Towards a Large Hadron electron Collider at the LHC

5-140 GeV $e^{\pm}$ on 1-7 TeV p,A

Max Klein

University of Liverpool and Cockcroft Institute
H1 and ATLAS

Report at the CERN Institute for Colliders Beyond the LHC, 18.02.09
Physics Programme: cf Emmanuelle Perez, ibid.

http://www.lhec.org.uk

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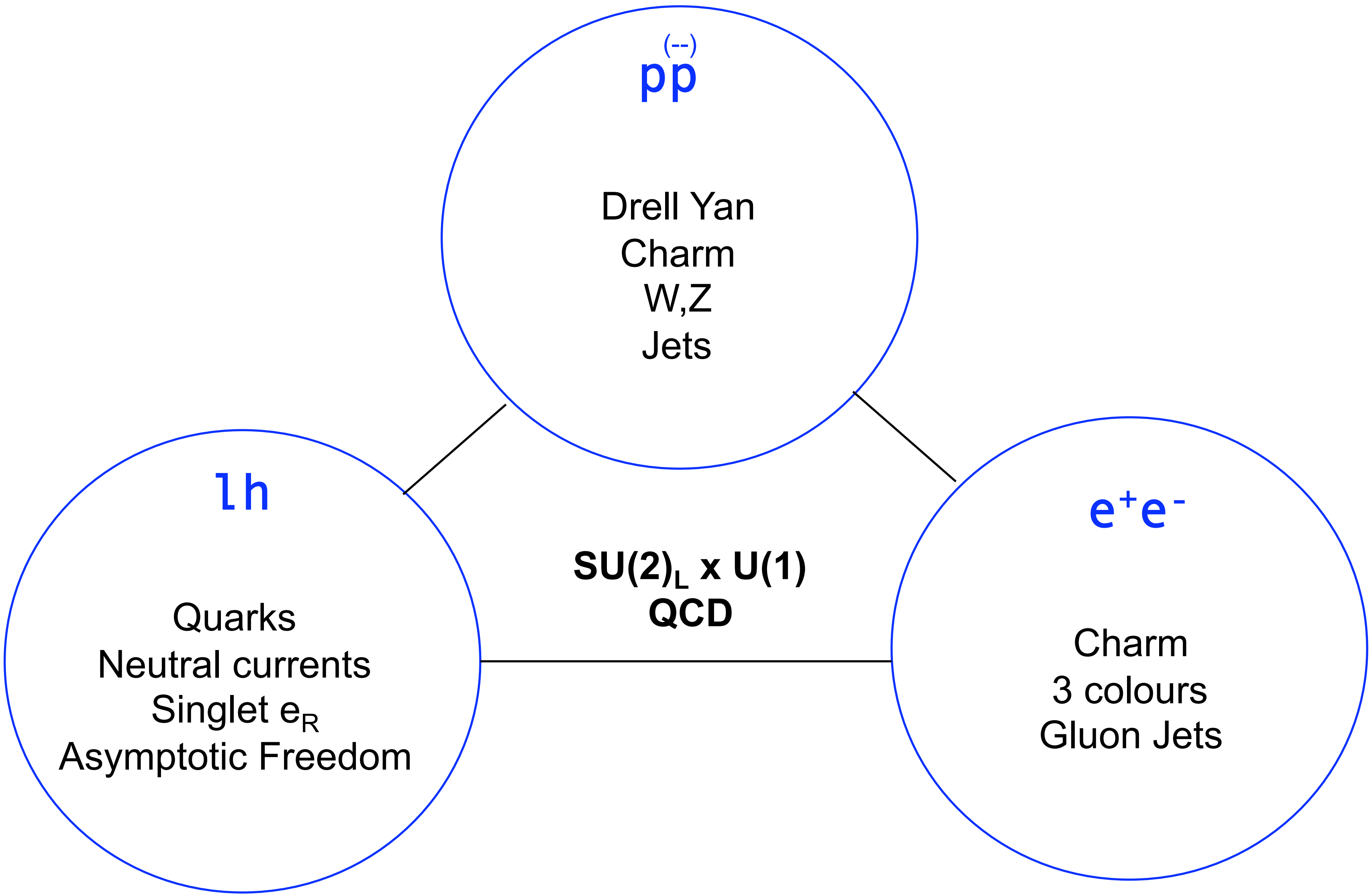
The 10-100 GeV Energy Scale [1968-1986]

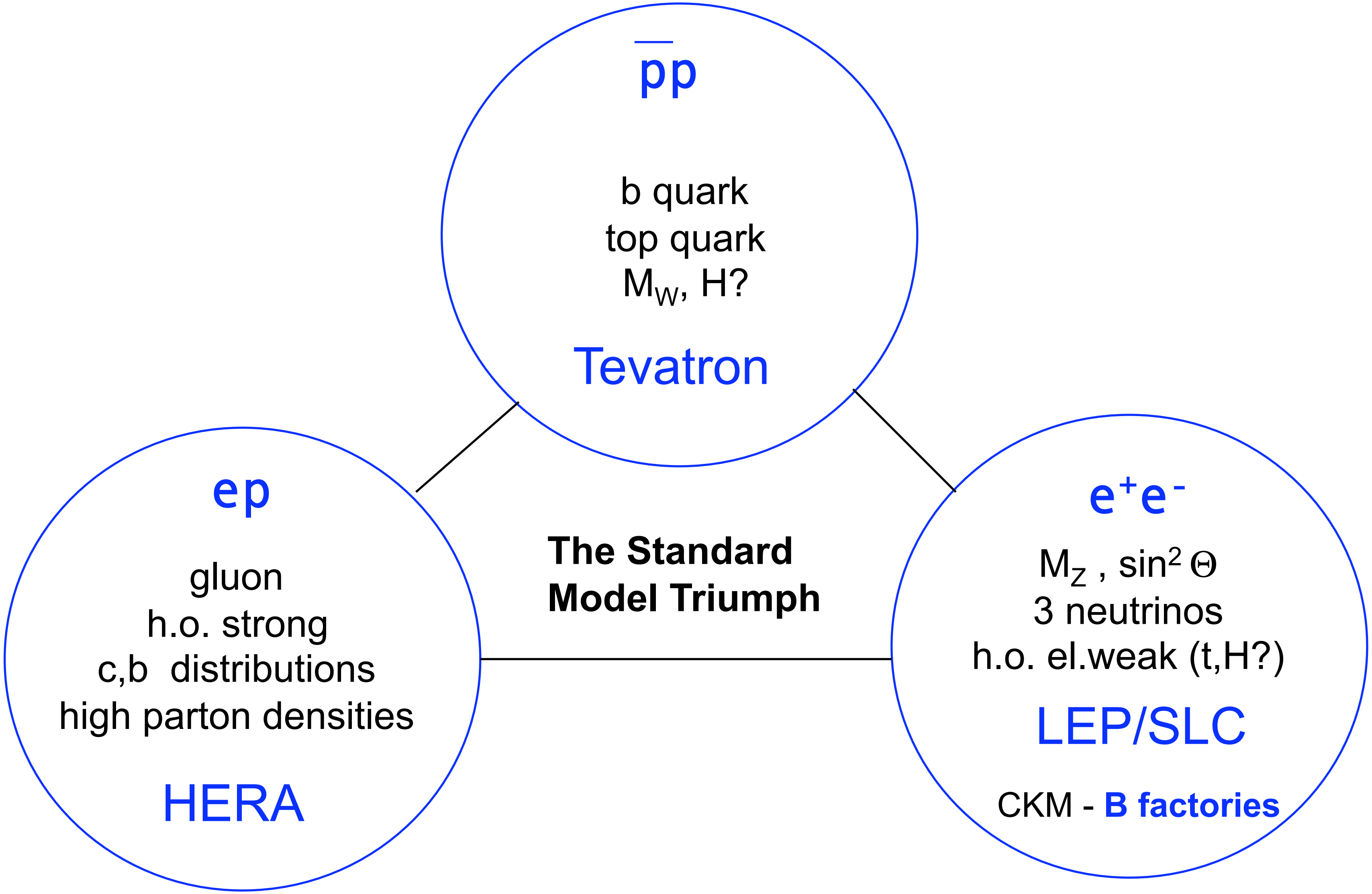


Electron-proton colliders open new horizons on all three of the fundamental questions: the spectroscopy of fundamental fermions, the spectroscopy of gauge bosons, and the problem of hadron structure. In addressing these issues, the ep collider is approaching the same physics as is studied in e^+e^- and $\bar{p}p$ colliders, but in a complementary way, with emphasis on the t-channel. Each technique has its own strengths and weaknesses, which I leave you to contemplate.

Chris Quigg
Fermi National Accelerator Laboratory

FERMILAB-Conf-81/52-THY

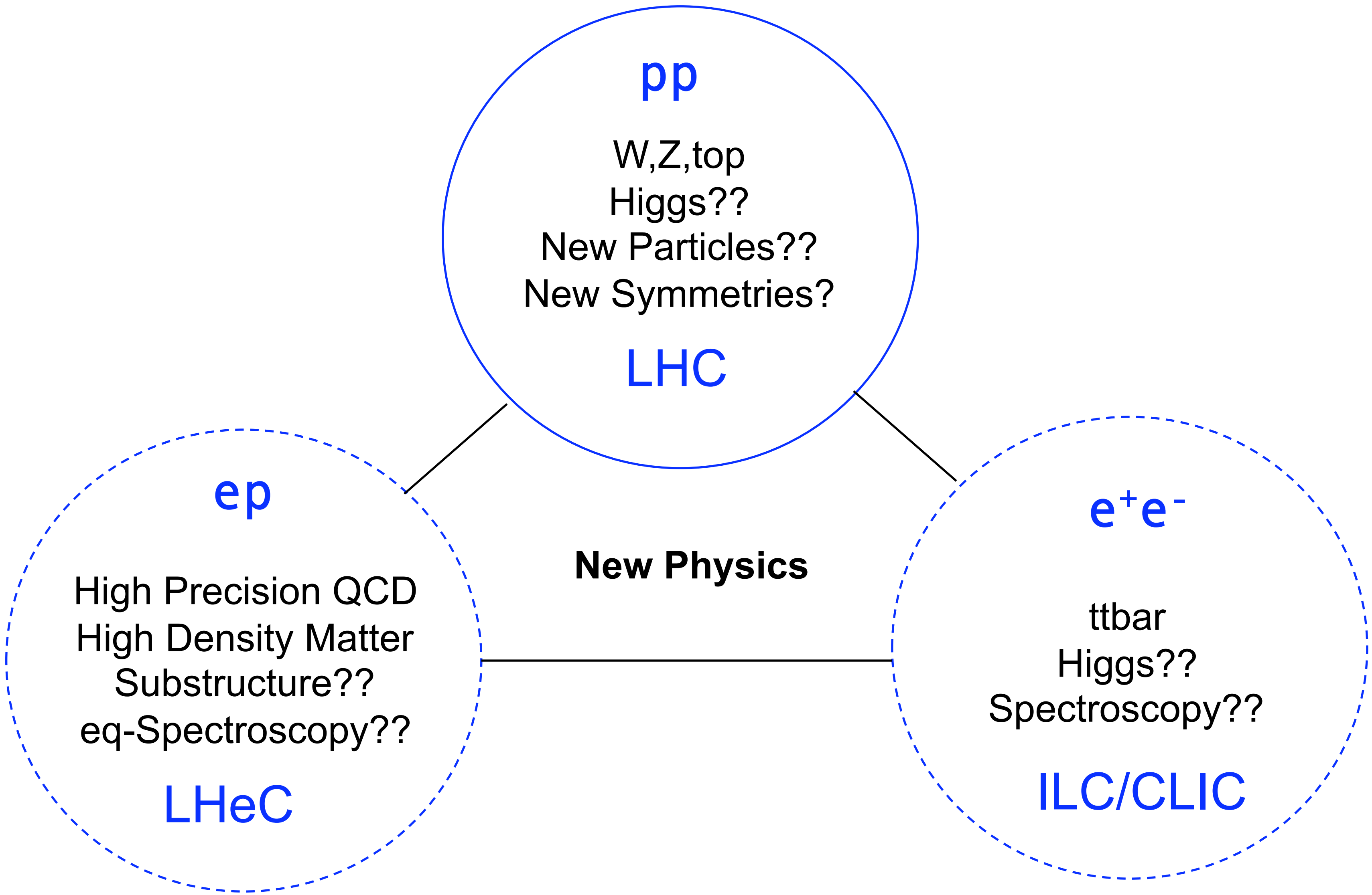
The Fermi Scale [1985-2010]



“Now we are entering the post-TeV era, jumping not one but two orders of magnitude to a lab equivalent of order 50 TeV at HERA. *)
If the LHC is successfully commissioned in the LEP tunnel in 1997, then we may hope to see collisions between electrons from LEP and protons from the LHC in the next millenium giving a lab equivalent around 10 TeV (1 PeV). “ F.Close Singapor 1990

*) For an exerimental review see:
M.K., R.Yoshida, ‘Collider Physics at HERA’’
arXiv 0805.3334, Prog.Part.Nucl.Phys.61,343(2008)
HERA II analysis still ongoing

The TeV Scale [2010-2035..]



