Summary of WG7: Future of DIS

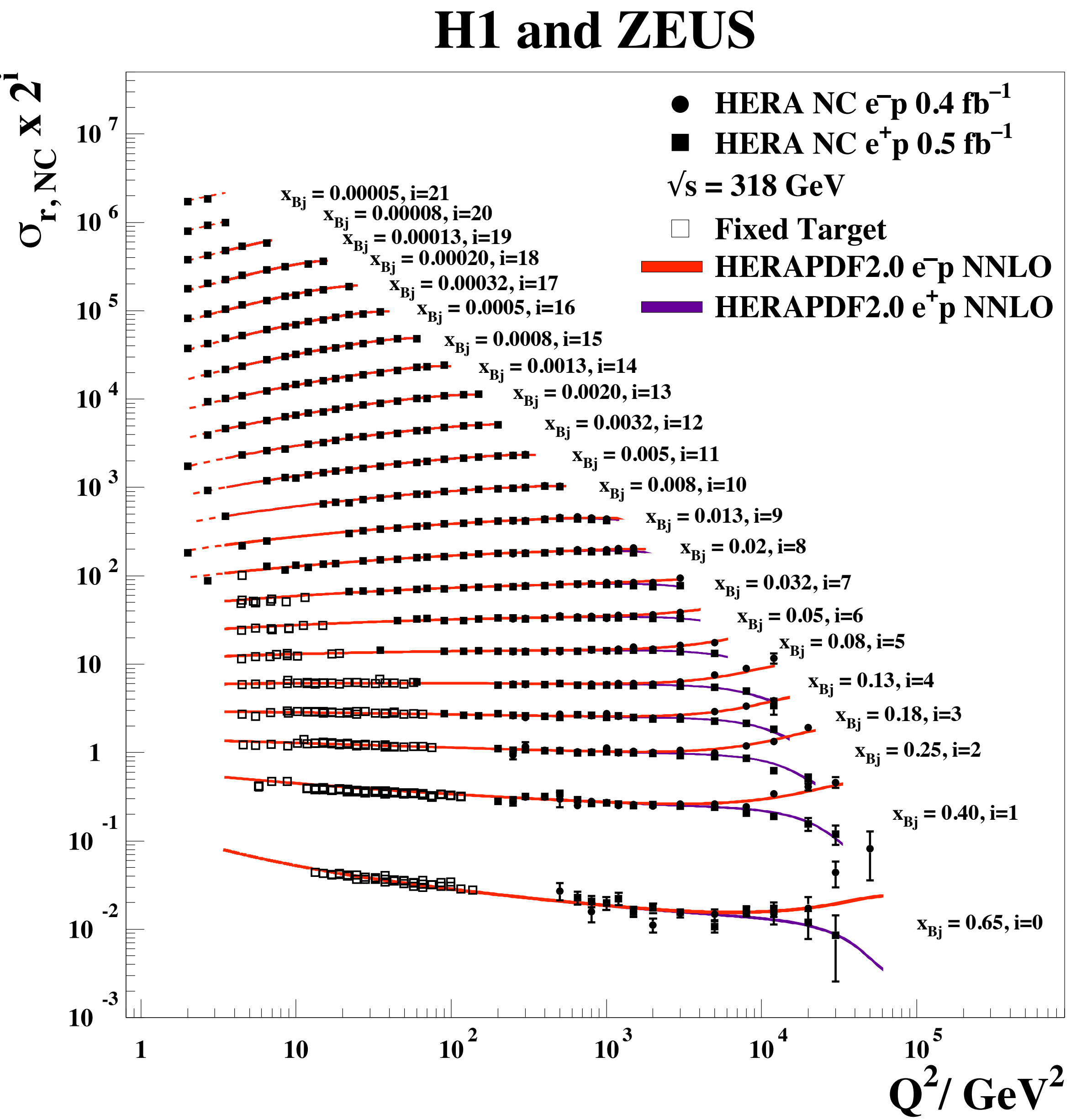
Alessandro Bacchetta (Università di Pavia),
Ernst Sichtermann (LBNL),
Matthew Wing (UCL / DESY)

- Motivation: what we know and don't know
- Overview of facilities and initiatives
- Proton PDFs at low and high *x*
- Higgs and electroweak
- Nuclear structure
- Spin
- Summary

HERA data

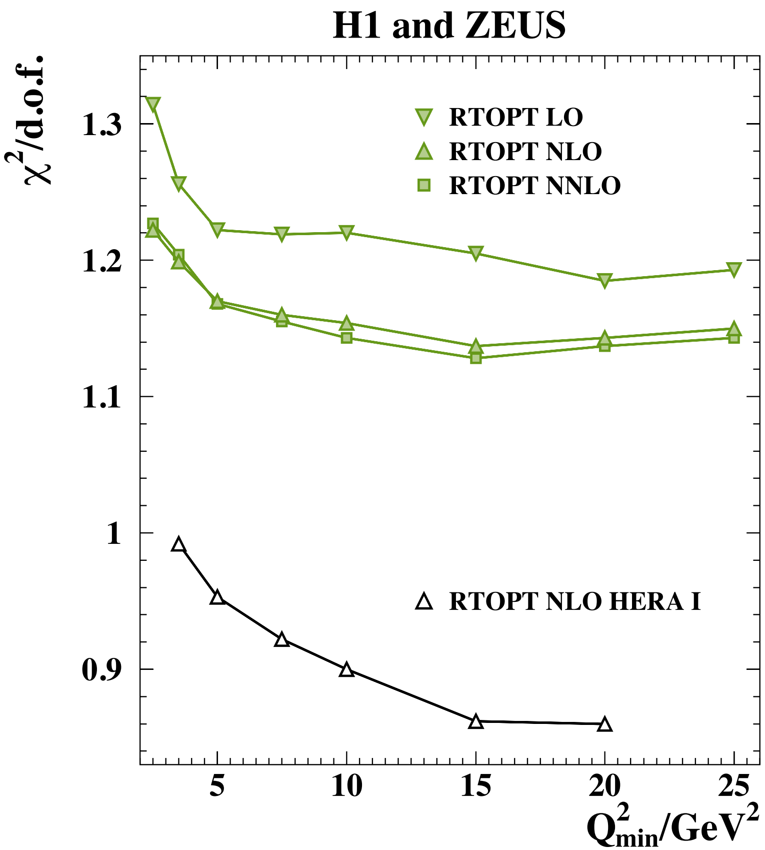
This is a beautiful plot with a lot of physics:

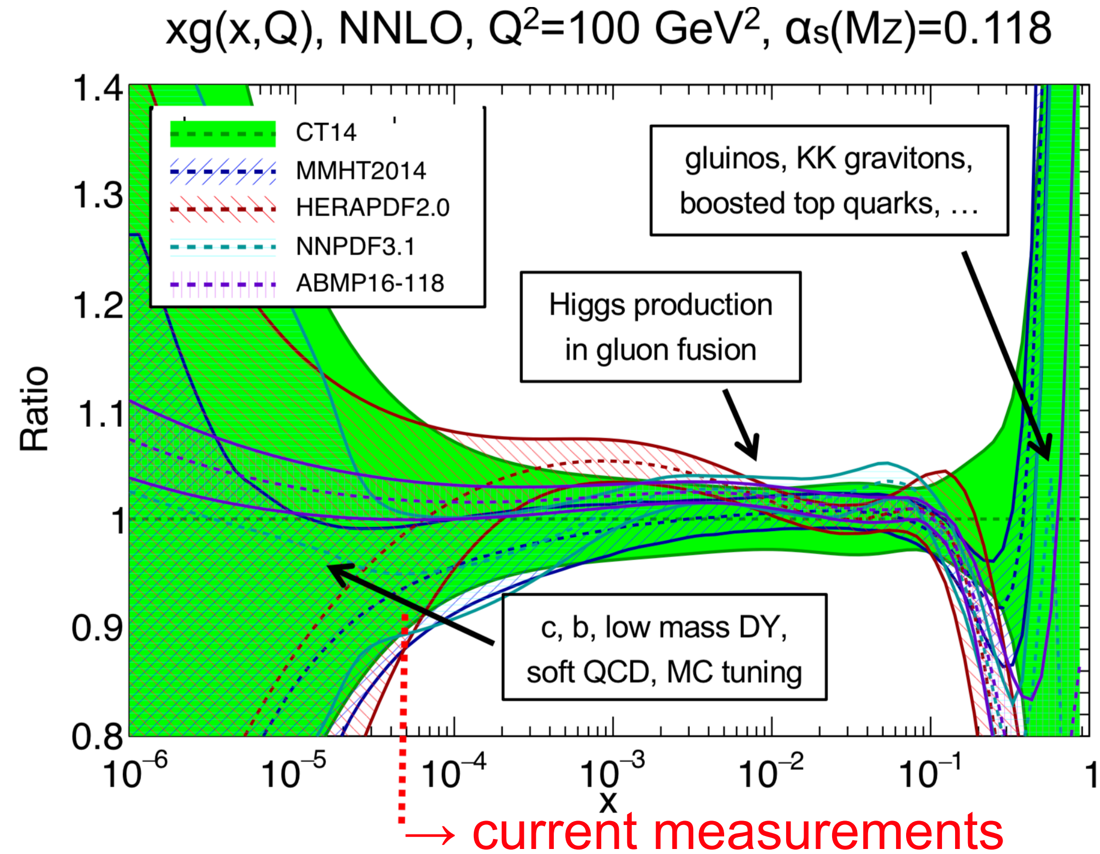
- Covers about five orders of magnitude in x and Q^2.
- Consistency of fixed-target and HERA data.
- Scaling at $x \sim 0.08$ and violations elsewhere.
- Again strong rise of gluon density.
- $\gamma - Z$ interference at high Q^2.
- Crucial input to PDF fits.
- **Still want to go to higher and lower *x*.**



QCD fits to current data

C. Gwenlan

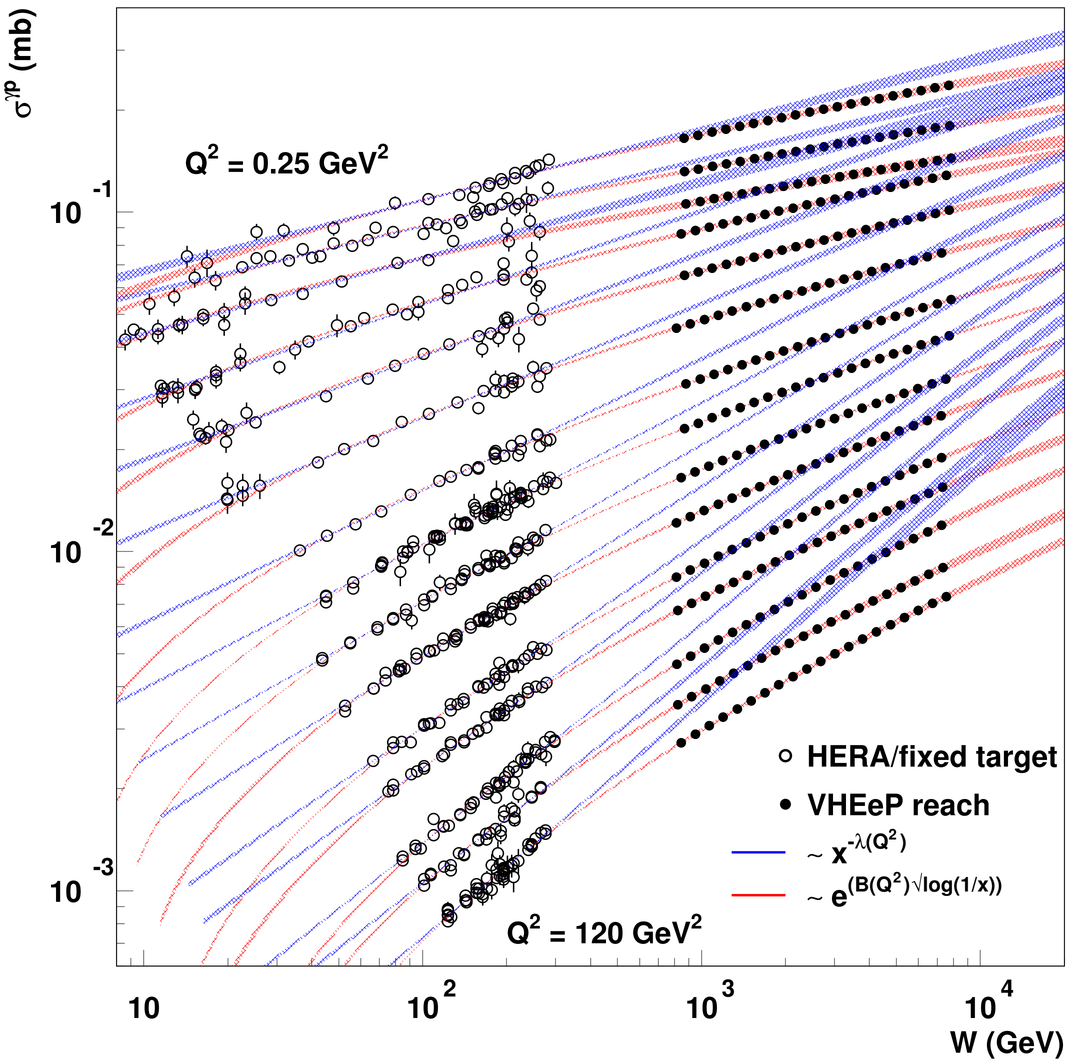




- We have limited knowledge of the proton structure at low x.
- There are indications that standard DGLAP is not enough at low x.
- High x also PDFs also suffer from large uncertainties.

Low *x* and high energy

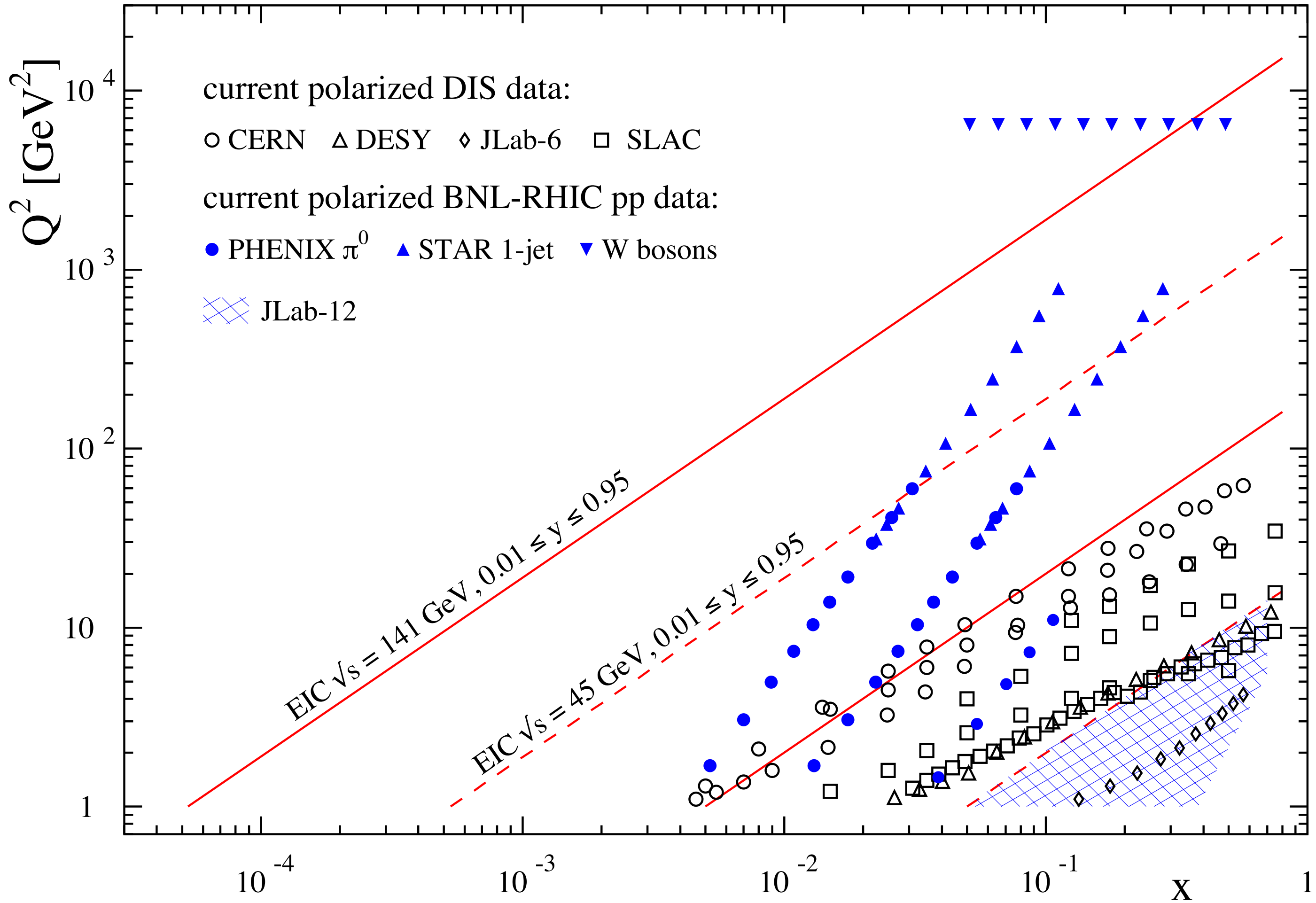
R. Yoshida



- Consider the total cross section as a function of $W_{\gamma p}$.
- Depending on the form, fits cross; physics does not make sense.
- Different forms deviate significantly from each other.
- What about saturation ? (Confinement ?)
- BFKL vs DGLAP.
- Related to UHE neutrino cross sections.
- Unique information on form of hadronic cross sections at high energy.

