# High-Energy DIS Studies with Nucleons

**Uta Klein**

Speaker's affiliations:

UNIVERSITY OF LIVERPOOL

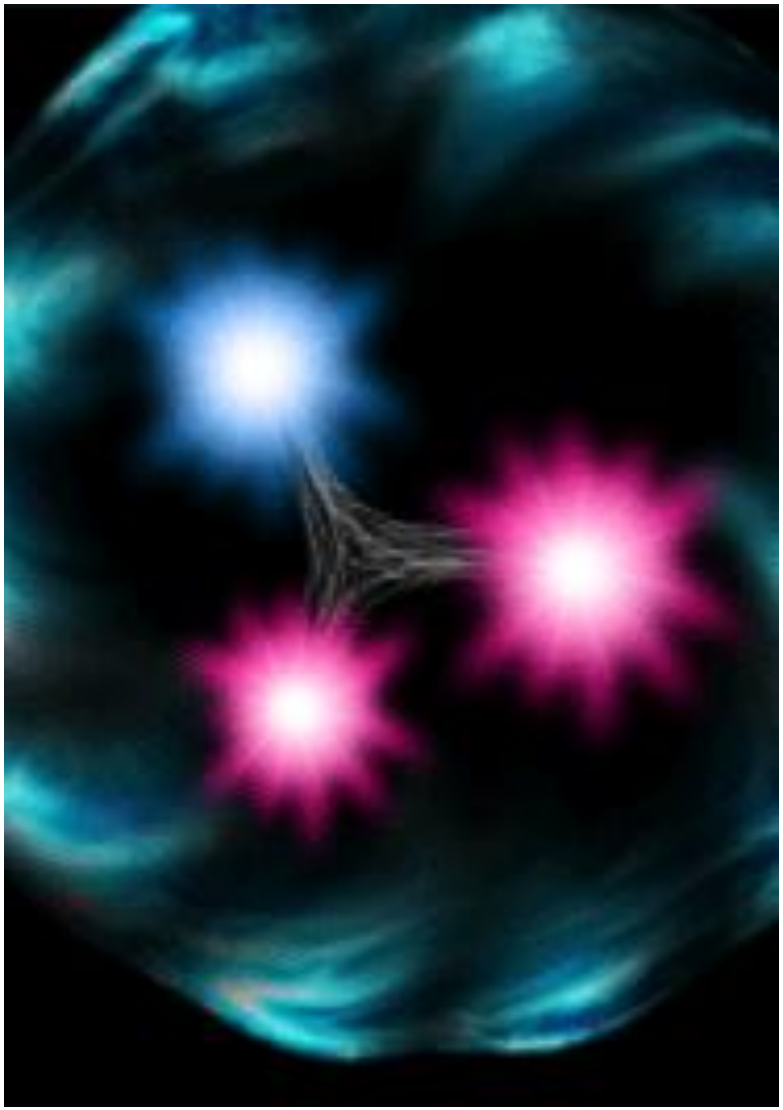
ATLAS

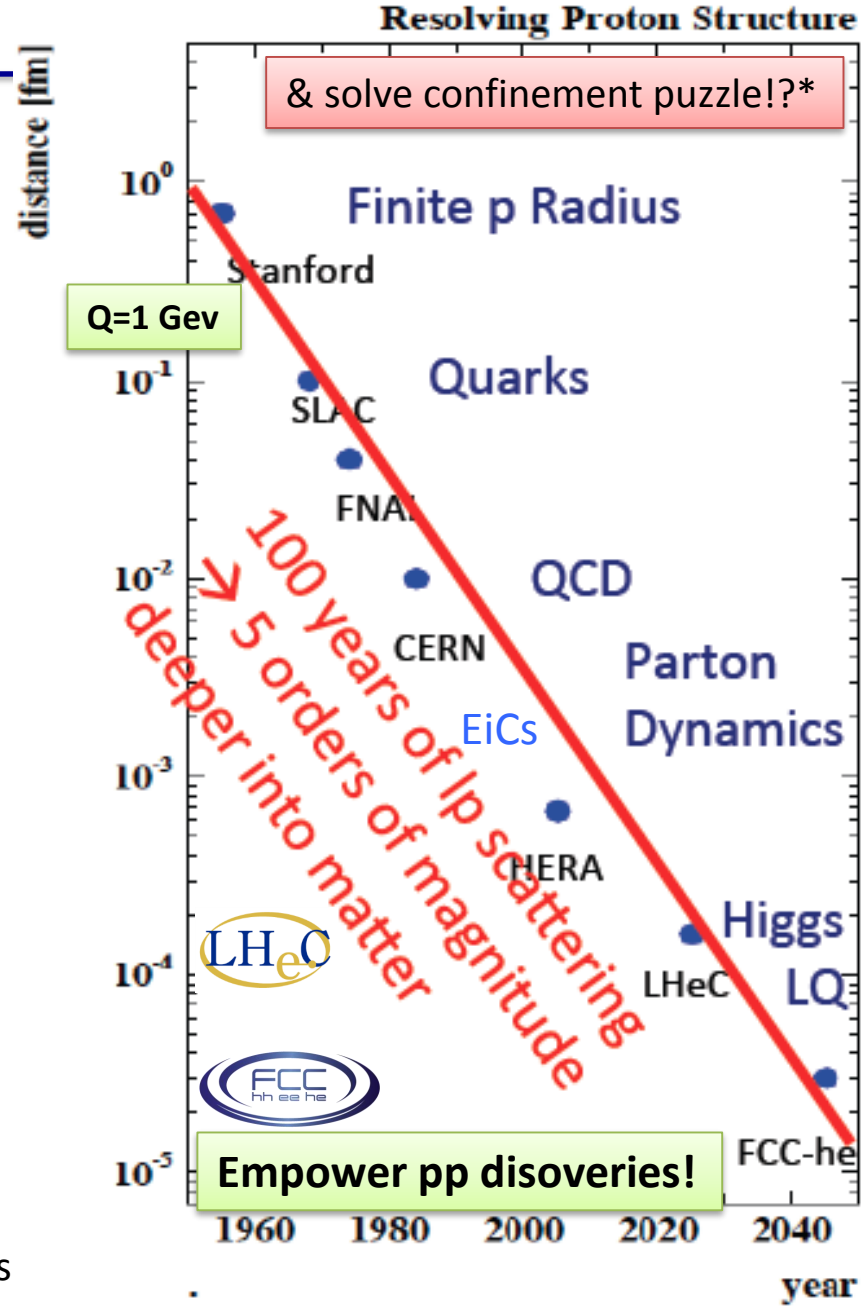
LHeC

FCC hh ee he

DIS 2018, Kobe, April 20th 2018

# ep: Resolving a non-trivial Structure…






*Jaffe&Witten 2000: 1 out of 7 millenium prize questions

# That's it?? That may not be it..

## Developments

AdS/CFT
Instantons
Odderons
TOTEM ? CERN EP 2017-335

Non pQCD, Spin, Mass
Quark Gluon Plasma

QCD of Higgs boson

$N^kLO$ PDFs, Monte Carlos..
Resummation
Saturation and BFKL

Photon, Pomeron, n PDFs
Non-conventional partons
(unintegrated, generalised)
Vector Mesons
The 3 D view on hadrons..

## Discoveries

Why no CP violation in QCD?
Massless quarks?? Would solve it..
Electric dipole moment of the neutron?
Axions, candidates for Dark Matter

Breaking of Factorisation [ep-pp]

Free Quarks

Unconfined Color

New kind of coloured matter

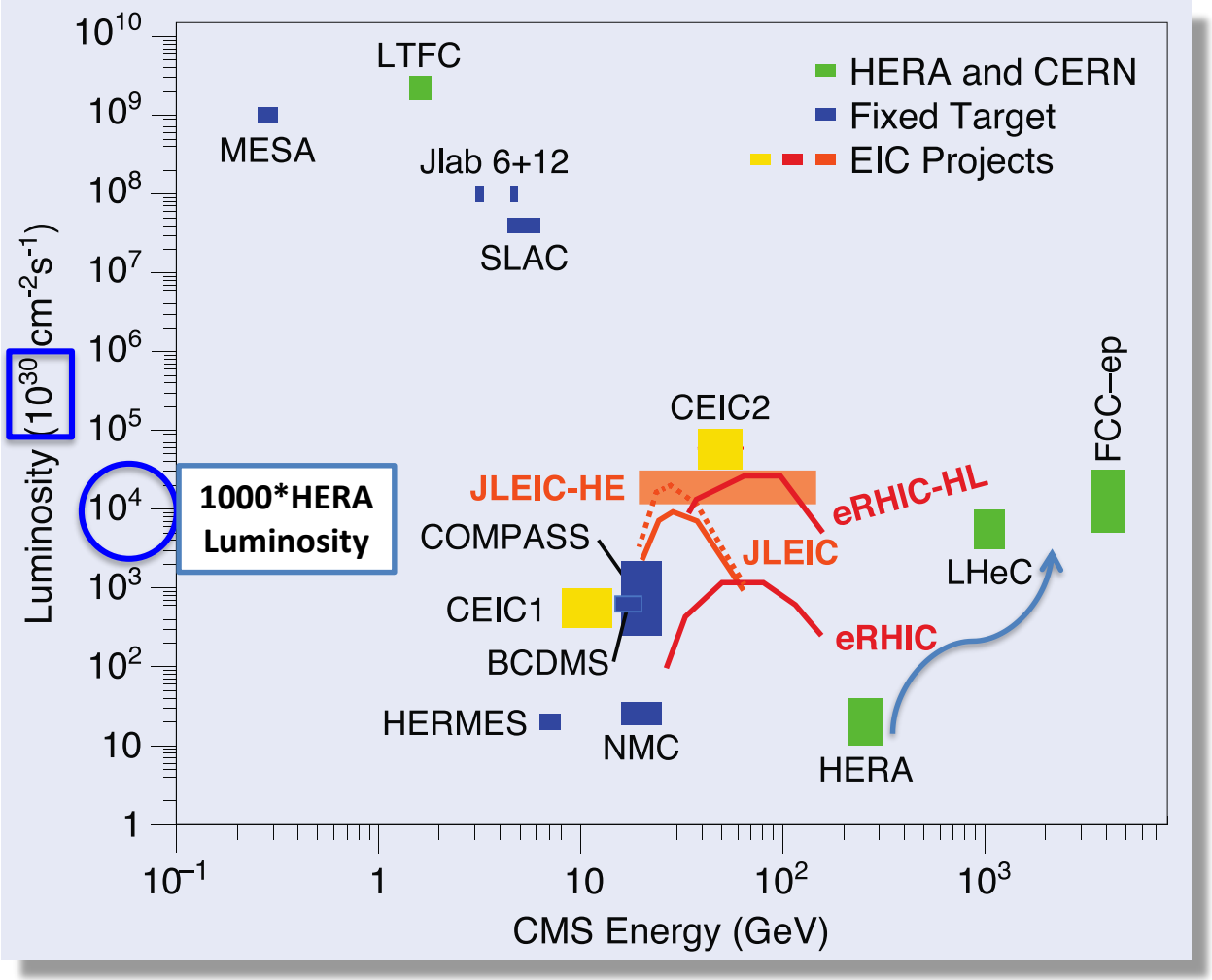
Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD has an exciting future

# The eh Landscape : Luminosity vs √s




**China**

**CEIC1 / 2 = EicC**

Chinese version of Electron-Ion Collider

**U.S.**

**JLEIC** / JLEIC-HE

= **EIC**@Jlab

**eRHIC** / eRHIC-HL

= **EIC**@BNL

**Europe**

**LHeC/FCC-ep**

= ep/eA collider@CERN

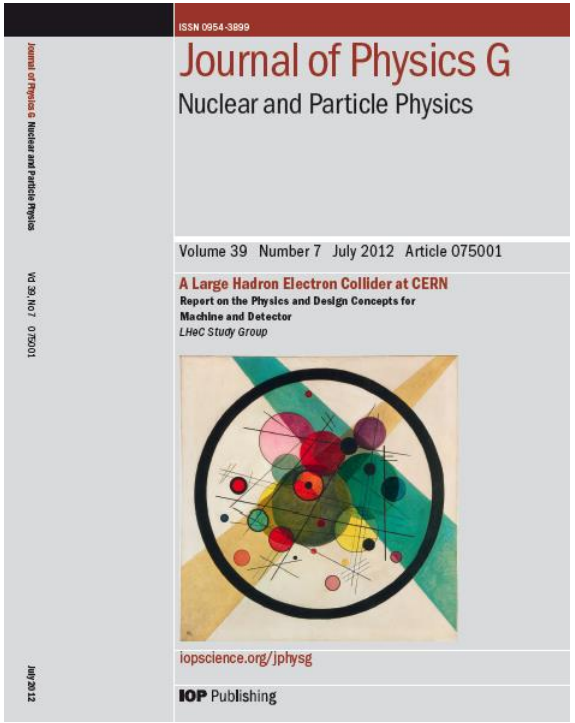
http://cerncourier.com/cws/article/cern/57304

+ Update by R Ent

Includes future HL and HE extensions.

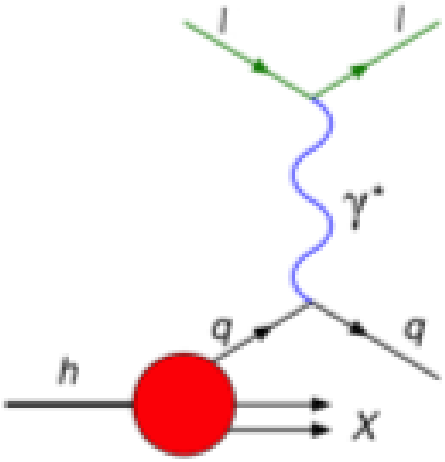
# The most advanced Proposals

At the high energy frontier
√s ~ 1.3 – 3.5 TeV

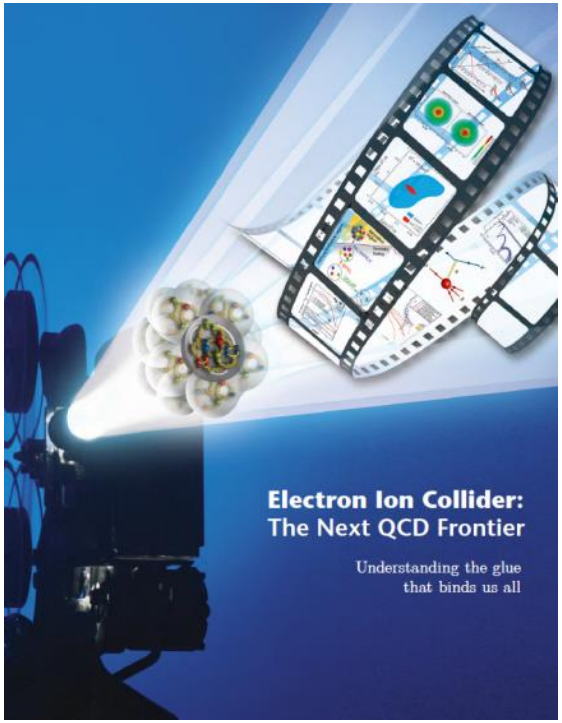



**LHeC Conceptual Design Report**
**J. Phys. G 39, 075001 (2012)**

http://lhec.web.cern.ch




Using *polarised* e&h-beams
√s ~ 0.01-0.14 TeV




**EIC White Paper**
**arXiv:1212.17010 (v2)**

http://web.mit.edu/eicc/index.html

http://www.bnl.gov/cad/eRhic/

eRHIC Design Study: An EIC at BNL
arXiv:1409.1633 ; 1708.01527

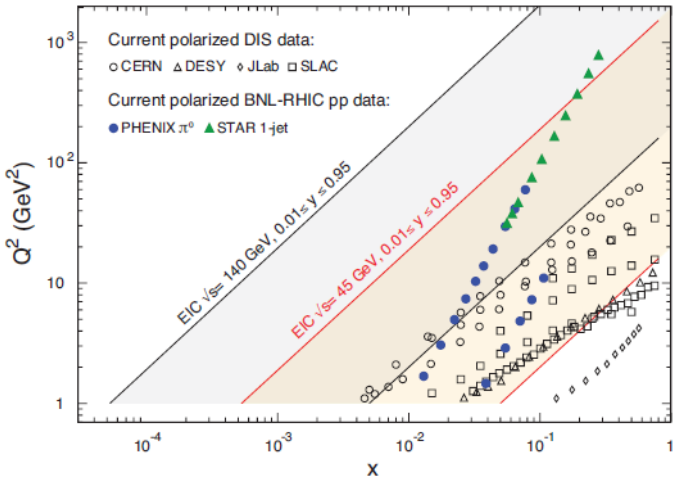
# Future eh Colliders: EIC *and* LHeC

## EIC: $E_{c.m.s.}$ ~ 20-140 GeV

- *Polarised electrons with $E_e$>3 GeV*
- ***Polarised proton** (70%) beams and unpolarised heavy ion beams (A≤200)*
- *High luminosity for **spin physics.***

**World's first polarised e-p collider and lower energy e-A collider → below HERA kinematics** ($x>10^{-5}$)

**$x_{min}$ ~ 1 x $10^{-4}$**

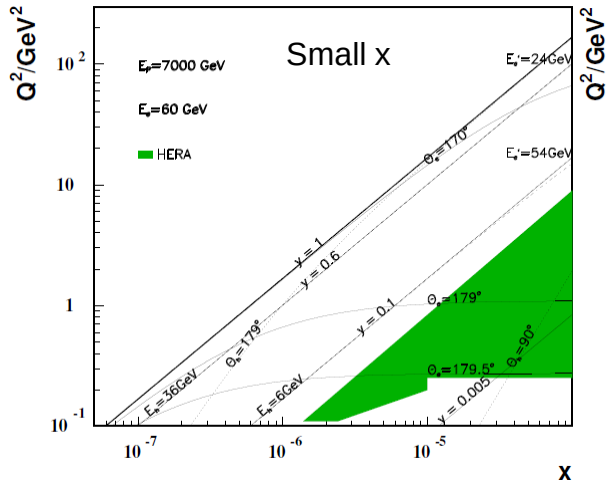


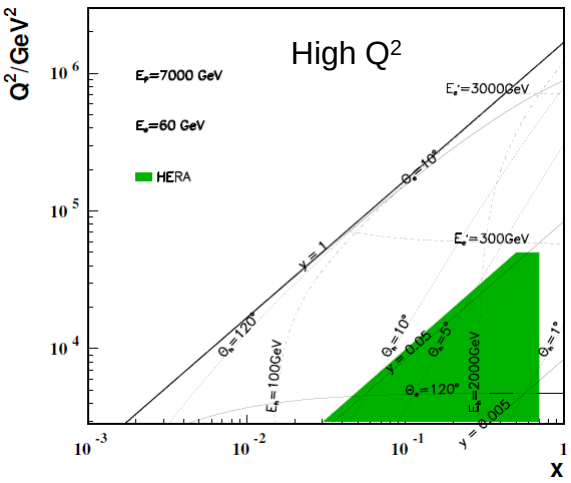

## LHeC: $E_{c.m.s.}$ 0.2 - 1.3 TeV

- *Add 30-**60** GeV **polarised** electrons to probe unpolarised LHC proton and ions*

**High-energy frontier e-p and e-A collider running simultaneously with HL-LHC, expanding hugely HERA kinematics → exploring QCD+EW sector (e.g. top, Higgs, BSM…)**

**$x_{min}$ ~ 6 x $10^{-7}$**



# The Structure of the Proton

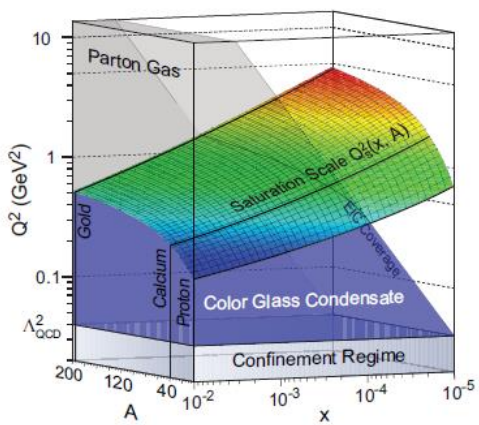
Naïve Quark Model: proton = uud (valence quarks)

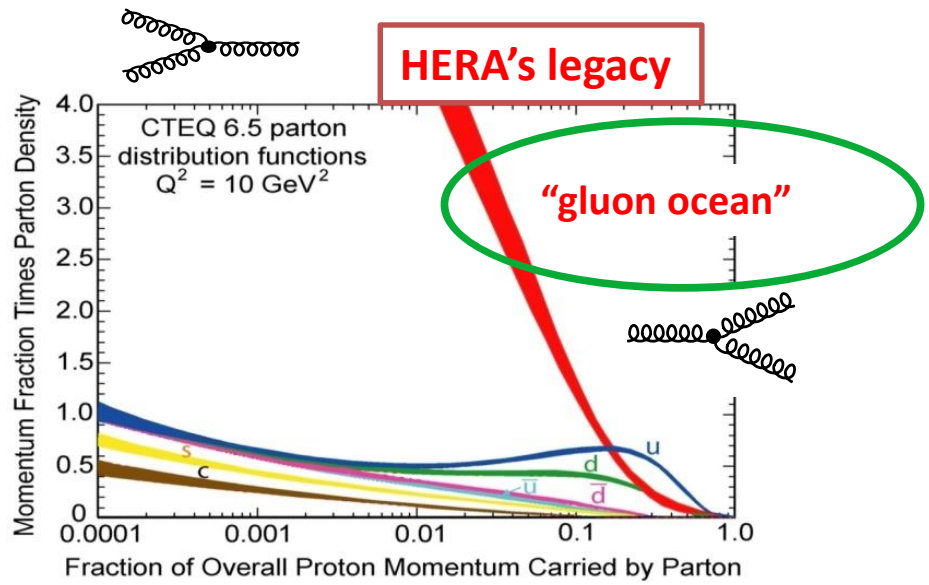
QCD: proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ + …

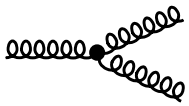
The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

& gluons are abundant

gluon dynamics

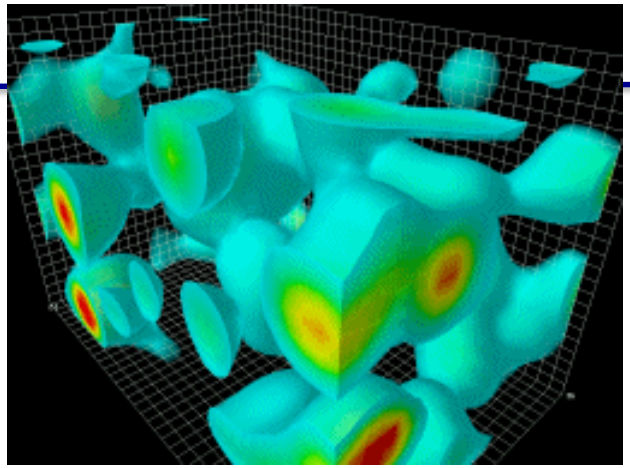



- The proton is **far more** than just its up + up + down (valence) quark structure
- Gluon $\neq$ photon: Radiates  and recombines: 