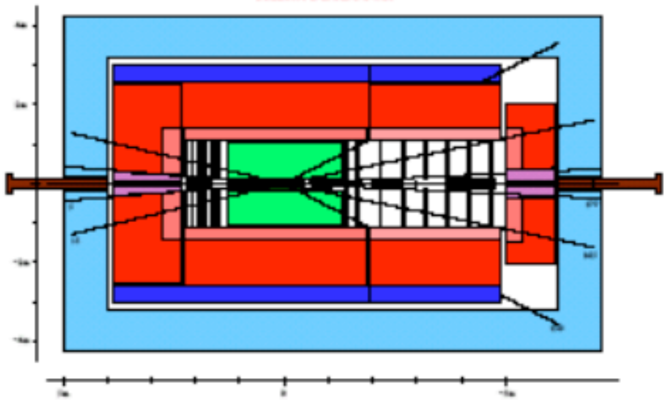
DIS at the TeV scale

DESY 01-123F vol. 4
DESY-LC-REV-2001-062
December 2001

Physics and Experimentation at a Linear Electron–Positron Collider

Volume 4: The THERA Book.
Electron–Proton Scattering at $\sqrt{s} \sim 1$ TeV

THERA DETECTOR



Editors: U. Katz, M. Klein, A. Levy and S. Schlenstedt

ISSN 0418-9833

LEP-LHC

A. Verdier LHC Workshop Aachen 90, p.820

E. Keil LHC Project Report 93 (1997)

THERA

R. Brinkmann, F. Willeke THERA book
and Proceedings Snowmass 2001

QCD explorer (CLIC-LHC')

D. Schulte, F. Zimmermann CLIC 608

LHEC F. Willeke (a study)

Jinst PUBLISHED BY INSTITUTE OF PHYSICS PUBLISHING AND SISSA
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REVISED: July 22, 2006
ACCEPTED: August 30, 2006
PUBLISHED: October 11, 2006

hep-ex/0306016

Deep inelastic electron-nucleon scattering at the LHC

J.B. Dainton,[a] M. Klein,[b*] P. Newman,[c] E. Perez[d] and F. Willeke[b]

Considerations on Deep Inelastic Scattering at Tera scale energies

Towards the CDR by 2010

Scientific Advisory Committee (12/08)

Guido Altarelli (Rome)
Stan Brodsky (SLAC)
Allen Caldwell -chair (MPI Munich)
Swapan Chattopadhyay (Cockcroft)
John Dainton (Liverpool)
John Ellis (CERN)
Jos Engelen (CERN)
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Aharon Levy (Tel Aviv)
Karlheinz Meier (Heidelberg, ECFA)
Richard Milner (Bates)
Steven Myers, (CERN)
Guenter Rosner (Glasgow, NuPECC)
Alexander Skrinsky (Novosibirsk)
Anthony Thomas (Jlab)
Steven Vigdor (BNL)
Frank Wilczek (MIT)
Ferdinand Willeke (BNL)

Following a suggestion of Council, ECFA + CERN in 11/07 set the task to work out a CDR within 2 years on the physics, machine and detector for a TeV energy ep/eA collider based on the LHC beams.

Steering Group

Oliver Bruening	(CERN)
John Dainton	(Cockcroft)
Albert DeRoeck	(CERN)
Stefano Forte	(Milano)
Max Klein - chair	(Liverpool)
Paul Newman	(Birmingham)
Emmanuelle Perez	(CERN)
Wesley Smith	(Wisconsin)
Bernd Surrow	(MIT)
Katsuo Tokushuku	(KEK)
Urs Wiedemann	(CERN)

DIS05, 06, 07, 08: Future of DIS and LHeC (Proceedings)

EPAC08 Genoa: 3 Papers on Accelerator

First ECFA-CERN Workshop on the LHeC Divonne 1.-3.9.08

Opening: J.Ellis, Kh.Meier, G.Rosner, J.Engelen, G.Altarelli

DIS09: April 25, Madrid: Pre-Meeting on the LHeC

PAC09 Vancouver, May 2009

September 7/8, 2009: 2nd ECFA-CERN Workshop

November 2009: Report to ECFA

May 2010: Delivery of CDR (~200 pages on Physics, Det,, ACC)

WG Convenors →

Accelerator Design [RR and LR]

Oliver Bruening (CERN),

John Dainton (CI/Liverpool)

Interaction Region and Fwd/Bwd

Bernhard Holzer (DESY),

Uwe Schneeekloth (DESY),

Pierre van Mechelen (Antwerpen)

Detector Design

Peter Kostka (DESY),

Rainer Wallny (UCLA),

Alessandro Polini (Bologna)

New Physics at Large Scales

Emmanuelle Perez (CERN),

Georg Weiglein (Durham)

Precision QCD and Electroweak

Olaf Behnke (DESY),

Paolo Gambino (Torino),

Thomas Gehrmann (Zuerich)

Claire Gwenlan (UCL)

Physics at High Parton Densities

Nestor Armesto (CERN),

Brian Cole (Columbia),

Paul Newman (B'ham),

Anna Stasto (MSU)

Machine Requirements

-New physics expected at (multi??) TeV scale. Low $x=Q^2/sx$, $s=4E_eE_p$

highest possible E_e and E_p **1 TeV with 50GeV on 5000 GeV**

-New physics is rare [σ_{ep} (Higgs) = O(100)fb] , rate at high Q^2 , large x

L has to exceed 10^{32} and preferentially reaches 10^{33} and beyond

-New states, DVCS, electroweak physics

Need electrons and positrons and high lepton beam polarisation

-Neutron structure terra incognita

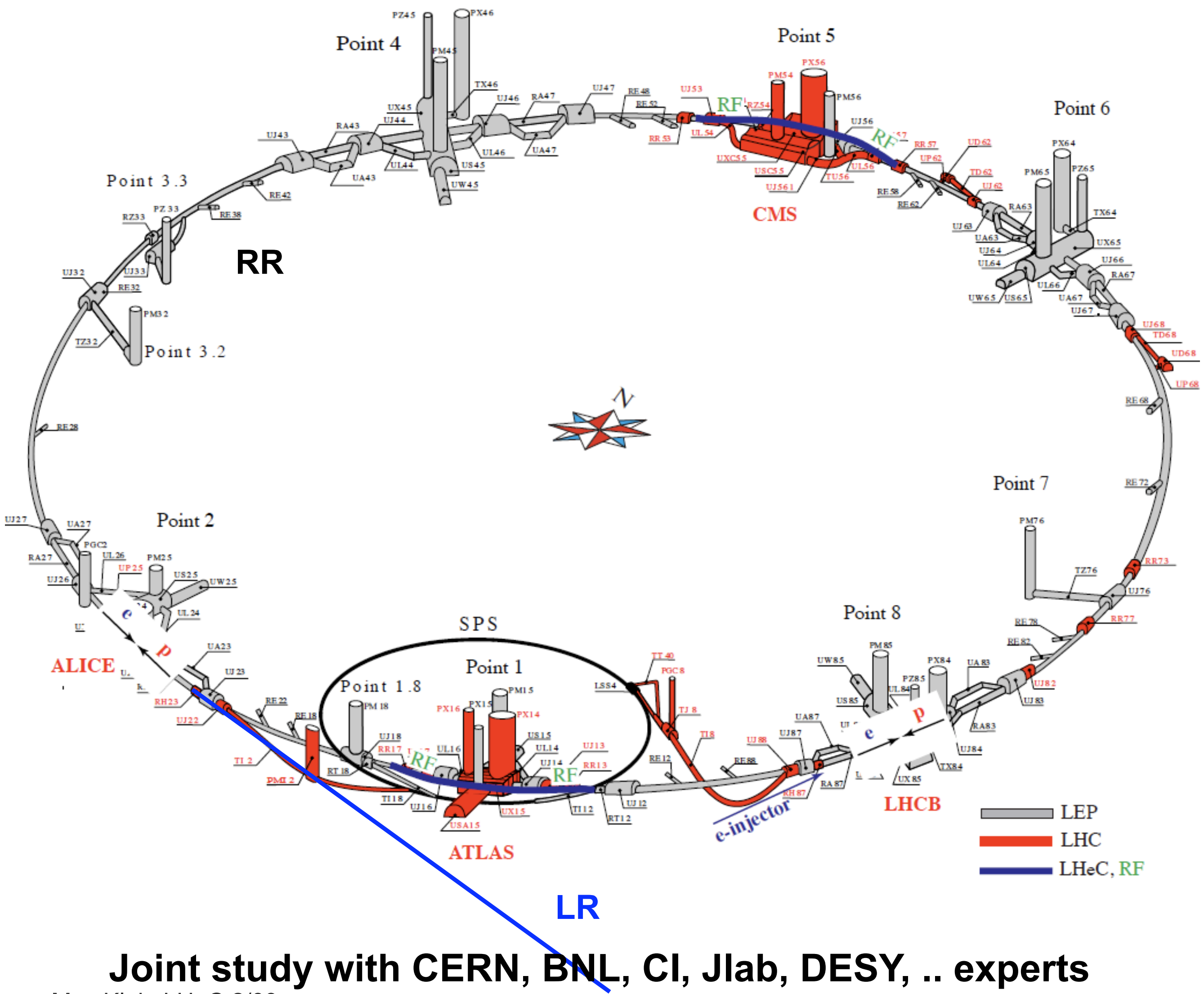
Deuterons

-Partonic Structure of Nuclei

a series of nuclei, Ca, Pb

Machine Considerations and Studies

high $E_{e,p,A}$, $e^{\pm}$ polarised, high Luminosity



Joint study with CERN, BNL, CI, Jlab, DESY, .. experts

generalities

simultaneous ep and pp

power limit set to 100MW

IR at 2 or 8

p/A:

SLHC - high intensity p (LPA/50ns or ESP/25ns)

Ions: via PS2
new source for deuterons

e Ring:

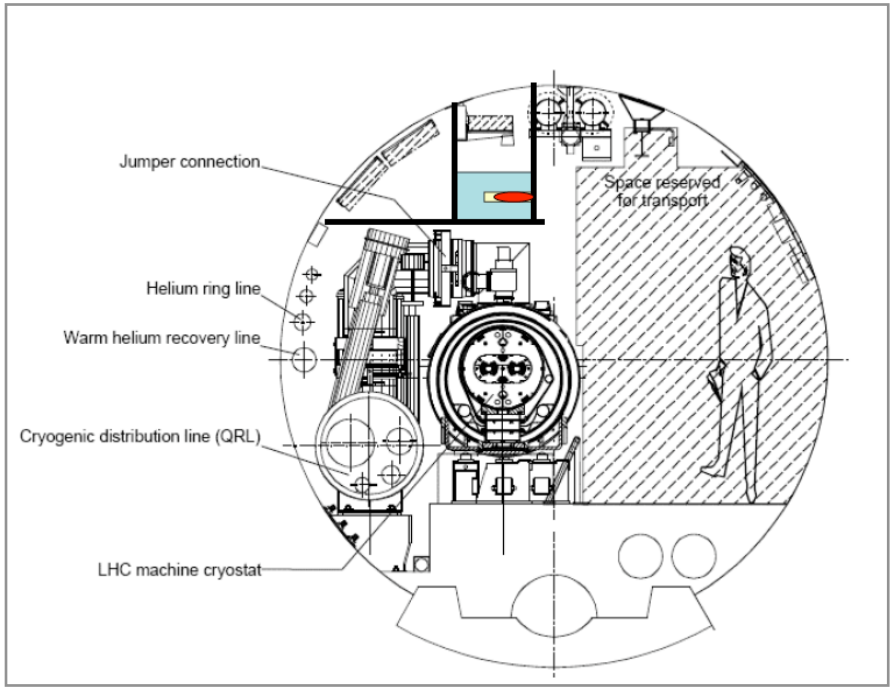
bypasses: 1 and 5
[use also for rf]

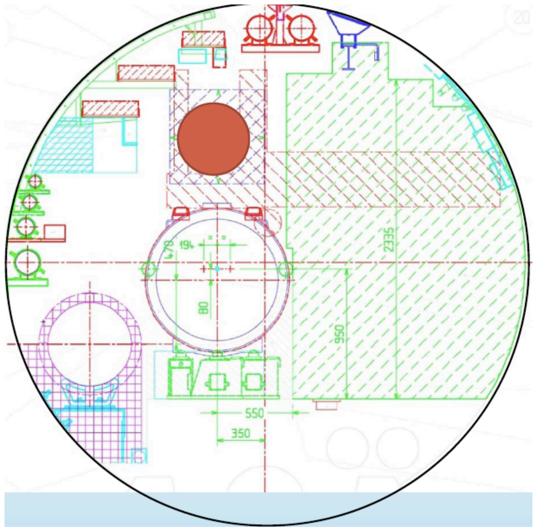
injector: SPL, or dedicated

e LINAC:

limited to ~6km (Rhone) for IP2, longer for IP8
CLIC/ILC tunnel.?

e Ring Further Considerations





Mount e on top of p - feasible at first sight
needs further, detailed study of pathway

Installation: 1-2 years during LHC shutdowns.
LEP installation was ~1 year into empty tunnel.
Radiation load of LHC pp will be studied.

