LHeC White Paper preparations: The LHeC at the frontline of particle and nuclear physics

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSITY

Monica D'Onofrio

Uta Klein

Christian Schwanenberger

UNIVERSITY OF LIVERPOOL

DESY.

ESPP white paper preparation meeting for LHeC

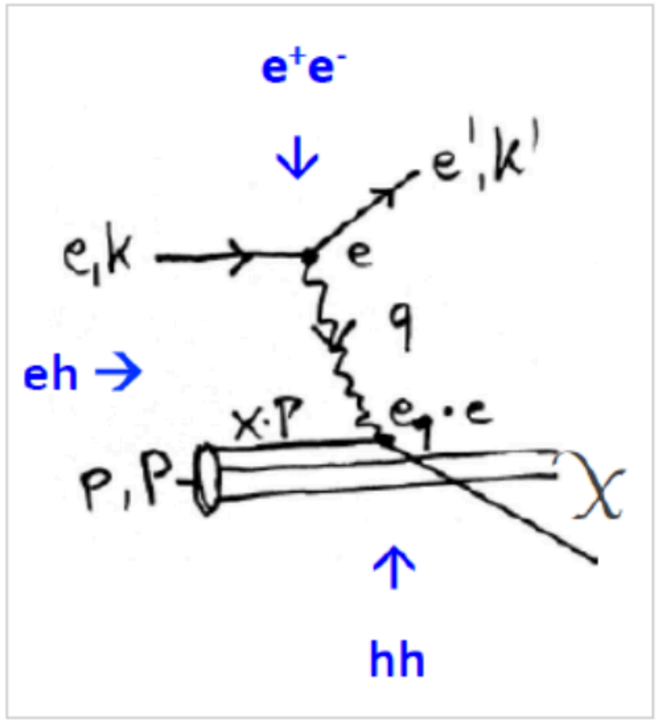
CERN

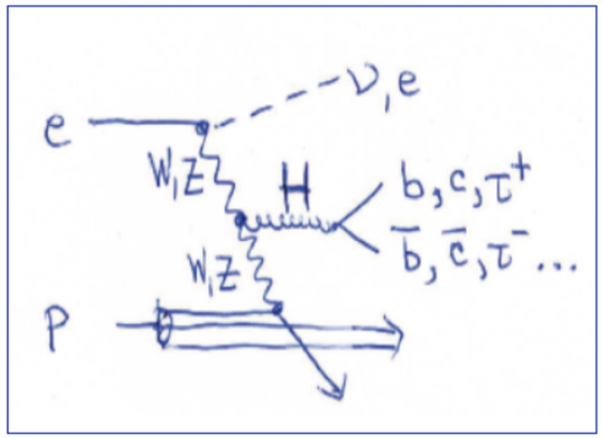
15 November 2024

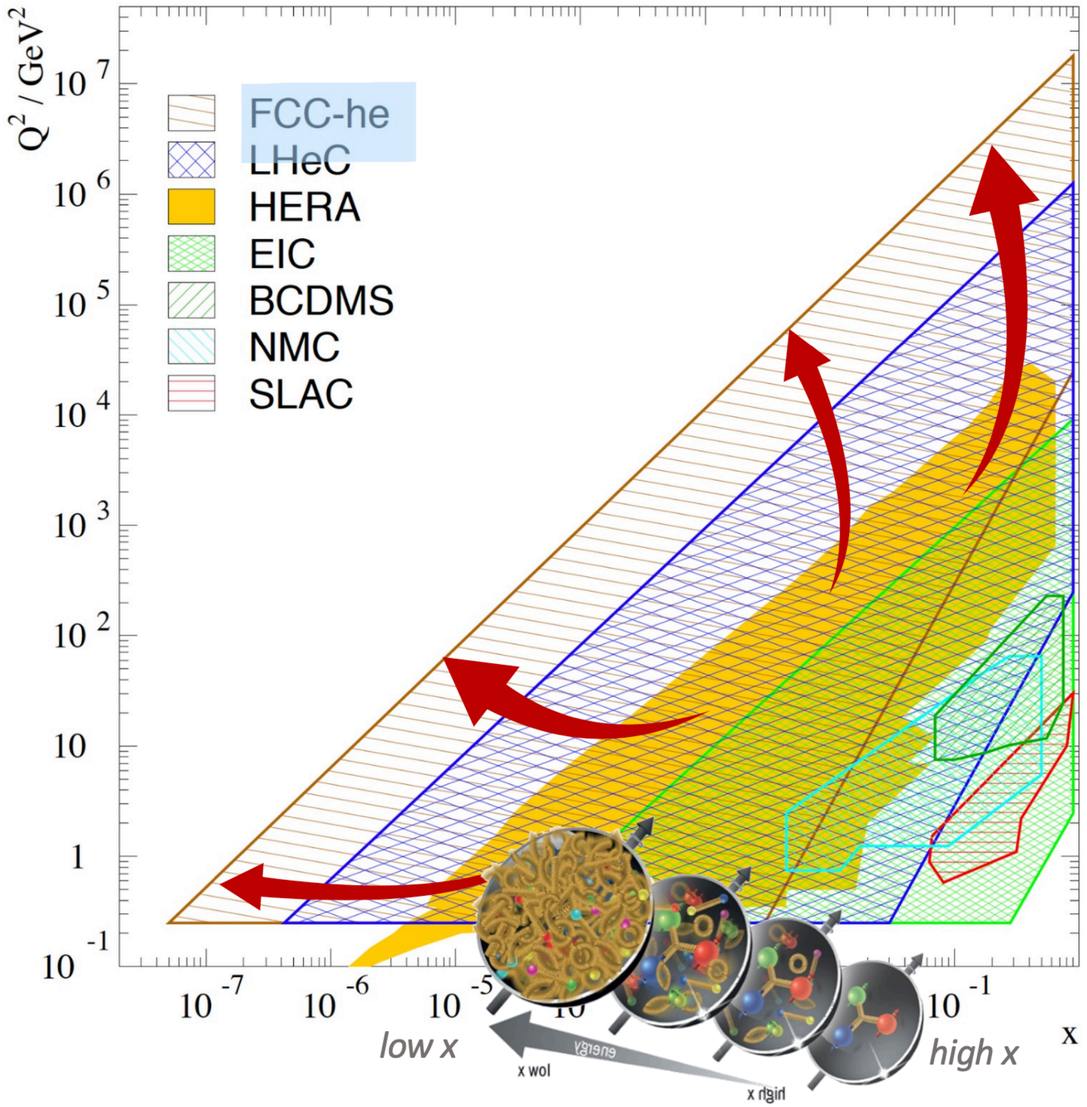
artwork by Jorgen D'Hondt

Special thanks to Max!

Deep Inelastic Scattering at the Energy Frontier





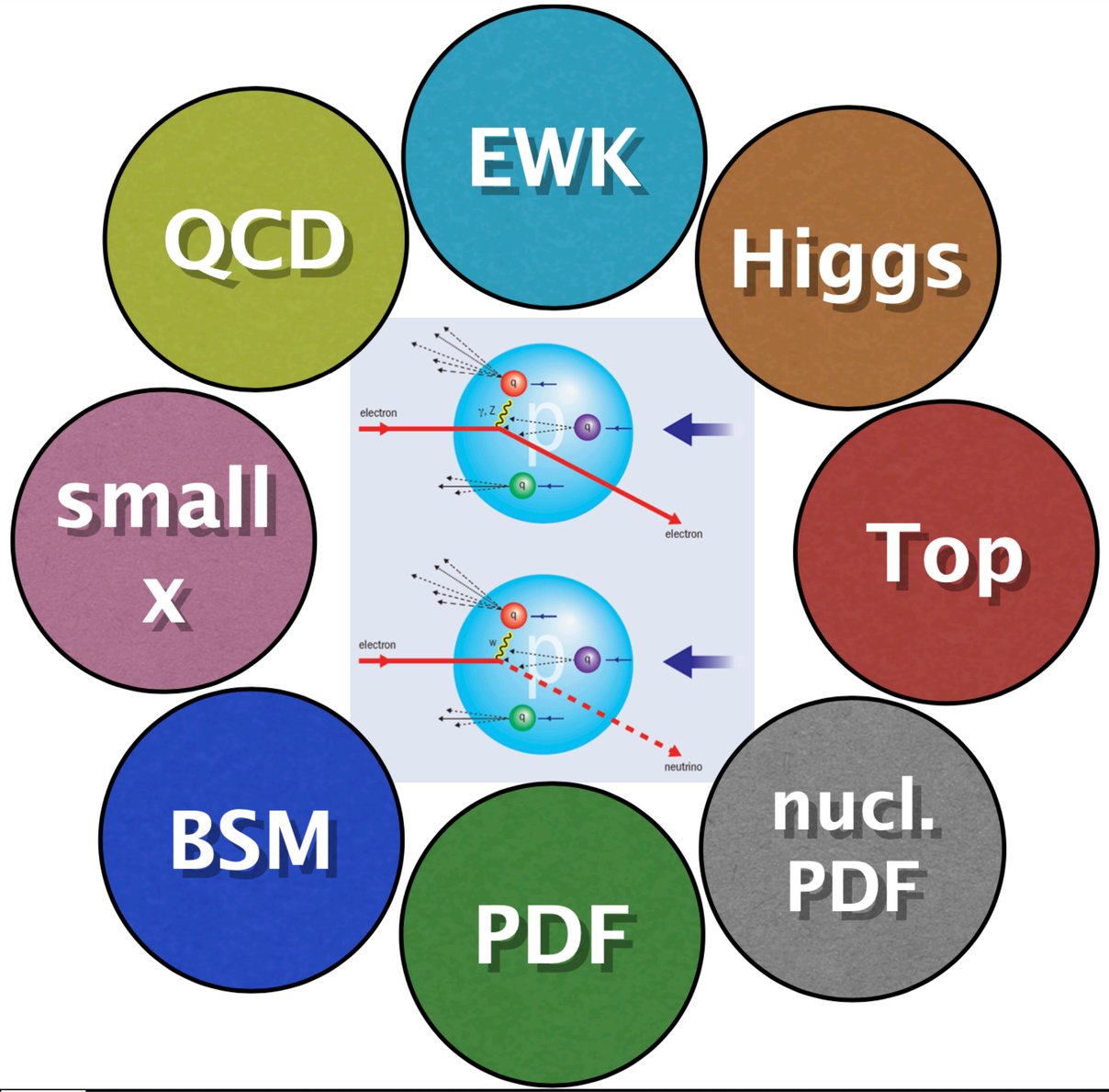


deliveries of ep/eA at the energy frontier

- cleanest high resolution microscope: QCD discovery
- empowering the LHC/FCC search program
- precision Higgs facility together with LHC/FCC-hh
- precision and discovery facility (top, EWK, BSM)
- unique nuclear physics facility

→ Combines properties of General Purpose energy frontier explorer and comprehensive scattering experiment, probing nucleon at unprecedented precision and parton densities

LHeC: A Broad Particle Physics Program at High Energy



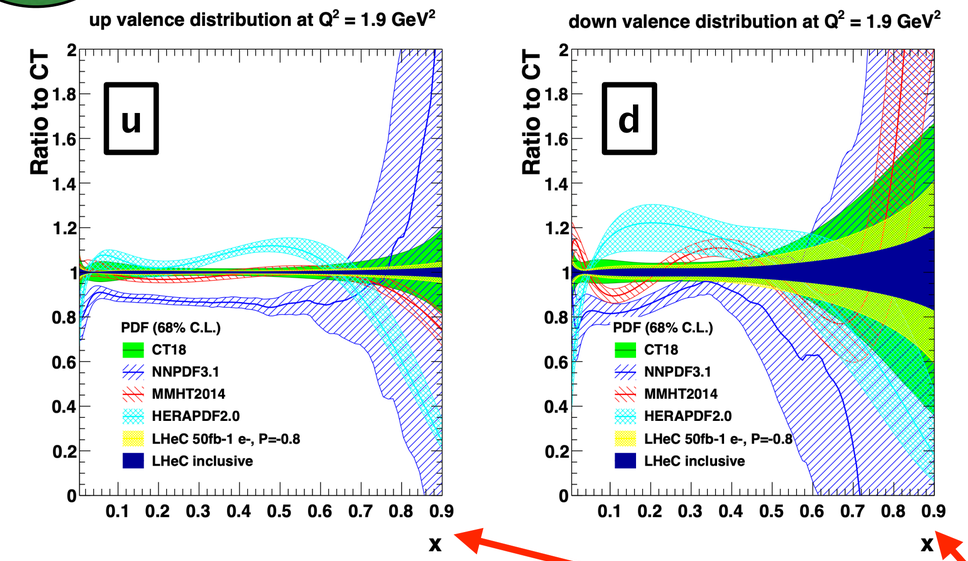
Wide-ranging and deep physics programme spans:

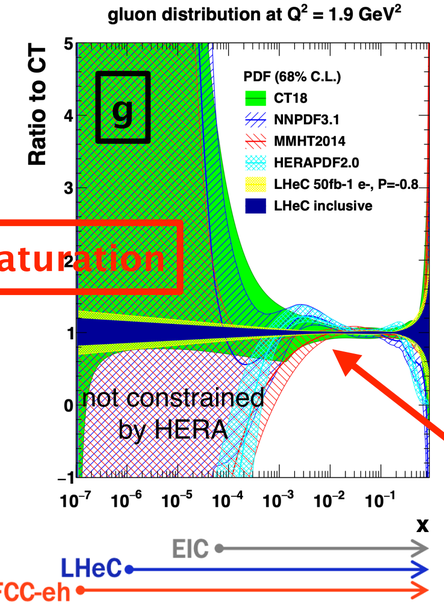
- **PDFs**, strong coupling constant, **low-x measurements**
- W mass, $\sin^2\theta$, top mass, V_{tb}, and other high precision measurements in EWK and top sectors
- **Higgs measurements** with additional sensitivity à precision Higgs facility together with LHC
- Searches for new physics, including prompt and long-lived new scalars from Higgs, SUSY particles, **heavy neutrinos**, dark photons and axions
- High-energy and high-density measurements of heavy ion collisions

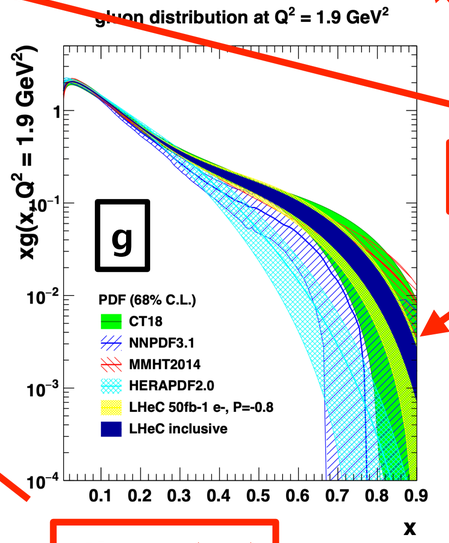
Parton Density Functions

PDF

QGP







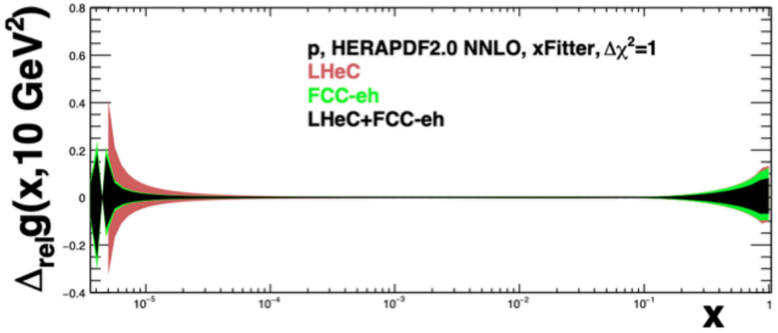
BSM (pp)

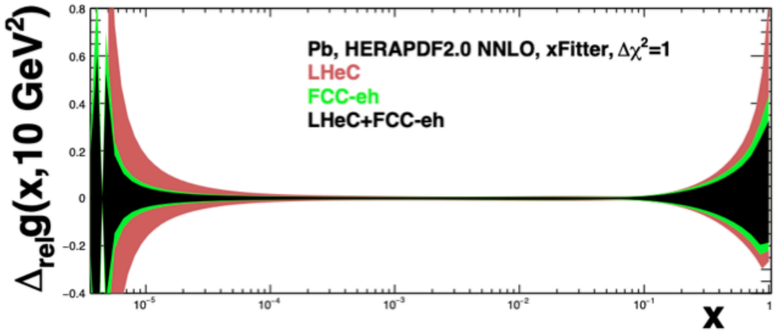
Higgs (pp)