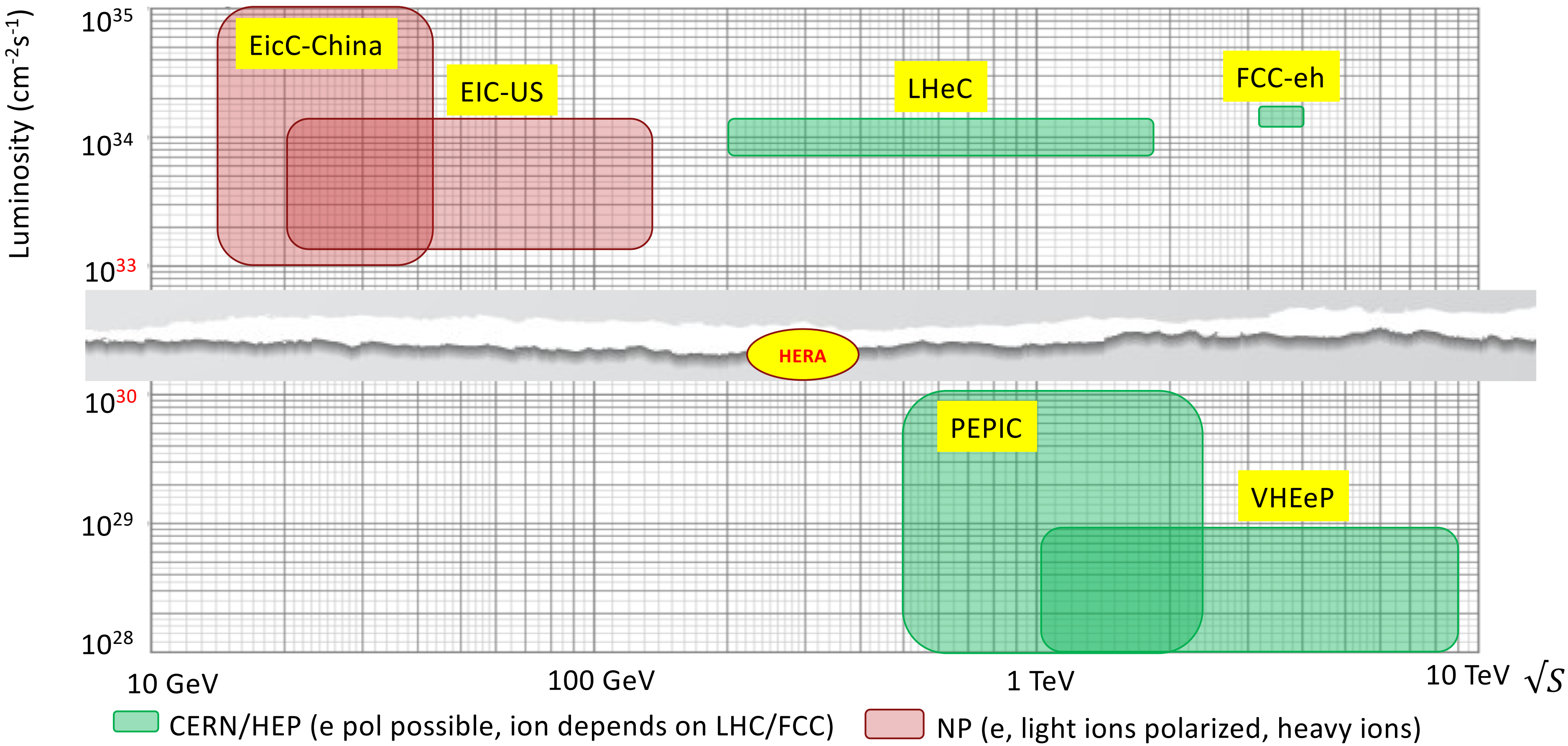
Polarised measurements and spin physics

- Collisions with polarised particles less well understood
- Several current measurements.
- Polarised data more limited in range.
- EIC will extend kinematic coverage by 2 orders in x and Q^2.
- Want to understand spin



Future DIS colliders

R. Yoshida



Comparison of DIS colliders

- EIC (U.S. & China):
  - is lowish energy, but high luminosity.
  - intrinsically flexible, with varying energy, ion species, etc.
  - has high polarisation of both beams.
  - is most advanced through approval.

- LHeC / FCC-eh:
  - is high energy and high luminosity.
  - has some flexibility in energy and particle species.
  - has broad physics programme including EW sector and high-Q^2 searches.

- VHEeP:
  - is very high energy, but low luminosity.
  - has flexibility in energy and also in other beam parameters.
  - relies on a new technology, also opportunity.

Overview talks of future DIS colliders

Tue 09/04 | **Wed 10/04** | All days

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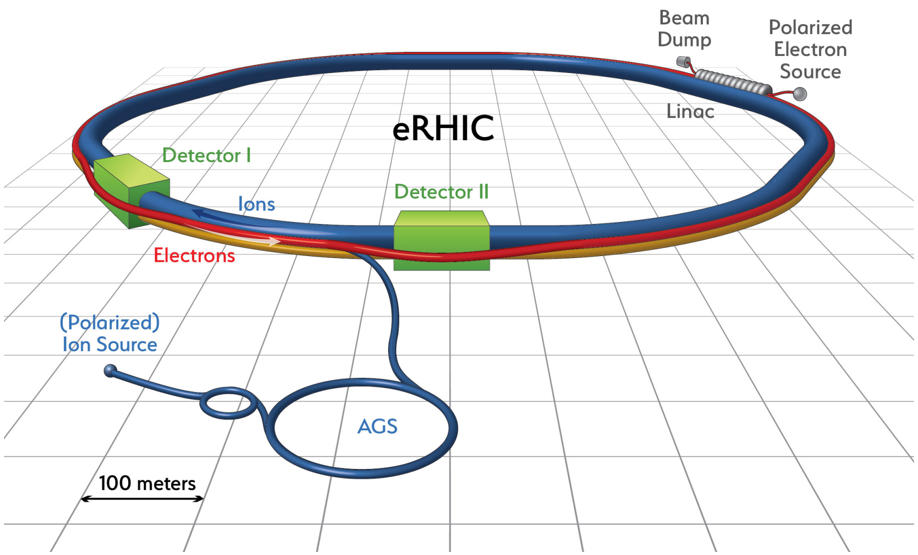
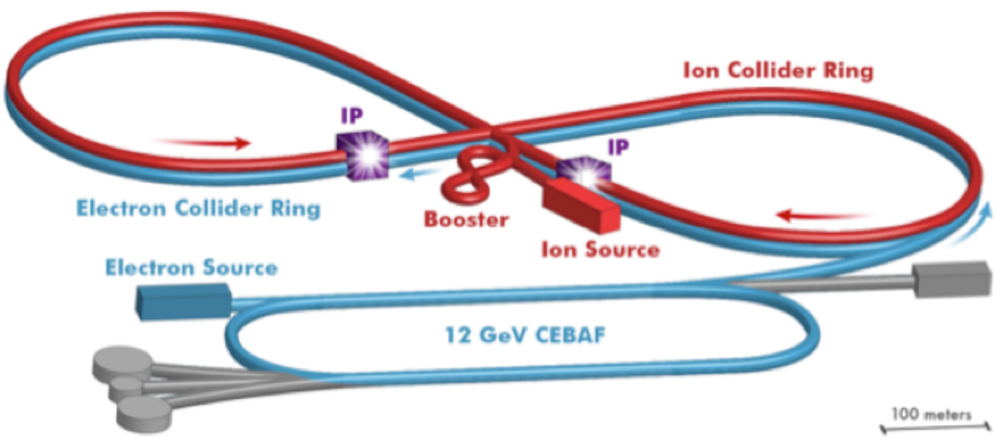
08:00		
	Overview of physics possibilities at future DIS facilities *Cavallerizza Reale - Aula Magna*	*Anna Stasto* 08:30 - 08:55
09:00	**Status and Perspectives of a US-based Electron-Ion Collider (EIC)** *Cavallerizza Reale - Aula Magna*	*Prof. Bernd Surrow* 08:55 - 09:20
	The Large Hadron-electron Collider: status and plans *Cavallerizza Reale - Aula Magna*	*Max Klein* 09:20 - 09:45
10:00	**An EIC proposed in China (EicC)** *Cavallerizza Reale - Aula Magna*	*Dr Yuxiang Zhao* 09:45 - 10:10

Facilities

The EIC

B. Surrow





Study structure and dynamics of matter at high luminosity, high energy with polarised beams and wide range of nuclei

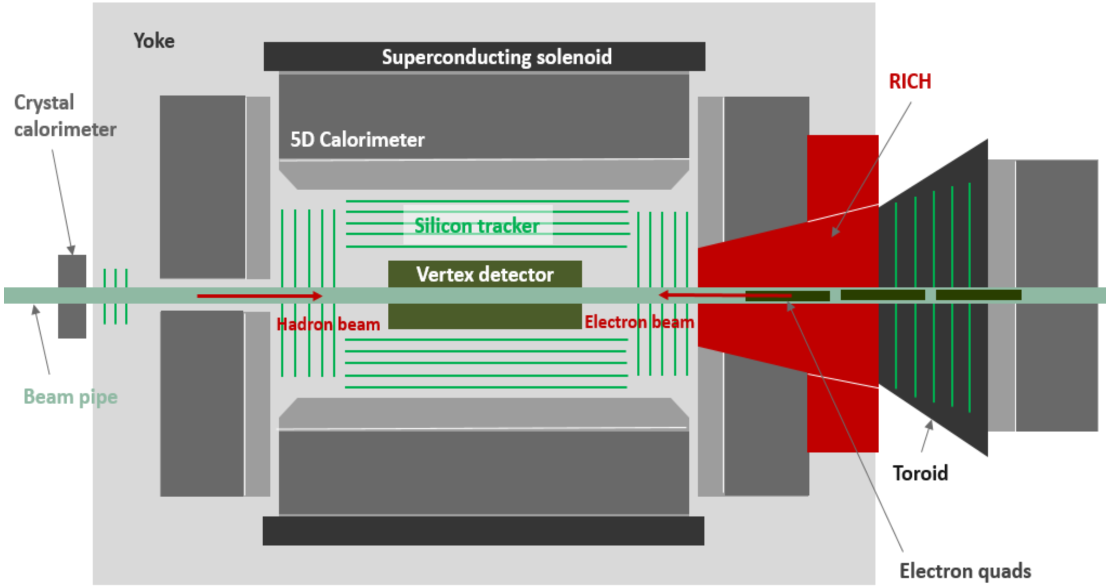
- Parton distributions in nuclei
- QCD at extreme densities - saturation
- Spin and flavour structure of the nucleon and nuclei
- Tomography

Possible CD0 mission statement FY19.

Possible construction start once FRIB constructions ramps down in 2022/23.

Detectors for EIC – TOPSIDE

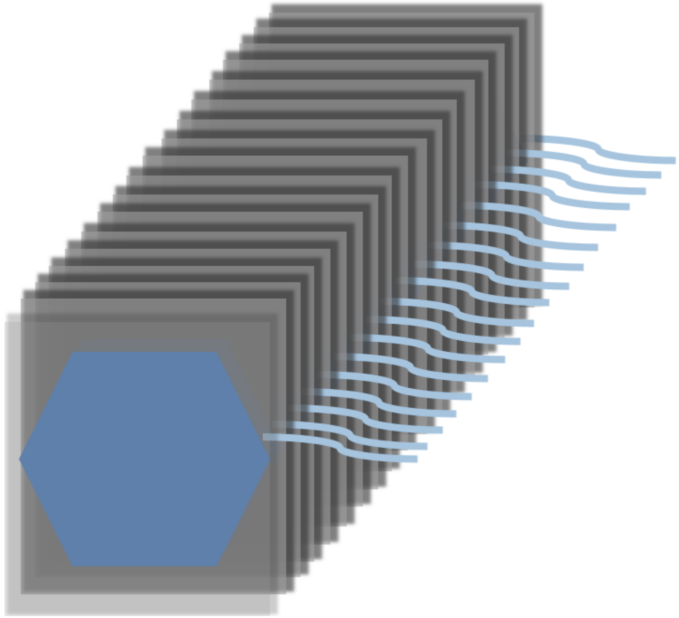
J. Repond



- Three similar concepts, BEAST, JLEIC and ePhenix and one different, TOPSiDE.
- Imaging detector.
- Identify particles.
- Novel, cost could be an issue.

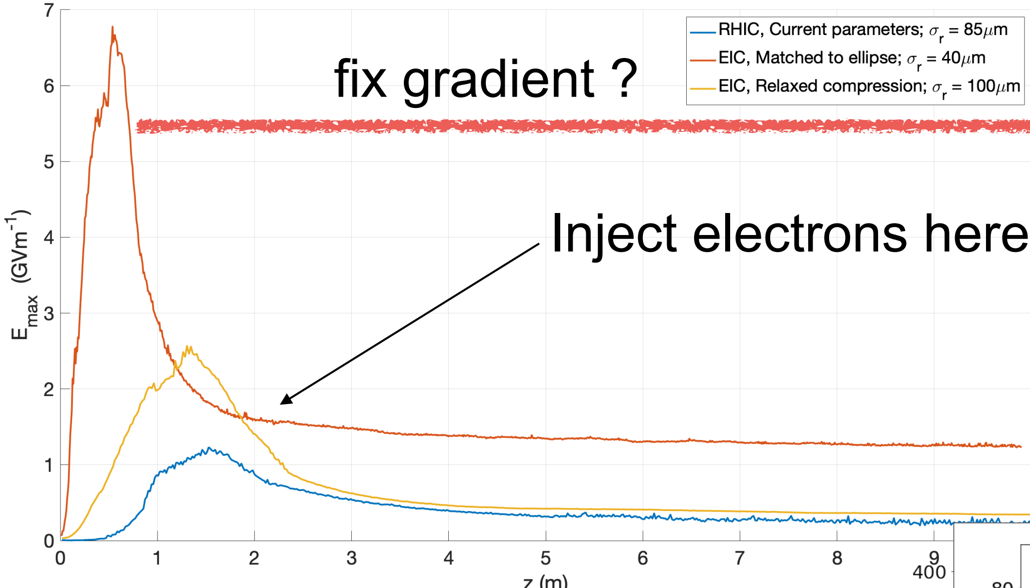
PENTACAL

- Prototype 5D electromagnetic calorimeter
- SiW with 1 × 1 mm^2 pixels
- Interest from EIC, AMBER, JLab …



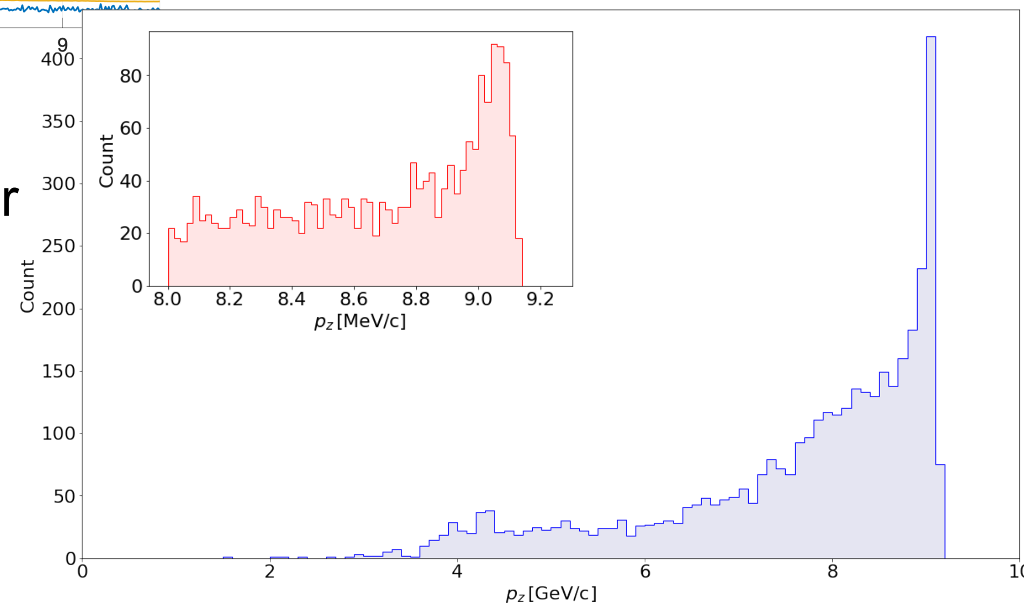
A compact electron injector for the EIC using plasma wakefield acceleration