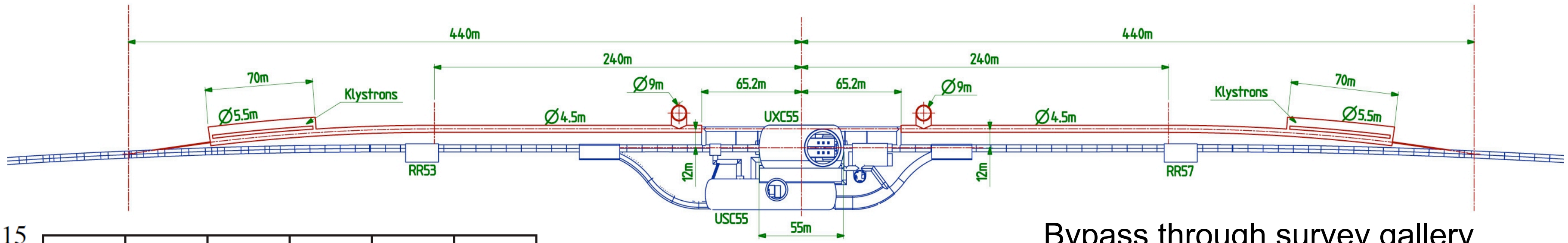
Injection:
LEP2 was 4 10^{11} e in 4 bunches
LHeC is 1.4 10^{10} in 2800 bunches
may inject at less than 20 GeV.

Power for 70 (50) GeV E_e fits into bypasses:

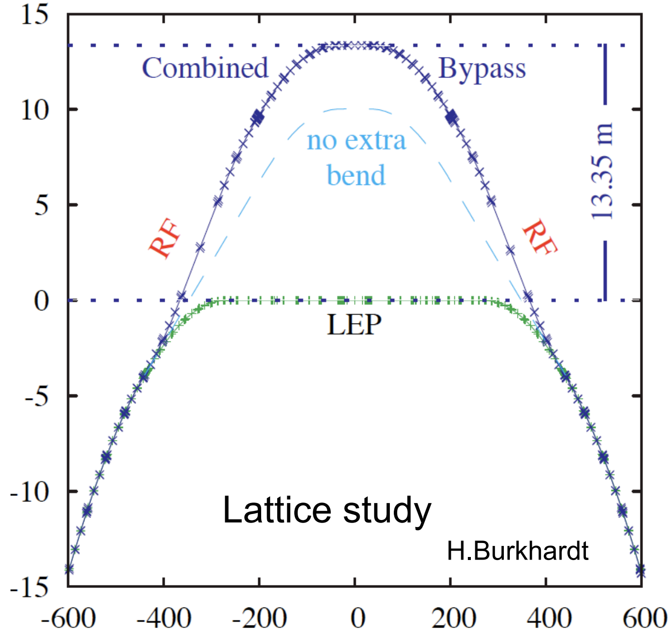
SC system at 1.9º K (1 GHz)
r.f. coupler to cavity: 500 kW CW - R+D
9 MV/cavity.
100(28) cavities for 900(250)MV
cavity: beam line of 150 (42) m
klystrons 100 (28) at 500kW
plus 90 m racks ..
gallery of 540 (150) m length required.

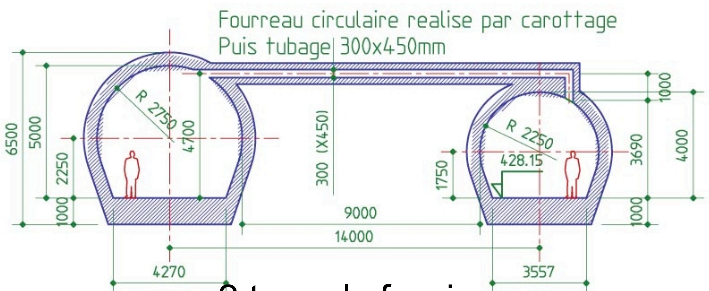
T.Linnecar

Bypass
point 5

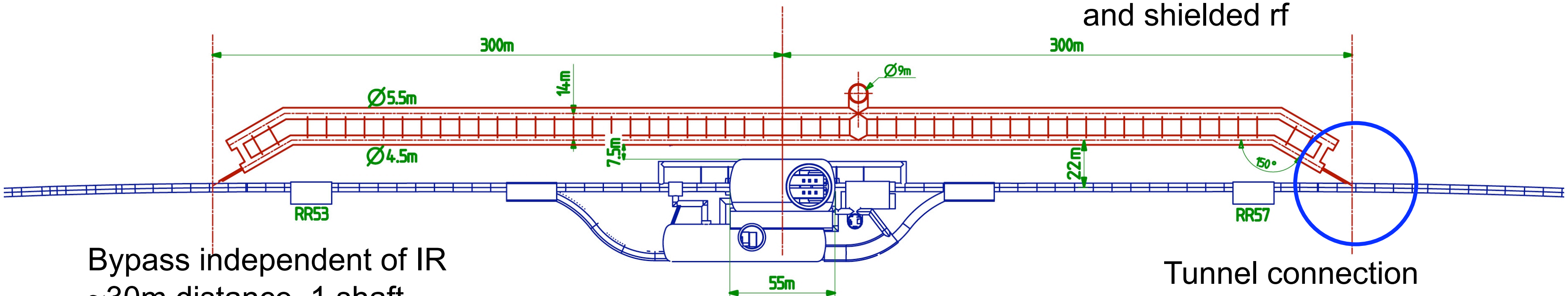


Bypass through survey gallery
13m distance, 2 shafts





2 tunnels for ring
and shielded rf

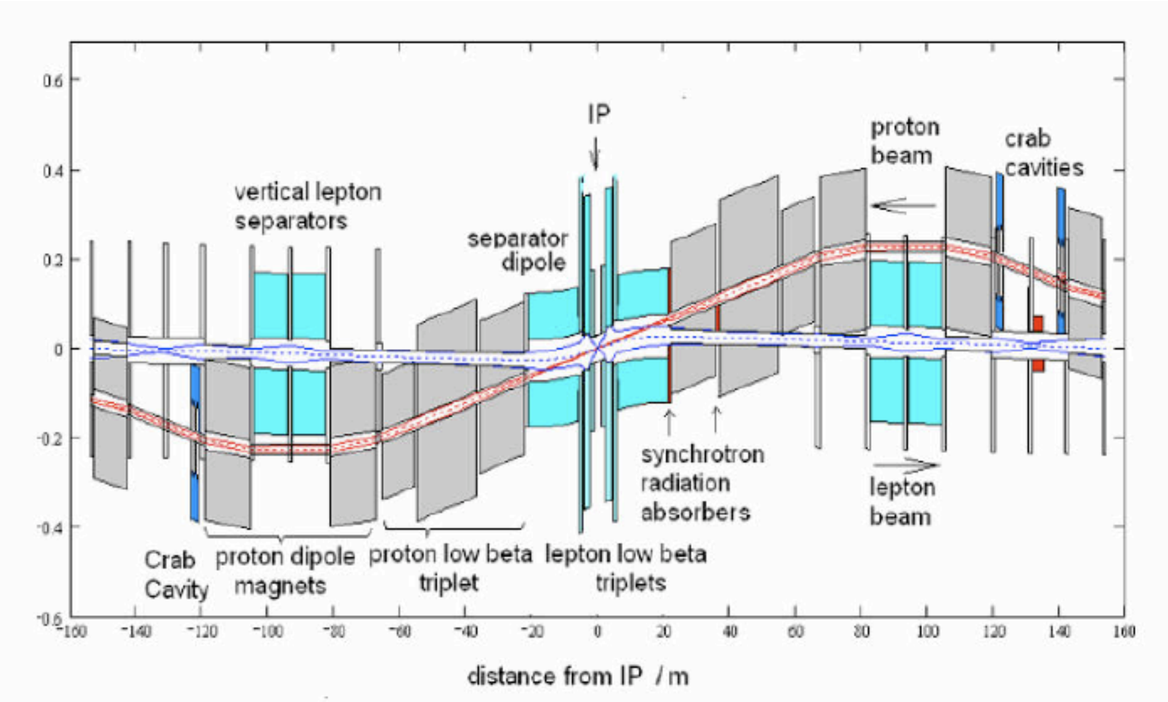


Bypass independent of IR
~30m distance, 1 shaft

Tunnel connection
(CNGS, DESY)

S.Myers, J.Osborne

Interaction Region Design



builds on F.Willeke et al, 2006 JINST 1 P10001
design for 70 GeV on 7000 GeV, 10^{33}
and simultaneous ep and pp operation

Need low x (1°) and hi L (~10°)

Separation (backscattering)

Synchrotron radiation (100 keV E_{crit})

Crab cavities (KEK)

e optics and beam line

p optics

Magnet designs for IR

S shaped IR for Linac-Ring option.

…

Input/experience from HERA, LHC, eRHIC, ..

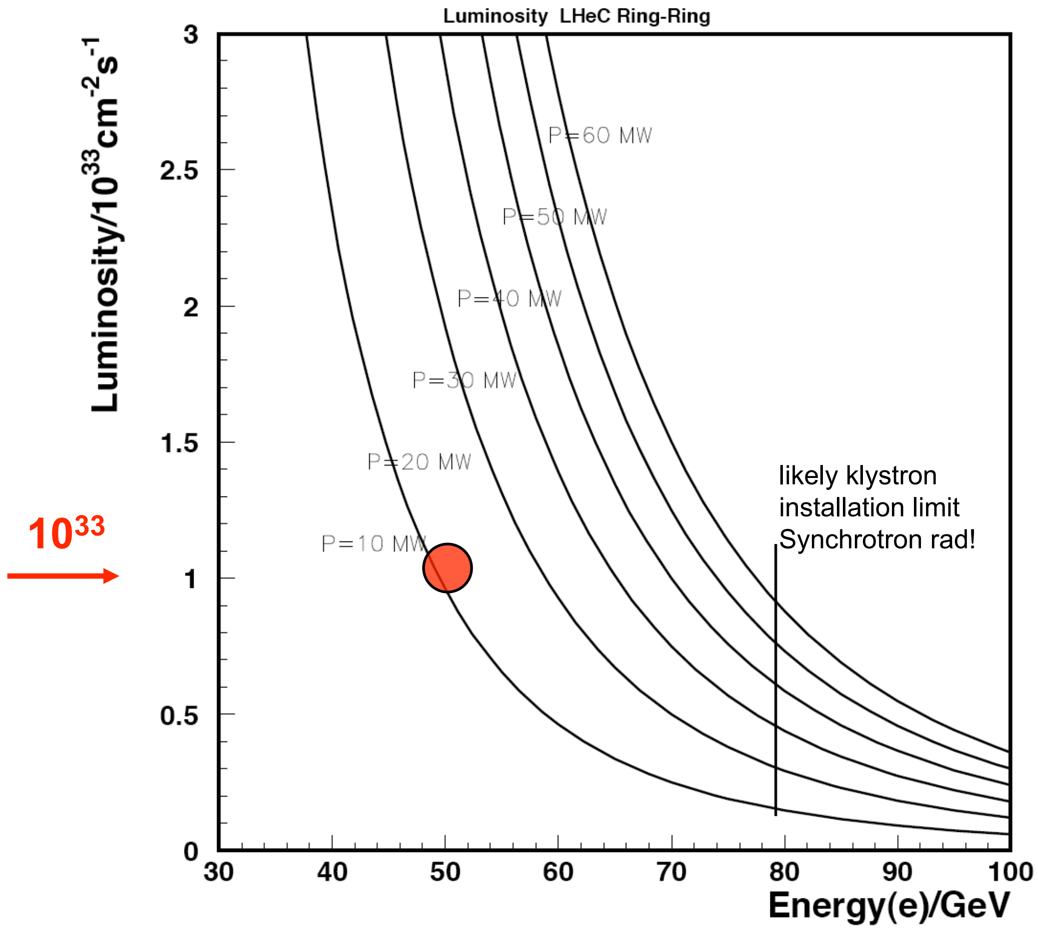
B.Holzer, A.Kling, et al

Luminosity: Ring-Ring

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}} = 8.3\,10^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

$$\varepsilon_{pn} = 3.8\mu m$$
$$N_p = 1.7 \cdot 10^{11}$$
$$\sigma_{p(x,y)} = \sigma_{e(x,y)}$$
$$\beta_{px} = 1.8m$$
$$\beta_{py} = 0.5m$$

$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$



10^{33} can be reached in RR
E_e = 40-80 GeV & P = 5-60 MW.

HERA was 1-5 10^{31} cm^{-2} s^{-1}

Gain O(100) with LHC p beam

Integrated luminosities of O(50)fb^{-1}

Ring-Ring Parameters

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$L = 8.310^{32} \cdot \frac{I_e}{50mA} \frac{m}{\sqrt{\beta_{px}\beta_{pn}}} cm^{-2}s^{-1}$$

Luminosity safely 10^{33}cm^{-2}s^{-1}
HERA was 1-5 10^{31}

Table values are for 14MW synrad loss (beam power) and 50 GeV on 7000 GeV. May have 50 MW and energies up to about 70 GeV.