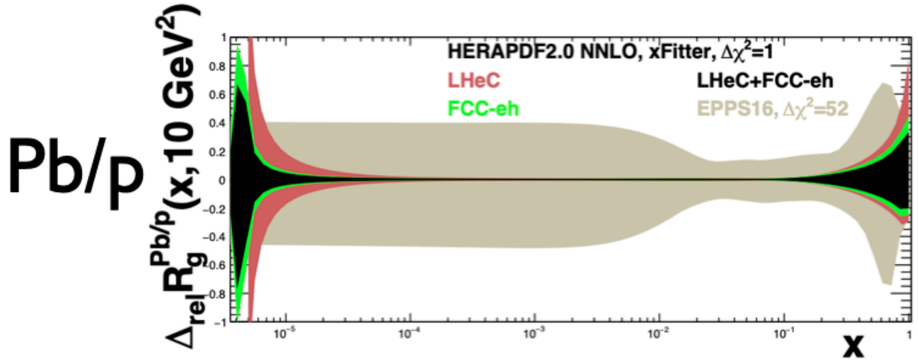
EIC

LHeC

FCC-eh





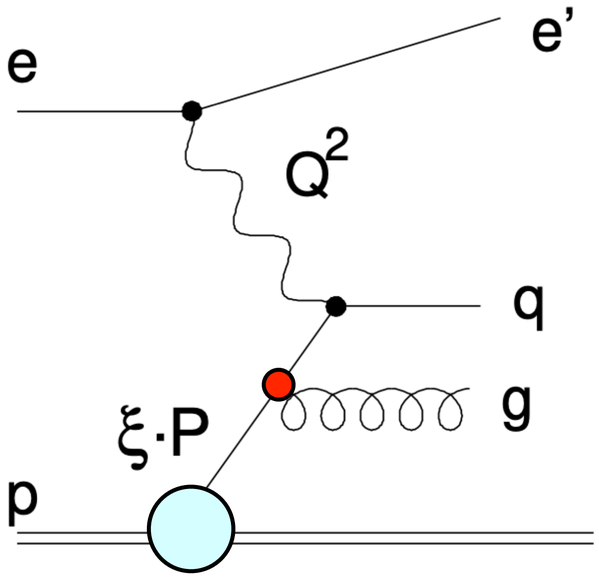


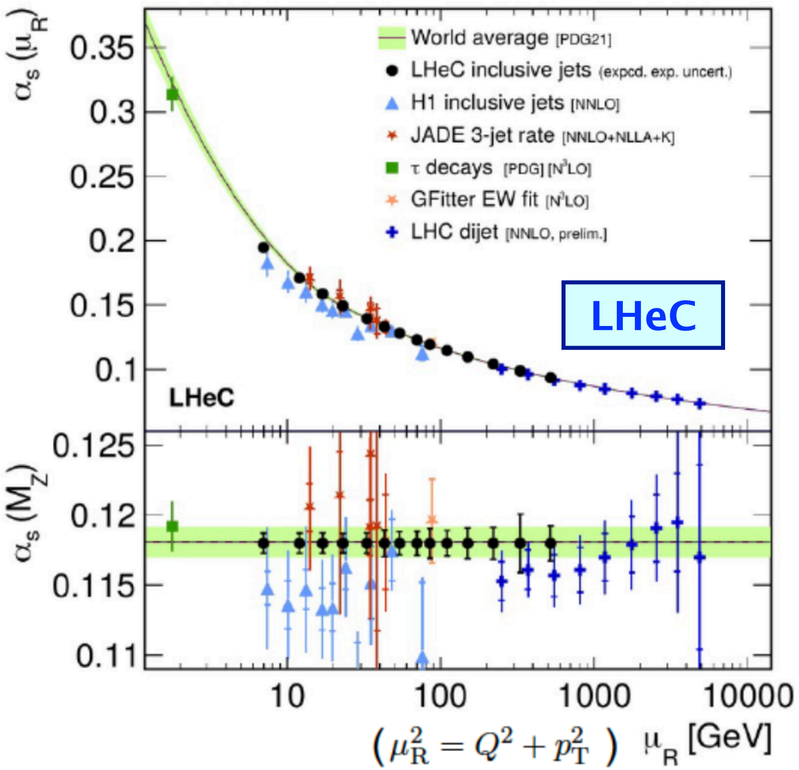
- High-energy and high-density measurements of heavy ion collisions

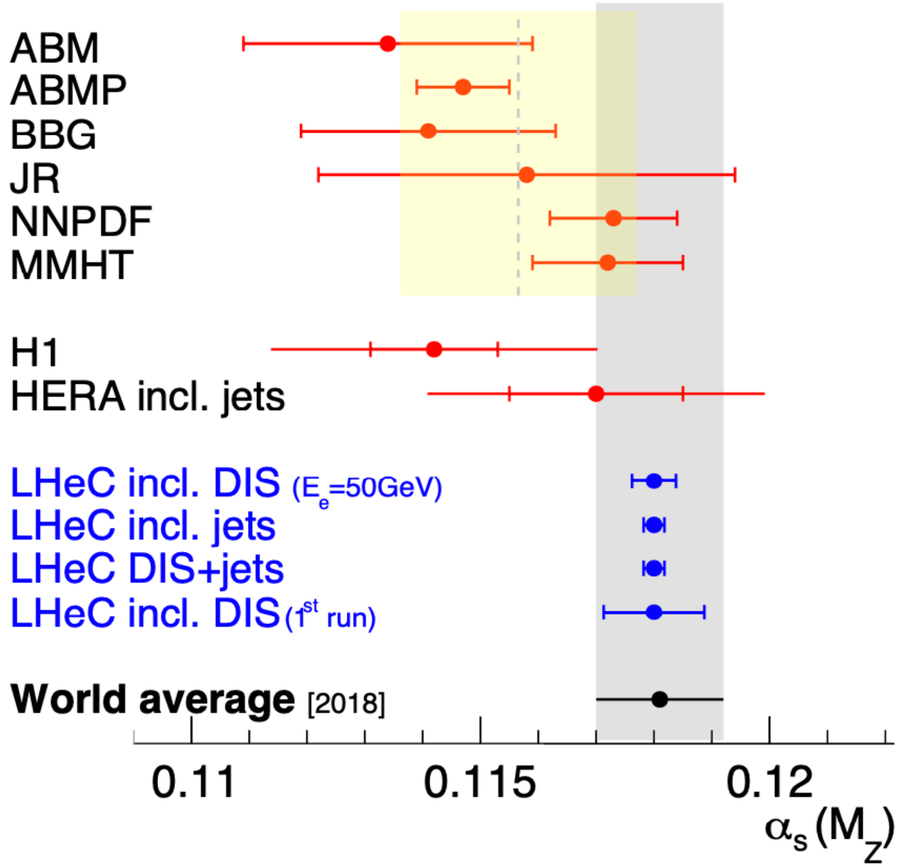
Determination of the strong coupling

QCD

- α_s is least known coupling constant







- α_S from fits to ep jet production

LHeC simultaneous PDF+α_s fit:

- $\Delta\alpha_s(m_Z) = \pm 0.00022_{(\text{exp.+PDF})}$
- $\Delta\alpha_s(m_Z) = \pm 0.00018$ (with ep jets)

LHeC CDRs and arXiv:2203.08271

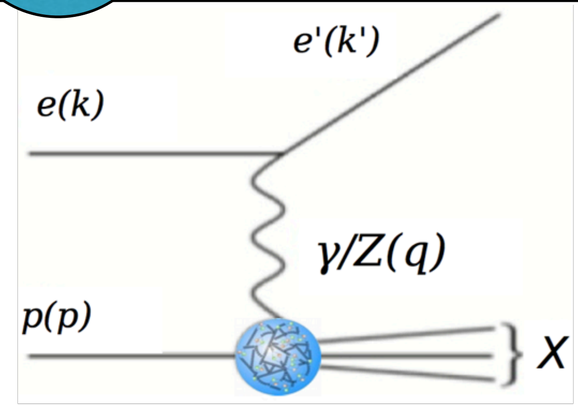
Achievable precision: $\mathcal{O}(0.1\%)$ - **x5-10** better than today

→ **unprecedented precision**

EWK Fermion Couplings and SMEFT couplings

EWK

BSM



$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}\,,$$

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f \kappa_{\mathrm{NC},f}\kappa'_{\mathrm{NC},f}\sin^2\theta_W\right)$$

Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

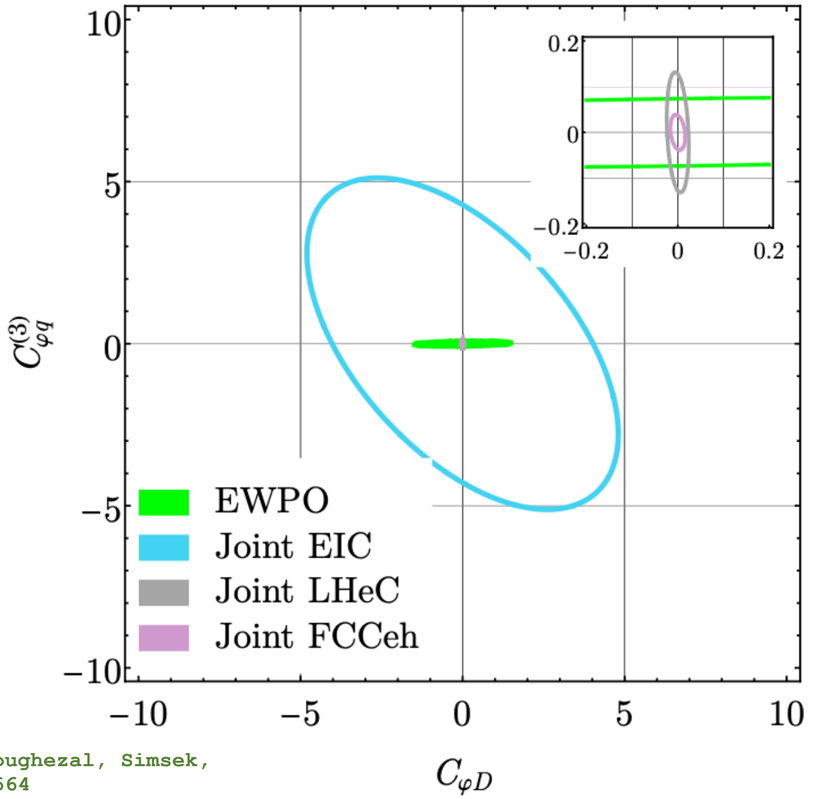
→ **precision on per mille level**

(largely unaccessible in e⁺e⁻)

$$O^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \tau^I \varphi)(\bar{q}\gamma^\mu \tau^I q)$$

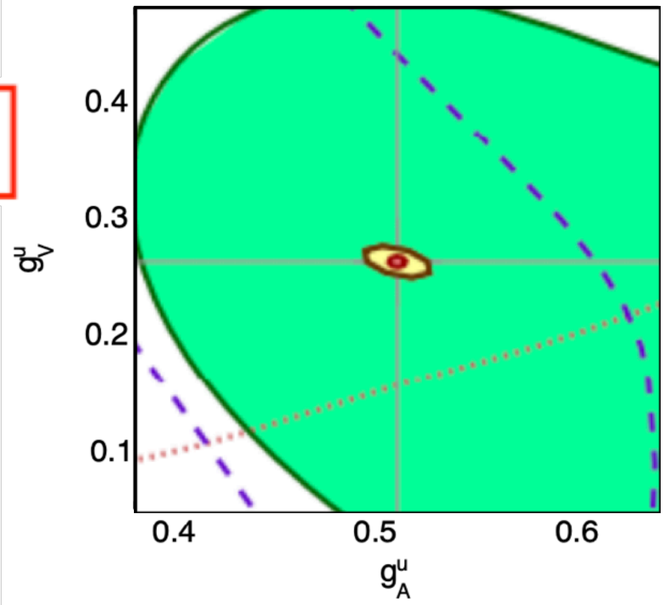
$$O_{\varphi D} = (\varphi^\dagger D_\mu \varphi)^*(\varphi^\dagger D^\mu \varphi)$$

95% CL, Λ = 1 TeV , 17 *d* fit

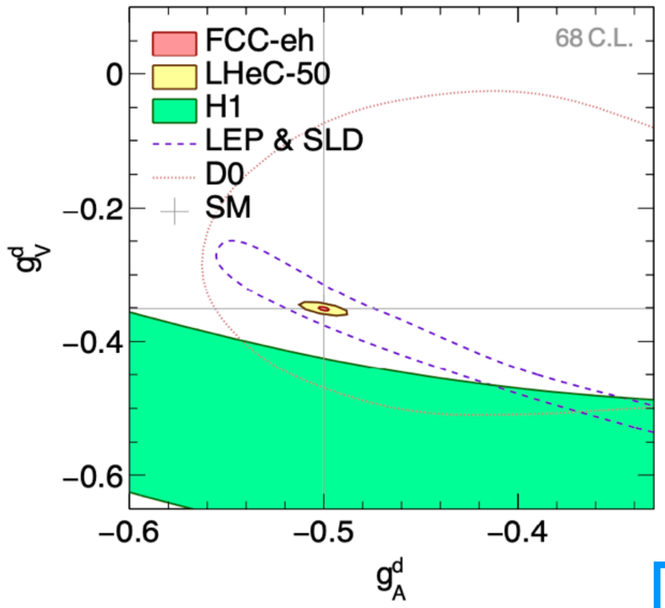


Bissolotti, Boughezal, Simsek, arXiv:2306.05564

u



d



Electroweak physics of 1st generation quarks are largely inaccessible in other colliders

FCC-eh and LHeC will improve upon existing precision electroweak bounds in SMEFT parameter space in many cases, also for correlations

Scale Dependence of $\sin^2\theta_W$

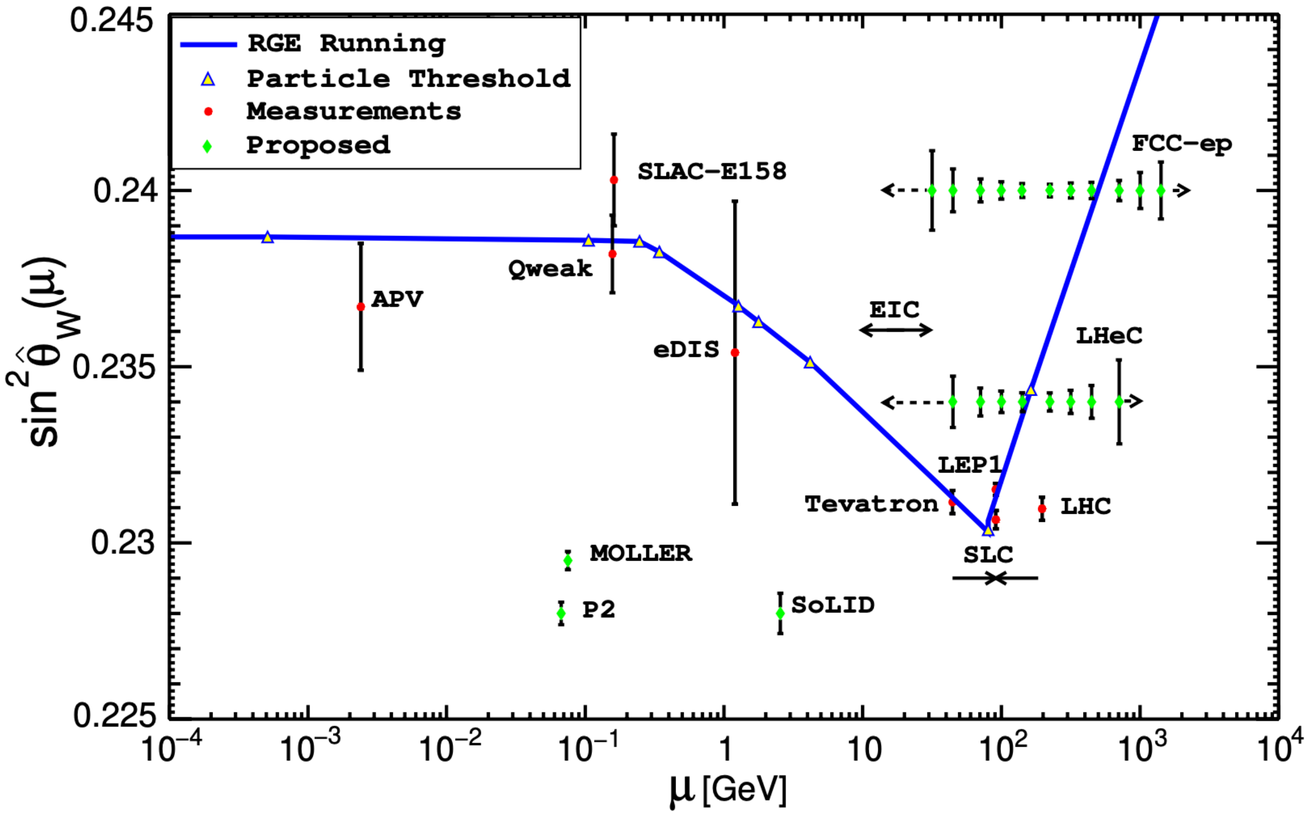
EWK

BSM

PERLE CDR,
CERN-ACC-NOTE-2018-0086

arXiv:2203.06237

LHeC CDR,
J.Phys. G39,
075001 (2012)



