Electron-Hadron Colliders
- New high precision Electron Microscopes for hadronic Matter -

Uta Klein

Speaker's affiliations :

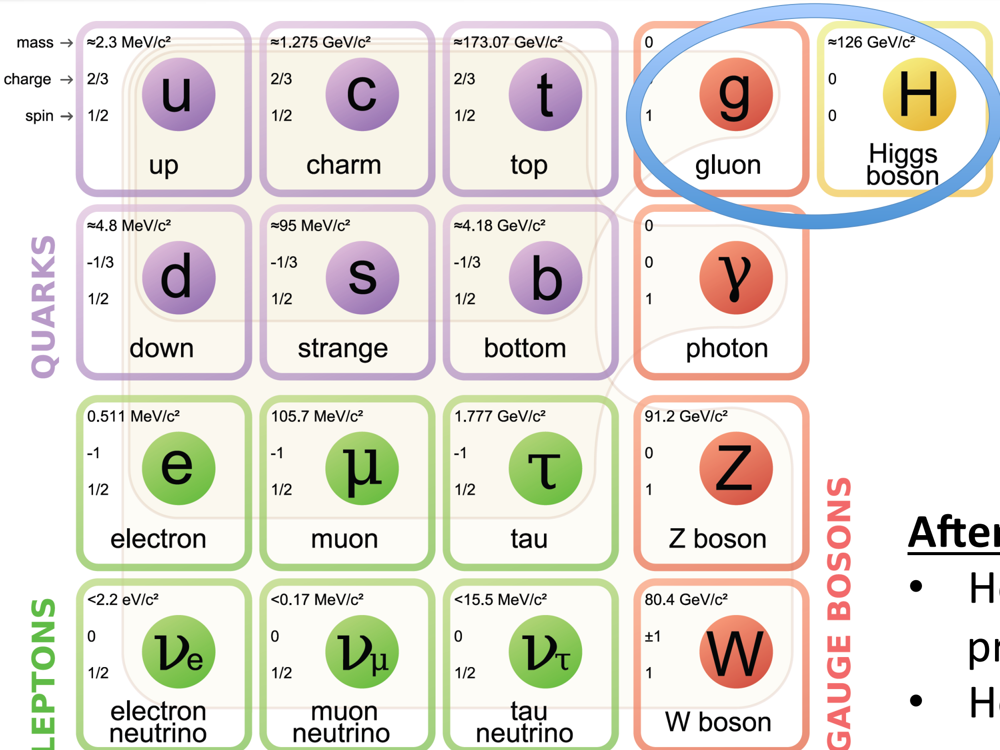
UNIVERSITY OF LIVERPOOL

ATLAS

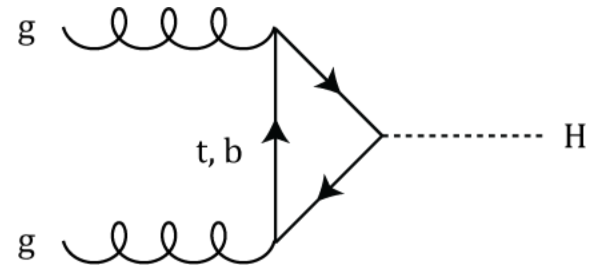
LHeC

FCC hh ee he

Standard Model Particles & QCD



Higgs discovery at LHC via gluon-gluon fusion



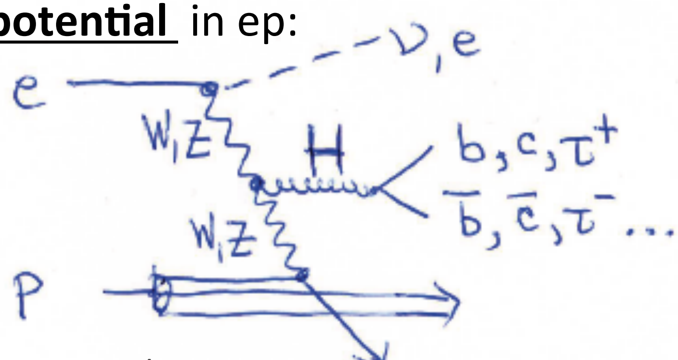
After the Higgs discovery:

- How can we reach a best understanding Higgs properties?
- How can we exploit best our highest energy machines for finding new physics/new particles? Synergies?
- **What role can ep/eA colliders play here?**

✓ Precision quark-gluon dynamics for sensitive searches (non-resonant NP contributions!).

✓ Compelling synergy for Higgs physics and searches.

Higgs potential in ep:



QCD "Discovery" Potential

Crucial questions to be addressed:

AdS/CFT & super-gravity

QCD predictions: Instantons & Odderons

Non pQCD : confinement (lattice)

pQCD : N^kLO, precision PDFs & α_S

Resummation (BFKL) and saturation (CGC) – new dynamical effects?

Non-conventional PDFs
& 'scan' proton structure in 3d

Spin of proton

Nuclear structure and matter modifications

"QCD may break .." (C. Quigg@DIS13)

Breaking of Factorisation

Free Quarks

Unconfined Color

New kind of coloured matter

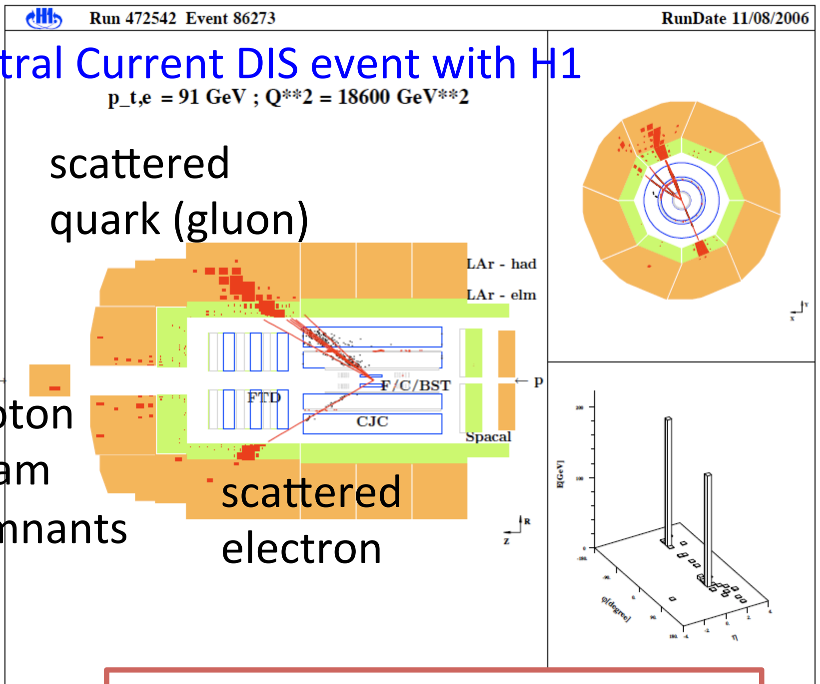
Quark substructure

New symmetry embedding QCD

Deep Inelastic Scattering

HERA : The 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

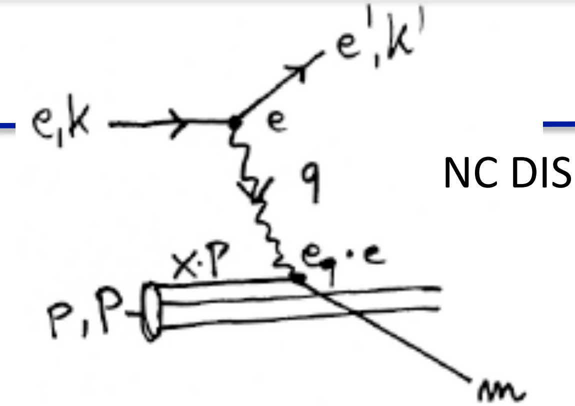


scattered quark (gluon)

proton beam remnants

scattered electron

- → **Luminosity limited.**
- → **No eA collider!**
- → **No polarised ep collider!**



NC DIS

$$q = (k - k'), q^2 = -Q^2$$

$$s = (k + P)^2$$

$$(xP + q)^2 = m^2, P^2 = M_p^2$$

$$if\,(Q^2 >> x^2 M_p^2, m^2):$$

$$q^2 + 2xPq = 0$$

$$x = \frac{Q^2}{2Pq}$$

$$Q^2 = sxy$$

relation to pp

$x_{1,2}$= (M/√s) exp(±y)

$Q^2 = M^2$

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

SLAC-PUB-642
August 1969

@SLAC: birth of DIS, 45 years ago.

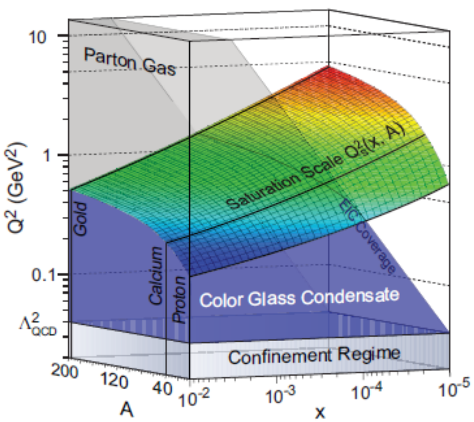
The Structure of the Proton

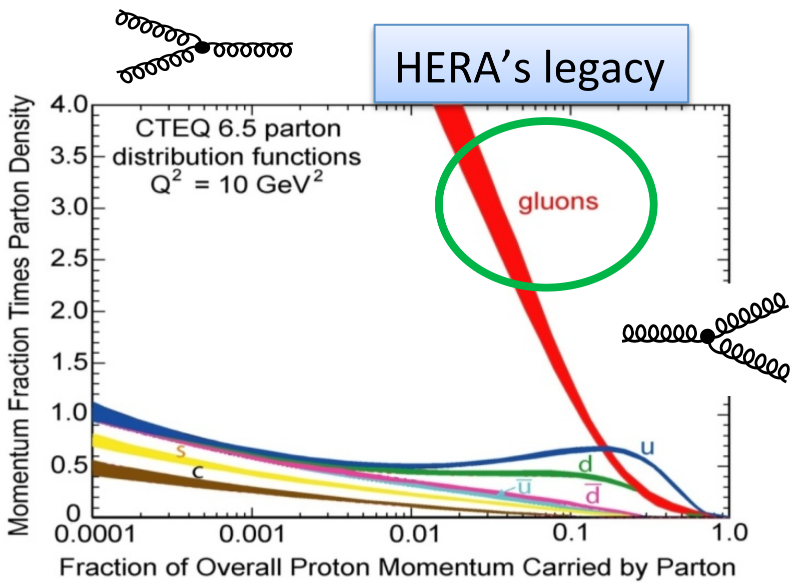
Naïve Quark Model: proton = uud (valence quarks)
QCD: proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ + …

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

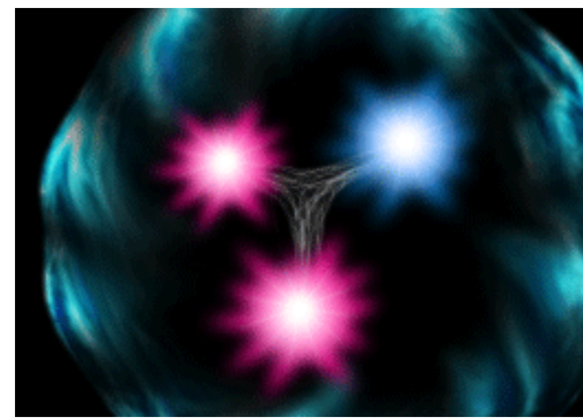
& gluons are abundant ("gluon ocean" discovered by HERA)

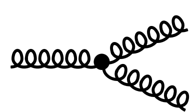
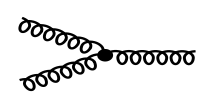
gluon dynamics



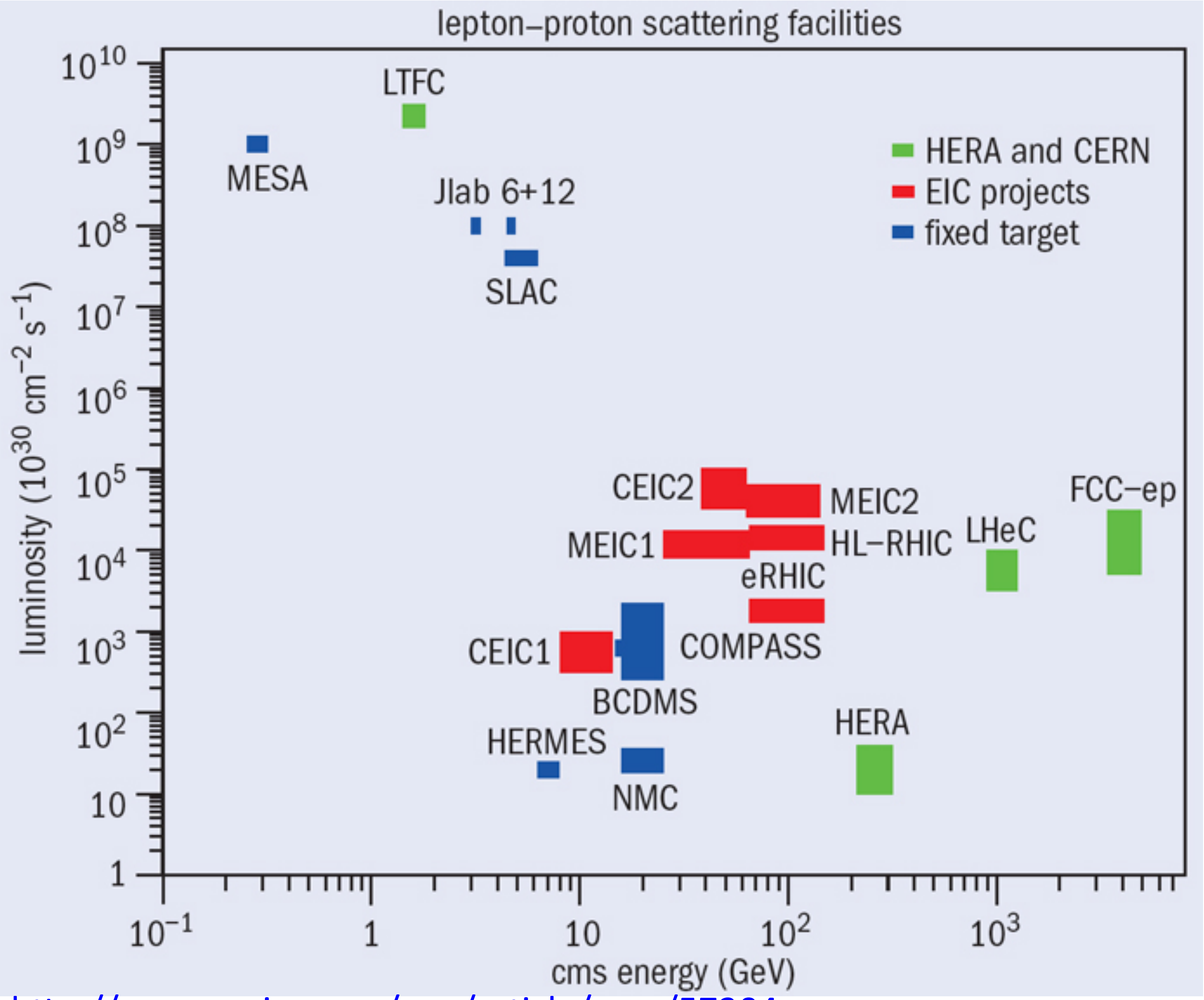


Non-trivial sea structure



- ❑ The proton is **far more** than just its up + up + down (valence) quark structure
- ❑ Gluon ≠ photon: Radiates  and recombines: 

The Landscape : Luminosity vs √s



http://cerncourier.com/cws/article/cern/57304

China
CEIC1 = Chinese version of Electron-Ion Collider
("A dilution-free mini-COMPASS")

U.S.
MEIC1 = **EIC**@Jlab

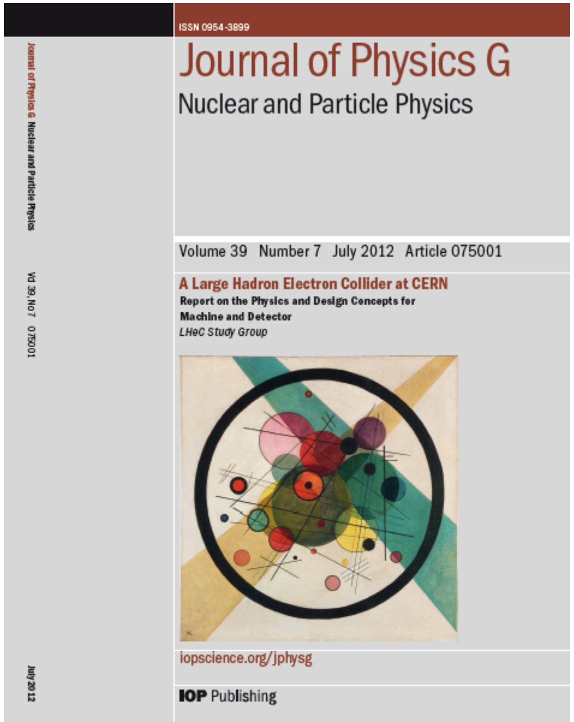
eRHIC = **EIC**@BNL

Europe
LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he
} future extensions

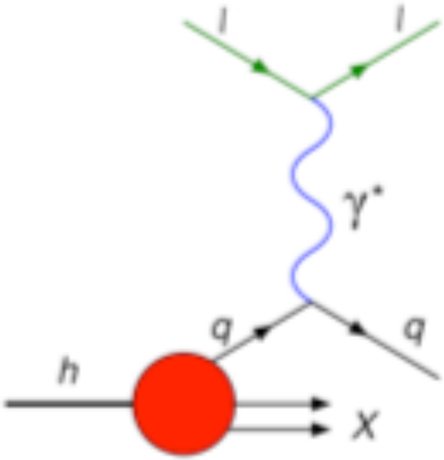
The most advanced Proposals

At the high energy frontier
$\sqrt{s} > 1$ TeV

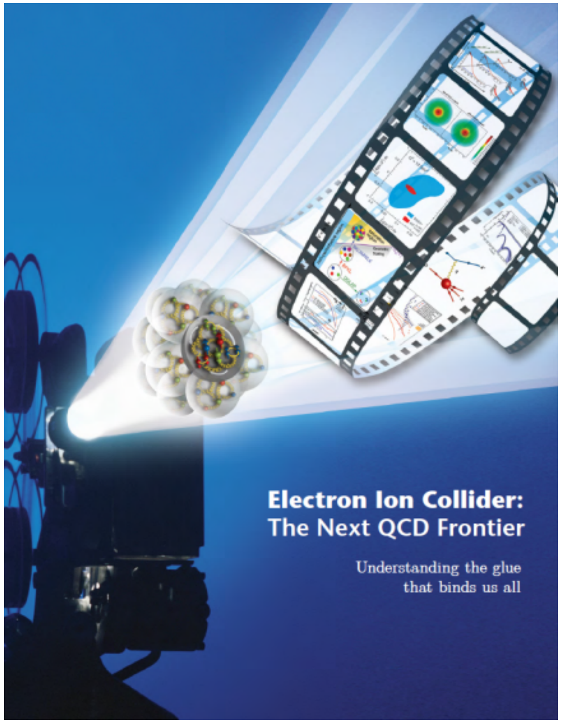


LHeC Conceptual Design Report
J. Phys. G 39, 075001 (2012)

http://lhec.web.cern.ch



Using polarised e&h-beams
$\sqrt{s} \sim 0.01$-0.1 TeV



EIC White Paper
arXiv:1212.17010 (v2)

http://web.mit.edu/eicc/index.html

http://www.bnl.gov/cad/eRhic/
eRHIC Design Study: An EIC at BNL
http://arxiv.org/abs/1409.1633

Additional Sources & Thanks to

11th **ICFA Seminar** in Beijing, 27.-30.10.14

- http://indico.ihep.ac.cn/conferenceOtherViews.py?view=standard&confId=3867

POETIC V Workshop in New Haven, 22.-26.9.14

- http://rhig.physics.yale.edu/poetic/Agenda.htm

LHeC Conveners Meeting in CERN, 4.11.2014

- http://indico.cern.ch/event/350727/

2014 Long-range plan Joint **Town Meetings on QCD** at Temple University, 13.-15.9.14

- https://indico.bnl.gov/conferenceDisplay.py?confId=857

Informal mini-review of **CEPC-SppC Pre-CD**R in Beijing, 13.-17.10.14

- http://indico.ihep.ac.cn/conferenceTimeTable.py?confId=4606#all

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

EIC vs LHeC with L ~ $10^{33\text{-}34}$ $cm^{-2}s^{-1}$

EIC: $E_{c.m.s.}$ ~ 20-100 GeV

- *Polarised electrons with E_e>3 GeV*
- ***Polarised proton*** *(70%) beams and unpolarised heavy ion beams (A≤200)*
- *High luminosity for* ***spin physics.***

World's first polarised e-p collider and lower energy e-A collider.

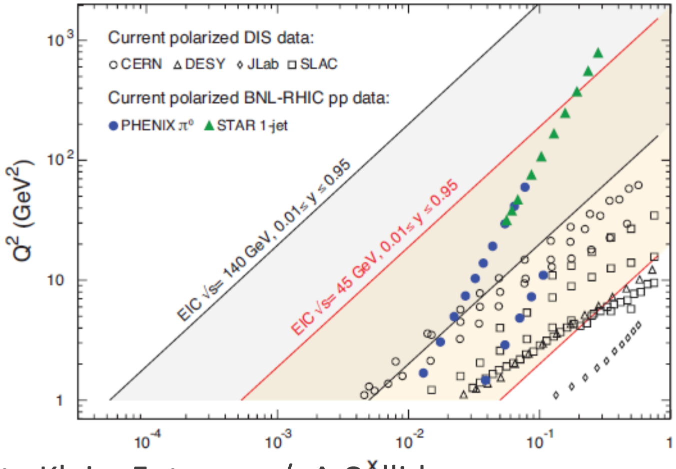
x_{min} ~ 1 x 10^{-4}

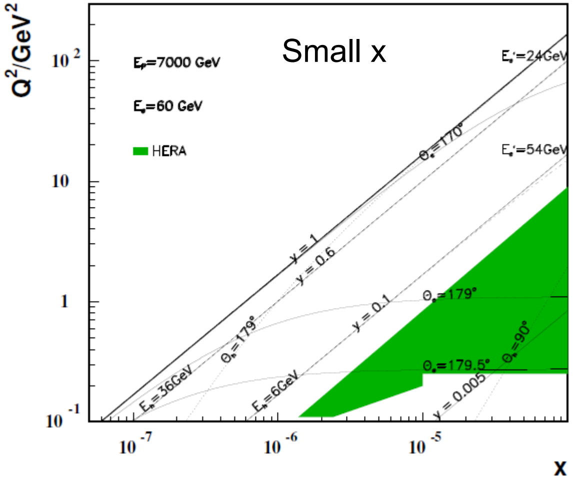
LHeC: $E_{c.m.s.}$ ~ 1.3 TeV

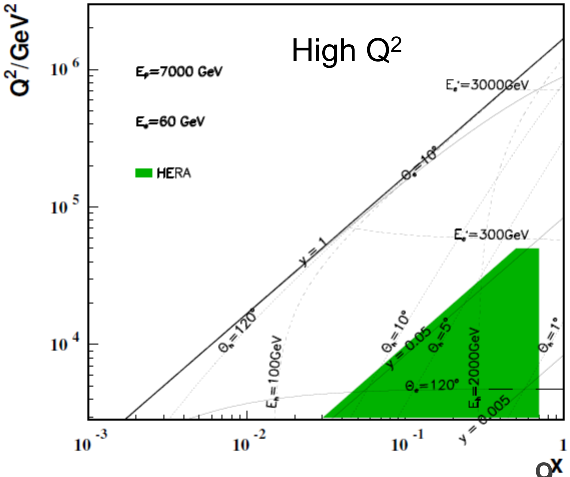
- *Add ~60 GeV* ***polarised*** *electrons to probe unpolarised LHC proton and ions*

High-energy frontier e-p and e-A collider to follow HERA with factor 1000 higher luminosity running simultaneously with HL-LHC.

x_{min} ~ 6 x 10^{-7}

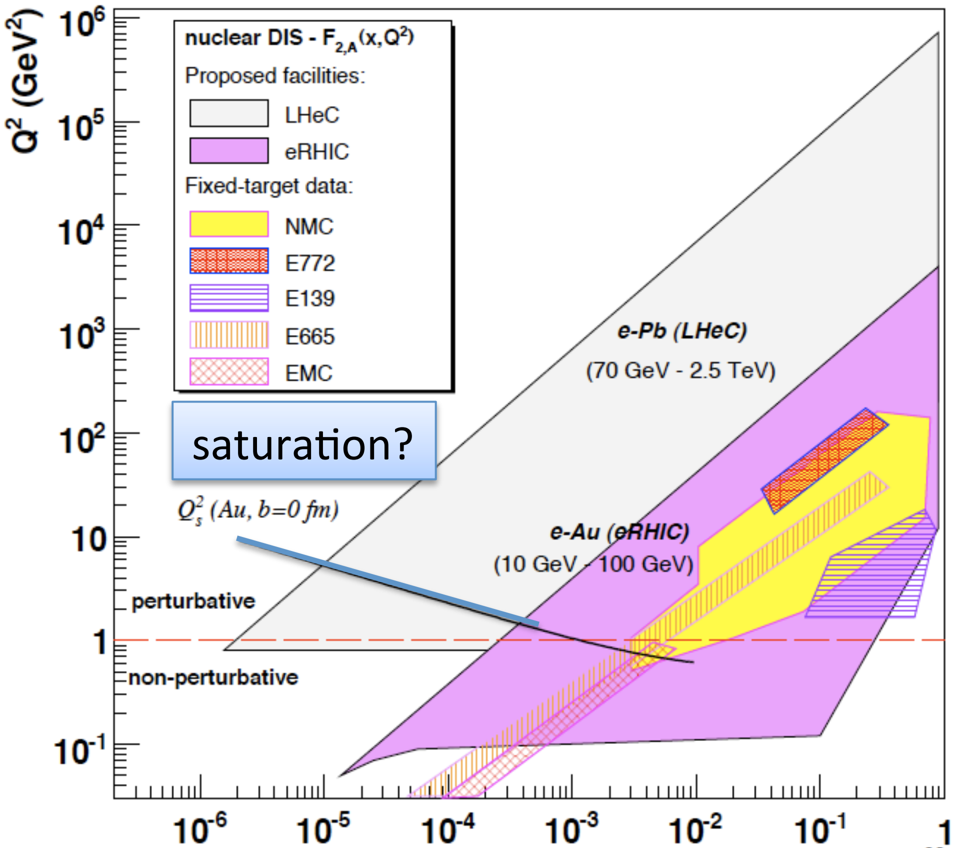






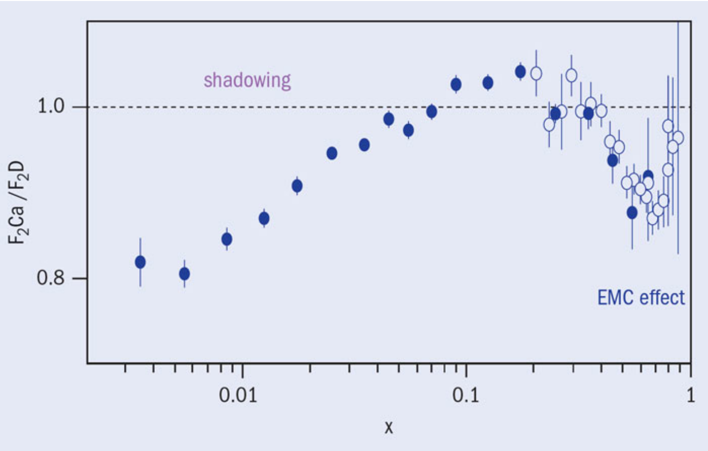
LHeC & EIC as electron-Ion colliders

- **Four orders of magnitude increase** in kinematic range over previous eA fixed target DIS experiments → **<u>into saturation region with p and with A</u>**



How would/does a nucleus look if we only saw its quarks and gluons?

EMC effect destroyed a particle-physics paradigm regarding QCD and nuclear structure [PLB 123, 275 (1983)]

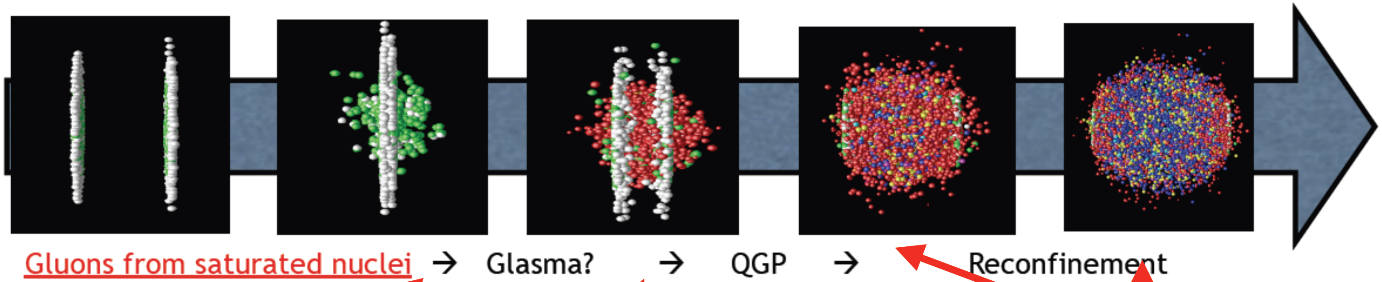


➔ unsolved puzzle since 30 years!

➔ Synergy with nuclear Drell-Yan data

e.g. CERN Courier 26.4.2013:
http://cerncourier.com/cws/article/cern/53091

Synergy : eA and AA



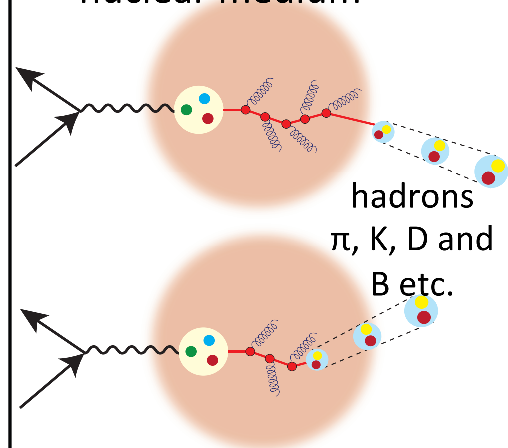
- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

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

eA: measure in semi-*inclusive* DIS modification of fragmentation/ hadronisation in dense nuclear medium



The LHeC-eA will explore a region overlapping (EIC-eA partially) **with the LHC-AA**
➜ in a cleaner experimental setup;
➜ on firmer theoretical grounds.

Partons in Nuclei

LHeC will measure all nuclear PDFs for the first time and in an unprecedented kinematic range.

Quarks through NC and CC DIS (flavour separation).

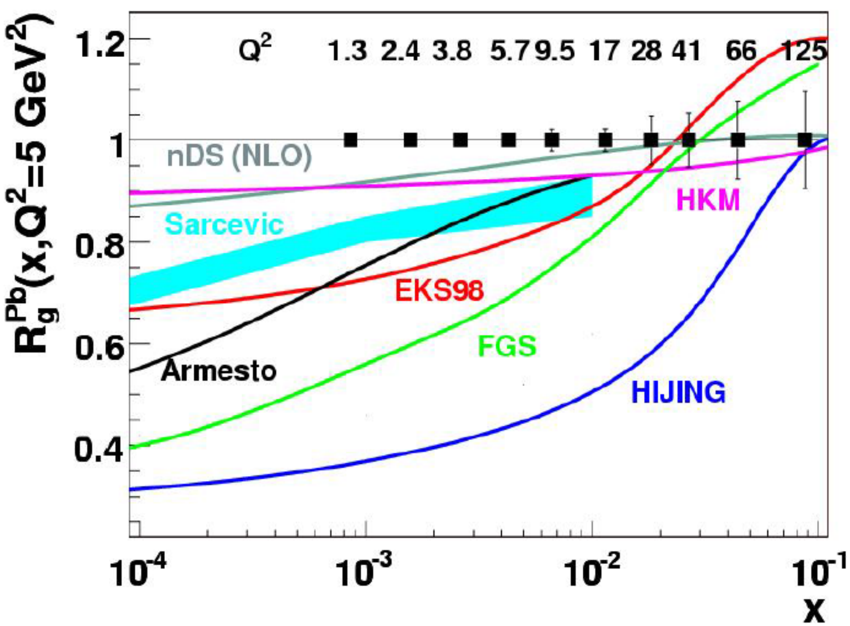
Gluons accessed through

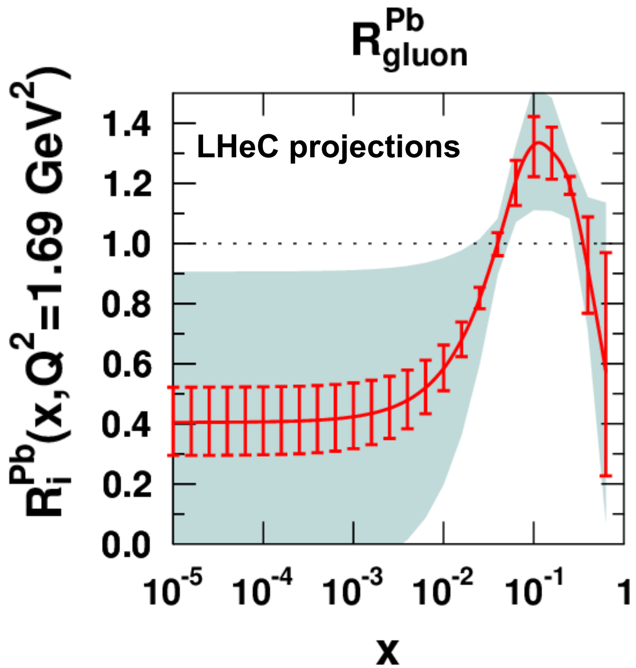
$dF_2/d\ln(Q^2)$ (large range in Q^2)

What do we know about gluons in a nucleus?

NOTHING!

Data fits: Ratio of gluons in lead to deuterium



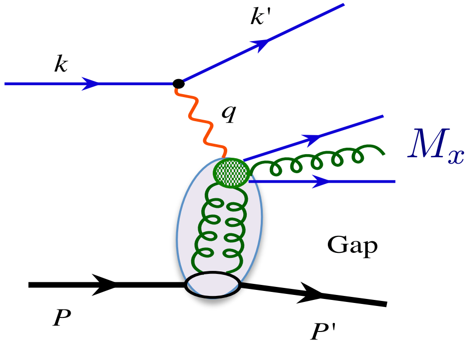


$$Q_s^2(eA) \propto Q_s^2(ep)\ A^{1/3}$$

Precision measurements of gluon distribution essential for quantitative studies of onset of **saturation as a high density (small x in ep) and matter ($A^{1/3}$) effect**.

