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(on behalf of the H1 and ZEUS collaborations)

QCD and the hadronic final states at HERA

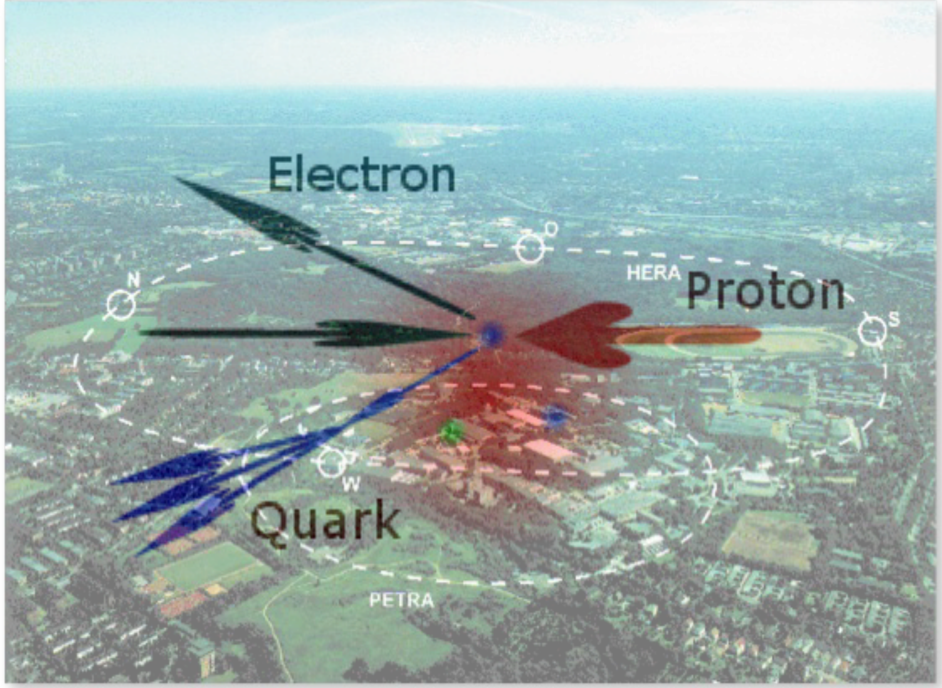
1. Jet measurements and extraction of α_s
2. Prompt photon production in DIS
3. Search for QCD instantons
4. Search for strange pentaquarks

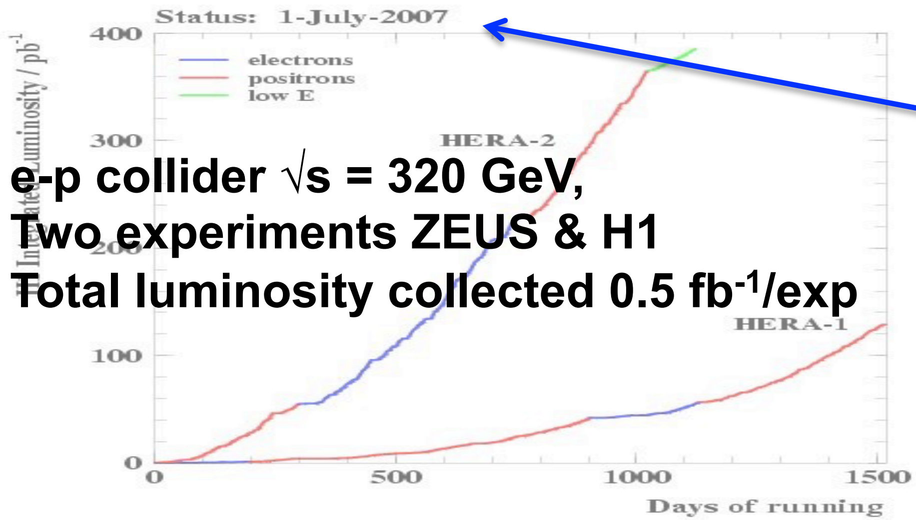
5th International Conference on New Frontiers in Physics ICNFP2016

6-14 July 2016
Europe/Athens timezone

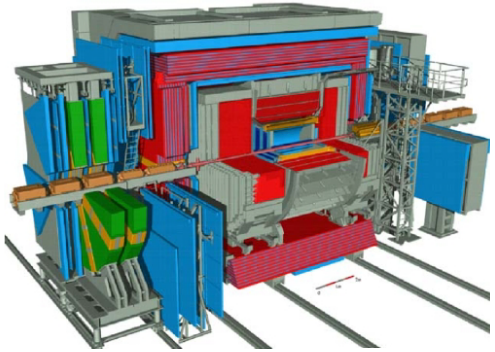
HERA

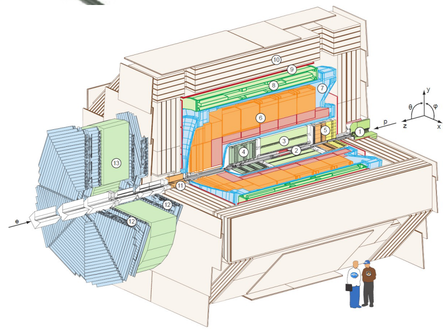
HERA-1 (1993-2000) ≃ **120** pb-1
HERA-2 (2000-2007) ≃ **380** pb-1





e-p collider √s = 320 GeV,
Two experiments ZEUS & H1
Total luminosity collected 0.5 fb^{-1}/exp





General-purpose 4π detectors

- Overconstrained system in DIS
- Electron meas: 0.5 – 1% scale unc.
- Jet energy scale: 1%
- Trigger and normalization unc: 1-2 %
- Luminosity: 1.8 – 2.5%

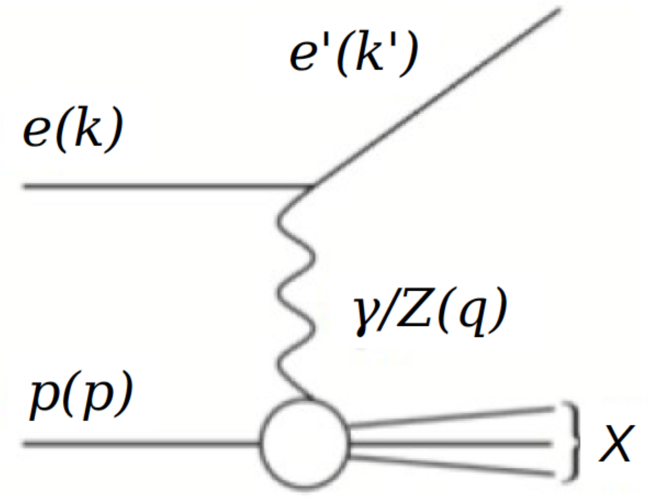
Almost 10 years ago,
but still valuable analyses!

Deep Inelastic Scattering

Neutral current deep-inelastic scattering

Process: $ep \to e'X$

Electron or positron



Kinematic variables

Virtuality of exchanged boson Q^2

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

Inelasticity

$$y = \frac{p \cdot q}{p \cdot k}$$

Factorisation in ep collisions

Hard scattering coefficients and parton distribution functions (PDFs)

$$\sigma_{ep \to eX} = f_{p \to i} \otimes \hat{\sigma}_{ei \to eX}$$

Predictions in perturbative QCD

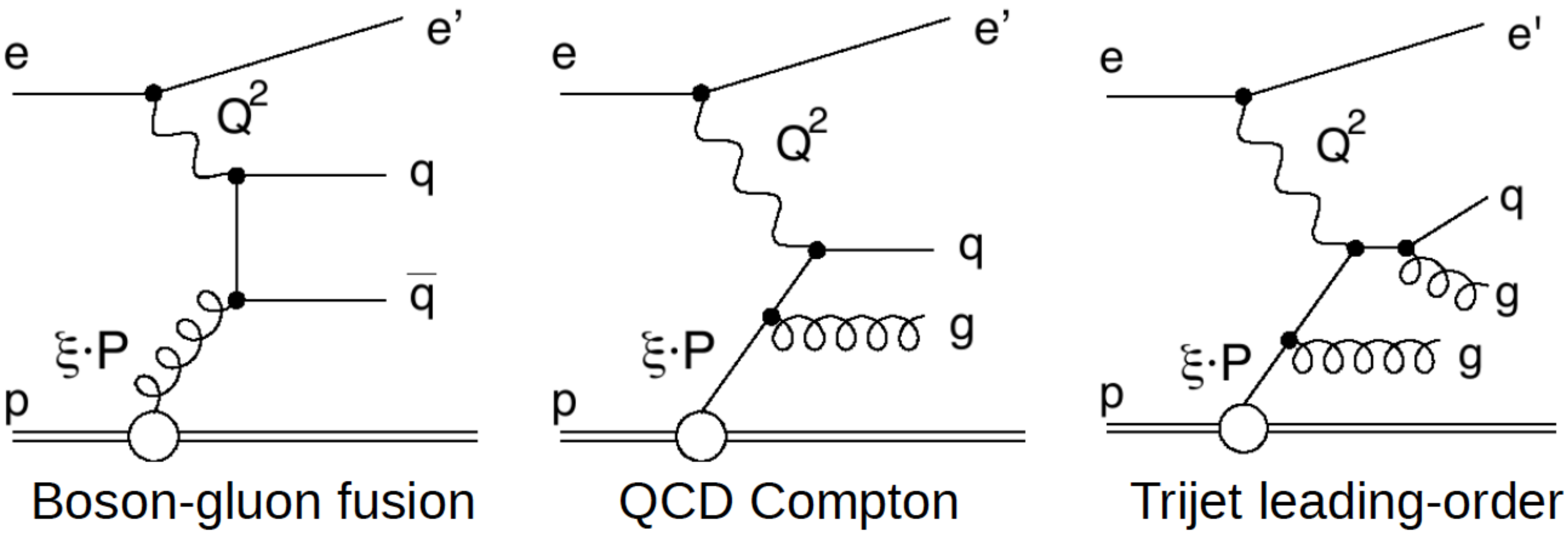
Hard scattering is calculated perturbatively

PDFs have to be determined from experimental data (usage of DGLAP)

(Dokshitzer–Gribov–Lipatov–Altarelli–Parisi)

Jet production at ep scattering (HERA)

