FCC-he
Working Group Highlights

Uta Klein
on behalf of
the LHeC/FCC-he WG

FCC Week, Amsterdam, April 13th, 2018

Contributions he: FCC-hadrons + ERL-e$^-$

Introduction: (Mo) B. Mellado, J. Rudermann

Joint Physics Session: (Tue) **QCD** – M. Klein, **Higgs** - M. Klute, **EW** – R. Tenchini, **Top** - C.Schwanenberger, **Global Fits** – J. deBlas

WG Part 1: (Thu) Accelerator and PERLE

Overview on FCC-eh design – O. Brüning

Civil Engineering – J. Osborne

Interaction Region – R. Martin

PERLE Facility – W. Kaabi

WG Part 2: (Thu) Physics and Detector

FCC-he as a Higgs Facility – U. Klein

BSM Physics in eh – M. d'Onofrio

Top Quark Physics – O. Cakir

A Detector for eh – P. Kostka

Concurrent he and FCC-hh operation!
Same concept holds for HL-LHC and HE-LHC.
ERL Design: CDR arXiv:1206.2913

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PERLE F

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U. Klein

– M. d'Onofrio

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The Future Circular Collider

FCC-hh: ENERGY

FCC-eh: a good mix of both

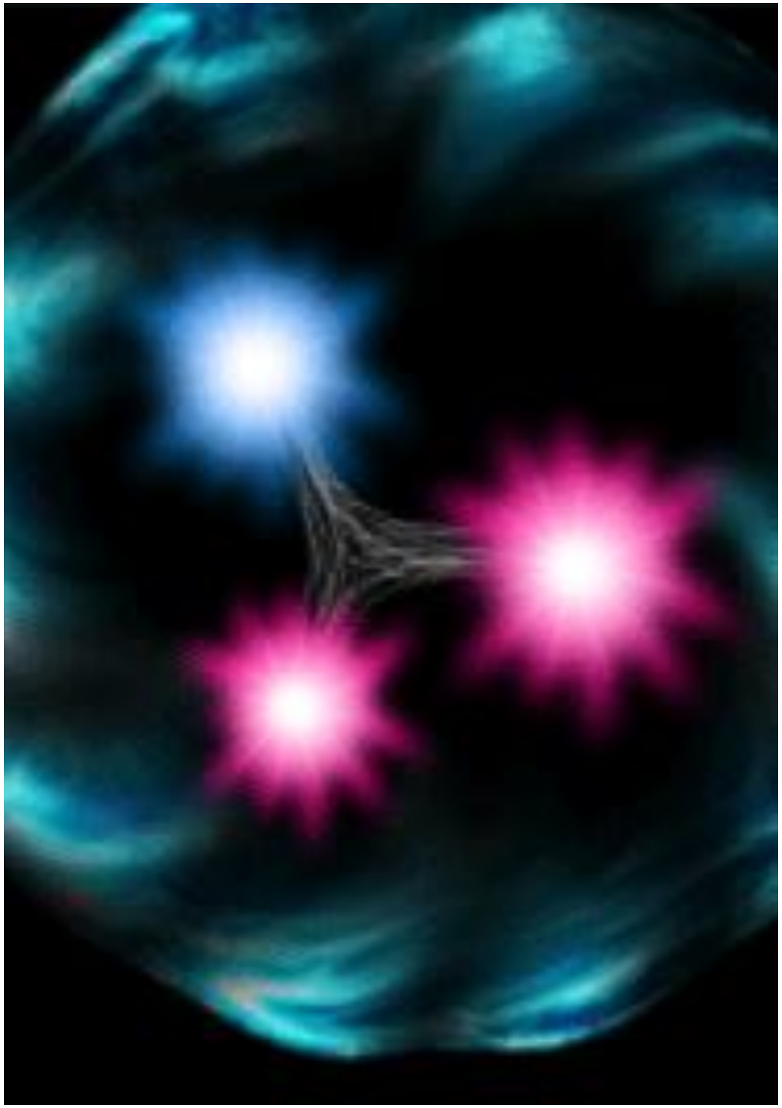
FCC-ee: Experimental PRECISION

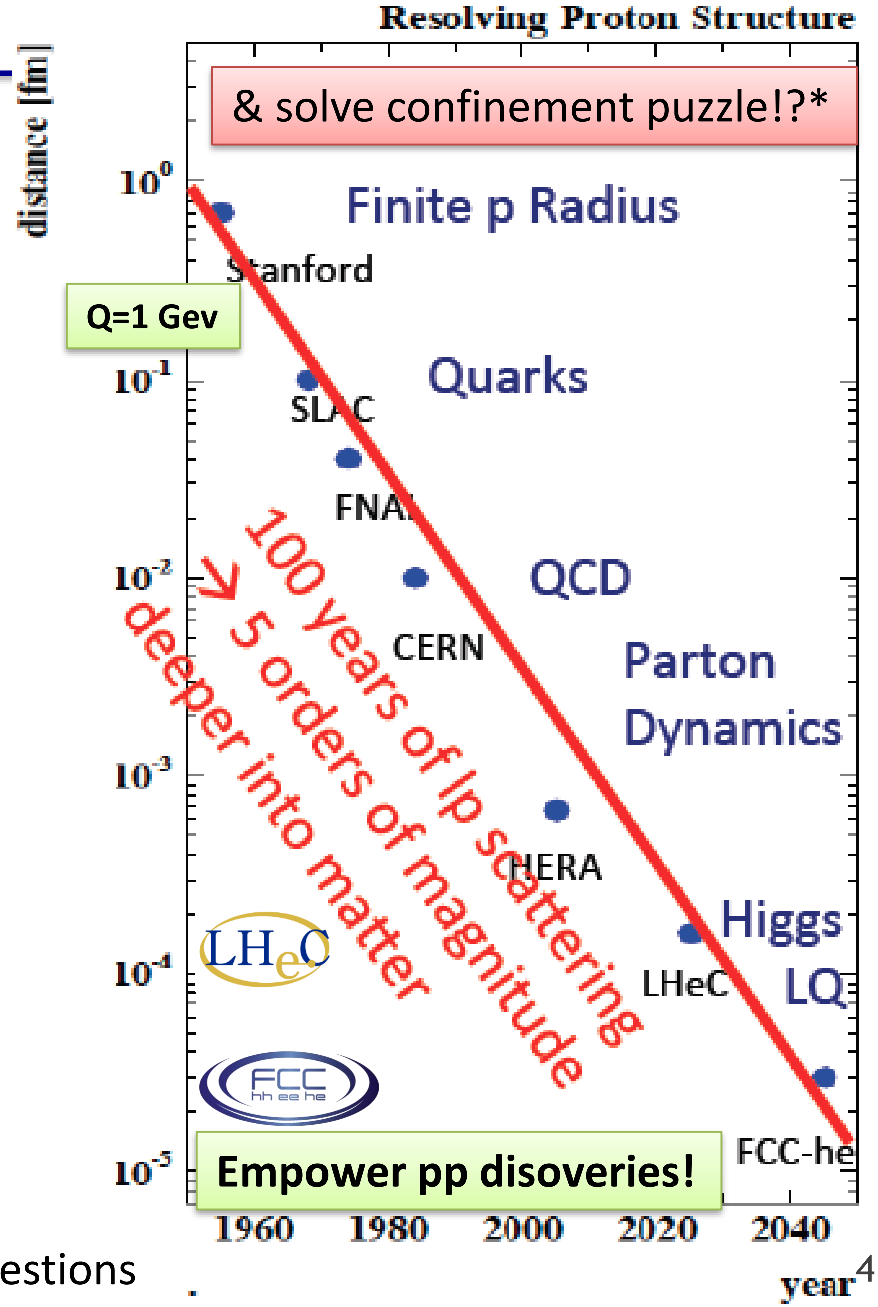
- In short:

Overlay from J. deBlas

Concurrent he and FCC-hh operation!
Same concept holds for HL-LHC and HE-LHC.
ERL Design: CDR arXiv:1206.2913

eh: Resolving a non-trivial Structure...





*Jaffe&Witten 2000: 1 out of 7 millenium prize questions

That's it??   That may not be it..

Talk by M Klein

Developments

AdS/CFT
Instantons
Odderons
TOTEM ? CERN EP 2017-335

Non pQCD, Spin
Quark Gluon Plasma

QCD of Higgs boson

N^kLO PDFs, Monte Carlos..
Resummation
Saturation and BFKL

Photon, Pomeron, n PDFs
Non-conventional partons
(unintegrated, generalised)
Vector Mesons
The 3 D view on hadrons..

