Higgs physics at the LHeC and FCC-he

B.Mellado

University of the Witwatersrand

On behalf of the LHeC Study Group

Many thanks to N.Armesto, S.Forte, M.Klein and U.Klein for slides

ICHEP2016, Chicago, 06/08/16

Outline

- ❑The LHeC project
- ❑The FCC he option
- ❑The LHeC Physics Program
    - ❑The proton PDF
- ❑The LHeC, a Higgs facility
    - ❑Sensitivity to coupling strength
    - ❑Sensitivity to HVV coupling structure
    - ❑Invisible decays
- ❑Double Higgs production at the FCC he
- ❑Outlook and conclusions

arXiv:1206.2913

arXiv:1211.4831 and 5102

CERN Referees

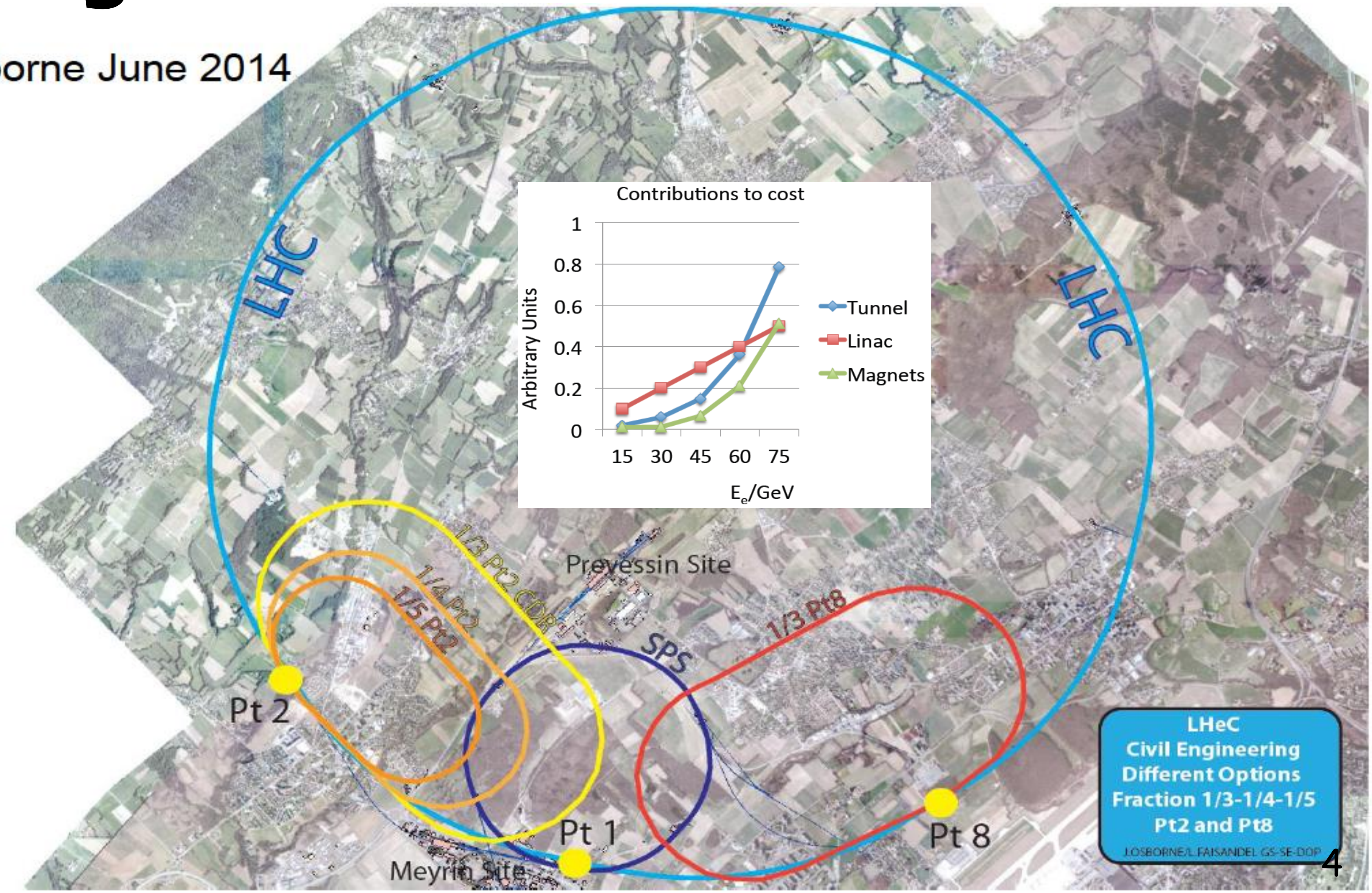
Ring Ring Design
Kurt Huebner (CERN)
Alexander N. Skrinsky (INP Novosibirsk)
Ferdinand Willeke (BNL)
Linac Ring Design
Reinhard Brinkmann (DESY)
Andy Wolski (Cockcroft)
Kaoru Yokoya (KEK)
Energy Recovery
Georg Hoffstaetter (Cornell)
Ilan Ben Zvi (BNL)
Magnets
Neil Marks (Cockcroft)
Martin Wilson (CERN)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

Published 600 pages conceptual design report (CDR) written by 150 authors from 60 Institutes.
Reviewed by ECFA, NuPECC (long range plan), Referees invited by CERN. Published June 2012.

See talk by M. Klein

Layout

John Osborne June 2014



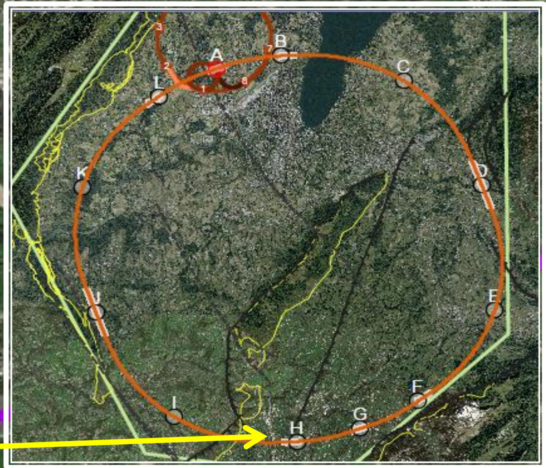
FCC-he Point H

FCC Long Straight Section H

Tunnel Geology
- Molasse rock (sandstone)

Construction
- Tunnel Boring Machine (TBM) in straight sections
- Roadheader in arcs

Civil Engineering challenges
- Low geological risk
- Interaction with main FCC tunnel(s)



CE: favoured eh site is point H

See talk by M. Klein

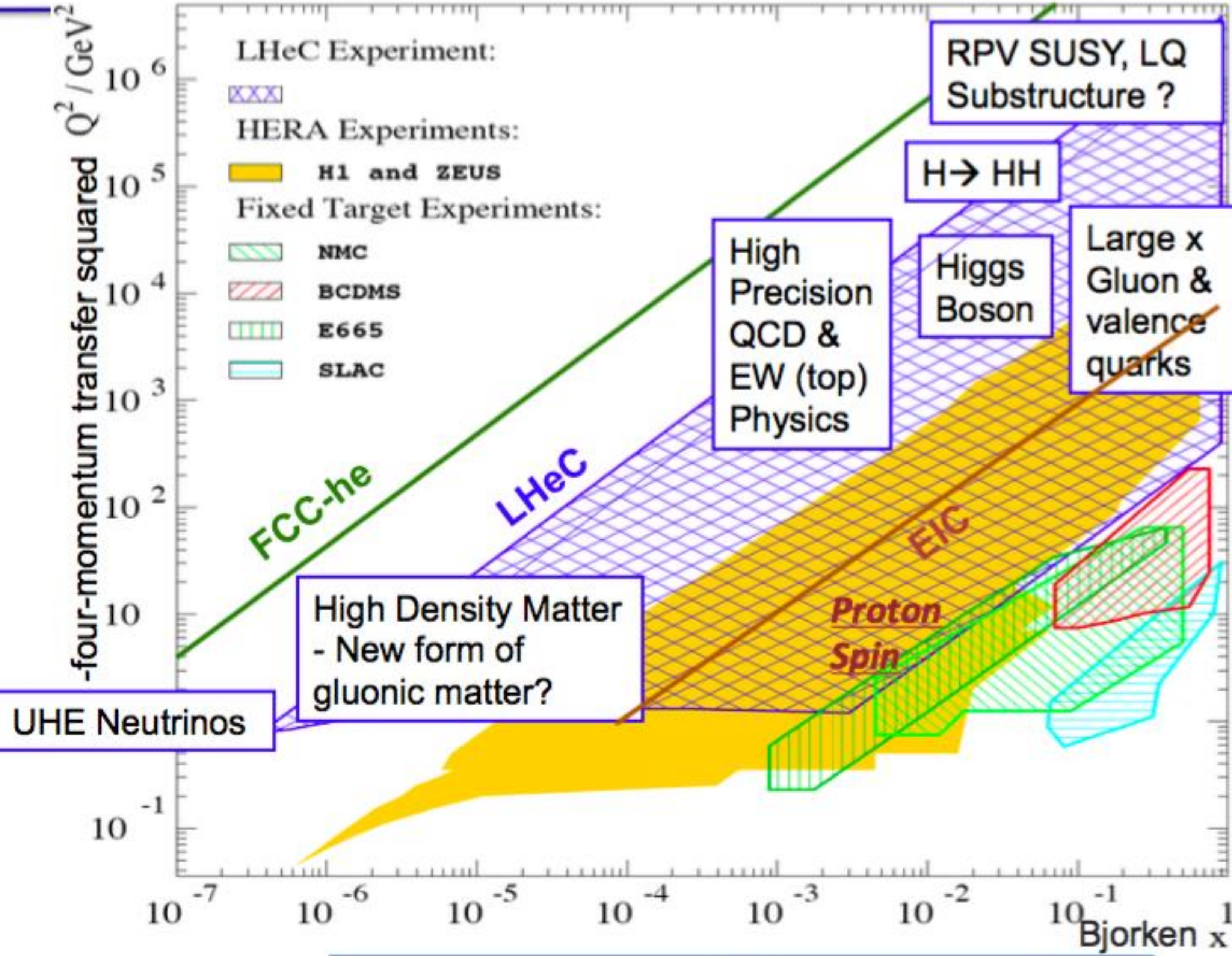
A Baseline for the FCC-he

Oliver Brüning[1] Max Klein[1,2], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool
March 3^{rd}, 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

work in progress (also eA)



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) & $Q^2 = M^2$

HERA AND LHC DATA: WHAT IS THE RELATIVE IMPACT?

S. Forte

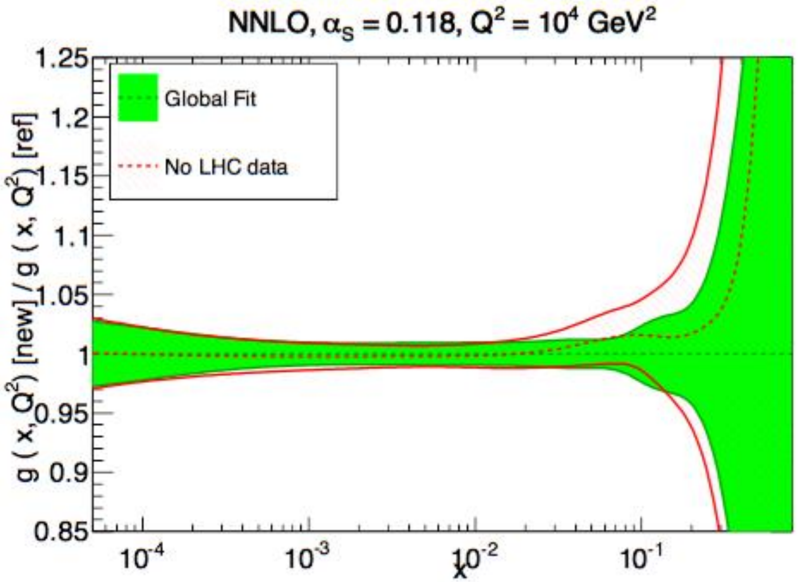
- OVERALL MEASURE OF IMPACT: $\varphi \Rightarrow$ FIT UNCERTAINTY/DATA UNCERTAINTY
- HERA-II IMPACT SIZABLE
- IMPACT OF LHC DATA MODERATE BUT VISIBLE
- IMPACT OF CMS OR ATLAS COMPARABLE TO (MODERATE) IMPACT OF NON-LHC, NON-HERA DATA

FRACTIONAL UNCERTAINTY

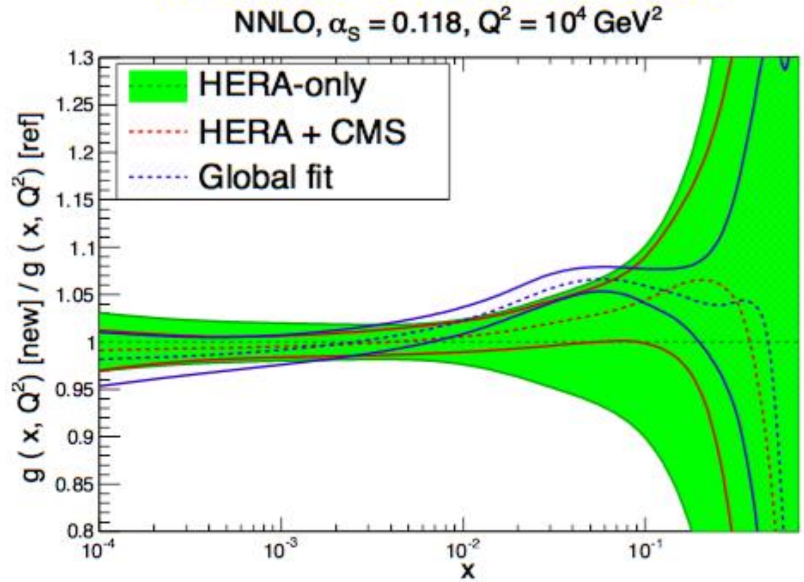
Dataset	φ NLO	φ NNLO
Global	0.291	0.302
HERA-I	0.453	0.439
HERA all	0.375	0.343
HERA+ATLAS	0.391	0.318
HERA+CMS	0.315	0.345
no LHC	0.312	0.316

THE GLUON

GLOBAL VS NO LHC



GLOBAL VS HERA+CMS



Very important for Higgs physics. Remove PDF+α_s

Very difficult to reduce uncertainty below 3-4% with hadron-hadron collisions. Need ep collisions

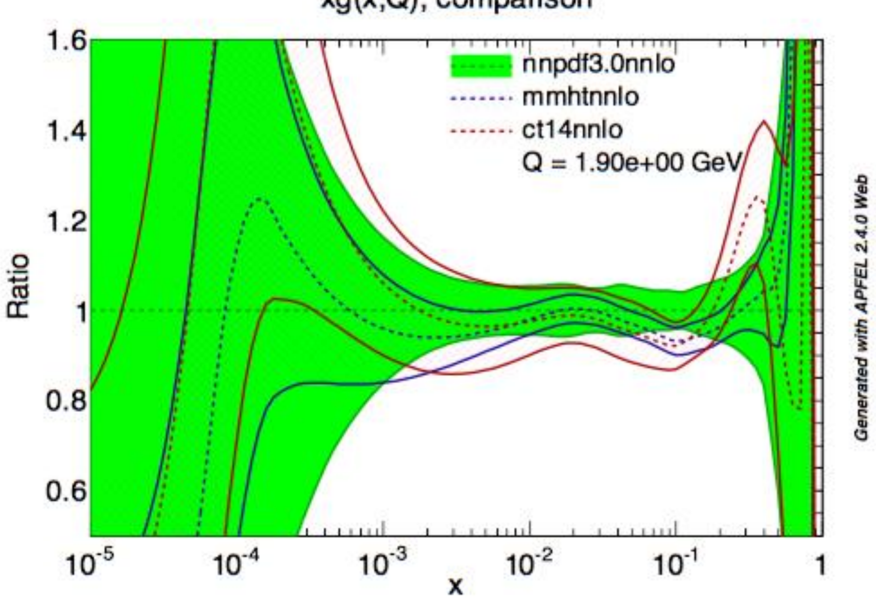
PDFS AT THE LHEC

S. Forte

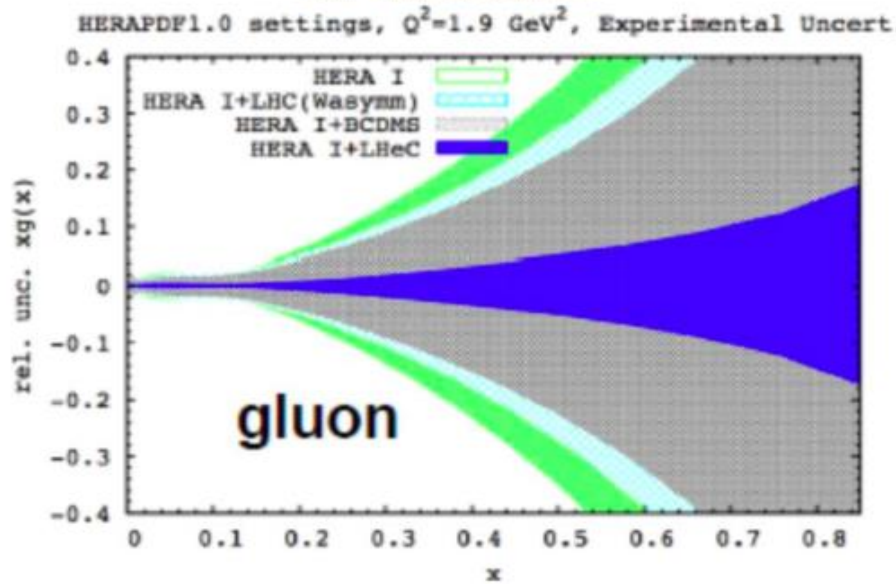
- UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION
- WITH DEUTERON BEAMS, FULL LIGHT FLAVOR DECOMPOSITION
- THANKS TO HIGH ENERGY, NC+CC ⇒ PRECISION STRANGENESS DETERMINATION

GLUON

NOW



AT THE LHEC



(A. Cooper-Sarkar & Voica Radescu, 2015)

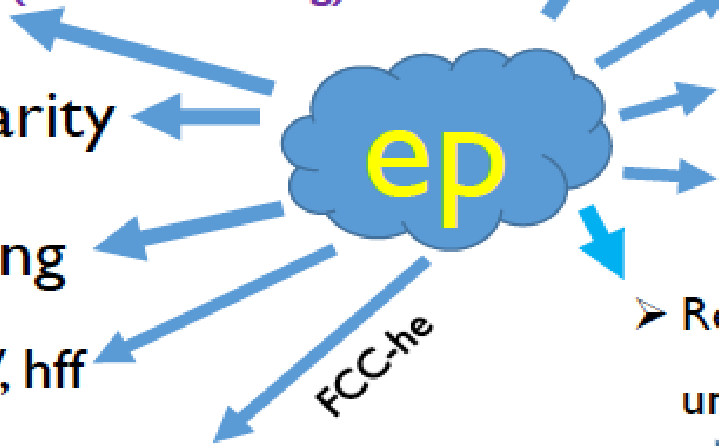
PDF uncertainty on Higgs production at LHC will become negligible due to measurements a the LHeC

LHeC, a Higgs facility

The Phenomenological Higgs Landscape (Revisited)

Future ep colliders could make important contribution to Higgs physics!

