Higgs and BSM Physics in ep collisions at CERN

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Wits & iThemba LABS

On behalf of the LHeC/FCC-he Study Group

LHeC

Institute for Collider Particle Physics
University of the Witwatersrand

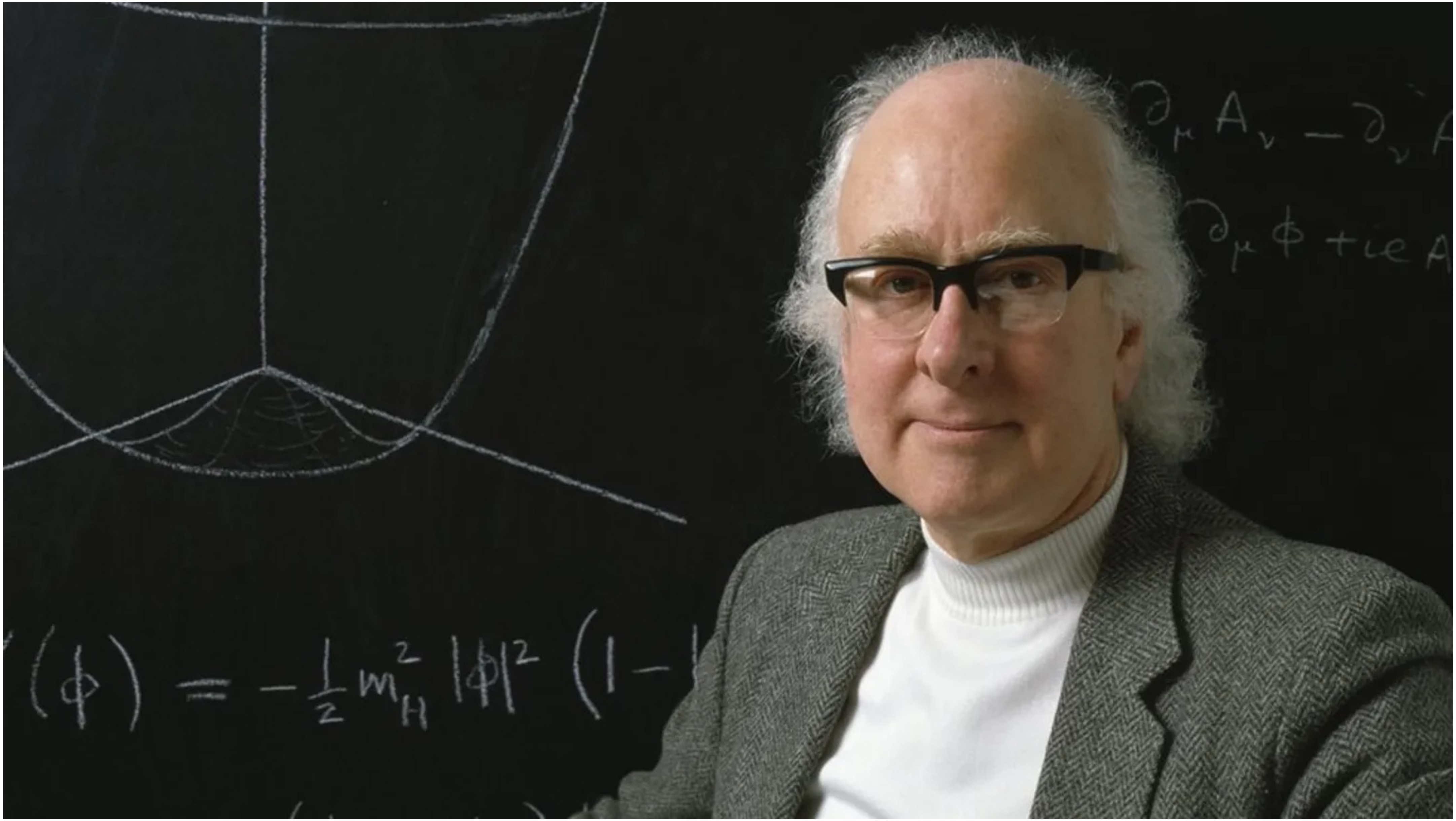
FCC
hh ee he

NRF
National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

DIS2024, Grenoble, 10/03/24

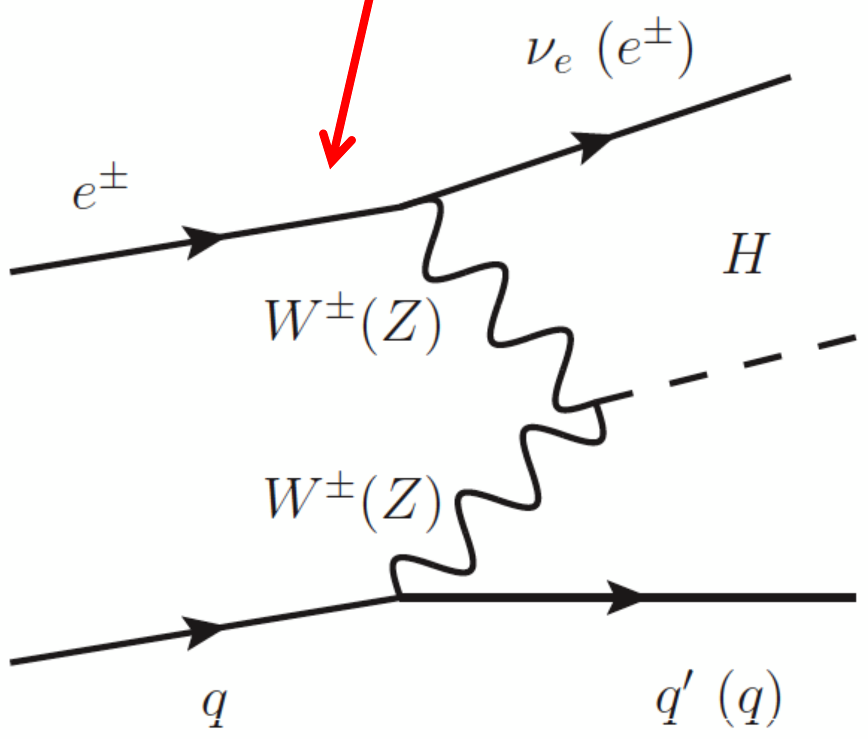
In Memoriam



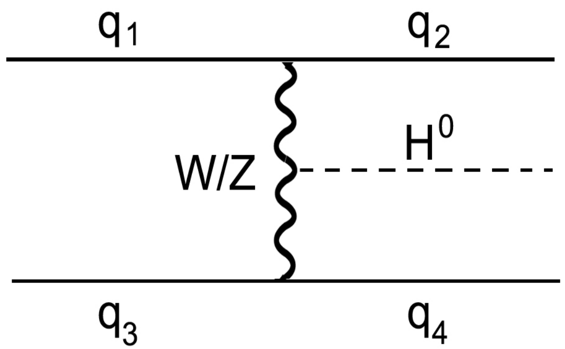
Higgs Boson in ep

- 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~1

At LHC replace lepton lines by quark lines



Higgs via VBF
Qualitative remarks



$$\sigma(fa \to f'X) \approx \int dx dp_T^2 P_{V/f}(x, p_T^2) \sigma(Va \to X)$$

$$P_{V/f}^T(x, p_T^2) = \frac{g_V^2 + g_V^2}{8\pi^2} \frac{1 + (1-x)^2}{x} \frac{p_T^2}{(p_T^2 + (1-x)M_V^2)^2}$$

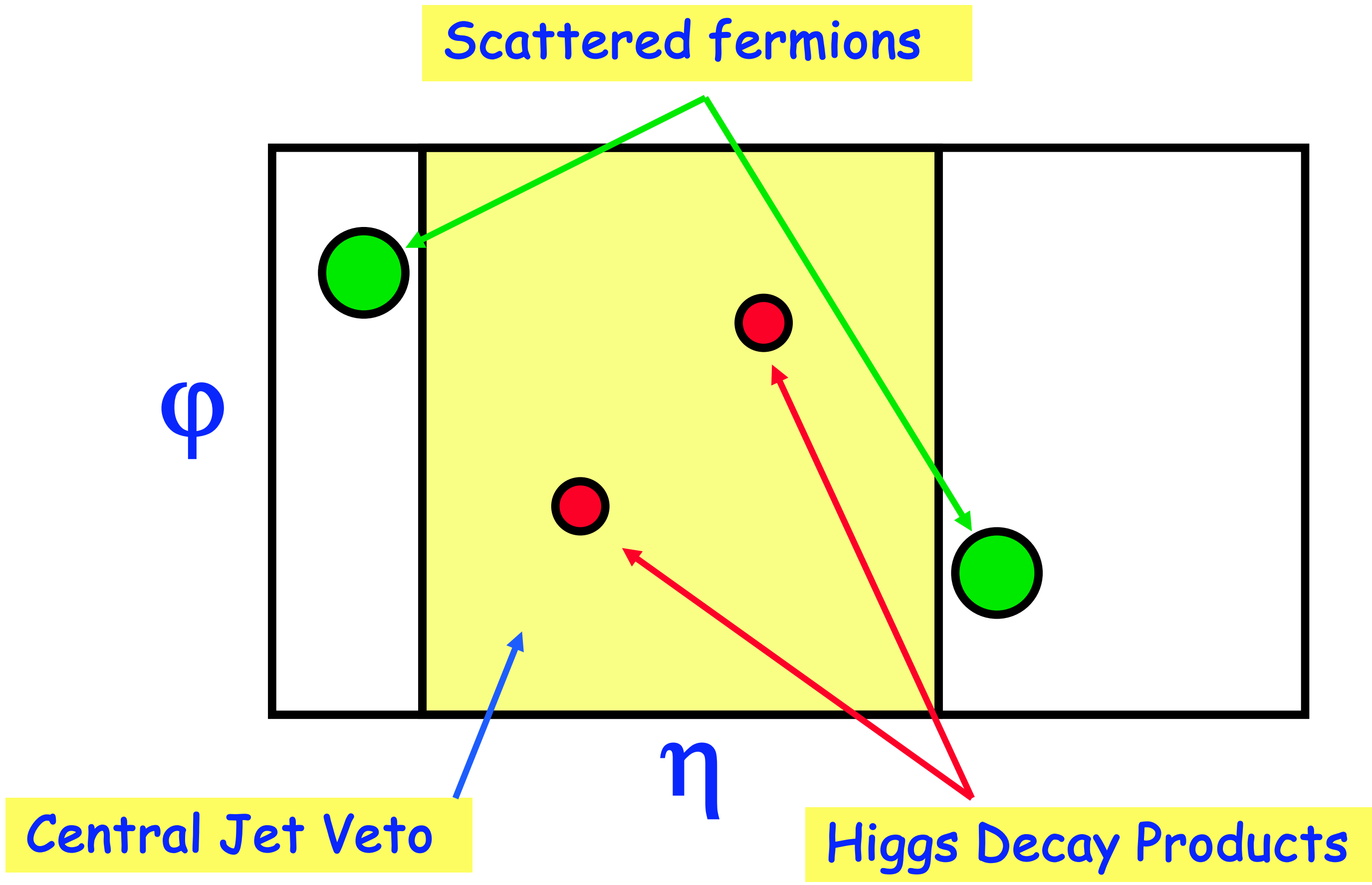
$$P_{V/f}^L(x, p_T^2) = \frac{g_V^2 + g_V^2}{4\pi^2} \frac{1-x}{x} \frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2}.$$