Discoveries

CP violation in QCD?
Massless quarks?? Would solve it..
Electric dipole moment of the neutron?
Axions, candidates for Dark Matter

Breaking of Factorisation [ep-pp]

Free Quarks

Unconfined Color

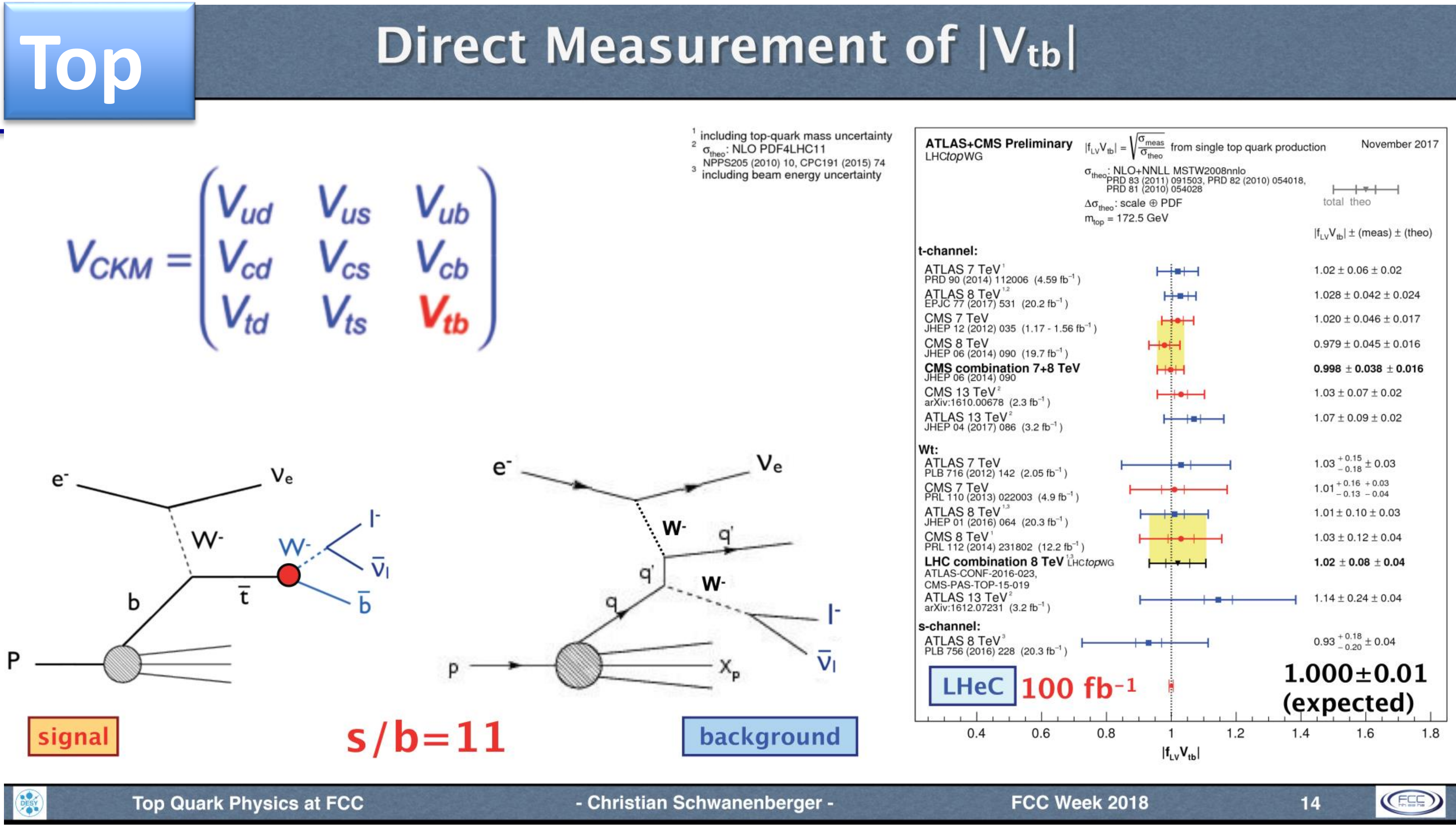
New kind of coloured matter

Quark substructure

New symmetry embedding QCD

C. Quigg, arXiv1308.6637

QCD has an exciting future with the FCC



→ amazing precision expected for $|V_{tb}|$ in ep

→ top cross section at FCC-he 15.3 pb (LHeC: 1.7 pb in CC DIS)

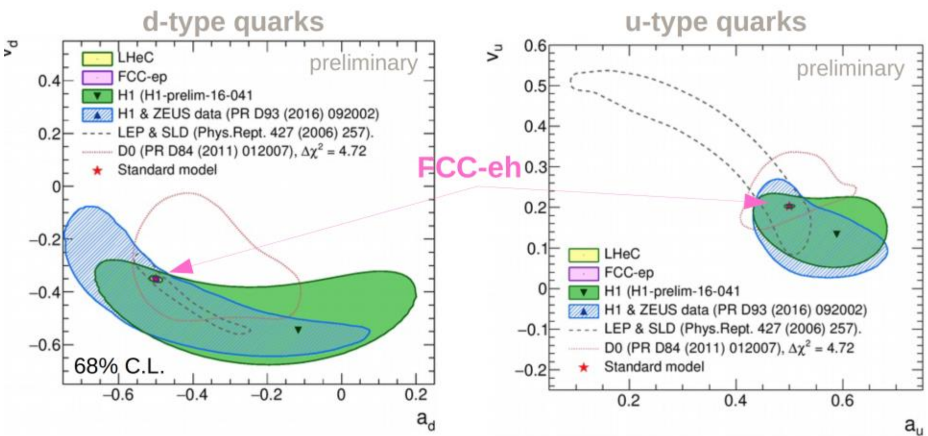
Talk by O. Cakir: Updates for FCC-he including $|V_{ts}|$ and $|V_{td}|$ → work ongoing by H. Sun for CDR

Electroweak precision observables at FCC eh

Talk by J deBlas

- **Electroweak precision measurements at FCC-eh**

Precision measurements of couplings to light quark families

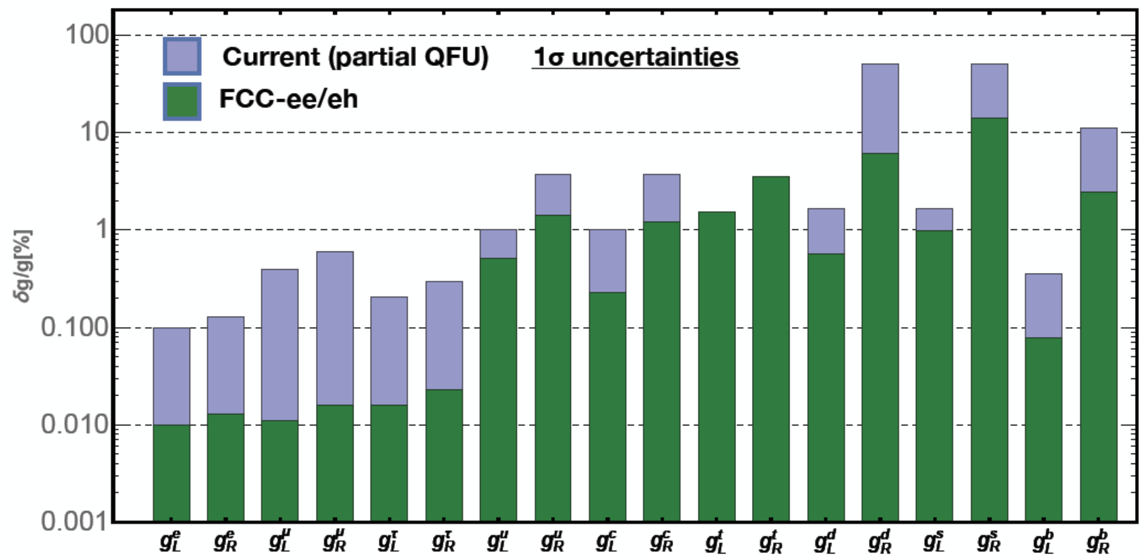


See Talk by D Britzger, FCC Physics Week 2018

Observable	Uncertainty	(Relative uncertainty)
g_V^u	0.0022	(1.1%)
g_A^u	0.0031	(0.6%)
g_V^d	0.0049	(1.4%)
g_A^d	0.0049	(0.97%)

