Detector Design for the LHeC - Some Essentials

P. Kostka, A. Polini, R. Wallny

- Accelerator ⇔ Detector Design; Beam-Pipe ⇔ Acceptance
  see talks [290] Design Status of the Large Hadron-Electron Collider by John JOWETT (CERN)
  [297] Luminosity Measurement at the LHeC by Sergey LEVONIAN (DESY)

- Requirements - Physics Motivated
  Physics Issues discussed in session contributions [305], [306], [312], [333], [44] ….

- Detector Layout

- Instrumentation Issues

Detector Design - The Driving Challenges

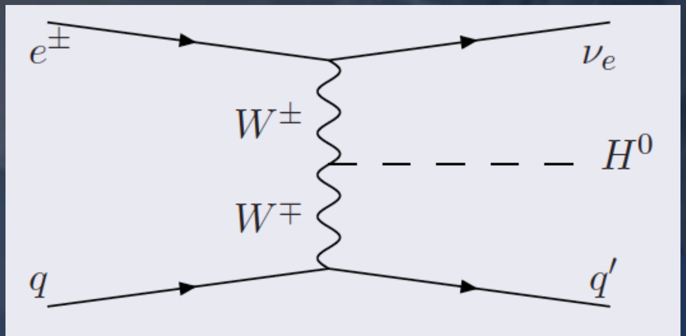
- The continuation of the already successful H1/ZEUS enterprises to study the inclusive DIS of highest possible precision in a extremely extended acceptance region (1^0-179^0). We aim for 2 times better energy and angle calibration and alignment accuracies with respect to H1.

- This new acceptance window and the envisaged precision allows the access to Higgs production and physics beyond the SM.

  One of the benchmark processes*:

  Vector Boson Fusion @ LHC CC $H^0 \Rightarrow b\bar{b}$

  where (one possible) BG process CC $\bar{t} \Rightarrow \bar{b}W \Rightarrow \bar{b}\bar{c}s$



will challenge the detector design -

requiring: large forward acceptance,

best resolution for hadrons produced,

good E_T recognition and

b tagging with maximal acceptance

* [44] Searching for a light Higgs in electron-hadron collisions at the TeV scale, Uta KLEIN (Liverpool)

Consequences for the Design

- Electron
  - final state: high resolution for final states
  - DIS: precision calibration employing over-constrained kinematics
    10%/ √E calibrated using the kinematic peak
  - acceptance: large angle acceptance to measure at low $Q^2 \geq 1$ GeV^2

- Hadrons
  - jets: few TeV in forward direction
  - DIS: precision calibration of E_h (p_{th} / p_{te} balance at low y)
    30%/√E (or better) calibrated with p_{th} /p_{te} to 1% accuracy
  - acceptance: measure hadronic energy down to few degrees

- Heavy Flavour Physics
  - efficient c and b tagging towards maximum η (large θ)
- Diffractive Processes and eD
  - forward tagging of p, n, d

- accurate luminosity measurement* and efficient e/γ tagging in backward direction

* [297] Luminosity Measurement at the LHeC by Sergey LEVONIAN (DESY)

Caveats

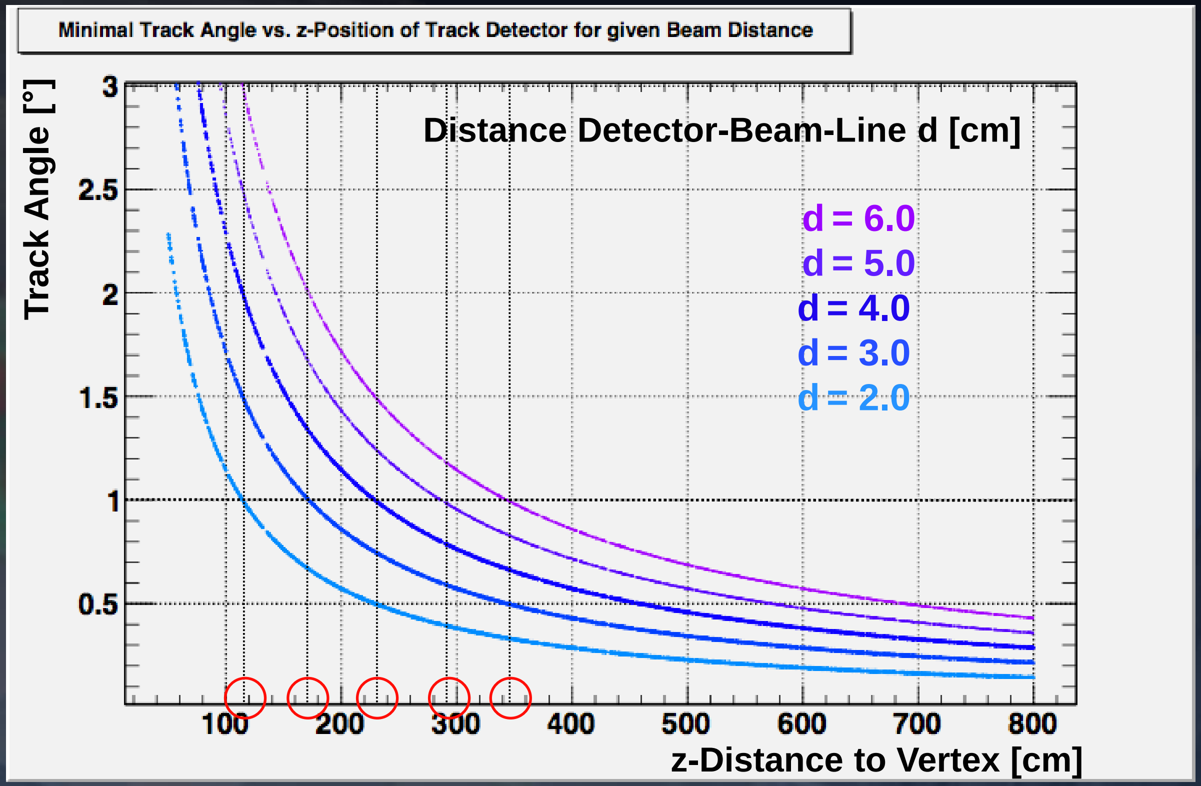
- Much/most of the design work and interfacing with physics requirements still to be done!

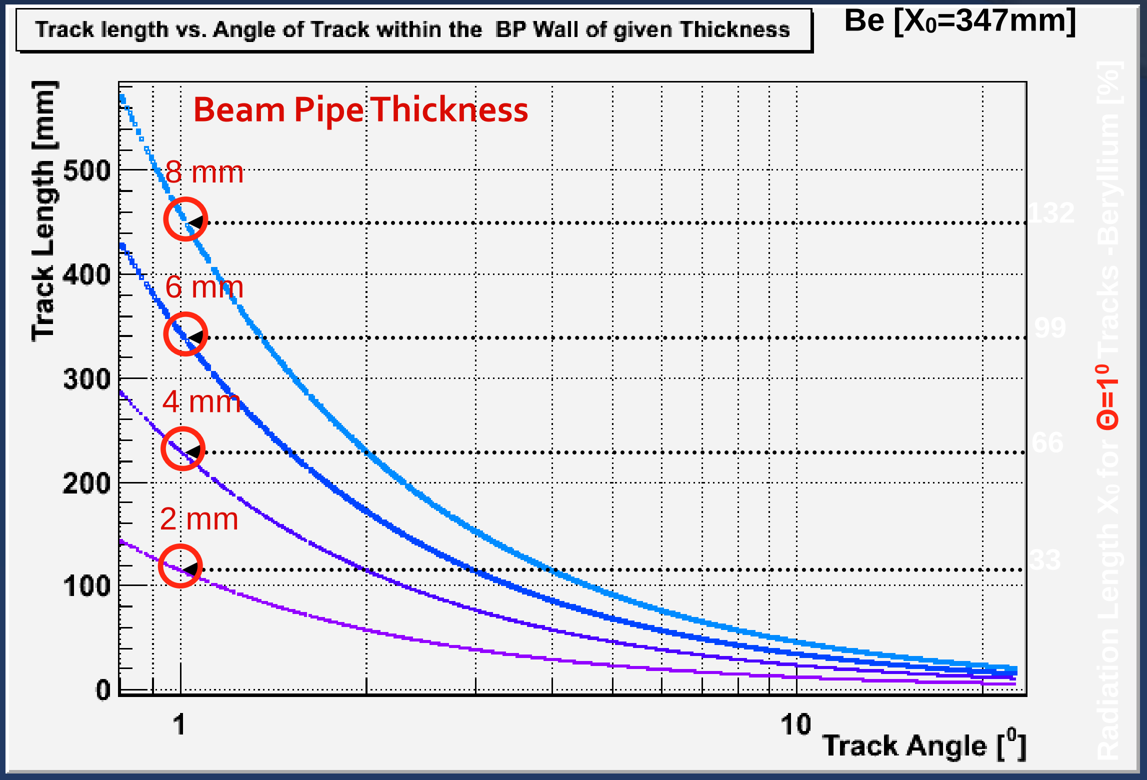
- We aim for a design concept for the CDR, not the proposal or technical design report yet!

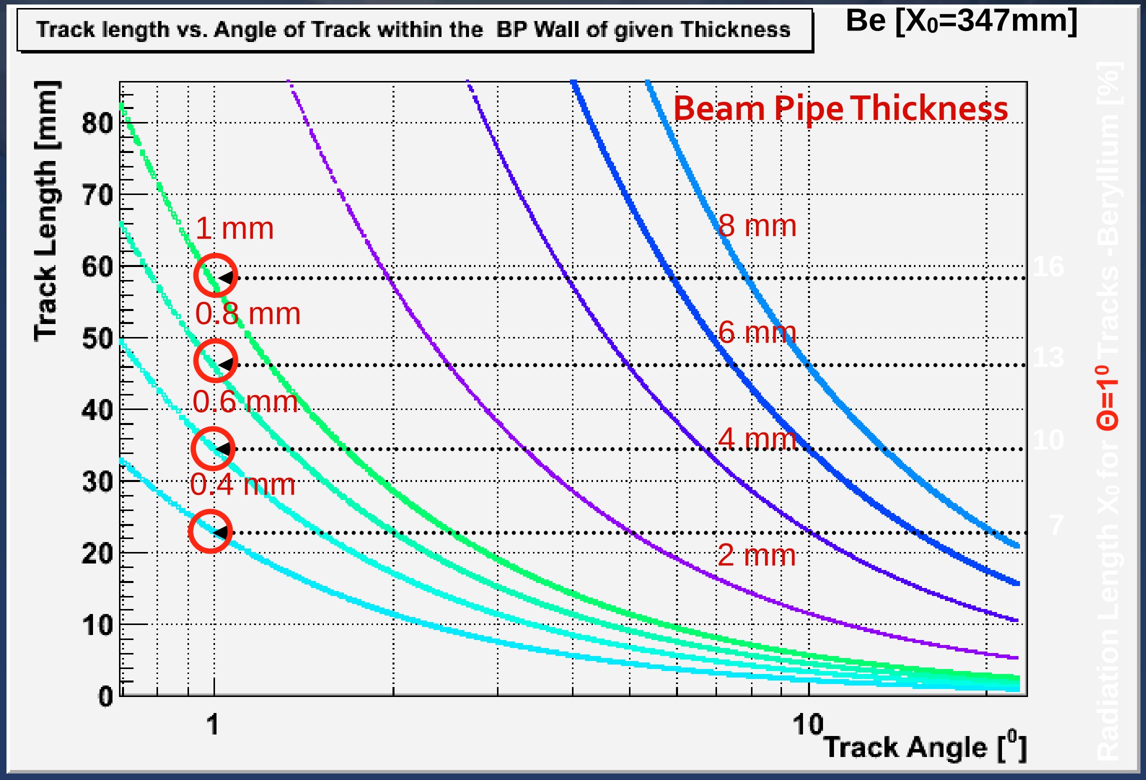
- Regular ongoing series of LHeC design meetings
  http://indico.cern.ch/categoryDisplay.py?categId=1874
  - I'll cite documents you'll find there

Accelerator ➡ Detector Design

- Beam Pipe Design drives the design:
  - Elliptical: Synchrotron Radiation has to pass leaving the detector untouched (direct and backscattered SR); No φ symmetry.
  - Length of detector - related at fixed angular acceptance to to beam pipe radii - see figure ➡ The dimensions of the BP defines the z-extension of the detector.
  - Multiple Scattering: BP as thin as possible! (see below)
  - SR collimators/absorbers incorporated;
  - 1^0 polar angle traversing tracks - radiation length optimisation







Beam Pipe - A Challenge

- Is it possible to build a long beam pipe as thin as necessary?

- BP sandwich structure:
  Metal - Carrier - Metal
  minimal thickness↑ and excellent radiation length↑
  but: little experiences⤵
  e.g. Be/Al - Nomex/Carbon foam - Be/Al *

* NIM 228 (1984) 207-209, A SANDWICH STRUCTURE BEAM PIPE FOR STORAGE RINGS, G.B. BOWDEN, H.DESTAEBLER, Ch. T. HOARD and A. E. JOHNSTON, SLAC (… The pipe has a radiation thickness of $5.8x10^{-3}X_0$, a failure pressure of 3.5 atm and was baked for high vacuum service; Al-NomexAl, length 560mm!)

arXiv:nucl-ex/0205008v1 (2002), Integration and Conventional Systems at STAR, H.S. Matis et.al.

➡ R&D required:
vacuum tight, mechanical-, electrical-, thermal stability

Accelerator* & Detector Design

Collaborations of CERN with experts from
Cockcroft, BNL, DESY, KEK, Lausanne, Novosibirsk, SLAC, TAC

- Luminosity and acceptance very much depend on physics program
  - Currently we prepare for two different interaction region setups
    $L_{ep} \approx 10^{33}\ cm^{-2}\ s^{-1}$, $10° < \theta < 170°$ - $HighQ^2$ Setup
    $L_{ep} \approx 10^{32}\ cm^{-2}\ s^{-1}$, $1° < \theta < 179°$ - $LowQ^2$ & $e^{\pm}A$ Setup
  - Interplay of optics, synchrotron radiation production and beam-beam interaction
    The design dominated by separation scheme -
    e.g. head-on collisions vs. crossing angle of beams + crab cavities?
    Linked with the detector layout and design
  - ➡ Iterative process finding the best solution

*see dedicated talk [290] Design Status of the Large Hadron-Electron Collider by Dr. John JOWETT (CERN)

Accelerator Complex - RR

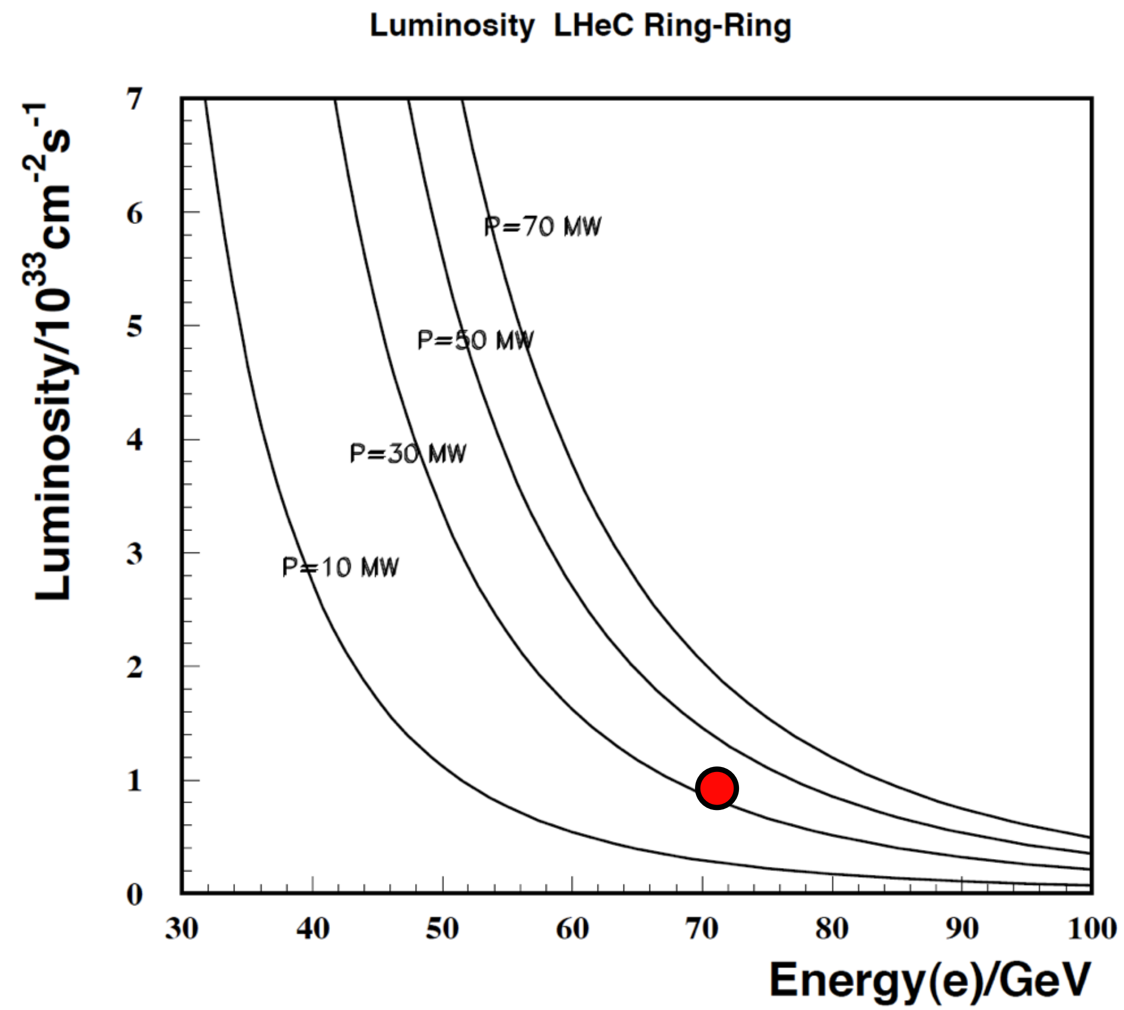
Preliminary!

