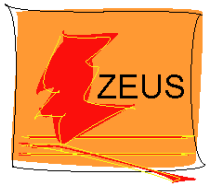
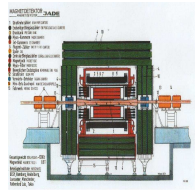





JADE, H1, OPAL and ZEUS

Andrii Verbytskyi

Annual Project Review, MPP,
Munich, 18 December 2017

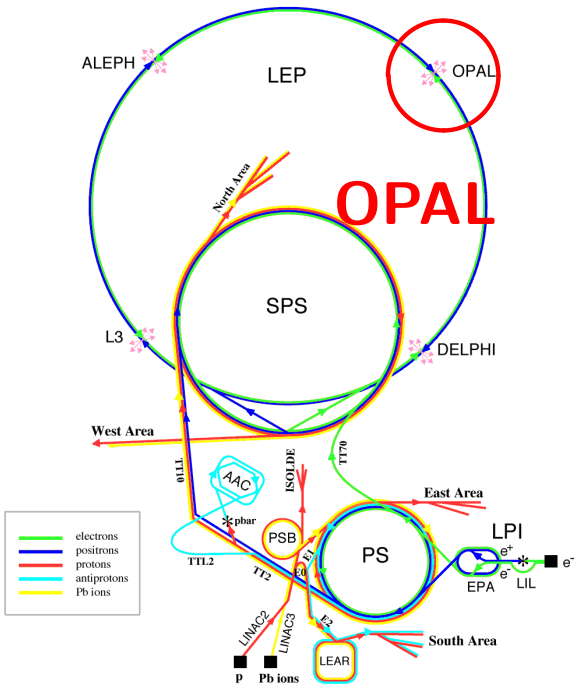
Intro

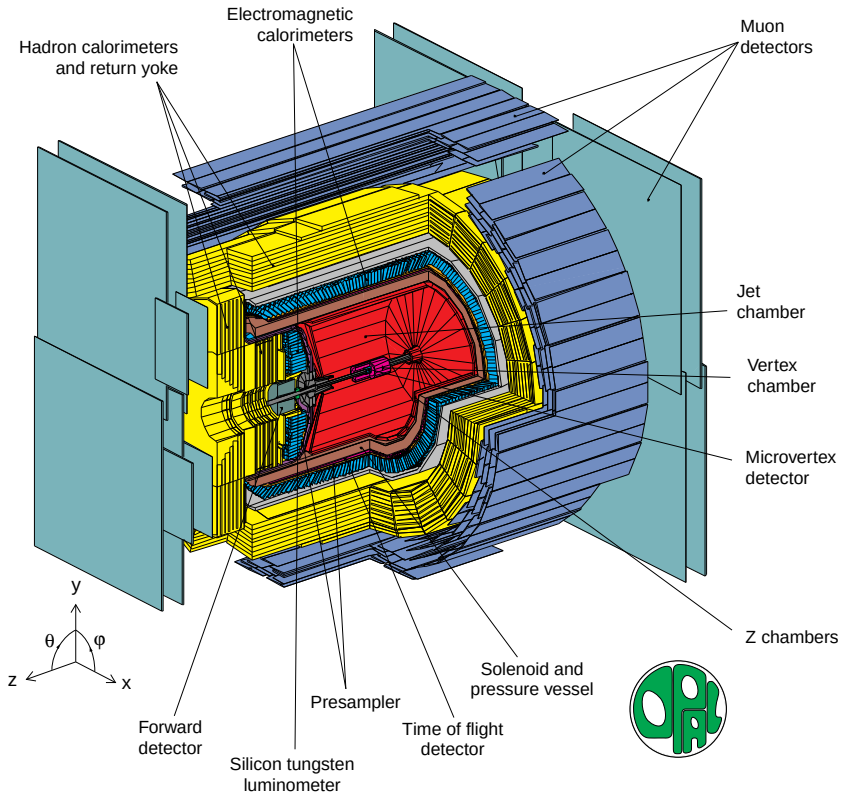
- Old experiments have a lot of interesting unexplored physics in the data.
- Sometimes good ideas/predictions are coming late. It is cheaper and faster to preserve than rebuild and re-run.

- Many official efforts claim to have data preservation activities, but few have dedicated manpower, results or even data.

- JADE, H1, OPAL and ZEUS

OPAL@LEP





- One of four big experiments at famous e^+e^- collider 1989-1995(LEP-I), 1996-2000(LEP-II).
- 300+ collaborators.
- $\sqrt{s} = 91 - 208\,\text{GeV}$ data available for re-analysis.

OPAL members in MPP: S.Bethke, S.Kluth + (A.Verbytskyi).

Jet physics with OPAL

Jets are the way to link partons to hadronic final state.

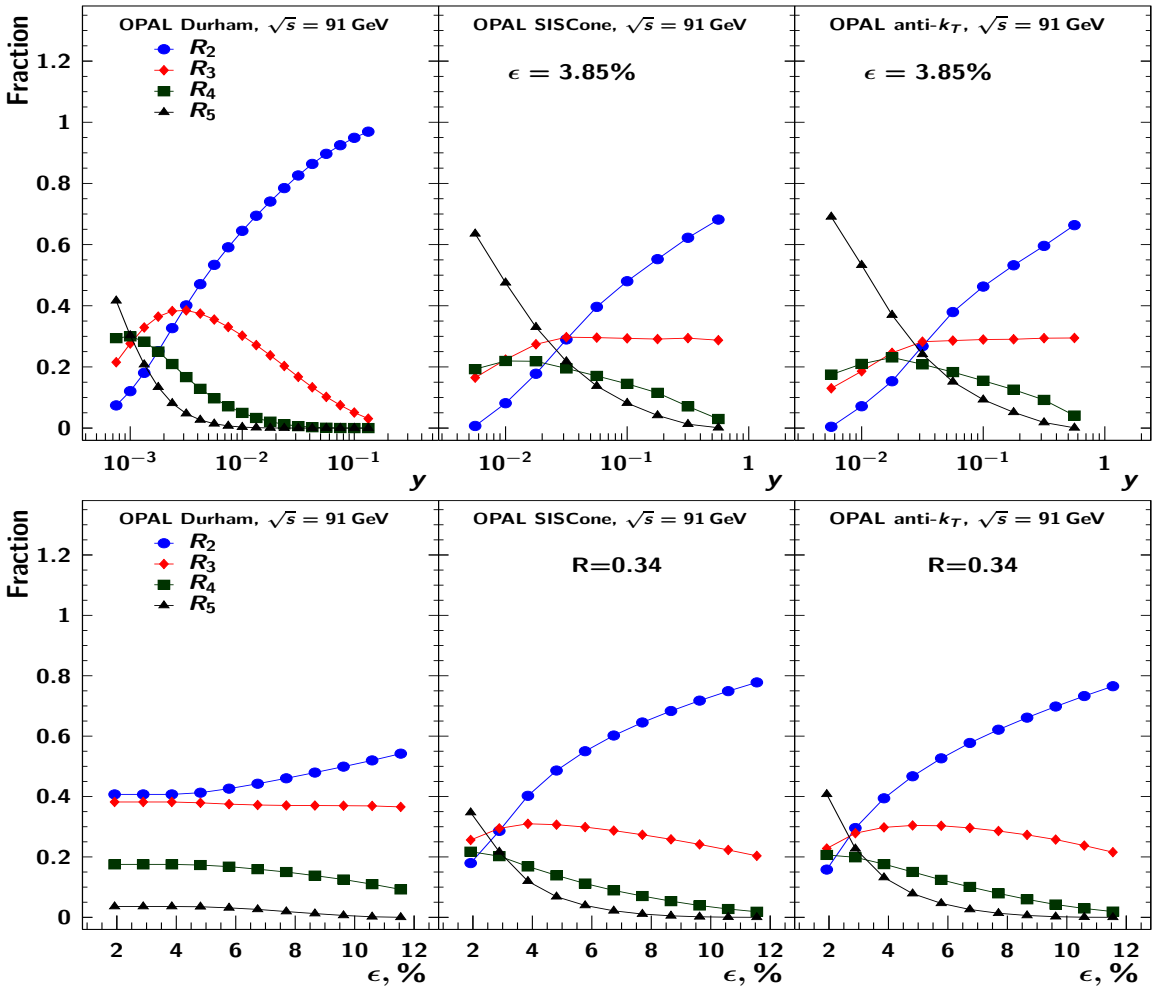
- Past: $3.OR.4.OR.5$- jet FS, now $2-5$ simultaneously.
- LHC jets for LEP/future e^+e^-: SISCone and anti-k_T.
- Modern NLO MC validation.

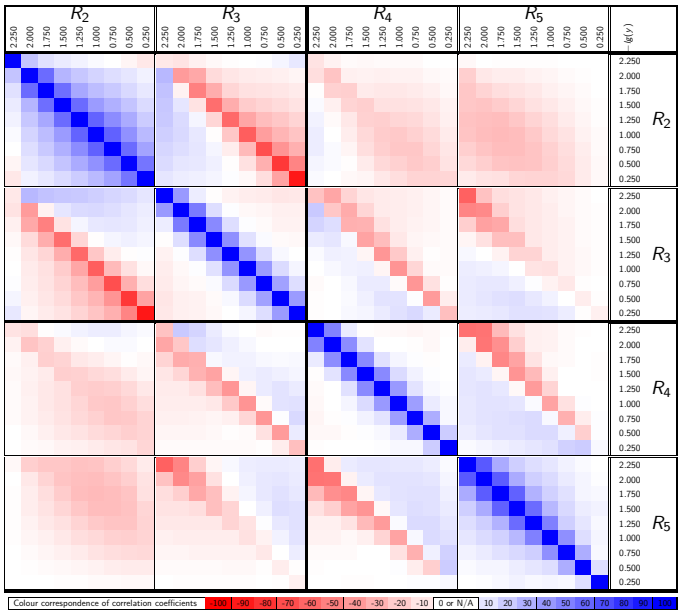
Measurement of jet rates, $R_n = \frac{\sigma(e^+e^- \to n\,jets)}{\sigma(e^+e^- \to hadrons)}$ vs. resolution parameters y or ϵ:

- $y = \frac{2min(E_i^2, E_j^2)(1-cos\theta_{ij})}{E_{vis}^2}$ for k_T, $y = 1 - cos\mathcal{R}$ for anti-k_T and SISCone
- $\epsilon = E_{cut}/E_{vis}$ for all.

