Exploring Confinement

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Challenges in Strong Interaction Physics

For what QCD is used?

To deliver the most precise information on:

- α_s
- *The flavour-, valence-sea-, spin- and momentum-dependent PDFs*
- *parton fragmentation functions in vacuum and in nuclear medium*

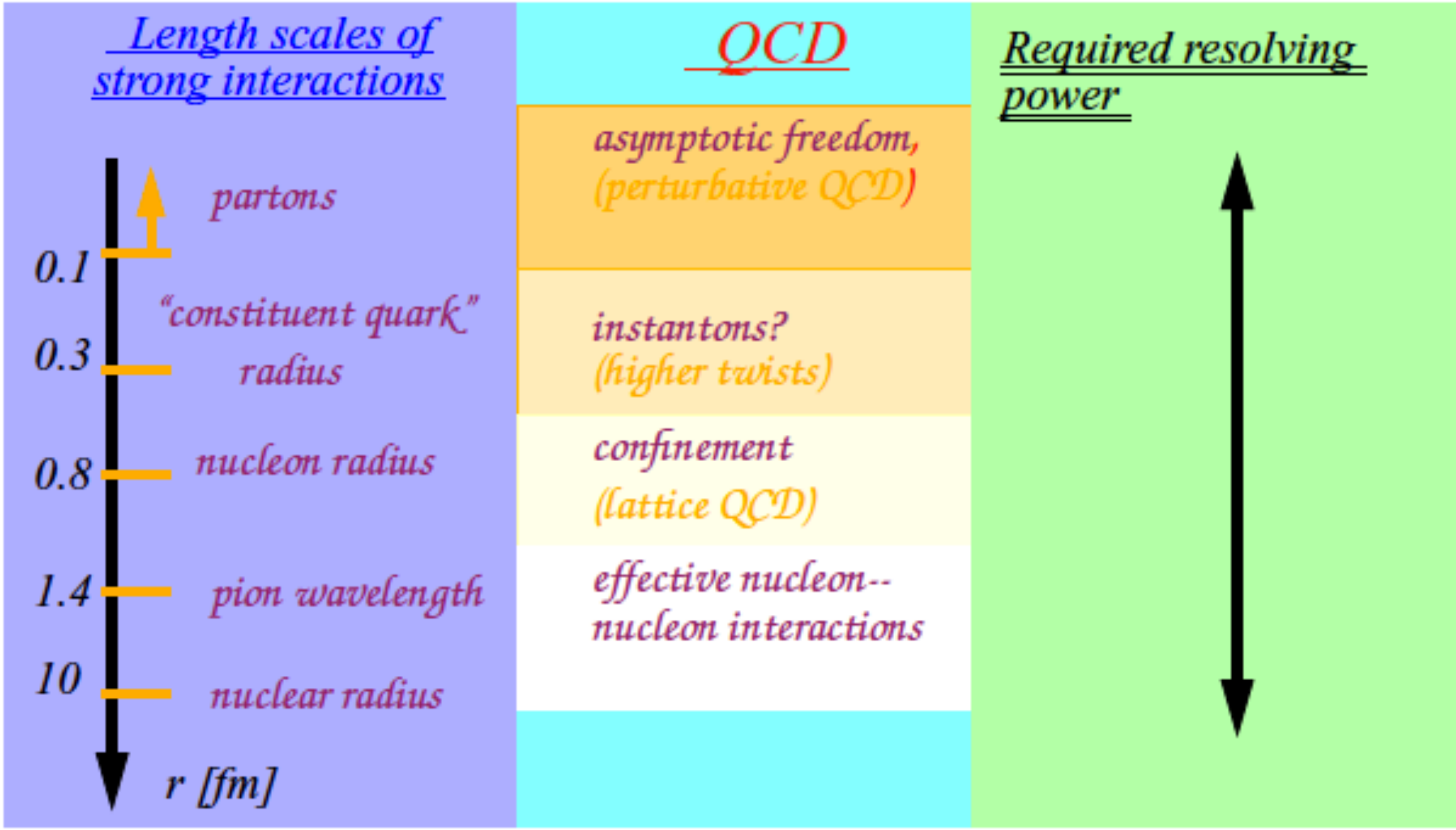
for the precision studies of the EW and BSM sector in the high energy limit
(the EW/QCD complementarity)

Challenges in Strong Interaction Physics

How does QCD work?

- The origin, the mechanism, and the dynamics of the confinement
- Flavour, spin, colour and momentum **correlations** of partons confined in hadrons
- The relationship between the partonic degrees of freedom (on the light cone) and the effective (rest-frame) degrees of freedom explaining binding of mesons, nucleons and nuclei
- The origin and dynamics of chiral symmetry breaking and θ_{QCD}

The Scales in Strong Interactions



Nuclear medium: 1) Filtering of various distance scales involved in a given process

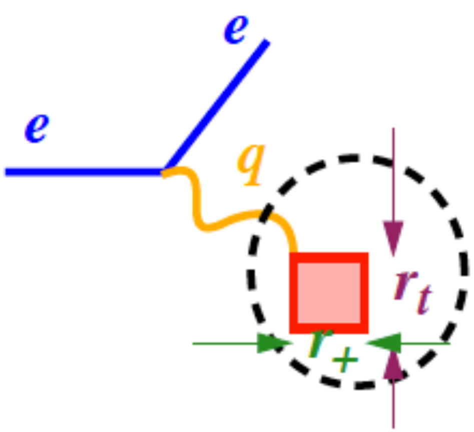
2) Femto-detector (1.4 fm resolution) for partonic processes --

Leptonic probes: -Fine-tuning of space-time resolution

The role of DIS

Resolution of an electron microscope

Light cone variables (Bjorken, Brodsky, Hoyer, ….)



