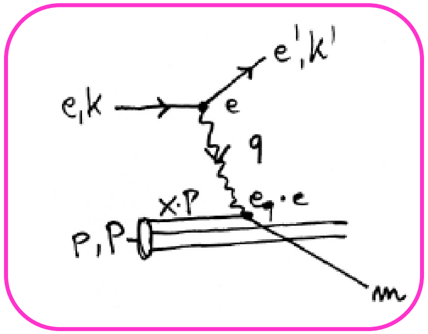
High Energy ep Scattering: Higgs and FCC

Monica D’Onofrio
University of Liverpool
(on behalf of many…)



DIS 2014, Warsaw
April 30th 2014

Outline

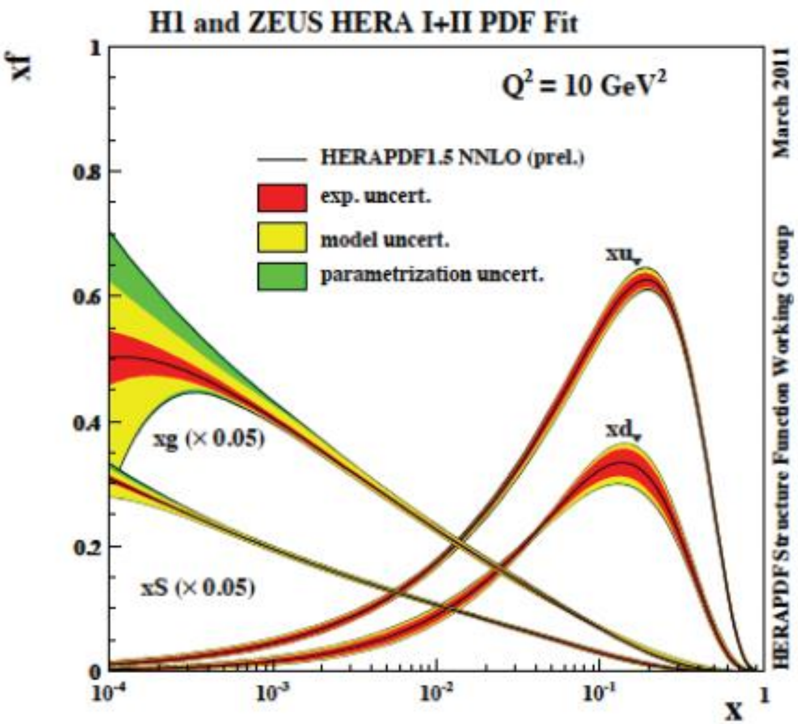
- The idea of an e-p collider at CERN, the **LHeC**, proposed in 2005, has been developed in the last years.
- The **FCC-he**: a realistic opportunity for energy frontier DIS → 3 order of magnitude higher lumi wrt HERA; huge step in energy (Q^2,1/x).
- In this talk:
  - Prospects for Higgs measurements at LHeC and FCC-he
  - Future Circular Collider (FCC) complex view
  - Highlights of physics programme (focus on e-p)

Other contributions

In this Conference, other talks on LHeC and/or FCC-he physics highlights:

- LHeC accelerator Development
  - Emilia CRUZ ALANIZ
- Electroweak and top physics at energy frontier DIS
  - Christian SCHWANENBERGER
- Parton distributions in the proton from the LHeC
  - Voica Ana Maria RADESCU
- eA collisions at the LHeC and FCC
  - Guilherme TEIXEIRA DE ALMEIDA MILHANO
- LHeC detector design and simulation
  - Paul NEWMAN

e-p at HERA .. and beyond



- At HERA, extensive tests of QCD, measurements of α_S and base for PDF fits in x range relevant for hadron colliders
- But also:
  - New limits for leptoquarks, excited electrons and neutrinos, quark substructure and compositness, RPV SUSY etc.

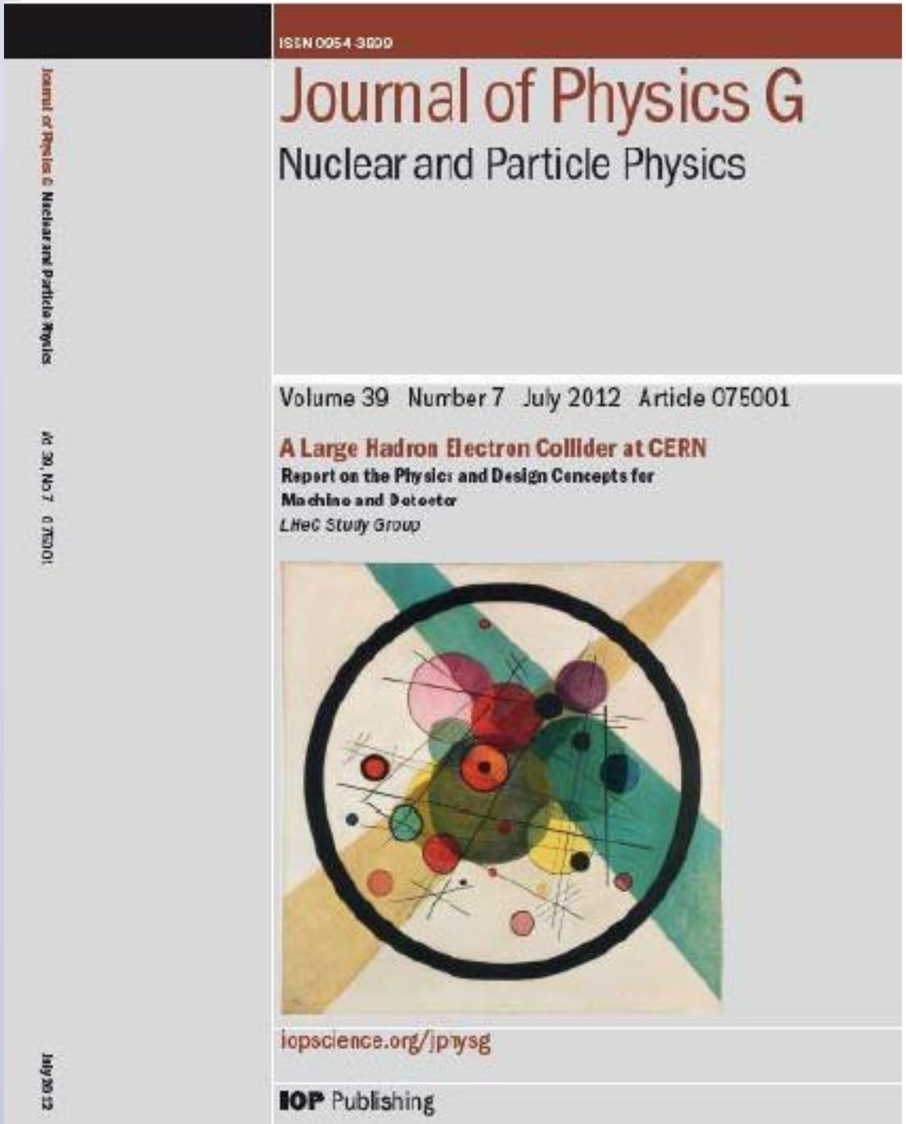
The LHeC, proposed in 2005, has been developed in the last years: http://cern.ch/LHeC

Tevatron/HERA/LEP → HL-LHC/LHeC/(ILC?)

(fermiscale) (Terascale)

(or, the complimentarity pattern)

LHeC: Conceptual Design Report (July 2012) and more



- 630 pages summarising 5 years of studies commissioned by CERN, ECFA and NuPECC
- About 200 participants, 69 institutes
- Further updates
  - *'A Large Hadron Electron Collider at CERN'* arXiV:1211.4831
  - *'On the relation of the LHeC and the LHC'* arXiV:1211.5102
  - *'The Large Hadron Electron Collider'* arXiV:1305.2090
  - *'Dig Deeper'* Nature Physics 9 (2013) 448
- Regular workshops and presentations in Conferences

Coordination group for future DIS at CERN

- Toward a concrete planning: 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 Womersley ()

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

The IAC was invited in 12/13 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.

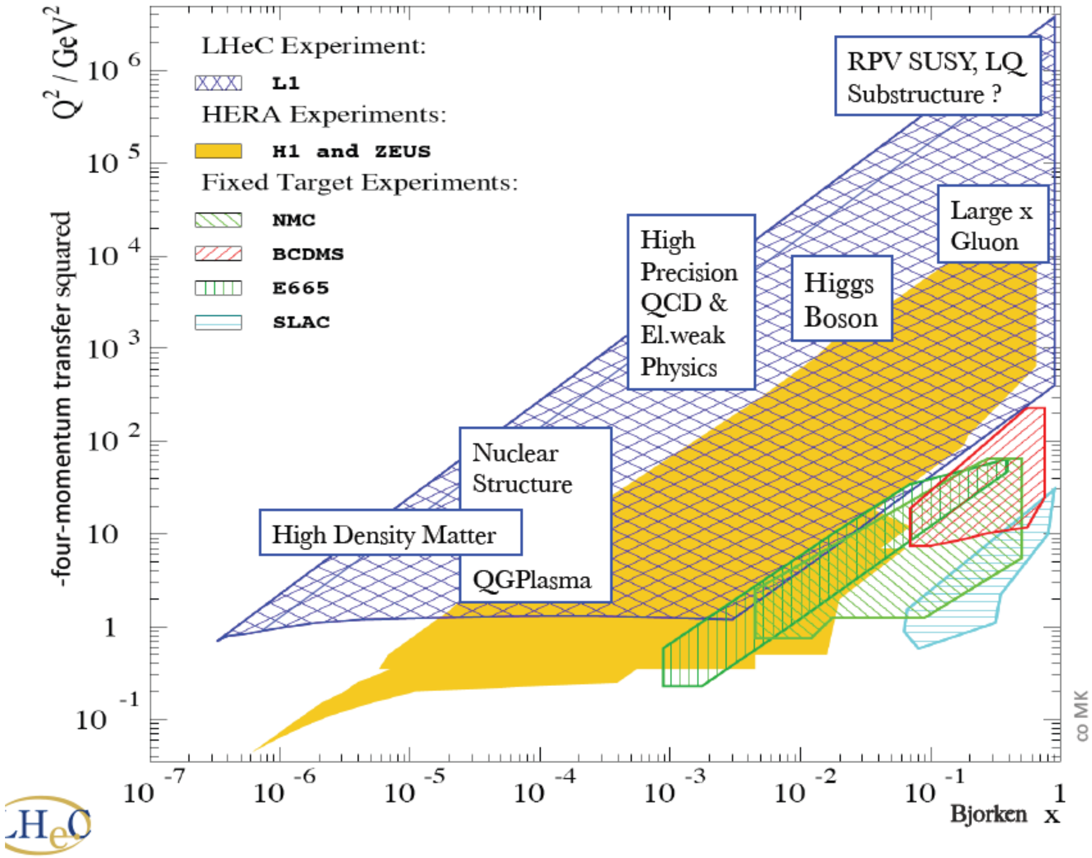
Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

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

The LHeC

- Unique opportunity to take lepton-hadron physics to the TeV centre-of-mass scale at high luminosity

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



Designed to exploit intense **hadron beams** in high luminosity phase of LHC running from mid 2020s:

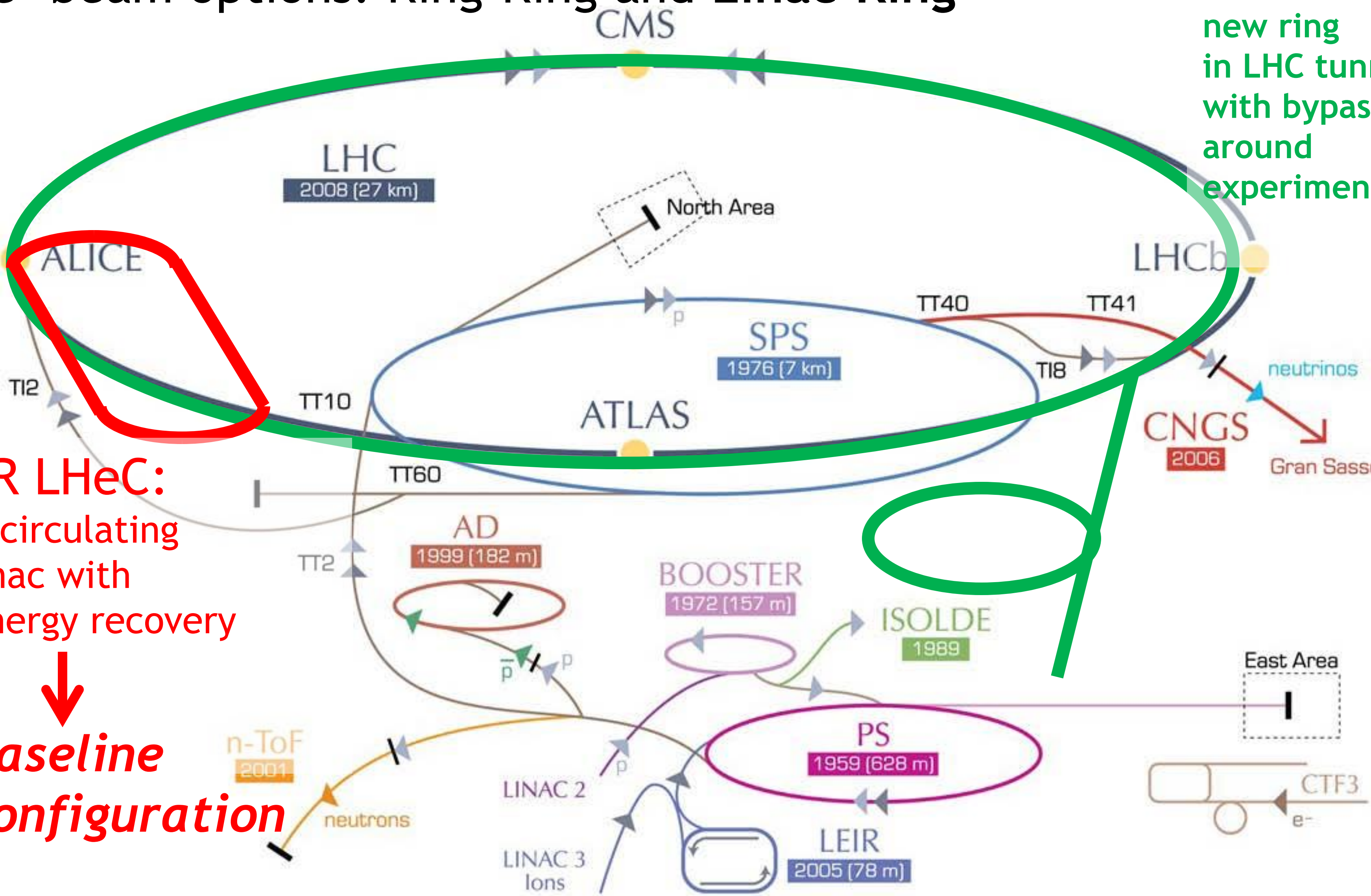
→ Use 7 TeV protons

→ Add an **electron beam** to the LHC

The LHeC 'facility'

$e^{\pm}$ beam options: Ring-Ring and **Linac-Ring**

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



LR LHeC:
recirculating linac with energy recovery

↓

baseline configuration

The LHeC baseline parameters

Luminosity [10^{33}cm^{-2}s^{-1}]	1-10**
Detector acceptance [deg]	1
Polarization [%]	90
IP beam sizes [μm]	7
Crossing angle [mrad]	0
e- L* [m]	30
Proton L* [m]	15
e- beta*$_{x,y}$ [m]	0.12
Proton beta*$_{x,y}$ [m]	0.1
Synchrotron power [kW]	10

e^-p and *e^+p* collisions (possibly with similar luminosity)
→ 60 GeV (ele), 7 TeV proton

e^-/e^+ polarization

Operations simultaneous with HL-LHC *pp* physics

- ep Lumi: 10^{33} (10^{34})** cm^{-2} s^{-1} *(**: according to recent studies)*
- 10-100 fb^{-1} per year
- 100 fb^{-1} – 1 ab^{-1} total
- eD and eA collisions integral part of the programme
  - e-nucleon Lumi estimates → 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)

LHeC Physics

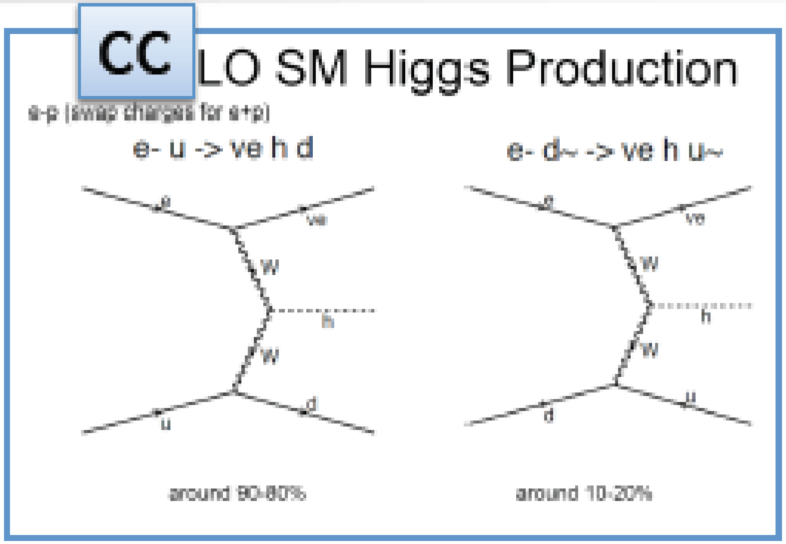
- Rich physics program for e-q physics at TeV energies:
  - Precision QCD,EWK physics
  - Higgs measurements and searches for BSM
  - Complimentarities to LHC physics program and boosting its precision (eg PDF at high x)

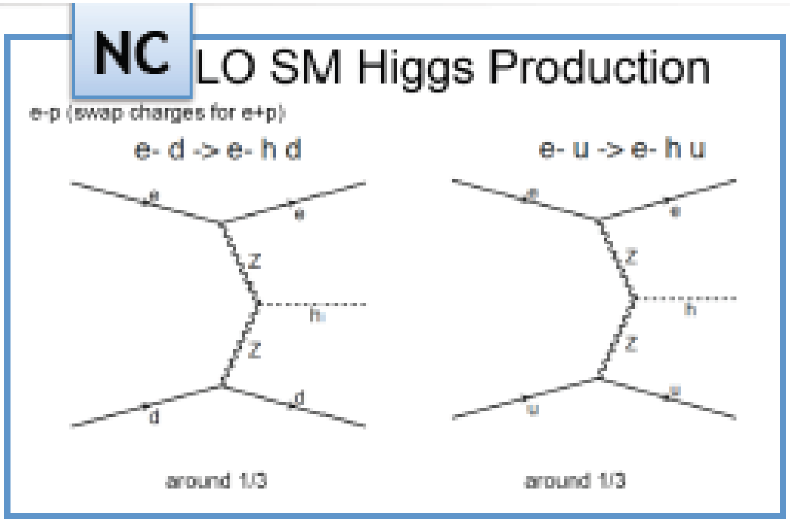
arXiv:1211:4831+5102

QCD Discoveries Higgs Substructure New and BSM Physics Top Quark	$\alpha_s < 0.12$, $q_{sea} \neq \overline{q}$, instanton, odderon, low x: (n0) saturation, $\overline{u} \neq \overline{d}$ WW and ZZ production, $H \to b\overline{b}$, $H \to 4l$, CP eigenstate electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H? leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s top PDF, $xt = x\overline{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution Precision DIS	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c $\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\text{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure Quark Distributions QCD	Proton, Deuteron, Neutron, Ions, Photon valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \overline{s}$?, charm, beauty, top N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron Heavy Ions Modified Partons	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing initial QGP, nPDFs, hadronisation inside media, black limit, saturation PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Table 3: Schematic overview on key physics topics for investigation with the LHeC.

