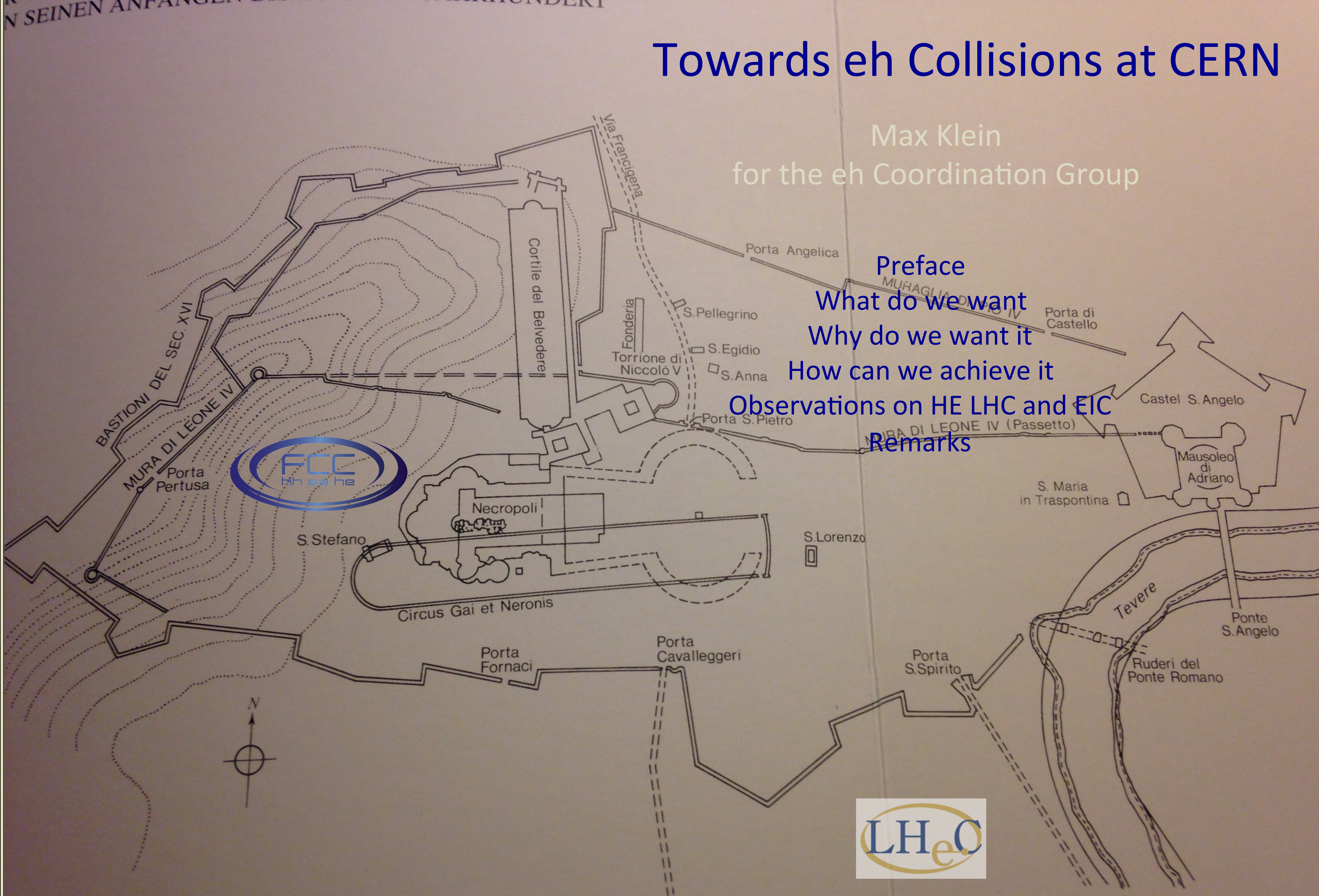
Towards eh Collisions at CERN

Max Klein
for the eh Coordination Group



Preface
What do we want
Why do we want it
How can we achieve it
Observations on HE LHC and EIC
Remarks

An early racetrack embedded in the Vatican (XV century)

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *

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G. PARISI ***

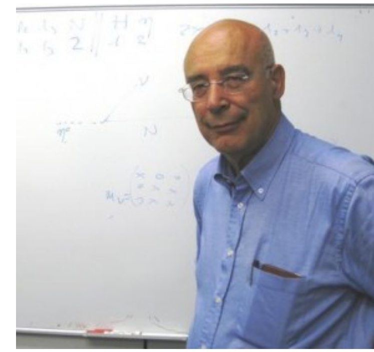
Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

A novel derivation of the Q^2 dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inleastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.

$$\frac{\mathrm{d}q^i(x,t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{\mathrm{d}y}{y} \left[\sum_{j=1}^{2f} q^j(y,t)\, P_{q^i q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{q^i G}\left(\frac{x}{y}\right) \right],$$

$$\frac{\mathrm{d}G(x,t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{\mathrm{d}y}{y} \left[\sum_{j=1}^{2f} q^j(y,t)\, P_{G q^j}\left(\frac{x}{y}\right) + G(y,t)\, P_{GG}\left(\frac{x}{y}\right) \right].$$



12.7.1941 Rome
30.9.2015 Geneva

Collider Physics within the Standard Model: a Primer. arXiv:1303.2842 (2013)

V.N. Gribov, L.N. Lipatov, *Gluboko neuprugoe ep-rasseyanie v teorii vozmushchenii*, Yadernaya fizika, 15(4), 781-807 (1972).

2.5.1940 Leningrad
4.9.2017 Dubna

The Pomeranchuk Singularity in Nonabelian Gauge Theories: E.A.**K**uraev, **L**, V.S.**F**adin, SJNP 45(77)199
The Pomeranchuk Singularity in QCD: Ya.Ya.**B**alitsky, L **L**ipatov: SJNP 28 (78) 822

Small x Physics in perturbative QCD Physics Reports 286 (1997)131, hep-ph/9610276

More recently Lipatov has taken these ideas into the hot, new field in theoretical physics: **the anti-de Sitter/conformal-field theory correspondence (ADS/CFT)** – a hypothesis put forward by Juan Maldacena in 1997. This states that there is a correspondence – a duality – in the description of the maximally supersymmetric N=4 modification of QCD from the standard field-theory side and, from the "gravity" side, in the spectrum of a string moving in a peculiar curved anti-de Sitter background – a seemingly unrelated problem. However, Lipatov's experience and deep understanding of re-summed perturbation theory has enabled him to move quickly into this new territory where he has developed and tested new ideas, considering first the BFKL and DGLAP equations in the N=4 theory and computing the anomalous dimensions of various operators. The high symmetry of this theory, in contrast to standard QCD, allows calculations to be made at unprecedented high orders and the results then compared with the "dual" predictions of string theory. It also facilitates finding the integrable structures in the theory (Lipatov 2009).

D Diakonov, CERN Courier July 2010

50 years ago

Robert Jungk (1966)
Die grosse Maschine
auf dem Weg in eine andere Welt
The big machine
on the road into a new world
A book on the Proton Synchrotron ..

Niels Bohr at 1st Council 1952
Council: highest level committee

ICHEP 1966

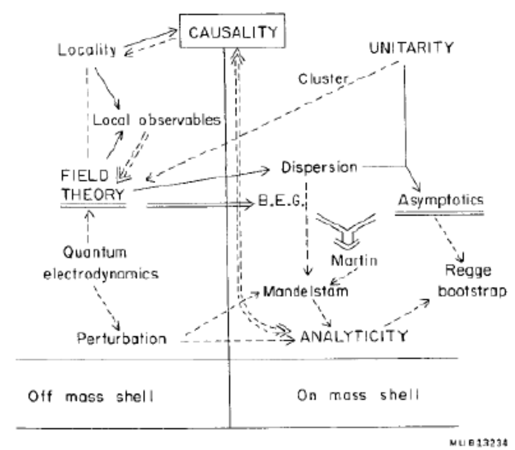


Fig. 1-1. Logical map of "Fundamental" concepts.

No Standard Model, Theory confused,
ECFA, Amaldi: SPS for CERN
Experiment paved the way:
Quarks (ep) → QCD, $SU_L(2)xU(1)$

MK, presented to UK PPAP, July 2017

Today in various aspects resembles 50 years ago:

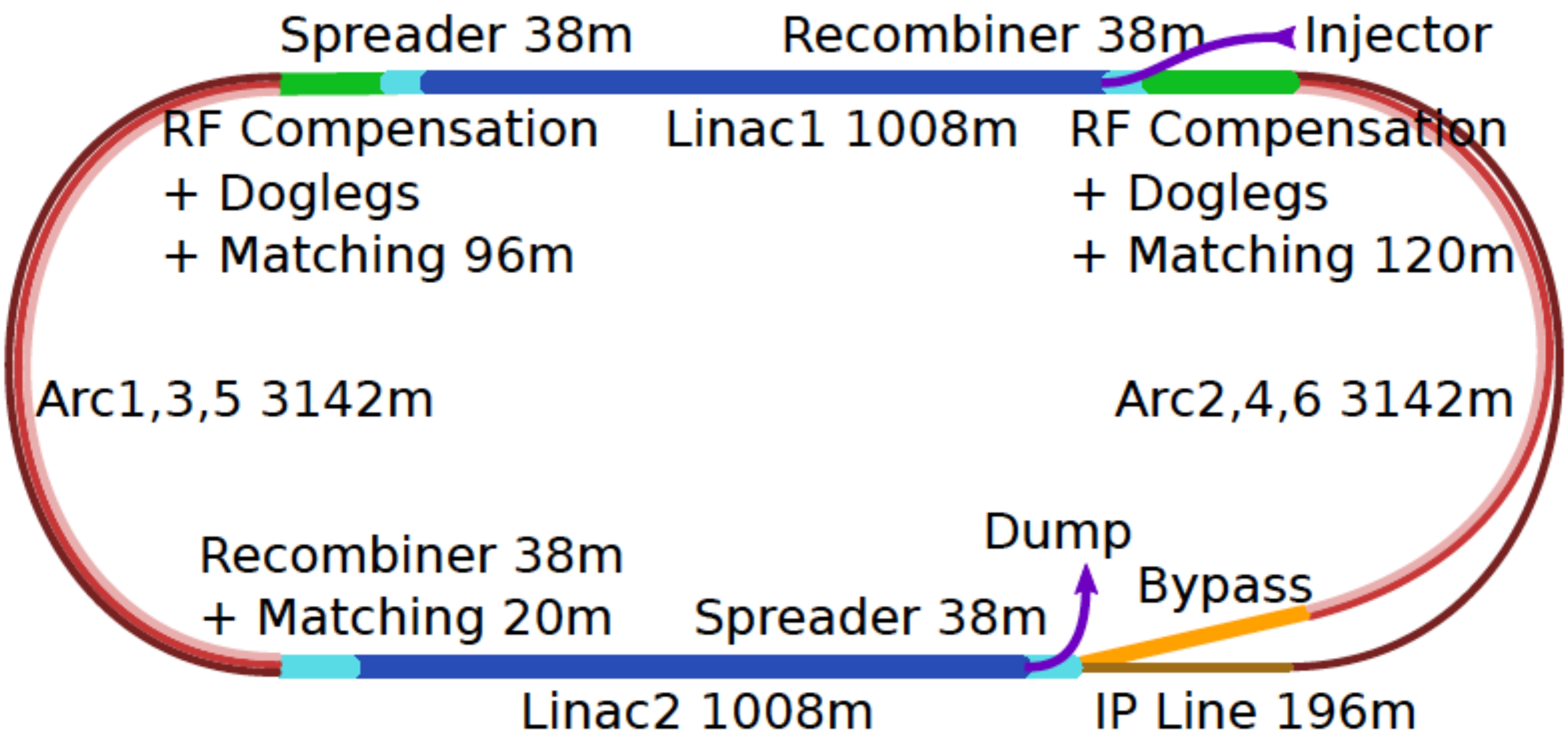
- Some think our dreams are too ambitious
- Our scientific standards are kept maximally high
- and the theory is pointing to every- or nowhere

Our science is experiment driven, it can't be pp alone

What do we want?