Jet rates vs. y and ϵ at Z pole

k_T reproduces old results. SISCone and anti-k_T are similar.

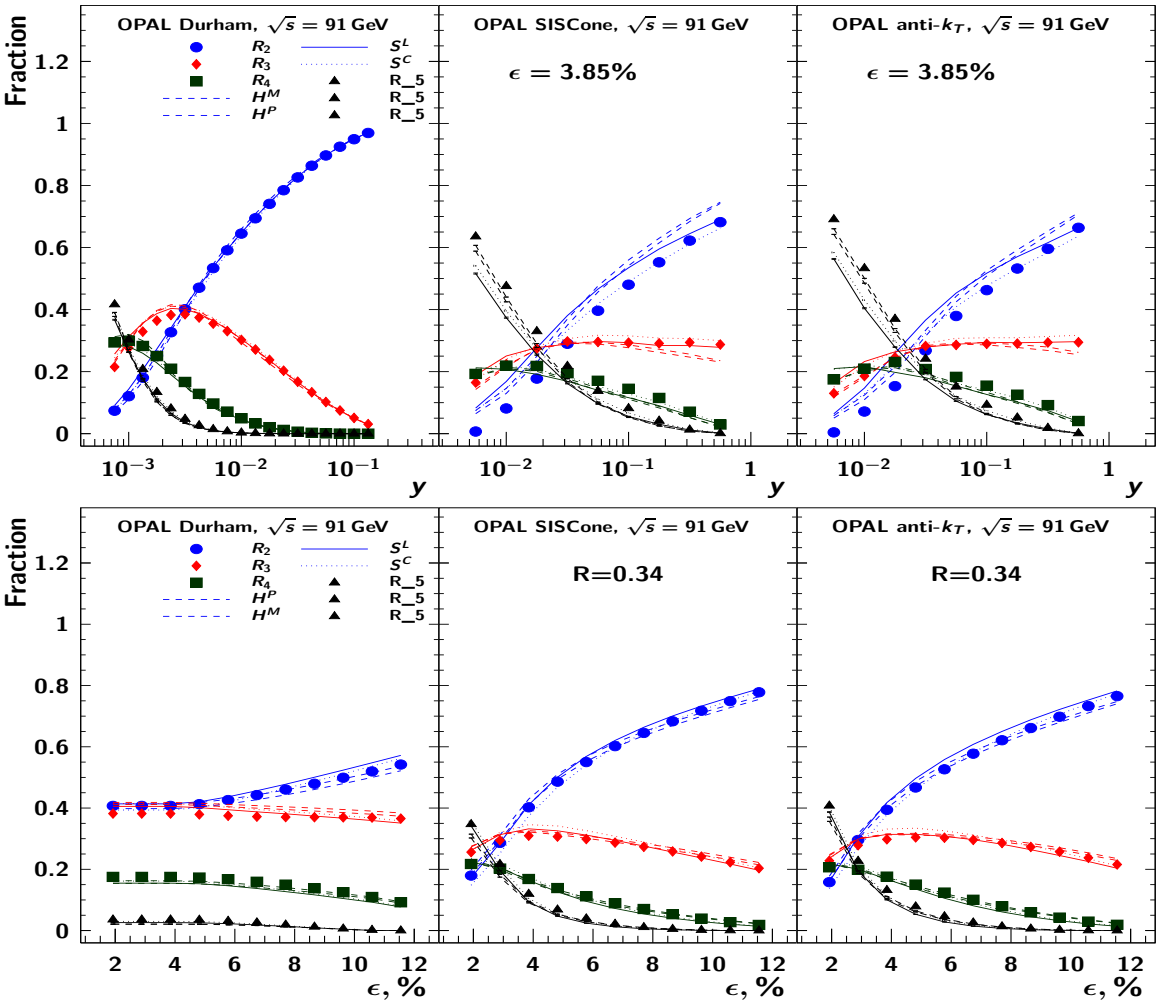




Covariance matrix for every measurement. (anti-k_t vs. y here).

See A. Verbytskyi, "Studies of correlations between measurements of jet observables," JINST **12** (2017) no.04, P04013.

NLO MC jet rates



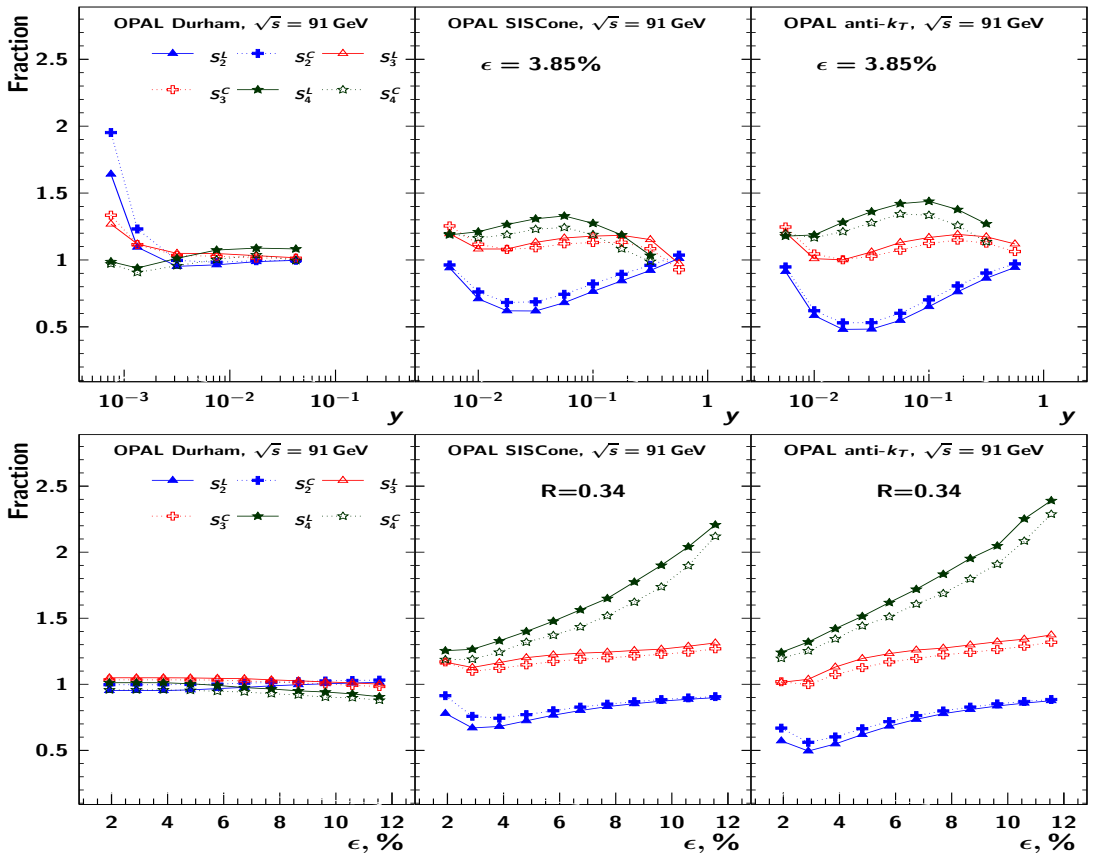
Modern NLO MC:

- S^L: Sherpa2.2/BlackHat, CSS shower, Lund hadronisation
- S^C: Sherpa2.2/BlackHat, CSS shower, cluster hadronisation
- H^P: Herwig7.0, POWHEG matching, cluster hadronisation
- H^M: Herwig7.0, MC@NLO matching, cluster hadronisation

Good description at $91\,GeV$, much worse for higher energies. k_T is described best of all.

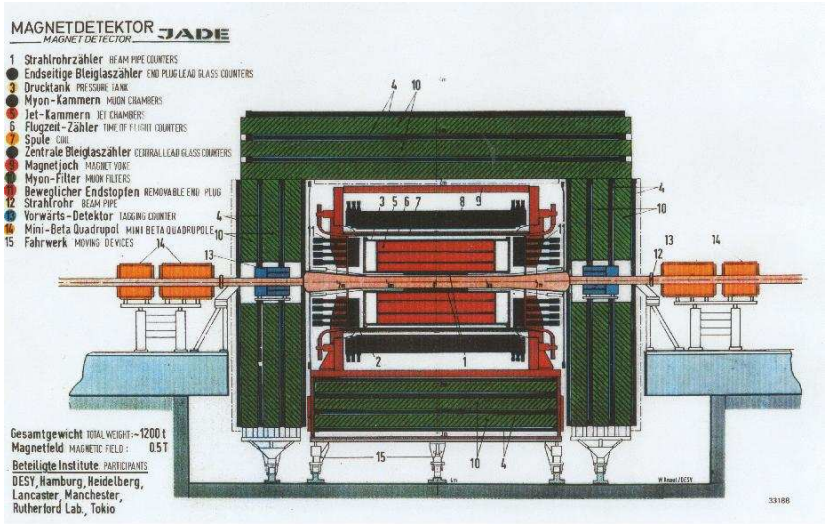
Hadronisation corrections vs. y and energy cut ϵ

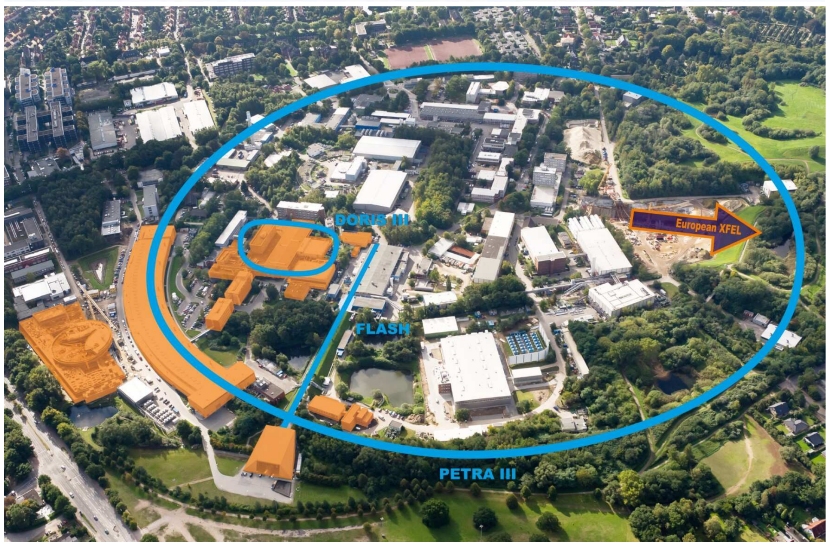
Hadronisation corrections are ratios of n-jet cross-sections at hadron and parton levels. Closest to unity for k_T. Almost flat for higher energies.

