Latest results on jets and the hadronic final state at HERA

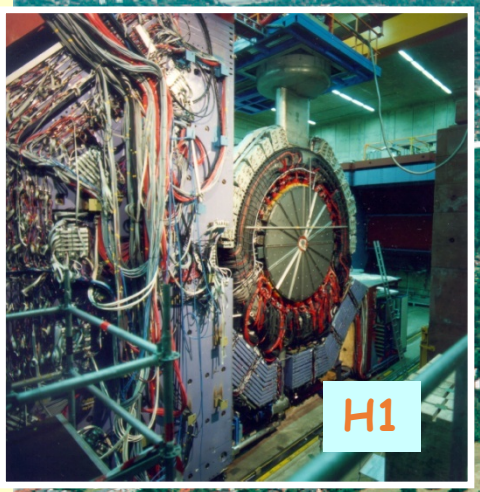
XLVI International Symposium on Multiparticle Dynamics (ISMD2016)
Seogwipo KAL Hotel, Jeju Island (30-Aug-2016)

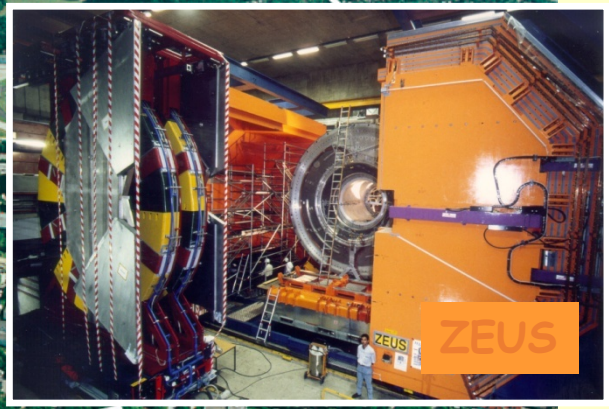
Katsuo Tokushuku (KEK)

On behalf of the H1 and ZEUS collaborations

DESY/HERA

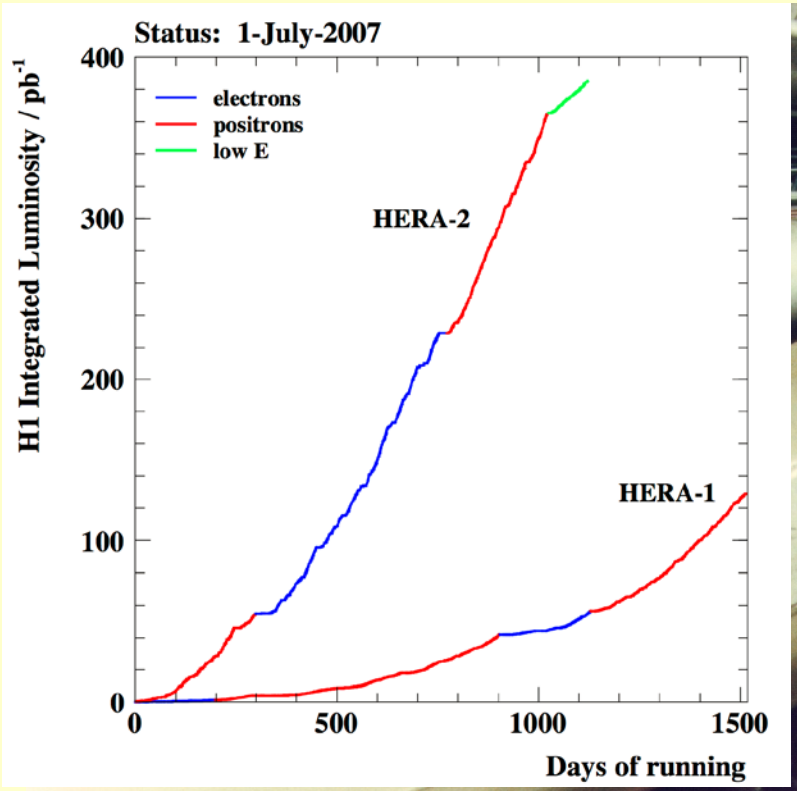
HERA 1992-2007





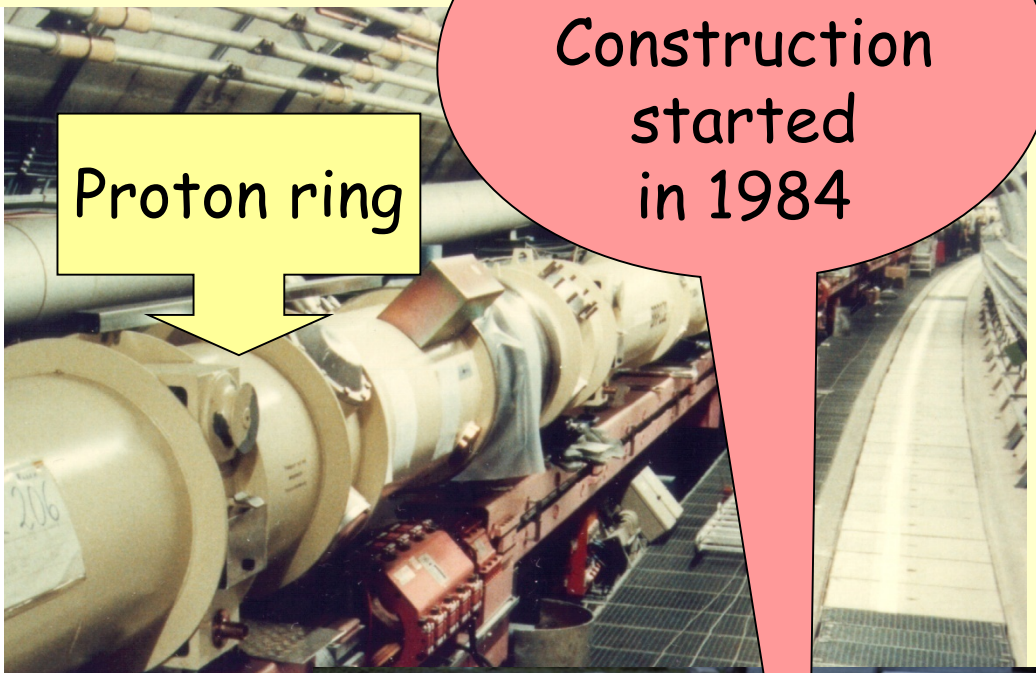
HERA:
(27.5GeV electron 920GeV proton)
the world largest electron microscope

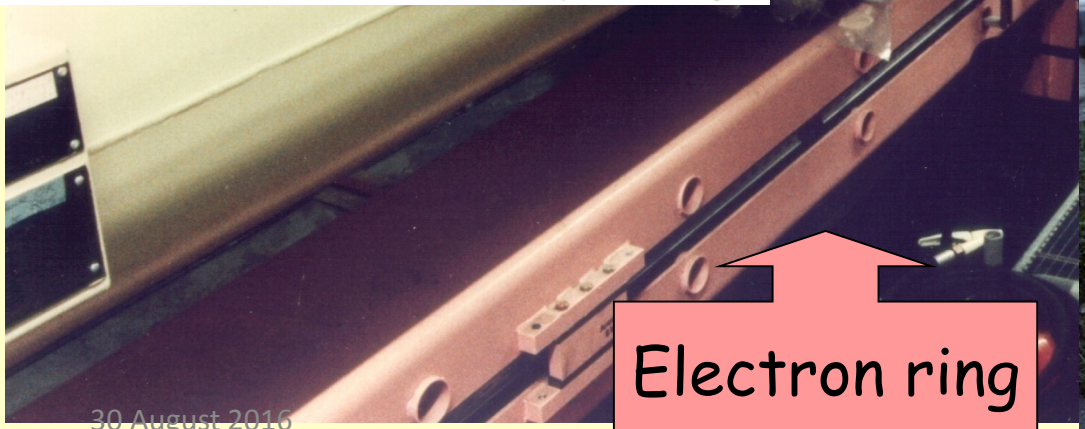
A view of the HERA ring tunnel



Tunnel Construction started in 1984

Proton ring

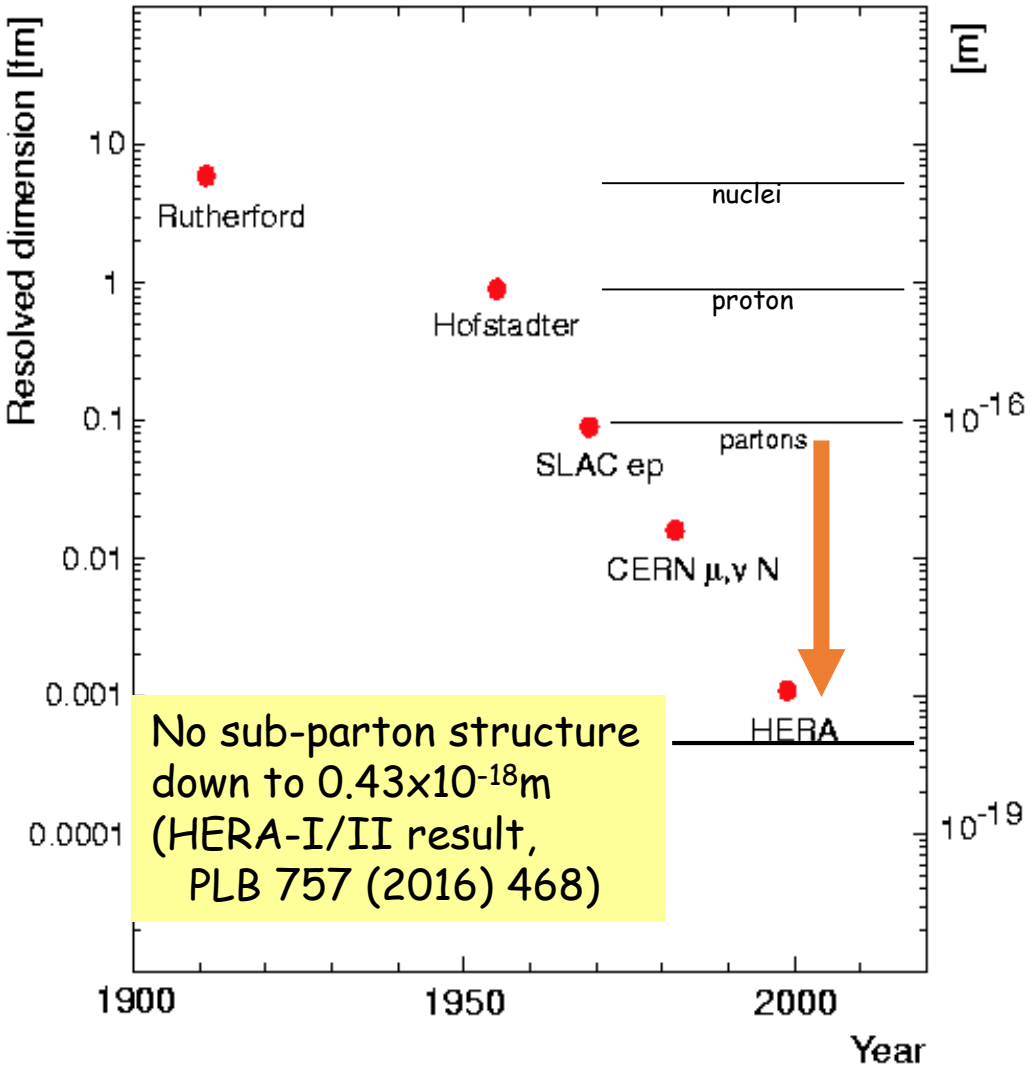




Electron ring

Resolution $\sim$ (Wavelength)$^{-1} \sim \hbar/Q$

$$Q^2 \equiv (q_i - q_f)^2$$



Progress in accelerator enables us to investigate the smaller structure.