Add an Electron Beam (ERL) to LHC (+FCC)

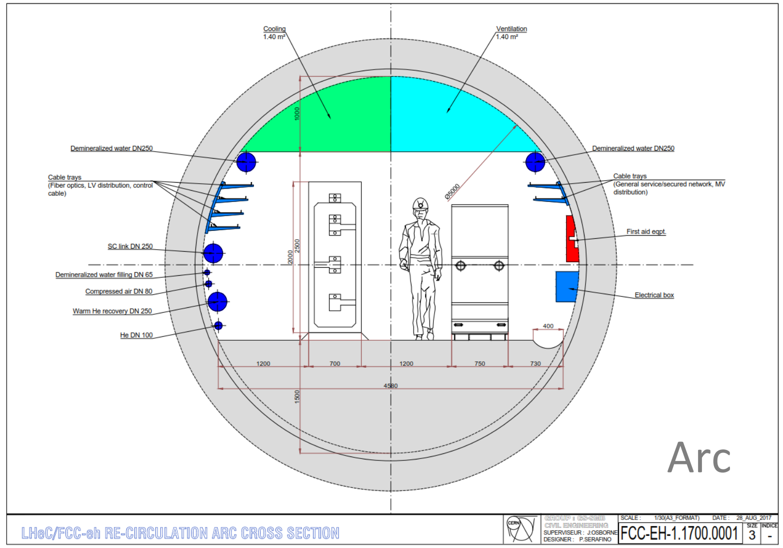
Conceptual Design Report (2012), Update for next European Strategy



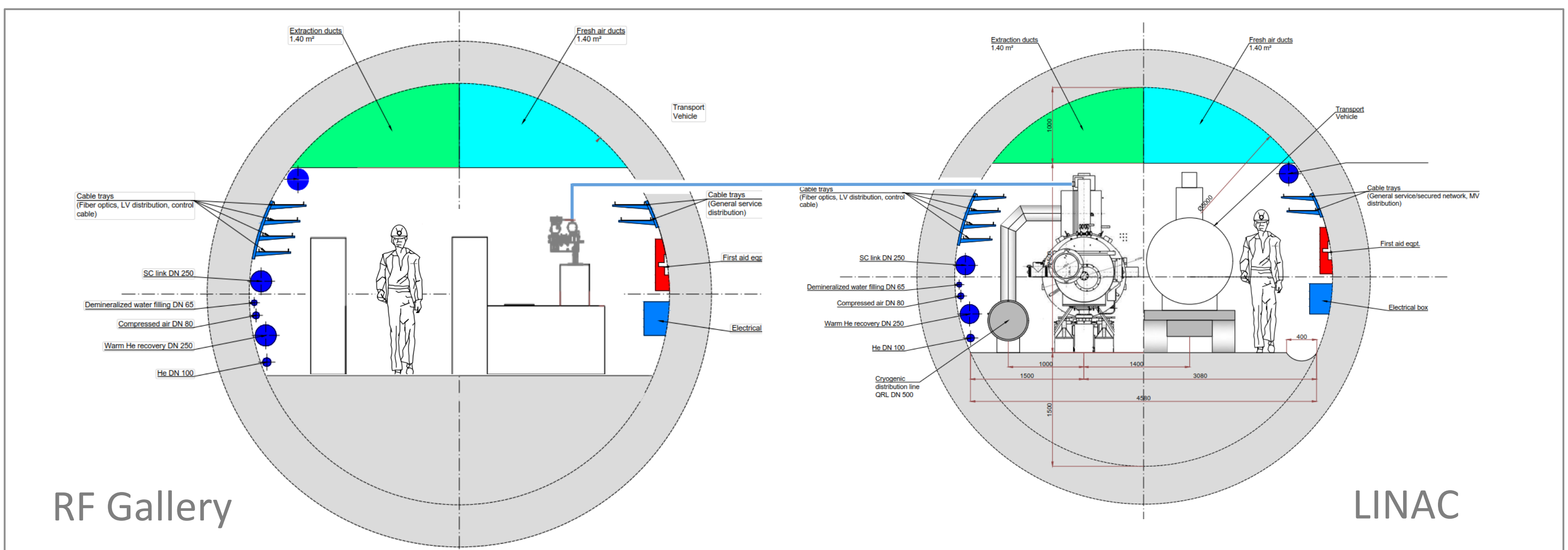
cf talk by Oliver Brüning next

Concurrent operation to pp, LHC/FCC become 3 beam facilities. P(e) < 100 MW
10^{34} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach vs HERA

Build, equip and walk through the ERL Tunnels



DRAFTs
cf Matt Stewart et al. 12.9.

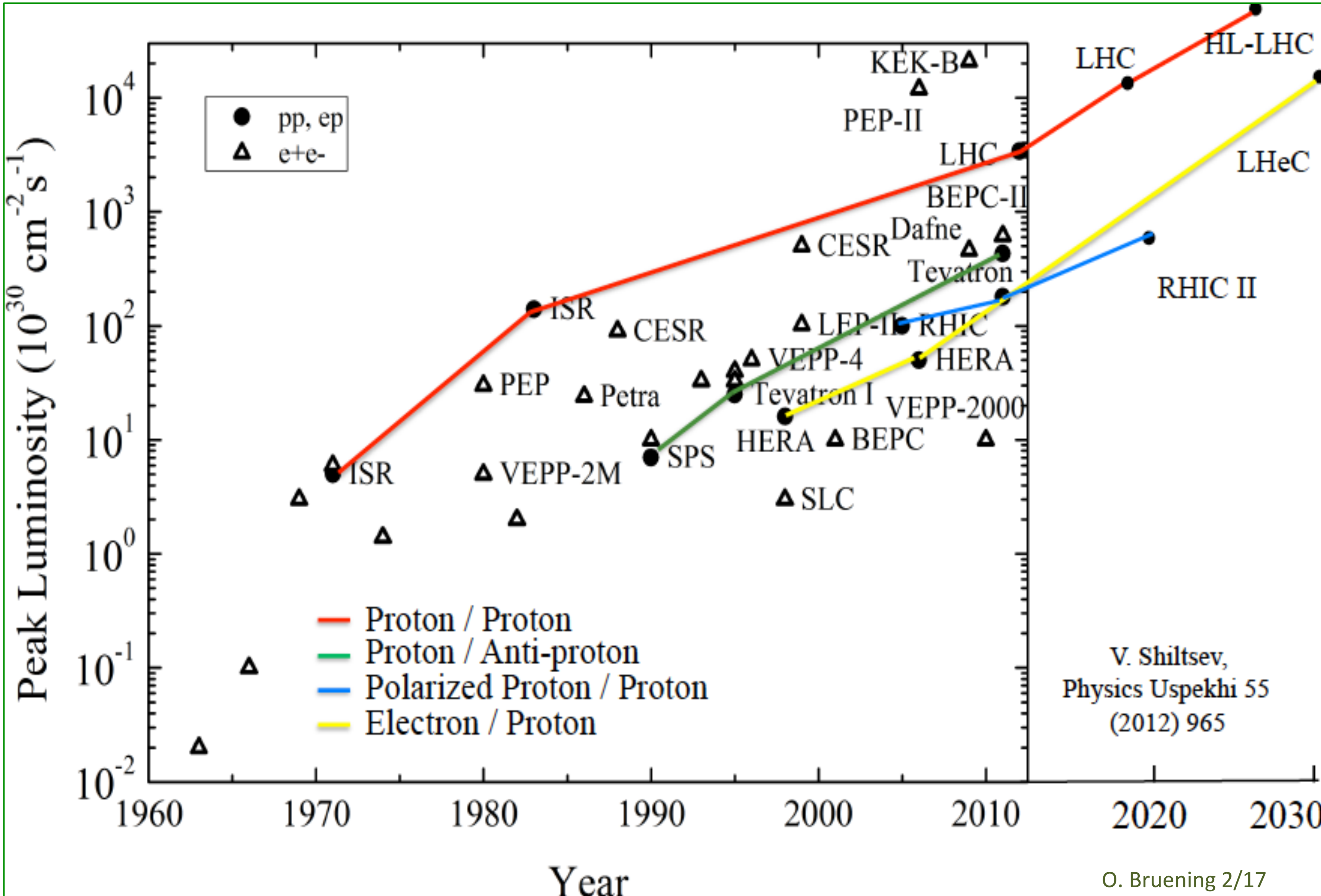


Luminosity for LHeC, HE-LHeC and FCC-ep

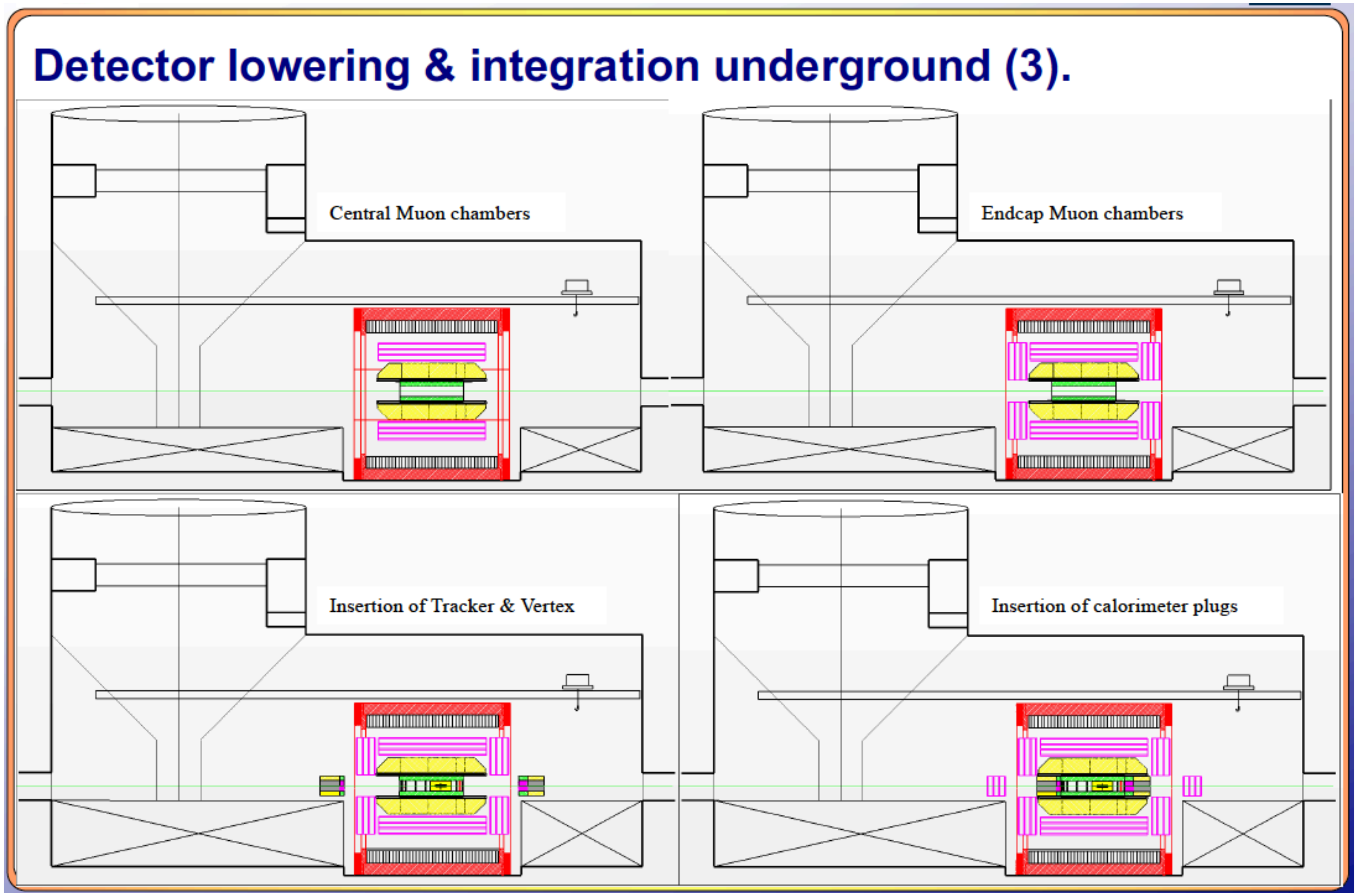
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[1,2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
April 6^{th}, 2017

Collider Luminosities vs Year (pp and ep)



