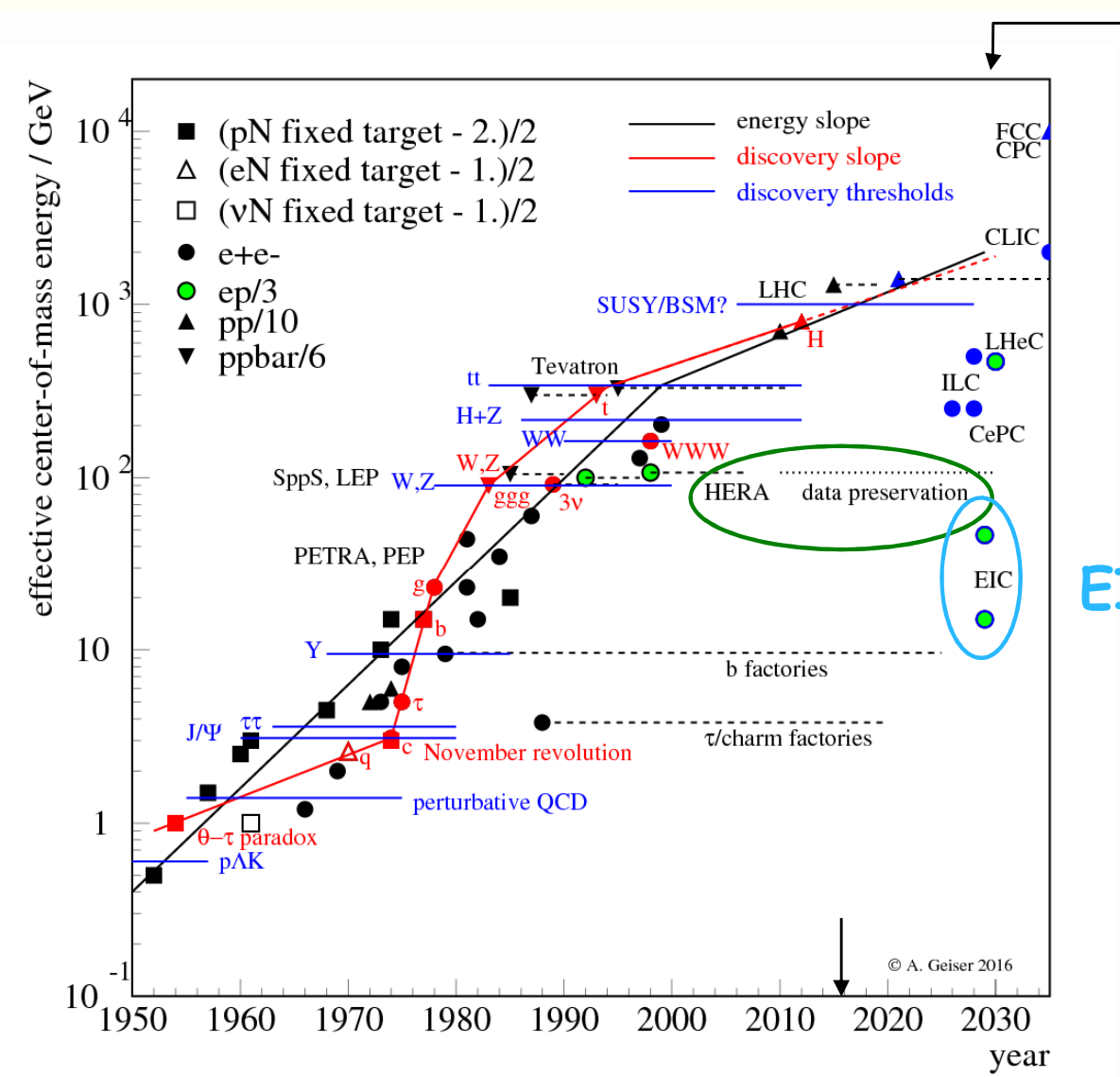
ZEUS data preservation and potential future analyses for EIC

Achim Geiser, DESY Hamburg

EIC-HERA workshop, 08. 06. 2022

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

Why analyze preserved HERA data?



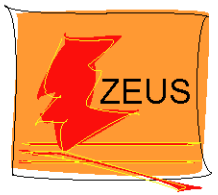
HERA data are unique!

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.

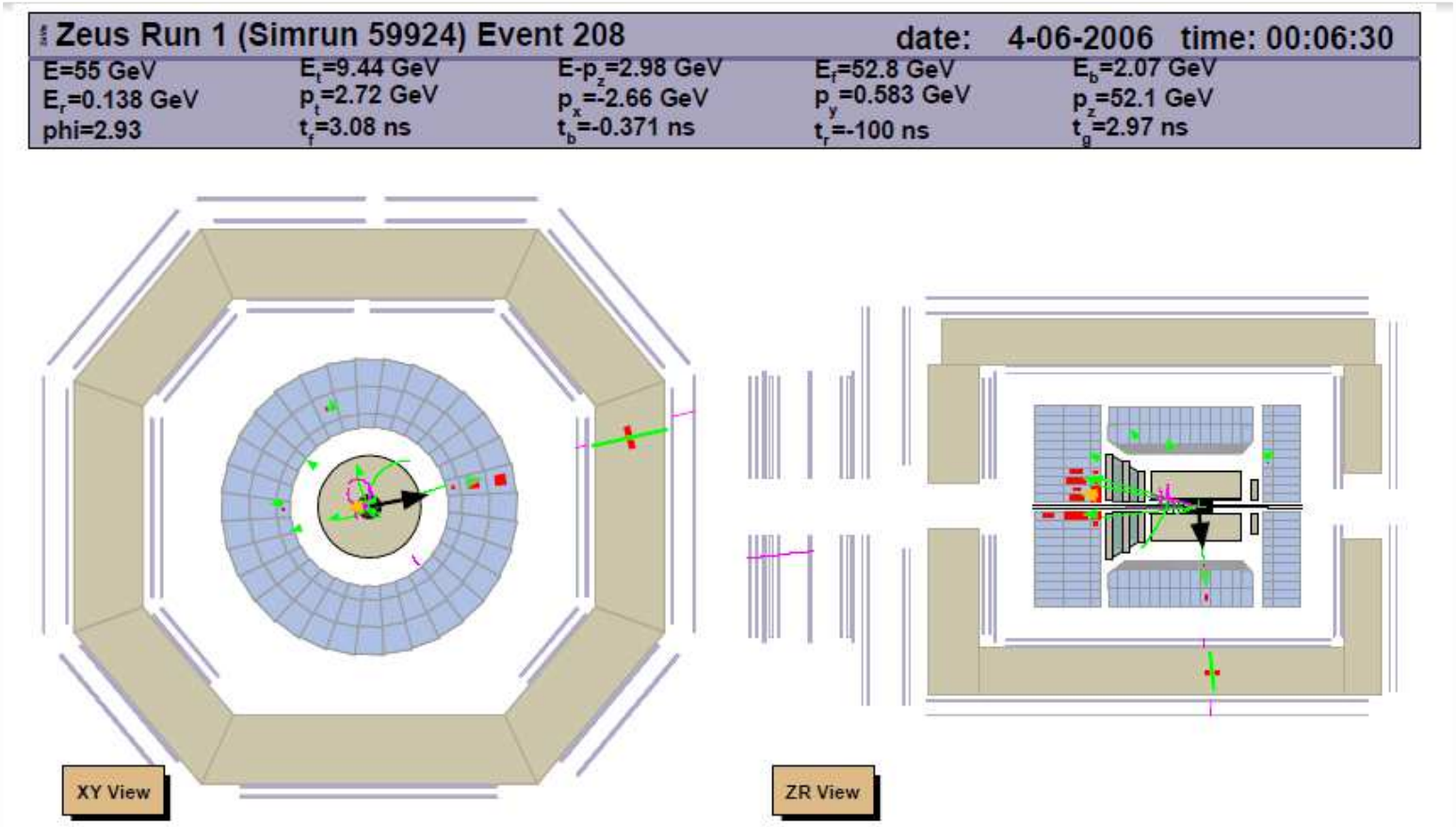


- Many aspects of EIC physics can be (partially) addressed with HERA data.

- 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, …

What do ZEUS data look like?



Event display from Common Ntuple

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,

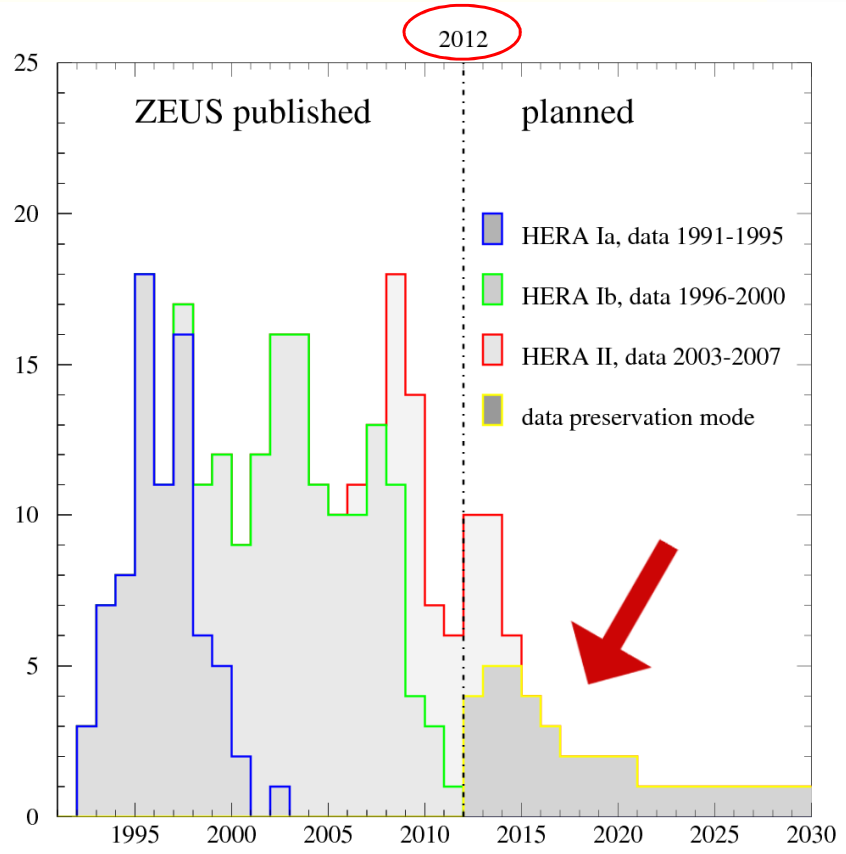
- **Well tested !**

  all recent ZEUS papers based on Common Ntuples

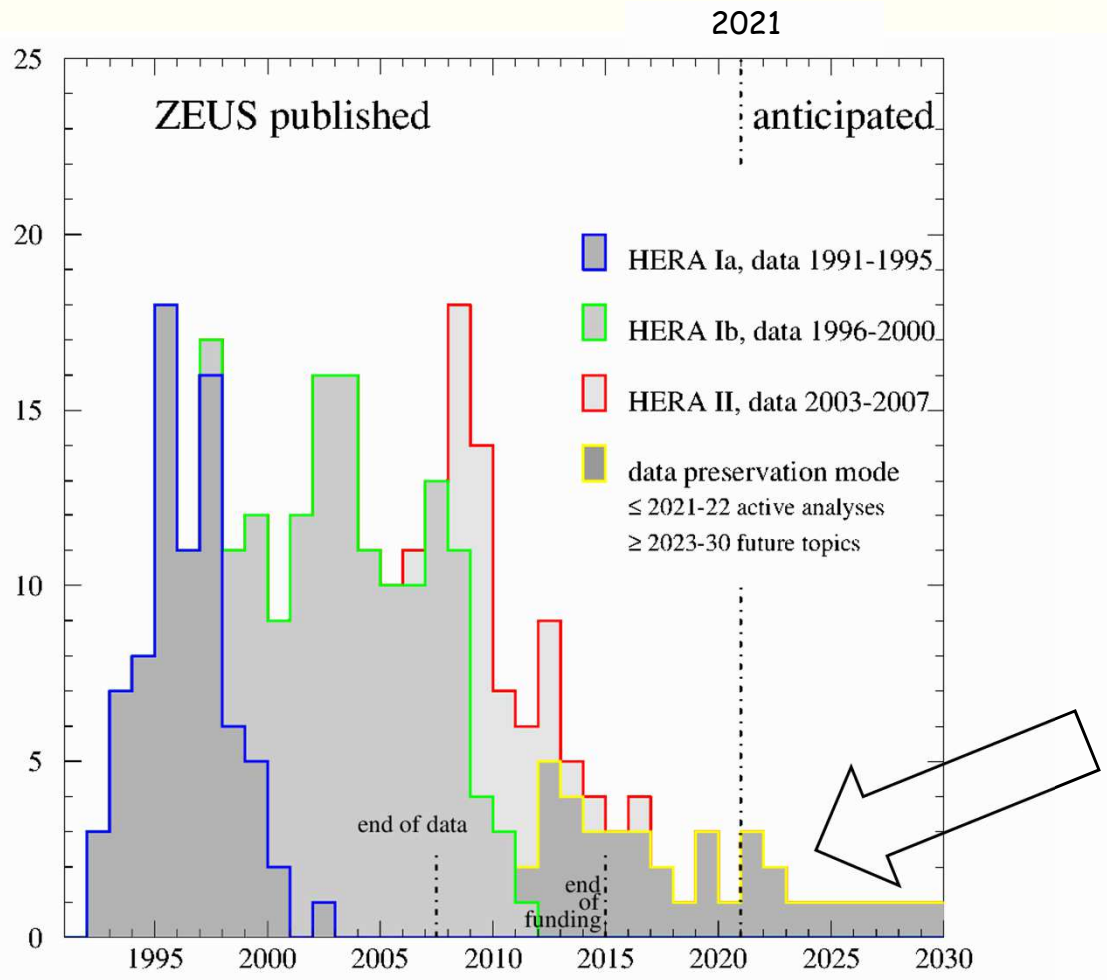
- **Easy to use**

  several recent ZEUS results based on results produced by Master students.

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



2021 update of papers vs. time plot



it works!

`plans'
for short, medium, and
long term

"Free Access to ZEUS Data" programme for PhD students and physicists
-> contact spokesperson

Size of data sets

Root files (officially preserved) units: Tb (status 4.9.13, still valid)

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 flavors, vector mesons**, …)

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

~ **4 billion MC events**, for almost any analysis

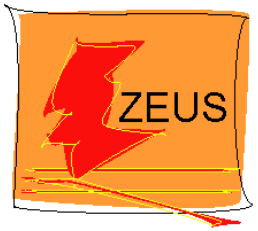
generation of additional MC samples possible (via MPI)

can technically read/analyze full ZEUS data set on one CPU 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)



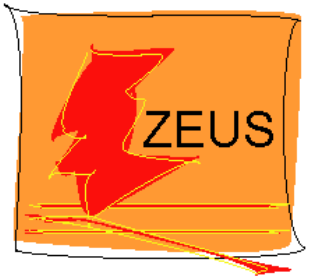
- need:
  - interest in some physics topic ☺
  - agreement with ZEUS management and DESY to obtain
  - ZEUS user account at DESY
    -> access to NAF/BIRD analysis farm via
    ZEUS NAF server (can log on from remote)
  - basic knowledge of ROOT
    (no special ZEUS software to learn!)
  - basic knowledge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

Win-Win-situation?