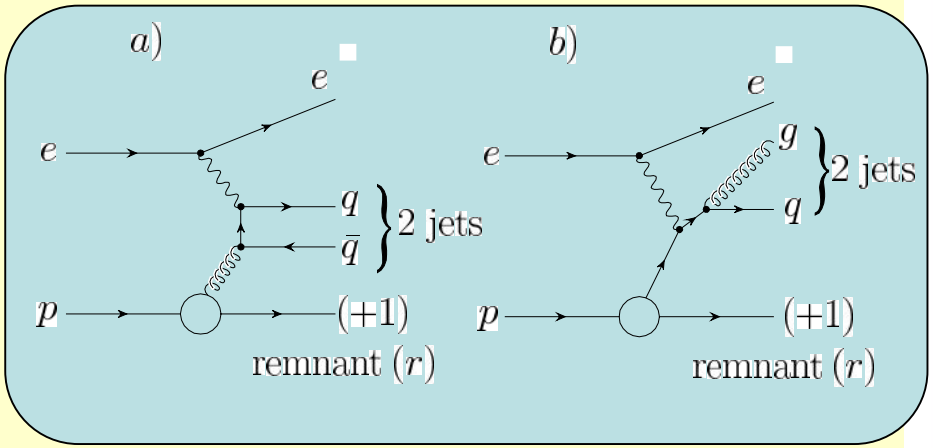
HERA:
(27.5GeV electron(positron) vs. 920 GeV proton)

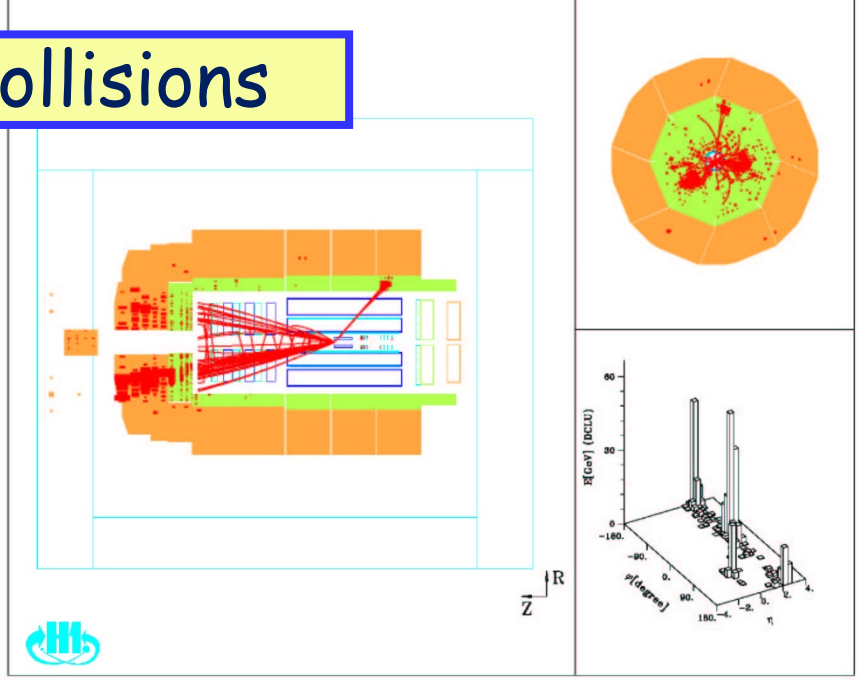
$Q^2_{max}=s=4E_eE_p\sim10000GeV^2$

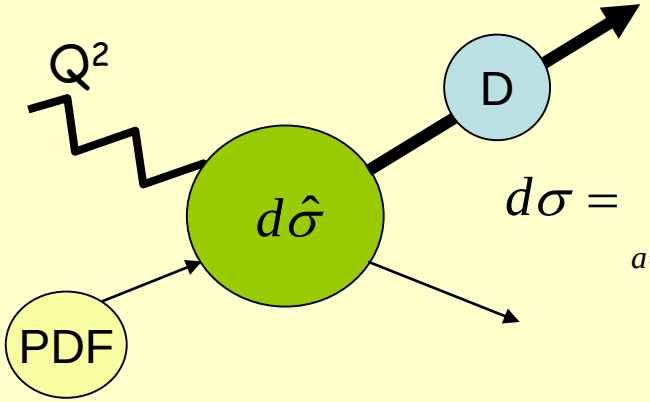
cf. in the rest frame
$s=2E_eM_p$

In order to obtain the same CMS energy as HERA in a fixed target experiment, it requires 54TeV electron beam.

Particle Production in *ep* collisions







$$d\sigma = \sum_{a=q,\bar{q},g} \int dx f_a(x,\mu_F;\alpha_s)\, d\hat{\sigma}(xP,\mu_F;\mu_R;\alpha_s(\mu_R)_s)\, D(z,\mu_{F'};\alpha_s)$$

source parton distribution | Hard scattering cross section | Fragmentation Function

HERA: A good test bench for QCD
under control of photon virtuality (Q^2)

Particle Production in *ep* collisions

In this talk, I will present recent results on particle production at HERA.

- Perturbative topics at small α_s
  - Jet cross section at DIS (H1)
  - Prompt photon at DIS (ZEUS)
- Non-perturbative topics at small α_s
  - Search for instanton process (H1)
- Non-perturbative topics at large α_s
  - Pentaquark searches (ZEUS)

Dijet update :H1

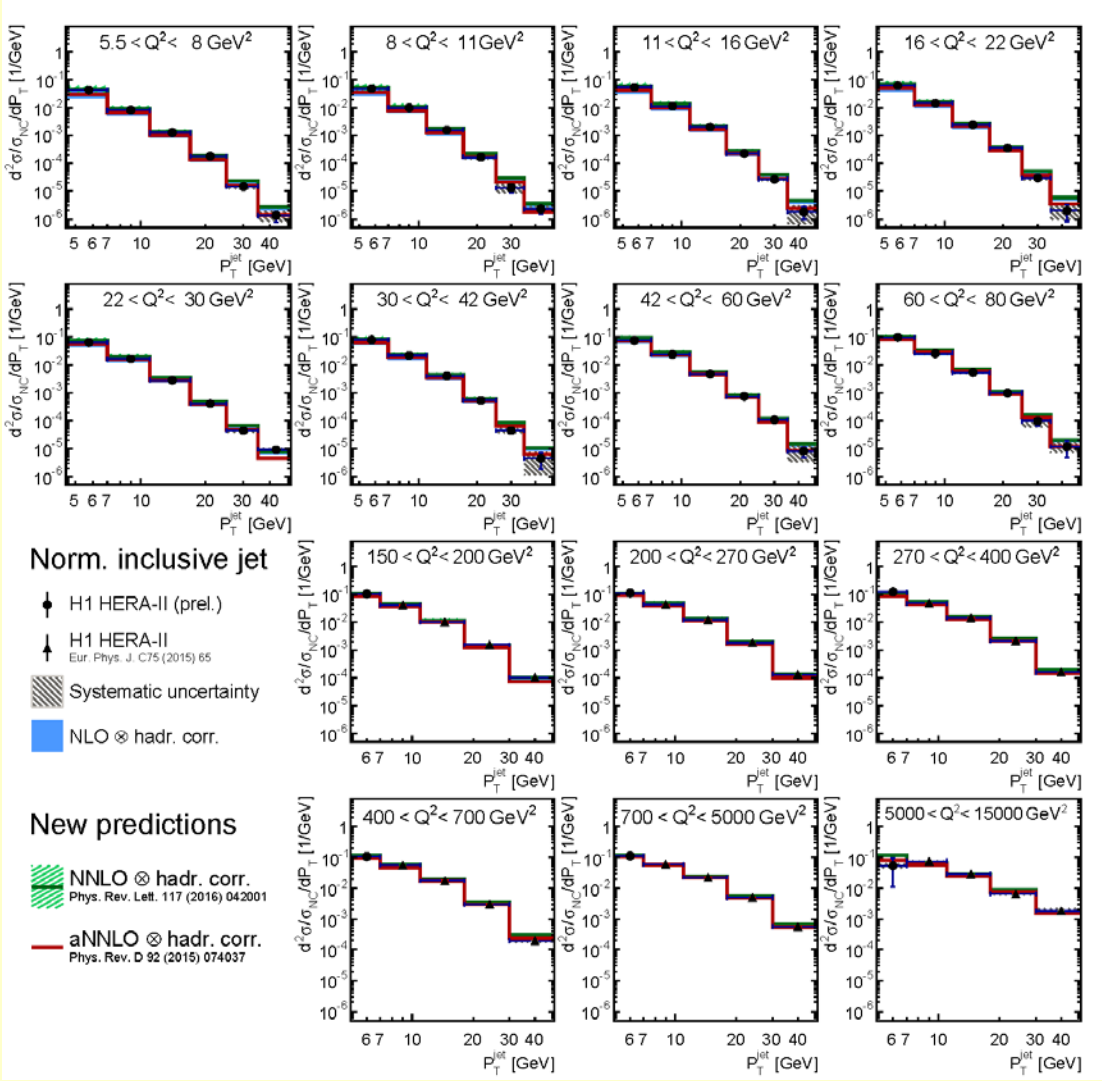
H1prelim-16-061 and H1prelim-16-062

Inclusive-/di-/tri-jet production at low Q^2 (5-100 GeV^2) with HERA-II data
(high-Q^2 results (150-15000 GeV^2 were published as EPJ C75 (2015) 2)

Normalized cross section to the inclusive DIS cross section. -> less correlation with the inclusive cross section -> suitable for the global fit.

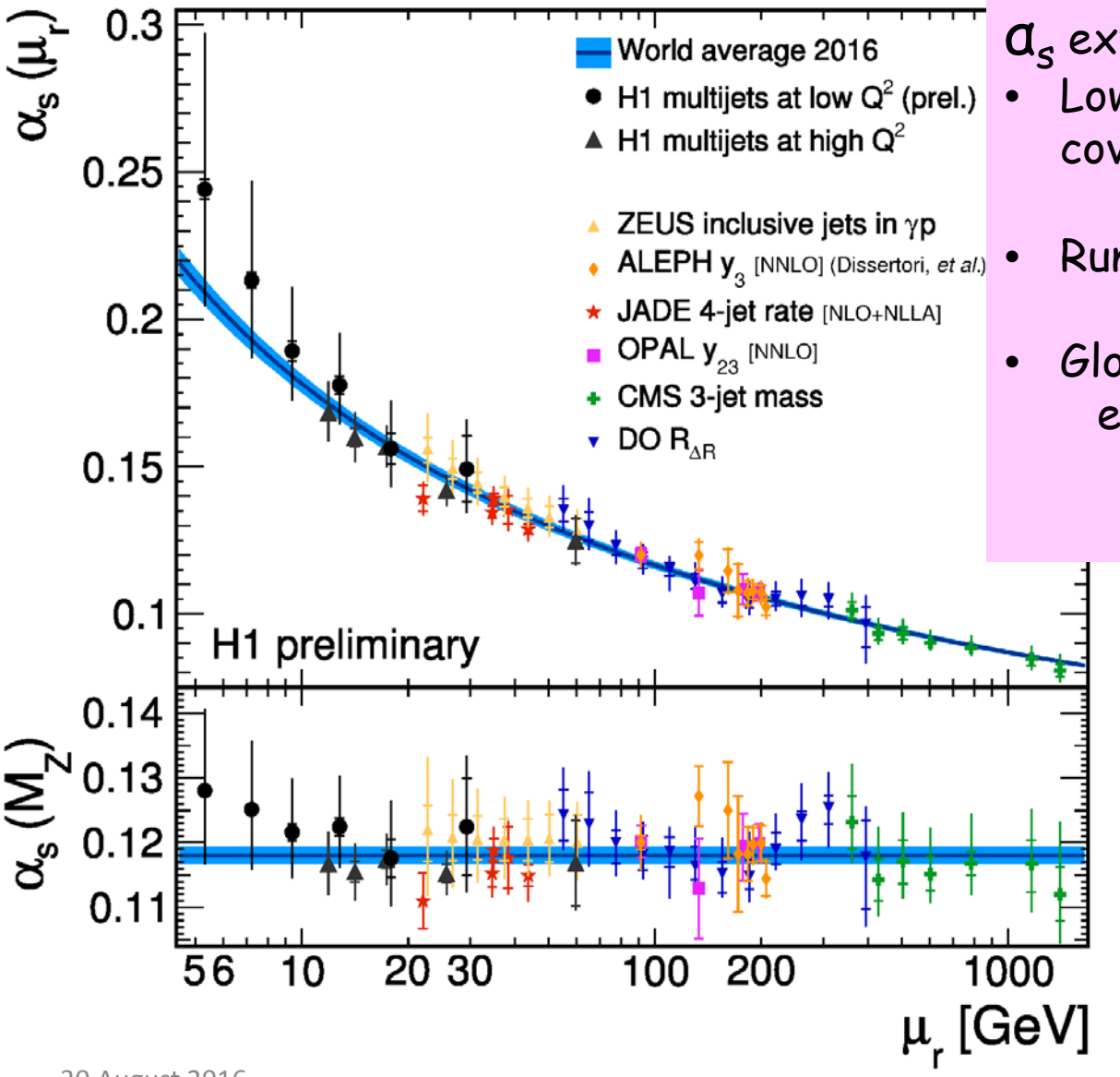
- Jets in the Breit frame.
  Pt_{jet} : 4.5 – 50 GeV
  Pt_{jet2}: 5 - 50 GeV (for di-jet)
  Pt_{jet3}: 5.5-50 GeV (for tri-jet)
- η^{lab}_{jet} : -1 – 2.5
- y : 0.2-0.6

