Summary for FCC-eh

work and thoughts in progress

Max Klein
U Liverpool and CERN
for the FCC-he/LHeC Study Group

FCC-eh Baseline
New Physics
Detector and IR
Directions of Work

Rome, 15th of April, 2016

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Summary of the FCC-eh Parallel Sessions at the Annual FCC Workshop, Rome 11-15.4.16

Presentations on FCC-eh This Week

Monday Plenary Opening

Uta Klein : Physics and Experiment

Tuesday: Pheno+Thy Session

Chen Zhang: Higgs Physics in ep

Nestor Armesto: Electron-Ion Scattering

Voica Radescu: PDFs and QCD

Thanks to all speakers and contributors,
Thanks to the LHeC/FCC-eh study group,
to the FCC coordination, ee/hh colleagues
and to the CERN directorate for support.

Thursday 2 Parallel Sessions

Oliver Bruening: Status of the LHeC

Daniel Schulte: FCC-eh Parameters

Alessandro Polini: Detector Development

Saleh Sultansoy: High Energy lh Colliders

Charlie Cook: Civil Engineering

Emilia Cruz: Interaction Region Design

Max Klein: New Physics with eh

Nestor Armesto: Low x Physics in ep

FCC-eh was discussed much informally
and also in other sessions (hh, RF..)

Organisation

International Advisory Committee

"..Direction for ep/A both at LHC+FCC"

Guido Altarelli (Rome) +
Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) – Chair
Jurgen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (STFC)

Coordination Group

Accelerator+Detector+Physics

Nestor Armesto
Oliver Brüning – Co-Chair
Stefano Forte
Andrea Gaddi
Erk Jensen
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(11): members of the FCC coordination team

OB+MK: FCC-eh responsibles

Working Groups

PDFs, QCD
Fred Olness,
Voica Radescu
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

April 2016

A Baseline for the FCC-he

Oliver Brüning[1] Max Klein[1,2], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
March 3rd, 2016

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

Synchronous ep and pp (eA and AA) operation

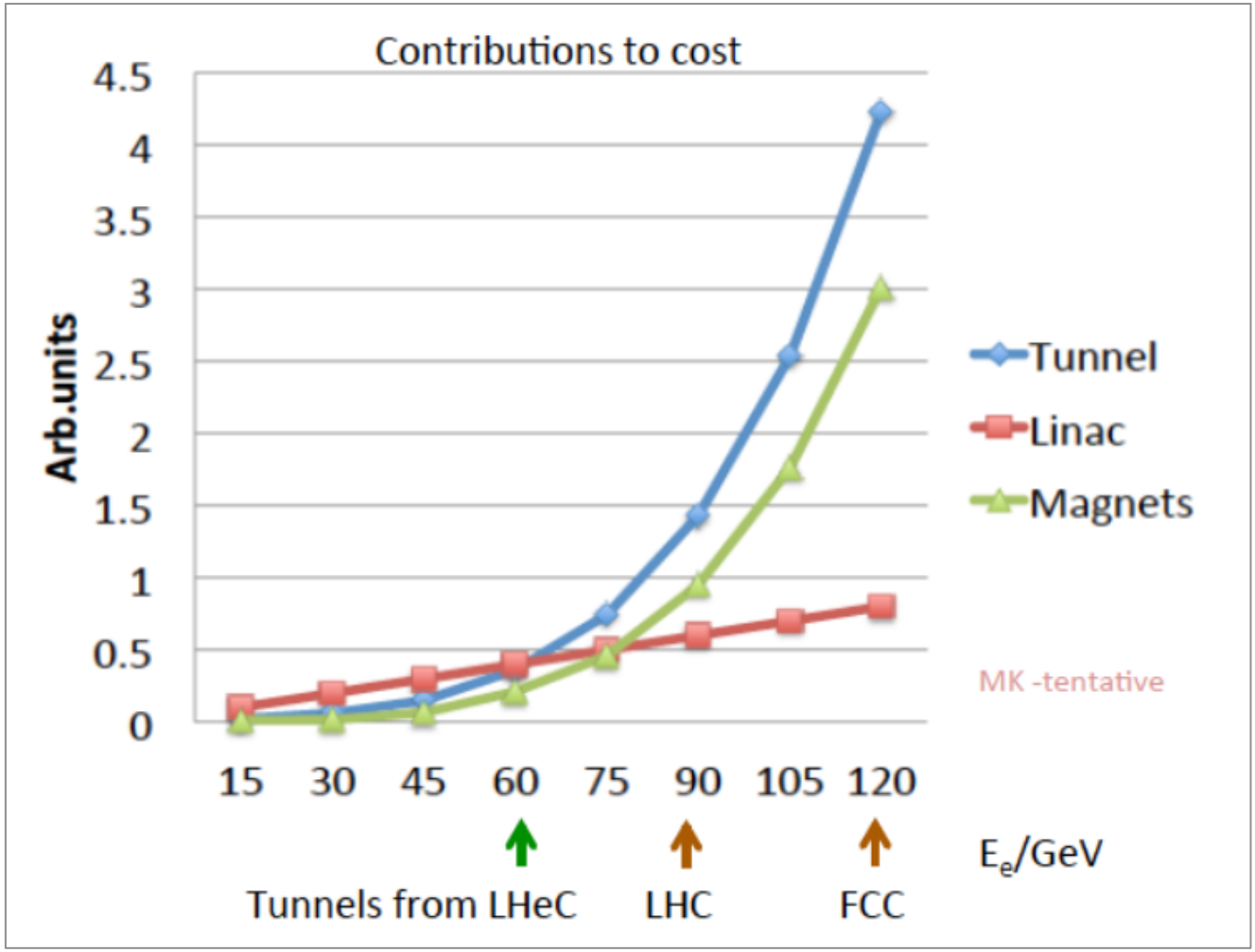
4.3.2016 - *work in progress* Study value of dedicated operation O(10^{35} cm^{-2} s^{-1}), also eA
14.4.: Presentation of Daniel Schulte (400 fb^{-1} in 5 years with 25ns, 150 fb^{-1} with 5ns only)

Beam Dynamics and 'front-end' Simulations:

- Key Studies (performed with PLACET2 code from CLIC):
  - ➔ Synchrotron radiation
    bunch shape and acceptance for deceleration and dump
  - ➔ Beam-beam interaction
    bunch shape and beam stability
  - ➔ RF Wakefields and HOM
    beam stability
  - ➔ Recombination patters
    beam stability (filling of the RF buckets can be controlled by tuning the arc lengths)
  - ➔ Cavity alignment requirements
    orbit and emittance control

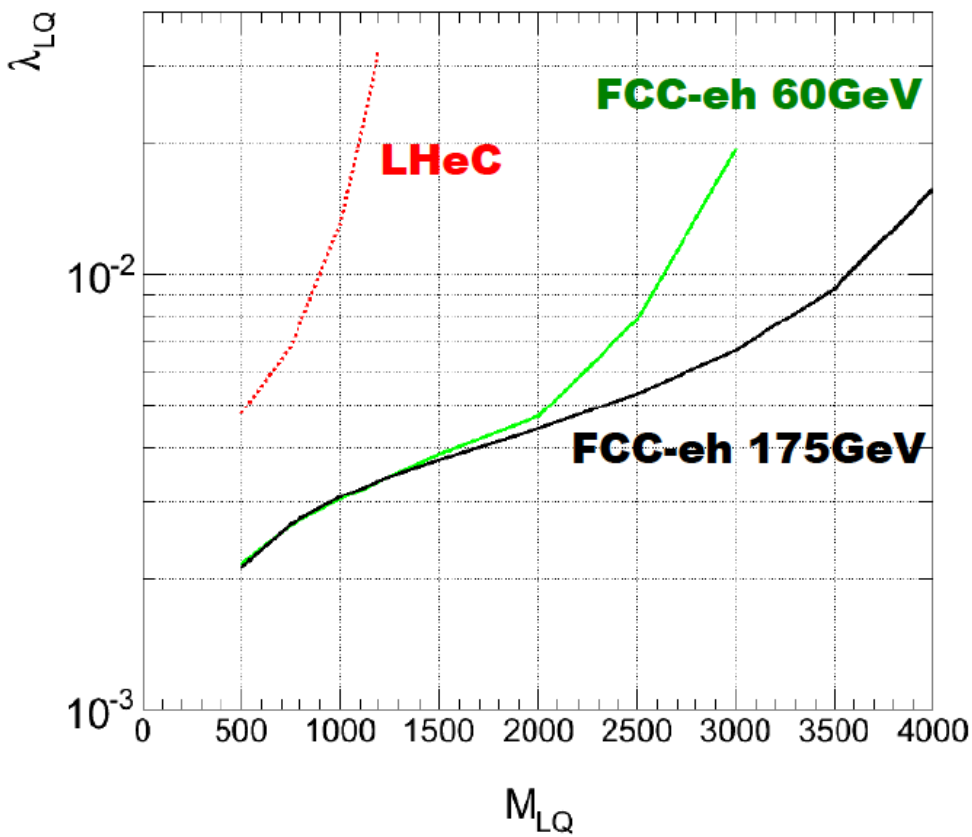
LHeC is a well developed baseline, but:
- It needs "proofs" for 10^{34} luminosity
- needs integration study into FCCpp/AA

Choice of Baseline Configuration = f(cost,E_e,s)



→ Cost strongly rising with tunnel circumference. Presently stick to LHeC default.
→ Maximise independence of ring installation, design for synchronous ep and pp OP

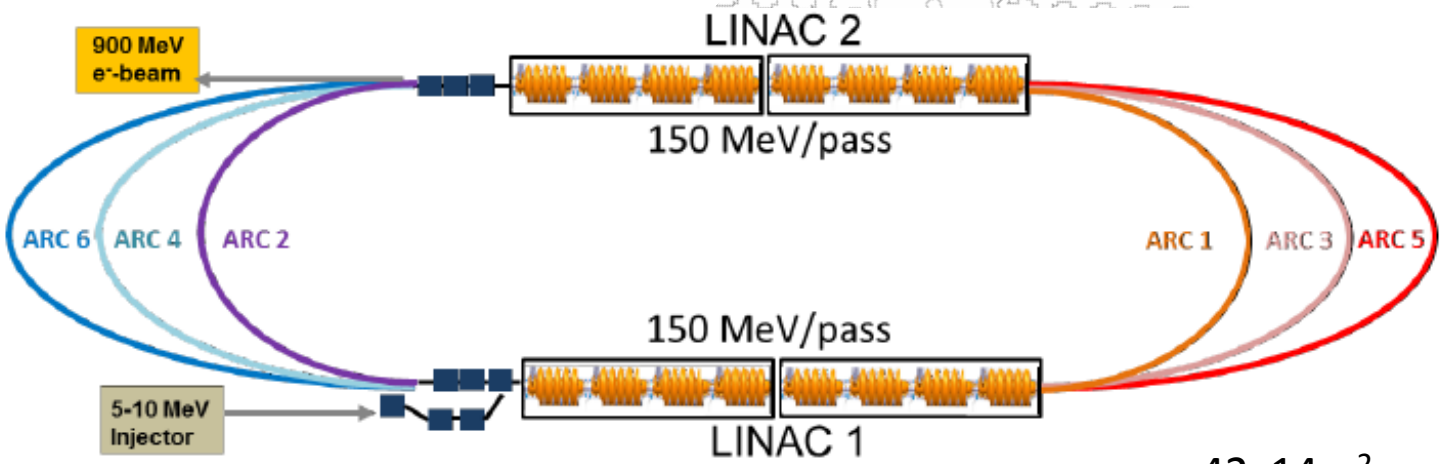
Choice of the Electron Beam Energy



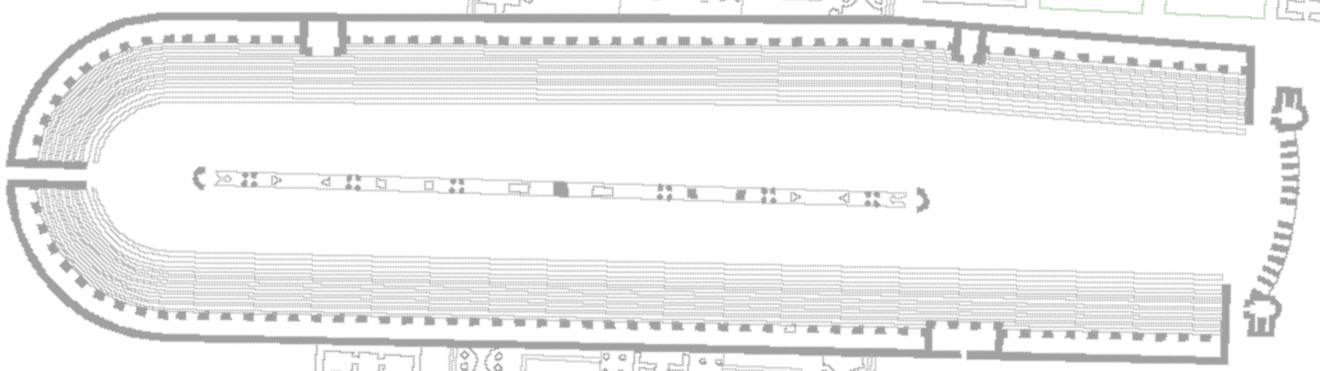
Stick to 60 GeV but consider reducing it keeping H, top, low x physics and stay open to go up

Major changes of lepton beam concept not in practical reach: LC, muon collider, PWA ..
Simultaneous installation and operation of e and p beams in the FCC tunnel is not considered, for reasons of power and logistics and complexity of installation. It is considered for Beijing.