Ring-Ring Option

Luminosity for $e^{\pm}p$ above $10^{33} cm^{-2} s^{-1}$

Simultaneous pp and ep running!

	Protons	Electrons
Number of bunches	2808	
Beam Energy	7 TeV	70 GeV
Number of particles per bunch	1.7×10^{11}	$1.4\ 10^{10}$
Beam current	860 mA	71 mA
Horizontal Beta	180 cm	12.7 cm
Vertical Beta	50 cm	7.1 cm
Normalized Emittance (horizontal)	3.75 μm rad	1.04 mm rad
Normalized Emittance (vertical)	3.75 μm rad	0.52 mm rad
RMS Emittance (horizontal)	0.50 nm rad	7.6 nm rad
RMS Emittance (vertical)	0.50 nm rad	3.8 nm rad
Beam Size (horizontal)	30.08 μm	31.07 μm
Beam Size (vertical)	15.85 μm	16.43 μm
Beam-Beam Parameter (horizontal)	0.000559	0.0512
Beam-Beam Parameter (vertical)	0.000294	0.0543
Luminosity	$1.21\ 10^{33}\ cm^{-2}\ s^{-1}$	



Power limit set to 100 MW

Energy limited by injection and synchrotron radiation losses

[290] Design Status of the Large Hadron-Electron Collider by Dr. John JOWETT (CERN)

M.Klein - ECFA at CERN Geneva 27. November 2009

Accelerator Complex - RL

Preliminary!

Linac-Ring Option

Luminosity for $e^{\pm}p$ at $8 \cdot 10^{31} cm^{-2} s^{-1}$, currently

The LR combination yet requires a still better p beam or/and E_e recovery to come to luminosity beyond 10^{32} $cm^{-2}s^{-1}$

Luminosity for ultimate beam

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8 \mu m, \beta^* = 0.2m, \gamma = 7000/0.94$$

$$L = 8 \cdot 10^{31} cm^{-2} s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^* / m} \cdot \frac{P/MW}{E_e / GeV}$$

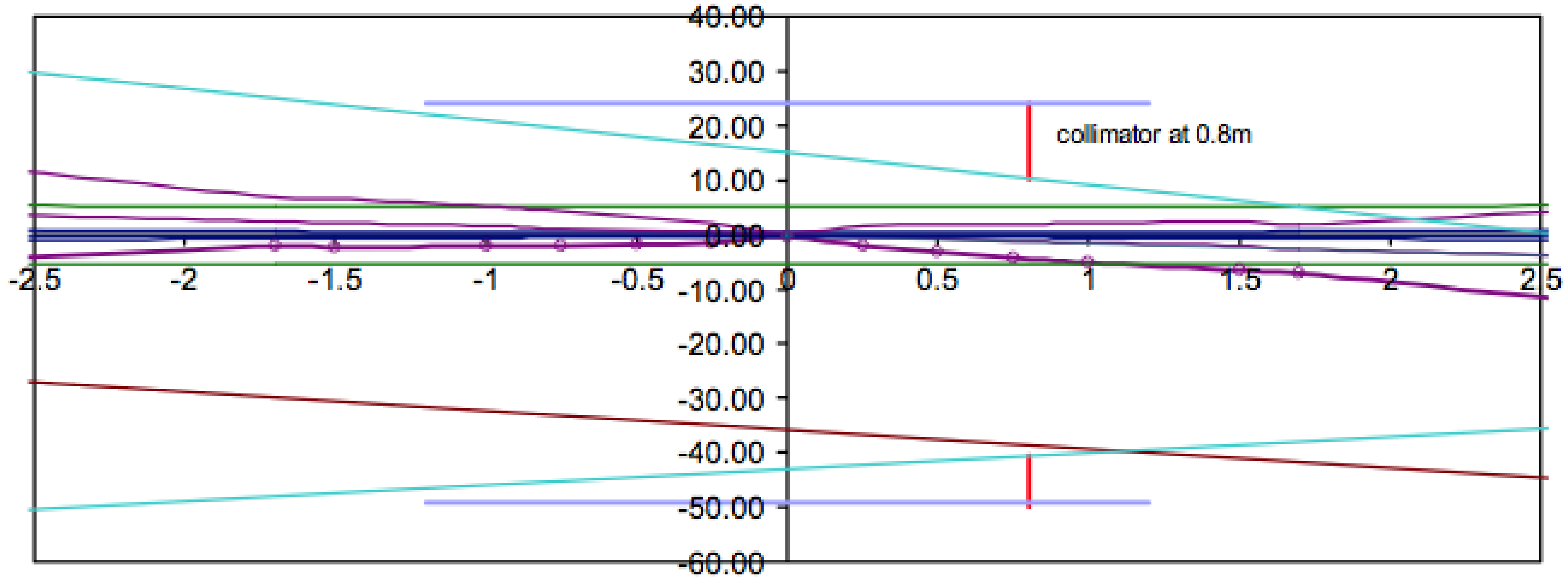
LINAC-Ring Parameters

Configuration	60 GeV, pulsed	60 GeV CW ERL	140 GeV pulsed
N_e/bunch/ 10^9/50ns	4	1.9	2
gradient MV/m	32	13	32
normalised ε/ μm	50	50	100
cryo power/MW	3	20	6
effective beam power/MW	50	$40/(1-\eta_{ERL})$	50

M.Klein - ECFA at CERN Geneva 27. November 2009

Synchrotron Radiation - RR

IR Sketch Top-view - Zoom



- Horizontal distance of collimator from proton beam 10.5mm
- Minimum width of central beam pipe 73mm
  - Horizontal distance to proton beam 24mm ring outside, 49mm ring inside

Direct synchrotron radiation fan to be checked

U. Schneekloth LHeC Ring-ring IR 10

presented by U.Schneekloth, LHeC Meeting CERN, 2.2.2010

Synchrotron Radiation - RR 2

(very preliminary)

Synchrotron Radiation in IR

- Beam separation very close to IP, starting at 1.2m
- Upstream collimation and partial absorption of synchrotron radiation not possible
- Direct synchrotron radiation must pass through IR
- Most SR absorbed by absorber at 21m
- Must protect detector from SR backscattered from absorber at 21m by downstream collimators
  - No space for moveable collimators
  - Collimators inside central detector, not accessible

  → use fixed collimators
- Size of central beam pipe determined by backscattered SR

U. Schneekloth LHeC Ring-ring IR 6

presented by U.Schneekloth, LHeC Meeting CERN, 2.2.2010

The Detector - Low Q^2 and eA

Muon chambers
(fwd,bwd,central)

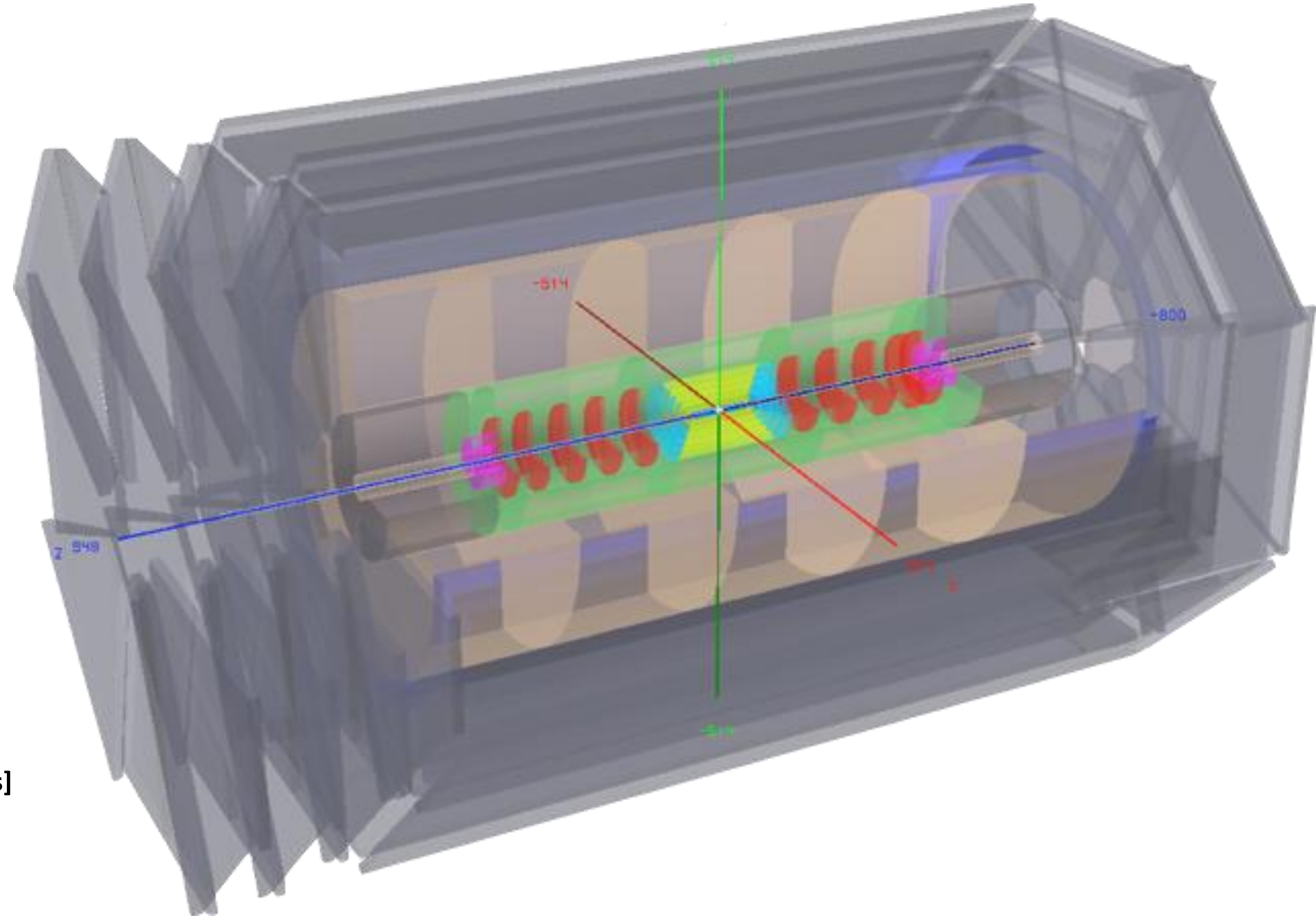
Coil (r=3m l=11.8m, 3.5T)
[Return Fe not drawn]

Central Detector

Pixels
Elliptic beam pipe (~3cm - or smaller)

Silicon (fwd/bwd+central)
[Strip or/and Gas on Slimmed Si Pixels]
[0.6m radius for 0.03% * p_t in 3.5T field]

El.magn. Calo (Pb,Scint. $30X_0$)
Hadronic Calo (Fe/LAr; Cu/Brass-Scint. 9-12λ)



Fwd Detectors

(down to 1°)
Silicon Tracker
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]

Calice (W/Si); dual ReadOut - Elm Calo
FwdHadrCalo:
Cu/Brass-Scintillator

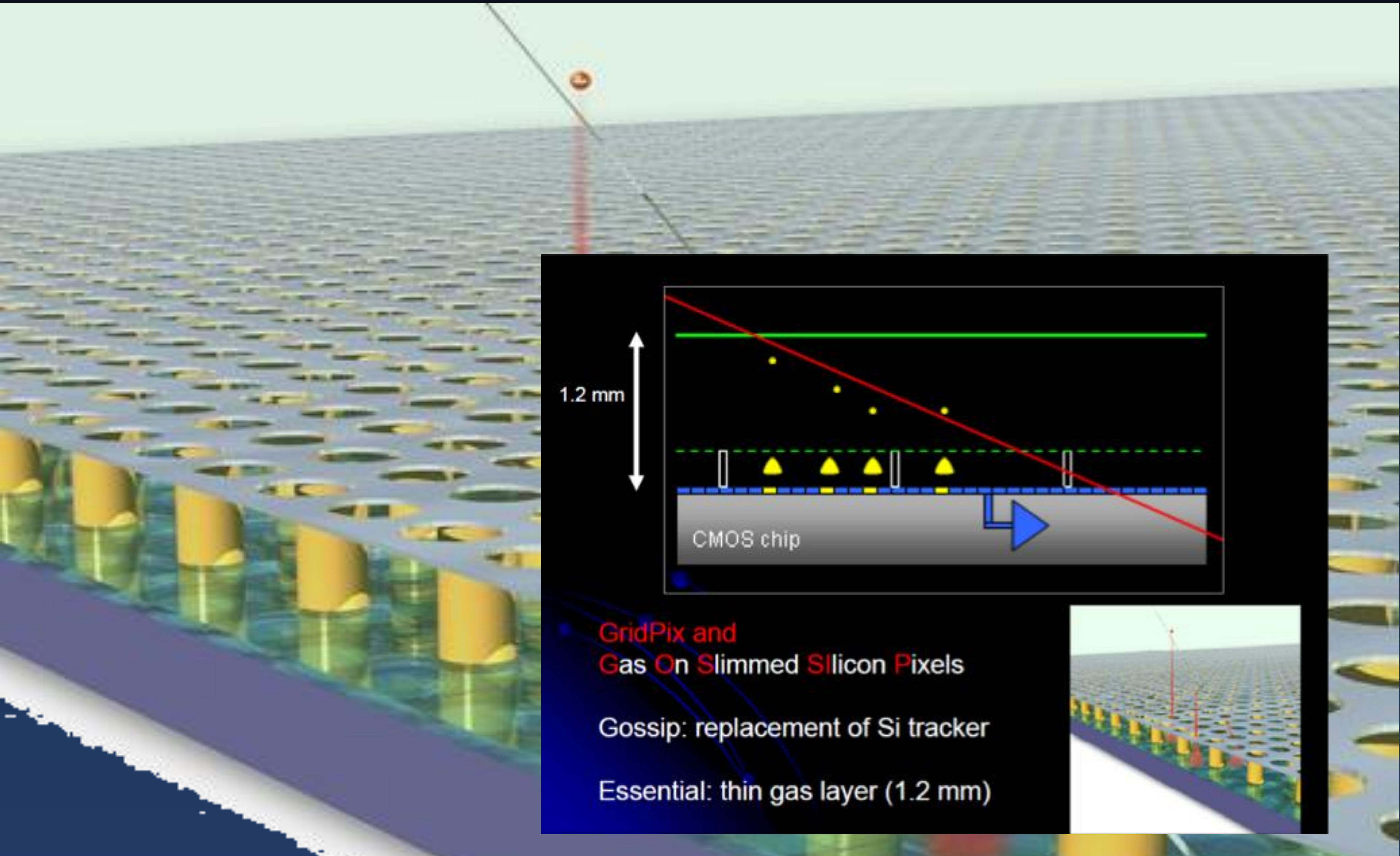
Bwd Detectors

(down to 179°)
Silicon Tracker
[Pix/Strip/Strixel/Pad Silicon or/and Gas on Slimmed Si Pixels]
Cu/Brass-Scintillator,
Pb-Scintillator (SpaCal - hadr, elm)