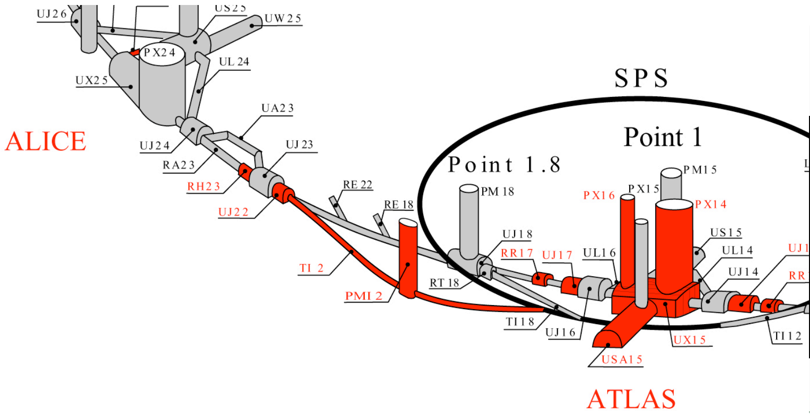
$$I_e = 0.35mA \cdot \frac{P}{MW} \cdot \left(\frac{100GeV}{E_e}\right)^4$$

LHC upgrade: N_p increased.
Need to keep e tune shift low:
by increasing β_p, decreasing β_e
but enlarging e emittance,
to keep e and p matched.

LHeC profits from LHC upgrade but not proportional to N_p

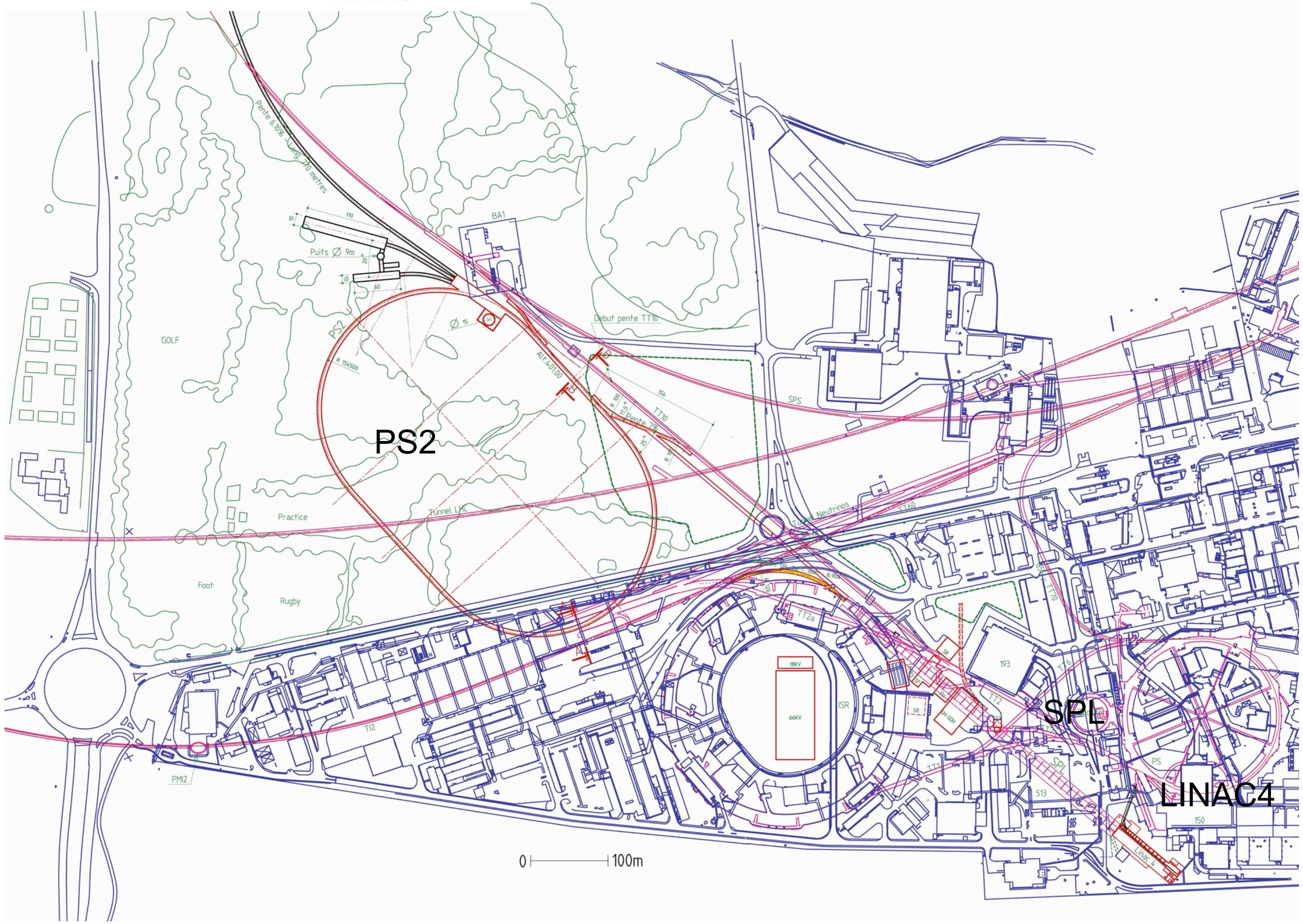
Standard Parameter	Protons	Elektrons
nb=2808	Np=1.15*10^{11}	Ne=1.4*10^{10}
	Ip=582 mA	Ie=71mA
Optics	βxp=180 cm	βxe=12.7 cm
	βyp= 50 cm	βye= 7.1 cm
	εxp=0.5 nm rad	εxe=7.6 nm rad
	εyp=0.5 nm rad	εye=3.8 nm rad
Beamsize	σx=30 µm	
	σy=15.8 µm	
Tuneshift	Δνx=0.00055	Δνx=0.0484
	Δνy=0.00029	Δνy=0.0510
Luminosity	**L=8.2*10^{32}**	
Ultimate [ESP]		
nb=2808	Np=1.7*10^{11}	Ne=1.4*10^{10}
	Ip=860mA	Ie=71mA
Optics	βxp=230 cm	βxe=12.7 cm
	βyp= 60 cm	βye= 7.1 cm
	εxp=0.5 nm rad	εxe=9 nm rad
	εyp=0.5 nm rad	εye=4 nm rad
Beamsize	σx=34 µm	
	σy=17 µm	
Tuneshift	Δνx=0.00061	Δνx=0.056
	Δνy=0.00032	Δνy=0.062
Luminosity	**L=1.03*10^{33}**	
Upgrade [LPA]		
nb=1404	Np=5*10^{11}	Ne=1.4*10^{10}
	Ip=1265mA	Ie=71mA
Optik	βxp=400 cm	βxe= 8 cm
	βyp=150 cm	βye= 5 cm
	εxp=0.5 nm rad	εxe=25 nm rad
	εyp=0.5 nm rad	εye=15 nm rad
Strahlgröße	σx=44 µm	
	σy=27 µm	
Tuneshift	Δνx=0.0011	Δνx=0.057
	Δνy=0.00069	Δνy=0.058
Luminosität	**L=1.44*10^{33}**	

B.Holzer



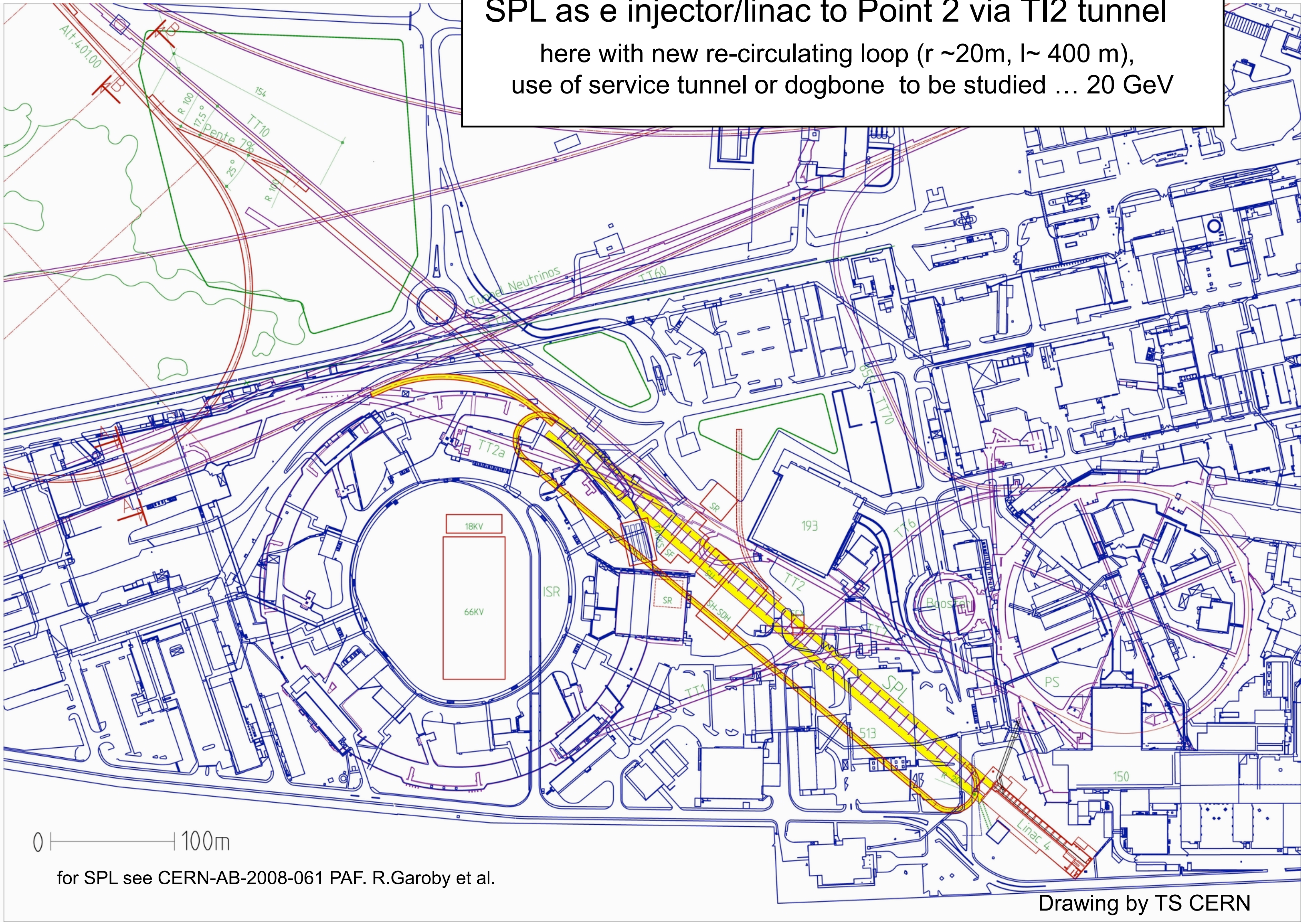
e injector from SPL to Point 2 via TI2

Alternative injectors considered too
(cf H. Burkhard, DIS08, Proceedings)



SPL as e injector/linac to Point 2 via TI2 tunnel

here with new re-circulating loop (r ~20m, l~ 400 m),
use of service tunnel or dogbone to be studied … 20 GeV



for SPL see CERN-AB-2008-061 PAF. R.Garoby et al.

Drawing by TS CERN

	Pulsed	CW	
e- energy [GeV]	30	100	100
comment	SPL* (20)+TI2	LINAC	LINAC
#passes	4+1	2	2
wall plug power RF+Cryo [MW]	100 (1 cr.)	100 (3 cr.)	100 (35 cr.)
bunch population [10^9]	10	3.0	0.1
duty factor [%]	5	5	100
average e- current [mA]	1.6	0.5	0.3
emittance $\gamma\varepsilon$ [μm]	50	50	50
RF gradient [MV/m]	25	25	13.9
total linac length β=1 [m]	350+333	3300	6000
minimum return arc radius [m]	240 (final bends)	1100	1100
beam power at IP [MW]	24	48	30
e- IP beta function [m]	0.06	0.2	0.2
ep hourglass reduction factor	0.62	0.86	0.86
disruption parameter D	56	17	17
luminosity [10^{32} cm^{-2} s^{-1}]	**2.5**	**2.2**	**1.3**

proton parameters: LPA upgrade sLHC: N_b=5x10^{11}, 50 ns spacing, $\gamma\varepsilon$=3.75 μm, β*=0.1 m, σ_z=11.8 cm