→ probe large range of scale dependence

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\sin^2\theta_W\right)$$
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}$$

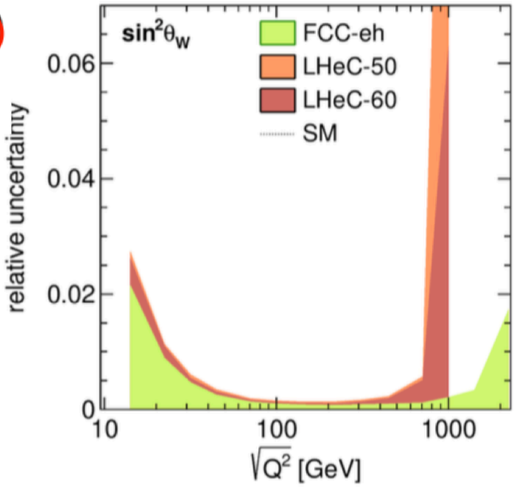
→ precision per mille level

→ scale dependence

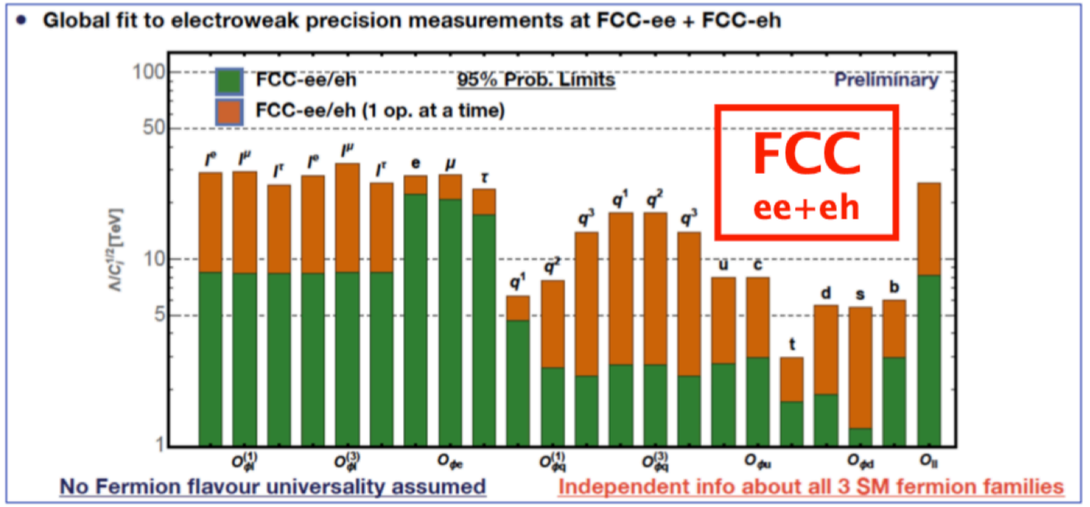
$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= $\pm 0.00010_{(exp)}$ $\pm 0.00004_{(PDF)}$

$\Delta m_W = \pm 4.5$ MeV

(includes PDF uncertainty of about ±3.6 MeV)



→ high sensitivity to NP

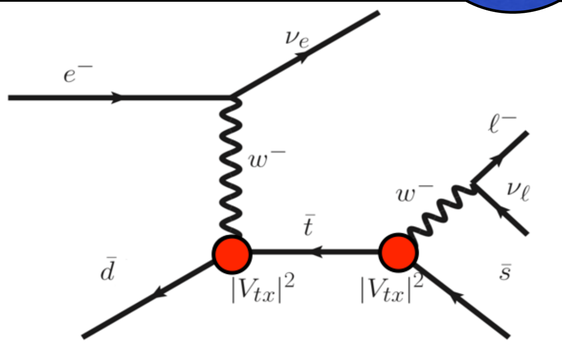


Top — Expected measurements of Wtb couplings — BSM

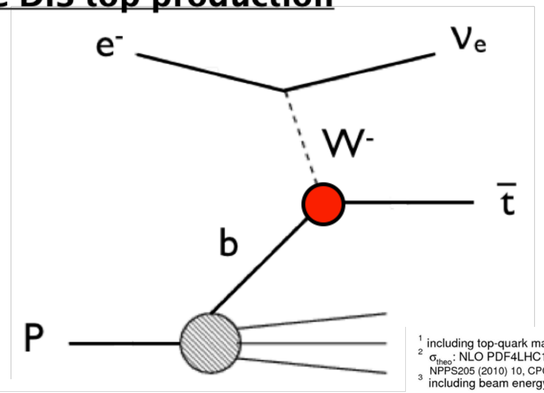
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

= 1 in SM

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.



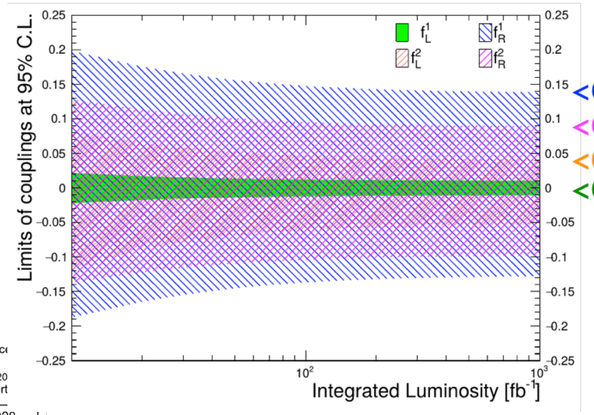
CC DIS top production



[1] including top-quark mass unc
[2] σ_{theo}: NLO PDF4LHC11
[3] NPPS205 (2010) 10, CPC191 (20
including beam energy uncert

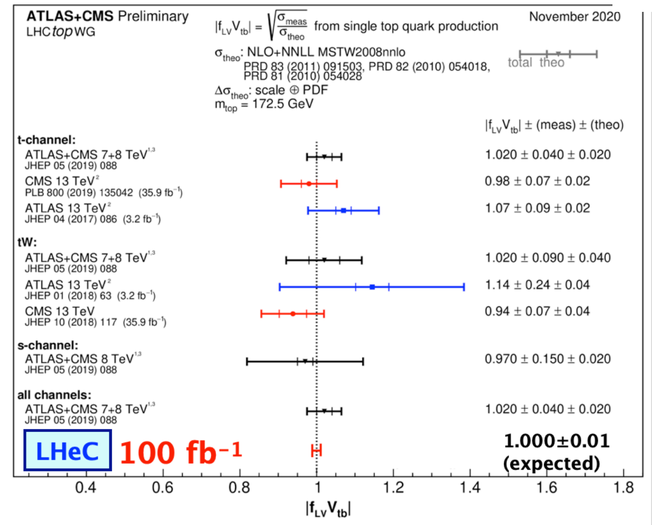
hadronic channel:

LHeC



<0.14
<0.09
<0.04
<0.01

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019) H. Sun PoS DIS 2018, 167 (2018)

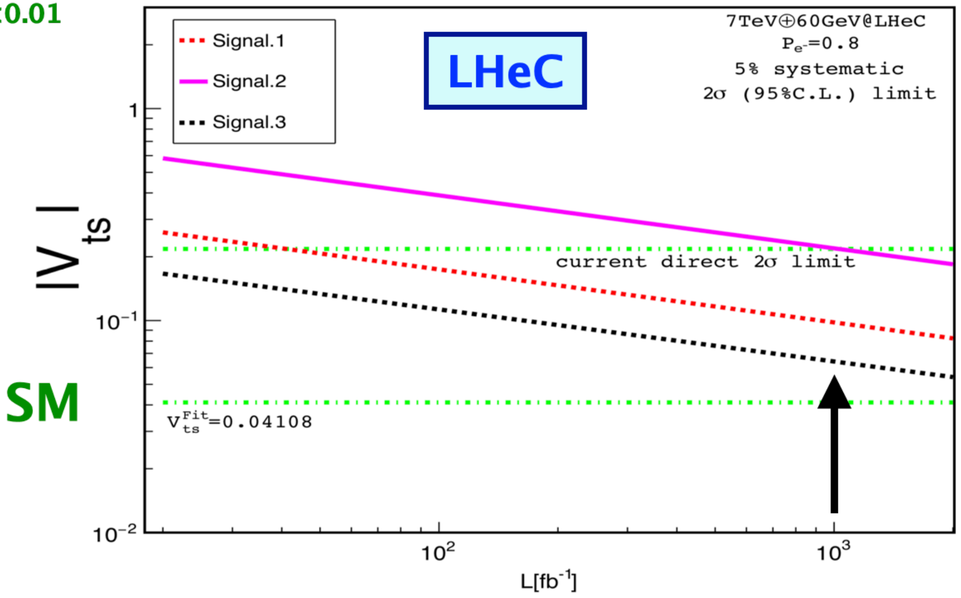


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

SM

Unprecedented precision < 1%

2σ



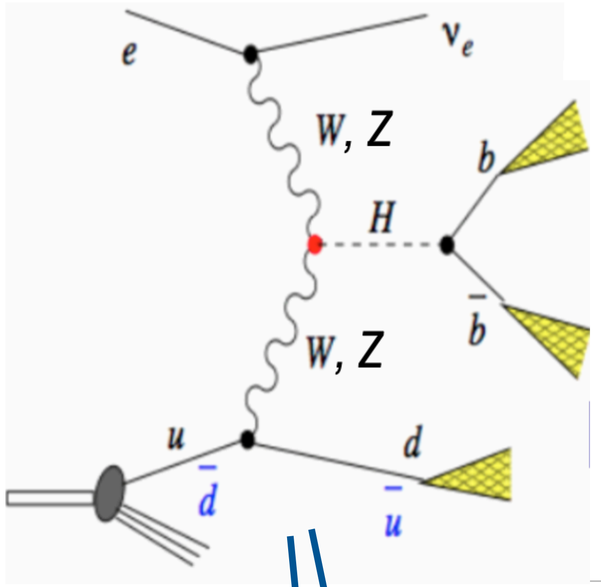
LHC

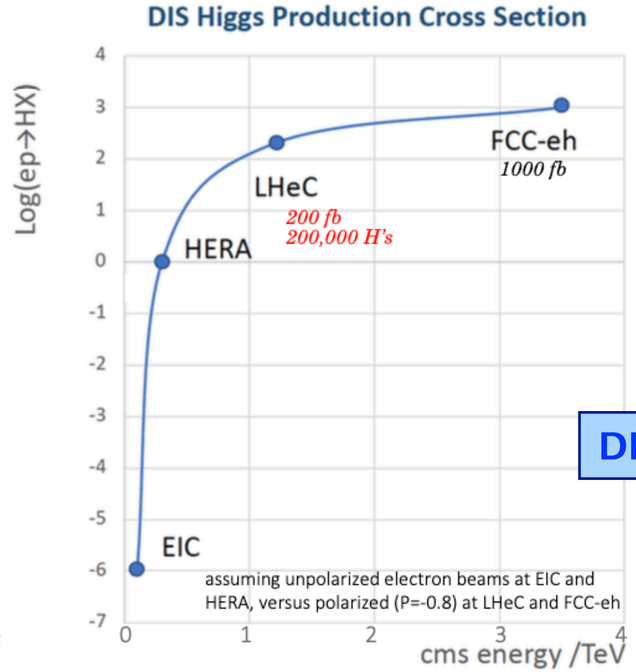
→ $|V_{ts}|<0.06$

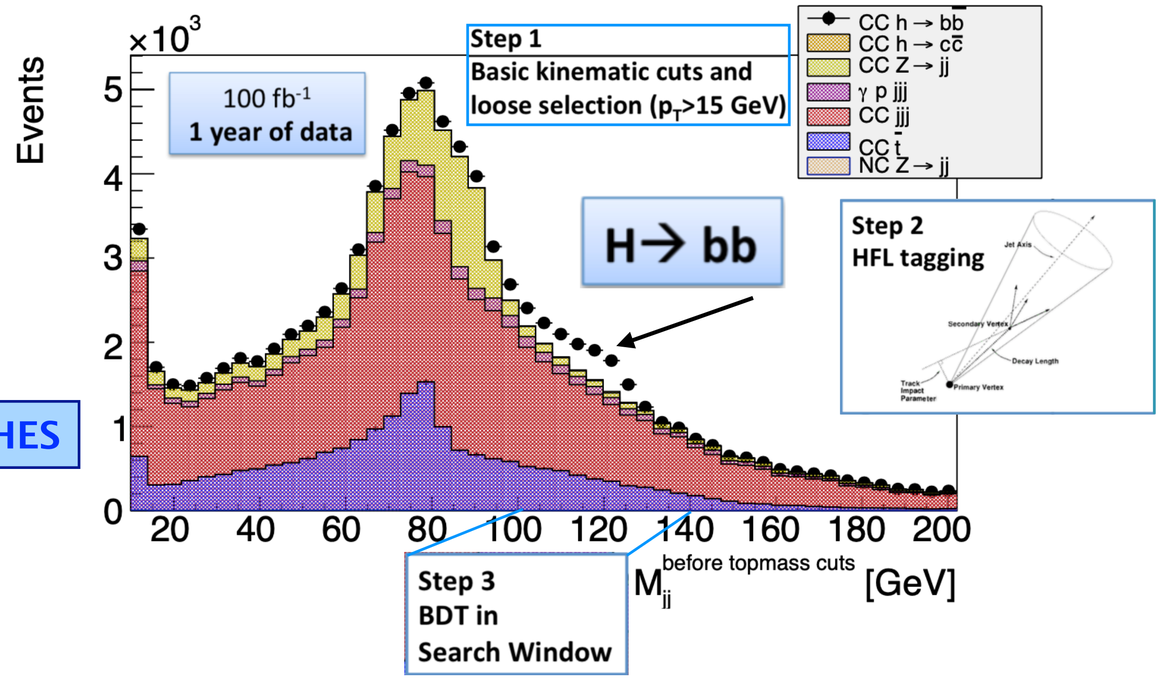
Probing SM prediction directly for the first time

Higgs coupling combinations in κ-framework

CC(e^-p)

