Open Symposium - Update of the European Strategy for Particle Physics

What strong interaction physics can one do with the LHC after the HL-LHC?

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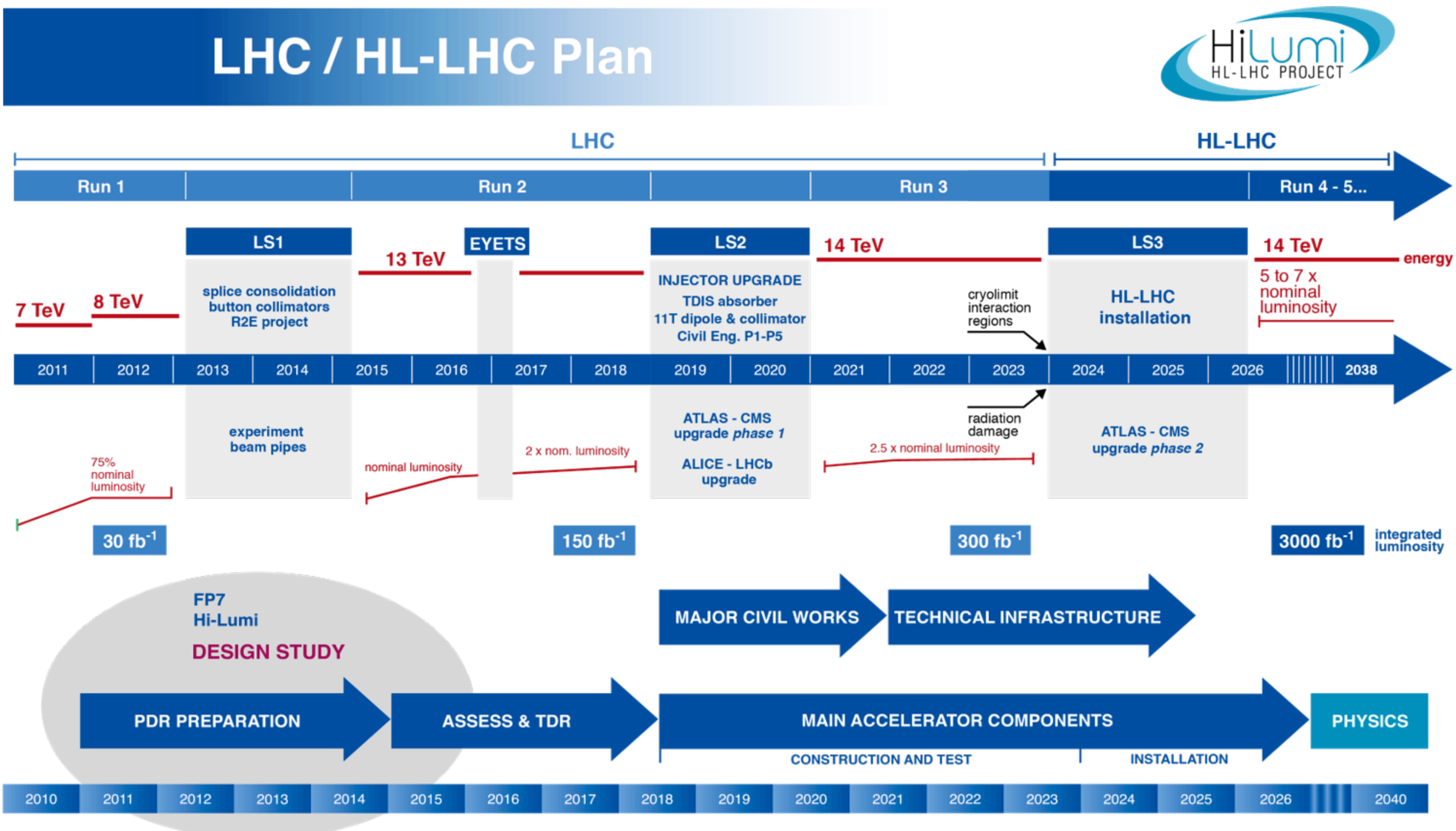
B6 - Strong Interactions - Granada, May 15, 2019

Questions to be addressed as a discussion starter:

- Is there a strong interaction physics case for continued use of the LHC after the HL-LHC?
- Where will we stand with QCD studies in 15-20 years?
- Which strong interaction topics will (still) be relevant then?
- What would be game changers for QCD studies?
- How can the LHC be used for such studies, e.g. when it is part of the pre-accelerator complex of a new collider?

Draws from the following ESPPU input documents:
Id47 [FT@ALICE] & Id67 [FT@LHC], Id160 [HE-LHC], Id50 [AWAKE],
Id58 [AWAKE++], Id103 [DIS], Id99 [EIC], Id159 [LHeC], Id163 [QCD Theory]

HL-LHC timeline: 2026-2038



Where will we stand with QCD around 2035-2040?

It is to be expected that much of the investigations of the strong interactions at high-energy colliders in the future will focus on:

- PDFs at small and large x
- Multi-dimensional PDFs
- Diffraction
- Double parton scattering
- Quarkonia
- Jets
- Collective effects

PDFs at small x: nonlinear QCD effects

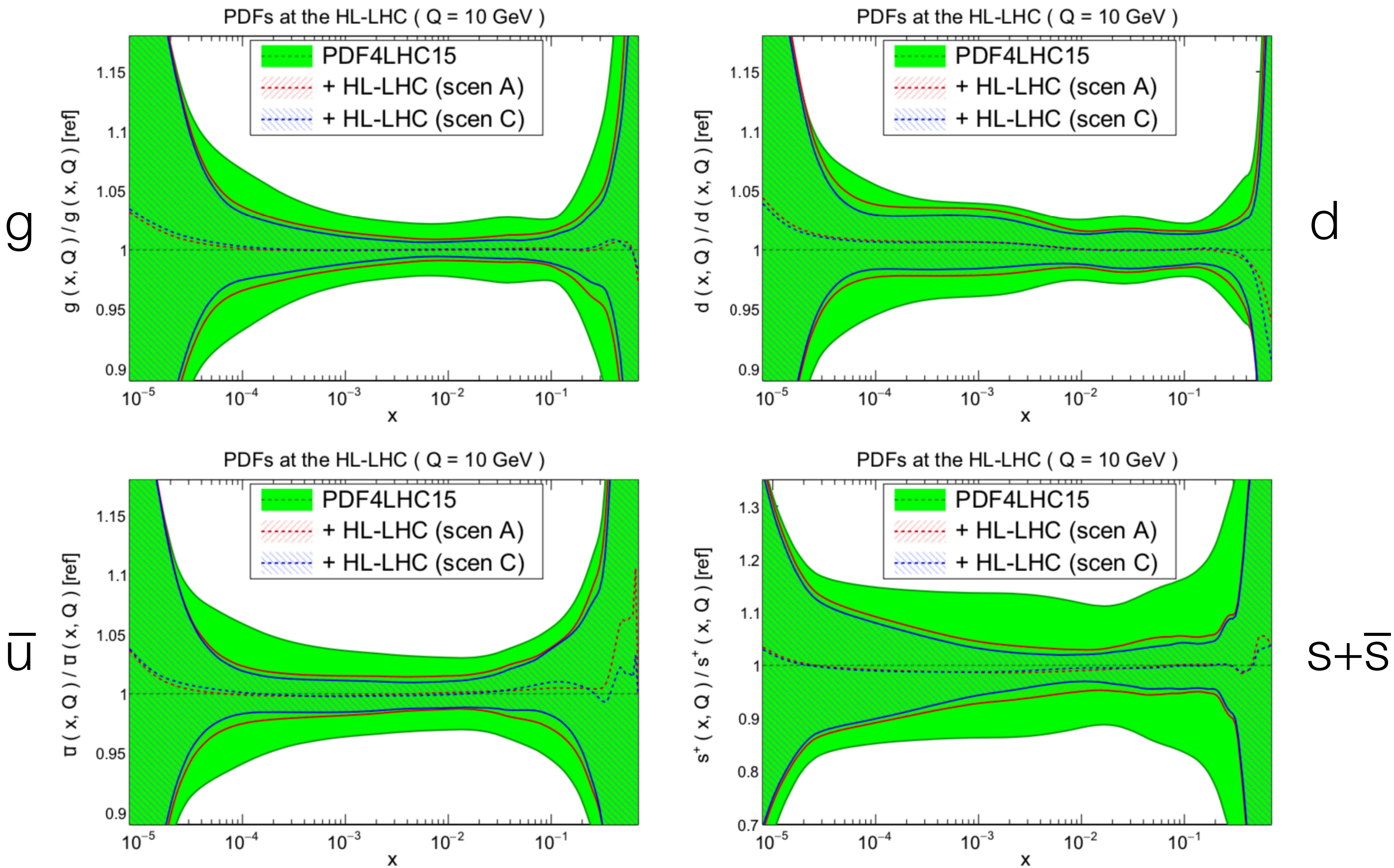
- **HL-LHC** will have produced a wealth of data on pp, pA and AA collisions [5-7x nominal luminosity @ 14 TeV, expected integrated luminosity 3 ab^{-1}] Few percent level accuracy of pdfs down to $x \sim 10^{-4}$

