LHeC & FCC

Uta Klein

Speaker's affiliations :

UNIVERSITY OF LIVERPOOL

PPAP Community Meeting 2015, London, September 24th, 2015

FCC Members

58 collaboration members & CERN as host institute, July 2015

ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA
EPFL, Switzerland
GWNU, Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey
JAI/Oxford, UK
JINR Dubna, Russia
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
U Oxford, UK
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wroclaw UT, Poland

FCC Kick-Off & Study Preparation Team

https://indico.cern.ch/event/282344

Future Circular Colliders - Conceptual Design Study
Study coordination, **M. Benedikt, F. Zimmermann**

Hadron collider	Hadron injectors	e+ e- collider and injectors	Infrastructure, cost estimates	Technology	Physics and experiments
D. Schulte	**B. Goddard**	**J. Wenninger**	**P. Lebrun**	High Field Magnets **L. Bottura**	Hadrons **A. Ball, J. Incadela M. Mangano**
				Supercon-ducting RF **E. Jensen**	e+ e- **A. Blondel J. Ellis, P. Janot**
				Cryogenics **L. Tavian**	e- p **M. Klein**
				Specific Technologies **JM. Jimenez**	

e- p option
Integration aspects **O. Brüning**

Operation aspects,
energy efficiency, safety, environment **P. Collier**

UK

Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann, J. Gutleber

Coordination Group

Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Ghaddi
Erk Jensen
Max Klein **(chair)**
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

LHeC/FCC-he Study Group

www.lhec.cern.ch

Study Groups (Convenors invited by CERN)

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
Detector	**Peter Kostka**

The eh design has been a strong community effort and has strong Liverpool / Birmingham leadership!

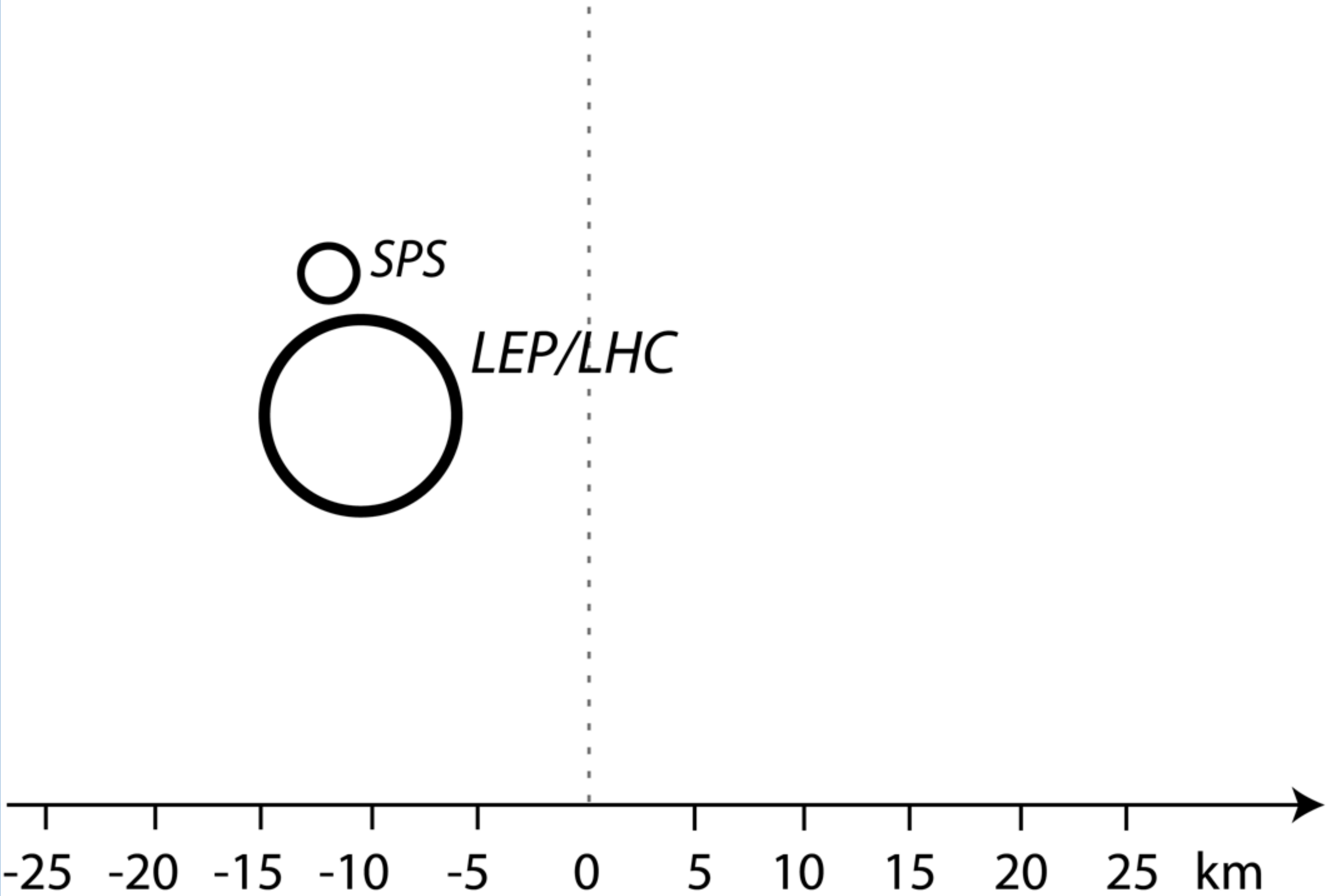
Referees for LHeC Design Report

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)

LHeC CDR: arXiv:1206.2913

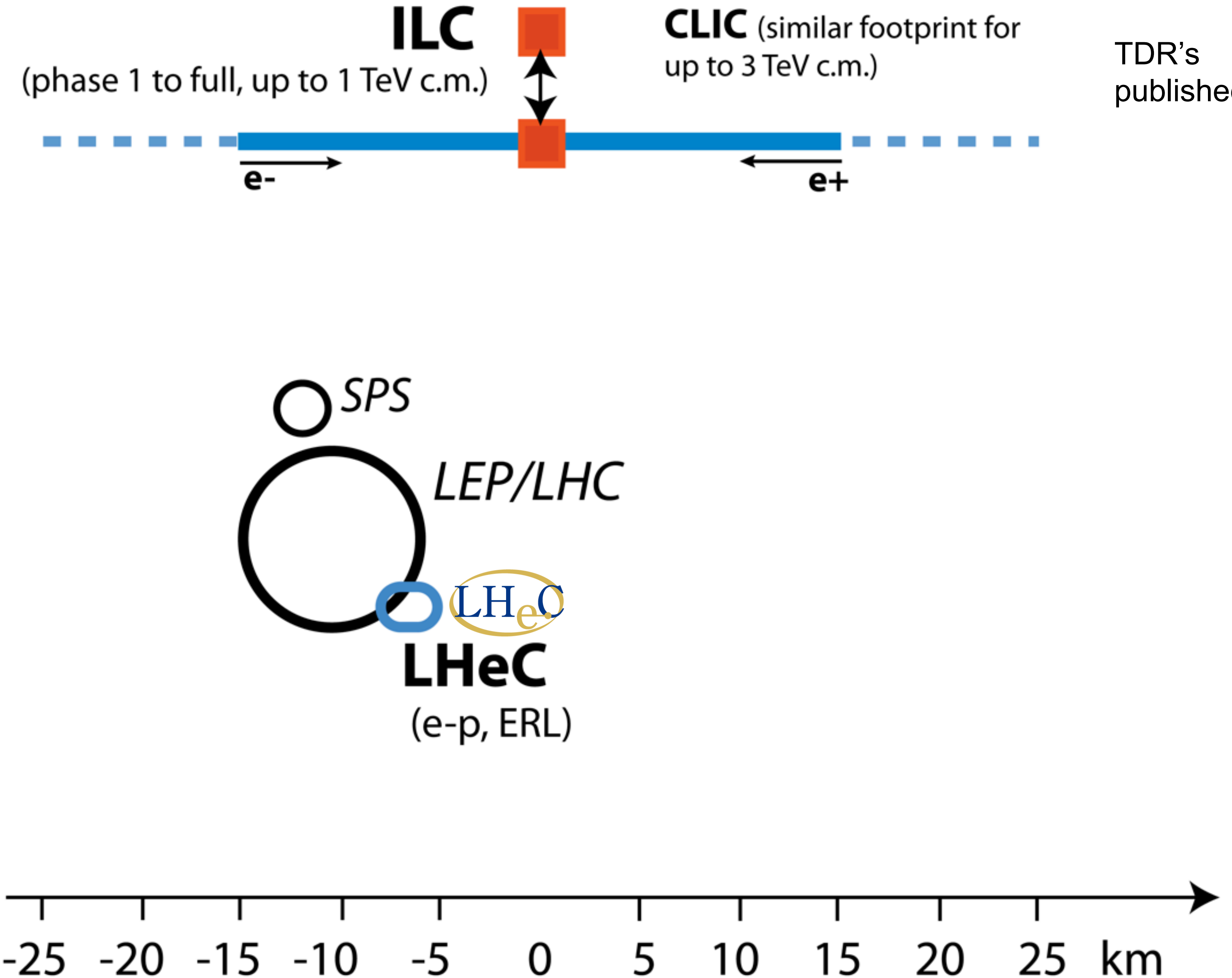
CERN Colliders : LHC-Run II

Slides by Ralf Assmann@EPS2013

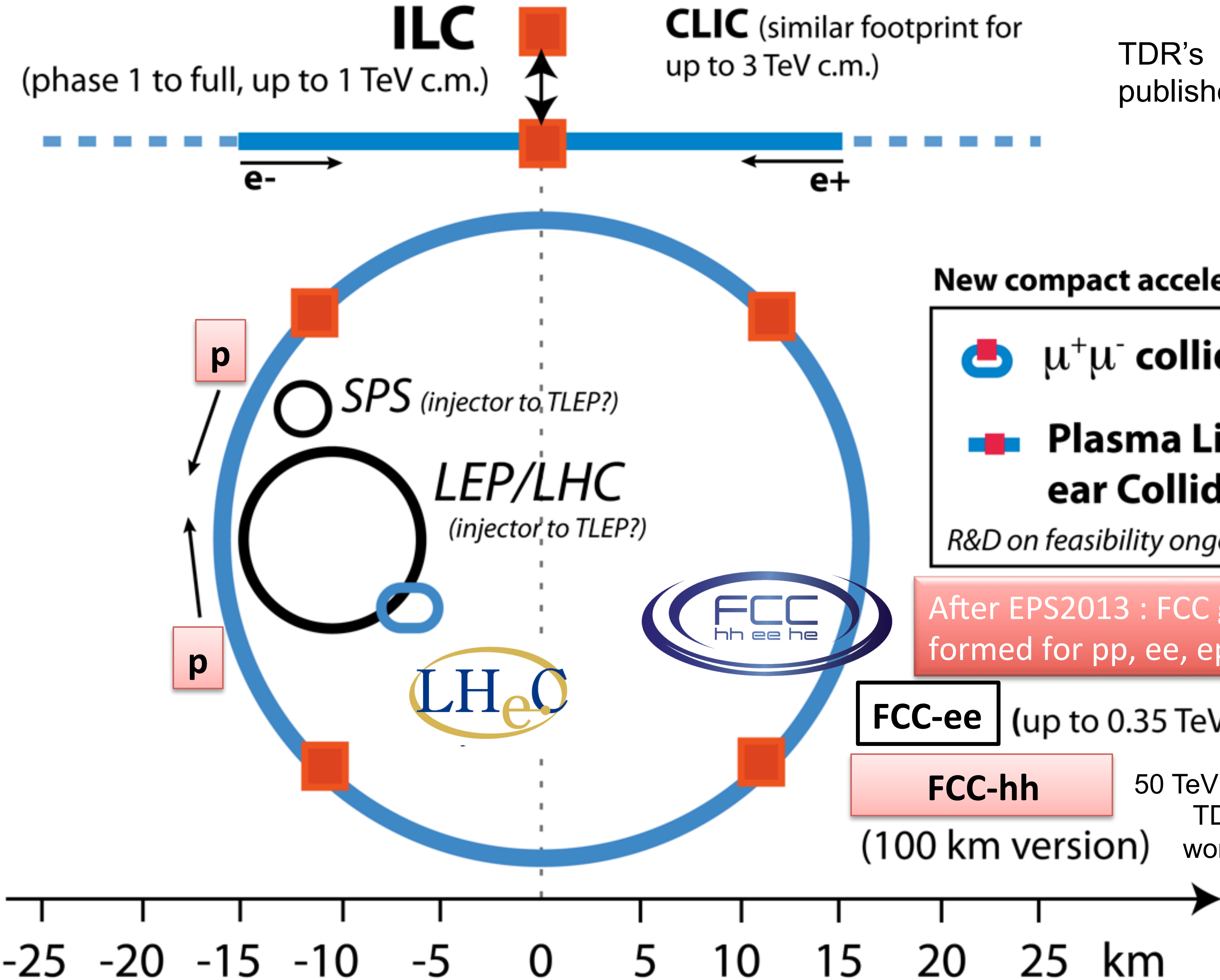


Collider options beyond LHC-Run II

TDR's published



Collider options beyond LHC-Run III



TDR's published

New compact accelerators

- $\mu^+\mu^-$ **collider**
- **Plasma Linear Collider**

R&D on feasibility ongoing

After EPS2013 : FCC group formed for pp, ee, ep

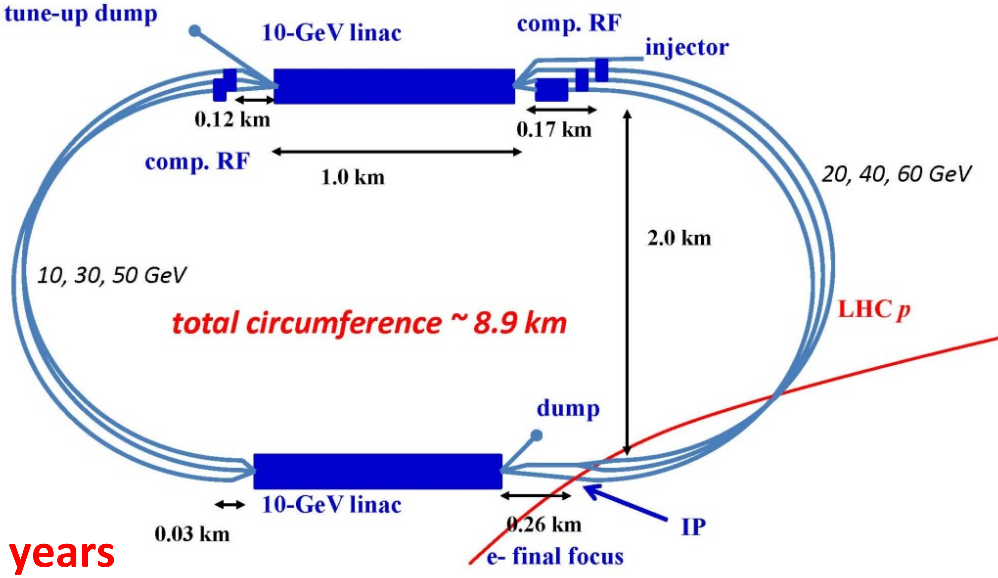
FCC-ee (up to 0.35 TeV c.m.)

FCC-hh (100 km version)

50 TeV protons TDR to be worked out

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} – 1000 fb^{-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 HL-LHC proposal

Oliver Bruning, FCC kickoff, Geneva 2014,
https://indico.cern.ch/event/282344/session/15/contribution/96/material/slides/1.pdf

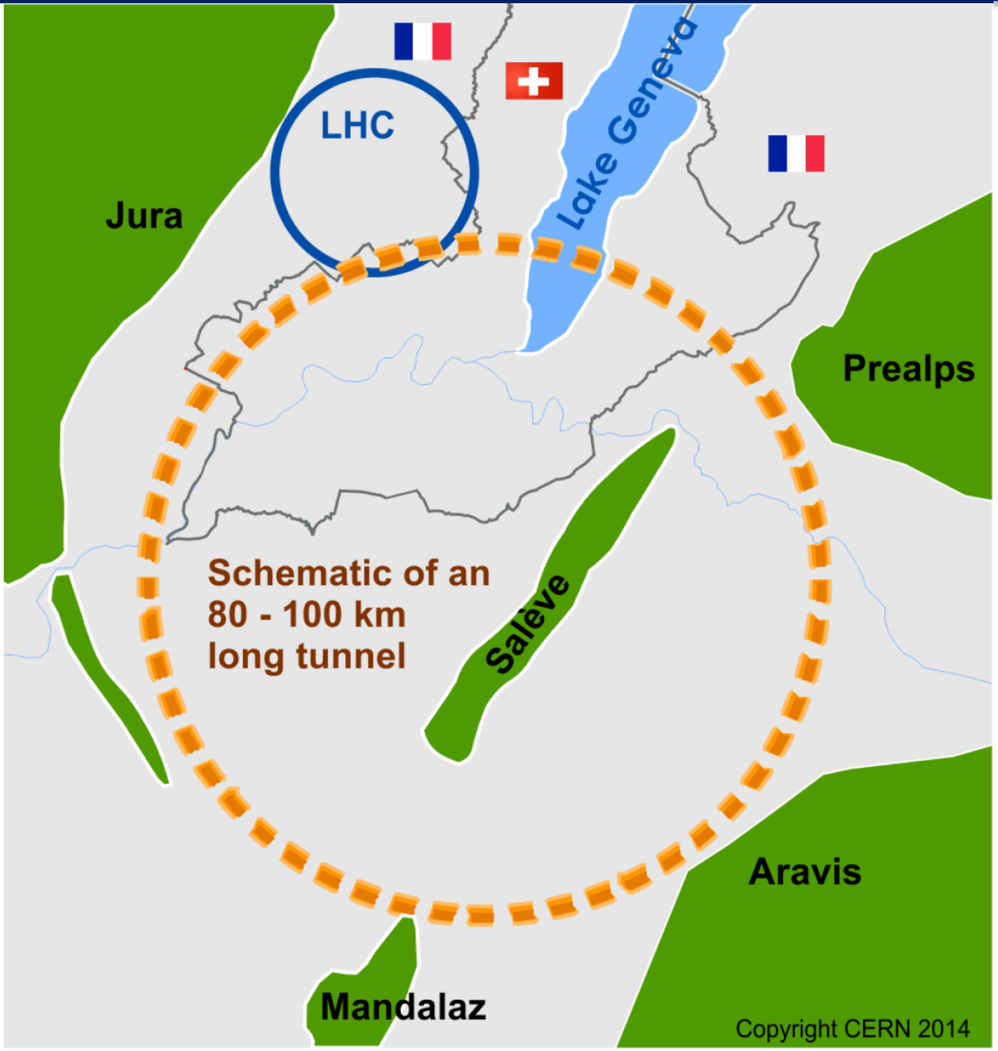
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

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

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

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



CHALLENGES FOR HIGHEST ENERGY CIRCULAR COLLIDERS

F Zimmermann et al., Proceedings of IPAC2014, Dresden, Germany, 2014

Table 1: Parameters of the Proposed FCC-hh, FCC-ee/TLEP and CepC, Compared with LEP2 and the LHC Design

parameter	LHC (pp) design	FCC-hh	LEP2 achieved	FCC-ee (TLEP) Z	FCC-ee (TLEP) Z (cr. w.)	FCC-ee (TLEP) W	FCC-ee (TLEP) H	FCC-ee (TLEP) $t\bar{t}$	CepC
species	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^+e^-
$E_{\rm beam}$ [GeV]	7,000	50,000	104	45.5	45	80	120	175	120
circumf. [km]	26.7	100	26.7	100	100	100	100	100	54
current [mA]	584	500	3.0	1450	1431	152	30	6.6	16.6
no. of bunches, n_b	2808	10600	4	16700	29791	4490	1360	98	50
N_b [10^{11}]	1.15	1.0	4.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ϵ_x [nm]	0.5	0.04	22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ϵ_y [pm]	500	41	250	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
β_x^* [m]	0.55	1.1	1.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
β_y^* [mm]	550	1100	50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
σ_x^* [μm]	16.7	6.8	162	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
σ_y^* [μm]	16.7	6.8	3.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
θ_c [mrad]	0.285	0.074	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$f_{\rm rf}$ [MHz]	400	400	352	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$V_{\rm rf}$ [GV]	0.016	>0.020	3.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
α_c [10^{-5}]	32	11	14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\delta^{\rm SR}_{\rm rms}$ [%]	—	—	0.16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\sigma^{\rm SR}_{z,{\rm rms}}$ [mm]	—	—	11.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\delta^{\rm tot}_{\rm rms}$ [%]	0.003	0.004	0.16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\sigma^{\rm tot}_{z,{\rm rms}}$ [mm]	75.5	80	11.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
F_{hg}	1.0	1.0	0.99	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\tau_{\parallel}$ [turns]	10^9	10^7	31	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ξ_x/IP	0.0033	0.005	0.04	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
ξ_y/IP	0.0033	0.005	0.06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
no. of IPs, n_{IP}	3 (4)	2 (4)	4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
L/IP [10^{34}/cm^2/s]	1	5	0.01	28	219	12	6	1.7	1.8
$\tau_{\rm beam}$ [min]	2760	1146	300	287	38	72	30	23	57
$P_{\rm SR}$/beam [MW]	0.0036	2.4	11	50	50	50	50	50	50
energy / beam [MJ]	392	8400	0.03	22	22	4	1	0.4	0.3

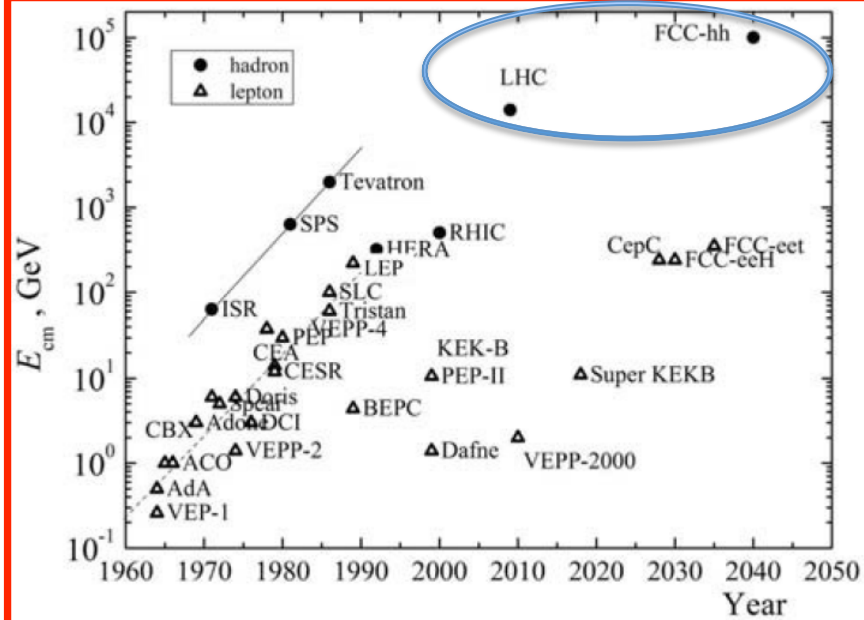
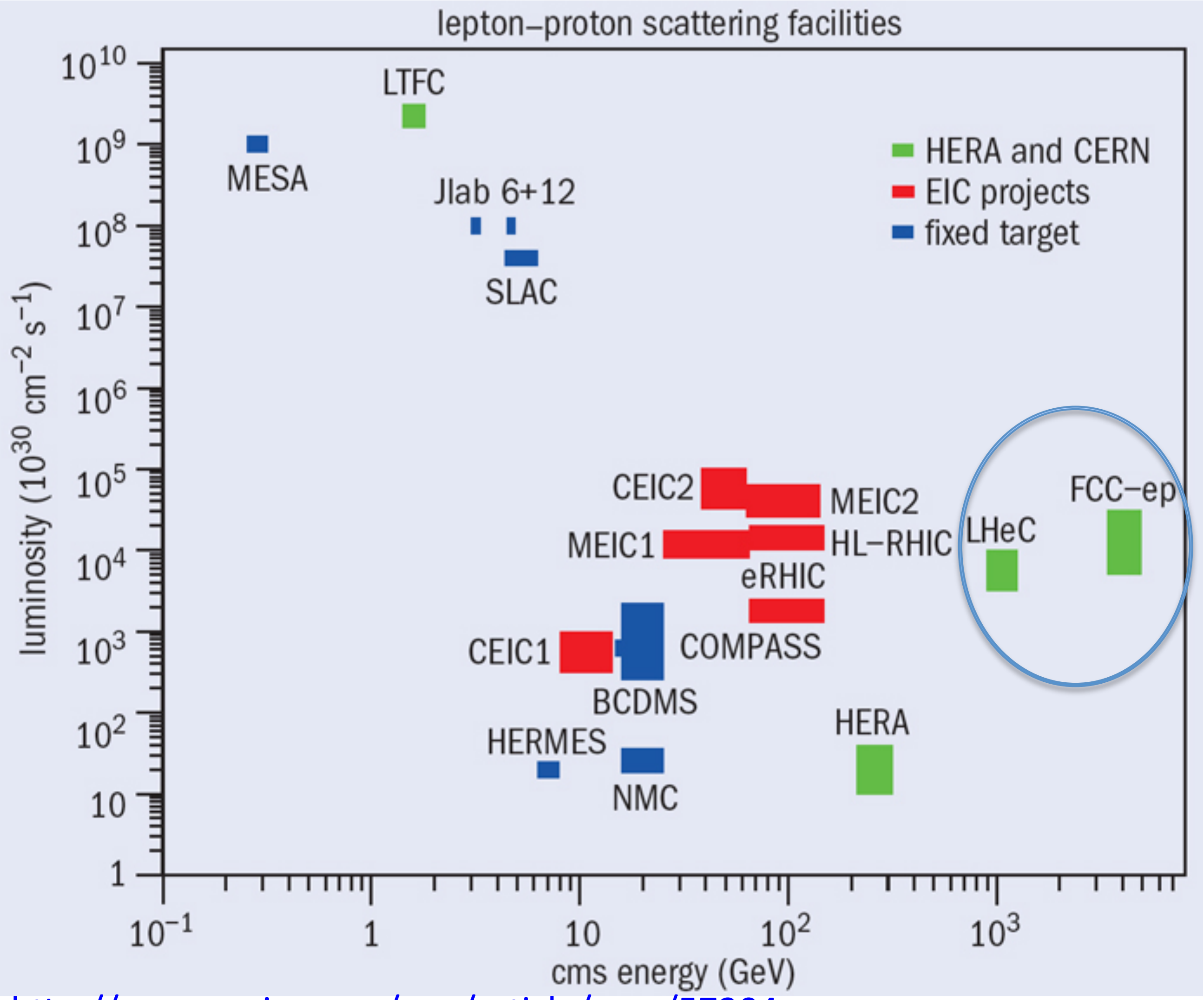


Figure 2: Collider energy vs. year [10] [V. Shiltsev].