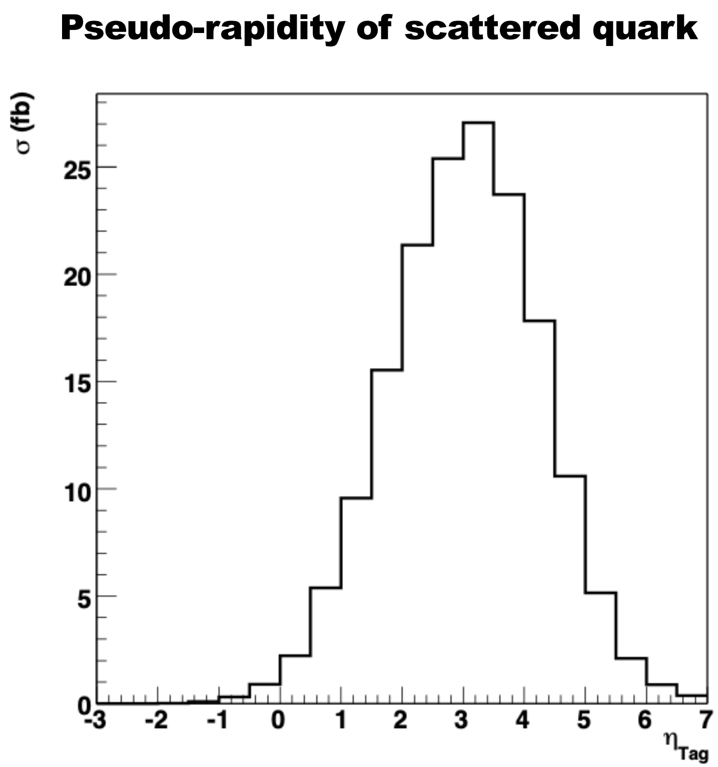
- **Unlike QCD partons that scale like $1/P_T^2$, here P_T~sqrt(1-x)M_W**

- **Due to the 1/x behavior of the Weak boson the outgoing parton energy (1-x)E is large forward jets**
- **At high P_T** $P_{V/f}^T \sim 1/p_T^2$ and $P_{V/f}^L \sim 1/p_T^4$

- **Contribution from longitudinally polarized Weak Bosons is suppressed in favor of transversely polarized WB at high p_T**

Well-defined prediction of the SM. Kinematics of scattered quarks, sensitive to new physics





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'

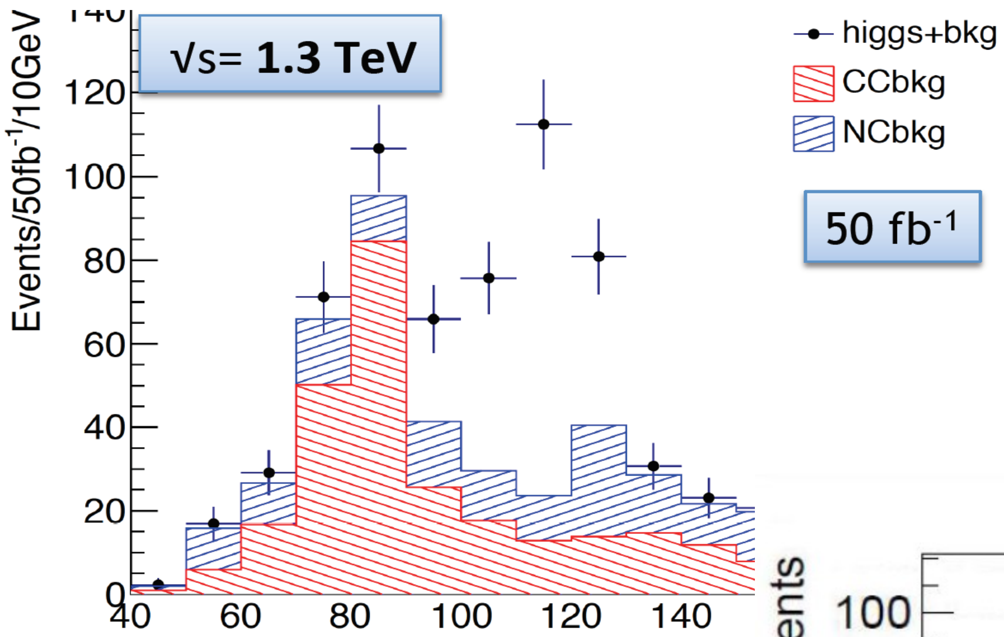
LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350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



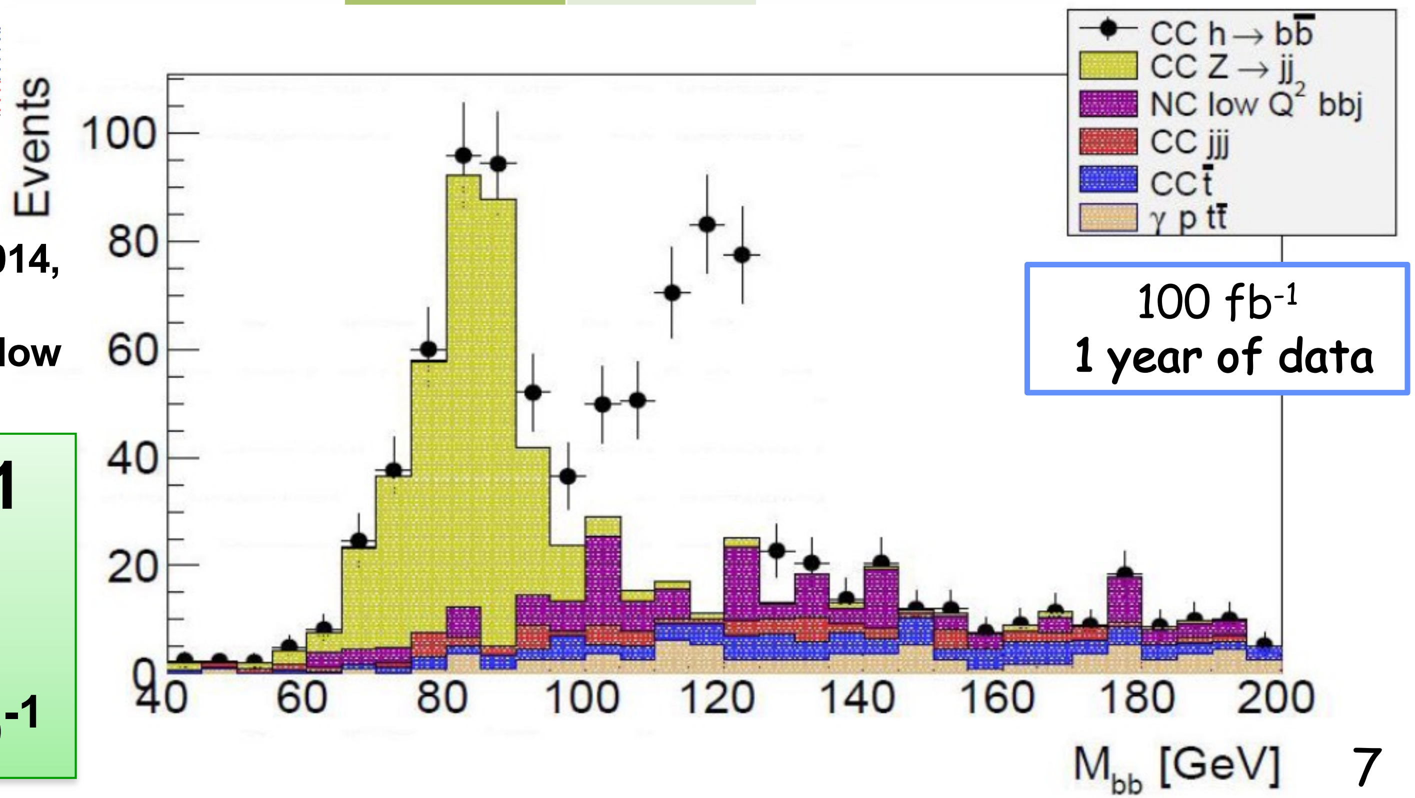
Masahiro Tanaka, BSc thesis, Tokyo Tech 2014

LHeC

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



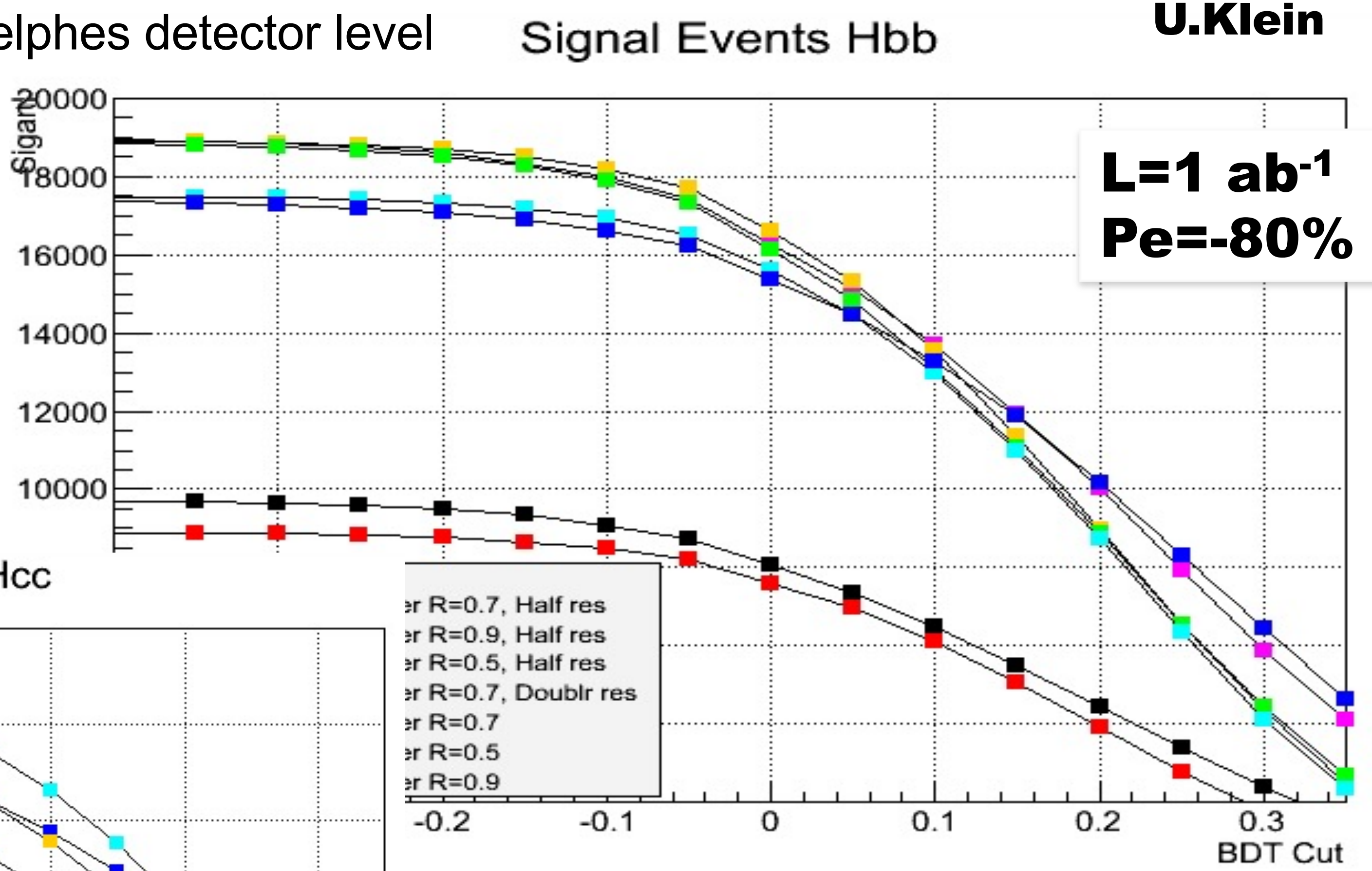
Confirmed CDR: S/N>1 using conservative light misID and cut-based δμ=2% for 1 ab^{-1}