Higgs measurements at LHeC



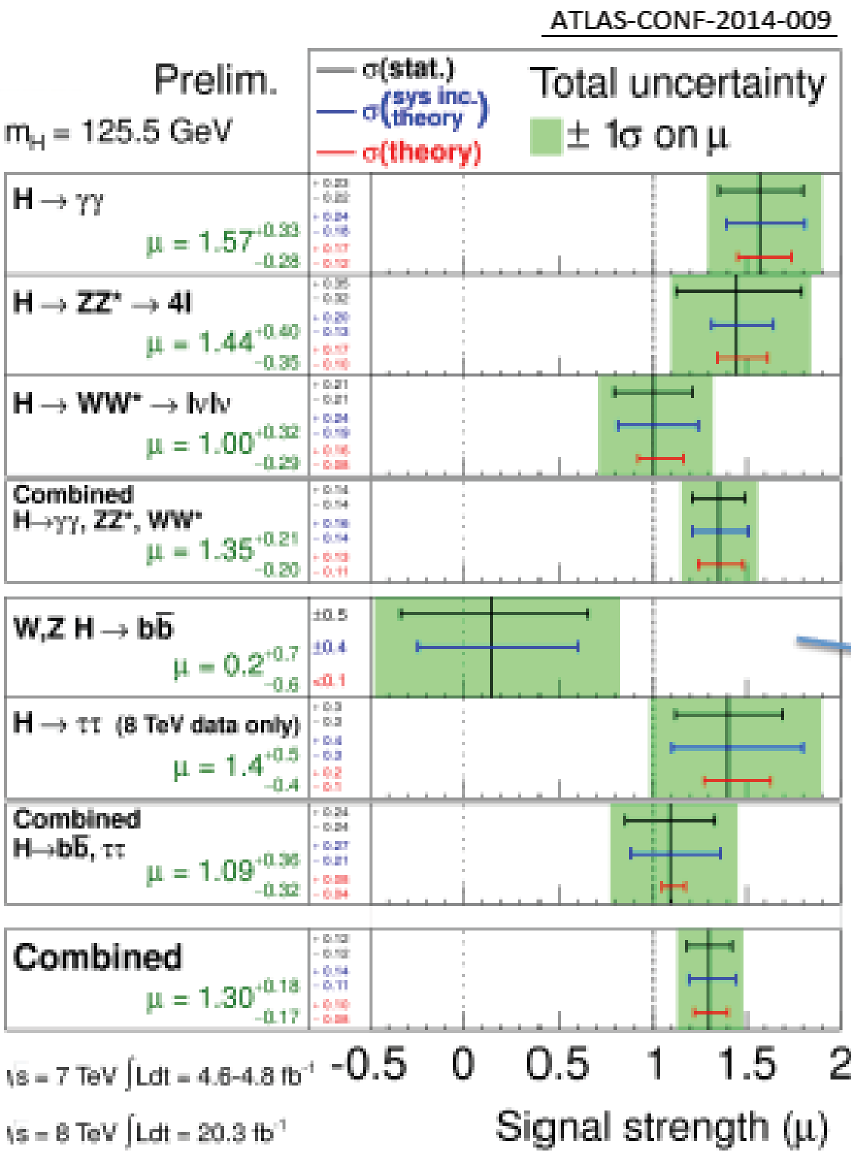


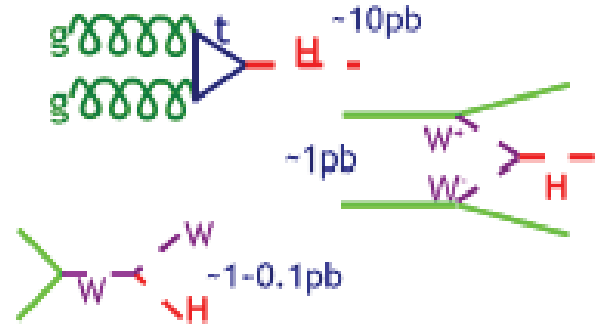
200 fb for CC, 25 fb for NC (polarized e beam)

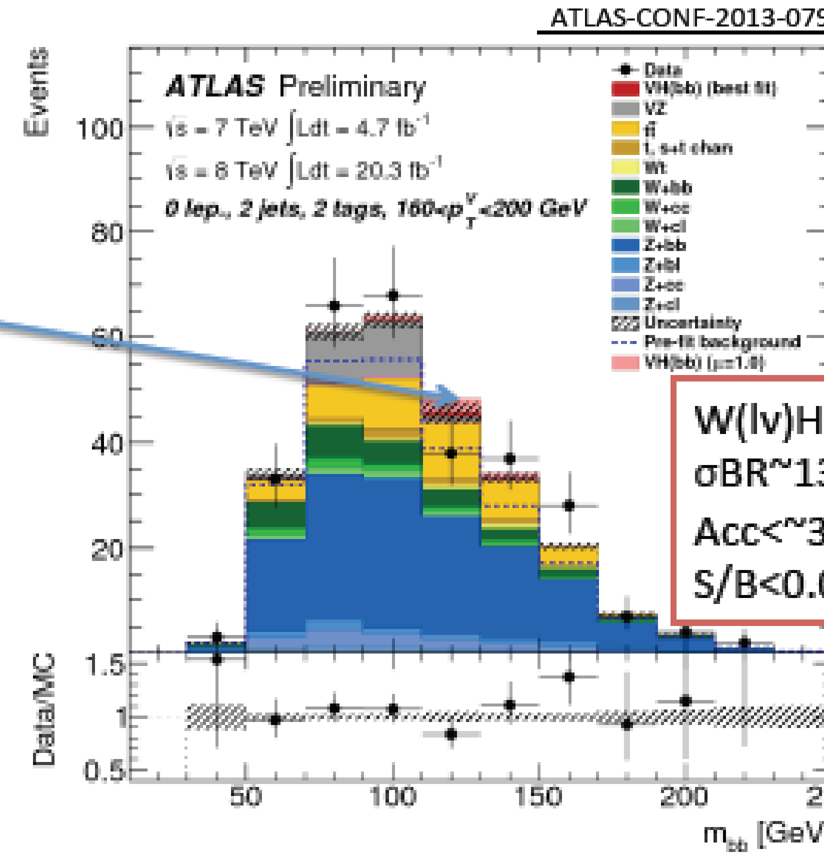
- *Less than LHC BUT less difficult*
- *Comparable to ILC*

In other words, GREAT POTENTIAL!

Status of the art on Higgs: ATLAS example



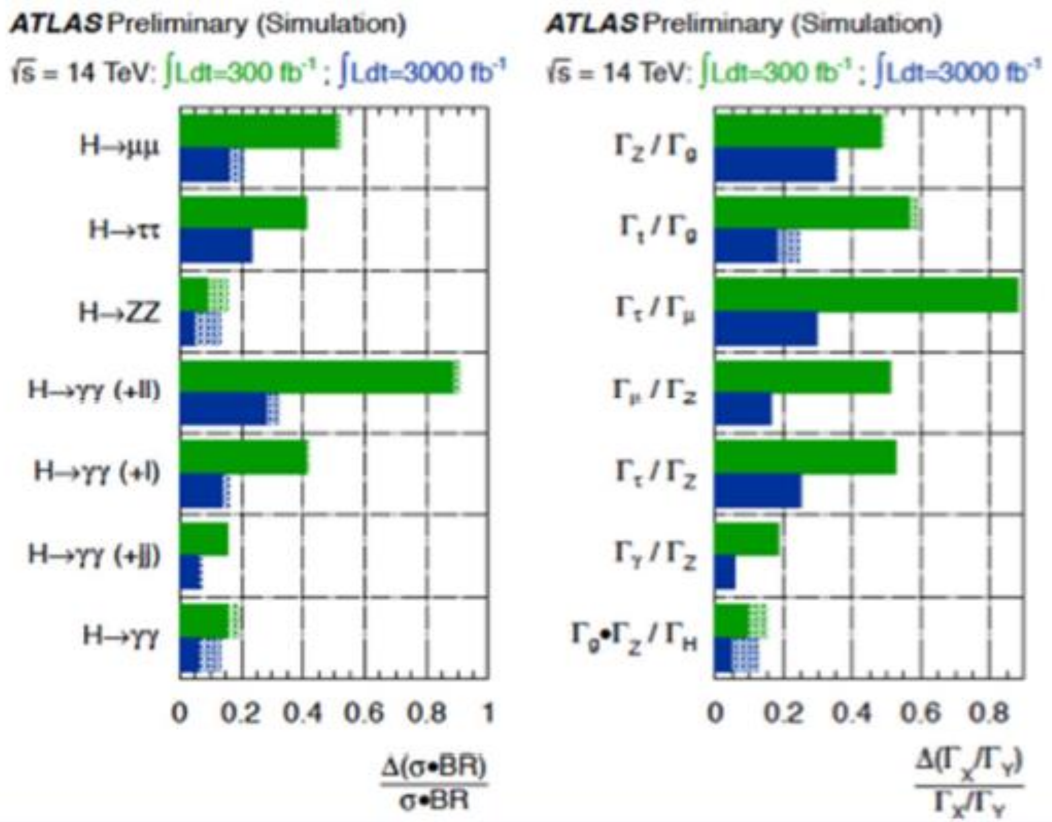




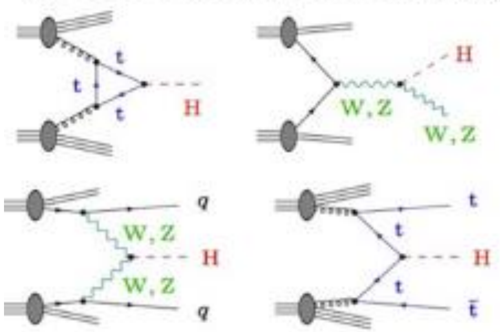
W(lv)H(bb)
σBR~130 fb
Acc<~3%
S/B<0.01

Higgs in *pp* HL-LHC and PDF uncertainties

- Studies for High Luminosity LHC shows that PDF uncertainties will be a limiting factor for several channels at the HL-LHC
- With LHeC: huge improvements in PDFs and precision in α_s → full exploitation of LHC data for Higgs physics



Processes at hadron colliders (pp̄/pp):



Dashed regions: scale & PDF contributions

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

Higgs in *pp* HL-LHC and PDF uncertainties

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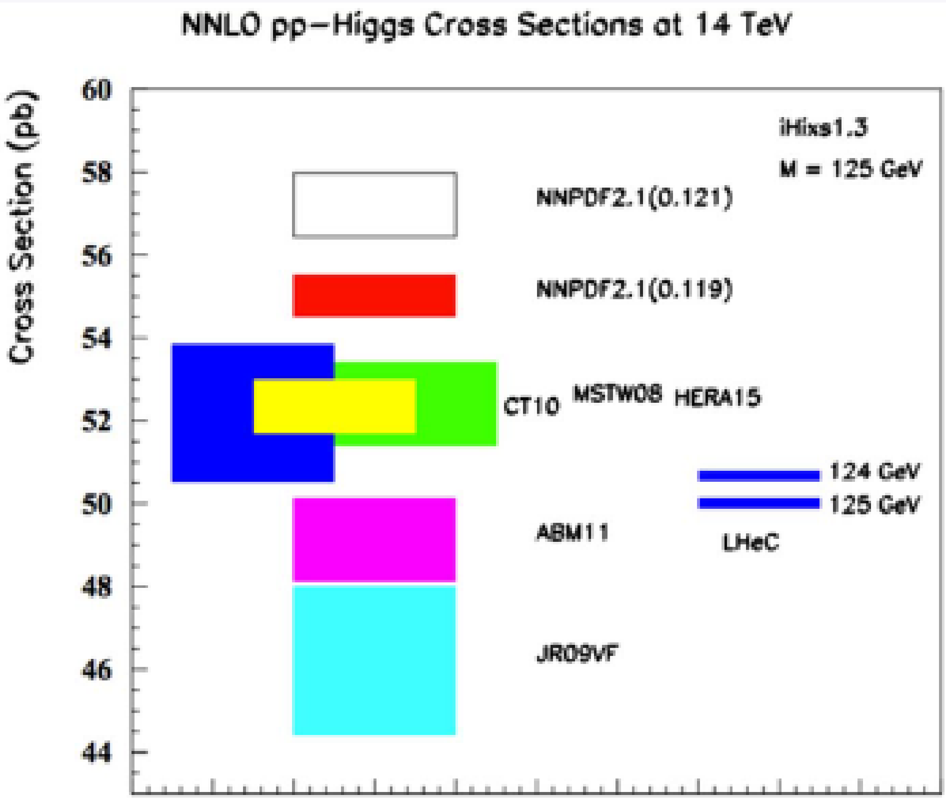
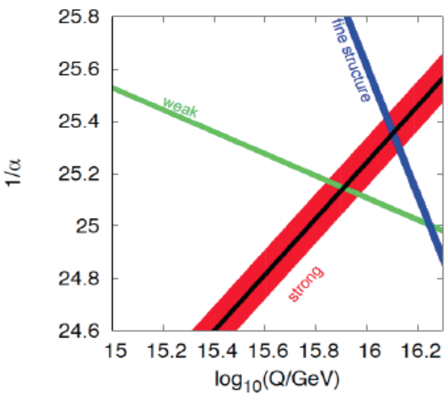


α_S = underlying parameter relevant for unc. (0.005 → 10%)
@ LHeC: measure to permille accuracy (0.0002)

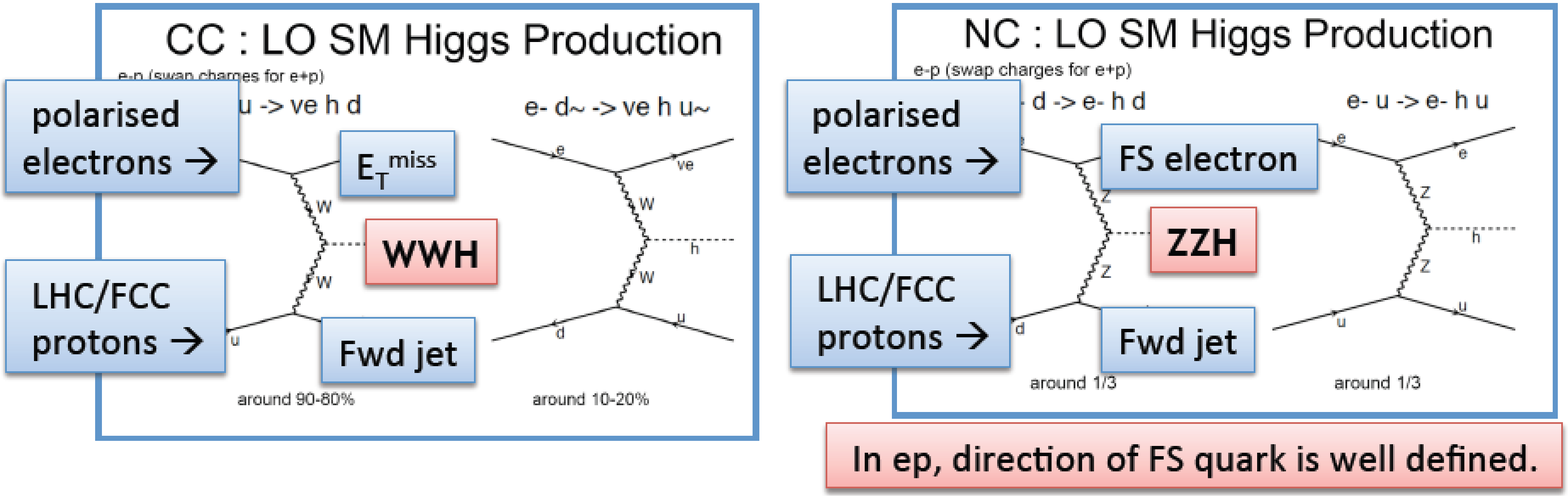
→ **precision from LHeC can add a very significant constraint on the Higgs mass** ***but also:***



Study unification of couplings

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

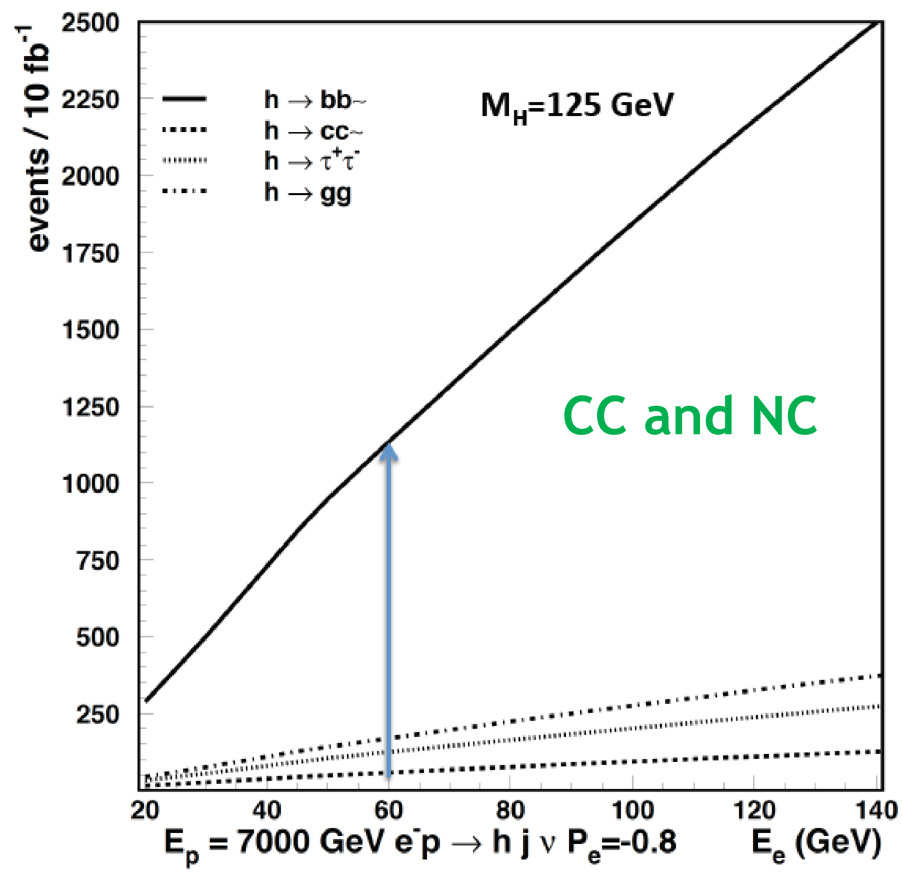
Study of Higgs production at e-p



Angles defined w.r.t. proton beam.