F.Zimmermann, S. Chattopadhyay

Luminosity: Linac-Ring

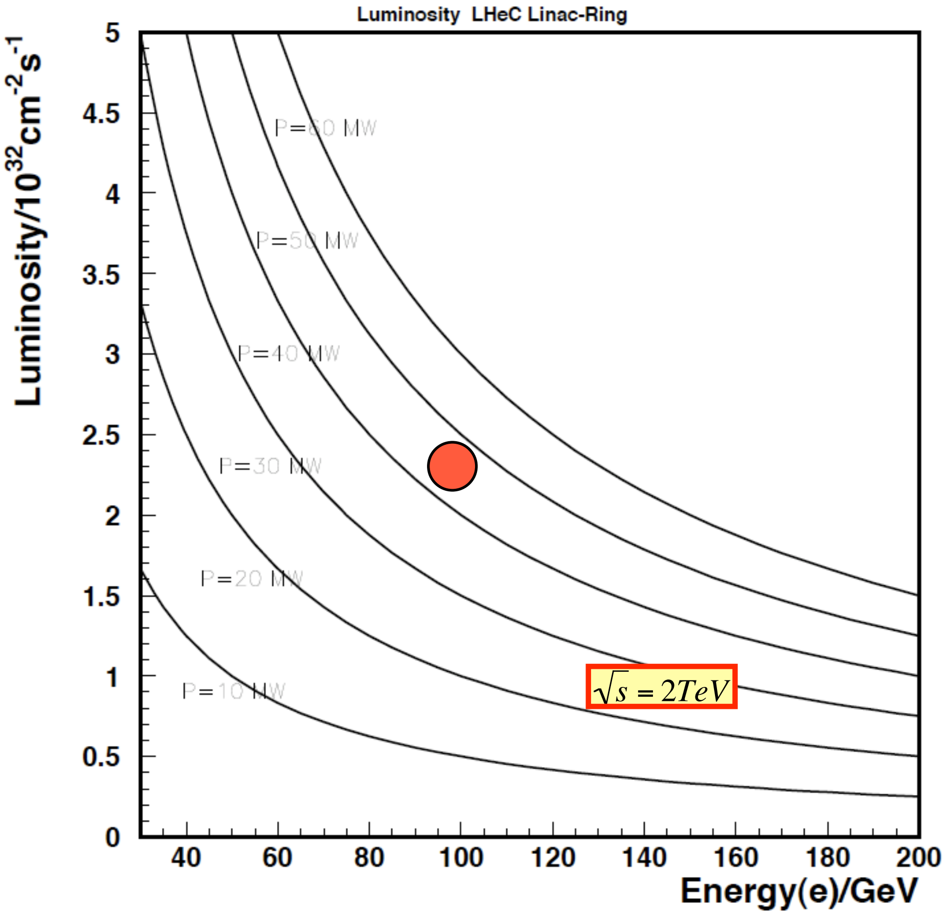
$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn} \beta^*} \cdot \frac{P}{E_e} = 5 \cdot 10^{32} \cdot \frac{P/MW}{E_e/GeV} cm^{-2} s^{-1}$$

M.Tigner, B.Wiik, F.Willeke, Acc.Conf, SanFr.(1991) 2910

SLHC - LPA

cf. R.Garoby EPS07,
J.Koutchouk et al PAC07

$\varepsilon_{pn} = 3.8 \mu m$
$N_p = 5 \cdot 10^{11}$
$\beta^* = 0.10 m$



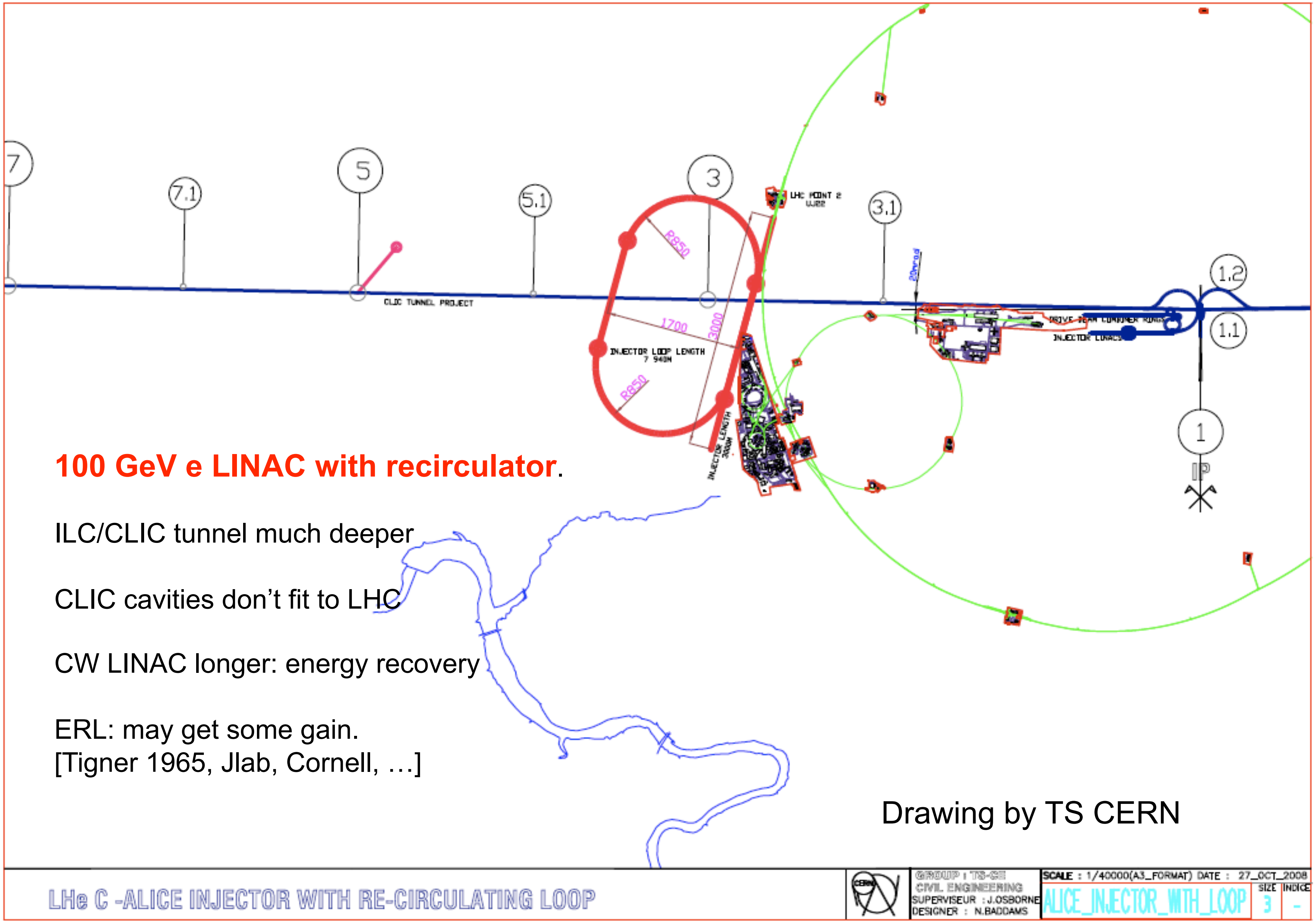
LINAC is not physics limited in energy, but by its cost/length + power

- **10^{32} are in reach at large E_e.**

LINAC - no periodic loss+refill, ~twice as efficient as ring…

Note: positron source challenge:

LHeC 10^{32} needs few times 10^{14} /sec



100 GeV e LINAC with recirculator.

ILC/CLIC tunnel much deeper

CLIC cavities don't fit to LHC

CW LINAC longer: energy recovery

ERL: may get some gain.
[Tigner 1965, Jlab, Cornell, …]

Drawing by TS CERN

Tasks on the Machine

for the CDR - incomplete

-Infrastructure (Interaction Region, SPL/TI2, LINAC site)

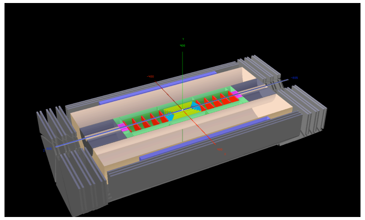
-IR for ring and for LINAC and its interface with LHC, e beam and the detector

-Optics and lattice designs (high luminosity and small angle acceptance)

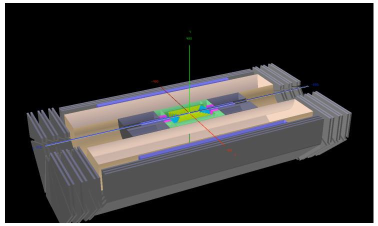
-Identification of R+D projects for LHeC (active magnets?, rf Coupler, …)

-LINAC: is ER feasible for a 100 GeV beam or is the LR limited to 10^{32} ?
what is the luminosity in e^+ ?

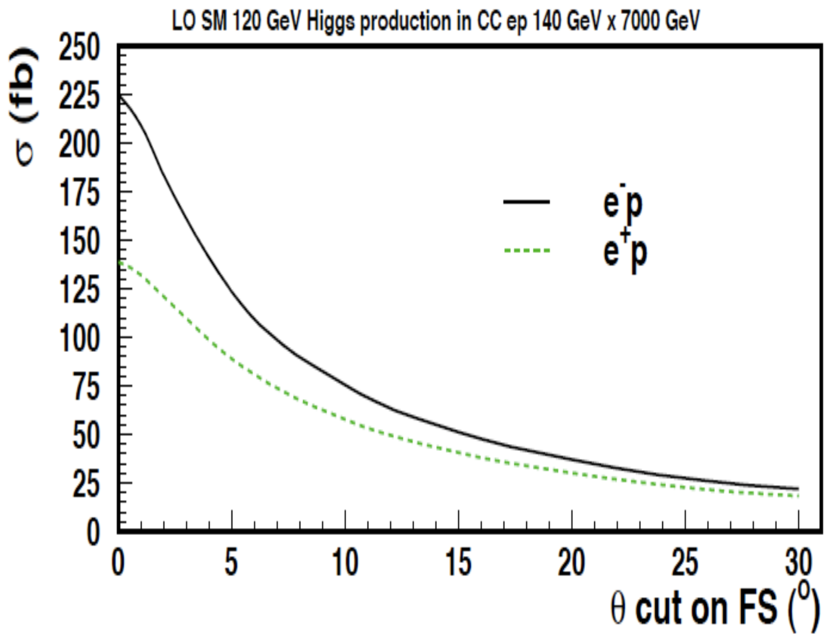
-Ring: installation: pathway and radiation
injector (SPL and its possible use for an initial eA phase)



Detector Design



Large fwd acceptance and high luminosity

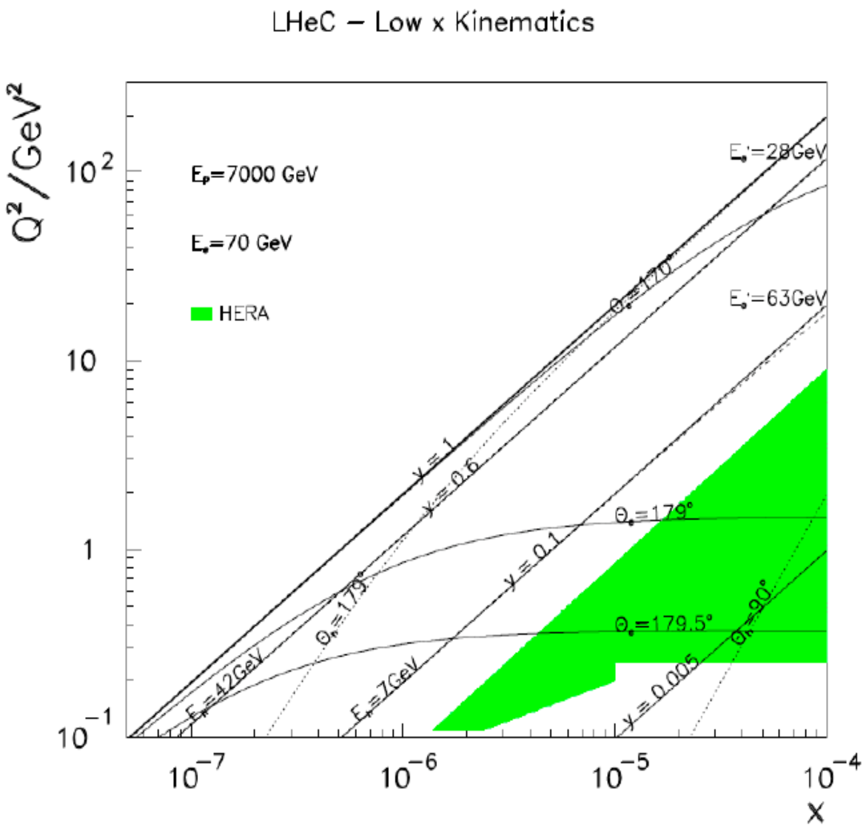


Forward tagging of p,n,d
Backward tagging of e,γ
Tagging of c and b in max. angular range
High resolution final state (Higgs to bbar)

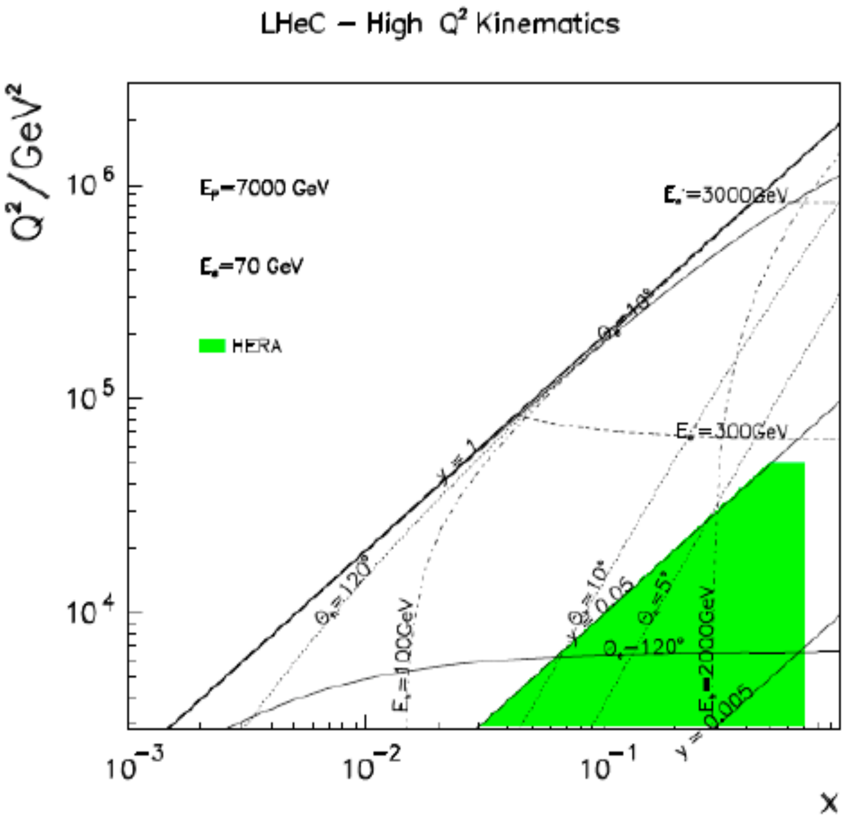
High precision tracking and calorimetry

Largest possible acceptance	
1-179°	7-177°
High resolution tracking	
0.1 mrad	0.2-1 mrad
Precision electromagnetic calorimetry	
0.1%	0.2-0.5%
Precision hadronic calorimetry	
0.5%	1%
High precision luminosity measurement	
0.5%	1%
LHeC	HERA

LHeC – HERA - Kinematics



Low x,Q^2 requires small angle acceptance for both e and hadronic final state.