2 tons of TNT

The ep 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

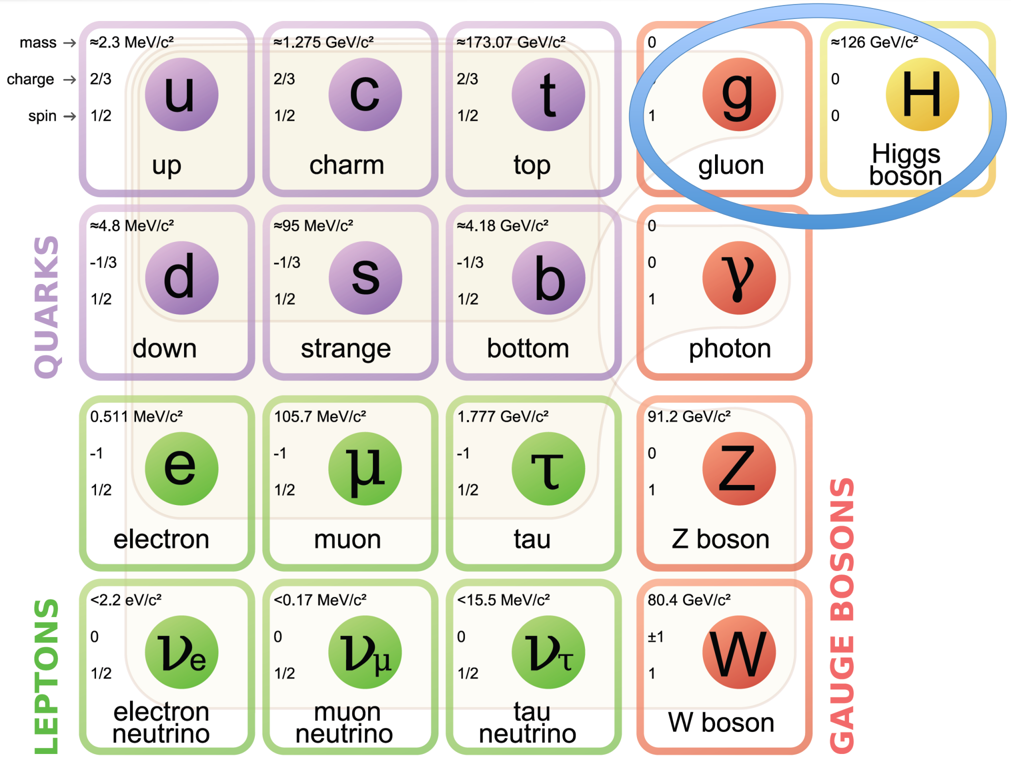
eRHIC = **EIC**@BNL

Europe
LHeC = ep/eA collider @ CERN

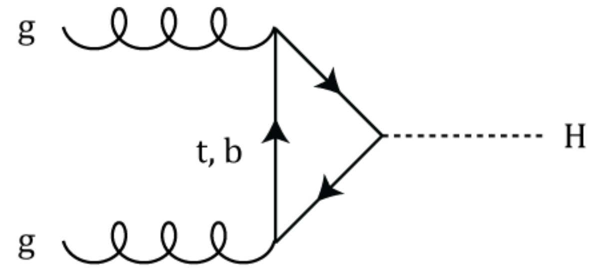
CEIC2
MEIC2
HL-eRHIC
FCC-he
} future extensions

ep colliders 11.2014 Max Klein	CEPC	MEIC	eRHIC	HERA 92-07	CepC	LHeC	SepC	FCC hh ee 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

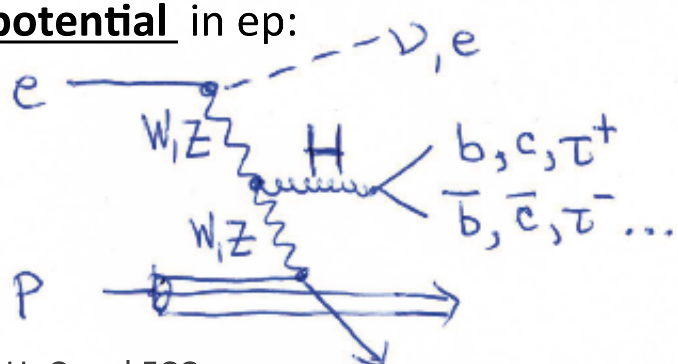
Standard Model Particles & QCD



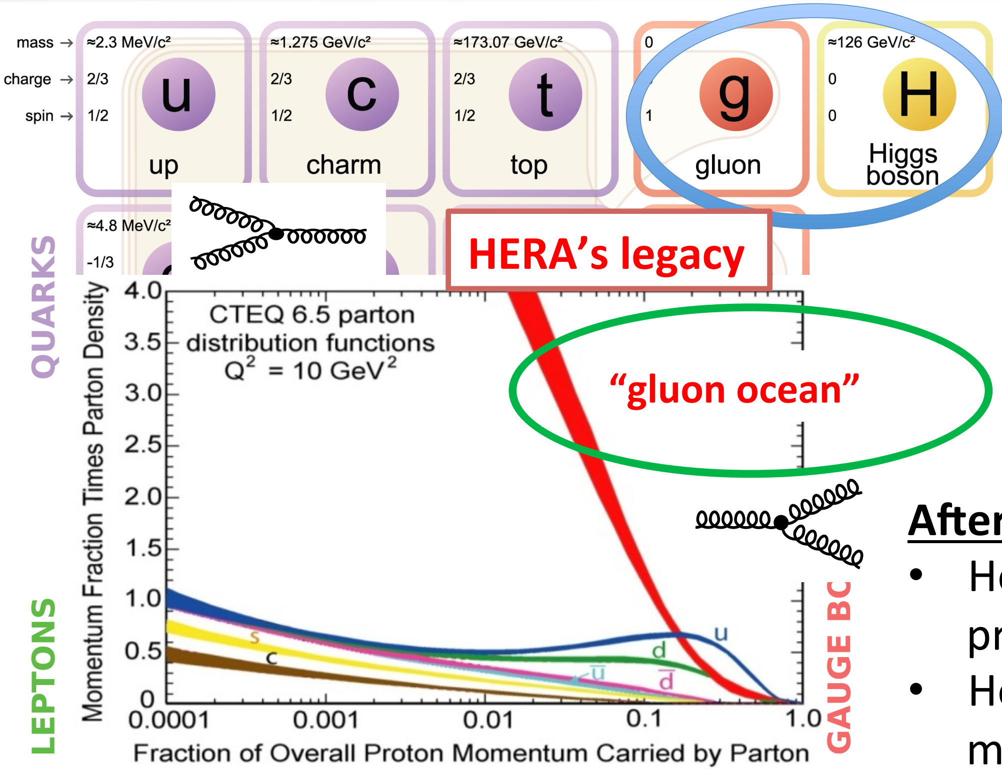
Higgs discovery at LHC via gluon-gluon fusion



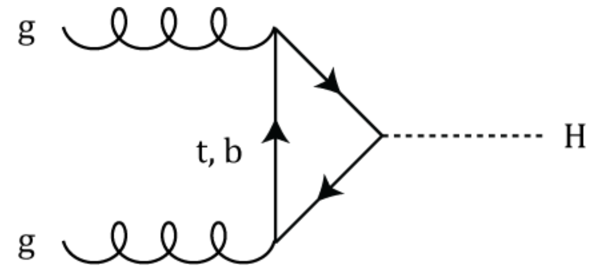
Higgs potential in ep:



Standard Model Particles & QCD



Higgs discovery at LHC via gluon-gluon fusion



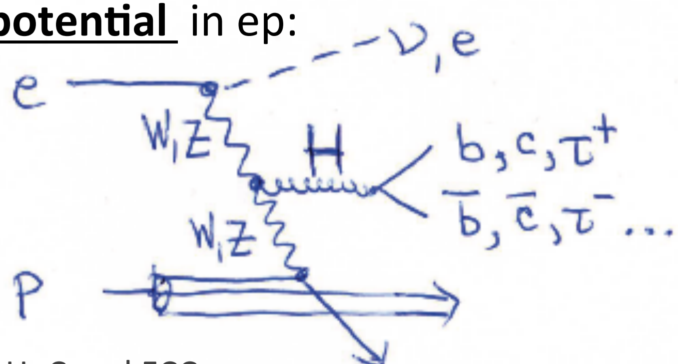
After the Higgs discovery:

- How can we reach a best understanding Higgs properties / EW symmetry breaking?
- How can we exploit best our highest energy machines for finding new physics/new particles?

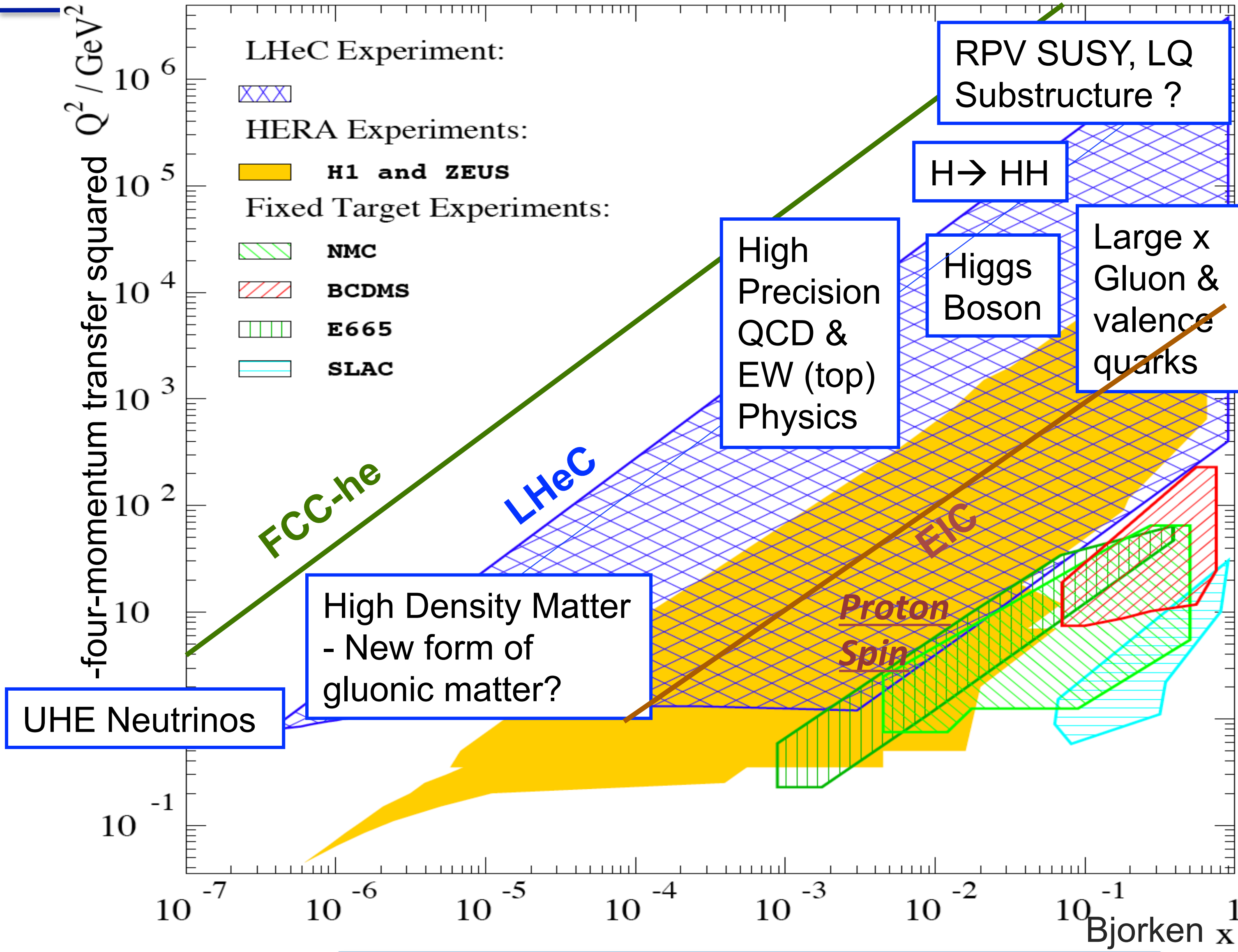
✓ ep : Precision quark-gluon dynamics for sensitive searches; top & Higgs physics

✓ **Synchronous running of pp and ep : Compelling synergy for exploring the EW and QCD sector to unprecedented precision.**

Higgs potential in ep:



The ep Physics at the Energy Frontier



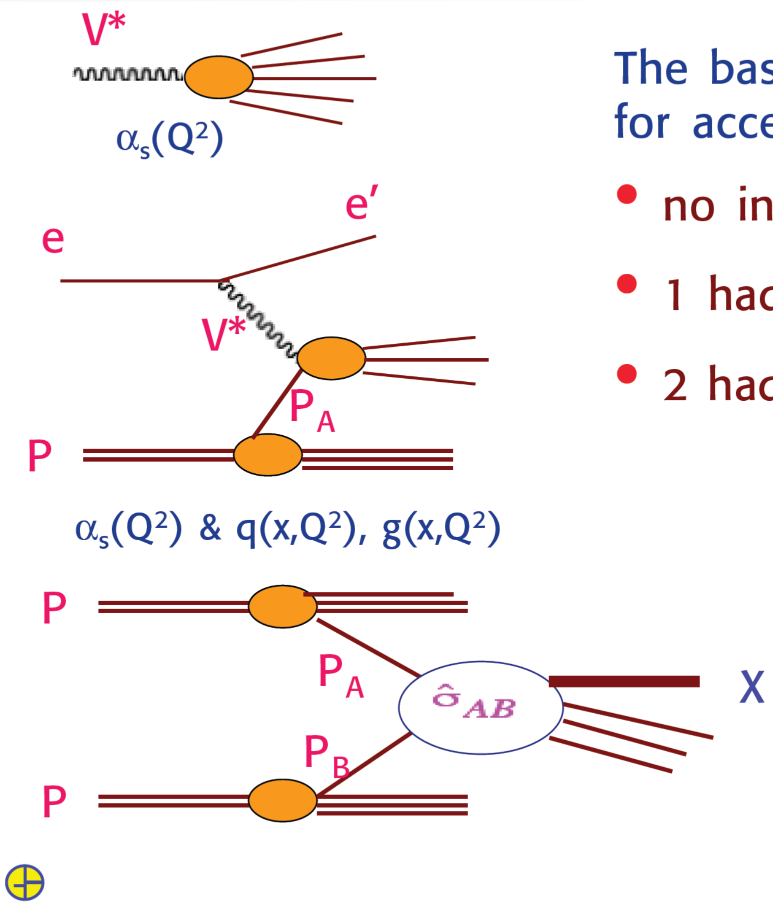
HERA established the validity of pQCD down to $x>10^{-4}$ (DGLAP) due to a very high lever arm in Q^2.

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

Relation to pp : $x_{1,2}$= (M/√s) exp(±y) & $Q^2 = M^2$

On the Synergies of ep and pp

Guido Altarelli
Cern 6/2015



The basic experimental set ups
for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

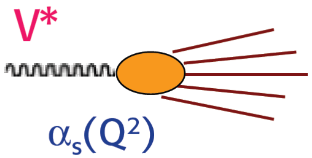
The pdf are defined
in DIS

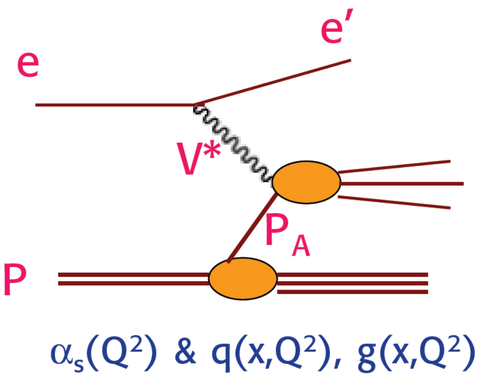
The theory of inclusive DIS
is crystal clear

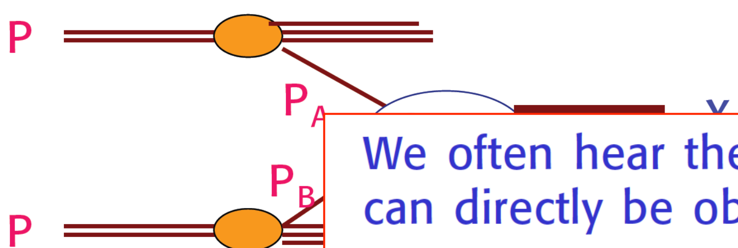
Thru the factorization
"theorem" the pdf's and α_s
determine the hadron
collider rates

On the Synergies of ep and pp

Guido Altaralli
Cern 6/2015







The basic experimental set ups for accelerator particle physics:

- no initial hadron (....LEP, ILC, CLIC)
- 1 hadron (....HERA, LHeC)
- 2 hadrons (Tevatron, LHC, FCC)

The pdf are defined in DIS

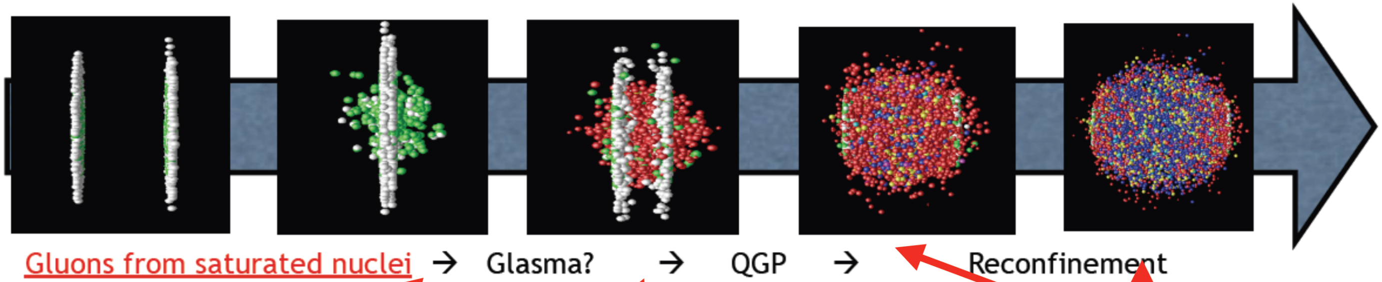
The theory of inclusive DIS is crystal clear

We often hear the statement that all the relevant info on pdf's can directly be obtained from the LHC without need of the LHeC

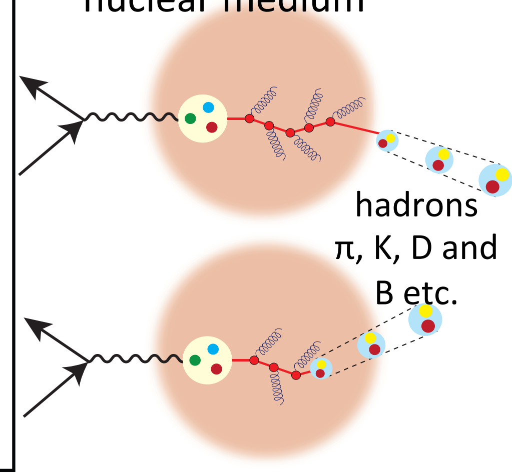
Not really true. Certainly not at the same level of precision
One example:

The factorization "theorem" is essential.
Not fully proved theoretically (beware of non pert. effects)
[nearly complete arguments only for Drell-Yan & similar]
Should finally be experimentally tested with precision

Synergy : eA and AA



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



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

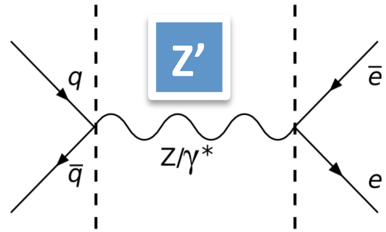
- Particle production at the very beginning: which factorisation in eA?

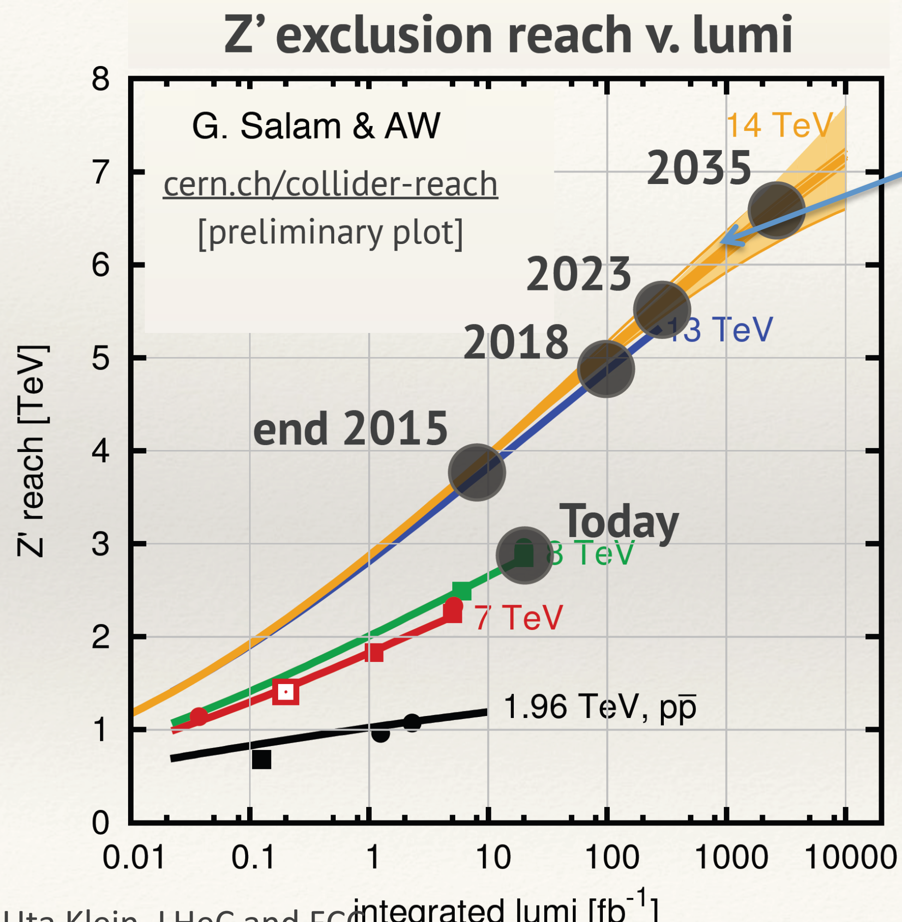
- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

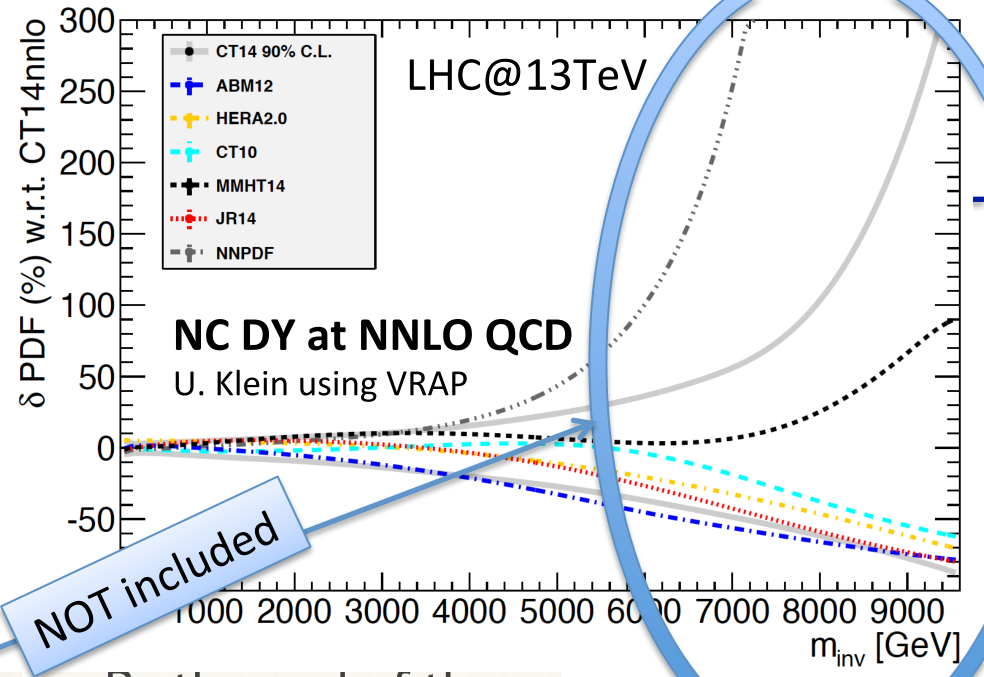
- Probing the medium through energetic particles (jet quenching etc.): modification of QCD radiation and hadronization in the nuclear medium.

The LHeC-eA will explore a region overlapping with the LHC-AA
➜ in a cleaner experimental setup;
➜ on firmer theoretical grounds.
LHeC-eA explores 2 orders of magnitude higher in Q^2 and 1/x compared to US-EIC.