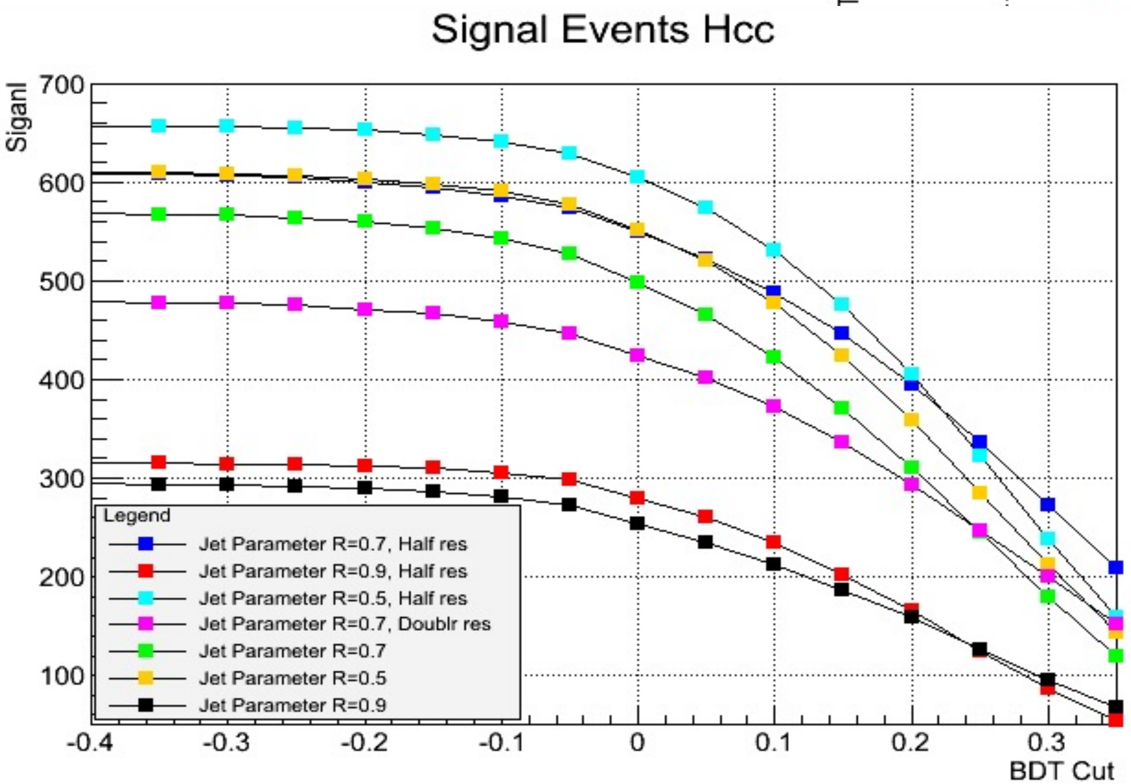
BDT Results for Higgs @ LHeC

using realistic HFL tagging at Delphes detector level

U.Klein

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

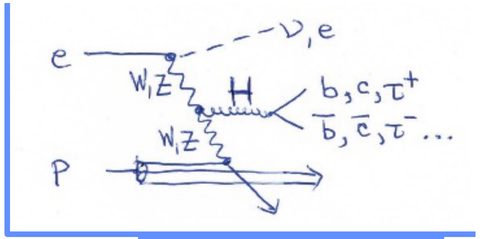




Hcc : High sensitivity to vertex resolution (nominal 10 μm) and jet radius

→ expect about 400-600 Hcc candidates

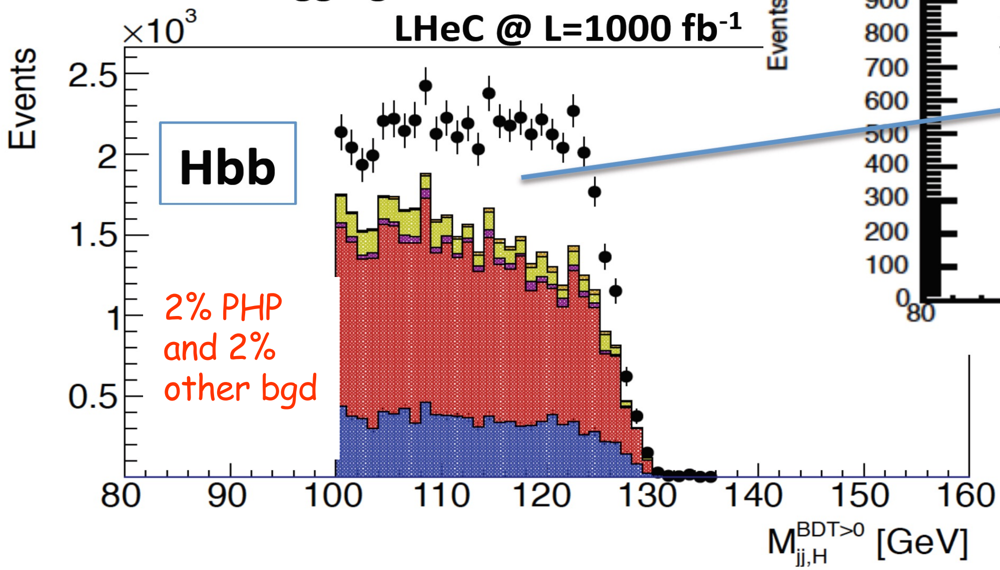
Higgs in ep – clean S/B, no pile-up

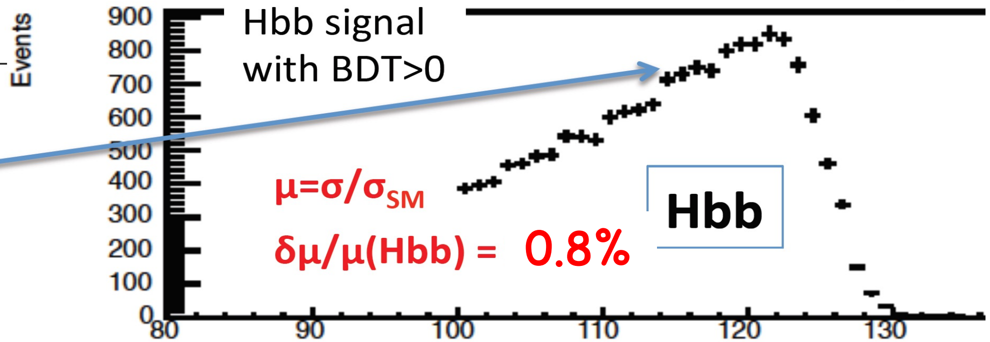


Uta Klein & Daniel Hampson

& Izzy Harris BSc

realistic HFL tagging & BDT





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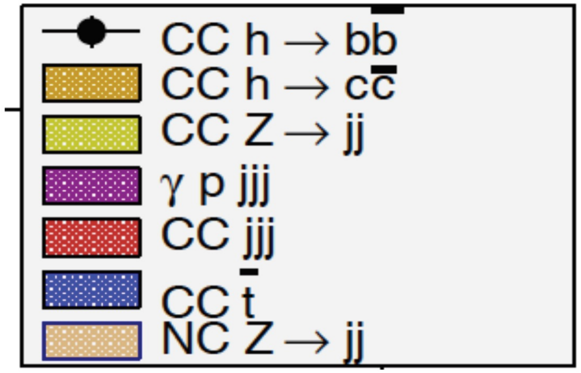
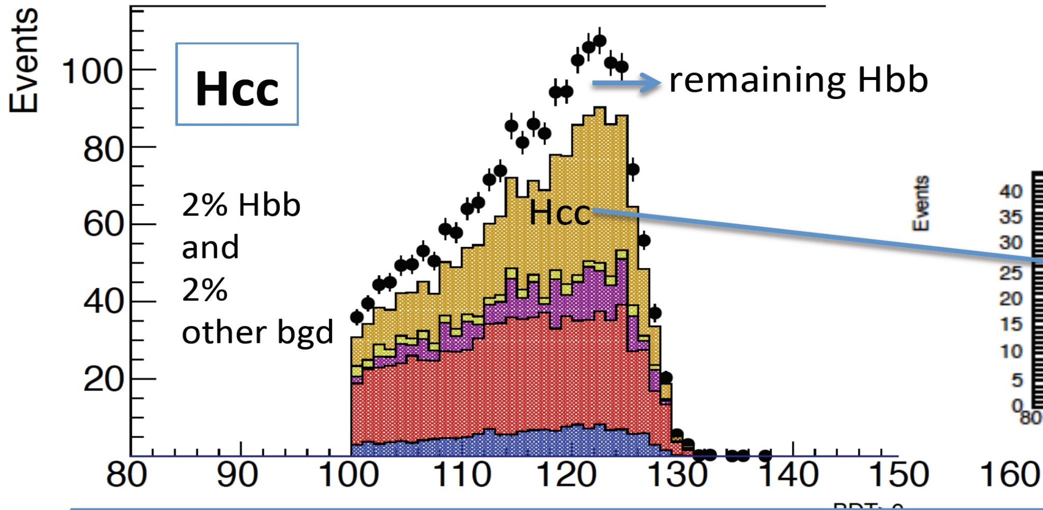
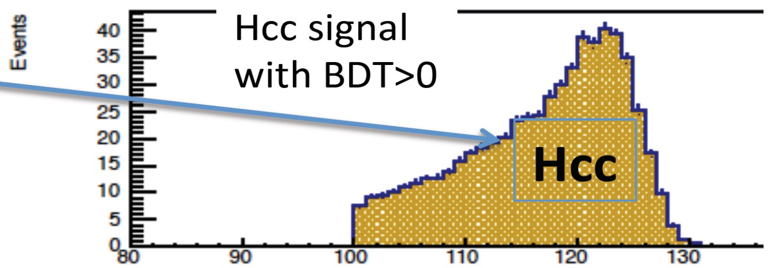






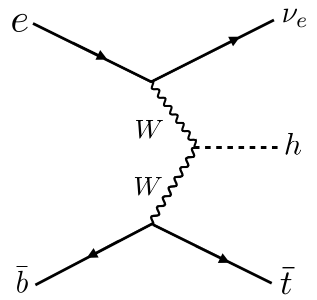
δμ/μ(Hcc) = 7.4 %

Assuming ATLAS light jet misID efficiencies

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

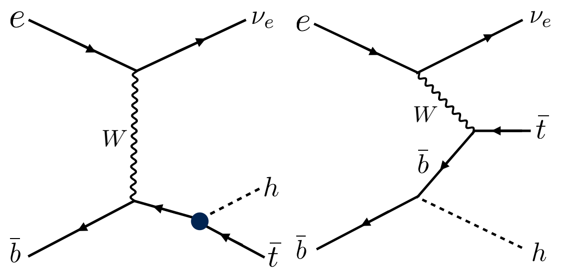
B.Coleppa, M.Kumar, S.Kumar, B.M., Phys. Lett. B770 (2017) 335

