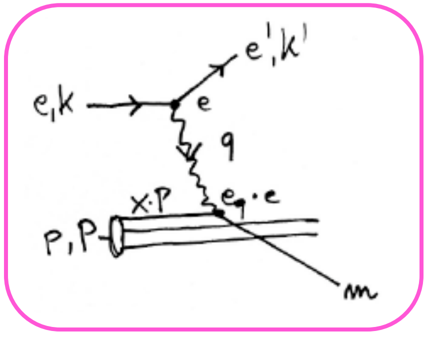
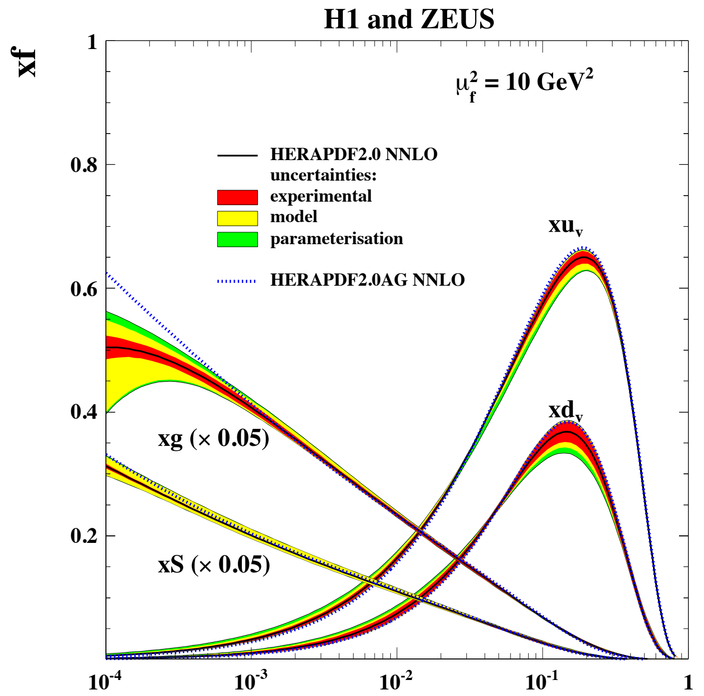
Physics at electron-proton collider

Monica D'Onofrio
University of Liverpool
On behalf of all the LHeC Physics Groups



LHeC Workshop - Open Seminar session
Geneva, June 24th 2015

e-p at HERA .. and beyond



http://arxiv.org/abs/1506.06042

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

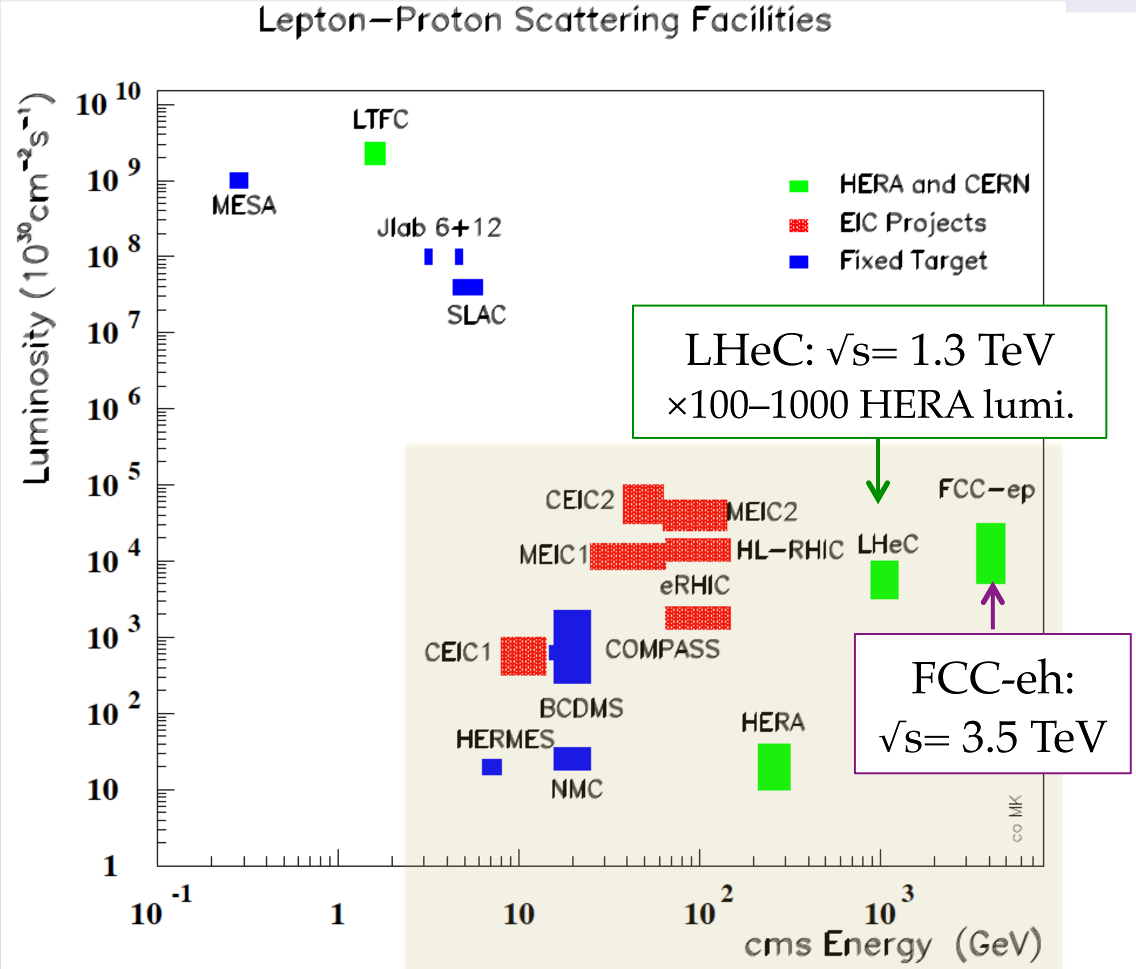
The idea of an e-p collider at CERN, the LHeC, proposed in 2005, has been developed in the last years: http://cern.ch/LHeC

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

(fermiscale) (Terascale)

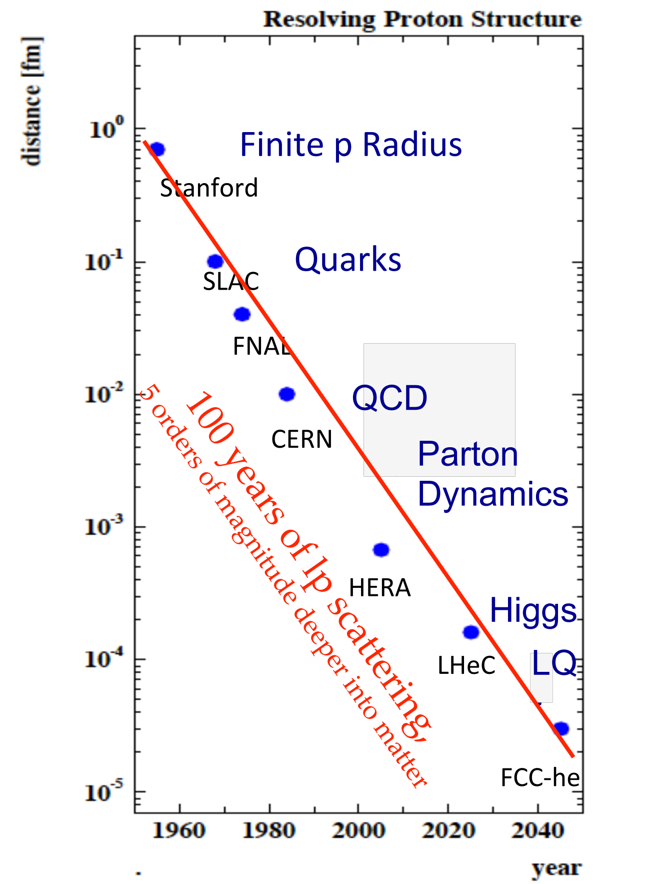
(or, the complementarity pattern)

Lepton-proton facilities



HERA-LHeC-FCC-eh:

finest microscopes, resolution as 1/Q

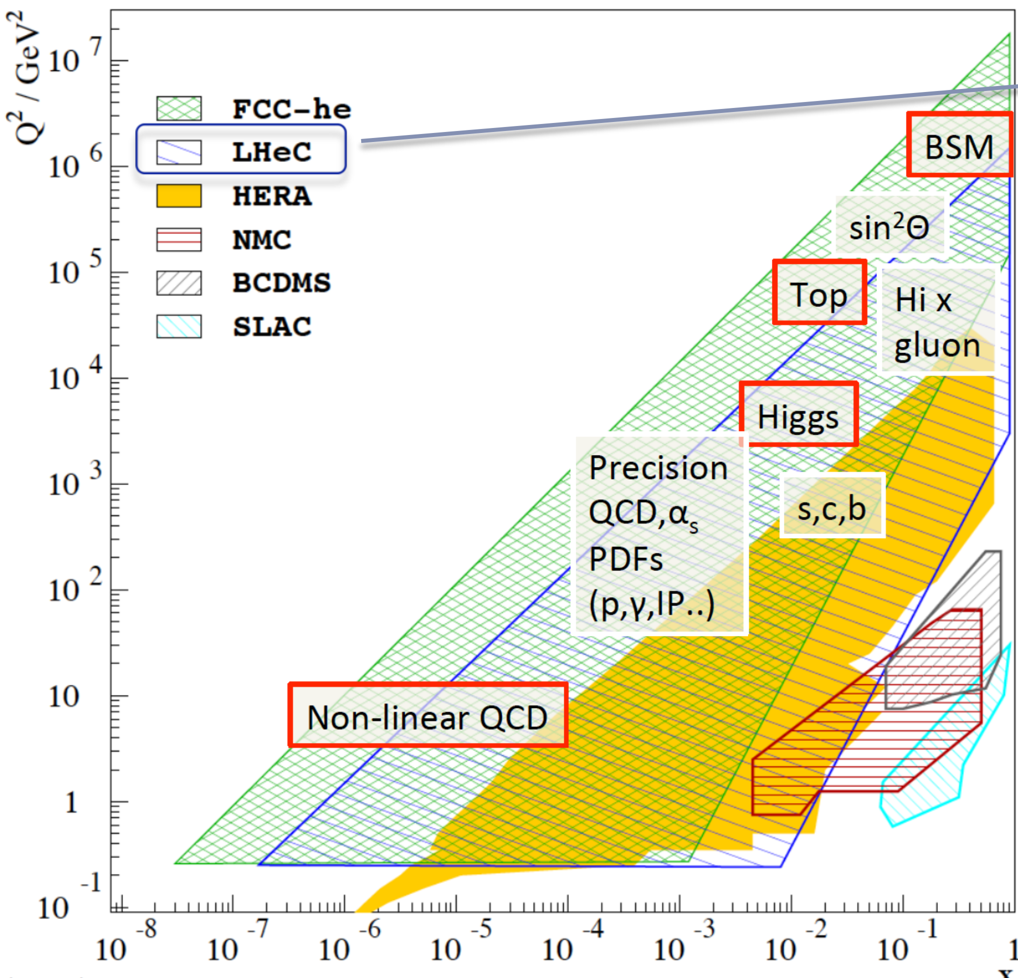


LHC (and, beyond, the FCC-hh) is/will be main discovery machine

LHeC not a competitor! Complementary & synchronous with HL-LHC

The LHeC as electron-proton Collider

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



-he Washington DC 27.3.2015

Designed to exploit intense **hadron beams** in high luminosity phase of LHC:

→ Use 7 TeV protons

→ Add an **electron beam** to the LHC

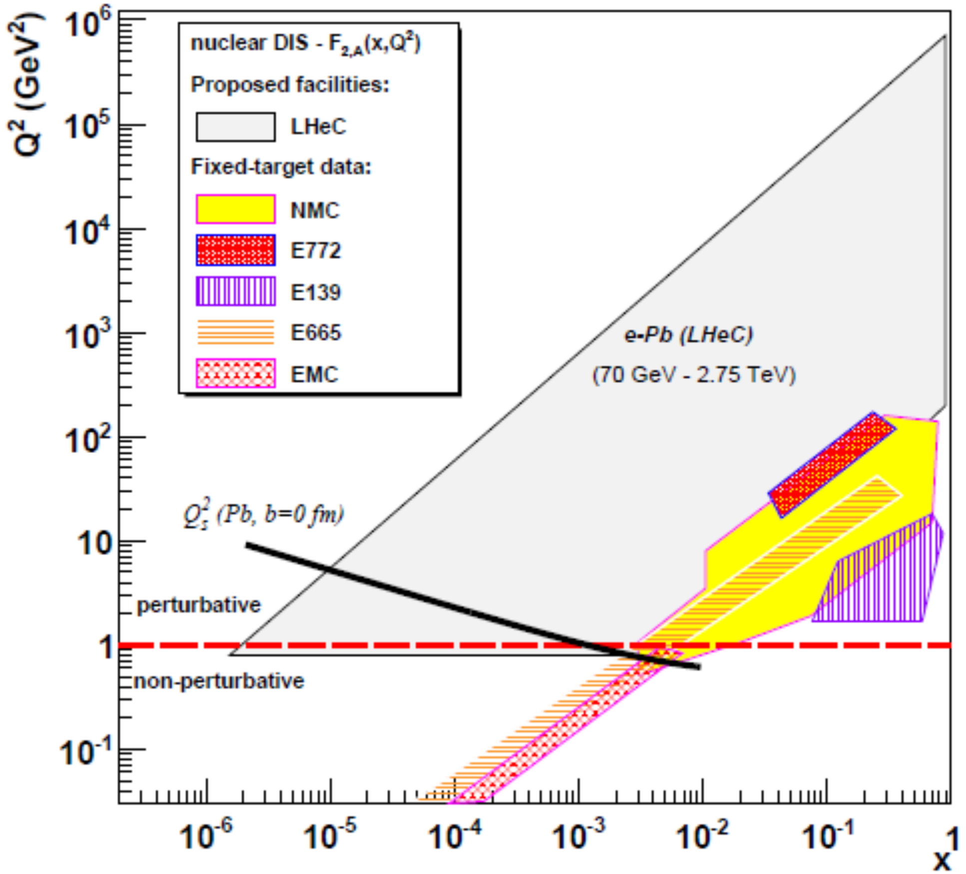
transforms p-p machines into high precision facilities

Plus, wealth of 'new' physics in its own right

LHeC as electron-Ion Collider

- **Four orders of magnitude increase** in kinematic range over previous DIS experiments

  → will change QCD view of the structure of nuclear matter



Study interactions of densely packed but weakly coupled partons

Precision QCD study of parton dynamics in nuclei

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

Baseline parameters

10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [$10^{33}cm^{-2}s^{-1}$]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Funtion $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'^*_{x,y}$ [μrad]	80	40
Beam Current @ IP[mA]	1112	25
Bunch Spacing [ns]	25	25
Bunch Population	$2.2*10^{11}$	$4*10^{9}$
Bunch charge [nC]	35	0.64

ep collisions (possibly with similar luminosity)
→ 60 GeV (ele), 7 TeV proton

High polarization

Operations simultaneous with HL-LHC *pp* physics

- ep Luminosity: up to 10^{34} cm^{-2} s^{-1}
- Integrated lumi: Up to 100 fb^{-1} per year
- **Up to 1 ab^{-1} total**
- eD and eA collisions integral part of the programme
  - E-nucleon Lumi estimates → 10^{31} (10^{32}) cm^{-2} s^{-1} for eD (ePb)

Coordination team

Coordination Group

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Oliver Brüning
Stefano Forte
Andrea Ghaddi
Erk Jensen
Max Klein
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann
Gianluigi Arduini

Physics Study Groups (Convenors)

PDFs, QCD	Fred Olness, Voica Radescu
Higgs	Uta Klein, Masahiro Khuze
BSM	Georges Azuelos, Monica D'Onofrio
Top	Olaf Behnke, Christian Schwanenberger
Nuclei	Nestor Armesto
Small x	Paul Newman, Anna Stasto

Thanks to the **LHeC Study Group** and

www.lhec.cern.ch

Referees for Design Report

Ring Ring Design
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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
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Installation and Infrastructure
Sylvain Weisz (CERN)
New Physics at Large Scales
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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)

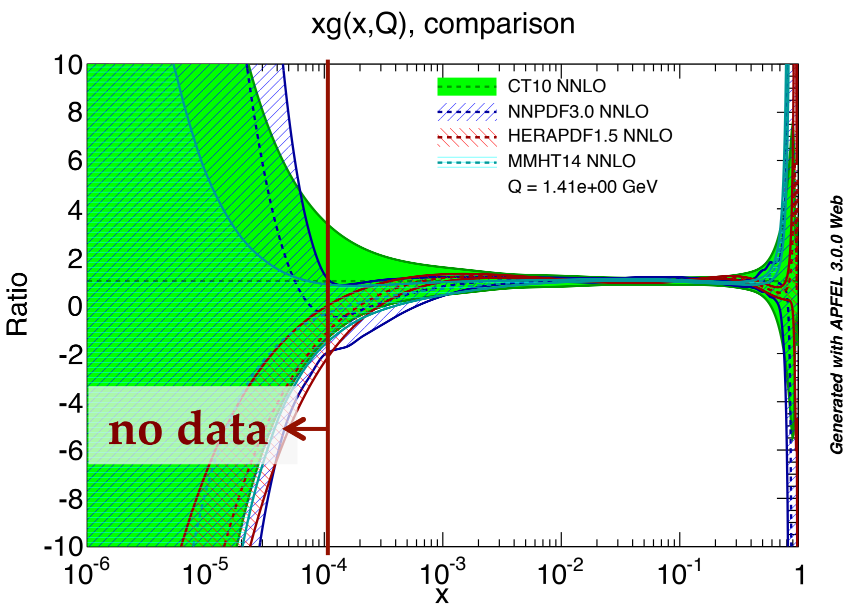
The LHeC design has been a strong community effort

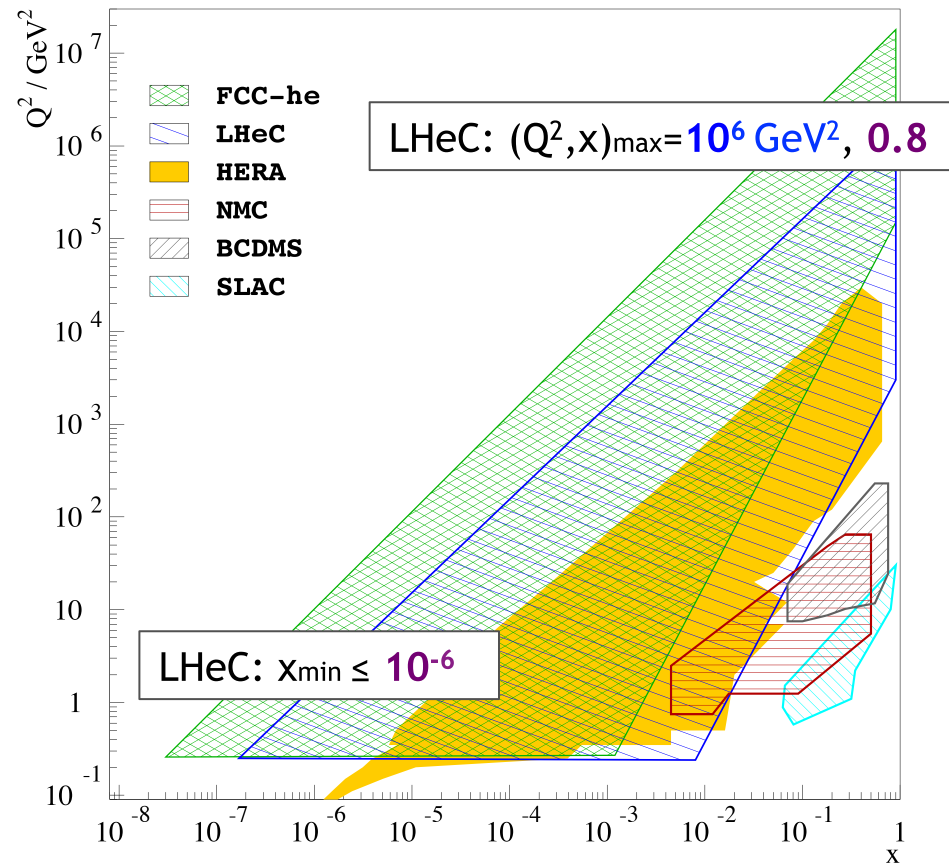
[M.Klein, ICFA Seminar, Bejing, China - October 2014]

Highlights in this talk: LHeC as …

- the finest microscope of the world
  - HERA established the validity of pQCD (very high lever arm in Q^2) → Extension of both x and Q^2 ranges crucial for new experiments and HEP theory developments
  - PDF fits, measurements of α_S and impact on higgs/BSM
- the next machine to see the Higgs
  - Measurements of H to bbbar and more
- complement to LHC for EWK measurements and new physics
  - EWK interactions
    - Top quark: anomalous couplings, Flavor Changing Neutral Current
    - Measurements of $\sin^2\theta_W$
  - Beyond SM physics: CI, LQ, SUSY
- revolution of nuclear structure
  - Electron-Ion highlights

