The LHeC Project and its Electron-Ion Physics

Introduction: hh-eh

LHeC in Brief

Physics: nPDFs and Beyond

Detector

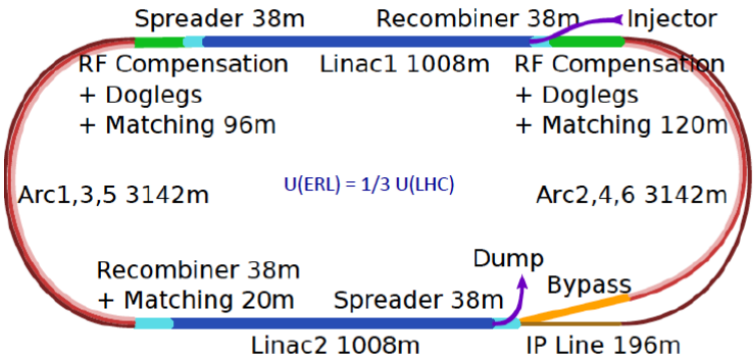
Prospects: Progress and Vision

Most recent workshop

http://lhec.web.cern.ch

Max Klein
For the LHeC/FCCeh+PERLE Collaboration

Presentation at “Hard Probes”, Aix-Les-Bains, 4.10.2018



Three Raisons d'etre of the LHeC

Sustainability and Cost

LHC:
- see: SM, Higgs and no BSM
- use: Investment of O(5) BSF
- run: HL LHC until ~2040

LHeC [1206.2913, update 2/19]
- 1.2 TeV ep/A for O(1)BSF

→ Establish novel ep+pp Twin Collider Facility at CERN:
sustains HL LHC and bridges to CERN's long term future
For installation during LS4 (2030+) and long term use (HE LHC, FCCeh)

Physics

- **Microscope**: World's Cleanest High Resolution
- **Empowerment** of the LHC Physics Programme
- **Creation** of a high precision, novel Higgs facility
- **Discovery** Beyond the Standard Model
- **Revolution** of Nuclear Particle Physics

Technology

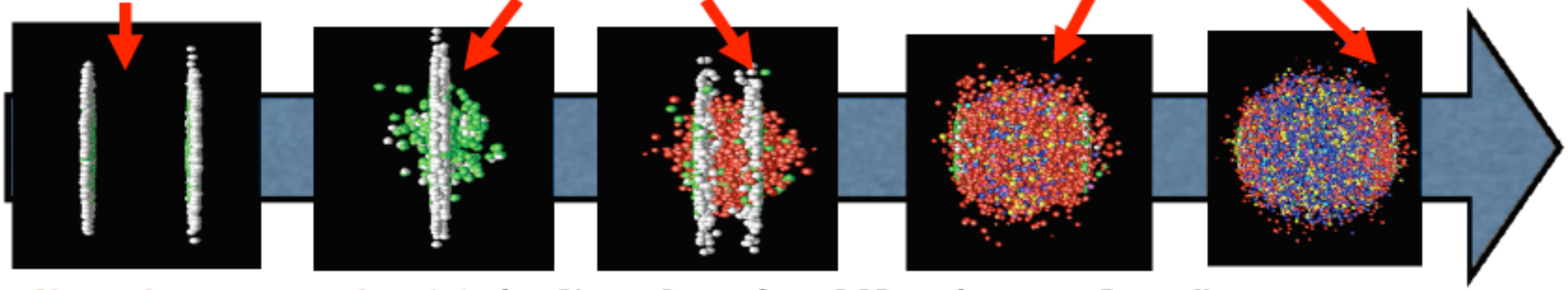
Accelerator: Novel SRF ERL, green power facility
Detector: Novel high tech (CMOS..) apparatus

→ Keep accelerator and detector base uptodate while preparing for colliders that cost O(10)BSF

What we can learn in an ep/eA collider

We do not have a **QUANTITATIVE** understanding of the nuclear behaviour → required for A-A and QGP studies

The colliding objects **Early stages** **Analyzing the medium**



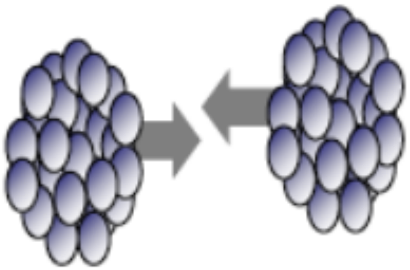
Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

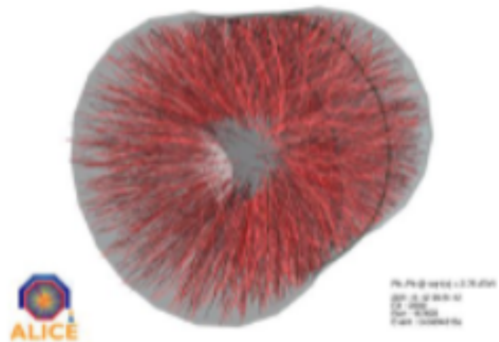
Dense regime: lack of information about	Particle production at the very beginning:	Probing the medium through energetic particles:
• small-x partons • correlations • transverse structure	• Which factorization? • How can a system behave as isotropised so fast?	• Dynamical mechanisms for opacity • How to extract accurately medium parameters?
ep and eA: • nuclear WF & PDFs • mechanism of particle production • tomography	ep and eA: • initial conditions for plasma formation • how small can a system be and still show collectivity?	ep and eA: • modification of radiation and hadronization in the nuclear medium • initial effects on hard probes

N. Armesto DIS2018, Kobe, 17.4.18, + today and E. Ferreiro, LHeC Workshop 2018, Orsay, 28.6.18

Old paradigm: the three systems (understanding before 2012)

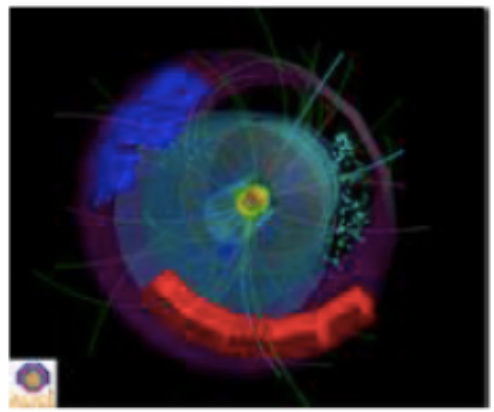
Pb-Pb





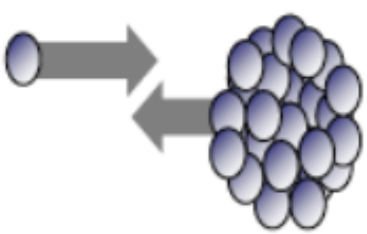
Hot QCD matter:
This is where we expect the QGP to be created in central collisions

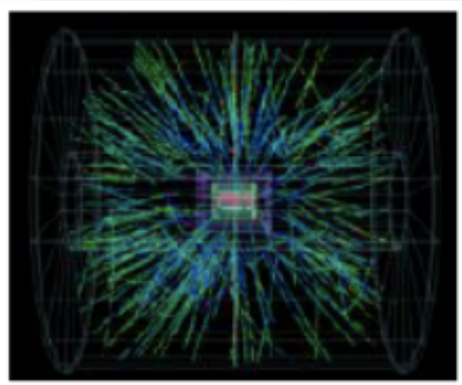
pp



QCD baseline:
This is the baseline for “standard” QCD phenomena

p-Pb





Cold QCD matter:
This is to isolate nuclear effects in absence of QGP, e.g. nuclear pdfs

New paradigm: small systems

Totally unexpected:

the discovery of correlations –ridge, flow- in small systems pA & pp

- Smooth continuation of heavy ion phenomena to small systems and low density
- Small systems as pA and pp show QGP-like features

Two serious contenders remain today:

- initial state: quantum correlations as calculated by CGC
- final state: interactions leading to collective flow described with hydrodynamics => equilibration?

The old paradigm that

- we study hot & dense matter properties in heavy ion AA collisions
- cold nuclear matter modifications in pA
- and we use pp primarily as comparison data   appears no longer sensible

We should examine a new paradigm, where the physics underlying soft collective signals can be the same in all high energy reactions, from e^+e^- to central AA

It becomes fundamental to have access to ep & eA collisions

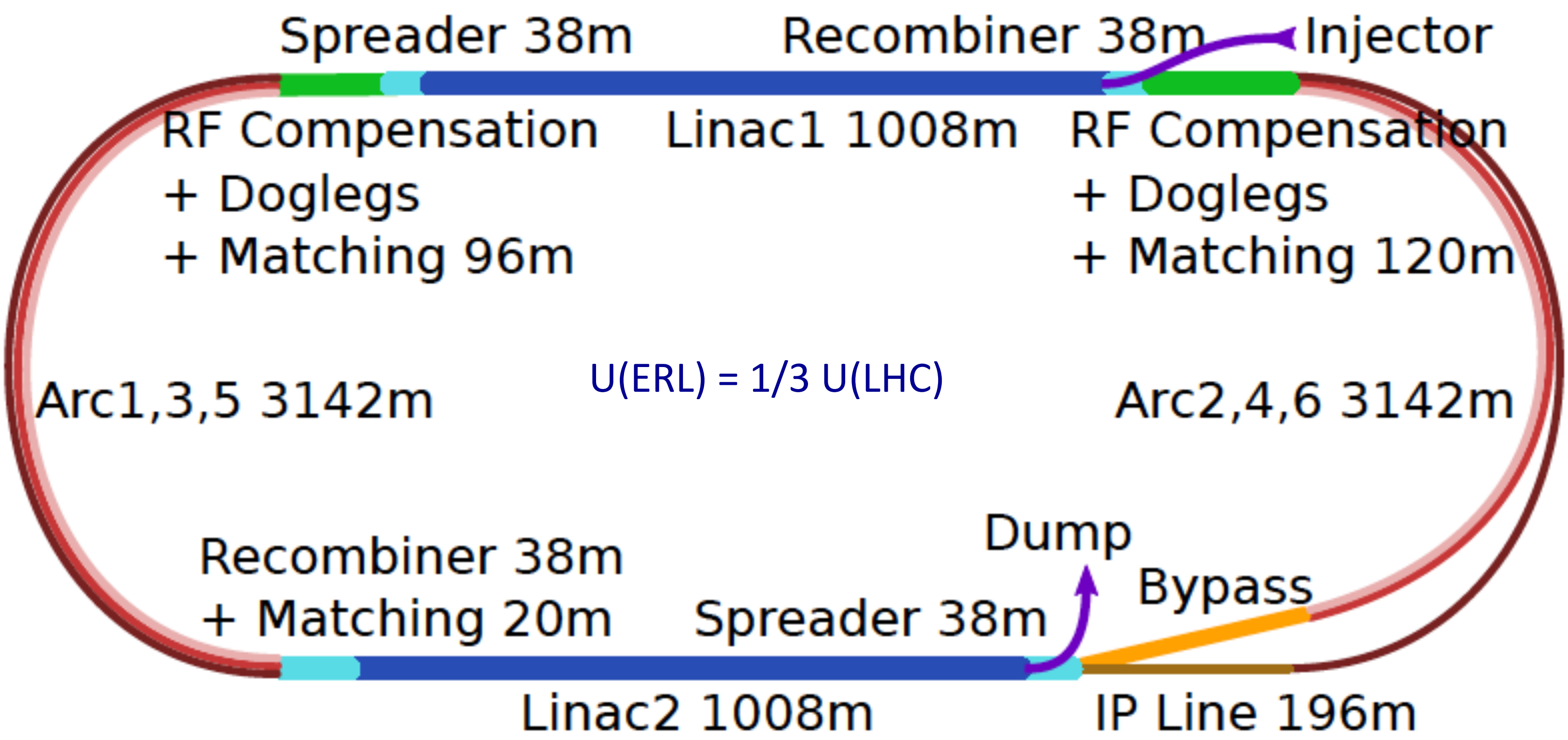
The LHeC Project in brief

Energy Recovery Linac

Civil Engineering and Configuration

Luminosity Performance for ePb
with HL-LHC, HE-LHC and FCC-eh

60 GeV Electron ERL added to LHC



Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
10^{34} cm^{-2} s^{-1} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach
1000 times HERA luminosity. It therefore extends up to x~1.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.

