Higgs Potential at ep Colliders

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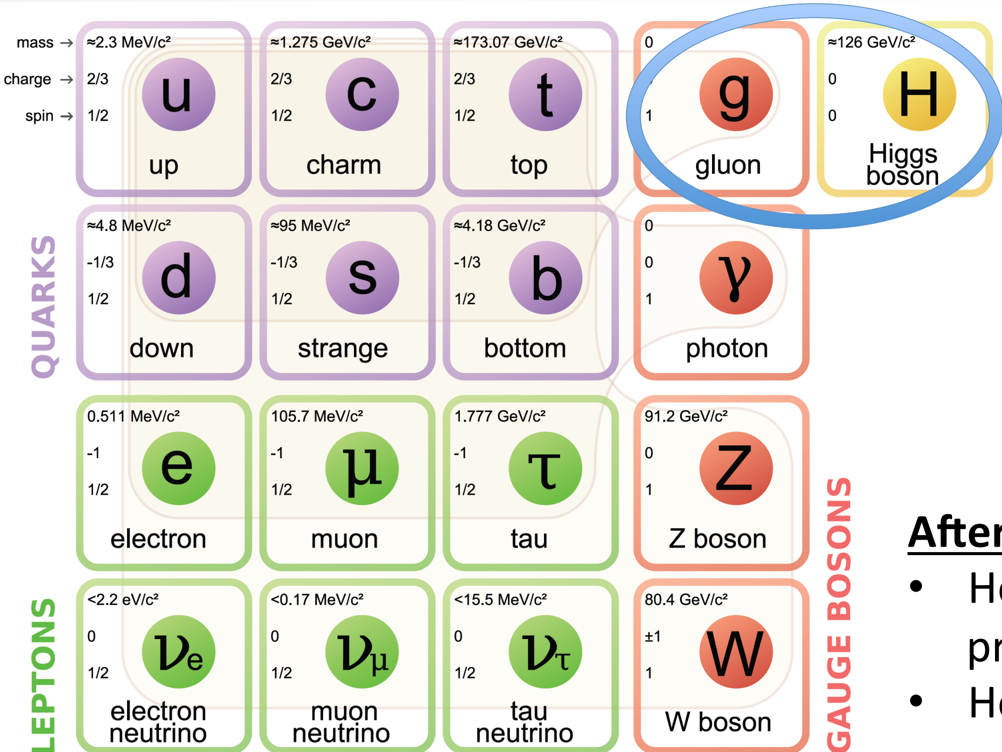
Speaker's affiliations :

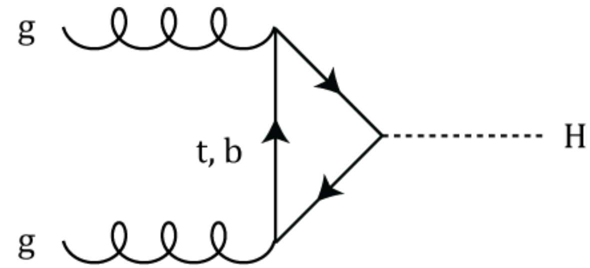
UNIVERSITY OF LIVERPOOL

FCC-ee Meeting #9, November, 24th, 2014

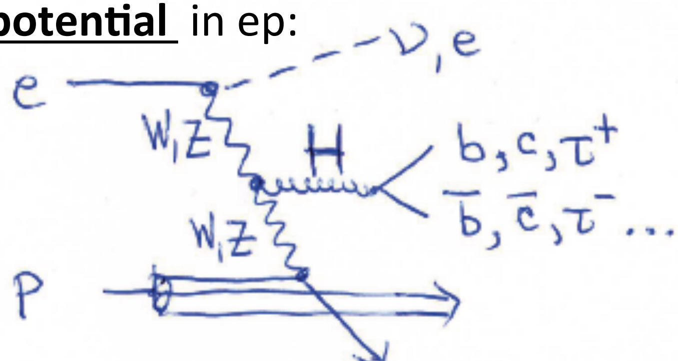
Standard Model Particles & QCD



Higgs discovery at LHC via gluon-gluon fusion



Higgs potential in ep:



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.

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

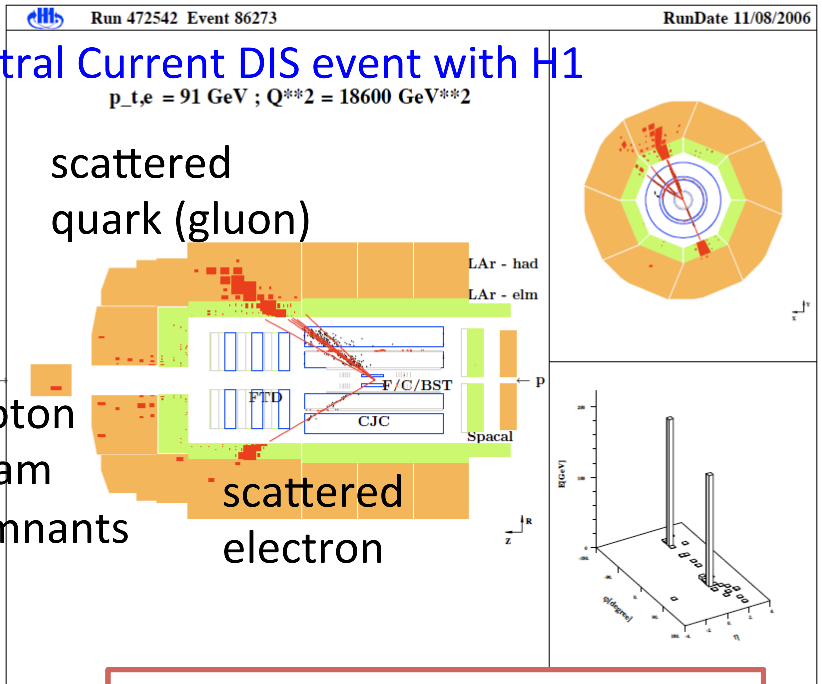
Quark substructure

New symmetry embedding QCD

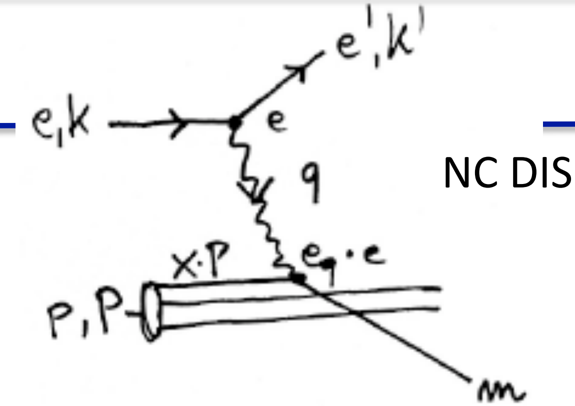
Deep Inelastic Scattering

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



- → **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)
$Q^2 = M^2$

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

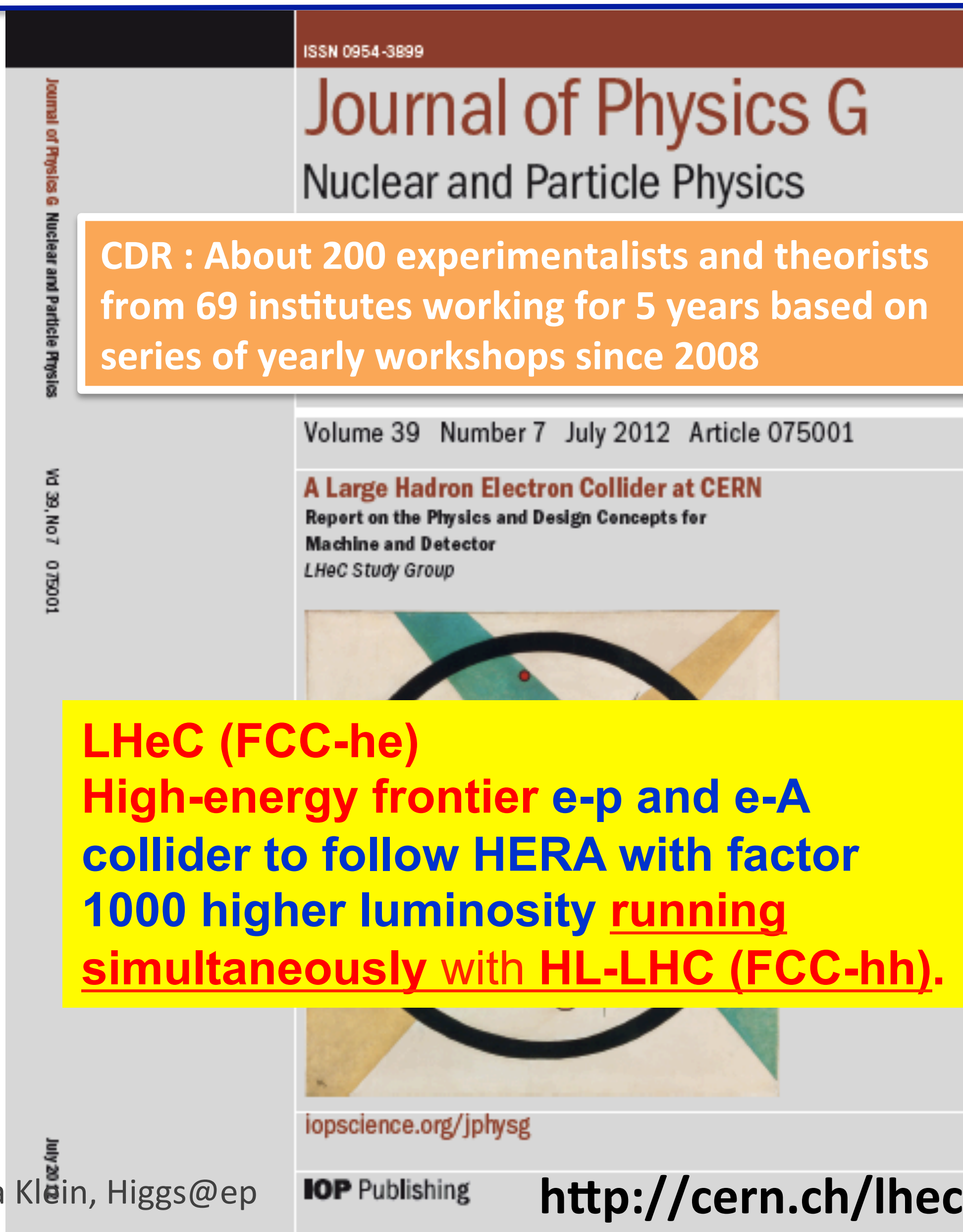
SLAC-PUB-642
August 1969

@SLAC: birth of DIS, 45 years ago.

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

LHeC (FCC-he)
High-energy frontier e-p and e-A collider to follow HERA with factor 1000 higher luminosity running simultaneously with HL-LHC (FCC-hh).

http://cern.ch/lhec

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)

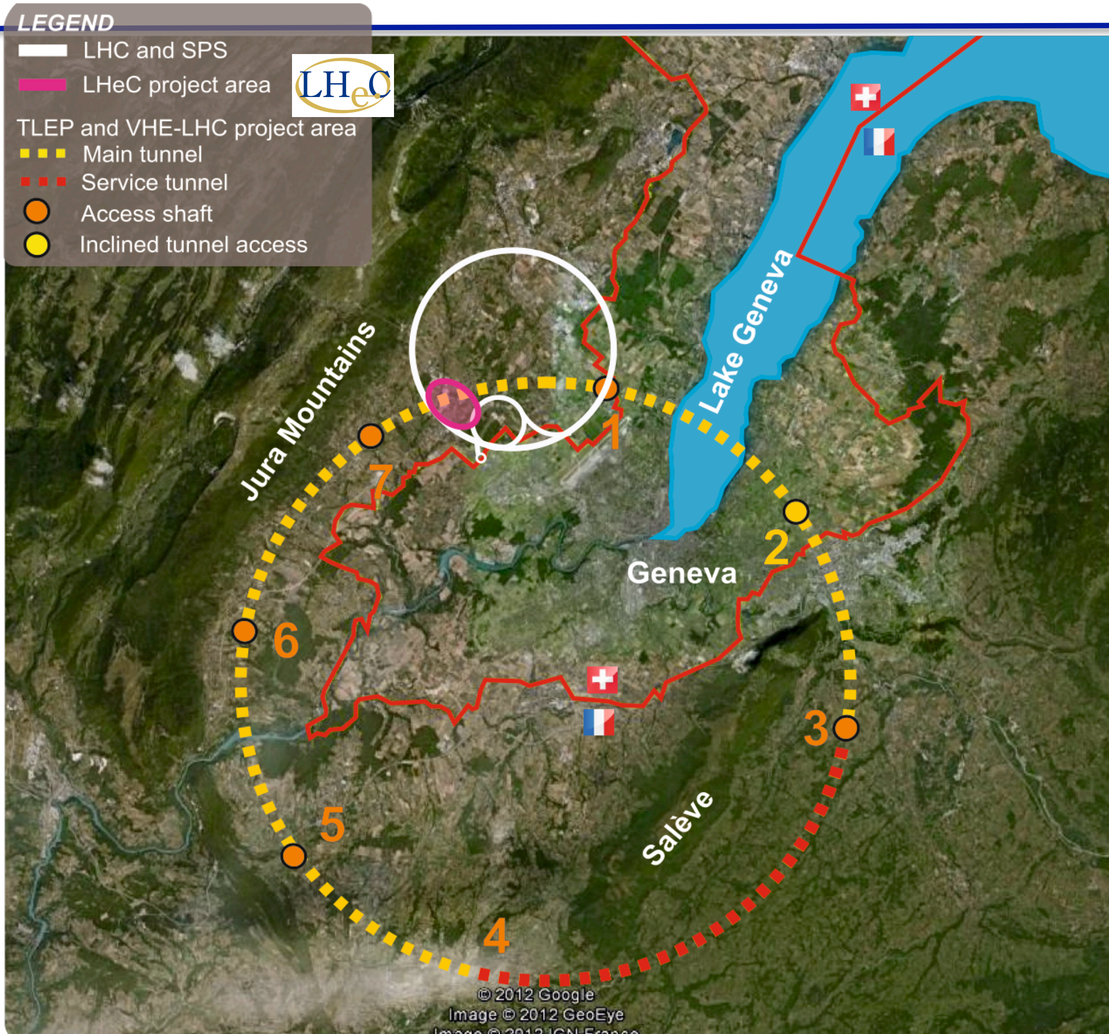
Post-CDR: LHeC baseline parameter

→ **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

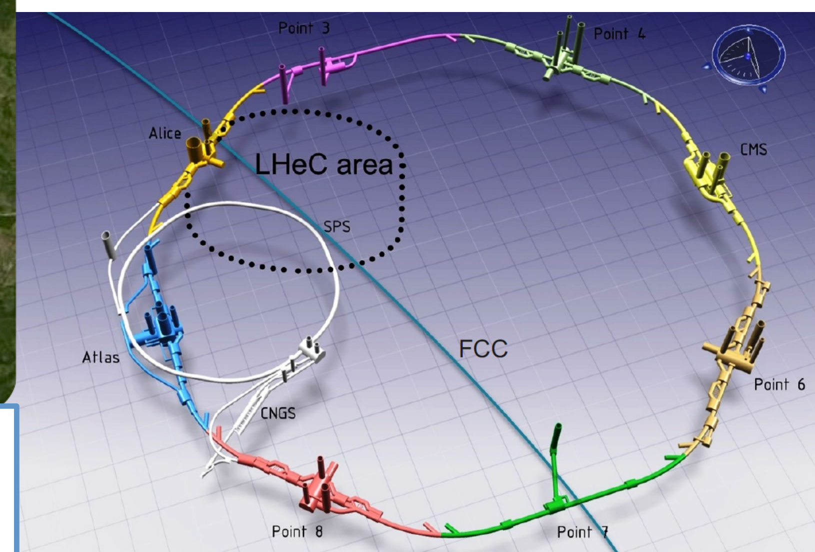
Future Circular Colliders at CERN*)



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

New tunnel may host a 'complete' Higgs facility → FCC design study for ee, ep, and pp potential

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



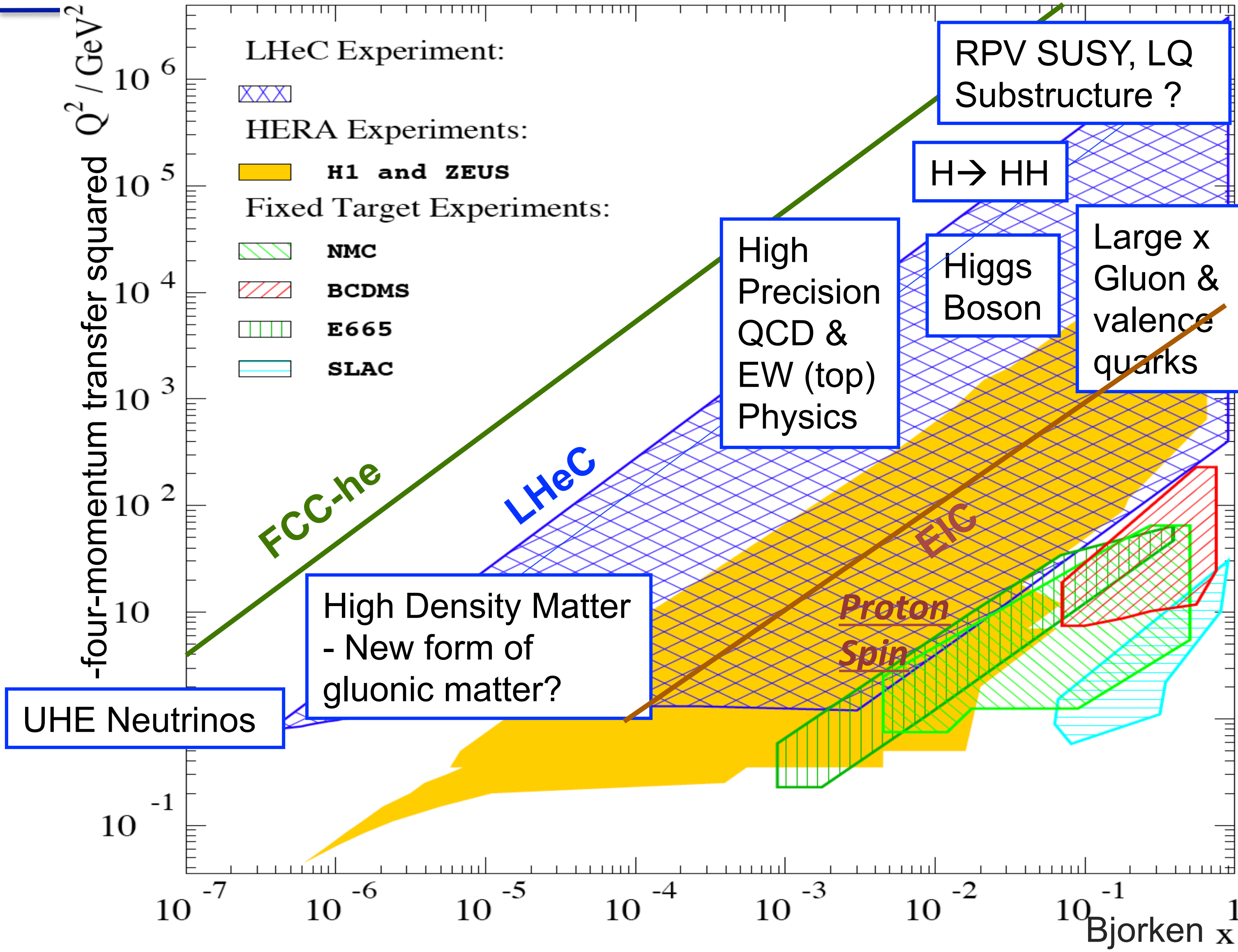
*) "Civil Engineering Feasibility Studies for Future Ring Colliders at CERN", Contributed by O.Brüning, M.Klein, S.Myers, J.Osborne, L.Rossi, C.Waaijer, F.Zimmerman to IPAC13 Shanghai