$$q^+ = (q^0 + q^3)\sqrt{2}$$

$$q^- = (q^0 - q^3)/\sqrt{2}$$

$$x = Q^2/2mq^0$$

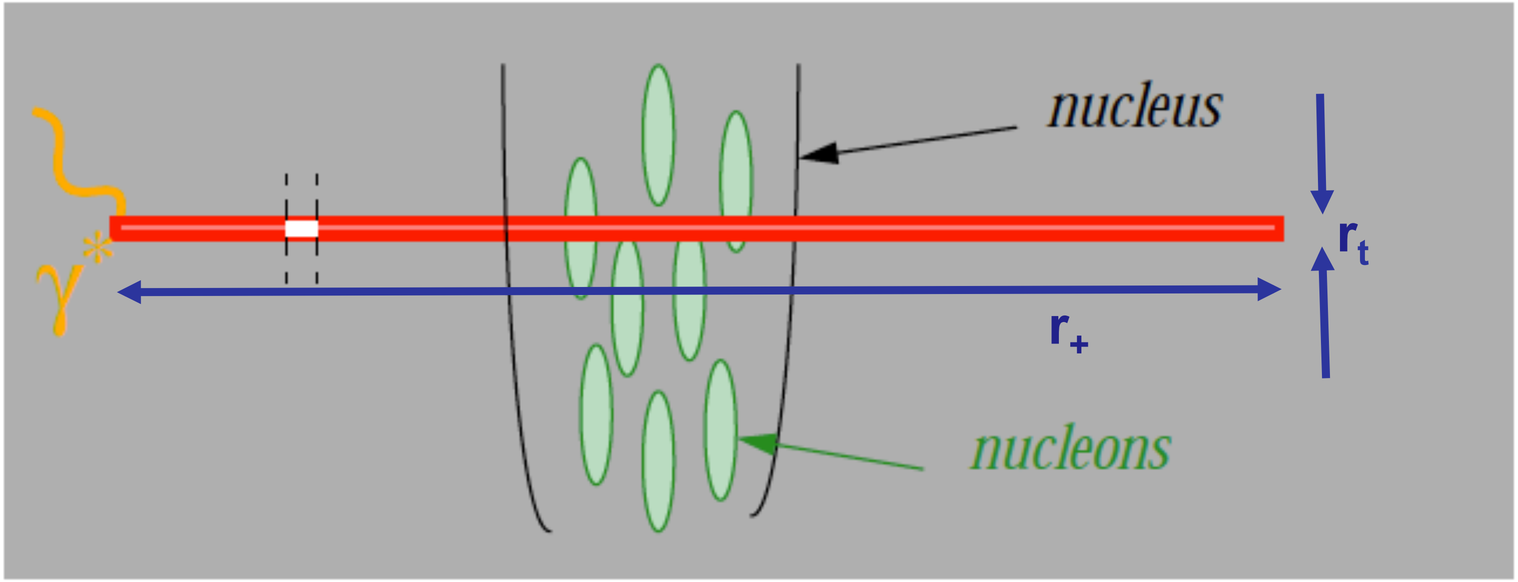
$$y = q^0/E_e$$

- *transverse distances:* — $r_t \sim 1/Q\sqrt{(1-y)}$
- *longitudinal distances:* — $r_+ \sim \sqrt{2}\,/\,mxy$

… probed on the light-cone ($r_+ = ct$) with the dispersion $r_- \sim 1/\sqrt{2}\,q^0$

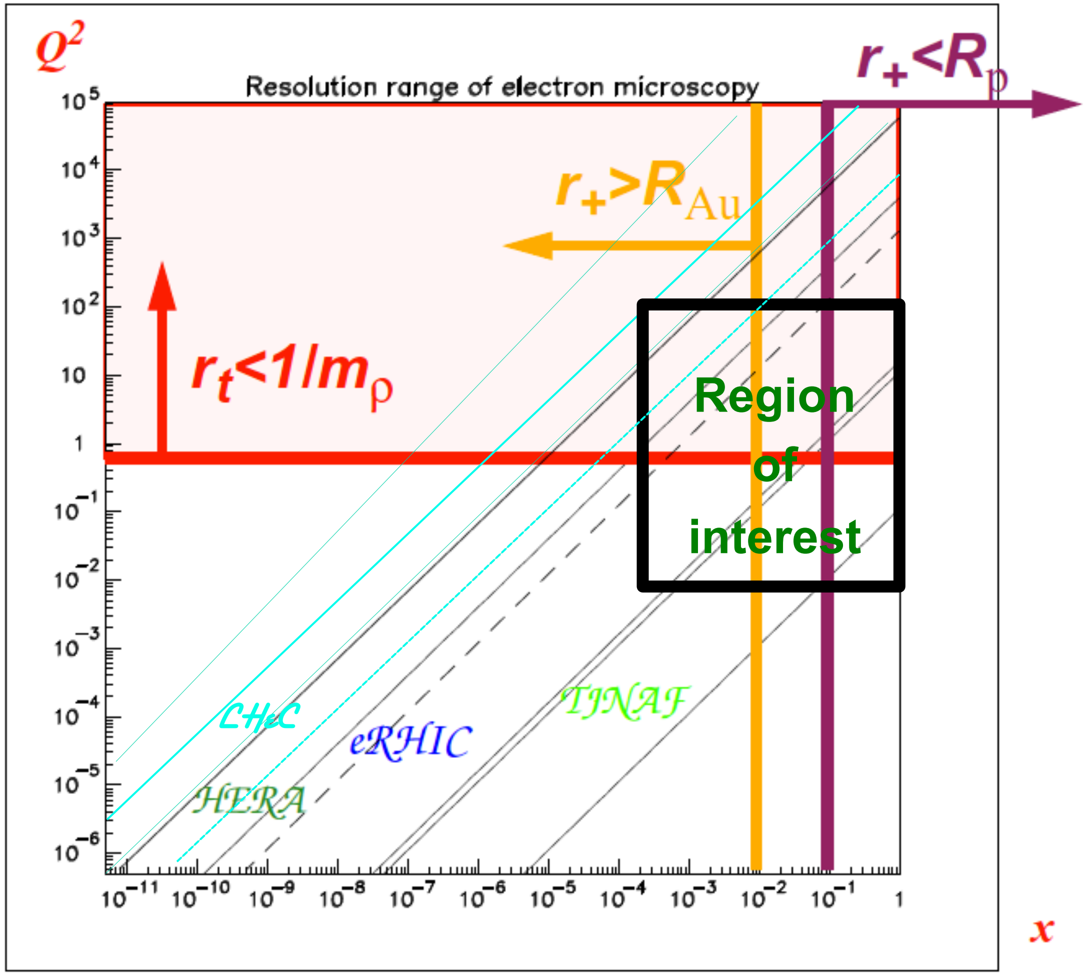
The role of nuclei in DIS

$$Q^2 = 1\ GeV^2,\ x = 0.001,\ y = 0.5$$



Existing and Future Facilities:

TJNAF, EIC and LHeC



1. Partonic structure of nuclei, validity of pert. QCD

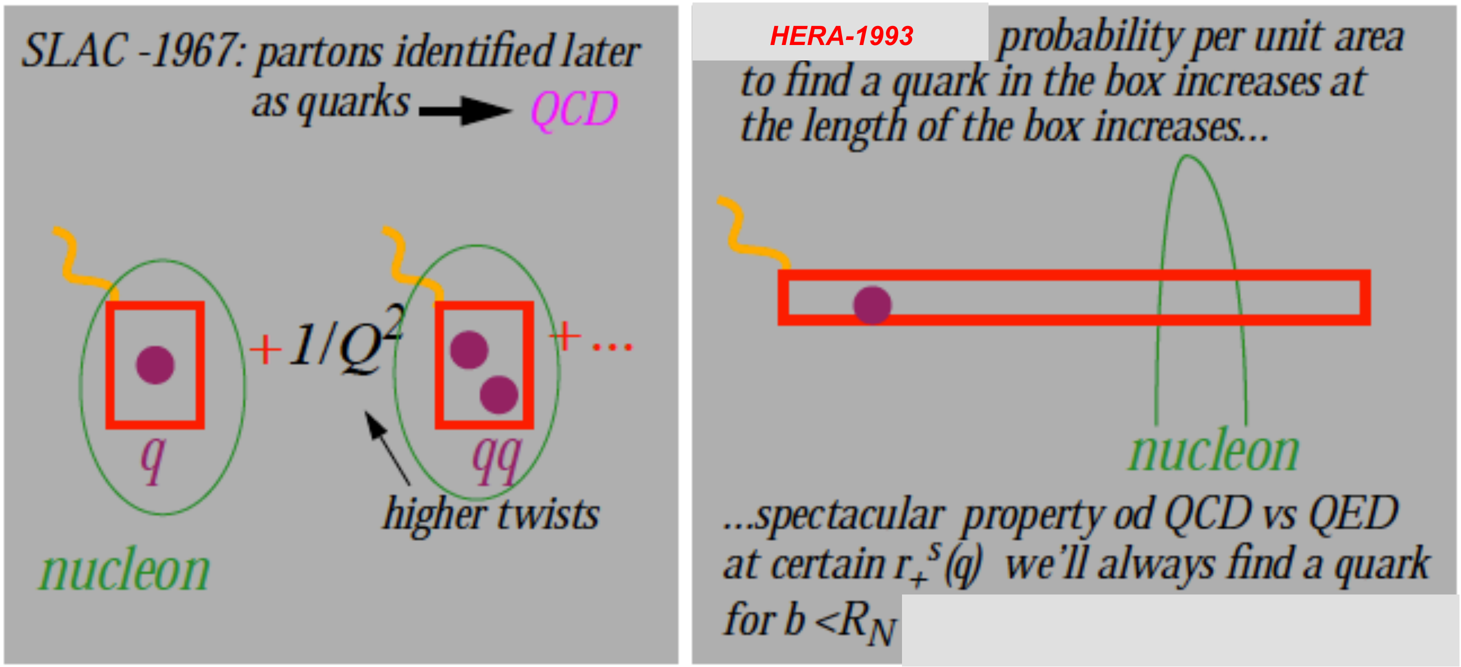
2. Longitudinal distances confined to nucleon size

3. Large distance coherent partonic processes

The role of QCD in DIS

What is in the box?

