Status of FCC-eh and LHeC

B.Mellado

Wits Institute for Collider Particle Physics & iThemba LABS

On behalf of the LHeC Study Group

Many thanks to M.D'Onofrio, M.Klein and U.Klein for slides

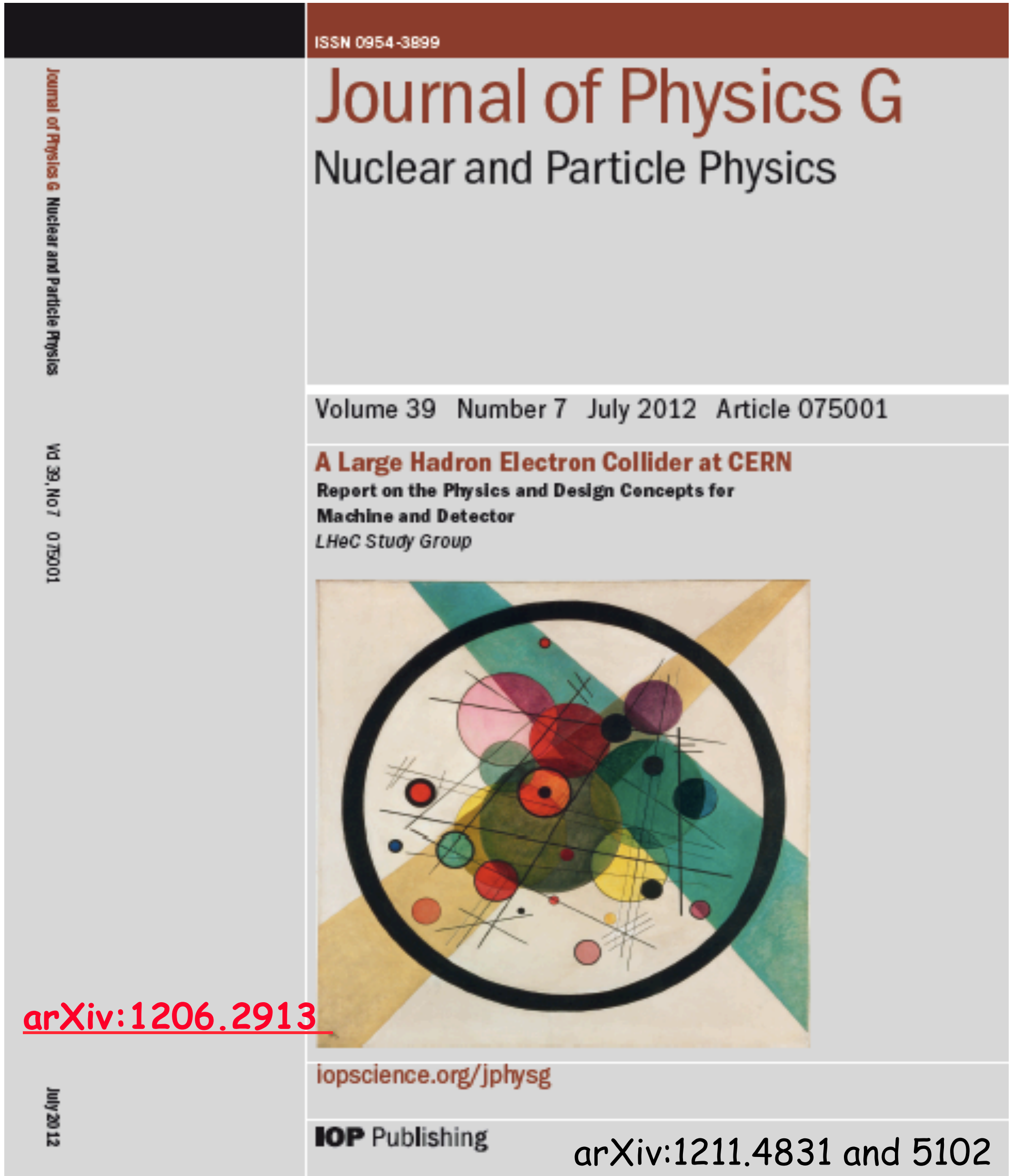
Institute for Collider Particle Physics

University of the Witwatersrand

National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

Interpreting the LHC Run 2 data and beyond, ICTP, 31/05/19



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.

LHeC + FCC-he

Organisation*)

International Advisory Committee with CERN mandate to provide "..Direction for ep/eA both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
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 (ESS)

*) 2018

Coordination Group

Accelerator+Detector+Physics

Nestor Armesto
Oliver Brüning – Co-Chair
Andrea Gaddi
Erk Jensen
Walid Kaabi
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(11) are members of the FCC coordination team

OB+MK: FCC-eh coordinators

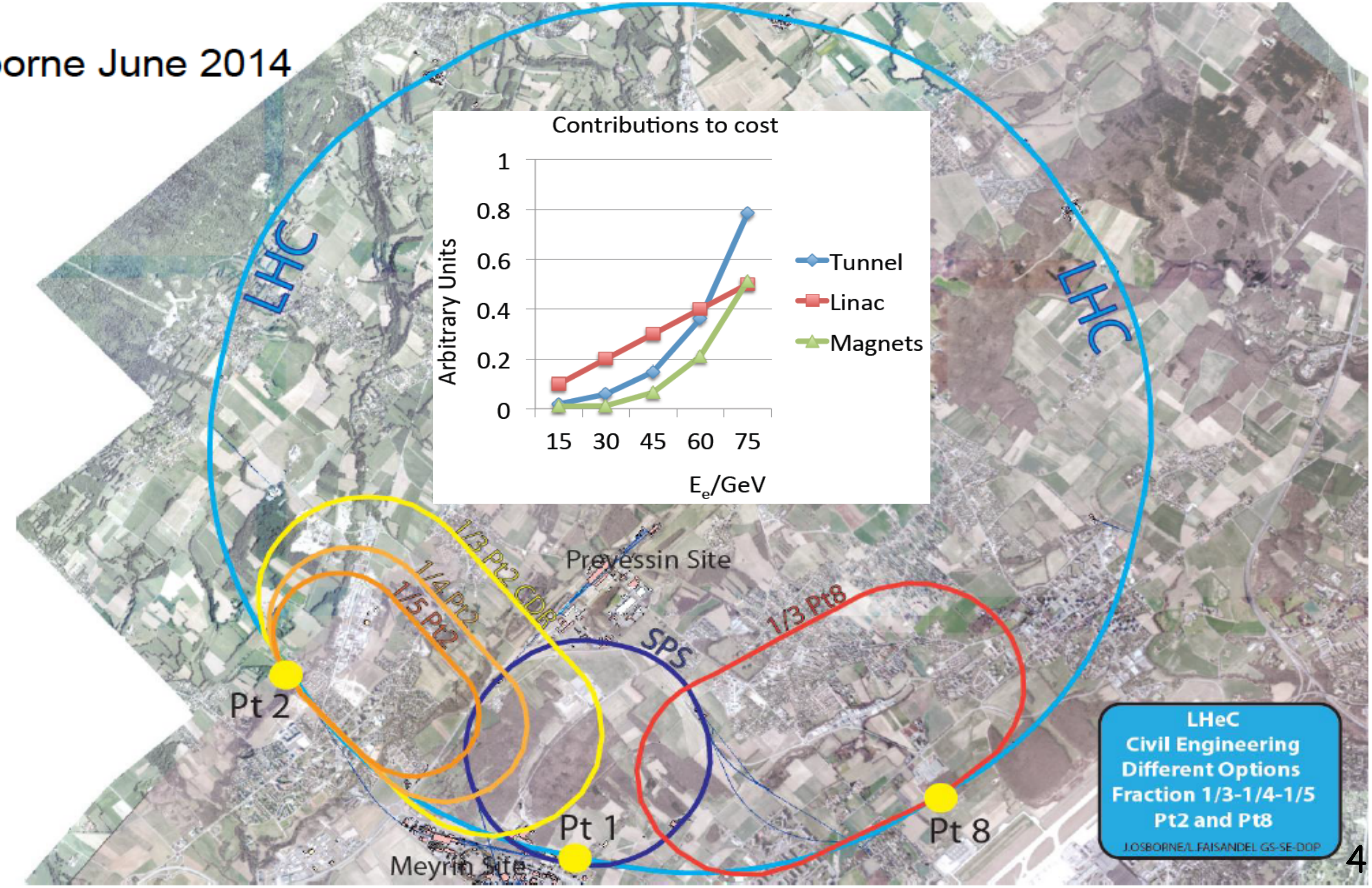
FCC IAC: Guenter Dissertori +

Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Oliver Fischer
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

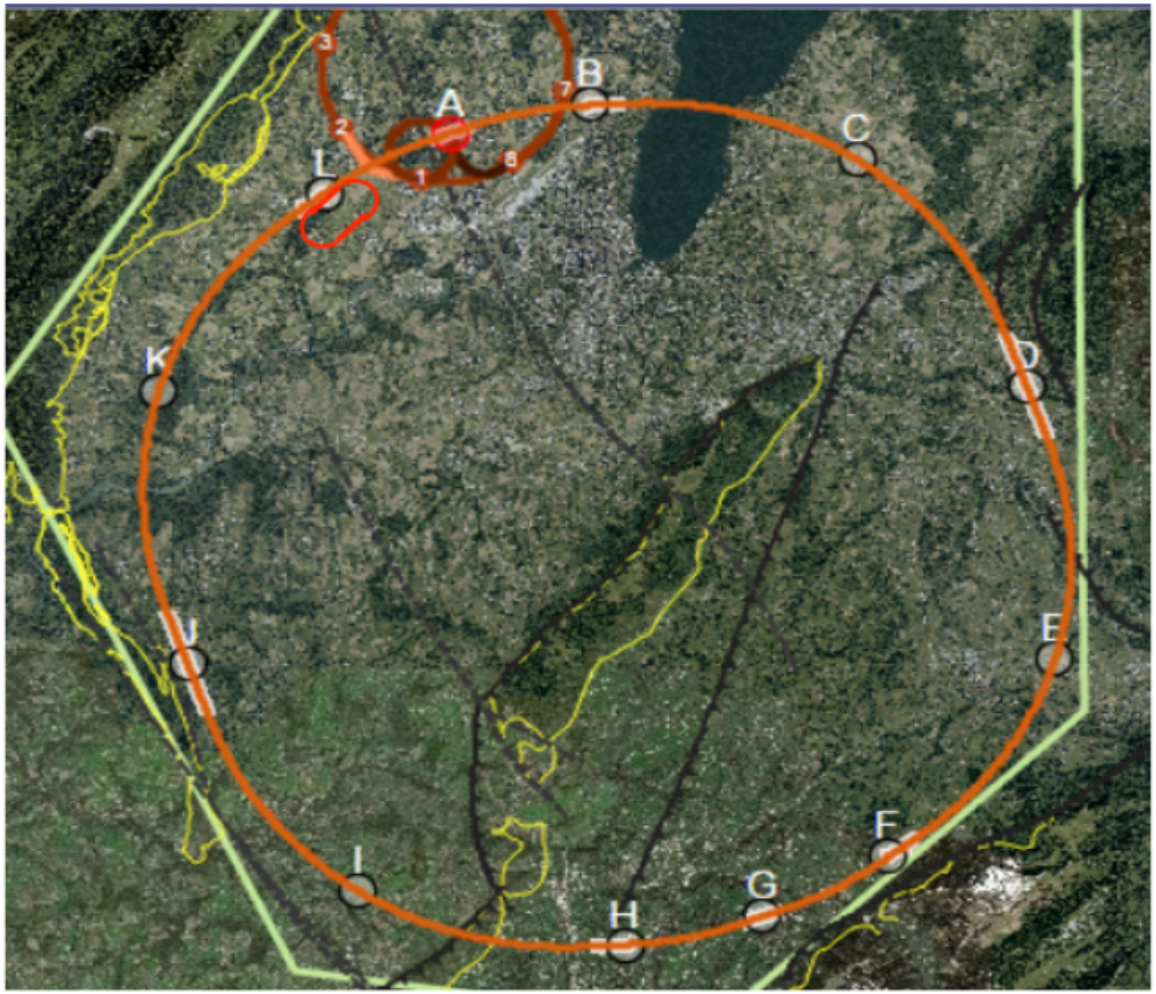
Layout

John Osborne June 2014



J.Osborne, et al

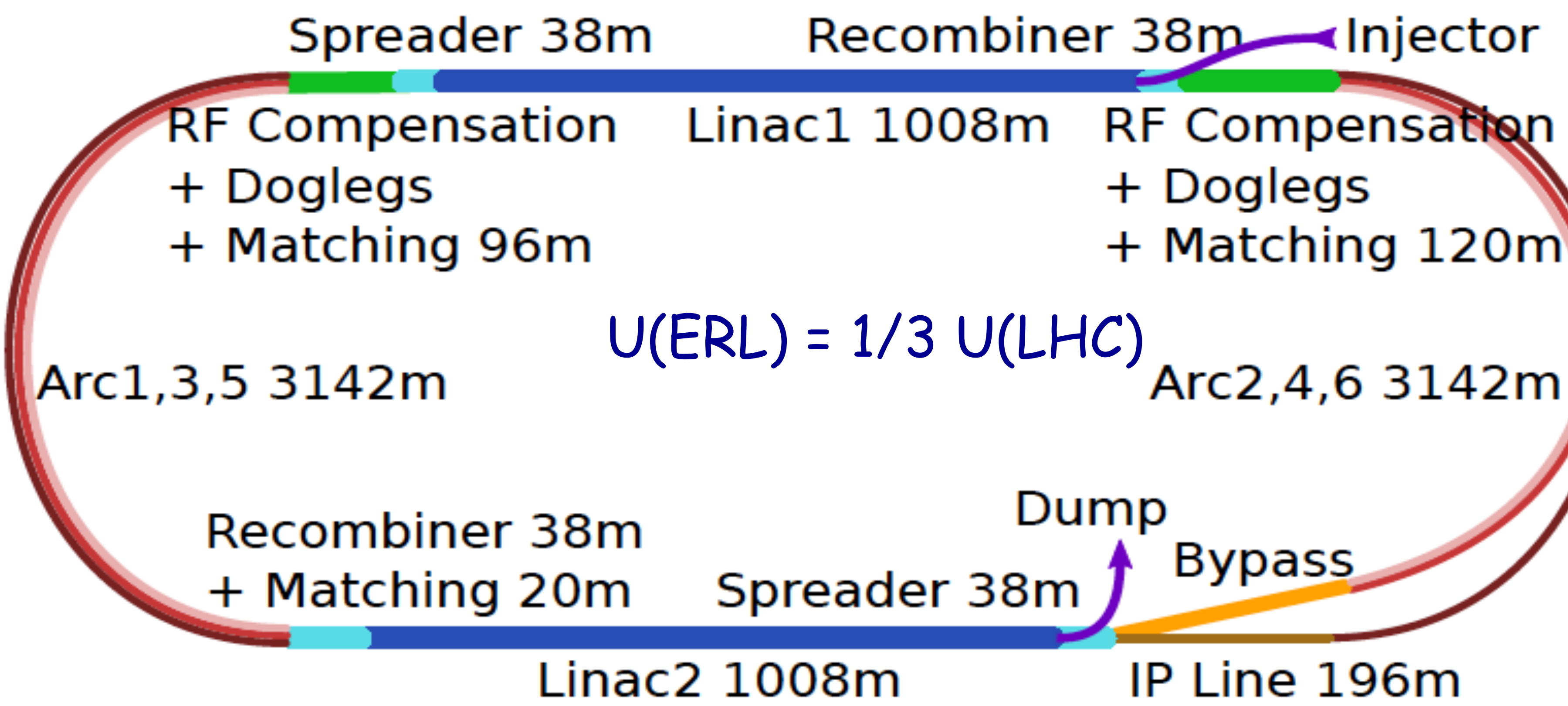
FCC-eh



60 GeV ERL tangential to FCC-hh. IP: L for geological reasons.
L= 1.5 10^{34} Higher s, Q^2, 1/x

M.Klein

Energy Recovery Linac for LHeC/FCCeh



Concurrent operation to pp, LHC/FCC become 3 beam facilities. Power limit: 100 MW
10^{34} cm^{-2} s^{-1} luminosity and factor of 15/120 (LHC/FCCeh) extension of Q^2, 1/x reach
1000 times HERA luminosity. It therefore extends up to x~1.
Four orders of magnitude extension in deep inelastic lepton-nucleus (ion) scattering.

Luminosity for LHeC, HE-LHeC and FCC

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]

EDMS 17979910 | FCC-ACC-RPT-0012

Contains update on eA: $6x10^{32}$ in e-Pb for LHeC.

Powerful ERL for Experiments

Collaboration of BINP, CERN, Daresbury/Liverpool, Jlab, Orsay INP+LAL
CDR 2016/17, TDR 2018/19 ..

of 115 AUTHOR SUBMITTED MANUSCRIPT - JPhysG-101971.R1

PERLE

PERLE

Powerful Energy Recovery Linac for Experiments

Conceptual Design Report

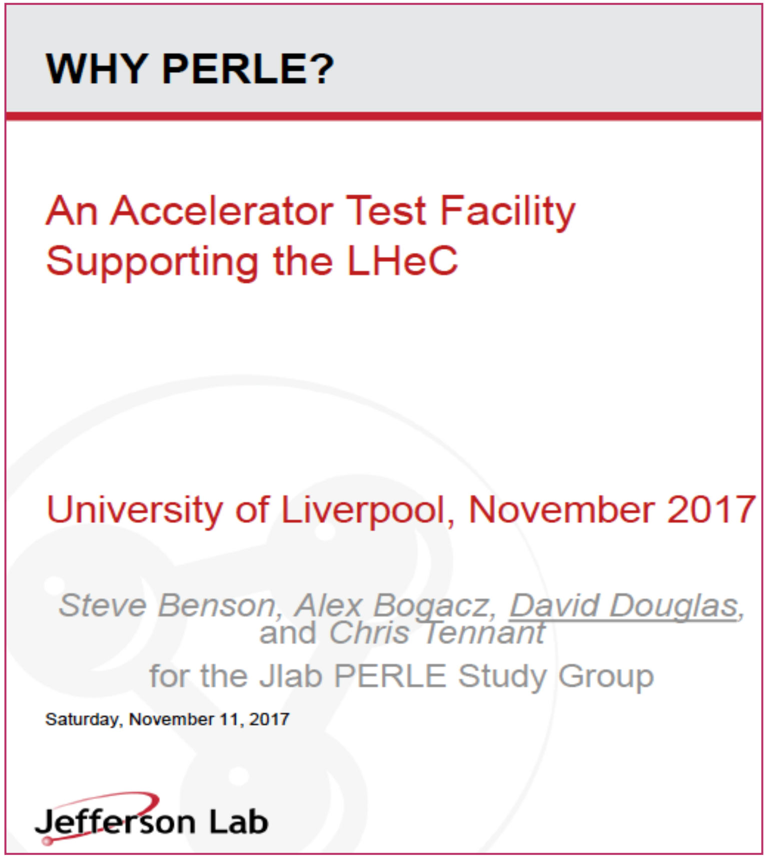
Version for Publication in J.Phys.G

CELIA Bordeaux, MIT Boston, CERN, Cockcroft and ASTeC Daresbury, TU Darmstadt, U Liverpool, Jefferson Lab Newport News, BINP Novosibirsk, IPN and LAL Orsay

October 23rd, 2017

arXiv:1705.08783

J. Phys. G45 (2018)



WHY PERLE?

An Accelerator Test Facility Supporting the LHeC

University of Liverpool, November 2017

Steve Benson, Alex Bogacz, David Douglas, and Chris Tennant

for the Jlab PERLE Study Group

Saturday, November 11, 2017

Jefferson Lab

https://indico.cern.ch/event/680603/

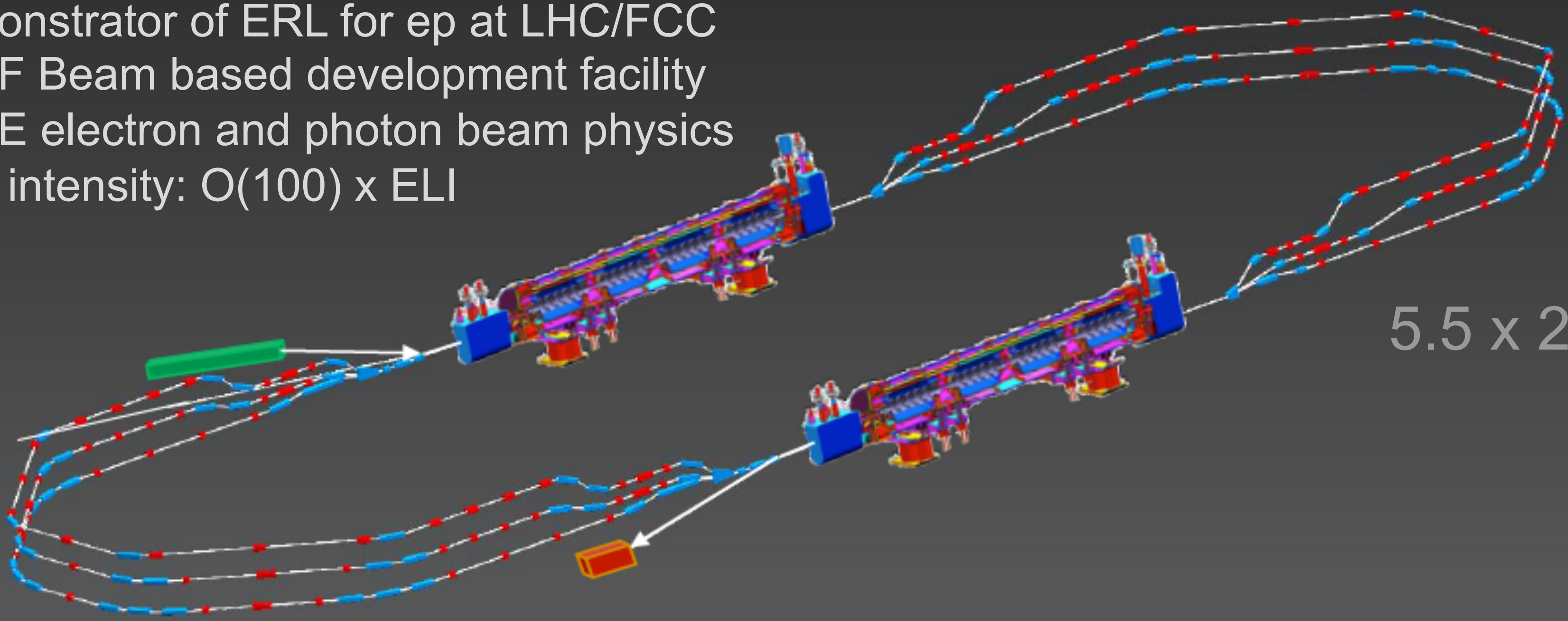
ERL facility: high current and energy
low energy nuclear, particle and astro-physics

PERLE at Orsay

PERLE at Orsay (LAL/INP) Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay

3 turns, 2 Linacs, 500 MeV, 20mA, 802 MHz, Energy Recovery Linac facility

-Demonstrator of ERL for ep at LHC/FCC
-SCRF Beam based development facility
-Low E electron and photon beam physics
-High intensity: O(100) x ELI



5.5 x 24m^2

CDR to appear in J Phys G [arXiv:1705. 08783]

Strong low energy physics program

A.Bogacz

https://indico.cern.ch/event/698368/

Why PERLE [as seen from LHeC]?

FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**

- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**
  ERLs are circular machines with tolerances and timing requirements similar to linear accelerators (no 'automatic' longitudinal phase stability, etc.)

- **Proof validity of fundamental design choices:**
  Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  Implications of high current operation (2 * 3 * [6mA – 25mA] ➔ 30-150mA!!)

- **Verify and test machine and operation tolerances before designing a large scale facility**
  Tolerances in terms of field quality of the arc magnets and cavity alignment
  Required RF phase stability (RF power) and LLRF requirements
  Halo and beam loss tolerances

PERLE Magnets

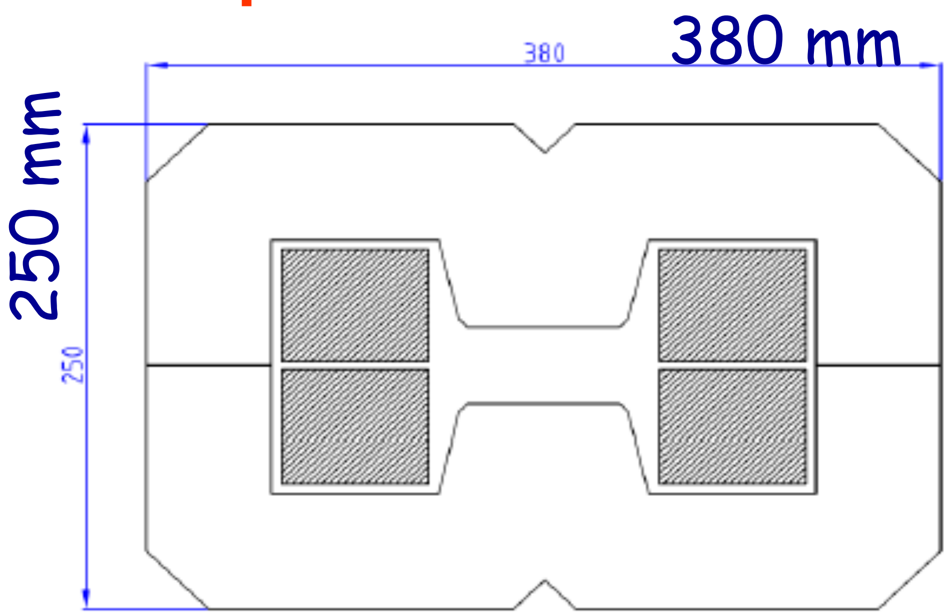
70 dipoles 0.45-1.29 T

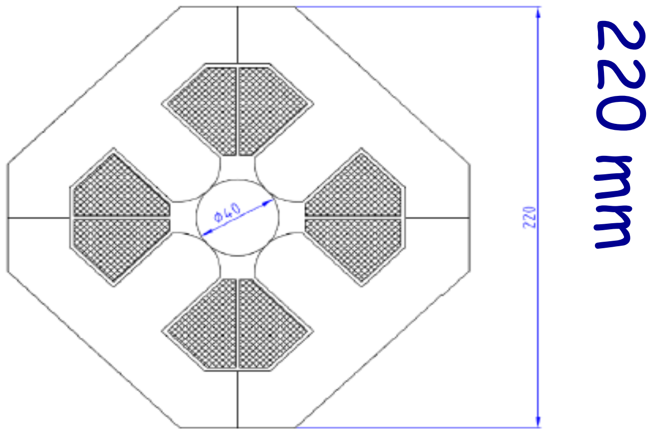
±20 mm aperture, l=200,300,400 mm

May be identical for hor+vert bend

7A/mm^2 (in grey area) water cooled

DC operated





114 quadrupoles max 28T/m

Common aperture of 40mm all arcs

Two lengths: 100 and 150mm

DC operated

P Thonet, A Milanese (CERN), C Vallerand (LAL), Y Pupkov (BINP)

F. Marhauser et al (Jlab)

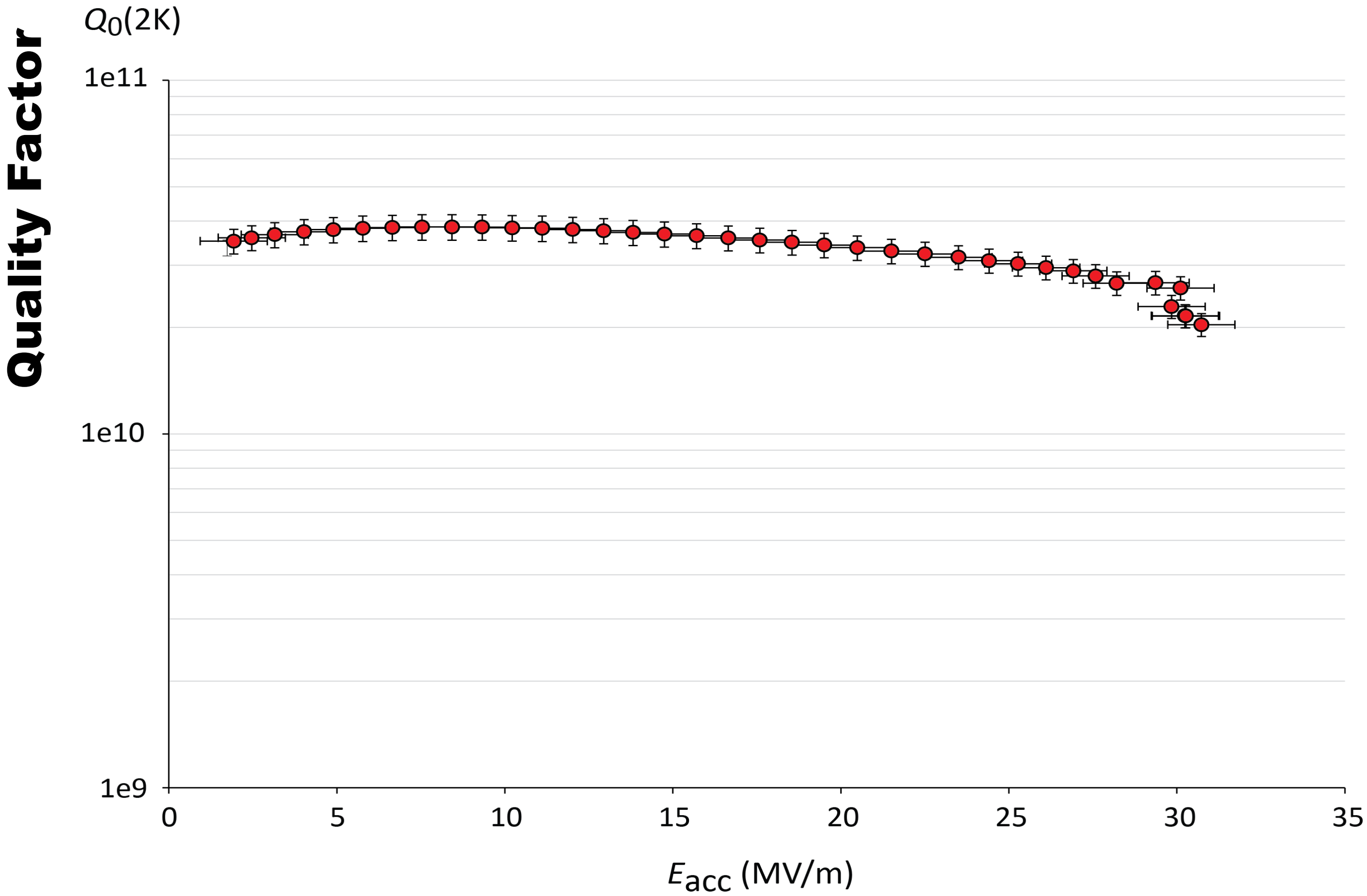
1st 802 MHz Cavity

CERN-Jlab design, produced at Jefferson Laboratory November 2017

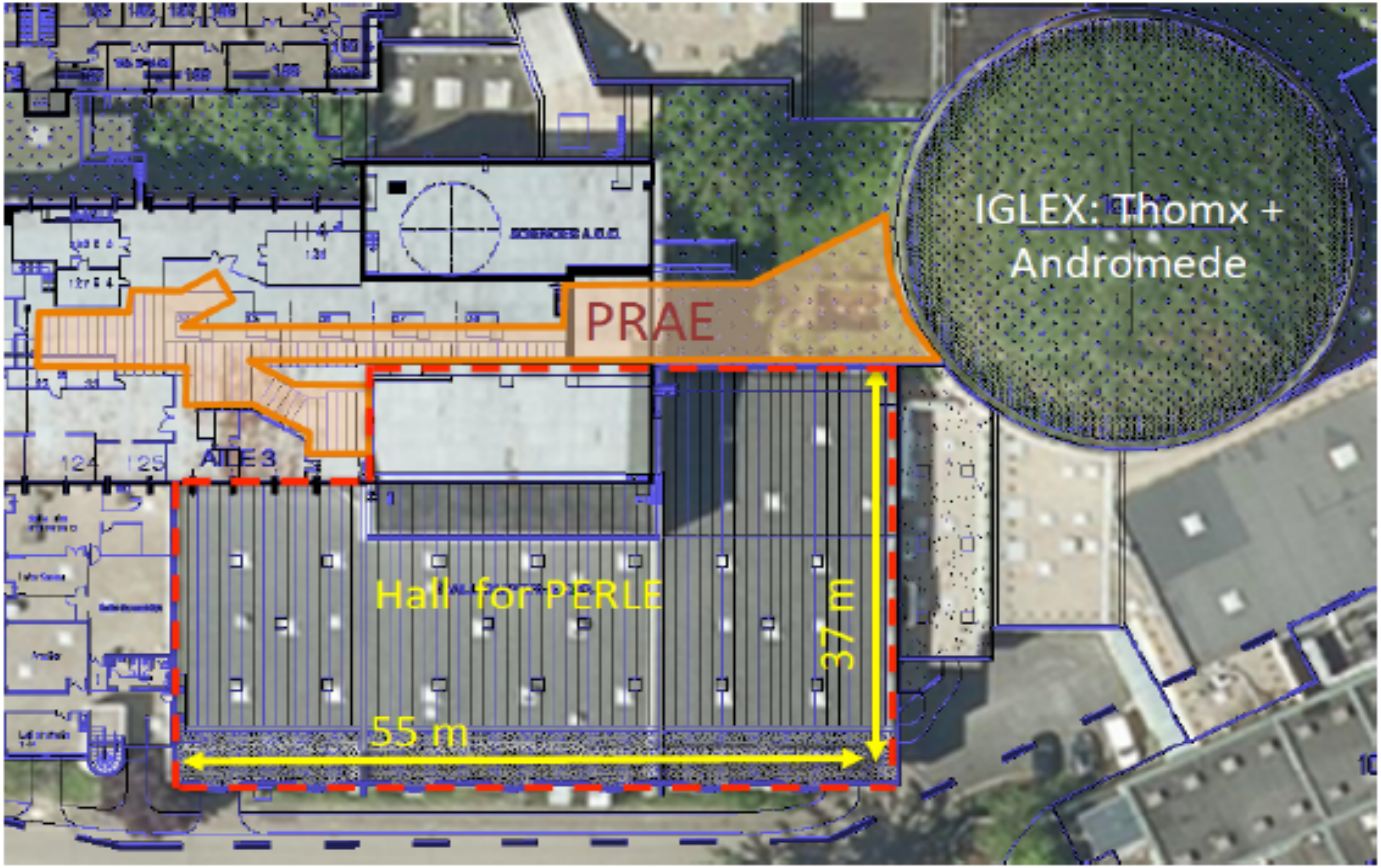
Goal: 16 MV/m, $Q_0 > 10^{10}$ operated in CW in the PERLE+LHeC ERLs, prototype also for FCC-ee

Initial 2K Test of 802 MHz Nb Cavity

December 2017

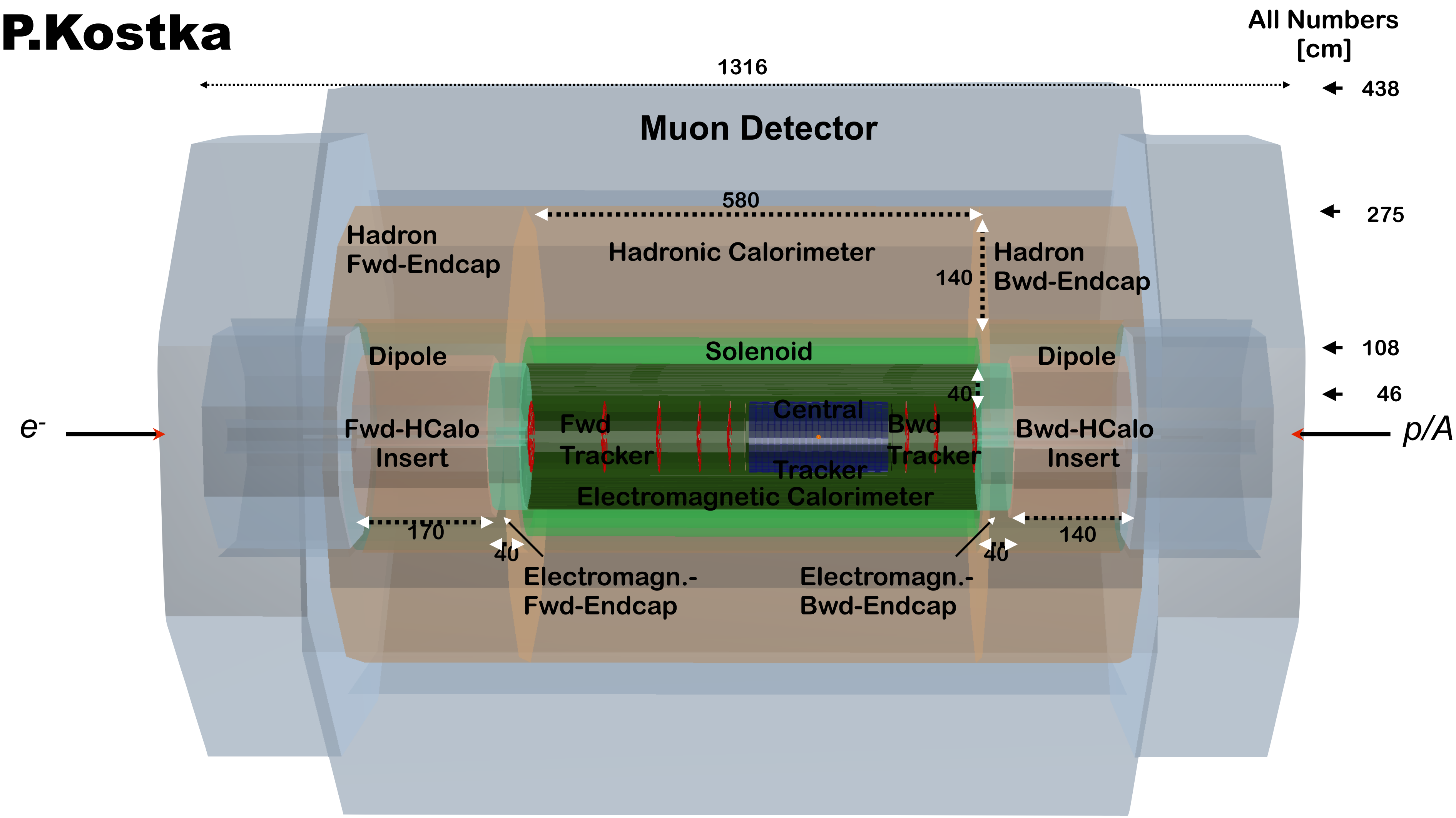


High quality, CW: operation point at about 18 MV/m. Quench at 31 MV/m
Rerinsing for field emission suppression, observed at higher gradients.
Next: HOM adapter and cryomodule design – cavity production to proceed.


IGLEX: Thomx +
Andromede
PRAE
Hall for PERLE
37 m
55 m

LHeC Detector Basic Layout

P.Kostka

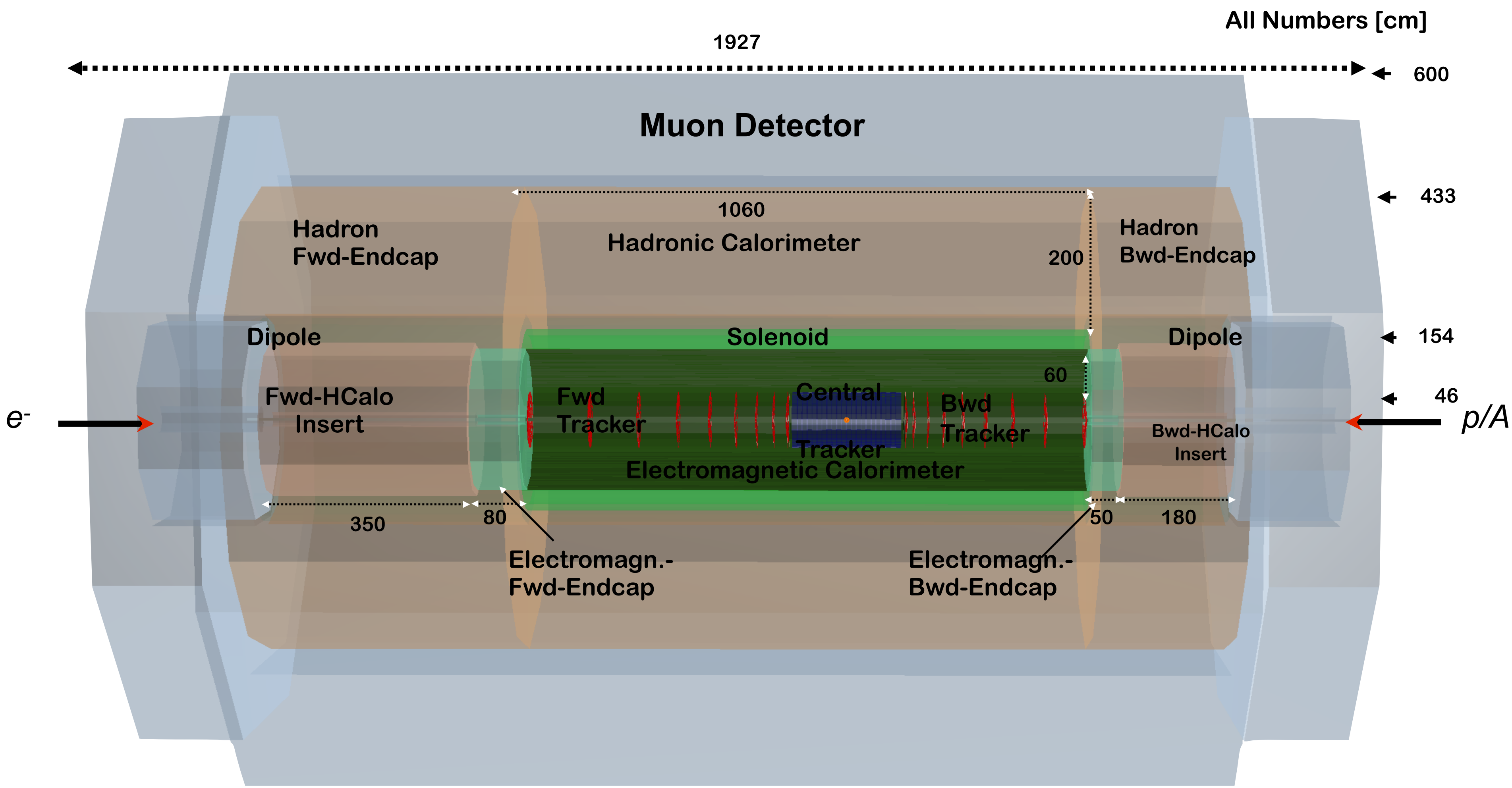


http://cern.ch/lhec
CDR: "A Large Hadron Electron Collider at CERN" ,
LHeC Study Group, [arXiv:1206.2913],
J. Phys. G: Nucl. Part. Phys. 39 (2012) 075001

"On the Relation of the LHeC and the LHC" [arXiv:1211.5102]

FCC-he Detector Basic Layout

P.Kostka



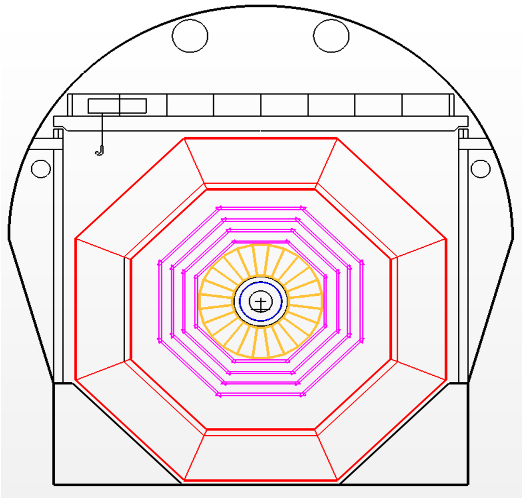
Length of Solenoid ~10m

Based on the LHeC design; Solenoid&Dipoles between Electromagnetic Calorimeter and Hadronic Calorimeter.