Large x requires small angle acceptance for hadronic final state. TeV energies in forward p direction

L1 Detector: version for low x Physics

Muon chambers
(fwd,bwd,central)

Coil (r=3m l=8.5m, 2T)
[Return Fe not drawn,
2 coils w/o return Fe studied]

Central Detector

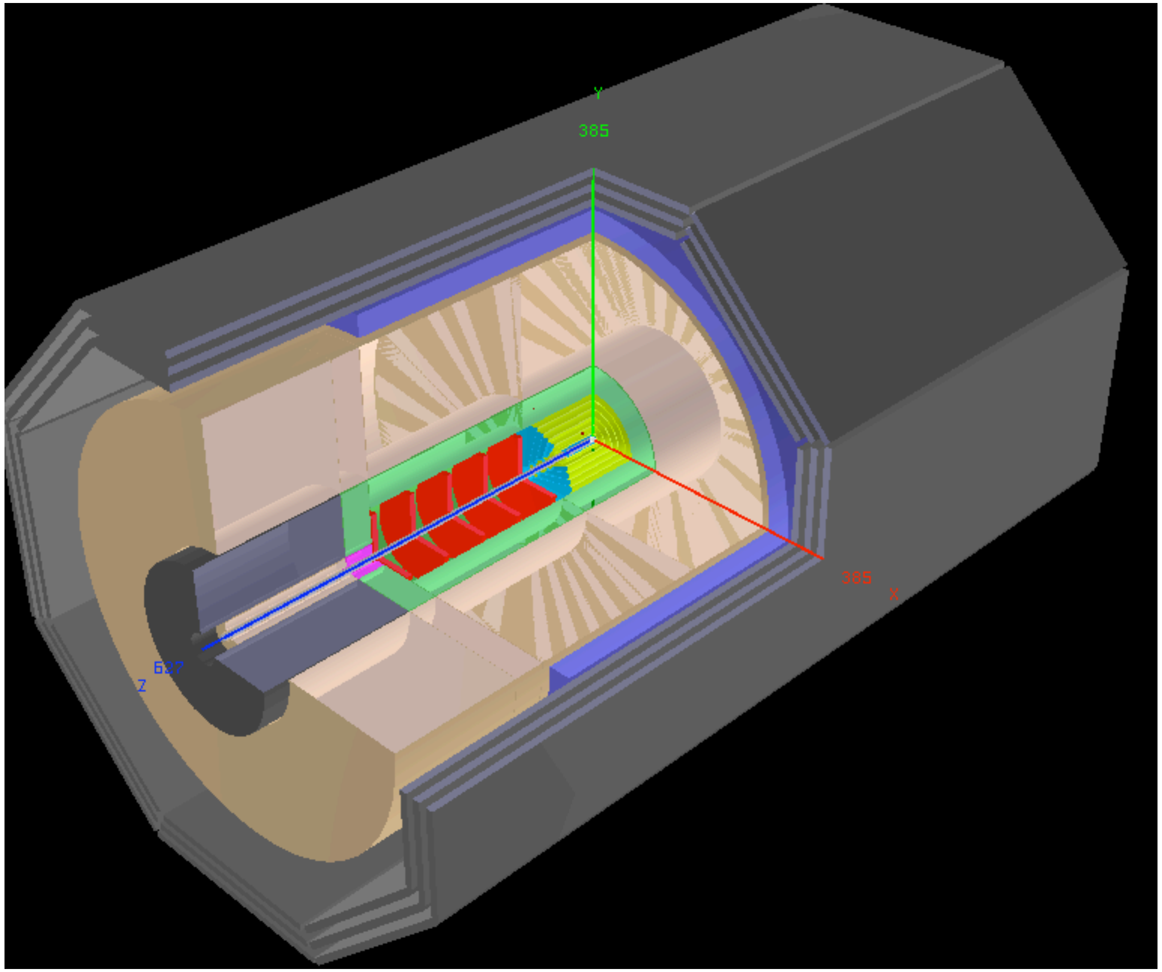
Hadronic Calo (Fe/LAr)
El.magn. Calo (Pb,Sc)
GOSSIP (fwd+central)
[Gas on Slimmed Si Pixels]
[0.6m radius for 0.05% * pt in 2T field]
Pixels
Elliptic beam pipe (~3cm)

Fwd Spectrometer
(down to 1°)

Tracker
Calice (W/Si)
FwdHadrCalo

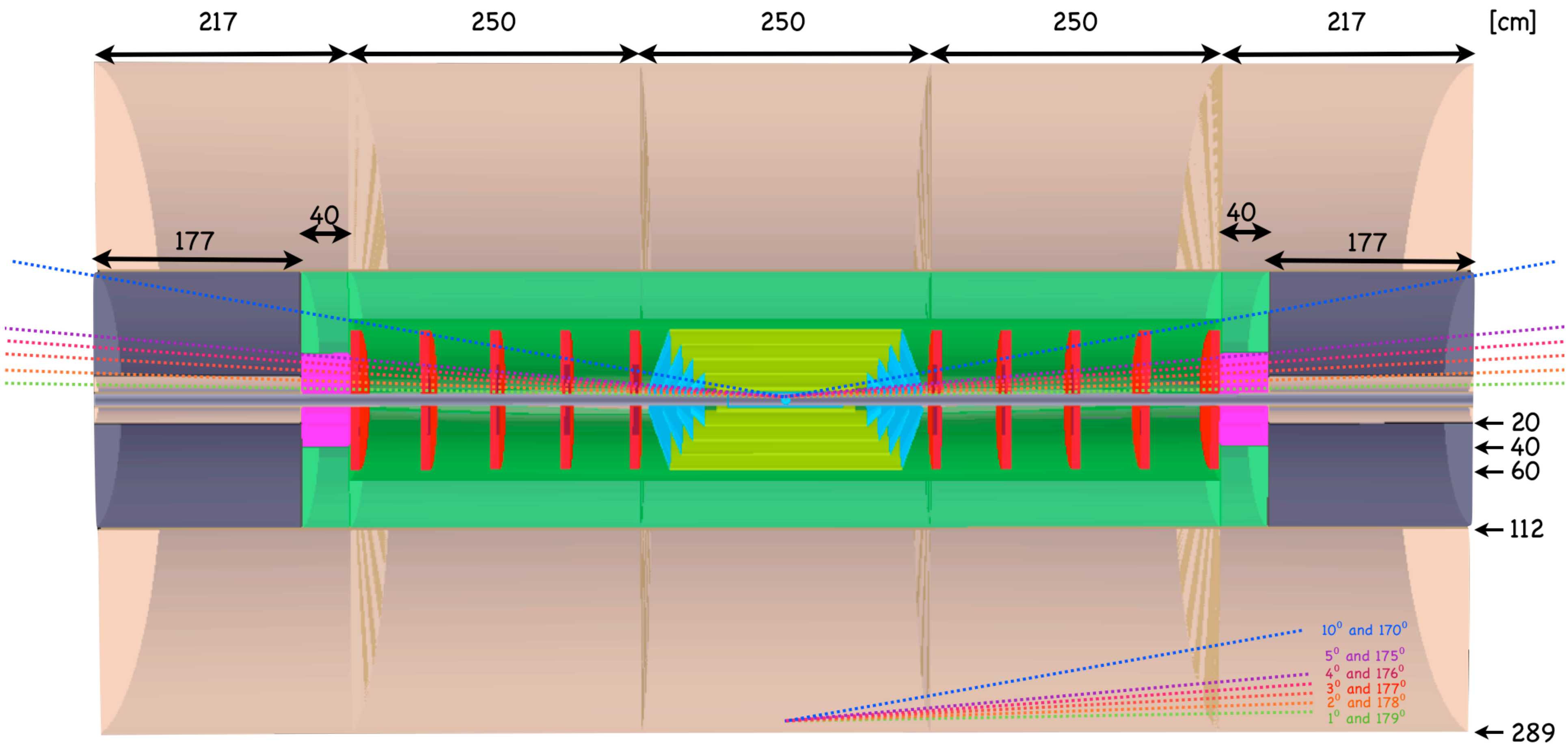
Bwd Spectrometer
(down to 179°)

Tracker
Spacal (elm, hadr)



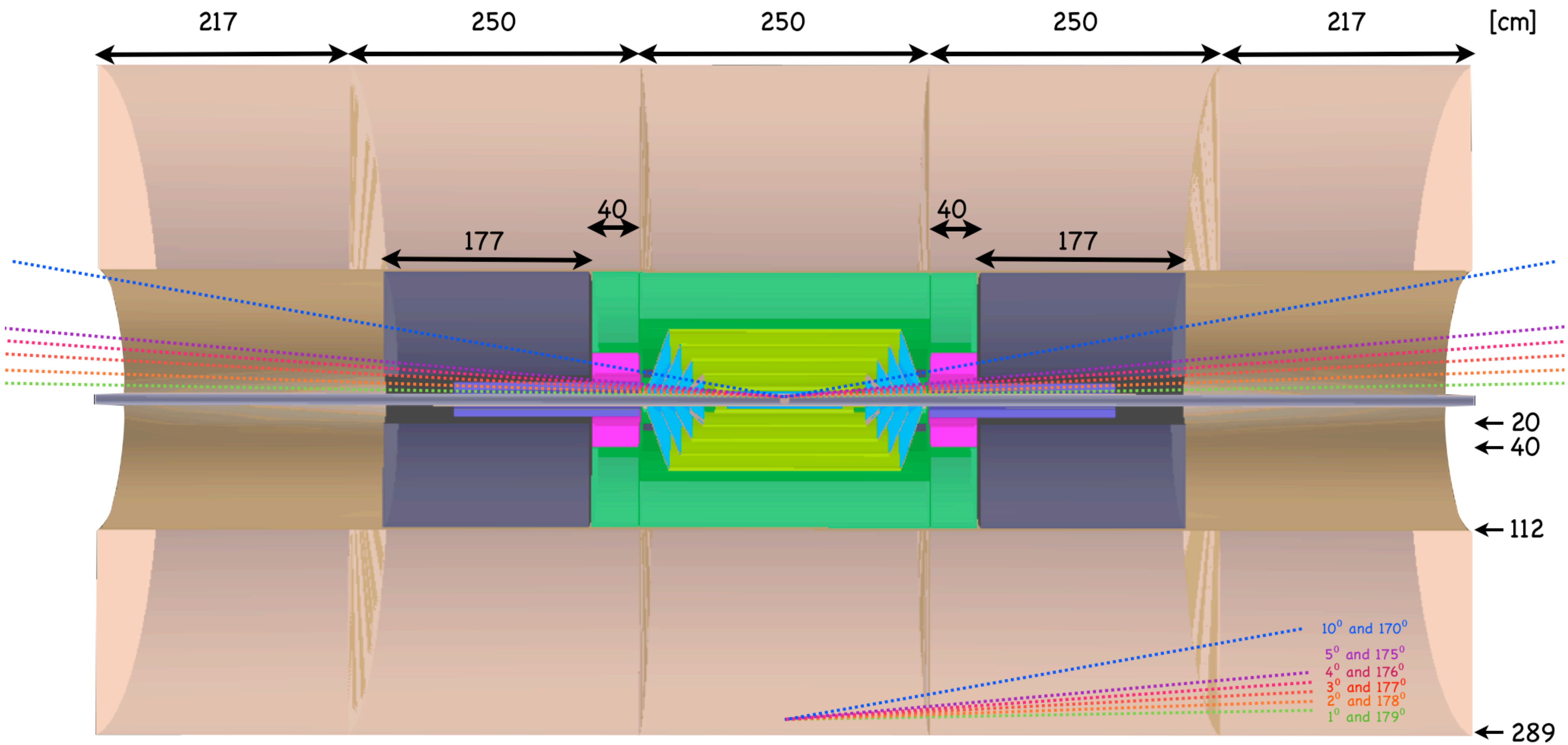
To be extended further in fwd direction. Tag p,n,d. Also e,γ (bwd)

Low x Detector – rz view



Max Klein LHeC 2/09

High Q^2 Detector – rz view



Max Klein LHeC 2/09

L1 Detector: version for hiQ^2 Physics

Muon chambers
(fwd,bwd,central)