$(r_t, r_+ < 0.3\ \mathrm{fm})$ $(r_t, < 0.1\ \mathrm{fm}, r_+ > 1000\ \mathrm{fm})$



The 1994 HERA puzzles?

1.Look at the electron recoil to find out what was hit

- at large x – single quark
- at small x - the energy deposited in the predicted direction significantly smaller that the calculated recoil quark energy

2. Try to determine the higher twist contribution at small x

Within the HERA measurement precision (and the measurement range) -- no way to exclude the presence of the higher twists in the F_2 evolution at small x **Phys.Lett. B337 (1994) 367-372**

3. The same proton structure measured in event with and without rapidity gaps - what is a Pomeron?

These question, of extreme importance for the upcoming RHIC and the LHC experimental programme, cannot be resolved at HERA using only proton beams !!!

A short (biased) history of the quest for the eA collider:

- 1995 - Paris DIS workshop (first workshop with sessions devoted to nuclei and the next generation ep(eA) colliders), followed by a DESY workshop -1996
- 1997 - Seeheim workshop (convergence of HERA_eA, ENC and ELFE, a birth of a project to build the ion pre-accelerators at DESY in cooperation with GSI)
- 1999 - Tragic accident of B. Wiik (the eA collider activity moves to the USA)
- 2000/2001 - BNL, Yale, MIT and Snowmass workshops (the birth of EIC)
- 2002 - The first EIC white paper
- 2002 and later - EIC competes with FRIB for the 1st place on the NSAC list

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- 2007 - LHeC endorsed by ECFA (2012 – detailed design report)
- 2013 - The European Strategy Group Proposal

… and the lessons for the future:

1. *The future ep(eA) collider project should be a single joint project of the LHeC (Europe) and the EIC (USA) communities and its program must be complementary to the TJNAF and FAIR programmes (the ILC-like path)*

   (the choice of the optimal range of collision energies was discussed already at length at the SNOWMASS 2001 workshop: the ep colliders cannot compete with the ee and/or pp colliders of the equivalent energy as far as the energy frontier physics is concerned)

… and the lessons for the future:

2. It should be recognised as important not only by the HEP community but, equally, by the nuclear physics community.

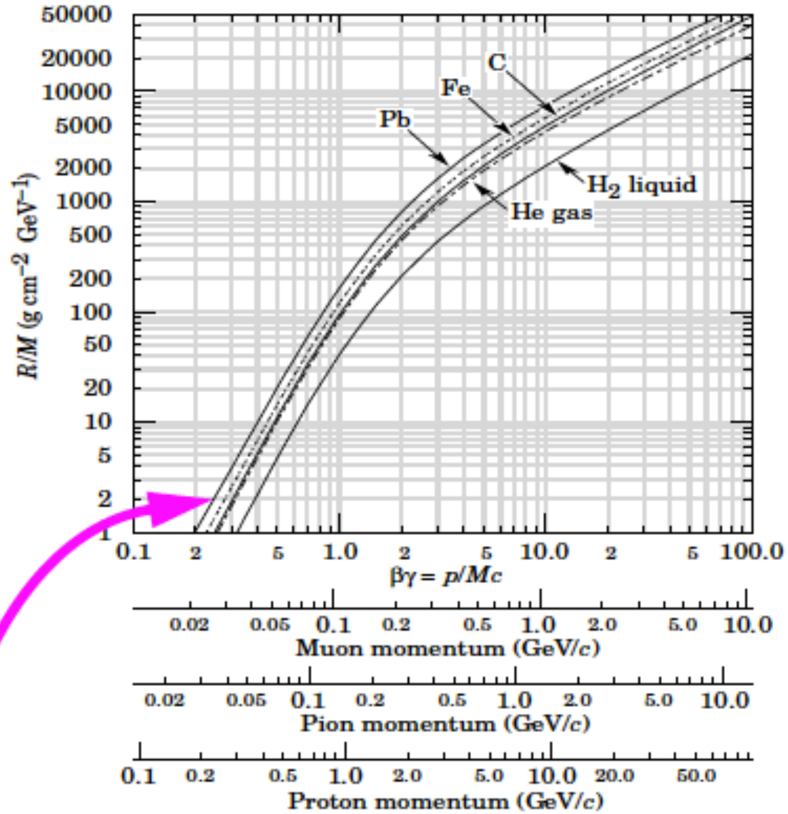
examples:

- *study of rigidity of nucleons and nuclei exposed to point-like perturbation*
- *study of nucleus evaporation process initiated by a hard point-like interaction*
- *photo-disintegration of light nuclei*

Examples →

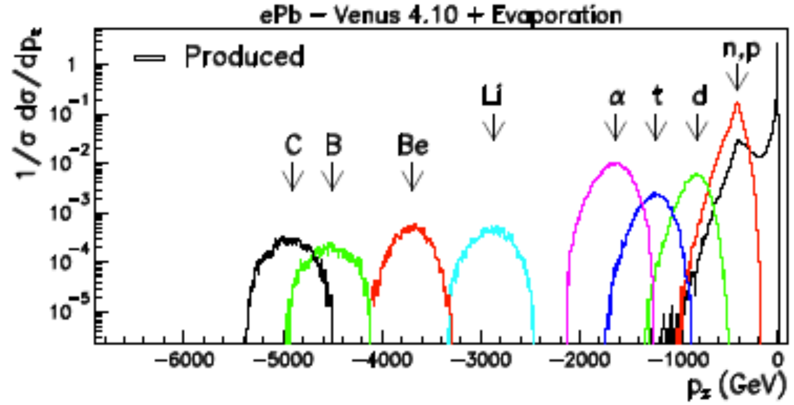
Detection of nuclear fragments in the fixed target and beam colliding mode

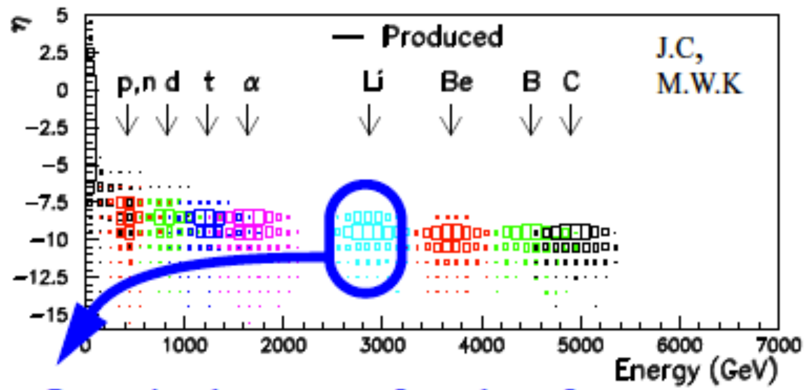
Fixed target mode



Range of nuclear fragments in large Z targets below 1 mm (Fermi motion momenta)