Comparison with NLO/NNLO predictions



Dijet update :H1

H1prelim-16-062

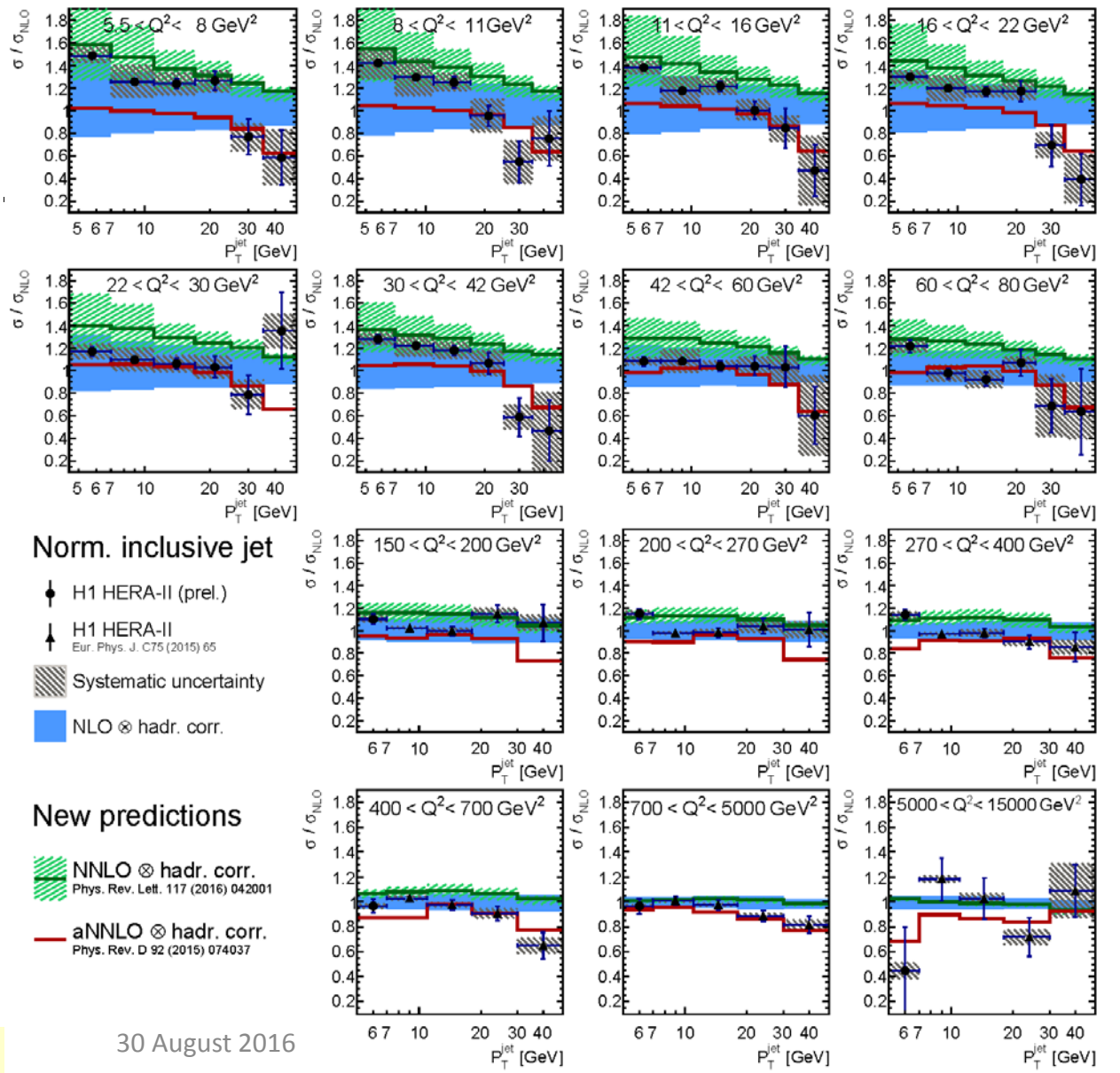


α_s extraction @NLO

- Low scale points are covered with this analysis
- Running! at μ: 5-30 GeV
- Global fit in progress expected precision for $\alpha_s(Mz)$: 0.4%

Inclusive-jet:H1

H1prelim-16-062



- Comparison with NLO/aNNLO/NLO

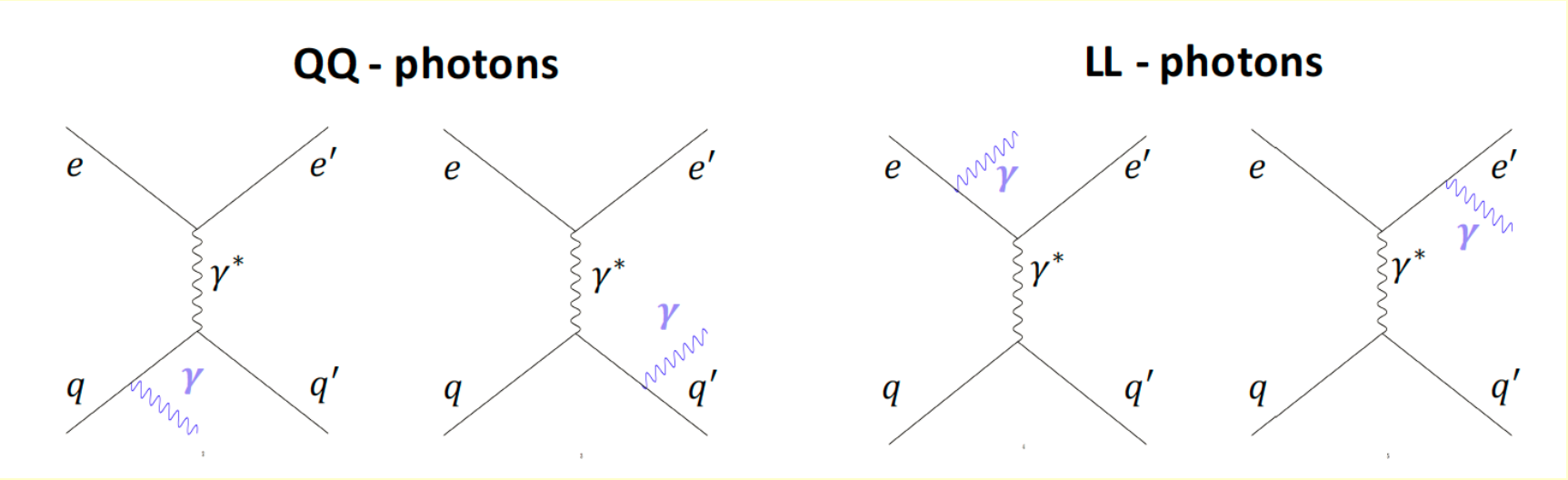
  aNNLO: Biekoetter, Klasen, Kramer, PRD92. (2015) 074037

  NNLO: Currie, Gehrmann, Niehues, PRL 117 (2016) 042001

- Good agreement with Data
- NNLO~NLO within uncertainty:
  Converging!
- Better Pt description with NNLO !

$\mu^2_r = \mu^2_f = (1/2)(Q^2 + P^2_T)$
$(\mu^2_f = Q^2,\ \text{for}\ Q^2 > 150)$

Prompt Photon : ZEUS



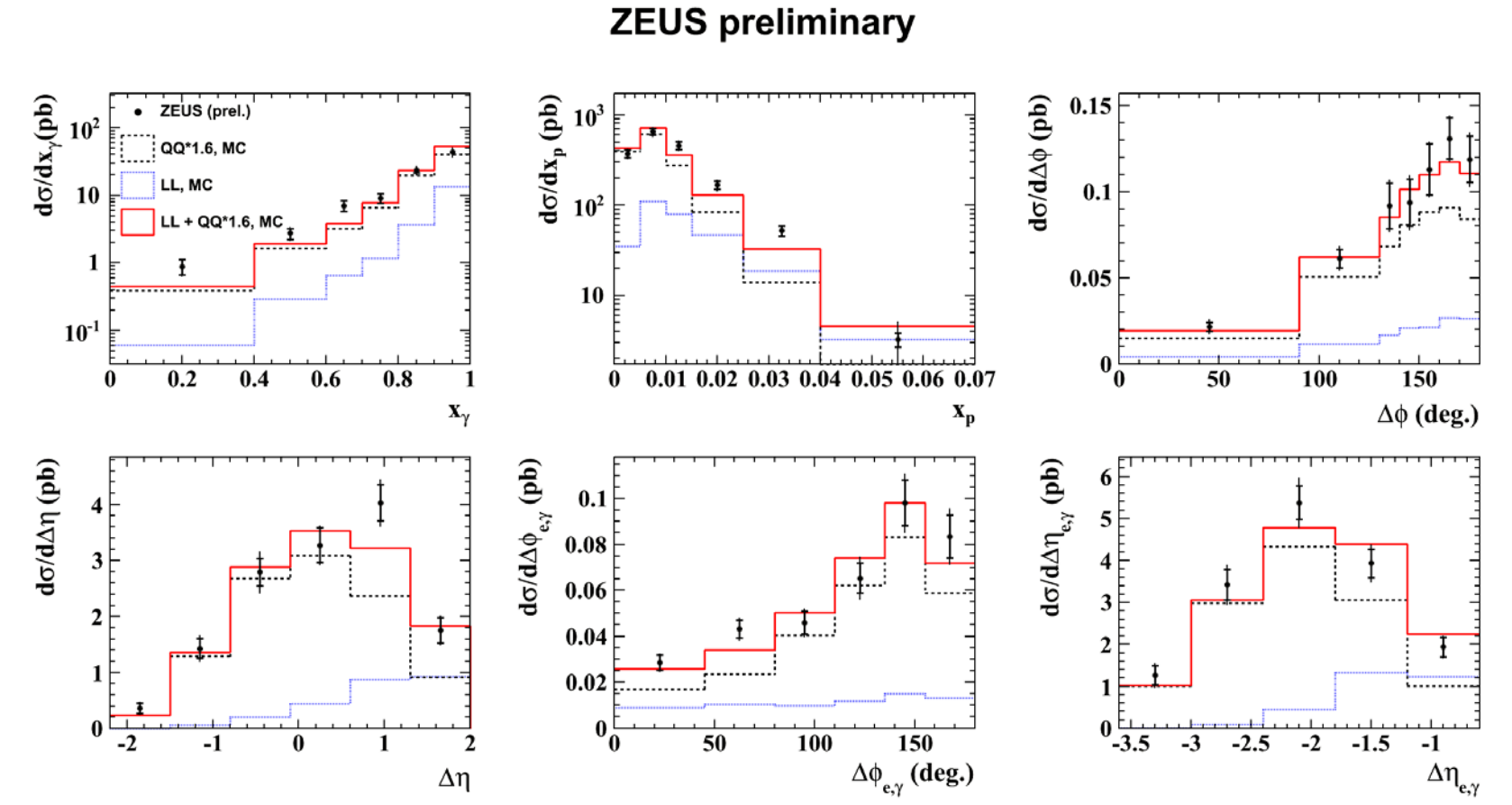
In the previous publications, inclusive distributions of photons and jets (PLB 715 (2012) 88) and those with x_γ (separation at 0.8) (JHEP 1408 (2014) 023) were shown and were compared with theories of NLO and K_T factorization.

Further tests with various jet-photon variables.