- The proposed U.S.-based **EIC** with a c.o.m. energy between 20-140 GeV could be in operation at the earliest in the period 2025-2030. It would probe the small-x region down to $x \sim 10^{-4}$, in both ep and eA collisions, also for polarized beams

- **LHeC** with c.o.m. energy 1.3 TeV could be in operation at the earliest around 2030. It would make high-precision measurements of the parton densities, probing from high x down to $x \sim 10^{-6}$.

- At small x signals from (the onset of) parton saturation are expected, due to nonlinear QCD effects. Needs validation from eA, pA and AA. Provides the initial conditions for QGP formation, important for HIC.

Ultimate PDFs from HL-LHC (pseudo-data)



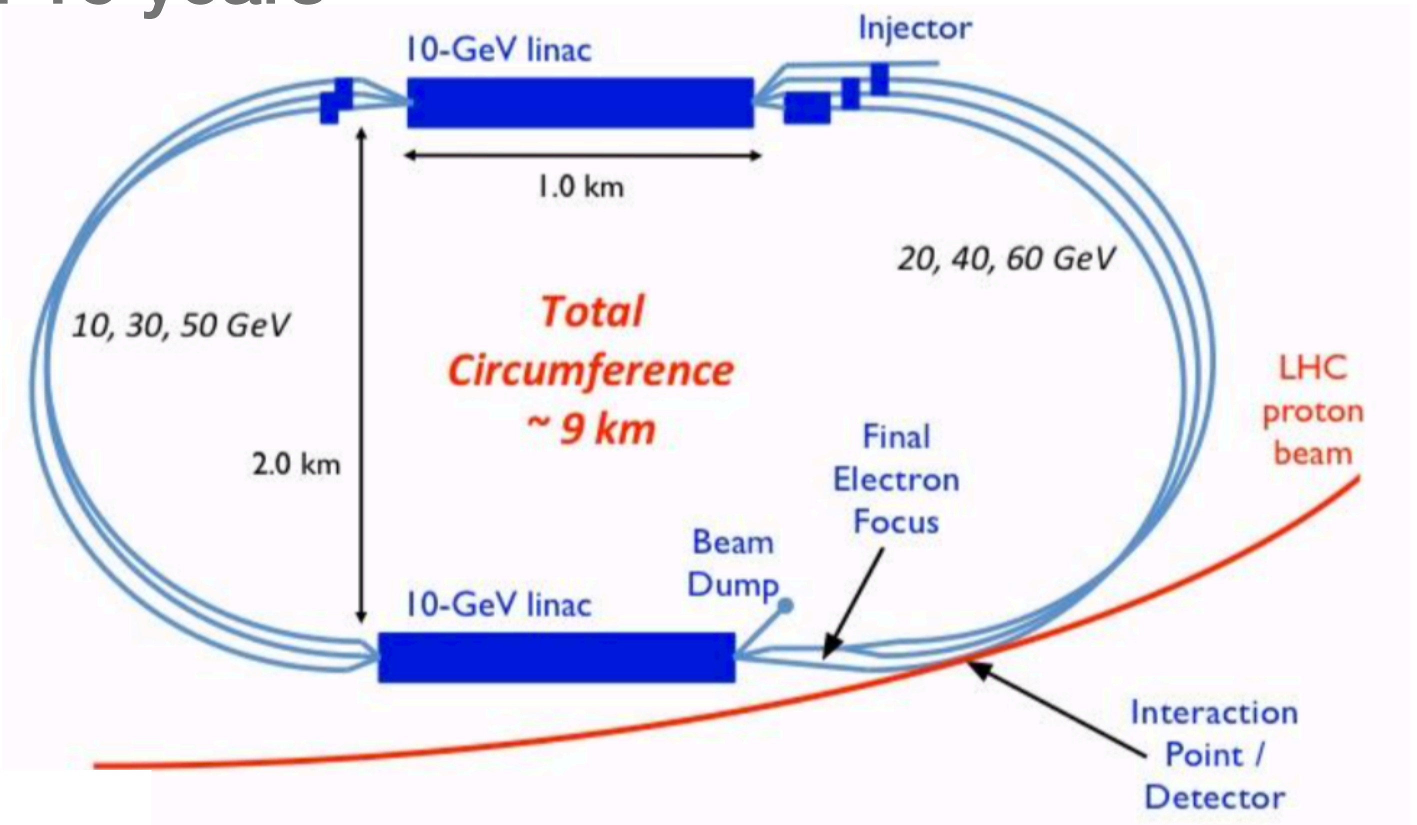
Khalek, Bailey, Gao, Harland-Lang, Rojo, EPJC 78 (2018) 962

LHeC: precision down to $x \sim 10^{-6}$

[ld159]

- A 60 GeV high current electron beam to operate e-p at $\sqrt{s}$ = 1.3 TeV concurrently with p-p of HL-LHC
- Uses a novel, energy recovery LINAC (**ERL**) to reach high luminosity, exceeding HERA's by nearly 3 orders of magnitude
- Integrated luminosity projected to be O(100) fb^{-1}, a factor 100 more than HERA over its lifetime of 15 years

"the cleanest, high resolution microscope"