- WWH and ZZH vertices can be probed uniquely and simultaneously
- Energy Recovery Linac: high electron polarization, 80-90% → lead to twice the CC rates!
- NLO QCD corrections in DIS small wrt to pp
- **For Higgs:** shape distortions of kinematic distributions up to 20% due to NLO QCD
- QED corrections: up to 5% [i.e.: arXiV:1001.3789]

Higgs Production rate at LHeC



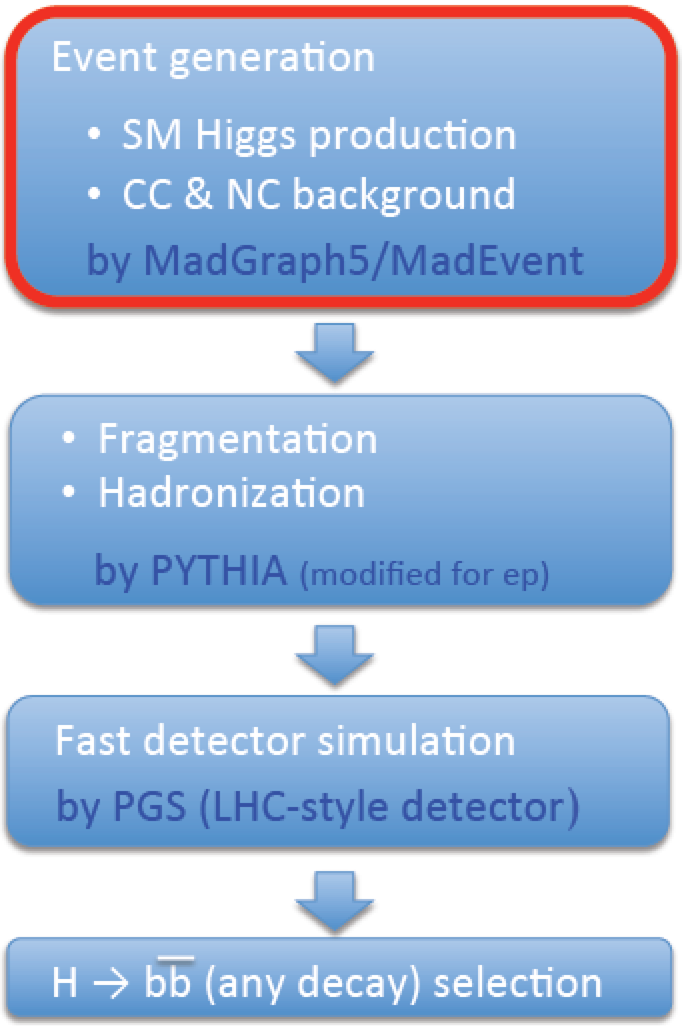
M_h=125 GeV
polarised lepton beam

E_e=60 GeV : √s= **1.3 TeV**

	CC e^-p	CC e^+p	NC ep	CC hh
cross section [fb]	109	58	20	0.01
polarised cross section [fb] P=-80%	**196**	N.A.	25	0.02

Total event rate for 10 fb^{-1}
= 1 month of high luminosity running using 60 GeV LINAC
1100 events H → bb ; 140 events H → ττ; 60 events H → cc

Analysis framework



- Calculate cross section with tree-level Feynman diagrams using <u>pT of scattered quark as scale (CDR: $\hat{s}$)</u> 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 <u>**ep-customised** Pythia</u>.

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

Valid for ep only.

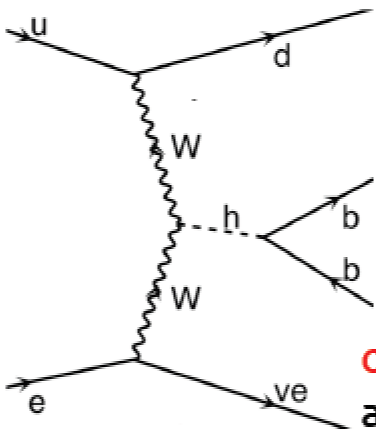
Courtesy of U.Klein

Example from CDR: Generated samples

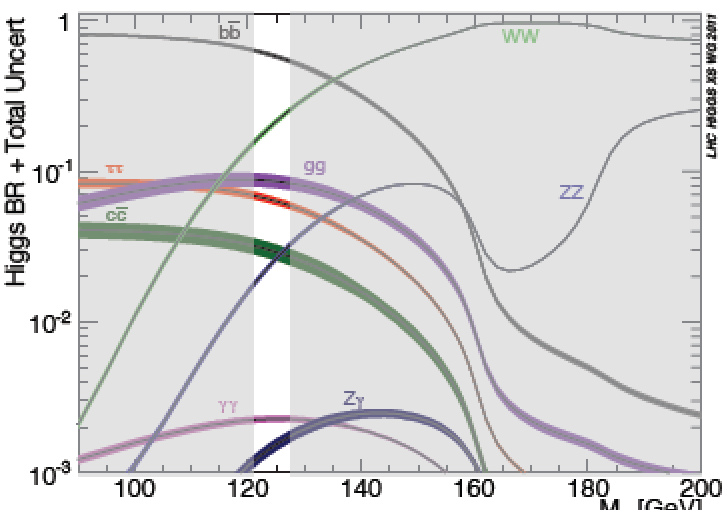
Graphs by MadGraph

Signal

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

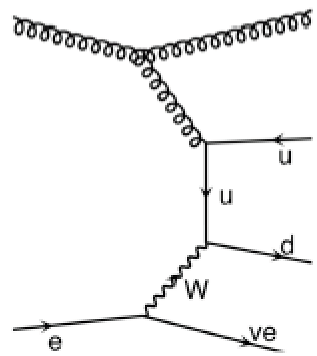


σ~ 0.16 pb
at √s=2.05TeV

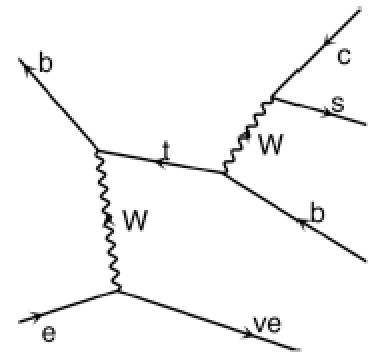


Background (examples)

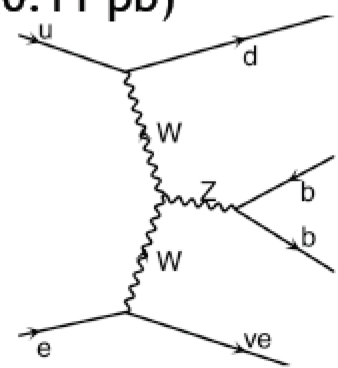
CC: 3 jets (~57 pb)



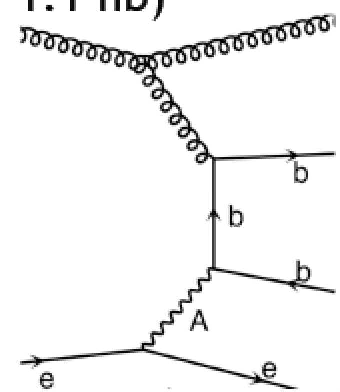
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)

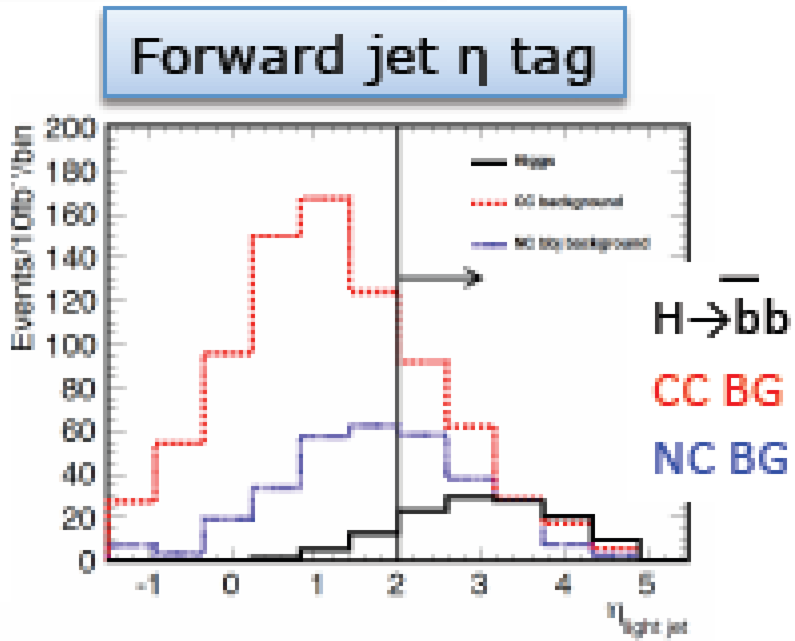


NOTE: Background sample cross sections are after pre-selection in generator and for Ee=150 GeV

H→ $b\bar{b}$ @ LHeC: CDR studies (mH=120 GeV)

- NC DIS rejection:
  - Exclude electron-tagged e
  - ETMiss>20 GeV, Njet(pT>20 GeV)≥3
  - $E_{T,total}$>100 GeV
  - y_{JB}>0.9, Q^2_{JB}>400 GeV^2
- **B-tagging:**
  - Assume flat efficiency ≈ 60% (10% c-tag, 1% mistag rate)
  - N b-jet ≥ 2 (20 GeV threshold)
- **90<M(higgs)<120 GeV**
- **Single top rejection (>40% of total remaining background):**
  - Mjjj,top>250 GeV
  - Mjj,W>130 GeV

- **Forward jet tagging**
  - η jet > 2 (lowest eta jet, anti-btagged)



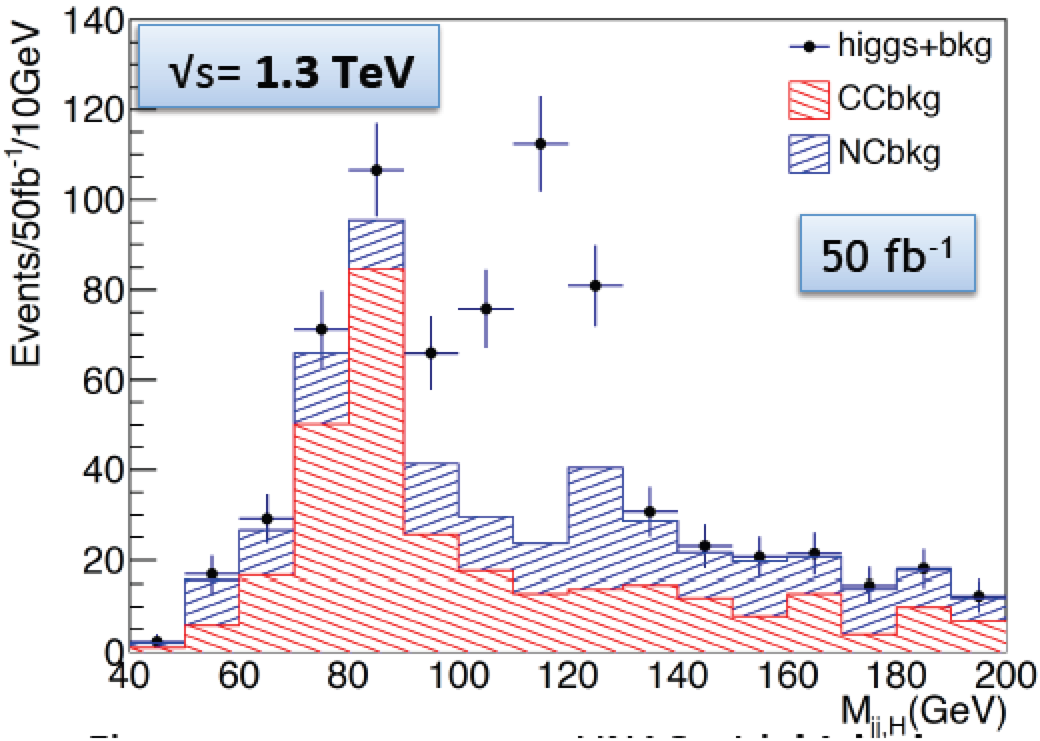
For 10 fb^{-1}, unpolarized beam and Ee=150 GeV, reach **S/√B ~ O(10)**

H→ $b\bar{b}$ @ LHeC: most recent results

- Use similar approach, cut and count analysis:
  - Very clear signal!

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



- LINAC with high *e* polarization of about 90% → around 10K Higgs!
  - Allow Hbb coupling measurements with 1% statistical precision (1 ab^{-1})
  - **H→ccbar** channel also under study
    - Low but still 'taggable' charm-jets → Clean environment wrt *pp*

H→ bbar and ccbar kinematic

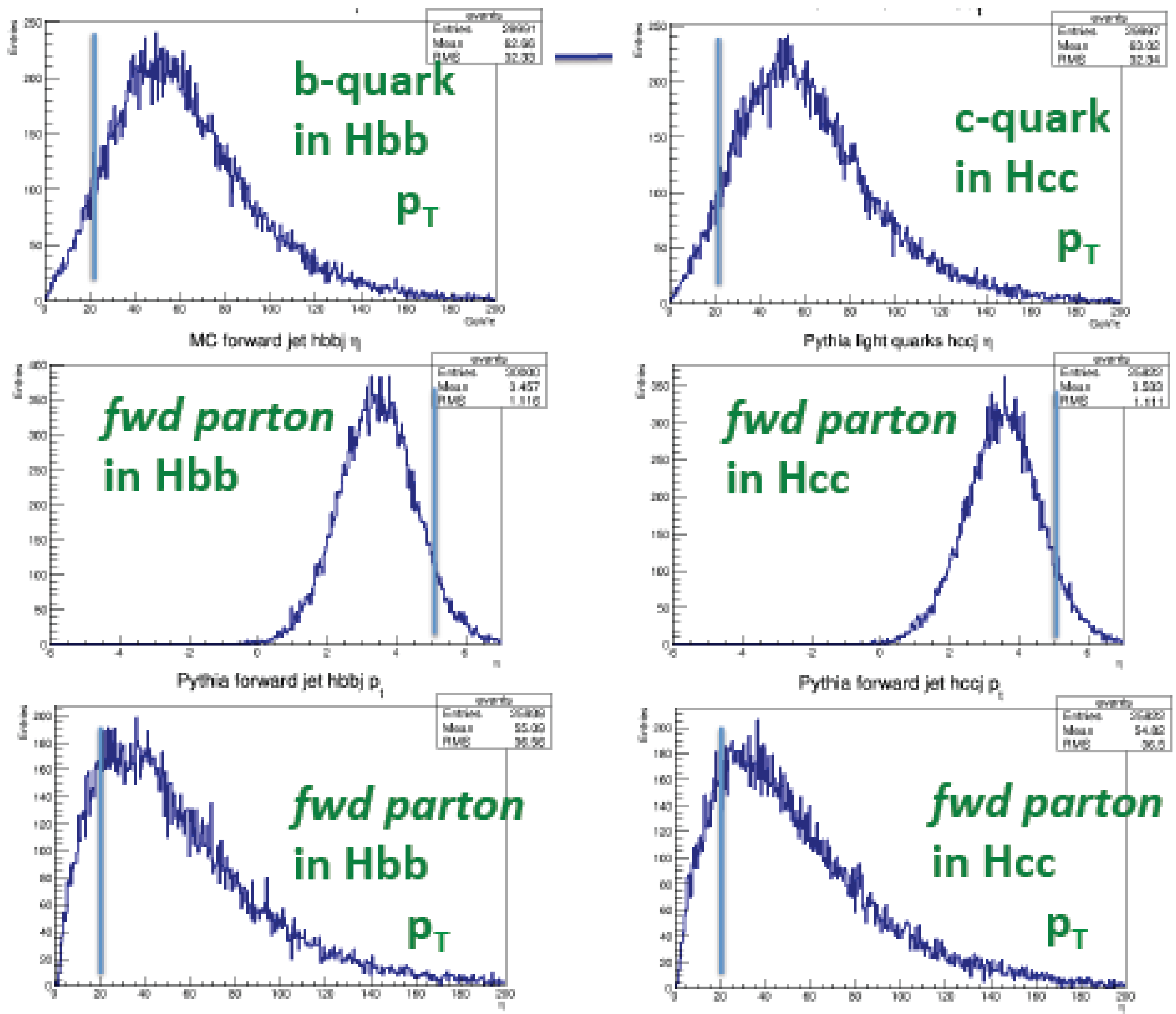
U.Klein

√s= 1.3 TeV

pythia-level p_T

pythia-level η(fwd parton)

pythia-level p_T(fwd parton)



Higgs → tau tau

- Feasibility studies on going
- Reasonable cross sections (expect 10% of H→bbbar)
- Promising channels:
  - mu+ tau_had
  - mu- tau_had
  - tau_had tau_had
  - e+ mu
- The main background will come from di-tau production:

SubProcesses and Feynman diagrams

Directory	# Diagrams	# Subprocesses	FEYNMAN DIAGRAMS	SUBPROCESS
P0_lq_vltaptamq	10	2	html postscript	e- u > ve ta+ ta- d , e- c > ve ta+ ta- s
	10	2	html postscript	e- d~ > ve ta+ ta- u~ , e- s~ > ve ta+ ta- c~

40 diagrams (20 independent).

Reducible thanks to Hard cuts that can be applied on tau pT and di-tau mass

- Next step is to look into the prospects of fakes, although if these channels are possible at the LHC → also possible at the LHeC!