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

The ep Physics at the Energy Frontier



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

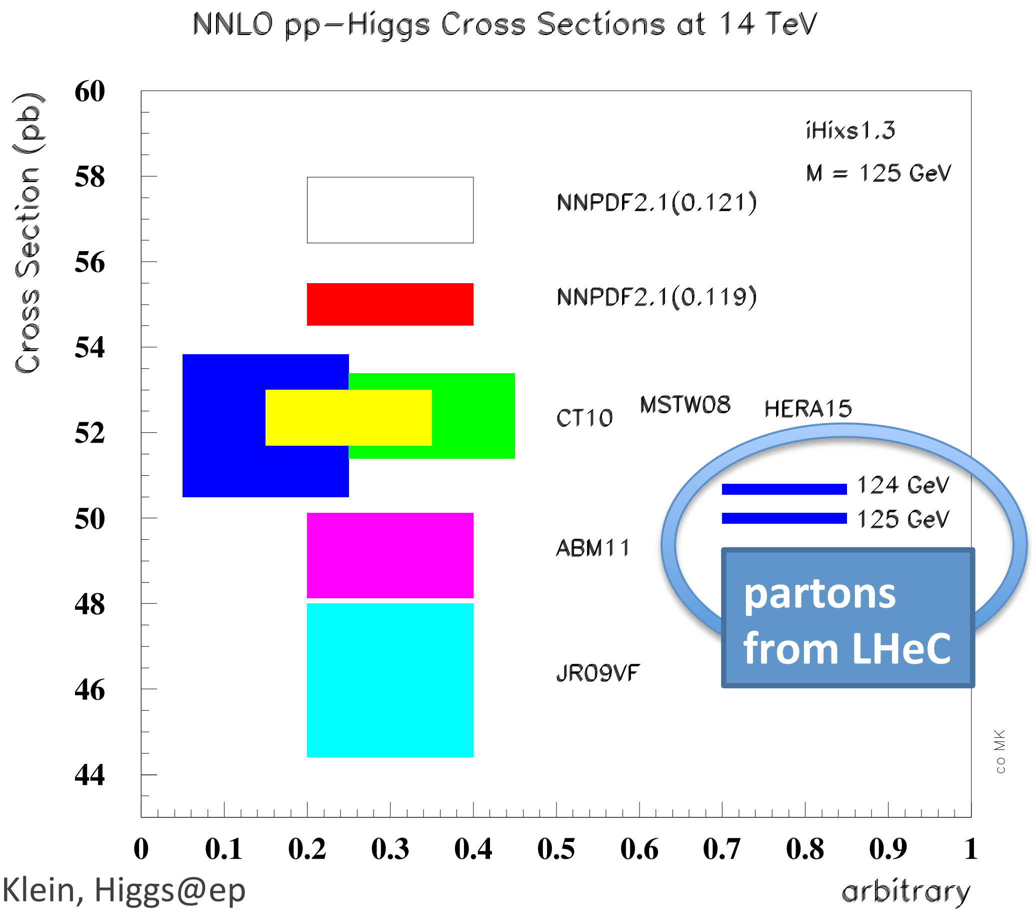
Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

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**

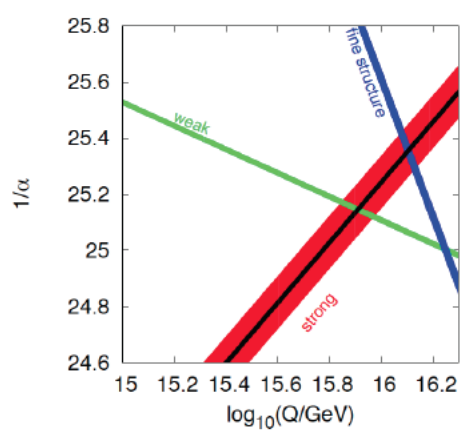
→ clear Higgs mass sensitivity in cross section predictions

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



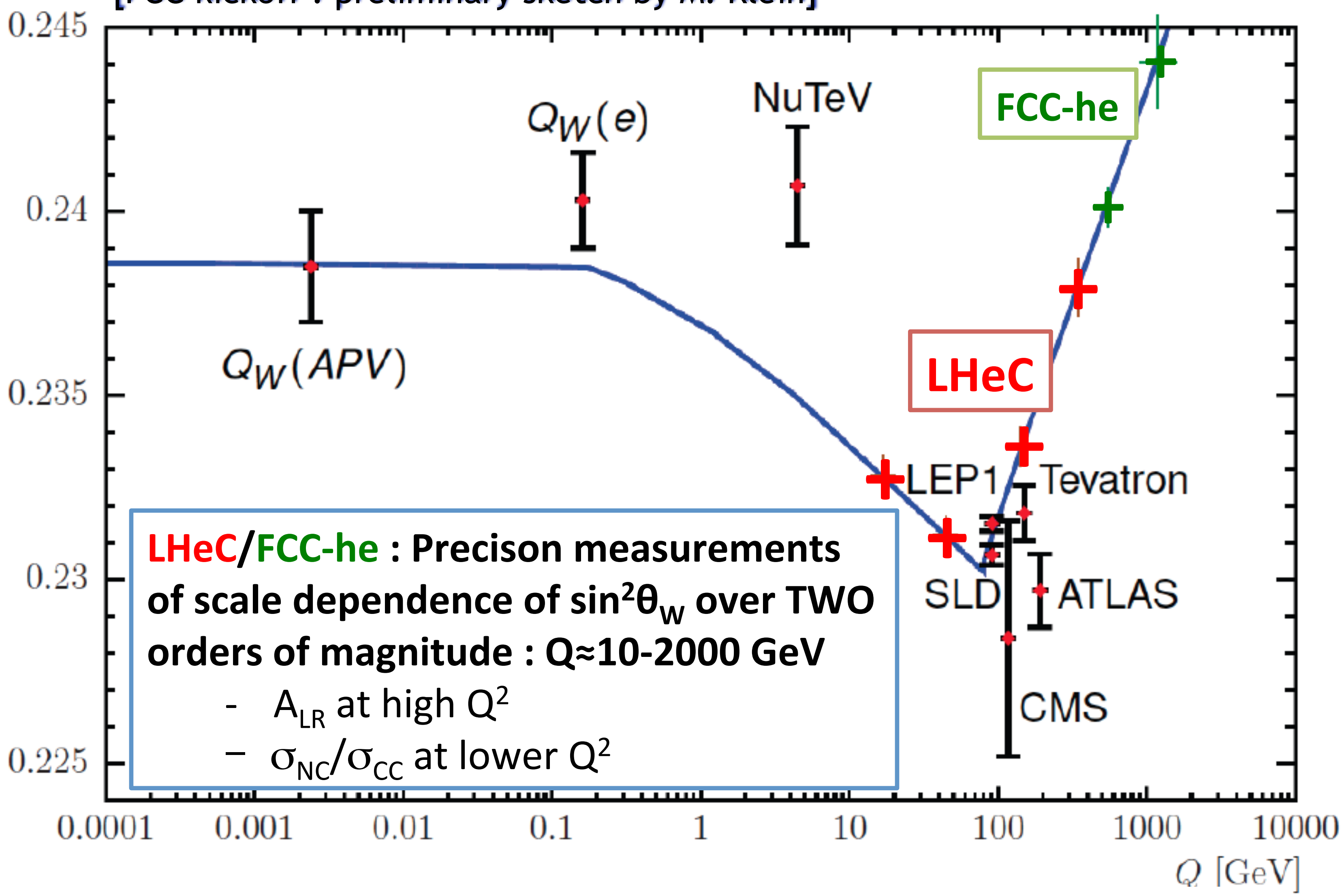
α_S = underlying parameter relevant for uncertainty (0.005 → 10%)
@ LHeC: measure to permille accuracy (0.0002)

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



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

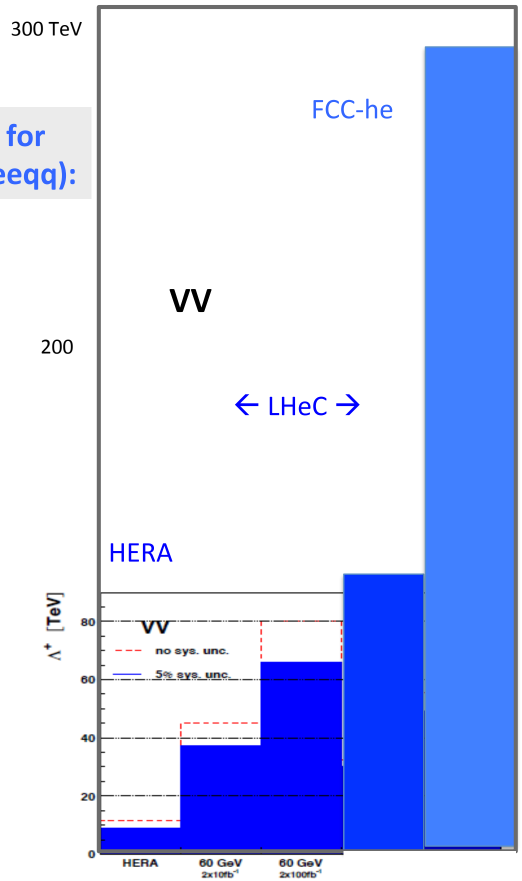
- A_{LR} at high Q^2
- σ_{NC}/σ_{CC} at lower Q^2

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

FCC-he Physics

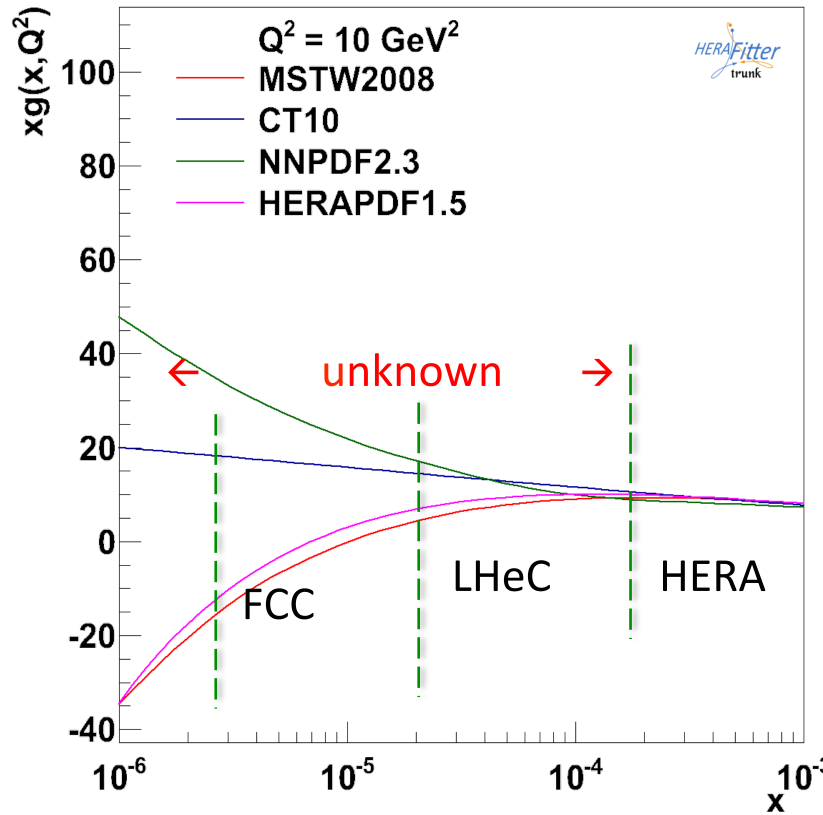
High mass and Q^2 region

Reach for Λ (CI eeqq):



LHeC: see CDR 2012

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



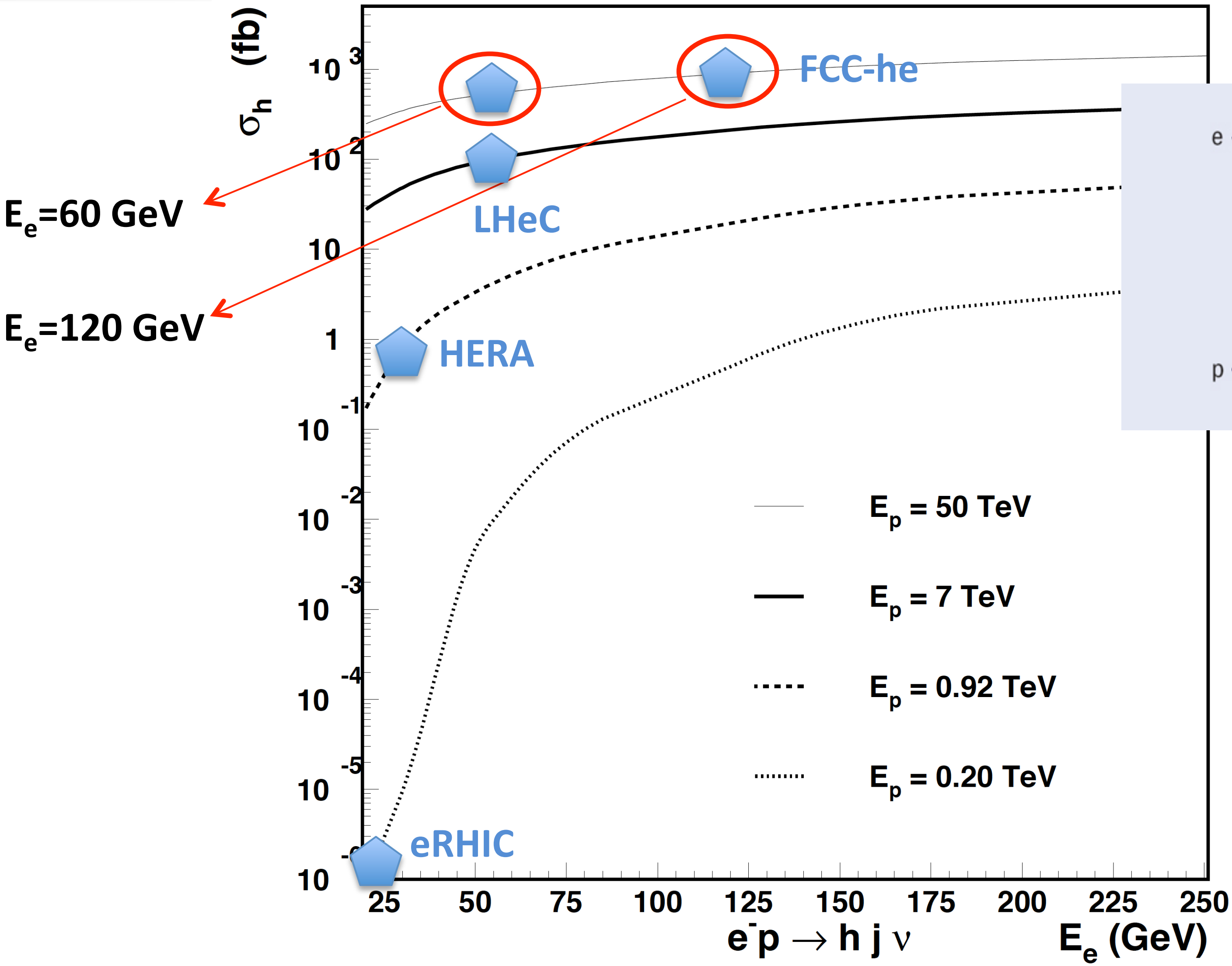
Huge extension of reach for new physics and to explore quark-gluon dynamics.

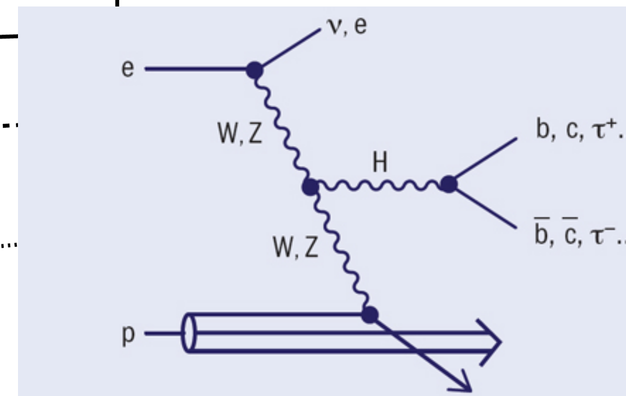
Leptoquark reach to up to √s ≈ 4 TeV .