- Mass
- Width (via VV scattering)
- Spin-Parity
- Coupling
  - hVV, hff
  - 3h,4h, hhVV
  - FCNC coupling



- Exotic Higgs Decay
  - h to invisible
  - h to 4b
  - …

➢ Reducing PDF & Alpha_s uncertainties in Higgs measurements

See talk given by Voica Radescu

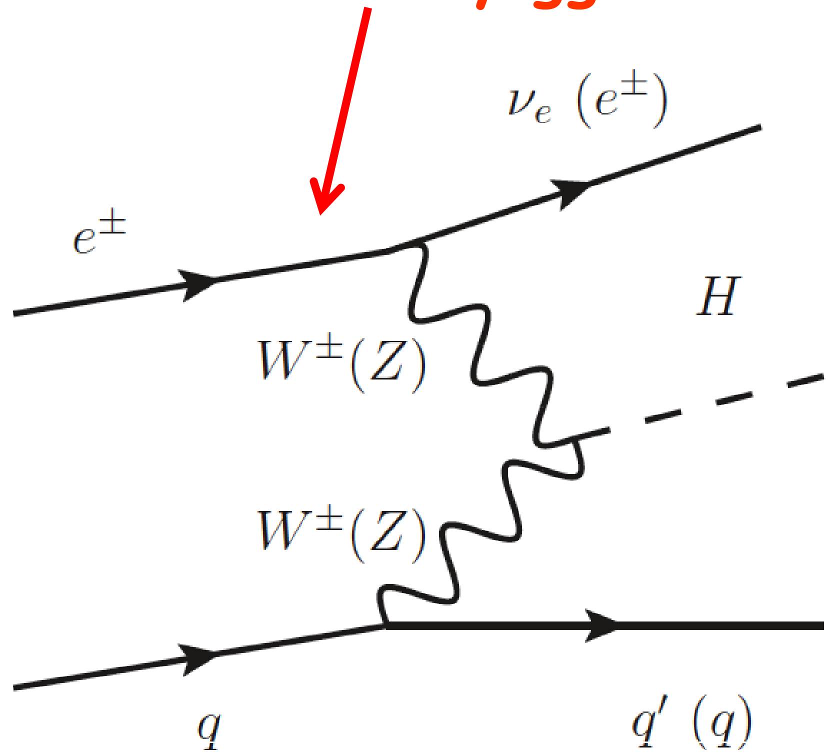
Philosophy could be traced back to Phys. Rev. D82 (2010) 016009 by T. Han and B. Mellado.

See also:
M. Kumar et al., 1509.04016
S. S. Biswal et al., Phys. Rev. Lett. 109 (2012) 261801
U. Klein, talk given at LHeC Workshop 2015

Chen Zhan 12.4.16

Higgs at LHeC

At LHC replace
lepton lines by quark lines
but dominantly gg → H



- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!

- Consider feasibility for the following LHeC point:

$$E_p = 7\,TeV, \quad E_e = 60\,GeV, \quad m_H = 125\,GeV$$

LHeC, a Higgs Facility

→ **for first time a realistic option of an 1 ab^{-1} ep collider** (stronger e-source, stronger focussing magnets) and **excellent performance of LHC** (higher brightness of proton beam); ERL : 960 superconducting cavities (20 MV/m) and 9 km tunnel [arXiv:1211.5102, arXiv:1305.2090; EPS2013 talk by D. Schulte]

√s= 1.3 TeV

→ need of different models :
cc: 'sm-full'
gg, γγ: 'heft'

LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

Ultimate polarised e-beam of 60 GeV and LHC-p beams, 10 years of operation

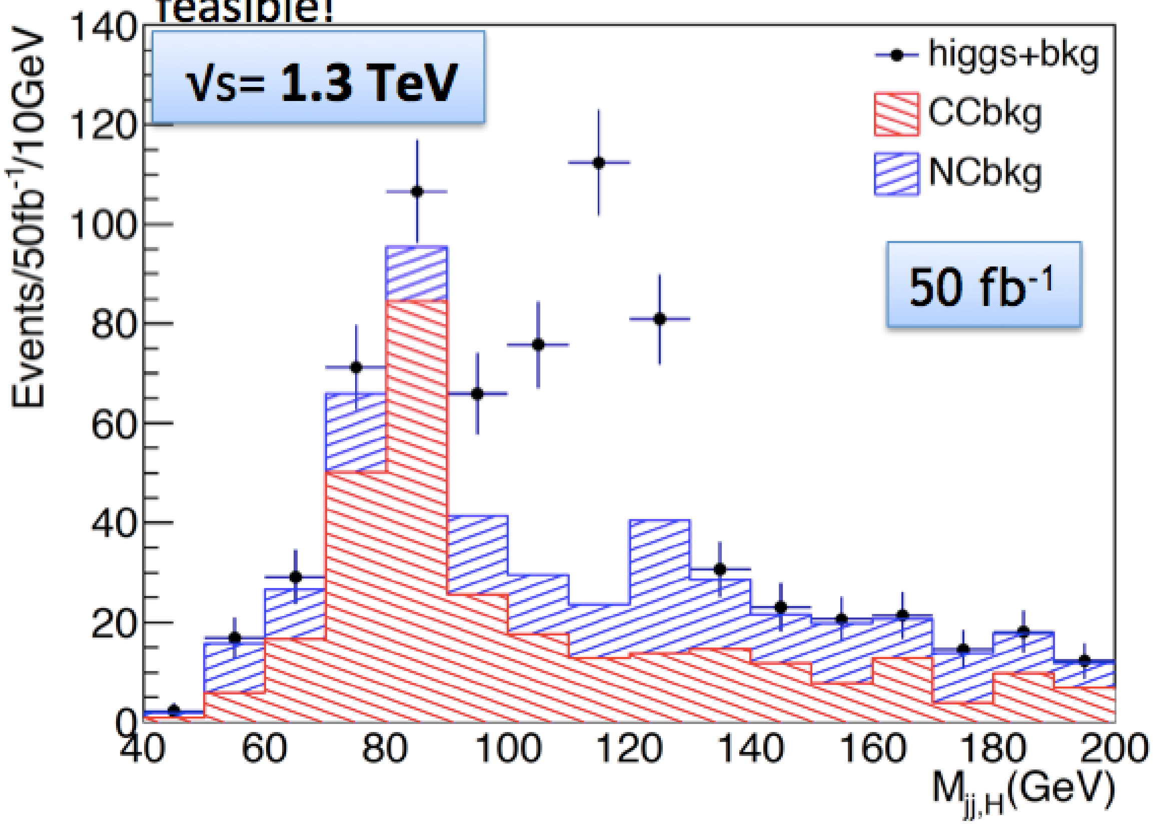
→ **Decay to bb is dominating HFL decay modes : Higgs decay to cc is factor 20 less likely than Hbb times the ratio of detection efficiencies-squared !**

H→$b\bar{b}$ results updated

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

M. Kuze

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



Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

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

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

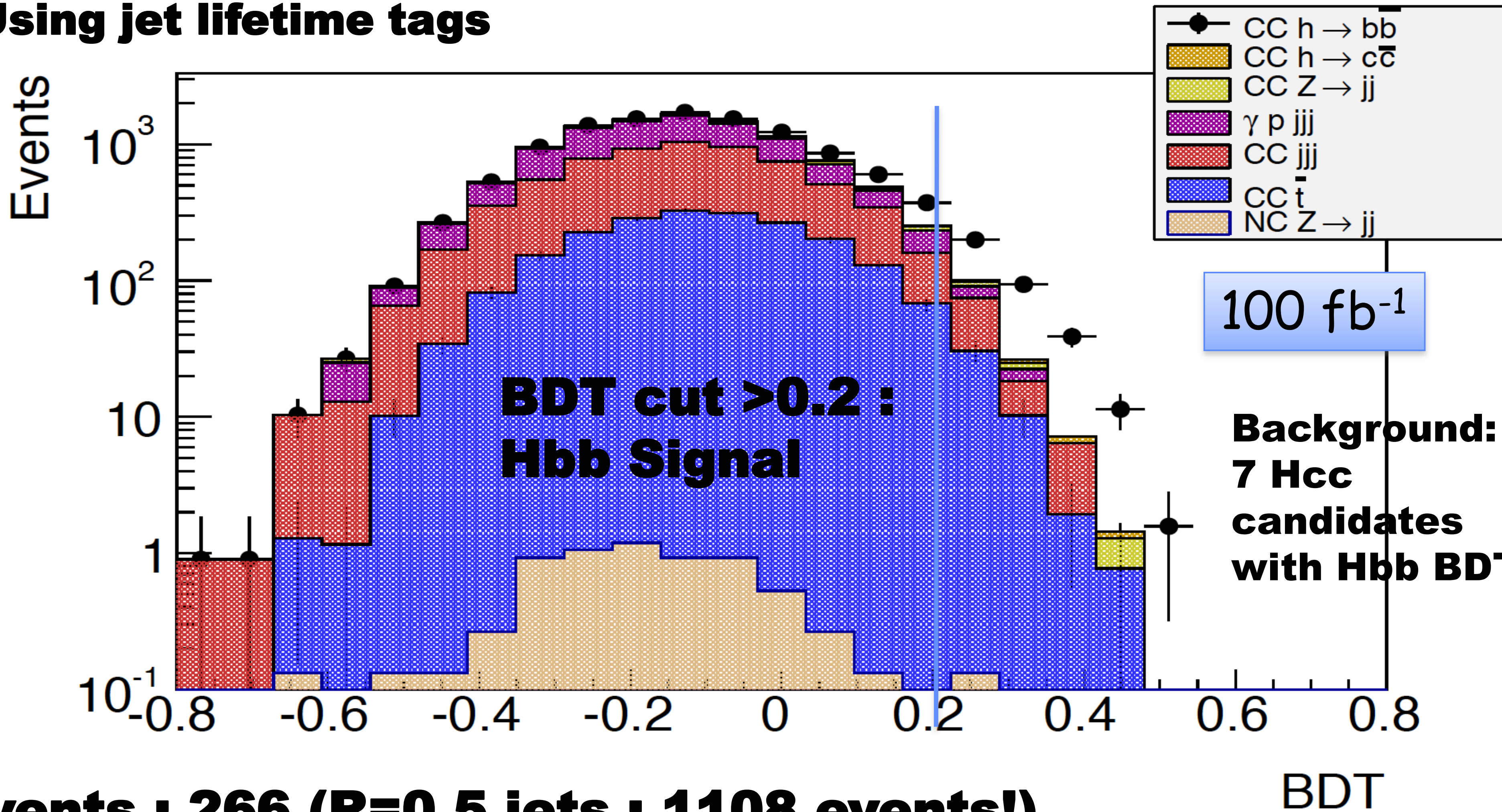
Cut based analysis based on Delphes output

U. Klein

[P=-0.8, BR=0.577]

First BDT results : Higgs→ bb

Using jet lifetime tags

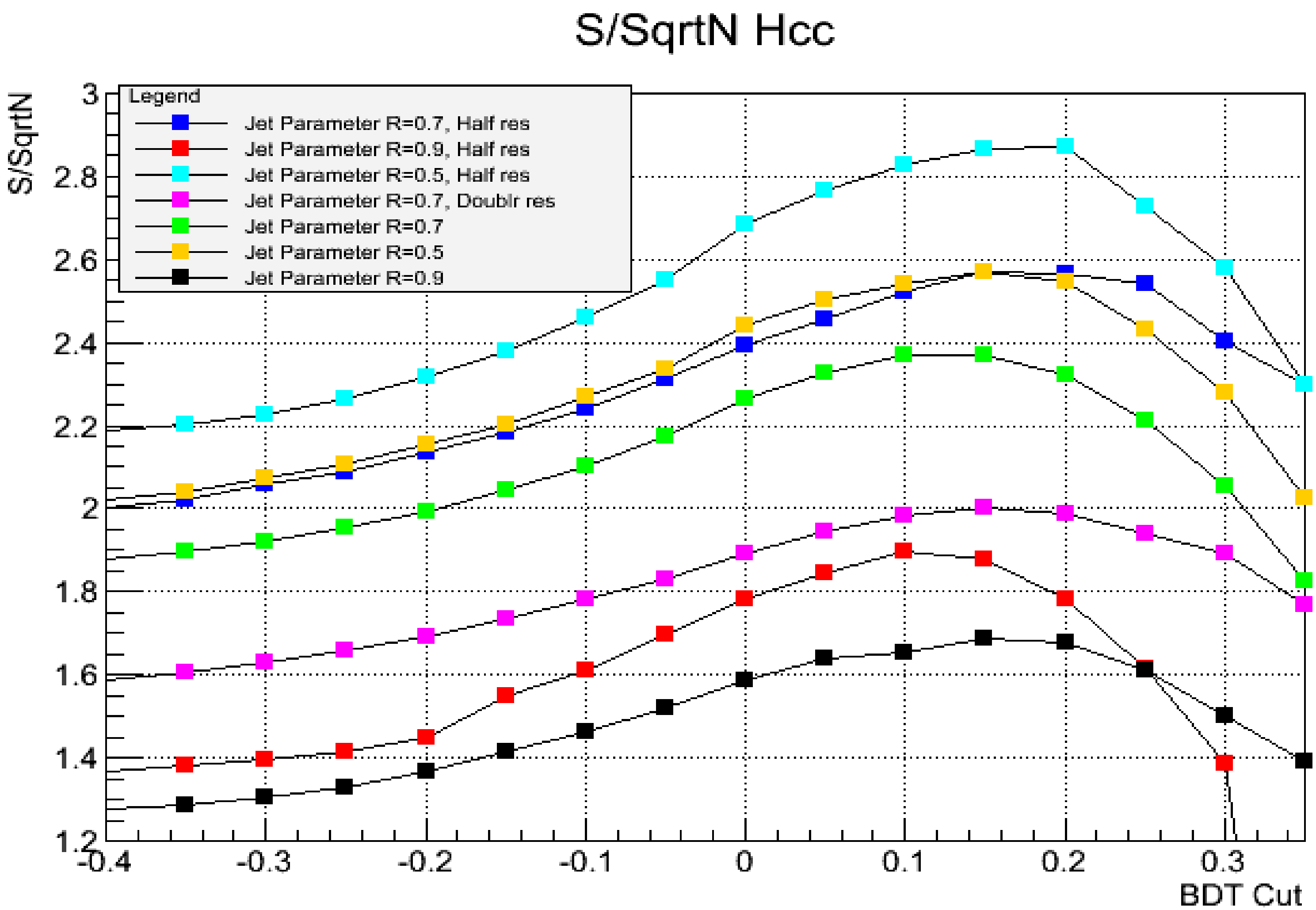


Events : 266 (R=0.5 jets : 1108 events!)

S/B = 1.16 and S/√S+B=12 → κ(Hbb) = 5% for 100 fb^{-1}

→κ(Hbb) ~ 1% for 1000 fb^{-1}

Hcc Preliminary S/√N Results



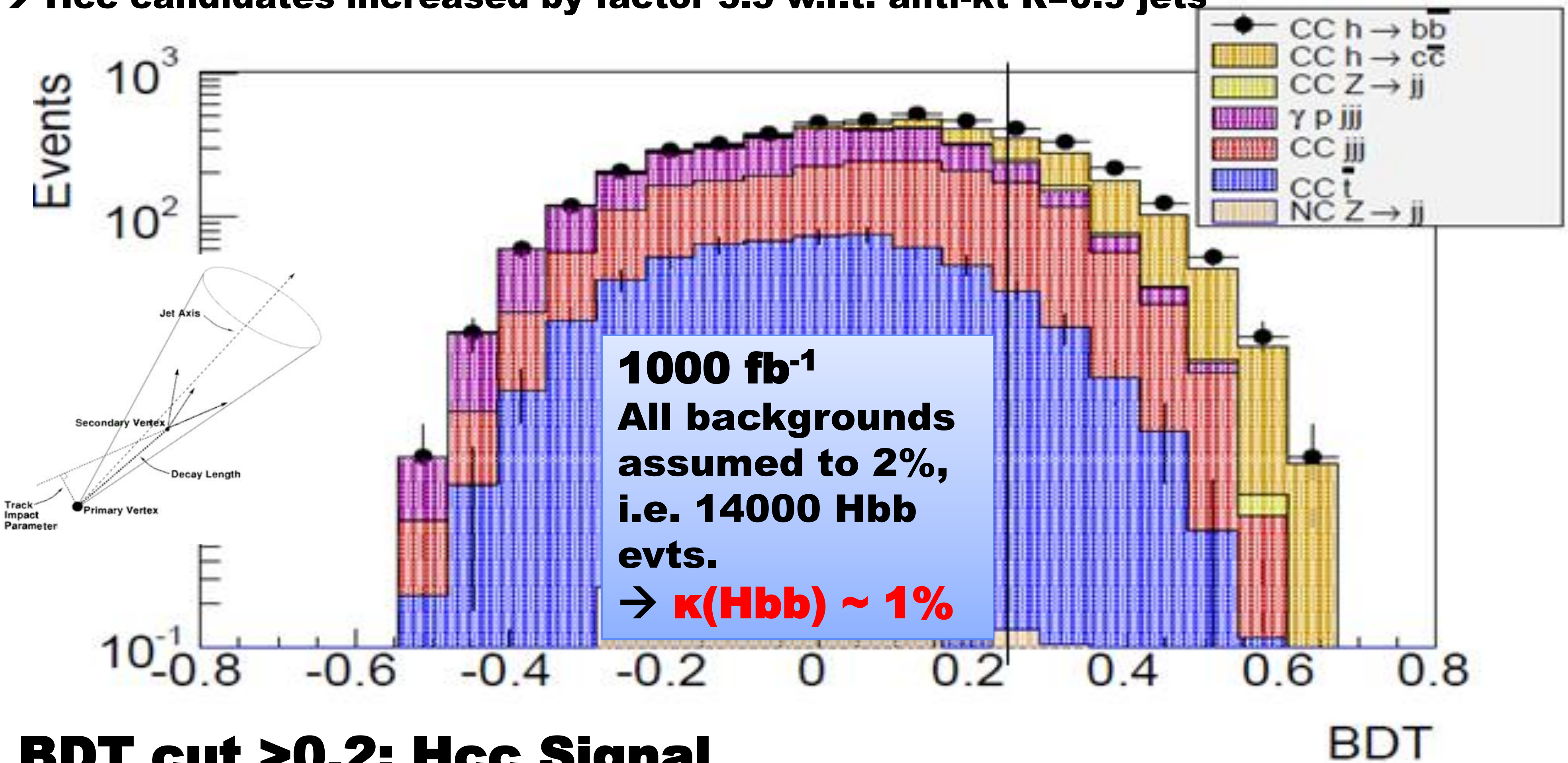
Using R = 0.5 anti-kt jets and half nominal vertex resolution improves Signal-to-background rates by factor 2.

Expected Higgs to charm coupling uncertainty improved by factor 2.