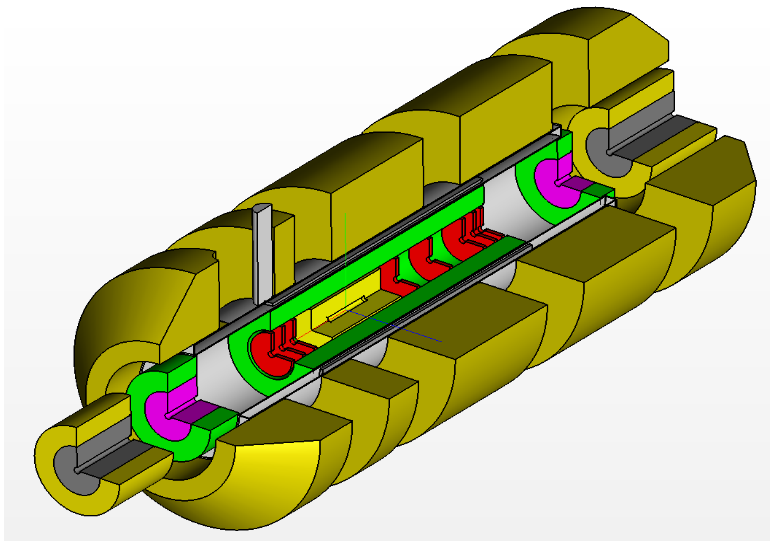
Installation Study

to fit into LHC shutdown needs directed to IP2

Andrea Gaddi *et al*

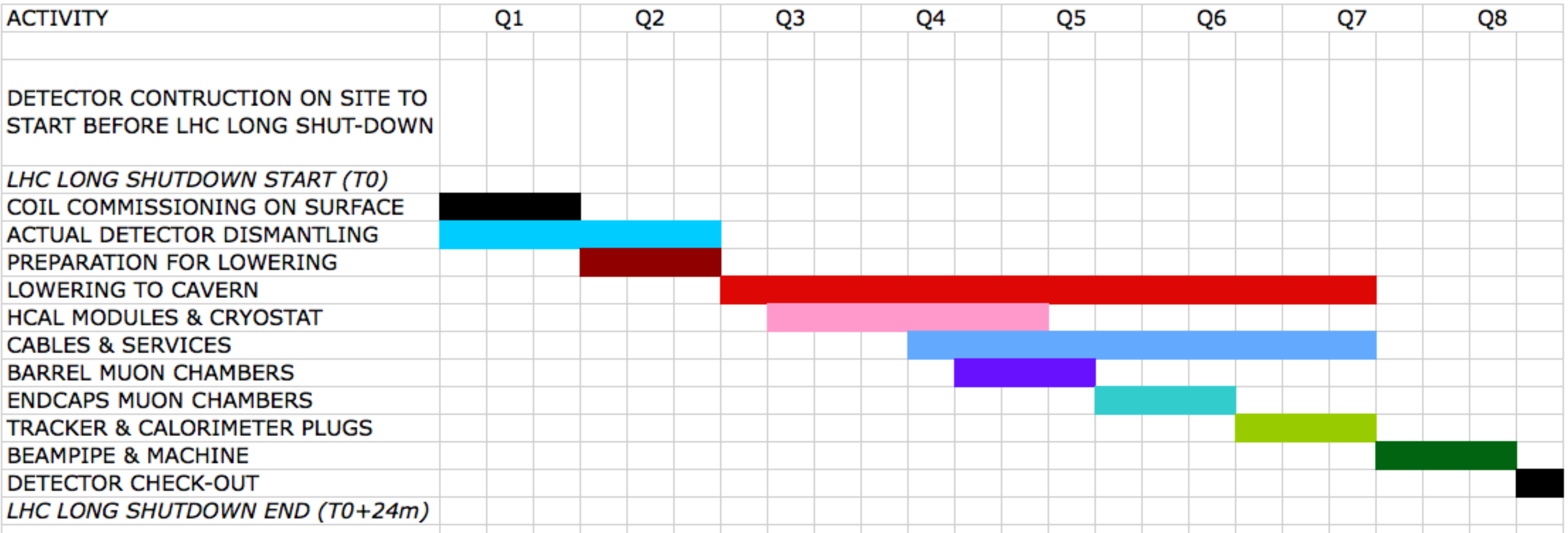


Detector fits in L3 magnet support



Modular structure

LHeC INSTALLATION SCHEDULE



Physics Highlights

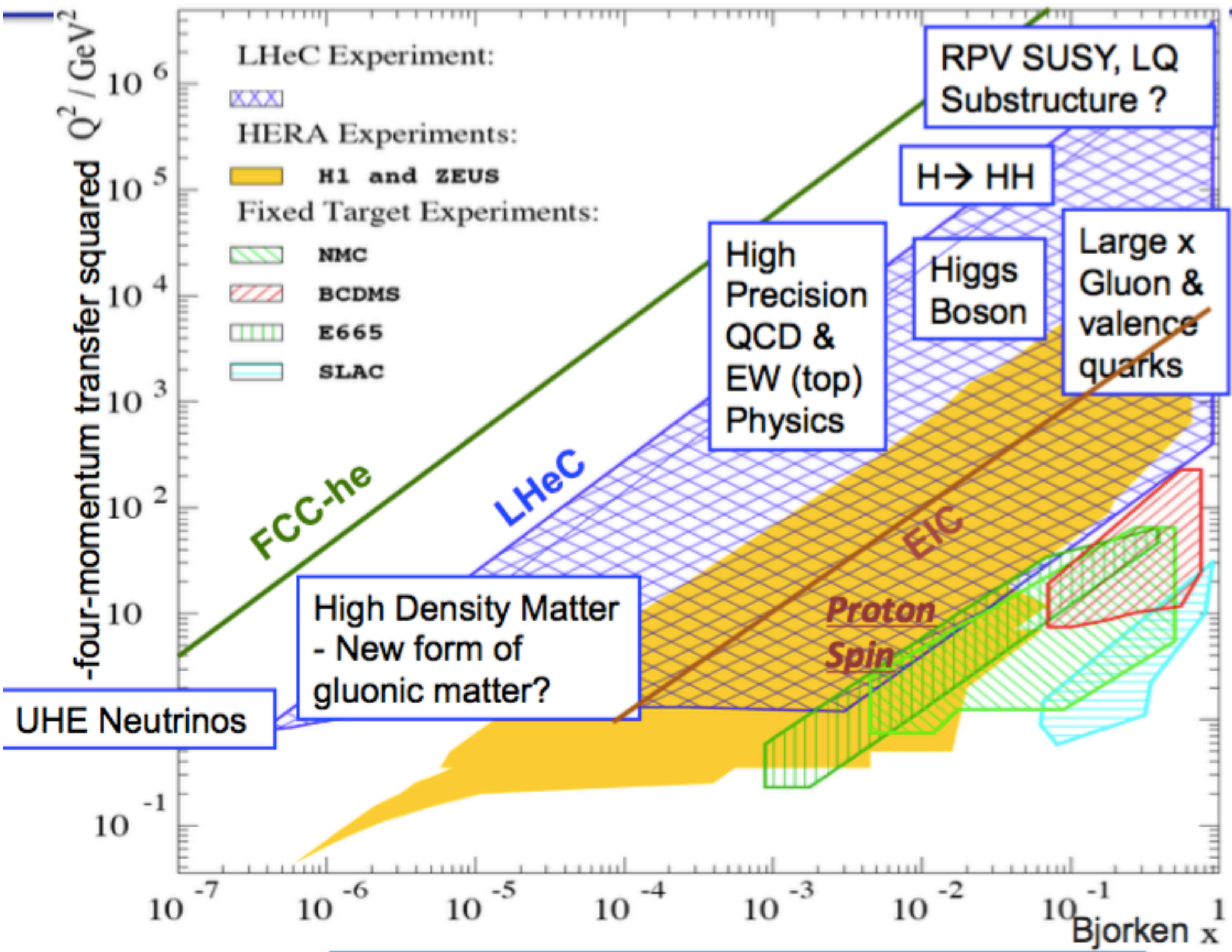
LHeC Physics Programme

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…

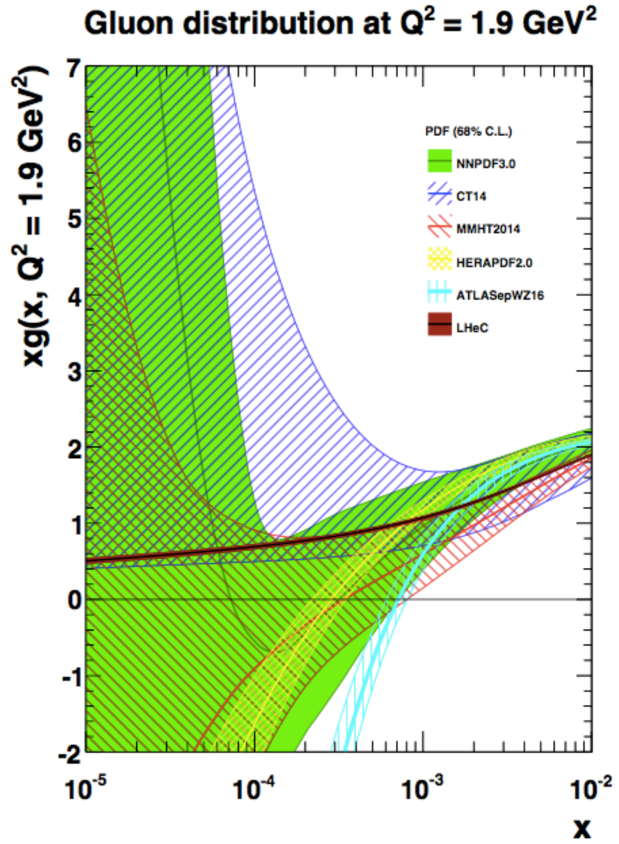


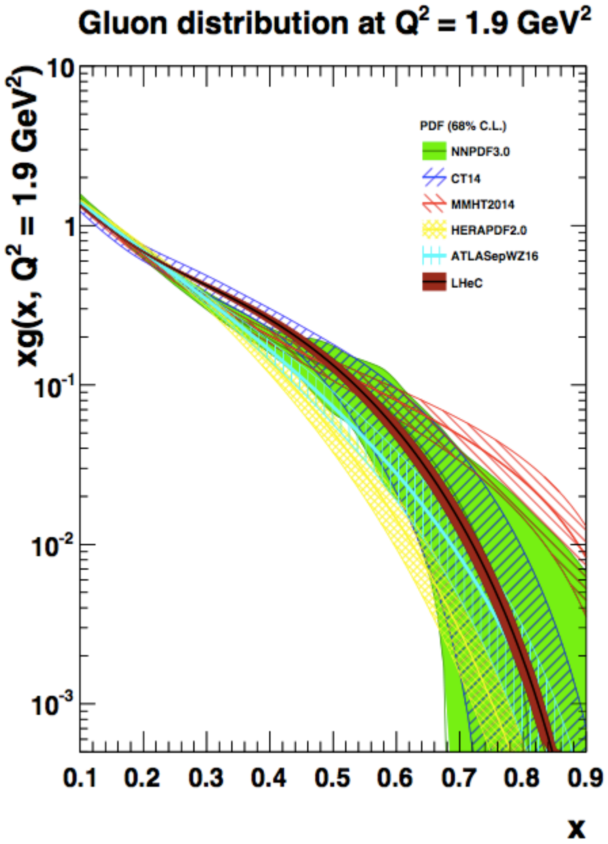
HERA established the validity of pQCD down to $x>10^{-4}$ (DGLAP) due to a very high lever arm in Q^2.

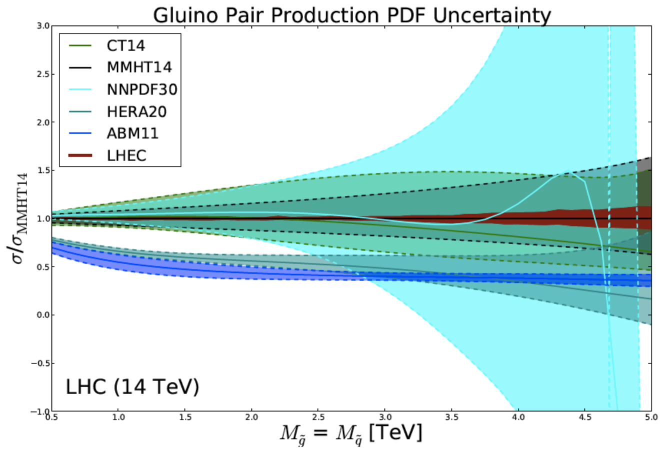
Extensions of both x and Q^2 ranges are crucial for new experiments and HEP theory developments!

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

arXiv:1802.043317







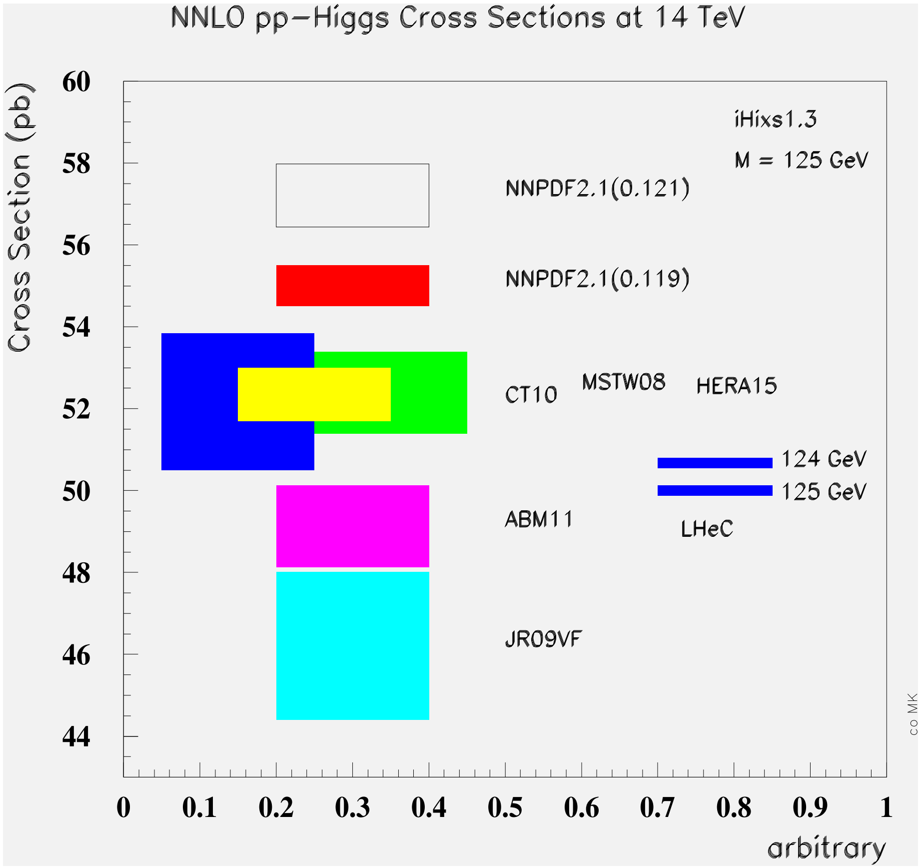
Strong reduction of parton pdf uncertainties, with largeimpact on high-x physics in pp

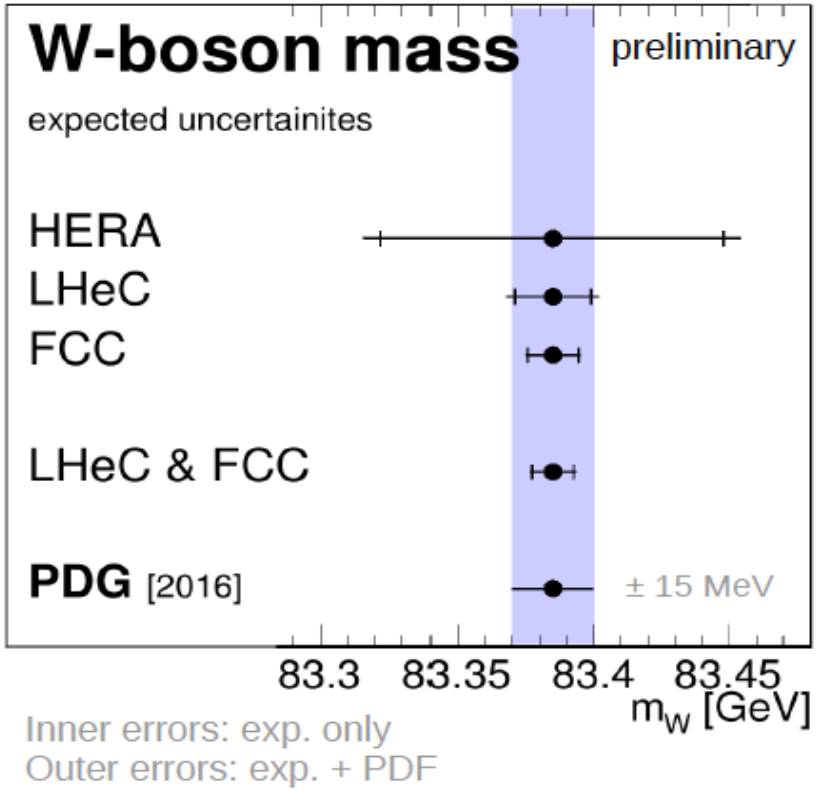
case	cut [Q^2 (GeV^2)]	uncertainty	relative precision (%)
HERA only	$Q^2 > 3.5$	0.00224	1.94
HERA+jets	$Q^2 > 3.5$	0.00099	0.82
LHeC only	$Q^2 > 3.5$	0.00020	0.17
LHeC+HERA	$Q^2 > 3.5$	0.00013	0.11
LHeC+HERA	$Q^2 > 7.0$	0.00024	0.20
LHeC+HERA	$Q^2 > 10.$	0.00030	0.26

Achieve down to 0.1% error in α_s

High Precision for pp

M.Klein





Can achieve <0.5% precision in pdf uncertainty, thus removing this uncertainty from the prediction of the Higgs cross-section.

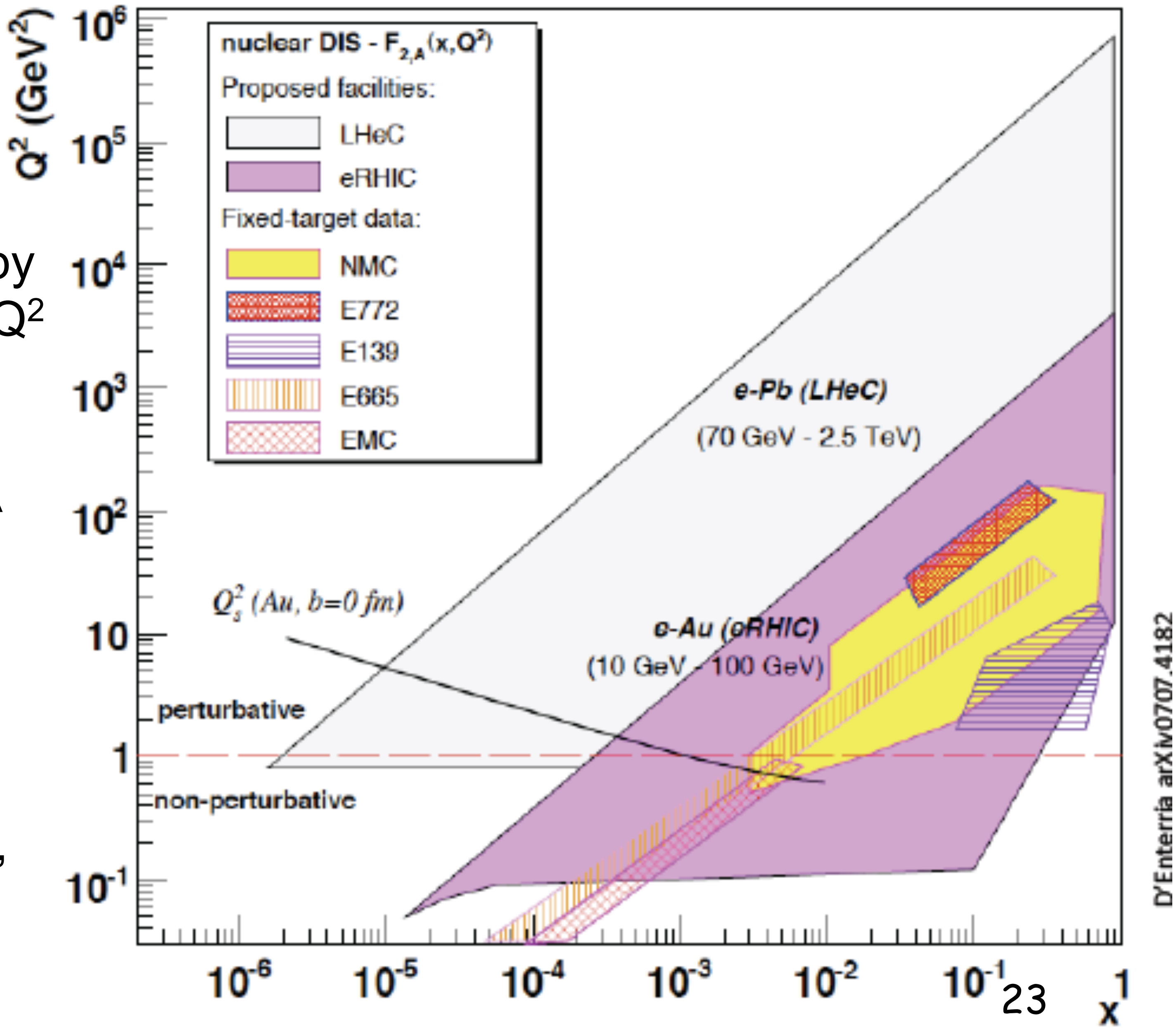
Reduce pdf error 2.8 MeV →
Remove PDF uncertainty on M_W LHC

