LHeC project: machine, physics case and prospects

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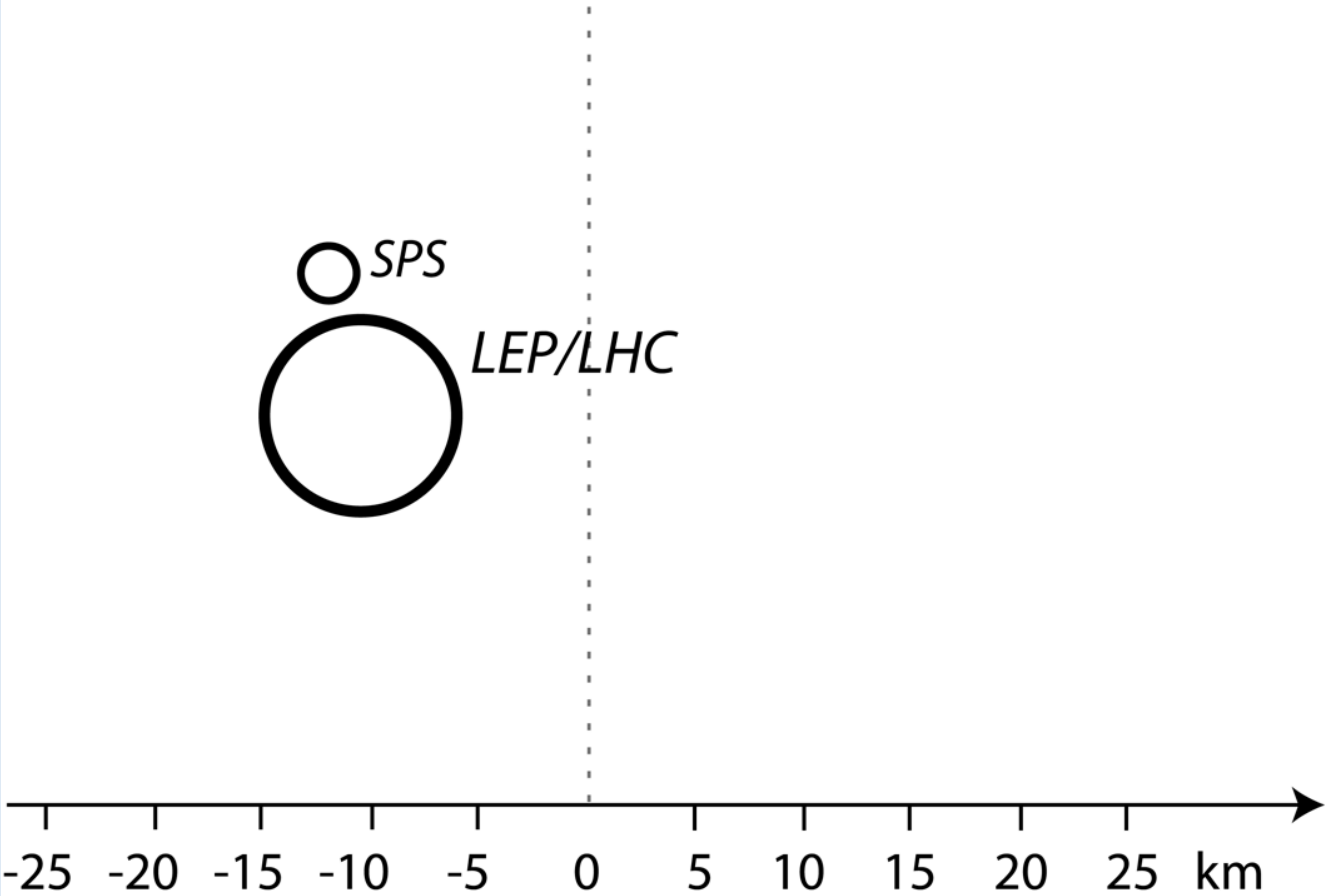
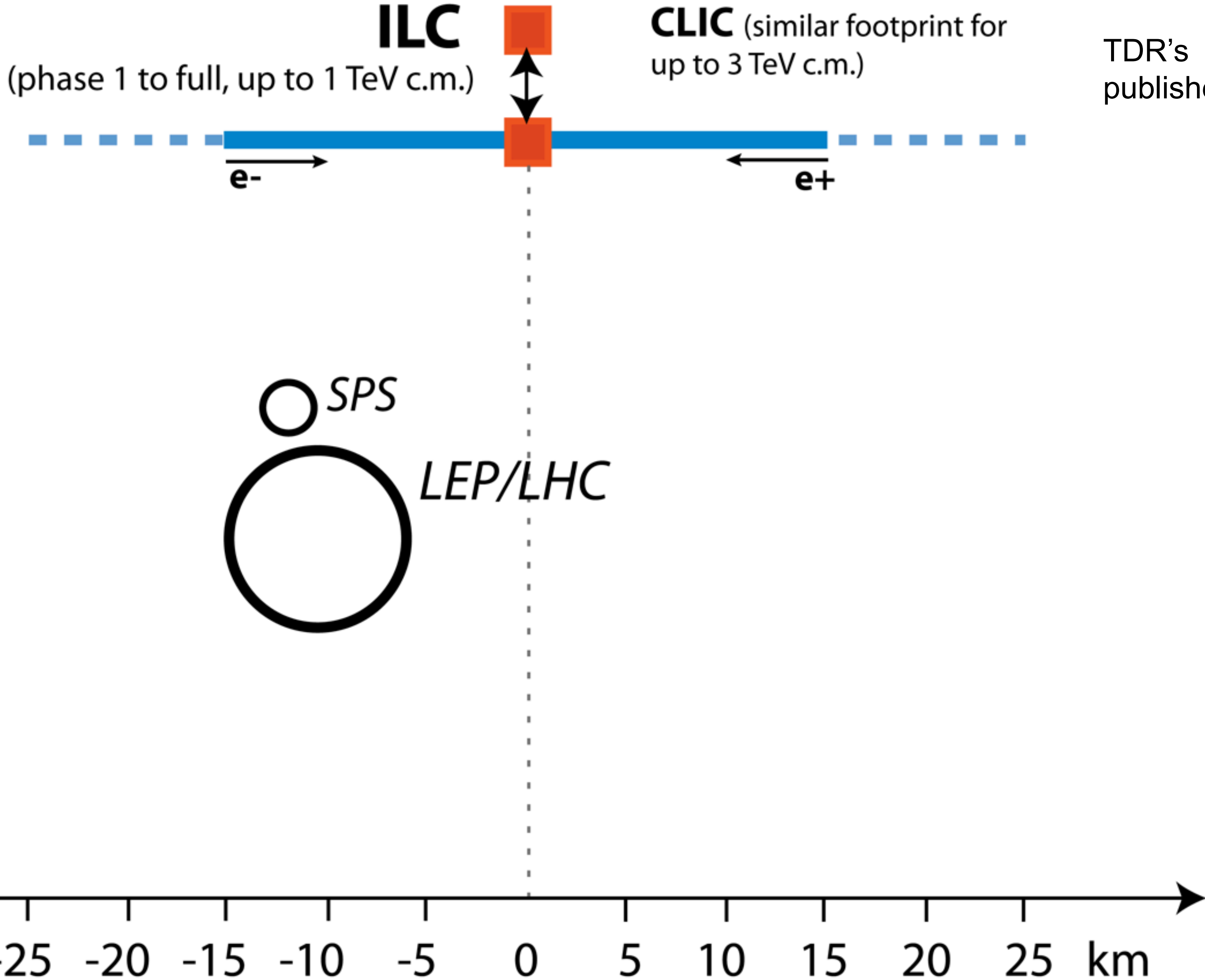
Seminar, MPI Munich, April, 8th, 2014

Slides by Ralf Assmann@EPS2013



Collider options beyond LHC-Run II

TDR's published



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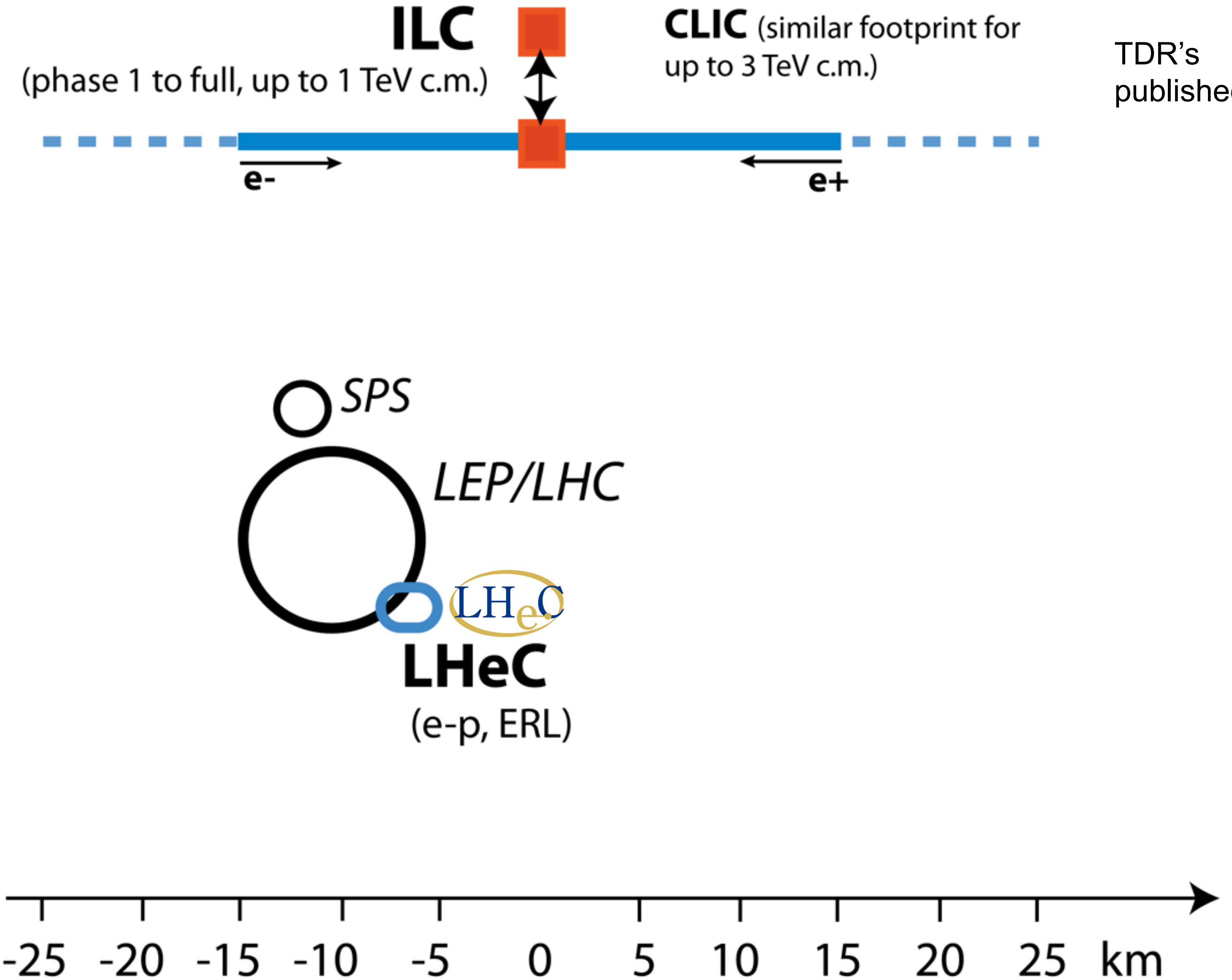
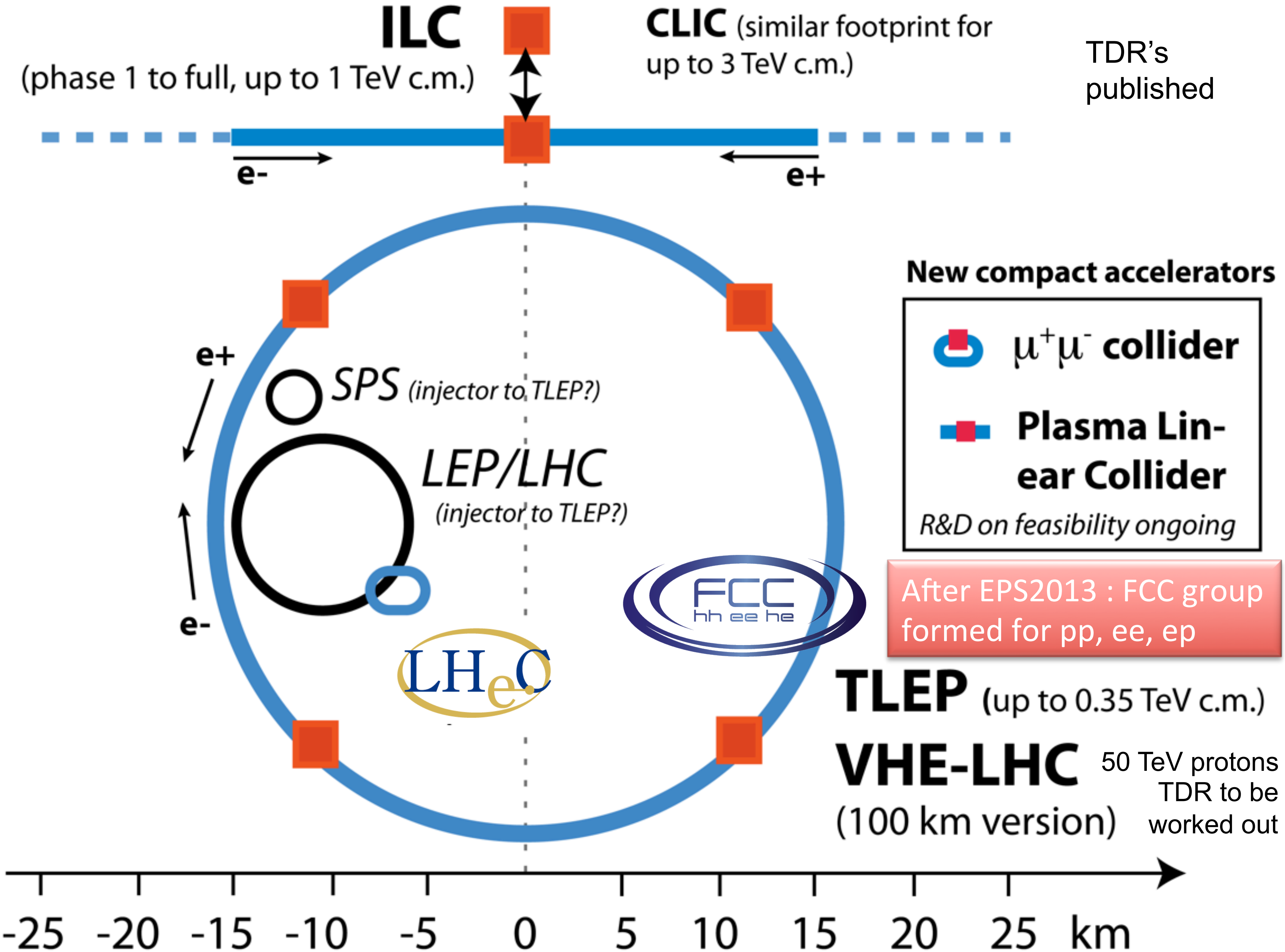
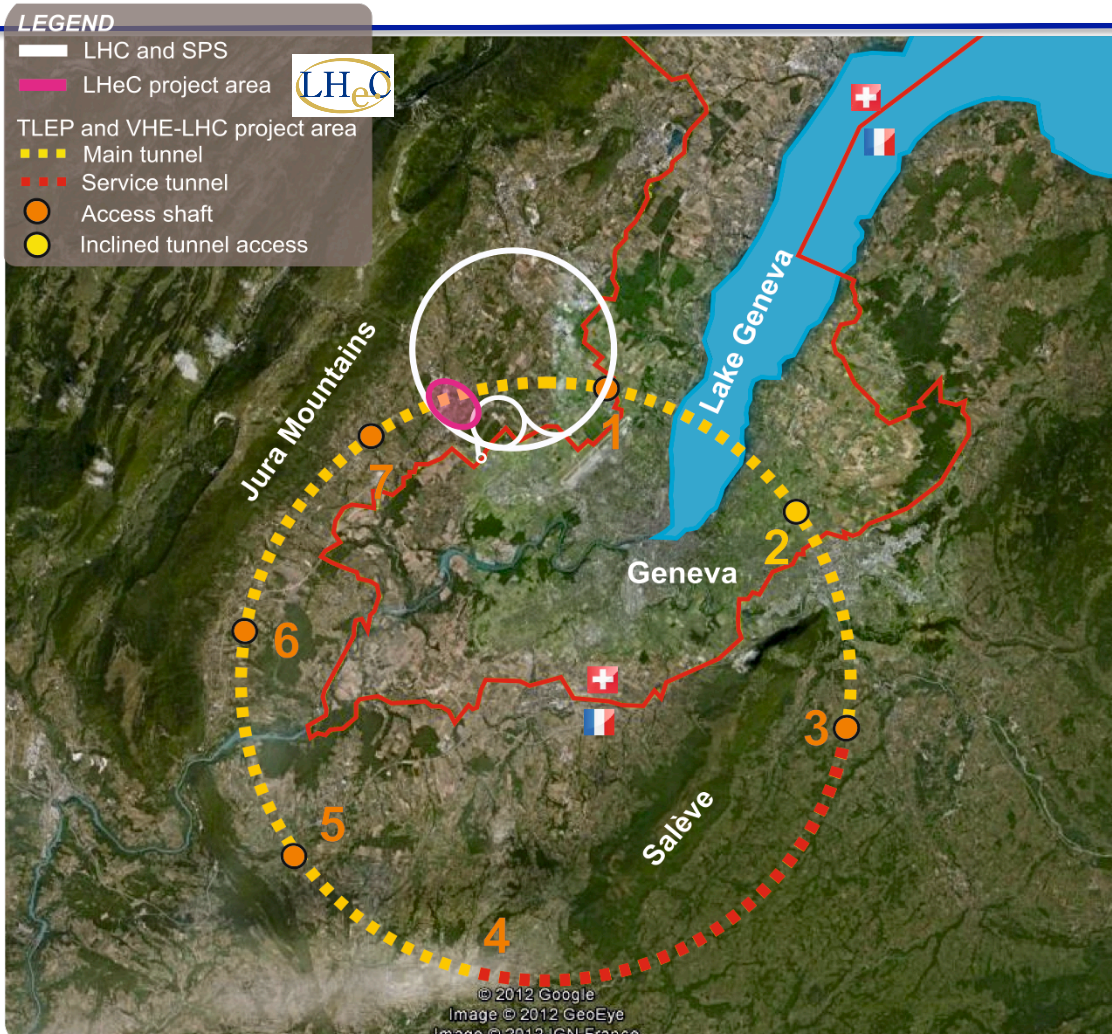


Collider options beyond LHC-Run II



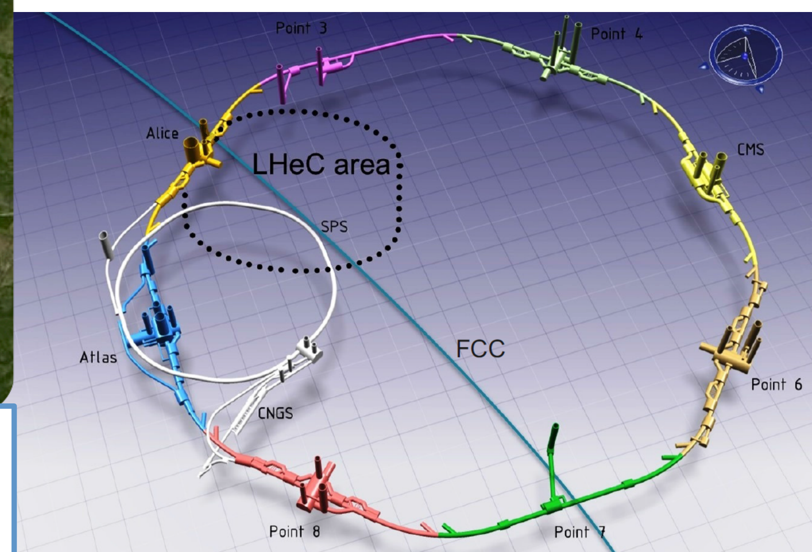
Future Circular Colliders at CERN*)



100 km with 20 T magnets provides 50 TeV per proton beam.

