New Physics with eh Scattering

work and thoughts in progress

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for the FCC-he/LHeC Study Group

BSM and 'the Gluon' in QCD
BSM with pp
Leptoquarks and Beam Energy
Recent developments

Rome, 14th of April, 2016

http://lhec.web.cern.ch

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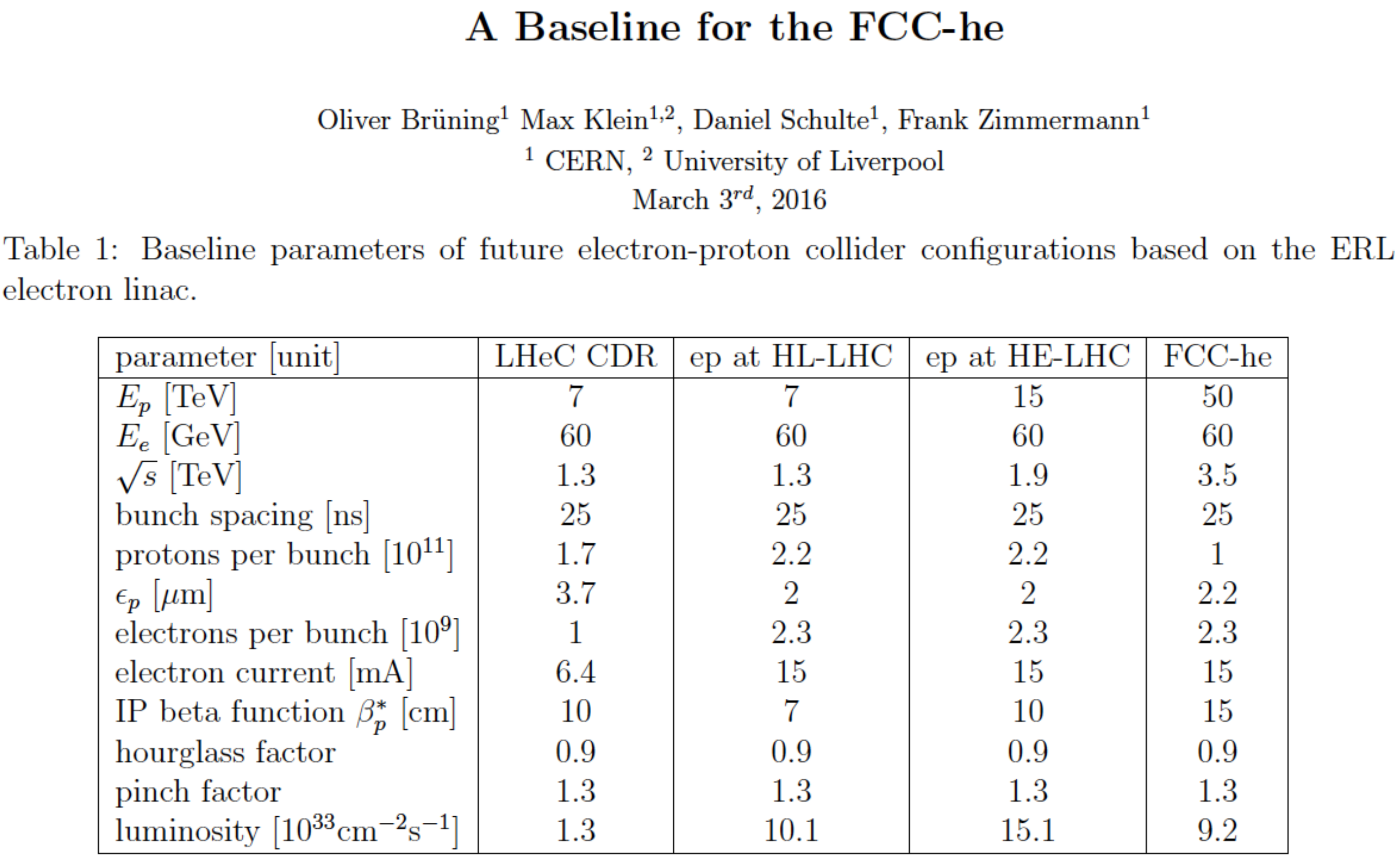
Contribution to the FCC-eh Parallel Session at the Annual FCC Workshop, Rome 11-15.4.16



A Baseline for the FCC-he

Oliver Brüning[1] Max Klein[1,2], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool

March 3rd, 2016

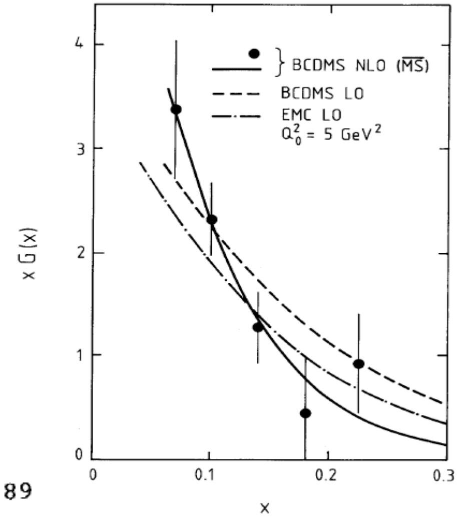
Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

4.3.2016 - *work in progress* Study value of dedicated operation O(10^{35} cm^{-2} s^{-1}), also eA

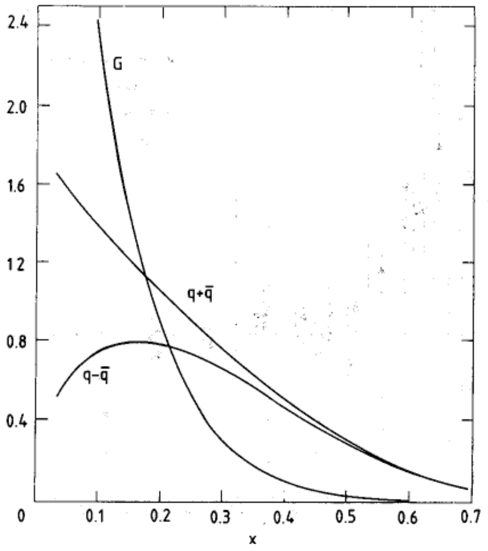
Gluons and Quarks 1989 → 2015

BCDMS



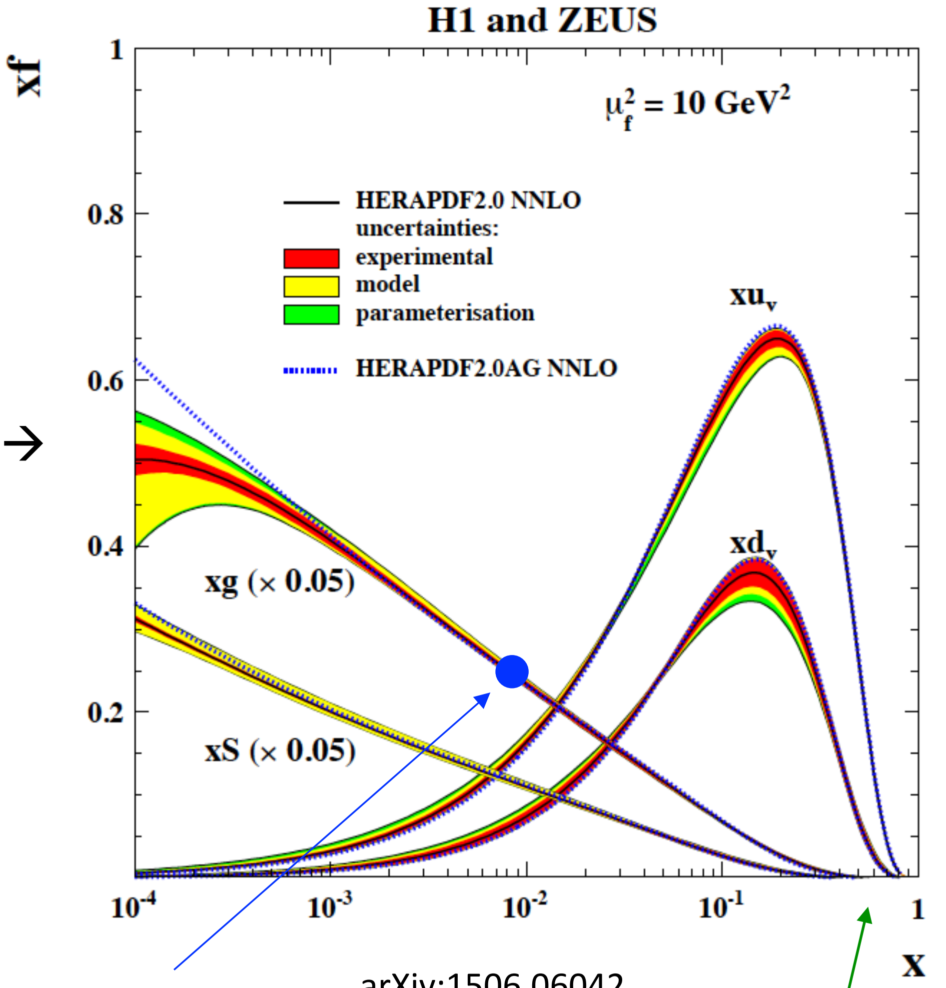
CERN-EP/89-07
January 17th, 1989

fixed target lN to ep collider →



CDHS

CERN-EP/89-103
15 August 1989

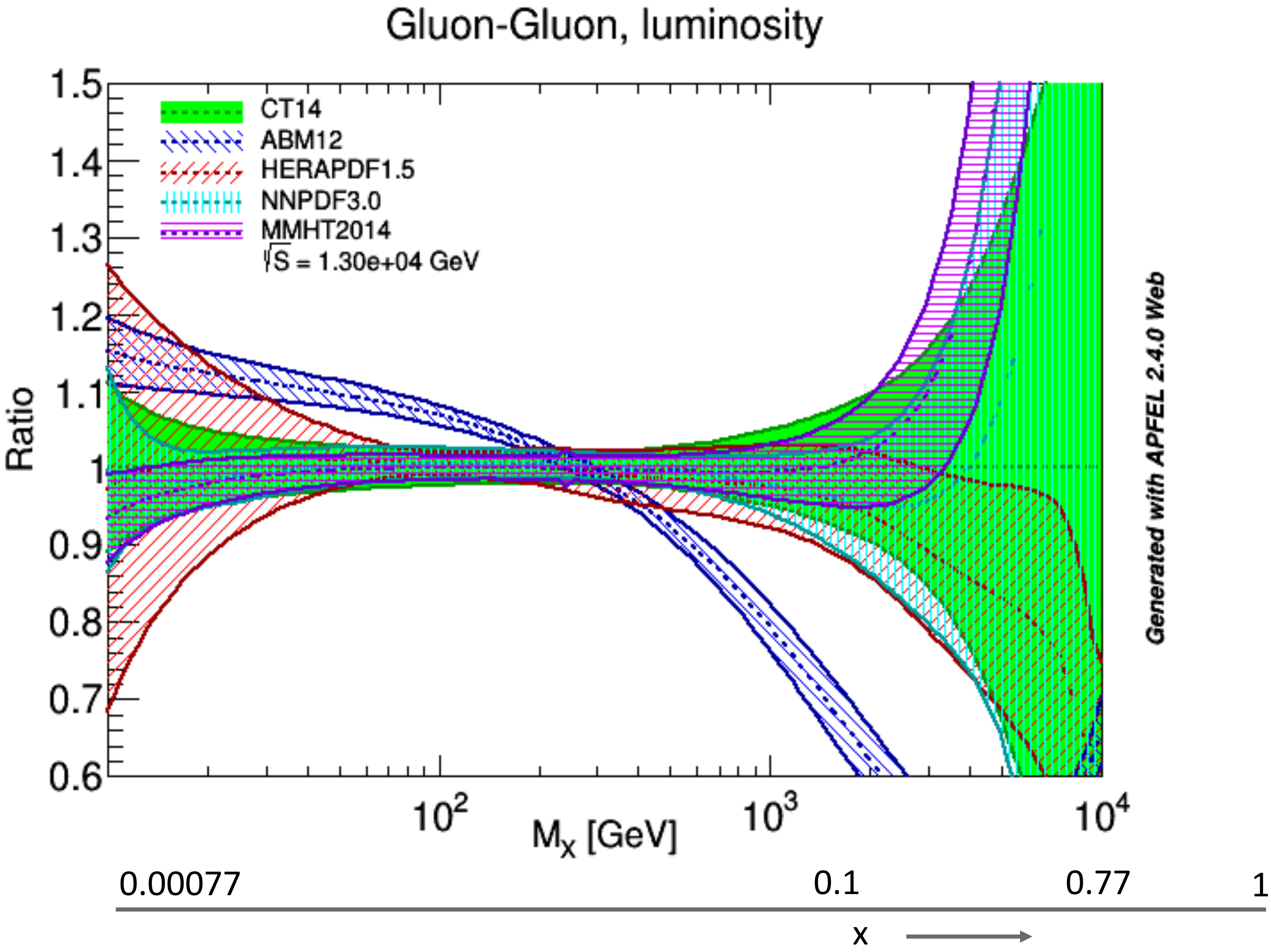


gg→H
(y=0)

arXiv:1506.06042
“Legacy” paper NC/CC
HERAPDF2.0 NNLO

High mass
HL-LHC

Parton-Parton “Luminosities”



A remark on gluon saturation

xg is defined via theory, not directly observable: HERA has discovered rise towards low x

Non-linear gg interactions are expected/predicted to exist (BFKL and GLR)

The only reliable measurement of xg at HERA at x <0.1 came from dF2/dlnQ2

It shows a huge variation (in DGLAP) of xg(x,Q2) also with Q2:
In particular xg is valence like at Q2 ~ 1 GeV2 → ~ZERO at small x

There thus are two reasons to require Q2 >~ 10 GeV2 in the search for saturation:

- The gluon density has to be large
- The strong coupling has to be small (<<1) for npQCD effects to not interfere

Searches for gluon saturation require energies in excess of those at HERA, not smaller

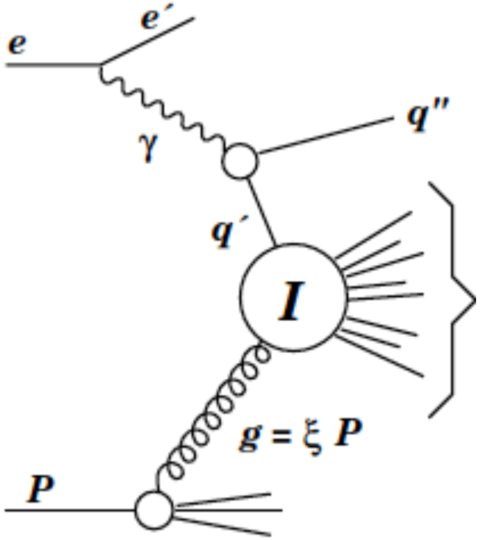
The in my view only hope to see that is to confront F2 (ep) with FL (ep) data.