Higgs selfcoupling (4b final state – under study, hh→4a envisaged)

Program being further investigated, Collaboration with hh and ee, Joint Software Group

SM Higgs in ep

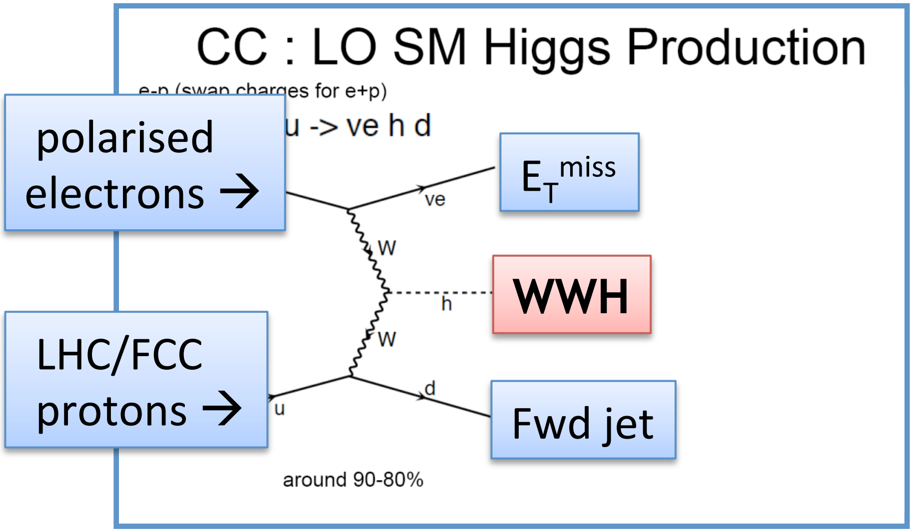


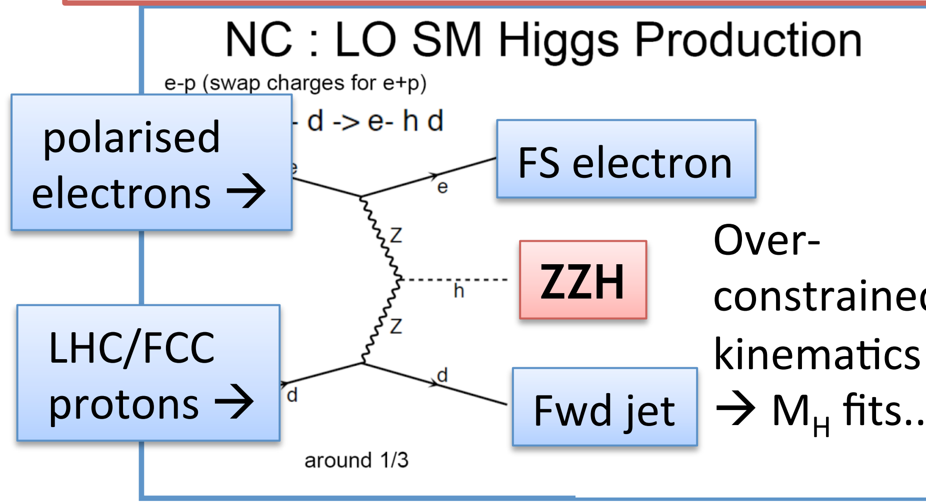


LHeC / FCC-he: Sizeable charged current DIS unpolarised **ep cross sections**

SM Higgs Production in ep

In ep, direction of FS quark is well defined.





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**

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 → **new: Delphes**

↓

H → $b\bar{b}$ (any decay) selection

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

→ Standard HERA tools can NOT to be used !

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

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

No pile-up ! Use fast detector simulation programs (PGS or now Delphes → signed impact parameters!)

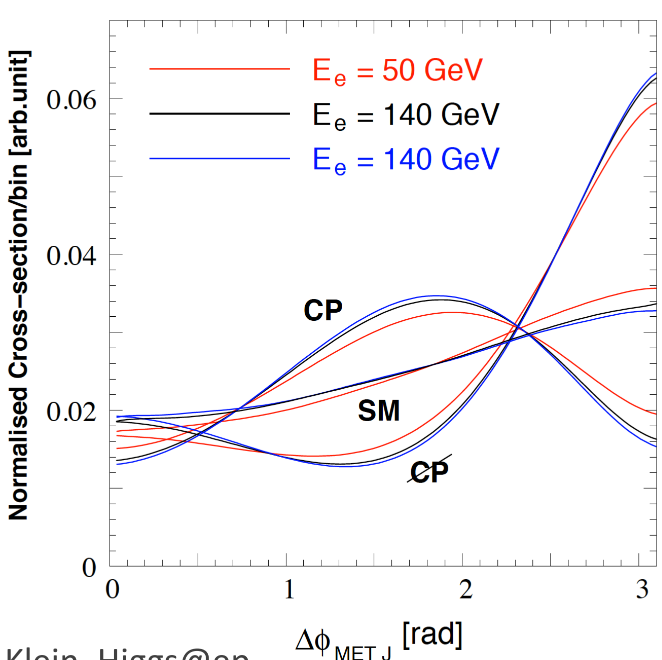
Measure CP properties of Higgs

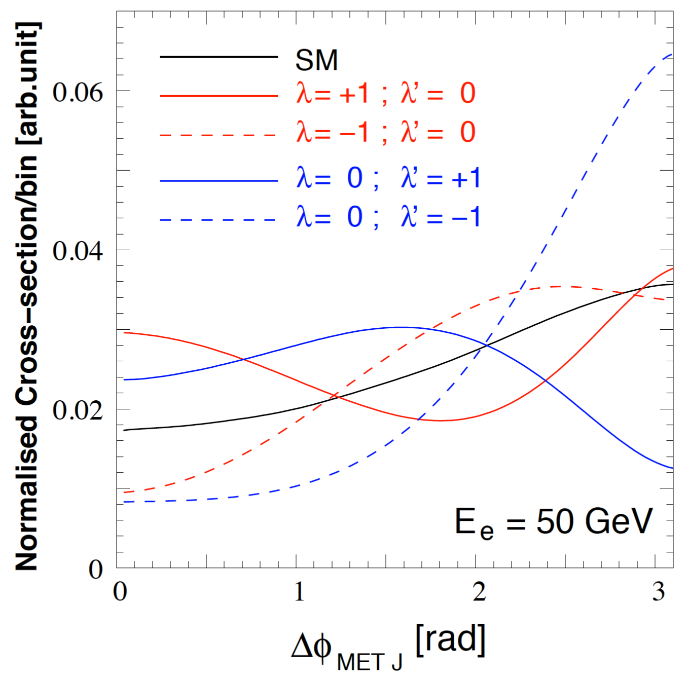
[LHeC CDR before Higgs discovery MH=120 GeV, E_p=7 TeV]

- 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

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

- 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

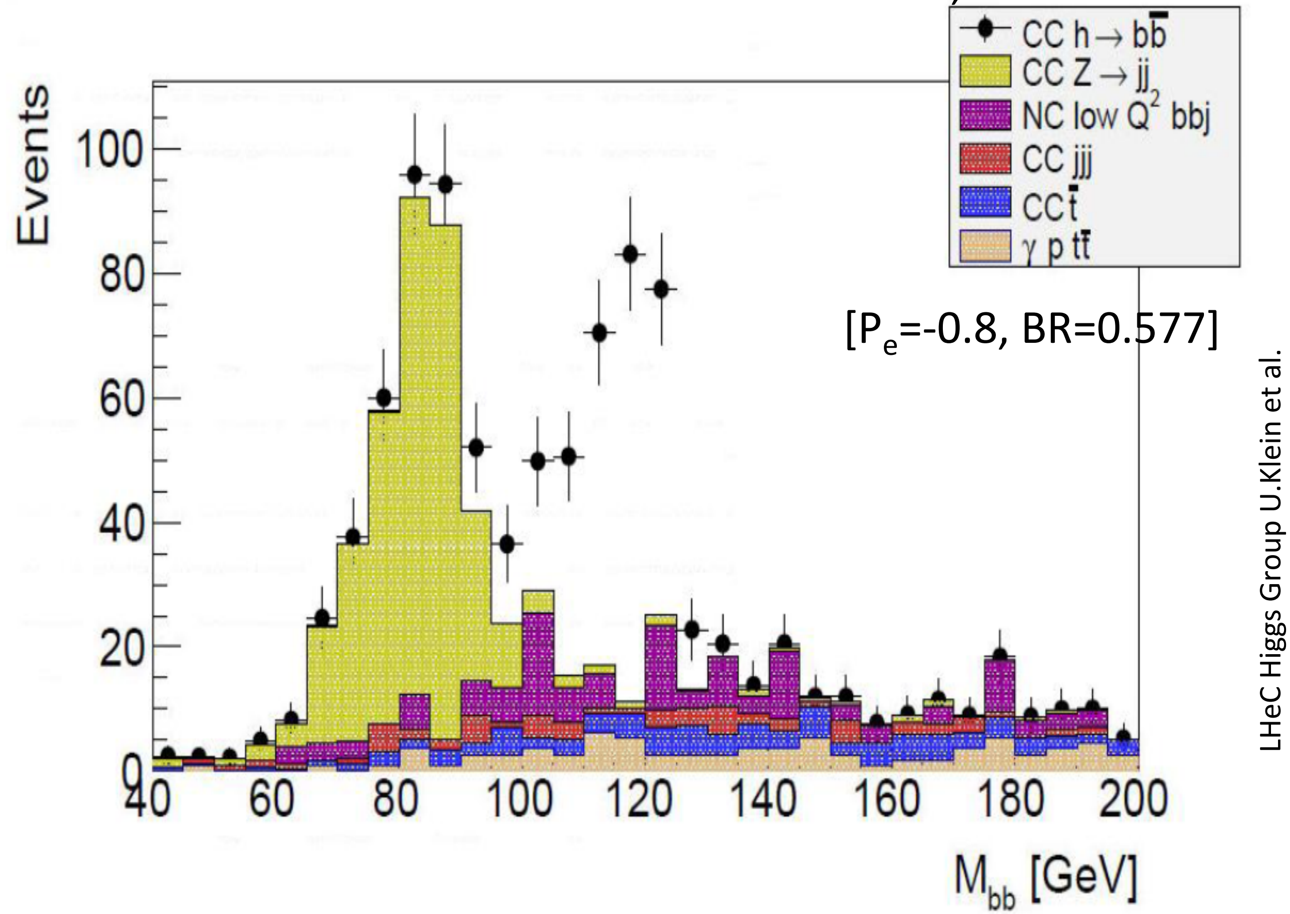
based on 50 fb^{-1}

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→ νH(bb)X
charged currents
σBR~120 fb
μ=0.1
S/B ~1-2
Cut based only
→ ongoing : MVA and lifetime tags
→ detector optimisation
[LHC: VH - BDT's
σ(VH) ~ 130fb 8 TeV
arXiv:1409.6212]



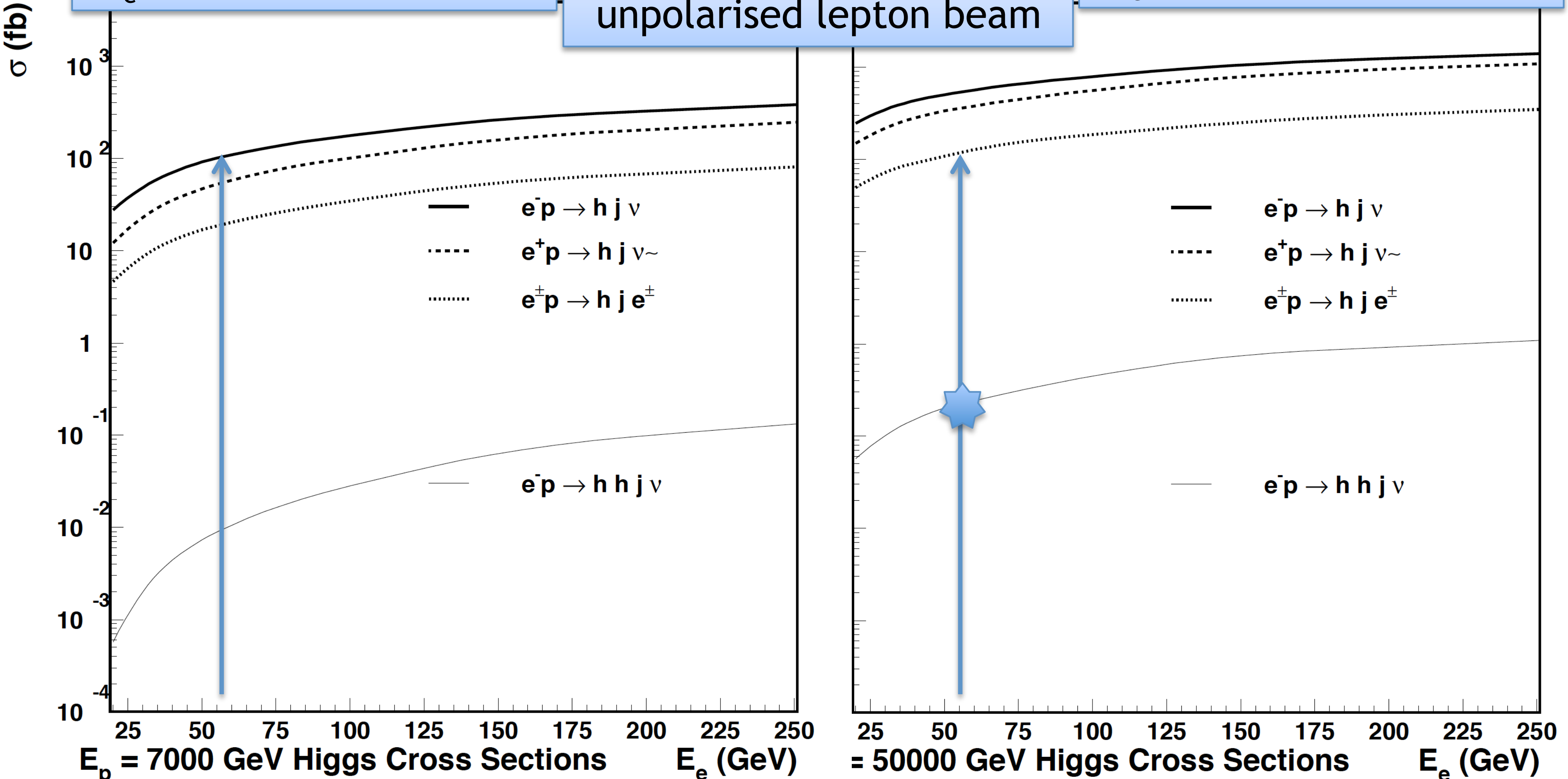
This reconstructs 60% of H in ep with comfortable S/B ~1 , in CC and NC
→ Enables BSM Higgs (tensor structure of HVV, CP, dark H?) , QCD(H)
→ **O(1)% precision on H-bb couplings with small thy uncertainty**. H-cc imminent

Total Higgs cross sections vs E_e

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

M_h=125 GeV
unpolarised lepton beam

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



7 TeV LHC protons

50 TeV FCC protons

and

electrons from a 60 GeV energy recovery LINAC

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** (LHeC) √s= **3.5 TeV** (FHeC)

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

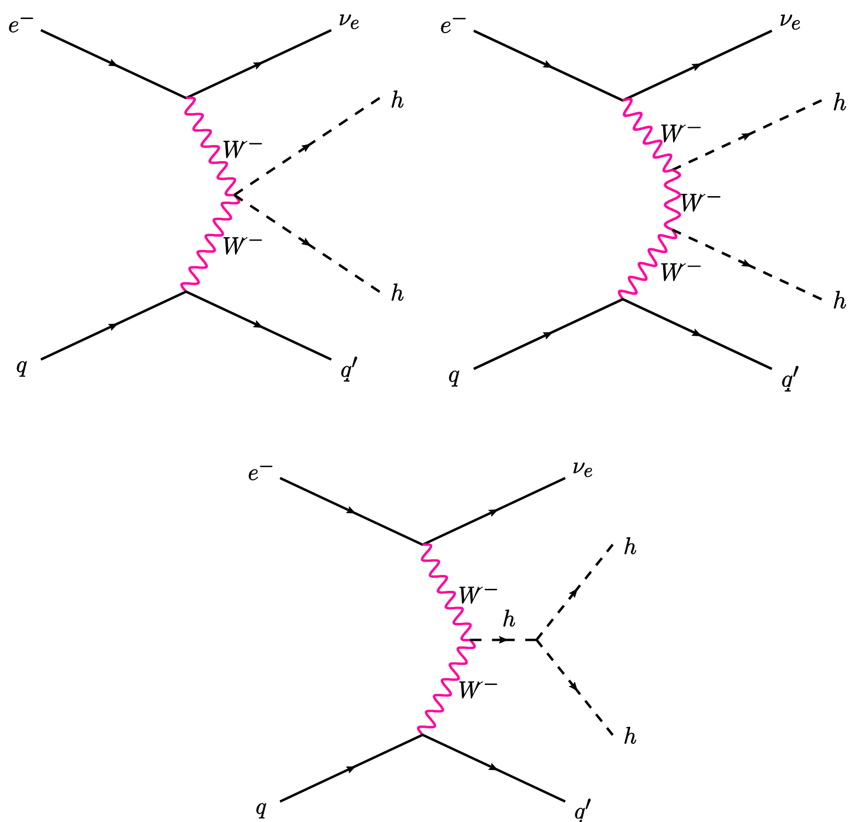
Cross section at FCC-he 1pb ep→ vHX

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)



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

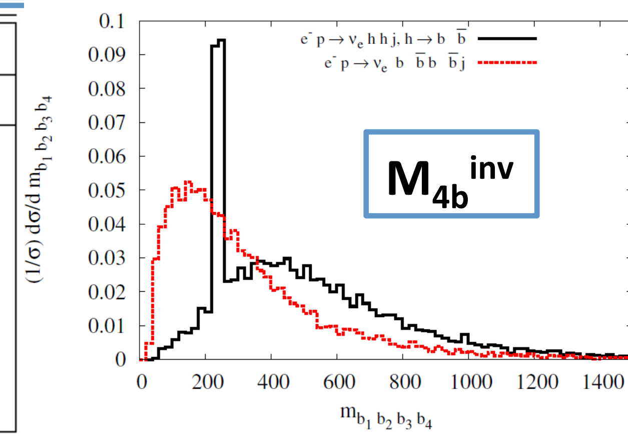
Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \rightarrow \nu_e hhj, h \rightarrow b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

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

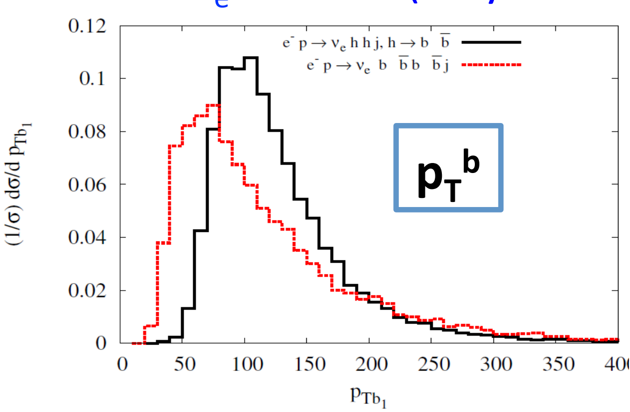
First *parton-level* feasibility studies

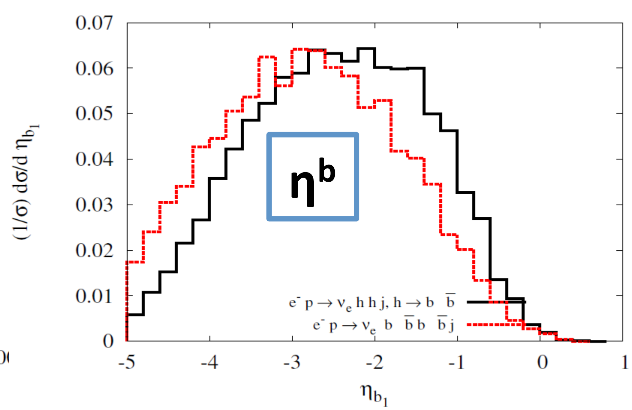
Cross-sections for CC backgrounds in fb for E_e=60,120,150 GeV