J. Chappell



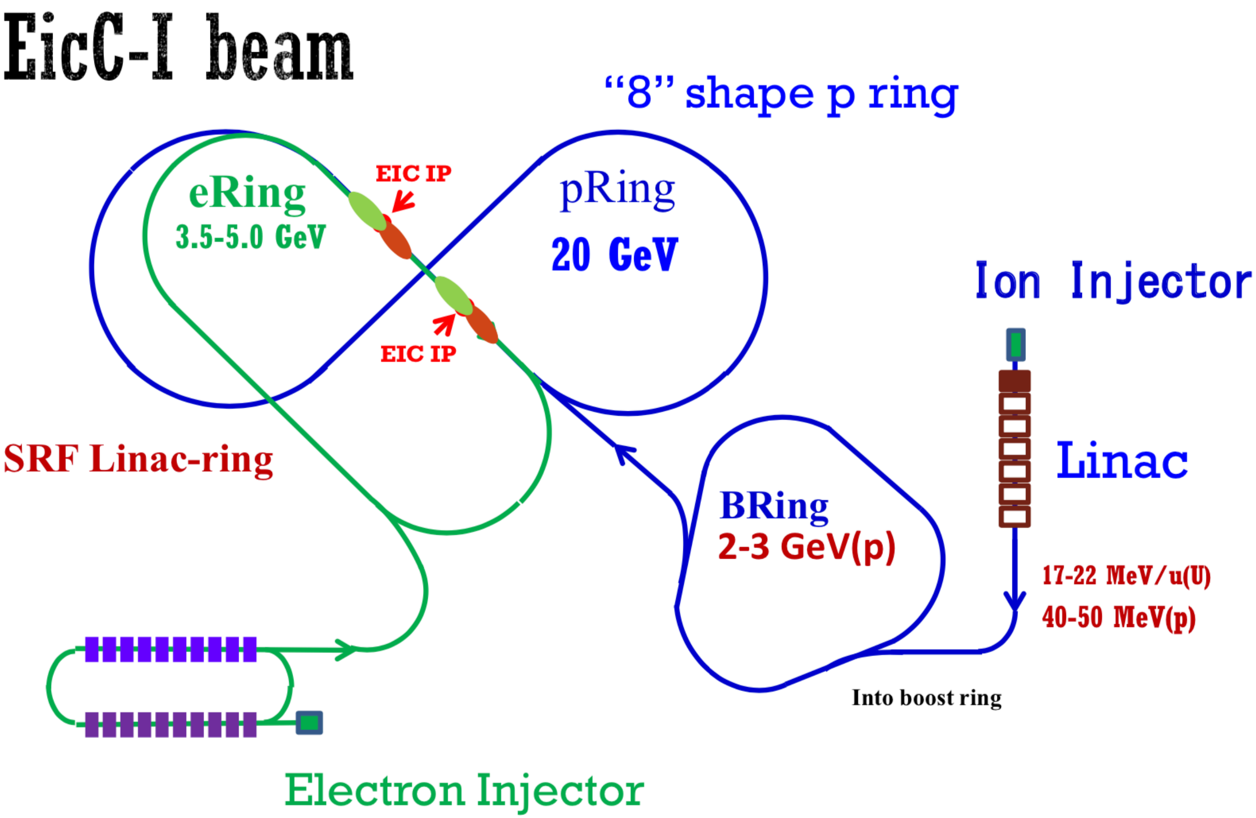
- To investigate fixing gradient at this level.
- Using stable gradients >*1 GV/m*, inject electrons.
- Note that current RHIC proton bunches already effective drivers.

- Achieved E_e ~ *9 GeV* over *8 m*
- To extend simulations over a longer distance to EIC-required energies
- Work on capture efficiency, i.e. N_e
- Storage ring needed only to maintain energy
- **Cost-effective electron injector**



EIC in China (EicC)

Y. Zhao



EicC-II:

- E_e = 10 GeV,
  E_p = 60−200 GeV
- P_e = 80%, P_p = 70%
- $L \sim 5 \times 10^{34}\ cm^{-2}\ s^{-1}$

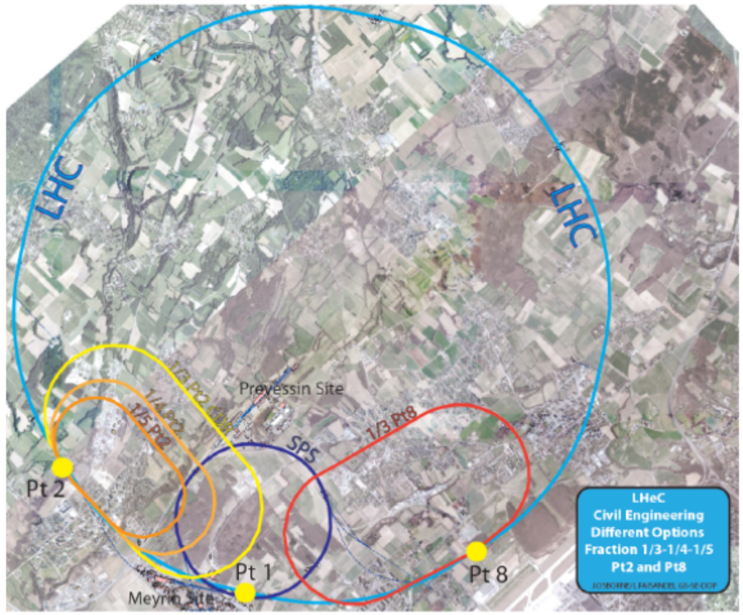
- Strong support from local government.
- EicC white paper to be submitted by end of 2019 to get in the next 5-year plan (starting in 2021).
- Aim for construction start 2026 and data-taking in 2032.

The LHeC / FCC-eh

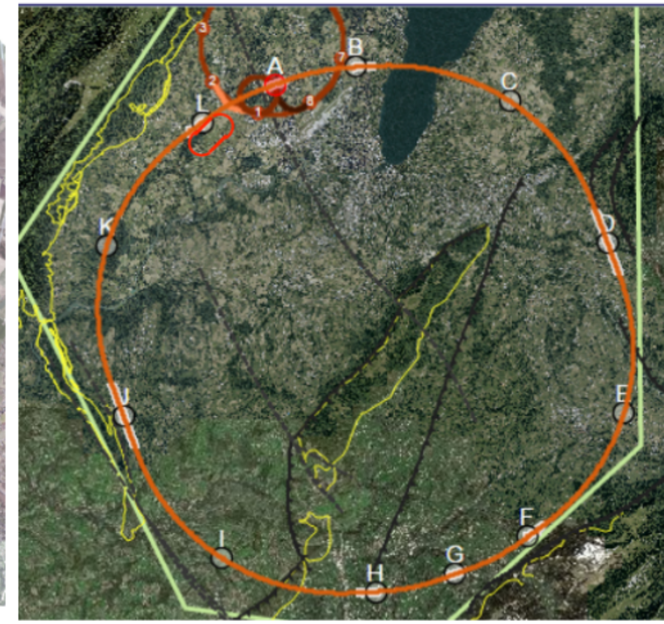
M. Klein

- E_p = 7 TeV,
  E_e = 50/60 GeV,
  $\sqrt{s}$ = 1.2/1.3 TeV
- Also *eA*
- For installation during LS4 (2030+)
- Run until 2040+
- O(ab^{-1})

LHC



FCC



- LHeC CDR to be update: “The Large Hadron Electron Collider at high luminosity”.
- Workshop 24−25/Oct/2019 (tbc) near CERN.

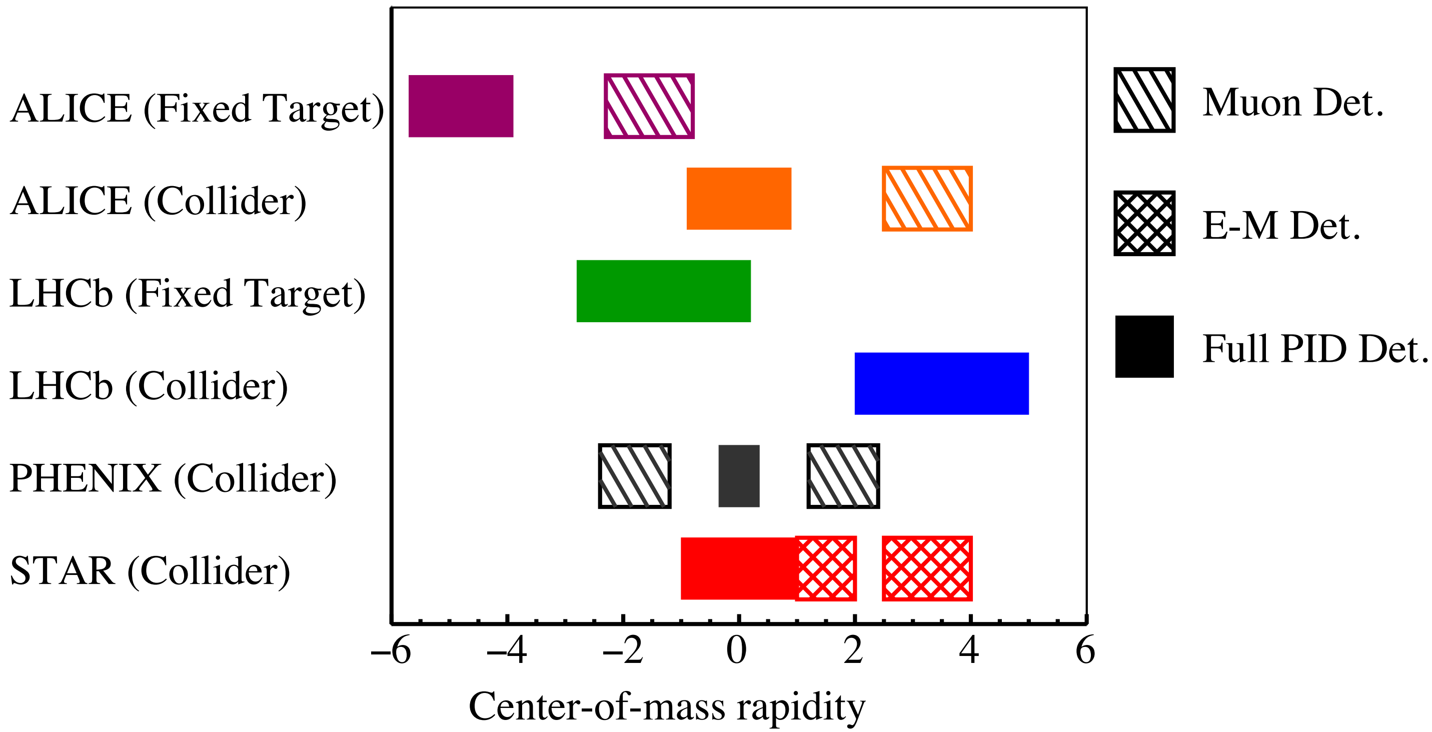
Other experiments / initiatives

- Fixed-target experiments using LHC protons.
- A new QCD facility at CERN's M2 beam line, COMPASS/AMBER.
- Use of LBNF neutrino beam with a near detector for νN scattering.
- SHiP experiment at CERN, search for long-lived particles, ν_τ physics, etc.
- NICA at JINR, Dubna
- Parton distributions determined using lattice QCD.
- Develops in theory and phenomenology, including Monte Carlos.
- …

LHC fixed-target and spin programme

A. Kusina
J. Lansberg
L. Pappalardo

- Studying high-x and constraining the PDFs
- Unravelling the nucleon 3D/spin structure
- Heavy ion collisions at large rapidities

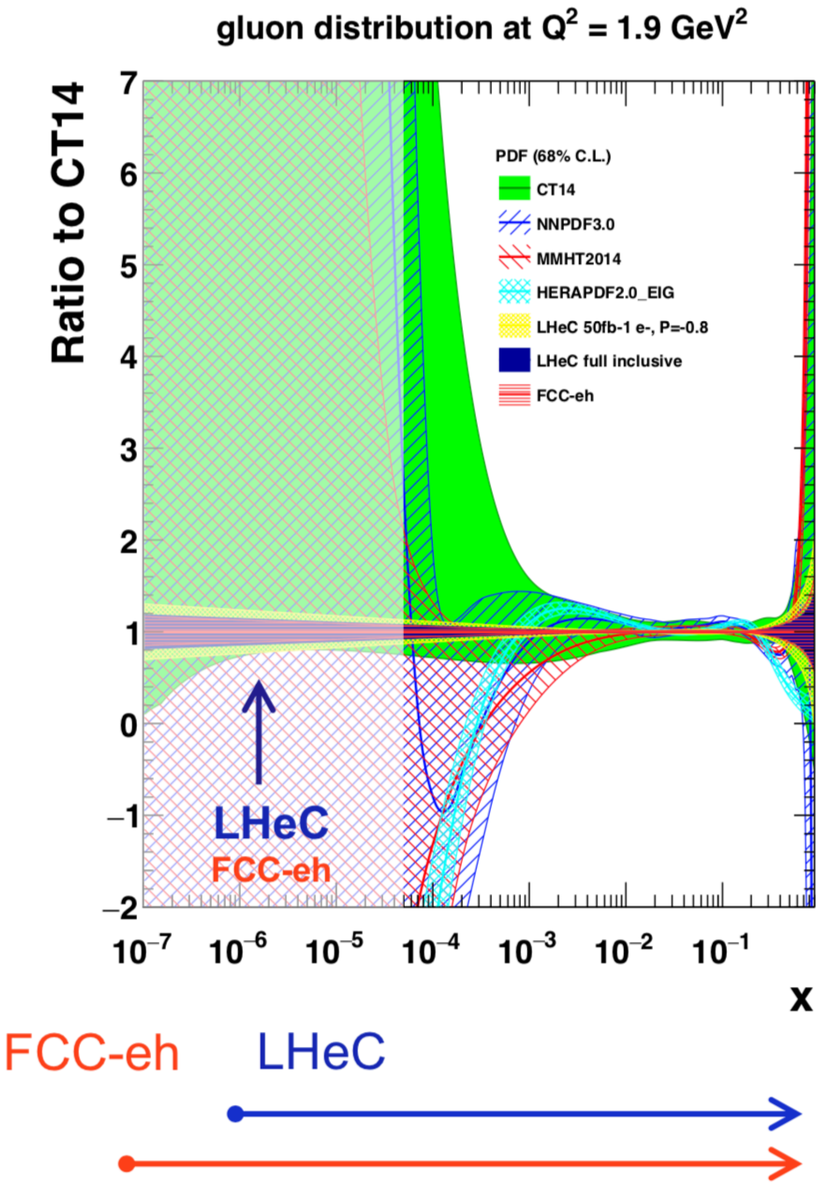


Centre-of-mass energy = 115 GeV for a proton beam

Proton PDFs at low and high *x*

Understanding low *x* gluons

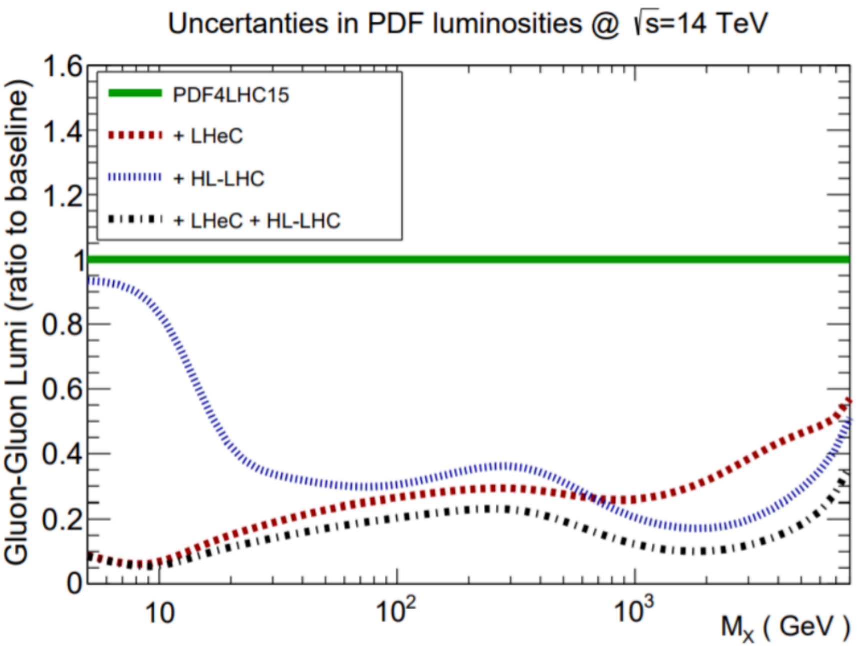
C. Gwenlan

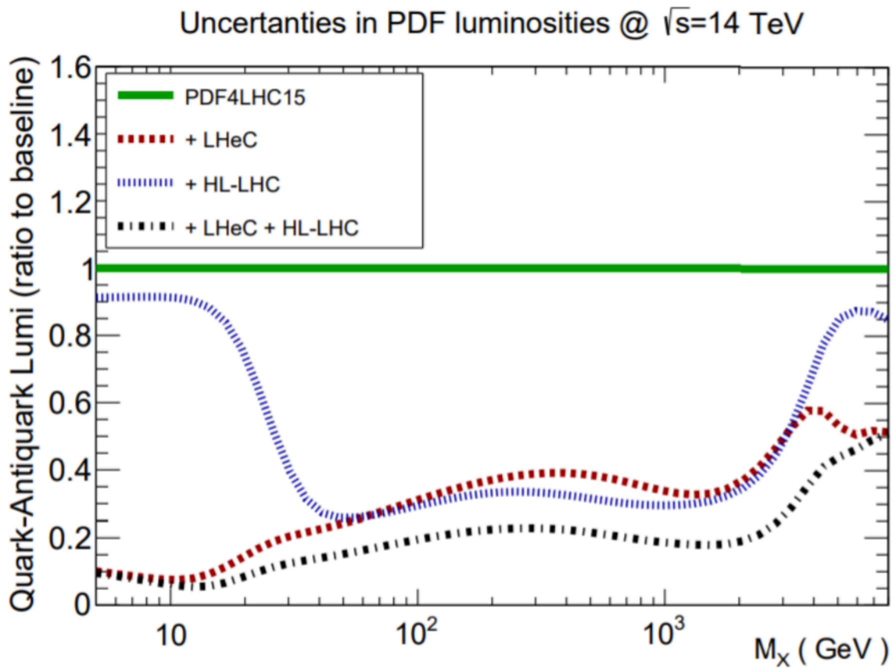


- Effect on *ggH* cross section.
- Measurement of F_L is important.
- Measurement of heavy quarks will add extra information.
- BFKL, saturation, etc.