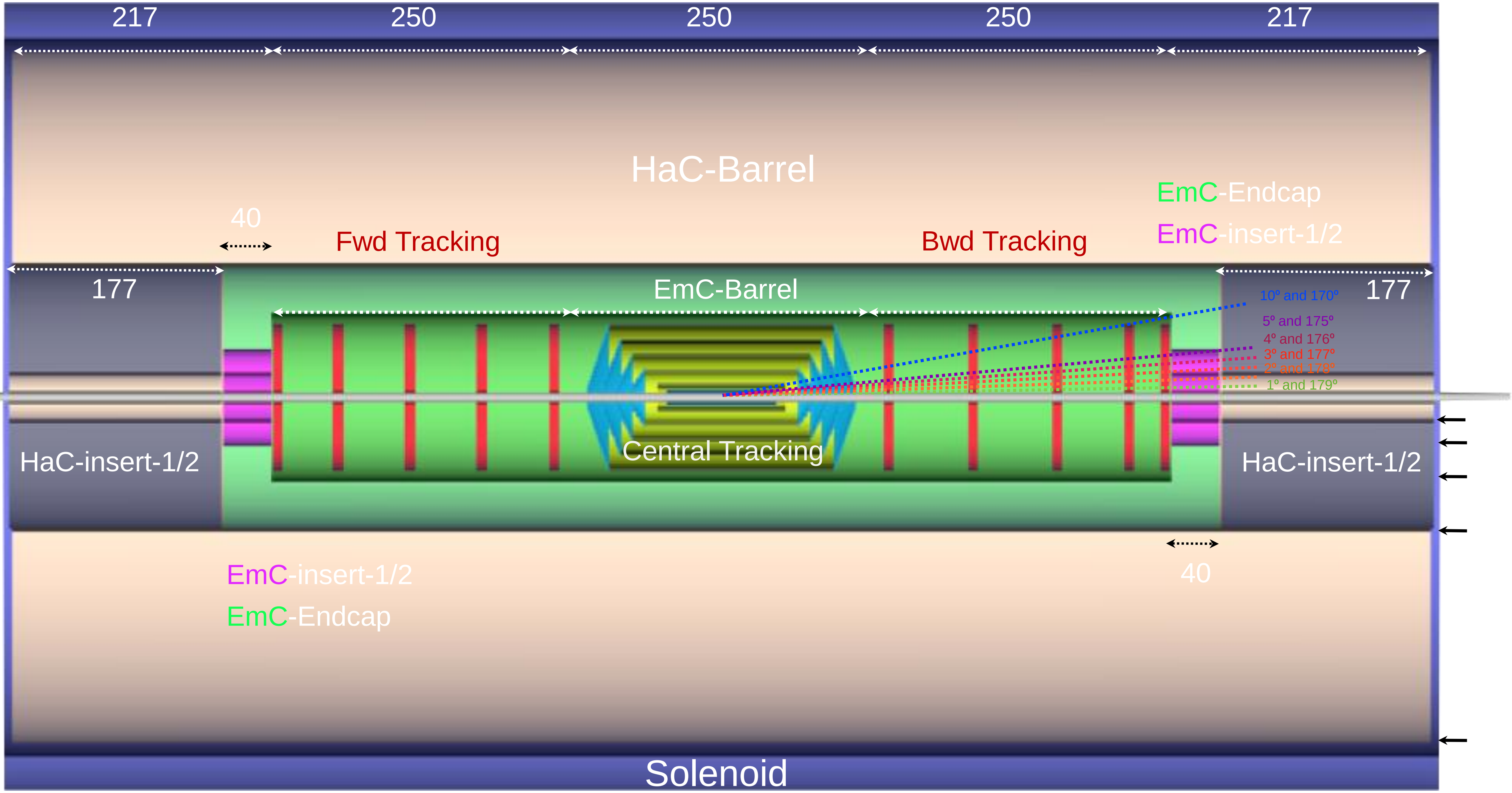
Precision Tracking: Si-Gas Tracker – GOSSIP

Gas on Slimmed Silicon Pixels

Henry van der Graaf (NIKHEF)



The Detector - Low Q^2 Setup



Low Q^2 (Draft)

Fwd Tracker - active Thickness 8. each
Si-Pix/Si-Strip/SiGas Tracker:
inner R = 4.86 cm; outer R = 61.3 cm
Planes 1 - 5:
$z_{1\text{-}5}$ = 140. / 200. / 260. / 320. / 370. cm

Barrel Tracker - active Radius 2.5 each
Si-Pix/Si-Strip/SiGas Tracker:
1. layer: inner R = 8.8 cm; outer R = 11.3 cm2.
layer: = 21.3 cm; = 23.8 cm3.
layer: = 33.8 cm; = 36.3 cm4.
layer: = 46.3 cm; = 48.8 cm5.
layer: = 58.8 cm; = 61.3 cm

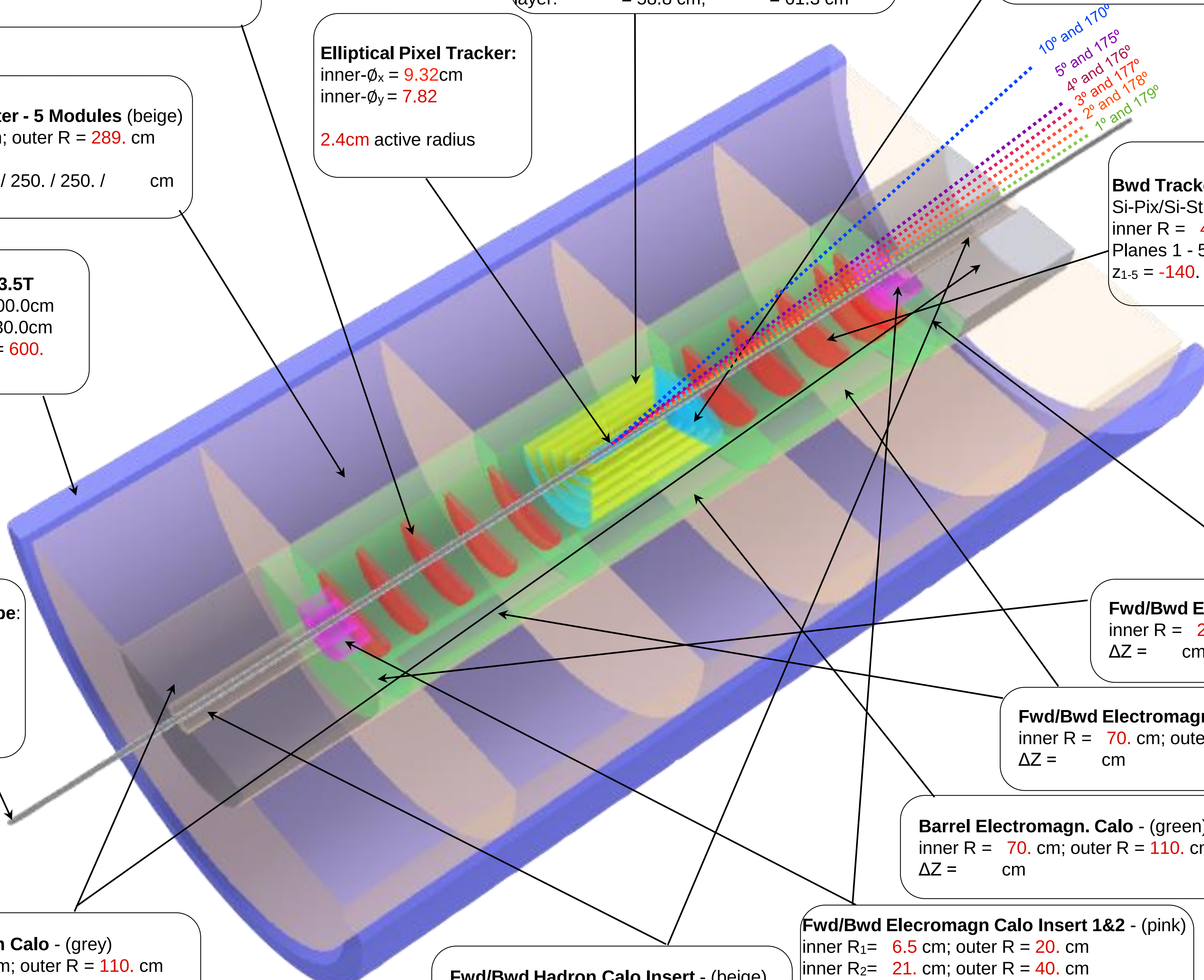
4 Cone structured fwd/bwd Si-pix/Si-strip/Si-gas **Tracker**
R_{min} = 4.86 cm
2.5 active thickness

Elliptical Pixel Tracker:
inner-$\emptyset_x$ = 9.32cm
inner-$\emptyset_y$ = 7.82

2.4cm active radius

Hadron Calorimeter - 5 Modules (beige)
inner R = 112. cm; outer R = 289. cm
Modules 1 - 5:
$\Delta Z_{1\text{-}5}$ = / 250. / 250. / 250. / cm

Solenoid - 3.5T
inner-R = 300.0cm
inner-R = 330.0cm
half length = 600.



Bwd Tracker - active Thickness 8. each
Si-Pix/Si-Strip/SiGas Tracker:
inner R = 4.86 cm; outer R = 61.3 cm
Planes 1 - 5:
$z_{1\text{-}5}$ = -140. /-210. /-280. /-340. /-370. cm

Elliptical Beam Pipe:
inner-$\emptyset_x$ = 7.3
inner-$\emptyset_y$ = 5.8
outer-$\emptyset_x$ = 8.1cm
outer-$\emptyset_y$ = 6.6cm
➟ thickness: 0.8cm

Fwd/Bwd Electromagn. Calo 2 - (green)
inner R = 21. cm; outer R = 110. cm
ΔZ = cm

Fwd/Bwd Electromagn. Calo 1 - (green)
inner R = 70. cm; outer R = 110. cm
ΔZ = cm

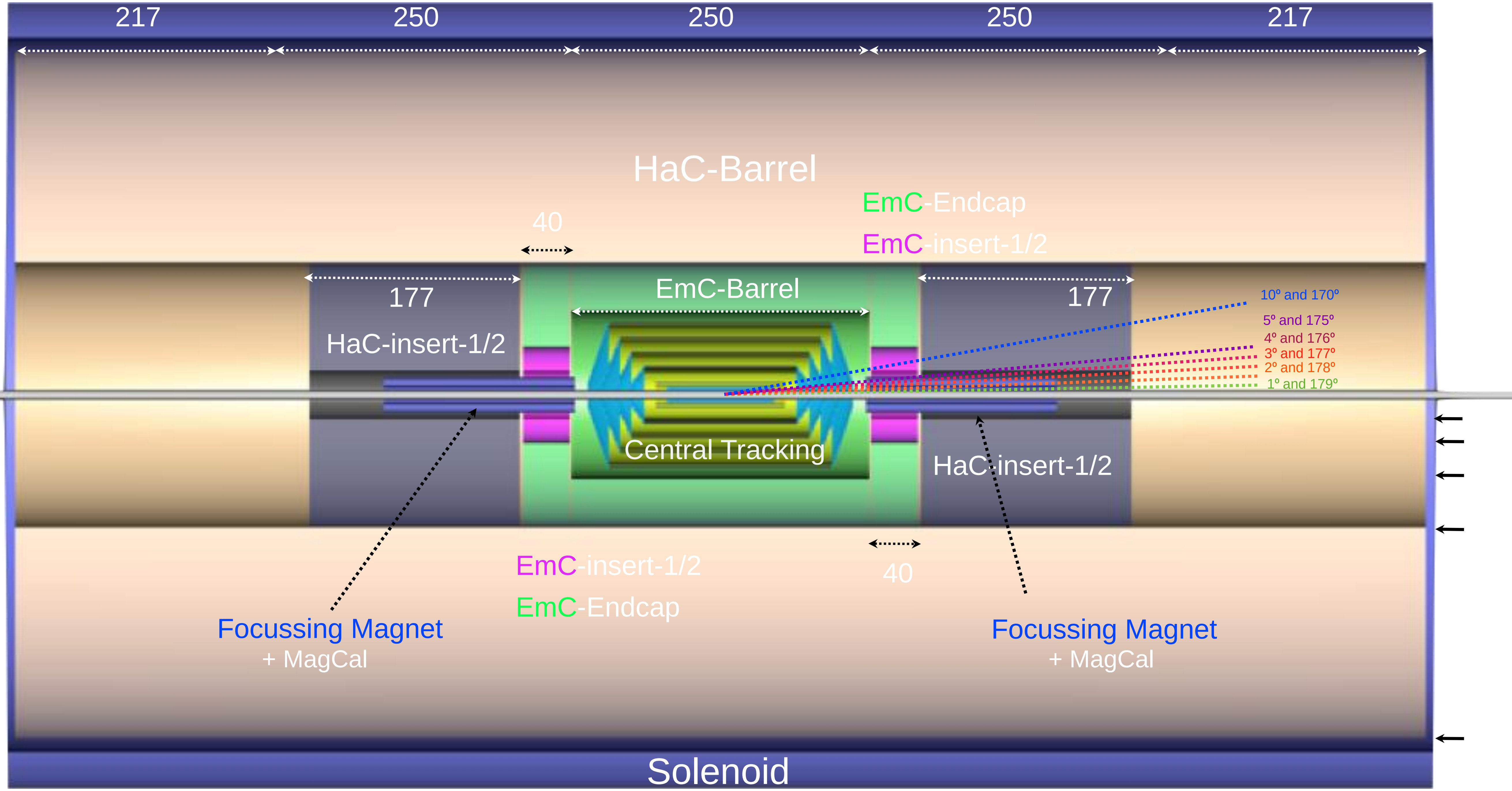
Barrel Electromagn. Calo - (green)
inner R = 70. cm; outer R = 110. cm
ΔZ = cm

Fwd/Bwd Hadron Calo - (grey)
inner R = 21.0 cm; outer R = 110. cm
ΔZ = cm

Fwd/Bwd Hadron Calo Insert - (beige)
inner R = 6.5 cm; outer R = 20. cm
ΔZ = cm

Fwd/Bwd Elecromagn Calo Insert 1&2 - (pink)
inner R_1= 6.5 cm; outer R = 20. cm
inner R_2= 21. cm; outer R = 40. cm
ΔZ = cm

The Detector - High Q^2 Setup



Instrumentation - Guidelines

- R&D for SLHC, CLIC-ILC in many areas exhibit interesting results;
  (see the presentations of Divonne'08, Divonne'09 and dedicated publications)

