FCC-eh Physics Potential

Daniel Britzger
FCC Physics Workshop
Feb. 2022, Liverpool

MAX-PLANCK-INSTITUT
FÜR PHYSIK

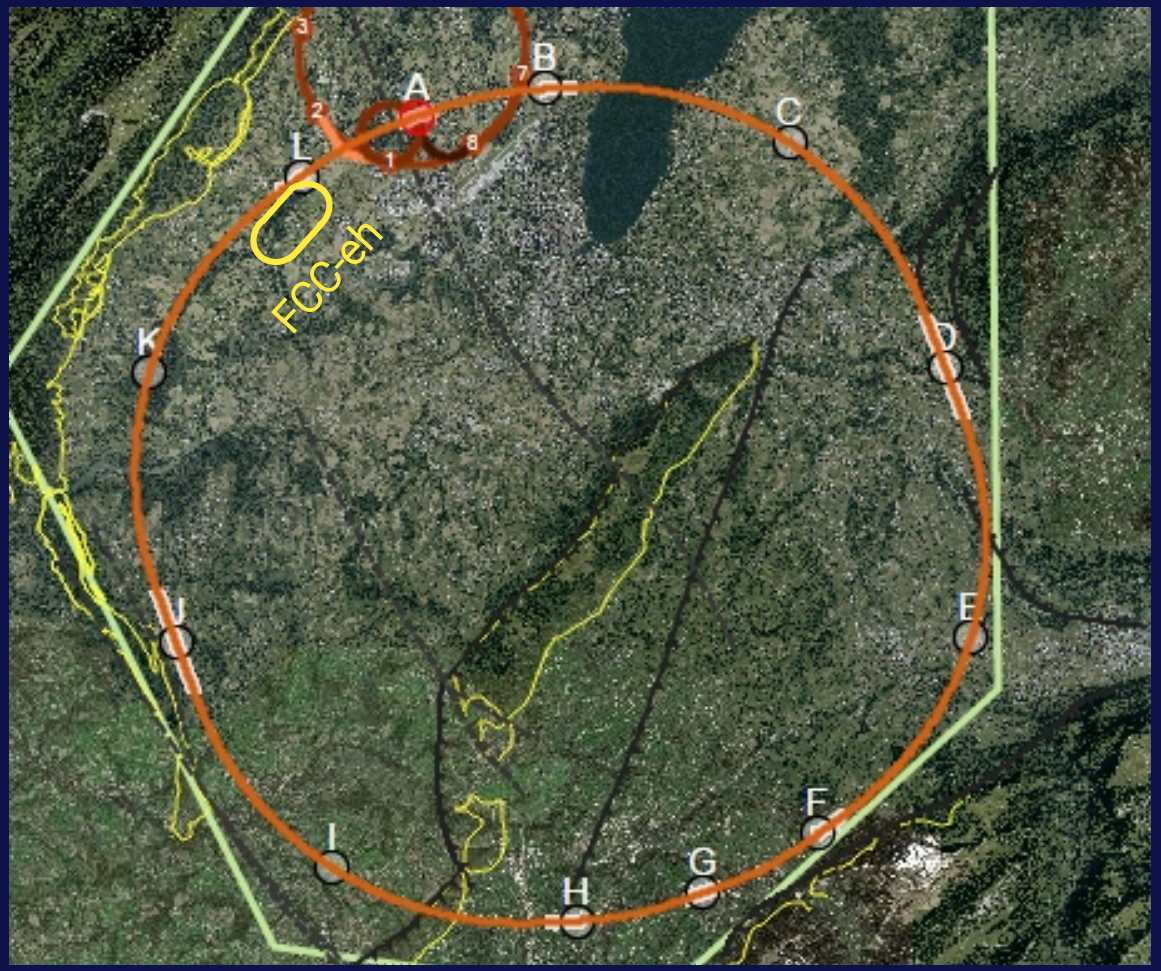
FCC-eh

Dedicated electron-ring attached to the FCC-hh

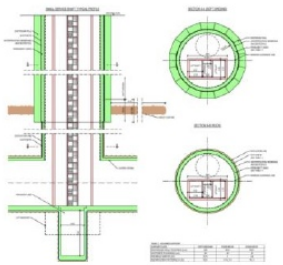
Energy recovery linac
E_e = 60 GeV
$\sqrt{s} \sim 3.5$ TeV

High Luminosity of
about 3 ab^{-1}

Concurrent operation with FCC-hh

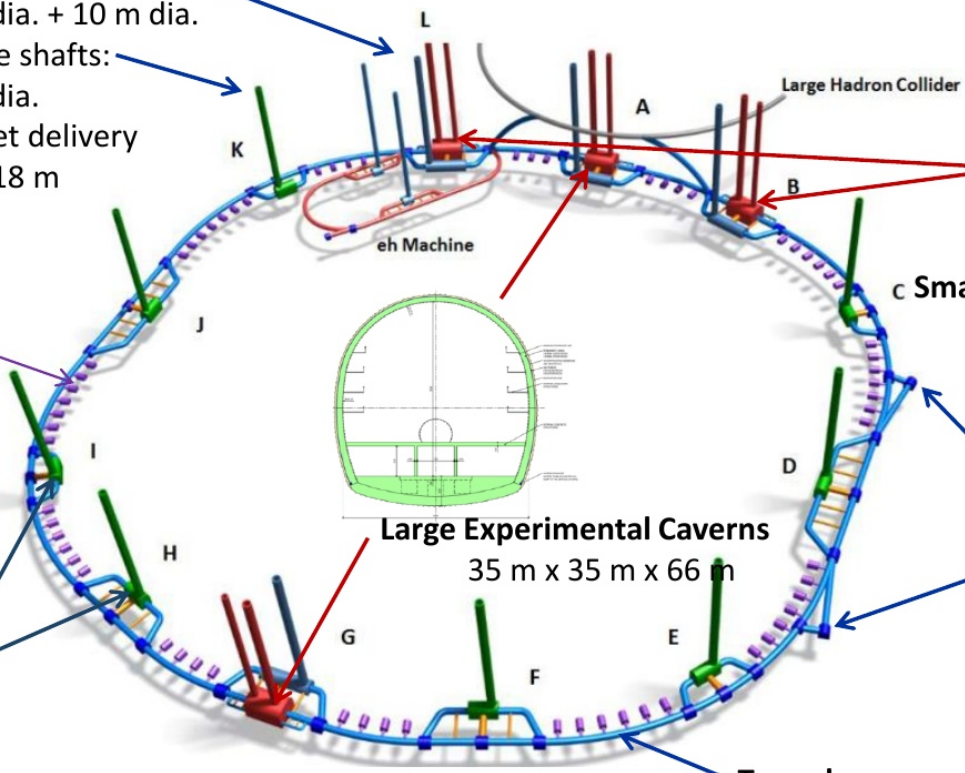


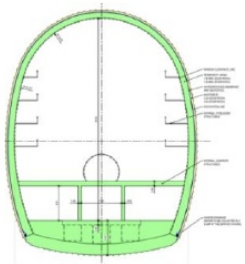
FCC-eh underground structures



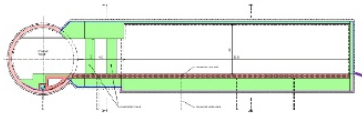
Shafts:
Experimental Shafts:
15 m dia. + 10 m dia.
Service shafts:
12 m dia.
Magnet delivery shaft:18 m

Underground civil infrastructure for FCC - 3D schematic (not to scale)



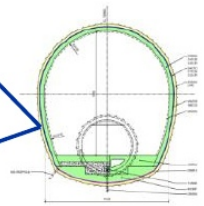


C Small Experimental Caverns
30 m x 35 m x 66m

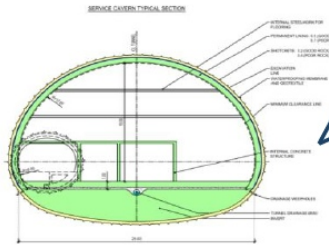


Alcoves
- 25 m x 6 m x 6 m
- Located at 1.5km spacing

Large Experimental Caverns
35 m x 35 m x 66 m



Beam Dump Caverns
- 10 m x 10 m x 50 m



Service Caverns
- 25 m x 15 m x 100 m

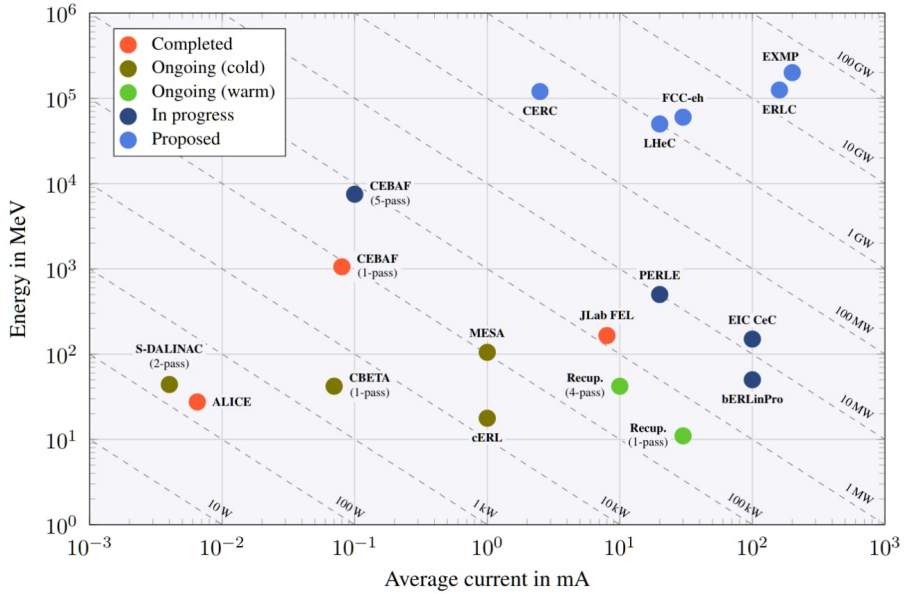
Tunnels:
- 97.75 km of 5.5 dia. machine tunnel
- Approx. 8 km 5.5 dia by-pass tunnels