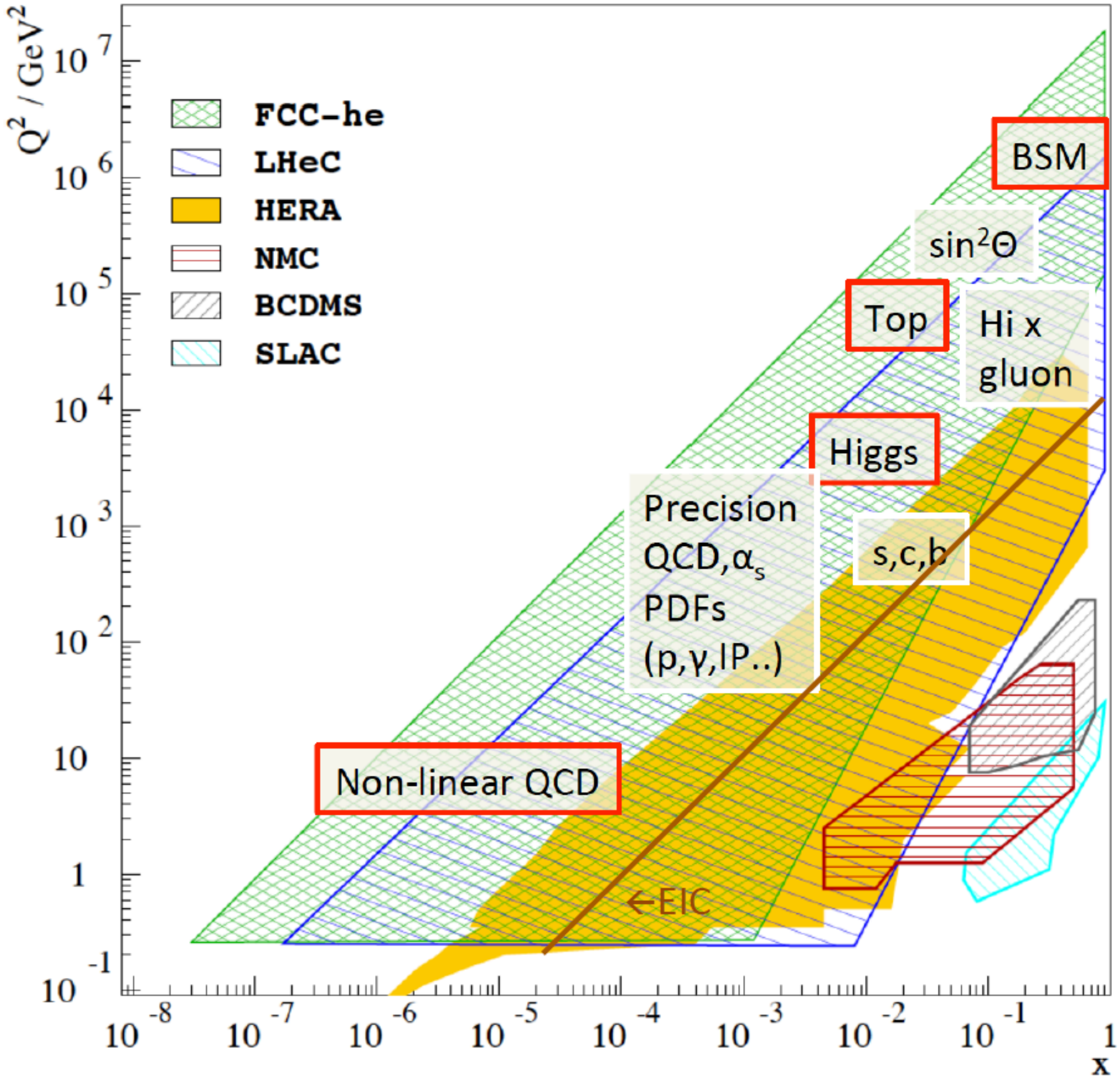
Install a Detector for Concurrent ep+pp Operation



cf Peter Kostka, Alessandro Polini, Andrea Gaddi and others 12.9.17

…most probable in IP2 (L3 magnet) - following the ALICE upgrade program completed at a time which allows large integrated luminosity to be accumulated for ep and eA

Pursue **New Physics** of Deep Inelastic Scattering



Why would we want to do that?

Because Particle Physics Needs DIS

SM was completed with a series of pp, ee and ep machines exploring the 10 GeV scale (ISR,SppS − PETRA, Tristan − electron, muon and neutrino experiments) and the Fermi scale (Tevatron − LEP, SLC − HERA), **besides further dedicated experiments [ep SLAC78..].**

All three types of colliding experiments were instrumental in the SM establishment:
For example: LEP predicted the top mass and Tevatron found the top quark;
HERA measured the gluon distribution and LHC discovered gg→**Higgs**→ 4l, yy.
Tevatron saw excess in high pt jets, yet attributed to PDFs with DIS etc

For the first time since decades we have NO definite guidance, no SM particle to find. Note, however, that the Tevatron, LEP and HERA proposals largely emphasised NOT the SM but the BSM (SUSY, LQ) physics. Rarely the SM was a funding argument before either and the theory was no less speculative . Theory only guides: e.g. Weinberg 1980 SU(5): end of colliders, go underground to see proton decay … to find neutrino oscillations ..

The LHC stands alone, it has no ep partner to explore the 1 TeV scale and it has no ee partner to study the Higgs boson. Can we build in time a 1 TeV ep collider (yes we could) and can we build a higher (than LEP) energy ee collider (for Phil to discuss)

The FCC study has hh, ee and eh: yet 5?: time, cost, technology, theory, detectors
+ the public acceptance of such a major step into the unknown and below Lac Leman

Five Major Themes of Electron-Hadron Physics

at the energy frontier

Cleanest High Resolution Microscope

Joint ep and pp Physics at LHC and FCC

High Precision Higgs Exploration

Discovery Beyond the Standard Model

A Unique Nuclear Physics Facility

CERN has the obligation to utilize its potential fully: the HL LHC programme cannot "fade away", new discoveries have to be correctly interpreted, and the world's Collider future is with CERN. DIS has to be part of it, as Guido and Lev had taught and told us, often.

cf the various physics sessions [hh-eh/H/t+BSM/QCD+PDFs/Heavy Ions and Low x]

How Can We Achieve This?

For FCC-eh: By carefully integrating eh with hh from the start

FCC-eh Geology

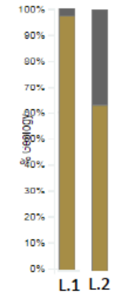
Geology:

Manipulated FCC TOT to show a cross section of geology through the location of the FCC-eh tunnels:

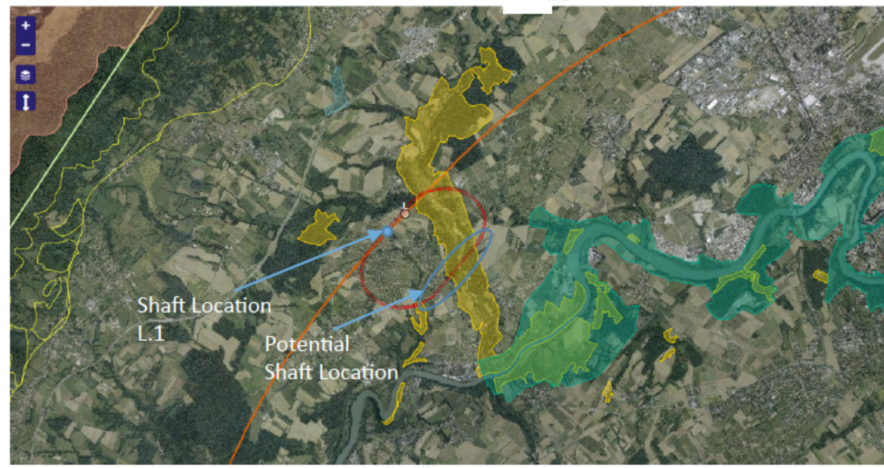
- FCC eh tunnels should aim to be located in 100% Molasse.
- Approximately 180m deep shafts located mainly in molasse with the exception of the moraines at the surface.
- Avoids Nature Reserves and watercourses.

Point	Actual	Shaft Depth (m) Molasse SA	Wildflysch	Quaternary	Molasse	Geology (m) Urgonian	Limestone
L.1	215	0	0	6	208	0	0
L.2	185	0	0	67	118	0	0

Small variation in shaft location will change the geology.