1



Jet measurements are performed in Breit reference frame

- Exchanged virtual boson collides 'head-on' with parton from proton

Jet measurement sensitive to α_s already at leading-order

- Boson-gluon fusion
- QCD compton

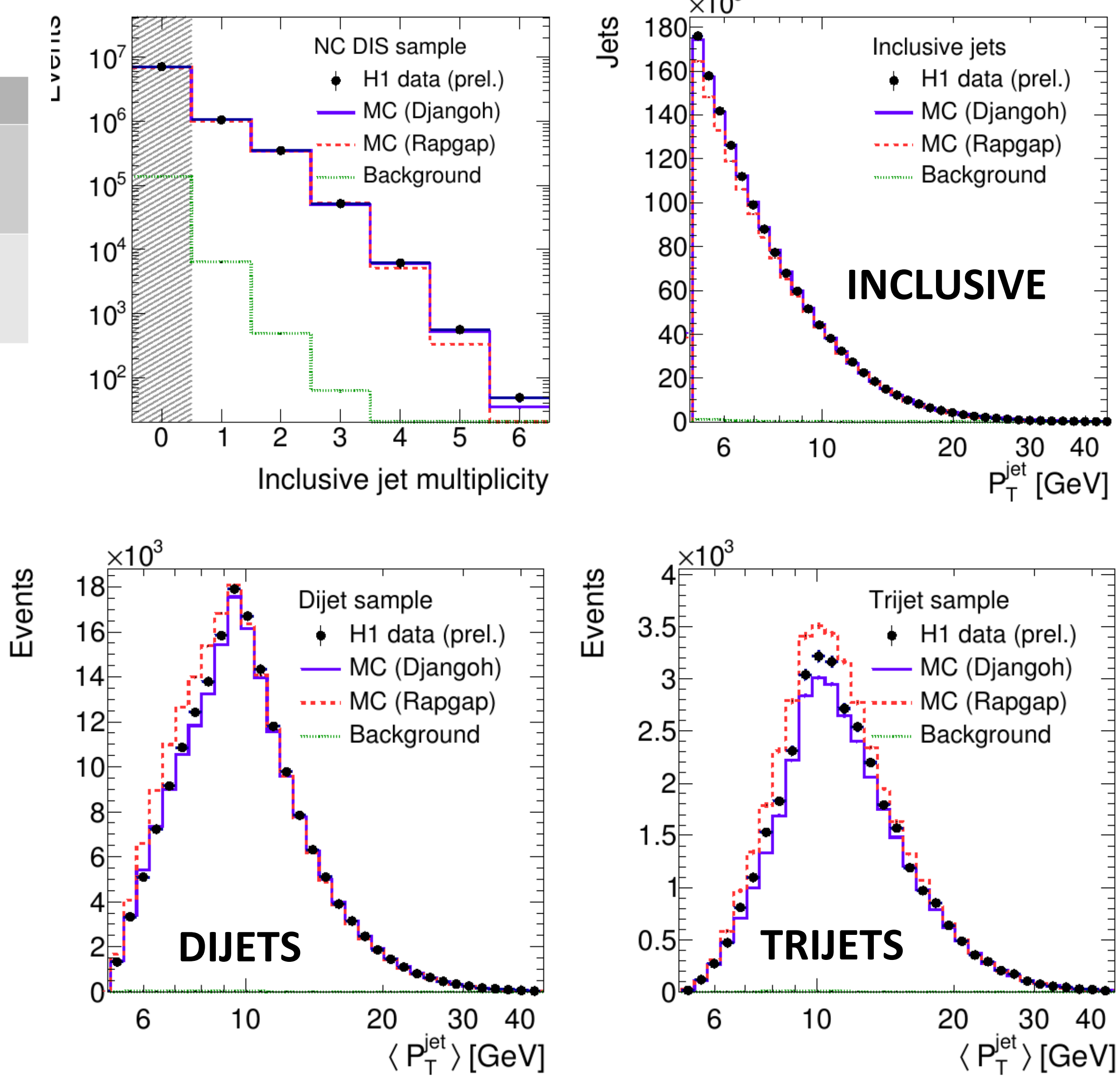
Trijet measurement

- More than three jets with significant transverse momenta
- Leading-order already at $O(\alpha_s^2)$

Multijet detection at low Q^2 (H1)

Last missing piece of H1 jet legacy

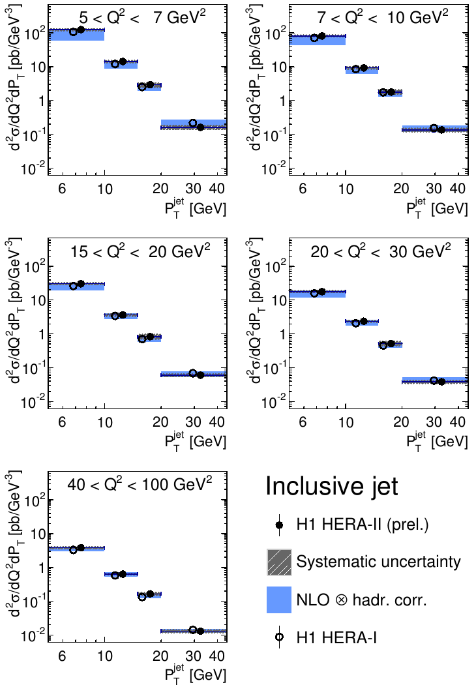
Process		HERA-I	HERA-II
Low Q^2	Inclusive jet Dijet Trijet	EPJ C 67 (2010) 1	This analysis H1prelim 16-061
High Q^2	Inclusive jet Dijet Trijet	EPJ C 65 (2010) 363	EPJ C 75 (2015) 2



- Jet reconstruction:
  - kT jet algorithm with R=1
  - Jets built from tracks and clusters
  - Jet energy calibration using NNs
- The cross-sections are obtained with regularised unfolding, deriving the full correlation matrix for the results.
- Compare to Theory:
  - calculation at NLO
  - hadronisation correct.s at NLO

Multijet cross-sections at low Q^2 (H1)

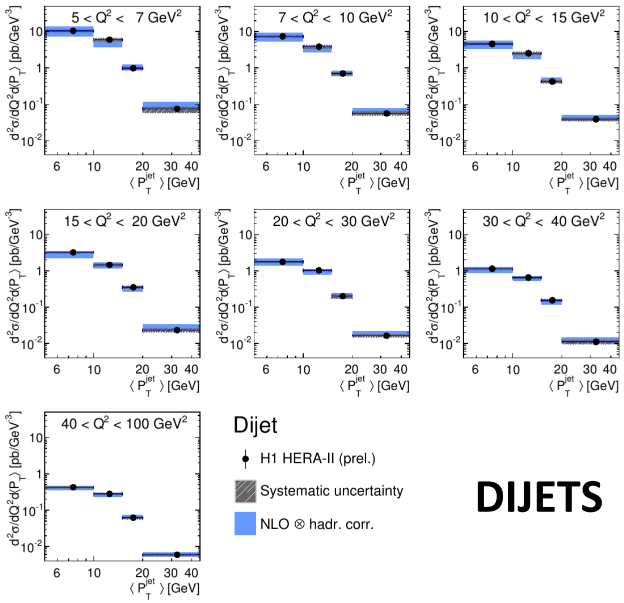
PRELIMINARY



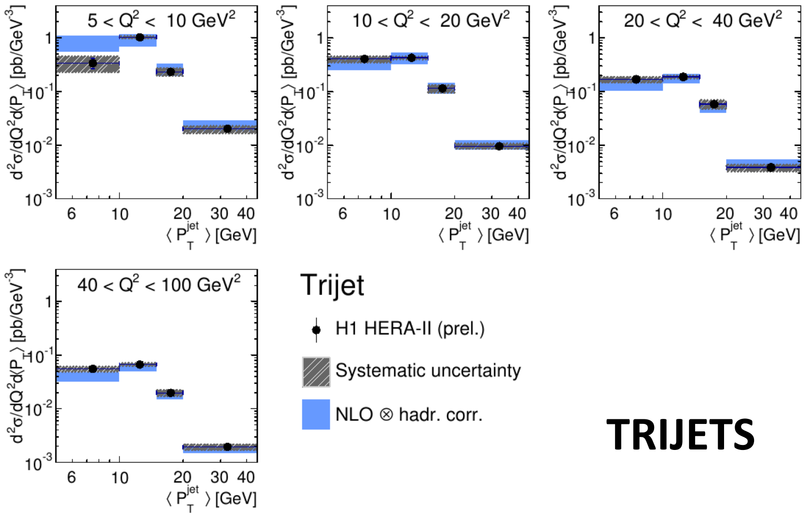
INCLUSIVE

Cross-sections are obtained with regularised unfolding, deriving the full correlation matrix for the results

- Data precision significantly overshoots NLO precision



DIJETS



TRIJETS

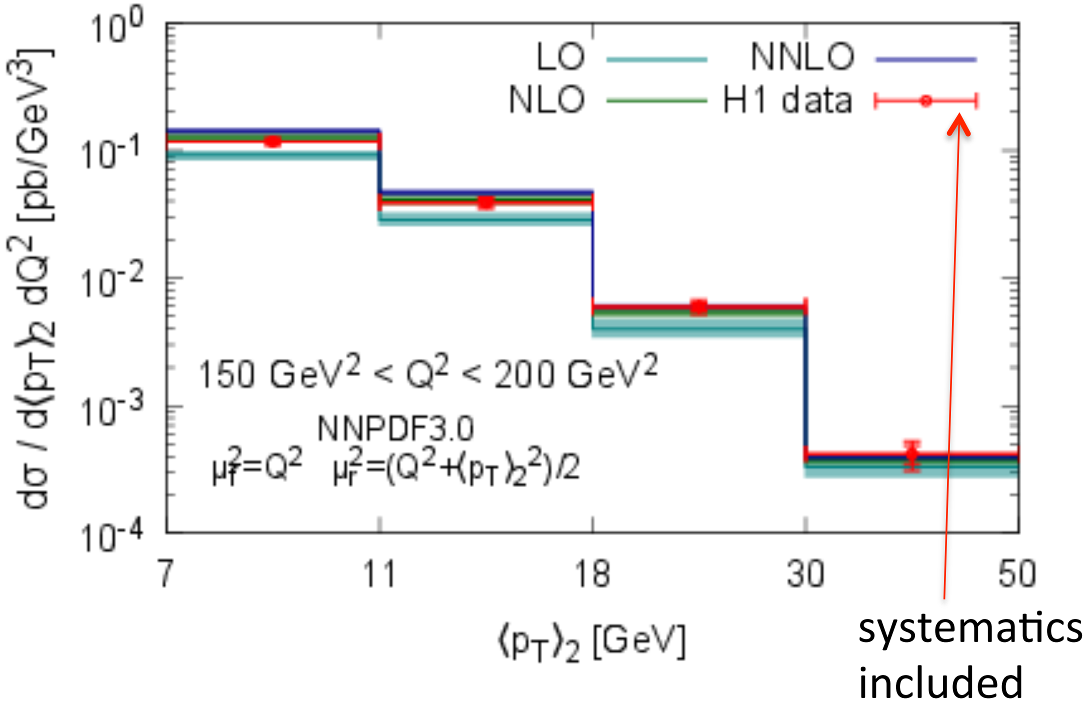
δ NLO Theory >> δ Experiment

e.g. with previous di-jets (H1)

The results can be used for the first α_s extraction at NNLO (2-jets) in DIS

Most precise dijet predictions:

- aNNLO T. Biekötter, M. Klasen and G. Kramer, Phys. Rev. D 92 (2015) no.7, 074037
- NNLO J. Currie, T. Gehrmann and J. Niehues, arXiv:1606.03991 [hep-ph].



