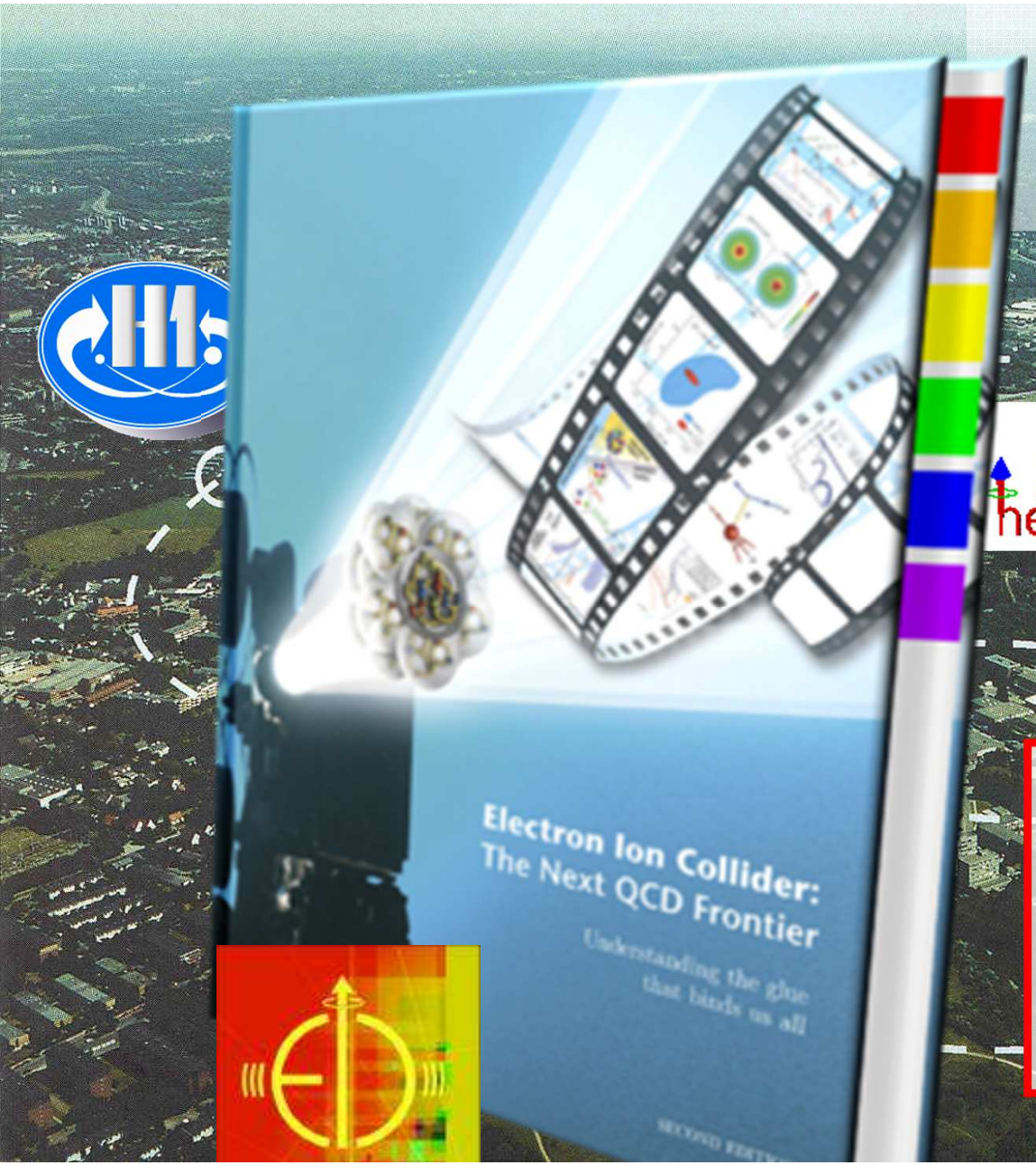
EW physics at HERA and connection to EIC

Achim Geiser, DESY Hamburg

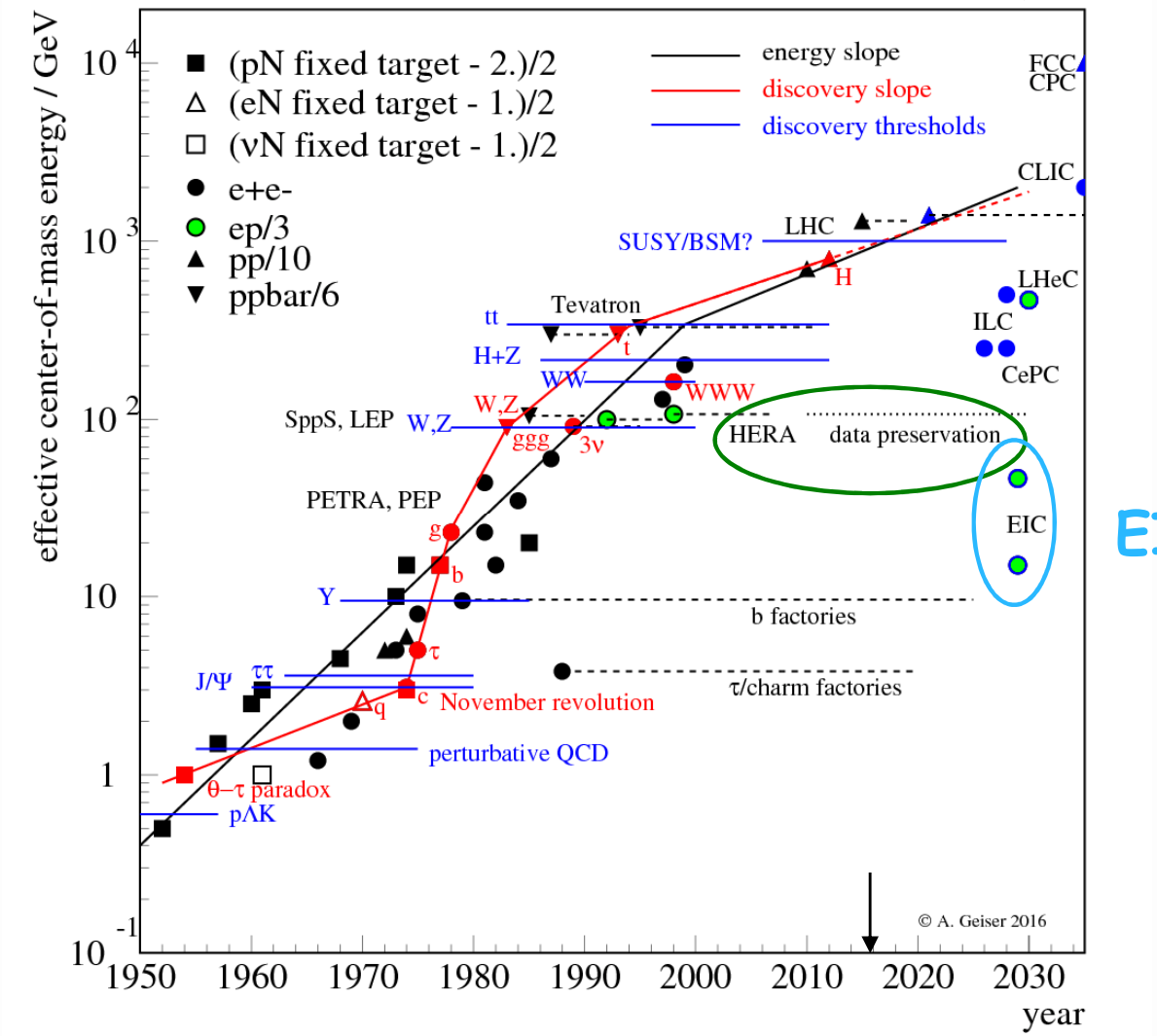
BSM/EW physics at EIC
mini ad-hoc workshop, 19. 12. 2017



- from ZEUS perspective
- Why?
- What? (examples)
- How?

Why analyze preserved HERA data?

planned new projects



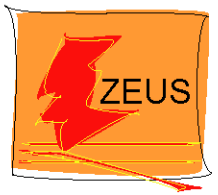
HERA data are unique!

EIC new and complementary!

use synergy!

Why analyze HERA data in context of EIC?

- Physics scopes of HERA and EIC differ but have significant overlap.



- Many aspects of EIC physics can be (partially) addressed with HERA data.

- EIC data lie significantly in the future, HERA data are readily available now.

- E.g. allows Master or PhD students to touch real data in conjunction with a hardware or MC study for EIC, including physics publications, talks at physics conferences, …

ZEUS is active collaboration (more in backup):

Common Ntuple analysis model

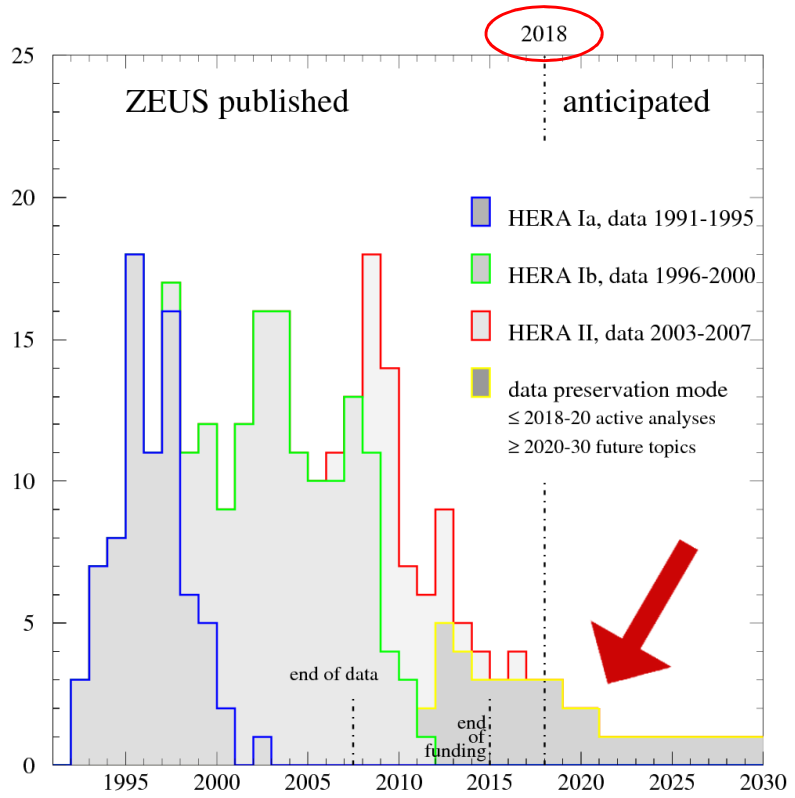
- **ZEUS Common Ntuple:** **Motto: keep it simple!**
  flat (simple) ROOT-based ntuple (same format as PAW ntuple converted with h2root)
  containing high level objects (electrons, muons, jets, energy flow objects, …)
  as well as low level objects (tracks, CAL cells, …)

- **Well tested !**
  almost all recent ZEUS papers based on
  on Common Ntuples

- **"Easy" to use**
  several recent ZEUS papers based on results produced by Master students.