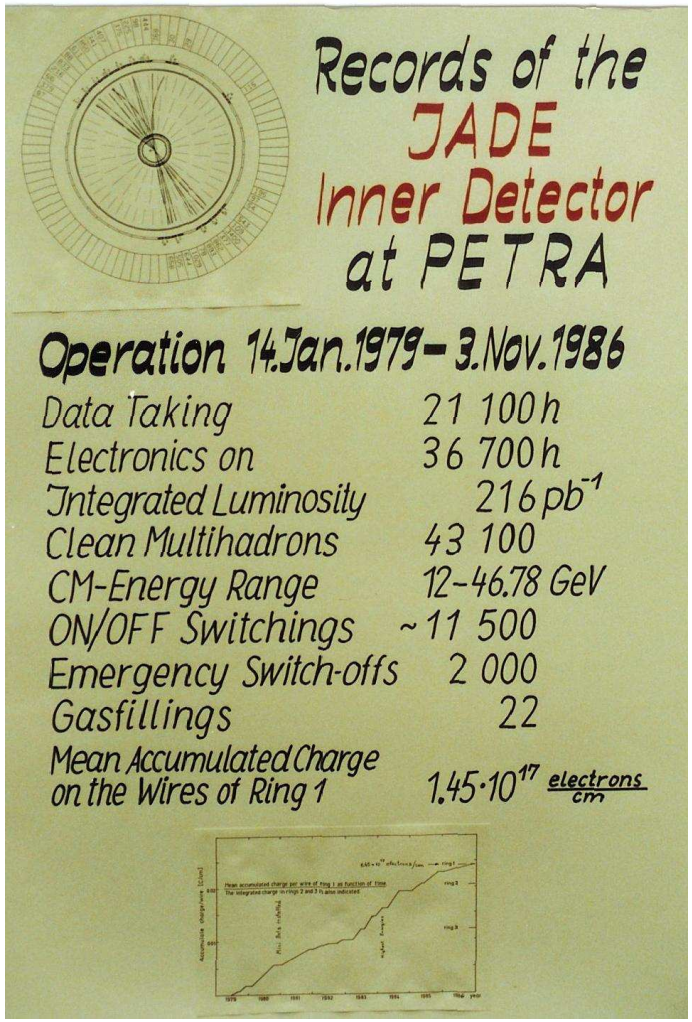


- Draft in the EB.
- Input for α_s determination once published.

JADE@PETRA







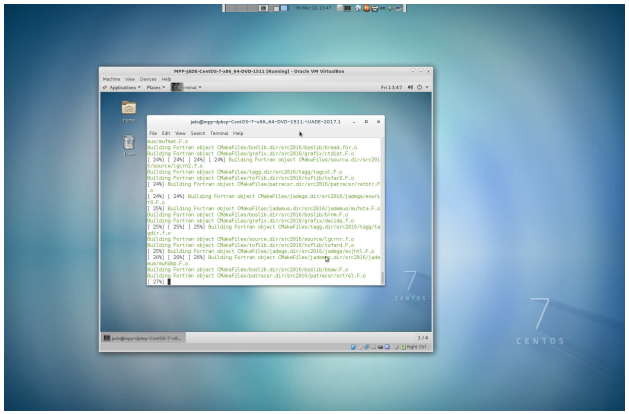
- One of key experiments for QCD: discovery of gluon, α_s measurements, data preserved at unique energy.
- **The oldest and most successful Data Preservation effort!**

- 1986: End of data taking.
- 1995-2003: First preservation effort: data transfer, software port to AIX4.3, interface to LEP-era MC programs.
- 1996-2013: Physics **11 papers,** $\mathcal{O}(40)$ **conference talks, theses, JADE notes**.
- 2017: Second preservation effort
  - Data is online;
  - All software ported to ROOT/Linux(Mac)@x86_64; Modern compilers and Cmake; Virtualisation.
  - Interface simulation and reconstruction to LHC-era MC programs (HepMC3).
  - Documentation (computing notes) is online.

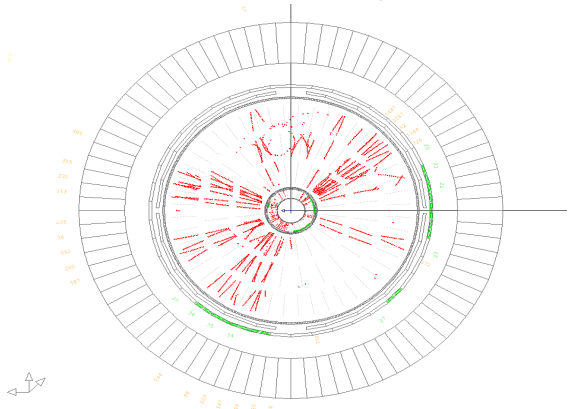
MPP: S. Bethke, S. Kluth + (A.Verbytskyi).
https://wwwjade.mpp.mpg.de

Preserved JADE and (potential) usage examples

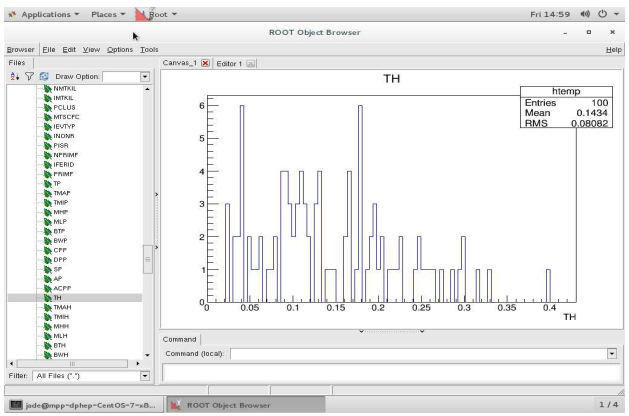
JADE software compilation in virtual machine



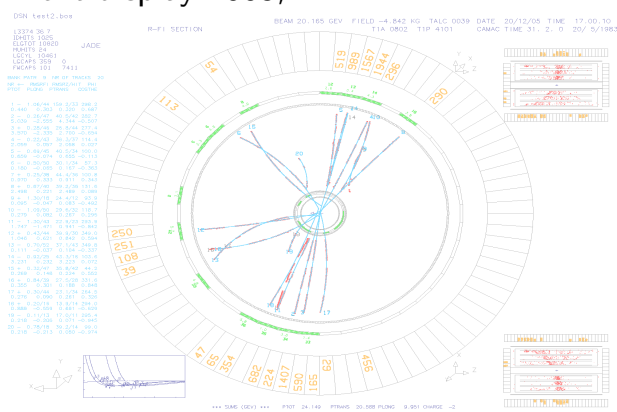
Event display 2017, Linux/Mac



Thrust MC detector level distribution in ROOT Ntuples.



Event display 2003, AIX



- JADE as DP primer – in collaboration with CERN IT.
- Potential physics cases:
  - QCD with modern theory.
  - Validation of modern analysis techniques.
  - Monte Carlo folding – simulation is fast!

Extra physics at e^+e^- colliders

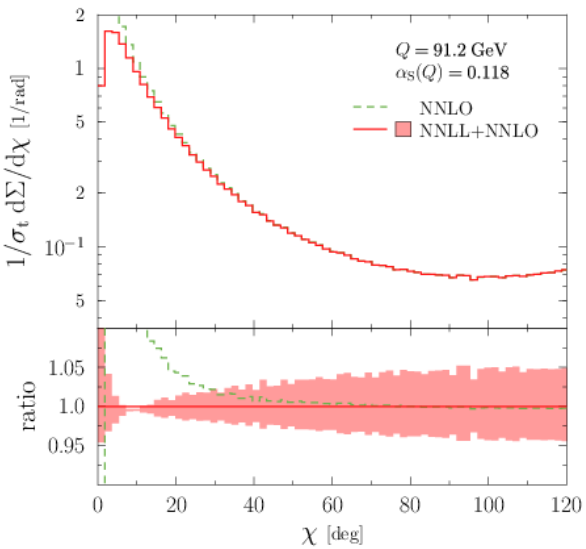
Collaboration with ext. groups on usage of theory predictions, e.g.

