BSM physics at the LHeC and the FCC-eh

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DESY
University of Hamburg

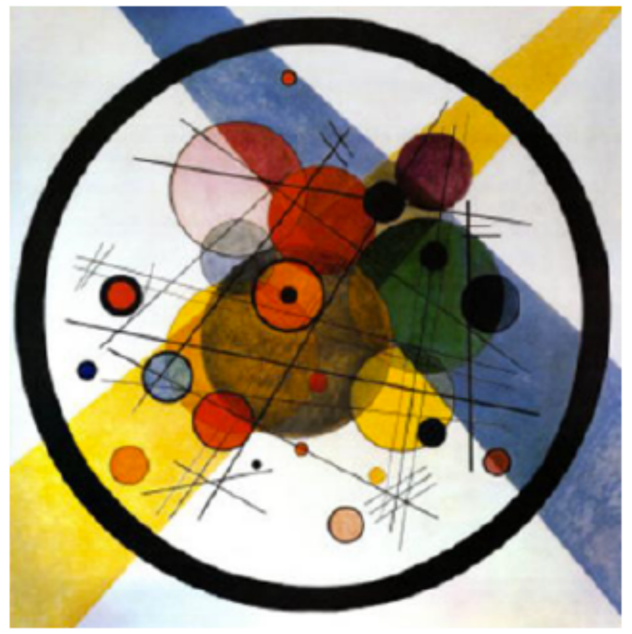
Thanks to Monica D'Onofrio!