- **Global fit to electroweak precision measurements at FCC-ee + FCC-eh**

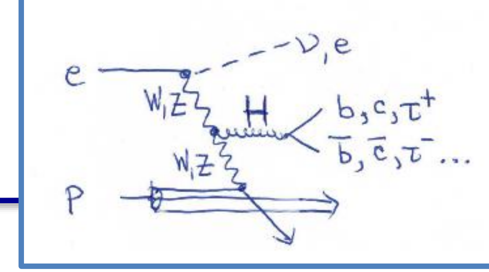
NEW
ee + ep

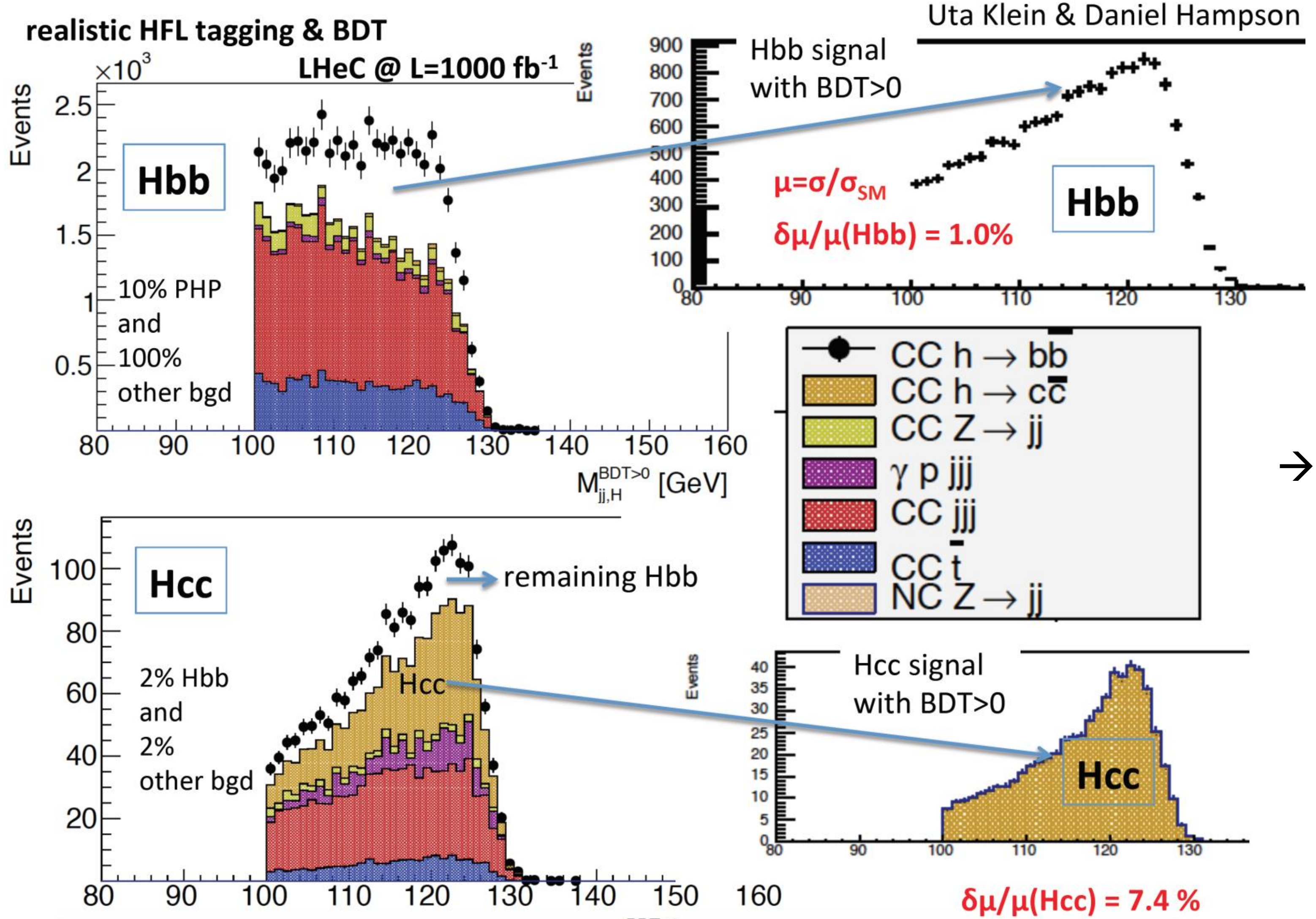


No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

Higgs in ep – clean S/B, no pile-up

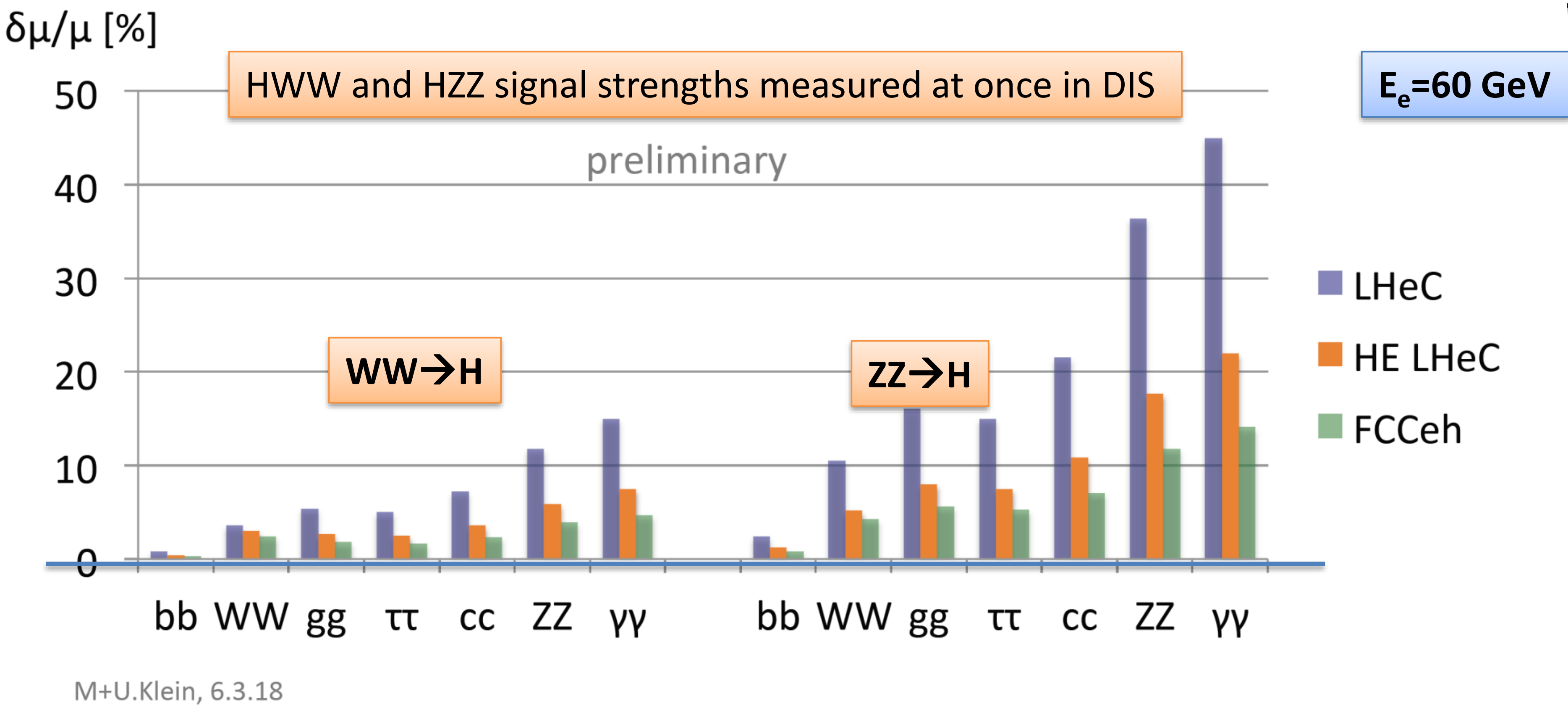




→ Hcc signal strength given for assumptions with Hbb background enhanced by factor 2!

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

Signal Strengths @ LHeC - HE-LHeC - FCCeh



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

→NC and CC DIS together over-constrain Higgs couplings in a combined 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}

Higgs precision observables at FCC ee and eh

Talk by J deBlas

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

NEW

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%
$\kappa_{Z\gamma}$	–

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

Higgs→ invisible: 1.2%
ttH: 1.85%
ep: see Talk by U Klein

Summary by J deBlas

- **All three FCC options complement each other very well:**
  - **FCC-ee allows not only very precise measurements of the Higgs and EWPO but also provides the normalization for more precise measurements at the FCC-eh and FCC-hh**
  - **FCC-eh complements FCC-ee providing information about light quark EW couplings. Similar precision in the Higgs sector**
  - **FCC-hh fills gaps in precision Higgs measurements for rare decays, top and the Higgs self-coupling**

NEW

Talk by J deBlas

Higgs complementarities: Global fit to Higgs couplings at FCC

- **All single Higgs couplings can be determined below the 1%**

FCC-ee/FCC-eh
Precise determinations for the leading couplings

HZZ Crucial for normalization of FCC-hh results

FCC-hh
Completes the picture with precise determinations of Top and coupling associated to rare decays

NOT MODEL-INDEPENDENT:
Results assume that, if there is New physics, it can only be in the Higgs couplings

HLLHC + FCC	
Coupling	Relative precision
κ_b	0.38%
κ_t	0.51%
κ_τ	0.58%
κ_c	0.79%
κ_μ	0.42%
κ_Z	0.14%
κ_W	0.17%
κ_g	0.74%
κ_γ	0.40%
$\kappa_{Z\gamma}$	0.52%

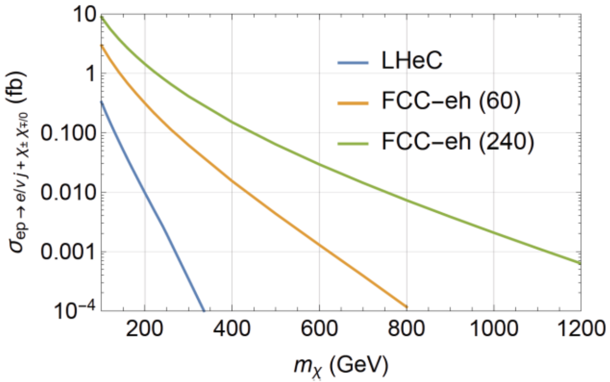
$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

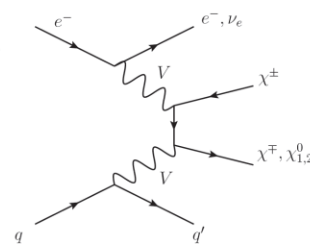
(long-lived) Higgsino

Curtin, Deshpande, Fischer, Zurita, arXiv:**1712.07135** (2017)

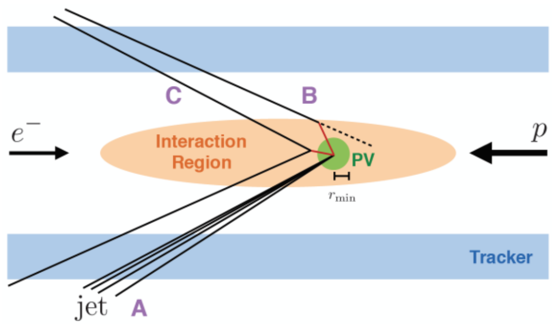
See Talks by J Rudermann and M. d'Onofrio