U Klein and D Hampson.
May 2016

BDT Results Higgs→ cc

NEW : Using R = 0.5 anti-kt jets and ATLAS IBL vertex resolution (5 μm)
→ Hcc candidates increased by factor 3.5 w.r.t. anti-kt R=0.9 jets



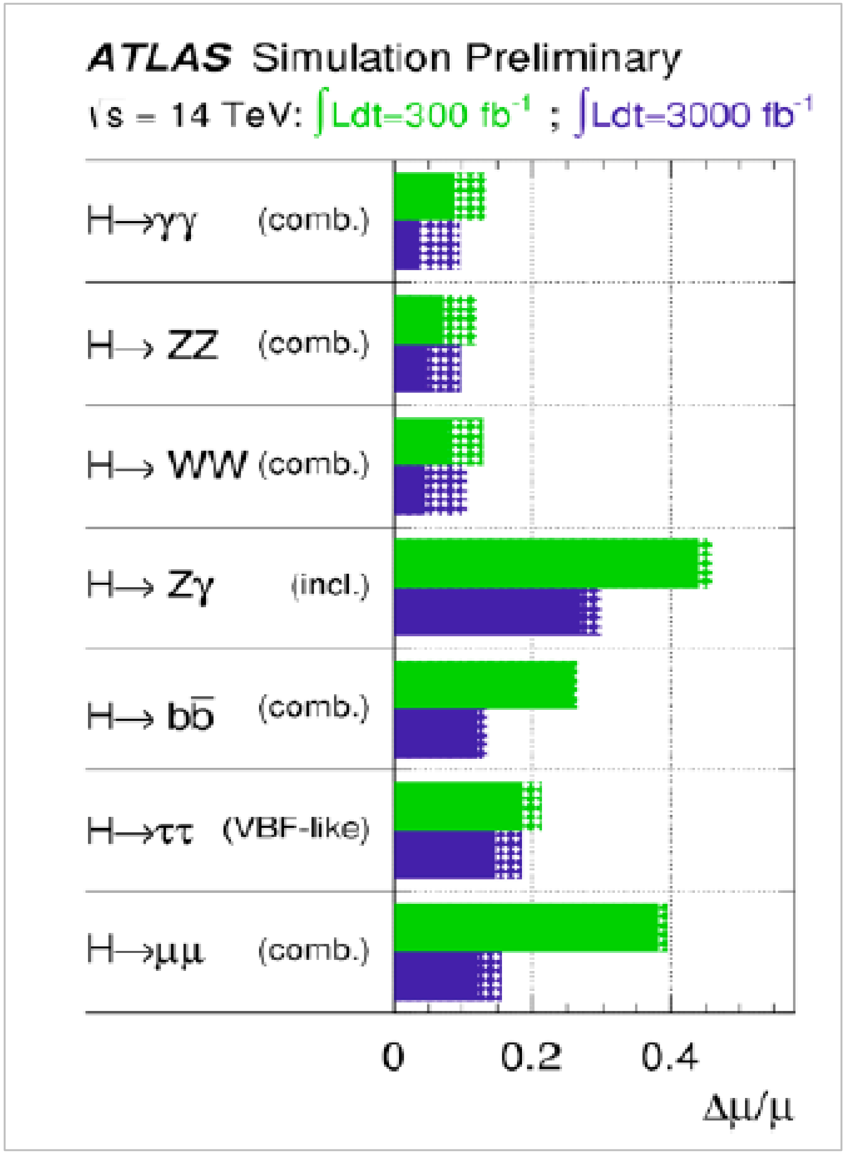
BDT cut >0.2: Hcc Signal events : 474; S/√S+B=12.8
→ κ(Hcc) = 5% for 1000 fb^{-1}

Clear potential to access the Higgs to charm decay channel at the LHeC.

Couplings: HL-LHC+LHeC

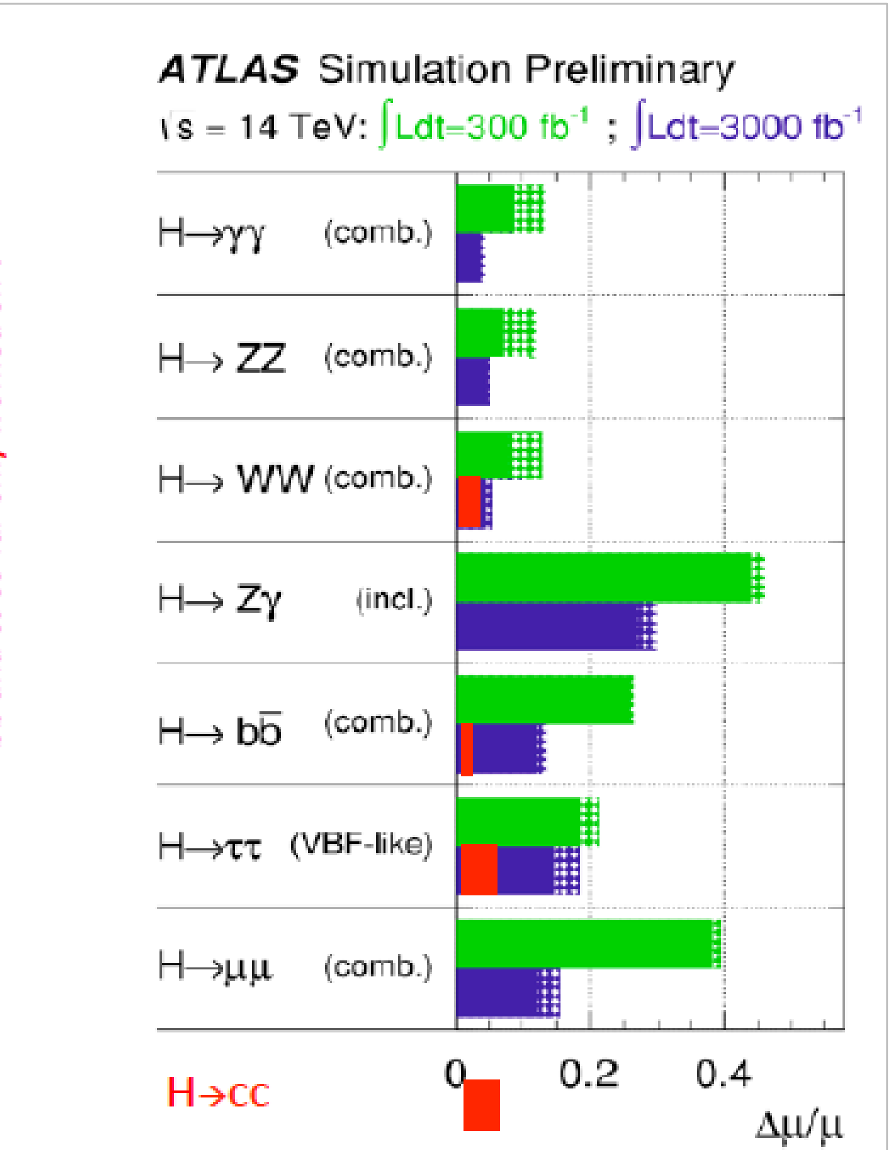
S. Forte

HL LHC

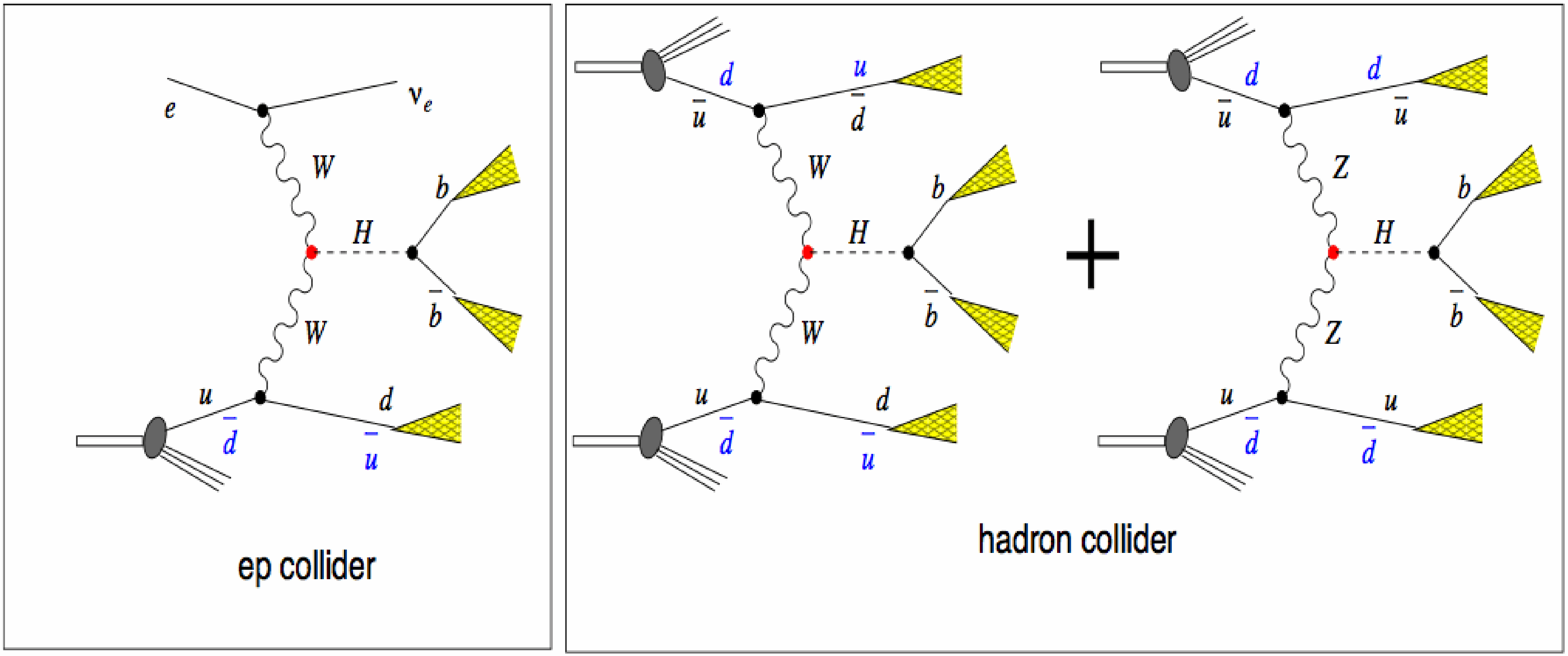


HL LHC + LHeC

bb and cc so far only worked on !



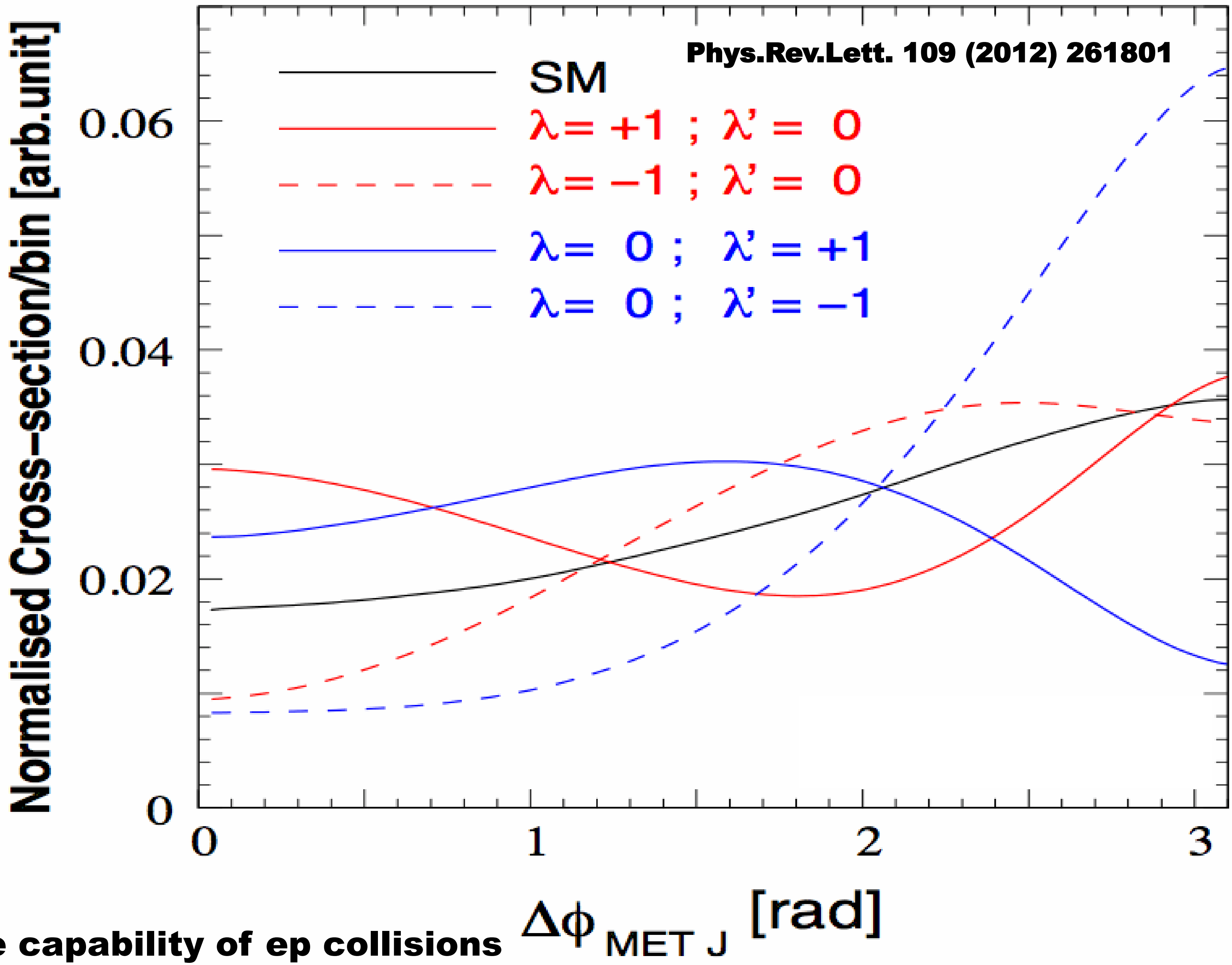
higgs + 2jets: VBF (LHC), higgs + jet + missing E_T (LHeC)



ep process uniquely addresses the HWW vertex.

$$\Gamma^{\rm SM}_{\mu\nu} = -g M_V\, g_{\mu\nu}$$

$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\,(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu) + \lambda'\,\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$



Unique capability of ep collisions

Invisible Higgs

Y.-L. Tang et al., Phys. Rev. D 94, 011702 (2016)

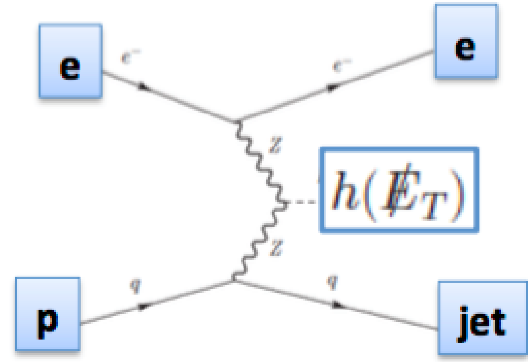
HL-LHC @ 3 ab^{-1} [arXiv:1411. 7699]

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

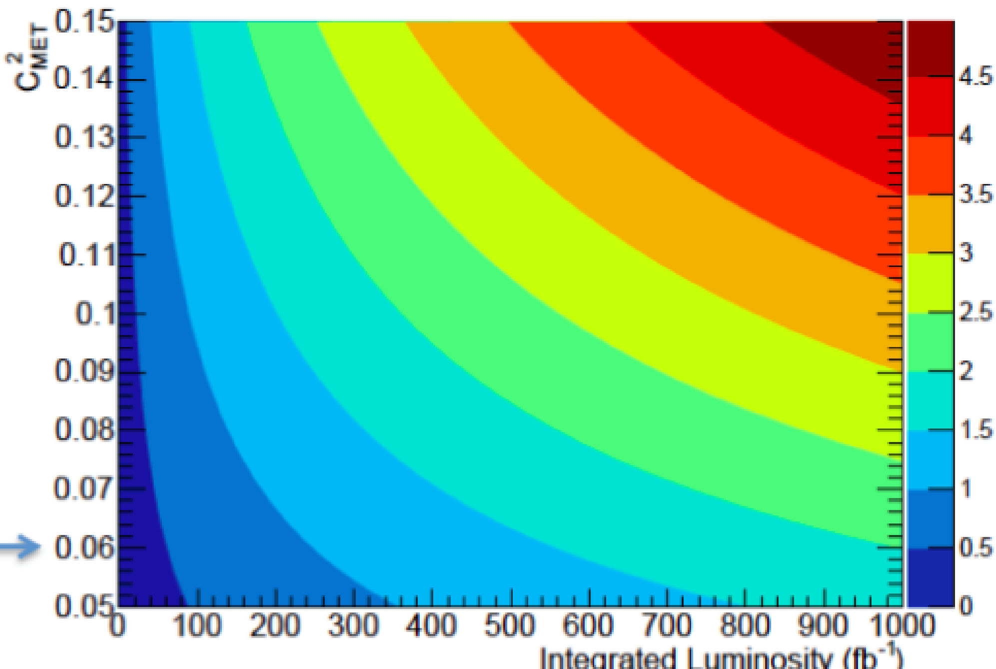
For **LHeC**, assume : 1ab^{-1}, P_e=-0.9, cut based

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

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



κ_Z : BSM w.r.t. SM HZZ coupling



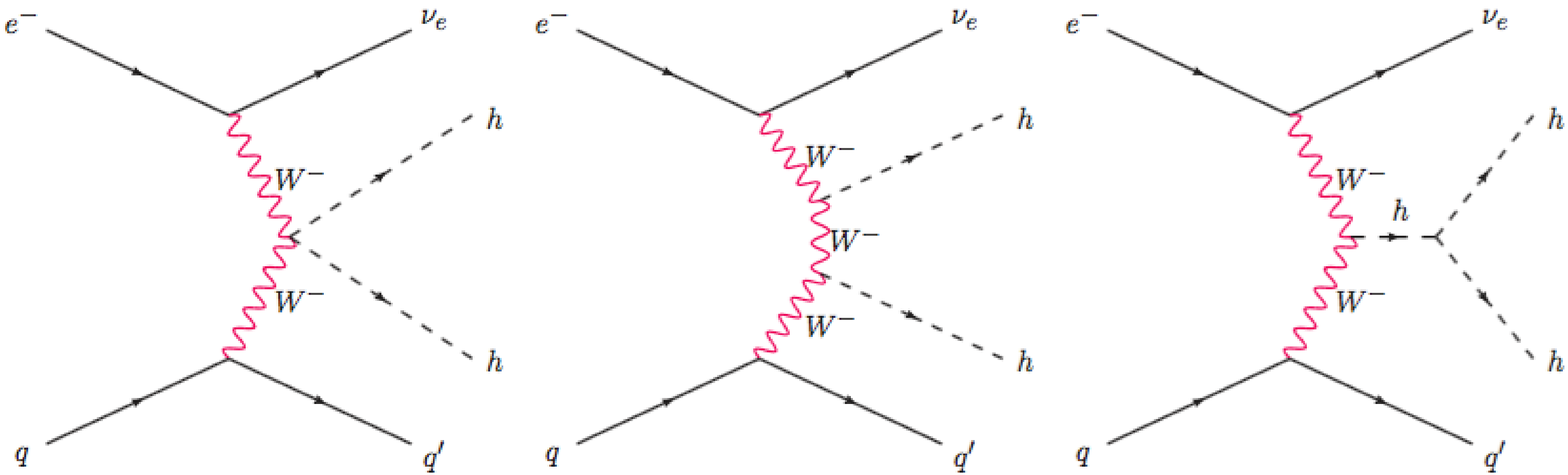
Colours:
expected statistical significance