Prompt Photon : ZEUS

Q^2 : 10 – 350 GeV^2
Jet: Et>2.5 GeV, η_{jet} : -1.5 – +1.8
Photon: Et: 4-15 GeV, η : -0.7 - +0.9
(with isolation cuts)

ZEUSprelim-16-01

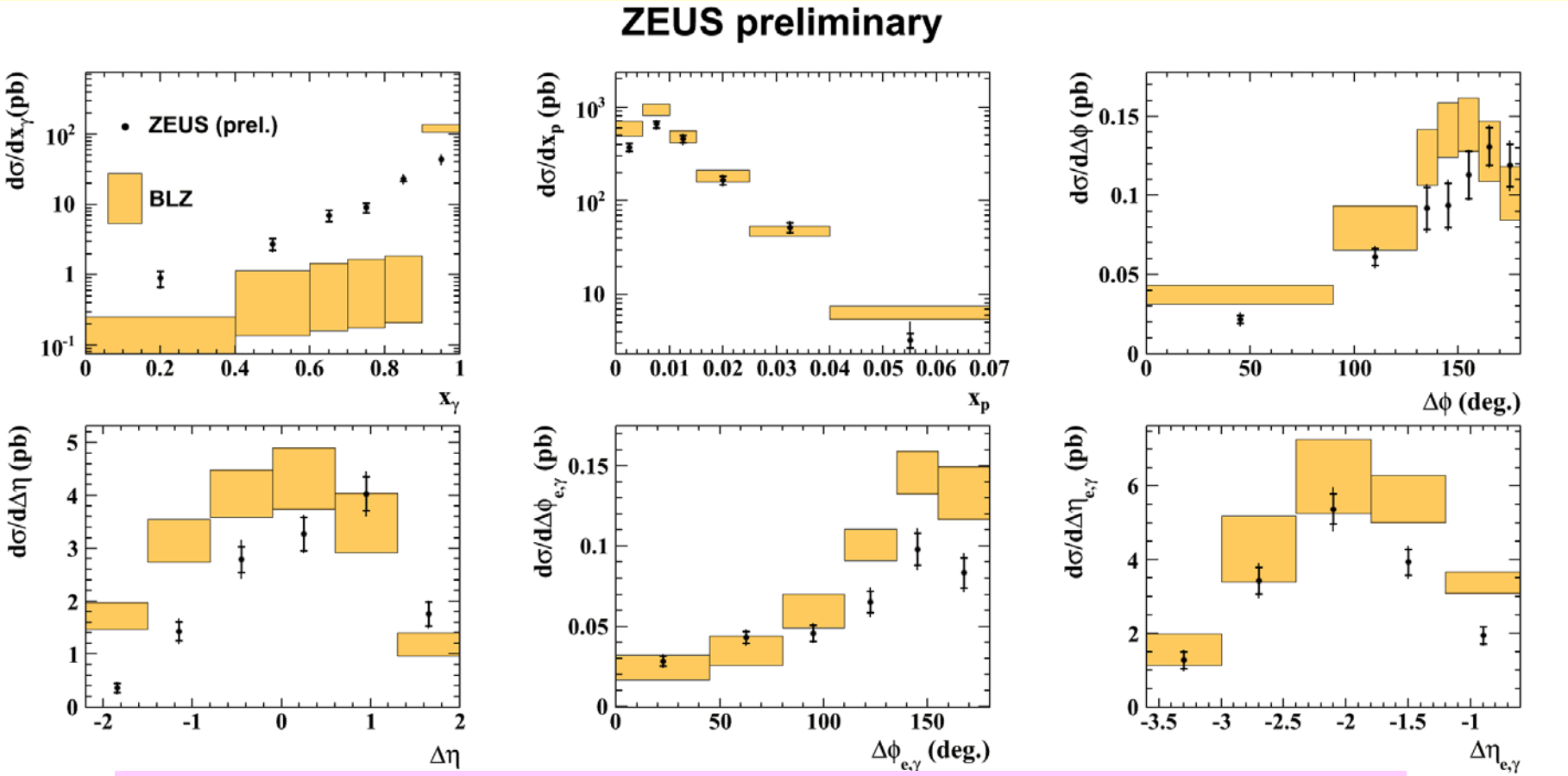


Comparison with Pythia : Good agreement once LL and QQ contribution is normalized.

Prompt Photon : ZEUS

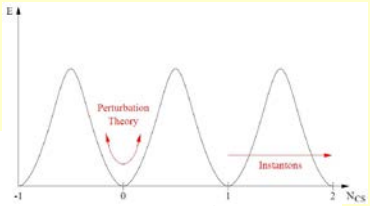
Q^2 : 10 – 350 GeV^2
Jet: Et>2.5 GeV, η_{jet} : -1.5 – +1.8
Photon: Et: 4-15 GeV, η : -0.7 - +0.9
(with isolation cuts)

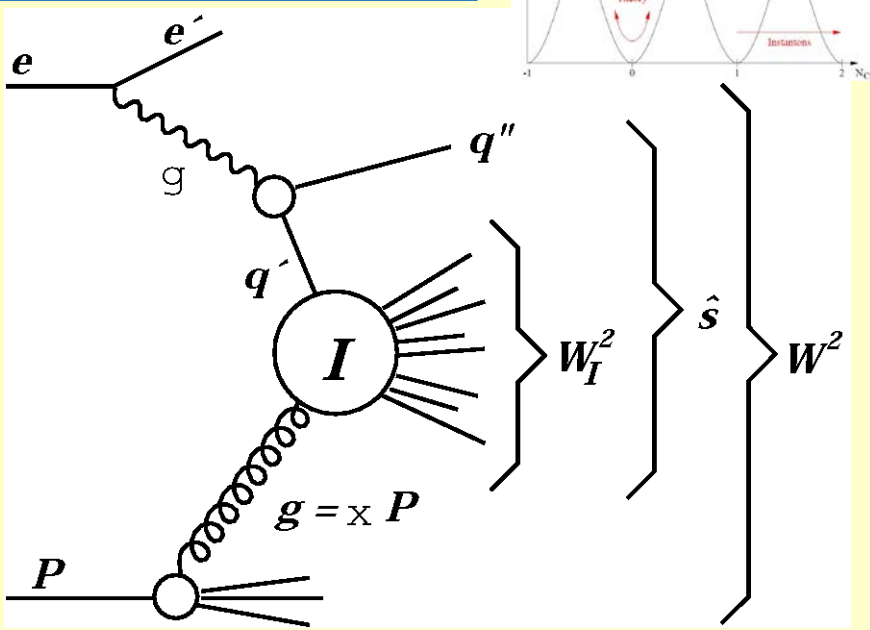
ZEUSprelim-16-01



Comparison with Baranov-Lipatov-Zotov (BLZ) theory with KT factorisation: (PRD 81 (2010) 09434).
A fair agreement except x_γ and $\Delta\eta$.

Instanton



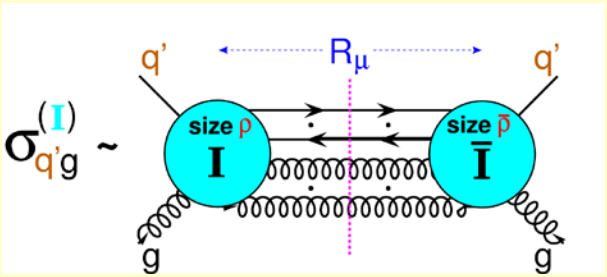


In QCD, certain processes violate the conservation of chirality. – Instantons.

--> Non-perturbative fluctuation of the gluon field. Tunnelling between 2 vacuum states.

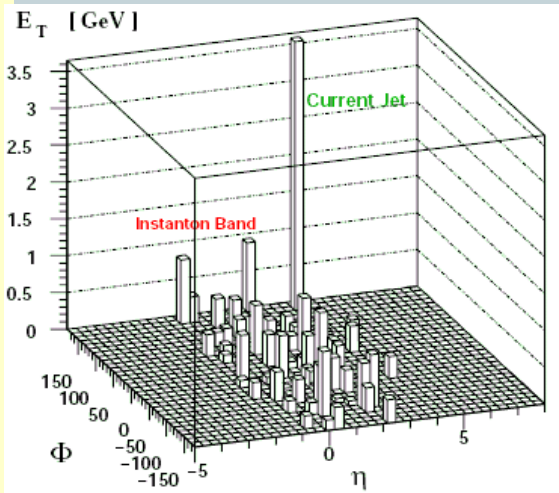
Ringwald and Schrempp pointed out that instanton-induced events can be seen in DIS. The cross section is calculable in a certain kinematical region (defined by q' and g (Q'^2,x')--> instanton size (r) and distance Rμ) .

σ=10 ~ 100 pb.



Events are simulated by the QCDINS. Events are expected to have distinct signature.

Many quark and gluons --> fireball like



$$q + g \xrightarrow{I} \sum_{n_f} (q_R + \bar{q}_R) + ng$$

$$q + g \xrightarrow{\bar{I}} \sum_{n_f} (q_L + \bar{q}_L) + ng$$

Instanton HERA-1 Results : H1

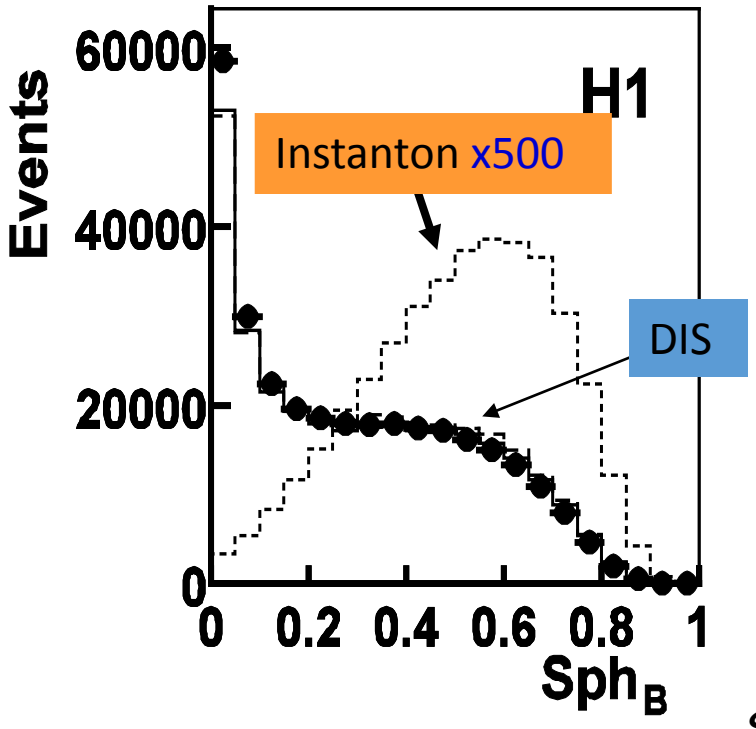
EPJ. C **25**, 495 (2002)

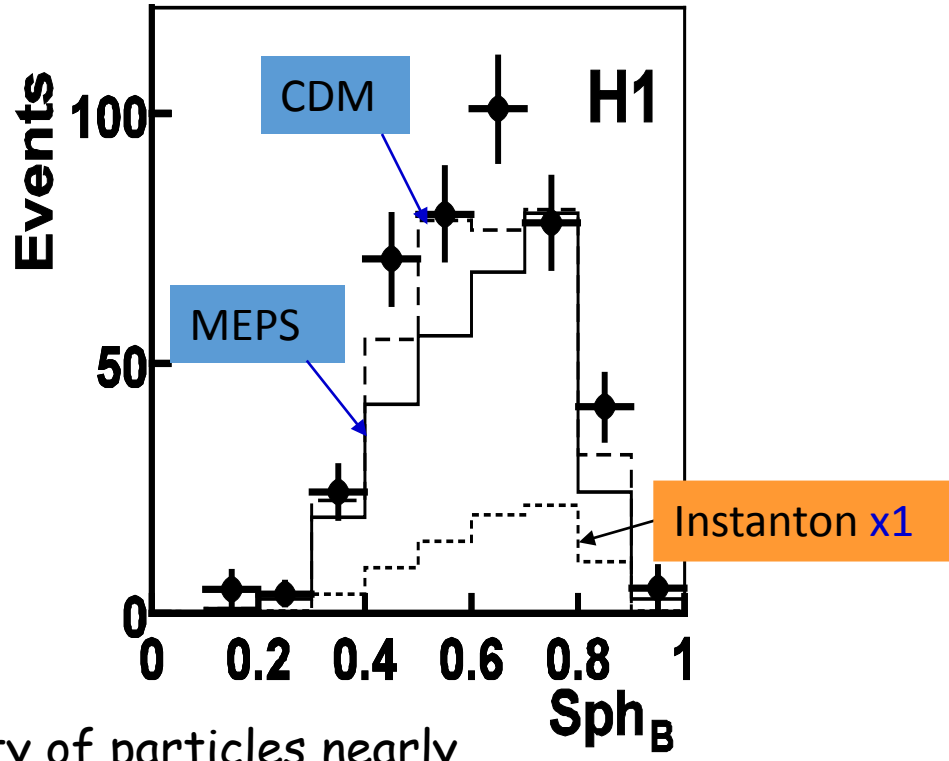
Instanton events have different particle emission patterns from the normal DIS.
But the expected production rate is not so large

One example

After the selection cut to enhance the instanton-like sample, the difference in the two normal-DIS MC's predictions are still large
(IntL=21.1pb^{-1} Q^2=10-100GeV^2)

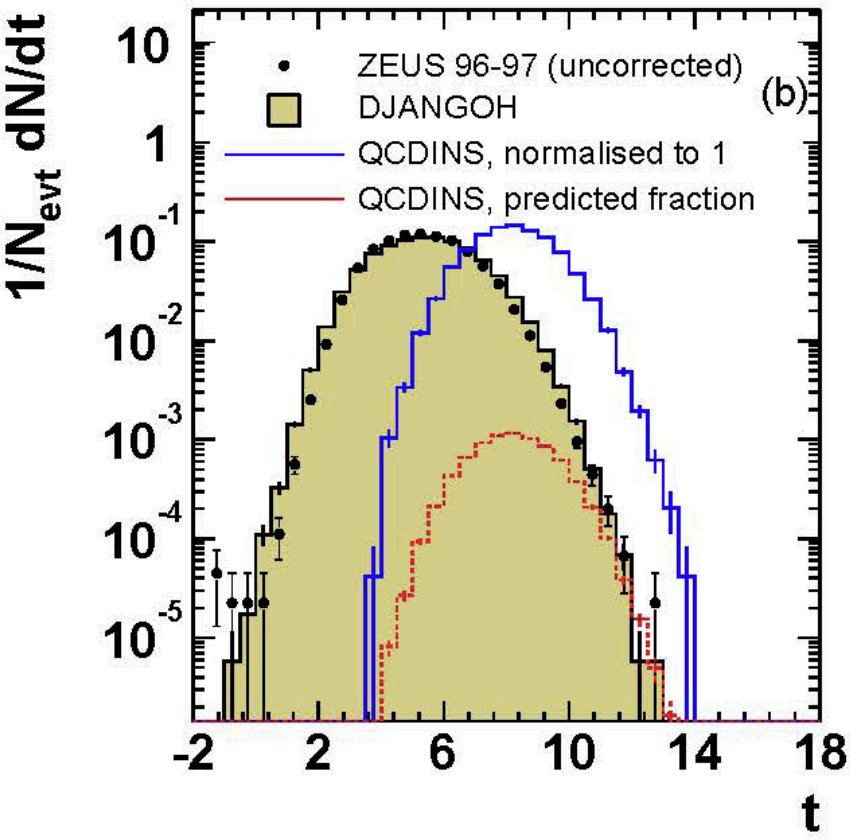
After Enrichment cuts.