A. Tudora
J. Osborne

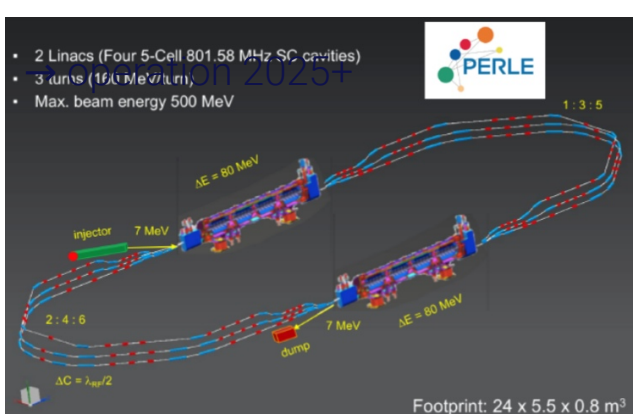
The FCC-eh energy recovery linac

Energy-recovery linacs (ERL)
→ Well-proven accelerator concept

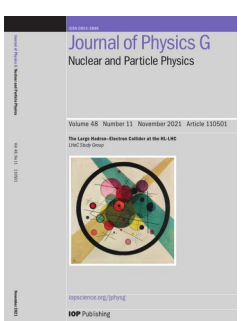
A new facility comprising all essential features ?
→ high-current & high-energy & multi-pass
→ optimised cavities & cryo-modules and a beam for collider experiments



PERLE at Orsay: ERL demonstrator facility for FCC-eh/LHeC needs 20mA, 802 MHz SRF, 3 turns



Accelerator R&D Roadmap [arXiv:2201.07895]

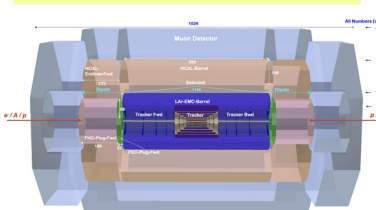


Update of LHeC-CDR JPhys.G 48 (2021) 110501

FCC Physics opportunities EPJ .C79 (2019) 474

DIS experiment at the HL-LHC EPJ C82 (2022) 40

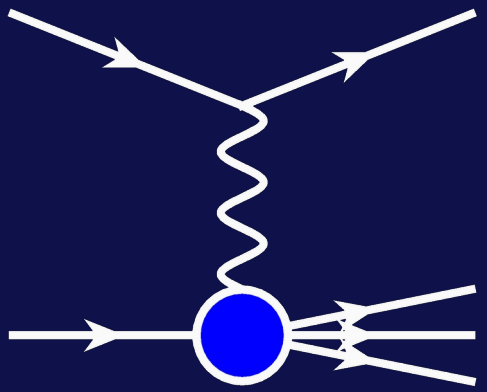
FCC-eh accelerator / IR and Common *hh* Detector
K. Andre,Thu 8:30



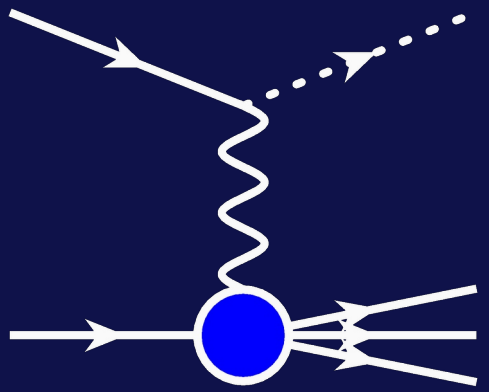
Symmetric detector to record ep and pp collisions at a single IP

Deep-inelastic scattering

Neutral current DIS
$ep \to e + X$

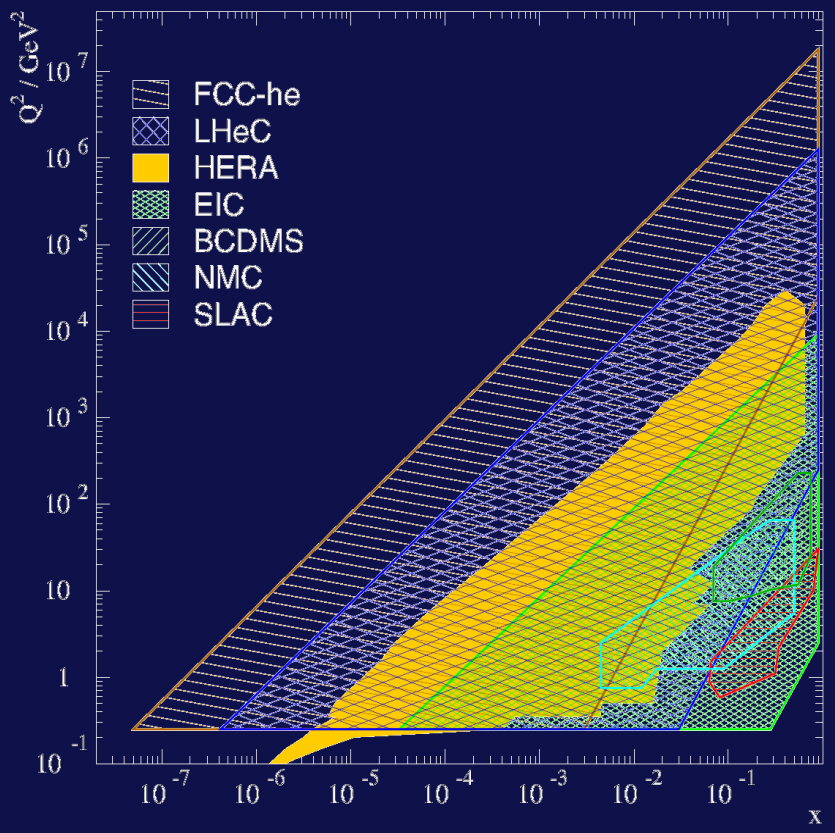


Charged current DIS
$ep \to \nu + X$



Deep-inelastic electron-proton scattering
mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

Deep-inelastic scattering



Cleanest High Resolution Microscope
→ Precision QCD and matter
→ QCD Discoveries

Empowering the FCC-hh Search Programme

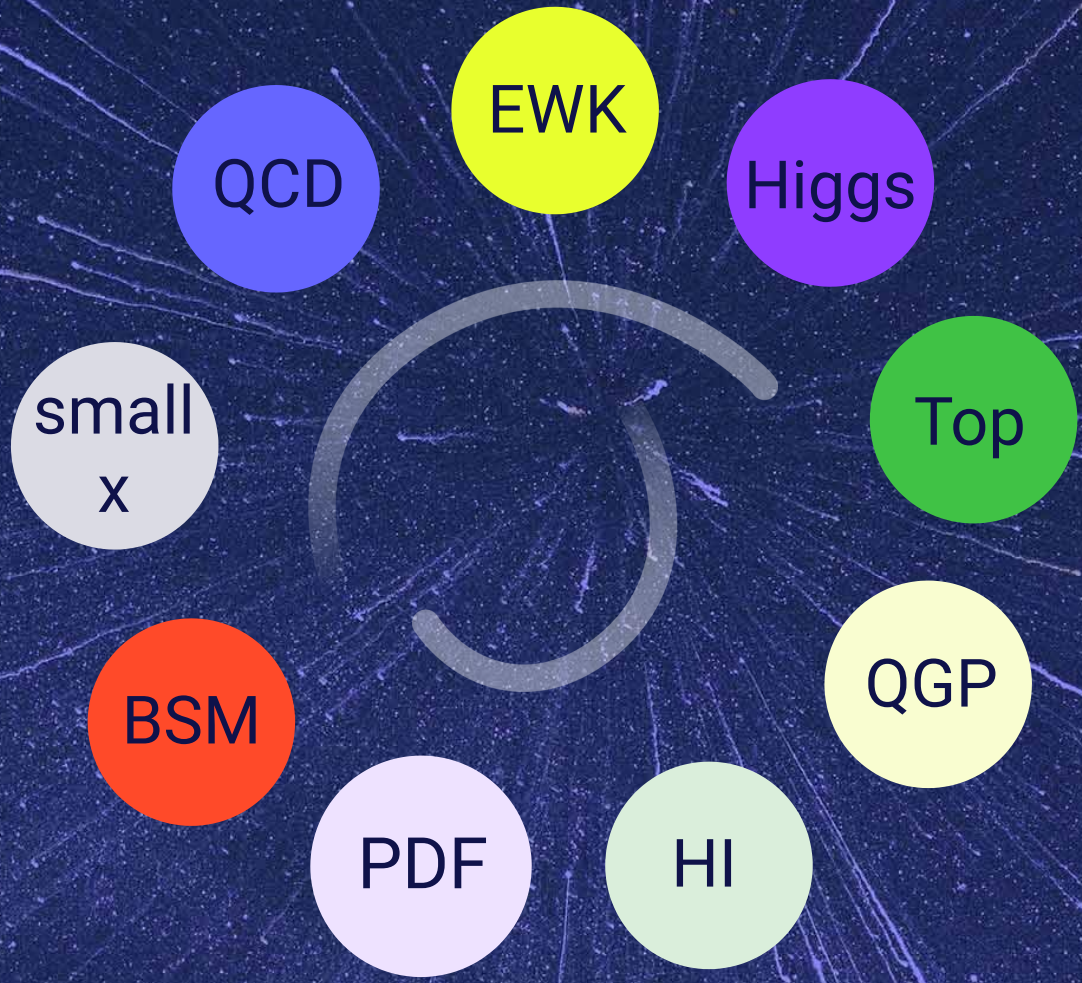
Transformation of FCC-hh into the desired Higgs and discovery machine