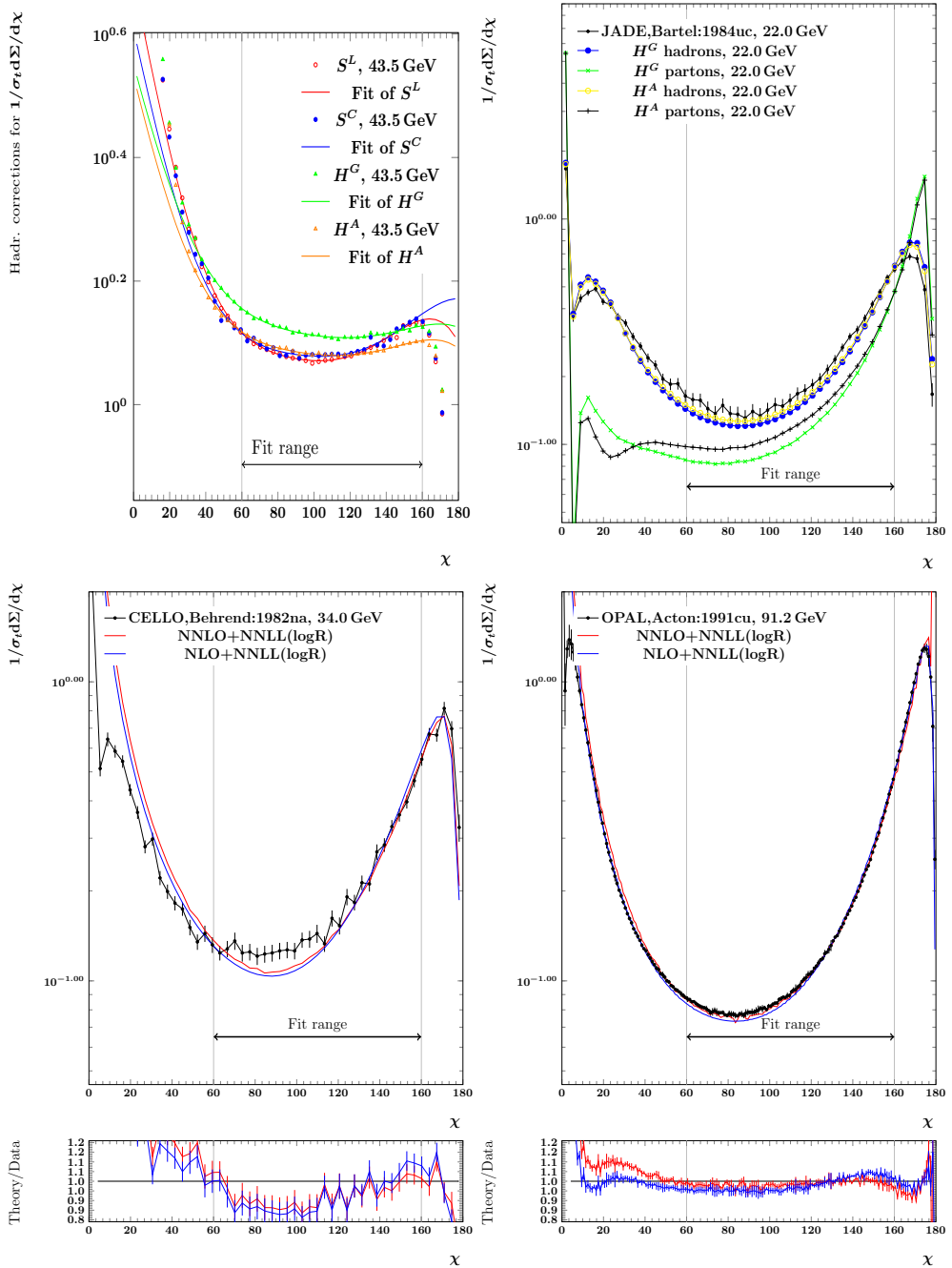
- Z. Tulipant, A. Kardos and G. Somogyi, "Energy–energy correlation in electron–positron annihilation at NNLL + NNLO accuracy," Eur. Phys. J. C **77** (2017) no.11, 749
- A. Banfi, H. McAslan, P. F. Monni and G. Zanderighi, "The two-jet rate in e^+e^- at next-to-next-to-leading-logarithmic order," Phys. Rev. Lett. **117** (2016) no.17, 172001

e^+e^-: in progress

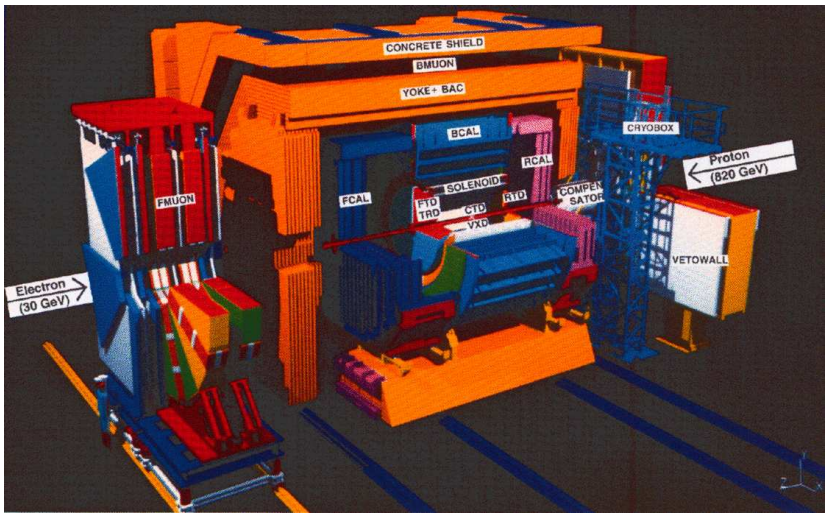
α_s fits with EEC:

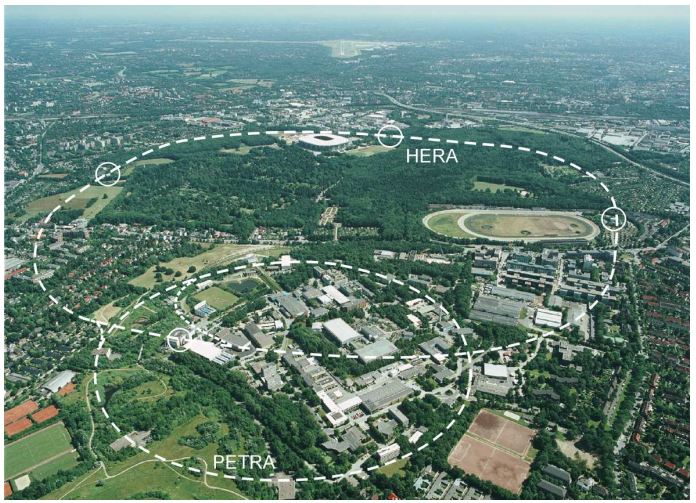
- Advanced theory
- A lot of data
- Modern MC
- Proper statistics
- $+$ some solvable problems





ZEUS@HERA





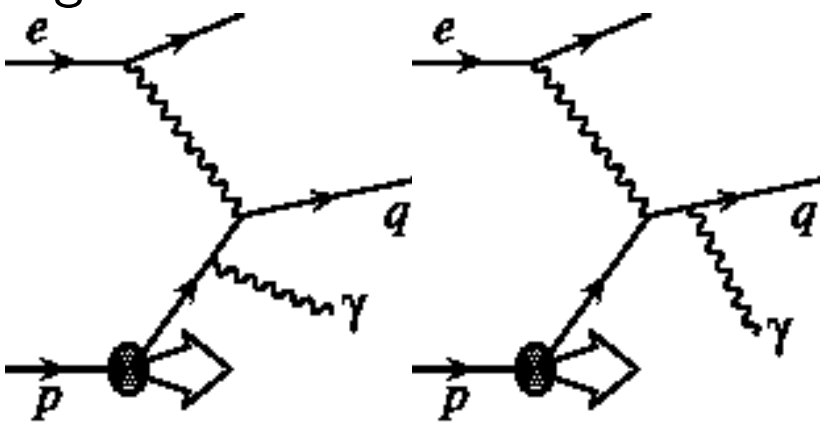
- One of two big experiments at HERA.
- $27.5 GeV$ $e^{\pm}$ collided with p ($460/575/820/920 GeV$) – widest spectrum of physics.
- $0.5 fb^{-1}$ of data, $\approx 500M$ events.
- $\mathcal{O}(300)$ members while running, 113 authors now.

ZEUS data preservation and recent results

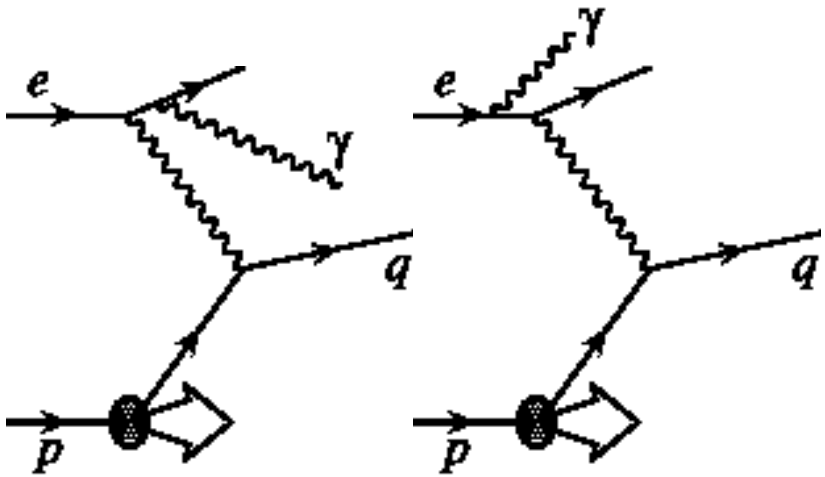
- Data, SW and documentation are stored in DESY&MPCDF.
- Software is virtualized in MPP.
- MC production with old/new generators is available in MPP.
- ZEUS members in MPP : I. Abt, H. Abramowicz, A. Caldwell and A. Verbytskyi.
- https://www-zeus.desy.de, https://wwwzeus.mpp.mpg.de
- Recent papers:
  - H. Abramowicz *et al.* [ZEUS Collaboration], "Studies of the diffractive photoproduction of isolated photons at HERA,"Phys. Rev. D **96** (2017) no.3, 032006
  - H. Abramowicz *et al.* [ZEUS Collaboration], "Further studies of isolated photon production with a jet in deep inelastic scattering at HERA," arXiv:1712.04273 [hep-ex]

Prompt photons are the direct probe of perturbative process.