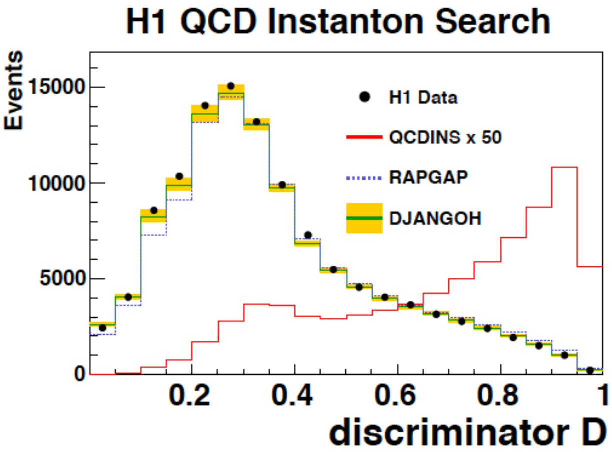
The direct extractions of xg in ep and eA THEN could reveal an amplification in eA..

Fluctuations of the Gluon Field - Instantons ?

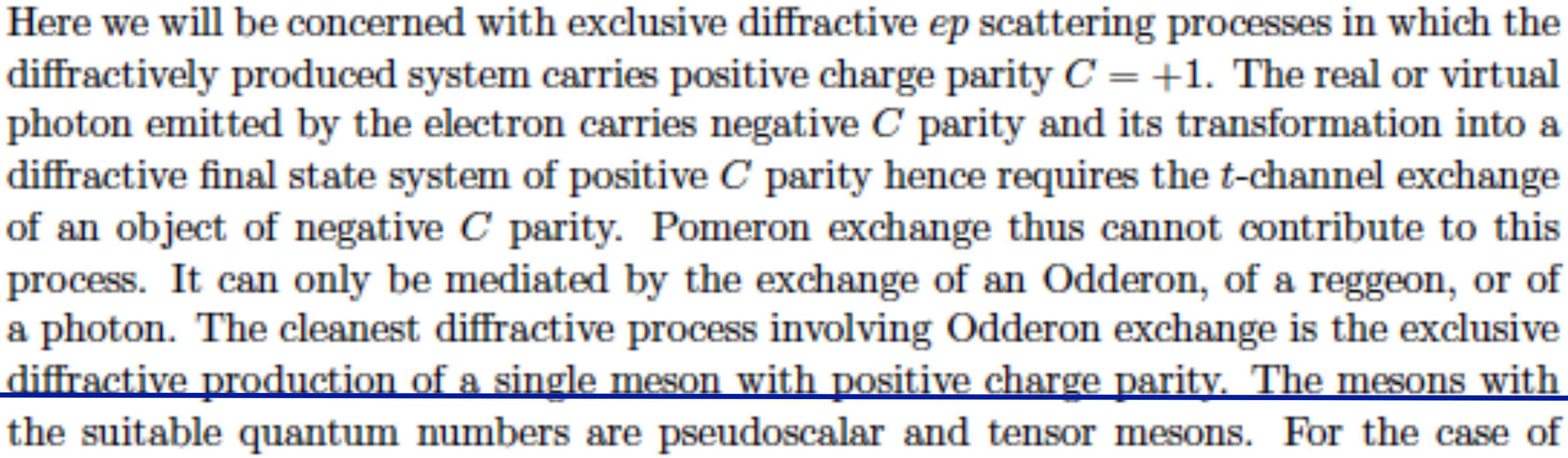
The Standard Model of particle physics contains certain anomalous processes induced by instantons which violate the conservation of baryon and lepton number ($B + L$) in the case of electroweak interactions and chirality in the case of strong interactions [1,2]. In quantum chromodynamics (QCD), the theory of strong interactions, instantons are non-perturbative fluctuations of the gluon field. They can be interpreted as tunnelling transitions between topologically different vacua. Deep-inelastic scattering (DIS) offers a unique opportunity [3] to discover a class of hard processes induced by QCD instantons.

NEW:
H1: DESY 16-150
March16
O(3)pb xsection limits





Odderon



Here we will be concerned with exclusive diffractive *ep* scattering processes in which the diffractively produced system carries positive charge parity $C = +1$. The real or virtual photon emitted by the electron carries negative C parity and its transformation into a diffractive final state system of positive C parity hence requires the t-channel exchange of an object of negative C parity. Pomeron exchange thus cannot contribute to this process. It can only be mediated by the exchange of an Odderon, of a reggeon, or of a photon. The cleanest diffractive process involving Odderon exchange is the exclusive diffractive production of a single meson with positive charge parity. The mesons with the suitable quantum numbers are pseudoscalar and tensor mesons. For the case of

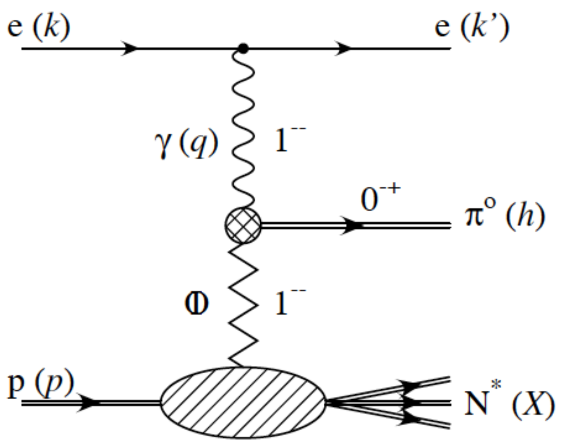


Figure 1: Diagram for the process $ep \to e\pi^{\circ}N^{*}$: the proton is excited into an (I=1/2)-isobar while a high energy single π° is produced by photon-Odderon fusion.

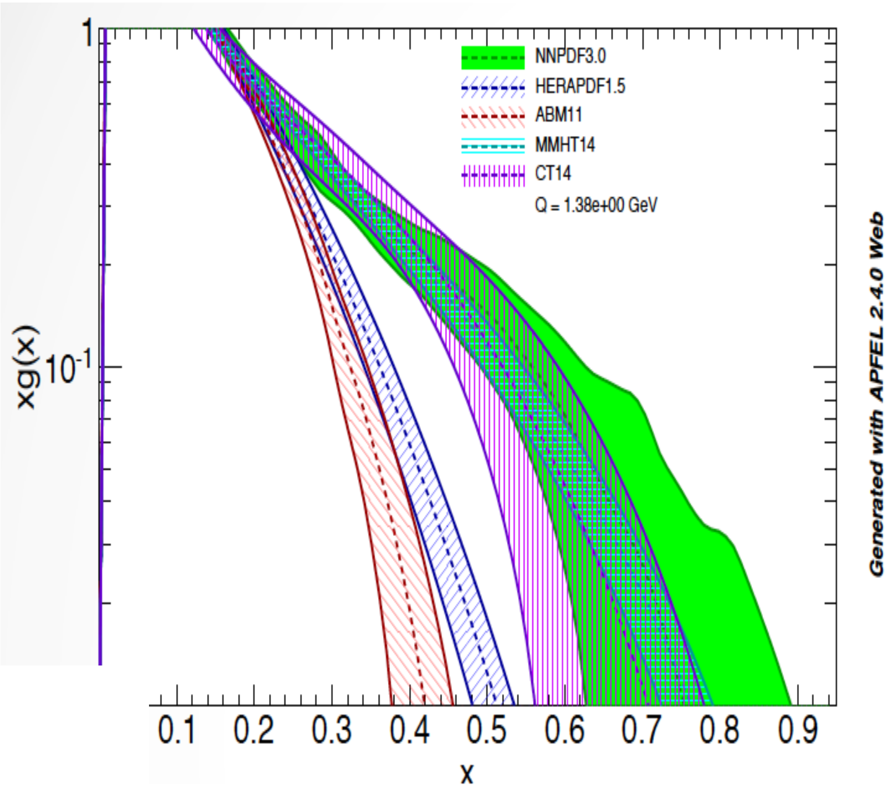
C.Ewerz
hep-ph/0306137

H1
arXiv:0206073

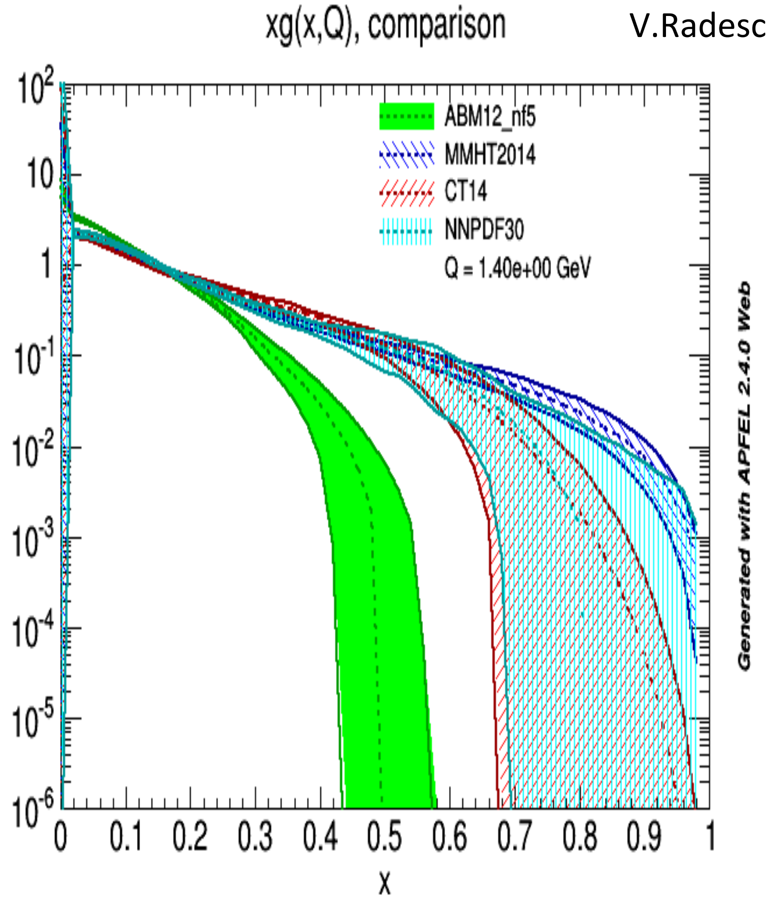
Three gluon state of parity C=-1. A small modification to Pomeron exchange/rapidity gaps..

Gluon at High x and Universality.?

C.Gwenlan



V.Radescu



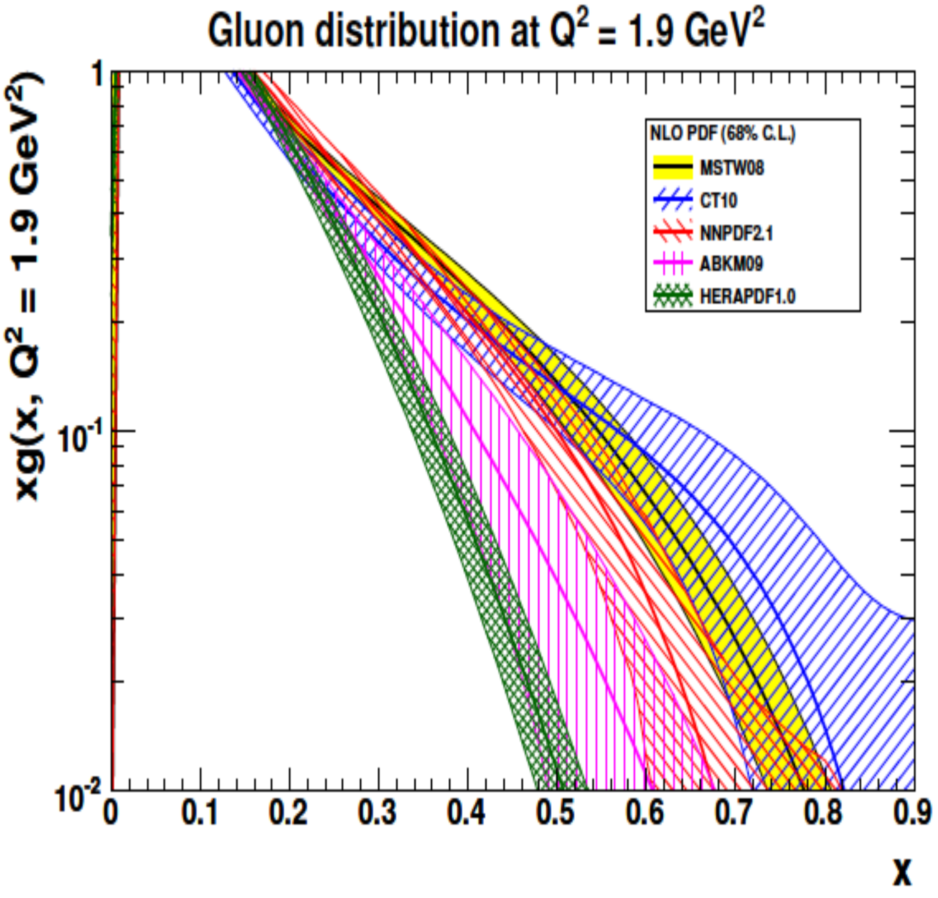
HERA and ABM gluons are much steeper at large x than those of MMHT,CT,NNPDF
→ Can we trust factorisation, how do we test it
Gluon at large x become very small and are hugely uncertain. But $M_X^2=sx_1x_2$ ..