Improving PDFs with the LHeC



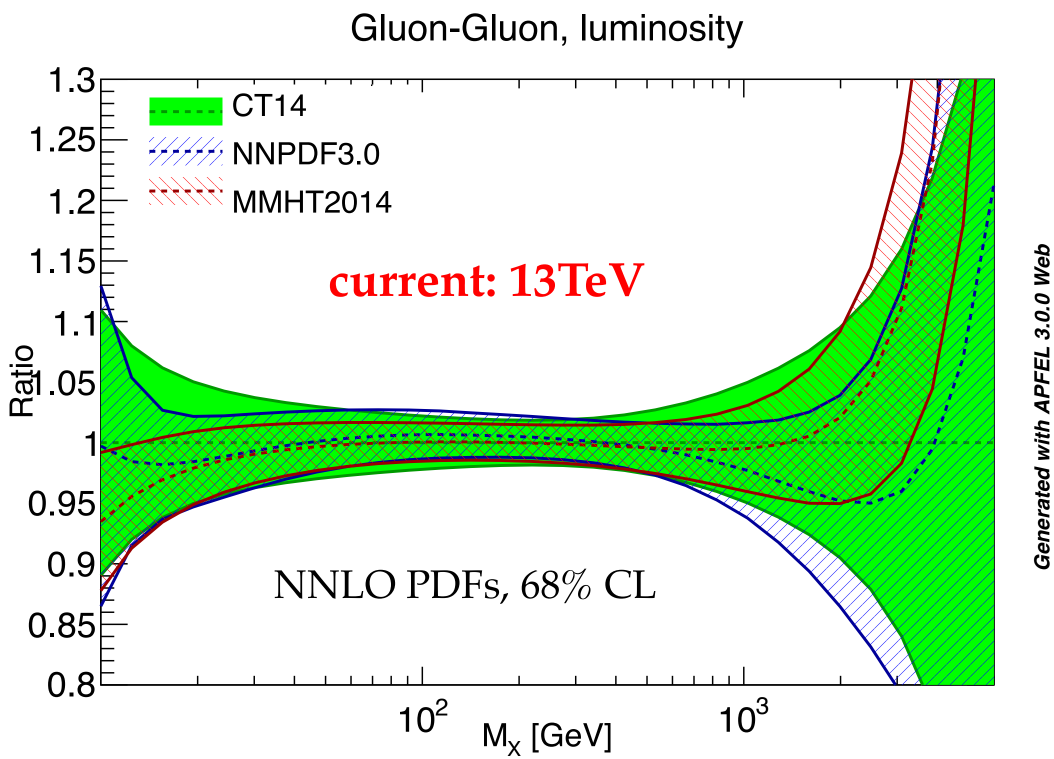


- **low-x:** no current data to constrain $x \leq 10^{-4}$; rely purely on extrapolation
  non-linear equations, gluon saturation?
- **mid-x:** need higher precision for Higgs
- **high-x:** very poorly constrained – limits searches for new, heavy particles

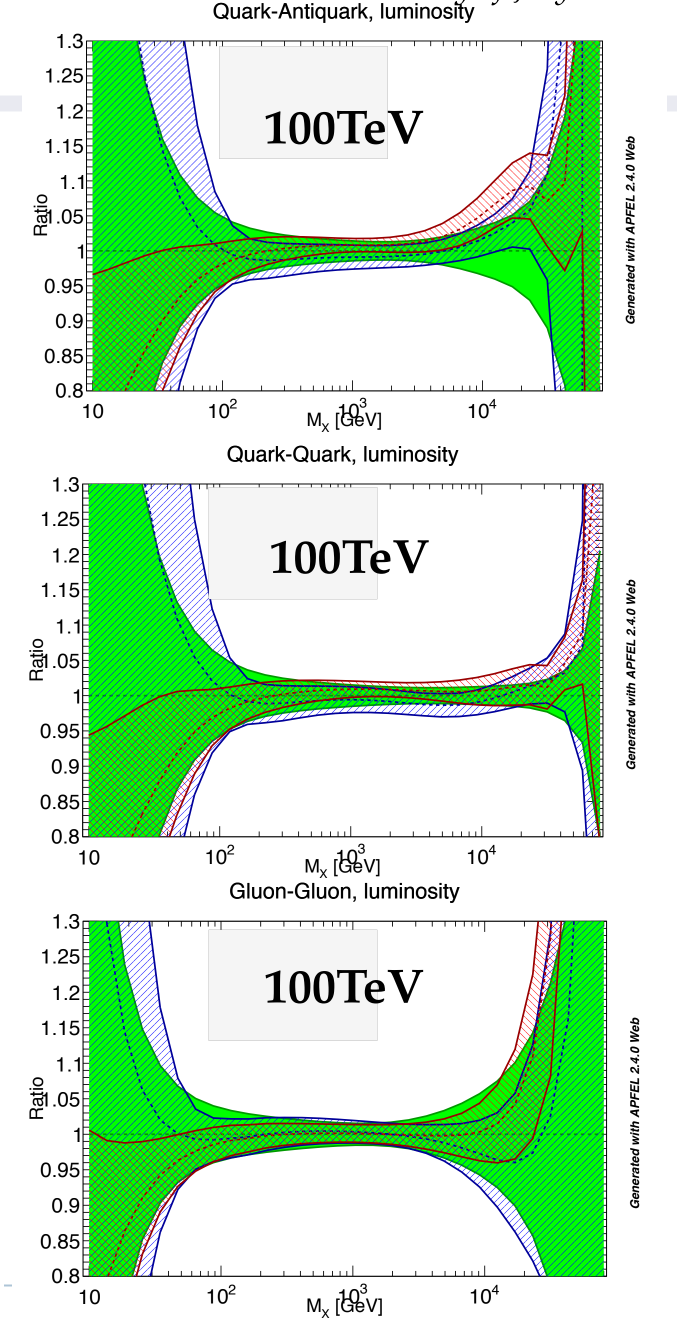
LHeC: access to much smaller x, larger Q^2 (1000× HERA luminosity);

and FCC-he extends even further

Proton PDFs, today



Courtesy of Joey Huston



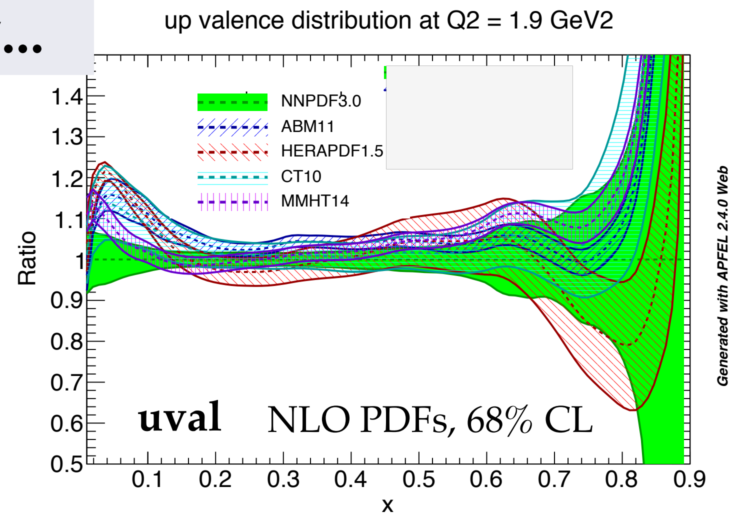
- **need to know PDFs much better than today, for:** nucleon structure; q-g dynamics; Higgs; BSM searches; future colliders, FCC-pp; development of QCD; ..
- LHC will provide further constraints, but cannot resolve precisely (shown are latest global PDFs, also including available LHC data)

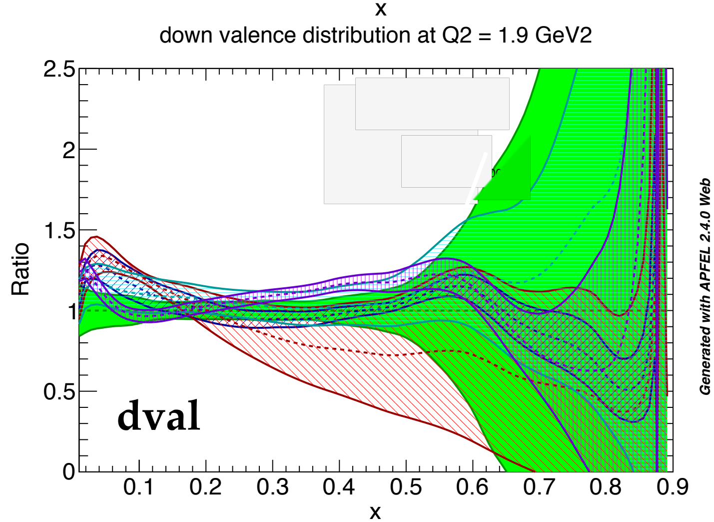
Valence quarks

CDR study: LHeC simulated NC, CC e±p, P=±0.4, including projected systematics

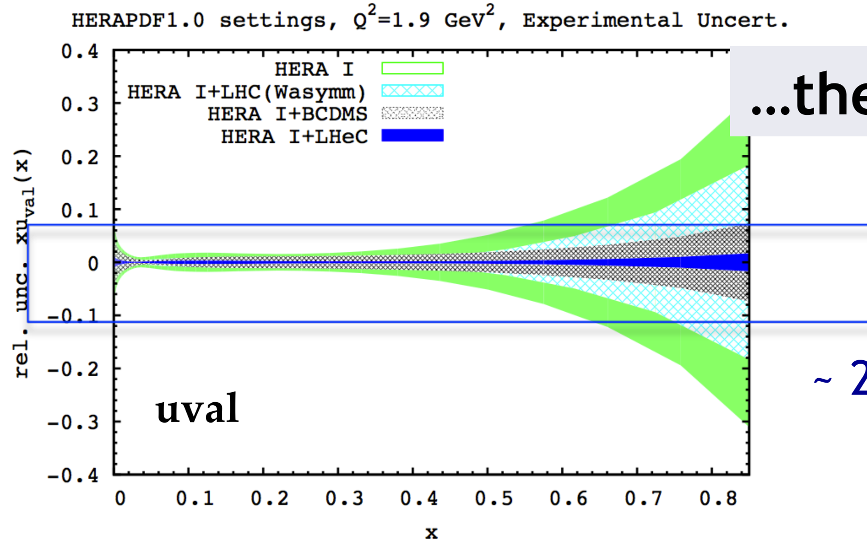
HERAfitter framework with HERAPDF1.0 NLO settings

now…

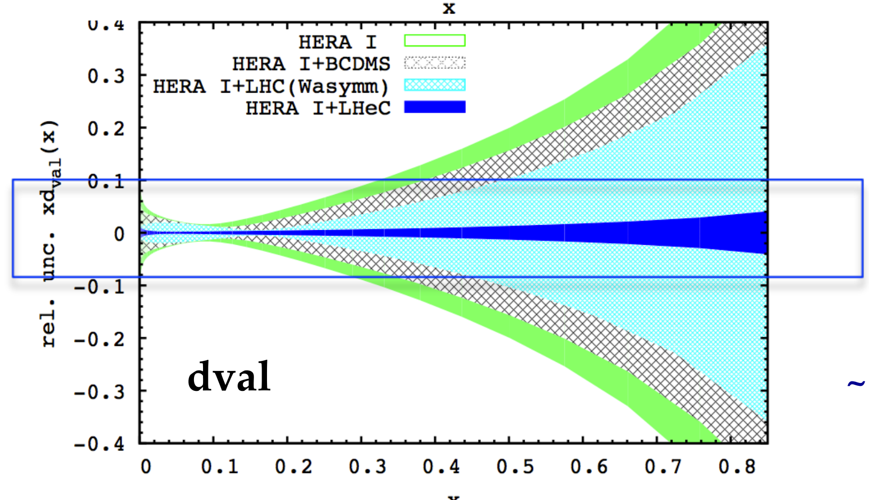




…then



~ 2%

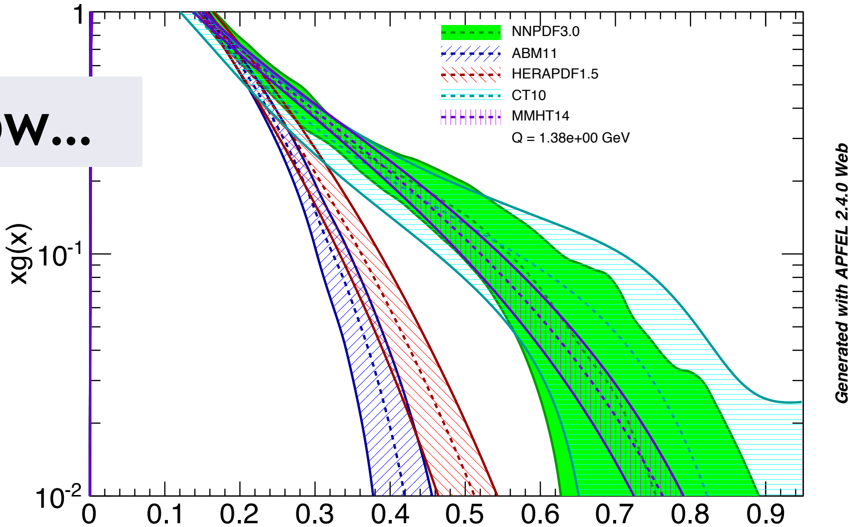


~ 4%

precision determination, free from higher twist corrections and nuclear uncertainties

Gluon PDF at high and low x

now…

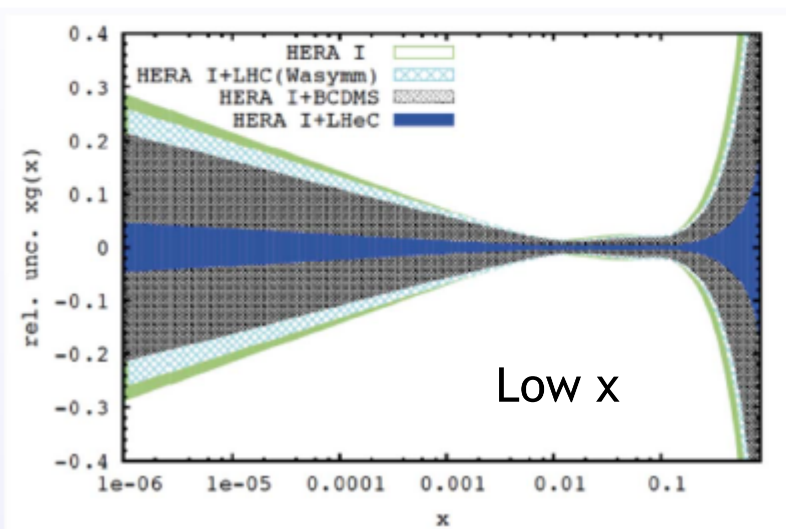


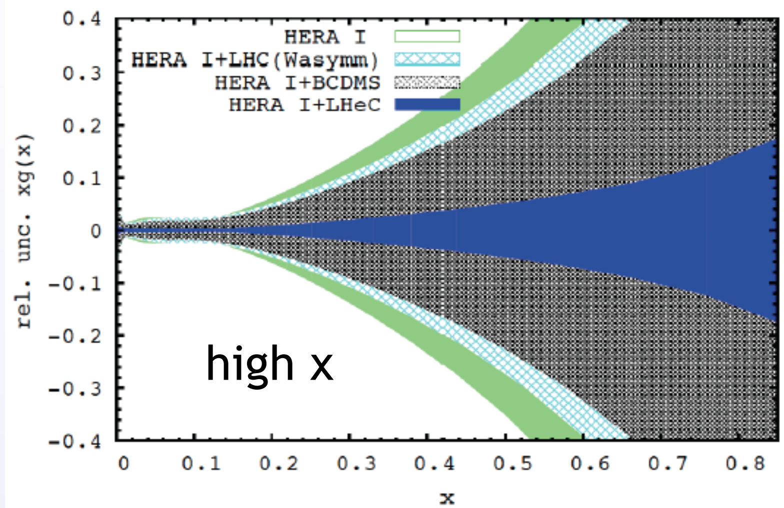
gluon PDF at high x poorly known

- gluon and sea evolution intimately related
- important to disentangle sea from valence at large x – can be done with precise LHeC measurements of CC cross sections and NC $F2^{\gamma Z}$, $xF3^{\gamma Z}$

then…

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

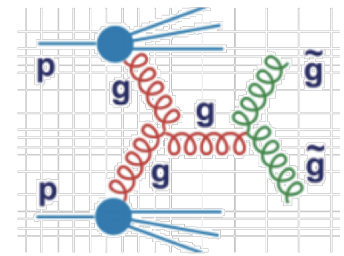


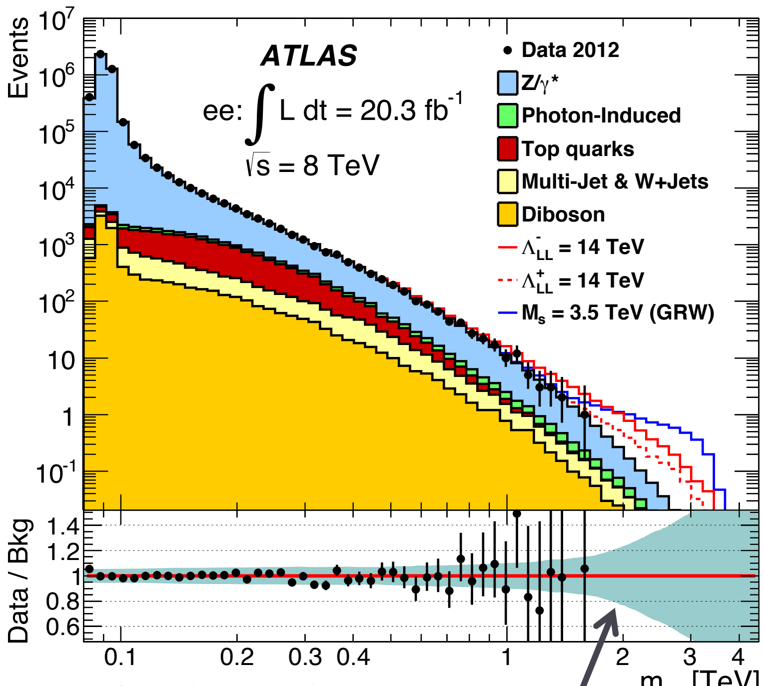


High x PDFs: link to LHC

- large uncertainties in high x PDFs limit searches for new physics at high scales

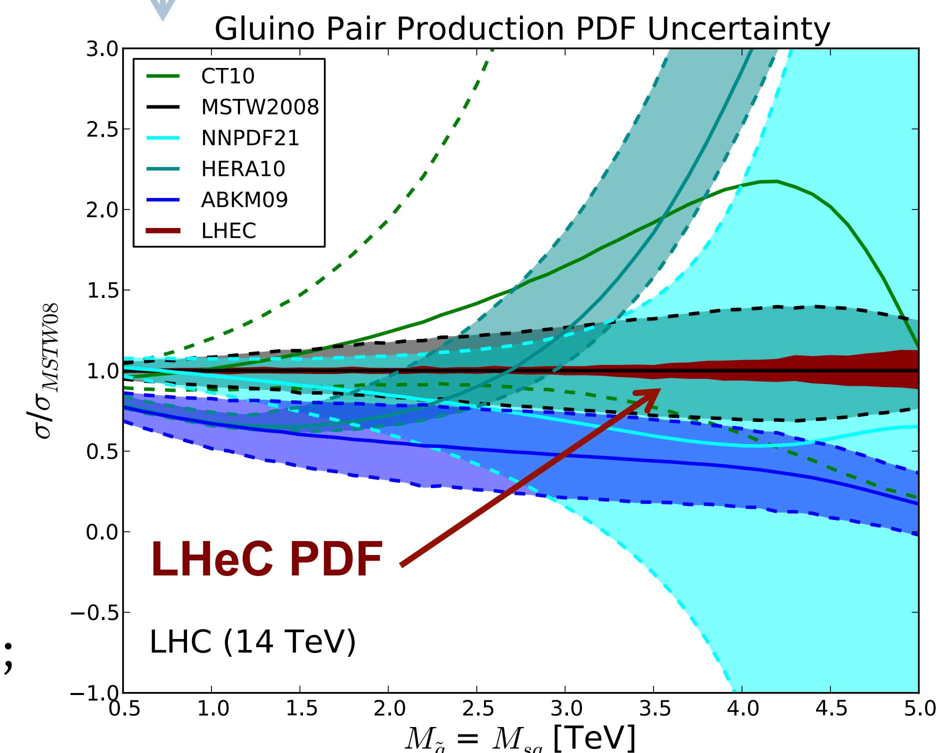
many interesting processes at LHC are gluon-gluon initiated:
top, Higgs, … and BSM processes, such as gluino pair production





arXiv:1407.2410

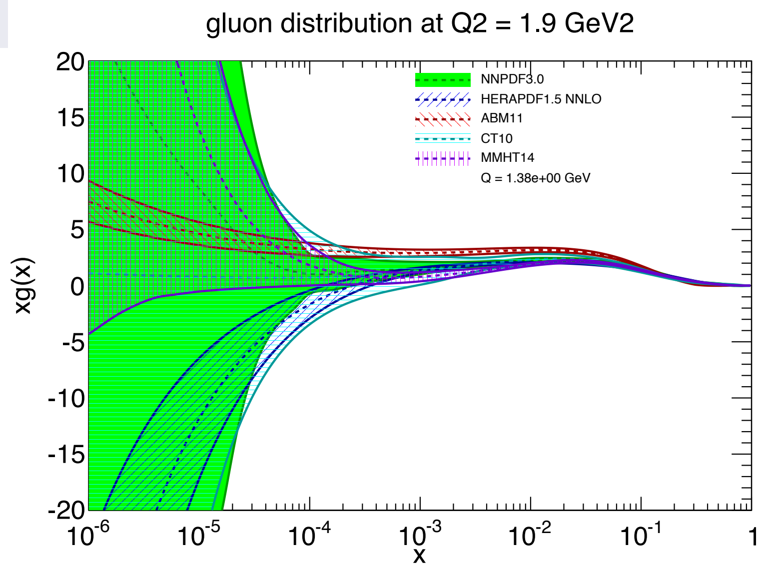
current BSM search in dilepton final state;
uncertainties on high-x (anti)quarks dominate