Nature Reserves
Wetlands
Nature Area

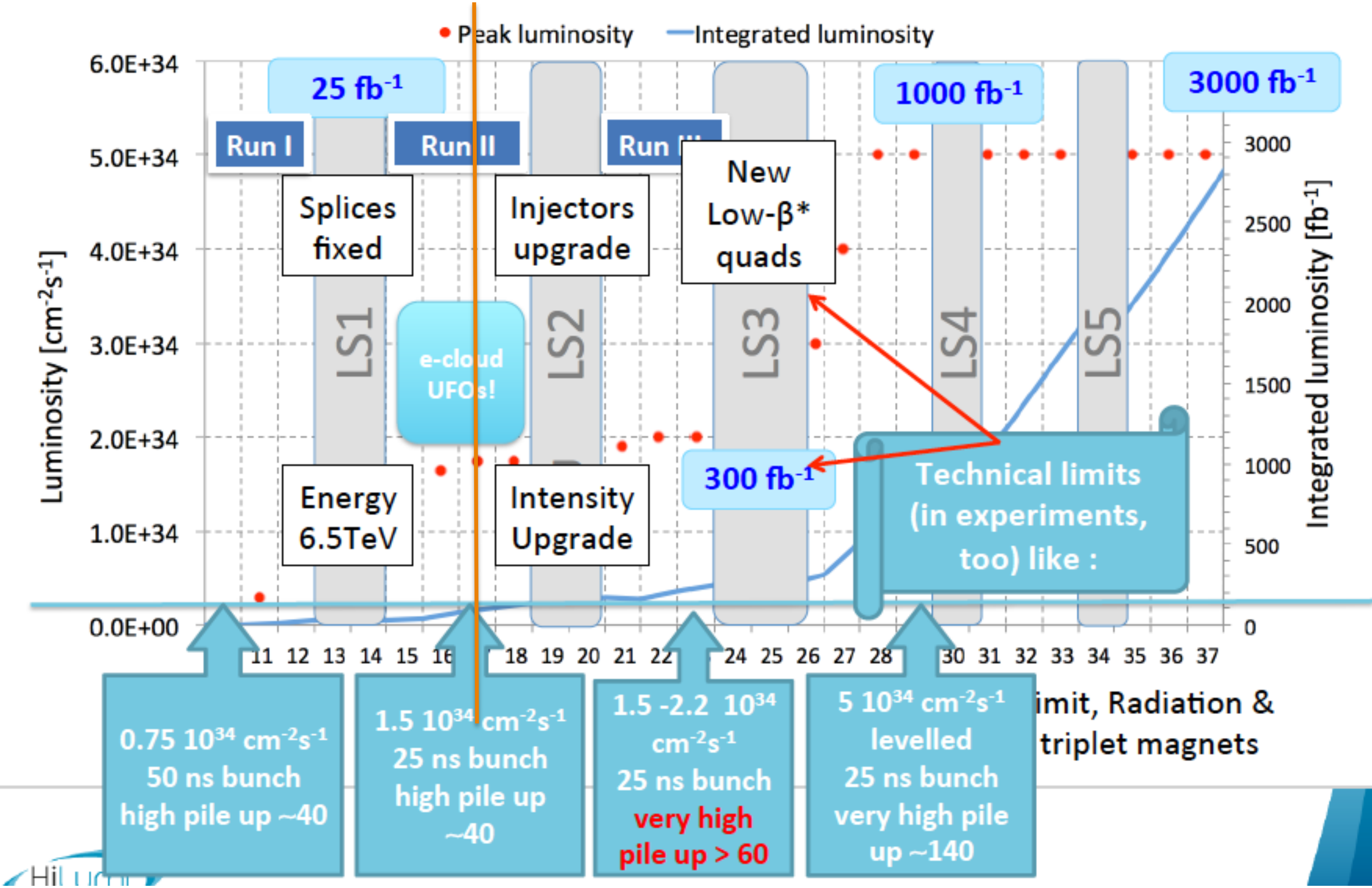


John Osborne, Jo Stanyard & Matthew Stuart (SMB-SE-FAS) 2017

LHeC and FCC-eh Workshop

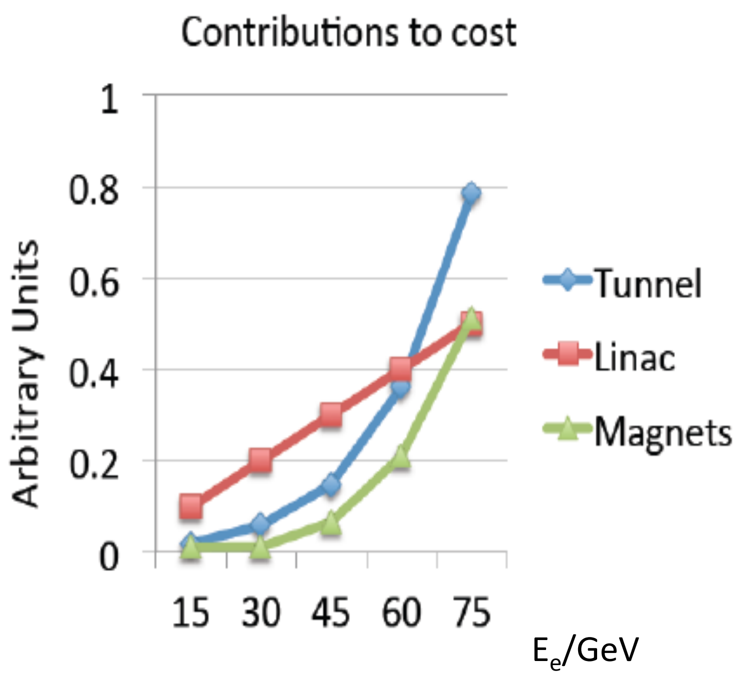
FCC-eh is integrated in joint coordination by Michael Benedikt and Frank Zimmermann, and is a part of Technical Developments (such as CE, RF), Detector and Physics work and review. It will also be considered in the forthcoming workshop on HL/HE LHC physics here at CERN

For HL LHC: With a courageous use of the time we have

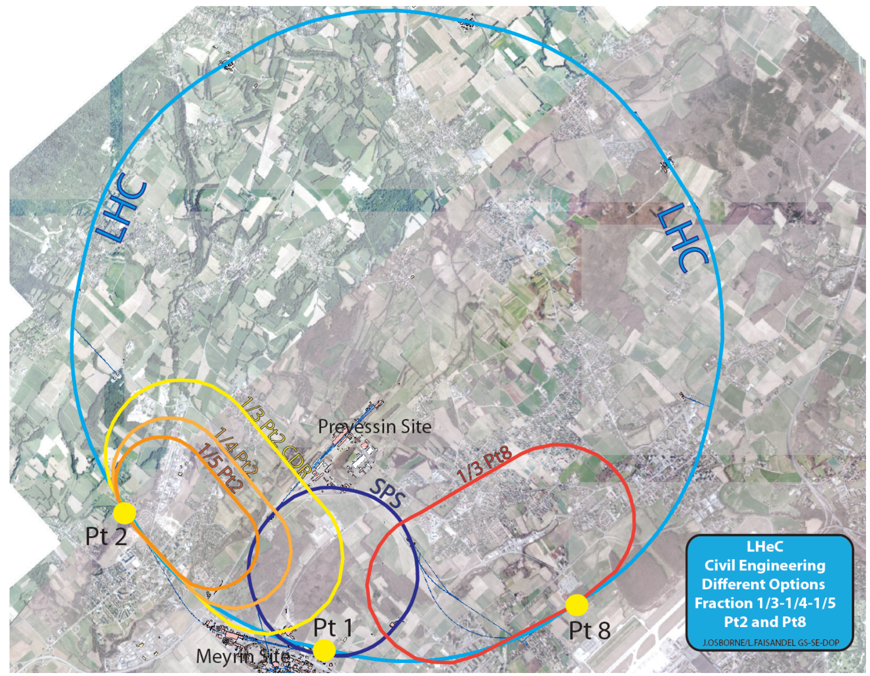


O Bruening, F Bordry

By Carefully Optimizing Physics vs. Cost



A rough extrapolation of a 3-turn ERL shows how the cost rises non-linearly with the electron beam energy. Reliable cost estimate: work in progress



9km: 1/3 of U(LHC) leads to 60 GeV e energy
5.4km : 1/5 of LHC circumference: 51 GeV

There is no real physics argument for lowering E_e, but how large does it HAVE to be? How much do we gain by reducing the size of the project and how do we ensure maximum flexibility to raise the energy should new physics require that (750 GeV saga..).

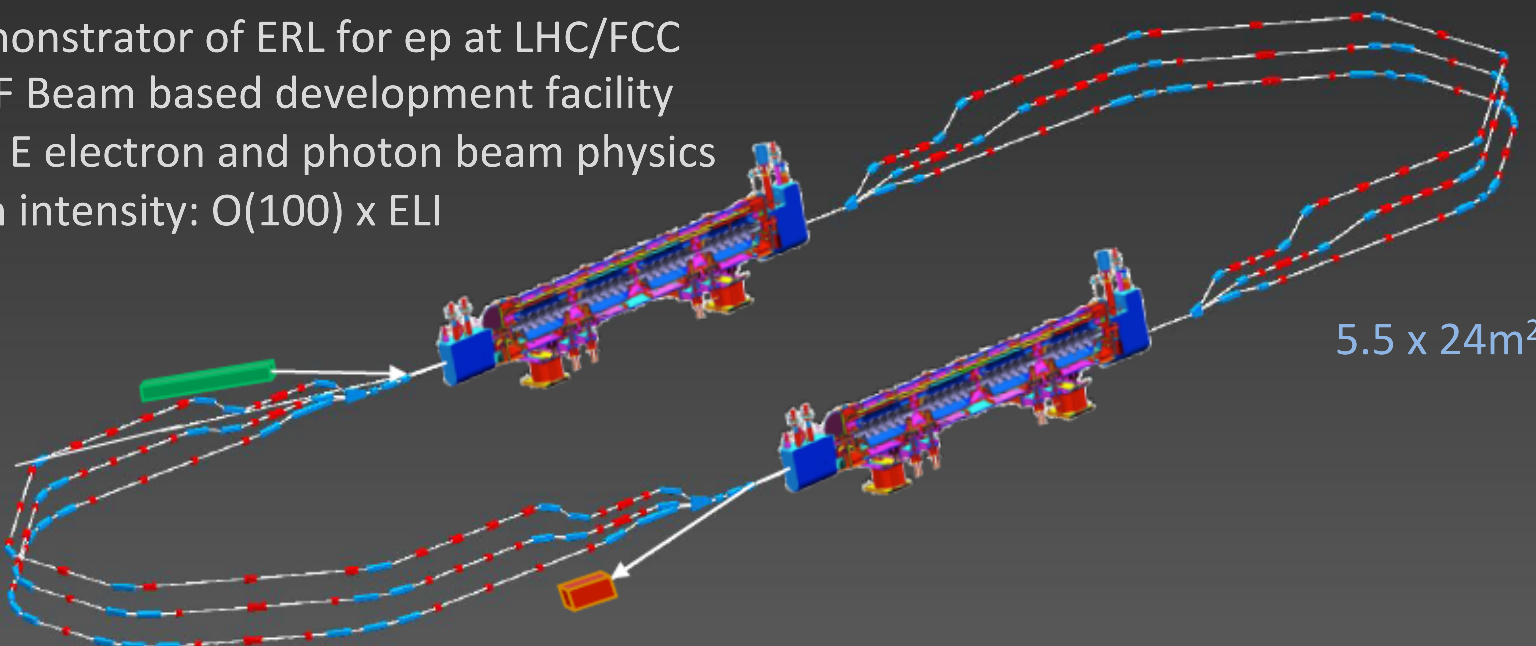
With PERLE at Orsay

title

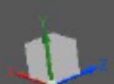
PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +

3 turns, 2 Linacs, 400 MeV, 15mA, 802 MHz, Energy Recovery Linac facility

-Demonstrator of ERL for ep at LHC/FCC
-SCRF Beam based development facility
-Low E electron and photon beam physics
-High intensity: O(100) x ELI



CDR to appear in J Phys G [arXiv:1705. 08783]



A.Bogacz

Strong low energy physics program:
p radius, sin2theta, dark photons, photon-nuclear physics, ..

cf Talk by W Kaabi next and PERLE session tomorrow. Note ERL workshop at CERN 6/17

A KICKOFF MEETING FOR PERLE, a proposed facility to test technology for the LHeC, was held on 24 February in Orsay, France. Among the participants were Max Klein (second row, fourth from right), Orsay Linear Accelerator Laboratory director Achille Stocchi (center, red shirt), CERN director for accelerators and technology Frédérick Bordry (second row, third from right), Oliver Brüning (front row, second from right), and Daresbury Laboratory director Susan Smith (front row, far right).

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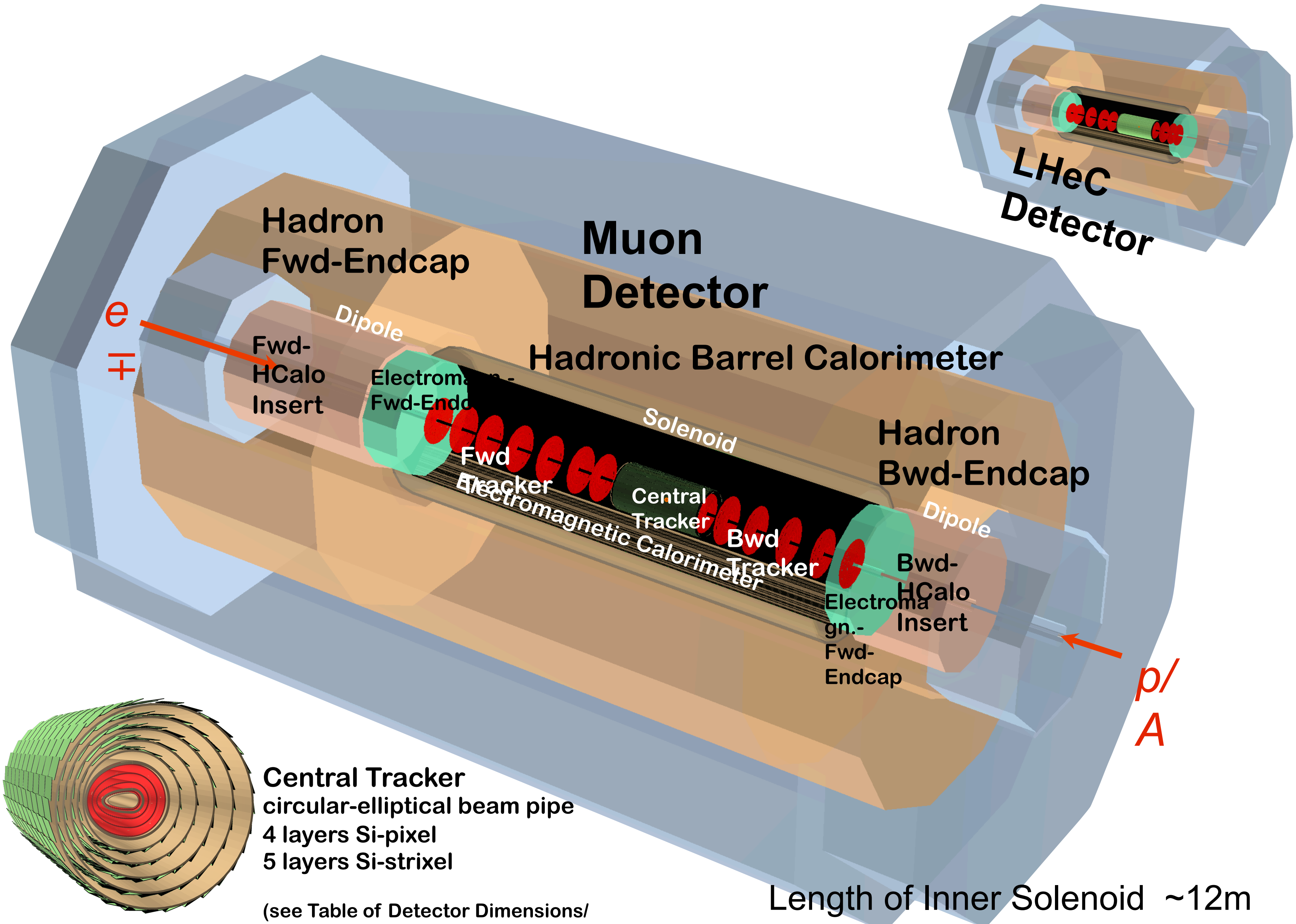
All that is left to do is to transform the happy optimism visible here into a real facility..