Extremely valuable input for the α_s extraction in DIS:

Probe running of α_s over one order of magnitude with all H1 jet data

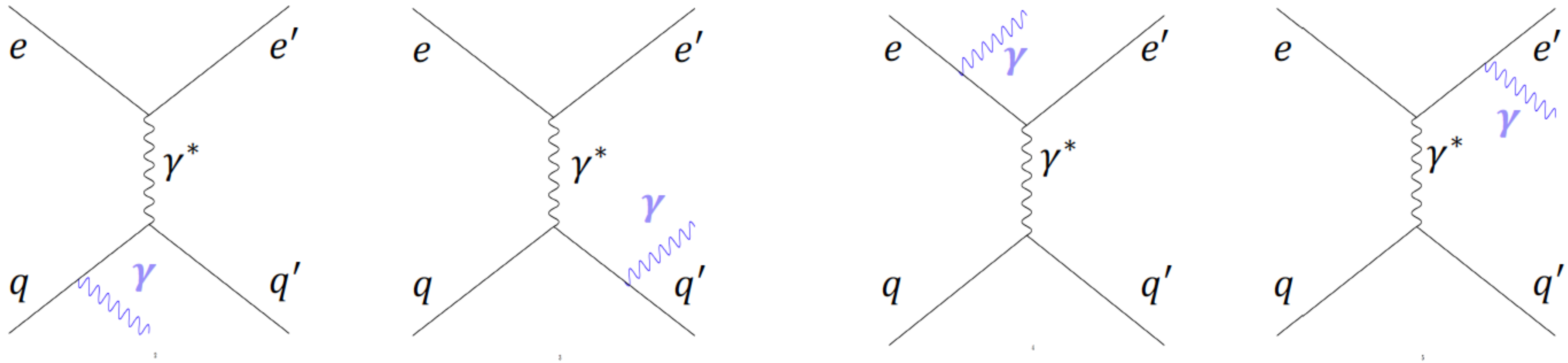
- Very high experimental precision on α_s(MZ)
  Expect experimental precision of ~ 0.5%

Prompt Photons at HERA

2

(Photons which are produced promptly in the collision - before quarks and gluons form hadrons)

QQ - photons **LL - photons**



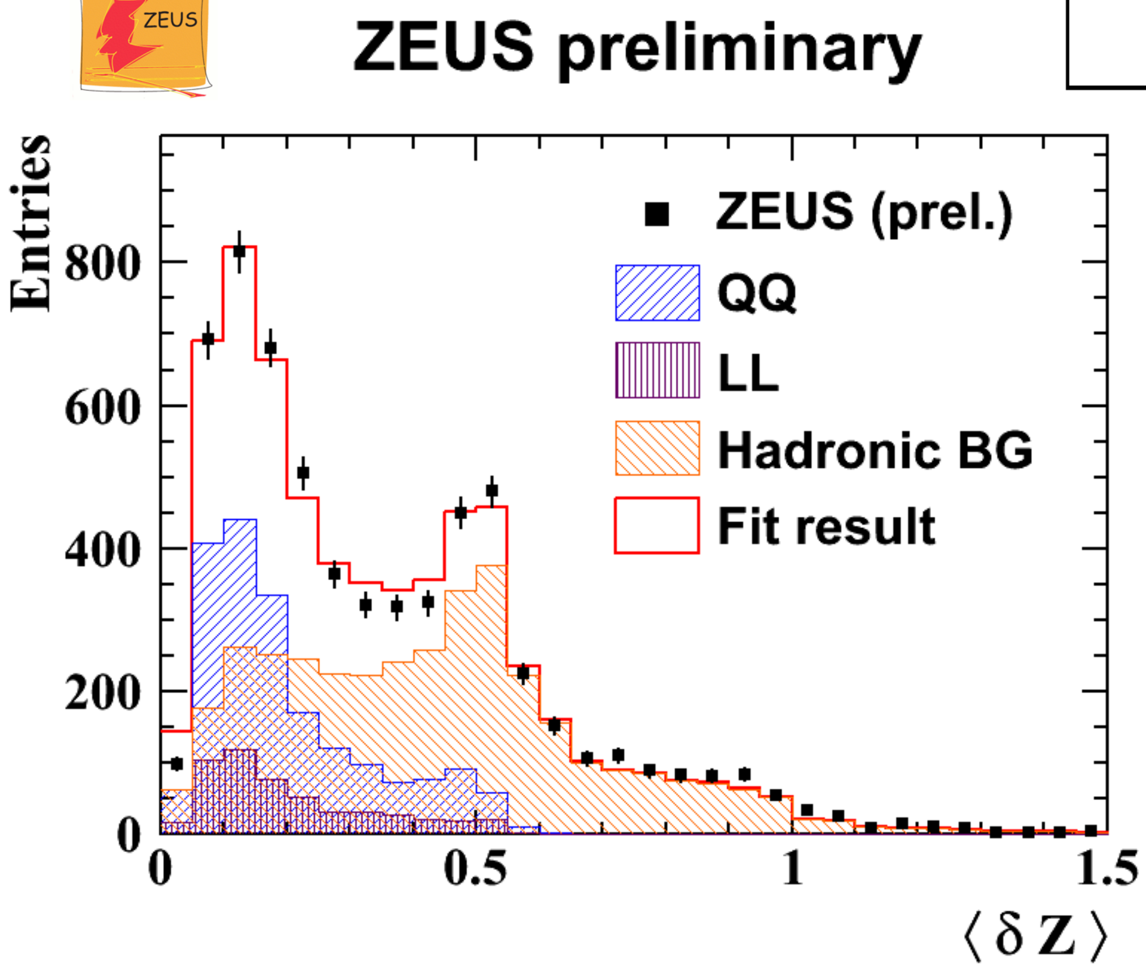
(prompt photon emitted before hadronisation)

Probe different theoretical models such as the k_t- and collinear factorisations and pQCD approaches

Previous publication - Physics Letters B 715 (2012) 88 by ZEUS with 326 pb^{-1} : inconclusive (data between GKS NLO and BLZ predictions)

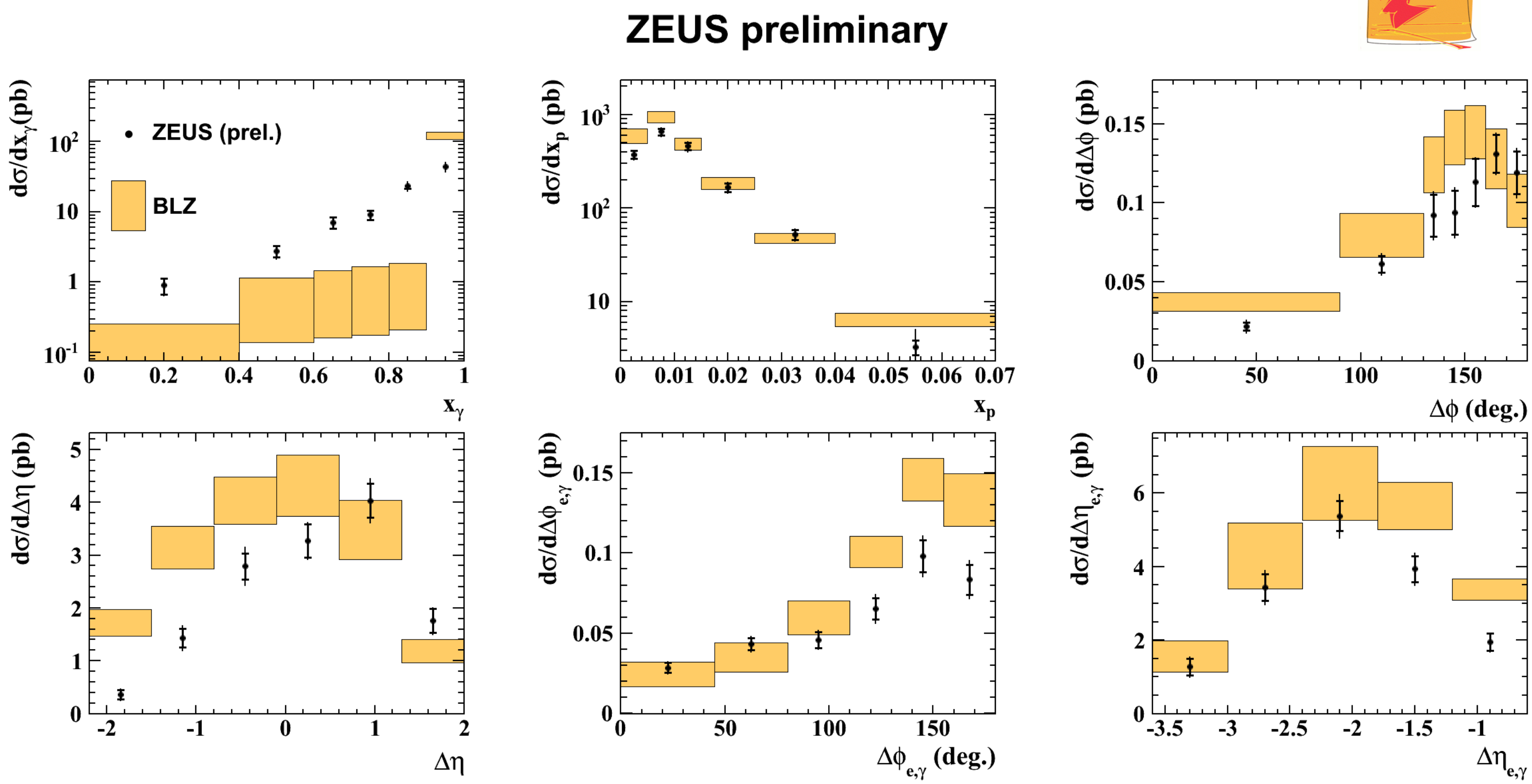
Hard life…

- $x_\gamma = \frac{\sum_{jet,\gamma}(E-p_z)}{2y_{JB}E_e}$
- $x_p = \frac{\sum_{jet,\gamma}(E+p_z)}{2E_p}$
- $\Delta\eta = \eta_{jet} - \eta_\gamma$
- $\Delta\varphi = \varphi_{jet} - \varphi_\gamma$
- $\Delta\varphi_{e,\gamma} = \varphi_e - \varphi_\gamma$
- $\Delta\eta_{e,\gamma} = \eta_e - \eta_\gamma$



<δZ>: Energy-weighted mean width of the electromagnetic shower(cluster) in calorimeter relative to its centroid

Comparison with Baranov-Lipatov-Zotov(BLZ) theory, PHYSICAL REVIEW D 81, 094034 (2010)



Comparison with k_t-factorisation model show a fair agreement of the Kinematic distributions of the data with exception of x_γ and $\Delta\eta$.
Further investigations needed to understand the results