802 MHz, High Current ERL Test and Physics Facility



42x14m^2



Circus Nero:

Begun 37AD by Caligula and finished by Claudius. Site of games, races and of the first, state sponsored martyrdoms of Christians in 65, including St Peter (in 67).

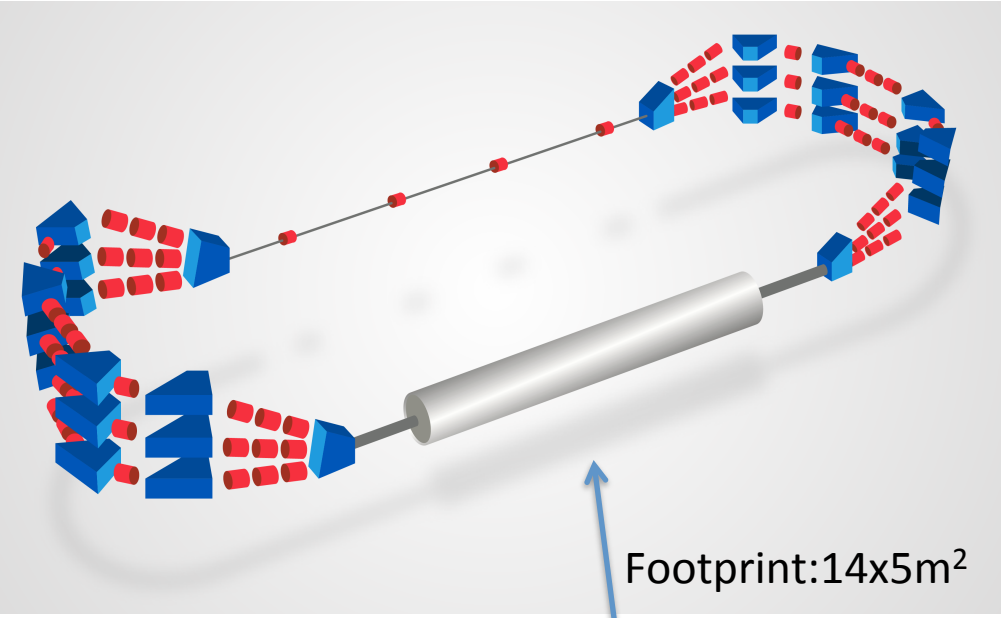
ERL Demonstrator

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

E_e = 200 (400) MeV with 1(2) module

A.Valloni 2/16



Parameter	Value
Dipoles per arc Dipole length Max B Field	3/4 50 cm 1.1 T
Quadrupoles per arc Quadrupoles in straight lines	5 4
Dipoles in Spreader/Combiner Quads in Spreader/Combiner	1-3 3
Dipoles for Injection-Extraction	6

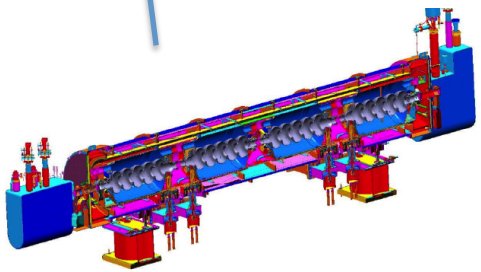
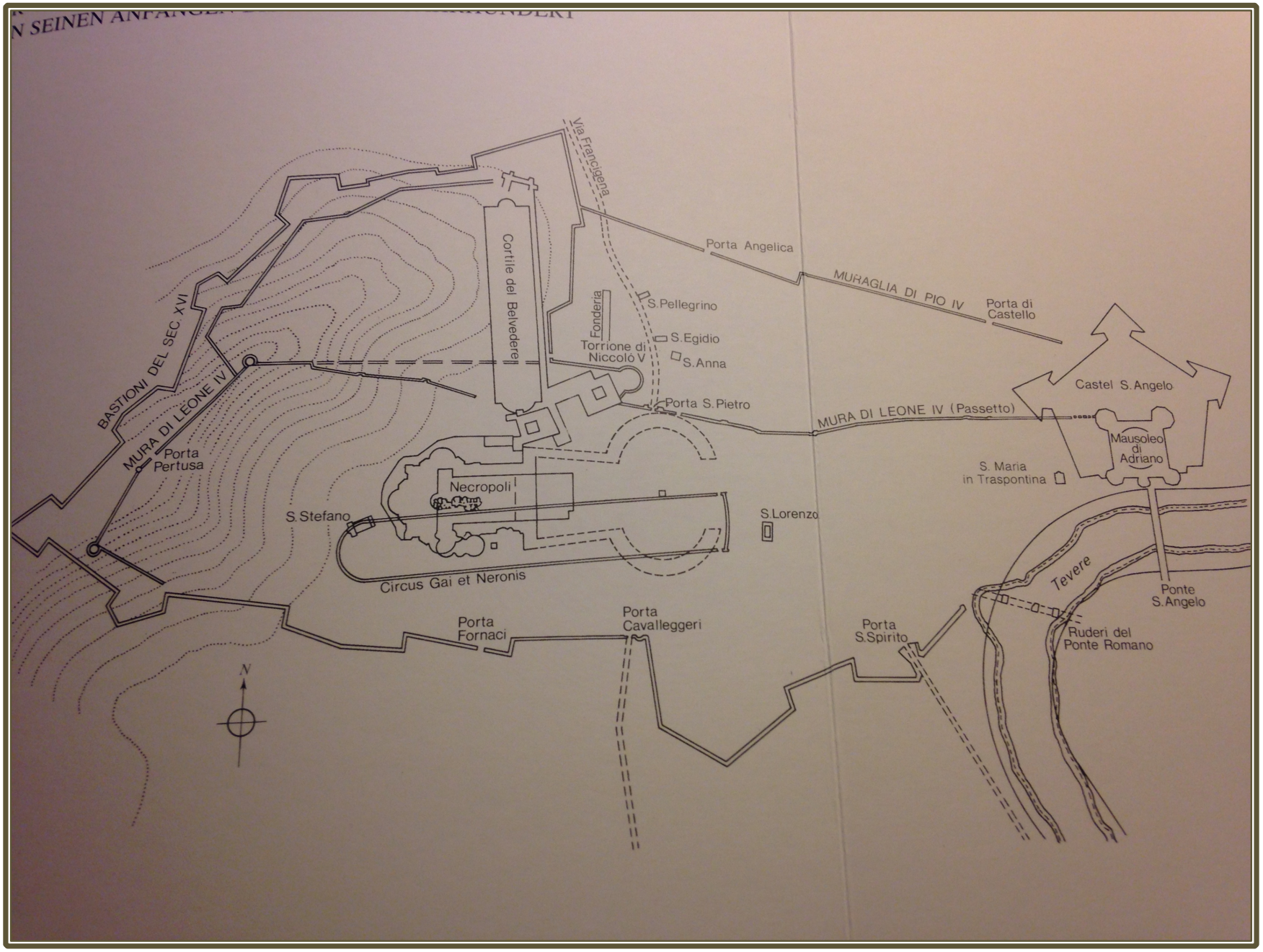


Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

M.Klein, Talk on FCC-eh at Istanbul 2/16

Work in progress

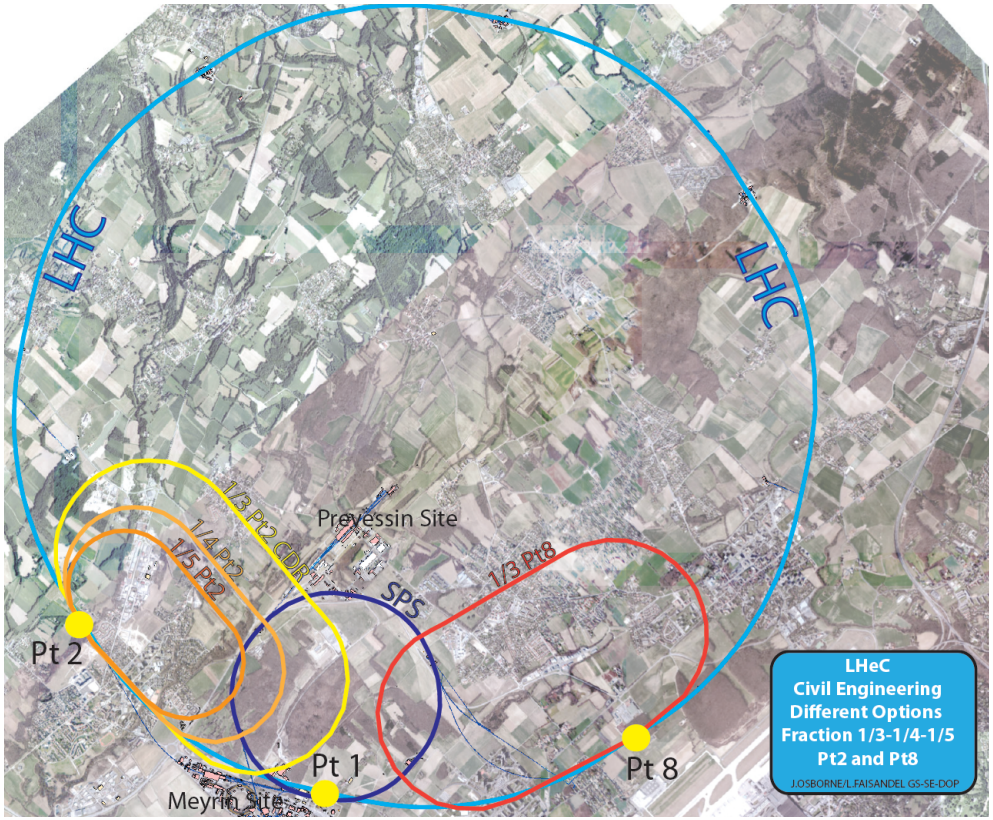


Vatican XV Century - a racetrack must be embedded in something bigger to make sense