PDF sets and their assumptions

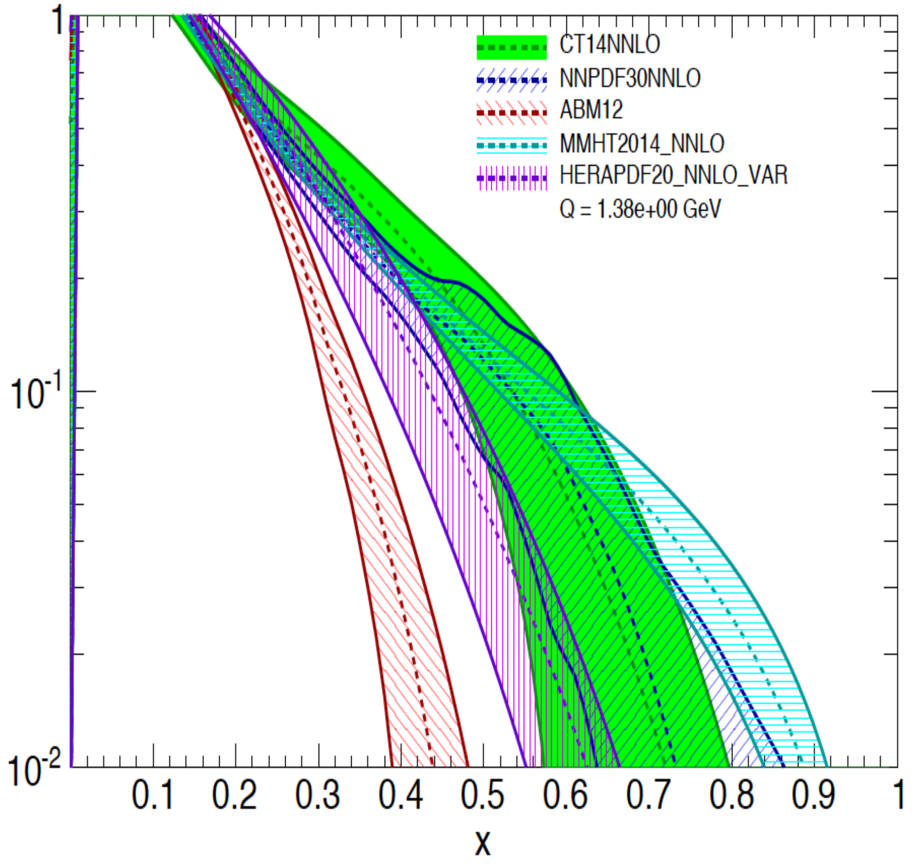
V.Radescu 10/15	CT14	MMHT15	NNPDF3.0	HERAPDF2.0	ABM12	CJ12	JR14
HQ scheme	VFNS (ACOT-χ)	VFNS (TR opt)	VFNS (FONLL)	VFNS (TR opt)	FFNS Run mc (ABM)	VFNS (ACOT)	FFNS (JR)
orders	LO, NLO, NLLO	LO, NLO, NLLO	LO, NLO, NLLO	LO, NLO, NLLO	NLLO	NLO	NLO, NLLO
α(Mz)	fixed(fitted)	fixed (fitted)	fixed	fixed	fitted	fixed	fitted
α(Mz) LO α(Mz) NLO α(Mz) NNLO	0.1300 0.1180 (0.117) 0.1180 (0.115)	0.1350 0.1180 (0.1201) 0.1180 (0.1172)	0.1180 0.1180 0.1180	0.1300 0.1180 0.1180	- - 0.1132	- 0.118 -	- 0.1158 0.1136
Nr param.	Pol. Bernst. 28	Pol. Cheb. 25	NN (259)	Pol. 14	Pol. 24	Pol. 22	Pol.25
PDF assumptions	ubar/dbar=1(x->0) u/d=1 (x->0)	s-sbar=fit. dbar-ubar=fit.	dbar-ubar=fit	ubar=dbar (x->0) sbar=0.67*dbar	s=sbar dbar-ubar=fit	dv/uv=const s+sbar=k(ubar+dbar)	dbar-ubar=fit
Stat. treatm.	Hessian $\Delta\chi2=100$ (90% CL)	Hessian $\Delta\chi2$ Dynamical (68% CL)	Monte Carlo (68% CL)	Hessian $\Delta\chi2=1$ (68% CL)	Hessian $\Delta\chi2=1$ (68% CL)	Hessian $\Delta\chi2=1$ (68% CL)	Hessian $\Delta\chi2=1$ (68% CL)
Q2min	2	2	3.5	3.5	2.5	1.69	2
HERA data	HERA I+ charm	HERA I charm jets	HERA I+ H1 and ZEUS II charm	HERA I+II	HERA I charm	HERA I	HERA I charm jets
Fix. Target DIS	✓	✓	✓	N/A	✓	JLAB, high x ✓	JLAB, high x ✓
Tevatron W,Z	✓	✓	✓	N/A	✗	✓	✗
Tevatron Jets	✓	✓	✓	N/A	✗	✗	✓
Fix. Target DY	✓	✓	✓	N/A	✓	✓	✓
LHC WZ	✓	✓	✓	N/A	✓	✗	✗
LHC jets	✓	✓	✓	N/A	✗	✗	✗
LHC top	✗	✓	✓	N/A	✓	✗	✗
LHC charm	✗	✗	✓	N/A	✗	✗	✗
References	arXiv:1506.07443	arXiv:1412.3989	arXiv:1410.8849	arXiv:1506.06042	arXiv:1310.3059	arXiv:1212.1702	arXiv:1403.1852

Gluon at High x ?

A QCD problem by itself and a key question for searches as luminosity increases …



Gluon prior to LHC data (2011)

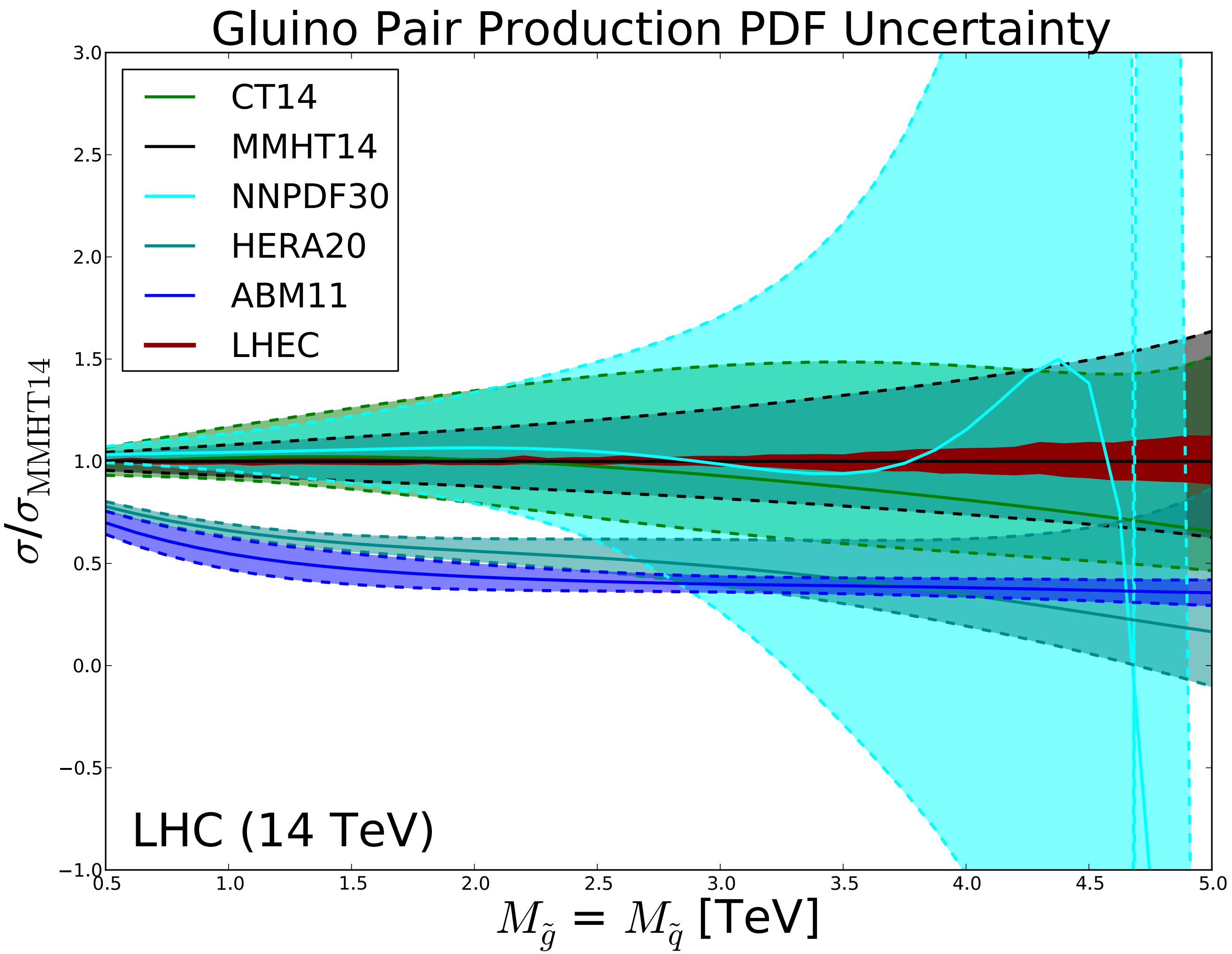


Gluon with (first) LHC data (2015)

used by CT14,NNPDF,MMHT

Related to quark distributions, low x, α_s, heavy flavour treatment, to resummation

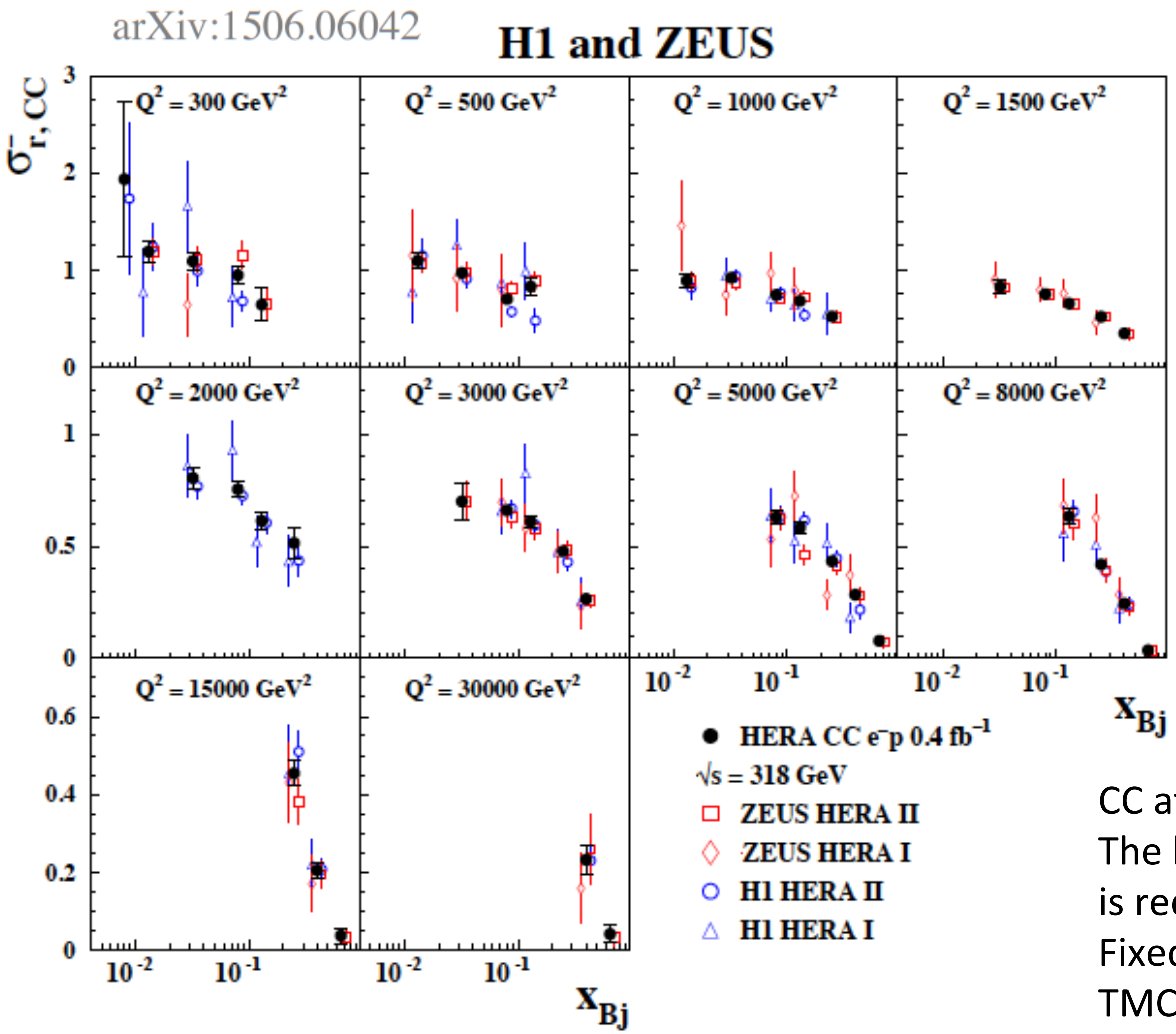
Understanding the High x = Large Mass region



Christoph Borschensky
Michael Kramer

Non resonant and smeared resonance searches at large masses require extra ep information at high x