Saturation and Diffraction

Diffractive cross section: $\sigma_{\text{diff}} \propto [g(x, Q^2)]^2$



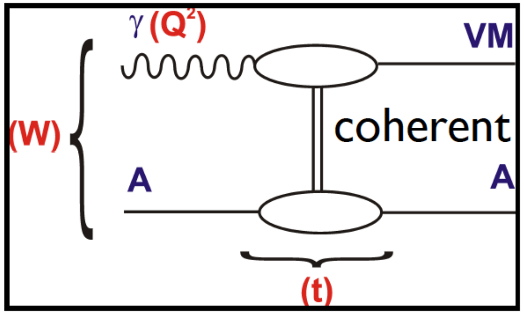
At HERA: 10-15% diffractive events

If saturation (CGC) – multiple coherent gluons

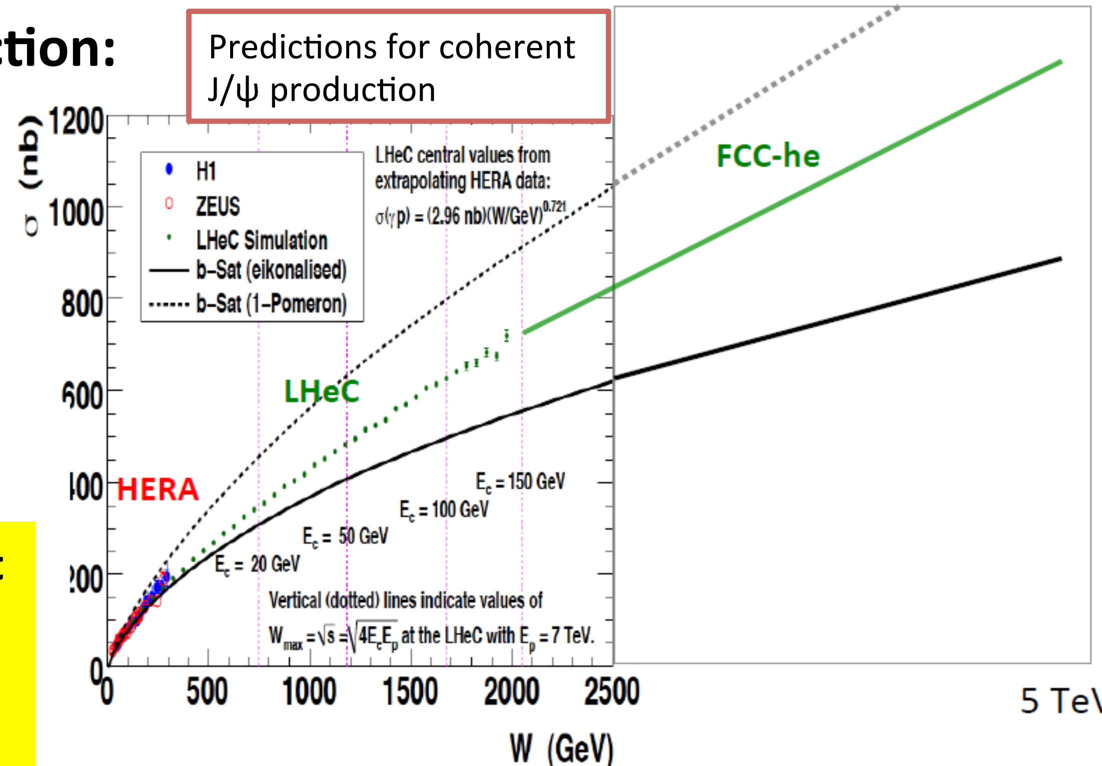
→ Diffraction in eA : ~25-30% diffractive contribution

Reminder: Factorization for diffractive processes works in DIS, not in pp, pA, AA

Diffractive vector meson production:



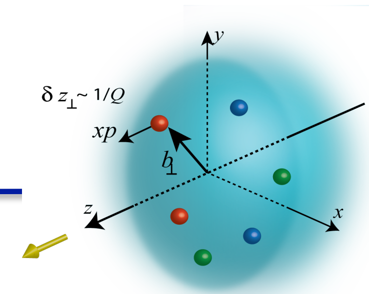
Predictions for coherent J/ψ production



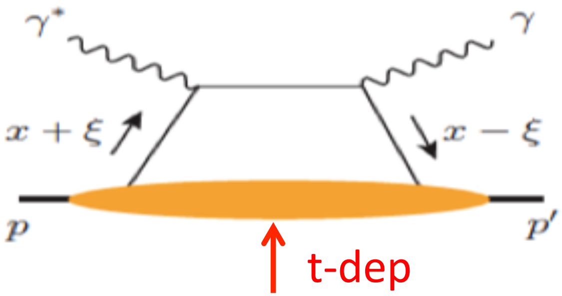
Experimental challenge : measurement of t (ZDC?) and detection of FS proton and neutron (incoherent: nucleus breaks up) in ep and eA.

Spatial Imaging of Partons

Where are the quarks and gluons?



Exclusive processes - DVCS:



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$t = (p' - p)^2$$

$$\xi = (P' - P) \cdot n/2$$

GPDs

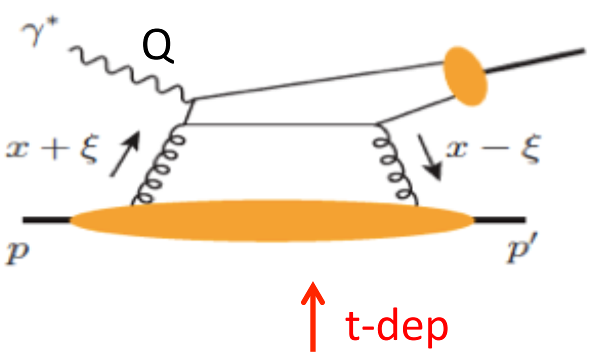
→ $H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$

F.T. of t-dep

→ Spatial distributions of valence quarks and sea-quarks at large and medium x values

Exclusive vector meson production:

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

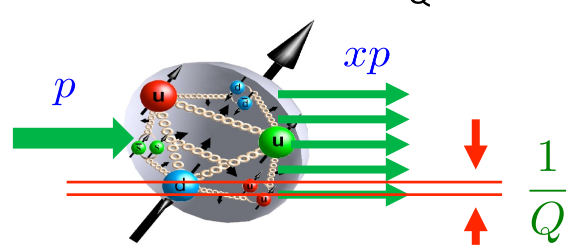


J/Ψ, Φ, …

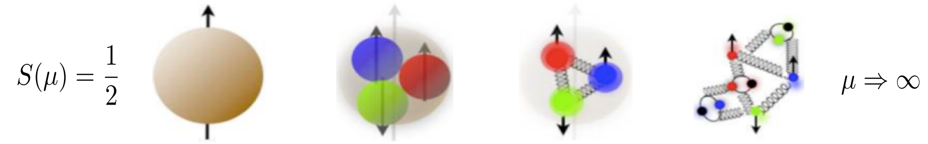
✧ Fourier transform of the t-dep

→ Spatial imaging of glue density

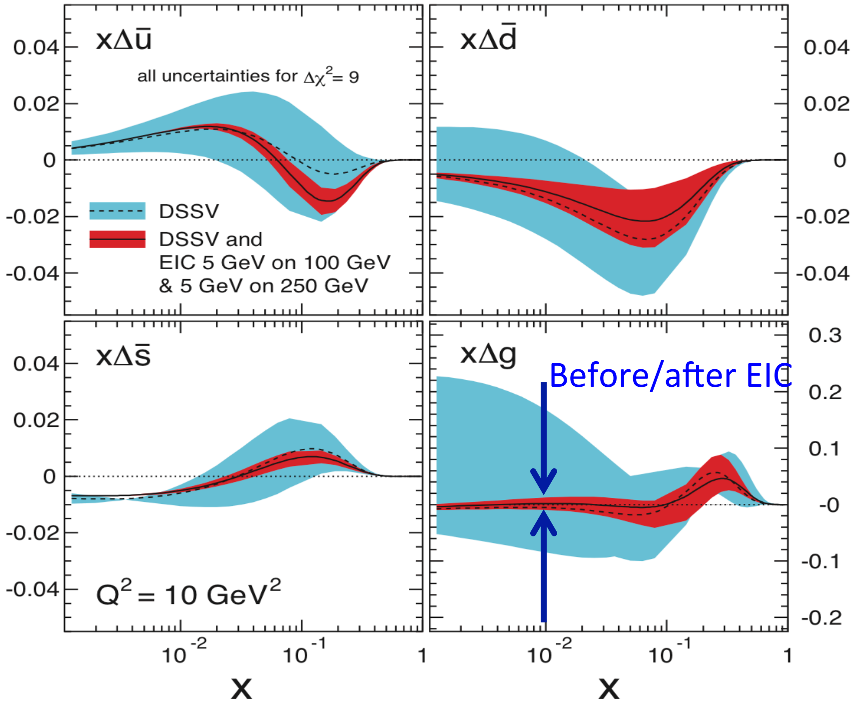
✧ Resolution ~ 1/Q or $1/M_Q$

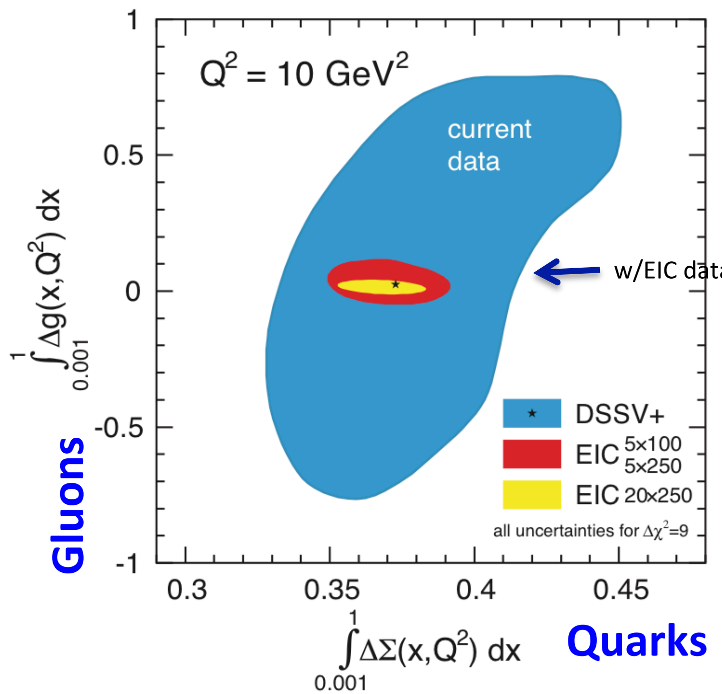


Proton Spin @ EIC



Requires longitudinally polarised hadron and electron beams ➔ unique for EIC !





Solution to the proton spin puzzle in reach:

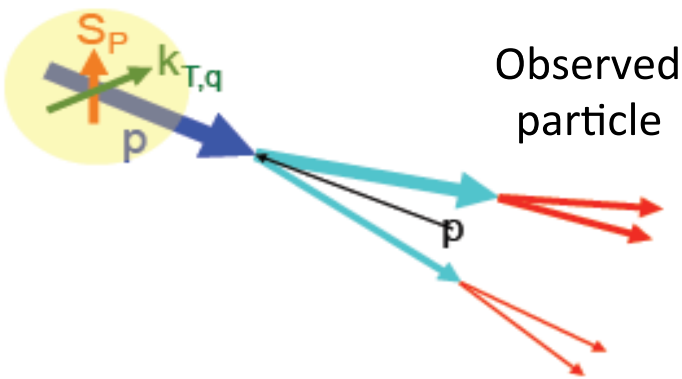
- ✧ *Precision measurement of ΔG – extends to smaller x regime*
- ✧ *Orbital angular momentum – motion transverse to proton's momentum*

Explore Spin & Quantum Correlations

Requires transversely polarised hadron beam → unique for EIC !

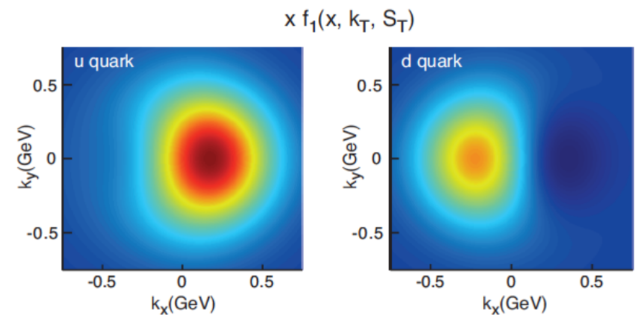
Quantum correlation between hadron spin and parton motion:

Sivers effect – Sivers function

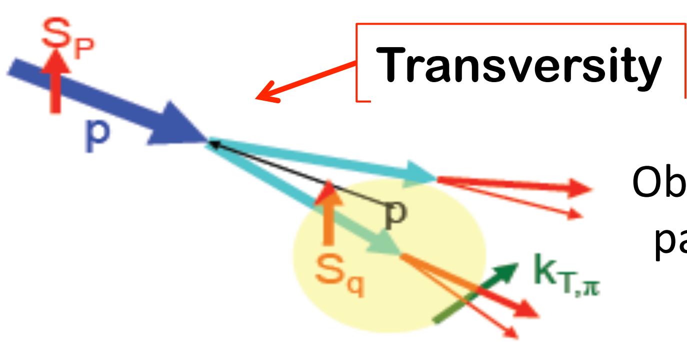


Observed particle

Hadron spin influences density of unpol. partons in transverse-momentum plane



Quantum correlation between parton spin and hadronization:



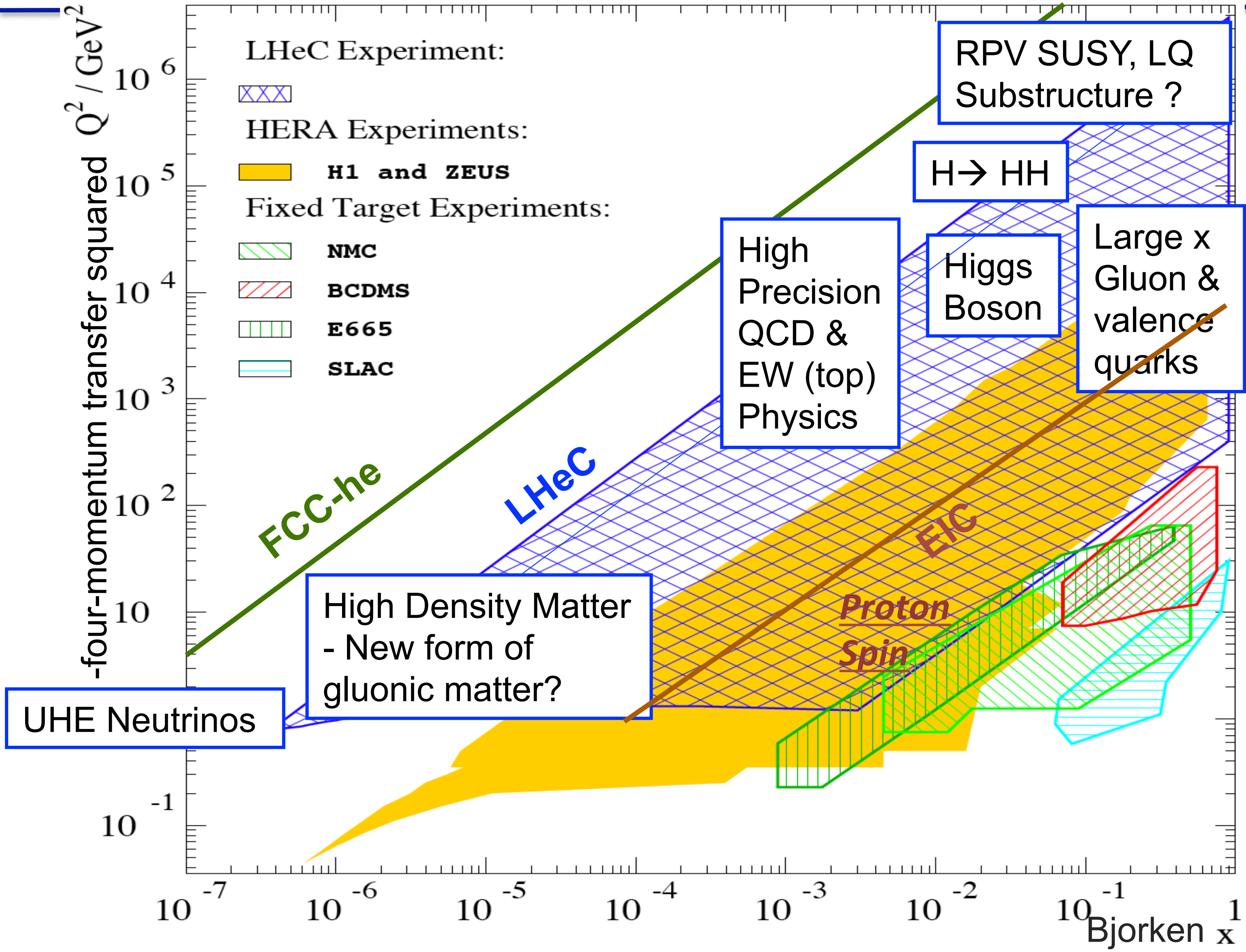
Observed particle

Collins effect – Collins function

Parton's transverse spin influence its hadronization

JLab12 GeV upgrade and COMPASS for valence, EIC covers sea-quarks and gluon!

The ep Physics at the Energy Frontier



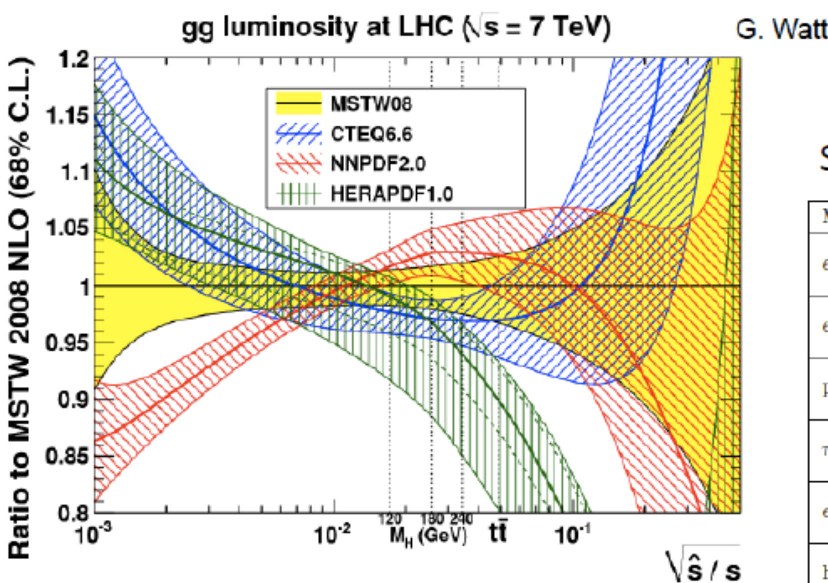
HERA established the validity of pQCD (DGLAP) due to a very high lever arm in Q^2.

Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

January-October 2013

"Snowmass" 2013

arXiv:1310.5189



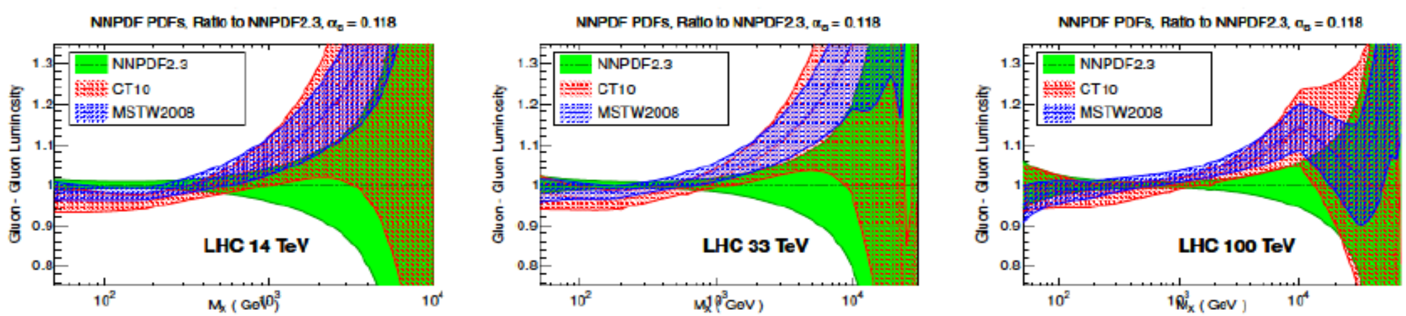
PDFs for QCD, H, BSM …

Important constraints from pp, but precision with ep! eA is unknown

Strong coupling constant to better than lattice precision

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9,29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, ~ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, ~ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30,31], (mostly theory, NNLO) [32,33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17,21,34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ (~ 5 yrs [38])

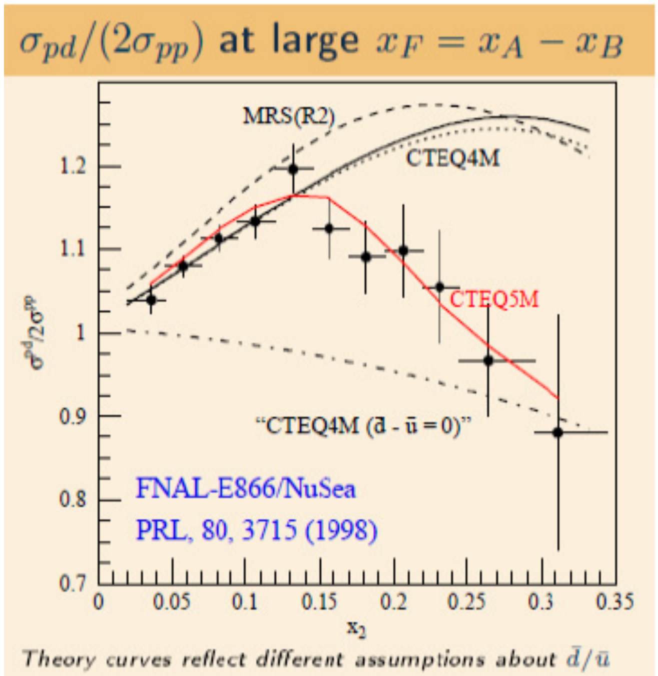
Gluon-gluon luminosity at the LHC, HE LHC and FCC



Synergy: Constraining Sea Quark PDFs

- Violation of Gottfried Sum Rule in **μN DIS** data

FNAL Drell-Yan → $\bar{d}(x) \neq \bar{u}(x)$

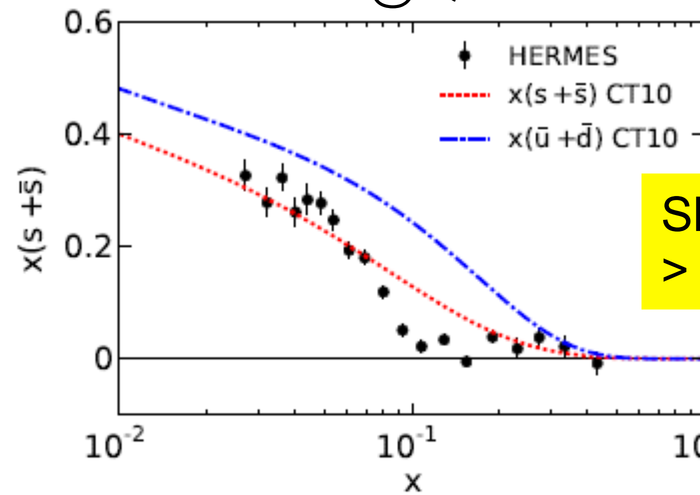


- Implications for all PDF fits
- Effect soon confirmed by HERMES w. **SIDIS** data (semi-inclusive DIS)
- Further data ongoing at FNAL/SeaQuest (x > 0.1)
- LHC **W/Z** data suggest flavour-symmetric sea ?
- LHC W+charm data → subject to cuts, FF/hadronisation…

- Strangeness constraints $\bar{s} < \bar{d}$ originally from **νN and $\bar{\nu}$N DIS** di-muon data

Strange sea s more (data) challenged

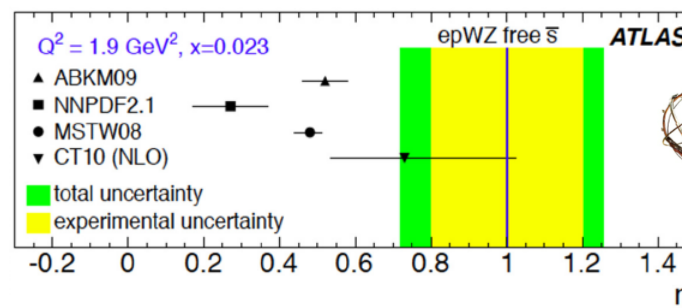
- HERMES **SIDIS** @ $Q^2 = 2.5\ GeV^2$



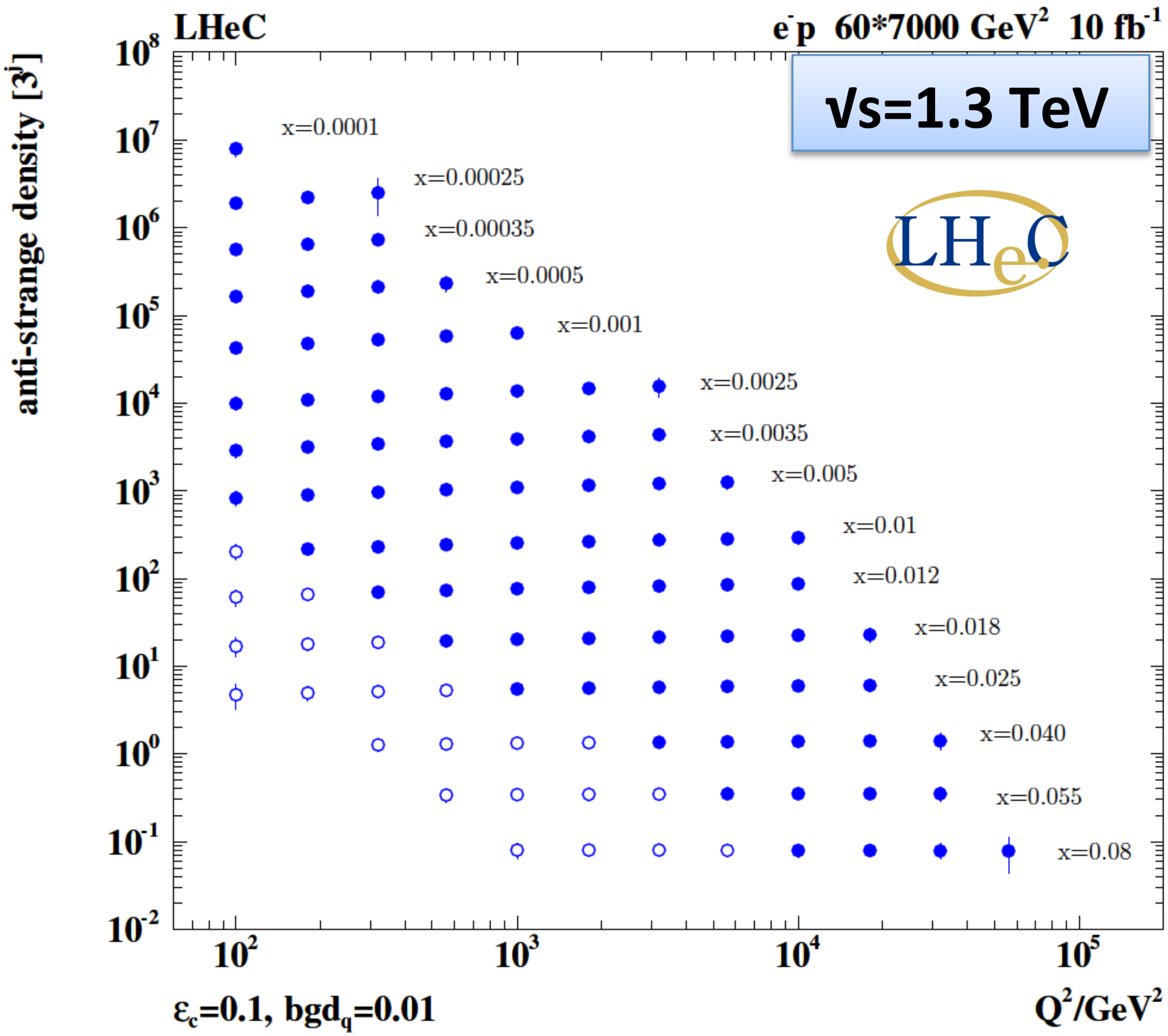
Shape x > 0.1?

- LHC **W/Z Production** preference for $\bar{s} \sim \bar{d}$

$$r_s = 0.5(s+\bar{s})/\bar{d} = 1.00^{+0.25}_{-0.28}$$



Precision Strange Quark Distributions



High luminosity

High Q^2 lever arm

Small beam spot

Modern Silicon detectors

NO pile-up..

→ **First (x,Q^2) measurement of the (anti-)strange density** (even intrinsic charm?) **over large phase space**

$x = 10^{-4}$ .. 0.05

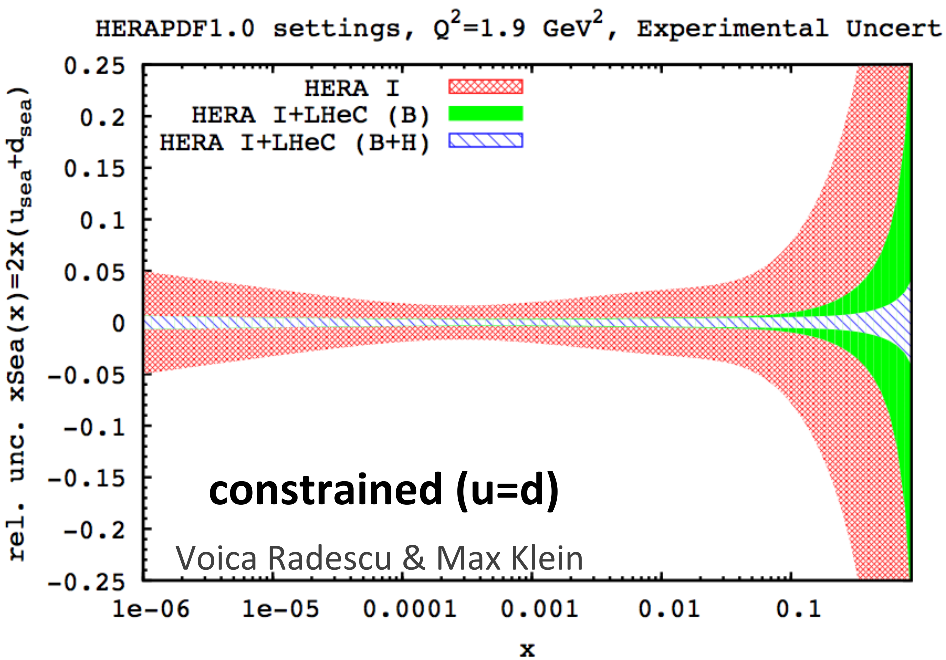
$Q^2 = 100 - 10^5$ GeV^2

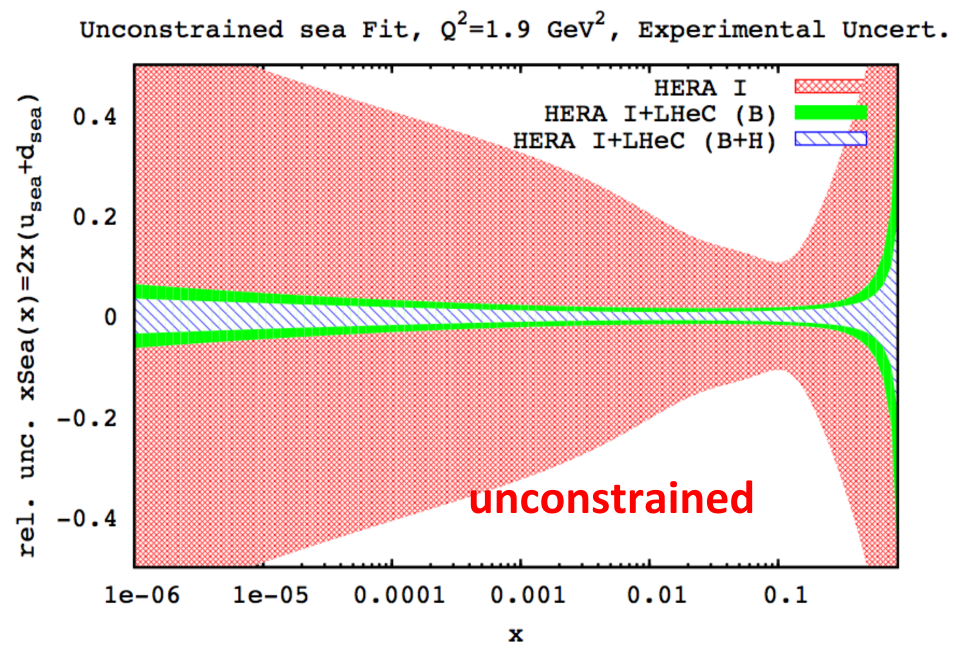
→ PDF fits with fewer assumptions

Initial study (CDR): Charm tagging efficiency of 10% and 1% light quark background in impact parameter

Resolving Partonic Structure

free of symmetry assumptions





- One can see that for HERA data, if we relax the low x constraint on u and d, the “PDF errors” are increased tremendously!
- However, when adding the LHeC simulated data, we observe that uncertainties are visibly improved even without this assumption.
- Further important cross check comes from the deuteron measurements, with tagged spectator and controlling shadowing with diffraction…

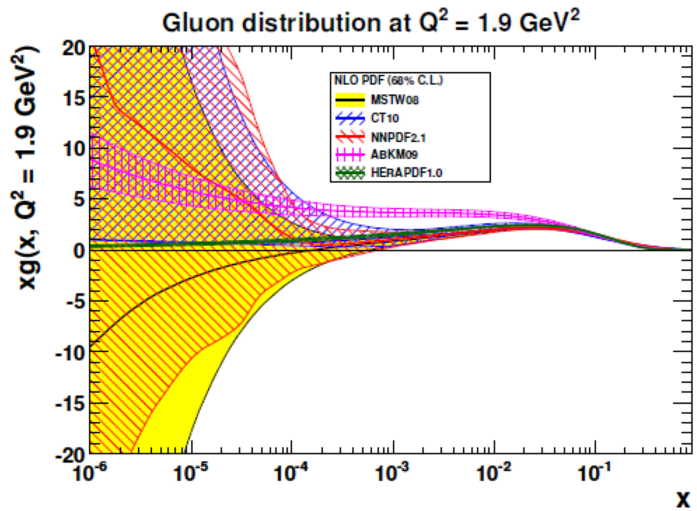
The Gluon PDF – much less known than we wish

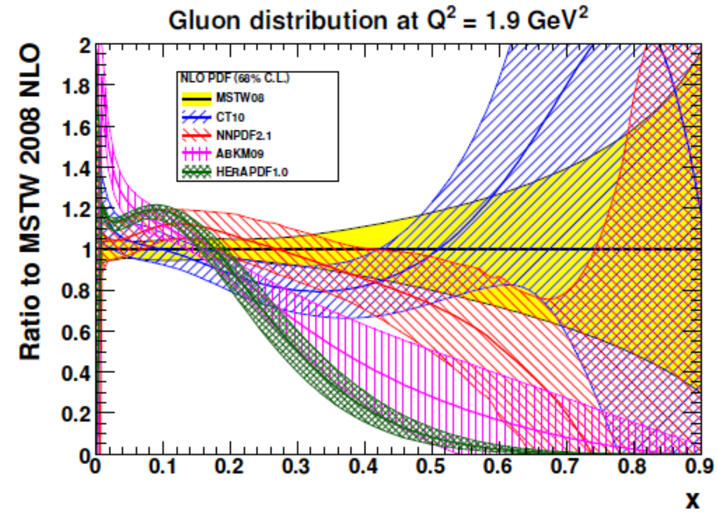
"You may not realize that you will need it…" (Rolf Ent)