Searches and PDF Uncertainties @ LHC







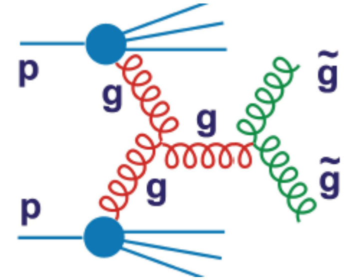
By the end of the year, most searches will beat 8 TeV results

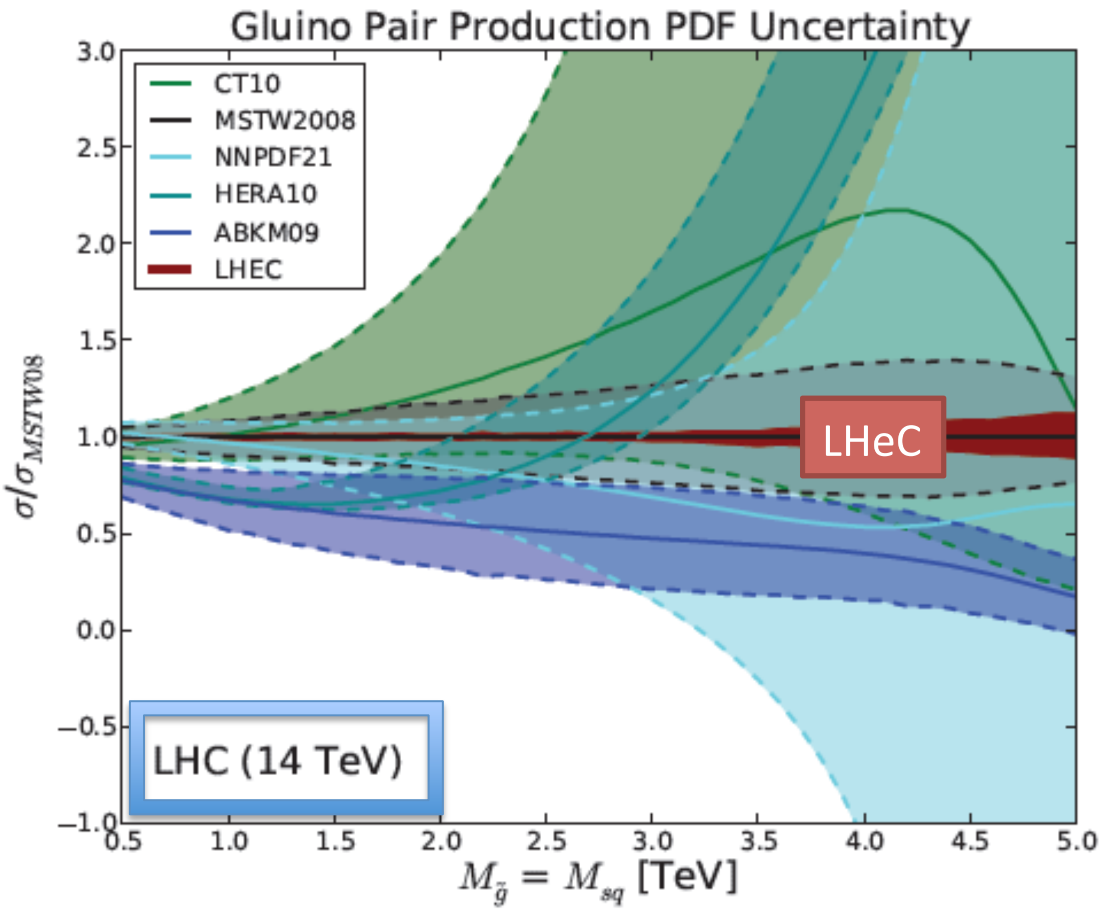
[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb^{-1}]

A. Weiler@EPS2105

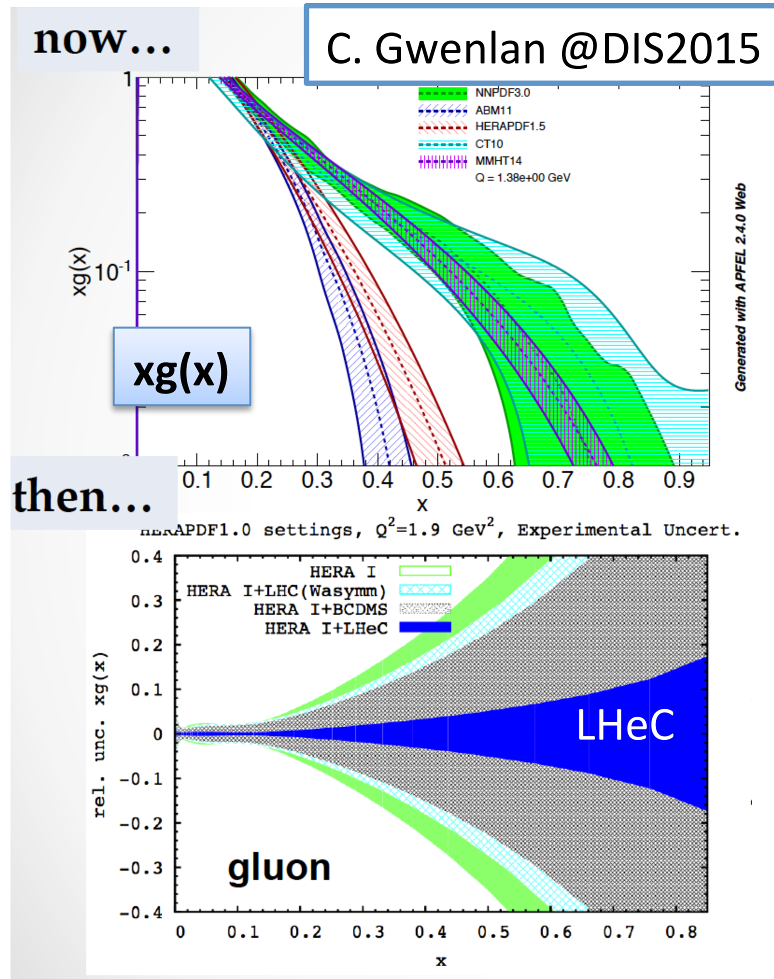
We do NOT know the structure of the proton at high x (high masses)

Precision gluons for SUSY



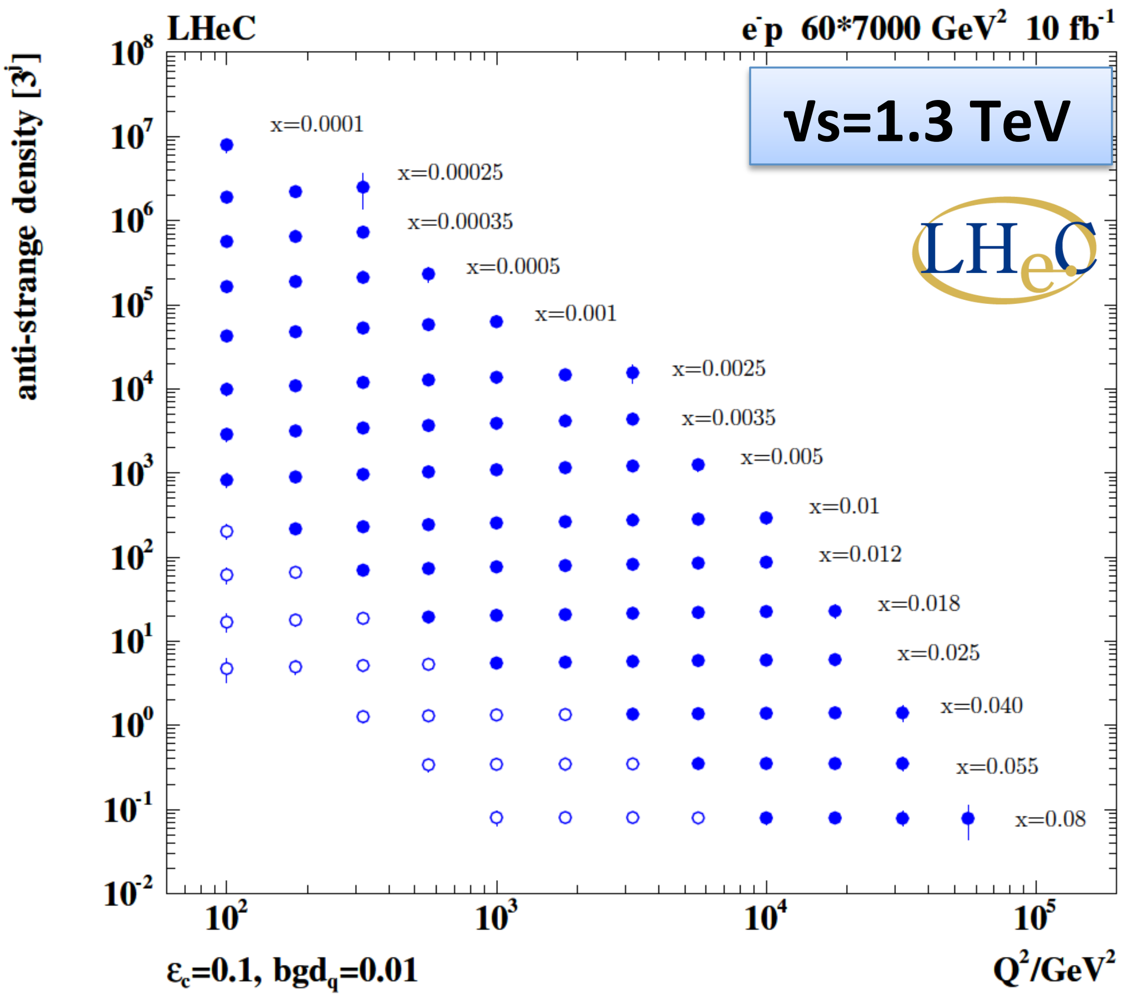


Using 2012 NLO PDFs
LHeC Note 2012-005
arXiv:1211.5102; LHeCPDF in LHAPDF



Using 2014 NNLO PDFs

Precision Strange Quark Distributions



- ✓ **High luminosity**
- ✓ **High Q^2 lever arm**
- ✓ **Small beam spot**
- ✓ **Modern Silicon detectors**
- ✓ **NO pile-up, no DPS …**
- ✓ **similar new measurements for <u>charm</u> and <u>beauty</u>**

→ δM_c reduced from 60 to 3 MeV → α_s precision

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

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

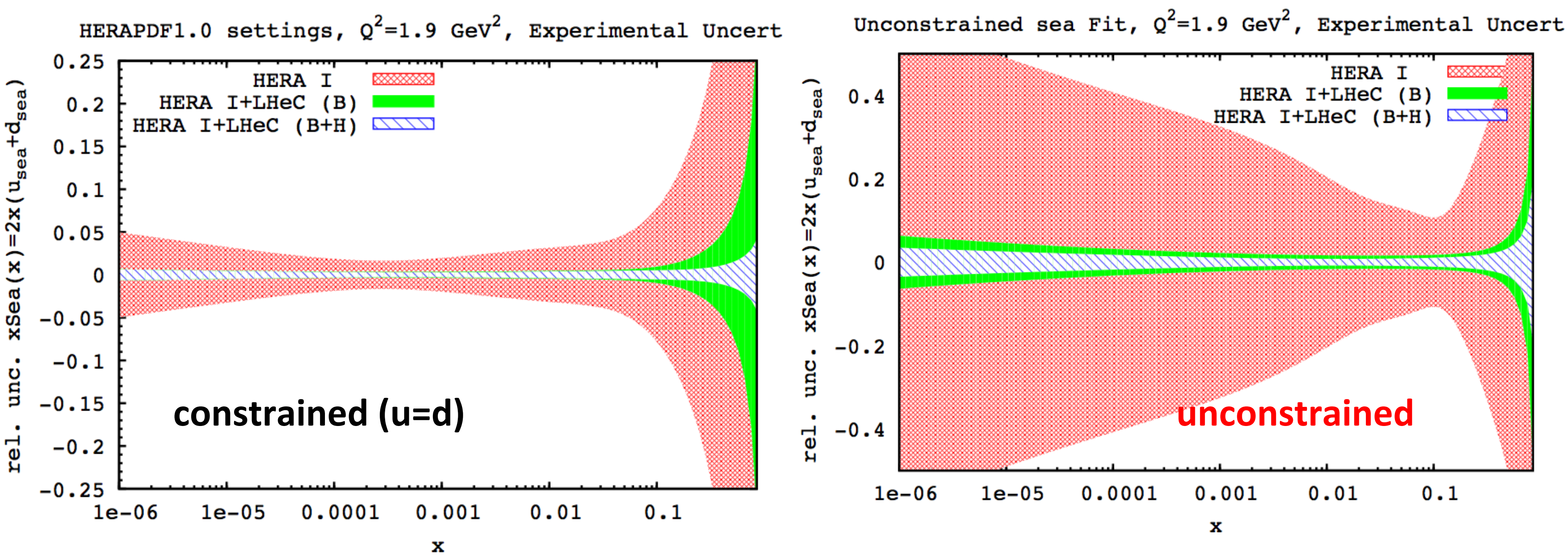
$Q^2 = 100 - 10^5$ GeV^2

Complete unfolding of the flavour structure of the proton for the first time.

Resolving Partonic Structure

free of symmetry assumptions

Voica Radescu & Max Klein , 2014



- 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 (small x partons) with diffraction…

Neutrino-Nucleon Cross Section at UHE

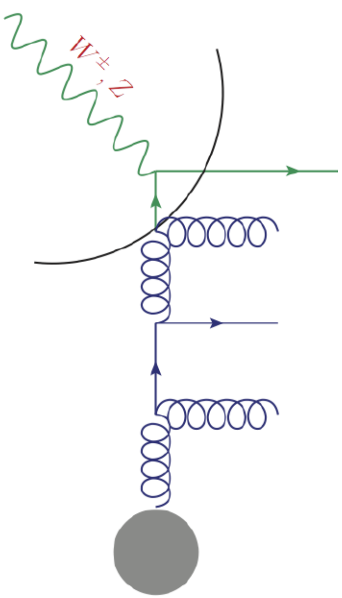
& its *astrophysical* Implications

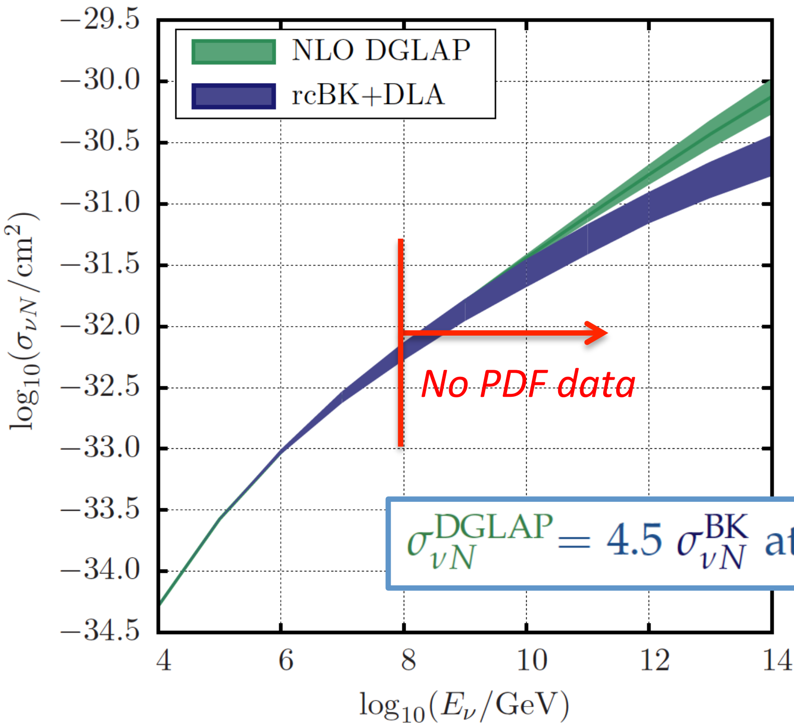
Alba SOTO ONTOSO,
@POETIC VI
PRD 92, 014027 (2015)

$$\sigma_{\nu N} \sim \underbrace{\begin{pmatrix}\text{Probability of}\\ \text{finding a quark/gluon}\\ \text{in nucleon}\end{pmatrix}}_{\text{Low energy QCD}} \otimes \underbrace{\sigma^{q/g-\nu}}_{\text{Perturbative}}$$

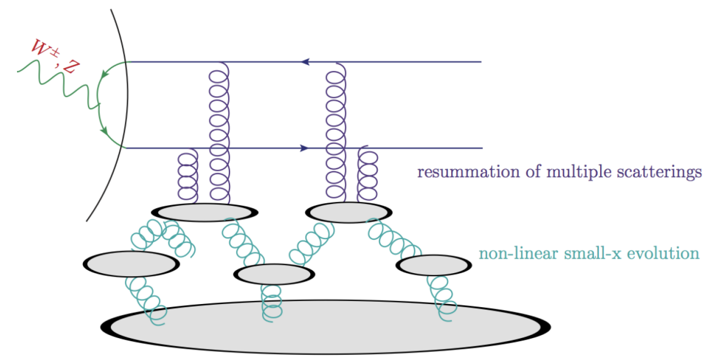
DGLAP approach $(\alpha_s \ln(Q^2/Q_0^2) \sim 1)$

À la BK $(\alpha_s \ln(x_0/x) \sim 1)$





$\sigma_{\nu N}^{\mathrm{DGLAP}} = 4.5\ \sigma_{\nu N}^{\mathrm{BK}}$ at $E_\nu = 10^{14}$ GeV.



Limits on astrophysical ν fluxes

… have a **much larger uncertainties** than currently assumed :

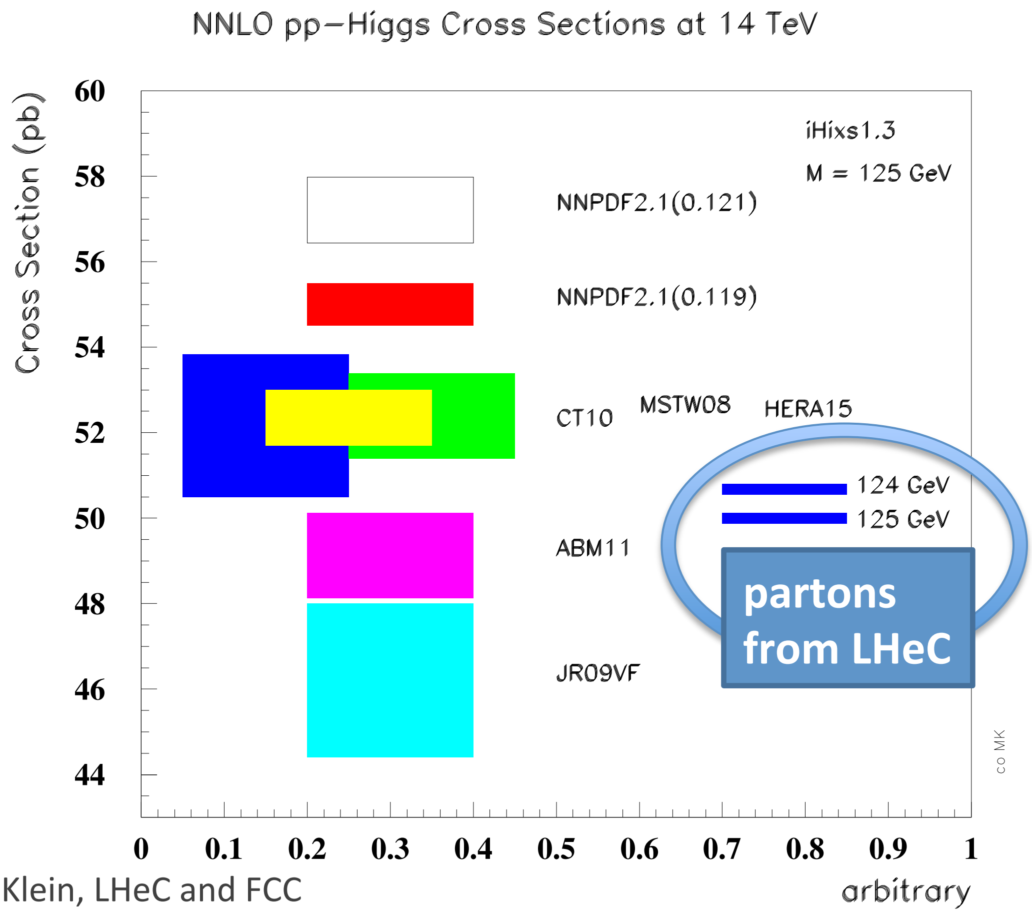
factors 1.4 to 4.5 for $10^9 < E_\nu < 10^{14}$ GeV.

LHeC 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**

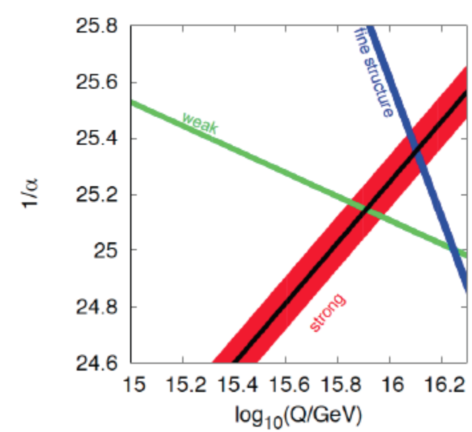
→ clear Higgs mass sensitivity in cross section predictions

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



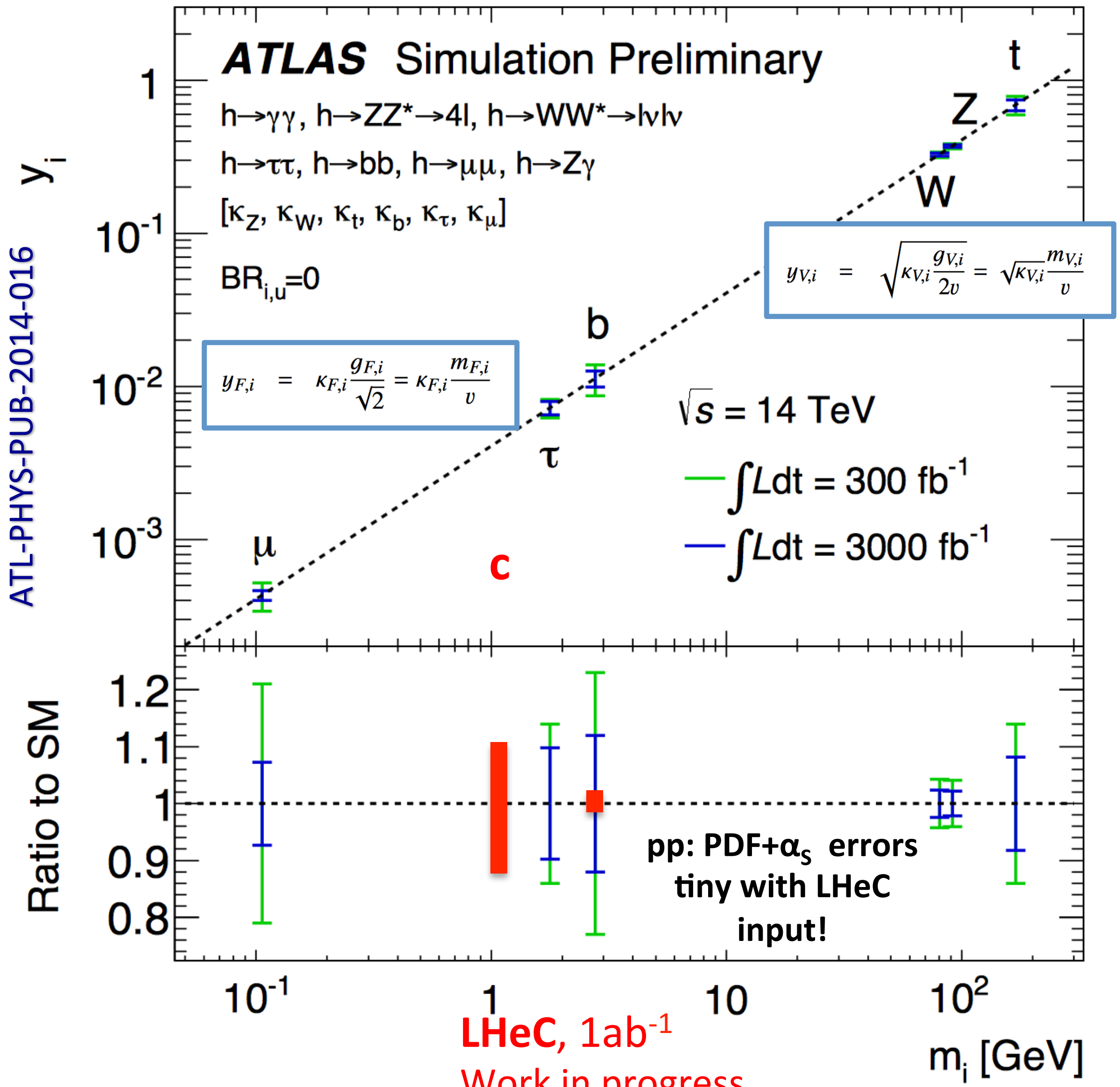
α_s = underlying parameter relevant for uncertainty (0.005 → 10%) @ LHeC: measure to permille accuracy (0.0002)

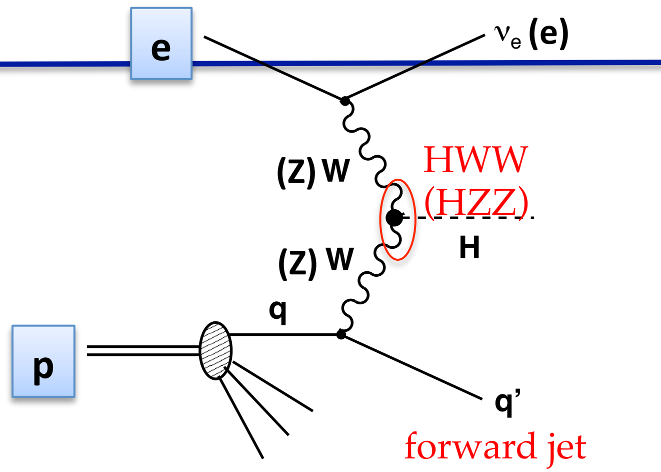
→ precision from LHeC can add a very significant constraint on the Higgs mass *but also:* ***Study unification of couplings***