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

European Physical Society Conference on High Energy Physics

EPS-HEP 2025



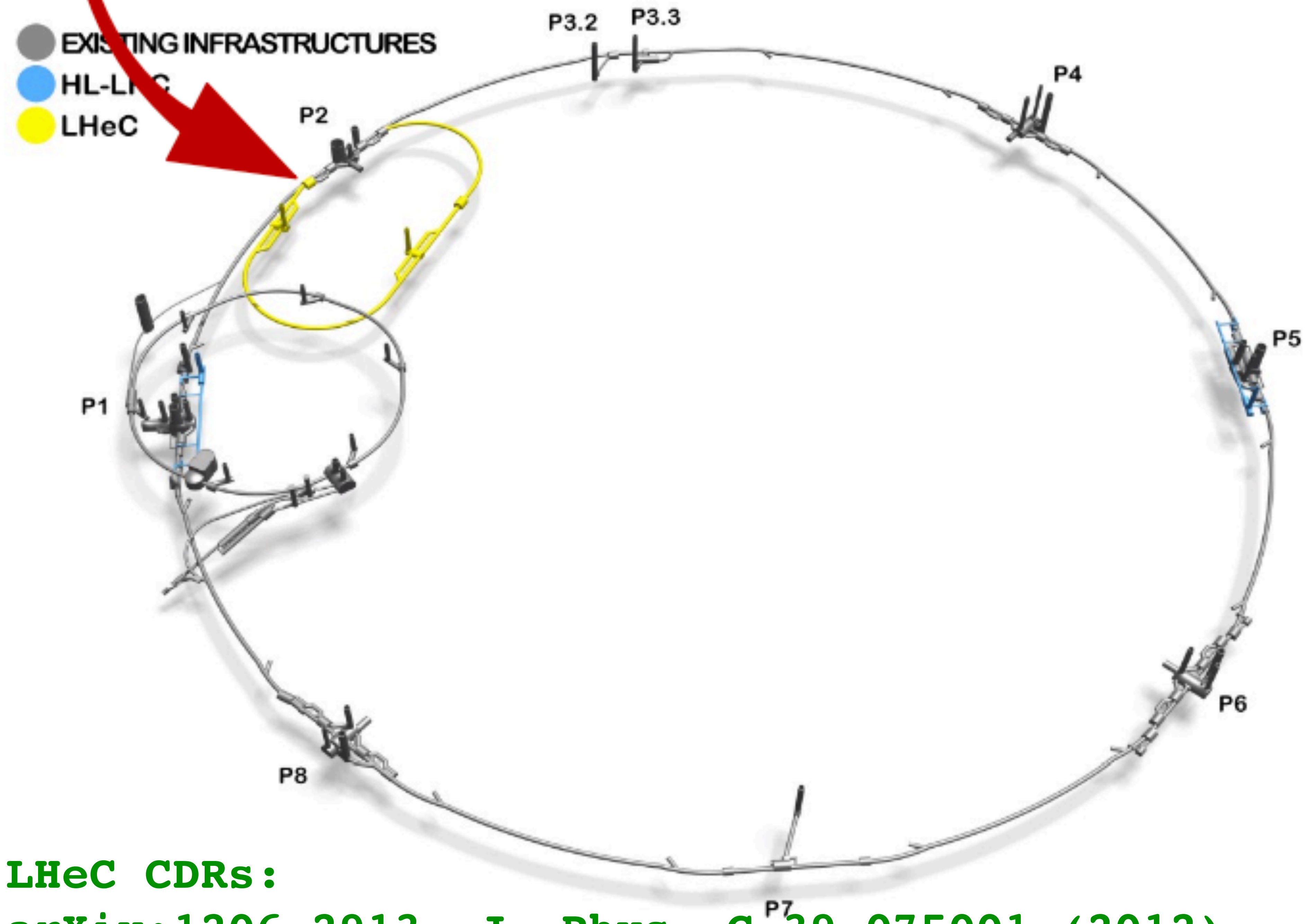
Circles in a circle
W Kandinsky

Marseille, France
8 July 2025

Linac-Ring Collider, LHeC and FCC-eh

LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC ($\gtrsim$Run5)

- operated **after** **HL-LHC data taking**



LHeC CDRs:
arXiv:1206.2913, J. Phys. G 39 075001 (2012)
arXiv:2007.14491, J. Phys. G 48, 11, 110501 (2021

arXiv:2503.17727

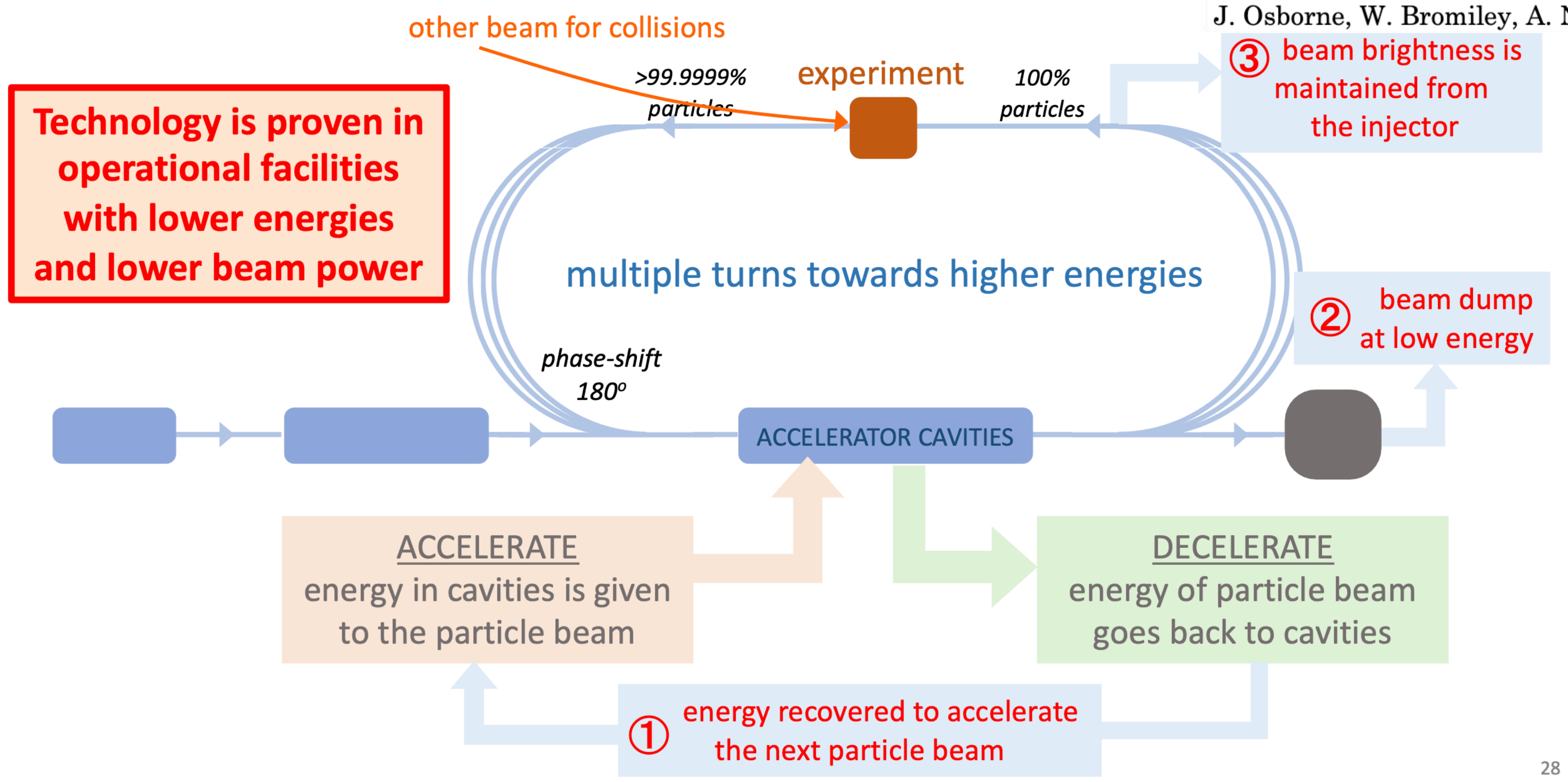
- operated **synchronously** with **FCC-hh**