Large Bjorken x

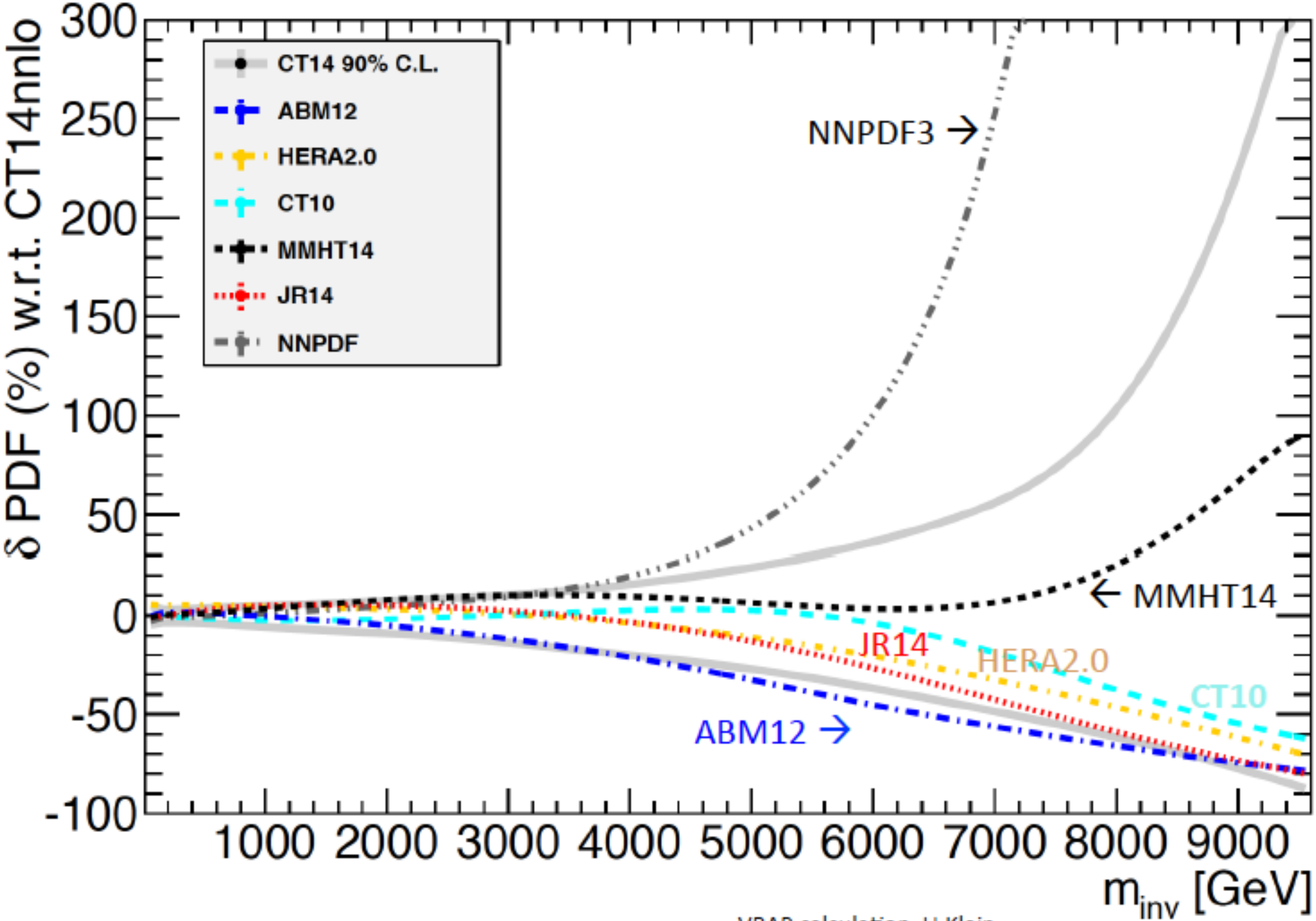


Final HERA data on charged currents

CC at HERA reached at best x=0.5.
The luminosity was 3 10^{31} while > 10^{33} is required as xq ~ $(1-x)^k$ for x → 1
Fixed target DIS data suffer from TMC, HT, nuclear corrections and inconsistencies

→ **There is no reliable base for predictions at large x**

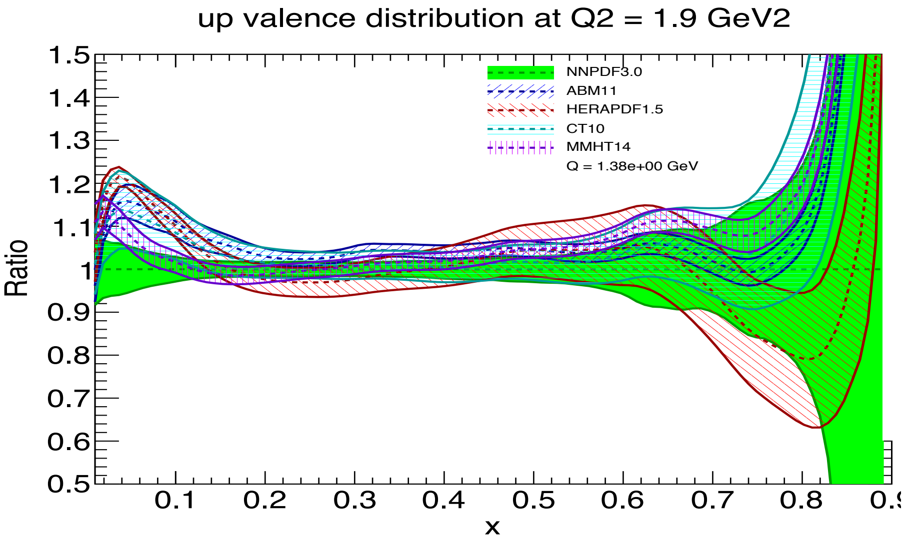
Very High Mass Dell Yan 13 TeV - σ(PDF)/σ(CT14)



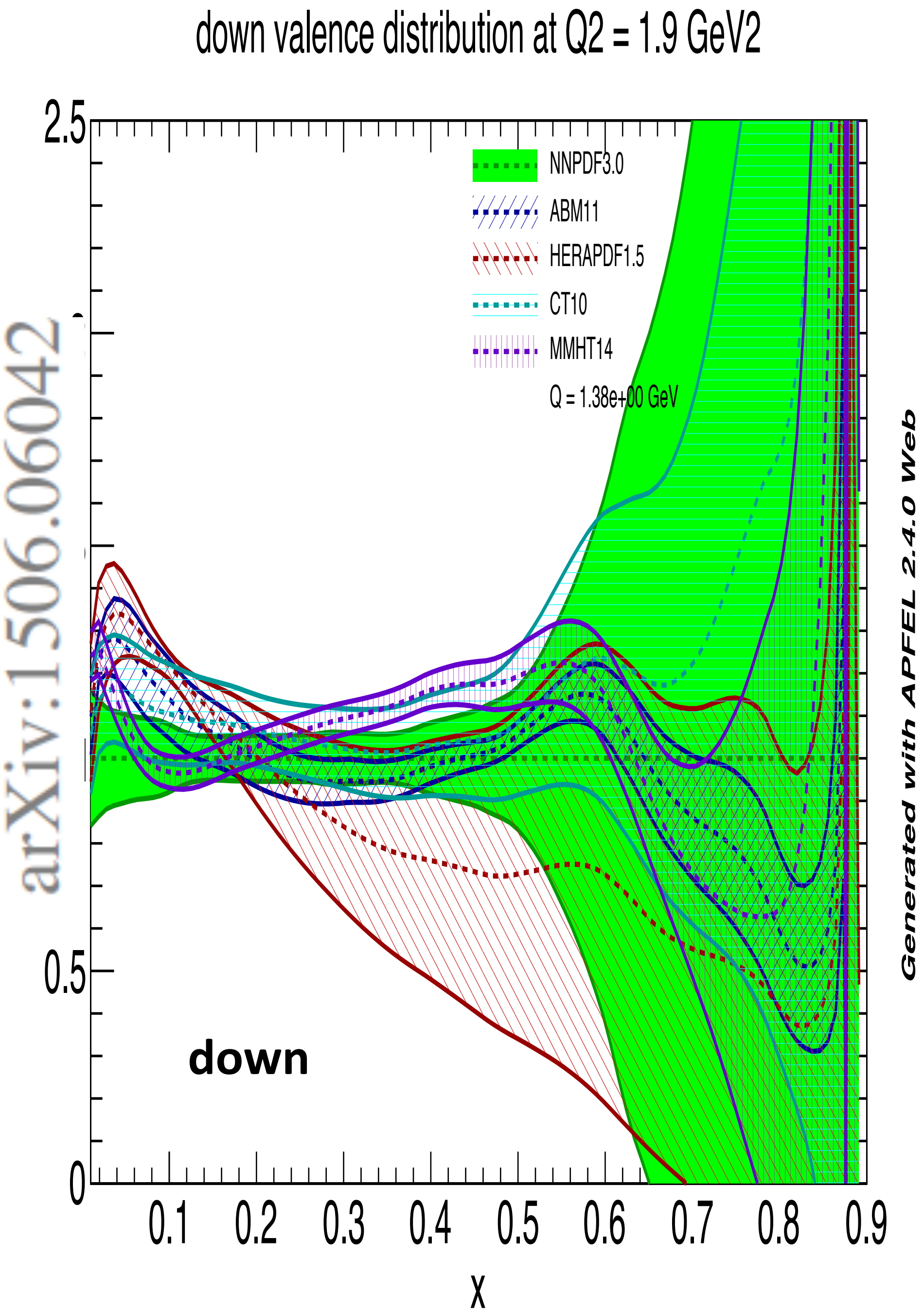
VRAP calculation, U.Klein

Valence quarks

up



up valence distribution at Q2 = 1.9 GeV2



down valence distribution at Q2 = 1.9 GeV2

down

Related to DY , W mass etc

Recall $xq_v \sim (1-x)^3$

d/u → 1 a classic question

Remarks on Precision Higgs Physics in ep

The Higgs is produced in ep predominantly via WW→ H in ep→ nuHX

The cross section at the LHeC is ~ 200fb, i.e. very similar to that of Z*→ZH in ee

With 1ab-1 integrated luminosity from 10^34 one reaches 1% precision on bb
and 7% on cc and corresponding numbers on other channels still to be studied.
These LHeC numbers will be better at HE-LHC and FCC-eh (1%→0.4%→0.3% for bb)

At the FCC-eh the cross section is almost 1pb. Therefore, statistically, FCC-ee, with 4 10^34 luminosity at ZH and FCC-eh with 10^34 luminosity are about comparable, subject also to the running times: ee at ZH plans 3 years, ep with pp plans O(10).

Both ee and ep thus provide high precision measurements on Higgs, much complementary wrt each other AND to pp: for example

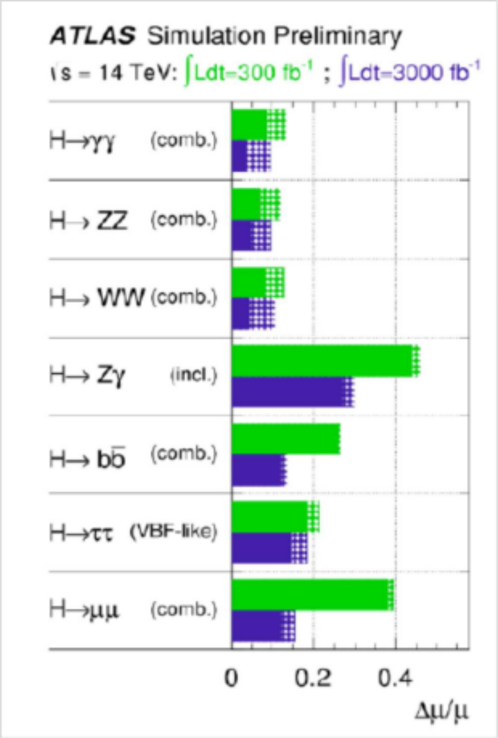
- ee uses mostly Z→ ZH, eh uses mostly WW→ H
- ee provides measurement of the Higgs boson width (to be studied in ZZ→ H at ep)
- ep provides N^3LO PDFs as are crucial for understanding the gg→H production
  it also provides prediction of Higgs mass with 100 MeV error (cf top mass and cross section physics)

Specifically: LHeC and HL-LHC are an exciting couple for precision Higgs physics at LHC

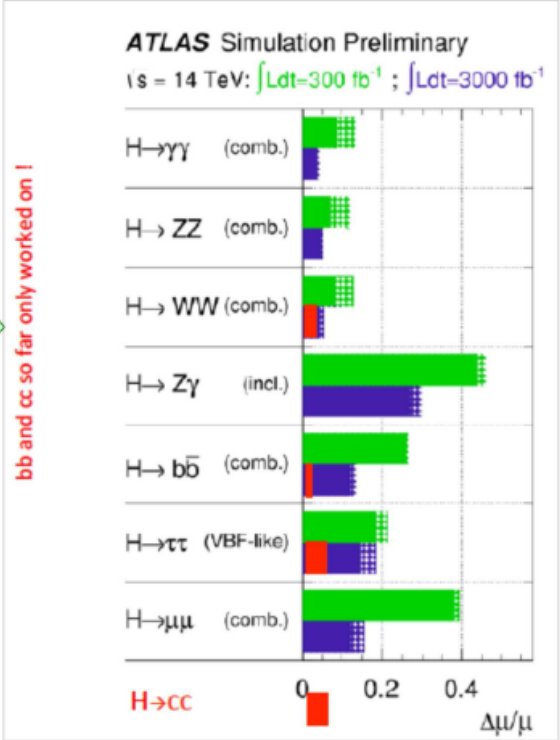
HIGGS PHYSICS AT THE LHEC

SUMMARY

HL LHC



HL LHC + LHeC

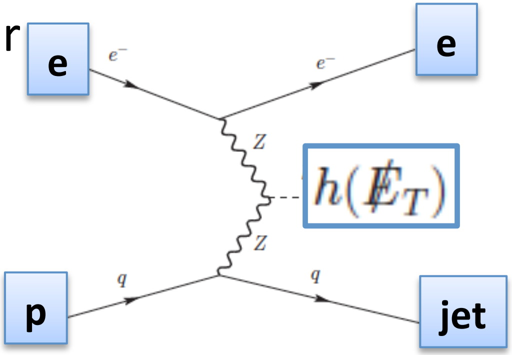


- GLUON FUSION AND W FUSION $\Rightarrow$ PDF+α_s UNCERTAINTY REMOVED (hatched bands)
- $H\bar{b}b$ MEASURED TO PERCENTAGE PRECISION;
- $\tau\tau$ AND $\bar{c}c$ ALSO MEASURABLE