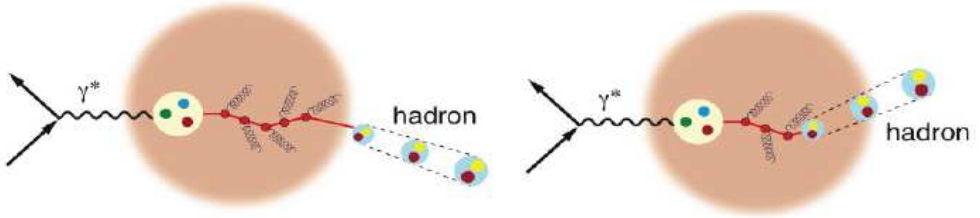
  PhD students could produce a ZEUS/EIC paper within only a fraction of their PhD time (e.g. ~6 months -1 year)

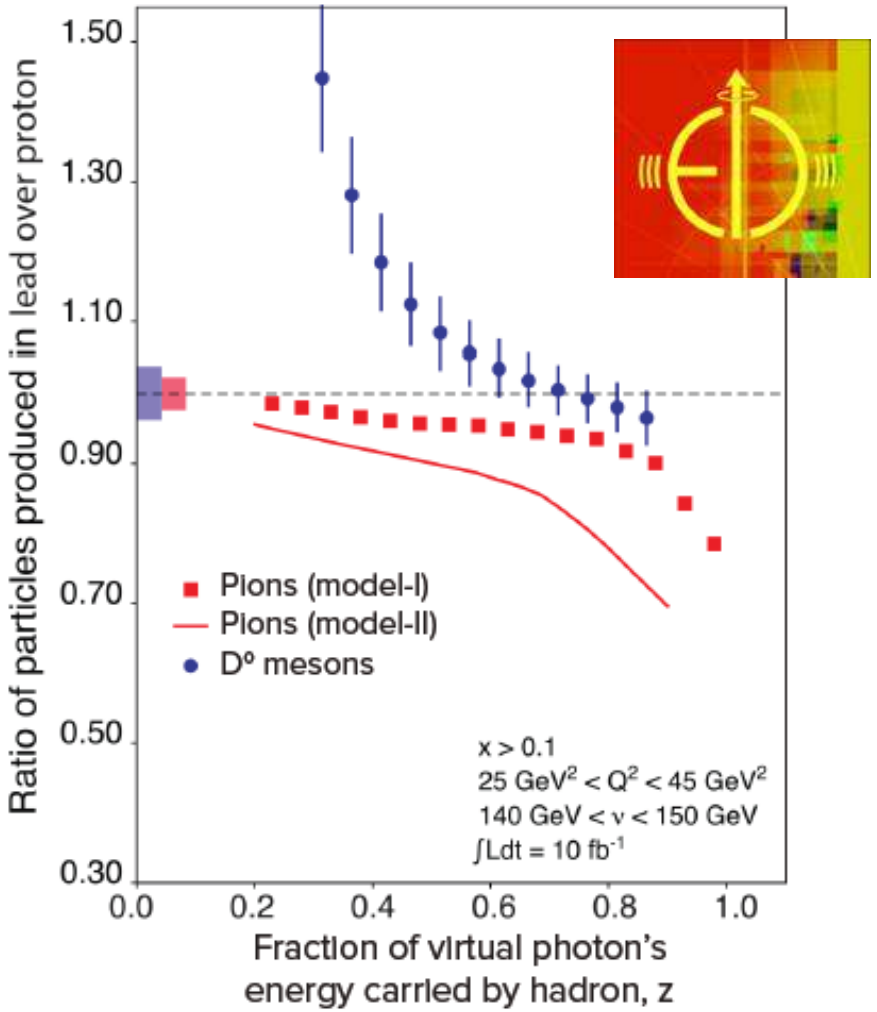
  two new groups recently joined



Example physics topics

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE





Possible HERA collider physics topics

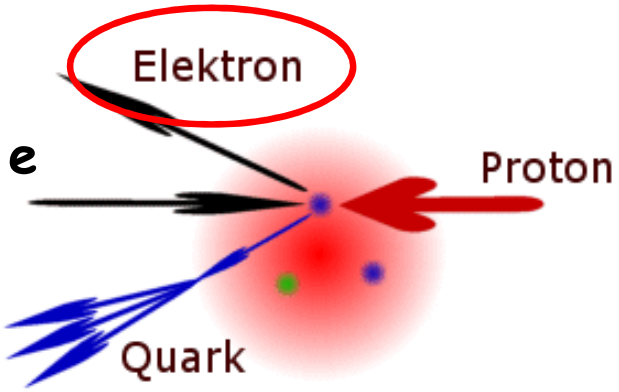
as discussed at Future Analysis with HERA data workshop 2014

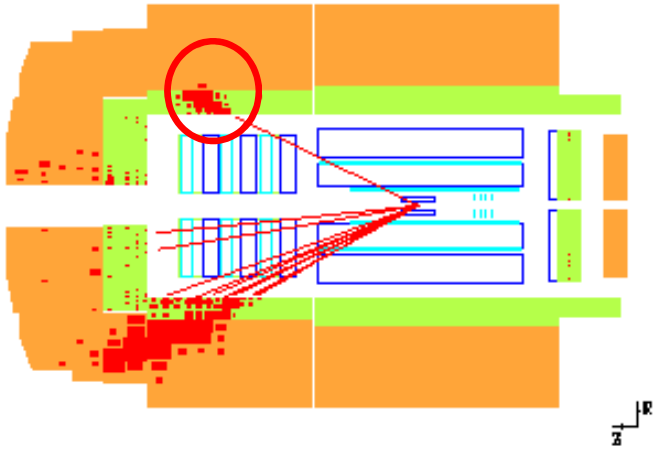
non-EW topics in backup

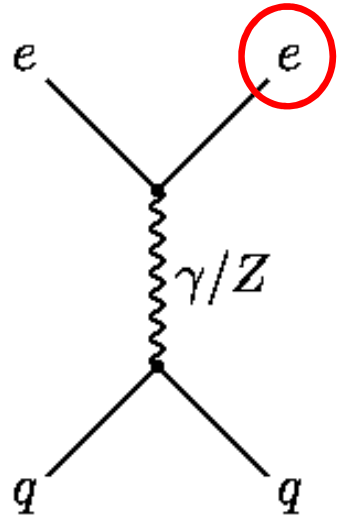
- **Electroweak and polarisation studies**
  - Finalize measurements of electroweak parameters, at NNLO QCD + NLO EW, **ongoing, difficult !**
  - Implement electroweak effects in PDFs **ongoing (theory)**
  - Measure higher order QED corrections e.g. to Bethe-Heitler dimuon production (e+ vs. e-, polarisation?) **not yet**
  - Continue studies of prompt photons **completed?**
  - Measure charm in charged current -> constrain strangeness in proton **ongoing**
- Check new theory developments
  - for all of the above
- **Synergies with other experimental programmes**
  - LHC, Tevatron, LEP, …
  - LHeC
  - **EIC (this talk)**

Electroweak Physics at HERA

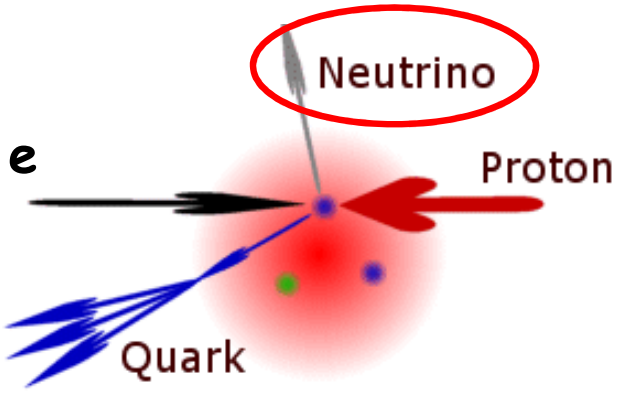
Neutral Current (NC) interactions

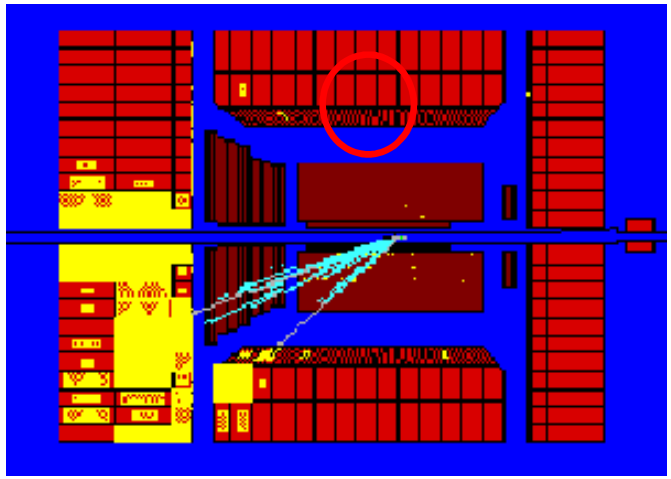


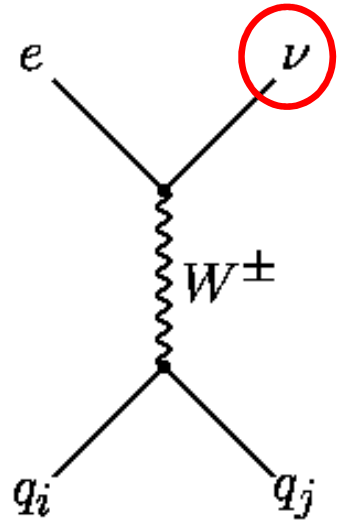




Charged Current (CC) interactions



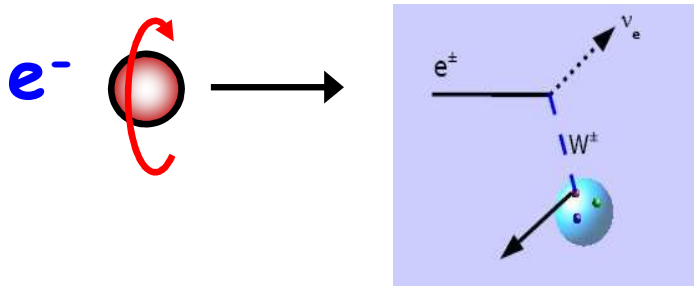




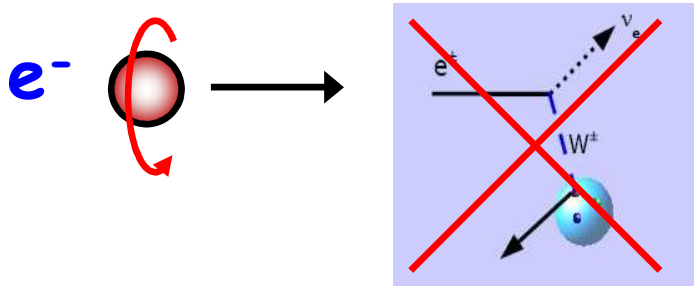
Weak interactions are "left-handed"

Eur.Phys.J. C75 (2015) no.12, 580

lefthanded electrons interact (CC)

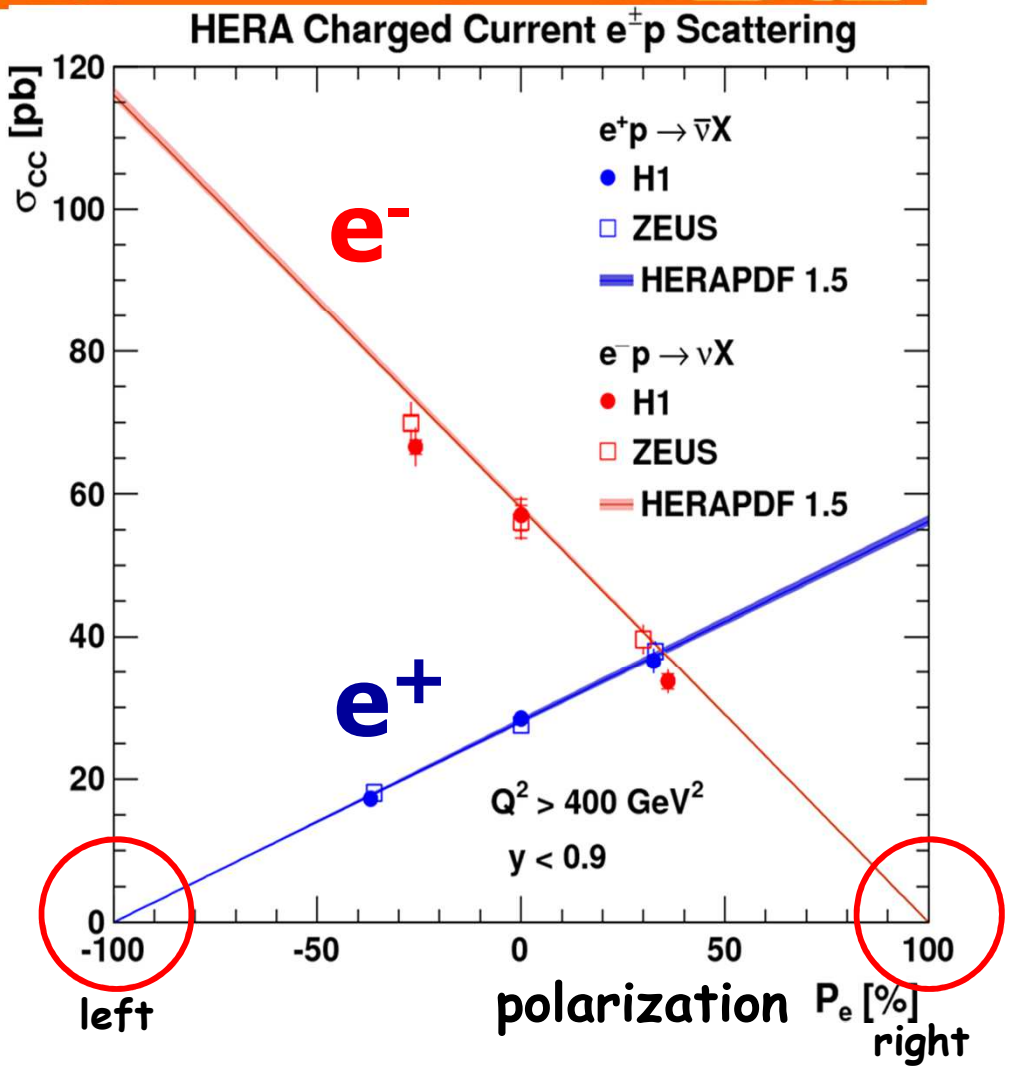


righthanded electrons do not!