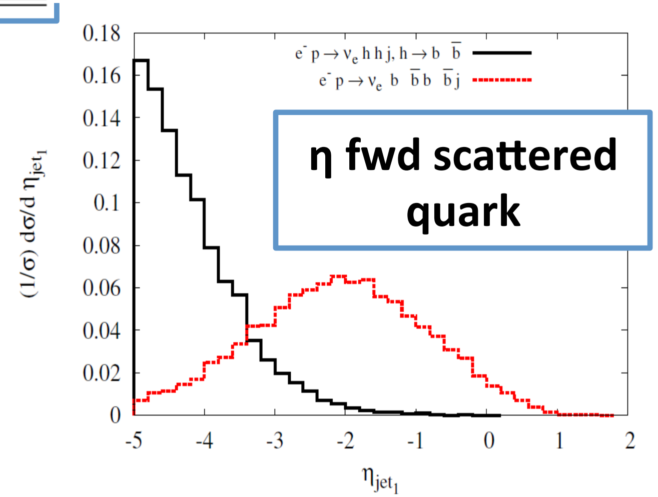
Processes	$E_e = 60$ GeV		$E_e = 120$ GeV		$E_e = 150$ GeV	
	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)	σ(fb)	σ_{eff}(fb)
$e^- p \to \nu_e b\bar{b}b\bar{b}j$	0.086	0.022	0.14	0.036	0.15	0.038
$e^- p \to \nu_e b\bar{b}c\bar{c}j$	0.12	1.7×10^{-5}	0.36	1.8×10^{-3}	0.44	2.2×10^{-3}
$e^- p \to \nu_e c\bar{c}c\bar{c}j$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



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





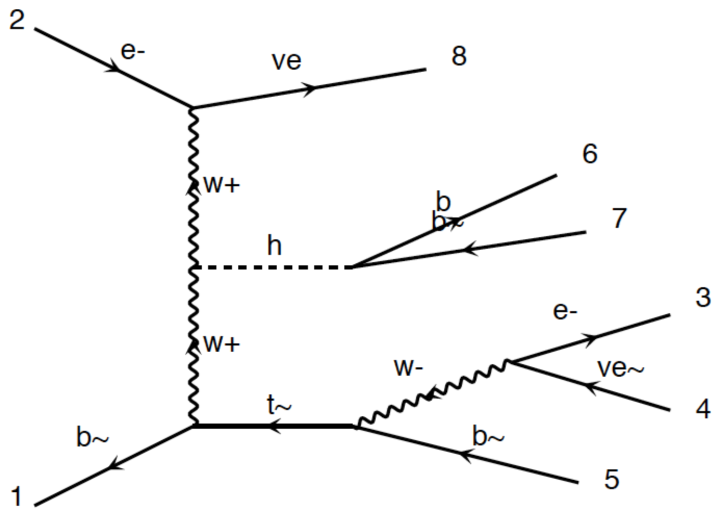


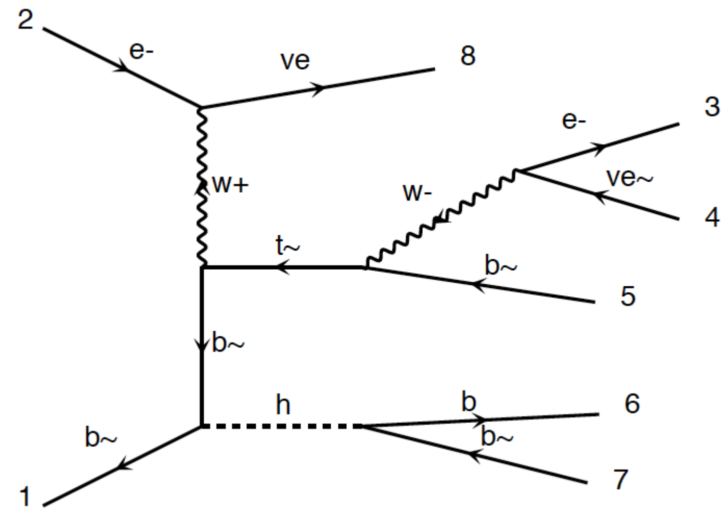
Despite large beam energy imbalance: "b-jets" are relatively central

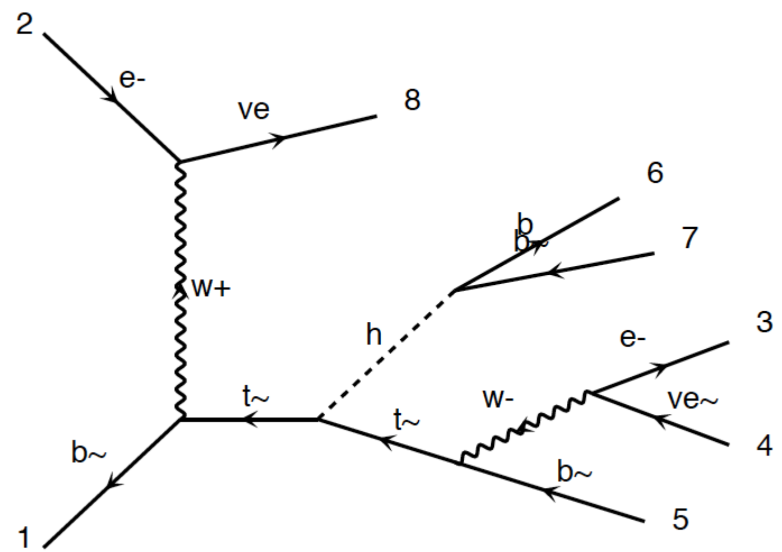
Scattered quark is more forward in signal → good discriminant!

Detector optimisation is crucial.

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

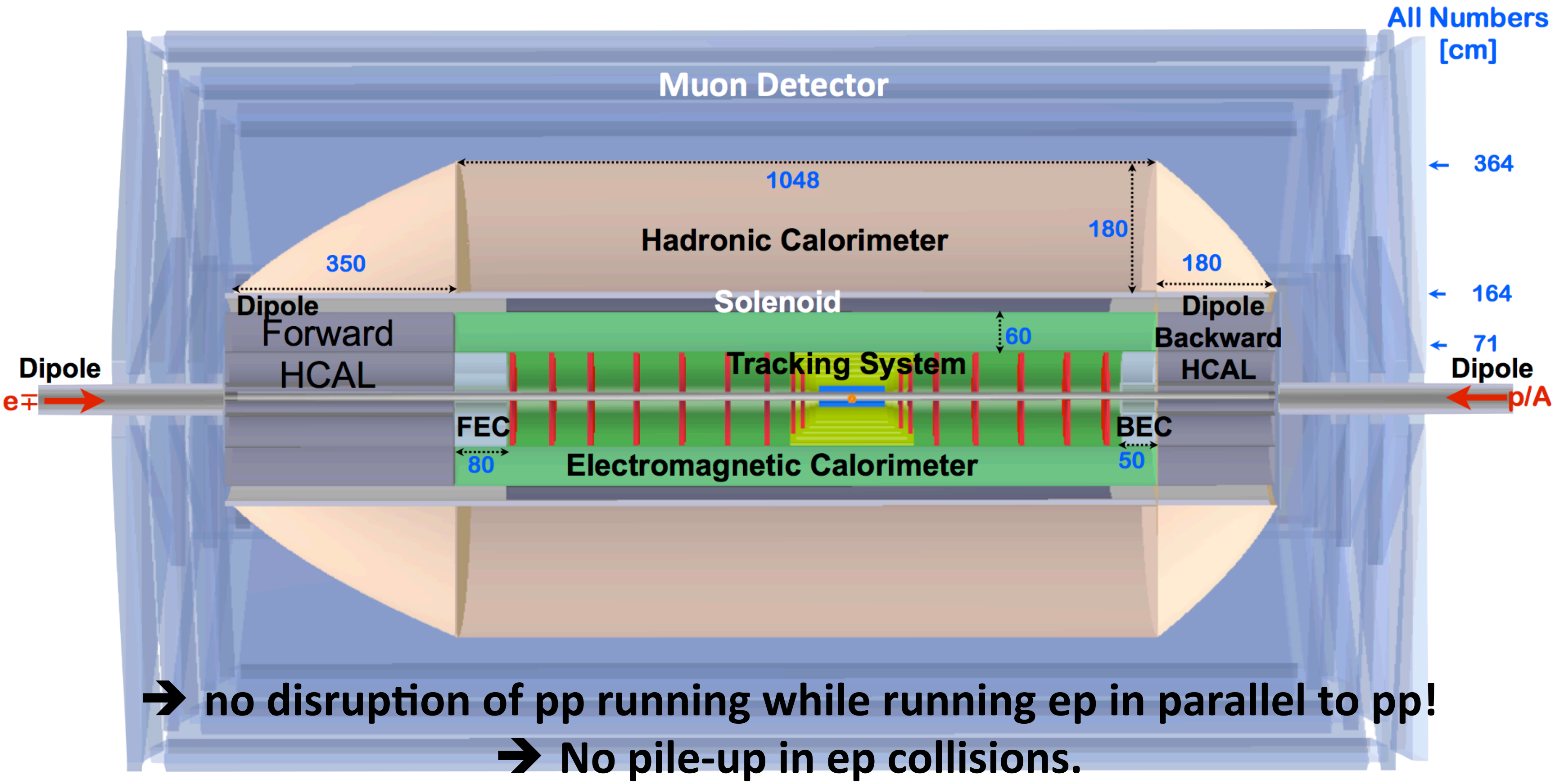
ΔR(j.b)>0.4

η(j) <5

η(b) < 3

FCC-he detector (~CMS size)

→ Longer in p direction (x 2 for calorimeters to contain showers) than LHeC detector
→ 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

Outlook - Exploring Synergies

- The Higgs cross sections are sizeable at LheC and FCC-he, and first LHeC studies show Hbb coupling could be measured to 1% using 1000 fb^{-1}.
- Now ongoing : further detector studies using

a) fast simulations for 'rough' estimates

b) using full simulation, e.g. W-Si Calice type calorimeter

→ very good synergy potential to use ILC/CLIC benchmark detector designs for high precision physics!

→ we are using already e.g. dd4hep, but there could be much more fruitful collaboration between ee, pp and ep regarding detector parameterisations, analysis strategies, agreement on definitions (e.g. b- or c-parton within cone of 0.3 or 0.5?), reconstruction software (e.g. particle flow)

→ would allow to measure Higgs properties based on different theoretical grounds, different background conditions and with totally different machines

→ joint 'global' fit of pp, ep and ee Higgs cross sections

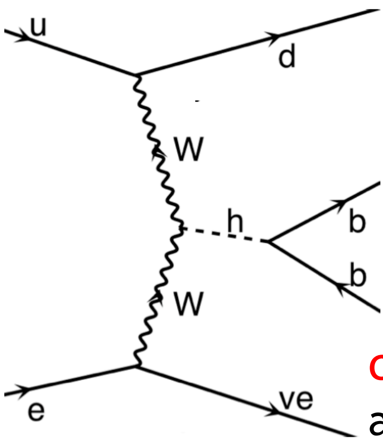
Additional material

Examples: Generated samples

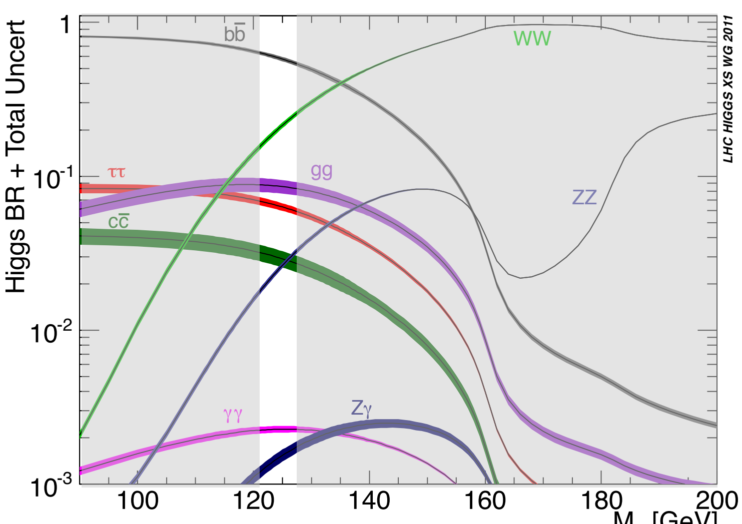
Graphs by MadGraph

Signal

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

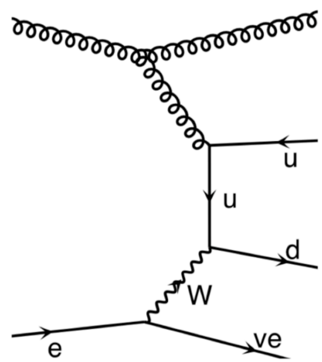


σ~ 0.16 pb
at √s=2.05TeV

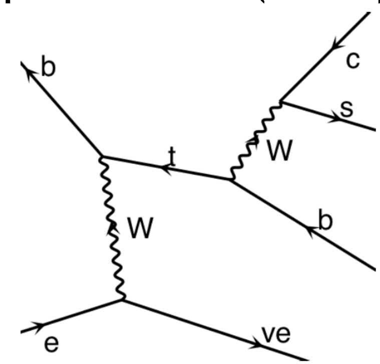


Background (examples)

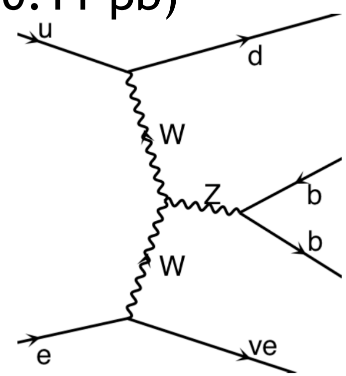
CC: 3 jets (~57 pb)



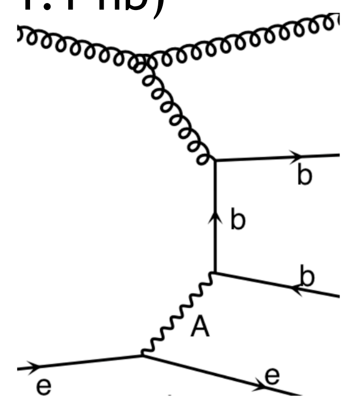
CC: single top production (~4.1 pb)



CC: Z production (~0.11 pb)



NC: b pair production (~1.1 nb)



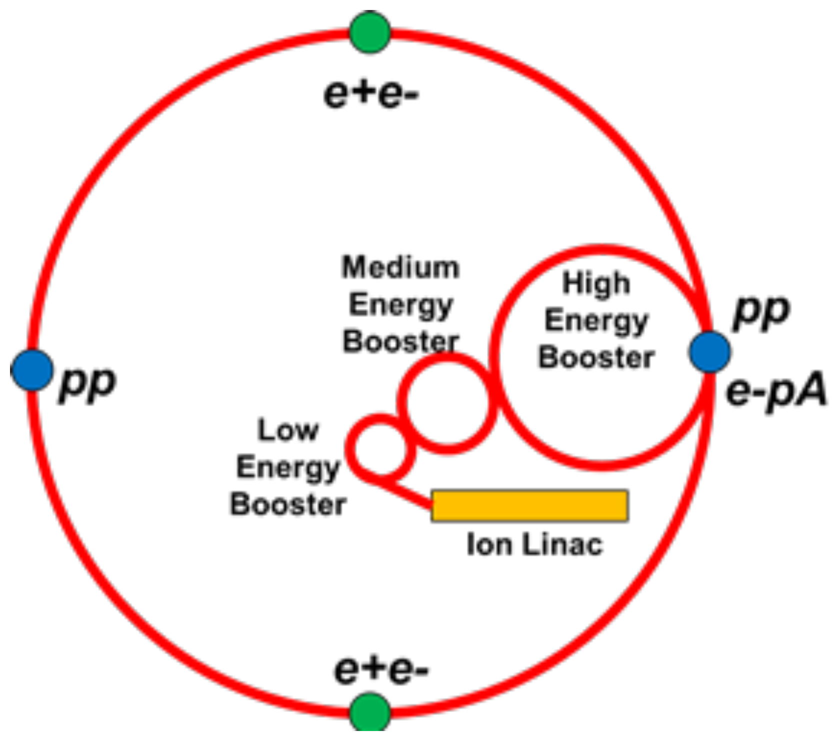
NOTE: Background sample cross sections are after pre-selection in generator and for Ee=150 GeV

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

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.***

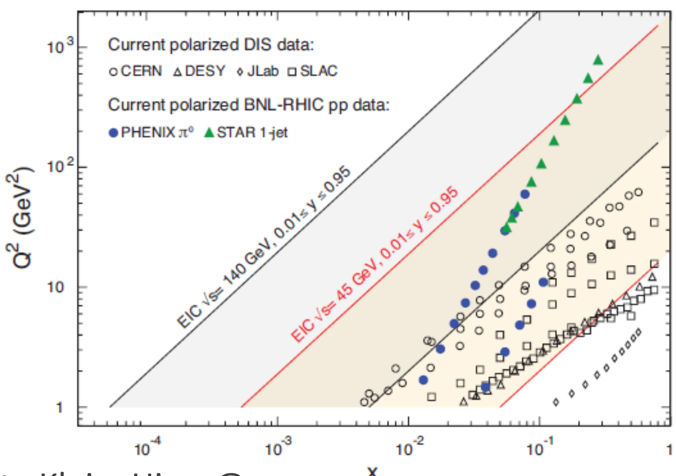
World's first polarised e-p collider and lower energy e-A collider.

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

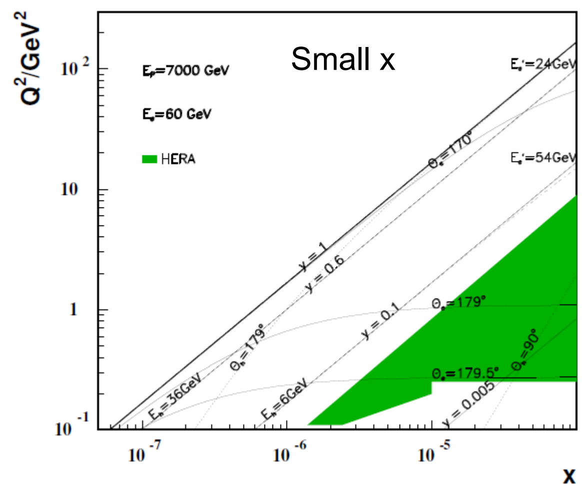
- *Add ~60 GeV **polarised** electrons to probe unpolarised LHC proton and ions*

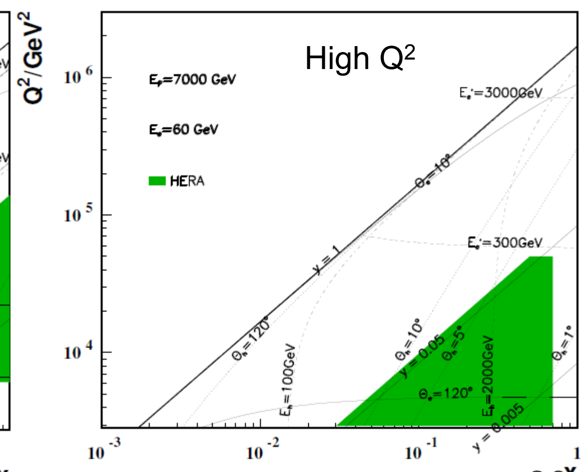
High-energy frontier e-p and e-A collider to follow HERA with factor 1000 higher luminosity running simultaneously with HL-LHC.