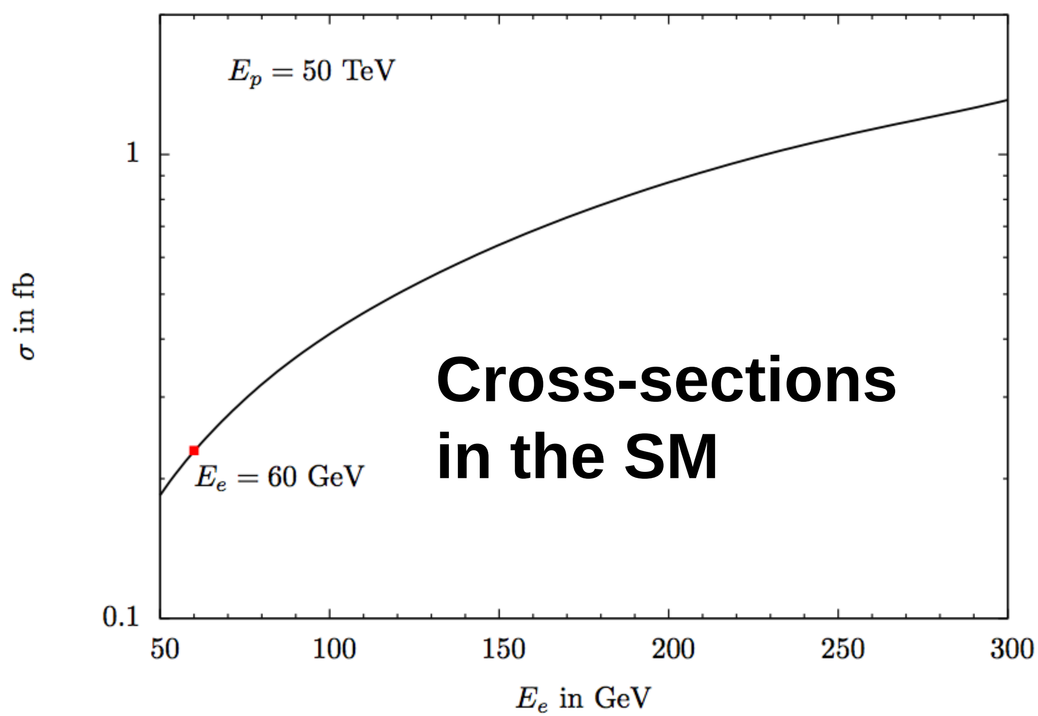
➔ potential much enhanced for **FCC-eh @ 3.5 TeV and HE-LHC-eh**

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}

Double Higgs production at the FCC-he





Considering highly asymmetric collisions

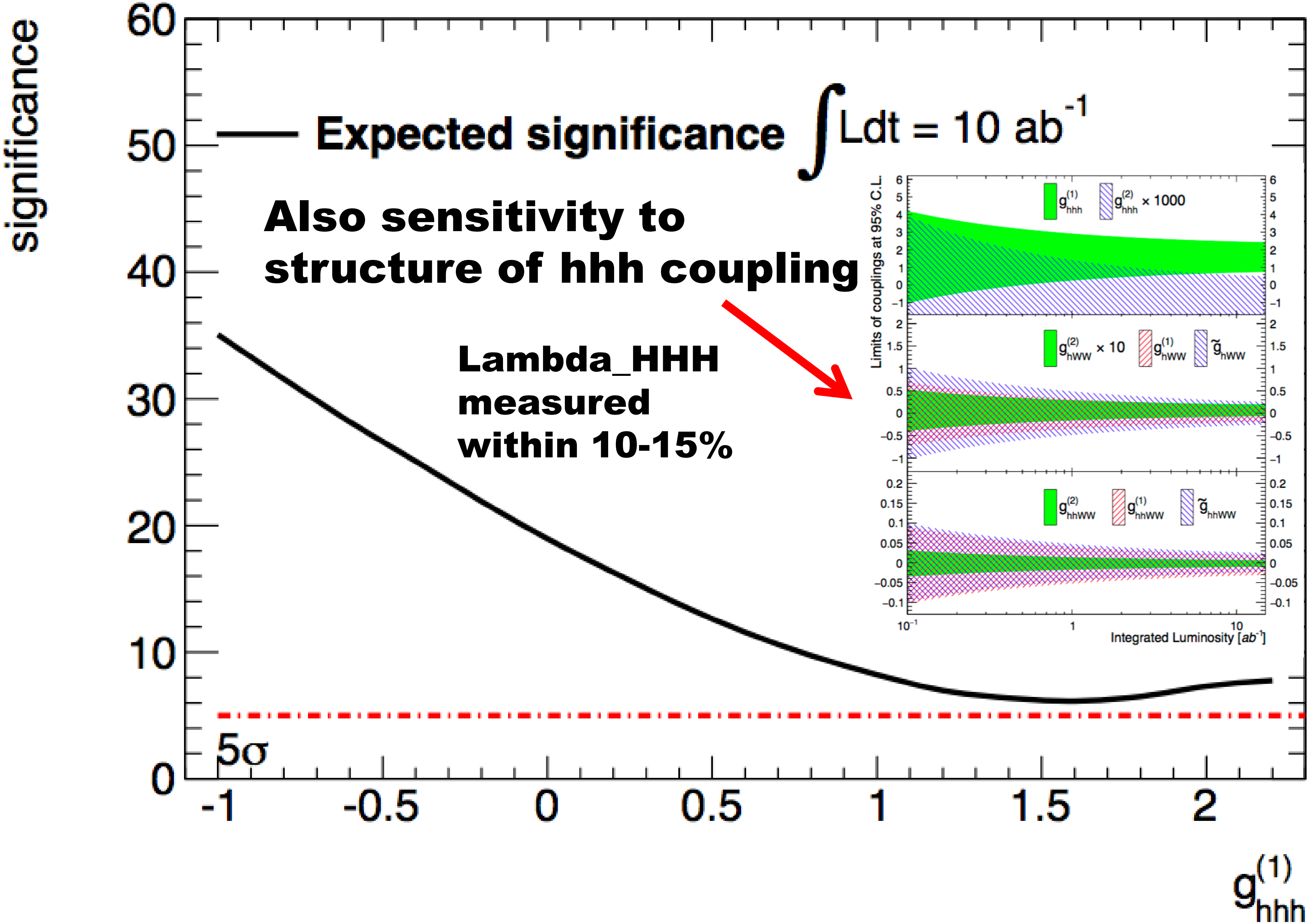
Effective vertices. Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.

$$\mathrm{i}\Gamma_{hhh} = -6\mathrm{i}v\lambda g^{(1)}_{hhh} - \mathrm{i}g^{(2)}_{hhh}(p_1\cdot p_2 + p_2\cdot p_3 + p_3\cdot p_1),$$

$$\begin{aligned}\mathrm{i}\Gamma_{hW^-W^+} =& \mathrm{i}\Big[\Big\{\frac{g^2}{2}v + \frac{g}{m_W}g^{(1)}_{hWW}p_2\cdot p_3 + \frac{g}{m_W}g^{(2)}_{hWW}(p_2^2+p_3^2)\Big\}\eta^{\mu_2\mu_3} \\ &-\frac{g}{m_W}g^{(1)}_{hWW}p_2^{\mu_3}p_3^{\mu_2} - \frac{g}{m_W}g^{(2)}_{hWW}(p_2^{\mu_2}p_2^{\mu_3}+p_3^{\mu_2}p_3^{\mu_3}) \\ &-\mathrm{i}\frac{g}{m_W}\tilde{g}_{hWW}\epsilon_{\mu_2\mu_3\mu\nu}p_2^{\mu}p_3^{\nu}\Big],\end{aligned}$$

$$\begin{aligned}\mathrm{i}\Gamma_{hhW^-W^+} =& \mathrm{i}\Big[\Big\{\frac{g^2}{2} + \frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3\cdot p_4 + \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^2+p_4^2)\Big\}\eta^{\mu_3\mu_4} \\ &-\frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3^{\mu_4}p_4^{\mu_3} - \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^{\mu_3}p_3^{\mu_4}+p_4^{\mu_3}p_4^{\mu_4}) \\ &-\mathrm{i}\frac{g^2}{m_W^2}\tilde{g}_{hhWW}\epsilon_{\mu_3\mu_4\mu\nu}p_3^{\mu}p_4^{\nu}\Big]\cdot\end{aligned}$$

M. Kumar et al.[1509.04016]



significance
Expected significance ∫Ldt = 10 ab⁻¹
Also sensitivity to structure of hhh coupling
Lambda_HHH measured within 10-15%
5σ
$g^{(1)}_{hhh}$
Limits of couplings at 95% C.L.
$g^{(1)}_{hhh}$
$g^{(2)}_{hhh}$ × 1000
$g^{(2)}_{hWW}$ × 10
$g^{(1)}_{hWW}$
$\tilde{g}_{hWW}$
$g^{(2)}_{hhWW}$
$g^{(1)}_{hhWW}$
$\tilde{g}_{hhWW}$
Integrated Luminosity [ab^{-1}]

Outlook and Conclusions

- The LHeC has a vast physics program, further boosting the physics potential of the LHC
  - Unique capability to measure proton PDFs+α_S, etc...
  - Critical to the LHC in the long term
- The LHeC is also a Higgs facility
  - Strong complementarities with the LHC
  - Better S/B, ability to tag charm decays
  - Unique sensitivity to HWW coupling in a model independent way (not possible elsewhere)
  - Strong sensitivity to invisible decays
- With FCC he option attain access to hh production
  - Sensitivity to structure of hhh coupling in addition to the coupling strength.

Additional Slides

DIS at the LHC:

Guido Altarelli (1941-2015)

CERN-ECFA workshop, Lausanne, March 1984:
a Large Hadron Collider in the LEP tunnel

PHYSICS OF ep COLLISIONS IN THE TeV ENERGY RANGE

G. Altarelli*), B. Mele*) and R. Rückl,
CERN, Geneva, Switzerland
(Presented by G. Altarelli)

ABSTRACT

We study the physics of electron-proton collisions in the range of centre-of-mass energies between $\sqrt{s} \simeq 0.3$ TeV (HERA) and $\sqrt{s} \simeq (1-2)$ TeV. The latter energies would be achieved if the electron or positron beam of LEP [$E_e \simeq (50-100)$ GeV] is made to collide with the proton beam of LHC [$E_p \simeq (5-10)$ TeV].

Proposal of the Large Hadron Electron Collider in 2006 (hep-ex/063016) taken up to CERN, ECFA and NuPECC

Study group formed in 2008 with regular workshops, groups meetings and publications

http://cern.ch/lhec

J.L.Abelleira Fernandez[16,23], C.Adolphsen[57], P.Adzic[74], A.N.Akay[03], H.Aksakal[39], J.L.Albacete[52], B.Allanach[73], S.Alekhin[17,54], P.Allport[24], V.Andreev[34], R.B.Appleby[14,30], E.Arikan[39], N.Armesto[53,a], G.Azuelos[33,64], M.Bai[37], D.Barber[14,17,24], J.Bartels[18], O.Behnke[17], J.Behr[17], A.S.Belyaev[15,56], I.Ben-Zvi[37], N.Bernard[25], S.Bertolucci[16], S.Bettoni[16], S.Biswal[41], J.Blümlein[17], H.Böttcher[17], A.Bogacz[36], C.Bracco[16], J.Bracinik[06], G.Brandt[44], H.Braun[65], S.Brodsky[57,b], O.Brüning[16], E.Bulyak[12], A.Buniatyan[17], H.Burkhardt[16], I.T.Cakir[02], O.Cakir[01], R.Calaga[16], A.Caldwell[70], V.Cetinkaya[01], V.Chekelian[70], E.Ciapala[16], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[38], J.C.Collins[48], O.Dadoun[42], J.Dainton[24], A.De.Roeck[16], D.d'Enterria[16], P.DiNezza[72], M.D'Onofrio[24], A.Dudarev[16], A.Eide[60], R.Enberg[63], E.Eroglu[62], K.J.Eskola[21], L.Favart[08], M.Fitterer[16], S.Forte[32], A.Gaddi[16], P.Gambino[59], H.García Morales[16], T.Gehrmann[69], P.Gladkikh[12], C.Glasman[28], A.Glazov[17], R.Godbole[35], B.Goddard[16], T.Greenshaw[24], A.Guffanti[13], V.Guzey[19,36], C.Gwenlan[44], T.Han[50], Y.Hao[37], F.Haug[16], W.Herr[16], A.Hervé[27], B.J.Holzer[16], M.Ishitsuka[58], M.Jacquet[42], B.Jeanneret[16], E.Jensen[16], J.M.Jimenez[16], J.M.Jowett[16], H.Jung[17], H.Karadeniz[02], D.Kayran[37], A.Kilic[62], K.Kimura[58], R.Klees[75], M.Klein[24], U.Klein[24], T.Kluge[24], F.Kocak[62], M.Korostelev[24], A.Kosmicki[16], P.Kostka[17], H.Kowalski[17], M.Kraemer[75], G.Kramer[18], D.Kuchler[16], M.Kuze[58], T.Lappi[21,c], P.Laycock[24], E.Levichev[40], S.Levonian[17], V.N.Litvinenko[37], A.Lombardi[16], J.Maeda[58], C.Marquet[16], B.Mellado[27], K.H.Mess[16], A.Milanese[16], J.G.Milhano[76], S.Moch[17], I.I.Morozov[40], Y.Muttoni[16], S.Myers[16], S.Nandi[55], Z.Nergiz[39], P.R.Newman[06], T.Omori[61], J.Osborne[16], E.Paoloni[49], Y.Papaphilippou[16], C.Pascaud[42], H.Paukkunen[53], E.Perez[16], T.Pieloni[23], E.Pilicer[62], B.Pire[45], R.Placakyte[17], A.Polini[07], V.Ptitsyn[37], Y.Pupkov[40], V.Radescu[17], S.Raychaudhuri[35], L.Rinolfi[16], E.Rizvi[71], R.Rohini[35], J.Rojo[16,31], S.Russenschuck[16], M.Sahin[03], C.A.Salgado[53,a], K.Sampei[58], R.Sassot[09], E.Sauvan[04], M.Schaefer[75], U.Schneekloth[17], T.Schörner-Sadenius[17], D.Schulte[16], A.Senol[22], A.Seryi[44], P.Sievers[16], A.N.Skrinsky[40], W.Smith[27], D.South[17], H.Spiesberger[29], A.M.Stasto[48,d], M.Strikman[48], M.Sullivan[57], S.Sultansoy[03,e], Y.P.Sun[57], B.Surrow[11], L.Szymanowski[66,f], P.Taels[05], I.Tapan[62], T.Tasci[22], E.Tassi[10], H.Ten.Kate[16], J.Terron[28], H.Thiesen[16], L.Thompson[14,30], P.Thompson[06], K.Tokushuku[61], R.Tomás García[16], D.Tommasini[16], D.Trbojevic[37], N.Tsoupas[37], J.Tuckmantel[16], S.Turkoz[01], T.N.Trinh[47], K.Tywoniuk[26], G.Unel[20], T.Ullrich[37], J.Urakawa[61], P.VanMechelen[05], A.Variola[52], R.Veness[16], A.Vivoli[16], P.Vobly[40], J.Wagner[66], R.Wallny[68], S.Wallon[43,46,f], G.Watt[69], C.Weiss[36], U.A.Wiedemann[16], U.Wienands[57], F.Willeke[37], B.-W.Xiao[48], V.Yakimenko[37], A.F.Zarnecki[67], Z.Zhang[42], F.Zimmermann[16], R.Zlebcik[51], F.Zomer[42]

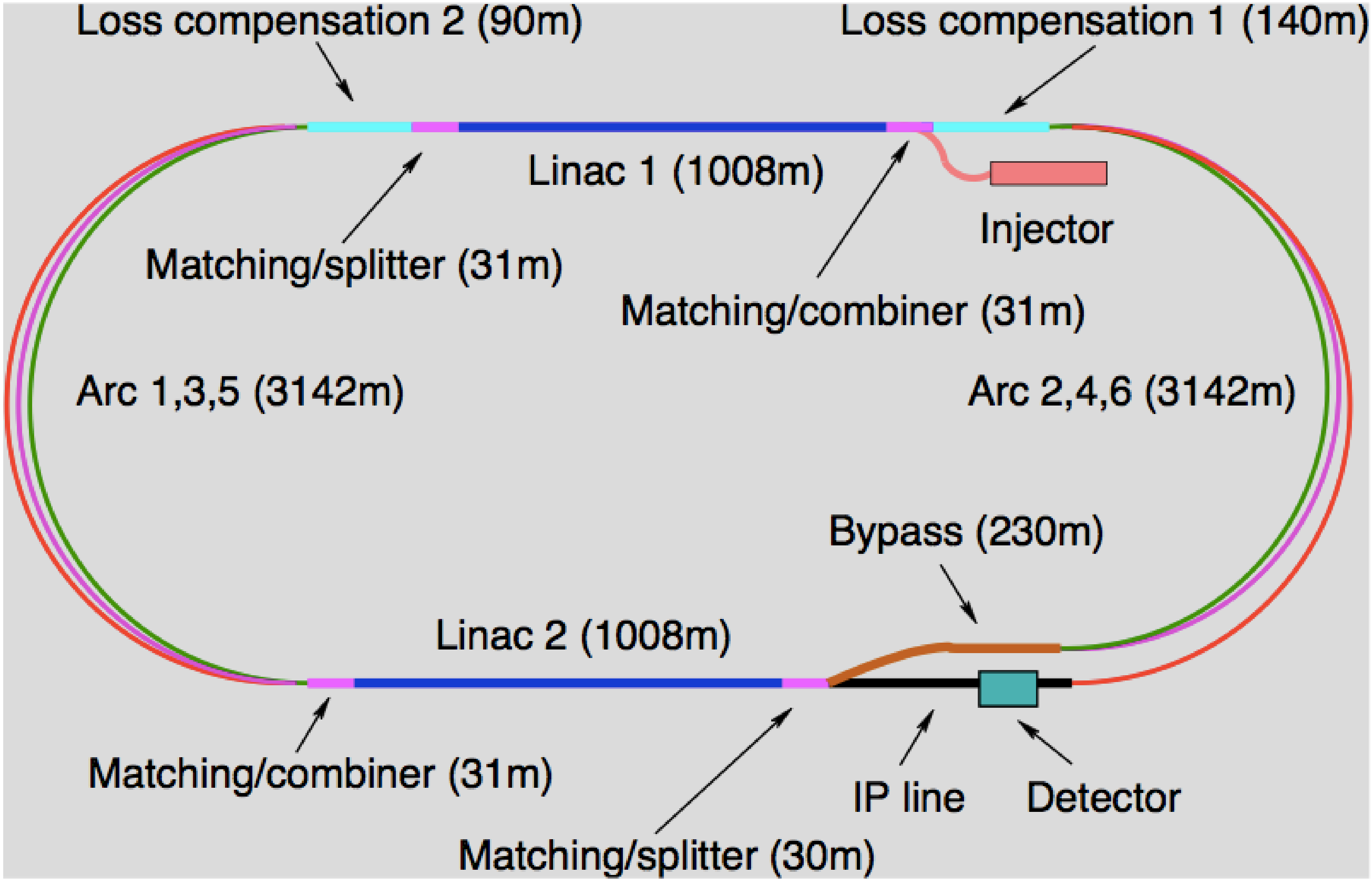
Present LHeC Study group and CDR authors