LOGARITHMIC Bjorken x SCALE

LINEAR Bjorken x SCALE

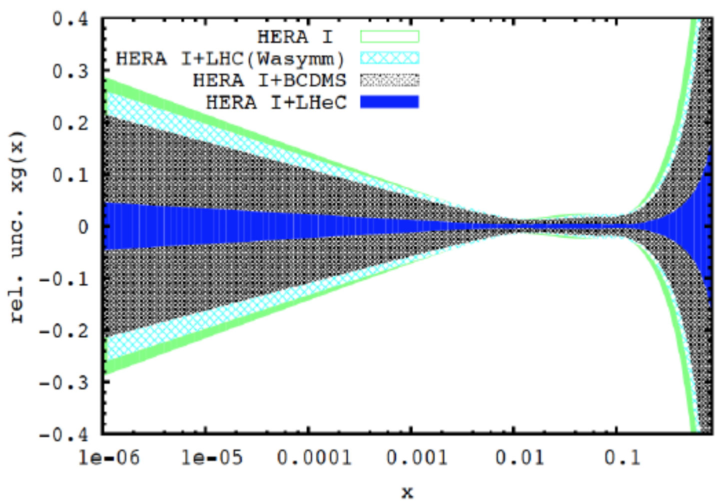
CURRENT

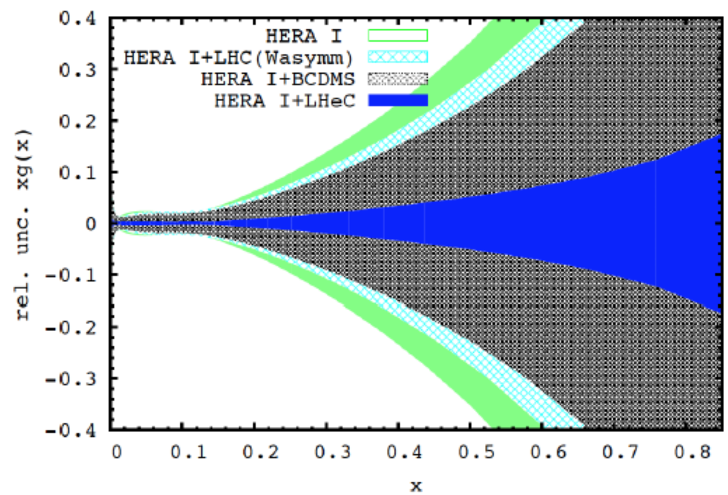




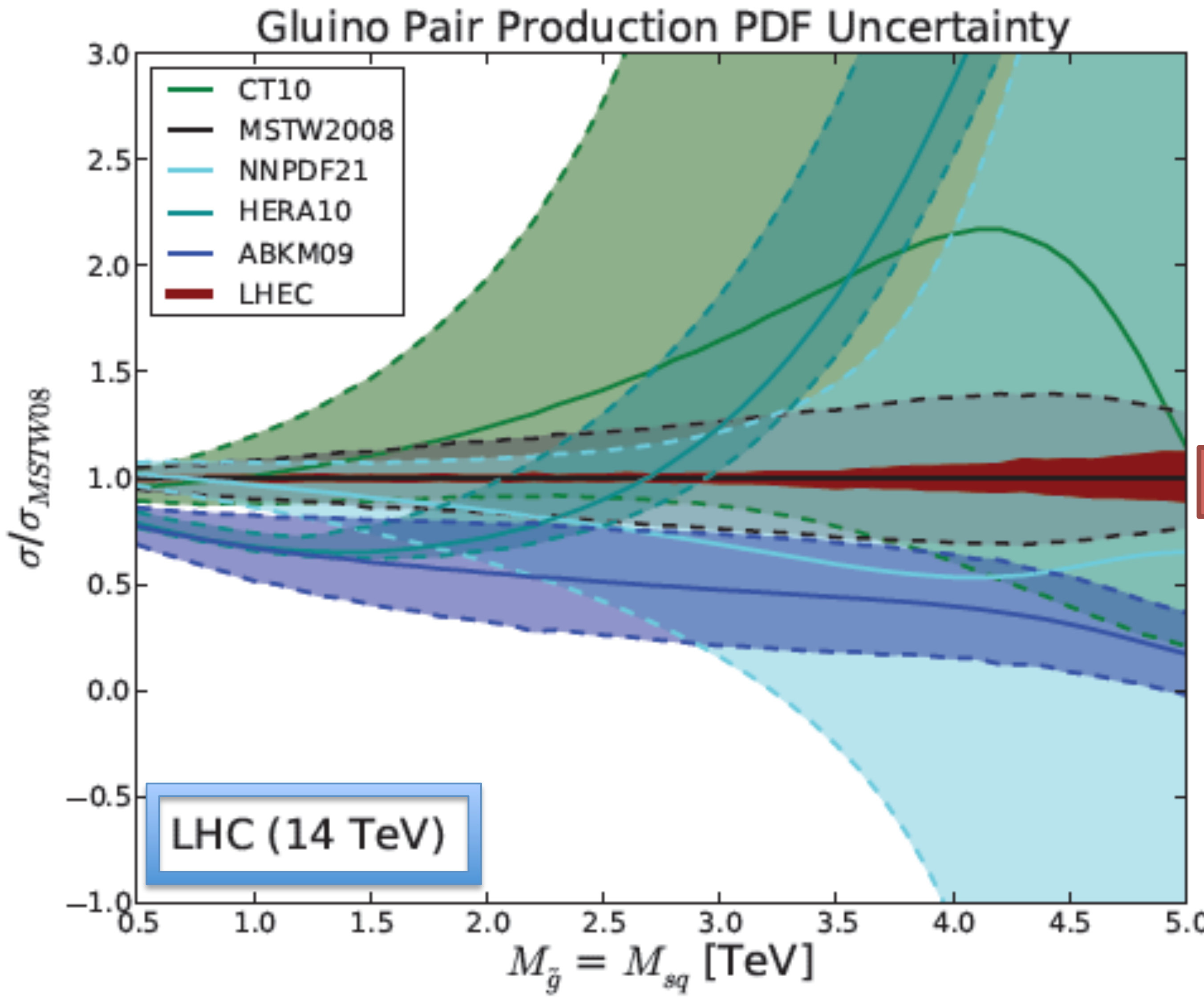
FUTURE

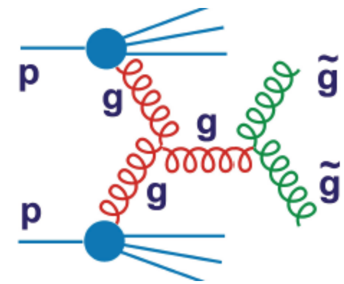
LHeC





Precision gluons for SUSY

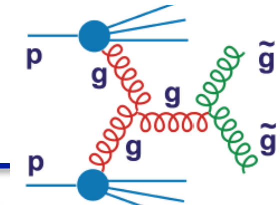


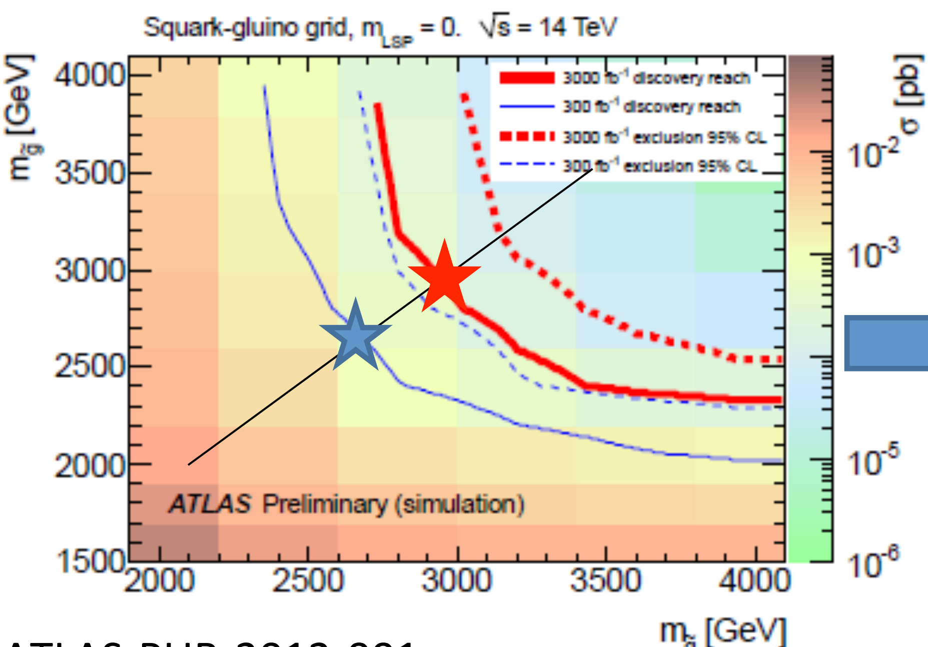


LHeC

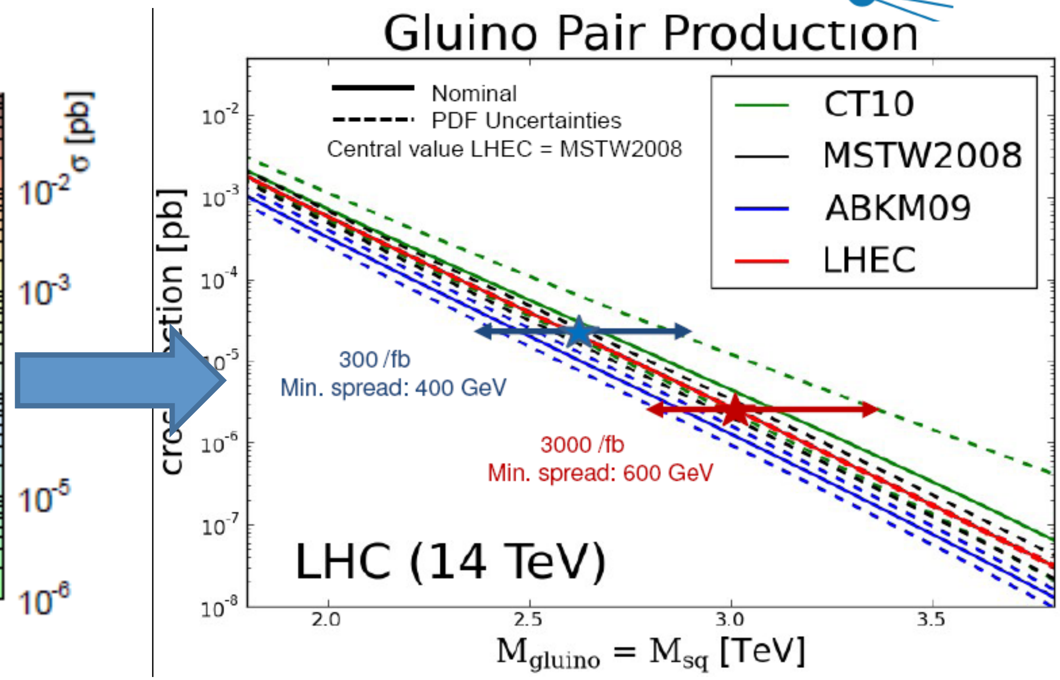
LHeC Note 2012-005
arXiv:1211.5102; LHeCPDF in LHAPDF

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)]

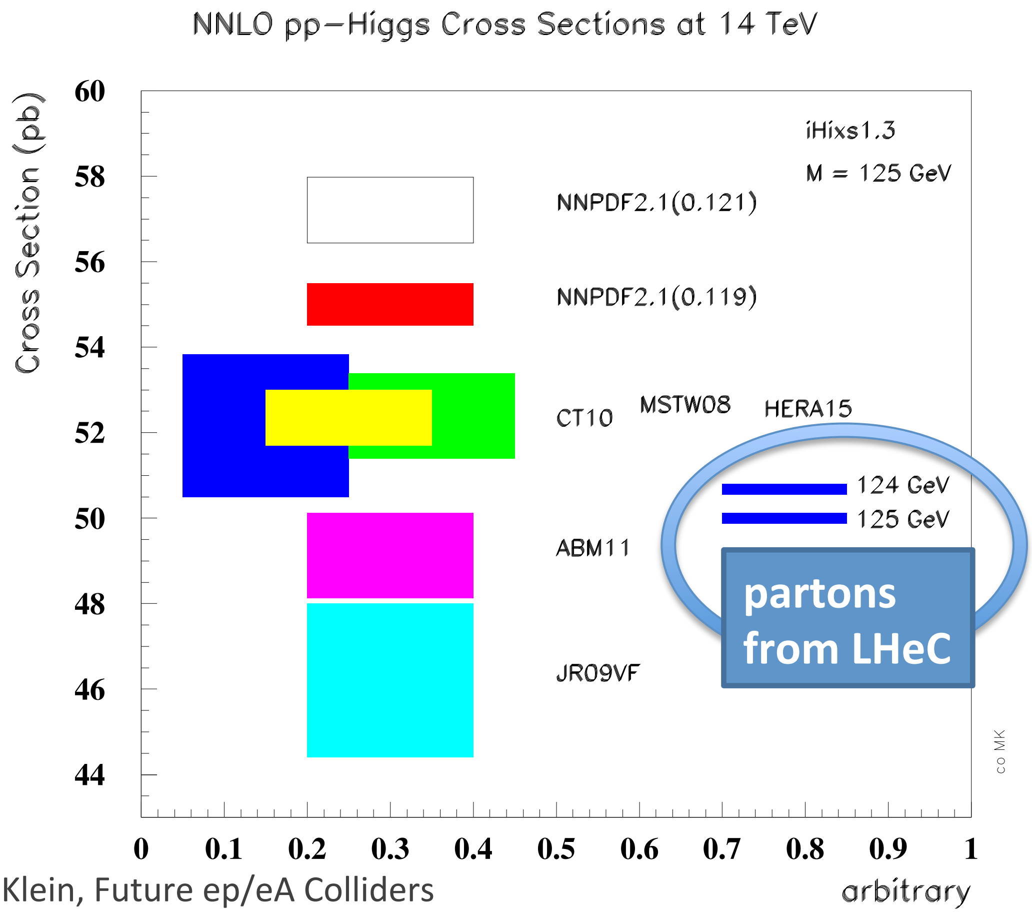
The HL-LHC and FCC-hh search programme requires a much more precise understanding of QCD, which the LHeC could provide (strong coupling, gluon, valence, factorisation, saturation, diffraction..)

Precision Partons for Higgs in *pp*

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

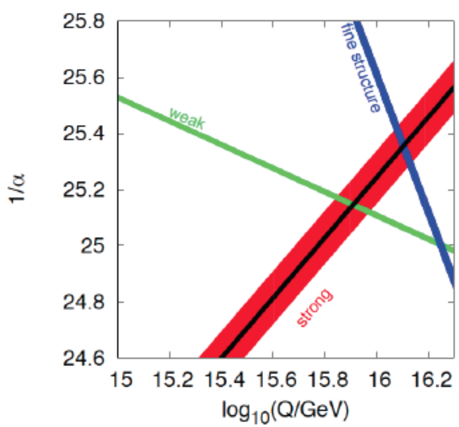
→ clear Higgs mass sensitivity in cross section predictions

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

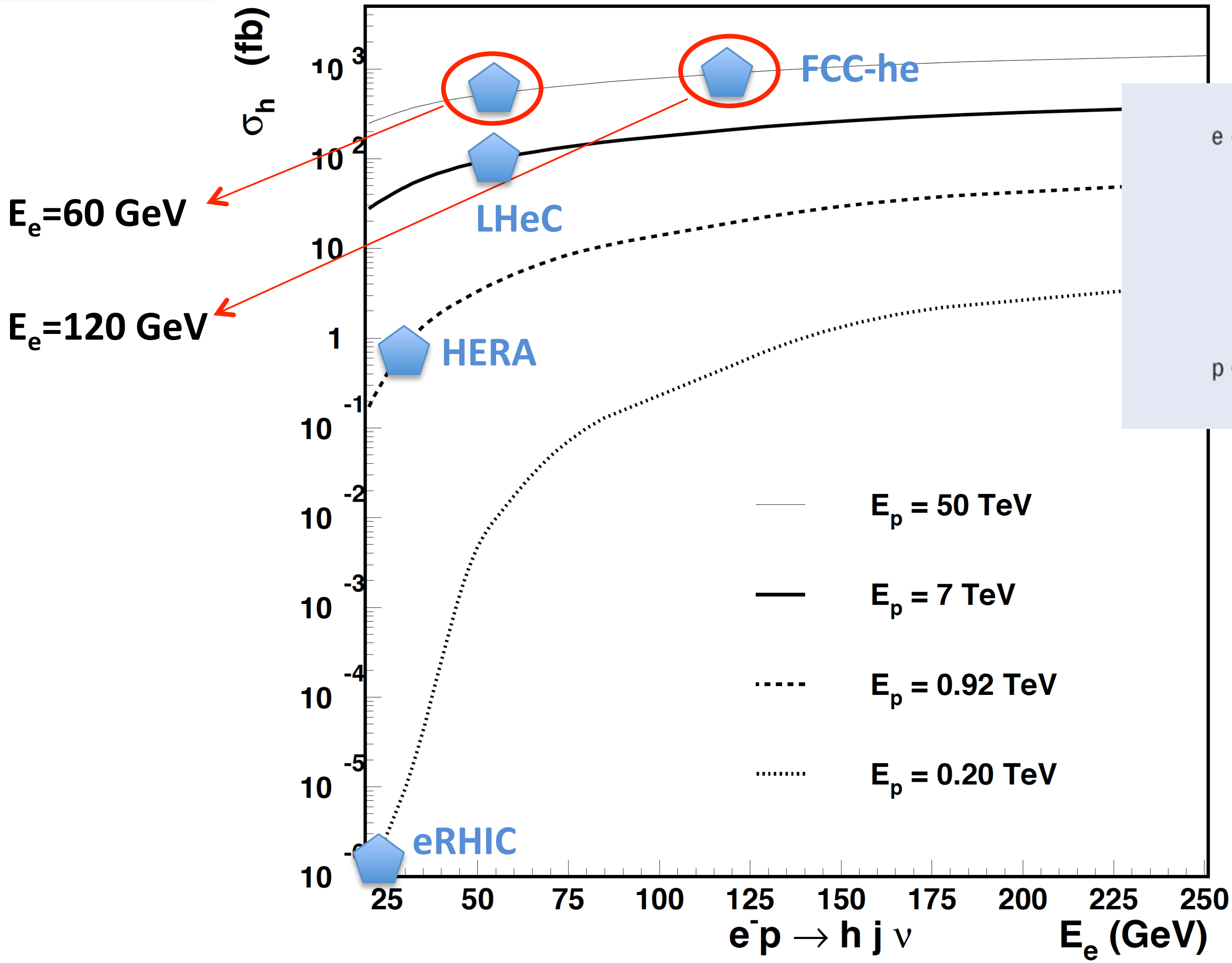


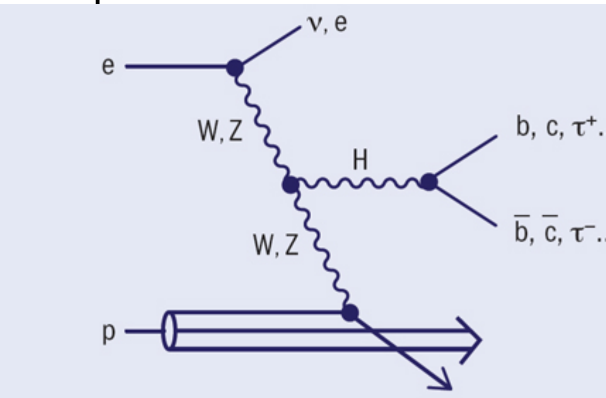
α_S = underlying parameter relevant for uncertainty (0.005 → 10%)
@ LHeC: measure to permille accuracy (0.0002)

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



SM Higgs in ep

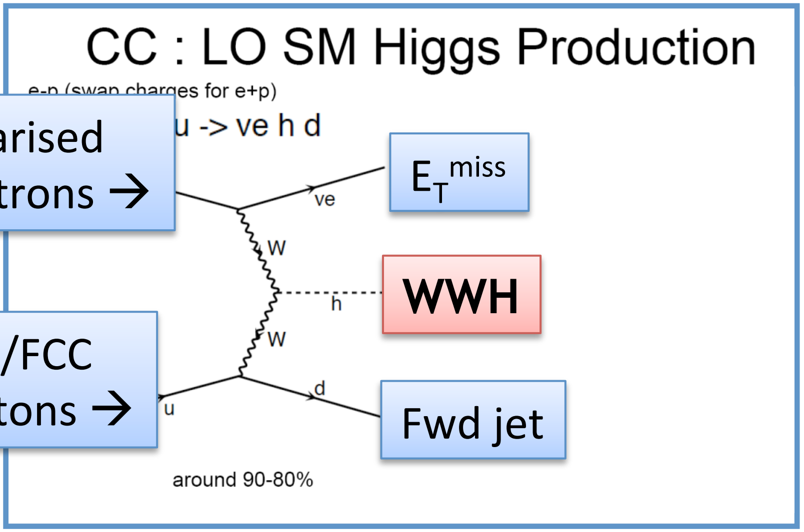


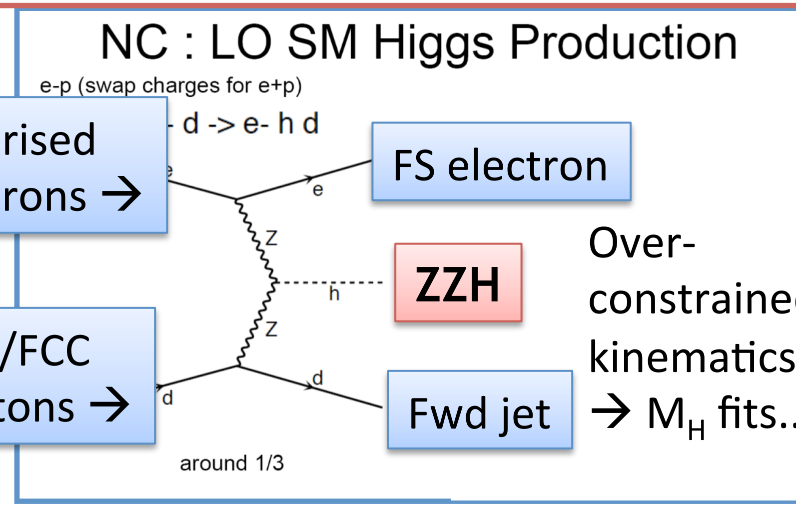


LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

SM Higgs Production in ep

In ep, direction of FS quark is well defined.





Over-constrained kinematics → M_H fits..

E_e=60 GeV P_e=-0.8	E_p=7 TeV : √s= **1.3 TeV**				E_p=50 TeV : √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_e=-80%	**196**	N.A.	25	0.02	**1019**	N.A.	**229**	**0.43**

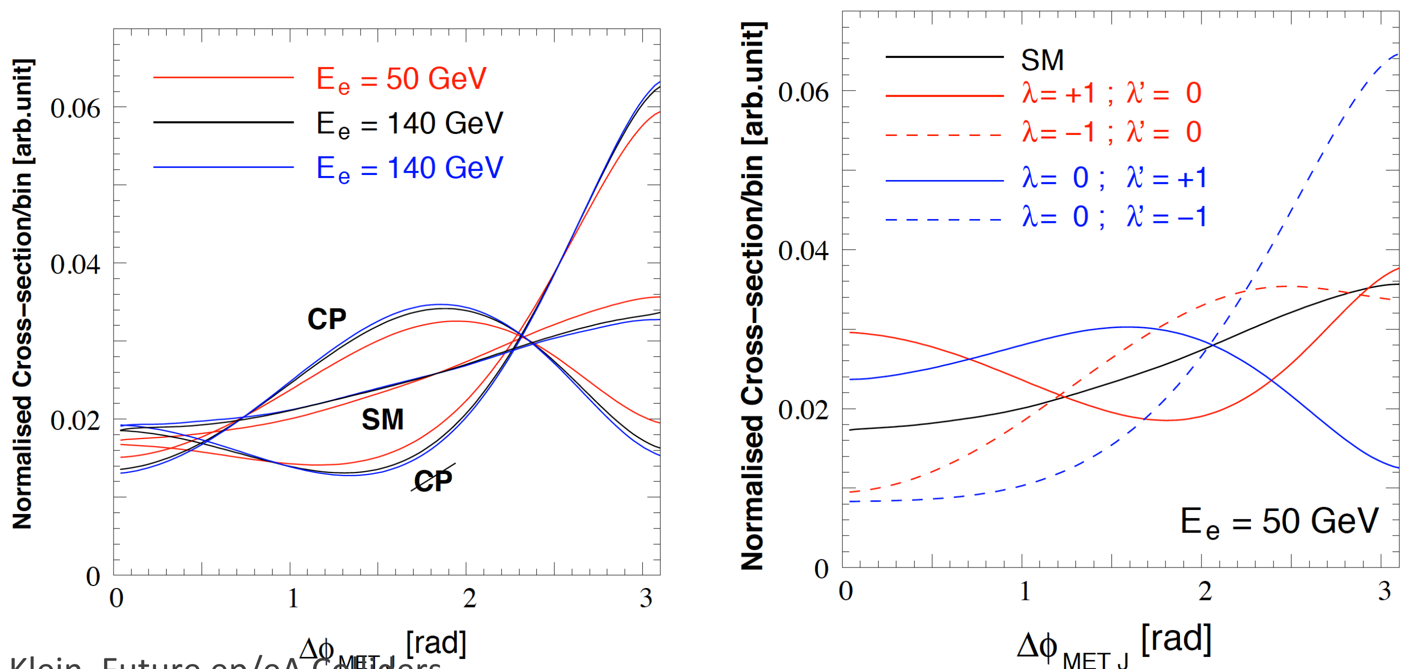
Measure CP properties of Higgs

[LHeC 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}

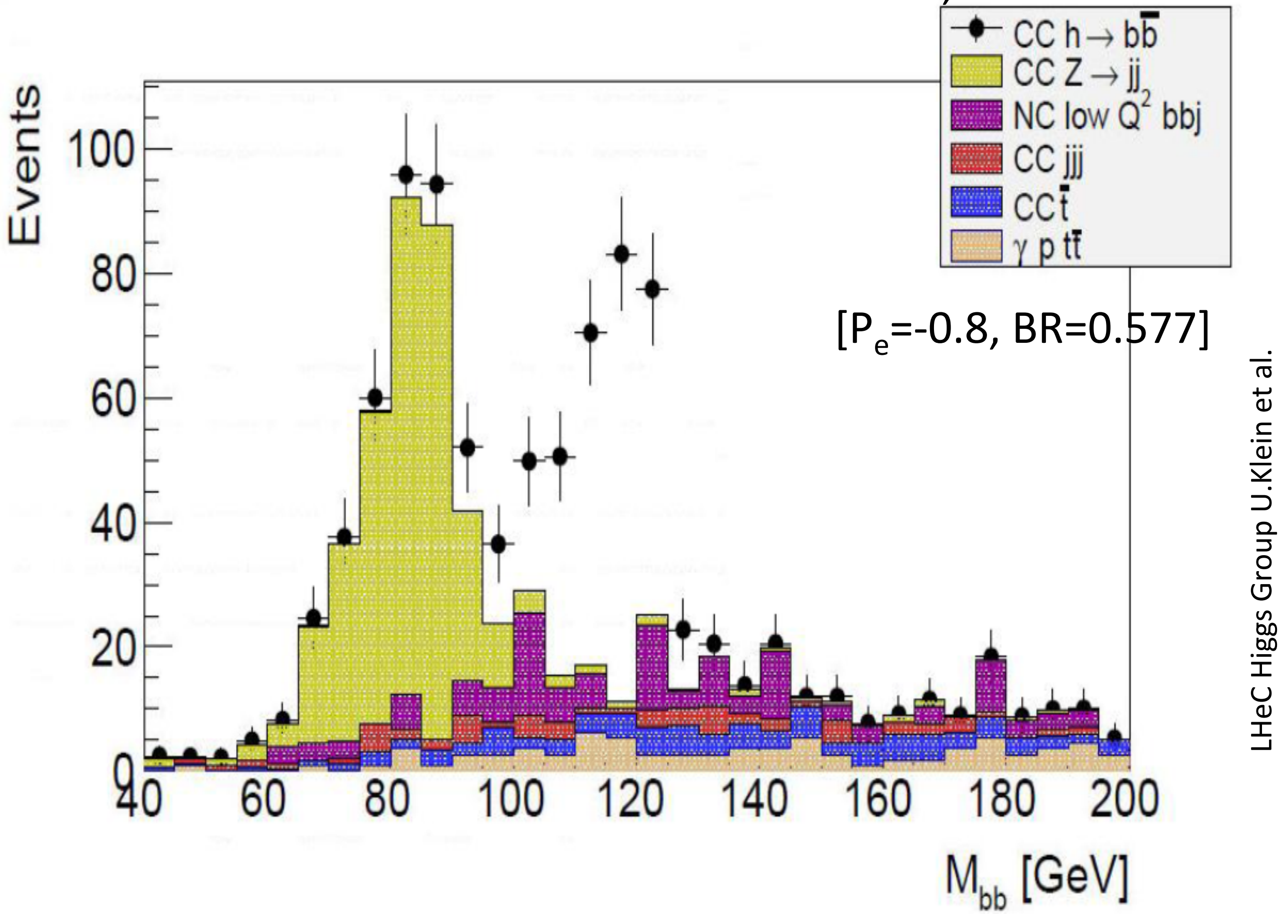
In ep, full Δφ range can be explored, here not shown yet.

SM Higgs in ep

M_H=125 GeV : Post-CDR simulation of H→ bb measurement at the LHeC, 100 fb^{-1}

ep→ vH(bb)X
charged currents
σBR~120 fb
μ=0.1
S/B ~1-2
Cut based only

[LHC: VH - BDT's
σ(VH) ~ 130fb 8 TeV
arXiv:1409.6212]



This reconstructs 60% of H in ep with comfortable S/B ~1 , in CC and NC
→ Enables BSM Higgs (tensor structure of HVV, CP, dark H?) , QCD(H)
→ **O(1)% precision on H-bb couplings with small thy uncertainty**. H-cc imminent

ep Higgs "Facility" @ 1 ab^{-1}

Post-CDR & Higgs discovery: 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).

Total event rates for 1ab^{-1}.

√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

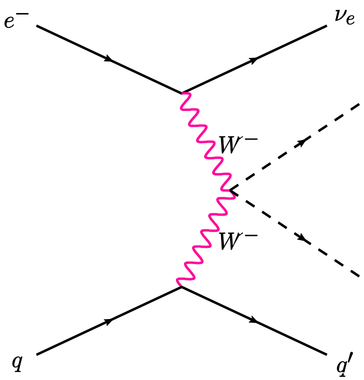
Cross section at FCC-he 1pb ep→ vHX

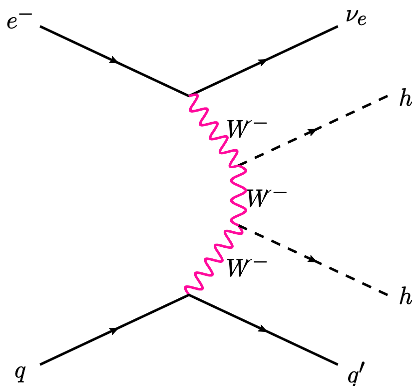
Luminosity O(10^{34} $cm^{-2}s^{-1}$) is crucial for H → HH [0.5 fb] and rare H decays

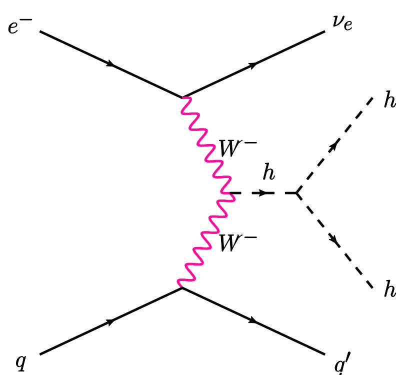
Note the LHeC WW-H cross section is as large as the Z*→ ZH cross section at the ILC or FCC- or CEPC, but it is much larger at the FCC-he.