Top Yukawa coupling

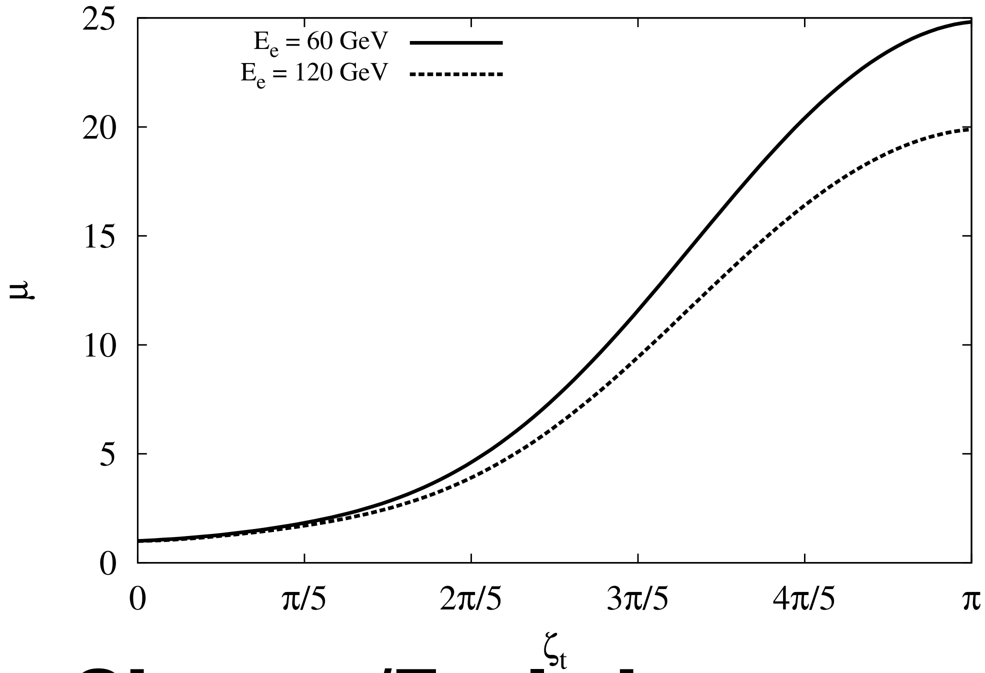


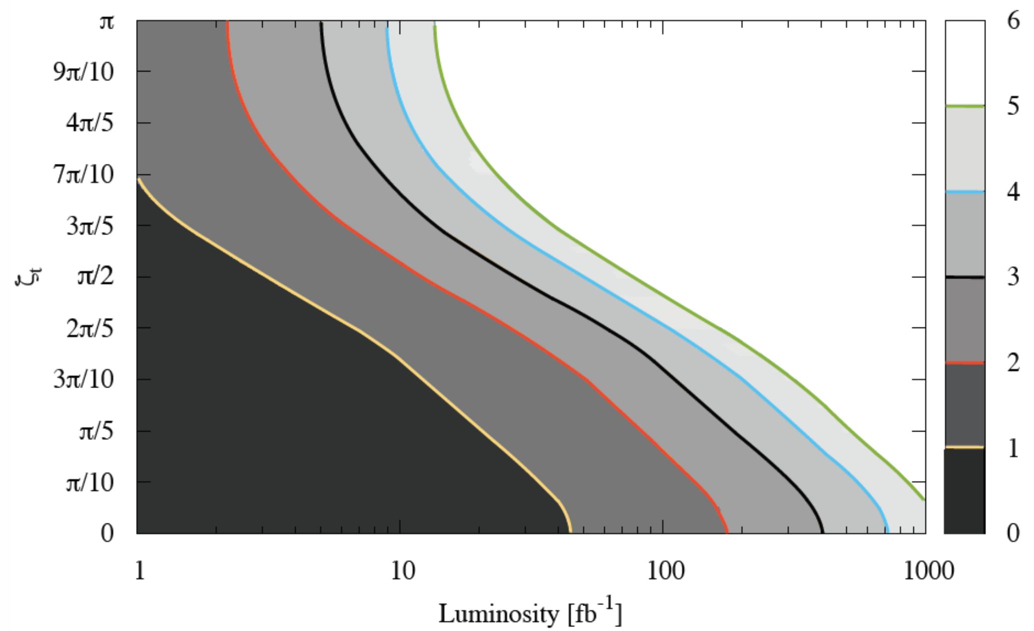
Introduce phase dependent top Yukawa coupling

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



Enhancement of the cross-section as a function of phase



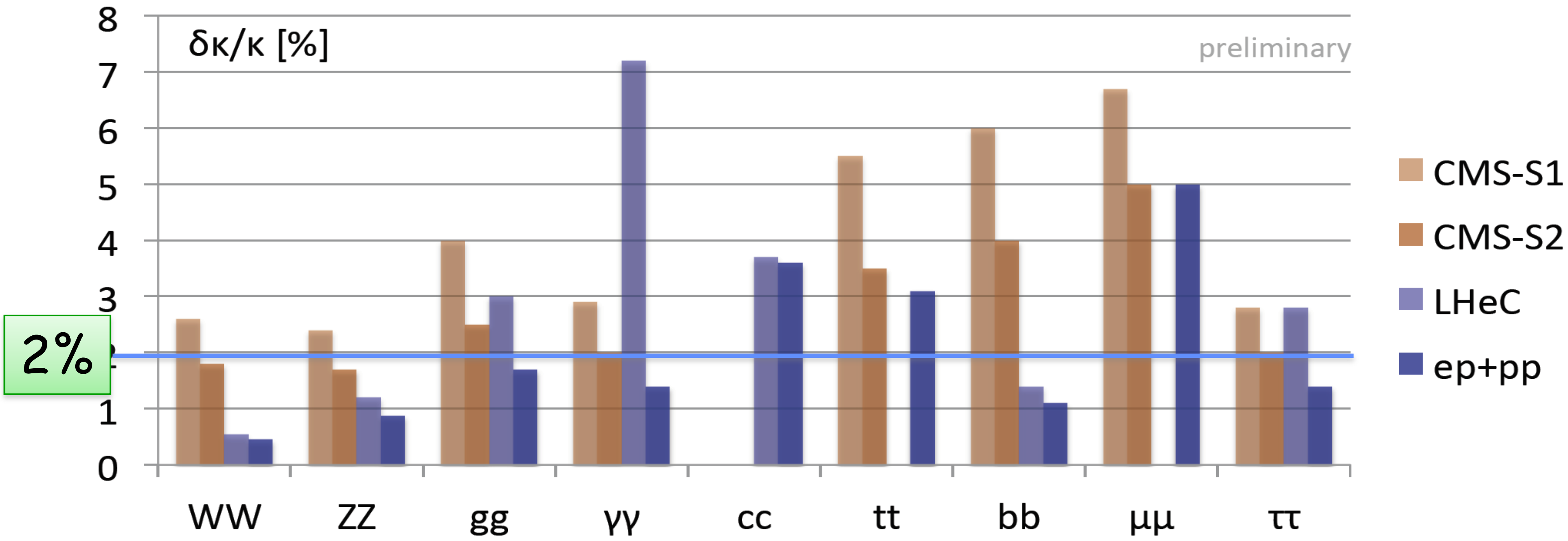


Observe/Exclude non-zero phase to better than 4σ at LHeC. Achieve <2% error on k_t at the FCC-eh.

LHeC and HL-LHC Higgs Prospects

M.Klein

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



→ **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

SM Higgs Signal Strengths in ep

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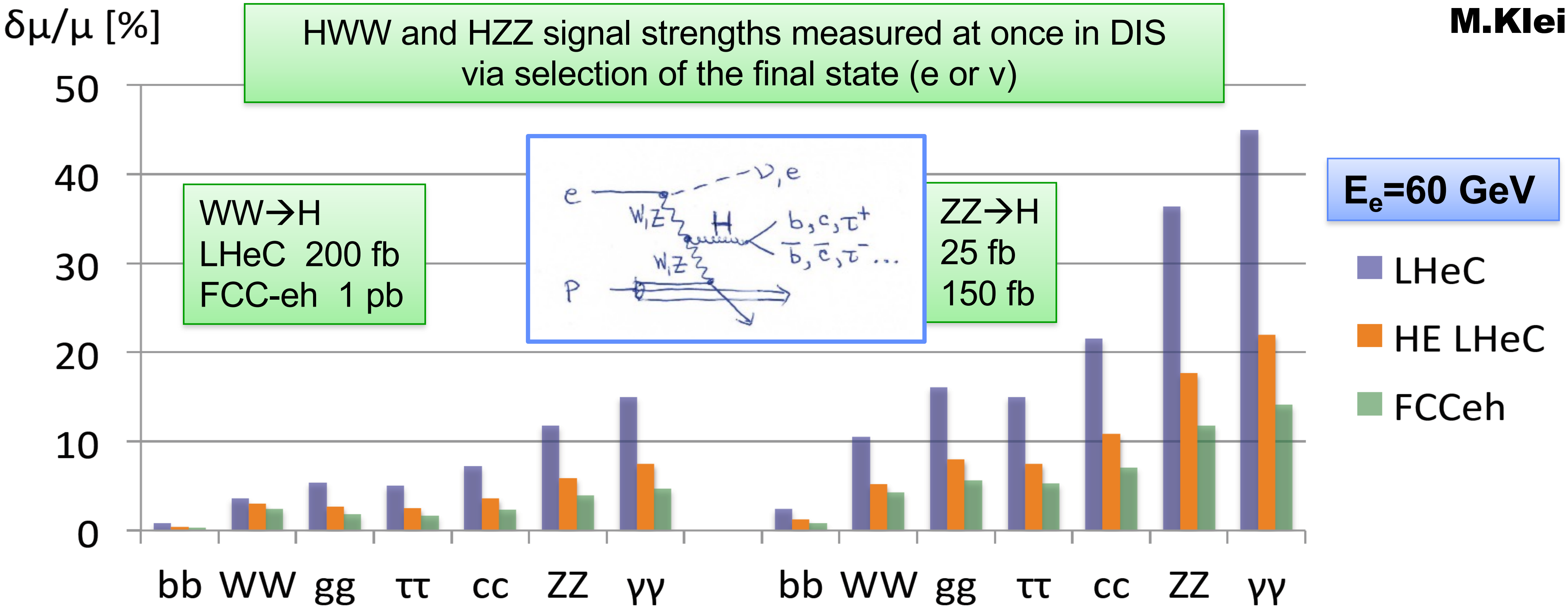


submitted to EU strategy CERN-ACC-Note-2018-0084

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}

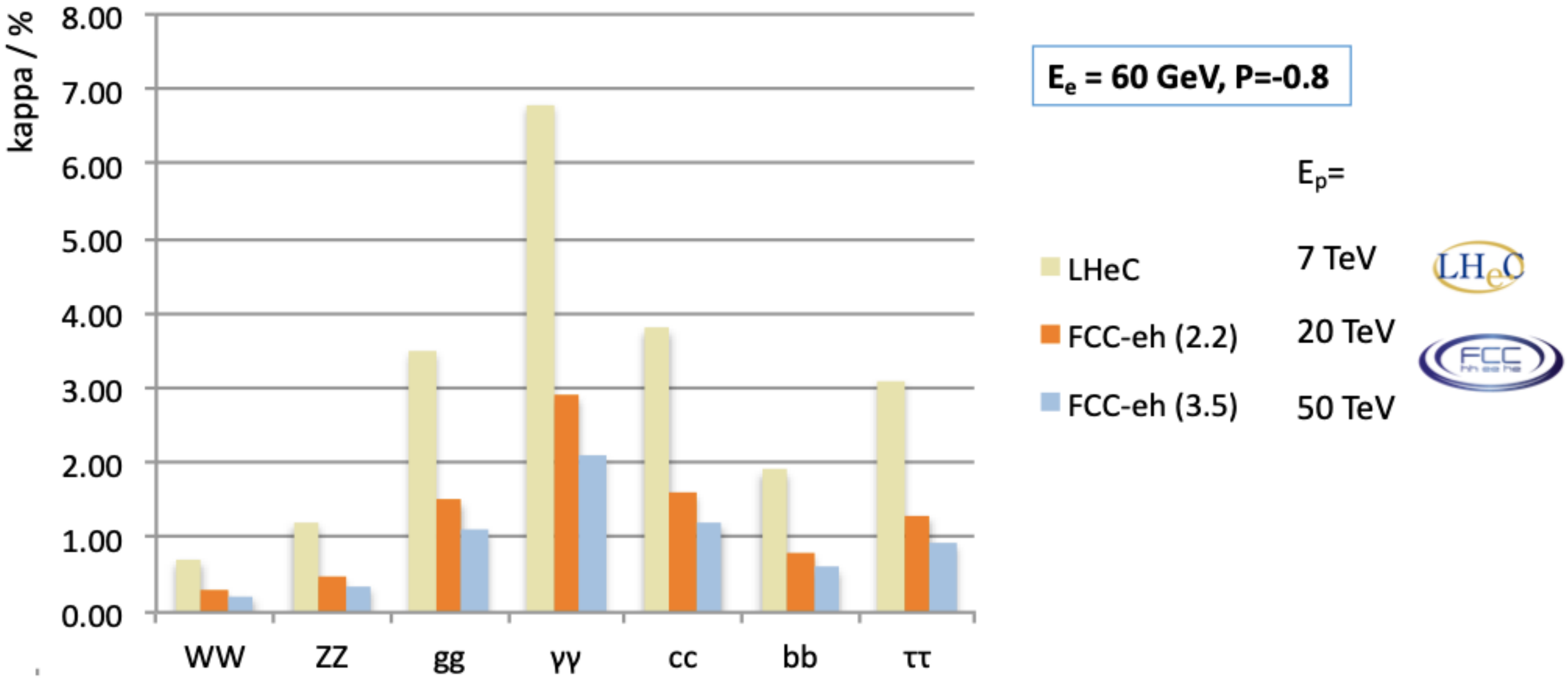
U.Klein

[arXiv:2007.14491]