Invisible Higgs@LHeC

Y.-L. Tang et al.,
arXiV: 1508.01095
→ Talk by C. Zhang

relating the Higgs and the ‘dark’ sector



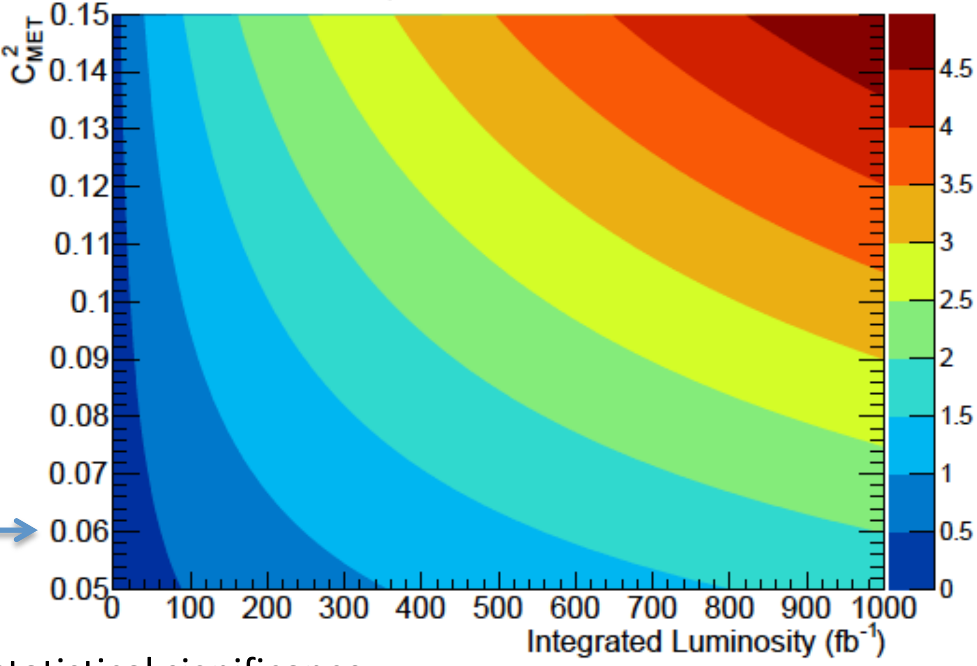
$\mathrm{Br}(h \to \not{E}_T)$
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

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

For **LHeC**, assume : 1ab^{-1}, P =-0.9, cut based

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

κ_Z : BSM w.r.t. SM HZZ coupling



Colours:
expected statistical significance

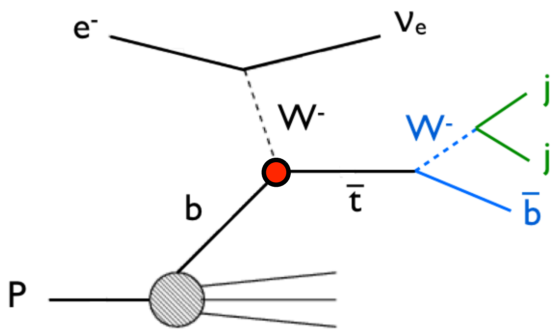
➔ potential much enhanced for **FCC-eh @ 3.5 TeV and HE-LHC-eh**

FCNC Top and Higgs couplings :
H. Sun [arXiv:1602.04670]
New study for HE-LHC
14 TeV p x 150 GeV e

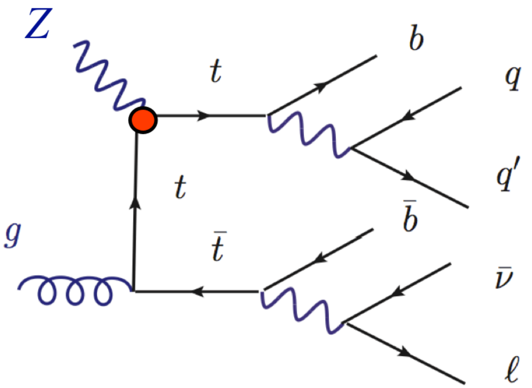
BR(t→ qh) < 0.23%
@ 95% C.L. and 100 fb^{-1}

top quark electroweak interactions

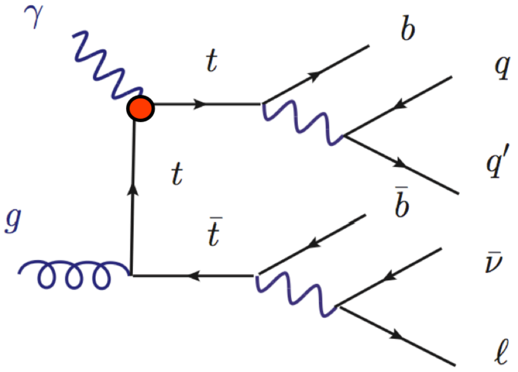
precise measurement of couplings between SM bosons and fermions sensitive test of new physics (search for deviations) : **top quark expected to be most sensitive to BSM physics, due to large mass**



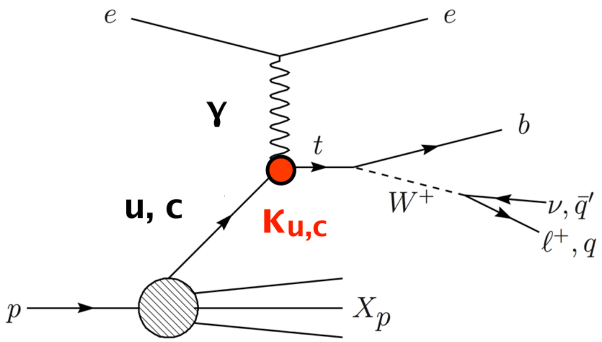
- high precision measurements of Vtb and search for anomalous Wtb couplings



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



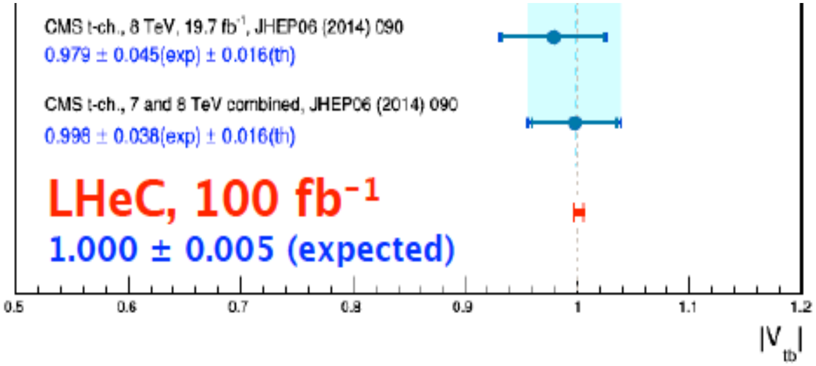
- direct measurement of top quark charge and search for anomalous ttbarγ couplings (eg. EDM, MDM)



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

Initial *ep* Top Results

V_{tb}



V_{tb}: High precision: 1306.1688

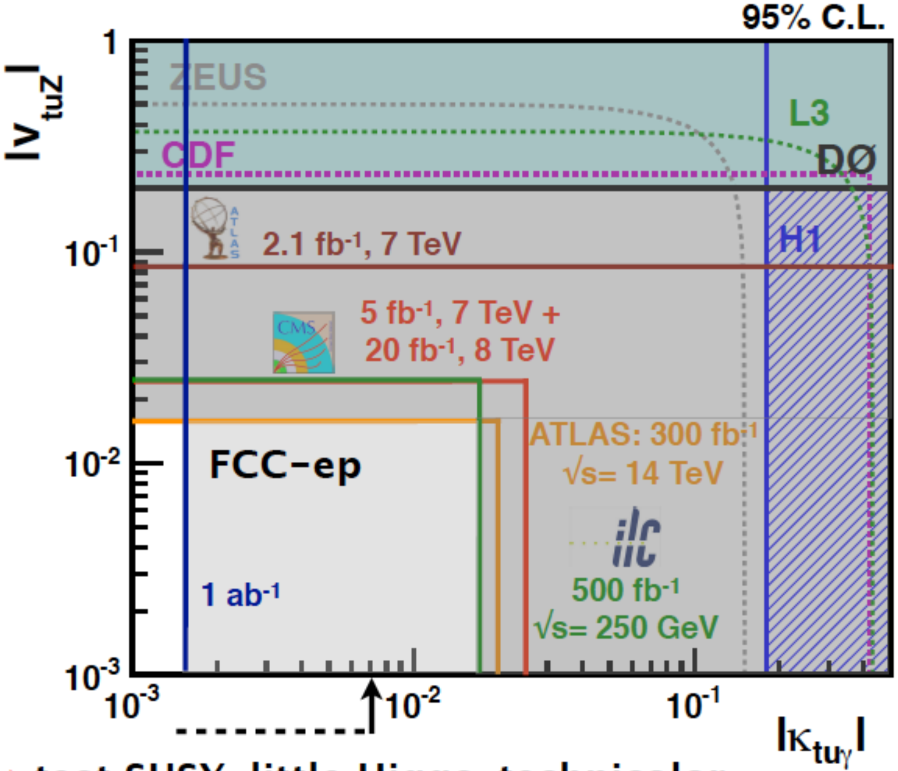
LHeC: 10x lumi, FCC-ep to be added

LHC and FCC possibilities to be considered

Anomalous Wtb Coupling

property	precision
f_V^L	0.001–0.01
f_V^R, f_T^L, f_T^R	0.01–0.1

FCNC



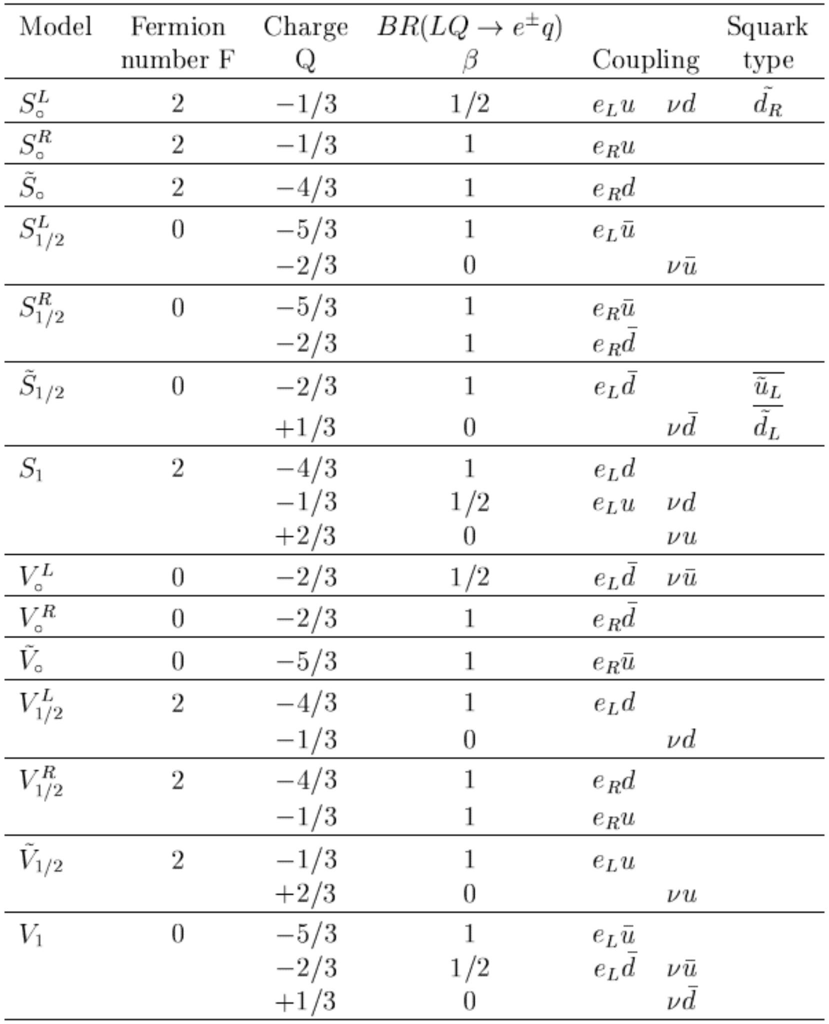
→ test SUSY, little Higgs, technicolor…

Top PDF (CDR LHeC and 1503.01590)

Mass of top? To study

Note Mass of Charm (b) to 3 (~10) MeV

Remarks on Lepto-Quarks



Model	Fermion number F	Charge Q	$BR(LQ \to e^{\pm}q)$ β	Coupling		Squark type
$S_\circ^L$	2	$-1/3$	$1/2$	$e_L u$	νd	$\tilde{d}_R$
$S_\circ^R$	2	$-1/3$	1	$e_R u$		
$\tilde{S}_\circ$	2	$-4/3$	1	$e_R d$		
$S_{1/2}^L$	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	0		$\nu \bar{u}$	
$S_{1/2}^R$	0	$-5/3$	1	$e_R \bar{u}$		
		$-2/3$	1	$e_R \bar{d}$		
$\tilde{S}_{1/2}$	0	$-2/3$	1	$e_L \bar{d}$		$\overline{\tilde{u}_L}$
		$+1/3$	0		$\nu \bar{d}$	$\overline{\tilde{d}_L}$
S_1	2	$-4/3$	1	$e_L d$		
		$-1/3$	$1/2$	$e_L u$	νd	
		$+2/3$	0		νu	
$V_\circ^L$	0	$-2/3$	$1/2$	$e_L \bar{d}$	$\nu \bar{u}$	
$V_\circ^R$	0	$-2/3$	1	$e_R \bar{d}$		
$\tilde{V}_\circ$	0	$-5/3$	1	$e_R \bar{u}$		
$V_{1/2}^L$	2	$-4/3$	1	$e_L d$		
		$-1/3$	0		νd	
$V_{1/2}^R$	2	$-4/3$	1	$e_R d$		
		$-1/3$	1	$e_R u$		
$\tilde{V}_{1/2}$	2	$-1/3$	1	$e_L u$		
		$+2/3$	0		νu	
V_1	0	$-5/3$	1	$e_L \bar{u}$		
		$-2/3$	$1/2$	$e_L \bar{d}$	$\nu \bar{u}$	
		$+1/3$	0		$\nu \bar{d}$	