Higgs Couplings at HL-LHC + LHeC

running simultaneously

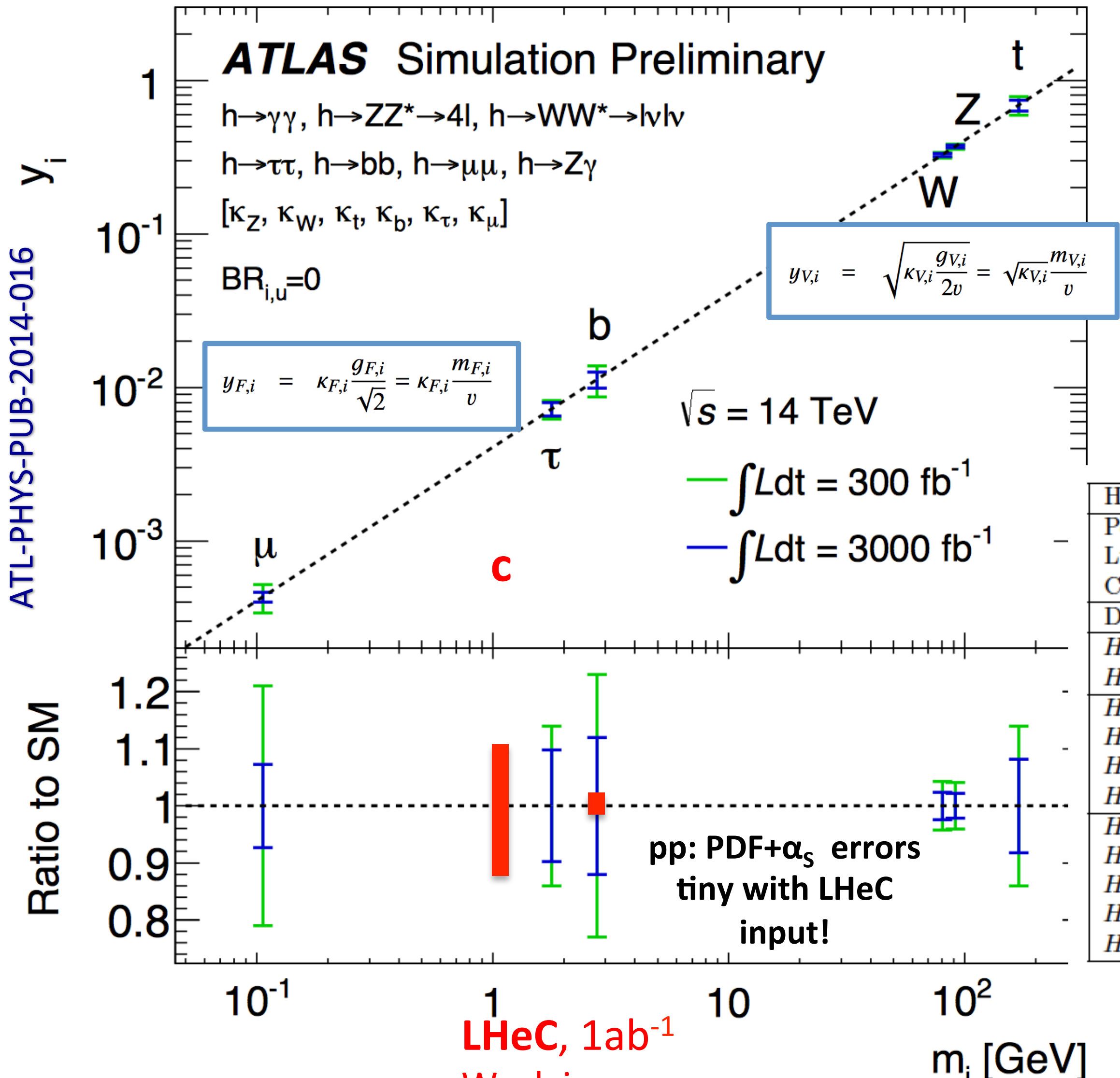




LHeC, 1ab^{-1}
Work in progress
Br: b 59% c 3%

Higgs Couplings at HL-LHC + LHeC

running simultaneously



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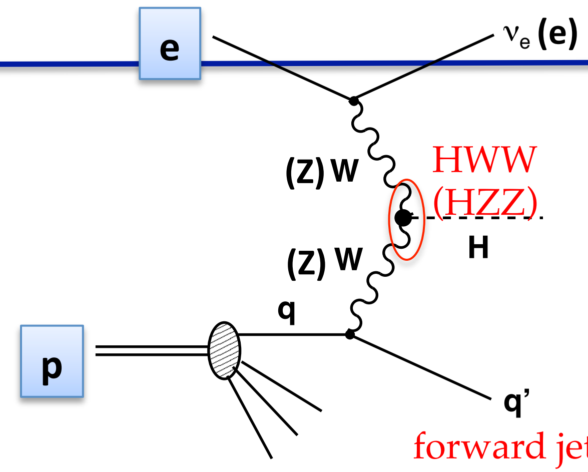
Work in progress
Br: b 59% c 3%



√s= **1.3 TeV 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

➔ in ep, much more decay channels to be explored

Invisible Higgs@LHeC

relating the Higgs and the 'dark' sectors

Y.-L. Tang et al., arXiV: 1508.01095

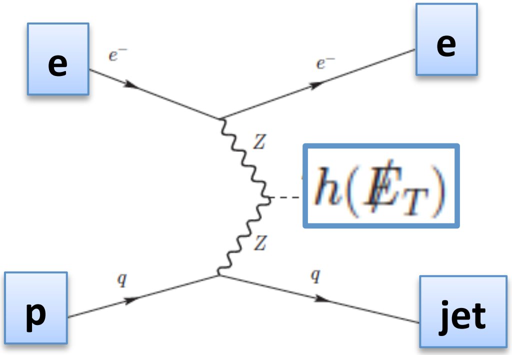
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

$\mathrm{Br}(h \rightarrow \not{E}_T)$ < 3.5% @90% C.L., MVA based

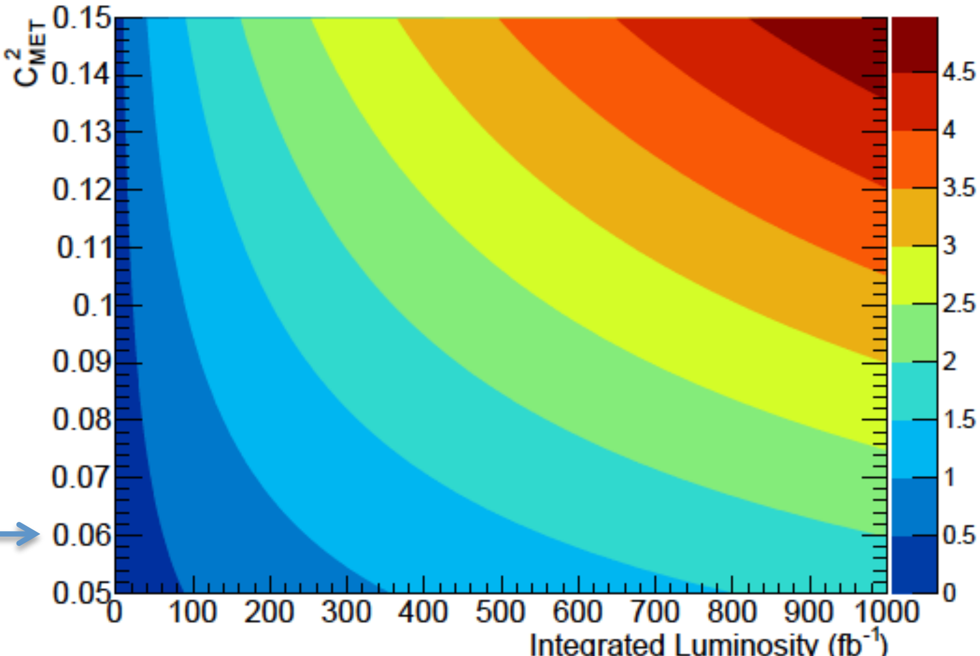
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, <u>cut based</u>

$\mathrm{Br}(h \rightarrow \not{E}_T)$ < 6% @ 2σ level

$$C^2_{\mathrm{MET}} = \kappa^2_Z \times \mathrm{Br}(h \rightarrow \not{E}_T)$$



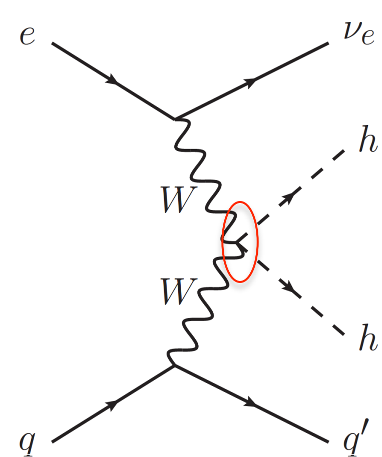
κ_Z : BSM w.r.t. SM HZZ coupling



Colours: expected statistical significance

➔ potential much enhanced for **FCC-he**

➔ e.g. significant sensitivity to BSM contributions to HHWW vertex [arXiv:1509.04016]

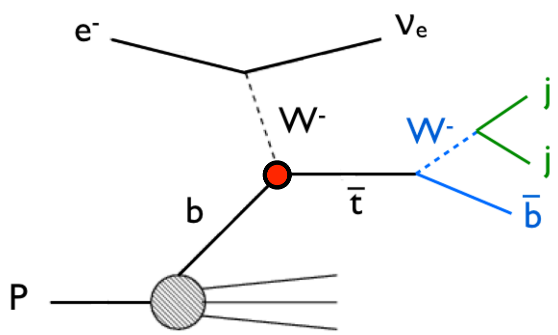


Top Quark & EW in ep

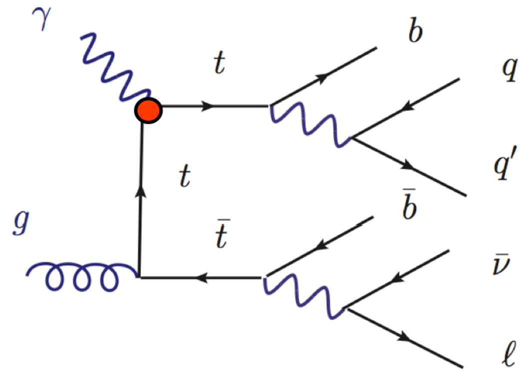
.... a few examples only

C. Schwanenberger, @DIS2015

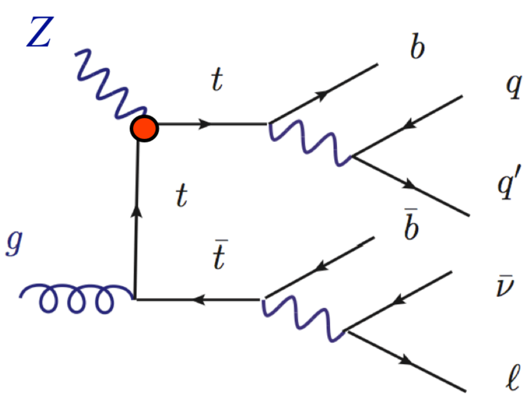
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



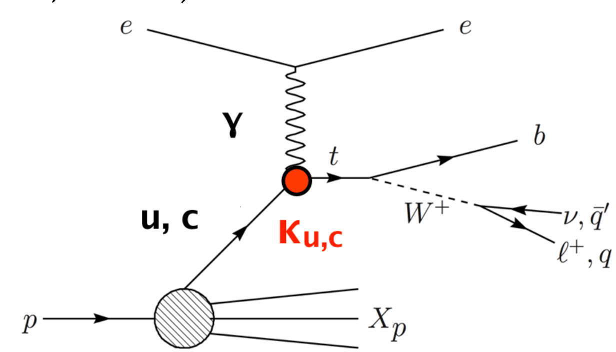
- high precision measurements of Vtb and search for **anomalous Wtb** couplings



- direct measurement of top quark charge and search for **anomalous ttbarγ** couplings (eg. EDM, MDM)



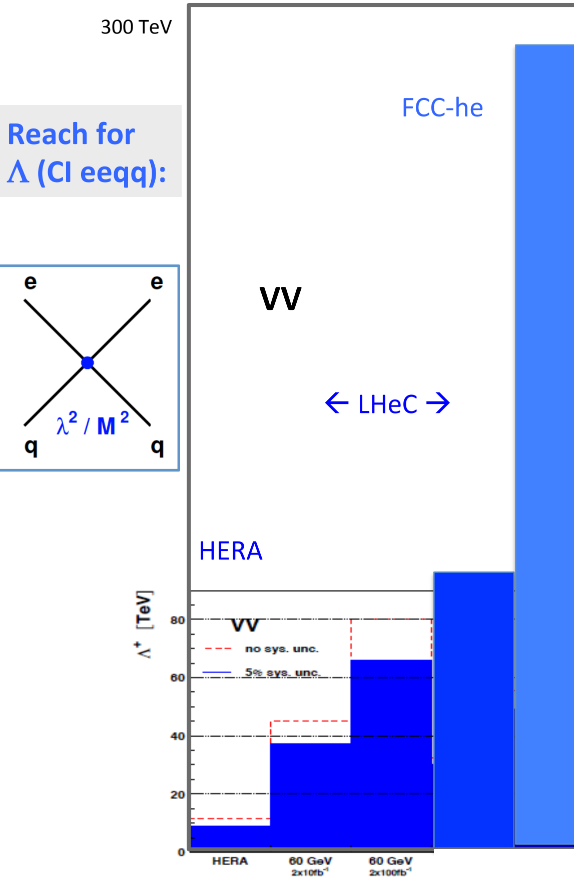
- measurement of top isospin and search for **anomalous ttbarZ** couplings (eg. EDM, MDM)



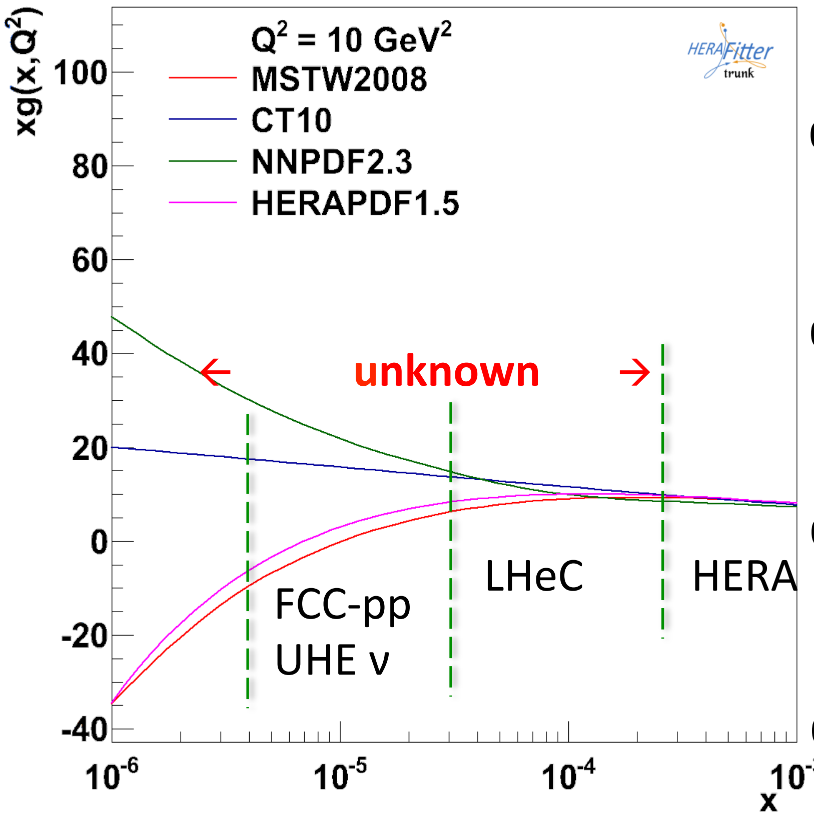
- sensitive search **for FCNC couplings** will constrain BSM models that predict FCNC (eg. SUSY, little Higgs, technicolour)

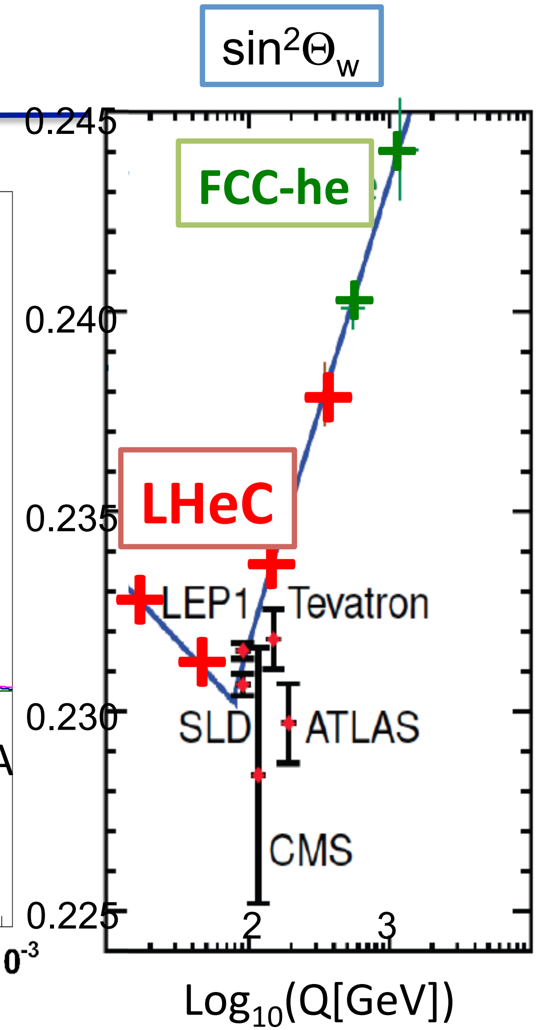
FCC-he Physics

High mass and Q^2 region



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





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

Leptoquark (closely related to RPV SUSY) reach to up to $\sqrt{s} \approx 4$ TeV .

Higgs selfcoupling (hh→4b [arXiv:1509.04016], hh→4a under study)

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

FCC-hh Physics

Luminosity Prospects

- **Two parameter sets for two operation phases:**
  - **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged)
    2500 fb^{-1} within 10 years (~HL LHC total luminosity)
  - **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged)
    ➔ 15,000 fb^{-1} within 15 years
  - **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

arXiv:1504.06108

LUMINOSITY GOALS FOR A 100-TEV PP COLLIDER

Ian Hinchliffe[a], Ashutosh Kotwal[b], Michelangelo L. Mangano[c], Chris Quigg[d], Lian-Tao Wang[e]

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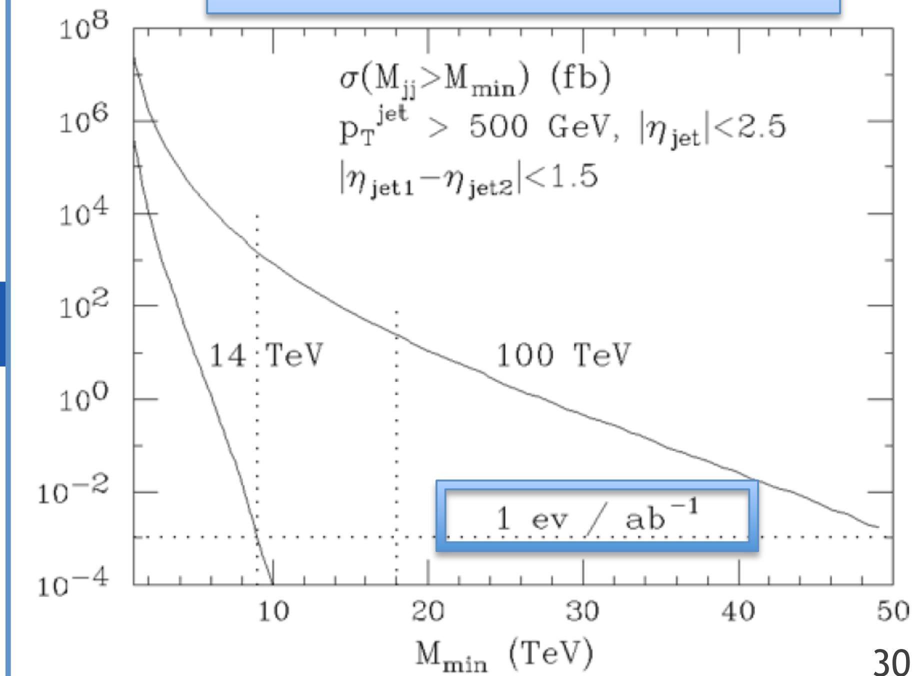
[b] Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
Duke University, Durham, North Carolina 27708, USA
[c] PH Department, TH Unit, CERN, CH-1211 Geneva 23, Switzerland
[d] Theoretical Physics Department, Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510 USA
Institut de Physique Théorique Philippe Meyer, École Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05, France
[e] Department of Physics and Enrico Fermi Institute, University of Chicago, Chicago, IL 60637 USA

April 24, 2015

Abstract

We consider diverse examples of science goals that provide a framework to assess luminosity ls for a future 100-TeV proton-proton collider.

Dijet Cross sections extend discovery potential up to m~50 TeV



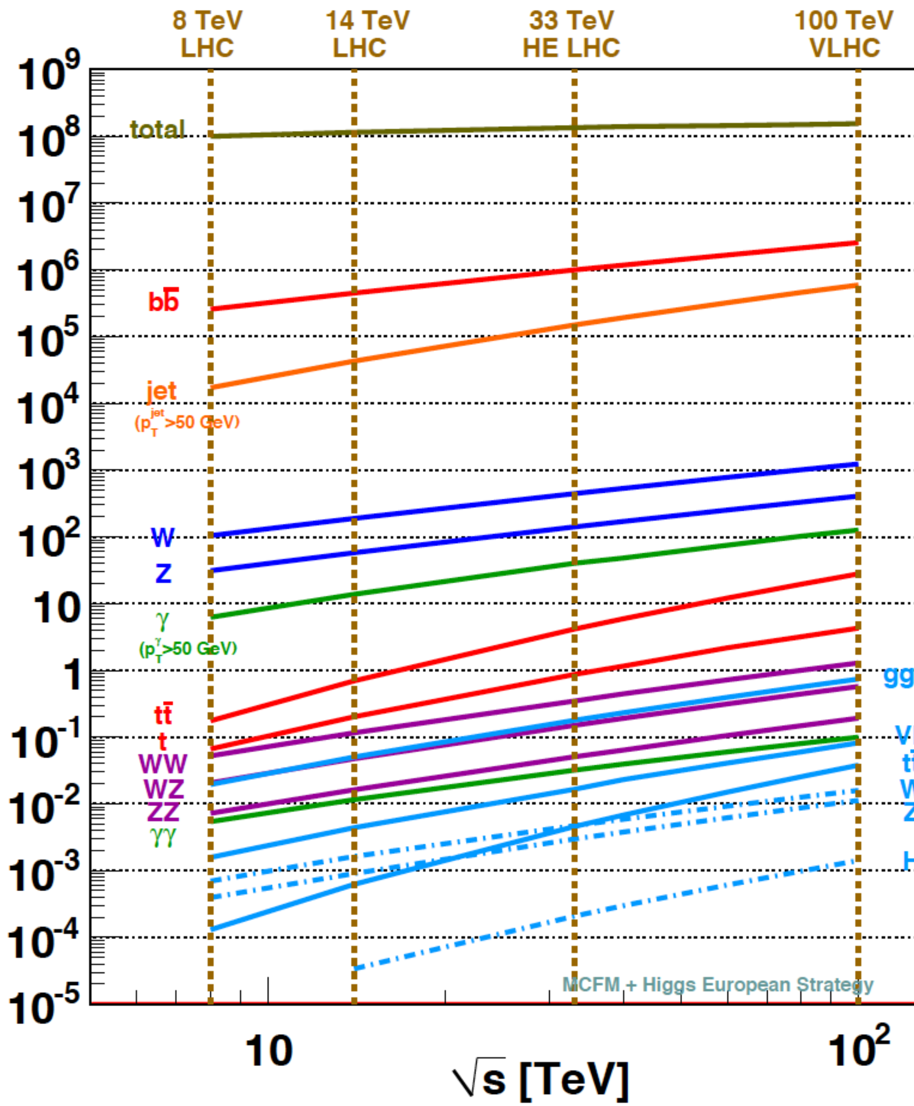
Future High Energy Circular Colliders
Michael Benedikt
Lepton Photon 2015, Ljubljana

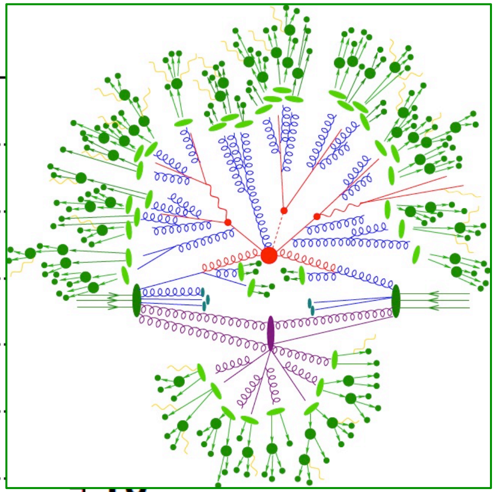
Mean pileup estimates:
5 x 10^{34} cm^{-2} s^{-1} @BC 25 ns : 170
5 x 10^{35} cm^{-2} s^{-1} @BC 25 (5) ns : 1700(340)

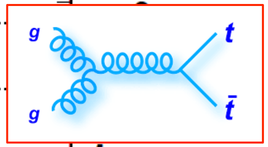
σ (100 TeV)/σ (14 TeV)=1.25

pp Cross Sections vs √s

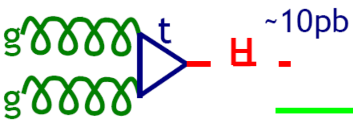
Snowmass 2013
arXiv:1310.5189

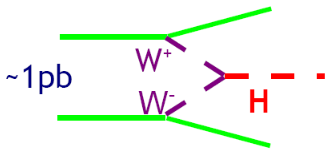


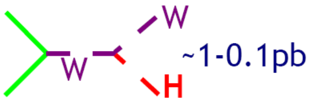




E.g. top Yukawa coupling M.Mangano et al. [arXiv: 1507.08169] htt to 1% 20 ab^{-1} – no PU,DPS







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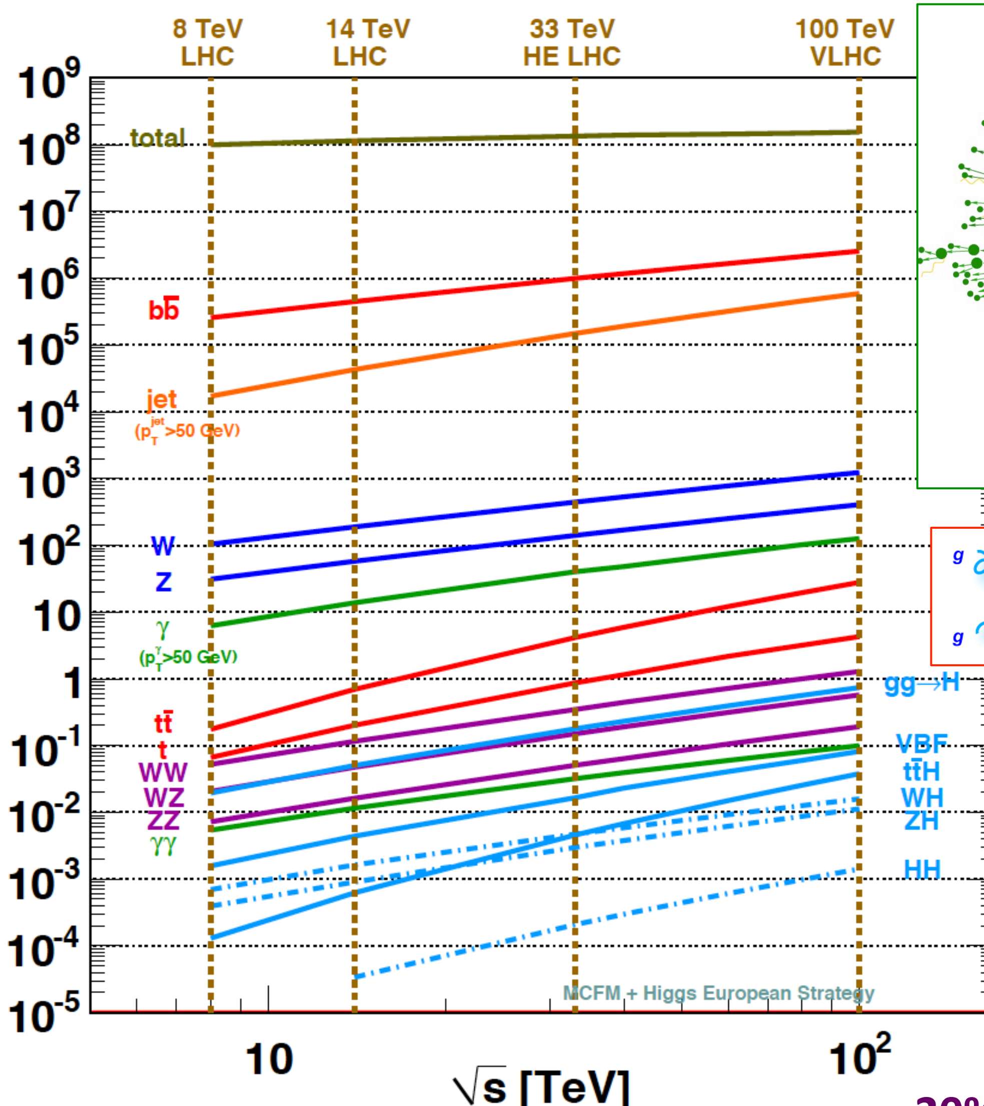

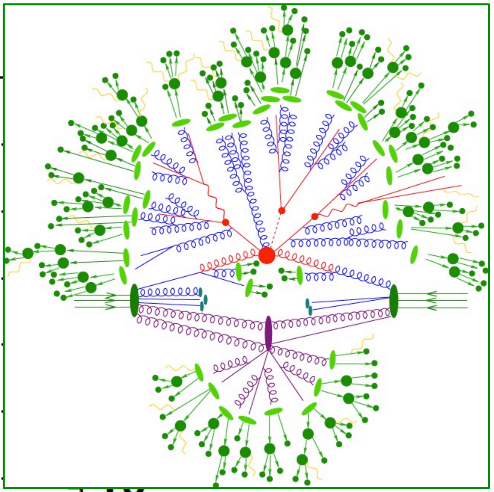

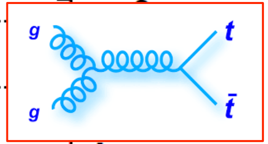

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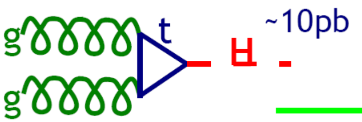
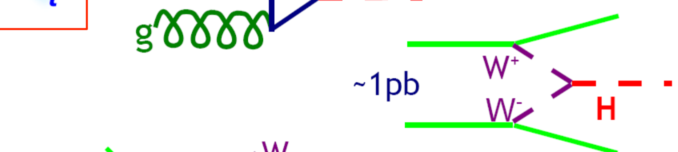
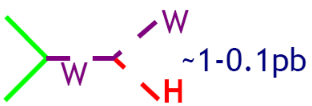
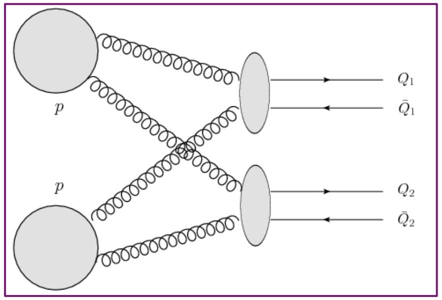






2% → **20% ? e.g. for DPS in bbbar FS**



Motivation for a 100 TeV pp Collider

N. Arkani-Hamed
@SUSY2013

* It's the OBVIOUS FUTURE

* BIG physics ideas, BIG ambitions and BIG machines are the lifeblood of our field. It's how we've attracted the best minds on the planet to work on the hardest, most fundamental, most long-term problems in all of Science.