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)





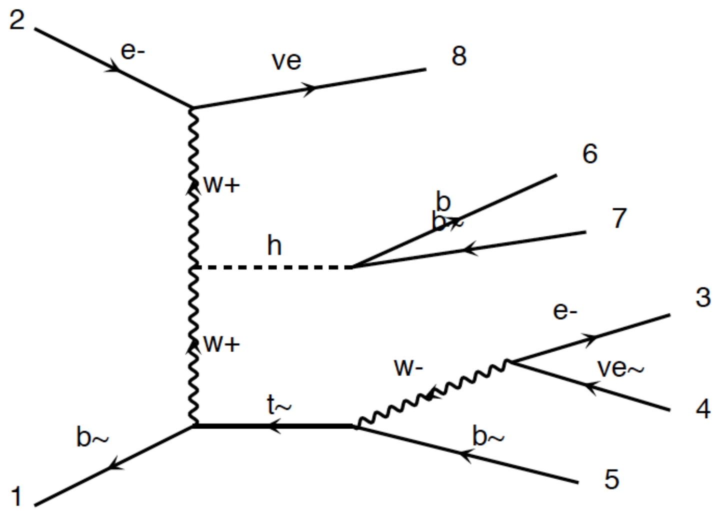


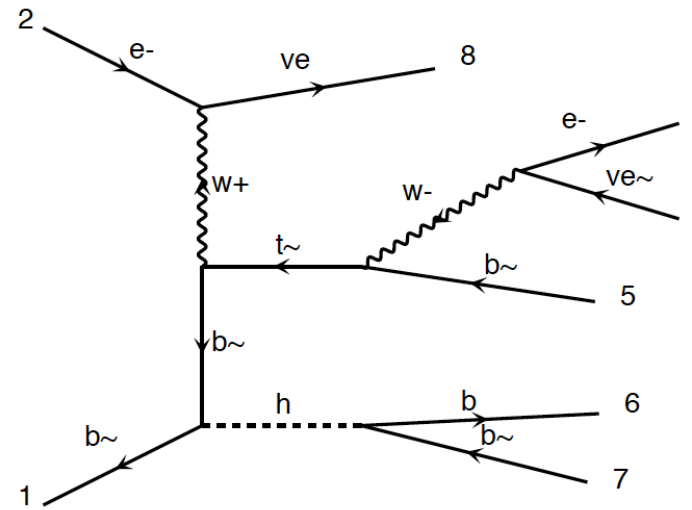
$p_{T_{j,b}} > 20\ GeV,$
$\not{E}_T > 25\ GeV,$
$|\eta_j| < 5,\ \Delta R = 0.4.$

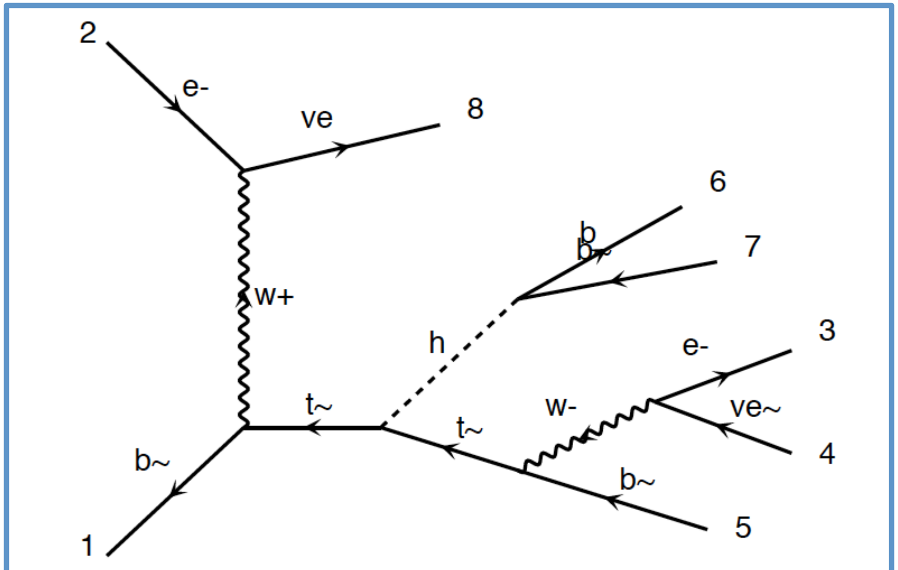
Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \rightarrow \nu_e hhj, h \rightarrow b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

Fiducial 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

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

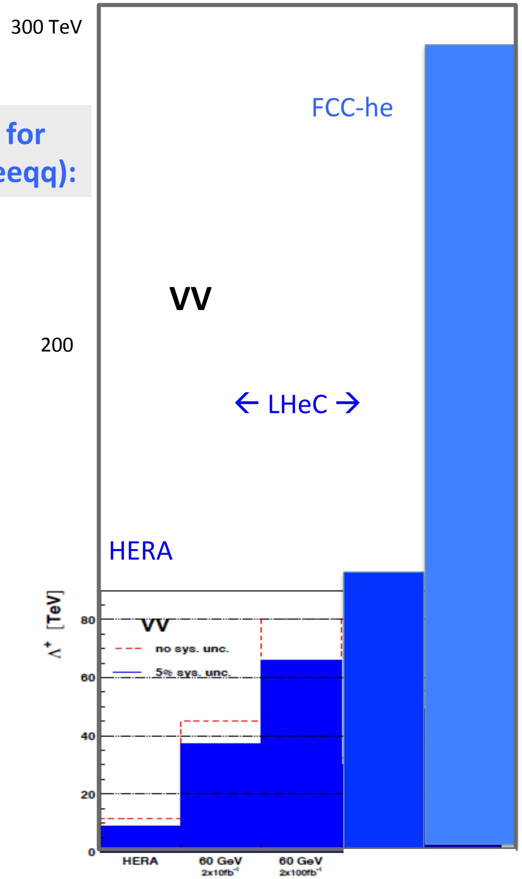
η(j) <5

η(b) < 3

FCC-he Physics

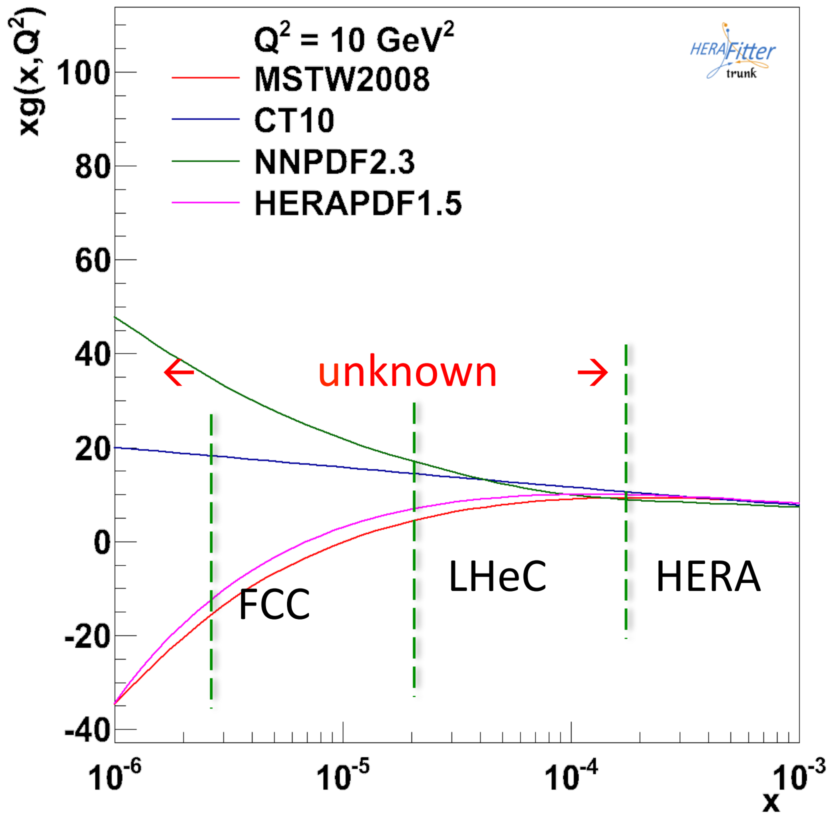
High mass and Q^2 region

Reach for
Λ (CI eeqq):



LHeC: see CDR 2012

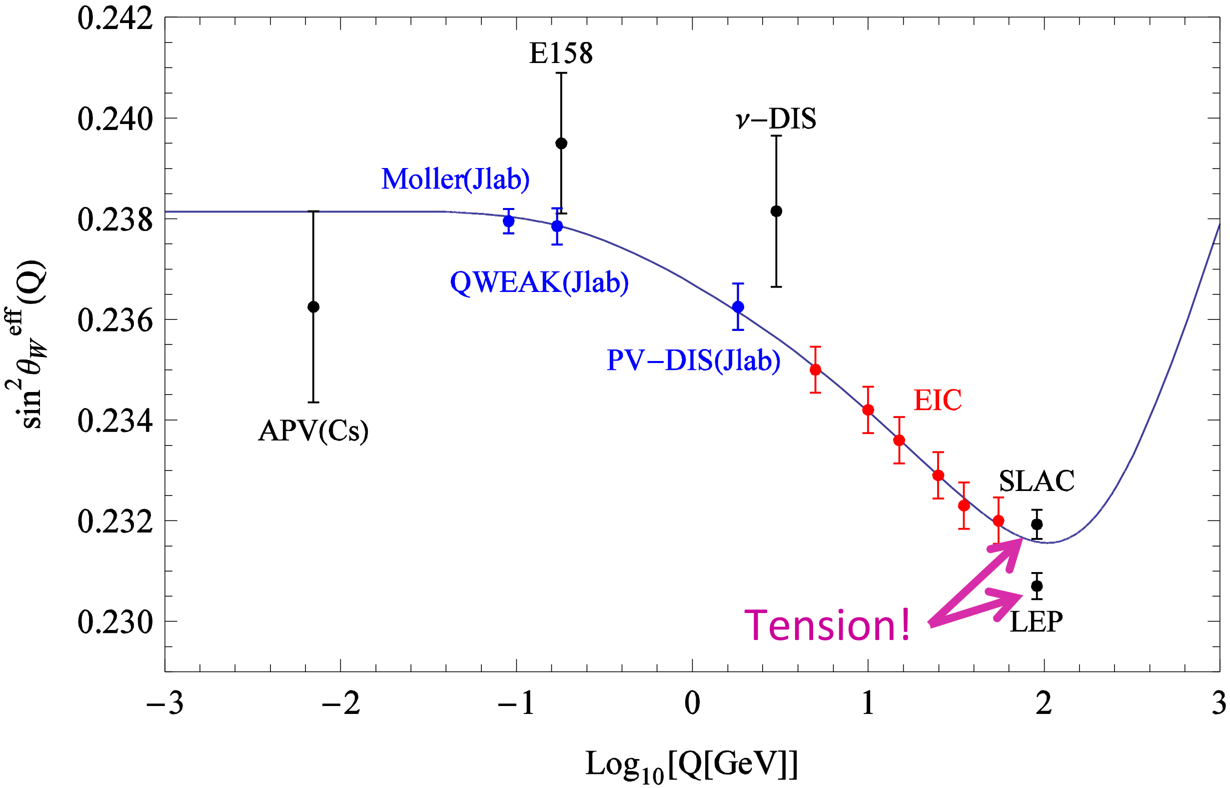
Low x Physics @ Q^2 =10 GeV^2

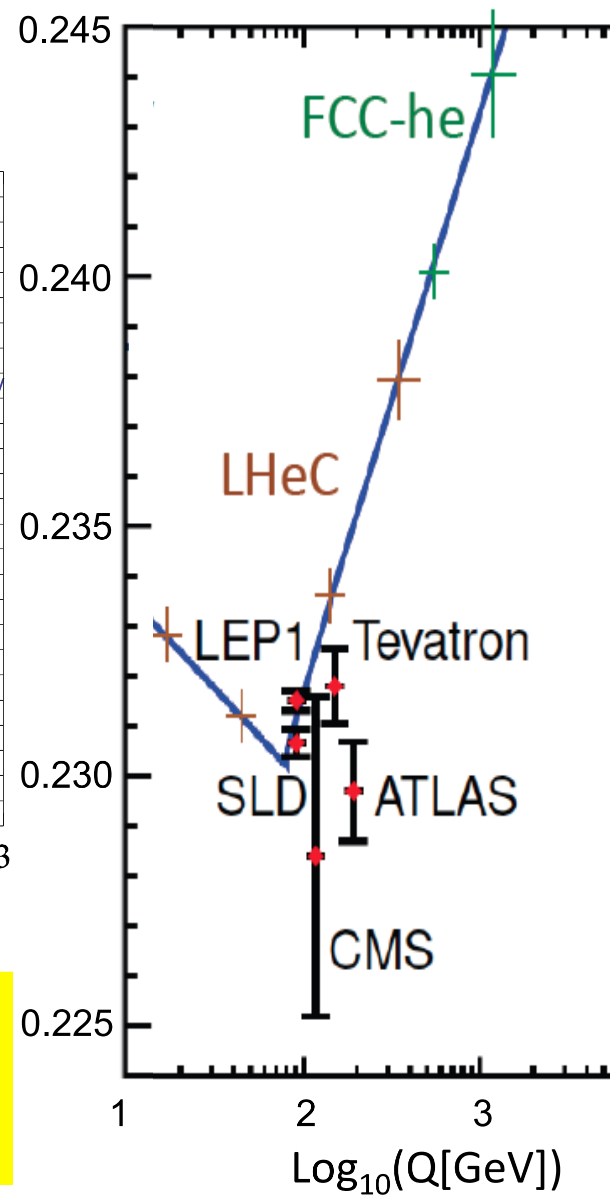


Huge extension of reach for new physics and to explore quark-gluon dynamics.
Leptoquark reach to up to √s ≈ 4 TeV .
Higgs selfcoupling (4b final state – under study, hh→4a envisaged)
Program being further investigated, Collaboration with hh and ee, Joint Software Group

Completed, planned, and possible EW measurements

Scale dependence of $\sin^2\Theta_W$
"Hunting for the unseen forces of the universe"

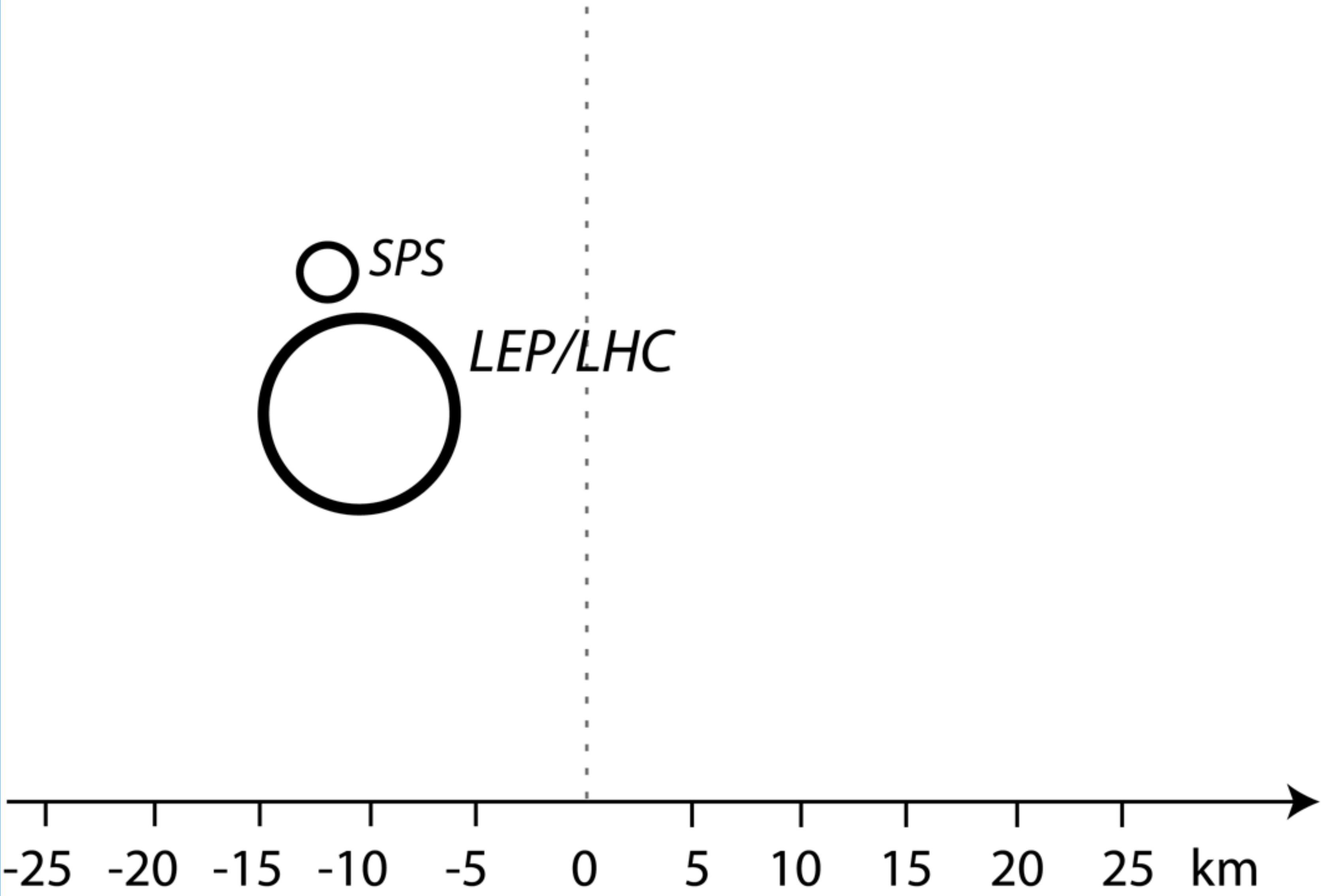


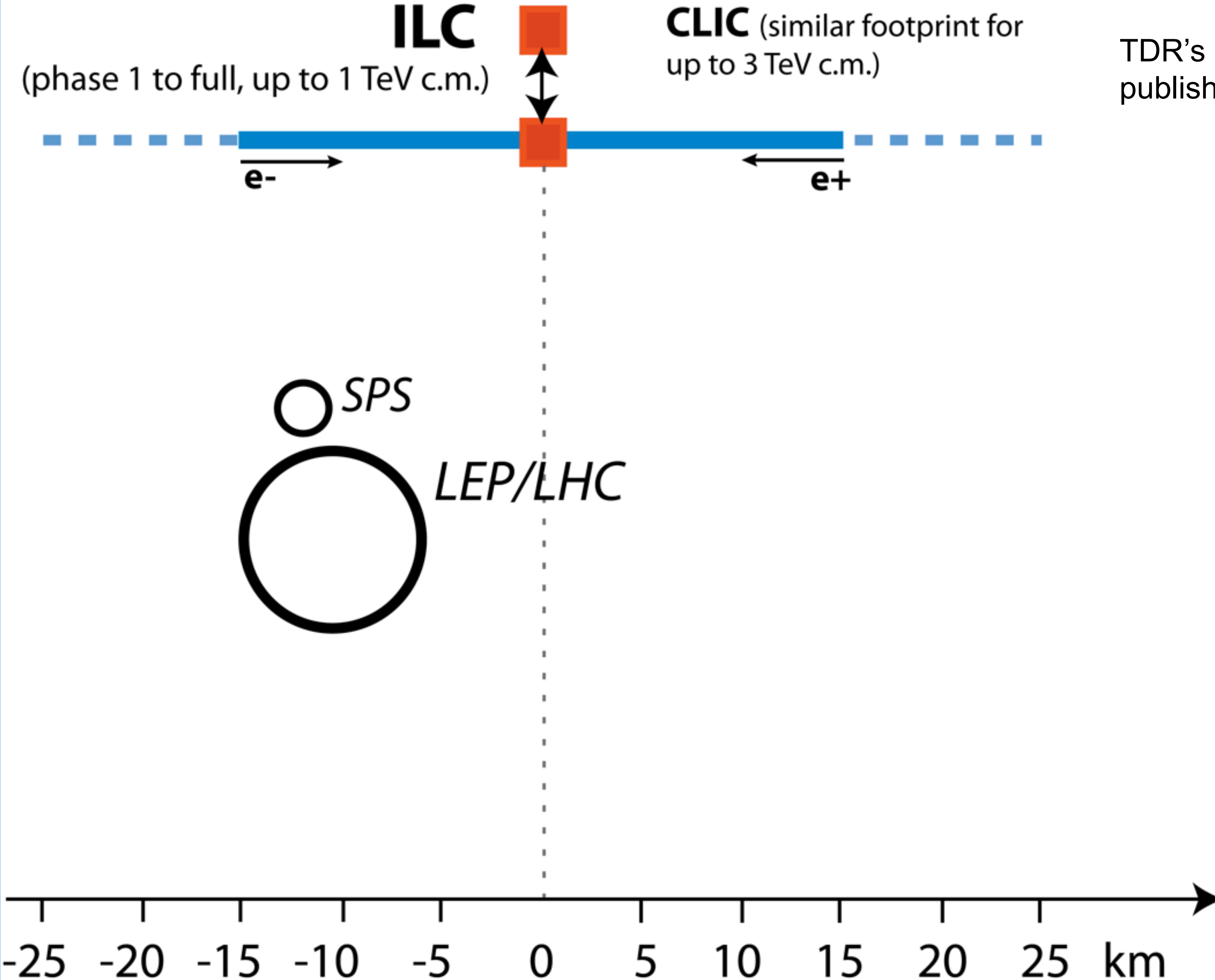


→ EIC & LHeC allow to probe the electroweak mixing angle over a tremendous range Q over three order of magnitudes

CERN Colliders : LHC-Run II

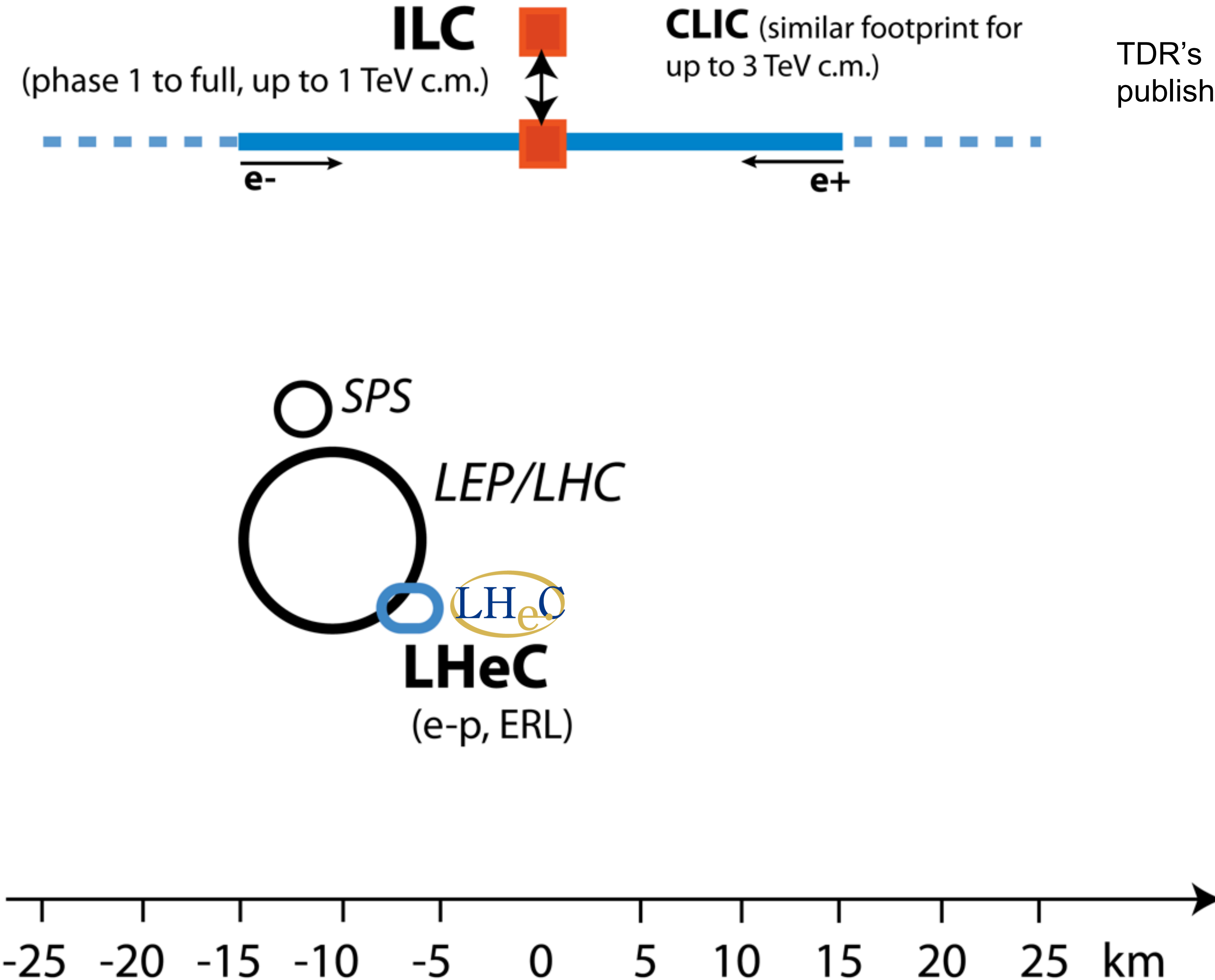
Slides by Ralf Assmann@EPS2013





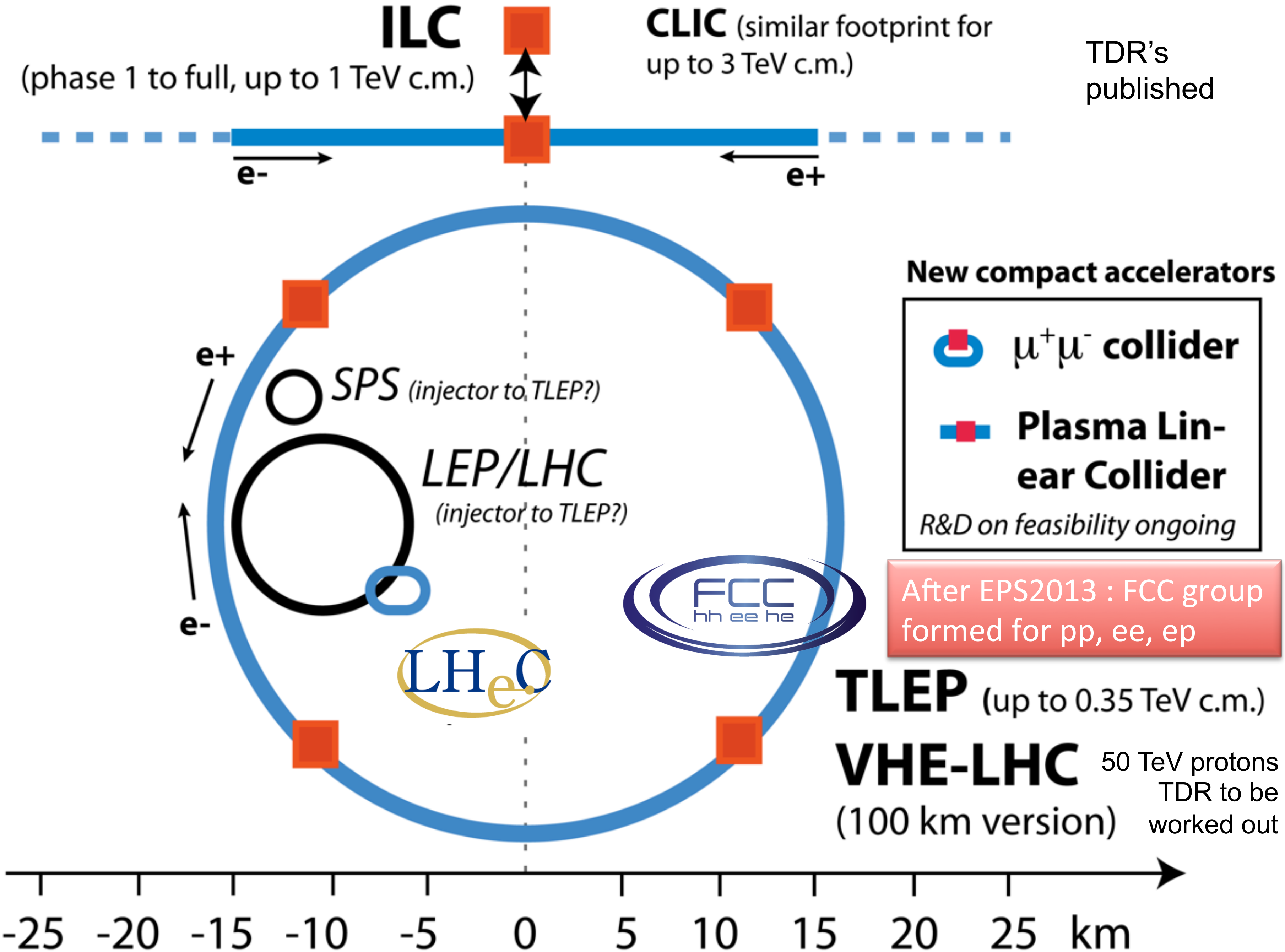
TDR's published

Collider options beyond LHC-Run II



TDR's published

Collider options beyond LHC-Run II



New LHeC International Advisory Committee

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

IAC Composition June 2014, plus
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.

Clarification and Tradition

Slide from Herwig Schopper

My clarifying remark:

Any ep/eA project **cannot be a major CERN flagship project**
Essentially only one experiment,
cannot satisfy > 8000 users

not in competition with main projects (HL-LHC, HE-LHC, CLIC, FCC)
complementary (in time, resources)

International collaboration will be essential

- **for experiments (detectors, intersections)**
- **accelerator design (parameters, optimisation)**
- **preparing necessary technology (SC rf cavities, possibly ERL test facility)**

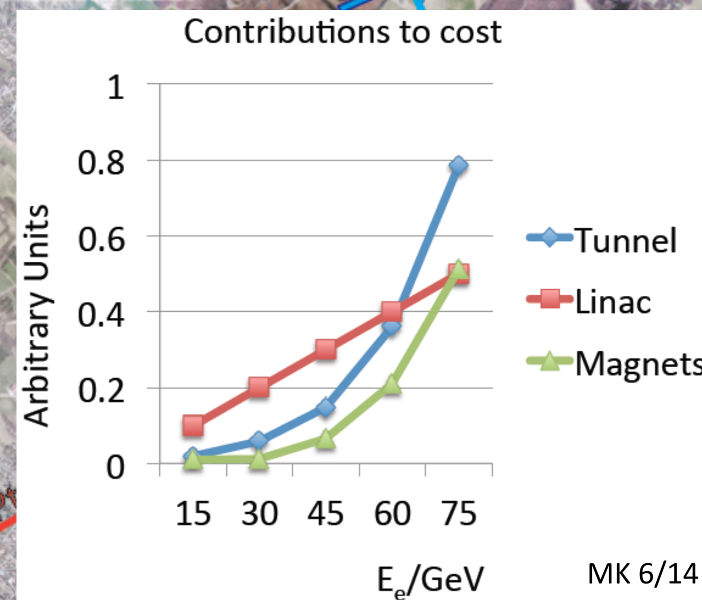
As in the tradition of CERN

Herwig Schopper (Chair IAC) at Chavannes in the Panel Discussion with the CERN Directorate
LHeC Workshop, Chavannes, 21.-22.1.2014
https://indico.cern.ch/conferenceDisplay.py?confId=278903

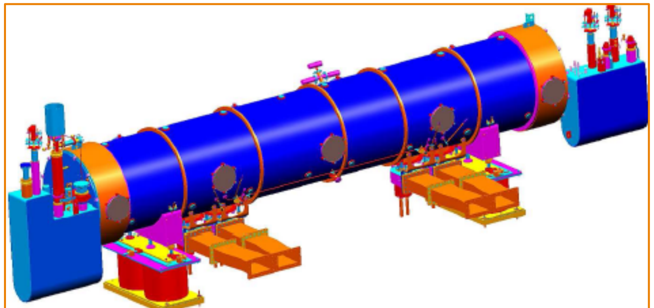
Civil Engineering Footprint

LHeC construction planning	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7
Land negotiations							
Environmental Impact Study							
Building permits							
Detailed design & tendering							
Construction							

7 years for 9km Civil Engineering



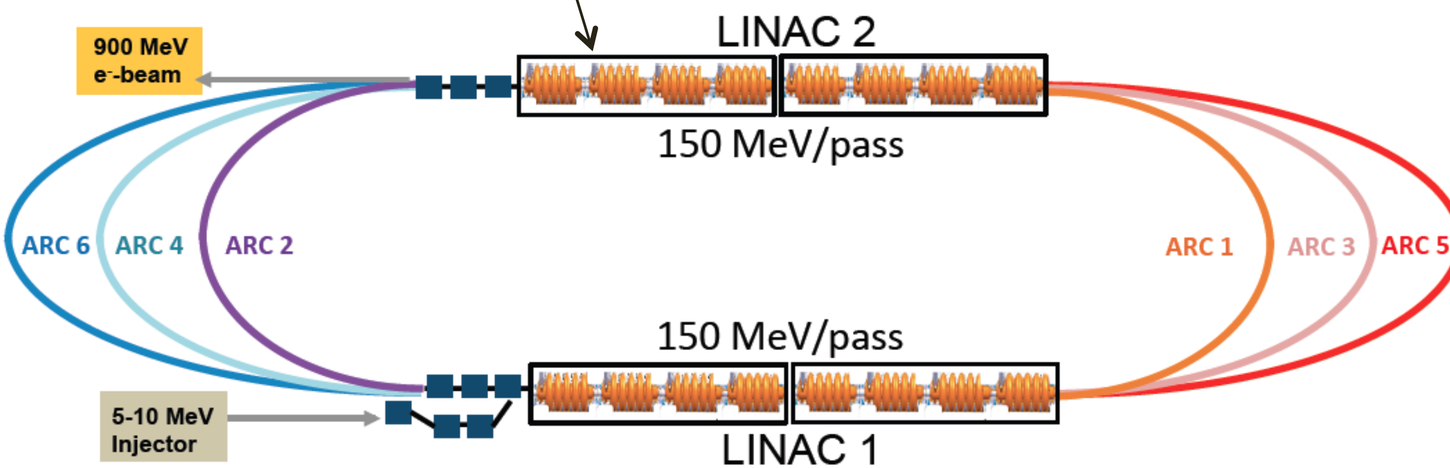
Superconducting RF and ERL Test Facility Design at CERN



R.Calaga, A.Hutton, B. Rimmer, E.Jensen et al.

Frequency 802 MHz
Design and built of 2 Modules (CERN+Jlab+)
Conceptual Design of the LTFC – end of 2015:
SCRF under beam conditions, applications,
high quality, high current, multipass, ERL

Interest for participation expressed by
BINP, BNL, CORNELL, IHEPBj, JLAB ..



Arc optics, Multipass linac optics, Lattice, Magnet specification, … first passes done

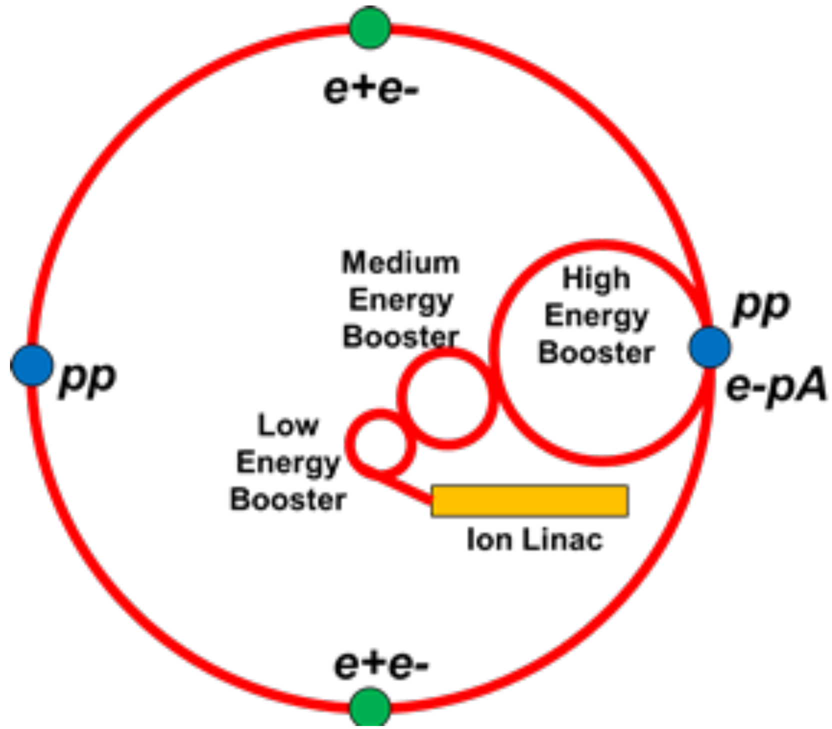
A. Bogazc, A.Valloni, A.Milanese et al.

ep colliders 11.2014 Max Klein	CEPC	MEIC	eRHIC	HERA 92-07	CepC	LHeC	SepC	FCC-he
√s/GeV	**13**	**35**	**122**	**319**	**1000**	**1300**	**3375**	**3464**
$L/10^{33}$ $cm^{-2}s^{-1}$	0.4	5.6	1.5	0.04	4.8	16	8.9	10
E_e /GeV	3	5	15.9	27.6	120	60	80	60
E_p /GeV	15	60	250	920	2100	7000	35600	50000
f /MHz	500	750	9.4	10.4	20	40	40	40
$N_{e/p}10^{10}$	3.7/0.54	2.5/0.42	3.3/3	3/7	1.3/16.7	0.4/22	3.3/5	0.5/10
$\varepsilon_{e/p}$ /µm	.03/.15	54/.35	32/.27	4.6/.09y	250/1	20/2.5	7.4/2.4	10/2
$\beta^*_{e/p}$/cm	10/2	10/2	5/5	28/18 y	4.2/10	10/5	9.3/75	9/40
comment	Lanzhou	full acc.	“Day1”	HERA II	Booster	ERL (H)	$E_e = M_W$	ERL (HH)
source	X.Chen July 14	McKoewn POETIC14	Litvinenko S.Brook 14	B.Holzer at CERN 2008	Y.Peng Oct. 2014	Frank Z. LHeC 2014	Y.Peng Oct. 2014	Frank Z. IPAC 2014

China: 55 km Ring option

Construction of a full energy SppC is envisioned years after completion of CepC and it also demands much high construction fund. A staging approach could realize an *e-p* collision based science program at the CepC-SppC facility much earlier though at lower energies.