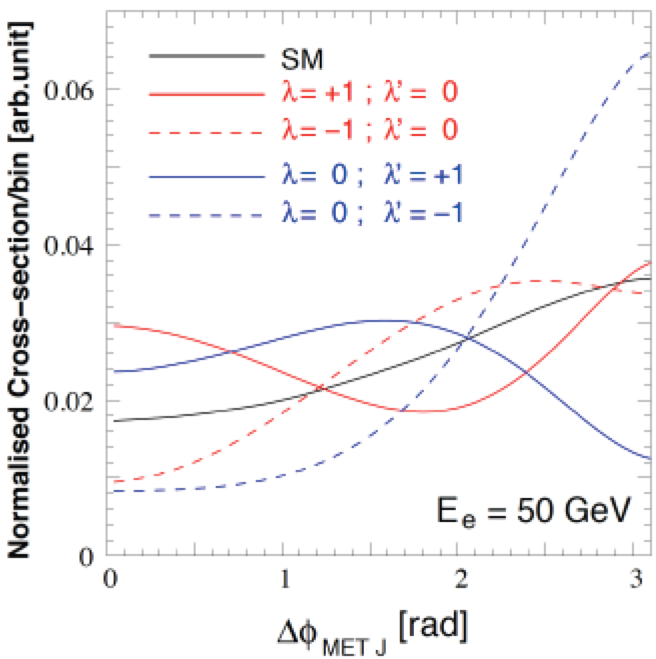
CP properties of the Higgs

- At the LHeC: unique access to HWW → searches for BSM exploring CP properties of HVV, since CP-even and CP-odd states would be differently modified by new physics

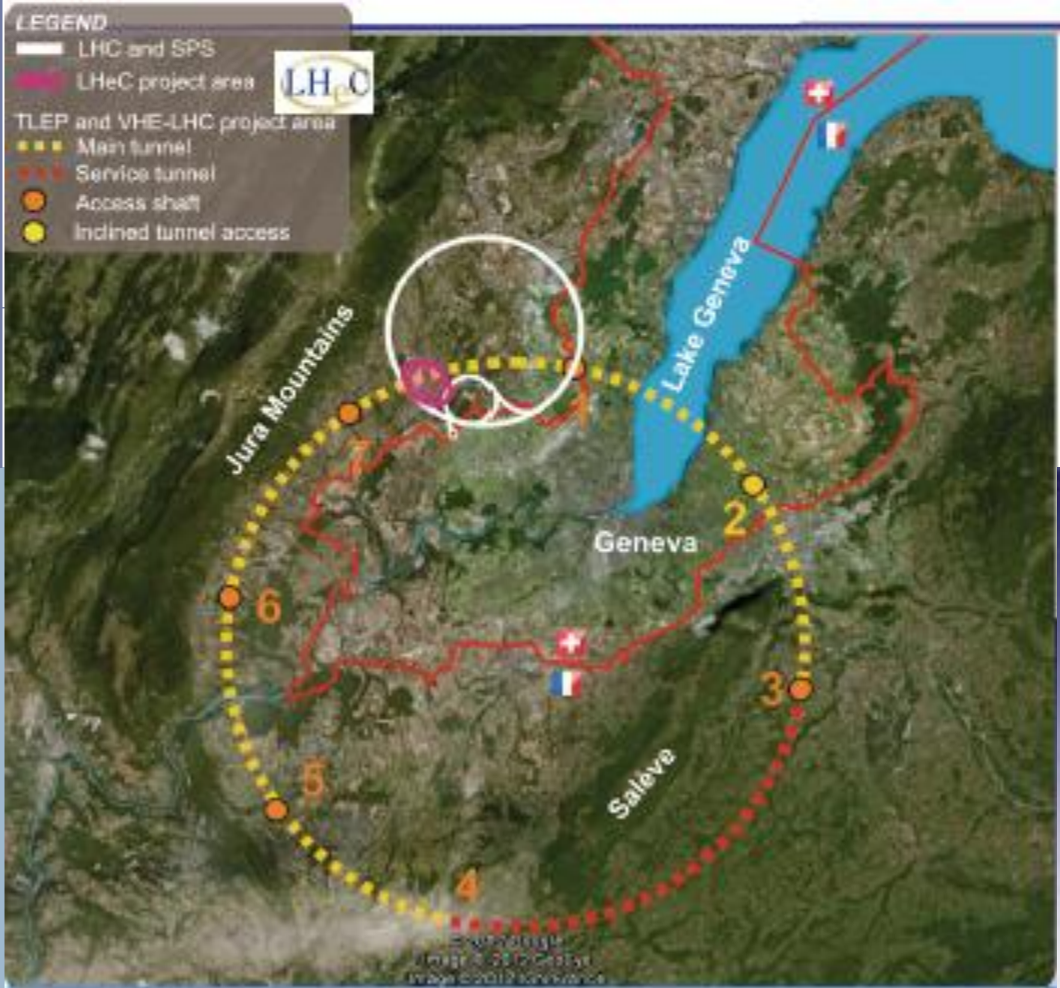
$$\Gamma^{\mu\nu}_{(SM)}(p,q) = g M_W\, g^{\mu\nu} \quad \rightarrow \quad \Gamma^{(BSM)}_{\mu\nu}(p,q) = \frac{-g}{M_W}\left[\lambda\,(p.q\, g_{\mu\nu} - p_\nu q_\mu) + i\,\lambda'\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

  - Analysis of LHC data indicate consistency with the SM 0+ hypothesis. However, we need to understand if there is a mixture of physics beyond the SM, even within the 0+ hypothesis.

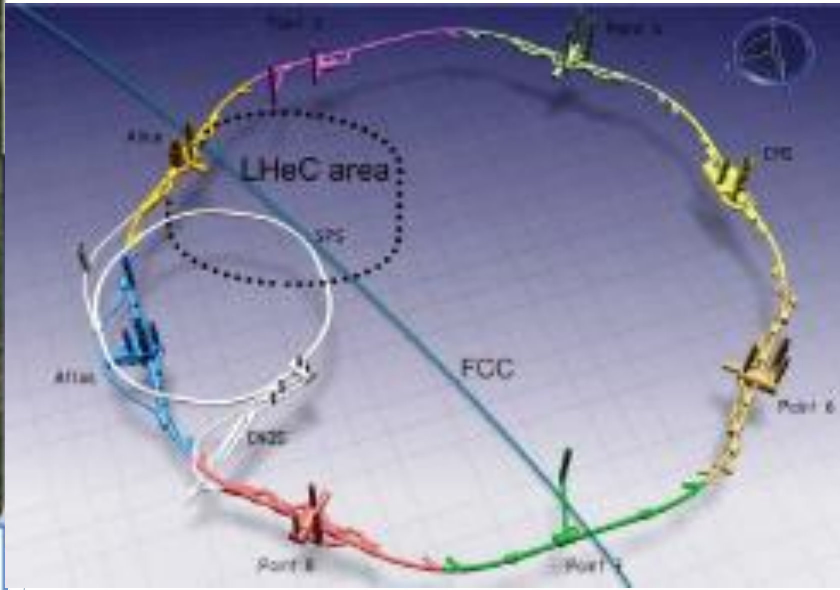
Study shape changes in DIS normalised CC Higgs→bbbar x-sect VS $\Delta\phi$(MET-forward jet)



Beyond the LHeC: the FCC-he

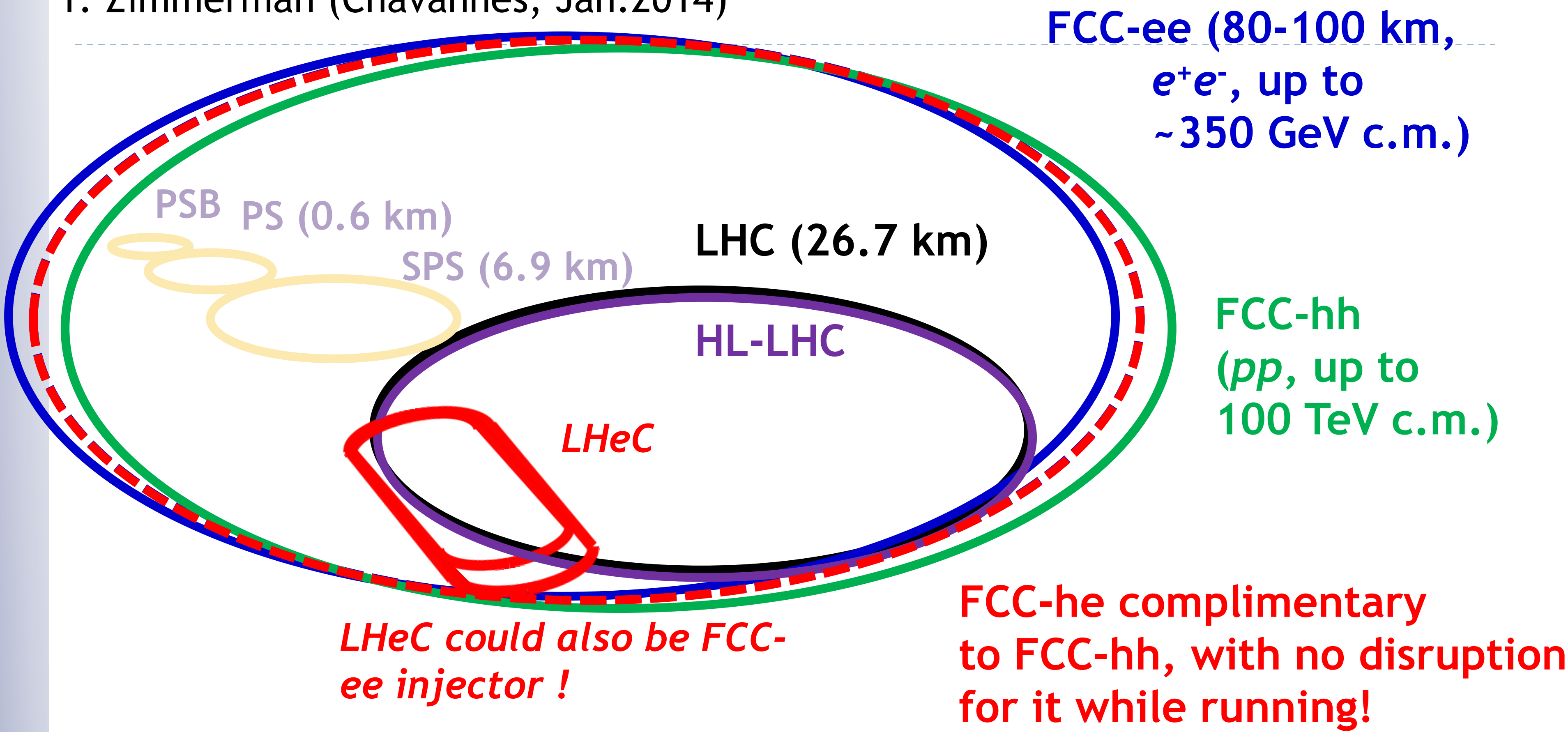


*) "Civil Engineering Feasibility Studies for Future Ring Colliders at CERN", Contributed by O.Brüning, M.Klein, S.Myers, J.Osborne, L.Rossi, C.Waaijer, F.Zimmerman to IPAC13 Shanghai



Possible view of FCC complex

F. Zimmerman (Chavannes, Jan.2014)

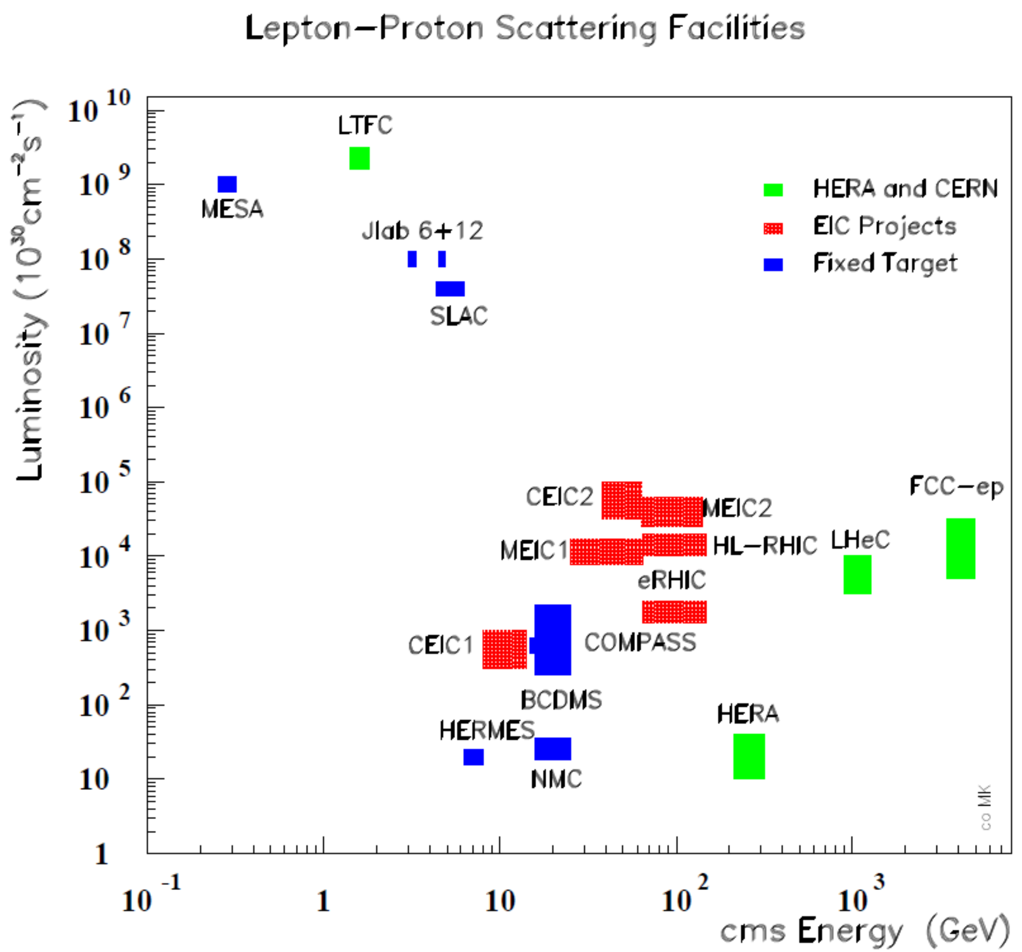


LHeC/FCC-he: $e^{\pm}$ (60-175 GeV) – *p* (7 and/or 50 TeV) collisions

≥50 years e^+e^-, *pp*, $e^{\pm}p/A$ physics at highest energies!

From the LHeC to the FCC-he

Tevatron/HERA/LEP → HL-LHC/LHeC/(ILC?) → FLHC/FHeC/FLC
(fermiscale) (Terascale) (Multi-Terascale)



Lepton-Proton Scattering Facilities

Realistic opportunity for energy frontier DIS → 3-4 order of magnitude higher lumi wrt HERA; huge step in energy (Q^2,1/x)

FCC-he preliminary parameters

e^- energy = 60, 120 GeV up to 175 GeV
(e^+ option open)

Energy recovery is 60 GeV
Ring-Ring might go up to 175 GeV

p energy = 50 TeV

CM energy [TeV] = 3.5 (60 GeV e), 4.9 (120 GeV e)

IP spot size determined by *p*

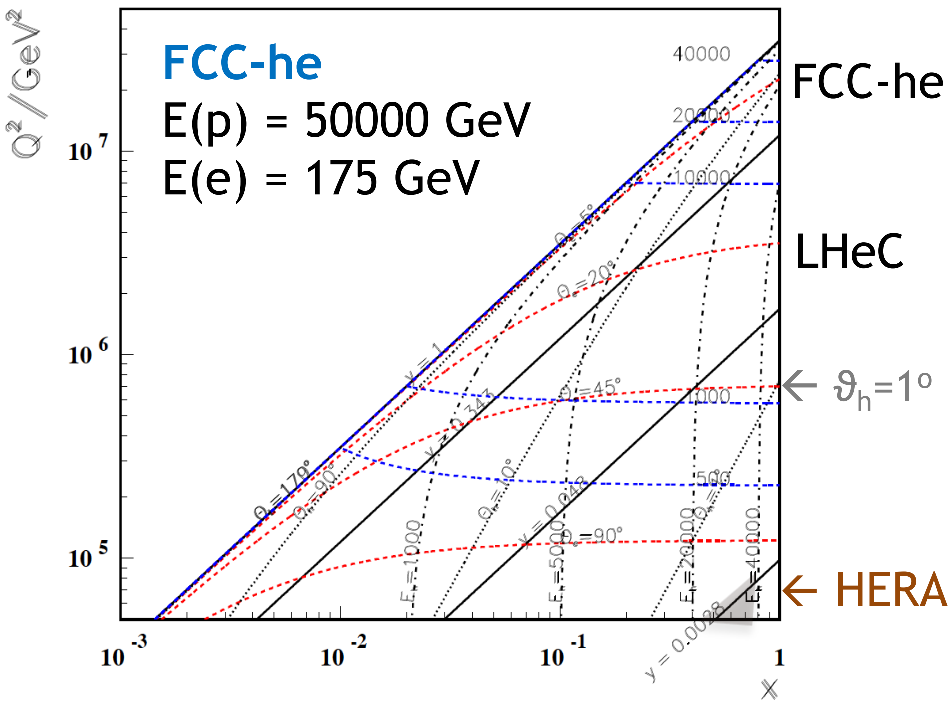
DIS: from HERA to FCC-he

Low x:
Q^2min ~ E_e^2 → keep 60 GeV electrons

Large x:
need very fwd tracking (@ 1 degree)