Based on Slide from R Ent

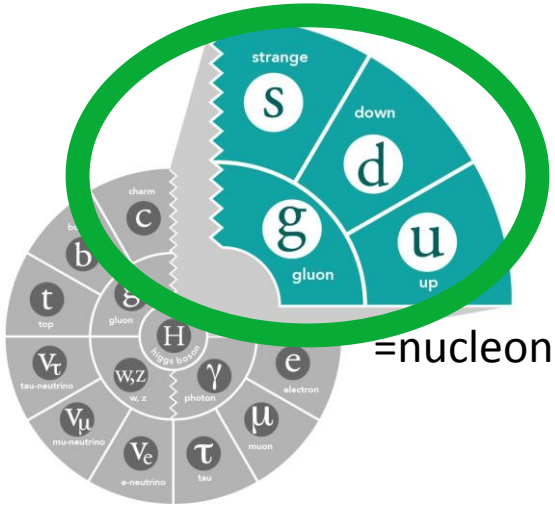
# Gluons: QCD and Higgs

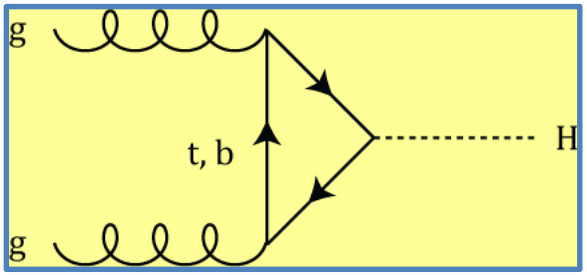


- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum

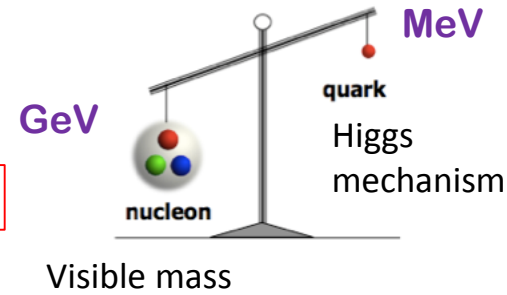
- Facts:
  - The essential features of QCD (e.g. a**symptotic freedom**, dynamical chiral symmetry breaking, and color confinement) are driven by gluons!
  - Unique aspect of QCD is the **self interaction** of the gluons
  - **Visible mass** from massless gluons and nearly massless quarks
    - Most of the mass of the visible universe emerges from quark-gluon interactions
    - **The Higgs mechanism** for mass of quarks 'only'

      ➔ but **fundamental to understand it thoroughly**



# EIC's : Understanding Nucleon Mass




Relativistic motion

χ Symmetry Breaking

Quantum fluctuation

$$M = E_q + E_g + \chi_{m_q} + T_g$$

Quark Energy

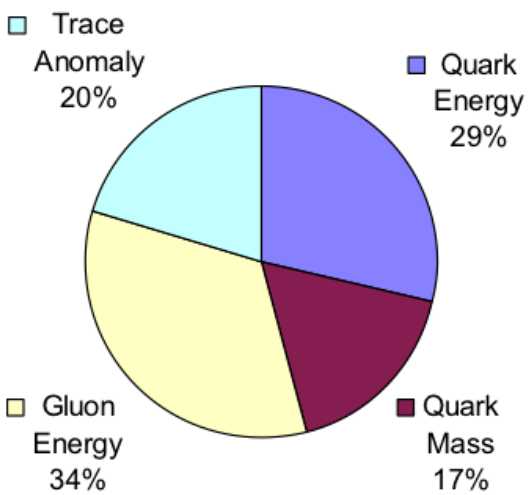
Gluon Energy

Quark Mass

Trace Anomaly

**"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"**

***Preliminary* Lattice QCD results:**

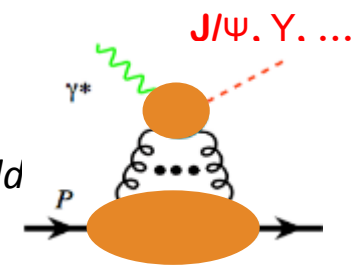



Based on slide from T Horn, ICFA 2017

**EIC's expected contribution in:**

- **Trace Anomaly:**

  *J/psi and Upsilon elastic production near the threshold*

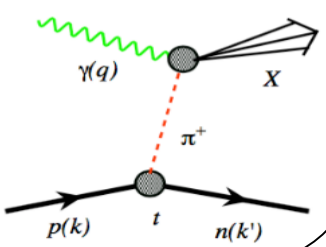



- **Quark-gluon Energy:**

  ∝ *quark-gluon momentum fractions*

  ***In nucleon with DIS and SIDIS***

  *In pions and kaons with Sullivan process*



# Understanding Quark-Gluon Dynamics

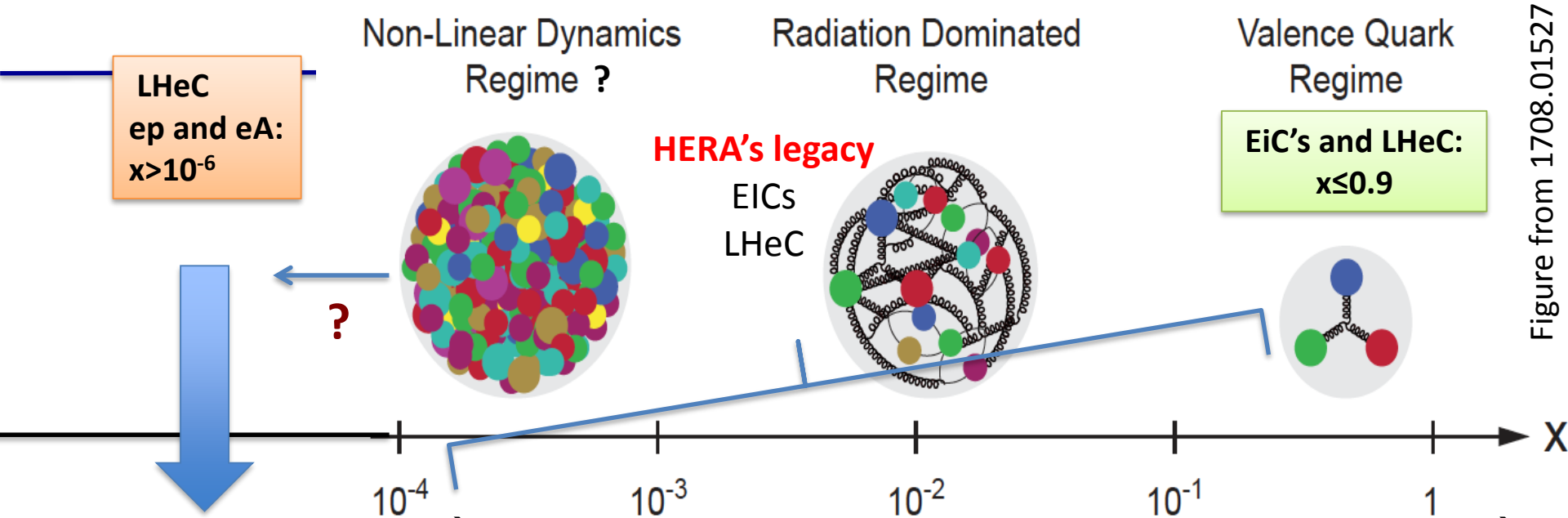



Figure from 1708.01527

Low-x resummation for x→0 : First signs seen at HERA?

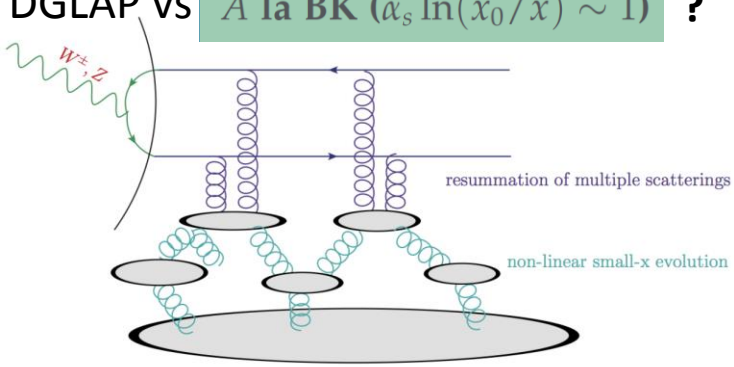
High-x resummation for x→ 1

***Measure*** change in QCD radiation pattern!?

For DY, DIS, Higgs, singular behavior when x→ 1

Eric Laenen, 2010 $\delta(1-x)$ $\left[\frac{\ln^i(1-x)}{1-x}\right]$ $\ln^k(1-x)$

DGLAP vs À la BK ($\alpha_s \ln(x_0/x) \sim 1$) ?




Resummation:

*The art of constructing for some quantity out of a subset of perturbative terms, aided by extra insight, an all-order expression*

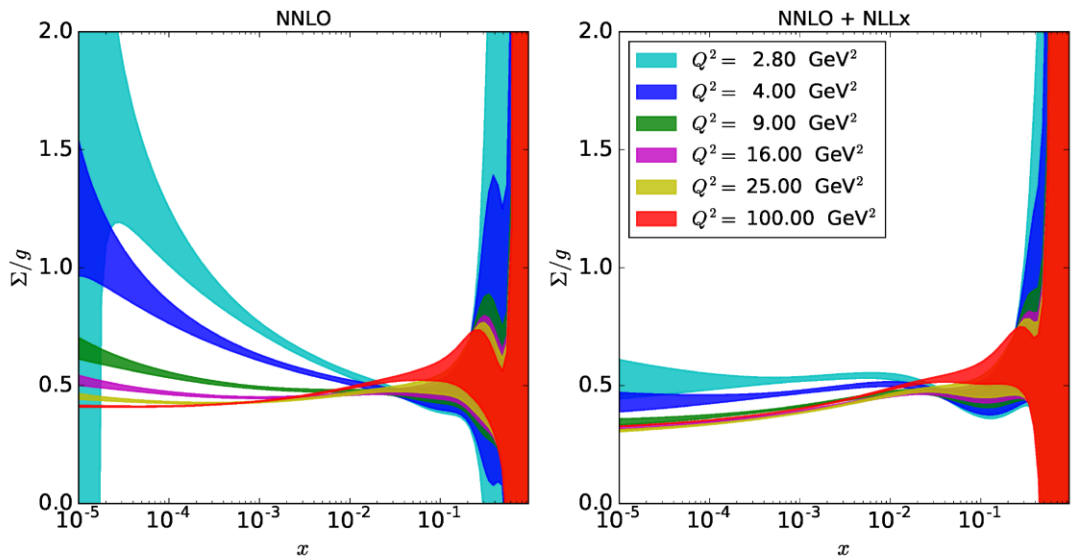
***Or measure gluon saturation?***

Disclaimer: I refer to high precision and unpolarised lN colliders for illustration.

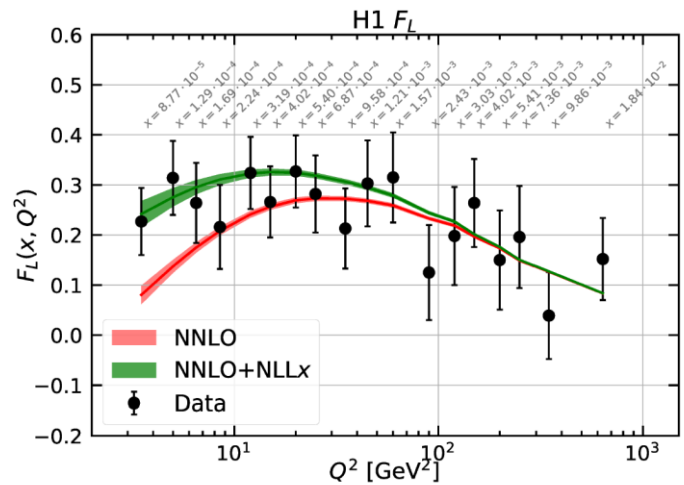
# Low-x Resummation@HERA ?

NNLO vs **NNLO**+NLLx

Ratio $\Sigma/g$




The structure function $F_L$




- Quantify the power of the rise of $xg$ and $x\Sigma$ by examining evolution of their ratio.
- Large evolution at NNLO, with the ratio exceeding unity at low scales.
- Ratio is $\leq 0.5$ when $\ln 1/x$ resummation is included.

$\rightarrow$ more inline with "dynamic" picture of PDFs in which the sea is generated from the gluon perturbativaly like in GRV fits.

**Needs new, most accurate ep data extending to smaller x in perturbative region!**

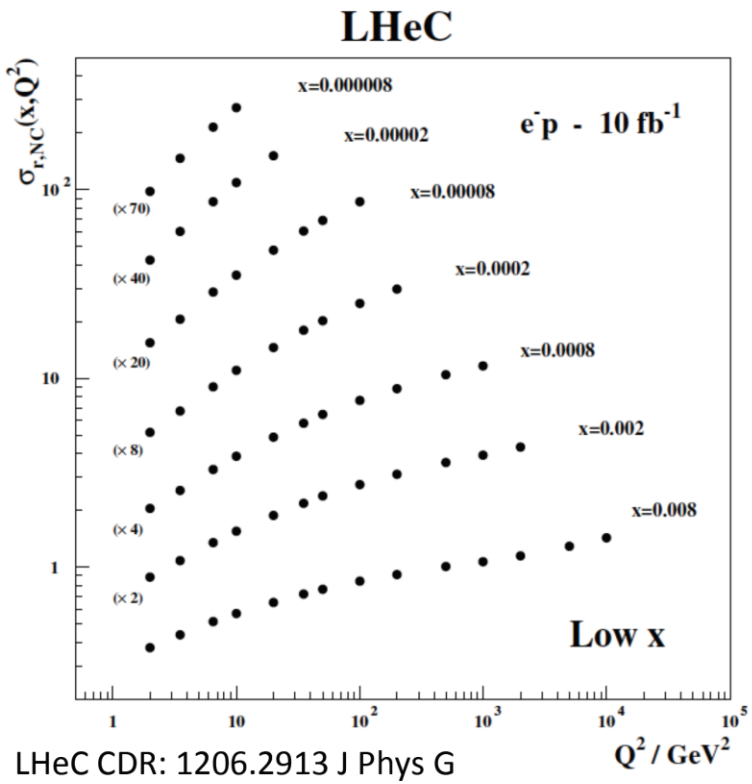
# How to determine low x evolution + discover saturation ?

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 dz\left[F_2(\frac{x}{z})P_{qq}(z) + 2\sum_{i=1}^{N_f} e_i^2 \cdot G(\frac{x}{z})P_{qG}(z)\right]$$

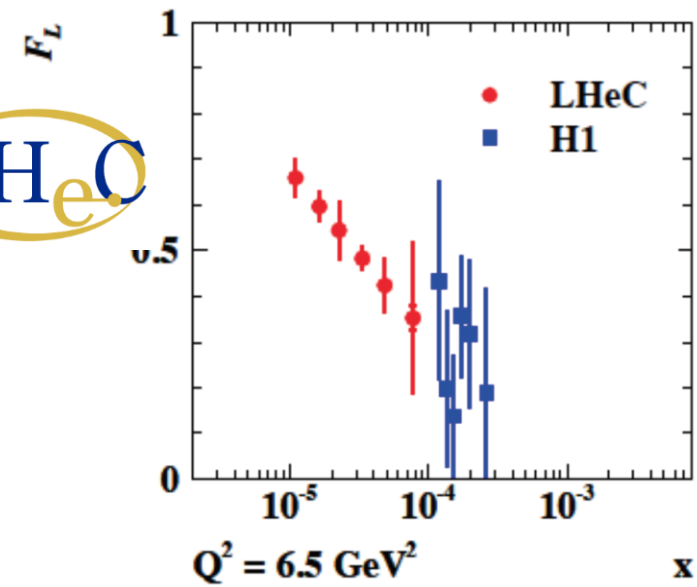
Needs cleanest DIS constraints, proton, not ion, high E: $F_2$+$F_L$

$$F_L(x,Q^2) = \frac{\alpha_s}{\pi}x^2\int_x^1 \frac{dz}{z^3}\left[\frac{4}{3}F_2(z,Q^2) + 2\sum_i^{N_f} e_i^2 \cdot G(z,Q^2)\left(1-\frac{x}{z}\right)\right]$$

**High precision $F_L$ from variation of $E_e$ independently of LHC/FCC**




LHeC CDR: 1206.2913 J Phys G




MK: 1802.04317

**High precision $F_2(x,Q^2)$ from few days of nominal ep running. Needs large $Q^2$ and low x ~ 1/s:**

**c.f. LHeC CDR to confirm DGLAP or rule it out**

Precision measurements of gluon distribution essential for quantitative studies of onset of **saturation as a high density (small x in ep) and matter ($A^{1/3}$) effect**.

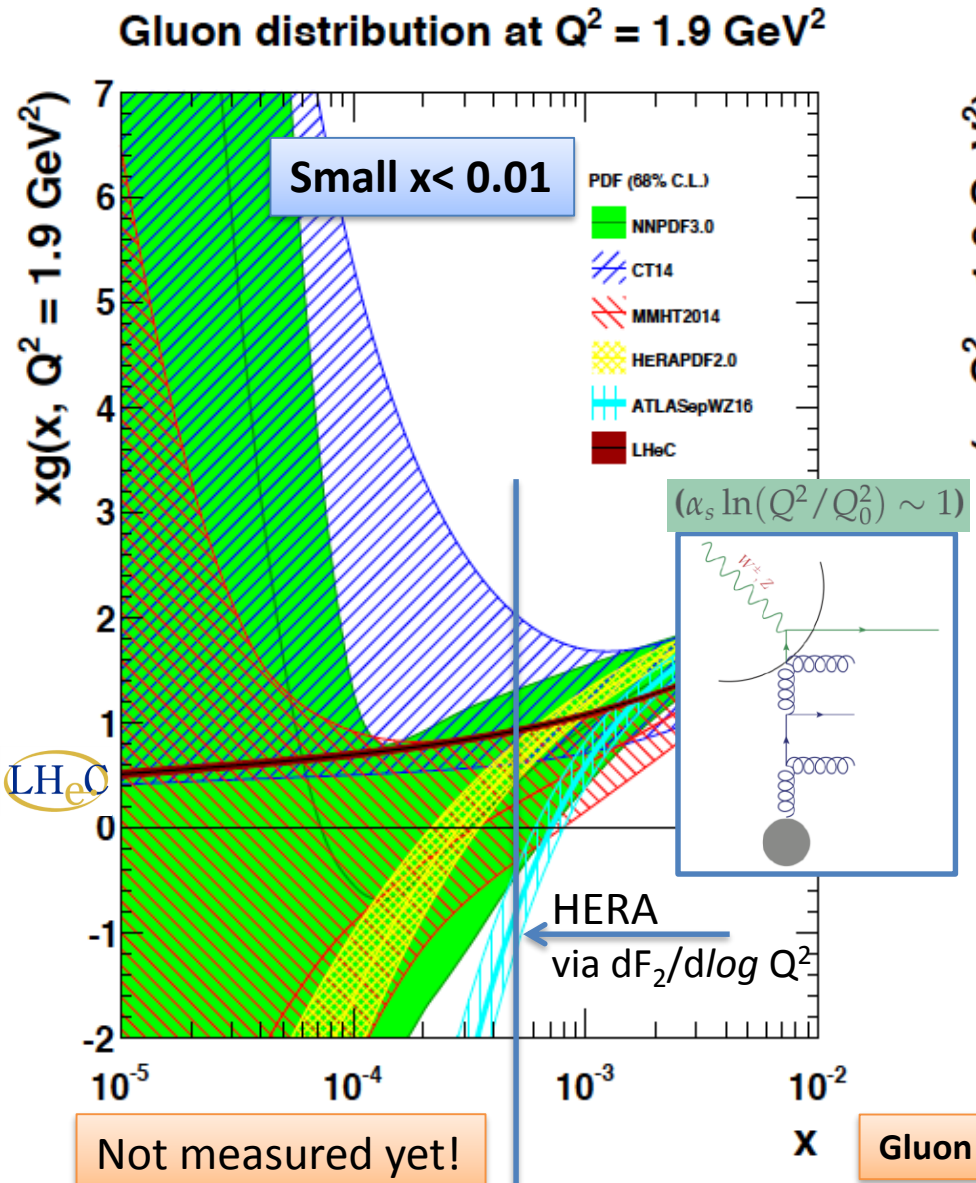
M Klein, FCC Week2018

# Understanding the Gluon

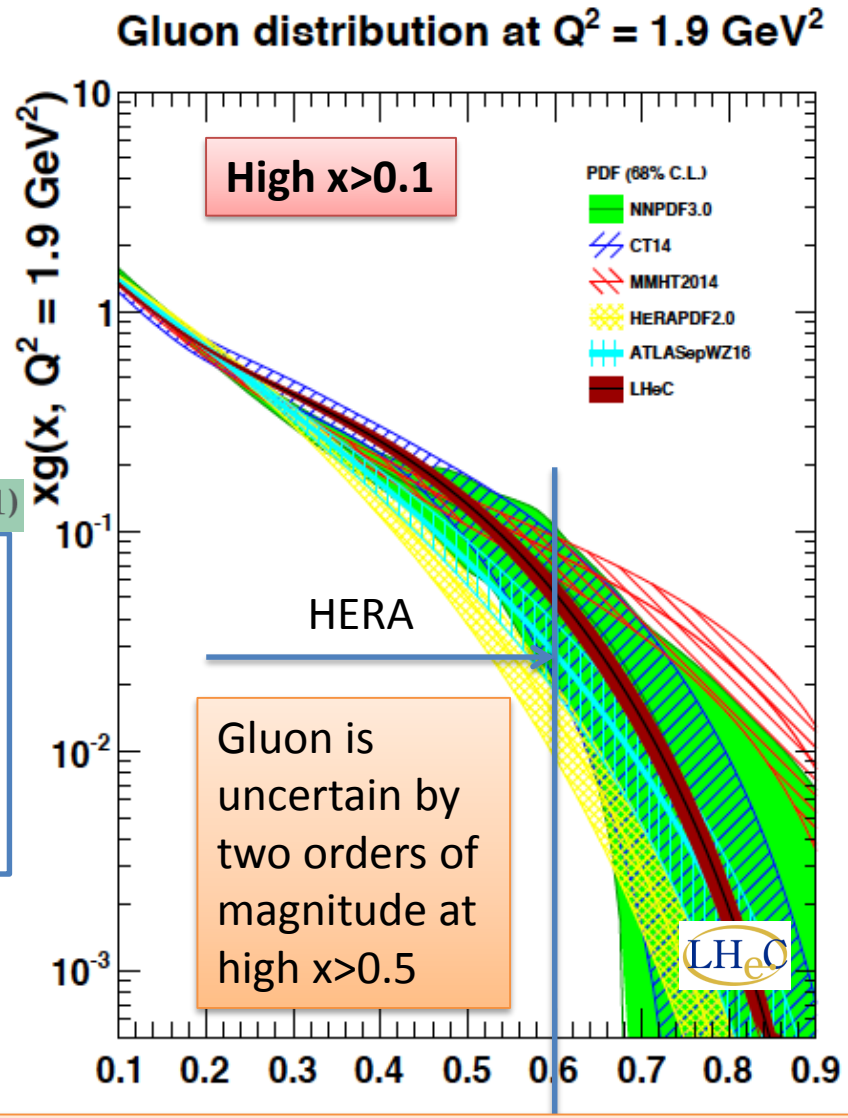
**Hera's legacy and limitation**

## DGLAP approach

Low and high x partons are intertwined by momentum sum rules!



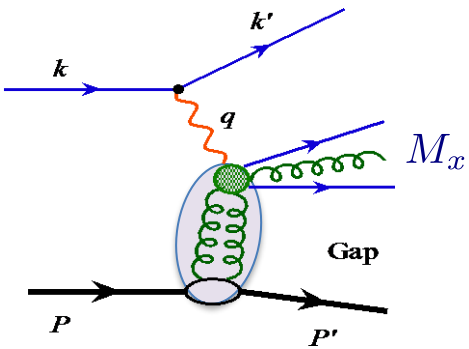

Not measured yet!