- Production at e-p via vector boson fusion

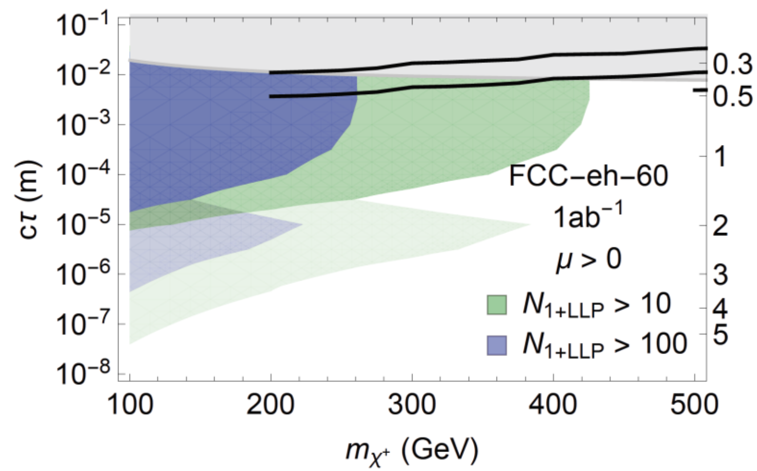




softly decaying, short-lived (~ μm) long-lived particles



Signal: **single soft displaced pion**
Beam remnant jet ⇒ primary vertex with O(10) μm precision



~ 450 GeV higgsino (thermal relic DM) can be discovered with 1/ab

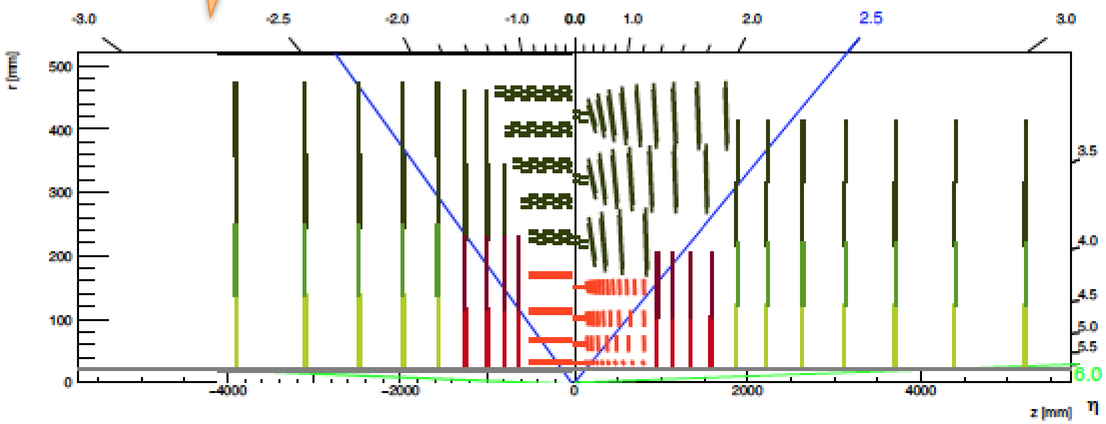
Many new ideas and papers on BSM in ep.

Displaced vertices! → ep potential for general BSM searches 'that look like hadronic noise' in pp.
[Cite D Curtin]
→ also: heavy neutrino-anti-neutrino oscillations, see 1709.03797; lepton number violation? Test the Majorana nature.

Talk by P Kostka

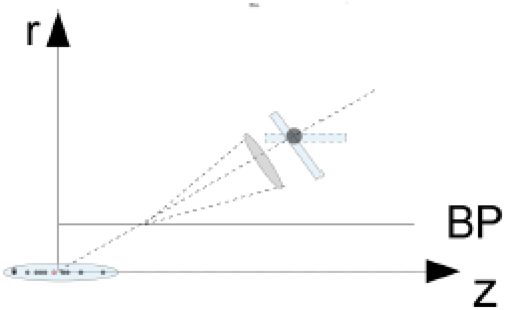
NEW

FCC-eh Tracker Layout



bwd - planar design fwd - tilted design

Going from planar design to
Inclined inner tracker modules
minimizing material budget



courtesy Anna Zaborowska

Very compact layout
Forward/backward boosted jet-/particle-flow

NO pile-up from FCC-eh BUT

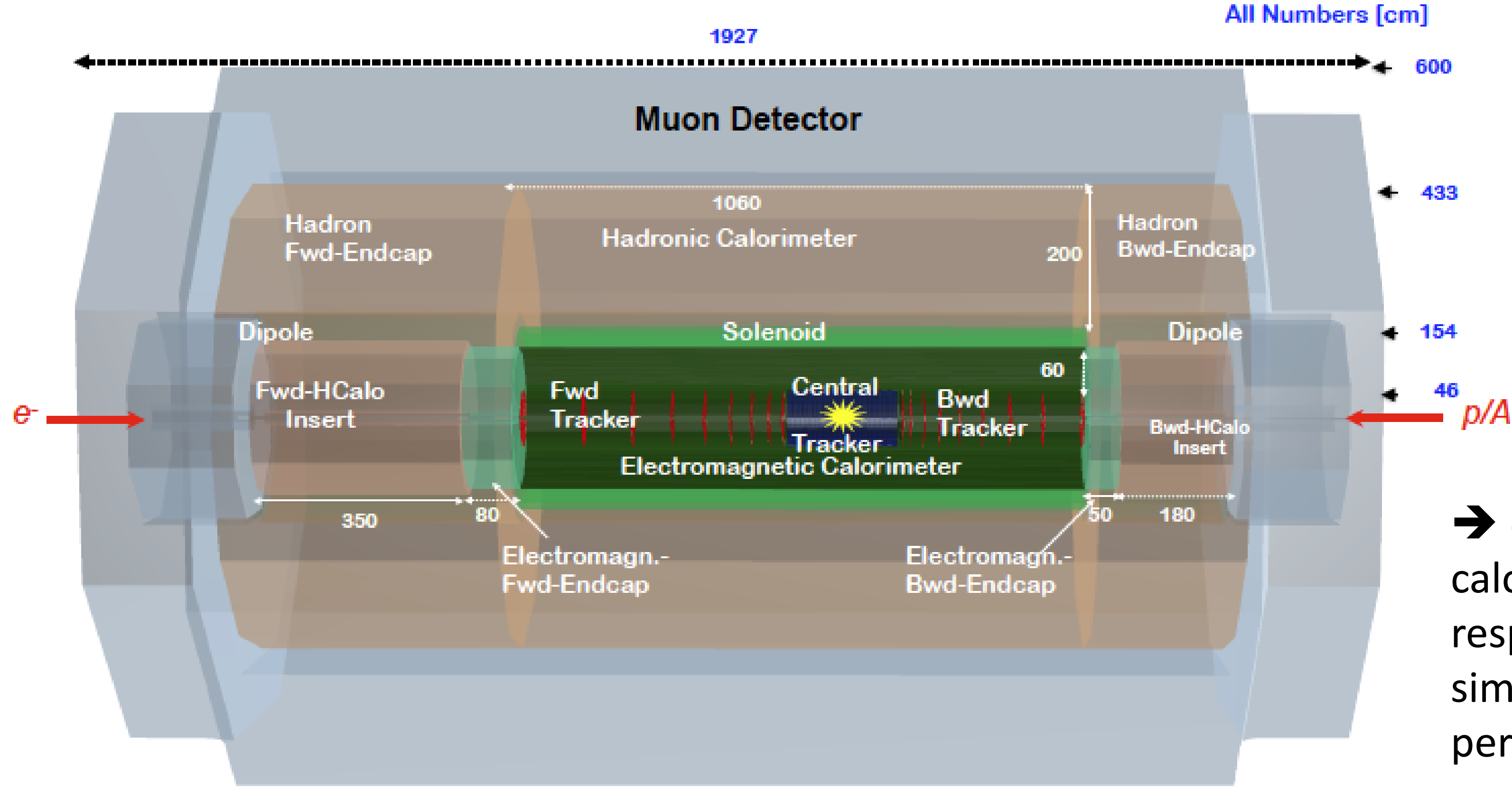
- effects of thick BP to be investigated in detail
- resolution of displaced vertices, secondary vertices, boosted daughters
- vertex tagging 5-10μm resolution required; accompanied by excellent calorimeter measurement - resolutions (warm option) have been presented (prel.)

Optimised by pattern recognition and vertexing
3.5mm beam pipe thickness
3.5T solenoidal field

Zbyněk Drásal:
https://github.com/drasal/tkLayout/tree/masterLite

FCC-he Detector Basic Layout

Talk by P Kostka



➔ detailed calorimeter response simulations performed

Based on the LHeC design; Solenoid&Dipoles between Electromagnetic Calorimeter and Hadronic Calorimeter. Length of Solenoid ~11m. detector setup in DD4hep.