QCD instantons at HERA

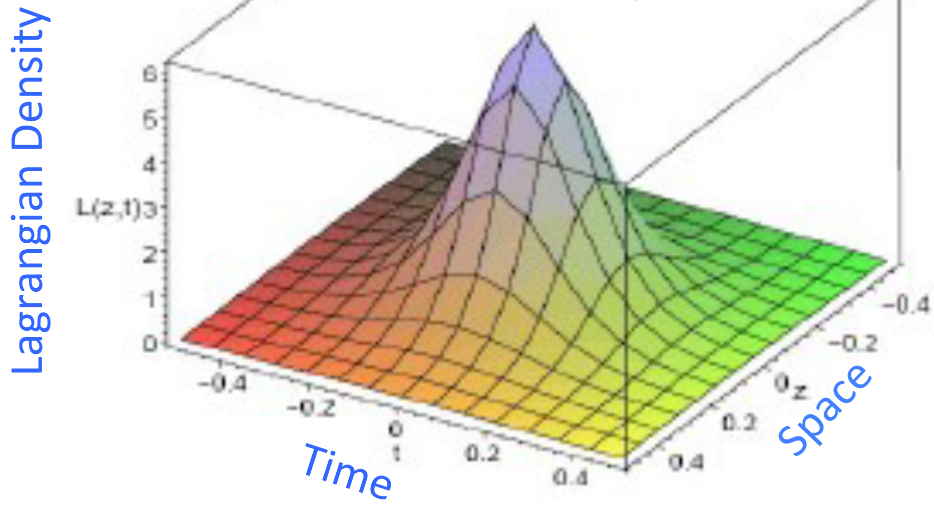
3

What is that ? **non-perturbative fluctuation of the gauge fields**

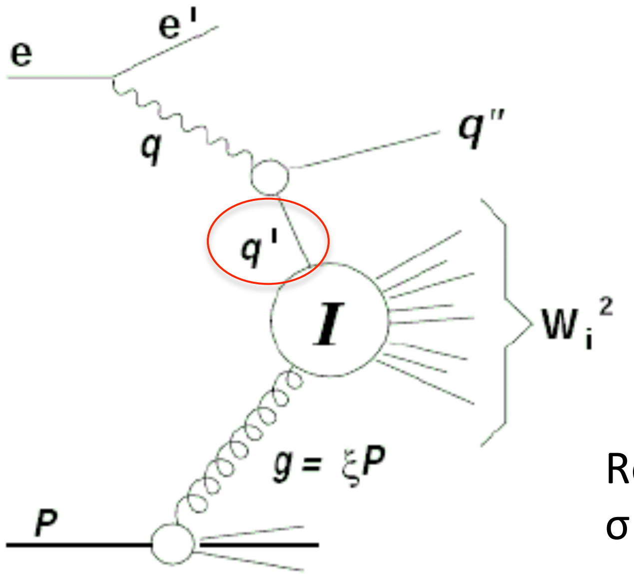
In SM they induce processes with B+L violation in EW theory in analogy with chirality violation in QCD (A. Ringwald and F. Schrempp [hep-ph/9411217])

Instanton interpretation (e.g):

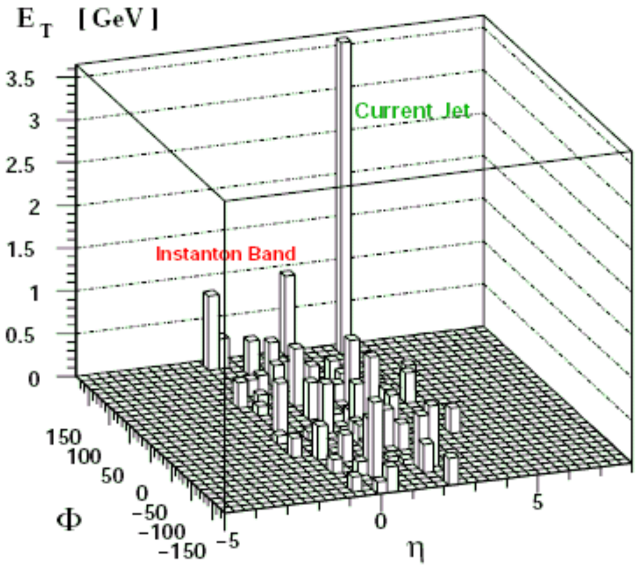
localized pseudoparticle in space and time

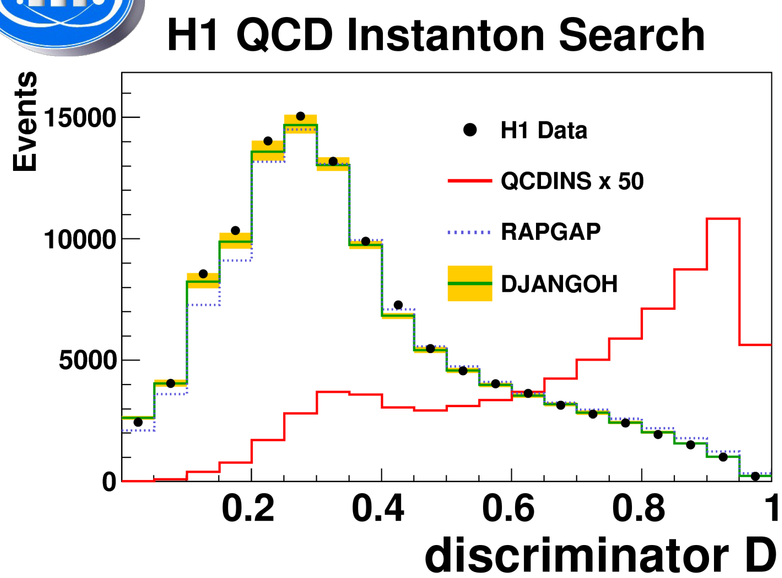


Produced in quark-gluon fusion



Relatively large cross-section expected in HERA phase-space:
σ ≈ 10 ± 3 *pb* with an uncertainty coming from Λ_{QCD}*(MSbar)*





Signatures at HERA:

- Hard jet;
- Densely populated narrow band in η, isotropic in ϕ;
- Isotropy in instanton rest frame;
- High charged particles multiplicity;
- Large total E_T .

H1 and ZEUS searches (early HERA-I data)
• No signal observed and upper limits set
• Upper limits above theory prediction
Eur.Phys.J.C25:495-509,2002 (H1)
Eur.Phys.J.C34:255-265,2004 (ZEUS)

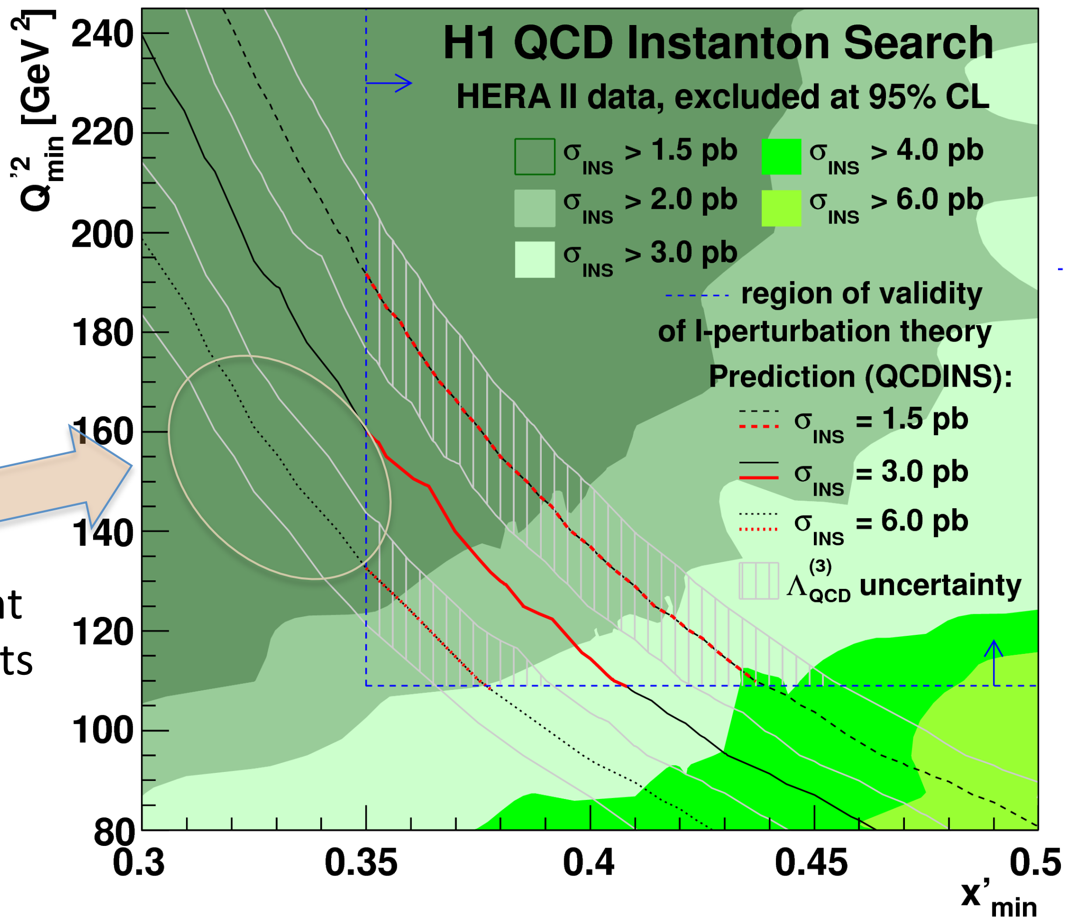
➔ New result from H1 with all data available (Sub. to EPJC, arXiv:1603.05567)

MULTIVARIATE Analysis
(based on E_{jet} ; number of charged particles; "Event shape" like observables)

➔ No signal;
➔ **Upper Limit 2 pb at 95% CL**

- **Instanton exclusion limits are improved by an order of magnitude and are challenging theory prediction for the first time**

- **The discovery of instantons would be the first evidence for topological fluctuations of a nonperturbative aspect of QCD**