LHC (HL+HE) Footprint of ERL FCC

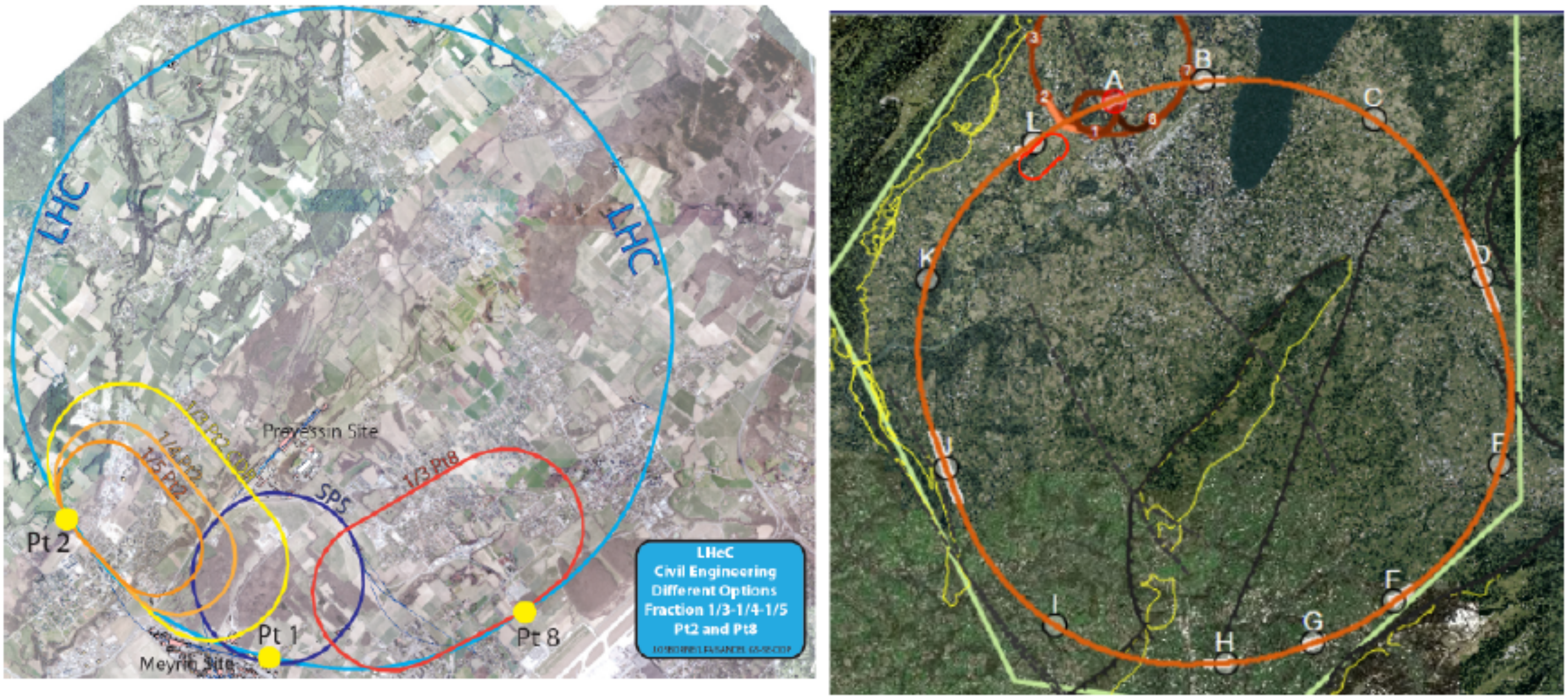
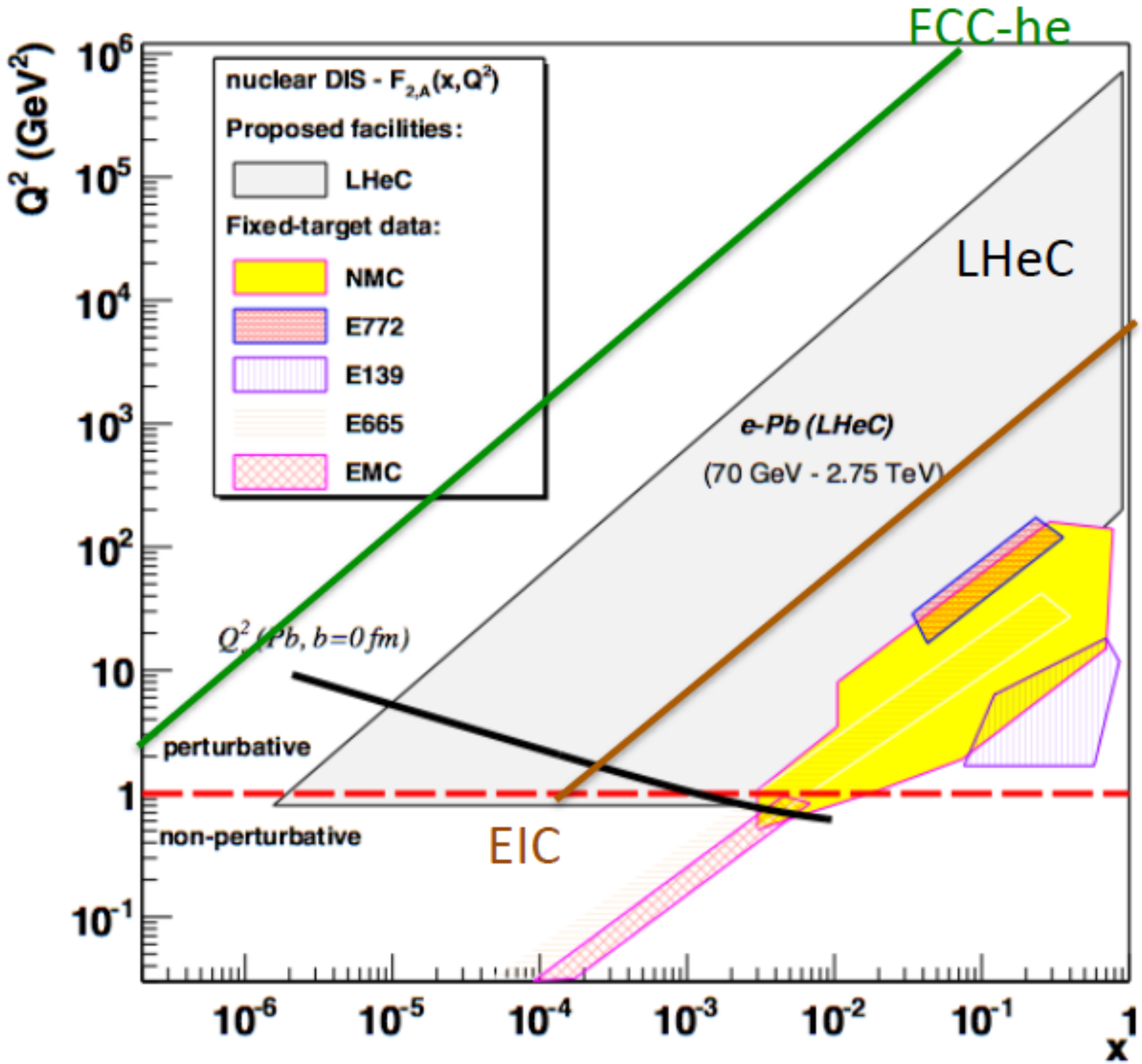


Figure 2: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60\,\text{GeV}$), 1/4 (the size of the SPS, $E_e = 56\,\text{GeV}$) and 1/5 (most inner track, $E_e = 52\,\text{GeV}$). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100 km ring of the FCC. Present considerations suggest that Point L may be preferred as the position of the ERL, while two GPDs would be located at A and G.

Kinematic Ranges of Future Electron-Ion Colliders

HERA missed the electron-ion phase. No deuterons either.



Expect saturation of rise at

$Q^2_s \approx xg\, \alpha_s \approx c\, x^{-\lambda} A^{1/3}$

Note that the gluon is valence like at low Q^2

Energy and Luminosity ePb Prospects

Table 3: Baseline parameters of future electron-ion collider configurations based on the electron ERL, in concurrent eA and AA operation mode.

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
bunch spacing [ns]	50	50	100
no. of bunches	1200	1200	2072
ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
electrons per bunch [10^9]	4.67	6.2	12.5
electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3
bunch filling H_{coll}	0.8	0.8	0.8
luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

