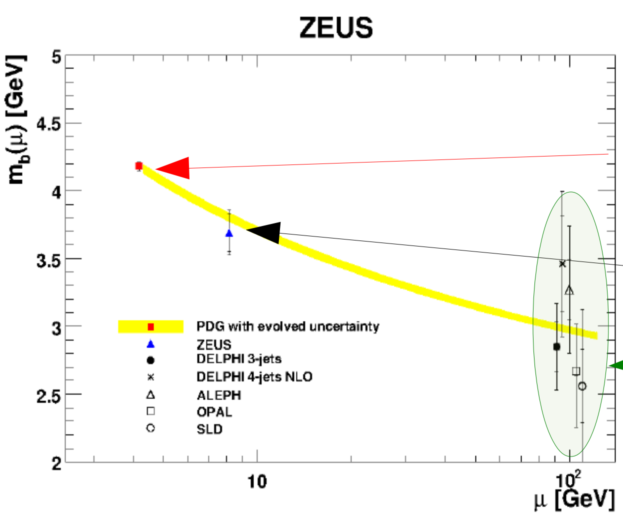
Left: distributions of Q^2 and jet's E_T of secondary vertices for b-enriched sample

$2 < m_{vrtx} < 6$; $|S| = |d/\delta d| > 8$

d=decay length

Right: Differential cross section for inclusive jet production in b-events as function of Q^2

Good description of the data by the NLO FFNS HVQDIS model



$$m_b(m_b) = 4.07 \pm 0.14(fit)^{+0.01}_{-0.07}(mod.)^{+0.05}_{-0.00}(param.)^{+0.08}_{-0.05}(theo.)\ GeV$$

PDG: 4.18 ± 0.03 GeV from lattice QCD + time-like processes

$m_b(m_b)$ translated to $m_b(\mu)$ with $\mu=2m_b$ and compared with PDG and LEP results

Mass running is consistent with QCD

QCD Instantons

QCD Instantons

Instantons

- **Solutions to Yang-Mills equations of motion**
- **Physical interpretations:**
  pseudo particle* or *tunneling process between topologically different vacuum states

QCD Instantons at HERA

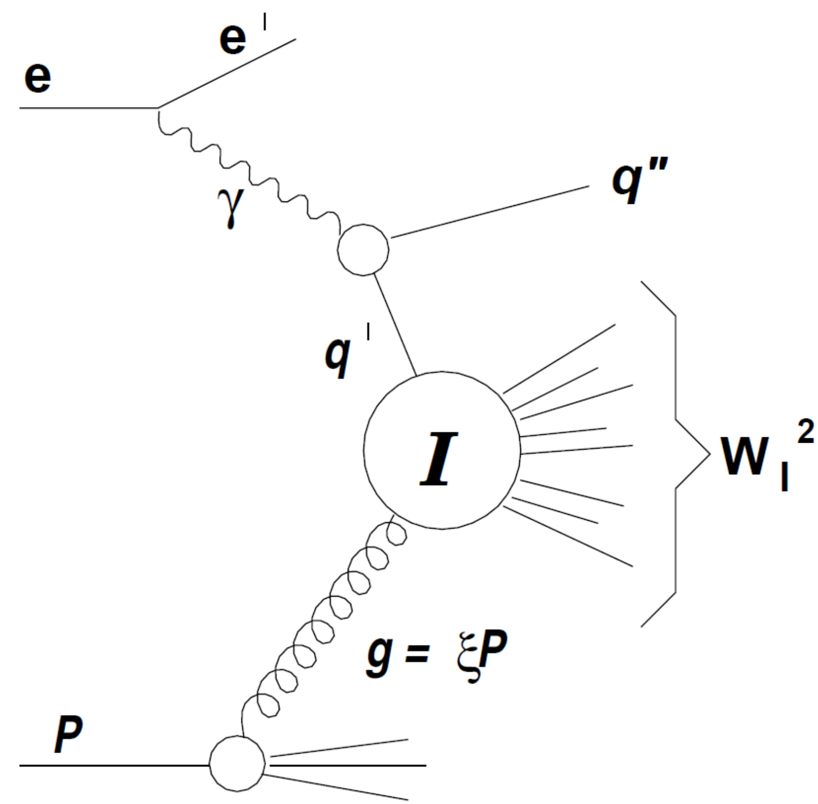
- **Produced in quark-gluon fusion***
- **Analysis phase space:**

$$150 < Q^2 < 15000 \text{ GeV}^2$$
$$0.2 < y < 0.7$$

- **QCDINS Monte Carlo: access to full event topology**

Selected Signatures

- **One hard jet**
- **Densely populated eta band, flat in φ**
- **Large particle multiplicities**



Variables of I-subprocess:

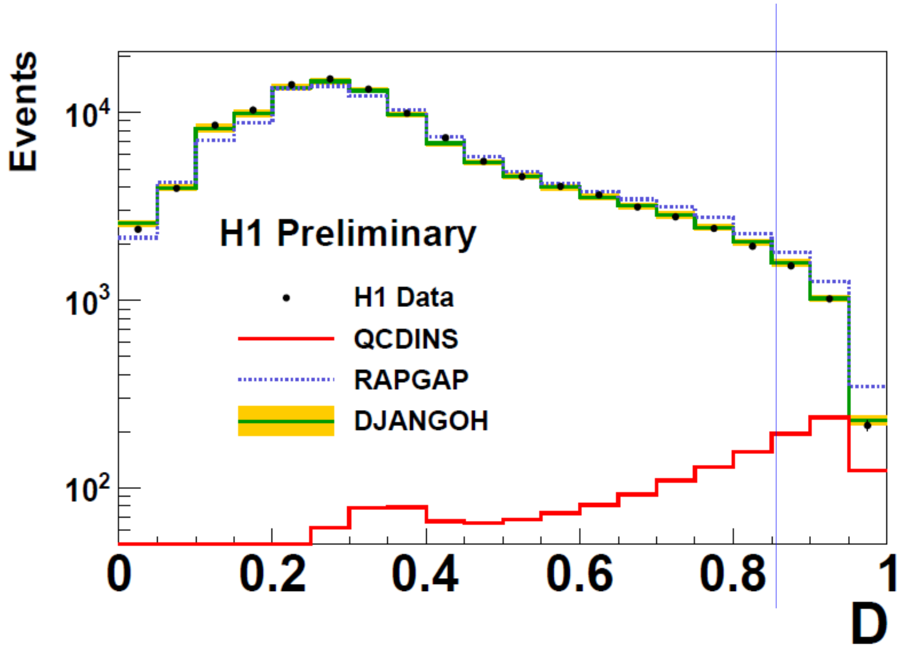
$$Q'^2 \equiv -q'^2 = -(\gamma - q'')^2$$
$$x' \equiv Q'^2 \;/\; (2\, g \cdot q')$$
$$W_I^2 \equiv (q' + g)^2 = Q'^2\ (1 - x'\ )/x'$$

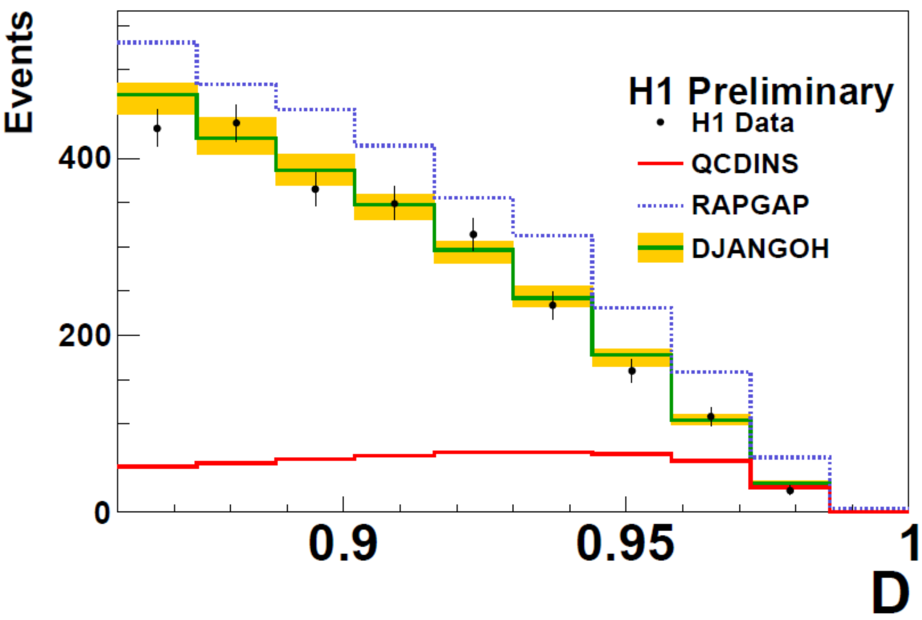
*S. Moch, A. Ringwald, F. Schrempp, Nucl Phys. B 507 (1997) 134 [hep-ph/9609445],
A. Ringwald, F. Schrempp, Phys. Lett. B 438 (1998) 217 [hep-ph/9806528],
A. Ringwald, F. Schrempp, Phys. Lett. B 459 (1999) 249 [hep-ph/9903039].