Spacelike M_W to 10 MeV from ep
→ Electroweak test at 0.01% !

eA Collisions

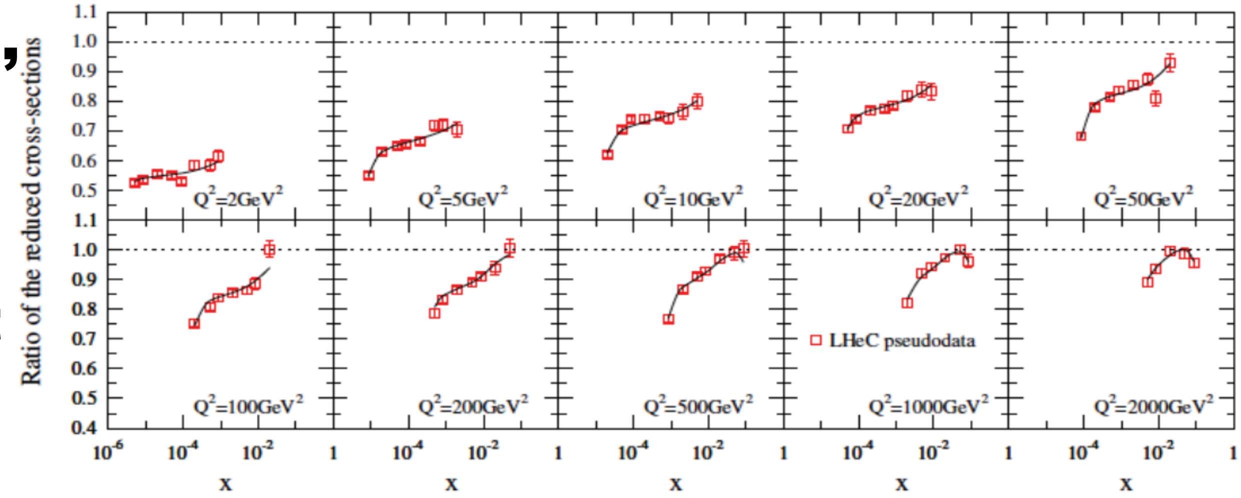
Extension of kinematic range of eN scattering by orders of magnitude in Q^2 and 1/x

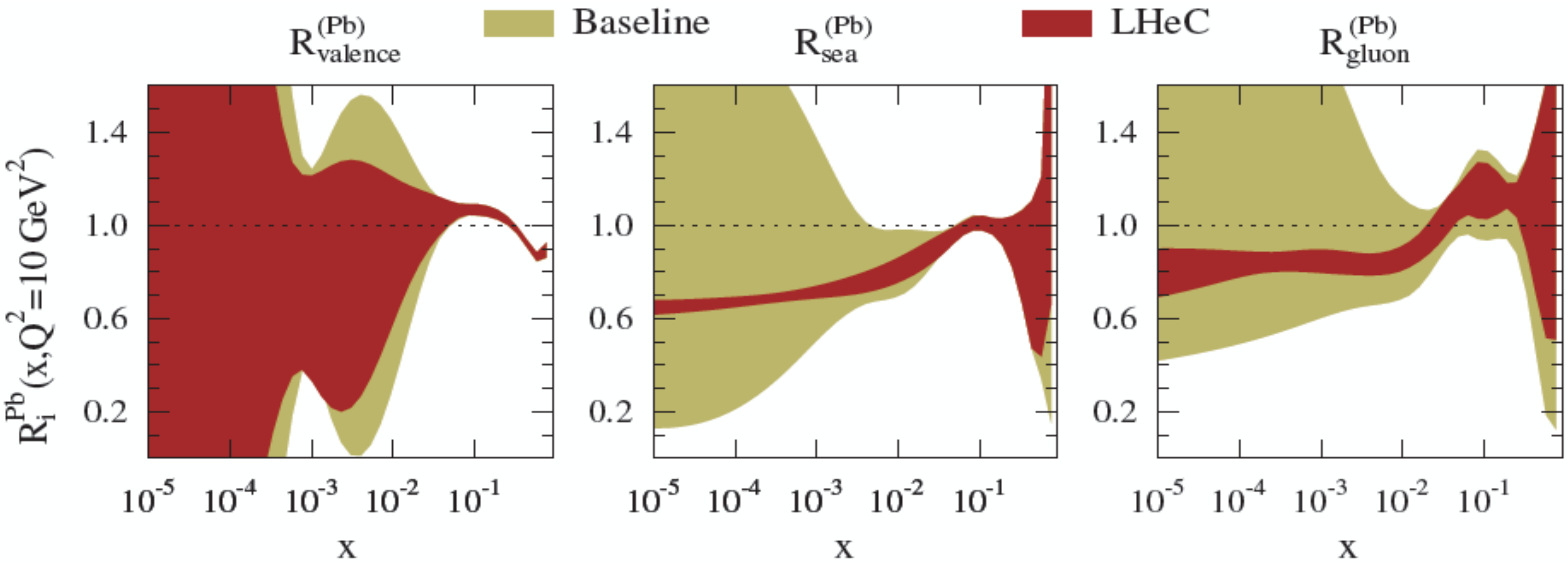
Complementarity to AA and pA physics: initial state of QGP, hadronisation and mechanism of confinement, colective phenomena seen in AA, pA and pp



eA: inclusive

- **Large impact on nPDFs, possible to make a Pb fit without proton PDFs**
- **Large room for improvements: NC+CC at several energies, flavour decomposition,...**

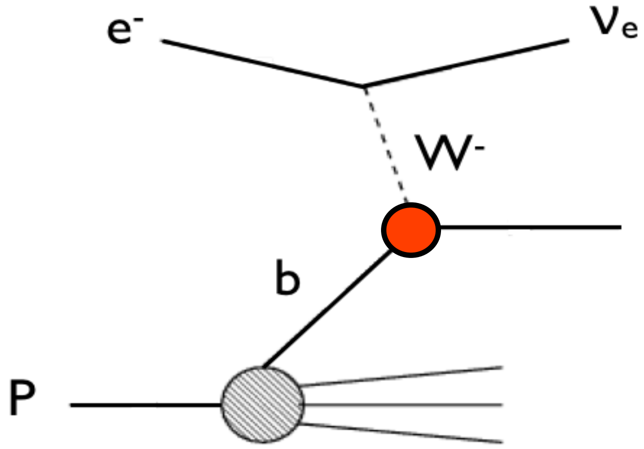




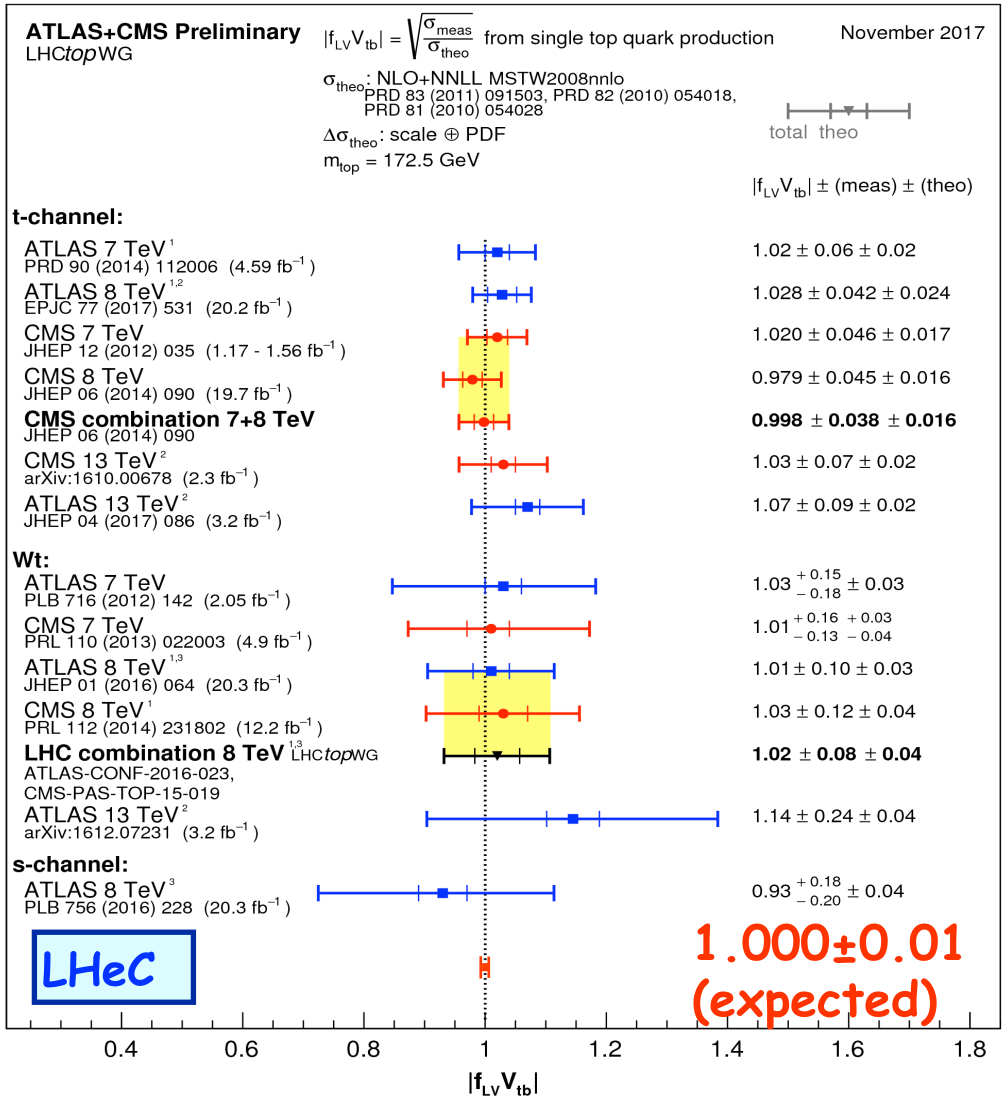
Direct Measurement of $|V_{tb}|$

C.Schwanenberger

[1] including top-quark mass uncertainty
[2] σ_{theo}: NLO PDF4LHC11
NPPS205 (2010) 10, CPC191 (2015) 74
[3] including beam energy uncertainty



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

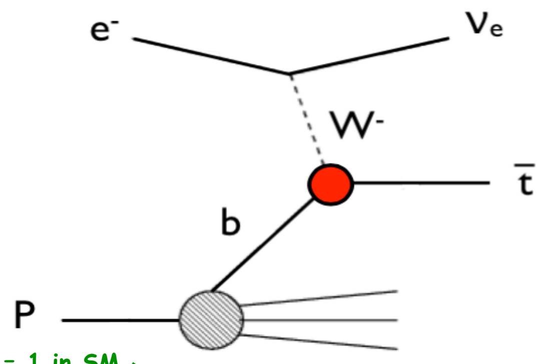


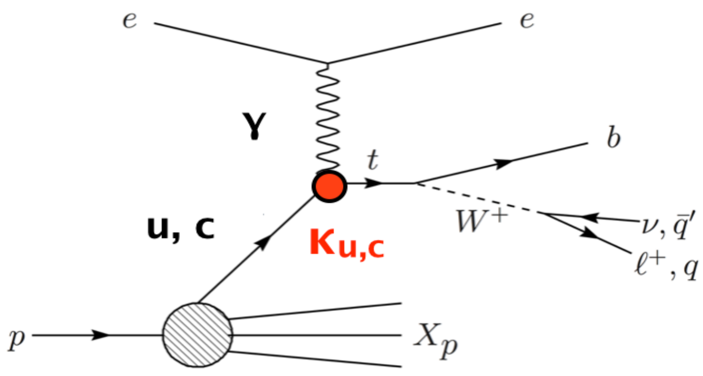
Takes advantage that tt production is suppressed in ep. FCC-eh with 2 ab^{-1} would further improve the result significantly.

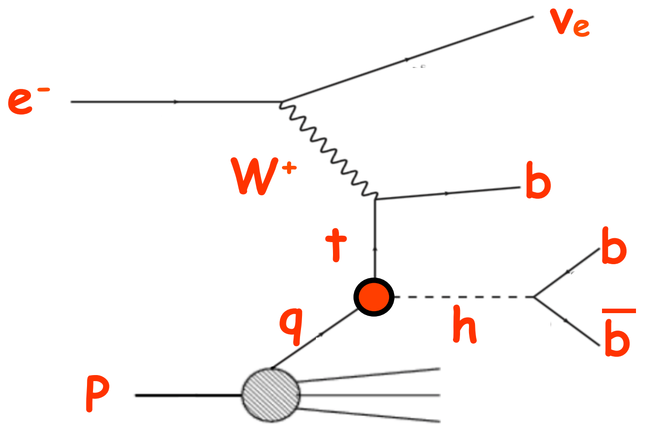
LHeC, 100 fb^{-1}

Top Quark Anomalous Couplings

C.Schwanenberger







= 1 in SM

$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

$$L = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda}\bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

$$\mathcal{L} = \kappa_{tuh}\bar{t}uh + \kappa_{tch}\bar{t}ch + h.c.$$

DELPHES

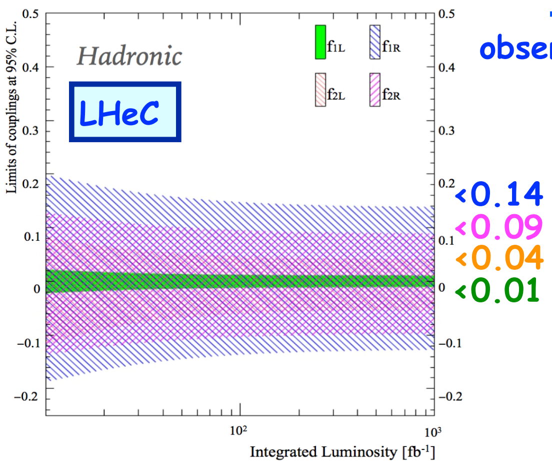
Dutta, Goyal, Kumar, Mellado, Eur. Phys. J. C75 (2015) no.12, 577
Kumar, Ruan, to be publ.

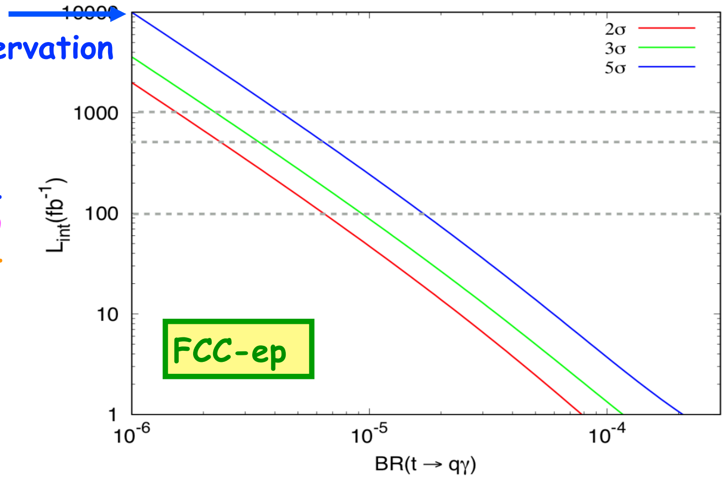
DELPHES

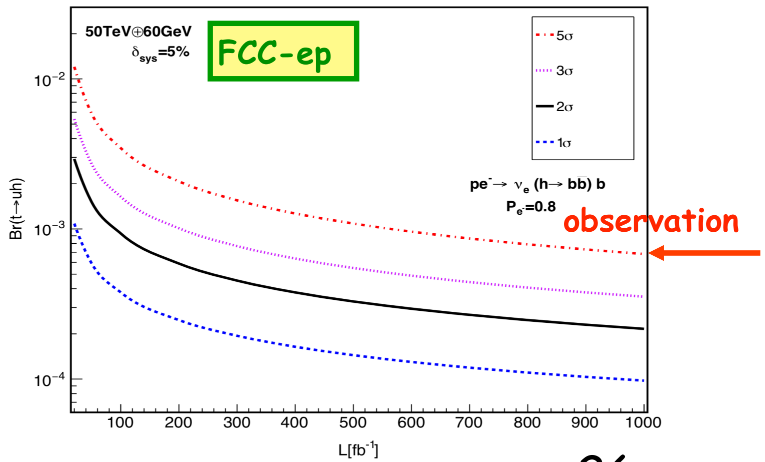
Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

parametrisation

Sun, Wang, arXiv:1602.04670



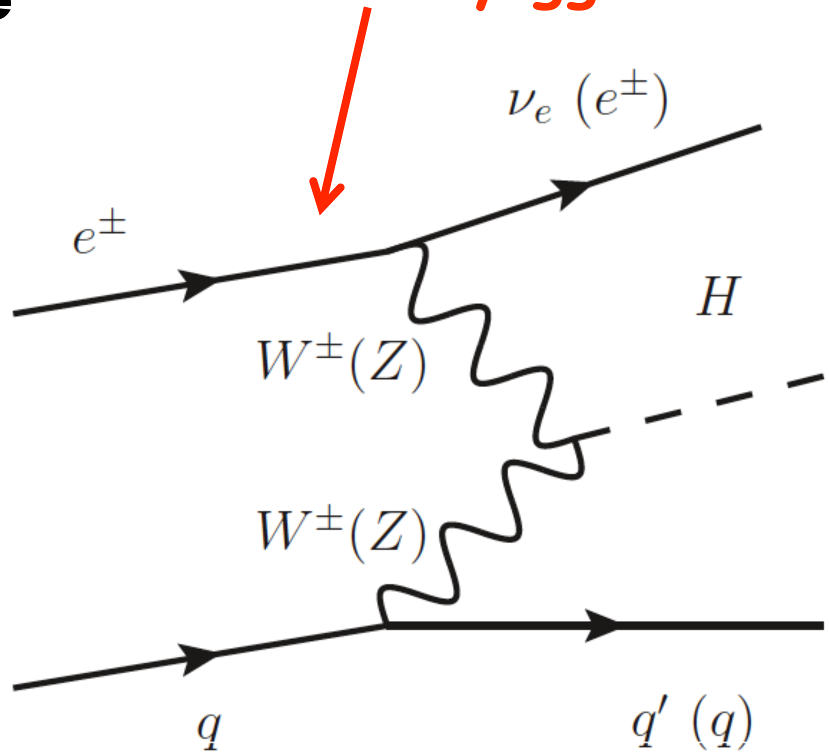




Higgs in ep

- It is remarkable that VBF diagrams were calculated for lepton nucleon collisions before for pp!
- Small theoretical uncertainties
- Topological requirements effective in background suppression
- Large S/B w.r.t. pp, e.g. in h→bb expect S/B=3

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



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’

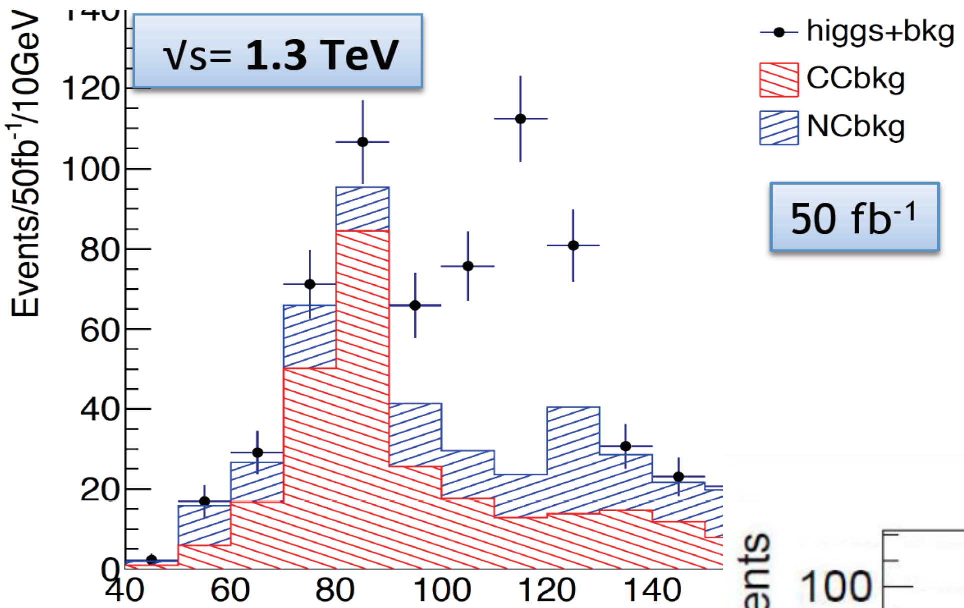
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	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 !