2017

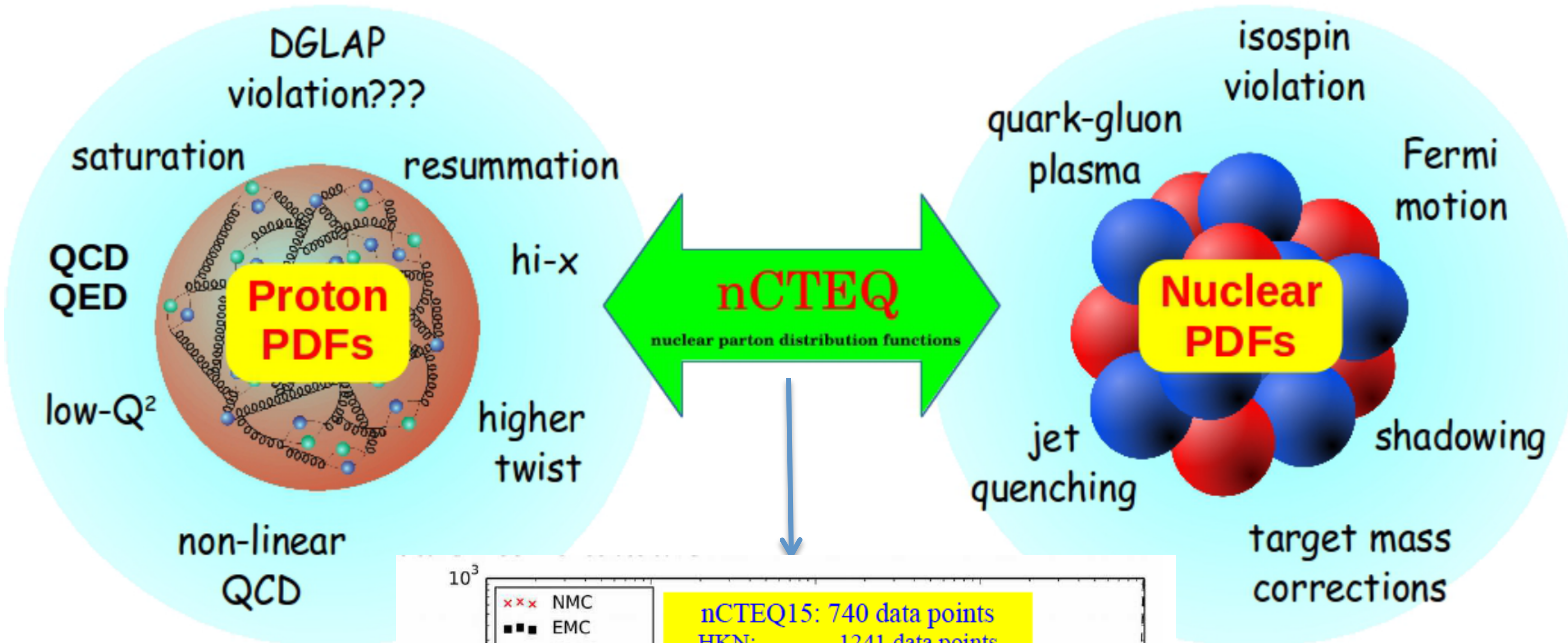
Nuclear Parton Distributions

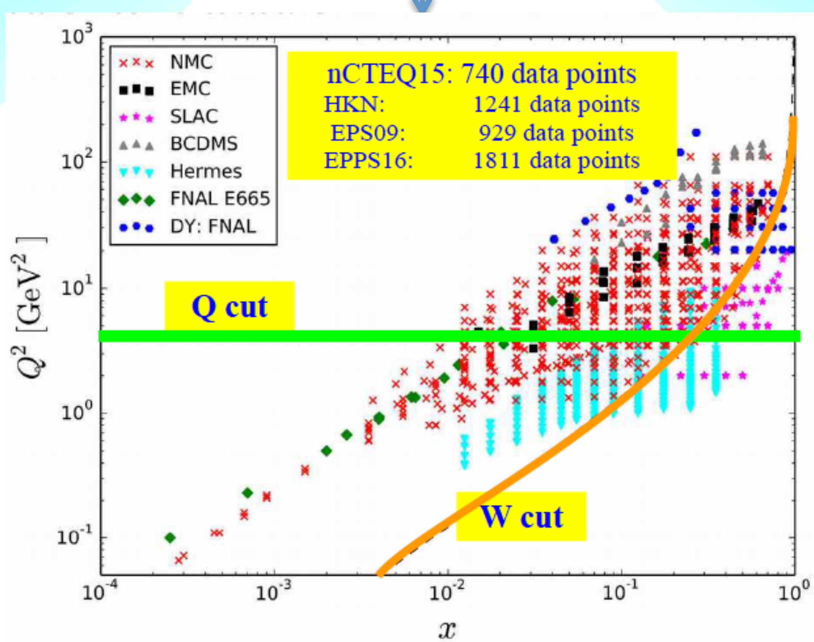
Remark on the current situation

The LHeC nuclear PDF programme

Simulations on xg, light and heavy flavours

Parton Distribution Functions



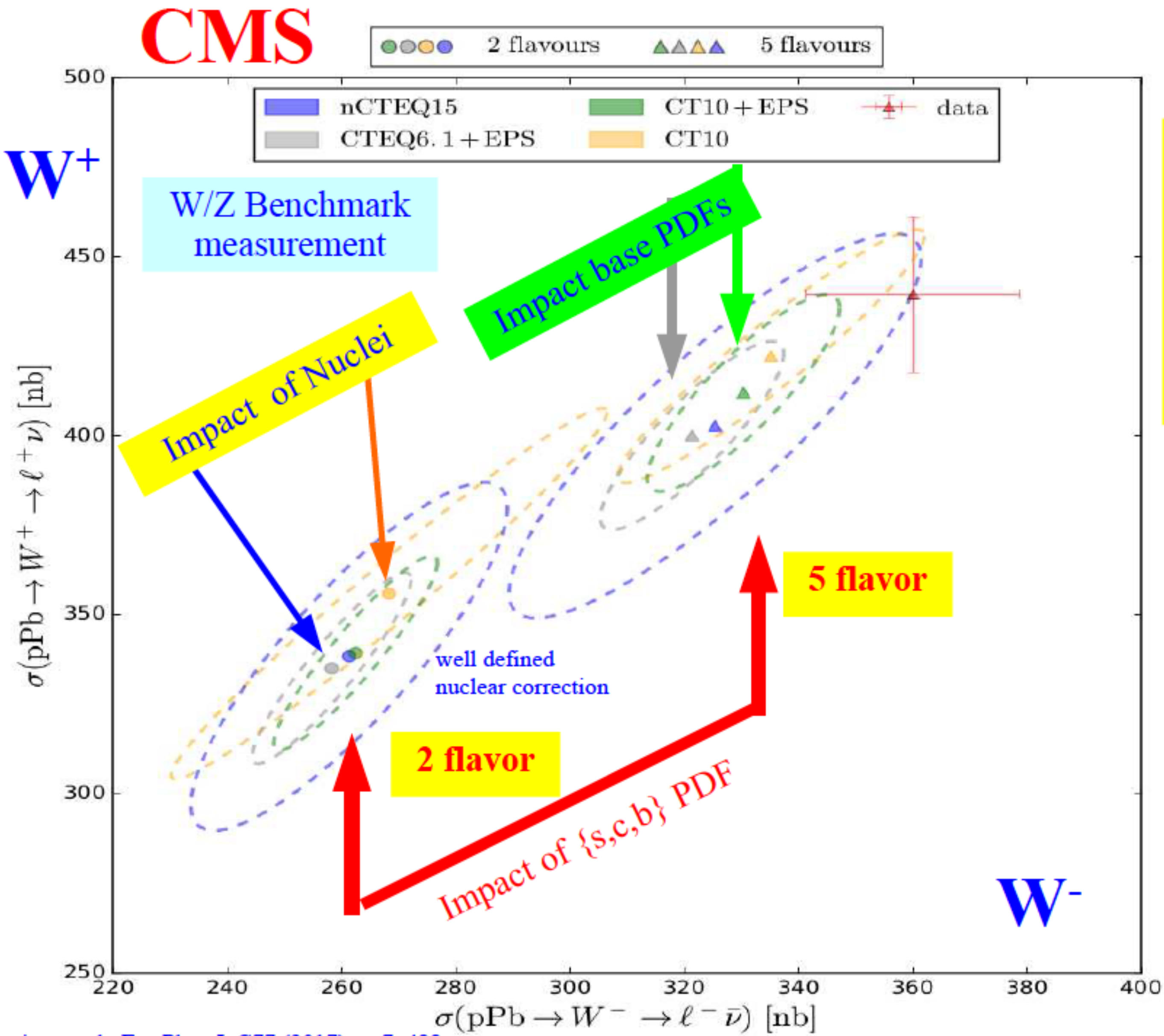


Kovarik et al

nPDF situation is like proton PDFs prior to HERA: huge uncertainties especially on the gluon and range restricted to $x > 0.01$.
fits on many nuclei

W,Z LHC HI data hint to enlarged strange as in ep/pp analysis. No strong impact n nPDFs
F Olness, DIS18

p Pb → W/Z: Impact of {s,c,b} PDF



Entangled:

- Nuc Corrections
- Base PDF
- PDF Flavors

This is an area where LHeC is particularly suited to help

F Olness, DIS18

A. Kusina, et al., Eur.Phys.J. C77 (2017) no.7, 488

The nuclear PDF Programme of the LHeC

Extend HERA range by factor of 20 for proton and DIS range by a few times 10^3
→ access x near 1 through huge luminosity increase and very low x for saturation

Establish new, single, coherent set for proton PDFs: gluon and all quarks.

This includes direct measurements of s, c, b through tagging, and u-d separation through photon, Z and W probes: free of nuclear corrections [and higher twists]

Measure the strong coupling constant to 0.1% precision in ep

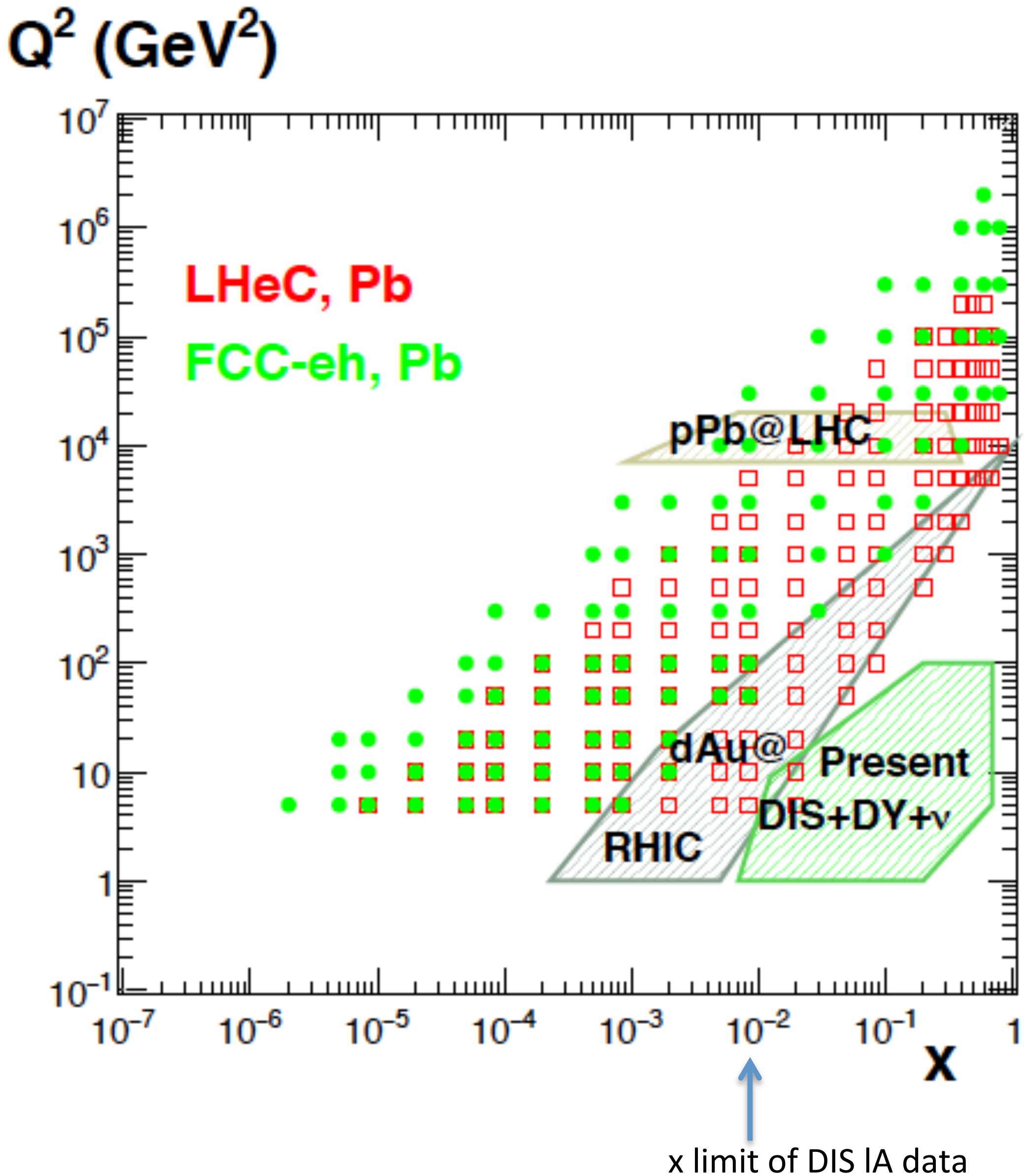
Establish non-linear parton interactions in ep through F_2 and F_L precision data, i.e. establish new evolution law at small x when ln(1/x) is large and α_s is small, independently of its occurrence ~$A^{1/3}$ in the nucleus

"Repeat" this ep programme with ePb scattering data, 10 fold of HERA ep lumi

This overcomes the proton PDF base fit approach, and disentangles flavour, nuclear and non-linear interaction effects.

It determines nuclear/proton rations $R_i(x,Q^2)$ for i=gluon and all quarks, with high precision as the inputs are precise and coherent and some systematics cancel in the ratios → get flavour dependend shadowing information etc.

DIS ePb data from LHeC (FCCeh)



Huge extension of range. For DIS: 3-4 orders of magnitude

Statistics 10 x HERA ep, about

Very precise: kinematics from scattered lepton and hadronic final state.

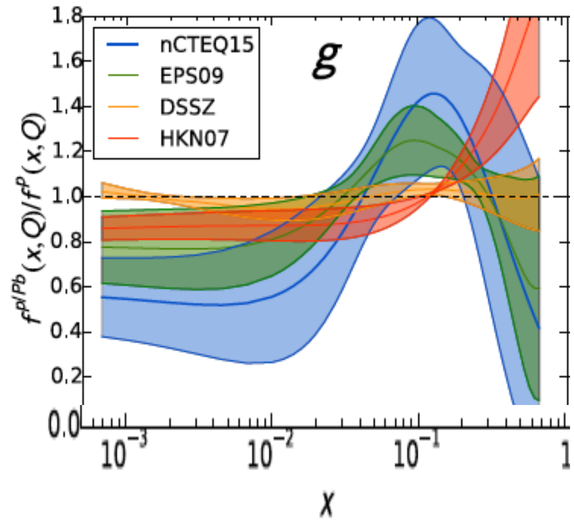
Neutral Current down to $10^{-5/6}$
- charm and beauty from ePb

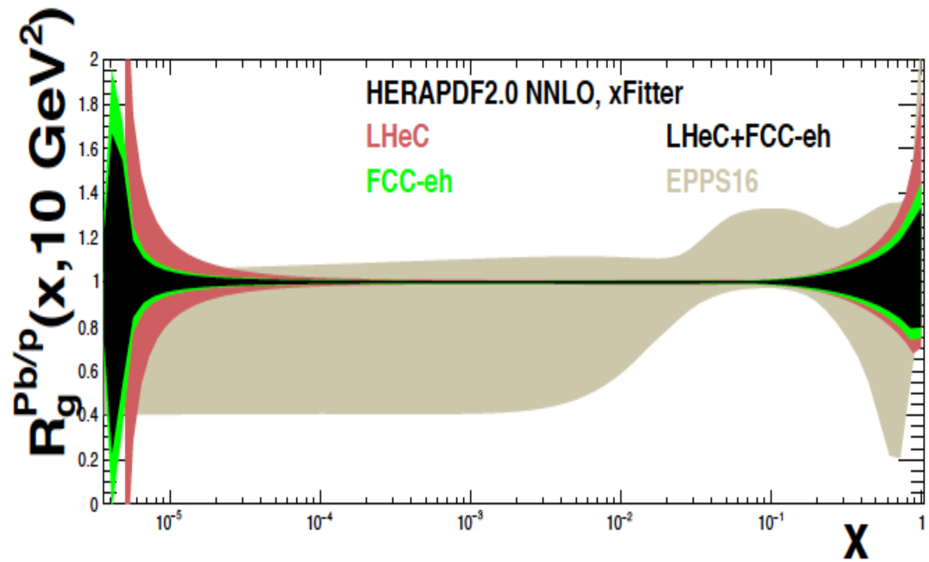
Precise Charged Currents in eA
- flavour decomposition
- strange density (Ws → c)