cross section linearly proportional to polarization

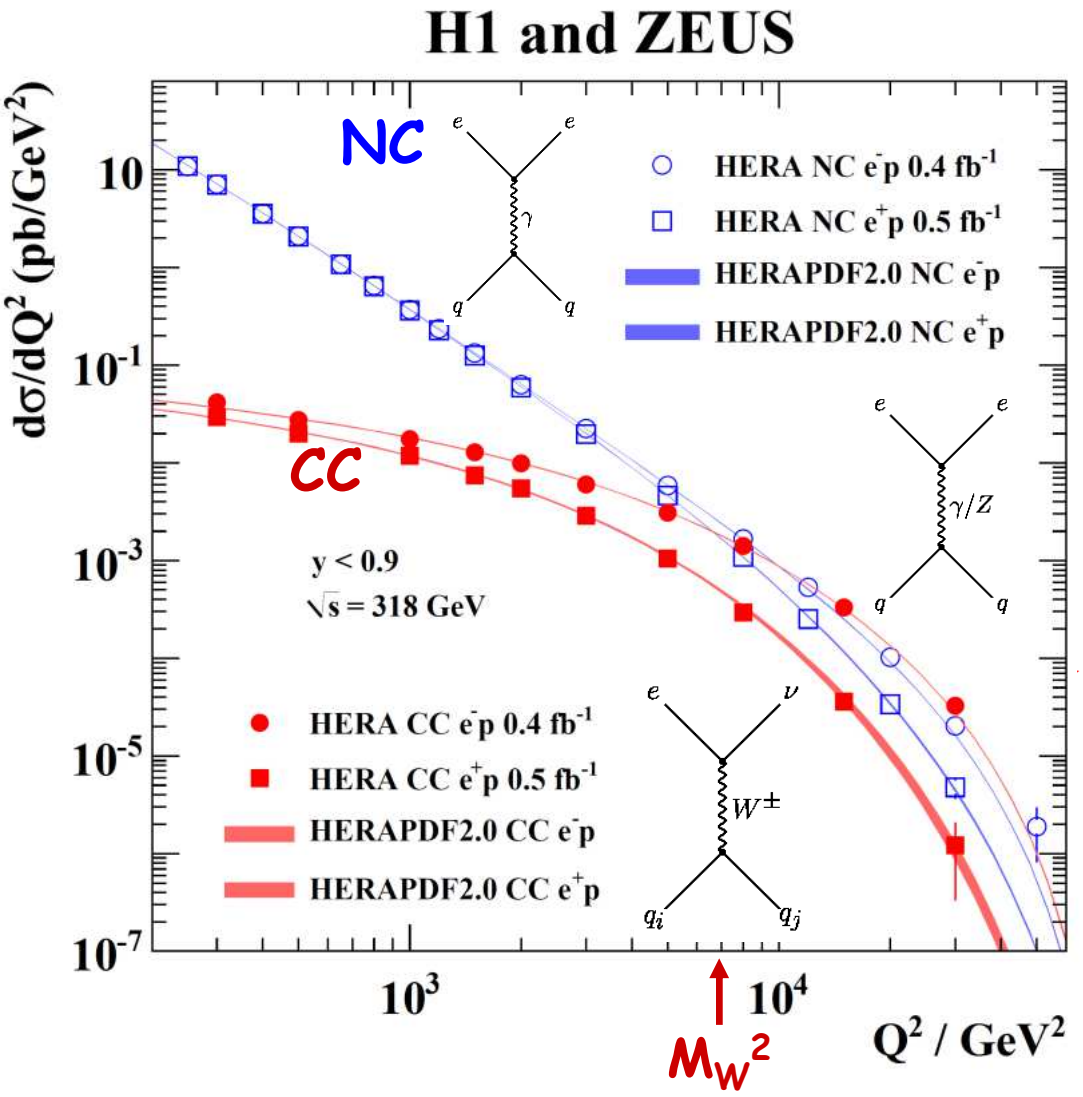
$$\sigma^{e^{\pm}p}_{polCC} = (1 \pm P_e) \cdot \sigma^{e^{\pm}p}_{unpolCC}$$



It works!

Electroweak Unification

Eur.Phys.J. C75 (2015) no.12, 580



Strength of weak and electromagentic forces become similar at scale $Q^2 \sim M_W^2$

$$\frac{\mathrm{d}^2\sigma_{NC}}{\mathrm{d}Q^2\,\mathrm{d}x} \sim \alpha^2 \frac{1}{Q^4} \frac{1}{x}\Phi_{NC}(x,Q^2)$$

$$\frac{\mathrm{d}^2\sigma_{CC}}{\mathrm{d}Q^2\,\mathrm{d}x} \sim G_F^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x}\Phi_{CC}(x,Q^2)$$

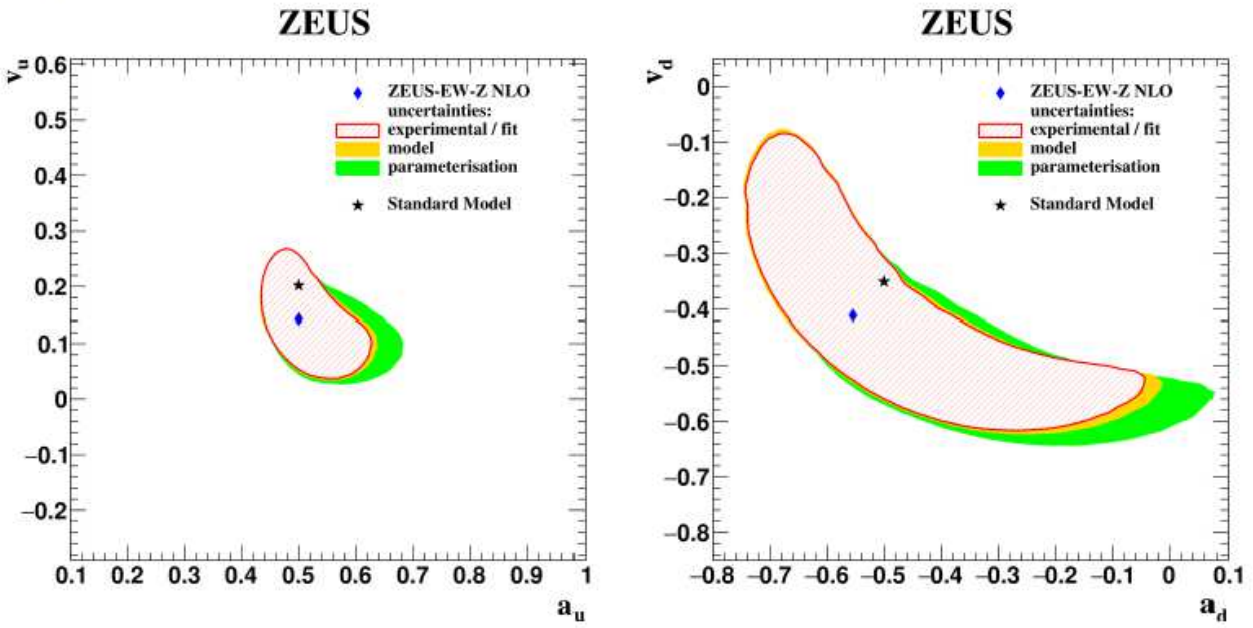
simultaneous PDF + EW fit of combined DIS data + ZEUS polarised data

Phys.Rev. D93 (2016) no.9, 092002

V. Myronenko
DIS2016

Couplings of quarks to Z boson

- Couplings were determined simultaneously with PDFs (ZEUS-EW-Z)



$$a_u = 0.50^{+0.09}_{-0.05}(\exp/fit)\,{}^{+0.04}_{-0.02}(mod)\,{}^{+0.08}_{-0.01}(par) = 0.50^{+0.12}_{-0.05}(tot)$$ **0.5**

$$a_d = -0.56^{+0.34}_{-0.14}(\exp/fit)\,{}^{+0.11}_{-0.05}(mod)\,{}^{+0.20}_{-0.00}(par) = -0.56^{+0.41}_{-0.15}(tot)$$ **-0.5**

$$v_u = 0.14^{+0.08}_{-0.08}(\exp/fit)\,{}^{+0.01}_{-0.00}(mod)\,{}^{+0.03}_{-0.01}(par) = 0.14^{+0.09}_{-0.09}(tot)$$ **0.202**

$$v_d = -0.41^{+0.24}_{-0.16}(\exp/fit)\,{}^{+0.04}_{-0.07}(mod)\,{}^{+0.00}_{-0.08}(par) = -0.41^{+0.25}_{-0.20}(tot)$$ **-0.351**

Standard Model

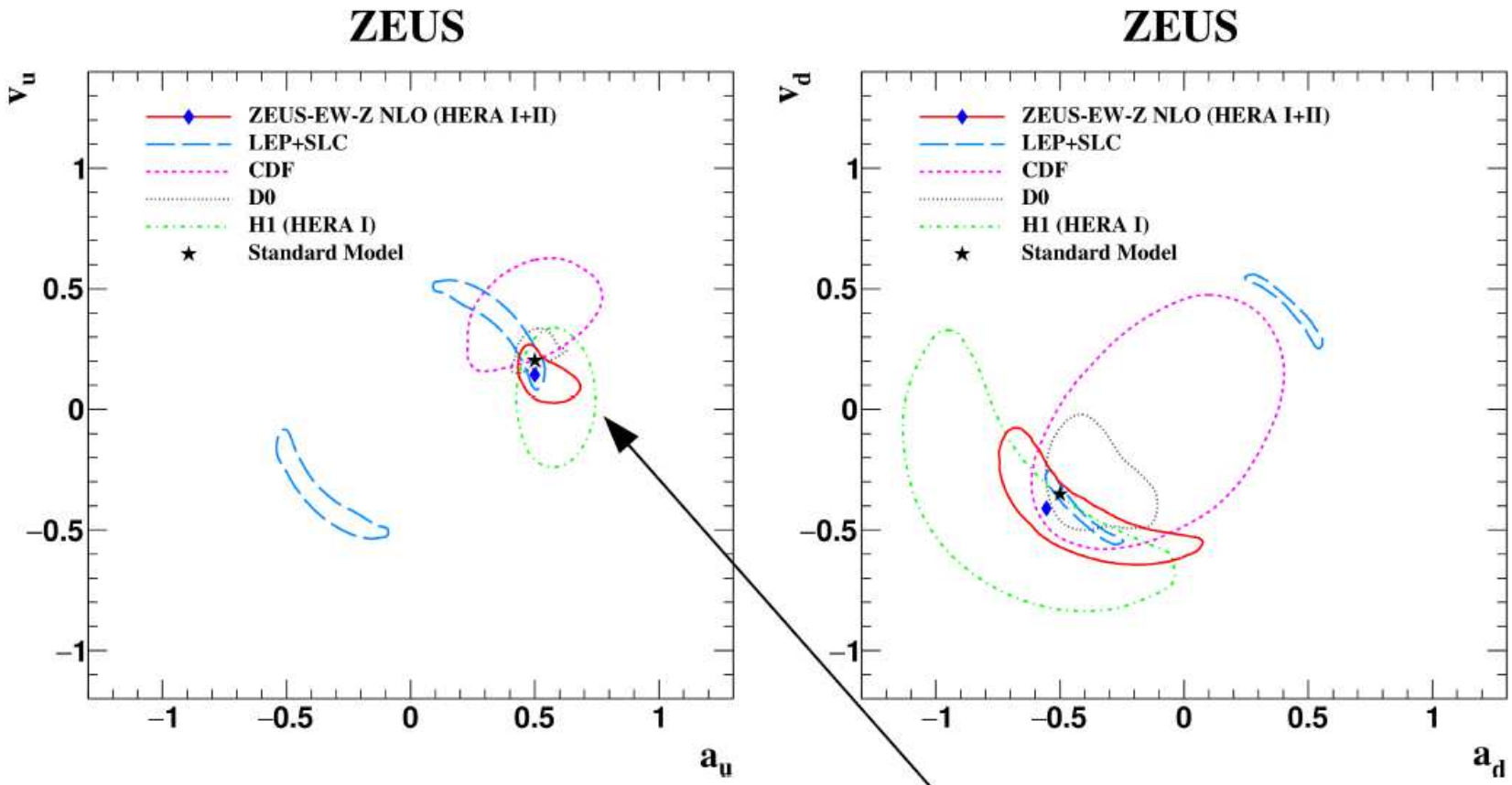
simultaneous PDF + EW fit of combined DIS data + ZEUS polarised data