CDR Updates: Two independent analyses

[after Higgs discovery M_H=125 GeV, E_p=7 TeV, E_e=60 GeV; cut-based & conservative]

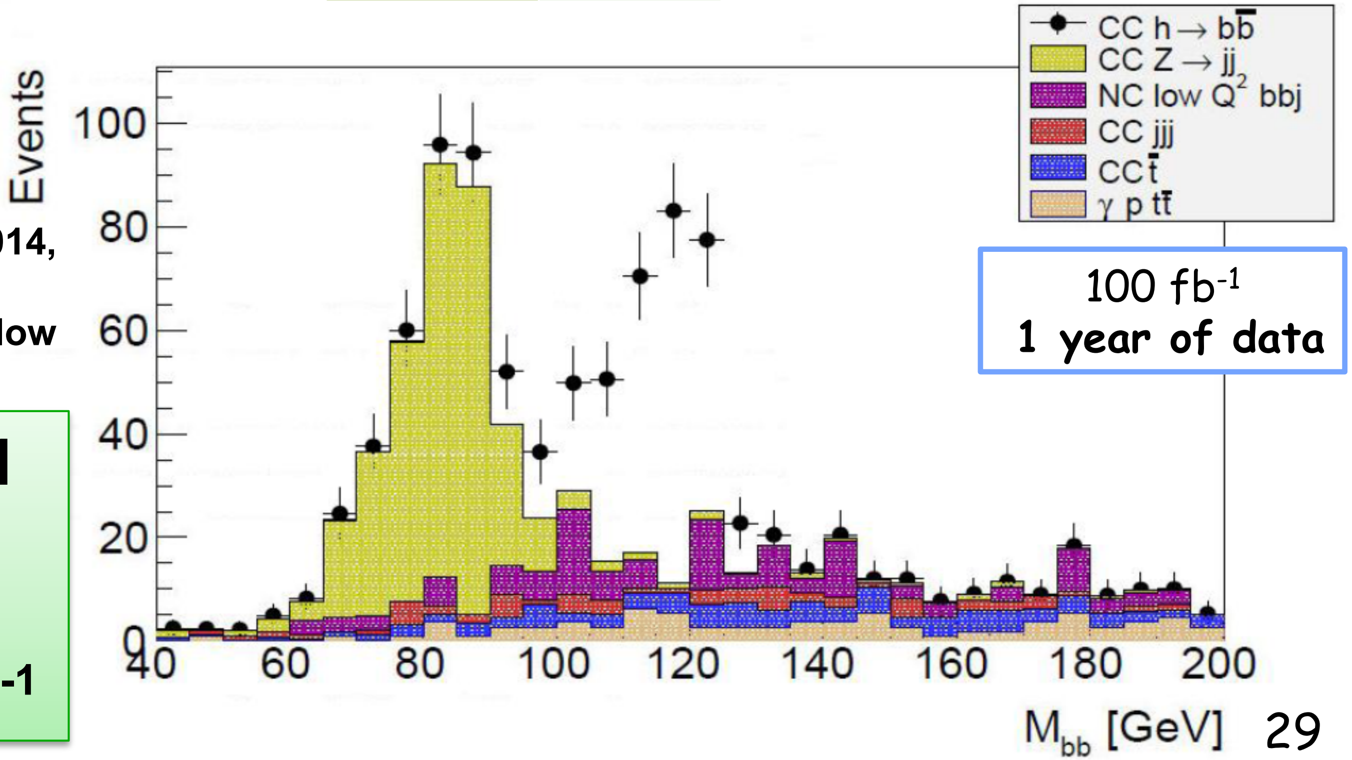


Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

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

PGS of LHC detector
+ flat parton-level b-tagging for |η|<3.0
b: 60%, c: 10%, **udsg: 1%**
CAL coverage |η|<5.0

ICHEP 2014
Master Thesis Ellis Kay, Liverpool 2014, PGS "detector" ATLAS-style and & modeling of PHP background using low Q^2 NC DIS



Confirmed CDR: S/N>1 using conservative light misID and cut-based δμ=2% for 1 ab^{-1}

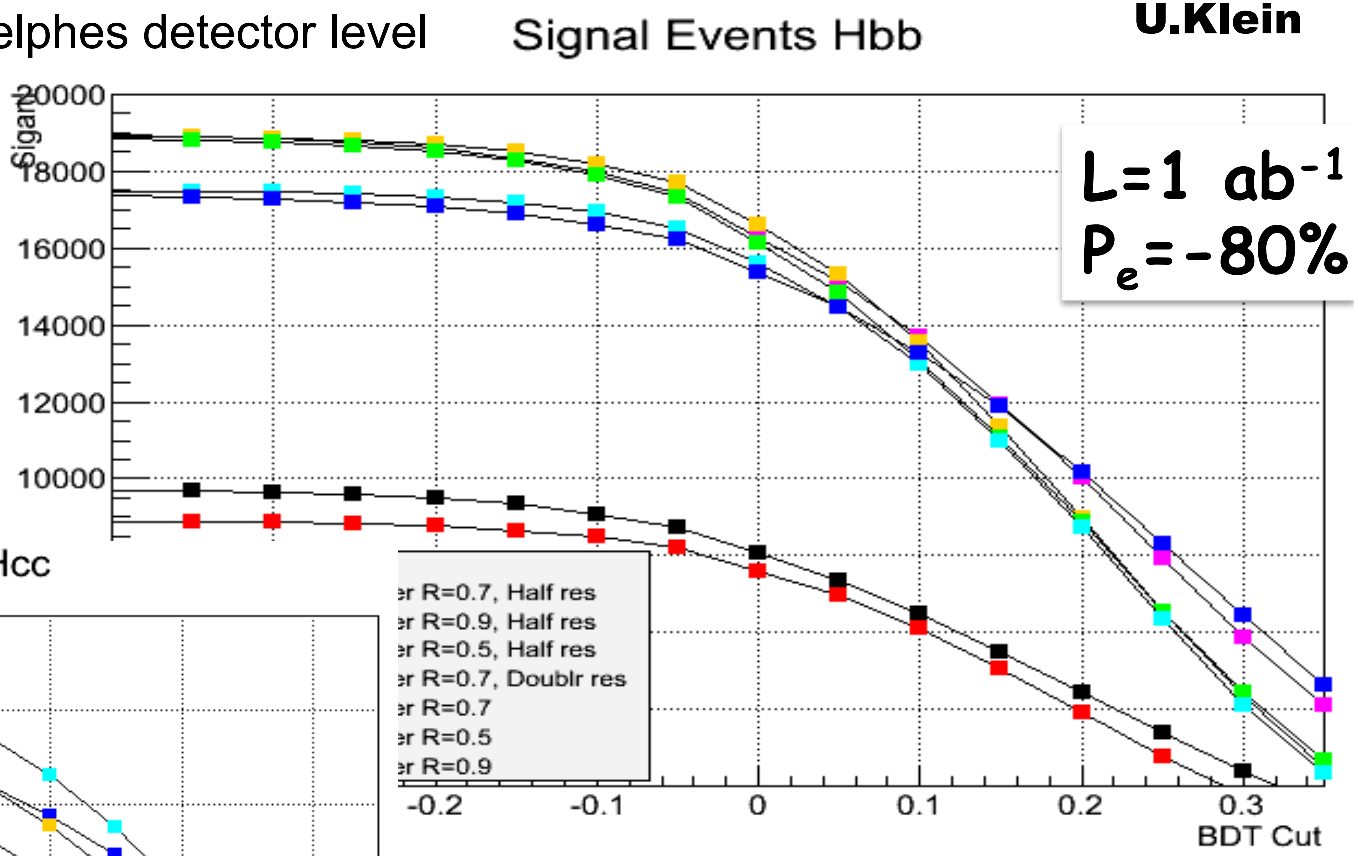
BDT Results for Higgs @ LHeC

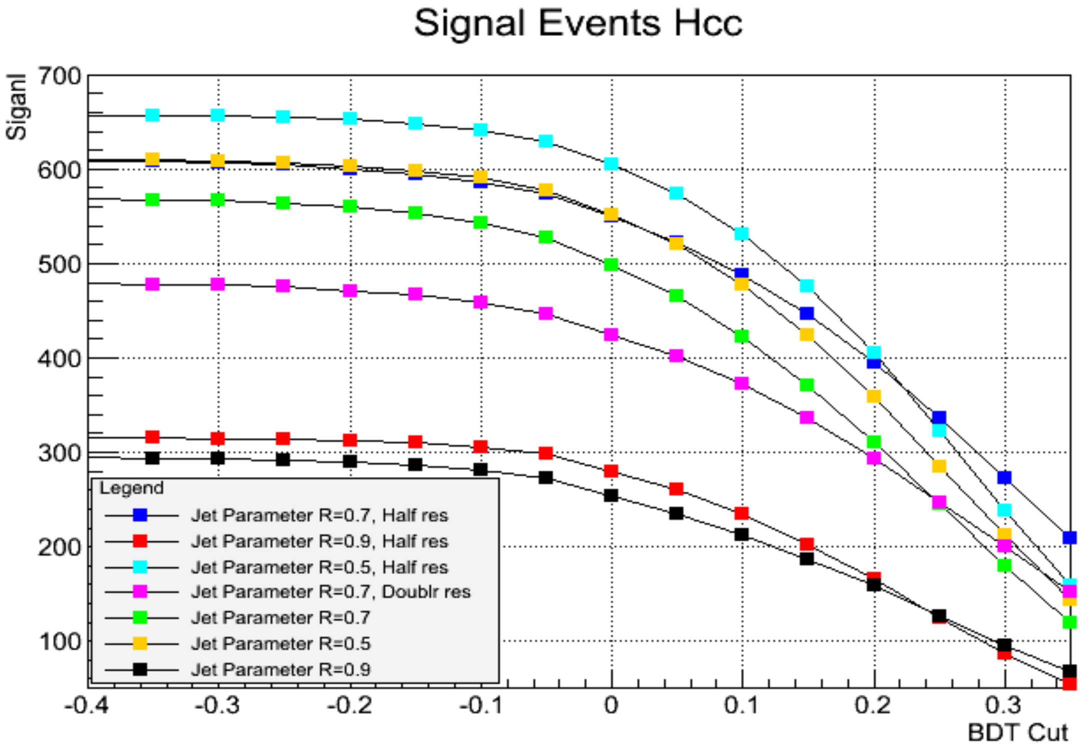
Daniel Hampson,
MPHYS 2016

U.Klein

using realistic HFL tagging at Delphes detector level

Hbb: Clear sensitivity to chosen jet radius; rather robust w.r.t. vertex resolution in range of 5 to 20 µm

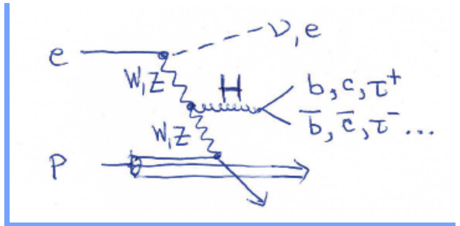




Hcc : High sensitivity to vertex resolution (nominal 10 µm) and jet radius

→ expect about 400-600 Hcc candidates

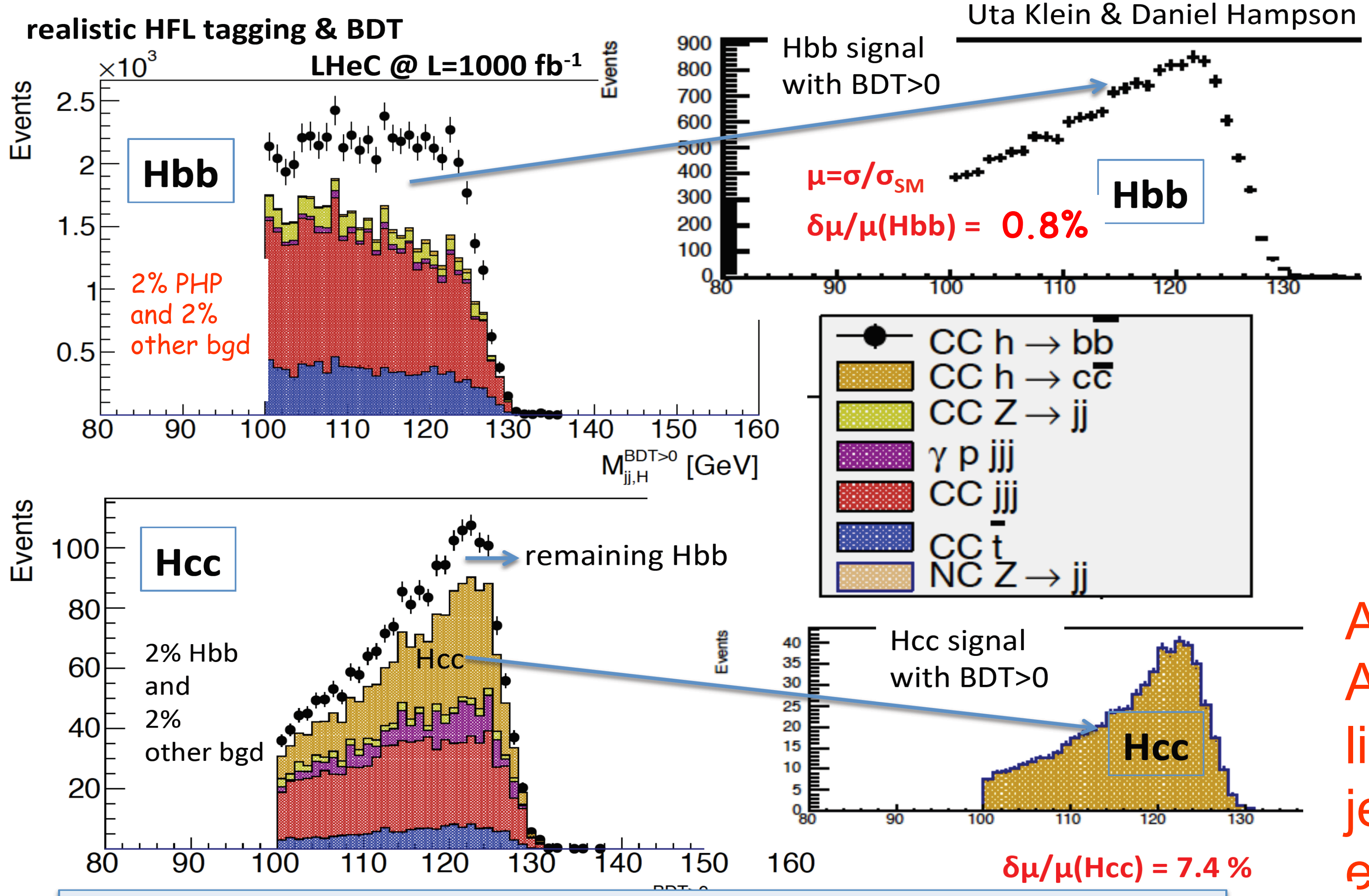
Higgs in ep – clean S/B, no pile-up



Uta Klein & Daniel Hampson

& Izzy Harris BSc 2017

U.Klein

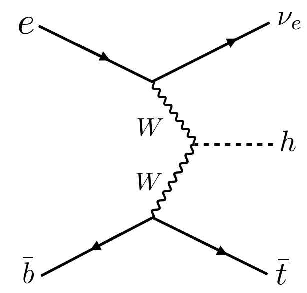


Assuming ATLAS light jet misID efficiencies

➔ Main systematic checks: variations of background contribution and tagging efficiencies

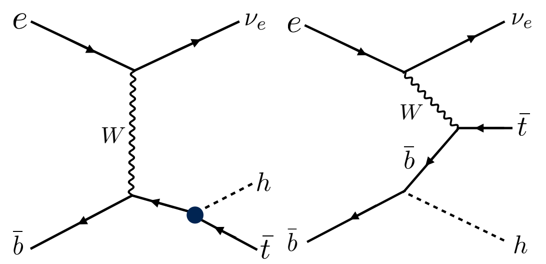
B.Coleppa, M.Kumar, S.Kumar, B.M., Phys. Lett. B770 (2017) 335

Top Yukawa coupling

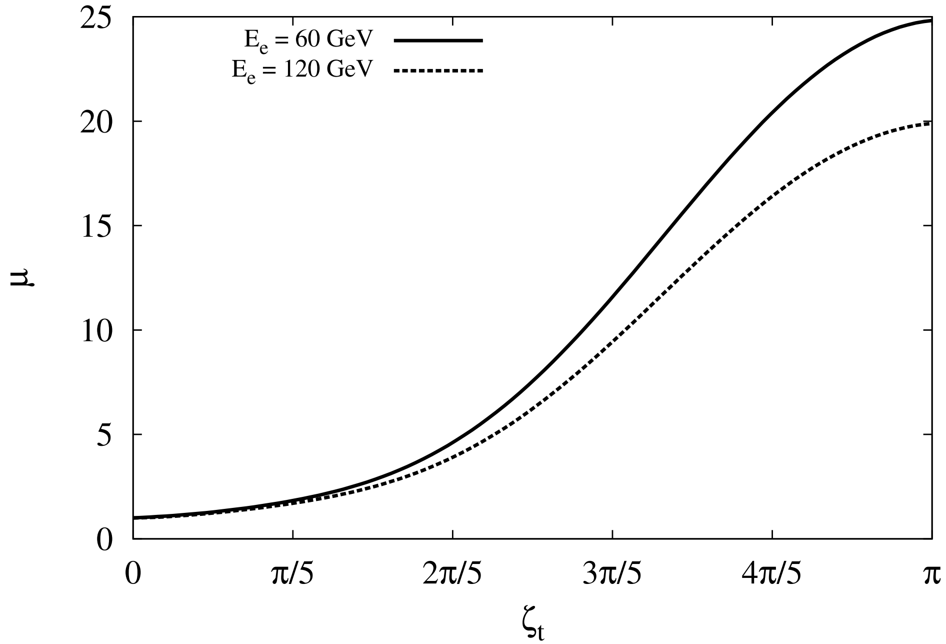


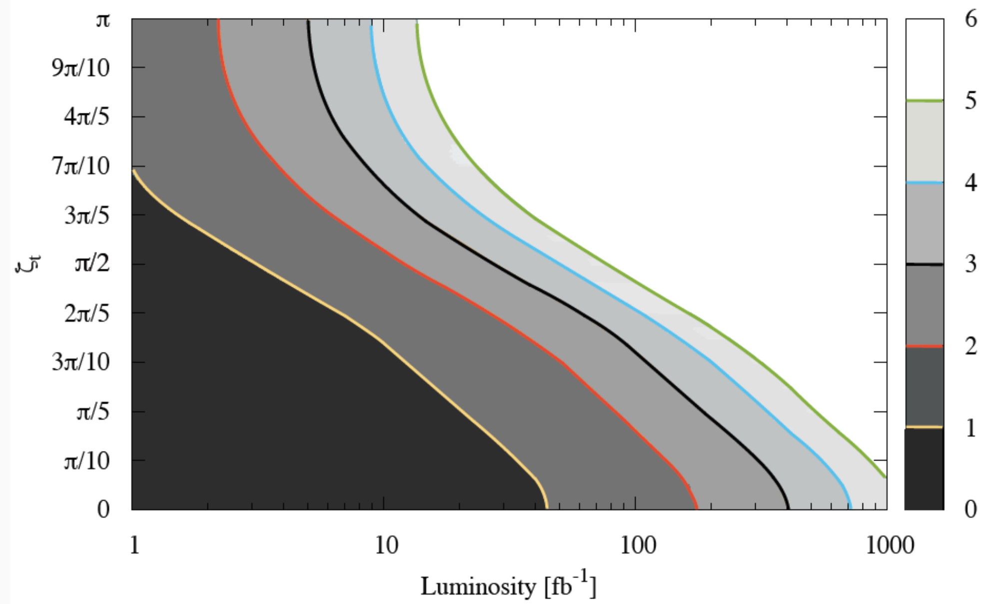
Introduce phase dependent top Yukawa coupling

$$\mathcal{L} = -i\frac{m_t}{v}\bar{t}\left[\cos\zeta_t + i\gamma_5 \sin\zeta_t\right] t\, h$$



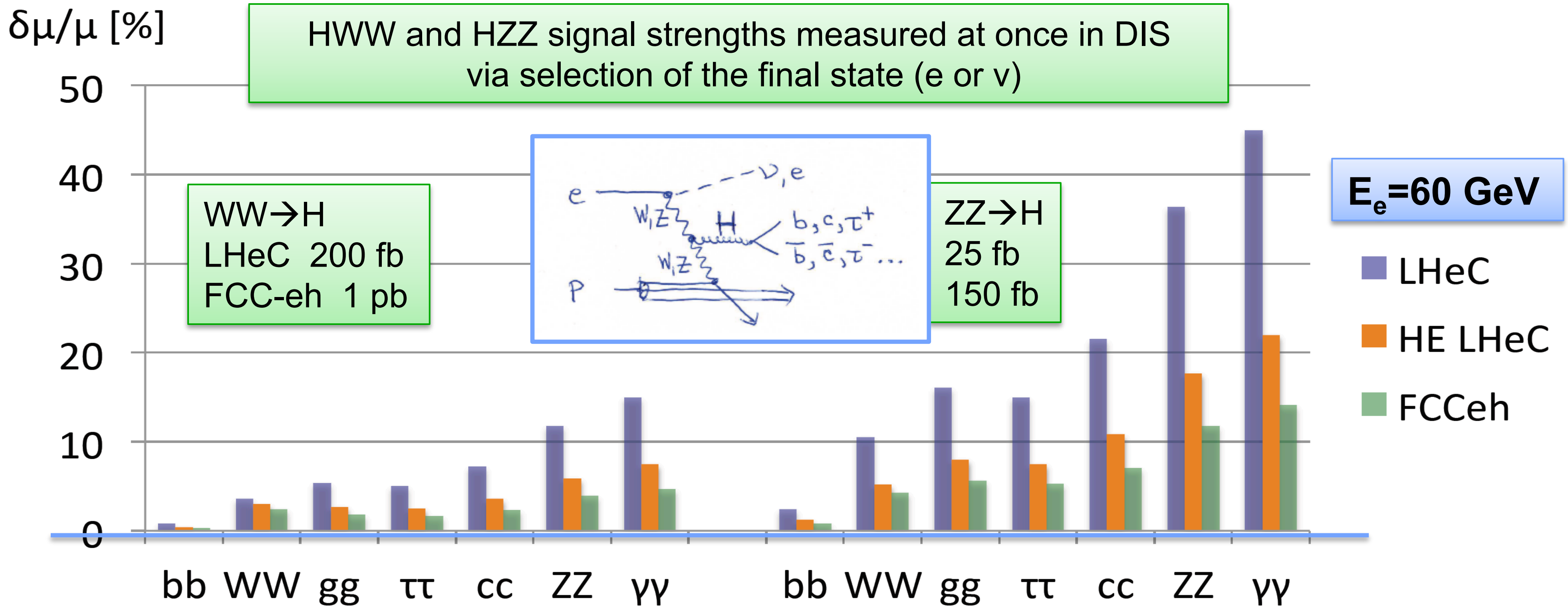
Enhancement of the cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ at LHeC. Achieve <2% error on k_t at the FCC-eh.