Coherent, precise determination of quark and gluon PDFs for protons and nucleus

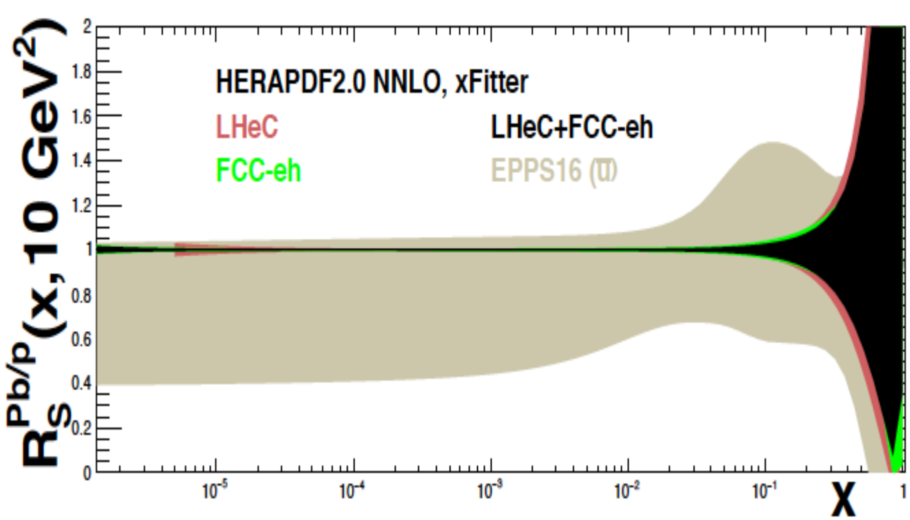
Determination of p and A PDFs at LHeC

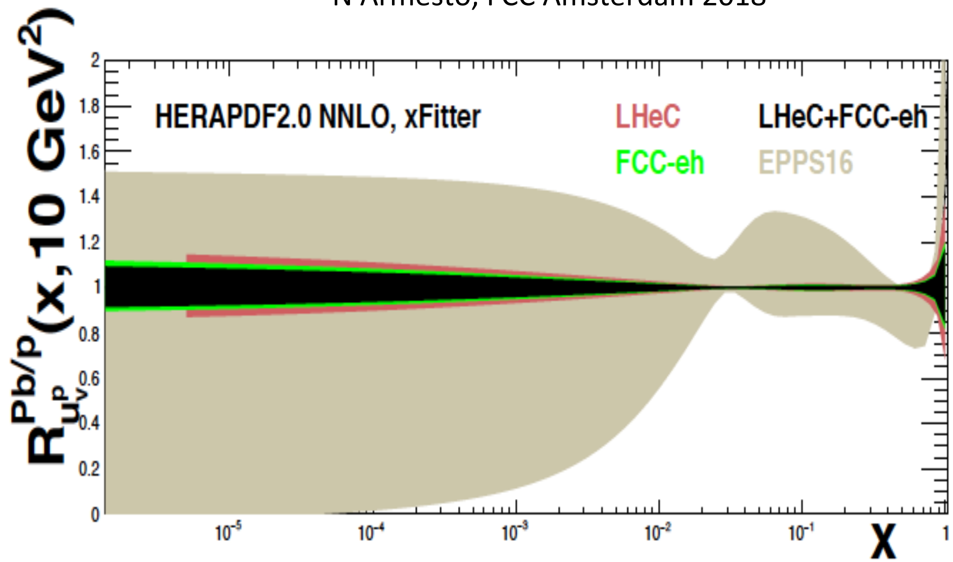
1509.00792



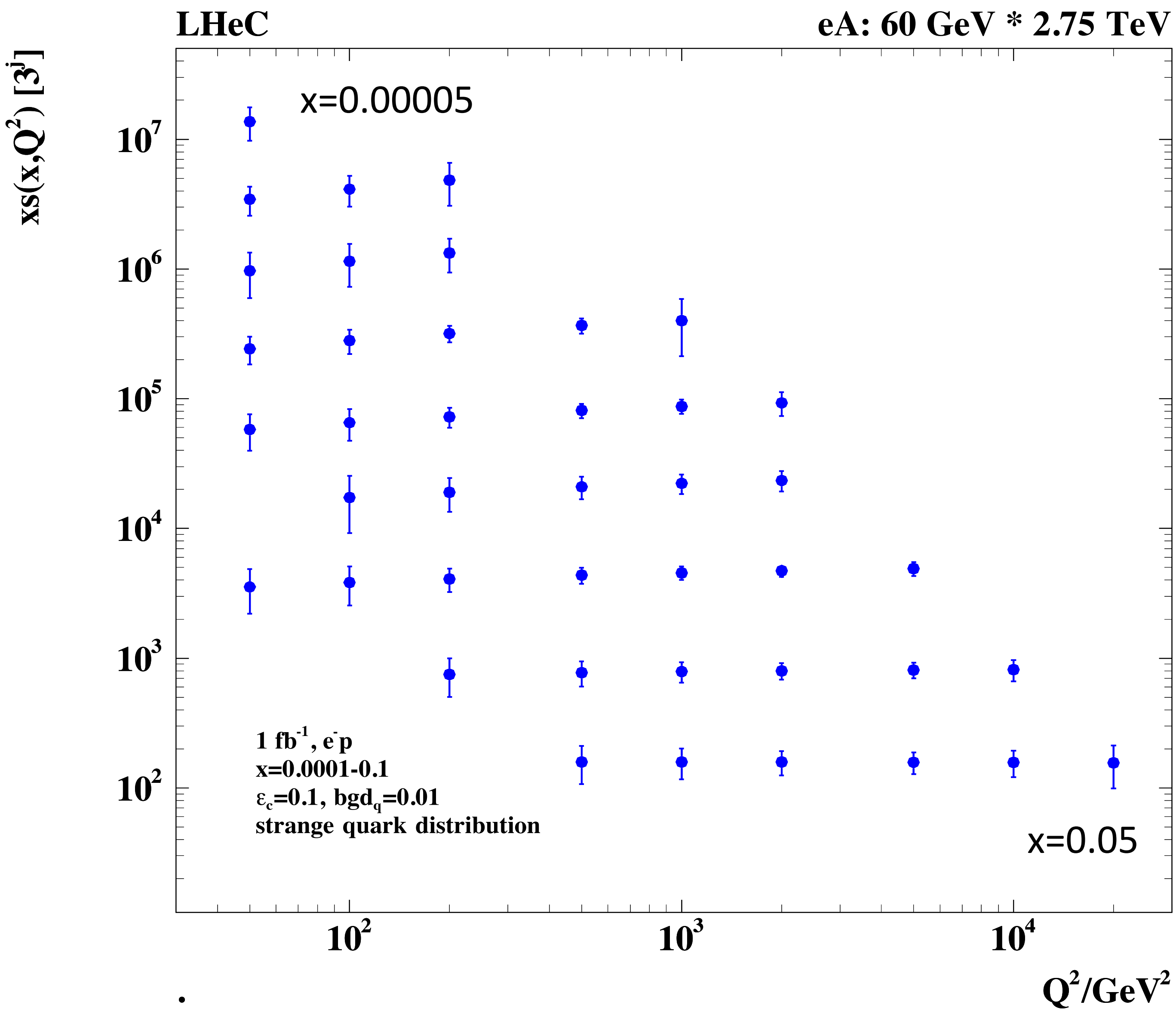


N Armesto, FCC Amsterdam 2018

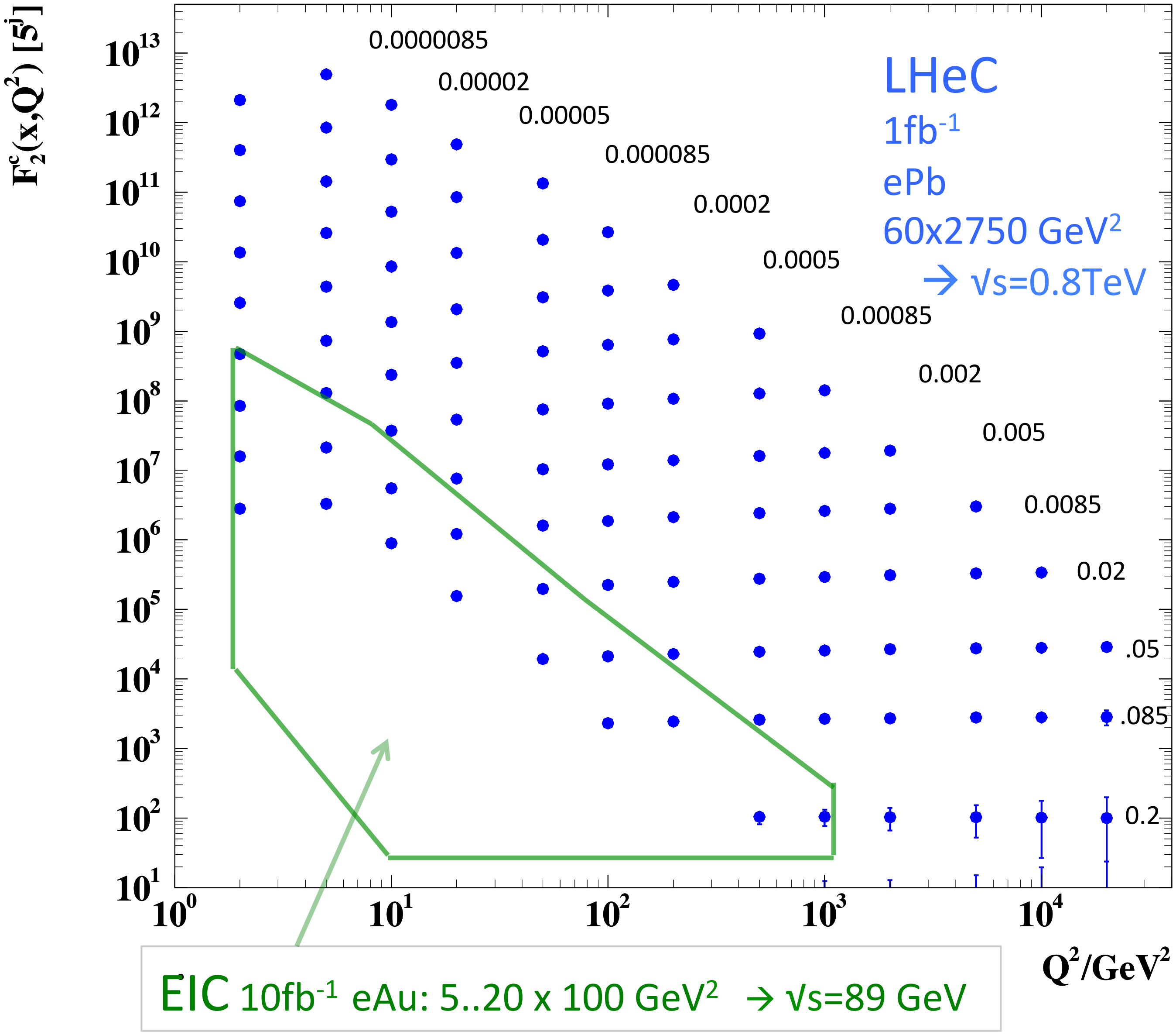




Heavy Flavour – Strange in ePb - from CC



Charm Structure Function in Nuclei



Also F_Lc and b

Physics at LHeC as an EIC

A too brief summary

Note the complementarity of LHEC to lower energy EICs

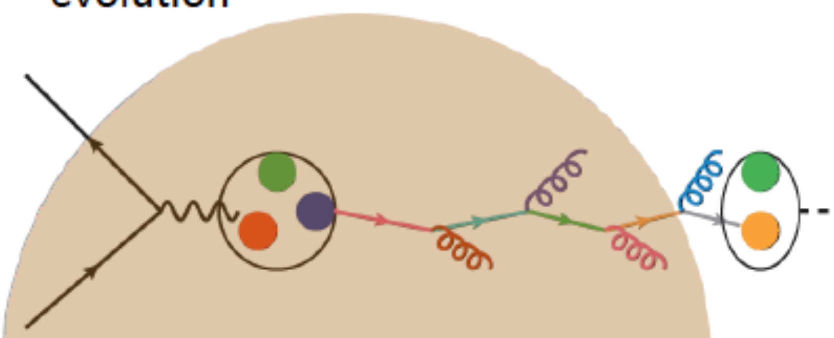
Partonic evolution and hadronization

Relevant for particle production and QGP analysis in HIC:

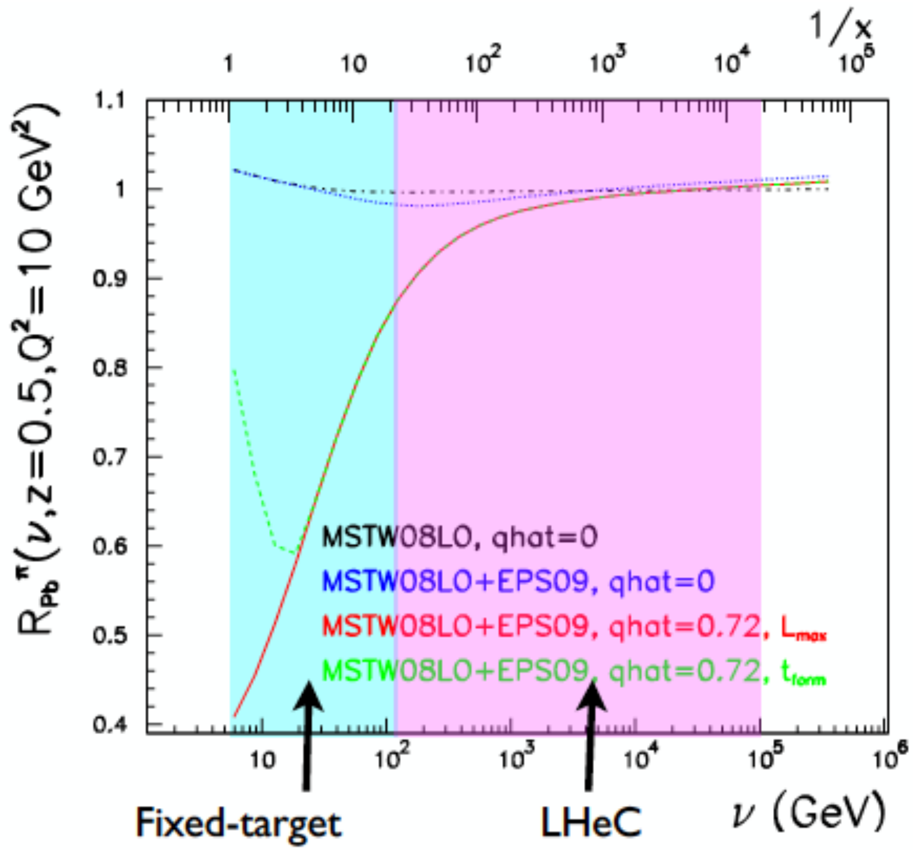
jets plentiful in eA
benchmark for jet quenching studies in AA

Low energy:
hadronization in matter
- (pre)hadronic absorption
- formation time

High energy:
- modification of partonic evolution



Ratio of fragmentation functions Pb/p



Other possible studies: quarkonium production

Production mechanism and polarization:

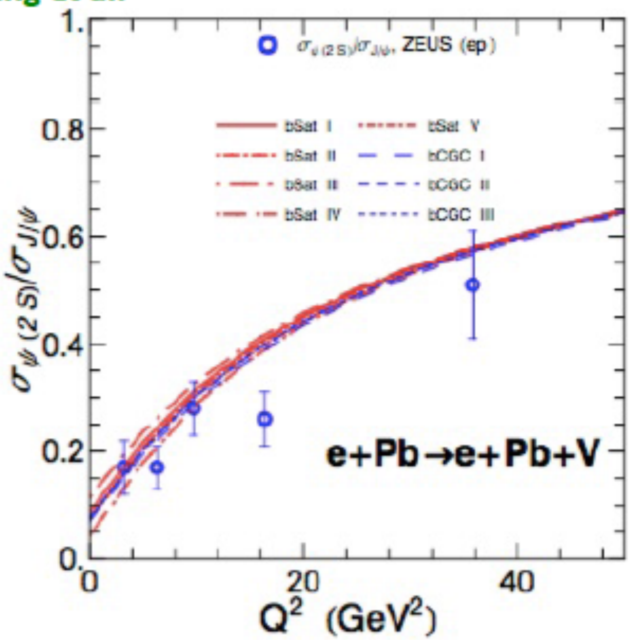
polarized J/ψ photoproduction can be studied more precisely and up to much larger values of p_T in ep @ LHeC

⇒ test NRQCD factorization in charmonium physics

Butenschoen Kniehl

Charmonium WF in diffractive DIS within the dipole formalism

Cheng et al.



Spatial and Momentum Tomography of Hadrons and Nuclei

Gluon TMDs could be directly probed by looking at p_T distributions and azimuthal asymmetries in $e\,p \to e\,Q\,\bar{Q}\,X$

Boer, Lansberg, Pisano

Gluon GPDs

Υ production at an EIC to determine the gluon density transverse spatial profiles in a wide range of x and consequently provide a path to determine the gluonic radius of the nucleon and the contribution of the total angular momentum of gluons to the nucleon spin

Joosten and Meziani

ep & eA collisions at high energy offer huge possibilities:

To provide information about QCD first principles:

- Partonic structure
- New regimes of QCD
- 3D structure of hadrons and nuclei
- The role of gluons in structure and dynamics
- Dynamics of QCD radiation and hadronization
- Confinement: understand the emergence of hadrons from color charge

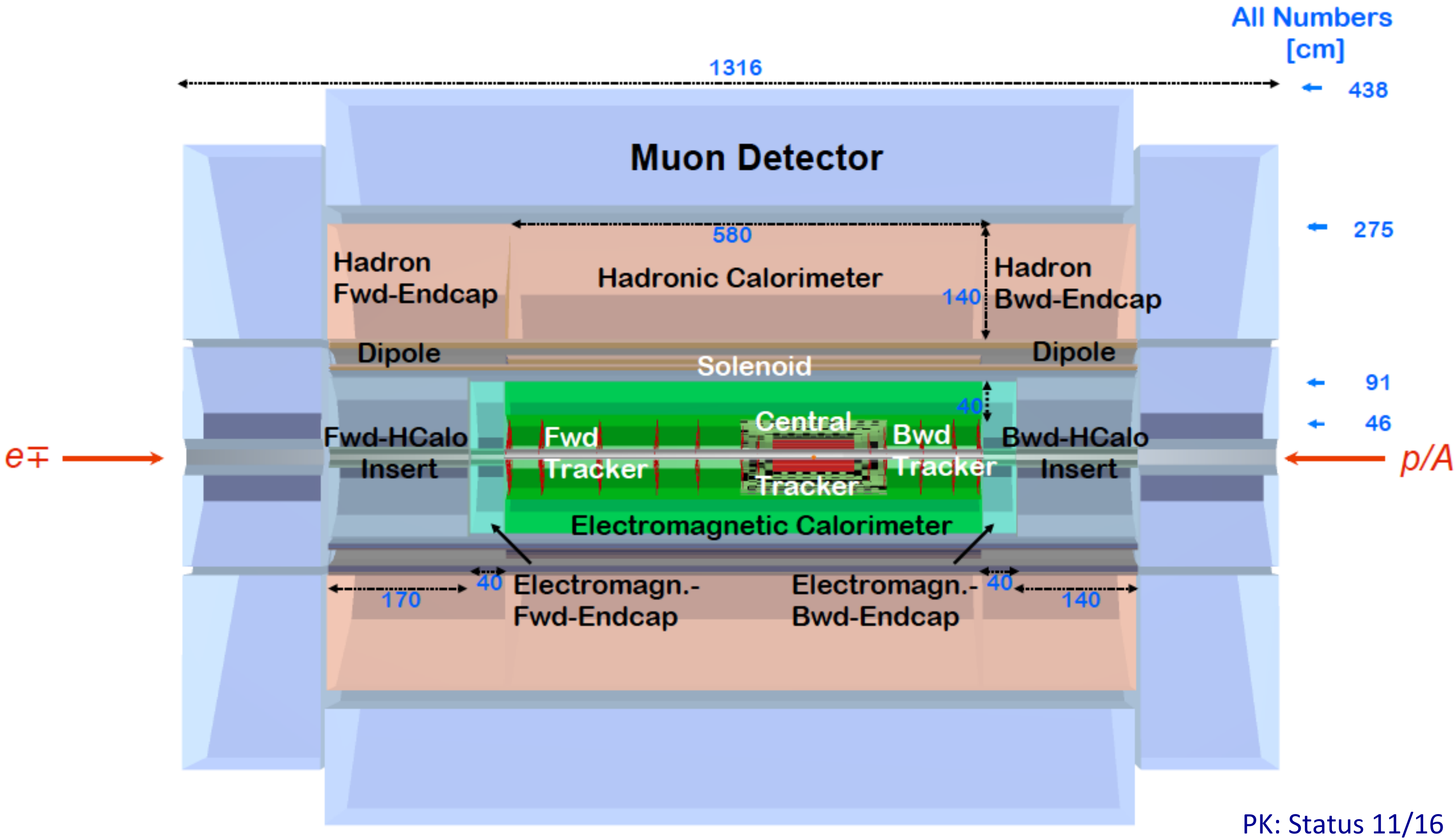
To clarify aspects of pp, pA and AA collisions at high energy:

- Initial conditions for macroscopic descriptions
- Nature of collectivity
- Thermalization
- Extraction of parameters of the medium
- Distinguish “genuine” QGP effects
- ...

Detector

Design, Components and Installation

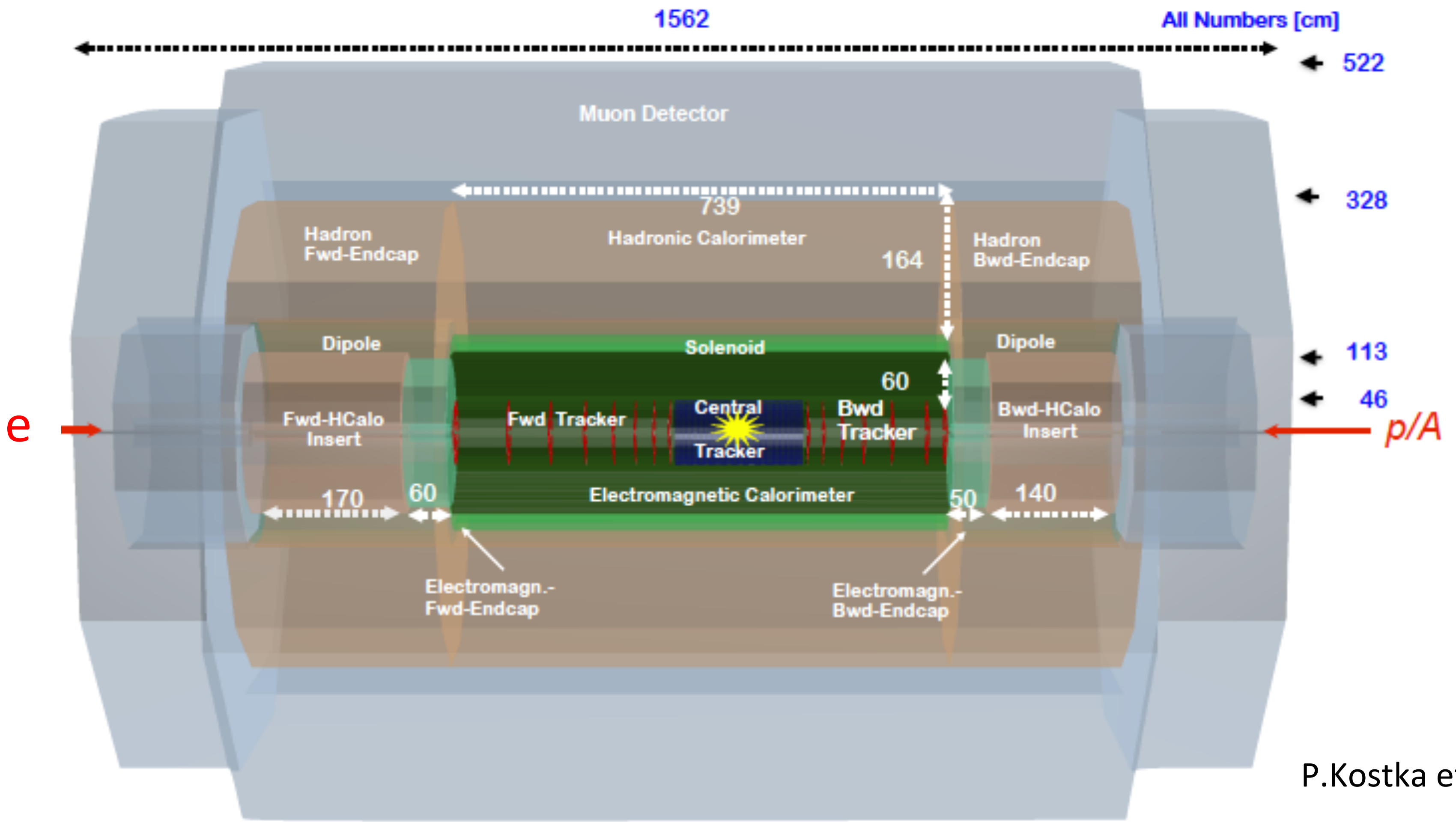
LHeC Detector



PK: Status 11/16

Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =13x9m^2 [CMS 21 x 15m^2 , ATLAS 45 x 25 m^2]
Taggers at -62m (e), 100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

LHeC Detector for the HL/HE LHC



P.Kostka et al

Length x Diameter: LHeC (13.3 x 9 m^2)   HE-LHC (15.6 x 10.4) FCCeh (19 x 12)

ATLAS (45 x 25) CMS (21 x 15): [LHeC < CMS, FCC-eh ~ CMS size]

Forward p+n taggers: cf presentation by P Newman at Orsay 6/18 LHeC workshop

LHeC (CDR) Solenoid 3.5 T, 2.24 m OD, 7.1 m L

It will look like.........a stretched and squeezed ATLAS solenoid,

2 T scaled up to 3.5T (2 layer coil, slightly less free bore but a bit longer)

Relatively small bore but long, and efficient coil with 1.8 m free bore, 7.1 m long

- ≈ 11 km Al stabilized NbTi/Cu superconductor for 10 kA
- ≈ 80 MJ stored energy and ≈ 24 t mass including cryostat.