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M. Mangano
@UKForum2014

'The "physics case" will emerge at the end, when confronting the potential against the explicit circumstances arising from the future 10 years of LHC running, DM searches, Belle2, etc., and in view of the overall synergy/complementarity with the other components of the project (ee and eh).'

Put "Naturalness" to an ultimate Test

N. Arkani-Hamed
@SUSY2013

* Tuning probe $\propto E_{CM}^2$
* Higgs + nothing else @ 100 TeV

$\Longrightarrow \sim 10^{-4}$ tuning!

* Never seen this level of tuning in particle physics – Dramatically new
* In my view, even this "worst-case scenario" would be ~ 100 X more shocking + dramatic than nothing but Higgs @ LHC

NAIL IN COFFIN OF NATURALNESS

This alone fully justifies the march to 100 TeV

* Tuning $\sim (10^{-4}) \times (10^{-2}) \sim 10^{-6}$!
* Kills all anthropic explanations

Put "Naturalness" to an ultimate Test

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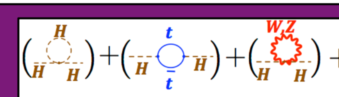
Fabiola Gianotti@EPS2015

Naturalness: (Distinguished) theorist 2:
"Naturalness is a fake problem"

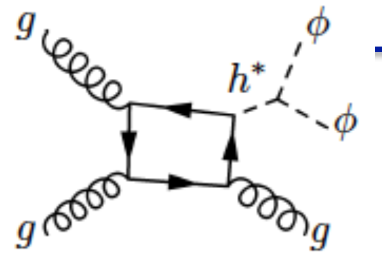
$\Delta M_H^2 \sim$  $+ \cdots \sim \Lambda^2$

100 TeV : 'Dark Matter Factory'?

N. Craig et al.
arXiv:1412.0258

E.g. Higgs portal to dark matter
3 to 30 ab^{-1}, no pileup considered

$\not{E}_T + j$



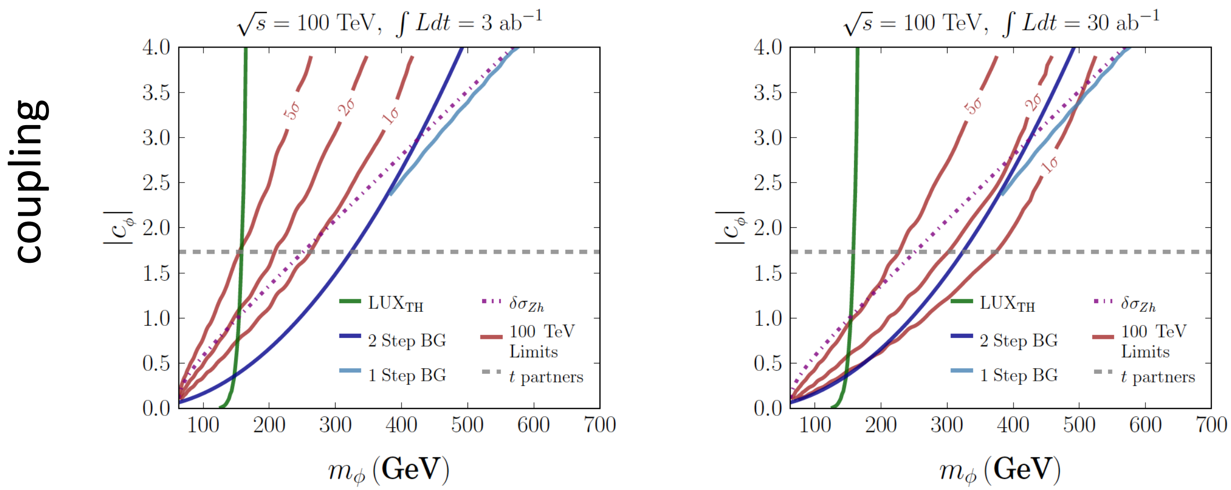


Figure 10: Combined reach of direct searches in VBF, ggH and $t\bar{t}H$ channels at $\sqrt{s} = 100$ TeV for 3 ab^{-1} (left) and 30 ab^{-1} (right) compared to select parameter spaces for motivated Higgs Portal scenarios. In each plot the red lines denotes the 1σ exclusion, 2σ exclusion, and 5σ discovery reach from direct searches at $\sqrt{s} = 100$ TeV. The region to the left of the green line denotes the LUX exclusion for Higgs Portal dark matter with thermal abundance given by c_ϕ, m_ϕ. The region to the left of the dark blue line denotes the possible parameter space for two-step baryogenesis, while the region between the light blue and dark blue lines denotes the possible parameter space for one-step baryogenesis (defined by $v_c/T_c \geq 0.6$). The purple line denotes the 2σ contour for $\delta\sigma_{Zh}$ at a future e^+e^- circular collider such as TLEP. The dashed gray line denotes the effective coupling of six complex scalar top partners.

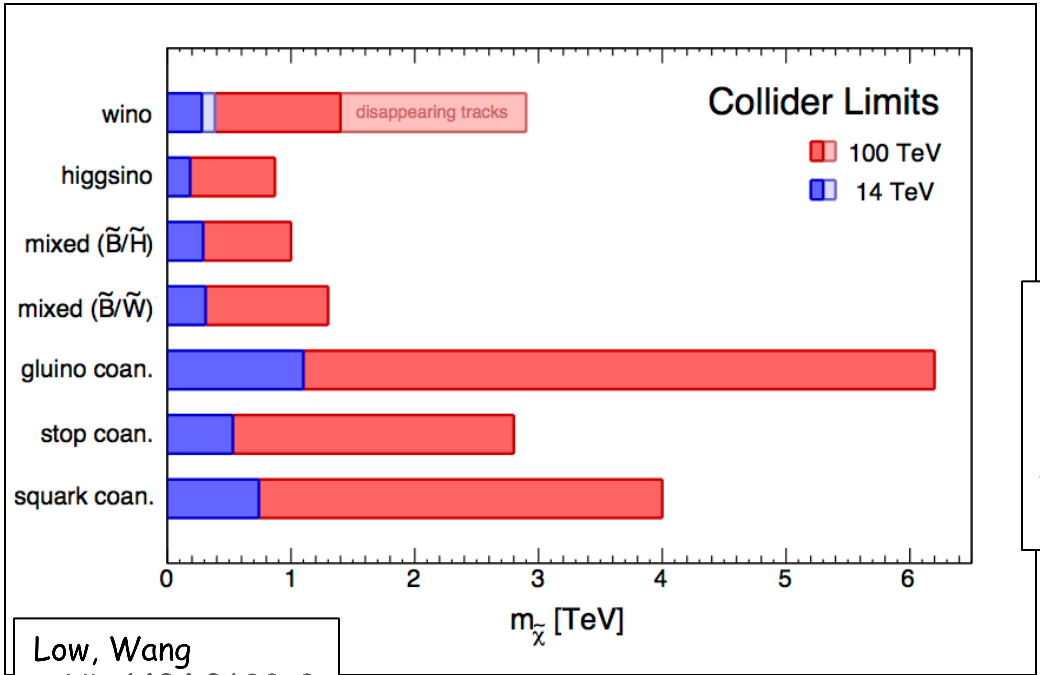
LUX *current* bounds [arXiv:1310.8214] plotted.

Huge DM direct & indirect search activities ongoing and DM landscape will be dramatically different in 10 years already.

Conclusive searches of TeV-scale WIMP dark matter ?

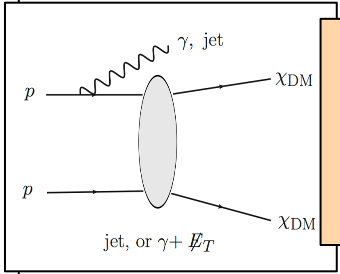
From relic abundance:

$$M_{\rm DM} \lesssim 1.8 \text{ TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right)$$



Low, Wang
arXiv:1404.0682v2

DM candidates from generic EW multiplets (direct pair production or from 1-step decays of nearly-degenerate heavier states)



Note: challenging experimental signatures (mainly based on ISR mono-object)

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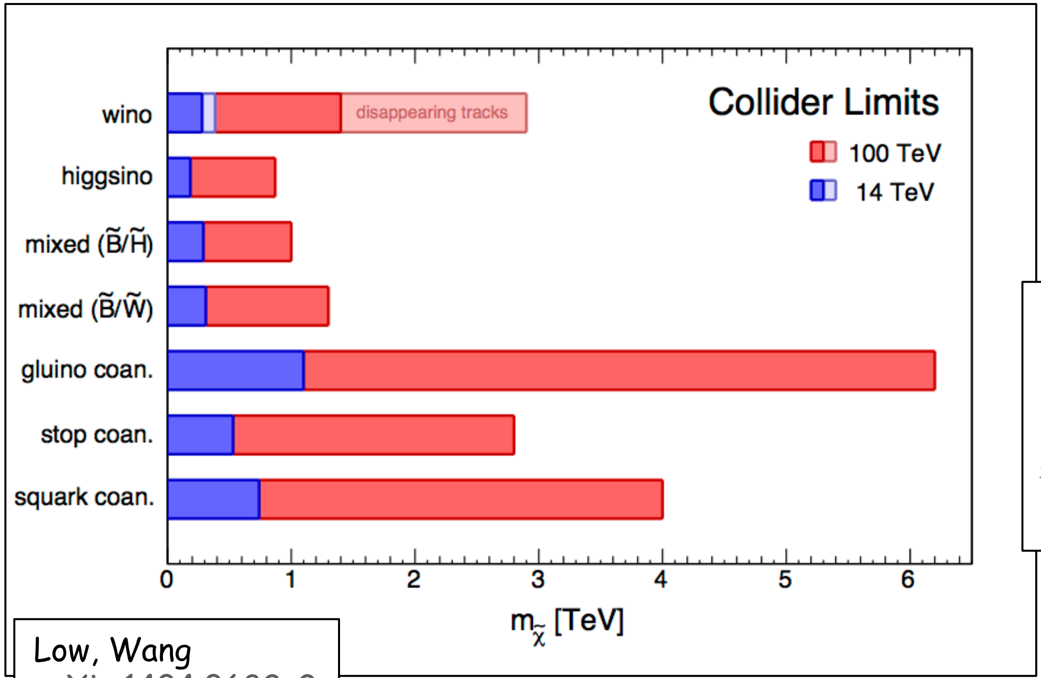

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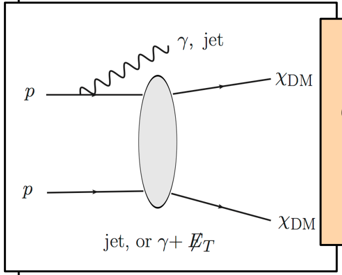


Note: challenging experimental signatures (mainly based on ISR mono-object)

… and of course exploration of unknown territory …

… to take home

- **We have a fantastic machine at work – the LHC**
- For the 'near' future : We have the big and realistic opportunity to upgrade the HL-LHC complex at CERN with an electron beam and to found a **'Higgs facility' challenging the QCD and electroweak sector of the SM to a state-of-the art level** – all this at moderate costs and **within the next 10 to 25 years** (using the lifetime of the LHC to the full – no regrets)
- For the far future – planning for 2040 : We have **a BIG dream of a next BIG machine** that needs starting work now and opens a dramatic extension of the accelerator-based high energy frontier in a global context – a major investment requiring new major technologies (16 T magnets) and theories.
- There is plenty of opportunities for HEP-UK to strengthen its contributions – physics, machines, detectors and maintain leadership.

Additional material

Additional Sources & Thanks to

POETIC VI Workshop, 7.-11.9.2015, Paris
http://poetic6.sciencesconf.org
Michael Benedikt, Lepton Photon Conference, 15.08.2015, Ljubljana
http://indico.cern.ch/event/325831/session/18/contribution/60/attachments/1143145/1638099/150822-MBE_FutureCircularColliders_ap.pdf
Fabiola Gianotti, EPS 2015, 29.07.2015, Vienna
https://indico.cern.ch/event/356420/timetable/#20150729.detailed
LHeC Workshop, CERN (24 June) and Chavannes-de-Bogis (25-26 June)
https://indico.cern.ch/event/356714/
DIS2015, 27. April -1 May 2015, Dallas, Texas
https://indico.cern.ch/event/341292/
First Annual FCC Meeting, 23-29 March 2015, Washington, U.S.A.
http://indico.cern.ch/event/340703/
Higgs & BSM at 100 TeV, 11-13 March 2015, CERN
http://indico.cern.ch/event/352868/
Nima Arkani-Hamed, SUSY2013, Trieste
https://www.youtube.com/watch?v=xNVZg694ct8
M. Mangano, "Future Colliders", UK Forum 11/2014
http://conference.ippp.dur.ac.uk/event/394/
11th ICFA Seminar in Beijing, 27.-30.10.14
http://indico.ihep.ac.cn/conferenceOtherViews.py?view=standard&confId=3867
"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

New ep/eA International Advisory Committee

Max Klein ICFA Beijing 10/2014

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 12/2013 by the CERN DG with the following

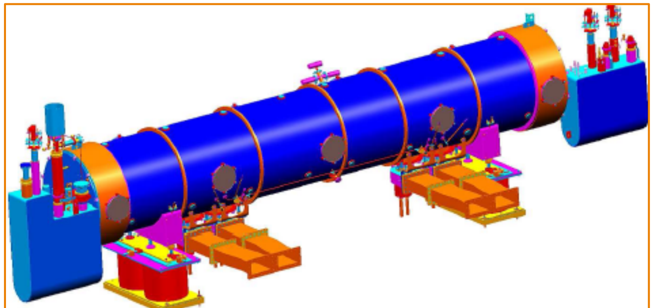
Mandate 2014-2017

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.

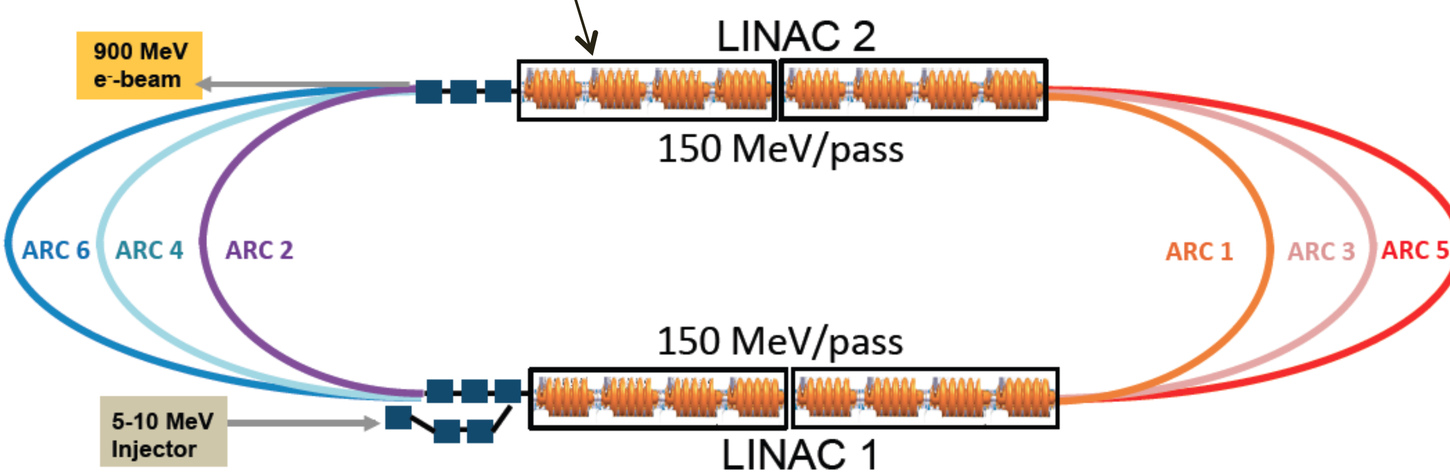
Superconducting RF and ERL Test Facility Design at CERN



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.

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

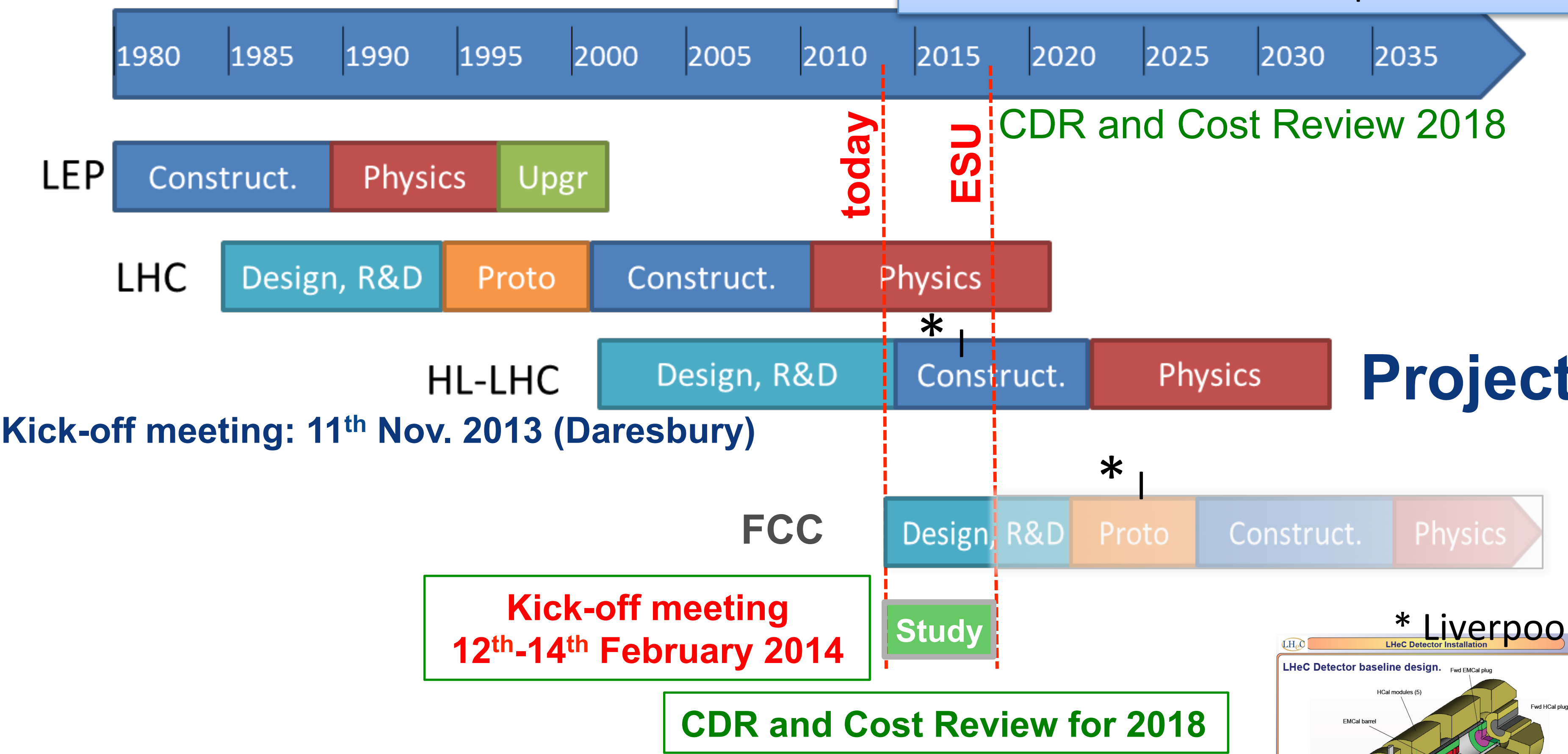
$$N(ep)=N(pp) \times s(yp)/s(pp) \times L(ep)/L(pp)$$
$$= 150 * 0.003 * 0.2$$
$$= 0.1$$

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

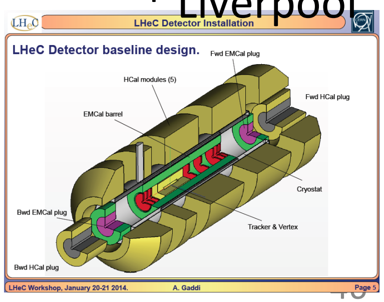
$$N(ep) = 300\ 10^{-6}\ 10^{-24}\ cm^2 \times 10^{34}\ cm^{-2}s^{-1} \times 25\ 10^{-9} s$$
$$= 0.075$$

FCC study milestones

23-24.3.15 FCC Workshop in Washington
23.-24.6.15 LHeC Workshop in Chavannes



* Liverpool

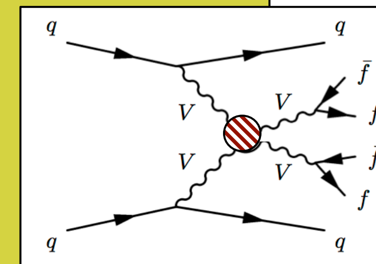


Timeslines from Weiren Chou, Beijing ICFA, Oct 2014

Other (equally strong) arguments for 100 TeV pp colliders: capability of addressing "structural issues"

Few examples.
Preliminary estimates

Conclusive elucidation of EWSB mechanism:
→ probe SM in regime where EW symmetry is restored ($\sqrt{\hat{s}} \gg v=246$ GeV)



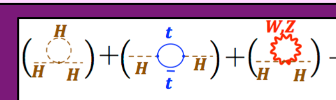
Without H: $V_L V_L$ scattering violates unitarity at m_{VV} ~TeV

- ❑ H regularizes the theory fully → a crucial "closure test" of the SM
- ❑ Else: new physics shows up: anomalous quartic couplings (VVVV, VVhh) and/or new heavy resonances

100 TeV pp: direct discovery potential of new resonances in the O(10 TeV) range

Naturalness:

- ❑ If no new physics at end of LHC → ~ 1% fine-tuning
- ❑ 100 TeV pp: direct sensitivity to stops and other top partners up to O(10) TeV → fine-tuning pushed to 10^{-4}

$\Delta M_H^2 \sim$  $\cdots \sim \Lambda^2$

(Distinguished) theorist 1: "Never seen 10^{-4} level of tuning in particle physics: qualitatively new, mortal blow to naturalness". (Distinguished) theorist 2: "Naturalness is a fake problem"

Nature of EW phase transition:
if first order (faster than in SM) could give rise to baryogenesis → need modification of the H potential, e.g. by adding a scalar singlet:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - c_\phi v h \phi^2$$

→ this (difficult) model can be constrained from precise measurements of HZ coupling at e^+e^- and H self-coupling at 100 TeV pp, and direct searches for new (invisible) particles at 100 TeV pp.