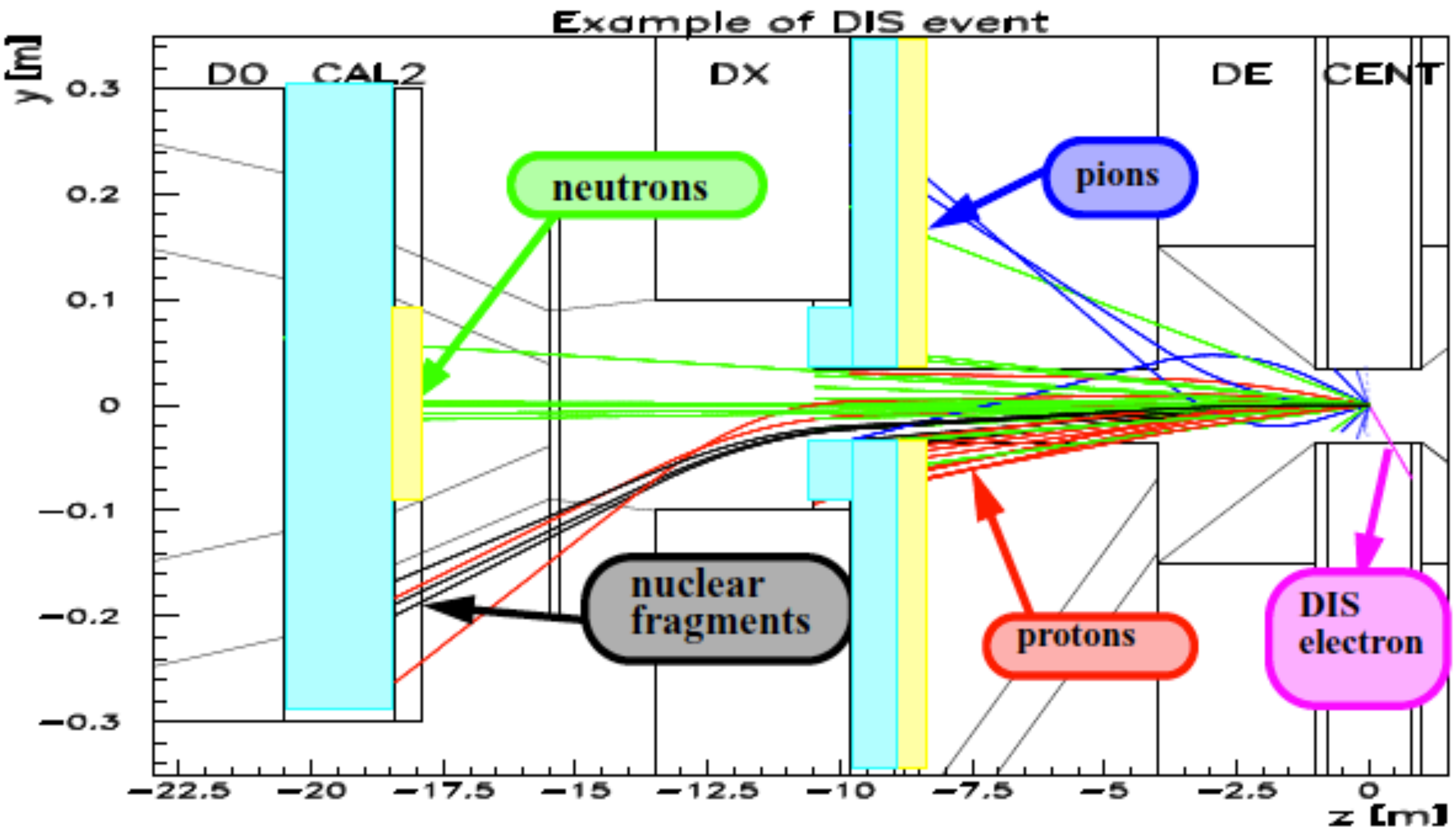
Beam colliding mode





Quantised energy of nuclear fragments recognition of fragment type on the base of energy measurement

An attempt to design the « Bj's dream » detector with the corresponding IR optics capable to measure all the particles produced in ep (eA) collision (E. Barrelet, J. Chwastwski, M.W.Krasny – Yale-work. 2000)



… and the lessons for the future:

3. It should address new physics questions (beyond those addressed already at HERA and TJNAF).

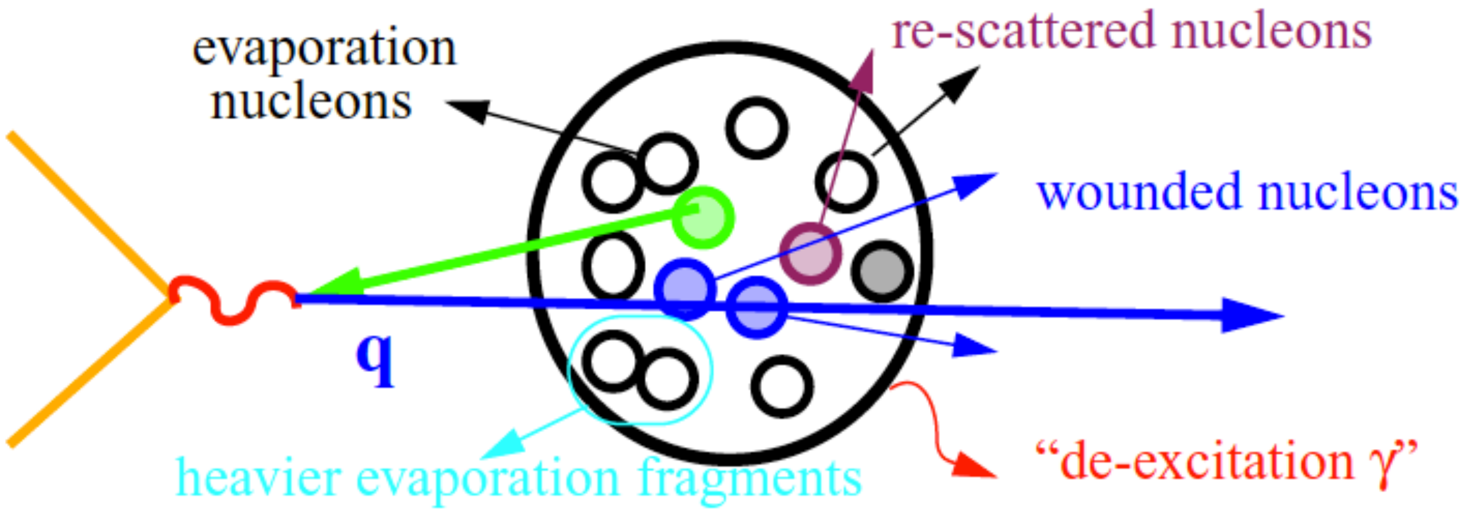
examples:

- *Multidimensional studies of hadronisation of quarks and gluons in vacuum and medium with a ~1 fm space-time resolution*
- *The shadowing mechanism (perturbative versus non-perturbative)*
- *Universality of the Pomeron*
- *Partonic correlations*