Phys.Rev. D93 (2016) no.9, 092002

V. Myronenko
DIS2016

Couplings of quarks to Z boson

- ZEUS-EW-Z results are compatible with previous measurements



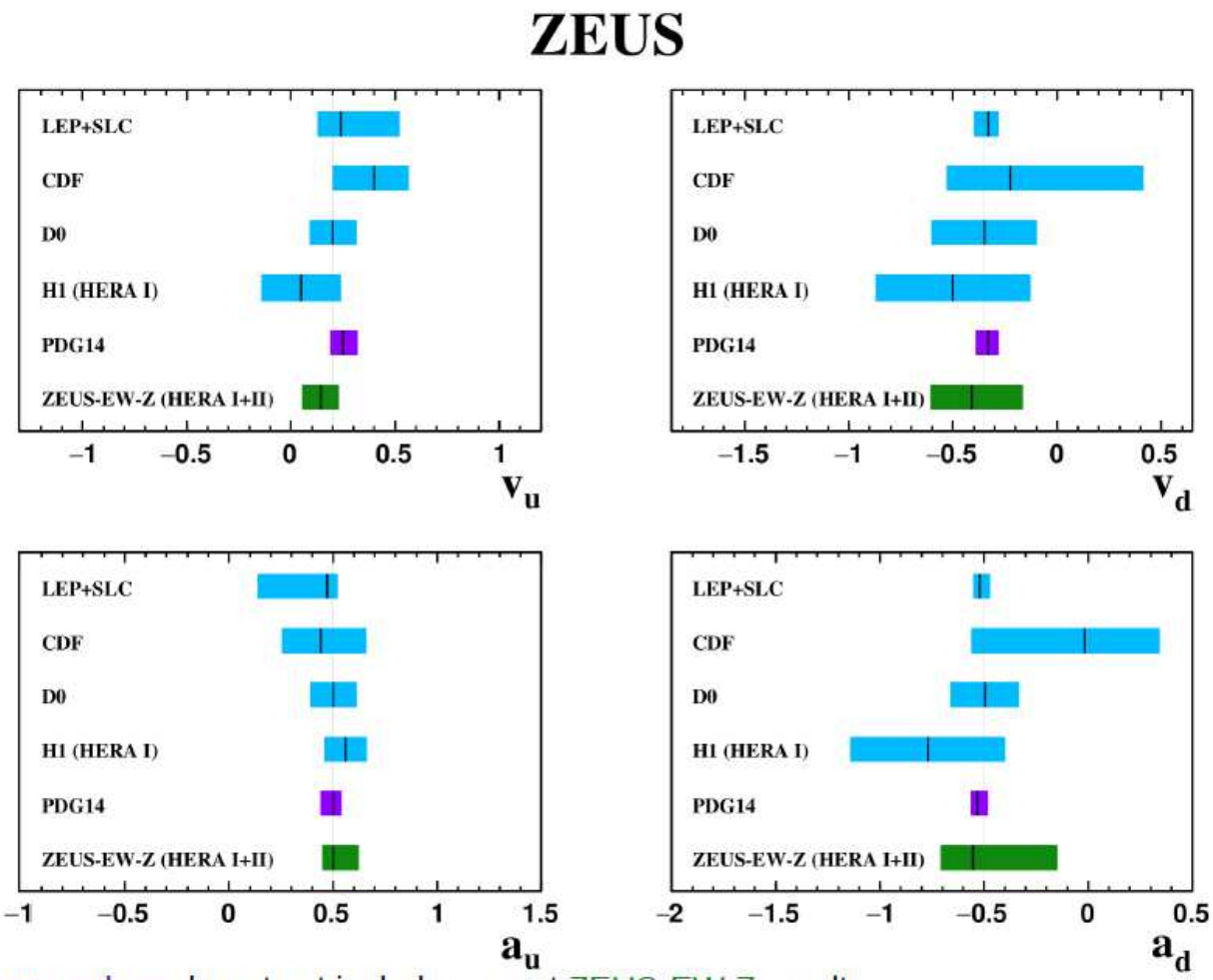
- HERA data show remarkable sensitivity to the u-type quark couplings.

simultaneous PDF + EW fit of combined DIS data + ZEUS polarised data

Phys.Rev. D93 (2016) no.9, 092002

V. Myronenko
DIS2016

Couplings of quarks to Z boson



- PDG average values do not yet include current ZEUS-EW-Z results.
- Results presented here have a potential to decrease uncertainties of average values (u-quark in particular)

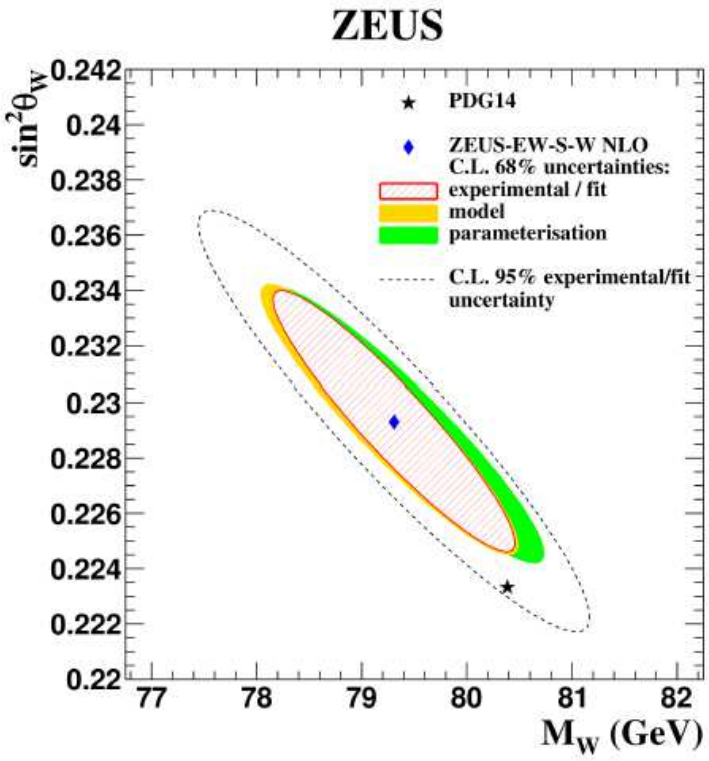
simultaneous PDF + EW fit of combined DIS data + ZEUS polarised data

Phys.Rev. D93 (2016) no.9, 092002

$\sin^2\theta_W$ and mass of W boson

V. Myronenko
DIS2016

- $\sin^2\theta_W$ and M_W were determined simultaneously with PDFs (ZEUS-EW-S-W)



$$M_W = 79.30 \pm 0.76_{(exp/fit)}\ ^{+0.38}_{-0.08(mod)}\ ^{+0.48}_{-0.10(par)}\ GeV = 79.30^{+0.98}_{-0.77(tot)}\ GeV$$

$$\sin^2\theta_W = 0.2293 \pm 0.0031_{(exp/fit)}\ ^{+0.0005}_{-0.0001(mod)}\ ^{+0.0003}_{-0.0001(par)} = 0.2293^{+0.0032}_{-0.0031(tot)}$$

$$corr\left(M_W, \sin^2\theta_W\right) = -0.930$$

$$M_W^{PDG\ 14} = 80.385 \pm 0.015\ GeV$$

$$\sin^2\theta_W^{PDG\ 14\ On-shell} = 0.22333 \pm 0.00011$$

- All extracted quantities agree with World average values.

simultaneous PDF + EW fit of combined DIS data + ZEUS polarised data

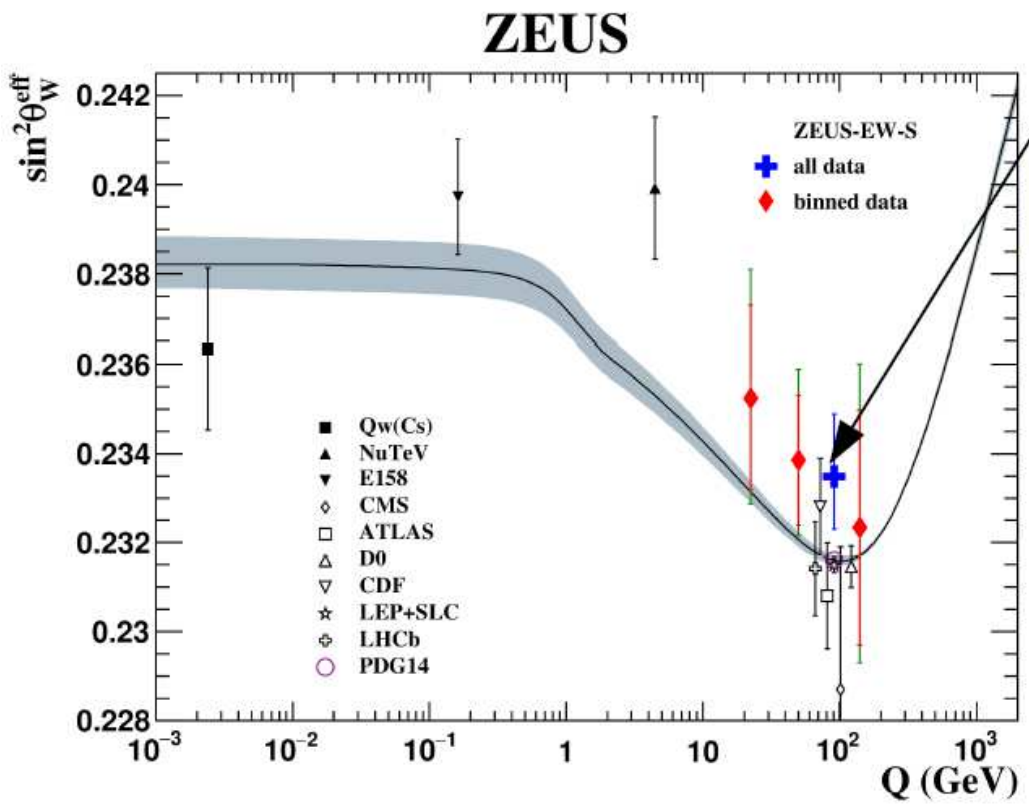
Phys.Rev. D93 (2016) no.9, 092002

$\sin^2\theta_W$ from HERA data

V. Myronenko
DIS2016

- $\sin^2\theta_W$ was determined simultaneously with PDFs (ZEUS-EW-S)

$$\sin^2\theta_W = 0.2252 \pm 0.0011_{(\mathrm{exp/fit})}\ {}^{+0.0003}_{-0.0001}{}_{(mod)}\ {}^{0.0007}_{-0.0001}{}_{(par)} = 0.2252^{+0.0013}_{-0.0011(tot)}$$



$$\sin^2\theta_W^{PDG\,14\,On-shell} = 0.22333 \pm 0.00011$$

- On-shell measurements were translated to $\sin^2\theta_W^{eff}$.

Similar preliminary results by H1

Daniel Britzger DIS2016

Light quark couplings

Couplings of light quarks to Z-boson

- χ^2 / ndf = 1370.5 / (1388 – 21)
- *u*-type coupling better constrained than *d*-type coupling
  -> sensitivity from valence quarks
- Results compatible with SM expectation
- PDF uncertainties are small

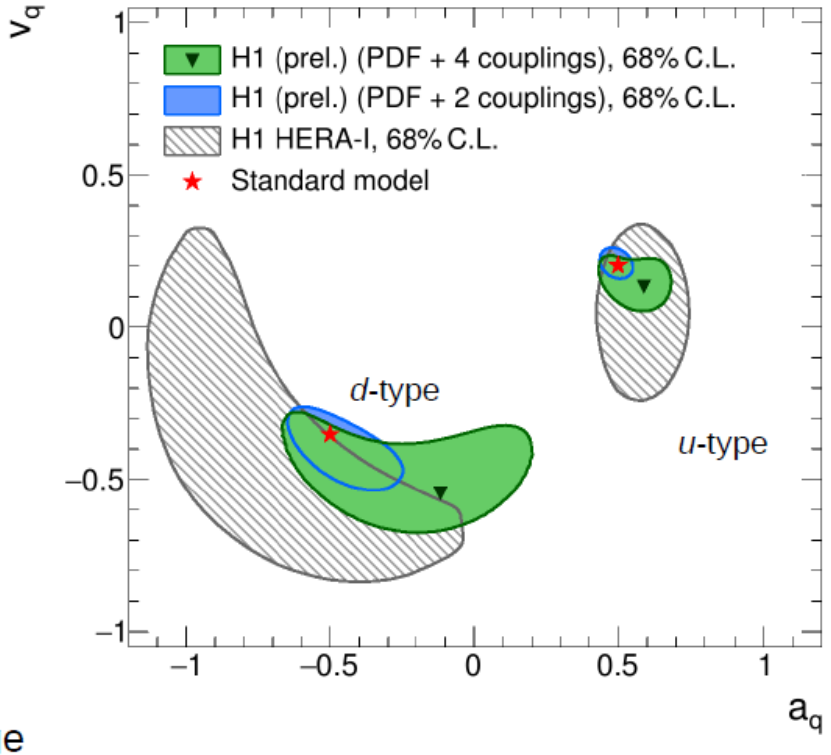
Comparison to H1 HERA-I

Phys.Lett.B 632 (2006) 35

- Considerably improved sensitivity using final H1 HERA-II data
- Polarisation in HERA-II important vor vector couplings

Fit: PDF + 2 couplings

- Reduced correlations and uncertainties
- Correlations between a_u-a_d and v_u-v_d are large