New tunnel may host a 'complete' Higgs facility → FCC design study kick-off chaired by Michael Benedikt

LHeC to run synchronously with HL-LHC or later with FCC

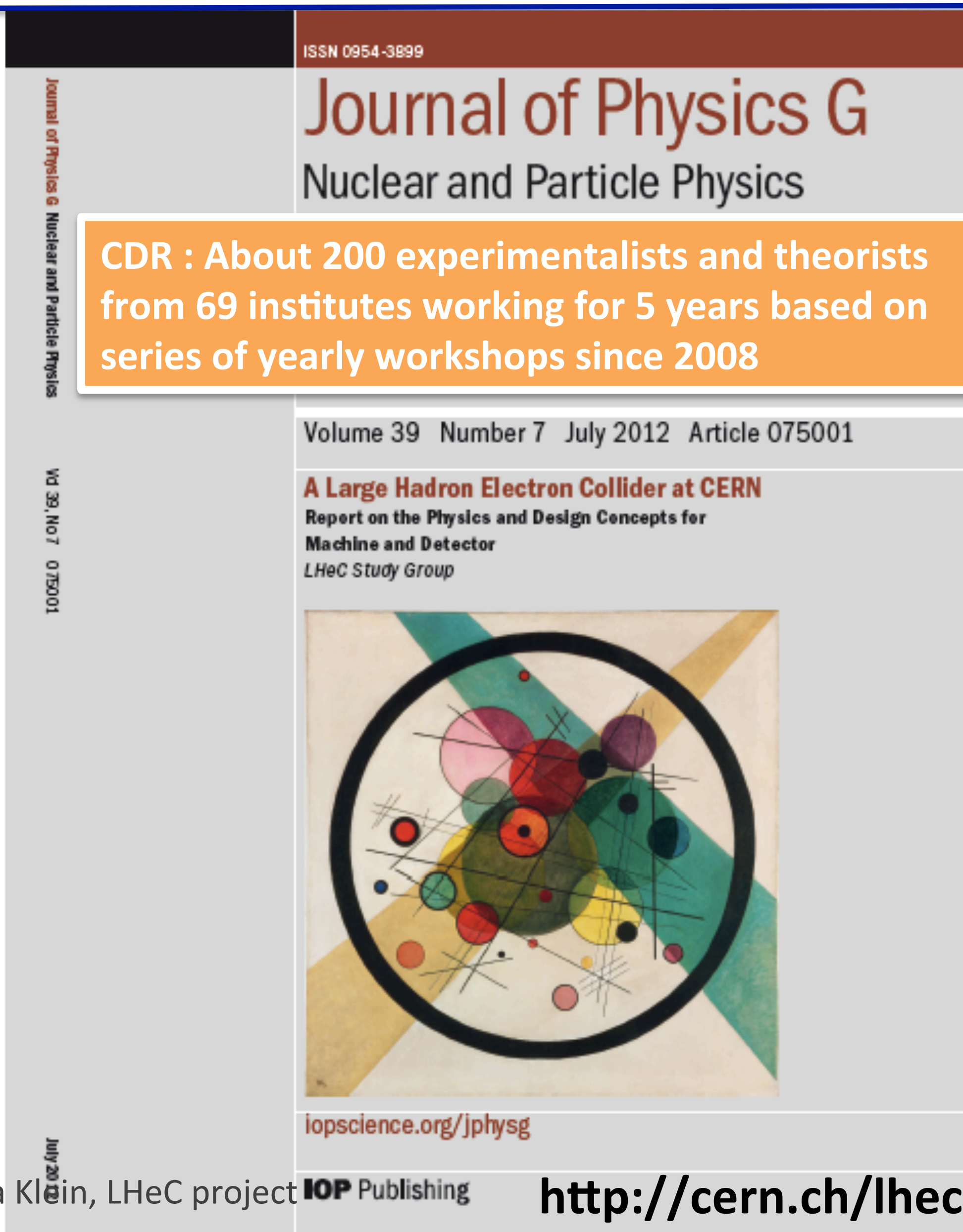


*) "Civil Engineering Feasibility Studies for Future Ring Colliders at CERN", Contributed by O.Brüning, M.Klein, S.Myers, J.Osborne, L.Rossi, C.Waaijer, F.Zimmerman to IPAC13 Shanghai

CDR "A Large Hadron Electron Collider at CERN"

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001 [arXiv:1206.2913]

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]



CDR : About 200 experimentalists and theorists from 69 institutes working for 5 years based on series of yearly workshops since 2008

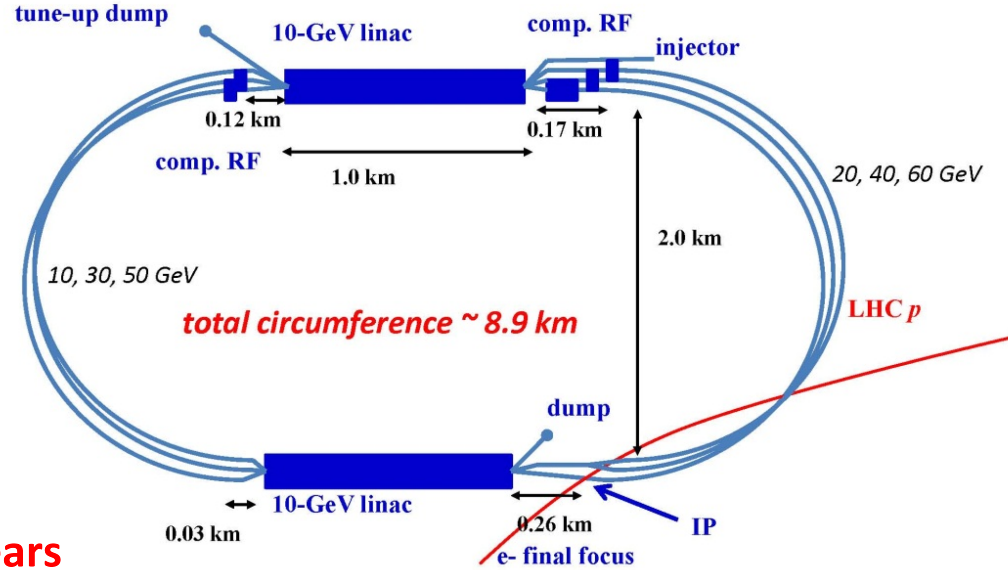
International referees invited by CERN

Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
Interaction Region
Daniel Pitzl (DESY)
Mike Sullivan (SLAC)
Detector Design
Philippe Bloch (CERN)
Roland Horisberger (PSI)
Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
Cristinel Diaconu (IN2P3 Marseille)
Gian Giudice (CERN)
Michelangelo Mangano (CERN)
Precision QCD and Electroweak
Guido Altarelli (Roma)
Vladimir Chekelian (MPI Munich)
Alan Martin (Durham)
Physics at High Parton Densities
Alfred Mueller (Columbia)
Raju Venugopalan (BNL)
Michele Arneodo (INFN Torino)

http://cern.ch/lhec

LHeC: Baseline Linac-Ring option

- Design constraint: power consumption < 100 MW → E_e = 60 GeV
- Two 10 GeV linacs with I_e>6 mA and high electron polarisation of 90%
- 3 return ARCs, 20 MV/m
- Energy recovery in same structure
- Installation fully decoupled from LHC operation!

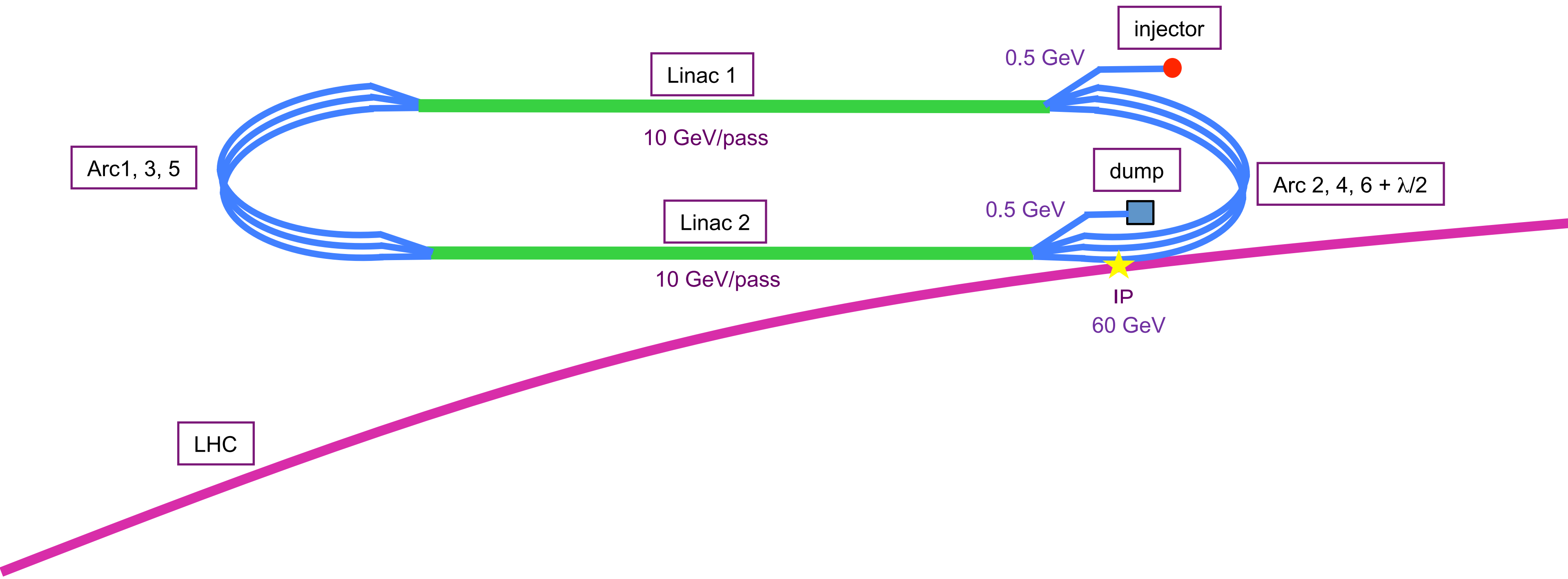


- ep Lumi 10^{33} - 10^{34} cm s^{-2} s^{-1} **
- 10 - 100 fb^{-1} per year
- 100 fb^{-1} – 1 ab^{-1} total collected in 10 years
- eD and eA collisions have always been integral to programme
- eA luminosity estimates ~ 10^{32} cm s^{-2} s^{-1} for eD (ePb)

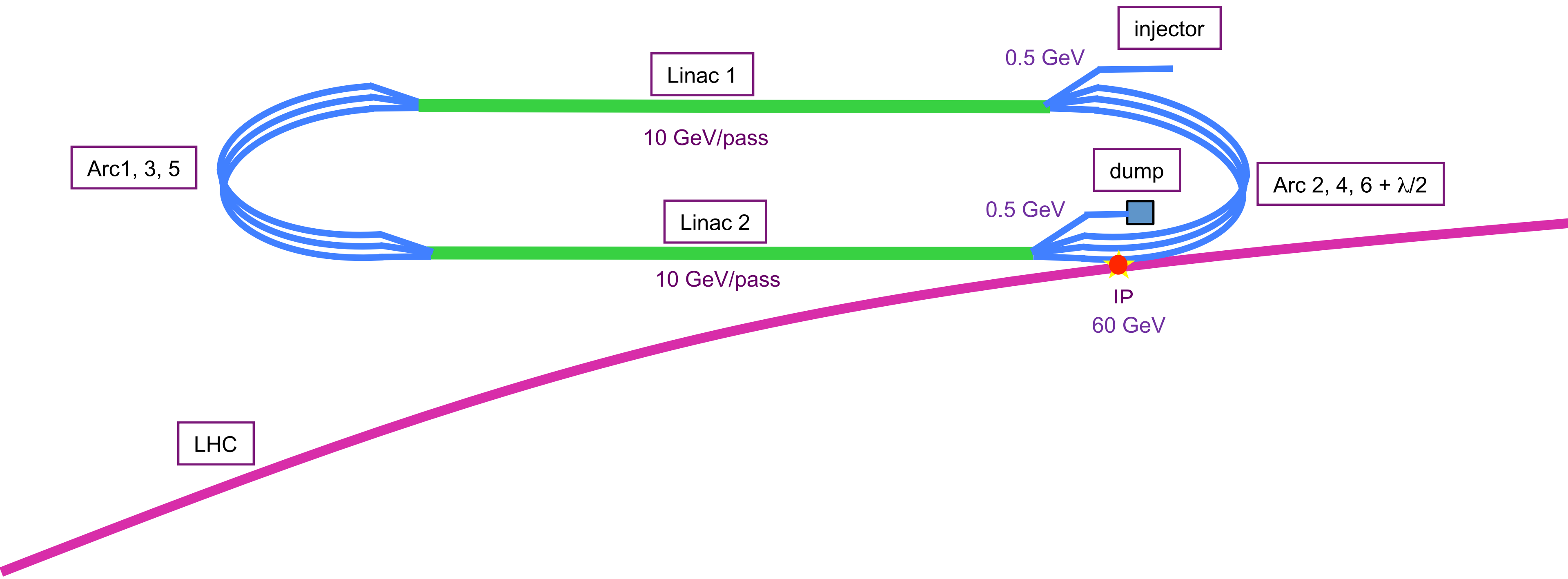
** based on existing high luminosity proposal

Oliver Bruning, FCC kickoff, https://indico.cern.ch/event/282344/session/15/contribution/96/material/slides/1.pdf

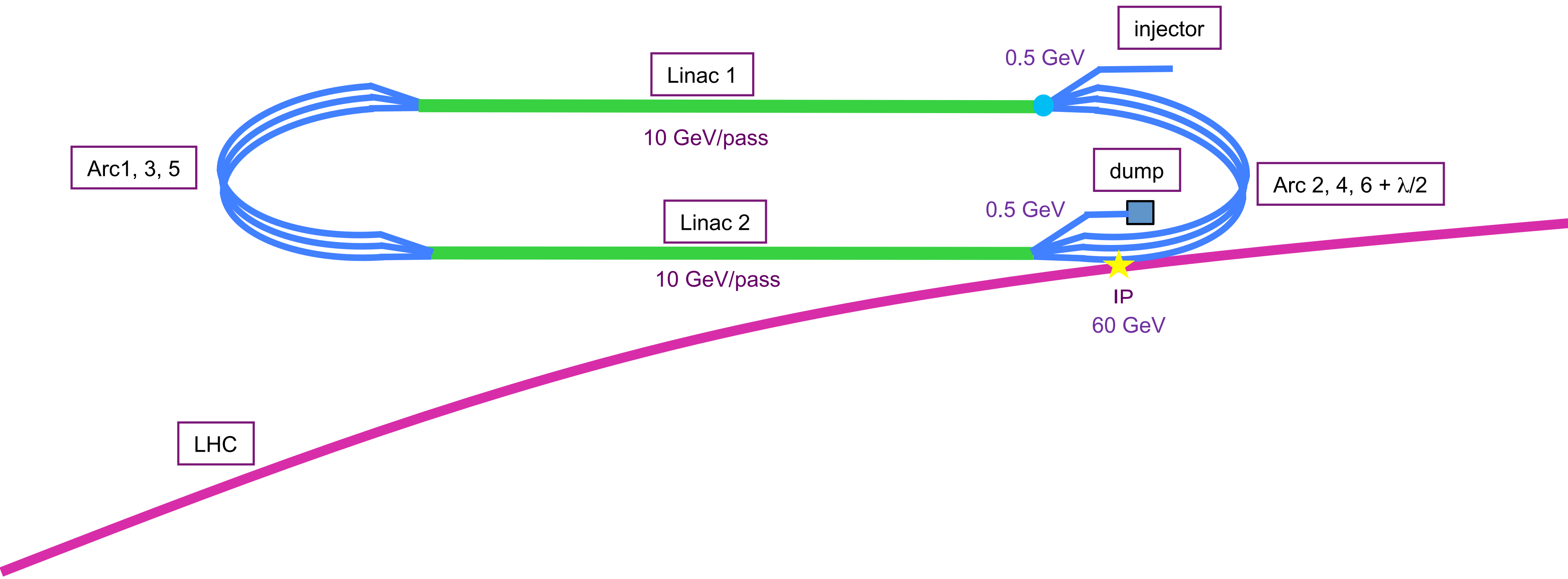
LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



Post-CDR: LHeC baseline parameter

→ **for first time a realistic option of an 1 ab^{-1} ep collider** also due to **excellent performance of LHC;** ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

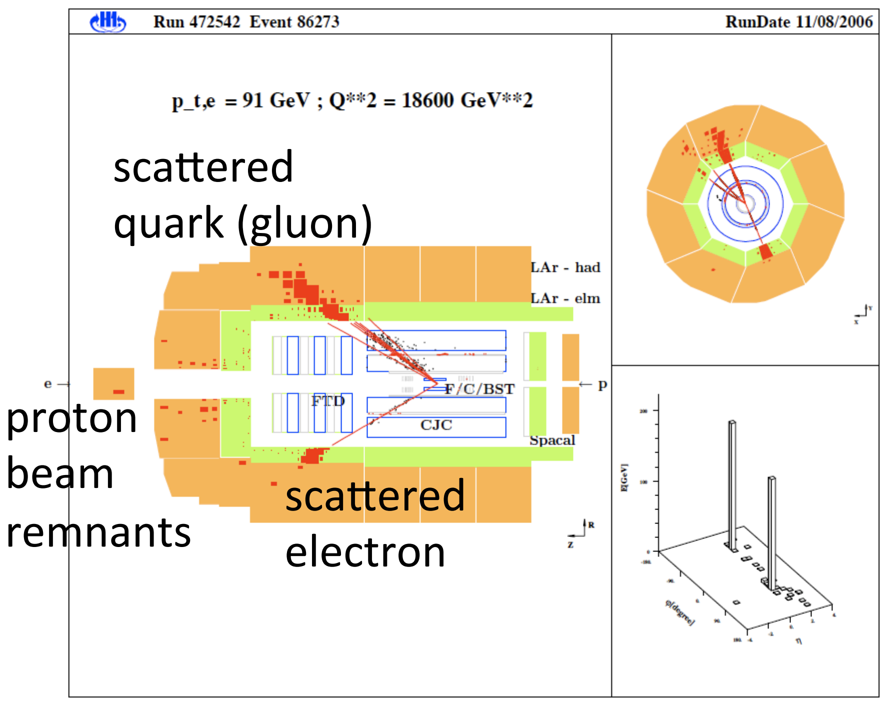
10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS		PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60		7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16		1	1
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20		3.75	50
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10		0.1	0.12
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4		7	7
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40		70	58
Beam Current [mA]	1112	25		430 (860)	6.6
Bunch Spacing [ns]	25	25		25 (50)	25 (50)
Bunch Population	$2.2*10^{11}$	$4*10^9$		$1.7*10^{11}$	$(1*10^9)$ $2*10^9$
Bunch charge [nC]	35	0.64		27	(0.16) 0.32

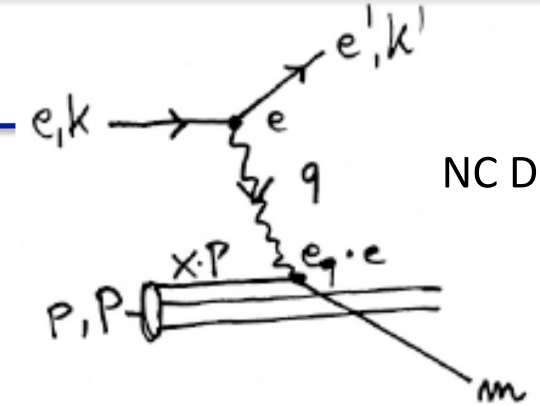
Operations simultaneous with HL-LHC *pp* physics

DIS : Some basics

HERA : Only ep collider so far!
c.m.s. energy of 0.32 TeV using
E_e= 27.6 GeV
E_p= 0.92 TeV [like Tevatron protons]

Neutral Current DIS event with H1





NC DIS

$$q = (k - k'), q^2 = -Q^2$$
$$s = (k + P)^2$$
$$(xP + q)^2 = m^2, P^2 = M_p^2$$
$$if\,(Q^2 >> x^2 M_p^2, m^2):$$
$$q^2 + 2xPq = 0$$
$$x = \frac{Q^2}{2Pq}$$
$$Q^2 = sxy$$

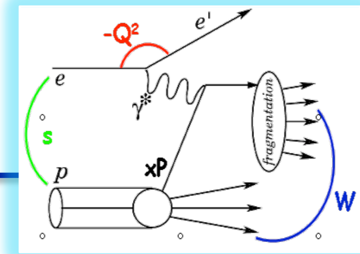
Graph: courtesy by M. Klein

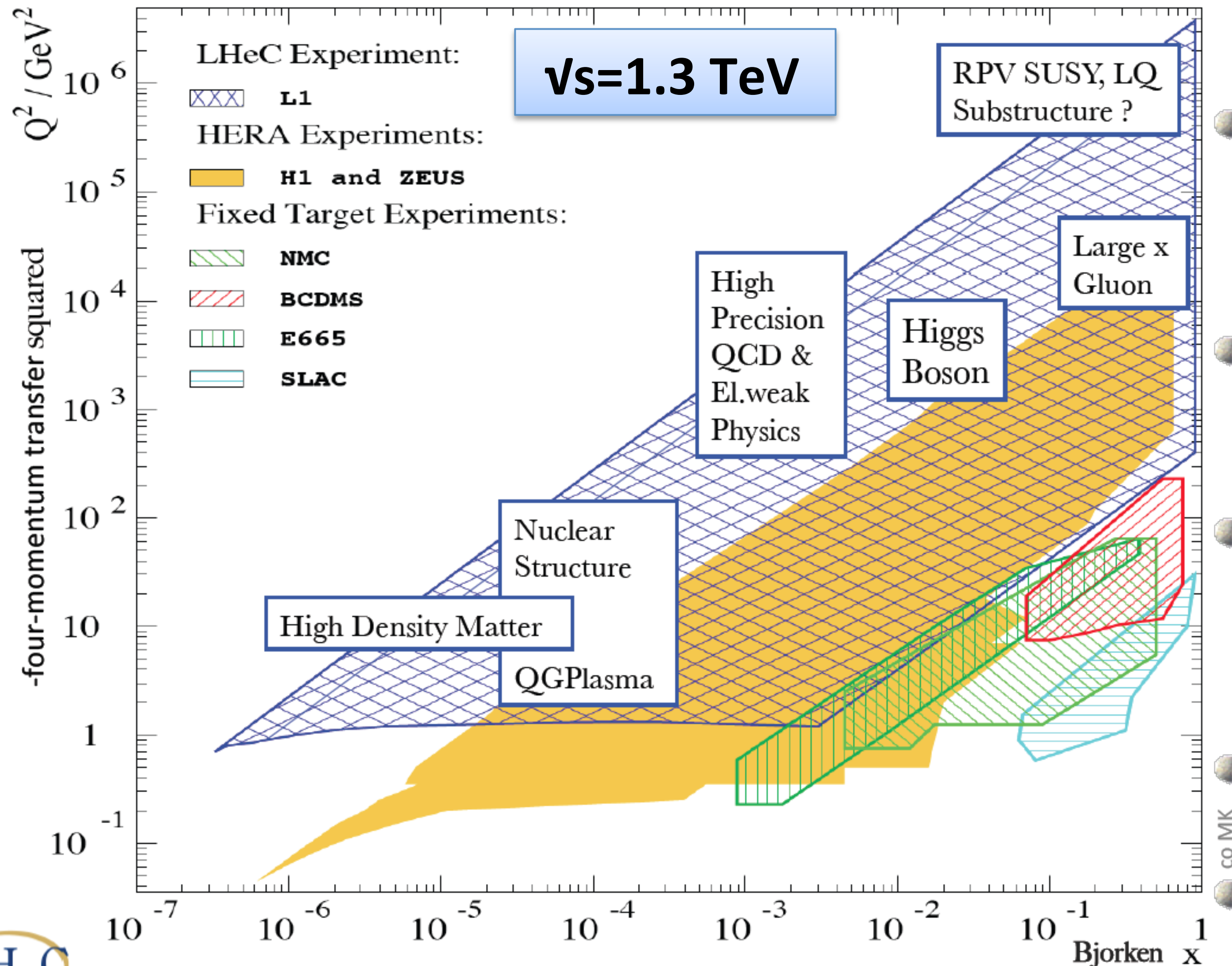
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{e^4 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \left[W_2(q^2, W) + 2W_1(q^2, W) \tan^2(\theta/2)\right]$$

SLAC-PUB-642
August 1969

@SLAC: birth of DIS, 45 years ago.