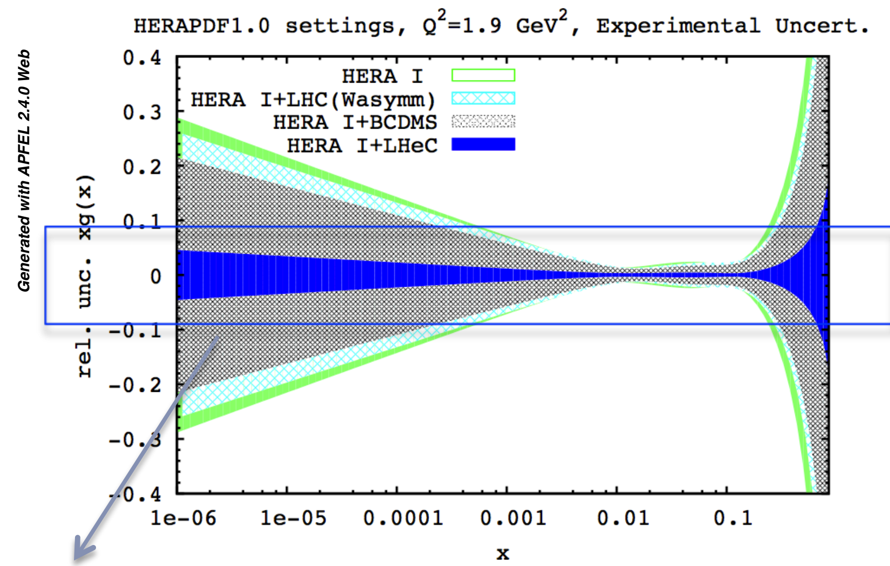
arXiv:1211.5102

Low x and gluon saturation

now…



then…

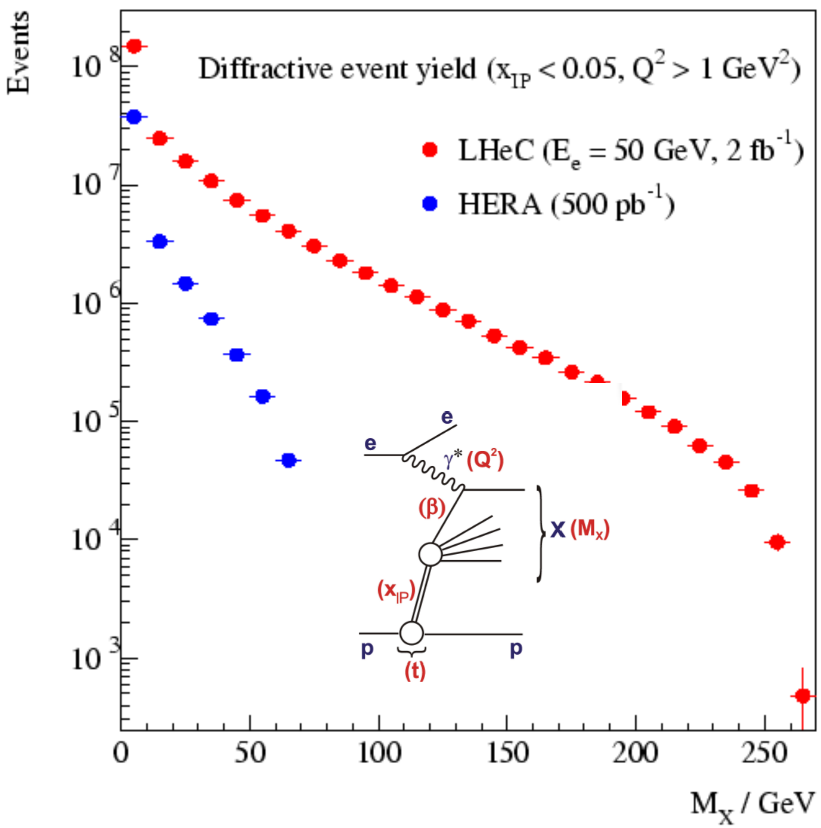


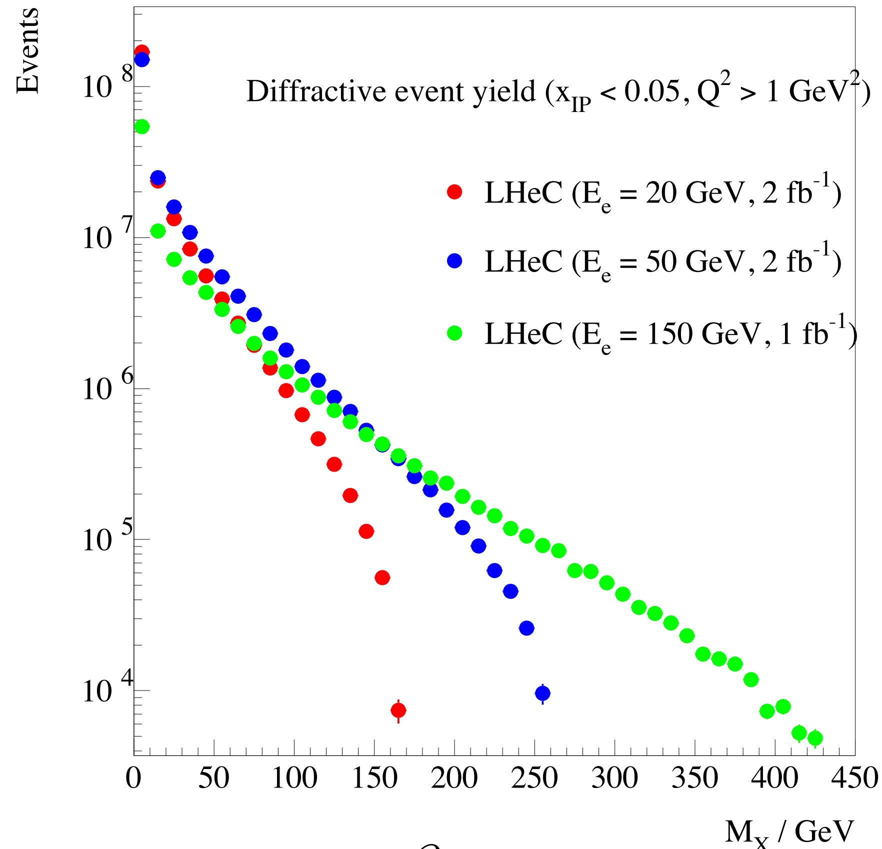
gluon measurement down to $x=10^{-6}$ → < 5%

- F_L measurements would improve further
- Allow understanding of possible non-linear evolution (not accommodated by DGLAP fits) leading to saturation at low x (tension between F_2 and F_L)
- Important for high energy neutrino cross sections
  - → E.g. essential input for ICECUBE observations

diffractive DIS

- Unique program for diffractive PDF and generalized parton distributions. DIS diffraction brought to a completely new regime with the extended kinematic range and higher luminosity



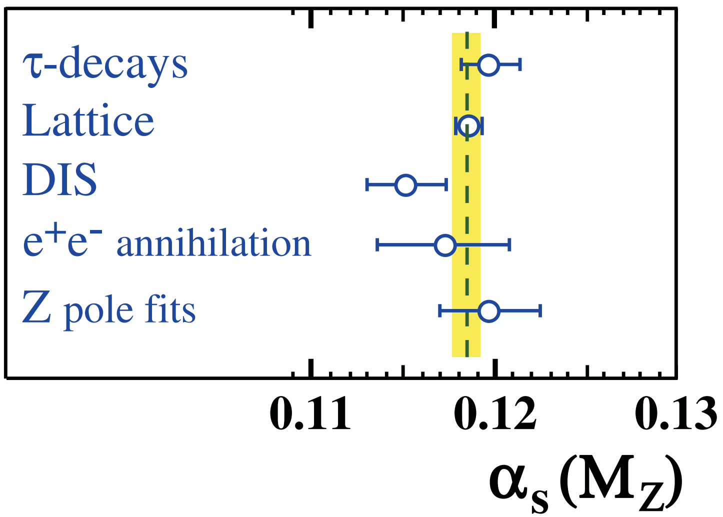


LHeC can explore very low values of β

New domain of diffractive masses.

M_X can include W/Z/beauty or any state with 1^-

strong coupling



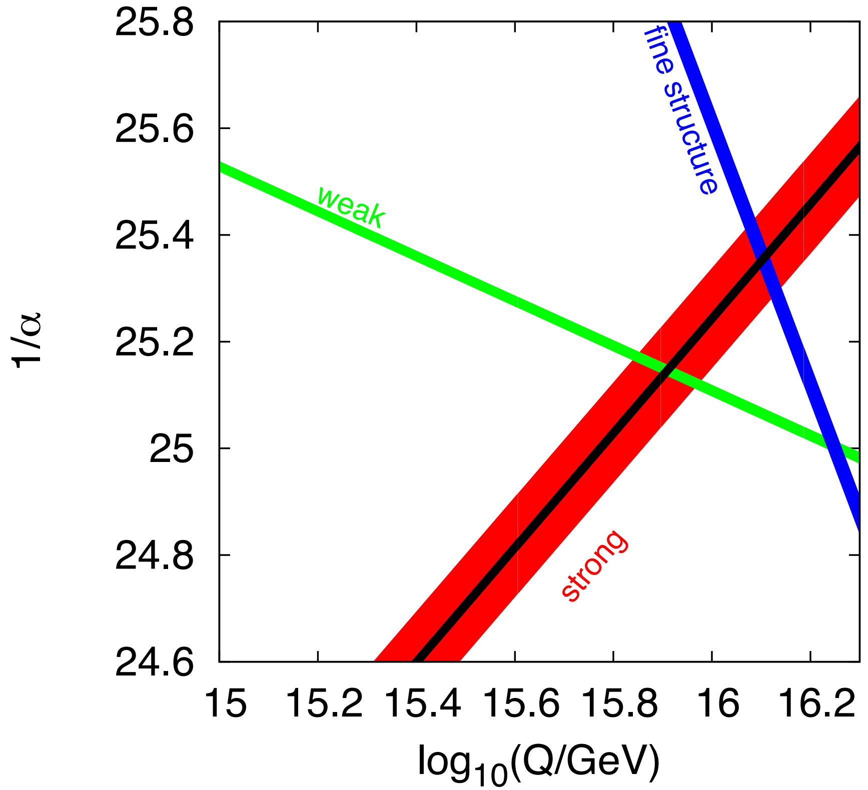
strong coupling α_s is fundamental parameter, not given by theory

extracted from experimental measurements in e+e-, ep, pp, and from lattice QCD calculations

PDG world ave.: $\alpha_s(Mz)=0.1184\pm0.0006$

without lattice input: $\alpha_s(Mz)=0.1183\pm0.0012$

but, measurements not all consistent – what is true central value; true uncertainty; role of lattice calculations?



precise $\alpha_s(Mz)$ important to constrain GUT scenarios, and for cross section predictions, such as Higgs

strong coupling: some comparisons

Snowmass13 report – arXiv:1310.5189

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])

per mille (precision EW)

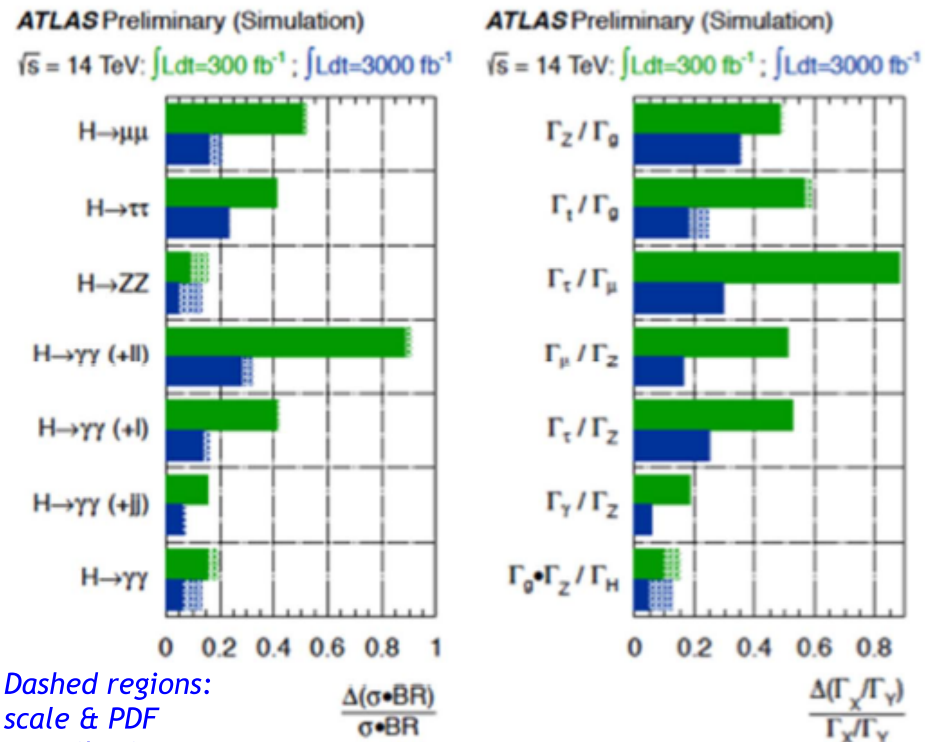
per mille (ep colliders)

per mille accuracy can challenge QCD lattice calculations

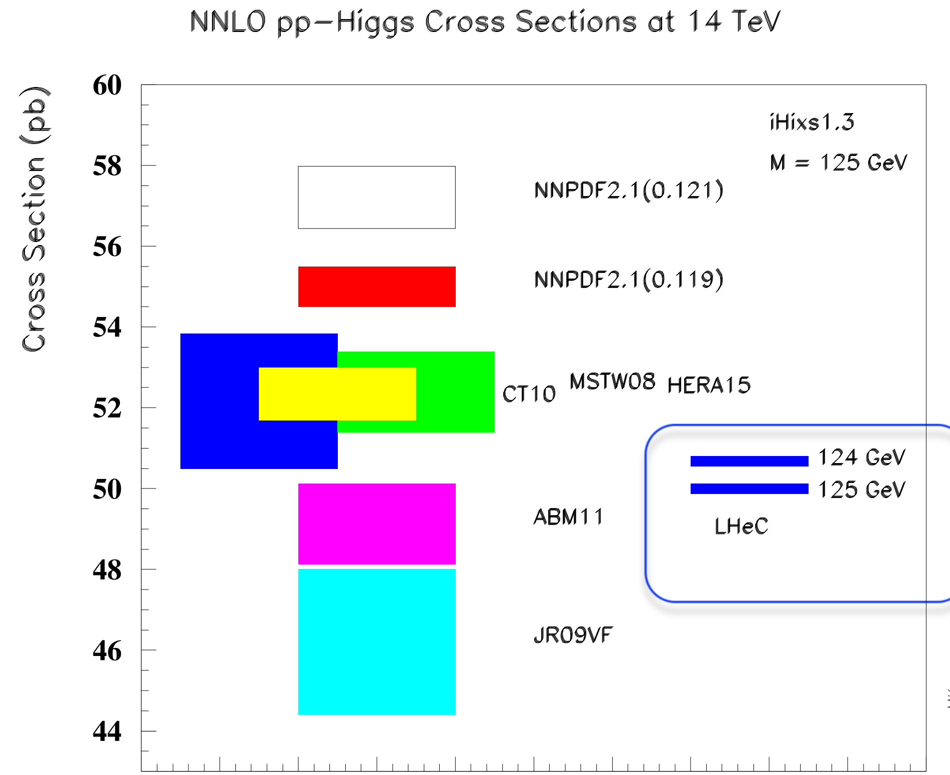
TLEP = old name for FCC-ee

PDF, α_s uncertainties and the Higgs

- With LHeC: huge improvements in PDFs and precision in α_s → full exploitation of LHC data for Higgs physics
  - PDF and α_s uncertainties as limiting factor for several channels at the HL-LHC
- Change of 0.005 on α_s corresponds to a 10% on cross section (@LHeC: 0.0002!)



Dashed regions: scale & PDF contributions

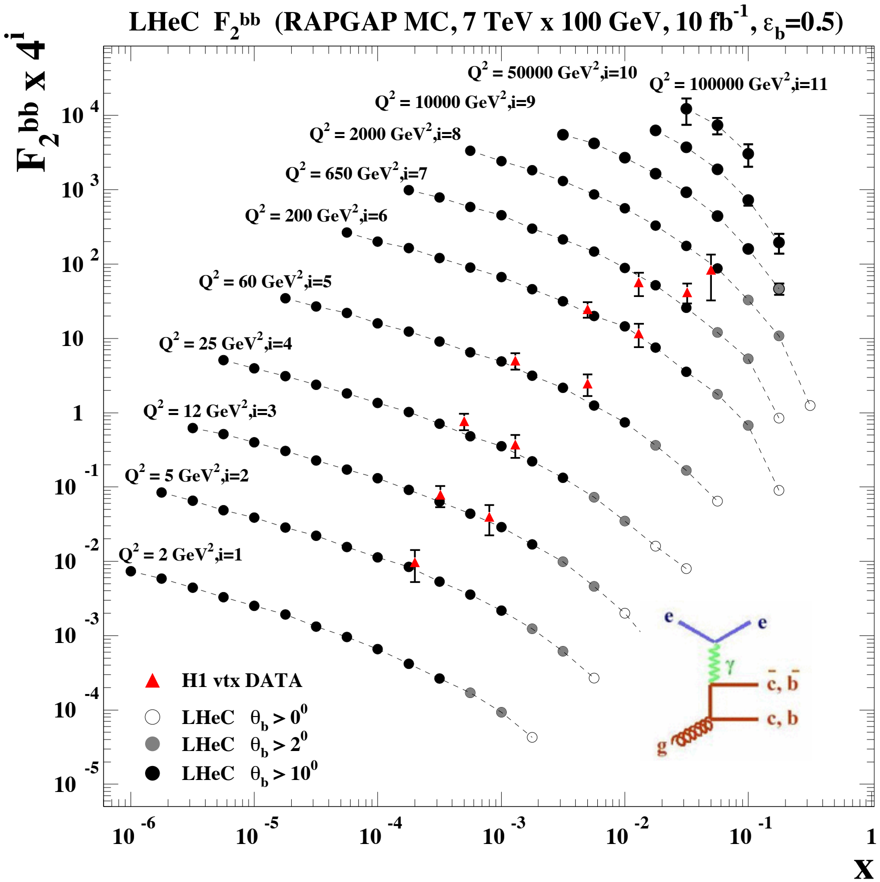


Higgs@LHC needs N^{3}LO: now calculated → need N^{3}LO PDFs → only from LHeC!