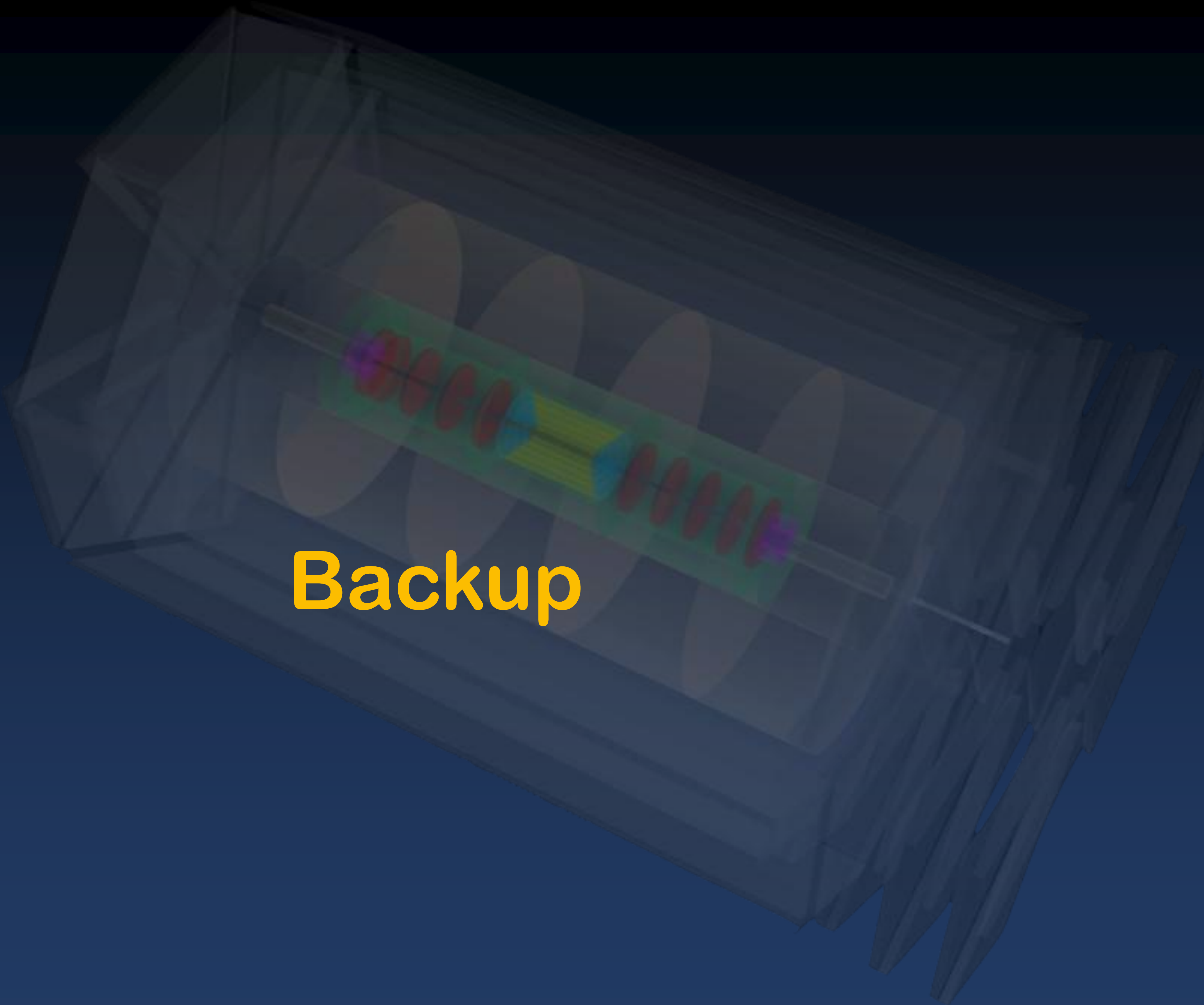
- Specifically the hadron calorimetry have to exploit new areas of resolution
  - detect, separate and measure all neutral and charged hadronic and electromagnetic components of the hadronic cascade best

- As the beam pipe, the tracking detectors have to be optimised for radiation length.
  The performance will ensure the identification and measurement:
  - primary/secondary vertex of tracks with small/large polar angle
  - particle ID (standalone or +calorimetry); e/γ/□^{0} separation, μ/τ/□$^{\pm}$/K$^{\pm}$ /p/d/n
  - + trigger capability - even for vertex preselection / exclusion

- The simulation of key processes in a proposed detector environment is being prepared
  e.g. realistic proposals for CC process $e^- p \Rightarrow \nu_e H j$ by detector simulation only - $b\bar{b}$ tagging)

Summary - Outlook

- The physics arguments for an LHeC experiment at CERN getting more pronounced
- A dedicated accelerator add-on complex for the LHC is being developed and the iterative process for a detector design started. The beam pipe design is a key part of the detector interfacing the accelerator and is currently in focus.
- A base design of a LHeC detector has been presented and some boundary conditions for set up and performance discussed
- The simulation of key processes for a possible detector acceptance is being prepared
- The LHeC detector is in some respects as complex and sizable as an LHC detector and aims for accuracy as an ILC detector. But we can rely on years of R&D already performed for those existing/planed experiments. It will be a fantastic challenge to eventually build the LHeC detector. Meanwhile you may wish to join the design work.

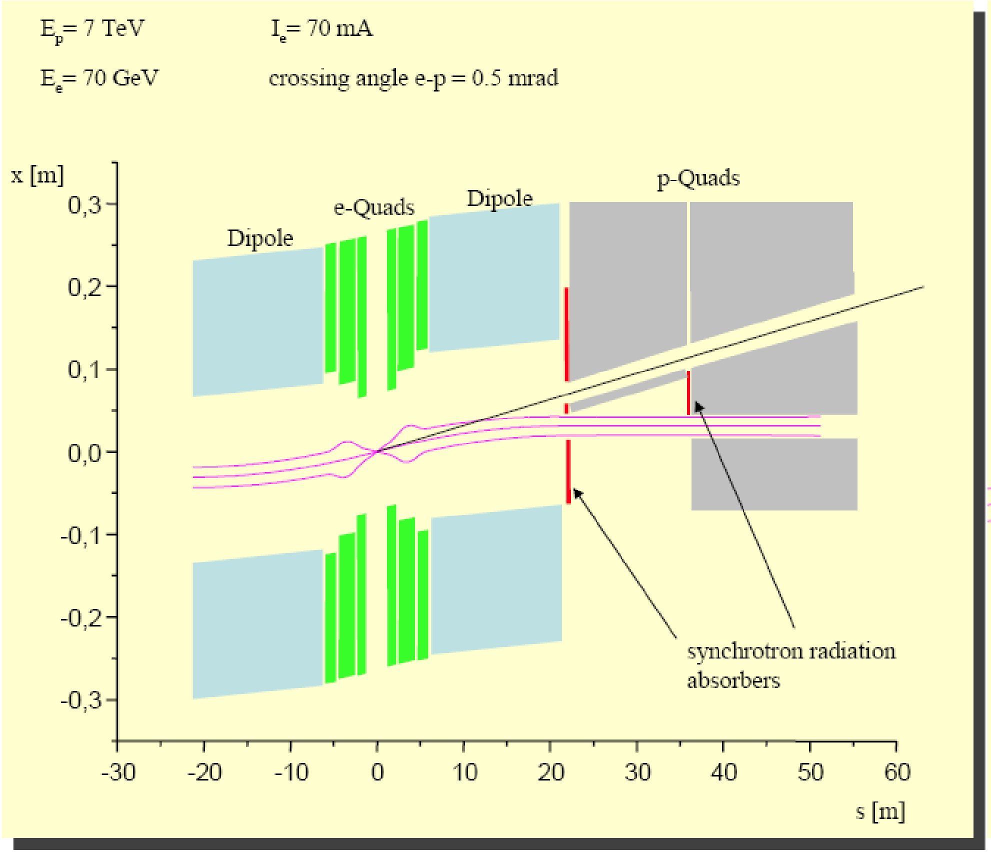


Backup

Synchrotron Radiation - RR

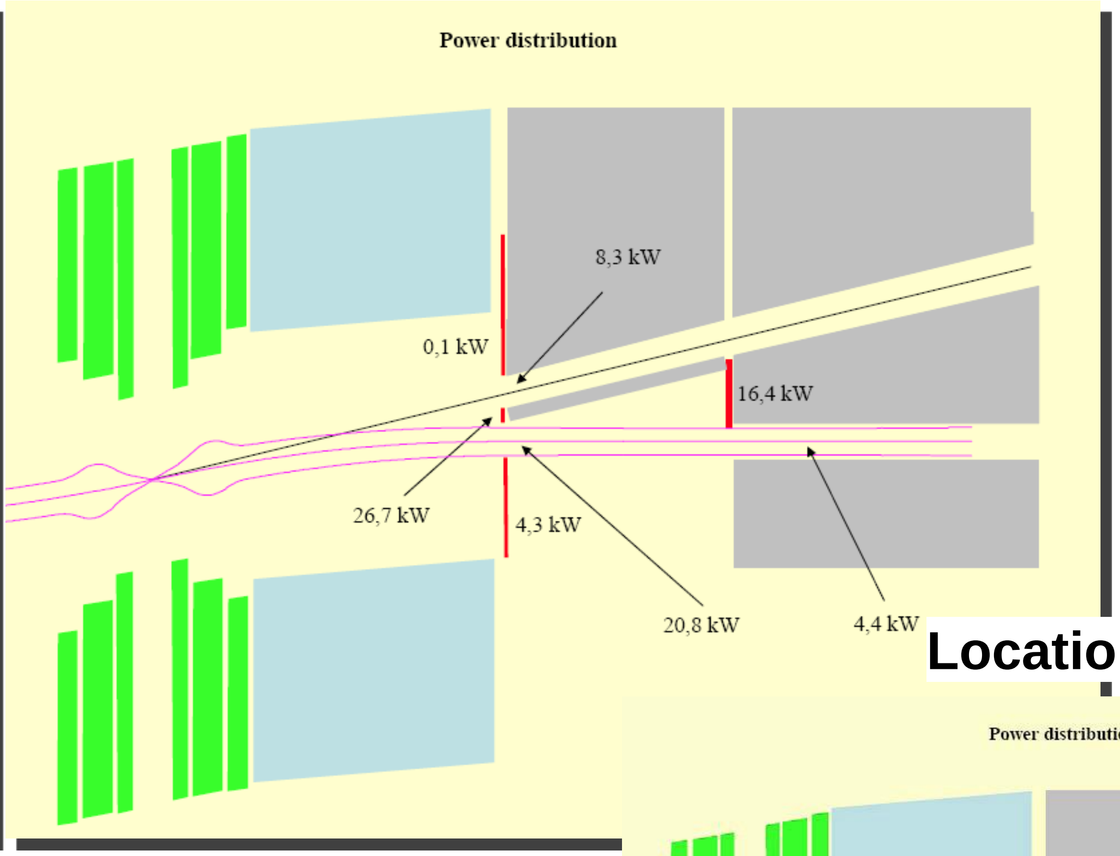
(very preliminary)