SM Higgs Signal Strengths in ep



submitted to EU strategy CERN-ACC-Note-2018-0084

Charged Currents: ep → νHX   Neutral Currents: ep → eHX

→NC and CC DIS together over-constrain Higgs couplings in a combined SM fit.

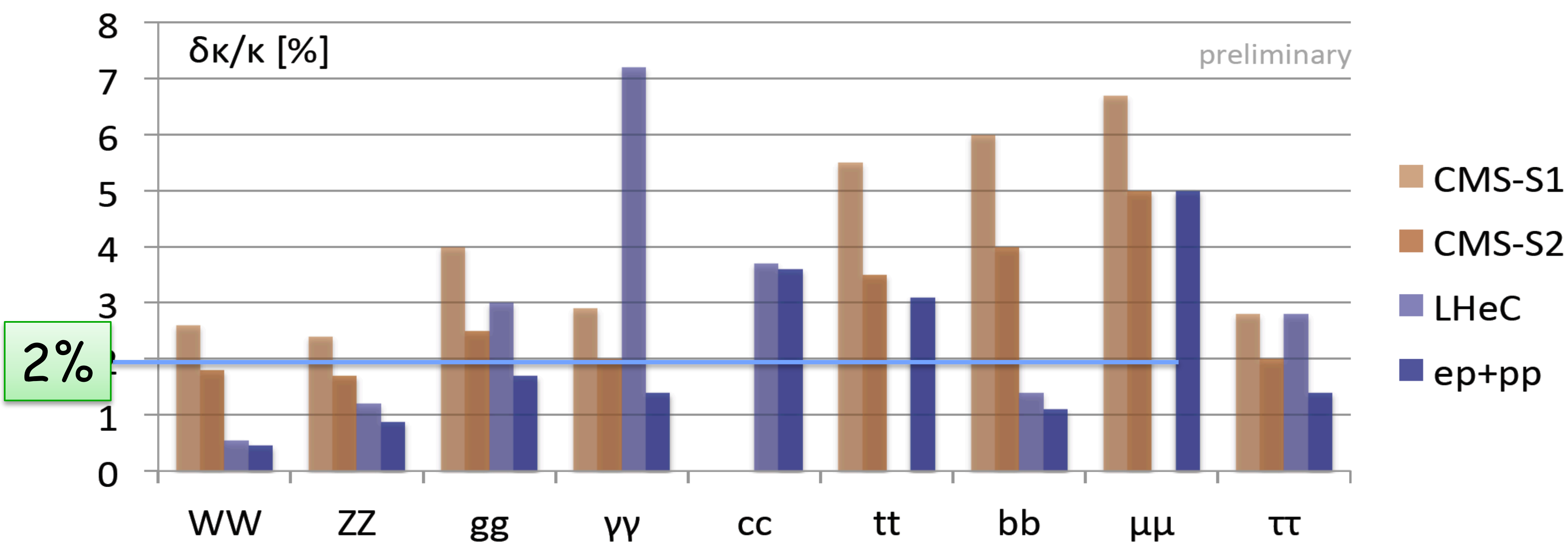
E_e = 60 GeV LHeC E_p = 7 TeV L=1ab^{-1} HE-LHC E_p = 14 TeV L=2ab^{-1} FCC: E_p = 50 TeV L=2ab^{-1}

LHeC and HL-LHC Higgs Prospects

Hcc@pp: ~2.0-5.5 σ_{SM}@HL-LHC
[HL-LHC Oct 2017]

submitted to ECFA:

preliminary



→ **Amazing prospect for measuring fundamental Higgs couplings to high precision (dark blue) at LHC with pp + ep using SM assumptions.**

HL-LHC prospects using new CMS projections (3ab^{-1}) with two scenarios, S1 and S2, in a SM coupling fit

Higgs precision observables at FCC ee and eh

- **Fit to modified Higgs couplings (assuming no extra invisible decays)**

FCC-ee	
Coupling	Relative precision
κ_b	0.58%
κ_t	—
κ_τ	0.78%
κ_c	1.05%
κ_μ	9.6%
κ_Z	0.16%
κ_W	0.41%
κ_g	1.23%
κ_γ	2.18%
$\kappa_{Z\gamma}$	—

FCC-eh	
Coupling	Relative precision
κ_b	0.74%
κ_t	—
κ_τ	1.10%
κ_c	1.35%
κ_μ	—
κ_Z	0.43%
κ_W	0.26%
κ_g	1.17%
κ_γ	2.35%
$\kappa_{Z\gamma}$	—

$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

Published in book 1 of FCC

Precision Higgs Physics at High-Energy Electron-Proton Colliders

Draft 9.4. – in preparation

LHeC Higgs Study Group

G. Azuelos, S. Behera, J. De Blas, D. Hampson, R. Islam, S. Kawaguchi, E. Kay, U. Klein, M. Klein, P. Kostka, M. Kumar, M. Kuze, B. Mellado, M. O'Keefe, R. Li, C. Gwenlan, R. Ruan, T. Sekine, A. Senol, H. Sun, M. Tanaka, K. Wang, C. Zhang

Tentative authorlist - TO BE UPDATED

Abstract. The Higgs boson and its physics have become a central topic of modern particle physics and a key parameter in the evaluation of future high energy collider projects. This paper provides a summary and overview on the potential of future luminous, energy frontier electron-proton colliders, especially the LHeC, the HE-LHC and the FCC-eh, for precision Standard Model measurements of the properties of the Higgs boson in deep inelastic scattering. Detailed analyses are presented on the prospects for accurate measurements of the Higgs boson decays into pairs of bottom and charm quarks. An extended study is performed for estimating the precision on the Higgs couplings in the most abundant decay channels, based on measurements in the charged and weak neutral current DIS reactions. The addition of *ep* information to the expected HL-LHC Higgs coupling measurements is demonstrated to lead to major improvements on the Higgs results one can expect to come from the LHC facility at large.

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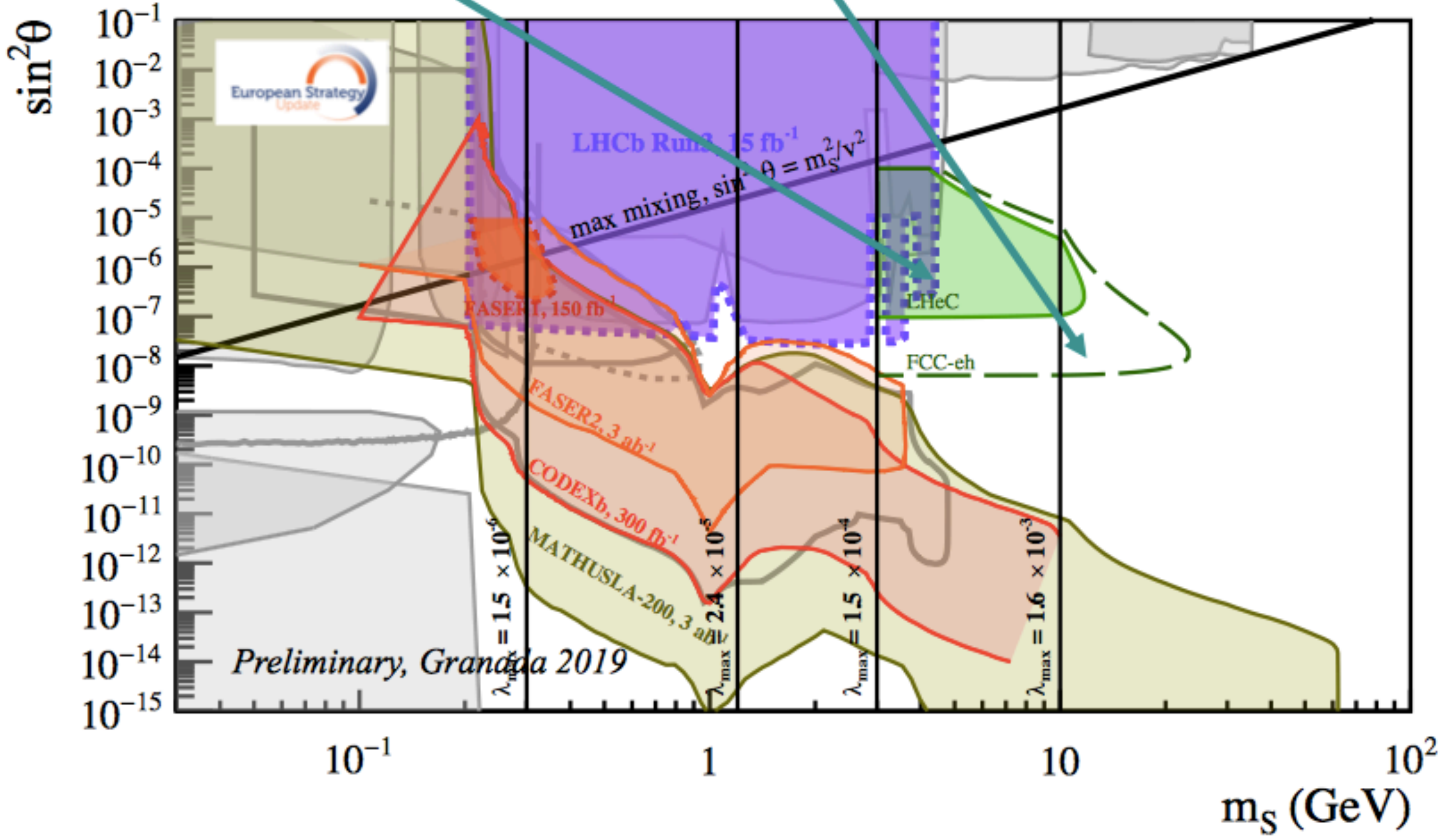
Thanks to Hao Sun

50 journal papers on BSM with LHeC in recent years

Scalar Portal: Dark Scalar

Projections for LHeC (1 ab^{-1}) and FCC-eh (3 ab^{-1}) - (fixed λ=4x10^{-3}).

$(\mu S + \lambda S^2)H^\dagger H$



LHeC and FCC-eh can extend the reach beyond LHCb.

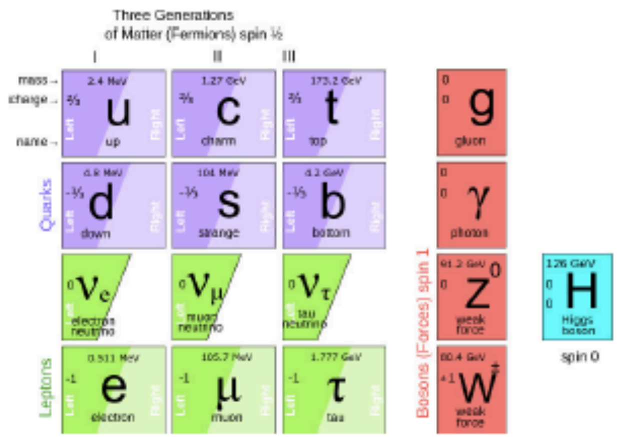
Source:
The LHeC/FCC-eh physics groups (O. Fischer et al.)

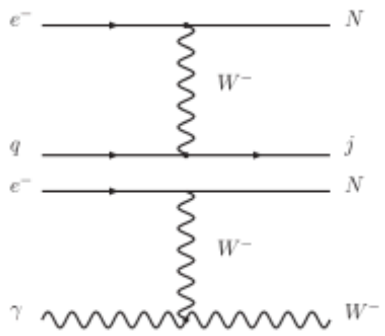
Method:
Higgs ⟶ SS
S ⟶ visible decays
(assuming fixed λ = 4x10^{-3})

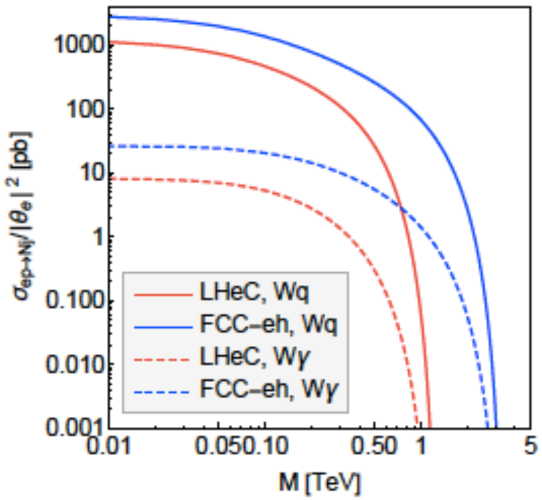
Sterile Neutrinos at ep colliders

O.Fischer

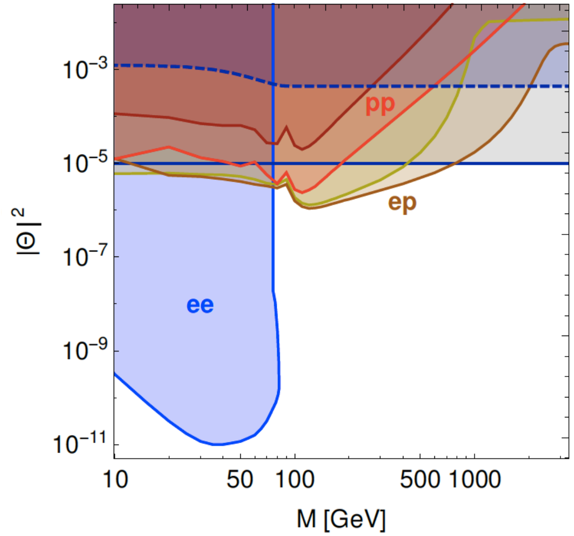
Antusch *et al.* Int. J. Mod. Phys. A 32 (2017) no.14, 1750078







- Neutrino oscillations $\rightarrow$ type I seesaw
- Lowscale seesaw models allow large production xsections at colliders
- Present constraints: $|\theta_e| \leq 10^{-3}$
- Searches via lepton-flavor violating final states: μ +jets, $\mu\tau$ + jets

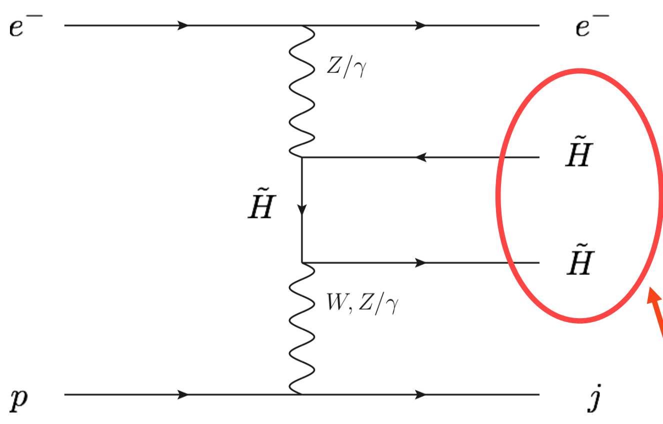


- Displaced vertex searches for heavy neutrino masses $< m_W$

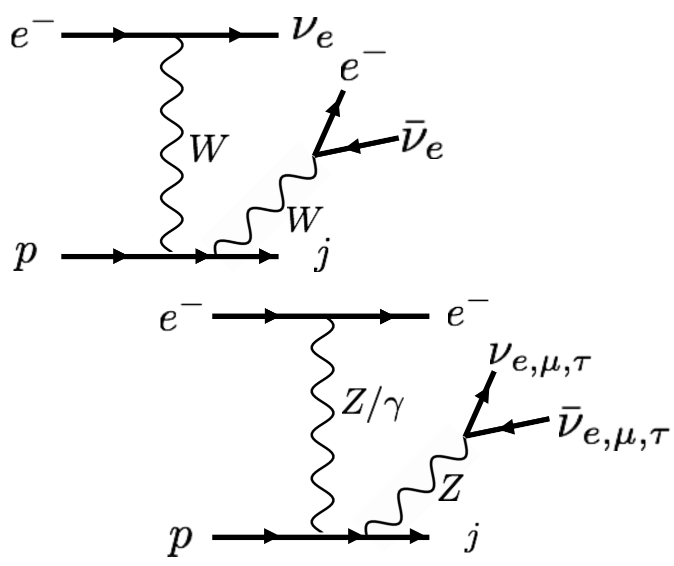
Higgsino search at FCC-eh

C. Han, R. Li, R. Pan, K. Wang, arXiv:1802.03679

Higgsino: Higgs partner in supersymmetry,
difficult to probe at the LHC(C. Han *et al*, JHEP 1402 (2014) 049)



Higgsino production

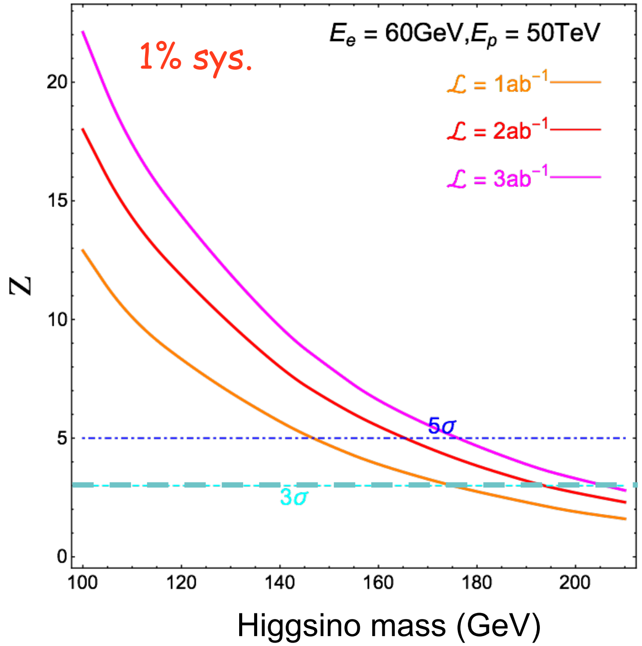


Standard model main backgrounds

Typical signal: electron + jet + missing energy

$$E_T^{miss} > 70 \text{ GeV}$$
$$5 \text{ GeV} < p_T^e < 25 \text{ GeV}, \ 1.0 < \eta^e < 5.0$$
$$p_T^j > 20 \text{ GeV}, \ -5.0 < \eta^j < -3.0$$
$$m_{ej} > 400 \text{ GeV}$$
$$y = \frac{k_p \cdot (k_e^{in} - k_e^{out})}{k_e^{in} \cdot k_p} > 0.2$$

preliminary result



Outlook and Conclusions

- Progress in devising concurrent ep/pp running
  - Unique DIS facility at CERN with 10^{34} instantaneous luminosity, opens new horizon for particle physics
- PERLE collaboration formed, conceptual design
  - Demonstrator for ERL; envisioned at Orsay
- First 802 MHz cavity produced
- Complete design of FCC-eh detector
- Complementarities of the ep/pp programs strongly benefits HL(HE)-LHC, FCC prospects:
  - Combining pp with ep, a very powerful Higgs facility
  - Precise measurements and discoveries in QCD
  - Exploration of new nuclear substructure in new domains
  - Unprecedented precision in top physics topics
  - Additional sensitivity to physics BSM

Additional slides

Why PERLE [as seen from LHeC]?

FUNDAMENTAL MOTIVATION:

- **Validation of key LHeC Design Choices**

- **Build up expertise in the design and operation for a facility with a fundamentally new operation mode:**
  ERLs are circular machines with tolerances and timing requirements
  similar to linear accelerators (no 'automatic' longitudinal phase stability, etc.)

- **Proof validity of fundamental design choices:**
  Multi-turn recirculation (other existing ERLs have only 1-2 passages)
  Implications of high current operation (2 * 3 * [6mA – 25mA] ➔ 30-150mA!!)