H ten Kate (EP-RD, 16.3.18)

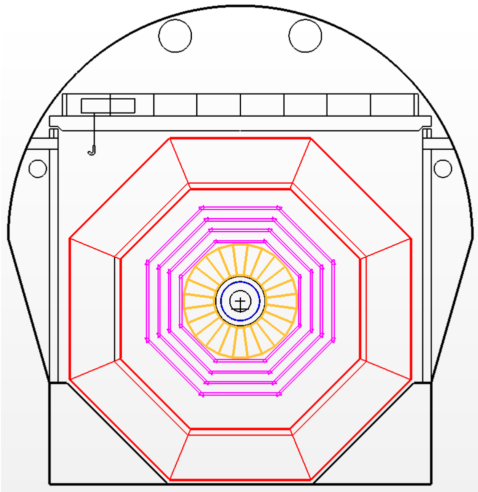
No specific R&D needed, except detailed analysis of the dipole load case

- Design concept: minimum cost, R&D and risk, relies on present technology for detectors magnets
- **3.5 T Solenoid & 2 Dipoles** in same cryostat around EMC, Muon tagging chambers in outer layer
- **Solenoid and dipoles have a common support cylinder in a single cryostat**; free bore of 1.8 m; extending along the detector with a length of 10 m.

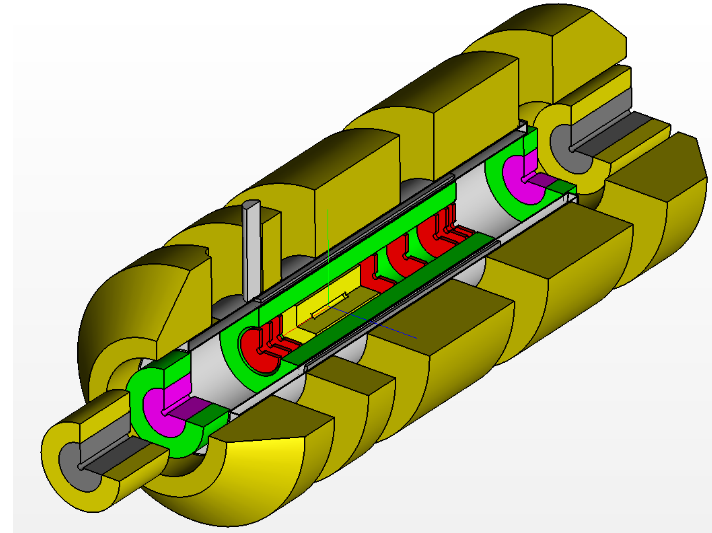
Installation Study

to fit into LHC shutdown needs directed to IP2

Andrea Gaddi et al

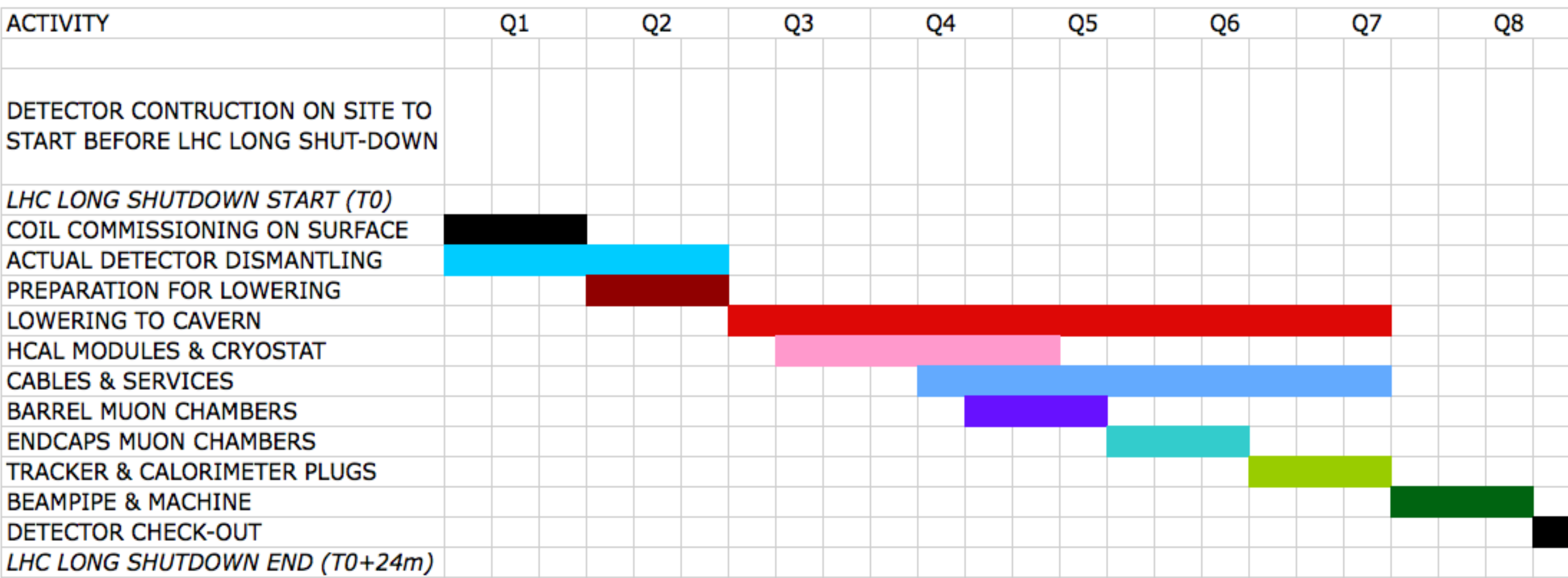


Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE



Prospects

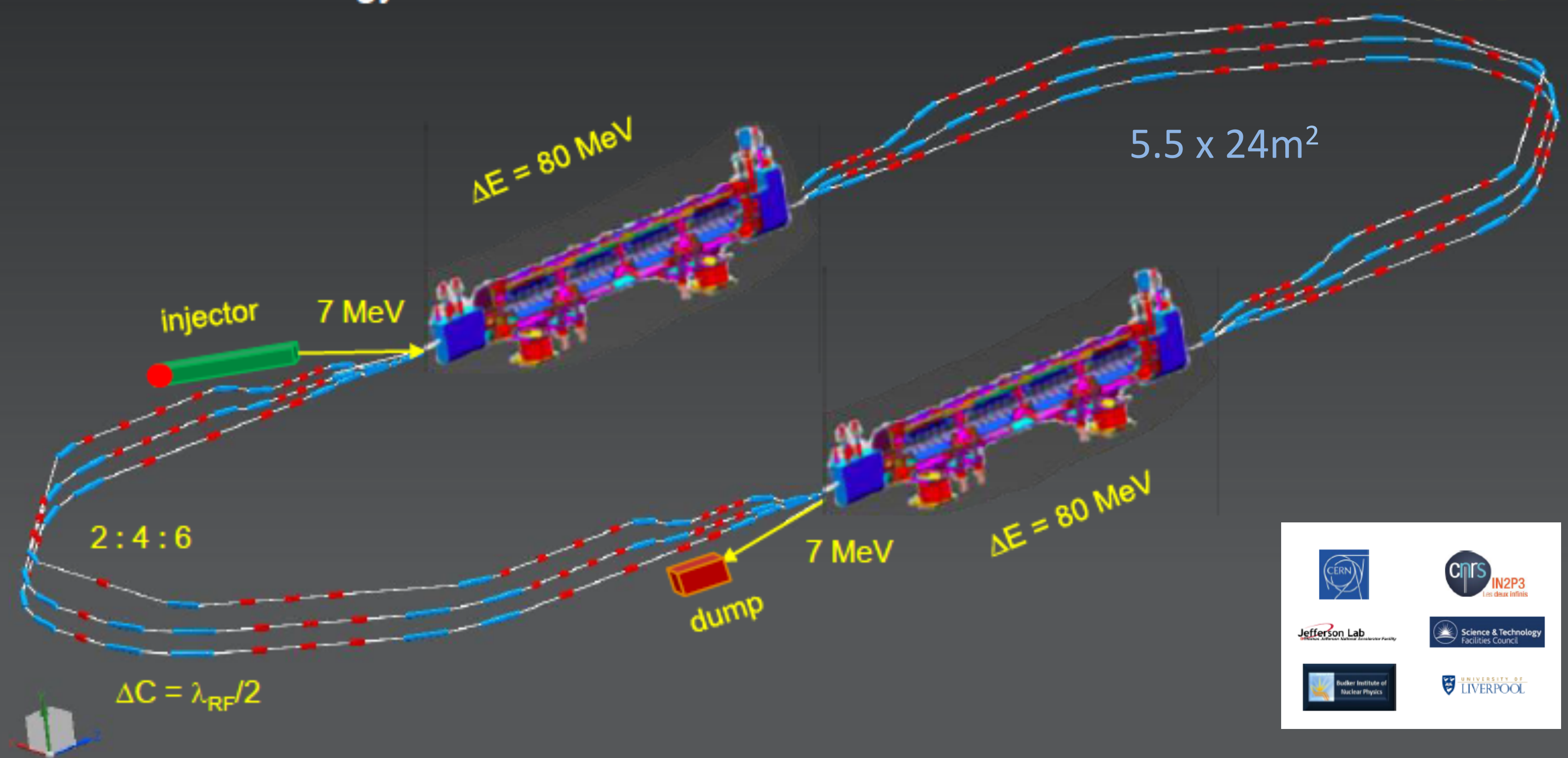
Technology Development in PERLE

General Physics Case

Strategy of exploring energy frontier particle physics

Powerful ERL for Experiments at Orsay

- 2 Linacs (Four 5-Cell 801.58 MHz SC cavities)
- 3 turns (160 MeV/turn)
- Max. beam energy 500 MeV at 20mA → 10 MW