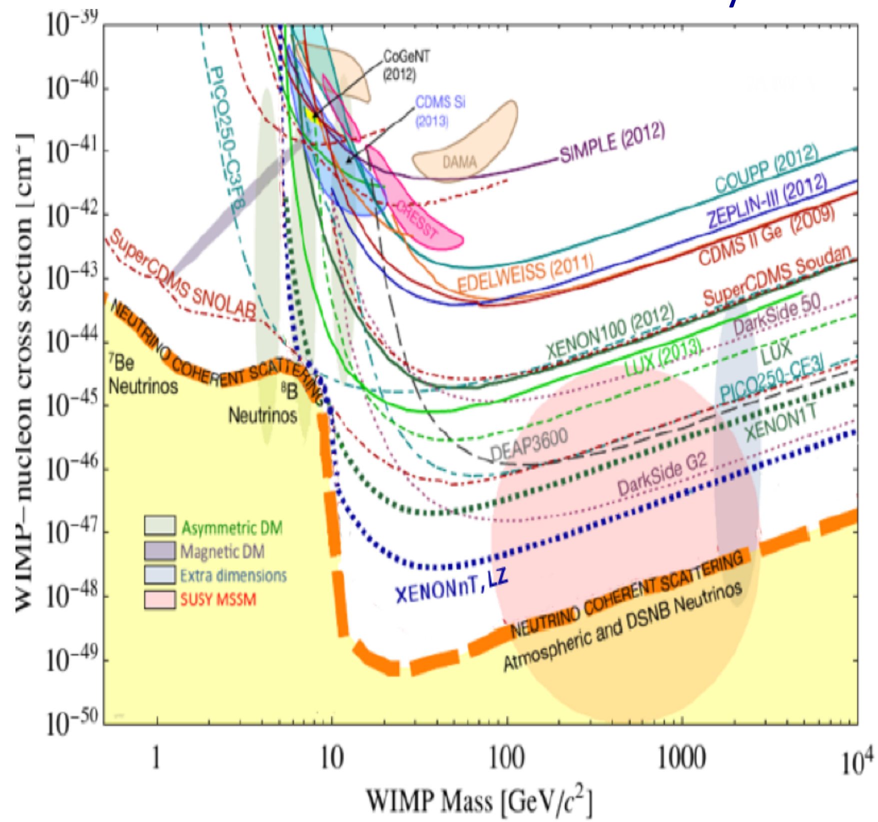
CepC-SppC http://cepc.ihep.ac.cn/preCDR/volume.html; see also Curtin et al., arXiv:1409.0005v4

Dark Matter

limits by 2022

In this image, dark matter (blue) has become separated from luminous matter (red) in the bullet cluster.
(Image courtesy: Chandra)

http://www.interactions.org/cms/?pid=1034004



Direct search experiments

ANAIS, ArDM, ADMX, COUP, CEDEX, PANDA-X, TEXONO, CoGeNT, CDMS, CRESST, DAMA/LIBRA, DARWIN DEAP, DARKSIDE, EDELWEISS, EURECA, FUNK, KIMS, LHC, LZ, PICASSO, SIMPLE, XENON100, XMASS

Indirect search experiments

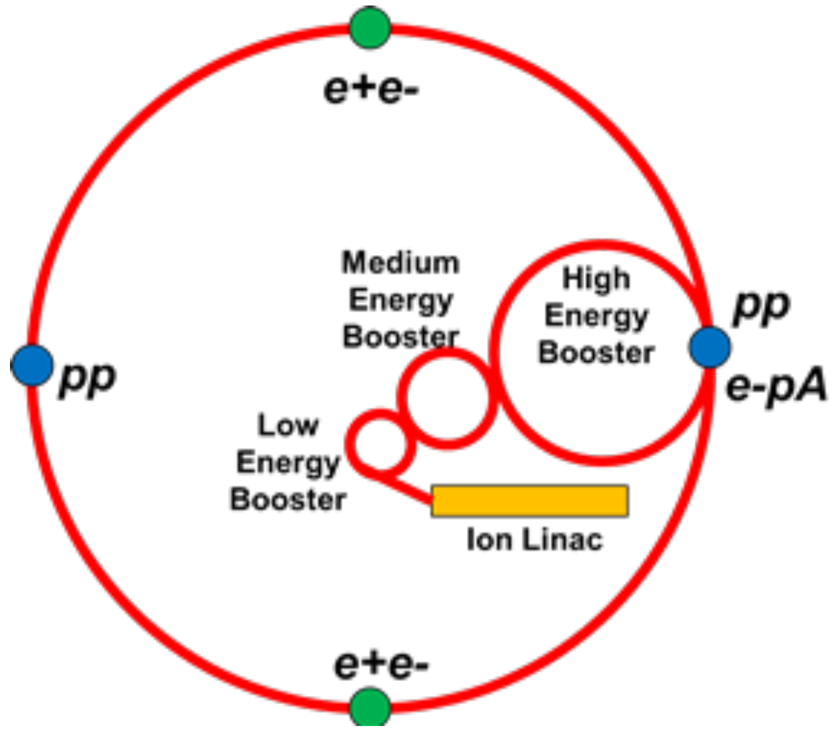
AMS, ALPS, ANTARES, BAIKAL, CTA, FGST-LAT, GAPS, HPS, HESS, ICECUBE, IMAX, MAGIC, PAMELA, SK VERITAS

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



Why eh?

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

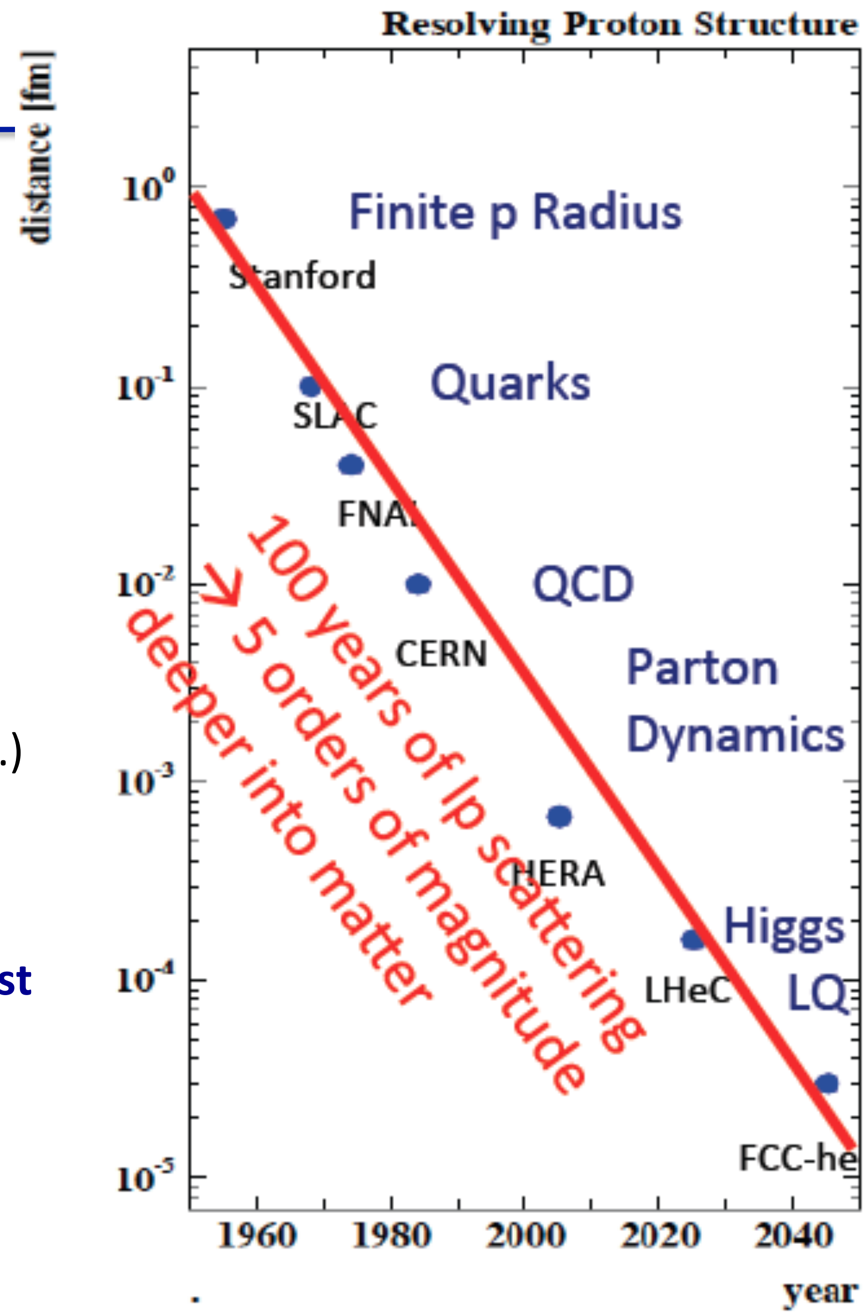
- Resolving structure (PDFs): Proton, Photon, Pomeron, GPDs, Neutron,…

→ huge synergy with HE pp-Colliders

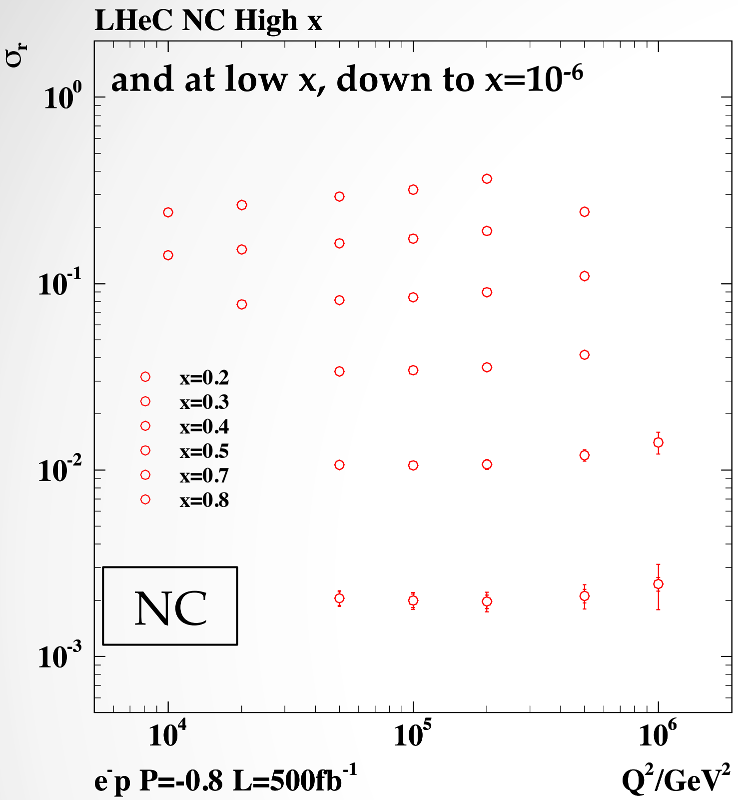
- QCD of Spin, Heavy Ion physics (CGC …)
- Higgs in WW and ZZ
- Electroweak Physics beyond Z and H
- Surprises …

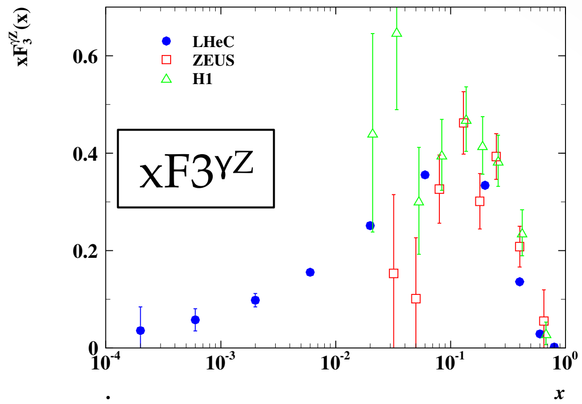
Future of ep/eA colliders and DIS must be maintained:

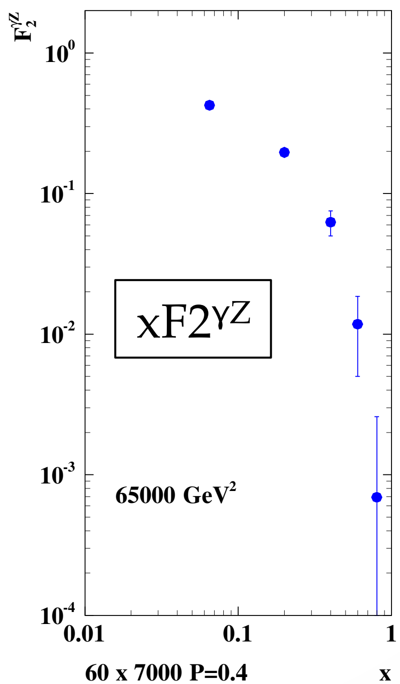
It is rich, from low to medium and highest energies, and the outcome cannot be fully simulated/predicted.
It is crucial to sustaining our field.

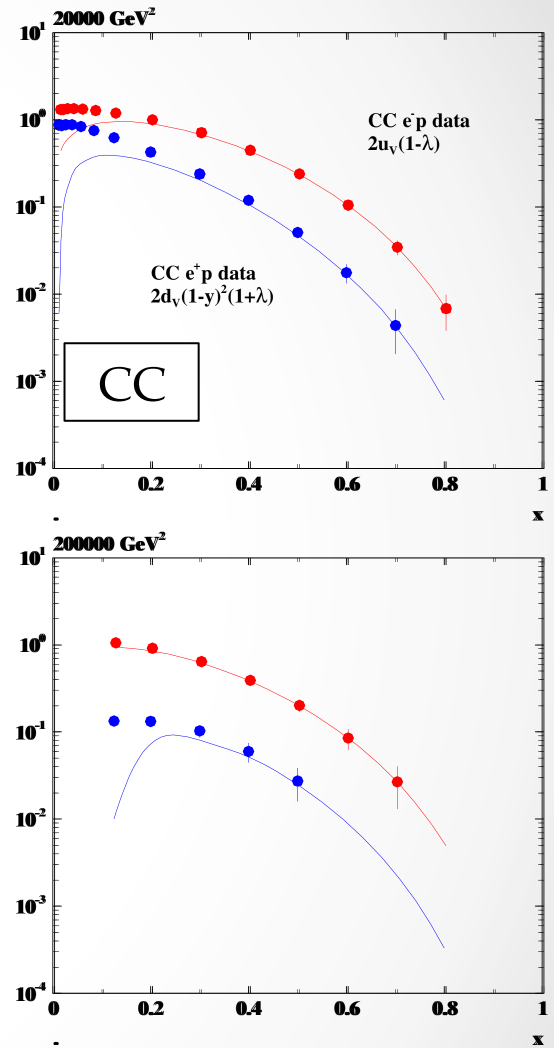


primary measurements – simulated – high Q^2









NC/CC cross sections to high precision

- structure functions, sensitive to quarks
- access high x, free from nuclear corrections (via high Q^2, high luminosity)
- different beam charge and polarisation: determination of all quark types

gluon via scaling violation (and F_L)

BSM in VBF

1. VBF Higgs production with BSM decays

   eg. RPV cases $H \rightarrow \chi_1^0 \chi_1^0 \rightarrow 3j\,3j$ (resonances)

   need to understand backgrounds

2. **Vector boson scattering at high mass**

   mass dependence of cross section

- anomalous TGC, QGC couplings?

  WWγ I.T.Cakir et al., arXiv:1406.7696

  studies show sensitivity comparable to LHC

- anomalous HZZ in NC DIS

  I.T.Cakir et al., arXiv:1304.3616

- is unitarity restored only by Higgs?

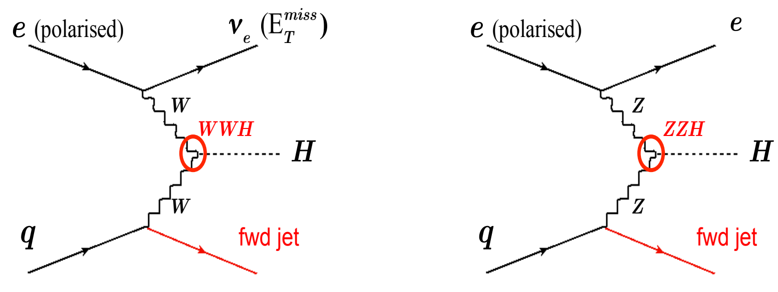
  are there new resonances (composite Higgs model)?

  expect below about 2 – 3 TeV:

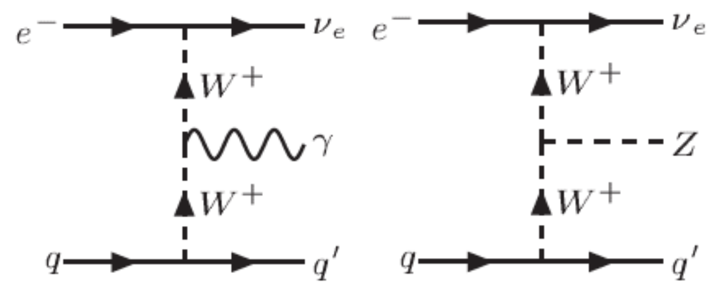
  e-q ➔ e-qWZ, νqWZ

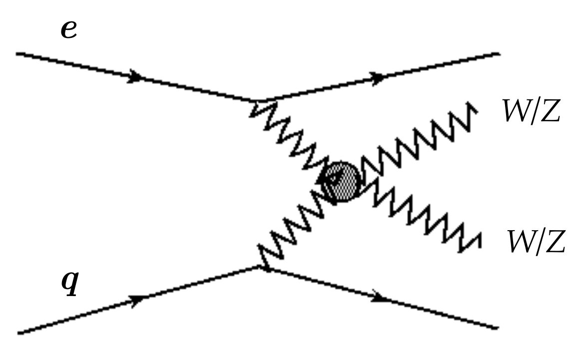
  search for deviations from SM predictions

- **LHC**: hadronic modes challenging (high QCD backgrounds & pileup not present in ep)



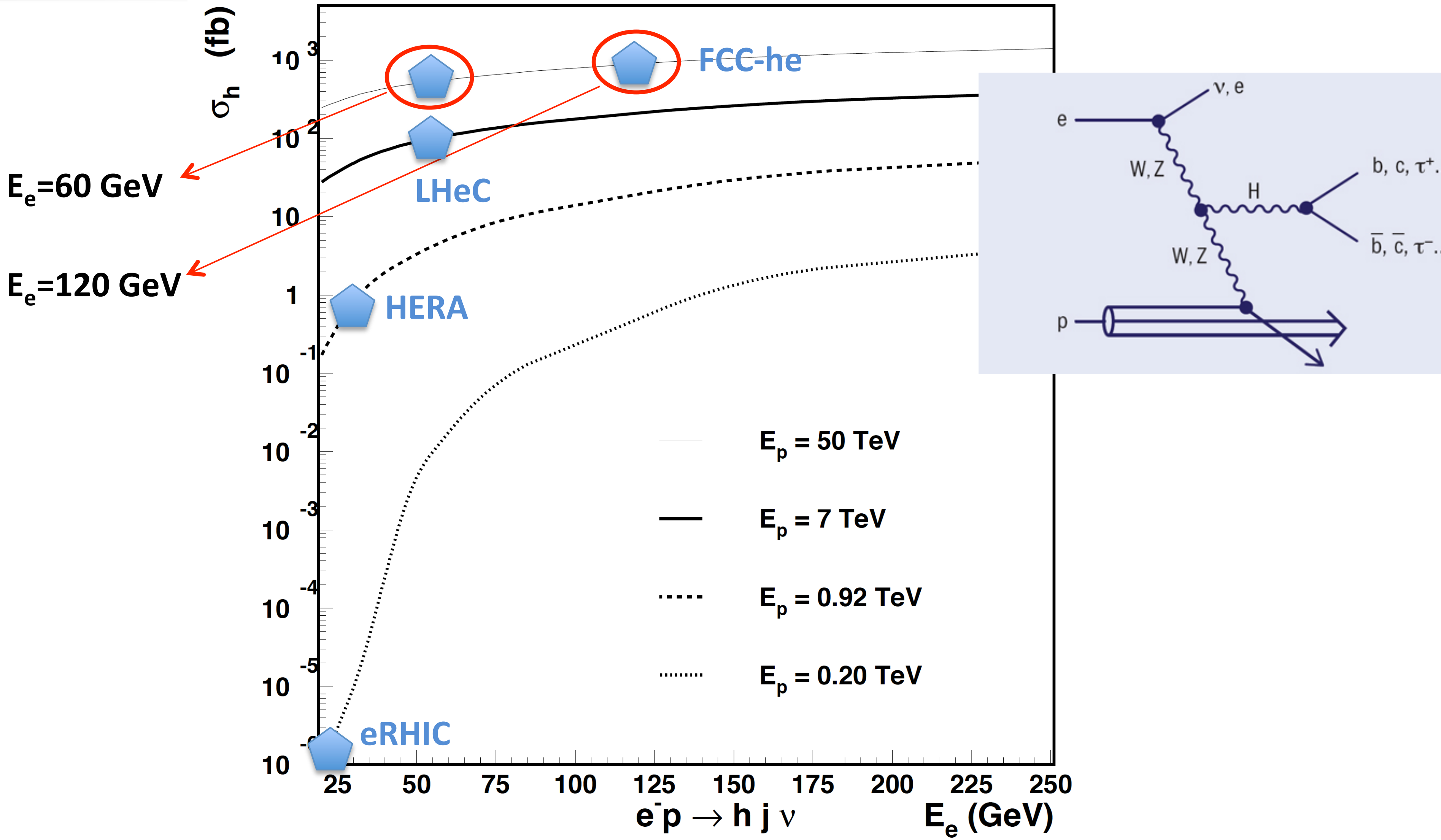
Charged Current   Neutral Current





SM Higgs in ep

U. Klein, @DIS2015



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

SM Higgs Production in ep

U. Klein, @DIS2015

In ep, direction of FS quark is well defined.

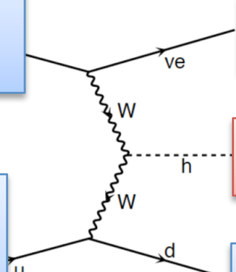
CC : LO SM Higgs Production

e-p (swap charges for e+p)

u -> νe h d

polarised electrons →

LHC/FCC protons →



E_T^{miss}

WWH

Fwd jet

around 90-80%

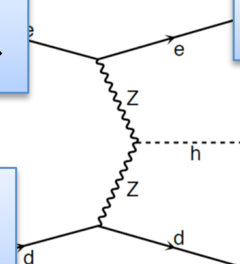
NC : LO SM Higgs Production

e-p (swap charges for e+p)

d -> e- h d

polarised electrons →

LHC/FCC protons →



FS electron

ZZH

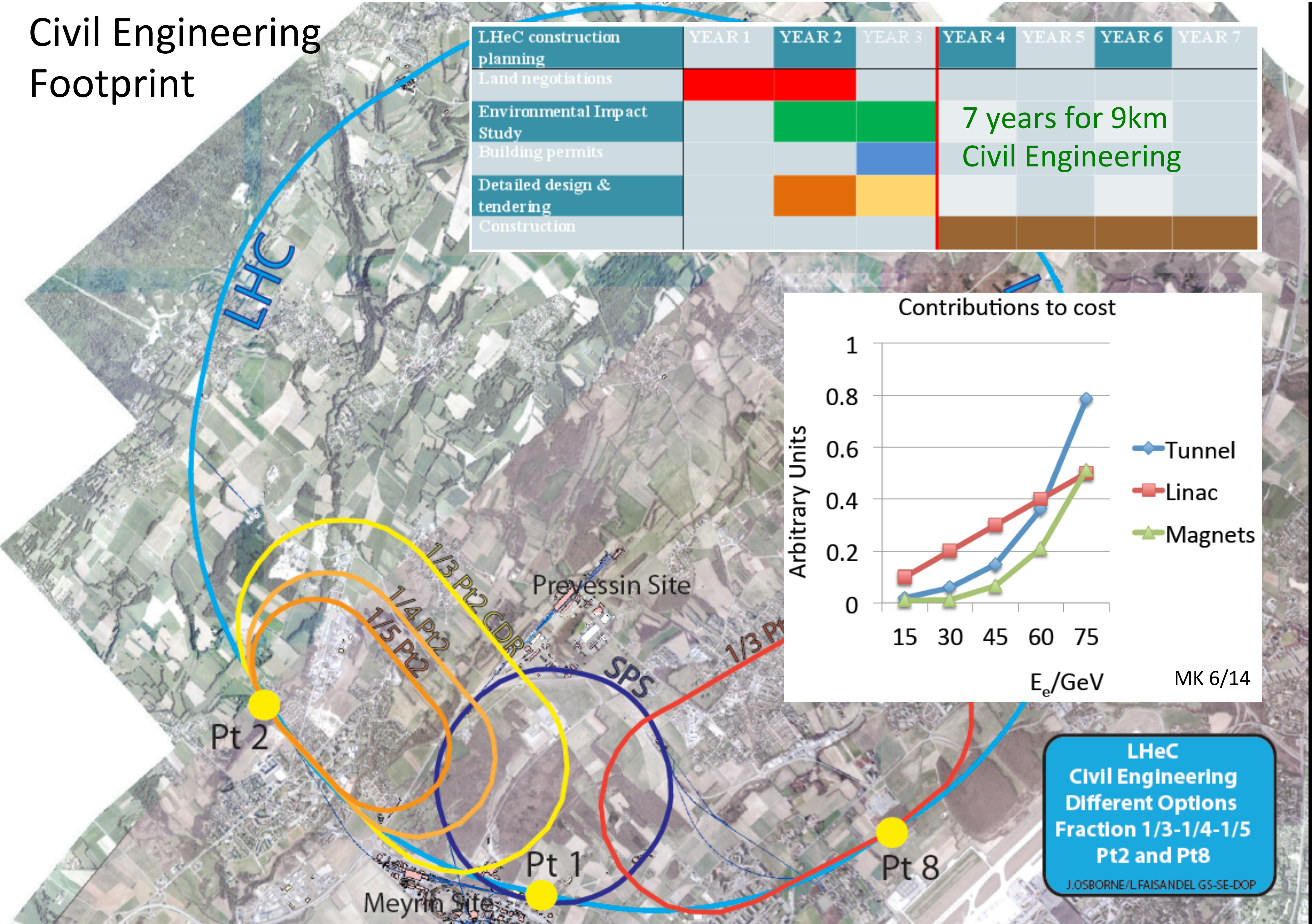
Fwd jet

around 1/3

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**

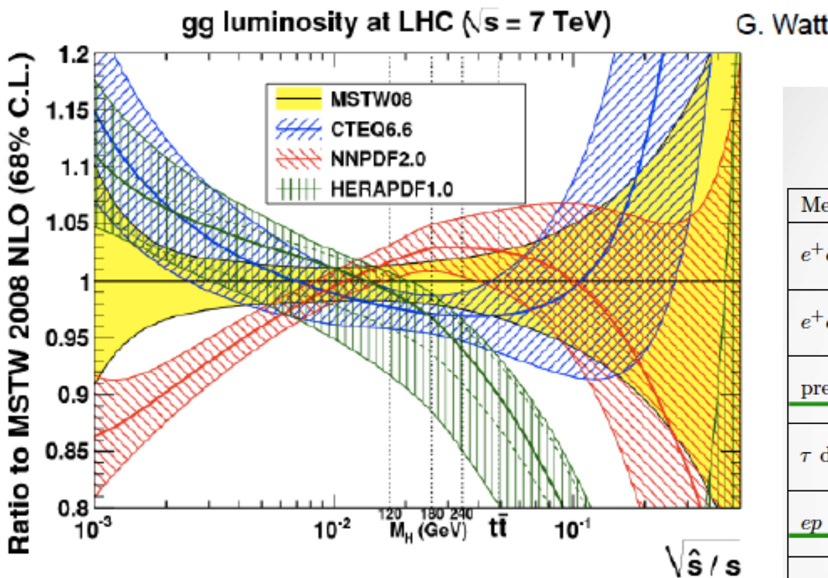
Civil Engineering Footprint



January-October 2013

PDFs and α_s

arXiv:1310.5189



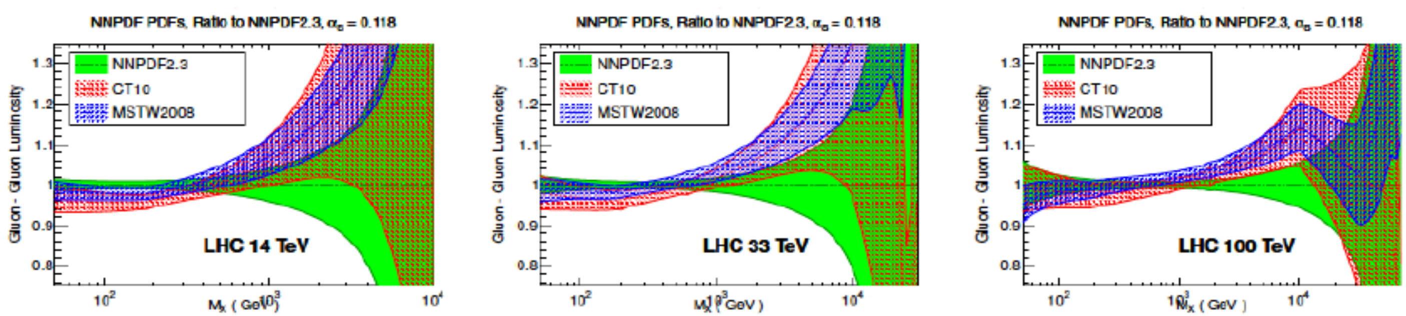
Important constraints from pp, but precision with ep! eA is unknown

PDFs for QCD, H, BSM ...