Low-*x* PDFs from the LHC too

S. Bailey



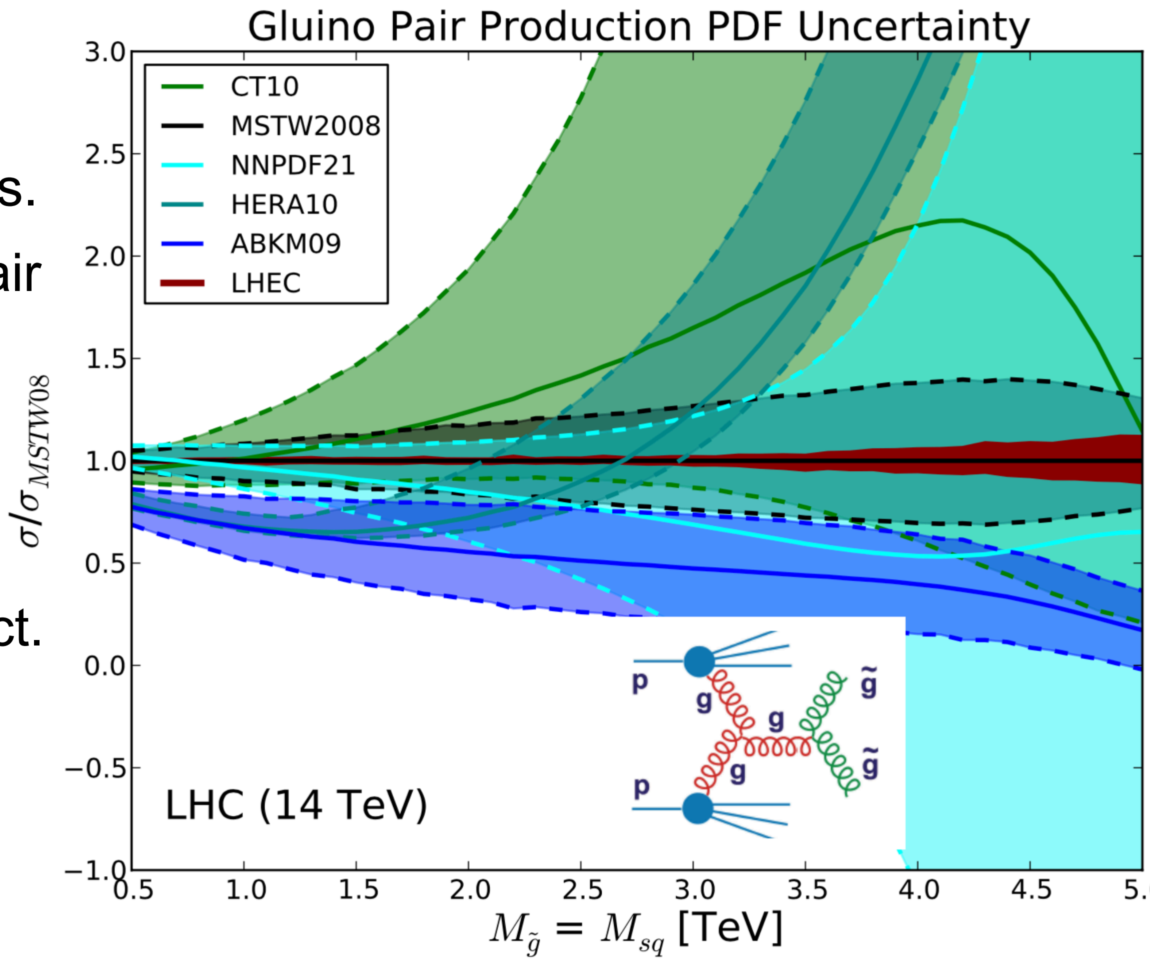


- Complementary constraints from HL-LHC potential.
- Further processes to be considered.
- Note that tolerance in χ^2 is $T = 3$; should be lower ($T = 1$) for LHeC.

High-*x* PDFs at LHeC

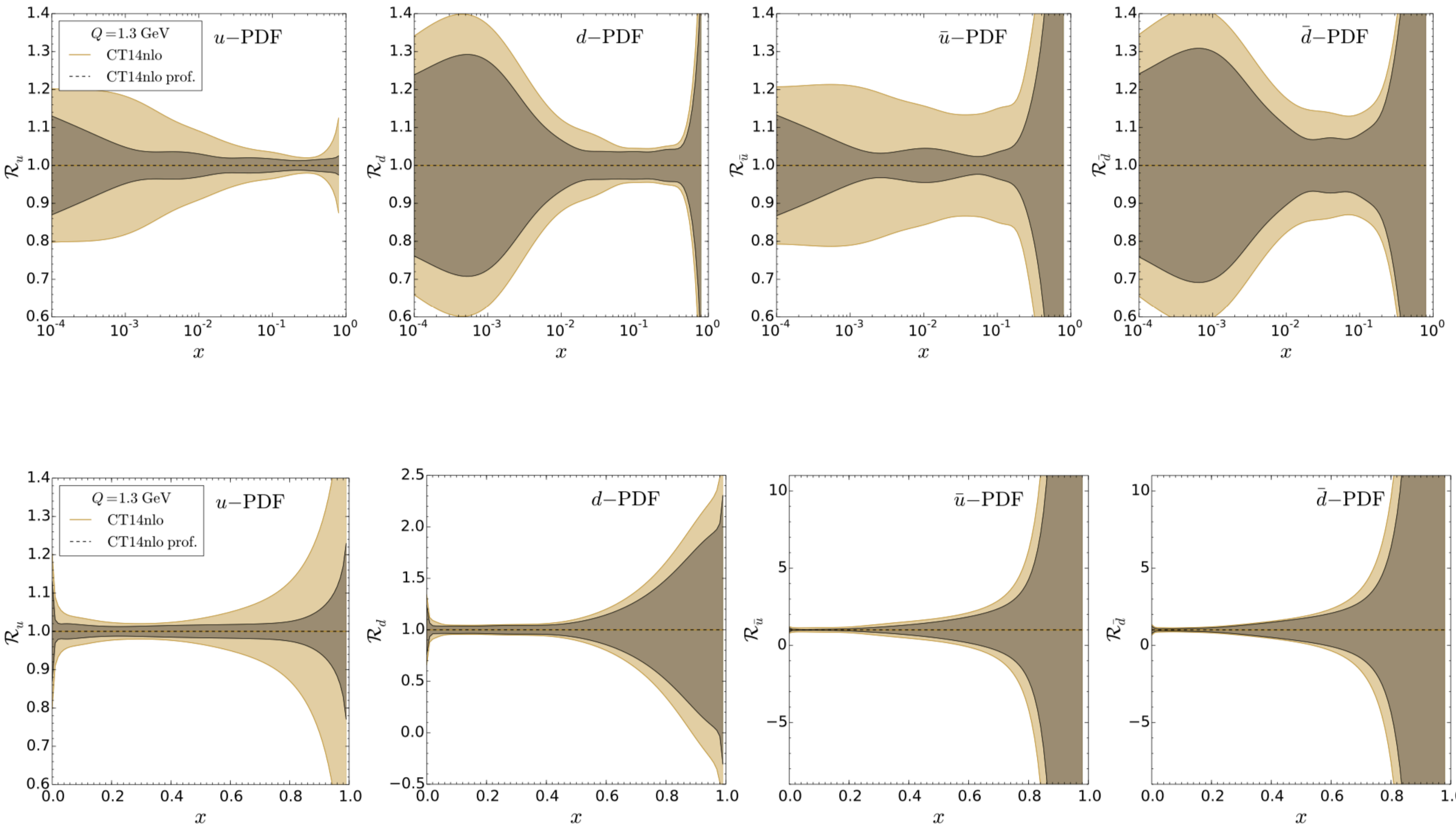
C. Gwenlan

- Empowering LHC discoveries.
- PDF uncertainty on gluino pair production versus gluino mass.
- Important to have PDFs determined independently.
- LHeC will have a huge impact.



High *x* at AFTER@LHC

A. Kusina



νN facility

R. Petti

- Turn the LBNF ND site into a general purpose ν physics facility with broad program complementary to ongoing fixed-target, collider and nuclear physics efforts:
  - Measurement of $sin^2\theta_W$ and electroweak physics;
  - Precision tests of isospin physics & sum rules (Adler, GLS);
  - Measurements of strangeness content of the nucleon ($s(x)$, Δs, etc.);
  - Studies of QCD and structure of nucleons and nuclei;
  - Precision tests of the structure of the weak current: PCAC, CVC;
  - Measurement of nuclear physics and (anti)-neutrino-nucleus interactions;
  - Precision measurements of cross-sections and particle production; etc. .....
  - Searches for New Physics (BSM) .....

- E.g. direct measurement of $F_2^{\nu n}/F_2^{\nu p}$ free from nuclear uncertainties and comparison with e/μ DIS
  - d/u at large x and verify limit for $x \rightarrow 1$.

PDFs on the lattice

S. Zafeiropoulos
K. Cichy

PDFs defined in factorisation theorems = matrix elements of operators containing quark fields separated by a light-cone distance

Light cone PDF

$$q(x) = \frac{1}{4\pi} \int_{-\infty}^{\infty} d\omega^- e^{-ixP^+\omega^-} \langle P|\bar{\psi}(\omega^-)W(\omega^-,0)\gamma^+\psi(0)|P\rangle$$

light-cone separation

They cannot be simulated on the lattice.

Novel alternative approach:

- Compute a **quasi distribution** $\tilde{q}$, which is purely spatial and uses nucleons with finite momentum:

$$\tilde{q}(x,\mu^2,P_3) = \int \frac{dz}{4\pi} e^{ixP_3z} \langle N|\overline{\psi}(z)\Gamma\mathcal{A}(z,0)\psi(0)|N\rangle.$$

spacelike separation

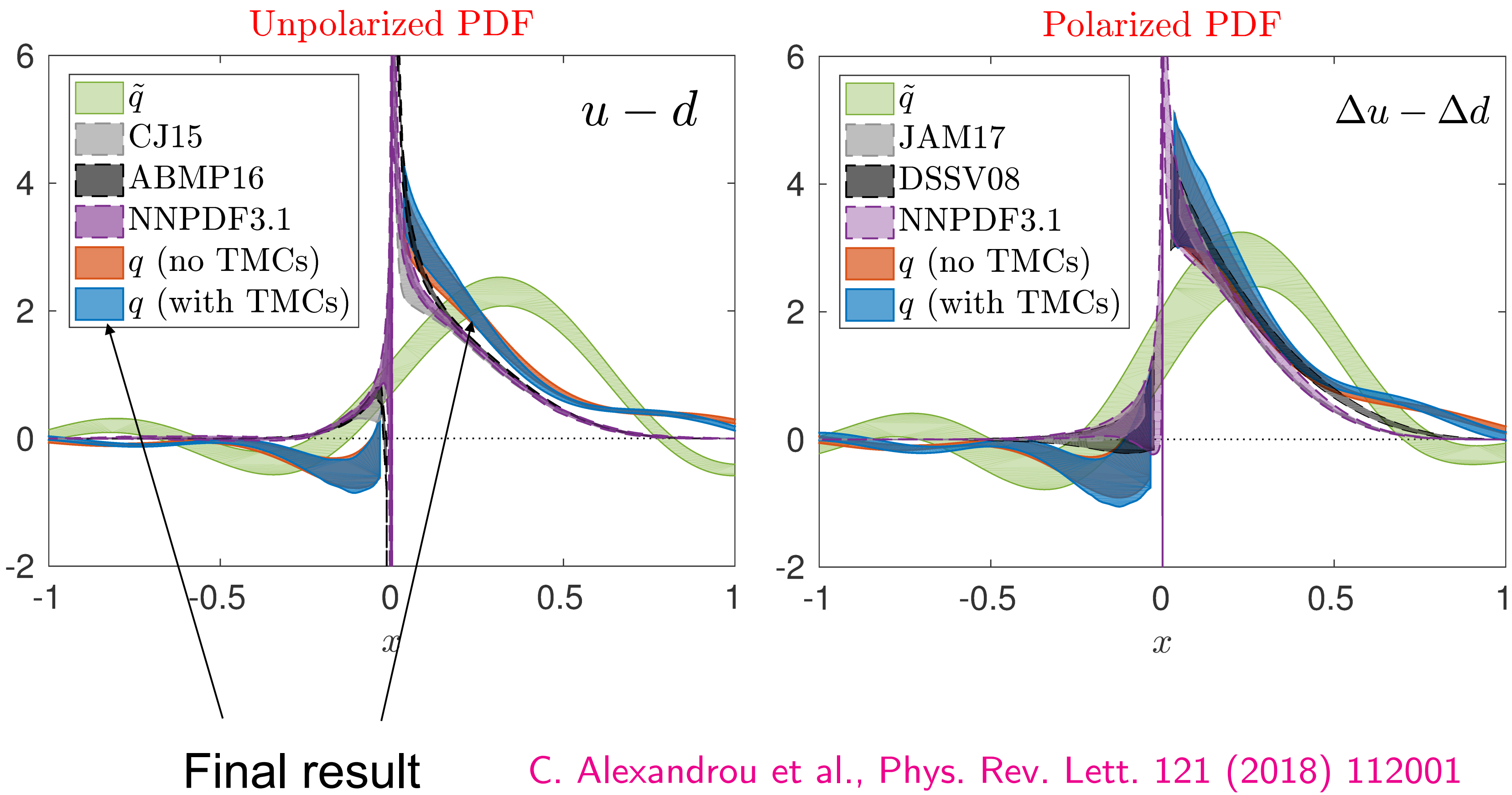
If P_3 is large enough, the difference w.r.t. light-cone are suppressed.

Different approaches (quasi-PDFs and pseudo-PDFs) differ in the way they connect the spacelike-separated matrix elements to standard PDFs

Recent results from quasi-PDFs

K. Cichy

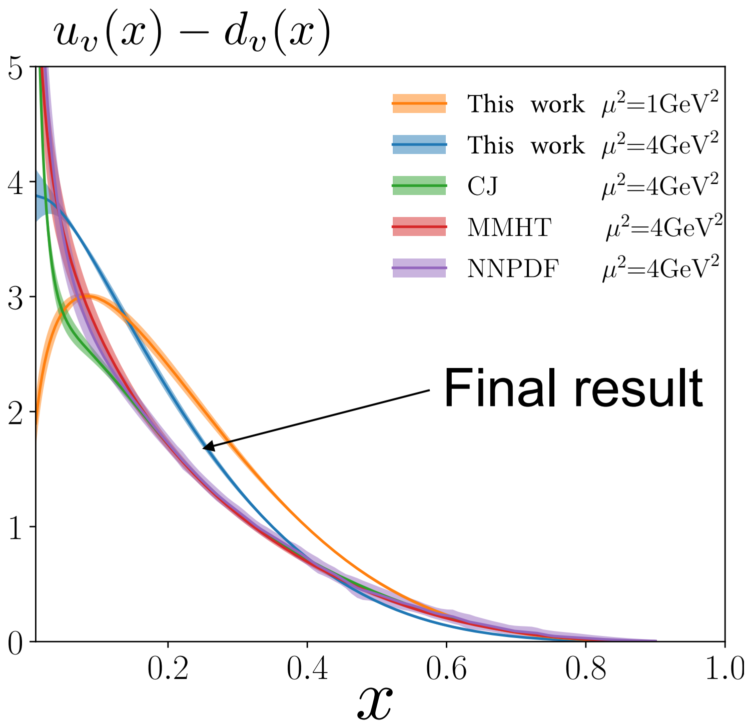
Nucleon momentum $\frac{10\pi}{48}$, $Q^2 = 4$ GeV^2



C. Alexandrou et al., Phys. Rev. Lett. 121 (2018) 112001

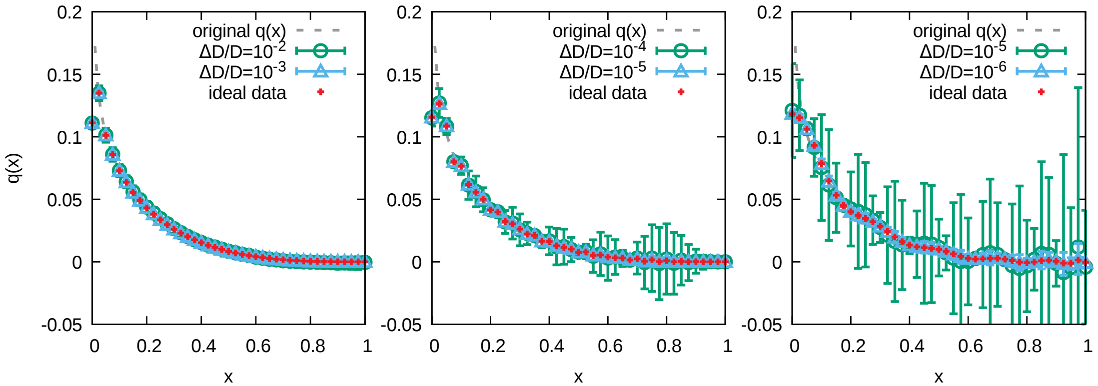
Recent results from pseudo-PDFs

S. Zafeiropoulos



- The task at hand is then to reconstruct the PDF $q_v(x, \mu^2)$ given a limited set of simulated data for $\mathfrak{M}_R(\nu, \mu^2)$.
- The extraction is highly ill-posed, so one has to resort to regularization strategies in order to find a way to reliably estimate the PDF from the data at hand