FCC-he Civil Engineering

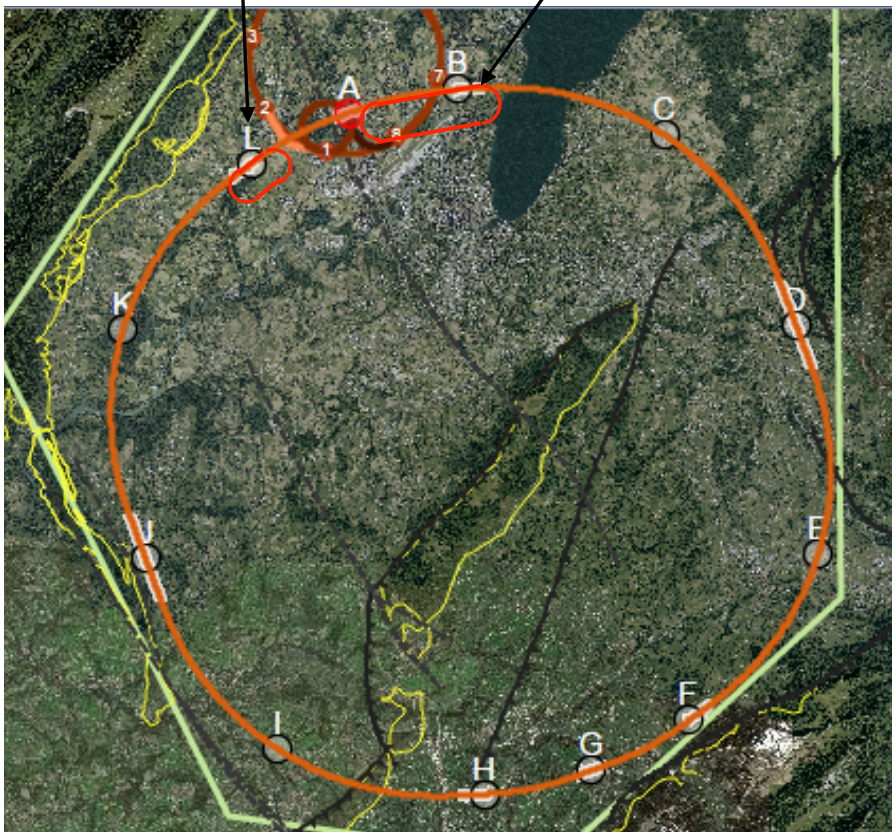
LHeC and FCC-he

LHeC Machine

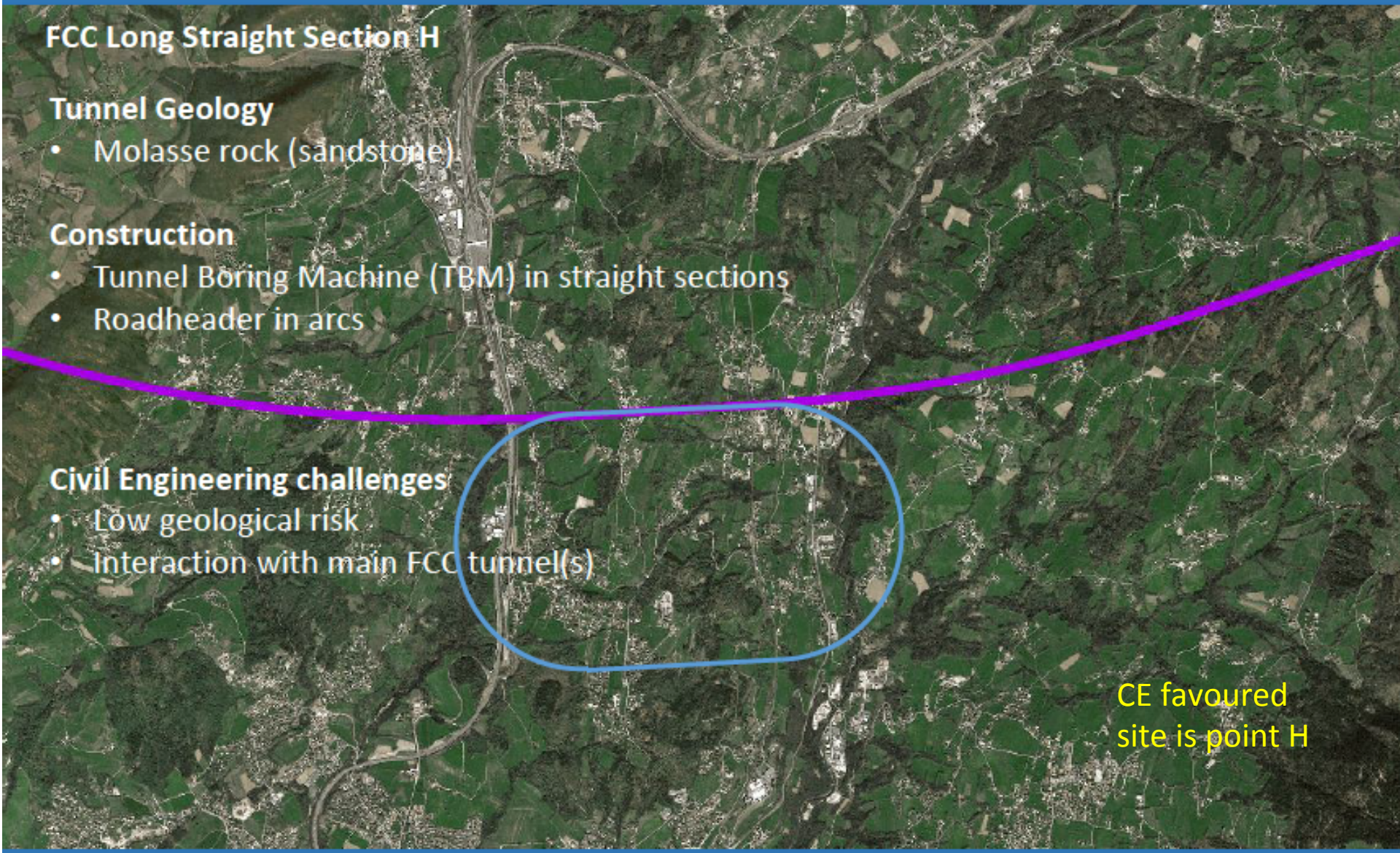


Independent FCC-he
Point L, F, H or B

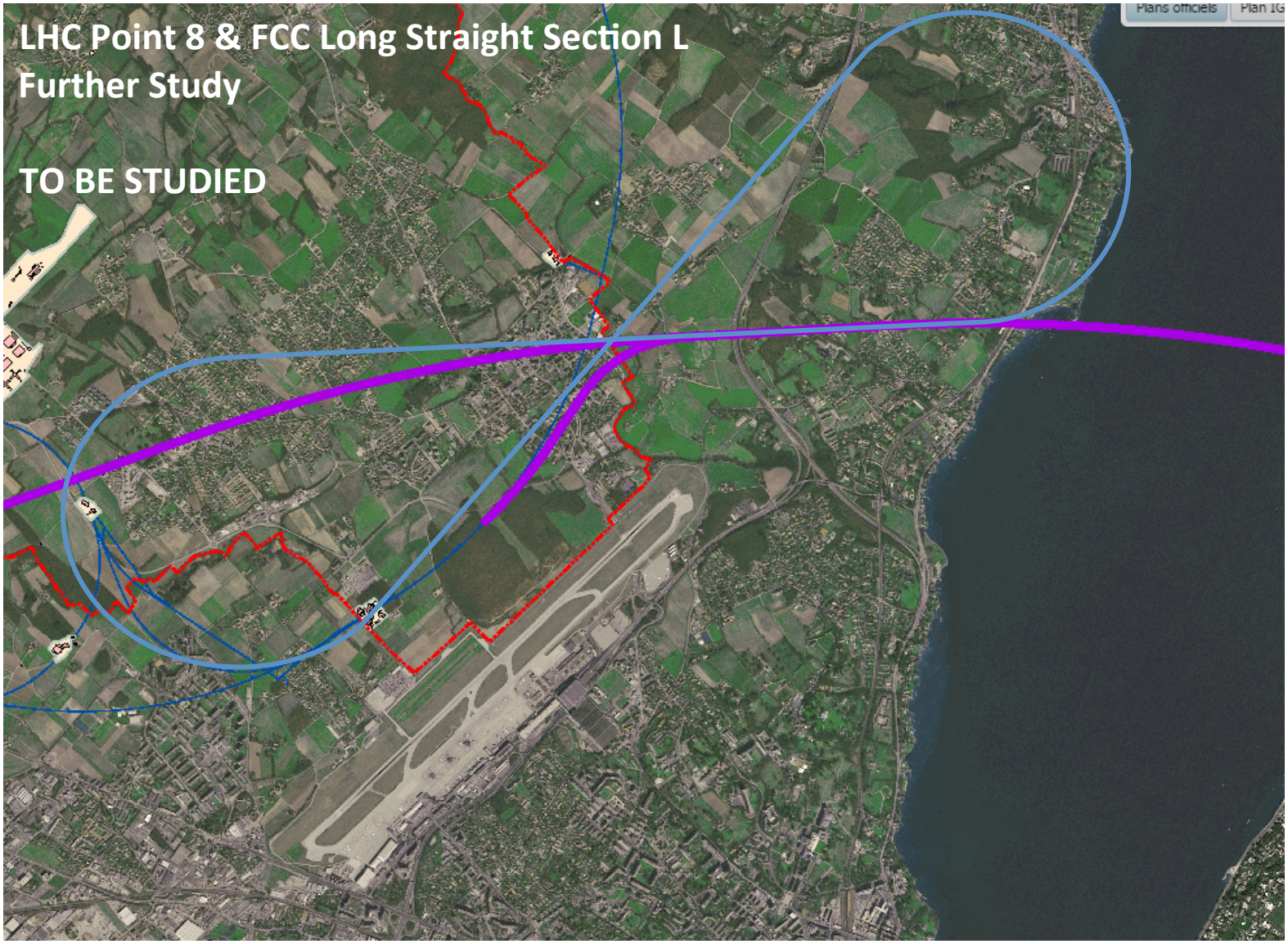
LHeC / FCC-he
LHC P8 & FCC PB



FCC-he Point H

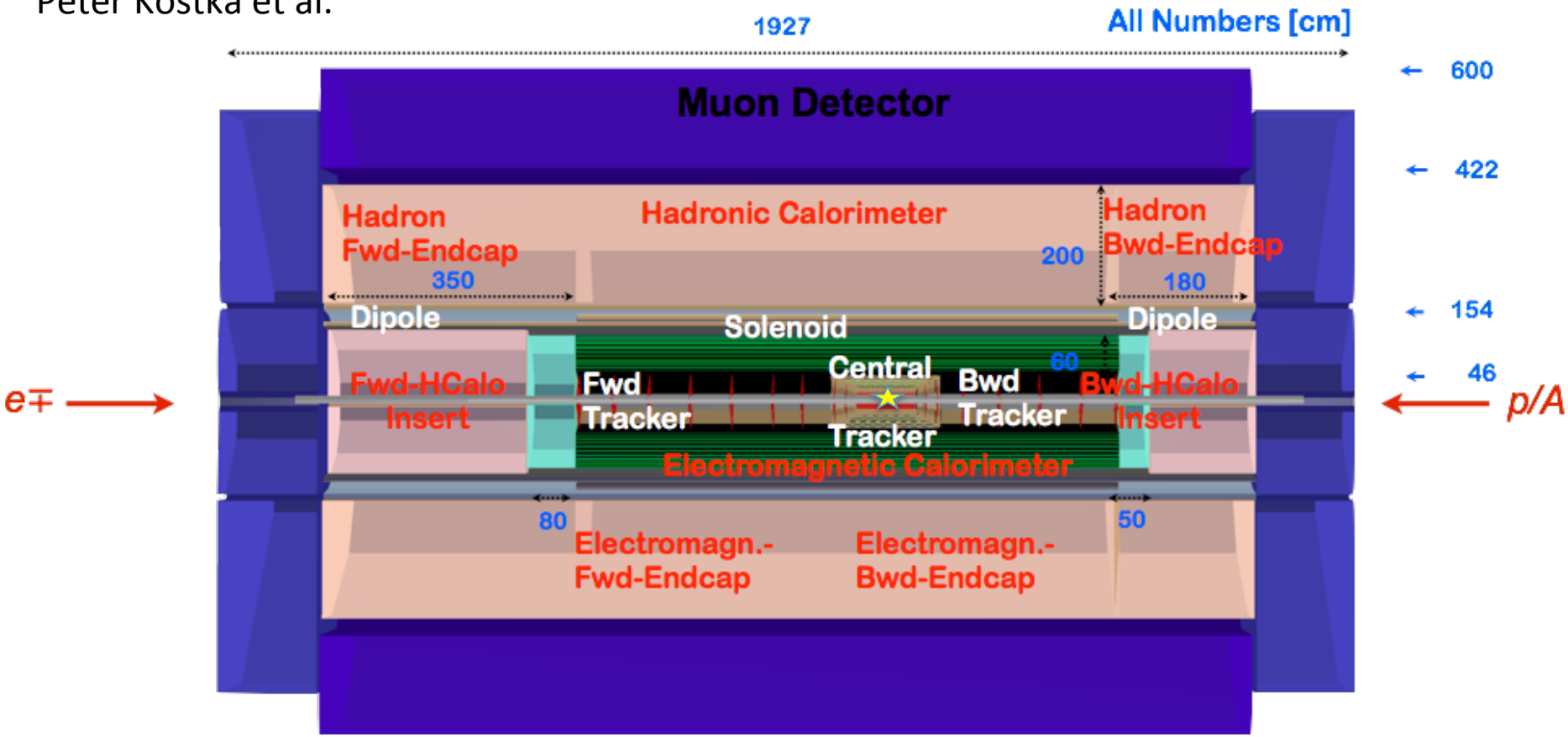


LHeC/FCC-he Civil Engineering



FCC-he Detector Study

Peter Kostka et al.

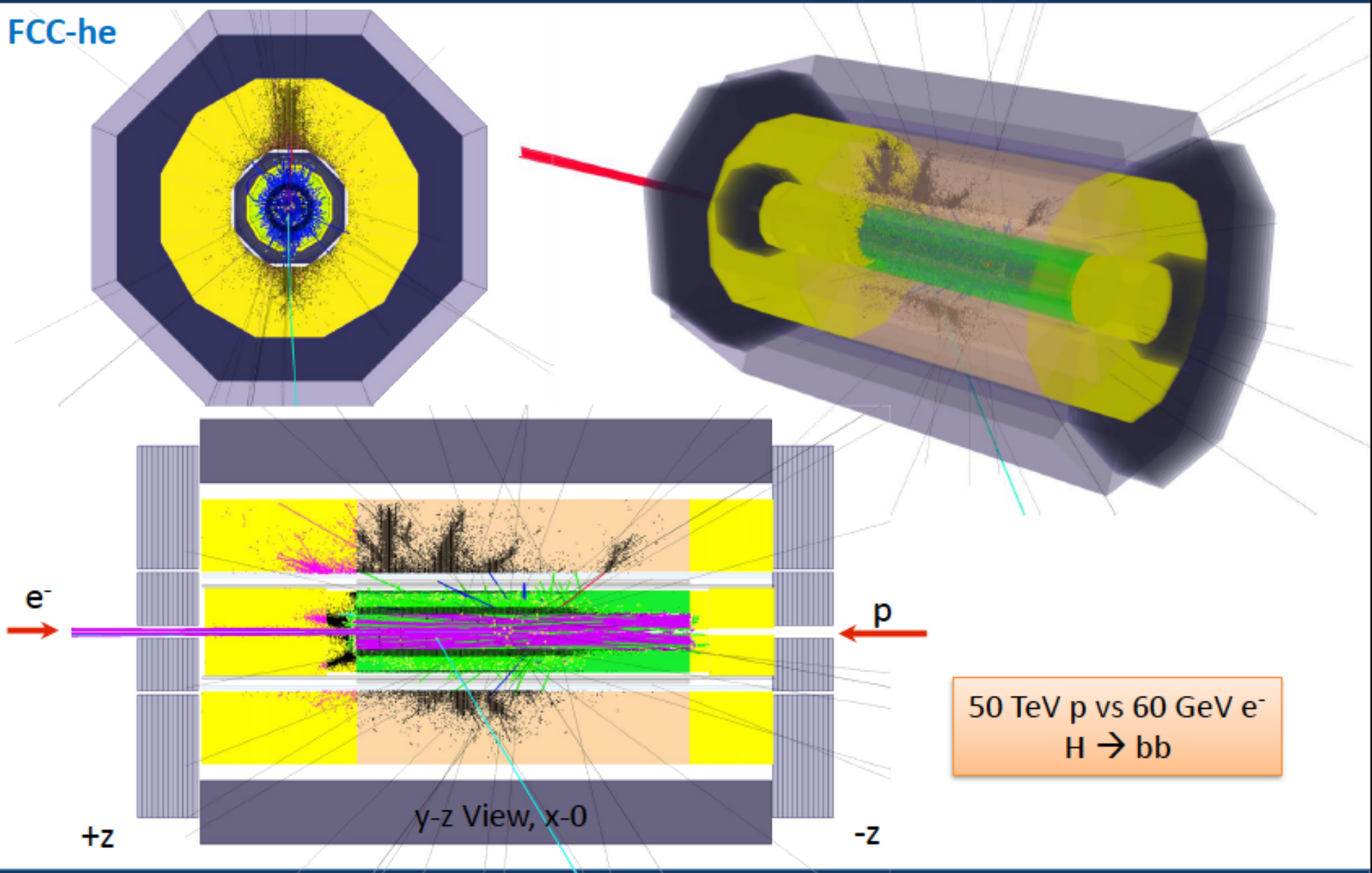


- Very preliminary FCC detector design: extension of LHeC baseline detector
- Dimensions 20 x 12 m, transverse and longitudinal (fwd) sizes scaled w.r.t. LHeC
- Assumption of similar electron beam steering dipoles as in LHeC baseline design