Top View of IR

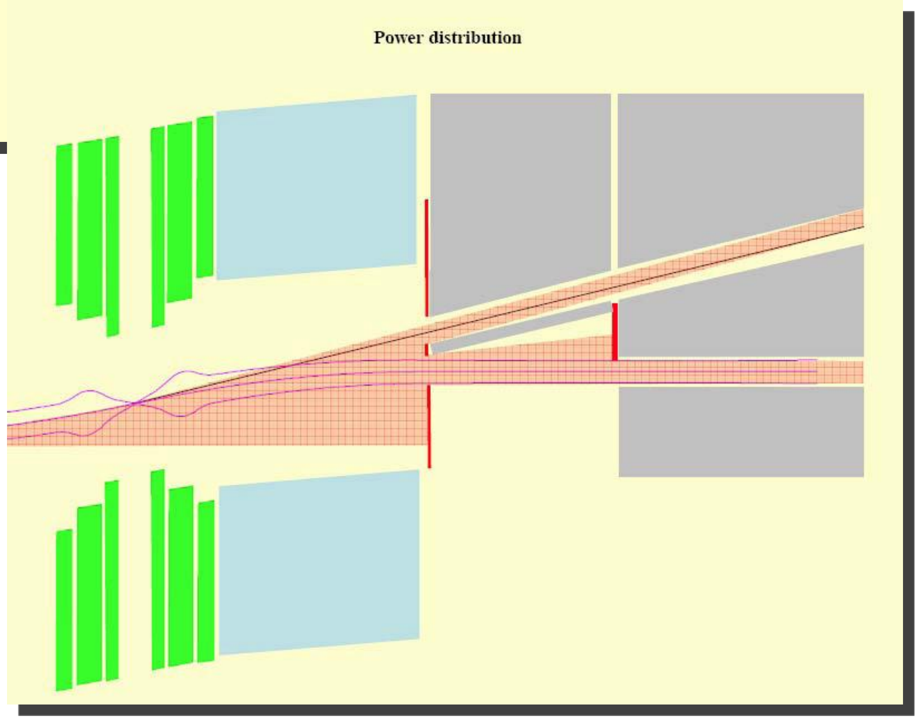


Synchrotron radiation power

B. Nagorny



Location of Absorbers

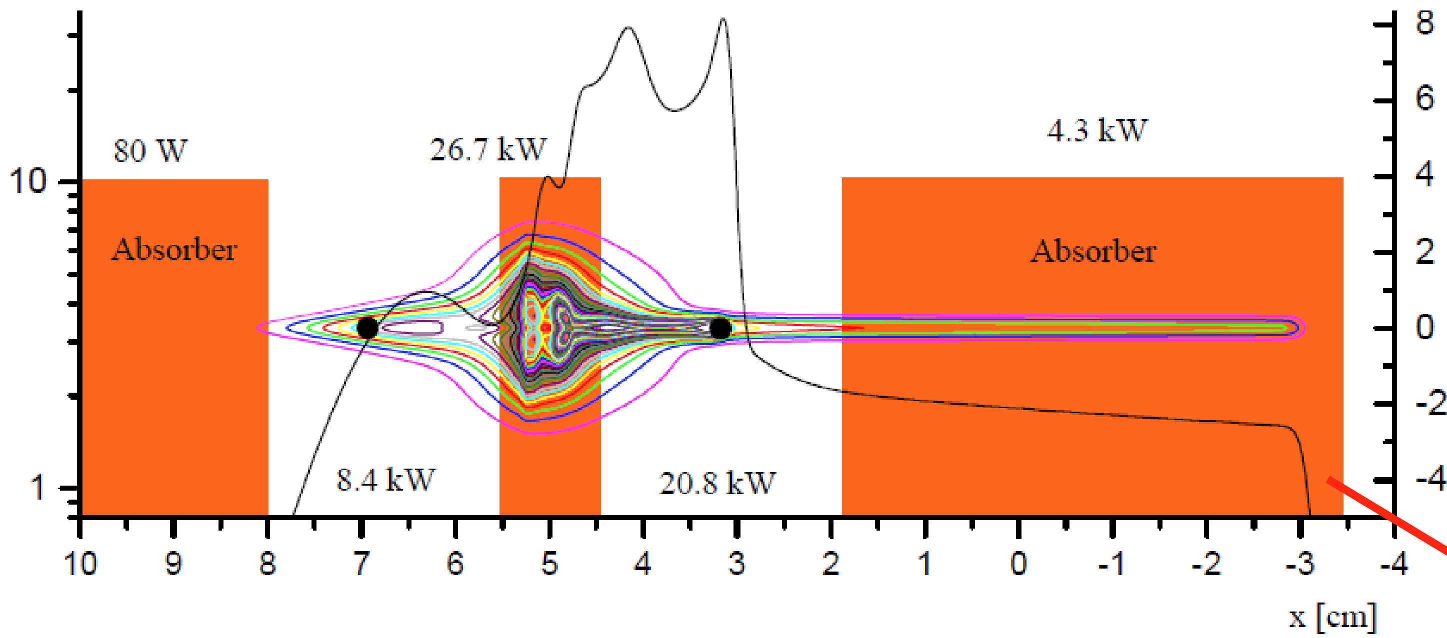


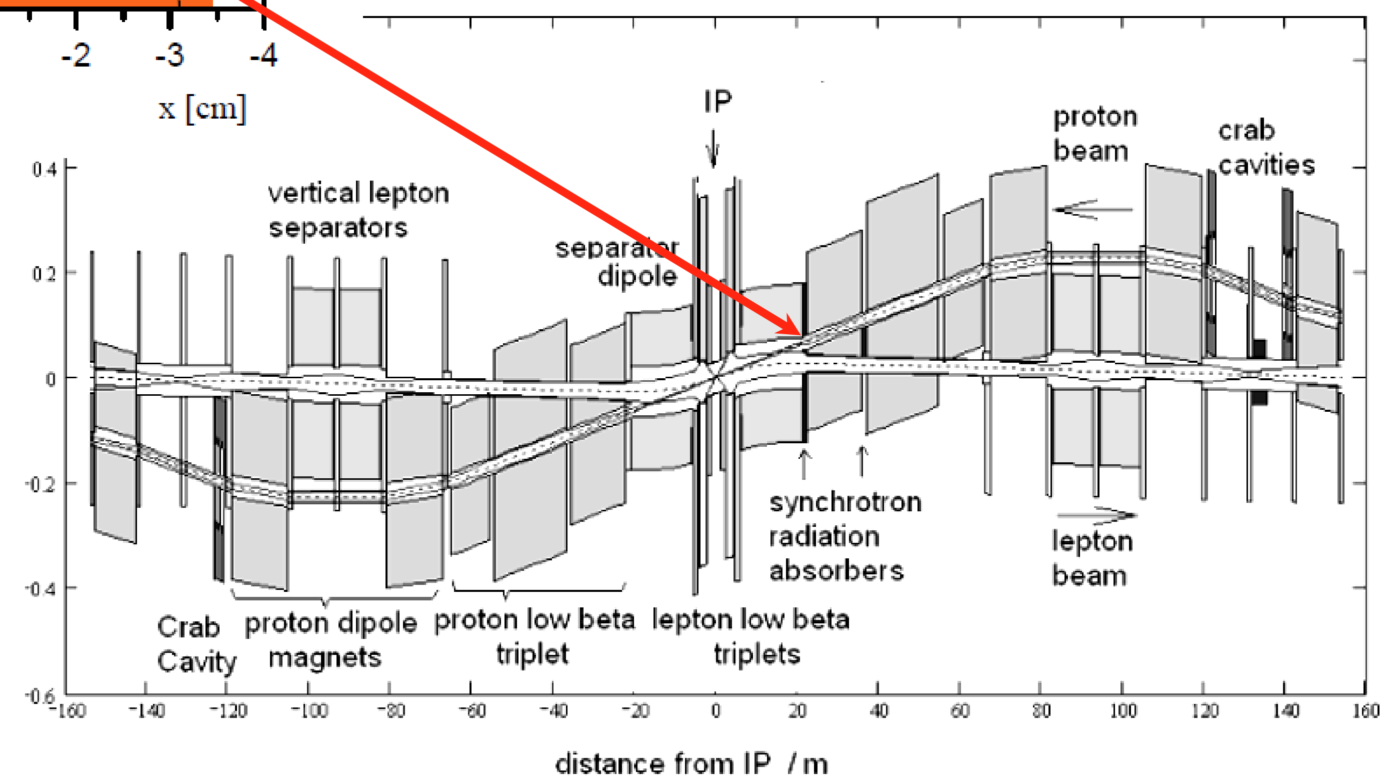
Synchrotron Radiation - RR

(very preliminary)

2D distribution of synchrotron radiation at absorber - power (kW/cm²)

B. Nagorny





Detector Requirements (I)

Tracking

- lowest mass tracker - essential for ©/$e^{\pm}$ ident (specifically bwd)
- high resolution Si-Detectors ("conventional" or SiGas)
- high resolution track definition in front of forward calo
- tracking trigger in front of fwd/bwd calo
- Early □^{0} ident - vertex detector/trigger

Detector Requirements (II)

Calorimeter

- Minimize longitudinal and lateral energy leakage
- Fwd/bwd Particle Flow Detector to achieve desired mass resolution ; $\gamma/e^{\pm}$; □^{o}; ...
  This technique combines the tracking/calorimetry information in an optimal way in order to get the best possible jet-energy resolution.
  Or Dream (dual readout) - event to event correction
- Both electromagnetic and hadron calorimetry inside the solenoid coil; minimum material inside EmCal;
- Prototyping, test at high energy!

Magnetic Field

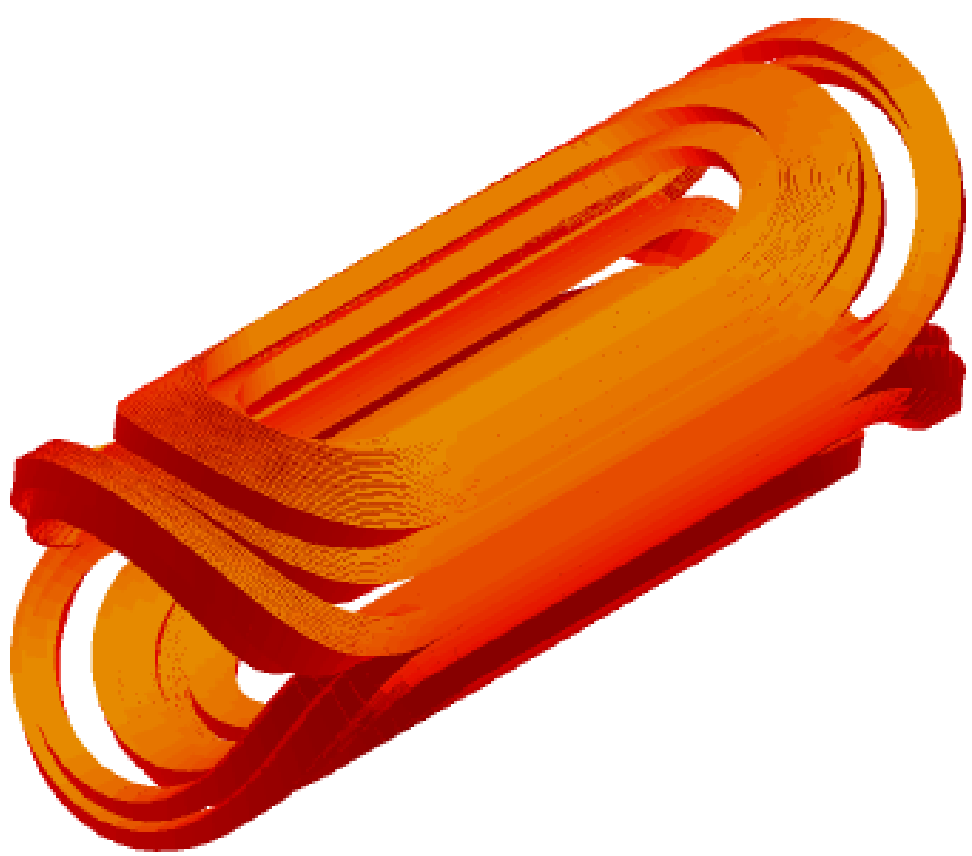
- 3.5 Tesla solenoidal field

Instrumented Magnets

Tim Greenshaw (Liverpool)

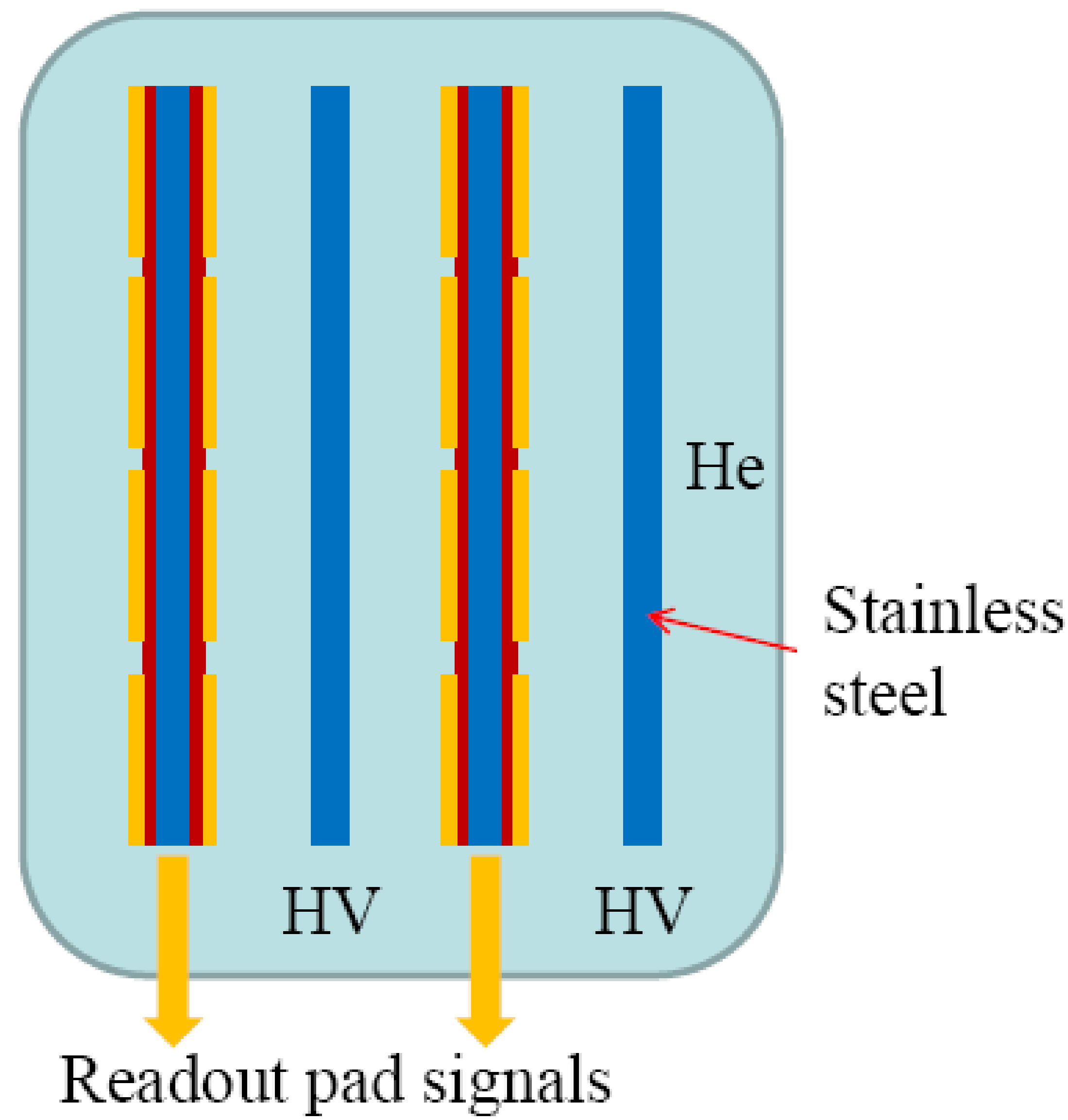
Superconducting magcal – take one

- Helium cooled SC magnet.
- Coils in He bath.



- Space for calorimeter using He as active component?

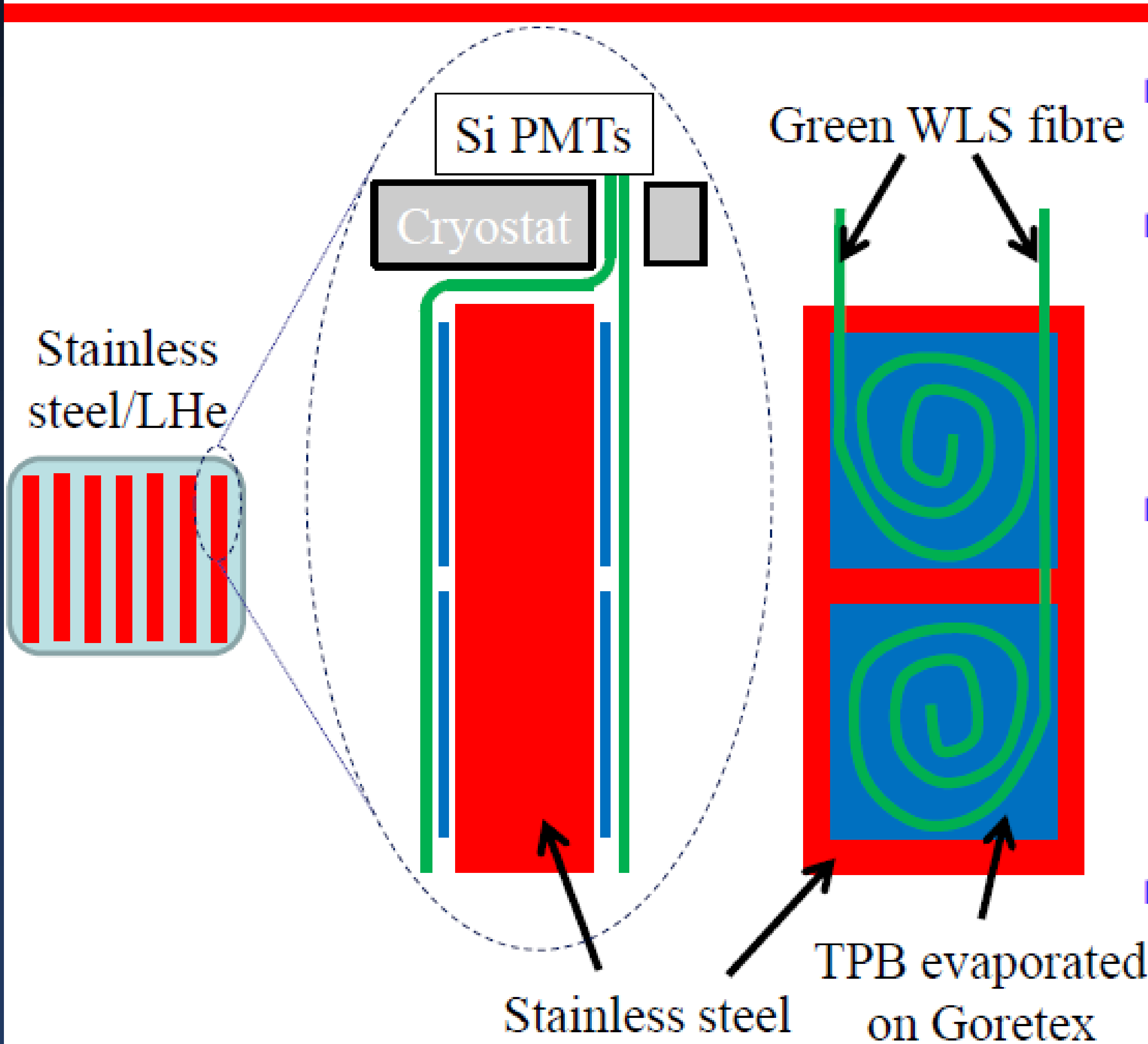
- Could add stainless steel plates as absorber with readout pads:



Instrumented Magnets

Tim Greenshaw
Divonne 08+09

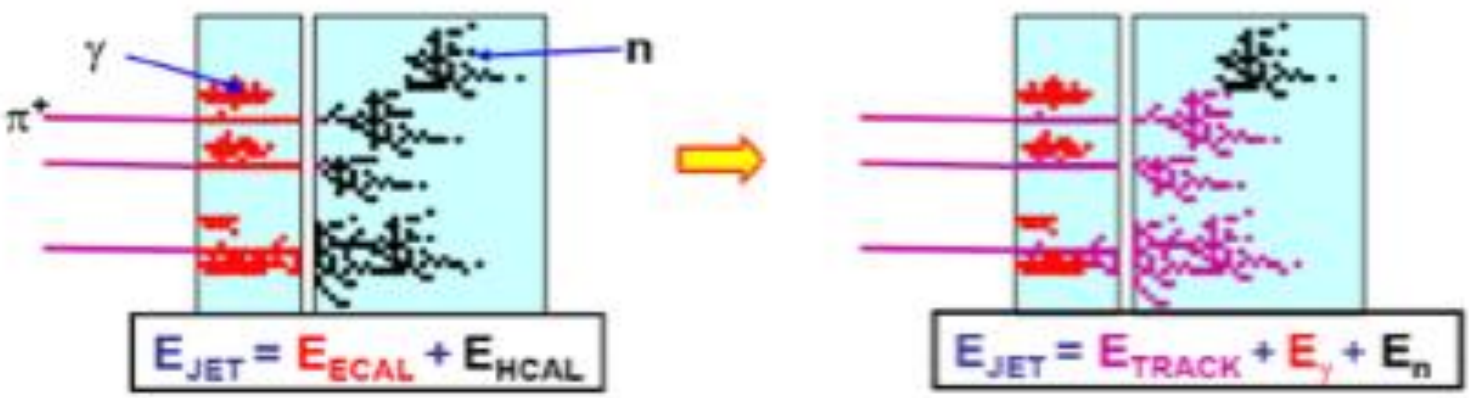
SC magcal – conceptual design



- Possible design stainless steel/LHe sandwich.
- 2 mm thick steel plates with similar width gaps:
  - $X_0 \sim 2$ cm.
  - $\lambda_I \sim 20$ cm.
- Use fluor tetraphenyl betadiene (TPB) to absorb scintillation light and re-emit in blue ($\lambda \sim$ 430 nm) – with efficiency 135%.
- (Using LHe as a scintillator is being considered for e.g. solar neutrino experiments.)