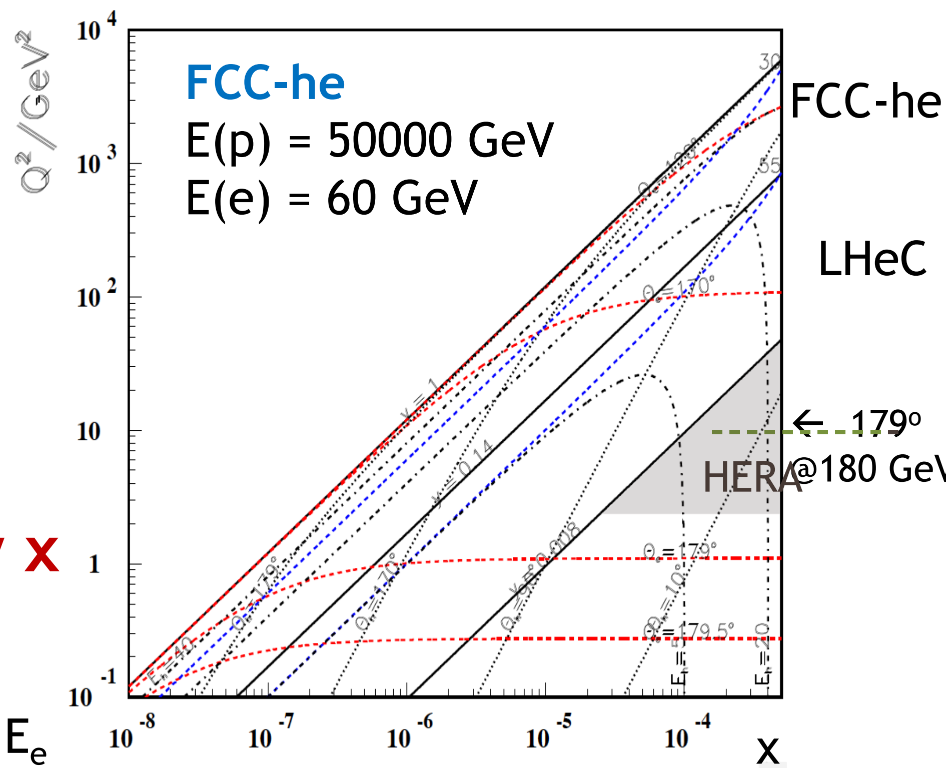
High Q^2

Rutherford backscattering of dozens of TeV e- energy



Low x

.. very low x requires not the maximum of E_e



Detector layout

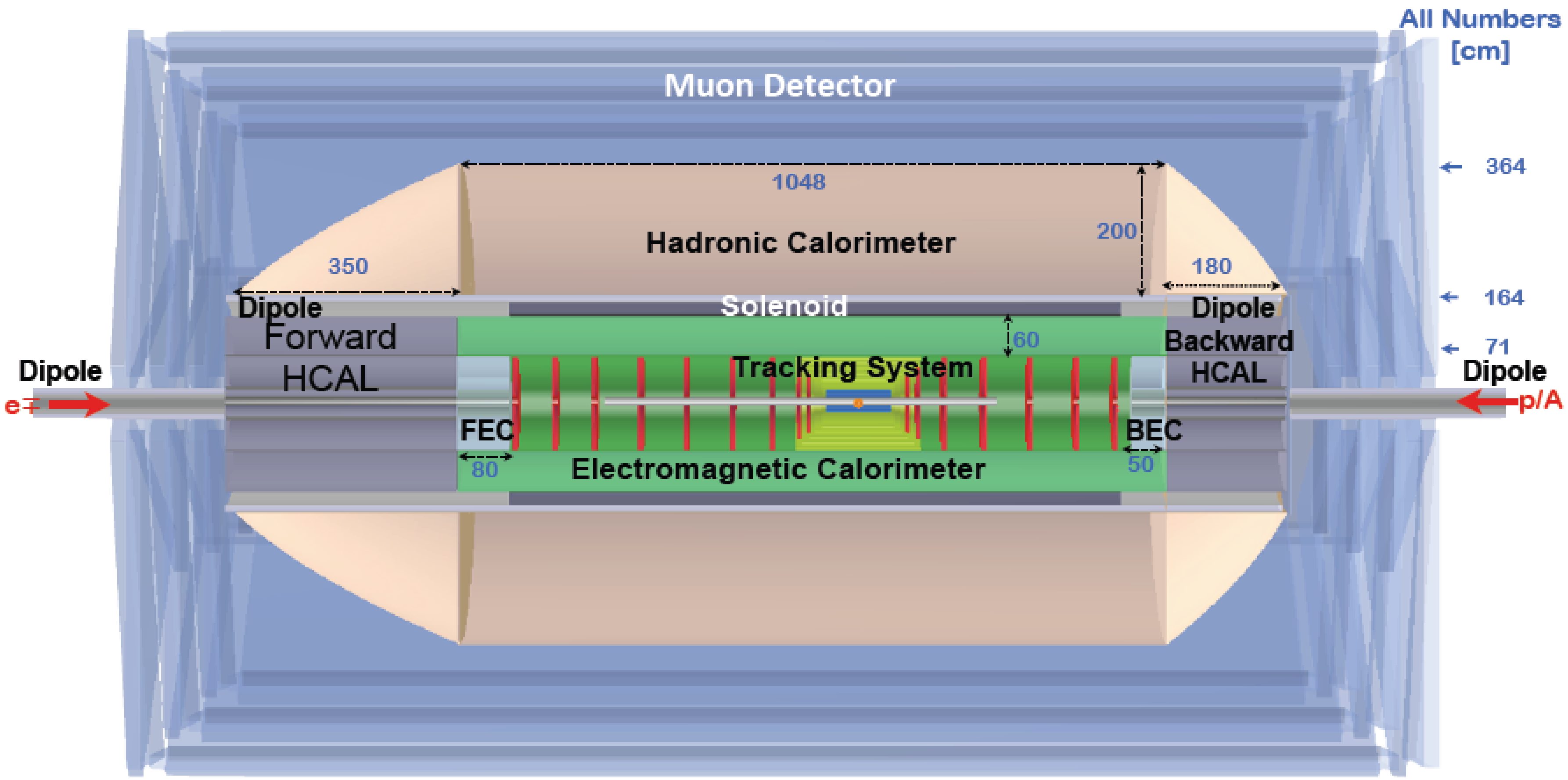
(More in P.Newman talk)

- **LHeC requirements:**
  - High acceptance silicon tracking system
  - Liquid Argon Electromagnetic Calorimeter
  - Iron-Scintillator Hadronic Calorimeter
  - Forward-Backward asymmetry in energy deposited hence in calorimeters geometry and technology: Si/W, Si/Cu
- **Detectors design:**
  - 14m x 9m (e.g.: CMS 21m x 15m; ATLAS 45m x 25m)
  - e/γ taggers ZDC, proton spectrometer integral to design from outset system providing tagging
    - At -62 m(e), 100m(γ,LR), -22.4m(γ,RR),+100m(n),+420m(p)
- **Magnets:**
  - Solenoid (3.5 T) + dual dipole 0.3 T
  - Might be embedded into EMC Lar Cryogenic System
    - Performance and impact of dead material in EMC-HAC sections under studies

FCC-he detector requirements very similar!

FCC-he detector layout

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



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

Physics Highlights

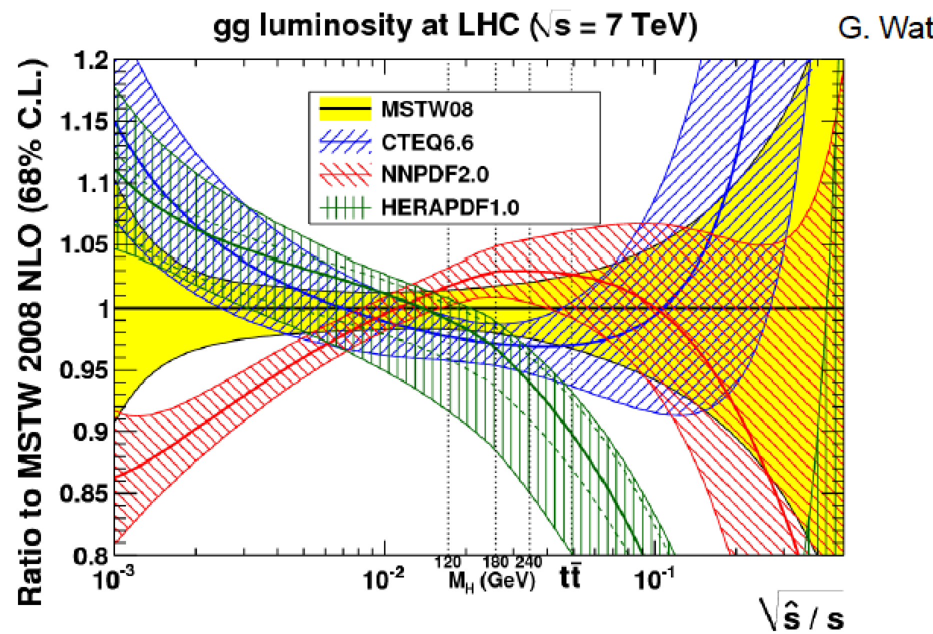
- PDF fits, measurements of α_S and impact on higgs/BSM
- Higgs measurements ($H \rightarrow$bbbar or ccbar, HHH couplings)
- New Physics (CI, LQ, RPV SUSY)
- EWK measurements ($\sin^2\theta_W$)

PDF fits @ 100 TeV

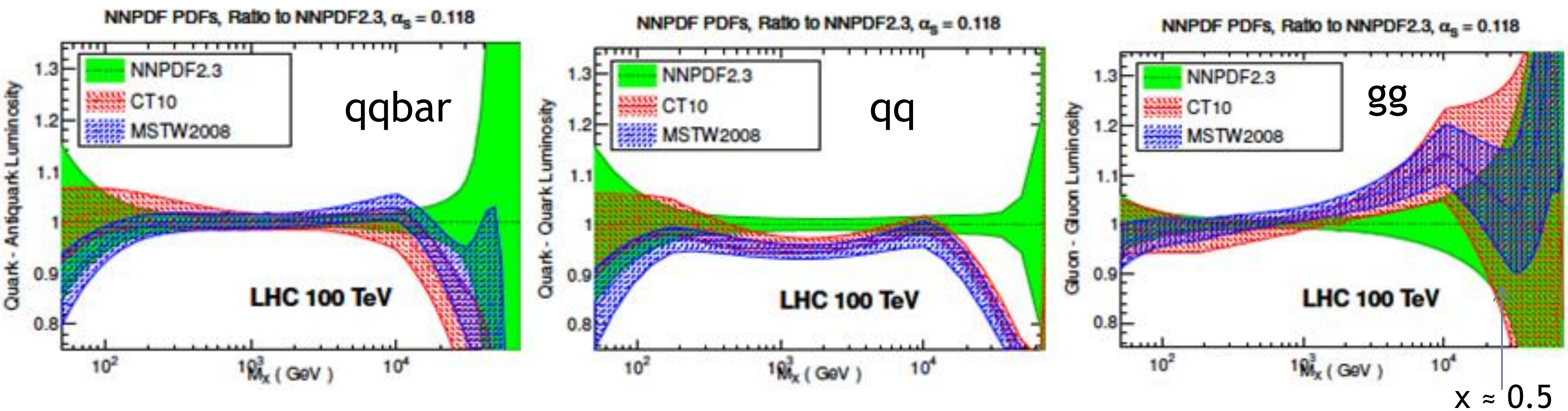
- Current status →

Need to know the PDFs much better than now at low and high x

  - E.g.: for QCD development, q-g dynamics, Higgs measurements and searches



The LHC will provide further constraints, but a new level of precision in determination of PDFs can only be achieved with the e-p

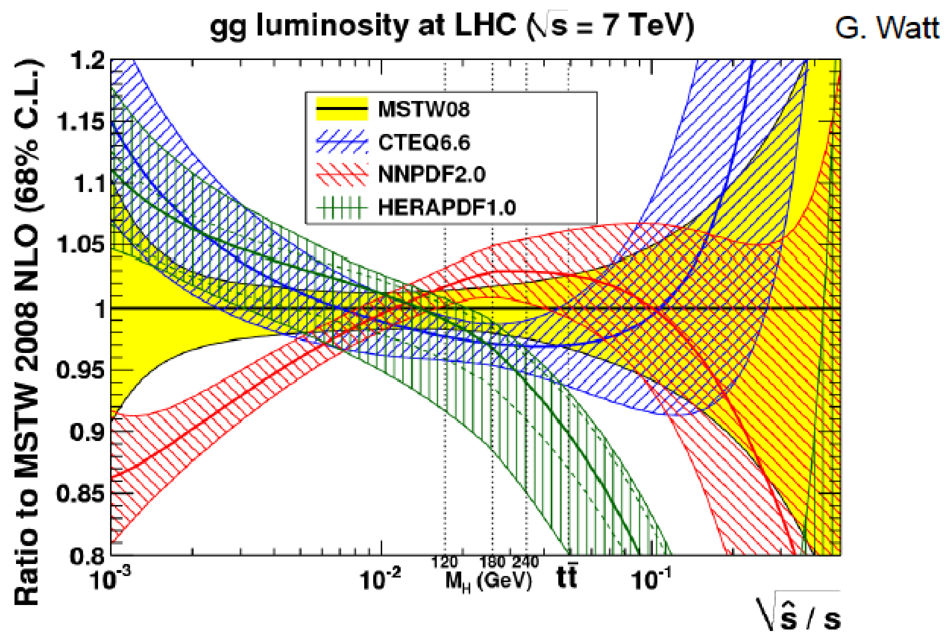


PDF fits

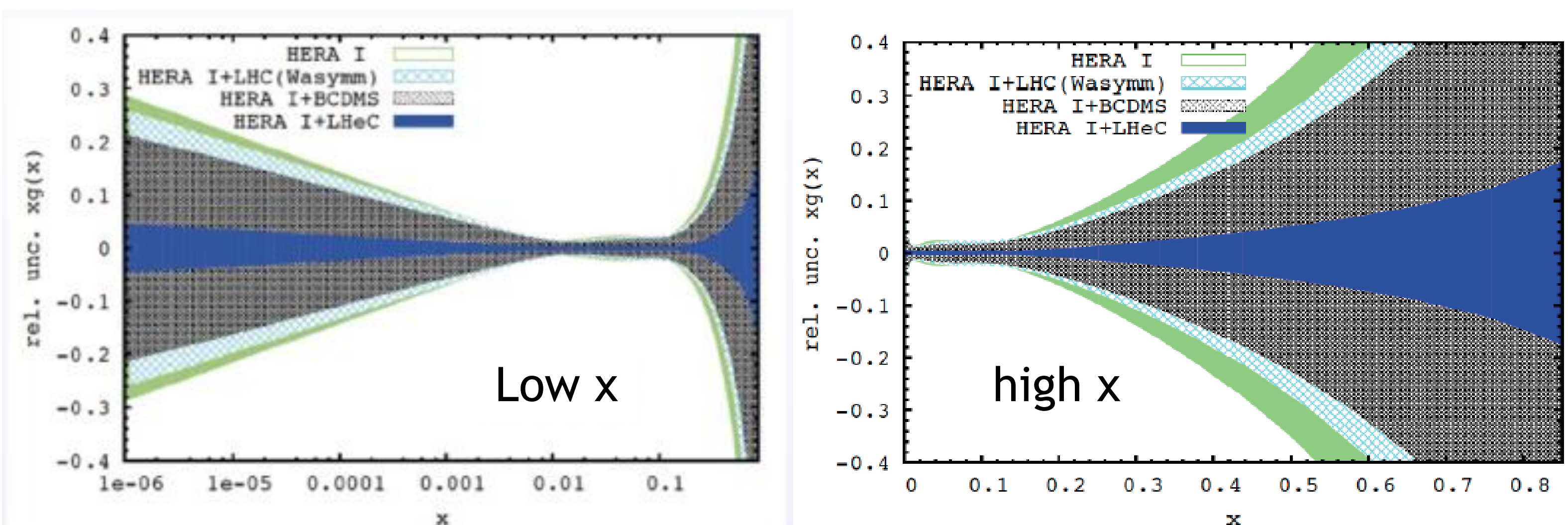
- Current status →

Need to know the PDFs much better than now at low and high x

- E.g.: for QCD development, q-g dynamics, Higgs measurements and searches



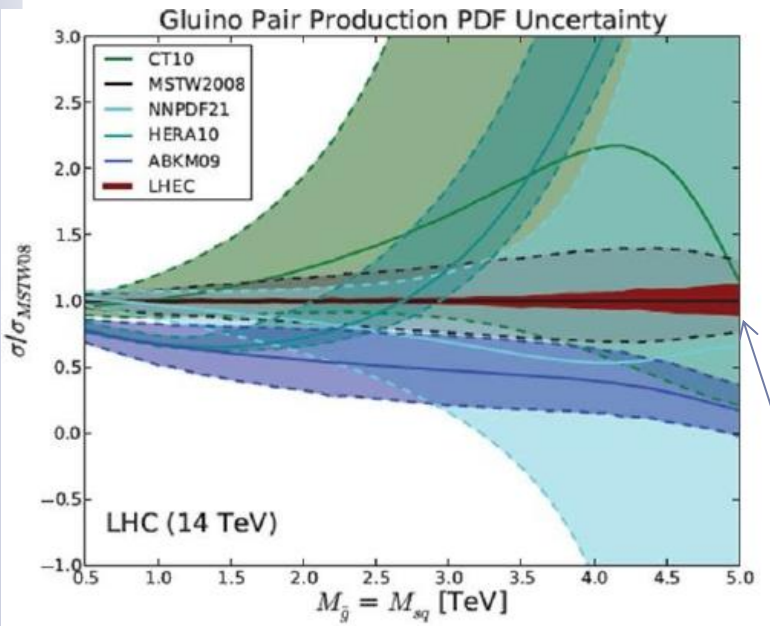
Example gluon PDF at the LHeC (blue band): < 5% at x=10^{-6} and x=0.5

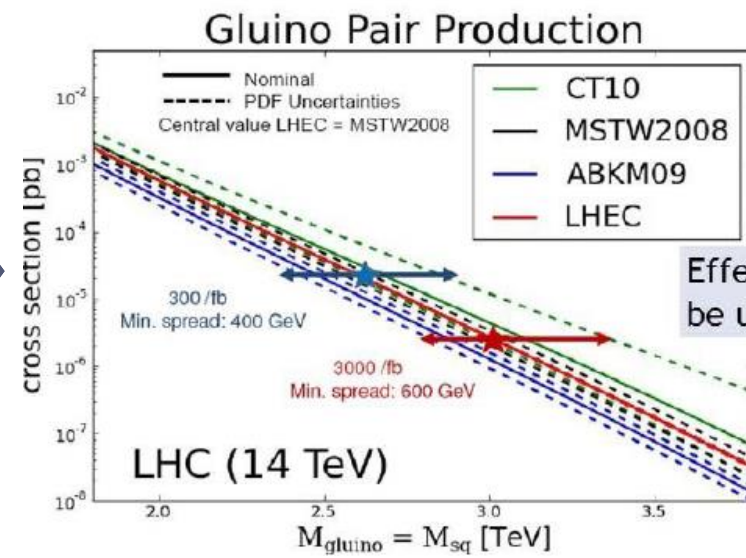


See also V. Radescu's talk

Impact of high-x PDF on HL-LHC/FCC-hh

- Searches near HL-LHC / FCC-hh kinematic boundary may ultimately be limited by knowledge of PDFs (especially gluon at x → 1)
  - Example: gluino production at HL LHC → Dependency on discovery potential and exclusion limits at 300 and 3000 /fb for 14 TeV c.o.m.