Note added: LHeC→HE-LHC→FCC-he: 1→1.4→2 scaling the fwd dimension

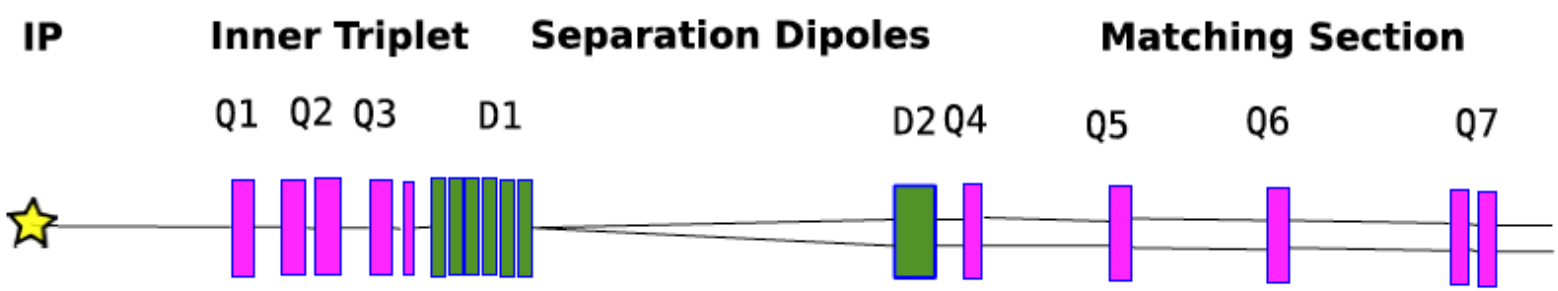
Alessandro Polini 14.4.

First FCC-eh Simulations



50 TeV p vs 60 GeV e^-
$H \rightarrow bb$

Interaction Region



Fcc-eh design presents some advantages:

1. IR can be design to be adapted to luminosity requirements (Not on a previous design).
2. More relaxed β* (15 cm instead of 10 cm)

Comparisson with FCC-hh:

R. Martin Talk

On-going work for β* below 20 cm.

FCC-he might provide more flexibility in L* (FCC-hh detector requires L*>45m)

Principal solutions exist from LHeC. However, the IR is the most challenging part and more dedicated study is required. Collaboration with 'sweet' B.Parker, R.Tomas et al

some bits of physics

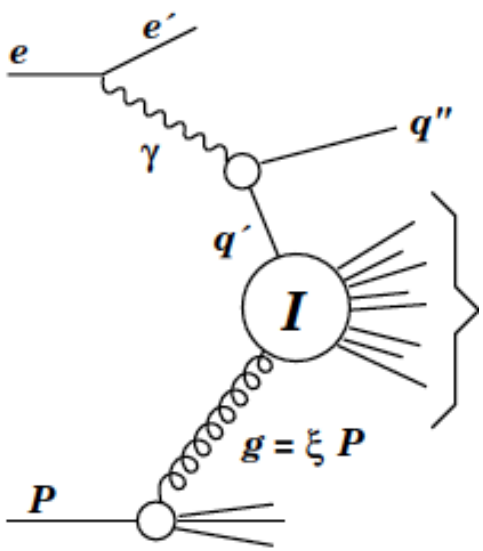
Gluon in many facettes
PDFs in ep and eA
top
Higgs
BSM Higgs
Low x
Heavy Neutrinos…
..

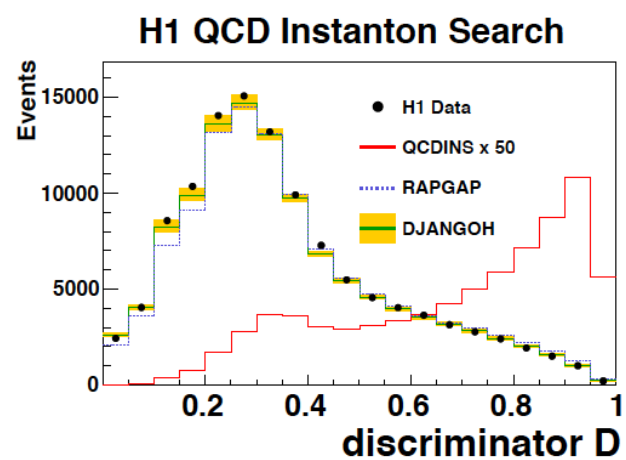
Deep Inelastic Scattering at the Energy and Intensity Frontier is a unique lab for PP

Fluctuations of the Gluon Field - Instantons ?

The Standard Model of particle physics contains certain anomalous processes induced by instantons which violate the conservation of baryon and lepton number $(B + L)$ in the case of electroweak interactions and chirality in the case of strong interactions [1,2]. In quantum chromodynamics (QCD), the theory of strong interactions, instantons are non-perturbative fluctuations of the gluon field. They can be interpreted as tunnelling transitions between topologically different vacua. Deep-inelastic scattering (DIS) offers a unique opportunity [3] to discover a class of hard processes induced by QCD instantons.

NEW:
H1: DESY 16-150
March16
O(3)pb xsection limits

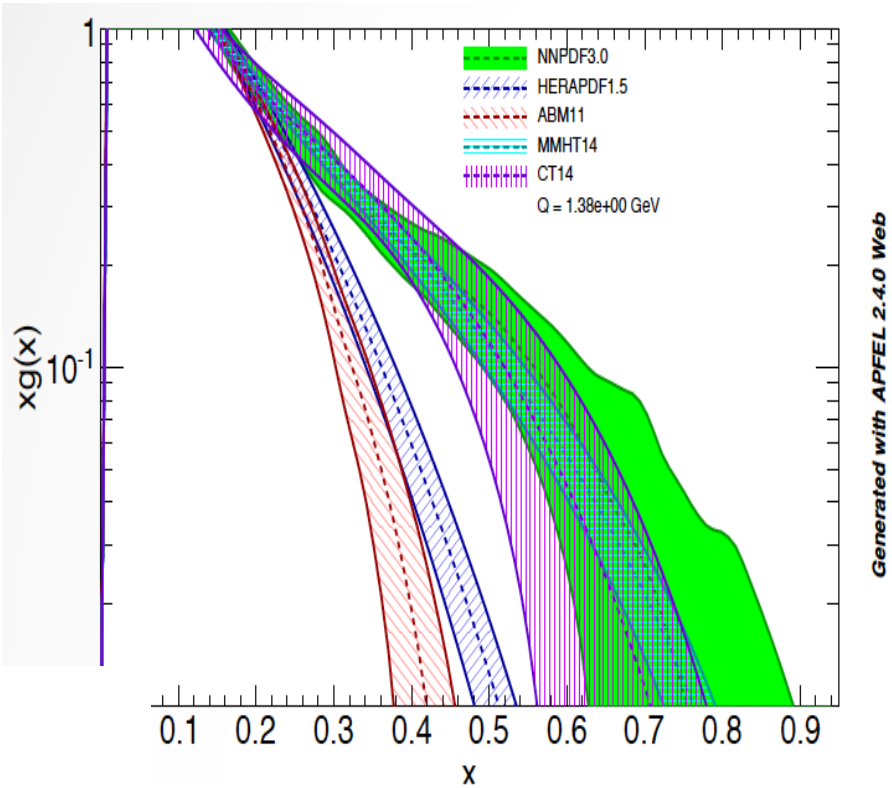




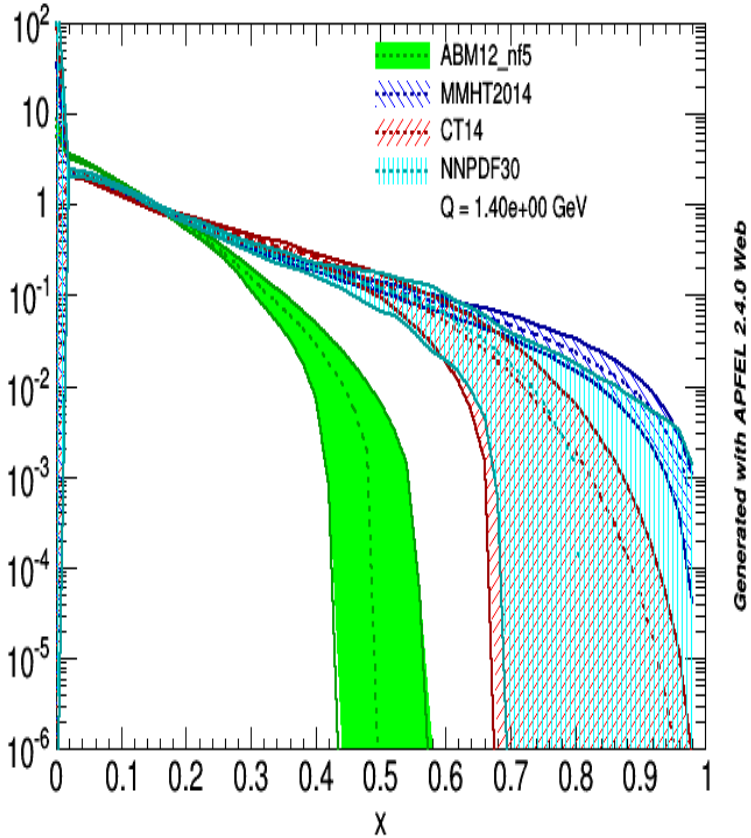
Max Klein, 14.4.

Gluon at High x and Universality.?