Buchmueller Rueckl Wyler Classification

LQs are produced in s channel eq fusion

DIS is ideal for LQ spectroscopy

The huge energy in pp implies that
LQs are more likely discovered in pp:

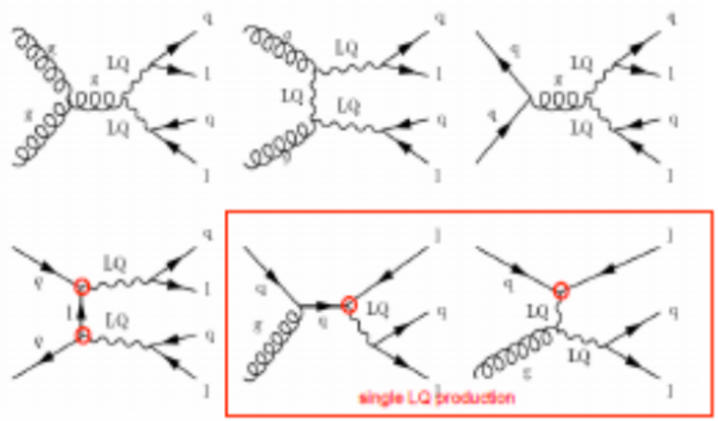
LHC limits are near sqrt(s) of LHeC

FCC-ep when operating in parallel with
FCC-pp has strong discovery potential
up to its maximum energy of 3.5 TeV

→ The choice of E_e is much dictated by
new physics (also Higgs and top and low x)

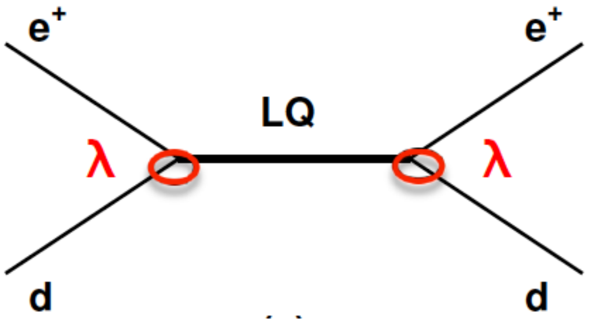
LQ production at LHC ad LHeC

- **leptoquarks (LQs)** appear in several extensions to SM: production $\sigma \sim \lambda^2 q(x)$
- can be **scalar** or **vector**, with fermion number 0 (e^-qbar) or 2 (e^-q)
- At LHC, mostly pair production (from gg or qq)
  - if λ not too strong (0.3 or lower), cross section independent on λ
  - Exclude up to 900 GeV for 1° generation
  - Expect to exclude up to 1.2 (1.5) TeV at 14 TeV 300 fb^{-1} for scalar (vector)-LQ

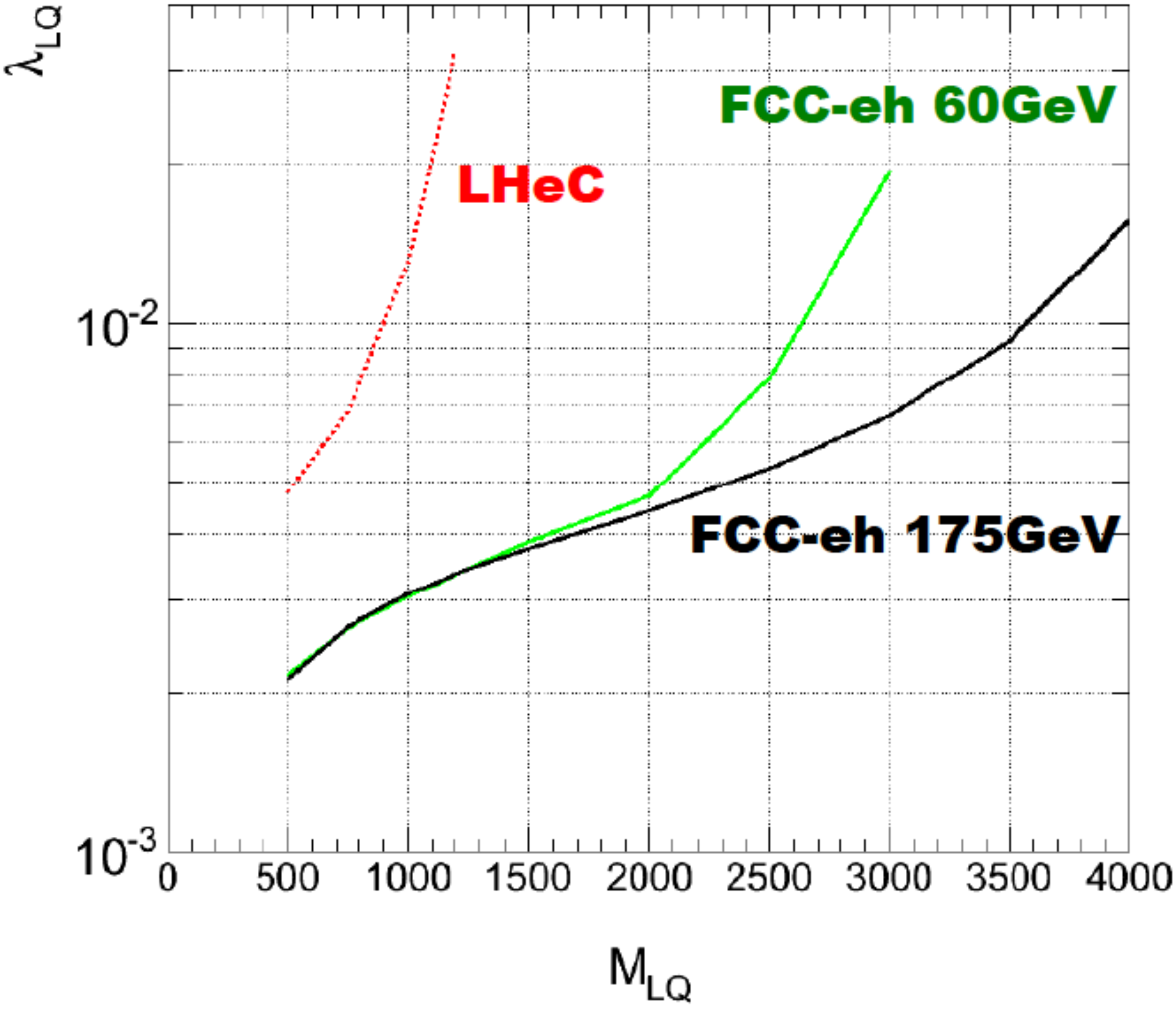


At the LHC, pair production is essentially independent of the LQ-q-e coupling λ → pair production abundant

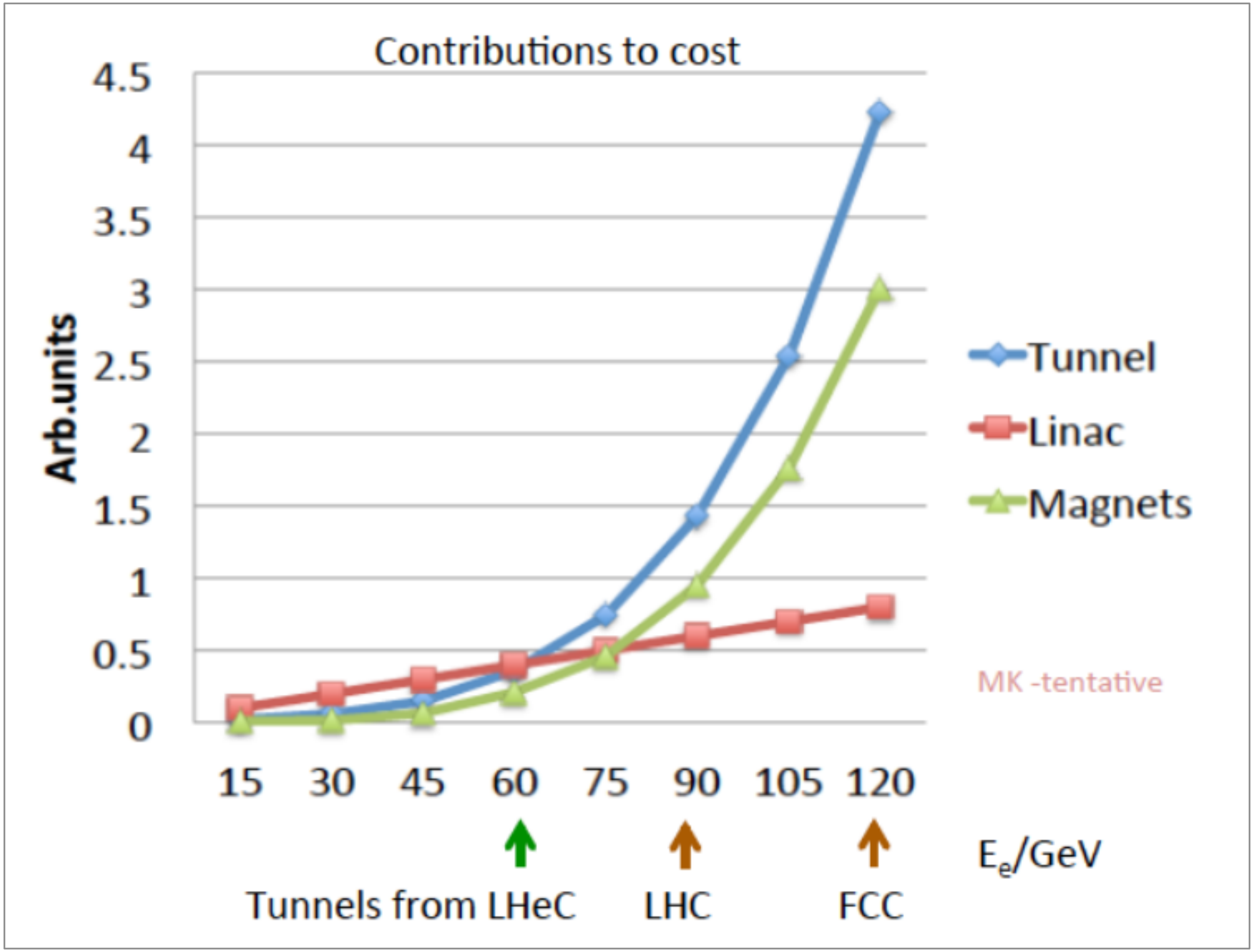
- **At the LHeC:** both baryon and lepton quantum numbers - ideally suited to search for and study properties of new particles coupling to both leptons and quarks



- single, resonant production; sensitive to λ


λ_{LQ}
FCC-eh 60GeV
LHeC
FCC-eh 175GeV
10^{-2}
10^{-3}
0
500
1000
1500
2000
2500
3000
3500
4000
M_{LQ}

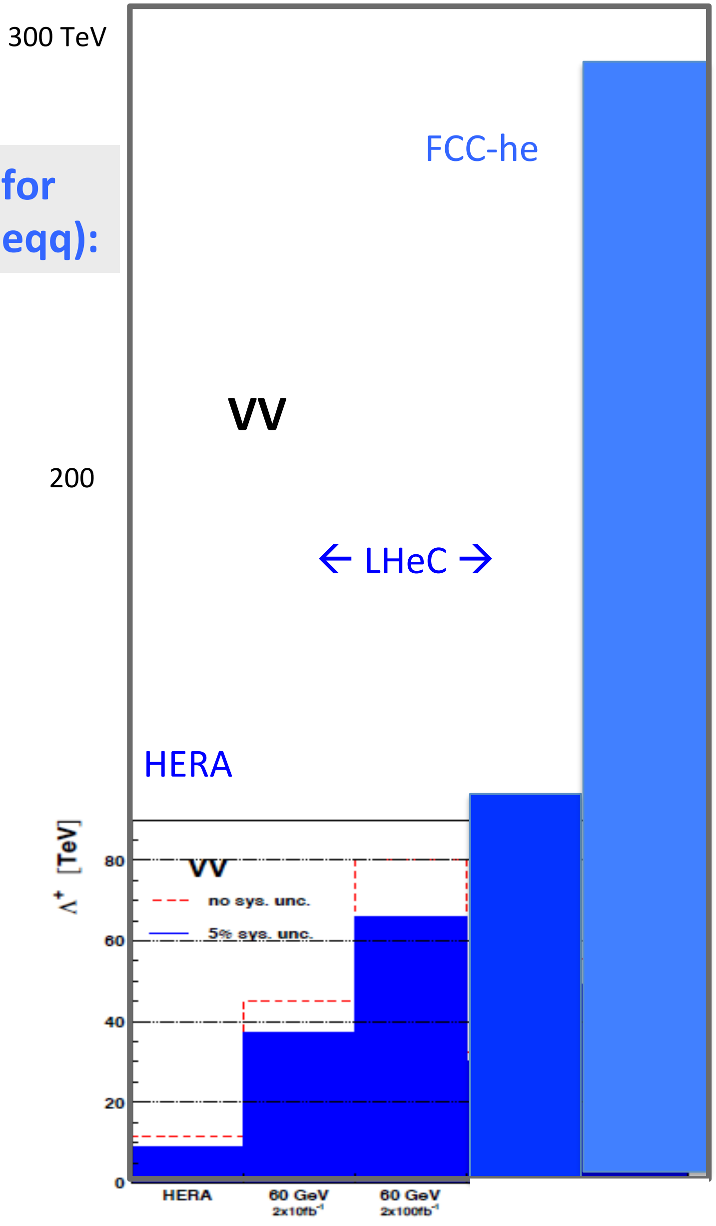
Choice of Baseline Configuration = f(cost,E_e,s)