Examples →

from passive beam-dump to active femto-detector

Event-by-event analysis of "all" products of the nucleus disintegration



femto-detector signal: local energy depositions (wounded nucleons), depth of energy deposition (re-scattered nucleons) and de-localized energy deposition (evaporation fragments and de-excitation γ)

and

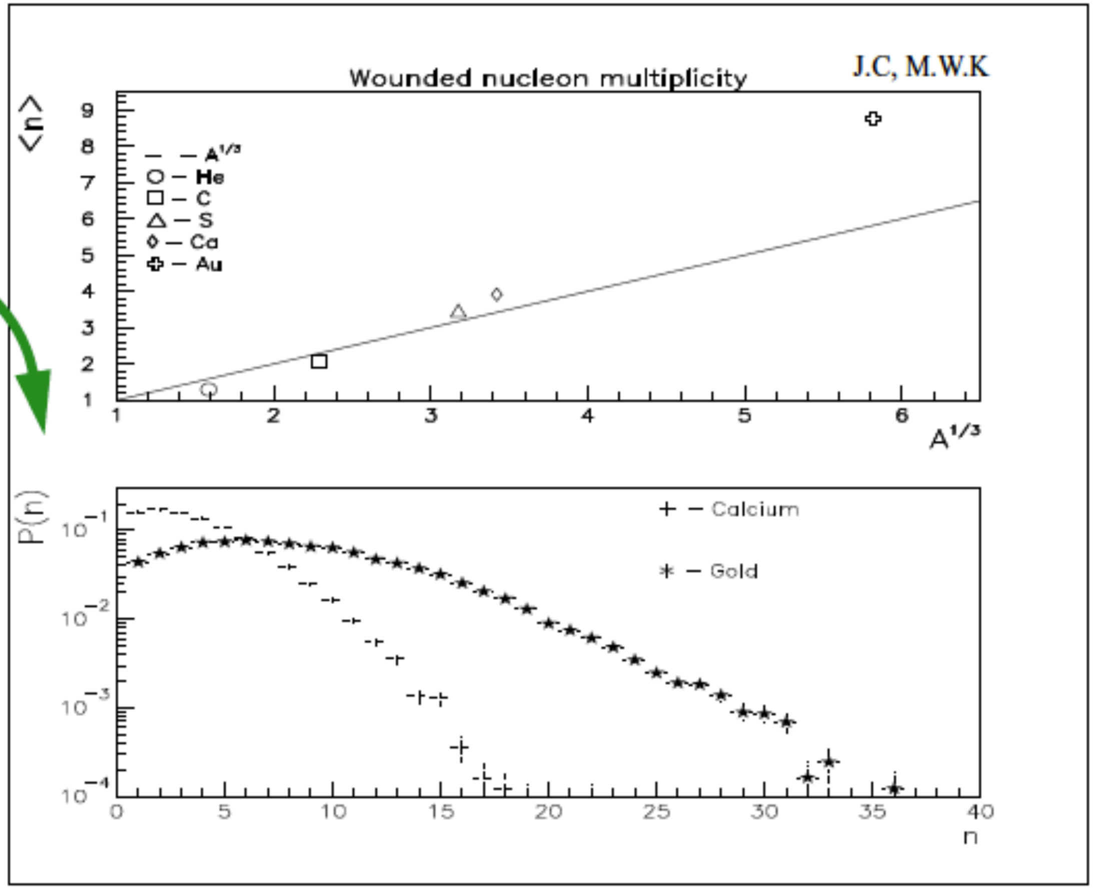
noise: Fermi motion of nucleons

- *multidimensional study of hadronisation (x, Q^2, z, y, p_t)*
- *filtering events on the basis of specific nucleus fragmentation*

.... example

average and event-by-event multiplicities of wounded nucleons

eRHIC



… and the lessons for the future:

4. Its role should be recognized as essential for the model independent interpretation of the LHC experimental results and as imperative for the LHC precision measurement programme.

examples:

- *Pinning down experimentally the Higher Twist (HT) contribution (interpretation of the ridge effects, jet quenching in AA collisions, rare event fluctuation in pp collisions)*
- *Measuring the $_2$GPDs and k_T-unintegrated PDFs for searches and precision measurements*
- *Delivering missing PDF info for precision EW physics*

Examples →

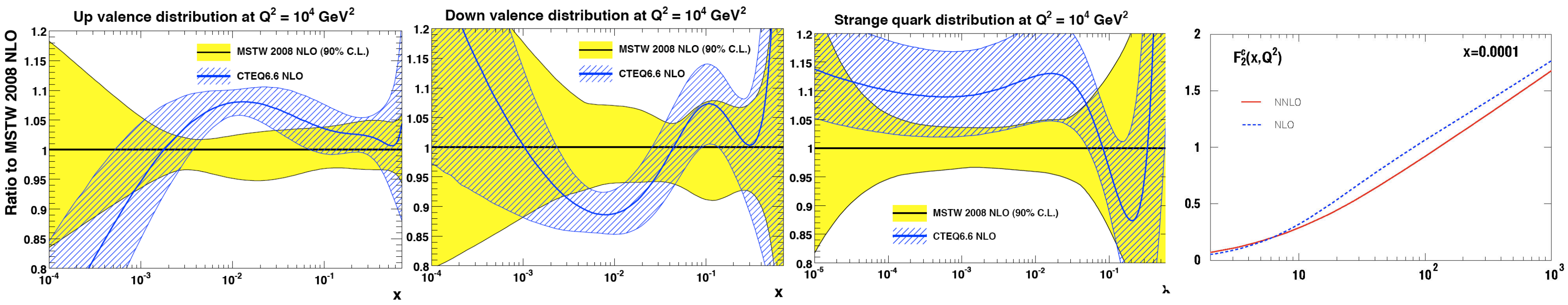
An example: Present precision of: "missing" PDF and its impact on the M_W measurement error

F.Dydak, F.Fayette, M.W. Krasny, W.Placzek, A.Siodmok

	ΔM_{W}
$u_{\mathrm{v}}^{\mathrm{bias}} = 1.05\, u_{\mathrm{v}}$ $d_{\mathrm{v}}^{\mathrm{bias}} = d_{\mathrm{v}} - 0.05\, u_{\mathrm{v}}$	$+79\ \mathrm{MeV}/c^2$
$u_{\mathrm{v}}^{\mathrm{bias}} = 0.95\, u_{\mathrm{v}}$ $d_{\mathrm{v}}^{\mathrm{bias}} = d_{\mathrm{v}} + 0.05\, u_{\mathrm{v}}$	$-64\ \mathrm{MeV}/c^2$

	ΔM_{W}
$c^{\mathrm{bias}} = 0.9\, c$ $s^{\mathrm{bias}} = s + 0.1\, c$	$+148\ \mathrm{MeV}/c^2$
$c^{\mathrm{bias}} = 1.1\, c$ $s^{\mathrm{bias}} = s - 0.1\, c$	$-111\ \mathrm{MeV}/c^2$

	ΔM_{W}
$b^{\mathrm{bias}} = 1.2\, b$	$+42\ \mathrm{MeV}/c^2$
$b^{\mathrm{bias}} = 0.8\, b$	$-39\ \mathrm{MeV}/c^2$



The uncertainty in the non-singlet distributions are driven by the precision of the experimental data and their phenomenological interpretation rather than by the precision of the QCD fits!!!

Example: u_v-d_v driven by the NMC "p/d" data (2%), E866 "D-Y" data (4%), nucl. corr (2%)

The way forward

- LHC-specific measurement and analysis strategy

and

- An extension of the canonical LHC proton collision programme:

deuteron-deuteron collisions at the LHC

or

ep and eD collisions

… and the lessons for the future:

5. It should be challenging for the accelerator R&D.

examples:

- *High beam power Energy Recovery Linacs (ERLs)*
- *High current polarized electron sources*
- *Advanced cooling techniques: electron cooling*
- *Sophisticated IR design, crab-crossing*

… and the lessons for the future:

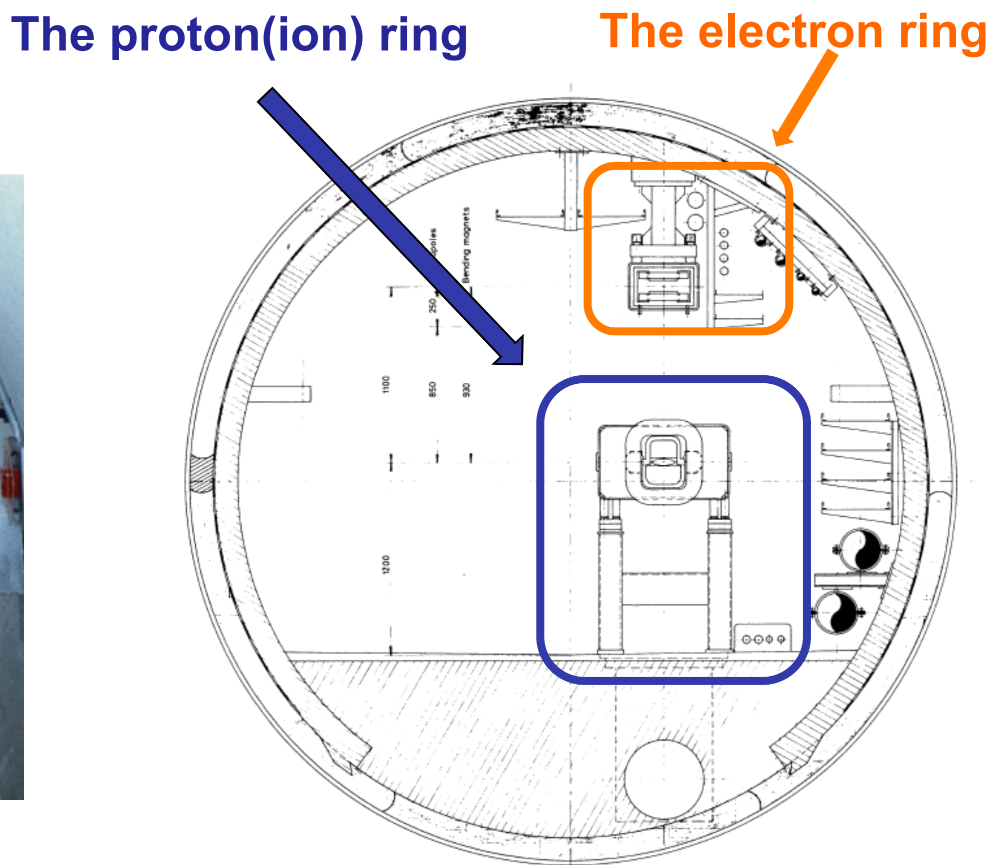
6. It should   be "CHEEP".

- *At least one of the accelerators must be already operational*
- *Minimise electron accelerator energy for a given physics goal the collider*
  (~E^4 proportionality of the cost of civil engineering work, IR-design)
- *Use as much as possible the existing infrastructures (tunnels, caverns)*
- *Minimise clashes with the layout of the present accelerators (bypasses)*
- *Minimise clashes with the operation modes of the existing accelerators*

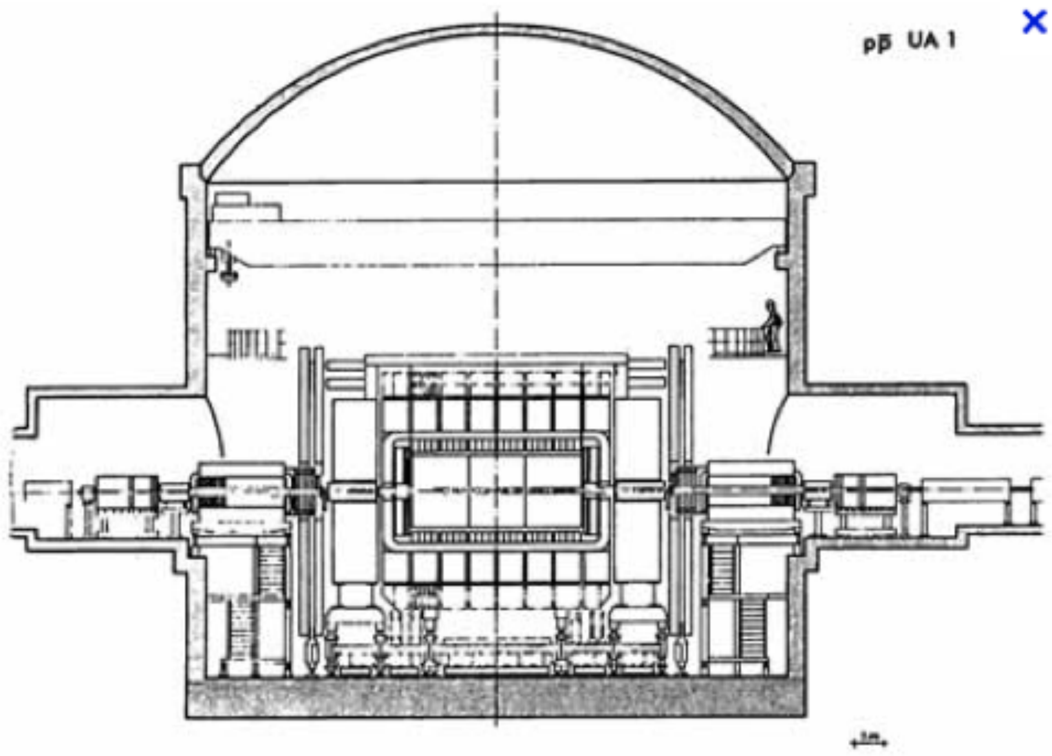
…the main purpose of this talk is to convey the message that:

An ep and eA collider *using the existing* ***SPS proton and ion beams*** *and the* ***electron beam from an Energy Recovery Linac*** *has the largest potential to fulfil all the above requirements*

B.Wiik legacy: the “CHEEP” design (1978)