QCD Instantons analysis

Multivariate Analysis

- **Probability density estimator with range search (PDERS)**
- **Training with Rapgap/Djangoh MC as background and QCDINS as signal MC**
- **Good discriminator description in the background region**
- **Signal region: D > 0.86**





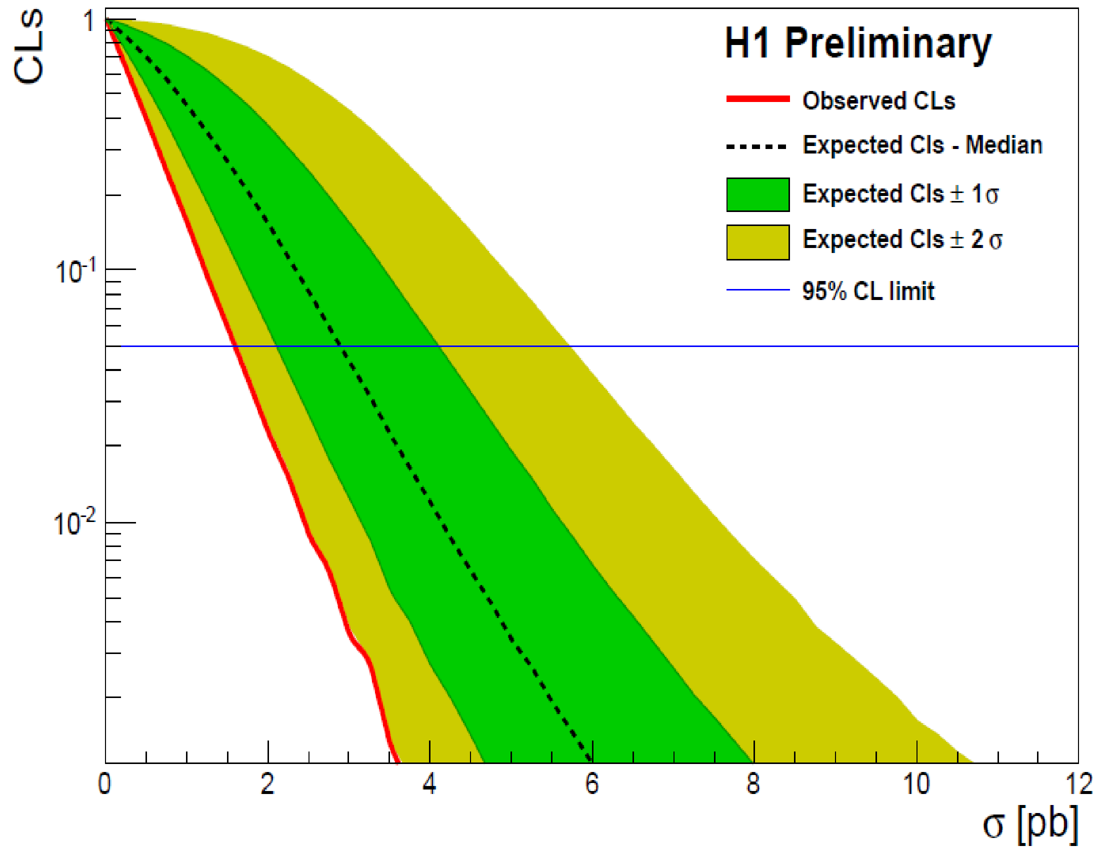
QCD Instantons - results

Data are *consistent with background*
No evidence for QCD Instantons

Limit calculations

- **CL_s method used**
- **Input for limit calculations:**
  QCD Instanton cross section
  Uncertainties: systematic and model
- **Full range of the PDERS discriminator for better method reliability**