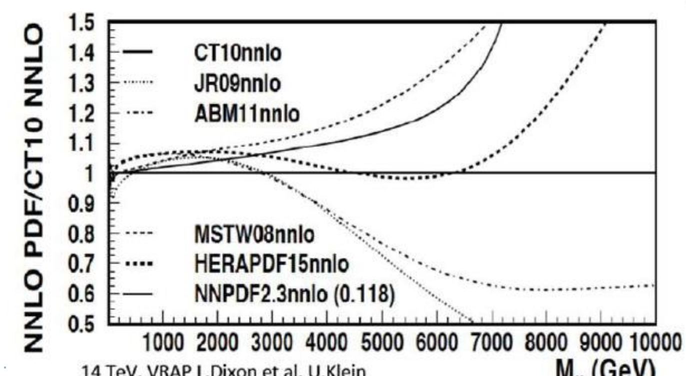




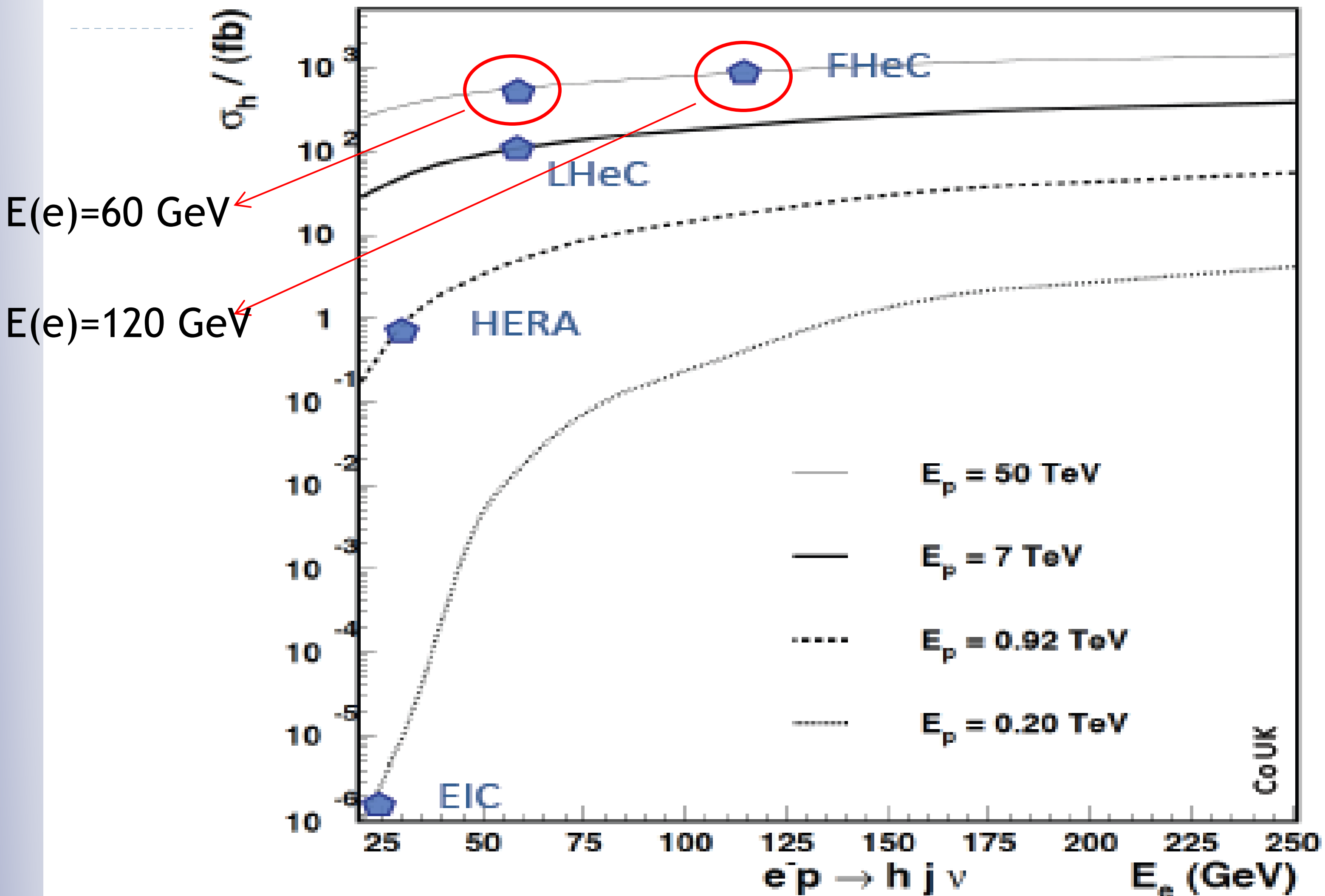
Effects could be up to 1 TeV

LHeC prospects

Similar conclusions for other non-resonant BSM signals involving high x partons (e.g. contact interactions signal in Drell Yan)



Higgs production rate: LHeC → FCC-he



- Charged current ep: cross section much larger than e+e-

Higgs production rate: LHeC → FCC-he (II)

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

Higgs production rate: LHeC → FCC-he (III)

M_h=125 GeV
polarised lepton beam

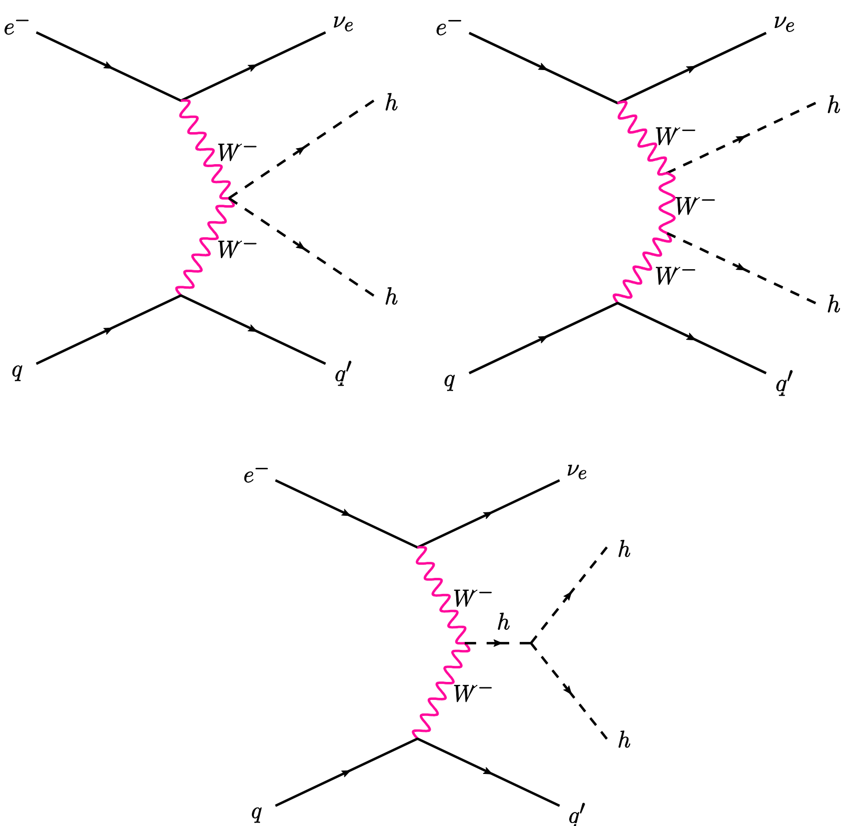
	E_e=60 GeV : √s= **1.3 TeV**				E_e=60 GeV : √s=**3.5 TeV**			
	CC e^-p	CC e^+p	NC ep	CC hh	CC e^-p	CC e^+p	NC ep	CC hh
cross section [fb]	109	58	20	0.01	566	380	127	0.24
polarised cross section [fb] P=-80%	**196**	N.A.	25	0.02	**1019**	N.A.	**229**	0.43

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

Extremely high precision measurements of Hbb
Can also explore H → HH !!

Double higgs production @ 50 TeV

- Electron-proton collisions offer the advantage of reduced QCD backgrounds and negligible pile-up with the possibility of using the 4b final state ($\sigma \times BR(HH \rightarrow 4b)$=0.08 fb).



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

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

Cross-sections for CC HH->4b
(branching ratios included)
for unpolarized electron beam

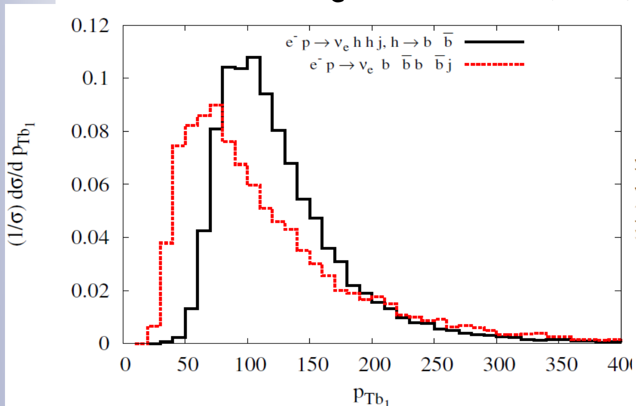
First feasibility studies

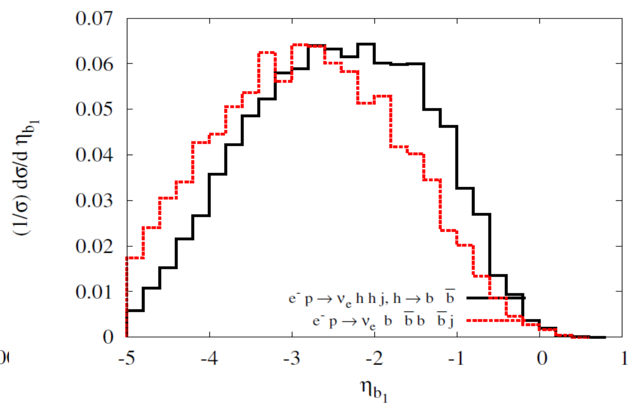
- Cross-sections for CC backgrounds in fb for E_e=60, 120,150 GeV

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}

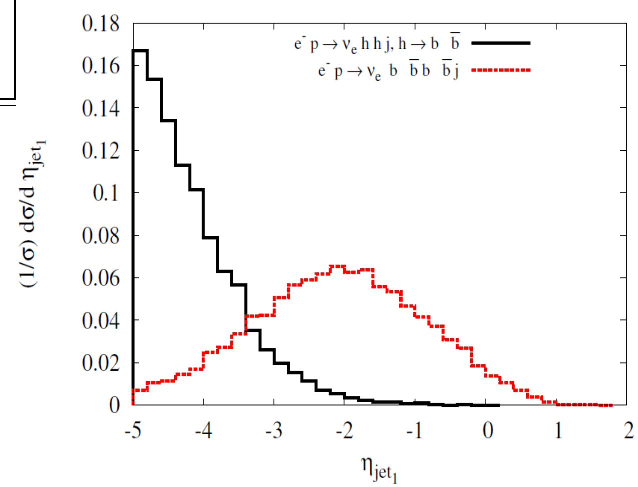
Results assume 70% b-tagging efficiency, 0.1 (0.01) fake rates for c (light) jets

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





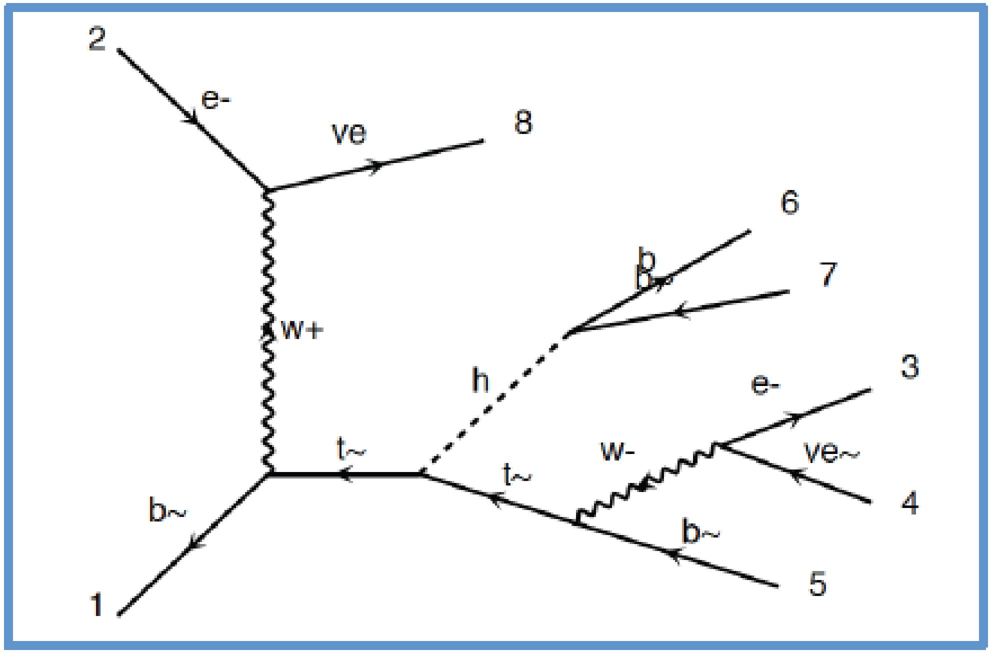
Despite large beam energy imbalance, b-jets are relatively central



Scattered quark is more forward in signal → good discriminant!

Httbar

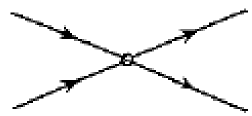
- Can also explore Httbar: 3bjets + W in final state!
  - Total cross section: 0.7 fb
  - Fiducial cross section: 0.2 fb, considering:
    - pT(b), pT(j)> 20 GeV
    - DR (j,b) > 0.4
    - Eta_jet < 5
    - Eta_bjet< 3



NP in inclusive DIS at high Q^2

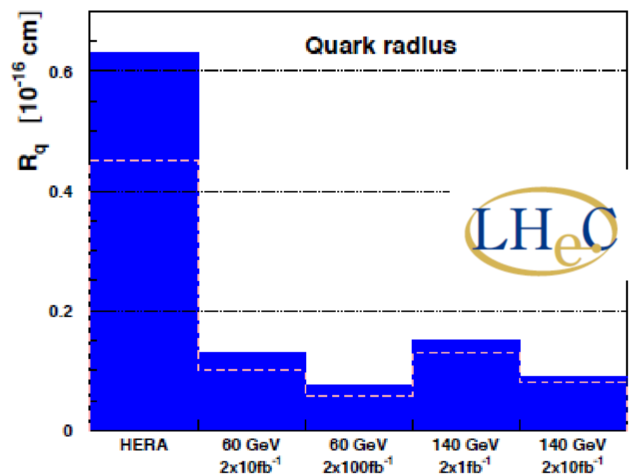
- At these small scales new phenomena not directly detectable may become observable as deviations from the SM predictions.
- A convenient tool: effective four-fermion contact interaction

4-fermion interaction $\Rightarrow M_{eq\to eq} \sim \Lambda^{-2}$



Λ : Compositeness scale

Observed as modification of the Q^2 dependence → all information in $d\sigma/dQ^2$
Also parametrized as form factors



- Radius for composite fermions:
  - Proportional to scale

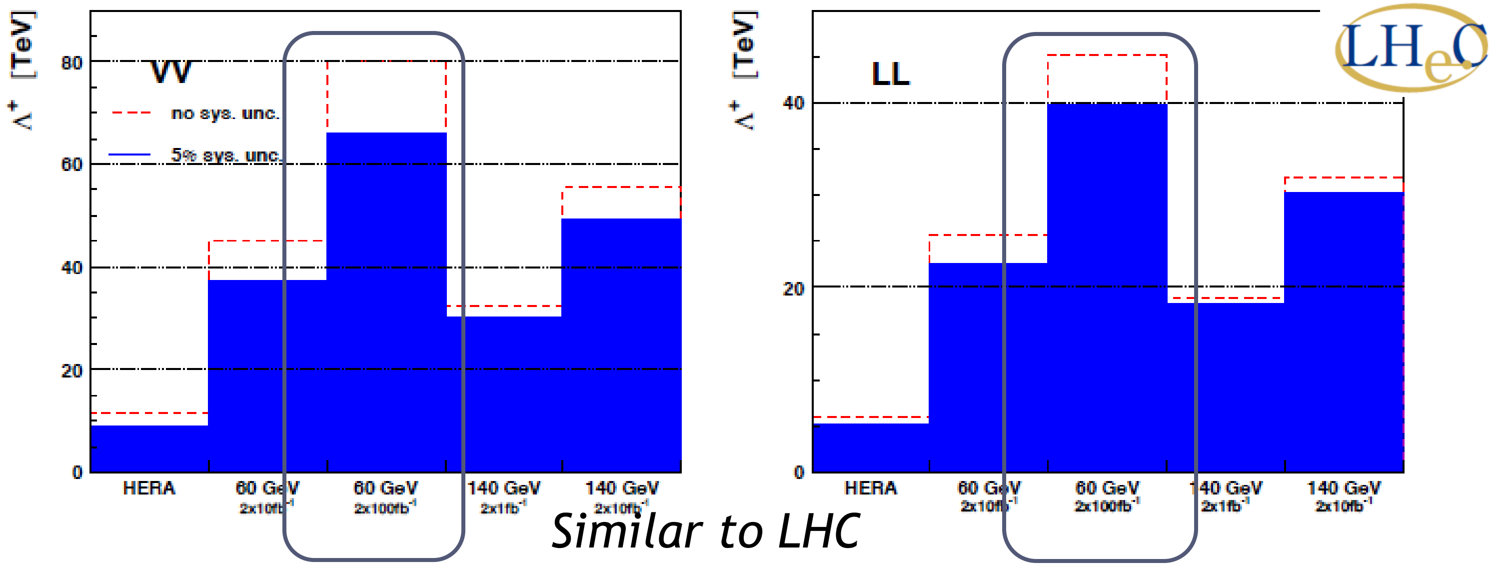
$$f(Q^2) = 1 - \frac{1}{6}\langle r^2\rangle Q^2 ,$$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} f_e^2(Q^2)\, f_q^2(Q^2)$$

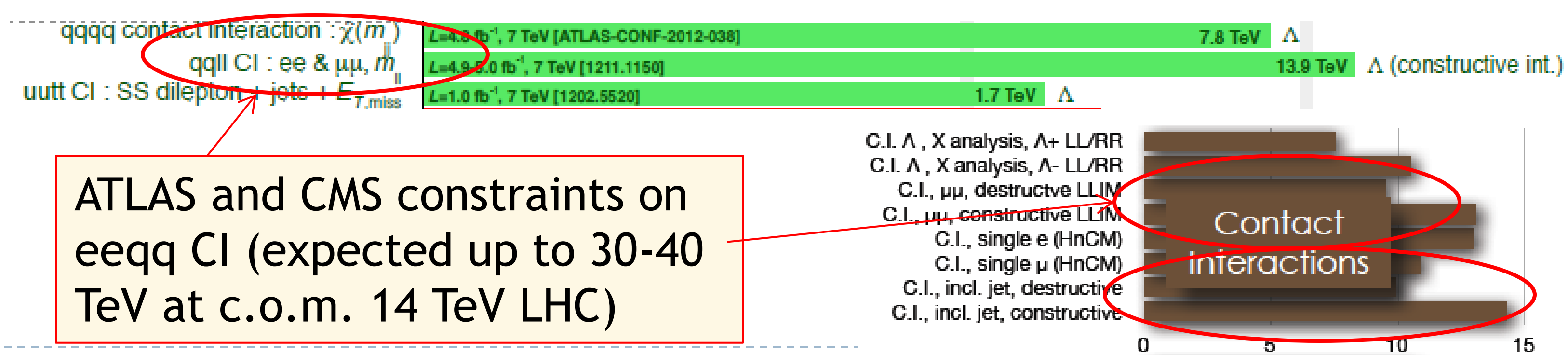
- reach **well below 10-^{19}(10-^{20}) m** (LHeC/FHeC)
- Complimentary to LHC/FCC-hh (not directly probing EWK Radius)

Contact interactions (eeqq)

- New currents or heavy bosons may produce indirect effect via new particle exchange interfering with γ/Z fields.
- Reach for Λ (CI eeqq): 40-65 TeV with 100 fb^{-1} of data depending on the model