L_{int} = 1-2 ab^{-1} (1000×HERA!)
(integrated lumi of 180 fb^{-1} per year)

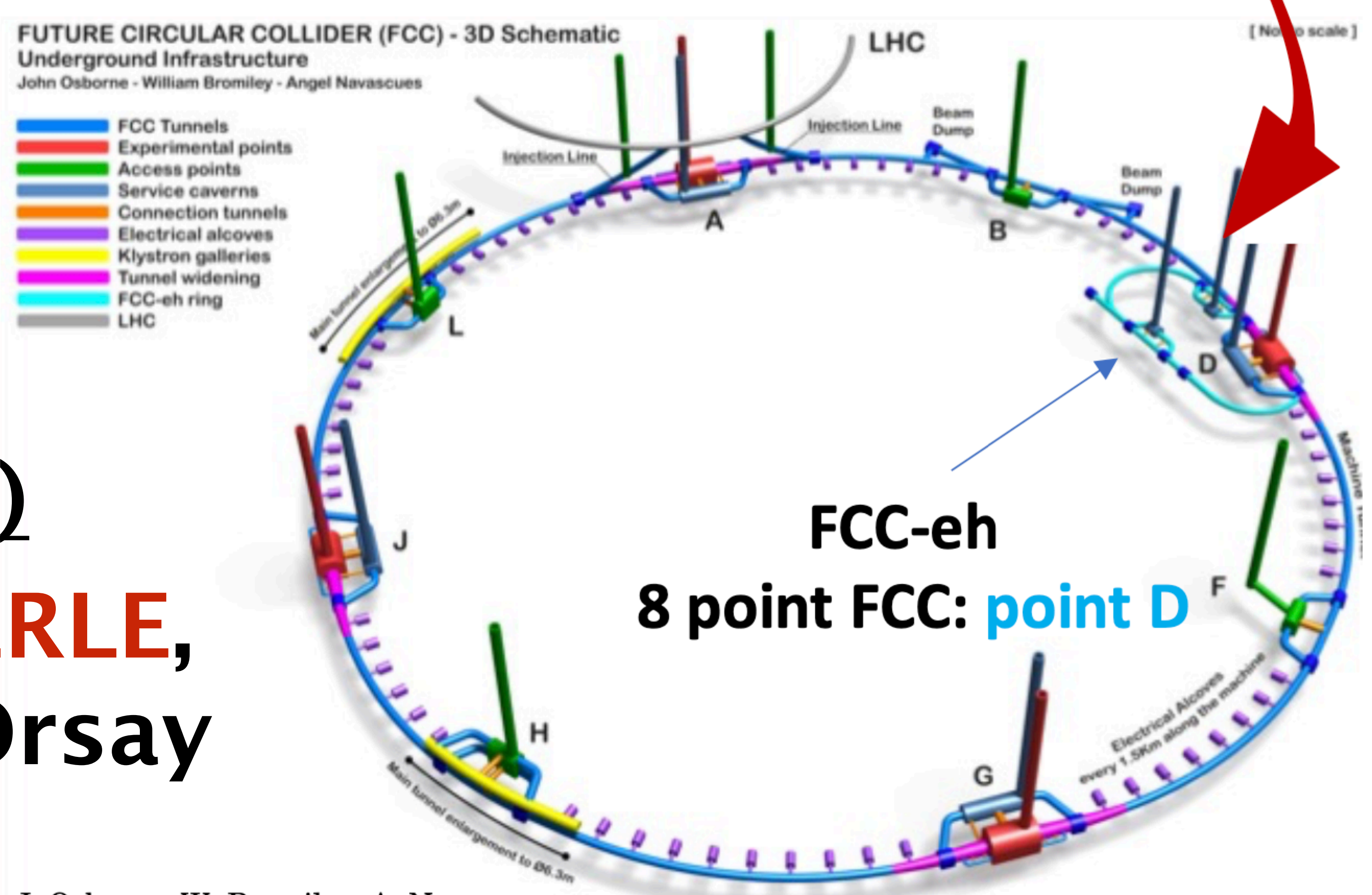
Energy Recovering Linac (ERL)