Unique Facility for Nuclear Physics

Complementary Higgs Programme

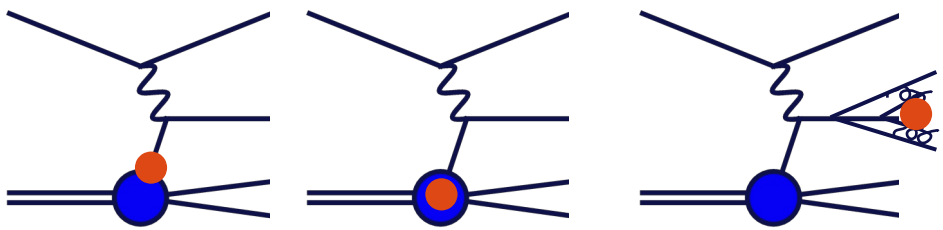
Top and EW Physics

High-luminosity Energy Frontier DIS



Precision QCD

Strong coupling constant α_s is one of the least known fundamental constants

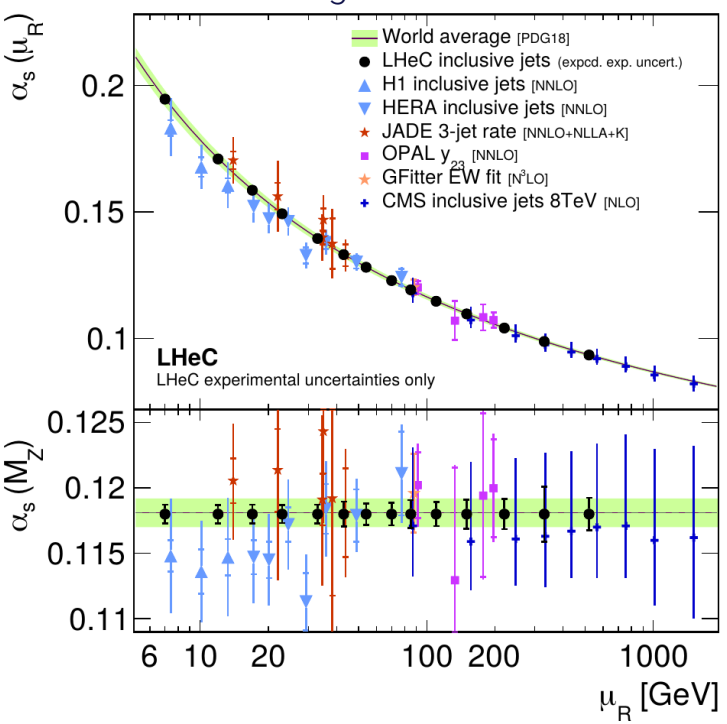


→ Jet production in Breit frame $O(\alpha_s)$
→ Proton internal dynamics (scaling)
→ Jet substructure and formation of hadrons

$\alpha_s(M_Z)$ from inclusive DIS

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00019\,_{(\text{exp+PDF})}$$

α_s from jet production (LHeC)
→ FCC-eh with higher precision and extended range

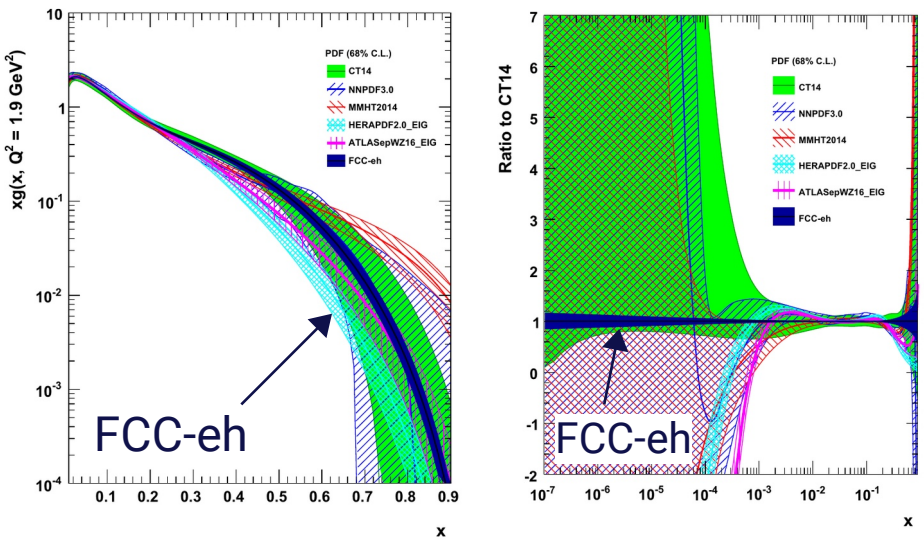


α_s seen as a benchmark parameter
→ A factor 10 more precise QCD measurements than nowadays possible

Proton structure measurements

Color-neutral particle probes the interior of the proton
→ Parton distribution functions (PDFs) of the proton are determined with unprecedented precision

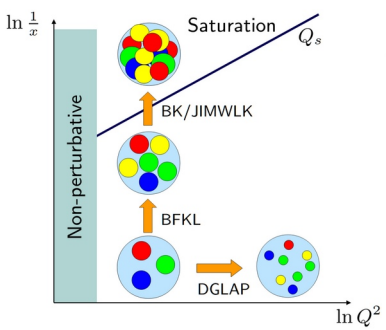
low-*x* – Gluon distribution – high-*x*

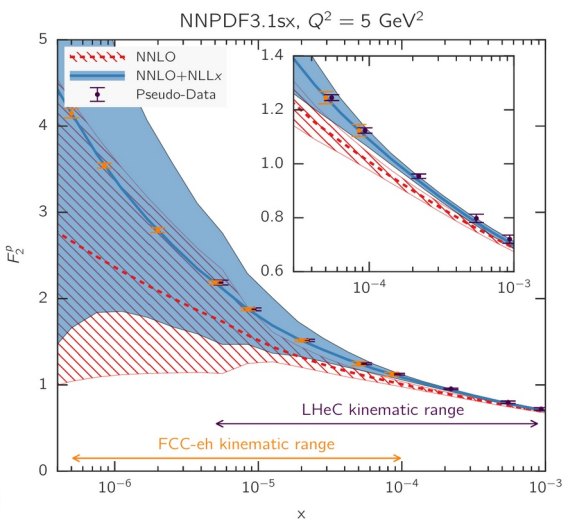


Full determination of all parton-flavors from heavy quark and jet cross section measurements

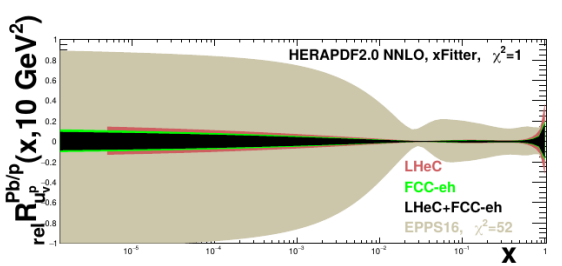
3D structure of the proton (TMDs, GPDs) from elastic diffractive and deeply-virtual Compton scattering

Low-x: a largely unexplored region with exciting QCD effects





eA scattering at FCC-eh will determine nuclear modification factor (*Pb*/*p*) many orders more precise and down to x~10^{-6}
→ gluon (anit-)shadowing, nuclear entanglement