**Gluon from $Q^2$ derivative of DIS cross section most accurate.**

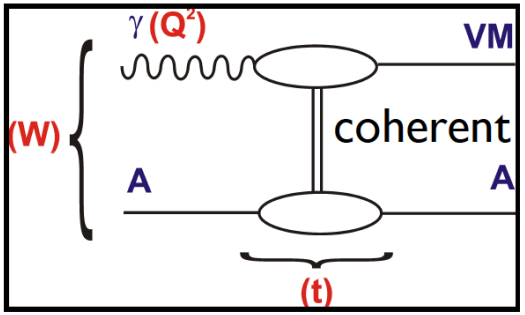
# Saturation and Diffraction

**Diffractive cross section:** $\sigma_{\rm diff} \propto [g(x, Q^2)]^2$

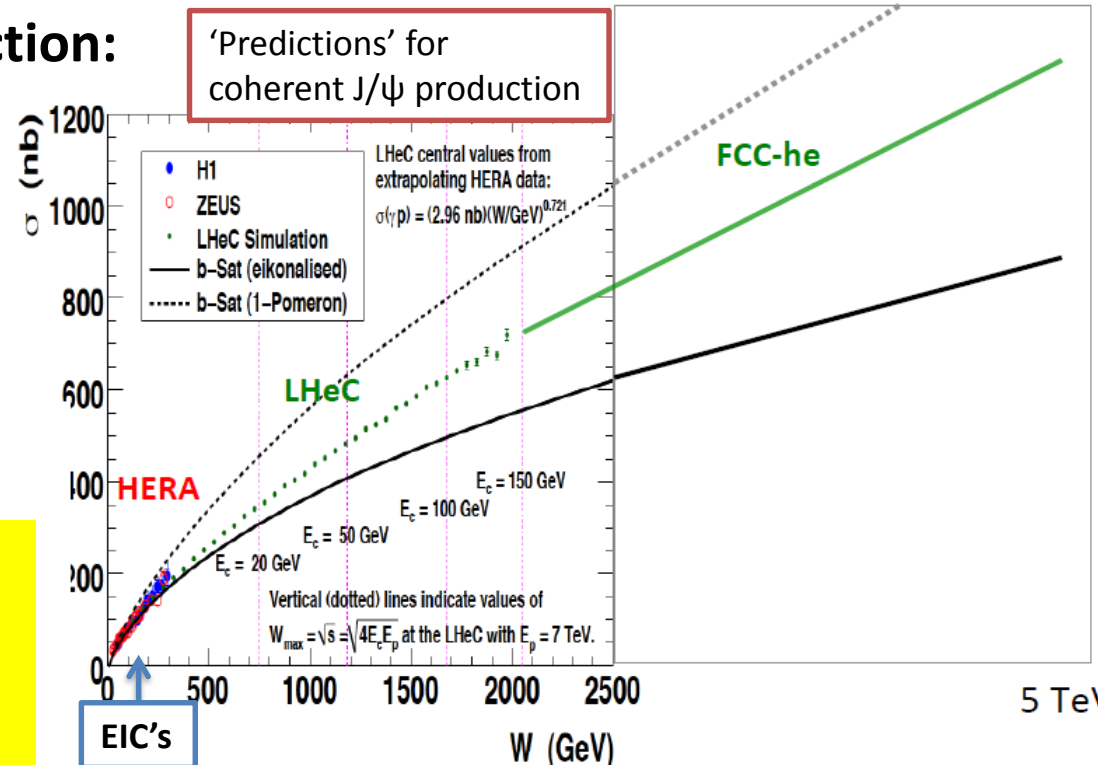



**<u>HERA legacy</u>: 10-15% diffractive events in ep**; $Q^2$ dep!
If saturation (CGC) – multiple coherent gluons
→ Diffraction in eA : ~25-30% diffractive contribution
Reminder: Factorization for diffractive processes works in DIS, not in pp, pA, AA

**Diffractive vector meson production:**



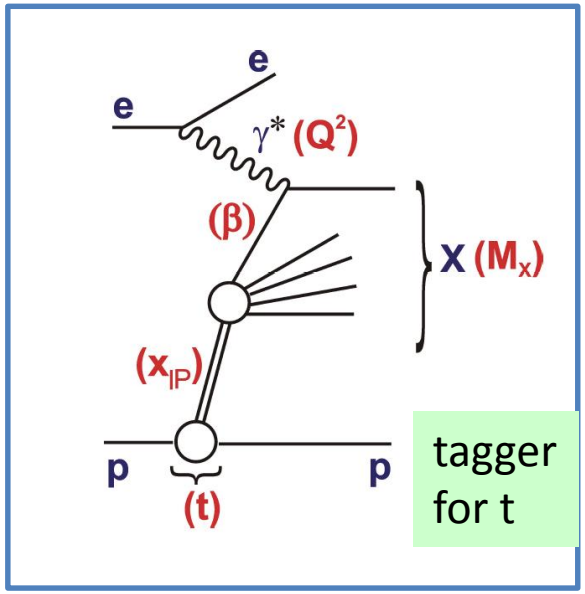

'Predictions' for coherent J/ψ production

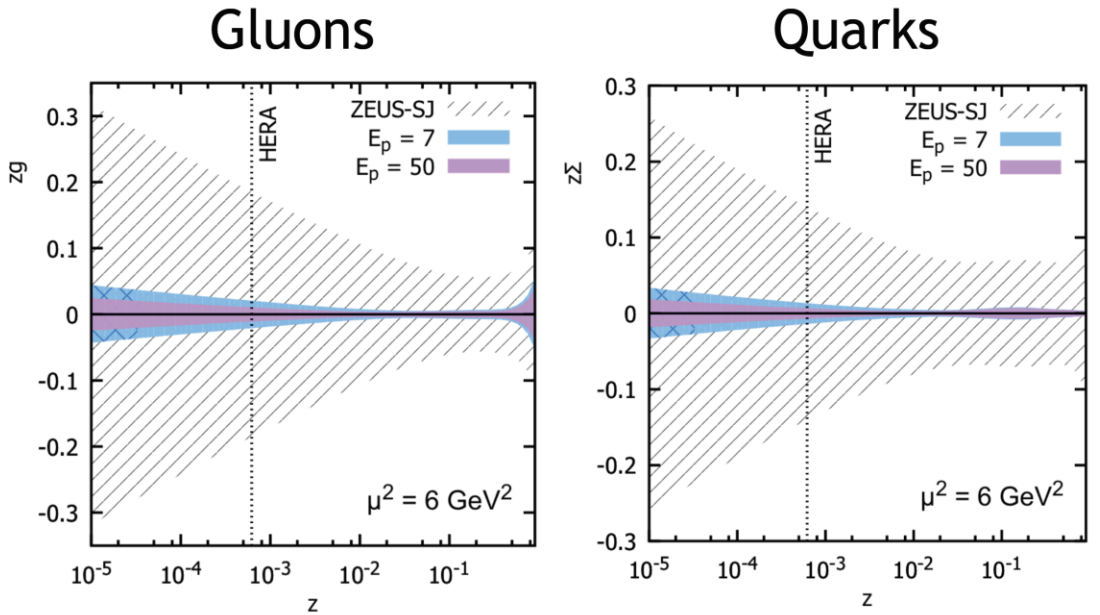


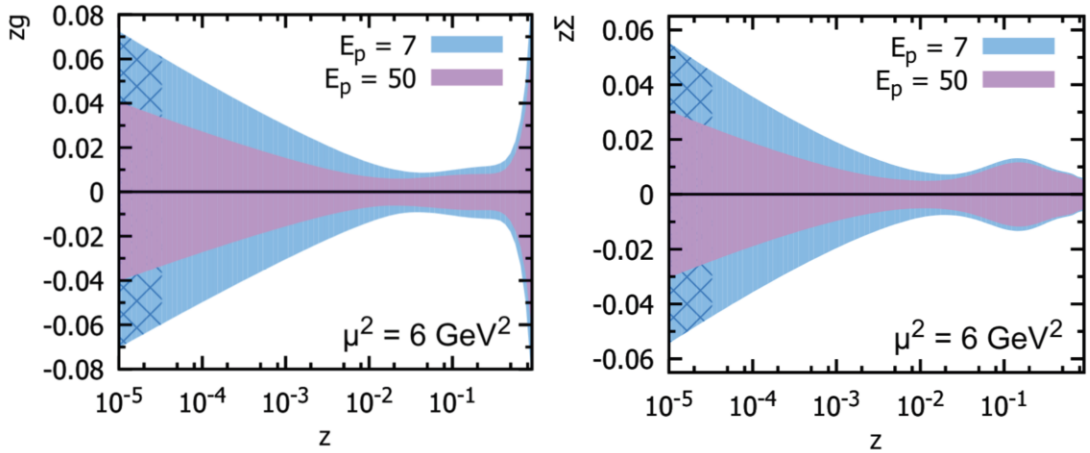

**Experimental challenge : measurement of t (ZDC?) and detection of FS proton and neutron (incoherent: nucleus breaks up) in ep and eA.**

# Diffractive PDFs

P Newman, DIS2018
Study by W Slominski



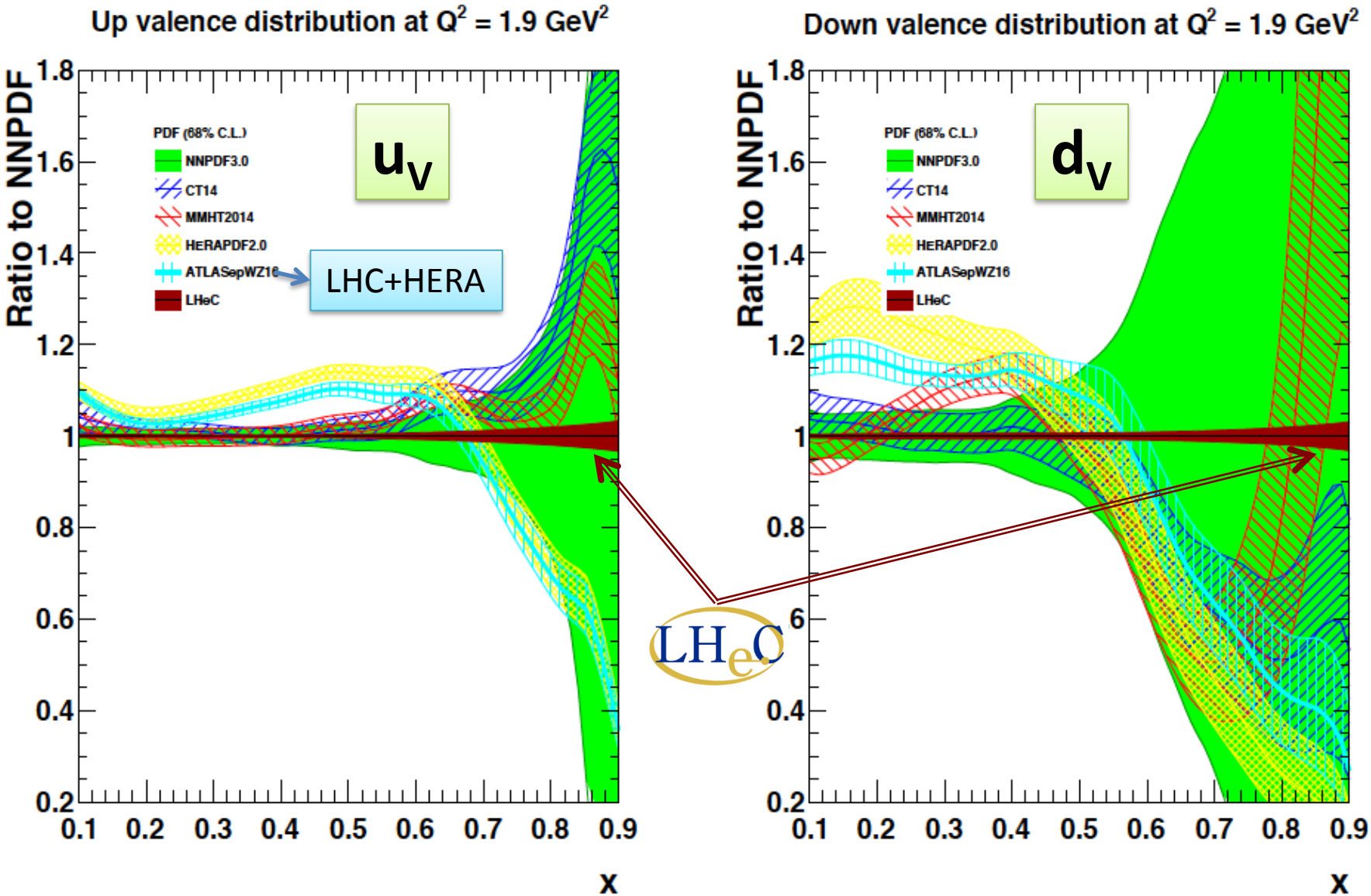




- Low $x_{IP}$ → cleanly separate diffraction
- Low β → Novel low x effects
- High $Q^2$ → Lever-arm for gluon,flavour
- Large $M_X$ → Jets, heavy flavours, W/Z ..
- Large $E_T$ → Precision QCD with jets …

EIC: Very precise measurements for a different kinematic range possible

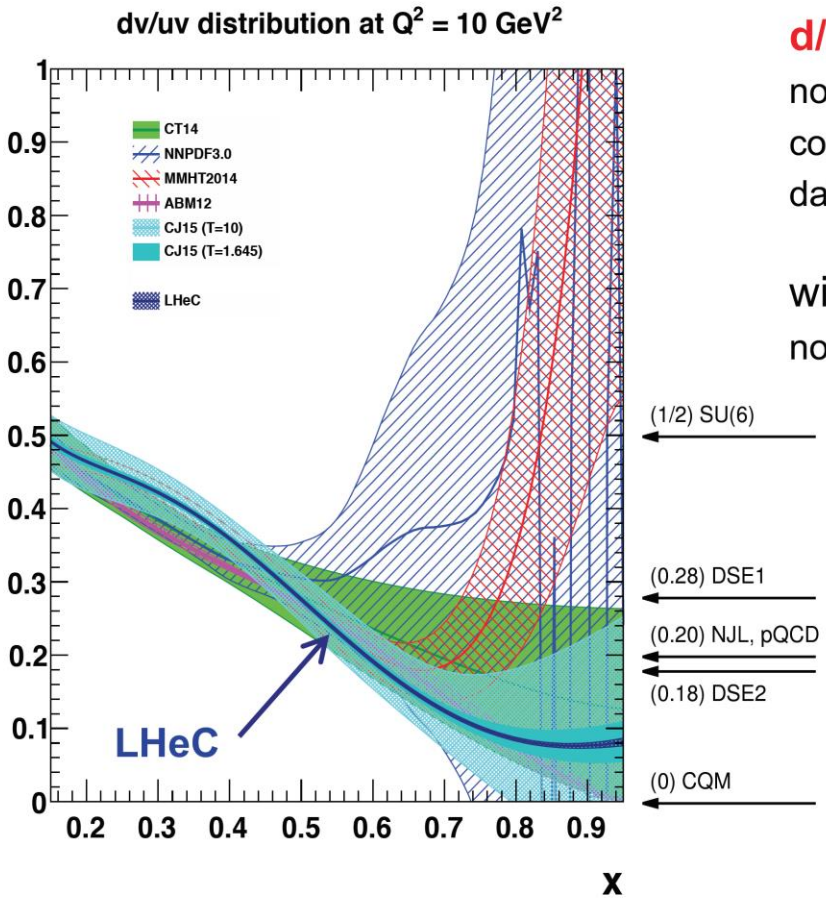
# Valence Quark Distributions

normalised to NNPDF 3.0



# d/u at large x

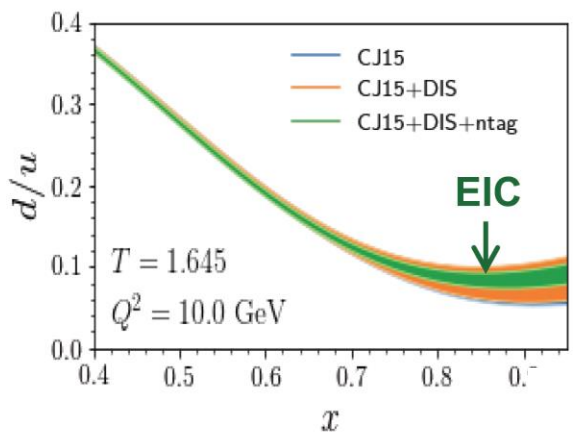
C Gwenlan, DIS2018

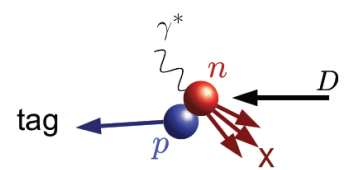



**d/u essentially unknown at large x**

no predictive power from current pdfs;
conflicting theory pictures;
data inconclusive, large nuclear uncerts.

with precision ep (n) data to v. large x:
no nuclear corrections; relax assumptions




**resolve long-standing mystery of d/u ratio at large x**

→ ***Subtle measurement: $u_V d_V$ drastically decrease for x→1***

✓ LHeC: Combination of NC and CC DIS at very high $Q^2$

✓ EIC's: NC DIS in ep and eD; tagged spectator proton

→ **Crucial test of pQCD: non-singlet quark distributions do 'not' evolve with Q2?**

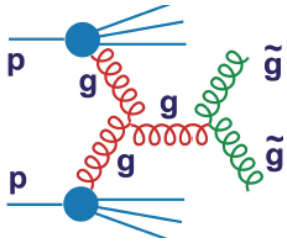
# Empowering Discoveries at LHC (pp)

**External, accurate input is crucial for search extension + non-resonant interpretations**

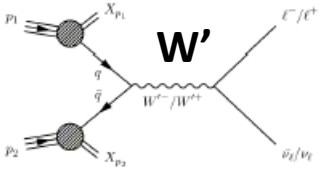
Two unknowns, PDFs and new physics, require two independent sources of input.

**GLUON**

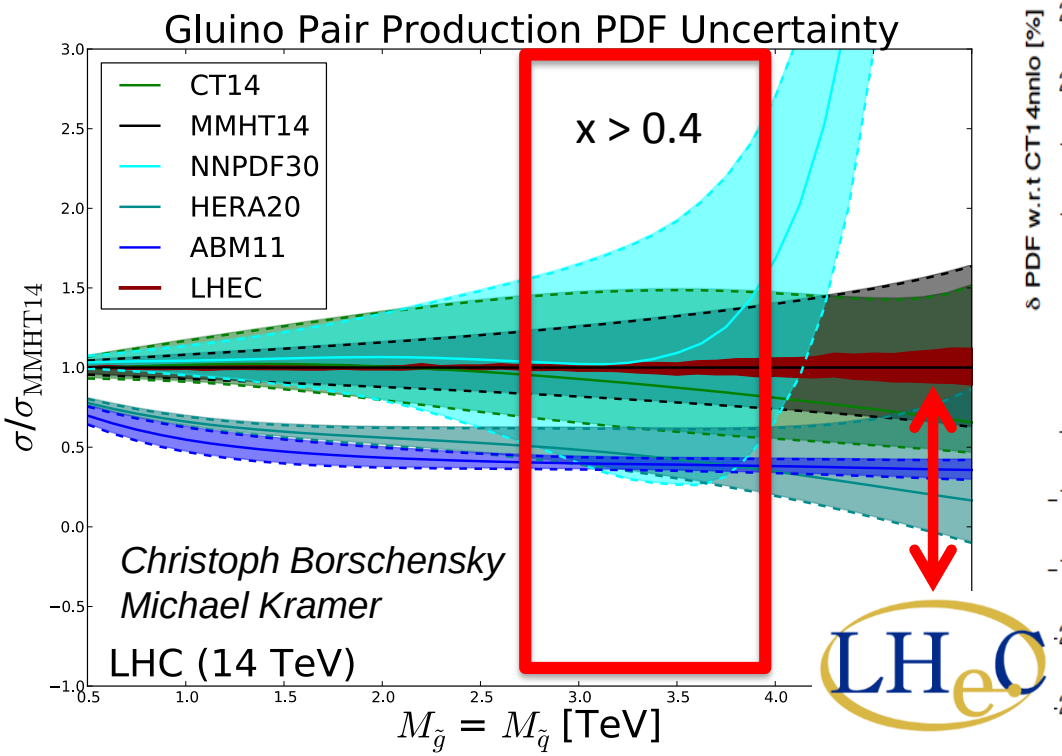
SUSY, RPC, RPV, LQS..

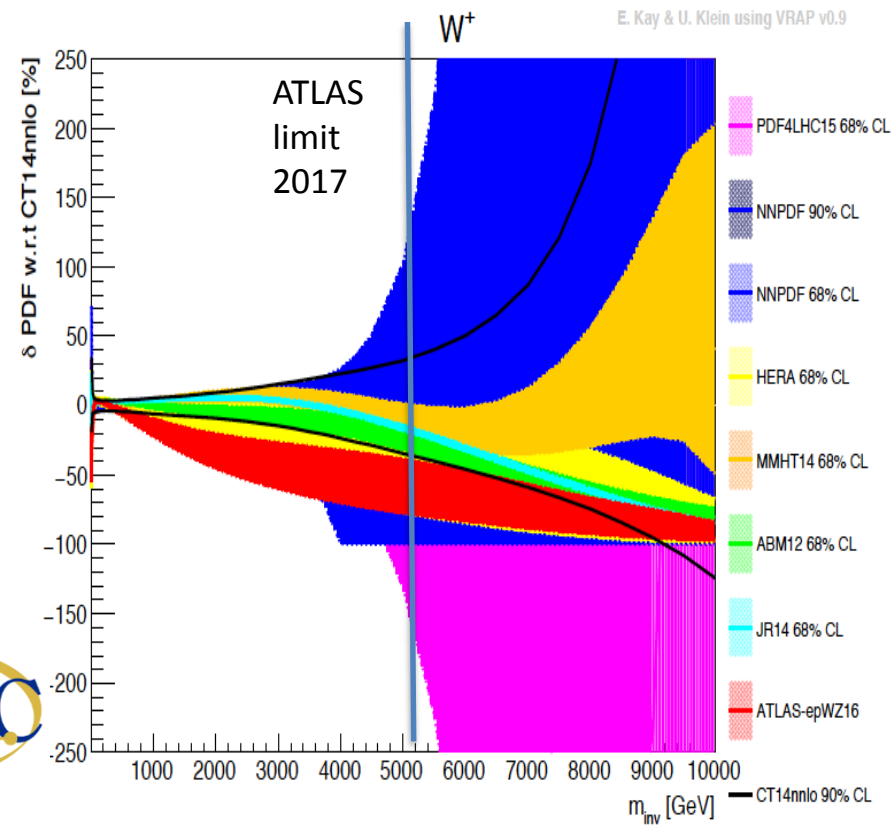



**QUARKS**




Exotic+ Extra boson searches at high mass




update of arXiv:1211.5102

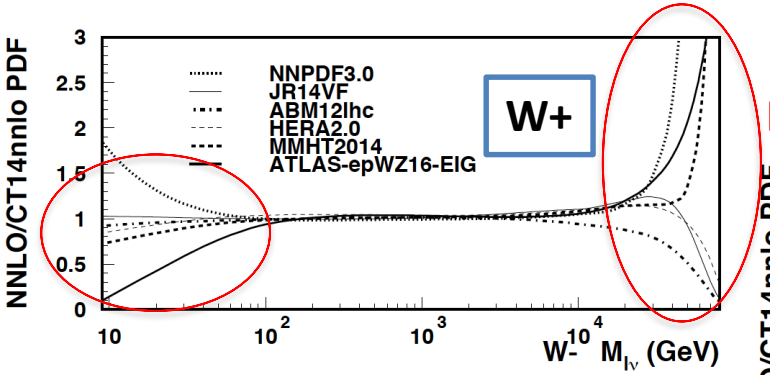
NNPDF3.0: 'Issues' with negative replica

# Impact of PDF: High mass Drell-Yan

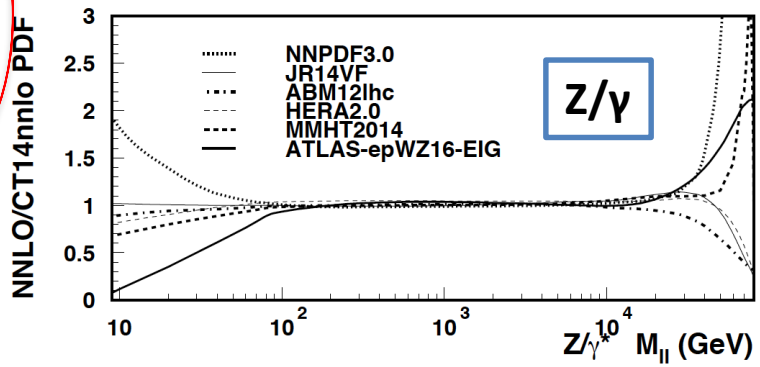
**Assuming collinear factorization & momentum sum rule…**