Coil (r=3m l=8.5m, 2T)

Central Detector

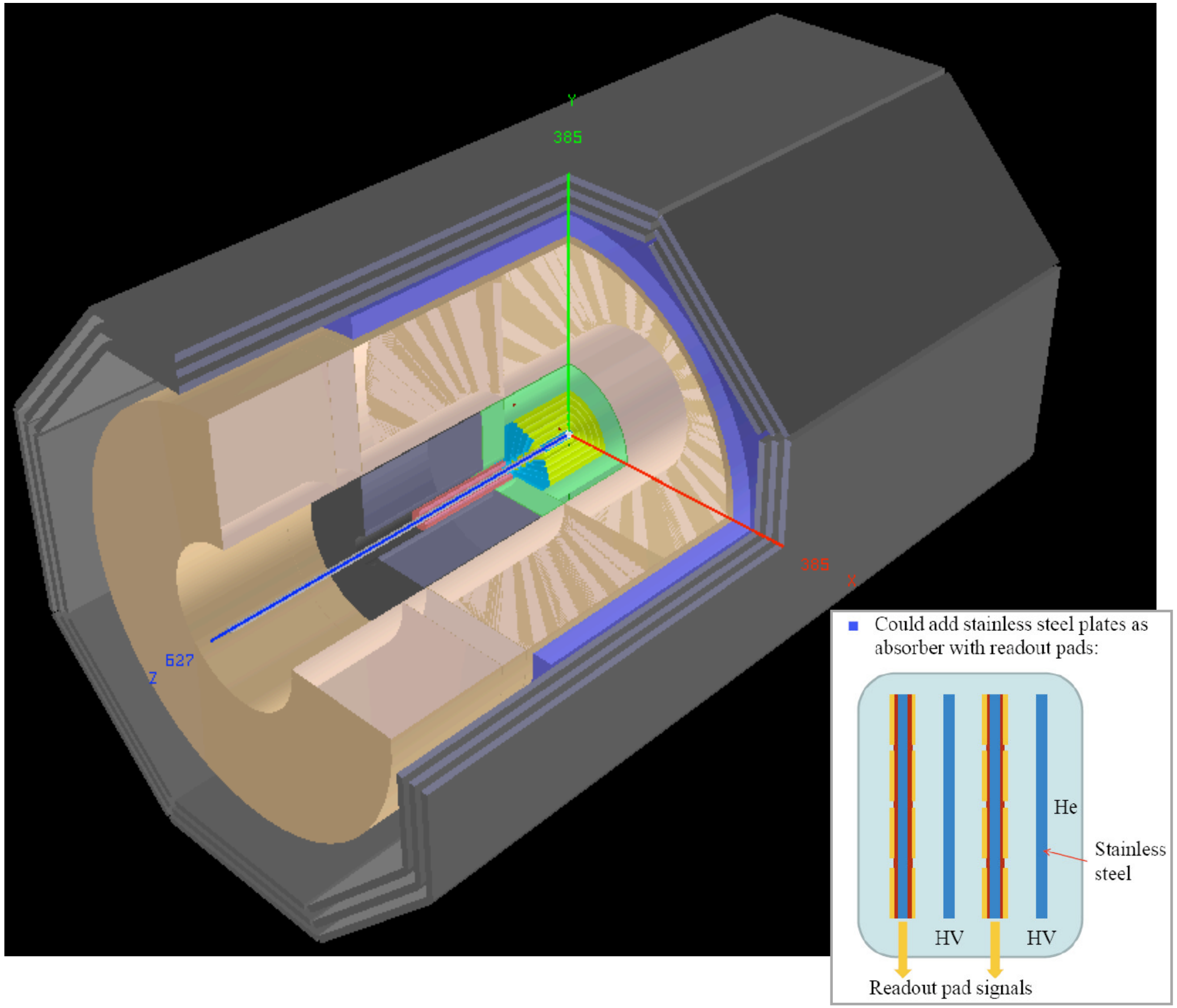
Hadronic Calo (Fe/LAr)
El.magn. Calo (Pb,Sc)
GOSSIP (fwd+central)
Pixels
Elliptic pipe (~3cm)

Fwd Calorimeter
(down to 10^o)

Lepton low β magnets
FwdHadrCalo

Bwd Spectrometer
(down to 170^o)

Lepton low β magnets
Spacal (elm, hadr)



Active magnets?
T.Greenshaw et al.

The LHeC is a PeV equivalent fixed target ep scattering experiment.

At ~50 000 times higher Q^2 than the SLAC MIT experiment it needs an only few times longer LINAC (or a ring).

Its physics potential is extremely rich. Both a LINAC and a ring look feasible.

The CDR is at midterm:

ECFA 11/07

NuPECC 9/08

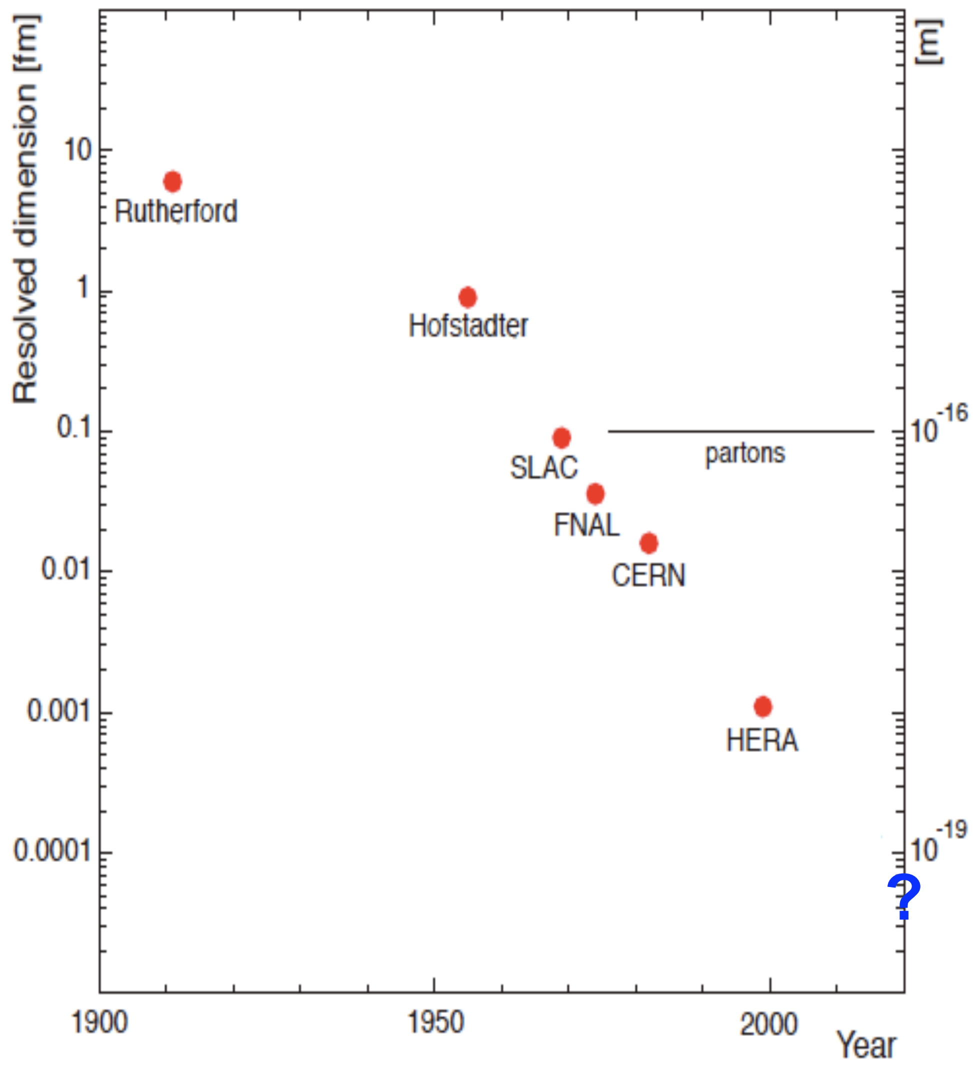
ICFA 10/08

ECFA 11/08

Final report to ECFA: 11/09.

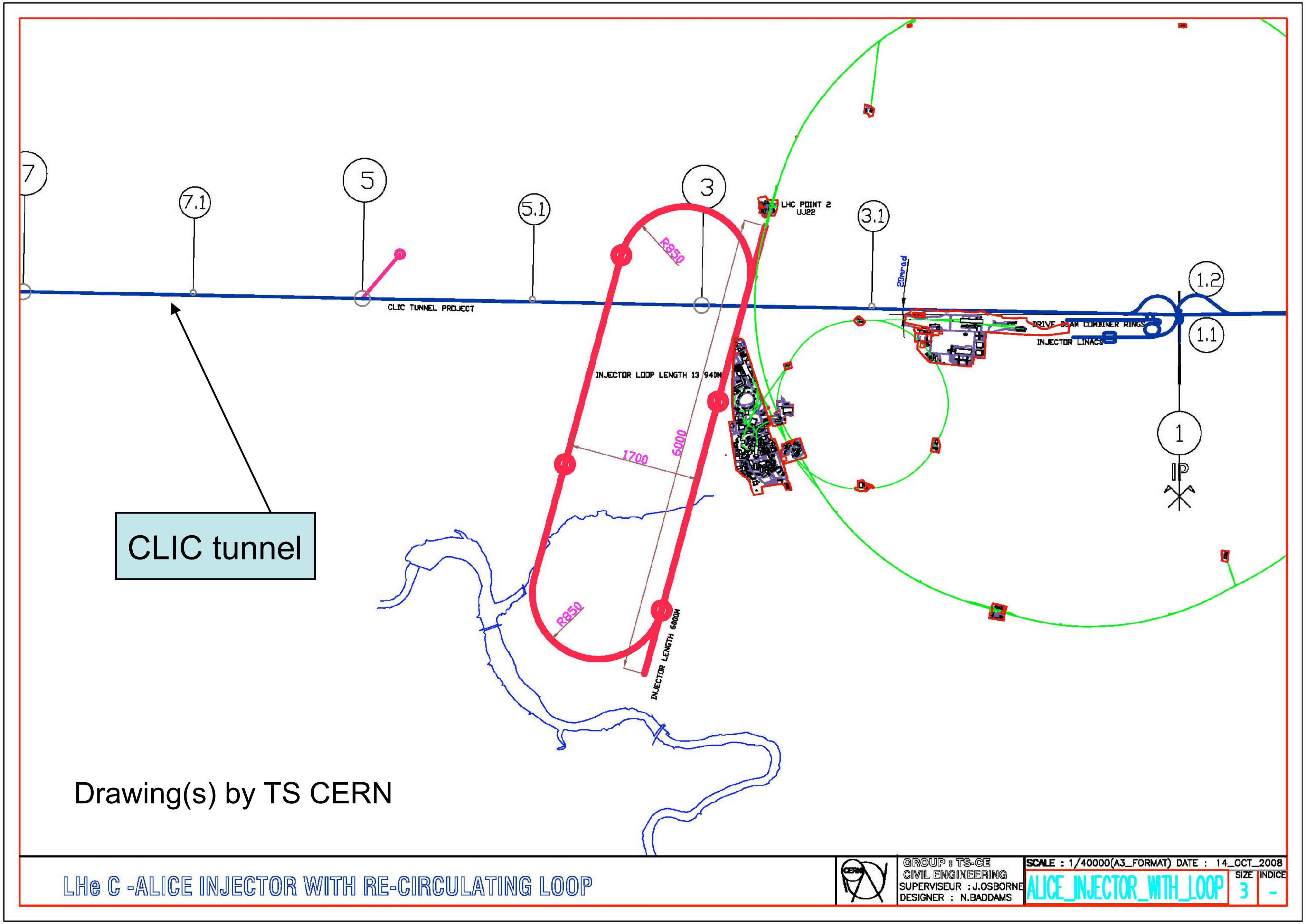
Written CDR 5/10

The CDR is a contribution to the discussion on the future of HEP which awaits LHC data. The LHeC may be built, with your support.



http://www.lhec.org.uk

Backup slides



7
7.1
5
5.1
3
3.1
1.2
1.1
1
IP
LHC POINT 2
UJ22
R850
R850
CLIC TUNNEL PROJECT
20mrad
DRIVE BEAM COMBINER RINGS
INJECTOR LINACS
INJECTOR LOOP LENGTH 13 940M
6000
1700
INJECTOR LENGTH 6000M
CLIC tunnel
Drawing(s) by TS CERN
LHe C -ALICE INJECTOR WITH RE-CIRCULATING LOOP
CERN
GROUP : TS-CE
CIVIL ENGINEERING
SUPERVISEUR : J.OSBORNE
DESIGNER : N.BADDAMS
SCALE : 1/40000(A3_FORMAT) DATE : 14_OCT_2008
ALICE_INJECTOR_WITH_LOOP
SIZE
3
INDICE
-

HERA - 'an unfinished business'

Low x: DGLAP holds though ln1/x is large
Saturation not proven

High x: would have required much higher luminosity
[u/d ?, xg ?]