About 200 Experimentalists and Theorists from 76 Institutes

Supported by
CERN, ECFA, NuPECC

CDR: Physics, Accelerator, Detector

M.Klein

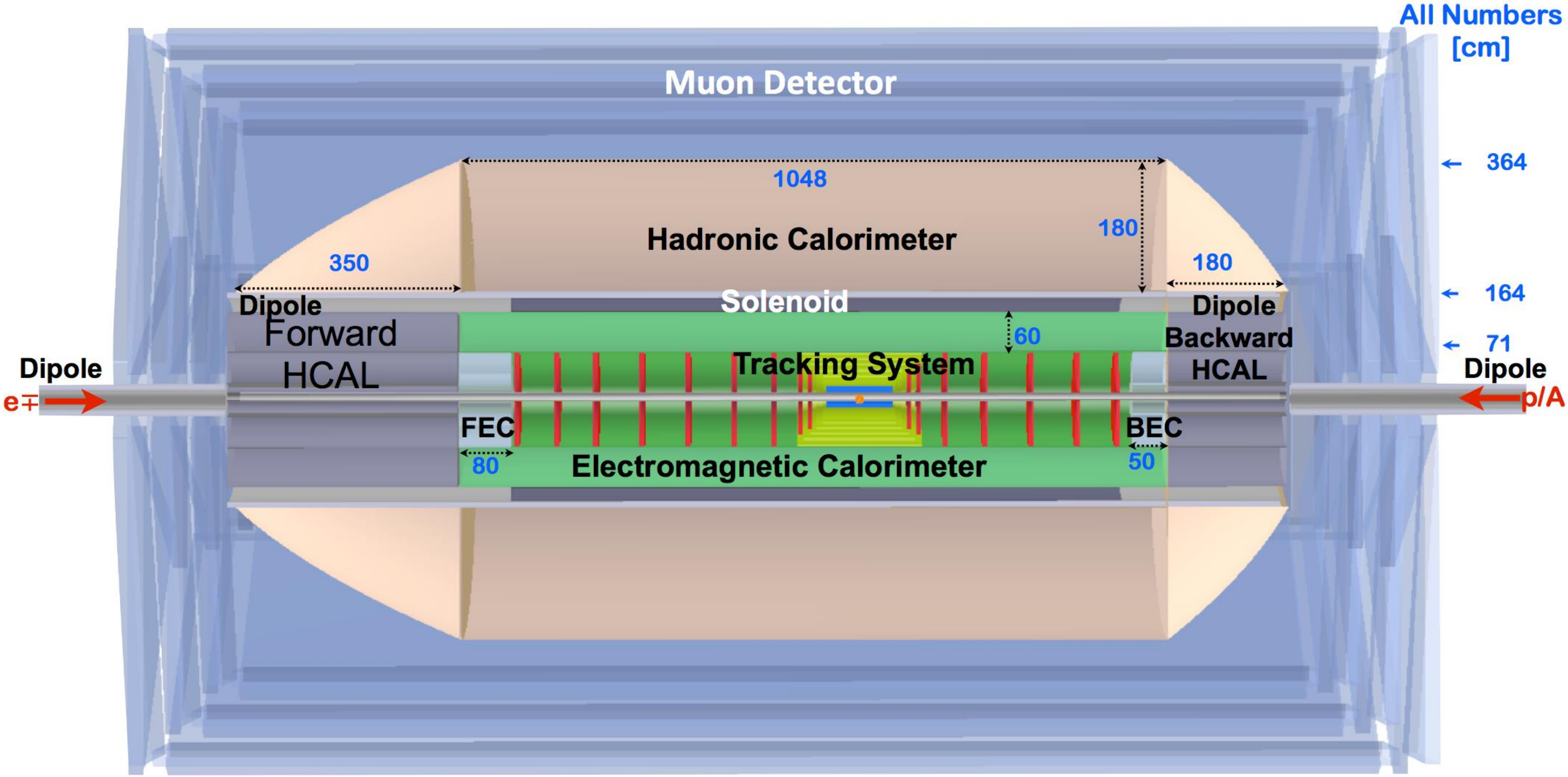


JPhysG:39(2012)075001, arXiv:1206.2913 http://cern.ch/lhec

CDR: default design. 60 GeV. L=$10^{33}cm^{-2}s^{-1}$, P< 100 MW → ERL, synchronous ep/pp

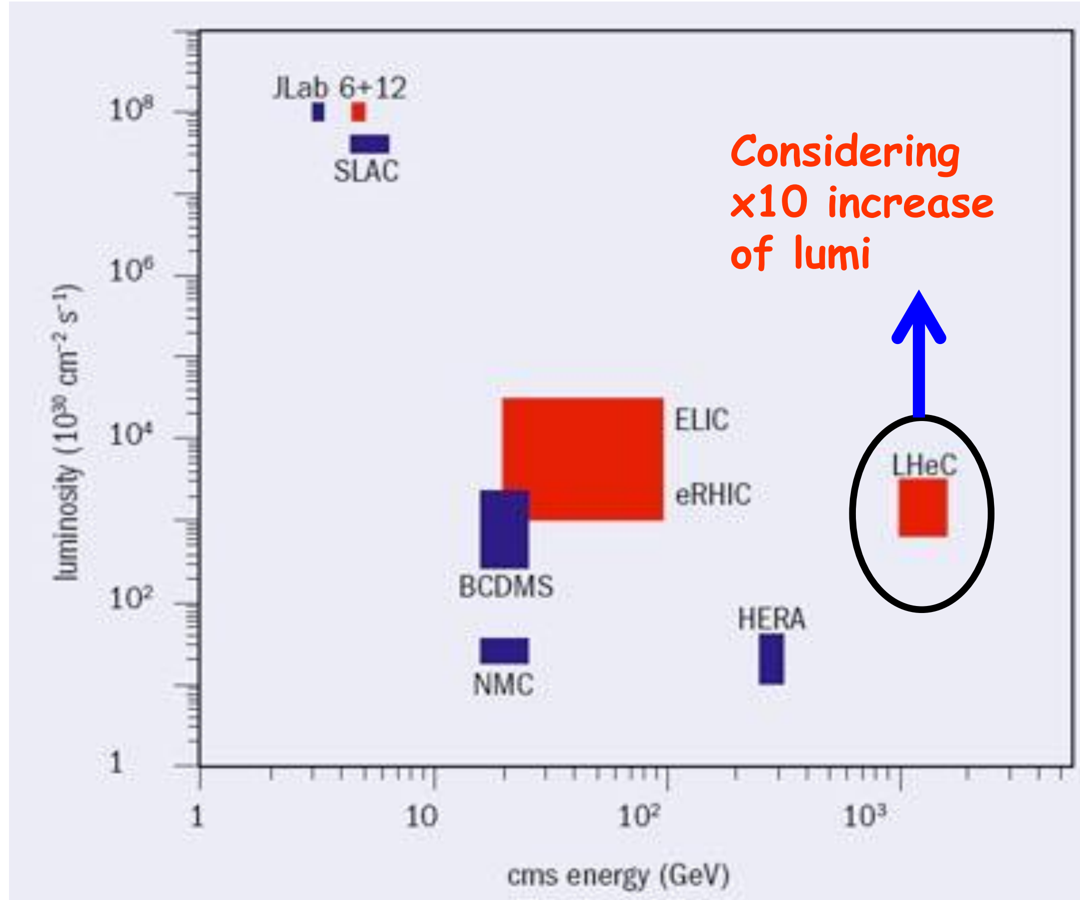
The LHeC Detector

P. Kostka



Some LHeC Context

The LHeC is not the first proposal for TeV scale DIS, but it is the first with the potential for significantly higher luminosity than HERA …



DESY 06-006
Cockcroft-06-05

Deep Inelastic Electron-Nucleon Scattering at the LHC*

J. B. Dainton[1], M. Klein[2], P. Newman[3], E. Perez[4], F. Willeke[2]

[1] Cockcroft Institute of Accelerator Science and Technology, Daresbury International Science Park, UK
[2] DESY, Hamburg and Zeuthen, Germany
[3] School of Physics and Astronomy, University of Birmingham, UK
[4] CE Saclay, DSM/DAPNIA/Spp, Gif-sur-Yvette, France

… achievable with a new electron accelerator at the LHC …

[JINST 1 (2006) P10001]

LHeC Physics Programme

CDR, arXiv:1211.4831 and 5102
http://cern.ch/lhec

QCD Discoveries	$\alpha_s < 0.12$, $q_{sea} \neq \bar{q}$, instanton, odderon, low x: (n0) saturation, $\bar{u} \neq \bar{d}$
Higgs	WW and ZZ production, $H \to b\bar{b}$, $H \to 4l$, CP eigenstate
Substructure	electromagnetic quark radius, e^*, ν^*, W?, Z?, top?, H?
New and BSM Physics	leptoquarks, RPV SUSY, Higgs CP, contact interactions, GUT through α_s
Top Quark	top PDF, $xt = x\bar{t}$?, single top in DIS, anomalous top
Relations to LHC	SUSY, high x partons and high mass SUSY, Higgs, LQs, QCD, precision PDFs
Gluon Distribution	saturation, $x \approx 1$, J/ψ, Υ, Pomeron, local spots?, F_L, F_2^c
Precision DIS	$\delta\alpha_s \simeq 0.1\,\%$, $\delta M_c \simeq 3\,\mathrm{MeV}$, $v_{u,d}$, $a_{u,d}$ to $2-3\,\%$, $\sin^2\Theta(\mu)$, F_L, F_2^b
Parton Structure	Proton, Deuteron, Neutron, Ions, Photon
Quark Distributions	valence $10^{-4} \lesssim x \lesssim 1$, light sea, d/u, $s = \bar{s}$?, charm, beauty, top
QCD	N^{3}LO, factorisation, resummation, emission, AdS/CFT, BFKL evolution
Deuteron	singlet evolution, light sea, hidden colour, neutron, diffraction-shadowing
Heavy Ions	initial QGP, nPDFs, hadronization inside media, black limit, saturation
Modified Partons	PDFs "independent" of fits, unintegrated, generalised, photonic, diffractive
HERA continuation	F_L, xF_3, $F_2^{\gamma Z}$, high x partons, α_s, nuclear structure, ..

Ultra high precision (detector, e-h redundancy) - new insight
Maximum luminosity and much extended range - rare, new effects
Deep relation to (HL-) LHC (precision+range) - complementarity

Strong coupling 0.1%; Full unfolding of PDFs; Gluon: low x: saturation?, high x: HL LHC searches…

ERL Demonstrator

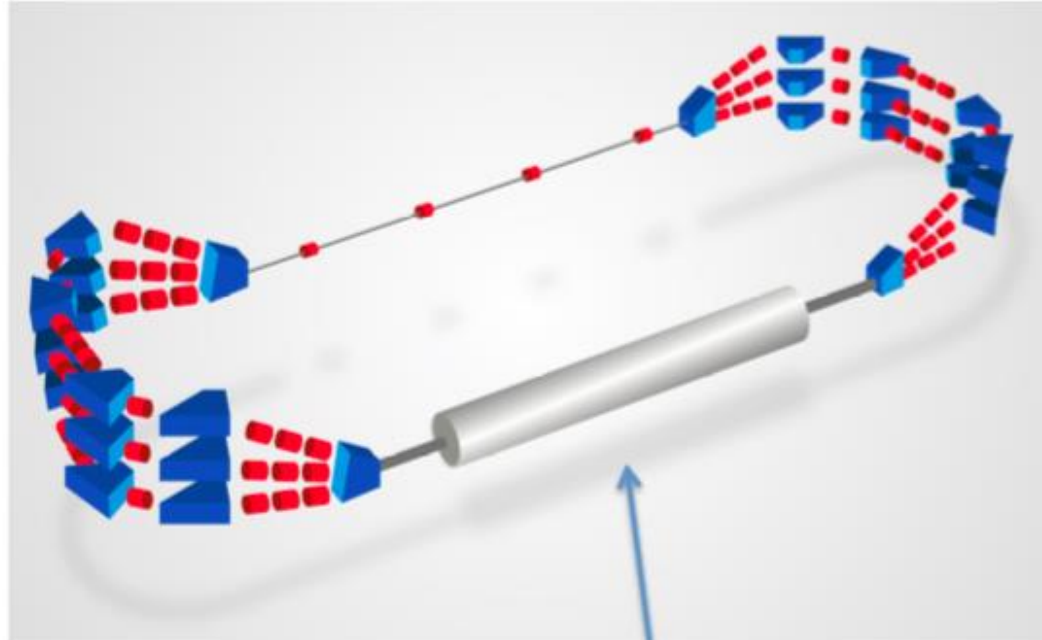
M.Klein

Demonstration of high current (10mA), multi(3)turn ERL

Test and development of 802MHz SCRF technology

E_e = 200 (400) MeV with 1(2) module

A.Valloni 2/16



Parameter	Value
Dipoles per arc Dipole length Max B Field	3/4 50 cm 1.1 T
Quadrupoles per arc Quadrupoles in straight lines	5 4
Dipoles in Spreader/Combiner Quads in Spreader/Combiner	1-3 3
Dipoles for Injection-Extraction	6

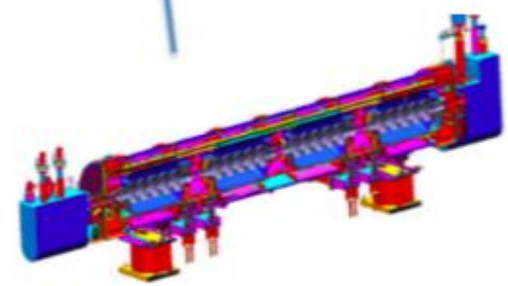


Figure 3.9: SNS high β module adapted to house β =1 5-cell cavities for LHeC.

Discussions with Orsay encouraging

Work in progress

After the Higgs discovery: LHeC $10^{33 \rightarrow 34}$ Luminosity

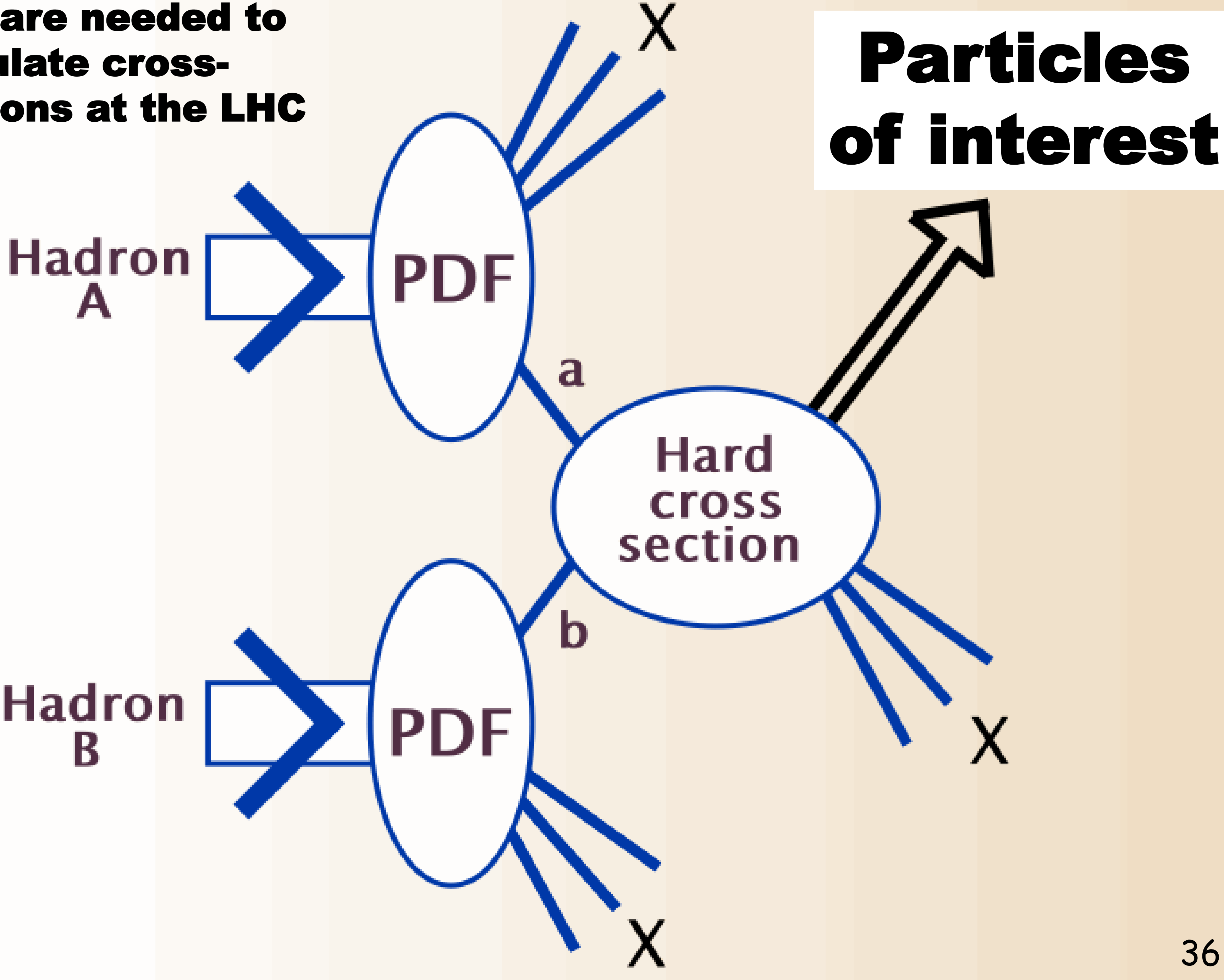
(parameters in parenthesis) Turn the LHeC into a Higgs factory

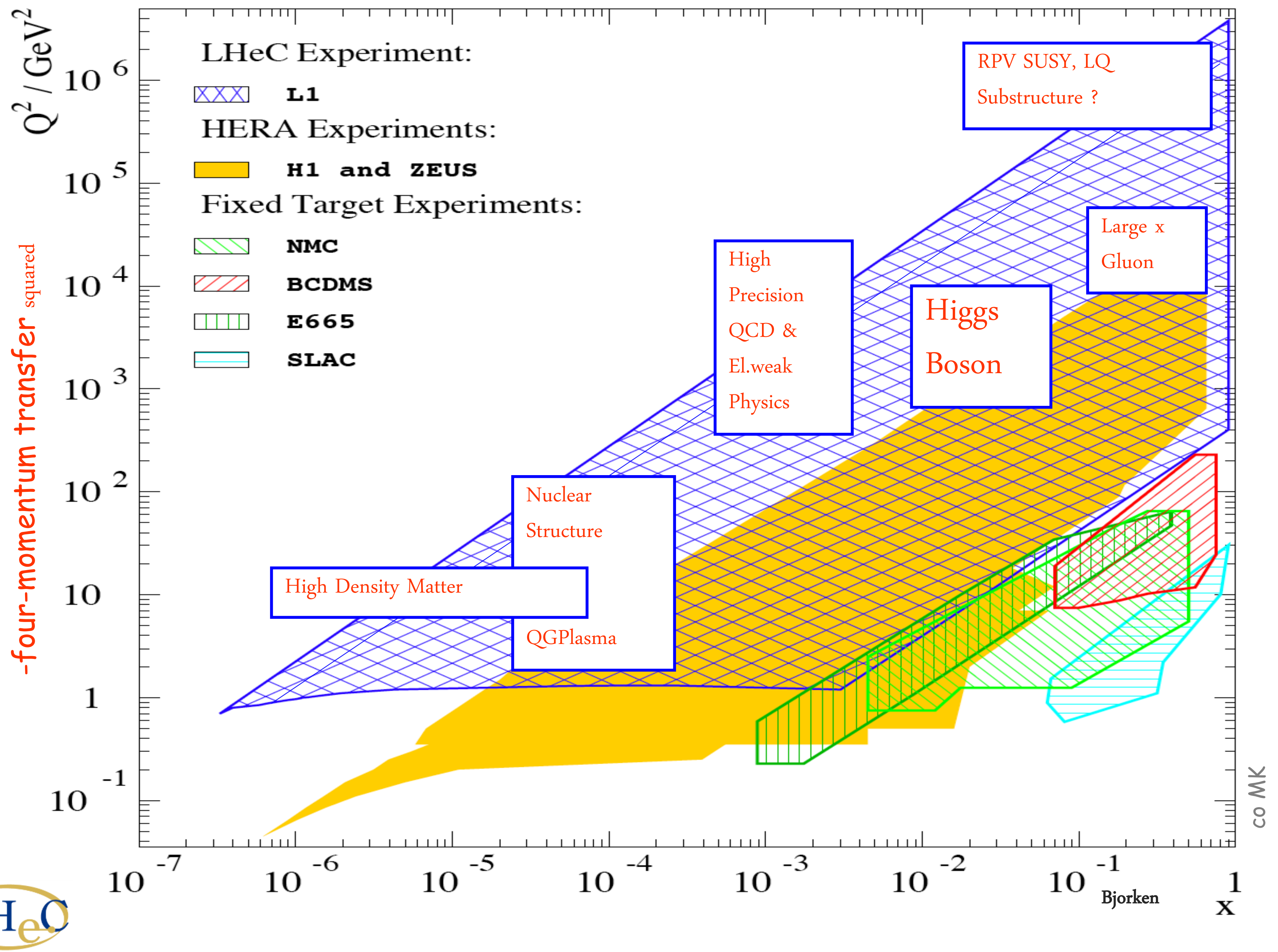
parameter [unit]	LHeC	
species	e^-	p, $^{208}Pb^{82+}$
beam energy (/nucleon) [GeV]	60	7000, 2760
bunch spacing [ns]	25, 100	25, 100
bunch intensity (nucleon) [10^{10}]	0.1 (0.2), 0.4	17 (22), 2.5
beam current [mA]	6.4 (12.8)	860 (1110), 6
rms bunch length [mm]	0.6	75.5
polarization [%]	90	none, none
normalized rms emittance [μm]	50	3.75 (2.0), 1.5
geometric rms emittance [nm]	0.43	0.50 (0.31)
IP beta function $\beta^*_{x,y}$ [m]	0.12 (0.032)	0.1 (0.05)
IP spot size [μm]	7.2 (3.7)	7.2 (3.7)
synchrotron tune Q_s	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)	
lepton disruption parameter D	6 (30)	
crossing angle	0 (detector-integrated dipole)	
hourglass reduction factor H_{hg}	0.91 (0.67)	
pinch enhancement factor H_D	1.35	
CM energy [TeV]	1300, 810	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1 (10), 0.2	

Table 1: LHeC ep and eA collider parameters. The numbers give the default CDR values, with optimum values for maximum ep luminosity in parentheses and values for the ePb configuration separated by a comma.