https://dd4hep.web.cern.ch/dc

Discussion of ep solenoids by H ten Kate, see CERN March 2018: **No R&D needed**

https://indico.cern.ch/event/696066/

FCC-he Interaction Region

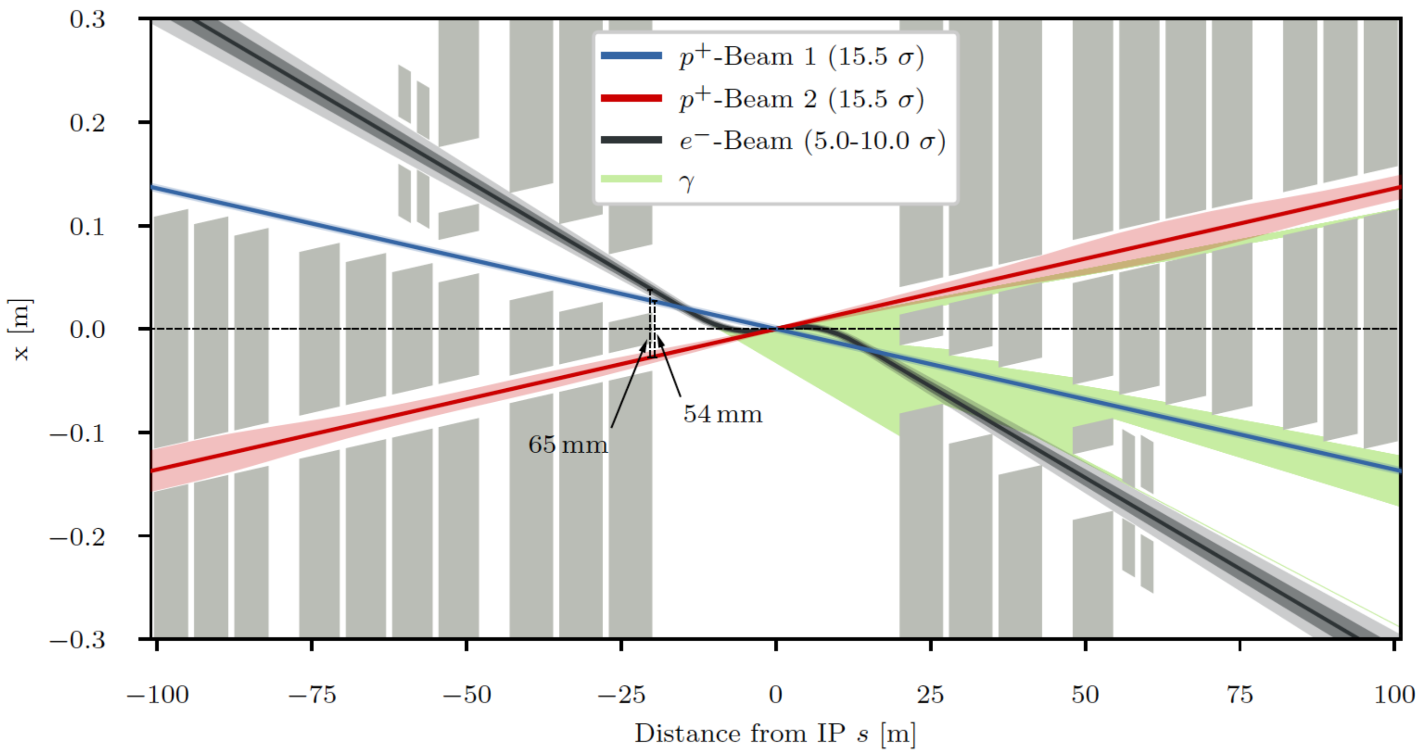
IR configuration with head-on collisions →
in-experiment dipole system ±0.073 T

R. Martin: NEW optics designed for FCC-he for β* =0.3m
Goal: β*~ 0.15m
Critical: Magnet apertures, gradients - progressing
Minimize Synchrotron Radiation, maximize Lumi

Talk by R Martin

Interaction region layout for $\beta^* = 0.3$ m

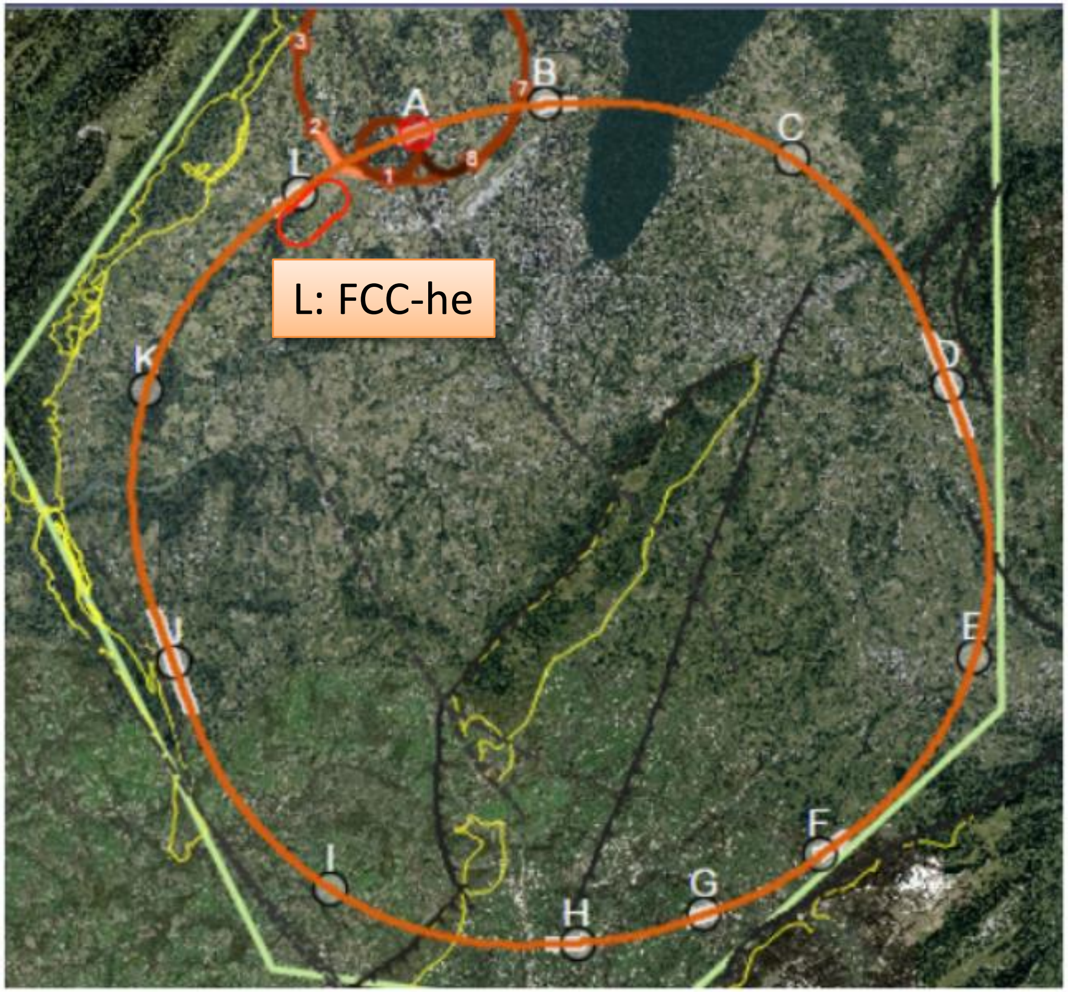
NEW



Note: β_e^* naively scaled to have $\beta_e^* \cdot \epsilon_e = \beta_p^* \cdot \epsilon_p$

FCC-he Site and Integration to FCC-hh

Talks by O Brüning and J Osborne



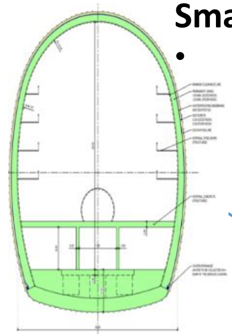
ep with 1000 times HERA luminosity and a new world for eA!

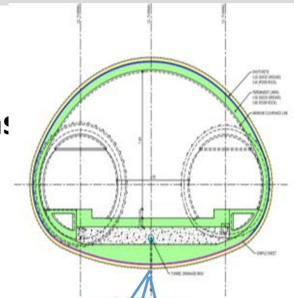
ERL Design: CDR
arXiv:1206.2913

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

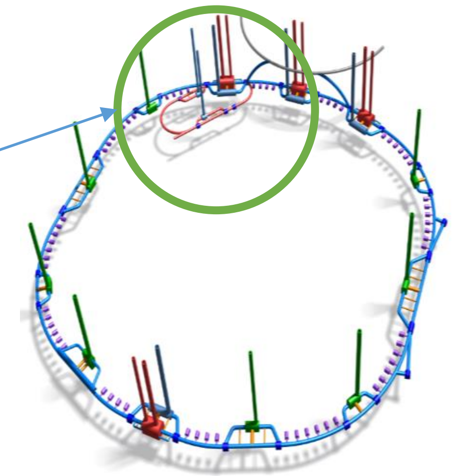
Scope of FCC-eh Structures

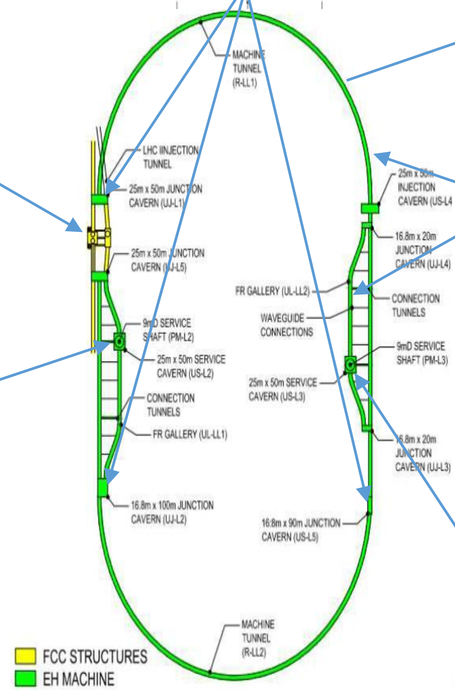
Small Experimental Caverns
- 30 m x 35 m x 66m

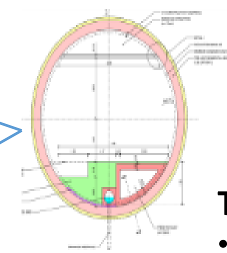




Junction Caverns
- 16.8 m x 15 m x 100 m
- 25 m x 15 m x 50 m
- 16.8 m x 15 m x 90 m