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



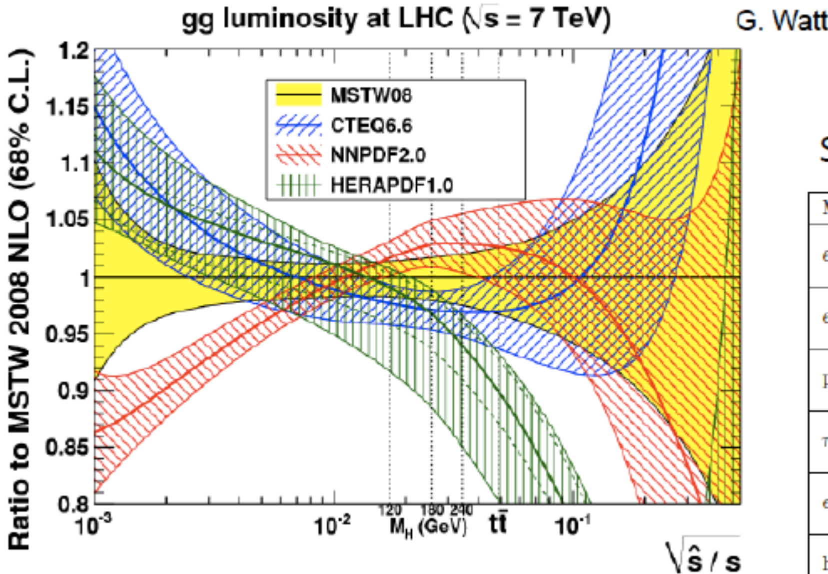
x_{min} ~ 6 x 10^{-7}





"Snowmass" 2013

arXiv:1310.5189



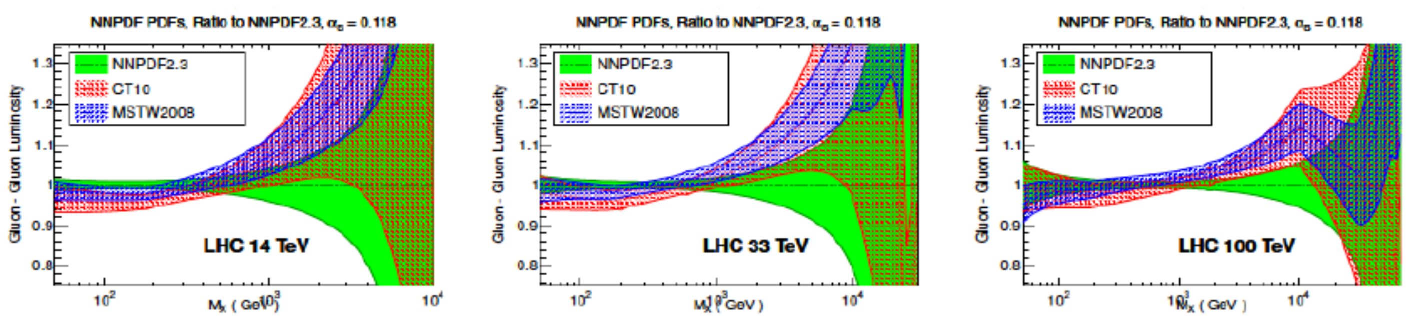
PDFs for QCD, H, BSM ...

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

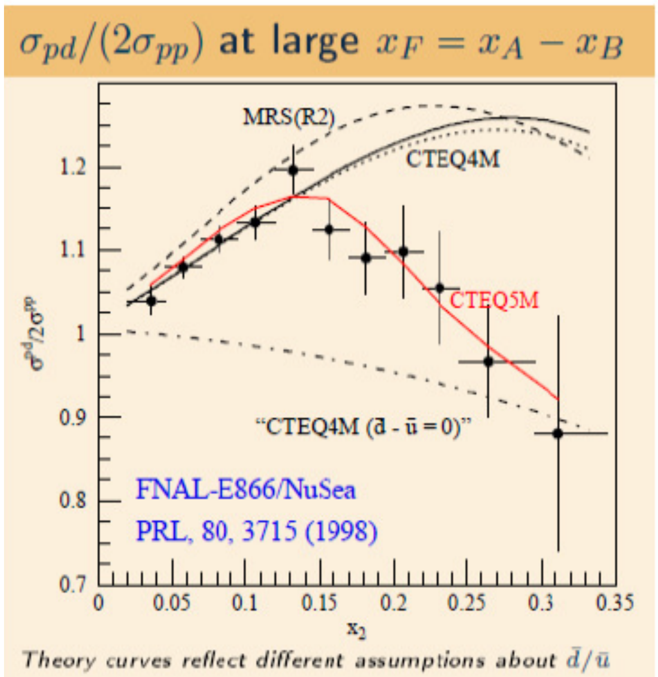
Gluon-gluon luminosity at the LHC, HE LHC and FCC



Synergy: Constraining Sea Quark PDFs

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

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

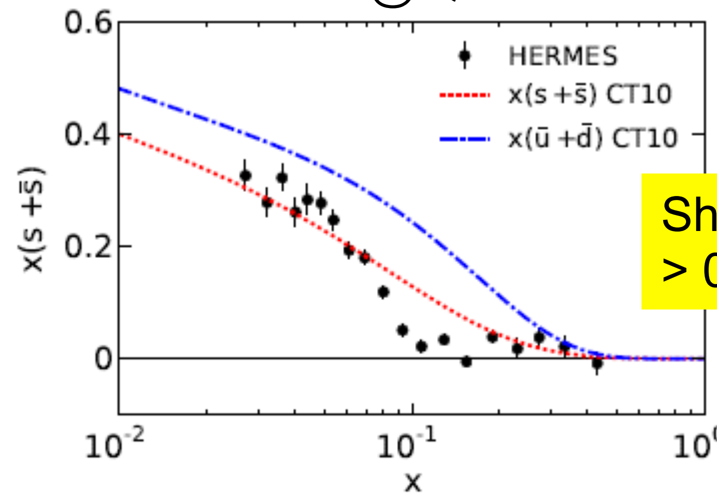


- Implications for all PDF fits
- Effect soon confirmed by HERMES w. **SIDIS** data (semi-inclusive DIS)
- Further data ongoing at FNAL/SeaQuest (x > 0.1)
- LHC **W/Z** data suggest flavour-symmetric sea ?
- LHC W+charm data → subject to cuts, FF/hadronisation…

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

Strange sea s more (data) challenged

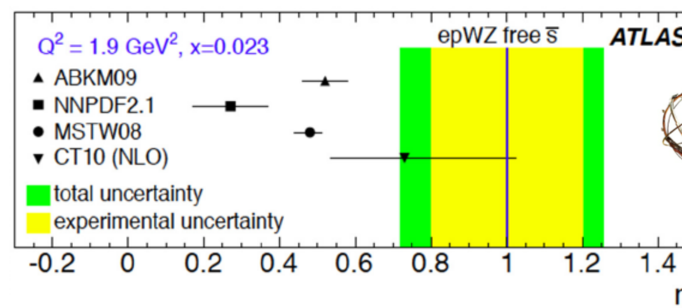
- HERMES **SIDIS** @ $Q^2 = 2.5$ GeV^2



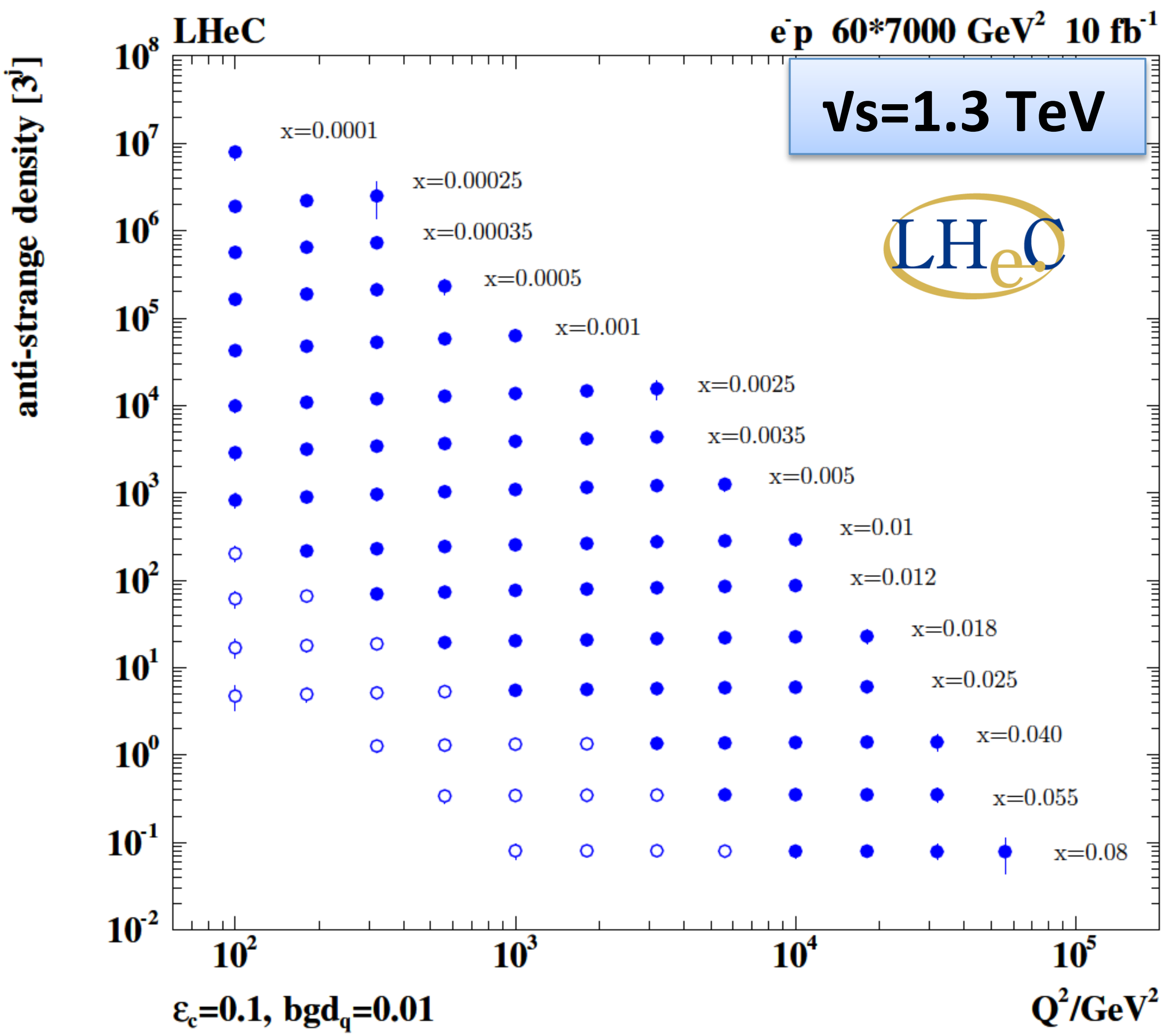
Shape x > 0.1?

- 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

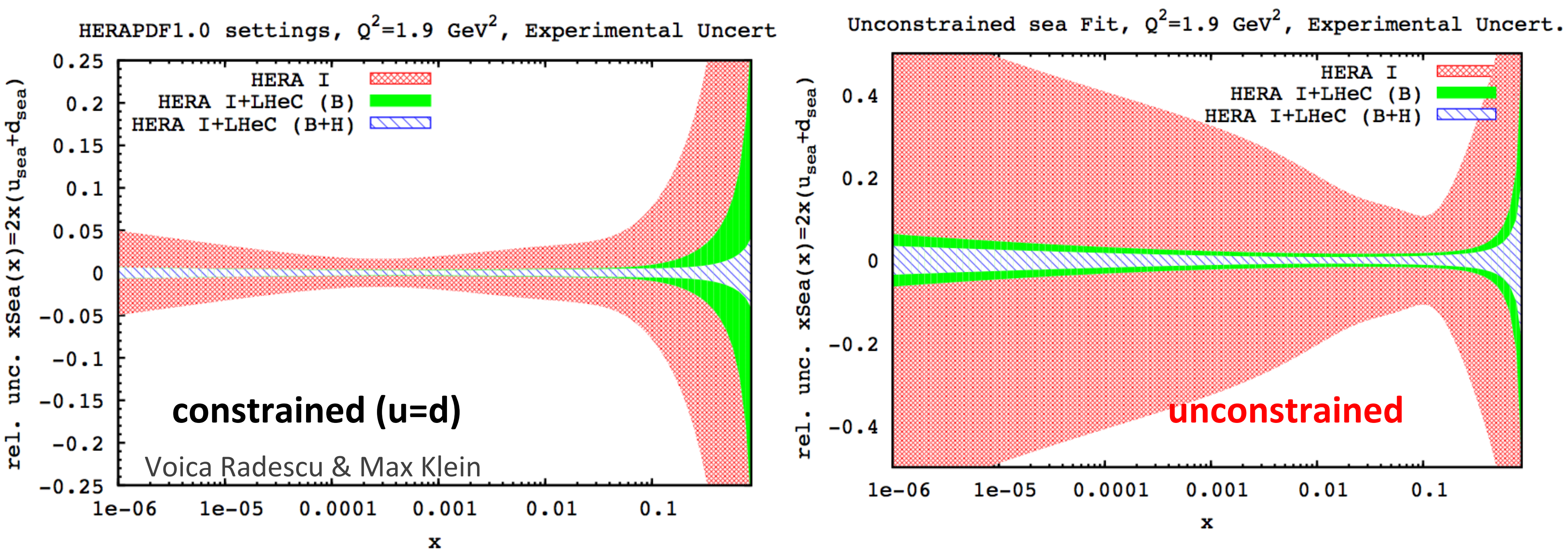
NO pile-up..

→ **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…

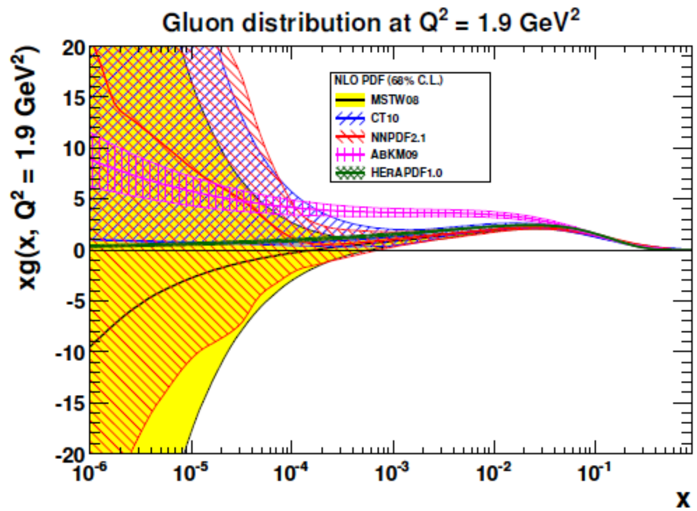
The Gluon PDF – much less known than we wish

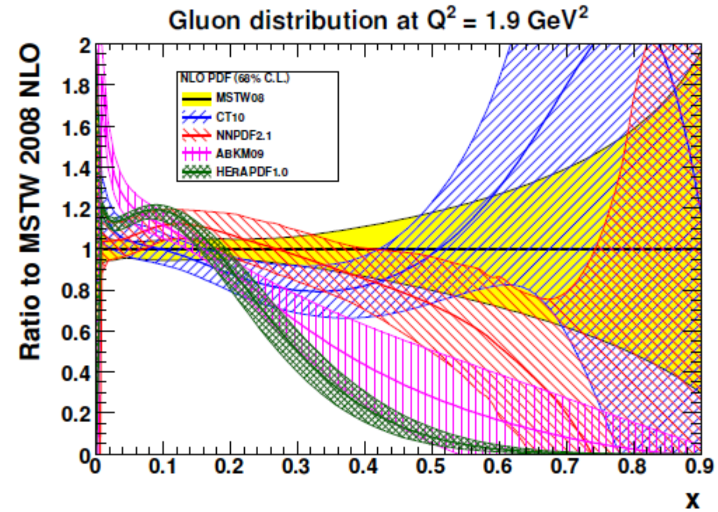
"You may not realize that you will need it…" (Rolf Ent)