α_s 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, $\sim$ 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, $\sim$ 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]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

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



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.***

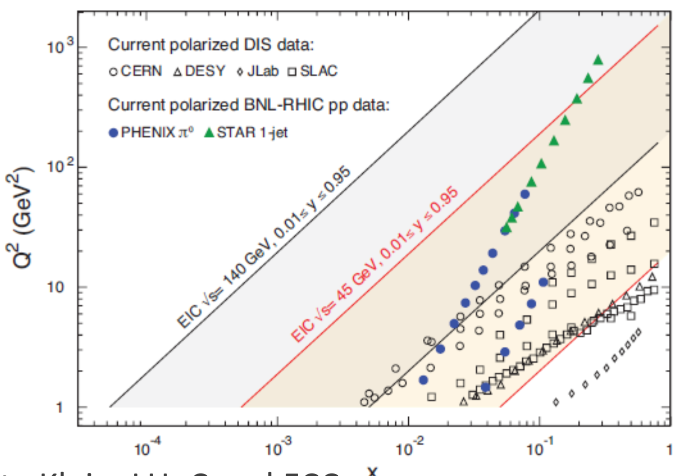
World's first polarised e-p collider and lower energy e-A collider.

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

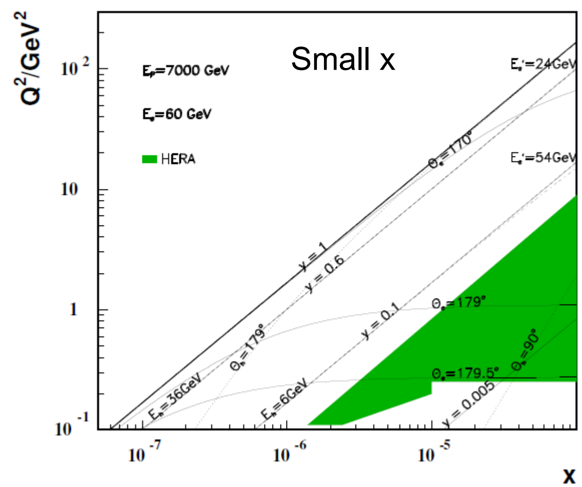
- *Add ~60 GeV **polarised** electrons to probe unpolarised LHC proton and ions*

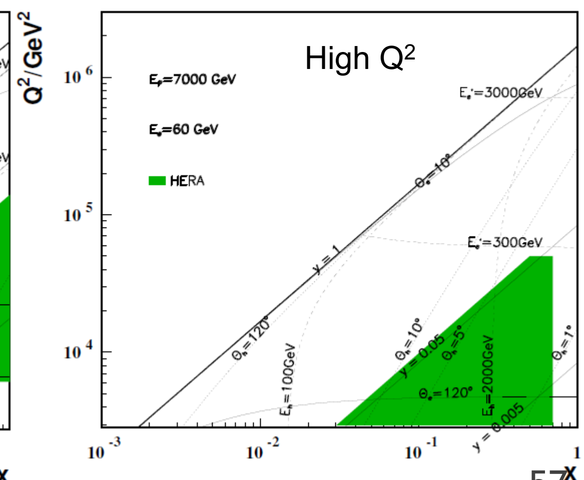
High-energy frontier e-p and e-A collider to follow HERA with factor 1000 higher luminosity <u>running simultaneously</u> with HL-LHC.

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

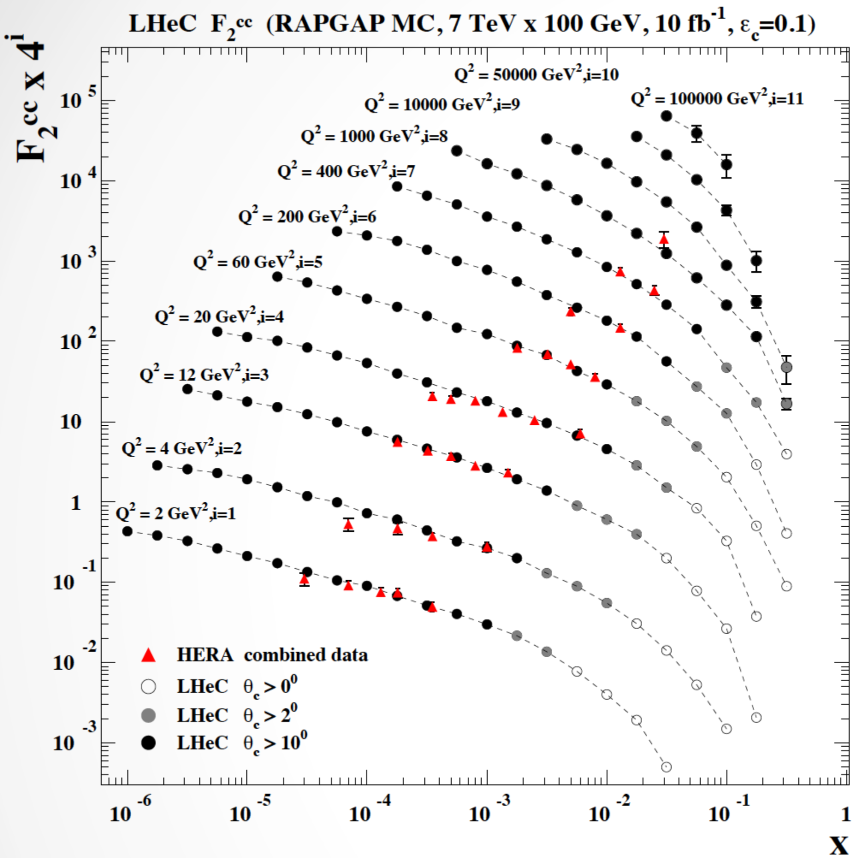


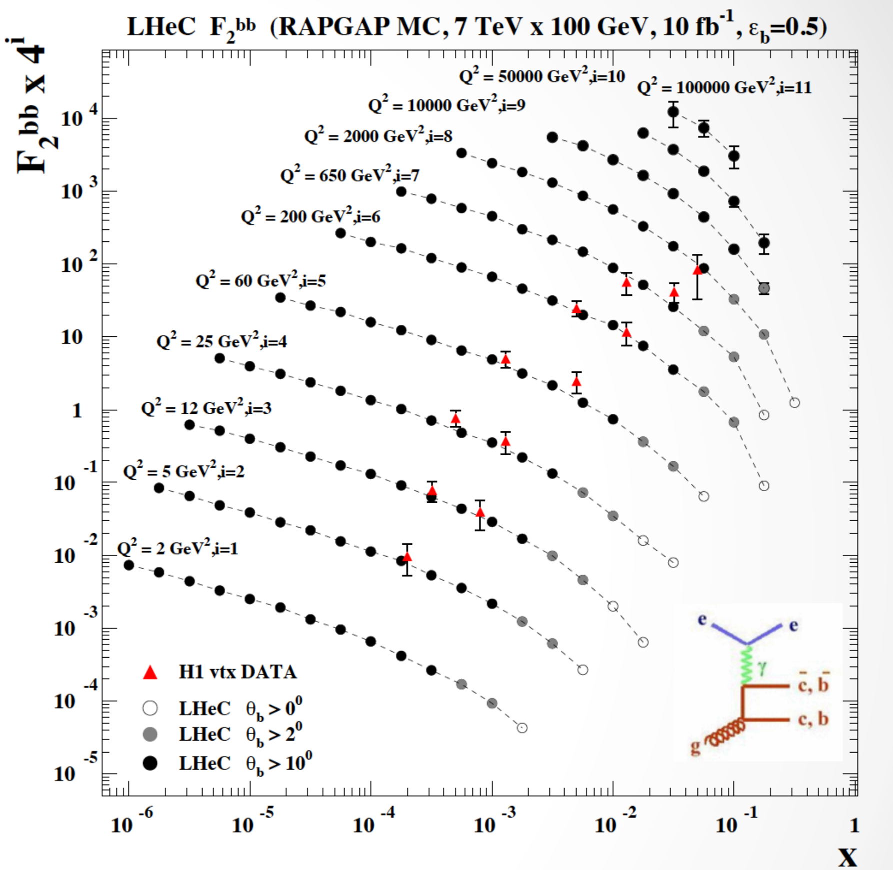
x_{min} ~ 6 x 10^{-7}





Flavour Decomposition : charm and beauty





LHeC: much more precise and kinematically extended measurements

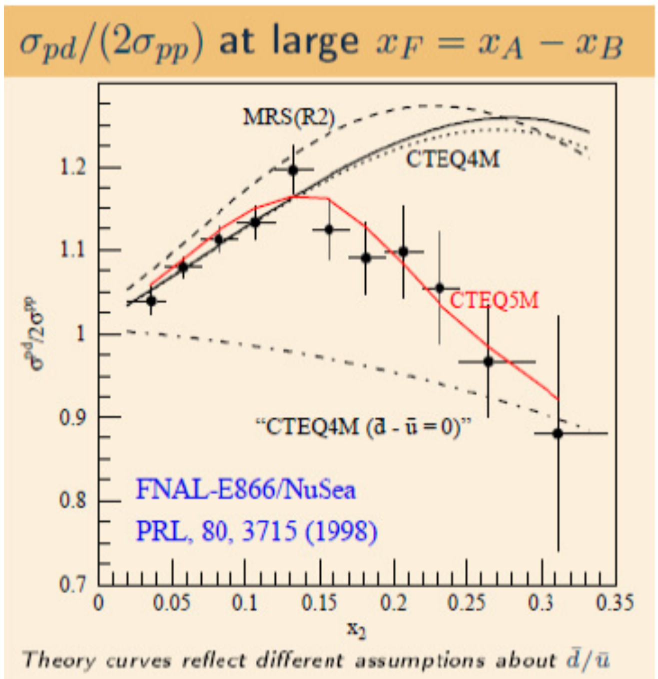
high Q^2 / cross section, high luminosity, no pileup, small beam spot, new generation of Si detectors

- δM_c = 60 (HERA) to 3MeV: impacts on αs, regulates ratio of charm to light, …
- MSSM: Higgs produced dominantly via $b\bar{b}$ ➔ A

Synergy: Constraining Sea Quark PDFs

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

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

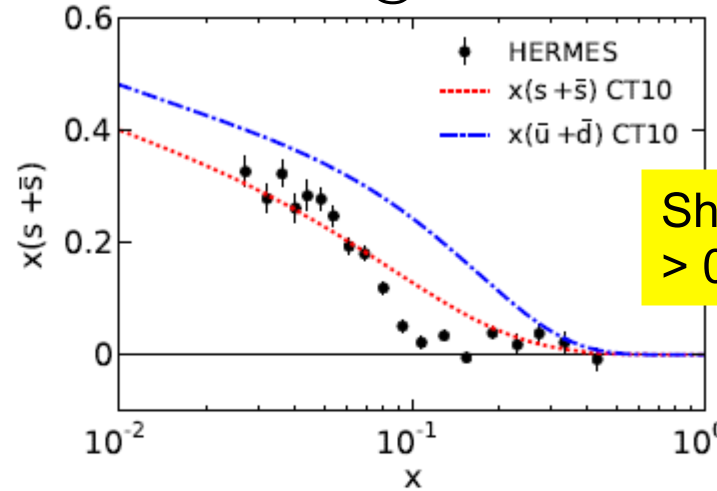


- Implications for all PDF fits
- Effect soon confirmed by HERMES w. **SIDIS** data (semi-inclusive DIS)
- Further data ongoing at FNAL/SeaQuest (x > 0.1)
- LHC **W/Z** data suggest flavour-symmetric sea ?
- LHC W+charm data → subject to cuts, FF/hadronisation…

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

Strange sea s more (data) challenged

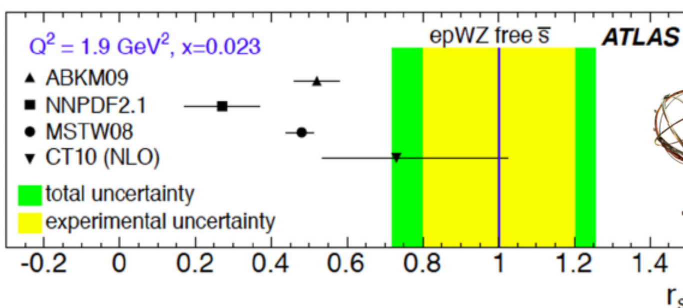
- HERMES **SIDIS** @ Q^2 = 2.5 GeV^2



Shape x > 0.1?

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

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

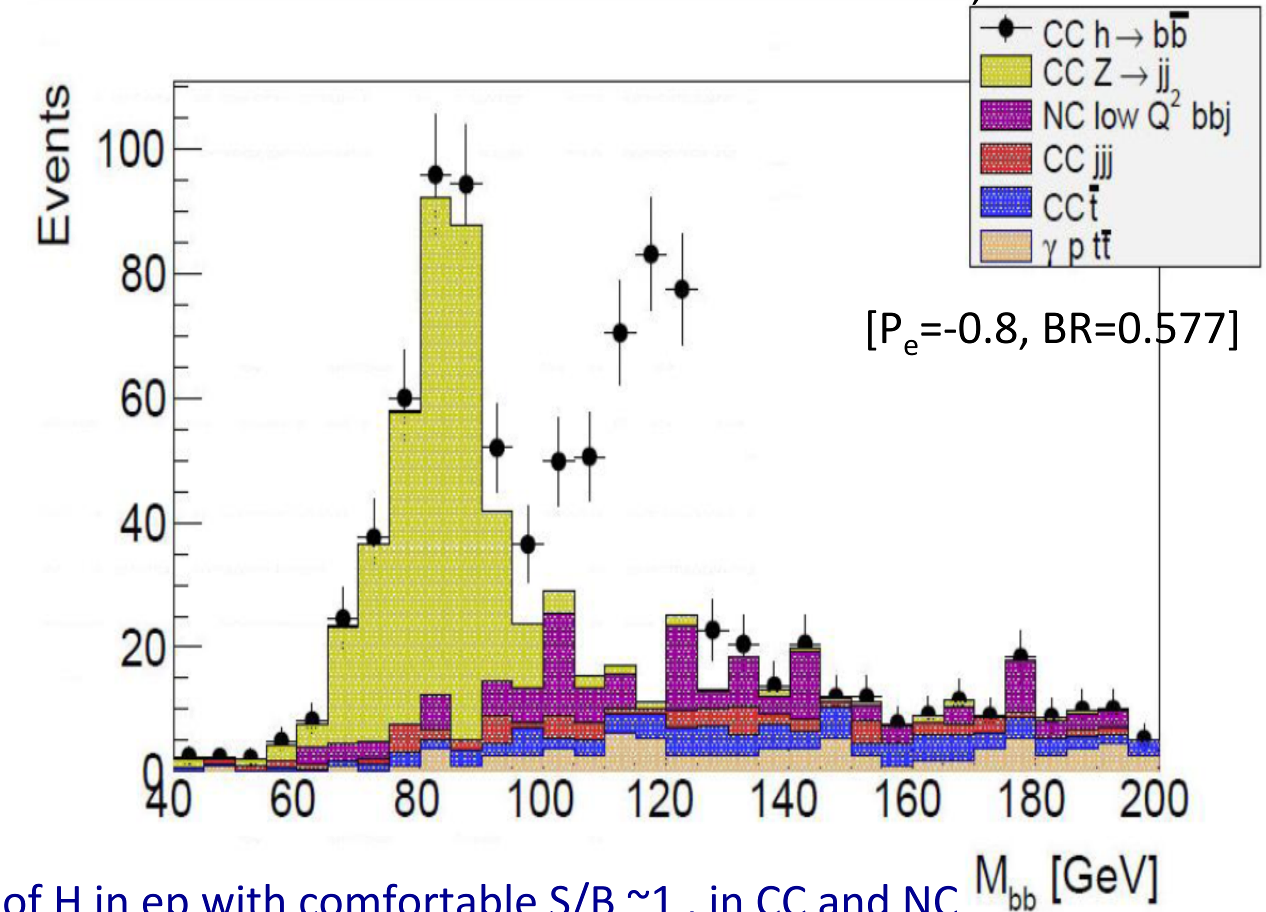


SM Higgs in ep

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

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



LHeC Higgs Group U.Klein et al.

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**.

→ **@Chavannes2015: First evidence of H-cc coupling to be measured 7-20%**

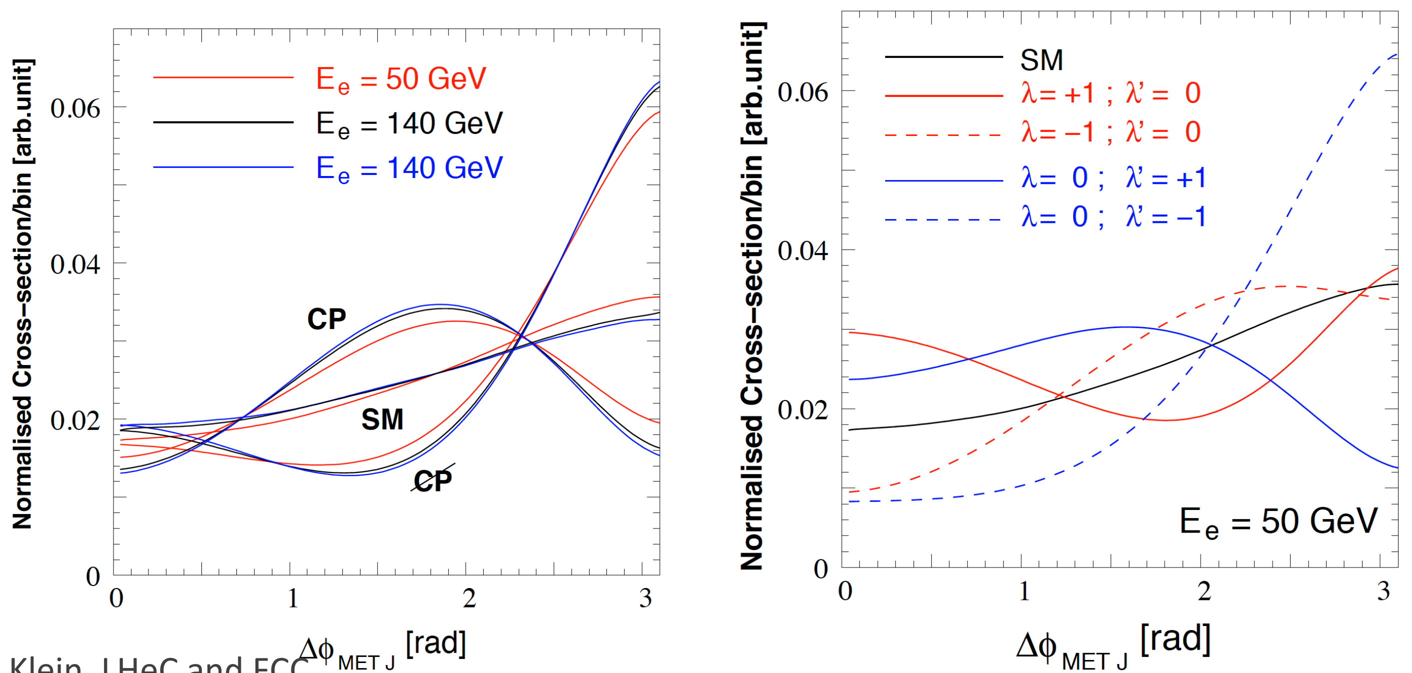
Measure CP properties of Higgs

[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

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

- 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:

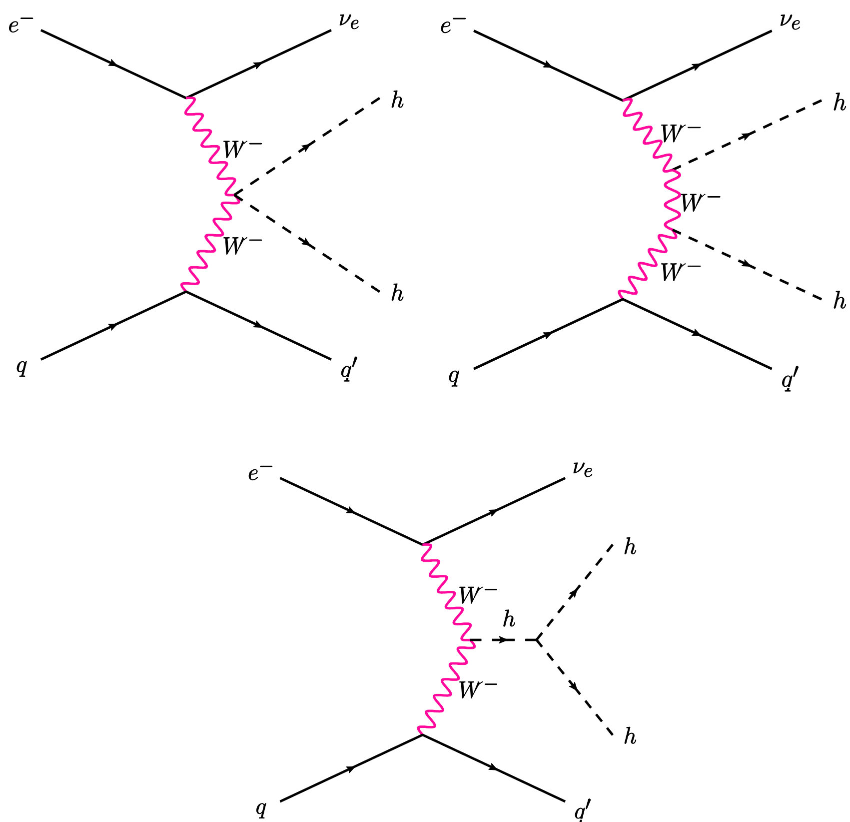
CP couplings probed to
λ~0.05
λ'~0.2

based on 50 fb^{-1}

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

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)

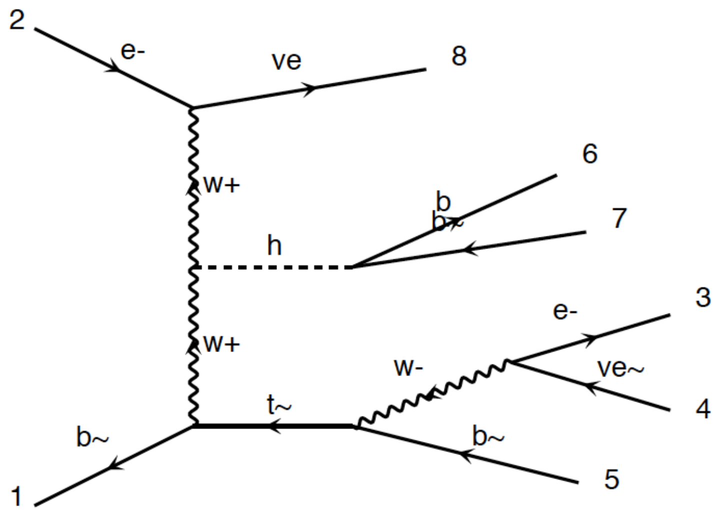


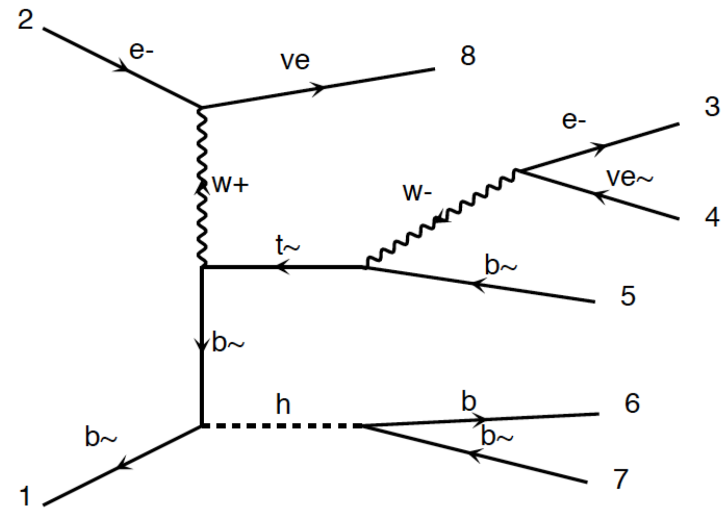
$$p_{T_{j,b}} > 20\ GeV,$$
$$\not{E}_T > 25\ GeV,$$
$$|\eta_j| < 5,\ \Delta R = 0.4.$$