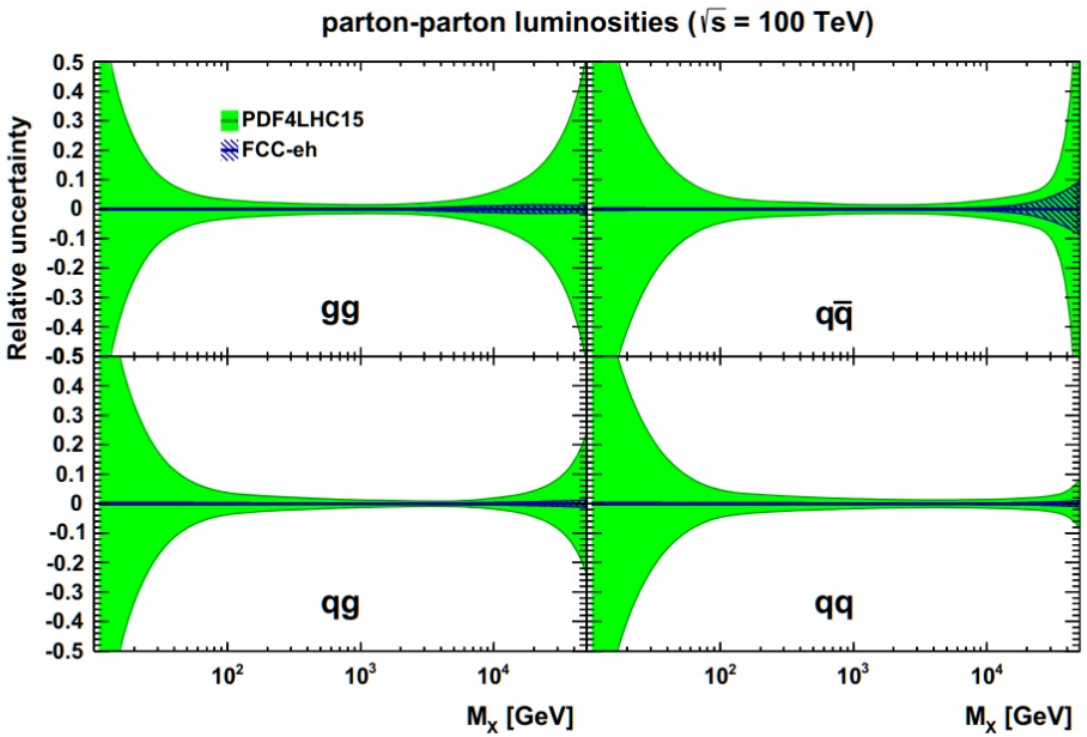


Improvement for parton luminosities at FCC-hh

PDFs are crucial ingredients to fully achieve the physics goals of FCC-hh (Higgs, high-mass,etc…)

The FCC-eh measurements will provide the most precise – and independent – constraints on PDFs

Note: at the level of precision of FCC-eh PDFs many new effects will be investigated
→ Small-x behaviour, high-x, mass-effects, non-perturbative effects, quantum-enganglement, shadowing,...



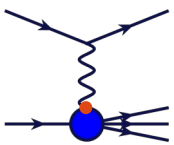
→ QCD evolution (DGLAP) from 1GeV up to ~50000 GeV

Parton structure, forward physics and *eA* at FCC-eh
K. Piotrzkowski, Wed 14:15

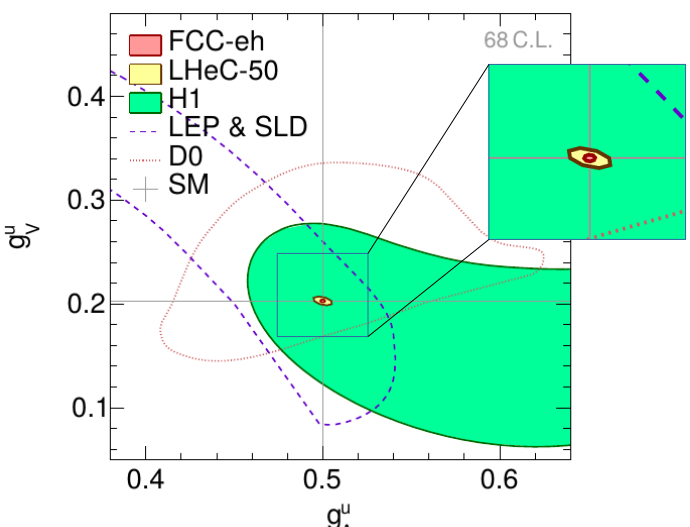
Electroweak physics

Electroweak physics of 1st gen. quarks

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\,\sin^2\theta_{\mathrm{W}}\right)$$
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\,I^3_{\mathrm{L},f}$$



g_V and g_A largely unaccessible in *ee*



→ PDFs are not a limiting factor for EW physics

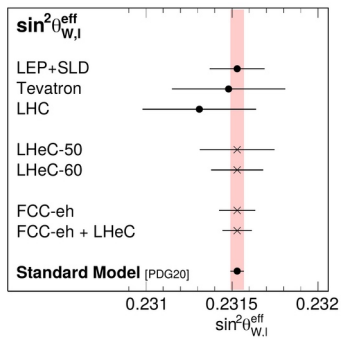
The effective weak mixing angle

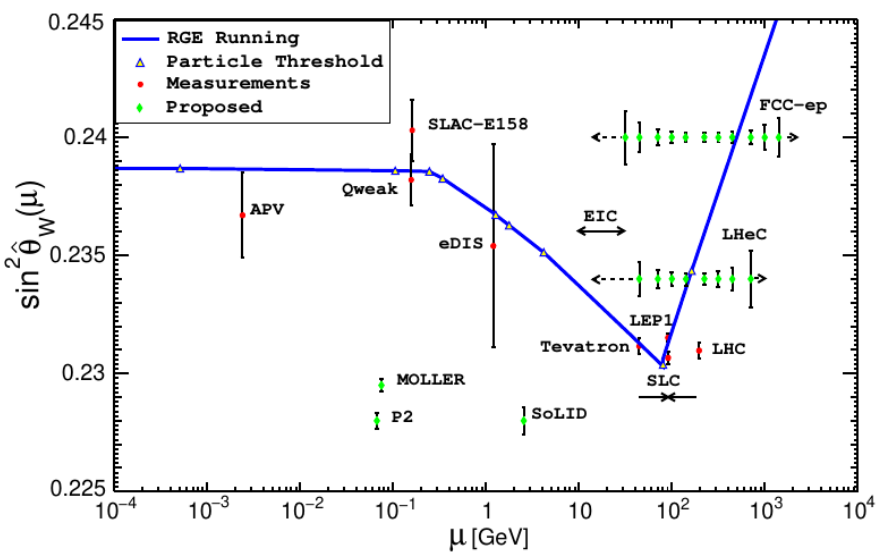
$\Delta\sin^2\theta_W$ (FCC-eh) = ±0.00011

= $\pm 0.00010_{(exp)}$ $\pm 0.00004_{(PDF)}$

corresponds to ~Δ*m*W = ± 4.5 MeV

Running: per mille uncertainties in
20 < Q < 2000 GeV in spacelike regime



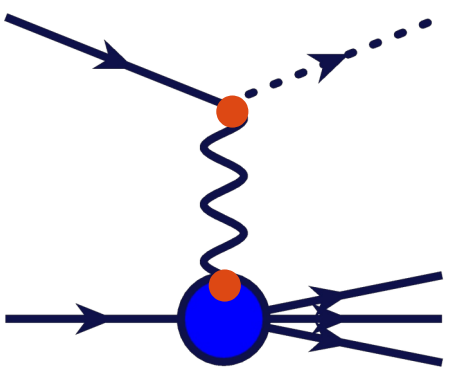


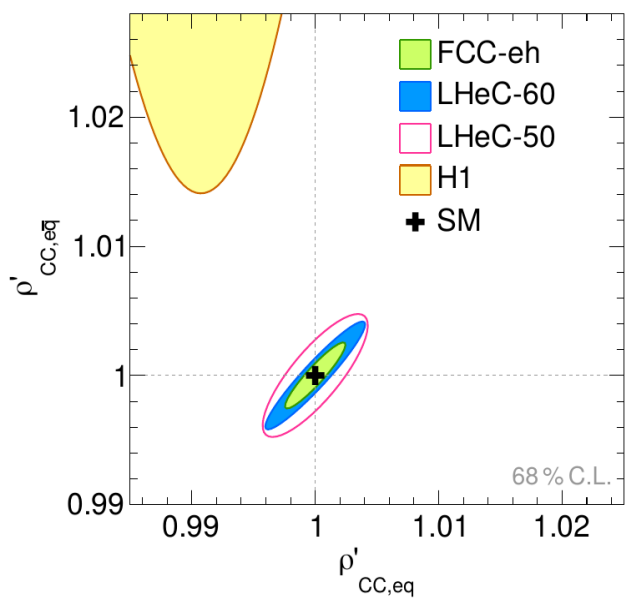
Unique measurement of 'running' at high scales