Expect to reduce uncertainties on predicted LHC σ_H to 0.4% due to PDF and α_s

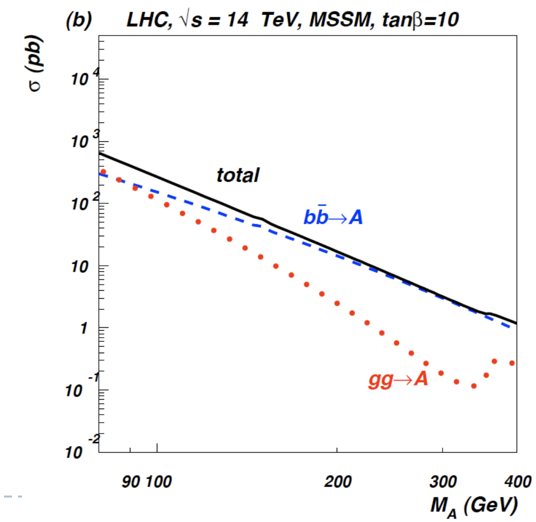
PDF, α_s uncertainties and the Higgs

- With LHeC: huge improvements in PDFs and precision in α_s → full exploitation of LHC data for Higgs physics
  - PDF and α_s uncertainties as limiting factor for several channels at the HL-LHC
  - **HQ treatment is crucial subject in QCD and matters at high scales!**



At LHeC: flavor decomposition (charm/ beauty) → 20 times better precision for charm and bottom mass

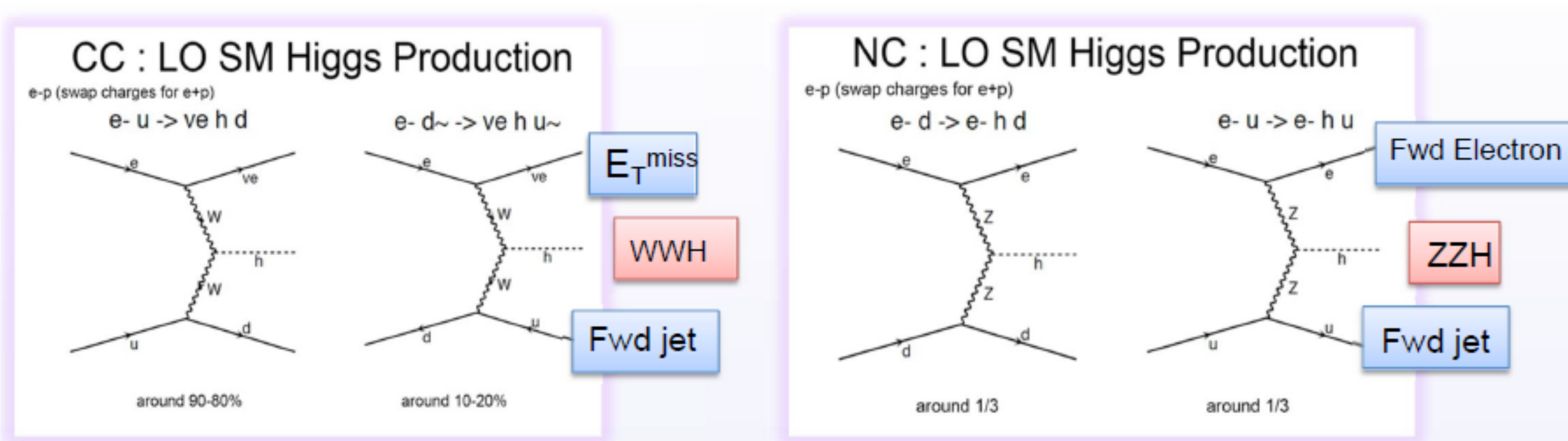
E.g. relevant for **MSSM Higgs production** with A produced predominantly via bbbar



CTEQ Belyayev et al. JHEP 0601:069,2006

Direct Higgs measurements

- In **e-p**: Higgs radiated from W or Z → unique production mode, with low theoretical uncertainties: clean and well distinct signatures



→ In ep, direction of quark (FS) is well defined

mH = 125 GeV	CC e^-p	CC e^+p	NC e^-p
cross section [fb]	109	58	20
polarised cross section [fb] Pol. = 80%	196	N.A.	25

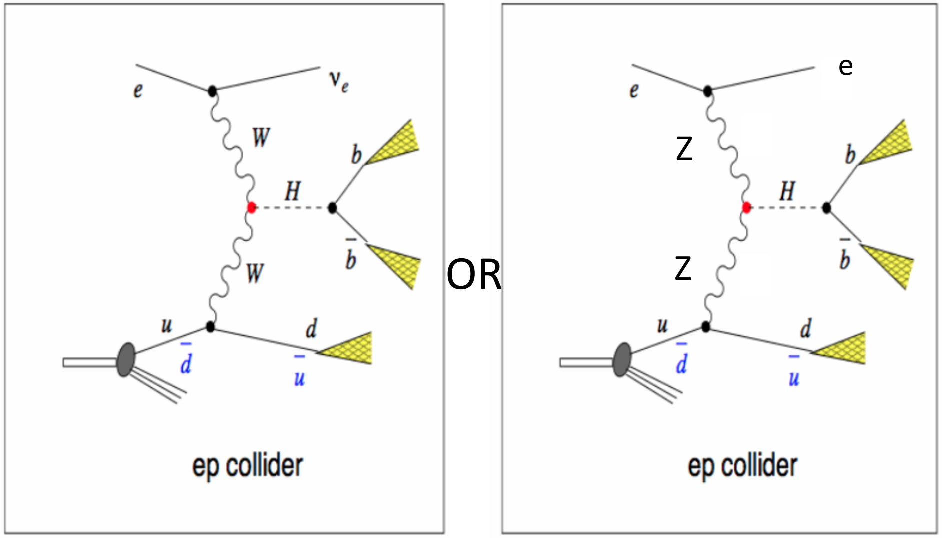
LHeC: E_e=60 GeV, $\sqrt{s}$ = 1.3 TeV

High production cross sections

The LHeC with high lumi is in itself a precision Higgs facility

VBF Higgs production: e-p vs p-p

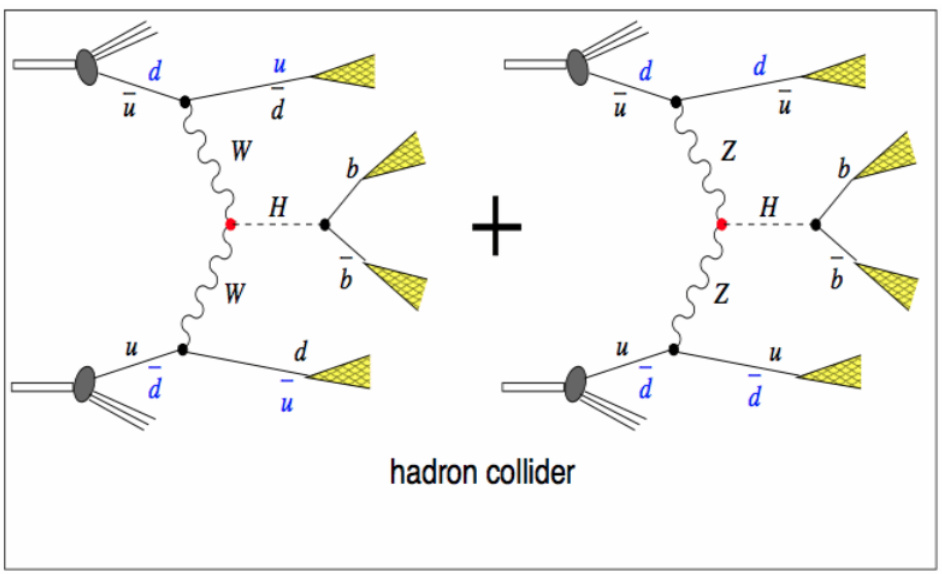
ep



- Higgs production in ep comes uniquely from either CC or NC
  - Pile-up in e-p at 10^{34} = 0.1
  - Clean(er) bb final state, S/B ~ 1

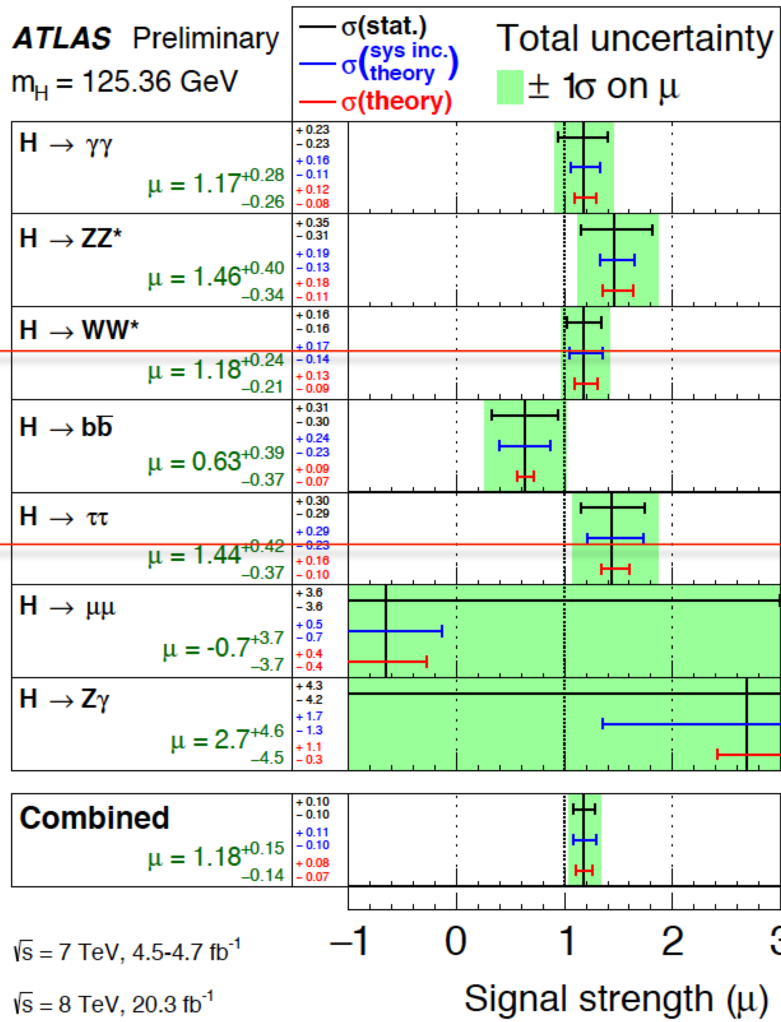
→ Clean, precise reconstruction and easy distinction of ZZH and WWH

pp



- Higgs production in pp comes predominantly from gg→H
  - VBF cross section about 200 fb (about as large as at the ILC).
  - Pile-up in pp at 5 x 10^{34} is 150, S/B very small for bb
  - Precision needs accurate PDFs

Latest Higgs results (ATLAS)



ATLAS-CONF-2015-007

18th March 2015

60% H to bb: strong potential at LHeC

- Theory will soon dominate the uncertainty. Can we get 10 times better? [N^3LO, PDFs, α_s]
- LHeC: 1% accuracy

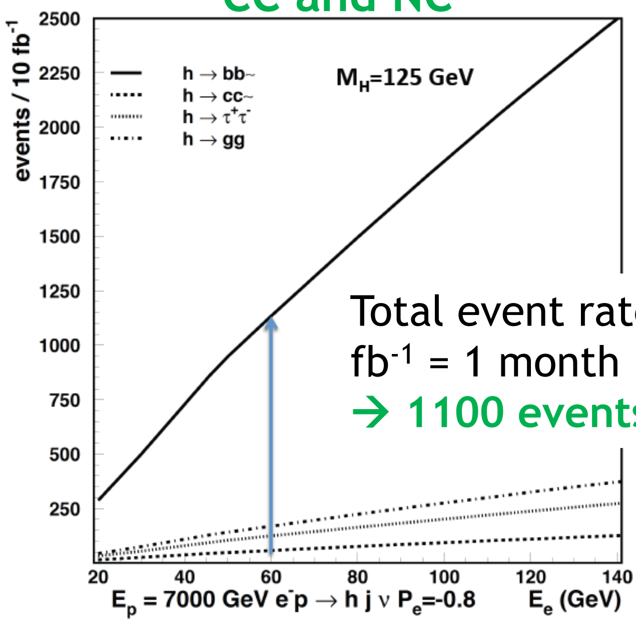
$$\mu = 1.18\,^{+0.15}_{-0.14} = 1.18 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{expt.})\,^{+0.08}_{-0.07}\,(\text{theo.})$$

H→ $b\bar{b}$ @ LHeC

- Clear signal obtained already with just cut based analysis

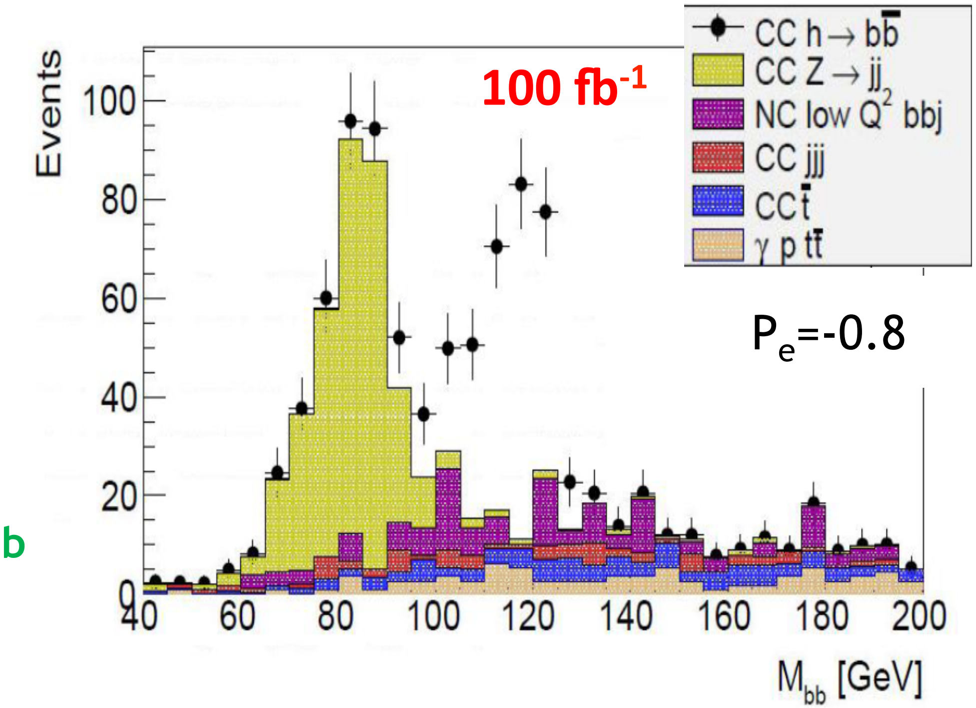
LHeC: E(e) = 60 GeV, P_e=-80%

CC and NC



Total event rate for 10 fb^{-1} = 1 month

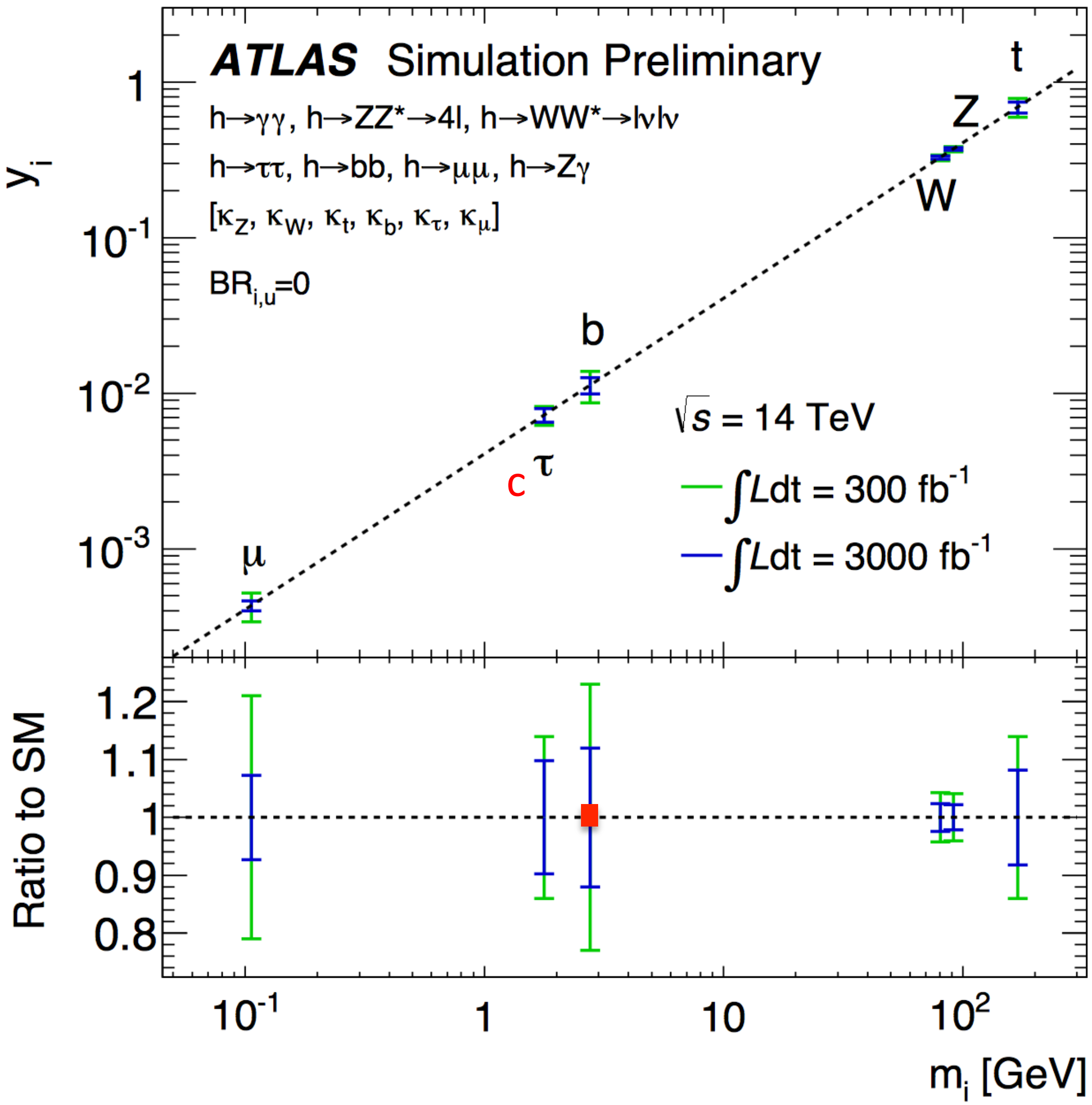
→ 1100 events H → bb



Allow H-bbbar coupling measurements with **1% statistical precision** (1 ab^{-1}) but more work ON-going! **Updates will be presented tomorrow at this Workshop**

- Complex neural network analysis being performed for bb/cc

Putting this in context



H→ccbar channel

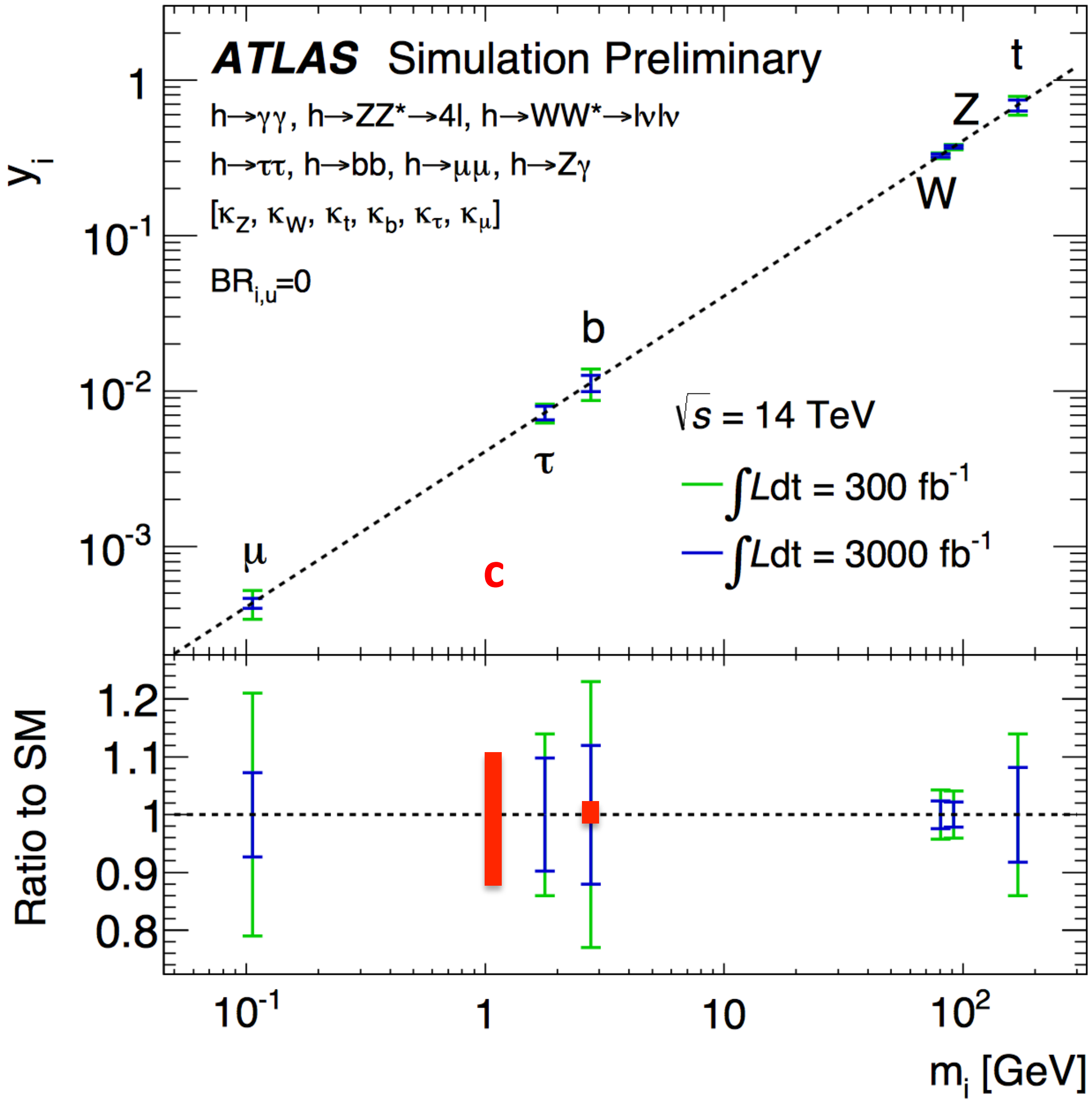
- Low but still ‘taggable’ charm-jets
- Clean environment wrt *pp*
- Challenging! bb is background

LHeC, $1ab^{-1}$

Work in progress

Br: b 59% c 3%

Putting this in context



H→ccbar channel

- Low but still 'taggable' charm-jets
- Clean environment wrt *pp*
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LHeC, $1ab^{-1}$