C.Gwenlan



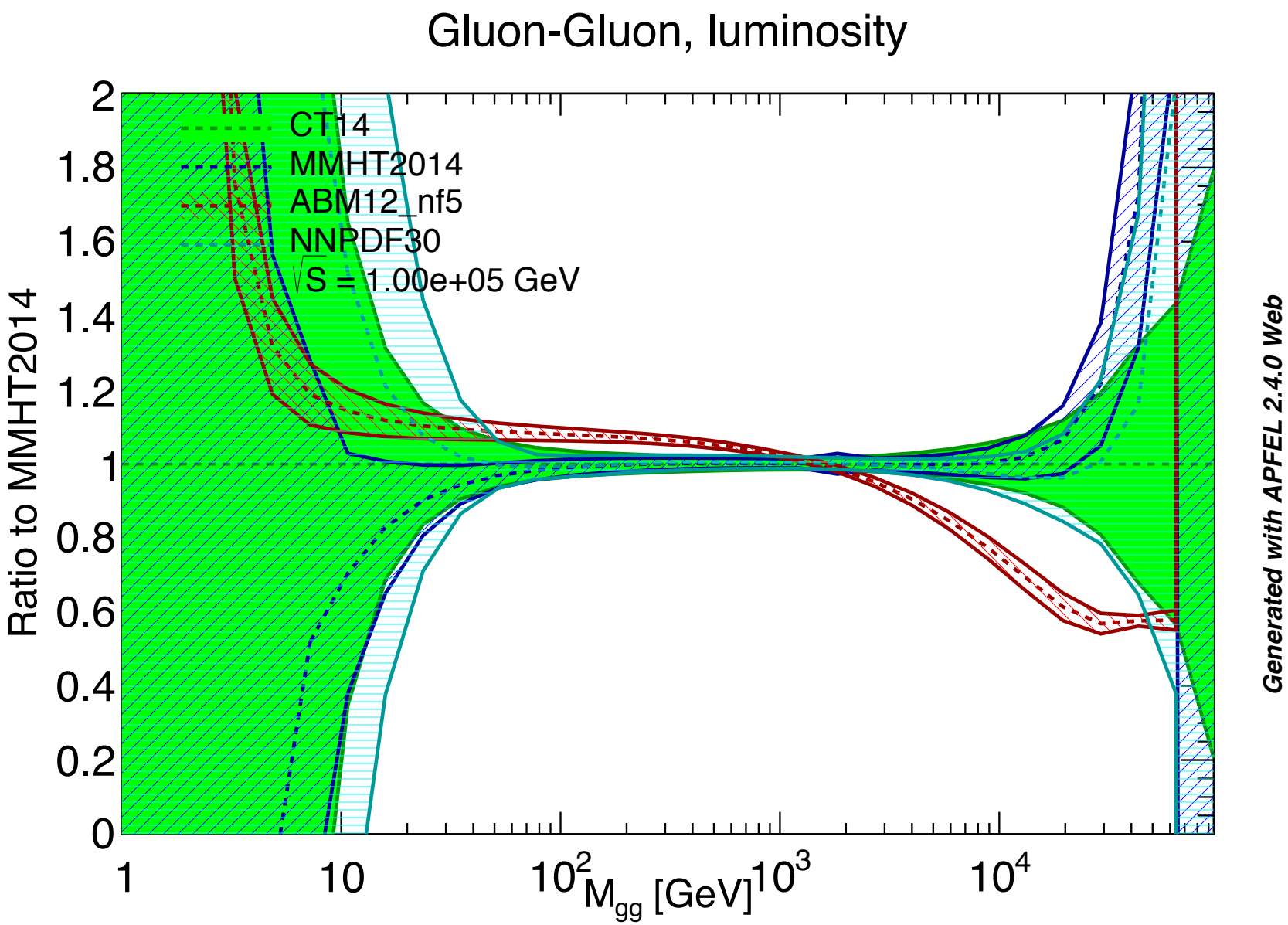
xg(x,Q), comparison V.Radescu



HERA and ABM gluons are much steeper at large x than those of MMHT,CT,NNPDF

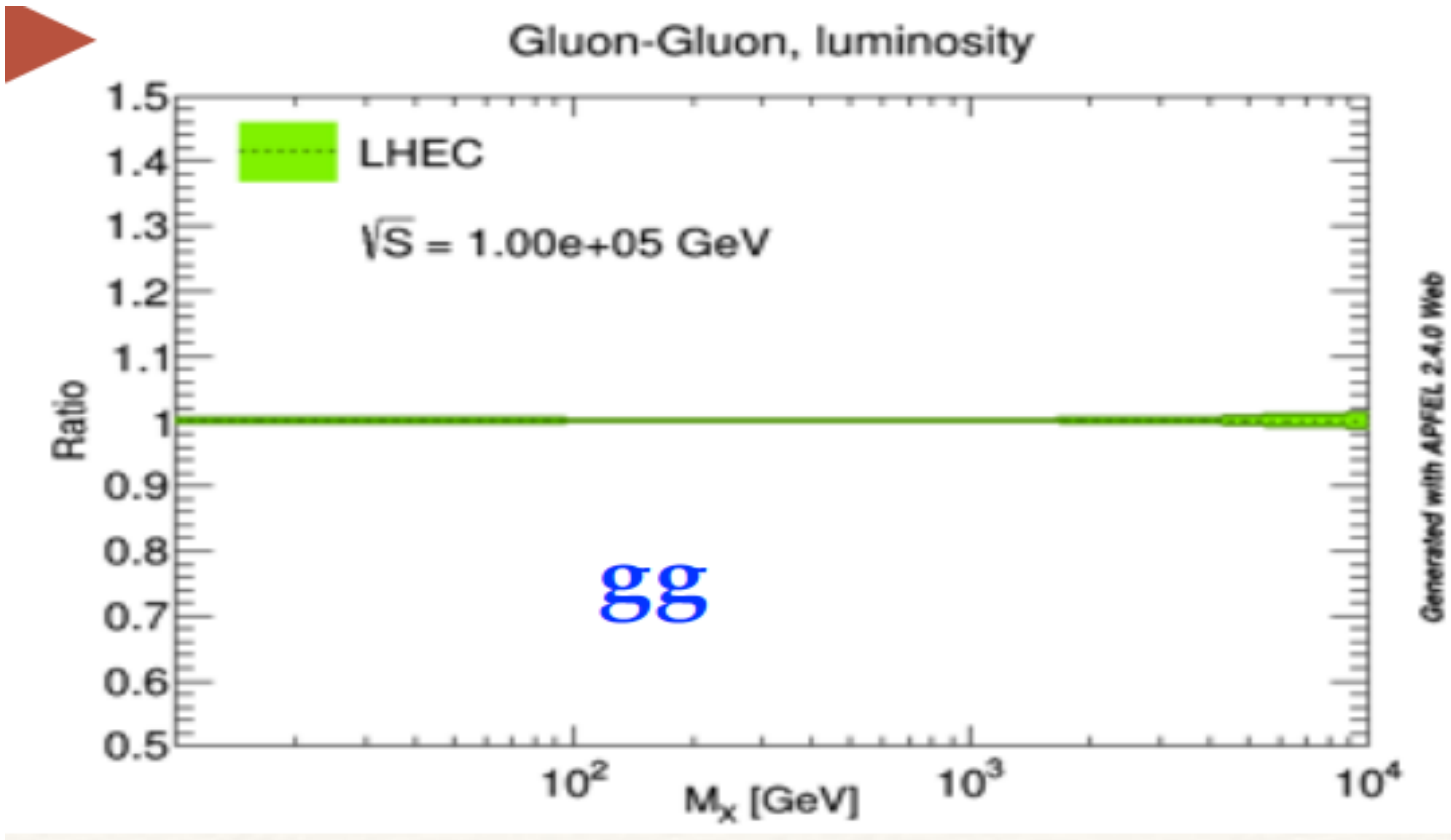
→ Can we trust factorisation, how do we test it

Gluon at large x become very small and are hugely uncertain. But $M_X^2=sx_1x_2$ ..



Current status of gluon-gluon sub-cross section uncertainty at FCC (hh) vs mass produced

The unique value of PDFs from ep DIS: Complete set of quark and gluons: Unprecedented precision, independence of symmetry assumptions, N^3LO
→ clean prediction for substructure, QCD, Higgs and searches in pp



Needs extension of grid beyond $Q^2=10^8$ GeV^2 ..

V.Radescu

Expected gluon-gluon sub-cross section uncertainty at FCC (eh) vs mass produced

Remarks on Precision Higgs Physics in ep

The Higgs is produced in ep predominantly via WW→ H in ep→ nuHX

The cross section at the LHeC is ~ 200fb, i.e. very similar to that of Z*→ZH in ee

With $1ab^{-1}$ integrated luminosity from 10^{34} one reaches 1% precision on bb
and 7% on cc and corresponding numbers on other channels still to be studied.
These LHeC numbers will be better at HE-LHC and FCC-eh (1%→0.4%→0.3% for bb)

At the FCC-eh the cross section is almost 1pb. Therefore, statistically, FCC-ee, with 4 10^34 luminosity at ZH and FCC-eh with 10^34 luminosity are about comparable, subject also to the running times: ee at ZH plans 3 years, ep with pp plans O(10).

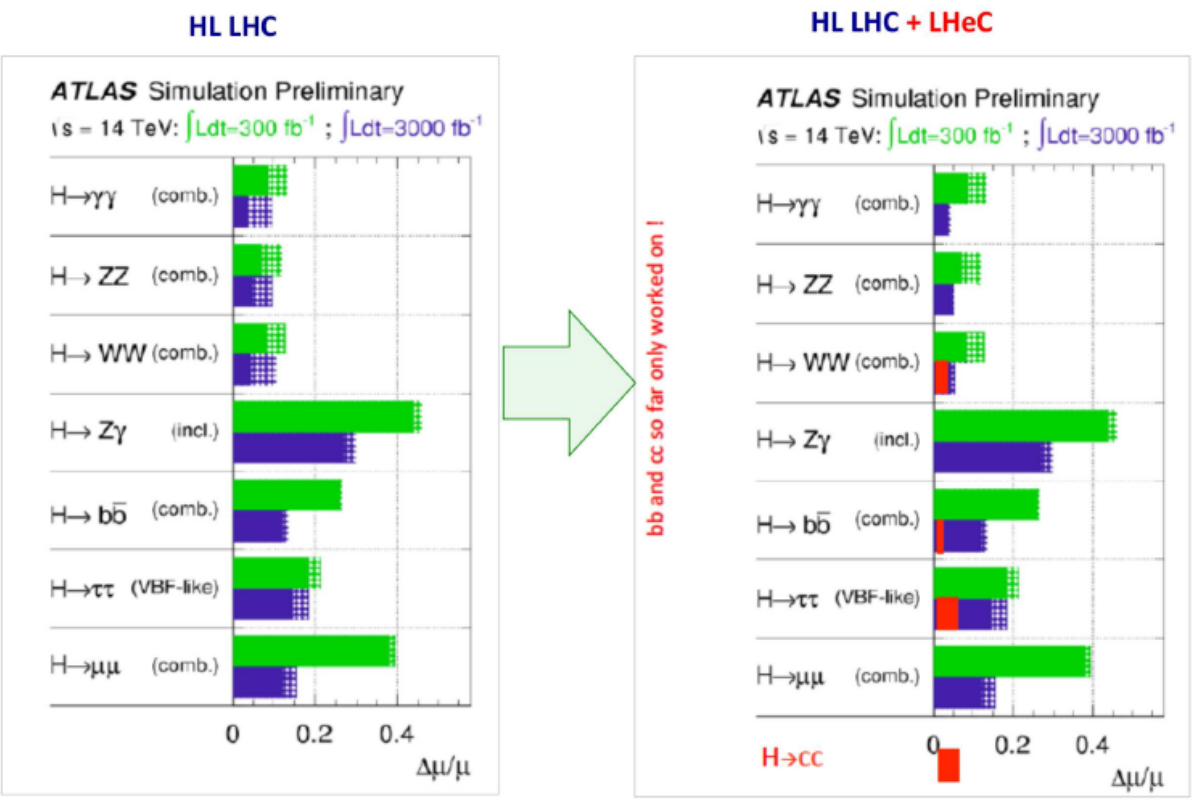
Both ee and ep thus provide high precision measurements on Higgs, much complementary wrt each other AND to pp: for example

- ee uses mostly Z→ ZH, eh uses mostly WW→ H
- ee provides measurement of the Higgs boson width (to be studied in ZZ→ H at ep)
- ep provides N^3LO PDFs as are crucial for understanding the gg→H production
  it also provides prediction of Higgs mass with 100 MeV error (cf top mass and cross section physics)
- ep also provides sensitive measurement of HHH,WWHH (arXiv:1509.04016)

Prior to FCC: LHeC and HL-LHC are an exciting couple for precision Higgs physics at LHC

HIGGS PHYSICS AT THE LHEC

SUMMARY



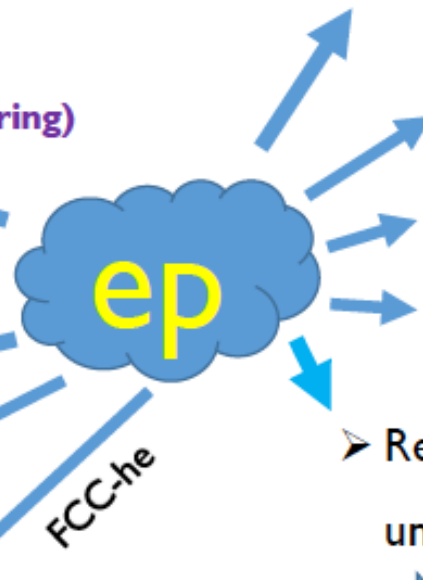
- GLUON FUSION AND W FUSION $\Rightarrow$ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

Turn LHC into precision Higgs facility: add PDFs add ep channels (bb,cc.)

The Phenomenological Higgs Landscape (Revisited)

Future ep colliders could make important contribution to Higgs physics!

- Mass
- Width (via VV scattering)
- Spin-Parity
- Coupling
  - hVV, hff
  - 3h,4h, hhVV
  - FCNC coupling



- Exotic Higgs Decay
  - h to invisible
  - h to 4b
  - …

➢ Reducing PDF & Alpha_s uncertainties in Higgs measurements

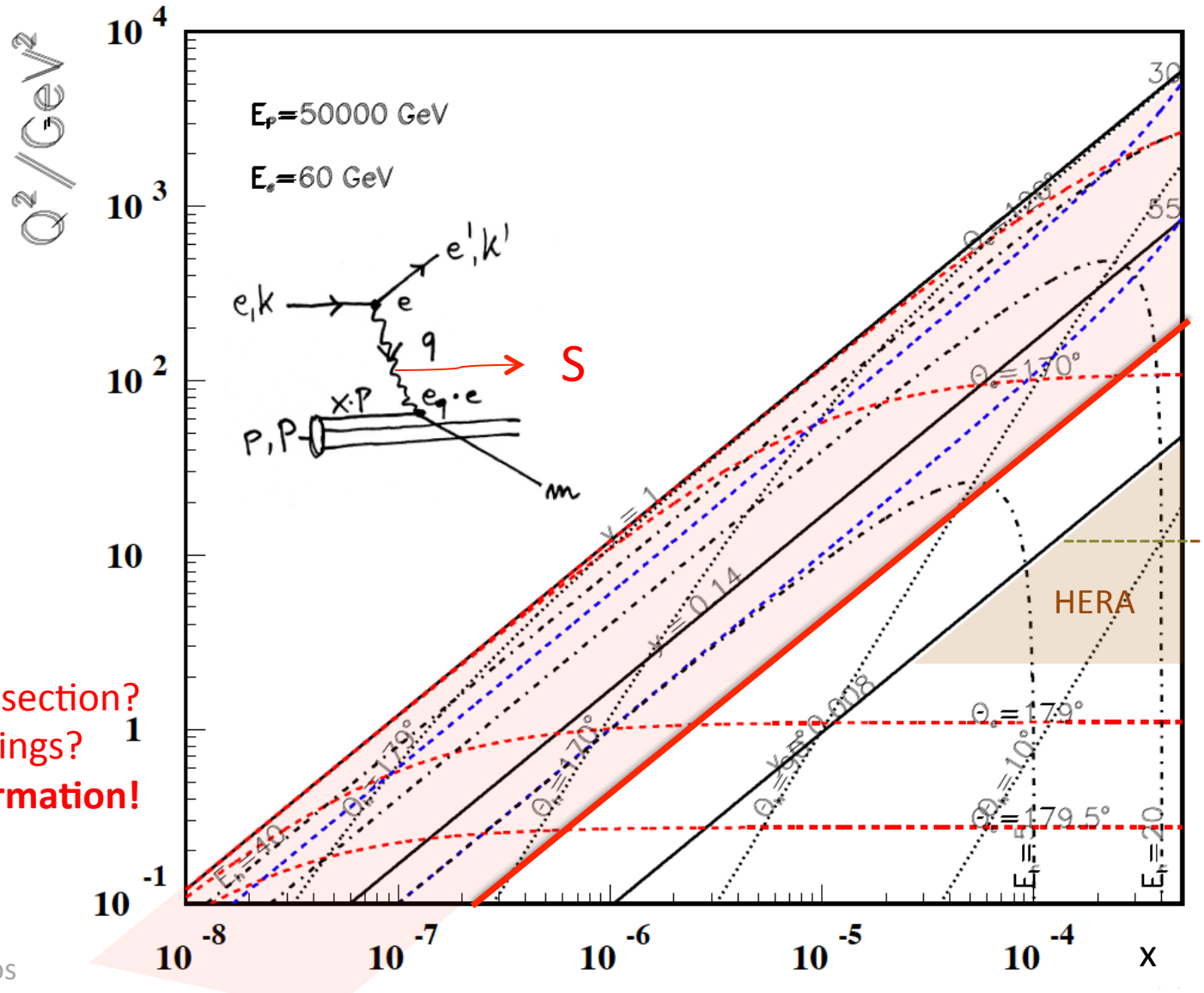
See talk given by Voica Radescu

Philosophy could be traced back to Phys. Rev. D82 (2010) 016009 by T. Han and B. Mellado.