$Q'^2 > 113$ GeV^2, $x' > 0.35$



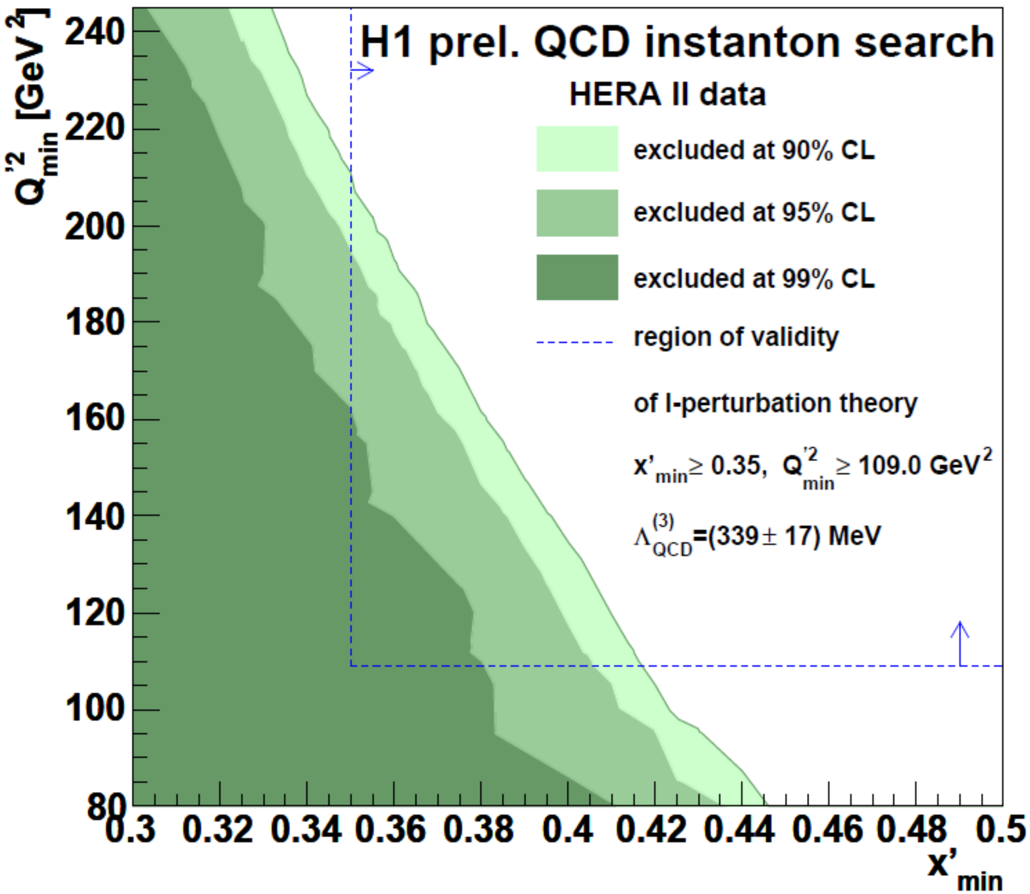
Theoretical prediction in the analysis phase space: 10±2 pb

Upper limit for the instanton cross section at 95%CL: 1.6 pb

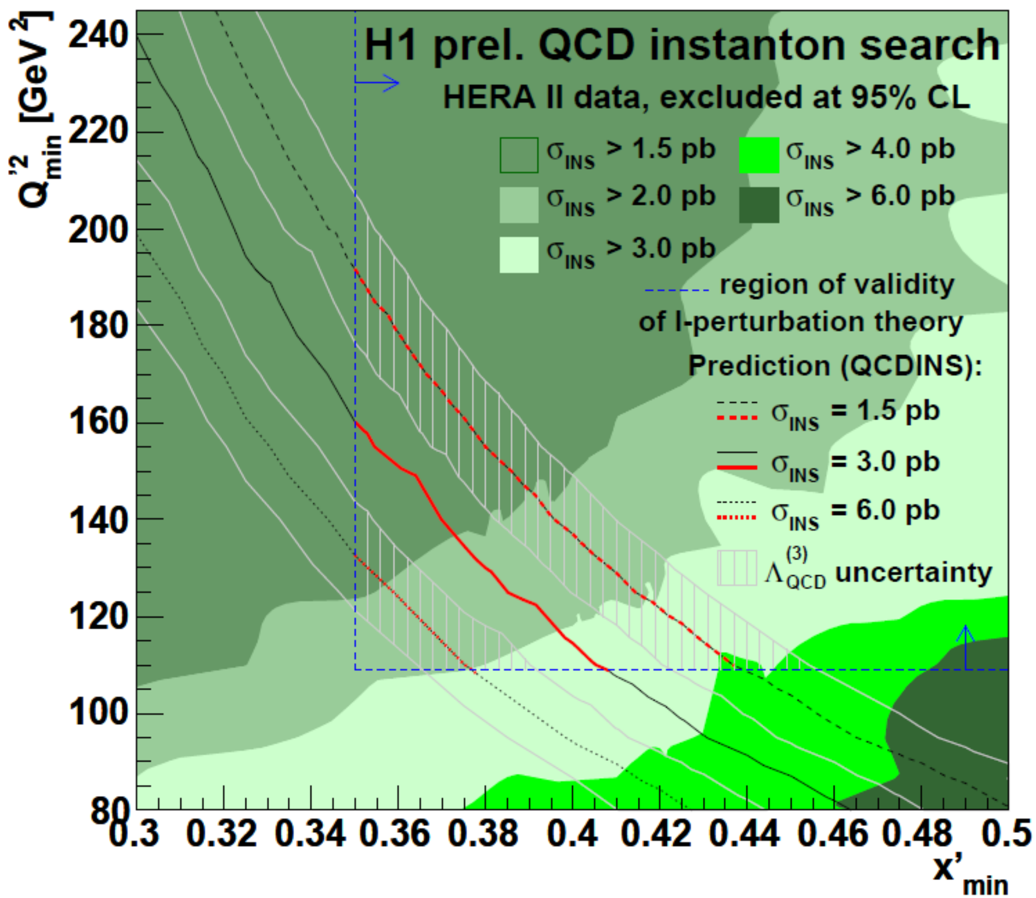
Exclusion of the Ringwald & Schrempp predictions for the QCD Instantons at HERA