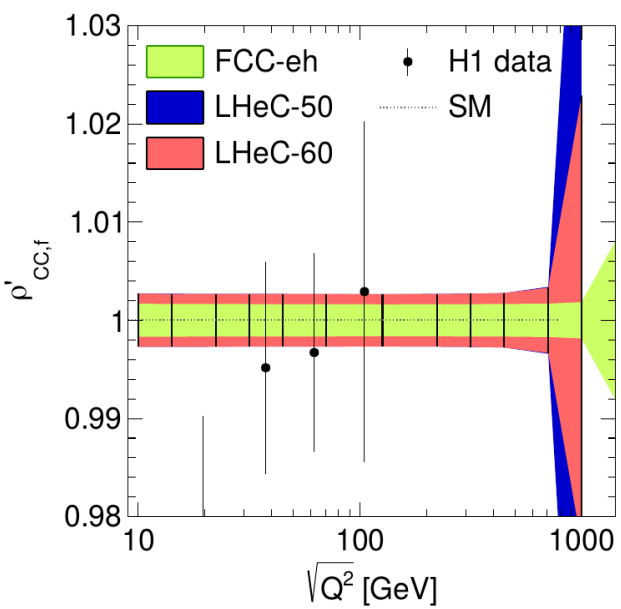
Weak couplings of the W-boson

EW theory provides precise predictions for charged currents, but CC processes are poorly measured
→ neutrino escapes undetected

In DIS, the kinematics of charged currents are completely measured from final state and incoming electron



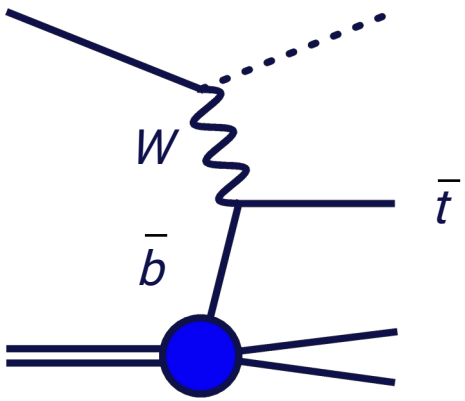




→ Weak couplings of the W-boson are precisely measured – even their scale dependence

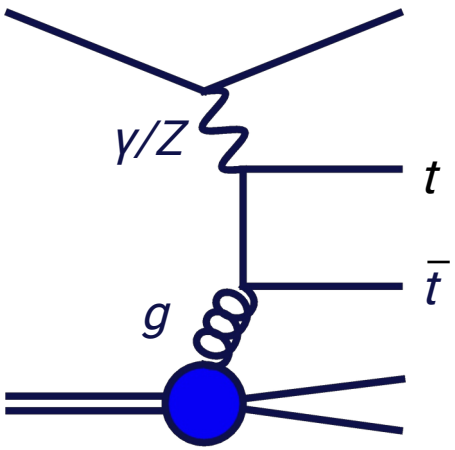
Top quark production in *ep*

CC DIS single-top quark production



LHeC σ~ 1.9pb
FCC-eh σ~15.3pb

NC (γp) top-quark pair production



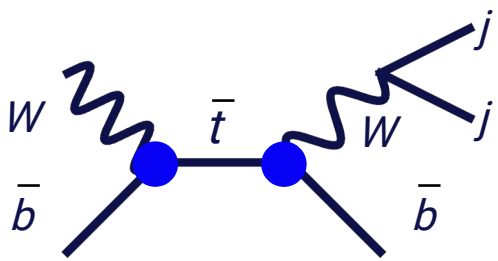
LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

Other channels are: top-quark pair in DIS (~0.6pb), single-top in DIS and *γp*

$|V_{tb}|$ in CC single-top production

BSM and Top-quark Physics with FCC-eh
O. Fischer, Thu 15:25

Direct measurement of $|V_{tb}|$

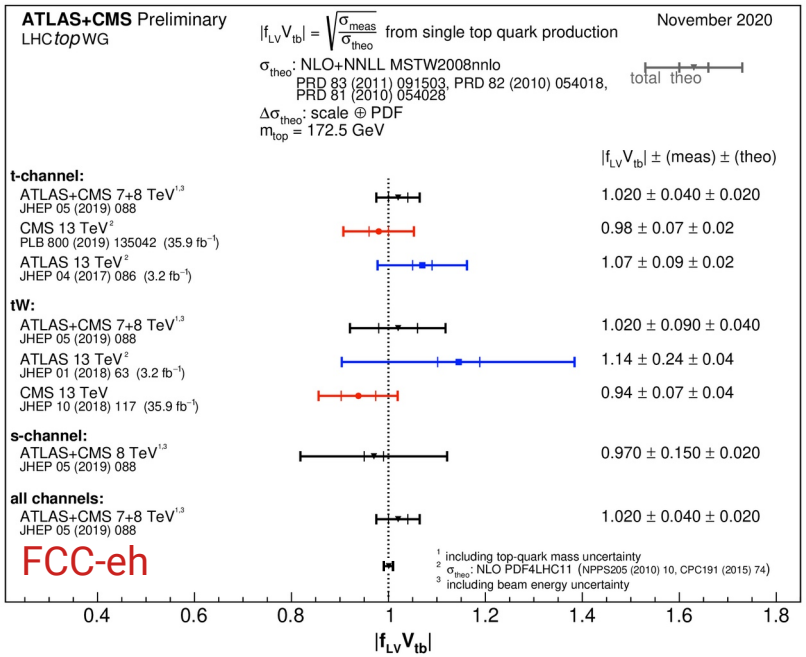


$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cut-based pseudo-analysis in hadronic channel incl. backgrounds

→ Estimated precision on V_{tb} below 1% precision

→ Limits on anomalous *Wtb* couplings: < 0.01



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{ts,td}|<0.04$

Many further subjects in top-quark sector: top-quark polarization, top-PDFs, CP-properties of *ttH* couplings, top-charge, anomalous tt-X couplings, ...

Top quark branching fractions

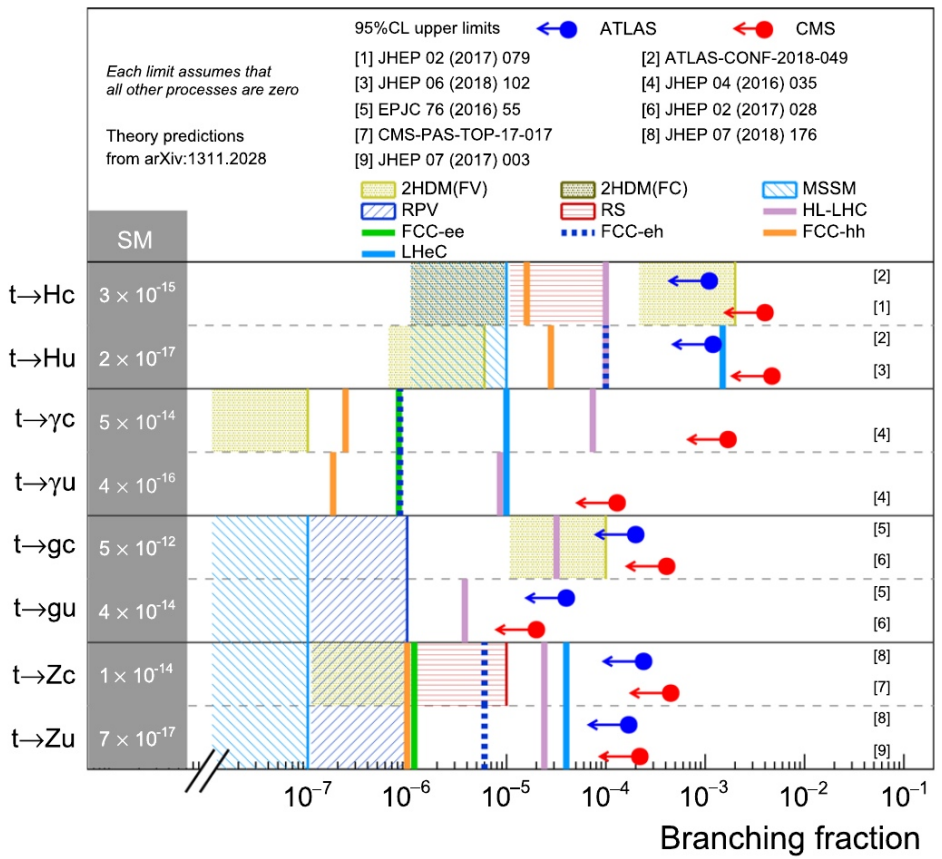
Top quark branching fractions
- Searches for FCNC
- 95% C.L.