Stand-alone ep κ Coupling Fits

→ Assuming SM branching fractions weighted by the measured κ values, and Γ_{md} (c.f. CLIC model-dependent method) see e.g. [arXiv:1608.07538]

Note: also H in ePb



Very high precision due to CC+NC DIS in clean environment in luminous, energy frontier ep scattering

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%
$\kappa_{Z\gamma}$	–

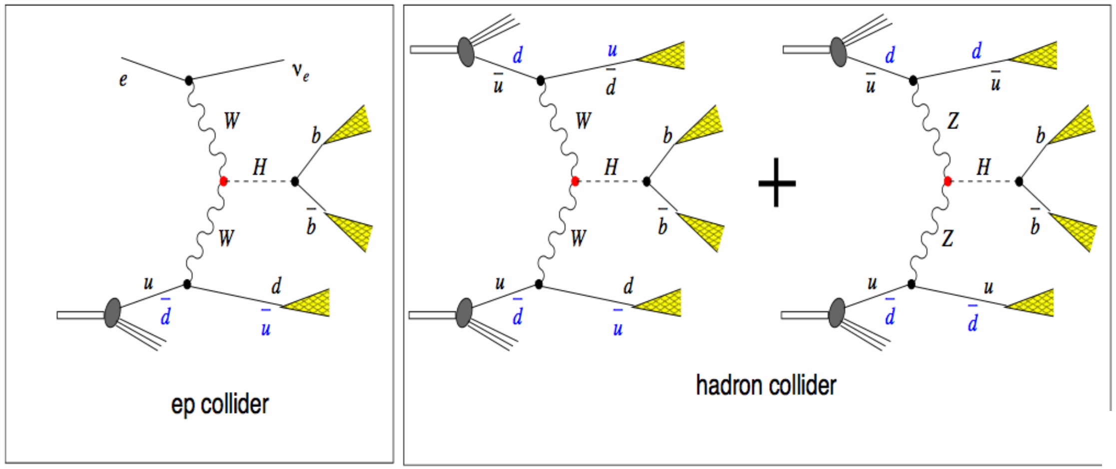
$$\kappa_i \equiv g_{hi}/g_{hi}^{SM}$$

Published in book 1 of FCC

Structure of HVV couplings

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

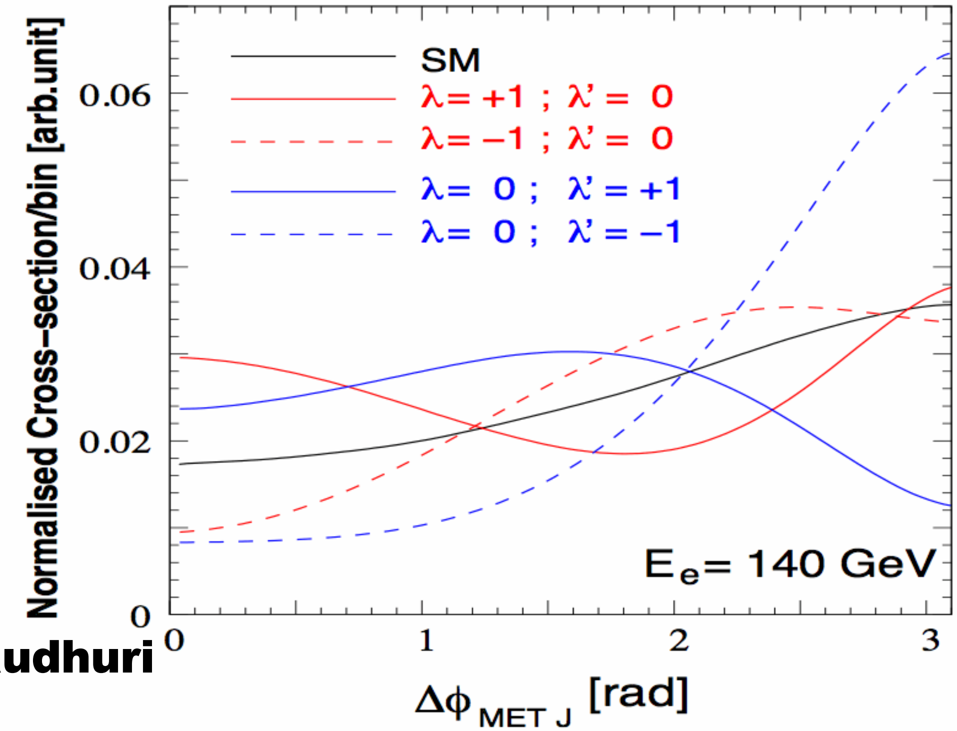
higgs + 2jets: VBF (LHC), higgs + jet + missing E_T (LHeC)



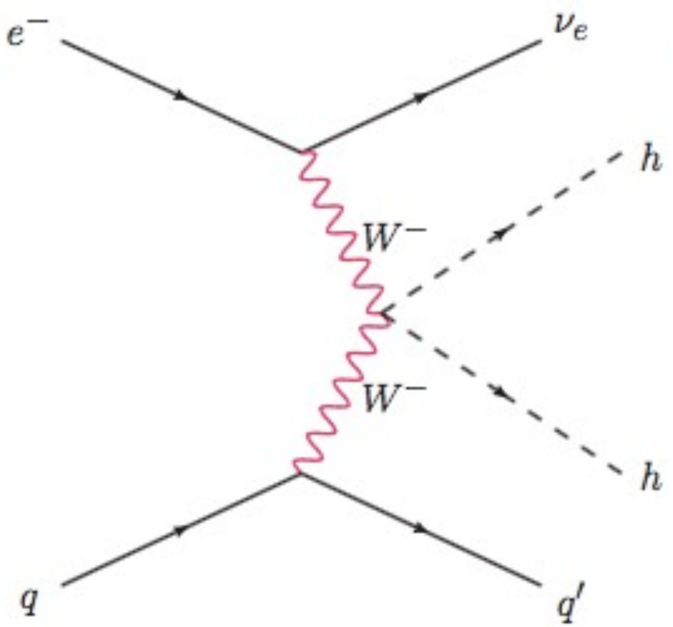
ep process uniquely addresses the HWW vertex.

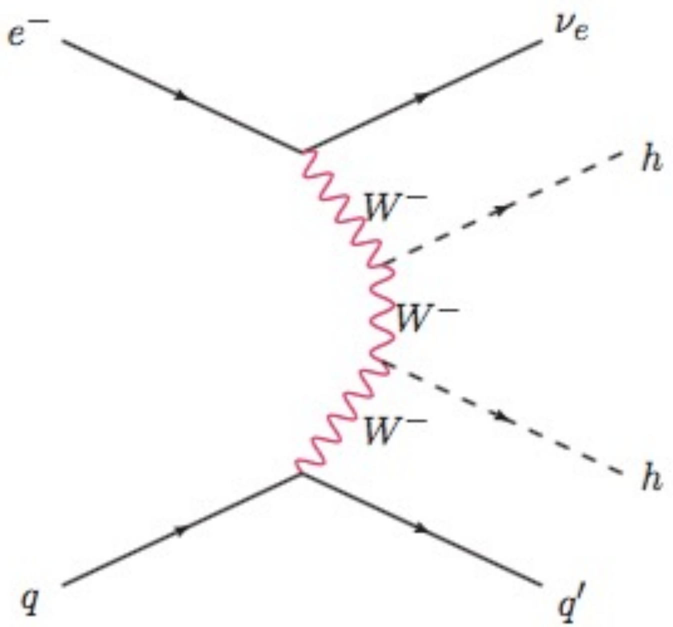
Can consider azimuthal angle correlation between scattered neutrino and quark. Other observables can be used too.

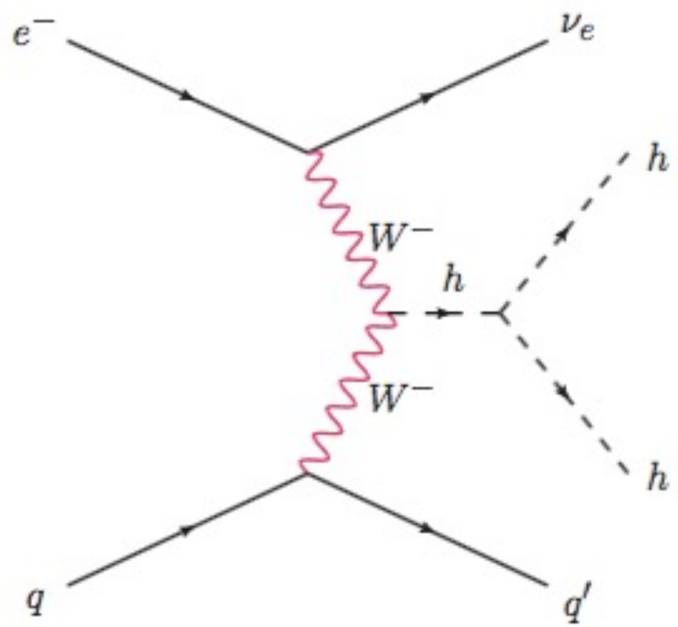
Model independent separation of HWW and HZZ coupling, unique capability of ep collisions, not available in pp and e⁺e⁻ collisions

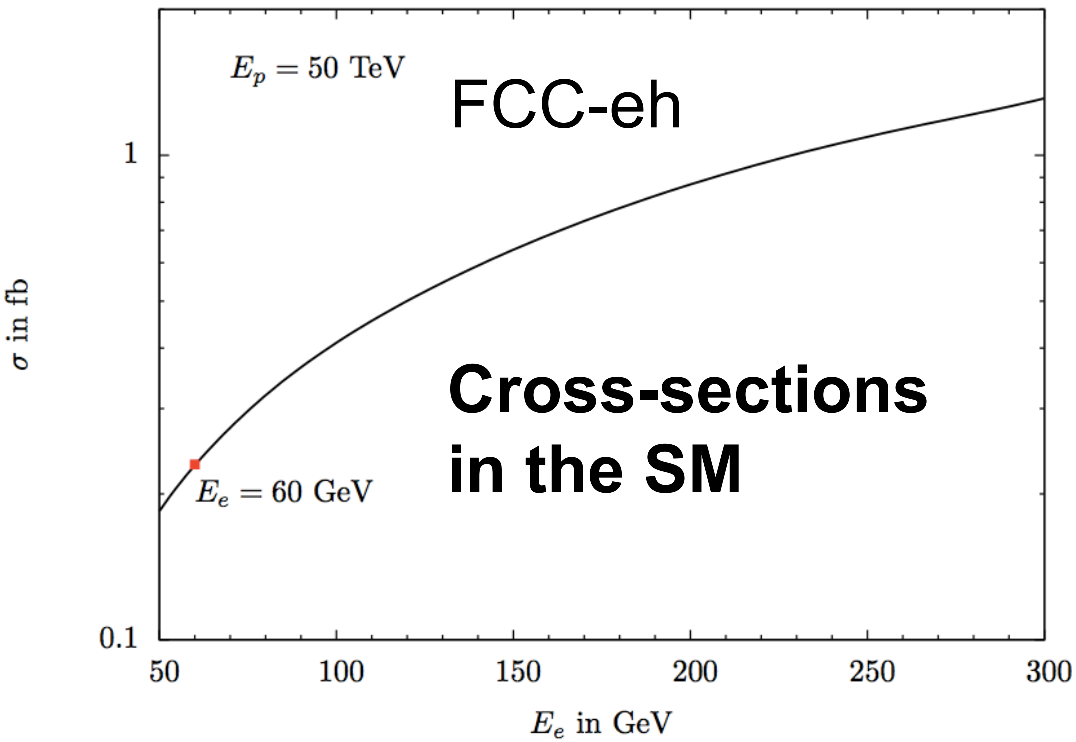


B.Biswal, R.Godbole, S.Kumar, B.M., S.Raychaudhuri Phys.Rev.Lett. 109 (2012) 261801