To construct the SppC ion injector either in parallel to or shortly after the CepC construction. SppC's high energy booster (HEB) synchrotron could be converted to an ion collider ring for the *e-p* collisions, it stores a proton beam with energy up to 2.1 TeV or an ion beam with the same magnetic rigidity.



Yuhong Zhang, Yuemei Peng
14.10.2014
for pre-CDR mini-review

Outlook

ep/eA's Big Questions
requires precision measurements

- Structure of the Visible Matter
- Lepton-Quark Symmetry
- BSM (Higgs+, CI's, RPV SUSY..)
- BSM (Free colour, low x Dynamics)

ep/eA's Prominent Contributions

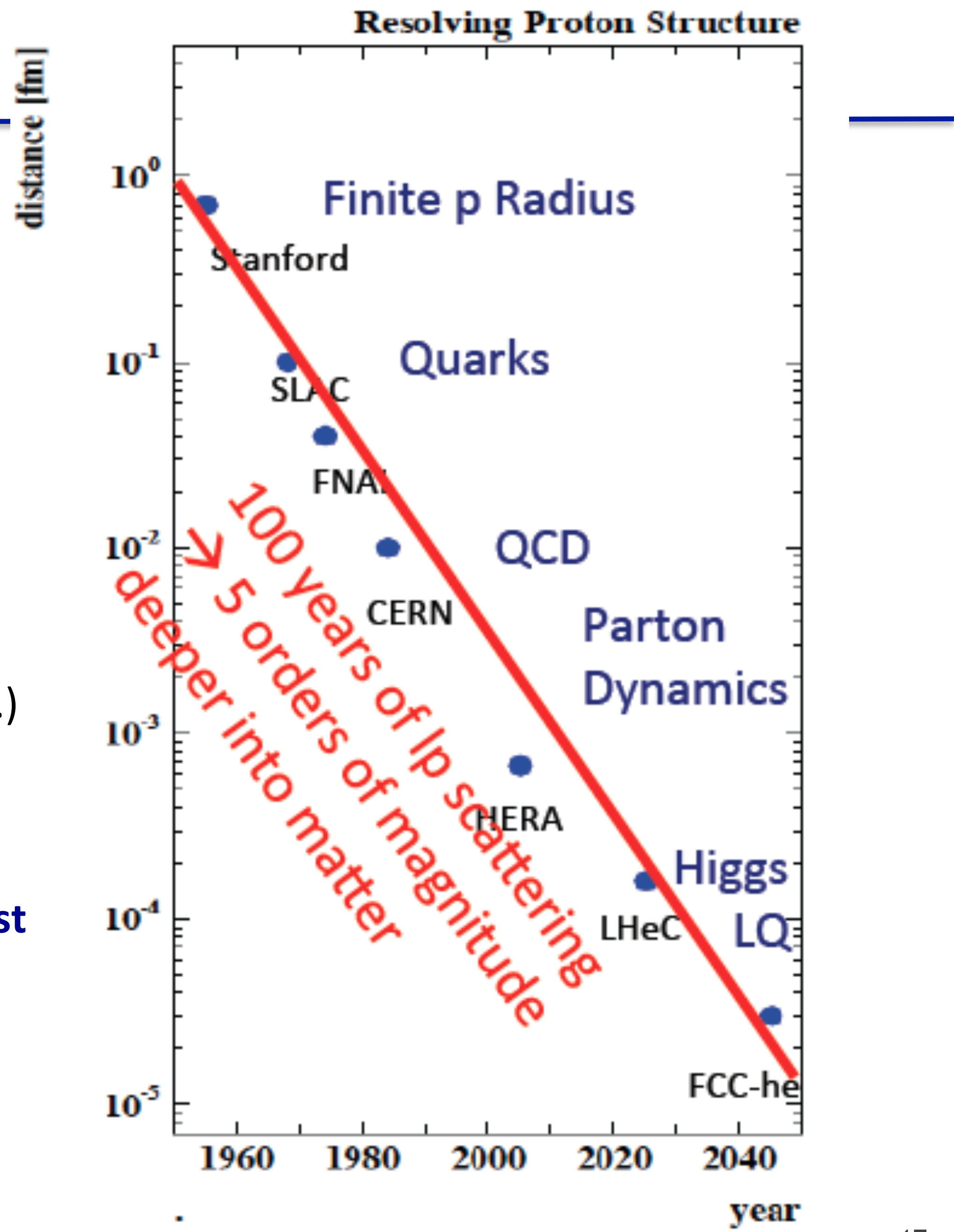
- Resolving structure (PDFs): Proton, Photon, Pomeron, GPDs, Neutron,…

→ huge synergy with HE pp-Colliders

- QCD of Spin, Heavy Ion physics (CGC …)
- Higgs in WW and ZZ
- Electroweak Physics beyond Z and H
- Surprises …

Future of ep/eA colliders and DIS must be maintained:

It is rich, from low to medium and highest energies, and the outcome cannot be fully simulated/predicted.
It is crucial to sustaining our field.



Additional material

EIC at Jefferson Lab

Jefferson Lab Design

- 12 GeV CEBAF is electron injector
- Figure 8 → high polarization
- Crab crossing → high luminosity
- Initial configuration (MEIC):
  3-12 GeV on 20-100 GeV ep/eA collider
- Upgradable to higher energies
  250 GeV protons + 20 GeV electrons

Present Activities

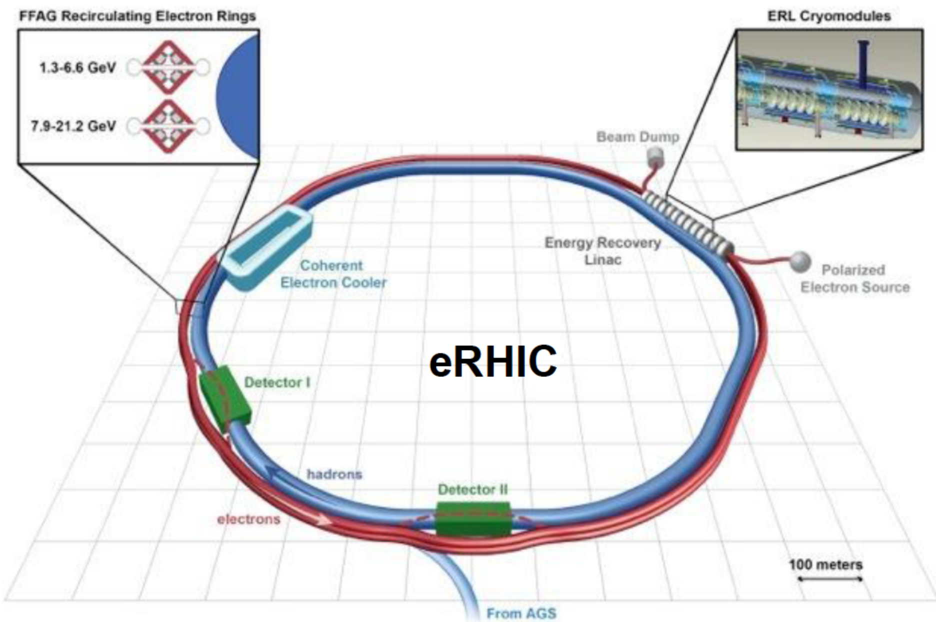
- Site evaluation
- Design optimization
- Accelerator, detector R&D
- Cost estimation

eRHIC

BNL's EIC Concept

eRHIC ERL + FFAG ring design @ $10^{33}/cm^2s$

15.9 GeV e^- + 255 GeV p or 100 GeV/u Au.



ePHENIX and eSTAR Letters of Intent

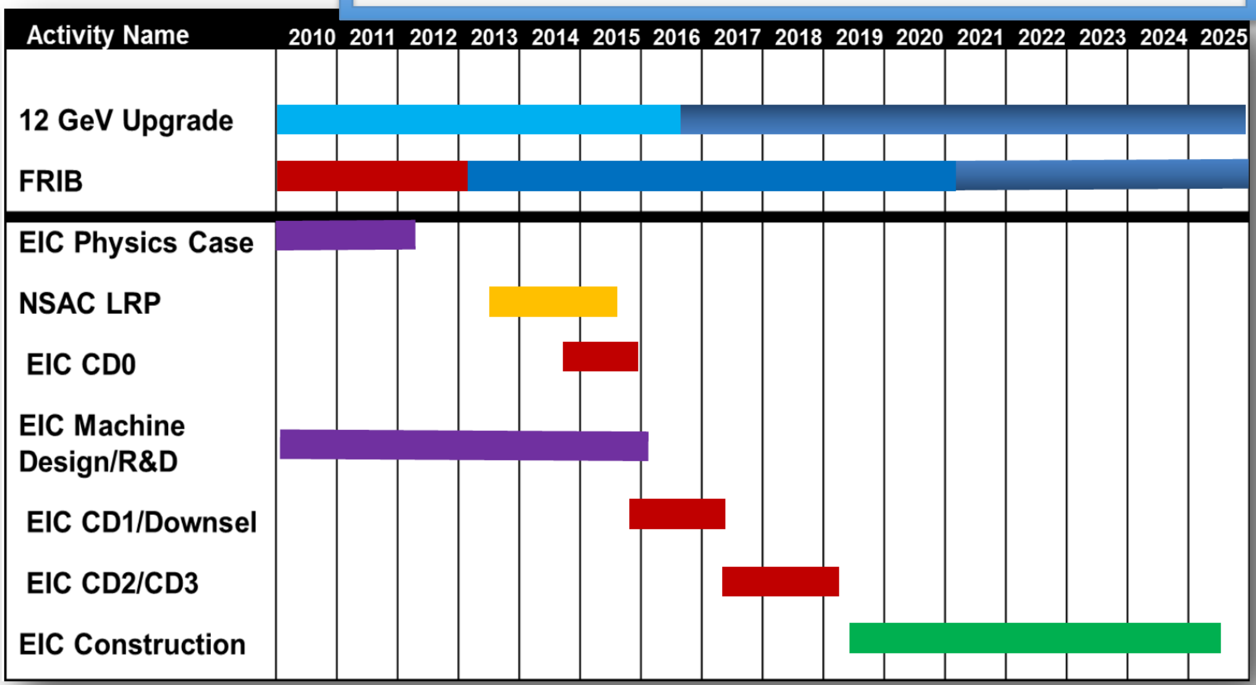
When completed, eRHIC will be the most advanced and energy efficient accelerator in the world

Brookhaven Science Associates

BROOKHAVEN NATIONAL LABORATORY

EIC Status

- NSAC Long Range Plan (2007)
  - EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities.
- NSAC Facilities Report (Redwine - 2013)
  - EIC absolutely central to future Nuclear Physics
- EICAC meeting (2/28-3/1 2014, BNL)
- EIC14 Accelerator workshop at Jefferson Lab (Mar 17-21, 2014)
- EIC Users Meeting SUNY Stony Brook, (June 24-27, 2014)
  - http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html
- NSAC Long Range Plan is considering EIC (2014-2015)



U.S. DEPARTMENT OF ENERGY | Office of Science JSA H.E. Montgomery ICFA Seminar, Beijing, 2014 19 Jefferson Lab

LHeC 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

LHeC 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)

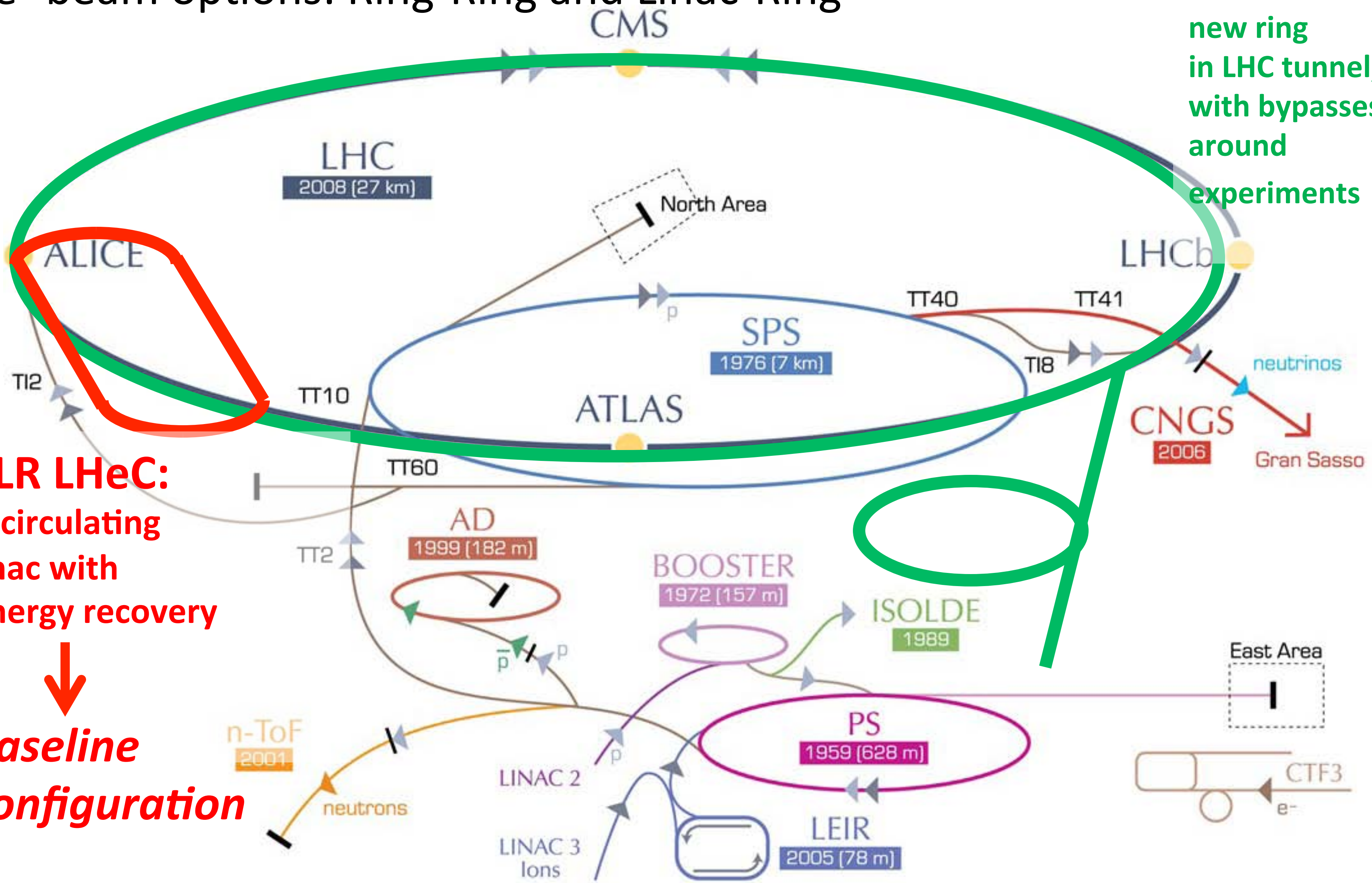
2010: Report to CERN SPC (June)
3rd CERN-ECFA-NuPECC Workshop at Chavannes-de-Bogis (12.-13.11.10)
NuPECC: LHeC on Longe Range Plan for Nuclear Physics (12/10)

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

The LHeC 'facility'

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



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

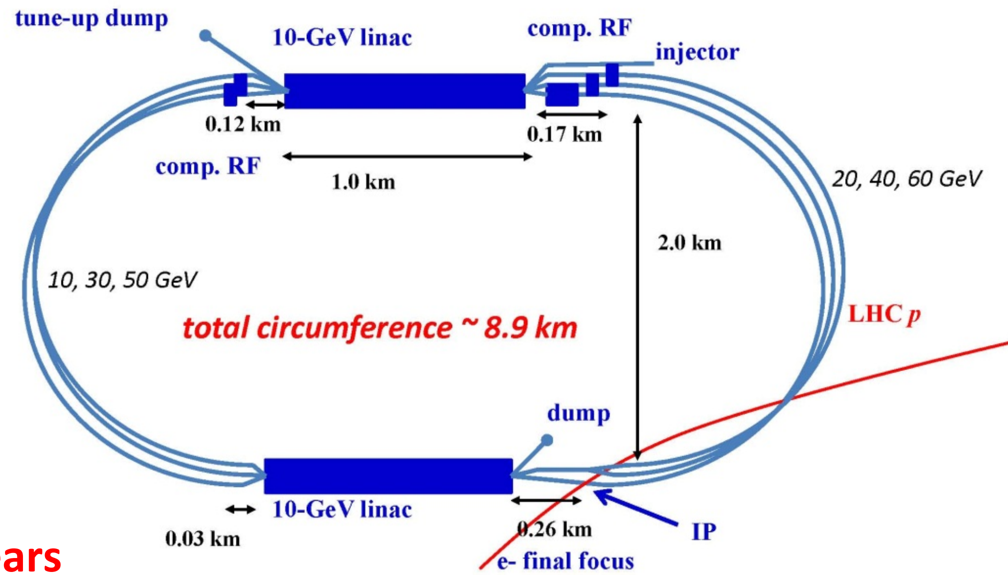
ELR LHeC:
recirculating linac with energy recovery

↓

baseline configuration

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 80-90%
- 3 return ARCs, 20 MV/m
- Energy recovery in same structure
- Installation fully decoupled from LHC operation!



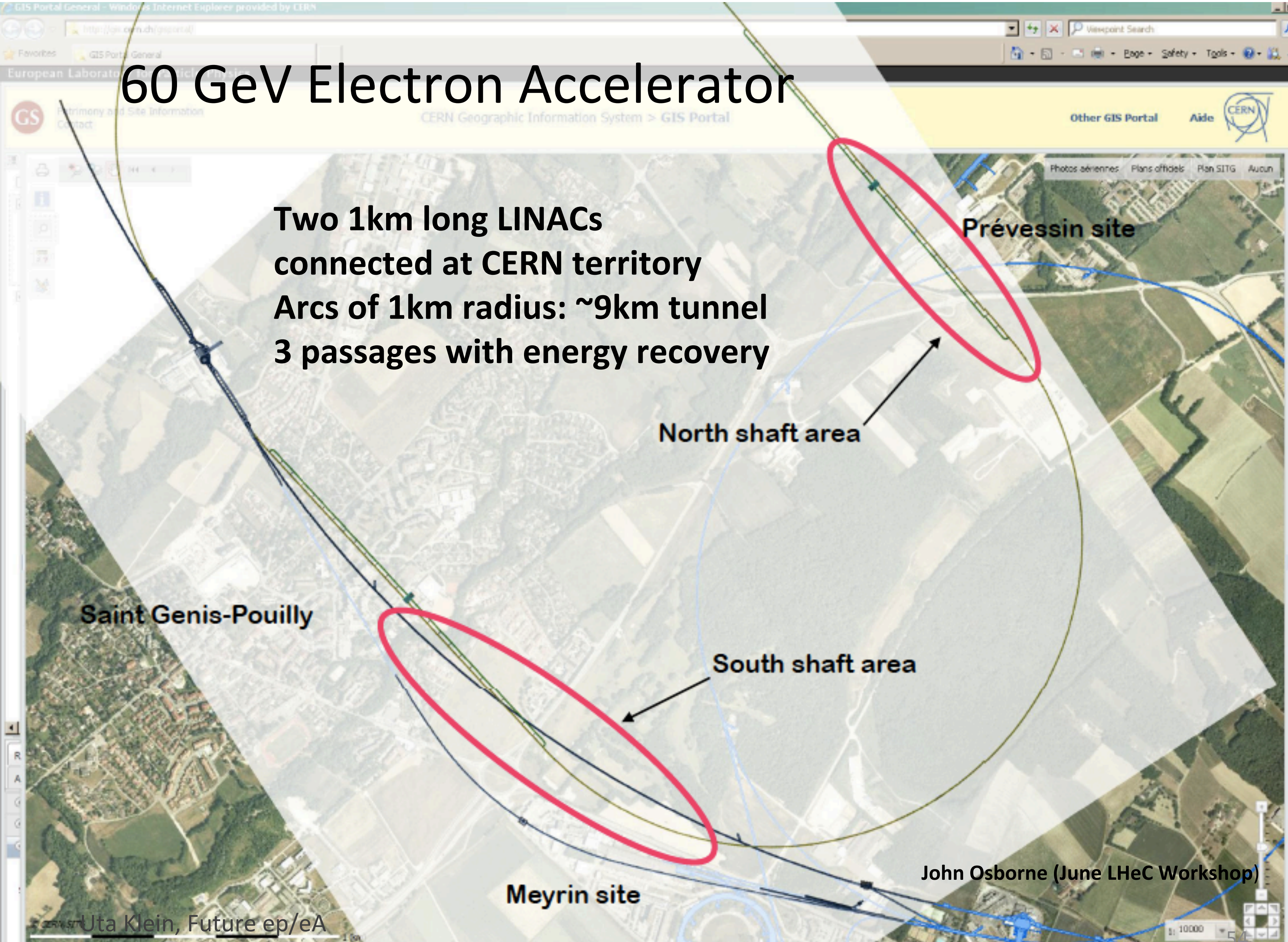
- ep Lumi 10^{33} - 10^{34} cm s^{-2} s^{-1} **
- 10 - 100 fb^{-1} per year
- 100 fb^{-1} – 1 ab^{-1} total collected in 10 years
- eD and eA collisions have always been integral to programme
- eA luminosity estimates ~ 10^{32} cm s^{-2} s^{-1} for eD (ePb)

** based on existing high luminosity proposal

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

60 GeV Electron Accelerator

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

Future Circular Collider (FCC) study ; goals: CDR and cost review for the next European Strategy Update (2018)

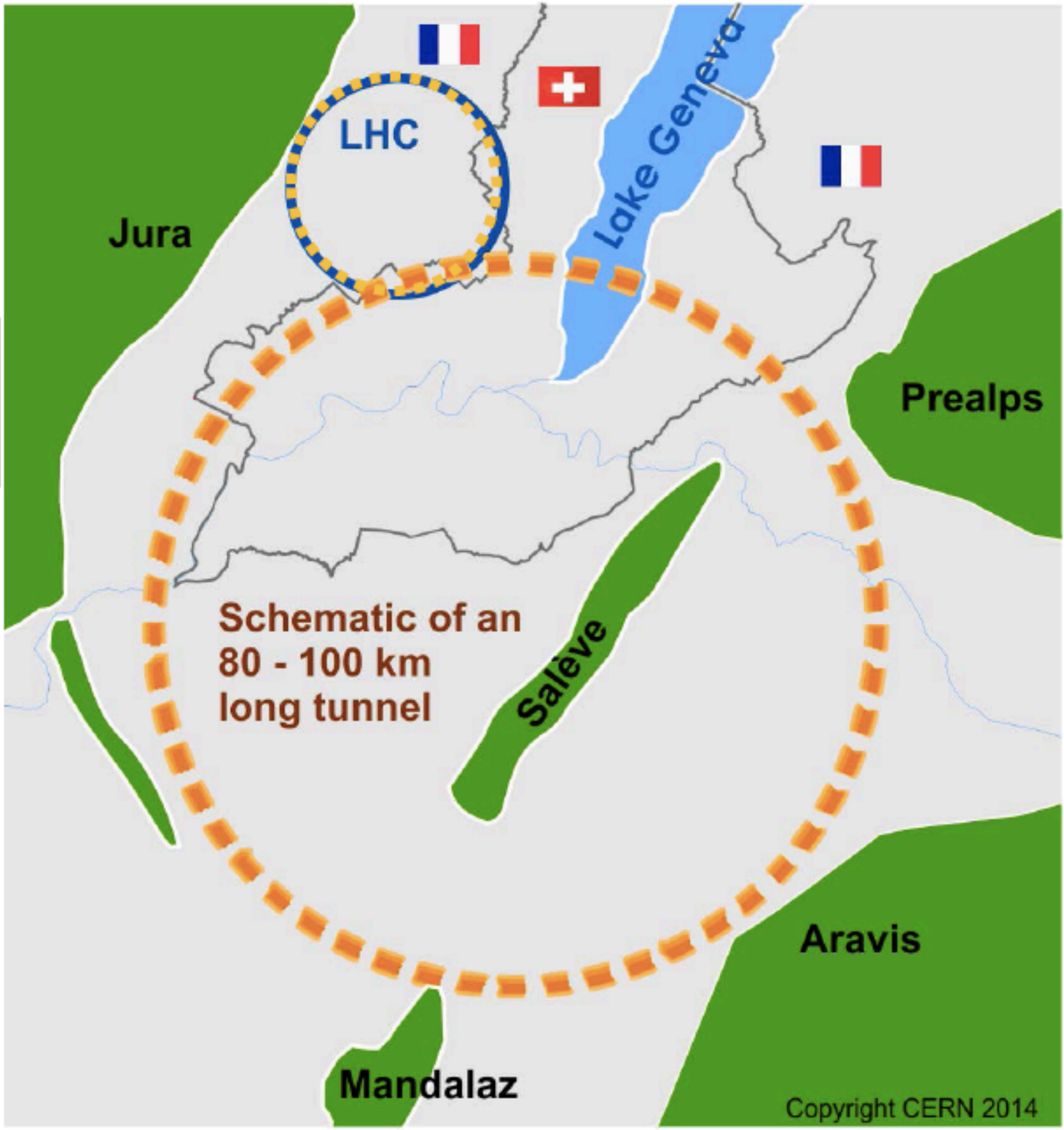
International collaboration :

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV in 100 km
~20 T ⇒ 100 TeV in 80 km

- including ***HE-LHC*** option: 16-20 T in LHC tunnel
- ***e^+e^-* collider (*FCC-ee/TLEP*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **100 km infrastructure** in Geneva area

M. Benedikt



collider parameters	FCC ERL	FCC-ee ring		protons
species	e^- (e^+?)	$e^\pm$	$e^\pm$	p
beam energy [GeV]	60	60	120	50000
bunches / beam	-	10600	1360	10600
bunch intensity [10^{11}]	0.05	0.94	0.46	1.0
beam current [mA]	25.6	480	30	500
rms bunch length [cm]	0.02	0.15	0.12	8
rms emittance [nm]	0.17	1.9 (*x*)	0.94 (*x*)	0.04 [0.02 *y*]
$\beta_{x,y}$*[mm]	94	8, 4	17, 8.5	400 [200 *y*]
$\sigma_{x,y}$* [μm]	4.0	4.0, 2.0		equal
beam-b. parameter ξ	(D=2)	**0.13**	**0.13**	0.022 (0.0002)
hourglass reduction	0.92 (H_D=1.35)	**~0.21**	~0.39	
CM energy [TeV]	3.5	3.5	4.9	
luminosity[10^{34}cm^{-2}s^{-1}]	**1.0**	**6.2**	**0.7**	

F.Zimmermann
ICHEP14, June

PRELIMINARY
L is 1000*HERA

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**	

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

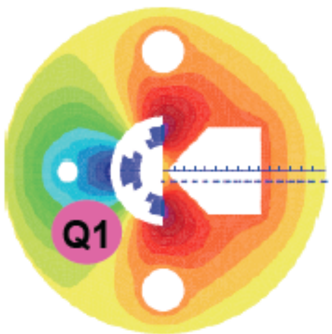
Using pp LHC pile-up estimates

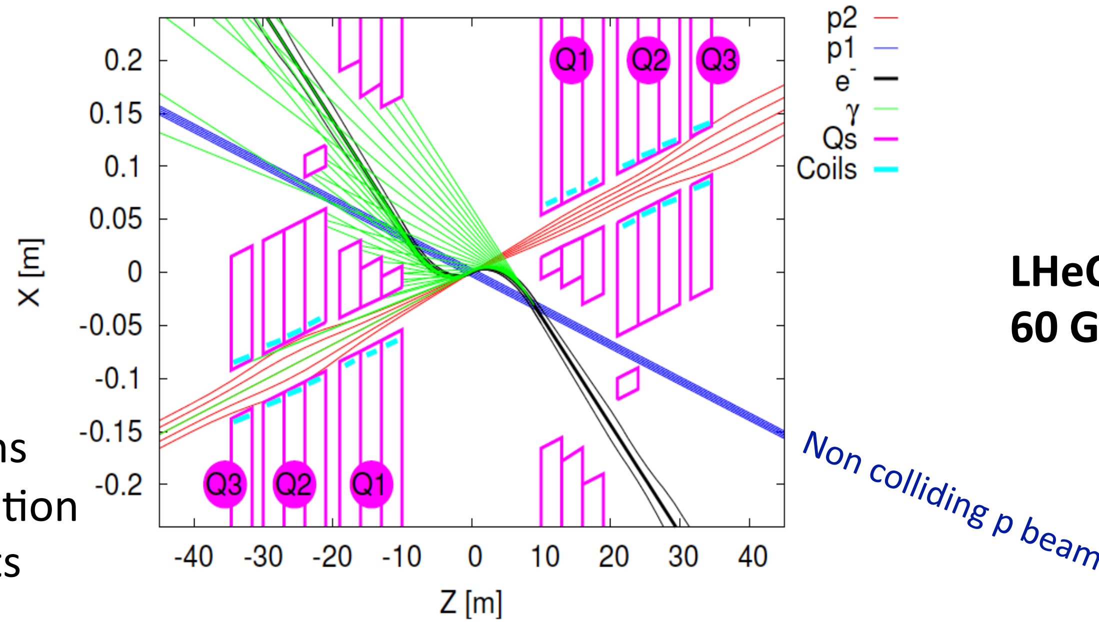
$$N(ep)=N(pp) \text{ x } s(yp)/s(pp) \text{ x } L(ep)/L(pp)$$
$$= 150 * 0.003 * 0.2$$
$$= 0.1$$

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

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

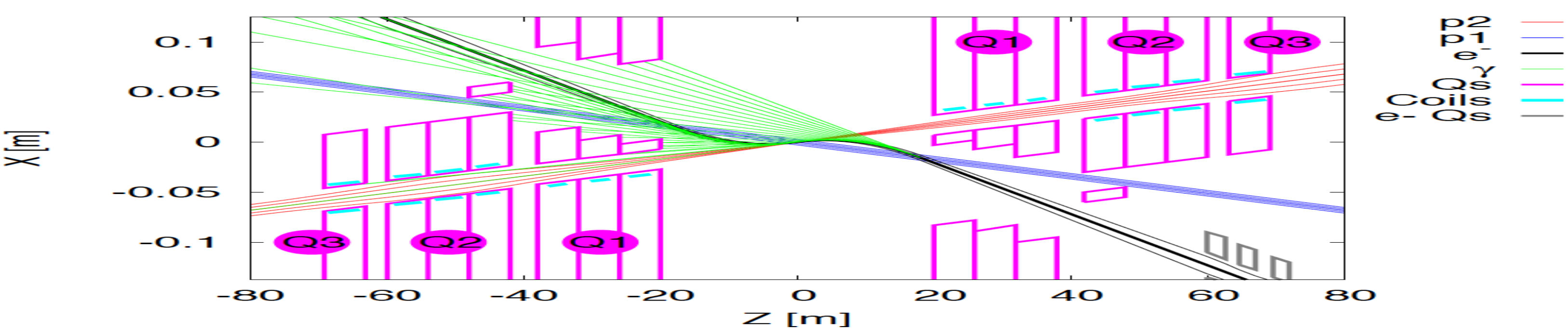
Interaction Regions for ep with Synchronous pp Operation





LHeC (CDR)
60 GeV * 7 TeV

Likely one IR.
Matching e and p beams
Limit synchrotron radiation
Design of inner magnets
Beam-beam effects ….

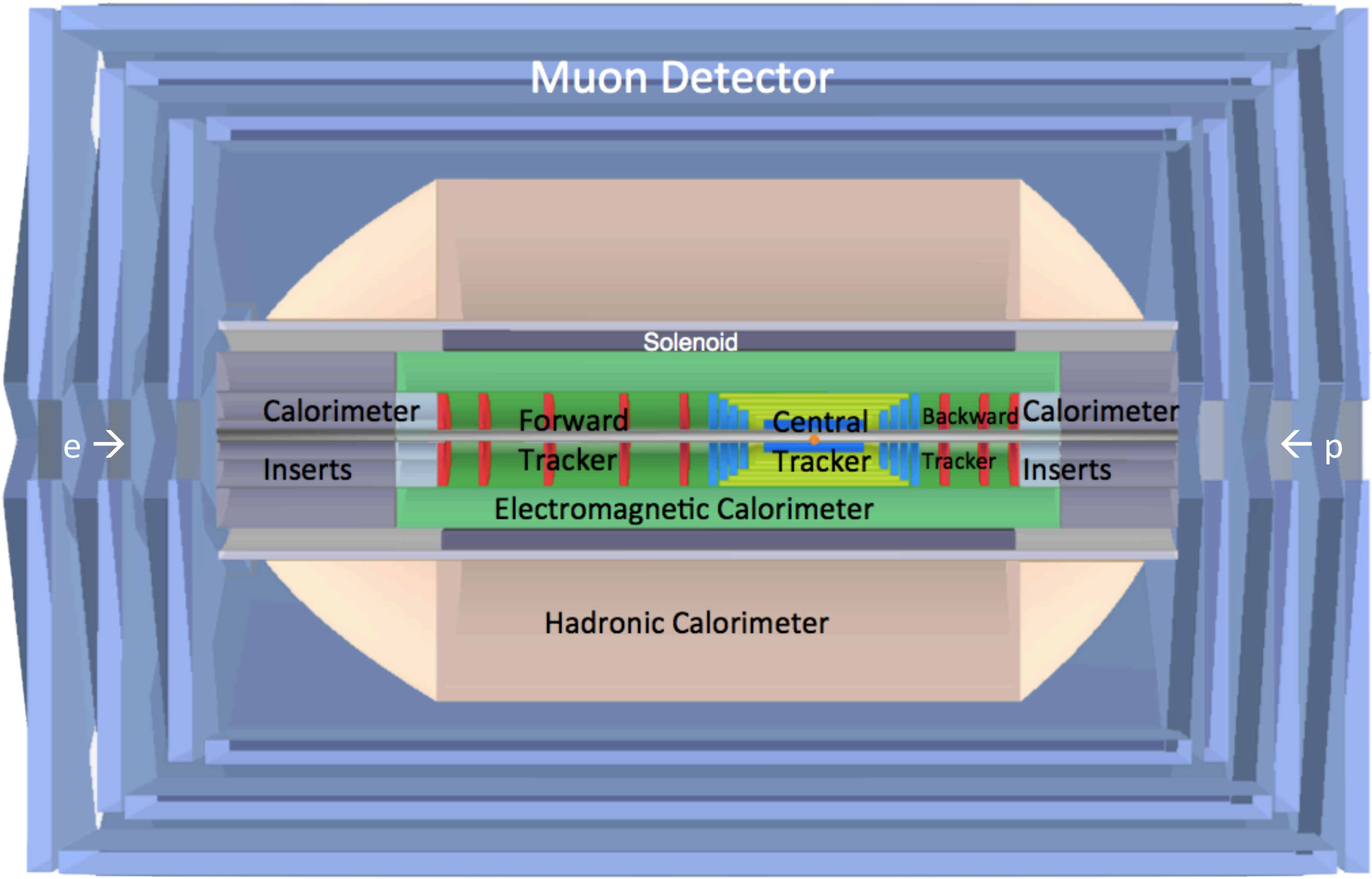


Tentative: ε_p=2µm, β*=20cm → σ_p=3µm ≈σ_e matched! ε_e=5µm ..