Compare future experiments
- FCC-ee
- FCC-hh
- FCC-eh

- LHeC
- HL-LHC (3000 fb^{-1})
- ILC/CLIC

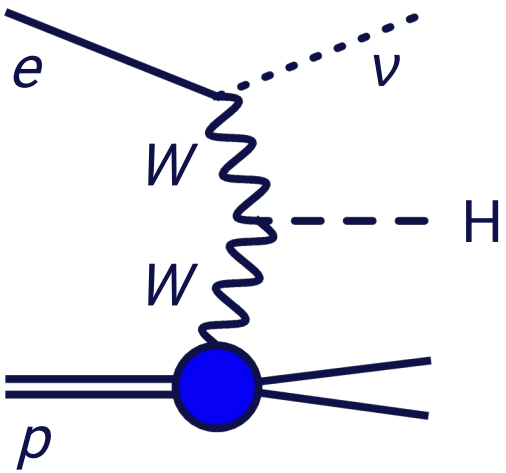
+ various theory predictions

pp, *ep* and *ee*
- LHeC complements HL-LHC in '30s
- FCC ee/hh/eh compete



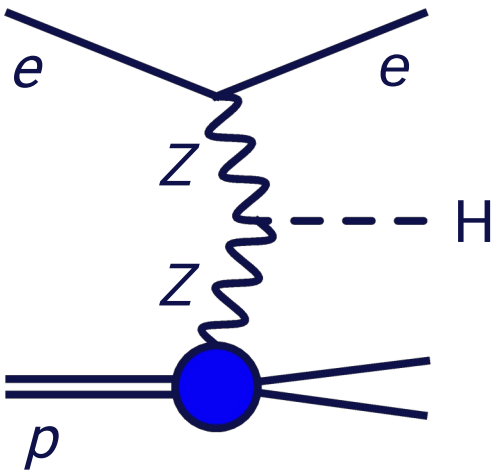
Higgs physics

Charged current



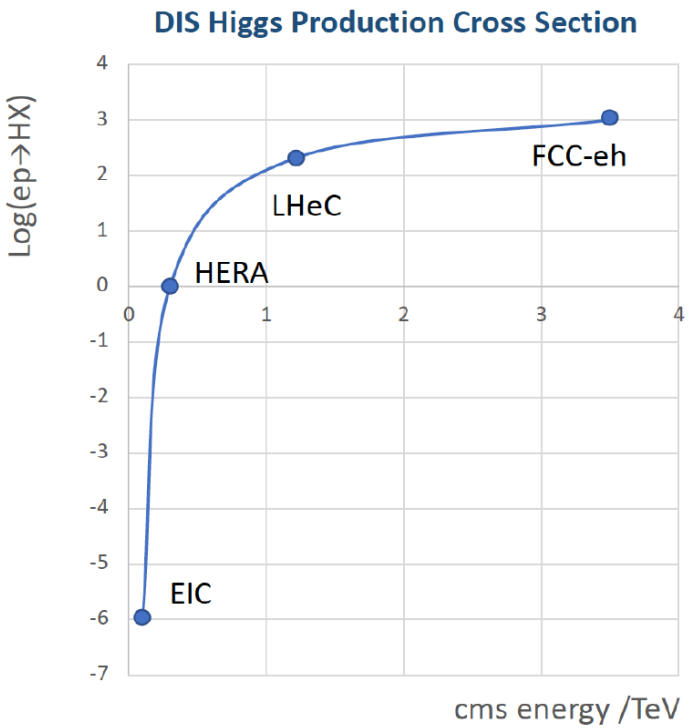
Higgs production through *WW*-fusion

Neutral current



Higgs production through *ZZ*-fusion

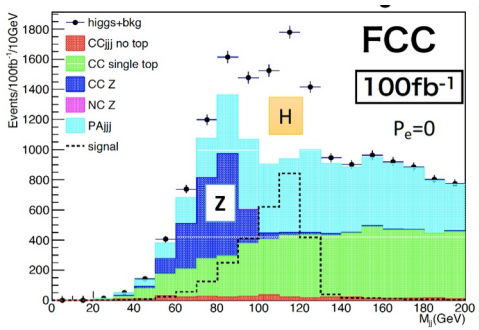
Higgs physics



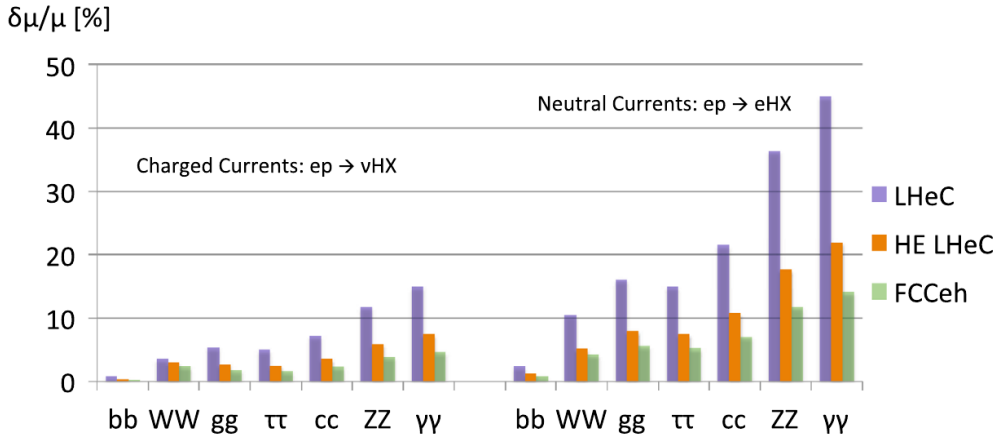
Higgs-production cross section ~1000fb
Sensitivity to the decay channels
bb, *WW*, *gg*, *ττ*, *cc*, *ZZ*, *(γγ)*

$ep \rightarrow H + \nu + X \rightarrow bb + \nu + X$

Full analyses of simulated data with full or fast detector
→ simulations show great signal over background ratio



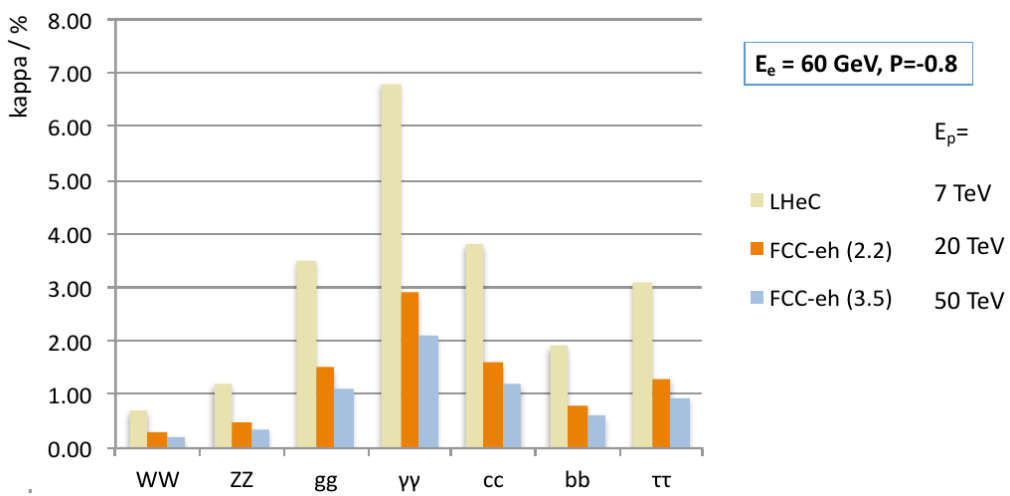
Signal strength in dominant decay channels (CC and NC)



HWW and *HZZ* signal strengths measured at once in DIS via selection of the final state (e or ν)

Higgs physics – interpretation in κ framework

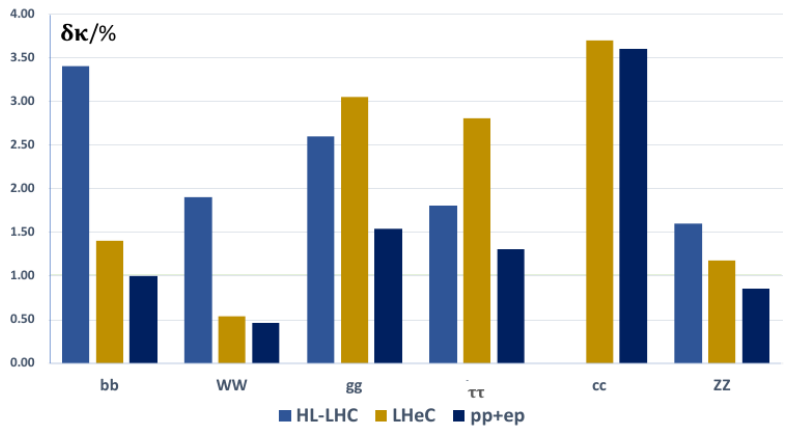
Higgs couplings in κ framework → Possible future *ep*-facilities



High sensitivity in all six decay channels → Significant improvement with increasing √s

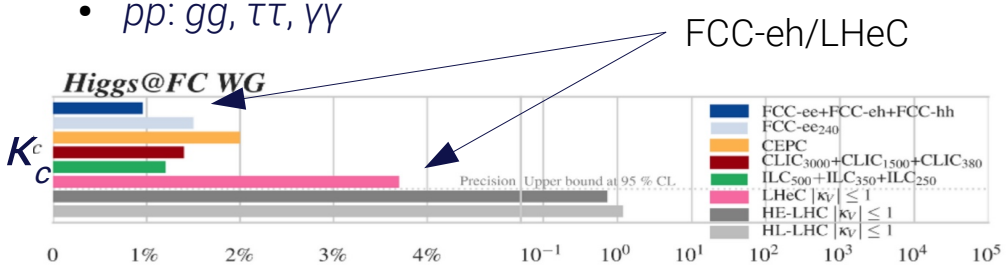
Interplay between *pp* and *ep*

(shown here: LHeC & HL-LHC – similarly for FCC-hh/eh)