Kinematic reach

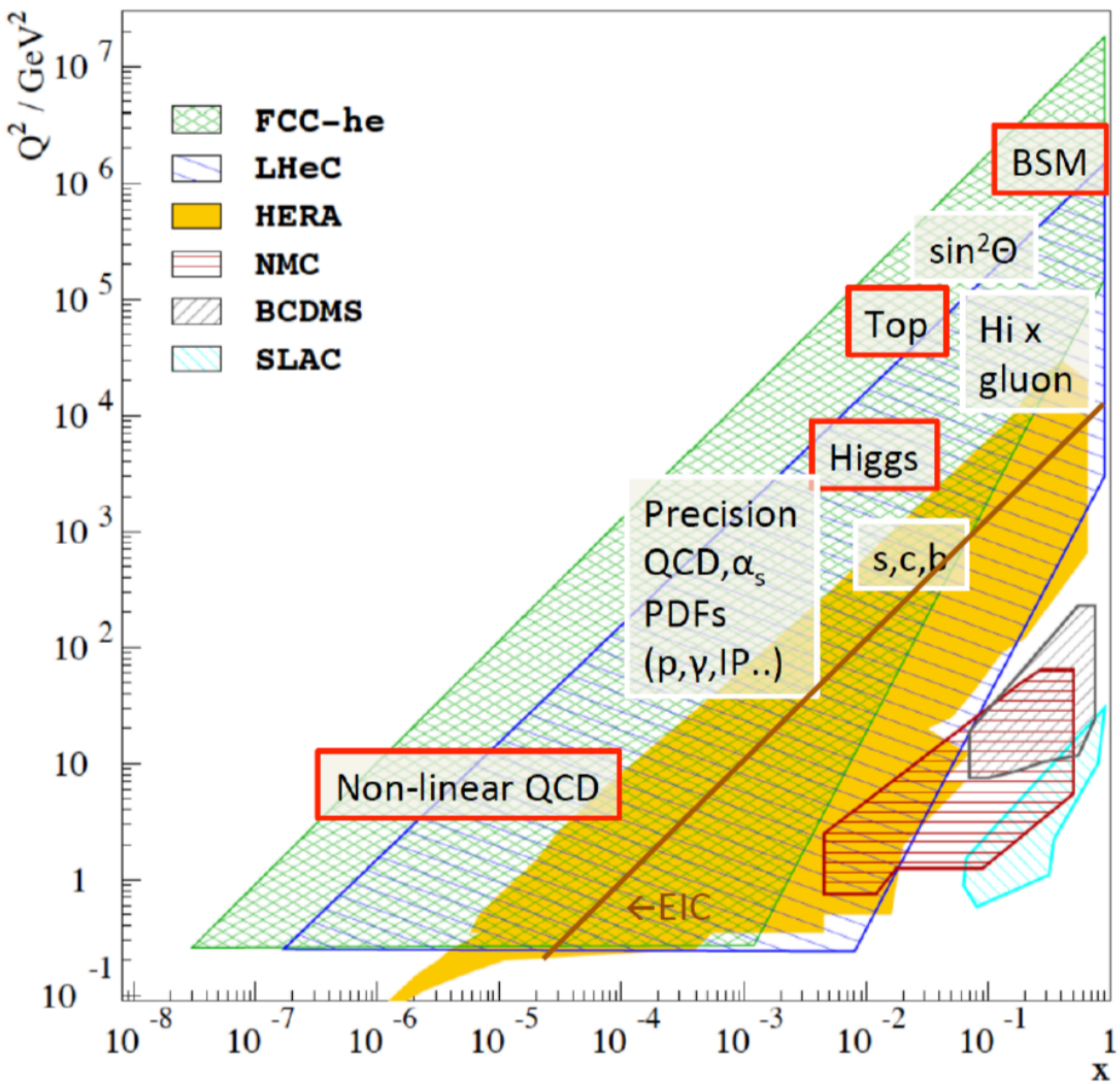
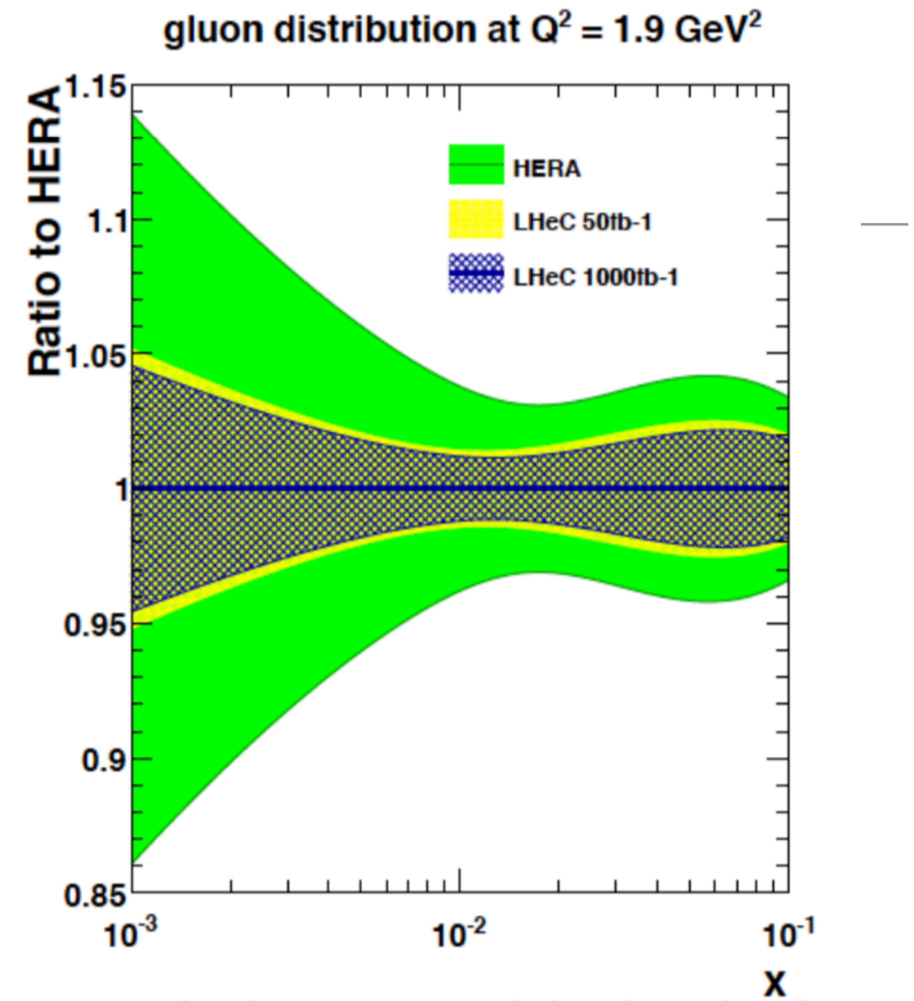
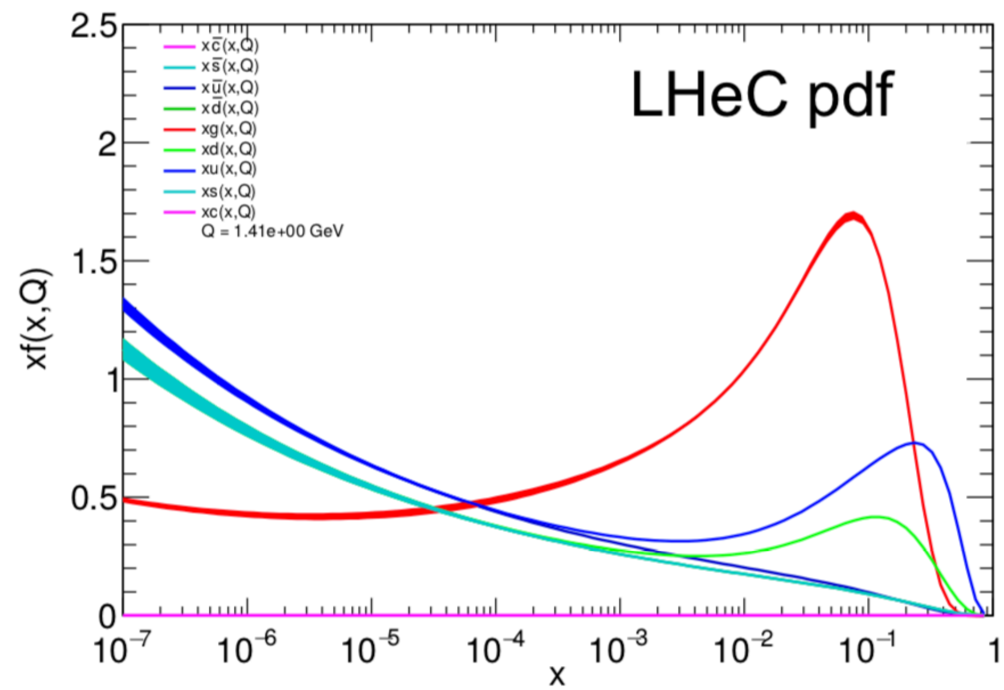