- We offer:

  access to real data (and MC)

  support for interpretation of data



- You offer:

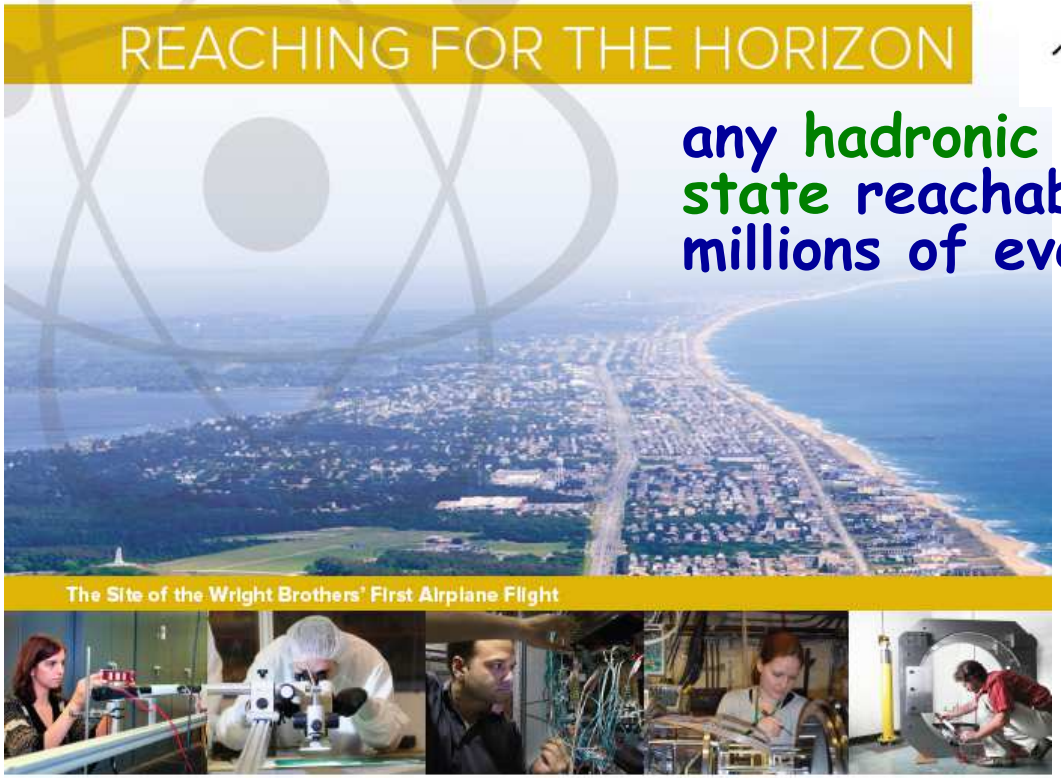
  person power

- We share:

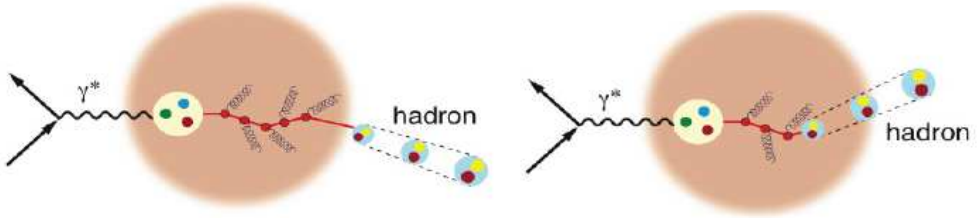
  student supervision (if wished),

  interest in physics results

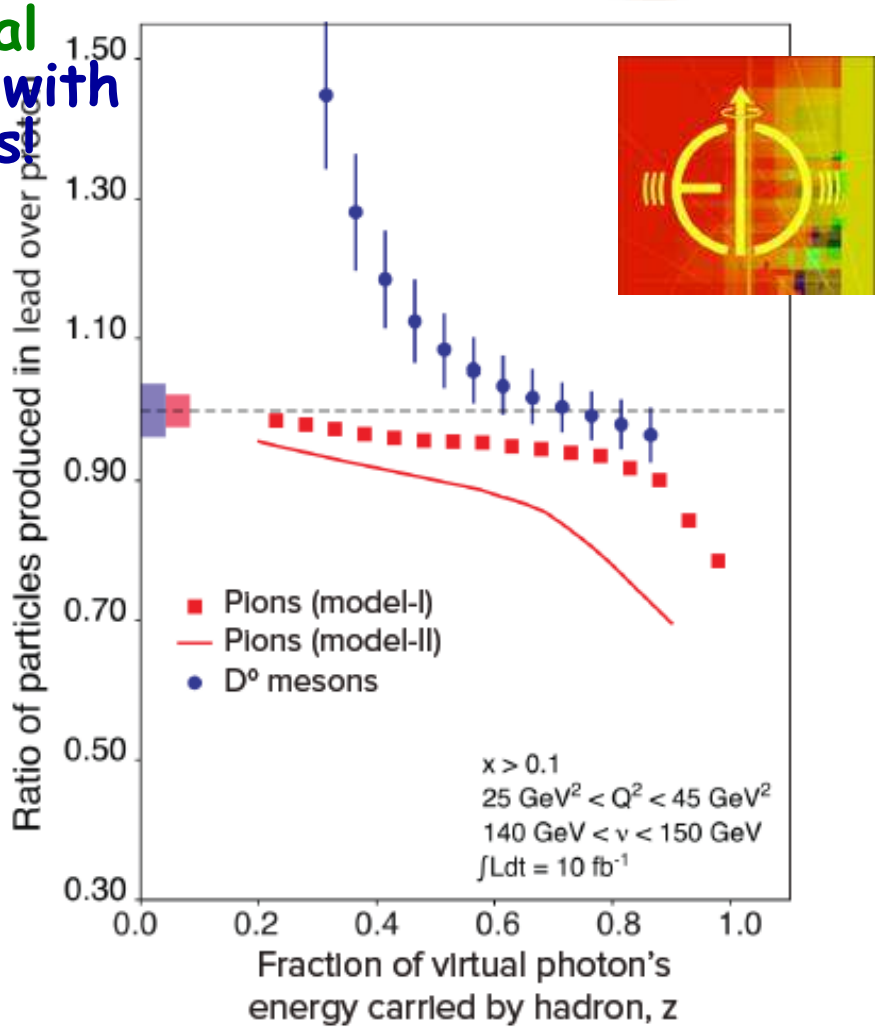
Example physics topics



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE



any hadronic final state reachable with millions of events!

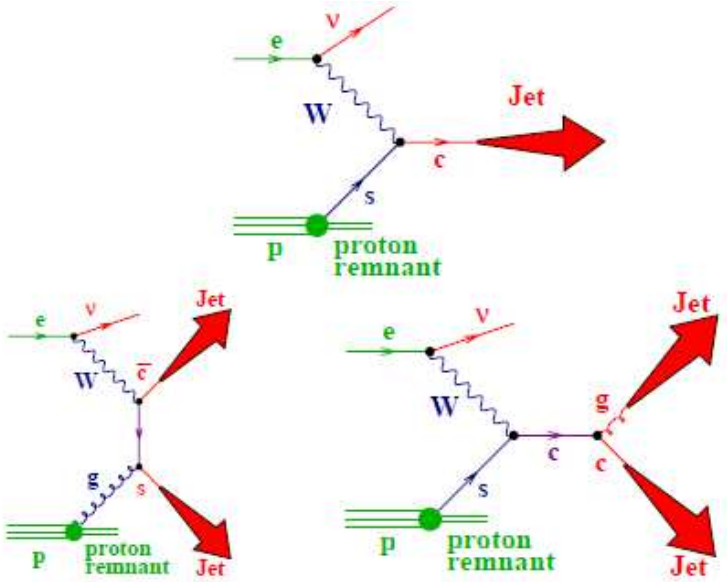


Planned & done: Charm in ep Charged Current reactions

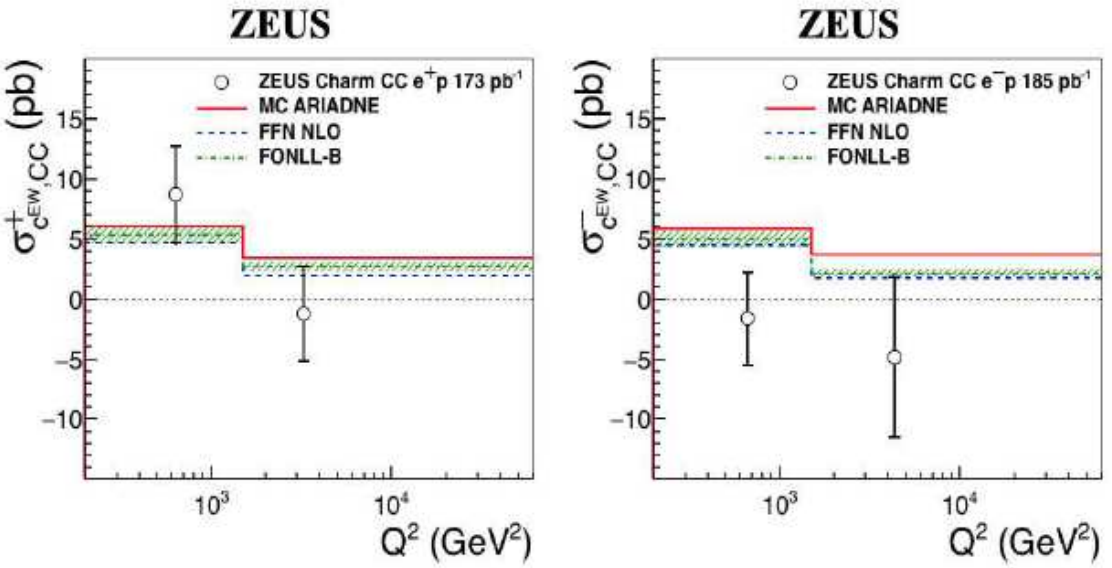
JHEP 05 (2019) 201, arXiv:1904.03261

First ever collider measurement, large uncertainties

PhD project of J. Nam, temple university



$ep \to \nu$+jet(s)+X (c tag), $\sqrt{s} = 318$ GeV, $\mathcal{L} = 358$ pb^{-1}



- **Visible cross section:**

$$\sigma^{+}_{c,\mathrm{vis}} = 4.0 \pm 2.8\ (\mathrm{stat})\ ^{+0.1}_{-0.6}\ (\mathrm{syst})\ \mathrm{pb}$$
$$\sigma^{-}_{c,\mathrm{vis}} = -3.0 \pm 3.8\ (\mathrm{stat})\ ^{+0.5}_{-0.1}\ (\mathrm{syst})\ \mathrm{pb}$$

Sets the stage for future measurements at EIC/LHeC/…

… but also unplanned & done (next slide)

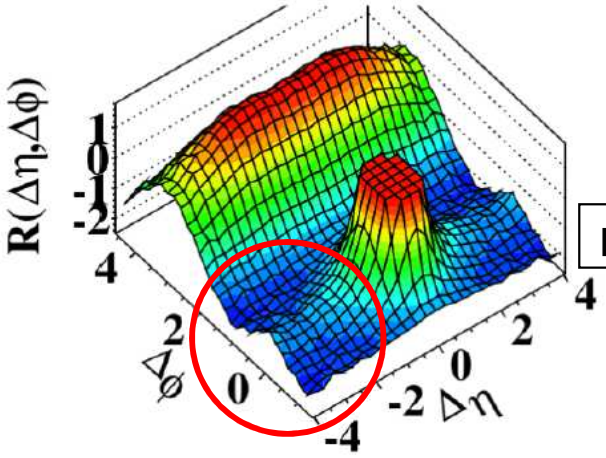
example candidate for cross-experiment archived/open data analysis: "Ridge" in long range particle correlations

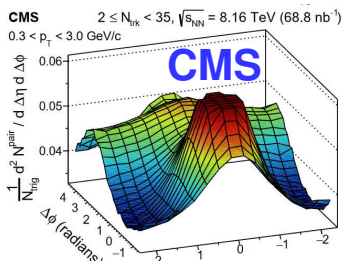
unexpected „Ridge" observed in CMS 2010 pp data

CMS paper

JHEP 1009 (2010) 091

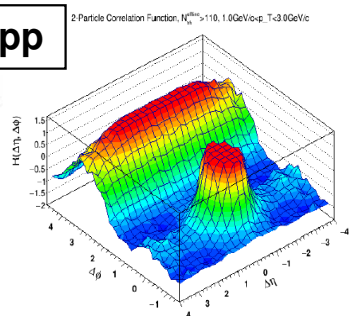
(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c



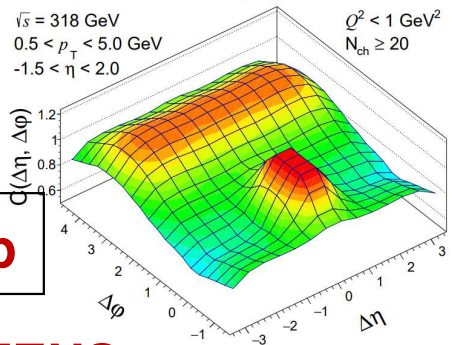


CMS Open Data
(summer student on office desktop)

pp

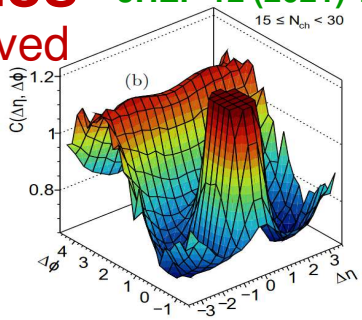


γp



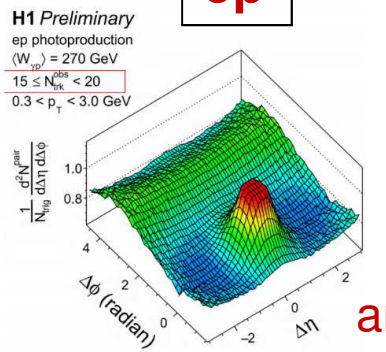
ZEUS
archived data

JHEP 12 (2021) 102

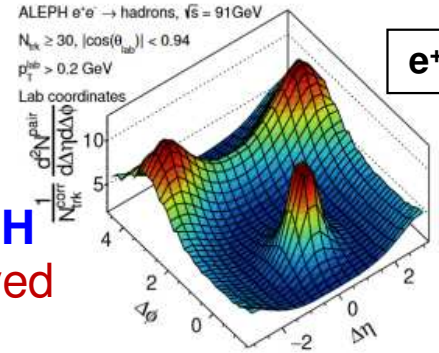


JHEP 04 (2020) 070

ep



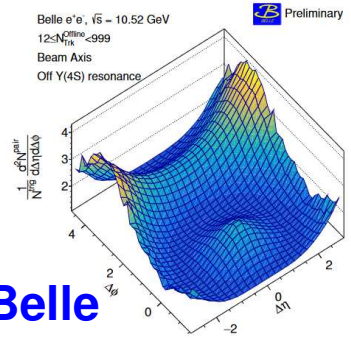
H1
archived data



e⁺e⁻

ALEPH
archived data

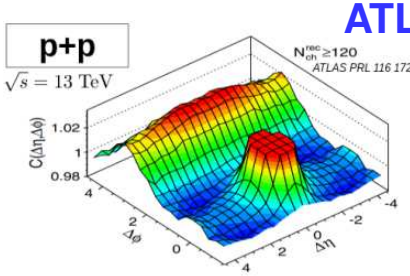
Phys. Rev. Lett.
123 (2019) 212002



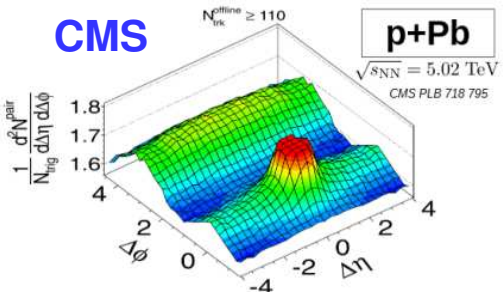
Belle

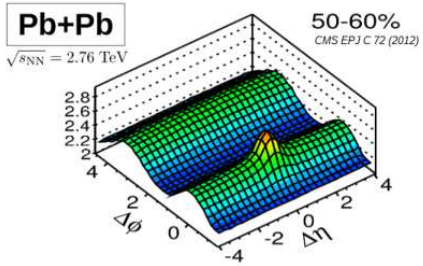
not complete!

ATLAS



CMS



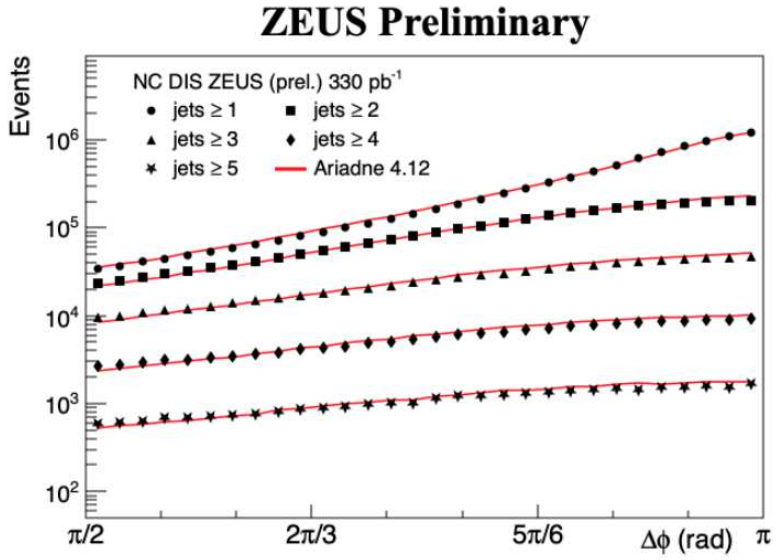


CMS Open Data available

see talks later in workshop

Some ongoing example physics topics

- semi-inclusive mini-jets in DIS



zeus-prel-19-002

A. Quintero, Temple

- Inclusive jets in DIS F. Lorkowski -> poster at ICHEP22
- Search for Lorentz-invariance violation, N. Sherill, E. Lunghi -> abstract for ICHEP22

Further example physics topics

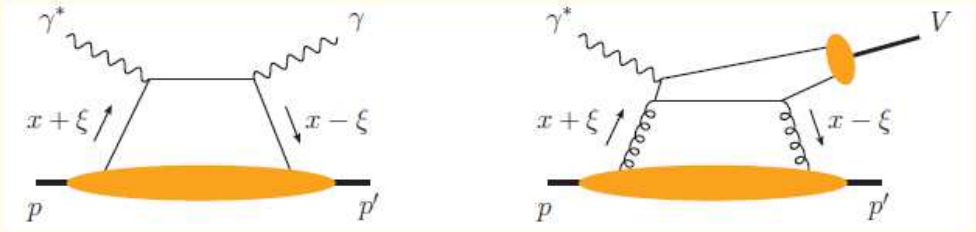


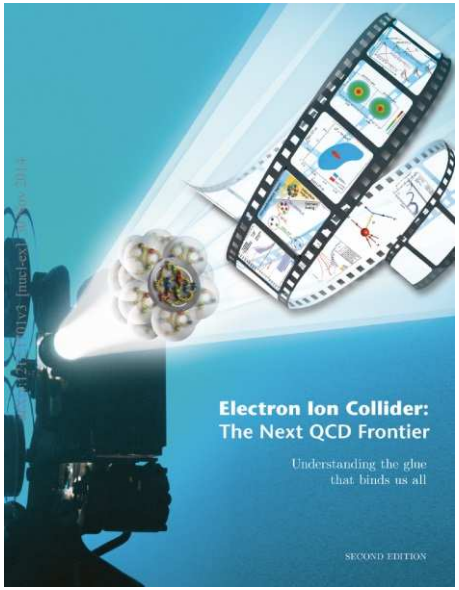
Figure 2.18: Graphs for deeply virtual Compton scattering (left) and for exclusive vector meson production (right) in terms of generalized parton distributions, which are represented by the lower blobs. The upper filled oval in the right figure represents the meson wave function.