Complementarity between *pp* and *ep*

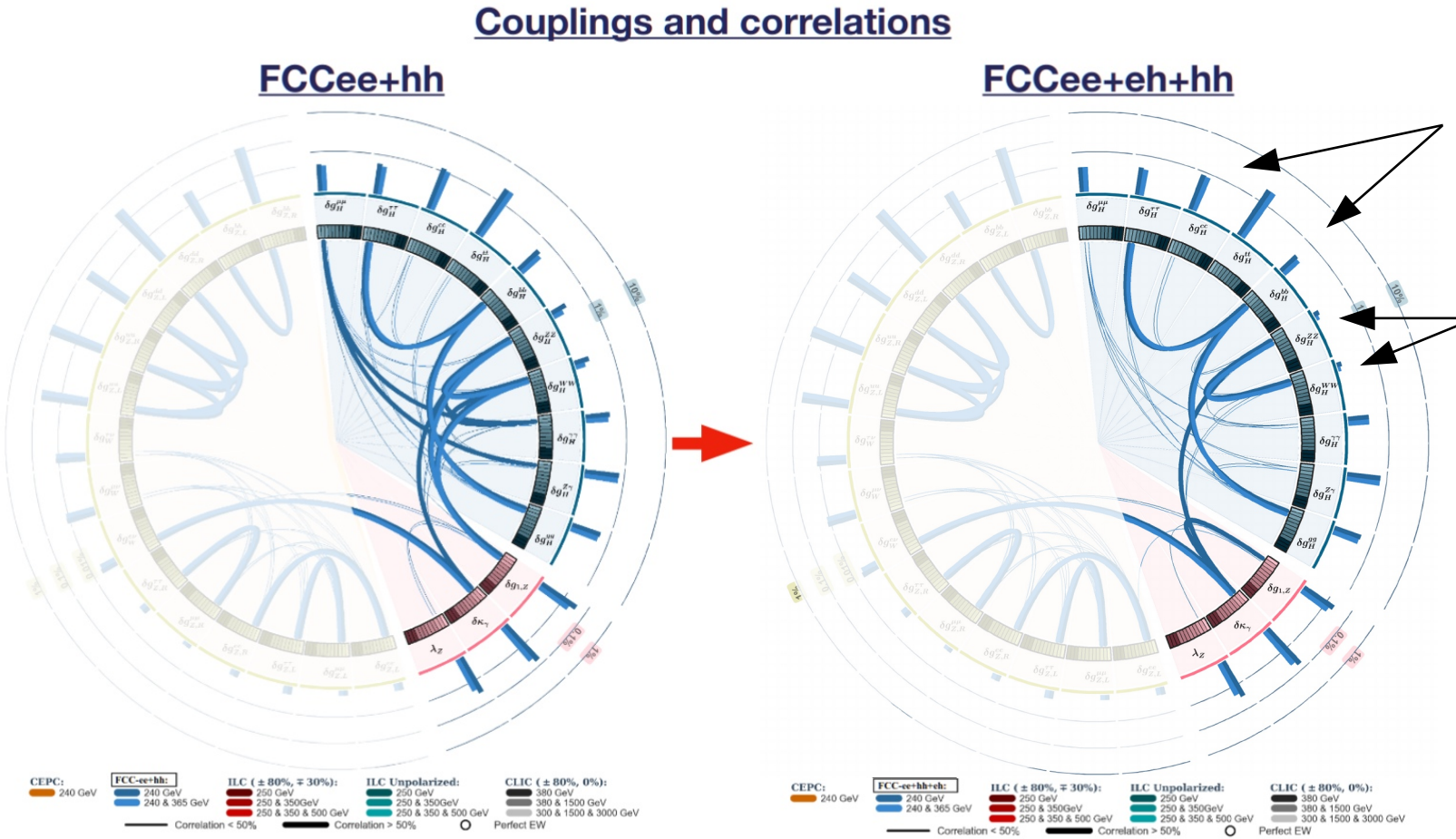
- *ep*: *bb*, *WW*, *ZZ*, *cc*
- *pp*: *gg*, *ττ*, *γγ*



JHEP01(2020)139

SMEFT fit results after FCC era

Higgs and Electroweak ep Physics at FCC-eh
Ch. Schwanenberger, Tue 8:30



Significant reductions for *Hcc* and *Hbb*

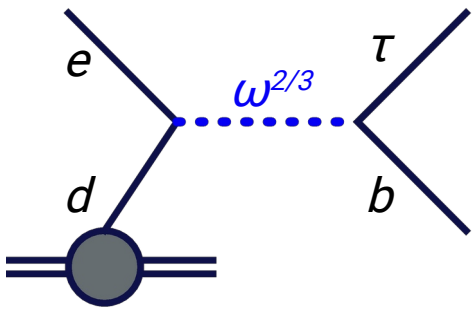
eh contributes to the *HWW* and *HZZ* couplings and resolves their correlation.

PRELIMINARY

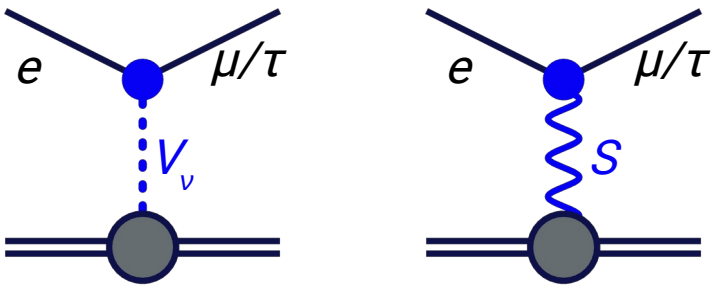
BSM and searches

BSM and Top-quark Physics with FCC-eh
O. Fischer, Thu 15:25

Leptoquarks

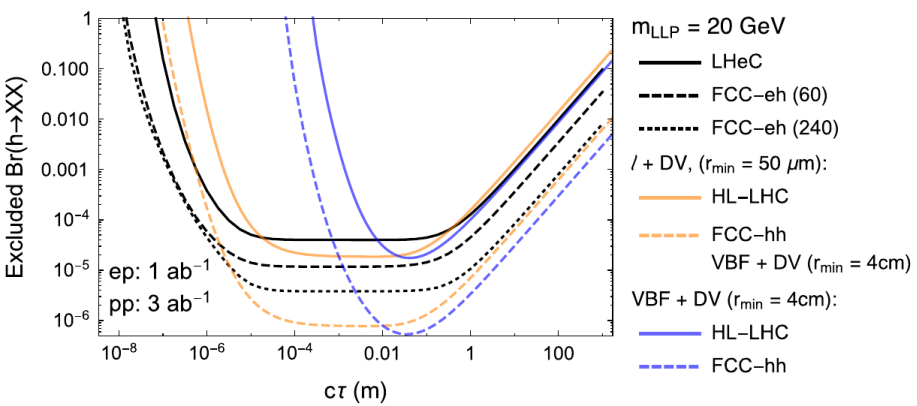


Lepton flavor violating processes



- SUSY: R-parity violating & R-parity conserving (prompt Higgsinos)
- BSM Higgs: charged higgs….
- anomalous couplings (VVV,VVVV)
- Contact-interactions,
- Compositness,
- high-precision EW,
- sterile neutrinos,
- … , … , … , …

Long-lived particles



Summary

The FCC-eh is operated concurrently with FCC-hh and has rich and versatile physics goals
→ impossible to adequately cover all physics subjects in a single talk

Primarily, *ep* experiments are QCD precision experiments
→ unique physics case from lowest scales up to the TeV regime
→ Precision QCD, structure of hadrons, hot & dense QCD phenomena

"Testing QCD is in fact more difficult than testing the electroweak sector".
Guido Altarelli

High-luminosity beam from the ERL adds exciting physics subjects
→ Higgs-programme with complementary channels than *pp*
→ Electroweak physics with complementarity to *ee* due to its scale dependence
→ Top-quark physics with clean single-top processes
→ Exciting and unique BSM programme

The *ep* measurements support the *pp* programme
→ through precision PDFs, fragmentation functions, α_s, parton shower constraints
→ indispensable ingredients for precision *pp* predictions