Work in progress

Br: b 59% c 3%

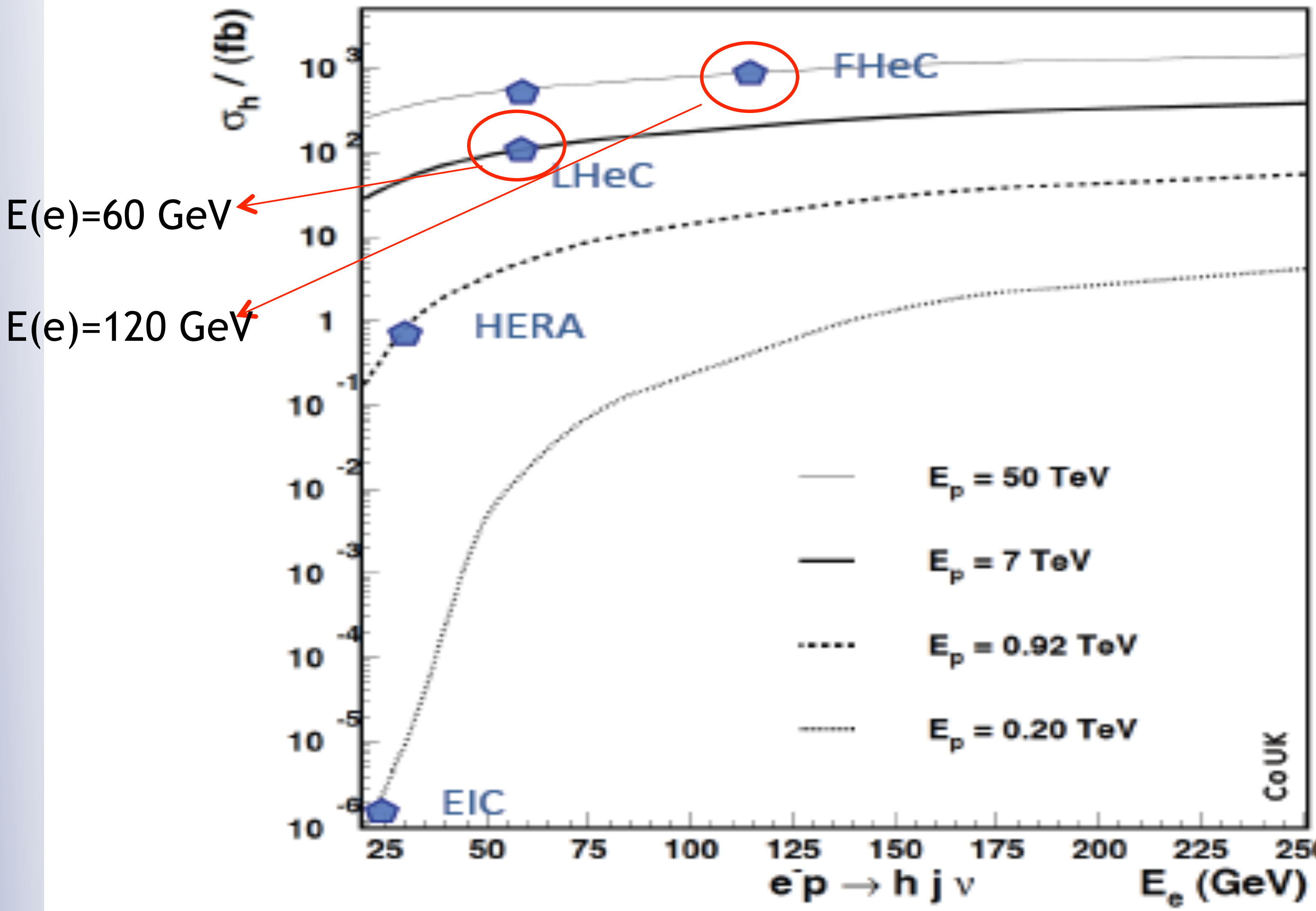
More tomorrow!!

Higgs production rate

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

With the full dataset, high production rate also for rarer modes:
14000 events H →ττ, 6000 events H → ccbar

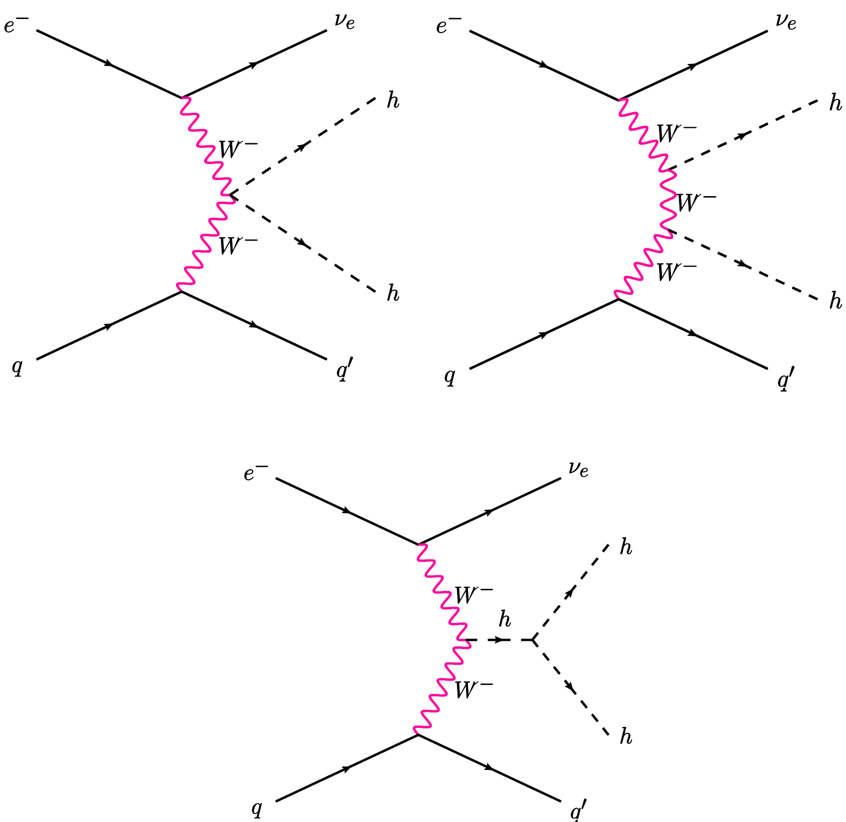
Higgs production rate: LHeC → FCC-he



- With an eye to the far future → FCC-he HH production!

Double higgs production @ 50 TeV

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



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

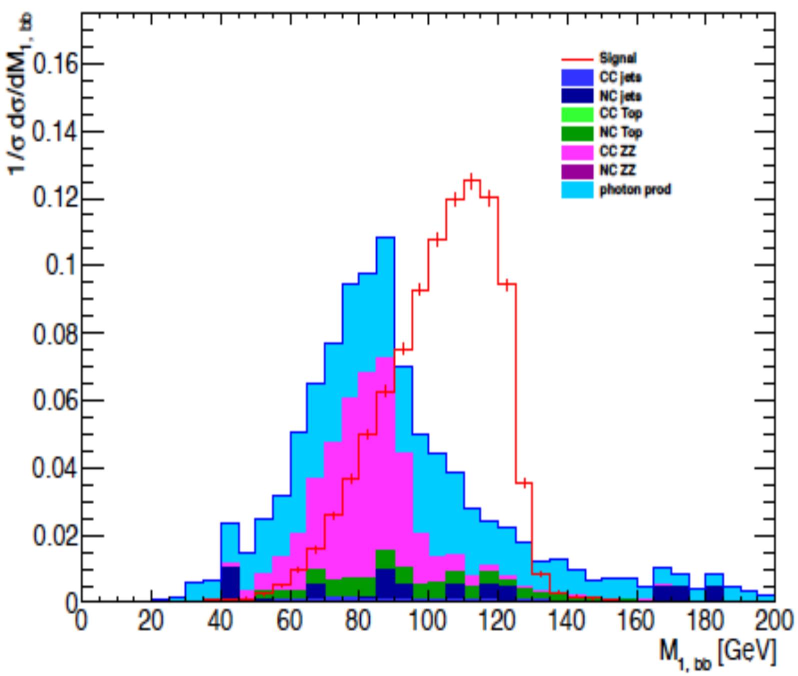
$$p_{T_{j,b}} > 20 \ GeV,$$
$$\not{E}_T > 25 \ GeV,$$
$$|\eta_j| < 5, \ \Delta R = 0.4.$$

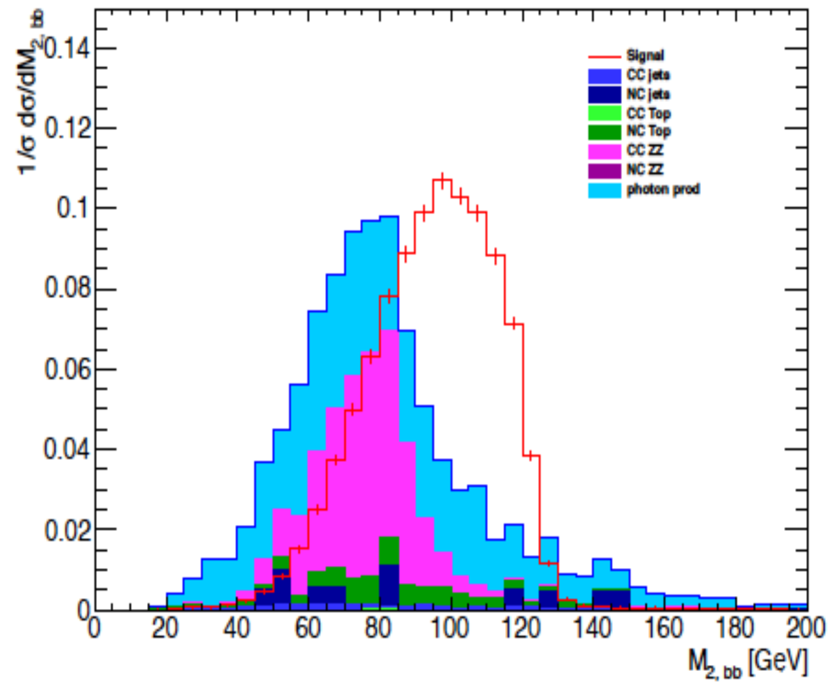
Cross-sections for CC HH->4b
(branching ratios included)
for unpolarized electron beam

Feasibility studies: HH at FCC-ep

- Publication in preparation
  - Assume E(e) = 60 GeV, polarized beam
  - proton energy = 50 TeV
- Double H→bbar:

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





Dominant background sources are from photoproduction processes and ZZ in CC

Will be shown at the workshop!

EWK measurements and BSM prospects

LHC (FCC-hh, …) main discovery machine, at energy frontier

- However, LHeC (and later, FCC-eh) have the potential for improving, or possibly discovering, new physics
- Via EWK precision measurements:
  - W/Z sector: $\sin^2\theta_W$
  - Top sector: Anomalous couplings, FCNC
  - Higgs sector: CP properties
  - Genuine BSM searches: BSM Higgs decays, Vector Boson production, R-parity violating SUSY, lepto-quarks, contact interactions etc..

Only selected results shown here

Electroweak Physics in ep: $\sin^2\theta_W$

- EWK precision measurements relevant for NP

Present situation

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

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

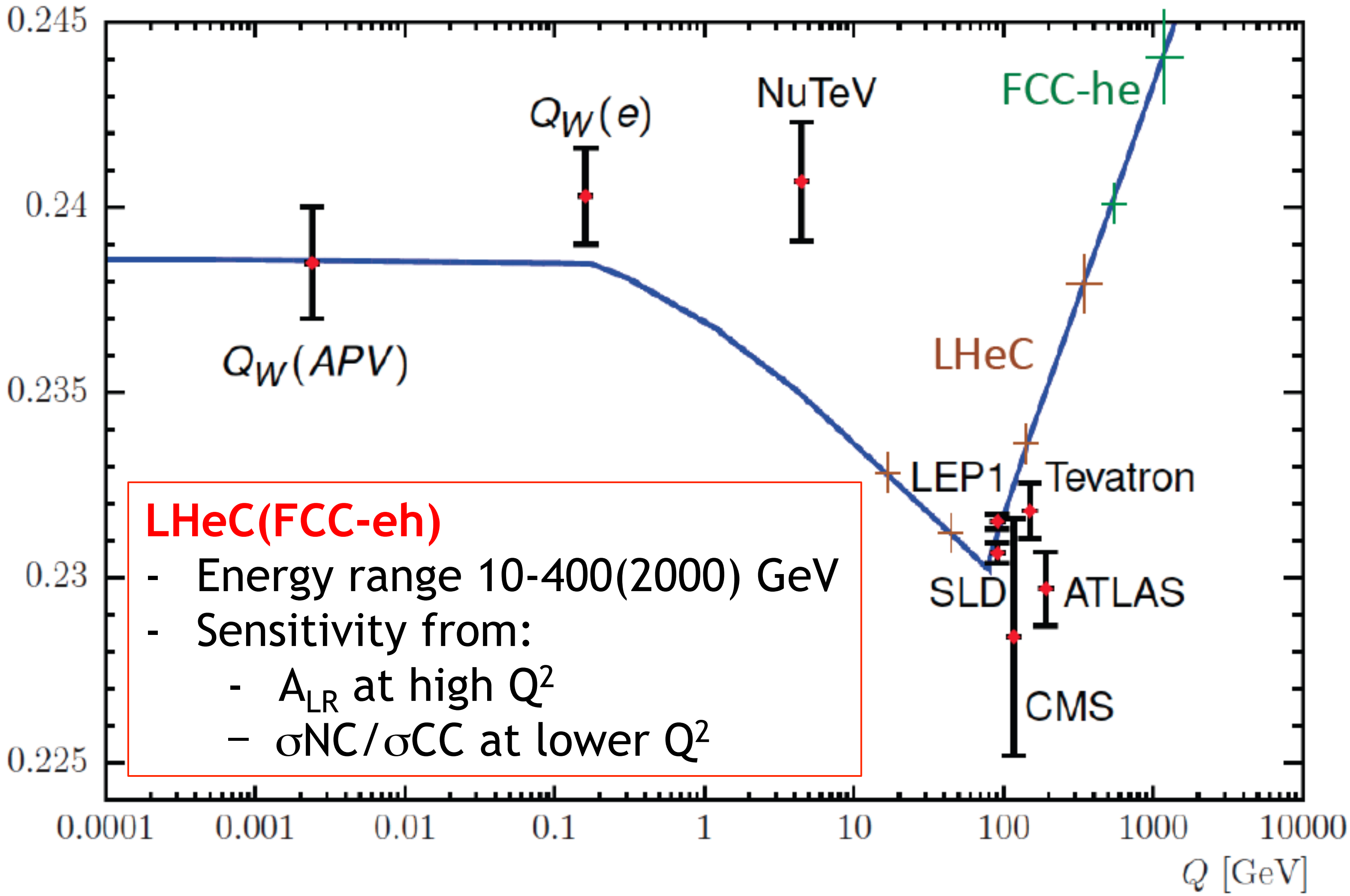
Very different implications for new physics:
look at S, T, U parameters, e.g.,

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

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

Scale dependence of $\sin^2\theta_W$

- Preliminary estimate



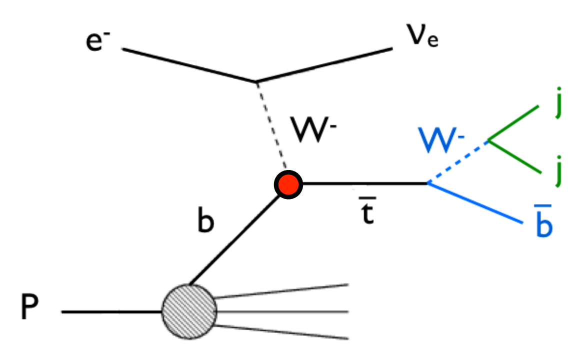
LHeC(FCC-eh)

- Energy range 10-400(2000) GeV
- Sensitivity from:
  - A_{LR} at high Q^2
  - $\sigma NC/\sigma CC$ at lower Q^2

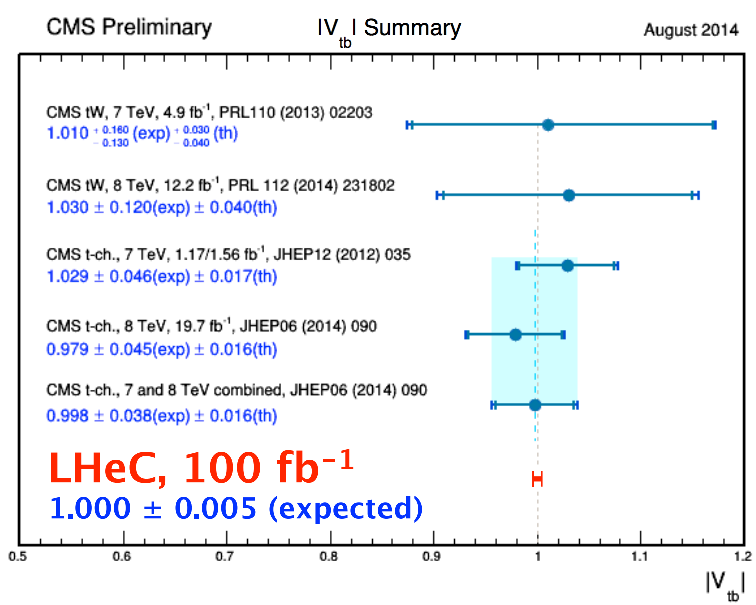
Top quark electroweak interactions

Precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) :

→ **top quark expected to be most sensitive to BSM physics, due to large mass**

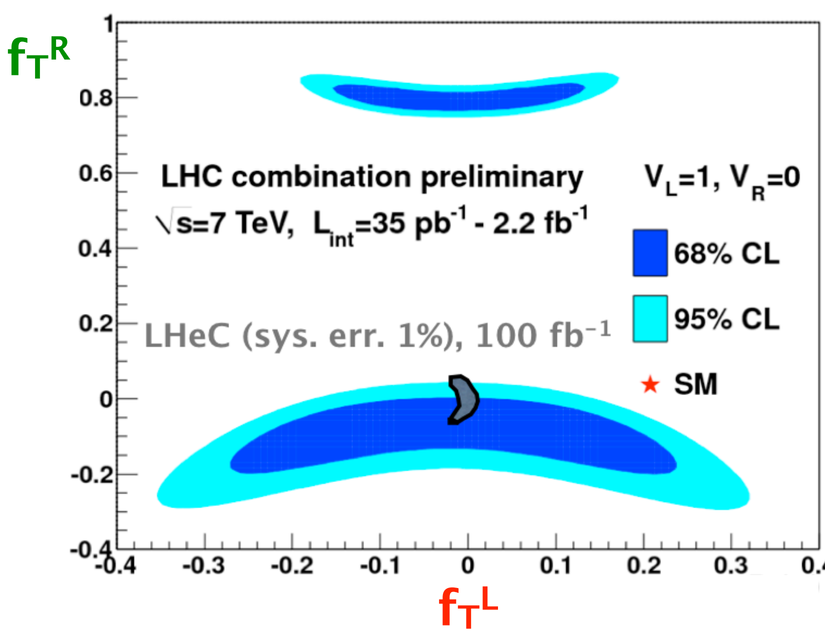


High precision measurements of Vtb



Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688

Search for anomalous Wtb couplings



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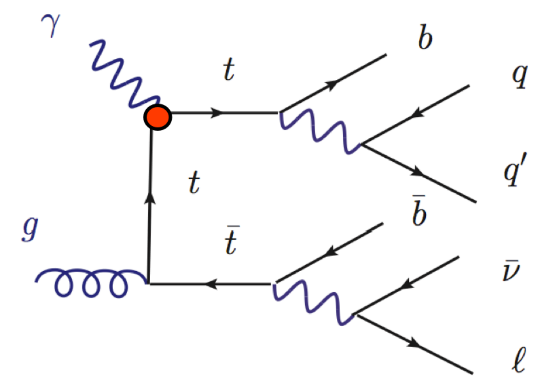
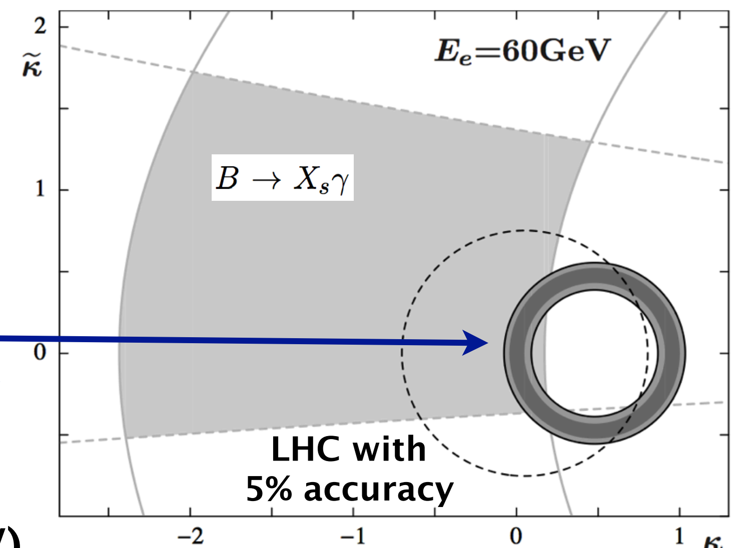


LHeC operating as γp collider!