Particle Flow

- Use tracking information to improve jet energy reconstruction
- Need to associate tracks with clusters
- Ideally only neutral cluster energy is taken from calorimeter



- "Confusion" is main source of errors
  - Need to separate neutral and charged clusters (B + radius)
  - Need highly granular calorimeter to see cluster structure

$$\text{Confusion} \propto B^{-0.3} R^{-1.0}$$

2nd September 2009, Christian Grefe — Page 19

Christian Grefe

A hardware and software challenge

Tungsten = compact HCAL to minimize solenoid radius

PFA Performance

- Empiric formula for PFA performance

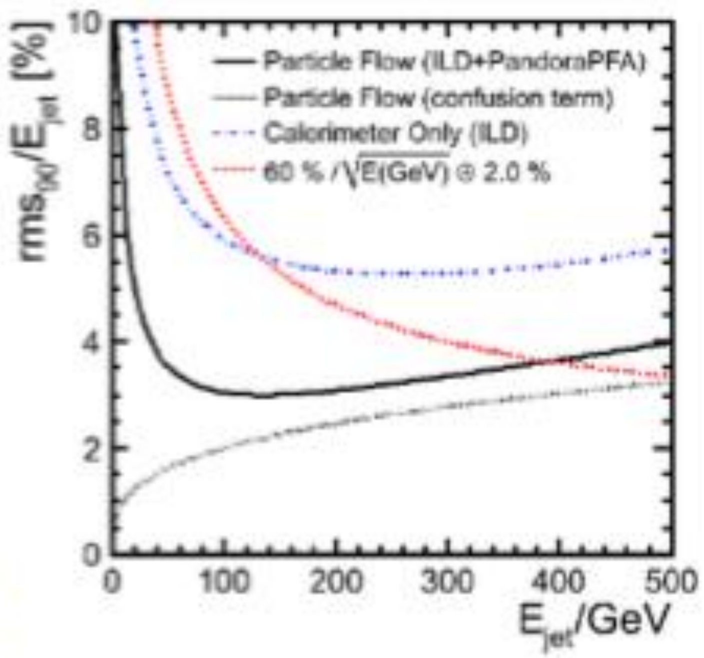
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution | Tracking | Leakage | Confusion

Barrel Region

Christian Grefe

- Comparing PFA and pure calorimetry:
  - PFA "wins" for E_{jet} < 400 GeV
  - There is room for improvement of the algorithm
  - Can chose reconstruction depending on event



- http://indico.cern.ch/contributionDisplay.py?contribId=268&sessionId=2&confId=30383
- http://indico.cern.ch/materialDisplay.py?contribId=1&materialId=slides&confId=56735

Mark Thomson

Default ILD: B = 3.5 T, 6 λ HCal

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %
375 GeV	81.4 %	3.6 %
500 GeV	91.6 %	4.1 %

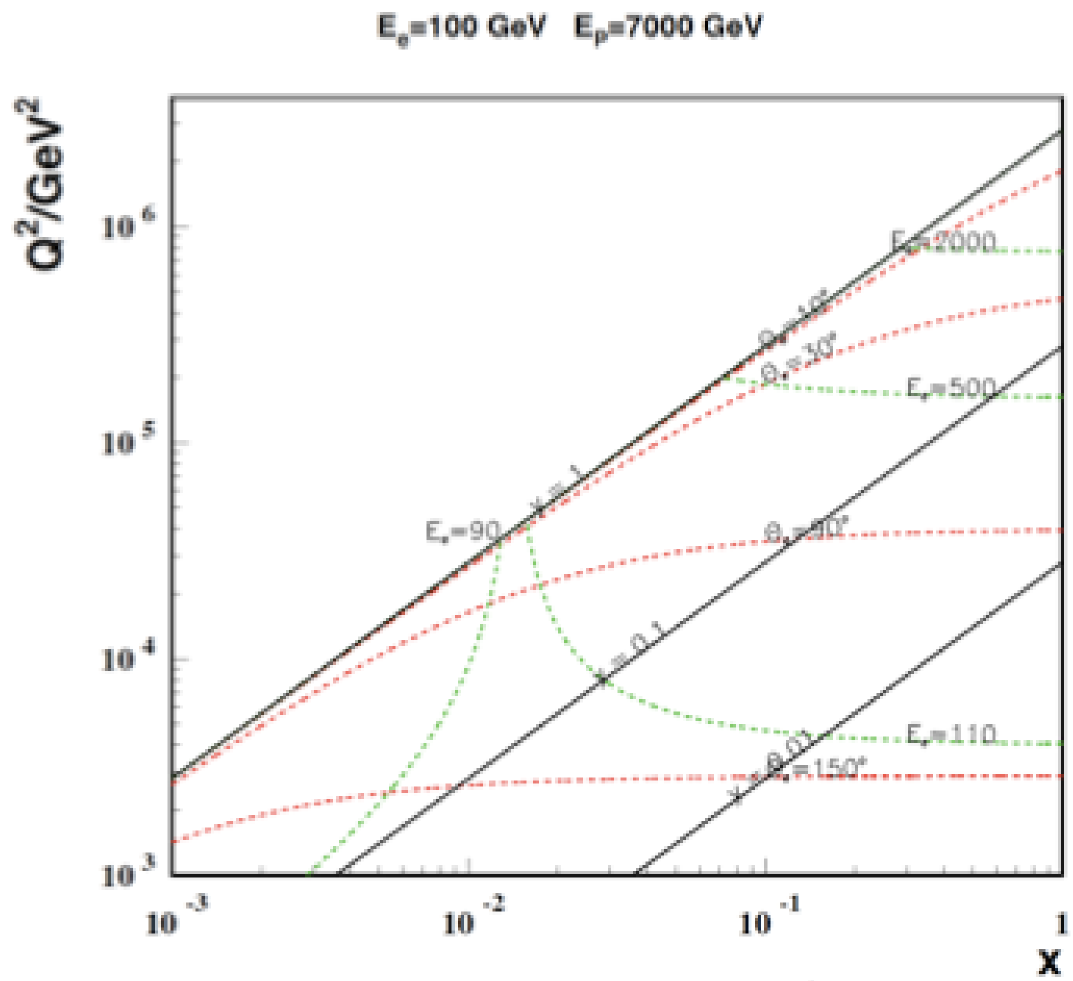
- Good option for barrel HCAL
  - need input from physics groups about mass and/or energy resolution
- PFA performance in fwd region unproven
- ⇒ consider "improved" conventional or "DREAM*" fwd calorimeter

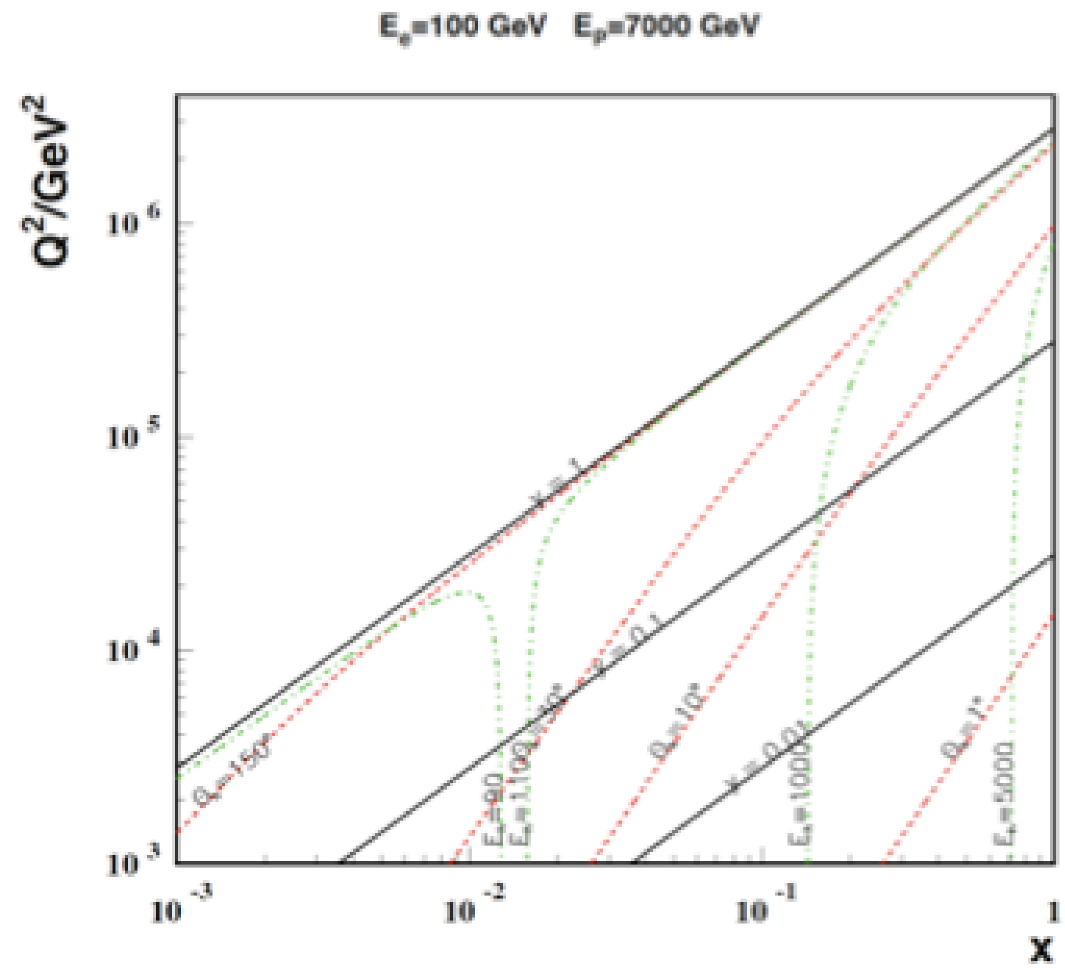
* DREAM Collaboration - double/triple R/O Calorimeter

Detector Simulation

- Precise detector simulations are needed:
  - optimize full detector designs for physics performance on mission critical processes
  - optimize the designs of subsystems and subdetectors
  - compare proposed detector technologies with each other (in concert with test beam)
- The hardware selection aspect makes use of world wide efforts for the preparation of ILC and SLHC experiments

Kinematics – high Q^2





The electron kinematics at high Q^2
Is no big problem, apart from extreme backscattering at very high Q^2 of electrons of a few TeV energy.

→**Need forward elm. calorimeter of few TeV energy range down to 10° and below with reasonable calibration accuracy.**

High x and high Q^2: few TeV HFS scattered forward:

→**Need forward had. calorimeter of few TeV energy range down to 10° and below. Mandatory for charged currents. Strong variations of cross section at high x demand hadronic energy calibration as good as 1%**

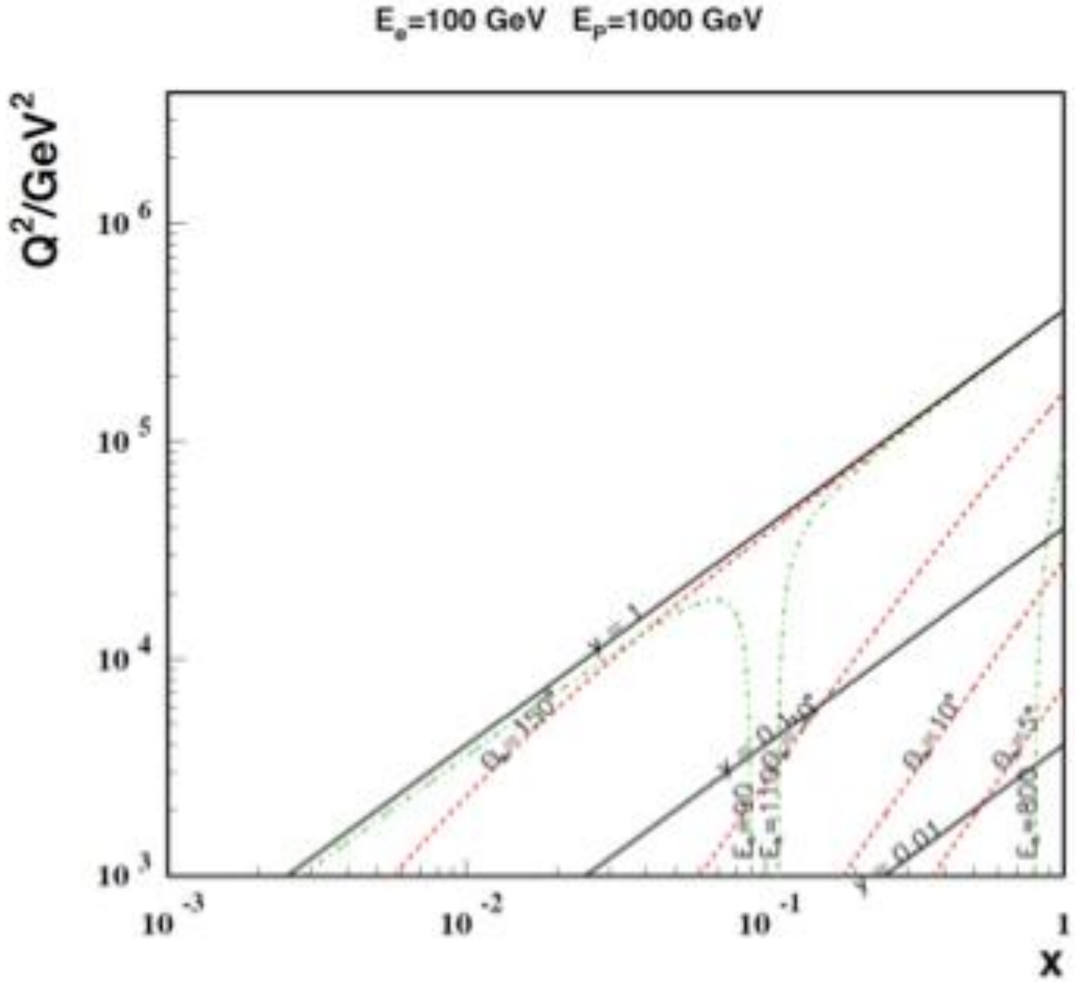
Max Klein - Scenarios and Measurements 7

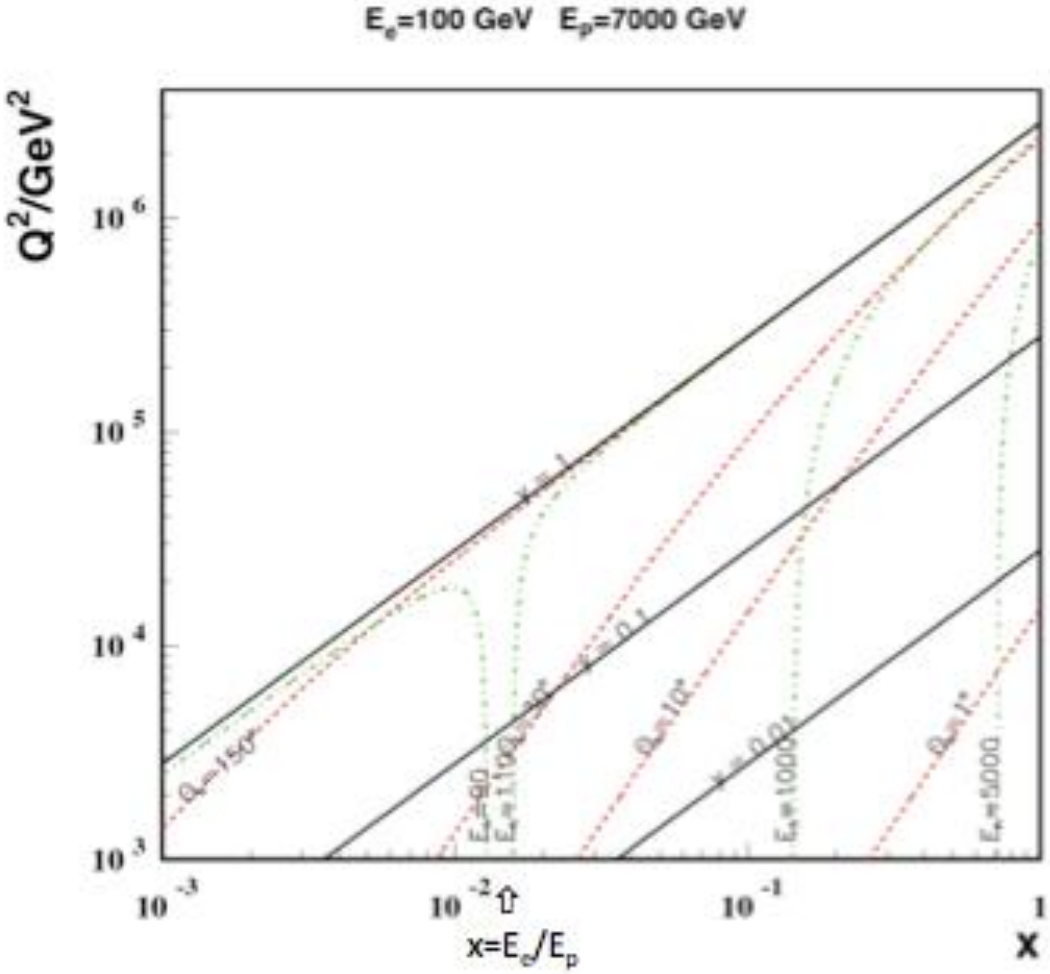
M.Klein - LHeC QCD and Electroweak Physics Workshop, DESY 8th April 2010