Physics at a glance

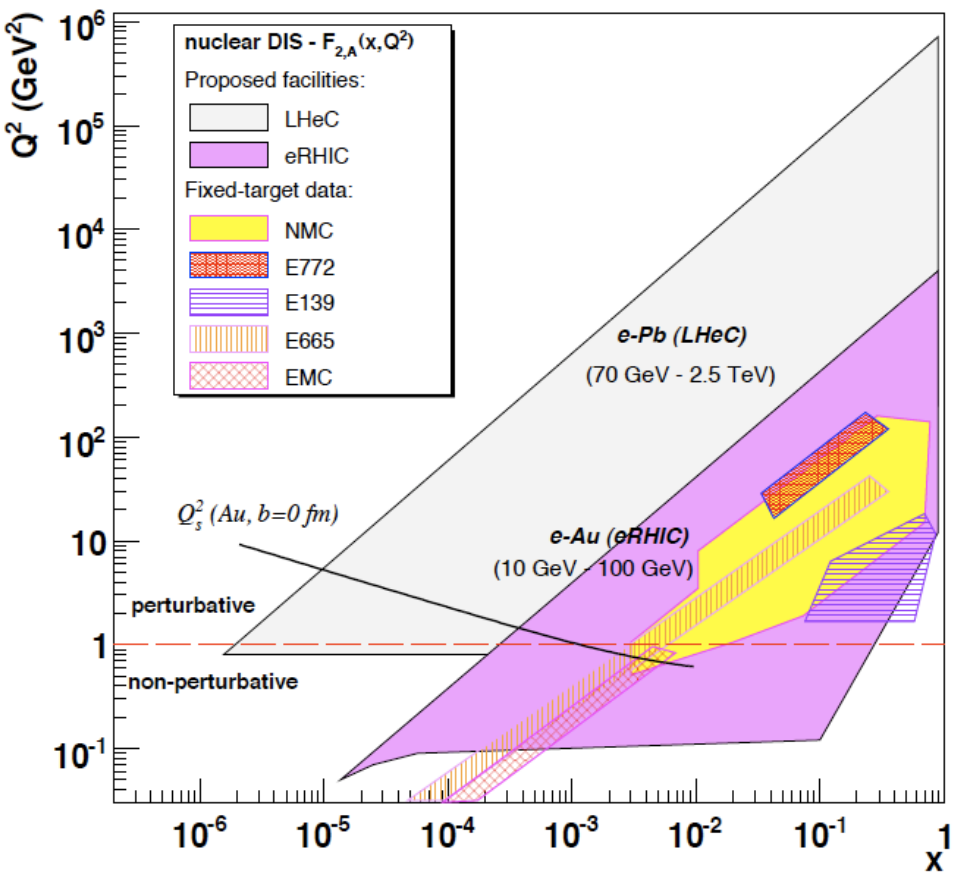




- LHeC : up to 100 to 1000 times HERA luminosity! (no pile-up)
- High precision proton PDFs, also for LHC searches
- High precision α_s to 0.1% challenging lattice QCD
- Higgs@HERA σ~0.5 fb …
- **Higgs@LHeC** with σ~200 fb

LHeC as electron-Ion collider

- **Four orders of magnitude increase** in kinematic range over previous eA DIS experiments →**into saturation region with p and with A**



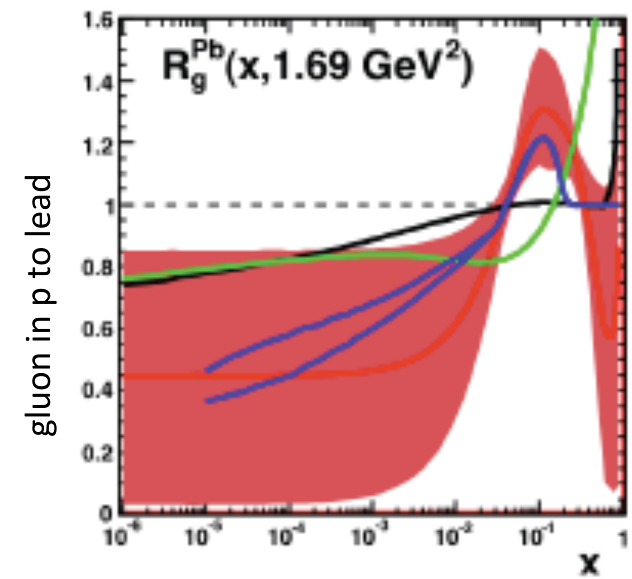
Qualitative change of behaviour

- blackbody limit of F_2

- saturation of cross sections amplified with $A^{1/3}$

- rise of diffraction to 50%?

- partons in nuclei – widely unknown

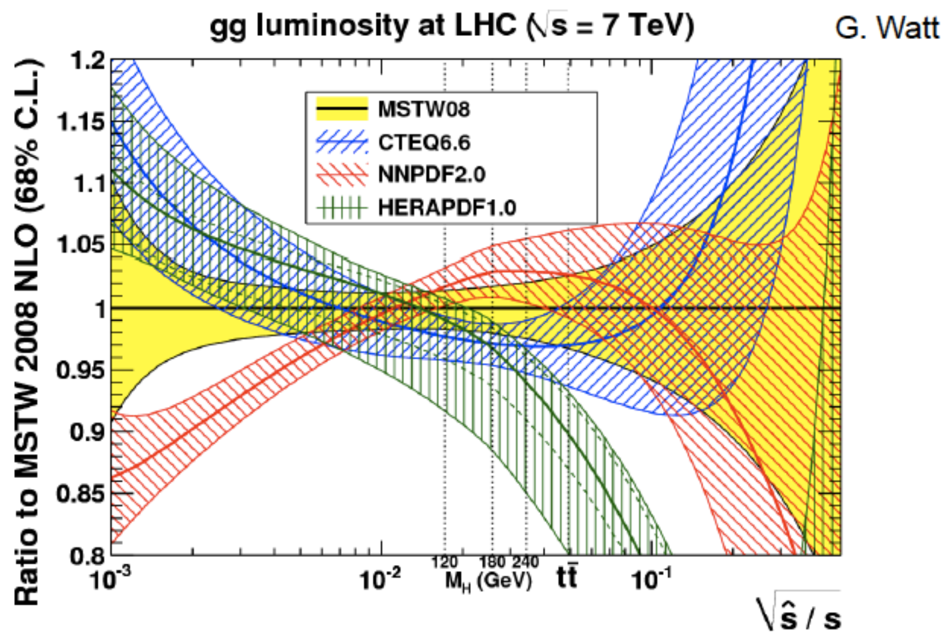


→ see talks at http://cern.ch/lhec

→ this talk focus on ep only

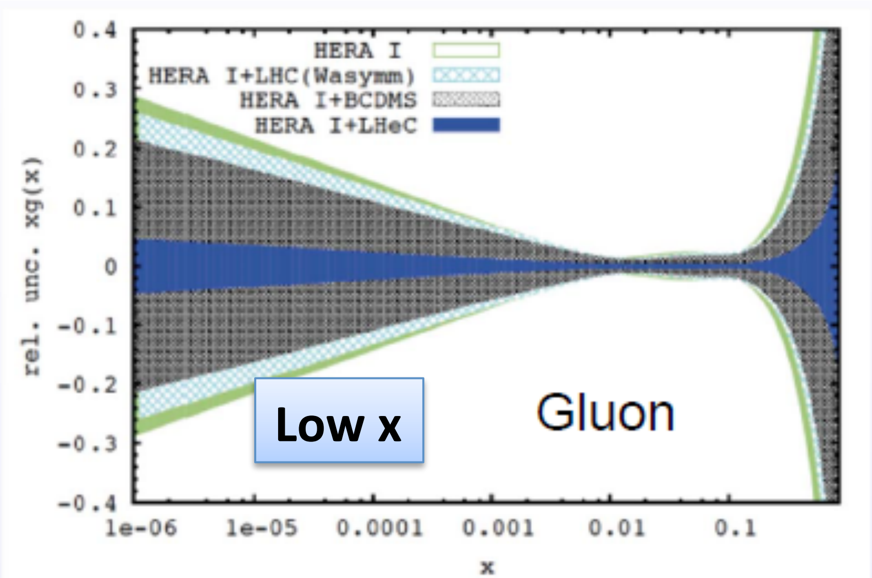
Hera's legacy

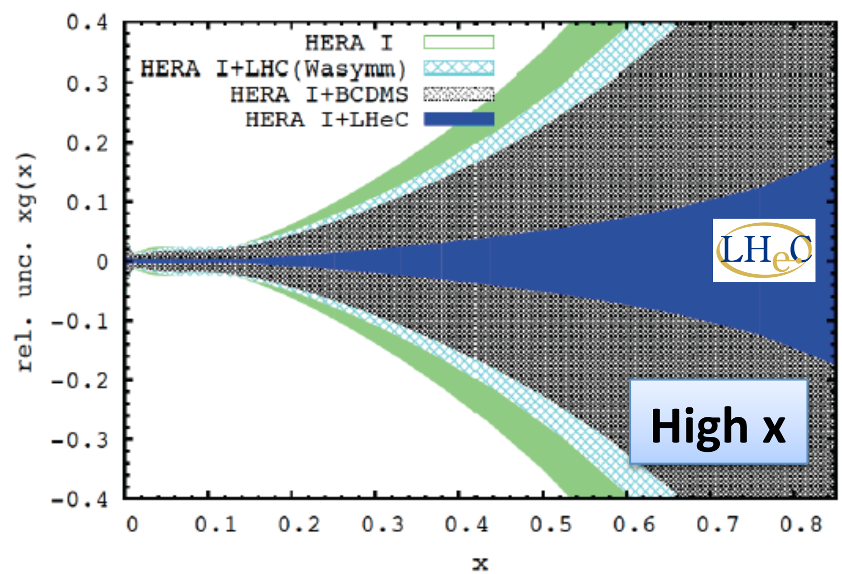
Proton structure : parton-gluon dynamics best knowledge currently →



For LHC searches and Higgs : Need to know the proton structure much better at low and high x

Example: gluon PDF measured at LHeC (blue band): < 5% at x=10^{-6} and x=0.5



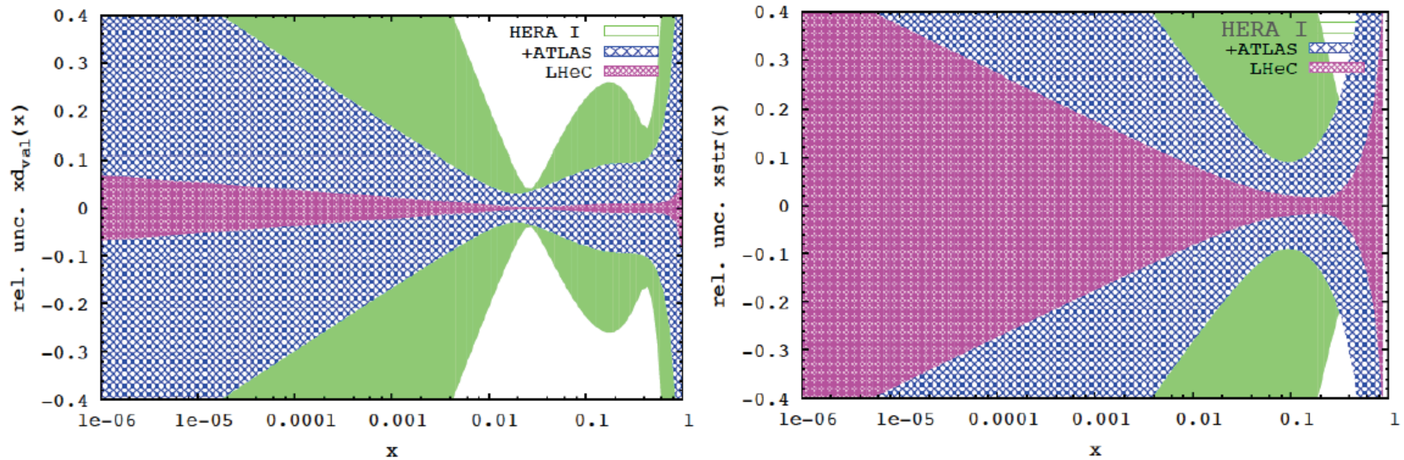


PDFs from HERA+LHC and LHeC

[ESG paper arXiv:1211.5102]

QCD fit with free u,d,s, HERA plus ultimate ATLAS and full systematic error simulation on LHeC

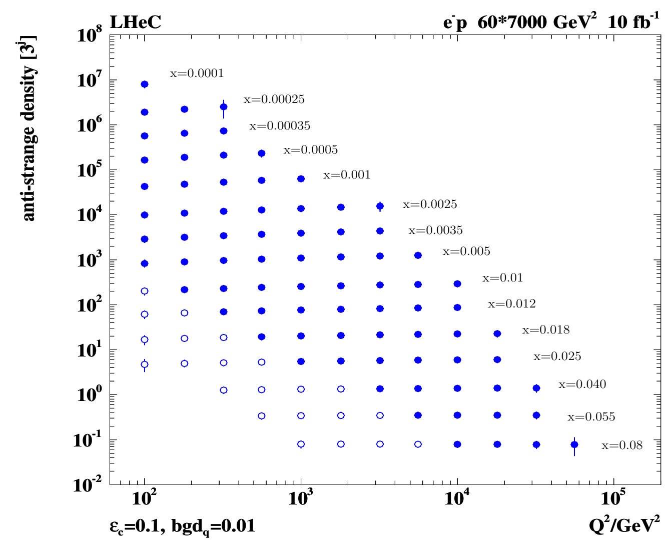
d valence | strange



DIS is the appropriate process to determine PDFs (rigorous theory, clean probe of proton stucture)

LHeC: first time ever to fully determine PDFs, free of quark symmetry and ad hoc assumptions in huge and unexplored kinematic range

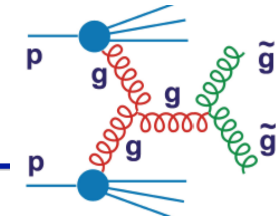
LHC: precision Drell-Yan data provide constraints *(cf for example the ATLAS determination of s/d)* Yet, high precision (<1%) only achievable at W,Z scale (miss the Q^2 evolution) and large EW&QCD theory uncertainties complicate interpretation

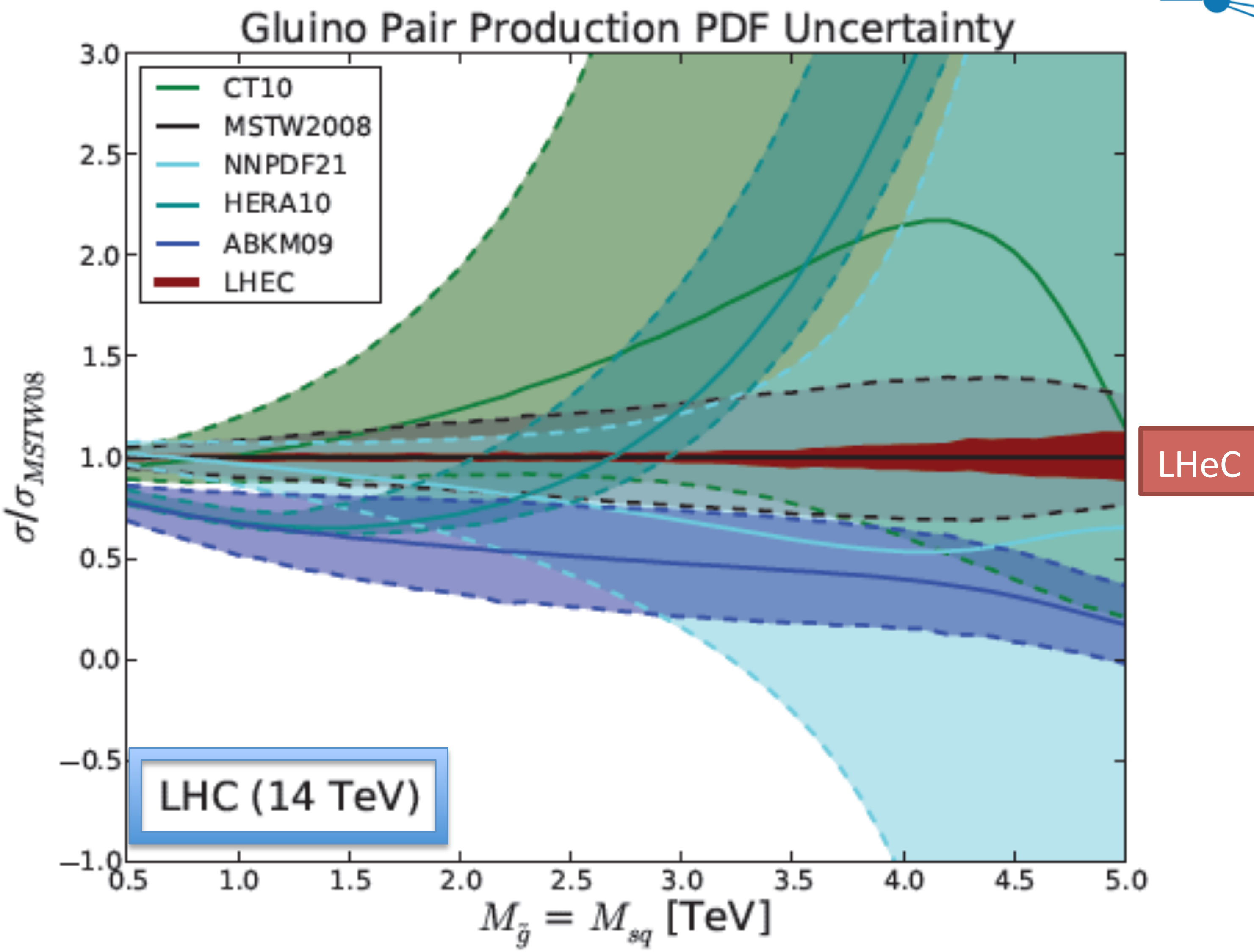


Direct strange measurement from CC DIS

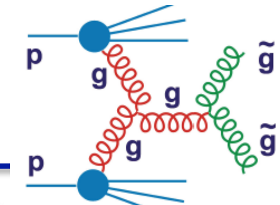
Ws→c in ep → νcX [high lumi, large range, small spot ~(7μm)^2]

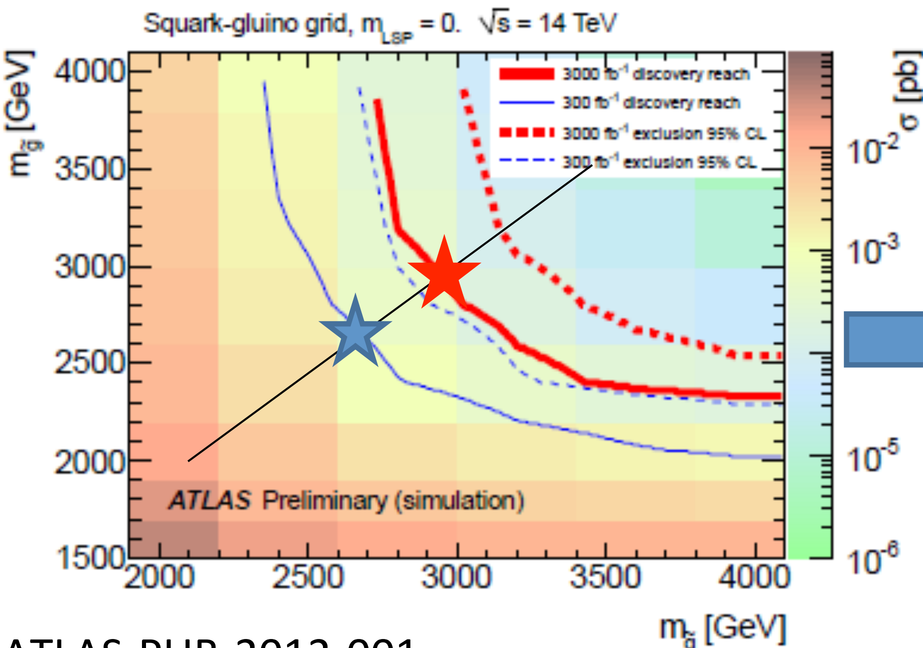
Precision gluons for SUSY



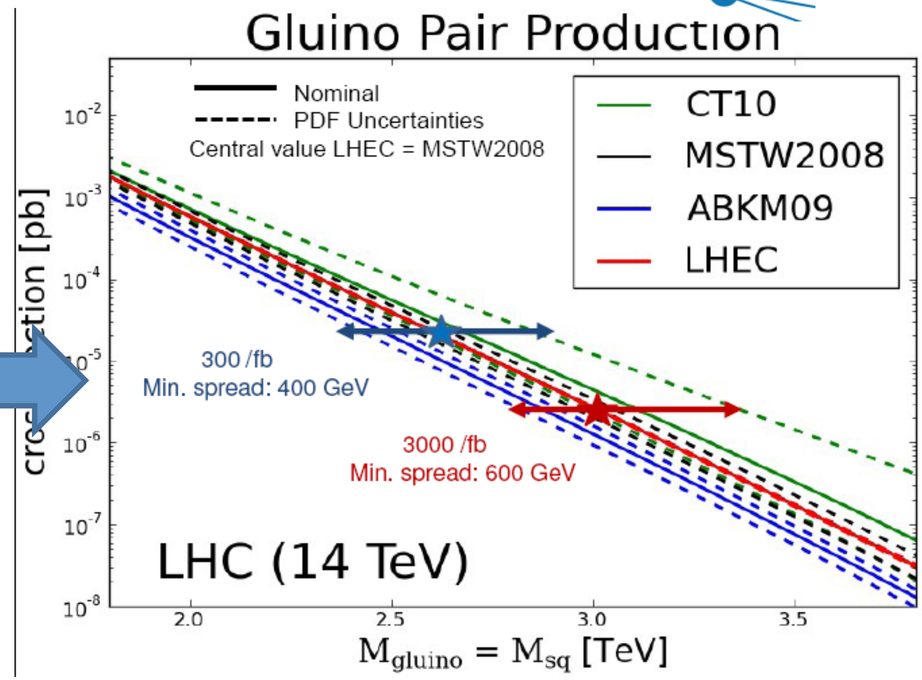


LHeC and the HL-LHC (SUSY searches)





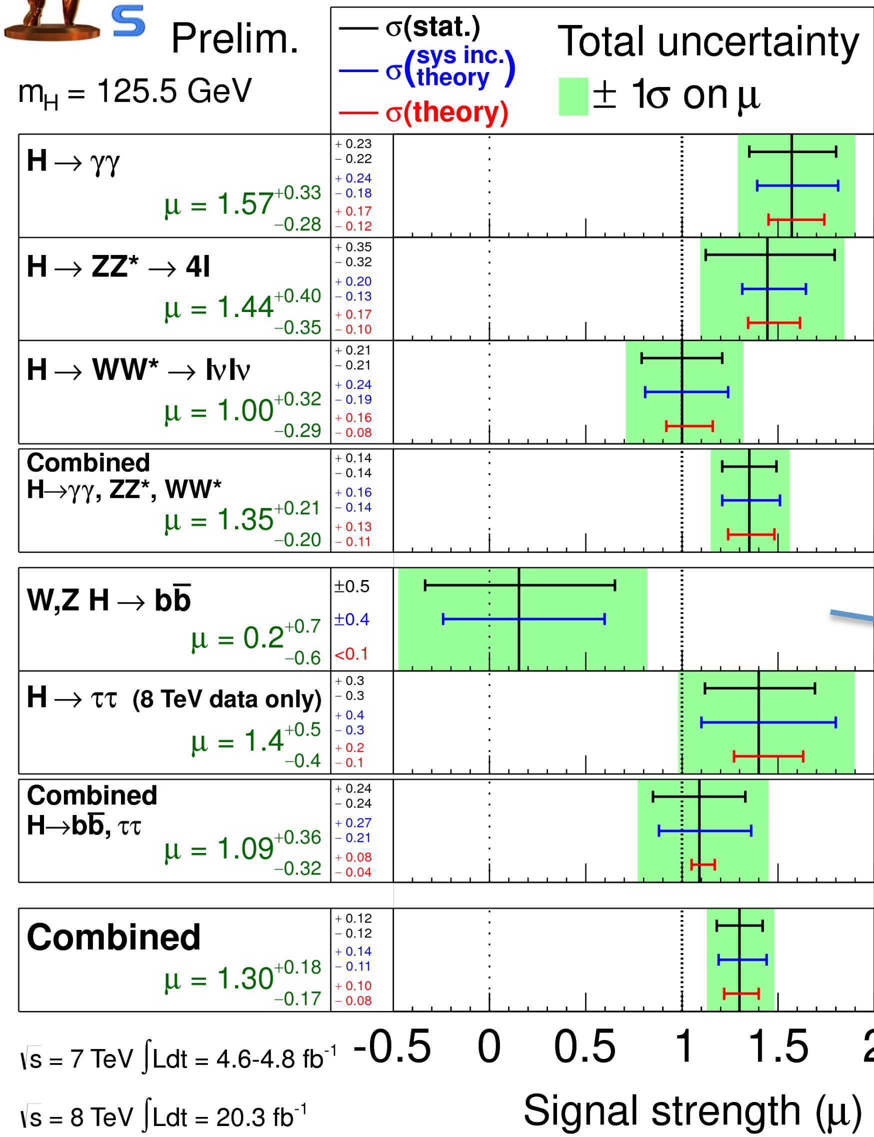
ATLAS-PUB-2012-001

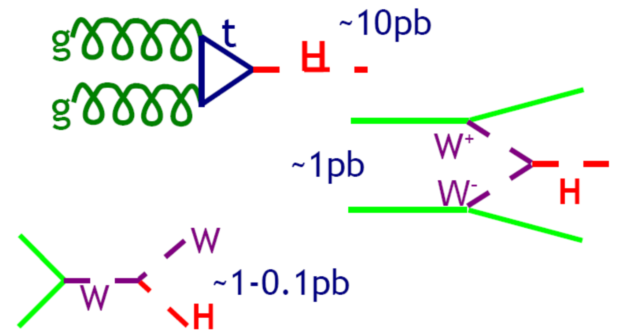


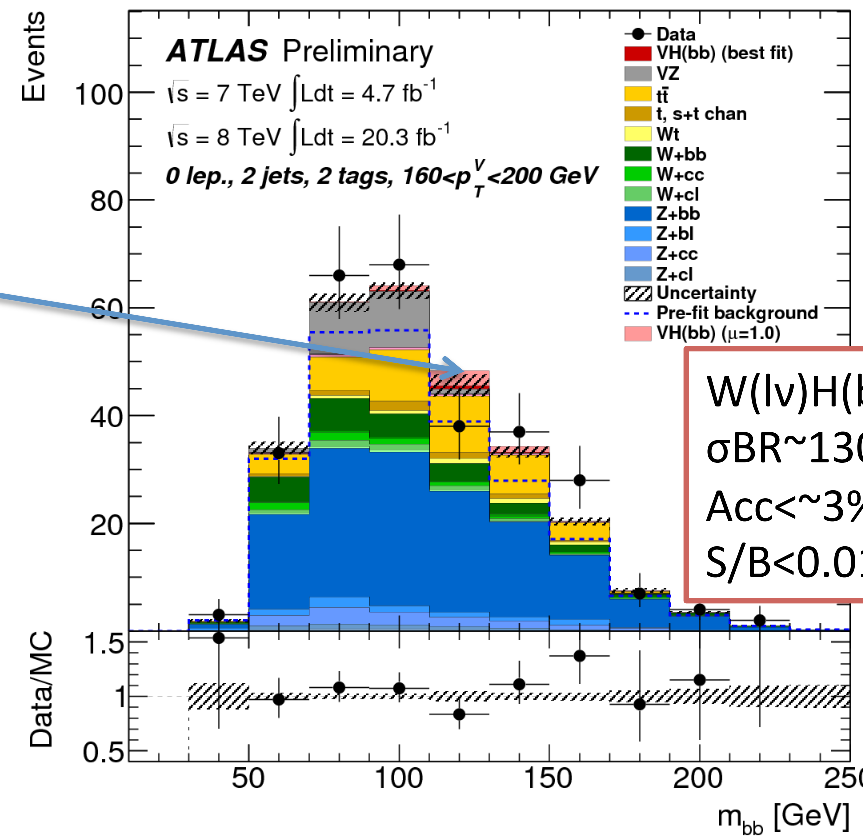
With high energy and luminosity, the LHC search range will be extended to high masses, up to 5 TeV in pair production → PDF uncertainties easily > 100% for high mass searches
→ gluon density from LHeC (10% at x=0.6, ~4TeV)]

The HL-LHC and FCC-hh search programme requires a much more precise understanding of QCD, which the LHeC could provide (strong coupling, gluon, valence, factorisation, saturation, diffraction..)