- **Technological innovation: PERLE, under construction@IJCLab, Orsay**

The principle of Energy Recovery



FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



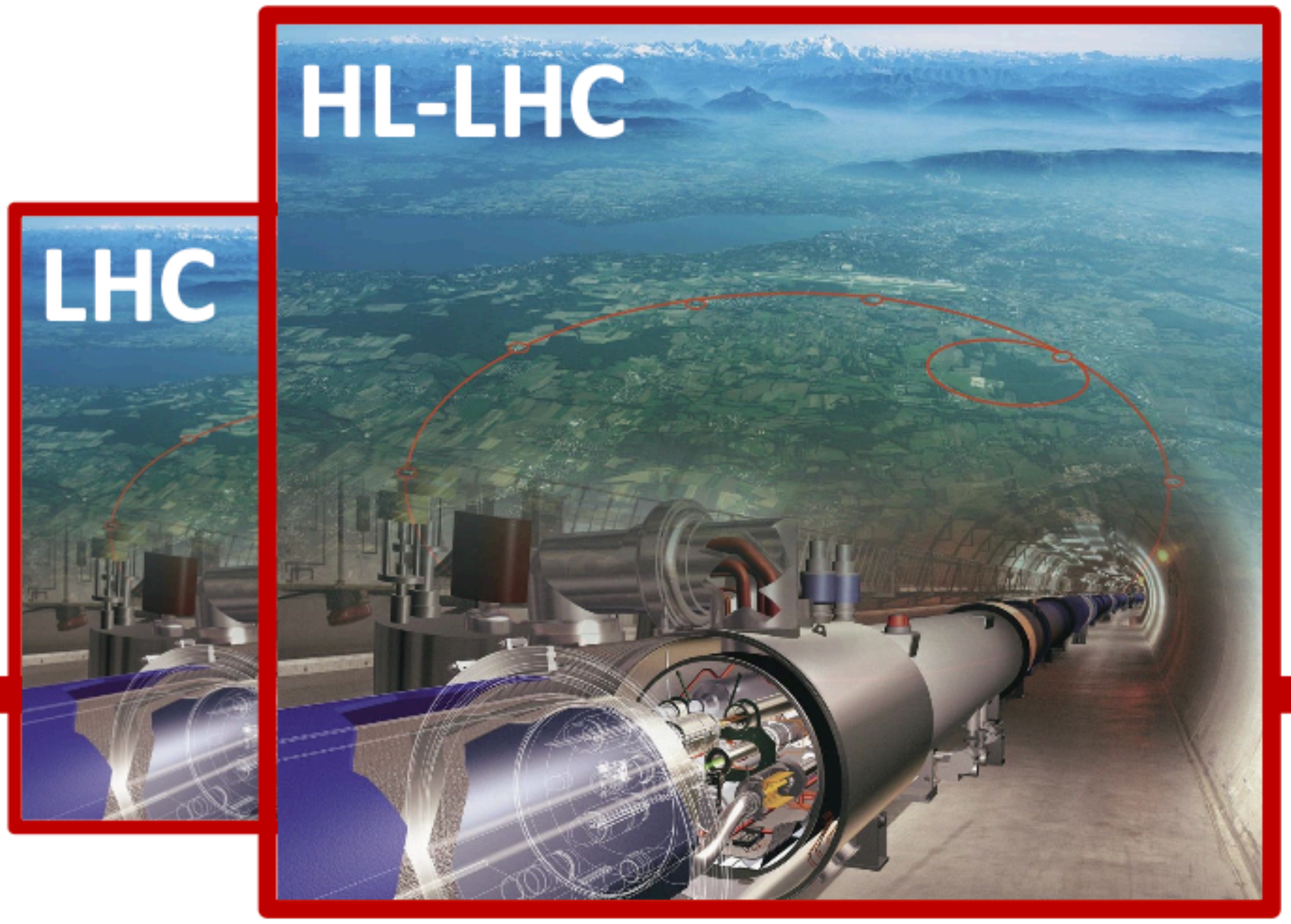
J. Osborne, W. Bromiley, A. Navascues

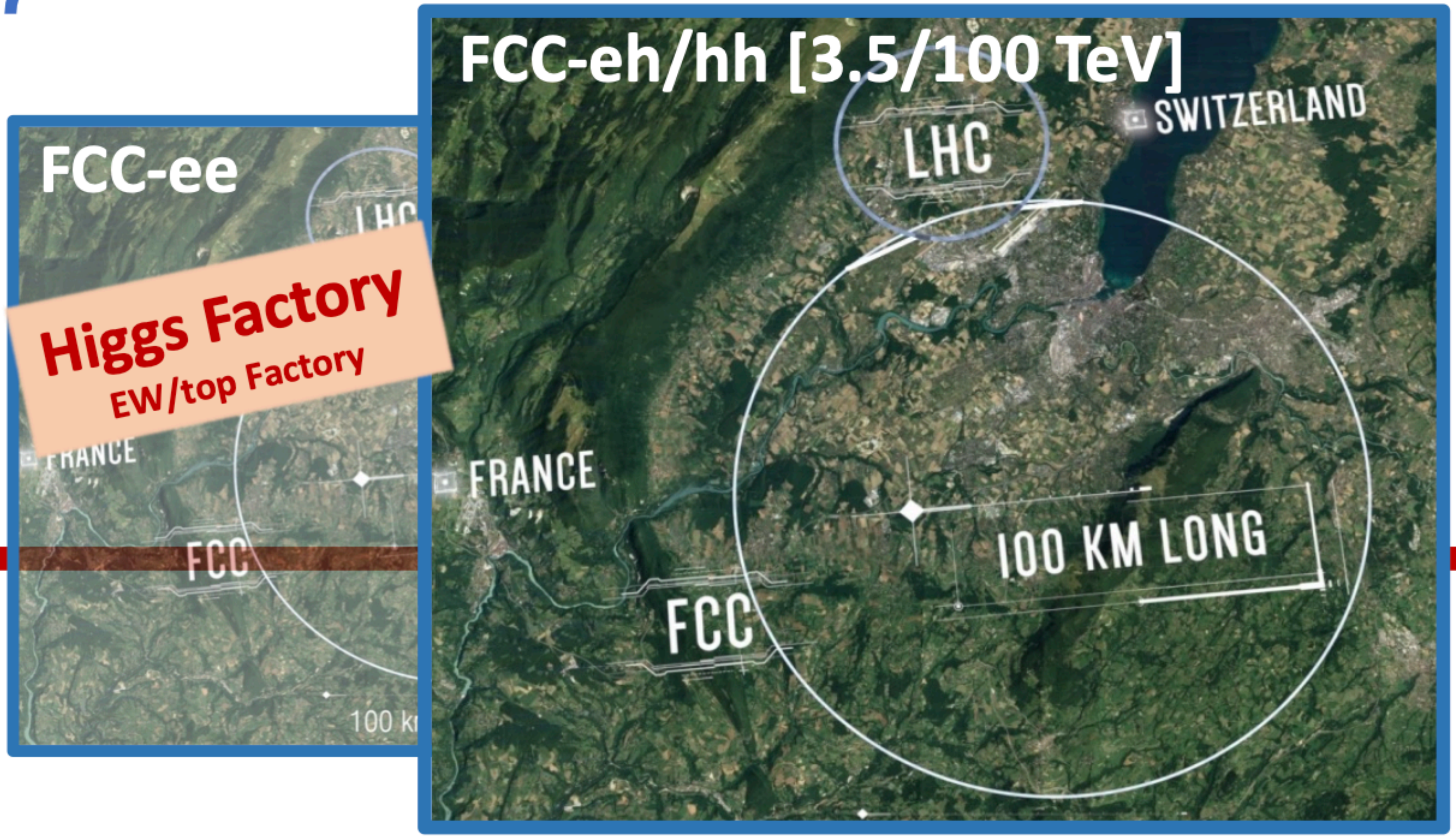
FCC CDR:
Eur. Phys. J. C 79, no. 6, 474 (2019) - Physics
Eur. Phys. J. ST 228, no. 4, 755 (2019) - FCC-hh/eh