LOGARITHMIC Bjorken x SCALE

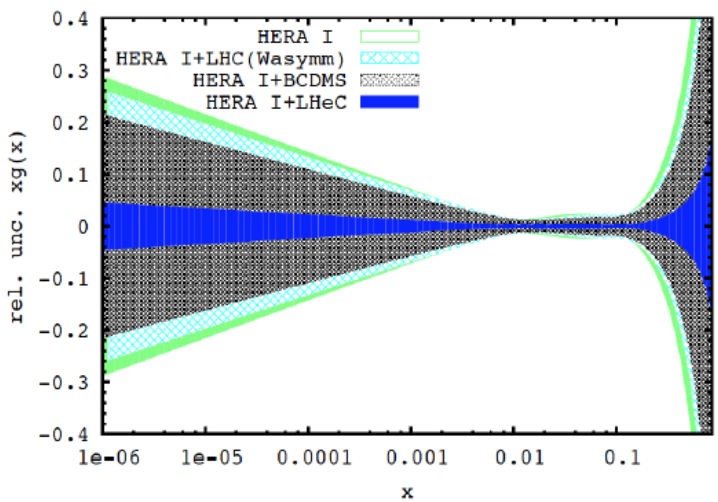
LINEAR Bjorken x SCALE

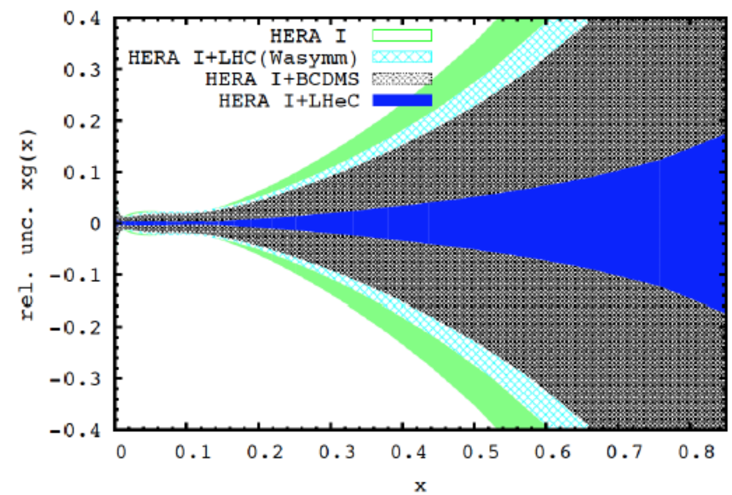
CURRENT



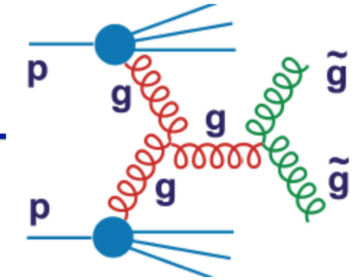


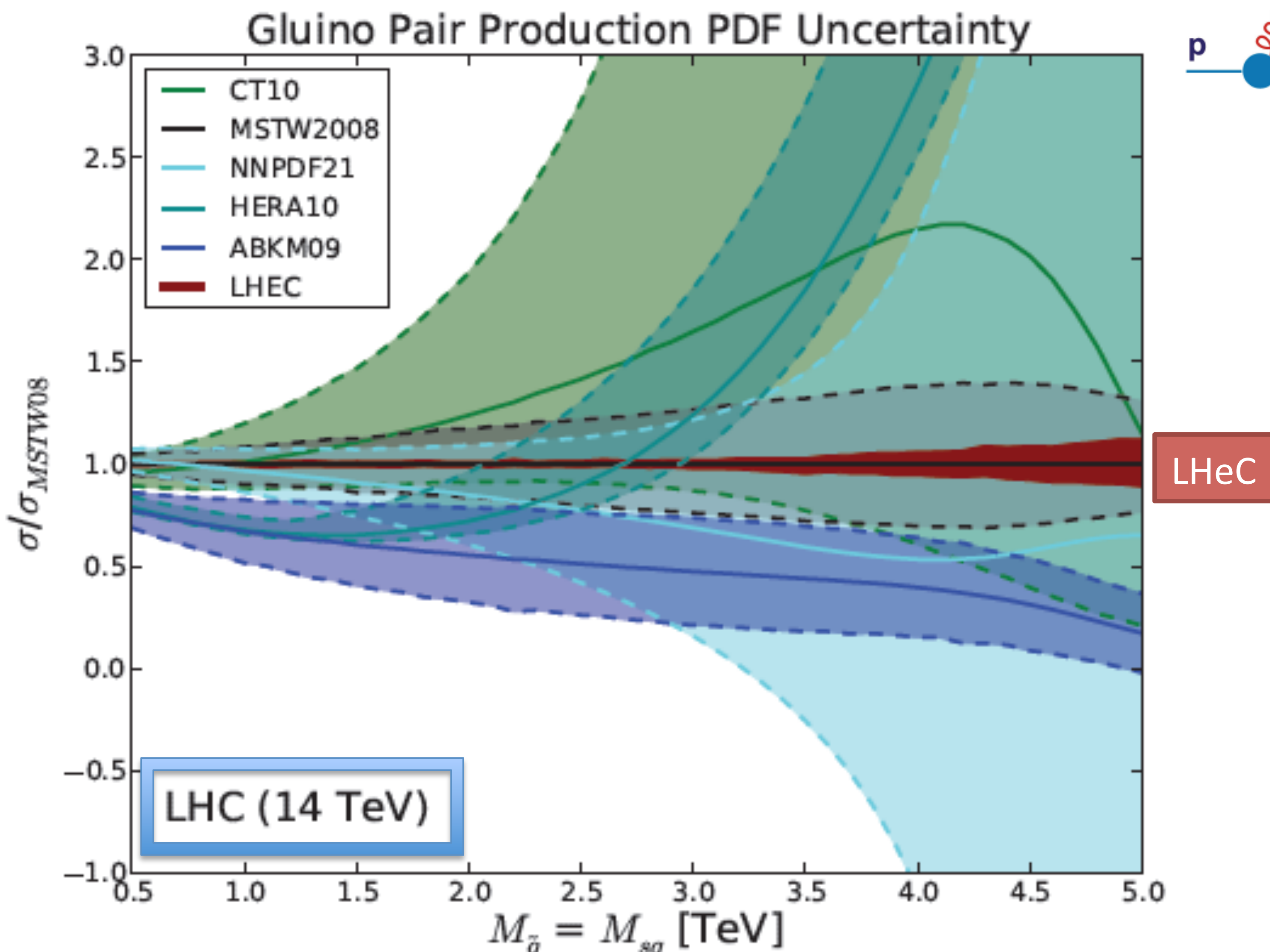
FUTURE





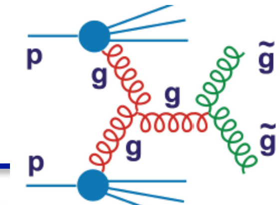
Precision gluons for SUSY

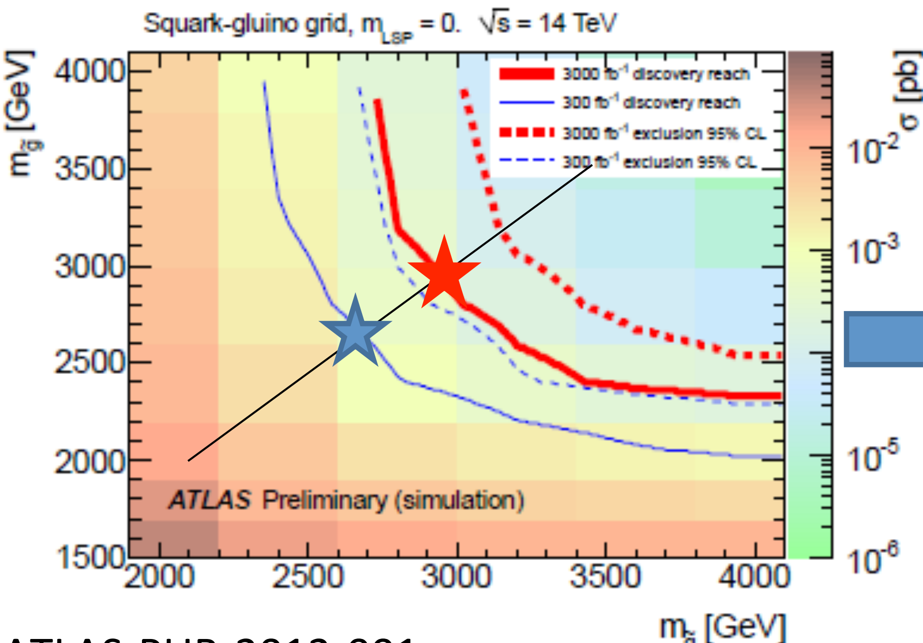




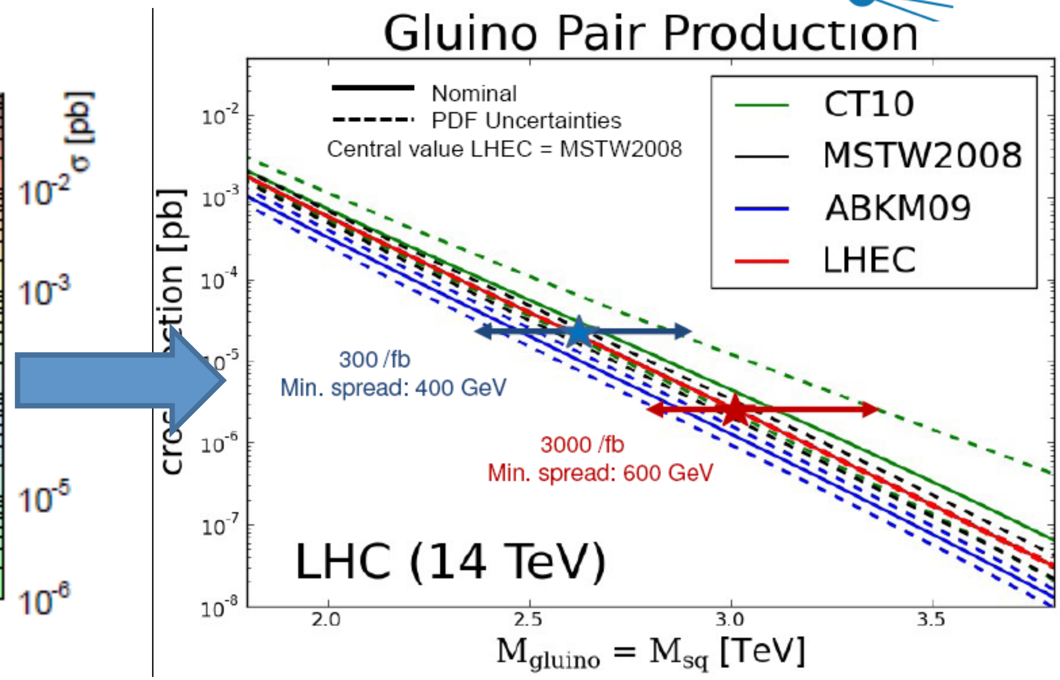
LHeC Note 2012-005
arXiv:1211.5102; LHeCPDF in LHAPDF

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..)

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)**

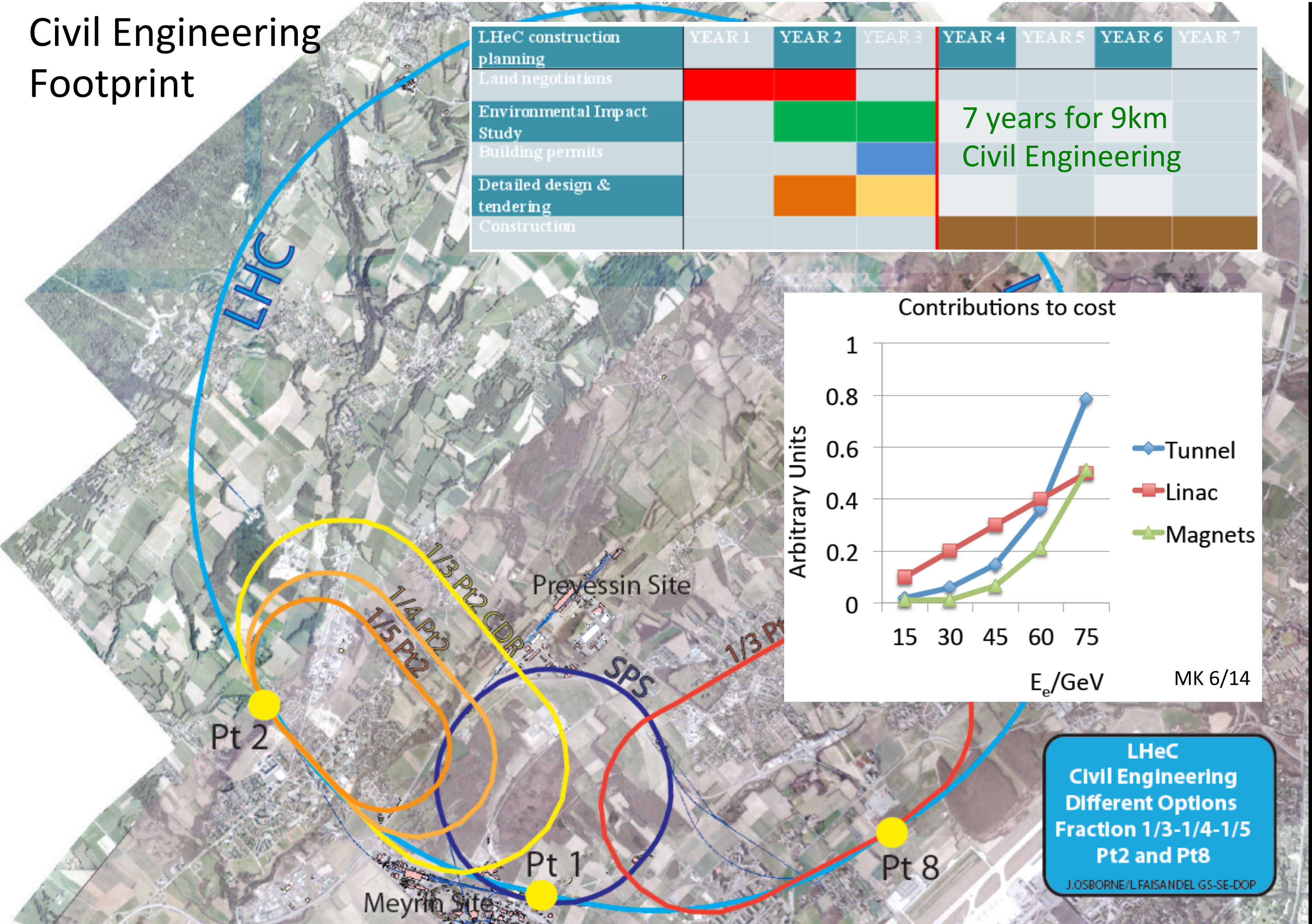
As in the tradition of CERN

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

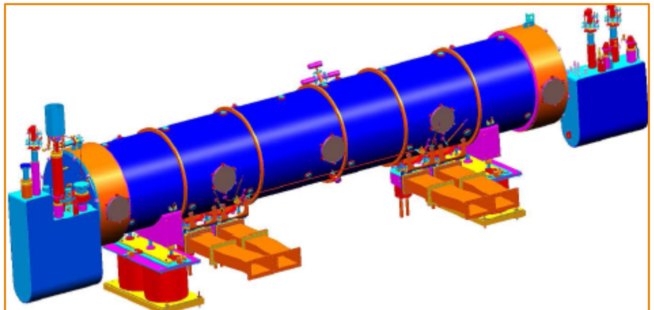
Civil Engineering Footprint

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



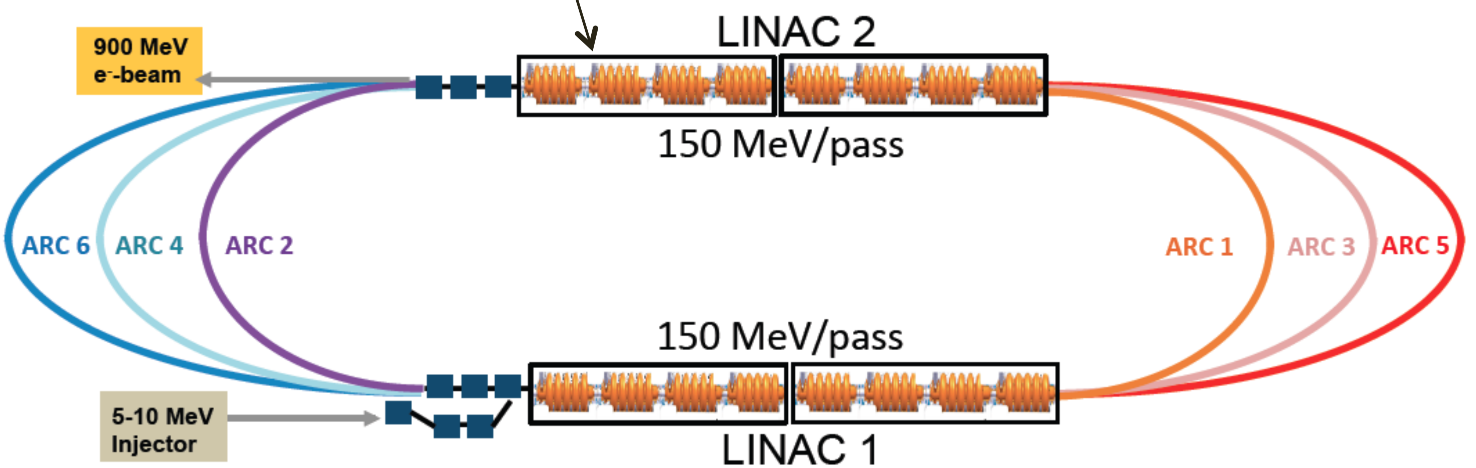
Superconducting RF and ERL Test Facility Design at CERN



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 ..

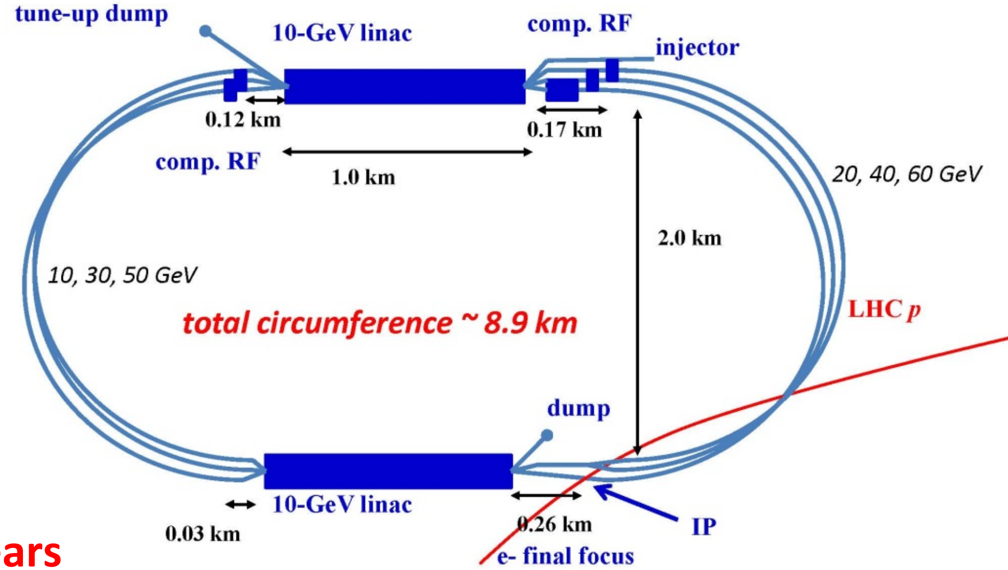


Arc optics, Multipass linac optics, Lattice, Magnet specification, … first passes done

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

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 <u>high electron polarisation of 80-90%</u>
- 3 return ARCs, 20 MV/m
- Energy recovery in same structure
- Installation fully decoupled from LHC operation!