- 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

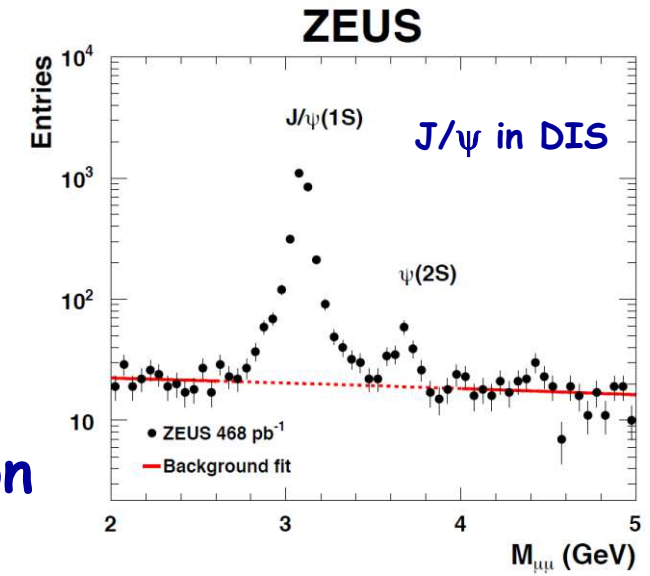
(lack of person power)

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	



see next presentation



A bit more on open heavy flavours

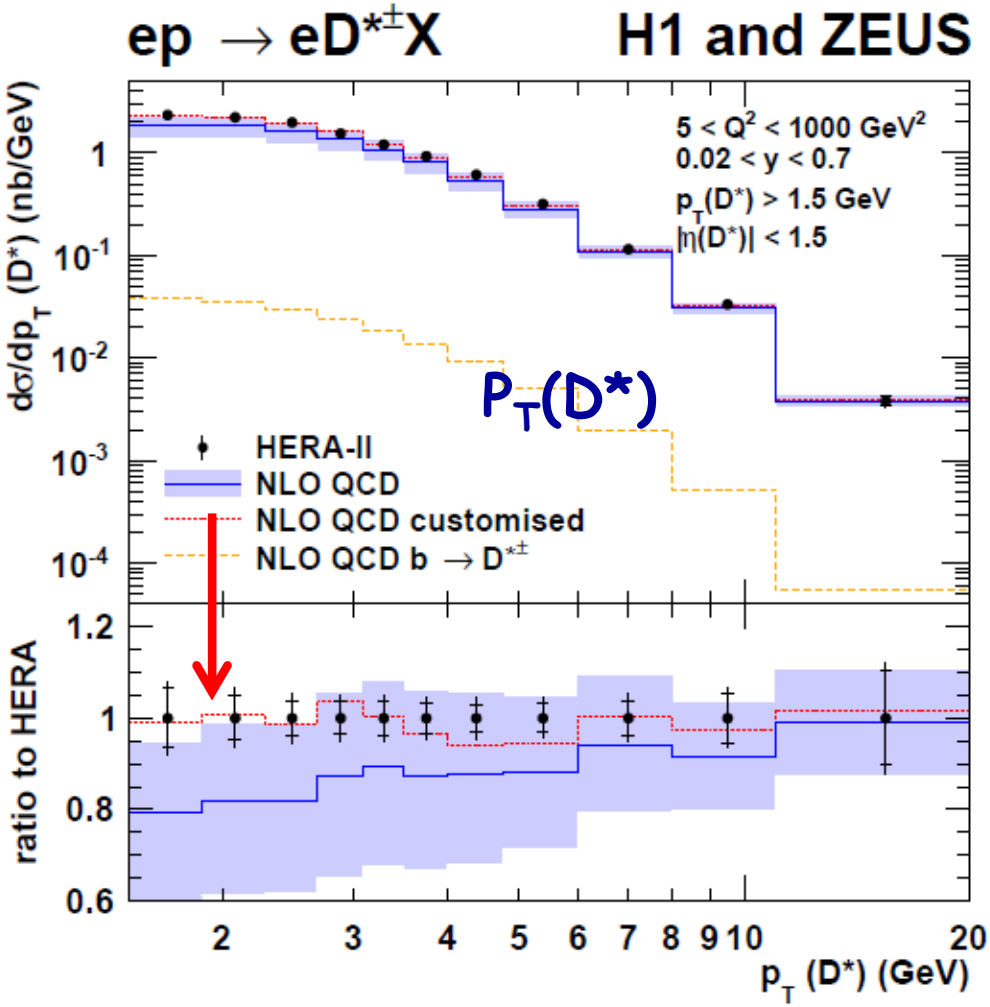
- Heavy flavours in DIS mostly finished in ZEUS (and H1) (see next slides)
- ZEUS had semi-inclusive triggers on heavy flavour final states in PHP active during the full HERA II period

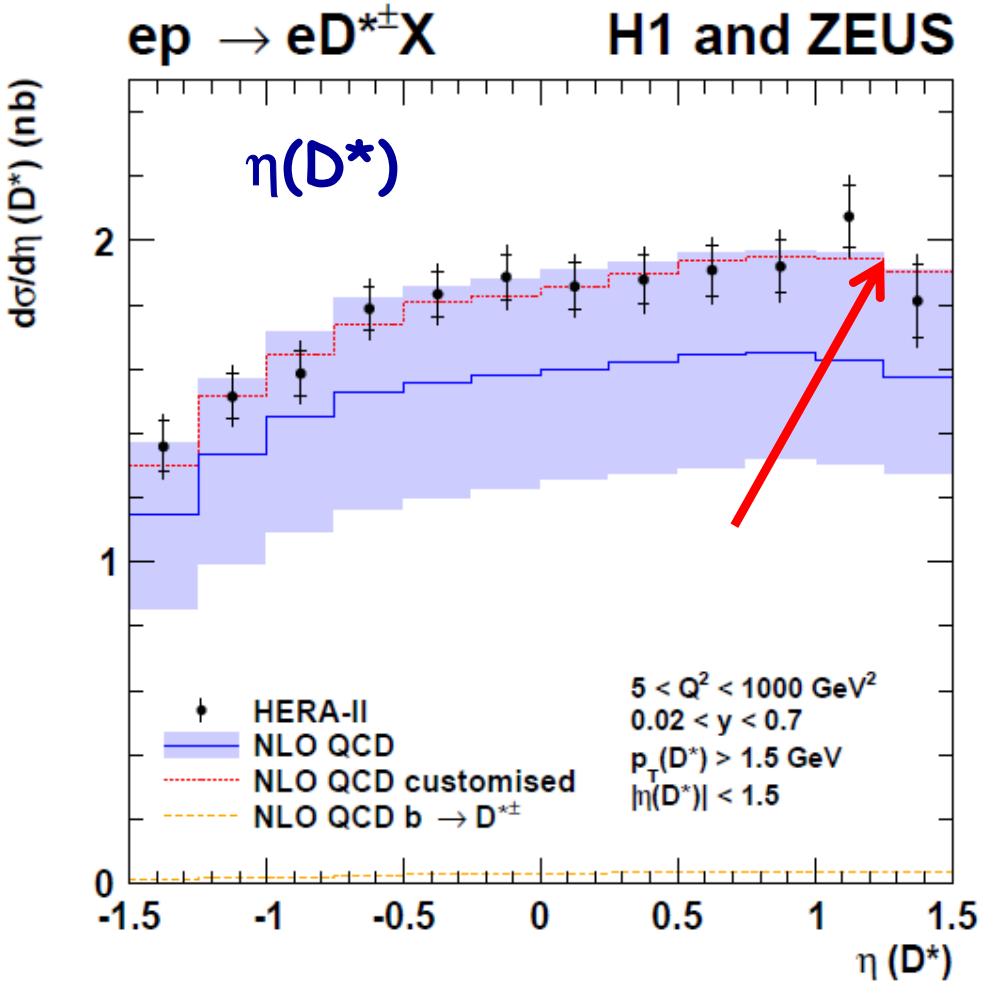
  (explicit meson final states, lepton final states, inclusive secondary vertex triggers)

-> many possibilities left completely untapped
(scarce person power was directed to DIS part)

Combined D* cross sections in DIS

arXiv:1503.06042, JHEP 1509 (2015) 149

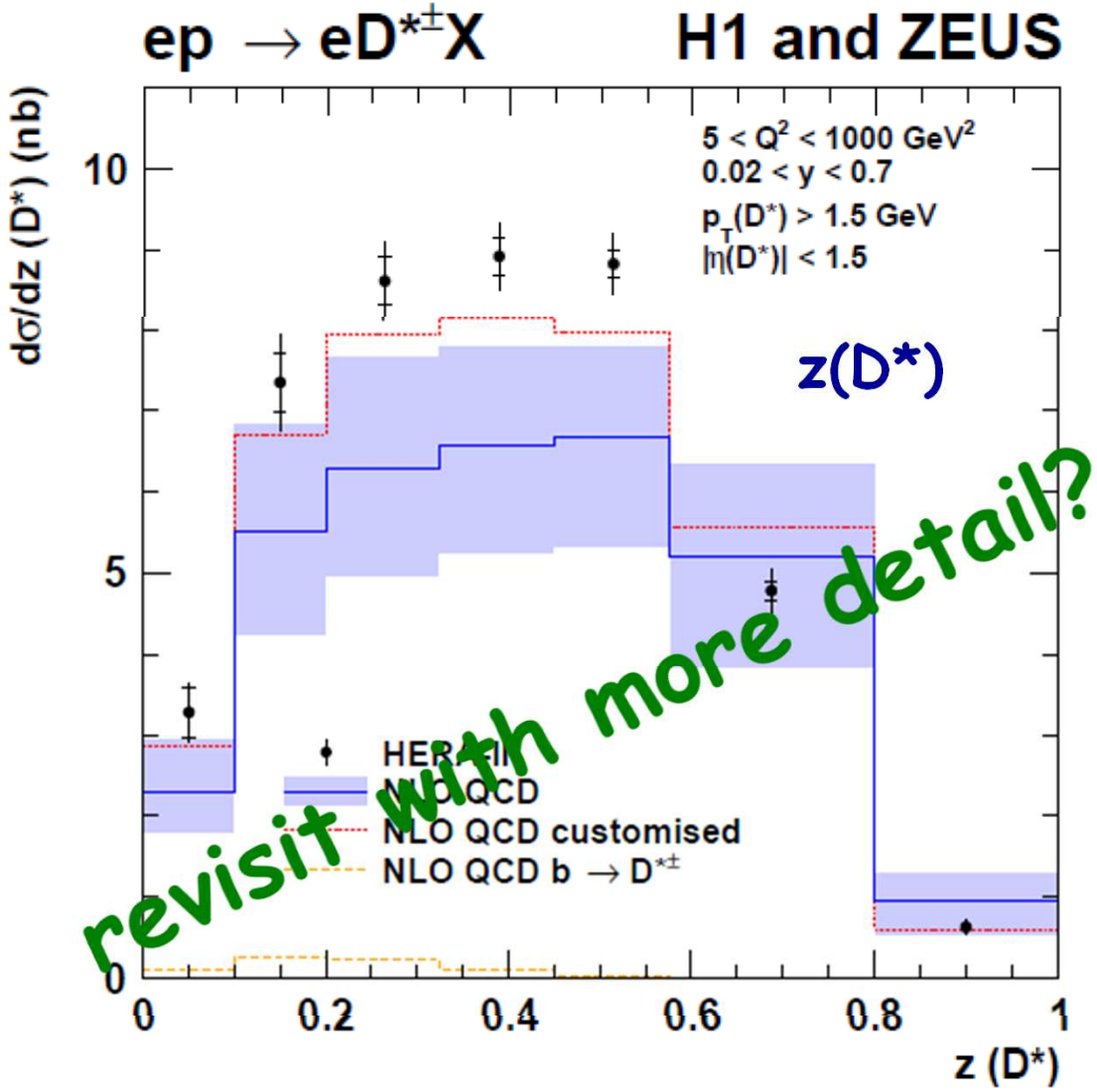




customised choice: - reduced renormalisation scale
- modified scale dependence of fragmentation
- slightly lower charm mass (all within uncertainty)

Charm fragmentation function

arXiv:1503.06042, JHEP 1509 (2015) 149



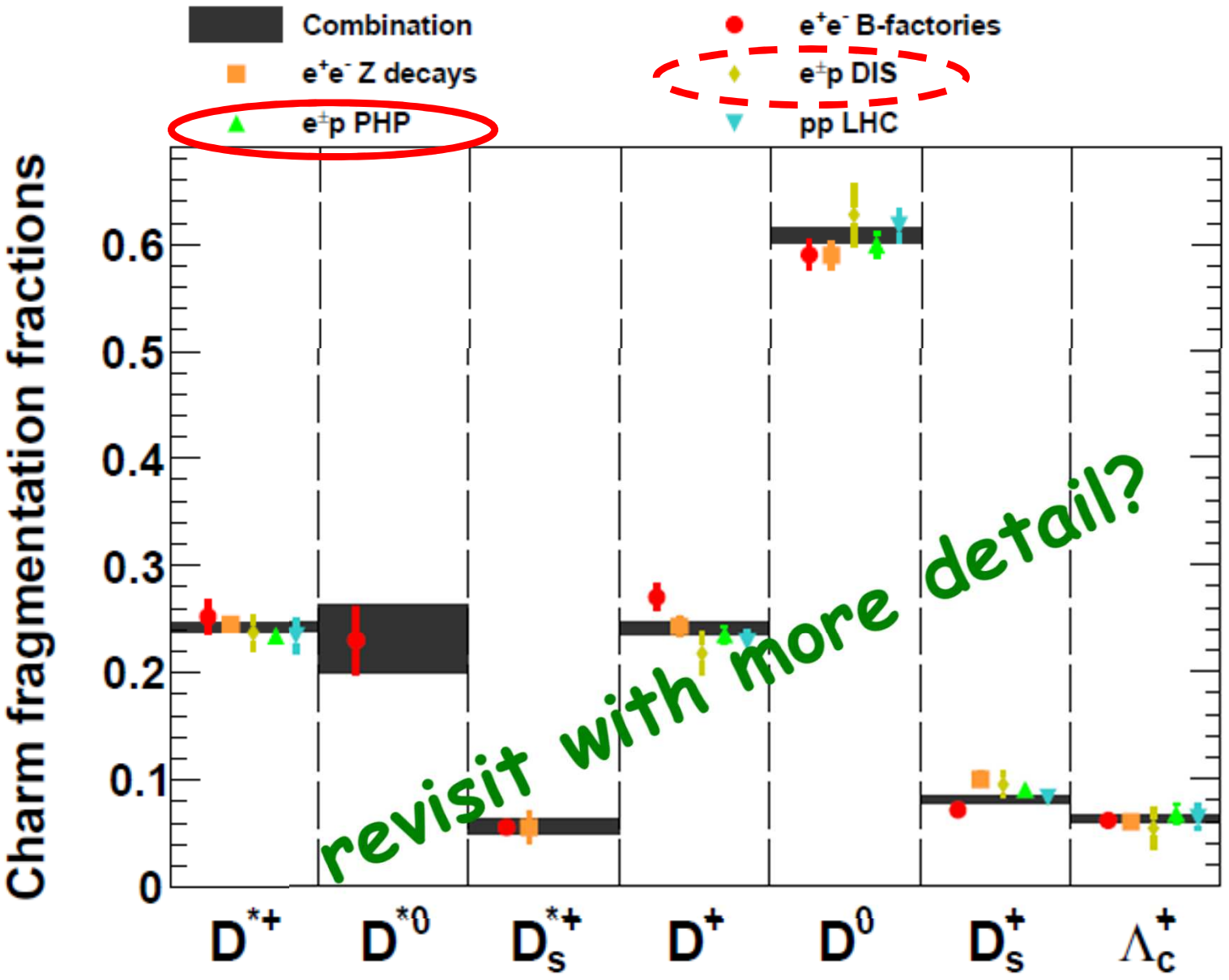
Combination of H1 and ZEUS D* measurements

example: z (energy/momentum fraction taken by D*) , shape directly sensitive to fragmentation parameters

more work on theory needed

Charm fragmentation fractions

arXiv 1509.01061, EPJC 76 (2016) 397
Lisovyi, Verbytskyi, Zenaiev



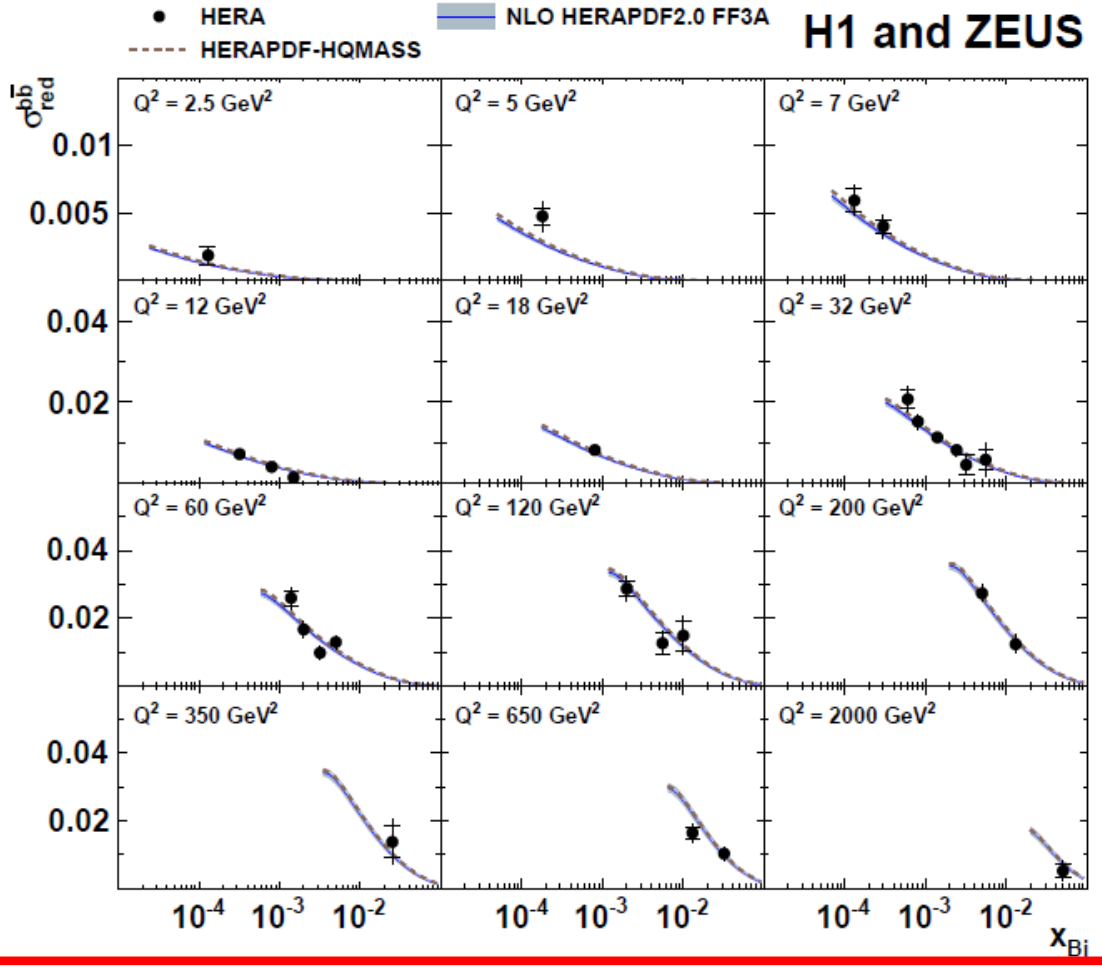
universality confirmed

HERA measurements make very substantial contribution to world average

QCD fit: beauty subset

Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019

fully consistent with HERAPDF FF3A



new: $m_b(m_b) = 4.05\ ^{+0.10}_{-0.11\ exp/fit}\ ^{+0.09}_{-0.03\ mod/scale}\ ^{+0.00}_{-0.03\ par}$ GeV