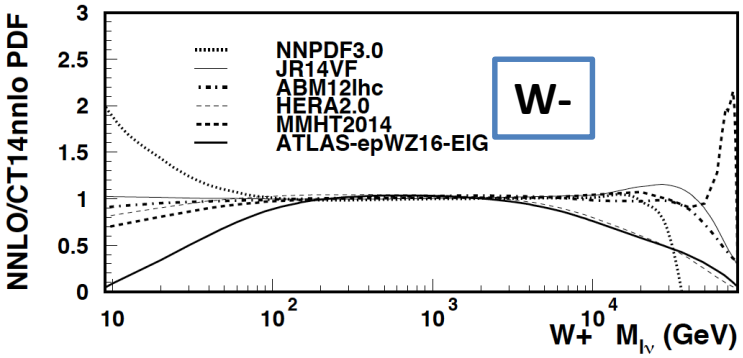
- Non resonant searches for ED (interference) sensitive to tails of DY distributions thus to PDF. Predominantly q-qbar

*Uta Klein*
VRAP 0.9 for NNLO QCD




**FCC-hh @100 TeV**



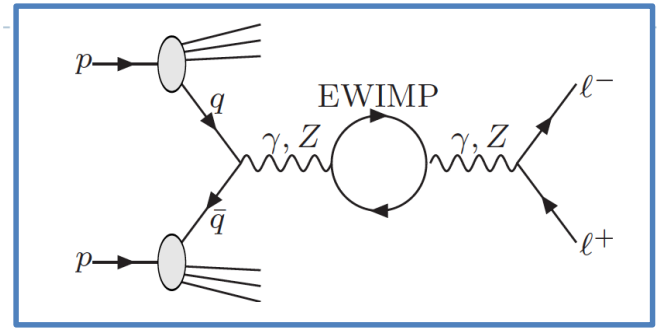

"Troubles" at low and high x

FCCeh (and before, LHeC) can improve low and high M(ll) and M(lv) precision for standard candle measurements and searches for new physics

QUESTIONs for pp/ pA / AA:

**-How 'safe' are our factorization assumptions?**
**-How may we test those w/o new accurate independent inputs from DIS?**
**- How to we treat 'dissident' PDF data / fits?**
**-Shall we fit LHC data in global PDFs?**

**Beware NP:**

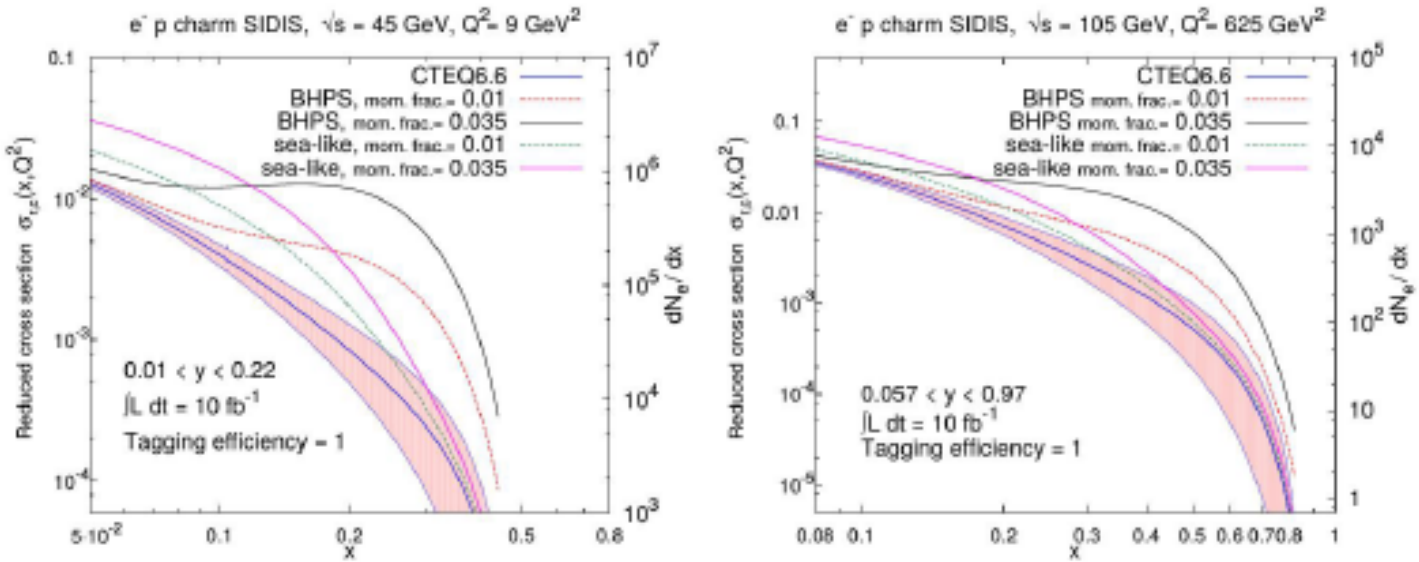



arXiv:1711.05449

**➔ new physics may appear as radiative corrections in DY and modify cross section by 0.1-10% at 200-1000 GeV (study for HL-LHC)**

# .. and more Puzzles

## intrinsic charm ?




arXiv:1108.1713

**EIC**: intrinsic charm may be probed via charm contributions to DIS reduced cross section, $F_{L,c}$ or angular distributions

sensitivity to intrinsic vs perturbative charm; and to different shapes of intrinsic charm

**LHeC**: challenge – charm tagging in very forward direction to access large x values of interest; could be favourably done with dedicated lower proton beam energy runs (CDR study)

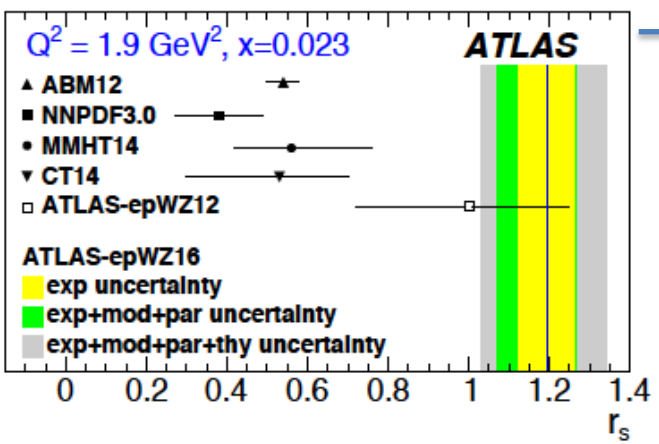
**LHC**: Z+c, γ+c; most recent measurements not yet discriminating (EG. M. Stockton, WG1)

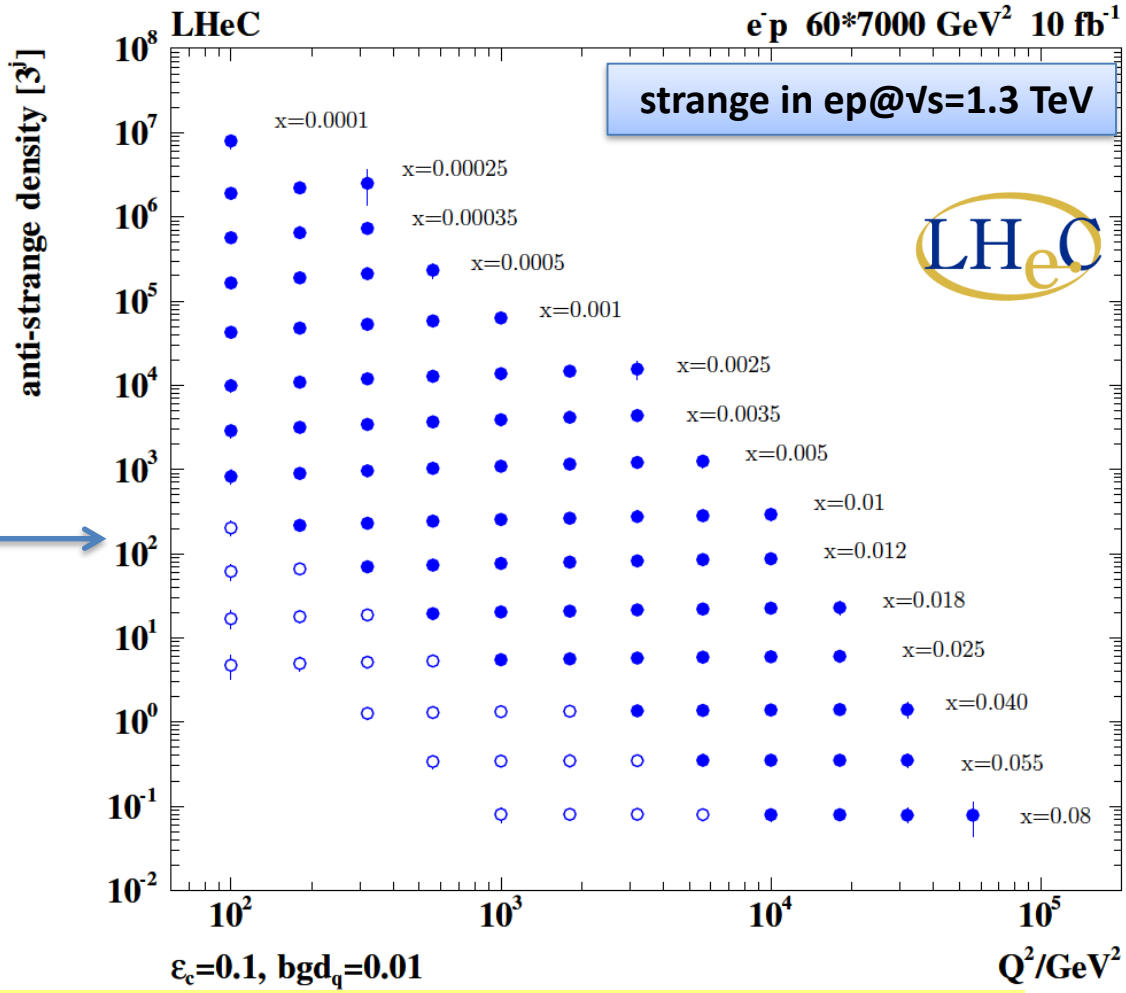
# Strange Strange Quark Distributions

**Evidence of enhanced strange-to-light sea density at x~0.01**

ATLAS 2016: 1612.0301, PRD

➔ based on high precision W and Z data and ~ 5 years of analysis and joint HERA+ATLAS QCD fit




**LHeC : Precision measurement of strange, also of charm, beauty and top → N$^3$LO**

**→ Complete unfolding of the flavour structure of the proton for the first time**

**→ Enables and requires a new kind of PDF fits and clarification of HFL scheme**

# $\alpha_s(\mu)$ at LHeC/FCCeh

M Klein, FCC Week2018

| case | cut [$Q^2$ (GeV$^2$)] | uncertainty | relative precision (%) |
|---|---|---|---|
| HERA only | $Q^2 > 3.5$ | 0.00224 | 1.94 |
| HERA+jets | $Q^2 > 3.5$ | 0.00099 | 0.82 |
| LHeC only | $Q^2 > 3.5$ | 0.00020 | 0.17 |
| LHeC+HERA | $Q^2 > 3.5$ | 0.00013 | 0.11 |
| LHeC+HERA | $Q^2 > 7.0$ | 0.00024 | 0.20 |
| LHeC+HERA | $Q^2 > 10.$ | 0.00030 | 0.26 |

CDR 2012

Table 3: Results of NLO QCD fits to HERA data (top, without and with jets) to the simulated LHeC data alone and to their combination, for details of the fit see [5]. The resulting uncertainty includes all the statistical and experimental systematic error sources taking their correlations into account. The LHeC result does not include jet data.

- LHeC/FCCeh lead to 0.1% uncertainty (stat+syst), free of previous DIS deficiencies (HT,nc)
- Joint determination with parton distributions (maybe simplified as H1 published in 2001)
- Needs clarity about low x behaviour as this uses DGLAP.
- Requires to control heavy flavour (theory) at new level (measure s, c, b, t also)
- Very high precision of NC (y and Z) and CC and extension to x near 1 will drastically reduce the PDF parameterisation uncertainties
- Scale uncertainties require that N$^3$LO formalism be applied (the bizarre 1/2 .. 2 rule.??)
- The attempt to measure the strong coupling in DIS to permille accuracy requires nothing less than a renaissance of experimental and theoretical DIS (ep) physics

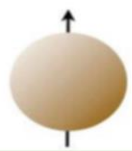
and do not forget strong coupling measurements from polarised DIS!

# The Proton Spin

J Qiu, DSI2018

- **The sum rule:** $$S(\mu) = \sum_f \langle P,S|\hat{J}^z_f(\mu)|P,S\rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$
  - Infinite possibilities of decompositions – connection to observables?
  - Intrinsic properties + dynamical motion and interactions
- **An incomplete story:** … after more than 20 years of efforts … see Spin WG Summary !

See H. Gao's Plenary Talk



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96, …

**Quark helicity**
**Best known**

$$\frac{1}{2}\int dx\left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$
$$\sim 30\%$$

**Gluon helicity**
**Start to know**

$$\Delta G = \int dx \Delta g(x)$$
$$\sim 40\% (\text{with RHIC data})$$

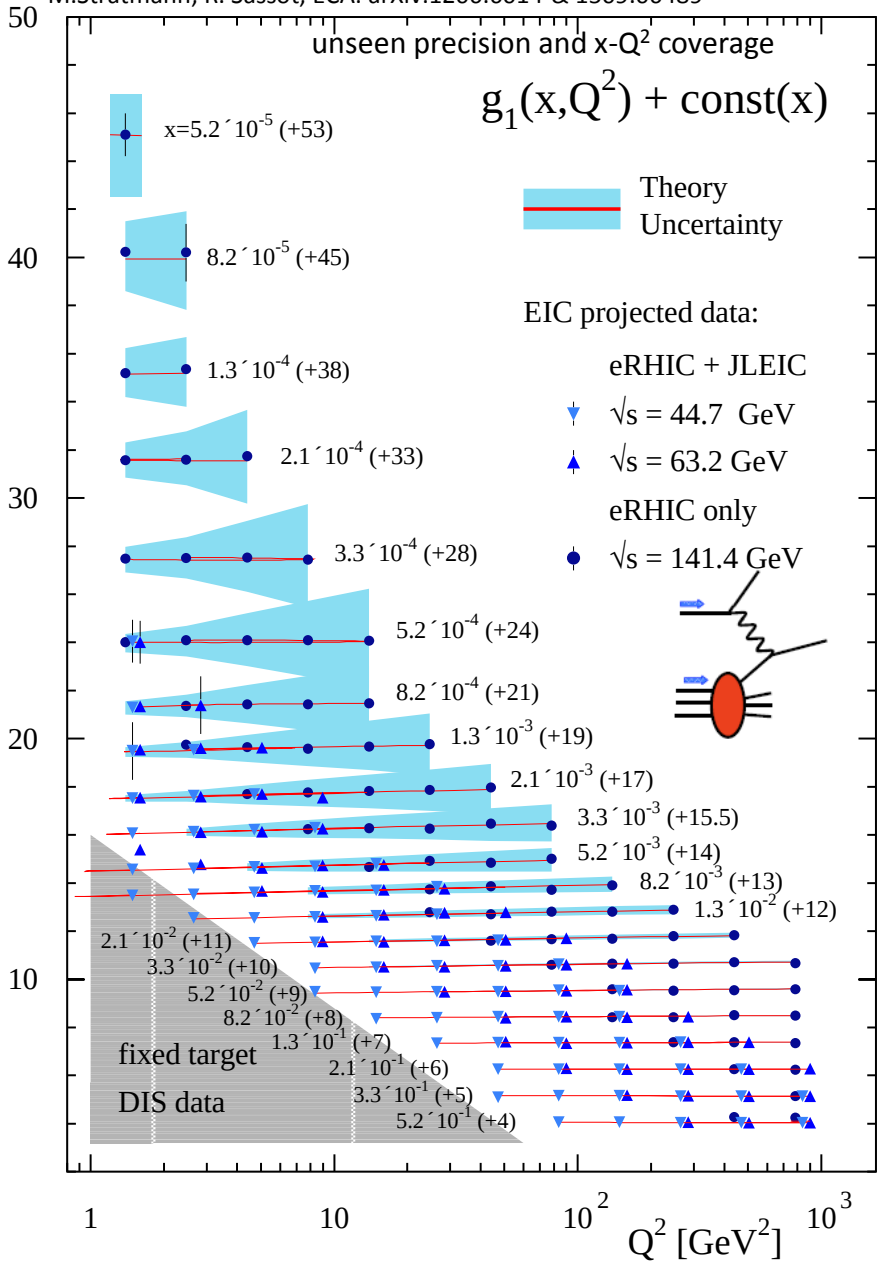
**Orbital Angular Momentum of quarks and gluons**
**Little known**

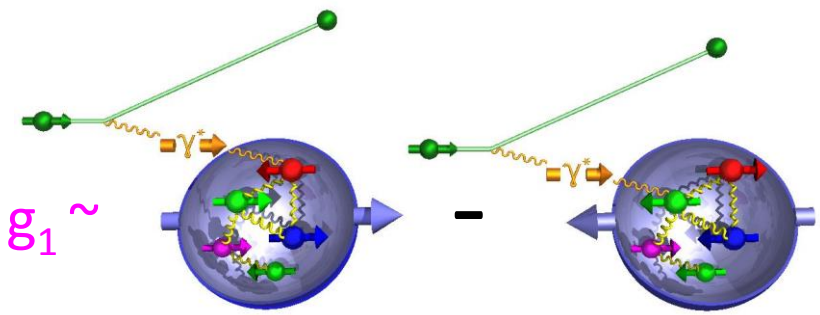
*Net effect of partons' transverse motion?*

**How to explore the polarised gluon and sea quark contribution fully?**
**How to quantify the role of orbital motion?**

# Spin at EIC: ΔΣ & Δg

M.Stratmann, R. Sassot, ECA: arXiv:1206.6014 & 1509.06489




pQCD scaling violations

$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x,Q^2)$$

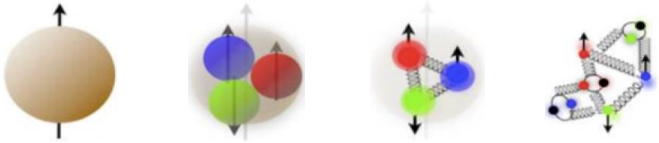
$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$

→ **Excellent EIC prospects!**

- **extremely challenging measurement**
- **spin asymmetries very small for x→0**
- **needs excellent control of detector stability, polarisation measurements and measurements of $F_2$ and $F_L$**

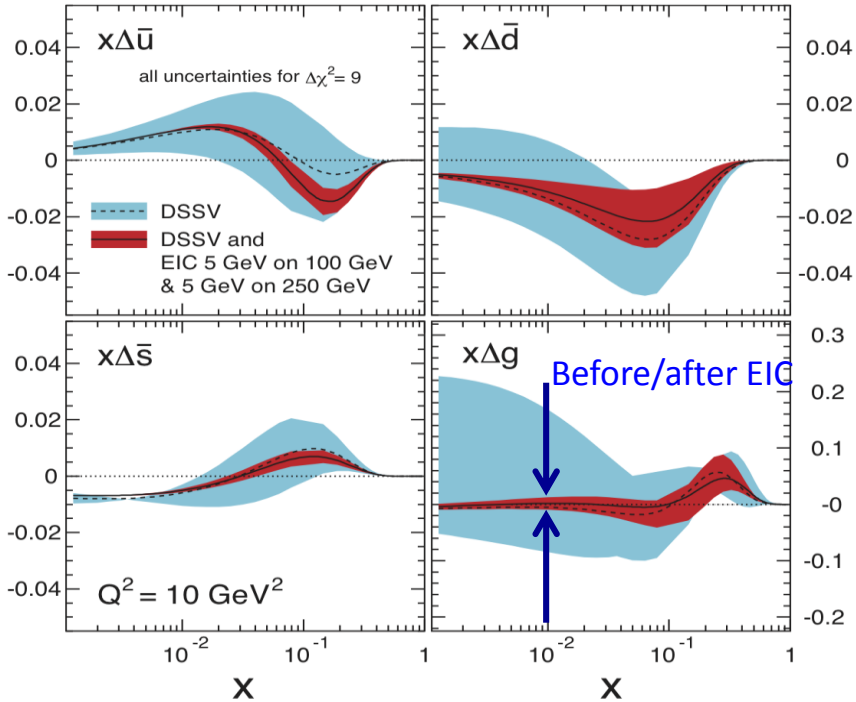
# Proton Spin @ EIC

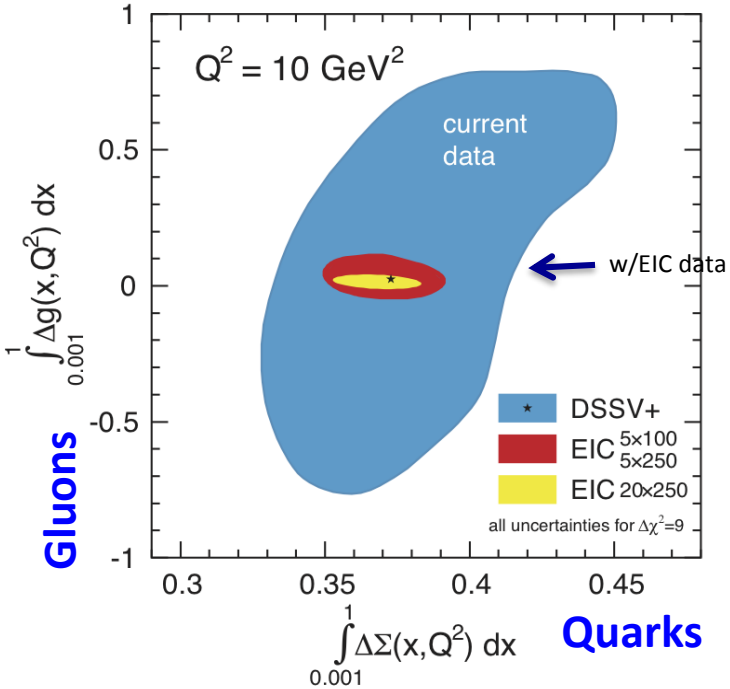
$S(\mu) = \frac{1}{2}$



$\mu \Rightarrow \infty$

**Requires longitudinally polarised hadron and electron beams ➔ unique for EIC !**




- ✧ *Precision measurement of ΔG and ΔΣ via extension to smaller x regime*
- ✧ *Orbital angular momentum?*

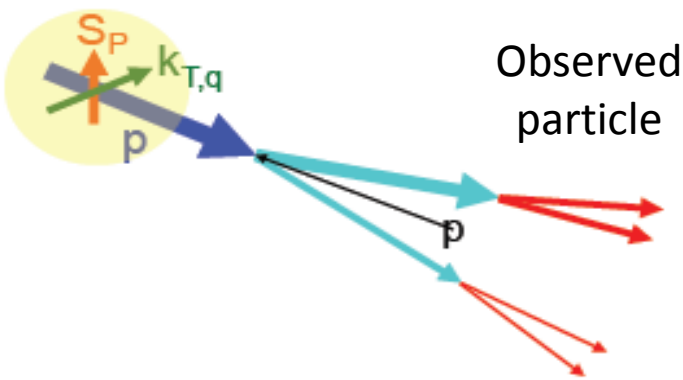
  → *(Spatial distance from origin) X (Transverse Momentum)*