Signal:



Background:

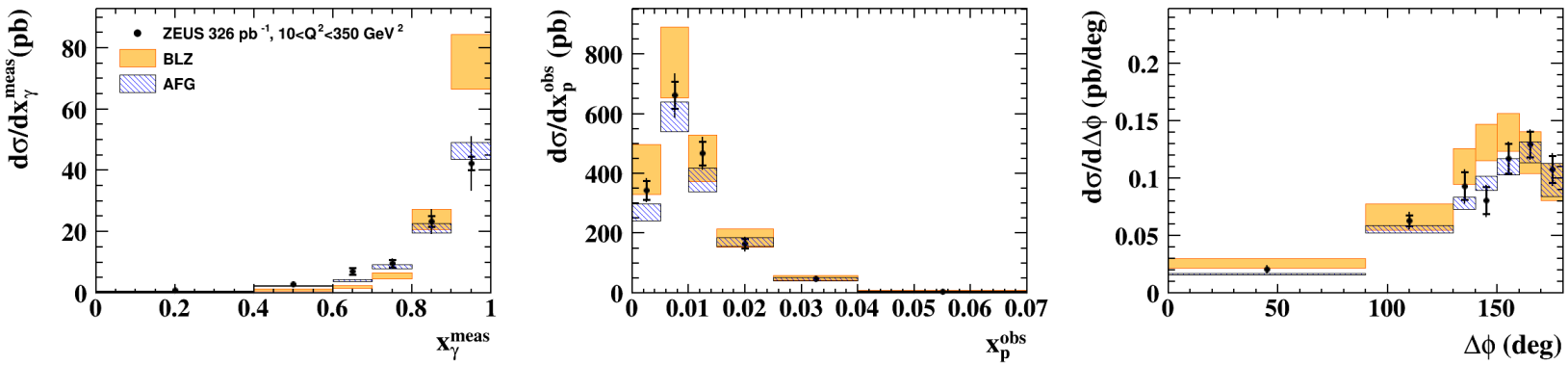


Measurement:

- $326\,\mathrm{pb}^{-1}$, $10 < Q^2 < 350\ \mathrm{GeV}^2$.
- Cross-sections in bins of transverse jet or γ momenta/rapidity and angular distances in pairs $e' - \gamma$, $e' - jet$, $jet - \gamma$.

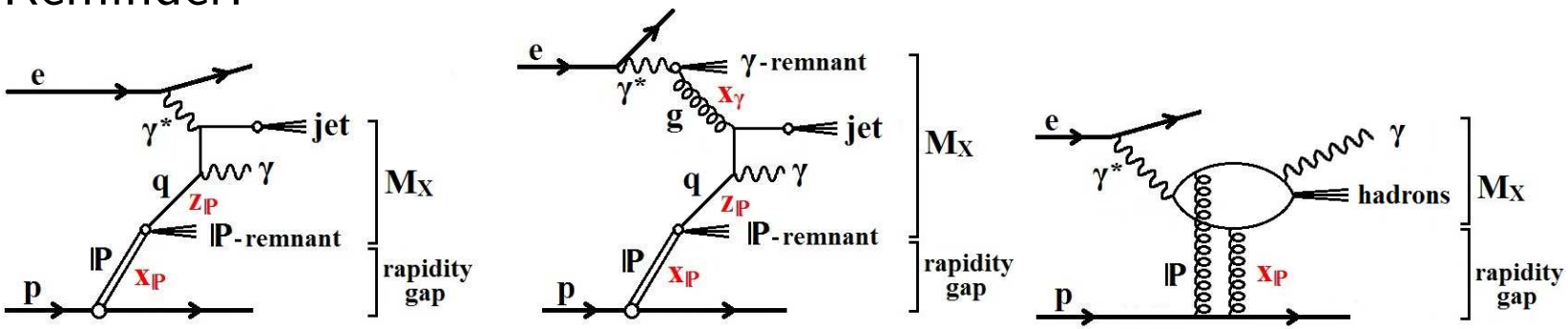
Further studies of isolated photon production with a jet in deep inelastic scattering at HERA

x_γ/x_p are fractions of the exchanged-photon/proton energy transferred to $\gamma + jet$.



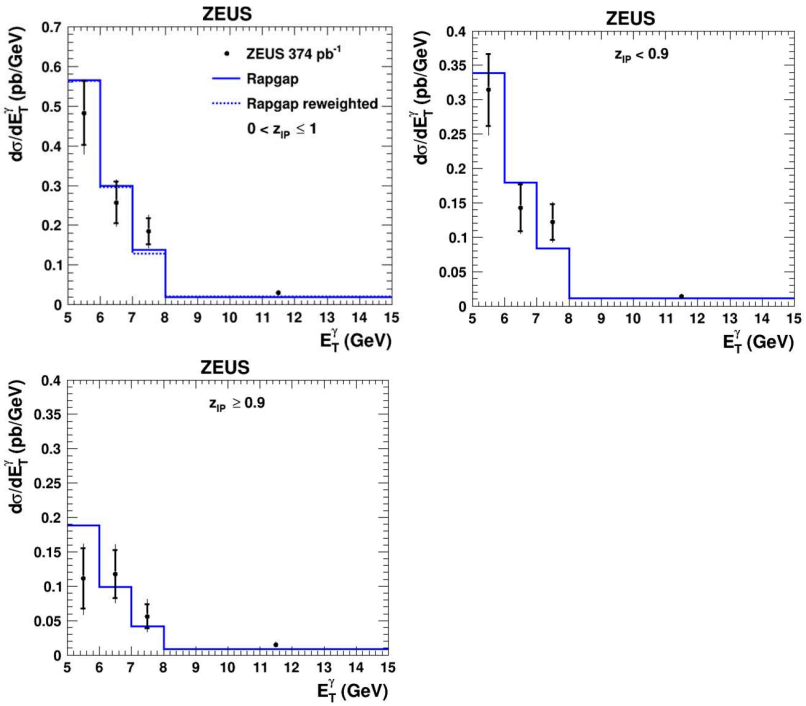
- Measurements are compared to theory:
  - P. Aurenche, M. Fontannaz, J.Ph. Guillet, Eur. Phys. J. C **44** (2005) 395, Eur. Phys. J. C **77** (2017) no.5, 324 – contains HO corrections. Agrees well with data.
  - S. P. Baranov, A. V. Lipatov and N. P. Zotov, Phys. Rev. D **81** (2010) 094034 – k_t-factorisation based. Overestimates cross-section.

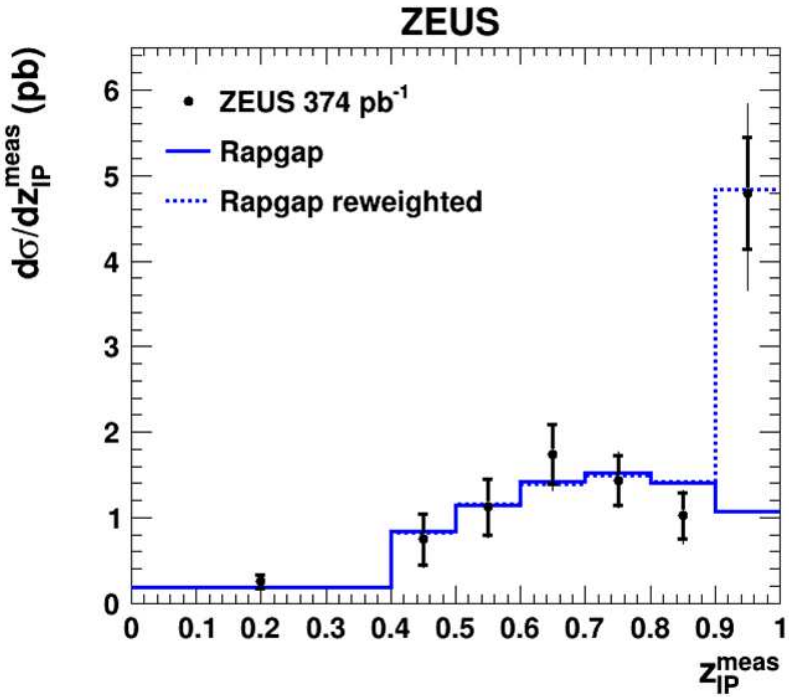
Reminder:



z_p – fraction of Pomeron momenta transferred to $\gamma + jet$.
x_γ – fraction of exchange boson momenta transferred to $\gamma + jet$.
x_p – fraction of proton energy carried by Pomeron.
Measurement:

- $456 pb^{-1}$ of data form HERA-I and HERA-II, $Q^2 < 1 GeV^2$, $0.2 < y < 0.7$
- k_T jets in lab. frame, cross-sections in bins of z_p, x_γ, x_p.

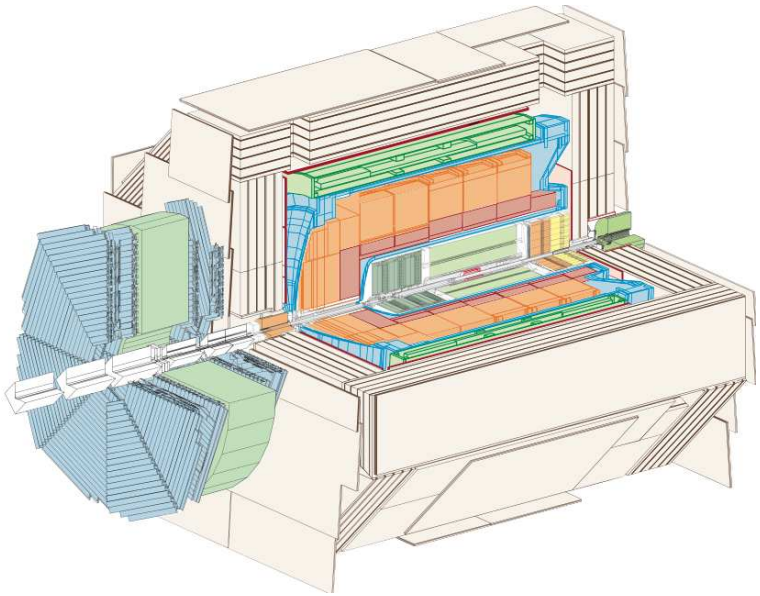


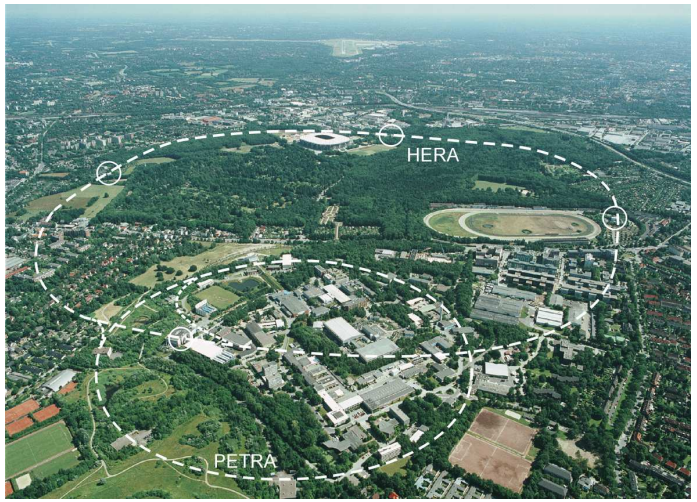


Measurement:

- First measurement, precious information on diffraction.
- There is still something new to be found, e.g. $z_P > 0.9$ **is not expected** and is not described by Rapgap3.2 MC. This is the case when Pomeron transfers almost all its energy to $\gamma + jet$.