Karpie, Orginos, Rothkopf, S.Z. - arXiv:1901.05408 - Accepted by JHEP

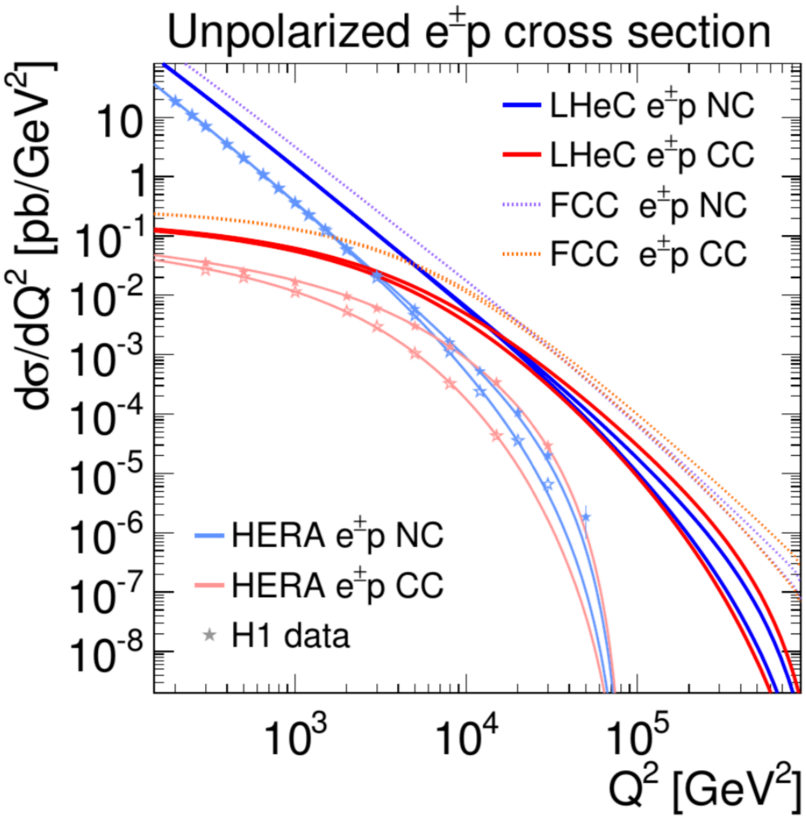


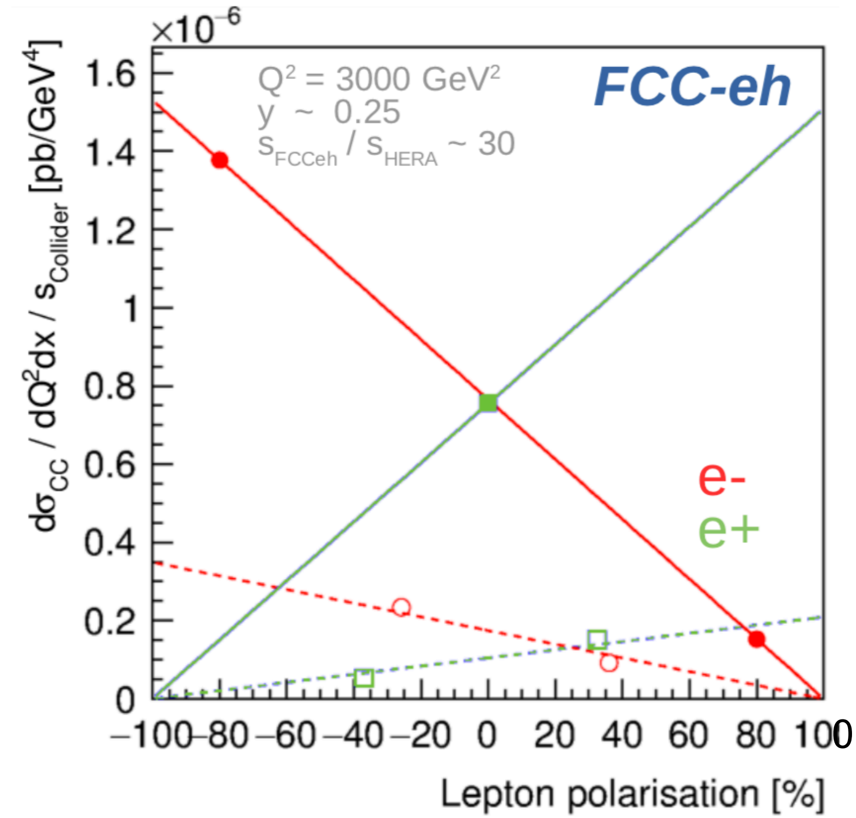
Large errors with naive methods. Need more sophisticated PDF reconstruction methods and careful assessment of systematics

Higgs and electroweak

Electroweak physics

D. Britzger

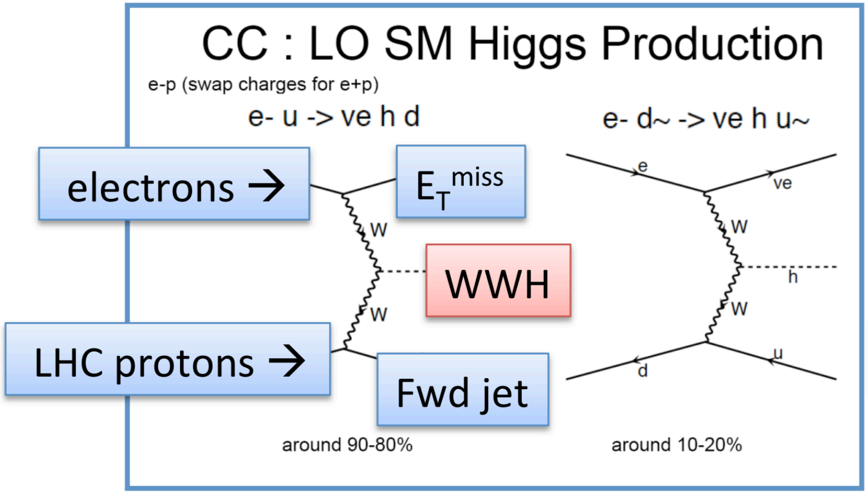


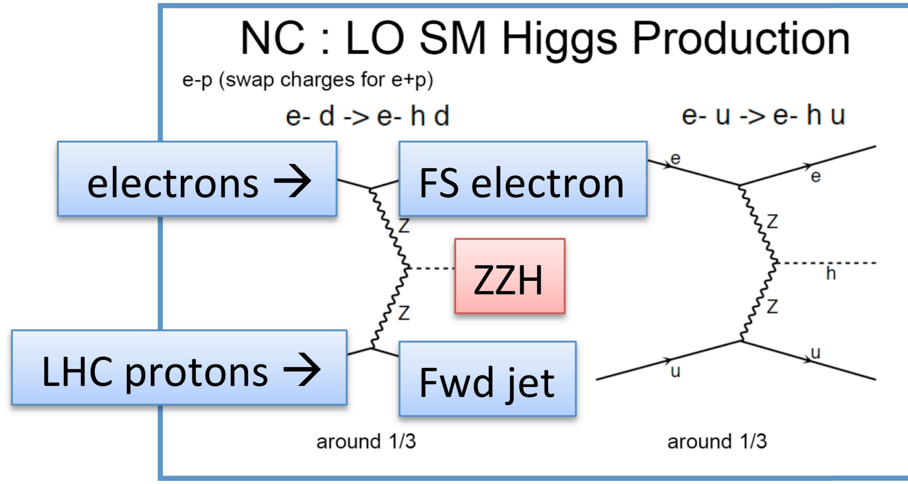


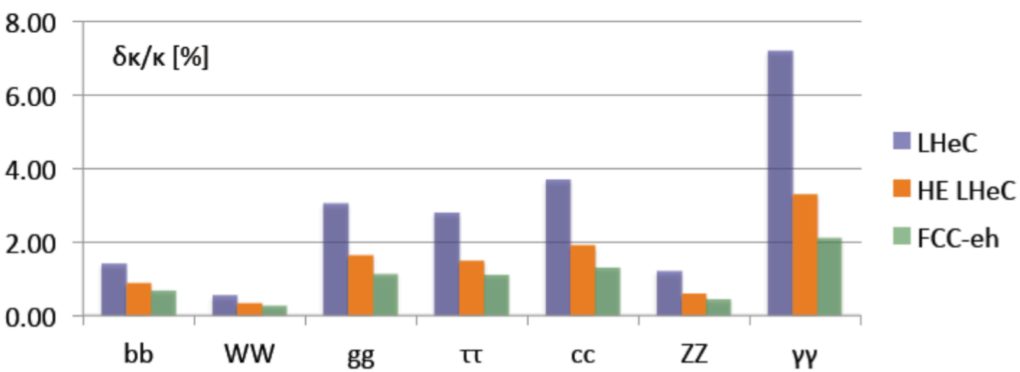
- Combination of high energy, large luminosity and polarisation.
- Also lots of top physics $|V_{tb}|$ ~ *1%*, FCNC, etc.
- Other EW parameters, e.g. $\sin^2\theta_W$, see also SoLID (**Y. Zhao**) and *vN* (**R. Petti**)

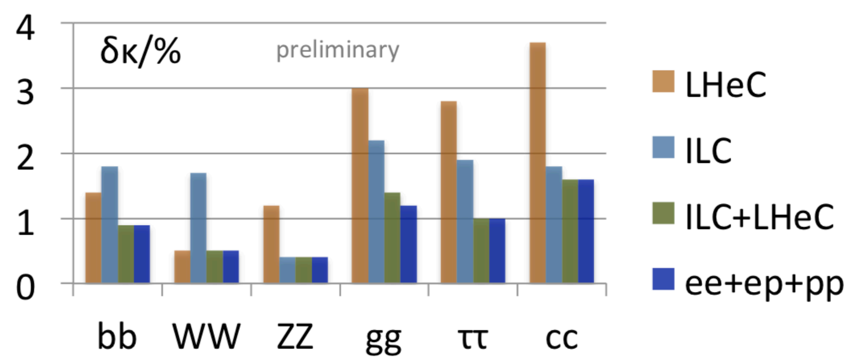
M. Klein
A. Stasto

Higgs production in *ep* colliders









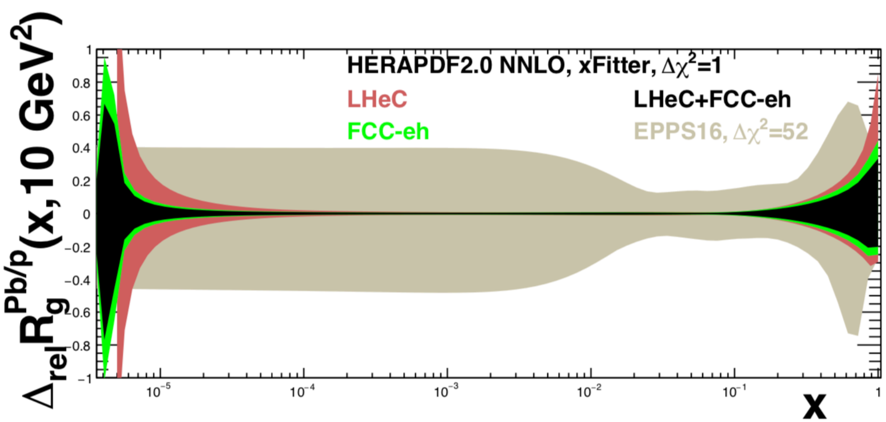
- Higgs physics requires high luminosities as expected with HL-LHC.
- Excellent interplay with *pp* and *ee* machines. Prospects for self-coupling.
- **Significant extra capability to LHeC/FCC-eh programme.**