LHeC Collaboration arXiv:1211:5102, see also O.Bruening and M.Klein arXiv:1305.2090

Pdfs are needed to calculate cross-sections at the LHC

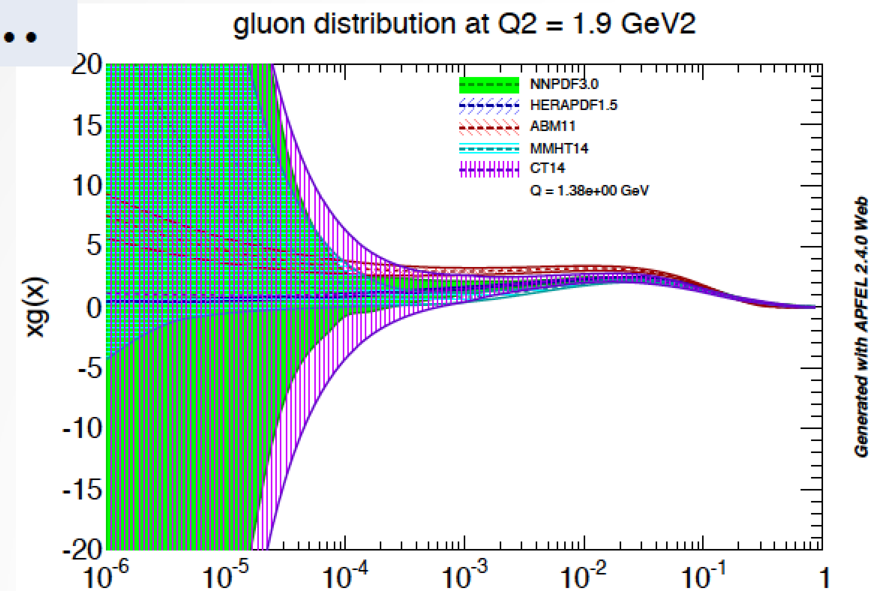




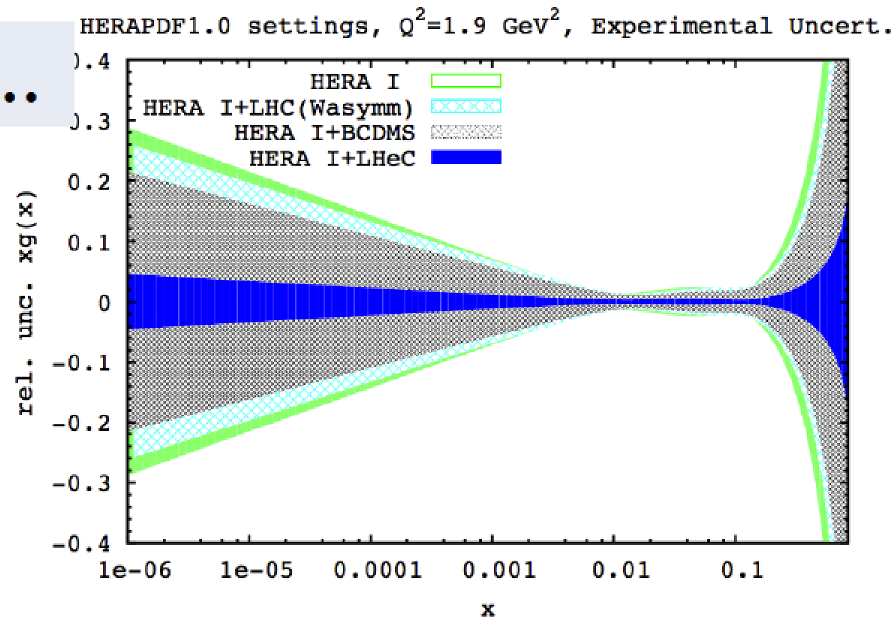
LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
RPV SUSY, LQ
Substructure ?
Large x
Gluon
High
Precision
QCD &
El.weak
Physics
Higgs
Boson
Nuclear
Structure
High Density Matter
QGPlasma
Q^2 / GeV^2
-four-momentum transfer squared
10^{-1}
1
10
10^2
10^3
10^4
10^5
10^6
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
Bjorken x
co MK
LHeC

Impact of LHeC at small x

now...

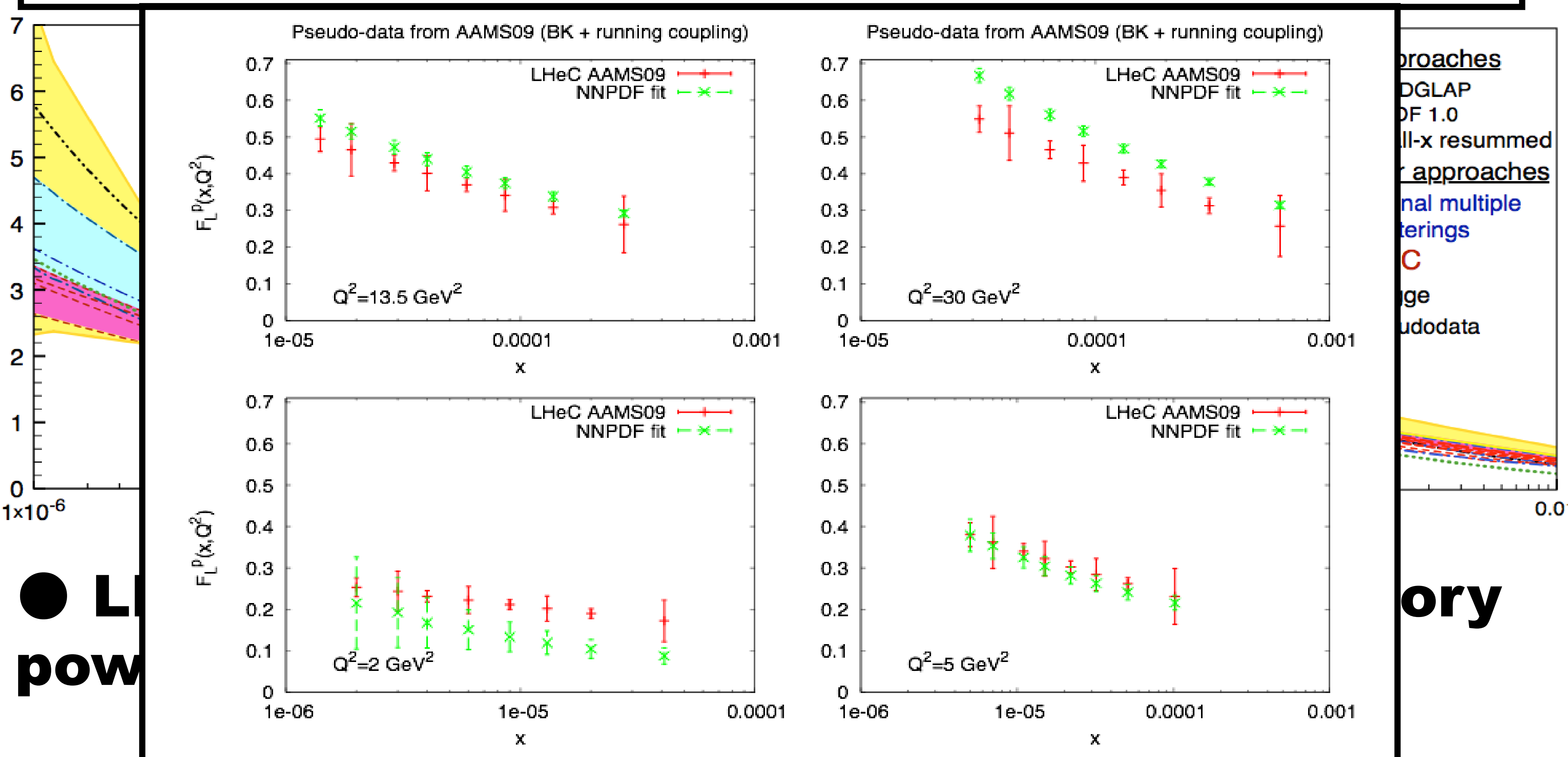


then...



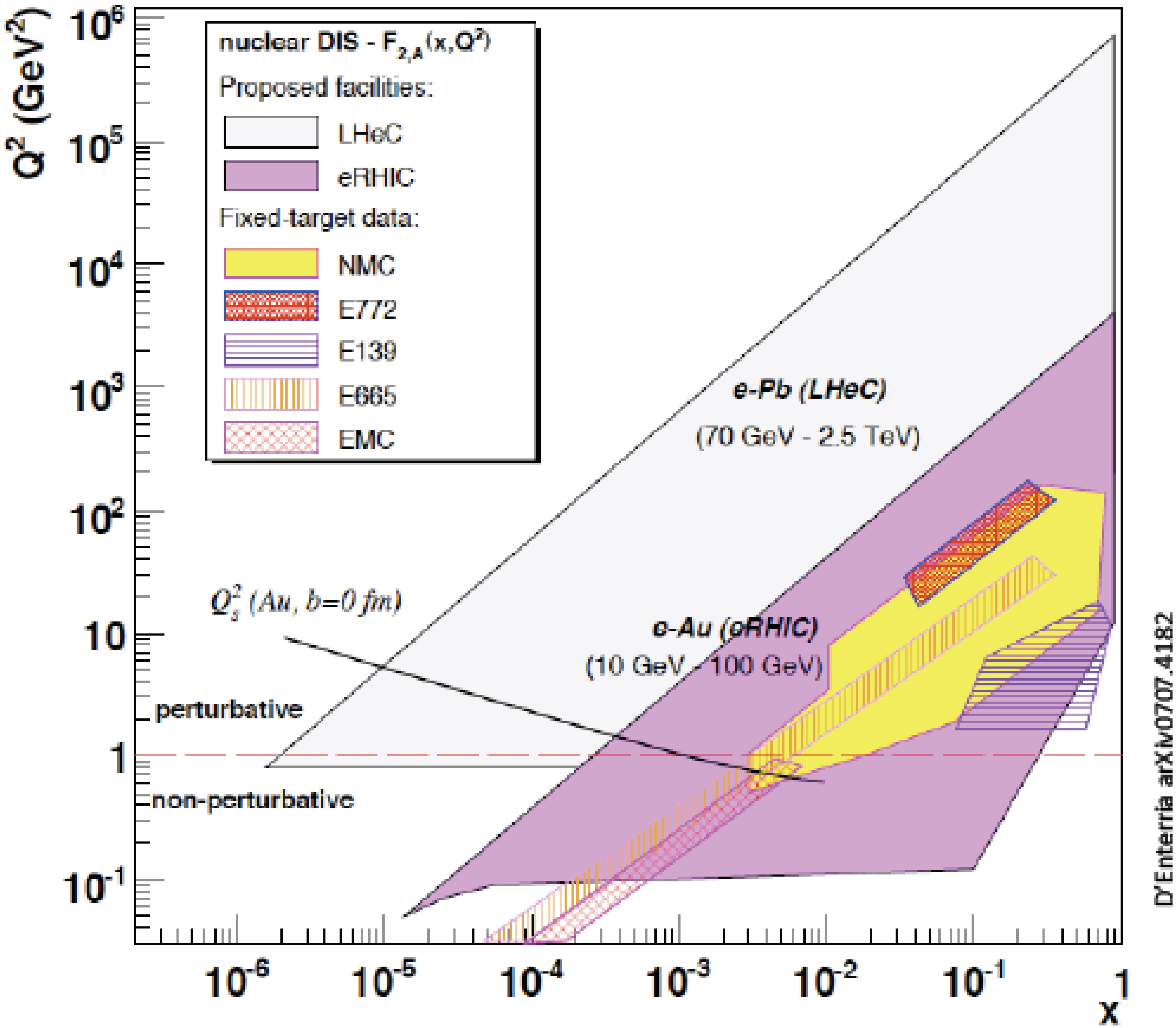
Small-x: inclusive

NLO DGLAP cannot accommodate F_2 and F_L in presence of saturation



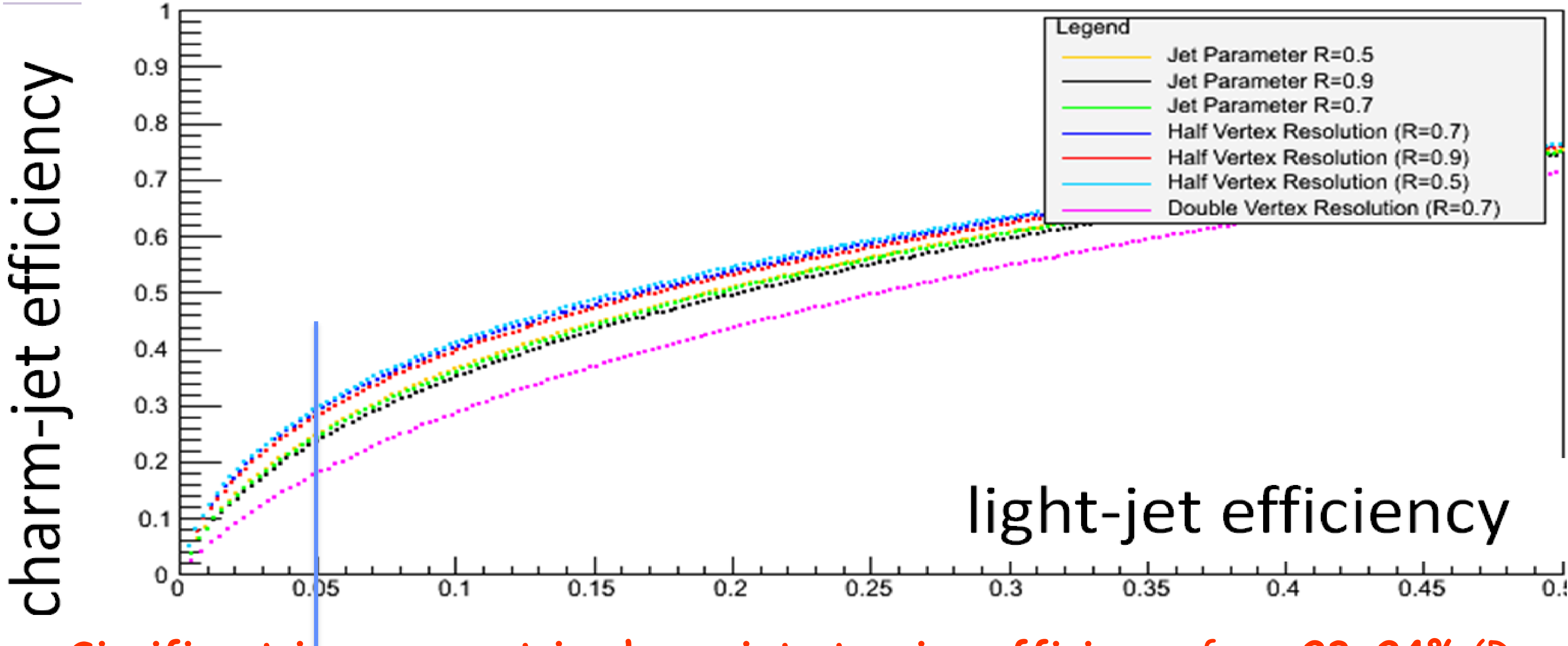
● Ll … ory
pow …

eA Collisions



HFL tagging efficiency

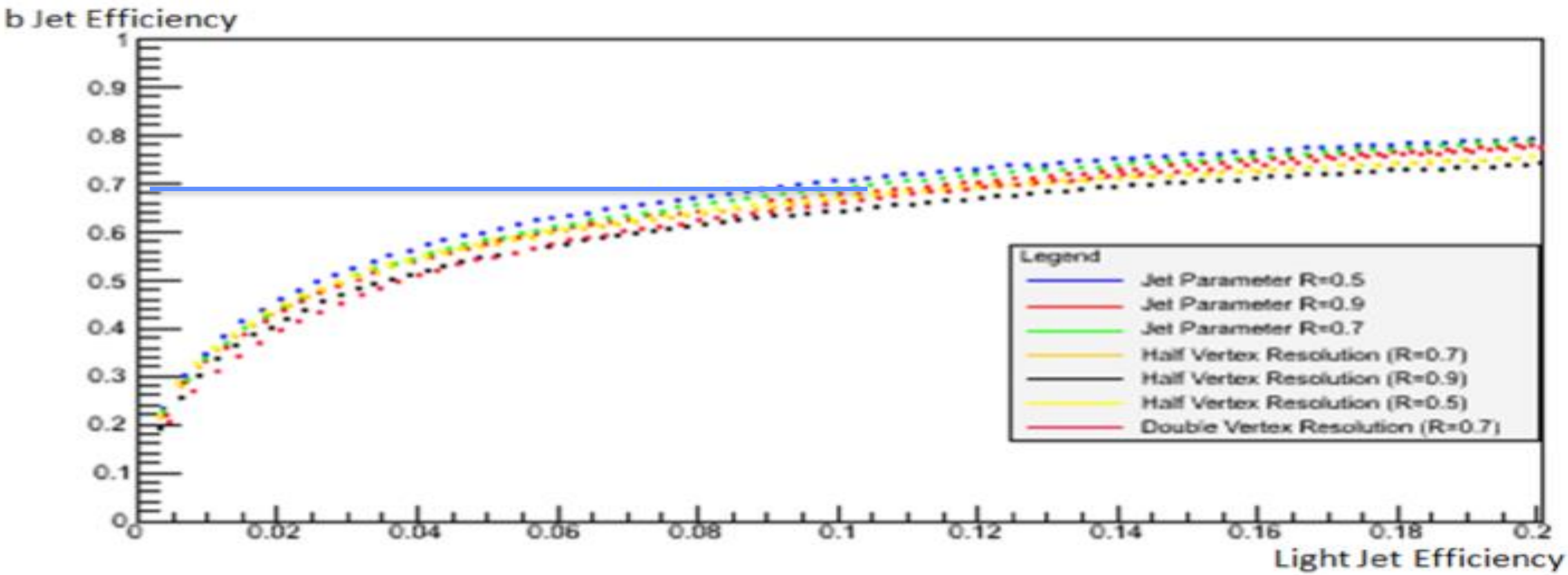
c.f. 9.5.16 talk



Significant improvement in charm jet tagging efficiency from **23-24%** (R = 0.9, nominal) to **30%** using R = 0.5 anti-kt jets and half nominal vertex resolution at light jet tagging efficiency 5%.