Higgs and Electroweak ep Physics at FCC-eh
Ch. Schwanenberger
Tue 8:30

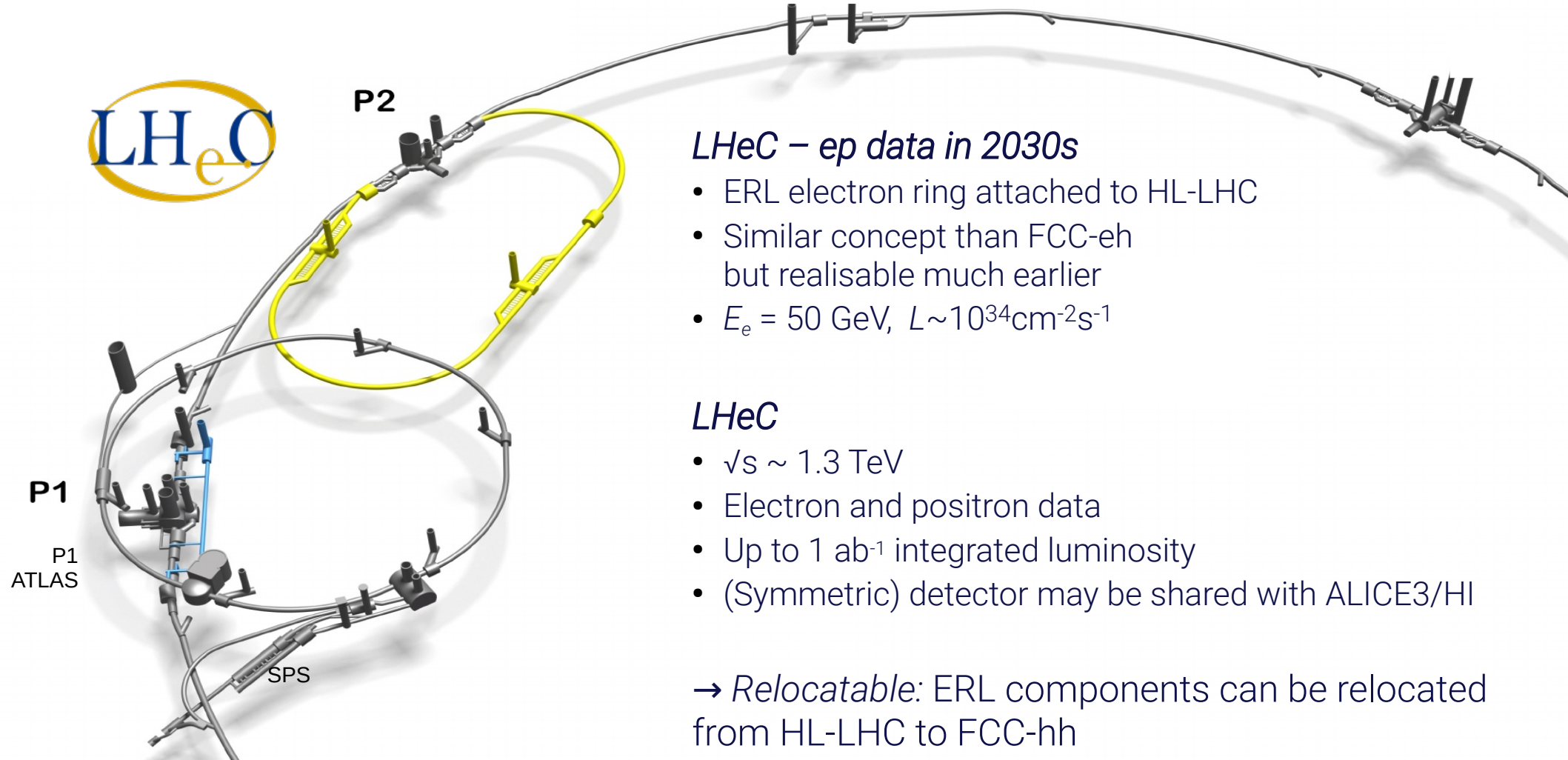
Parton structure, forward physics and *eA* at FCC-eh
K. Piotrzkowski
Wed 14:15

FCC-eh accelerator / IR and Common *hh* Detector
K. Andre
Thu 8:30

BSM and Top-quark Physics with FCC-eh
O. Fischer
Thu 15:25

Backup

Energy-frontier *ep* physics in the '30 – the LHeC



LHeC – ep data in 2030s

- ERL electron ring attached to HL-LHC
- Similar concept than FCC-eh but realisable much earlier
- E_e = 50 GeV, $L \sim 10^{34} cm^{-2} s^{-1}$

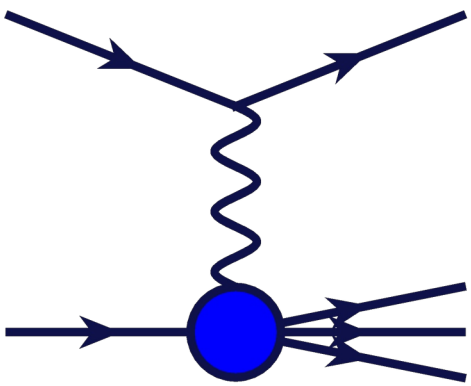
LHeC

- $\sqrt{s}$ ~ 1.3 TeV
- Electron and positron data
- Up to 1 ab^{-1} integrated luminosity
- (Symmetric) detector may be shared with ALICE3/HI

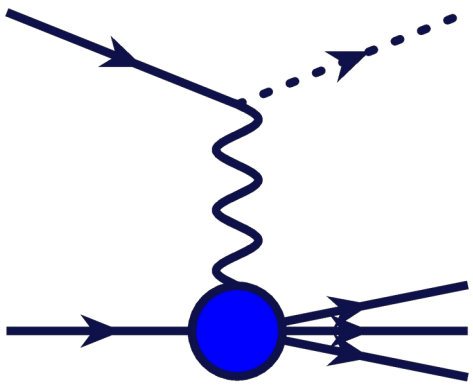
→ *Relocatable*: ERL components can be relocated from HL-LHC to FCC-hh

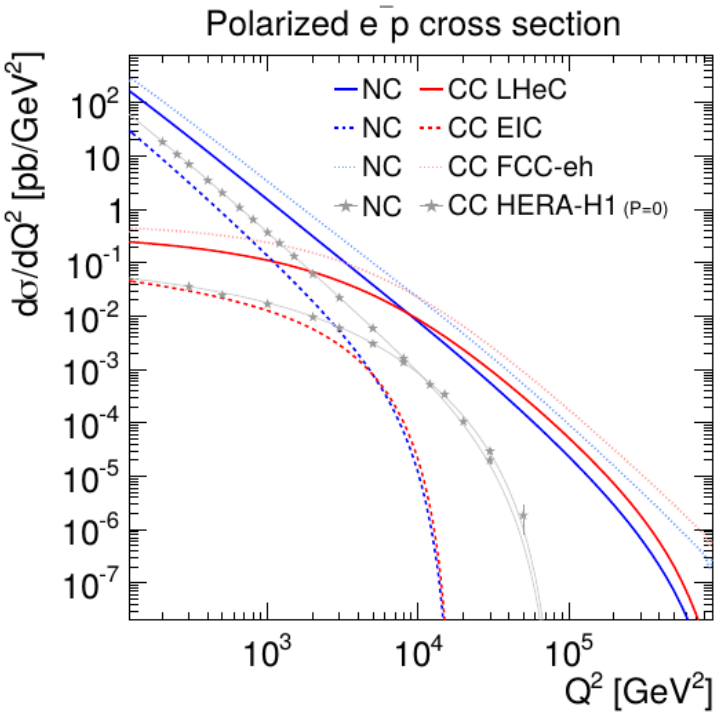
Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \rightarrow e' + X$



Charged current scattering
$ep \rightarrow \nu_e + X$



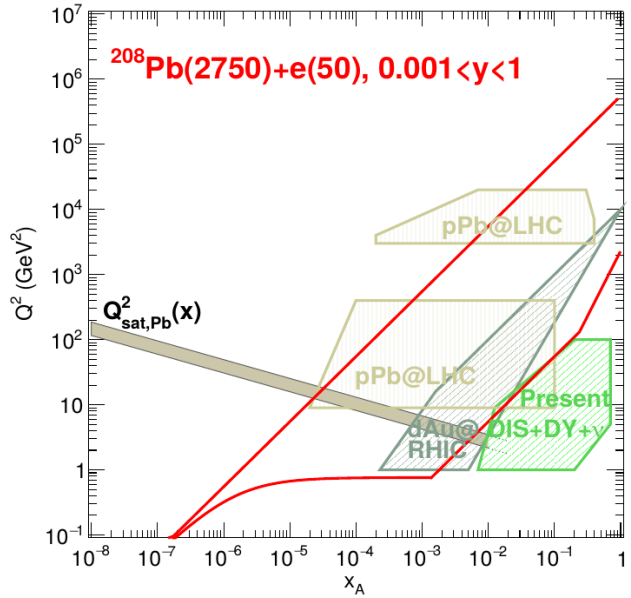


Deep-inelastic electron-proton scattering
mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

→ Ideal QCD and Electroweak laboratory and complementary to e^+e^- or pp

Heavy ion physics – *e*A and *AA* physics

eA unexplored kinematic region



Nuclear structure

- Complementary with HL-LHC
  (if factorization holds to such low-x?)
- LHeC much cleaner measurements, full flavor sensitivity, TMDs, GPDs, ...

pp and AA collisions

Recently updated accelerator-optics define the IP's of eA, AA and pp running-mode at the same vertex point

Full physics programme of *pp* and AA collision thinkable
→ 'only' subject to beam-time discussion

Cross-calibration of measurements in ep, pp, AA (syst. uncertianties, normalised measurements)

Benefit from excellently calibrated DIS-detector

FCC Physics Potential