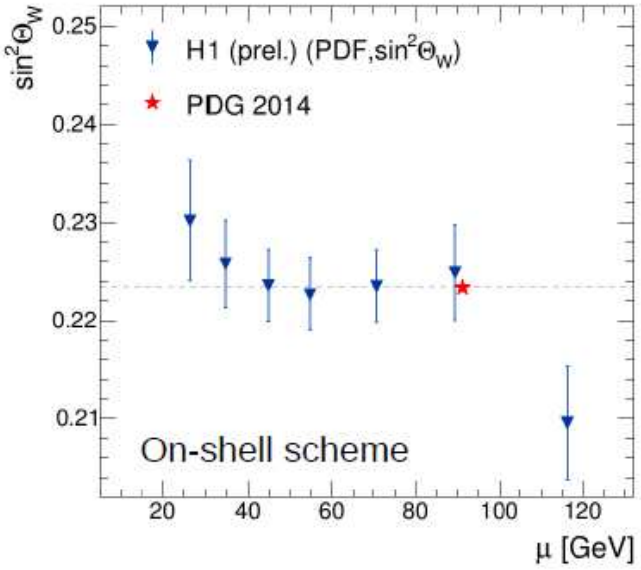
Similar preliminary results by H1

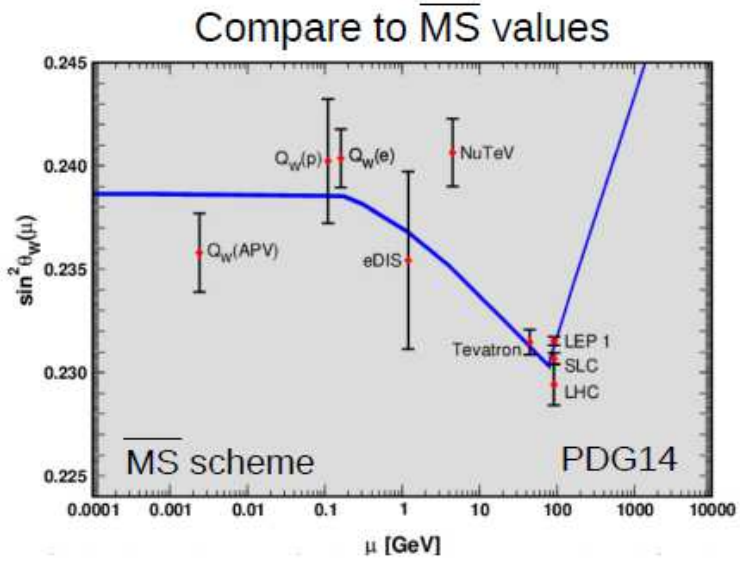
Daniel Britzger DIS2016

Exploit Q^2 dependence of data

Virtually exchanged bosons allow for SM tests at various energy scales

- Weak mixing angle is extracted for different scales $\mu=\sqrt{Q^2}$
- Simultaneous fit of PDF and values of $\sin^2\theta_W$
- Data are subdivided into different Q^2 regions each with independent $\sin^2\theta_W(Q^2)$





Results

- Results compatible with precise value from Z-pole measurements
- Unique measurement of weak mixing angle at different scales
- Comparison to MSbar values straight forward

Issues to be addressed in the future

personal remarks

Leading order EW parameter extractions are in good shape

for a combined NNLO QCD + NLO EW fit:

The EW NLO theory corrections need to
be implemented in a fully consistent way,
including proper NLO EW PDF treatment
(so far only partial implementation)

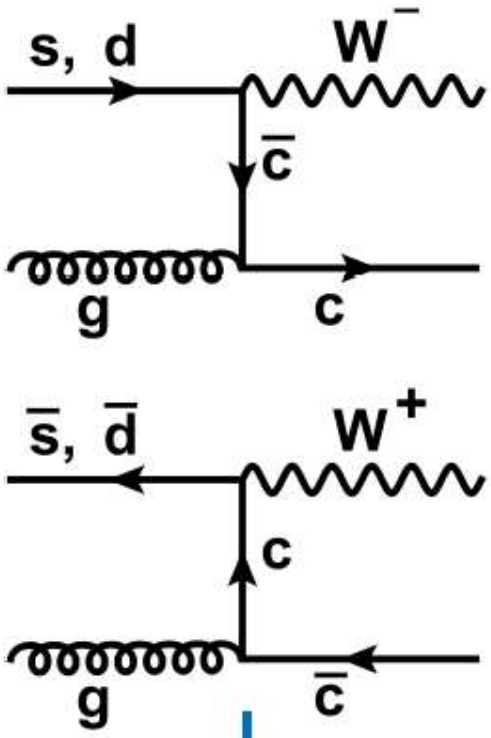
Recommendation to EIC:

Avoid correction of cross sections to Born level using LO+PS MC's (might make NLO EW analysis impossible)

W+c and strangeness in proton

see also B. Roland, DIS17

[JHEP 1402 (2014) 013]



direct probe of a possible s - s̄ asymmetry

differential cross section versus the rapidity of the lepton from the W decay

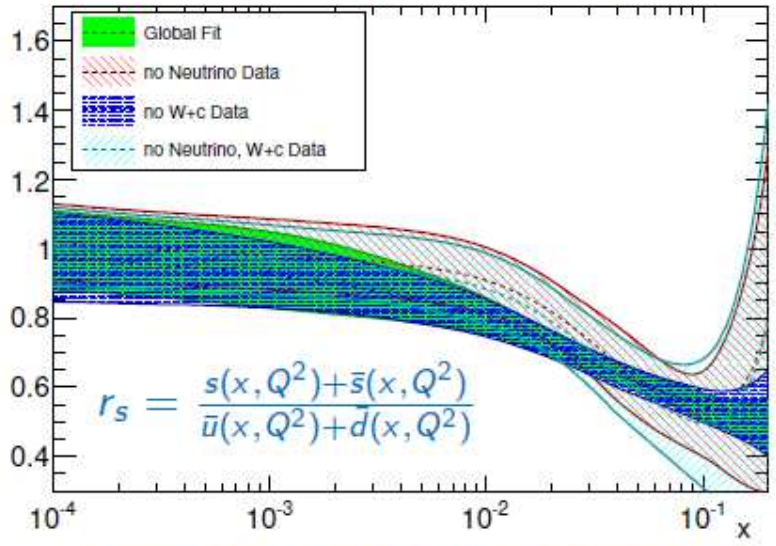
→ direct probe of the strange content at the electroweak scale

$g\,s \to c\,W^-$, $g\,\bar{s} \to \bar{c}\,W^+$ dominate at LO

$g\,d \to c\,W^-$, $g\,\bar{d} \to \bar{c}\,W^+$ are Cabibbo suppressed

CMS results included into NNPDF3.0

NNLO, $\alpha_S = 0.118$, $Q^2 = 10^4$ GeV^2



JHEP 1504 (2015) 040 (NNPDF3.0)

consistent with neutrino data,

also Phys.Rev. D91 (2015) 094002

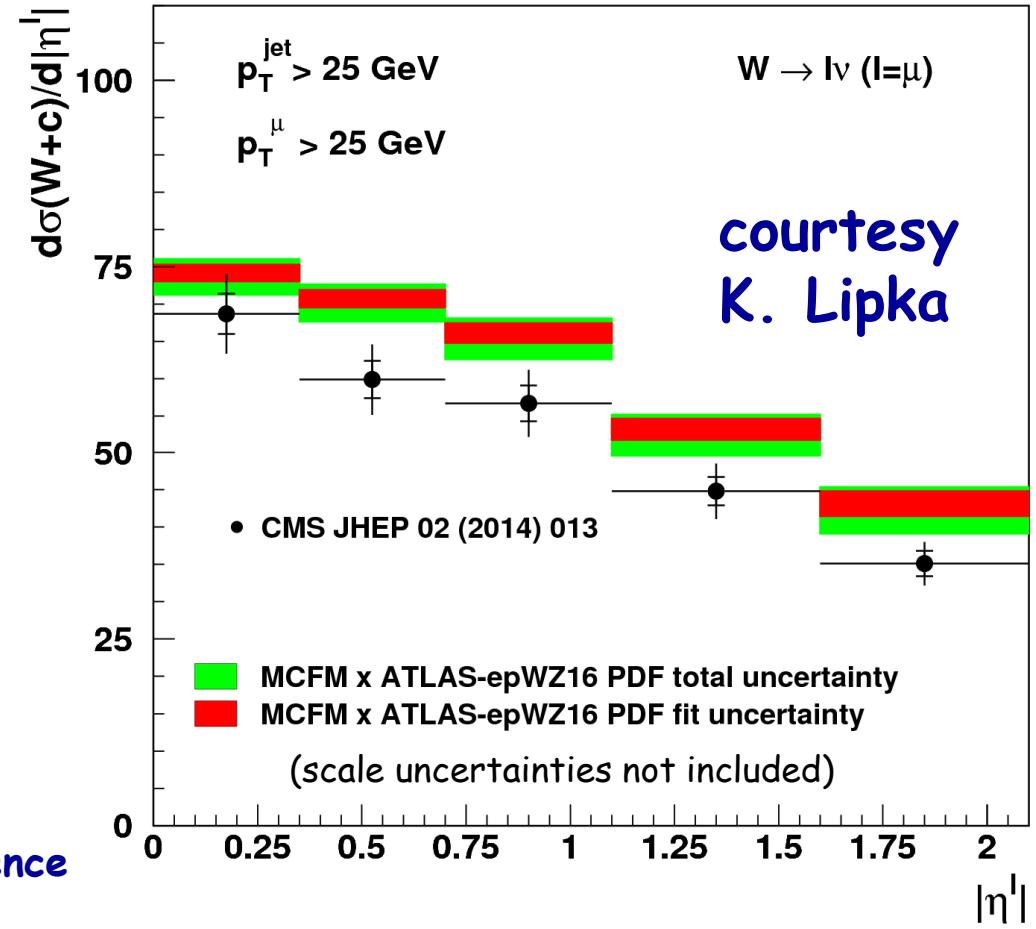
Associated W+c: comparison to ATLAS

- data: CMS
  JHEP 02 (2014) 013

- prediction:

MCFM NLO using
ATLAS-epWZ pdf
arXiv:1612.03016
(based on ATLAS
inclusive W,Z + HERA)

see also talk N. Zakharchuk this conference

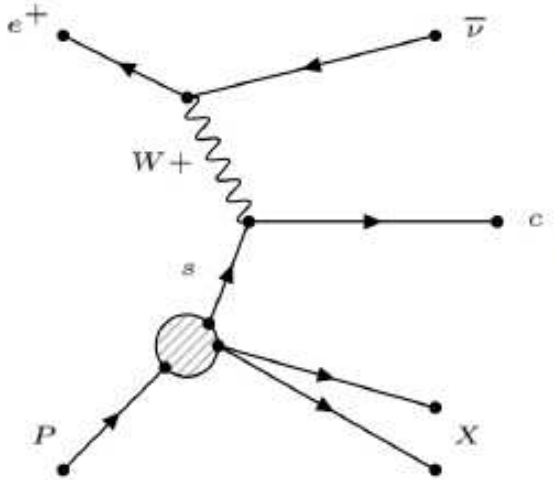


predicts larger cross section than CMS data

-> strangeness contribution too large?

Charm production in CC at HERA

Quark Initiated Process (QI, LO)



- Via *d/b* is Cabibbo-suppressed
- Probes the strangeness in the sea

- ZEUS analysis ongoing through person power also involved in EIC,
  will hopefully contribute to resolving ATLAS/CMS tension (also future topic for EIC)

Charm production in CC at HERA

J. Nam, JPOS17 workshop

Current Status & Summary

- CC events have been selected from all HERA II data.
- Charm signal with suppressed LQ contribution has been observed in the mirrored L_{xy} and S_{xy} plots.
- Detector-level & Reconstruction-level corrections will be quantified along with analysis on systematic uncertainty
- The charm cross section will be extracted by sub-dividing the kinematic plane into Q^2 bins.

Conclusions and Outlook

- The EIC project is unique and exciting !
- HERA data are unique, exciting, and available !

- many HERA data topics continue to be of interest,
  and quite a few are still not finished or even not yet started
  arXiv:1601.01499 arXiv:1512.03624 (also see backup)
- Many, including EW, have overlap with topics relevant for EIC
  -> of particular interest until EIC data become available

- bottleneck: manpower after end of HERA funding

in the interest of advancing ep/eA physics it might be worthwhile to team up interest in future EIC data and existing HERA data to boost the EIC project and to fully exploit the HERA physics program

Backup

List of topics from HERA perspective

List for EW topics in main part of talk.

Here: other topics (QCD and other)

Should be cross-calibrated with and further extended by topics particularly interesting for EIC.