Kinematics – large x

Low proton beam energy: access large x. Needs high luminosity: L ~ $1/E_p^2$

Nominal proton beam energy: need very fwd. angle acceptance for accessing large x





$$Q^2(x,\theta_h) = sx/[1+E_e cot^2(\theta_h/2)/xE_p] \simeq (2xE_p cot(\theta_h/2))^2$$

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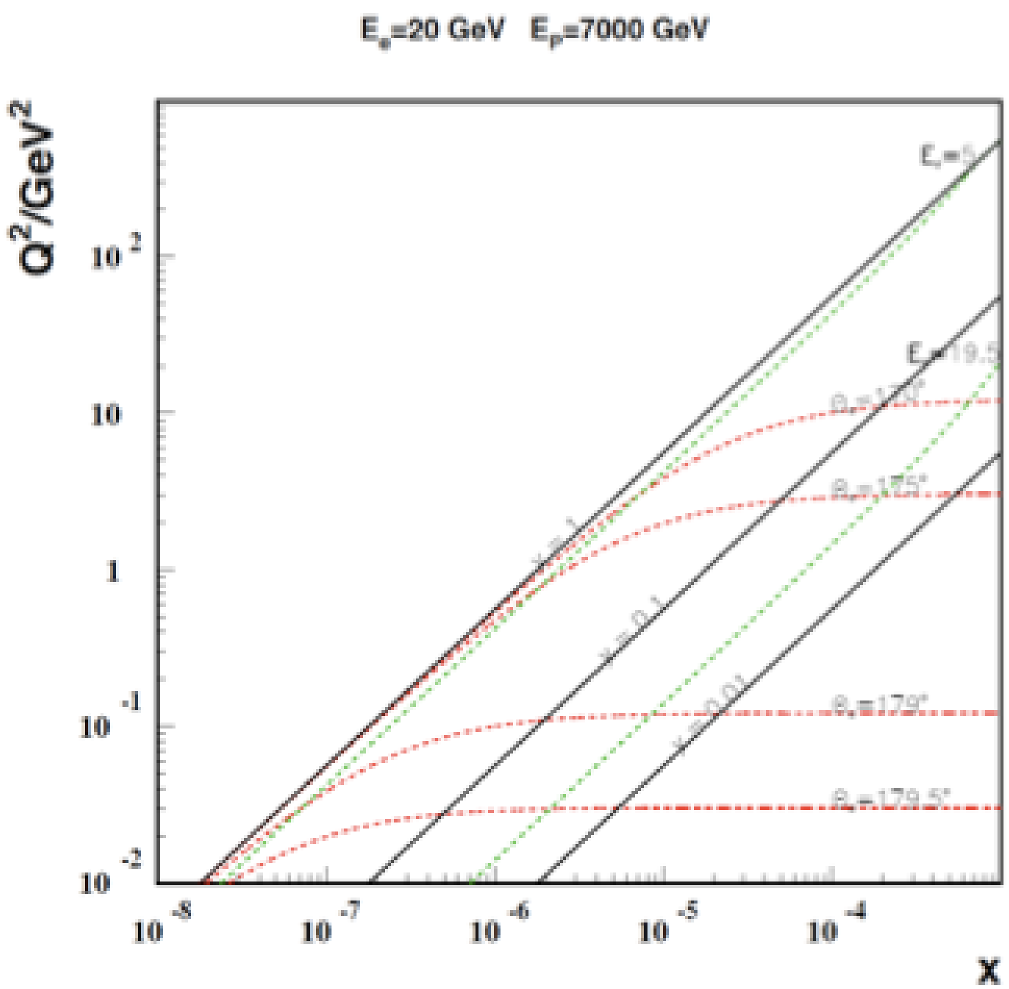
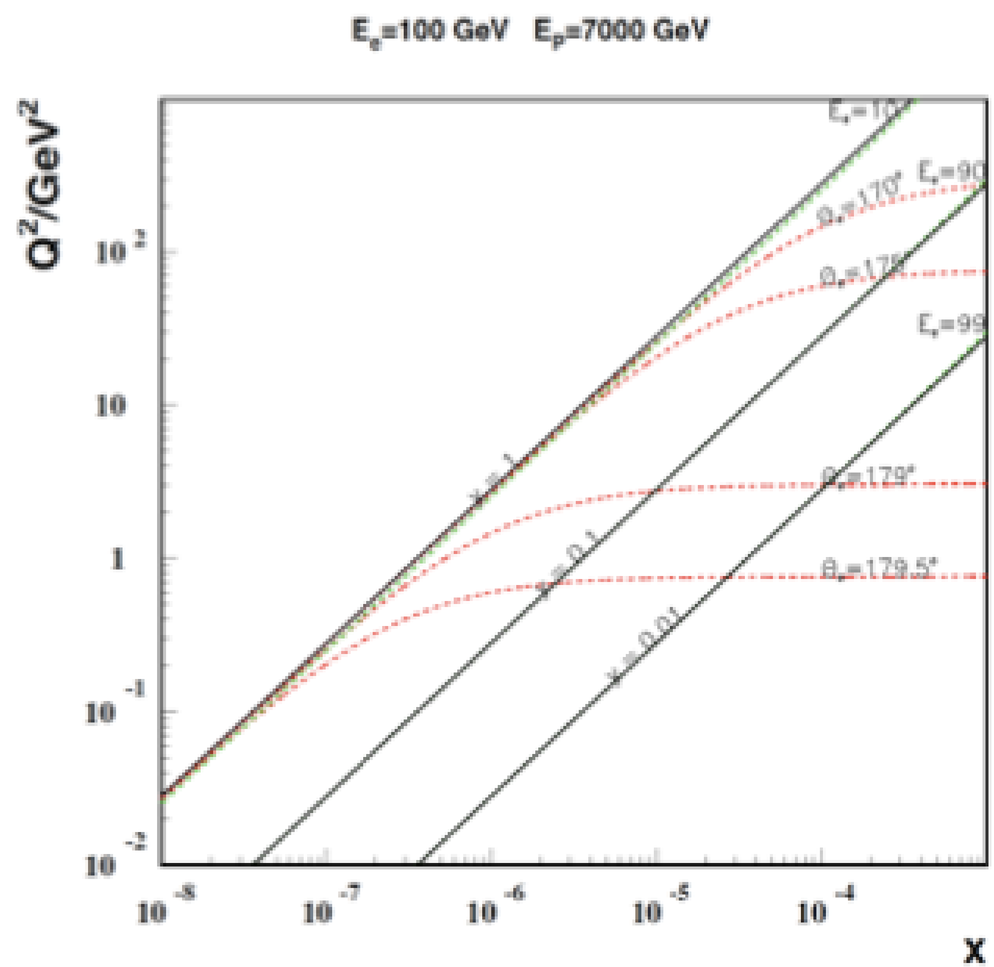
Kinematics – low Q^2,x

Low electron beam energy: access low x. Needs only small luminosity. SPL for low Q^2 physics, however, lowest x require max s.

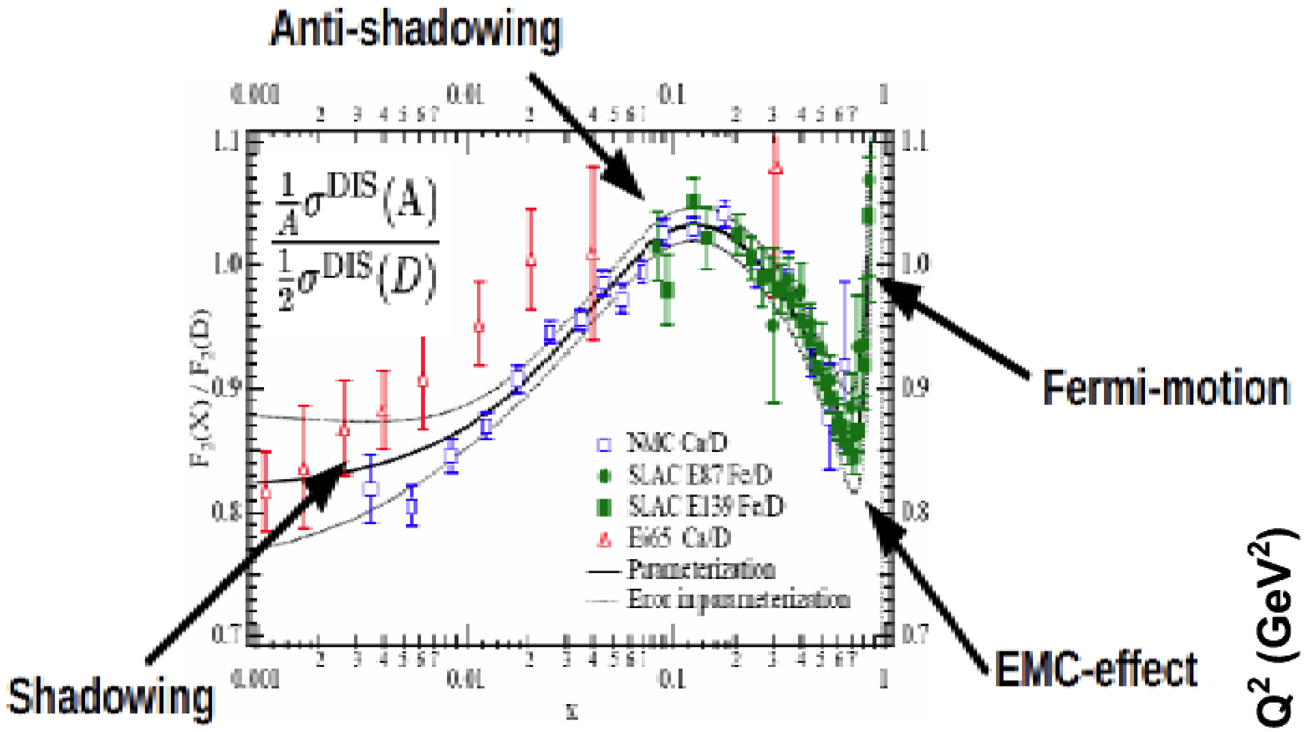
Nominal proton beam energy: need very bwd angle acceptance for accessing low x and Q^2





$$Q^2(x,\theta_e) = sx/[1 + xE_p cot^2(\theta_e/2)/E_e] \simeq (2E_e cot(\theta_e/2))^2$$

Physics - eA Interactions

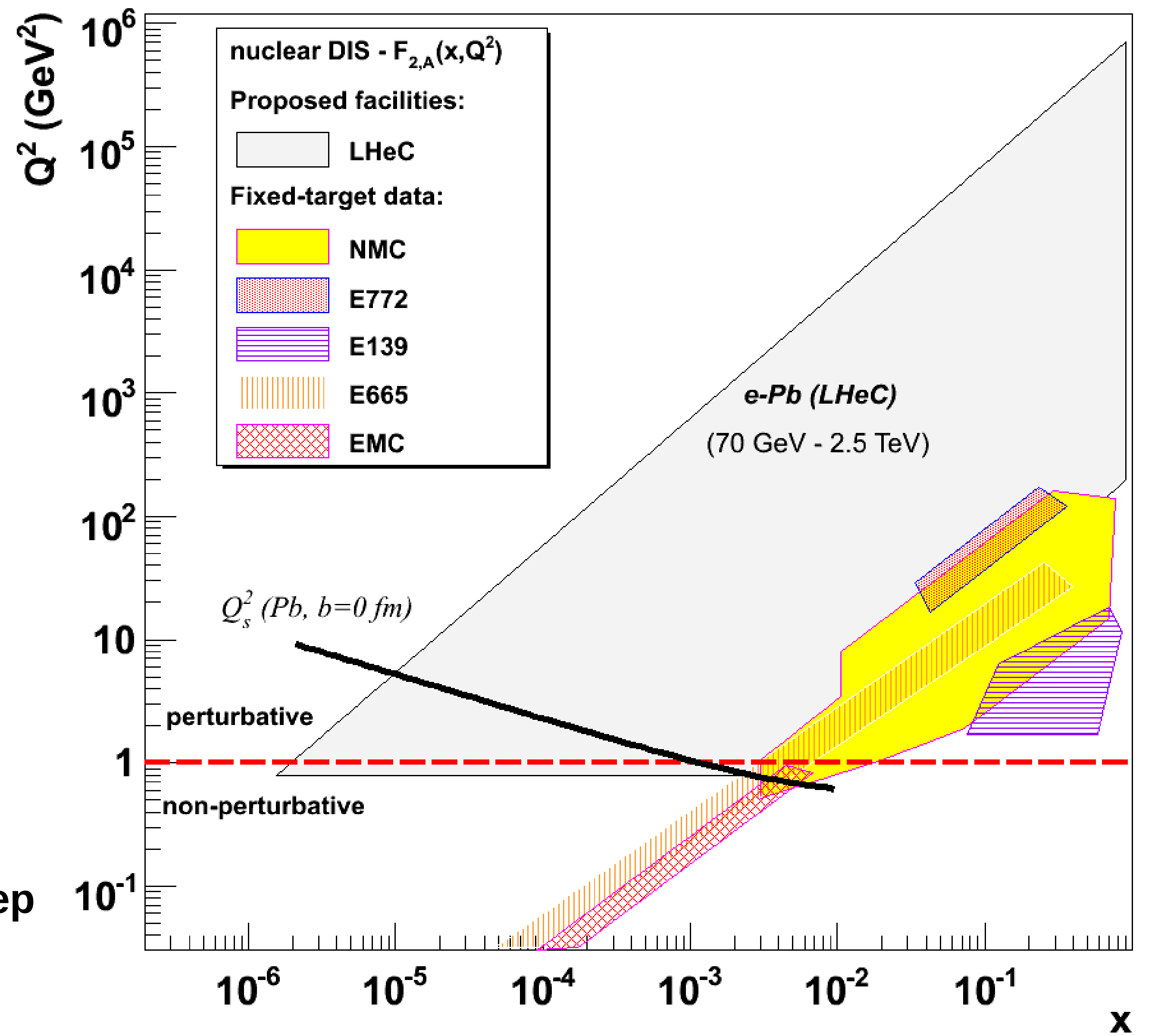


Extension of Q^2, 1/x range by 10^4

Fermi motion -- p tagging
Shadowing -- diffraction

p, D, Ca, Pb beams

Complete determination of nPDFs into nonlinear regime
LHeC is bound to discover parton saturation in eA AND ep