The SPS tunnel

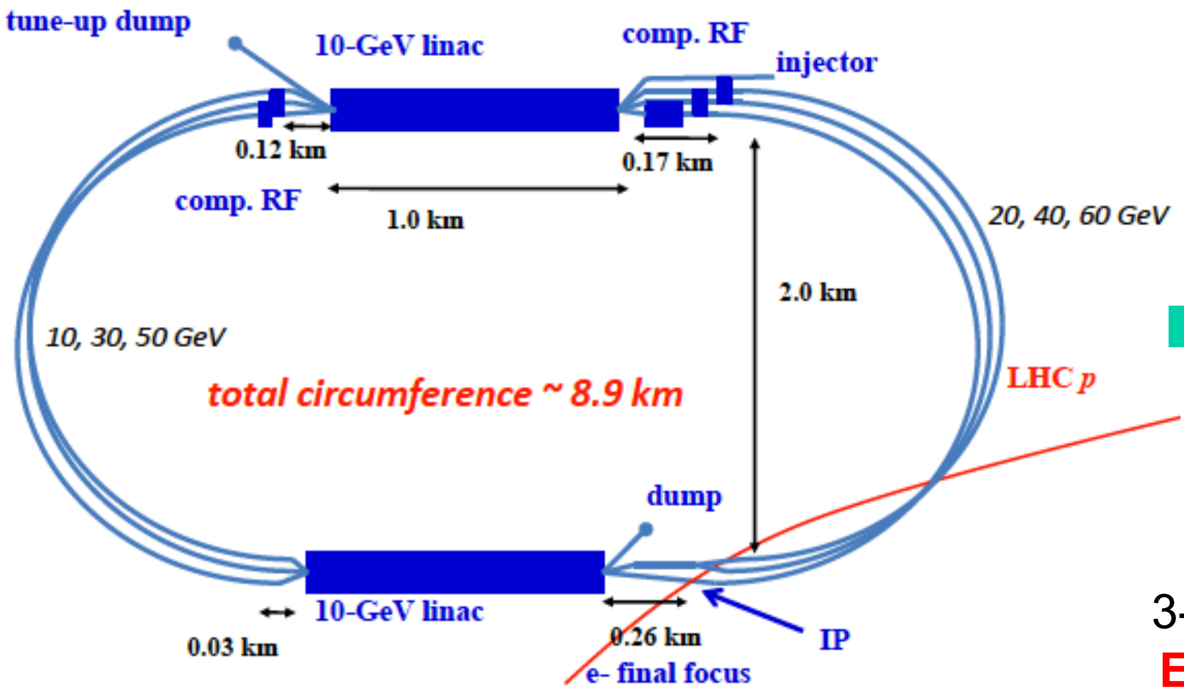


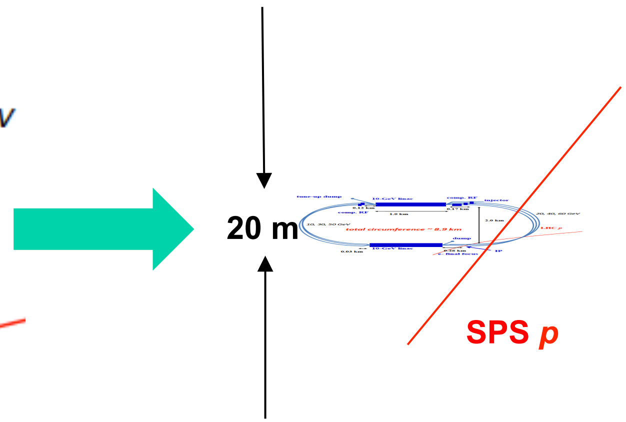
The existing UA1 cavern

The (1978) CHEEP parameters

		p-ring	e-ring a)
Luminosity (peak)	cm^{-2} sec^{-1}	0.5×10^{32}	
Nominal energy	GeV	270	25(30)
Total number of particles		2×10^{13}	1.5×10^{13}
Circulating current	mA	140	104
Number of bunches		60	60
Circumference	m	$2\pi \times 1100$	$2\pi \times 1100.013$
Bending radius	m	741.3	741.3
Energy range for collisions	GeV	150-400	5-25(30)
Injection momentum	GeV/c	14	4.8
Crossing angle	mrad	±2.5	
Beta function β_x^*/β_z^*	m	6.5/0.6	1.5/0.3
Dispersion function D_x^*/D_z^*	m	0	0
Free space for detector	m	±5 m	
Beam size at crossing σ_x^*	mm	0.34	0.39
Beam size at crossing σ_z^*	mm	0.072	0.039
Bunch length σ_s	mm	300	30
Energy spread $\sigma_{E/E}$		0.8×10^{-3}	1.4×10^{-3}
Beam-beam tune shift $\Delta Q_x/\Delta Q_z$		0.008/0.008	0.006/0.014
Lifetime		SPS cycle	20 h
Filling time (p e^-/e^+)		1.8 sec	0.5/40 min
Polarization time	min	-	30(40)
Energy loss/turn	MeV	-	51.8(96.7)
Total RF power	MW	-	8(15)

A modern version of CHEEP: “ iCHEEP$_1$”





2.5 GeV ERLs

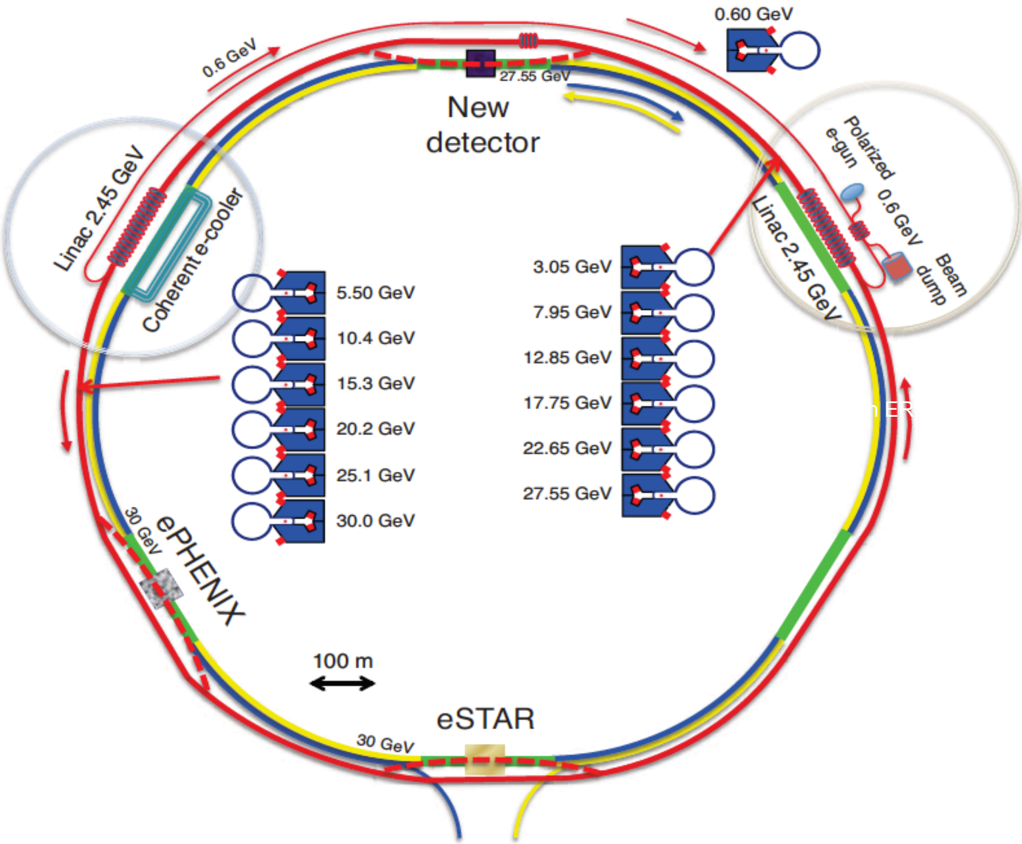
3-pass mode: 5,10,15 GeV

E_{CM}(ep/eA) = 14-164 GeV

(covers the energy range of eRHIC, MEIC and ENC@FAIR)

The scaled down ERL of the LHeC project

A modern version of CHEEP: " iCHEEP$_2$"



2.45 GeV ERLs

(no bypasses necessary)

6 vertically stacked recirculation passes in the arcs : 5.5, 10.4, 15.3, 20.2, 25.1, 30.0 GeV

E_{CM}(ep/eA) = 14-230 GeV

(covers the energy range of eRHIC, MEIC and ENC@FAIR, overlap with PIE@LHC – easy cross-normalisation of the iCHEEP and LHC cross-sections)

The scaled up (factor 1.81) eRHIC project

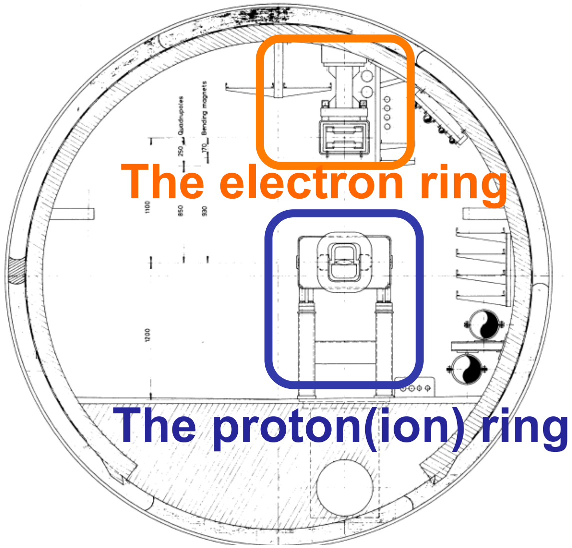
Instead of conclusions – an evaluation attempt