“Bridge” between current and future major collider @ CERN

Current flagship (27km)
impressive program up to 2041

Future Circular Collider (FCC)
big sister future ambition (90km), beyond 2048





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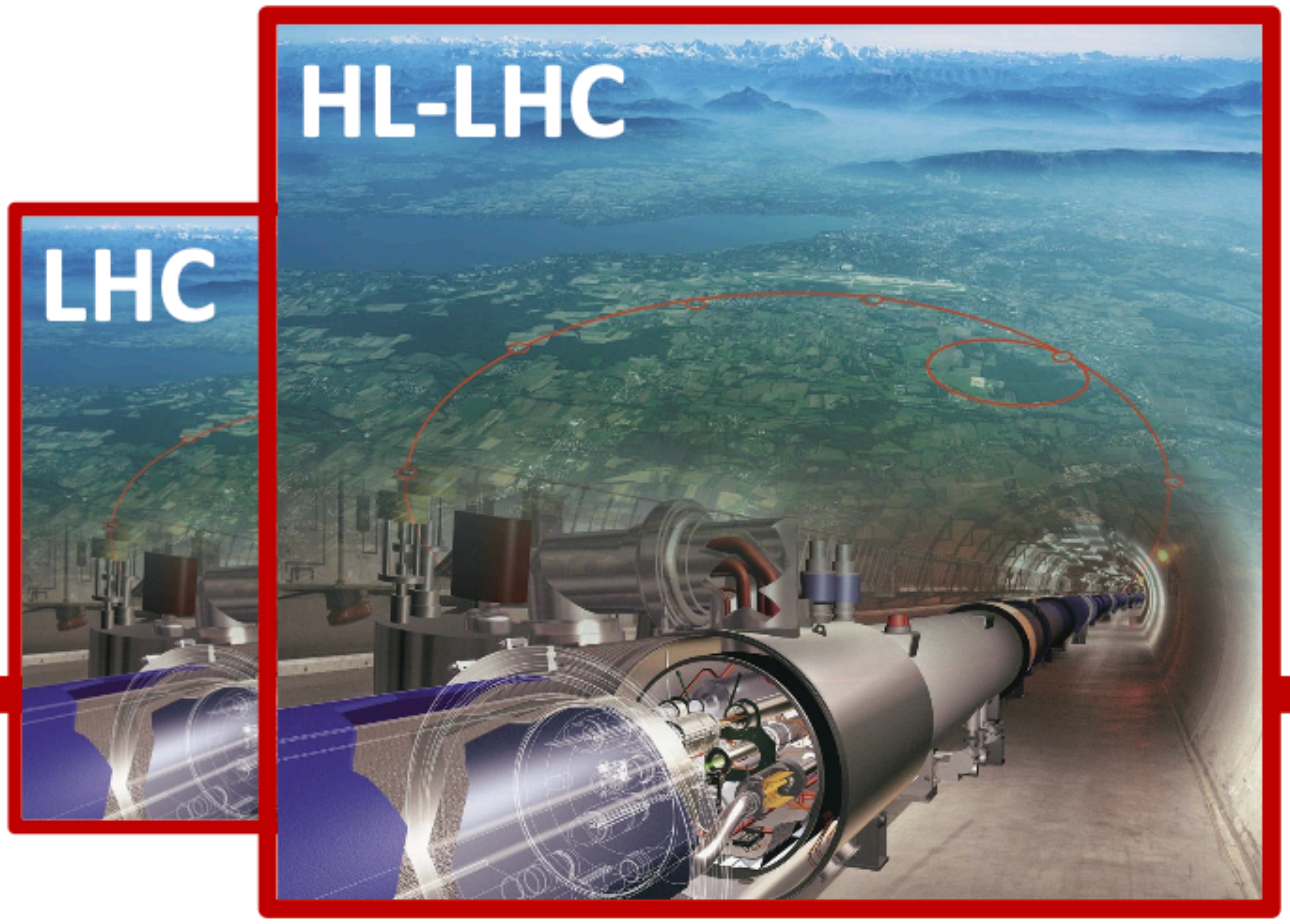
cost ~2 BCHF ⊕ one detector
operational cost similar to HL-LHC