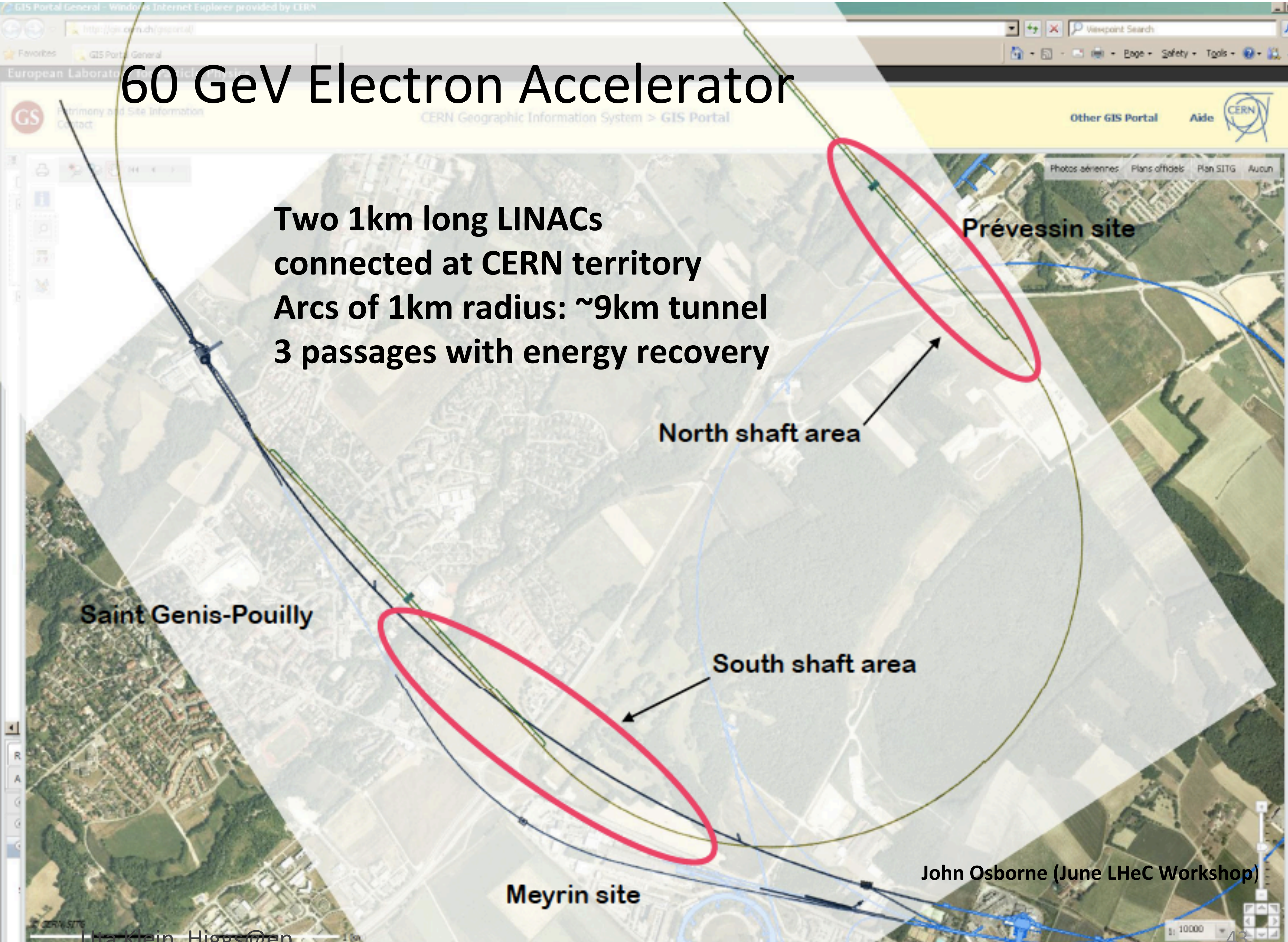
- ep Lumi 10^{33} - 10^{34} cm s^{-2} s^{-1} **
- 10 - 100 fb^{-1} per year
- 100 fb^{-1} – 1 ab^{-1} total collected in 10 years
- eD and eA collisions have always been integral to programme
- eA luminosity estimates ~ 10^{32} cm s^{-2} s^{-1} for eD (ePb)

** 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



John Osborne (June LHeC Workshop)

Pile-up estimate for LHeC

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

➔ Pile-up events expected for LHeC <~0.1

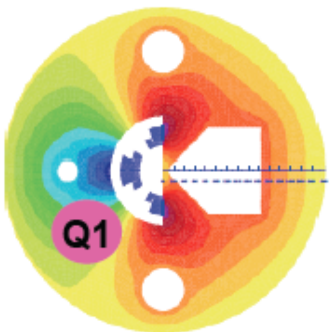
Using pp LHC pile-up estimates

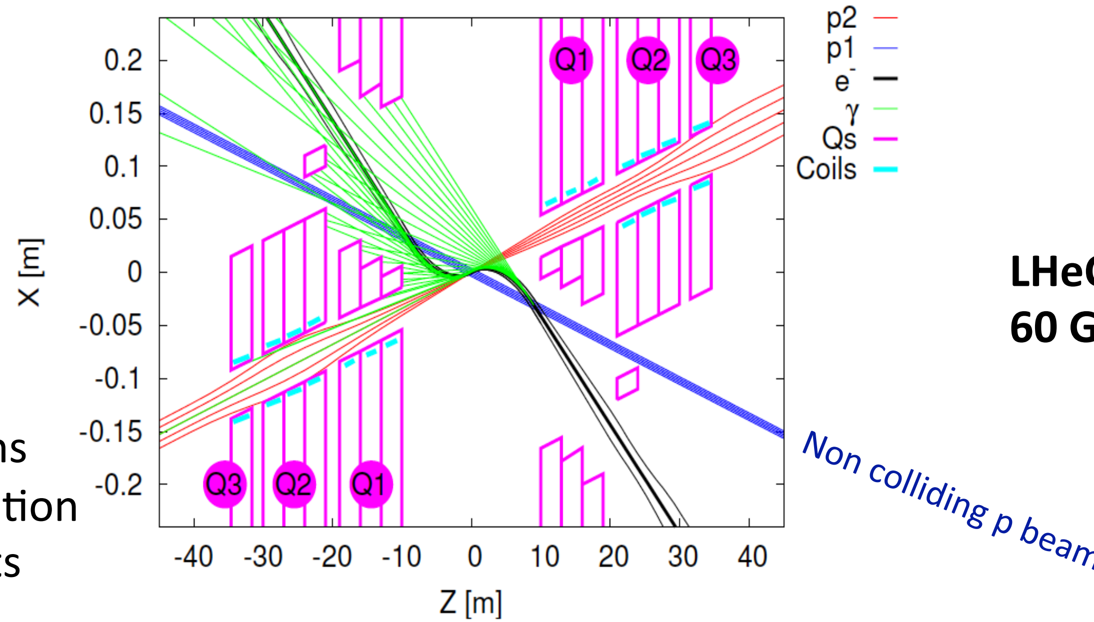
$$N(ep)=N(pp) \times s(\gamma p)/s(pp) \times L(ep)/L(pp)$$
$$= 150 * 0.003 * 0.2$$
$$= 0.1$$

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

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

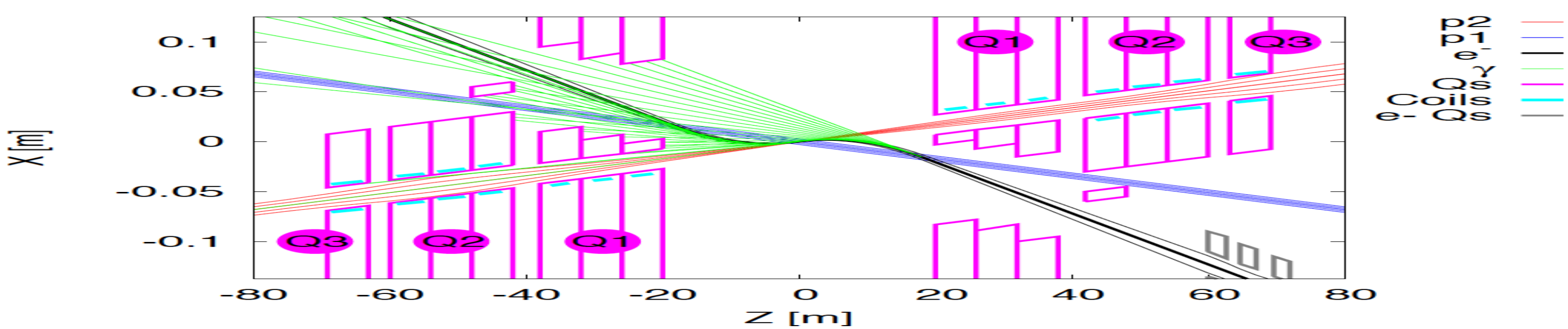
Interaction Regions for ep with Synchronous pp Operation





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

LHeC (CDR)
60 GeV * 7 TeV

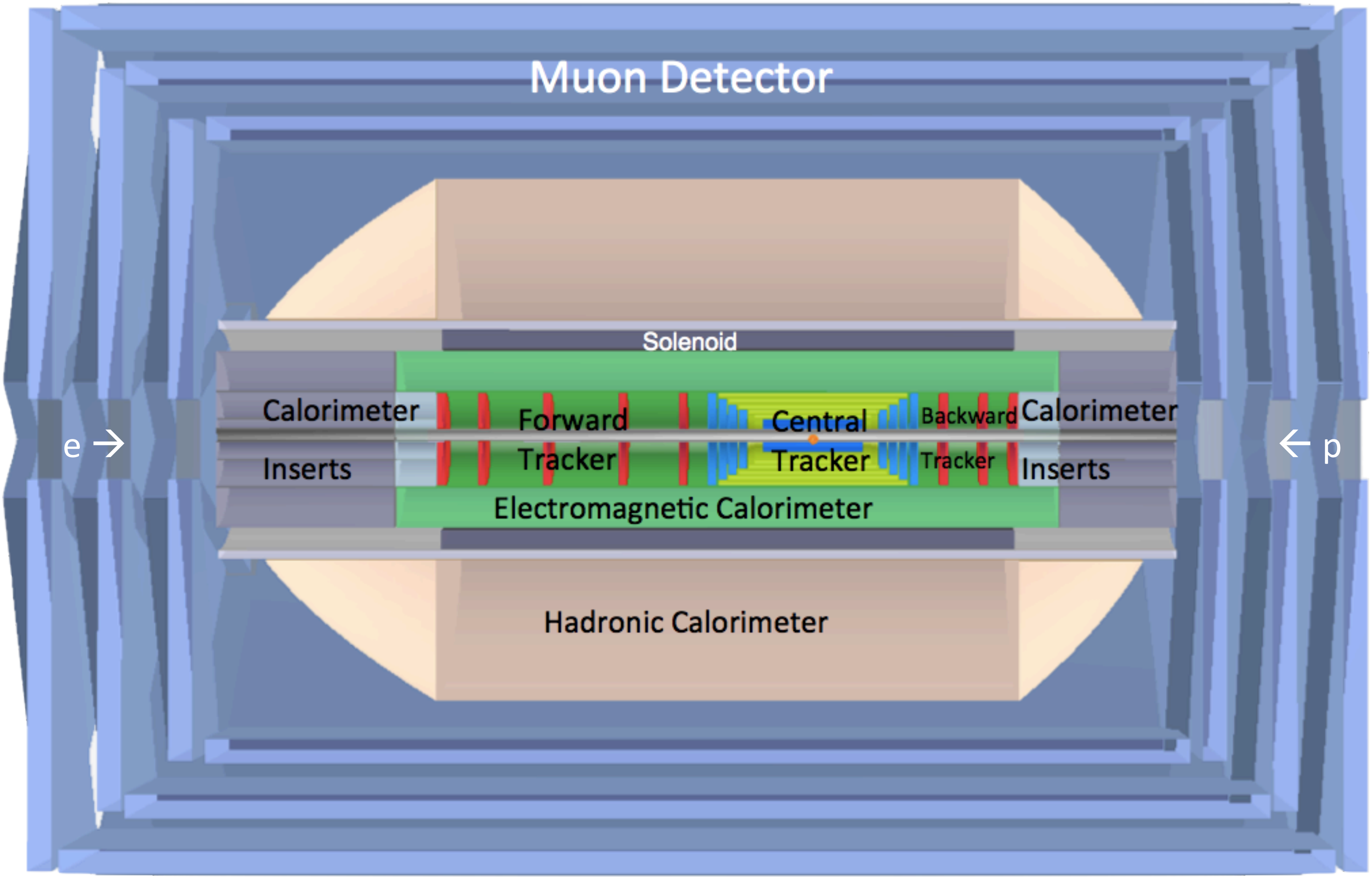


Tentative: ε_p=2µm, β*=20cm → σ_p=3µm ≈σ_e matched! ε_e=5µm ..

FCC-he (ERL)
60 GeV * 50 TeV

Rogelio Tomas, Max Klein, ICHEP14

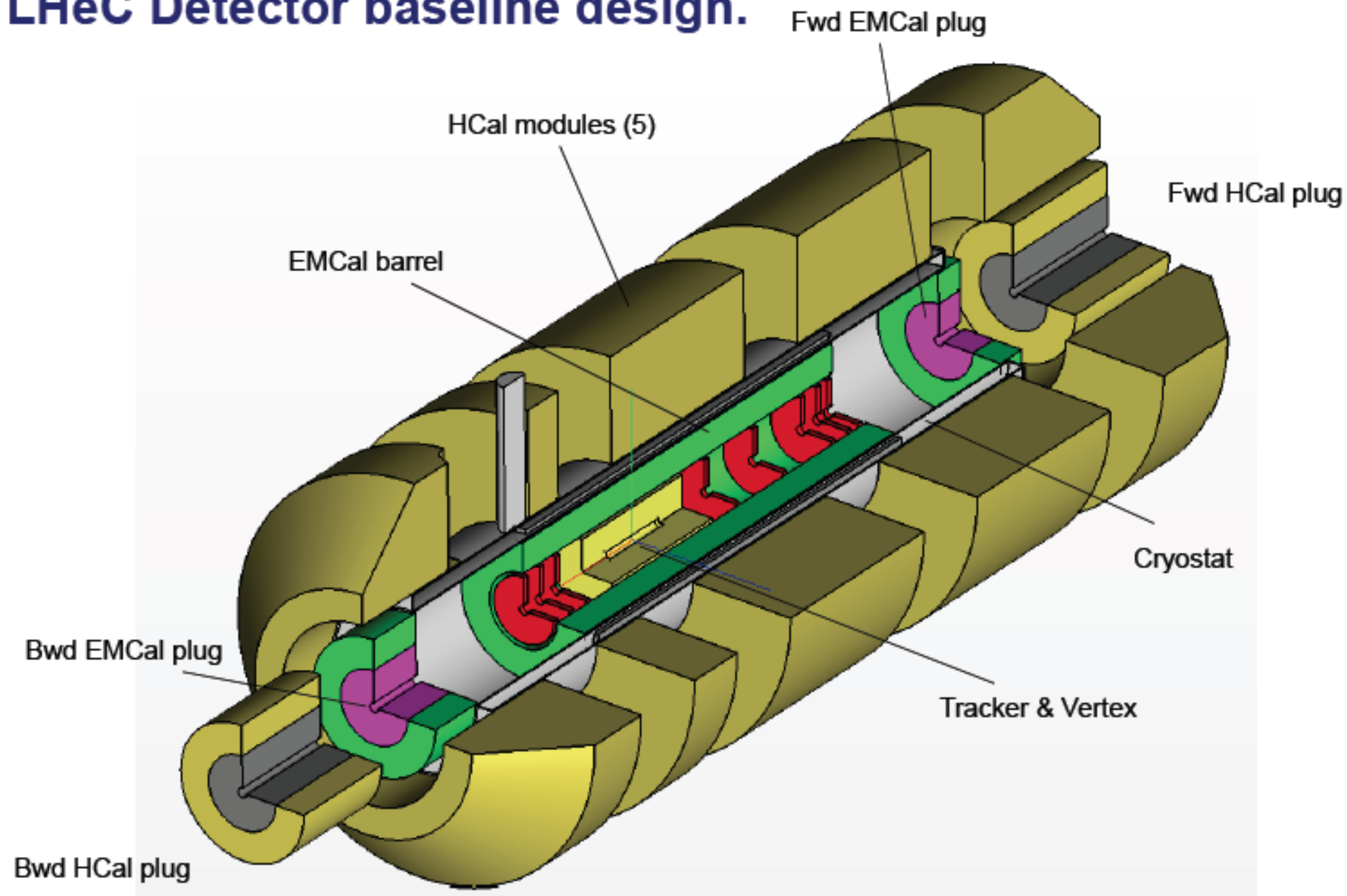
LHeC Detector Overview



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)

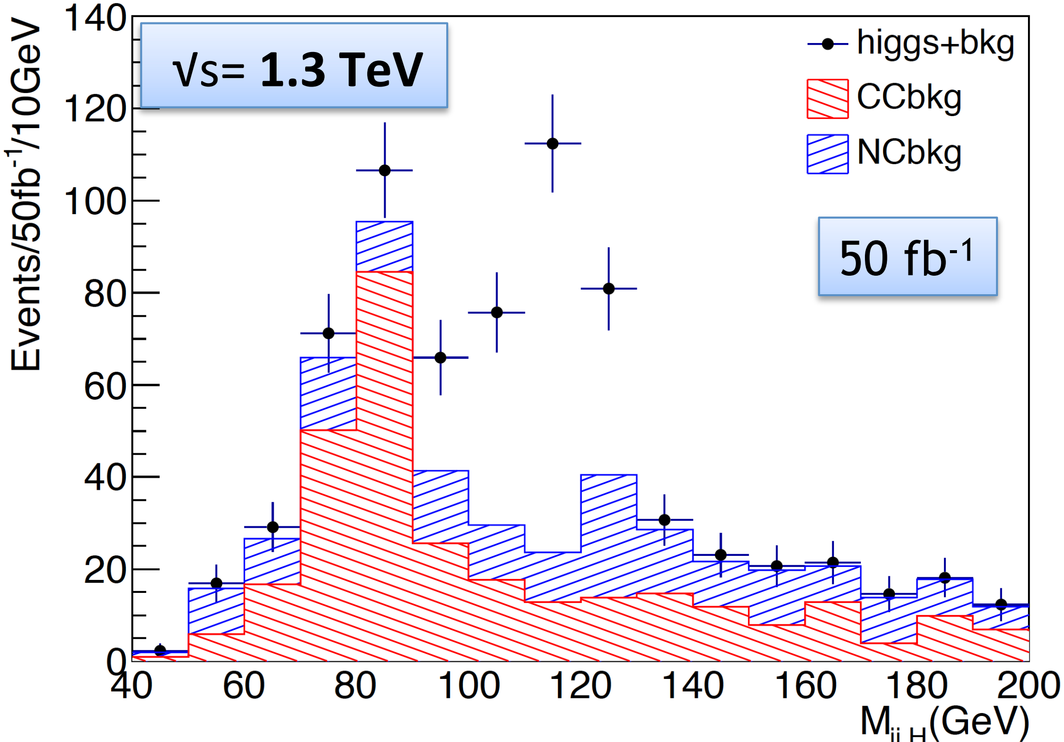
LHeC Detector baseline design.