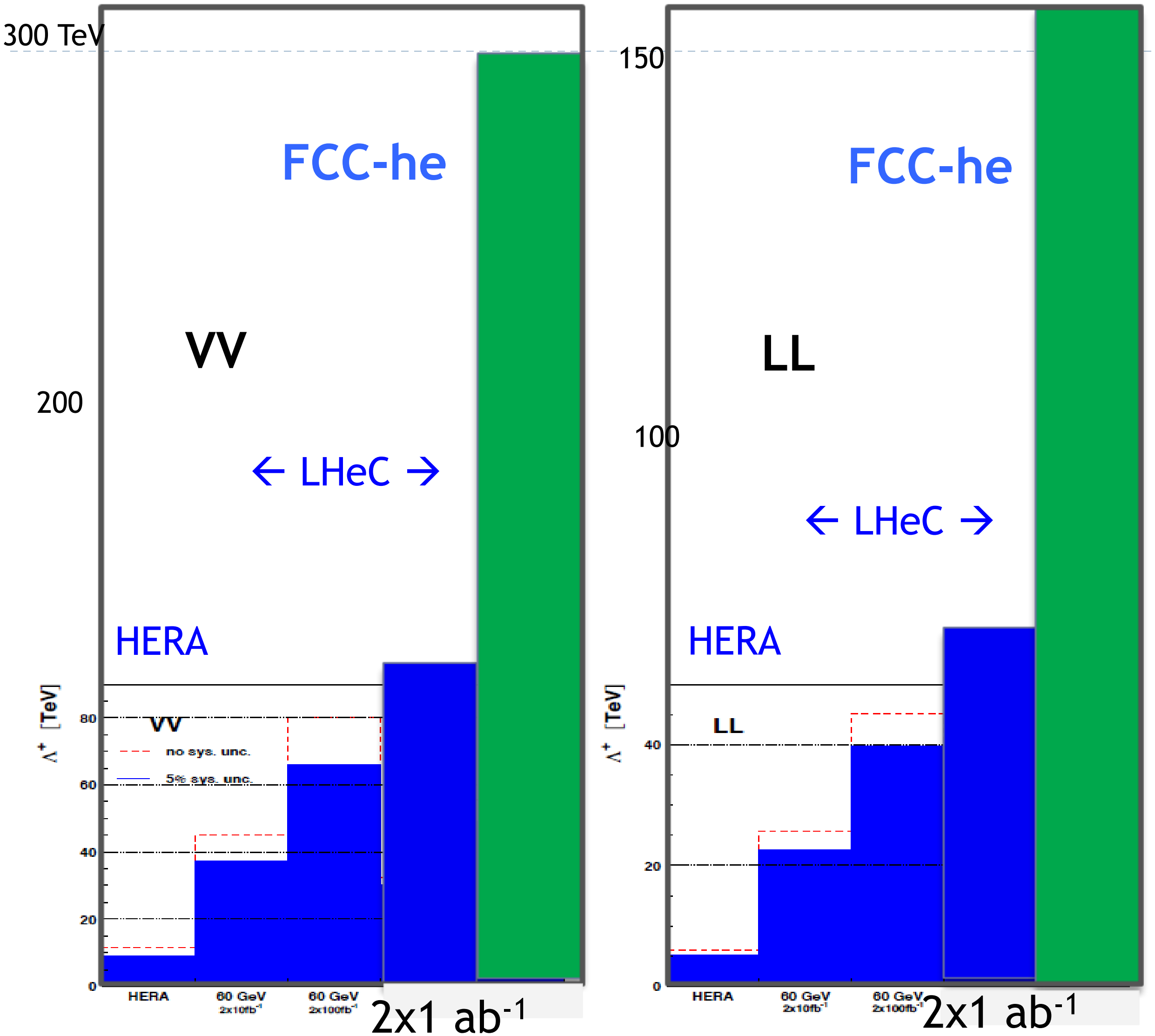


Similar to LHC



ATLAS and CMS constraints on eeqq CI (expected up to 30-40 TeV at c.o.m. 14 TeV LHC)

Reach for CI (eeqq) at FCC-he



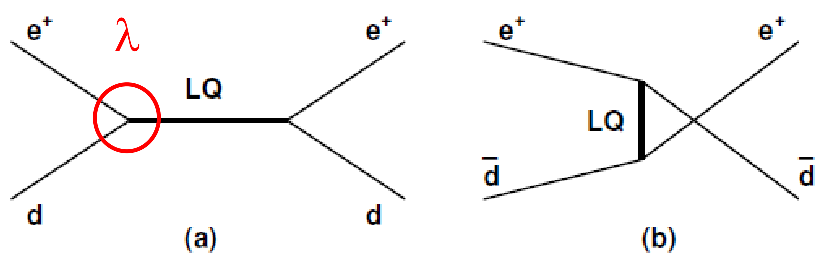
- Very preliminary scaling
- Reach about O(100) TeV, expected to be competitive with FHC

Lepto-Quark

- High Q^2 e-p collider competitive with p-p collider for NP models where initial state lepton is an advantage
  - By providing both B and L in the initial state, ideal to study the properties of new particles with couplings to an e-q pair
  - Probe single particle prod.

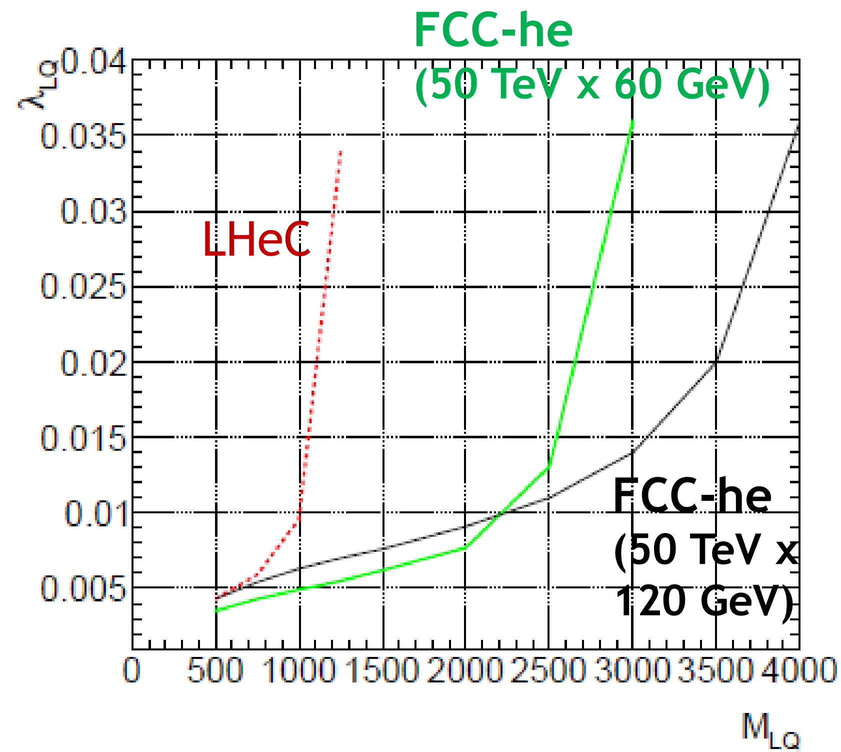
First gen. LQ

$$\sigma \approx \lambda^2 q(x)$$



- **Can probe up to 4 TeV LQ at FCC-he**
- If LQ are observed in p-p →

in e-p can measure fermion number (red) and flavor structure (blue)

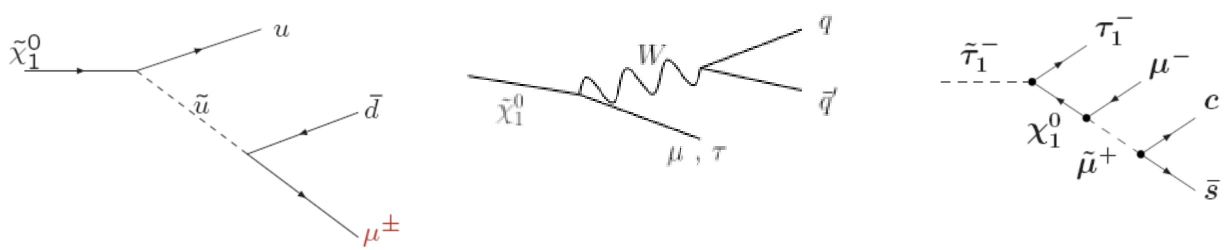


Preliminary studies in progress (G.Azuelos)
Assume 20 fb-1 for FCC)

R-parity violating SUSY

- Several final states to explore:
  - LSP no longer stable
  - > 700 possibilities + bilinear couplings! Examples:

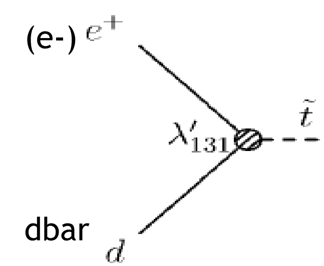
$$\begin{pmatrix} \text{pair production: } \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g} \\ \text{resonant } \tilde{\ell} \text{ production} \end{pmatrix} \otimes \begin{pmatrix} \underline{\text{LSP}} \\ \tilde{\chi}_1^0 \\ \tilde{\chi}_1^{\pm} \\ \tilde{\nu}_L \\ \tilde{\ell}^{\pm}_{L,R} \\ \tilde{\tau}_1^{\pm} \\ \tilde{q}_{L,R} \\ \tilde{t}_1 \\ \tilde{g} \end{pmatrix} \otimes \begin{pmatrix} \underline{\text{Operator}} \\ L_1 L_2 \bar{E}_1 \\ \vdots \\ L_2 L_3 \bar{E}_3 \\ L_e Q_1 \bar{D}_1 \\ \vdots \\ L_\mu Q_1 \bar{D}_1 \\ \vdots \\ L_\tau Q_3 \bar{D}_3 \\ \bar{U}_i \bar{D}_j \bar{D}_k \end{pmatrix}$$



Relevant for e-p: squark production (e.g. stop): → λ_{131}' couplings relevant in e-p production, several can be explored for decays

Example for LHeC: 1107.4461.pdf

Assume decay via μ+b $\quad \lambda'_{131} \leq 0.03, \quad \lambda'_{233} \leq 0.45$



Sensitivity for high stop mass with 50-100 fb^{-1}

M (GeV)	$\sigma(e^+p)$ (pb)	exclusion $\mathcal{L}(e^+p)$ (pb^{-1})	$\sigma(e^-p)$ (pb)	exclusion $\mathcal{L}(e^-p)$ (pb^{-1})
600	0.14	50.03	2.73×10^{-2}	330.43
700	6.94×10^{-2}	109.36	8.52×10^{-3}	1.69×10^3
800	3.10×10^{-2}	282.27	2.22×10^{-3}	1.61×10^4

Many more decay modes (RPV or RPC) hard at LHC/FCChh can be explored
(sbottom investigated as well)

Electroweak Physics in ep [$\sin^2\theta_W$]

- EWK precision measurements relevant for NP

See also C. Schwanenberger's talk

Present situation

- $\sin^2\hat{\theta}_w(m_Z) = 0.23070 \pm 0.00026$ from A_{LR}, SLD
- $\sin^2\hat{\theta}_w(m_Z) = 0.23193 \pm 0.00029$ from $A_{FB}^{b\bar{b}}$, LEP1

  ➜ 3σ difference !
- $\sin^2\hat{\theta}_w(m_Z) = 0.23125 \pm 0.00016$ world average
- $\sin^2\hat{\theta}_w(m_Z) = 0.23104 \pm 0.00015$ from α, G_μ, m_Z and m_W

Very different implications for new physics:
look at S, T, U parameters, e.g.,

- from A_{LR} ➜ $S = -0.18 \pm 0.15$ ➜ Susy?
- from $A_{FB}^{b\bar{b}}$ ➜ $S = +0.46 \pm 0.17$ ➜ heavy Higgs? KK at 1 - 2 TeV?
- from average ➜ $S = +0.11 \pm 0.11$ ➜ new heavy doublets? KK above 3 TeV?

H. Spiesberger (Mainz) LHeC, 20. 1. 2014

Electroweak Physics in ep (II)

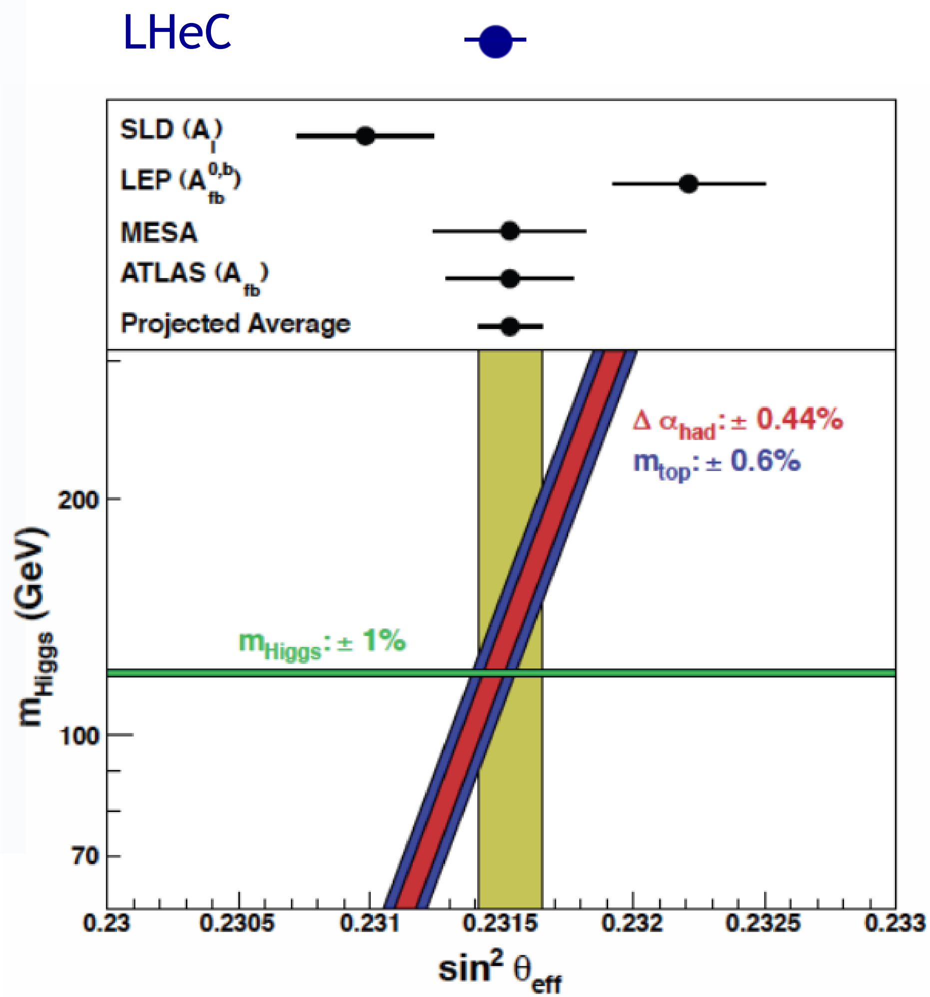
Polarisation Asymmetry $A^-(Q)$

NC-to-CC Ratio R- for P=±0.8

Measure weak mixing angle redundantly with very high precision of about 0.0001 as a function of the scale.

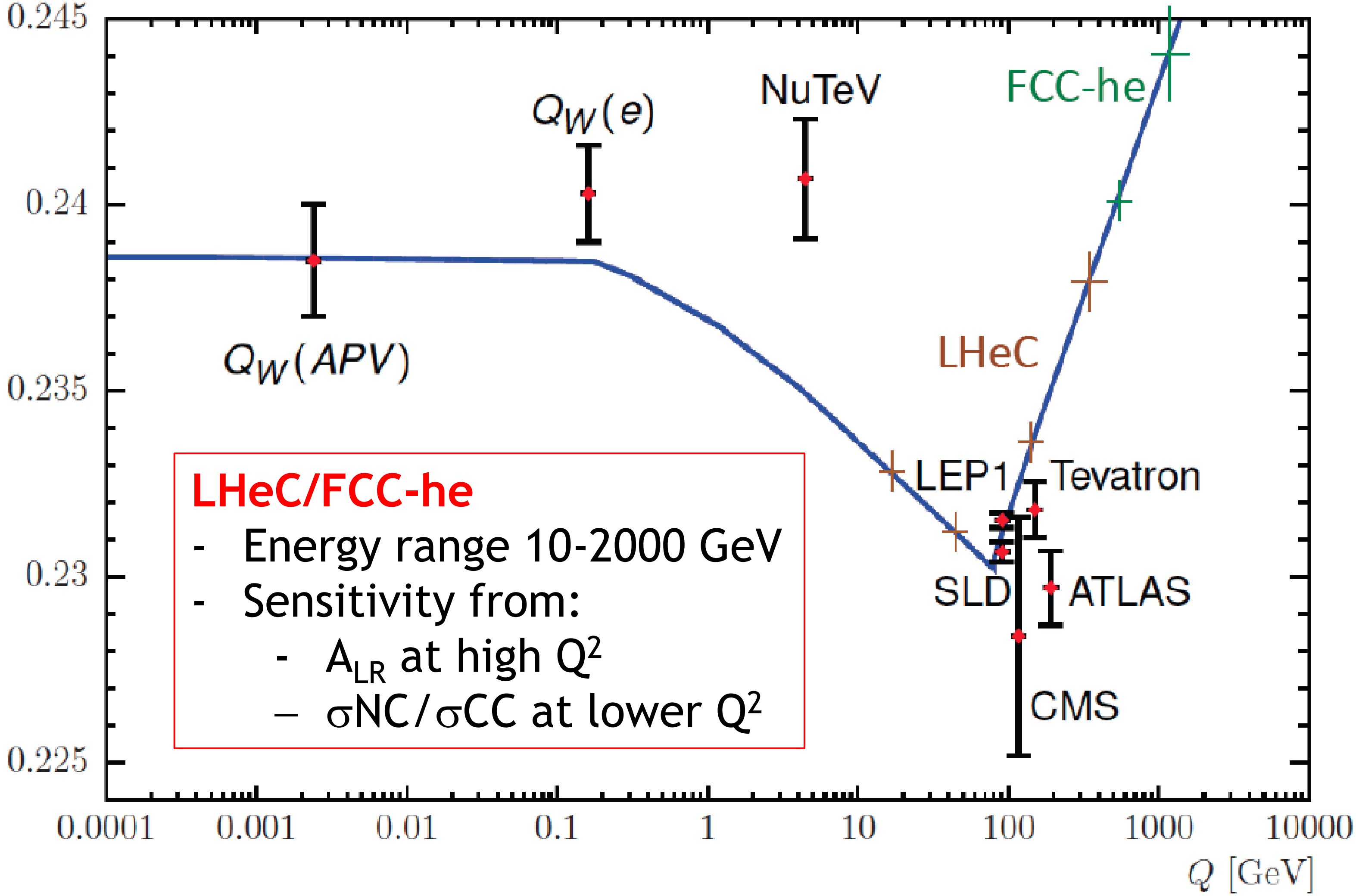
1% δM_{top} is about δ = 0.0001

PDF uncertainty comes in at second order and ep provides very precise PDFs



Scale dependence of $\sin^2\theta_W$

- Preliminary sketch



Summary

- LHeC design matured over past 6 years; CDR published in 2012 and more publications followed up
- Great physics potential, complementary to HL-LHC
  - Very exciting possibilities for Higgs measurements, competitive with pp !
- LHeC compatible with long-term strategy (FCC)
  - FCC-he : 60...175 GeV E_e x 50 TeV
  - Rich physics program under development (in parallel with consolidation studies for LHeC)
    - E.g. double higgs production

→ The FCC-he is a great opportunity for precision DIS, BMS and Higgs genuinely complementary also to FCC-hh and FCC-ee