QCD Instantons - results

QCD Instanton cross section limits in extended phase space



Instanton production exclusion limits for different confidence levels



Upper limits on the instanton production cross section at 95% CL

Isolines of fixed predicted σ_{Inst} and effects of varying the strong coupling

Summary

New interesting QCD results from the HERA experiments

Multi-jets and determination of α_s

- **ZEUS and H1 measurements consistent with NLO calculations**
- **Most precise $\alpha_s(M_z)$ is extracted from fit to the normalised multijet cross section, yielding**

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

- **The running of $\alpha_s(\mu_r)$ consistent with results from other jet data**
- **Precision of the measurement (H1) is better than that of NLO calculations**

Need NNLO

Heavy flavours – charm(ing)&beauty(full)

- **H1 and ZEUS provide new results with HERA data, making tighter constraints on QCD**
- **New precise (combined) measurements – well described by NLO QCD, but still challenge to theory and fragmentation models**
- **Masses of b/c quarks agree with PDG values. Running of m_b consistent with QCD**

QCD Instantons searches

- **Ringwald & Schrempp predictions for the QCD Instantons at HERA appear to be excluded**

Thank you for your attention

Backup slides

H1 High Q^2 Jet Production Analysis

Jets reconstruction

- **Overconstrained system in DIS**
- **Energy flow algorithm**
  - **Calibration using neural networks**
- **k_T and anti-k_T algorithm in the Breit frame**

Hadronic energy scale uncertainty 1%

Phase space and Jet samples

- **HERA II data, 351 pb^{-1}**
- **Inclusive jets: every jet in an event exceeding a min P_T contribute to a cross section σ_{jet}**
- **Dijets (Trijets): events with at least 2 (3) jets above a given PT contribute to a cross section $\sigma_{dijet\ (trijet)}$**
- **Normalised cross sections: σ_{jet} / $\sigma_{NC\ DIS}$**

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

Unfolding

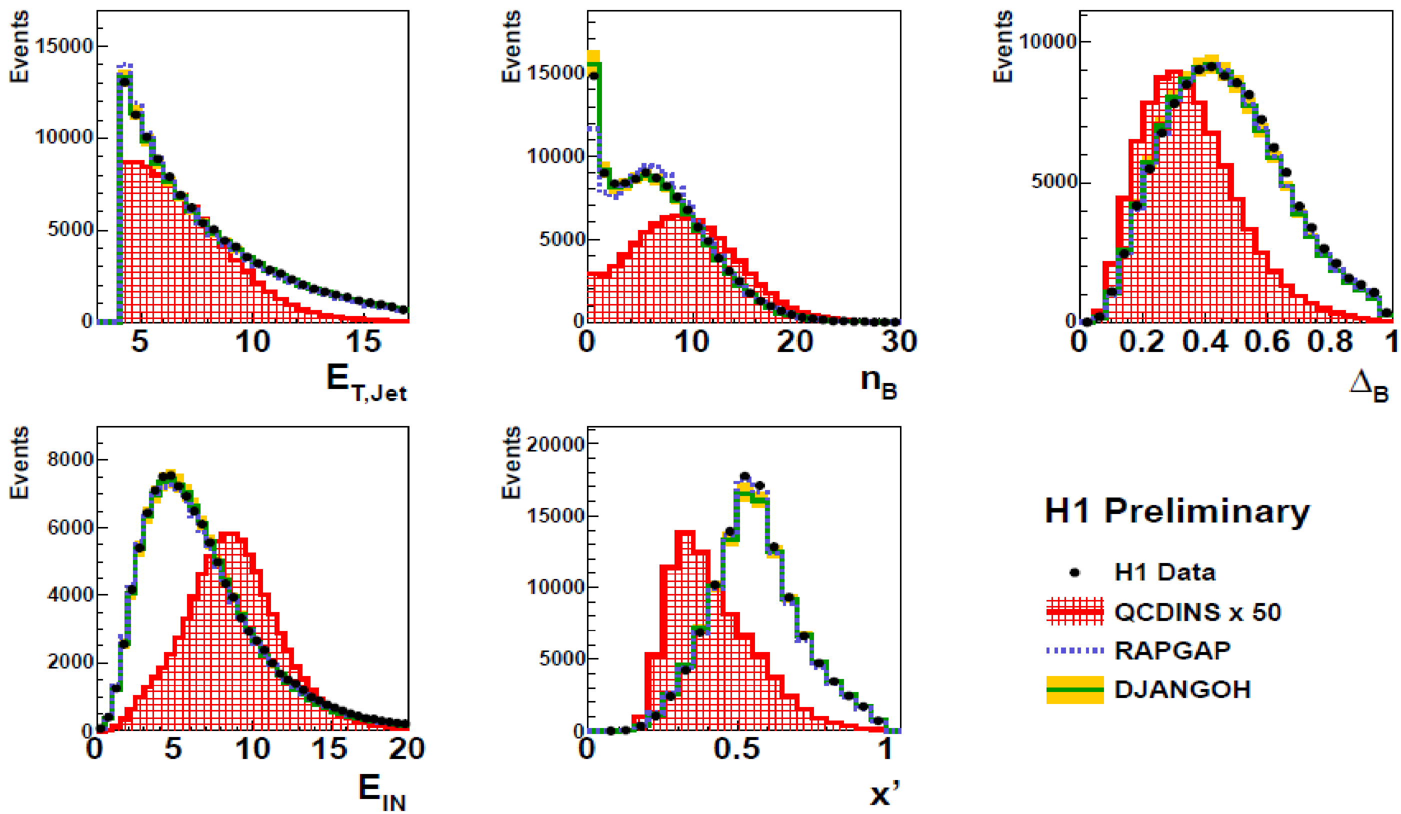
- **Regularised unfolding with TUnfold***
- **Multidimensional unfolding in Q^2, y, P_T**
- **Migrations of up to 7 observables and correlations between samples taken into account**