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

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

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



Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

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

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

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

Strong Coupling Constant

α_s least known of coupling constants

Grand Unification predictions suffer from $\delta\alpha_s$

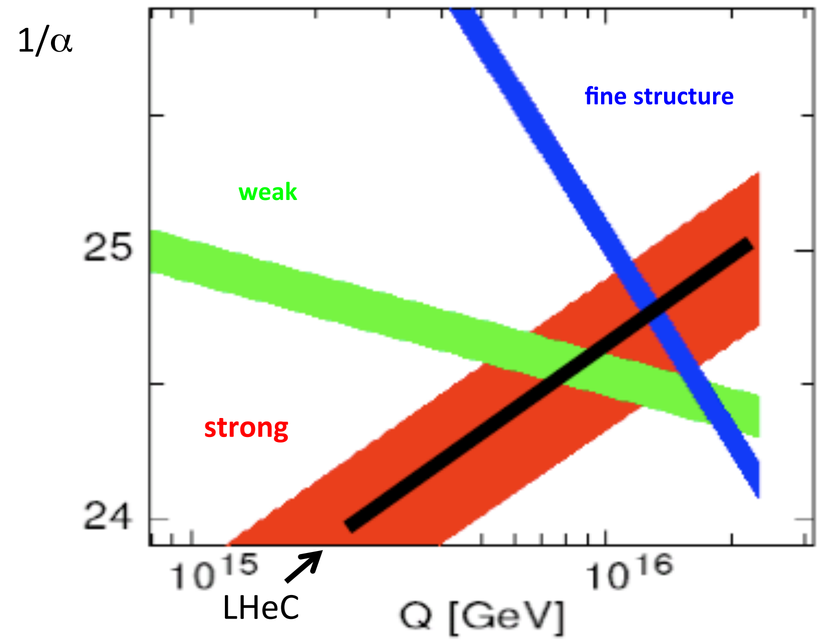
Is DIS lower than world average (?)

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)

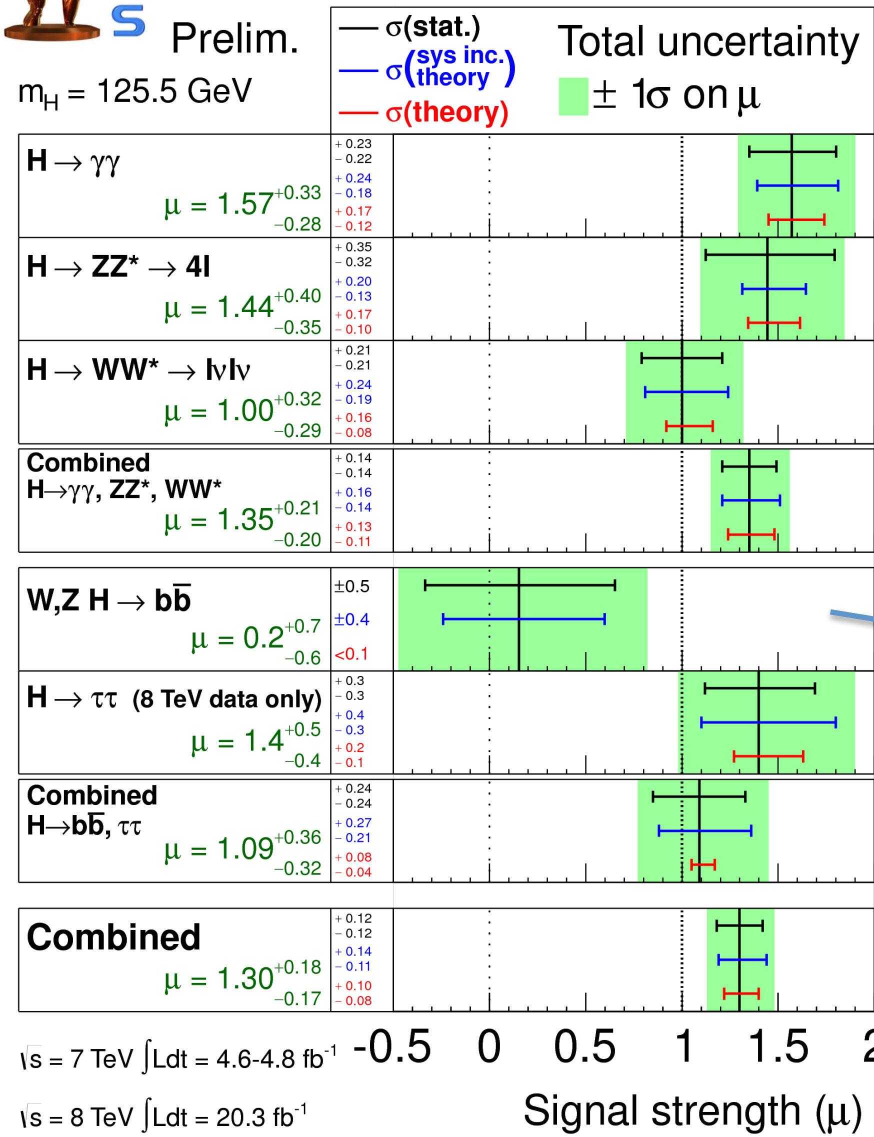


case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 >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

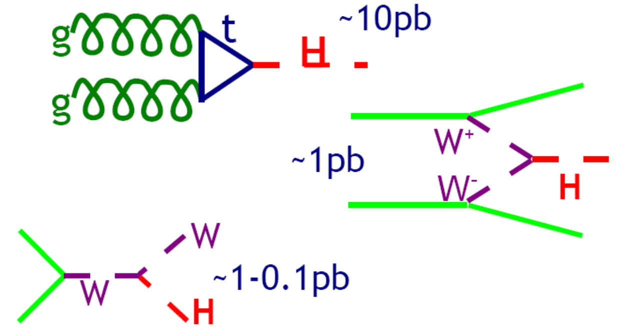
Two independent QCD analyses using LHeC+HERA/BCDMS

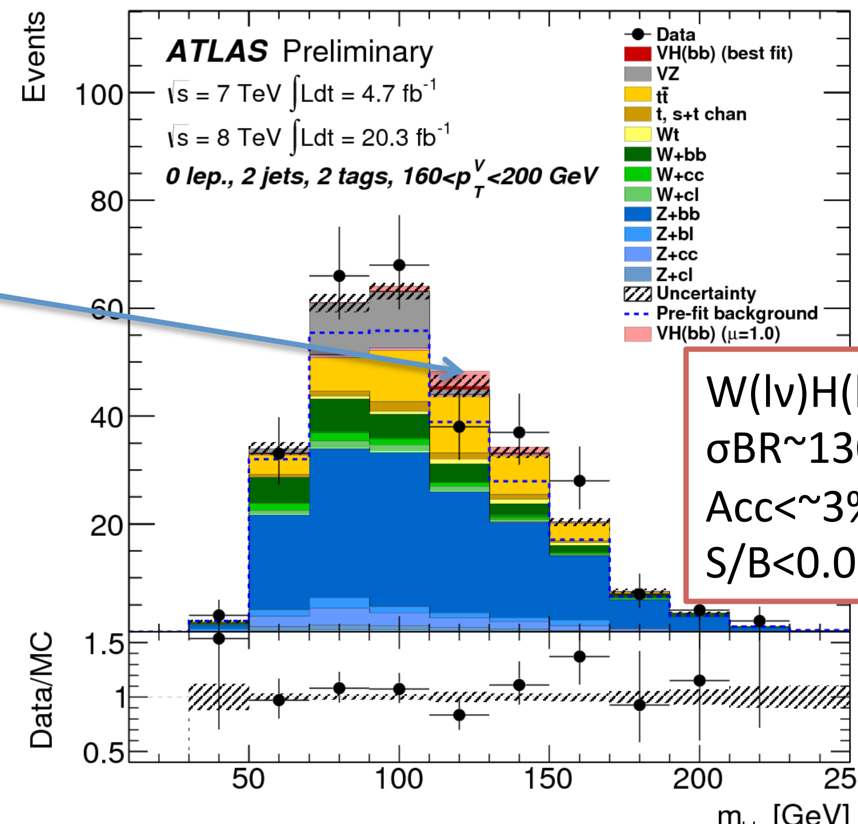
DATA	exp. error on α_s
NC e^+ only	0.48%
NC	0.41%
NC & CC	**0.23% :=(1)**
(1) $\gamma_h > 5°$	0.36% :=(2)
(1) +BCDMS	0.22%
(2) +BCDMS	0.22%
(1) stat. *= 2	0.35%

Status : Higgs coupling strength



ATLAS-CONF-2014-009



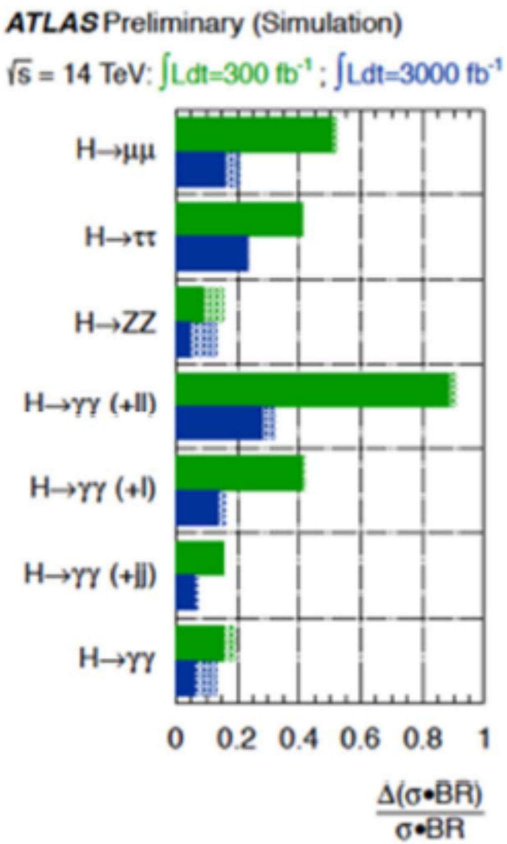


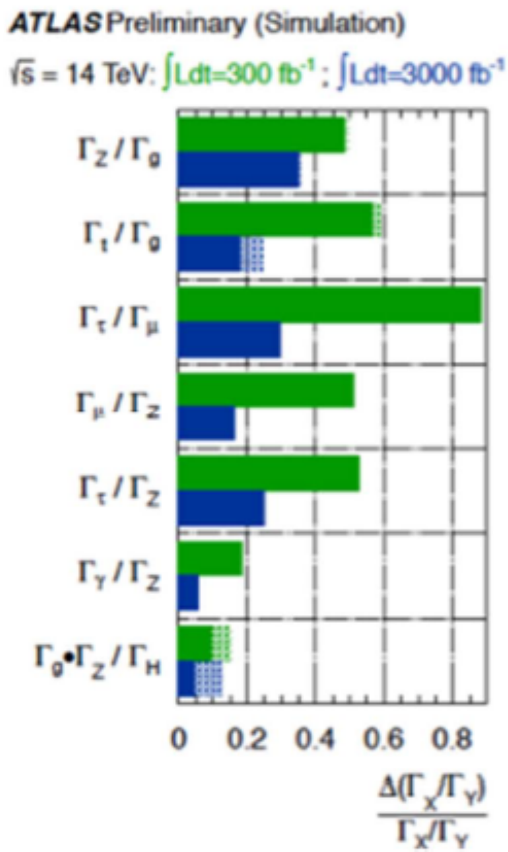
W(lν)H(bb)
σBR~130 fb
Acc<~3%
S/B<0.01

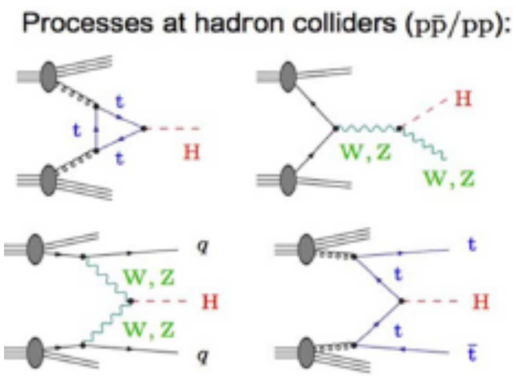
ATLAS-CONF-2013-079

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

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

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

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

⇒ 44% of remaining BG is single-top…

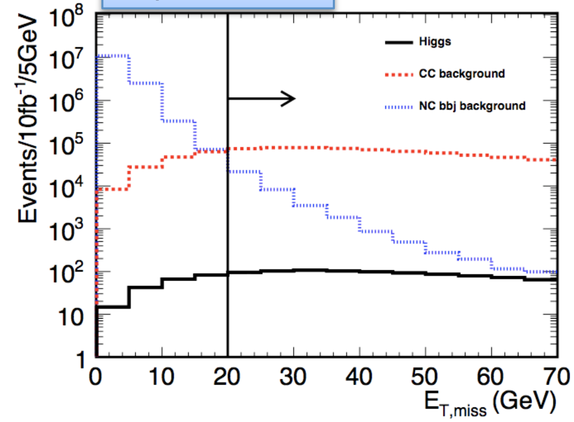
- Single top rejection
  - $M_{jjj,top} > 250$ GeV
  - $M_{jj,W} > 130$ GeV

$H \to b\bar{b}$

CC BG

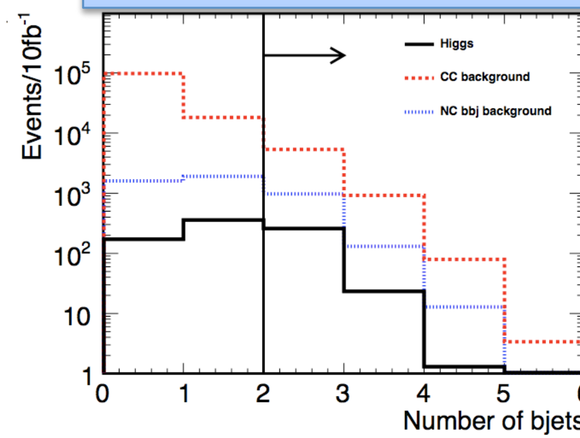
NC BG

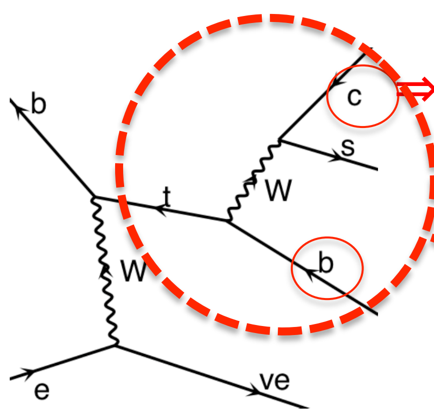
E_T^{miss} cut



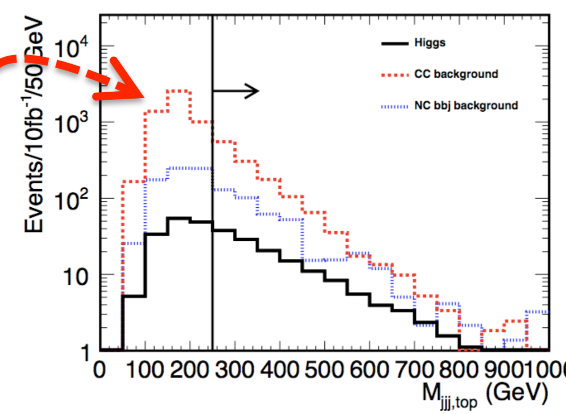
b-tag requirement

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





⇒10% mis-ID



CDR: A Large Hadron Electron Collider at CERN
J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001

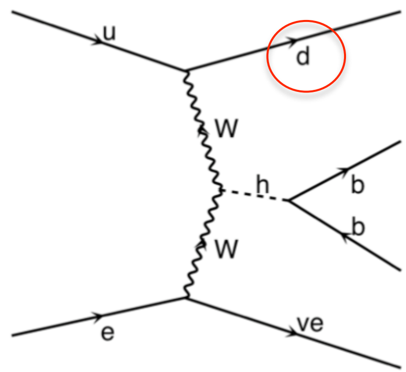
CDR : H→b$\bar{b}$ results

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

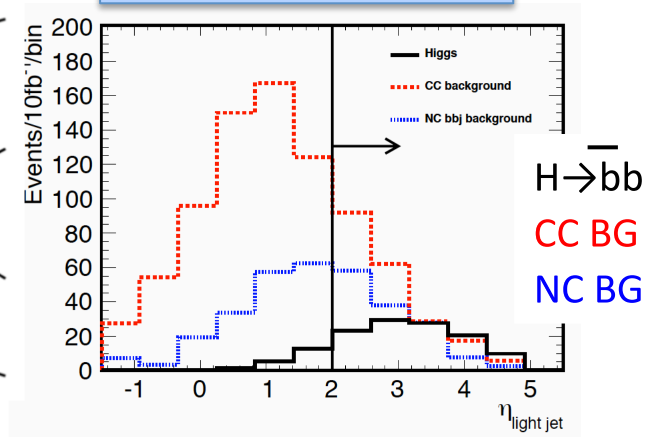
- Forward jet tagging
  - η_{jet} > 2 (lowest η jet excluding b-tagged jets)

Coordinate:
Fwd: +z-axis along proton beam

H → b$\bar{b}$ signal

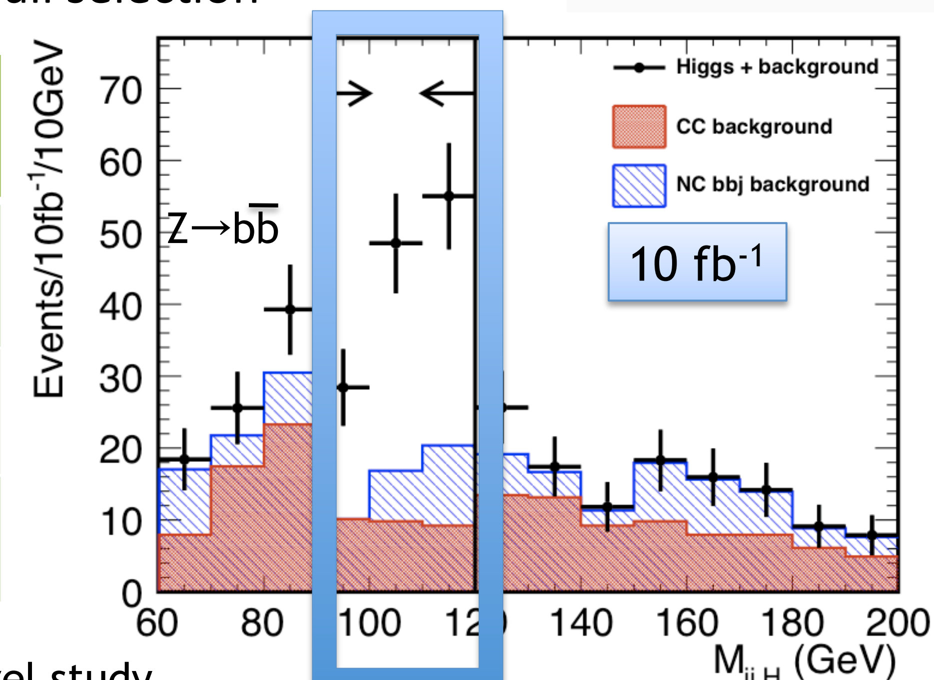


Forward jet η tag



- Higgs invariant mass after all selection

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



Clear signal obtained with just cut based analysis already!

*parton-level study.