ZEUS: $m_b(m_b) = 4.07 \pm 0.14_{exp/fit}\ ^{+0.08}_{-0.08\ mod/scale}\ ^{+0.05}_{-0.00\ par}$ GeV

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

Input data sets

HERA I combined inclusive + HERA combined charm + ZEUS beauty + LHCb charm + LHCb beauty

JHEP 01 (2010) 109
HERA inclusive DIS $3.5<Q^2<30000$ GeV^2, $4.32\times10^{-4}<x_{Bj}<0.65$

JHEP 1409 (2014) 127
ZEUS beauty $6.5<Q^2<600$ GeV^2, $1.5\times10^{-4}<x_{Bj}<3.5\times10^{-2}$

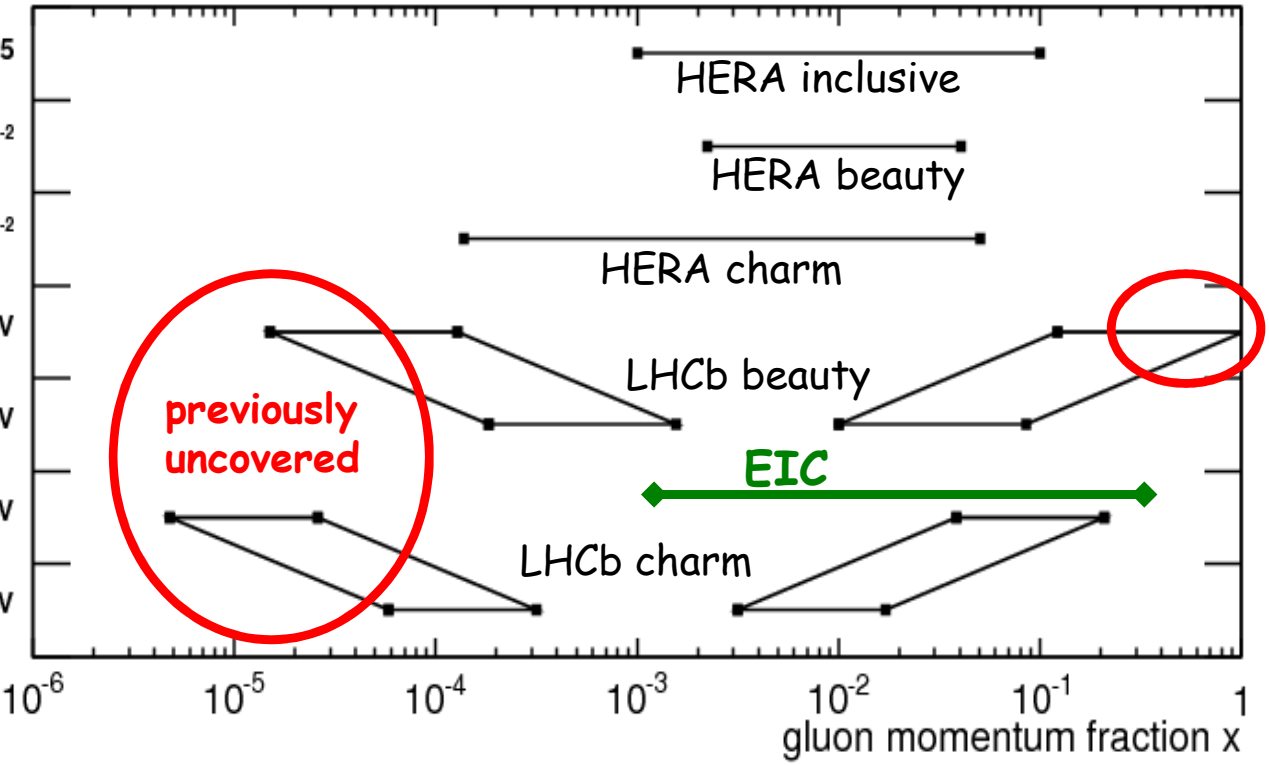
Eur. Phys. J. C 73 (2013) 2311
HERA charm $2.5<Q^2<2000$ GeV^2, $3\times10^{-5}<x_{Bj}<5\times10^{-2}$

LHCb beauty y=4.5, $0<p_T<40$ GeV

JHEP 08 (2013) 117
LHCb beauty y=2.0, $0<p_T<40$ GeV

LHCb charm y=4.5, $0<p_T<8$ GeV

Nucl. Phys. B 871 (2013) 1
LHCb charm y=2.0, $0<p_T<8$ GeV



combination of data sets "bridges" complete x range

Input data sets

HERA I combined inclusive + HERA combined charm + ZEUS beauty + LHCb charm + LHCb beauty

add photoproduction information?

JHEP 01 (2010) 109
HERA inclusive DIS $3.5<Q^2<30000$ GeV^2, $4.32\times10^{-4}<x_{Bj}<0.65$

JHEP 1409 (2014) 127
ZEUS beauty $6.5<Q^2<600$ GeV^2, $1.5\times10^{-4}<x_{Bj}<3.5\times10^{-2}$

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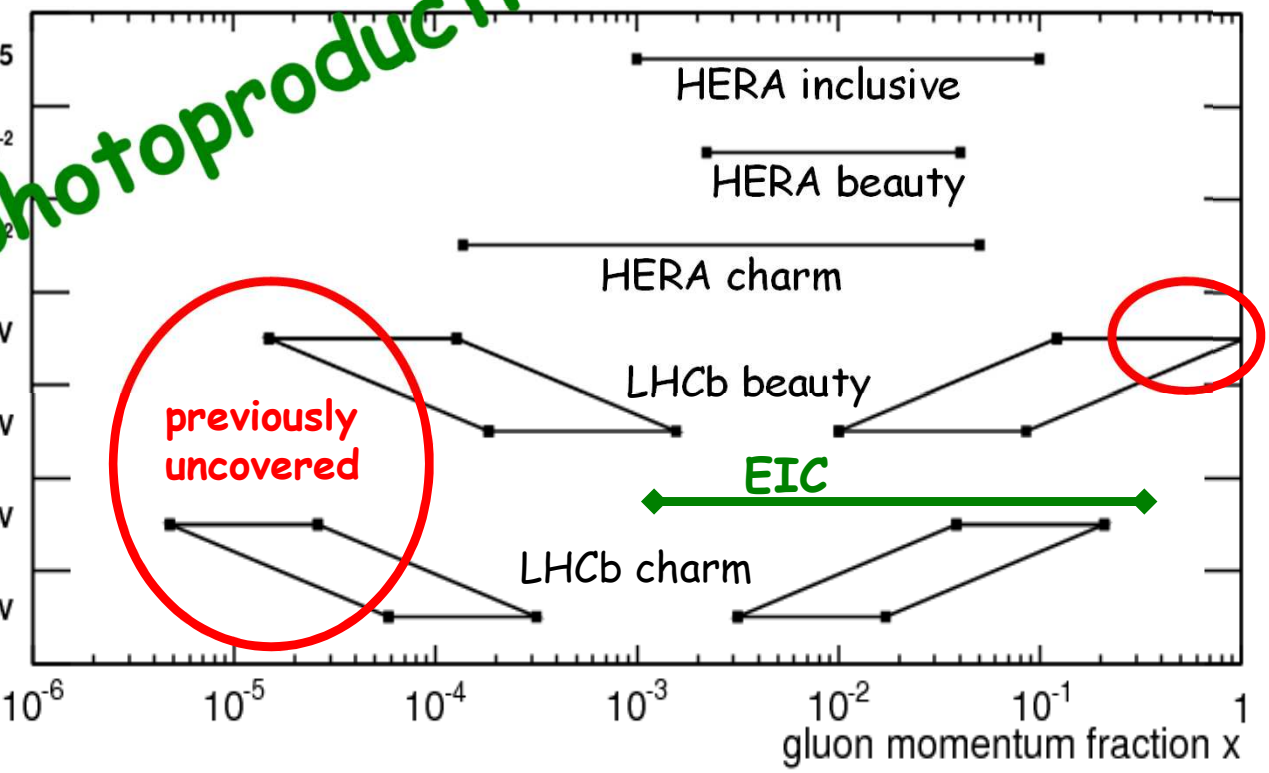
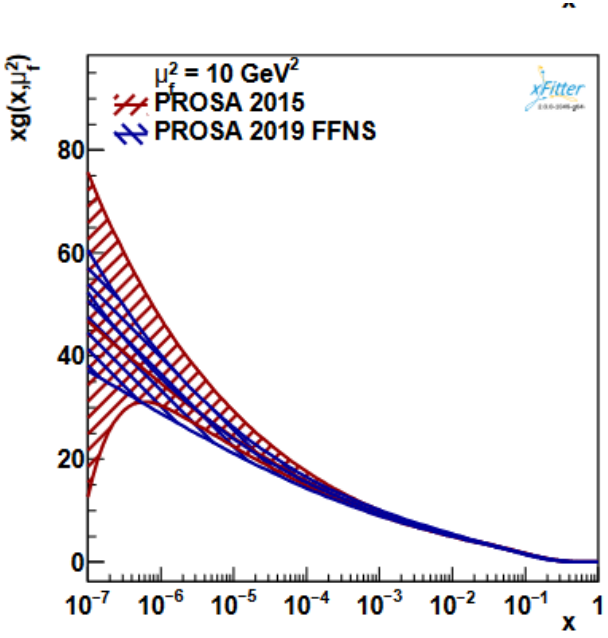
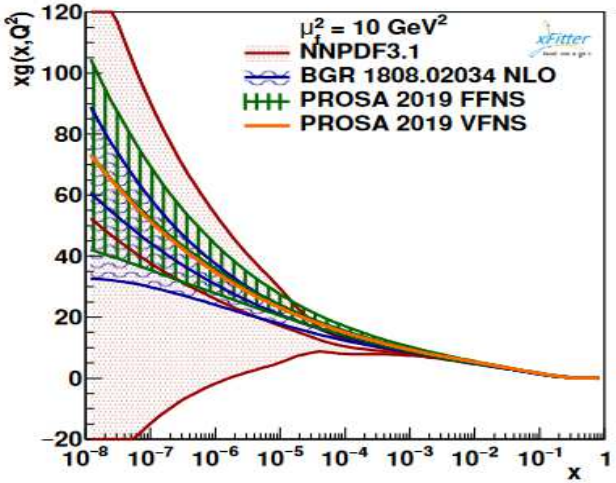


combination of data sets "bridges" complete x range

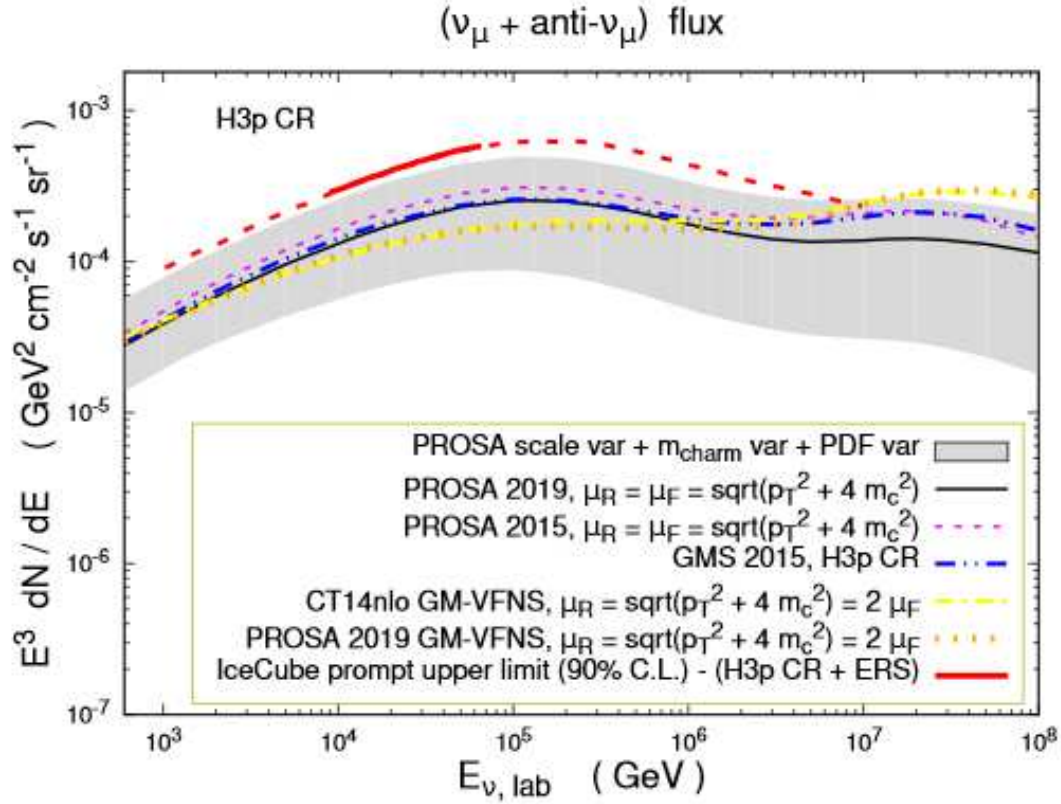
update, and cosmic ray predictions

arXiv 1611.03815, JHEP 05 (2017) 004 arXiv 1911.13164, JHEP 04 (2020) 118



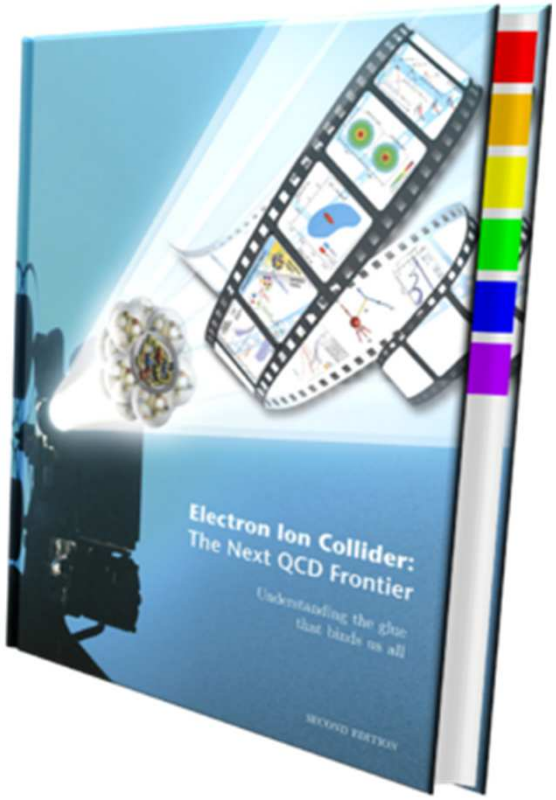


use final HERA DIS data, include more LHCb data, and ALICE data -> **constrain cosmic ray prompt neutrino spectrum (e.g. Ice Cube)**



More example physics topics

- **Your favourite EIC topic ☺**



The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

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

Conclusions and Outlook

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

  analysis and publication ongoing
- 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 have overlap with topics relevant for EIC

  -> of particular interest until EIC data become available

- bottleneck: person power after end of HERA funding

purpose of this contribution:

motivate that it is 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

A list of topics from HERA collider perspective (and more).