H1@HERA reminder



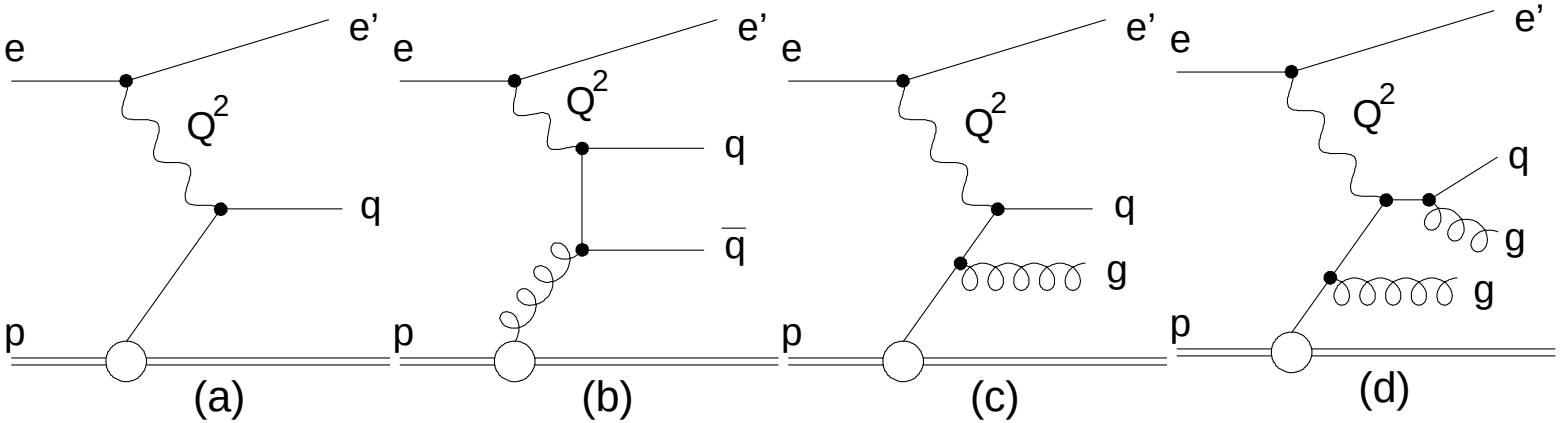


- Second of two big experiments at HERA.
- $27.5 GeV$ $e^{\pm}$ collided with p ($460/575/820/920 GeV$) – widest spectrum of physics.
- $0.5 fb^{-1}$ of data, $\approx 500M$ events.
- $\mathcal{O}(300)$ members while running, 147 authors now.

H1 data preservation and recent results

- H1 data is stored in DESY and in RZG.
- H1 members in MPP: V. Chekalian, G. Grindhammer, C. Kiesling.
- https://www-h1.desy.de, https://wwwh1.mpp.mpg.de
- Recent papers:
  - V. Andreev *et al.* [H1 Collaboration], "Determination of the strong coupling constant $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements," Eur. Phys. J. C **77** (2017) no.11, 791
  - V. Andreev *et al.* [H1 Collaboration], "Measurement of Jet Production Cross Sections in Deep-inelastic ep Scattering at HERA," Eur. Phys. J. C **77** (2017) no.4, 215
  - V. Andreev *et al.* [H1 Collaboration], "Measurement of D^* production in diffractive deep inelastic scattering at HERA," Eur. Phys. J. C **77** (2017) no.5, 340

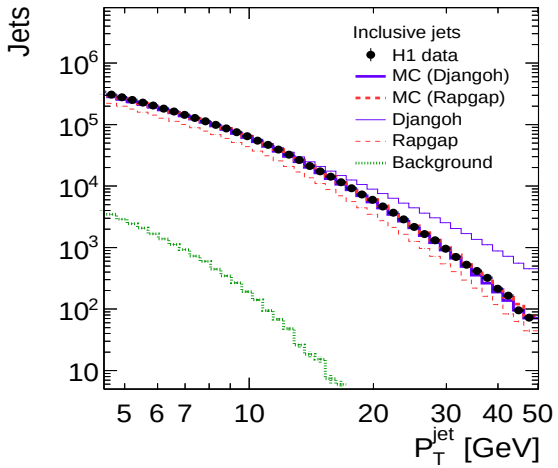
Reminder:

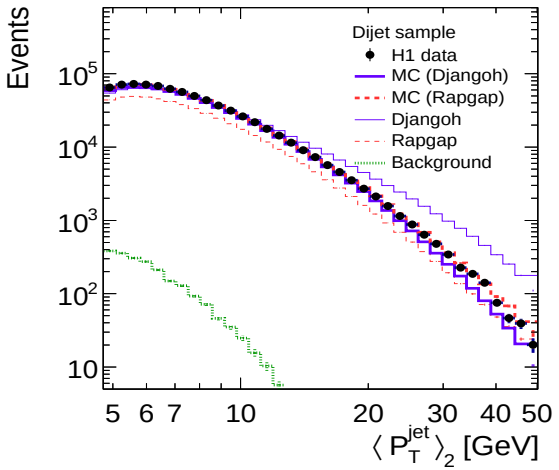


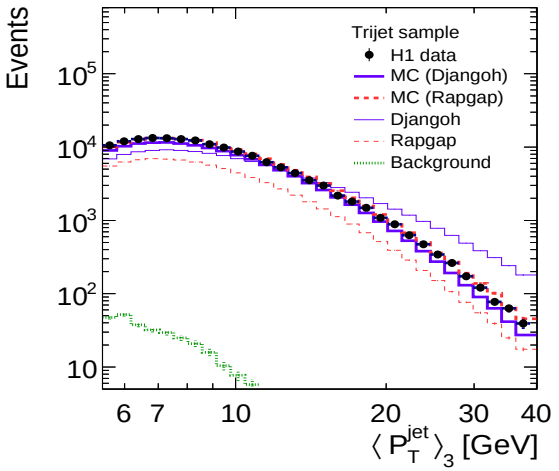
Measurement:

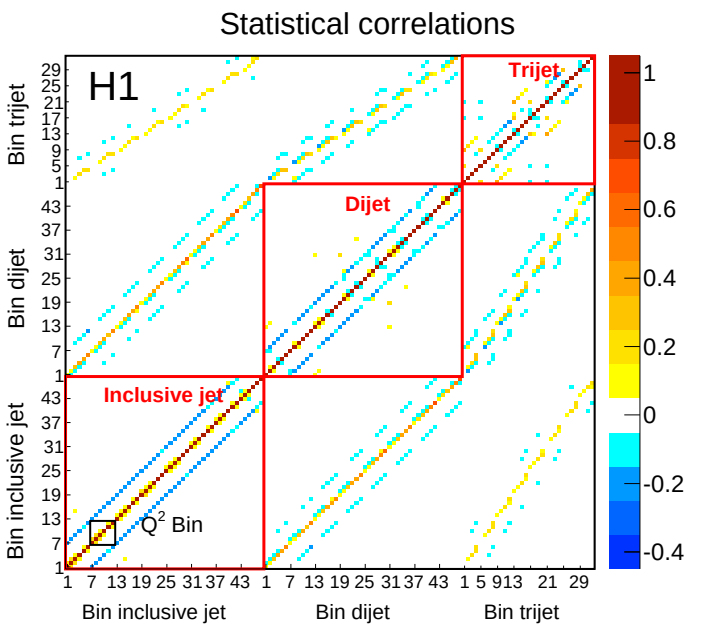
- Neutral current DIS, $290 pb^{-1}$ of data. $5.5 < Q^2 < 80 GeV^2$ and $0.2 < y < 0.6$.
- k_T jets in Breit frame are used.
- Cross-sections of inclusive jets, dijet and trijets **simultaneously**.
- As functions of jet p_T (or combination of) in Q^2 bins.