Possible HERA collider physics topics

as discussed at Future Analysis with HERA data workshop

- BSM:
  - Provide standard candles against which new physics searches can be calibrated
- Proton structure:
  - FL combination, integration of high x results into PDF fit, finalize heavy flavour combinations and fit, improved transverse momentum dependent PDFs, investigation of low x phenomenology, …

  -> understand the proton, understand QCD, provide detailed descriptions for other colliders
  - Are we starting to hit the nonperturbative limit?
  - Can we make further decisive measurements from existing data?
  - Can we achieve improved theoretical interpretations from existing results?
  - Can statements about new physics at high scales be made from the low energy data?
- Diffraction and DVCS
  - Finalize inclusive diffractive measurements, make them more differential
  - Finalize measurements of elastic vector meson production and compare to improved theory models and to other experiments
  - Measure elastic scalar model production, test odderon hypothesis
  - Finalize measurements of DVCS

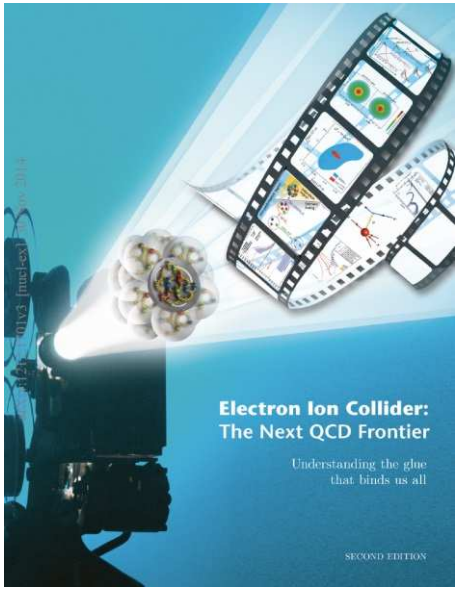
Possible HERA collider physics topics

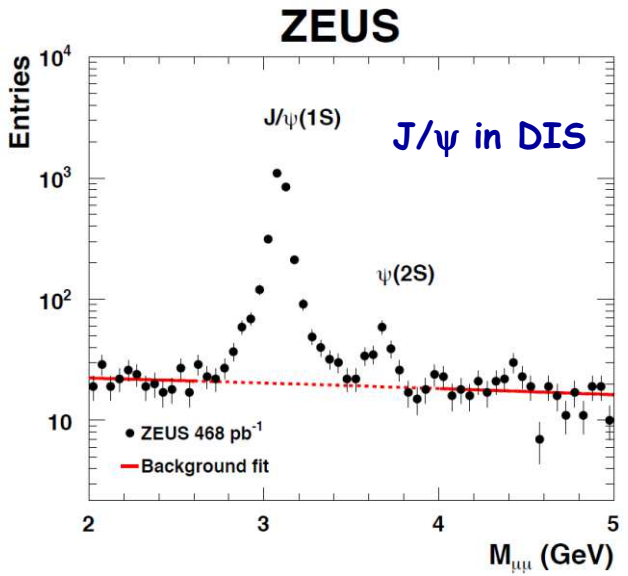
as discussed at Future Analysis with HERA data workshop

- Jets:
  - Finalize (ZEUS) measurements, combine,
  - make more differential measurements, event shape measurements,
  - apply NNLO theory, remeasure alphas
- Hadronic final states:
  - Study multiparton interactions and other nonperturbative effects
  - (re)measure photon structure
  - (re)measure QCD instanton production
  - Search for exotic resonances
  - Complete total gamma-p cross section
- Heavy Flavours:
  - Intrinsic charm
  - NNLO measurements of c- and b-masses
  - Multi-differential heavy flavour cross sections
  - More cross section combinations
  - Improved measurements of charm fragmentation functions

Example physics topics

Deliverables	Observables	What we learn	Requirements
GPDs of sea quarks and gluons	DVCS and $J/\Psi, \rho^0, \phi$ production cross-section and polarization asymmetries	transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations	$\int dt\, L \sim 10$ to $100\,\mathrm{fb}^{-1}$; ~0.5 fb^{-1} leading proton detection; polarized e^- and p beams; wide range of x and Q^2; range of beam energies; e^+ beam valuable for DVCS
GPDs of valence and sea quarks	electro-production of π^+, K and ρ^+, K^* ?	dependence on quark flavor and polarization	





Example physics topics

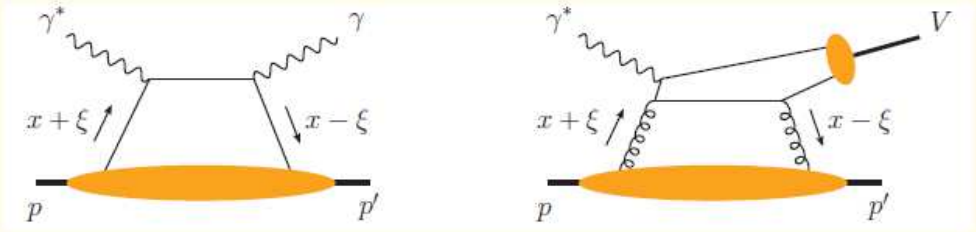
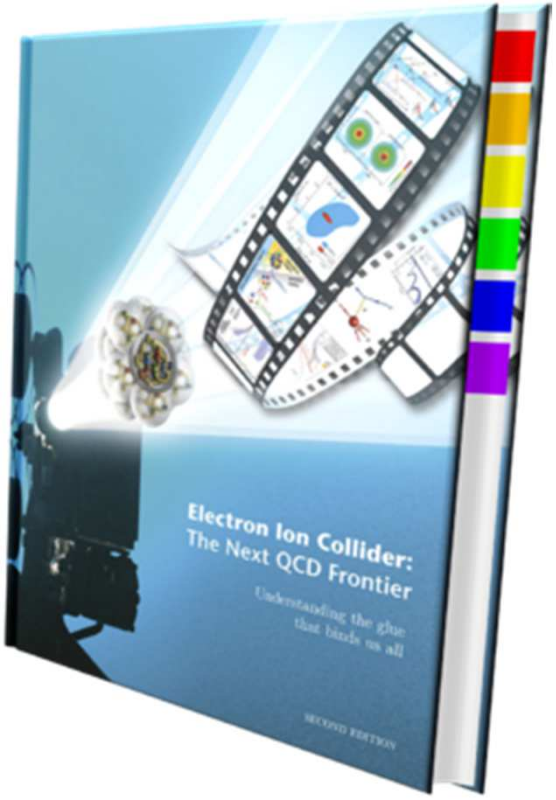


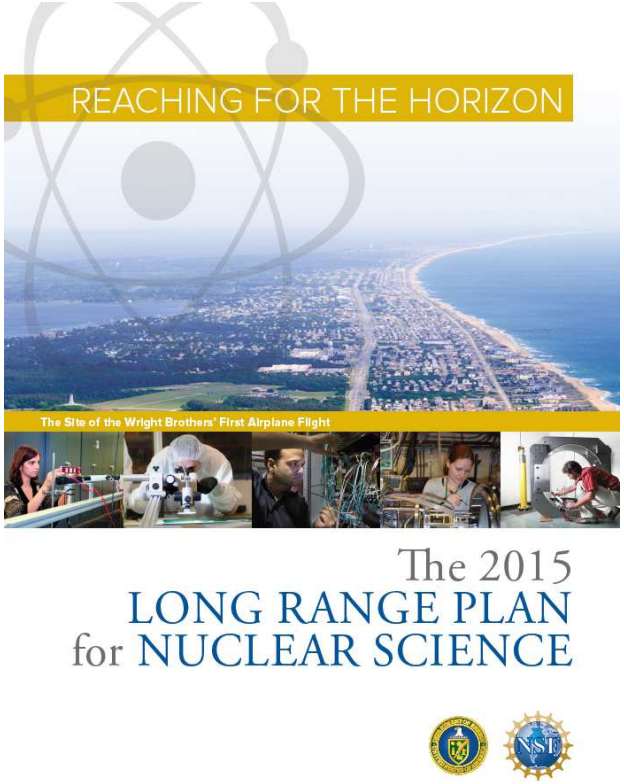
Figure 2.18: Graphs for deeply virtual Compton scattering (left) and for exclusive vector meson production (right) in terms of generalized parton distributions, which are represented by the lower blobs. The upper filled oval in the right figure represents the meson wave function.

- ZEUS DVCS analysis for HERA II not completed
- many possible exclusive vector (or other) meson analyses for HERA II not completed or not even started (lack of manpower)

Example physics topics

- Your favourite EIC topic ☺





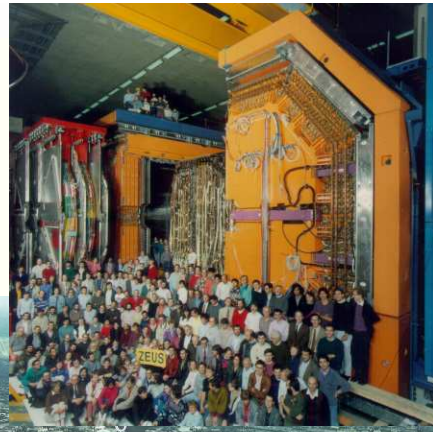
- for list of topics from HERA perspective, see backup, and workshop on Future Analysis with HERA data, arXiv:1601.01499 arXiv:1512.03624

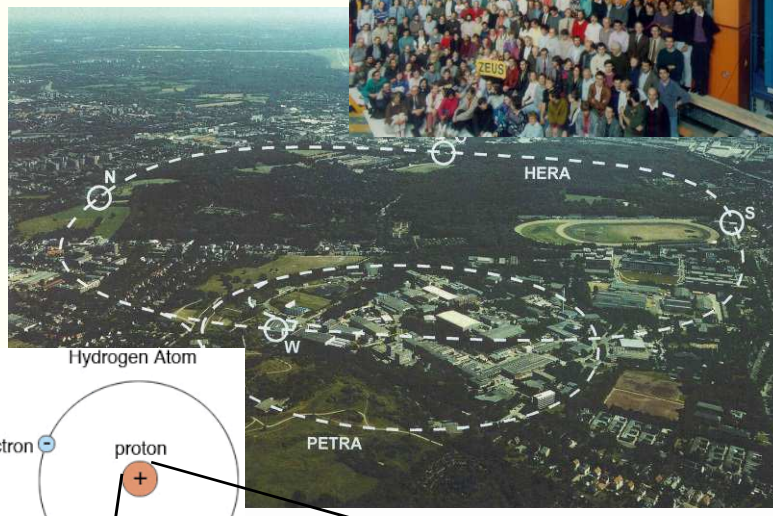
Analysis of preserved ZEUS data

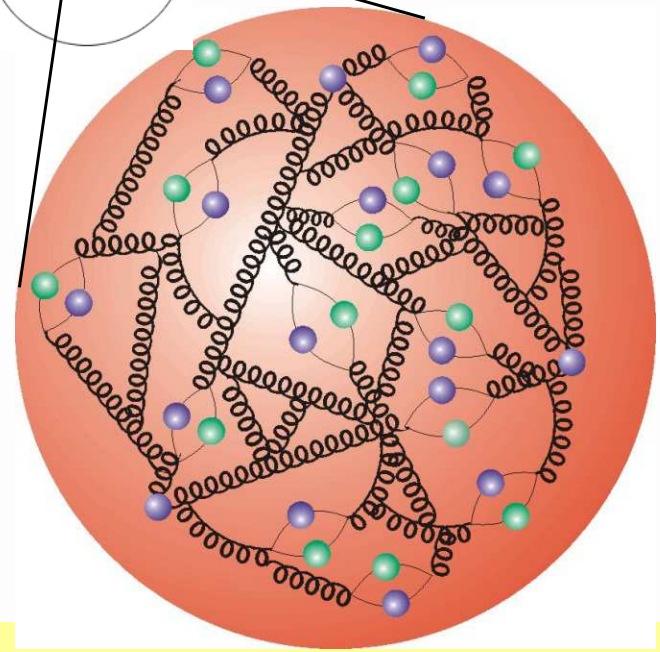
EIC is still some time away.

Most items in list of topics can be addressed now with HERA data. Here: focus on ZEUS

What is ZEUS?