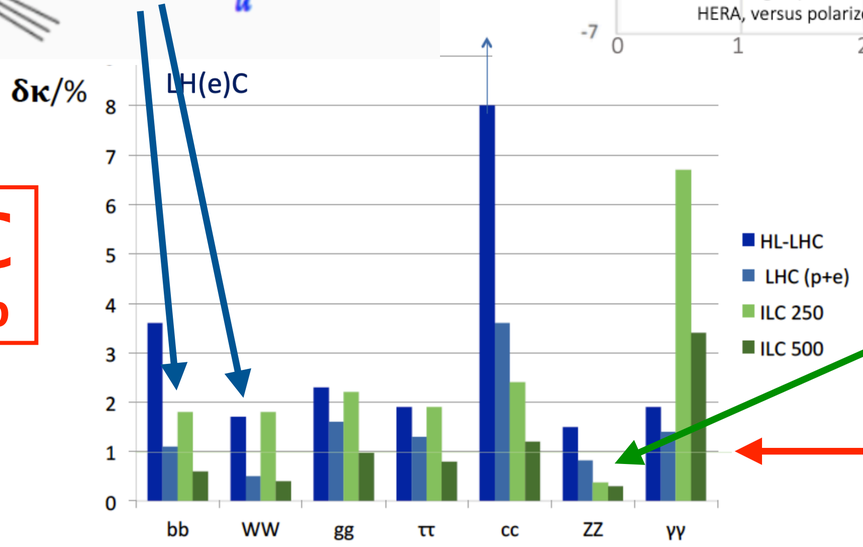




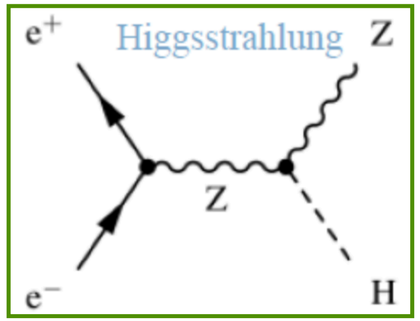


DELPHES

LHC
ep+pp



1%



we profit from diversity through complementarity

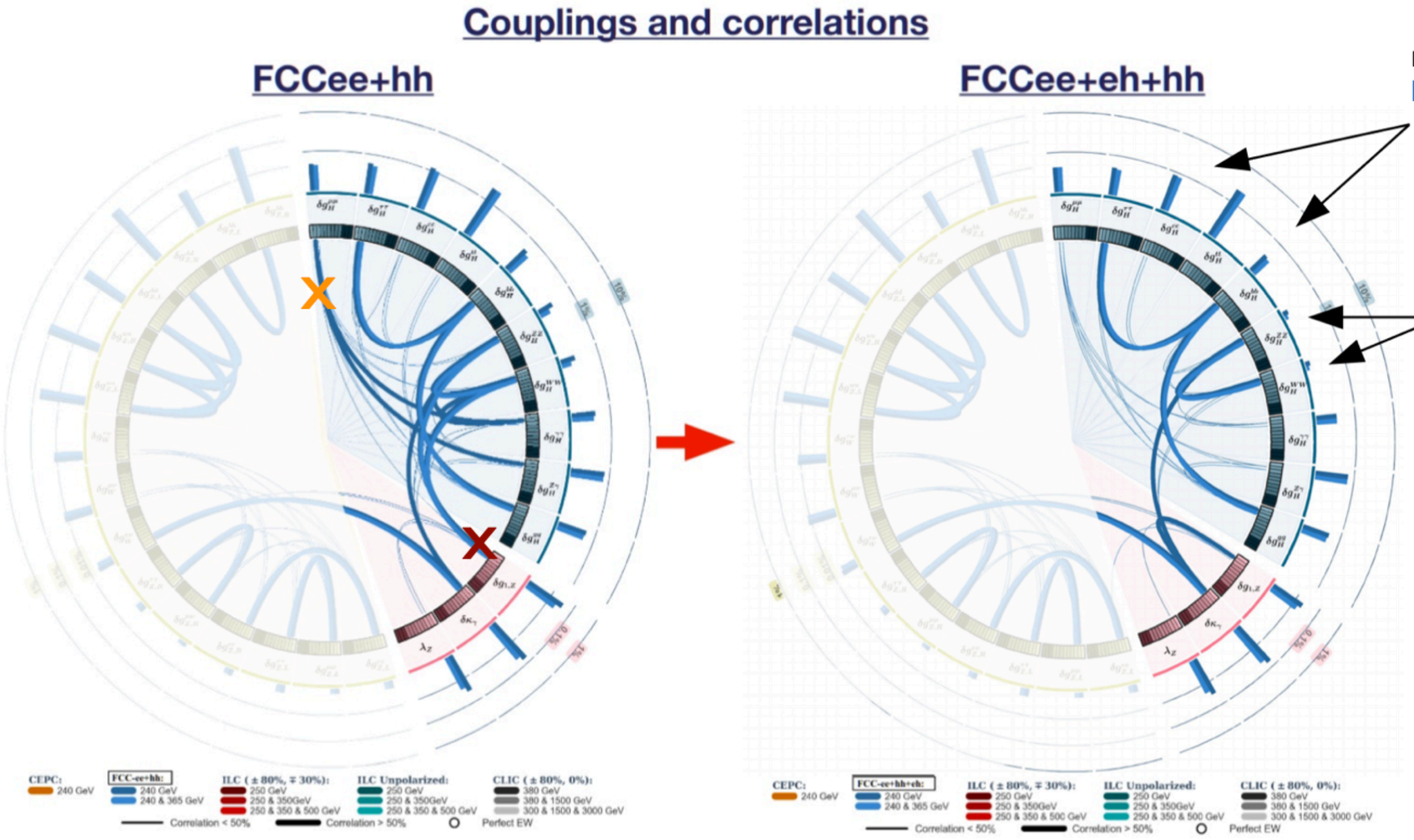
→ adding electrons makes the LHC a Higgs precision facility

SMEFT fit results after FCC era

Higgs

BSM

Couplings and correlations



reduction for Hcc and Hbb

eh contributes to the HWW and HZZ couplings and resolves their correlation X

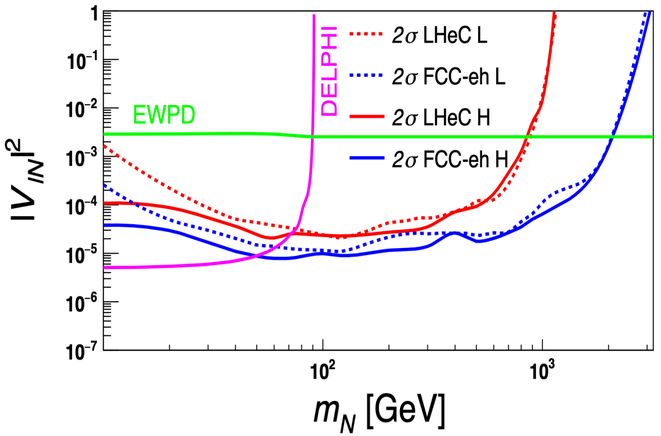
reduces further correlations X

Higgs SMEFT coupling combinations profit from diversity: ee, ep, and pp

Complementary searches for BSM: heavy neutrinos

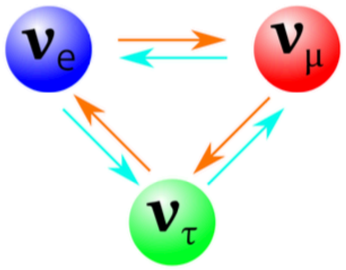
BSM

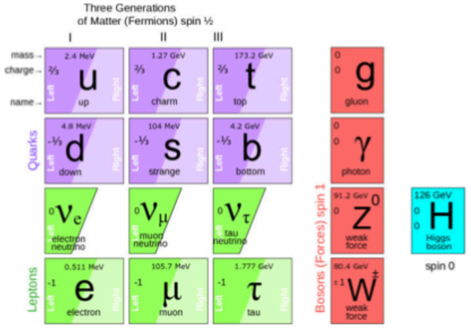
Search for heavy Majorana neutrinos in the τ final state



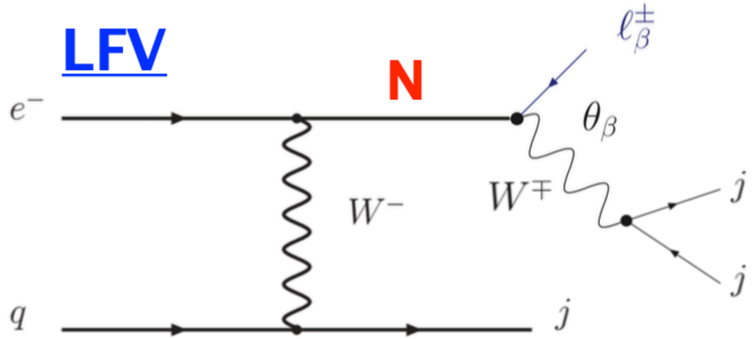
arXiv:2210.17050

Search for heavy sterile neutrinos

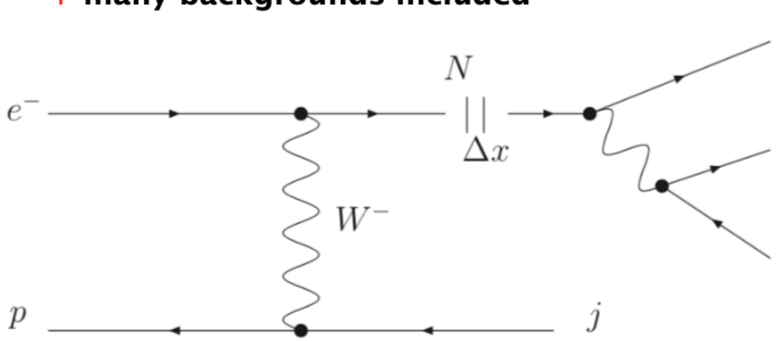




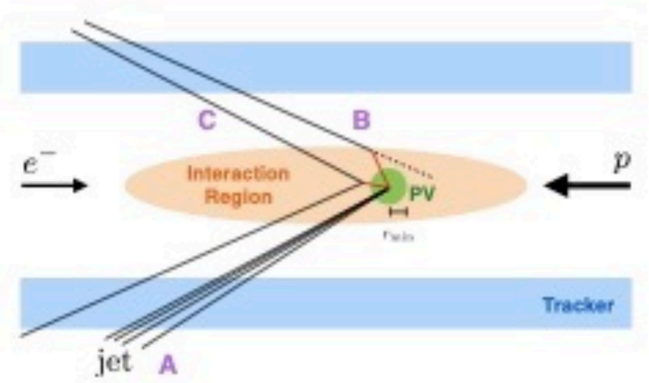
LFV

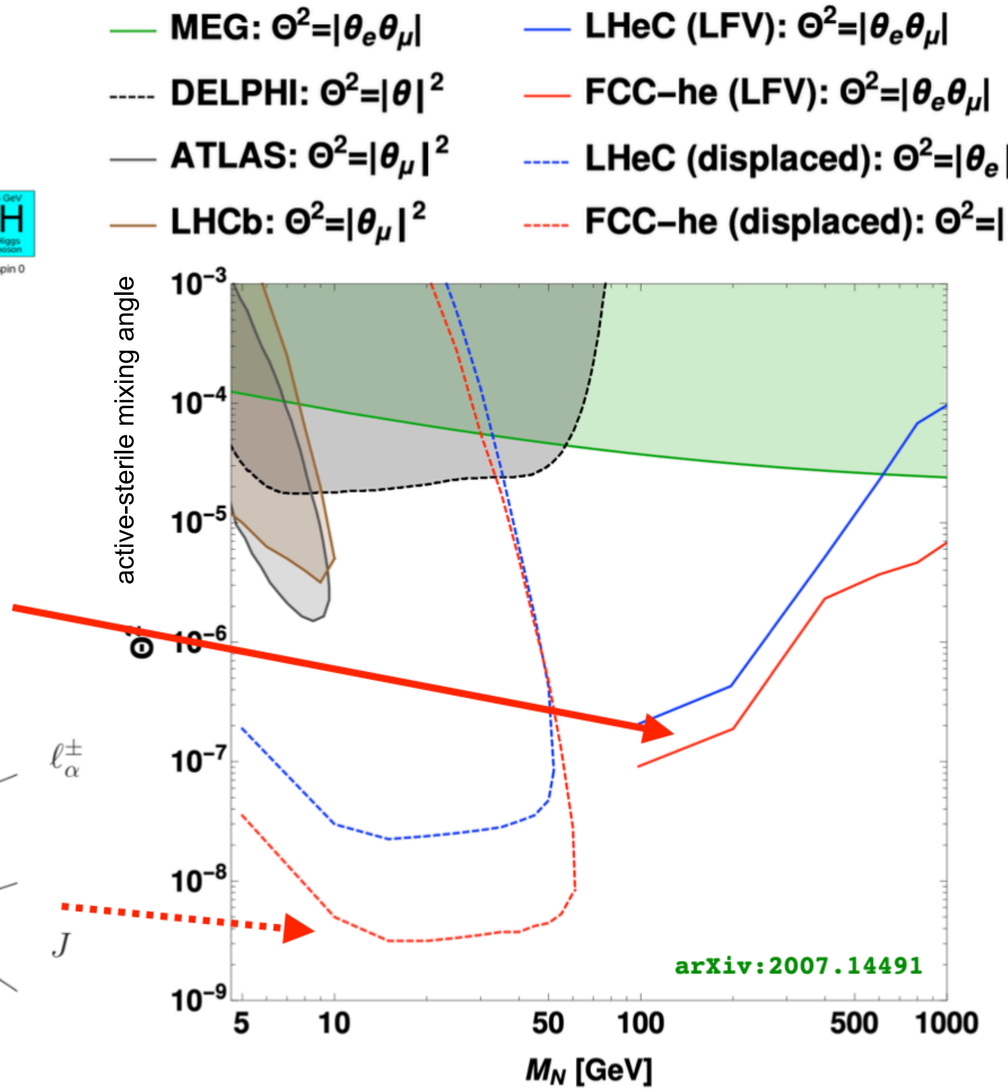


+ many backgrounds included



arXiv:1908.02852



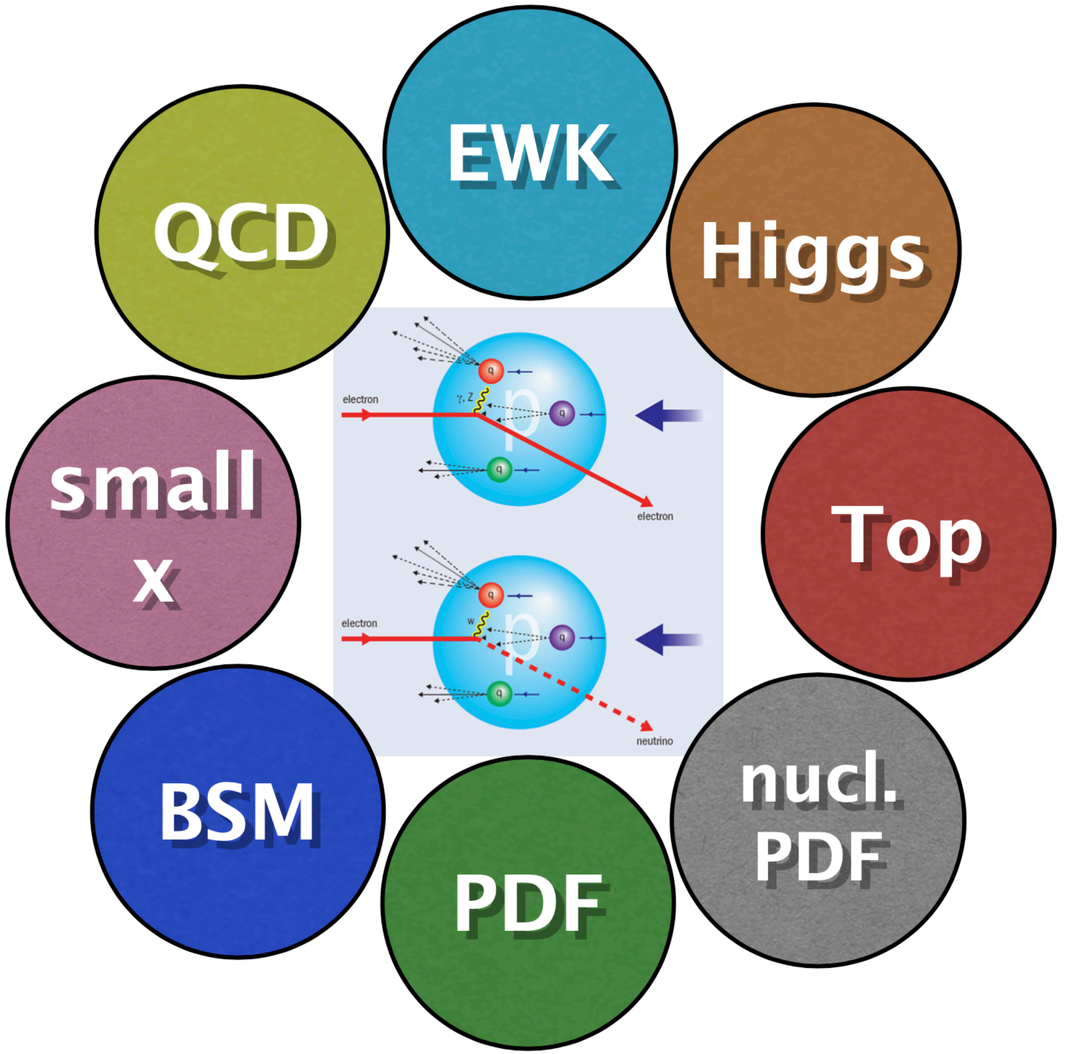


arXiv:2007.14491

Final remarks

Wide-ranging and deep physics programme spans:

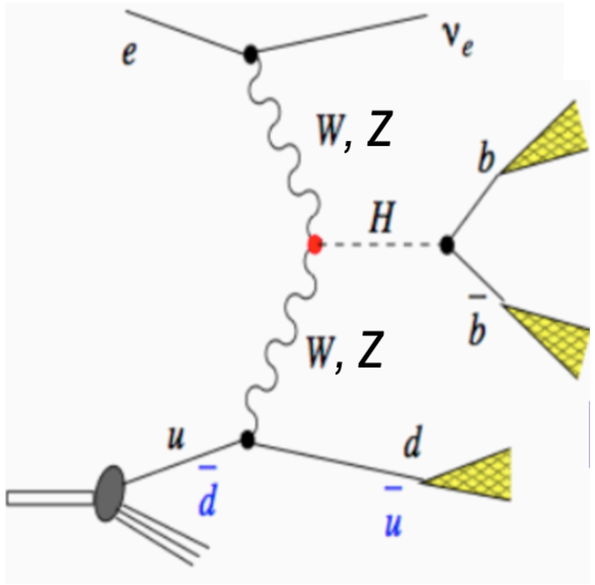
- **List of topics:** we have to decide which goes here and which goes into other chapters, which are missing, which we do not need to cover explicitly
- **LHC empowerment:** using LHeC input for HL-LHC analyses not included here. Will have to go to next chapter by Claire and Maarten
- 20 GeV staged option for ERL: we would have to study the impact on different physics topics. e.g. for BSM the loss is major in almost all scenarios of interest, which is something we should carefully reassess. We should discuss this!