Charm tagging is very sensitive to vertex resolution → double resolution set-up (in pink) clearly disfavoured

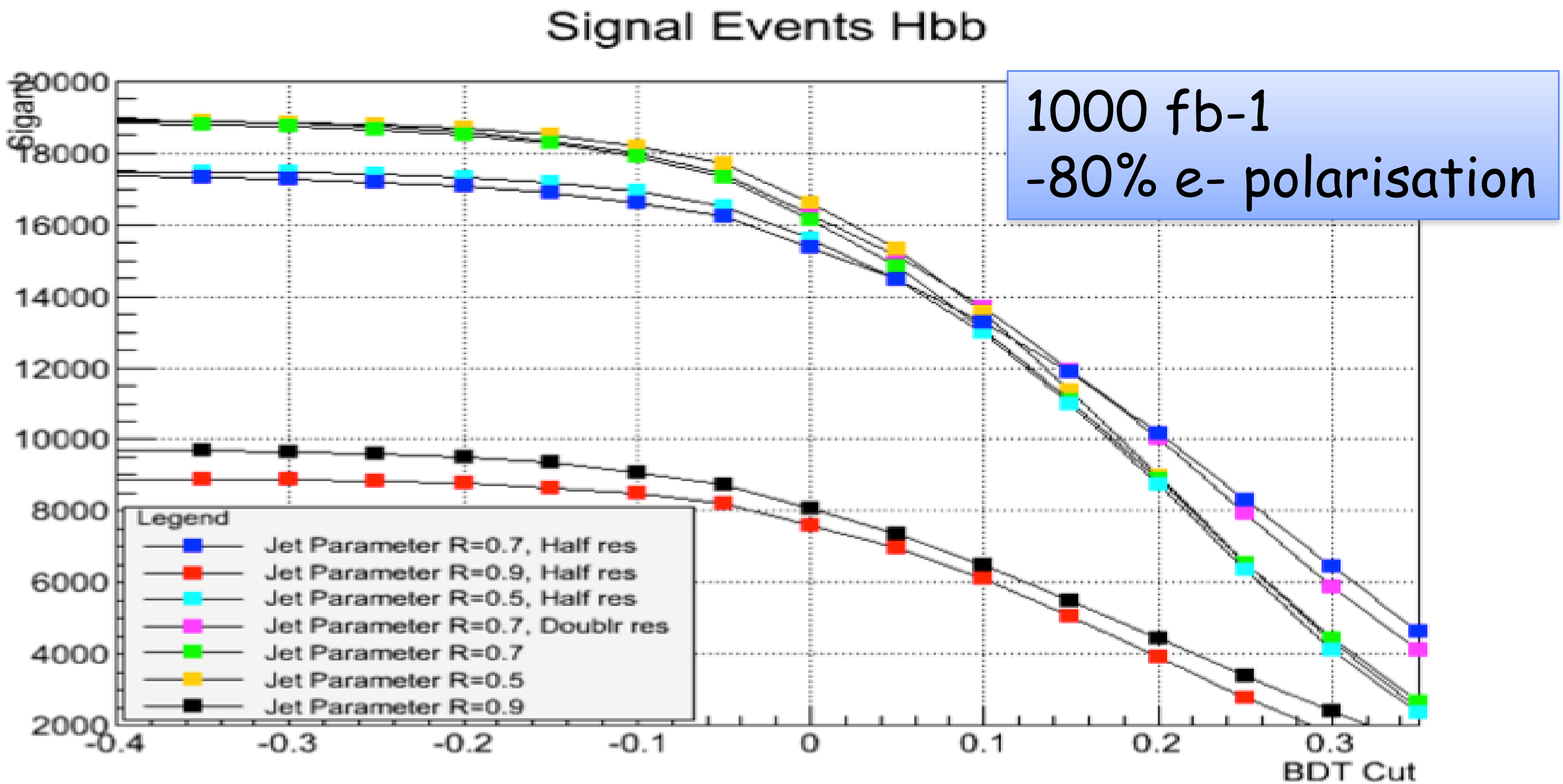
B-tagging Efficiency



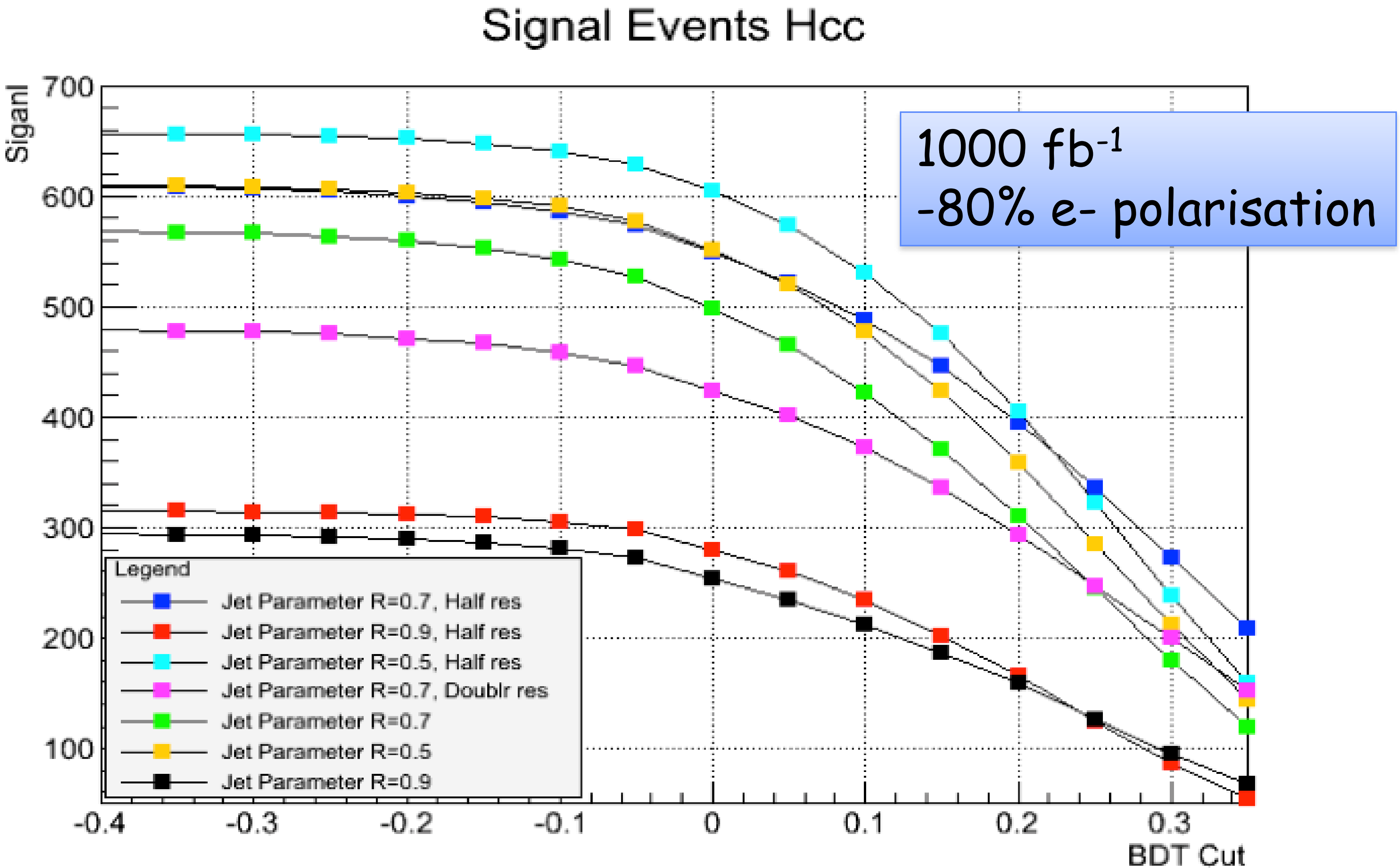
→we get less light jet contamination at 60% b-tag efficiency using smaller jet radii

→**we can release cuts and get an increased Higgs signal**

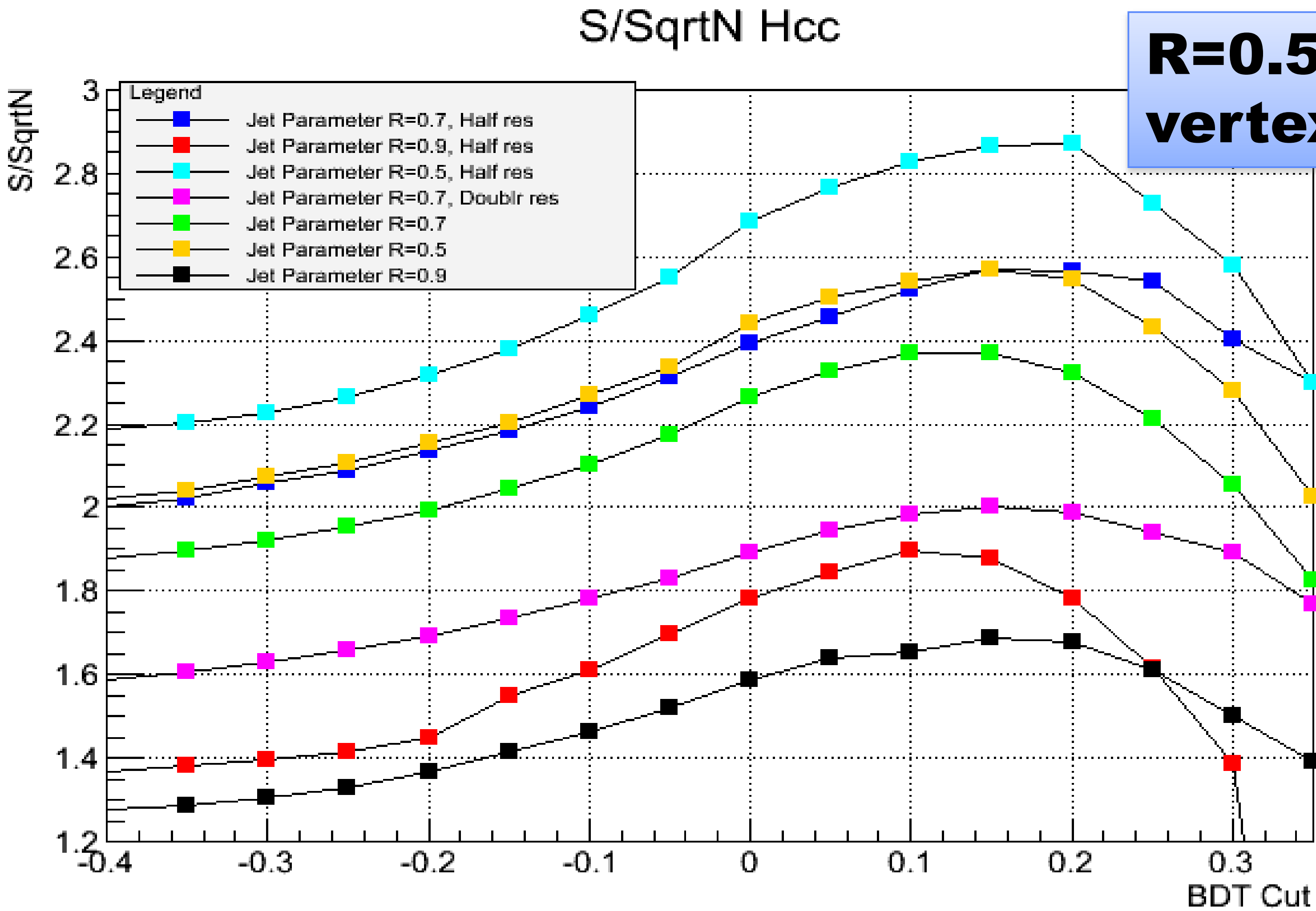
Hbb Signal Events vs Detector Setup



Hcc Signal Events vs Detector Setup



Hcc Preliminary S/√N Results



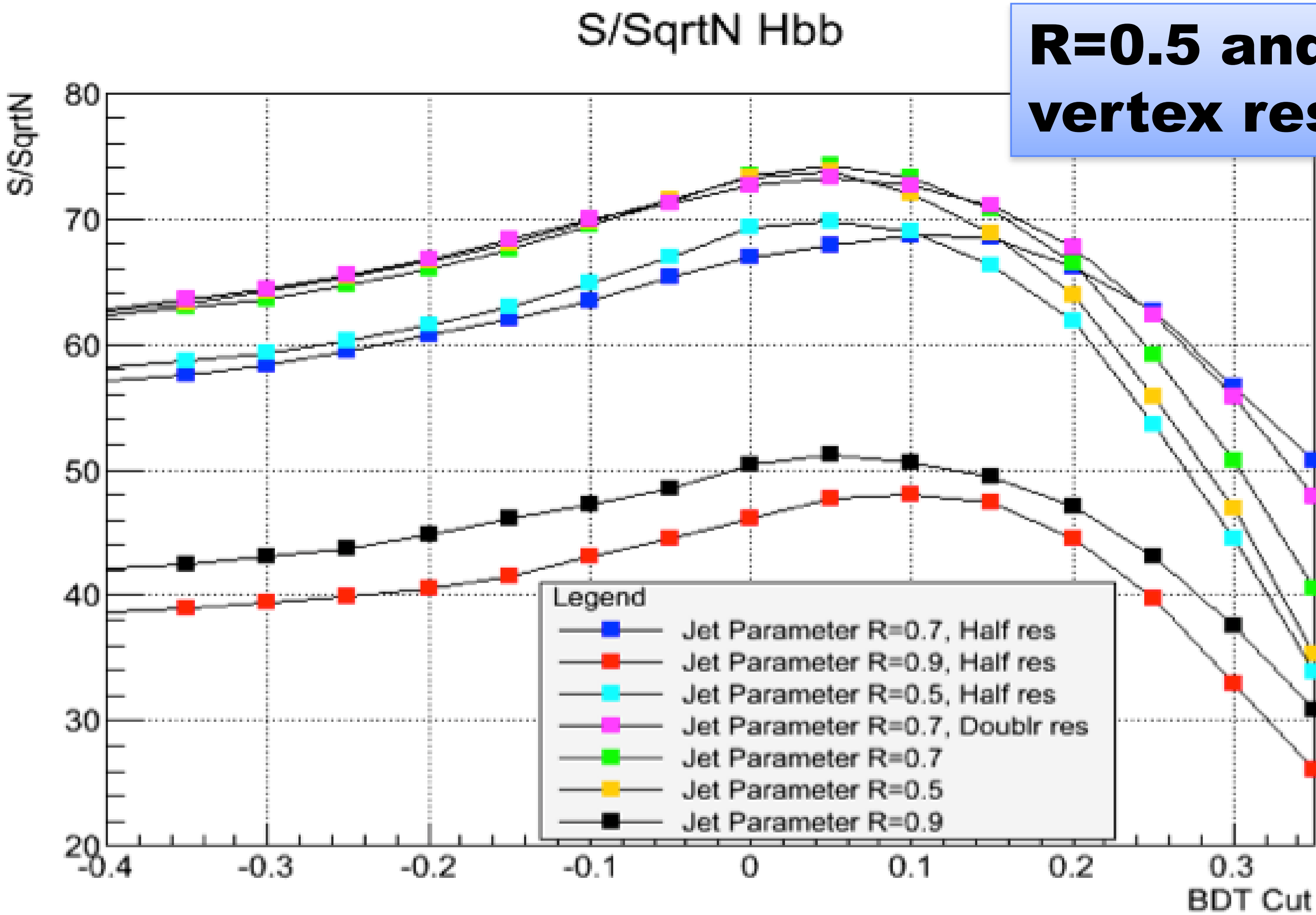
R=0.5 and Half vertex resolution

Using R = 0.5 anti-kt jets and half nominal vertex resolution improves Signal-to-background rates by factor 2.

Expected Higgs to charm coupling uncertainty improved by factor 2.