# Explore Spin & Quantum Correlations

EIC: transversely polarised hadron beam

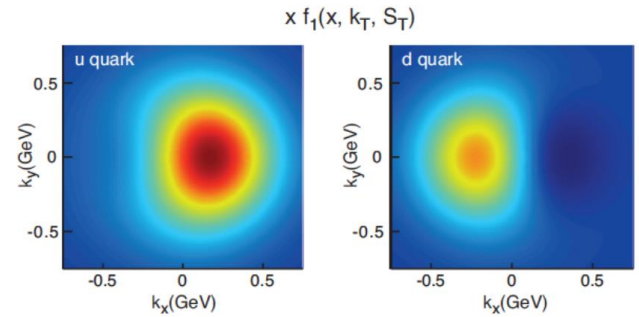
## Quantum correlation between hadron spin and parton motion:

Sivers effect – Sivers function

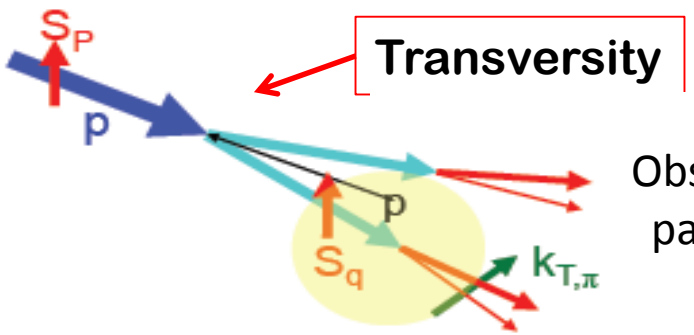



Observed particle

**Hadron spin influences density of unpol. partons in transverse-momentum plane**




## Quantum correlation between parton spin and hadronization:




Observed particle

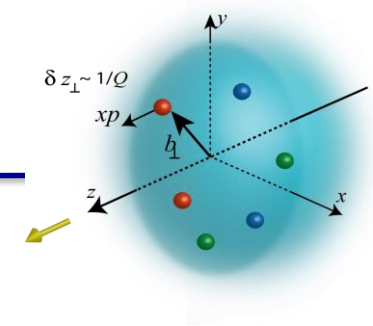
Collins effect – Collins function

**Parton's transverse spin influence its hadronization**

***JLab12 GeV upgrade and COMPASS for valence, EIC covers sea-quarks and gluon!***

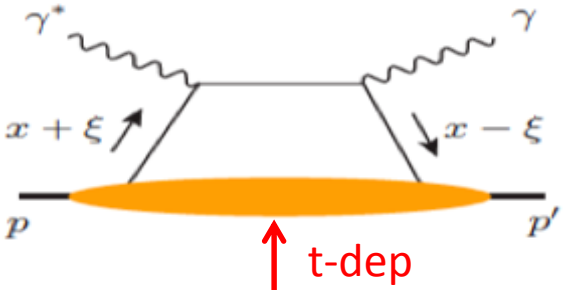
➔ connection of observables to L remains a theoretical challenge

# Spatial Imaging of Partons &




**Ji Sum Rule** $\lim_{t\to 0} \int x dx [H_f(x,\xi,t)+E_f(x,\xi,t)] = 2\, J_f$

## Exclusive processes - DVCS:




$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$t = (p' - p)^2$$

$$\xi = (P' - P)\cdot n/2$$

F.T. of t-dep

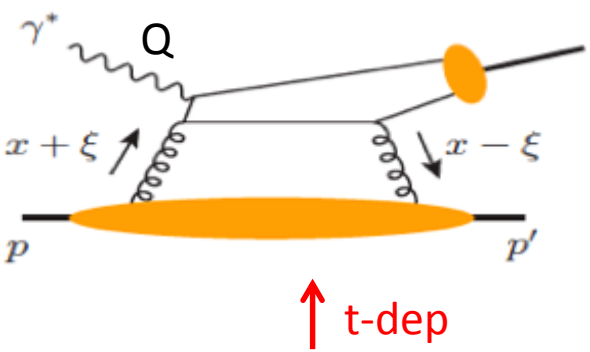
**GPDs**

$$H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$$

Spatial distributions of valence quarks and sea-quarks at large and medium x values

## Exclusive vector meson production:

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

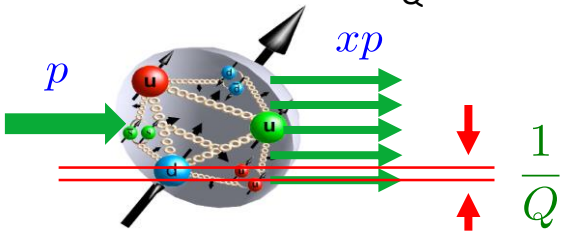



J/Ψ, Φ, …

✧ Fourier transform of the t-dependence

→ Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$



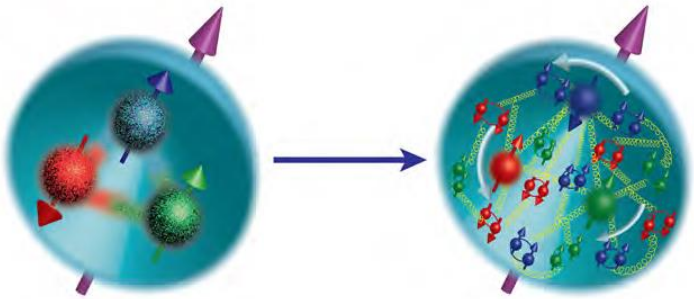

→ Collect as *much flavour-separated* data as possible on TMDs and GPDs

→ **Huge experimental task!**

3-dimensional exploration of nucleon has ~~just~~ started:
collect as much data as possible on TMDs and GPDs
and try to reconstruct the complete phase-space distribution

M Anselmino, 2010

ideal machine:
high luminosity
x-range including the valence region
$Q^2$ high enough to neglect higher-twist corrections
$P_T$ high enough to see transition from TMDs to pQCD
precise $P_T$-$Q^2$ bins
measure jet asymmetries....



plenty of challenging theoretical issues....

**Status of Ji Sum Rule**
C Hyde, DIS2018

- $H_f(x,0,t)$ essentially known from fits to $F_{1f}(-t)\otimes q_f(x)$
  - Measure $H_f(x,x,t)$ → Determines DD Profile function
  - JLab 12 → higher $x$, $Q^2$ range
- $E_f(x,0,t)$ constrained from $F_{2f}(-t)$ and *assumption* $e_f(x)$ does not change sign.
  - Test this assumption
    - x≈0.1 COMPASS 2020
    - x≈0.4 Jlab12
    - Lattice QCD
- My prediction: In 10 years, we will be confident in value of $J_{u,d}$

Based on slides from Y Aoki, DIS2018

# Proton spin "puzzle"

'solved' on the Lattice?

- Nucleon Spin and Momentum Decomposition Using Lattice QCD Simulations
  - ETMC: C. Alexandrou et al [PRL 119 (2017) 142002]
  - using Ji's gauge invariant decomposition

$$J_N = \sum_{q=u,d,s,c\cdots} \left(\frac{1}{2}\Delta\Sigma_q + L_q\right) + J_g$$

TABLE II: Our results for the intrinsic spin ($\frac{1}{2}\Delta\Sigma$), angular ($L$) and total ($J$) momentum contributions to the nucleon spin and to the nucleon momentum $\langle x \rangle$, in the $\overline{\text{MS}}$-scheme at 2 GeV, from up (u), down (d) and strange (s) quarks and from gluons (g), as well as the sum of all contributions (tot.), where the first error is statistical and the second a systematic due to excited states.

| | $\frac{1}{2}\Delta\Sigma$ | $J$ | $L$ | $\langle x \rangle$ |
|---|---|---|---|---|
| u | 0.415(13)(2) | 0.308(30)(24) | -0.107(32)(24) | 0.453(57)(48) |
| d | -0.193(8)(3) | 0.054(29)(24) | 0.247(30)(24) | 0.259(57)(47) |
| s | -0.021(5)(1) | 0.046(21)(0) | 0.067(21)(1) | 0.092(41)(0) |
| g | - | 0.133(11)(14) | - | 0.267(22)(27) |
| tot. | 0.201(17)(5) | 0.541(62)(49) | 0.207(64)(45) | 1.07(12)(10) |

40% from L

- on-physical point simulation
- only one lattice spacing
- total J consistent with 1/2
  claiming
  "resolving a long standing puzzle"
- systematic errors not fully investigated
  - twisted mass → isospin violation should be investigated
  - adding another lattice spacing will help!

→ **Lattice calculations have been impressively improving over the past decade**

→ **Lattice calculations 'deserve' to be challenged by precise and accurate measurements for fundamental QCD properties like proton spin&mass and the strong coupling as they could be enabled by EIC and LHeC.**

# … to take home …

**Deep Inelastic lepton-Nucleon Scattering is a fantastic and unique tool to study nucleon structure and unravel QCD (mass, spin, 3D nucleon structure, nucleon's flavour structure, N$^3$LO, $\alpha_S$) and search for BSM and Higgs physics** (not discussed here)

**with high precision data and and on firm theoretical grounds.**

**Luminosity and excellent detectors are KEY for a new level of PRECISION in DIS.**

The quest of new generation DIS machines is now imminent: for a full exploitation of our highest energy machine(s) and for unraveling the secrets of nuclear and particle physics: by employing fully the complementarity of ee, ep and pp – in the tradition of Tevatron, HERA & LEP side by side with a wealth of Fixed Target experiments.

**The future of DIS experiments is bright with wealth of new proposed machines for various energy ranges to tackle 'old' and 'new' problems -**

**to explore the *'unknown knowns and unknown unknowns'***

# Thank You!

Special thanks to my ‘old’ and ‘new’ colleagues in the LHeC/FCC-study group, and the EIC colleagues R Ent, B Surrow, R Yoshida, E Aschenauer, J Furletova.

A very warm Thank You to the spirit of this DIS conference, guided by the endless efforts of Y Yamazaki.

And sorry, if I missed to mention someone’s name here.

All mistakes are mine.

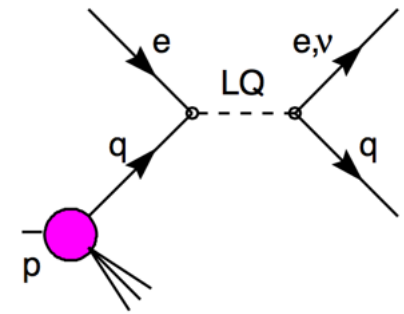
# Additional Material

# Exploring SM EFT & New Physics

M. Trott @ LHeC Workshop 2014
http://lhec.web.cern.ch

*In the absence of any explicit new states, or overwhelming theory prejudice, the goal is to systematically study the SM EFT for hints of NP, using all possible future facilities to maximize physics conclusions.*

*What is the SM EFT? A linear realization of gauge symmetry and the new state is a 0+ scalar:*




*Four fermion operators with leptons and quark fields:*

| $8:(\bar{L}L)(\bar{L}L)$ | |
|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ |

| $8:(\bar{R}R)(\bar{R}R)$ | |
|---|---|
| $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $8:(\bar{L}L)(\bar{R}R)$ | |
|---|---|
| $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

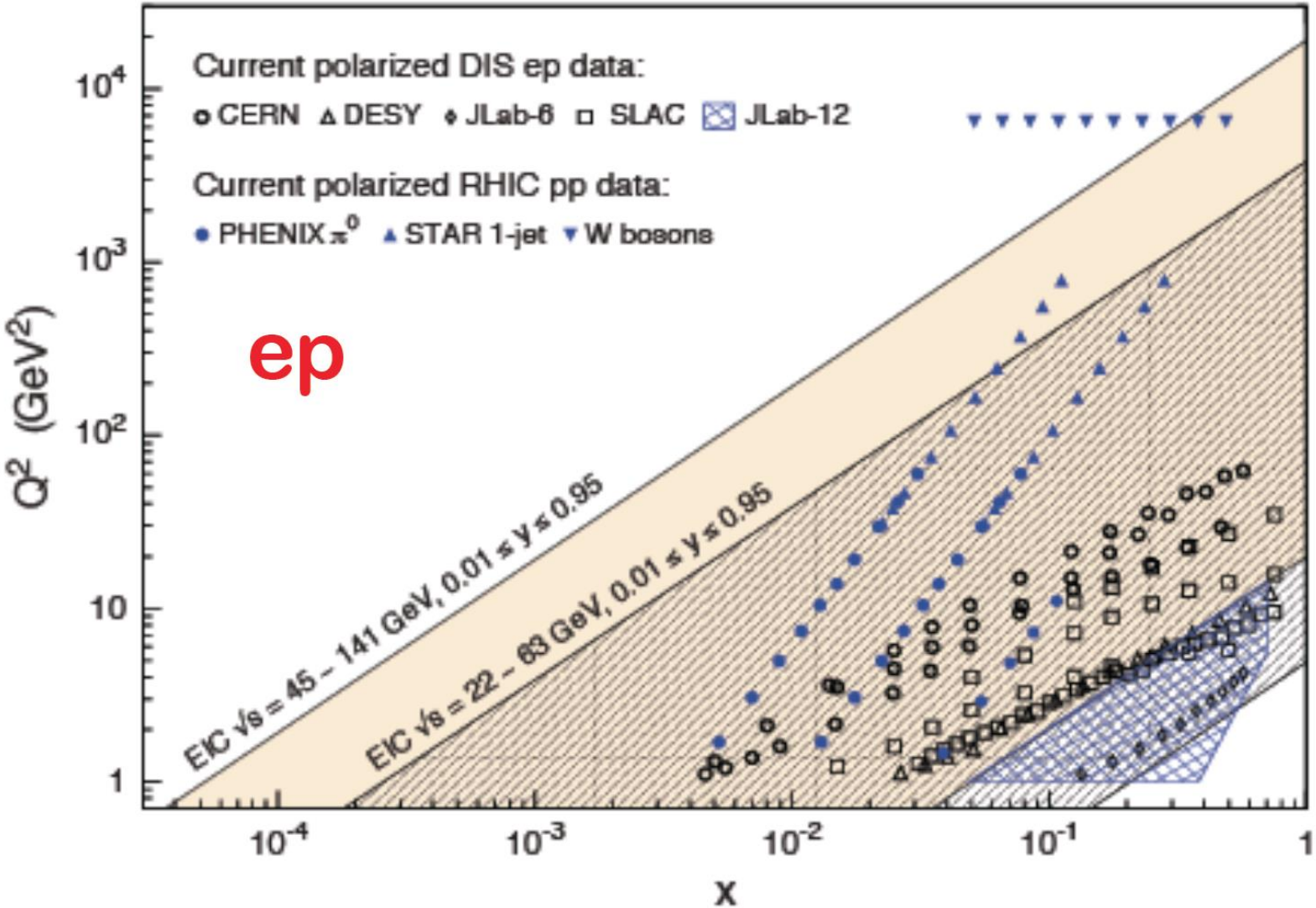
| $8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$ | |
|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$ |

| $8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$ | |
|---|---|
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$ |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$ |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$ |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$ |

- ➔ 59 operators or 2499 parameters experimentally to constraint!
- ➔ where nearly 50% of the parameters (1053) are sensitive to lepton-quark interactions – not just about lepto-quarks
- ➔ **ep potential for general BSM searches 'that look like hadronic noise' in pp**

# Kinematic Plane for Spin

1708.01527



# EIC Science: Nuclei and quarks/gluons (Deuterons)

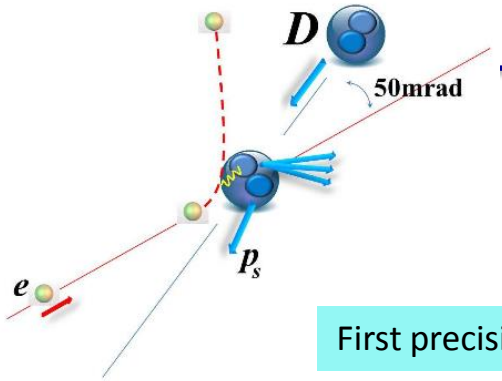
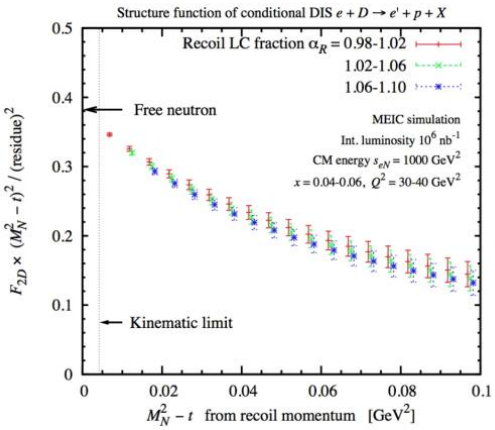



Figure-8 design enables polarized (vector and tensor) deuteron beams (>80% polarization).

Collider → allows a *precision measurement* of the spectator nucleon.

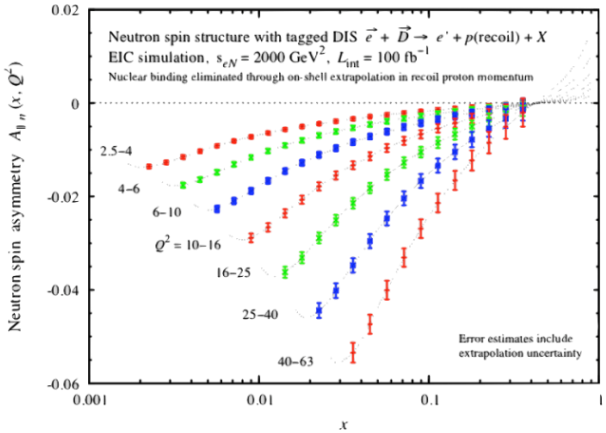
First precision measurement of *polarized* (and unpolarized) neutron is possible at EIC



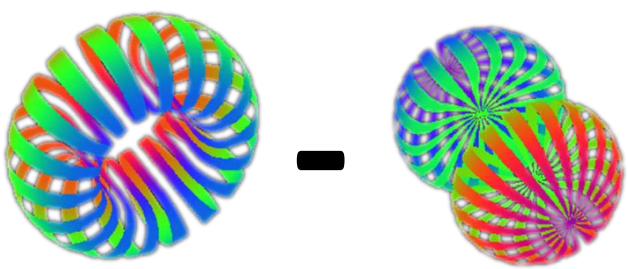

Extrapolation from bound to free neutron under control

$F_2^n$ can be extracted at % level accuracy

Polarized Neutron Structure



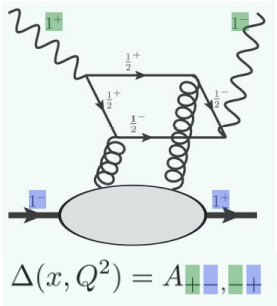

Investigate nuclear effects at the level of partons with Tensor Polarization Observables



Slide from R Ent

Polarized Deuteron Structure Function $b_1$

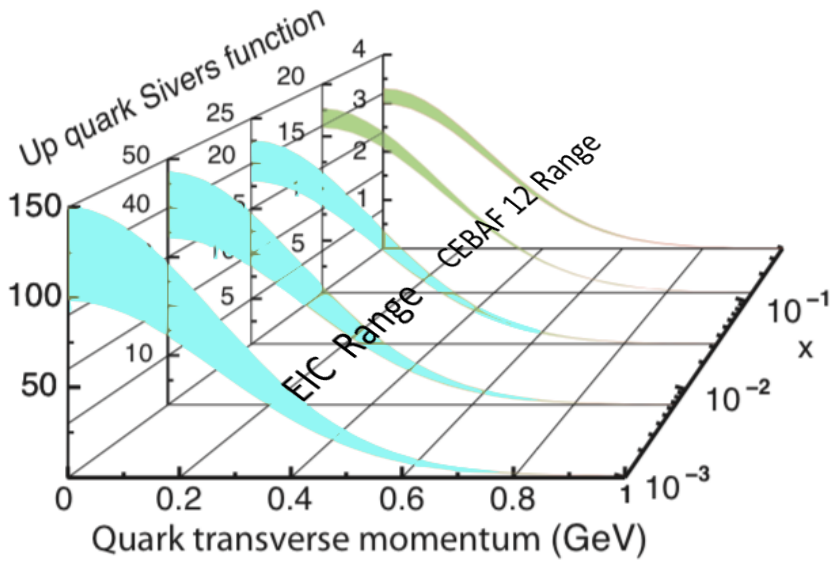
Are quarks sensitive to the shape of the nucleus?



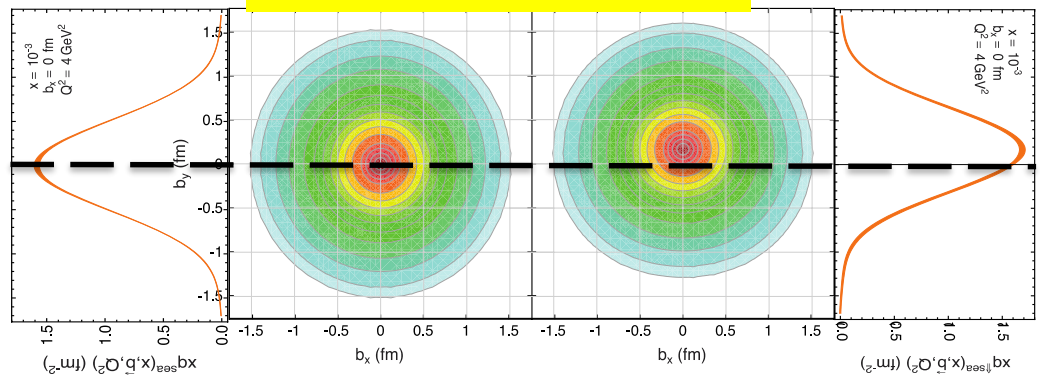

Double helicity-flip distribution $\Delta(x,Q^2)$
→ Gluon Transversity

- Non-nucleonic gluon component!
- Lattice results ≠ 0!