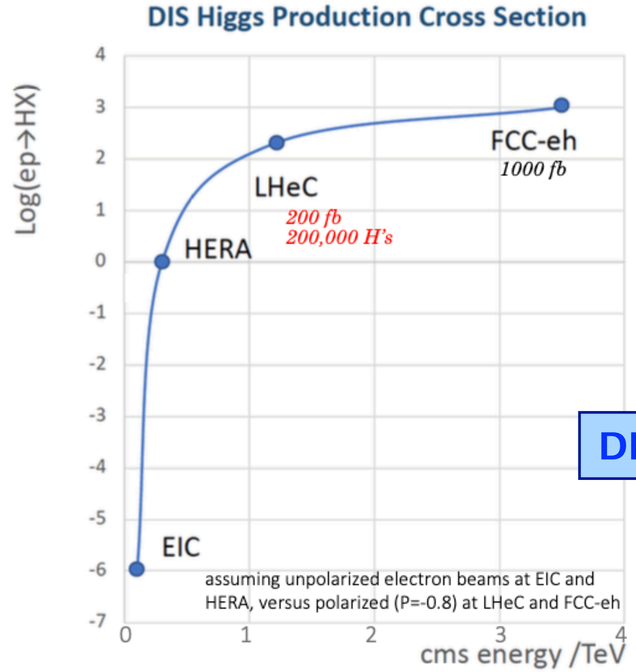


Backup

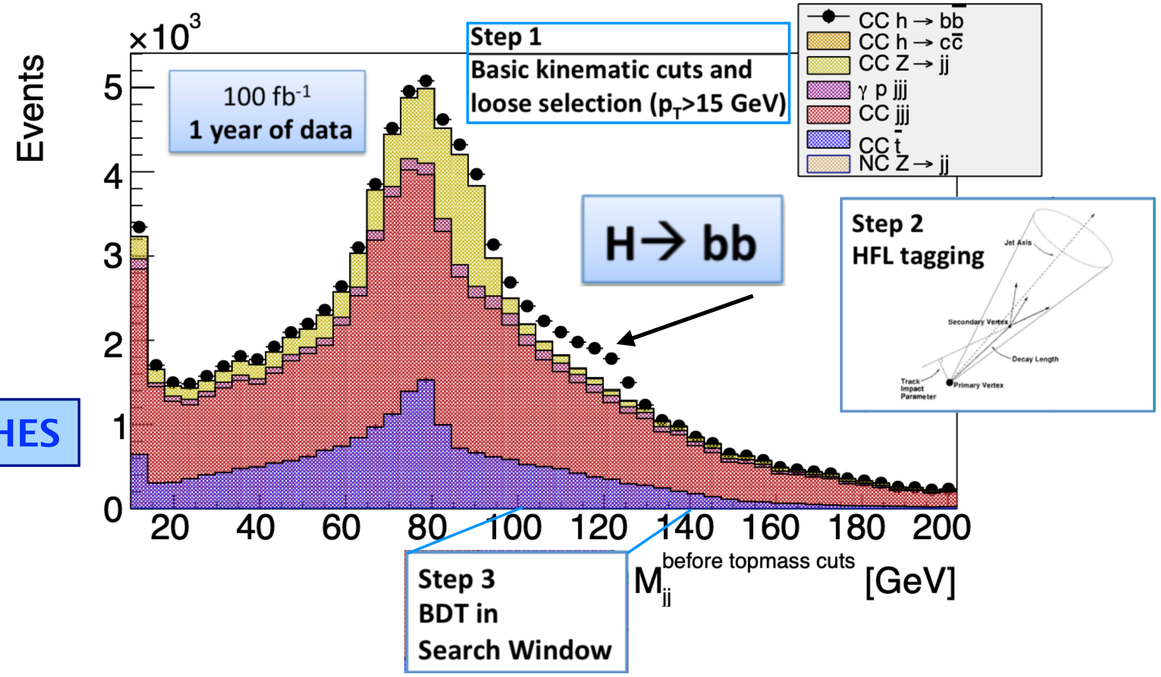
Higgs coupling combinations in κ-framework

CC(e^-p)

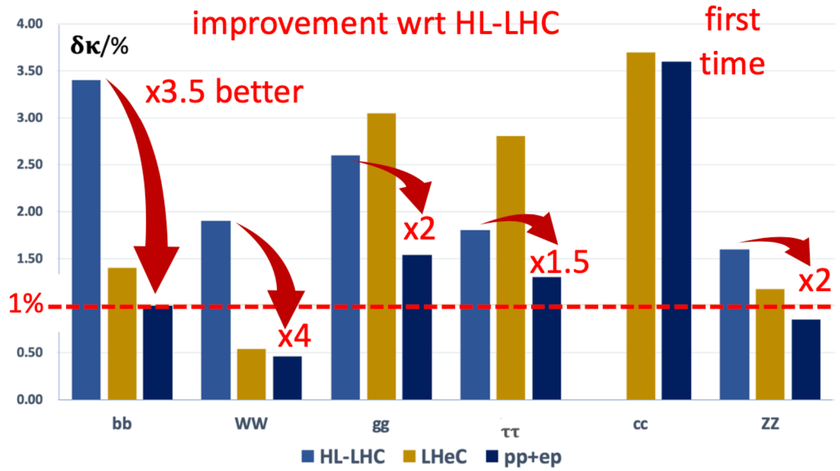




DELPHES



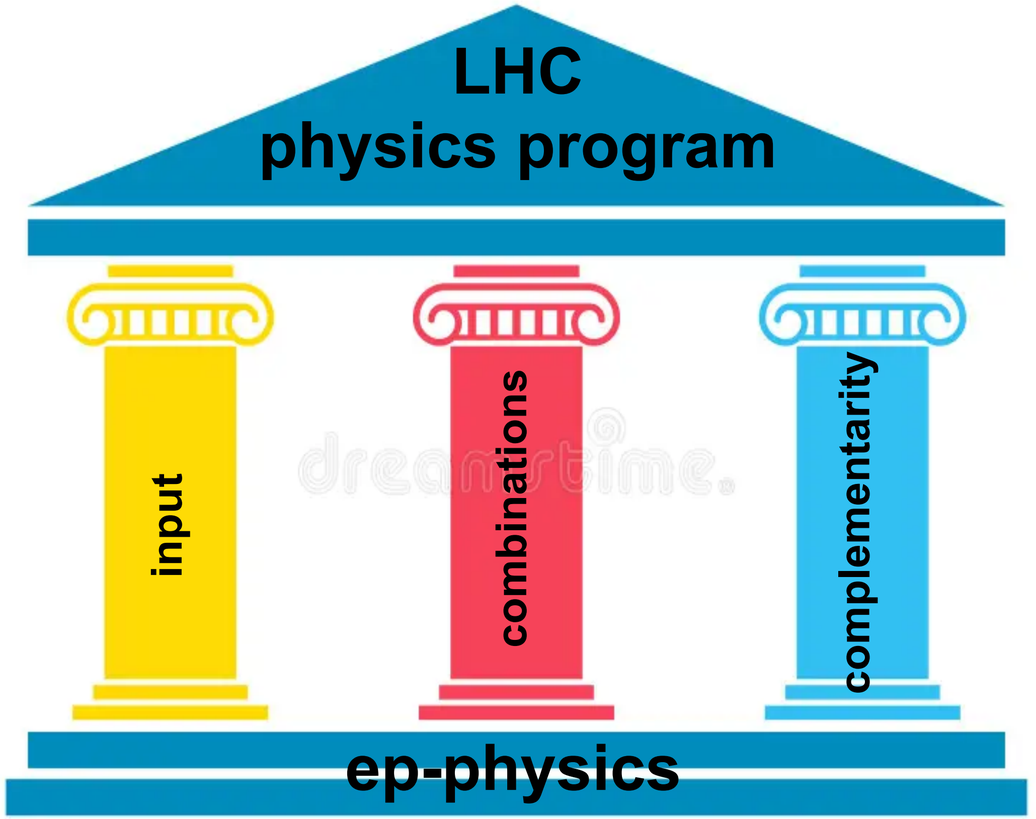
LHC
ep+pp



← **1%**

→ adding electrons makes the LHC a Higgs precision facility

Empowering HL-LHC physics through LHeC



High precision *ep* measurements used as input in LHC analyses for their improvements

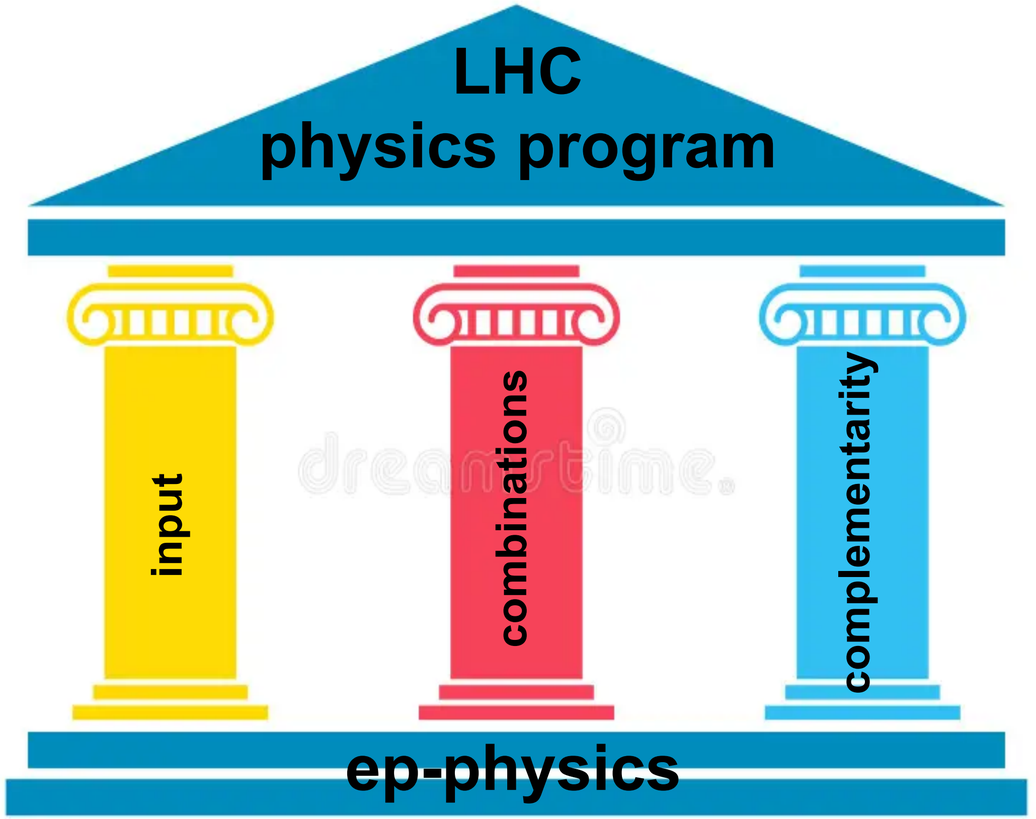
ep analyses with sensitivity complementary to LHC analyses to complete the overall LHC physics program

ep measurements to considerably improve LHC physics output, e.g. in final combinations

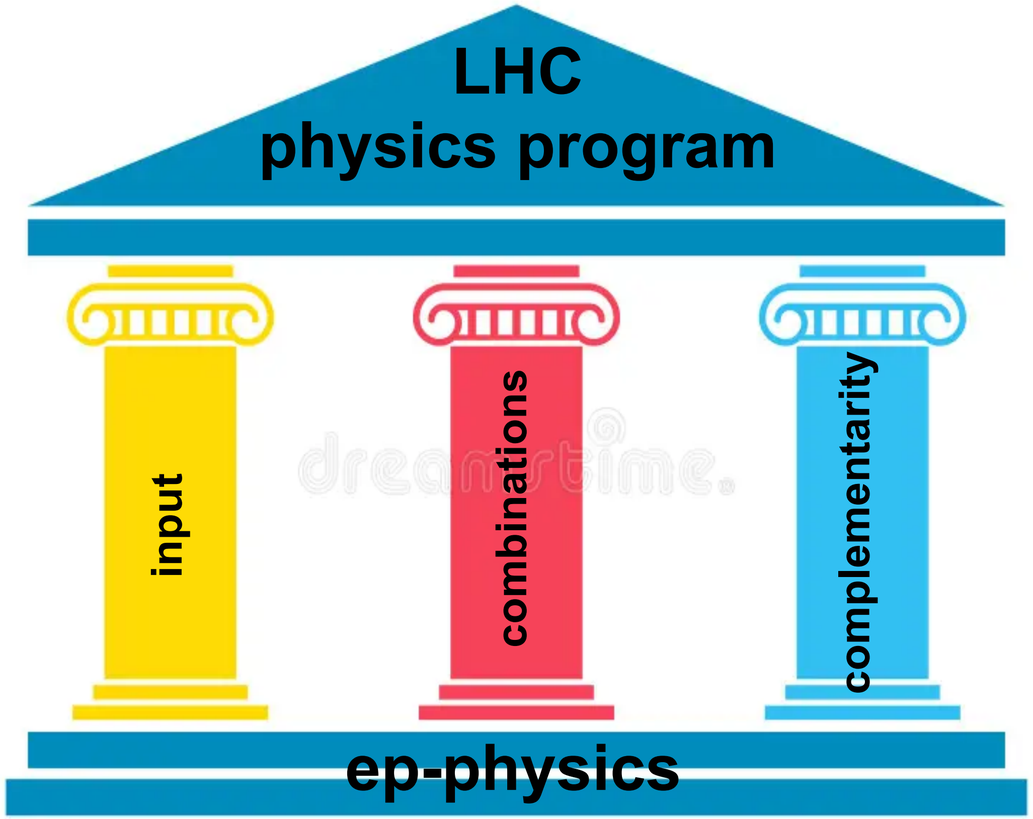
Empowering HL-LHC physics through LHeC

→ Empowerment of LHC program
→ Input to pp physics analyses improving sizable uncertainties and limitations

High precision *ep* measurements used as input in LHC analyses for their improvements