Note: 'preliminary' means Hcc as signal and 100% Hbb + CC DIS multijets as background

Hbb Preliminary S/√N Results



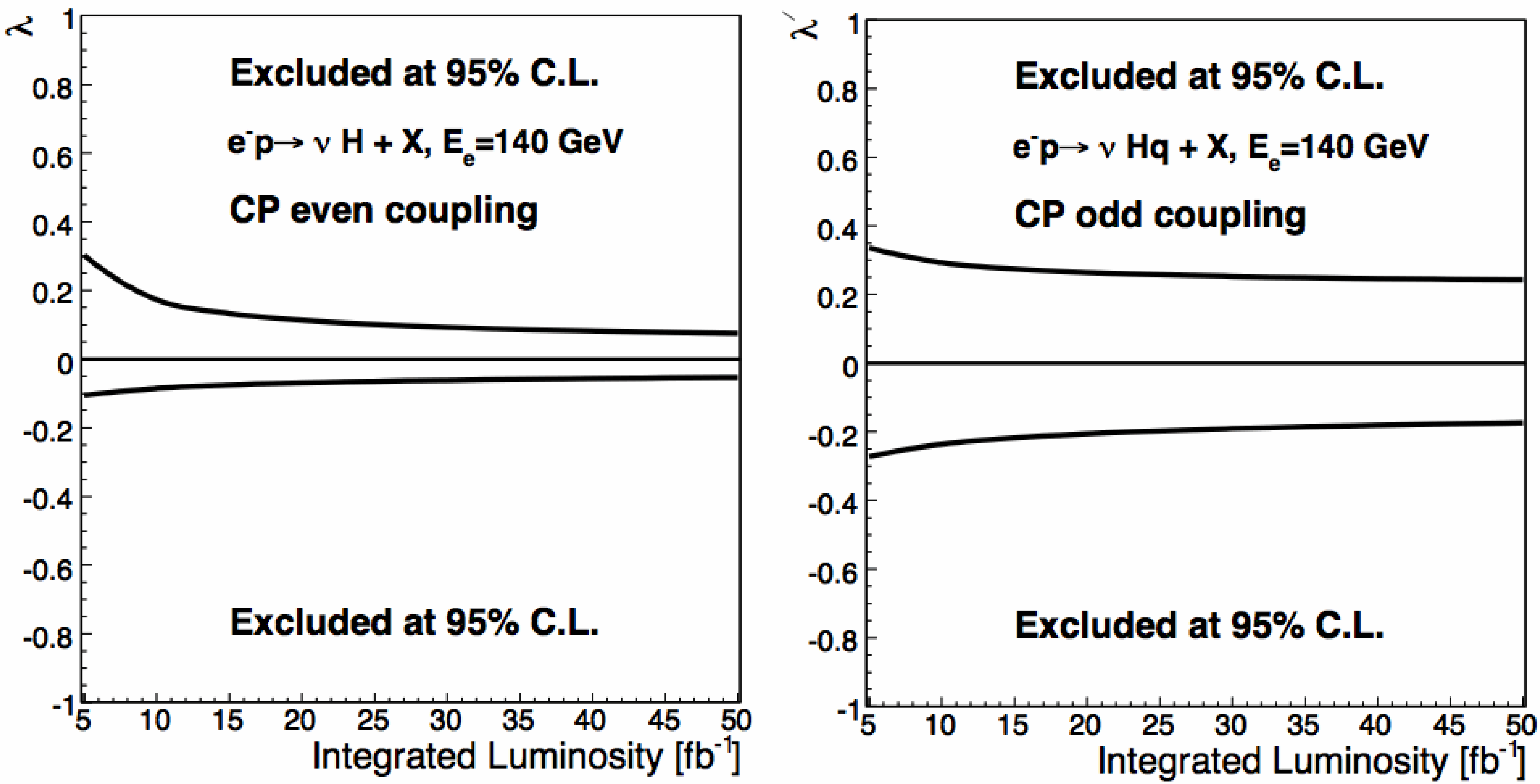
R=0.5 and Half vertex resolution

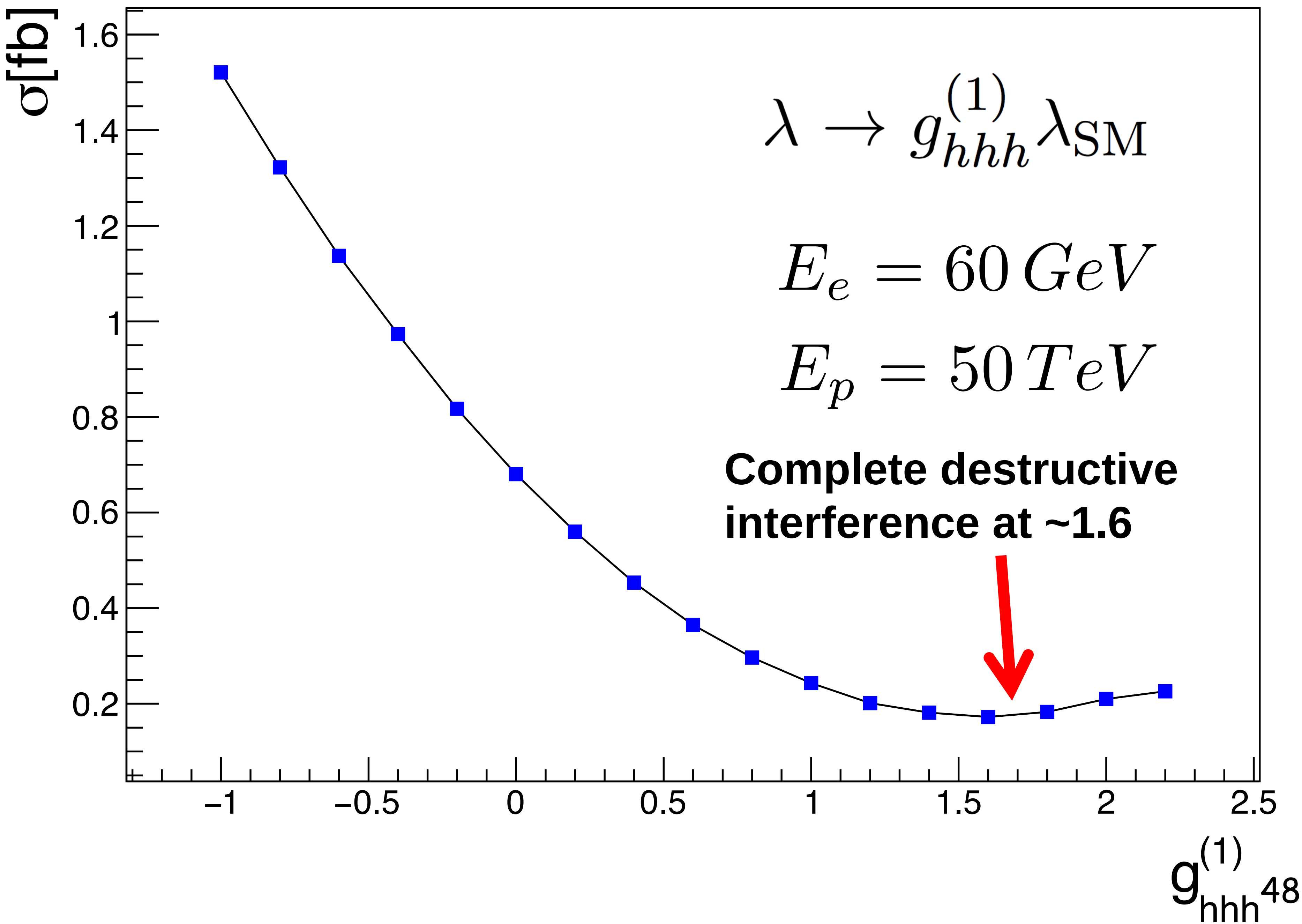
For Hbb, results are quite stable for R = 0.5-0.7 anti-kt jets
➔ R=0.9 anti-kt jets are clearly dis-favoured with the present Delphes set-ups

Note: 'preliminary' means Hbb as signal and 100% Hcc + CC DIS multijets as background

Results on the sensitivity with updated background as per the simulations of U. Klein (DIS 2011)

URL: http://www.ep.ph.bham.ac.uk/exp/LHeC/talks/DIS11.Klein2.pdf





σ[fb]
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
−1
−0.5
0
0.5
1
1.5
2
2.5
$g^{(1)}_{hhh}$
$\lambda \rightarrow g^{(1)}_{hhh}\lambda_{\mathrm{SM}}$
$E_e = 60\,GeV$
$E_p = 50\,TeV$
Complete destructive
interference at ~1.6

Background classification

(Charm and light partons also considered)

- CC processes: $$pe^- \to \begin{cases} b\bar{b}b\bar{b}j\nu_e; \\ b\bar{b}jjj\nu_e; \\ zzj\nu_e, z \to b\bar{b}; \\ t\bar{t}j\nu_e, \text{(hadronic/semi-leptonic)}; \end{cases}$$

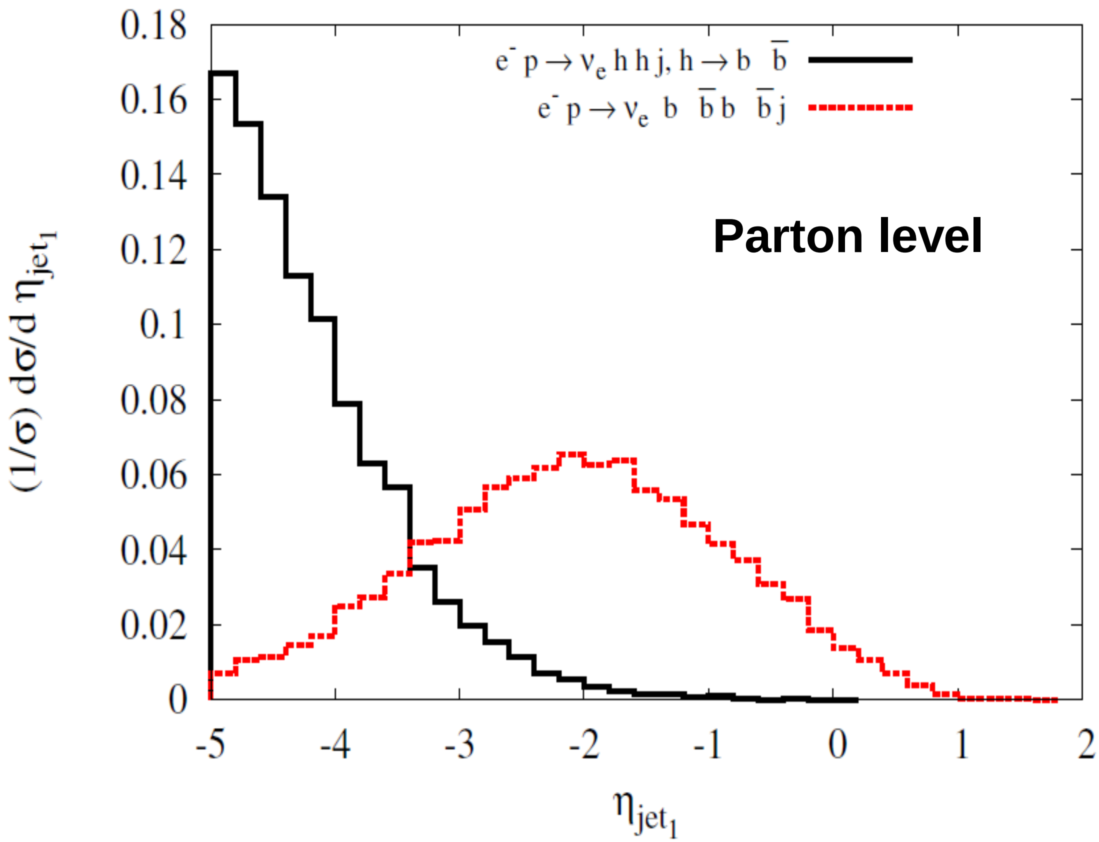
- NC processes: $$pe^- \to \begin{cases} b\bar{b}b\bar{b}je^-; \\ b\bar{b}jjje^-; \\ zzje^-, z \to b\bar{b}; \\ t\bar{t}je^-, \text{(hadronic/semi-leptonic)}; \end{cases}$$

Particularly dangerous background

- PHOTO-production: $$p\gamma \to \begin{cases} b\bar{b}b\bar{b}j; \\ b\bar{b}jjj; \\ zzj, z \to b\bar{b}; \\ t\bar{t}j, \text{(hadronic/semi-leptonic)}. \end{cases}$$

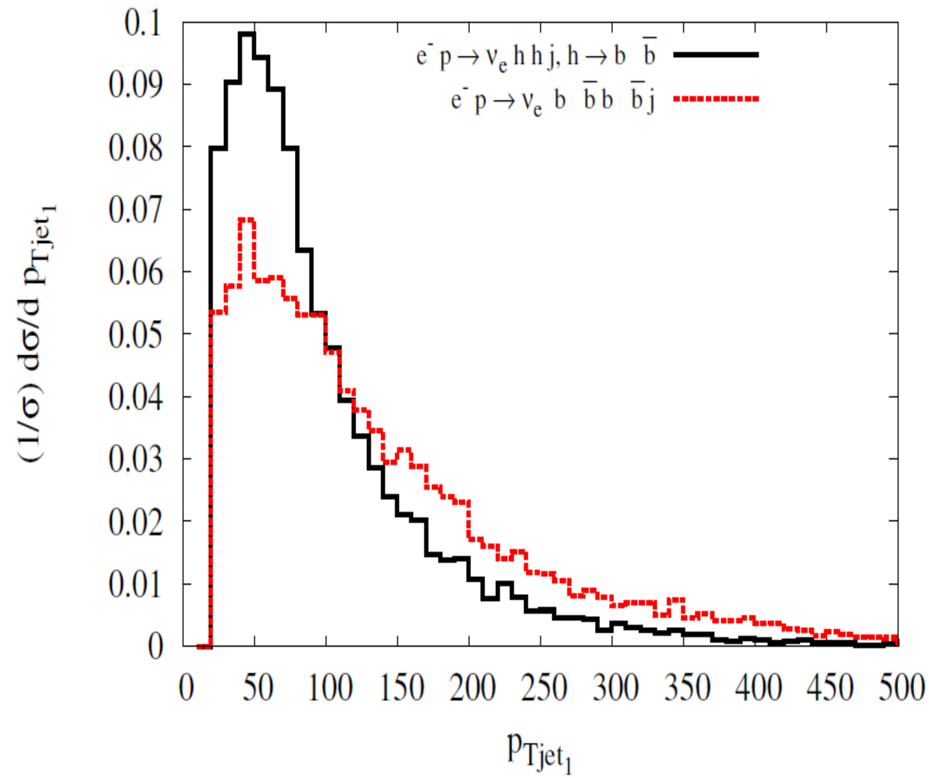
Effective vertices. Note the dependence on momenta in non-SM vertices. This induces significant impact on scattering kinematics.

$$
\begin{aligned}
\mathrm{i}\Gamma_{hhh} =& -6\mathrm{i}v\lambda g^{(1)}_{hhh} - \mathrm{i}g^{(2)}_{hhh}(p_1\cdot p_2 + p_2\cdot p_3 + p_3\cdot p_1),\\
\mathrm{i}\Gamma_{hW^-W^+} =& \mathrm{i}\Bigg[\left\{\frac{g^2}{2}v + \frac{g}{m_W}g^{(1)}_{hWW}p_2\cdot p_3 + \frac{g}{m_W}g^{(2)}_{hWW}(p_2^2+p_3^2)\right\}\eta^{\mu_2\mu_3}\\
&-\frac{g}{m_W}g^{(1)}_{hWW}p_2^{\mu_3}p_3^{\mu_2} - \frac{g}{m_W}g^{(2)}_{hWW}(p_2^{\mu_2}p_2^{\mu_3} + p_3^{\mu_2}p_3^{\mu_3})\\
&-\mathrm{i}\frac{g}{m_W}\tilde{g}_{hWW}\epsilon_{\mu_2\mu_3\mu\nu}p_2^{\mu}p_3^{\nu}\Bigg],\\
\mathrm{i}\Gamma_{hhW^-W^+} =& \mathrm{i}\Bigg[\left\{\frac{g^2}{2} + \frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3\cdot p_4 + \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^2+p_4^2)\right\}\eta^{\mu_3\mu_4}\\
&-\frac{g^2}{m_W^2}g^{(1)}_{hhWW}p_3^{\mu_4}p_4^{\mu_3} - \frac{g^2}{m_W^2}g^{(2)}_{hhWW}(p_3^{\mu_3}p_3^{\mu_4} + p_4^{\mu_3}p_4^{\mu_4})\\
&-\mathrm{i}\frac{g^2}{m_W^2}\tilde{g}_{hhWW}\epsilon_{\mu_3\mu_4\mu\nu}p_3^{\mu}p_4^{\nu}\Bigg].
\end{aligned}
$$



This is a important discriminator to distinguish EW from QCD multi-jet production

Scattered quark is more forward in signal



This is an important characteristic of SM production in VBF that is, in turn, sensitive to coupling structures. Strong advantage of the LHeC

Case Study: Invisible Higgs Decay @ LHeC

(Based on 1508.01095, Yi-Lei Tang, Chen Zhang and Shou-hua Zhu)

Signal (100% invisible)~1.8fb
Total background~2.7fb

$$C_{\mathrm{MET}}^2 = \kappa_V^2 \times \mathrm{Br}(\mathrm{h} \to invisible)$$

Br(h->inv)=6%@2σ level with 1 ab^{-1}, exceeding ZH@HL-LHC!

Cross Section (fb)	Basic Cuts	$\not{E}_T > 70$ GeV	$I > 1$	$\eta_j - \eta_e > 3.0$	$\Delta\phi_{ej} < 1.2$	$\eta_e \in [-1.2, 0.6]$	$y \in [0.06, 0.5$	Lepton Veto
Signal ($C_{\mathrm{MET}}^2 = 1$)	16.1	8.80	8.23	4.68	2.37	2.16	1.77	1.77
Wje	816	158	143	51.7	13.9	11.3	9.13	1.96
$Wj\nu$	192	102	101	5.68	2.36	1.33	0.387	0.387
Zje	42.7	13.8	12.1	1.64	0.683	0.464	0.326	0.326

TABLE I: The cross section (in unit of fb) of the signal and major backgrounds after application of each cut in the corresponding column. Other backgrounds contribute less than 0.1 fb in total after all cuts and are not displayed in the table.

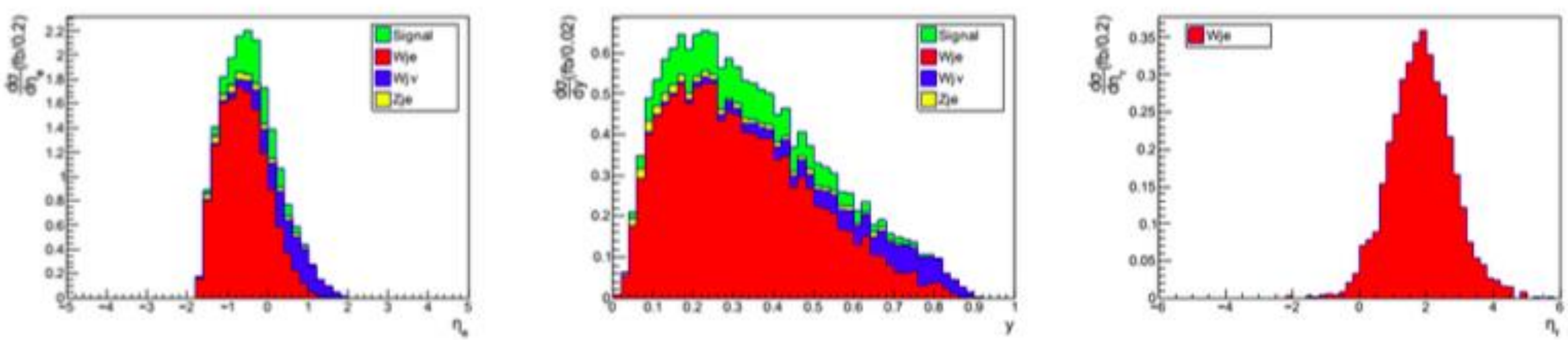


FIG. 2: Left: η_e distribution of the signal and major backgrounds just before the η_e cut. Middle: y distribution of the signal and major backgrounds just before the y cut. Right: τ lepton pseudorapidity distribution of the $Wje(W \to \tau\nu)$ background just before the lepton veto.

Further Path Determined with IAC Mandate

M.Klein

Guido Altarelli (Rome) *)
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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)

The IAC was invited in 12/13 by the DG with the following

Mandate 2014-2017

Advice to the LHeC Coordination Group and the CERN directorate by following the development of options of an ep/eA collider at the LHC and at FCC, especially with:

Provision of scientific and technical direction for the physics potential of the ep/eA collider, both at LHC and at FCC, as a function of the machine parameters and of a realistic detector design, as well as for the design and possible approval of an ERL test facility at CERN.

Assistance in building the international case for the accelerator and detector developments as well as guidance to the resource, infrastructure and science policy aspects of the ep/eA collider.

*) IAC Composition End of January 2014 +
Oliver Brüning Max Klein ex officio

Coordination Group for Future DIS at CERN

M.Klein

LCG (2014-2017) *)

Nestor Armesto
Oliver Brüning
Stefano Forte
Andrea Gaddi
Bruce Mellado
Max Klein
Peter Kostka
Daniel Schulte
Frank Zimmermann

Directors (ex-officio)
Sergio Bertolucci, Frederick Bordry

The coordination group was invited end of December 2013 by the CERN directorate with the following mandate (2014-2017)

The group has the task to coordinate the study of the scientific potential and possible technical realisation of an ep/eA collider and the associated detectors at CERN, with the LHC and the FCC, over the next four years. It also should coordinate the design of an ERL test facility at CERN as part of the preparations for a larger energy electron accelerator employing ERL techniques.

The group will cooperate with CERN and an International Advisory Committee, chaired by the emeritus DG of CERN, Professor Herwig Schopper, who also advises the CERN directorate. The Coordination Group is asked to represent the ep/eA collider development towards CERN, its committees and the international community. The currently tentative composition is listed *left*. CERN has asked Max Klein to chair and Oliver Brüning to co-chair this activity

*) LCG Composition early January 14