Sphericity of particles nearly I-rest frame

Instanton HERA-I Results : ZEUS



t: combination of several separation variables

EPJ C 34(2004) 255

IntL =38pb^{-1} Q^2>120GeV^2

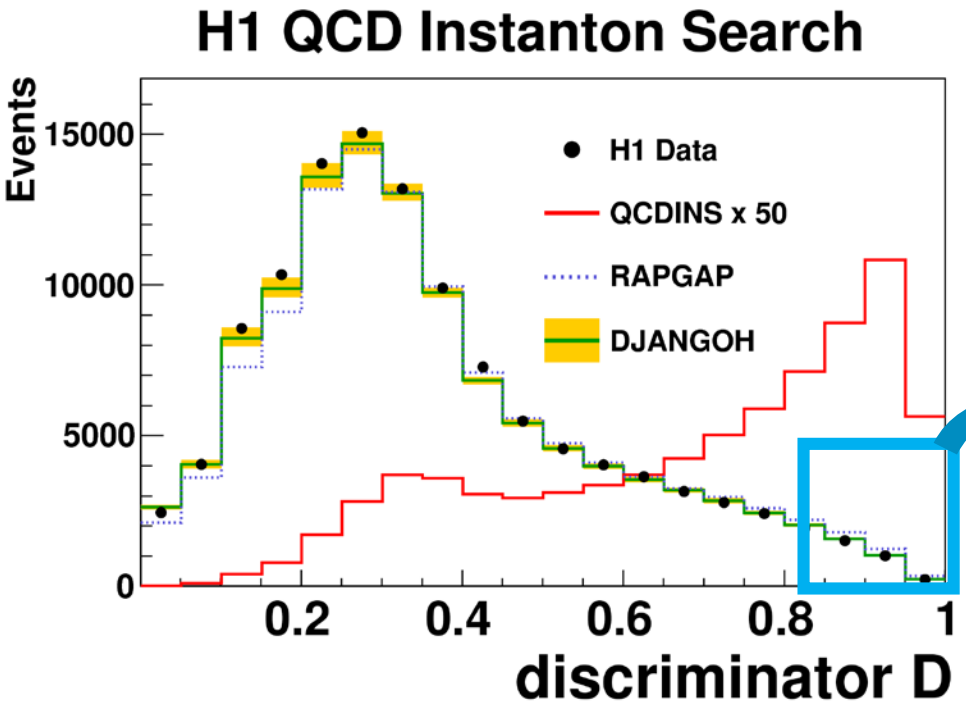
Assuming all data with t>t0 is the instanton events, very conservative limit was set as

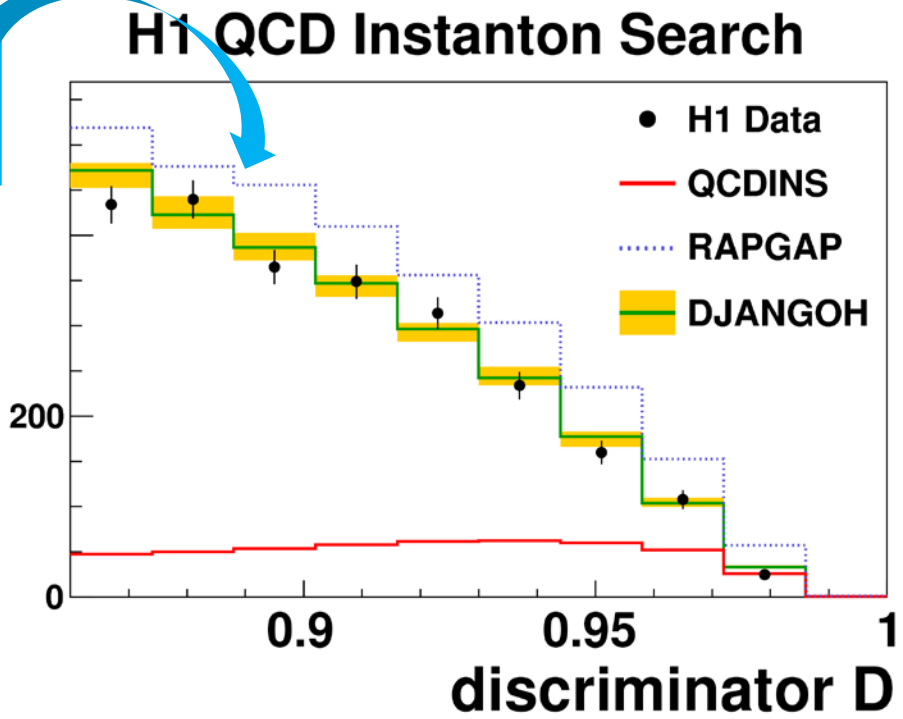
σ<26pb (95%CL),
while the prediction is 8.9pb

Instanton: HERA-II Results: H1

EPJ C76 (2016) 7, 1

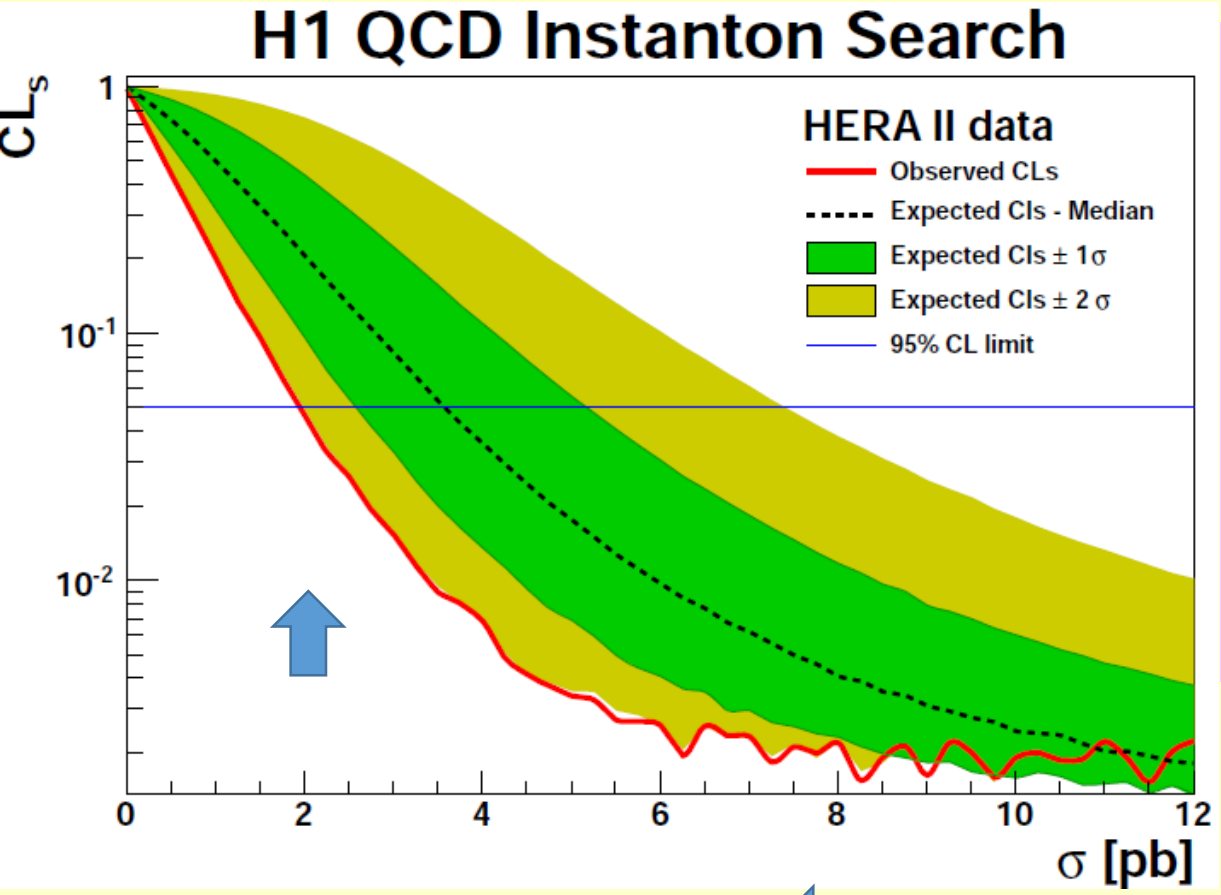
the high statistics of HERA-II data
(IntL = 351 pb^{-1})
-> higher Q^2 ($Q2 > 150\ GeV^2$)





Instanton: HERA-II Results

EPJ C76 (2016) 7, 1



Observed limit: 2pb
while the prediction is
10 ± 3 pb^{-1}
in the kinematic region of
$150 < Q^2 < 15000$ GeV^2 ,
$0.2 < y < 0.7$

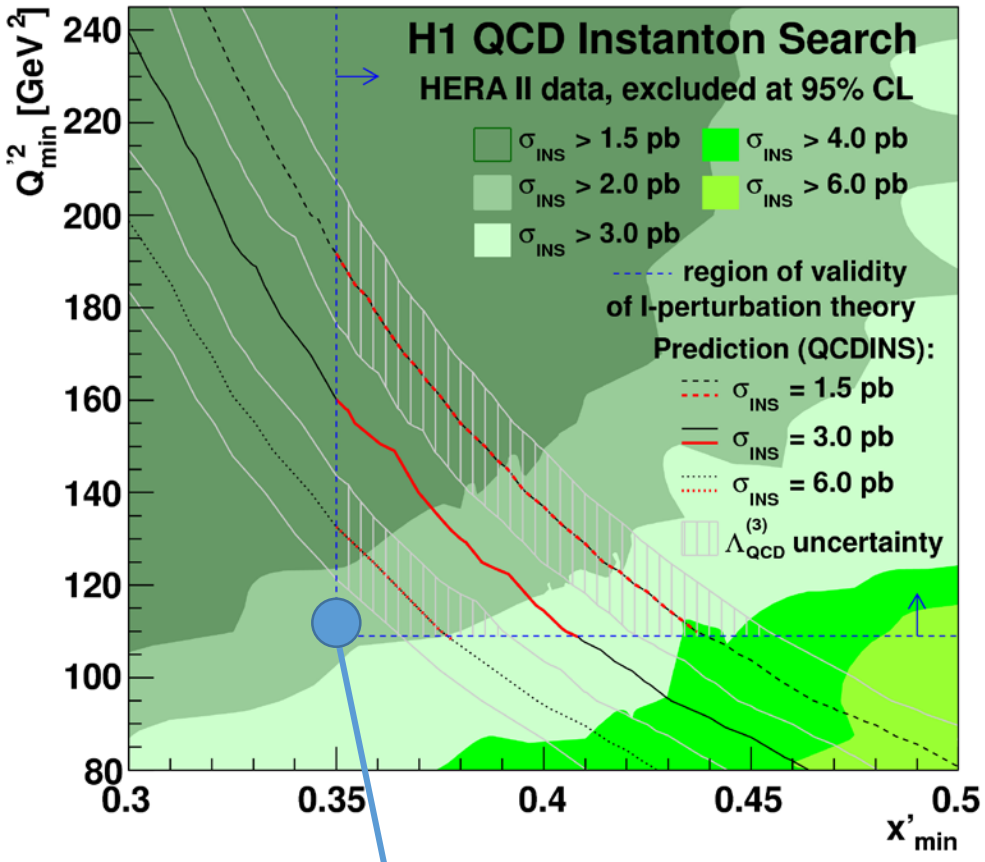
$Q'^2_{min} = 113$ GeV^2 ,
$x'_{min} = 0.35$