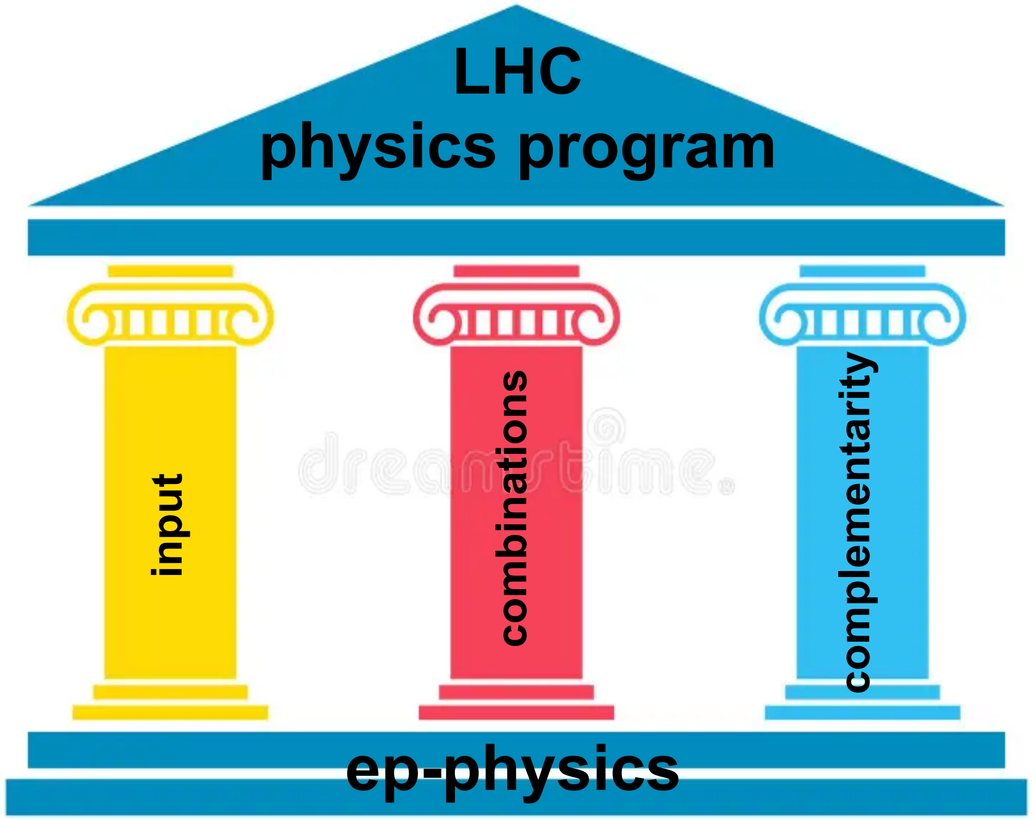
Empowering HL-LHC physics through LHeC



→ Competitive precision of measurements and combination of results
→ uncorrelated uncertainties
→ resolve correlations in parameters of interest
→ resolve common/ correlated uncertainties between ATLAS&CMS
→ empowers global fits

***ep* measurements to considerably improve LHC physics output, e.g. in final combinations**

Empowering HL-LHC physics through LHeC



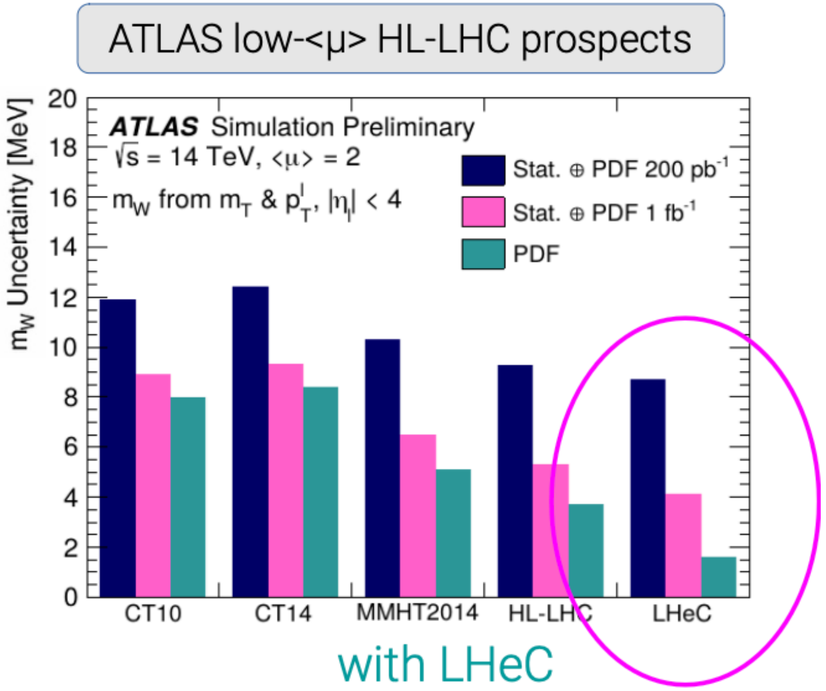
***ep* analyses with sensitivity complementary to LHC analyses to complete the overall LHC physics program**

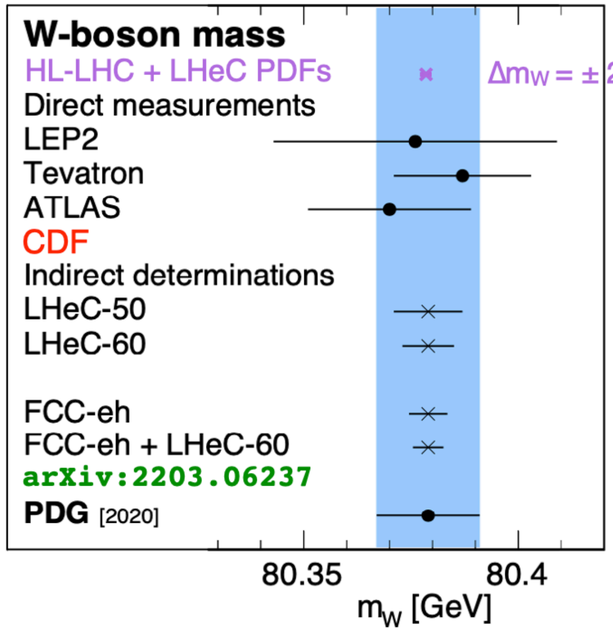
→ high precision QCD analyses
→ high precision measurements of specific parameters
→ searches in complementary phase space regions

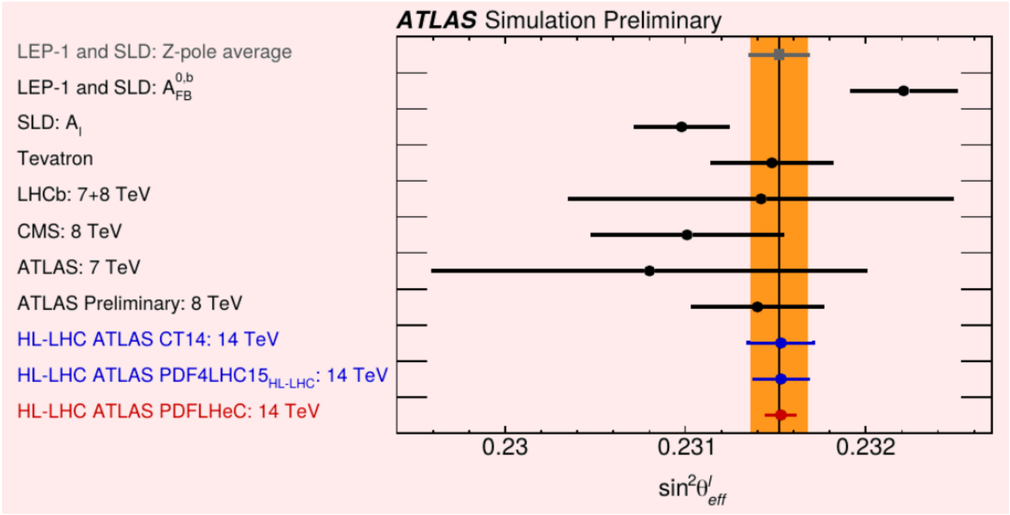
Precision of W mass and effective electroweak mixing angle

W mass uncertainty prospects @ HL-LHC

$\sin^2\Theta_W$ prospects @ HL-LHC

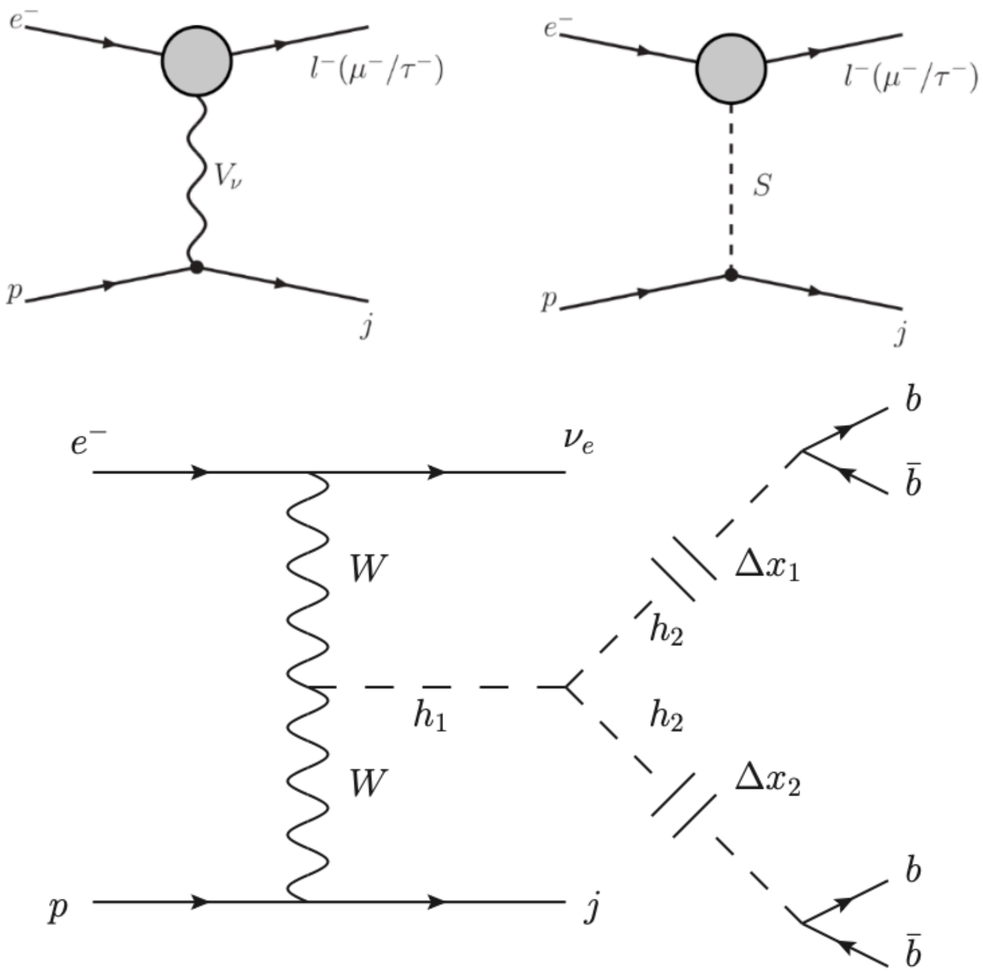






LHeC PDFs will shrink uncertainties in HL-LHC measurements of many (not only electroweak) parameters dramatically

Complementary searches for new phenomena

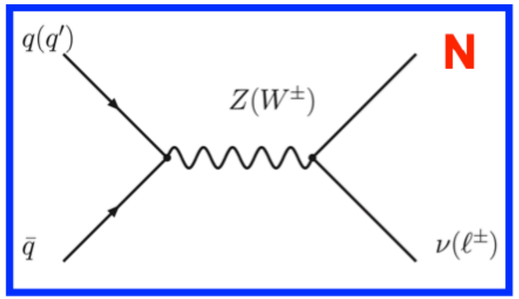


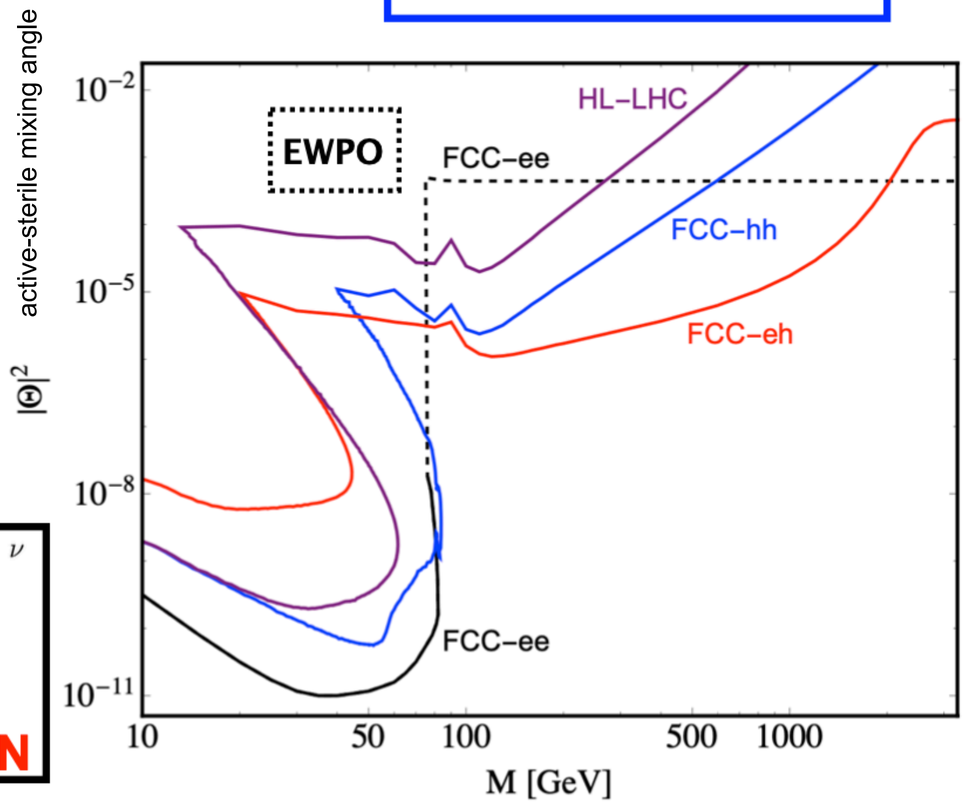
… and much more

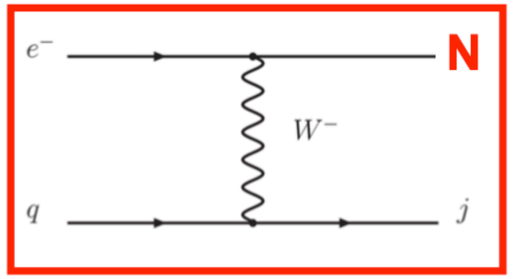
LHeC and FCC CDRs: and several dedicated publications

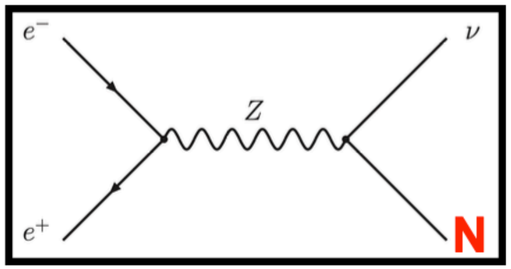
Search for heavy sterile neutrinos

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)
arXiv:1612.02728 [hep-ph]