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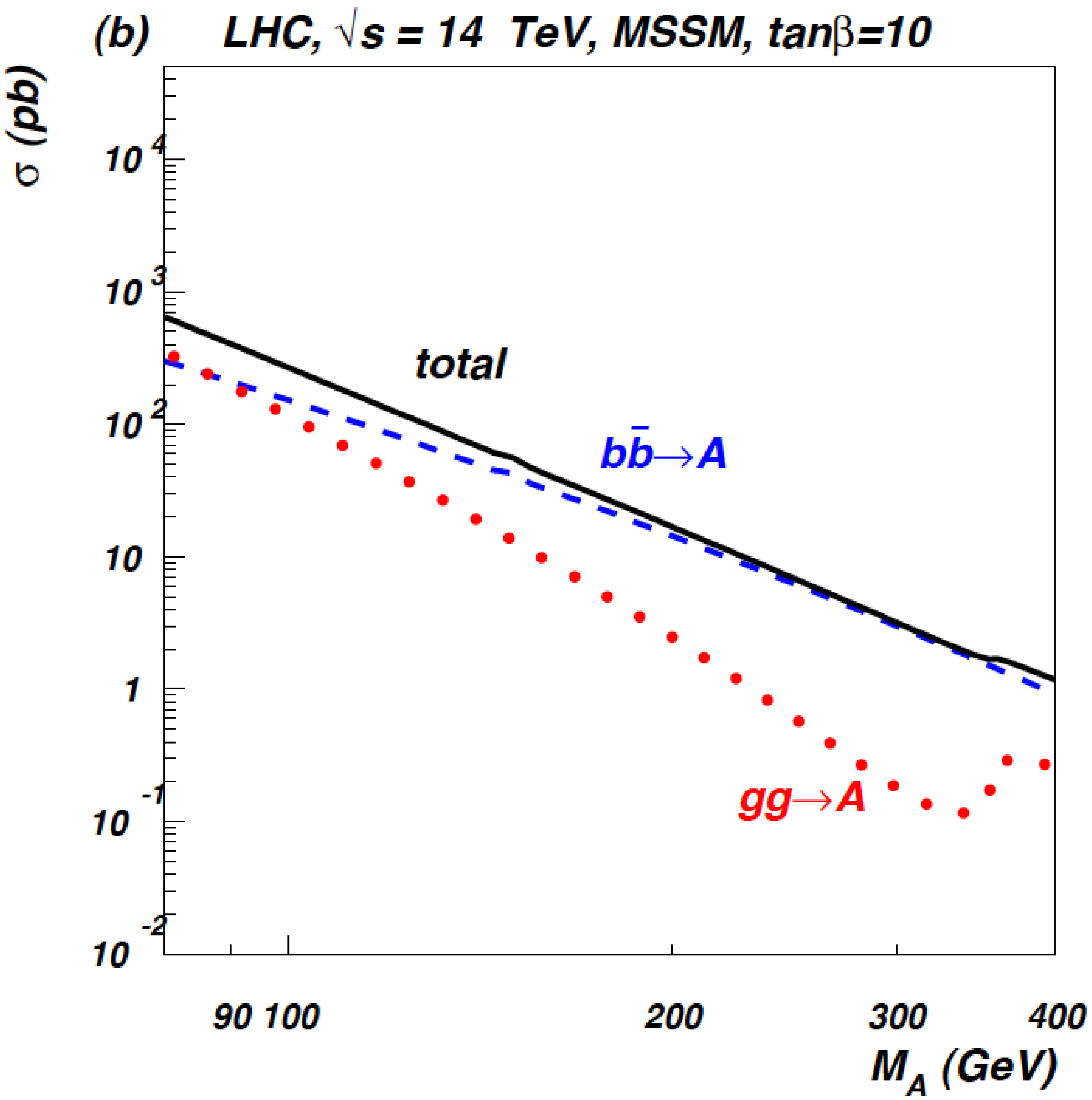
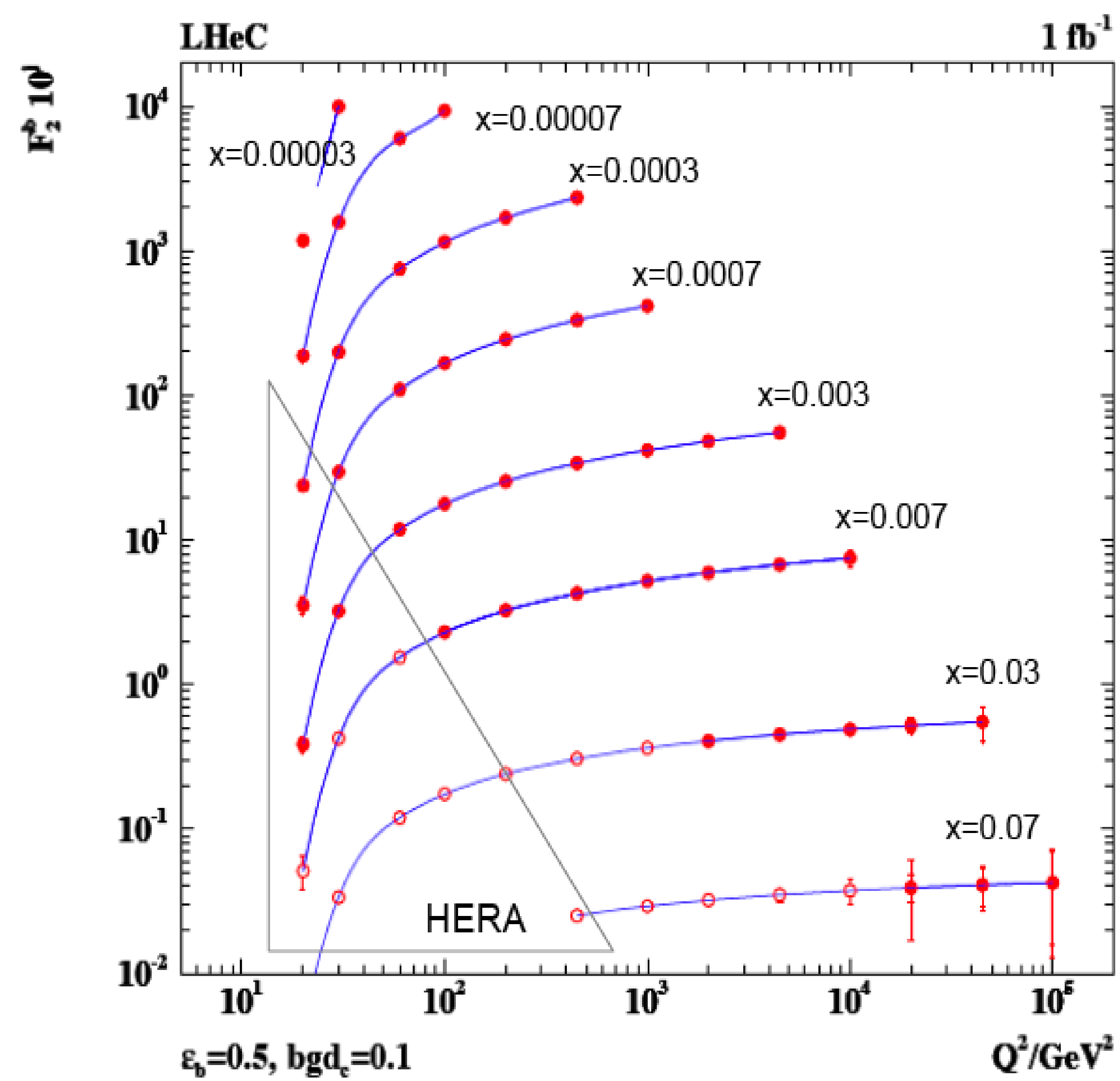
Physics - $e^{\pm}p$ Interactions



Beauty - MSSM Higgs



In MSSM Higgs production is b dominated

First measurement of b at HERA can be turned to precision measurement.

LHeC: higher fraction of b, larger range, smaller beam spot, better Si detectors

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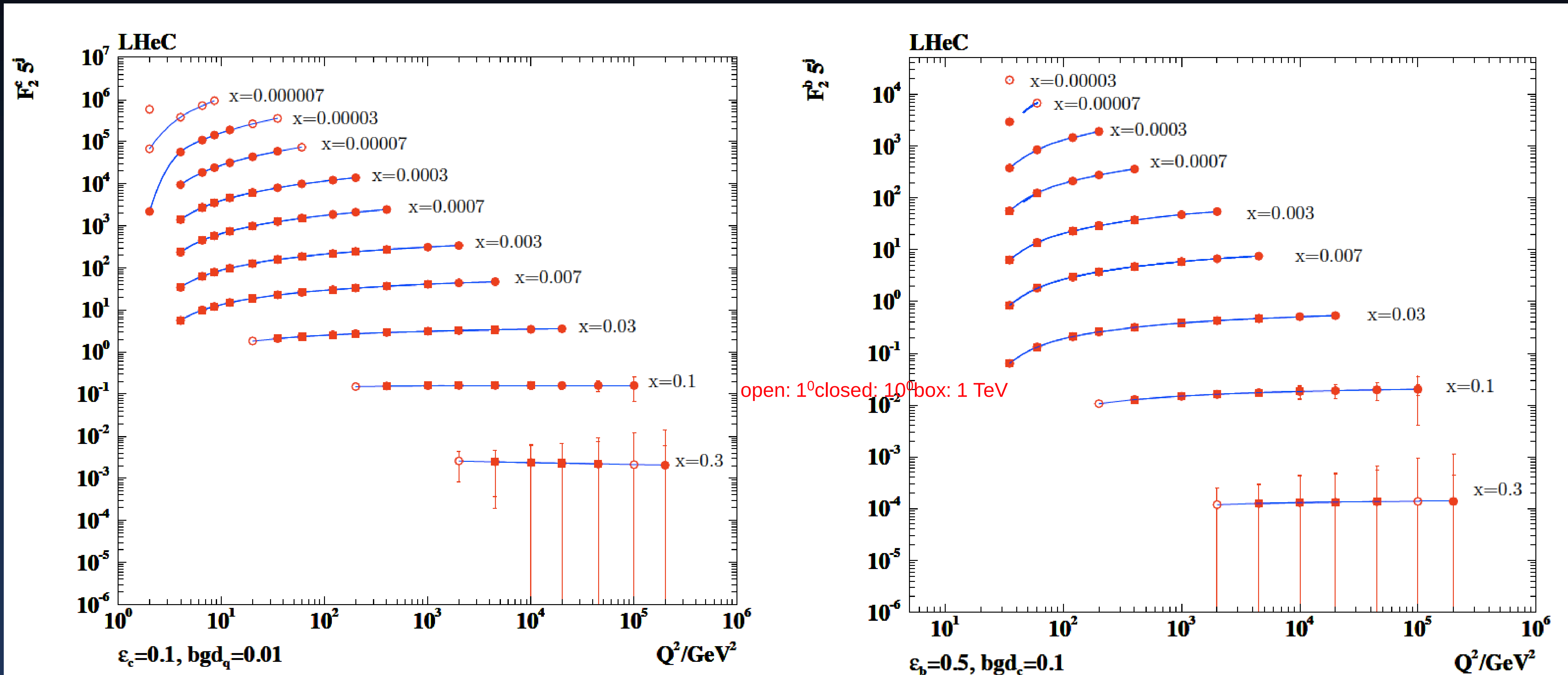
CHARM & BEAUTY



Systematic error dominates (so far 3%)Precise measurement near threshold and up to 105 GeV^{2}F2^{cc} will become precision testing ground for QCD and proton structure

Systematic error dominates (so far 5%)Precise measurement near threshold and up to 105 GeV^{2}Beauty may become crucial if MSSM Higgs is found

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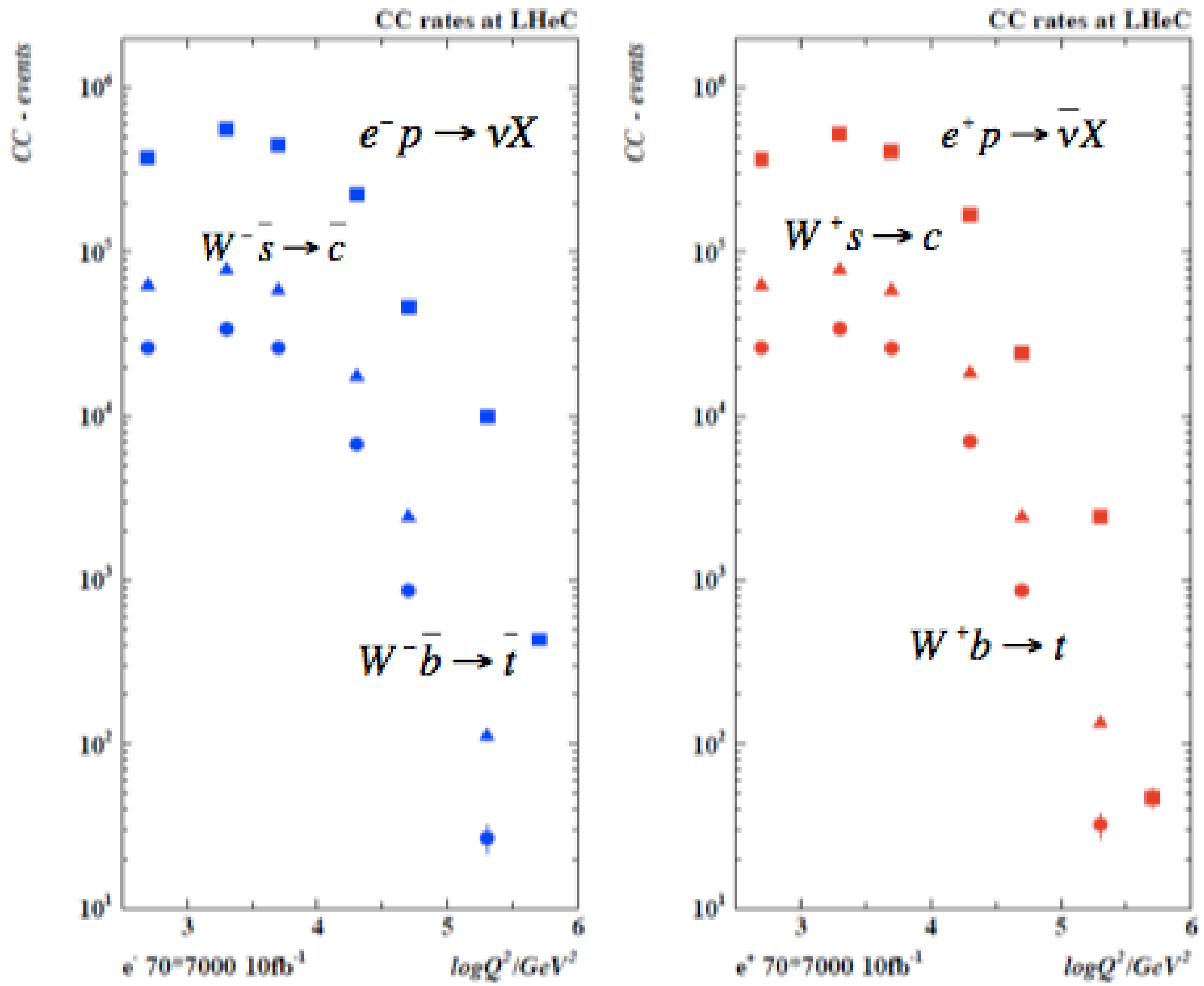
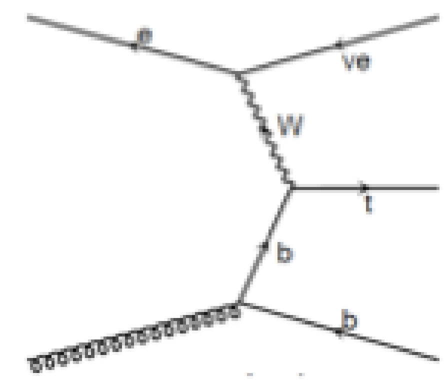
Even in the most favourable beam energy setting, a search for intrinsic charm at x≥0.1 would require charm tagging down to few degrees…

Requesting stringent Heavy Flavor tagging capabilities!

TOP

$\overline{\text{Top}}$ and Top Production at the LHeC (CC)





LHeC is a single top and anti-top quark factory

with a CC cross section of O(10)pb

Top at HERA essentially impossible to study. Single top at Tevatron barely seen and at LHC very challenging