Status : Higgs coupling strength







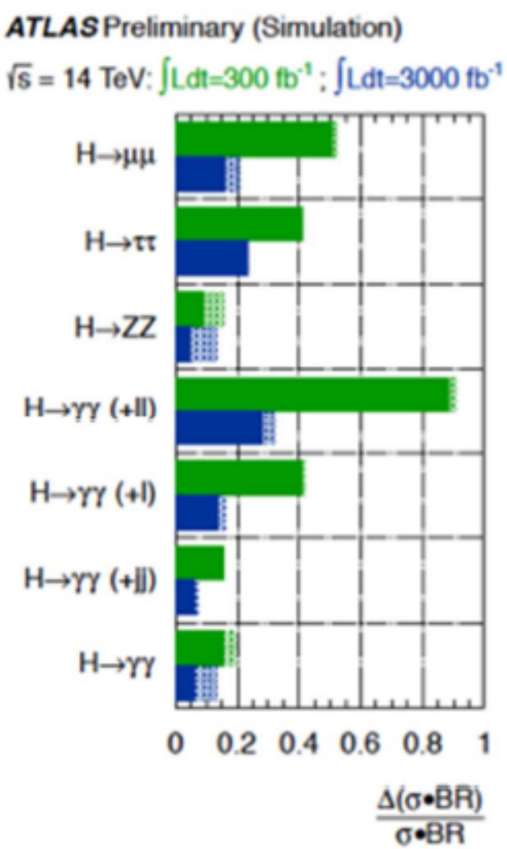
W(lν)H(bb)
σBR~130 fb
Acc<~3%
S/B<0.01

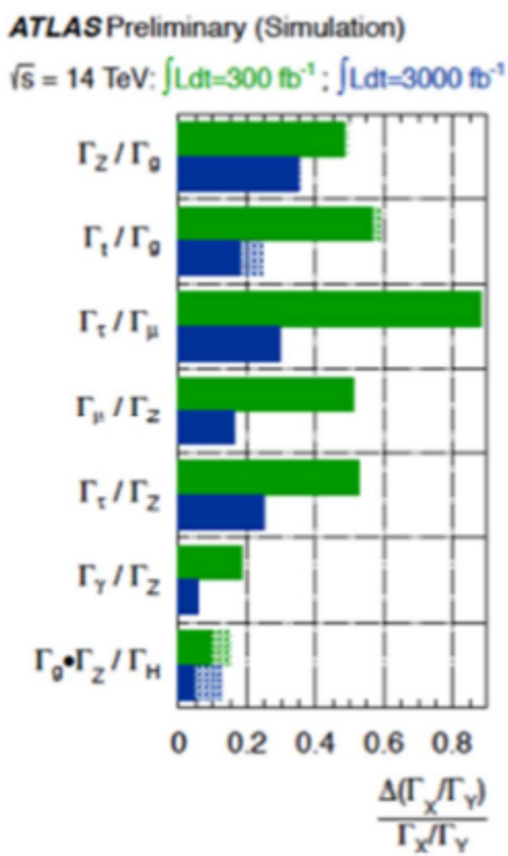
ATLAS-CONF-2014-009

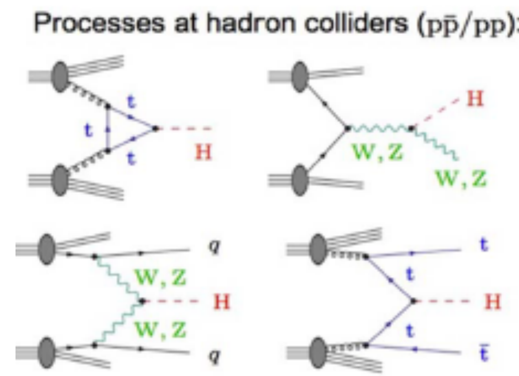
ATLAS-CONF-2013-079

PDF uncertainties and Higgs in *pp*

- PDF and α_s uncertainties as limiting factors for several channels at the HL-LHC
- Similar conclusion expected for FCC-hh (being worked worked out)







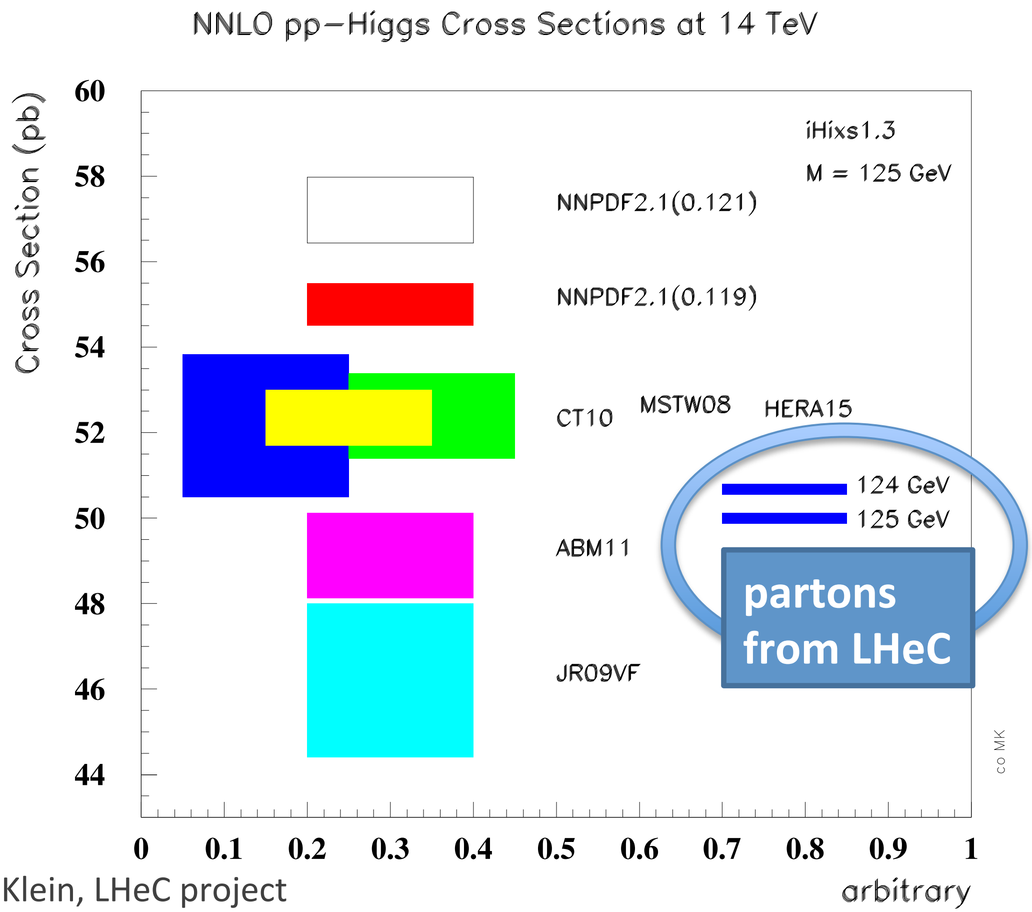
Dashed regions: scale & PDF contributions

Precision partons for Higgs in *pp*

→ **<u>Using LHeC input</u>**: experimental uncertainty of predicted **LHC Higgs cross section** is strongly **reduced to 0.4% due to PDFs and α_s**

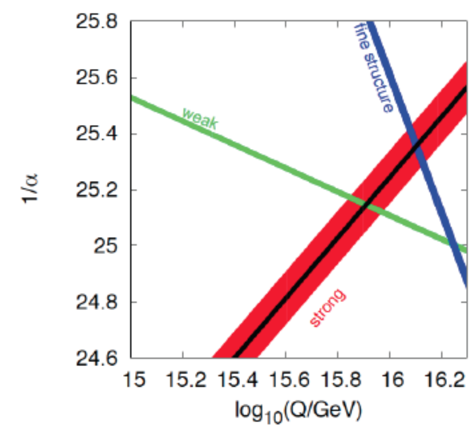
→ clear Higgs mass sensitivity in cross section predictions

→ **Similar conclusion and relations expected for FCC-hh and FCC-he**

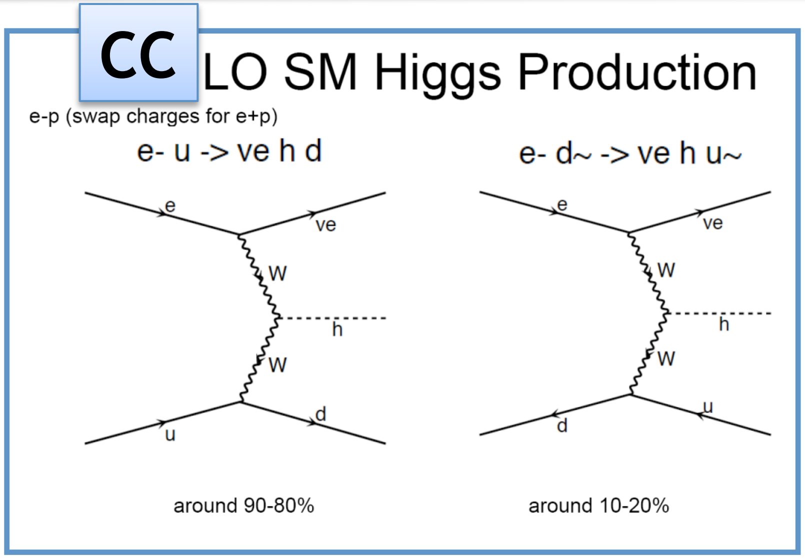


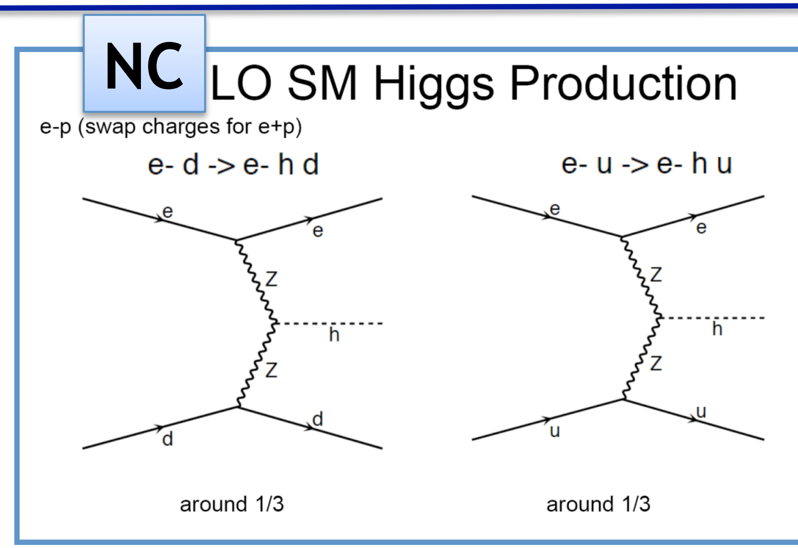
α_s = underlying parameter relevant for uncertainty (0.005 → 10%) @ LHeC: measure to permille accuracy (0.0002)

→ **precision from LHeC can add a very significant constraint on the Higgs mass** *but also:* ***Study unification of couplings***

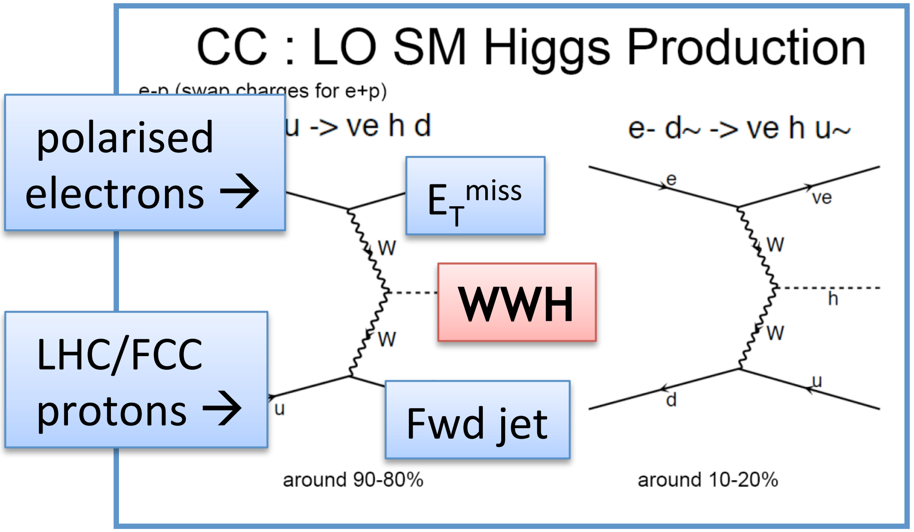


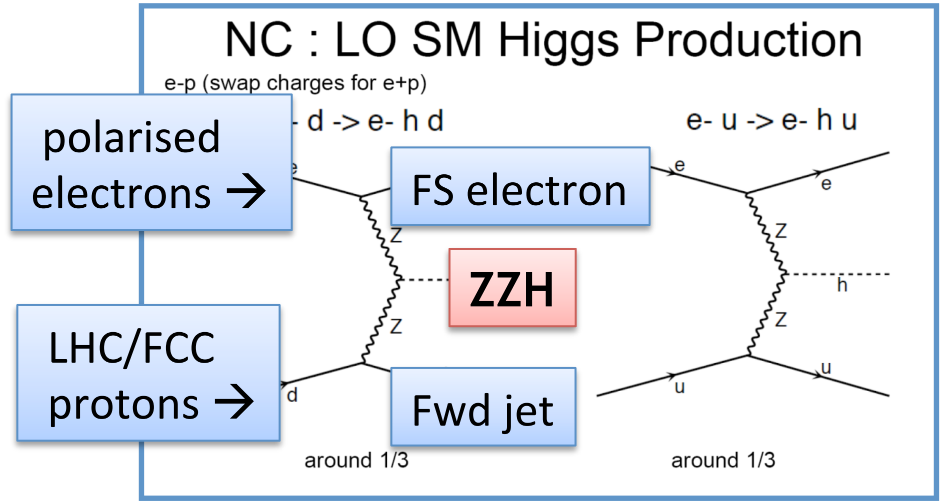
SM Higgs production in ep





SM Higgs production in ep





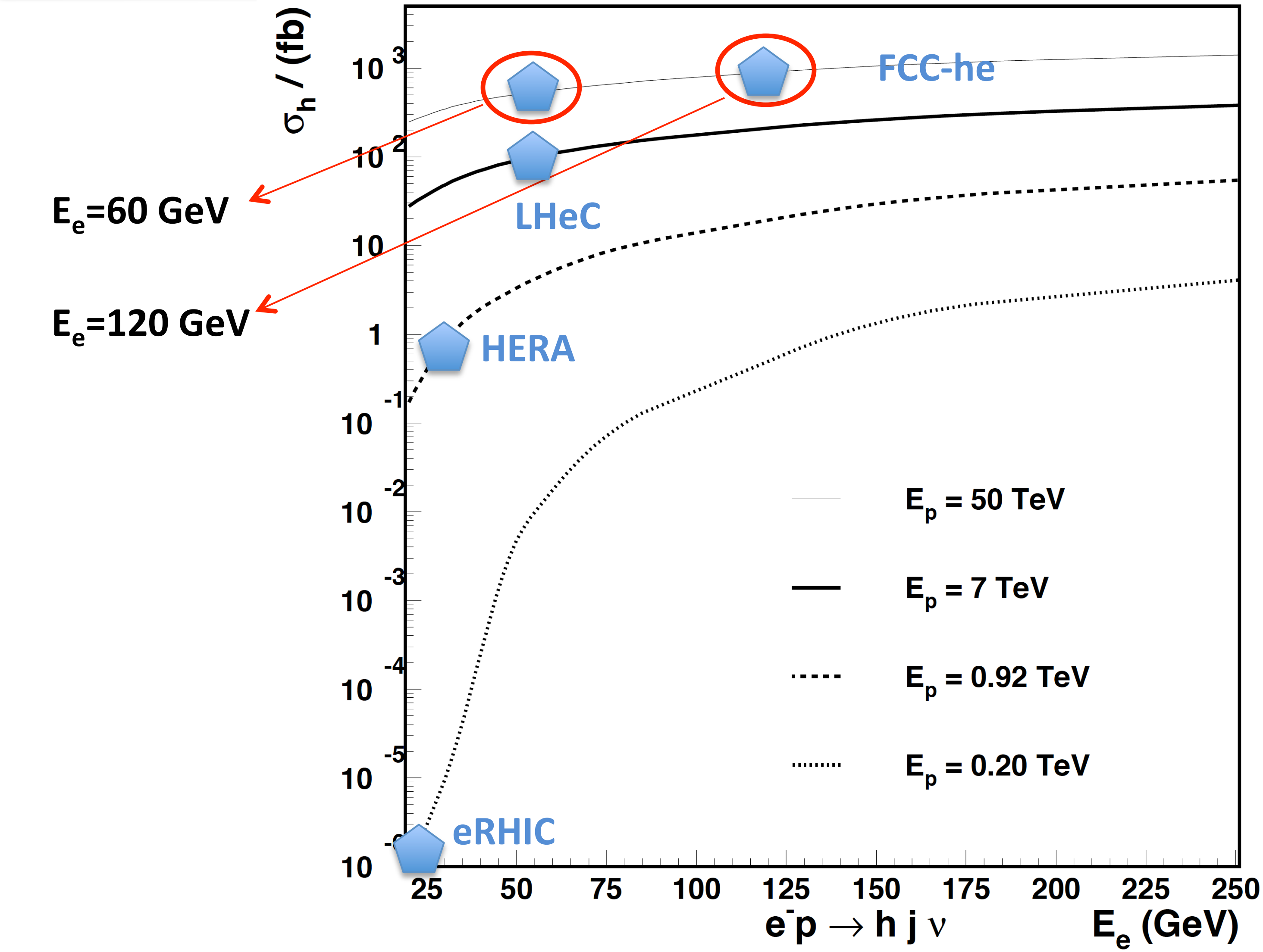
In ep, direction of FS quark is well defined.

Angles defined w.r.t. proton beam.

- **WWH and ZZH vertices can be probed <u>uniquely *and* simultaneously</u>**
- **ERL : high electron polarisation of 80-90% → doubling of CC rates!**
- Scale dependencies of the LO σ(Higgs) calculations are in the range of 5-10%.
- NLO QCD corrections in DIS are small in comparison to pp
- For Higgs : shape distortions of kinematic distributions up to 20% due to NLO QCD.

QED corrections up to -5%. [J. Blumlein, G.J. van Oldenborgh , R. Ruckl, Nucl.Phys.B395:35-59,1993] [B.Jager, arXiv:1001.3789]

Higgs production rates



LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

Analysis framework

Event generation

- SM Higgs production
- CC & NC background

by MadGraph5/MadEvent

↓

- Fragmentation
- Hadronization

by PYTHIA (modified for ep)

↓

Fast detector simulation

by PGS (LHC-style detector)

↓

H → $b\bar{b}$ (any decay) selection

- Calculate cross section with tree-level Feynman diagrams using pT of scattered quark as scale (CDR: $\hat{s}$) for ep processes like single t, Z, W, H

→ Standard HERA tools can NOT to be used !

- **NEW:** full update for Madgraph5 v2.1 (CDR: MG4)
- **Higgs mass 125 GeV as default since MG5 v2.1** (CDR: 120 GeV)
- MG5 and Pythia fully interfaced to most modern LHAPDF → test of LHeC PDFs
- Fragmentation & hadronisation uses **ep-customised** Pythia.

Any other model (UFO) can be easily tested → non-SM higgs, SUSY etc.

Valid for ep only.