Figure by M. Klein

Probing very small x (below 10^{-4}) before 2040 requires the LHeC

High precision pdfs





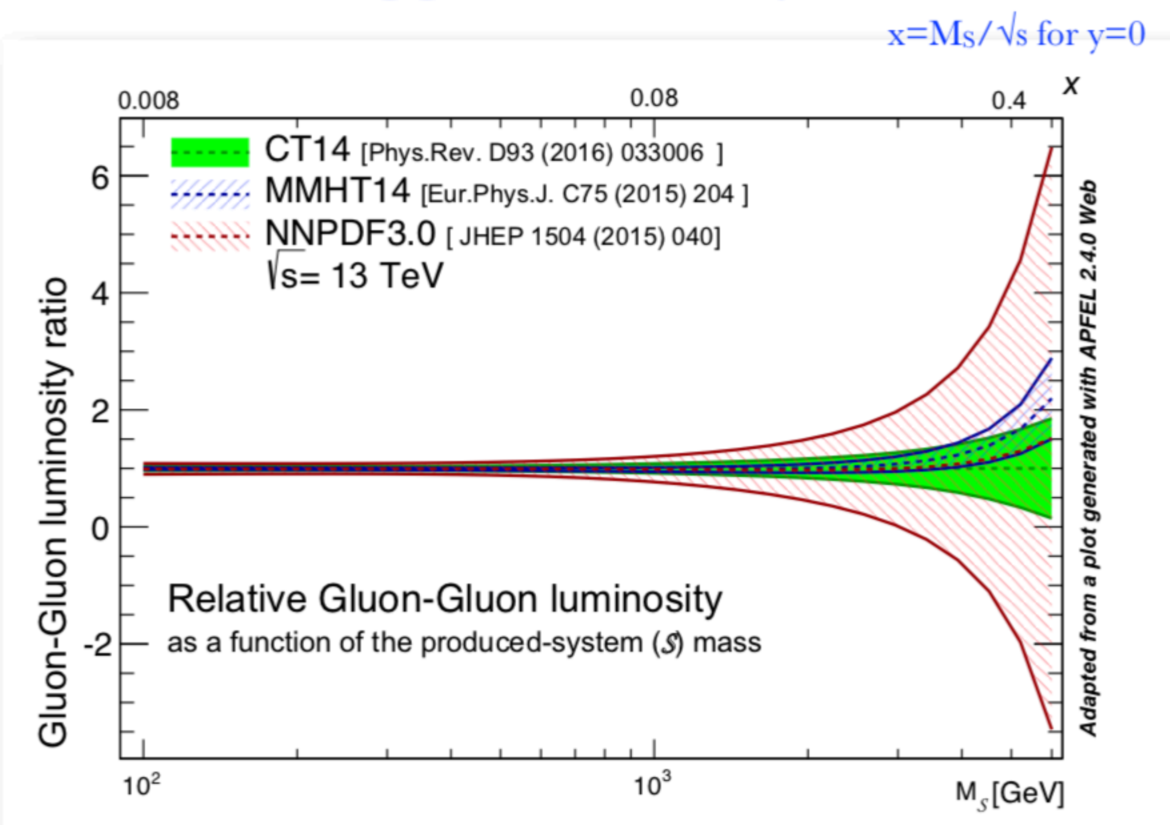
From C. Gwenlan, DIS2018

PDFs at large x

PDFs at large x can be studied especially at **LHeC** and/or at **Fixed-Target** experiments at the **(HL-)LHC** (at LHCb and/or ALICE) [Id47, Id67]

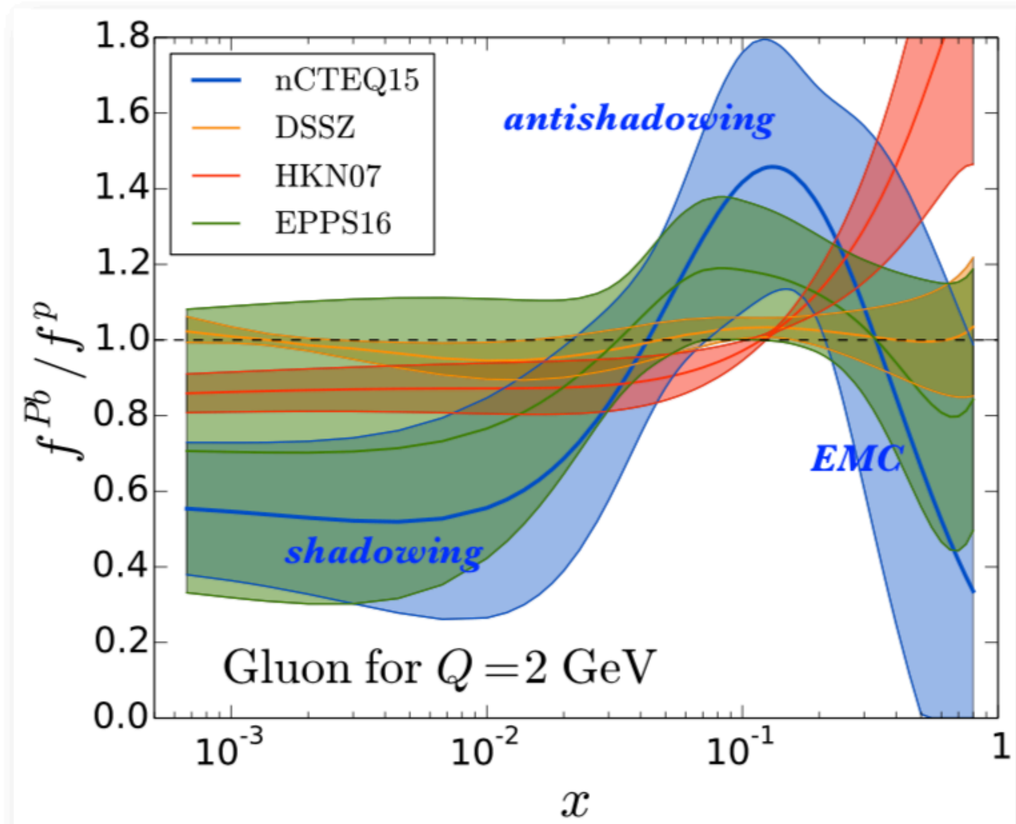
Partly to support high-energy BSM searches at the LHC, but also of interest for counting rules, sum rules, charm content, nuclear PDFs

gg luminosity



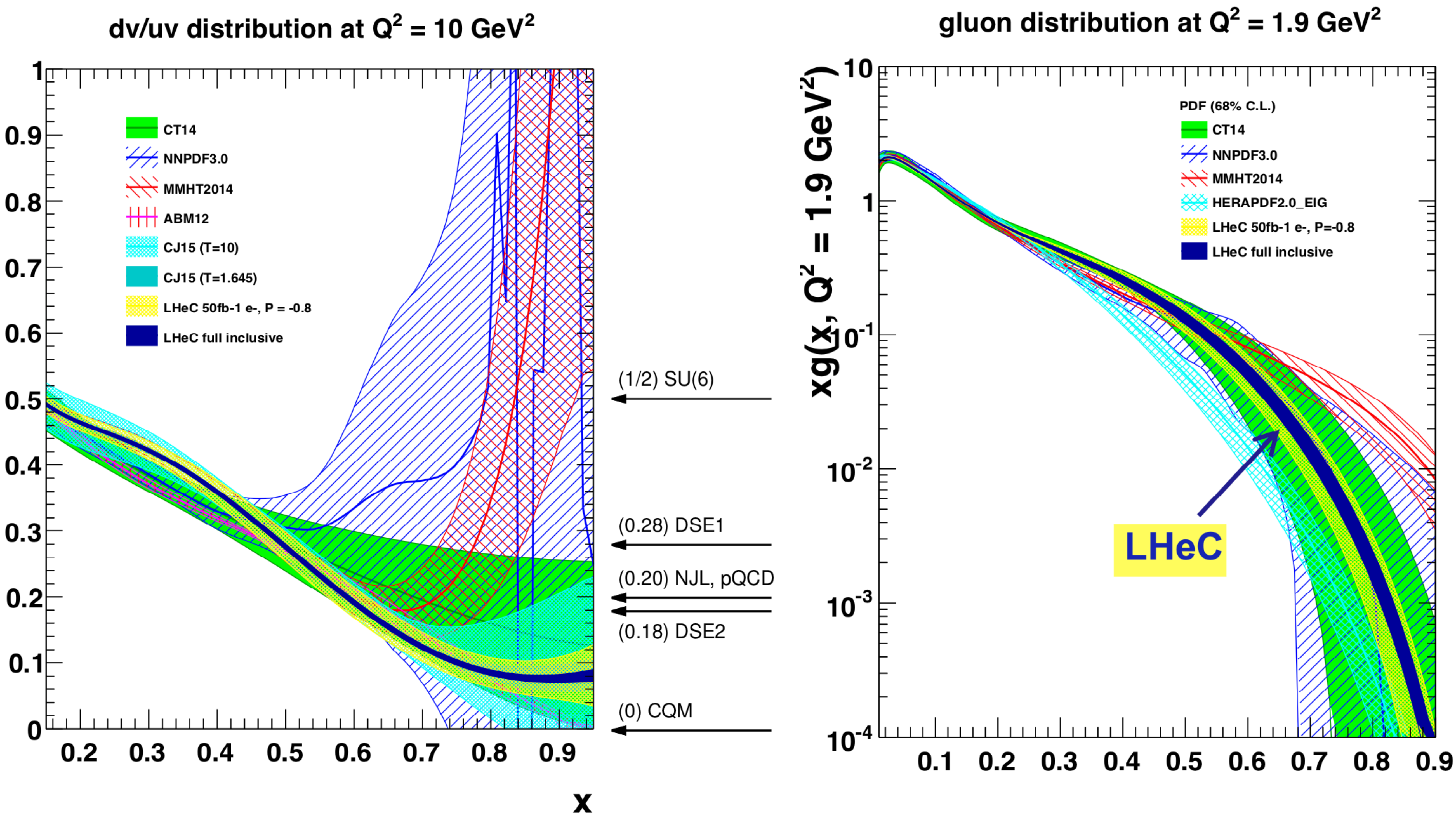
$$\frac{\partial \mathcal{L}_{ab}}{\partial \tau} = \frac{1}{s} \int_{\tau}^{1} \frac{dx}{x} f_a(x, M_S^2) \, f_b(\tau/x, M_S^2), \qquad \tau = M_S^2/s$$

gluon nuclear PDF (Pb)