See also:
M. Kumar et al., 1509.04016
S. S. Biswal et al., Phys. Rev. Lett. 109 (2012) 261801
U. Klein, talk given at LHeC Workshop 2015

Chen Zhan 12.4.

Acceptance of a 750 GeV Ghost S



FCC-he
60 GeV

LHeC

← y >0.047
(=0.33 LHeC)

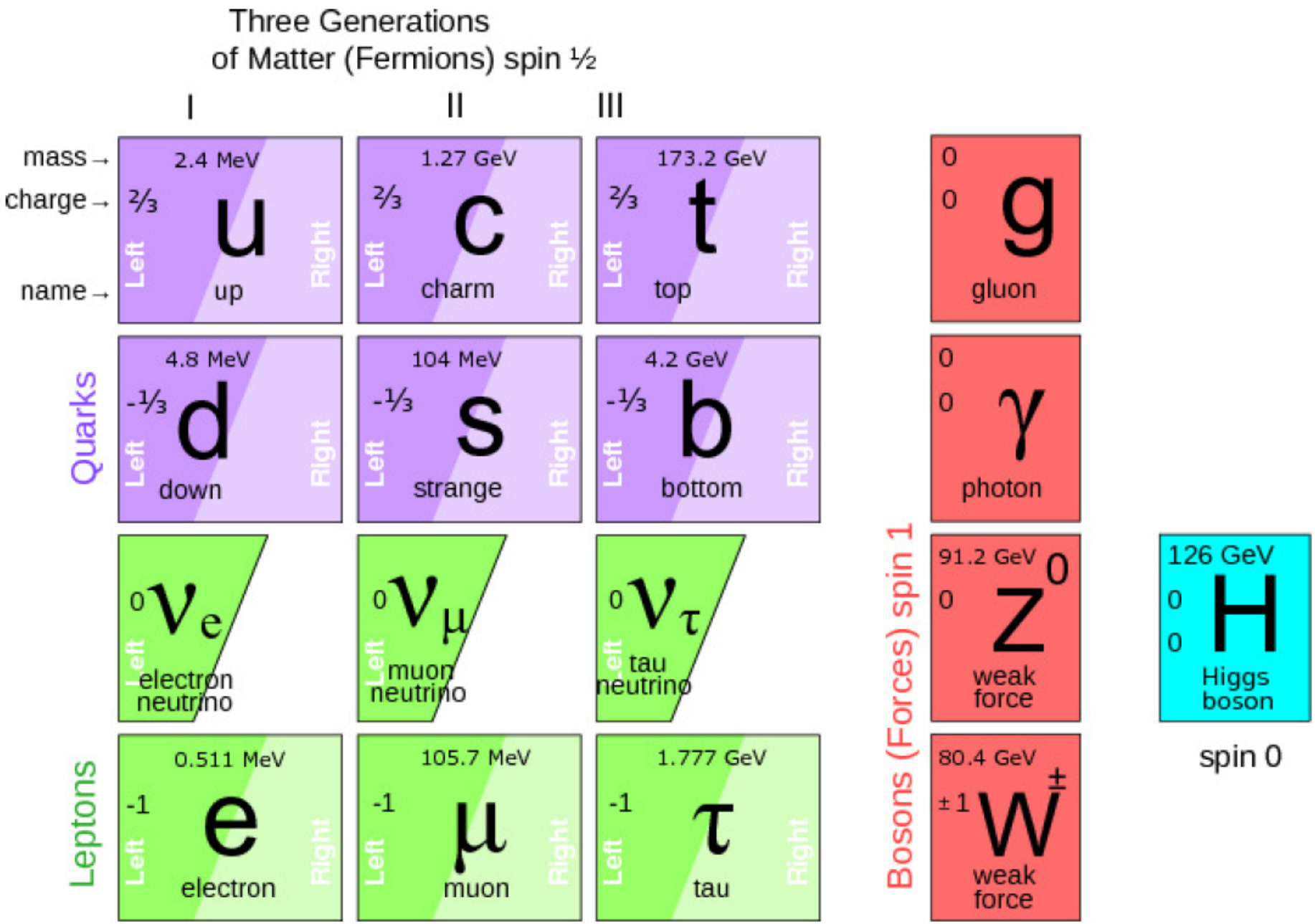
← 179°
@ 180 GeV
.. very low x requires not the maximum of E_e

3 C's

Cross section?
Couplings?
Confirmation!

G Azuelos
U,M.Klein

For x < 10^{-3} no (average) energy deposition exceeding the electron beam energy


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
173.2 GeV
⅔
t
top
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
0
Z0
weak force
80.4 GeV
±1
W±
weak force
126 GeV
0
0
H
Higgs boson
spin 0
Quarks
Leptons
Bosons (Forces) spin 1
Left
Right
0
νe
electron neutrino
0
νμ
muon neutrino
0
ντ
tau neutrino
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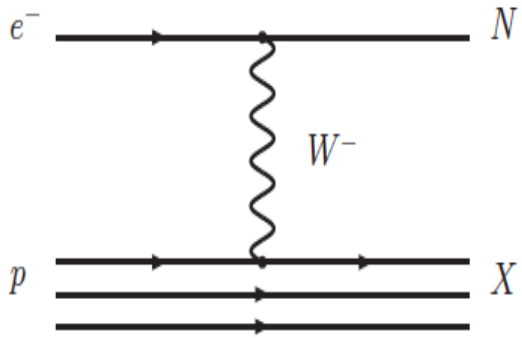
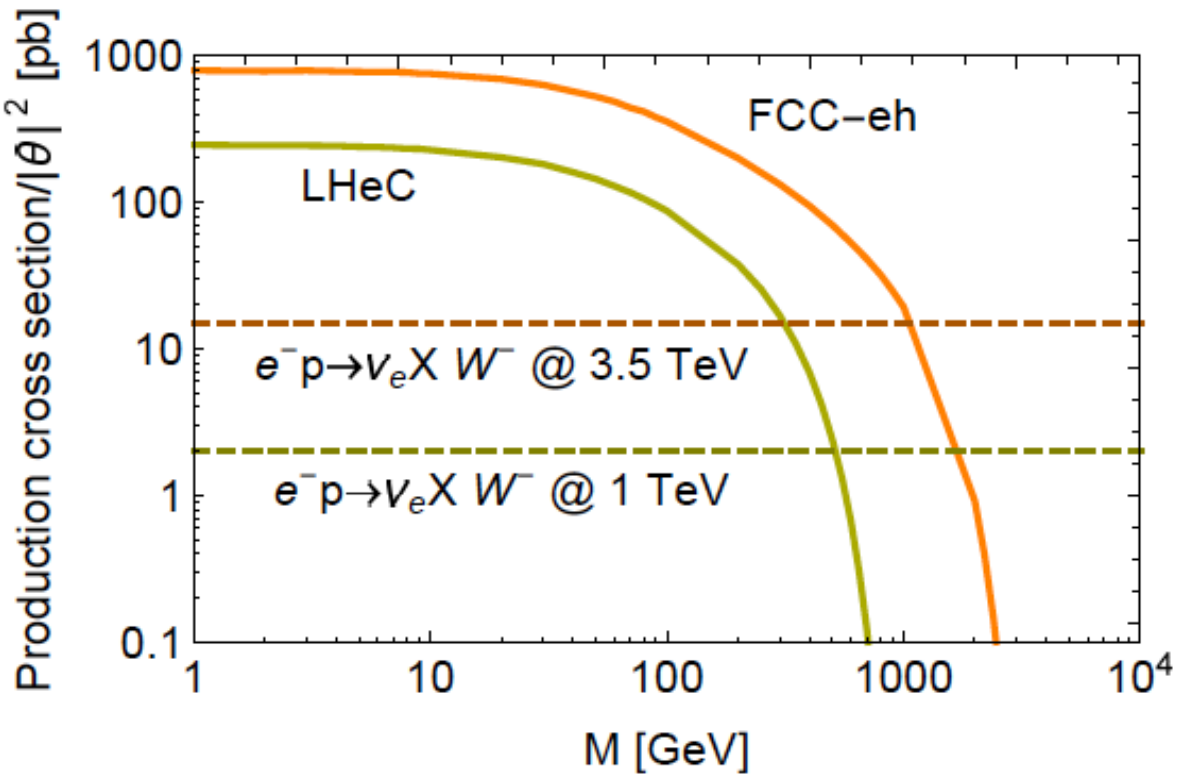
Heavy Neutrino Search at FCC (ee,hh,eh)

Oliver Fischer
Rome Talk
Sterile Neutrinos



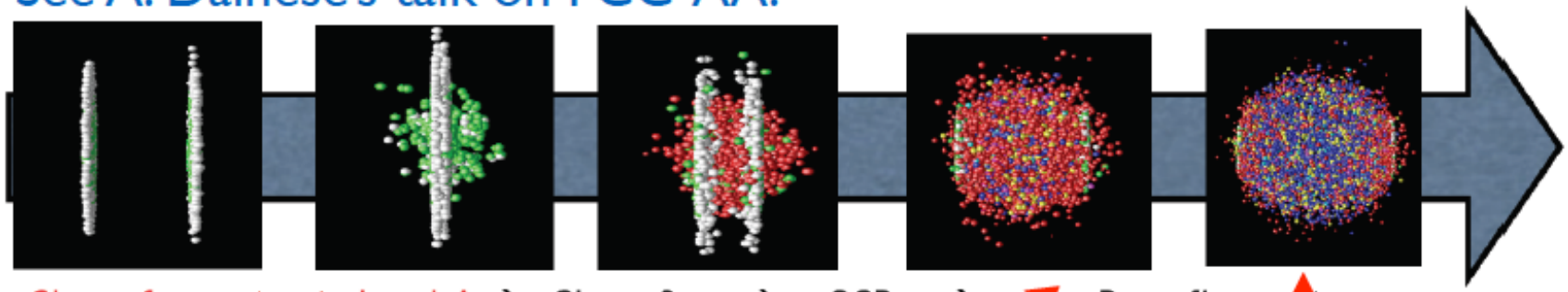


⇒ The FCCs provide great prospects for discovering the origin of neutrino masses.

- Future electron-proton colliders provide significant gain in mass reach and fairly "stable" production cross sections.

Relevance for HIC:

See A. Dainese's talk on FCC-AA.



Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?
- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

Discussed intimate relation of eA and AA physics, also the question of integrating HI detection into GPDs

Some Remarks on Physics and Detector

The ep configuration has much to offer by itself and in complementarity to ee and pp. For the FCC-eh, more studies are under way and need to be pursued.

The LHeC Study has been the base for FCC-eh also, and time and energy order need to be imposed by us in order to have clearer what can be gained where. This will also need to include the HE-LHC configuration which looks good to eh.

Basically: high x may be done by LHeC, but low x and high masses (equivalent) require FCC-ep

Areas of further study: top, Higgs, BSM

If you want to join, please do so

Areas of renewed study: low x, PDFs, ions

Areas of new directions: Heavy neutrinos, BSM Higgs, 750 (if)

Much effort has been put in the detector software and design which needs to be coupled closer to the physics analyses..

→ Lots to be done for CDR on LHeC (10^{34}) and 'eh' or 'he' for FCC, while eh physics remains fascinating to some of us and useful to everybody

… to take home

- **Integrating a 'green' electron recovery LINAC into LHC-pp and FCC-pp allows to challenge the QCD and electroweak sector of the SM to a state-of-the art level** – all this at moderate cost and **simultaneously → turning our big investments to the powerful and sustainable 'Higgs and search facilities'.**
- **There is a unique discovery potential in ep and eA.**
- **The value of the eh configuration at the energy frontier and its physics and technologies challenges deserve further study and support.**

It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.

R.P Feynman

Jan Mateiko, “Sala Sobieski”, King of Poland frees Vienna 1683

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

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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.