Should be further cross-calibrated with and 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

Possible HERA collider physics topics

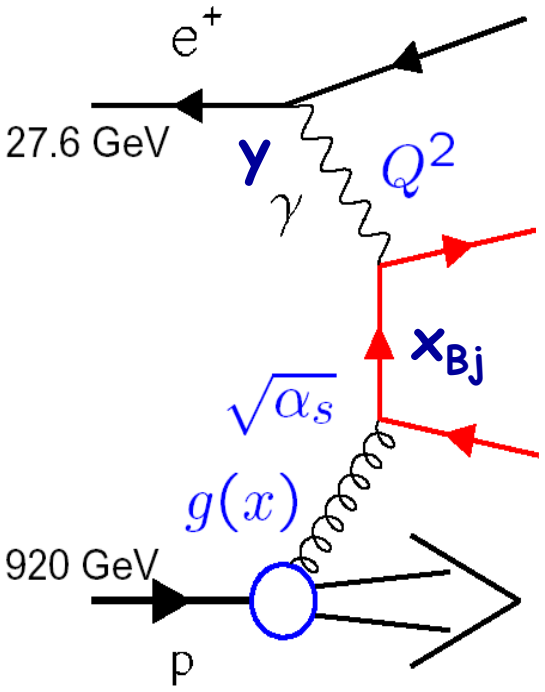
as discussed at Future Analysis with HERA data workshop 2014

- **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)**

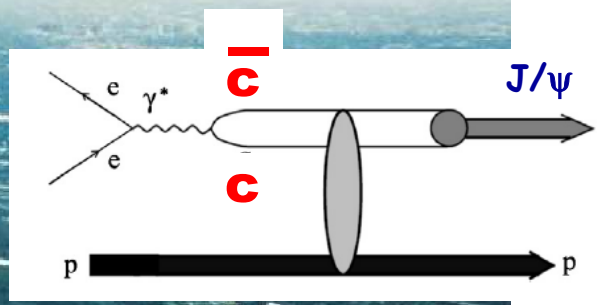
Backup

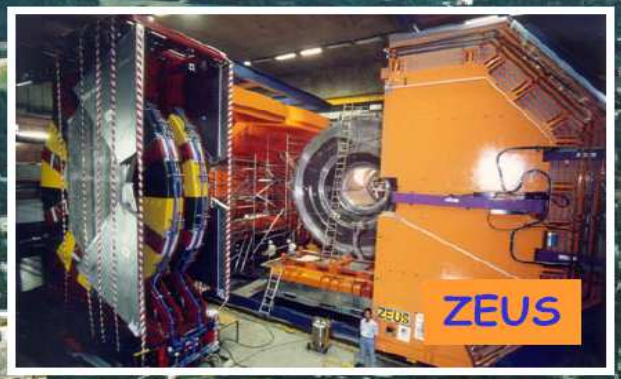
For heavy-flavor part

The HERA ep collider and experiments



up to 30%
of cross section





HERA I: ~ 130 pb^{-1} (physics)

HERA II: ~ 380 pb^{-1}(physics)

combined: ~ 2 x 0.5 fb^{-1}

HERA:

p (920 GeV) e (27.6 GeV)

How to get access to the HERA data

ZEUS: (common ntuples, flat root ntuples, only software needed: plain root, almost any version); both HERA I and HERA II data

contact Matthew.Wing@desy.de (ZEUS spokesperson) (or me)

- either access for specific single project/paper for common publication, or
- become full ZEUS member (no fees/chores beyond working on the physics) and participate in all papers

H1: (dedicated OO framework)

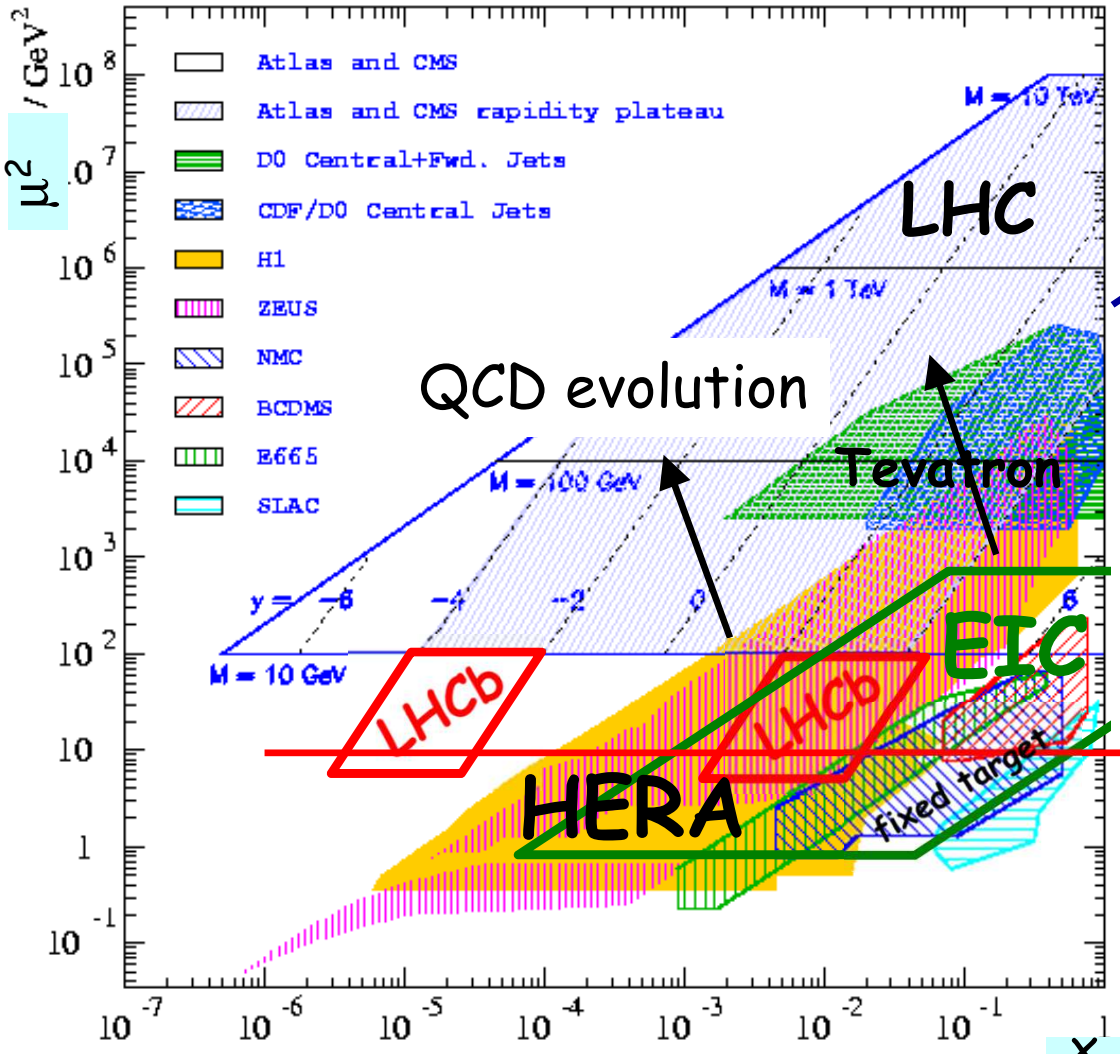
contact Stefan.Schmitt@desy.de (H1 spokesperson)

to become H1 member (no fees fees/chores beyond working on the physics)

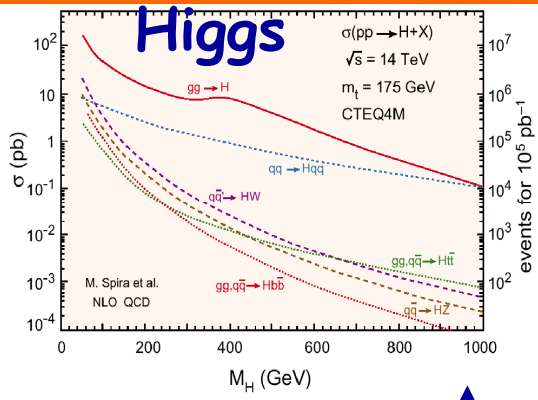
HERMES: contact Gunar.Schnell@desy.de (HERMES spokesperson)

for more details, see also
https://indico.bnl.gov/event/9287/contributions/41457/attachments/30600/48033/EIC_2020.pdf

Parton density functions (PDF)

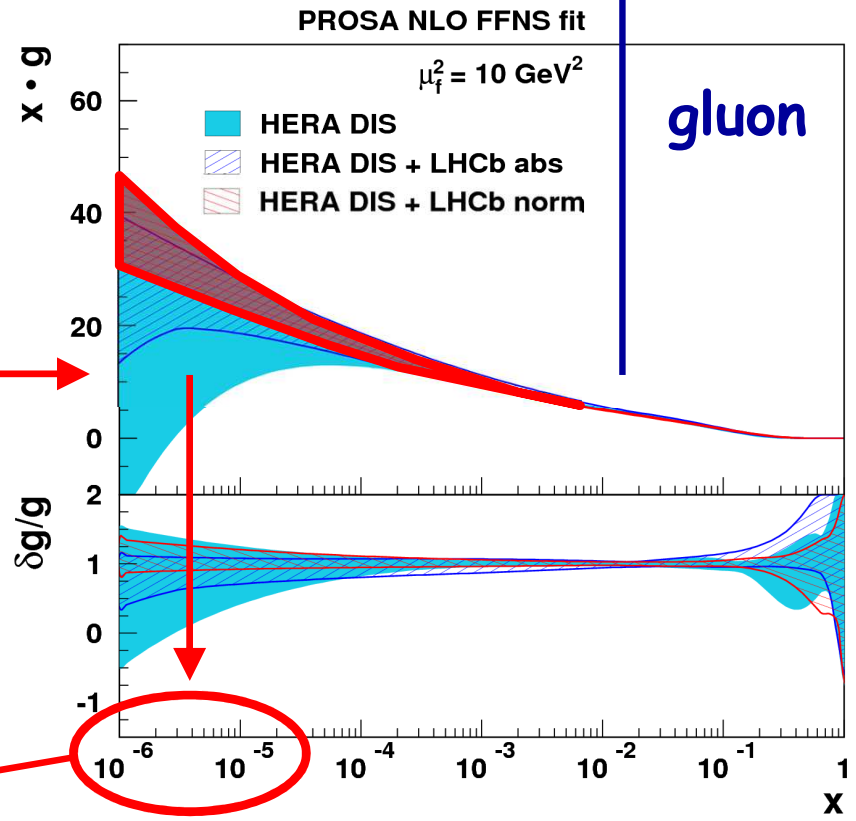


Higgs



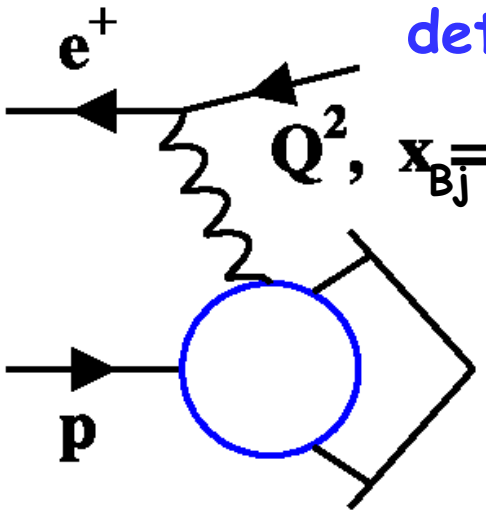
top, jets, ...

gluon



parton densities from HERA and LHC data
-> cross sections at LHC, cosmic rays, ...

Heavy flavour contributions to σ_r



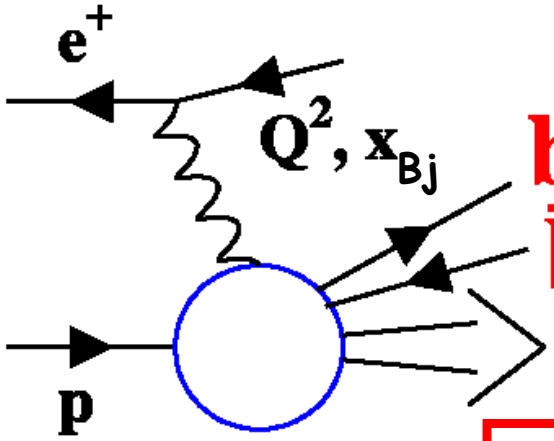
detect ⟷

Measure cross section

$$\frac{d^2\sigma}{dx_{Bj}\,dQ^2} \cong \frac{2\pi\alpha^2}{Q^4 x_{Bj}}\left[1+(1-y)^2\right]\sigma_r(x_{Bj},Q^2)$$

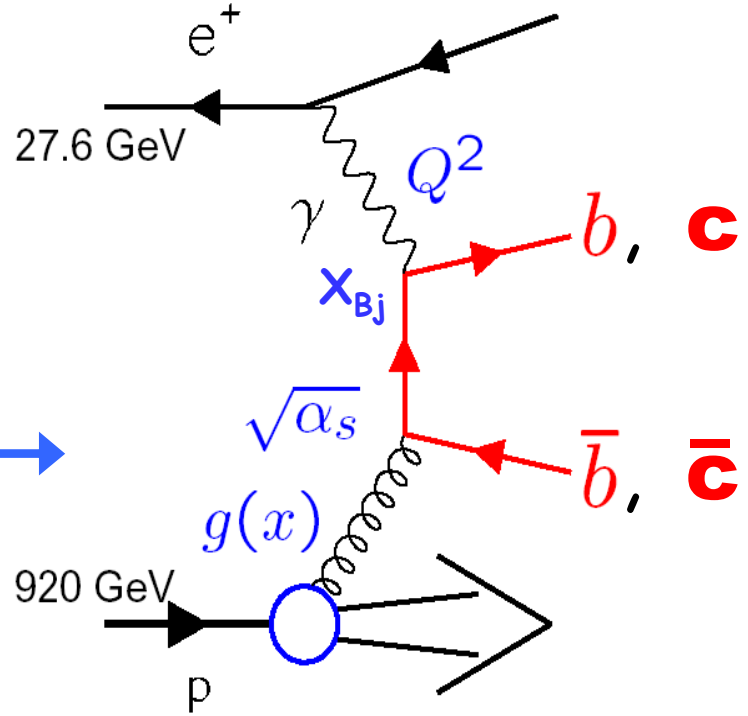
see also talk R. Thorne

flavour tagging ↓



$\mathbf{b}\ \bar{\mathbf{b}}$ or $\mathbf{c}\ \bar{\mathbf{c}}$

QCD ⟷

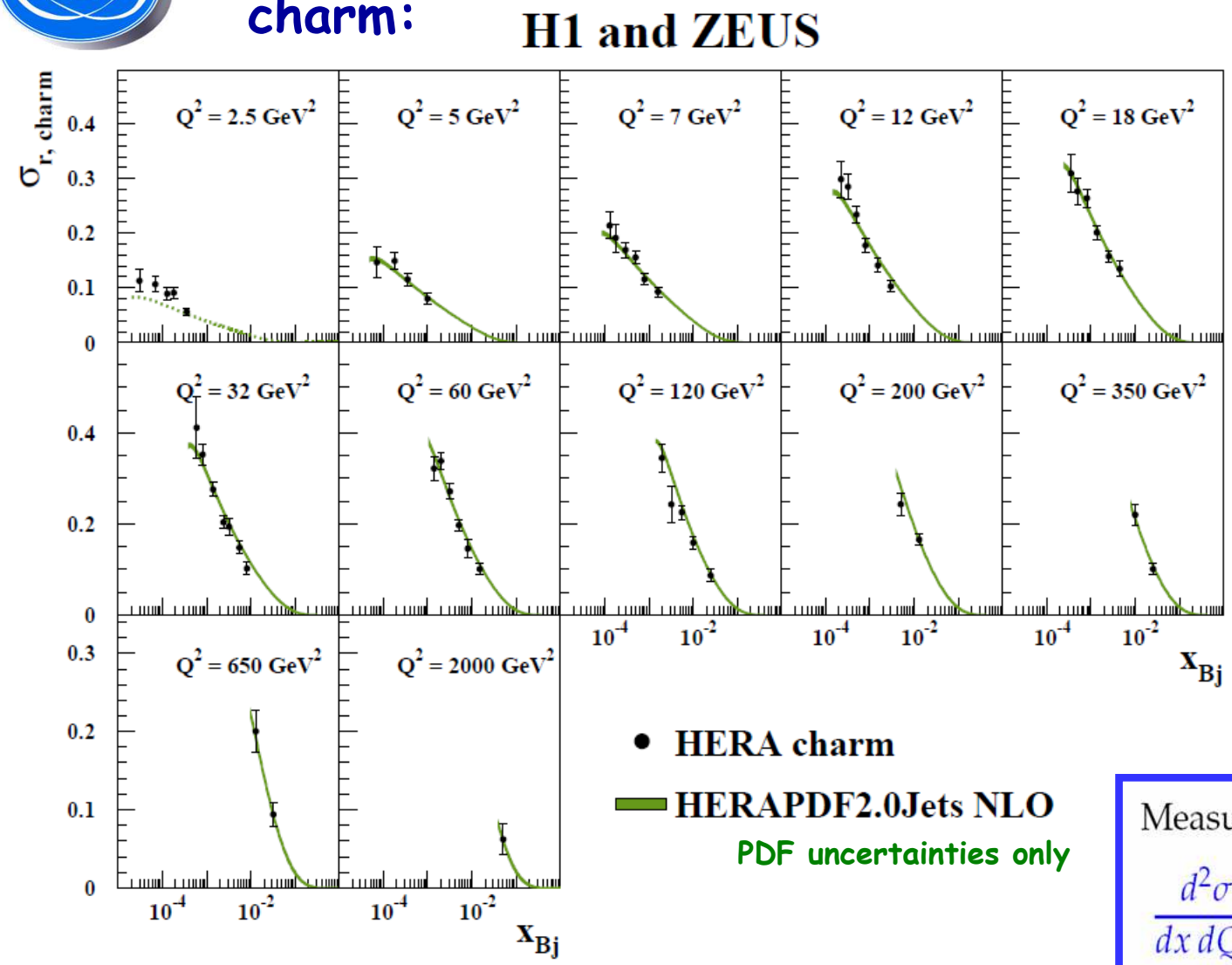


-> $\sigma_r^{b\bar{b}}$, $\sigma_r^{c\bar{c}}$

includes fit of inclusive charm + jet DIS data

arXiv 1506.06042, EPJC 75 (2015) 580

charm:



well described by fit

Measure cross section

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left\{\left[1+(1-y)^2\right]\sigma_{red}^{cc}\right.$$