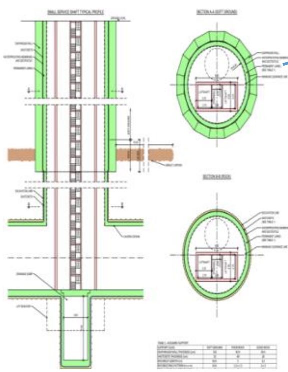


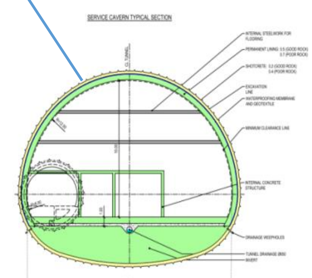




Tunnels:
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

Shafts:
2 x Service shafts:
9 m dia. x 175 m depth





Service Caverns
- 25 m x 15 m x 50 m

Talk by J Osborne

NEW

LHeC Configuration: Size variations

Work in progress

SRF as the main cost driver for the 60 GeV Configuration:

- Reducing the electron beam energy can almost half the ERL cost
- Design and build the arcs for higher beam energy to allow for later upgrades
- Provide free space in the linac sections for later upgrades

30GeV to 50GeV Variation:

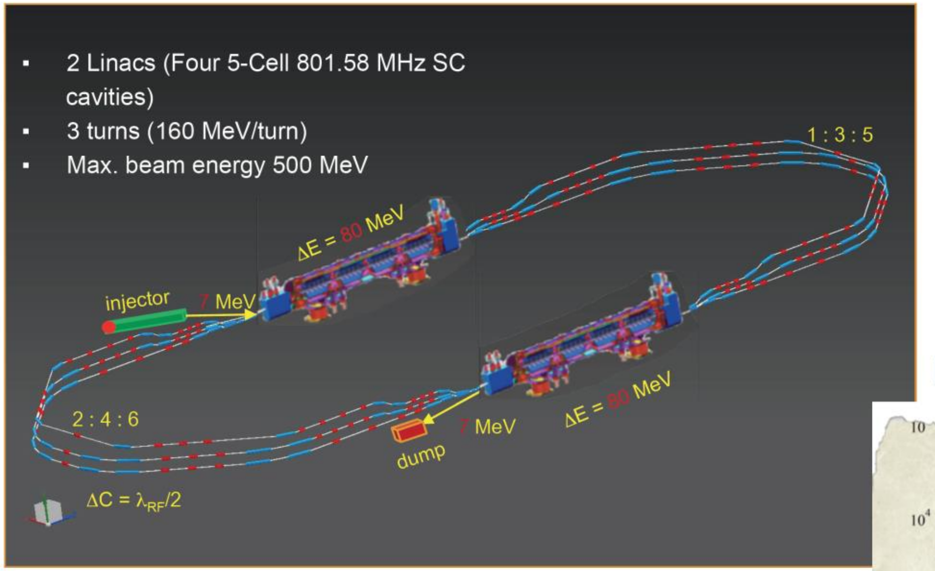
- Reducing the initial SRF cost by 50%
- Provide upgrade potential for up to 50GeV
- Overall size from 1/3rd to 1/5th of the LHC circumference

The LHeC could be re-used for the first installation phase for the FCC-eh

PERLE: Powerful ERL for Experiments @ Orsay

Talk by W Kaabi

PERLE configuration:



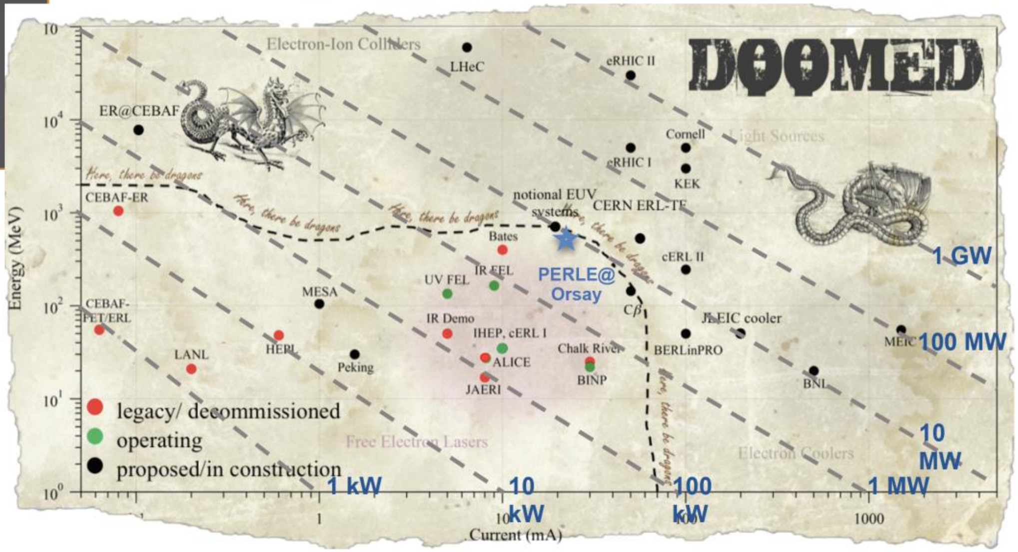
Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

PERLE

PERLE Collaboration today:

CERN · CNRS IN2P3 Les deux infinis · Jefferson Lab · Science & Technology Facilities Council · University of Liverpool · Budker Institute of Nuclear Physics

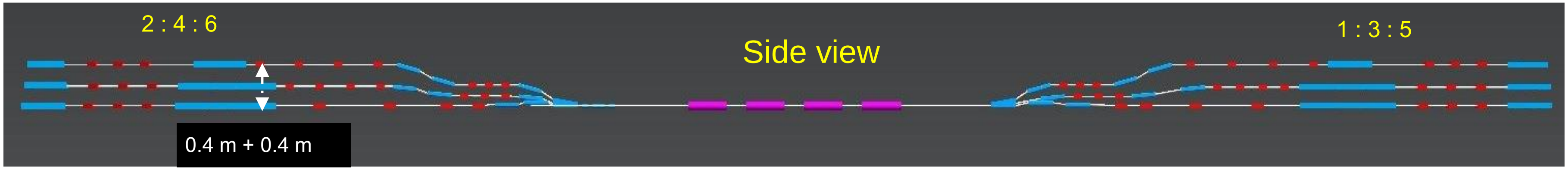
PERLE in the global landscape:



PERLE: Powerful ERL for Experiments @ Orsay

Talks by O Brüning and W Kaabi

20 mA; 500 MeV, up to 10 MW;Footprint: 24 x 5.5 x 0.8 m^3



PERLE Collaboration: CERN, JLAB, Daresbury, Liverpool, Novosibirsk, LAL and IPN Orsay
CDR: arXiv:1705.08783; 802 MHz cavity tested, see Talk by F Marhauser; TDR for 2019

Machine Study Goals:

- **-High current, multi-turn (3) ERL concept with 802MHz SRF**
- -Beam Breakup intensity limit and filling patterns,
- -ERL efficiency,
- -beam size evolution etc.
- -SRF LLRF feedback and control
- -Failure scenarios
- -Beam Halo formation and dump line acceptance
- -Beam Instrumentation
- -Build up operational experience
- -Source and injector

Potential for low energy electron and photon physics being explored.

Workshops

Recent: September 2017
https://indico.cern.ch/event/639067/

Next: 27-29 June 2018 Orsay
https://indico.cern.ch/event/698368/
Preparation for strategy:
Physics, Accelerator, Detector, PERLE

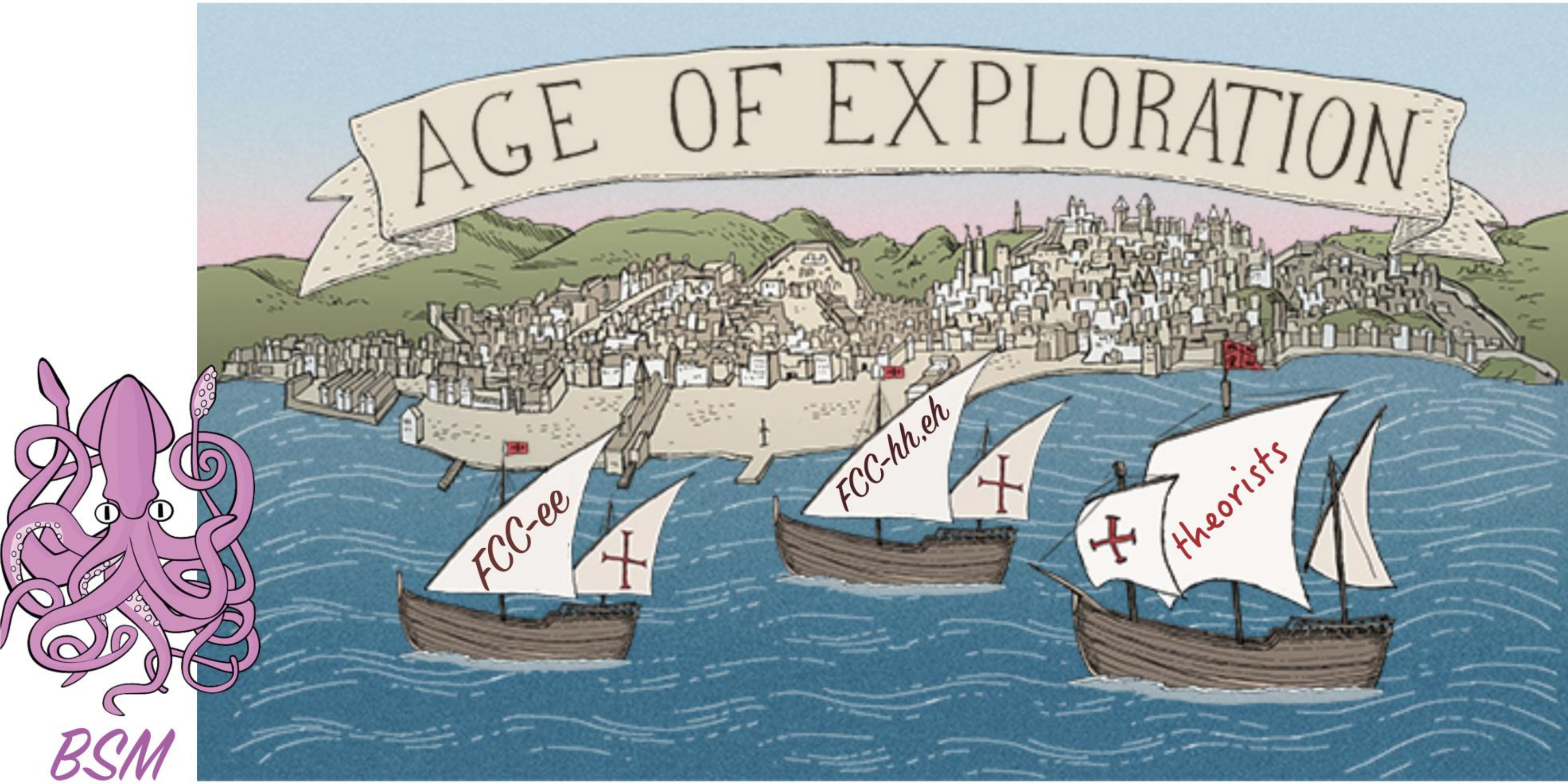
Many eh related workshops
FCC Physics Week CERN Jan 2018)
FCC Week:April 2018 (Amsterdam)
Next Week: DIS 2018 April (Kobe)
HL-HE LHC Physics June 2018 (CERN)
which includes ep/eA