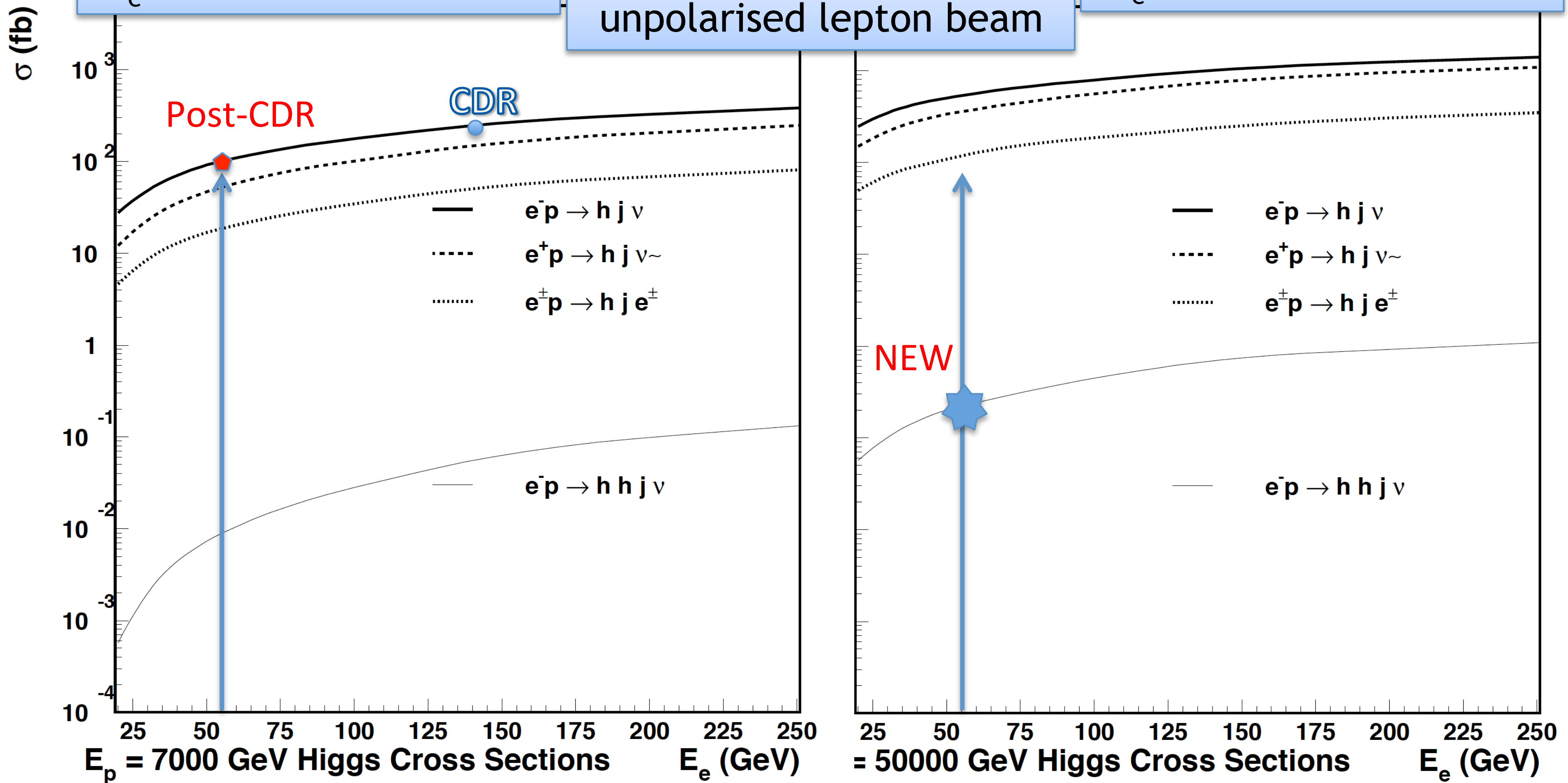
[eA needs modelling of nuclear fragmentation]

Total Higgs cross sections

E_e=60 GeV : $\sqrt{s}$= **1.3 TeV**

M_h=125 GeV
unpolarised lepton beam

E_e=60 GeV : $\sqrt{s}$=**3.5 TeV**



7 TeV LHC protons

50 TeV FCC protons

and

electrons from a 60 GeV energy recovery LINAC

... and P_e=-0.8

M_h=125 GeV
polarised lepton beam

	E_e=60 GeV : √s= **1.3 TeV**				E_e=60 GeV : √s=**3.5 TeV**			
	CC e^-p	CC e^+p	NC ep	CC hh	CC e^-p	CC e^+p	NC ep	CC hh
cross section [fb]	109	58	20	0.01	566	380	127	0.24
polarised cross section [fb] P=-80%	**196**	N.A.	25	0.02	**1019**	N.A.	**229**	0.43

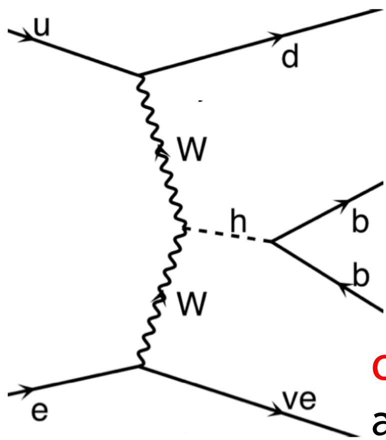
7 TeV LHC protons | 50 TeV FCC protons
and
electrons from a 60 GeV energy recovery LINAC

LHeC Examples: Generated samples

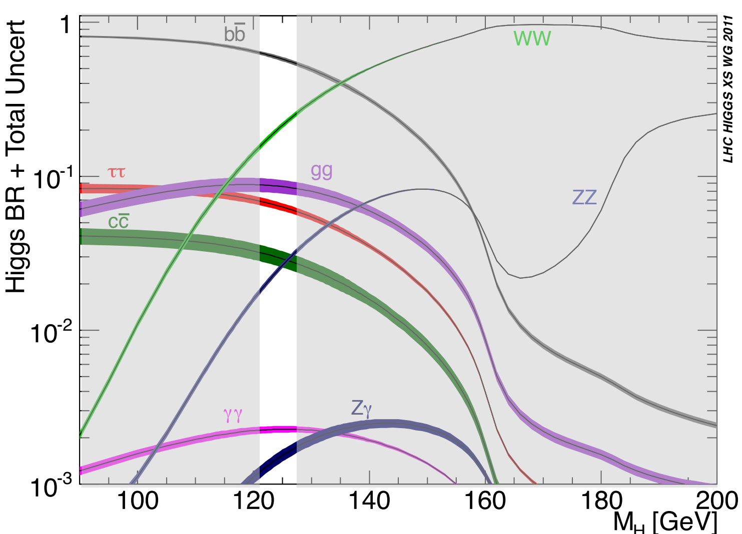
Graphs by MadGraph

Signal

CC: H → $\bar{b}b$ (BR ~ 0.7 at M_H=120GeV)

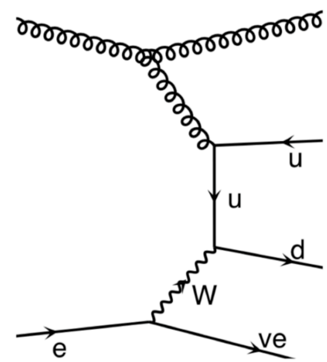


σ~ 0.16 pb
at √s=2.05TeV

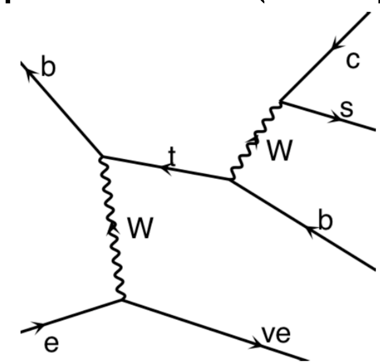


Background (examples)

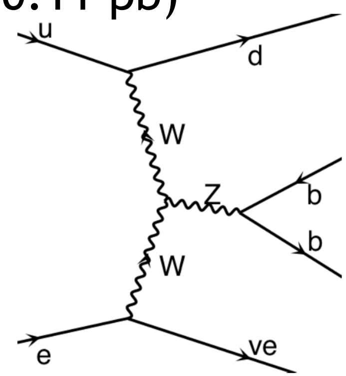
CC: 3 jets (~57 pb)



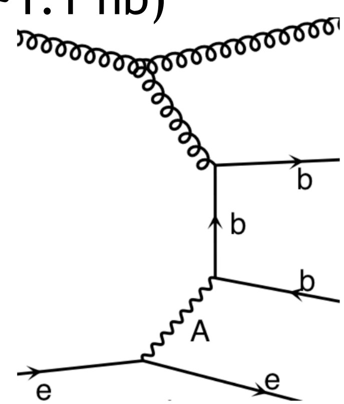
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)



NOTE: Background sample cross sections are after pre-selection in generator and for Ee=150 GeV

CDR : Selection of $H \rightarrow b\bar{b}$

[before Higgs discovery M_H=120 GeV, E_p=7 TeV]

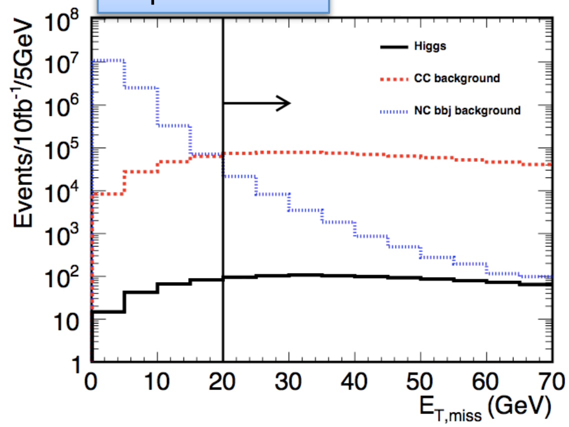
- NC DIS rejection
  - Exclude electron-tagged events
  - $E_{T,miss}$ > 20 GeV
  - N_{jet} (p_T > 20 GeV) ≧ 3
  - $E_{T,total}$ > 100 GeV
  - y_{JB} < 0.9, Q^2_{JB} > 400 GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ (p_T > 20 GeV) ≧ 2
- Higgs invariant mass
  - 90 < M_H < 120 GeV

$H \rightarrow b\bar{b}$

CC BG

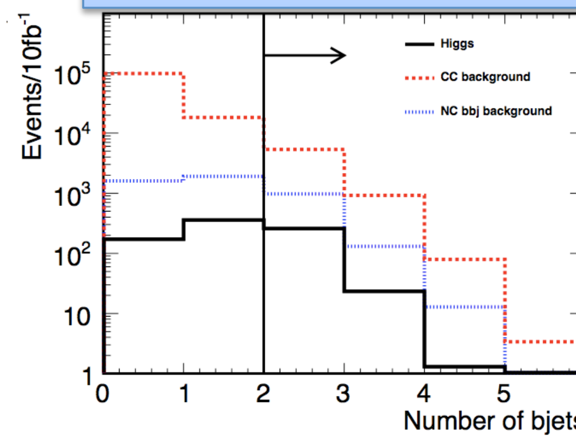
NC BG

E_T^{miss} cut



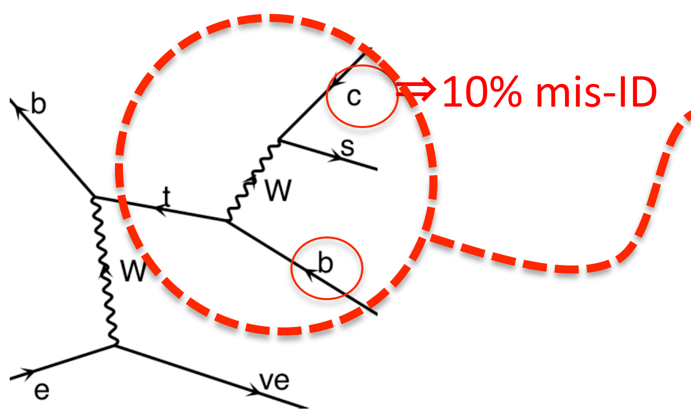
b-tag requirement

Flat efficiency for |η| < 3 of 60% (c:10%, lq,g:1%)

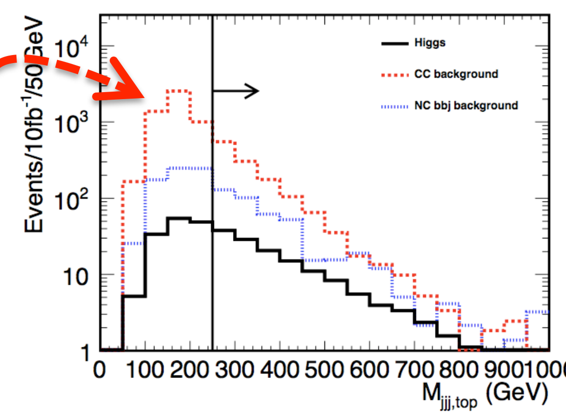


⇒ 44% of remaining BG is single-top…

- Single top rejection
  - $M_{jjj,top}$ > 250 GeV
  - $M_{jj,W}$ > 130 GeV



⇒10% mis-ID



CDR: A Large Hadron Electron Collider at CERN

J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001

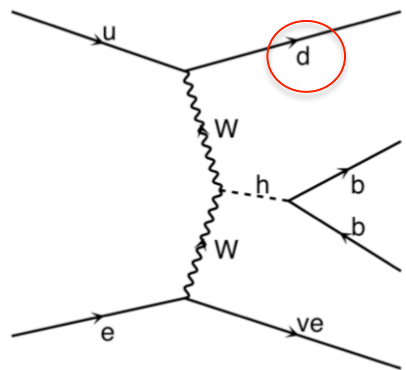
CDR : H→b$\bar{b}$ results

[before Higgs discovery M_H=120 GeV, E_p=7 TeV]

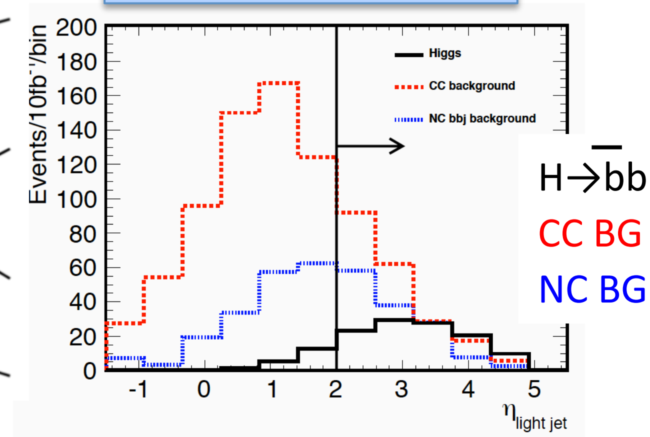
- Forward jet tagging
  - η_{jet} > 2 (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

H → b$\bar{b}$ signal

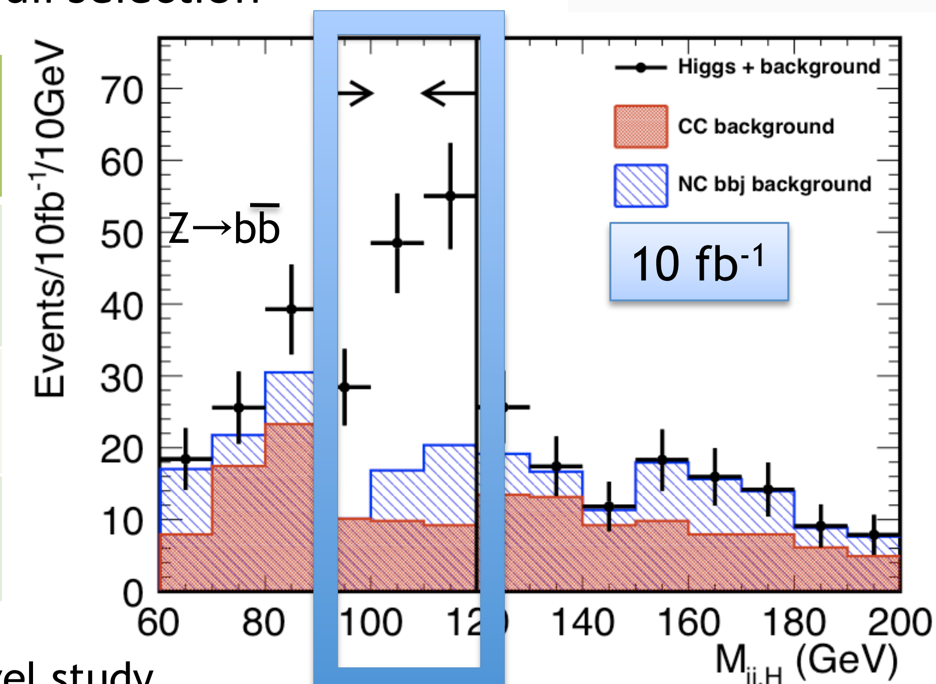


Forward jet η tag



- Higgs invariant mass after all selection

	E_e = 150 GeV (10 fb^{-1}, P=0)
H → bb signal	84.6
S/N	1.79 (4.7*)
S/√N	12.3



Clear signal obtained with just cut based analysis already!

*parton-level study.

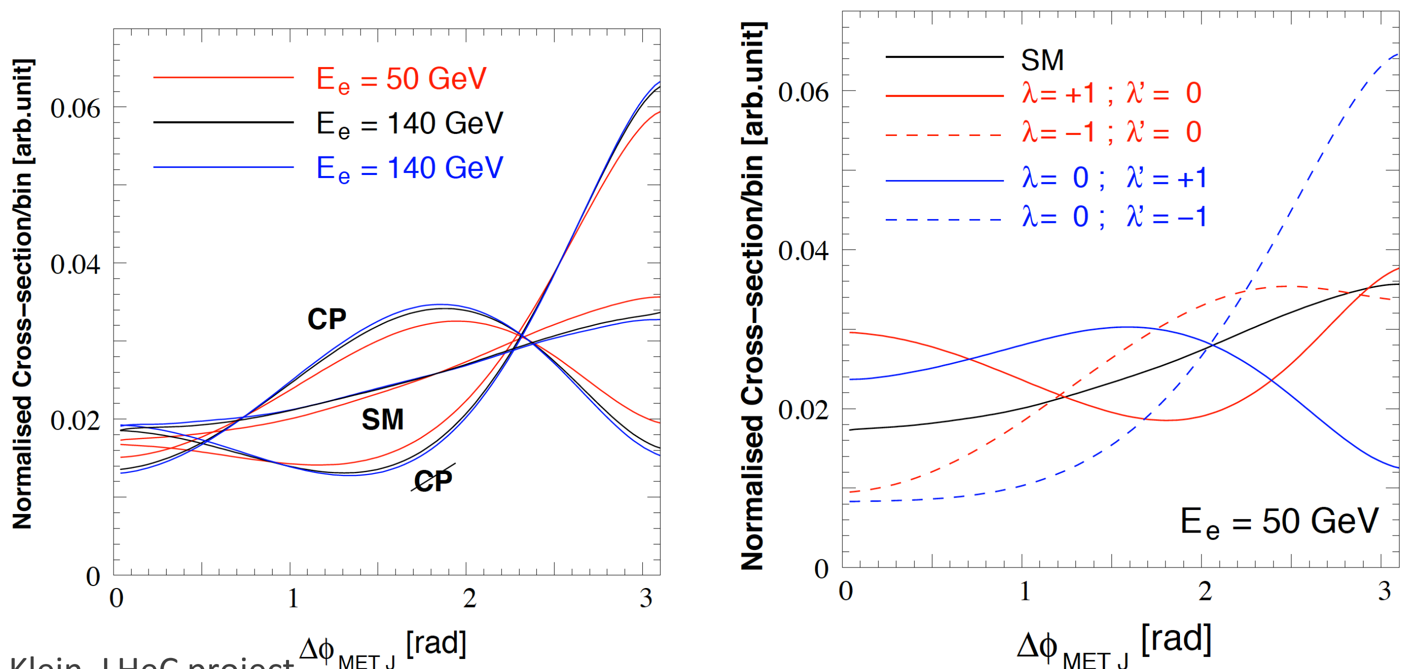
Measure CP properties of Higgs

[CDR before Higgs discovery MH=120 GeV, E_p=7 TeV]

- Higgs couplings with a pair of gauge bosons (WW/ZZ) and a pair of heavy fermions (t/b/τ) are largest.
- Higgs@LHeC allows uniquely to access HWW vertex → explore the CP properties of HVV couplings: BSM will modify CP-even (λ) and CP-odd (λ') states differently

$$\Gamma^{\mu\nu}_{(\mathrm{SM})}(p,q) = g M_W\, g^{\mu\nu} \quad \rightarrow \quad \Gamma^{(\mathrm{BSM})}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\,(p.q\, g_{\mu\nu} - p_\nu q_\mu) + i\,\lambda'\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

- Study ***shape changes*** in DIS normalised CC Higgs→ bb cross section versus the azimuthal angle, $\Delta\phi_{MET,J}$, between $E_{T,miss}$ and forward jet.



CDR initial study of HWW vertex:

CP couplings probed to λ~0.05

λ'~0.2

based on 50 fb^{-1}

In ep, full Δϕ range can be explored, here not shown yet.

ep Higgs “Facility” @ 1 ab^{-1}

Post-CDR: **For first time a realistic option of an 1 ab^{-1} ep collider** (stronger e-source, stronger focussing magnets) and **excellent performance of LHC** (higher brightness of proton beam).

√s= **1.3 TeV**

→ need of different models :
cc: ‘sm-full’

gg, γγ: **‘heft’**

LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

Ultimate polarised e-beam of 60 GeV and LHC-p beams, 10 years of operation

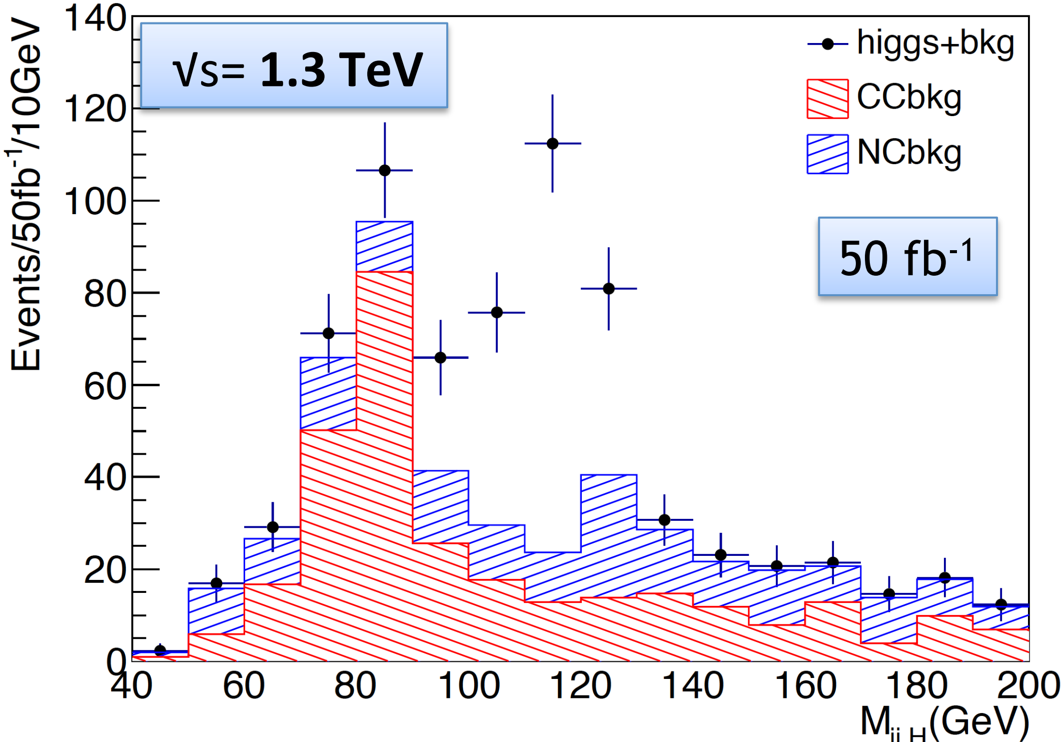
➔ **other BR’s started to be explored, e.g. cc, gg, and ττ (use BR’s from HDECAY!)**

Note : EW parameters, HQ masses different for different models!

$H \rightarrow b\bar{b}$ results updated

[after Higgs discovery M_H=125 GeV, E_p=7 TeV]

- Case study for electron beam energy of 60 GeV using same analysis strategy
  - luminosity values of 50 fb^{-1} → with high luminosity LHeC 100 fb^{-1}/year would be feasible!



Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

M_H selection [100-130 GeV]	E_e = 60 GeV (50 fb^{-1}, P=0)
H → bb signal	175
S/N	1.9
S/√N	18.1

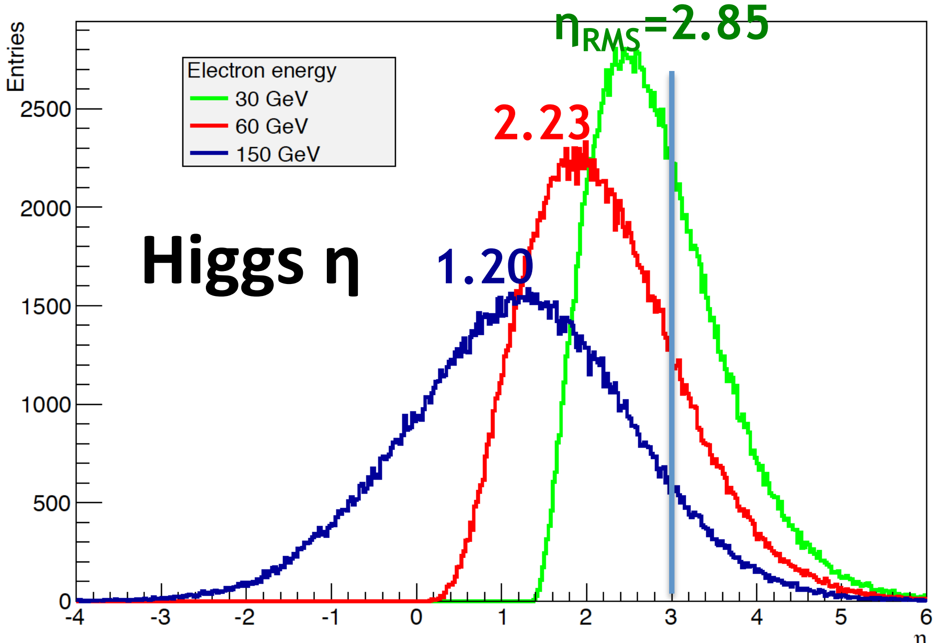
- Electron energy recovery LINAC with **high electron polarisation of 80% and 10^{34} cm^{-2} s^{-1}** ➔ enhancement by factor 20*1.8 feasible, i.e. around 6300 Higgs candidates for E_e=60 GeV allowing to measure Hbb coupling with ~ **0.5 % - 1%** statistical precision.

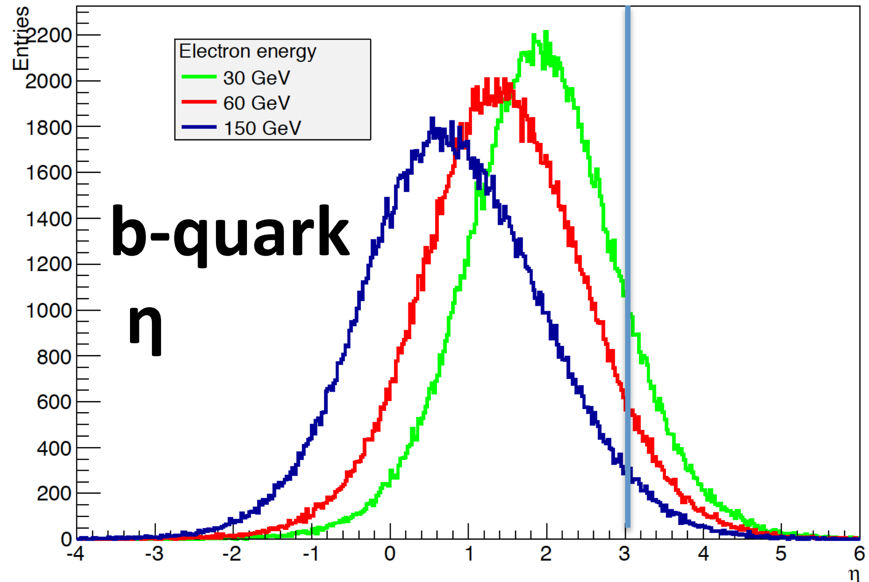
- Very promising estimate of S/N ➔ more sophisticated analysis and detector optimisations may enhance those prospects further

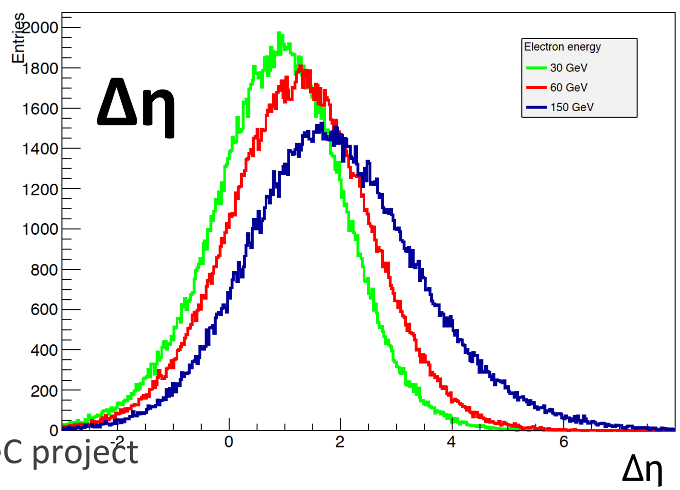
Higgs acceptance vs E_e

[after Higgs discovery M_H=125 GeV, E_p=7 TeV]

[Master thesis by Sergio Mandelli, Liverpool 2013]



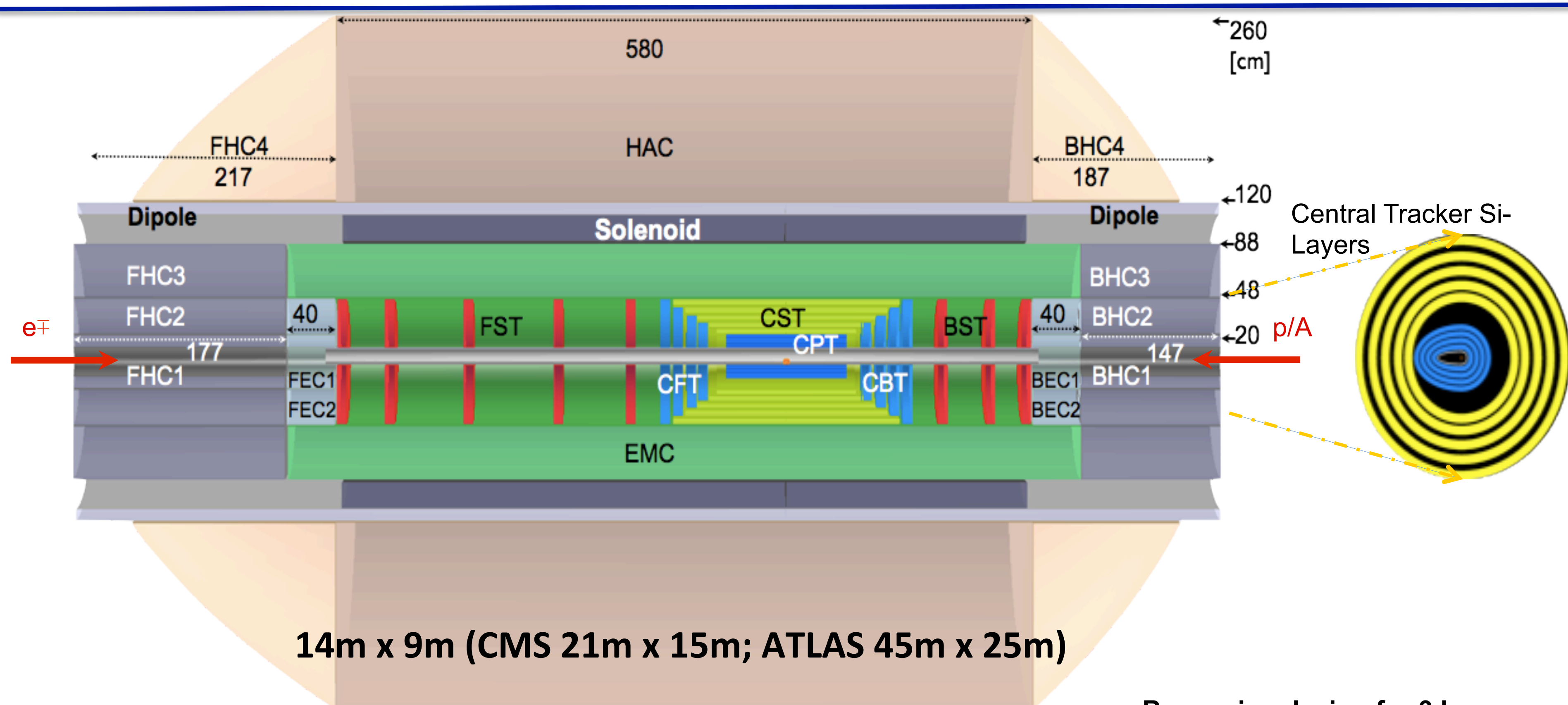




- ➔ lowering of electron beam energy (more cost efficient) will challenge more detector design: worse separation between higgs and forward jet (Δη shrinks by 1 unit) and b-quarks from Higgs decay are more forward
- ➔ <u>**stick with 60 GeV**</u> E_e : decay products of Higgs scattered at ~28° (η~1.4)

Baseline detector design

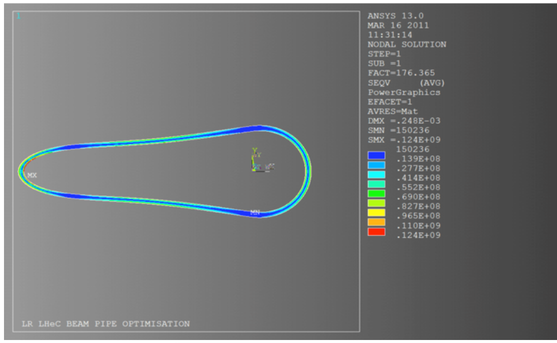
A. Polini and P. Kostka



14m x 9m (CMS 21m x 15m; ATLAS 45m x 25m)

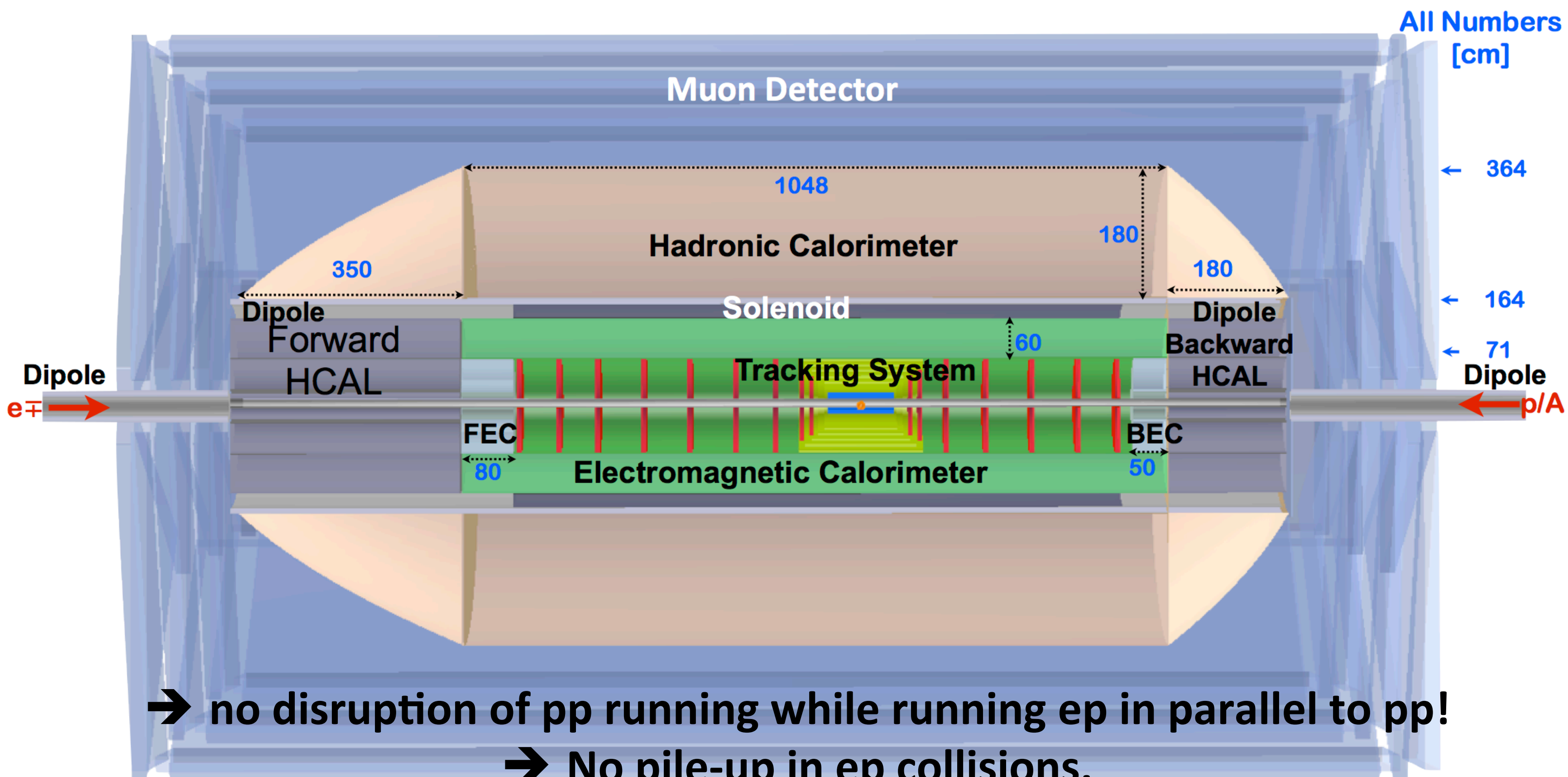
- **High acceptance Silicon Tracking System ~1° (high tagging capabilities e.g. for b-jets up to η~3)**
- **Liquid Argon EM Calorimeter**
- **Iron-Scintillator Hadronic Calorimeter**
- **Forward Backward Calorimeters: Si/W Si/Cu**

Beam pipe design for 3 beams



FCC-he detector

→ Longer in p direction (x 2 for calorimeters to contain showers)
→ Same or slightly longer in electron direction (about 1.3 for 120 GeV)



→ no disruption of pp running while running ep in parallel to pp!
→ No pile-up in ep collisions.

Alessandro Pollini and Peter Kostka
https://indico.cern.ch/event/282344/session/15/contribution/100/material/slides/0.pdf

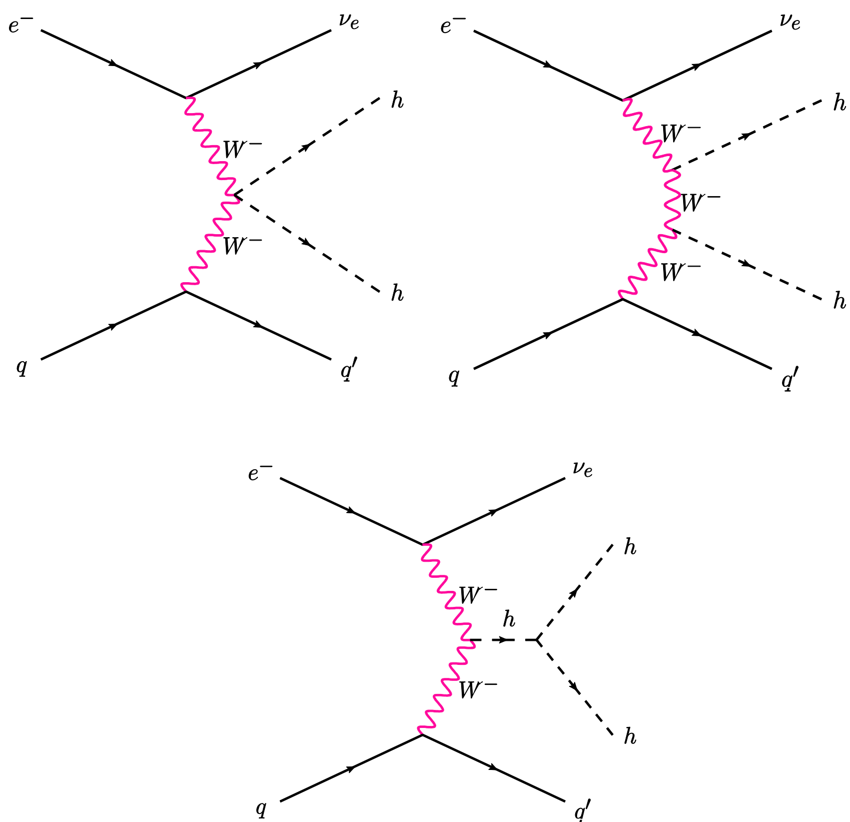
SM Higgs prospects in DIS

	√s= 1.3 TeV		√s= 3.5 TeV
Higgs in e^-p	CC - LHeC	NC - LHeC	CC - FHeC
Polarisation	-0.8	-0.8	-0.8
Luminosity [ab^{-1}]	1	1	5
Cross Section [fb]	196	25	850
Decay / BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$ 0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$ 0.029	5 700	700	123 000
$H \to \tau^+\tau^-$ 0.063	12 350	1 600	270 000
$H \to \mu\mu$ 0.00022	50	5	1 000
$H \to 4l$ 0.00013	30	3	550
$H \to 2l2\nu$ 0.0106	2 080	250	45 000
$H \to gg$ 0.086	16 850	2 050	365 000
$H \to WW$ 0.215	42 100	5 150	915 000
$H \to ZZ$ 0.0264	5 200	600	110 000
$H \to \gamma\gamma$ 0.00228	450	60	10 000
$H \to Z\gamma$ 0.00154	300	40	6 500

FFC-he, H→HH cross section ~0.4fb

Double higgs production

- Electron-proton collisions offer the advantage of reduced QCD backgrounds and negligible pile-up with the possibility of using the 4b final state : $\sigma \times BR(HH \rightarrow 4b)$=0.04 fb ($P_e$=0)



$$p_{T_{j,b}} > 20 \ GeV,$$
$$\not{E}_T > 25 \ GeV,$$
$$|\eta_j| < 5, \ \Delta R = 0.4.$$

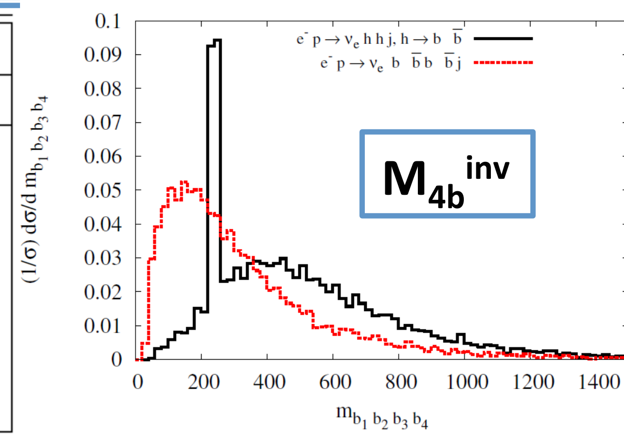
Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e hhj, h \to b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

<u>Fiducial</u> cross-sections for CC e$^-$p DIS : HH->4b (branching ratios included) and *un*polarised electron beam; assume 70% b-tagging efficiency, 0.1 (0.01) fake rates for c (light) jets

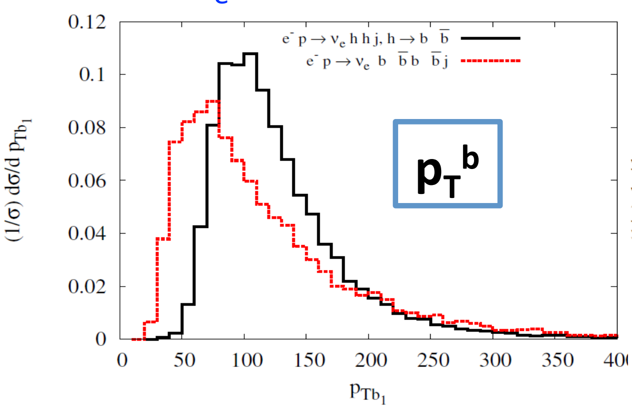
First *parton-level* feasibility studies

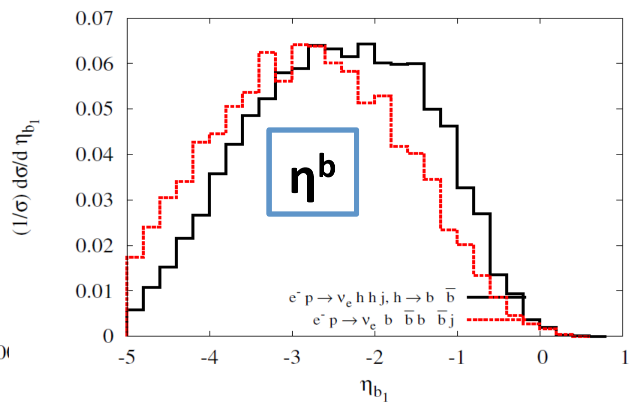
Cross-sections for CC backgrounds in fb for E_e=60,120,150 GeV

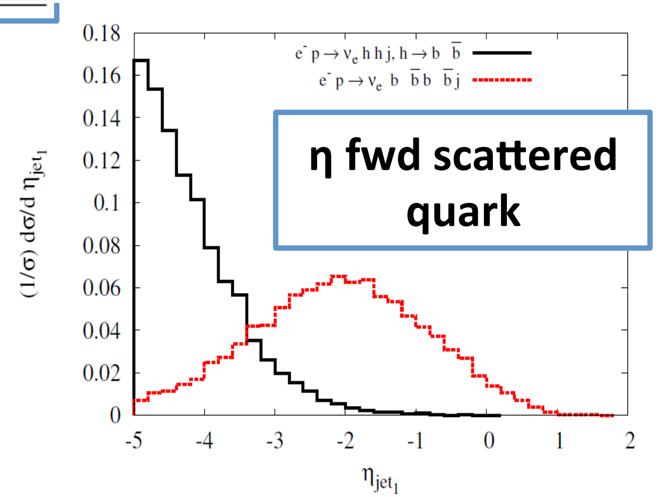
Processes	$E_e = 60$ GeV		$E_e = 120$ GeV		$E_e = 150$ GeV	
	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e b\bar{b}b\bar{b}j$	0.086	0.022	0.14	0.036	0.15	0.038
$e^- p \to \nu_e b\bar{b}c\bar{c}j$	0.12	1.7×10^{-5}	0.36	1.8×10^{-3}	0.44	2.2×10^{-3}
$e^- p \to \nu_e c\bar{c}c\bar{c}j$	0.20	1.0×10^{-6}	0.24	3.4×10^{-5}	0.31	4.3×10^{-5}
$e^- p \to \nu_e b\bar{b}jjj$	26.1	3.9×10^{-3}	54.2	0.008	67.5	0.01
$e^- p \to \nu_e c\bar{c}jjj$	29.6	9.5×10^{-5}	66.9	2.0×10^{-4}	85.4	2.7×10^{-4}
$e^- p \to \nu_e jjjjj$	823.6	4.1×10^{-5}	1986	9.9×10^{-5}	2586	1.3×10^{-4}



Plots for E_e=60 GeV (very similar for 120,150 GeV)