Direct measurement of top quark charge

Search for anomalous ttbarγ couplings
(and searches for anomalous ttbarZ)

electric dipole moment: $\tilde{\kappa}$



magnetic dipole moment: κ

`Bouzas, Larios,`
`Physical Review D 88, 094007 (2013)`

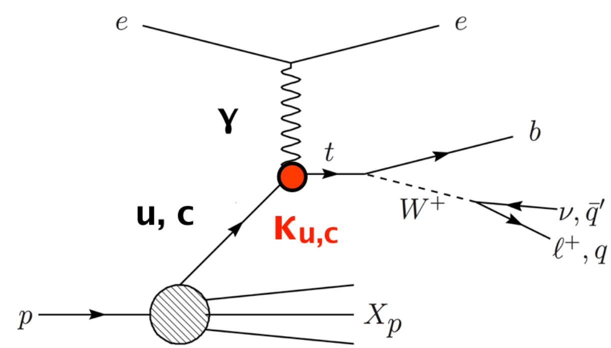
LHeC:
10% and 18% accuracy

27% accuracy
(4.59fb^{-1}, 7 TeV)

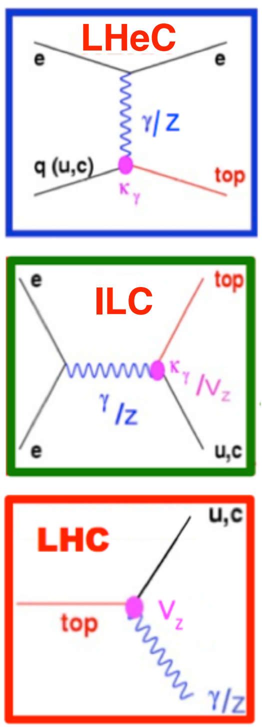
Top quark electroweak interactions

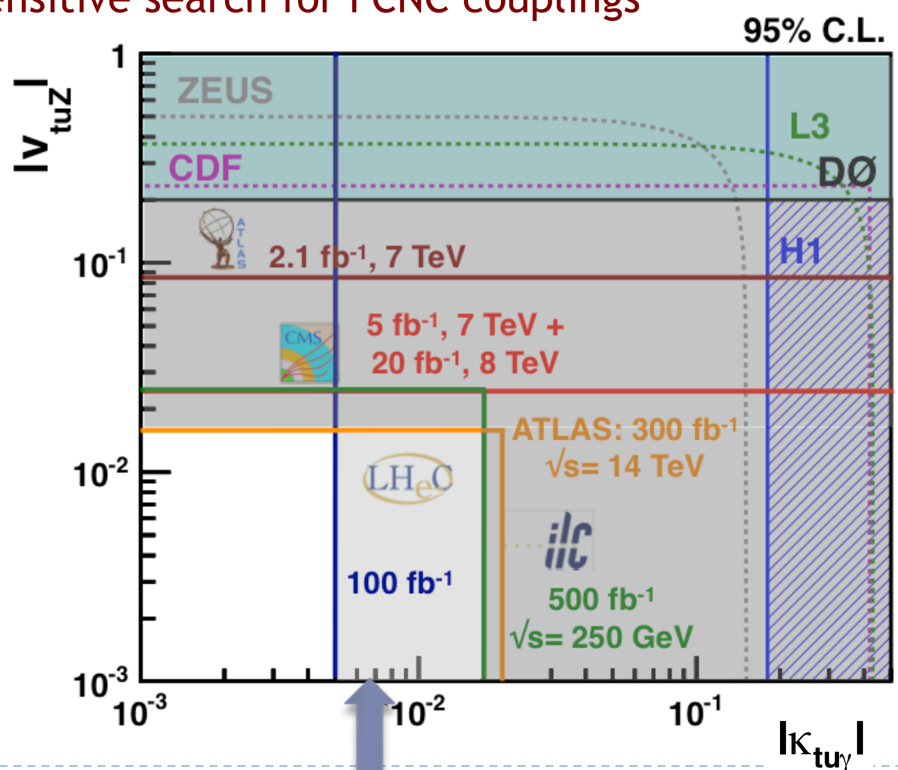
Precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) :

→ **top quark expected to be most sensitive to BSM physics, due to large mass**



sensitive search for FCNC couplings





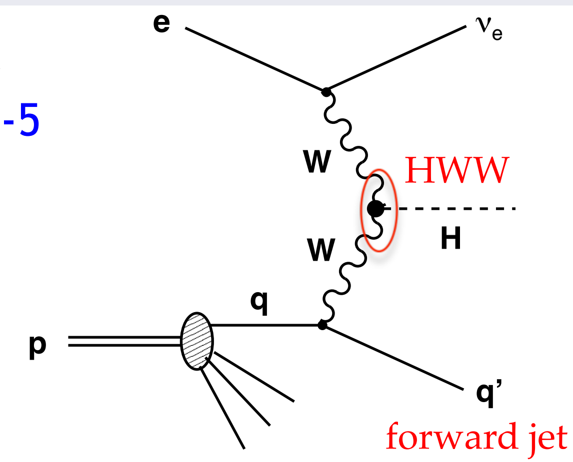
new physics models:
SUSY, technicolour, little Higgs, extra dimensions, ..
→ predict BR=O(10^{-5})
→ LHeC can access this!

CP properties of Higgs

- LHC has shown that discovered Higgs boson consistent with 0+ state, but: are there small additional dimension-5 anomalous couplings to the HWW vertex?

$$i\Gamma^{\mu\nu}(p_-,p_+)\varepsilon_\mu(p_-)\varepsilon^*_\nu(p_+)$$

$$\Gamma^{\mu\nu} = g M_W \left(-g^{\mu\nu} + \frac{1}{M_W^2}\left[\lambda\left(p_- \cdot p_+ \, g^{\mu\nu} - p_-^\nu p_+^\mu\right) + i\lambda' \varepsilon^{\mu\nu\rho\sigma} p_{-\rho} p_{+\sigma} \right] \right)$$

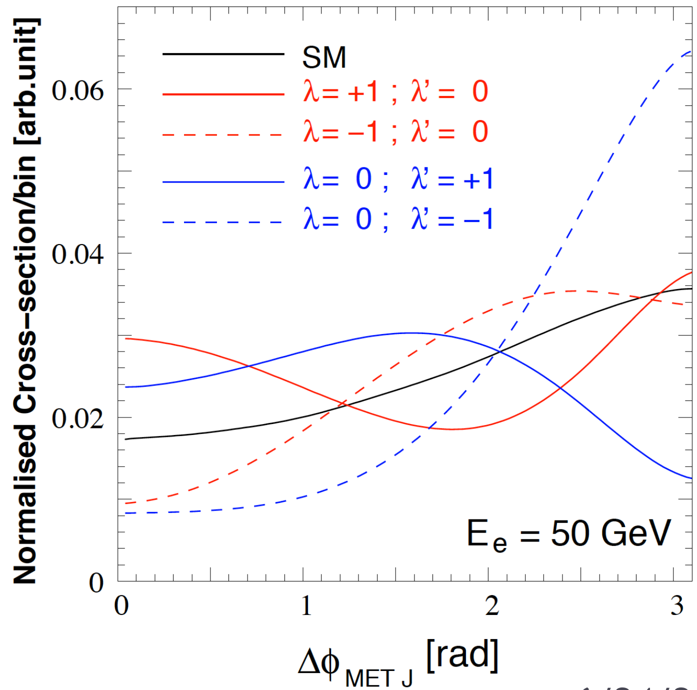


(BSM will modify CP even (λ) and odd (λ') states differently)

- measure **azimuthal angular distribution** between $E_T$miss and forward jets
- sensitive probe of nature of **HWW vertex** and hence **CP properties**

with 50 fb^{-1}, sensitivity up to λ ~ 0.05 and λ' ~ 0.2

(T. Plenh et al, hep-ph/0105325
S. Biswal et al, arXiv:1203.6285, and update)

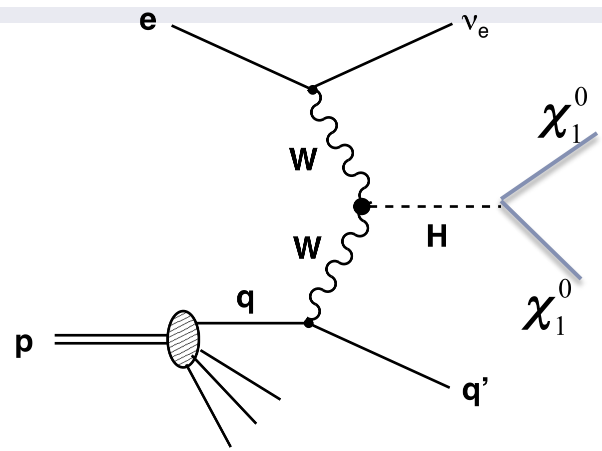


BSM in Vector Boson (VB) scattering

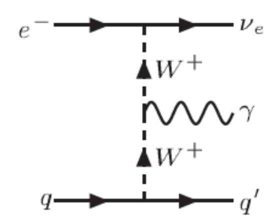
- VB Higgs production with BSM decay
  - explore SUSY-R-parity Violating cases. E.g.

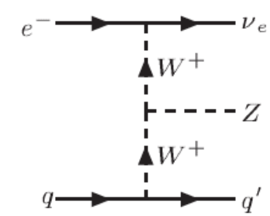
$$H \rightarrow \chi_1^0 \chi_1^0 \rightarrow 3j\, 3j \text{ (resonances)}$$

  - BUT need to understand background…



- VB scattering at high mass (more for FCC-he) :
  - Mass dependence of cross section
  - anomalous TGC, QGC couplings in VVV, VVVV ?





I.T. Cakir et al, 1406.7696 → *sensitivity comparable to LHC*

  - Is unitarity restored only by Higgs? Are there new resonances (CH model) ?
    - expect below ~ 2-3 TeV $\quad e^- q \rightarrow e^-(q)WZ, \quad (\nu q)WZ$

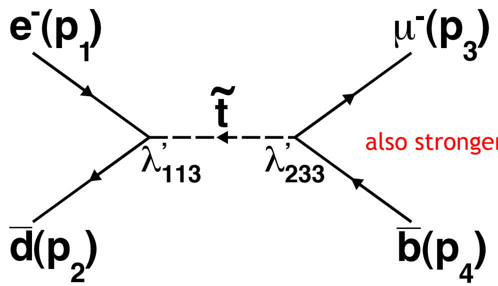
      → *look for deviations from SM predictions:*
    - high background from QCD diagrams at LHC, absent at FCC-eh
    - challenging at LHC if no lepton trigger is used, and because of pileup

SUSY – R-parity violating

single squark production, in RPV SUSY (signal like leptoquarks, with generation mixing)

[general LQ studies and more – in back-up]

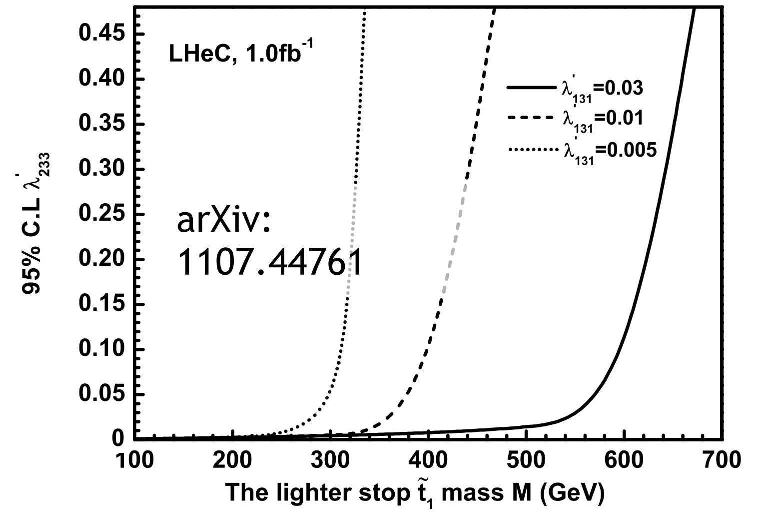
stop



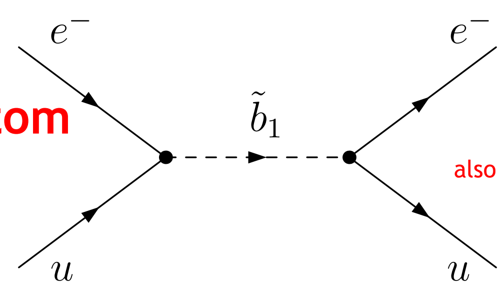
Λ'$_{131}$< 0.03

also stronger bounds from ββ0ν

- sensitivity up to 700 – 800 GeV with only 1fb^{-1}
- LHC will also provide constraints
- very promising with high luminosity, 100 fb^{-1}
- requires good b-tagging



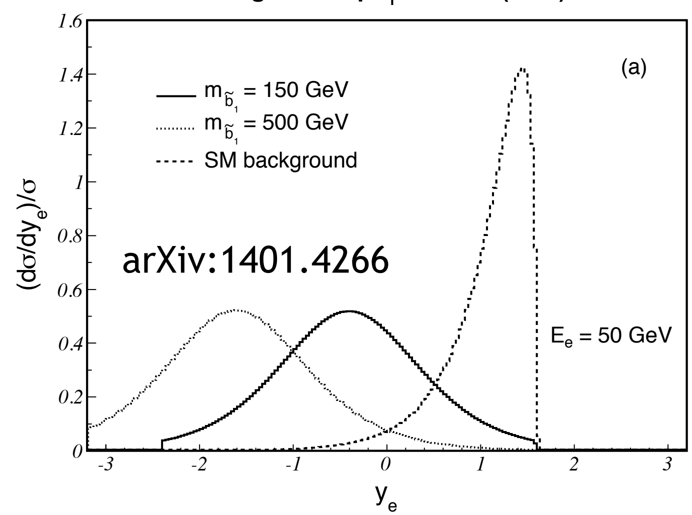
sbottom



Λ'$_{131}$< 0.02

also stronger bounds from ββ0ν

- < 100 fb^{-1} needed for 1TeV RPV sbottom discovery

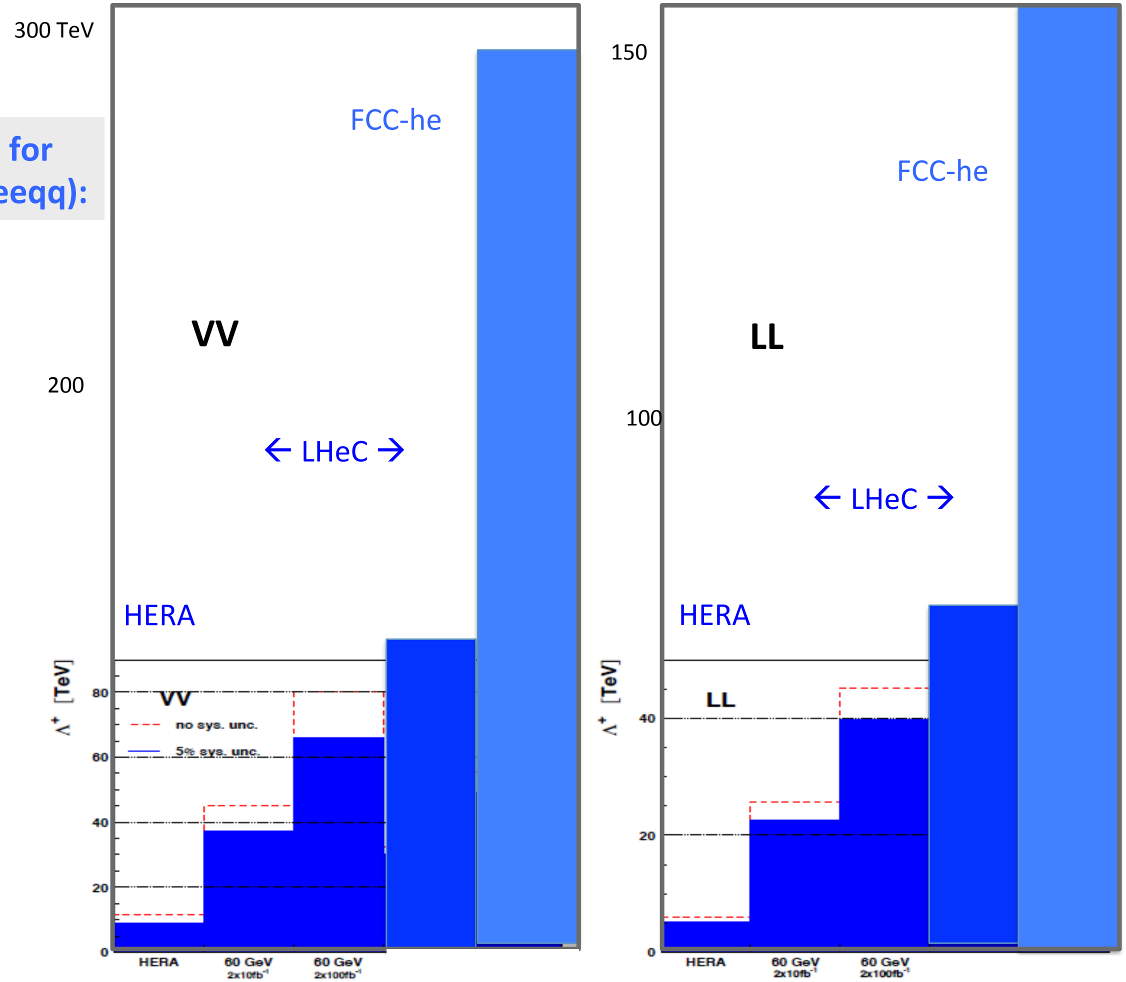


RPV interaction can be probed at unprecedented levels

Contact Interactions at future colliders

- if new physics enters at higher scales: Λ>> √s

Reach for
Λ (CI eeqq):



present LHC constraints on scale of qqll contact interactions: 15 – 26 TeV, depending on model (expected up to **40 TeV** at LHC@14TeV)

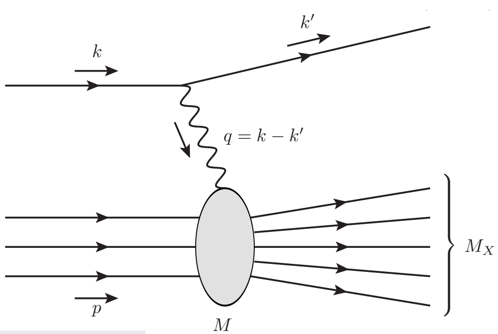
also advantages over, and complementarities with, pp (and e+e-) in characterising nature of new physics

LHeC: see CDR 2012

FCC rough scaling only, preliminary

e-Ion physics

- Rich program, e.g. for Nuclear Parton density determination

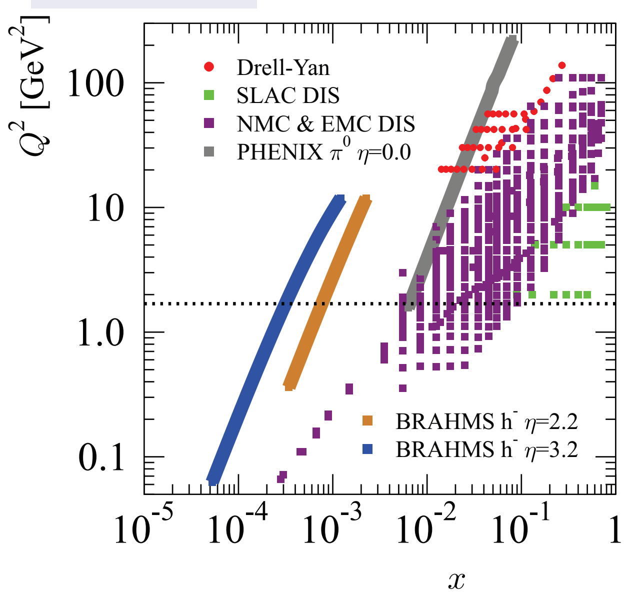


Structure functions are modified in Nuclear collisions
Get process independent nuclear PDF

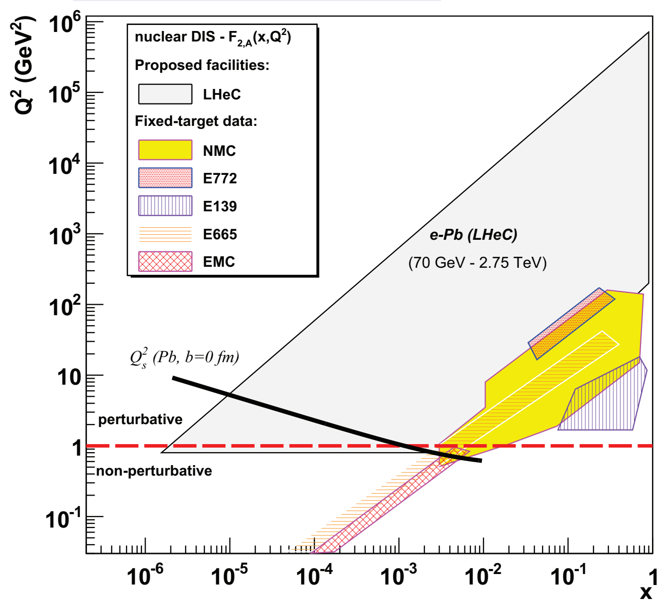
$$f_i^A(x,Q^2) = R_i^A(x,Q^2)\, f_i(x,Q^2)$$