Most stringent exclusion limits

region of validity of I-perturbation theory

$x'_{min} \geq 0.35$, $Q'^2_{min} \geq 109.0\ \mathrm{GeV}^2$

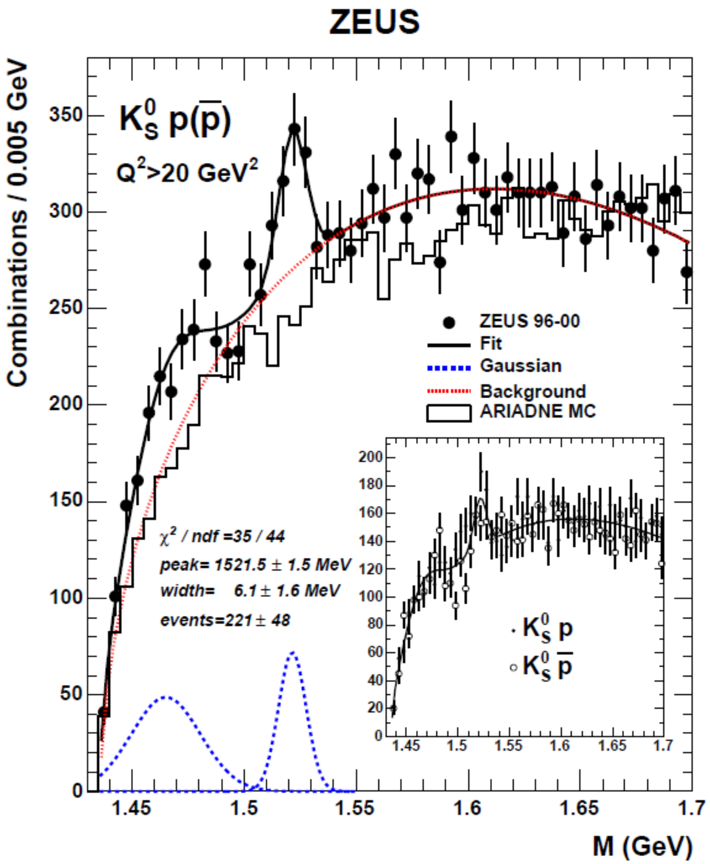
$\Lambda^{(3)}_{QCD} = (339 \pm 17)$ MeV

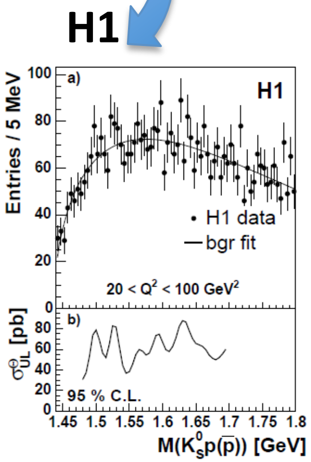
Strange penta-quarks at HERA

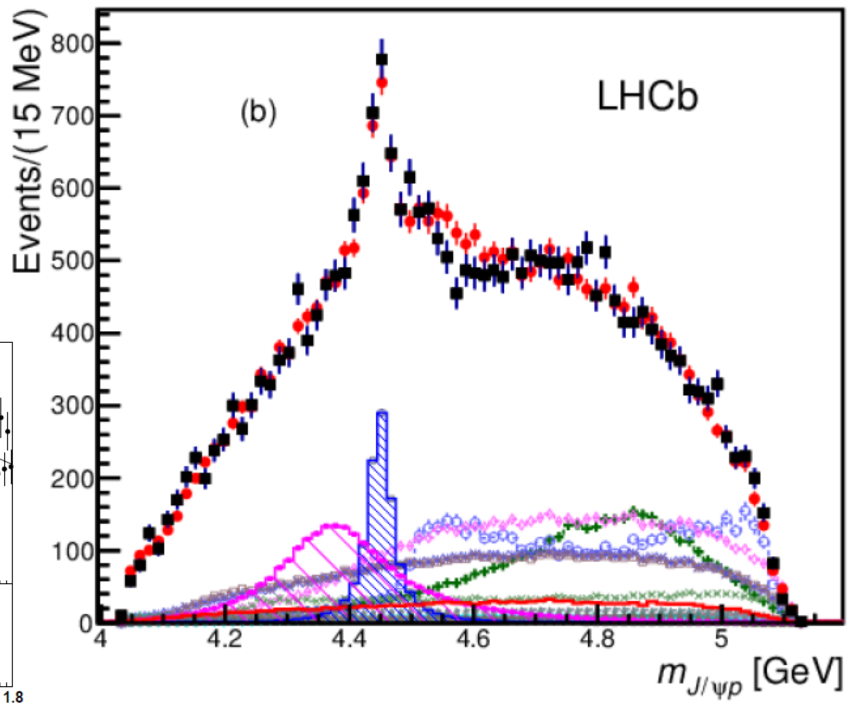
Search for a narrow baryonic state decaying to p-K^0_S and pbar-K^0_S in DIS at HERA

A candidate for a uudd-sbar state θ^+ was observed at HERA-I in M(p-K^0_S)
Phys. Lett. B 591 (2004)

The recent observation of LHCb can be considered as a strong evidence of existence of 5q states,
Phys. Rev. Lett. 115 (2015) 072001.

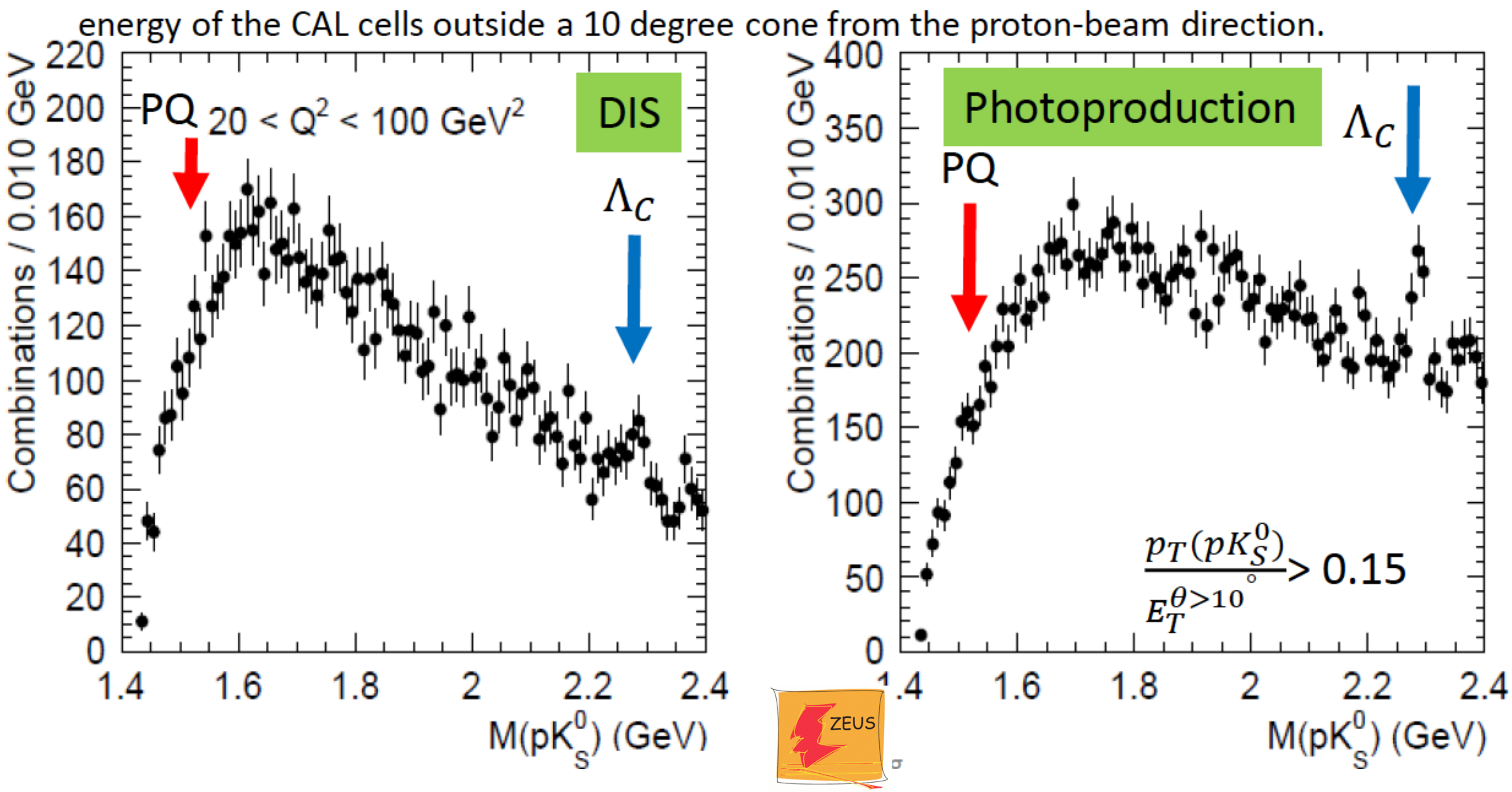






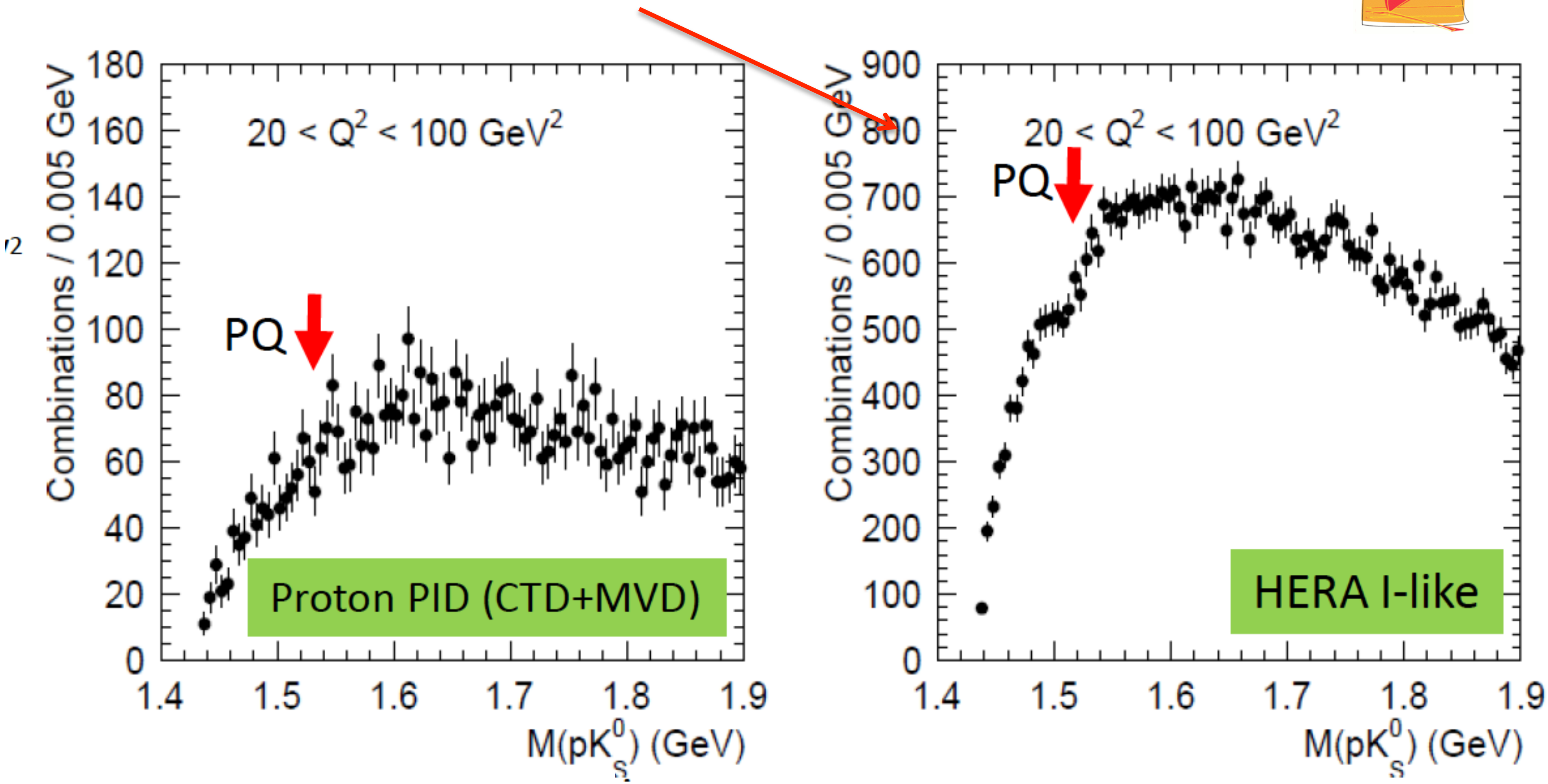
A clear motivation to look for the θ^{+} signal in HERA-II data.