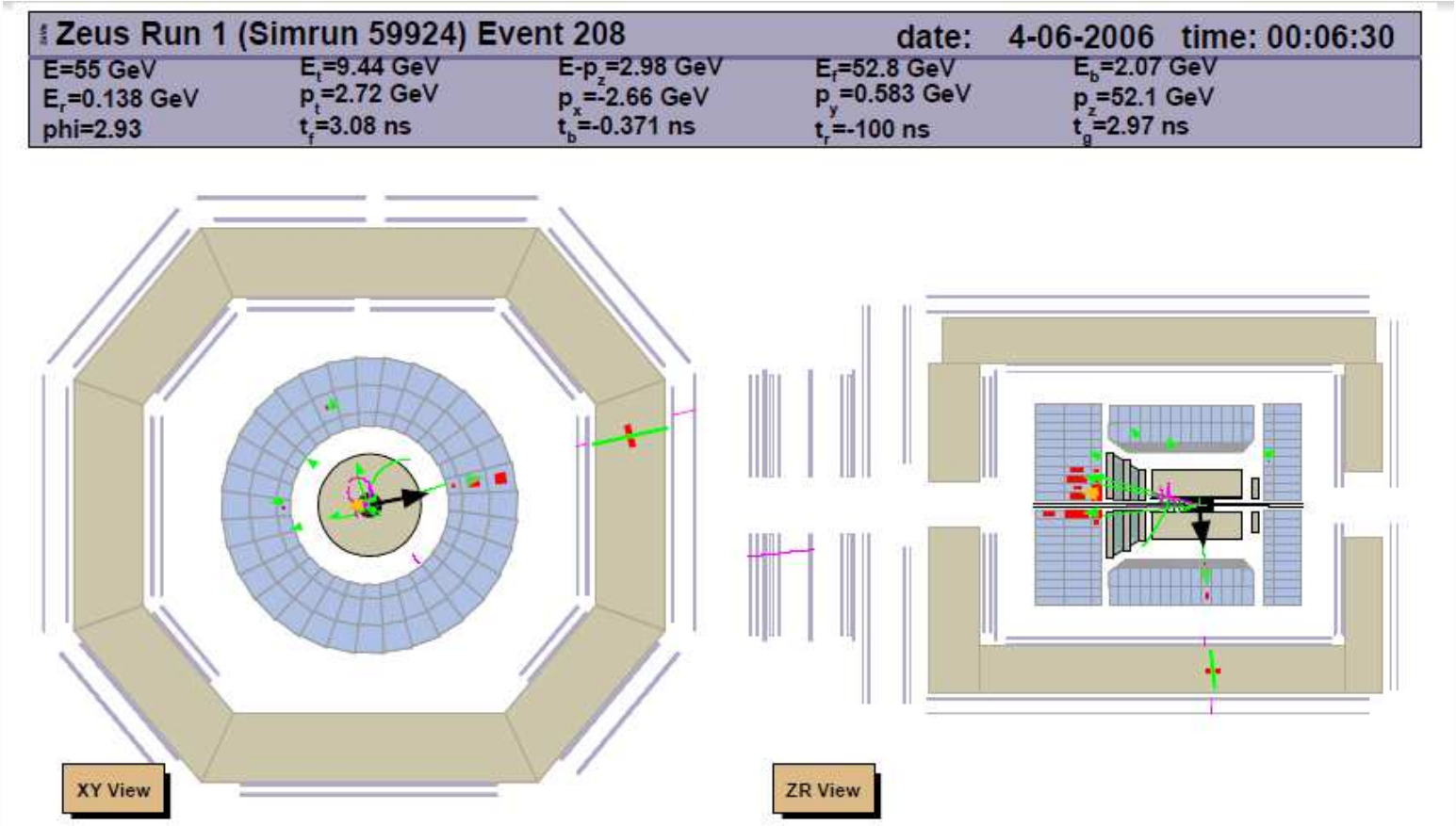
- **International Particle Physics Experiment** which recorded high energy electron-proton collisions at the world's (so far) unique lepton-proton collider **HERA** at DESY in Hamburg, Germany

- **Physics data taking: 1992-2007**

- one of main physics goals:
  measure structure of the proton to ~10^{-18} m, i.e. 1/1000 of proton size
  ("X ray" of proton with electrons)

- also well suited to study **general QCD** and **electroweak physics**

What do ZEUS data look like?

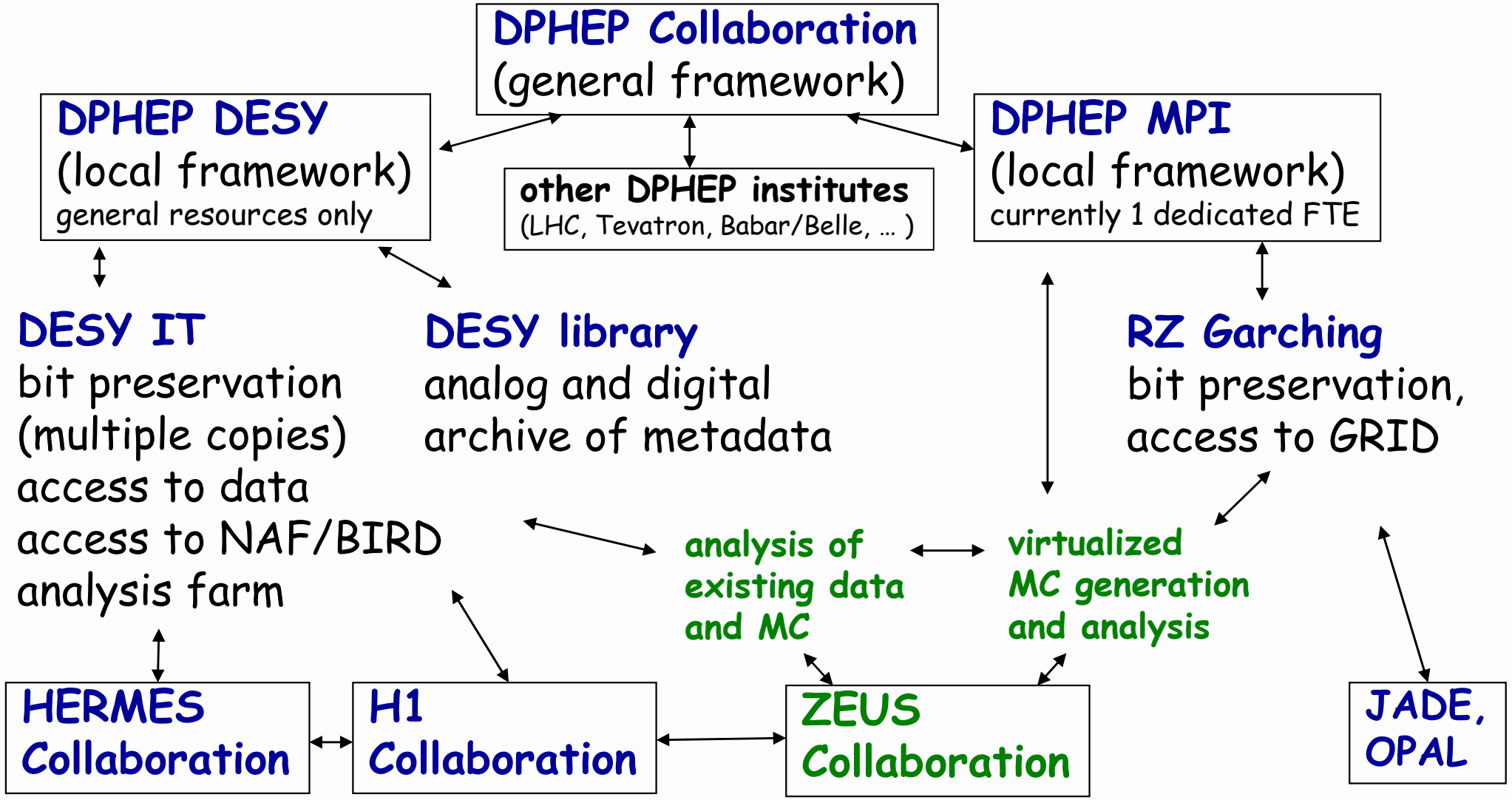


event display from "Common Ntuple"

complicated data format and content: for useful analysis, need

significant expert knowledge + documentation + guidance how to use it

Data Preservation Challenge: How to organize the Management?



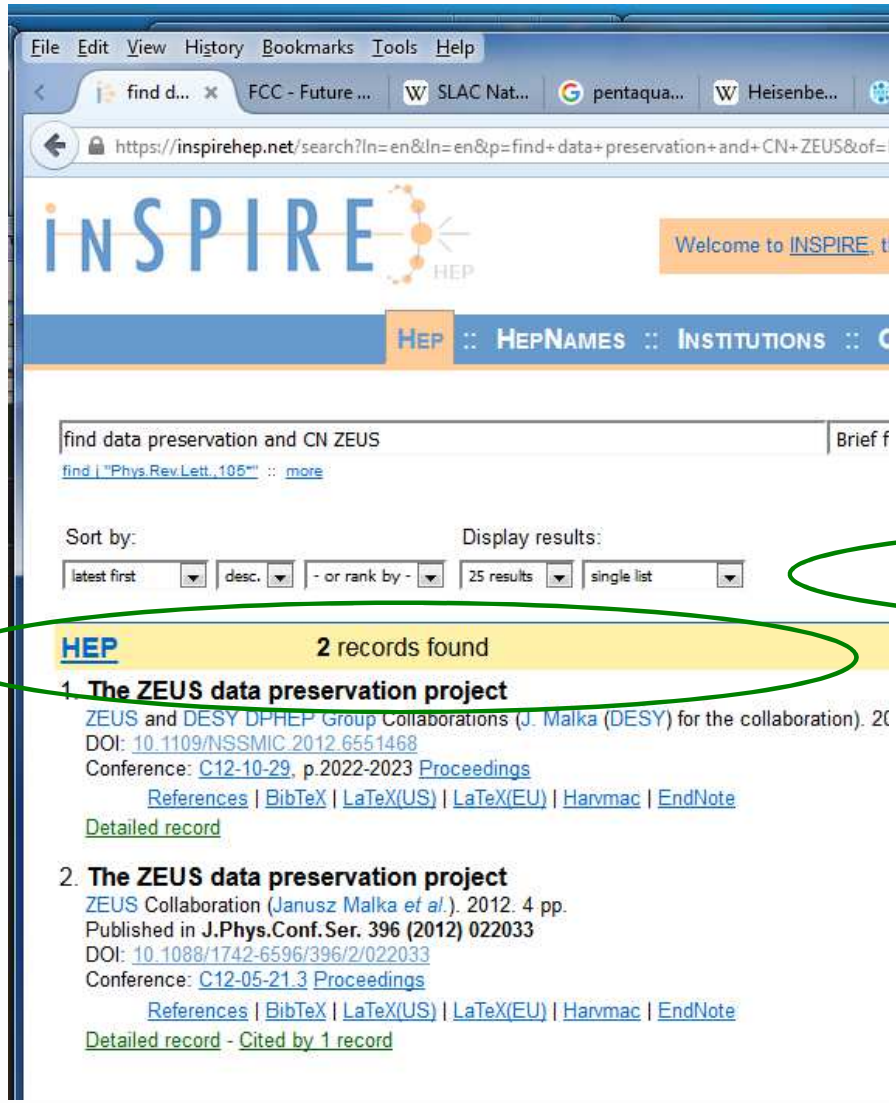
DPHEP data preservation levels

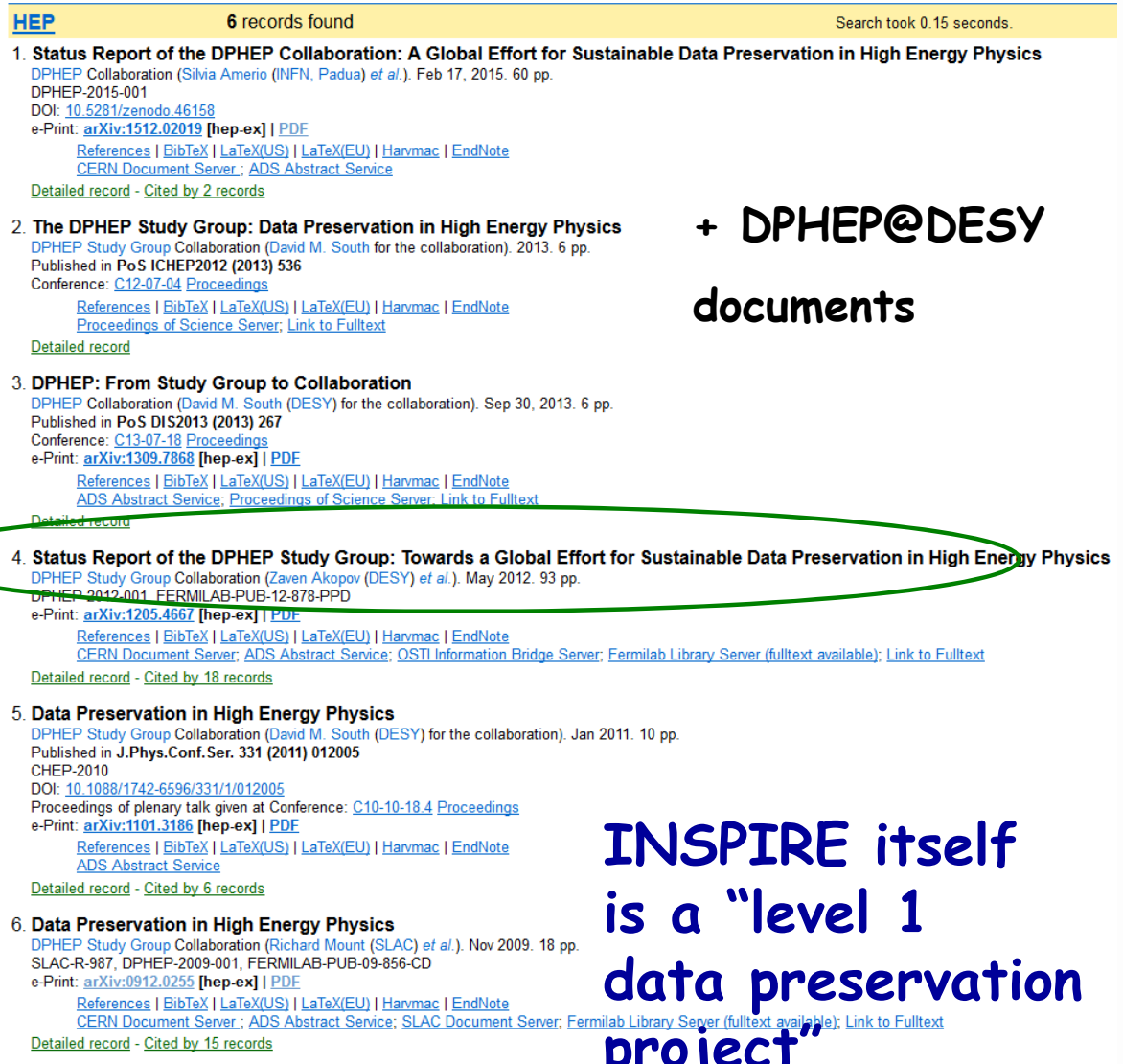
Preservation Model	Use case
1. Provide additional documentation	Publication-related information search
2. Preserve the data in a simplified format	Outreach, simple training analyses -> education
3. Preserve the analysis level software and data format	Full scientific analysis based on existing reconstruction
4. Preserve the reconstruction and simulation software and basic level data	Full potential of the experimental data

Table 3: Various preservation models, listed in order of increasing complexity.