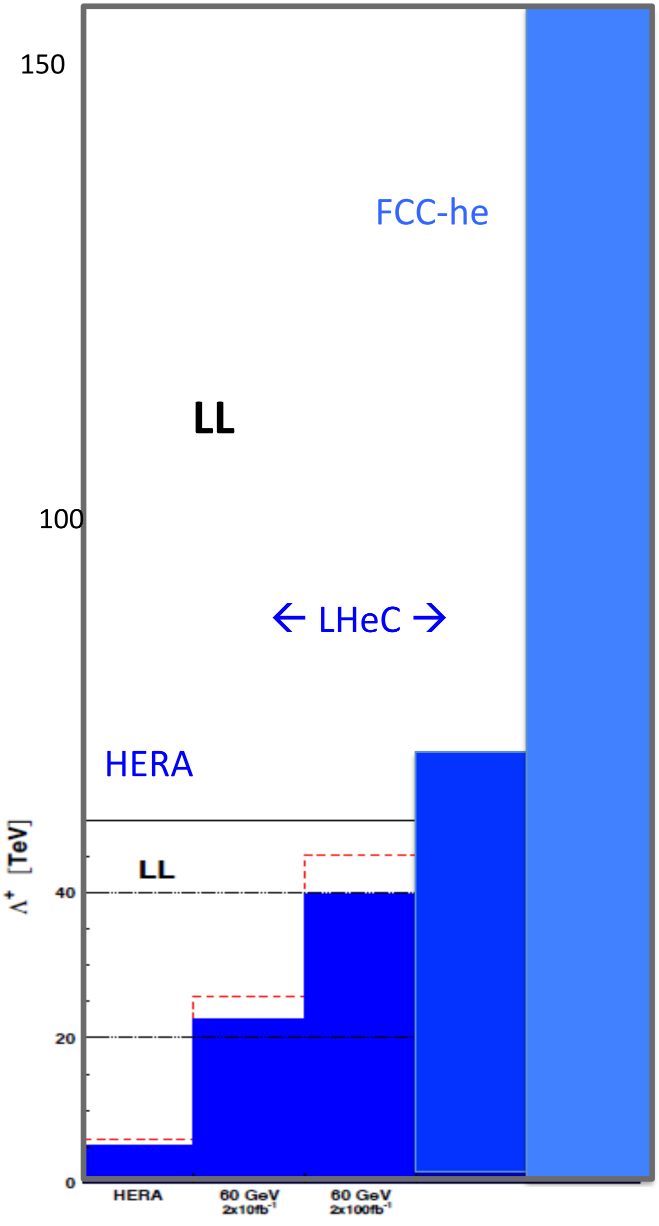


→ Cost strongly rising with tunnel circumference. Presently stick to LHeC default.

→ Maximise independence of ring installation, design for synchronous ep and pp OP

Reach for Λ (CI eeqq):

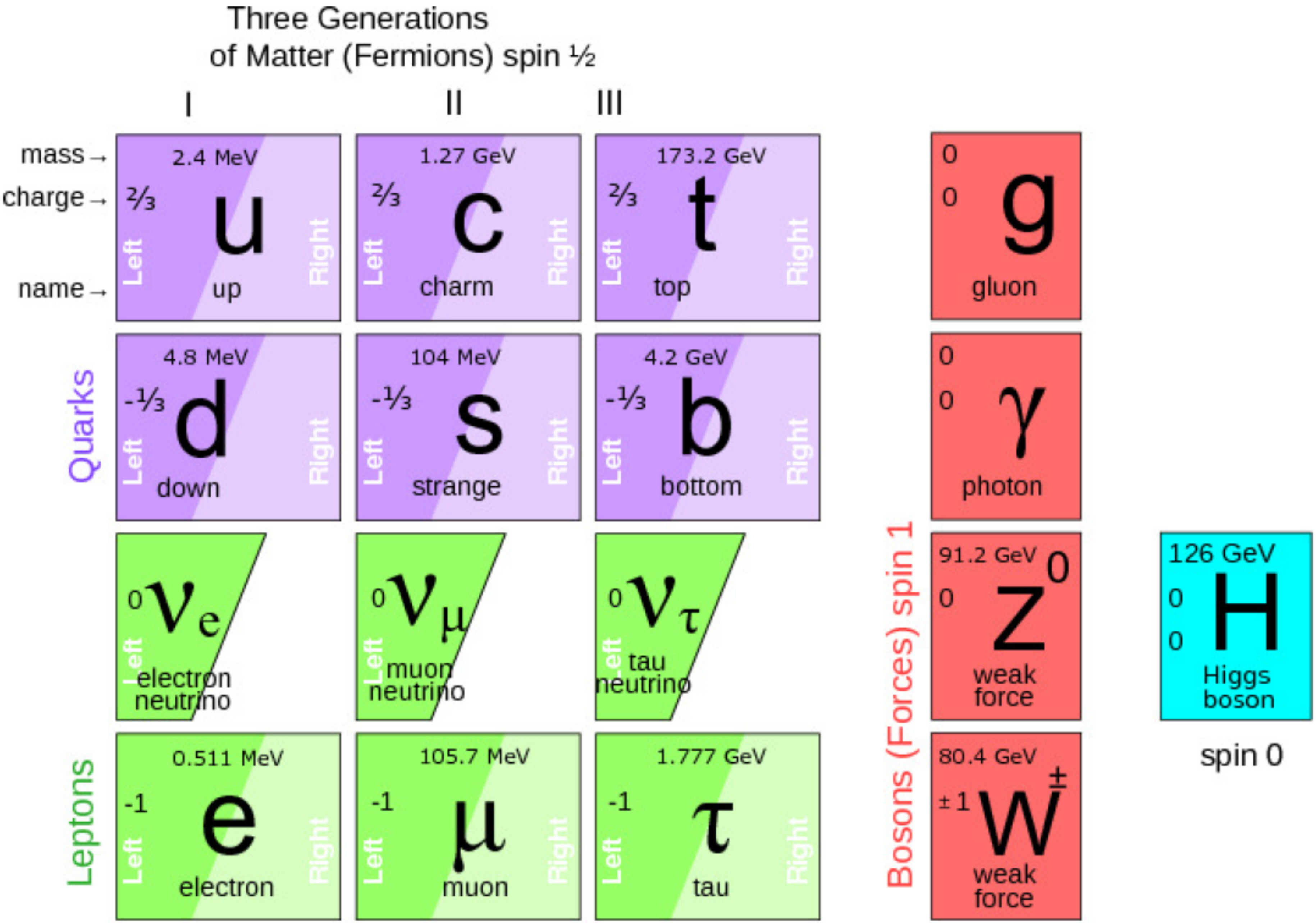




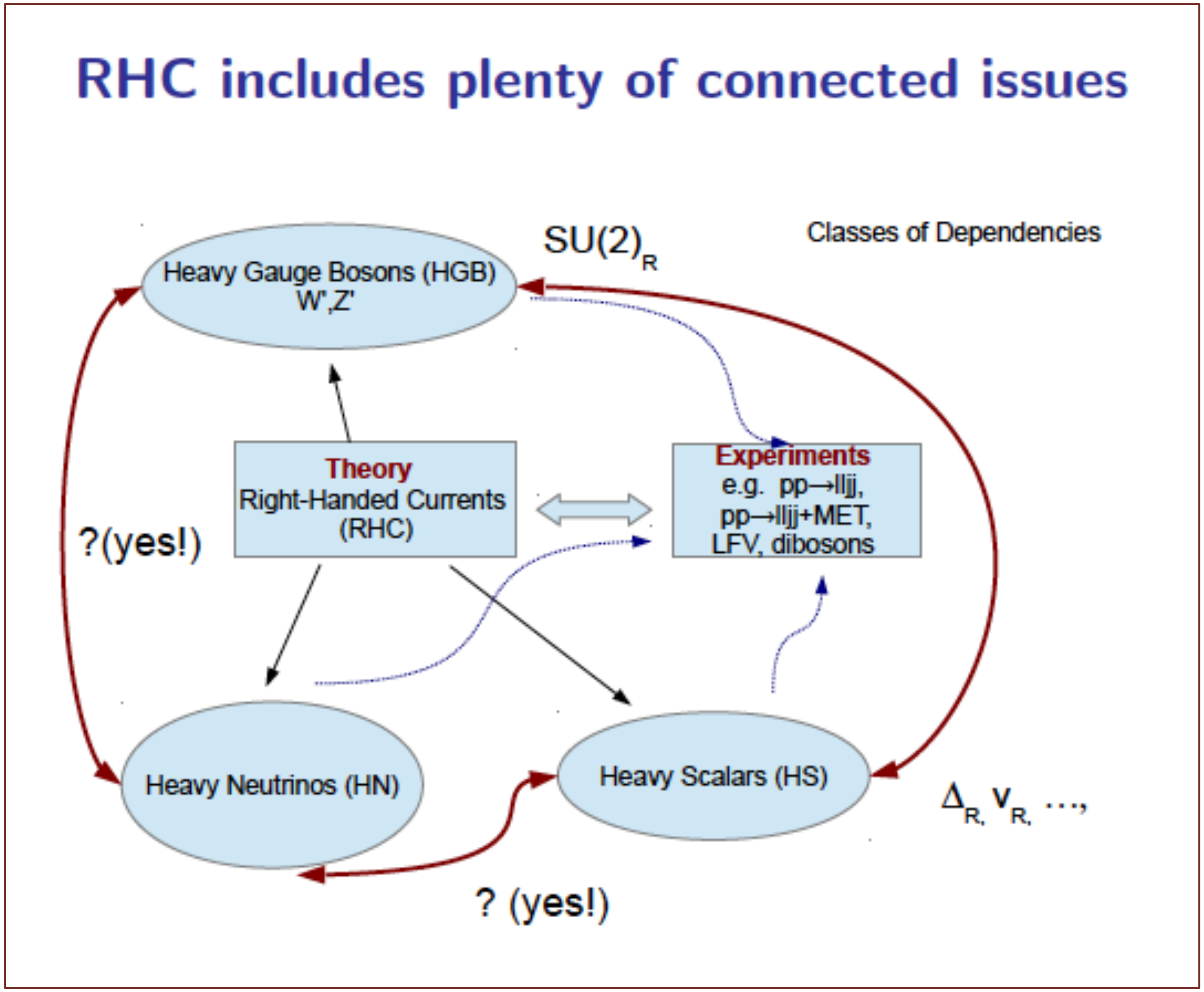
LHeC: see CDR 2012

FCC - rough scaling only – very preliminary

Search for + verification of Contact Interactions into O(100)TeV. eq Fusion: Leptoquarks $M<\sqrt{s}$


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
Left
Right
1.27 GeV
⅔
c
charm
Left
Right
173.2 GeV
⅔
t
top
Left
Right
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
Left
Right
104 MeV
-⅓
s
strange
Left
Right
4.2 GeV
-⅓
b
bottom
Left
Right
0
0
γ
photon
0
ν_e
Left
electron
neutrino
0
ν_μ
Left
muon
neutrino
0
ν_τ
Left
tau
neutrino
Bosons (Forces) spin 1
91.2 GeV
0
Z^0
weak
force
126 GeV
0
0
H
Higgs
boson
spin 0
Leptons
0.511 MeV
-1
e
electron
Left
Right
105.7 MeV
-1
μ
muon
Left
Right
1.777 GeV
-1
τ
tau
Left
Right
80.4 GeV
±1
$W^\pm$
weak
force

Right Handed Currents and Heavy Neutrinos



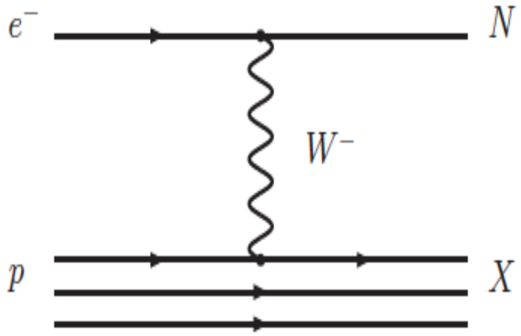
RHC includes plenty of connected issues

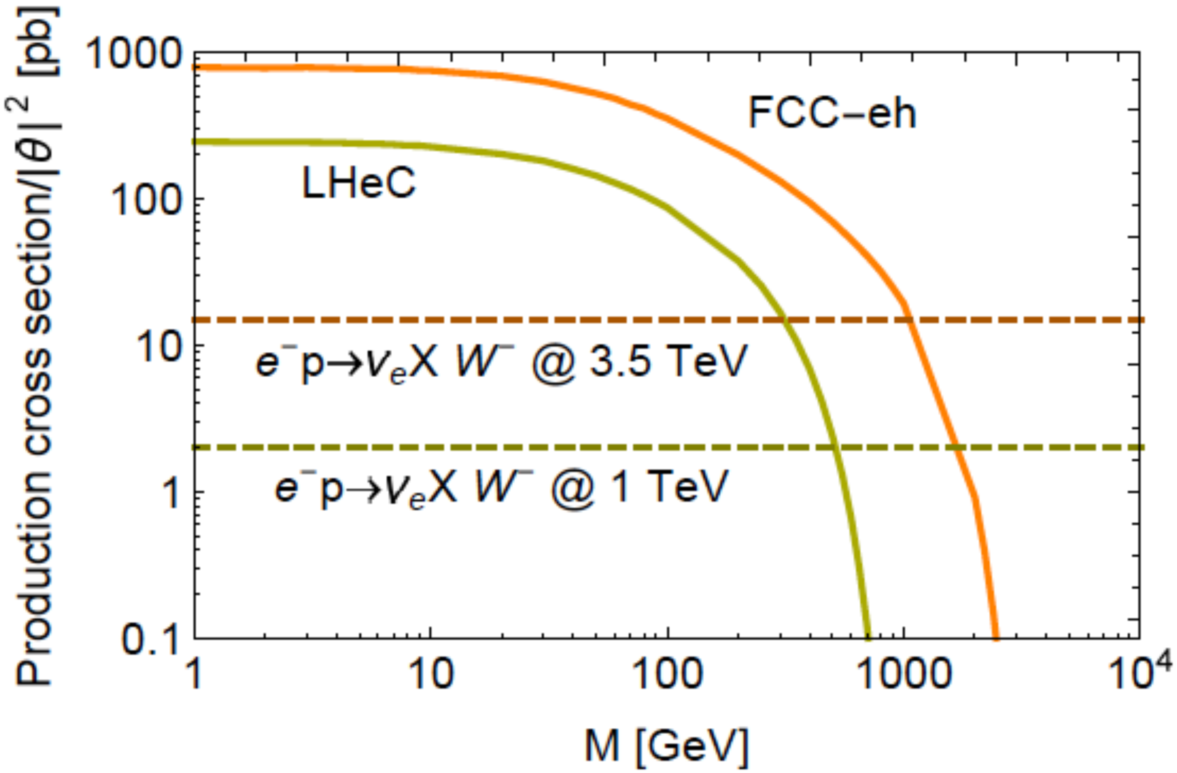
$$\begin{pmatrix} \nu_L \\ N_R \end{pmatrix} = \begin{pmatrix} U_{3\times3} & V_{3\times n} \\ X_{n\times3} & {K_R}^{\dagger}{}_{n\times n} \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