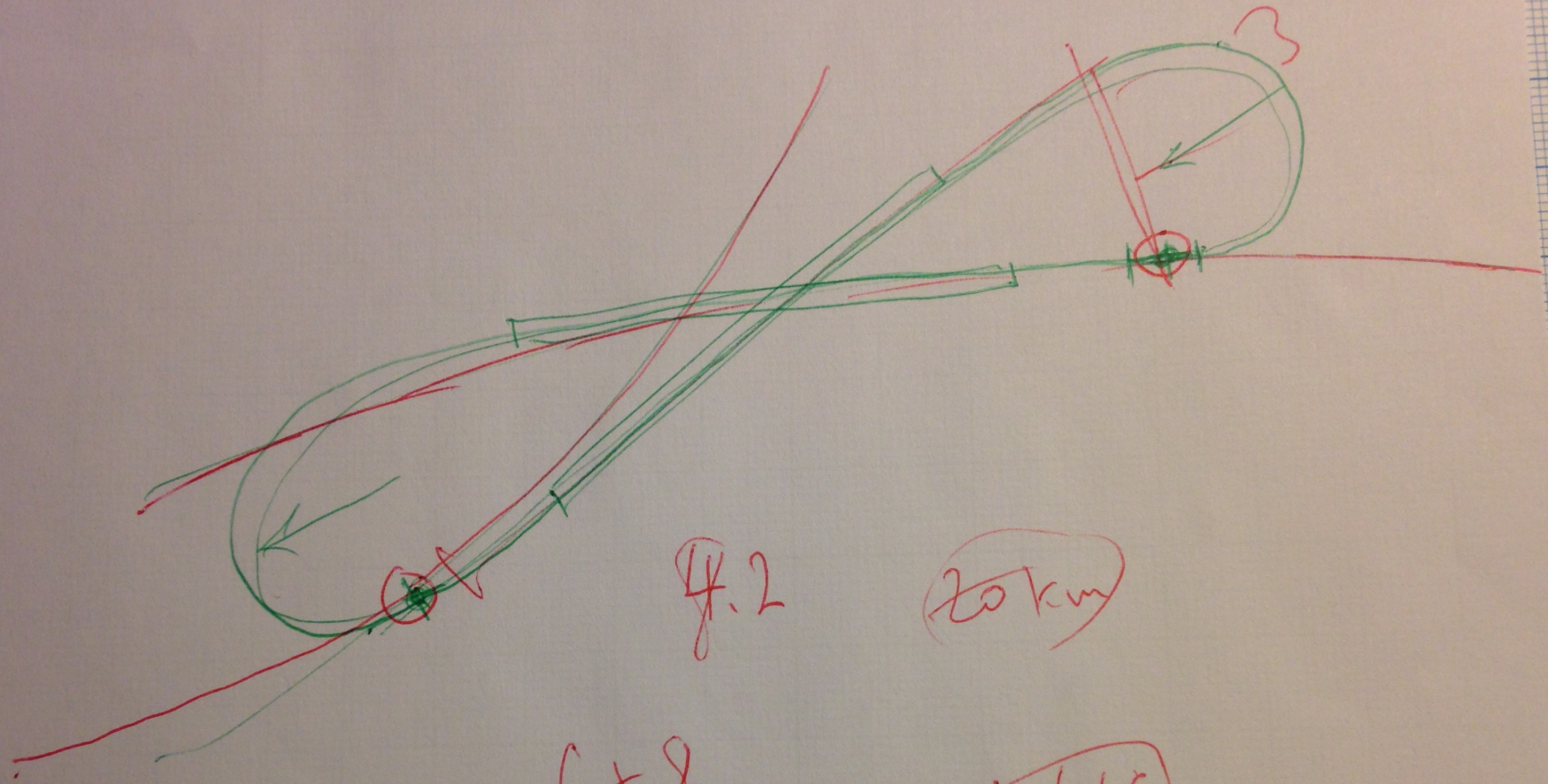
$$\frac{\mathrm{d}q^i(x,t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y}\left[\sum_{j=1}^{2f} q^j(y,t)\,P_{\mathrm{q}^i\mathrm{q}^j}\left(\frac{x}{y}\right) + G(y,t)\,P_{\mathrm{q}^i\mathrm{G}}\left(\frac{x}{y}\right)\right],$$

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

Collider Physics within the Standard Model: a Primer

arXiv:1303.2842

Guido Altarelli [1] (1941-2015)