Work on CDRs progressing well!

https://lhec.web.cern.ch

The Journey just started…

Slide from J Rudermann



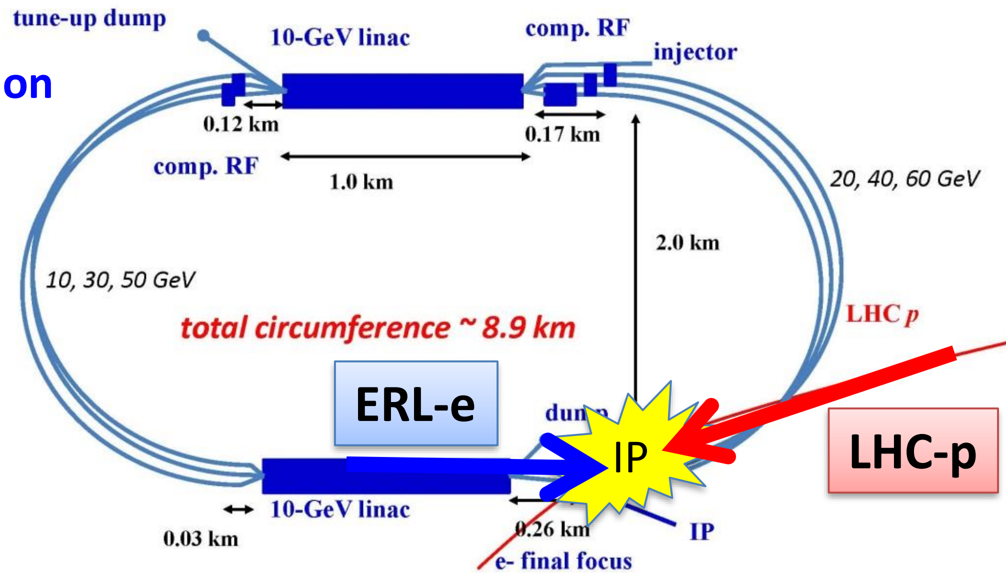
things "we don't know we don't know"

Additional material

electrons for pp : ERL + LHC

- Two Electron LINACs + 3 return arcs: using energy recovery in same structure: 'green' technology with power consumption < 100 MW : nominal E_e = 60 GeV
- Beam dump: no radioactive waste!
- high electron polarisation of 80-90%
- Installation decoupled from LHC operation

Concurrent ep and HL-LHC operation!
Same idea holds for HE-LHC and FCC-hh



- ep Lumi 10^{34} cm s^{-2} s^{-1} **
- 100 fb^{-1} per year, e.g. ~2030-2040 (HL-LHC)
- L= 1000 fb^{-1} total collected in 10 years
- eA luminosity estimates ~ 10^{33} cm s^{-2} s^{-1} eA

** based on existing HL-LHC proposal

Detector Design
for HL+HE+FCC ep
Peter Kostka et al.
→ installation in 2 years, e.g. during LS4

LHeC CDR: arXiv:1206.2913 and updates at LheC/FCC-eh WS@CERN, 9/17

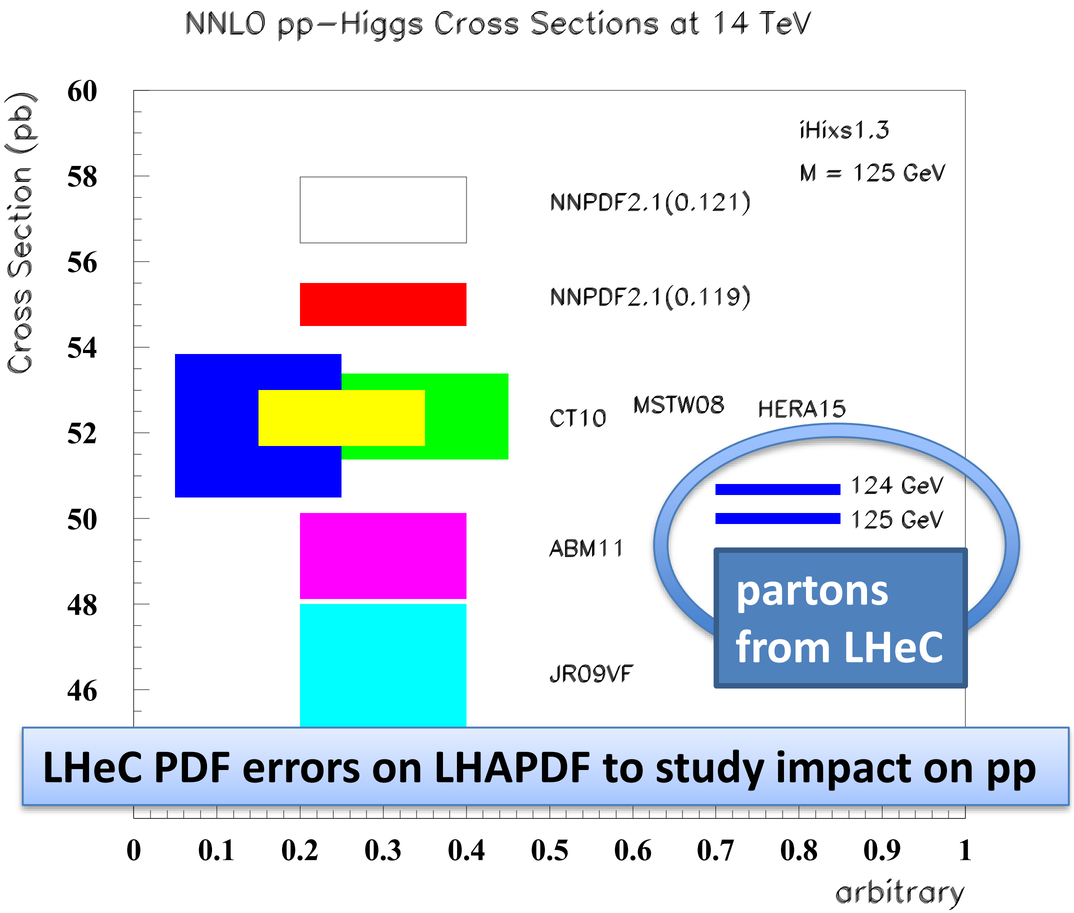
See also talk by C Gwenlan

LHeC Precision Partons for Higgs@pp

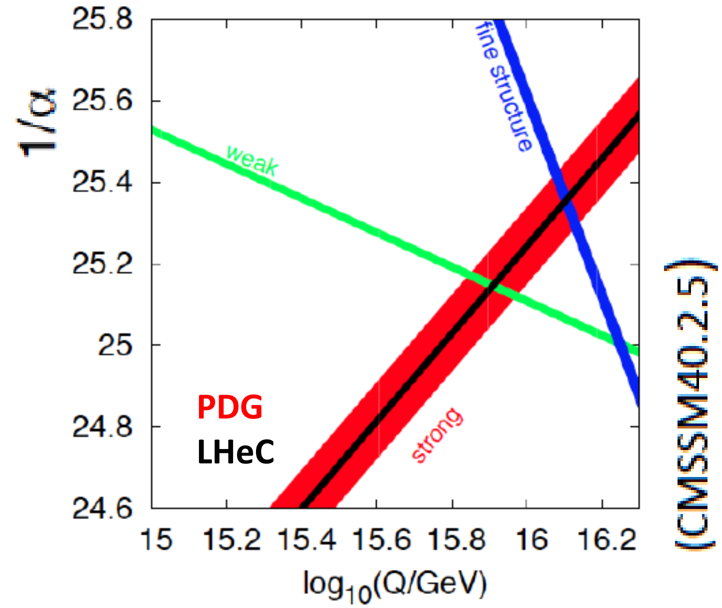
→ **Using LHeC input**: experimental uncertainty of predicted **LHC Higgs cross section due to PDFs and α_s** is strongly **reduced to <~0.5%**