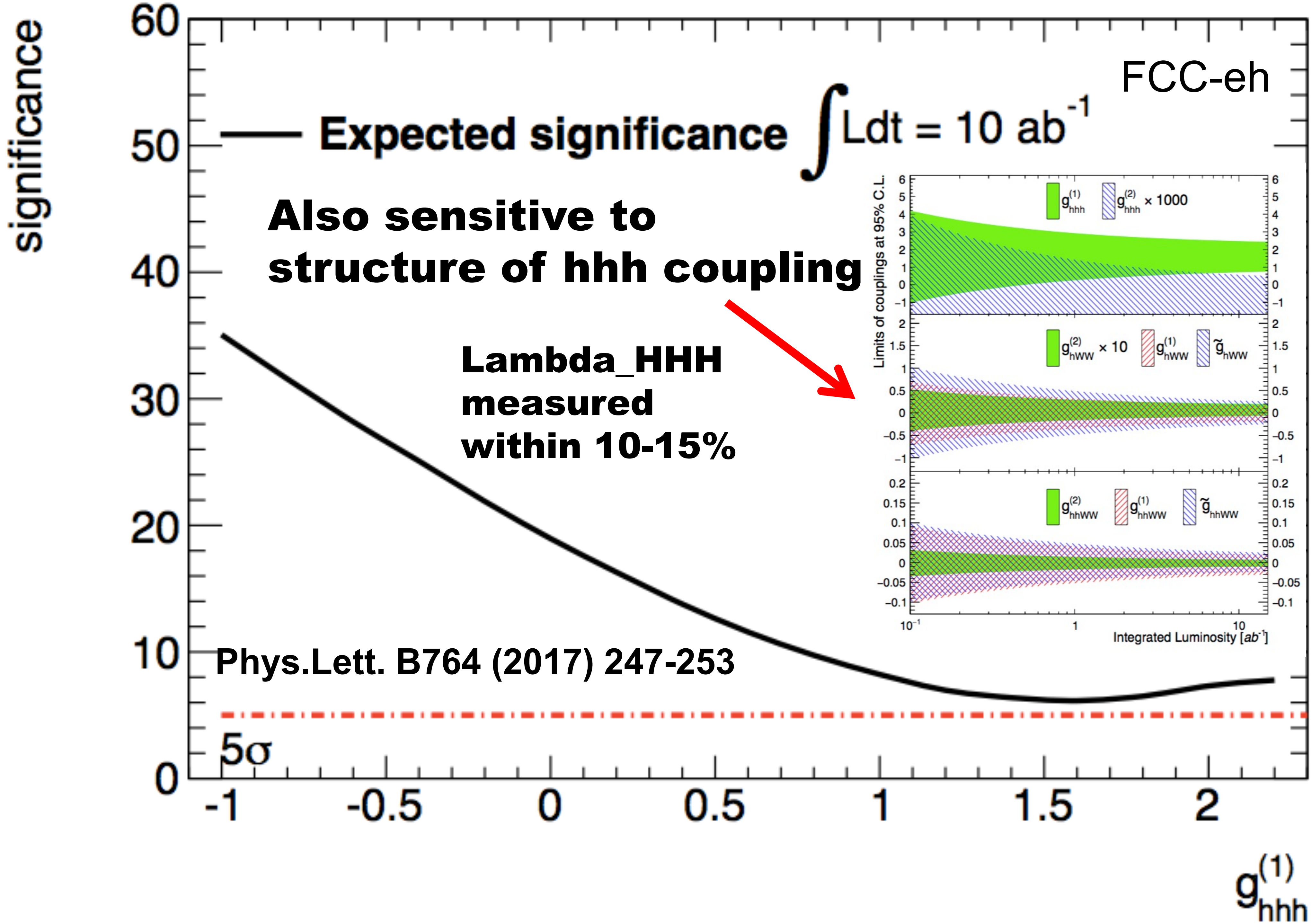








Considering highly asymmetric collisions

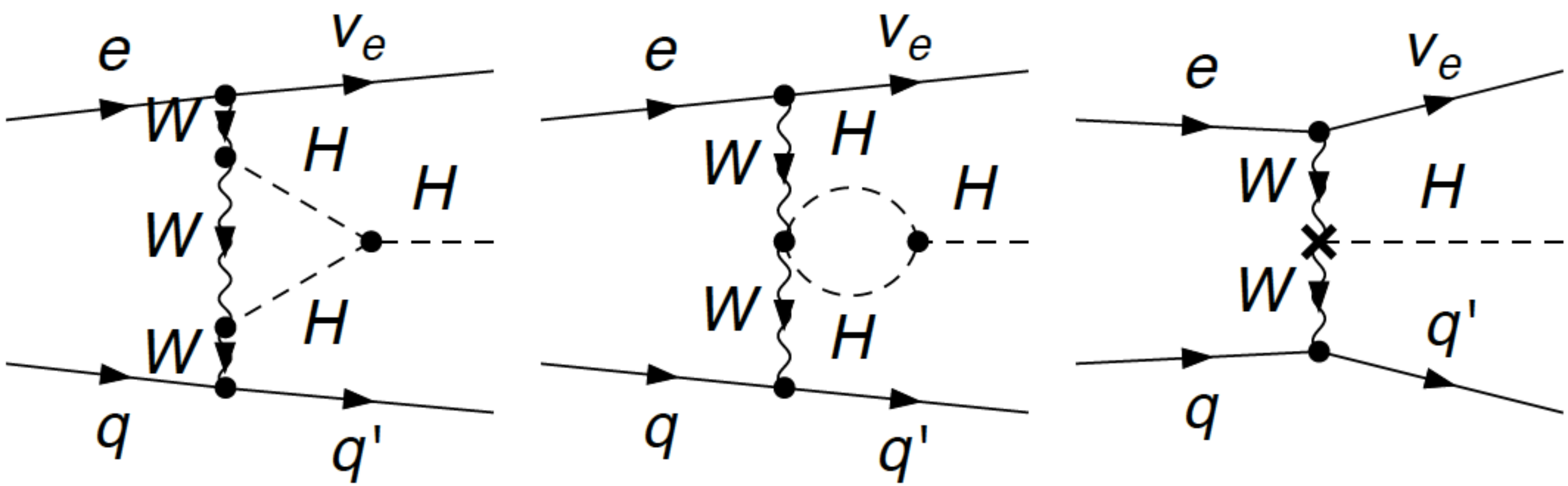


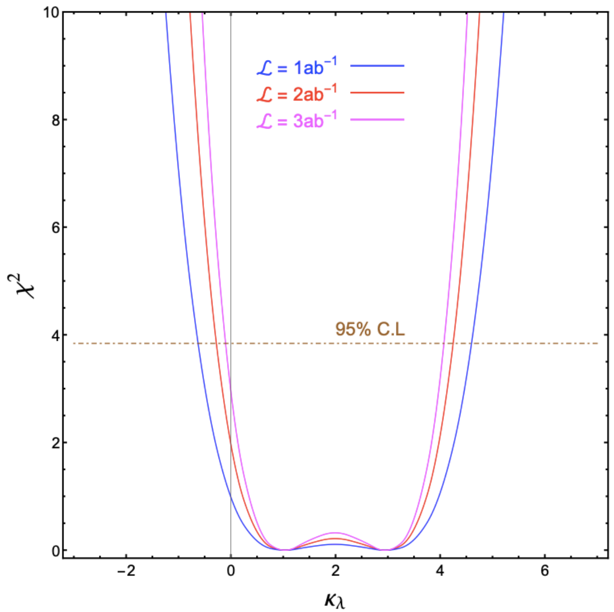
significance
FCC-eh
Expected significance $\int Ldt = 10\ ab^{-1}$
Also sensitive to structure of hhh coupling
Lambda_HHH measured within 10-15%
Phys.Lett. B764 (2017) 247-253
5σ
$g^{(1)}_{hhh}$
Limits of couplings at 95% C.L.
$g^{(1)}_{hhh}$ $g^{(2)}_{hhh}$ × 1000
$g^{(2)}_{hWW}$ × 10 $g^{(1)}_{hWW}$ $\tilde{g}_{hWW}$
$g^{(2)}_{hhWW}$ $g^{(1)}_{hhWW}$ $\tilde{g}_{hhWW}$
Integrated Luminosity [ab^{-1}]

Probing Trilinear coupling via single h prod. (LHeC)

K.Wang et al. Phys. Rev. D 101, 075036 (2020)

Diagrams sensitive to λ_{hhh}





No cuts

The integrated luminosity	Bounds of the κ_λ	10% h acceptance
$\mathcal{L} = 1\ \mathrm{ab}^{-1}$	[-0.63, 4.61]	[-2.65, 6.62]
$\mathcal{L} = 2\ \mathrm{ab}^{-1}$	[-0.28, 4.25]	[-1.95, 5.93]
$\mathcal{L} = 3\ \mathrm{ab}^{-1}$	[-0.11, 4.08]	[-1.59, 5.57]

Results can be significantly improved. Sensitivity will help the HL-LHC: $0.5 < k_\lambda < 1.5$

BSM Physics

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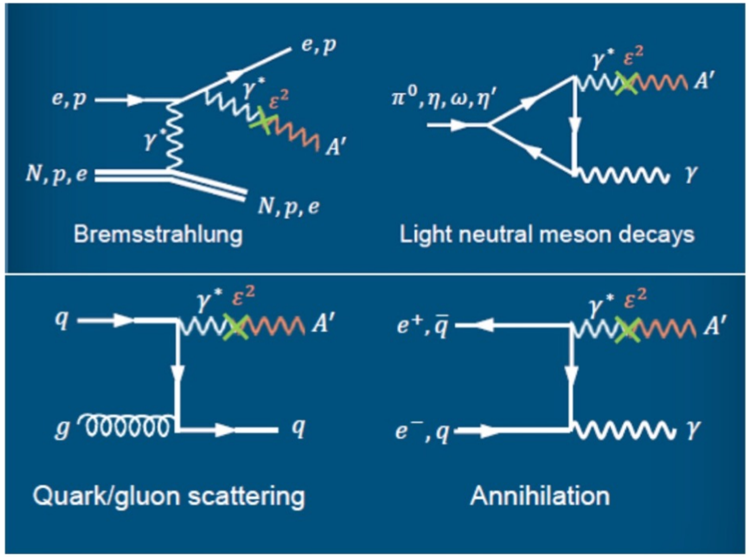
>50 journal papers on BSM with LHeC in recent years