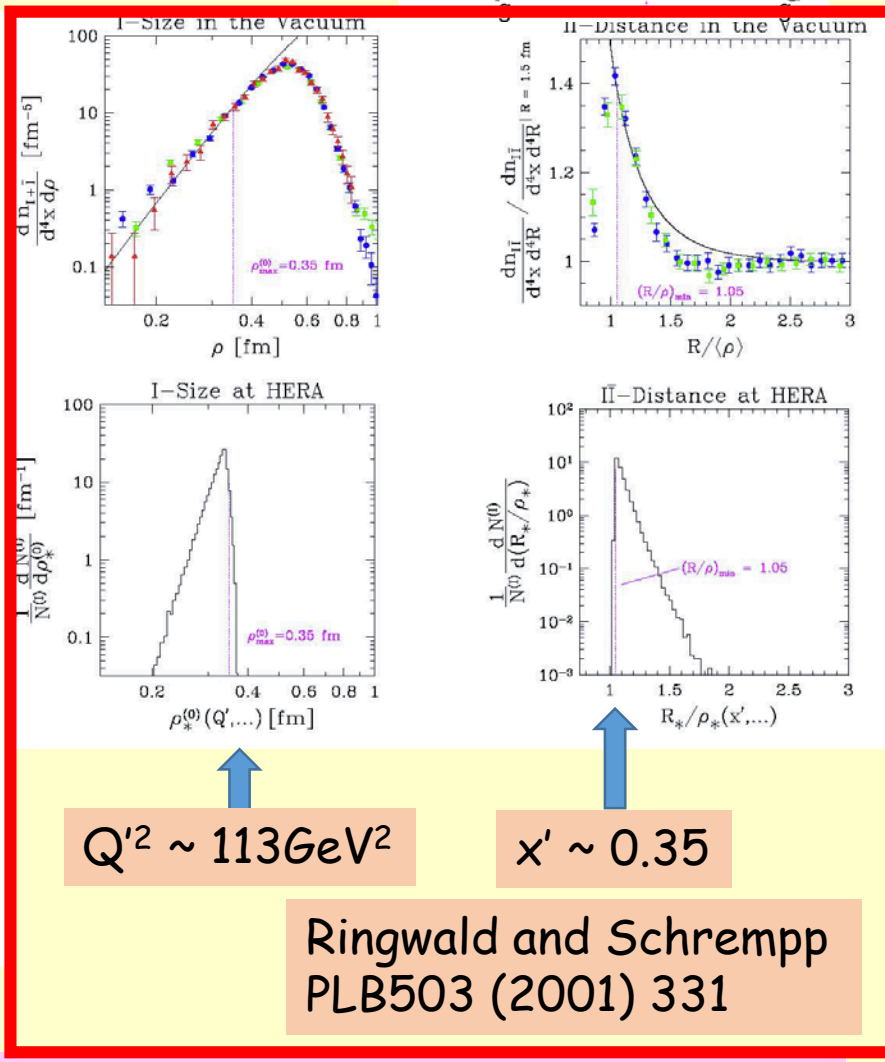
Challenge to the theory!

Prediction from QCDINS

Instanton: HERA-II Results

EPJ C76 (2016) 7, 1





$Q'^2 \sim 113 GeV^2$

$x' \sim 0.35$

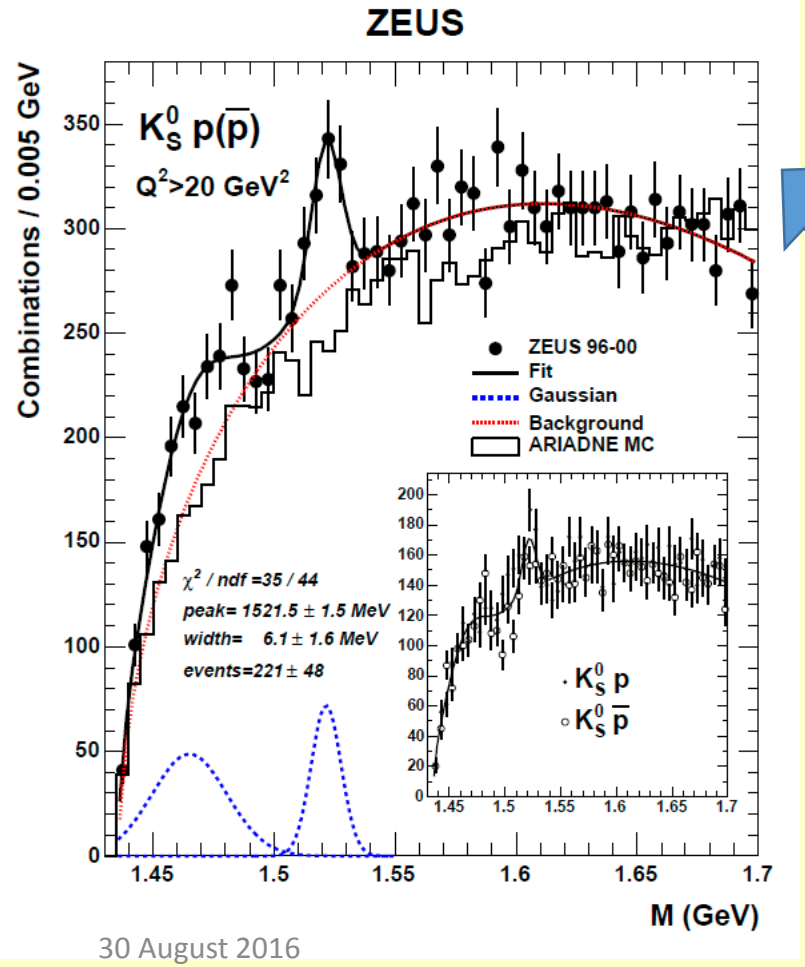
Ringwald and Schrempp
PLB503 (2001) 331

95% CL Cross section limit as a function of Q'^2_{min} and x'_{min}

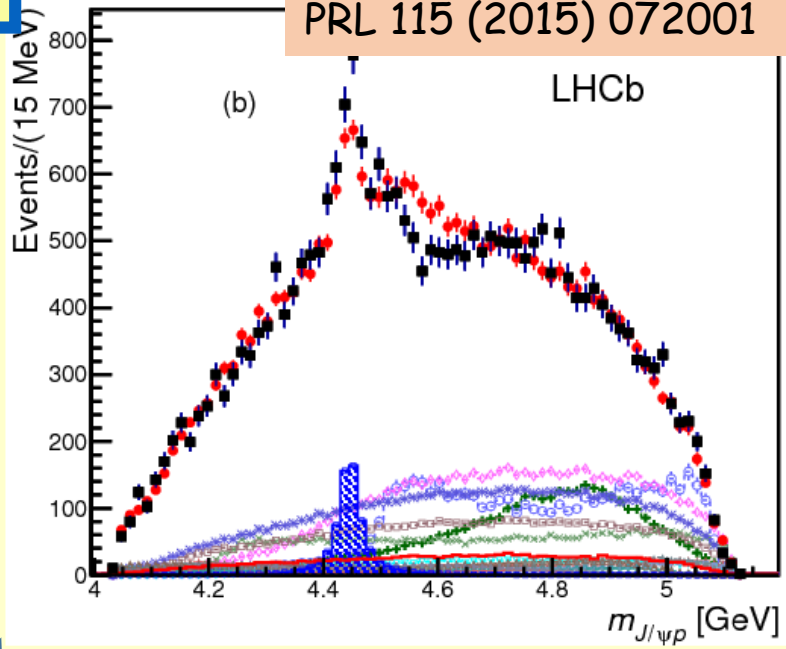
$Q'^2_{min}=113 GeV^2$, $x'_{min}=0.35$ -> 10pb with QCDINS

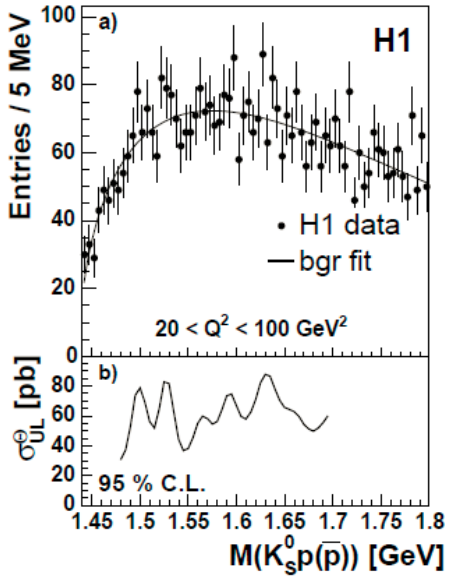
Pentaquark in pK system

Search for a narrow baryonic state
Decaying to pK^0_S at HERA-I:
ZEUS observed a peak consistent to
Θ^+ ($uudd\bar{s}$) PLB 591 (2004)



New excitement from
LHCb Λ_b -> (p J/Ψ) K
PRL 115 (2015) 072001

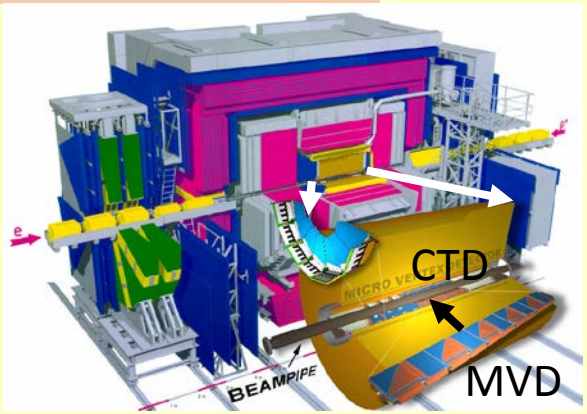




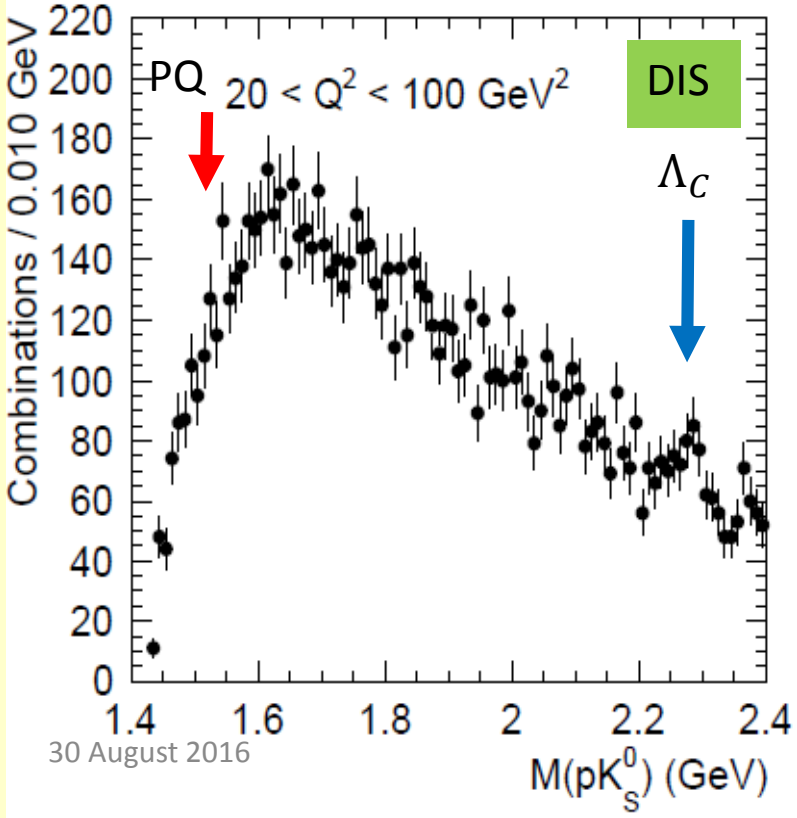
H1 did not see the peak but still two results were compatible.
->
We needed HERA-II data