4.2

20 km

6 + 8

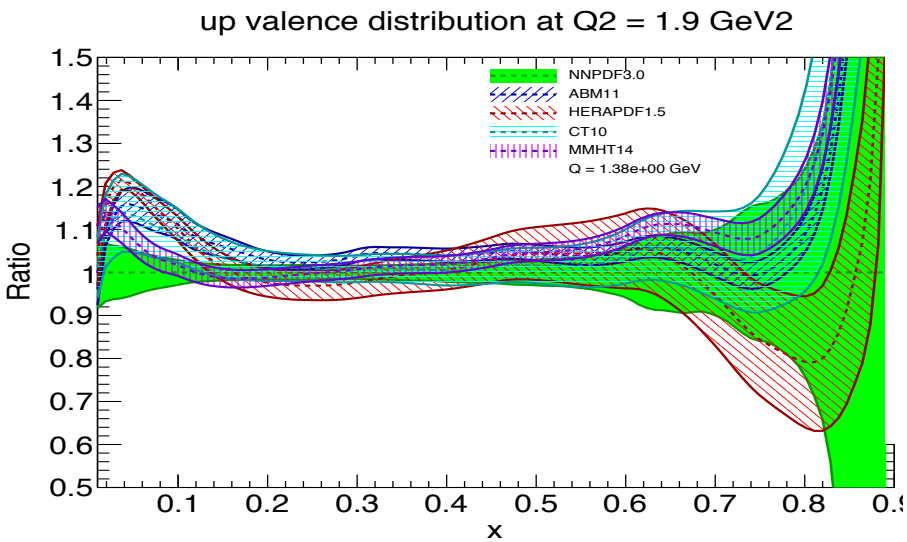
14

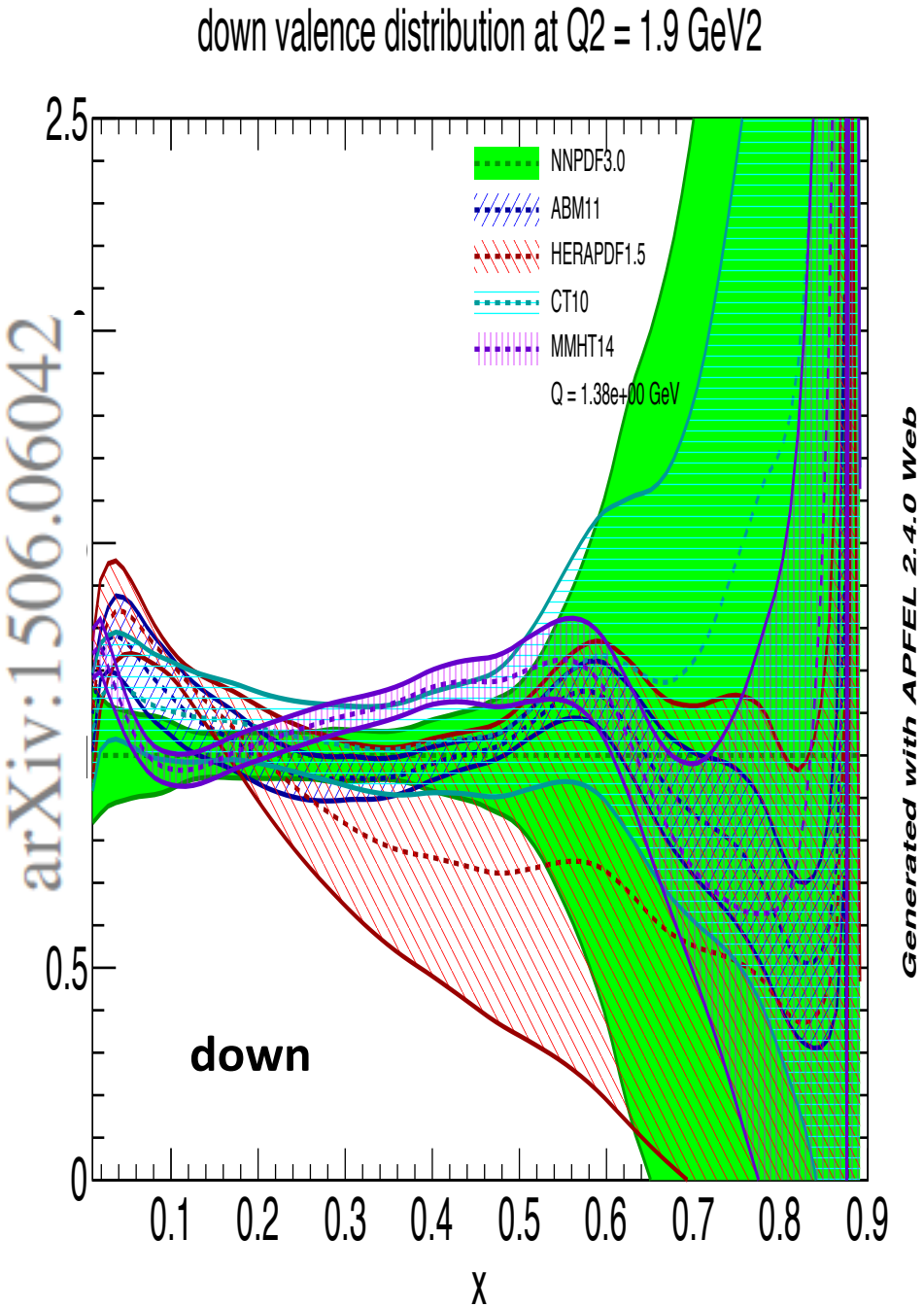
$\frac{1}{2}$ Kate

Max 7.4.16

Valence quarks

up

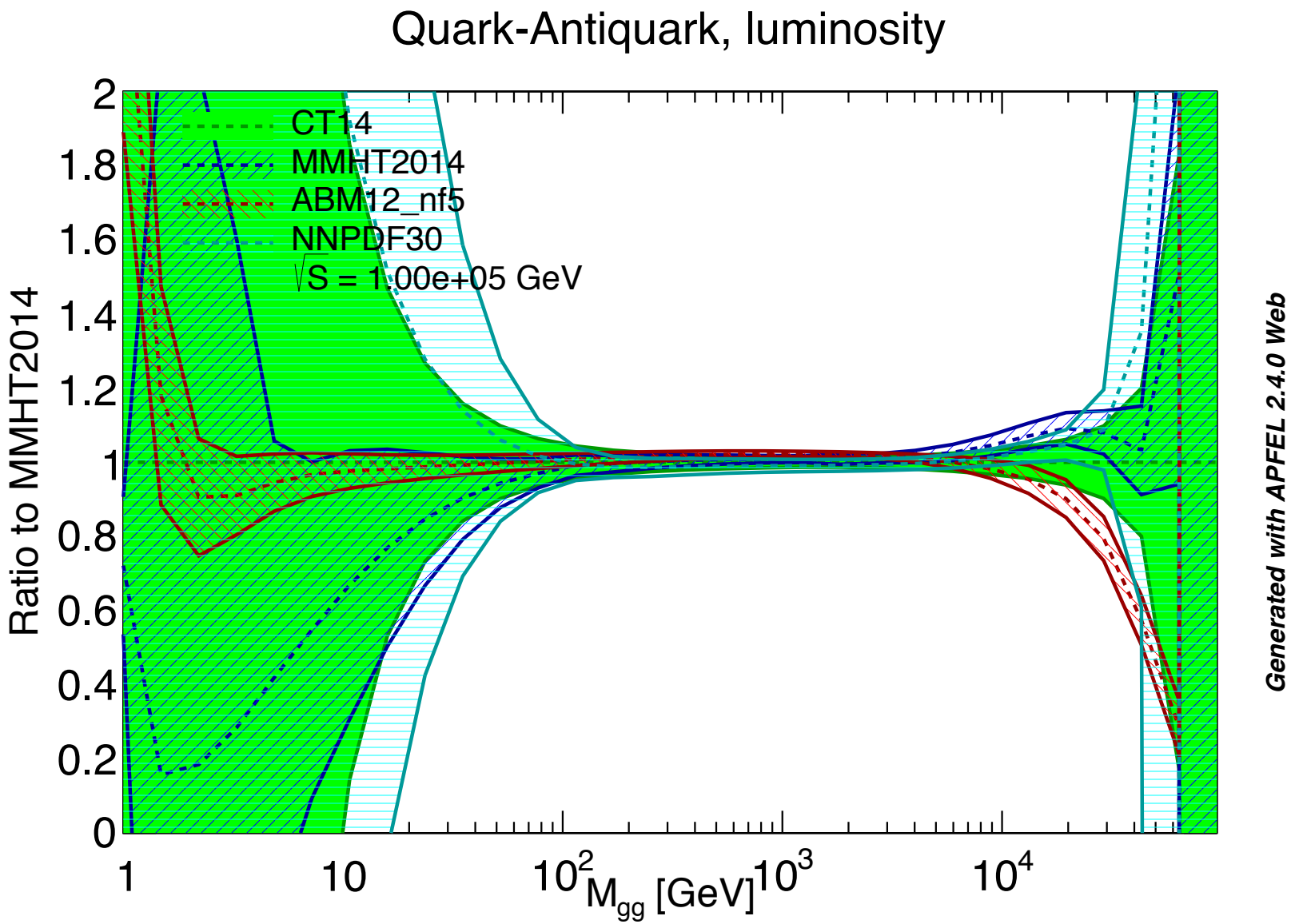




Related to DY , W mass etc

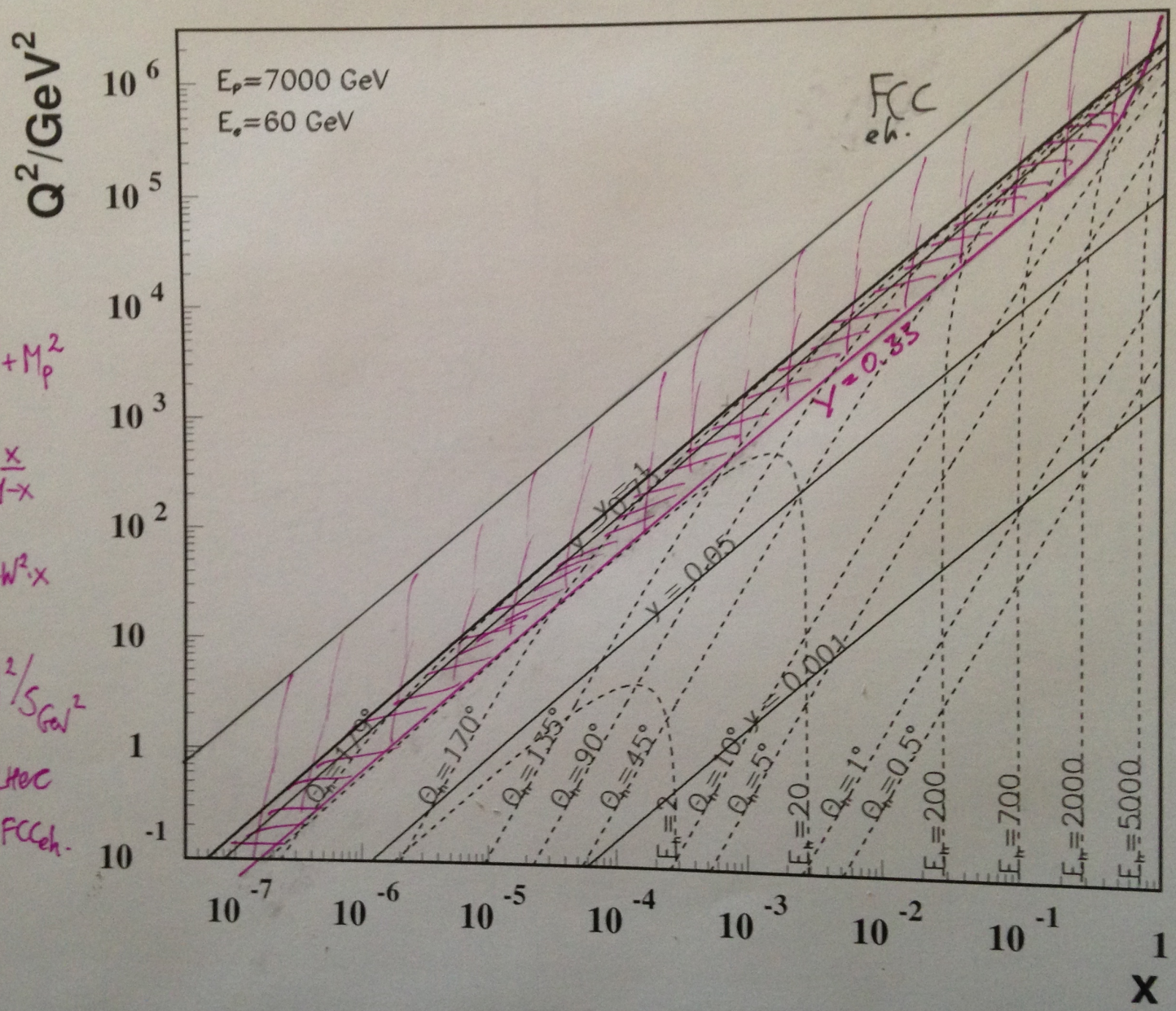
Recall $xq_v \sim (1-x)^3$

d/u → 1 a classic question



Current status of quark-aquark sub-cross section uncertainty at FCC (hh) vs mass produced

LHeC - hadronic final state kinematics



$W^2 = Q^2 \frac{1-x}{x} + M_p^2$

$\rightarrow Q^2 \simeq W^2 \cdot \frac{x}{1-x}$

$x \ll 1: Q^2 \simeq W^2 \cdot x$

$W^2 = sy$

$y \geq (750)^2 / s_{GeV^2}$

$= 0.33$ LHeC

0.047 FCCeh.

Increasing Energy without or with ERL

Figure 7.8: Pulsed single straight 140-GeV linac for higher-energy ep collisions.

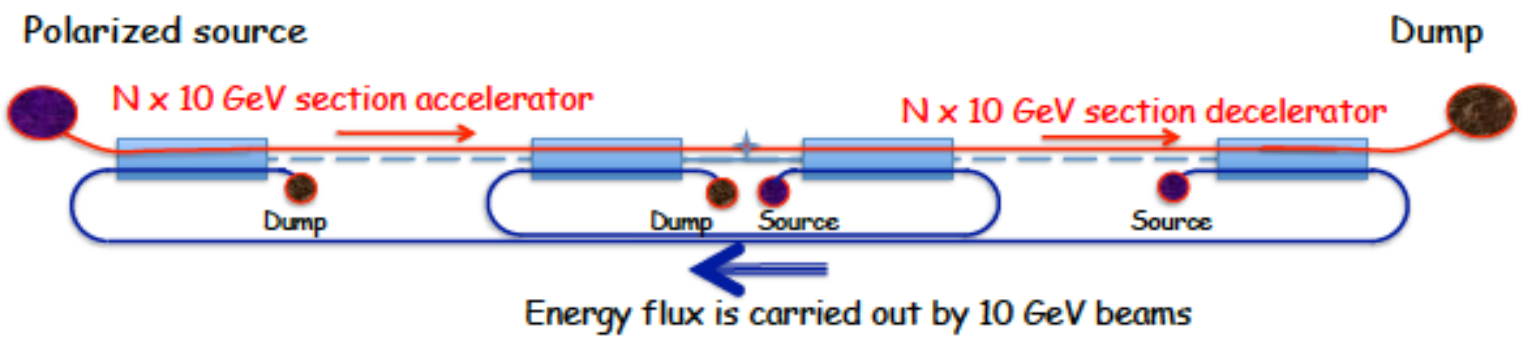


Figure 7.9: Highest-energy high-luminosity ERL option based on two straight linacs and multiple 10-GeV energy-transfer beams [725].

Pulsed: high cost, low luminosity. ERL: high cost → ERL racetrack was chosen as baseline

Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

Y.-L. Tang et al., arXiV: 1508.01095
→ Talk by C. Zhang

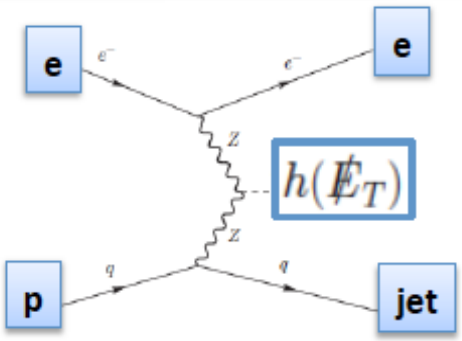
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

$\mathrm{Br}(h \to \not{E}_T)$ < 3.5% @90% C.L., MVA based

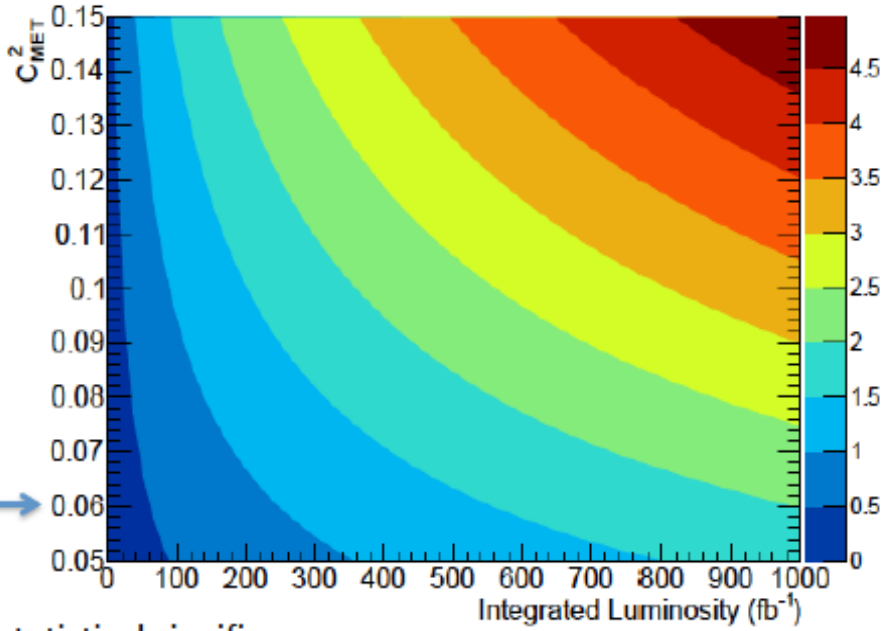
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, cut based

$\mathrm{Br}(h \to \not{E}_T)$ < 6% @ 2σ level

$$C^2_{\mathrm{MET}} = \kappa_Z^2 \times \mathrm{Br}(h \to \not{E}_T)$$



κ_Z : BSM w.r.t. SM HZZ coupling



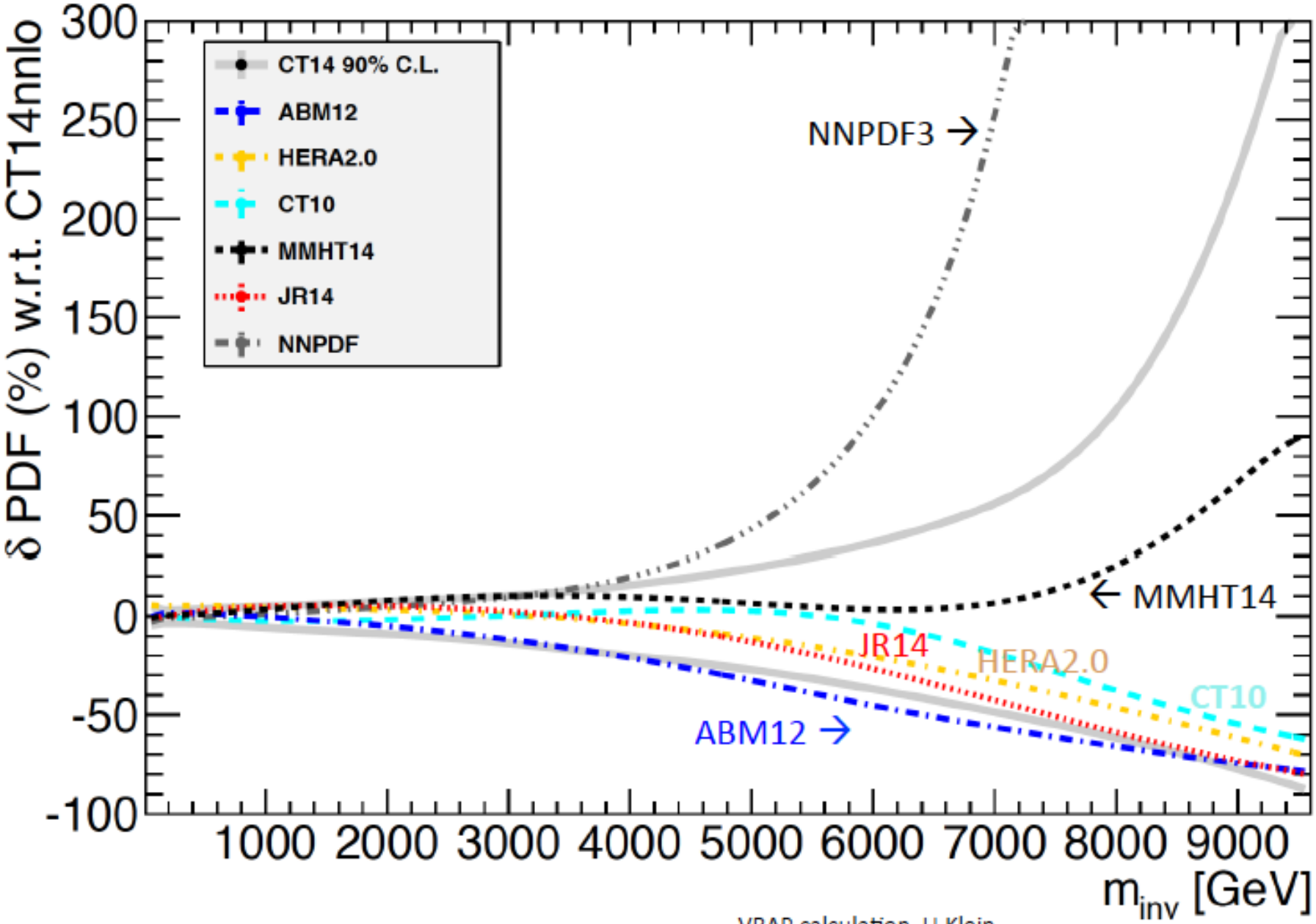
Colours: expected statistical significance

→ potential much enhanced for **FCC-eh @ 3.5 TeV and HE-LHC-eh**

FCNC Top and Higgs couplings :
H. Sun [arXiv:1602.04670]
New study for HE-LHC
14 TeV p x 150 GeV e

BR(t→ qh) < 0.23%
@ 95% C.L. and 100 fb^{-1}

Very High Mass Dell Yan 13 TeV - σ(PDF)/σ(CT14)



VRAP calculation, U.Klein