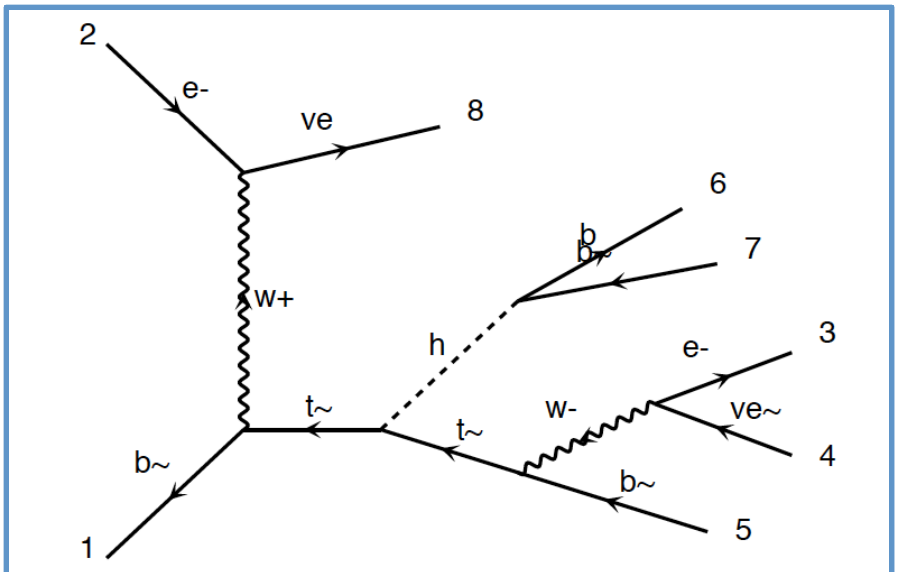
Processes	E_e (GeV)	σ(fb)	σ_{eff}(fb)
$e^- p \rightarrow \nu_e hhj, h \rightarrow b\bar{b}$	60	0.04	0.01
	120	0.10	0.024
	150	0.14	0.034

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

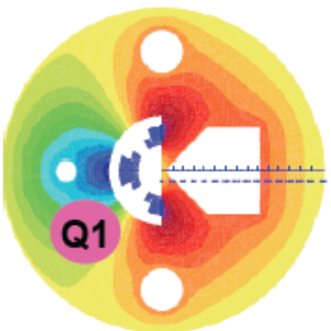
using pt(b,j)>20 GeV

ΔR(j.b)>0.4

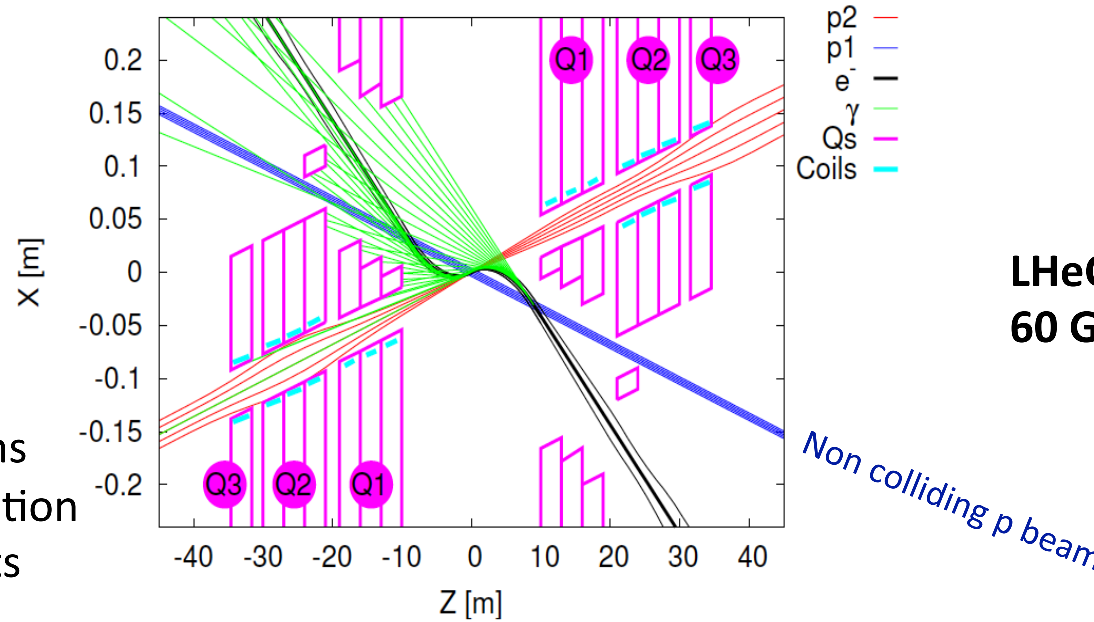
η(j) <5

η(b) < 3

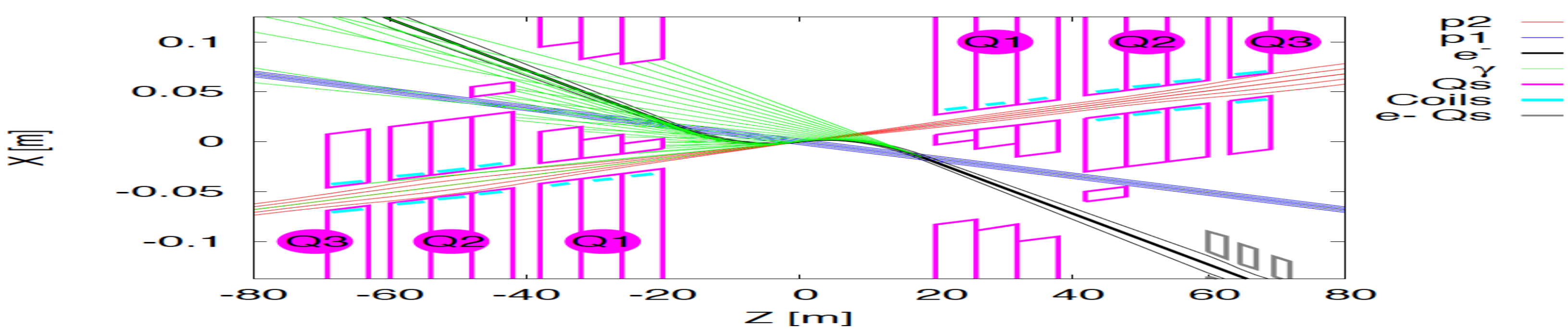
Interaction Regions for ep with Synchronous pp Operation



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



LHeC (CDR)
60 GeV * 7 TeV

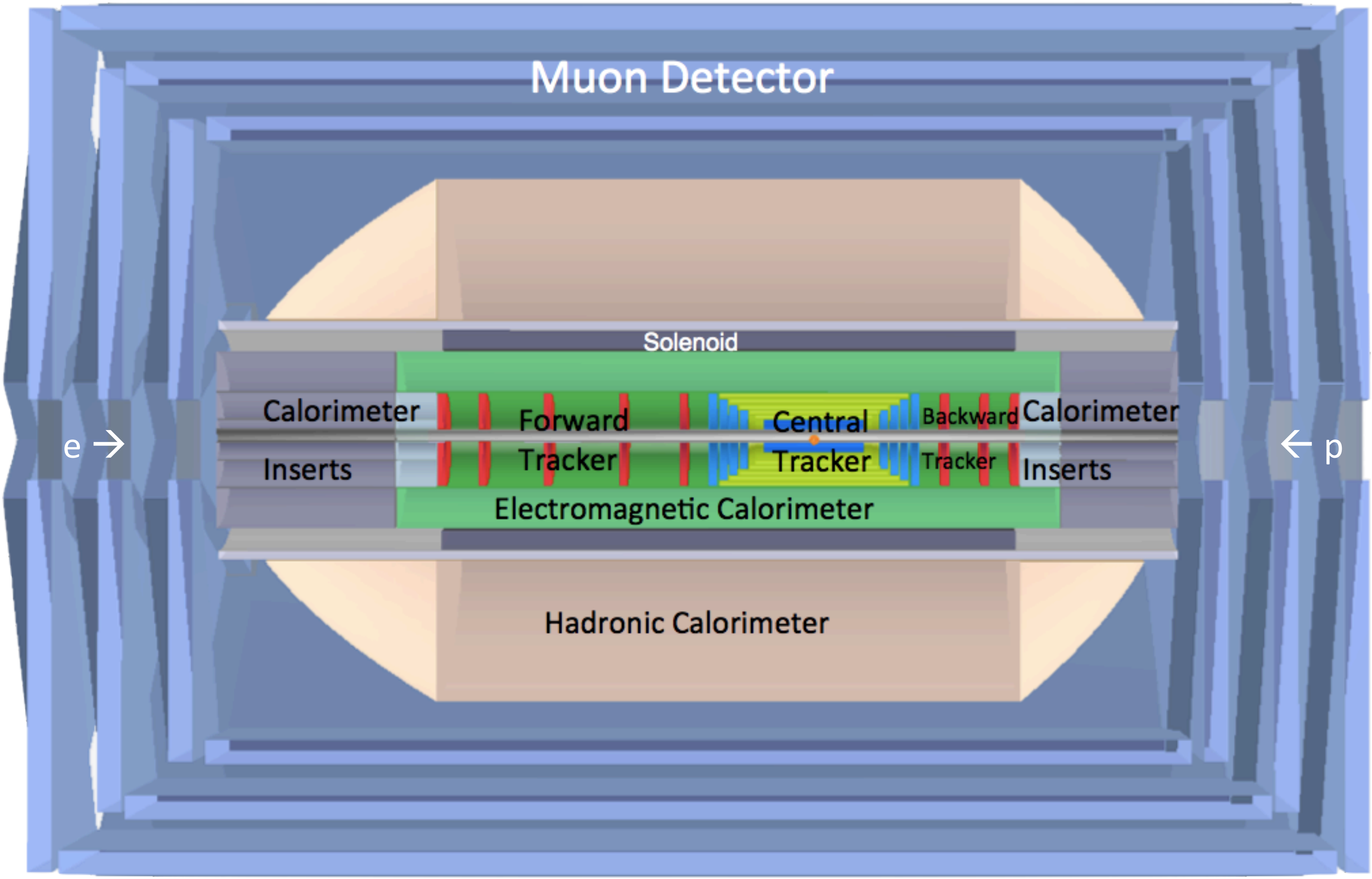


Rogelio Tomas, Max Klein, ICHEP14

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

FCC-he (ERL)
60 GeV * 50 TeV

LHeC Detector Overview



Detector option 1 for LR and full acceptance coverage

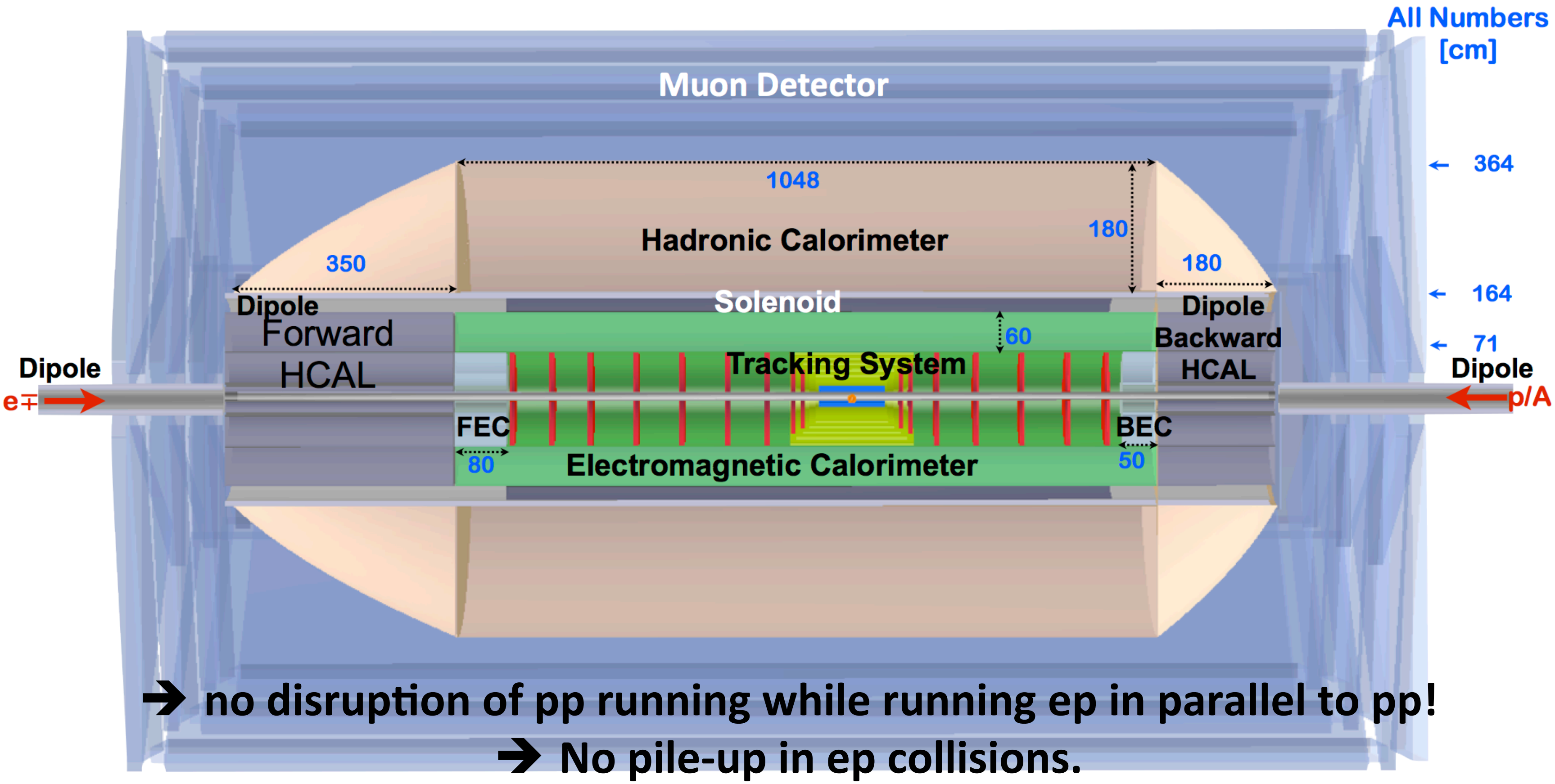
Forward/backward asymmetry in energy deposited and thus in geometry and technology

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)

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.

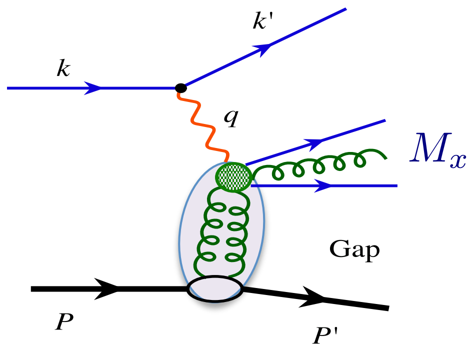
Alessandro Pollini and Peter Kostka
https://indico.cern.ch/event/282344/session/15/contribution/100/material/slides/0.pdf

Hadron Collider Parameters

Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	25	12	1	5
events/bx	170	850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchr. rad. [W/m/apert.]	30		58	0.2	0.35

Saturation and Diffraction

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



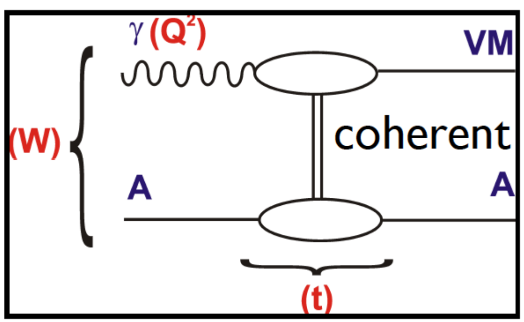
At HERA: 10-15% diffractive events

If saturation (CGC) – multiple coherent gluons

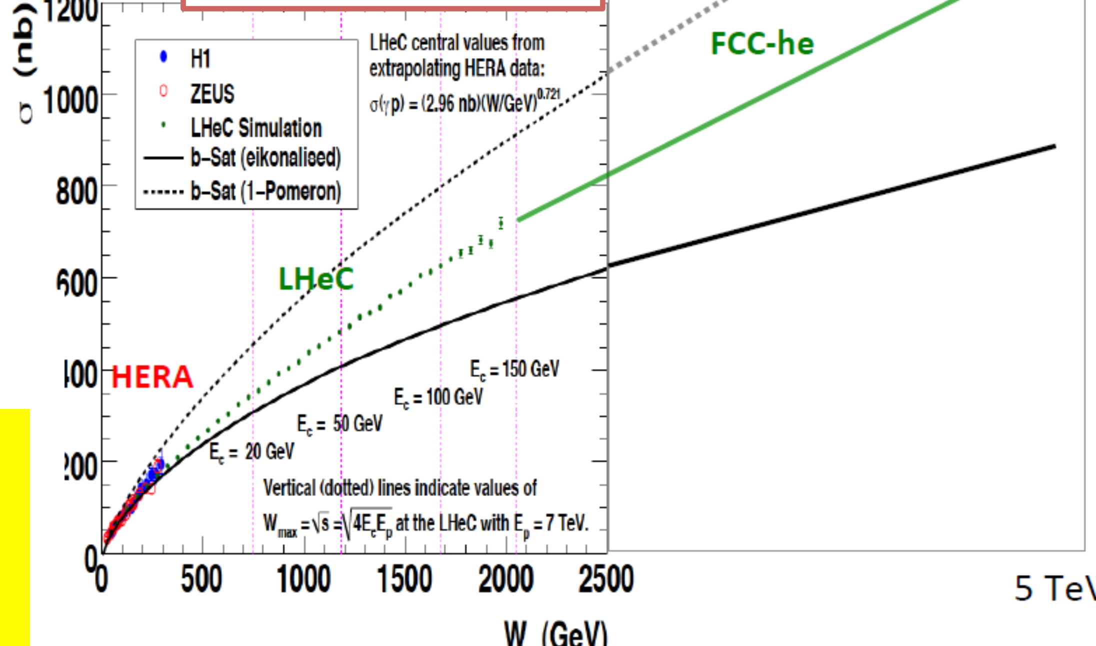
→ Diffraction in eA : ~25-30% diffractive contribution

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

Diffractive vector meson production:

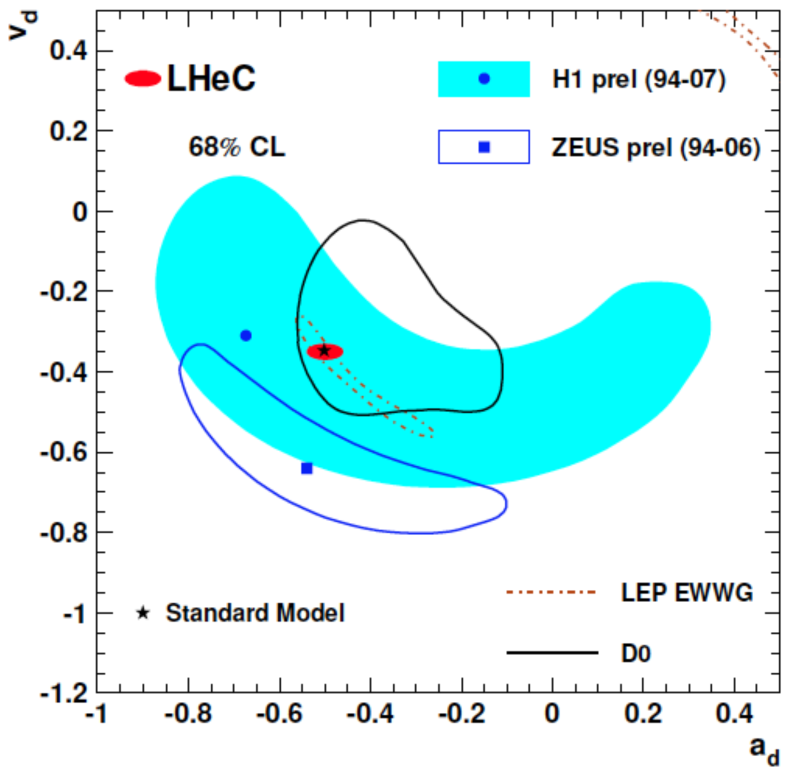


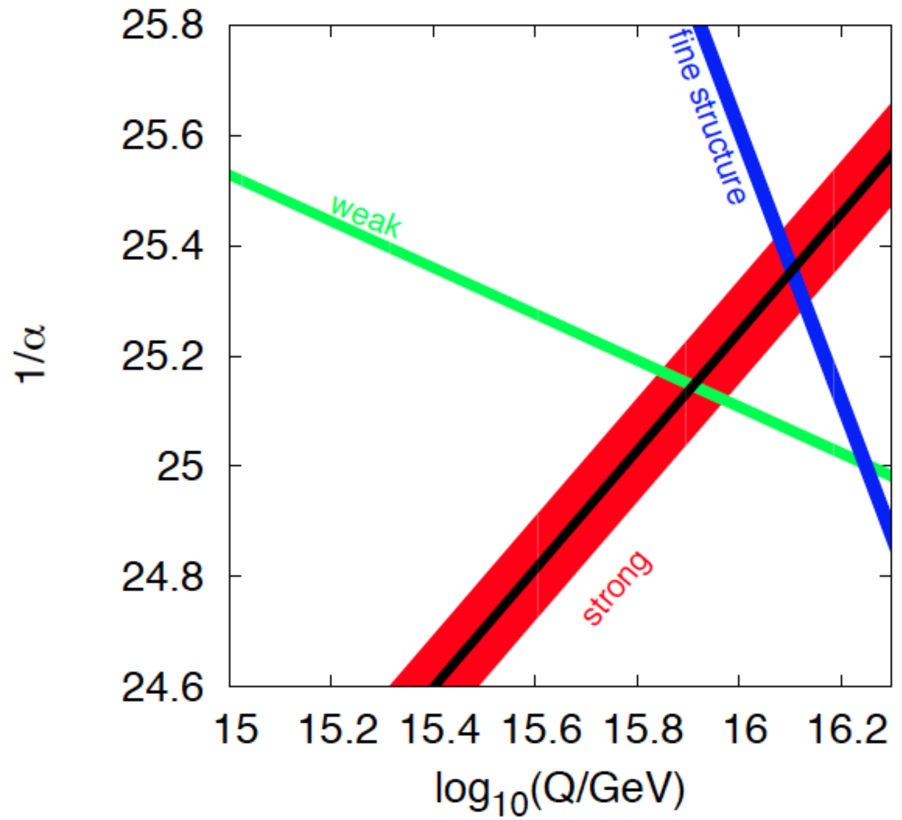
Predictions for coherent J/ψ production



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

High precision QCD





$Q^2 >> M_{Z,W}^2$, 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

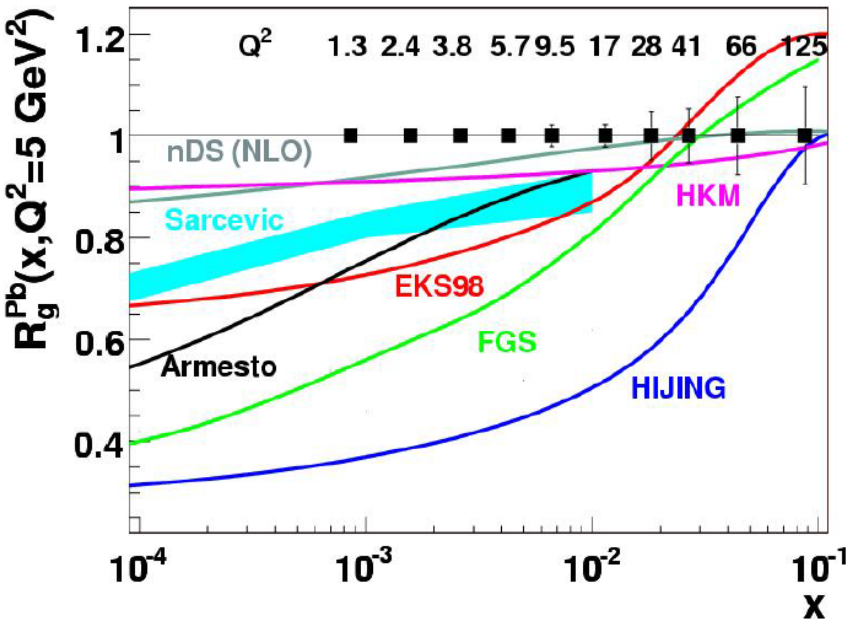
→ A renaissance of deep inelastic scattering ←

Partons in Nuclei

What do we know about gluons in a nucleus?

NOTHING!

Data fits: Ratio of gluons in lead to deuterium



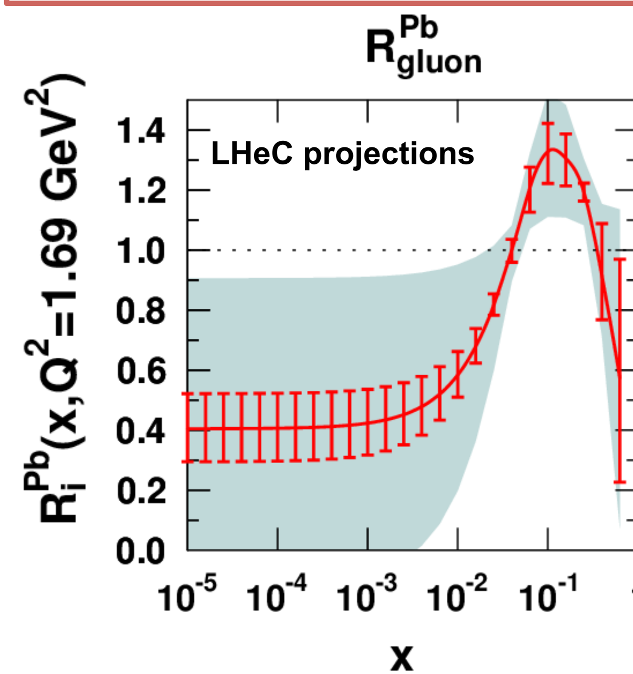
$$Q_s^2(eA) \propto Q_s^2(ep)\ A^{1/3}$$

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)



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**.