There is a PERLE Collaboration meeting as follow up of the workshop, on Wednesday

By making the ep/eA detector a test bed for new technology in the twenties

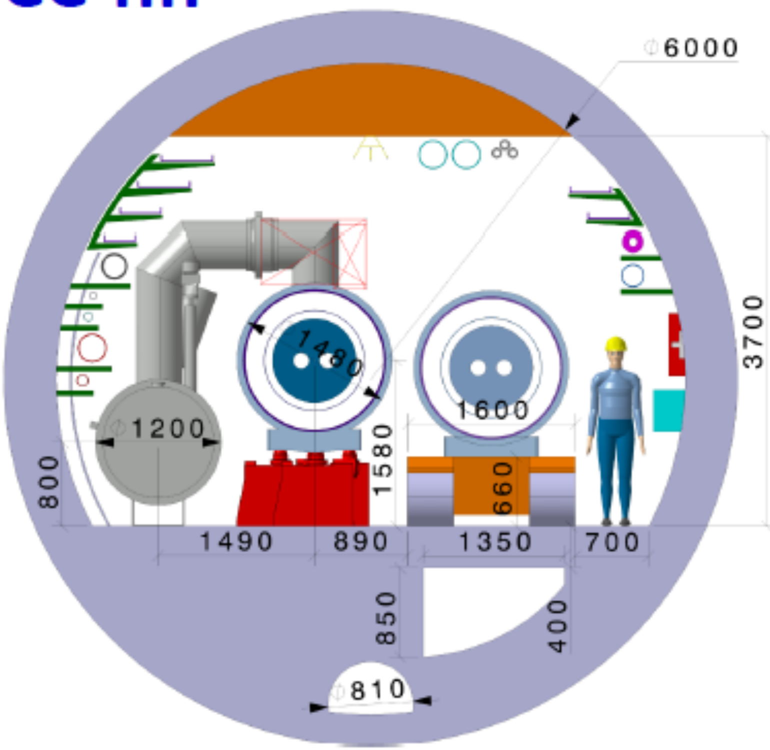


Remarks on the HE LHC

tunnel integration

V. Mertens et al.

FCC-hh

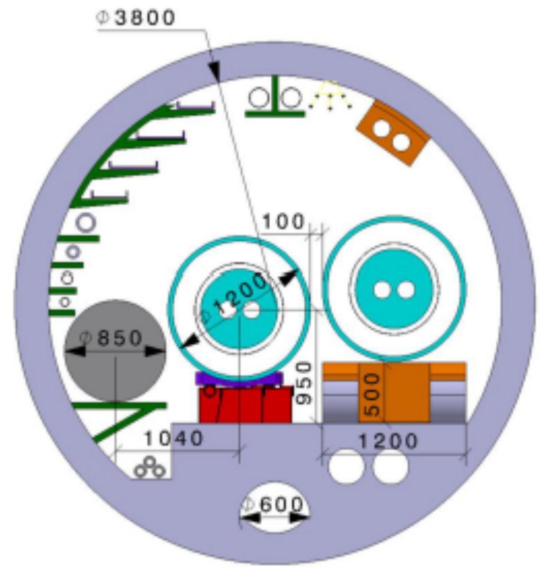


6 m inner tunnel diameter

main space allocation:

- 1200 mm cryo distribution line (QRL)
- 1500 mm installed cryomagnet
- 1600 cryomagnet magnet transport
- >700 mm free passage.

HE-LHC



3.8 m inner tunnel diameter

main space allocation:

- 850 mm cryo distribution line (QRL)
- 1200 mm installed cryomagnet
- 1200 cryomagnet magnet transport

challenging

HE LHC Time Schedule

Remark

We recall that the US Nb_3Sn conductor program started in 1999 aiming at the same target cost as the one set for the FCC. After 5 years the program stopped: the target cost was not achieved, remaining about three times higher than the target (presently we are exactly in the same situation, with no advancement with respect to the outcome of that US program). However the program was very successful and resulted in practically doubling the critical current and decreasing the cost of the conductor by more than a factor of 2.

This is to say that a vigurous R&D program, probably over 5-10 years, will be necessary before a massive production for a HE-LHC or a FCC can start.

D Tommassini (June 17)

Production of HE LHC Components: O(10) years.

Injector: Currently scSPS disfavoured and SPS 450 GeV considered. 80 years old by 2050

Detectors: ATLAS and CMS at twice the proton beam energy – major upgrades to study

HL LHC: $3ab^{-1}$ estimated duration: until 2038 – 2040

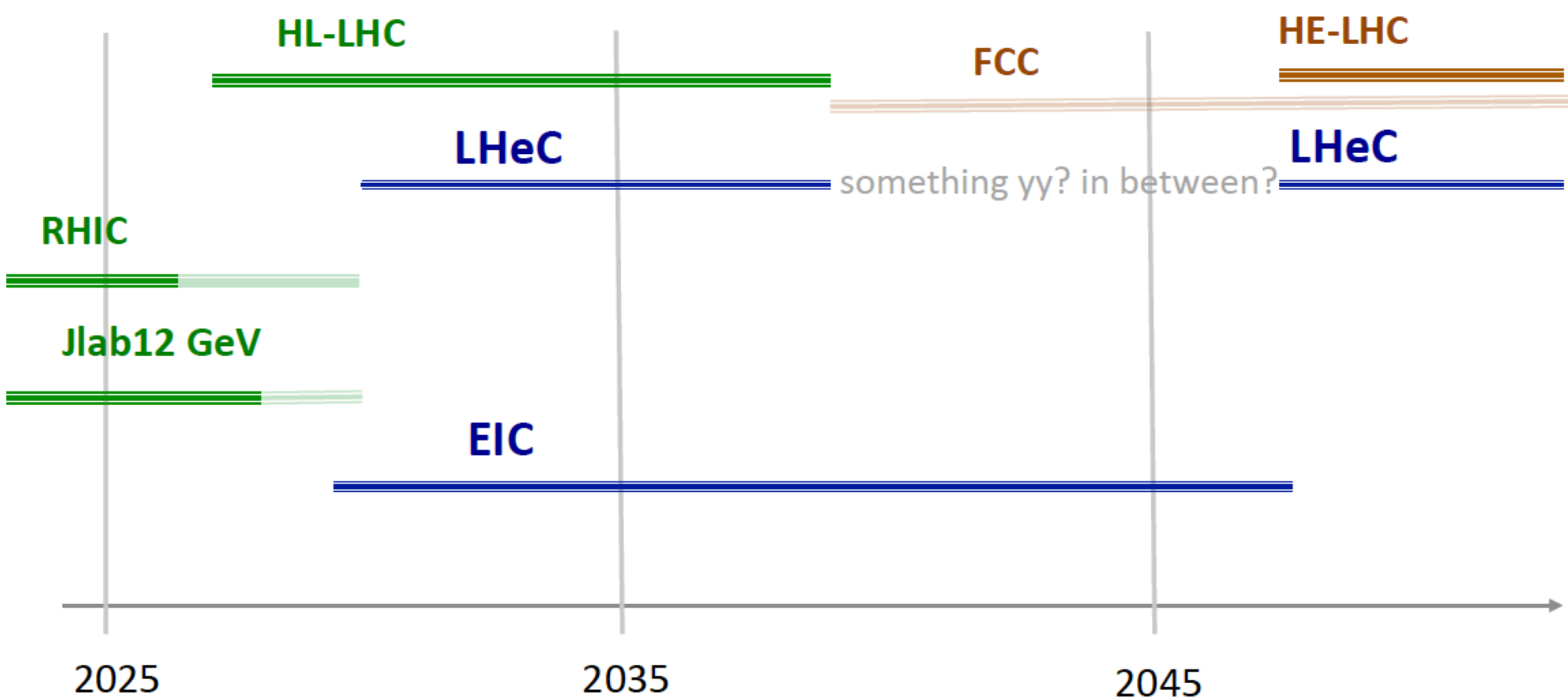
Dismantling LHC, Installing HE LHC O(10) years: **HE LHC in 2050** maybe a bit earlier.

Total cost O(5) BSF: 25 years of 200 MSF. Magnet cost crucial to reduce. **Physics ?**

MK, presented to UK PPAP, July 2017

With the prospect of HE LHC: the ERL better be built in the 20ies at significantly less cost than HE LHC

Projected Timelines for Future ep/eA Colliders



HERA: Proposal 1984, Data 1992-2007, Publications 1993-2018

VHEep: Plasma e – LHC. **Chinese ep/A** projects: Lanzhou (low E) and CEPC/SPPC

Developed with Rik Yoshida (Jlab) for discussion (only), at DIS2017, Birmingham

IF or when ☺ : the CERN scenario may indeed be realized as sketched above, then there is a time of O(10) years for new physics with the ERL, cf session on Wednesday

From a talk on **EIC and LHeC Side by Side**

In time: - The EIC and the LHeC will not be operational before 2030
[cf B. Mueller on eRHIC Monday and LH(e)C time schedule (LS4),
HERA took 8 years to build: approval in 1984 data 1992 → 2007. XFEL ~9 years]
- They should be considered to be operational together, not sequential *)
- EIC needs decades for spin, ep and eA data, much beyond the Trump time
- LHeC will be terminated with the LHC but may reappear with HE LHC (FCC)

In their technology choice:
- currently (BNL?) both the two US EICs and the LHeC use ERLs for the e beam
- they have similar challenges (multi-turn, high current ERL)
- all luminosity goals are very ambitious and need R+D:
a common problem is a high current polarised e^- source (LHeC 15, BNL 50mA)
- they almost certainly will have 100 times less or no positrons, P=0

In their kinematics: $Q^2_{max} = s = 10^4$ GeV^2 (EIC) 10^6 GeV^2 (LHeC), $x > 1$ GeV^2 /s in DIS

In their role: seen from the perspective of genuine deep inelastic scattering:
- EIC will "replace BCDMS/NMC (suspicious at high x) and HERMES/COMPASS"
- LHeC will "replace HERA (uncertain at high x and no CC x > 0.5)"

*) Predicting is difficult, in particular if it concerns the future (V. Weisskopf)

MK at POETIC 2016, Philadelphia

Main physics goals of new DIS Colliders*)

Substructure of nucleons
Development of QCD, Discoveries
Structure of γ, Pomeron, n, D, A..
Precision eweak measurements ..

Low energy (smaller HERA)

Nuclear structure
Electroweak below Z
p Spin composition
Spin structure
"Proton Holography 3d" ...

High Energy (bigger HERA)

Unfolding of *all* partons (NC+CC)
New physics (Higgs, DM, RPV SUSY, LQs..)
Electroweak below and beyond Z
Non linear QCD in ep and eA (QGP)
Top physics ...