Tomasz Jelinsky Rom Talk

Heavy Neutrino Search at FCC (ee,hh,eh)

Oliver Fischer
Rome Talk
Sterile Neutrinos

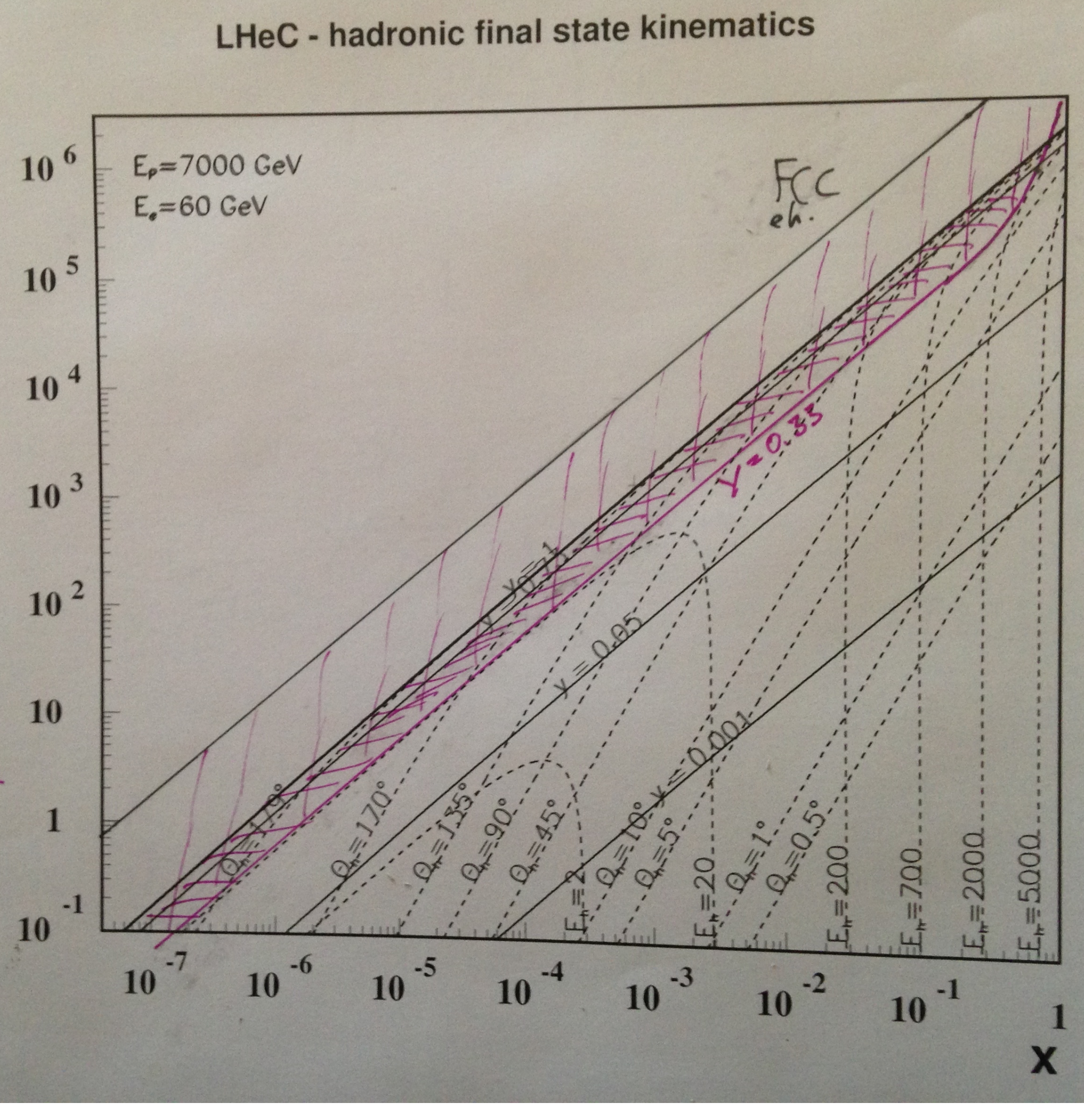




⇒ The FCCs provide great prospects for discovering the origin of neutrino masses.

- Future electron-proton colliders provide significant gain in mass reach and fairly “stable” production cross sections.

Kinematic Range of Acceptance of a 750 GeV Particle coupling to γγ (and ZZ?)



$W^2 = Q^2 \frac{1-x}{x} + M_p^2$

$\rightarrow Q^2 \simeq W^2 \cdot \frac{x}{1-x}$

$x \ll 1: Q^2 \simeq W^2 \cdot x$

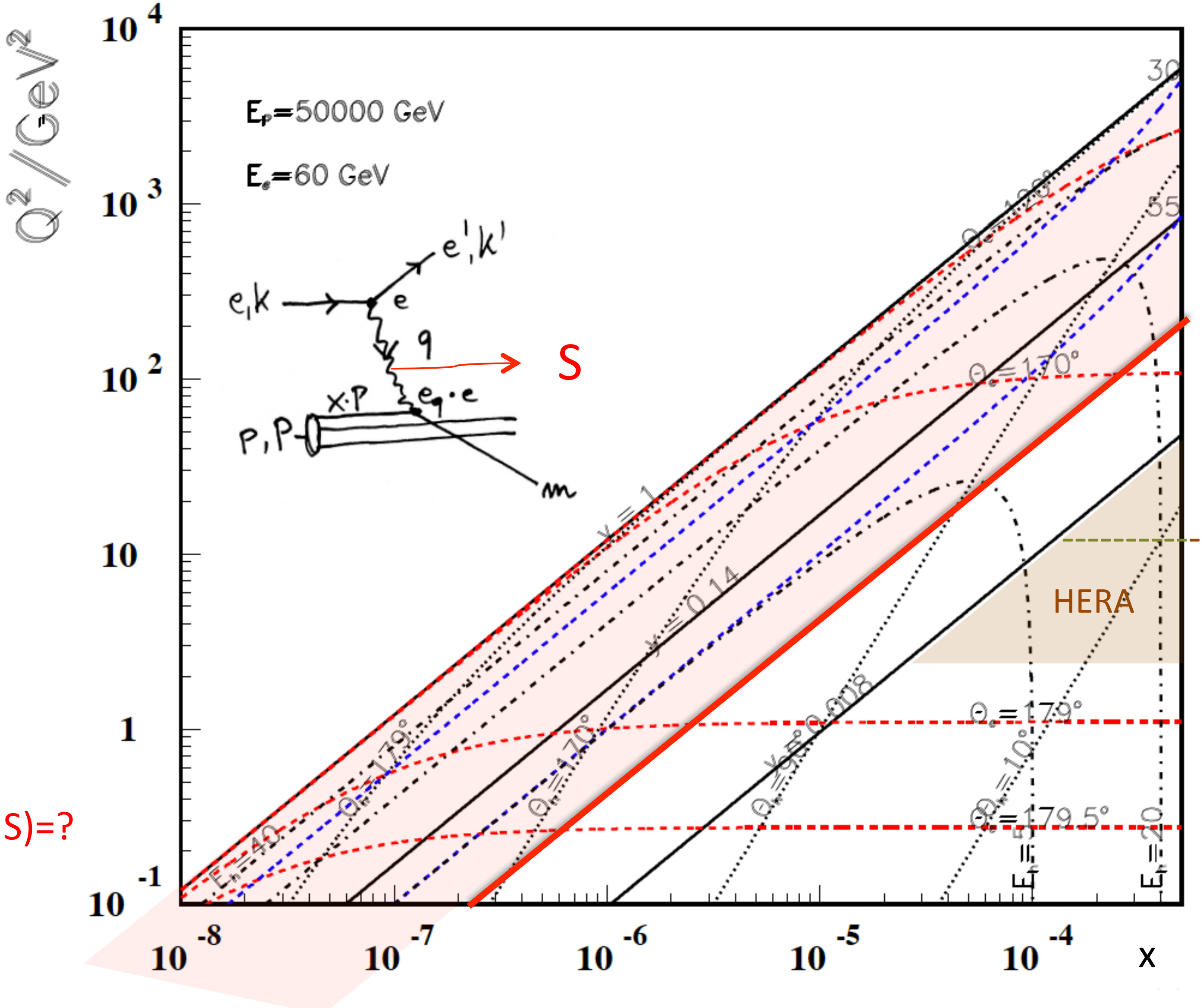
$W^2 \simeq sy$

$y \geq (750)^2 / s_{\mathrm{GeV}^2}$

$= 0.33$ LHeC

0.047 FCCeh.

Acceptance of a 750 GeV Ghost S



FCC-he
60 GeV

LHeC

← y >0.047
(=0.33 LHeC)

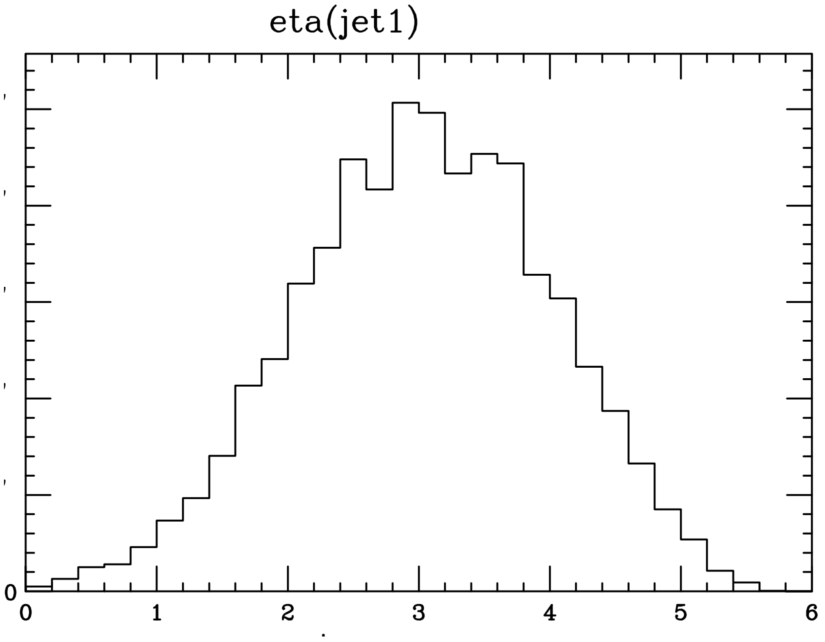
← 179°
@ 180 GeV
.. very low x
requires not
the maximum
of E_e

σ(γγ→ S)=?

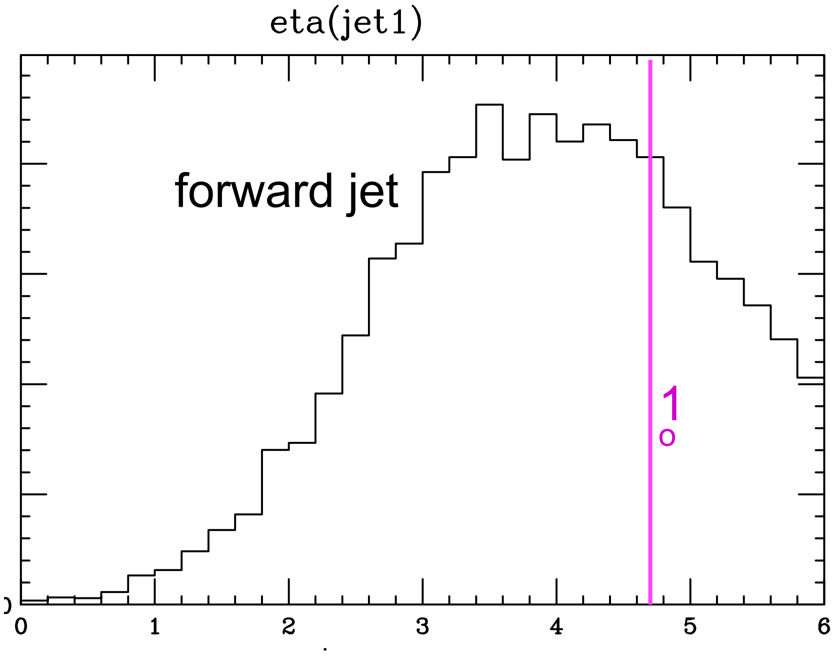
For x < 10^{-3} no (average) energy deposition exceeding the electron beam energy

The 750 GeV Ghost in ep

LHeC



FCC-ep



Initial simulations of the 750 GeV signal and backgrounds (G.Azuelos)

Couplings, Cross Section, Confirmation – three big unknowns …

Some Remarks

The ep configuration has much to offer by itself and in complementarity to ee and pp. For the FCC-eh, more studies are under way and need to be pursued.

The LHeC Study has been the base for FCC-eh also, and time and energy order need to be imposed by us in order to have clearer what can be gained where. This will also need to include the HE-LHC configuration which looks good to eh.

Basically: high x may be done by LHeC, but low x and high masses (equivalent) require FCC-ep

Areas of further study: top, Higgs, BSM

If you want to join, please do so

Areas of renewed study: low x, PDFs

Areas of new directions: Heavy neutrinos, BSM Higgs, 750 (if)

Much effort has been put in the detector software and design which needs to be coupled closer to the physics analyses..

Lots to be done for CDR on LHeC (1034) and FCC,
while eh physics remains fascinating to some of us and useful to everybody