pK^0_S invariant mass distribution in DIS and photoproduction samples:



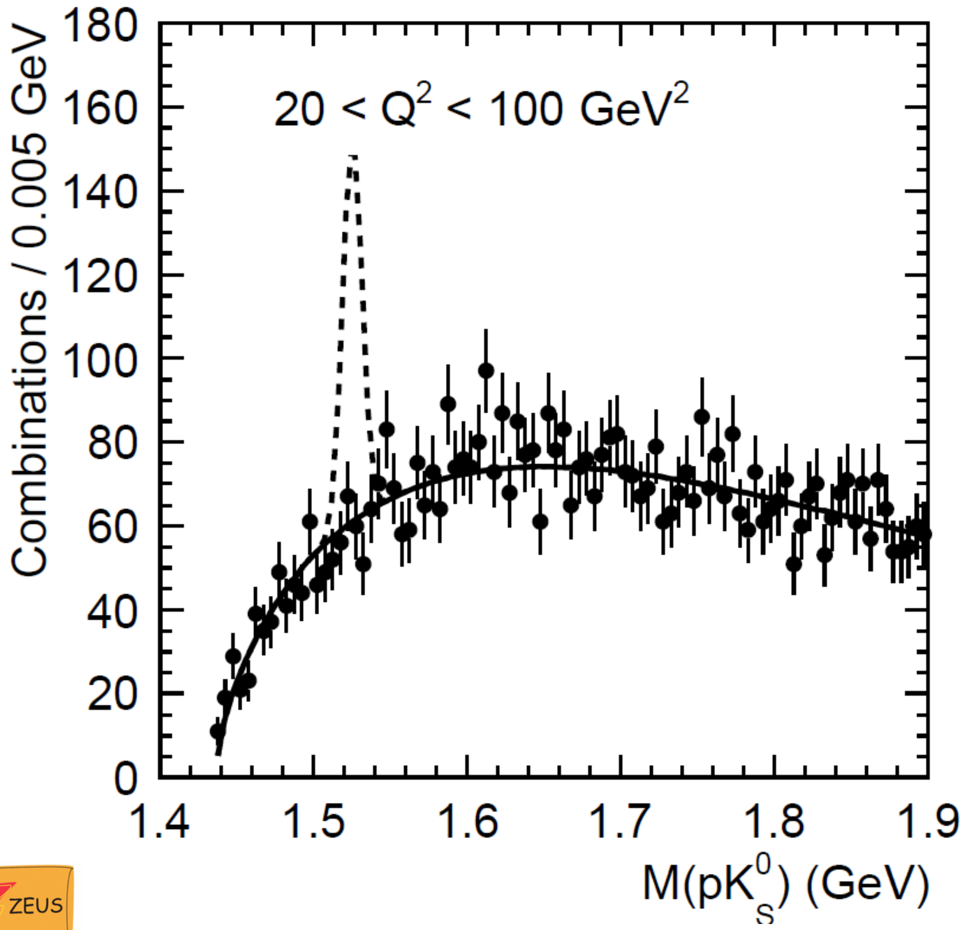
No PQ peak at the mass of Θ⁺(red arrow) is seen

A closer look (also with similar cuts to HERA-I) in DIS sample



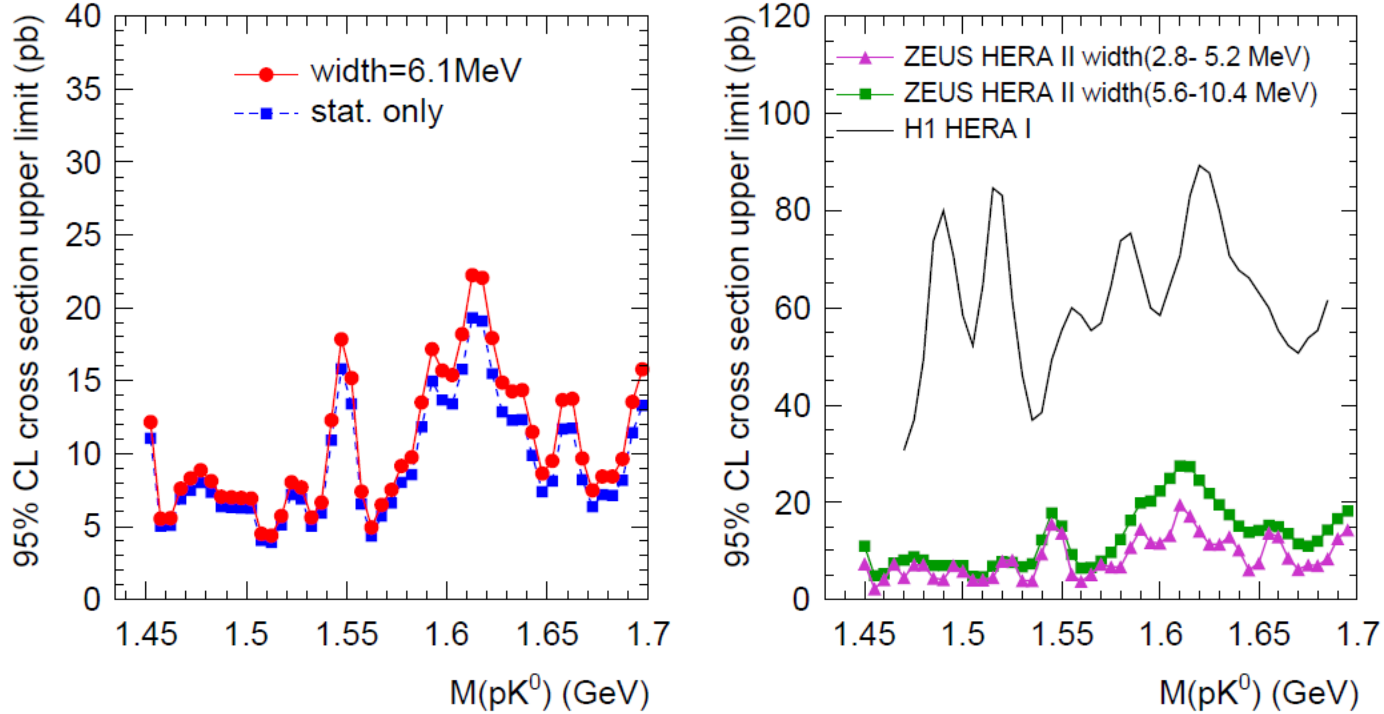
No PQ peak is seen, ever

Comparison with ZEUS HERA I analysis



The dashed line represents the Θ+ signal as it would be observed if it had the same strength as reported in the ZEUS HERA-I analysis
(expected 286 events)

As no clear signal is seen, the limits on the production cross-section of $\Theta^{\pm}$ is set.
B (Θ → *p K S*0) = 1 is assumed;
different widths hypotheses are tested;
results are compared with H1.



The search contributes to the 5*q* **state puzzle.**
Published *(today)***: Phys. Lett. B 759 (2016) 446.**

L. Maiani' conclusions at La Thuile, March 2016:

- until now, exotics seen contain heavy quark flavours: an experimental reexamination of the lack of existence of light exotic mesons ("bad" diquarks) and positive strangeness baryons is in order.
- much remains to be done, in theory and experiments,
- we look forward to exciting times for hadron spectroscopy: maybe we can understand QCD better.

Conclusions

- ➢ Nine years after the end of data taking, HERA experiments continue to deliver innovative, valuable physics results.

- ➢ Some result are unique and will remain the only source for the tests of state-of-the-art theoretical predictions for a long time.

- ◆ Multijet results in low Q2 region ➔ α_s extraction in DIS at NNLO
- ◆ Prompt Photon comparison with k_t-factorisation ➔ further compare with theory
- ◆ Instantons search ➔ exclusion region in non-perturbative regime
- ◆ Strange Pentaquarks ➔ stronger exclusion than previous results

BACKUP

Regularised unfolding

Regularised unfolding using ROOT::TUnfold

- Calculate unfolded distribution *x* by minimising

$$\chi^2(x,\tau)=(y-Ax)^T V_y^{-1}(y-Ax)+\tau L^2$$

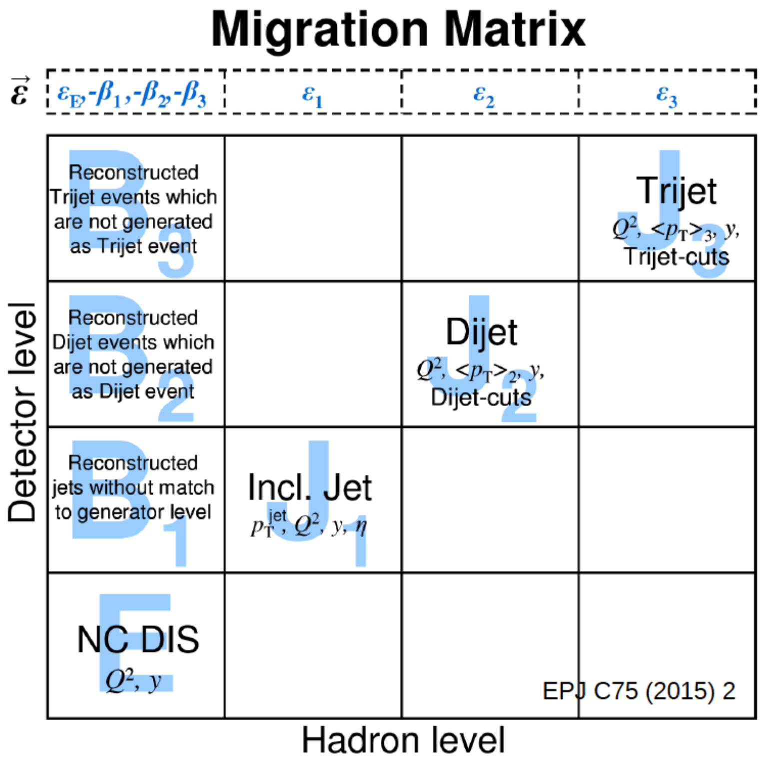
- Linear analytic solution
- Linear propagation of all uncertainties
- Statistical correlations are considered in V_y