Back-up

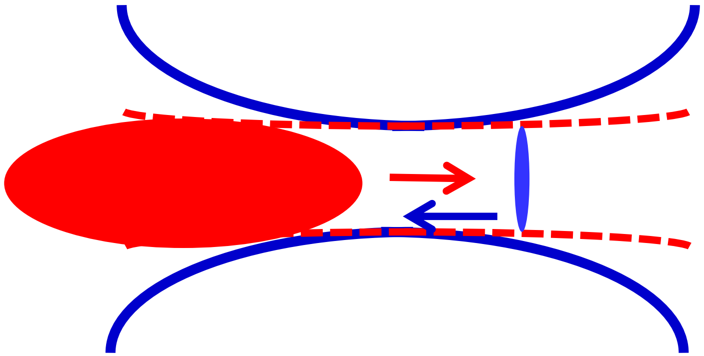
LHeC Higgs factory (LHeC-HF) parameters

parameter [unit]		
species	*e-*	*p*
beam energy (/nucleon) [GeV]	60	7000
bunch spacing [ns]	25	25
bunch intensity (nucleon) [10^{10}]	**0.1 → 0.4**	**17→ 22**
beam current [mA]	**6.4 → 25.6**	**860 → 1110**
normalized rms emittance [μm]	50 → **20**	**3.75 → 2.5**
geometric rms emittance [nm]	**0.43 → 0.17**	**0.50 → 0.34**
IP beta function $\beta_{x,y}^*$ [m]	**0.12 → 0.10**	**0.10 → 0.05**
IP rms spot size [μm]	7.2 → **4.1**	7.2 → **4.1**
lepton *D* & hadron ξ	**6 → 23**	**0.0001→ 0.0004**
hourglass reduction factor H_{hg}	0.91→ **0.70**	
pinch enhancement factor H_D	1.35	
luminosity / nucleon [10^{33} cm^{-1}s^{-1}]	**1.3 → 16**	

Electron possibilities

ring-ring

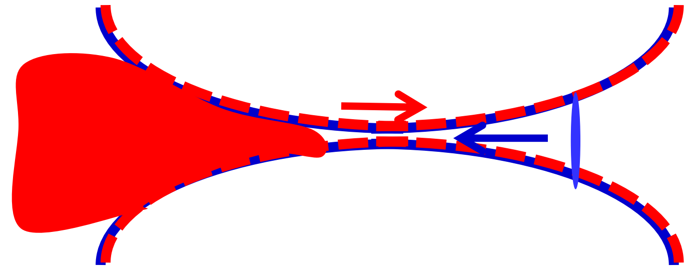
$\varepsilon_e >> \varepsilon_p$, $\beta_e^* << \beta_p^*$



minimum *e*⁻ beta function and **beam sizes** **limited by hourglass effect**; **small crossing angle acceptable; little disruption**

ring-linac

$\varepsilon_e \approx \varepsilon_p$, $\beta_e^* \approx \beta_p^*$



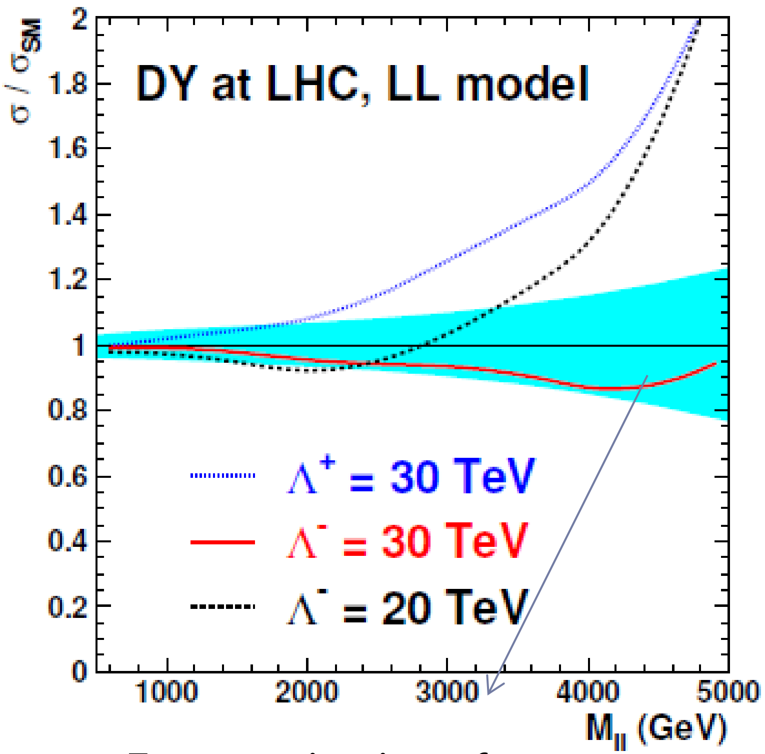
much smaller *e*⁻ emittance **smaller** beta function and **beam sizes** possible; **head-on collision required; significant disruption**

hourglass reduction factor

$$H_{hg} = \frac{\sqrt{\pi} z e^{z^2} \mathrm{erfc}(z)}{S} \; ; \; z \equiv 2 \frac{(\beta_e^*/\sigma_{z;p})(\varepsilon_e/\varepsilon_p)}{\sqrt{1+(\varepsilon_e/\varepsilon_p)^2}} S \; ; \; S \equiv \sqrt{1+\frac{\sigma_{z,p}^2 \theta_c^2}{8\sigma^{*2}}}$$

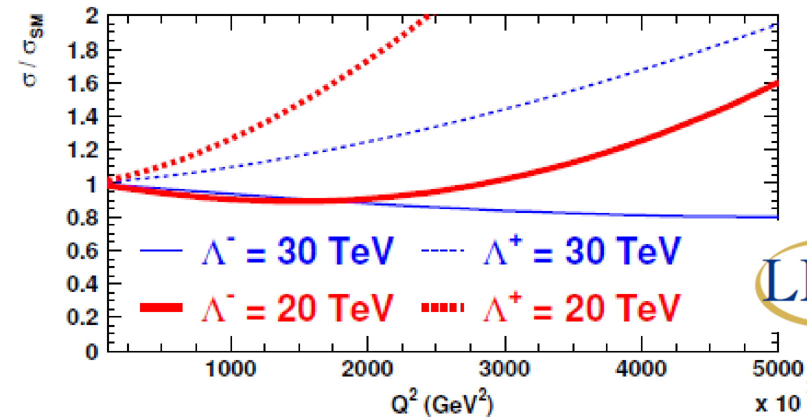
CI at LHC and LHeC

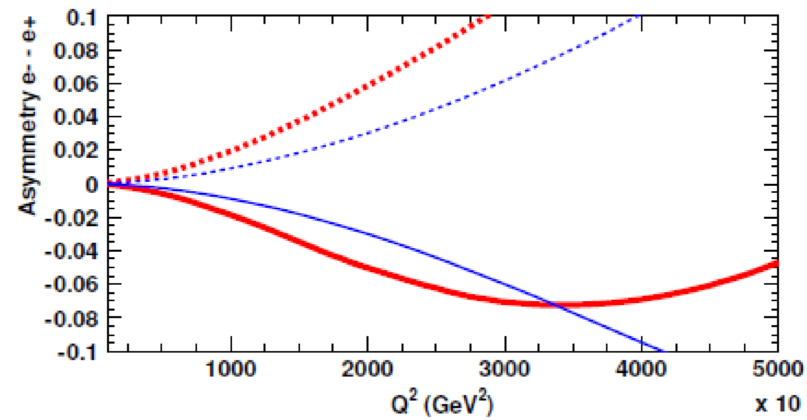
- LHC: Variation of DY cross section for CI model
  - Cannot determine simultaneously Λ and sign of interference of the new amplitudes wrt SM (ε)



Ex: negative interference too small to be disentagled

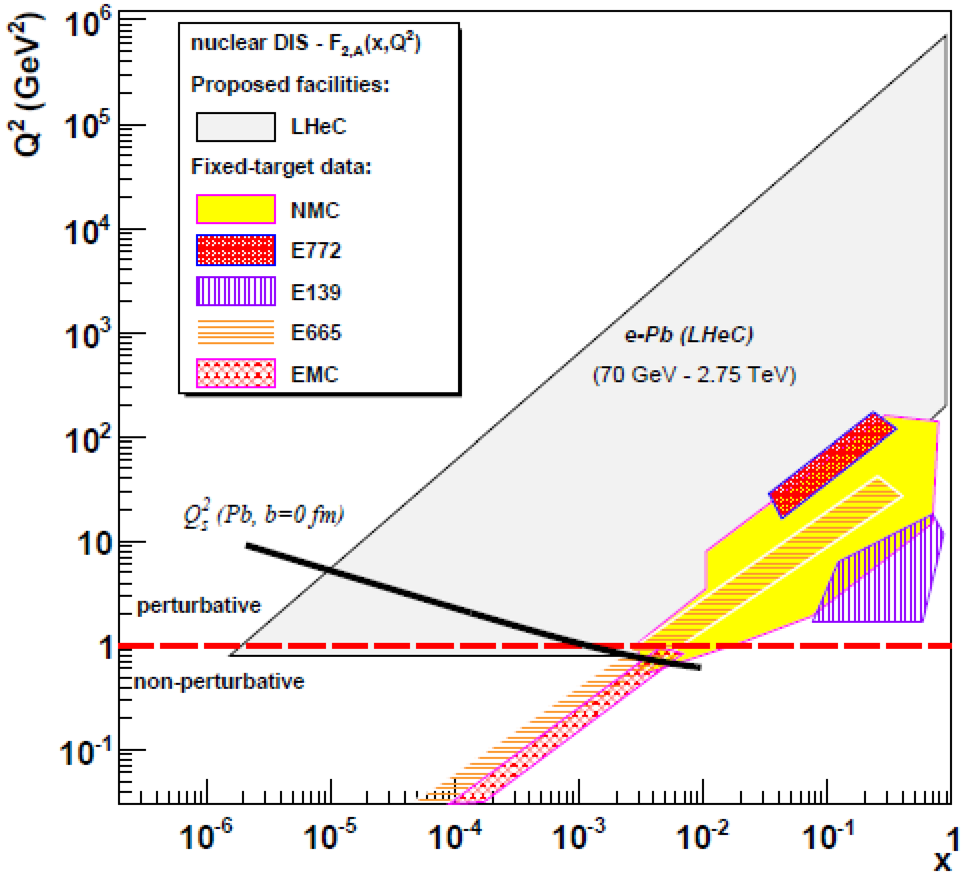
LHeC: sign ε from asymmetry of σ/σ_{sm} in e+p and e-p data





LHeC as electron-Ion Collider

- **Four orders of magnitude increase** in kinematic range over previous DIS experiments
  → will change QCD view of the structure of nuclear matter



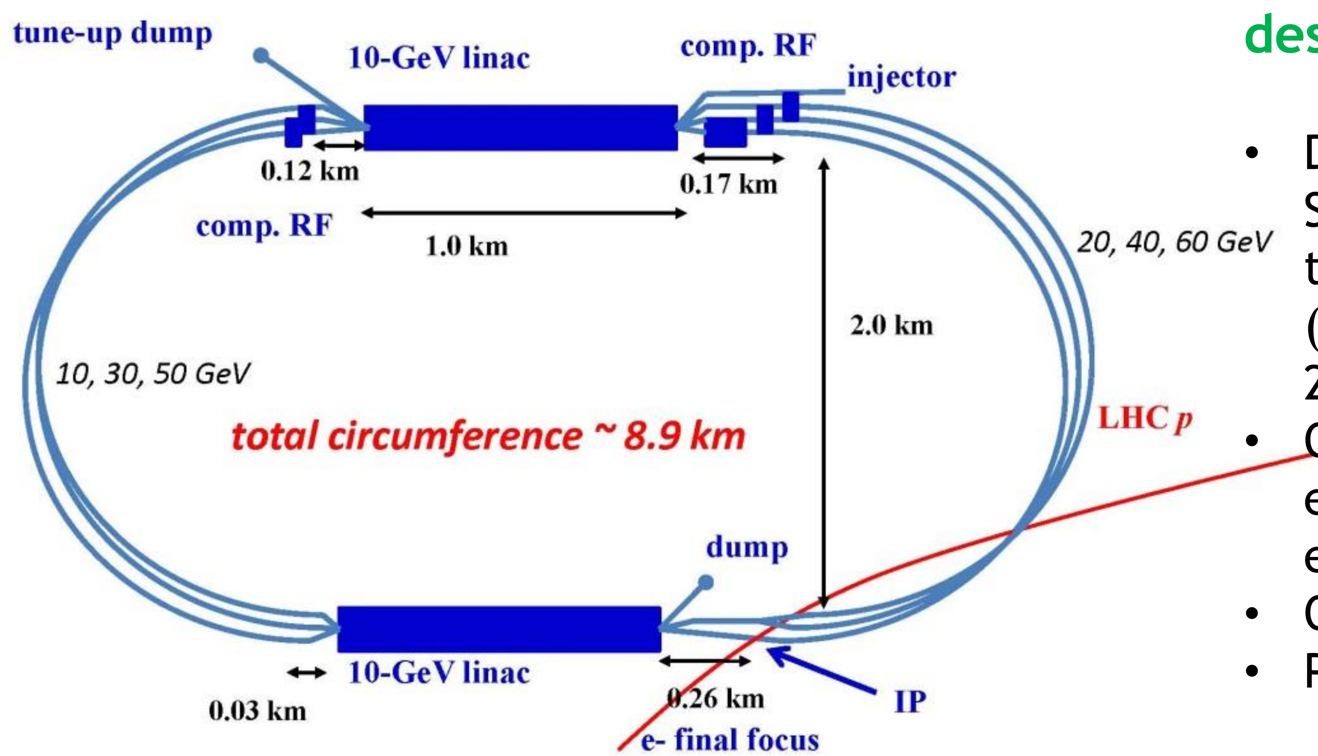
Study interactions of densely packed but weakly decoupled partons

Precision QCD study of parton dynamics in nuclei

May lead to genuine surprises:
- no saturation of $xg(x,Q^2)$,
- broken isospin invariance
- …

Energy Recovery Linac

- Power consumption < 100 MW, **E(ele)=60 GeV** *(design constraints)*
- Two 10 GeV Linacs; 3 returns, 20 MV/m
- Energy recovery in same structures
- 60 GeV e-'s collide w. LHC protons/ions



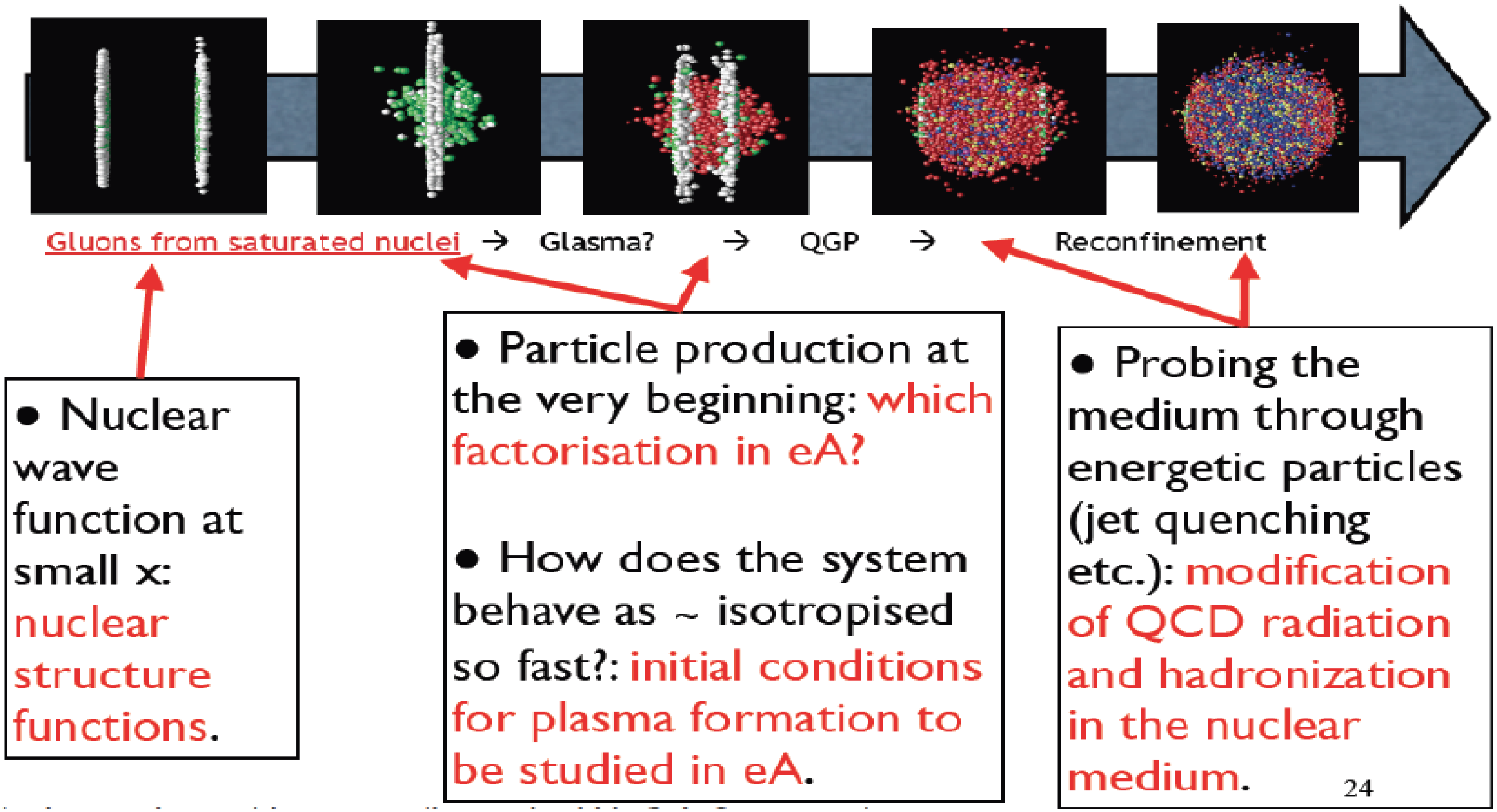
Test Facility under design

- Development of SuperConducting RF technology at CERN (Approved November 2013)
- Operation and experience with S.C. energy recovery linac
- Quench tests of magnets
- Possible e/γ experiments

More in O. Brunig and F. Zimmerman talks on Friday

e-Ion physics

- Rich program, e.g. for Nuclear Parton density determination
  - More in B.Cole talk on tomorrow



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	

R-parity violating SUSY

Squarks in RPV models could be an example of 'Leptoquarks'

- R-parity = $(-1)^{3(B-L)+2s}$ (R = 1 for SM particles, -1 for MSSM partners)

If not conserved (RPV) → different terms, couplings constraint by proton decay

L-number violating terms

$$W_{\not R p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

B-number violating terms

$\Delta L = 1$, 9 λ couplings, 27 λ' couplings

Plethora of new couplings, only partially constraints (m/100 GeV)

	$\lambda_{ijk}L_iL_j\bar{E}_k$	$\lambda'_{1jk}L_1Q_j\bar{D}_k$	$\lambda'_{2jk}L_2Q_j\bar{D}_k$	$\lambda'_{3jk}L_3Q_j\bar{D}_k$
weakest	0.07	0.28	0.56	0.52
strongest	0.05	$5.\cdot 10^{-4}$	0.06	0.11

Various strong constraints from LHC on Lambda and Lambda'' (from multilepton and multijet searches)