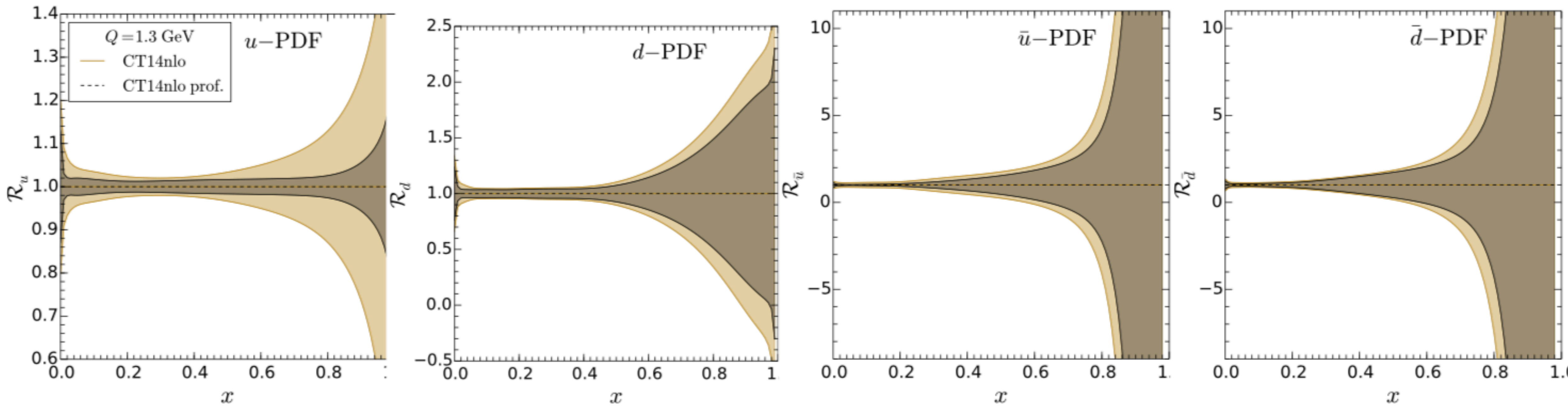
From M. Echevarria, DIS2019 & 1807.00603

Large x at LHeC

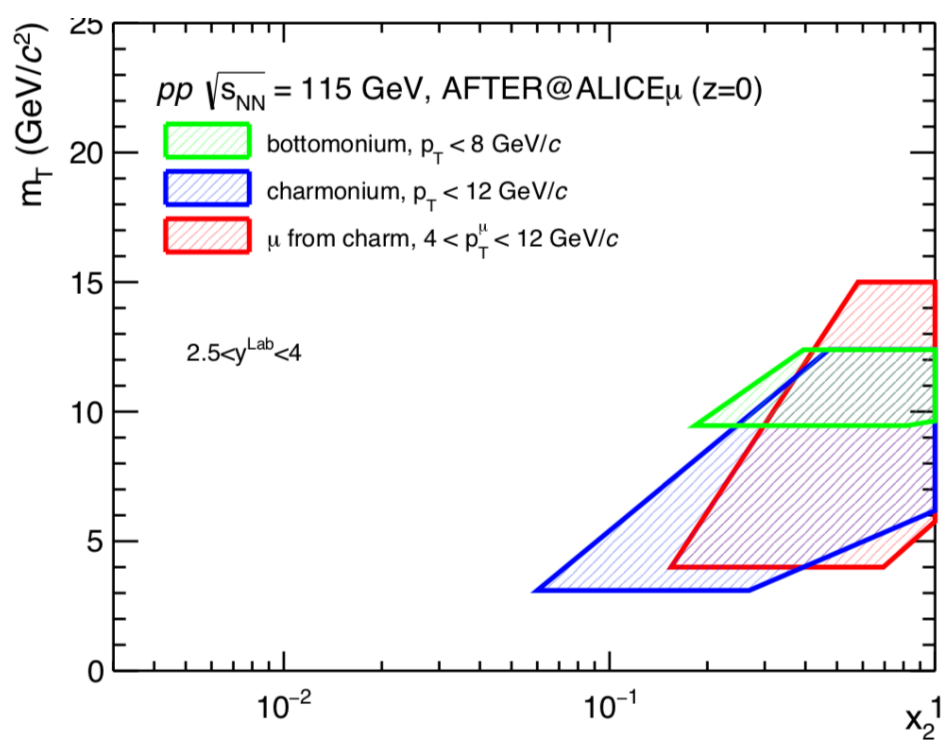


Large x studies in Fixed-Target experiments at LHC

Projections for FT experiment at LHCb (10 fb^{-1}) [1807.00603 & Id67]



(a) u PDF (b) d PDF (c) $\bar{u}$ PDF (d) $\bar{d}$ PDF



Large-x gluon studies e.g. in Υ(1S) production at ALICE

FT@ALICE [Id47]

Multi-dimensional parton distributions

TMDs: transverse momentum dependent PDFs

GPDs: off-forward PDFs

GTMD = off-forward TMD = Fourier transform of a Wigner distribution

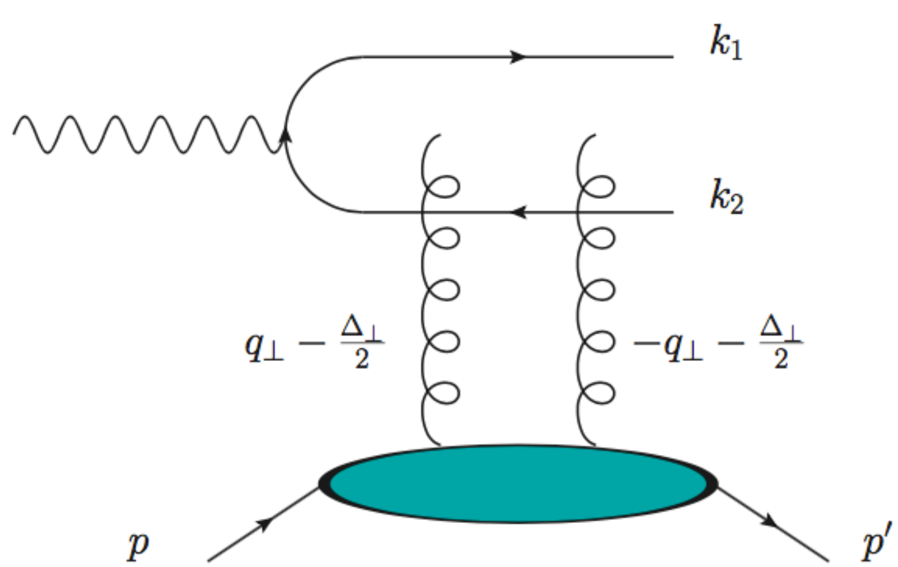
$$G(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T) \overset{FT}{\longleftrightarrow} W(x, \boldsymbol{k}_T, \boldsymbol{b}_T)$$

Meißner, Metz, Schlegel, 2009

Ji, 2003; Belitsky, Ji & Yuan, 2004

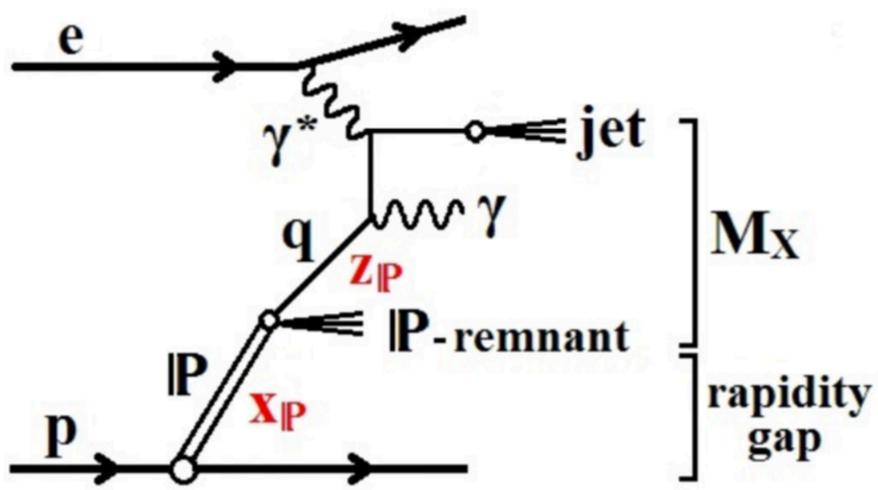
Diffraction dijet production in eA at EIC and/or LHeC could be used to probe GTMDs for the first time