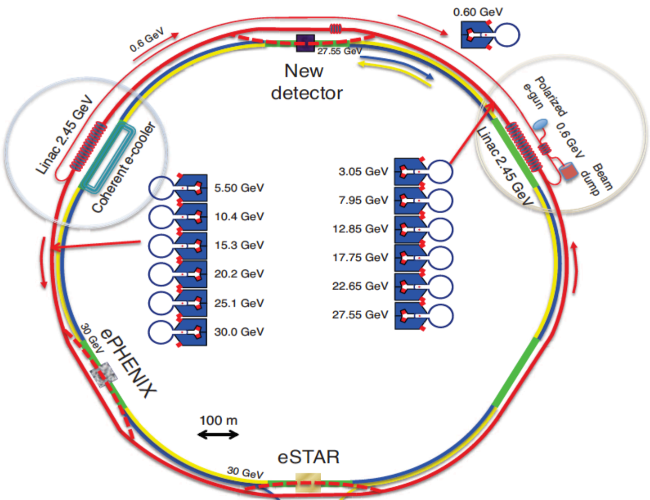
	ENC@FAIR (GSI)	MEIC (TJNAF)	eRHIC (BNL)	iCHEEPx (CERN)	LHeC (CERN)
E_{CM} range [GeV]	14	10-65	45-175	14-230[1]	800-1300
Peak Lumi [10^{33} cm^{-2} s^{-1}]	0.2 (0.6)	14.2	9.7	1-10[1]	1-1.7
Polarisation, p,e [%,%]	80,80	70,80	70,80	0,80[1]	0,90
Adequacy of collider parameters for the quest to understand QCD	***	****	*****	*****	***
Attractiveness to the nuclear physics community	****	****	****	****	**
New observables and new physics questions	***	*****	*****	*****	***
Importance for the LHC experimental programme	**	***	****	*****	****
Challenging accelerator R&D	***	*****	*****	*****	*****
Financing probability/cost	****	***	***	*****	**

[1] to be confirmed

Supplementary transparencies

The ep(eA) collider in the SPS tunnel – an optimal facility to study the confinement phenomena





The scaled up (fac. 1.81) eRHIC project

2.45 GeV ERLs
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6 vertically stacked recirculation passes in the arcs : 5.5, 10.4, 15.3, 20.2, 25.1, 30.0 GeV

E_{CM}(ep/eA) = 14-230 GeV

(covers the energy range of eRHIC, MEIC and ENC@FAIR, overlap with PIE@LHC – easy cross-normalisation of the iCHEEP and LHC cross-sections)

August 19, 1996

Dear Dr. Krasny,

Thank you very much for your contribution to the HERA workshop and for your remarks to the HERA programme.

I agree with you that HERA will make a solid contribution to strong interaction physics and that colliding electrons with nuclei may open up new vistas and should be explored further. Indeed we want to do this in collaboratoin with GSI and I hope that you will be able to participate and contribute to this work. In order to carry out a prgramme in this direction there must be a well reasoned physics programme, a strong support including funds from the community, and GSI must be interested in a collaboration.

I'm not so sure that I agree with your comments concerning the luminosity frontier - at least I would feel somewhat uneasy if we neglected this frontier.

With my best wishes

Björn H. Wiik

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Electron beam for LHC

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Abstract

A method of delivering a small energy spread electron beam to the LHC interaction points is proposed. In this method, heavy ions are used as carriers of projectile electrons. Acceleration, storage and collision-stability aspects of such a hybrid beam is discussed and a new beam-cooling method is presented. This discussion is followed by a proposal of the Parasitic Ion–Electron collider at LHC (PIE@LHC). The PIE@LHC provides an opportunity, for the present LHC detectors, to enlarge the scope of their research program by including the program of electron–proton and electron–nucleus collisions with minor machine and detector investments.

Unconstrained PDF degrees of freedom at the LHC

Assume: $s(x)=\bar{s}(x)$, $c(x)=\bar{c}(x)$, $b(x)=\bar{b}(x)$ then:

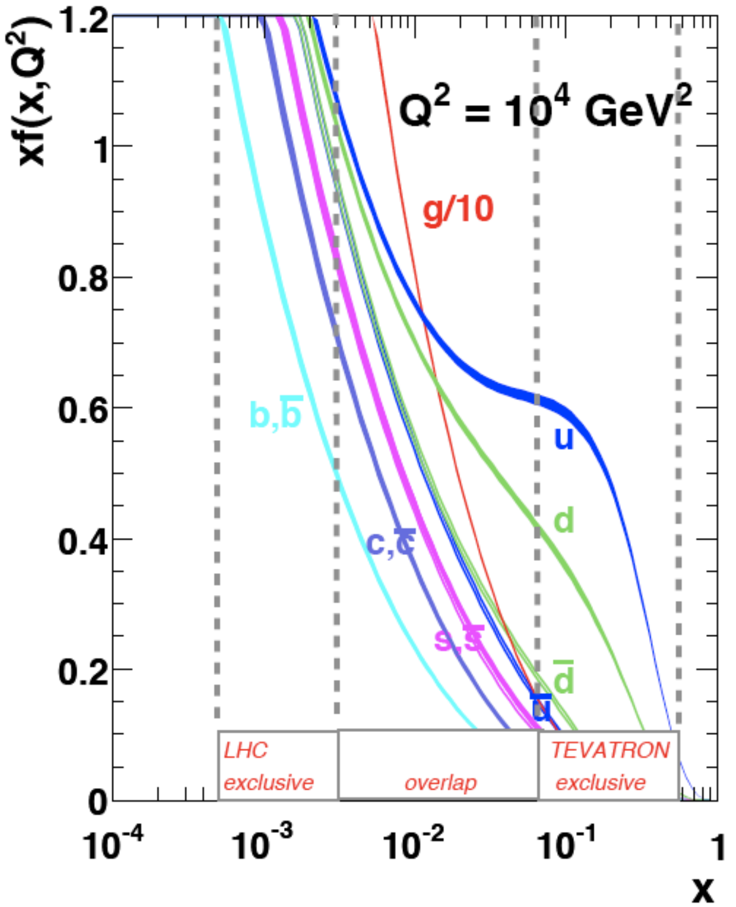
- 5 sea-quark flavours (u,d,s,c,b) + 2 valence quark flavours ($u^{(v)}$, $d^{(v)}$) 7 unknown PDFs:
- 4 constraints coming from the ($p_{T,l}$, η_l) spectra for W^{+}, W^{-}, "Z^{+}" and "Z^{-}" decays
- 7-4=3 degrees of freedom in the flavour-dependent pdf's remain unconstrained at the LHC

Important note:

At the Tevatron only the first quark family is relevant. In addition p collides with $\bar{p}$.

This leaves only 2 (out of 7) flavour dependent pdf's. They are over-constrained by the the η_l dependence of the Z and W cross-sections

The need for the new proton/neutron DIS cross-section asymmetry measurement - unmatched precision of the present DIS data and the future LHC data)



$\mathcal{O}_{D\text{-}Y} \sim \bar{q}(x_{low})q(x_{high}) + q(x_{low})\bar{q}(x_{high})$

Tevatron:

need only u/d, use W^-/W^+ data

…ambiguity $u/d(x_{low})$ vs $u/d(x_{high})$

LHC:

need u/d, but also u_v/d_v, and $(u_v+d_v)/(u+d)$

…both at x_{low} and x_{high}

In the overlap region use W^-/W^+ (Tevatron and LHC) + F-B asymmetry in Z-decays (LHC)

Adequate external constraint needed either in the Tevatron exclusive region (SPS) or in the LHC exclusive region (eRHIC)

The form of the constraint:

$A(p,n) \sim u_v - d_v + 2(u+d-u_v-d_v)$