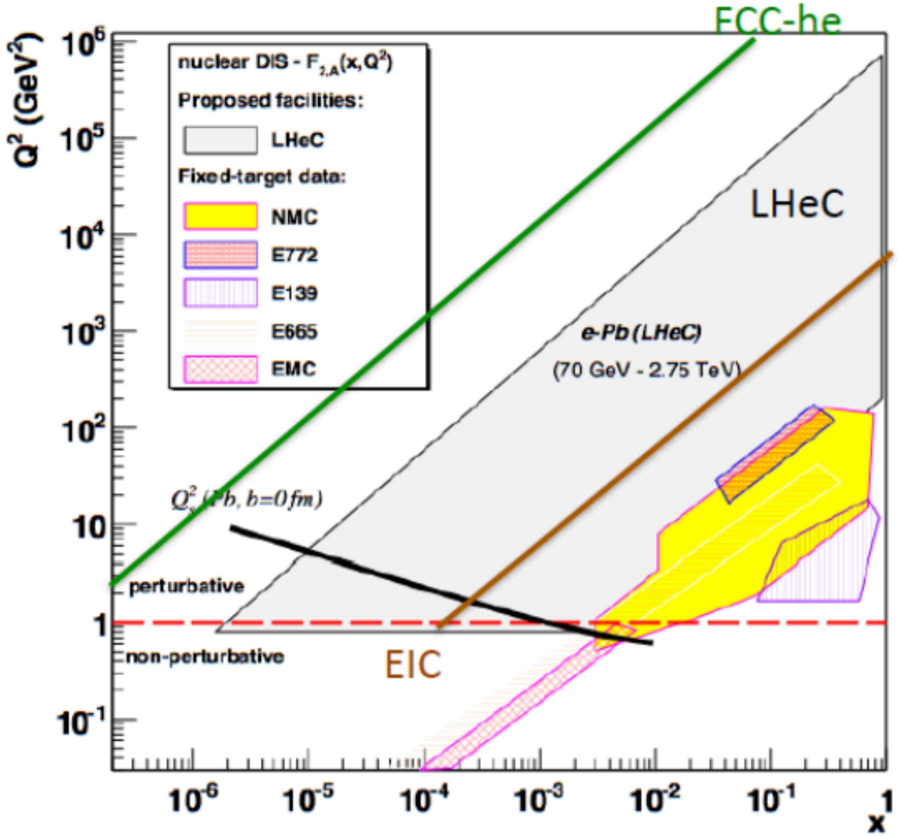
Why are quarks and leptons different?
Salam 1976

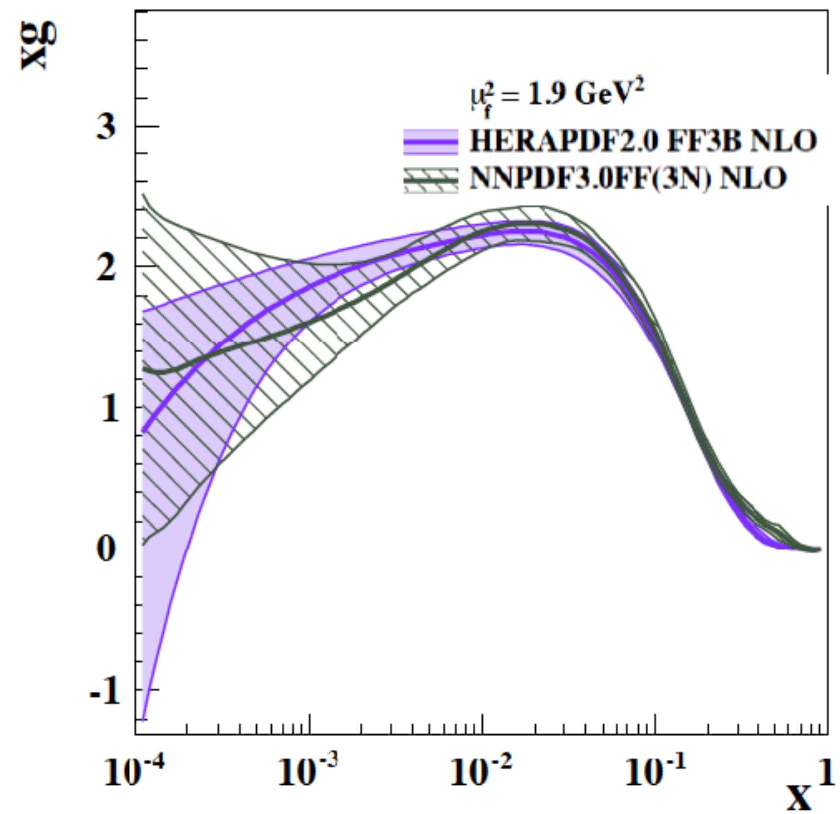
FCC-he: 10 times higher H-HH cross section
10 times lower x
4 times larger mass range for NP ..
as compared to LHeC
but the FCC is later + more expensive.

*) incomplete

A low energy EIC cannot replace the high energy LHeC. The LHeC cannot measure p spin composition and is not set to study hadron structure at medium x. Like H1/ZEUS and HERMES/Compass, both have a task while NOT being the same.

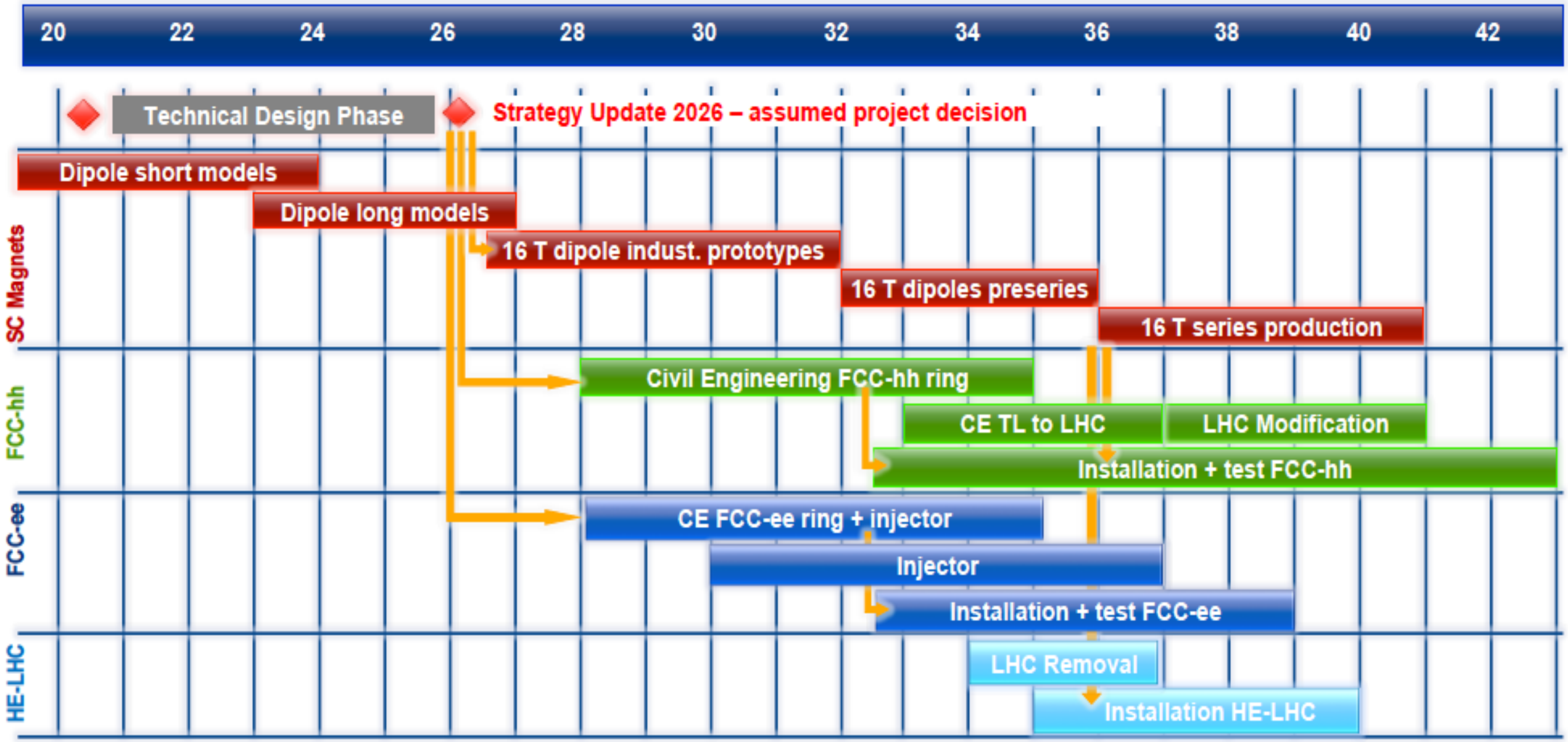
eA Kinematics and xg near the Saturation Line





To see saturation you need xg to be large, the strong coupling small, ep and eA.
To discover subtleties such as log(1/x) terms one needs high precision data of $\delta F_2/\delta \ln Q^2$ which requires to include data to $Q^2 \sim 10$ GeV^2 [x_{min}=10/s] and of F_L.
This has been demonstrated for the LHeC kinematic range in the CDR (cf MCS talk).

Draft Schedule Considerations



Remarks

“The future belongs to those who believe in the beauty of their dreams.”

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015

An Important Remark

An electron–proton collider could bridge the gap between the LHC and its successor

Frédérick Bordry, CERN's director for accelerators and technology. The project needs more support from the particle-physics community, he notes. "The next European strategy for particle physics will be very important for the LHeC." The strategy recommendations are slated to come out in 2020, and decisions may be delayed beyond that. **Toni Feder**

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The preparations of the LHeC and FCC-eh documents for the strategy will be discussed on Wednesday.

Status + Framework of the Development

Following the CDR in 2012: Mandate issued by CERN:2014 (RH), confirmed in 2016 (FG)

Mandate to the International Advisory Committee

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

Chair: Herwig Schopper, em. DG of CERN. IAC+CERN have invited four of its members to follow the study and this workshop with special attention (Stefano Forte, Andrew Hutton, Leandro Nisati and Lenny Rifkin). Collaboration also with the FCC Review Committee chaired by Guenther Dissertori.

LHeC has been a development for and initiated by CERN, ECFA and NuPECC, so far, it's formal status is that of a community study, not a proposal, which holds for the FCC also, of which 'eh' is a part.

Poster by Vassili, Celine and Audrey

Welcome to the workshop.

Thanks to all speakers, the convenors, Voica Radescu included, and Committees, see the poster left

Please note:

Group photo at 10.40 TODAY

Dinner at 19.30 TODAY

Have one bus and cars to go to the White House:

Golf Restaurant Maison Blanche Echenevex (France): Route from St Genis to Gex D984C, left when having passed Chevry

Sincere thanks to CERN, LAL Orsay, and Aries for supporting the meeting.