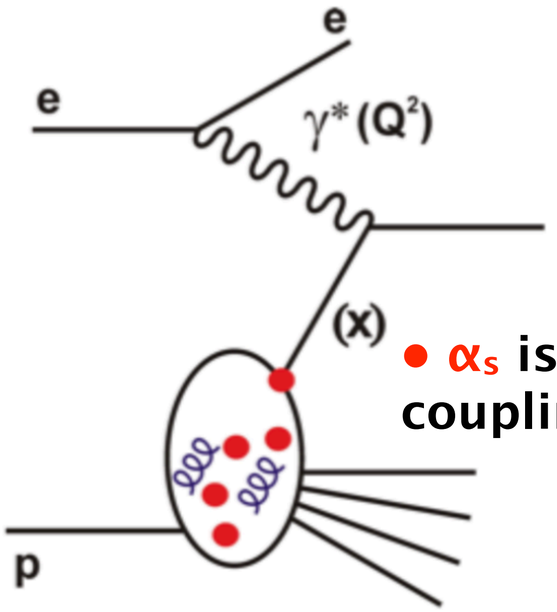




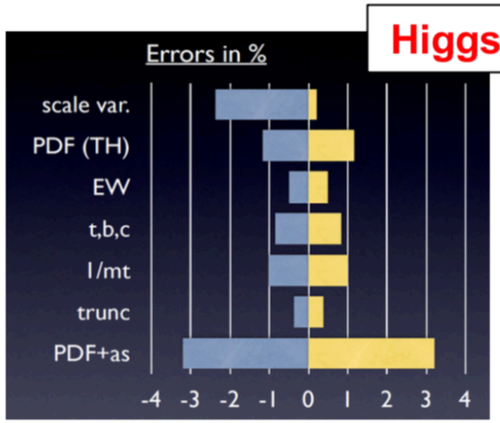


→ complementary prospects for discovery in ee, ep and pp

Determination of Strong Coupling QCD



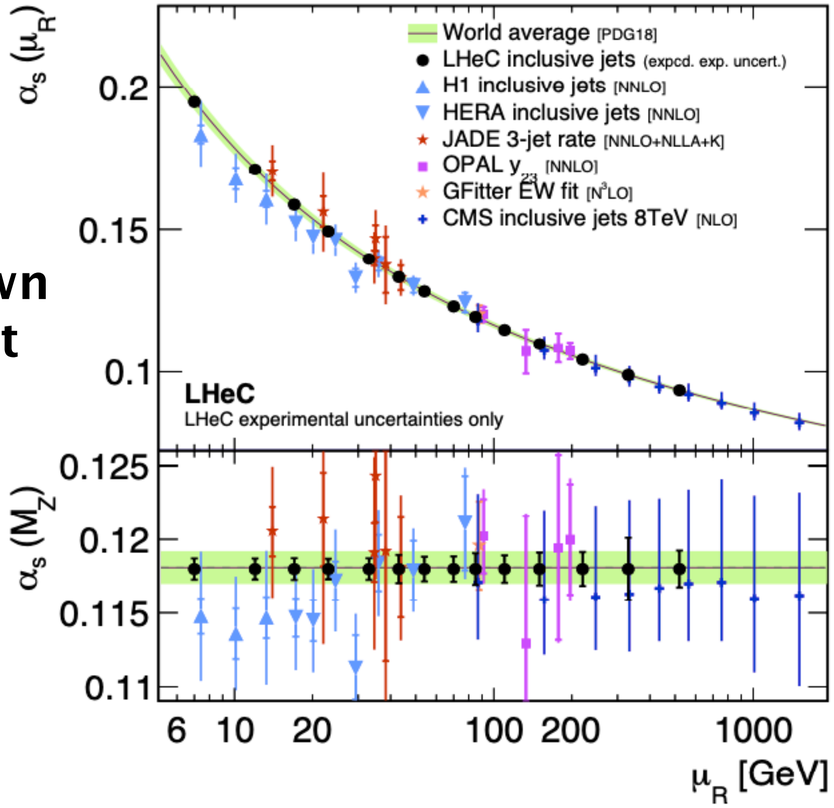
- α_s is least known coupling constant



Higgs XS

(G. Zanderighi, Moriond16;
from C. Anastasiou et al, arXiv:1602.00695)

- QCD fit of inclusive NC and CC DIS

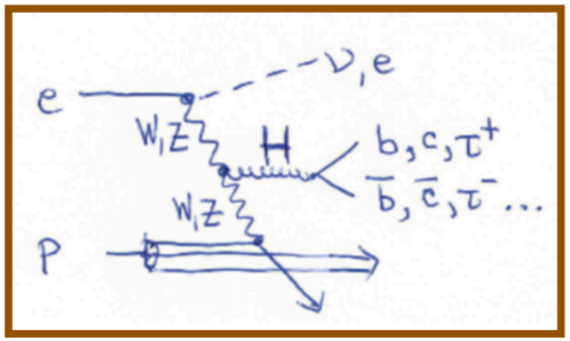


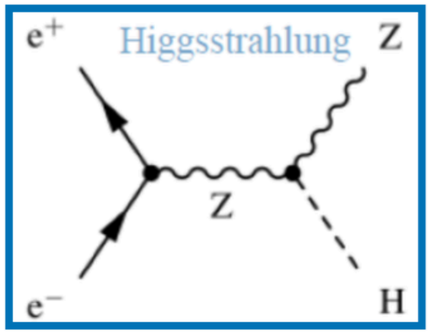
$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$ LHeC

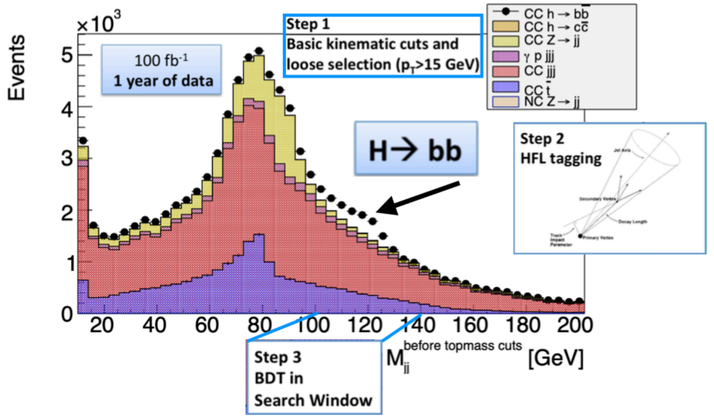
$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00019_{(\text{exp+PDF})}$$ FCC-eh

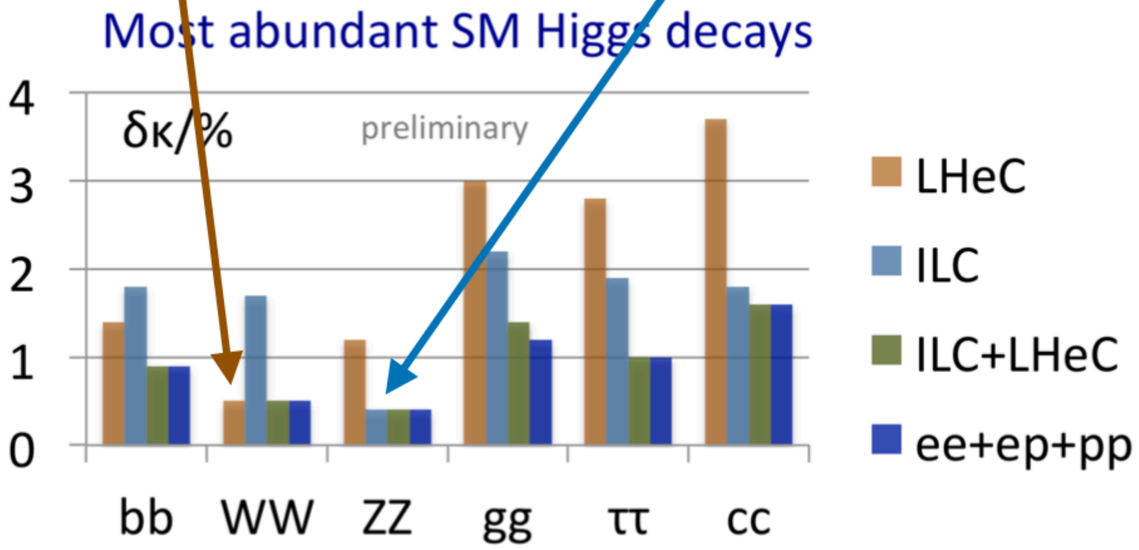
→ considerable improvement of world average

Higgs Couplings (κ-framework)



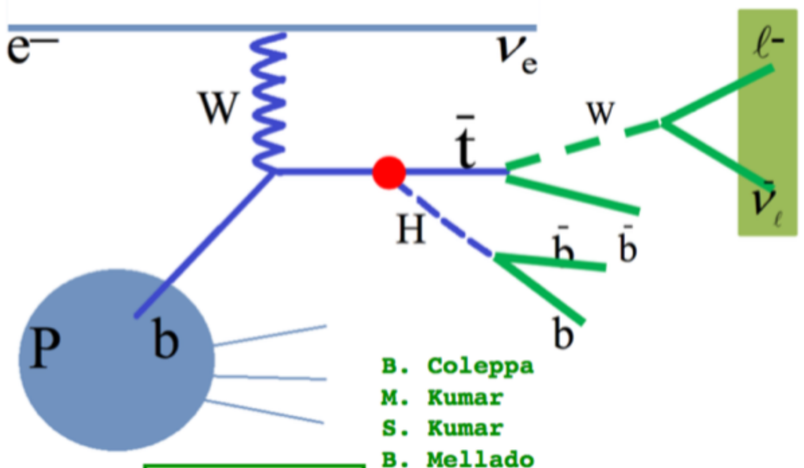






→ **complementarity of colliders**

Top Quark Yukawa Coupling and CP Nature

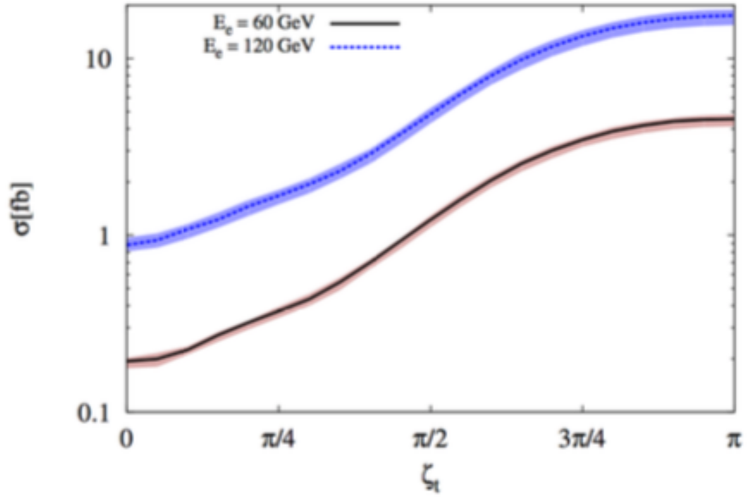


B. Coleppa
M. Kumar
S. Kumar
B. Mellado

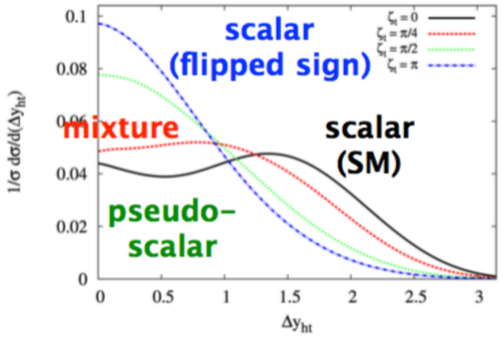
parton level

Phys. Lett. B770 (2017) 335

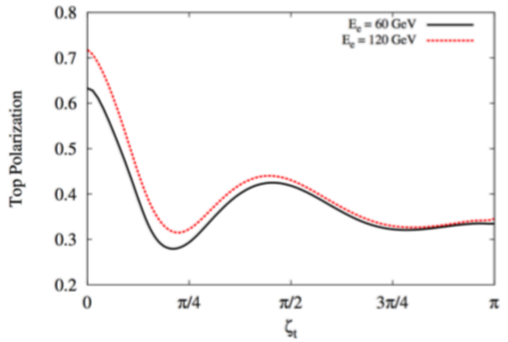
fiducial incl. cross-section



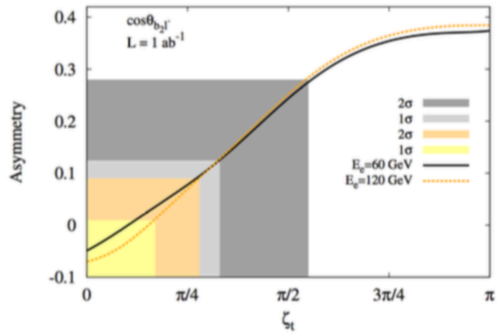
rapidity difference ($H,\bar{t}$)



top polarisation



angular asymmetries (b_2,l^-)



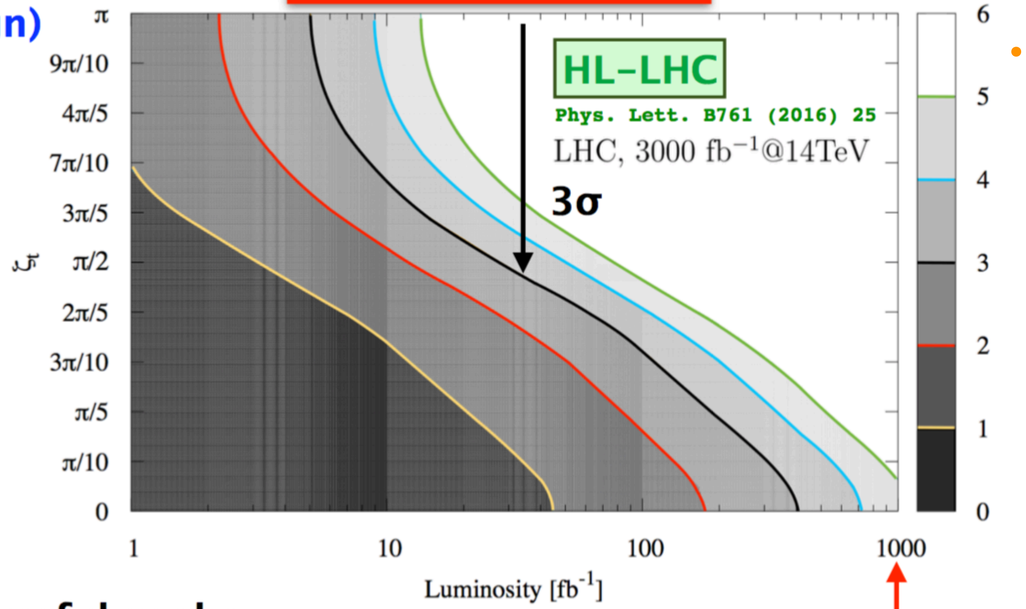
$$\mathcal{L} = -\frac{m_t}{v}\bar{t}\,[\kappa\cos\zeta_t + i\gamma_5\sin\zeta_t]\,t\,h$$

LHeC

CP-even (flipped sign)

CP-odd

CP-even (SM)



→ powerful probe of ttH coupling

10% uncertainty on background yields

$\kappa = 1.00 \pm 0.17$

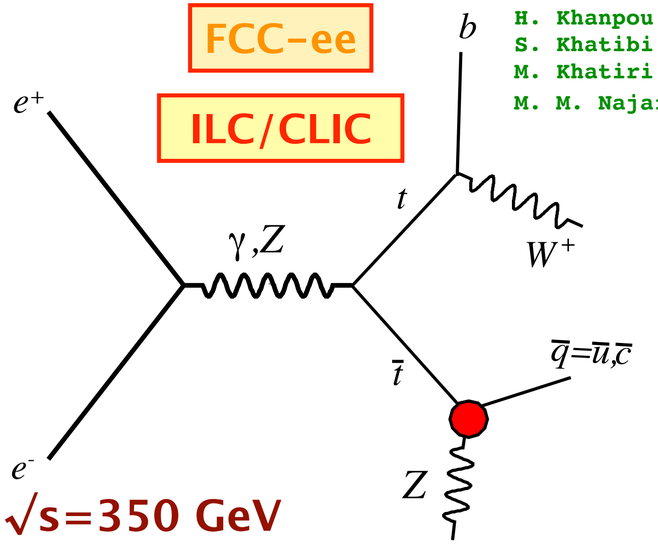
- LC: analysis of CP nature profits from direct production at high energies