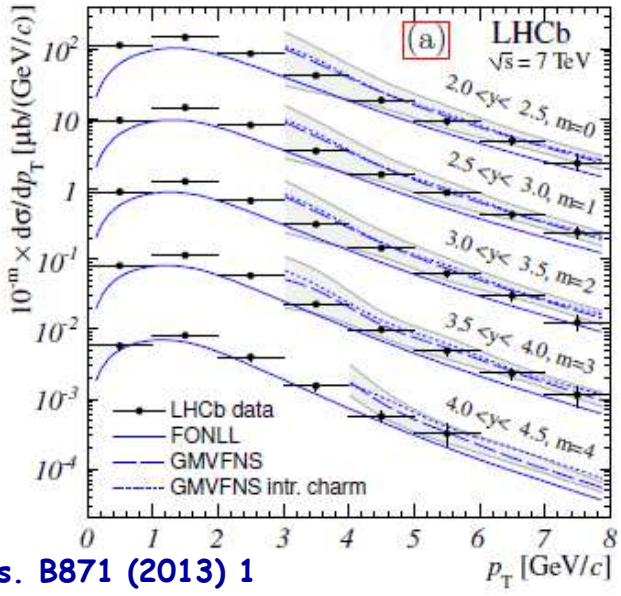
Constraint of gluon at very low x

arXiv 1503.04581, Eur.Phys.J. C75 (2015) 396

Combined fit of

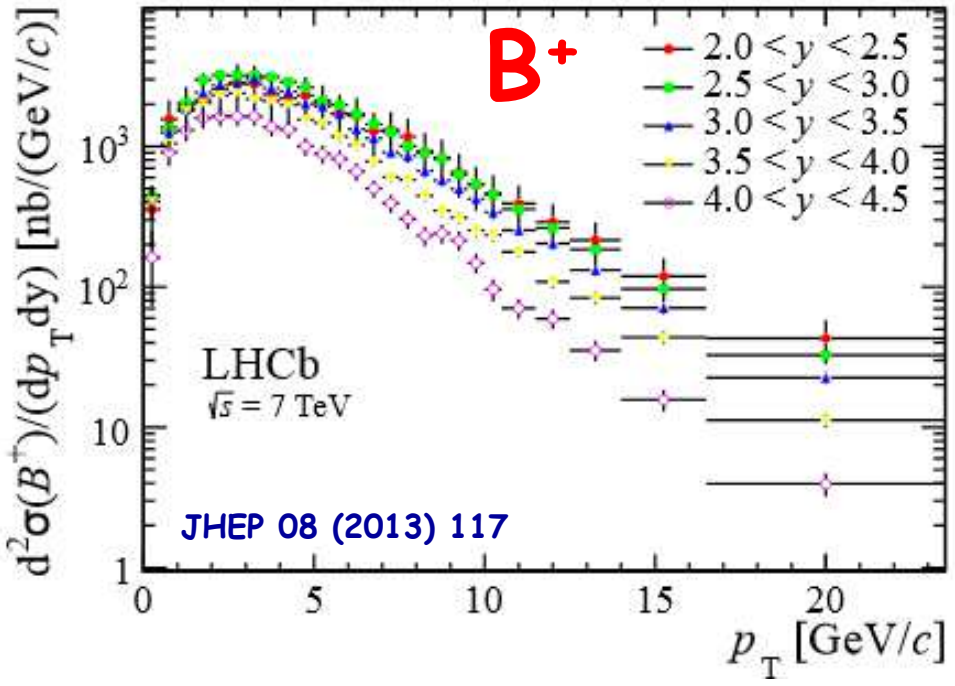
- HERA I inclusive data: main PDF constraint
- HERA charm and beauty data: constrain m_c, m_b and gluon at low x: 10^{-2} -10^{-4}
- **LHCb charm and beauty data**, constrain gluon at very low x: 10^{-3}- 10^{-6}

D^0



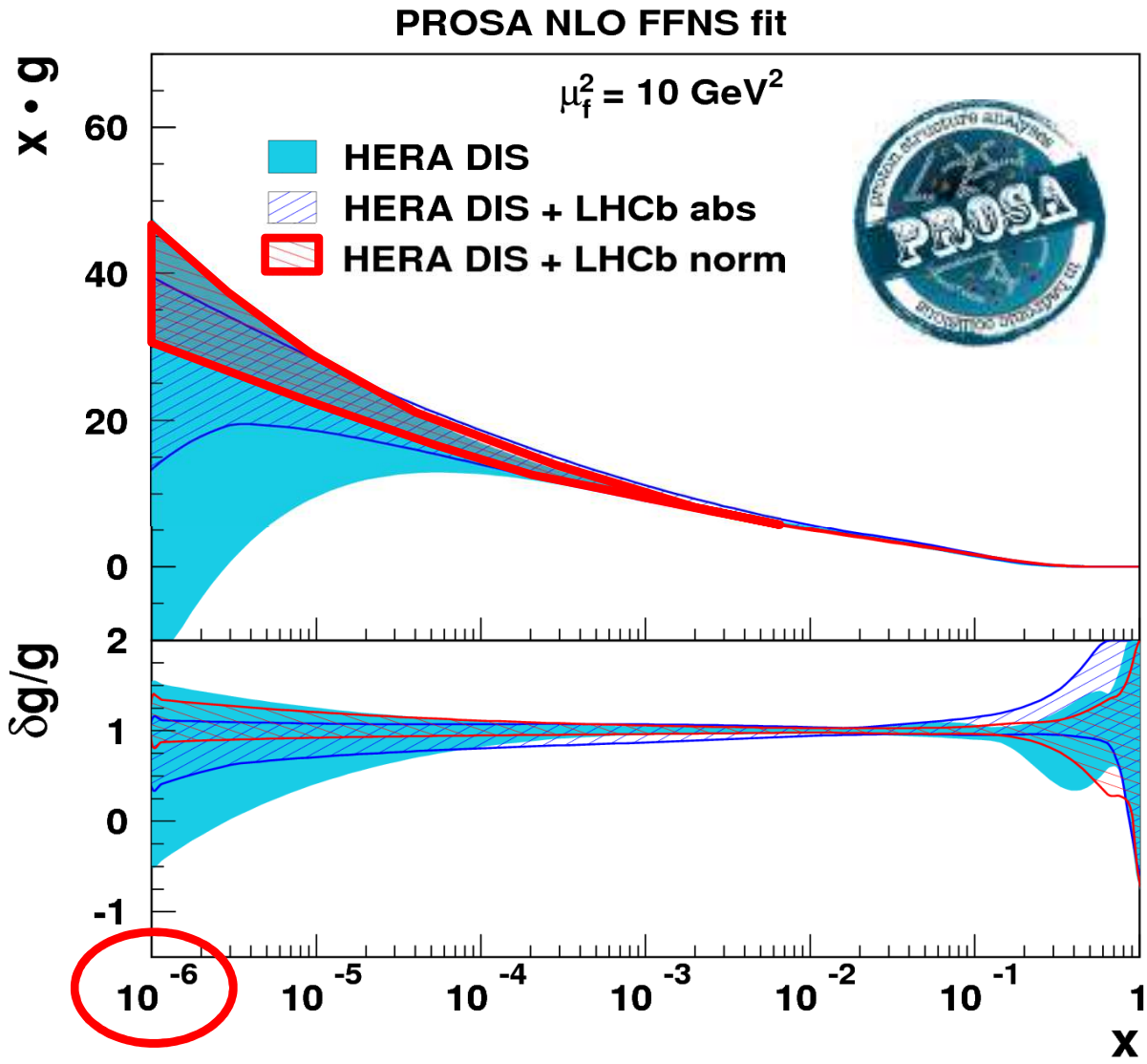
Nucl.Phys. B871 (2013) 1

B^+



final comparison of gluon fits

arXiv 1503.04581, Eur.Phys.J. C75 (2015) 396



gluon positive and well constrained down to $x \sim 10^{-6}$

first constraint from data for $x << 10^{-4}$

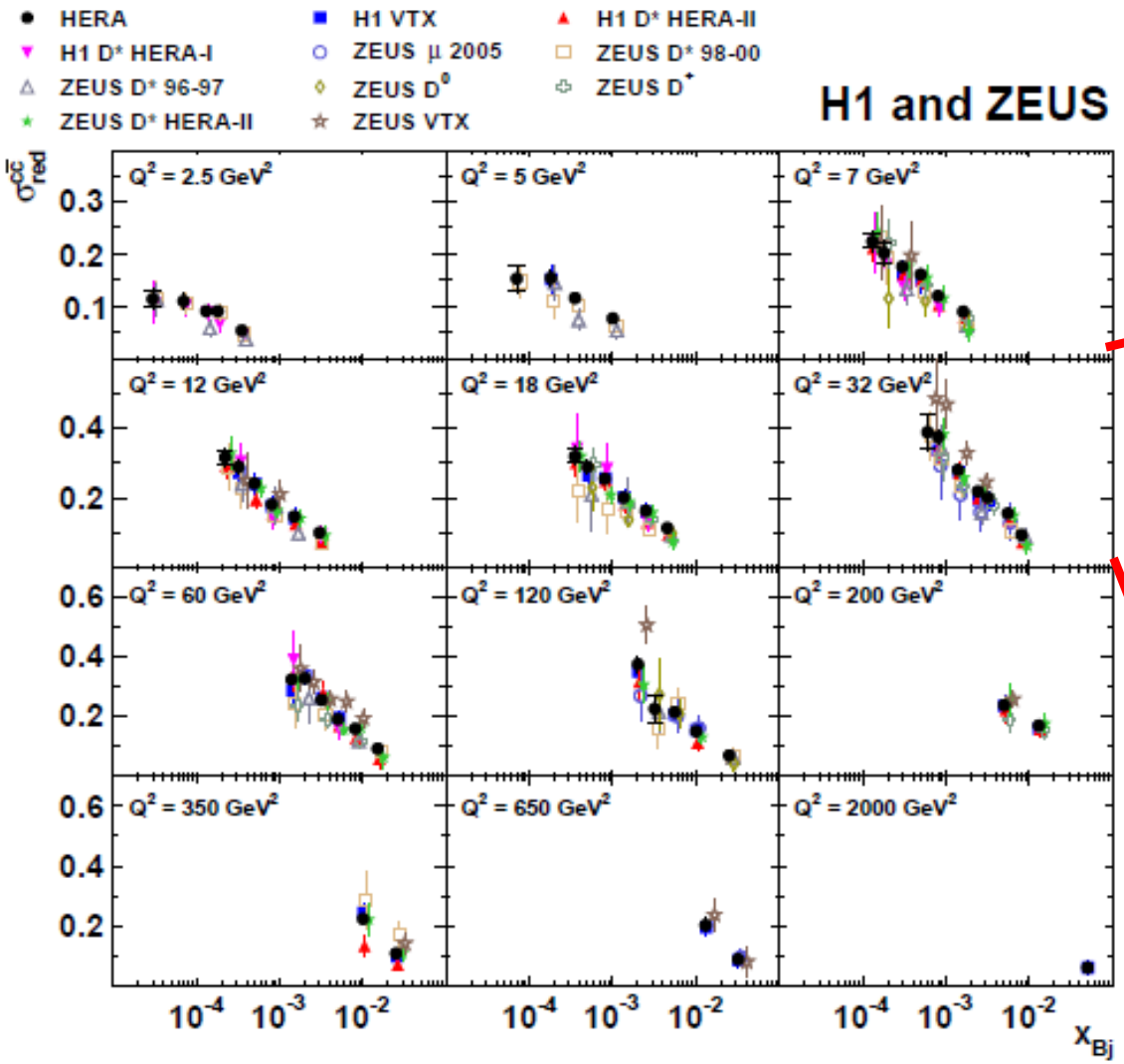
already in use to constrain cosmic ray prompt neutrino spectrum (e.g. Ice Cube)

Final HERA Charm combination

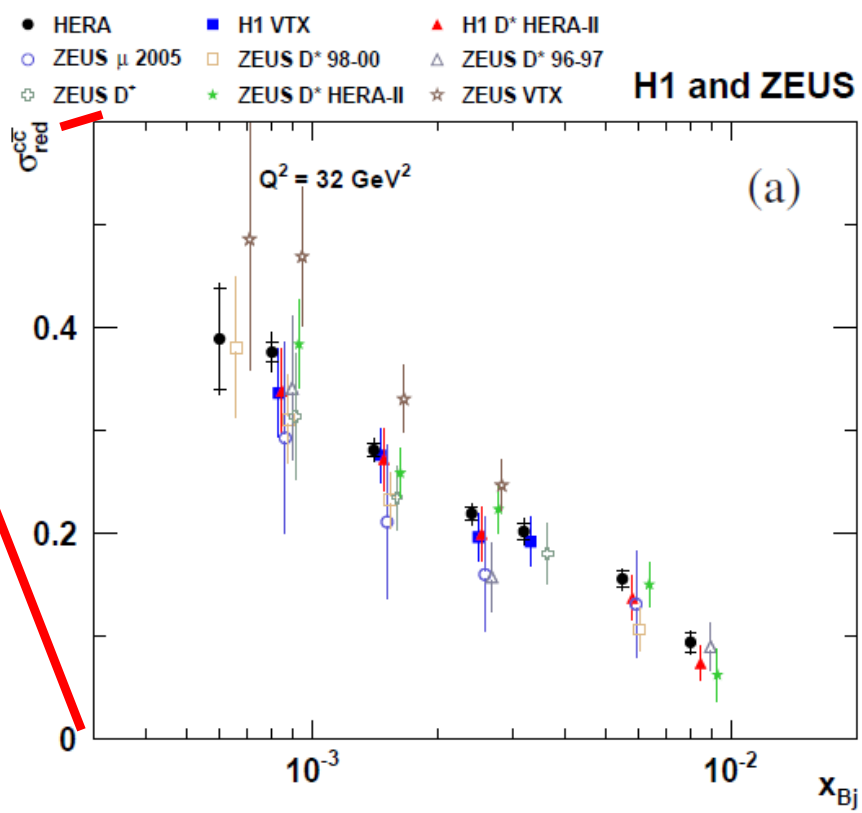
Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019

209 -> 52 data points

(+ beauty combination, see backup)



3 HERA II data sets added
-> 20% improvement



QCD fit: charm x slope

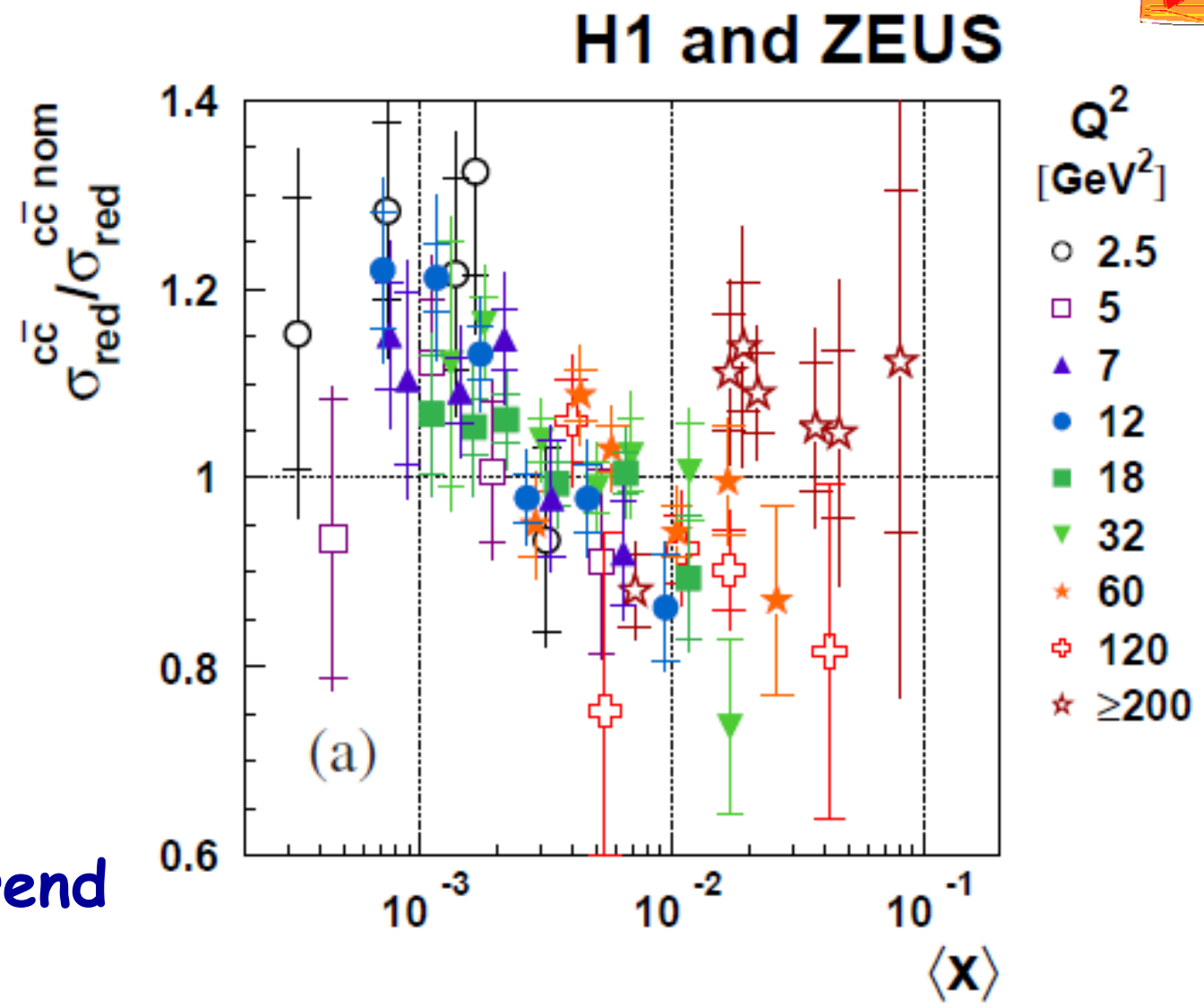
Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019

plot **data/fit**
vs. <x> of
incoming partons
(rather than x_{Bj})
for each data point