Measurement of Jet Production Cross Sections in Deep-inelastic ep Scattering at HERA



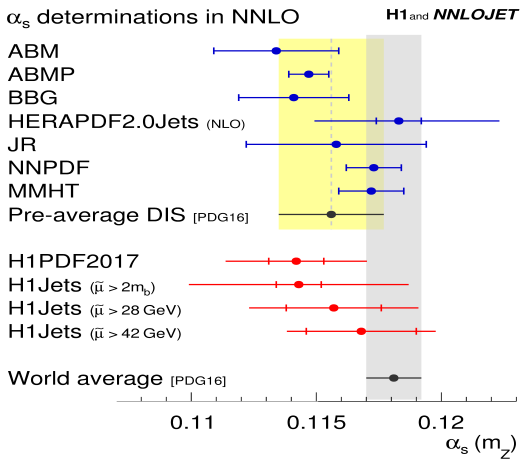


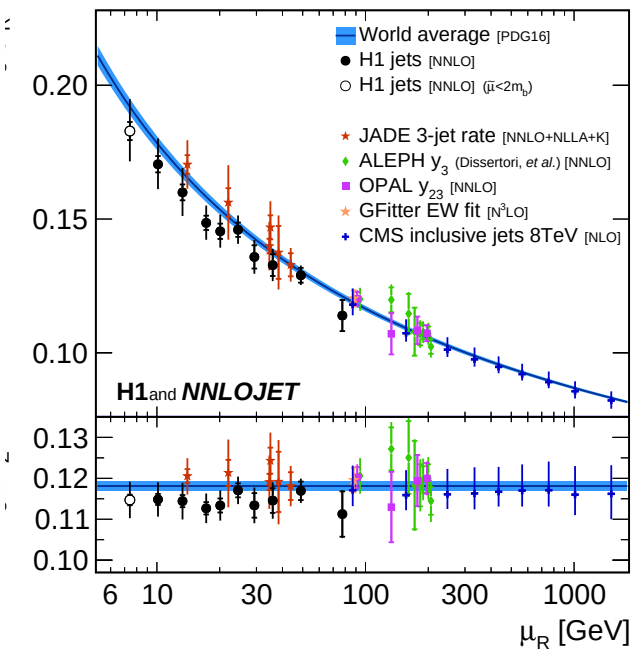




- Completed jet program at H1.
- Measurement includes statistical correlations.
- Recent progress in theory adds to value: J. Currie, T. Gehrmann and J. Niehues, Phys. Rev. Lett. **117** (2016) no.4, 042001

Determination of the strong coupling constant $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements





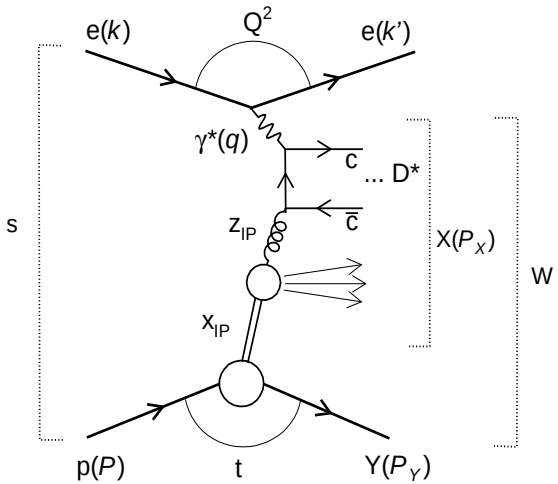
- First NNLO DIS fit.
- Multiple measurements, $\sqrt{s} = 300, 319$, $5 < Q^2 < 15000 GeV^2$, $0.2 < y < 0.7$, Breit frame k_T jets.
- Explicit α_s running.
- Two approaches:
  - Simultaneous fit of PDFs and α_s to all DIS data using NNLO predictions.
  - Use existing PDFs and NNLO predictions to fit α_s.

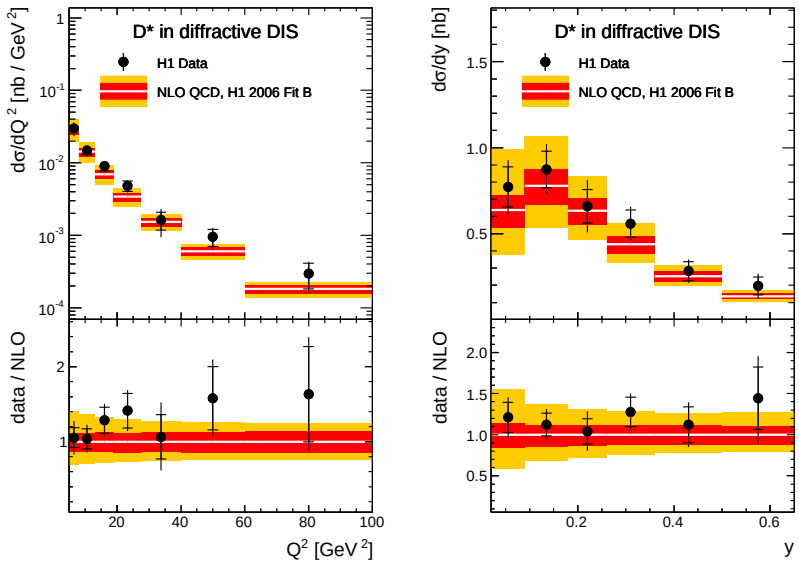
Determination of the strong coupling constant $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements

- Both fits have $\chi^2/NDoF$ close to unity or less.
- Multiple scale choices were tested.
- α_S fit
  - $0.1157\,(20)_{\mathrm{exp}}\,(6)_{\mathrm{had}}\,(3)_{\mathrm{PDF}}\,(2)_{\mathrm{PDF}\alpha}\,(3)_{\mathrm{PDFset}}\,(27)_{\mathrm{scale}}$.
  - $\mu > 28\,\mathrm{GeV}$ as central, multiple other choices tested.
  - NNPDF3.1 PDFs.
  - Interplay between exp. and theory uncertainty.
  - Scale uncertainty is dominant.
- PDF+α_S fit
  - $0.1142\,(11)_{\mathrm{exp,NP,PDF}}\,(2)_{\mathrm{mod}}\,(2)_{\mathrm{par}}\,(26)_{\mathrm{scale}}$
  - $Q^2 > 10\,\mathrm{GeV}^2$, H1 data only.
  - PDFs are released as H1PDF2017, consistency with NNPDF3.1 was checked.
  - Scale uncertainty is dominant.

Measurement of D^* production in diffractive deep inelastic scattering at HERA

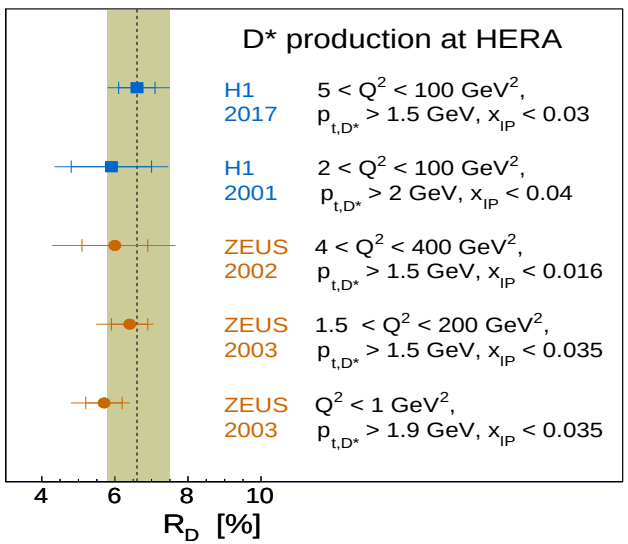
Reminder:





- Determined fraction of diffractive/inclusive D^{*+} production ratio.
- Compatibility with previous measurements and NLO predictions.

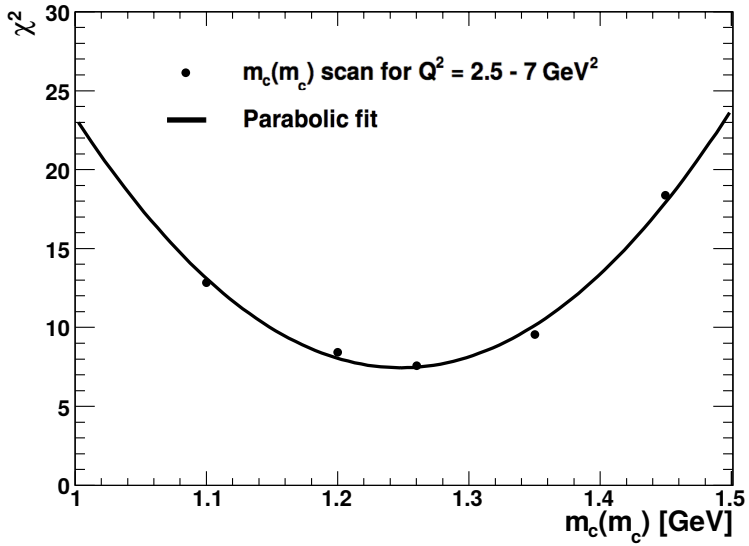
Diffractive fraction

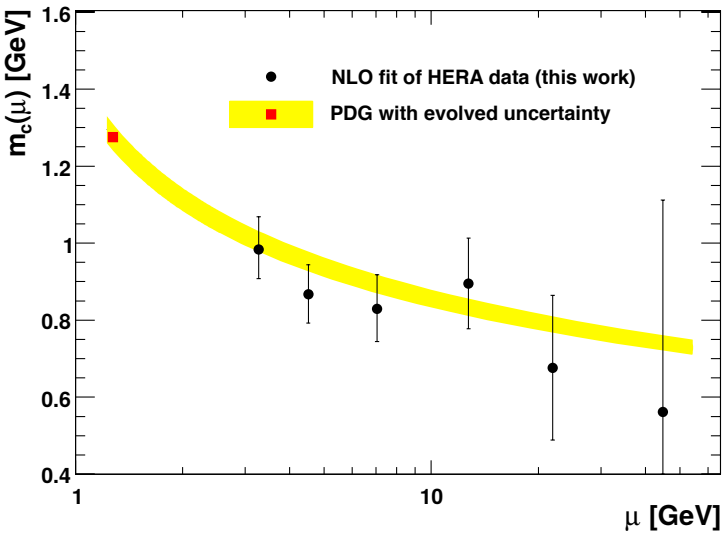


Extra physics at HERA

- A. Gizhko *et al.*, [and H1, ZEUS, PROSA] "Running of the Charm-Quark Mass from HERA Deep-Inelastic Scattering Data," Phys. Lett. B **775** (2017) 233.
- I. Abt *et al.*, "Investigation into the limits of perturbation theory at low Q^2 using HERA deep inelastic scattering data," Phys. Rev. D **96** (2017) no.1, 014001
- More H1+ZEUS papers in preparation.