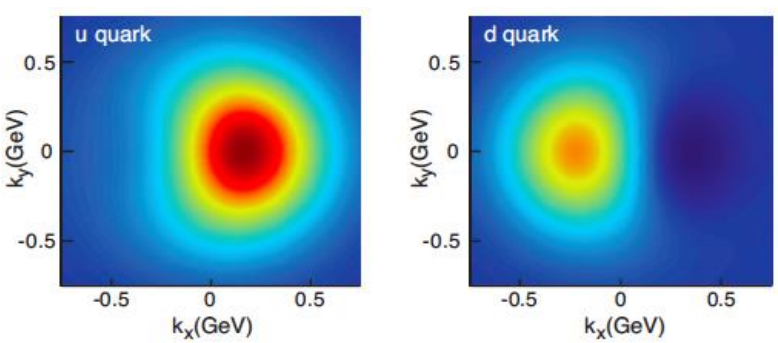
# EIC Science: Imaging quarks and gluons in nucleons



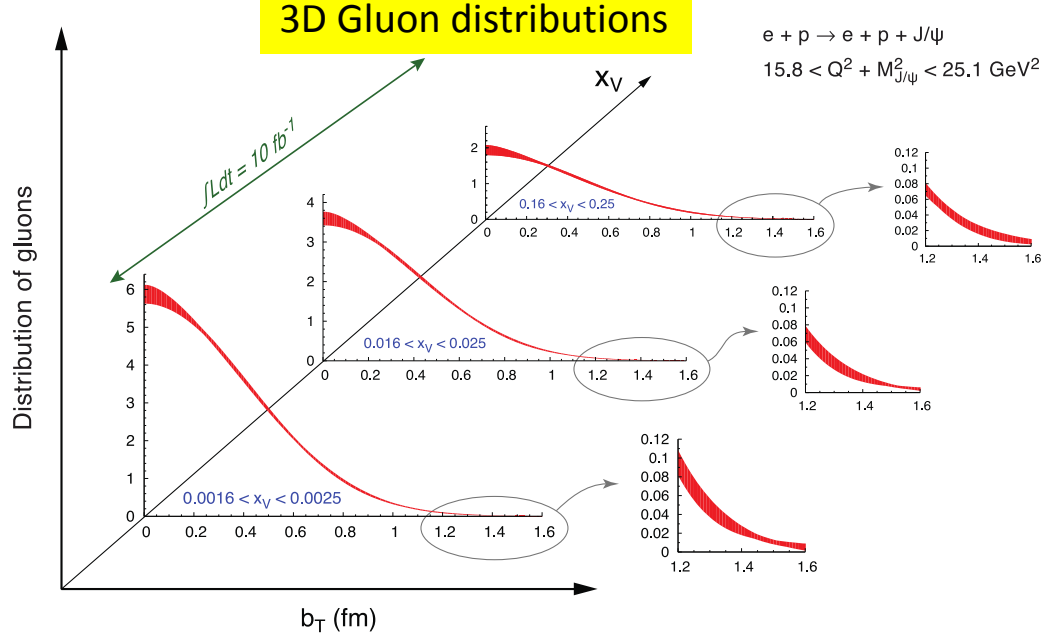

3D Sea Quark distributions unpolarized and polarized




Polarized Quark 3D Momentum distributions




3D Gluon distributions

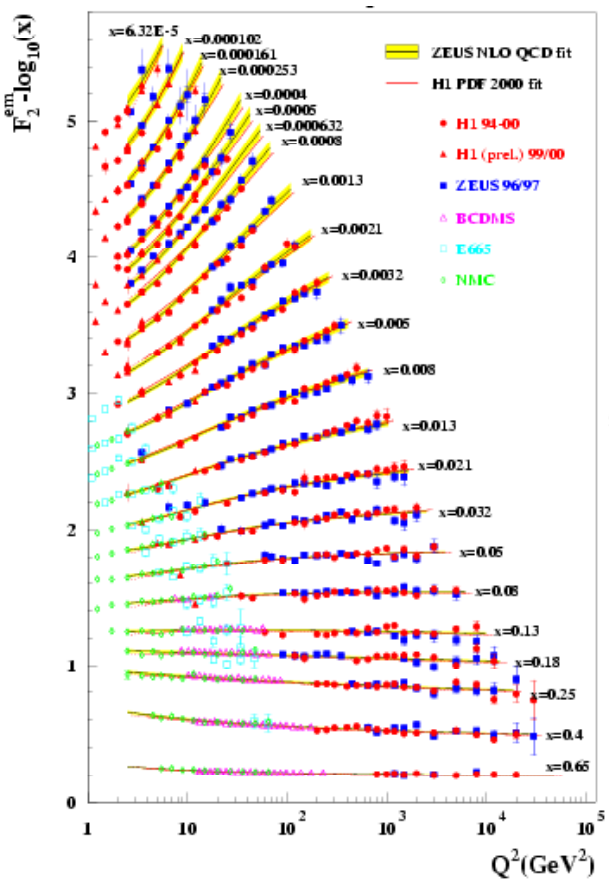


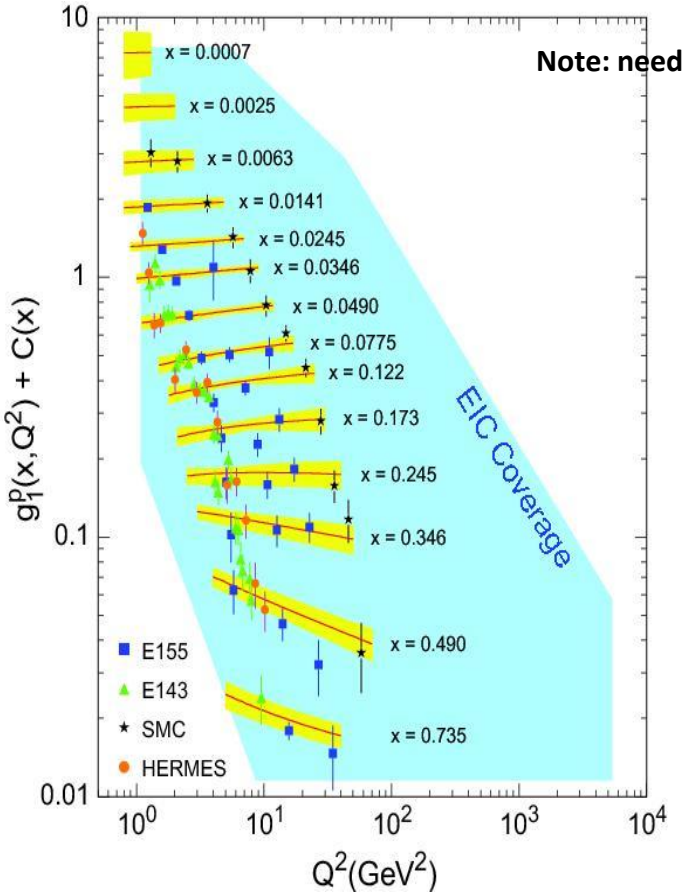

Slide from R Ent

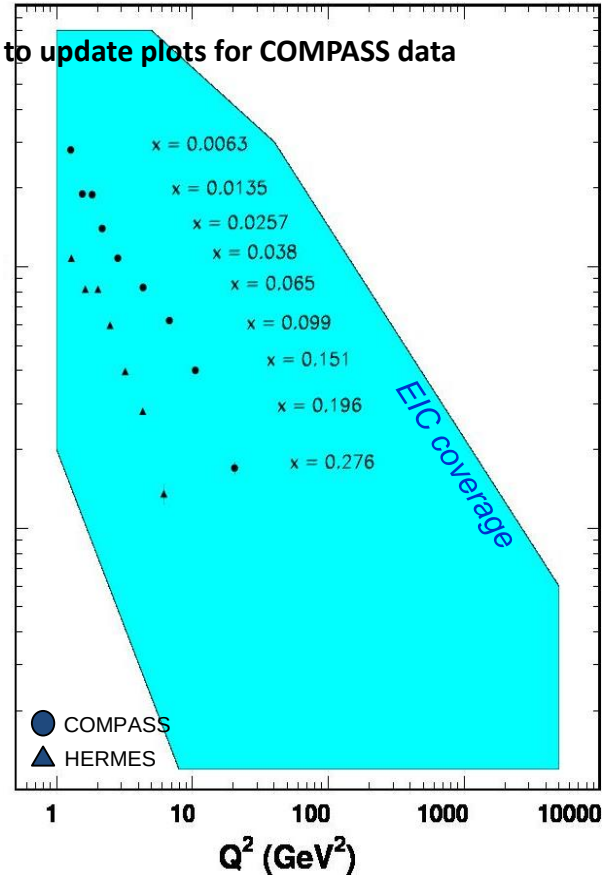
# World Data on $F_2^p$ World Data on $g_1^p$ World Data on $h_1^p$

**An EIC makes it possible!**

**Similar for $F_2^n$** **Similar for $g_2^p$, $g_2^n$ (and $b_1^d$)** $F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$



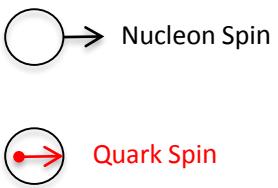

**momentum** **spin** **transverse spin ~ angular momentum**

Based on slide from R Ent

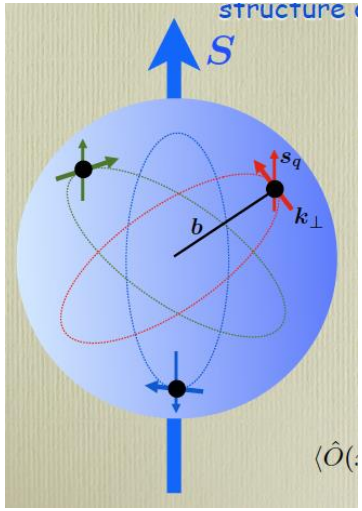
# Transverse Momentum Distributions

- **TMDs - rich quantum correlations:**

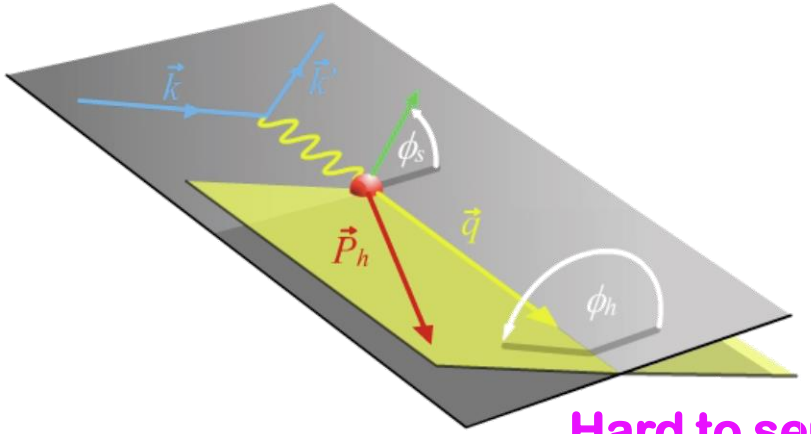
Similar for gluons




| | | Quark Polarization | | |
|---|---|---|---|---|
| | | Un-Polarized (U) | Longitudinally Polarized (L) | Transversely Polarized (T) |
| Nucleon Polarization | U | $f_1 =$ | | $h_1^{\perp} =$ — Boer-Mulders |
| | L | | $g_{1L} =$ — Helicity | $h_{1L}^{\perp} =$ — |
| | T | $f_{1T}^{\perp} =$ — Sivers | $g_{1T}^{\perp} =$ — | $h_1 =$ — Transversity; $h_{1T}^{\perp} =$ — |




- **Naturally, two scales and two planes:**




- ✧ Two scales:
  high Q - localized probe
  Low $p_T$ - sensitive to confining scale
- ✧ Two planes:
  angular modulation to separate TMDs

**Hard to separate TMDs in hadronic collisions**

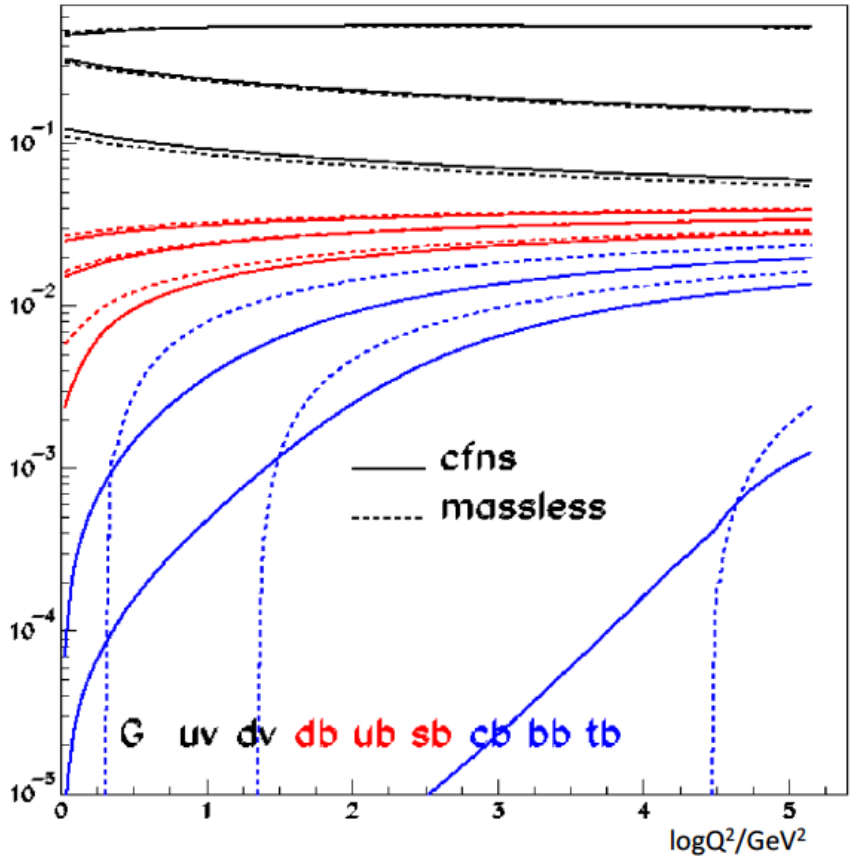
# Top PDF ?

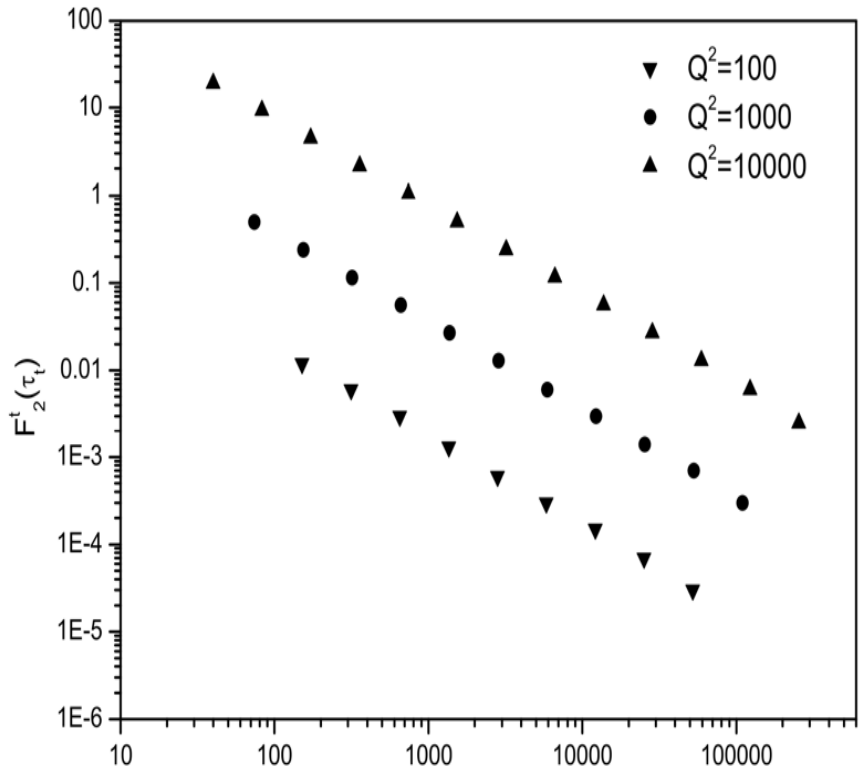
c.f. Talk by M Klein at HL-LHC 10/17

"

At high $Q^2 \sim m_t^2$ top demands a fraction of proton's momentum – need to understand what a "top PDF" is. Scheme dependence

LHeC CDR arXiv:1206.2913




Boroun, Phys. Lett. B744, 142 (2015)

$$\tau_t = (1 + \frac{4m_t^2}{Q^2})^{1+\lambda} \frac{Q^2}{Q_0^2} (\frac{x_B}{x_0})^{\lambda}$$

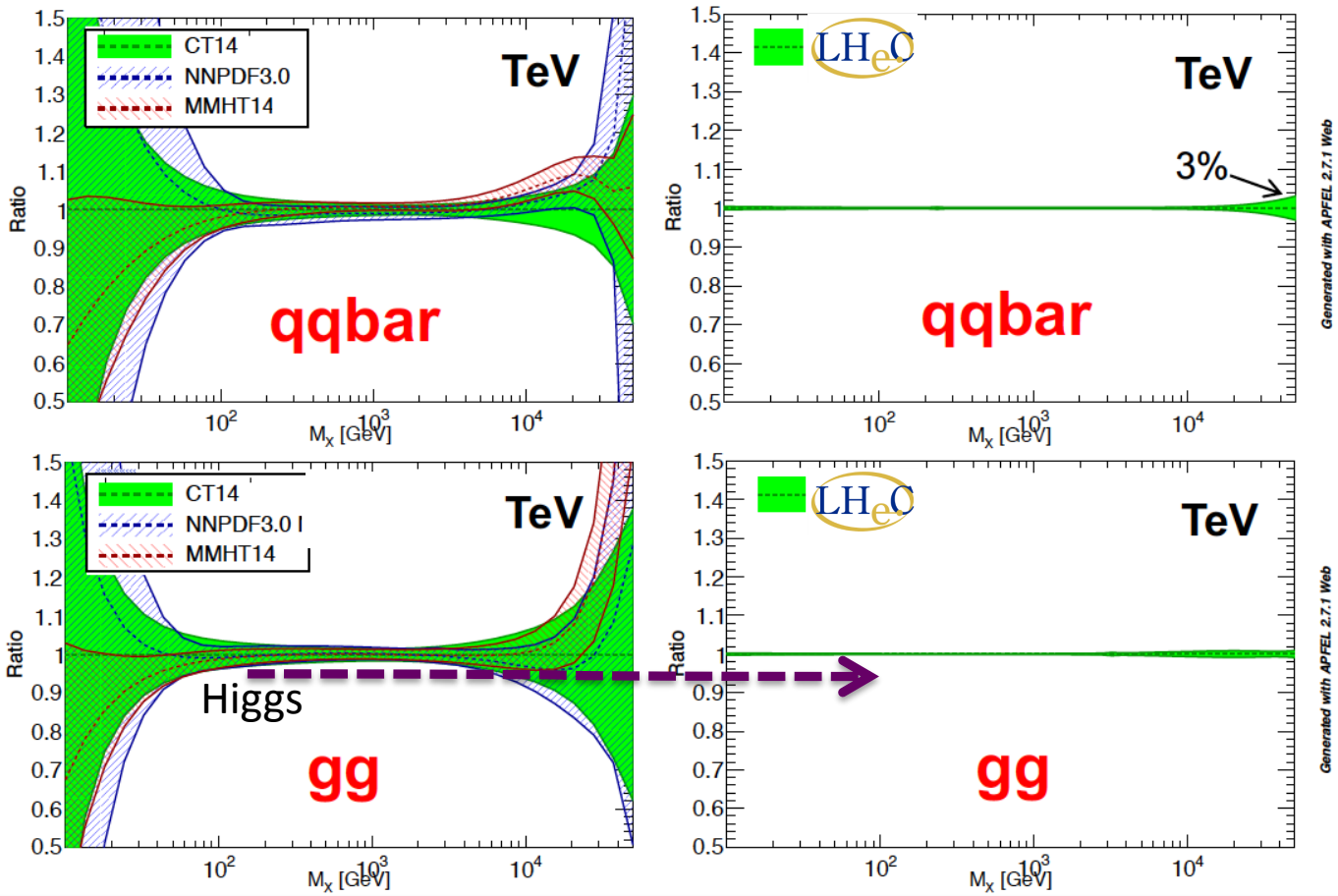
.. a totally new challenge …

# The LHeC PDF Programme

**Resolve parton structure of the proton completely: $u_v$,$d_v$,$s_v$?,u,d,s,c,b,t and xg**
**Unprecedented range, sub% precision, free of parameterisation assumptions,**
**Resolve p structure, solve non linear and saturation issues, test QCD, $N^3LO$…**

Strong Coupling in inclusive DIS at LHeC to 0.1%

Lattice??
Jets??
BCDMS??
GUTs?
Higgs in pp




**Solve the PDF issues for pp and test QCD with permille measurement of strong coupling**

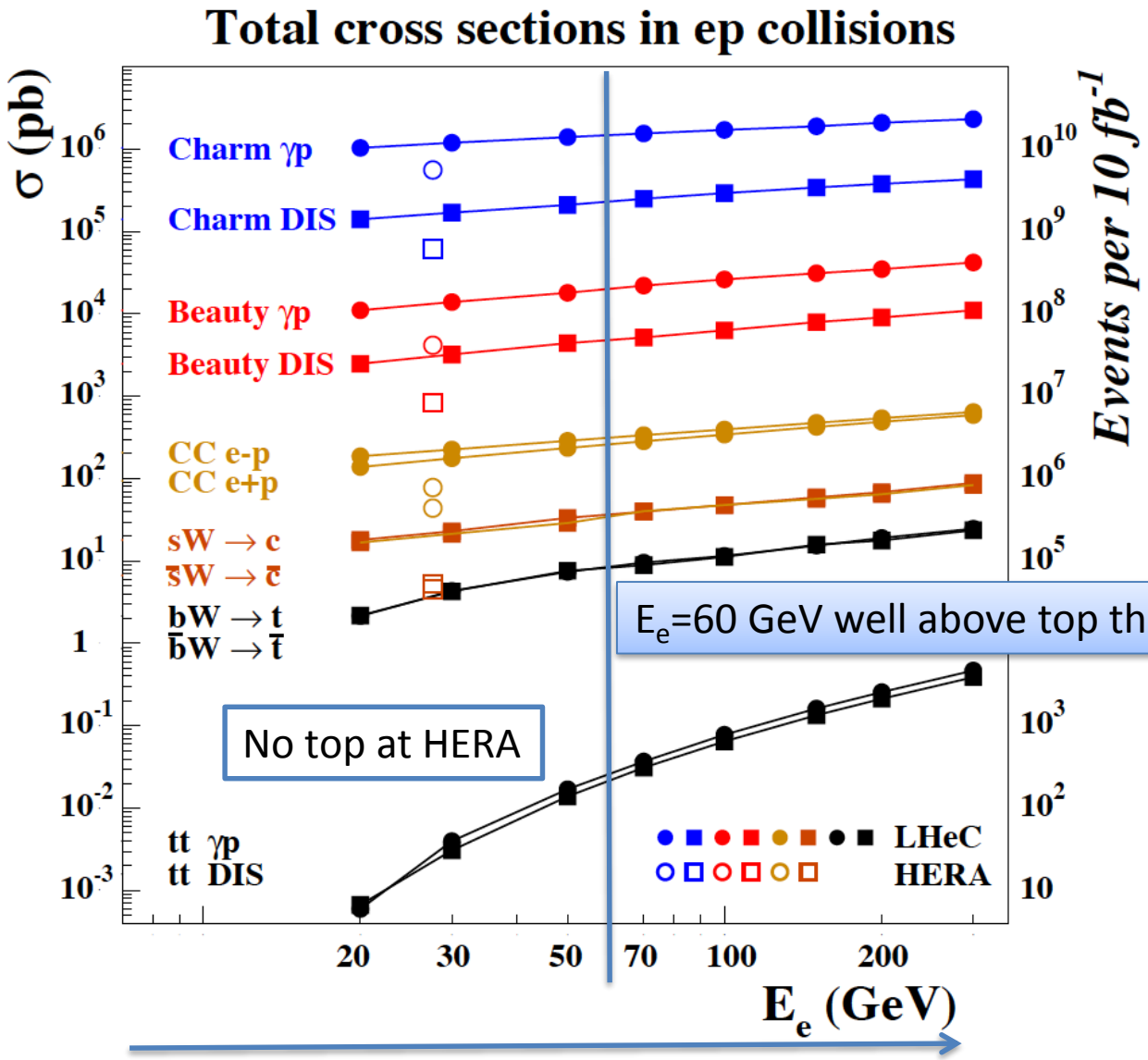
# Plenty of charm, beauty and top

…to explore in detail and with high precision heavy flavour schemes

$E_p$=7 TeV

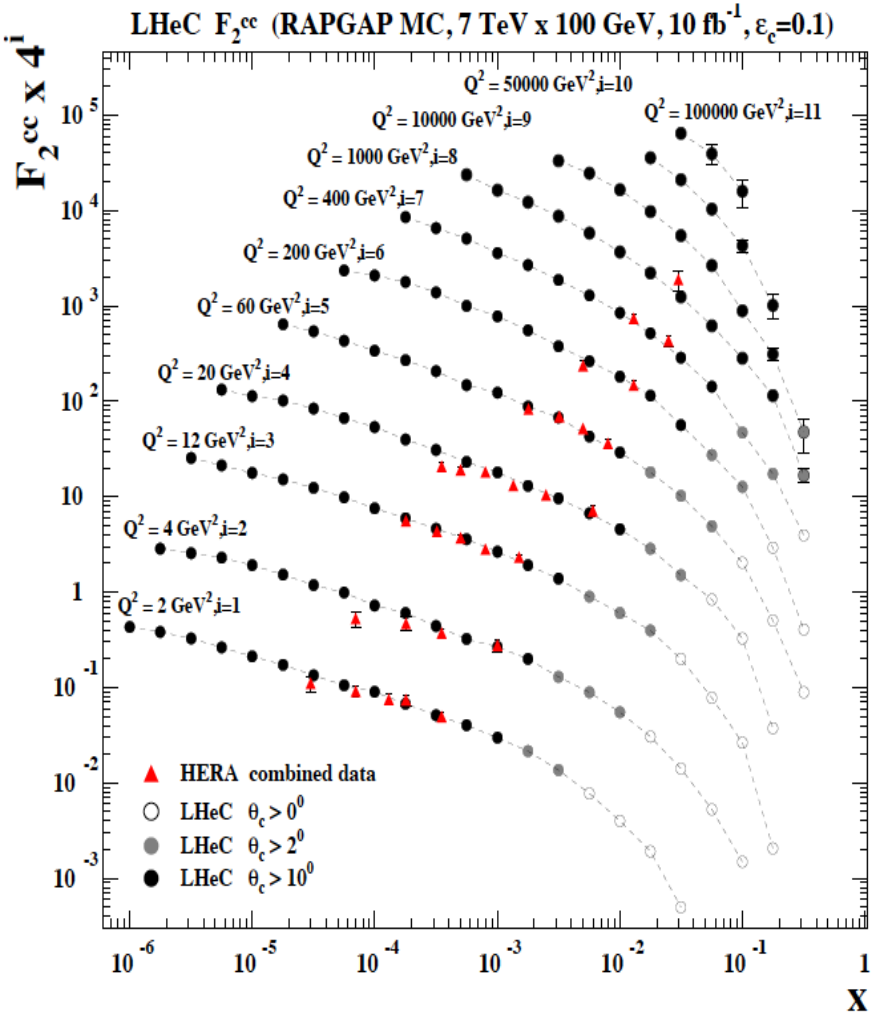
Plot by O Behnke

titl




LHeC CDR arXiv:1206.2913

# Charm $F_2^{cc}$ and Mass




LHeC CDR arXiv:1206.2913

HERA 0.0005 - 0.05 for 2.5-2000 GeV$^2$
LHeC 0.00001- 0.2 for 1-200000 GeV$^2$

ε(c) assumed 10%, 1% light background, ~3% δ(syst)