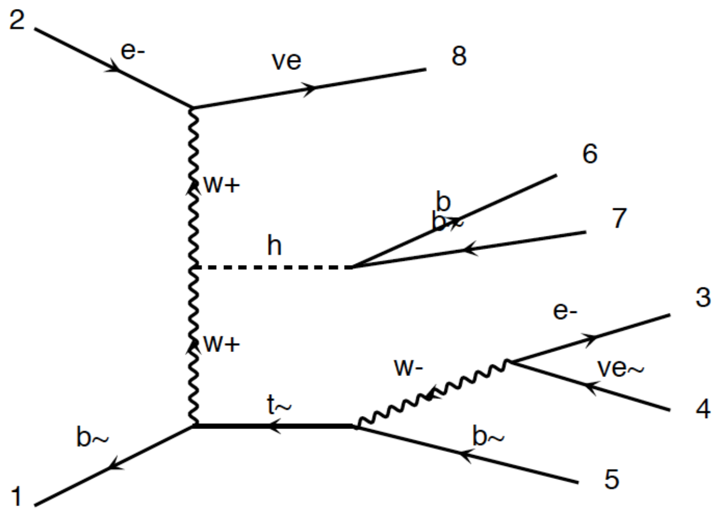


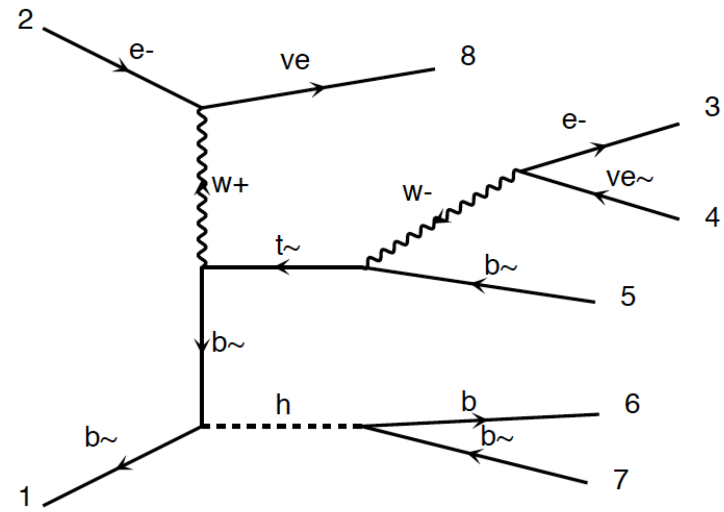


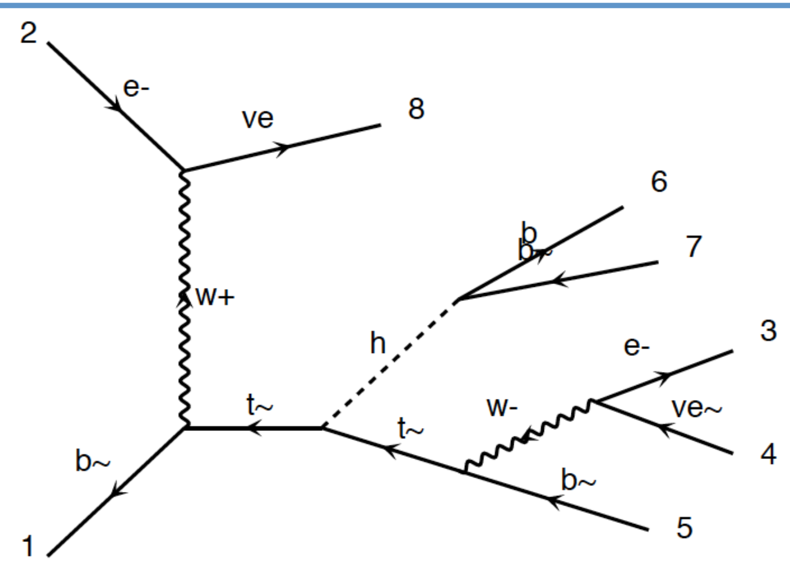
Despite large beam energy imbalance: "b-jets" are relatively central

Scattered quark is more forward in signal → good discriminant!

Exploring htt







<u>FCC-he unpolarised cross section at 3.5 TeV:</u>

total : 0.7 fb

fiducial : 0.2 fb

using pt(b,j)>20 GeV

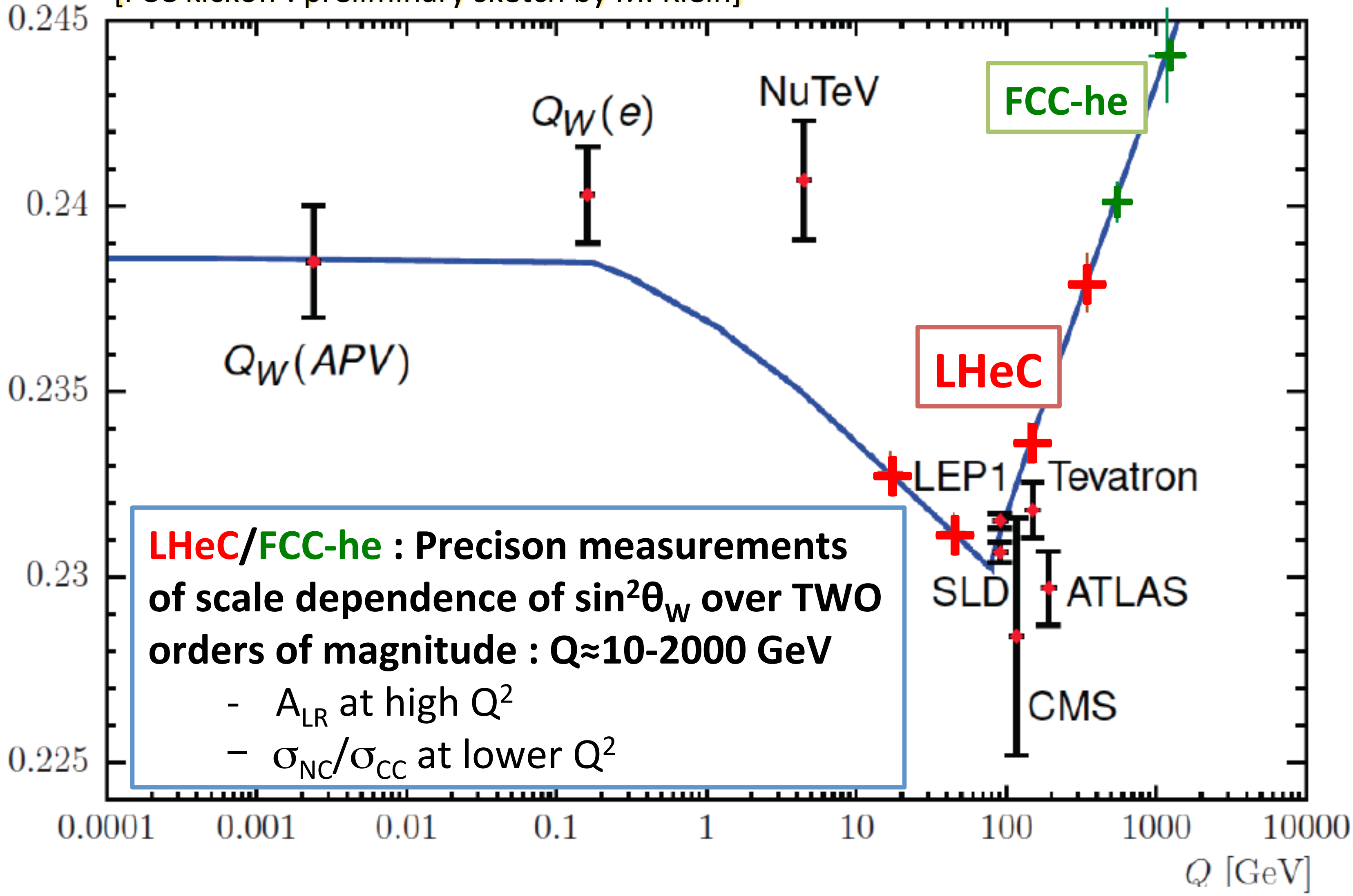
ΔR(j.b)>0.4

η(j) <5

η(b) < 3

EW physics in ep: $\sin^2\theta_W$

[FCC kickoff : preliminary sketch by M. Klein]



LHeC/FCC-he : Precison measurements of scale dependence of $\sin^2\theta_W$ over TWO orders of magnitude : Q≈10-2000 GeV

- A_{LR} at high Q^2
- σ_{NC}/σ_{CC} at lower Q^2

See also: https://indico.cern.ch/event/282344/session/5/contribution/37/material/slides/1.pdf

International Advisory Committee

NEW : Towards TDRs for future DIS at CERN: **International Advisory Committee**

Guido Altarelli (Rome)
Sergio Bertolucci (CERN)
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 Wormersley (STFC)

*)

The IAC was invited in December 2013 by the DG with the following

Mandate 2014-2017

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.

*) IAC Composition March 2014 +
Oliver Brüning Max Klein ex officio

See also Panel discussion at the recent LHeC workshop (Chavannes, 20-21 Jan 2014) led by Herwig Schopper : https://indico.cern.ch/event/278903/contribution/55

Towards an LHeC ERL Test Facility@CERN

Contribution to IPAC13

STRAWMAN OPTICS DESIGN FOR THE LHeC ERL TEST FACILITY

A. Valloni*, O. Bruning, R. Calaga, E. Jensen, M. Klein, R.Tomas, F. Zimmermann,
CERN, Geneva, Switzerland
A. Bogacz, D. Douglas, Jefferson Lab, Newport News Virginia

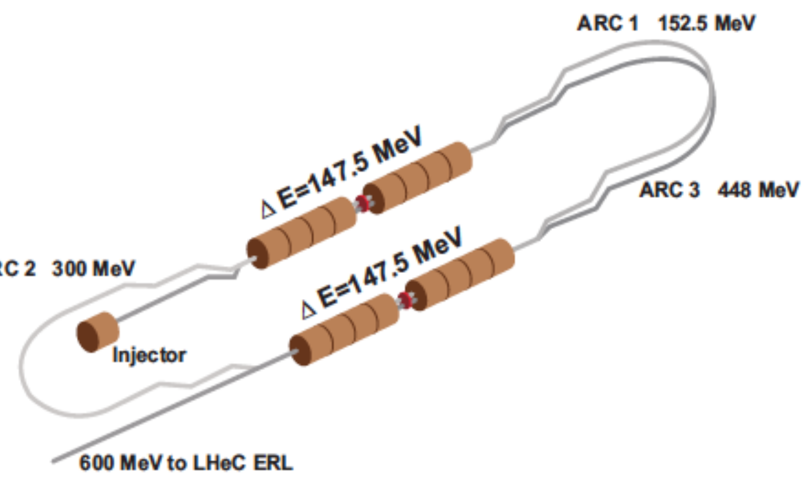


Figure 2: Consequent upgrade to LHeC pre-accelerator. By modifying the machine backleg to include a second full cryomodule, the recirculator can deliver higher beam energy of 600 MeV.

Proposal for an LHeC ERL Test Facility at CERN

R. Calaga, E. Ciapala, E. Jensen
CERN, Geneva, Switzerland

CERN-LHeC-Note-2012-001 ACC
October 17, 2012
Rama.Calaga@cern.ch

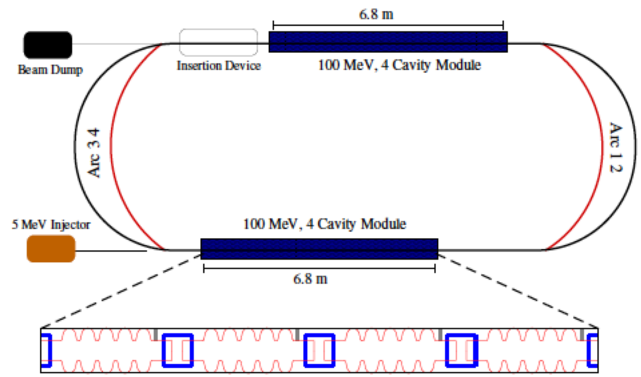
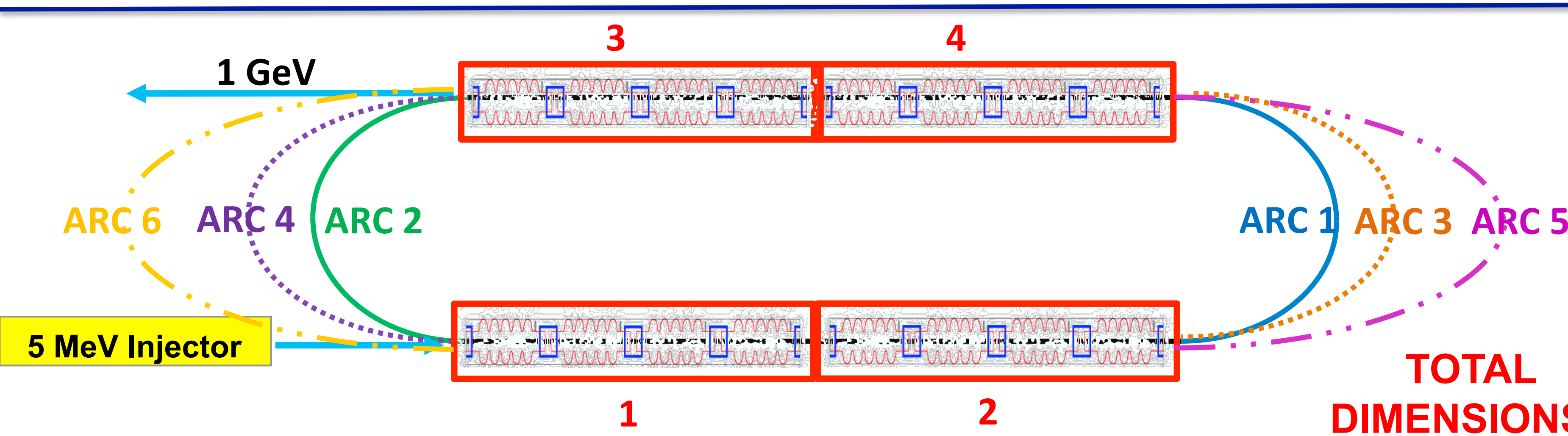


Table 3: Future ERLs for electron-hadron colliders

Parameter	JLab MEIC	BNL eRHIC	CERN LHeC
Energy [GeV]	5-10	20	60
Frequency [MHz]	750	704	n×40
# of passes	-	6	3
Current/pass [mA]	3	50	6.6
Charge [nC]	4	3.5	0.3
Bunch Length [mm]	7.5	2.0	0.3

Current test facility design



TOTAL DIMENSIONS 42 m x 13.7 m

From step 1 ARCs 1&2+2 cryo→ 155 MeV to ARCs 1-6+4 cryo→ 905 MeV

Daresbury workshop: January 2013: 802 MHz, basic parameters reviewed

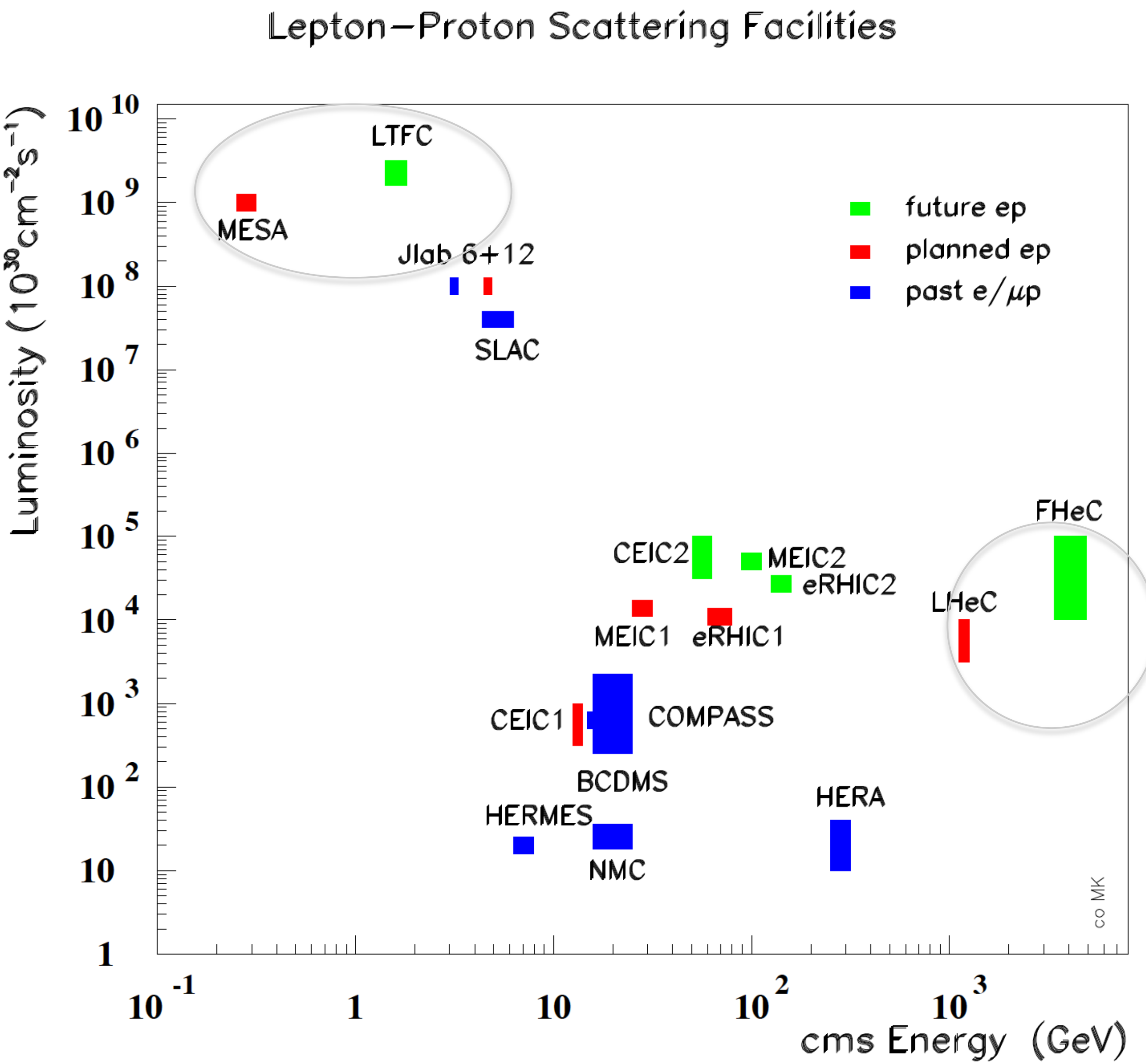
Strong international interest in collaborating:
AsTEC, IHEP Beijing, BINP Novosibirsk, BNL, Cornell**, Jefferson Lab (MoU), U Mainz..**

CERN mandate (approved 11/13) : Development of <u>two</u> cavity cryo-modules by 2016 and design of the test facility by the end of 2015

Alessandra Valloni
https://indico.cern.ch/event/282344/session/15/contribution/97/material/slides/1.pdf

Summary

- **LHeC** and **FCC-he**, in **ep**(A) collisions **synchronous** with **pp** (AA) running, could deliver fundamentally new insights on the structure of the proton (and nucleus) and the strong coupling α_S with high precision ➔ thus strengthen enormously the HL-LHC/FCC-hh physics case for searches
- LHeC sensitivity to H→bb is estimated by an initial simulation study : LHeC has the potential to measure H → bb coupling with an S/N >~1 and to 1% accuracy with 60 GeV electron beam based on a luminosity of 10^{34} cm^{-2} s^{-1}.
- At LHeC, various Higgs boson decays and Higgs CP eigenstates could be accessed via WW and ZZ fusion at c.m.s. energies of **1.3 TeV** and with **1000 fb**$^{-1}$ - complementary to LHC experiments.
- There are exiting prospects to measure **double Higgs boson** production **at FCC-he** that deserve further detailed studies.
- **New high luminosity and high energy prospects in ep have just started to be explored and open exciting new potential for complementary, precision Higgs physics at the LHC and FCC facilities.**



CERN: LHC+FCC: the only realistic opportunity for **energy frontier deep inelastic scattering.** Huge step in energy (Q^2,1/x) and **3 orders of magnitude higher luminosity than HERA .**

See also https://indico.cern.ch/event/282344/session/15/contribution/95/material/slides/0.pdf

For an overview:

The CDR: J.Phys.G: arXiv:1206.2013
Web page http://cern.ch/lhec ← **New web and communication page coming**

LHeC Meetings: http://indico.cern.ch/categoryDisplay.py?categId=1874

A recent brief overview paper: Oliver Bruening and Max Klein, arXiv:1305.2090

Conferences in 2013: LPCC (April), DIS Marseille, IPAC Shanghai, EPS Stockholm

LHeC Workshop, Chavannes, 21.-22.1.2014
https://indico.cern.ch/conferenceDisplay.py?confId=278903
Two sessions: Detector+Physics and Test facility+Accelerator
FCC Kickoff Meeting, CERN, 12.-15.2. 2014, separate ee, ep, and pp sessions & plenary talks
https://indico.cern.ch/event/282344/timetable/#all.detailed

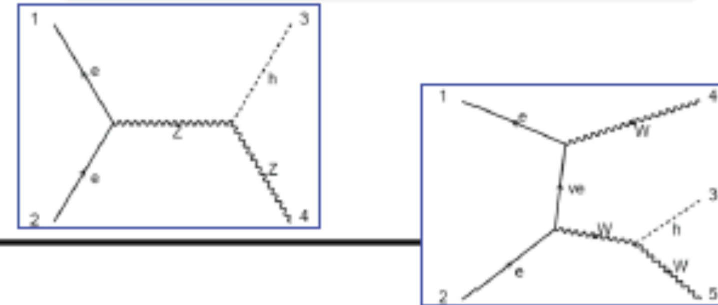
For the TDR : IAC formed, chaired by em. CERN DG Herwig Schopper