Nuclear modifications

now…



With LHeC…

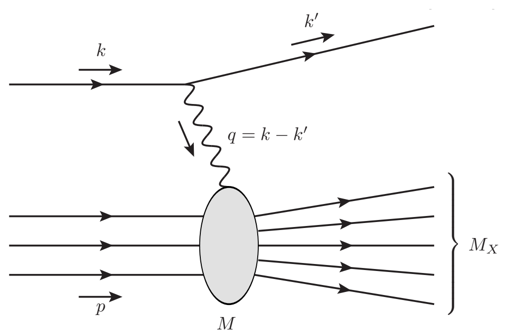


LHeC improves greatly the kinematic range

e+A much cleaner than p+A

e-Ion physics

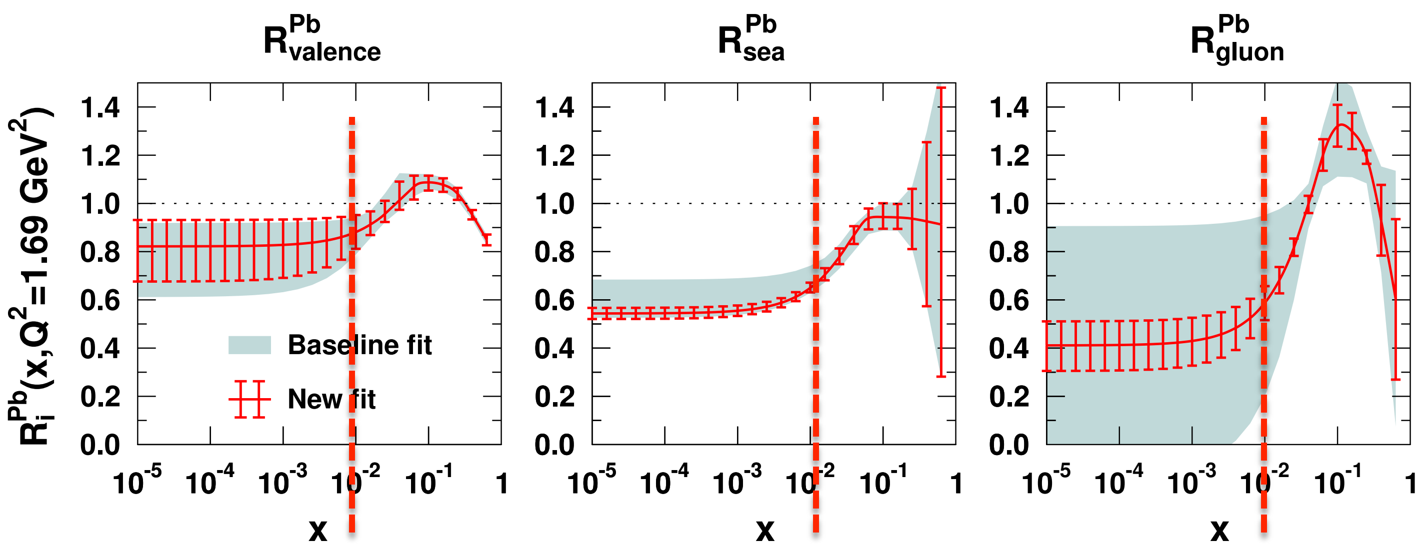
- Rich program, e.g. for Nuclear Parton density determination



Structure functions are modified in Nuclear collisions
Get process independent nuclear PDF

$$f_i^A(x,Q^2) = R_i^A(x,Q^2) f_i(x,Q^2)$$

Nuclear modifications



Huge reduction of the small-x uncertainties for gluons and sea quarks

new results at the workshop!

Other e+A physics: Clean environment to study small-x phenomena as **saturation**

summary and conclusion

The LHeC is going to be:

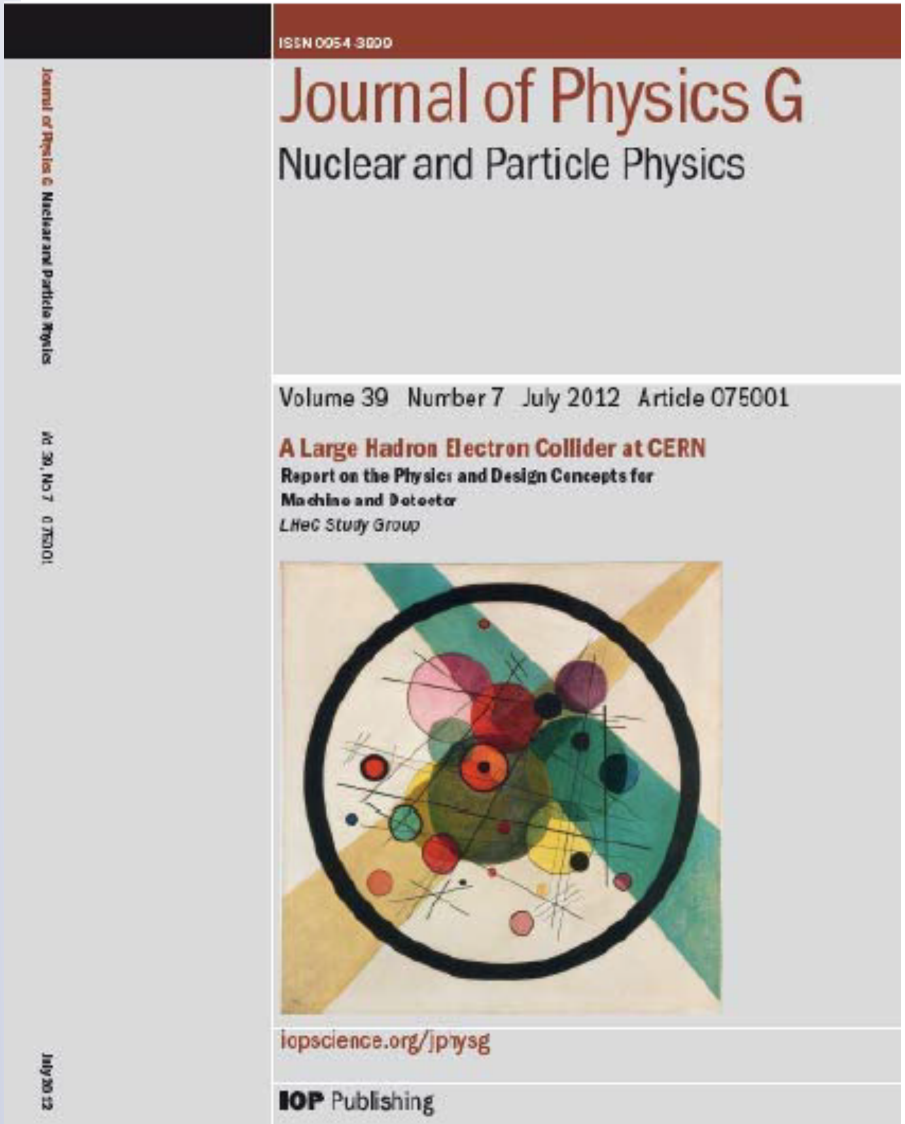
- the finest microscope of the world
  - PDF fits, measurements of α_S and impact on higgs/BSM
- the next machine to see the Higgs
  - Measurements of H to bbbar and more
- complement to LHC for EWK measurements and new physics
  - EWK interactions
    - Top quark: anomalous couplings, Flavor Changing Neutral Current
    - Measurements of $\sin^2\theta_W$
  - Beyond SM physics: CI, LQ, SUSY
- revolution of nuclear structure
  - Electron-Ion highlights

The Physics potential of this machine deserves strong support from the community while studies evolve as the LHC runs ..

We have simulated part of the "known", but surprises could be around the corner and we shall be ready for that

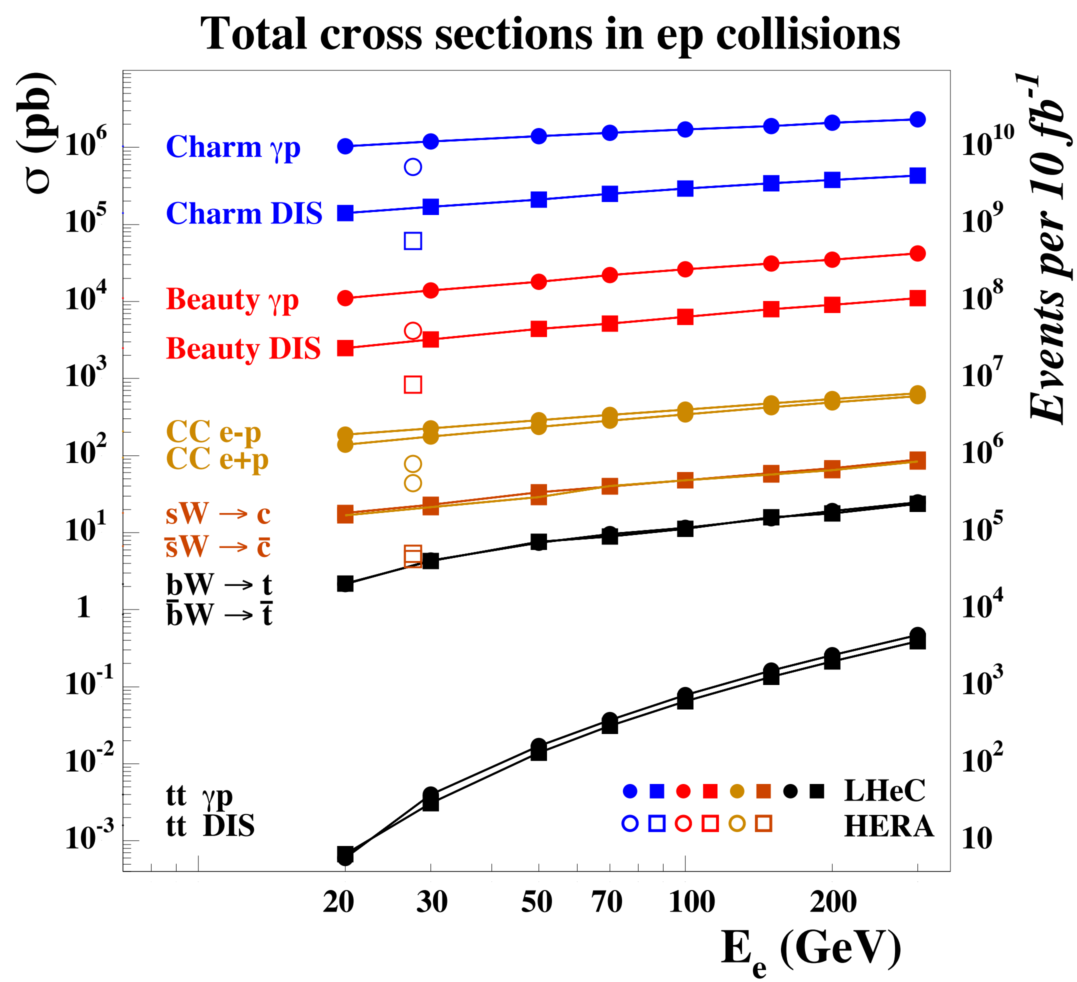
Back-up

LHeC: Conceptual Design Report (July 2012) and more



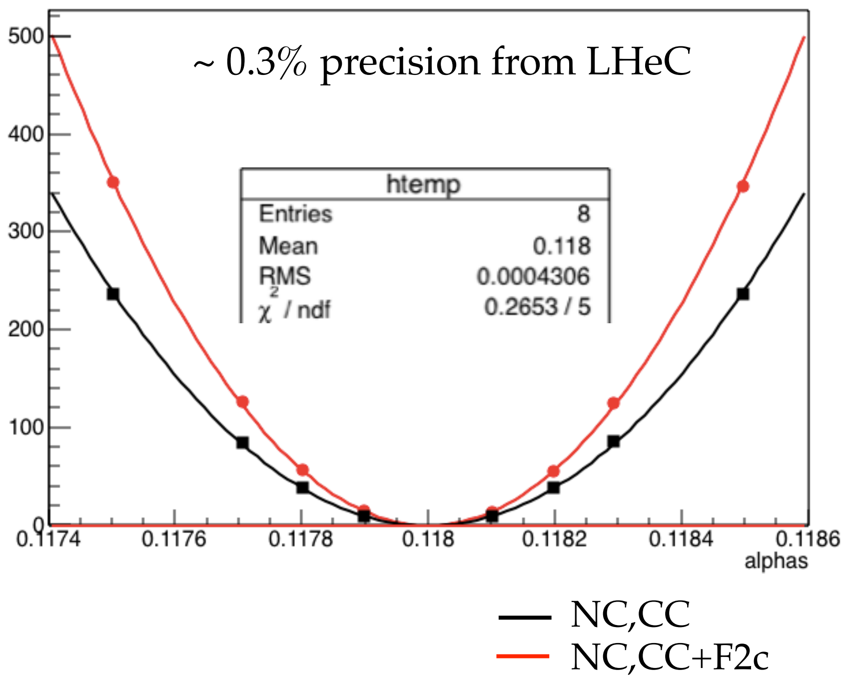
- 630 pages summarising 5 years of studies commissioned by CERN, ECFA and NuPECC
- About 200 participants, 69 institutes
- Further updates
  - *'A Large Hadron Electron Collider at CERN'* arXiV:1211.4831
  - *'On the relation of the LHeC and the LHC'* arXZiV:1211.5102
  - *'The Large Hadron Electron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

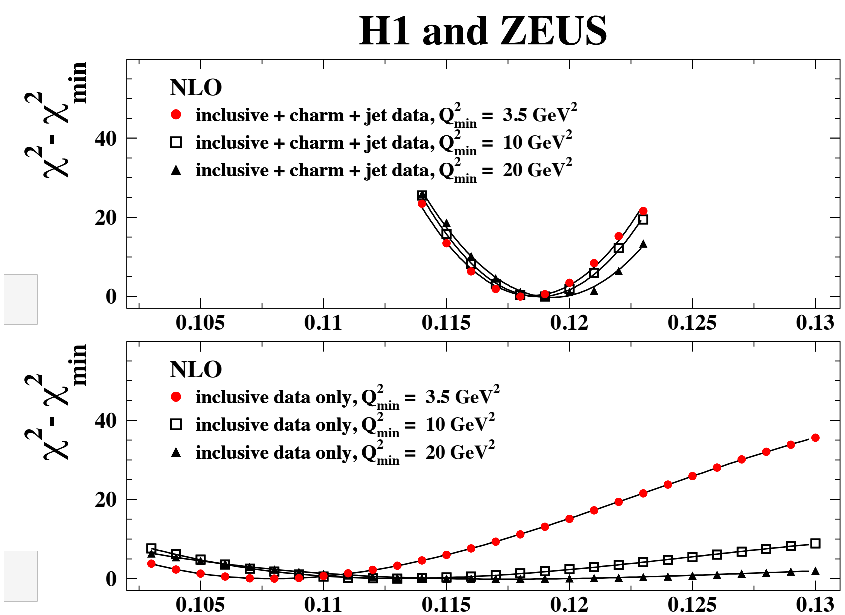
LHeC heavy flavour cross sections

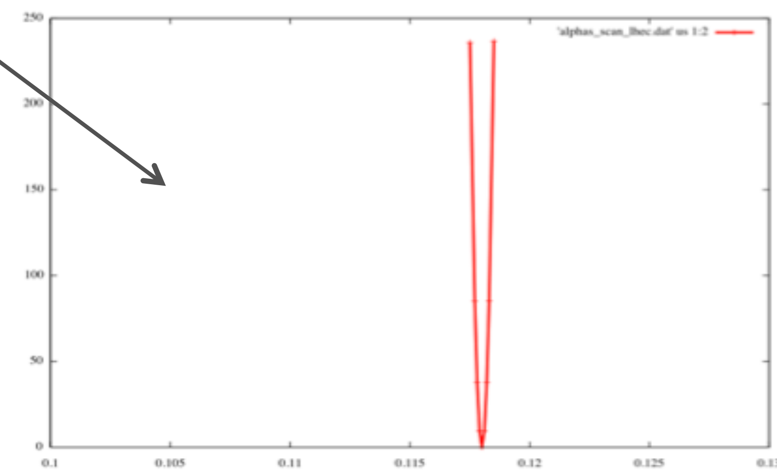


Strong coupling from LHeC

combined fit to PDFs+αs using LHeC data







LHeC could resolve a > 30-year old puzzle:

α_s consistent in inclusive DIS, versus jets?

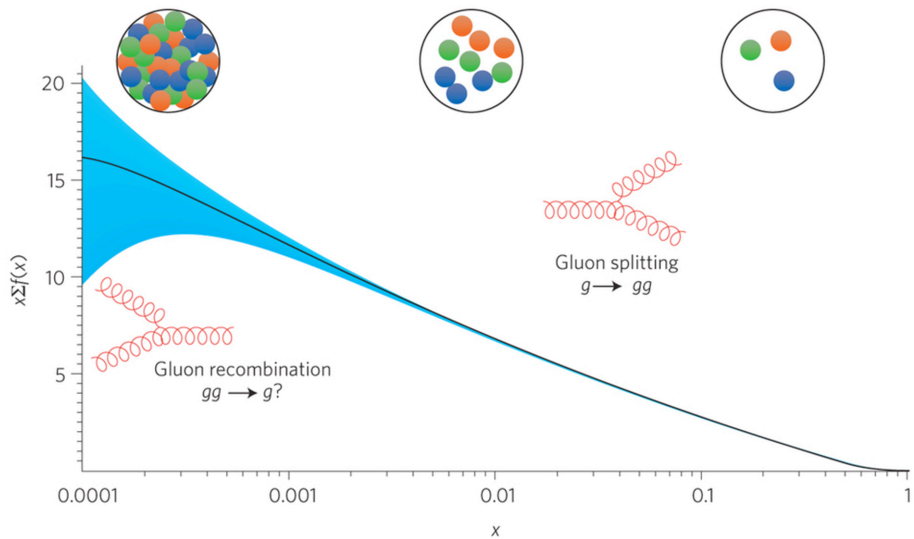
expected 0.1% precision when combined with HERA

Why small x is interesting?

Important lesson from HERA :

Observation of strong growth of the proton structure function at small x.
It is driven by the growth of the gluon density.

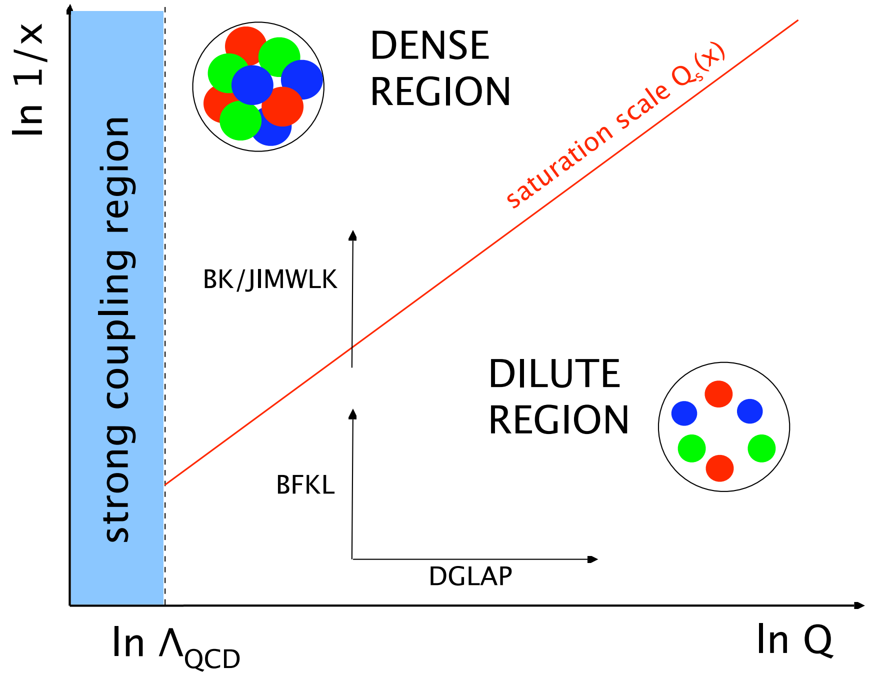
sum of parton densities



- Parton evolution needs to be modified to include potentially very large logs, resummation of log(1/x)
- Further increase in the energy could lead to the importance of the recombination effects. Unitarity of the scattering amplitude.
- Modification of parton evolution by including non-linear or saturation effects in the parton density.

Small x, saturation regime

DIS 2015, A.Stasto



Theory predicts the existence of the energy dependent (x dependent) saturation scale.

$$\frac{A \times xg(x, Q_s^2)}{\pi A^{2/3}} \times \frac{\alpha_s(Q_s^2)}{Q_s^2} \sim 1$$

$$Q_s^2 \sim A^{1/3} Q_0^2 \left(\frac{1}{x}\right)^{\lambda}$$

The boundary between the two regimes needs to be determined experimentally.