FCC-he (ERL)
60 GeV * 50 TeV

Rogelio Tomas, Max Klein, ICHEP14

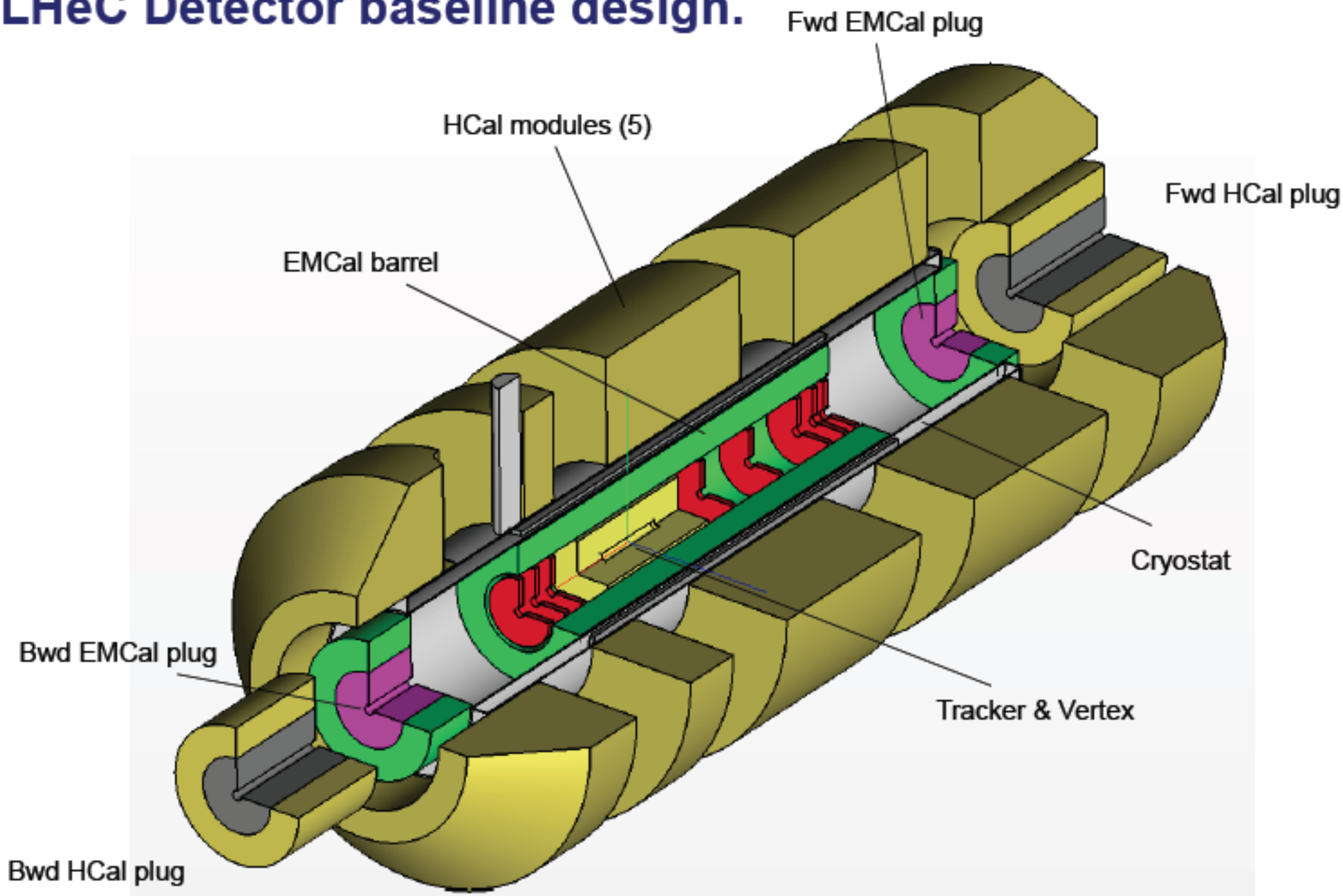
LHeC Detector Overview



Detector option 1 for LR and full acceptance coverage

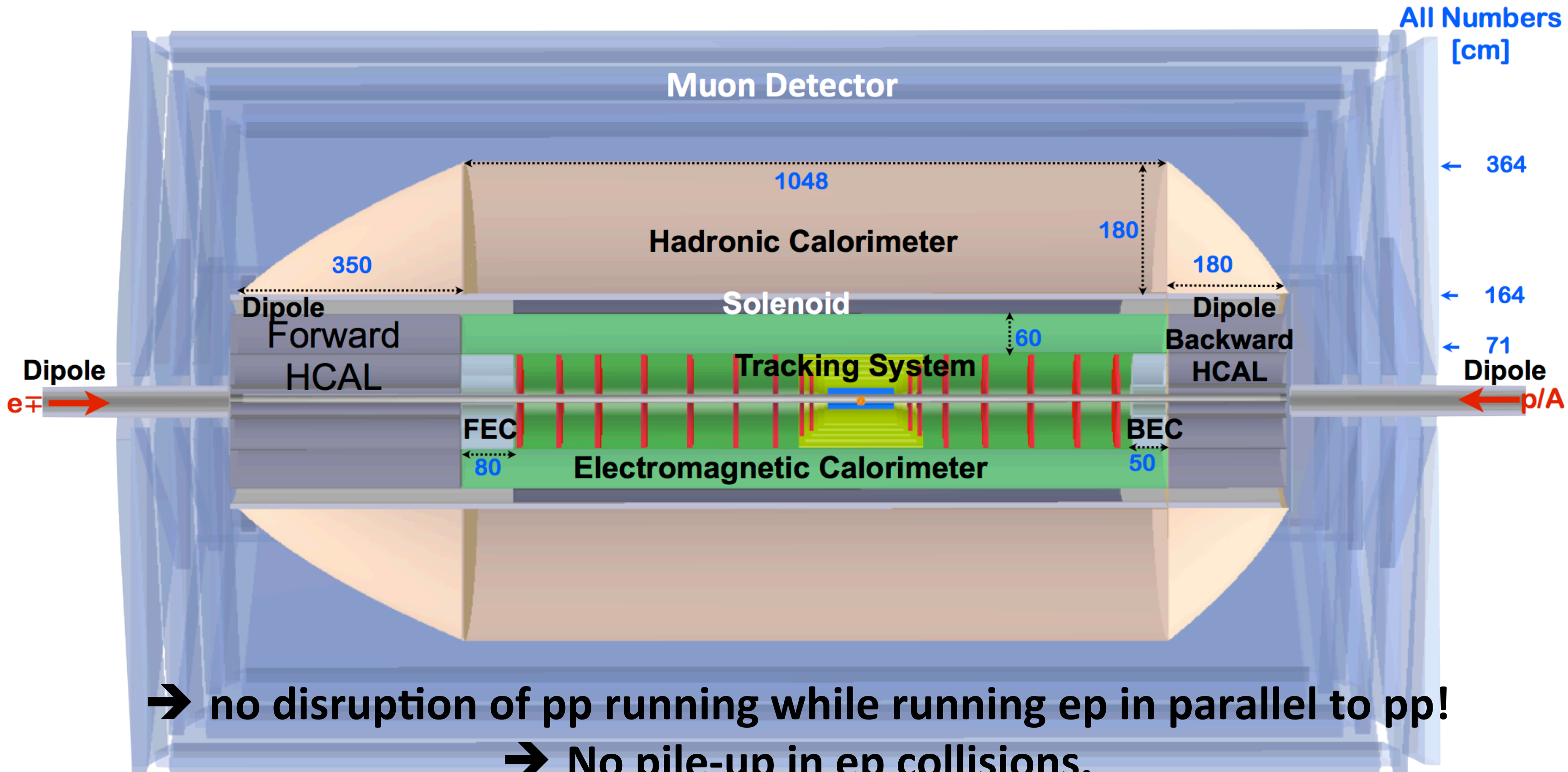
Forward/backward asymmetry in energy deposited and thus in geometry and technology
Present dimensions: LxD =14x9m^2 [CMS 21 x 15m^2 , ATLAS 45 x 25 m^2]
Taggers at -62m (e),100m (γ,LR), -22.4m (γ,RR), +100m (n), +420m (p)

LHeC Detector baseline design.



FCC-he detector

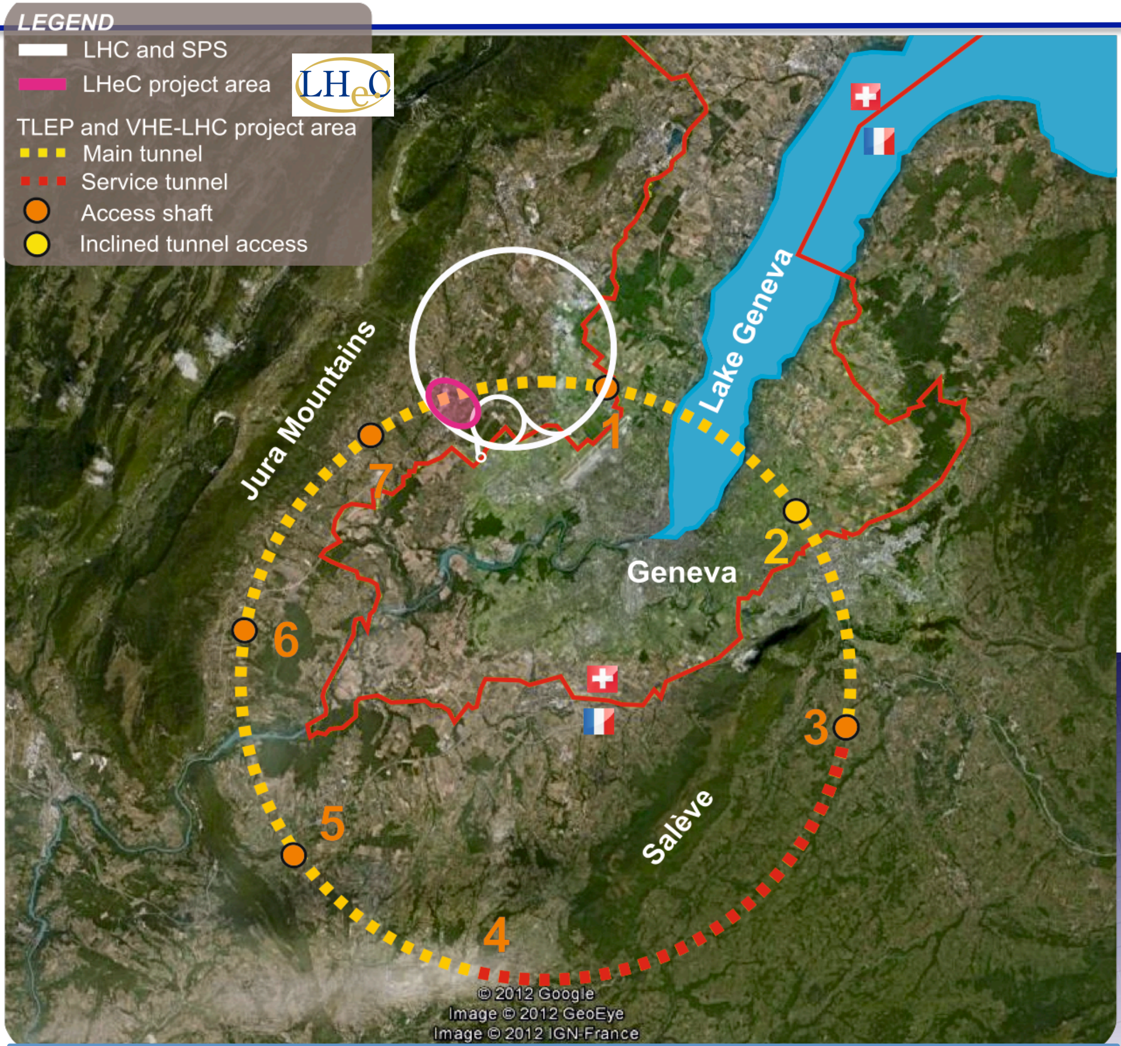
→ **Longer in p direction (x 2 for calorimeters to contain showers)**
→ **Same or slightly longer in electron direction (about 1.3 for 120 GeV)**



→ **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

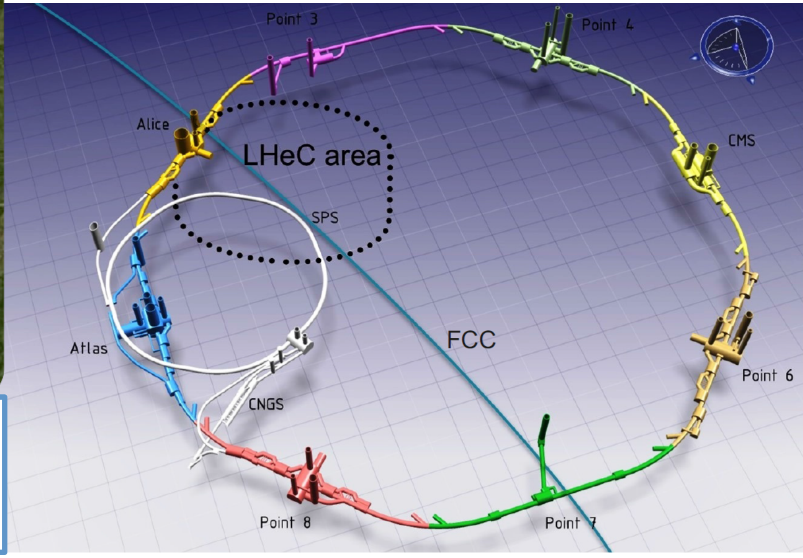
Future Circular Colliders at CERN*)



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

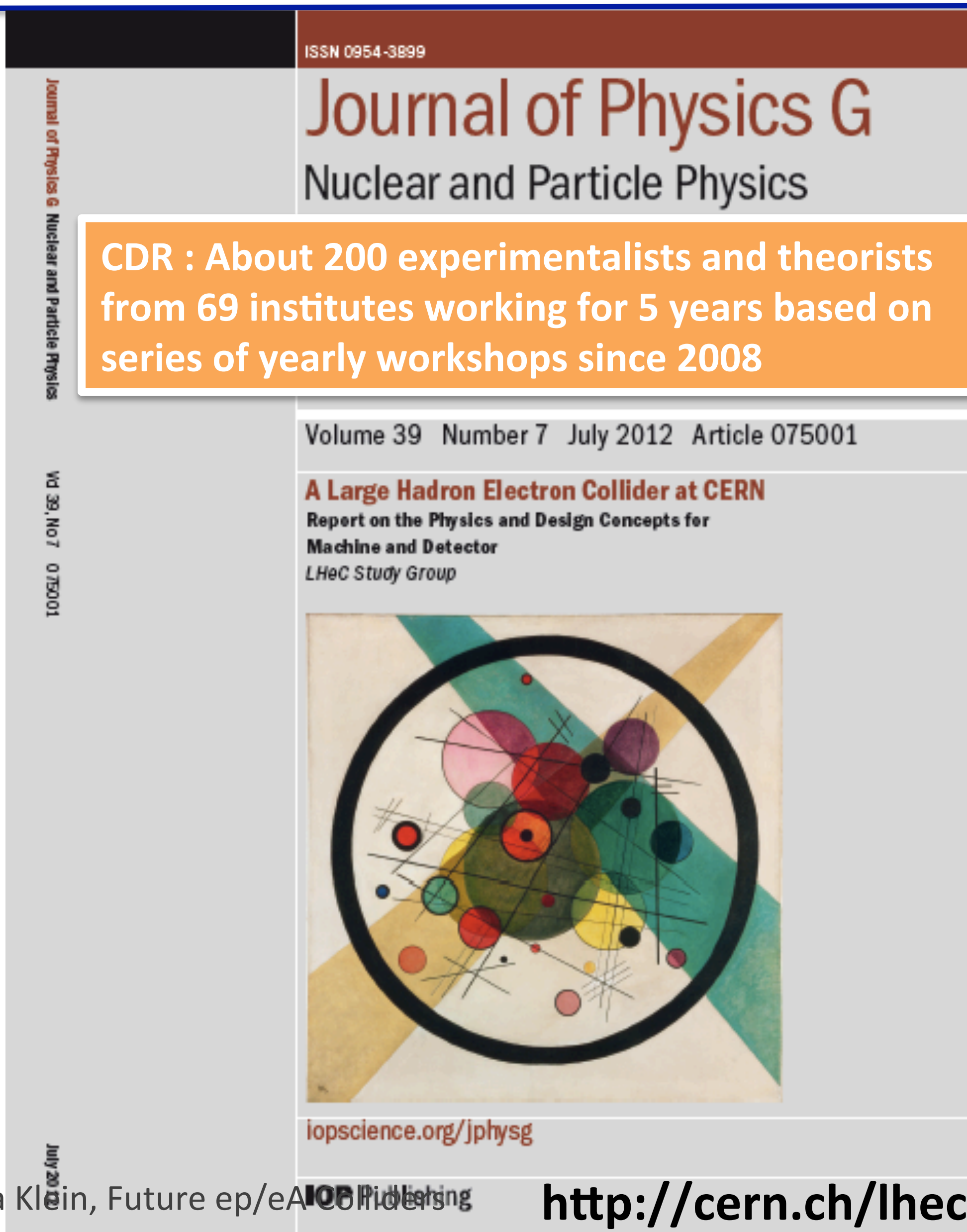


*) "Civil Engineering Feasibility Studies for Future Ring Colliders at CERN", Contributed by O.Brüning, M.Klein, S.Myers, J.Osborne, L.Rossi, C.Waaijer, F.Zimmerman to IPAC13 Shanghai

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

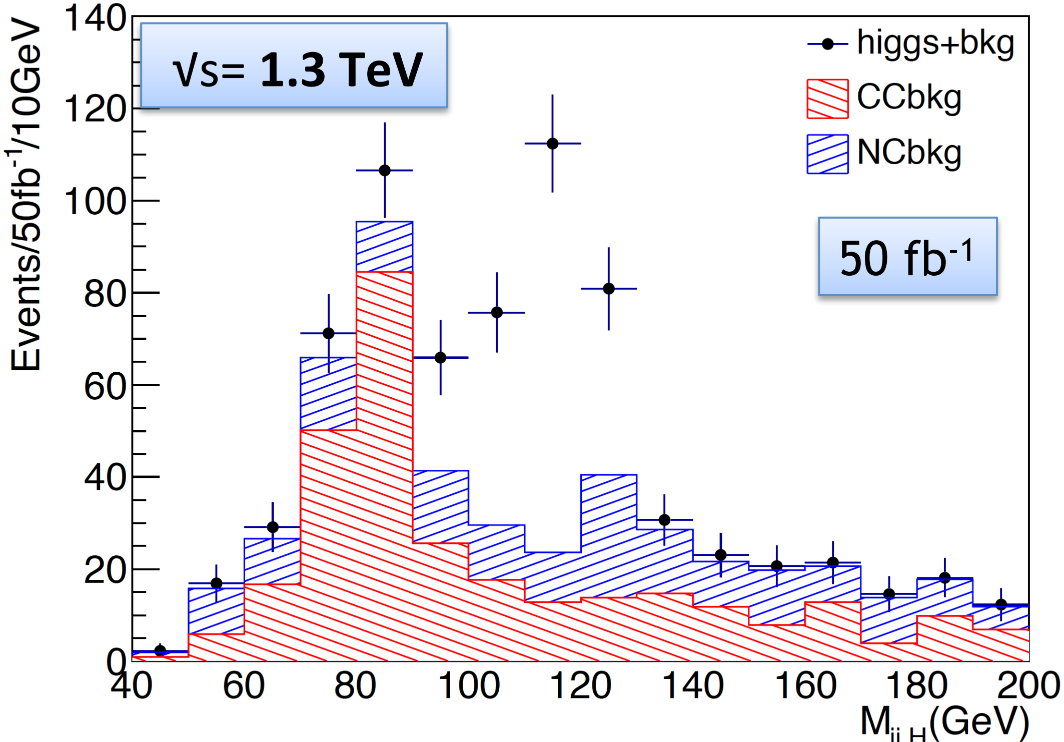
Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)
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

H→$b\bar{b}$ 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

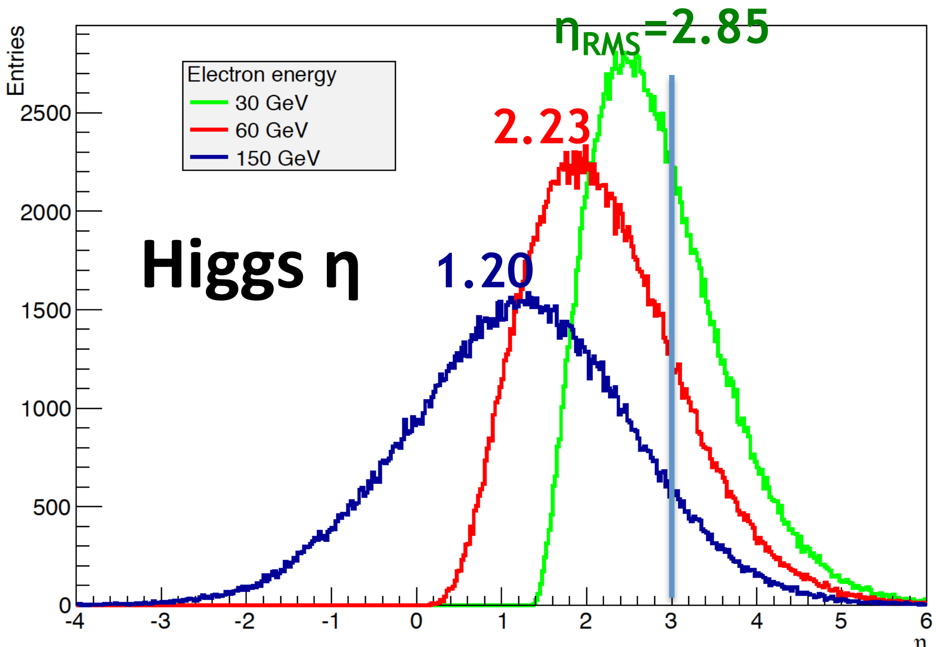
- Electron energy recovery LINAC with **high electron polarisation of 80% and 10^{34} cm^{-2} s^{-1}** ➔ enhancement by factor 20*1.8 feasible, i.e. around 6300 Higgs candidates for E_e=60 GeV allowing to measure Hbb coupling with ~ **0.5 % - 1%** statistical precision.

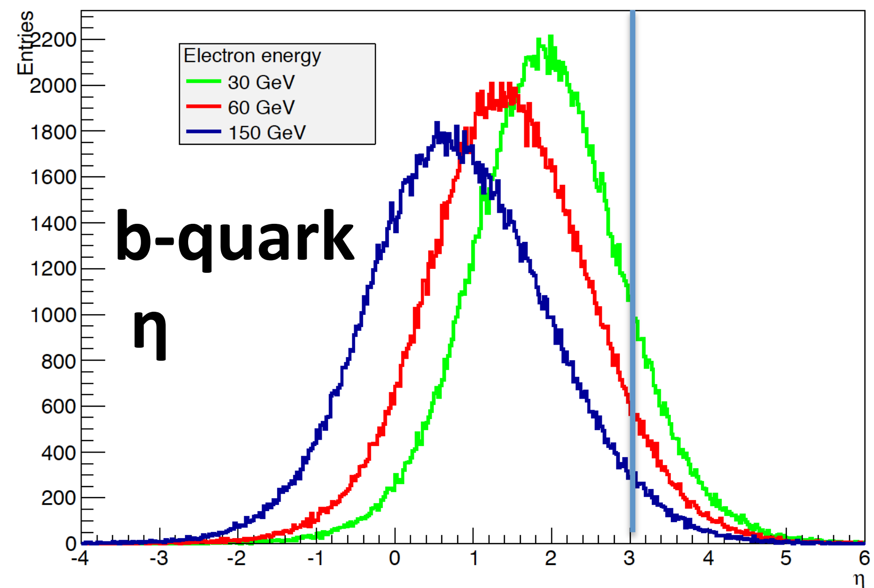
- Very promising estimate of S/N ➔ more sophisticated analysis and detector optimisations may enhance those prospects further

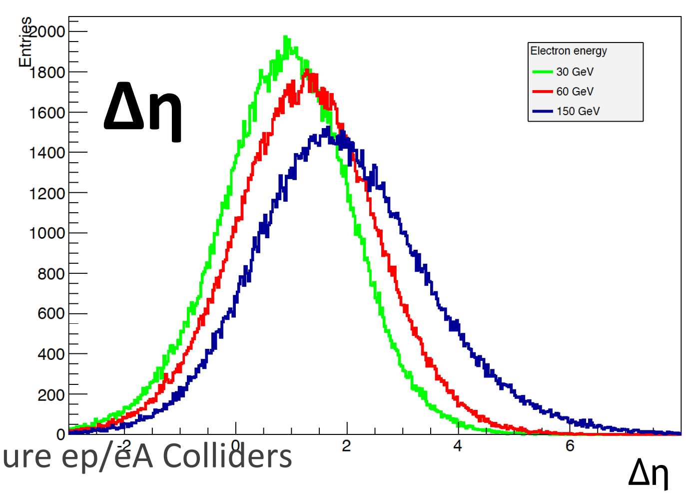
Higgs acceptance vs E_e

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

[Master thesis by Sergio Mandelli, Liverpool 2013]



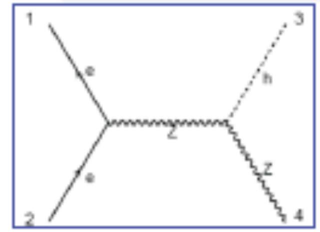


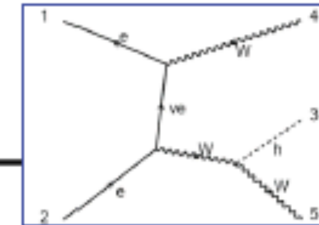


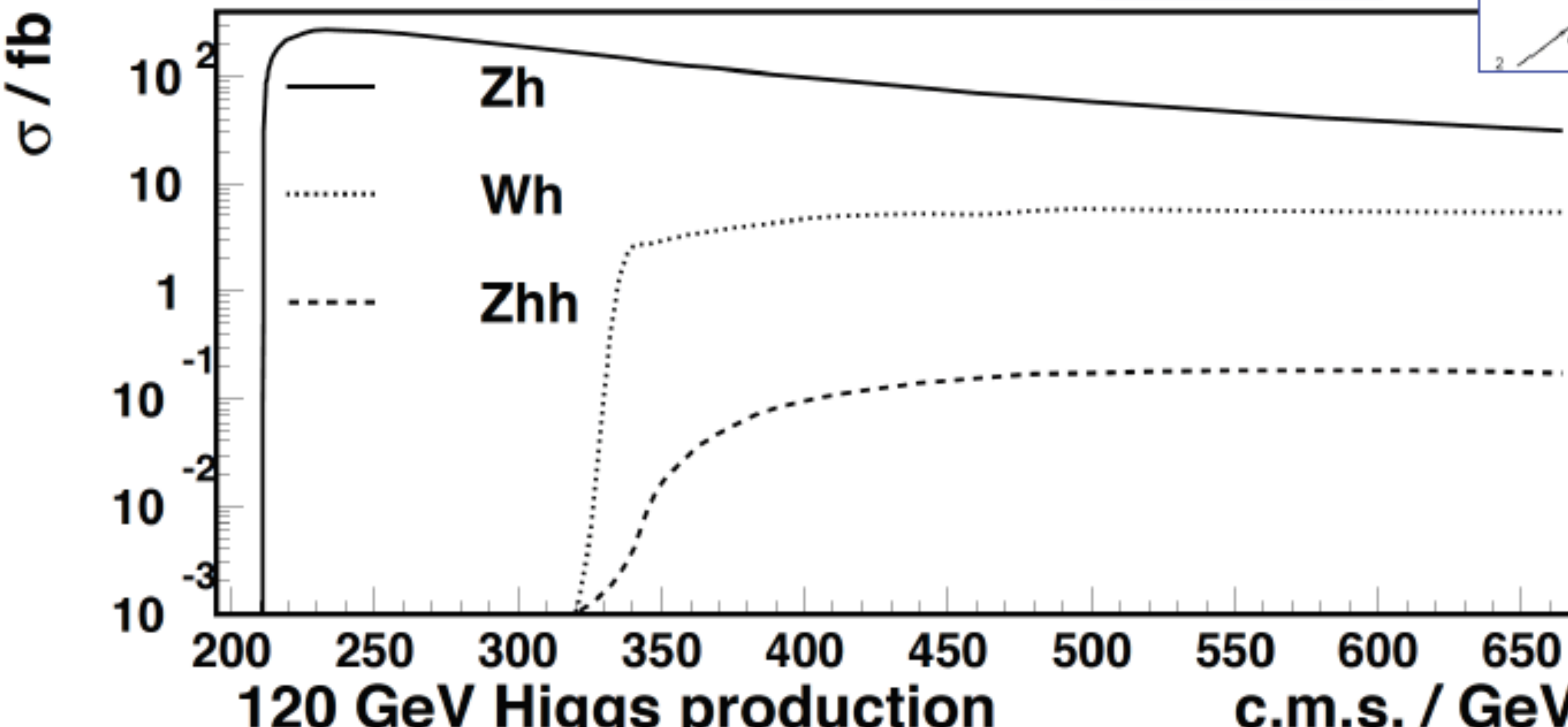
- ➔ lowering of electron beam energy (more cost efficient) will challenge more detector design: worse separation between higgs and forward jet (Δη shrinks by 1 unit) and b-quarks from Higgs decay are more forward
- ➔ **<u>stick with 60 GeV</u>** E_e : decay products of Higgs scattered at ~28° (η~1.4)

120 GeV Higgs in e+e-

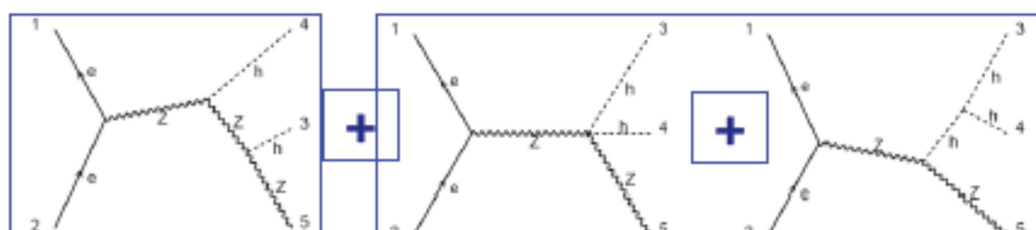
Madgraph5, CTEQ6L1, $M_H^2+P_t^2$, narrow width
Decay into h→ bb and Z→ee : factor 0.025