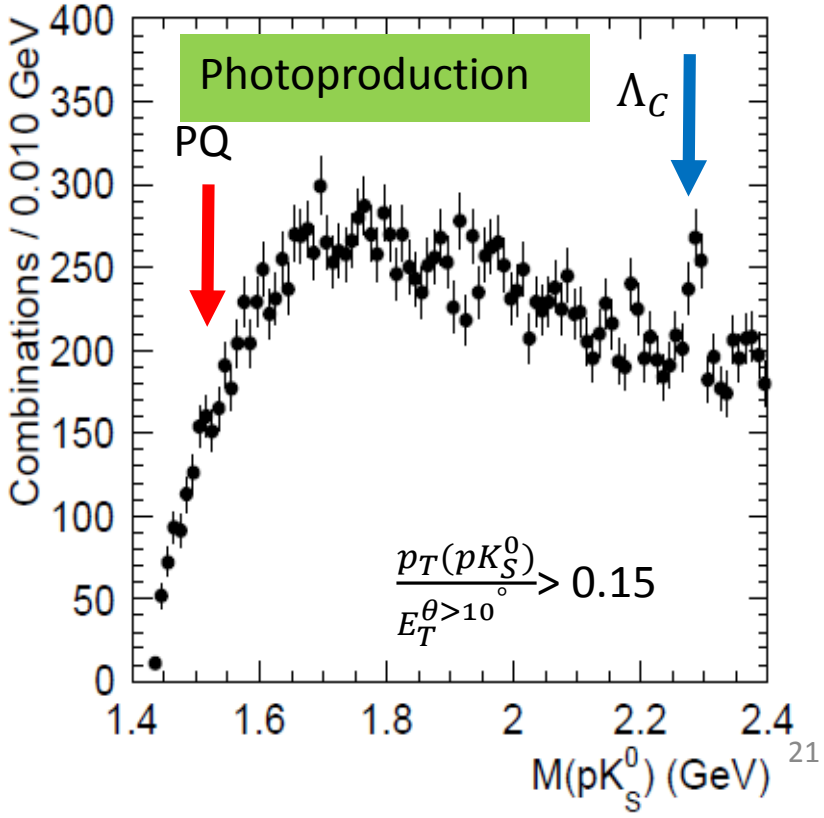
Pentaquark in pK system: ZEUS HERA-II

PLB 759 (2016) 446



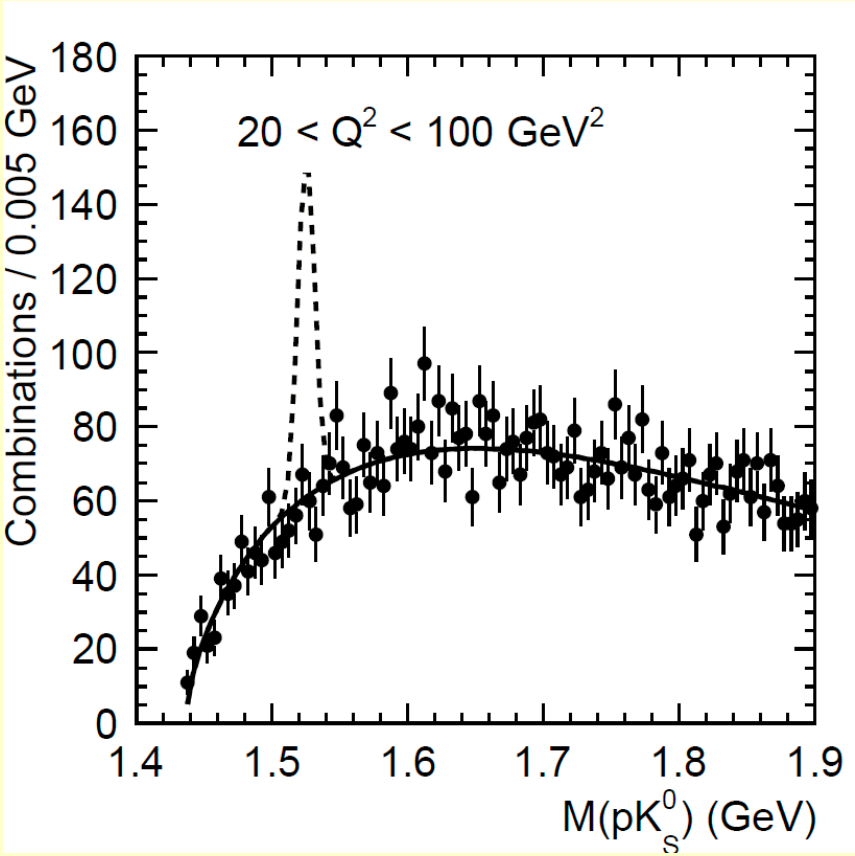
DeDx from micro vertex detector (MVD) (Si-strip)
: Better PID
Larger L_{int}
(121 -> 358 pb^{-1})





Pentaquark in pK system

PLB 759 (2016) 446

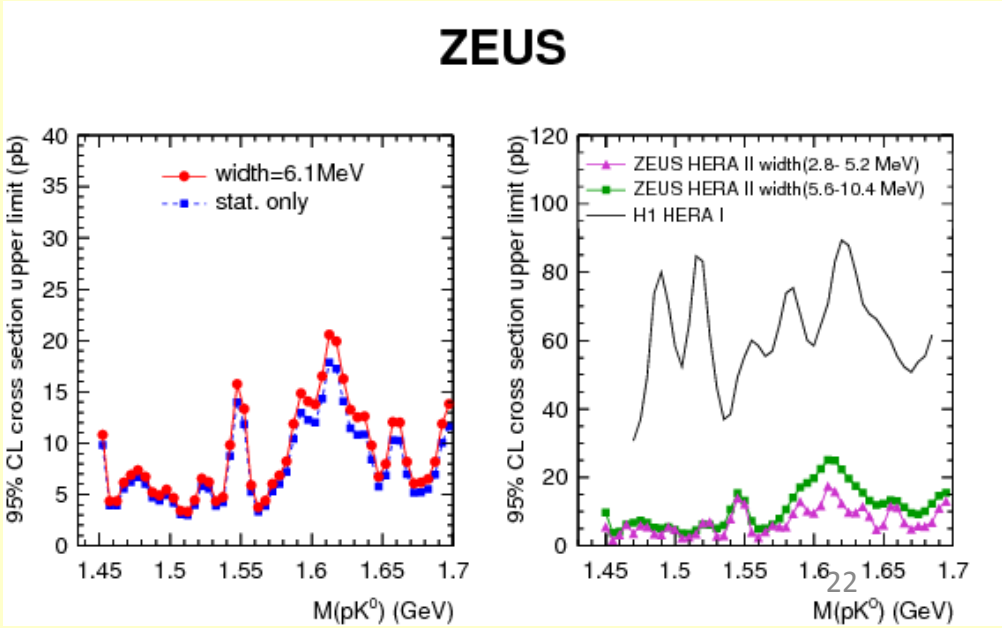


The dashed line represents the Θ^+ signal as would be observed if it had the same strength as reported in the ZEUS HERA I analysis (expected 286 events).

<-> 25.8 event

(as the upper limit with 95%CL)

The structure in the HERAI data is assumed to be a background fluctuation.



Summary

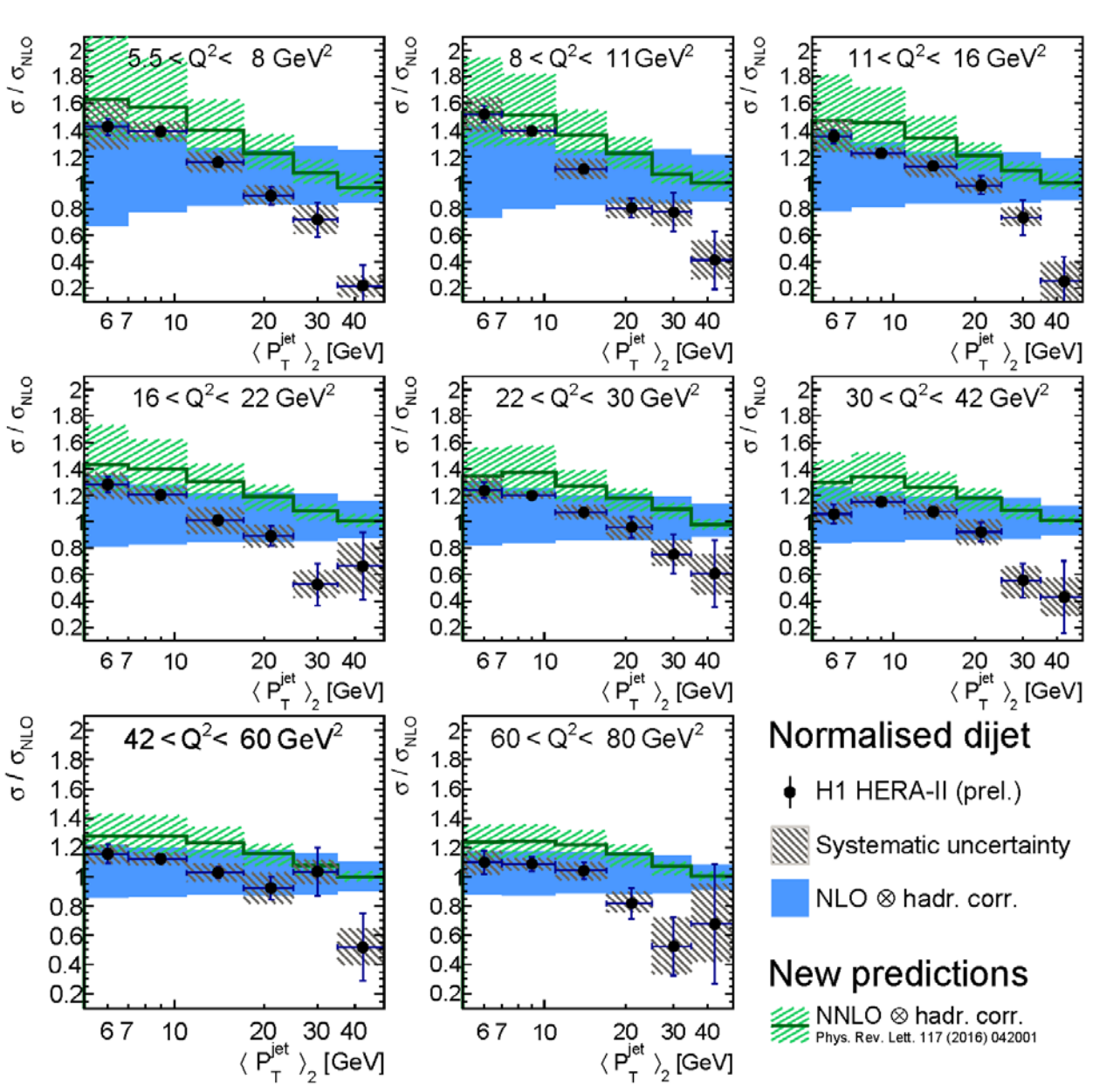
- With the recent results from H1/ZEUS, I am trying to demonstrate that HERA covers the diverse area of the QCD.

- Jet production:
  NLO->NNLO better description of data.
  Extraction of α_s is on-going
- Prompt photon:
  In progress on the comparison with the theories
- Instanton:
  Stringent limit: Challenge to the theory?
- Strange penta-quark (pK^0_S, $p\bar{K}^0_S$) at 1.52GeV
  Not confirmed with HERA-II data