Flavor Changing Neutral Current Couplings

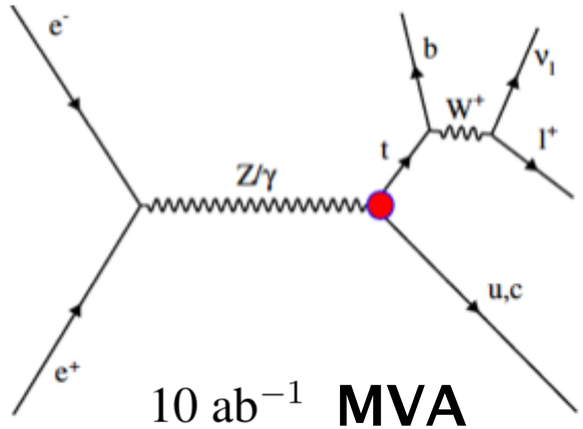
FCC-ee

ILC/CLIC

H. Khanpou
S. Khatibi
M. Khatiri
M. M. Najafabadi



$\sqrt{s}$=350 GeV

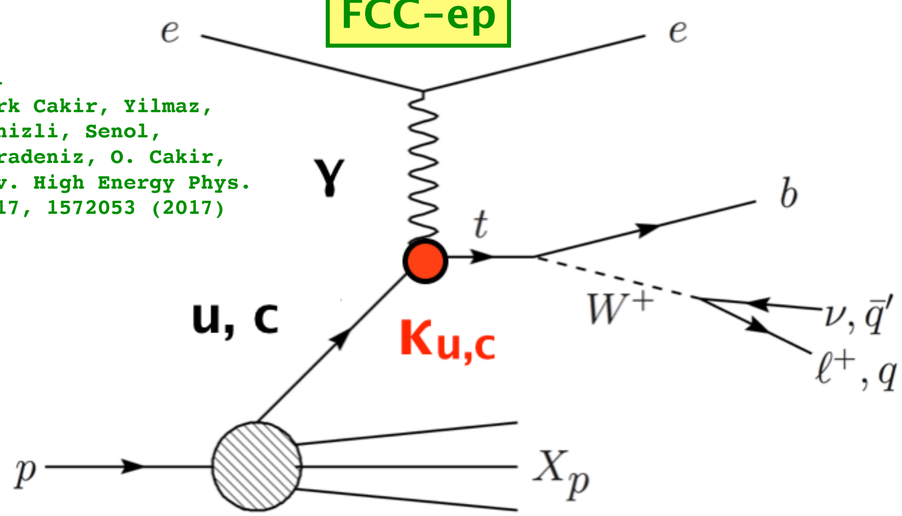


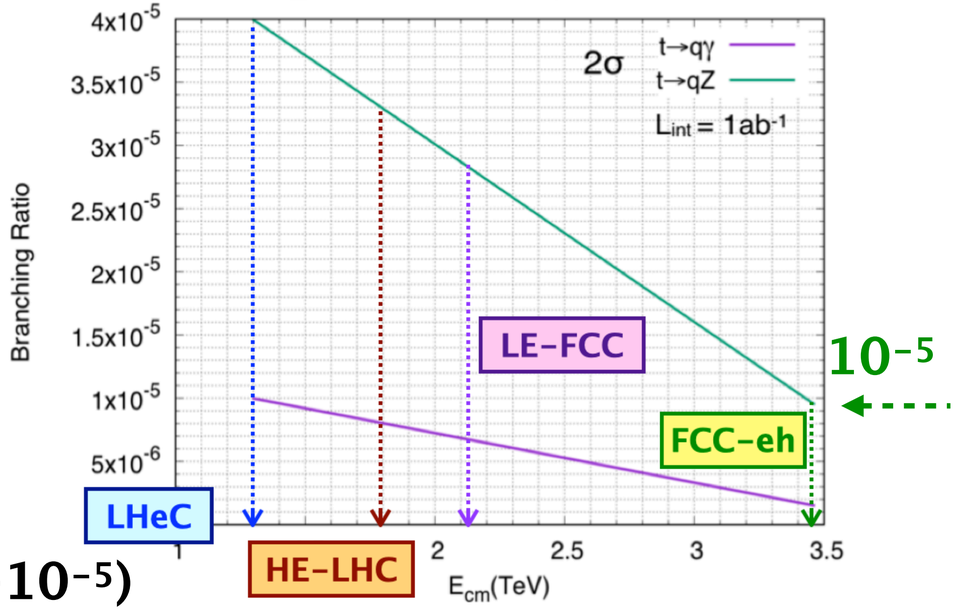
10 ab^{-1} **MVA**

$\sqrt{s}$=240 GeV and $\sqrt{s}$=350 GeV

FCC-ep

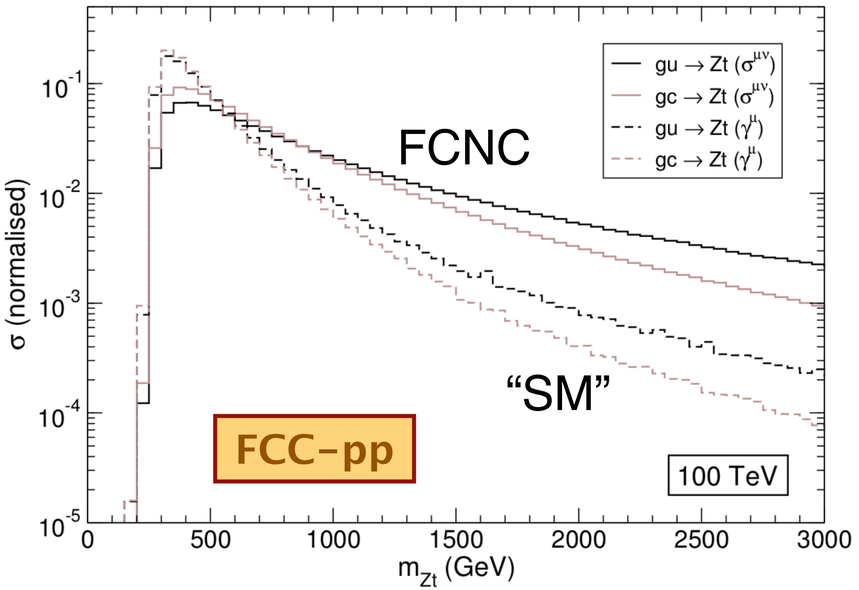
Turk Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

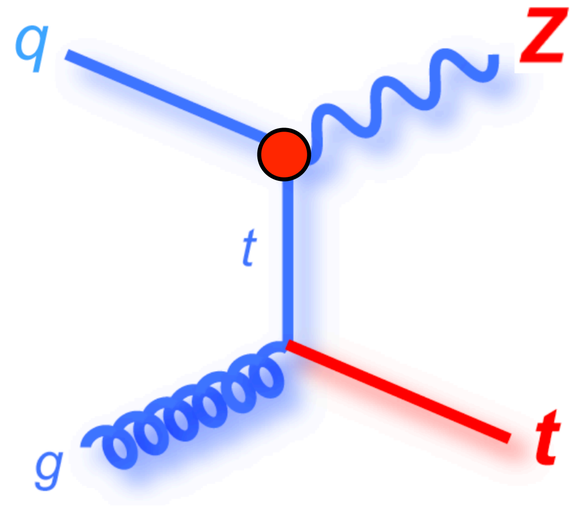




Br(t→qγ), Br(t→qZ)<O(10^{-6}–10^{-5})

Mangano et al., arXiv:1607.01831

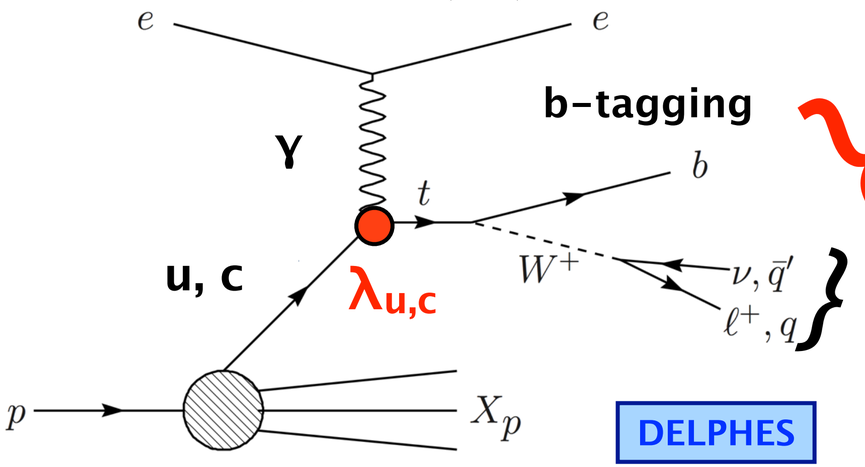




Search for Anomalous FCNC tuγ Coupling

signal

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



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

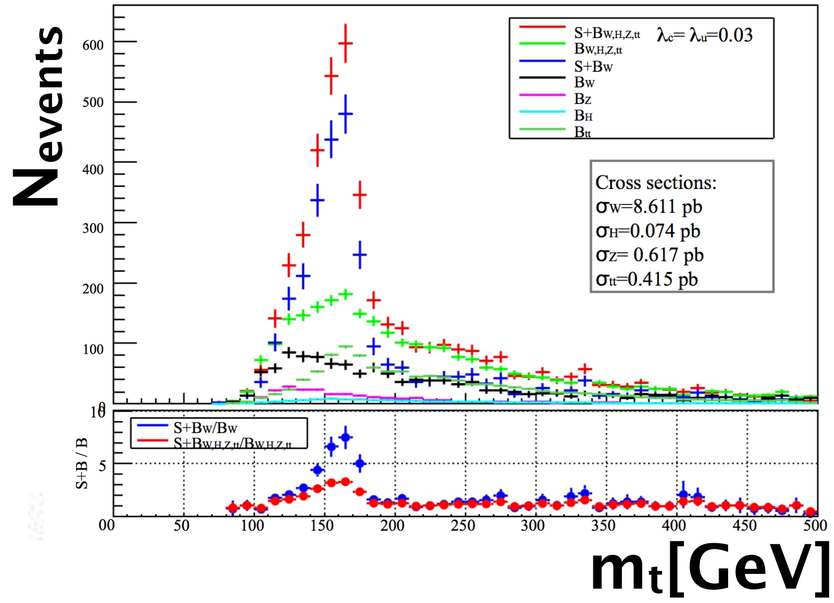
130<M_{Wb}<190 GeV

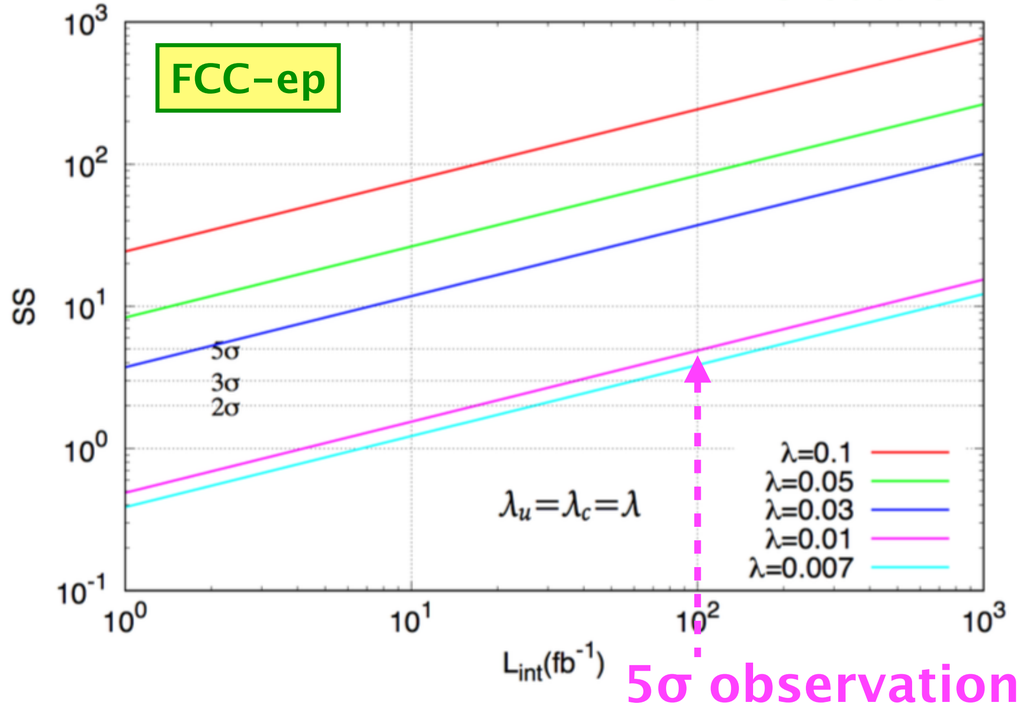
ATLAS: 300 fb^{-1}, √s= 14 TeV: λ<0.022 @ 95% C.L.

50<M_{jj}<100 GeV

ILC: 500 fb^{-1} , √s= 250 GeV: λ<0.02 @ 95% C.L.

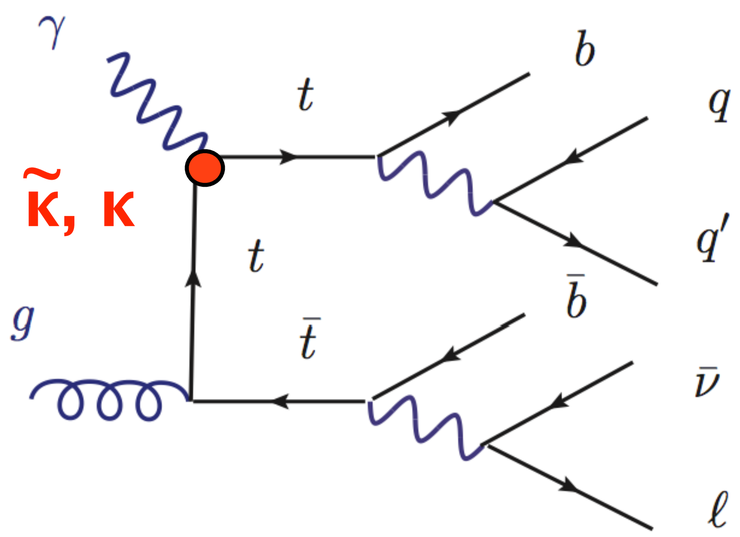
DELPHES





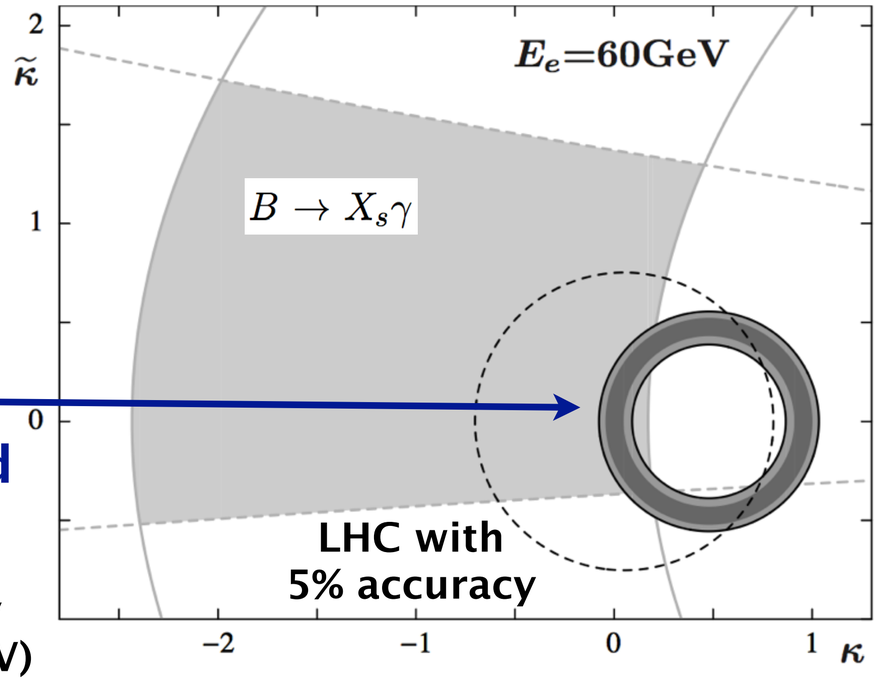
5σ observation

Search for Anomalous $t\bar{t}\gamma$ Couplings



$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

electric dipole moment: $\tilde{\kappa}$



magnetic dipole moment: κ

LHeC

10% and 18% accuracy assumed

ATLAS **27% accuracy**
(4.59fb^{-1}, 7 TeV)

Bouzas, Larios,
Physical Review D 88, 094007 (2013)