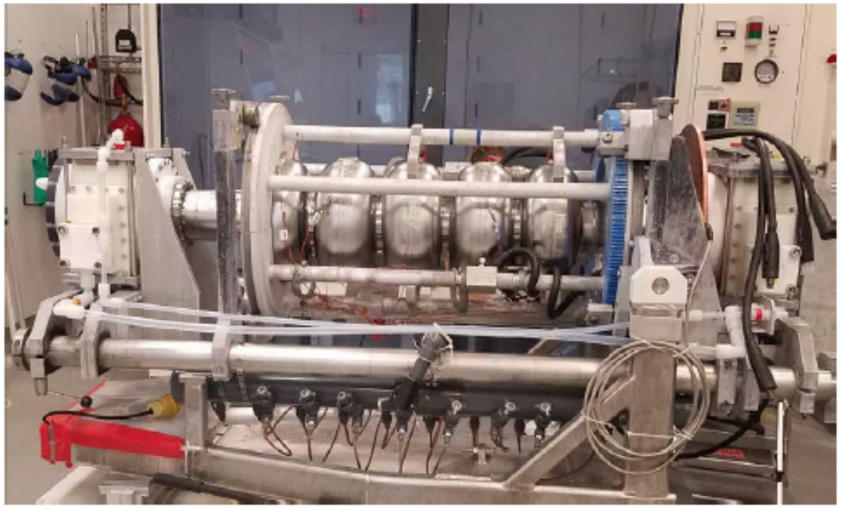


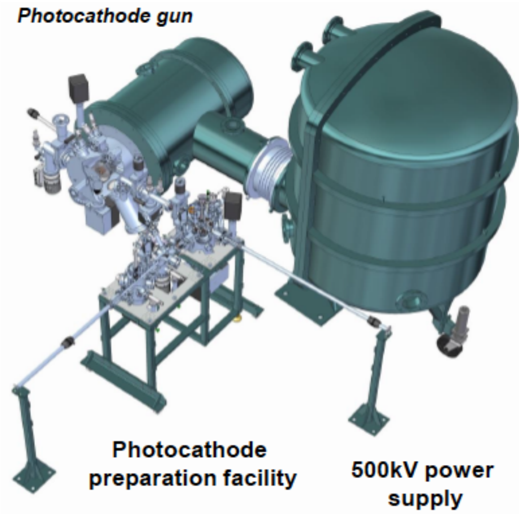
cf Walid Kaabi at Amsterdam FCC

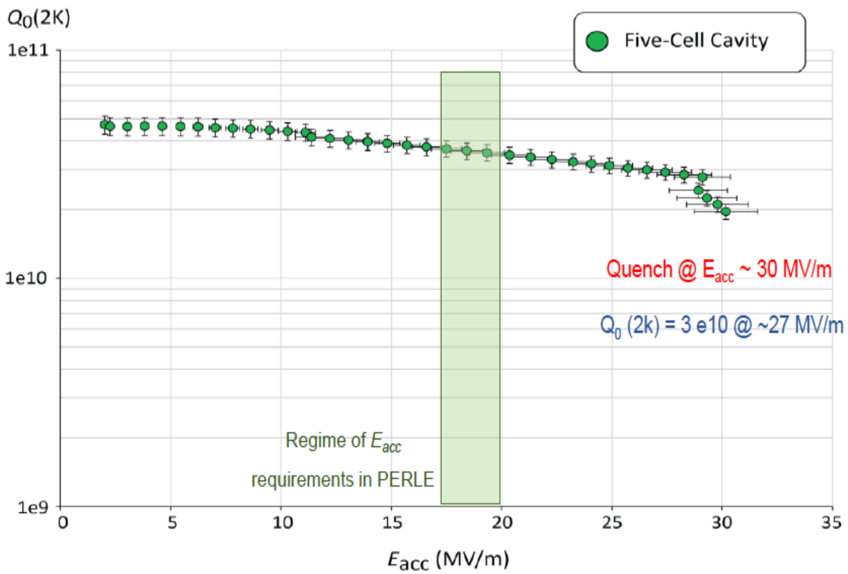
New SCRF, High Intensity (100 x ELI) ERL Development Facility with unique low E Physics

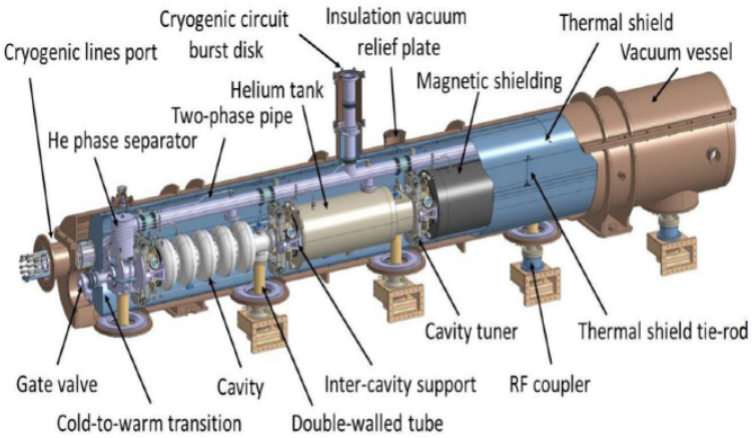
Towards PERLE: 802 MHz cavity, Source, Cryomodule, Magnets

First 802 MHz cavity successfully built (Jlab)



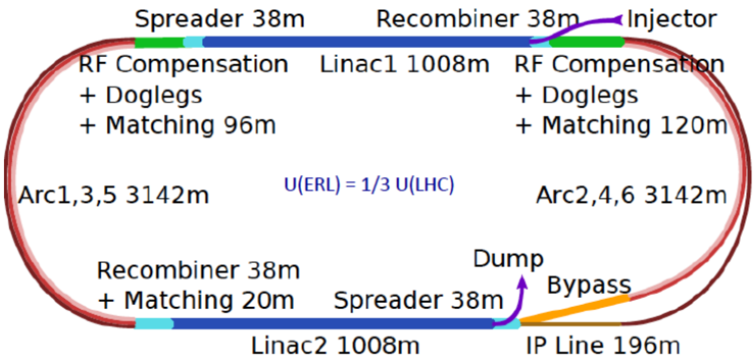






BINP, CERN, Daresbury/Liverpool, Jlab, Orsay, +

CDR 1705.08783 [J.Phys G] → TDR in 2019



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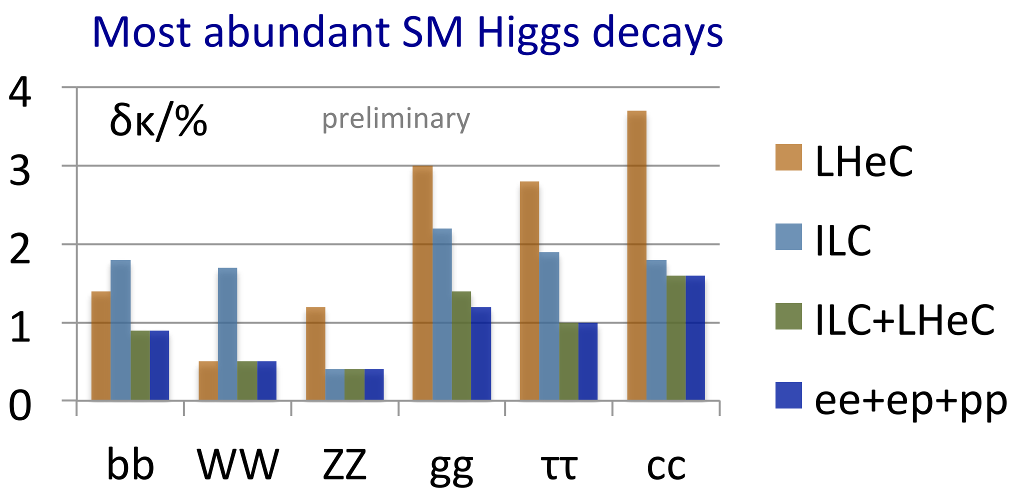
SM Higgs Physics Prospects: pp+ep+ee



Huge potential for exploring Higgs at percent accuracy with pp+ep+ee in the about 20 years ahead.

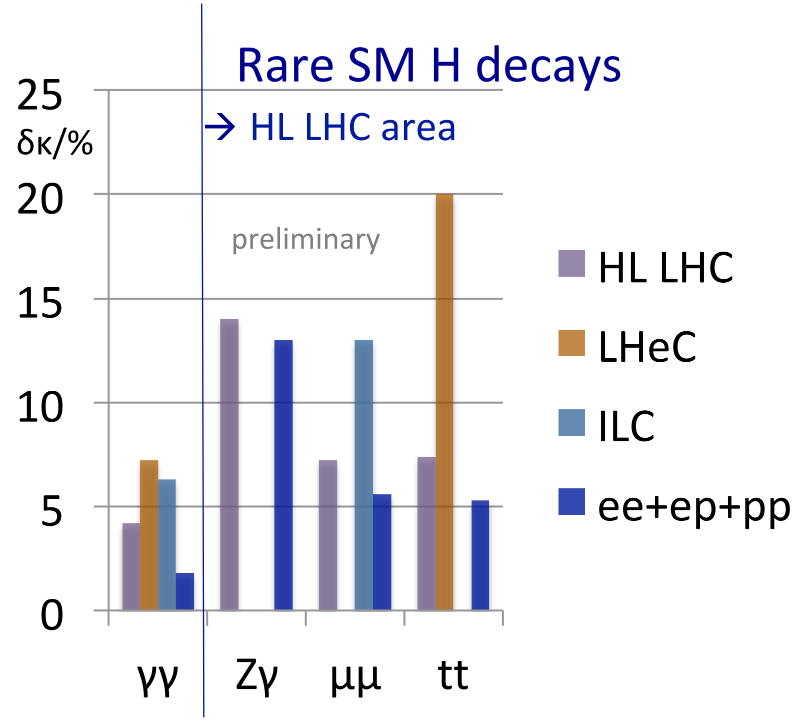
Striking example for pp+ep+ee synergy at TeV scale.

≤ 1% from ee and ep combination.

Note WW & ZZ synergy. Γ_{tot} in ee

Little influence of HL LHC on dominant channels

SM rare Higgs decays are for the pp collider →

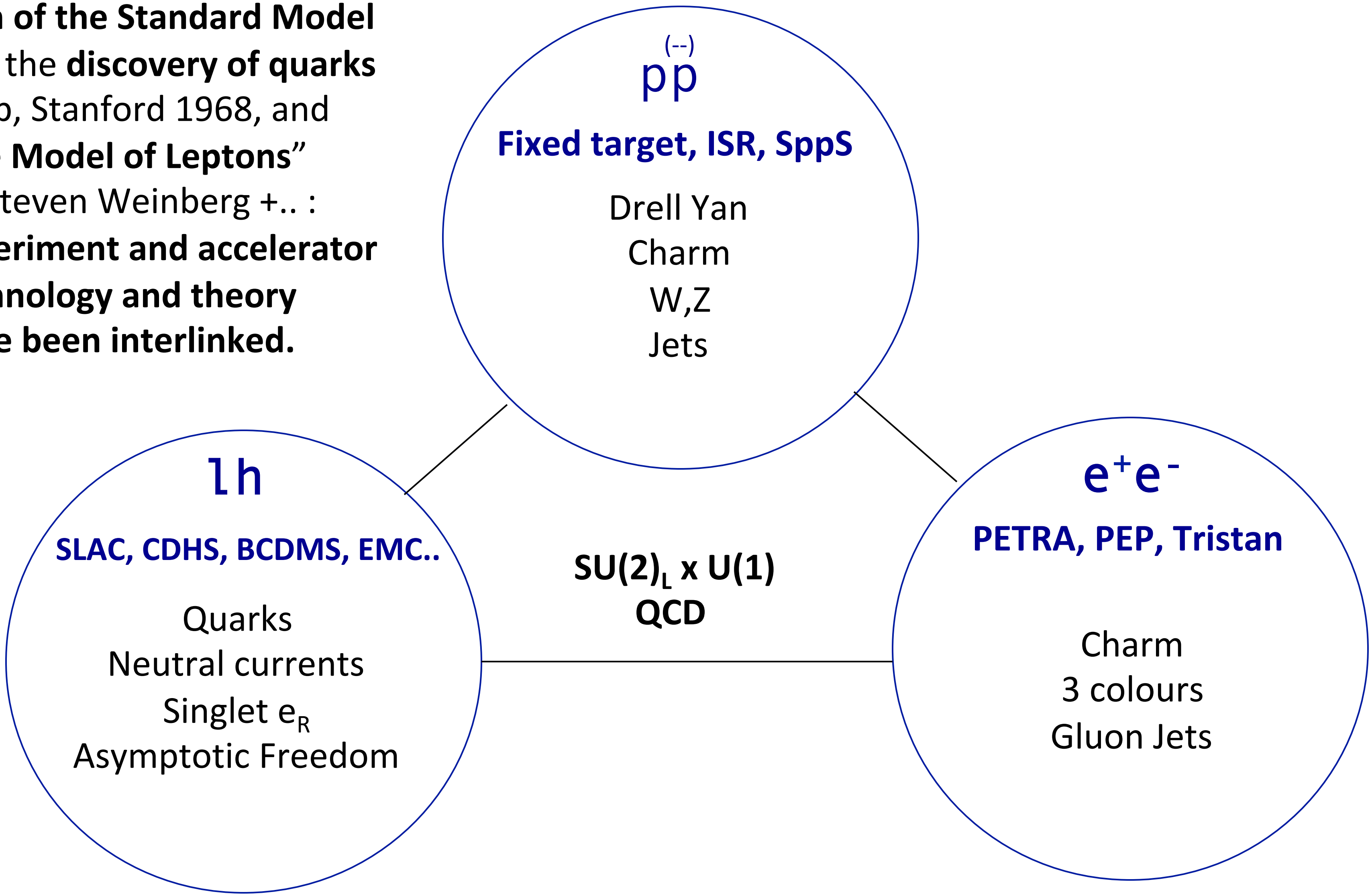


Kappa framework analysis by J. De Blas, prel.: Input:
pp: 3 ab^{-1} ATLAS'14 w/o thy unc.– update: HL LHC WS ..
ep: 1ab^{-1}, LHeC Study Group, U.Klein et al., prel.,
ee: 2 ab^{-1} ILC250 signal strength 1708.08912

Particle Physics at O(10) GeV ~1968-1988

Two Decades

One may connect the **birth of the Standard Model** with the **discovery of quarks** in ep, Stanford 1968, and “**The Model of Leptons**” by Steven Weinberg +.. : **Experiment and accelerator technology and theory have been interlinked.**



Particle Physics at O(100) GeV ~1985-2015

Three Decades

Tevatron, LEP and HERA established the SM, its missing center, the Higgs Boson was then discovered at the LHC. They found no BSM sign. **Particle Physics had managed to have hh, ee and eh collisions, for securing its progress**.