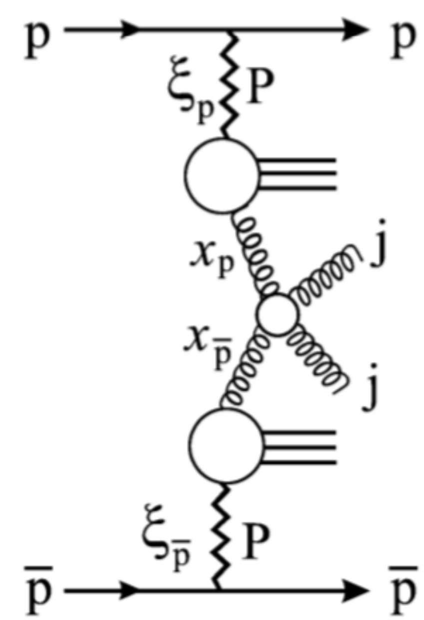
Altinoluk, Armesto, Beuf, Rezaeian, 2016;
Hatta, Xiao, Yuan, 2016



Multi-dimensional parton distributions

Diffractive dijet production indicates non-factorization in pp and p$\bar{p}$ collisions [SPS, Tevatron, LHC] compared to ep [HERA]





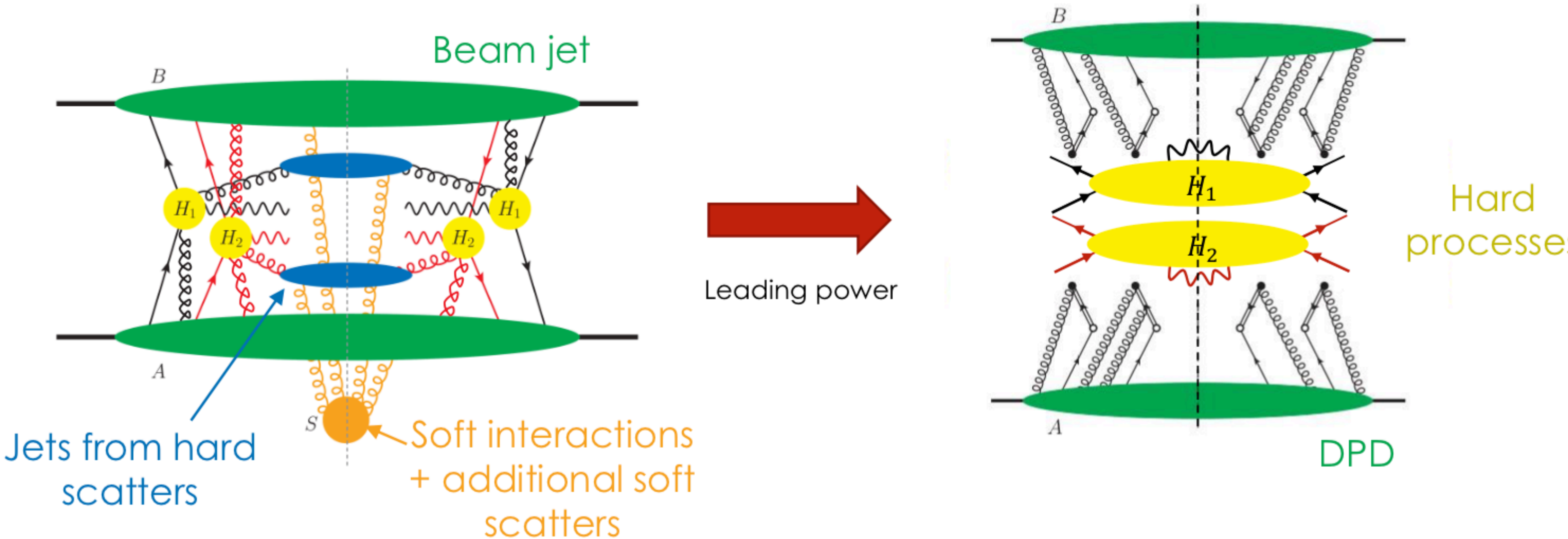
Inclusive dijet observables in pp that probe TMDs (transverse momentum dependent PDFs) are also expected to be non-factorizing

New knowledge on the origin and magnitude of the non-factorization is expected and is needed for global analyses of multi-dimensional PDFs

Double Parton Scattering

- **Factorization theorems for DPS will allow to go from the "pocket formula" to quantitative and predictive studies of DPDs and various types of correlations (in color, spin & flavor)**

- **DGS formalism** "Double hard scattering without double counting" by Diehl, Gaunt, Schönwald, JHEP 1706 (2017) 083