backup

Parameters of CERN pp Colliders

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

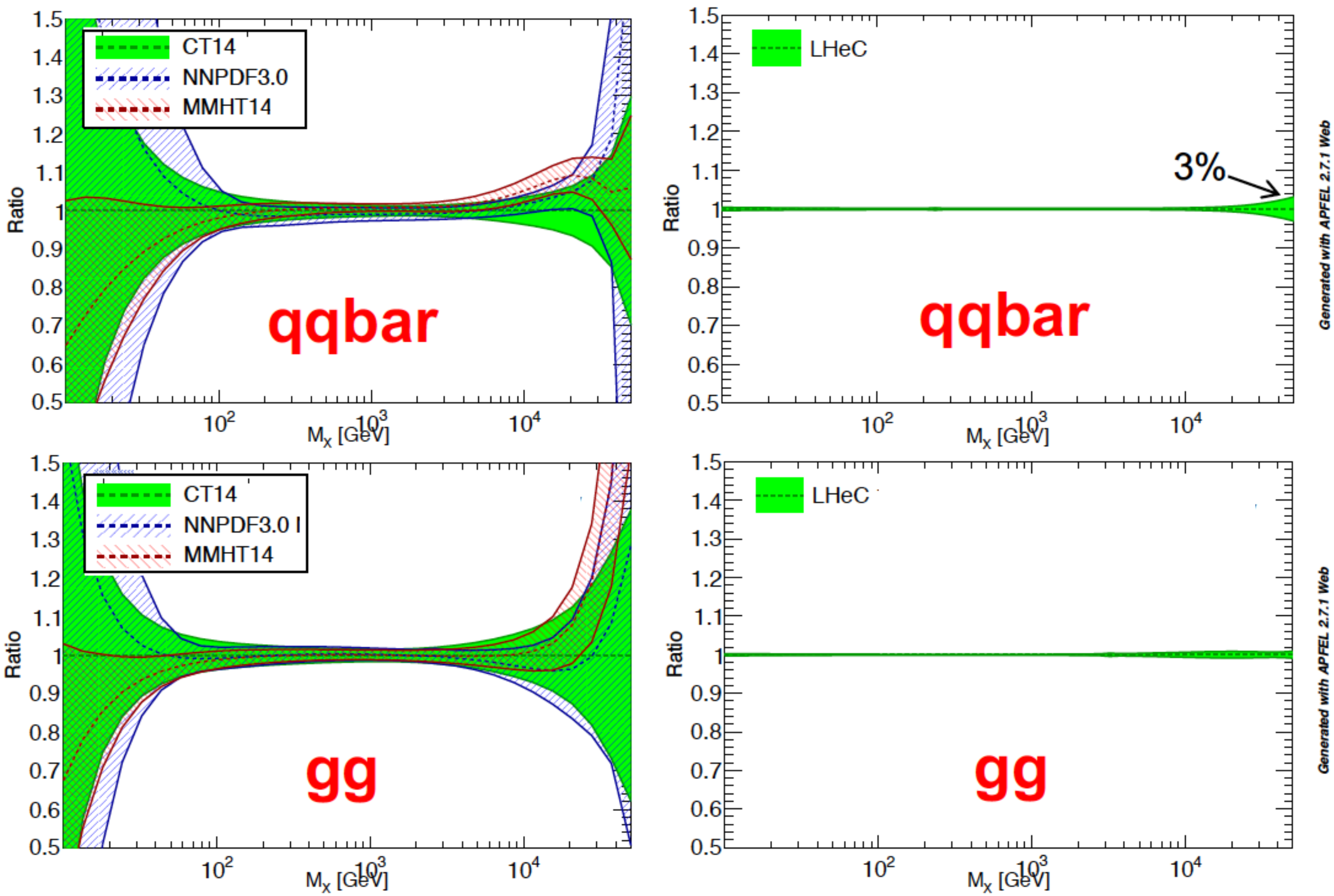
F Zimmermann, June 2017

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…

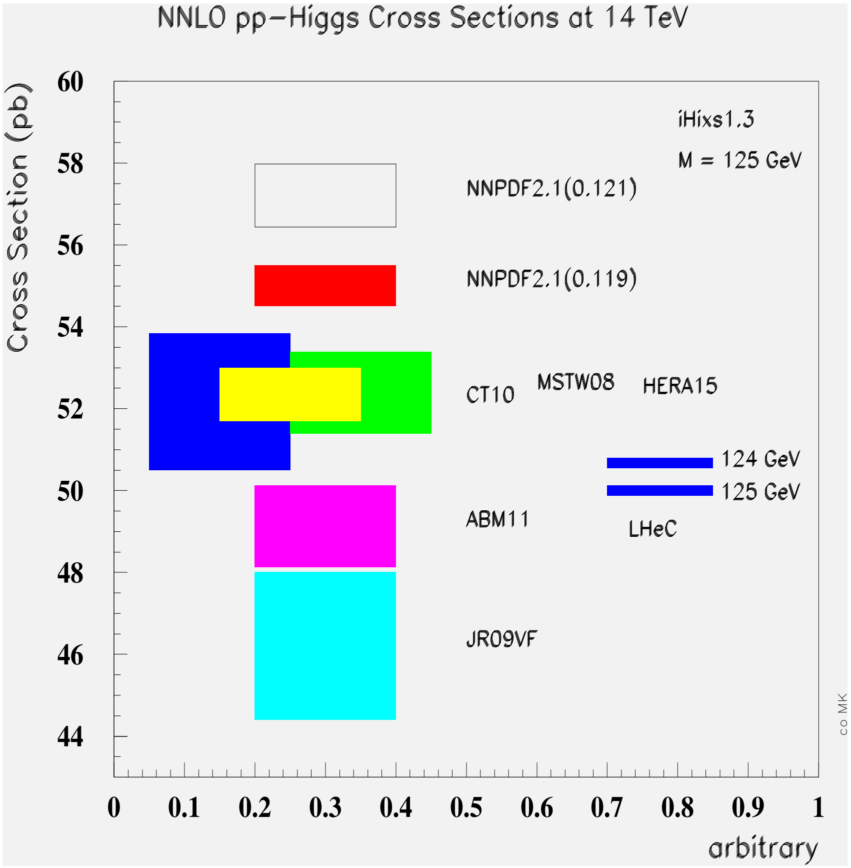
Strong Coupling in inclusive DIS at LHeC to 0.1%

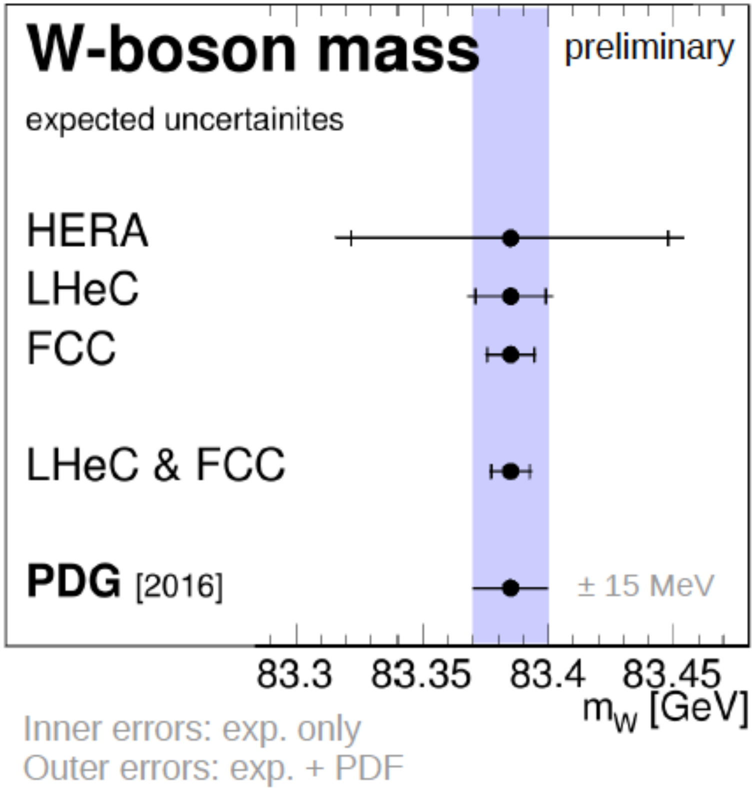
Lattice??
Jets??
BCDMS??
GUTs?
Higgs in pp



Note that LHC is about to reach its own limits on PDFs. pp is NOT DIS, cf ATLAS W,Z to 0.5%

High Precision for the LHC





Predict the Higg cross section in pp to 0.2% precision which matches the M_H measurement and removes the PDF error

Spacelike M_W to 10 MeV from ep
→ Electroweak thy test at 0.01% !

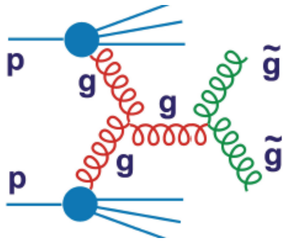
Predict M_W in pp to 2.8 MeV → Remove PDF uncertainty on M_W LHC

Empowering pp Discoveries

External, reliable input (PDFs, factorisation..) is crucial for range extension + CI interpretation

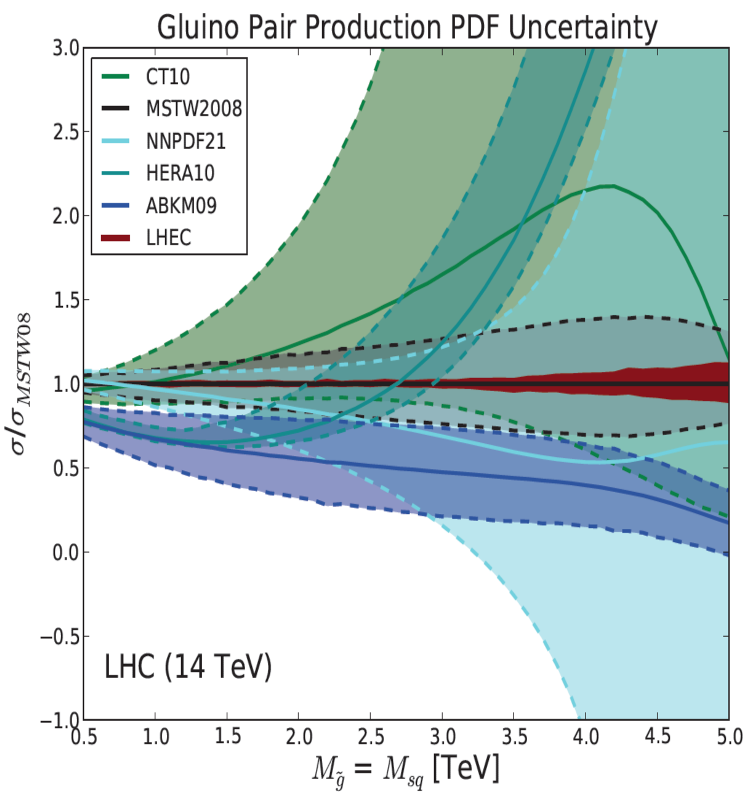
GLUON

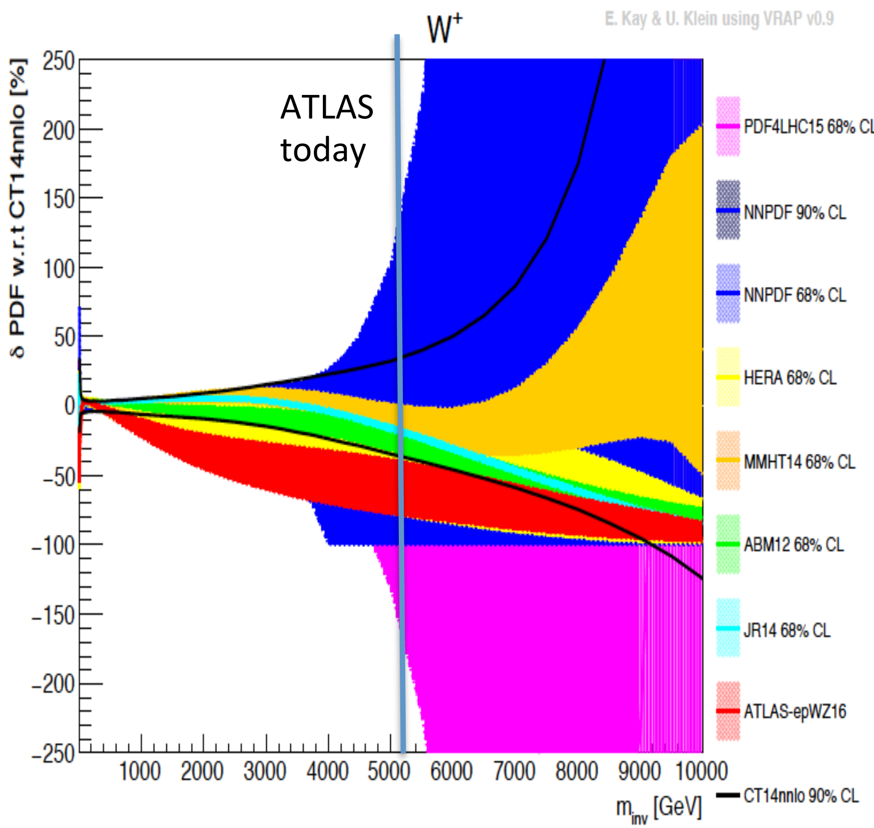
SUSY, RPC, RPV, LQS..