LO: $x = x_{Bj} \cdot \left(1 + \frac{\hat{s}}{Q^2}\right)$

<x> calculated at **NLO**
using HVQDIS

-> common <x> trend
for all Q^2



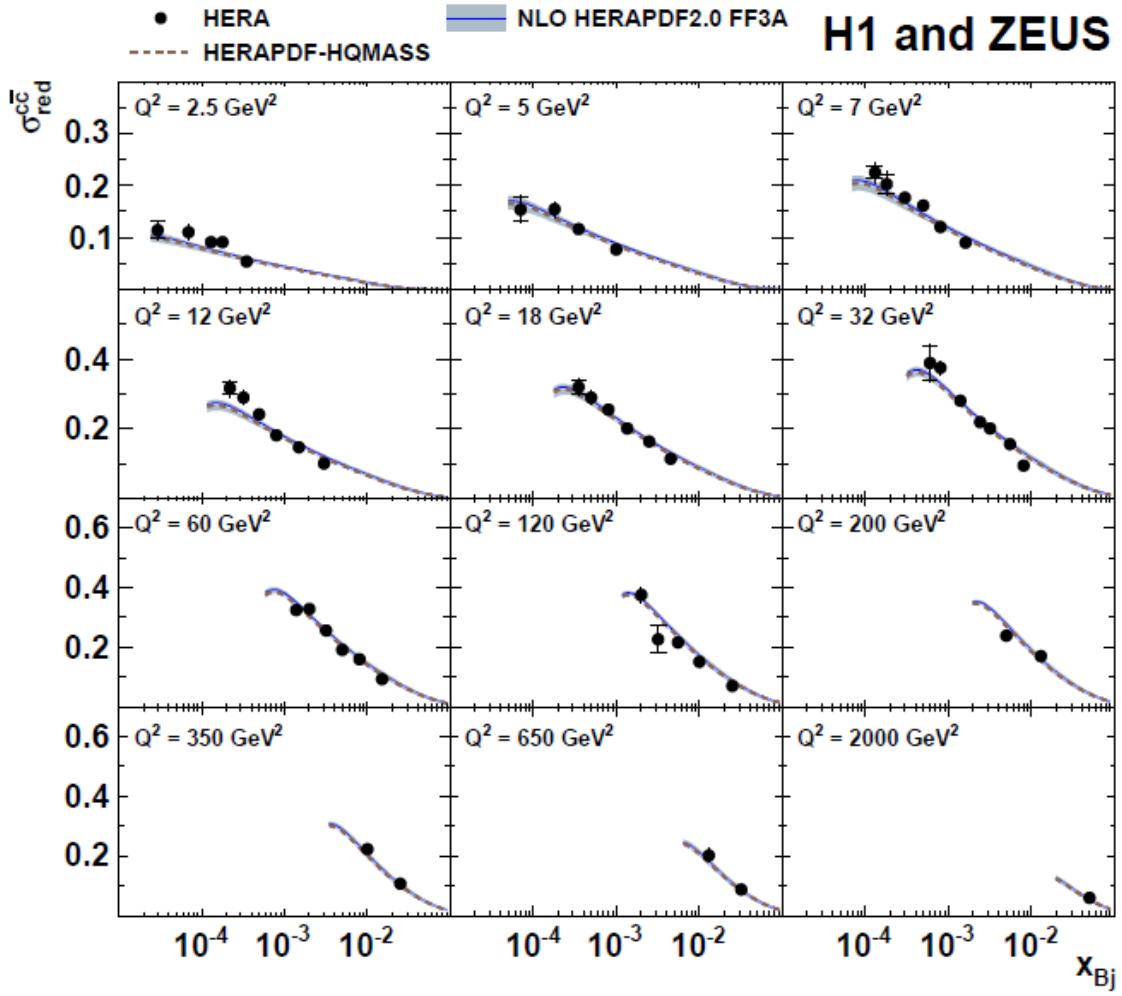
further discussion (gluon shape (?), low x resummation (?), …) **see backup**

QCD fit: charm subset

Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019

fully consistent
with HERAPDF2.0 FF3A

uncertainty breakdown
in backup



$$m_c(m_c) = 1.29\ ^{+0.05}_{-0.04\ exp/fit}\ ^{+0.06}_{-0.01\ mod/scale}\ ^{+0.00}_{-0.03\ par}\ GeV$$

PDG: 1.27 ±0.03 GeV (lattice QCD + time-like processes)

Comparison with other $m_c(m_c)$ determinations

Eur.Phys.J.C 78 (2018) 473, arXiv:1804.01019

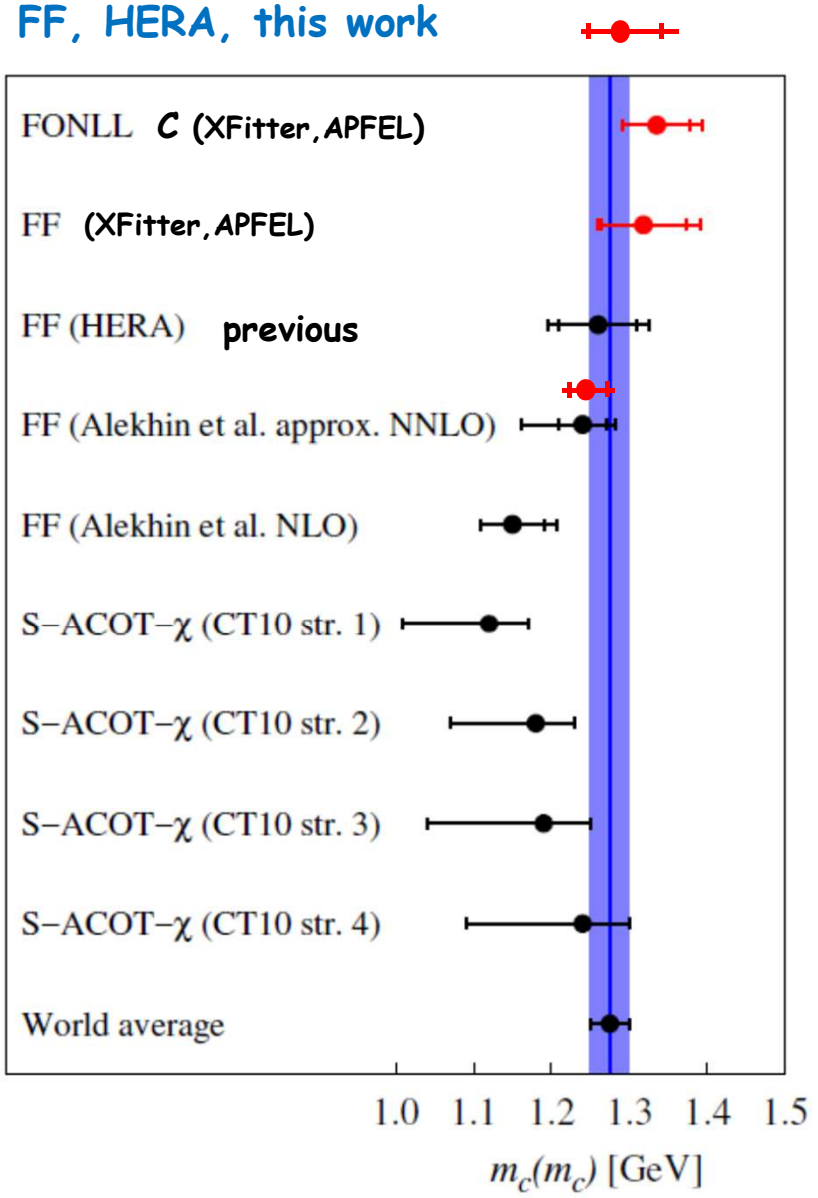
this work:

$$m_c(m_c) = 1.29\ ^{+0.05}_{-0.04\ \text{exp/fit}}\ ^{+0.06}_{-0.01\ \text{mod/scale}}\ ^{+0.00}_{-0.03\ \text{par}}\ \text{GeV}$$

latest ABMP16 result: $m_c(m_c) = 1.252 \pm 0.018 \pm 0.032$ GeV
S. Alekhin et al., arXiv:1701.05383,
Phys. Rev. D96 (2017) 014011

previous results summarized in
V. Bertone et al., arXiv:1605.01946,
JHEP 1608 (2016) 050 :

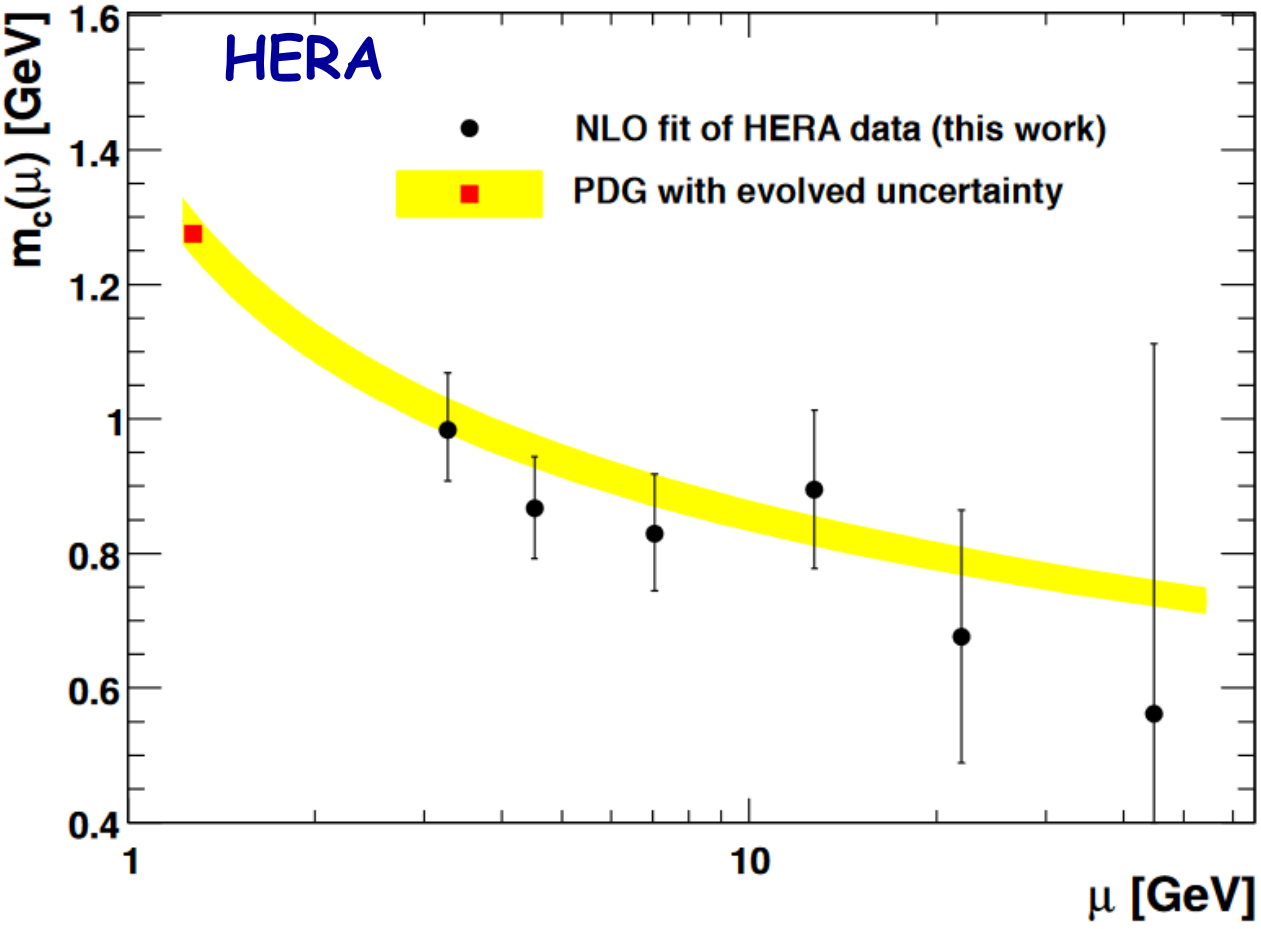
scheme	$m_c(m_c)$ [GeV]
FONLL (this work)	$1.335 \pm 0.043(\text{exp})^{+0.019}_{-0.000}(\text{param})^{+0.011}_{-0.008}(\text{mod})^{+0.033}_{-0.008}(\text{th})$
FFN (this work)	$1.318 \pm 0.054(\text{exp})^{+0.011}_{-0.010}(\text{param})^{+0.015}_{-0.019}(\text{mod})^{+0.045}_{-0.004}(\text{th})$
FFN (HERA) [9]	$1.26 \pm 0.05(\text{exp}) \pm 0.03(\text{mod}) \pm 0.02(\text{param}) \pm 0.02(\alpha_s)$
FFN (Alekhin *et al.*) [24]	$1.24 \pm 0.03(\text{exp})^{+0.03}_{-0.02}(\text{scale})^{+0.00}_{-0.07}(\text{th})$ (approx. NNLO)
	$1.15 \pm 0.04(\text{exp})^{+0.04}_{-0.00}(\text{scale})$ (NLO)
S-ACOT-χ (CT10) [29]	$1.12^{+0.05}_{-0.11}$ (strategy 1)
	$1.18^{+0.05}_{-0.11}$ (strategy 2)
	$1.19^{+0.06}_{-0.15}$ (strategy 3)
	$1.24^{+0.06}_{-0.15}$ (strategy 4)
World average [53]	1.275 ± 0.025



the running charm quark mass

Phys.Lett.B 775 (2017) 233-238, arxiv:1705.08863

Do mass determination separately for different Q^2+4m^2



running mass concept in QCD is self-consistent !

but mass is also manifestation of Higgs Yukawa couplings !