*** S.Schmitt, JINST 7 (2012) T1003, (arXiv:1205.6201)***

QCD Instantons analysis

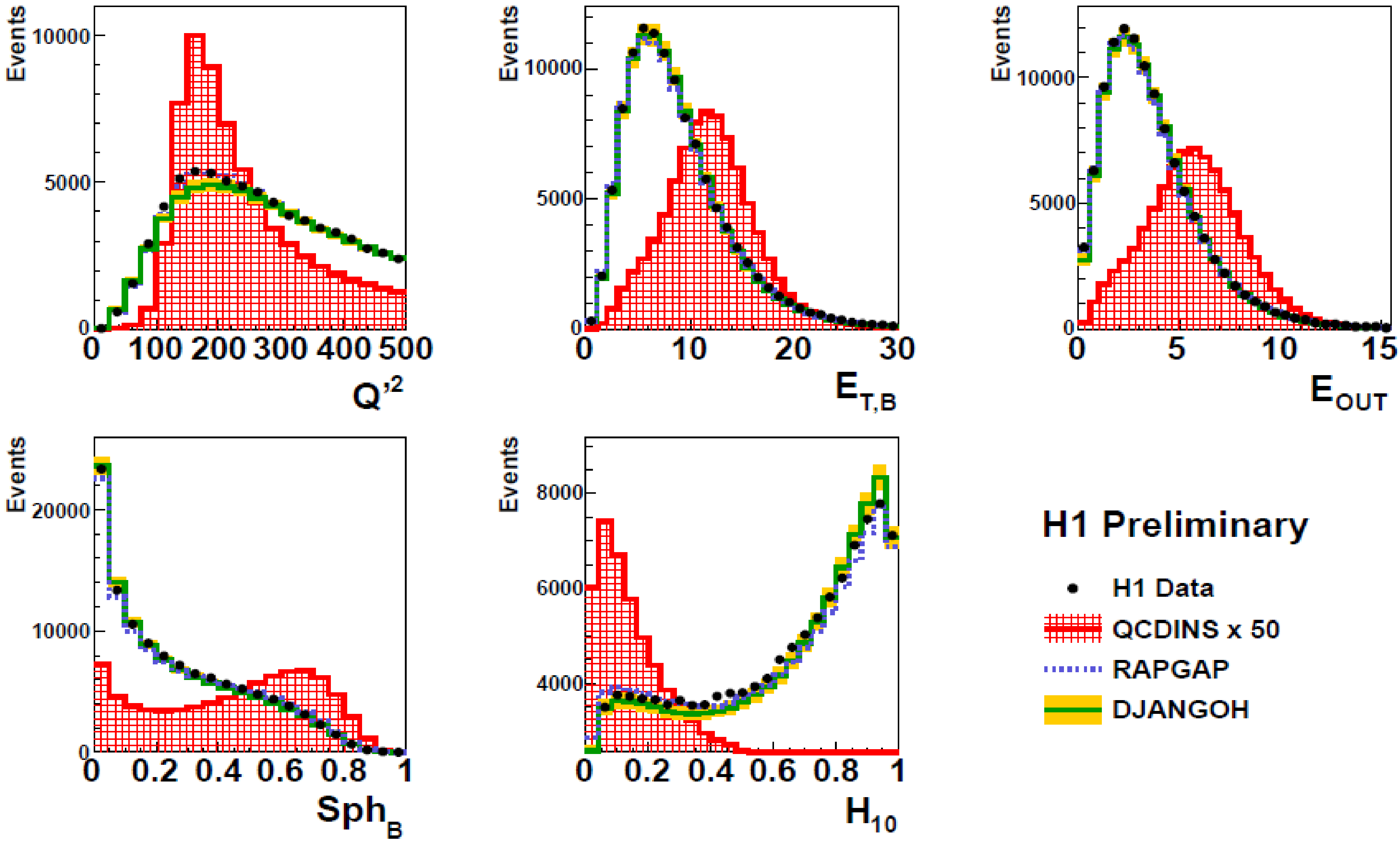
Search strategy

- **Find jets in hadronic centre of mass frame**
  - **- Remove hardest jet from objects of hadronic final state (HFS)**
- **Boost to instanton rest frame and define variables**