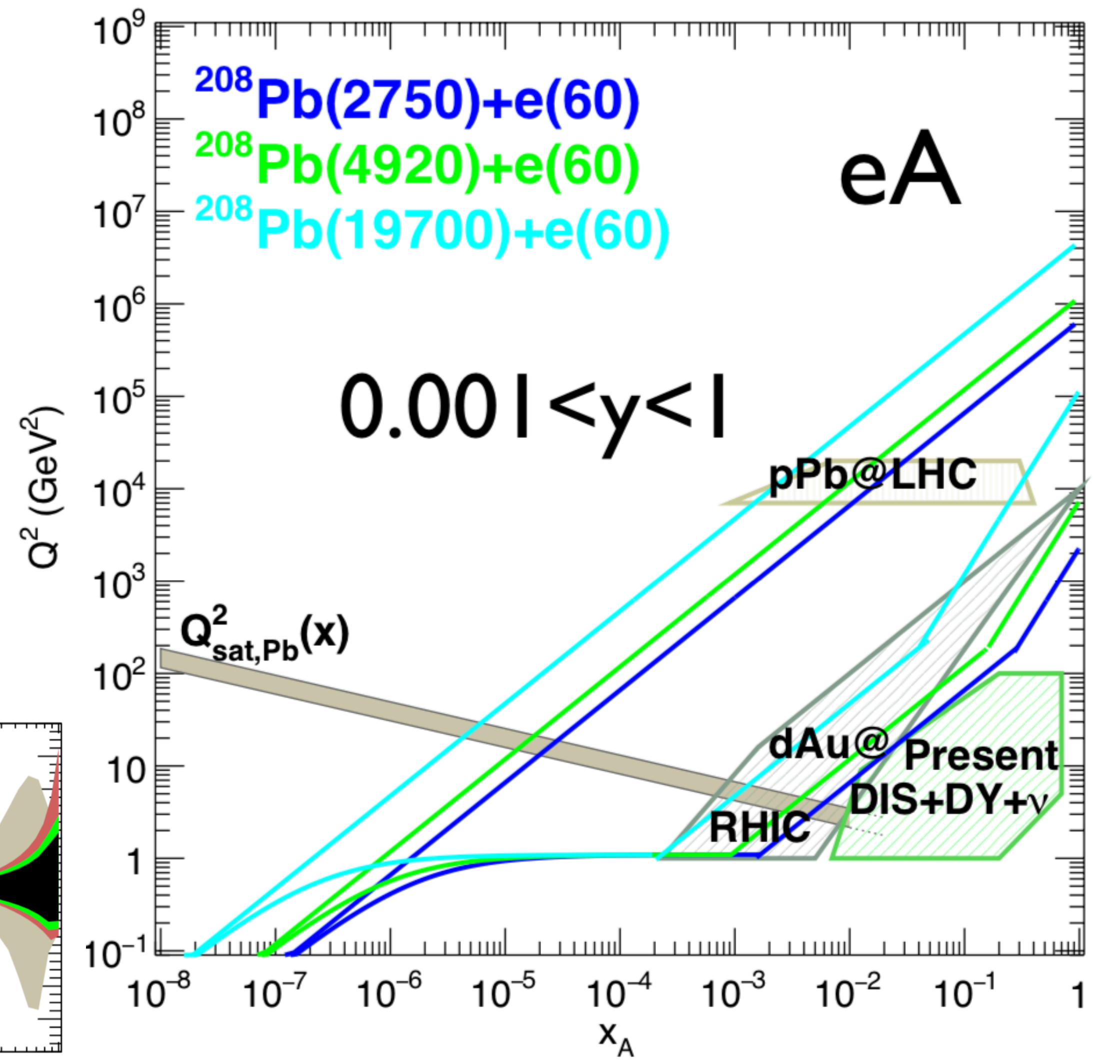
Nuclear structure

eA collisions at LHeC/FCC-eh

N. Armesto

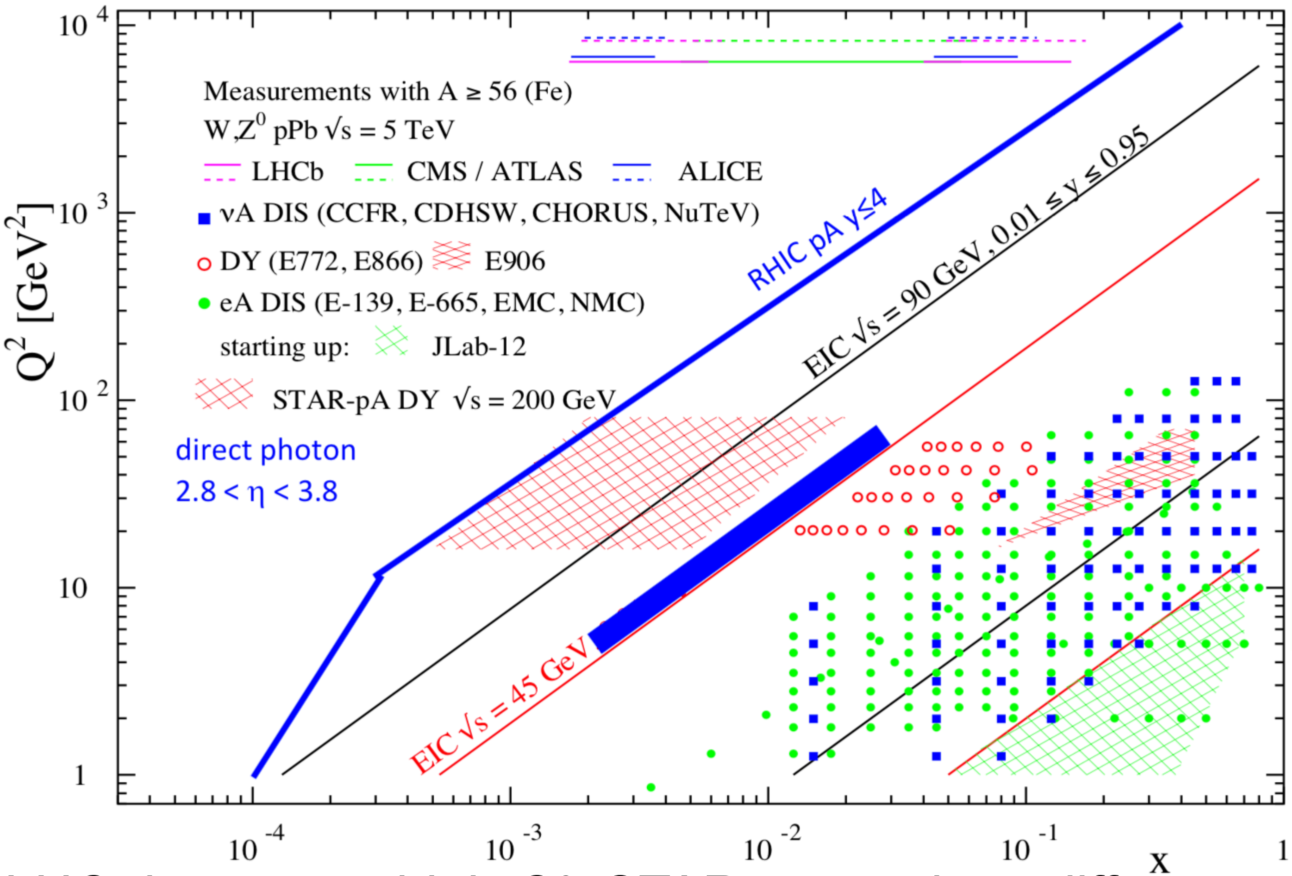
- Extension of 4–5 orders of magnitude in x and Q^2.
- Use pseudo-data to get a handle on precision.
- Large improvement in gluon PDF, but note tolerances.

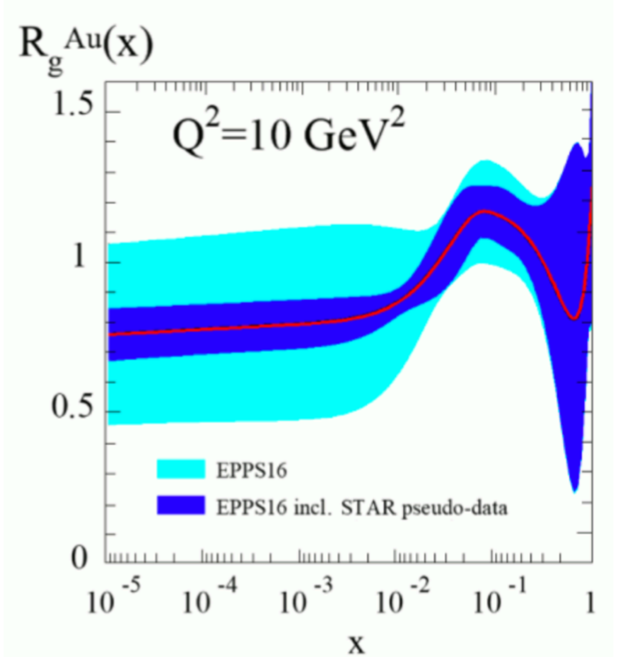




Nuclear PDFs with STAR upgrade

Z. Ye



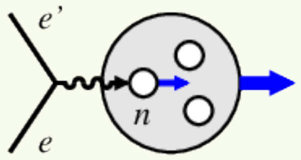


LHC data are at high Q^2; STAR can make a difference at low x with its excellent kinematic coverage in the forward region.

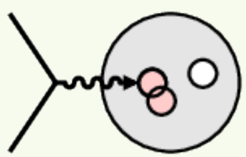
- Direct photons → gluon PDF.
- Drell–Yan production → sea quarks.
- Hope for data 2021+.

Light ions at EIC: physics

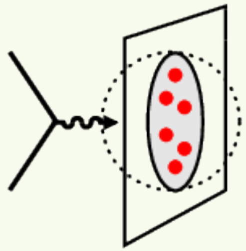
W. Cosyn



- **Neutron** structure
  - flavor decomposition of quark PDFs/GPDs/TMDs
  - flavor structure of the nucleon sea
  - singlet vs non-singlet QCD evolution, leading/higher-twist effects



- Nucleon **interactions** in QCD
  - medium modification of quark/gluon structure
  - QCD origin of short-range nuclear force
  - nuclear gluons
  - coherence and saturation



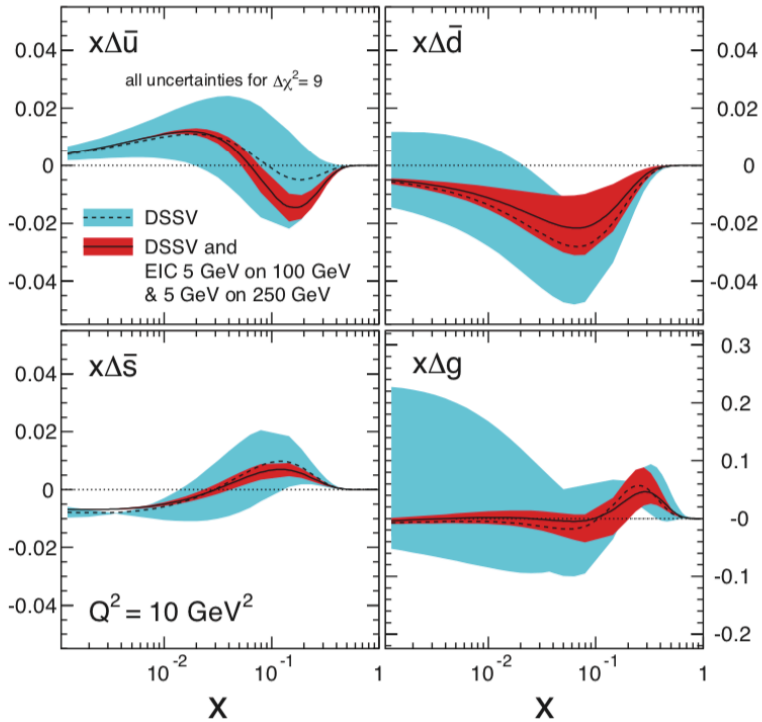
- **Imaging** nuclear bound states
  - imaging of quark-gluon degrees of freedom in nuclei through GPDs
  - clustering in nuclei

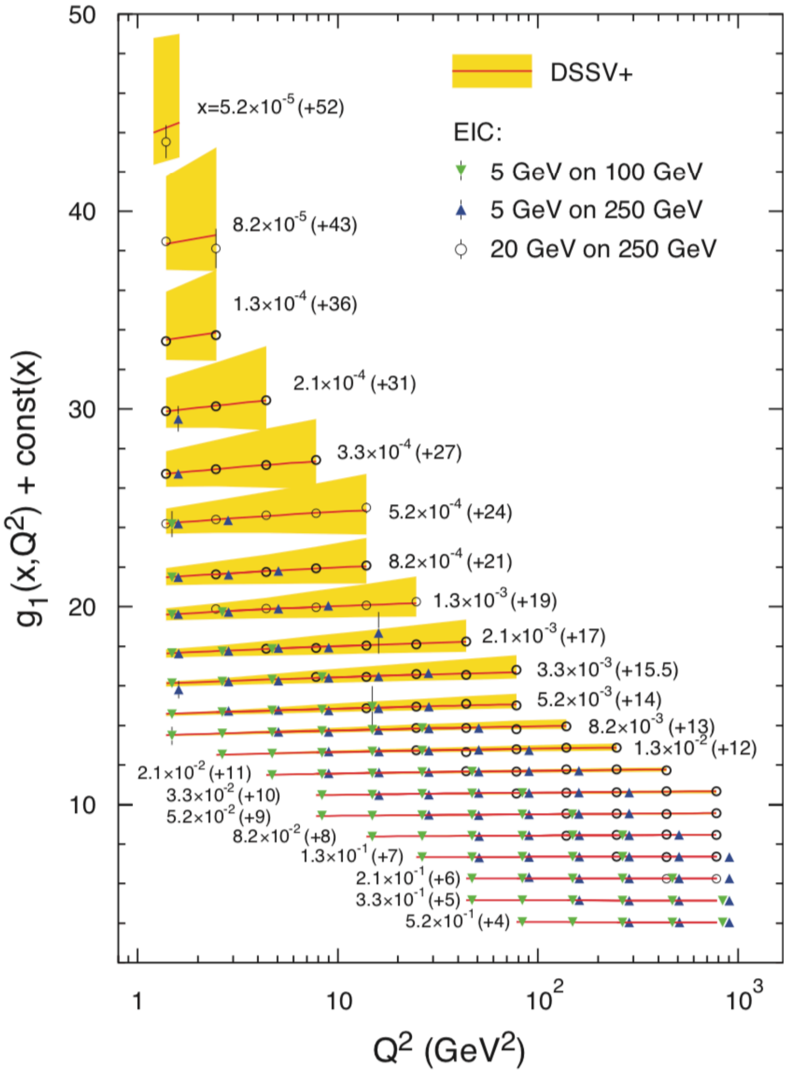
- Deuterons are particularly interesting due to their spin-1 nature. Several vector and tensor-polarised structure functions can be introduced and studied.
- Can extend to LHC fixed-target programme

Spin

Spin and flavour structure of the nucleon

A. Stasto
B. Surrow





EIC possibilities:

- g_1 projections for *10 fb^{-1}*
- Impact on quarks and gluon distributions

LHCSpin motivation

L. Pappalardo

✓ **Unique kinematic conditions**

- $E_p = 7\ \mathrm{TeV} \implies \sqrt{s} \approx 115\ \mathrm{GeV}$ (fills the gap between between SPS & RHIC)
- backward CM rapidity region ($x_F \to -1$)
- sensitive to poorly explored high x-Bjorken region

✓ **Broad variety of possible reactions**:

- polarized: $\mathrm{pp}^{\uparrow}$, $\mathrm{pd}^{\uparrow}$
- unpolarized: pA , PbA (A=H, D, He, O, Ne, Ar, Kr, Xe)

✓ **Marginal impact on LHC beam and mainstream physics at current experiments**

✓ **Polarized gas target technology well established (10 years @ HERMES)**

✓ **Very high performances ($P \sim 80\ \%$)**

✓ **Broad and ambitious physics program**

- 3D mapping of the nucleon structure (quark and gluon PDFs)
- fundamental tests of QCD (universality, factorization, etc)
- study of cold nuclear matter effects
- search for intrinsic heavy quarks
- study of QGP formation

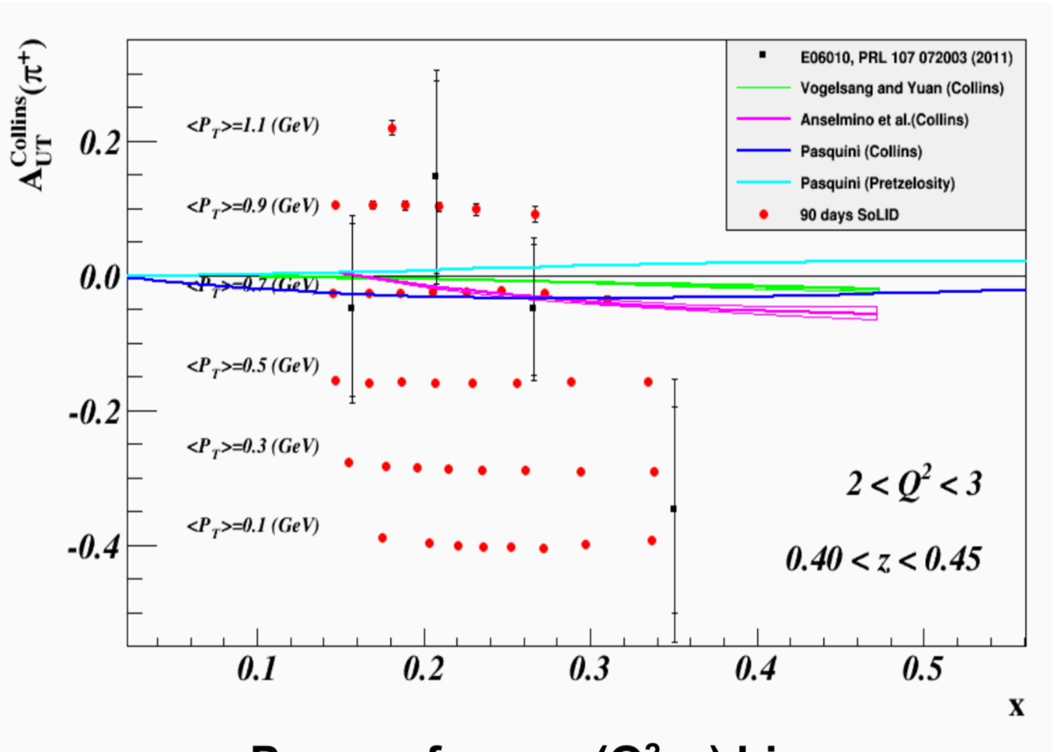
- ... and much more!

UCL

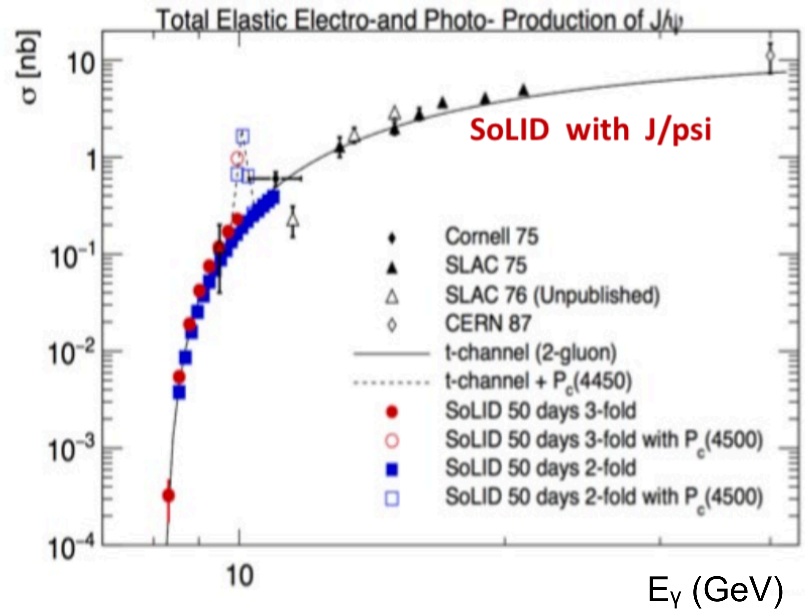
Y. Zhao

Prospects of SoLID at JLab

One example on Collins asymmetry



P_T vs. x for one (Q^2, z) bin
Total > 1400 data points



- Upsilon production can be done at EicC (**Y. Zhao**)
- Also parity-violating DIS and other topics

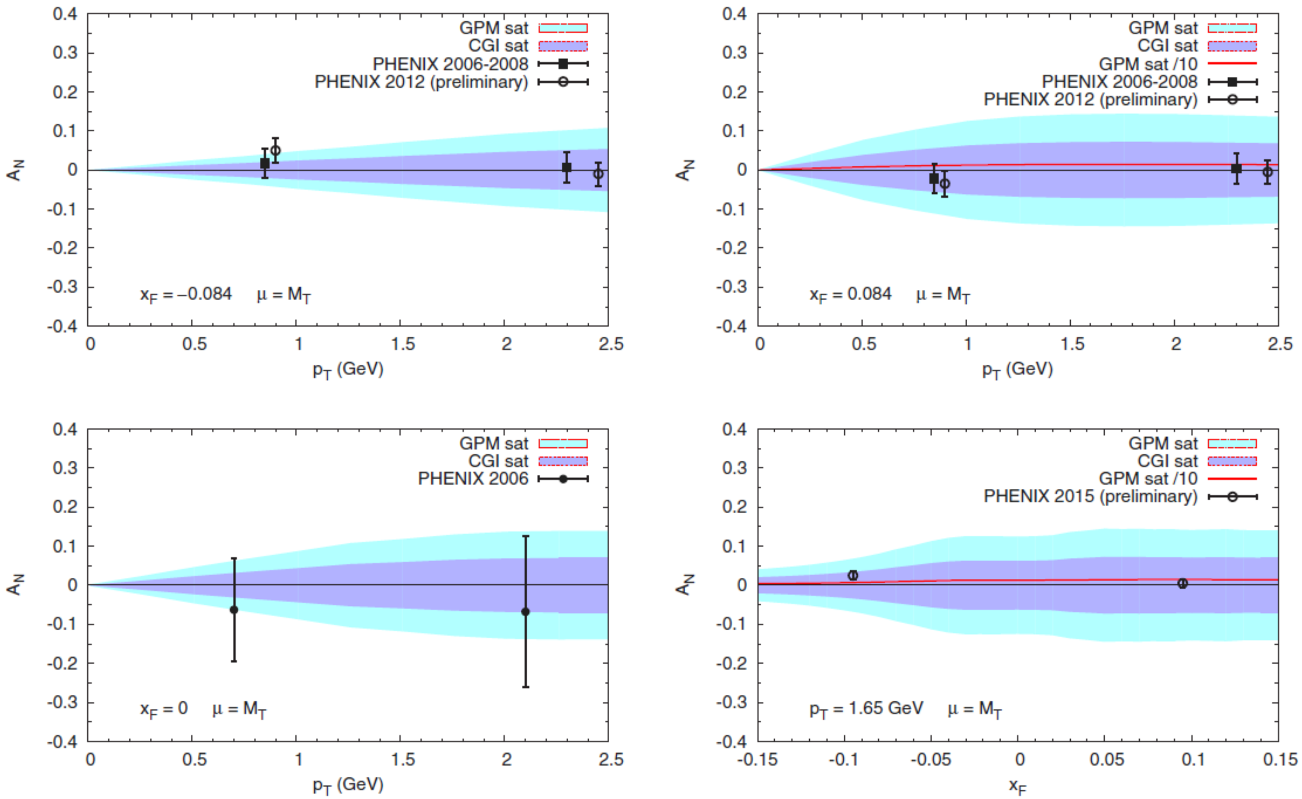
Timeline:

- The 2019 Director's review will be held soon. After that, science review will be requested.
- Hope that project will start in FY21 and will take around 5 years to have experiment running.