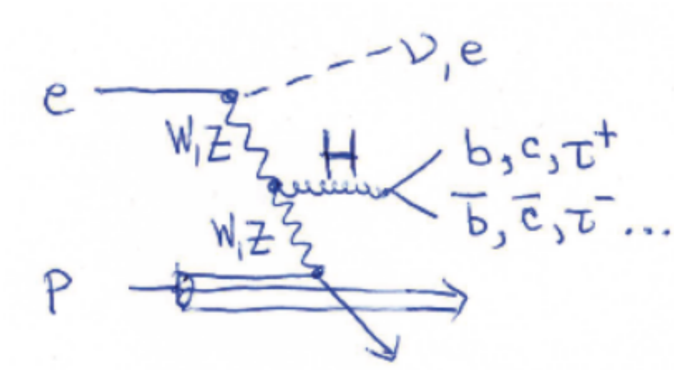
QUARKS

Exotic+ Extra boson searches at high mass





Higgs Physics with ep



High cross section (cc: LHeC 200fb, FCC-eh 1pb)

Electroweak production, uniquely CC vs NC

Access to WW-H-WW and ZZ-H-ZZ

No pileup, clean theory, challenging simulations

SM coupling measurement expectations

κ in %	HL LHC	LHeC HL	LHeC HE	FCC-eh
H → bb	10?	0.5	0.3	0.2
H → cc	50??	4	2.8	1.8

Expected number of signal events
(E_e = 60 GeV)

FCC ep (~85,000 H→bb events)

DLHC (~35,000 H→bb events)

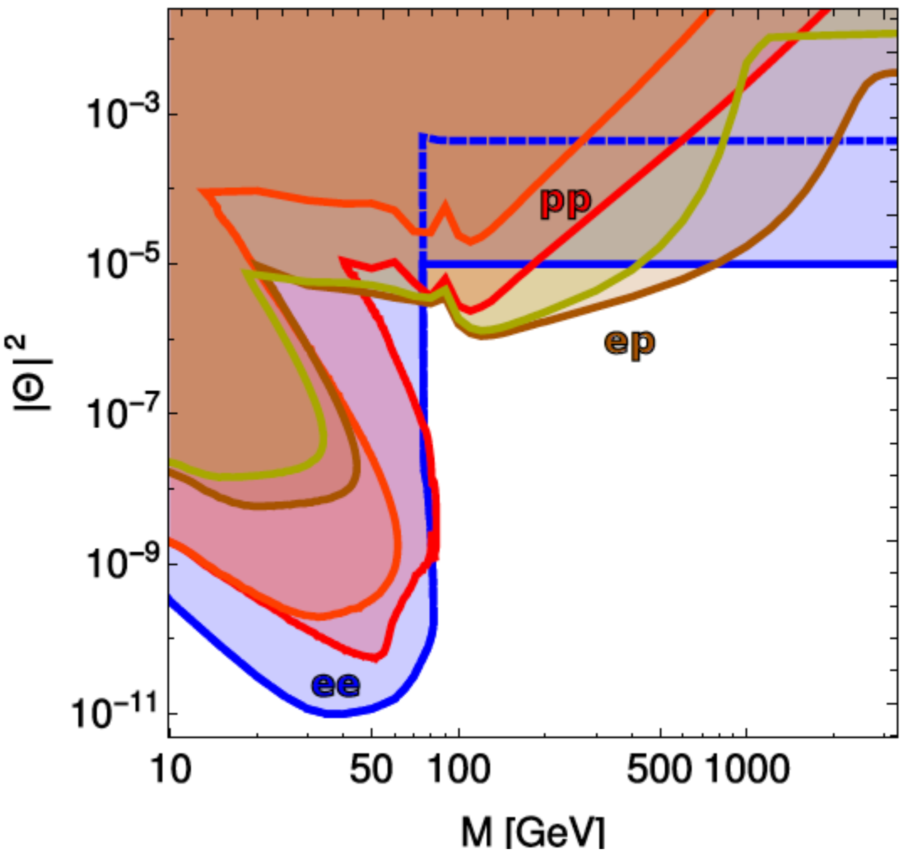
LHeC (~15,000 H→bb events)

Recent Higgs-in-ep studies for CDR: Higgs self coupling from FCC-eh associated top-Higgs production, Higgs into invisible (dark matter),
Exotic Higgs physics: H into light scalars, H^{--} and others
cf U Klein at FCC Berlin for references and summary

ep when added to pp turns the pp colliders into high precision Higgs facilities.
Removes PDF and coupling constant uncertainties in pp gg fusion process.

Possible Discoveries Beyond SM with eh

Search for Sterile Neutrinos
(LHC/FCChh FCCee LHeC/FCCeh)



QCD:

(No) saturation of the gluon density

QCD radiation pattern (BFKL?) – hh!

New QCD states (instantons)

Higher symmetry embedding QCD

Electroweak:

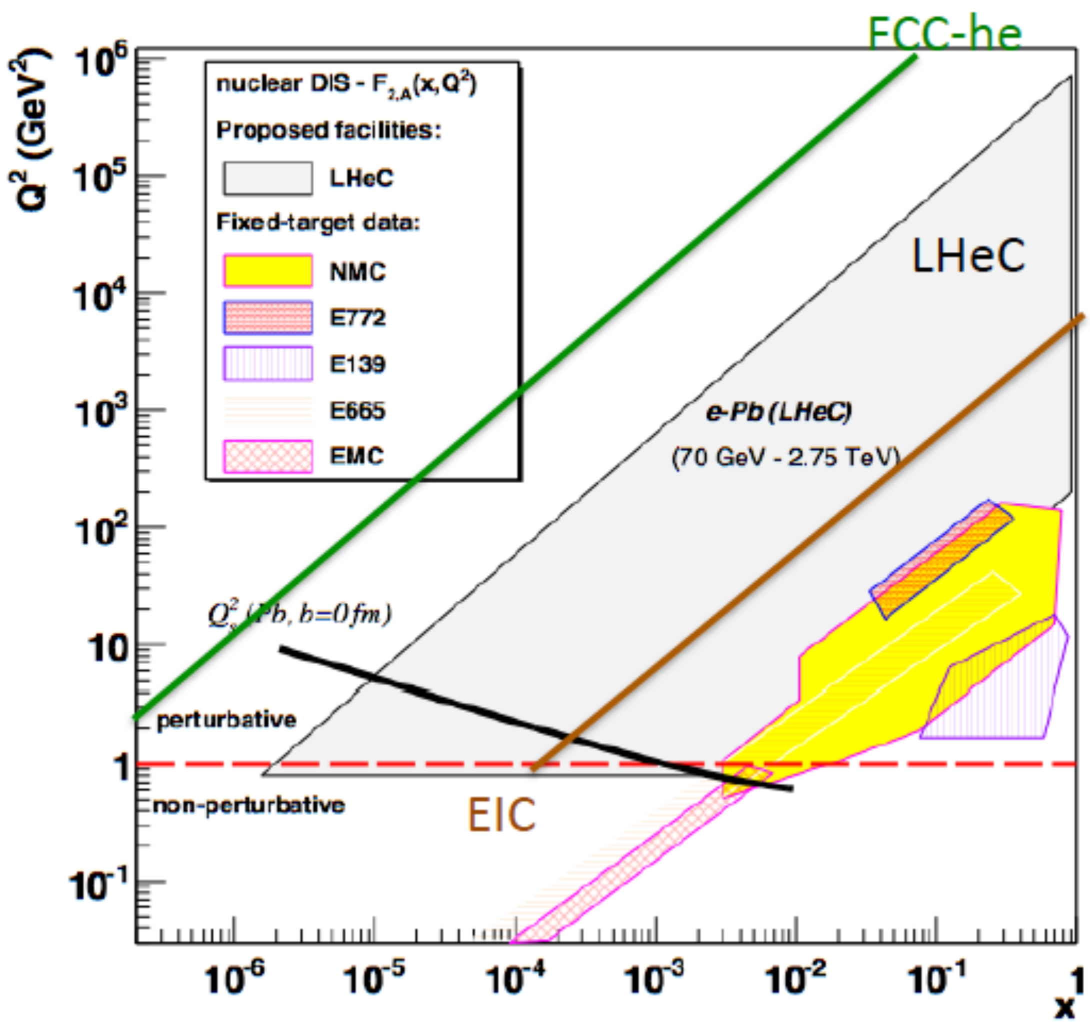
EFTs, CI to 300 TeV, RPV SUSY

Exotic Higgs Decays (Dark Matter..)

Extension of Higgs Sector (H^{++}..)

Sterile Neutrinos …

Electron-Ion Nuclear and Particle Physics



Extension of kinematic range in lA by 4 orders of magnitude:
will change QCD view on nuclear structure and parton dynamics

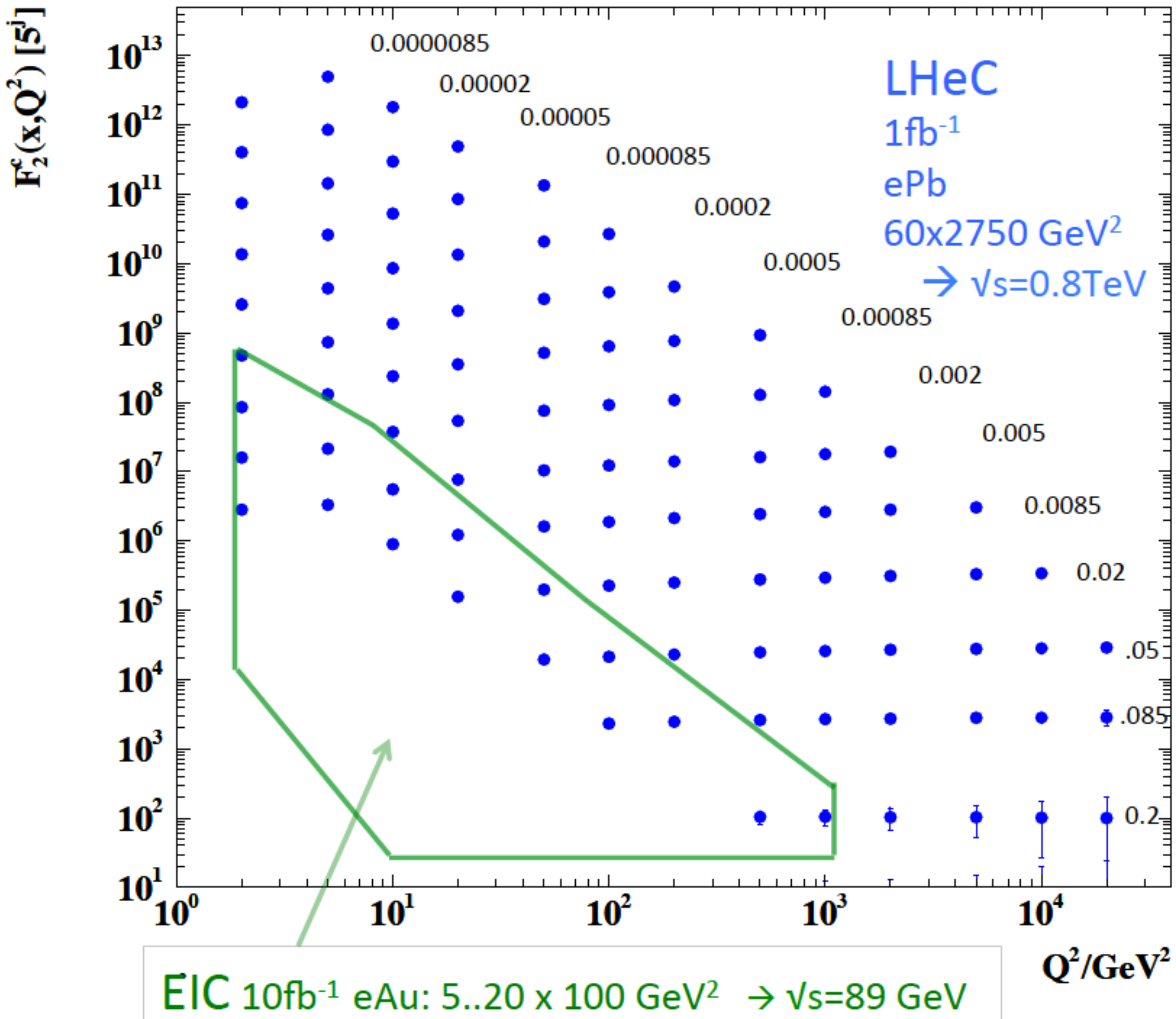
May lead to genuine surprises…

- No saturation of xg (x,Q^2) ?
- Small fraction of diffraction ?
- Broken isospin invariance ?
- Flavour dependent shadowing ?

Relates to LHC Heavy Ion Physics
- Quark Gluon Plasma
- Collectivity of small nuclei (p)?
- ..

Saturation: needs large xg at small x
ep and eA

Charm Structure Function in Nuclei



Also F_Lc and b

Until the end of 2018

We have to work hard in order to deliver what we have been asked to do.

We have to work differently if we want to indeed succeed and make LHeC a reality.

The next European strategy will hardly decide anything as it is five years before the 2 BSF HL upgrade takes place, and no one knows how to reach out to O(10)BSF. The demand to make HL LHC a success will be overriding, adding ep and eA is a golden key to this.

Directions may become visible in a global context (an asiatic e+e- machine decision would be important). HEP is remarkably in the hands of the J+Ch governments.

The ERL development and the detector+physics study has a long term future with CERN as we consider this accelerator as a modular addition to HL/HE LHC and the FCC hh.

Thank you all and many thanks to new and elder collaborators who generate a stream of ideas which make the ep/A physics program very attractive.

Taken from a presentation to a meeting of physics convenors and coordination group 9th of June, 17