Neutron structure not explored

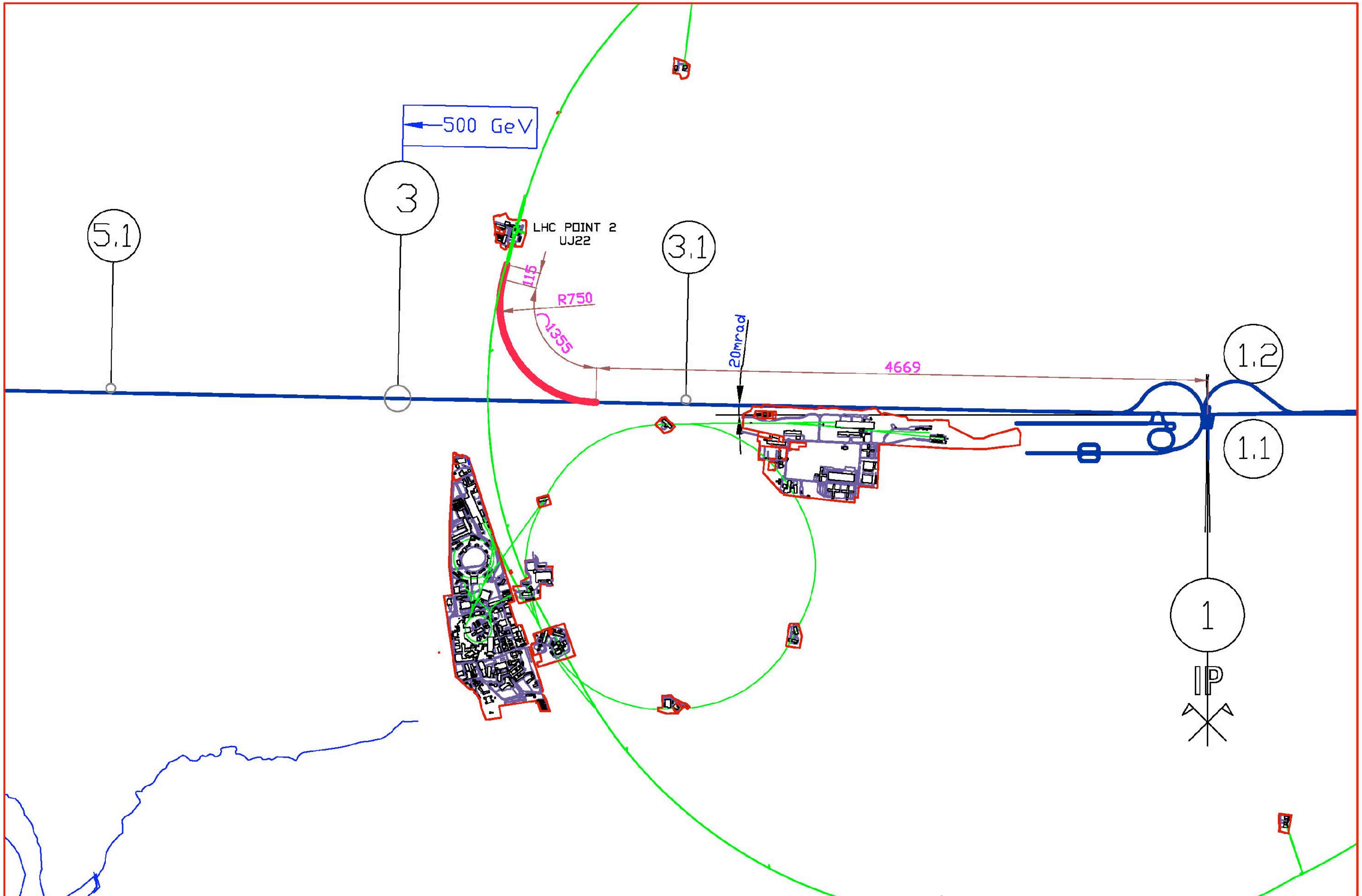
Nuclear structure not explored

New concepts introduced, investigation just started:
-parton amplitudes (GPD's, proton hologram)
-diffractive partons
-unintegrated partons

Instantons not observed

Odderons not found
…

Lepton-quark states not observed



LHe C -ALICE INJECTOR FROM CLIC 500 GeV PHASE

GROUP : TS-CE
CIVIL ENGINEERING
SUPERVISEUR : J.OSBORNE
DESIGNER : N.BADDAMS

SCALE : 1/20000(A3_FORMAT) DATE : 14_OCT_2008

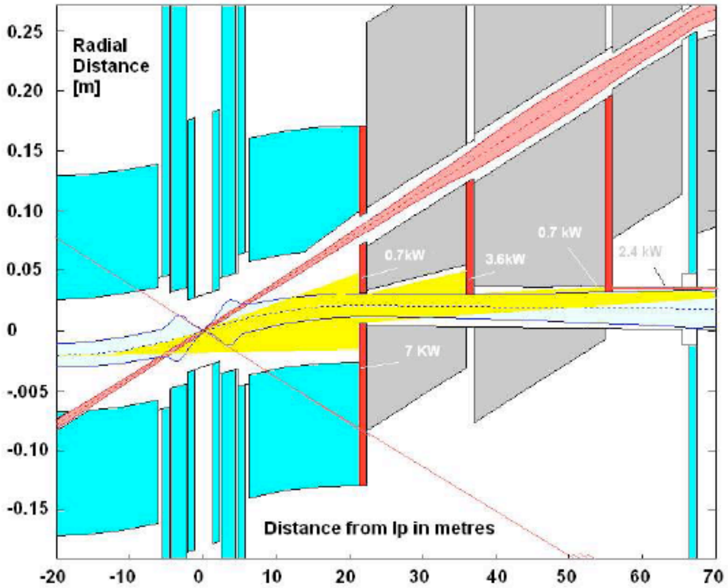
ALICE_INJECTOR_FROM_CLIC_500_GEV

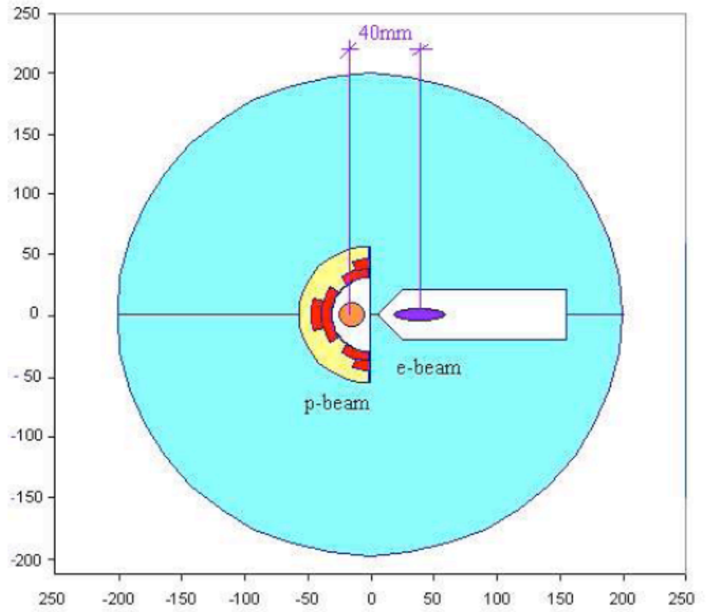
SIZE 3

INDICE -

LHeC
View from UPS54 Survey Gallery into CMS Cavern on Walkways

Design Details





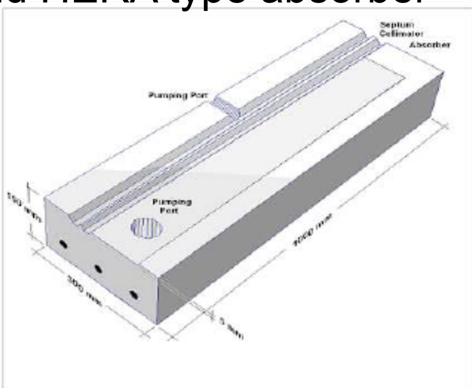
Synchrotron radiation fan

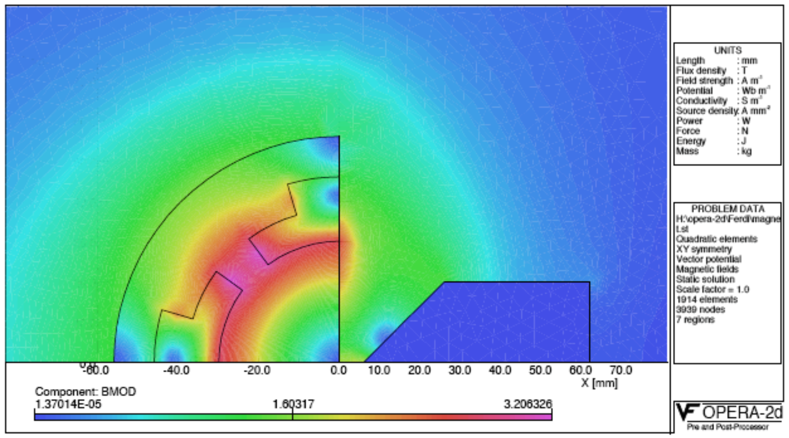
and HERA type absorber

$9.1kW$

$E_{crit} = 76keV$

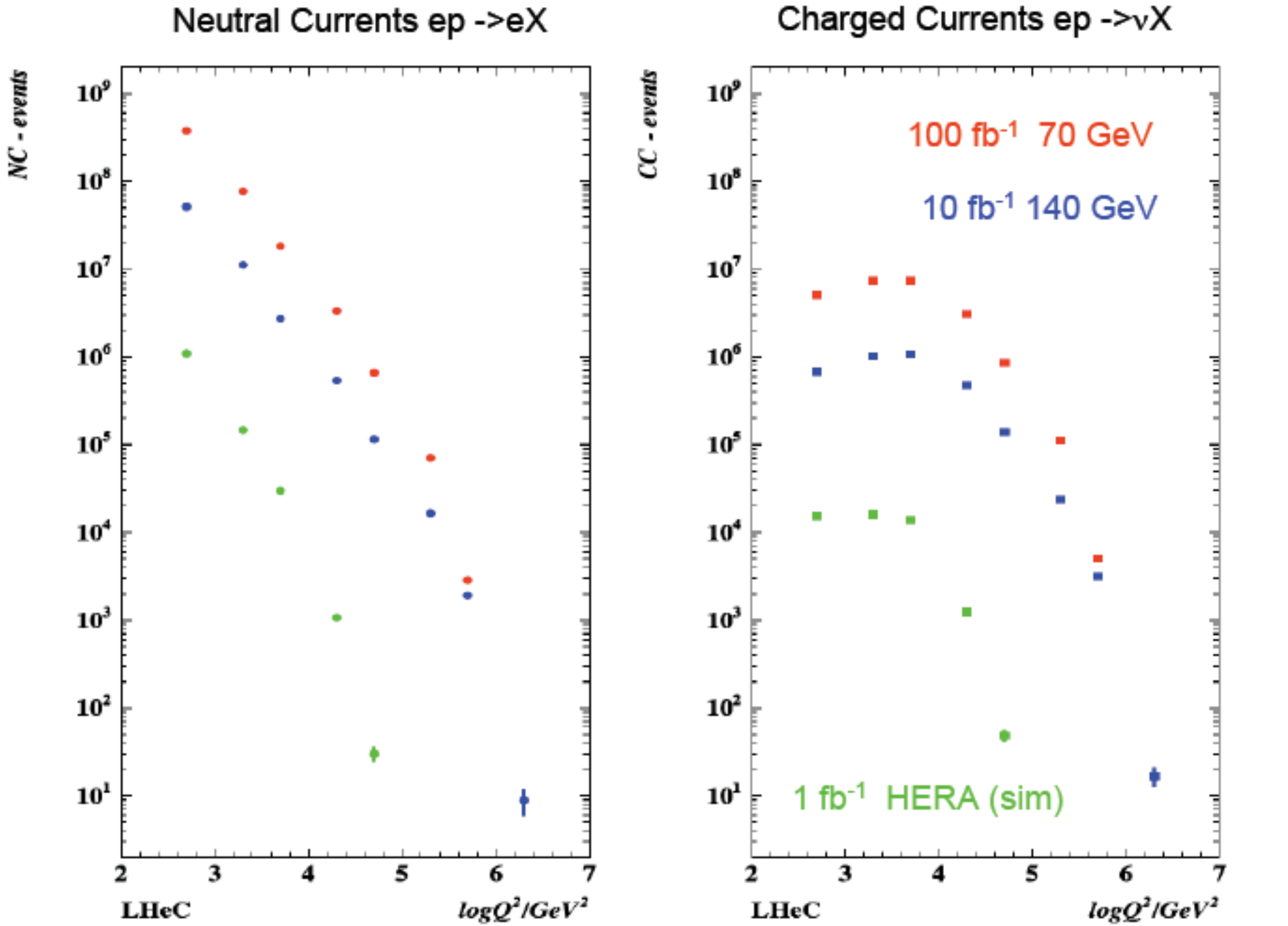
First p beam lens: septum quadrupole.
Cross section and Field calculation





$100W/mm^2$

cf also W.Bartel
Aachen 1990



Neutral Currents ep ->eX
NC - events
LHeC
logQ²/GeV²
Charged Currents ep ->νX
CC - events
100 fb⁻¹ 70 GeV
10 fb⁻¹ 140 GeV
1 fb⁻¹ HERA (sim)
LHeC
logQ²/GeV²