Gluon TMDs in *pp* collisions

F. Murgia

$pp^{(\uparrow)} \to J/\psi + X$ - Comparison with PHENIX data



U. D'Alesio, FM, C. Pisano, P. Taels, PRD 96, 036011 (2017)

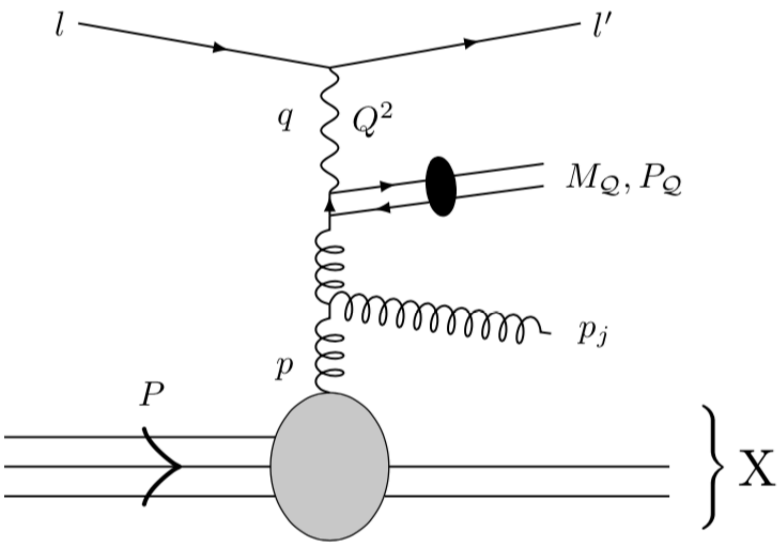
- One of the LHCSpin physics possibilities.
- PHENIX data on single-spin asymmetries can already help constraining the magnitude of gluon Sivers function.
- Also discussed in WG6

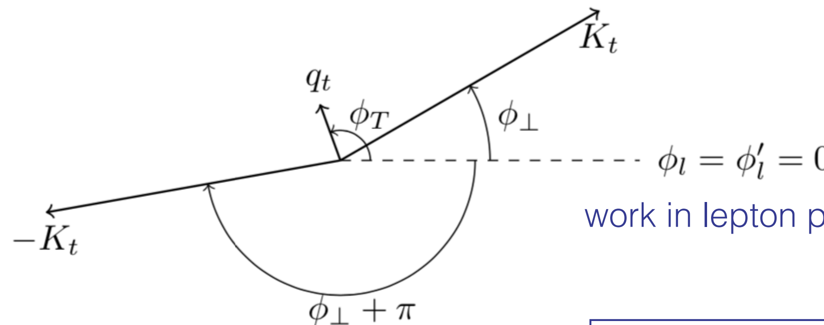
Bands obtained by maximising the Sivers effect and applying different approaches

Gluon TMDs in *ep* collisions

P. Taels

$$e + p \to e + J/\Psi + \text{jet}$$





work in lepton plane

$$|K_\perp| = \frac{P_{\mathcal{Q}\perp} - p_{j\perp}}{2}$$
$$|q_\perp| = P_{\mathcal{Q}\perp} + p_{j\perp}$$
TMD regime:
$$|q_\perp| \ll |K_\perp|$$

$$\begin{aligned} d\sigma^U = \mathcal{N}\Big[& \left(A_0^U + A_1^U \cos\phi_\perp + A_2^U \cos 2\phi_\perp\right) \times \boxed{f_1^g(x, p_T)} \\ & + \Big(B_0^U \cos 2\phi_T + B_1^U \cos(2\phi_T - \phi_\perp) + B_2^U \cos 2(\phi_T - \phi_\perp) \\ & + B_3^U \cos(2\phi_T - 3\phi_\perp) + B_4^U \cos(2\phi_T - 4\phi_\perp)\Big) \times \boxed{h_1^{\perp\, g}(x, p_T)}\Big] \end{aligned}$$

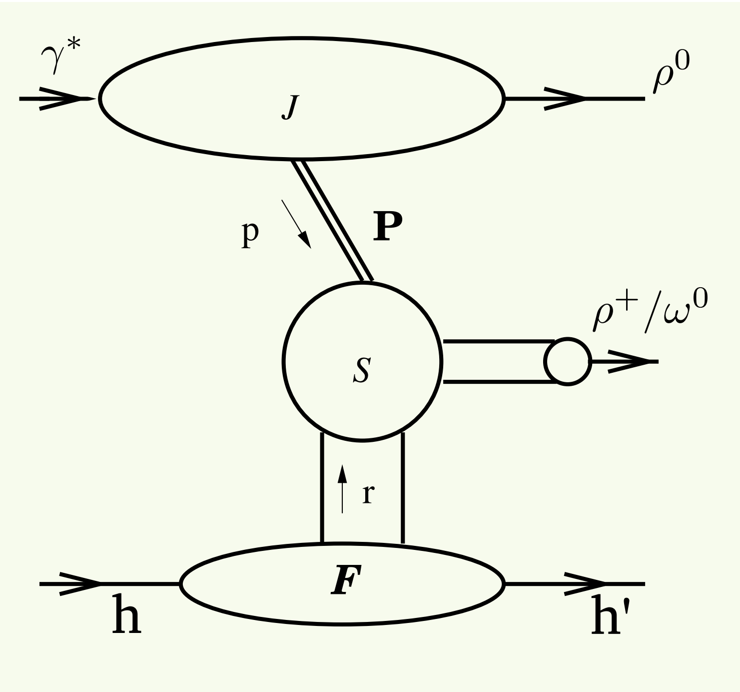
Asymmetries of >10% in observable regions

Linearly polarised gluons in unpolarised target.

Chiral-odd GPDs at EIC

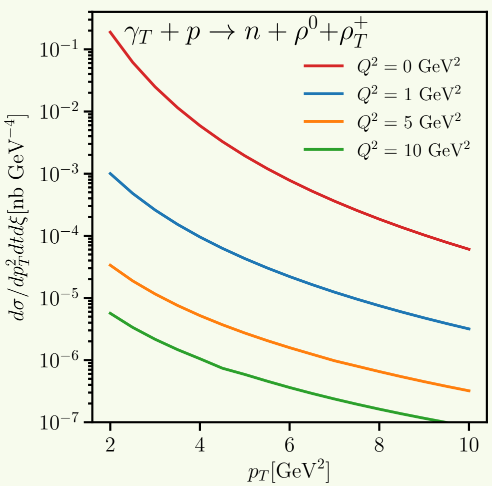
W. Cosyn

Diffractive electroproduction of two vector mesons



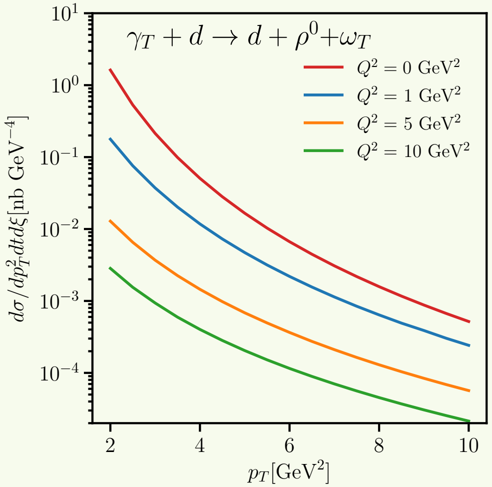
$\gamma_{L/T}\, p \to n \rho^0_L \rho^+_T$ PRELIM

- Chiral odd nucleon GPD
- Calculation at $\xi = 0.3$, $t = t_{min}$



$\gamma_{L/T}\, d \to d \rho^0_L \omega^0_T$ PRELIM

- Chiral odd deuteron GPD
- Calculation at $\xi = 0.1$, $t \approx t_{min}$

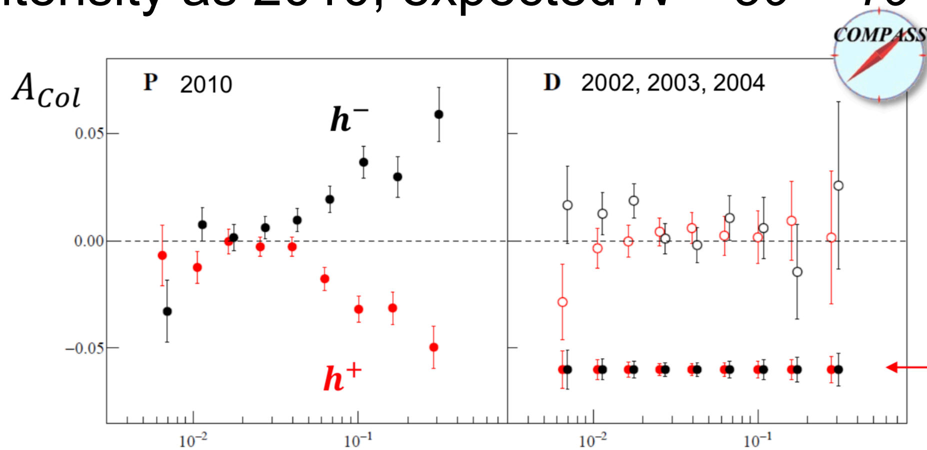


SIDIS off transversely polarised deuterons at CERN

Approved to run at SPS in 2021.

^{6}LiD target, 160 GeV muon beam with the same integrated intensity as 2010, expected $N = 80 \times 10^6$

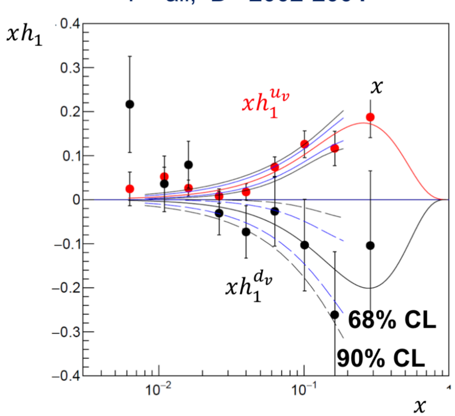
A. Martin



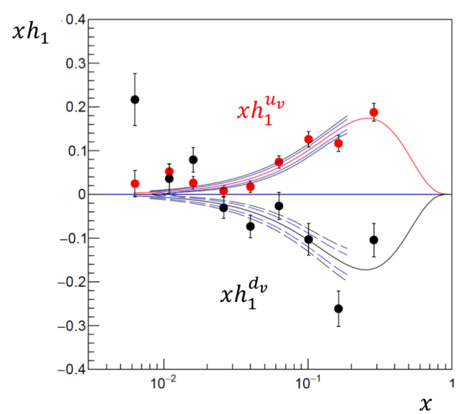
expected 2021 uncertainties

A gain of factor 2 – 5 for Collins asymmetry on deuteron

present
P all, **D 2002-2004**



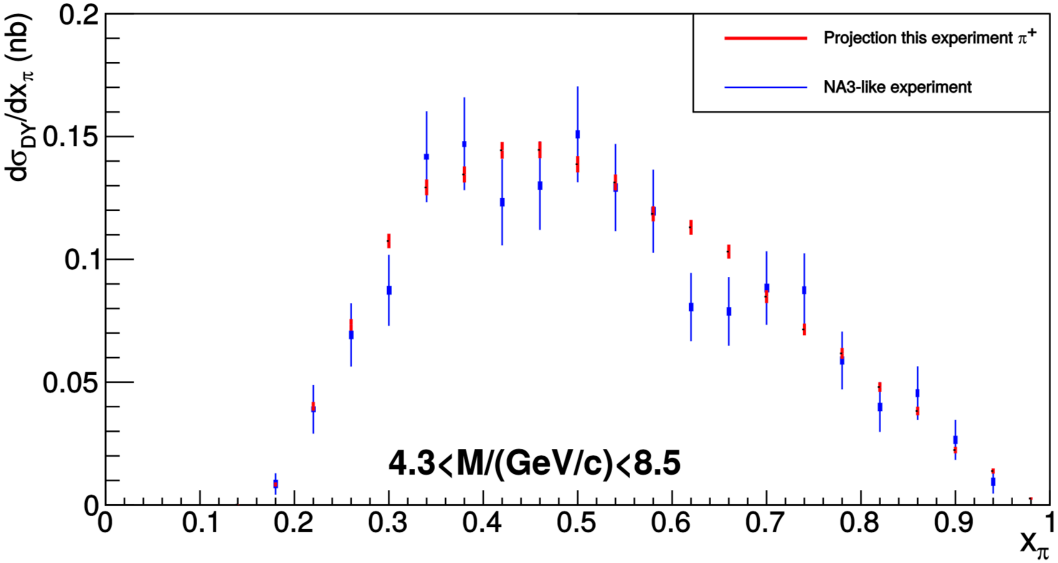
projected
P all, **D 2021 only**



A gain of factor 2 – 4 for u_v and d_v.

QCD facility at CERN, COMPASS/AMBER

V. Andrieux
B. Badelek
S. Gevorkyan



Pion structure

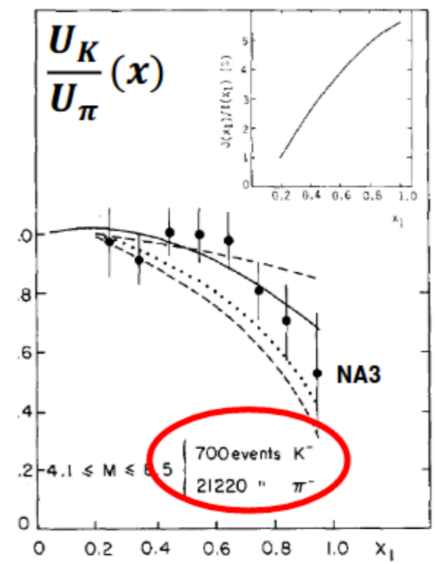
In Drell–Yan process

- A factor of 10 more statistics than currently available.
- To make first precise direct measurement of pion sea.

Kaon structure

Use prompt photon and *J/ψ* channel and K^+ and K^- beams

- About 10^6 events in each channel.
- No competition.
- Also kaon-induced spectroscopy.