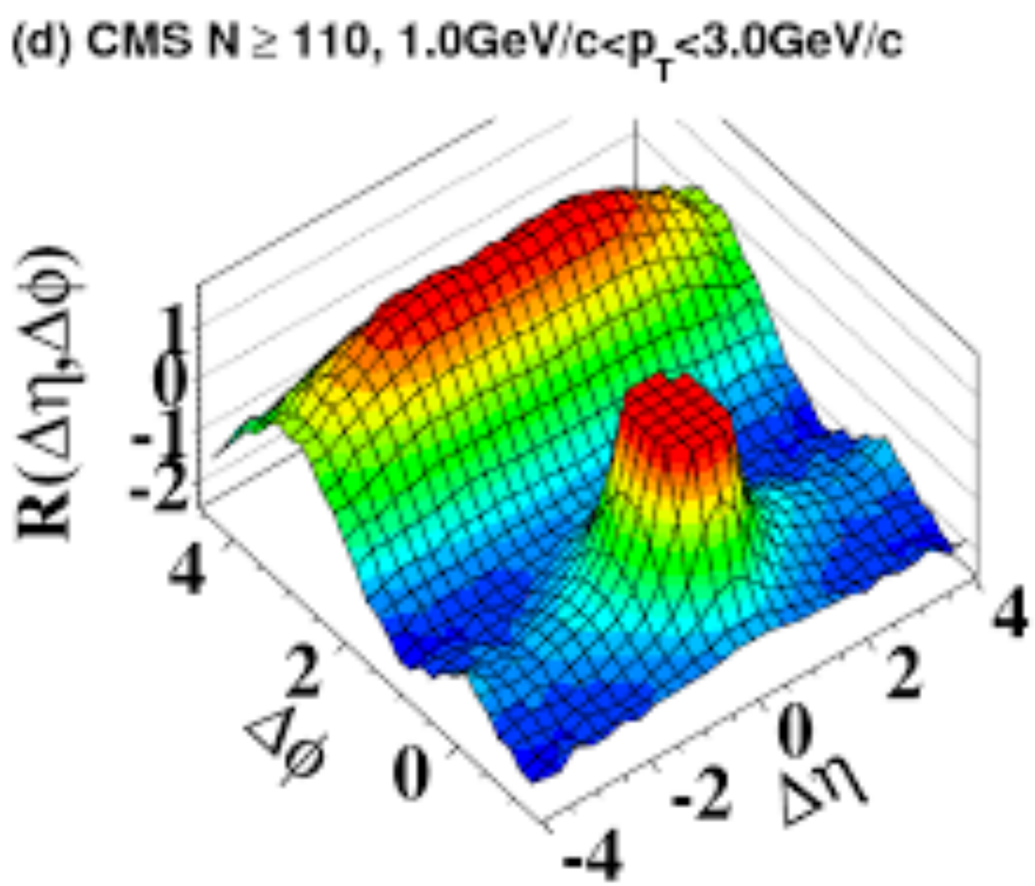


Collective effects in pp collisions

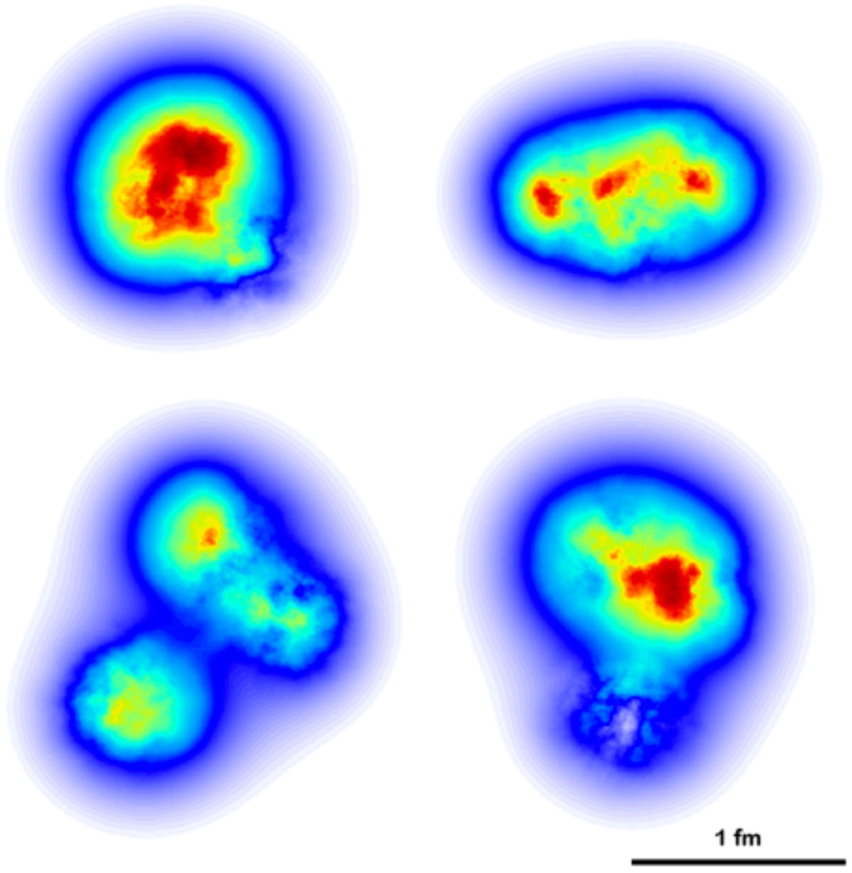
[Id163]

Collective effects (flow, ridge, …) in small systems like in pp collisions compared to pA and AA

Does hydrodynamics apply in small systems or effects from initial state (CGC, proton shape)? What about factorization?



From JHEP 1009 (2010) 091,2010



From Mäntysaari and Schenke, PRL 2016

Possible game changers for QCD

- **Unambiguous signals for small-x gluon saturation**
- **Control over less-inclusive and diffractive processes in pp** will open the road towards global analyses of multi-dimensional PDFs (TMDs, GPDs, GTMDs, DPDs, DPDFs)
- Possible observation of **new strongly interacting particles** (gluinos, leptoquarks, …) to point towards the role or the embedding of QCD in BSM theory

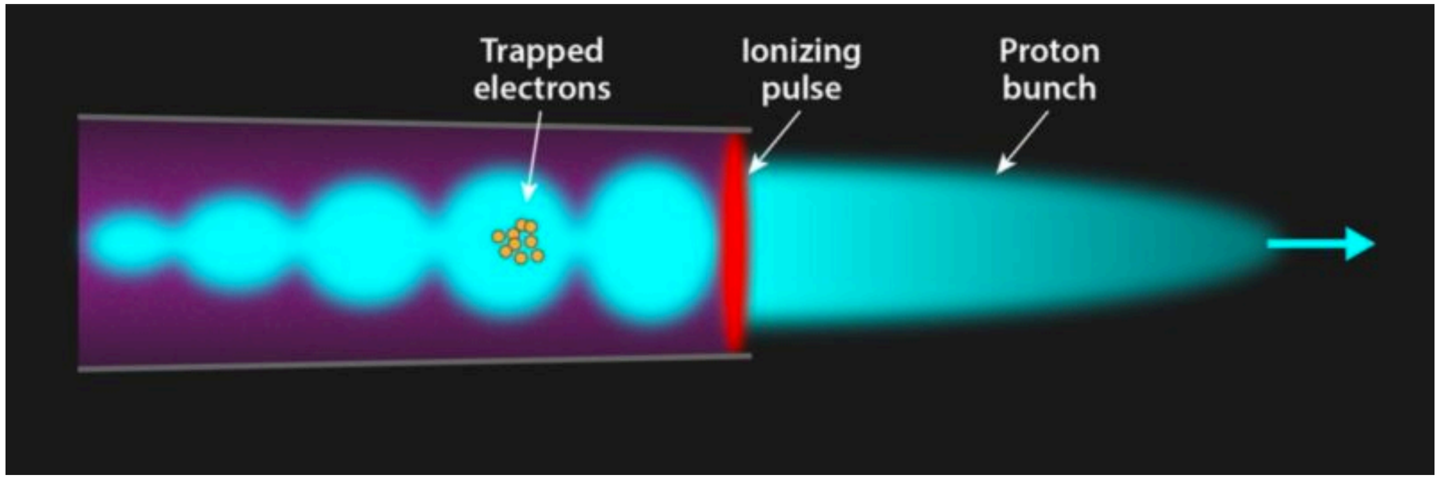
These would offer new opportunities and challenges

Possible novel future uses of the LHC

- **HE-LHC:** 2040+, c.o.m. energy 27 TeV [Id160]
    - **FT experiments** (like @LHC but instead of $\sqrt{s}$ = 115 GeV, now at $\sqrt{s}$ = 163 GeV)
    - **HE-LHeC**: $\sqrt{s}$ = 1.8 TeV
- **AWAKE++:** Proton-driven plasma wakefield accelerated electrons can collide with fixed target or with LHC protons (PEPIC & VHEeP) [Id50,Id58]

AWAKE++

- Proton-driven plasma wakefield acceleration allows the transfer of energy from a proton bunch to a trailing bunch of particles, the 'witness' particles, via plasma electrons.



- Because of their high energy and mass, proton bunches can drive wakefields over much longer plasma lengths than electron bunches

- Using SPS proton bunches, electron energies of 50–70 GeV are expected to be possible, whereas TeV-scale electrons should be possible using LHC proton bunches as drivers

AWAKE++ options

c.o.m. energy $\sqrt{s}$	Fixed target	LHC proton
SPS-driven (70 GeV e^-)	11.5 GeV	1.4 TeV (PEPIC)
LHC-driven (3 TeV e^-)	75 GeV	9 TeV (VHEeP)

Overview of future ep/eA Colliders

DIS Collider Plan Comparison (from EPPSU DIS document)