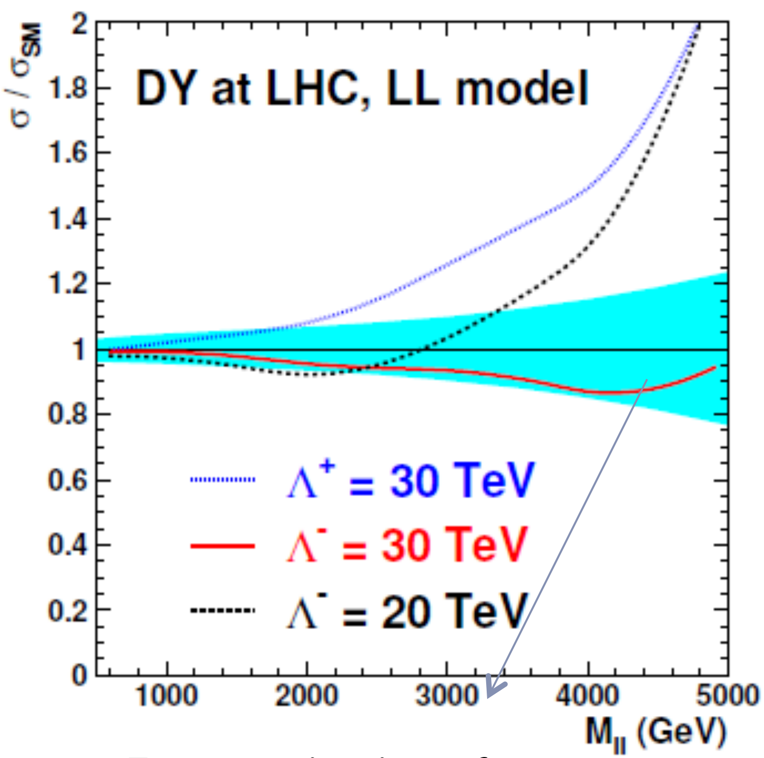
Saturation studies within the context of dipole models.

At HERA the data consistent with very low saturation scale, $Q_s^2 \leq 1 \text{ GeV}^2$ therefore partonic interpretation rather uncertain.

Unique feature of the LHeC: can access the dense regime at fixed, semihard scales Q, while decreasing x.

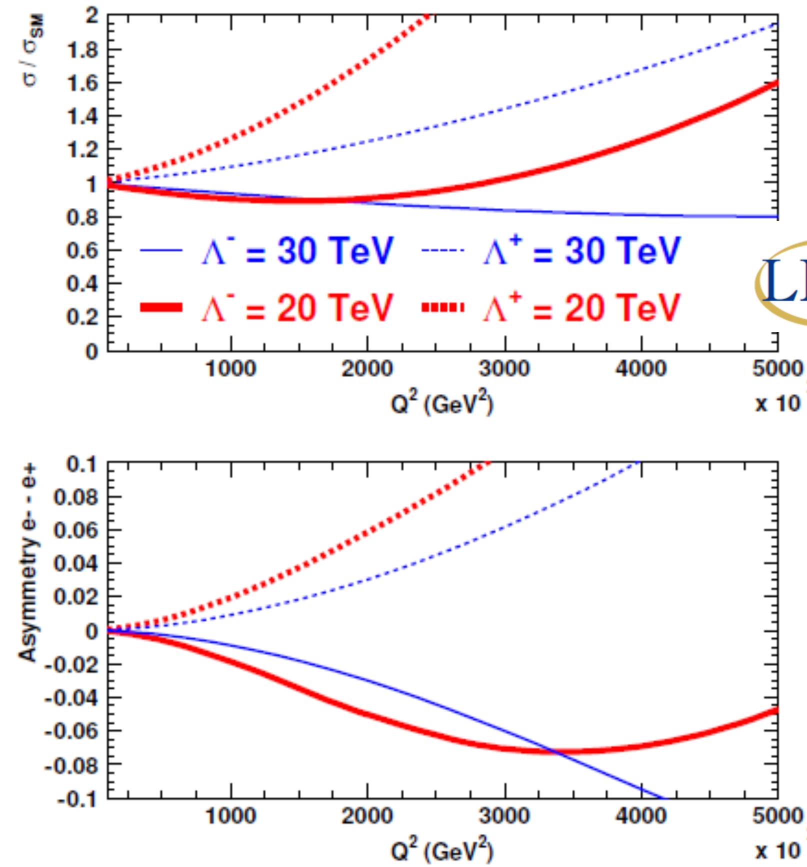
CI at LHC and LHeC

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



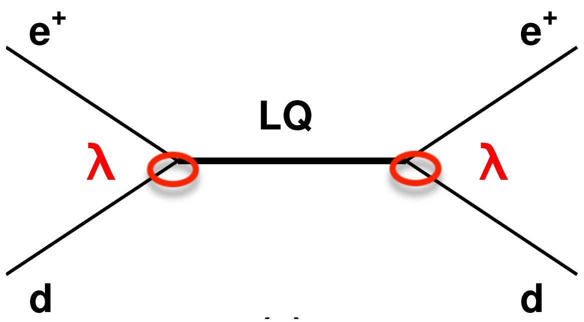
Ex: negative interference too small to be disentagled

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



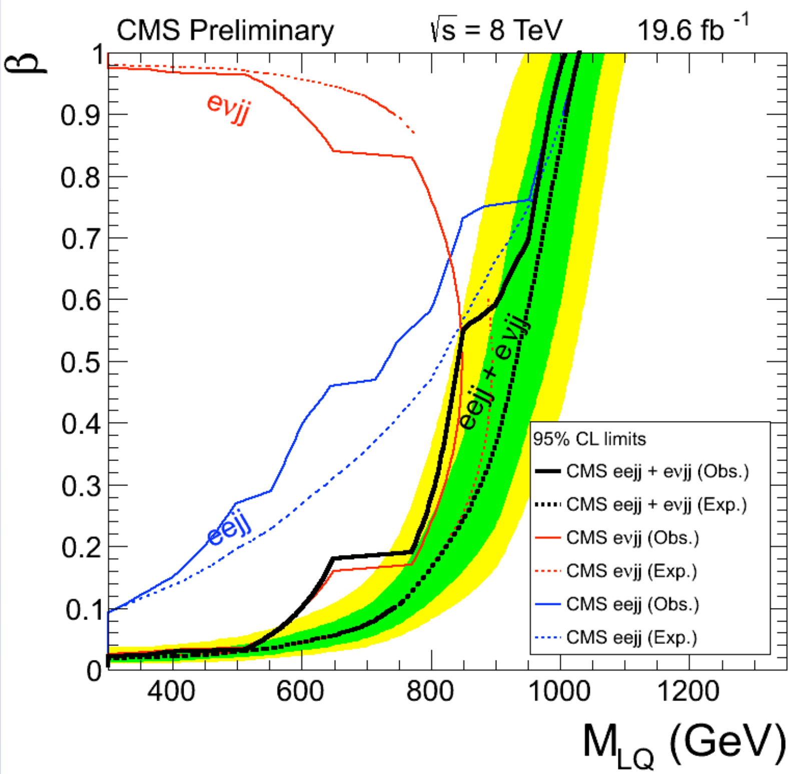
Leptoquarks

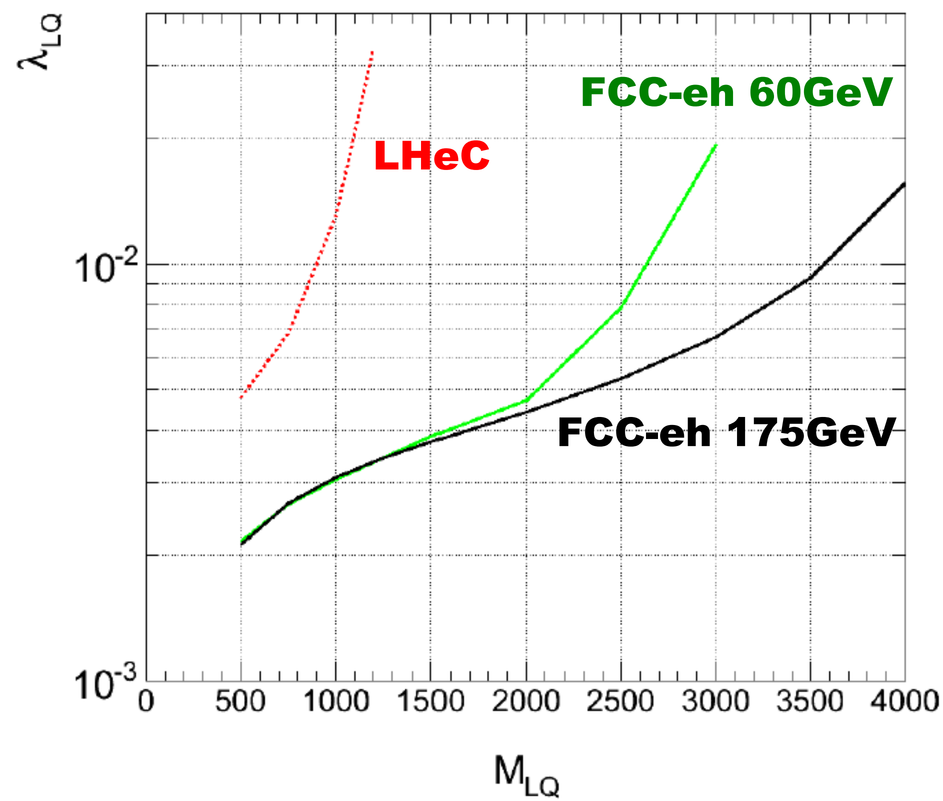
- **LHeC**: both baryon and lepton quantum numbers – ideally suited to search for and study properties of new particles coupling to both leptons and quarks
- **leptoquarks (LQs)** appear in several extensions to SM
- can be **scalar** or **vector**, with fermion number 0 (e^-qbar) or 2 (e^-q)
- **LHC**: mainly pair-production via gg or qq – essentially insensitive to LQ q-e coupling, λ
- **LHeC**: single, resonant production; sensitive to λ



LQs: comparison with current LHC bounds

PAS-EXO-12-041





1st generation LQs; ß=BR(LQ→eq)=1

ATLAS+CMS (20fb^{-1}): $m_{LQ} \leq 1000$ GeV

expect up to 1.2 (1.5)TeV (pair production) with 300fb^{-1} at LHC@14TeV for scalar (vector)

ep scenarios:

also sensitive to $\lambda \ll e=\sqrt{4\pi\alpha}=0.3$

preliminary study: in progress

Contact interactions

- if new physics enters at higher scales: Λ>> √s
- such indirect signatures can be seen as effective 4-fermion interaction

$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu^{(e)} j^{\mu(q)}; \quad j_\mu^{(f=e,q)} = \eta_L \bar{f}_L \gamma_\mu f_L + \eta_R \bar{f}_R \gamma_\mu f_R + h.c.$$

$$\Rightarrow \text{ all combinations of couplings } \eta_{ij} = \eta_i^{(e)} \eta_j^{(q)}; \quad q = u, d$$

- may be applied very generally to new phenomena

Λ
- LQ mass >> √s
- Planck scale (Ms) of extra dimensional models
- compositeness scale
- …

present LHC constraints on scale of qqll contact interactions: 15 – 26 TeV, depending on model (expected up to **40 TeV** at LHC@14TeV)

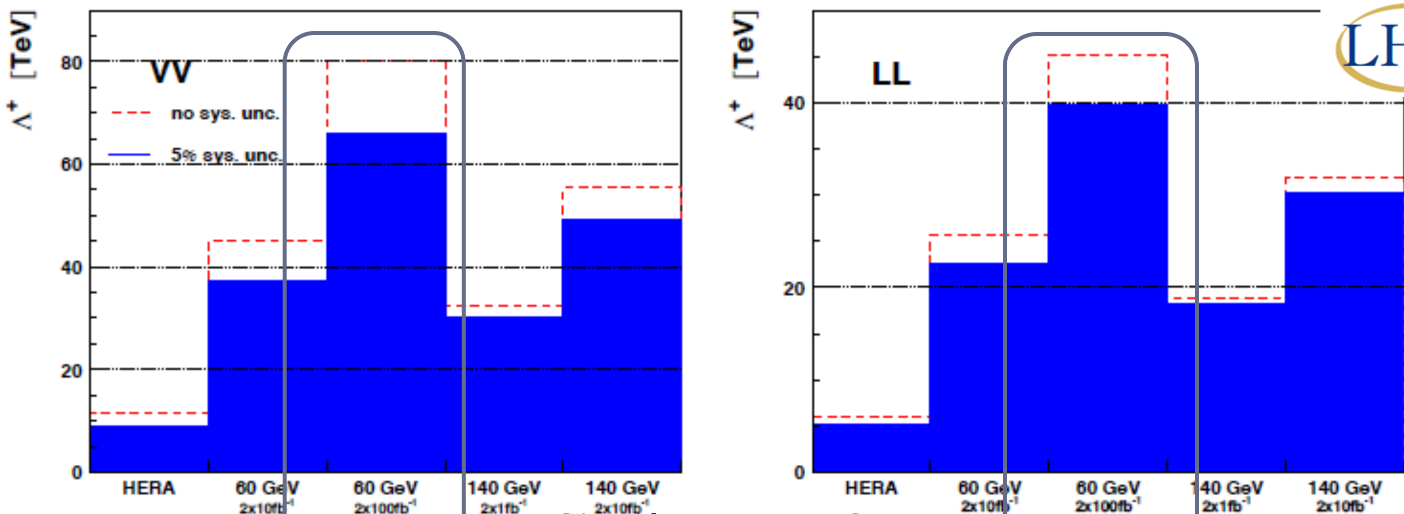
- sensitivity to fermion radius below 10^{-19}-10^{-20}m at LHeC (FCC-eh) $\frac{\hbar c}{1.3\,\text{TeV}} = 1.5\times 10^{-4}\,\text{fm}$

$$\text{form factor: } f(Q^2) = 1 - \frac{1}{6}\langle r^2 \rangle Q^2$$

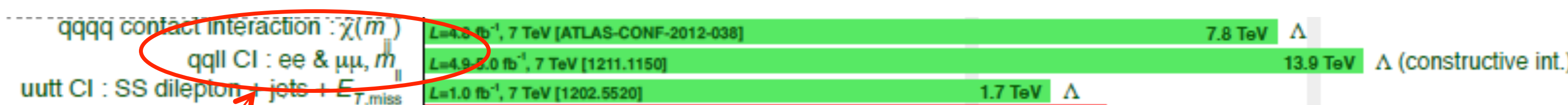
$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_{SM}}{dQ^2} f_e^2(Q^2) f_q^2(Q^2)$$

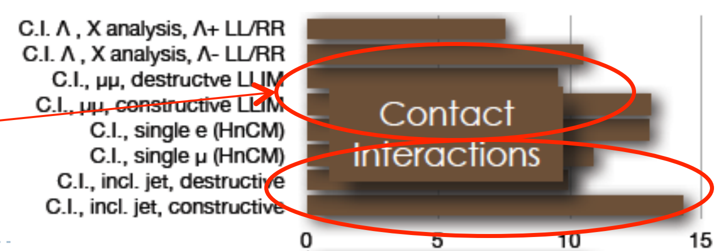
Contact interactions (eeqq)

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



Similar to LHC





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

Ttbar-gamma details

- From http://arxiv.org/pdf/1308.5634v2.pdf

$$
\begin{aligned}
\mathcal{L}_{t\bar{t}\gamma} &= \frac{g}{\sqrt{2}}\bar{t}\left(\gamma^\mu W_\mu^+ (F_1^L P_L + F_1^R P_R) - \frac{1}{2m_W}\sigma^{\mu\nu} W_{\mu\nu}^+ (F_2^L P_L + F_2^R P_R)\right) b\,, \\
&+ e\bar{t}\left(Q_t \gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu} F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right) t \\
&+ \frac{g}{2c_W}\bar{t}\gamma^\mu Z_\mu \left((1 - \frac{4}{3}s_W^2 + F_{1Z}^L)P_L + (-\frac{4}{3}s_W^2 + F_{1Z}^R)P_R\right) t \\
&+ \frac{g}{2c_W}\bar{t}\left(\frac{1}{4m_t}\sigma^{\mu\nu} Z_{\mu\nu}(\kappa_Z + i\tilde{\kappa}_Z\gamma_5)\right) t
\end{aligned}
$$

$$
\begin{aligned}
\kappa &= -F_{2V}^\gamma = \frac{2m_t}{e}\mu_t = Q_t a_t \\
\tilde{\kappa} &= F_{2A}^\gamma = \frac{2m_t}{e} d_t,
\end{aligned}
$$

$$a_t = (g_t - 2)/2$$

$$
\begin{aligned}
F_1^L &= V_{tb} + \frac{v^2}{\Lambda^2} C_{\phi q}\,, & F_1^R &= \frac{1}{2}\frac{v^2}{\Lambda^2} C_{\phi\phi}^r\,, \\
F_2^L &= -\sqrt{2}\frac{v^2}{\Lambda^2} C_{tW}^r\,, & F_2^R &= -\sqrt{2}\frac{v^2}{\Lambda^2} C_{bW}^r\,, \\
F_{1Z}^L &= \frac{v^2}{\Lambda^2} C_{\phi q}\,, & F_{1Z}^R &= \frac{1}{2}\frac{v^2}{\Lambda^2} C_{\phi t}\,,
\end{aligned}
$$

$$
\kappa = \frac{2\sqrt{2}}{e}\frac{v m_t}{\Lambda^2}\left(s_W C_{tW}^r + c_W C_{tB}^r\right)\,, \quad \kappa_Z = \frac{4\sqrt{2}}{e}\frac{v m_t}{\Lambda^2} s_W c_W \left(c_W C_{tW}^r - s_W C_{tB}^r\right)
$$

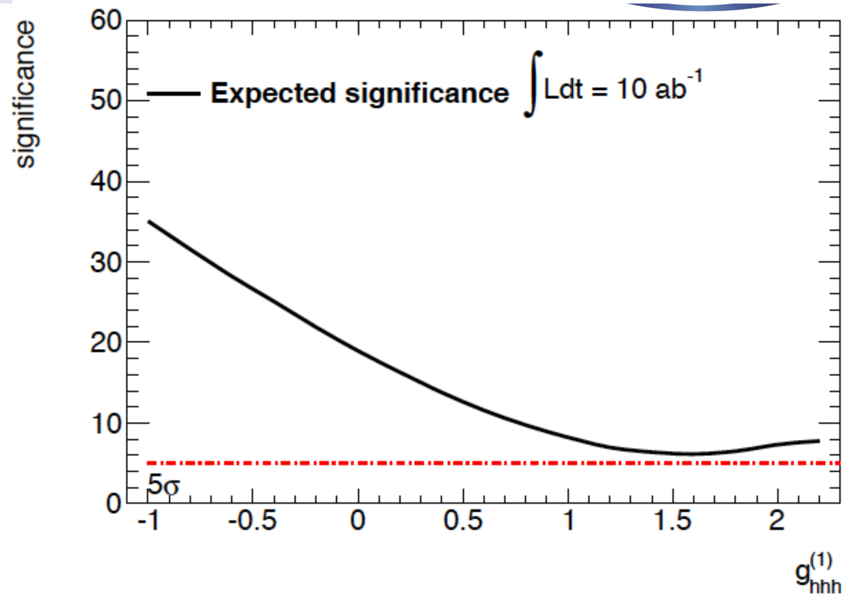
Recent constraints coming from the branching ratio and a CP-asymmetry for b→s γ

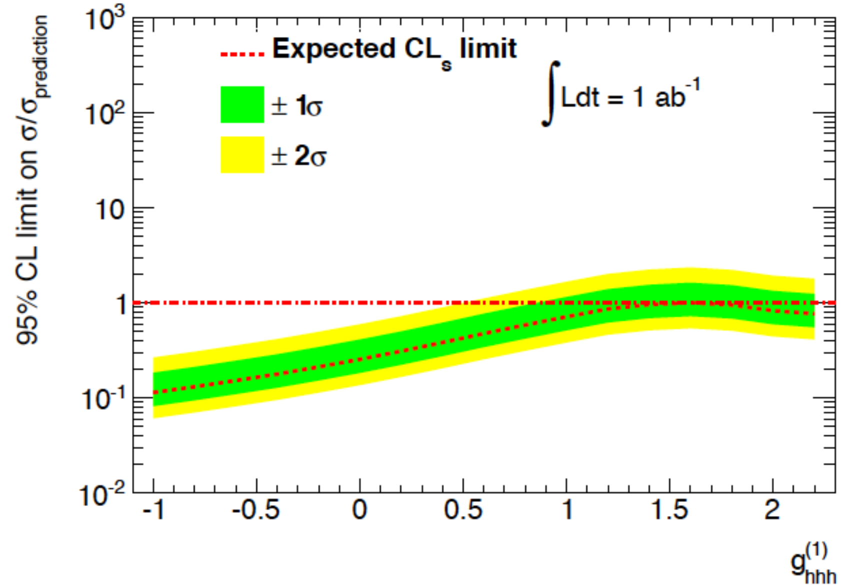
Feasibility studies: HH at FCC-ep

- Publication in preparation
  - Assume E(e) = 60 GeV, polarized beam
  - proton energy = 50 TeV
- Double H→bbar:

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

Will be shown at the workshop!





For the SM value $g_{HHH} = 1$ the H-HH coupling can be measured to 5-10 std: f(E_e, eta acceptance, lumi, syst.)

Coupling HHH: there is a HUGE potential to be looked at

Electroweak Physics in ep: $\sin^2\theta_W$

In Deep Inelastic Scattering:

Polarisation Asymmetry $A^-(Q)$

NC-to-CC Ratio R- for P=±0.8

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

1% δM_{top} is about δ = 0.0001

PDF uncertainty comes in at second order and e-p provides very precise PDFs