  - **- Topological: sphericity, Fox-Wolfram moments, azimuthal isotropy (Δ_B), ...**
  - **- Number of charged particles n_B**
  - **- Transverse energy of the band...**
- **Variables are used as input to MVA**



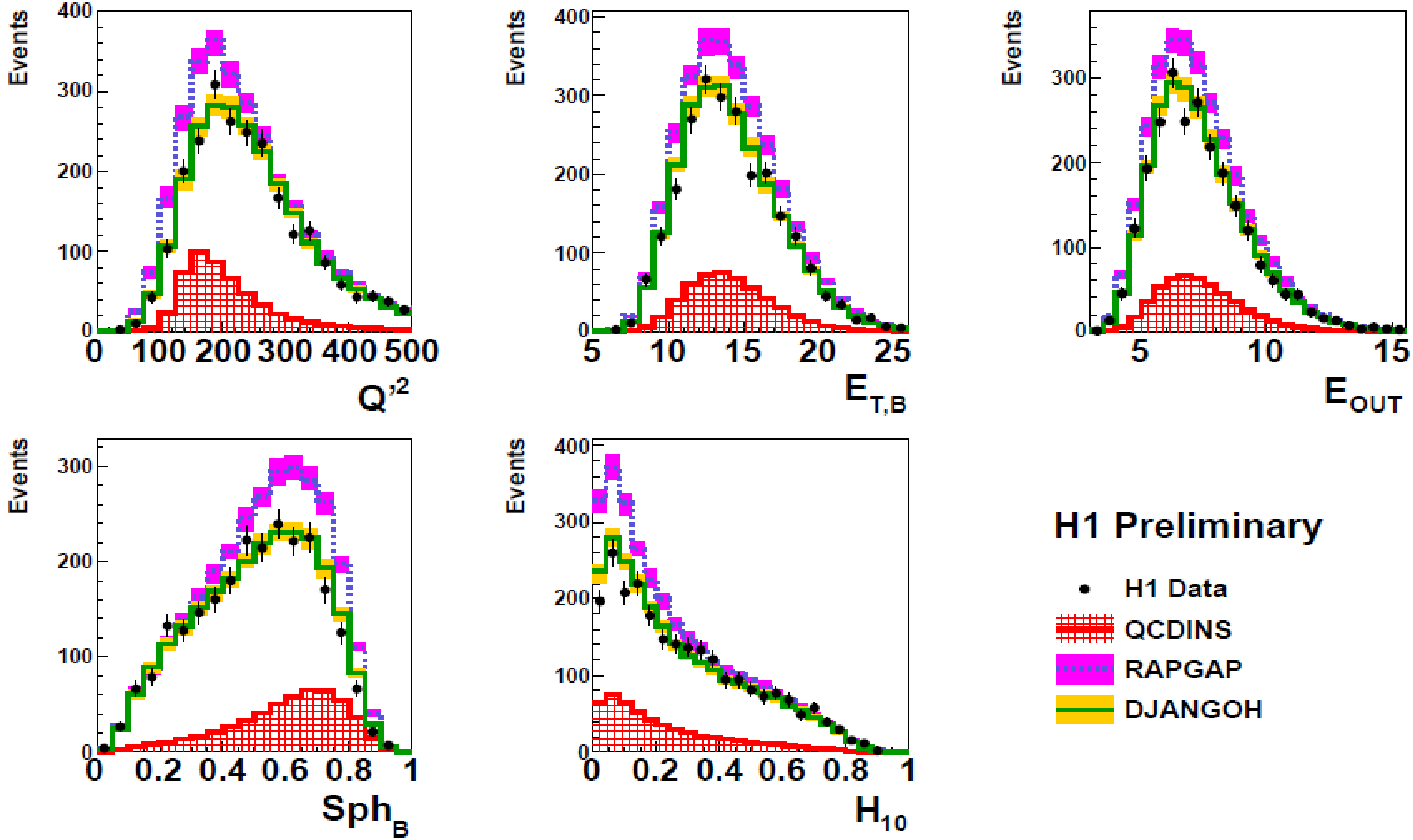
Observables not used in the TMVA training