$\bar{p}p$

Tevatron

b quark
top quark
M_W
No SUSY, BSM

ep

HERA

Gluon dominance, low x
Electroweak Unification
h.o. strong → PDFs, c, b
No SUSY, BSM

e^+e^-

LEP/SLC

M_Z , $\sin^2 \Theta$
Three neutrino families
h.o. el.weak → mt,mH
No SUSY, BSM

CKM - **B factories**

The Standard Model Triumph

Neutrino Physics
Oscillations, PMNS

Particle Physics at O(1) TeV ~2010-2050

Four Decades

The goal of current developments is to maximally exploit the LHC and to complement It with ep (LHeC) and ee (ILC, CepC..??) colliders to explore the TeV scale and find new directions of HEP as theory is less prescriptive

Electrons may be brought to the LHC and a new 1 TeV energy eh collider can be built, with its own fundamental physics, at a cost O(1/10) that of the ee machines in sight.

pp

LHC(b)

Rare Higgs Decays, H-HH?
Precision W,Z,top,
QCD, Flavour
No SUSY, BSM - yet

ep

LHeC

Maximise LHC Physics:
Precision QCD, α_s , el.weak
Precision Higgs
BSM?

eA

Higgs + New Physics?
High Precision & Searches

e^+e^-

ILC, CepC, CLIC

Precision Higgs
Precision el.weak
α_s
BSM?

SuperB

Neutrino Physics
Hierarchy, CP, .. factory

The early beginning

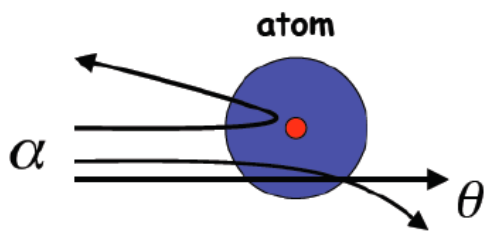
1900

The electron was discovered,
next to 92 chemical elements.

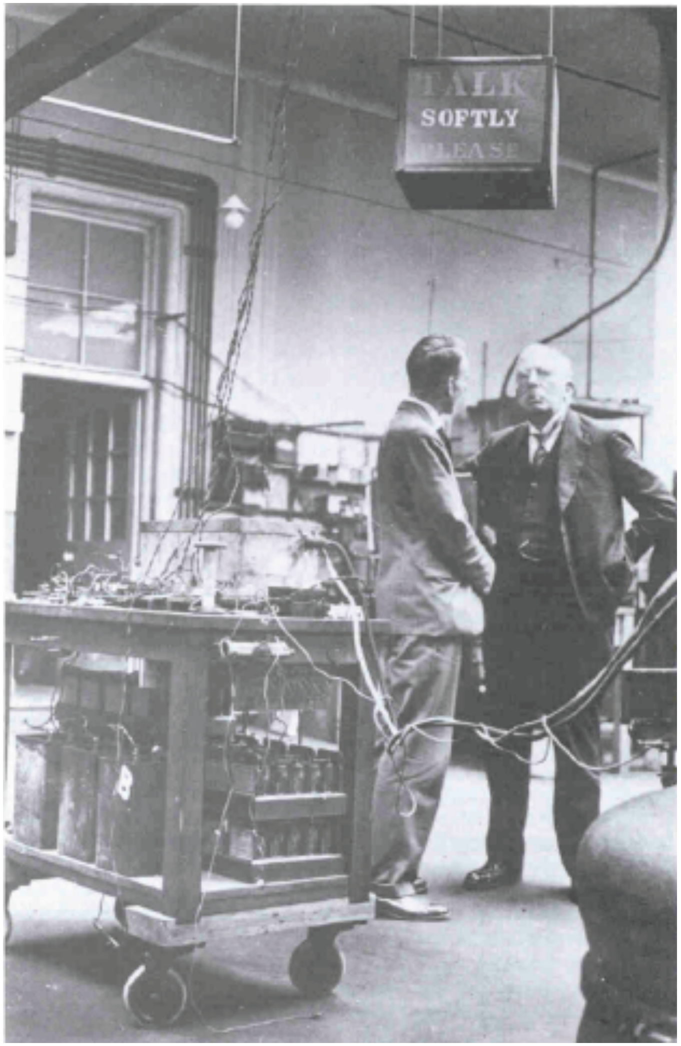
Lord Kelvin: There is nothing new to be discovered in physics. All that remains is more and more precise measurement.

1909

Discovery of the atomic nucleus in a scattering experiment



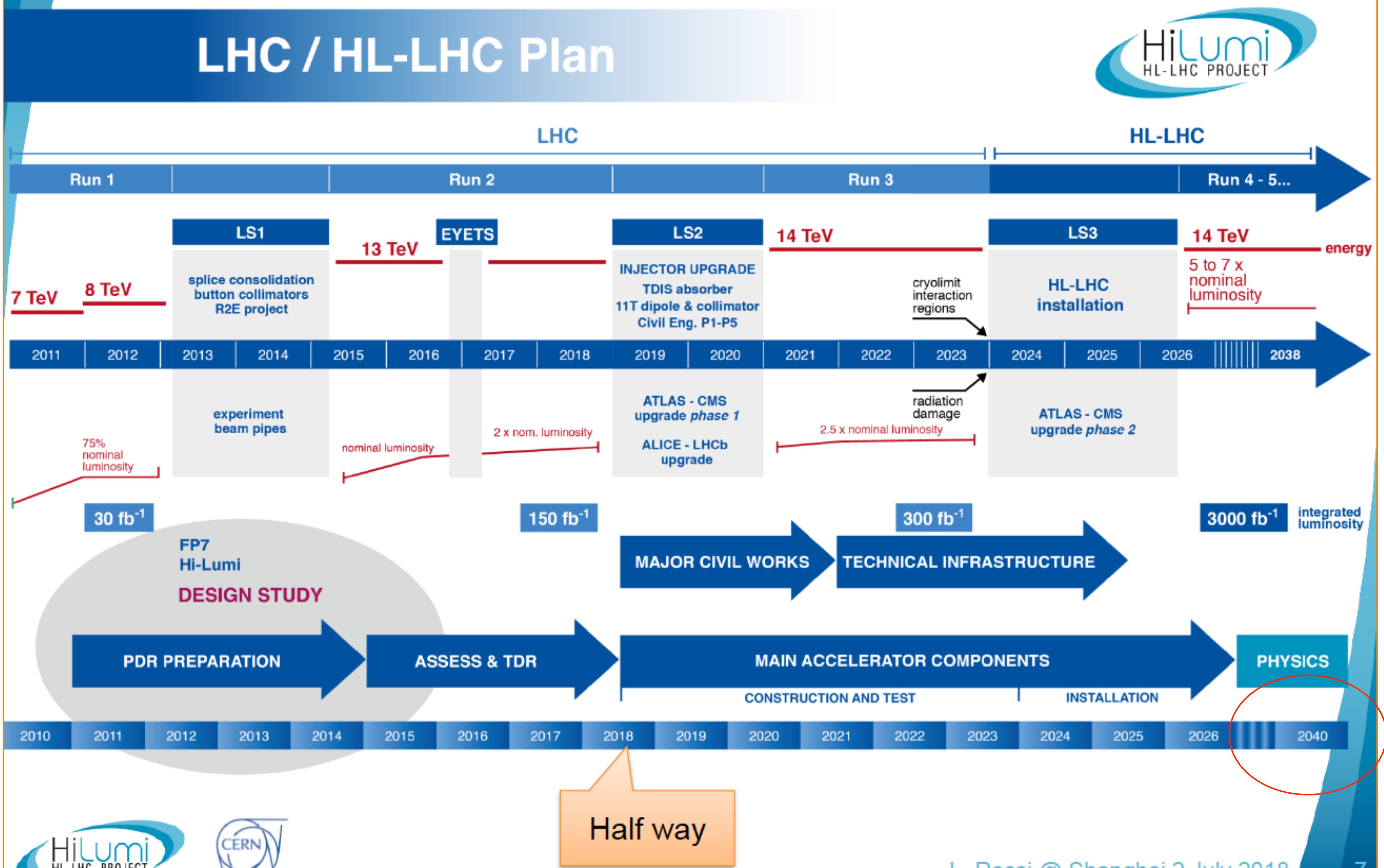
E = 5 MeV



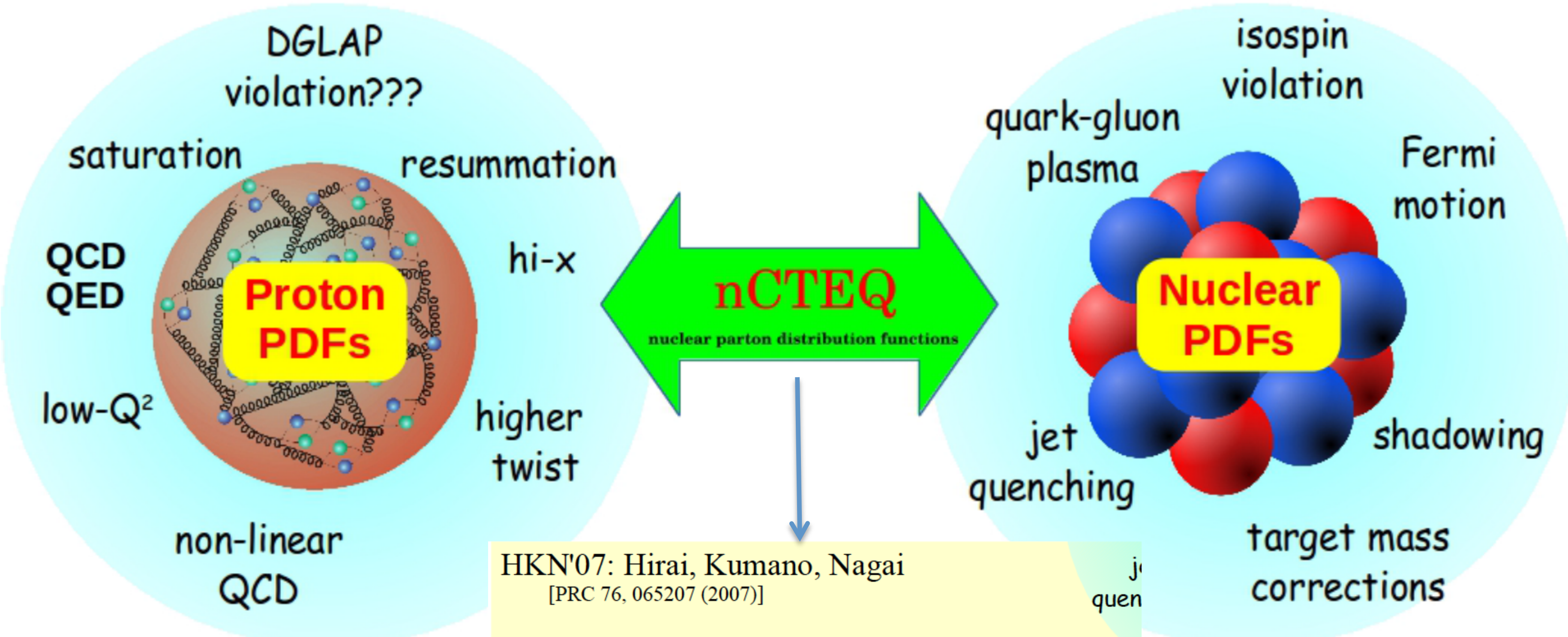
Geiger, Marsden, **Rutherford**

title

High Luminosity: a luminous future for LHC!



Parton Distribution Functions



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[PRC 76, 065207 (2007)]

EPS'09: Eskola, Paukkunen, Salgado
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DSSZ'11: de Florian, Sassot, Stratmann, Zurita
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