**Heavy Flavour with LHeC**

Beam spot (in xy): 7μm
Impact parameter: better than 10μm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

| | HERA | LHeC |
|---|---|---|
| $m_c(m_c)$/GeV | 1.26 | ? |
| δ(exp) | 0.05 | 0.003 |
| δ(mod) | 0.03 | ~0.002 |
| δ(par) | 0.02 | ~0.002 |
| $\delta(\alpha_s)$ | 0.02 | 0.001 |

**LHeC determines strong coupling to 0.1%**

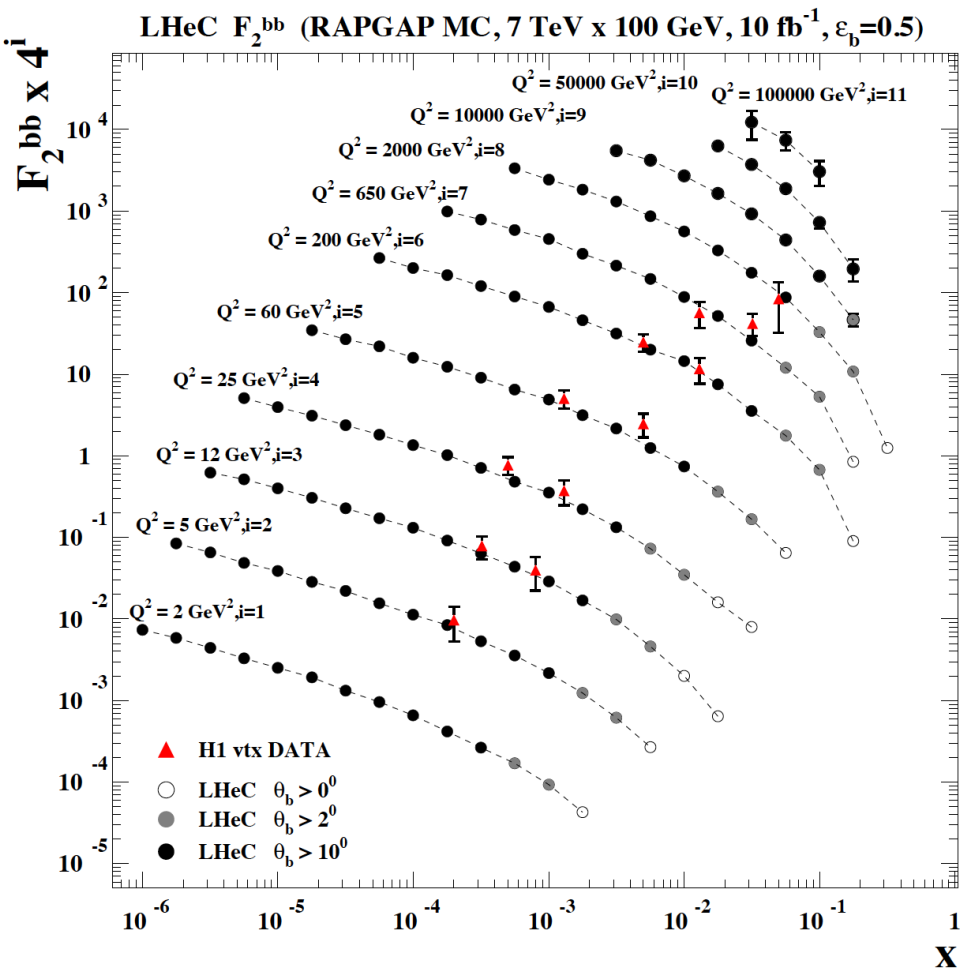
High precision PDF data will reduce the model and parameterization uncertainties.

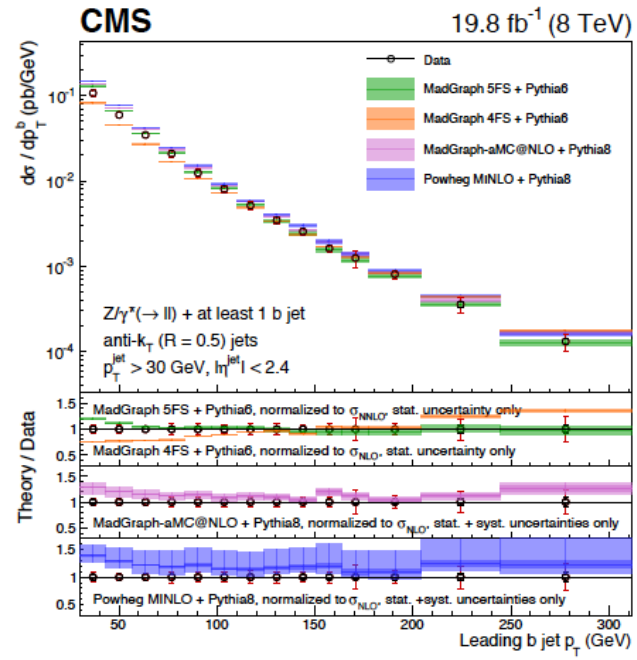
**Determination of charm mass to 3 MeV: crucial for $M_W$ in pp or H→ cc in ep**

cf also NNPDF3.1 (arXiv:1706.00428) and refs

# Bottom $F_2^{bb}$ and Mass

LHeC CDR arXiv:1206.2913




Bottom density not well known

Scheme dependence affects LHC interpretations

In MSSM: Higgs from bb→ H not gg (we only miss the MSSM..)

Huge improvement vs HERA for the same reasons as for charm

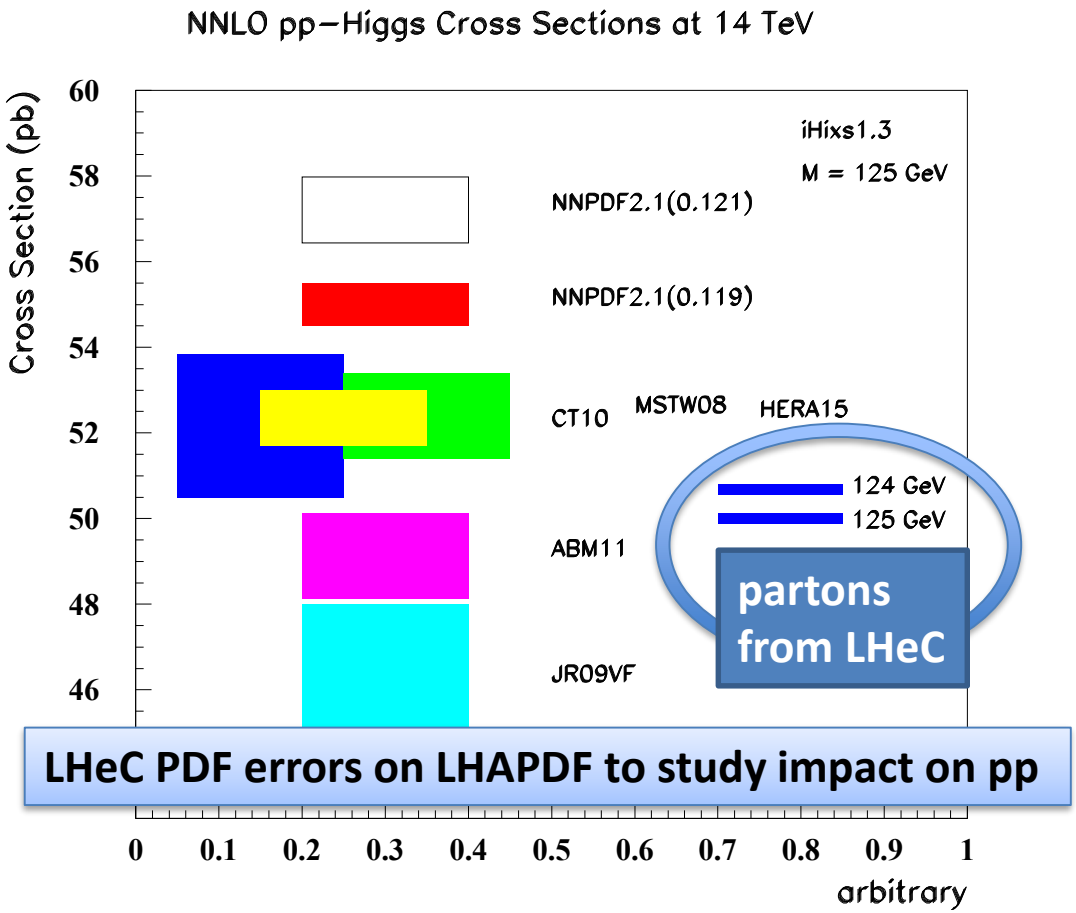
**$m_b(m_b)$ with LHeC to 10 MeV**

# LHeC Precision Partons for Higgs@pp

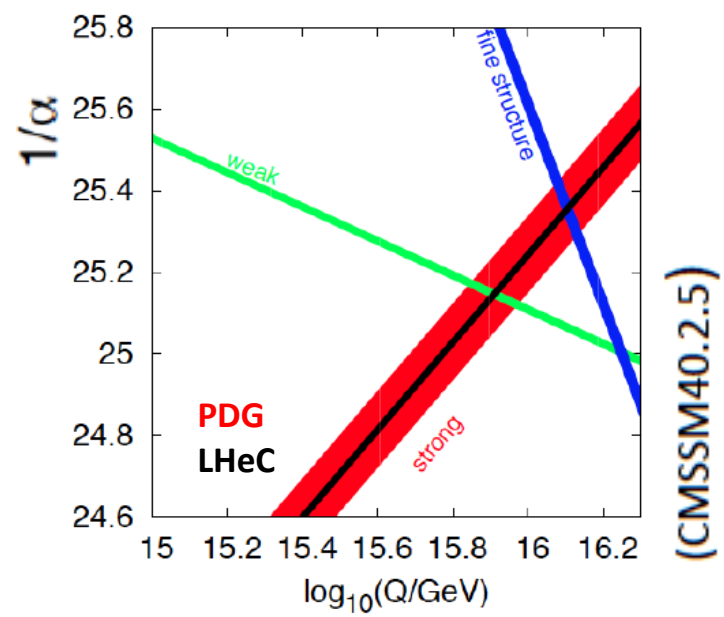
→ **<u>Using LHeC input</u>**: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and $\alpha_S$** is strongly **reduced to <0.5%**

→ ***theoretically clean path to determine N³LO PDFs*** using ep DIS

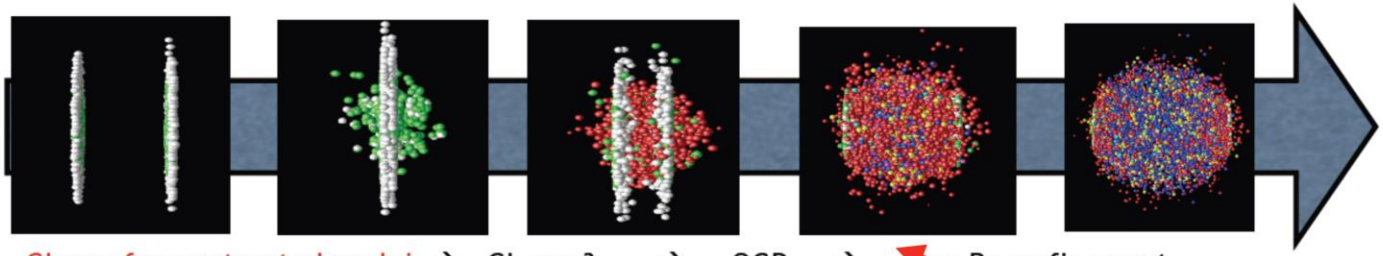
→ ***ALL those 'benefits' for pp within the first few years, using ~100 fb⁻¹ ep data***




→ **precision from LHeC can add a very significant constraint on the Higgs mass** *and challenge Lattice QCD calculations for $\alpha_S$:*



# Synergy : eA and AA

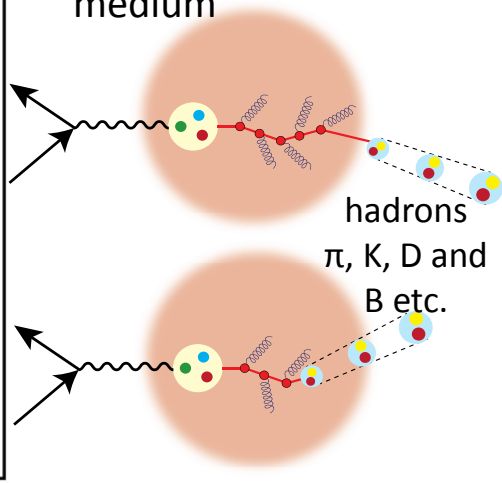
Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?
- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

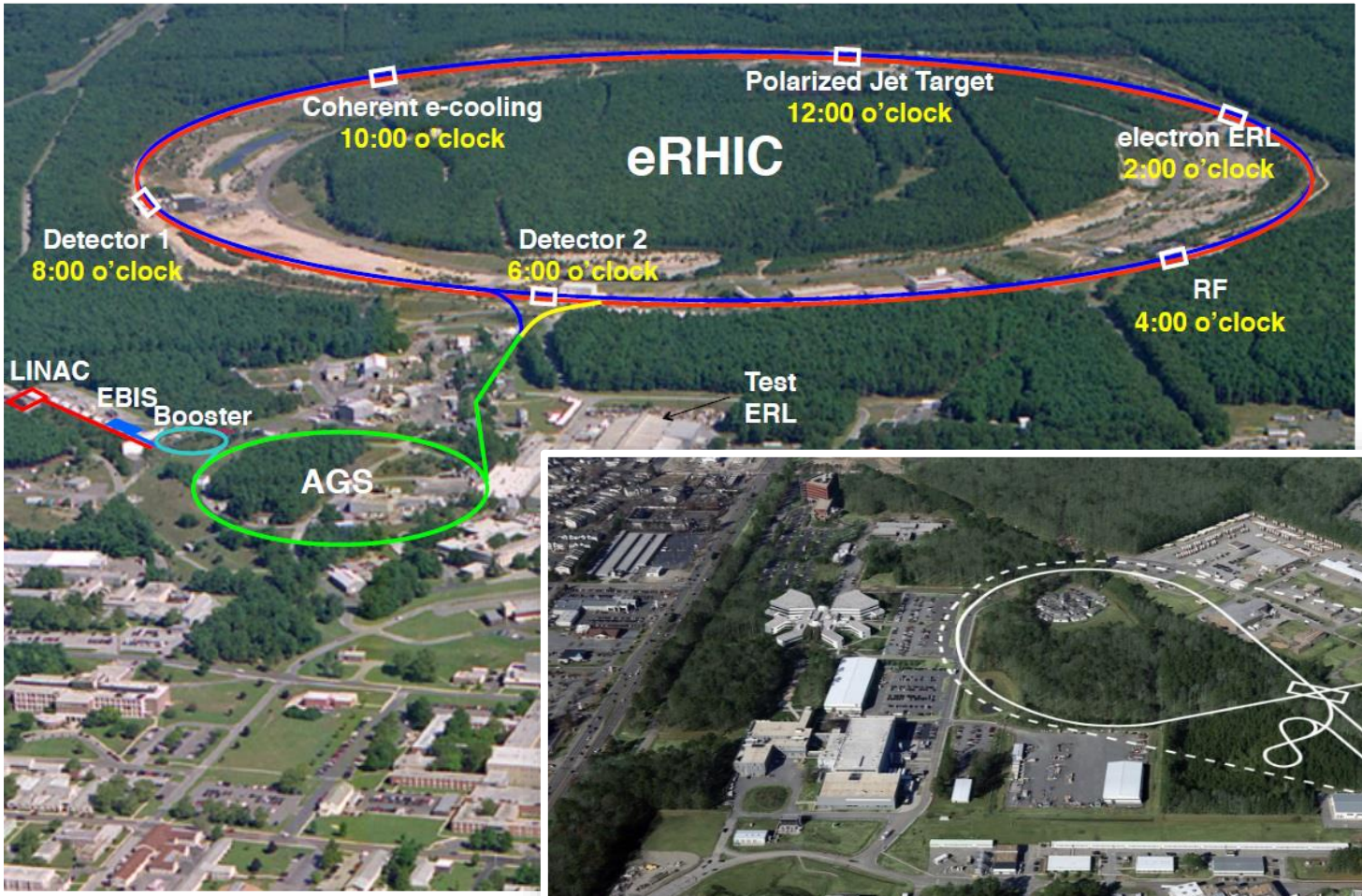
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

**eA**: measure in semi-*inclusive* DIS modification of fragmentation/hadronisation in dense nuclear medium

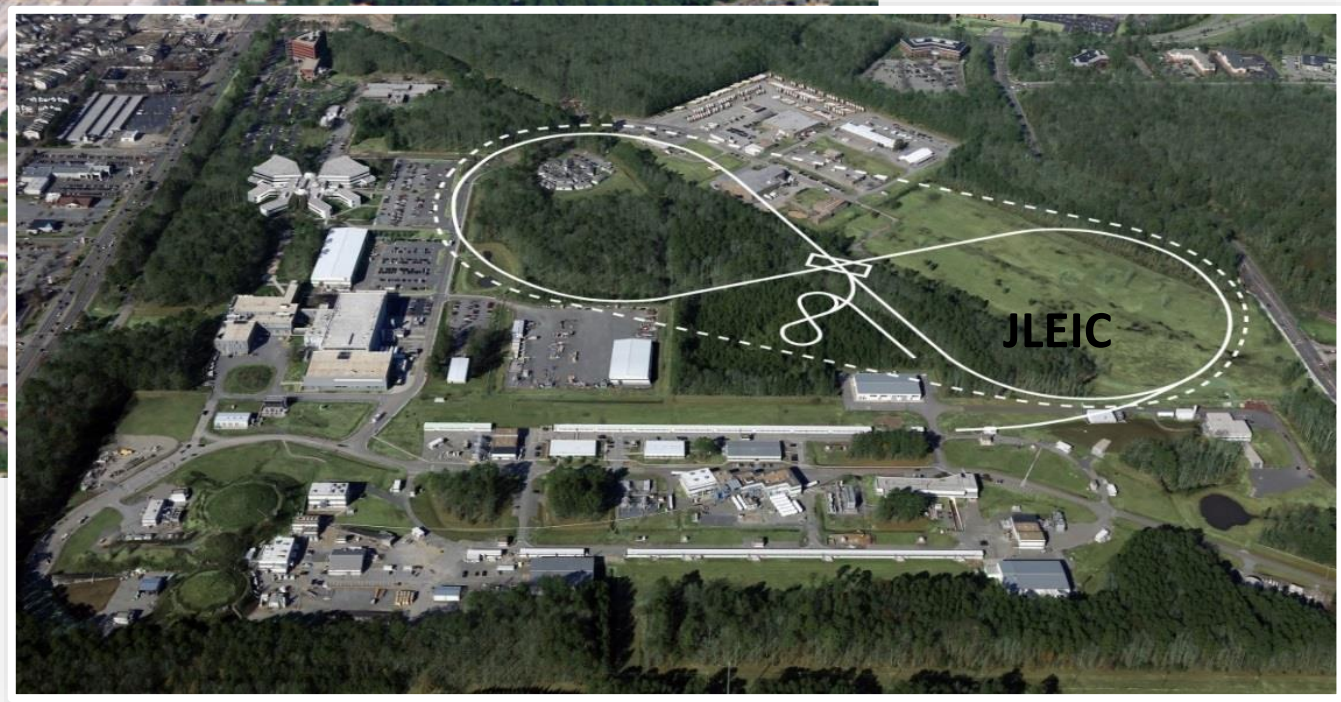



**The LHeC-eA will explore a region overlapping** (EIC-eA partially) **with the LHC-AA**
**➜ in a cleaner experimental setup;**
**➜ on firmer theoretical grounds.**