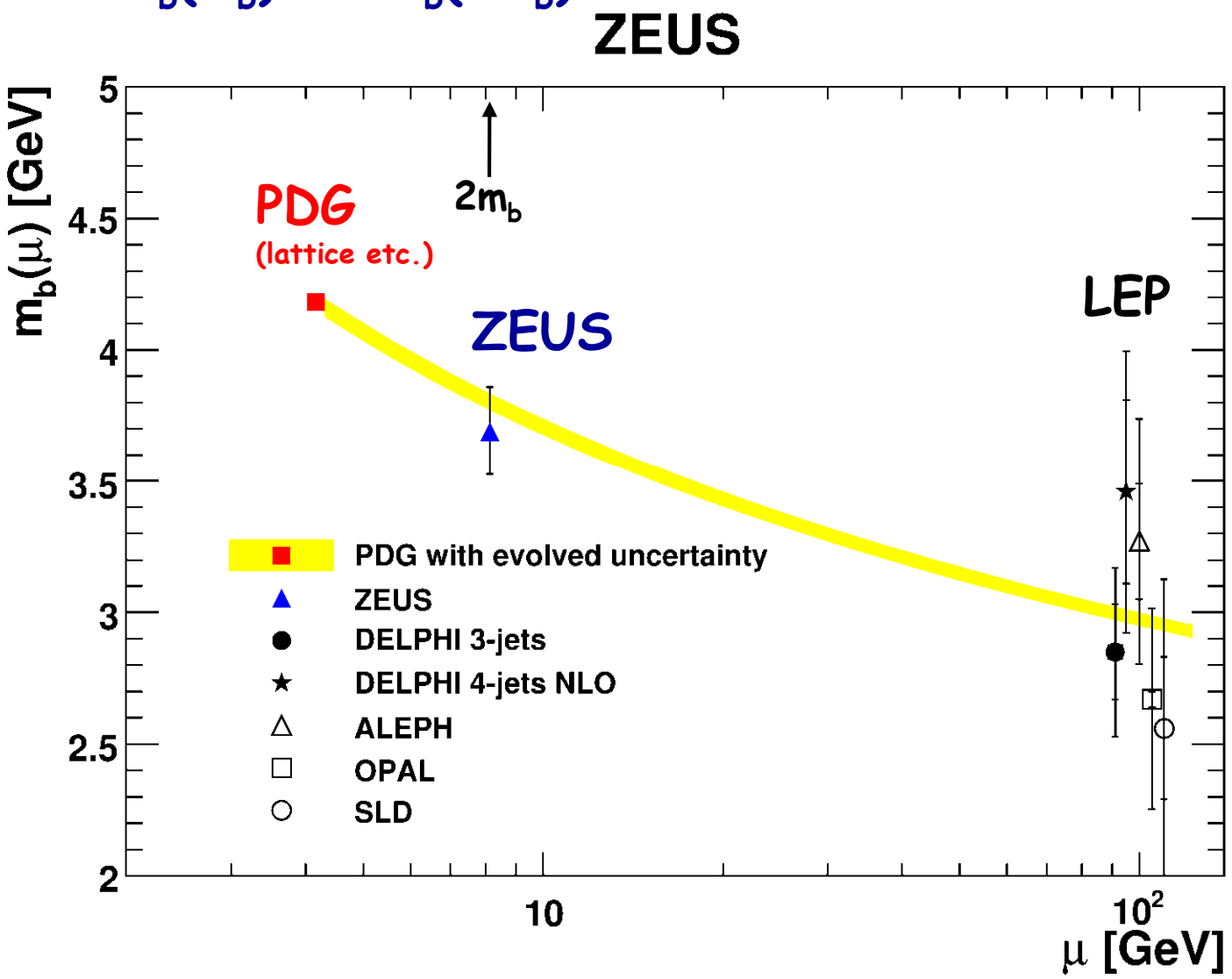
$y_Q = \sqrt{2}m_Q/v$

the running beauty quark mass

arXiv:1506.07519

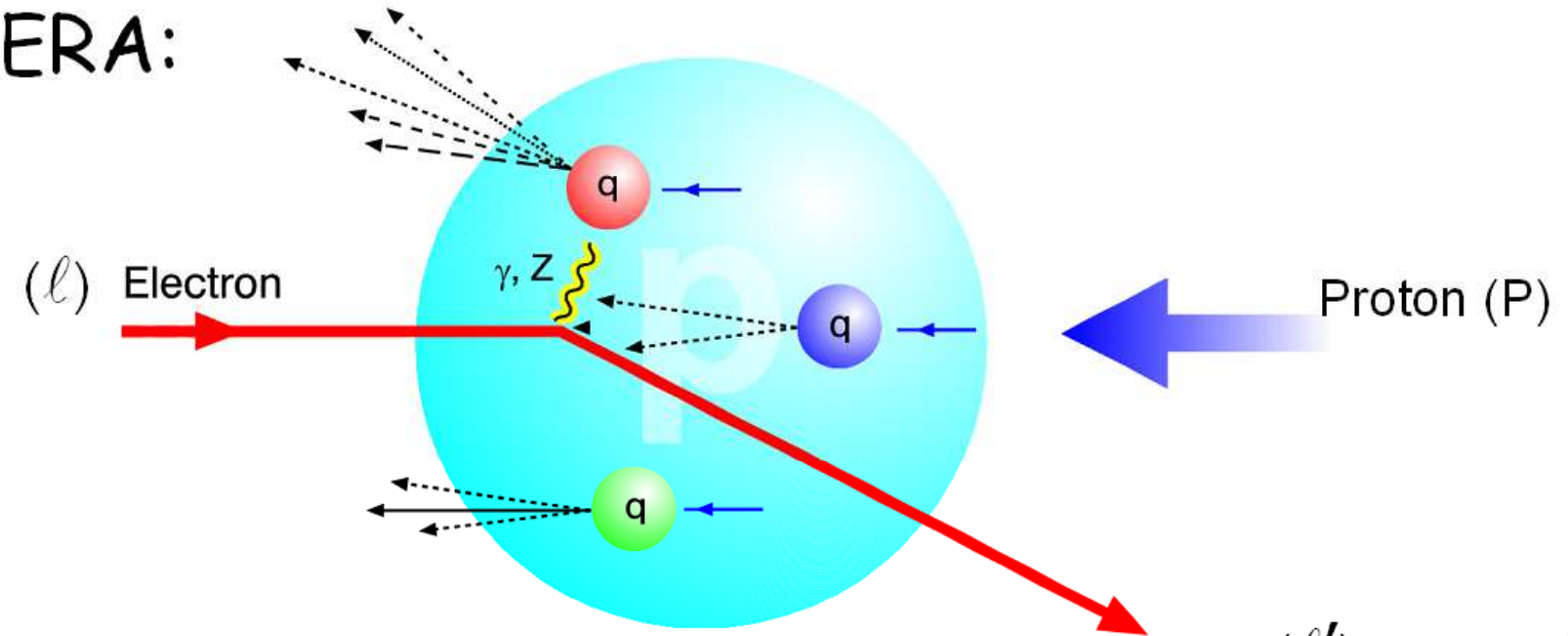
Prog. Part. Nucl. Phys. 84 (2015) 1

translate $m_b(m_b)$ -> $m_b(2m_b)$



Deep Inelastic ep Scattering at HERA

HERA:



kinematic variables:

$Q^2 = -q^2$ photon (or Z) virtuality, squared momentum transfer

$x = \frac{Q^2}{2Pq}$ Bjorken scaling variable,
for $Q^2 \gg (2m_q)^2$: momentum fraction of p constituent

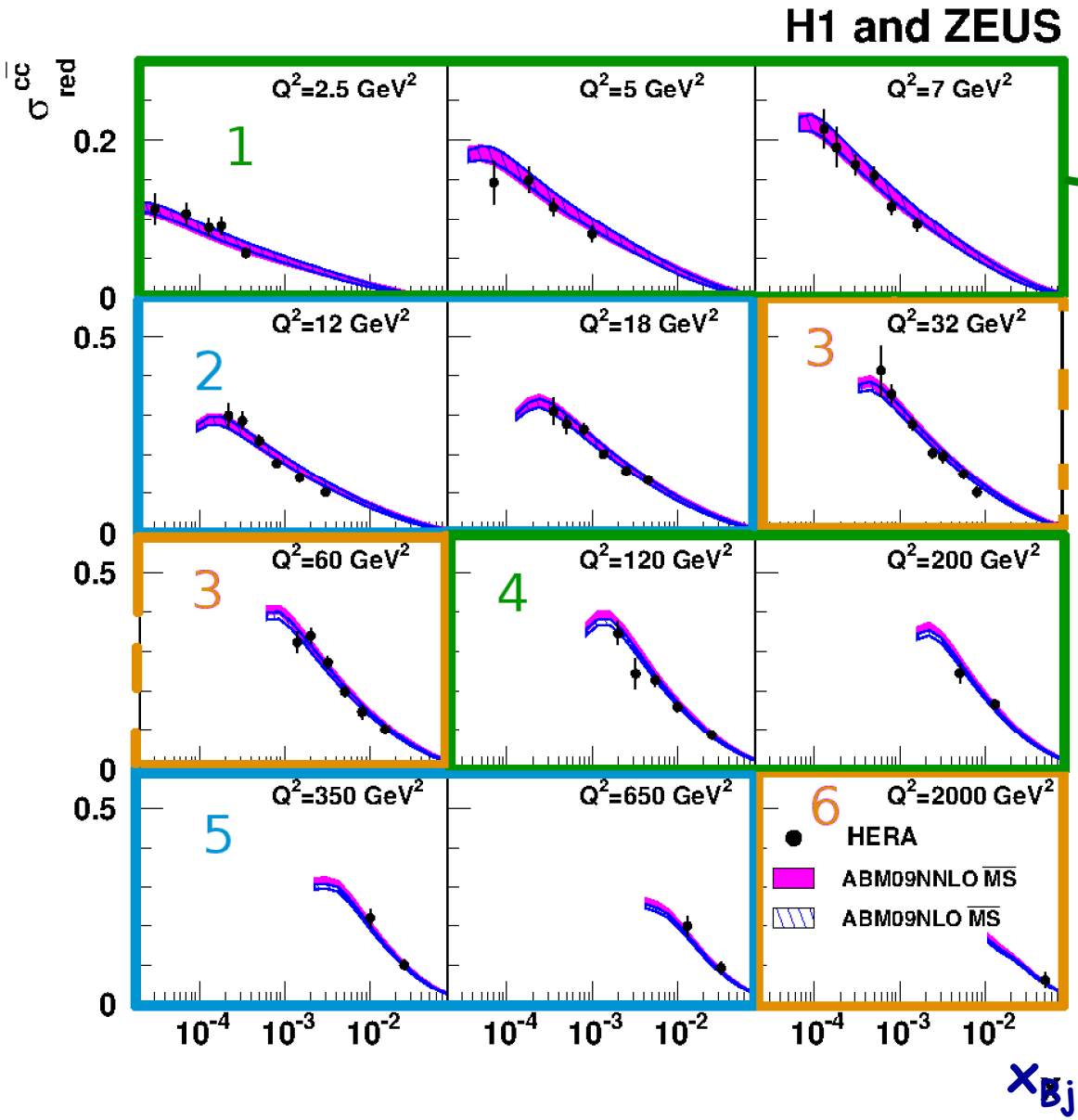
$y = \frac{qP}{\ell P}$ inelasticity,
γ momentum fraction (of e)

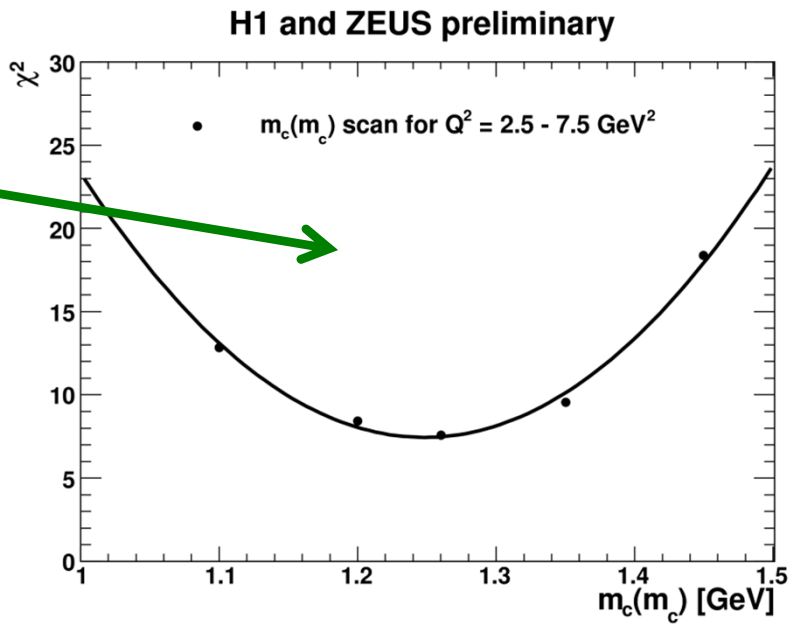
$Q^2 \lesssim 1$ GeV^2: photoproduction

$Q^2 \gtrsim 1$ GeV^2: DIS

measurement of m_c running

Phys.Lett.B 775 (2017) 233-238, arxiv:1705.08863





extract $m_c(\mu)$ separately for 6 different kinematic ranges in $\mu^2 = Q^2+4m_c^2$

(take log average for central scale)

QCD fit

Eur.Phys.J.C 78 (2018) 473, **arXiv:1804.01019**

simultaneous NLO QCD fit of

- combined **inclusive DIS** data (arXiv:1506.06042), Q^2_{min}=3.5 GeV^2
- new combined **charm and beauty DIS** data

simultaneously fit **PDF's** (a la **HERAPDF** FF) in FFNS at NLO and **charm quark and beauty quark "running" masses** in MSbar scheme

- using xFitter [www.xfitter.org], 14 parameters (±1)
- NLO DGLAP [QCDNUM] and matrix elements [OPENQCDRAD], nf = 3
- $\mu_F = \mu_R = \sqrt{Q^2 + 4m_Q^2}$, varied by factor 2 (for heavy flavour part only)
- **free $m_c(m_c)$, $m_b(m_b)$**
- $\alpha_s(M_Z)^{nf=3} = 0.106$, equivalent to $\alpha_s(M_Z)^{nf=5} = 0.118 \pm 0.002$
- fit uncertainty using $\Delta\chi^2 = 1$

-> HERAPDF-HQMASS

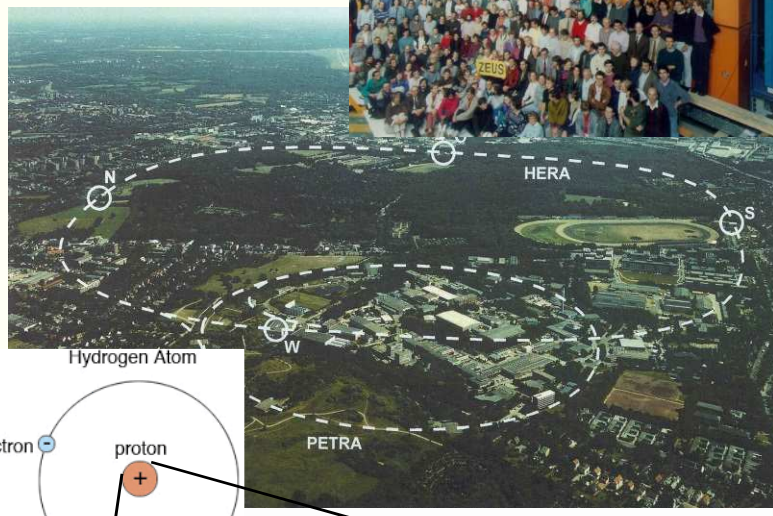
What is ZEUS?

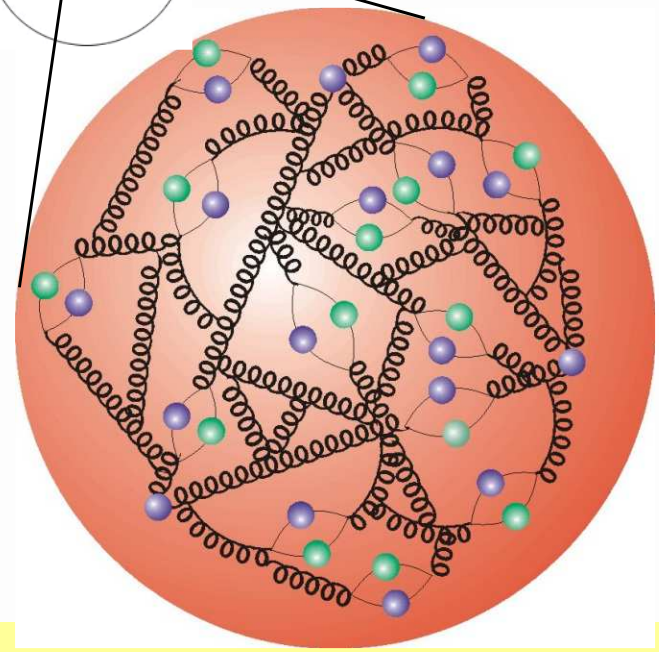
- **International Particle Physics Experiment** which recorded high energy electron-proton collisions at the world's (so far) unique lepton-proton collider **HERA** at DESY in Hamburg, Germany

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

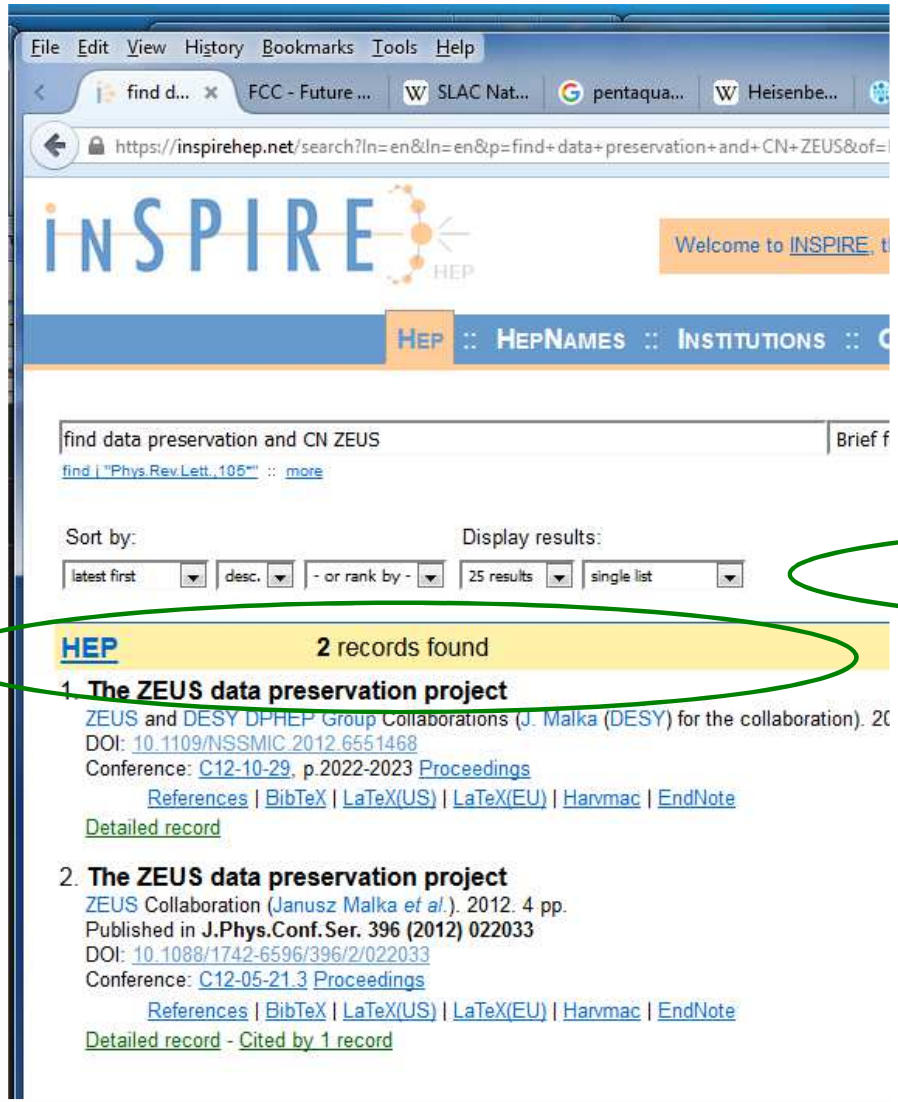
- one of main physics goals:
  measure structure of the proton to ~10^{-18} m, i.e. 1/1000 of proton size
  ("X ray" of proton with electrons)

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





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

(**person power** …, 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/