More plots

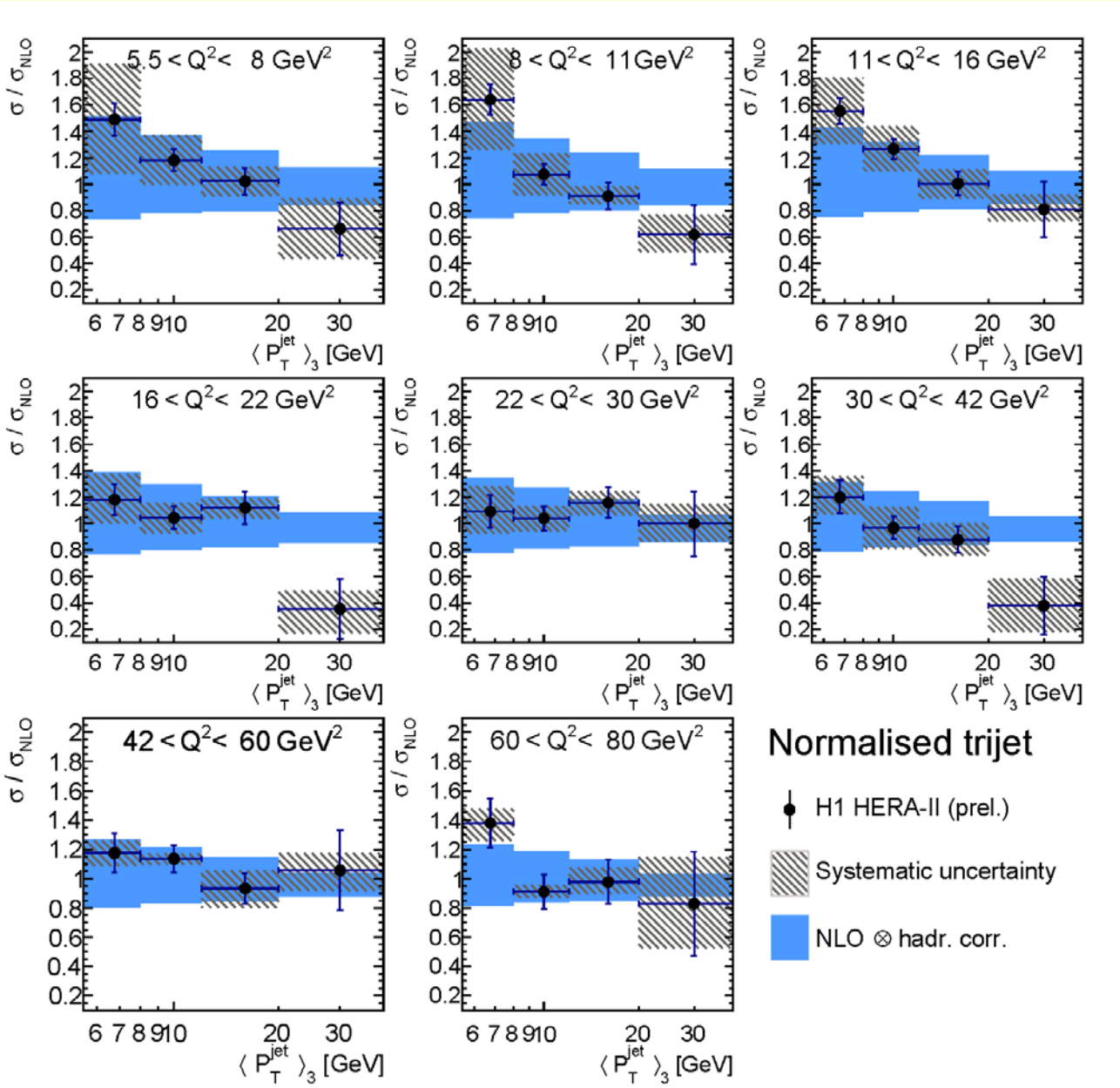
Di-jet:H1

H1prelim-16-062

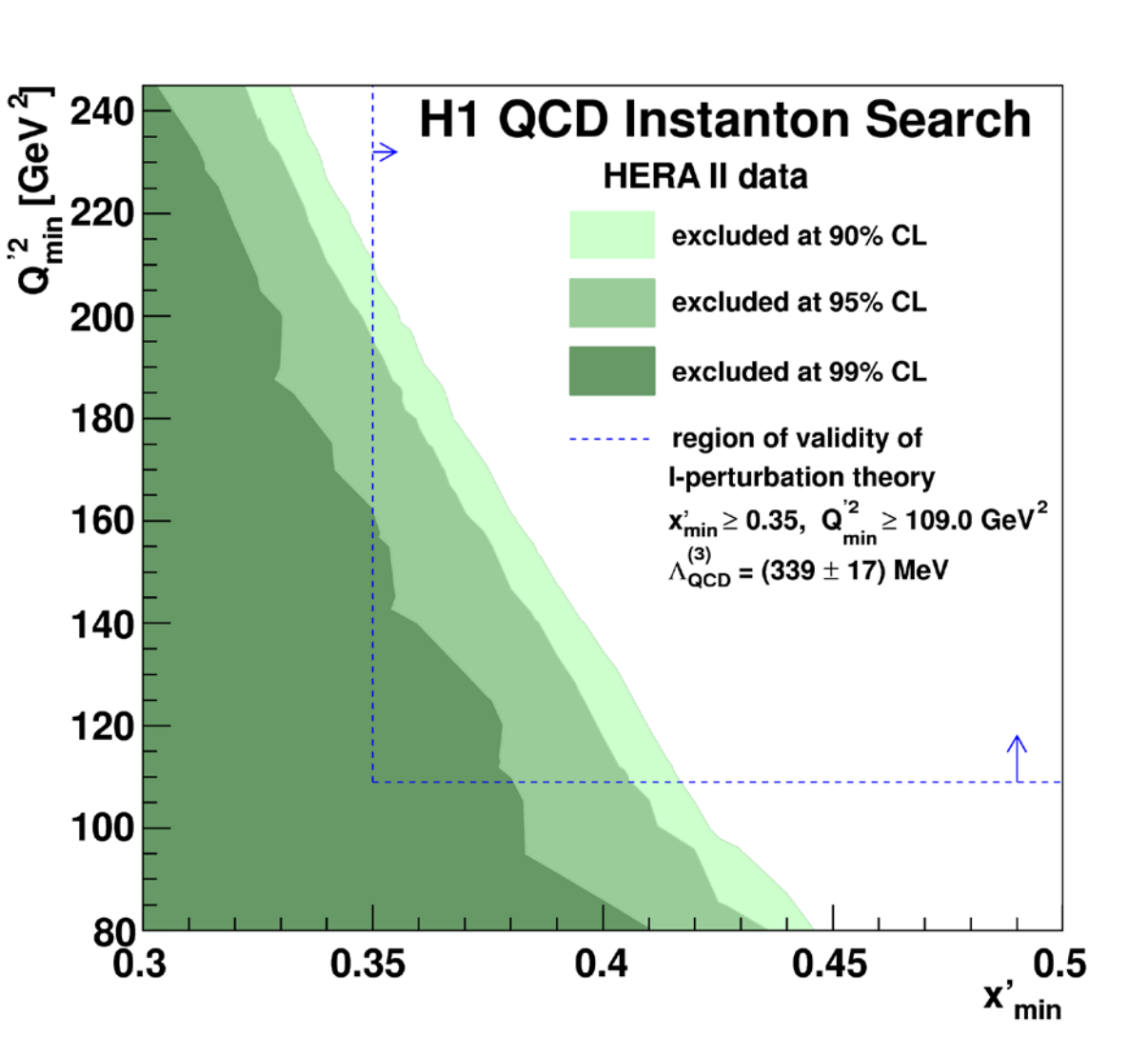


tri-jet:H1

H1prelim-16-062

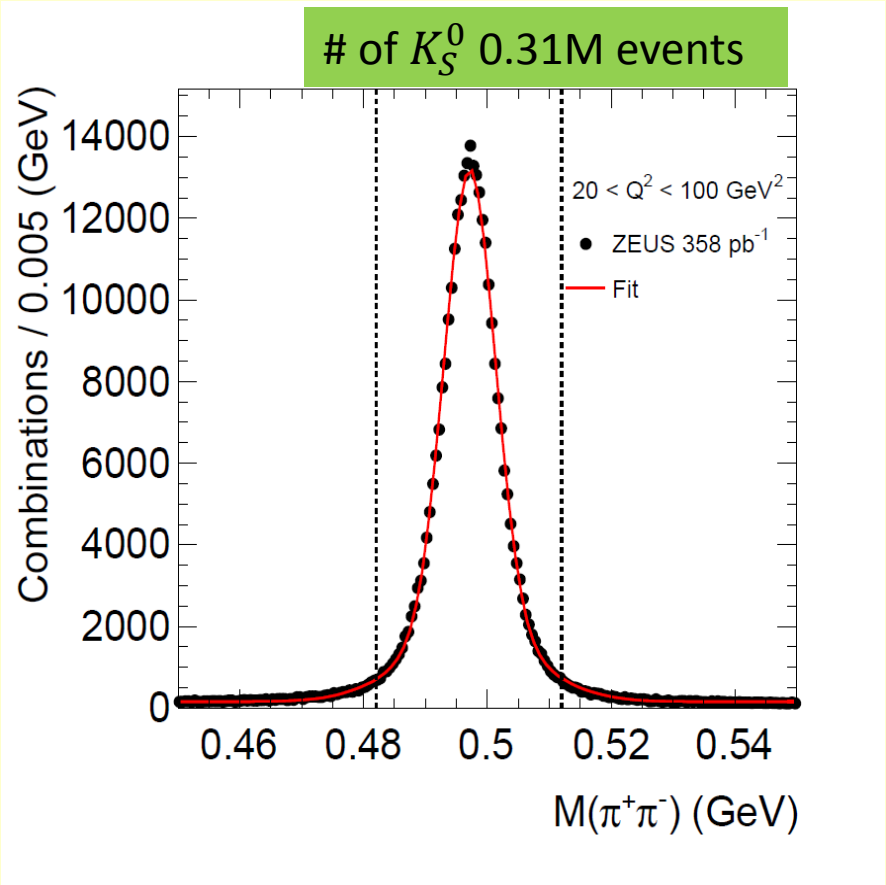


Instanton: HERA-II Results



Pentaquark in pK system: ZEUS HERA-II

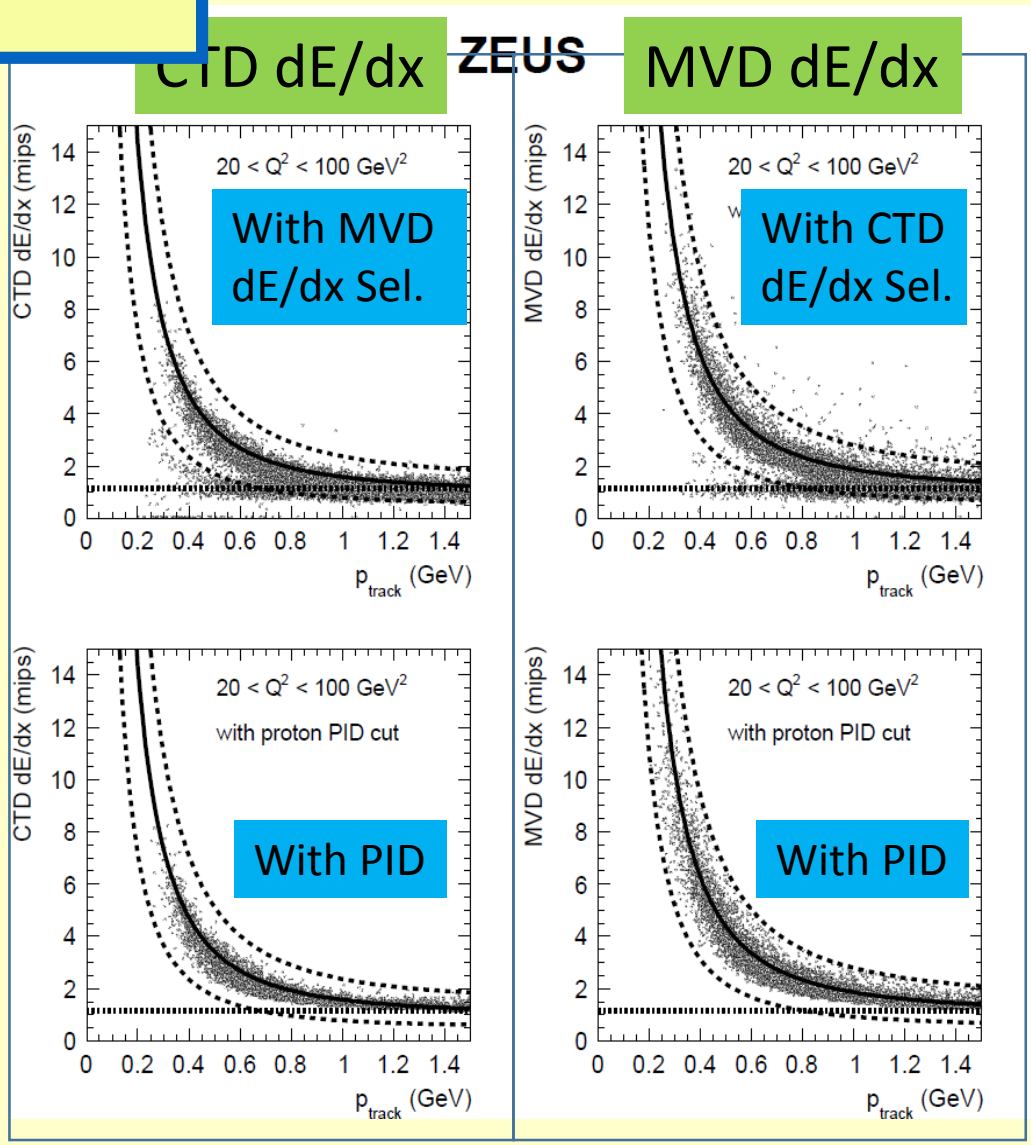
$K_S^0 \to \pi^+\pi^-$ selection



Pentaquark in pK system: ZEUS HERA-II

- Track selections
  - not used as π of K_S^0
  - 0.2 < p(p) < 1.5 GeV
  - CTD innermost layer = 1
  - CTD outermost layer >= 3
  - PID by both of CTD and MVD dE/d
- CTD dE/dx
  - Maximum ~70 hits with full length track.
  - Truncated mean method.

    (the lowest 10% and the highest 30% hits are excluded from the mean.)
  - Resolution for protons ~9.4%.
- MVD dE/dx
  - Nominal 6 hits with full length track.
  - Calculation with probability density function of hit.
  - Resolution for protons ~11.7%.



Pentaquark in pK system: ZEUS HERA-II

- Q^2 requirement
  - $20 < Q^2 < 100$ GeV^2
- pK_S^0 requirements
  - $0.5 < p_T < 3.0$ GeV
  - $|\eta| < 1.5$