J. Badier et al., Phys. Lett. B 93 (1980) 354

Proton radius at COMPASS/AMBER

C. Dreisbach
arXiv:1706.00696 & EPPSU input 143, COMPASS/AMBER

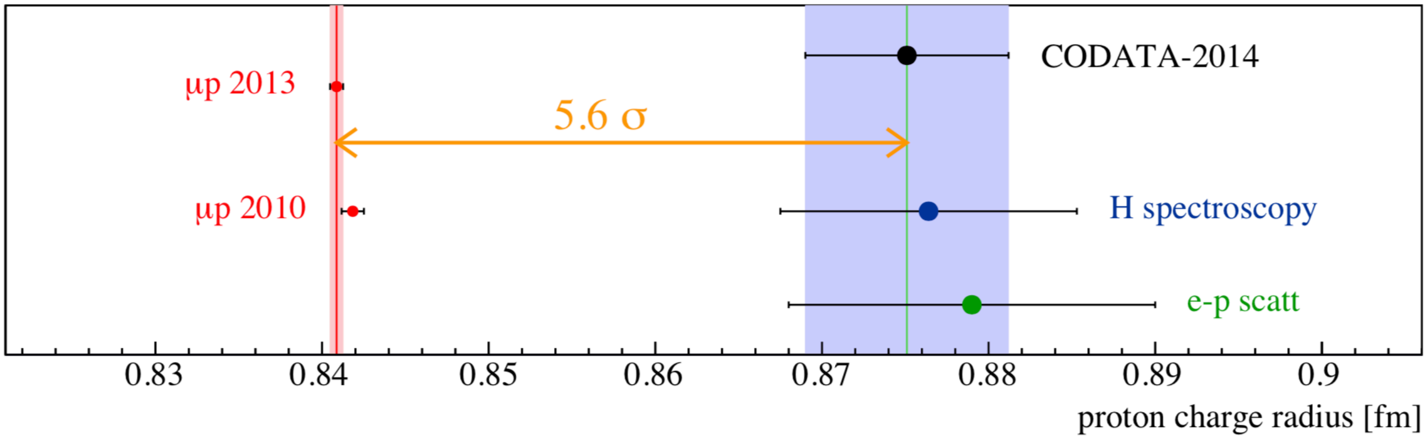
Propose to measure proton charge radius in high-energy μp scattering

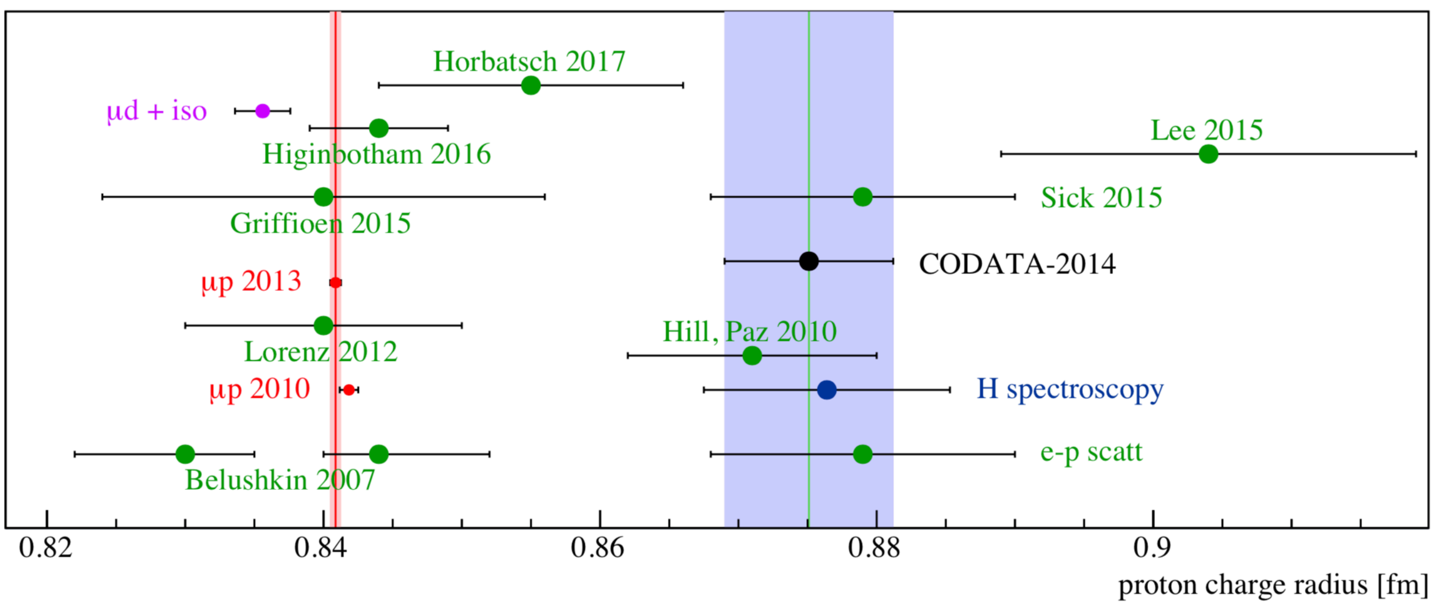
Part of COMPASS/AMBER proposed programme.

To measure “with a statistical accuracy of 0.01 and considerably smaller systematic uncertainty.”

Address issues of current values.

Very important, but challenging measurement.





Summary

- Several exciting *ep/eA* colliders in the future and we hope that > 1 will be realised.
- They will investigate a wide range of physics and we will learn a lot particularly about QCD.
- There are many possible experiments which will complement these efforts in physics and timeliness.
- Let’s hope a lot of the futures session moves to the present !
- Thanks to all the speakers and organisers.

Back-up

Shear forces and tensor polarisation

O. Teryaev

Similarly to EM form factors, also gravitational form factors can be introduced, in a decomposition of the matrix element of the energy-momentum tensor operator *T*.

Spin-1/2 hadrons:

$$\langle p'|T^{\mu\nu}_{q,g}|p\rangle = \bar{u}(p')\Big[A_{q,g}(\Delta^2)\gamma^{(\mu}p^{\nu)} + B_{q,g}(\Delta^2)P^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha/2M\Big]u(p)$$

Spin-1 hadrons

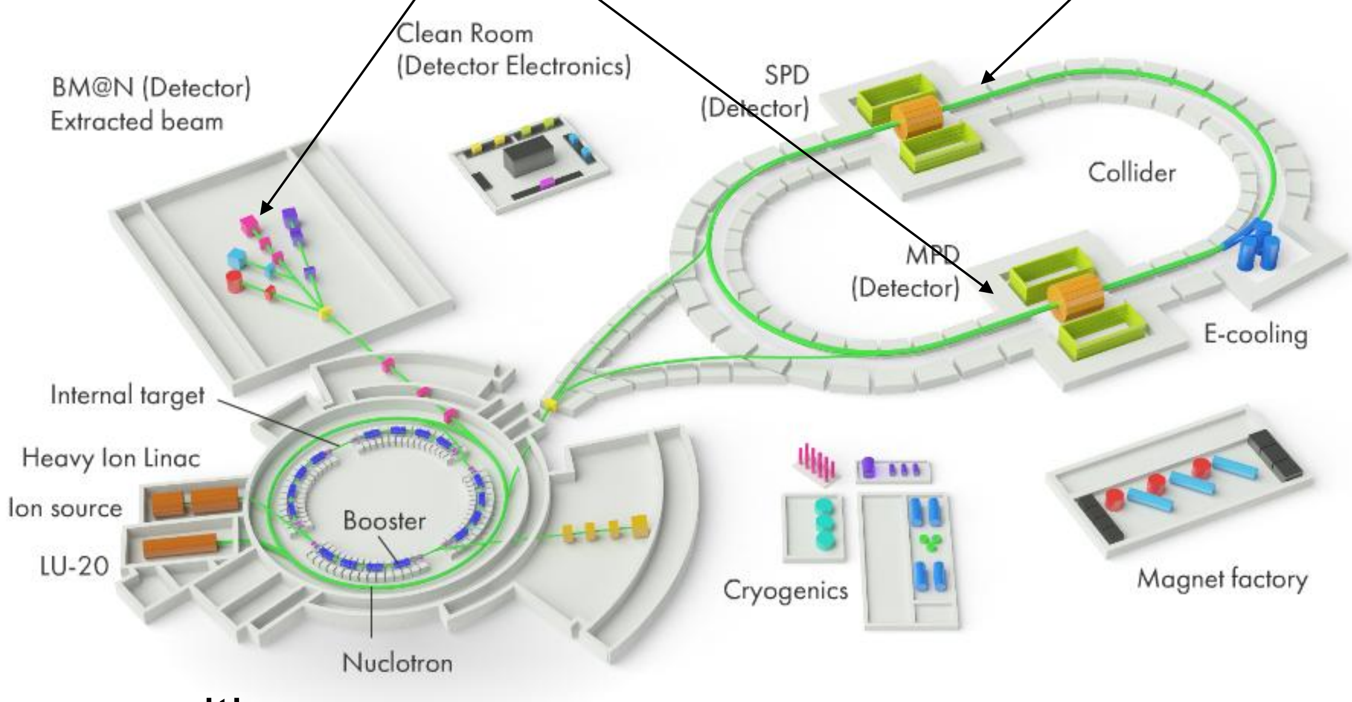
- MANY new FFs!
- Recent extensive analysis
- Cosyn,Cotogno, Freese,Lorce: 1903.00408
- Polyakov, Sun: 1903.02738

Spin 1 may be particularly interesting because tensor polarisation could couple to the energy-momentum tensor

NICA at JINR Dubna

O. Teryaev

NICA: heavy ions and hadrons



Proton and ion beams with energy

pp $\sqrt{s_{pp}} = 12 - 26$ GeV $\quad L_{max} \approx 1{\times}10^{32}$ cm^{-2}s^{-1}

dd $\sqrt{s_{NN}} = 4 - 13.8$ GeV

Possibility to include also electron beam and perform *eA* scattering; electron beam parameters to be determined

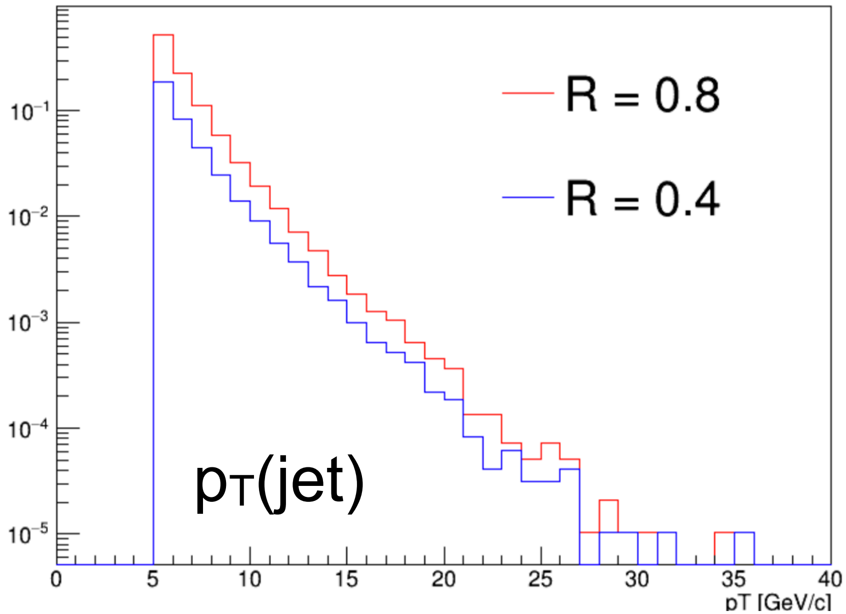
Detectors for future colliders

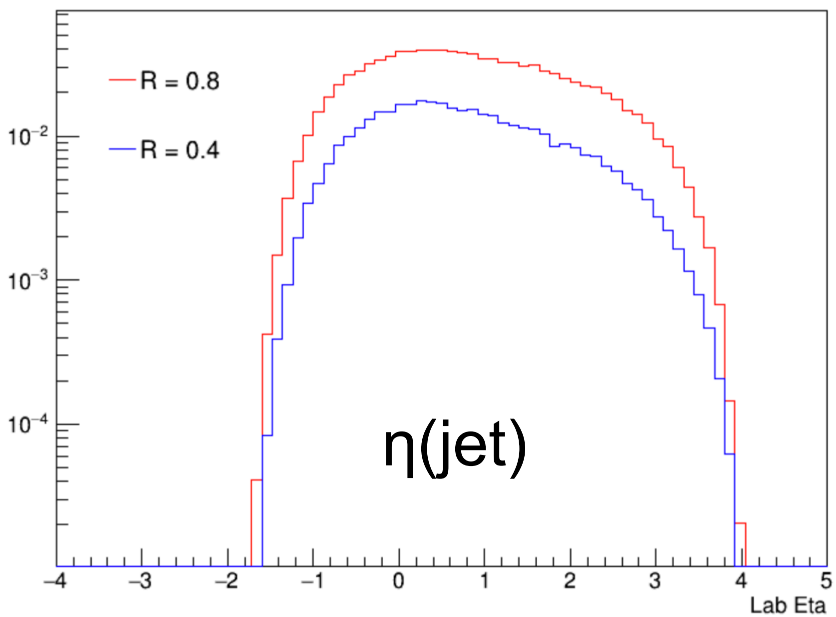
A. Kiselev
P. Newman

- LHeC design and issues:
  - Baseline borrows from e.g. ATLAS experience and developed for 2012 CDR.
  - Needs some re-consideration given high-luminosity running, e.g. heavy-flavour tagging for Higgs events.
  - Interaction region and integration with ERL are challenging.
- EIC design and issues:
  - Three similar concepts, BEAST, JLEIC and ePhenix and one different, TOPSiDE.
  - Jets are typically low multiplicity and soft → need good HCAL.
  - Need calculation of luminosity for polarised beam (invitation to theorists).
- We want to measure the lowest and highest x values possible.
  - Full angular coverage a challenge.
  - Proton and other forward taggers need to careful integration.
  - Integrated detector and beam line design from the start.

Jet physics at EIC

B. Page
K. Lauder





Dominated by resolved processes; 95% jets have $p_T(jet) < 10$ *GeV*.

Consider jet substructure, e.g. angularity:

$$\tau_a \equiv \frac{1}{p_T} \sum_{i \in J} p_T^i \left(\Delta R_{iJ}\right)^{2-a}$$

Investigating higher-order theories and power corrections.

Jets are going to be important at the EIC.

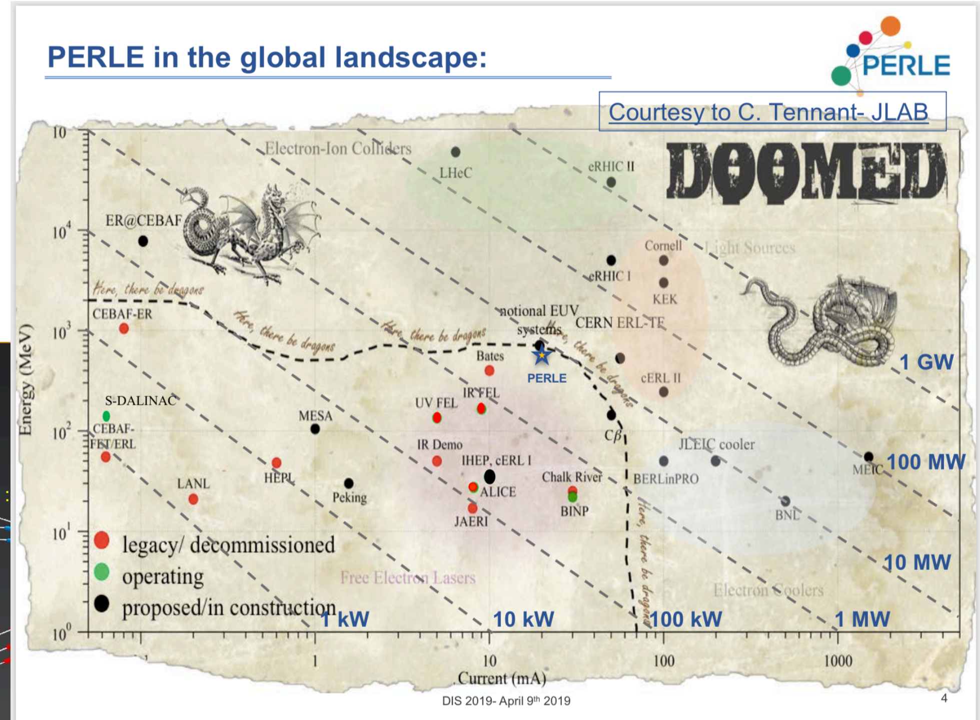
New MCs for EIC, e.g. JETSCAPE.

Will need good detector for jet and jet substructure studies.

PERLE

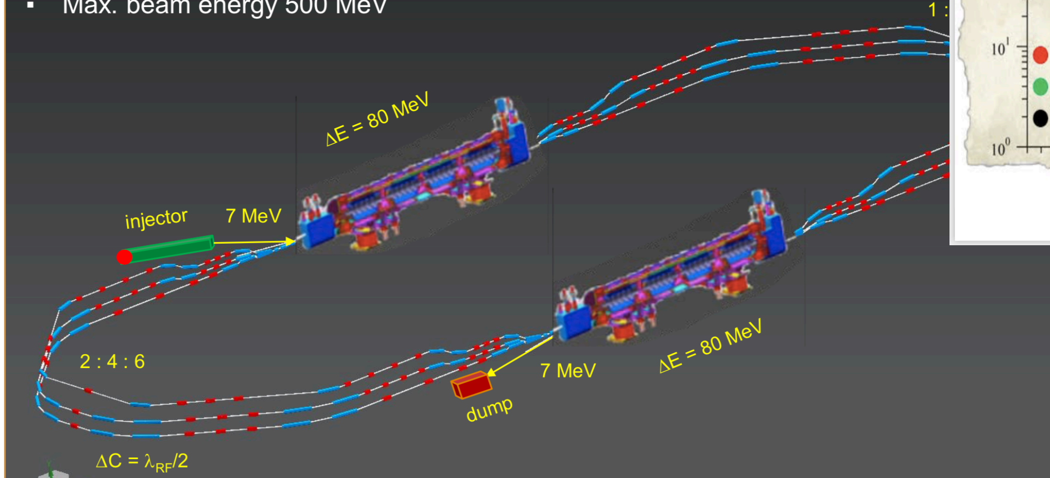
W. Kaabi

A proposed multiple pass ERL based on SRF technology, to serve as a testbed for validating and testing a broad range of accelerator phenomena & technical choices for future projects, in particular the LHeC.



An ERL represents most effective system to have 50/60 GeV electrons for LHeC.

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV



Footprint: 24 x 5.5 x 0.8 m^3

Very valuable accelerator R&D