- ZEUS: level 3 (data and existing Monte Carlo (MC) data),
  level 4 (additional Monte Carlo data)
- other HERA experiments: level 4

Publicly available information on DPHEP and ZEUS data preservation





+ DPHEP@DESY documents

INSPIRE itself is a "level 1 data preservation project"

"Discoverability"

DPHEP portal:

- http://hep-project-dphep-portal.web.cern.ch

ZEUS web page:

- http://www-zeus.desy.de/

information on ZEUS far from perfect

(**manpower** …, in case of availability conflict, content/useability takes preference over (organisation of) documentation)

… but we are proud of what we achieved ☺

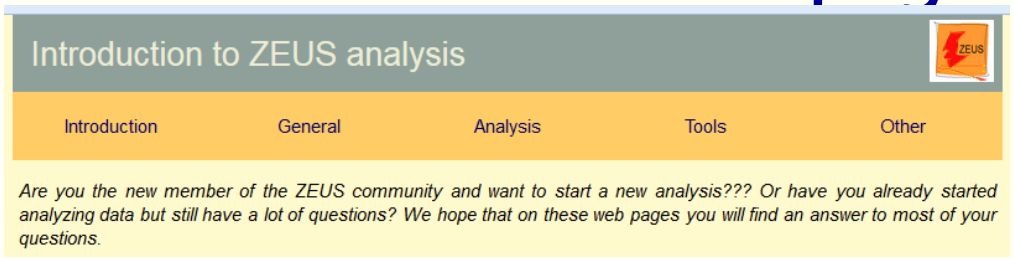
see also presentation A. Verbytskyi at DIS2016 conference
https://indico.desy.de/contributionDisplay.py?contribId=176&sessionId=7&confId=12482

and ZEUS MPI web page https://wwwzeus.mpp.mpg.de/

Analog and digital archive

- analog archive in DESY library

- ZEUS technical notes digitized on INSPIRE (via DESY library)
- frozen plain html documentation web pages (DESY web office)

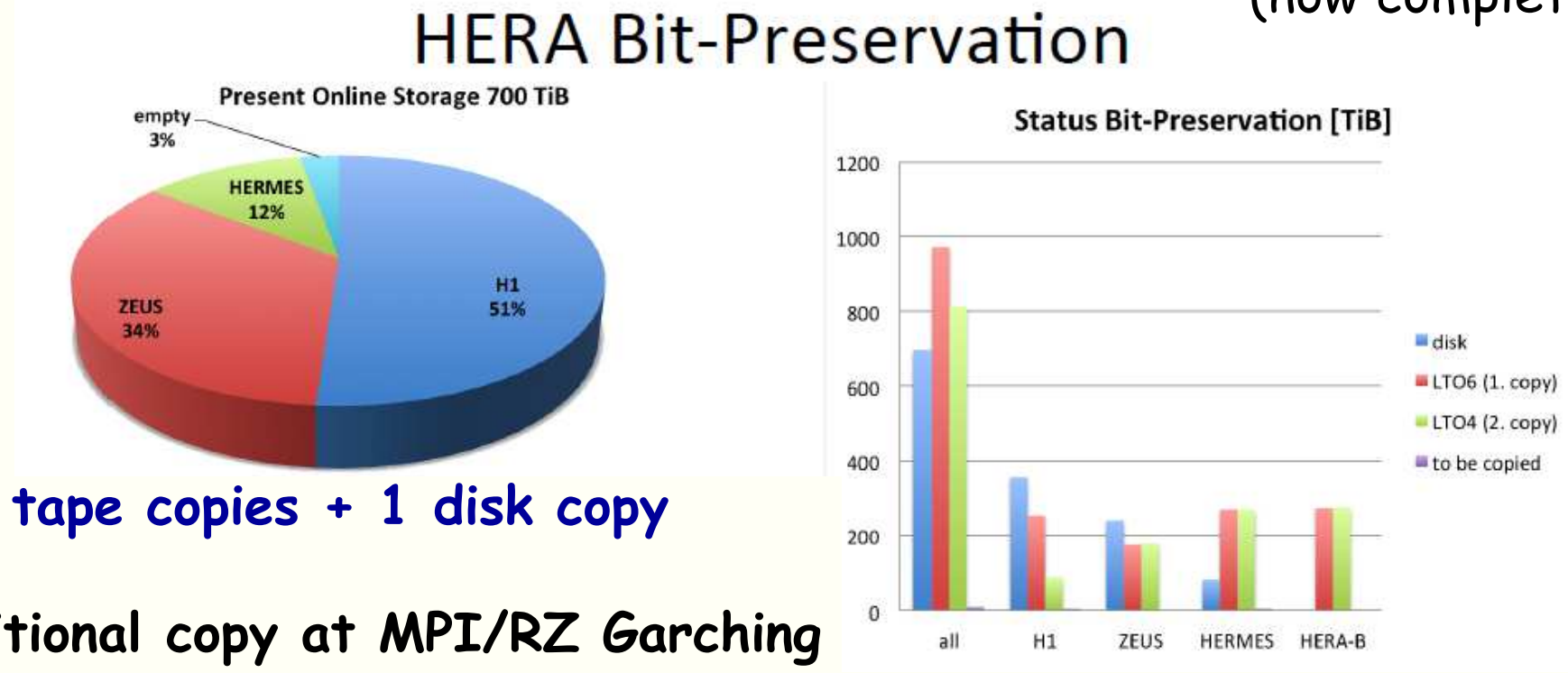


- knowledge preservation in "human neural networks" (ZEUS collaboration)

Challenge: Bit preservation

- at DESY: common approach for all three HERA experiments

status 06/2015
(now complete)

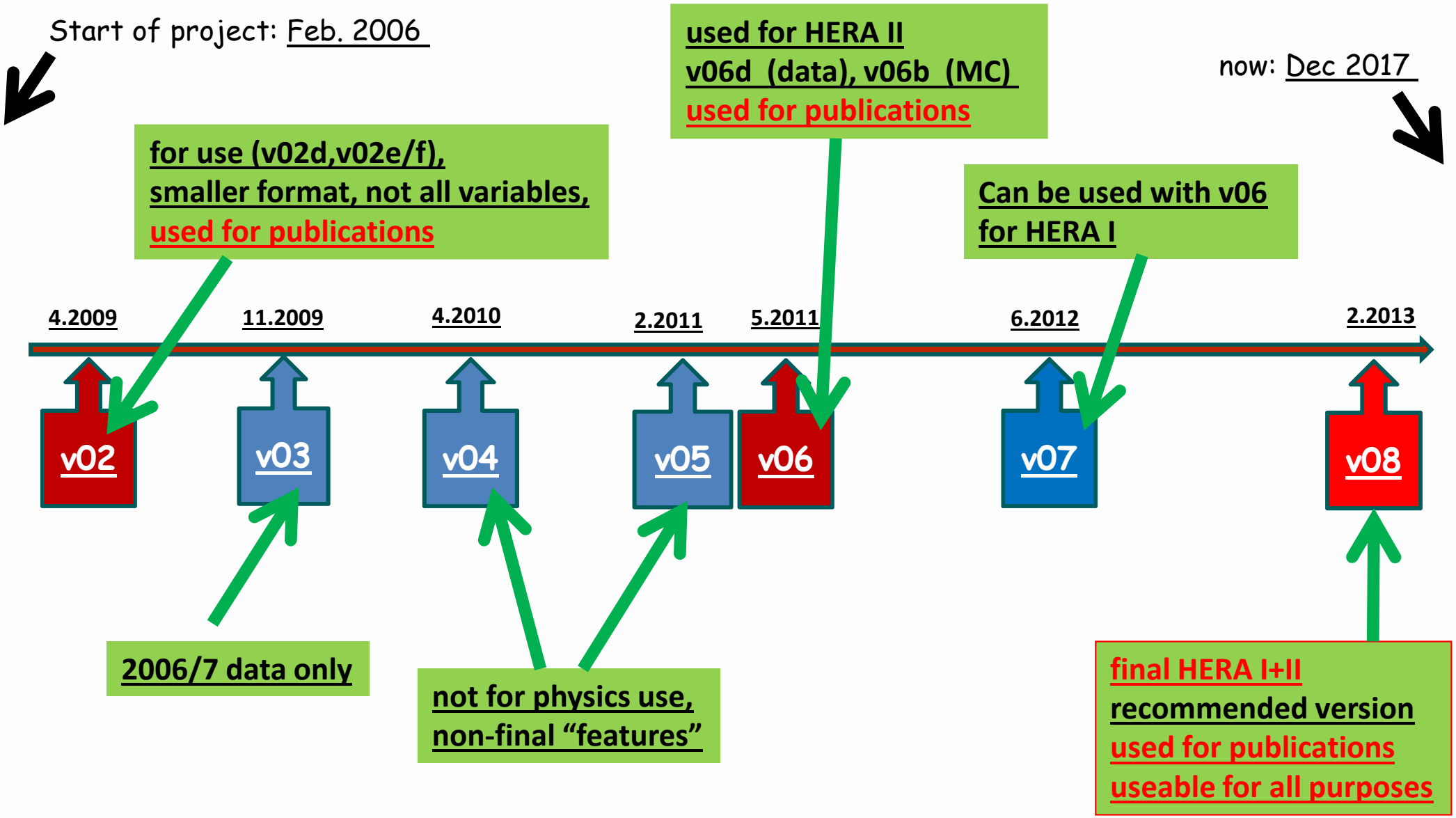


2 tape copies + 1 disk copy

+ additional copy at MPI/RZ Garching (for ZEUS part)

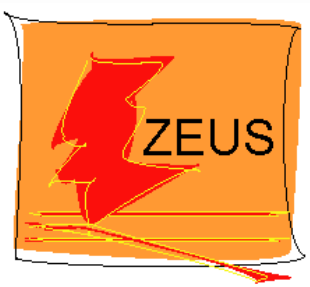
Available Common Ntuples

compiled by D. Szuba



Size of data sets

compiled by D. Zotkin/A.G.



Root files (officially preserved) units: Tb (status 4.9.13)

HERA II	v02	v06	v08	HERA I	v08 +v07	total
Data	1.9	5.2	7.0	1.7+1.		17.
MC	10.5	64.0	70.	4.8+4.		153.

+30 for future MC

~ 100 million inclusive DIS events (Q^2>5 GeV^2, triggered almost bias-free)

~ 100 million semi-inclusive photoproduction events (mainly via p_T>4 GeV dijet trigger)

smaller sets of more specialised triggers/samples (e.g. heavy flavours, vector mesons, …)

~ equal sample sizes for e+, e-, righthanded/lefthanded polarisation

~ 4 billion MC events, for almost any analysis

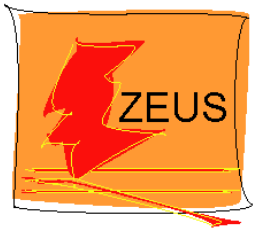
generation of additional MC samples might be possible (see talk A. Verbytskyi)

can technically read/analyze full ZEUS data set on NAF/BIRD at DESY within ~1 day

(for even faster access, many analyzers produce their own mini-ntuples for analysis)

How to analyze ZEUS data at DESY?

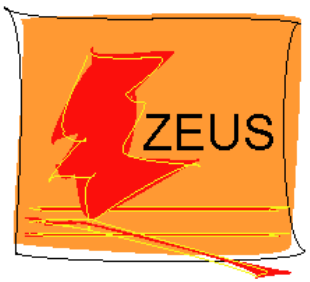
(additional possibilities at MPI)



- need:
  - interest in some physics topic ☺
  - agreement with ZEUS management and DESY to obtain
  - ZEUS user account at DESY
    -> access to NAF/BIRD analysis farm via
    ZEUS NAF server (can log on from remote)
  - basic knowledge of ROOT
    (no special ZEUS software to learn!)
  - basic knowledge of particle physics

Instead of a conclusion: Win-Win-situation?

- We offer:
  access to real data (and MC)
  support for interpretation of data



- You offer:
  (wo)manpower

- We share:
  student supervision (if wished and person power allows),
  interest in physics results ☺