Running of the Charm-Quark Mass from HERA Deep-Inelastic Scattering Data





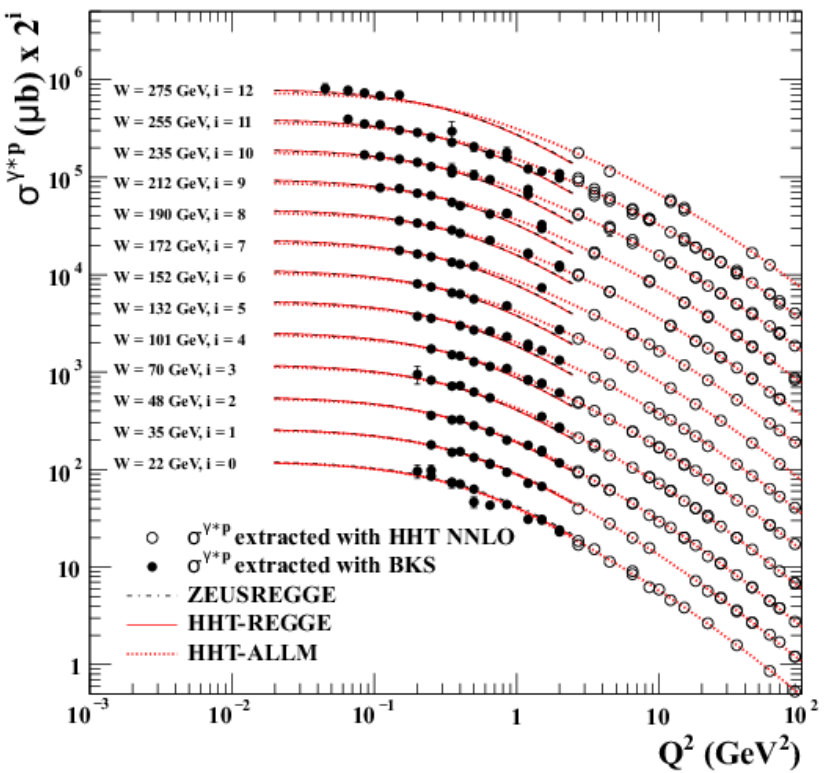
- Multiple datasets, neutral current DIS, $2.5 < Q^2 < 2000\,GeV^2$.
- NLO fits: xFitter/OPENQCDRAD and FFNS $n_f = 3$ ABM PDFs in multiple Q^2 bins.
- First running of m_c from HERA data.

Q^2 range	$m_c(m_c)$	$m_c(\mu)$
2.5–7	$1.256\ ^{+0.078}_{-0.070}\ ^{+0.054}_{-0.000}$	$0.984\ ^{+0.085}_{-0.076}$
12–18	$1.192\ ^{+0.075}_{-0.073}\ ^{+0.043}_{-0.000}$	$0.867\ ^{+0.077}_{-0.075}$
32–60	$1.208\ ^{+0.092}_{-0.088}\ ^{+0.045}_{-0.000}$	$0.830\ ^{+0.089}_{-0.085}$
120–200	$1.344\ ^{+0.130}_{-0.131}\ ^{+0.073}_{-0.074}$	0.90 ± 0.12
350–650	$1.14\ ^{+0.22}_{-0.22}\ ^{+0.13}_{-0.16}$	0.68 ± 0.19
2000	$1.05\ ^{+0.68}_{-0.76}\ ^{+0.40}_{-0.15}$	0.56 ± 0.56

PDG: 1.28 ± 0.03 GeV

Investigation into the limits of perturbation theory at low Q^2 using HERA deep inelastic scattering data

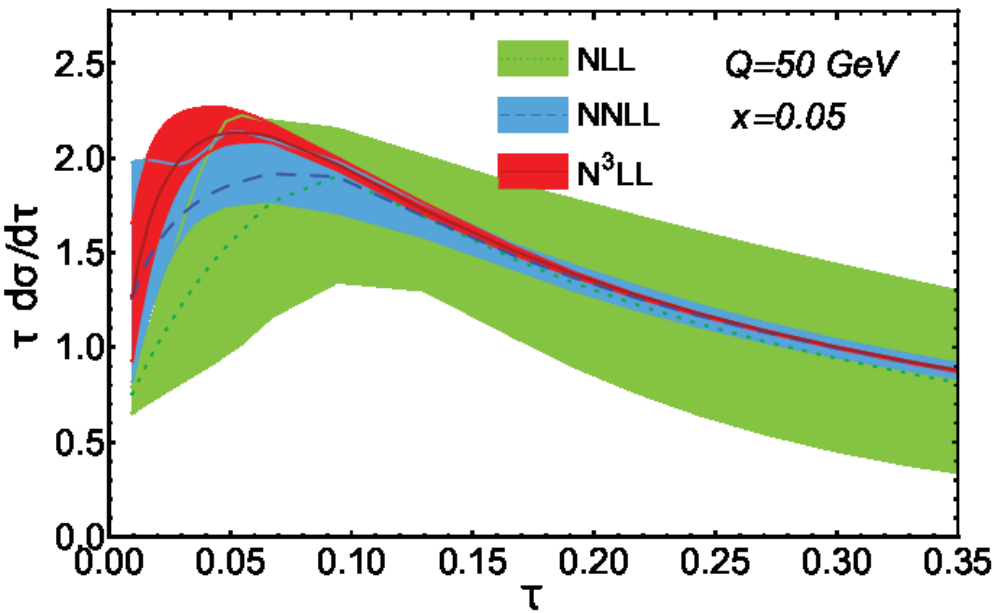
Fits in $0.045 < Q^2 < 30000 GeV^2$, $6 \times 10^{-7} < x_{Bj} < 0.65$, $10.7 < W < 301.2 GeV$ with multiple datasets. Extraction of $\sigma^{\gamma p}$ and comparison to different models/parametrisation that are valid in Regge or pQCD regions **in overlap region**.



- Data suggests smooth transition between Regge and pQCD regions, confirms A. Caldwell, "The evolution of $\sigma^{\gamma P}$ with coherence length," New J. Phys. **18** (2016) no.7, 073019
- No changes in behaviour between regions $\rightarrow$ **nature does not know about ppereturbation theory**.

ZEUS: in progress

- Dominant uncertainty on α_s in jet analysis is scale variation.
- Can be reduced with resummation for some HFS observables, e.g. for event shapes.



D. Kang, C. Lee and I. W. Stewart,"DIS Event Shape at N3LL," PoS DIS **2015** (2015) 142

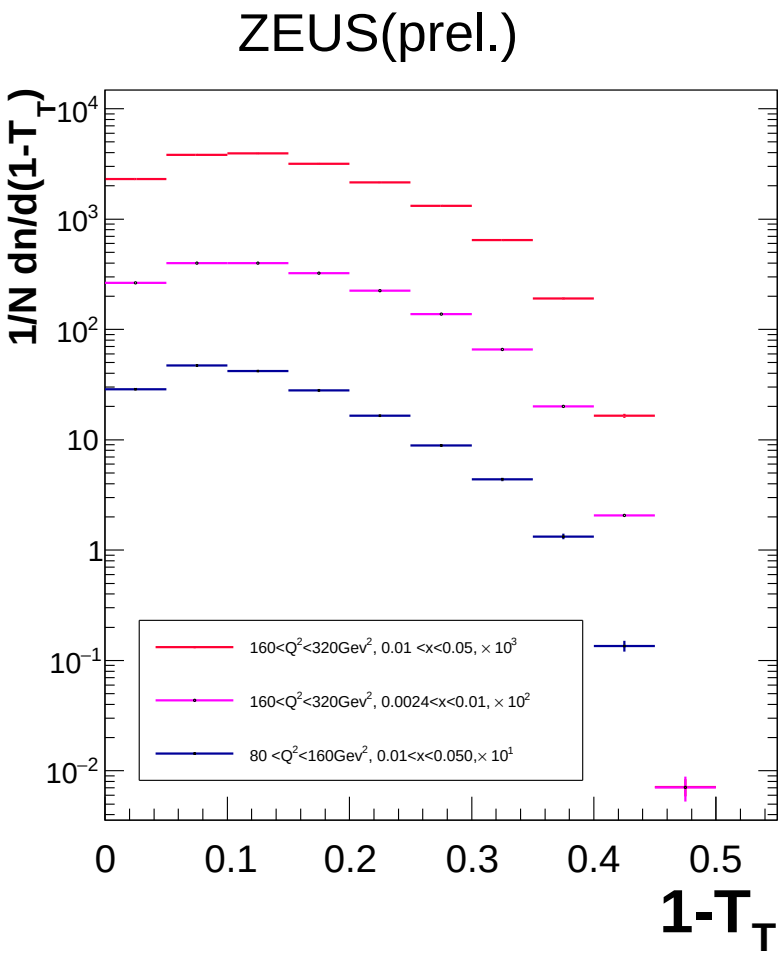
Example of event shape: thrust, calculated in current hemisphere of Breit frame.

$$T = \frac{\sum_i |\vec{p_i} \cdot \vec{n}|}{\sum_i |\vec{p_i}|},$$

where $\vec{n}$ is the virtual-photon direction (T_γ) or the axis that minimises the thrust (T_h). Very similar to e^+e^- event shapes.

ZEUS: in progress

- No event shape measurement exists with HERA-II data.
- Will be a valuable input for comparison to *NNLO* and/or N^3LL calculations.



- HERA-II neutral current.
- **Simultaneous** measurement in 16 $x - Q^2$ bins:
  $10 < Q^2 < 20480\,GeV^2$,
  $0.0006 < x < 0.6$.
- Six event shapes: T_γ, T_h, B_γ, B_h, C and M^2.

Conclusions

- Extremely interesting and valuable results obtained by the collaborations.
- Manpower problem is visible, but **more interesting and novel analysis are in development**.
- The preserved data in DESY and MPP makes it available and attracts physicists outside of experiments H1 and ZEUS have successful examples of collaboration with external theoretical and experimental groups.

Sometimes good ideas/predictions are coming late. Cheaper and faster to preserve than rebuild and re-run. New ideas in physics and analyses are welcome.