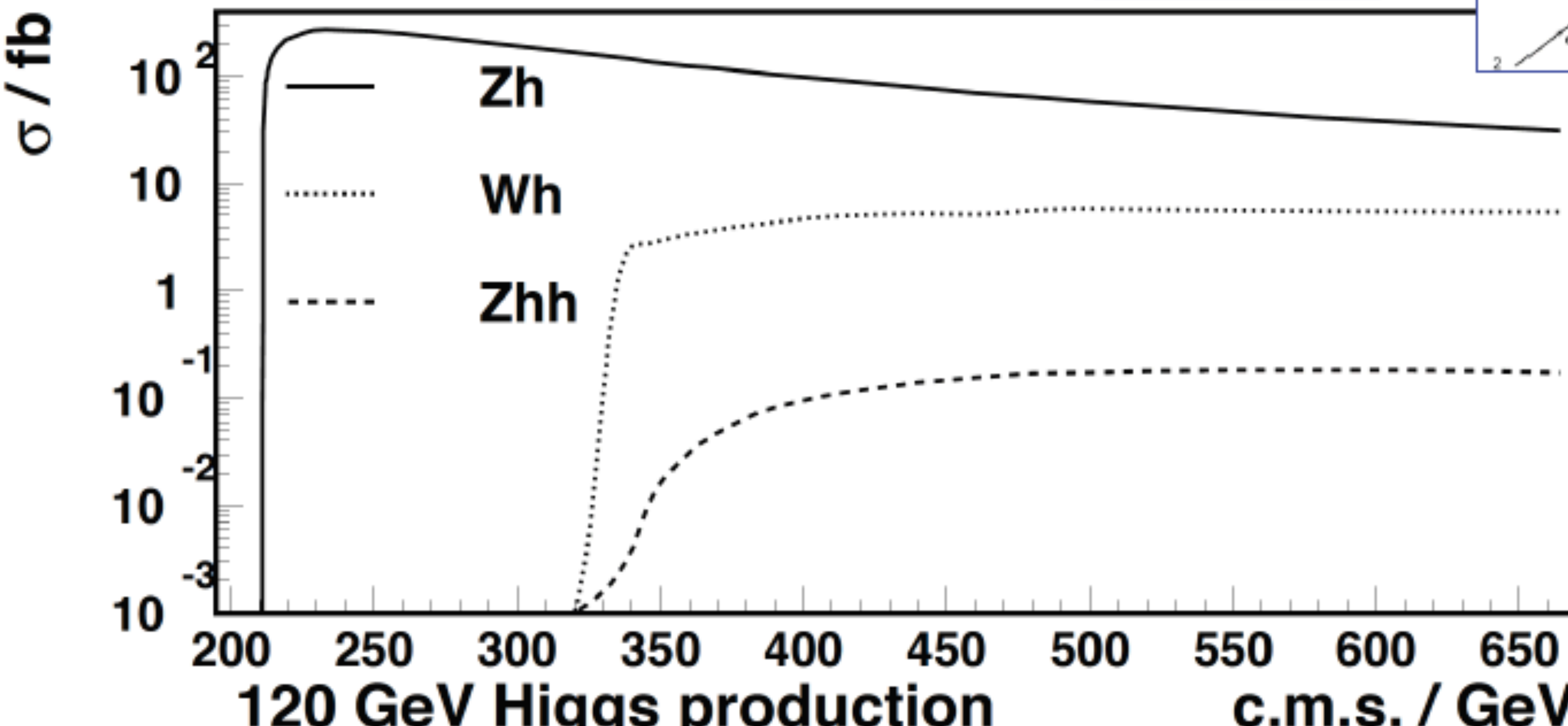
Additional material

120 GeV Higgs in e+e-

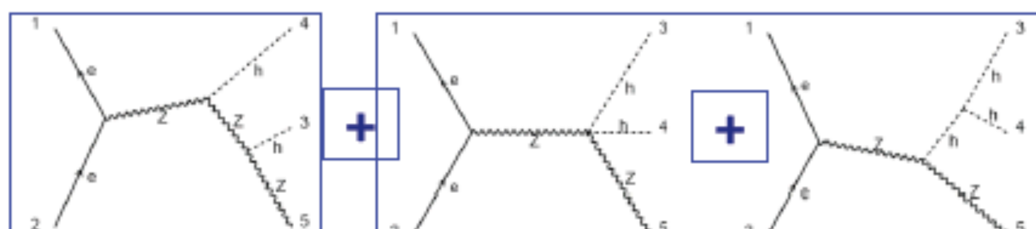
Madgraph5, CTEQ6L1, $M_H^2+P_t^2$, narrow width
Decay into h→ bb and Z→ee : factor 0.025

$\sqrt{s}$=0.2 – 0.66TeV





Zh threshold
at 211 GeV
= (120+91) GeV



Project development : 2007-2012

2007: Invitation by SPC to ECFA and by (r)ECFA to work out a design concept
2008: First CERN-ECFA Workshop in Divonne (1.-3.9.08)
2009: 2nd CERN-ECFA-NuPECC Workshop at Divonne (1.-3.9.09)

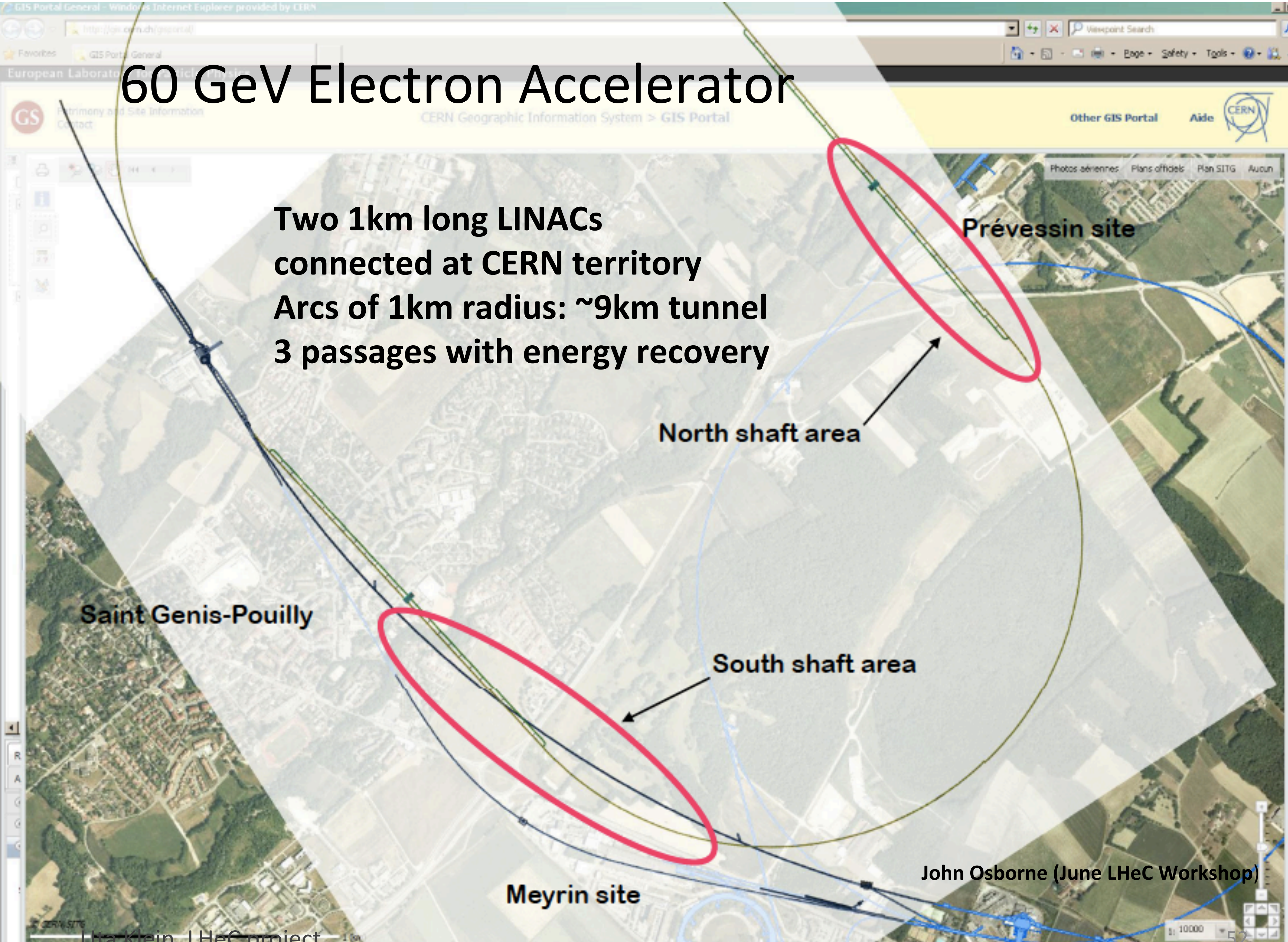
2010: Report to CERN SPC (June)
3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
NuPECC: LHeC on Longe Range Plan for Nuclear Physics (12/10)

2011: Draft CDR (530 pages on Physics, Detector and Accelerator) (5.8.11)
refereed and being updated

2012: Discussion of LHeC at LHC Machine Workshop (Chamonix)
Publication of CDR + 2 Contributions to European Strategy [arXiv]
Chavannes workshop (14-15.6.) : strong Liverpool participation
PPAP roadmap discussion and recommendation
CERN: Linac+TDR Mandate
ECFA final endorsement of CDR

60 GeV Electron Accelerator

Two 1km long LINACs
connected at CERN territory
Arcs of 1km radius: ~9km tunnel
3 passages with energy recovery



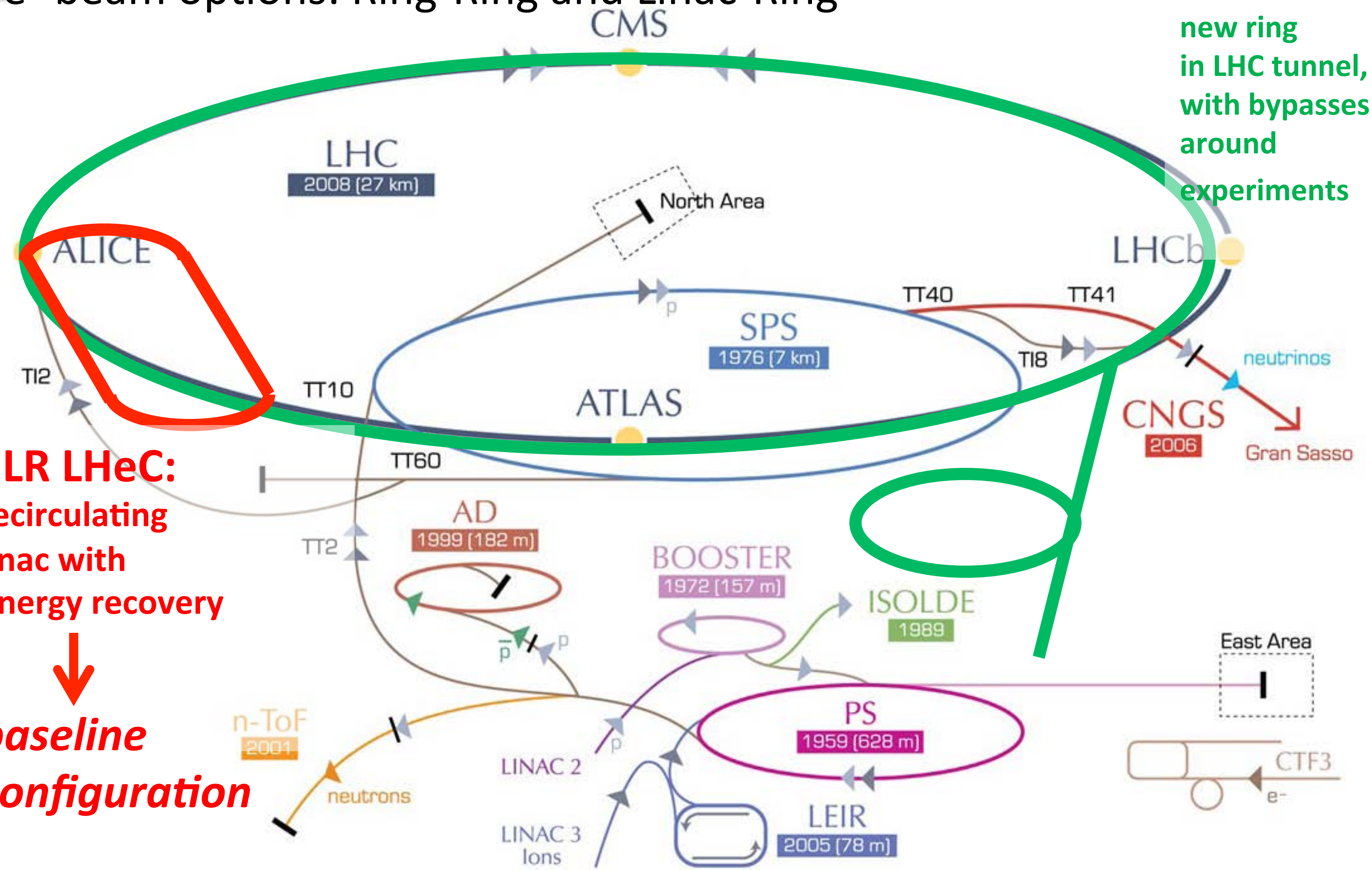
John Osborne (June LHeC Workshop)

The LHeC 'facility'

e± beam options: Ring-Ring and Linac-Ring

RR LHeC:
new ring in LHC tunnel, with bypasses around experiments

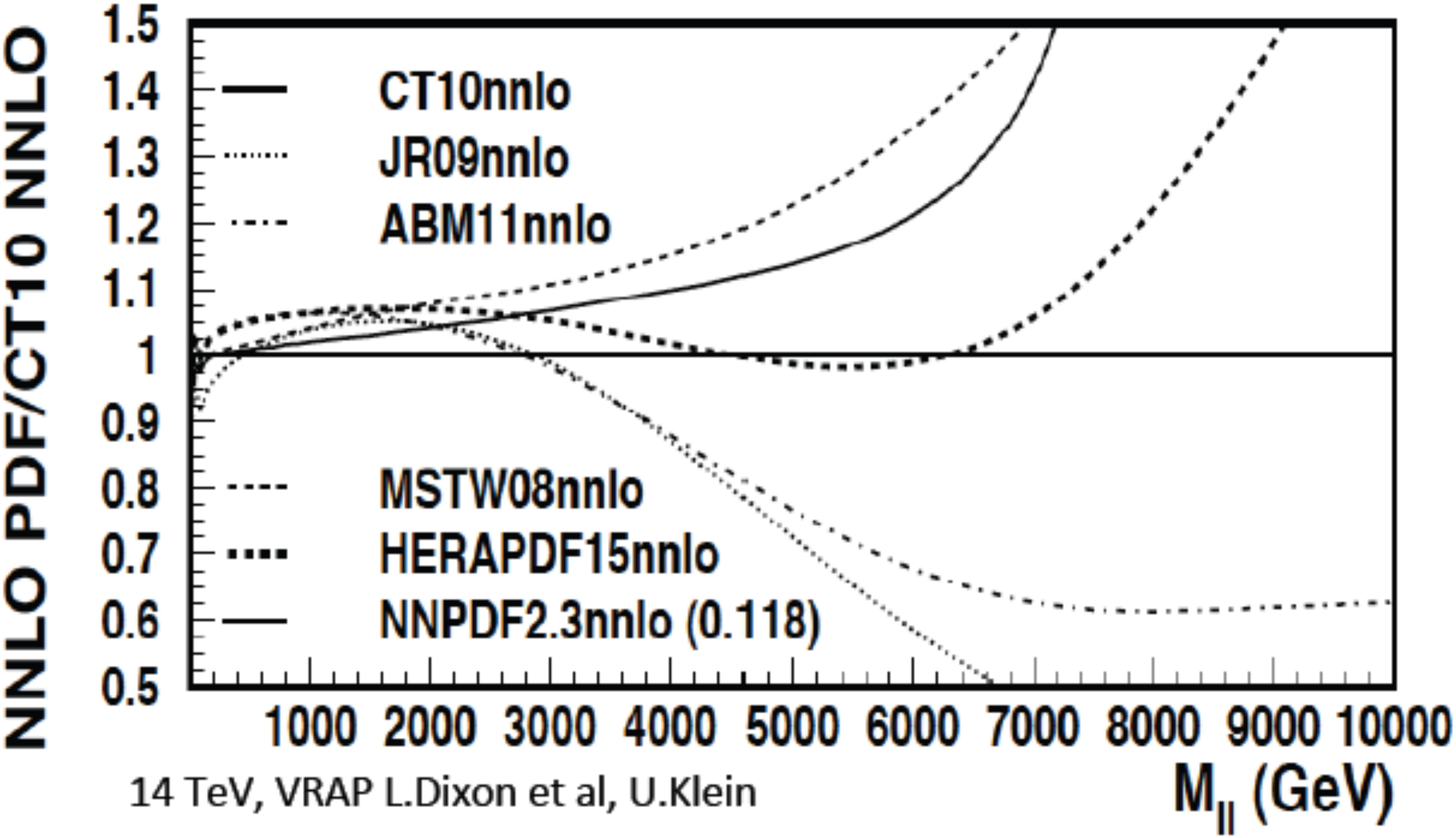
ELR LHeC:
recirculating linac with energy recovery
↓
baseline configuration



Key parameters of the FCC-he

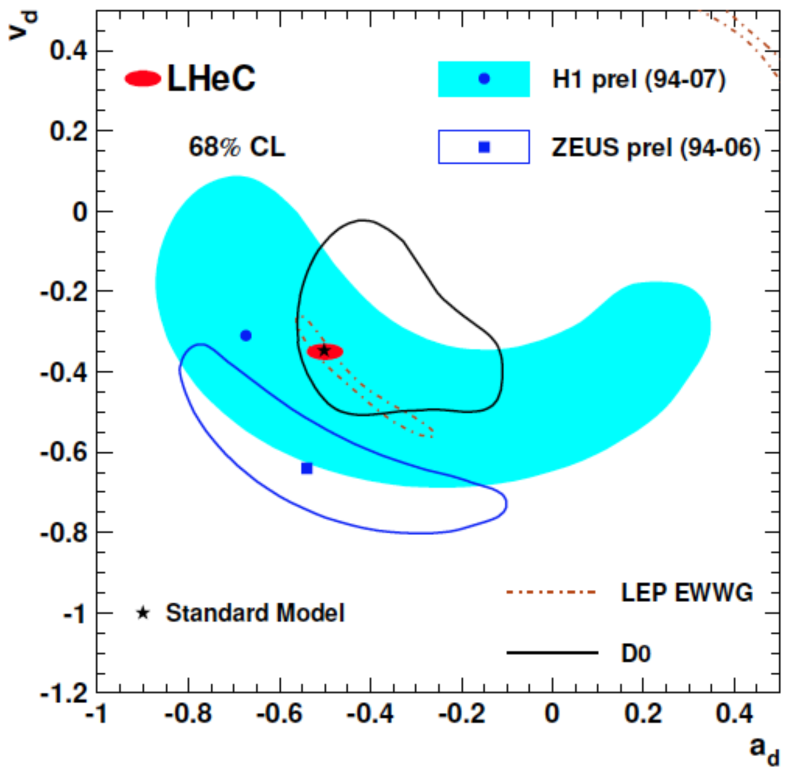
collider parameters	$e^{\pm}$ scenarios			protons
species	$e^{\pm}$	$e^{\pm}$	$e^{\pm}$	p
beam energy [GeV]	**60**	**120**	**250**	**50000**
bunch spacing [μs]	0.125	2	33	**0.125 to 33**
bunch intensity [10^{11}]	3.8	3.7	3.3	**3.0**
beam current [mA]	477	29.8	1.6	384 (max)
rms bunch length [cm]	0.25	0.21	0.18	**2**
rms emittance [nm]	6.0, 3.0	7.5, 3.75	4, 2	0.06, 0.03
$\beta_{x,y}^*$ [mm]	5.0, 2.5	4.0, 2.0	9.3, 4.5	500, 250
$\sigma_{x,y}^*$ [μm]	5.5, 2.7			
beam-b. parameter ξ	**0.13**	0.050	0.056	0.017
hourglass reduction	**0.42**	**0.36**	0.68	
CM energy [TeV]	3.5	4.9	7.1	
luminosity[$10^{34}cm^{-2}s^{-1}$]	**21**	**1.2**	**0.07**	

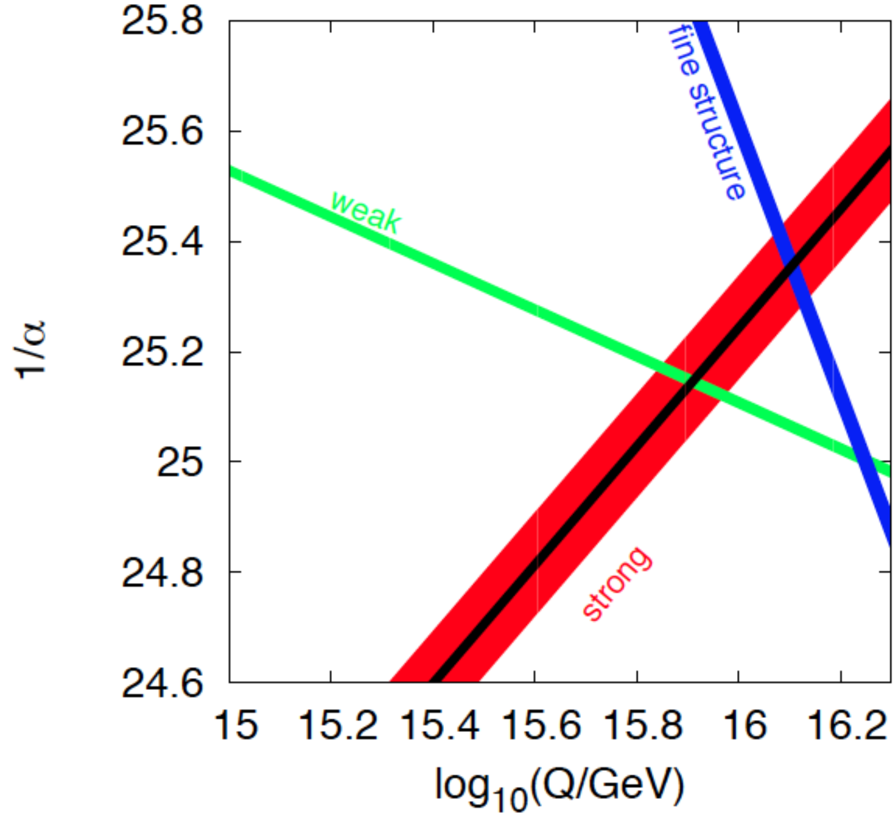
NC DY : current PDF uncertainties



14 TeV, VRAP L.Dixon et al, U.Klein

High precision QCD





$Q^2 >> M_{Z,W}^2$, hi luminosity, large acceptance
Unprecedented precision in NC and CC
Contact interactions probed to 50 TeV
Scale dependence of $\sin^2\theta$ left and right to LEP

→ A renaissance of deep inelastic scattering ←

Pile-up estimate for LHeC

- high luminosity option using $L=10^{34}$ $cm^{-2}s^{-1}$ (LHeC) and $L=5x10^{34}$ $cm^{-2}s^{-1}$ (HL-LHC) with 150 pile-up events (25 ns)
  [calculations by M. Klein]

➔ Pile-up events expected for LHeC <~0.1

Using pp LHC pile-up estimates

$$N(ep)=N(pp) \times s(yp)/s(pp) \times L(ep)/L(pp)$$
$$= 150 * 0.003 * 0.2$$
$$= 0.1$$

Direct calculation using total gamma-proton cross section of 300 µb

$$N(ep) = 300\ 10^{-6}\ 10^{-24}\ cm^2 \times 10^{34}\ cm^{-2}s^{-1} \times 25\ 10^{-9}s$$
$$= 0.075$$

α_s

Per mille precision
NNNLO PDFs
Heavy quarks →
Full set of PDFs

Data input	Experimental uncertainty on m_c [MeV]
HERA: NC+CC	100
HERA: NC+CC+ F_2^{cc}	60
LHeC: NC+CC	25
LHeC: NC+CC+ F_2^{cc}	3

Full exp. error

case	cut [Q^2 (GeV^2)]	α_S	uncertainty	relative precision (%)
HERA only (14p)	$Q^2 > 3.5$	0.11529	0.002238	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.12203	0.000995	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.11680	0.000180	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.11796	0.000199	0.17
LHeC only (14p)	$Q^2 > 20.$	0.11602	0.000292	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11769	0.000132	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.11831	0.000238	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.11839	0.000304	0.26

From LHeC CDR

CDR : Measurement Simulations

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Table 3.1: Assumptions used in the simulation of the NC cross sections on the size of uncertainties from various sources. These assumptions correspond to typical best values achieved in the H1 experiment. Note that in the cross section measurement, the energy scale and angular uncertainties are relative to the Monte Carlo and not to be confused with resolution effects which determine the purity and stability of binned cross sections. The total cross section error due to these uncertainties, e.g. for $Q^2 = 100\,\mathrm{GeV}^2$, is about 1.2, 0.7 and 2.0 % for $y = 0.84,\ 0.1,\ 0.004$.

Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – checked against H1 MC