→ ***theoretically clean path to determine N^3LO PDFs*** using ep DIS

→ ***ALL those 'benefits' for pp within the first few years, using ~100 fb^{-1} ep data***

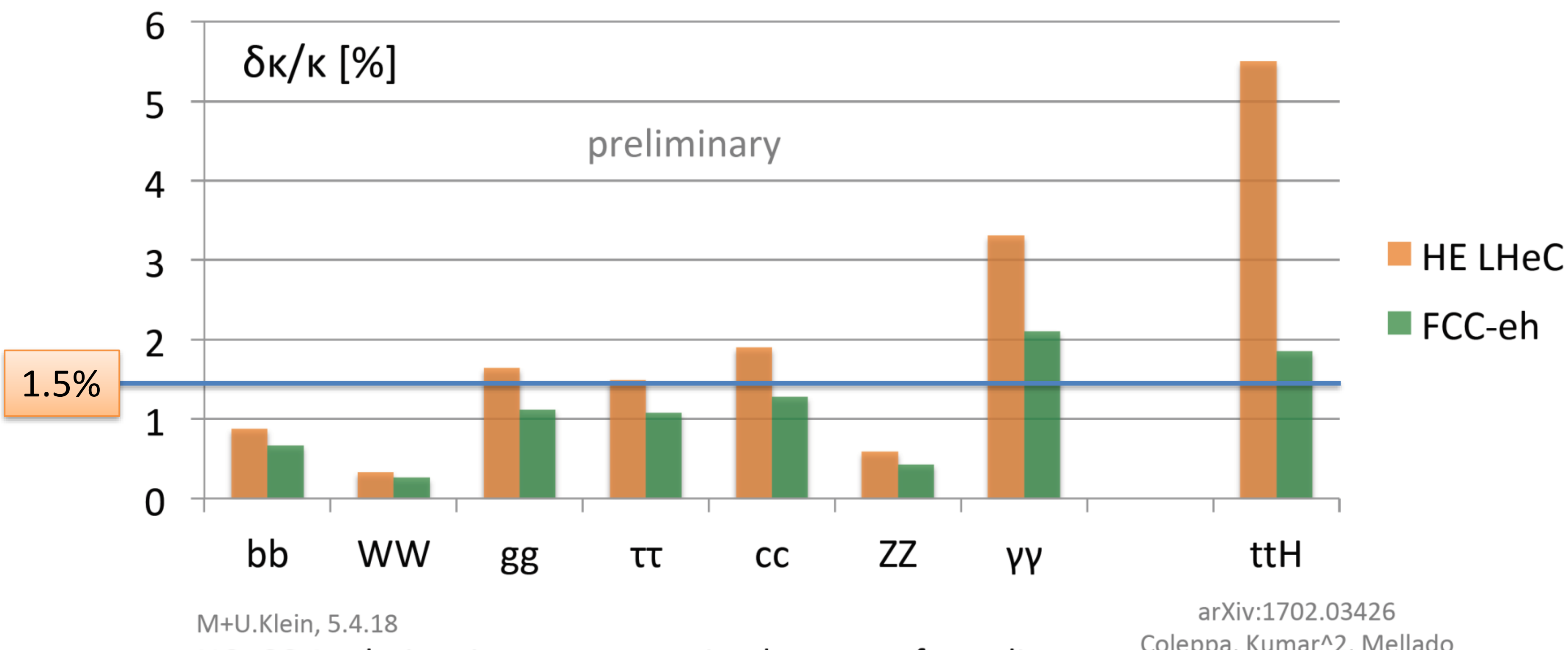


→ **precision from LHeC can add a very significant constraint on the Higgs mass** *and challenge Lattice QCD calculations for α_S:*



Model-dependent Coupling Fit

→ Assuming SM branching fractions weighted by the measured κ values, and Γ_{md} (c.f. CLIC model-dependent method)



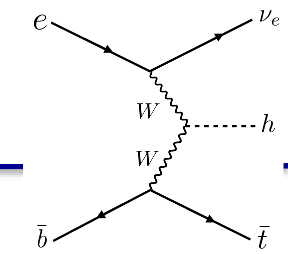
NC+CC Analysis using overconstrained system of couplings

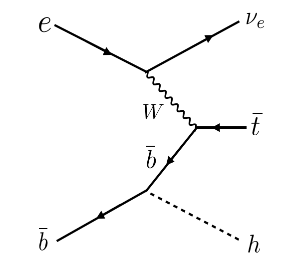
E_e = 60 GeV L=2ab^{-1} HE-LHC E_p = 14 TeV FCC: E_p = 50 TeV

See also talk by Jorge de Blas at this workshop for further fits and ep+ee combinations.

Top Yukawa Coupling @ LHeC

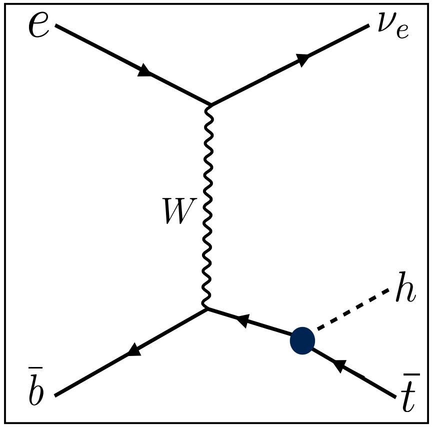
B.Coleppa, M.Kumar, S.Kumar, B.Mellado, Phys. Lett. B770 (2017) 335



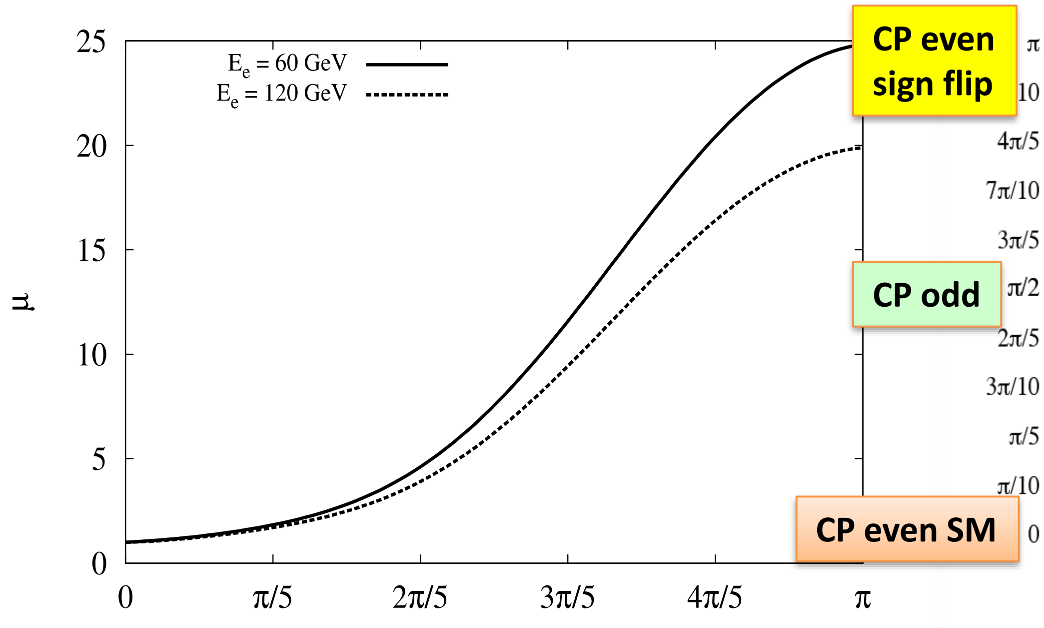


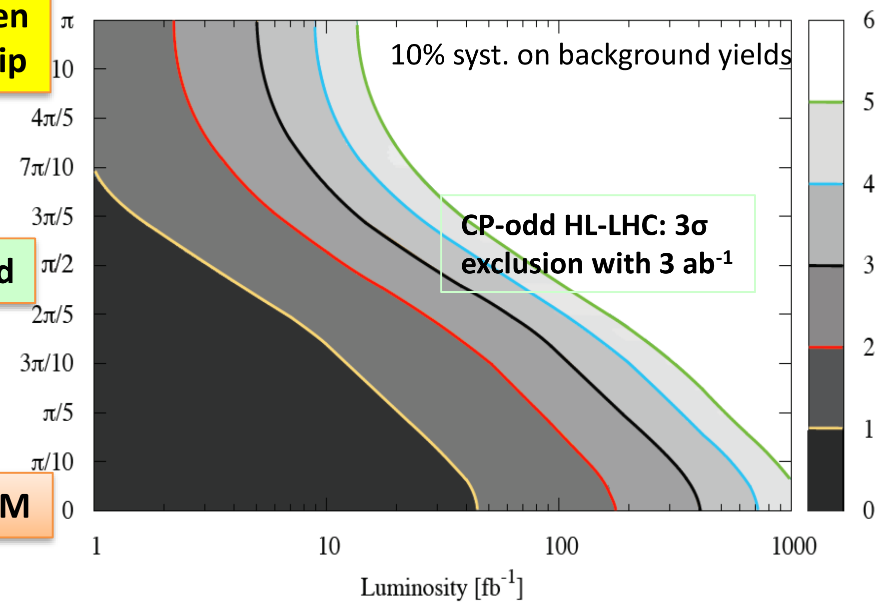
Introduce phase dependent top Yukawa coupling

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



Enhancement of the DIS cross-section as a function of phase





Observe/Exclude non-zero phase to better than 4σ ➔ With Zero Phase: Measure **ttH** coupling with **17% accuracy at LHeC** ➔ **extrapolation to FCCeh: ttH to 1.85%**