- **Verify and test machine and operation tolerances before designing a large scale facility**
  Tolerances in terms of field quality of the arc magnets and cavity alignment
  Required RF phase stability (RF power) and LLRF requirements
  Halo and beam loss tolerances

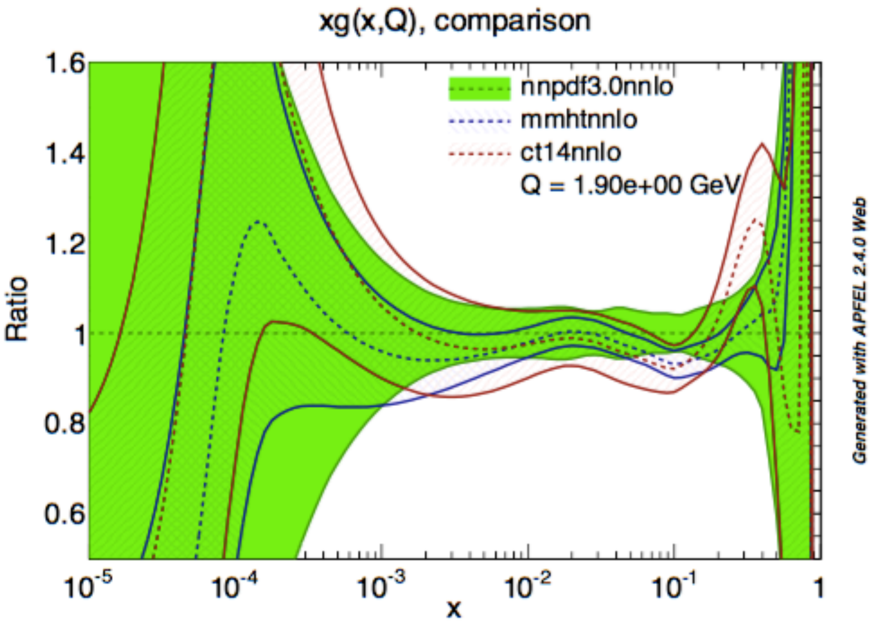
PDFS AT THE LHEC

S.Forte

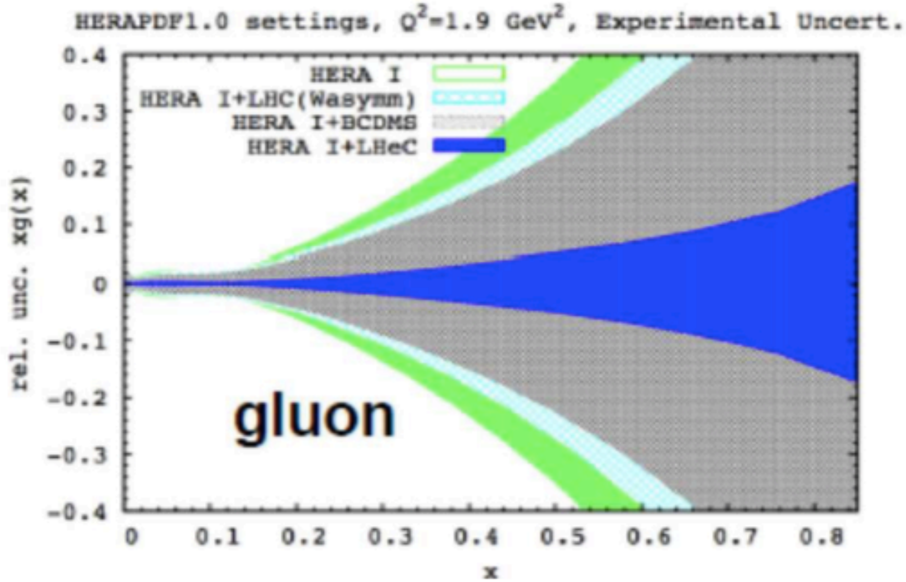
- UNCERTAINTIES DOWN TO PERCENT LEVEL IN WIDE KINEMATIC REGION
- WITH DEUTERON BEAMS, FULL LIGHT FLAVOR DECOMPOSITION
- THANKS TO HIGH ENERGY, NC+CC ⇒ PRECISION STRANGENESS DETERMINATION

GLUON

NOW



AT THE LHEC

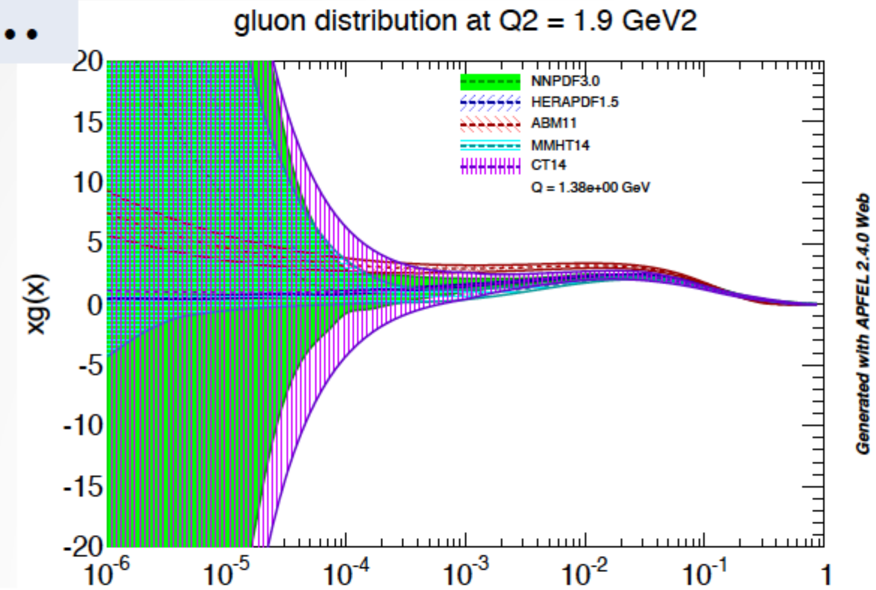


(A. Cooper-Sarkar & Voica Radescu, 2015)

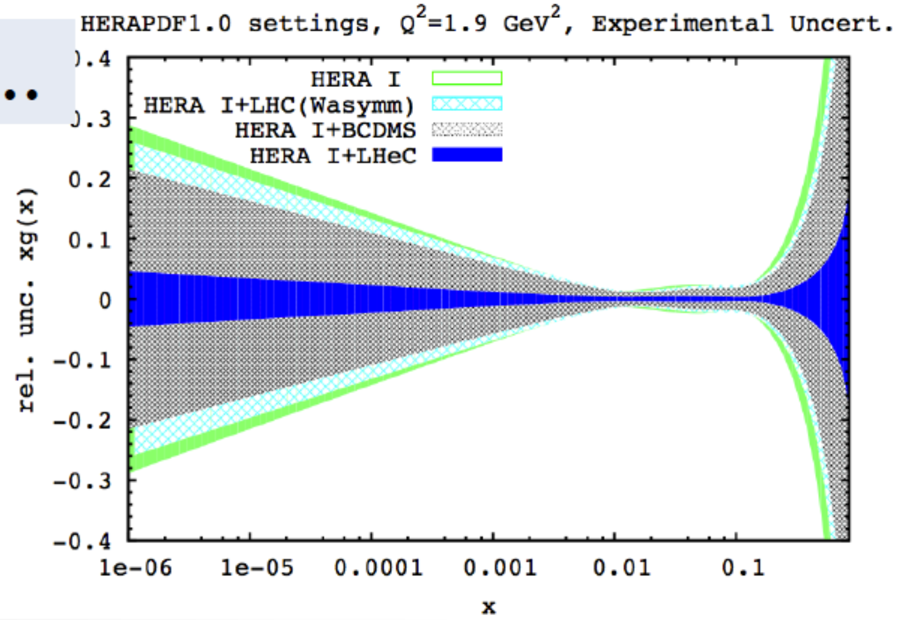
PDF uncertainty on Higgs production at LHC will become negligible due to measurements a the LHeC

Impact of LHeC at small x

now...

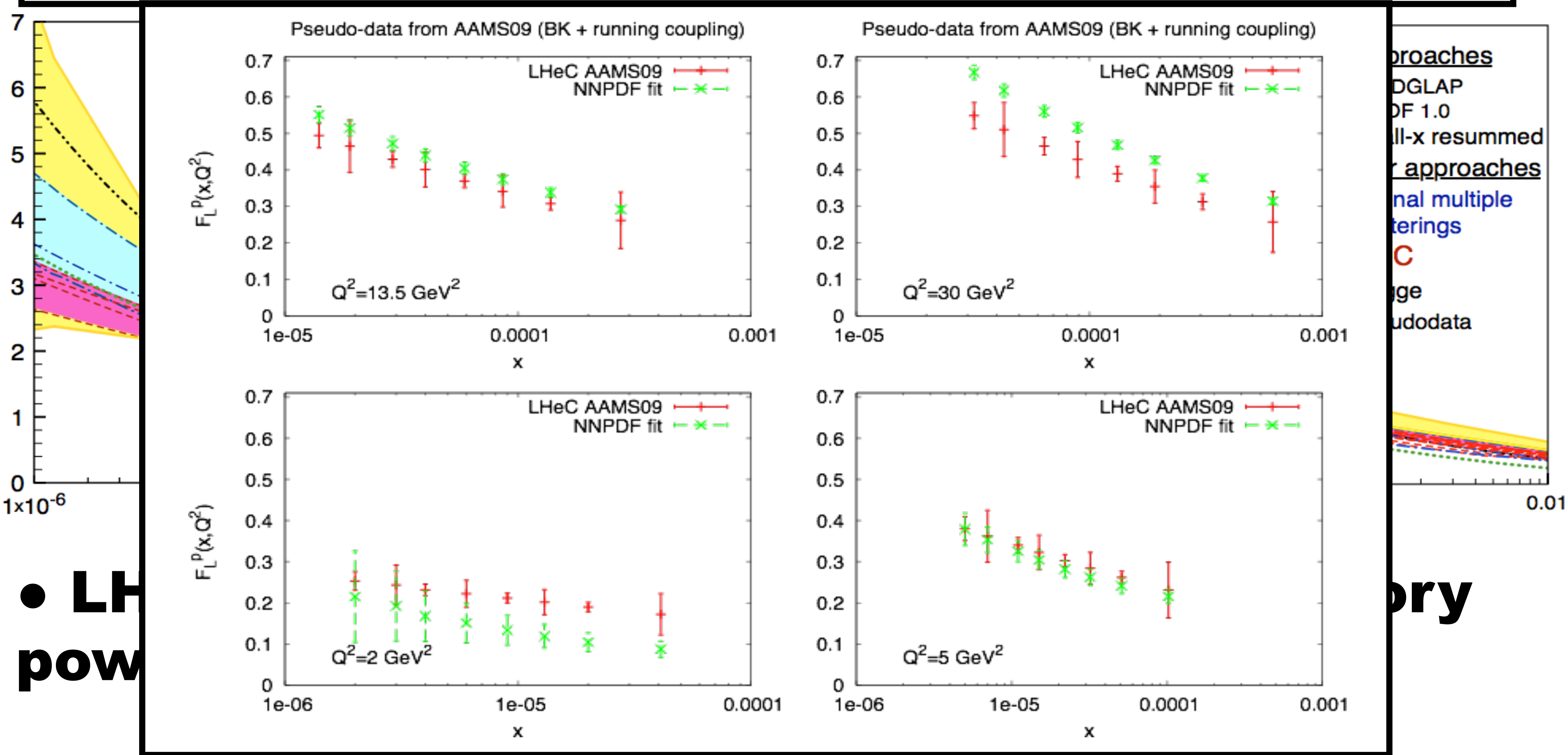


then...



Small-x: inclusive

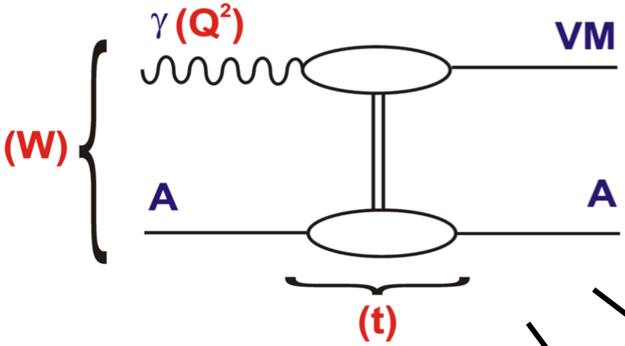
NLO DGLAP cannot accommodate F_2 and F_L in presence of saturation

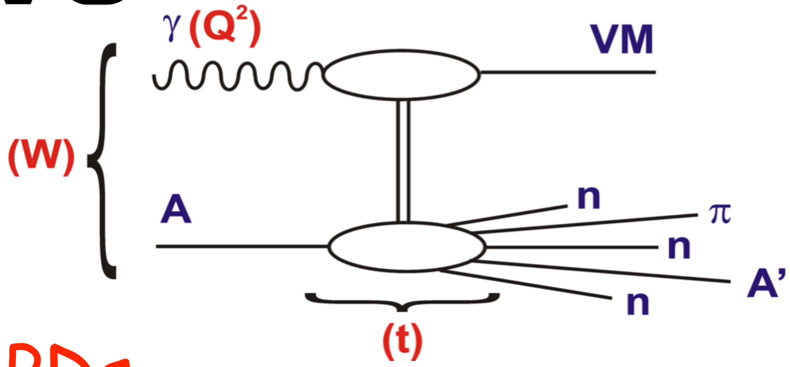


• LH ... ory pow...

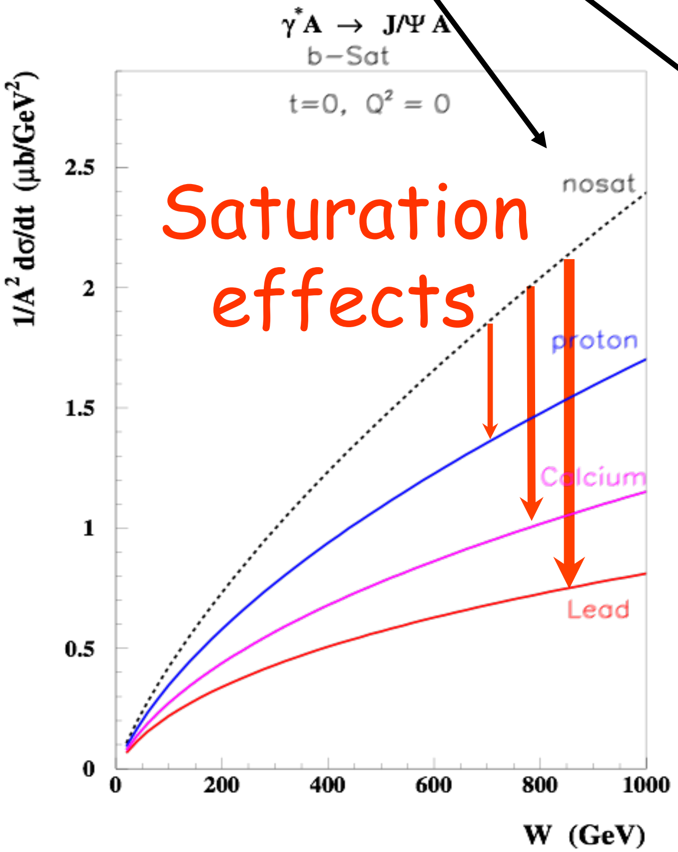
N. Armesto

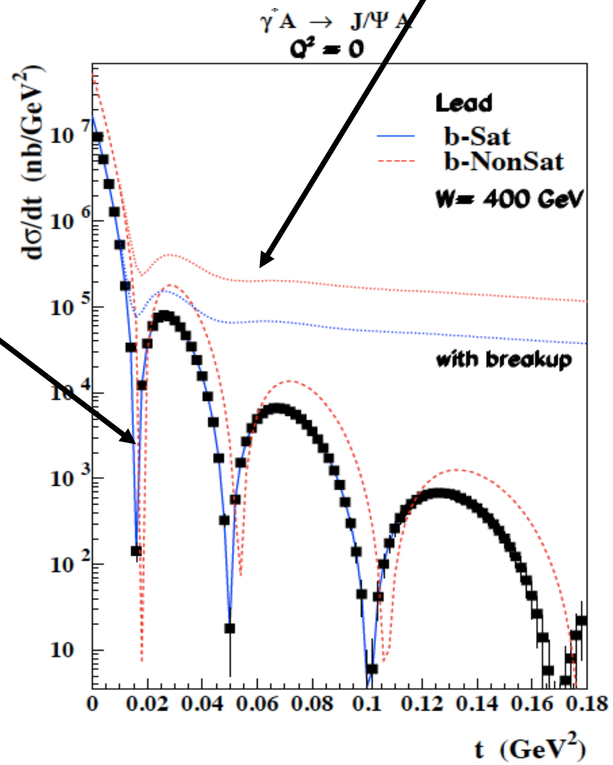
eA: diffractive





- Elastic VM: saturation, nGPDs.

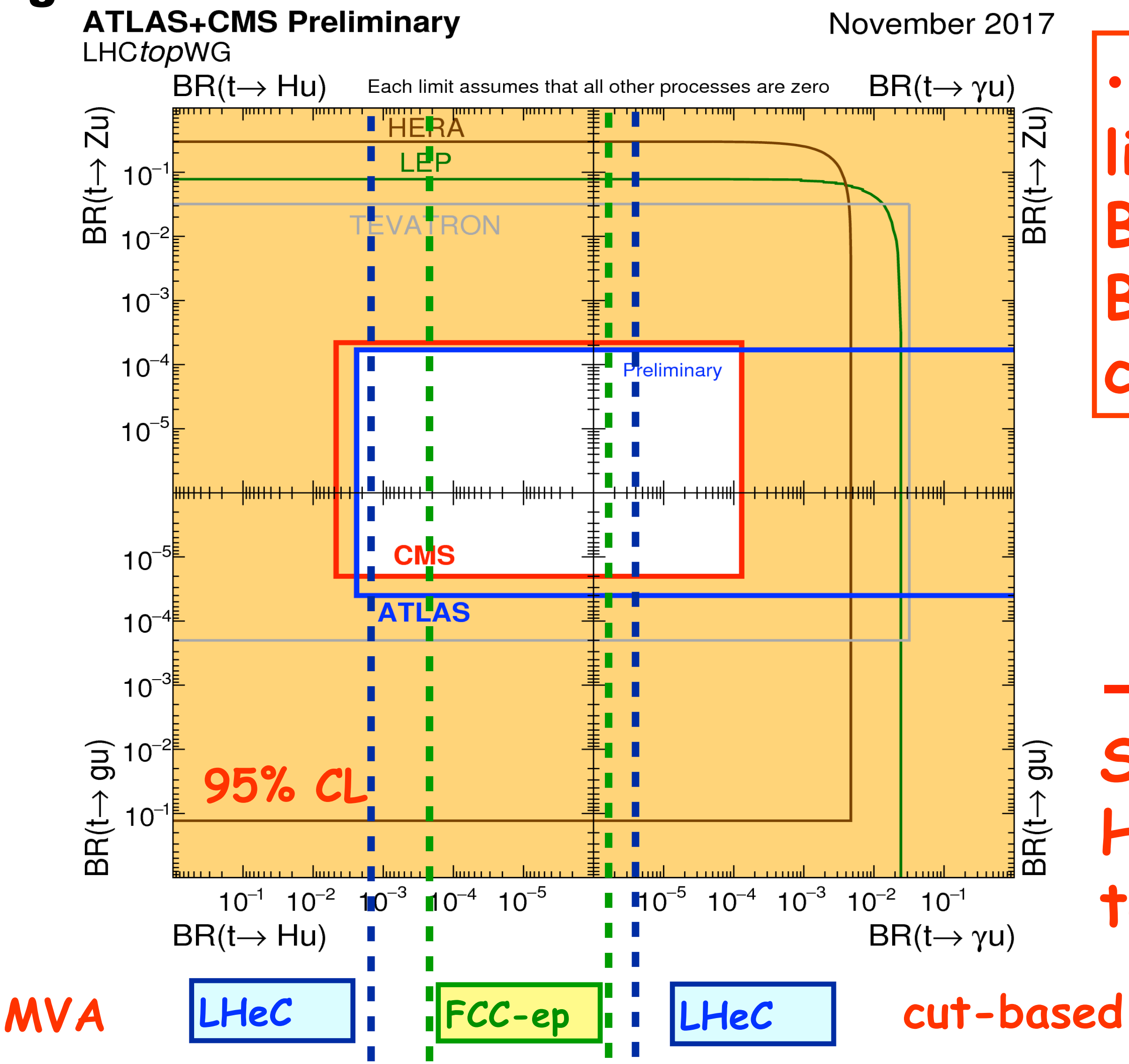




N. Armesto

FCNC Branching Ratios at Colliders

C.Schwanenberger

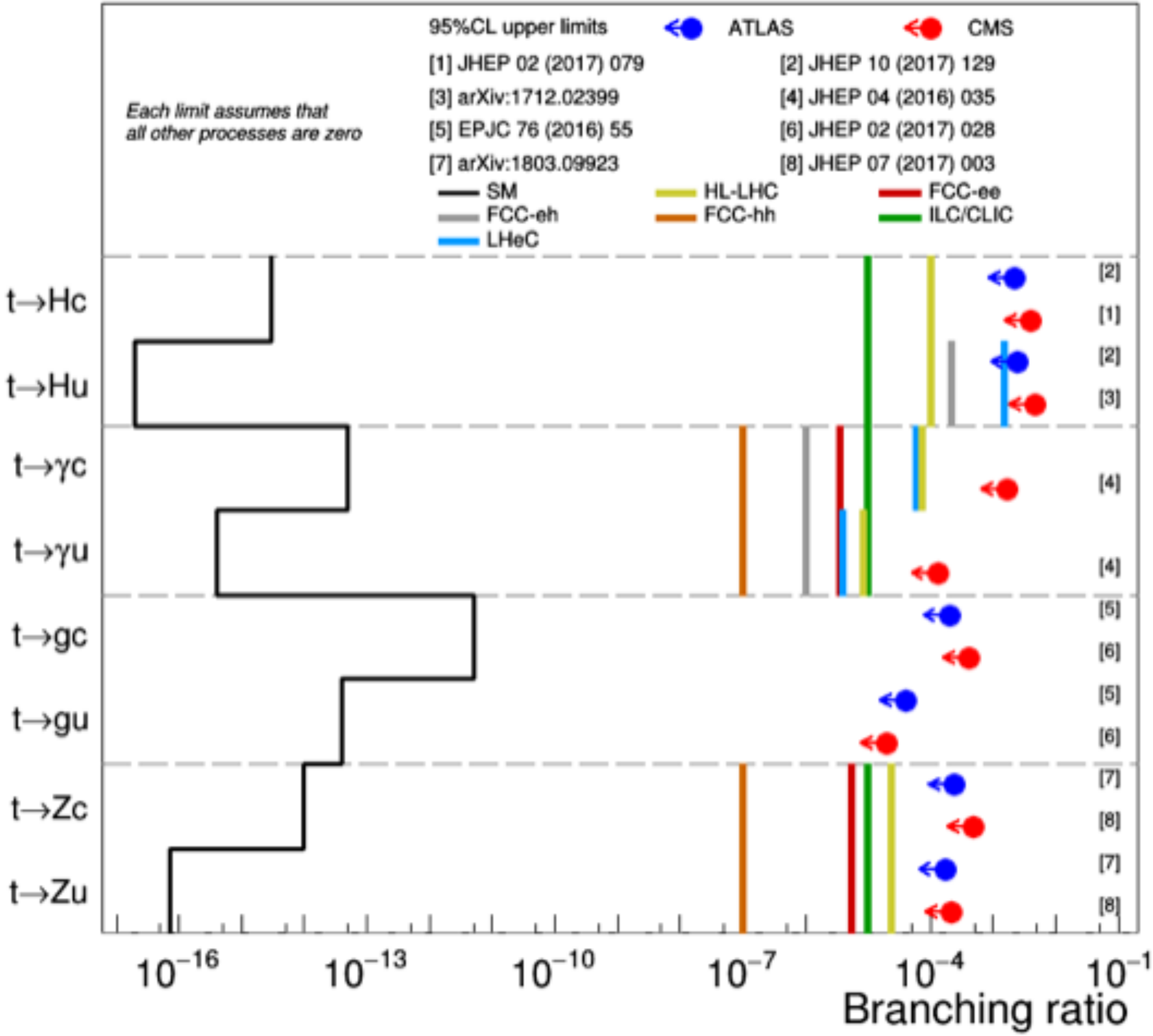


- improve limits on BR(t→γu), BR(t→Hu) considerably

→ test SUSY, little Higgs, technicolor...