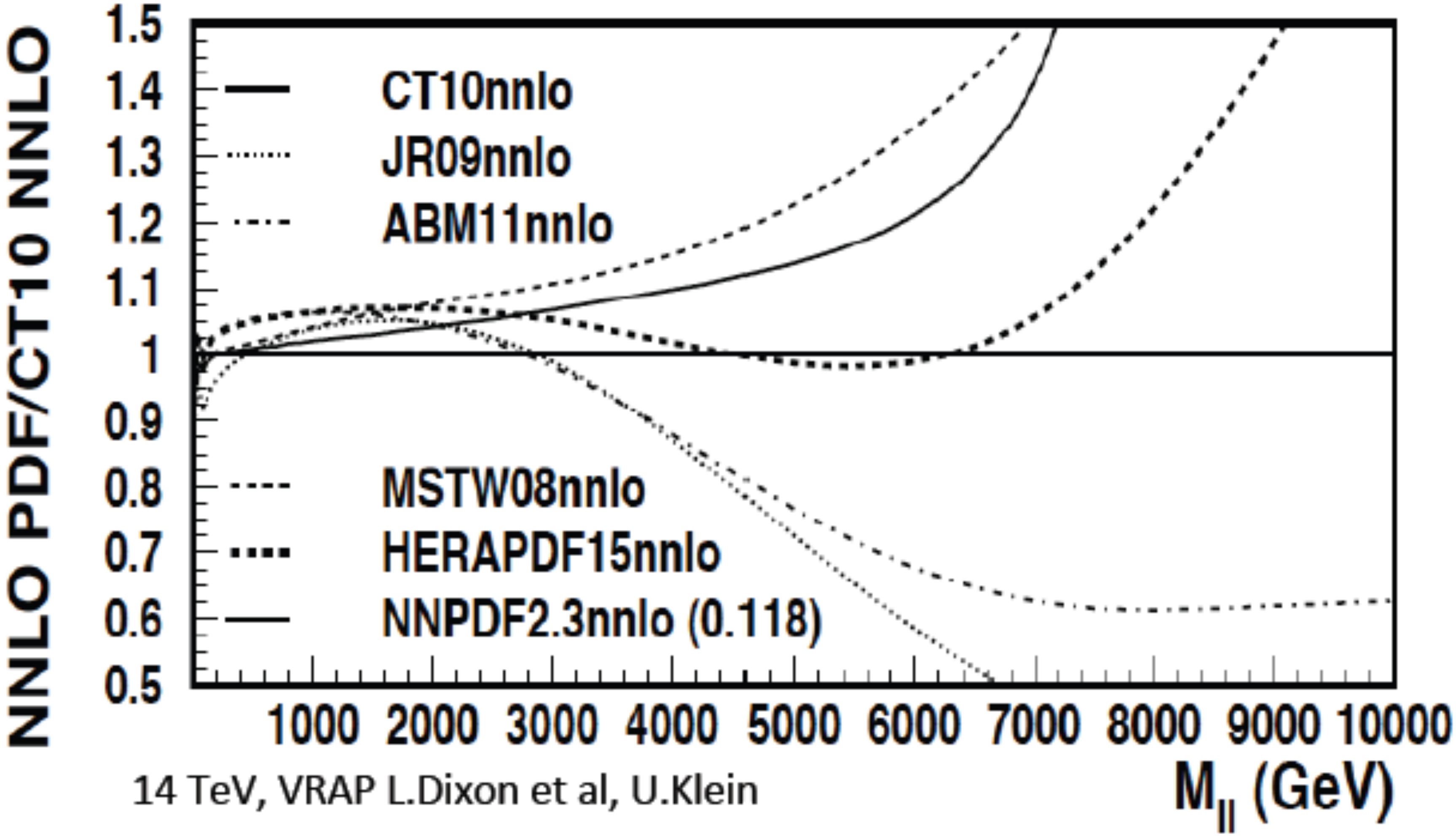




Zh threshold
at 211 GeV
= (120+91) GeV

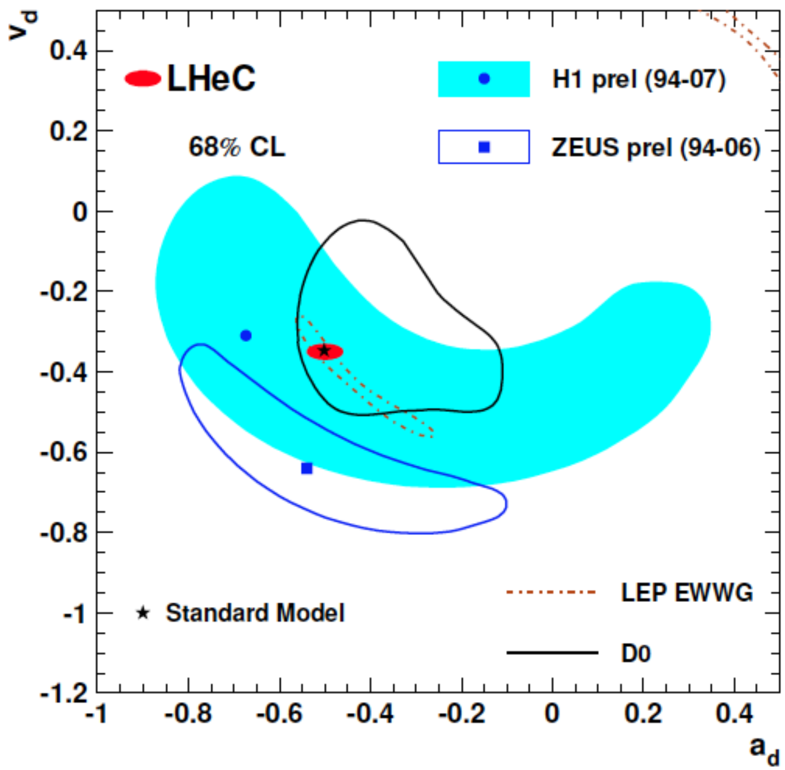


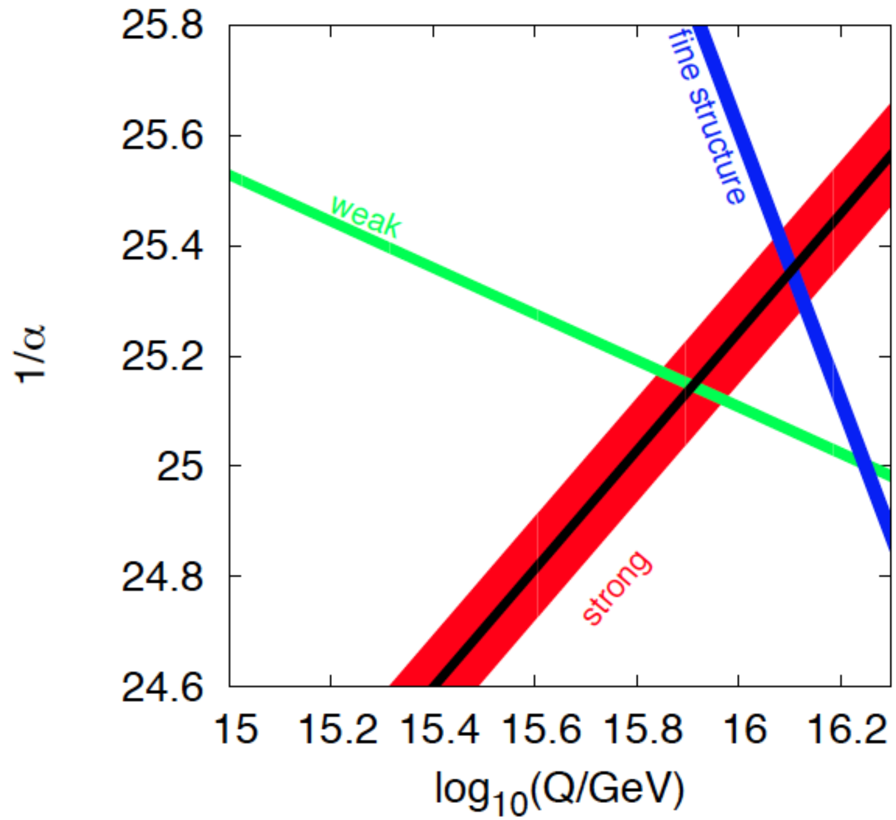
NC DY : current PDF uncertainties



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

High precision QCD





$Q^2 \gg M_{Z,W}^2$, 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 ←

Strong Coupling Constant

α_s least known of coupling constants

Grand Unification predictions suffer from $\delta\alpha_s$

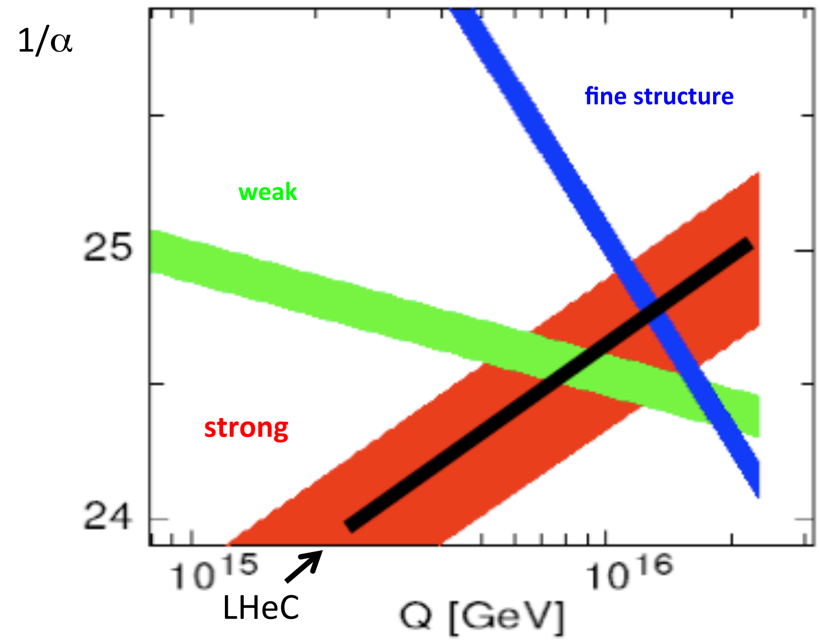
Is DIS lower than world average (?)

LHeC: per mille - indep. of BCDMS.

Challenge to experiment and to h.o. QCD →
A genuine DIS research programme rather than one outstanding measurement only.

More or as accurate as lattice QCD

(cf Les Houches 2013)



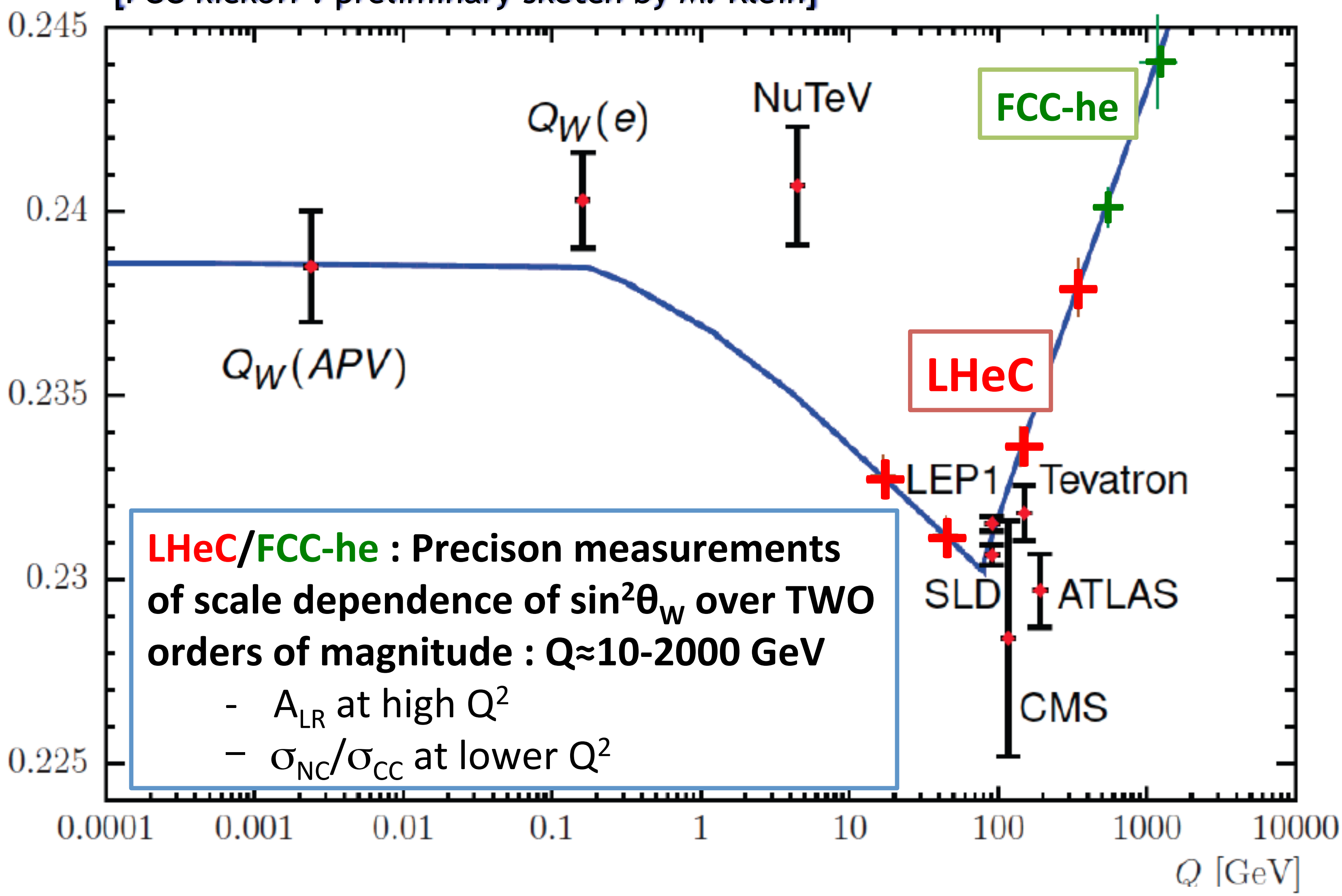
case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

Two independent QCD analyses using LHeC+HERA/BCDMS

DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) γ_h>5°	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

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

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

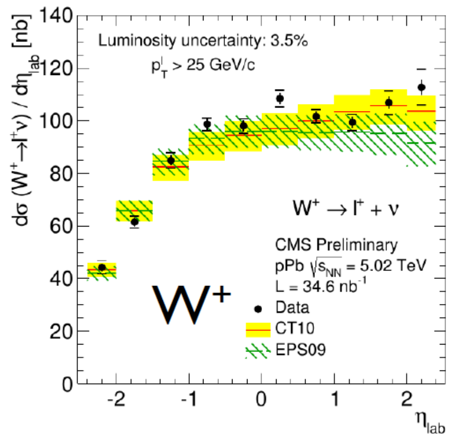
CDR : Measurement Simulations

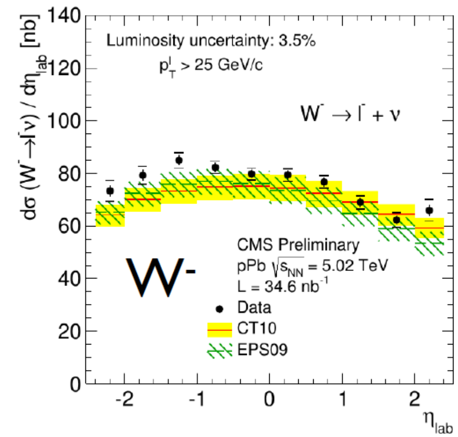
source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	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 $y = 0.84,\ 0.1,\ 0.004$.

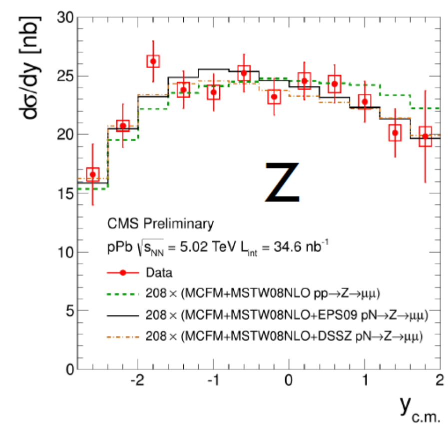
Full simulation of NC and CC inclusive cross section measurements including statistics, uncorrelated and correlated uncertainties – checked against H1 MC

Synergy : nuclear PDFs in pp





- EW bosons used to test factorisation in pA/AA, and offer some constrain to nPDFs (e.g. u/d).



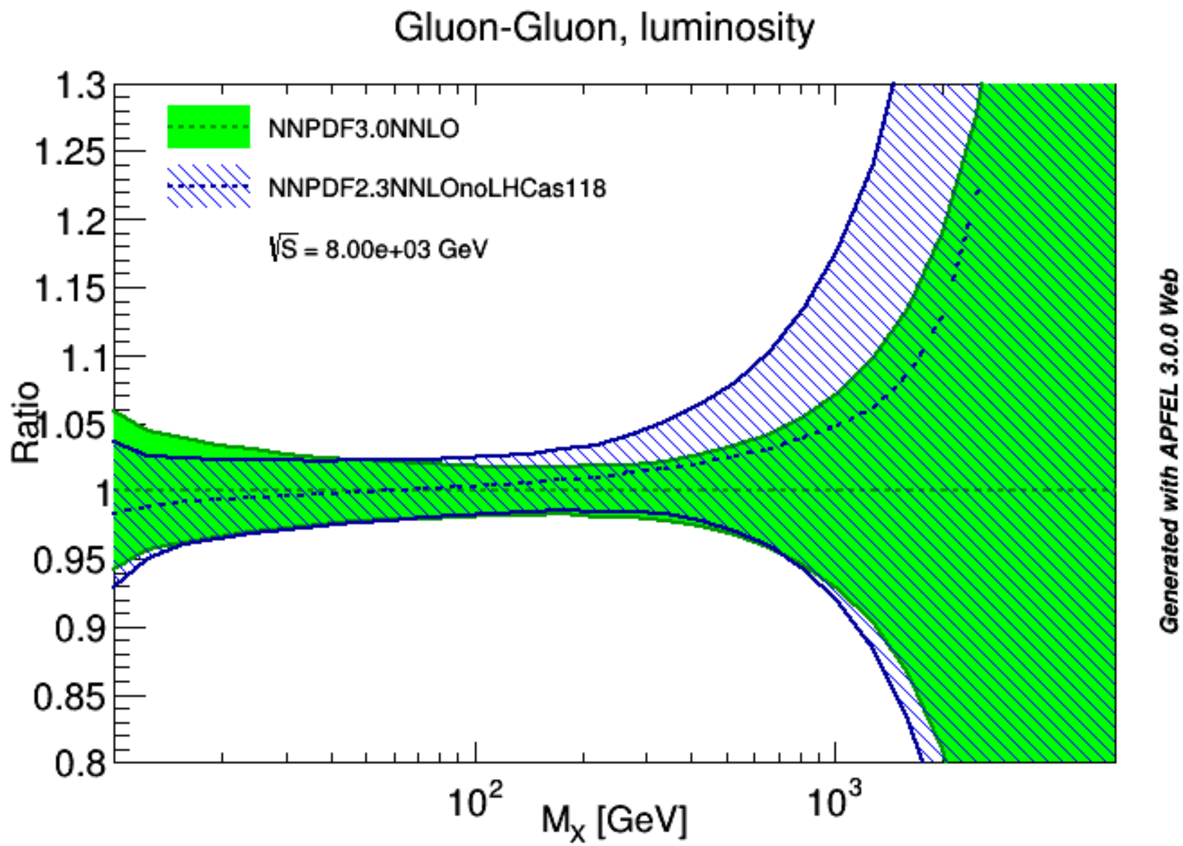
- Constrains to nPDFs at moderate /large x are to appear.

- Constrains to nPDFs at small x are problematic: use of small p_T data for benchmarking dubious as probably there are collective effects in pPb@LHC (breakdown of factorisation).

- The same holds for the search of non-linear dynamics at small x.

- UPC data will offer some constrains for nPDFs, but they are limited by statistics and, above all, for the theoretical modelling required.

Sensitivity of PDFs to LHC - Gluon



No LHC
With LHC
NNPDF3.0
(Oct. 2014)
S.Forte et al

Large uncertainties at high mass
- γγ induced proc.s
- k factors
- eweak corrections

...

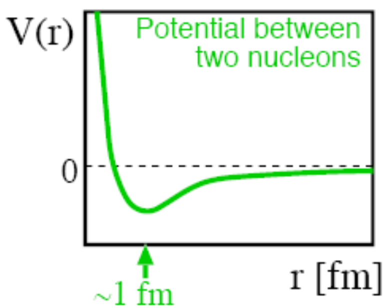
U.Klein LesHouches
arXiv:1405.1063

LHC: W+c, P_T(W), top, double differential W,Z data + previous input to NNPDF

New physics appearing as contact interaction would be confused with PDFs
Long range onset effects of new resonances: new physics or PDFs ??
High luminosity, high mass searches requires independent, precise PDFs ep--pp

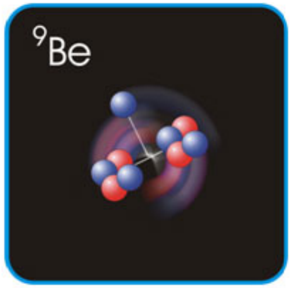
Gluons in nuclei

What do we know about gluons in a nucleus? **NOTHING!!!**

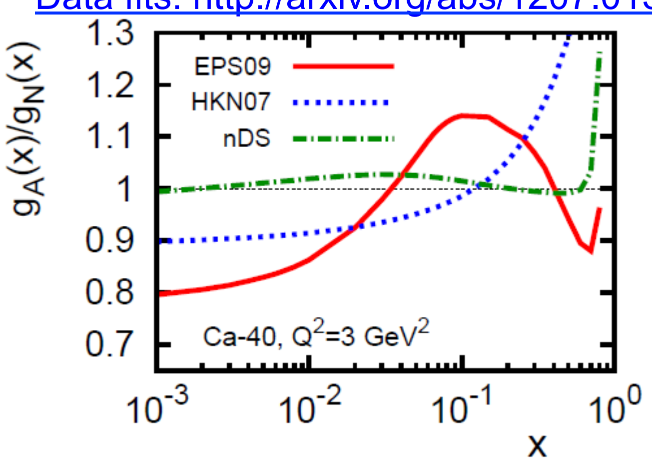


Nucleons (spin-1/2 fermions) see a strong repulsive core at short distances. JLab data found a striking correlation of the number of N-N pairs at short distances and the EMC effect – the parton dynamics. Gluons are spin-1 so may not be sensitive to this

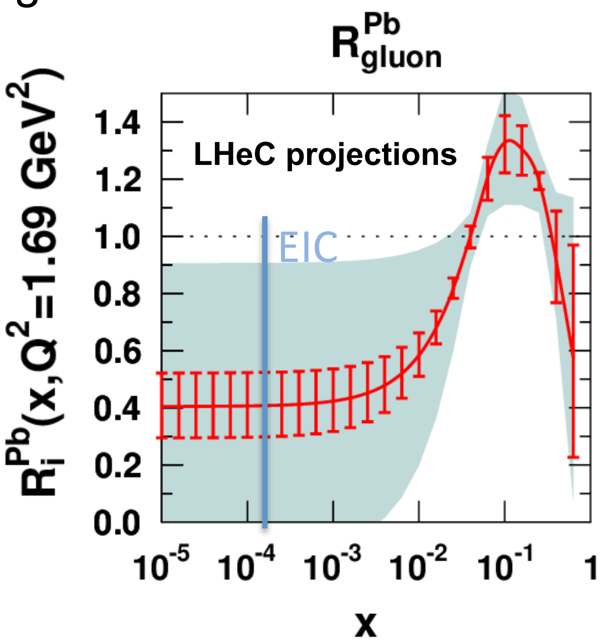
→ we know *even less* than we thought.



Data fits: http://arxiv.org/abs/1207.0131



EIC/LHeC: access gluons through two structure functions: $\mathbf{F_L}$ (needs variable energy) and $d\mathbf{F_2}/d\ln(Q^2)$ (needs large range in energies)



$$Q_s^2(eA) \propto Q_s^2(ep)\ A^{1/3}$$

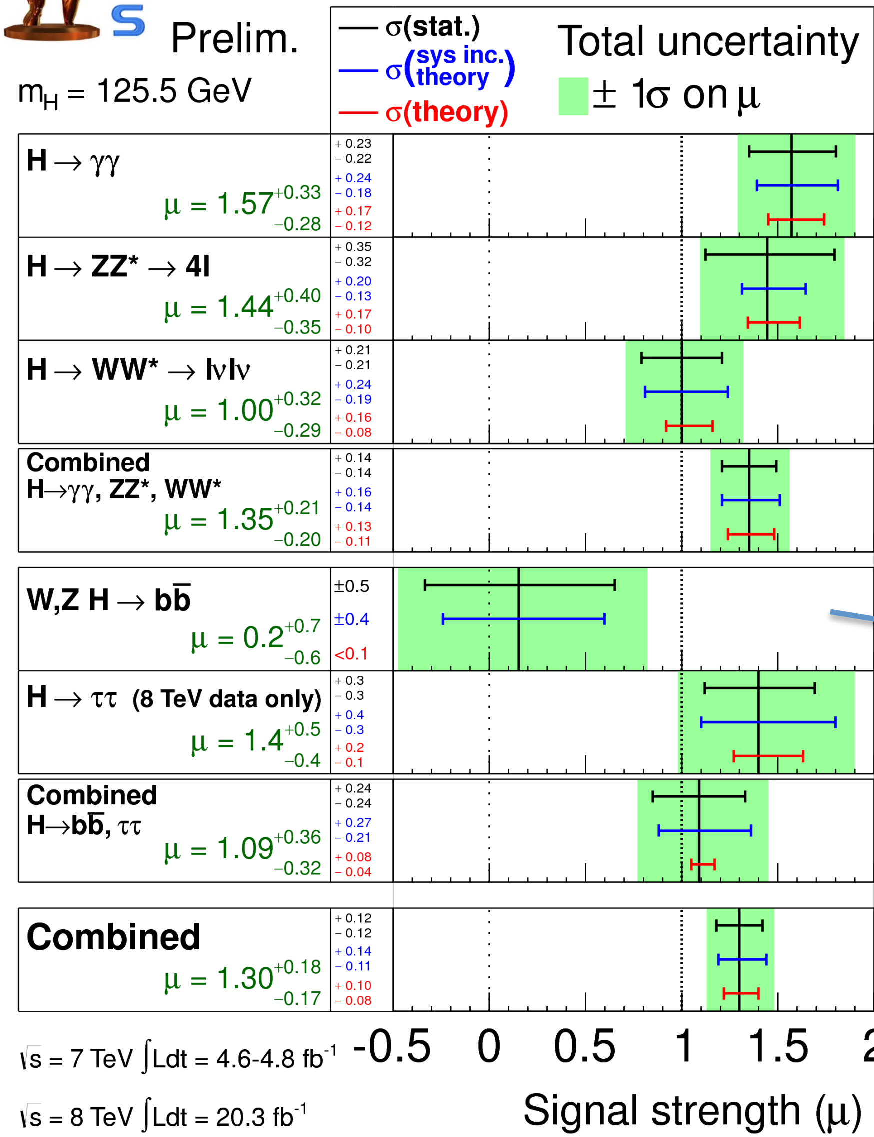
Precision measurements of gluon distribution essential for quantitative studies of onset of **saturation as a high density (small x in ep) and matter ($A^{1/3}$) effect**.

Unpolarised Quark and Gluon PDFs

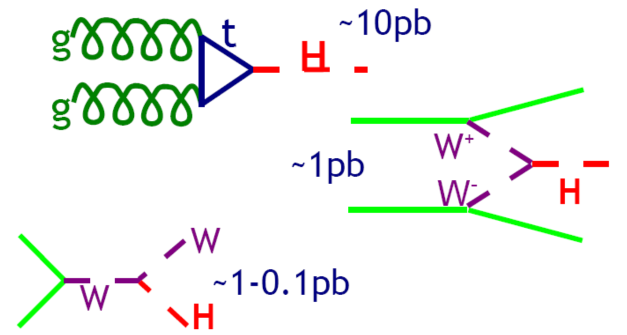
PDF	comment	LHeC
u valence d valence	after 40 years still do no know d/u at high x	CC free of nuclear effects
up sea down sea	not distinguished at HERA	NC and CC
strange	unknown basically (neutrinos, W,Z)	Ws → c : CC at high Q^2
charm	HERA to ~5%, threshold, intrinsic charm?	NC
beauty	HERA ~20%. bb→ A ? HQ treatment in QCD	NC
top	takes % of p momentum	CC at LHeC
gluon	low x saturation?, medium x Higgs, high x BSM	$dF_2/dlnQ^2$, vary E_e/E_p

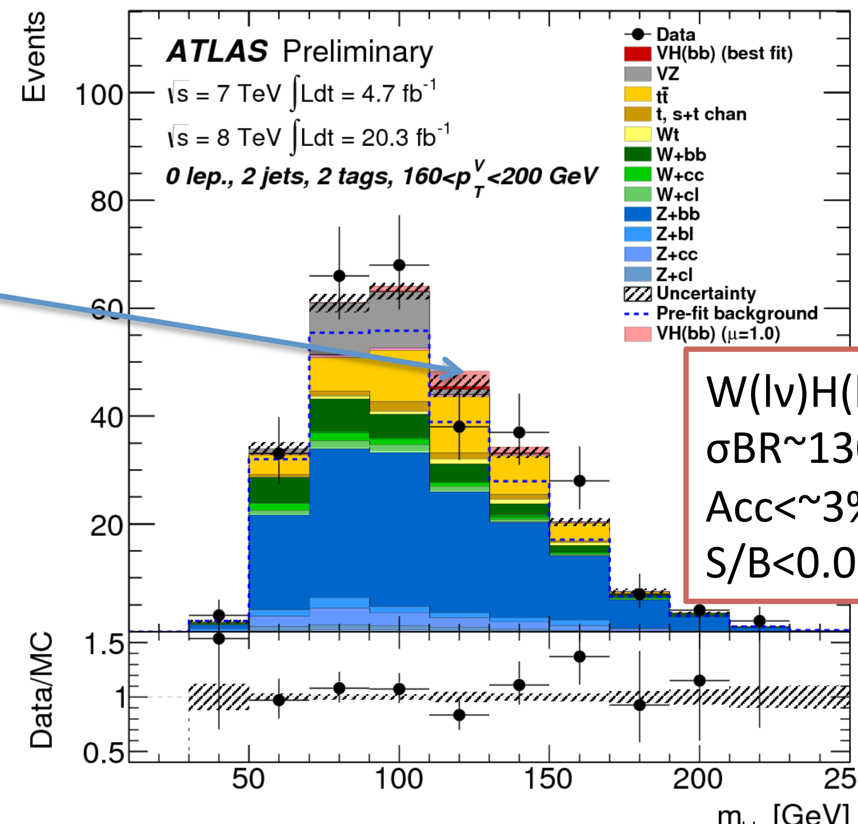
LHeC: extended kinematic range: low x, high x, high Q^2 → the ONLY way to unfold all PDFs
ep/eA further determine neutron, photon, pomeron, nuclear densities – HUGE potential

Status : Higgs coupling strength



ATLAS-CONF-2014-009



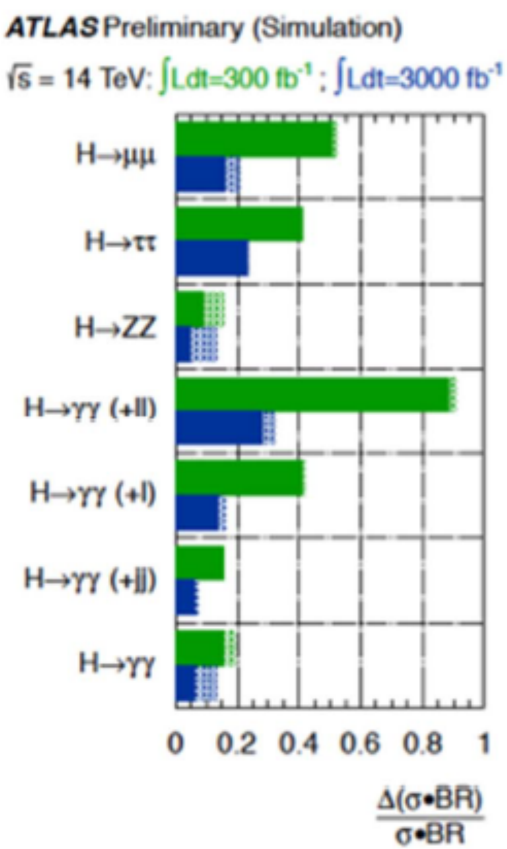


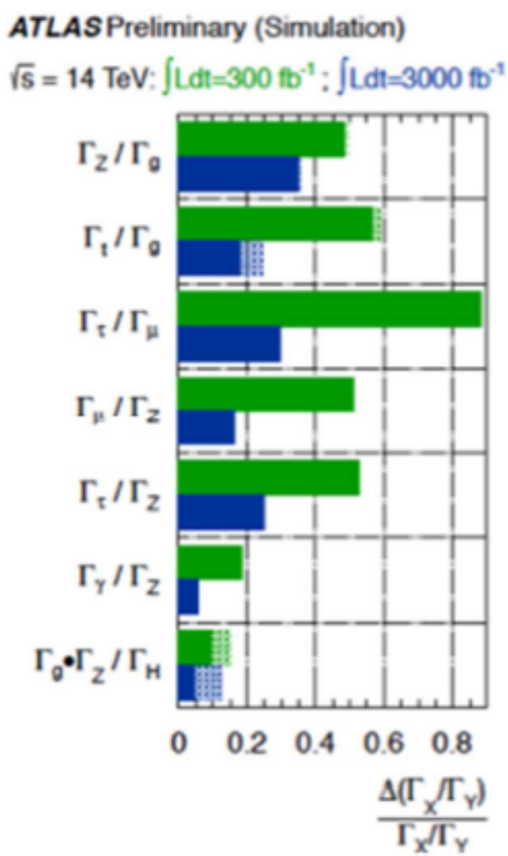
W(lν)H(bb)
σBR~130 fb
Acc<~3%
S/B<0.01

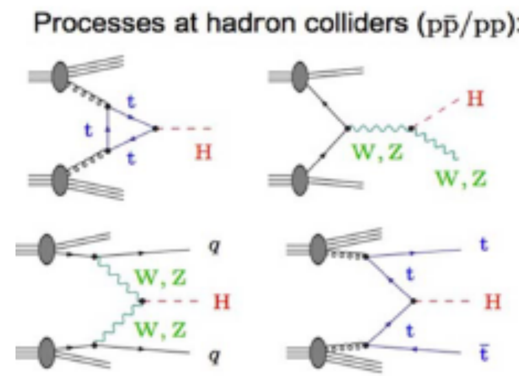
ATLAS-CONF-2013-079

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)

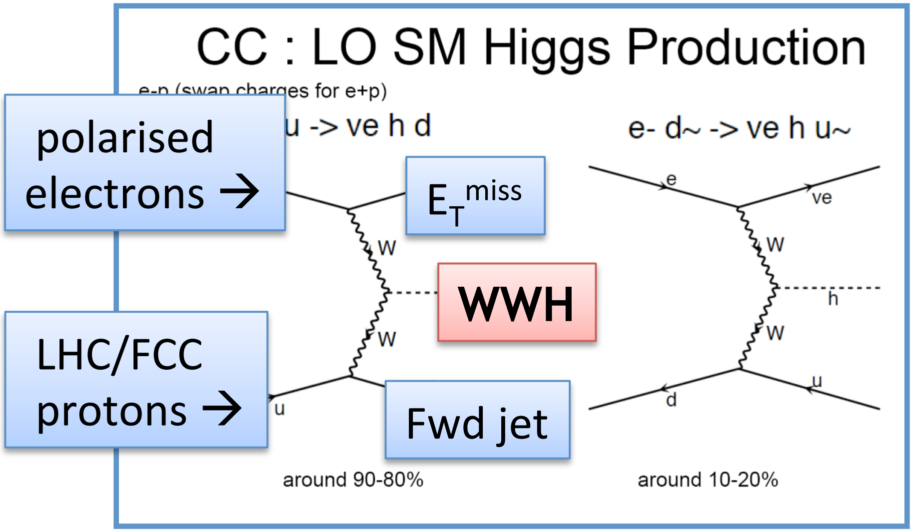


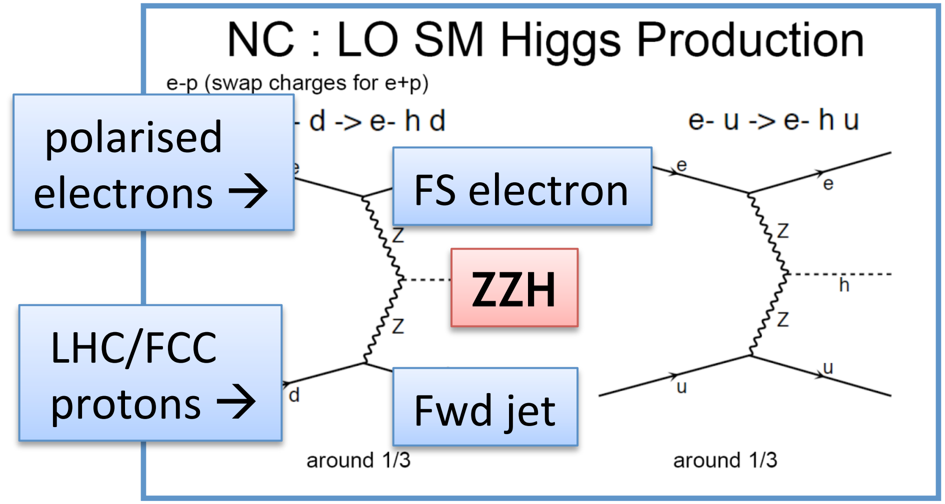




Dashed regions: scale & PDF contributions

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]

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 <u>pT of scattered quark as scale (CDR: ŝ)</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.