Thanks to Hao Sun

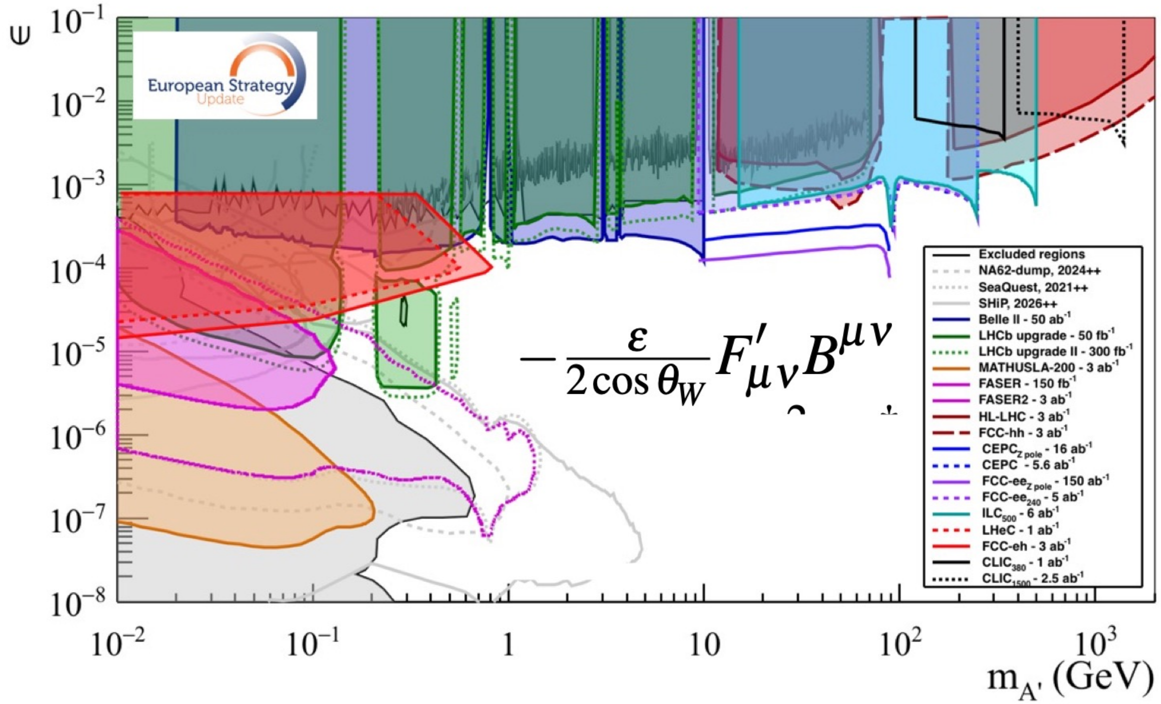
Monica D'Onofrio

Dark Photons

- Vector portal minimal models: have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.
- Quite versatile as can be produced in various ways
  - ep/eA/pp/pA/AA …



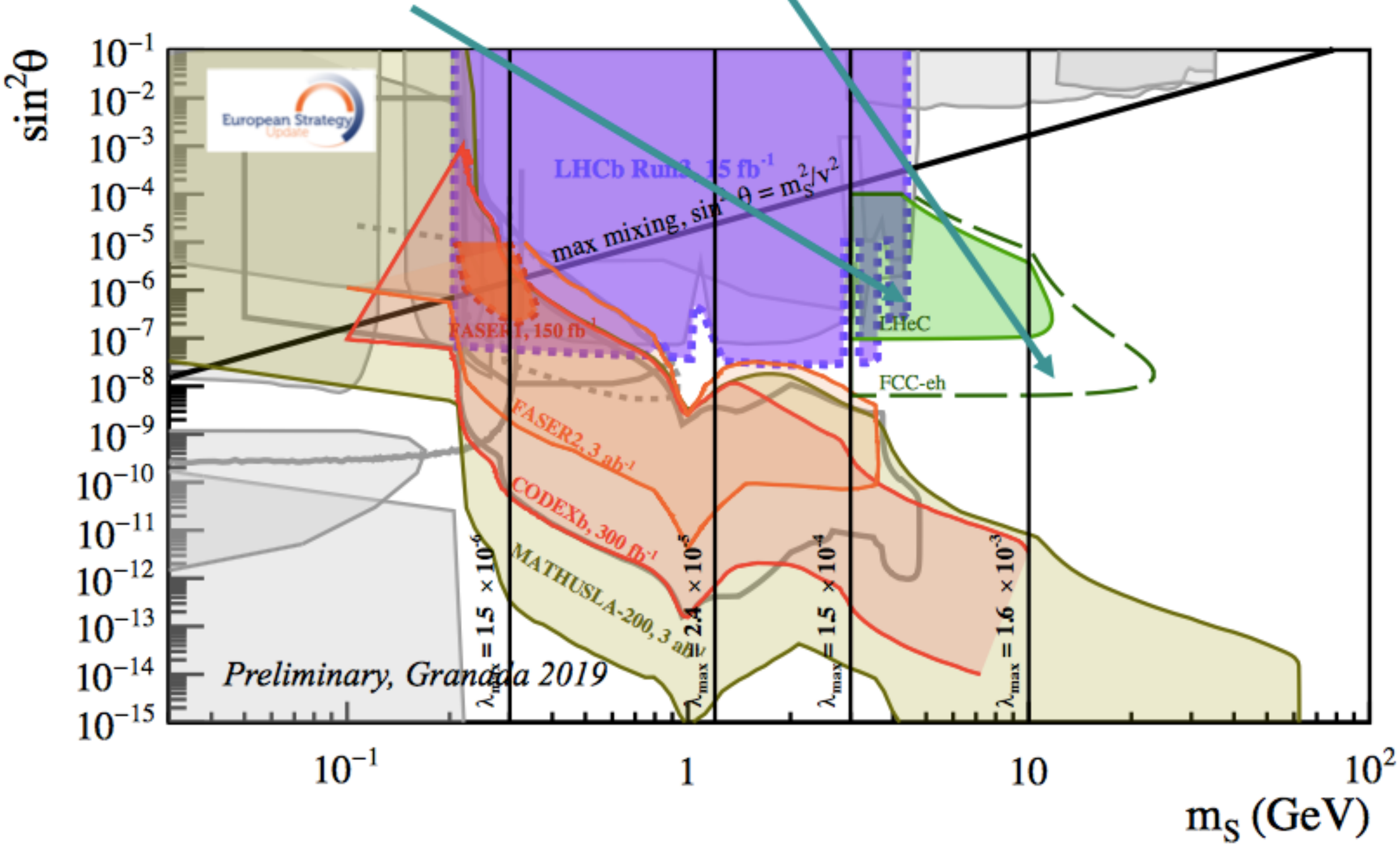
R. Jacobsson (CERN) LHC Operations Workshop, Evian, 2019



Scalar Portal: Dark Scalar

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

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



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

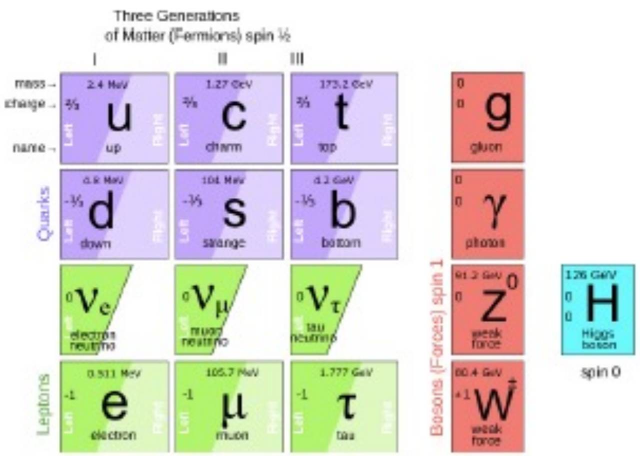
Method:
Higgs ⟶ SS
S ⟶ visible decays
(assuming fixed λ = 4x10^{-3})

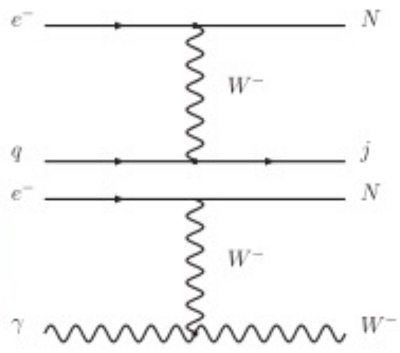
LHeC and FCC-eh can extend the reach beyond LHCb.

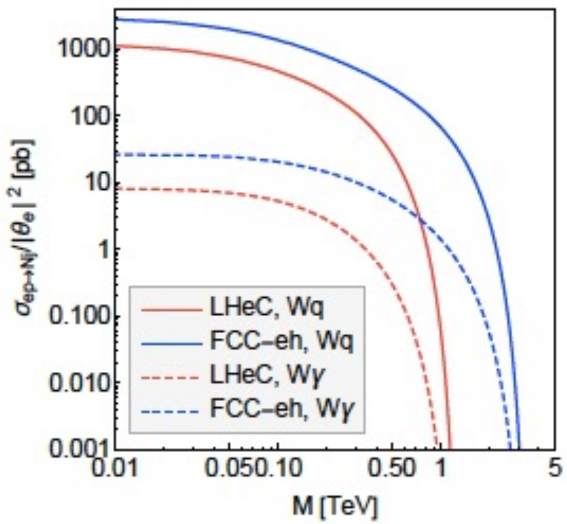
Sterile Neutrinos at ep colliders

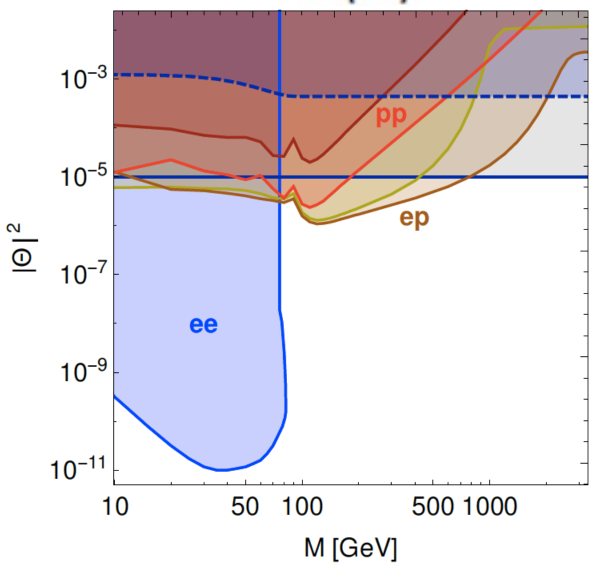
O.Fischer

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







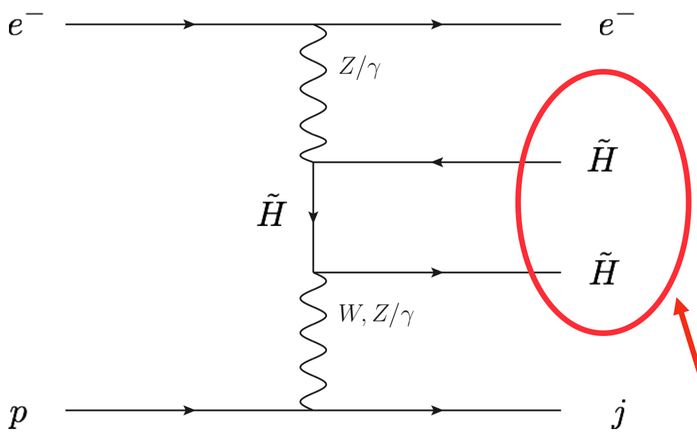


- Neutrino oscillations $\rightarrow$ type I seesaw
- Lowscale seesaw models allow large production xsections at colliders
- Present constraints: $|\theta_e| \leq 10^{-3}$
- Searches via lepton-flavor violating final states: μ +jets, $\mu\tau$ + jets
- Displaced vertex searches for heavy neutrino masses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