E_e=60 GeV
1000 fb^{-1}

C.Schwanenberger

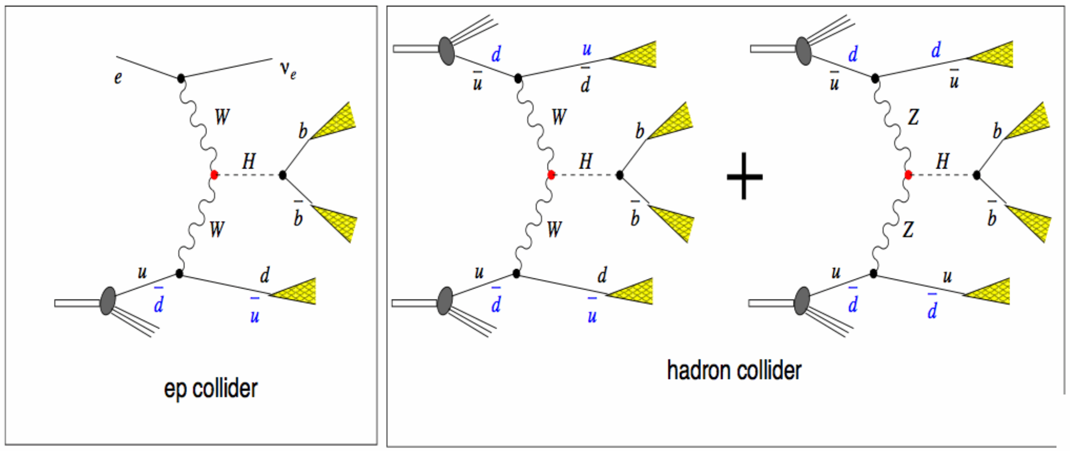


Structure of HVV couplings

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

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

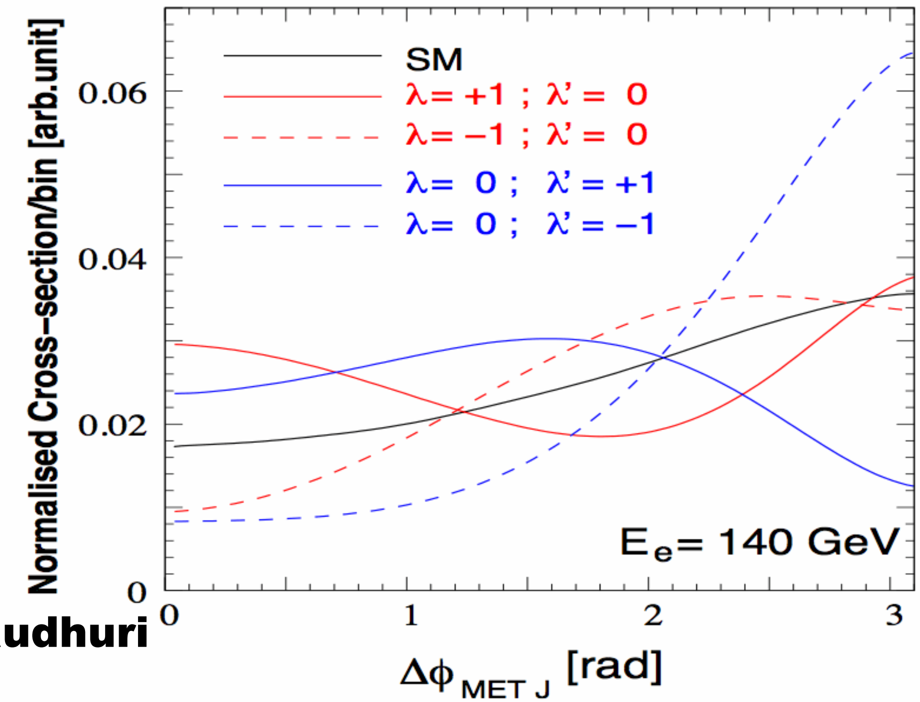
higgs + 2jets: VBF (LHC), higgs + jet + missing E_T (LHeC)



ep process uniquely addresses the HWW vertex.

Can consider azimuthal angle correlation between scattered neutrino and quark. Other observables can be used too.

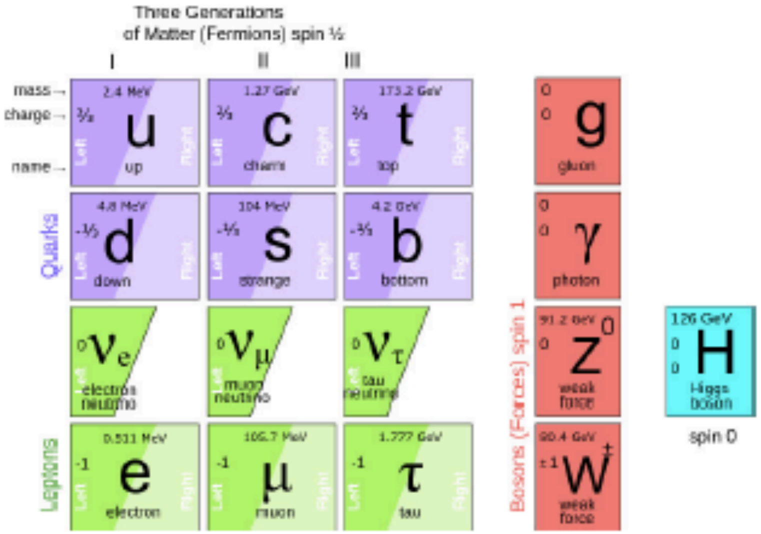
Model independent separation of HWW and HZZ coupling, unique capability of ep collisions, not available in pp and e^+e^- collisions

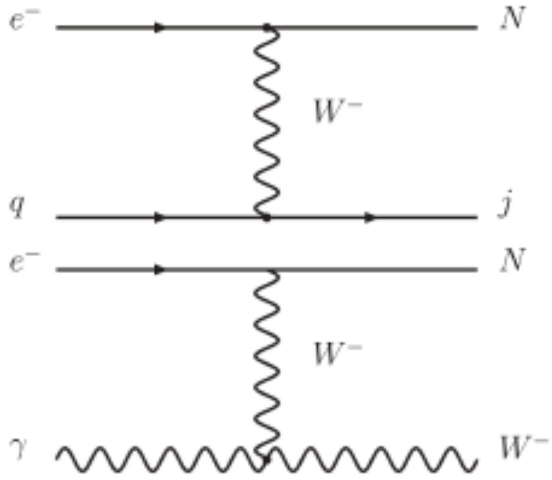


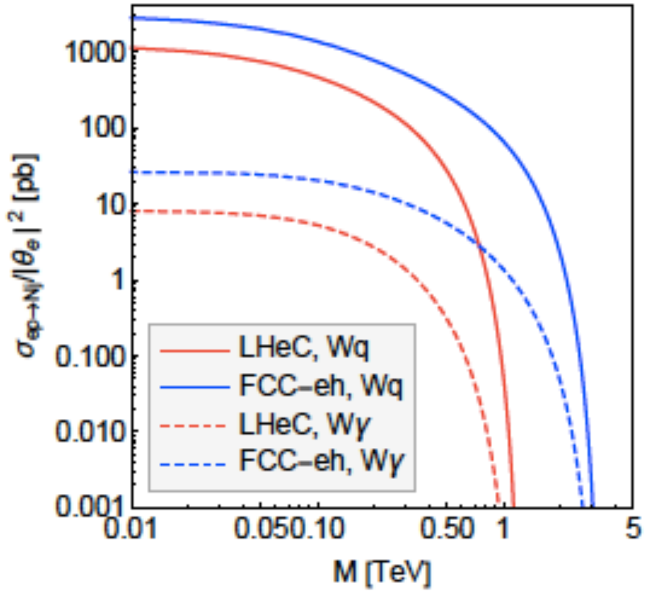
B.Biswal, R.Godbole, S.Kumar, B.M., S.Raychaudhuri
Phys.Rev.Lett. 109 (2012) 261801

Compositeness	• *4-fermion EFT: Lepton-quark compositeness scale* • ***Quark radius***
Leptoquarks and RPV squark decay	• *Accessible range largely excluded, but not completely* • ***Better measure of LQ characteristics, if they exist***
Anomalous Triple Gauge Couplings	• *Comparable to LHC*
Top FCNC couplings	• ***couplings – great potential wrt HL-LHC***
Vector-like leptons, heavy/excited leptons, bileptons, higher isospin lepton multiplets	• *No constraints on VLL, so far, at LHC* • *Extend sensitivity to for lower masses*
Heavy neutrinos, Majorana neutrinos, sterile neutrinos	• *Symmetry-protected see-saw model* • ***LHeC reach similar or better than HL-LHC***
SUSY EW: compressed scenario, **Higgsino**, (dark sector)	• *Long-lived neutral particles* • ***Disappearing tracks – low background, compensate the low signal production rate***
Anomalous Quartic Gauge Couplings	• *Better control on background: no gluon exchange diagrams (mostly FCC?)*
extended Higgs sector: higher isospin multiplet	• *Singly- and doubly- charged higgs by VBF (mostly FCC)*

Sterile Neutrinos at ep colliders







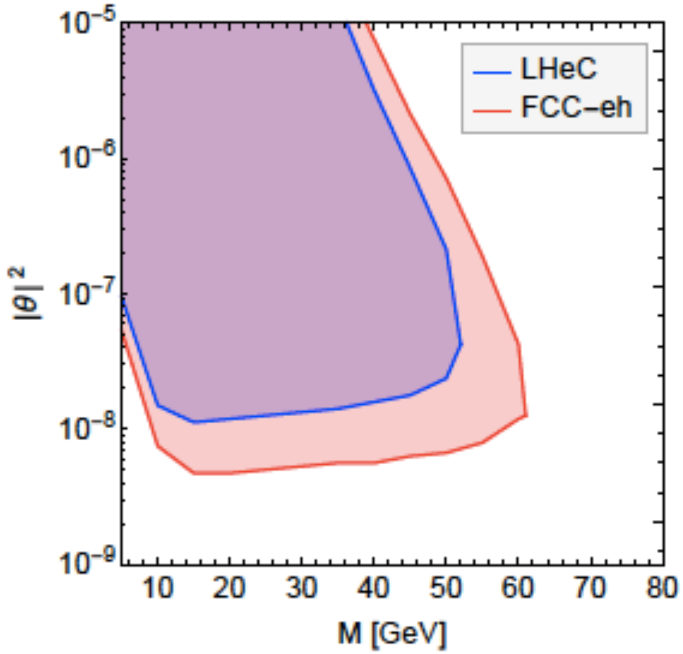
Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

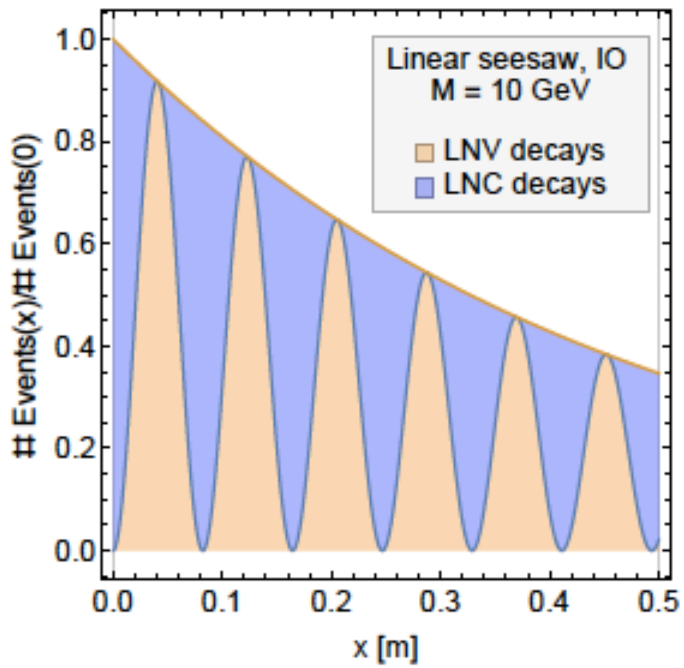
O.Fischer

- Neutrino oscillations are evidence for non-zero m_ν.
- Lowscale type I seesaw with sterile neutrinos
  $\rightarrow$ heavy neutrino mass eigenstates with $M \sim v_{\mathrm{EW}}$
- Neutrino mixing $|\theta_\alpha|$, $\alpha = e, \mu, \tau \Rightarrow$ Weak current production.
- Present constraints: $|\theta_e| \leq 10^{-3} \Rightarrow$ sizable cross sections at ep.

Antusch, Fischer; JHEP **1410** (2014) 094

O.Fischer





Displaced vertices:

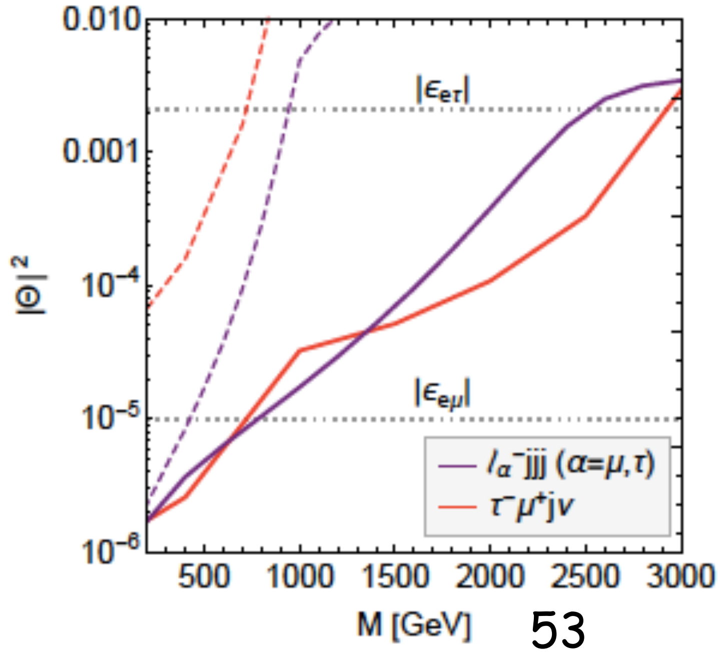
- Heavy neutrino-antineutrino oscillations
- Oscillation from Δm_ν^2, can be $\sim$ mm.

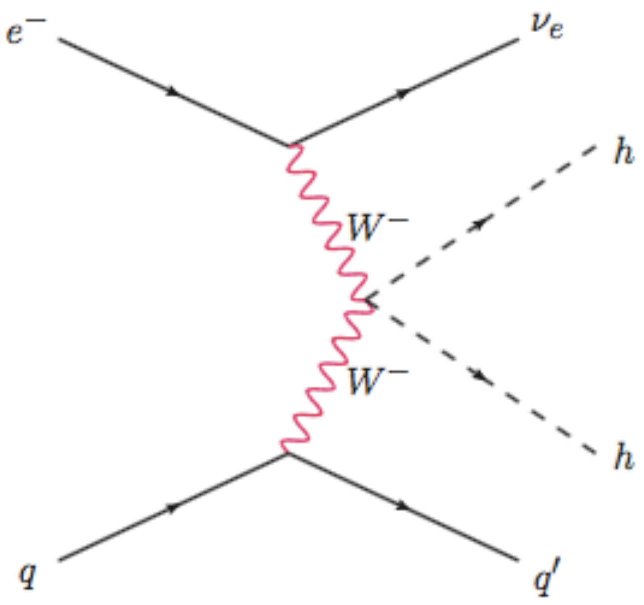
Antusch *et al.*; [1709.03797]

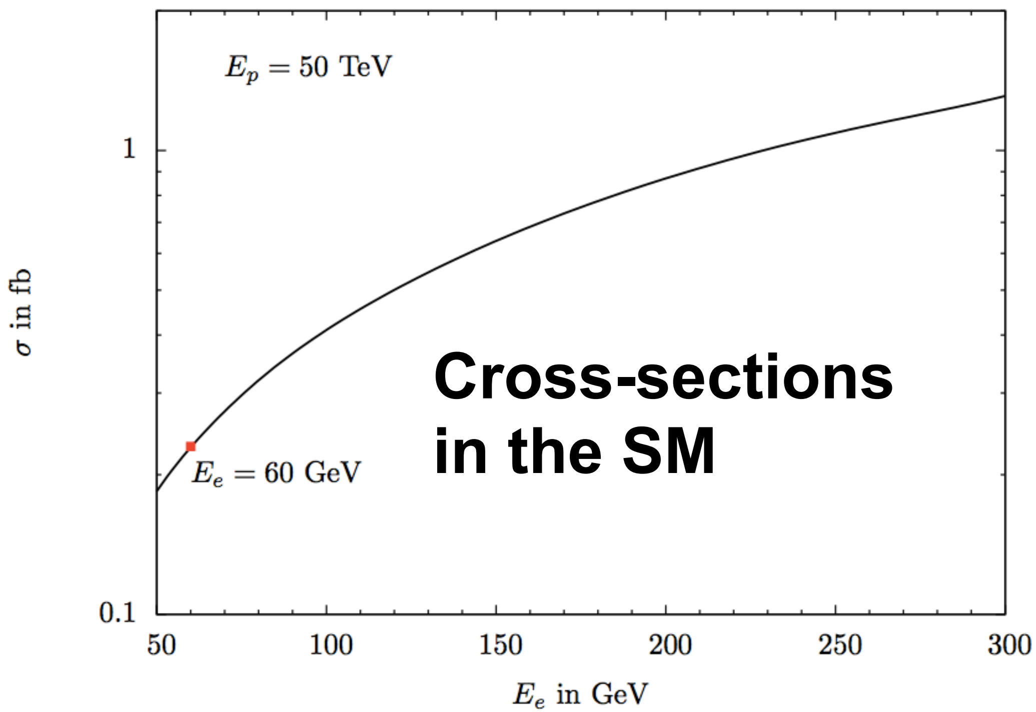
Lepton flavor violation:

- Unambiguous: μ +jets, τ +jets, $\mu\tau$ + jets
- Highest sensitivity to $|\theta_e \theta_\alpha|^2$, $\alpha = \mu, \tau$

Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078





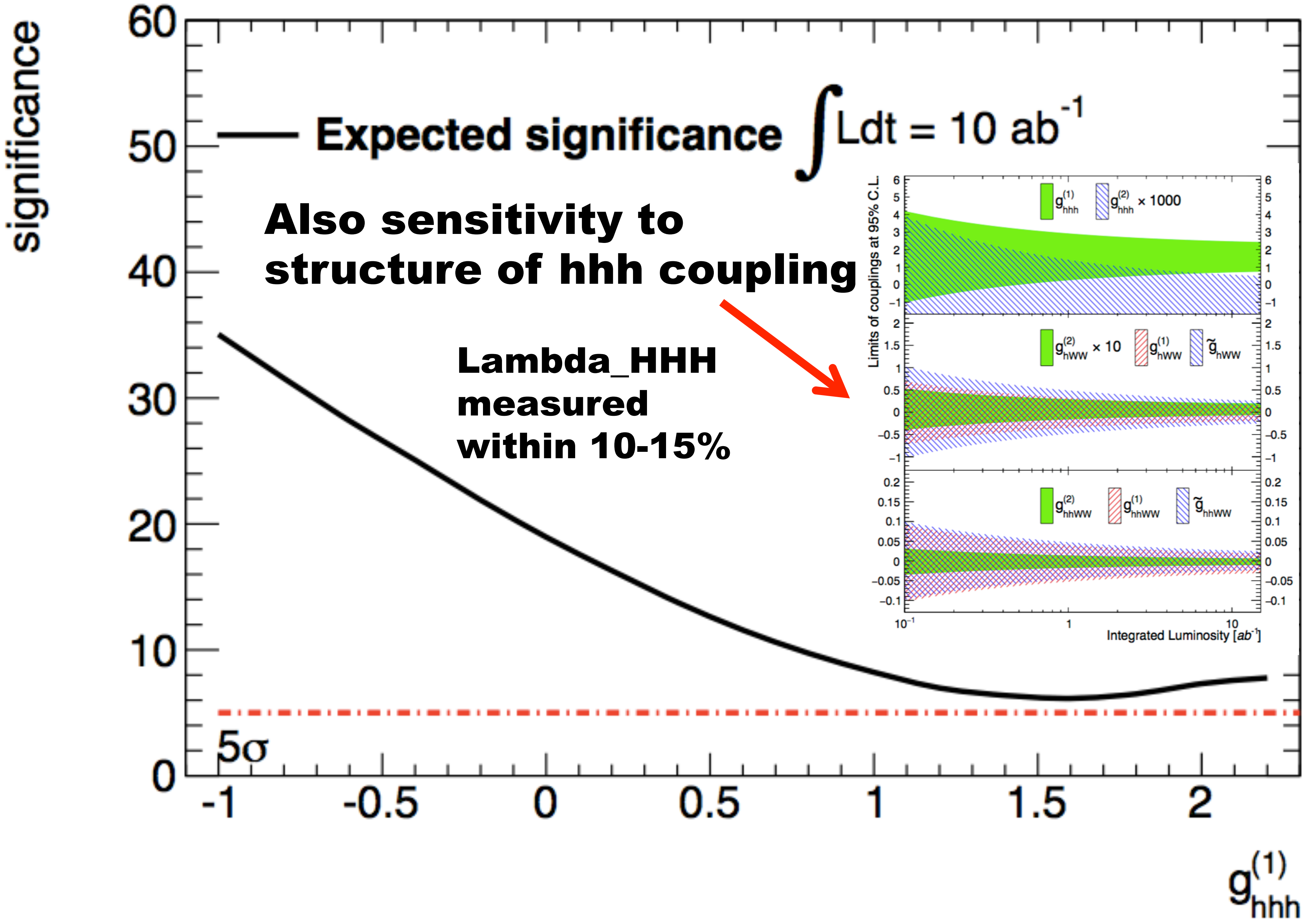


Considering highly asymmetric collisions

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

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

M. Kumar et al.[1509.04016]


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