Full range of the discriminator



Observables not used in the TMVA training

Signal range of the discriminator

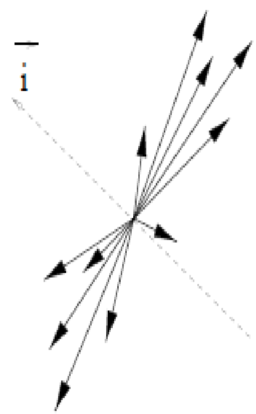


No excess of events in the signal region

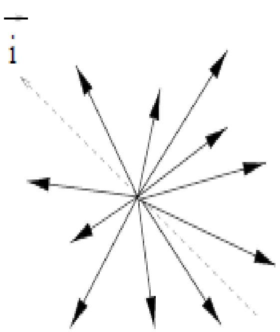
Azimuthal isotropy

$$\Delta_b = (E'_{in,B} - E'_{out,B}) \,/\, E'_{in,B}$$

$$\begin{aligned} E_{out} &= \min \textstyle\sum_{n\ Hadr.} |\, \vec{p_n} \cdot \vec{i}\, | \\ E_{in} &= \max \textstyle\sum_{n\ Hadr.} |\, \vec{p_n} \cdot \vec{i}\, | \end{aligned}$$



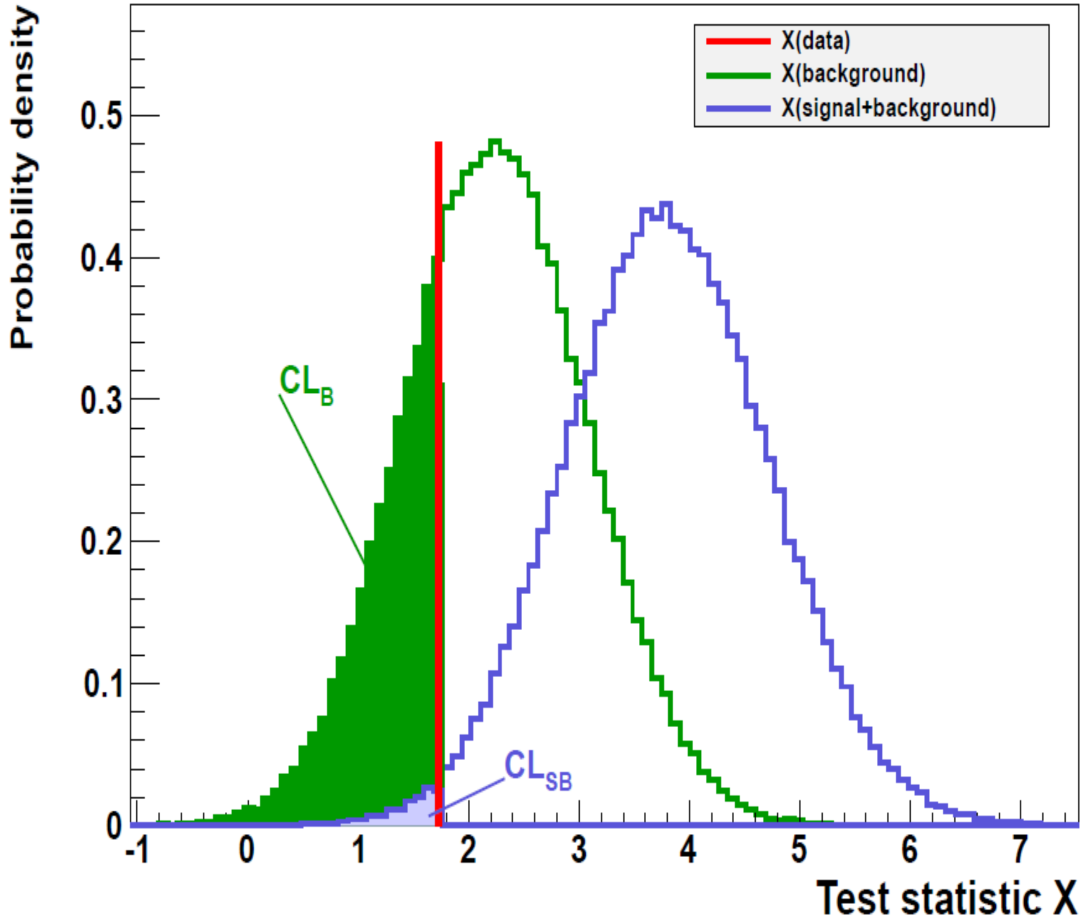
$\Delta_b \approx 1$



$\Delta_b \approx 0$

Test statistic distribution

Construct test statistics for Data, Background and Backgr+Signal



$$CL_S = \frac{CL_{SB}}{Cl_B}$$

$$Confidence\ Level : CL = 1 - CL_S$$