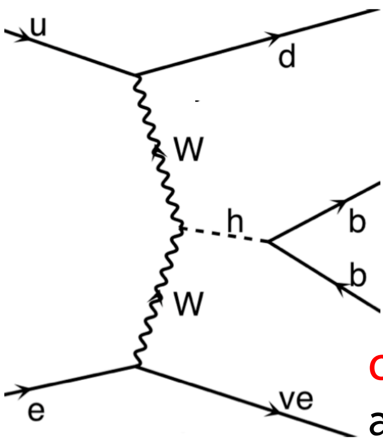
[eA needs modelling of nuclear fragmentation]

Examples: Generated samples

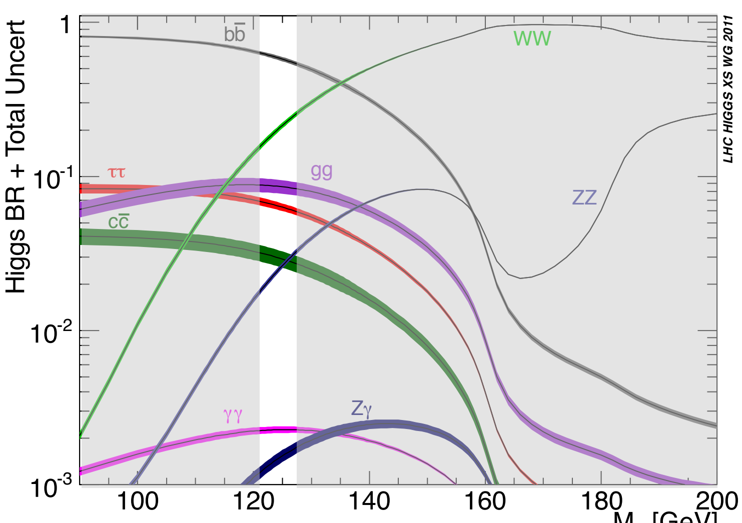
Graphs by MadGraph

Signal

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

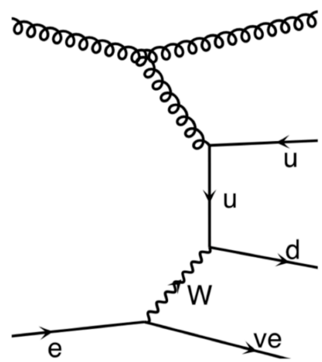


σ~ 0.16 pb
at √s=2.05TeV

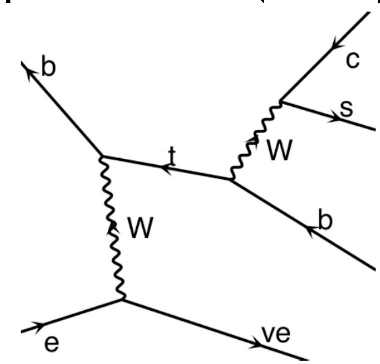


Background (examples)

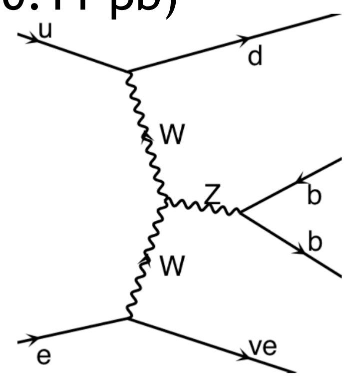
CC: 3 jets (~57 pb)



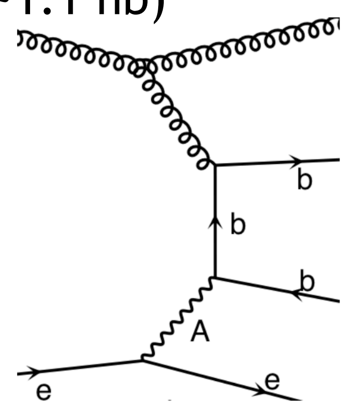
CC: single top production (~4.1 pb)



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]

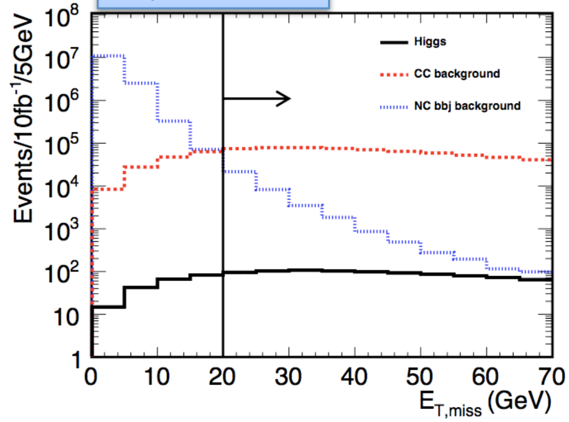
- NC DIS rejection
  - Exclude electron-tagged events
  - $E_{T,miss} > 20$ GeV
  - N_{jet} ($p_T > 20$ GeV) $\geqq 3$
  - $E_{T,total} > 100$ GeV
  - $y_{JB} < 0.9$, $Q^2_{JB} > 400$ GeV^2
- b-tag requirement
  - $N_{b\text{-}jet}$ ($p_T > 20$ GeV) $\geqq 2$
- Higgs invariant mass
  - $90 < M_H < 120$ GeV
- Single top rejection
  - $M_{jjj,top} > 250$ GeV
  - $M_{jj,W} > 130$ GeV

$H \rightarrow b\bar{b}$

CC BG

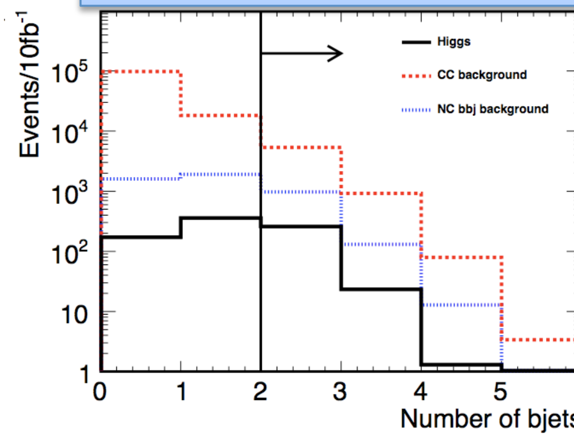
NC BG

E_T^{miss} cut

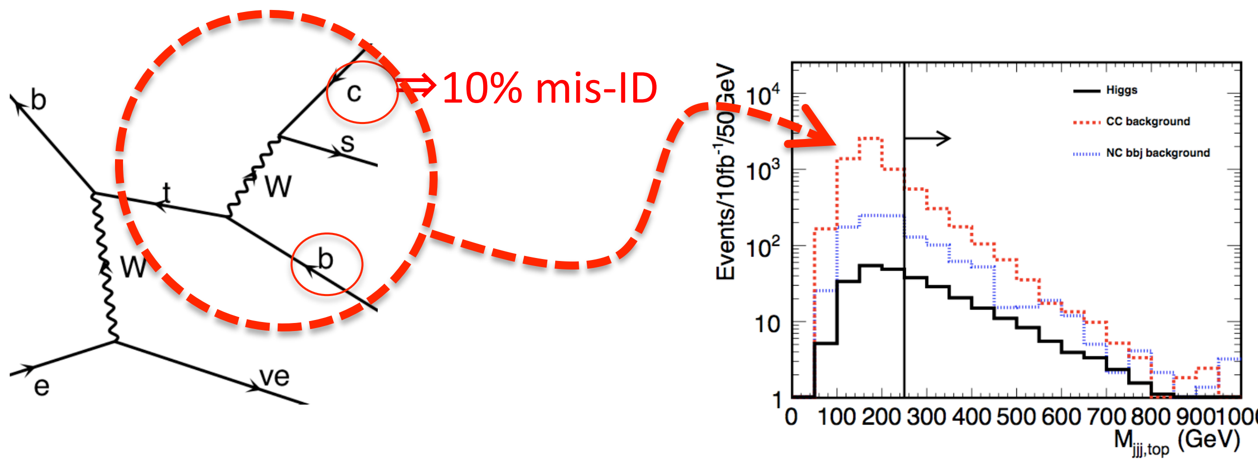


b-tag requirement

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



⇒ 44% of remaining BG is single-top…



CDR: A Large Hadron Electron Collider at CERN

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

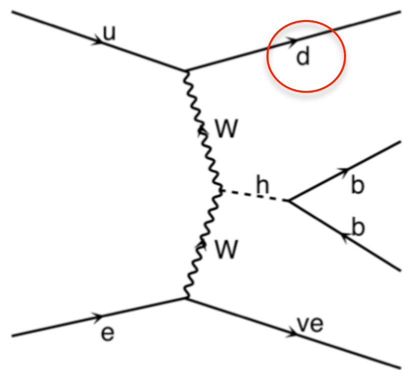
CDR : H→b$\bar{b}$ results

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

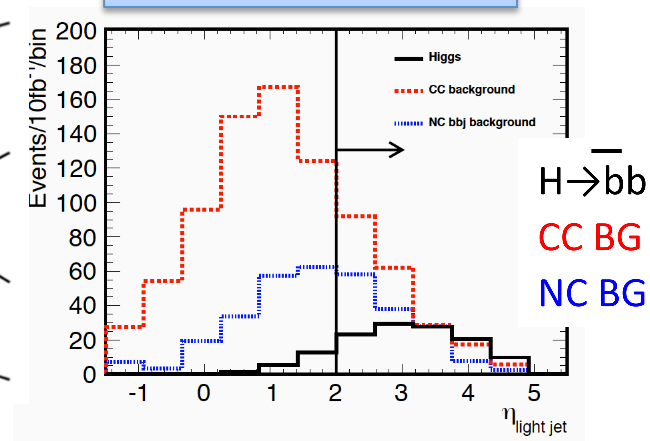
- Forward jet tagging
  - η_{jet} > 2 (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

H → b$\bar{b}$ signal

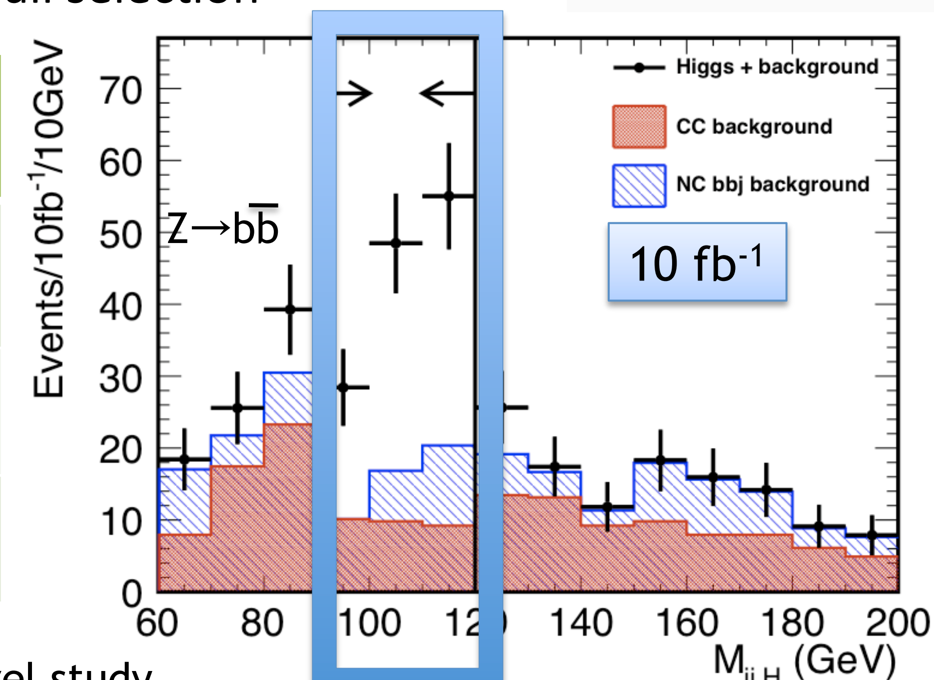


Forward jet η tag



- 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



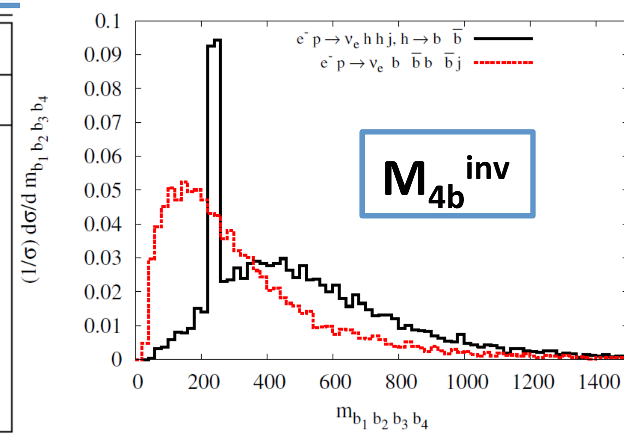
Clear signal obtained with just cut based analysis already!

*parton-level study.

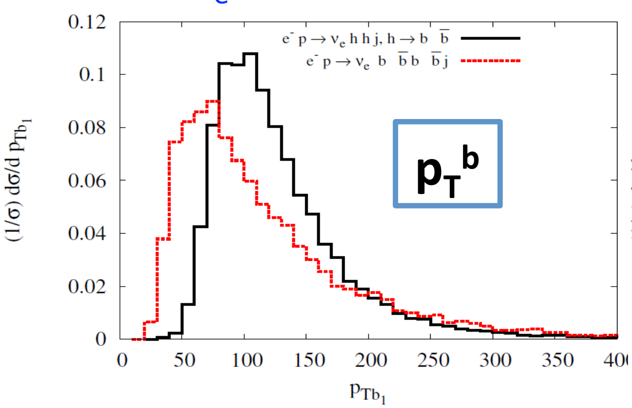
First *parton-level* feasibility studies

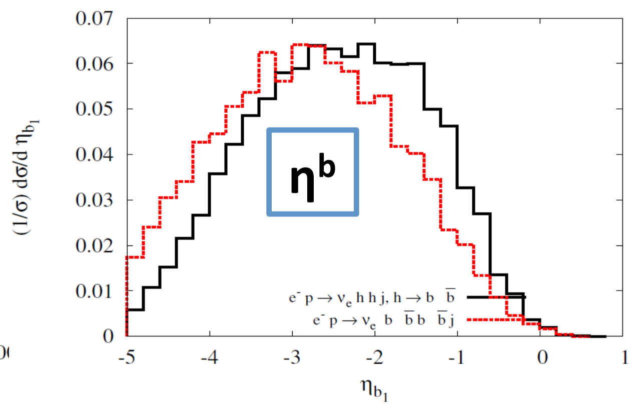
Cross-sections for CC backgrounds in fb for E_e=60,120,150 GeV

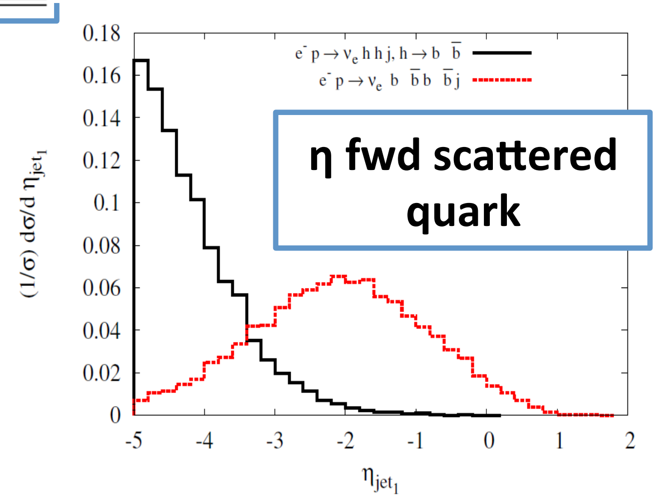
Processes	$E_e = 60$ GeV		$E_e = 120$ GeV		$E_e = 150$ GeV	
	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)
$e^-p \to \nu_e b\bar{b}b\bar{b}j$	0.086	0.022	0.14	0.036	0.15	0.038
$e^-p \to \nu_e b\bar{b}c\bar{c}j$	0.12	1.7×10^{-5}	0.36	1.8×10^{-3}	0.44	2.2×10^{-3}
$e^-p \to \nu_e c\bar{c}c\bar{c}j$	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)





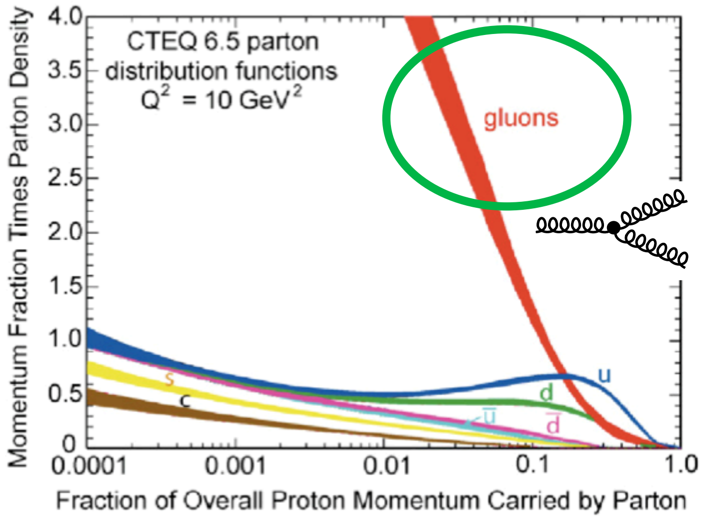


Despite large beam energy imbalance: "b-jets" are relatively central

Scattered quark is more forward in signal → good discriminant!

Does the gluon density 'saturate'?

- **HERA's discovery: proliferation of soft gluons ("gluon ocean"):**

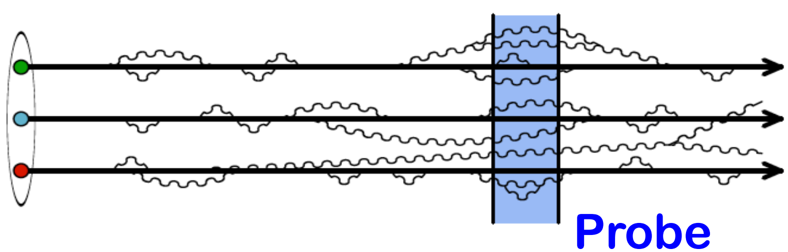


How does the unitarity bound of the hadronic cross section survive if soft gluons in a proton or nucleus continue to grow in numbers?

QCD: Dynamical balance between radiation and recombination?

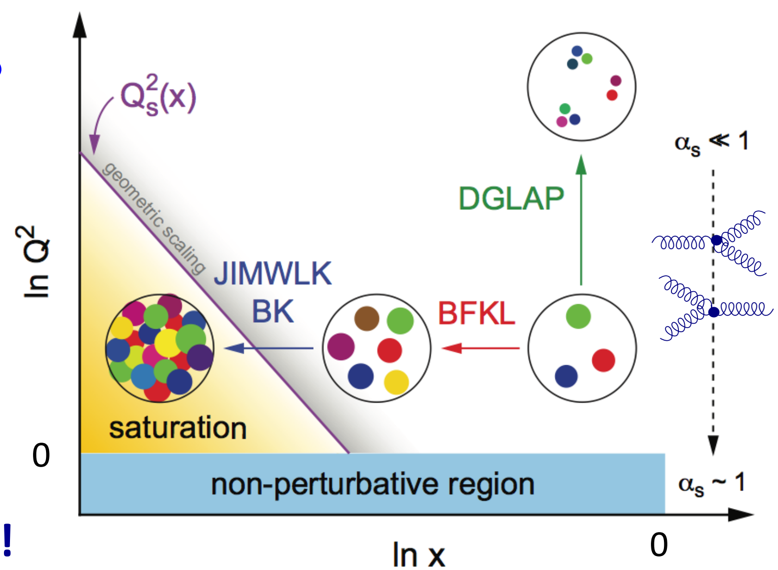
Saturation of gluons?

- **Gluon saturation has to be there!?**



A new regime of **dense, weakly coupled** Color Glass Condensate (CGC) ?

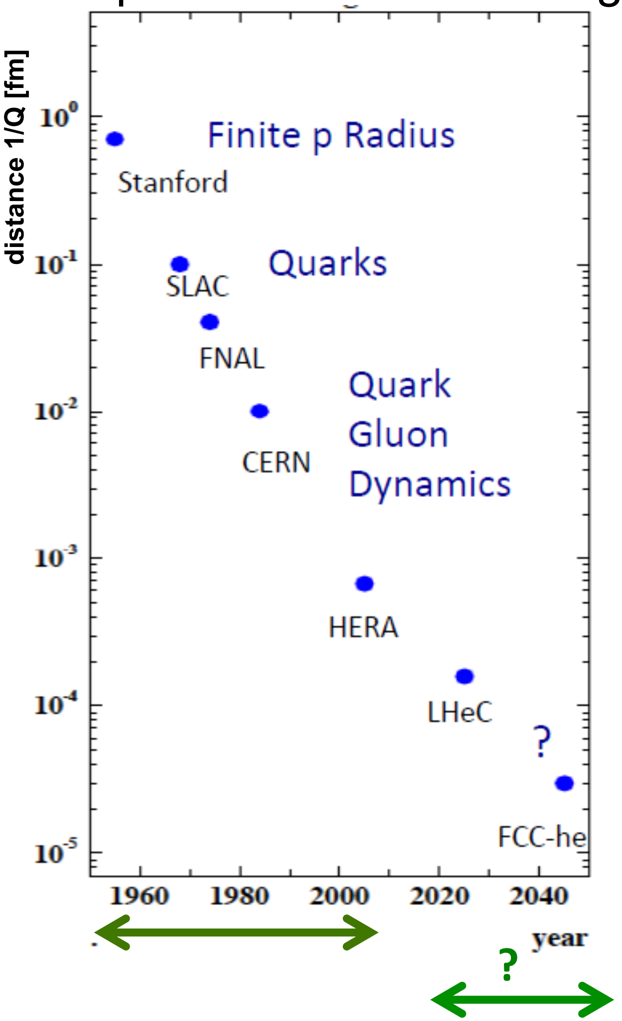
Hints from HERA, RHIC and LHC – no proof yet!

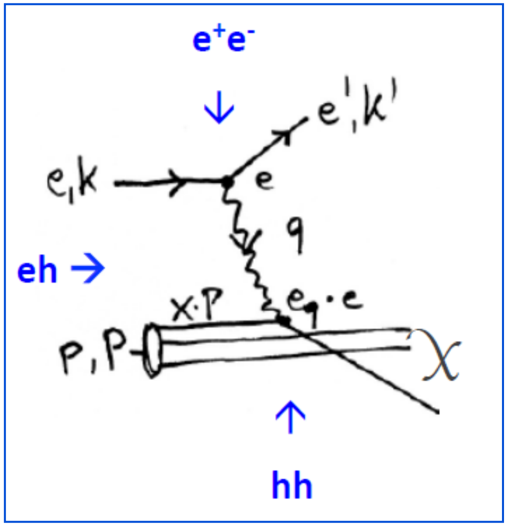


Can we find this regime for sure and study/understand its properties?

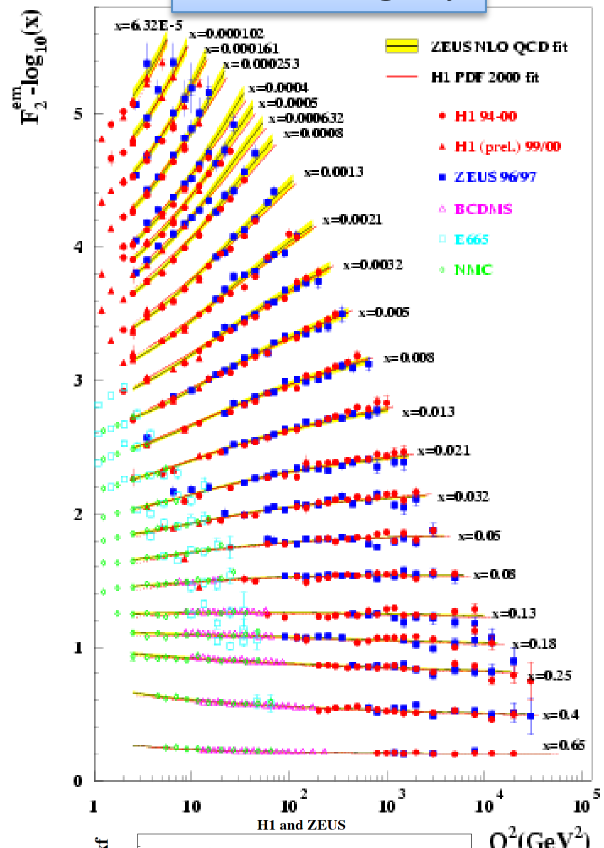
Deep Inelastic Scattering and Related Subjects

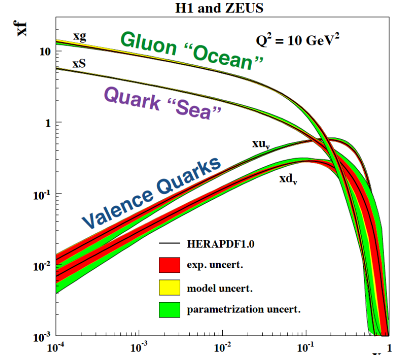
Resolving proton structure in lepton-Nucleon scattering





HERA's legacy





Different roles :

- **hh** : reach highest c.m.s. energies & direct NP searches
- **e^+e^-** : precision EW measurements and indirect searches
- **DIS/eh : precision hadron structure / quark-gluon dynamics** in a clean environment and theoretically rigorous

Proton Spin and Hadron Structure

Requires Longitudinally polarised hadron (p) beam → unique for EIC !

Proton – composite particle of quarks and gluons:

Spin = intrinsic (partons spin) + motion (orbital angular momentum)

$S(\mu) = \frac{1}{2}$

$\mu \Rightarrow \infty$

Over 20 years effort (“spin crisis”)

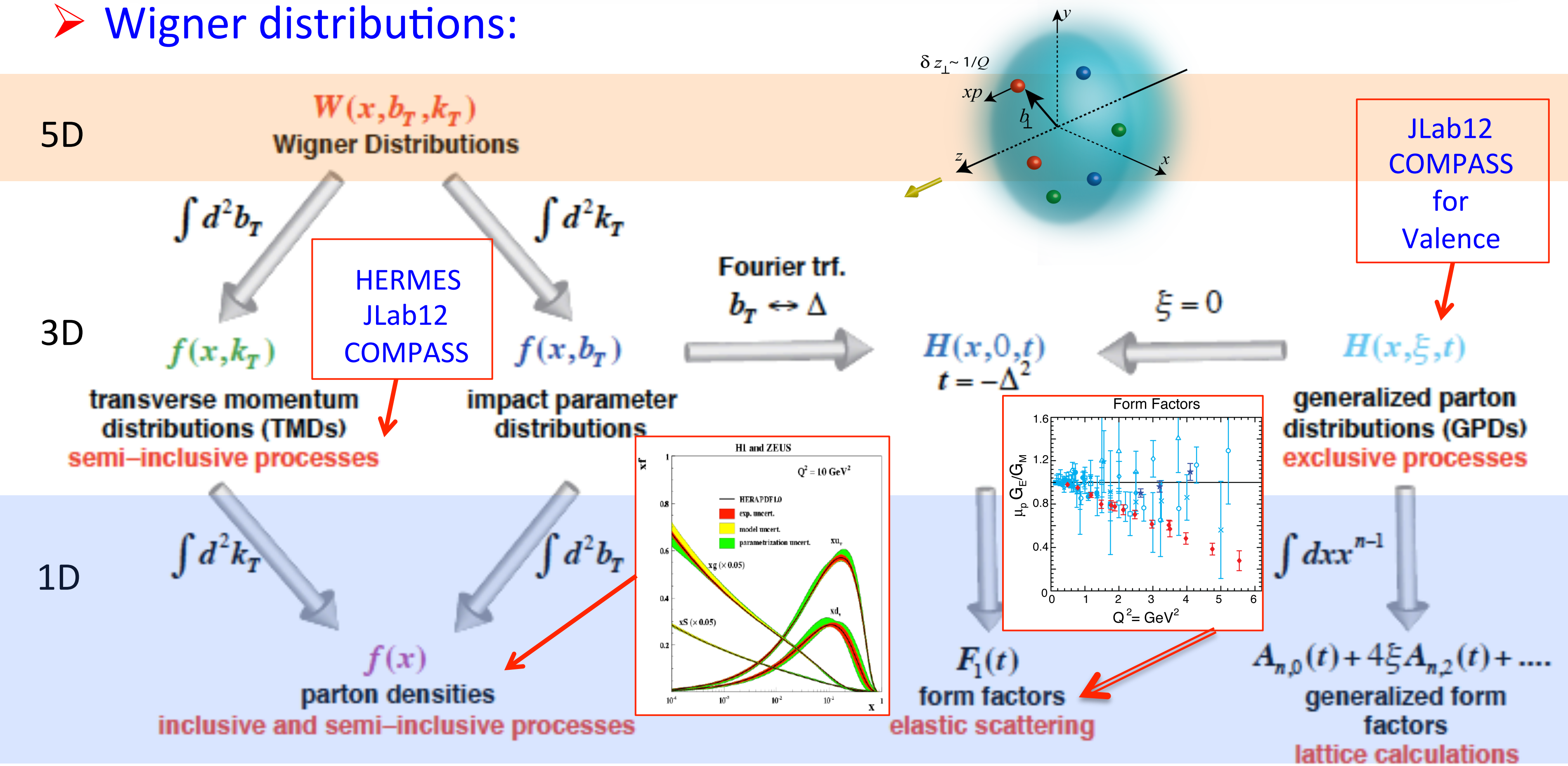
Today we know from polarised measurements :

- contribution of quarks is ~25%; contributions from sea quarks is zero, with considerable uncertainty
- contribution of gluons is comparable to that of quarks but with large uncertainty from limited x range

→ ***How to explore the polarised gluon and sea quark contribution fully?***
How to quantify the role of orbital motion?

Unified view of nucleon structure

- Wigner distributions:

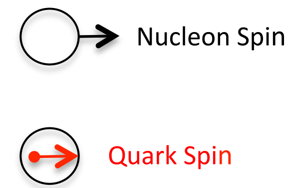


- EIC – 3D imaging of sea and gluons:
  - **TMDs – confined motion in a nucleon (semi-inclusive DIS)**
  - **GPDs – Spatial imaging of quarks and gluons (exclusive DIS)**

EIC is the best for probing TMDs

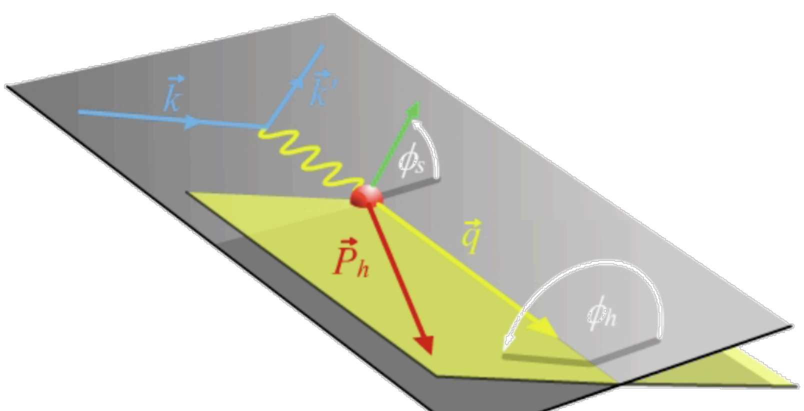
➢ TMDs - rich quantum correlations:

Nucleon Polarization		Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	U	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
	L		g_{1L} = − Helicity	$h_{1L}^{\perp}$ = −
	T	$f_{1T}^{\perp}$ = − Sivers	$g_{1T}^{\perp}$ = −	h_1 = − Transversity $h_{1T}^{\perp}$ = −



Similar for gluons

➢ Naturally, two scales and two planes:



✧ Two scales:

high Q - localized probe

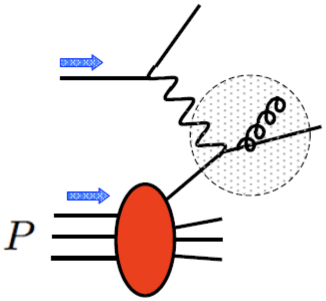
Low p_T - sensitive to confining scale

✧ Two planes:

angular modulation to separate TMDs

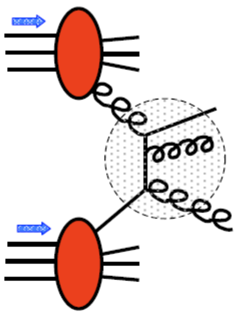
Hard to separate TMDs in hadronic collisions

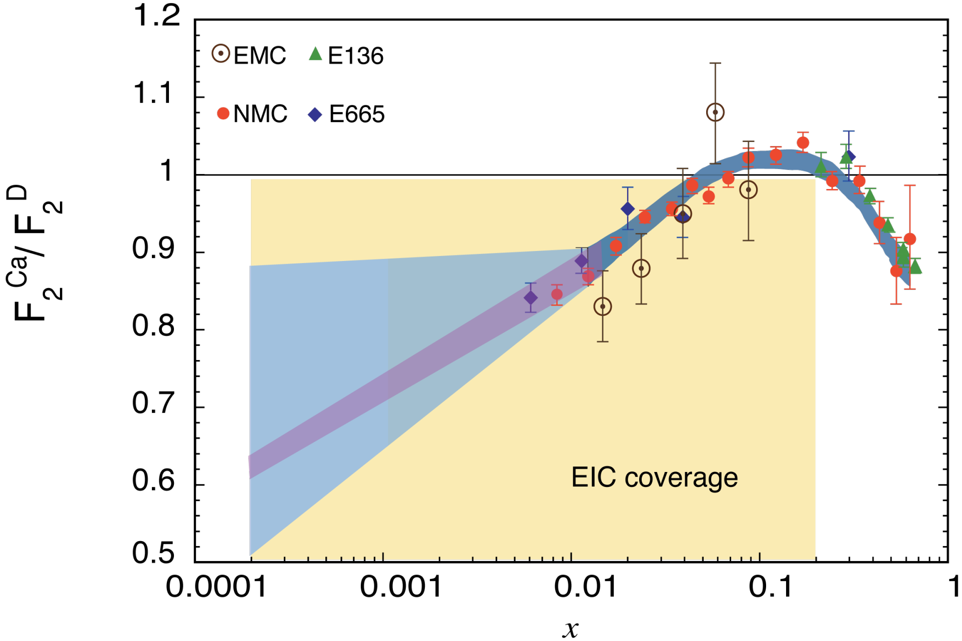
Synergy: Quarks & Anti-Quarks in Nuclei

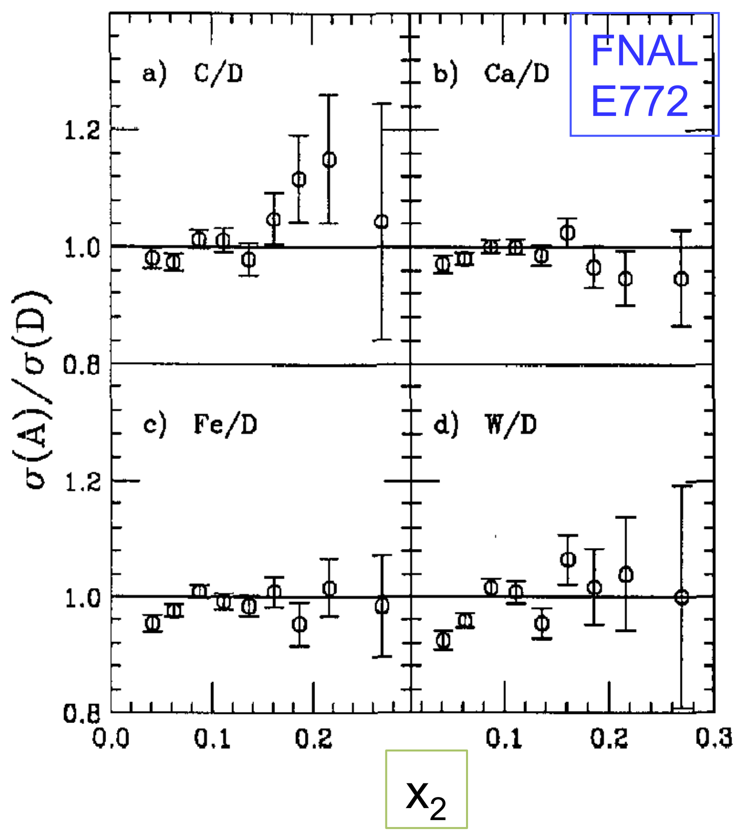


- F_2 **DIS** structure functions are altered in nuclei
~1000 papers on the topic to explain EMC effects
→ EMC effect with light points to local density effect!

Drell-Yan: Is the EMC effect a valence quark phenomenon or are sea quarks involved?







The puzzle posed by the EMC effect will only be solved by **conducting new experiments that expose novel aspects of the EMC effect like spin and flavour dependencies.**