# US-based EIC's

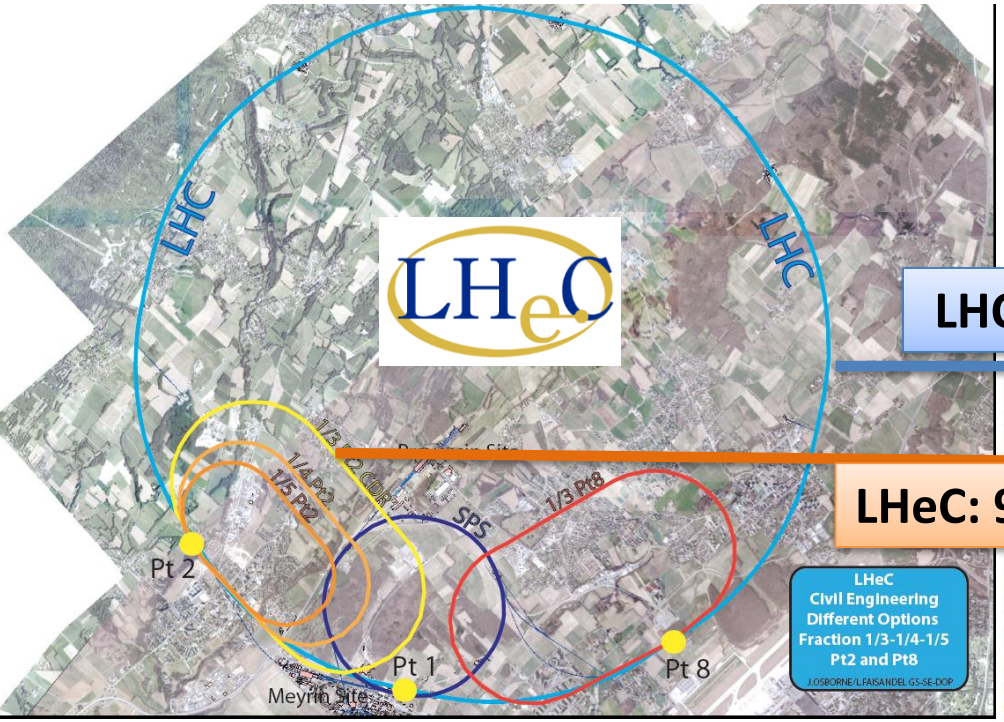



Brookhaven Lab
Long Island, NY




Jefferson Lab
Newport News, VA

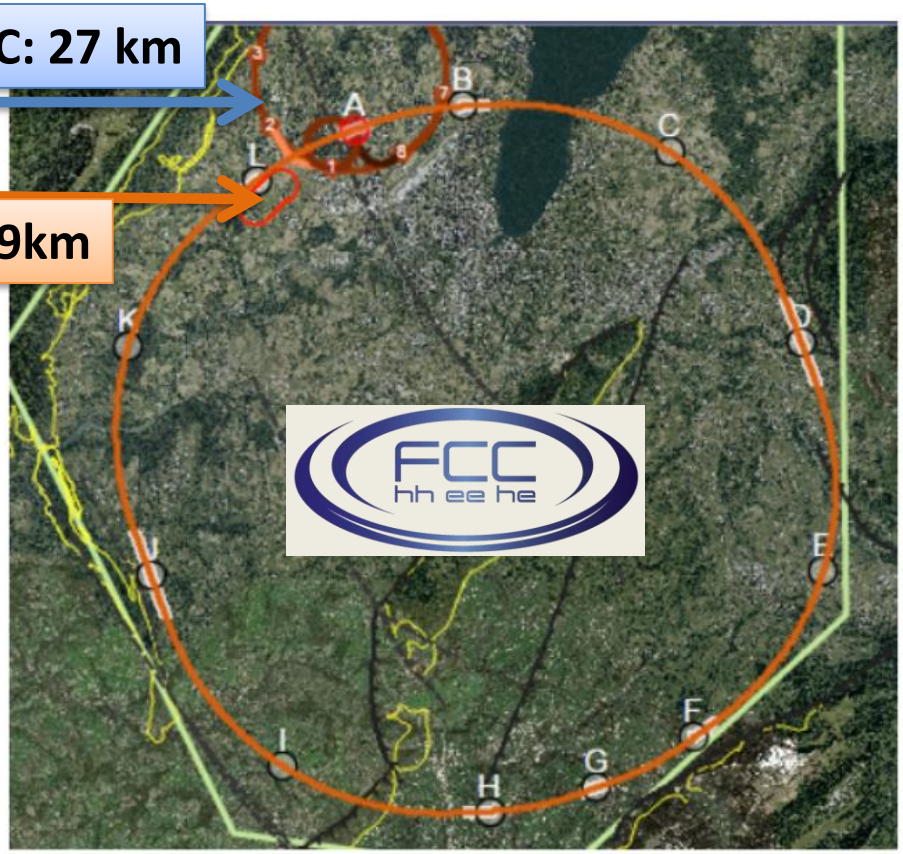
# LHeC and FCC-he: Sites at CERN




FCC-hh (98km)/ HE-LHC: 16 T magnets not before 2040, c.f. M Benedikt FCC physics week 1/2018 ➔ joint FCC-hh and eh

LHC: 27 km

LHeC: 9km




**High-Luminosity LHC anticipated to run until ~2040**

**➔ Potential for 10 years LHeC (2030-2040) with ~1000 fb$^{-1}$**

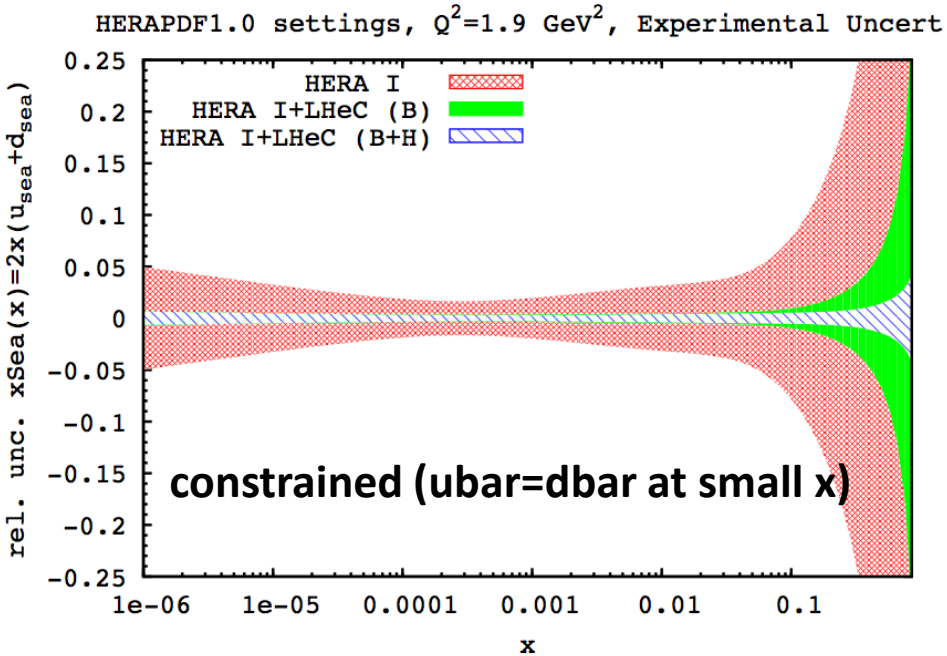
**➔ joint ep and pp data taking!**

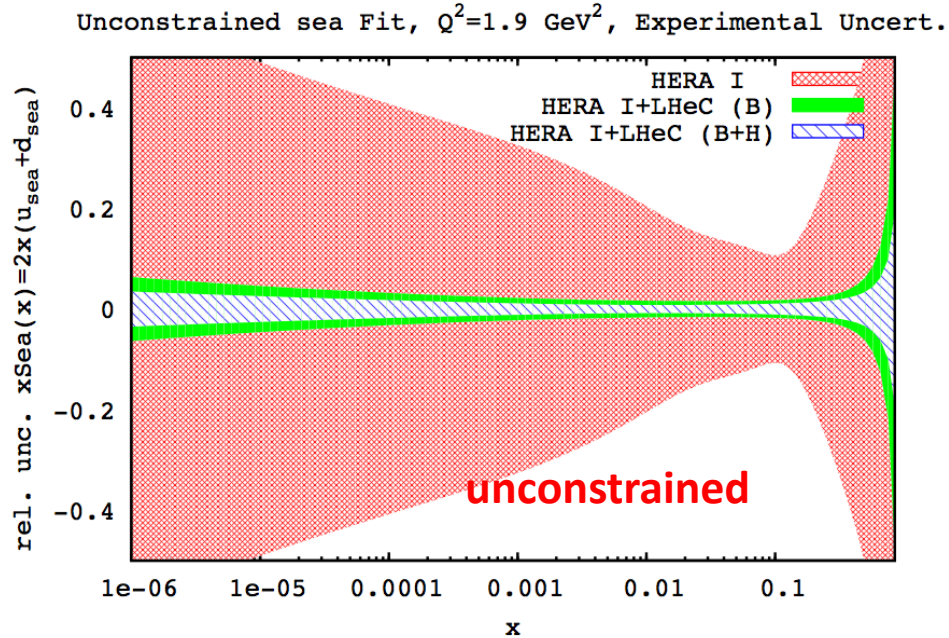
Update 2017: Interaction point L

# Resolving Partonic Structure

*accurate and free of symmetry assumptions*

Voica Radescu &
Max Klein , 2014



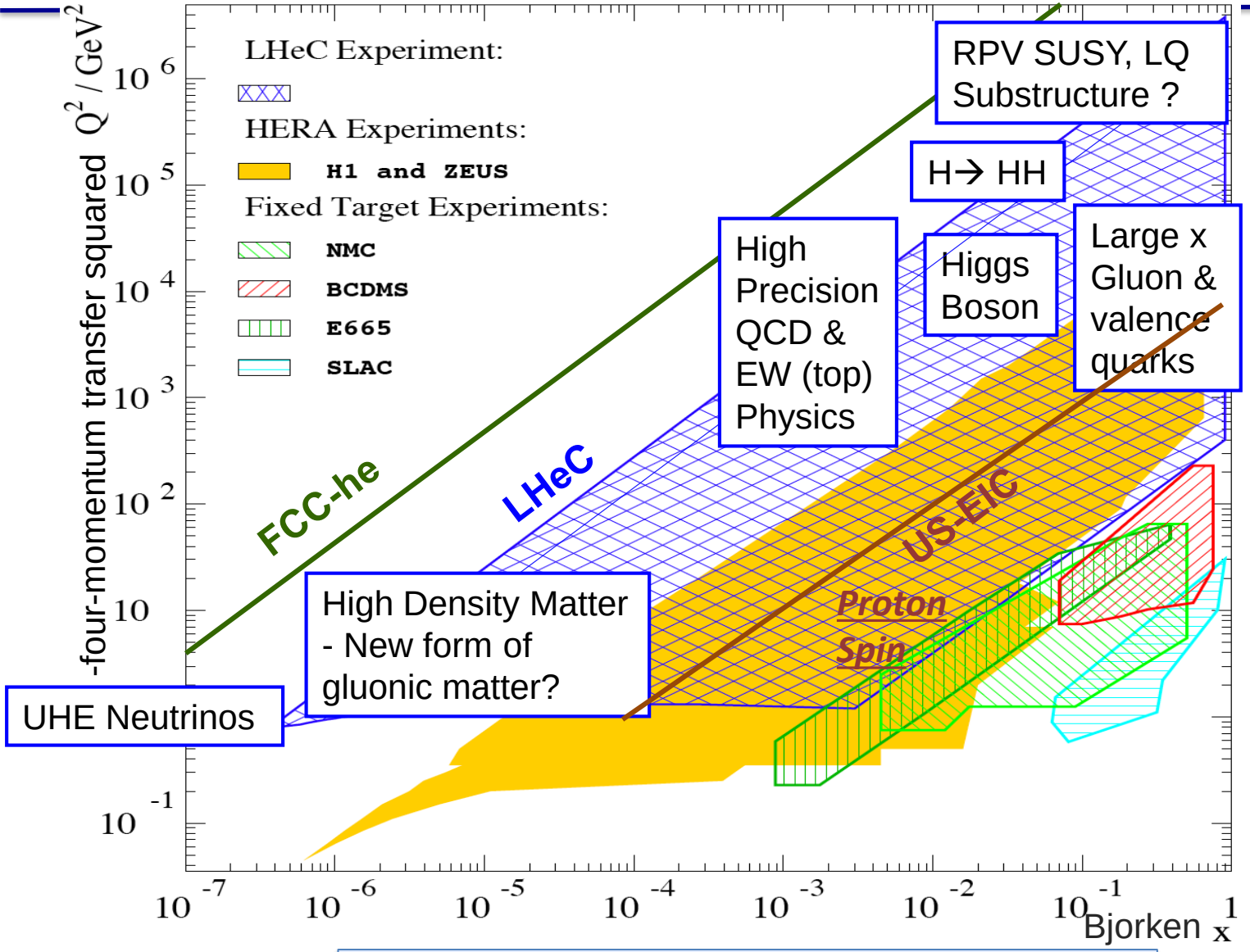




- One can see that for HERA data, if we relax the low x constraint on u and d, the "PDF errors" are increased tremendously!

➔ when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.

- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing (small x partons) with diffraction…
- **All parton distribution functions of the proton at $N^3LO$ !**

# The ep Physics at the Energy Frontier



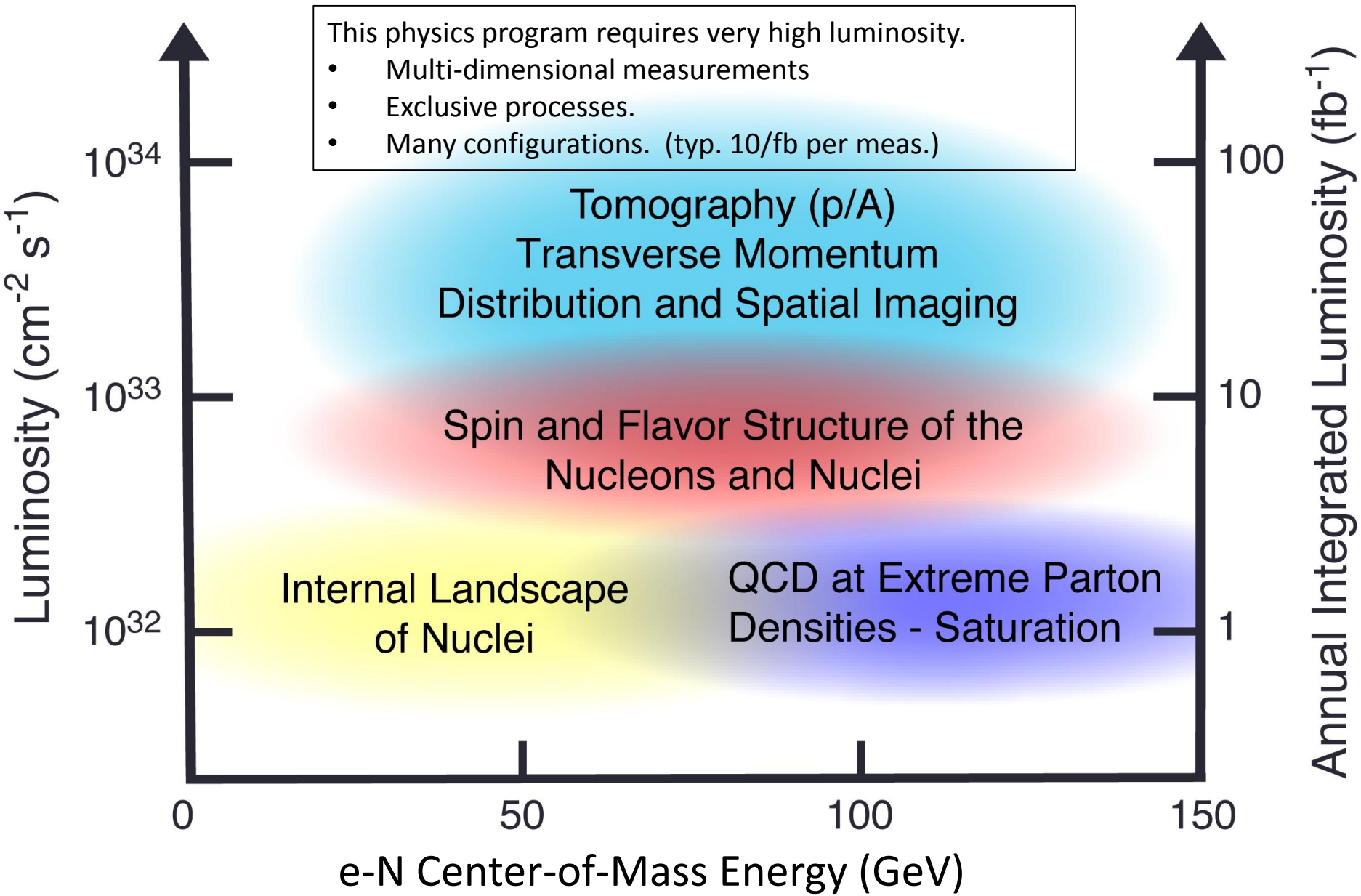

HERA established the validity of pQCD down to $x>10^{-4}$ (DGLAP) due to a very high lever arm in $Q^2$.

Extensions of both x and $Q^2$ ranges are crucial for new experiments and HEP theory developments!

**Relation to pp : $x_{1,2} = (M/\sqrt{s}) \exp(\pm y)$ & $Q^2 = M^2$**

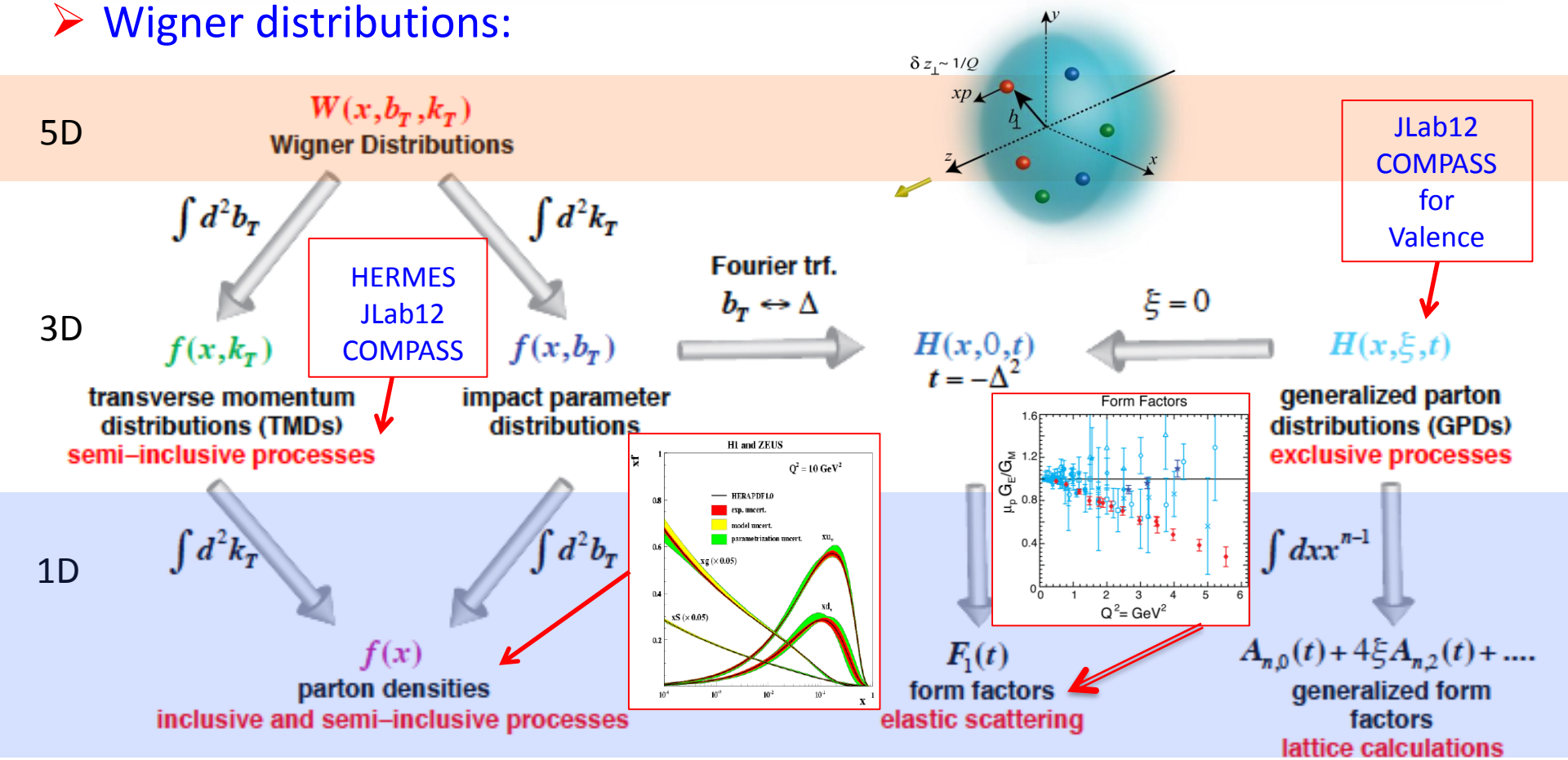
# EIC Science Program

Slide from T Horn, ICFA 2017



# Unified view of nucleon structure

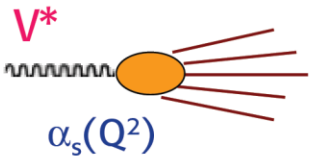
- Wigner distributions:

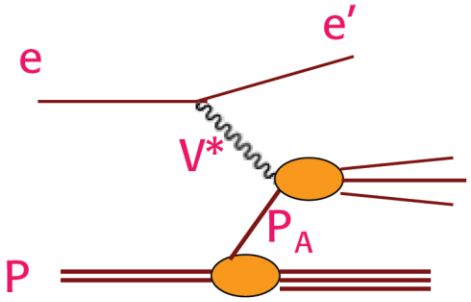



- EIC – 3D imaging of sea and gluons:
  - **TMDs – confined motion in a nucleon (semi-inclusive DIS)**
  - **GPDs – Spatial imaging of quarks and gluons (exclusive DIS)**

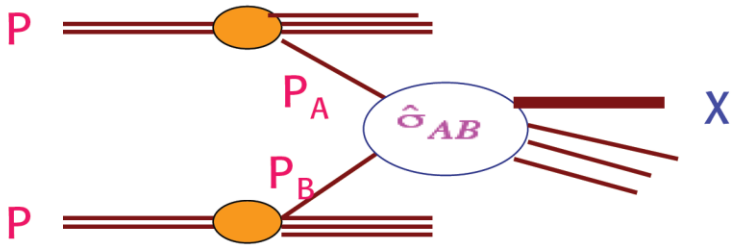
# On the Synergies of ee, ep and pp

Guido Altaralli
Cern June 2015




$\alpha_s(Q^2)$ & $q(x,Q^2)$, $g(x,Q^2)$




The basic experimental set ups for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

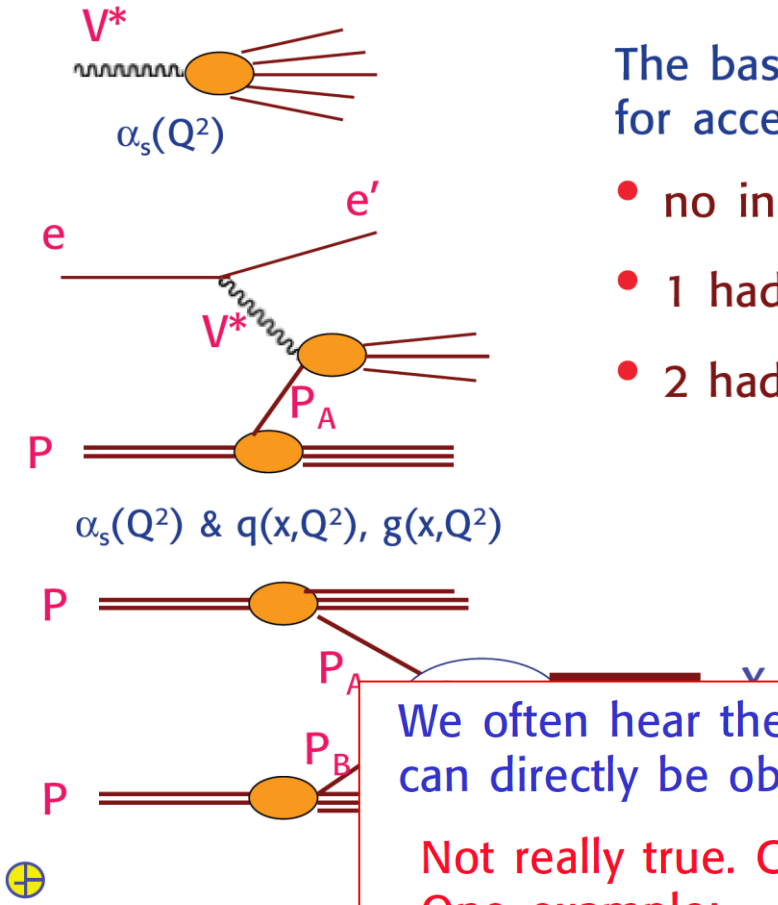
The pdf are defined in DIS

The theory of inclusive DIS is crystal clear

Thru the factorization "theorem" the pdf's and $\alpha_s$ determine the hadron collider rates

# On the Synergies of ee, ep and pp

Guido Altaralli
Cern 6/2015




The basic experimental set ups for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

The pdf are defined in DIS

The theory of inclusive DIS is crystal clear

We often hear the statement that all the relevant info on pdf's can directly be obtained from the LHC without need of the LHeC

Not really true. Certainly not at the same level of precision
One example:

The factorization "theorem" is essential.
Not fully proved theoretically (beware of non pert. effects)
[nearly complete arguments only for Drell-Yan & similar]
Should finally be experimentally tested with precision