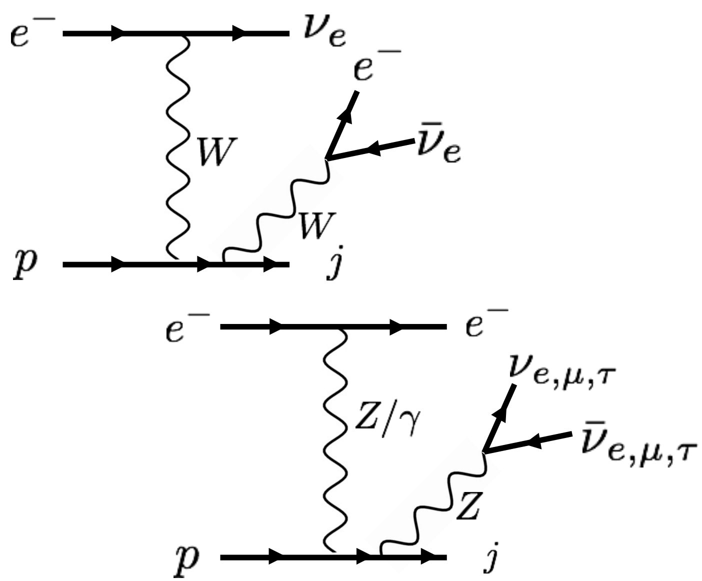
Higgsino search at FCC-eh

C. Han, R. Li, R. Pan, K. Wang, Phys. Rev. D 98, 115003 (2018)

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



Higgsino production

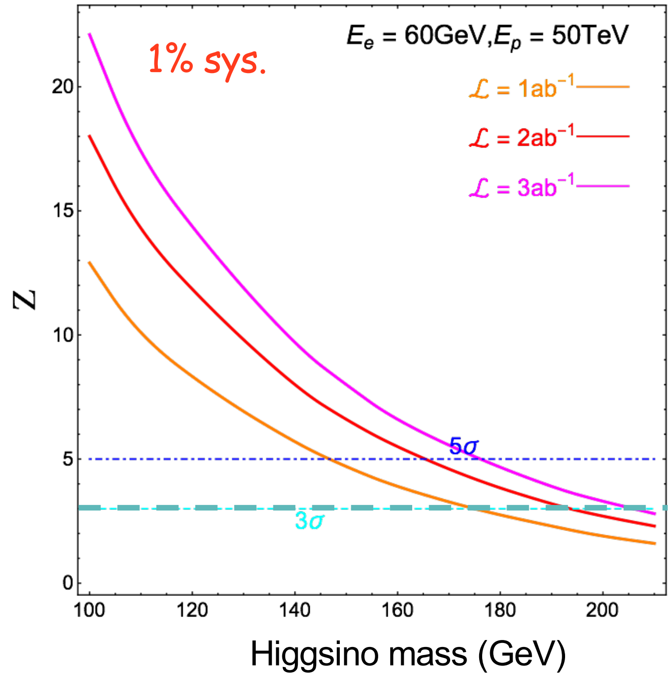


Standard model main backgrounds

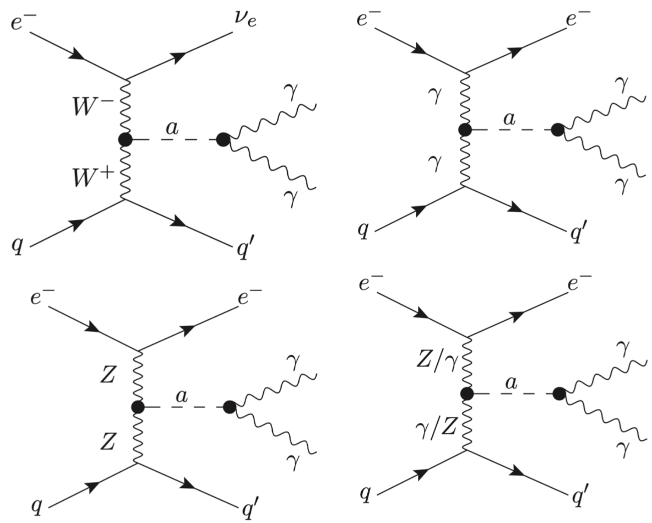
Typical signal: electron + jet + missing energy

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

preliminary result

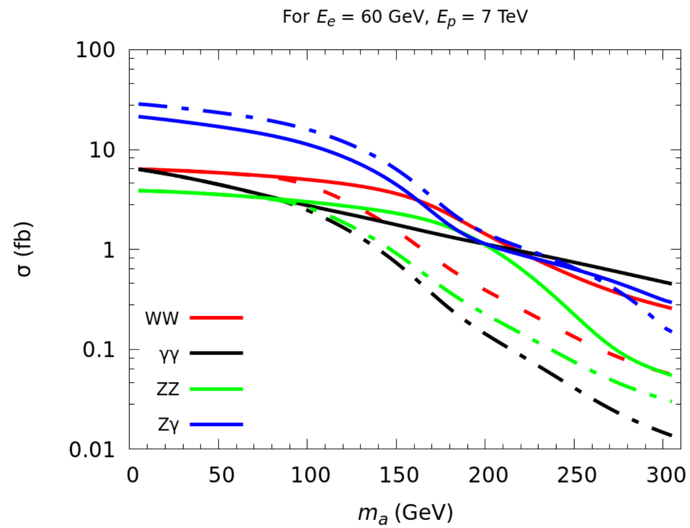


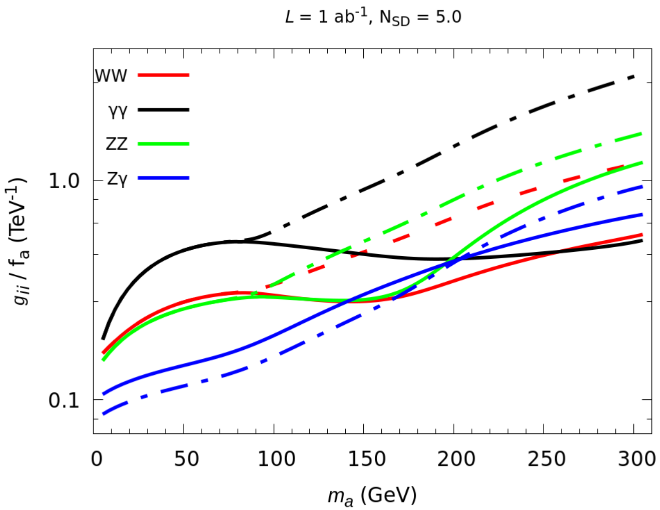
Axion-like particles at future e^-p collider; Mosala et al
Eur.Phys.J.C 84 (2024) 1, 44

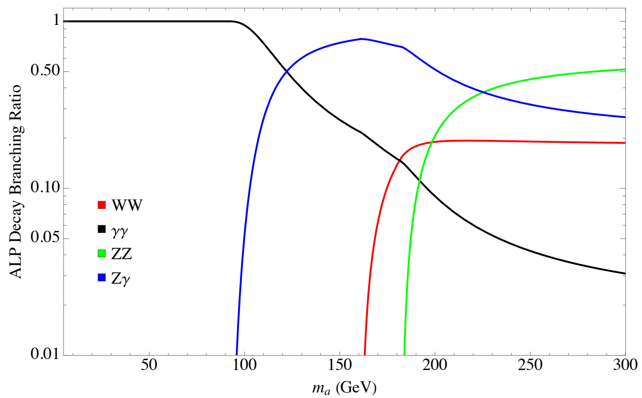


$$\mathcal{L}_{\text{eff}} \supset e^2 \frac{a}{f_a} g_{\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^2}{c_w s_w} \frac{a}{f_a} g_{Z\gamma} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{c_w^2 s_w^2} \frac{a}{f_a} g_{ZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2} \frac{a}{f_a} g_{WW} W_{\mu\nu} \tilde{W}^{\mu\nu}.$$

Case (I) coupling is set to 1 and others to 0 [solid lines]; and
Case (II), where all couplings g_{ij} are uniformly set to 1 [dashed]







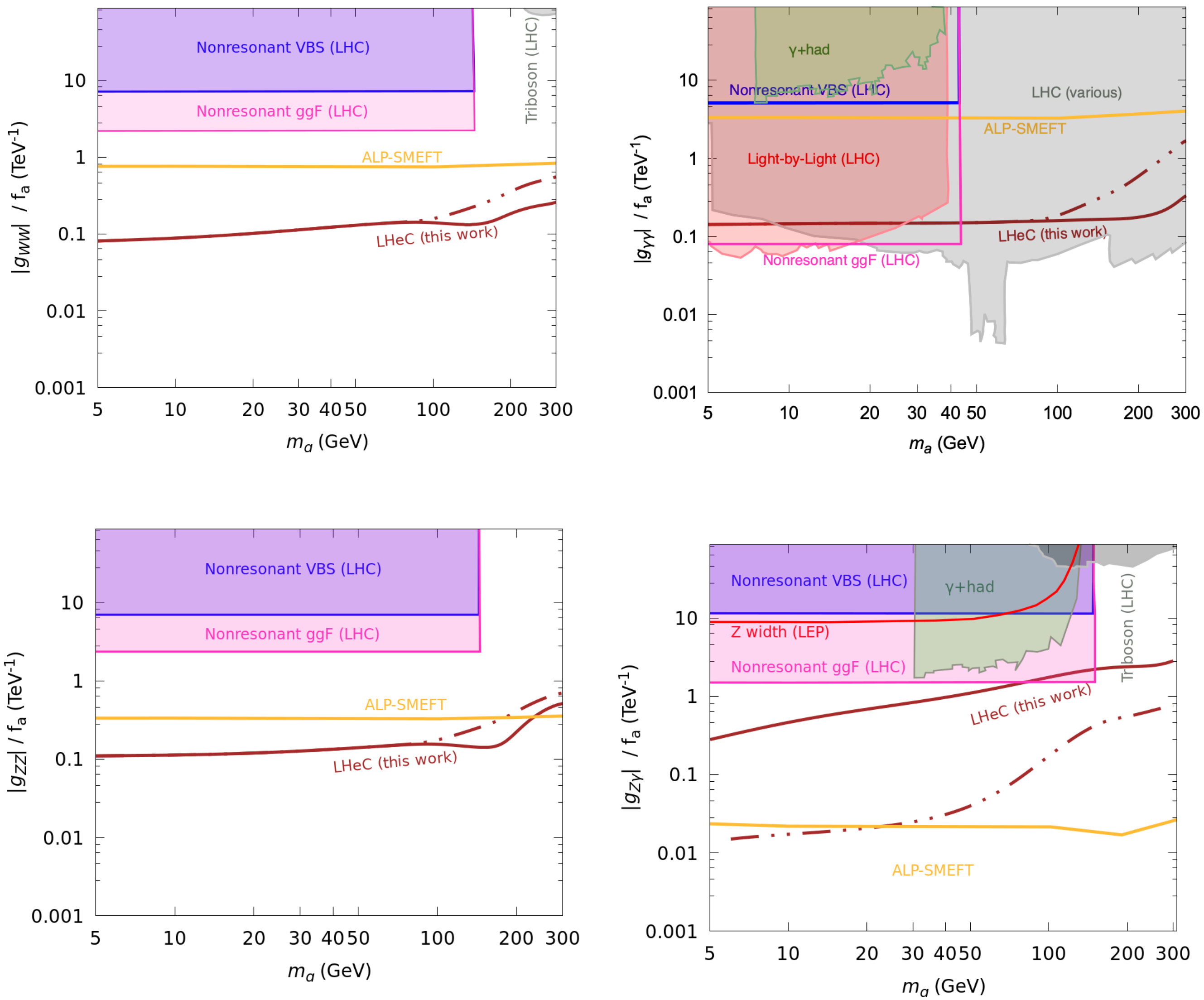
$$N_{\text{SD}} = \frac{S}{\sqrt{S + B + (\delta_s \cdot S)^2 + (\delta_s \cdot B)^2}},$$

Axion-like particles at future $e^{-}p$ collider; Mosala et al
Eur.Phys.J.C 84 (2024) 1, 44

$$\chi^2 = \sum_{k=1}^{n} \left(\frac{N_k(g_{ij}) - N_k^{\mathrm{SM}}}{\Delta N_k} \right)^2.$$

$$\Delta N_k = \sqrt{N_k^{\mathrm{SM}} \left(1 + \delta_s^2 N_k^{\mathrm{SM}}\right)}.$$

95% CL; $\delta_S = 5\%$; $L = 1\ \mathrm{ab}^{-1}$



Case (I) coupling is set to 1 and others to 0 [solid lines]; and

Case (II), where all couplings g_{ij} are uniformly set to 1 [dashed]

Overall the limits found in this work performs better sensi- tivity for all three ALP couplings, namely, g_{WW}, g_{ZZ} and $g_{Z\gamma}$ comparing to available studies in different collider scenario, whereby, the limits on $g_{\gamma\gamma}$ are competitive with respect to few cases. In ALP-SMEFT bounds, the performance of $g_{Z\gamma}$ is relatively poor.

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)*

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, in particular in the space of precision measurements
- Combining pp with ep, turns the LHC into a precision machine
  - Reach <1%-<2% precision for HL-LHC/LHeC, depending on coupling
  - Competitive and complementary to e^+e^-
- Broad access to Physics Beyond the SM with unique opportunities and complementarities
  - Compositeness, leptoquarks, anomalous gauge couplings, vector leptons, dark sector, heavy neutrinos, SUSY, etc...