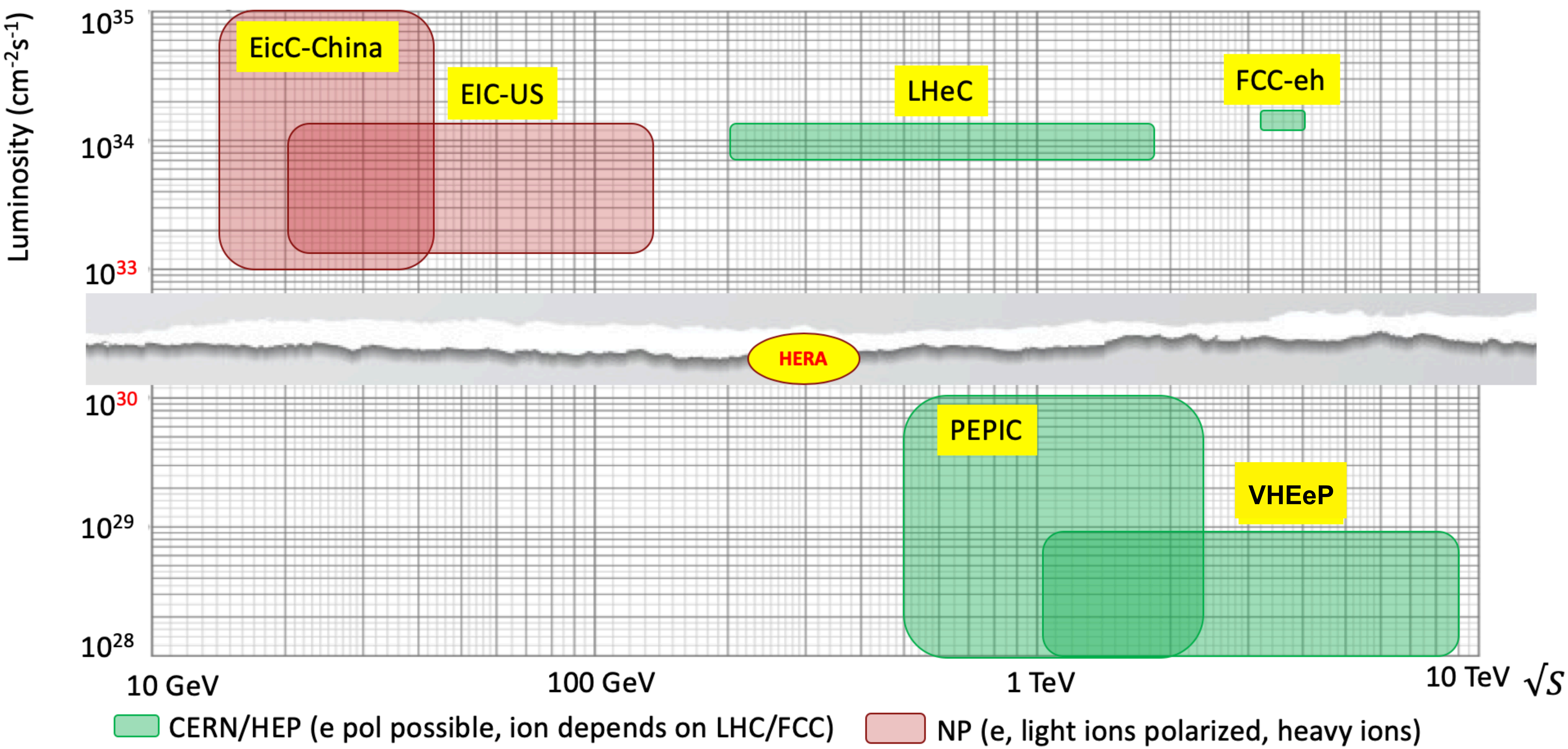


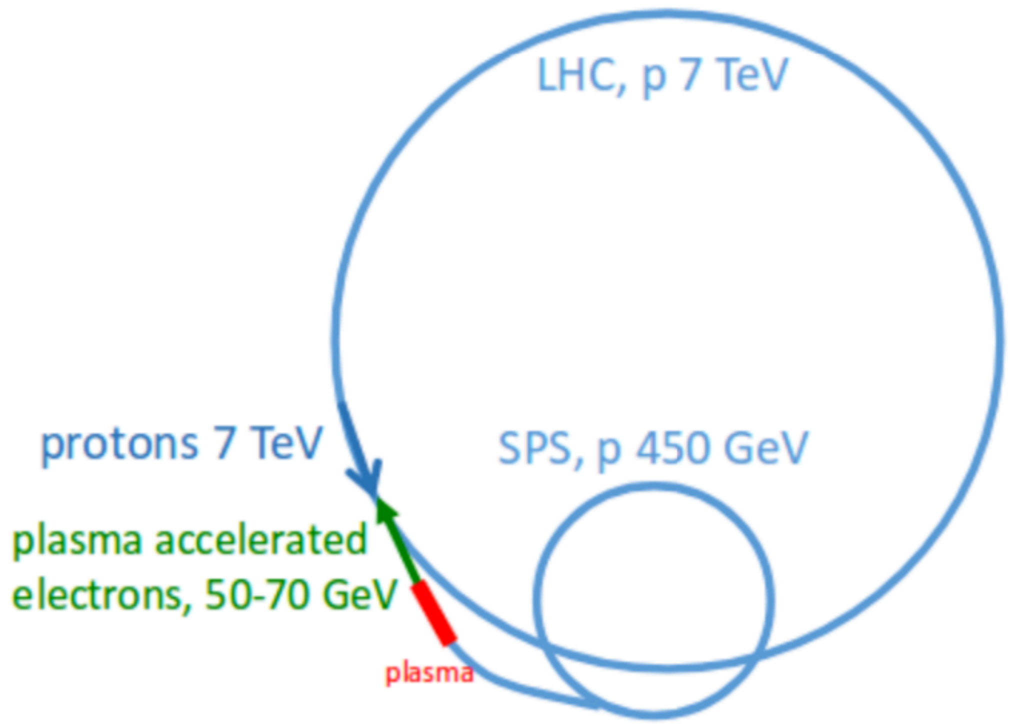
Figure by Rik Yoshida

AWAKE++: PEPIC

[Id58]

- SPS-driven e^- (70 GeV) on LHC proton (PEPIC): $\sqrt{s}$ = 1.4 TeV, **like LHeC, but with luminosities several orders of magnitude lower** (1.46×10^{27} cm^{-2} s^{-1}). For a running period of about 10^7 s per year the integrated luminosity would be about 10 nb^{-1}

- **PEPIC (Plasma Electron-Proton/Ion Collider) "could though be an interesting option for CERN should the LHeC not be realized"**

- 

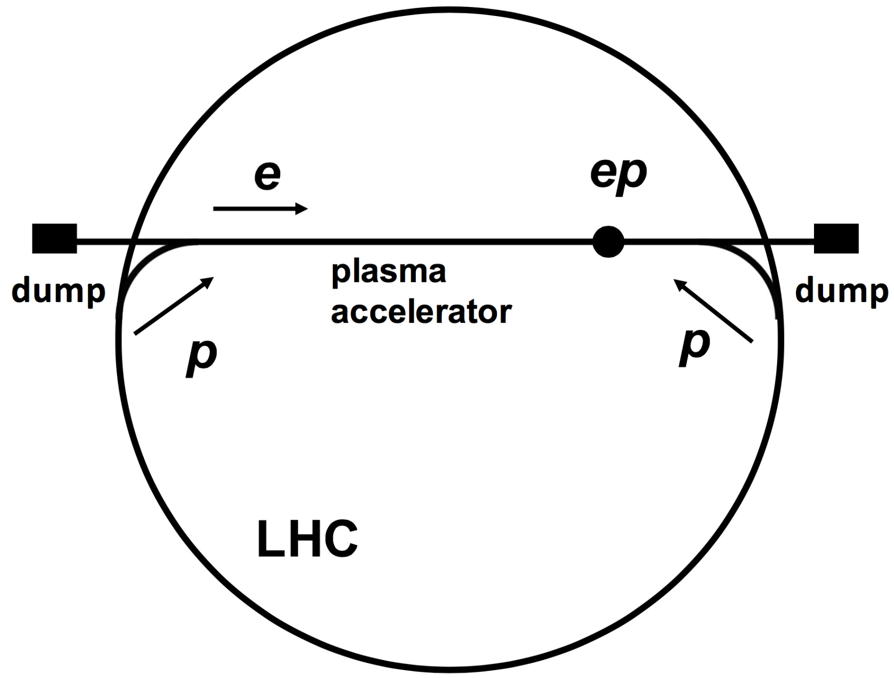
The extraction line tunnel TI2 from SPS to LHC needs to be widened

Will drive wakefields in a ~130 m long plasma cell in TI2

AWAKE++: VHEeP

- LHC-driven 3 TeV electron beam on LHC proton beam (VHEeP): $\sqrt{s}$ ~ 9 TeV (6x LHeC and 30x HERA energies). Modest luminosity expected (goal: 10 pb^{-1} over lifetime of the collider)
- c.o.m. energy surpasses even the **FCC-eh** (for the 60 GeV ERL e^-beam on the 50 TeV p-beam of the Future Circular Collider: $\sqrt{s}$ ~ 3.5 TeV)

This will probe x down to an unprecedented 10^{-8}



Summary of opportunities and challenges

Opportunities and challenges for the strong interaction physics case for continued use of the LHC after the HL-LHC:

- **Unambiguous signals of small-x gluon saturation** [opportunities]
  Should one go for the smallest x (i.e. highest energy), even when the luminosity is modest?

- **Control over less-inclusive and diffractive processes in pp** [challenges]
  Required for global analyses of multi-dimensional PDFs

- **Observation of new strongly interacting particles** [opportunities]
  Elucidation of the role or the embedding of QCD in BSM theory

Other opportunities/challenges for QCD@LHC after 2040?