Simultaneous unfolding of
Inclusive jet, Dijet, Trijet, NC DIS

- Similar to EPJ C75 (2015) 2
  -> One measurement of multiple observables
- Matrix constituted from O(10^6) entries
- Migrations in up to 6 variables considered for a single measurement
- 'detector-level-only' jets/events are contrained with NC DIS data
- System of linear equation becomes overconstrained when using more bins on detector than on generator level

JINST 7 (2012) T10003

x	Hadron level
y	Detector level
V_y	Covariance matrix
A	Migration matrix
τL^2	Regularisation term



Correlation matrix of multijets

Covariance matrix

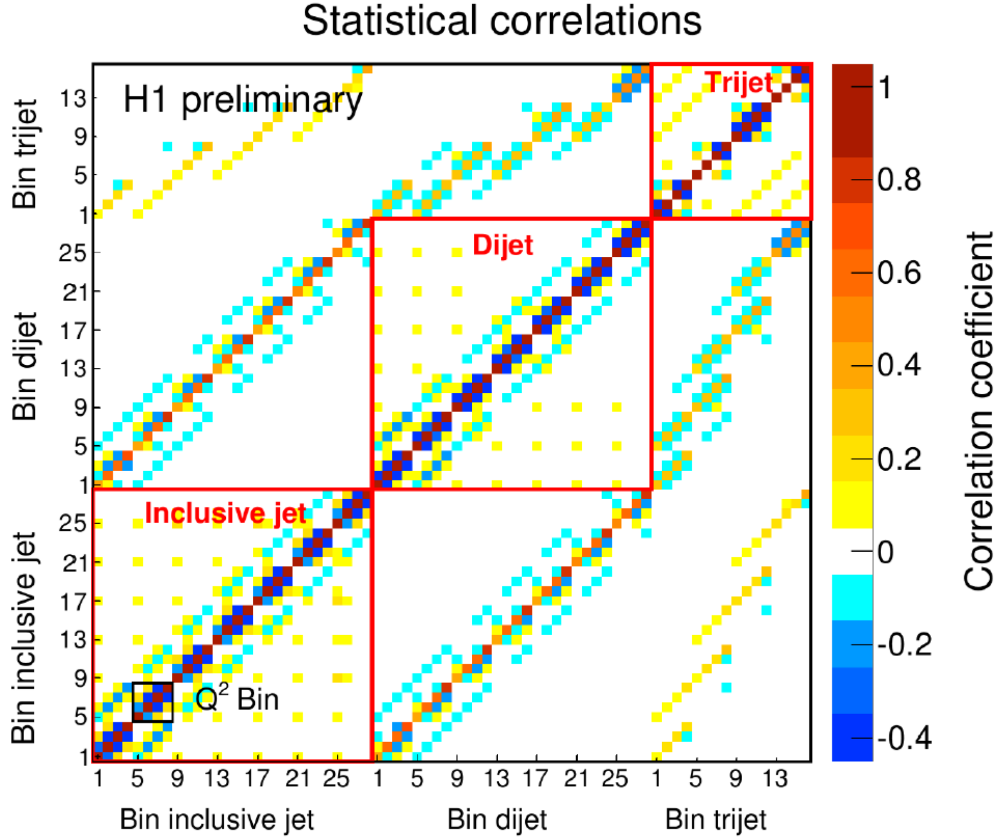
- Correlations beteween all data points are measured
- Obtained through linear error propagation of statistical uncertainties

Correlations

- Resulting from unfolding
- Physical correlations
  - Between measurements
  - Within inclusive jet

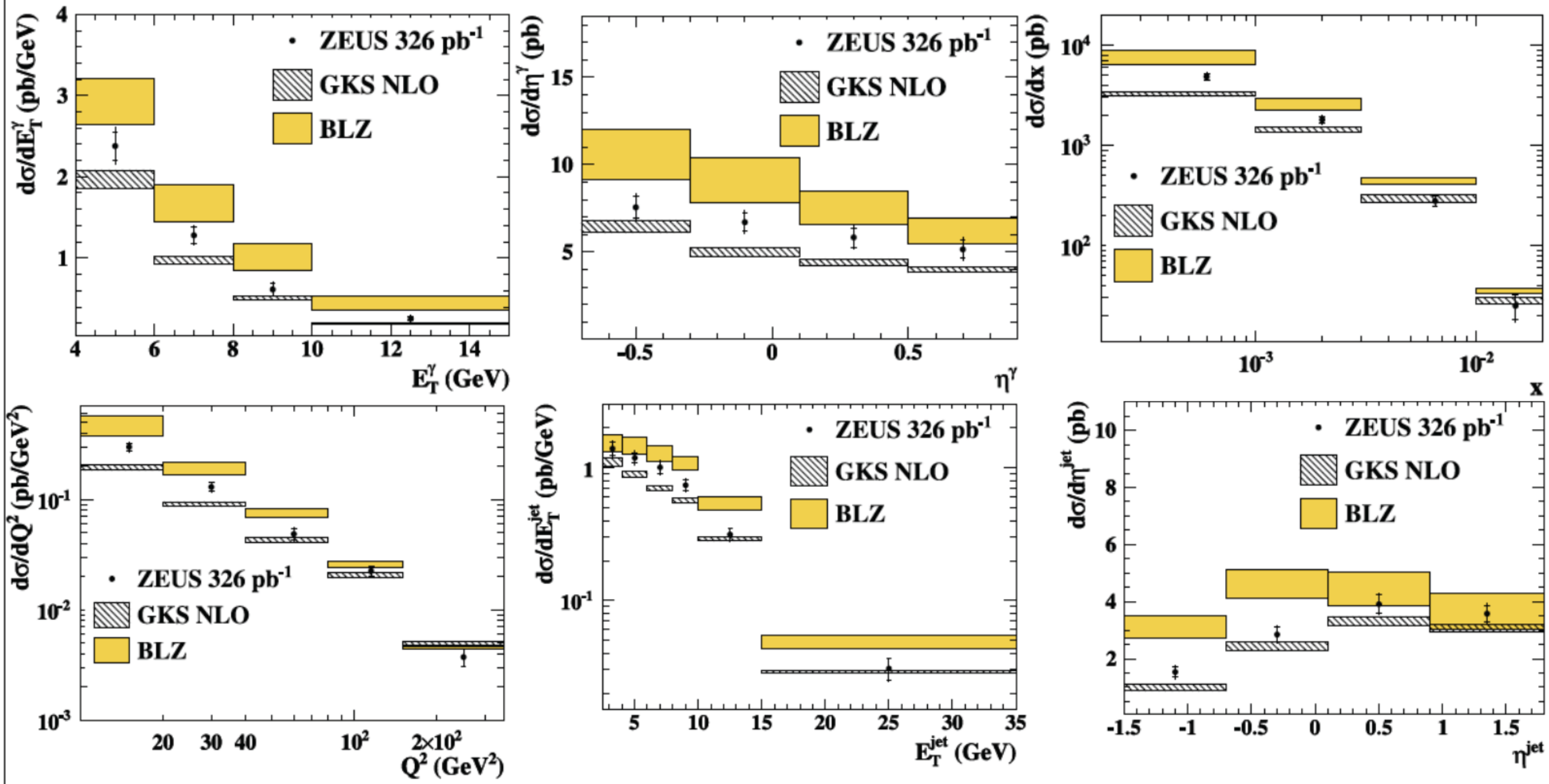
Useful for

- Cross section ratios
- Combined fits
- Normalised cross sections



Prompt Photon production

Previous study



- A previous publication (Physics Letters B 715 (2012) 88-97) has covered x, Q^2, E_T^{γ}, η_{γ}, E_T^{jet} and η_{jet}.

INSTANTONS: Exclusion limits on the plane Q'^2 vs x'

Calculation of instanton cross-section involves

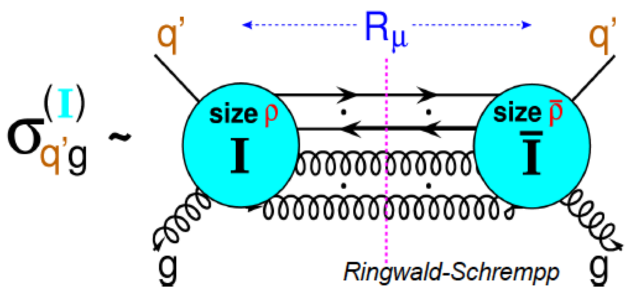
I-size distribution (ρ) and

I-$\bar{\text{I}}$-distance distribution (R/ρ)

<u>Key feature</u> : there is a one-to-one relation between variables in momentum space (Q',x') and space variables (ρ,R)

Large Q' ↔ small ρ

Large x' ↔ large R/ρ



Region of validity of **I**-perturbation theory in (Q',x')

from

Confrontation with lattice results for QCD(nf=0):

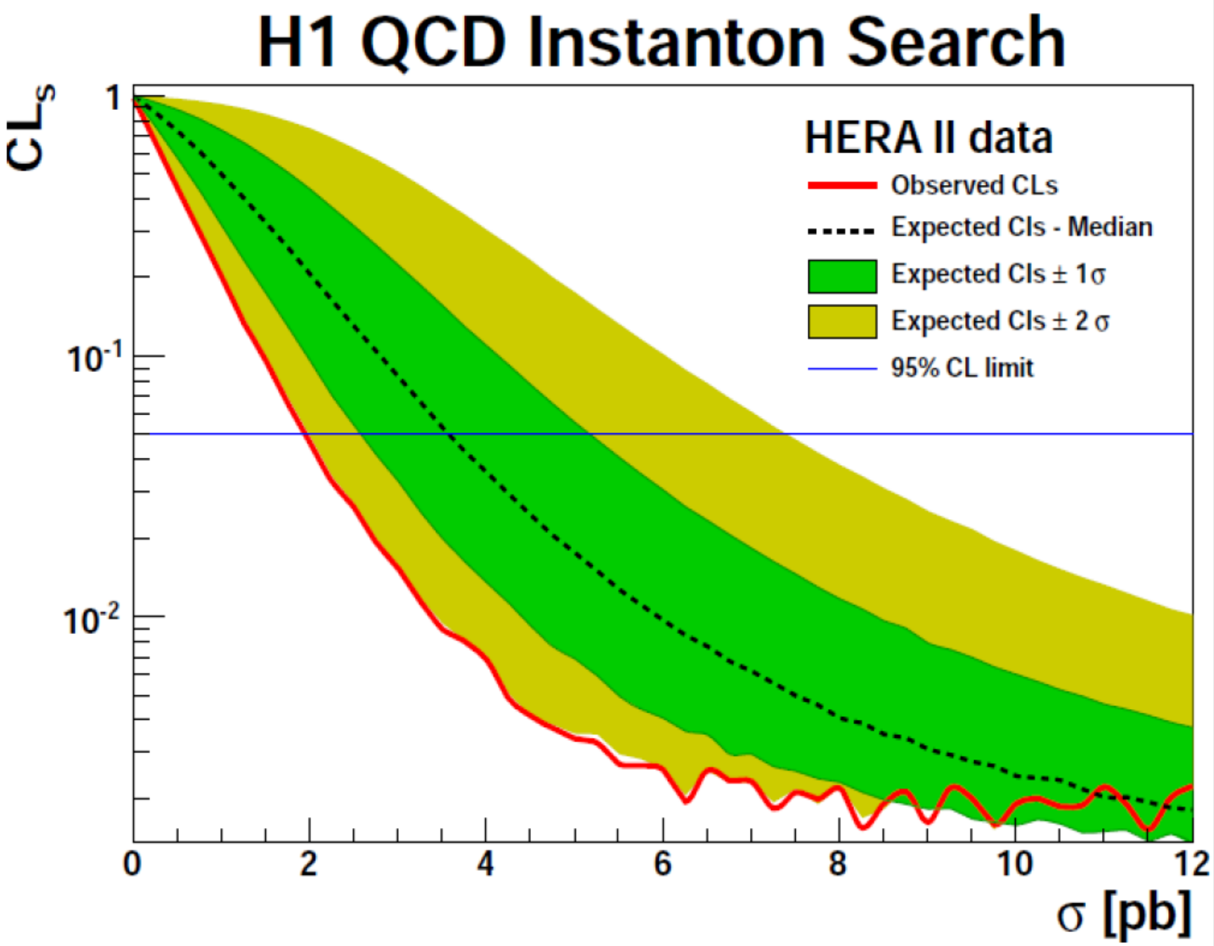
Limits:

- contain additional meaning in terms of instantons size/distance
- allow to assess the effect of the steeply falling x' and Q' distributions

INSTANTONS: Upper Limit

- CLs method
- Using full range discriminator
- Background:DJANGOH

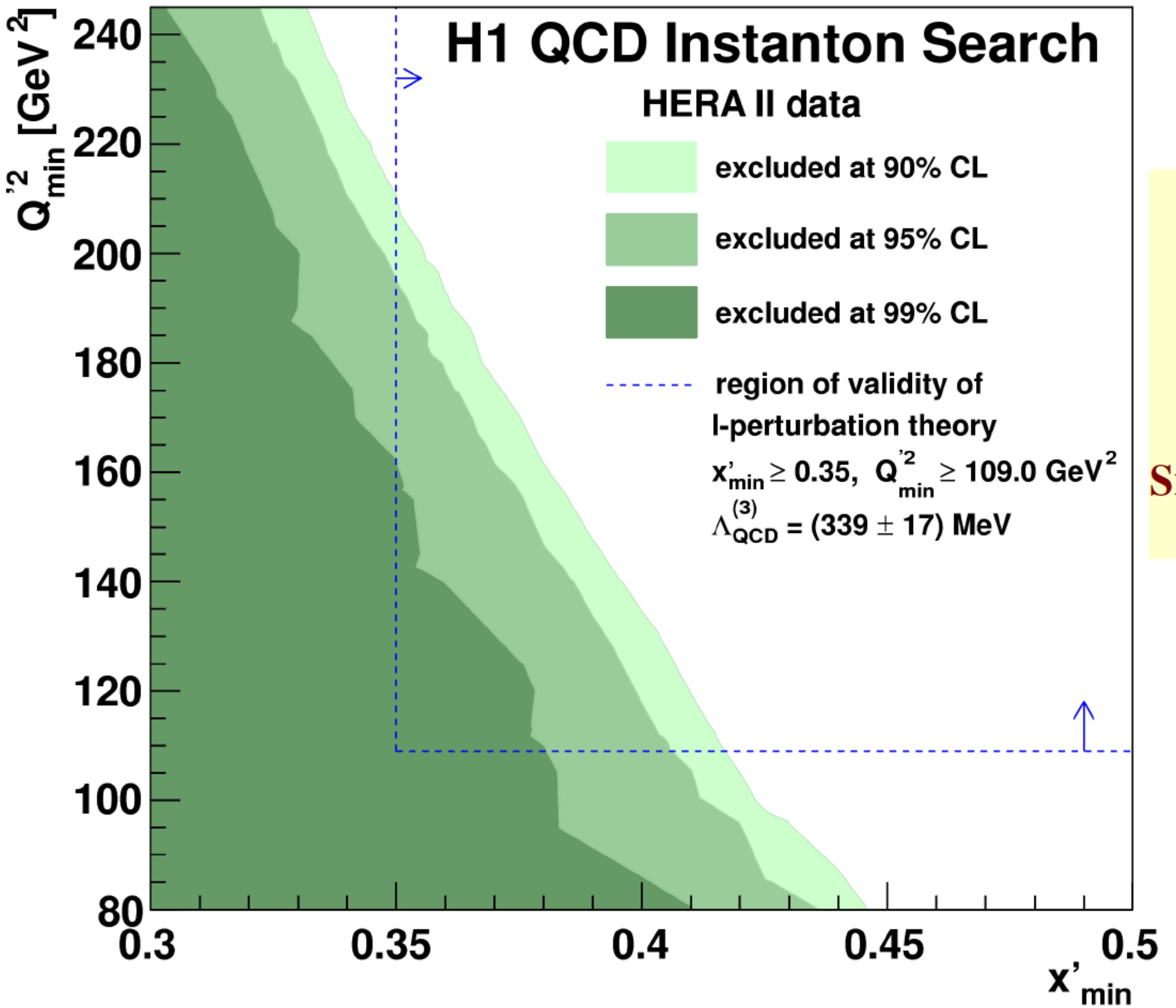
- Experimental syst uncertainties
- Difference DJANGOH-RAPGAP as ± background model uncertainty
- 30% uncertainty of predicted signal cross section due to Λ_{QCD} uncertainty



Observed Upper Limit:
2 pb at 95% CL

Predicted cross section:

$$150 < Q^2 < 15000\,\mathrm{GeV}^2,\quad 0.2 < y < 0.7$$
$$Q'^2 > 109\,\mathrm{GeV}^2,\quad x' > 0.35$$
$$\sigma^{(I)} = 10\,\mathrm{pb}$$



Exclusion limits

on Q'^2-x' plane as

$Q'^2 > Q'^2_{min}$, $x' > x'_{min}$

Significant part is excluded

STRANGE PENTAQUARKS (Hi)STORY

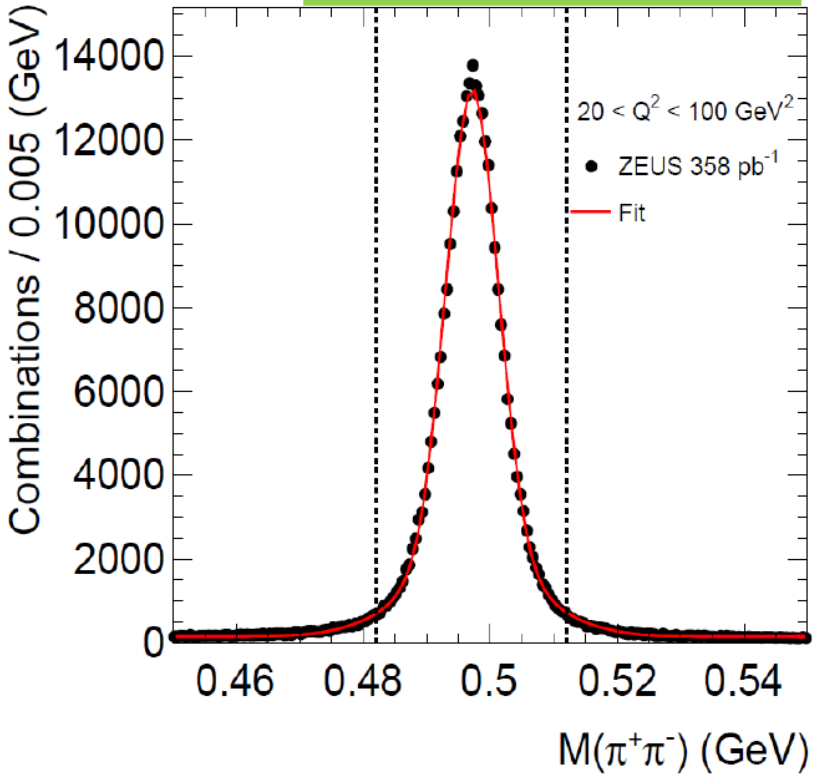
- The observation of a narrow baryon resonance with a mass of ~1.53 GeV was reported first by the LEPS experiment in 2003 in the missing-mass distribution for $\gamma A \rightarrow nK+$ reaction. Such a baryon would be manifestly exotic and impossible for a three-quark state. But could be explained as a bound state of five quark state i.e. a pentaquark, named Θ+(*uudd-sbar*). Many experimental groups have looked for this state via various production processes in decay mode $nK+$ or p-K^0_S (pbar-K^0_S).
  Some experiments confirmed the signal while others refuted it.

- Recently, interest in pentaquark state has arisen with the discovery of two pentaquark candidates by the LHCb experiment at 4.38 and 4.45 GeV.
  They have a valence quark content of *uudc-cbar* and were observed with high significance.

- The ZEUS experiment reported the evidence of a peak structure in p-K^0_S (pbar-K^0_S) mass distribution in deep inelastic scattering (DIS) data in HERA I period (1996-2000).
  The present search for a Θ+ pentaquark in the p-K^0_S (pbar-K^0_S) system is reported with the ZEUS data taken at HERA II period (2003-2007).
  The HERA II period not only provided larger statistics (358pb-1), but the ZEUS tracking system was upgraded. Looking for pentaquarks in DIS event with $20 < Q^2 < 100$ GeV^2 in order to compare with the HERA I results.

$K_S^0 \to \pi^+\pi^-$ selection

of K_S^0 0.31M events



- Two tracks with opposite charge
- $p_T(\pi) > 150$MeV
- $|\eta(\pi)| < 1.75$
- π track's MVD hit > 2
- $p_T(\pi\pi) > 250$MeV
- $|\eta(\pi\pi)| < 1.6$
- Pion mass constraint fitting
  - χ^2 of fit < 5.0 (of the two tracks fit)
  - DCA between two tracks < 1.5 cm
  - DCA between beam spot and K_S^0 vertex > 0.2 cm
- 2D co-linearity < 0.06 rad
- 3D co-linearity < 0.15 rad

  (co-linearity; the angle between position and momentum vectors.)
- K_S^0 decay length (DL) > 0.5 cm
- When we assign the electron mass to the track, M(ee) > 0.070 GeV
- When we assign the proton mass to one of the tracks, M(pπ) > 1.121 GeV
- Finally, we set a K_S^0 mass window (0.482 < M(ππ) < 0.512 GeV, dashed line).