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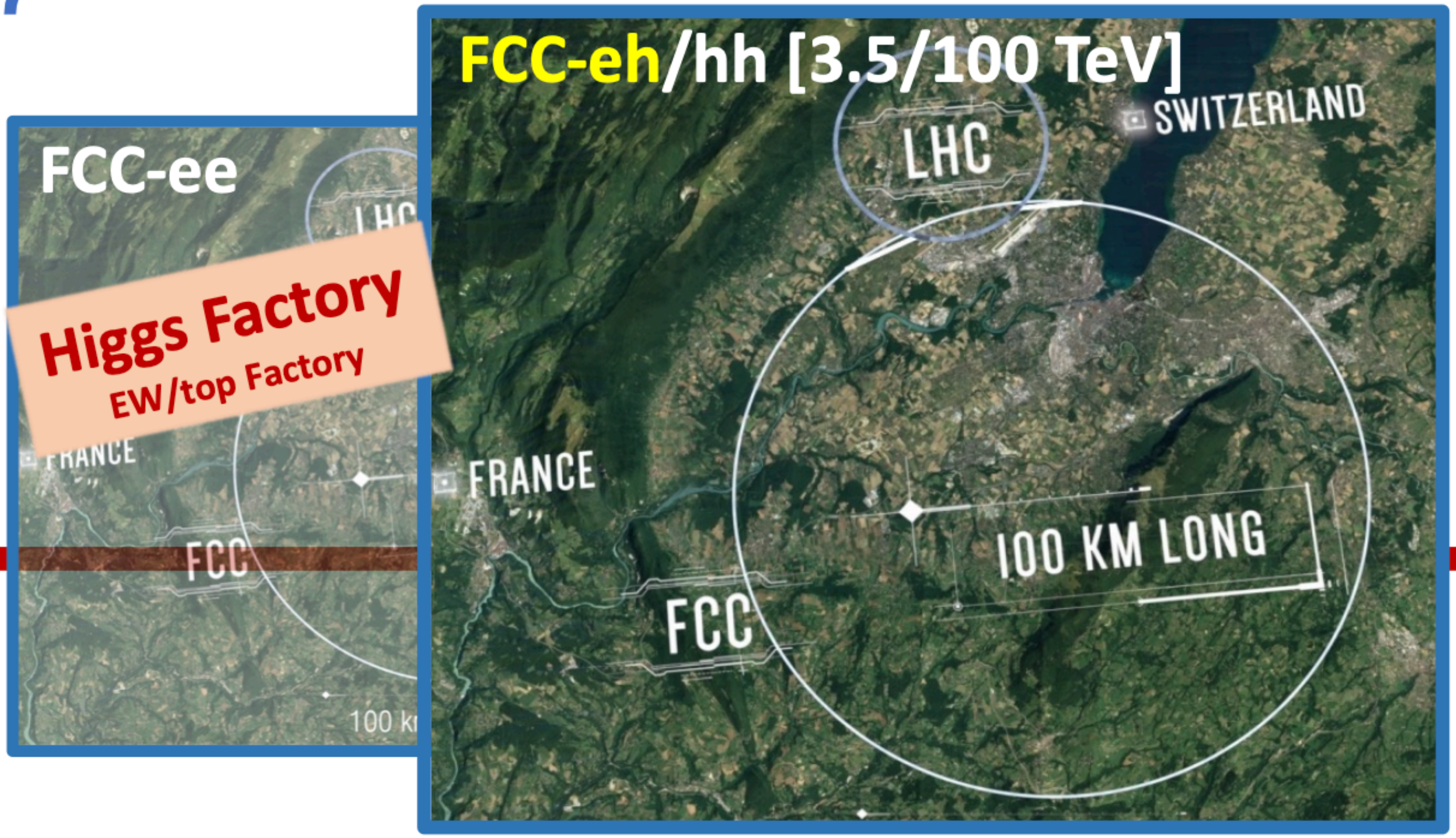
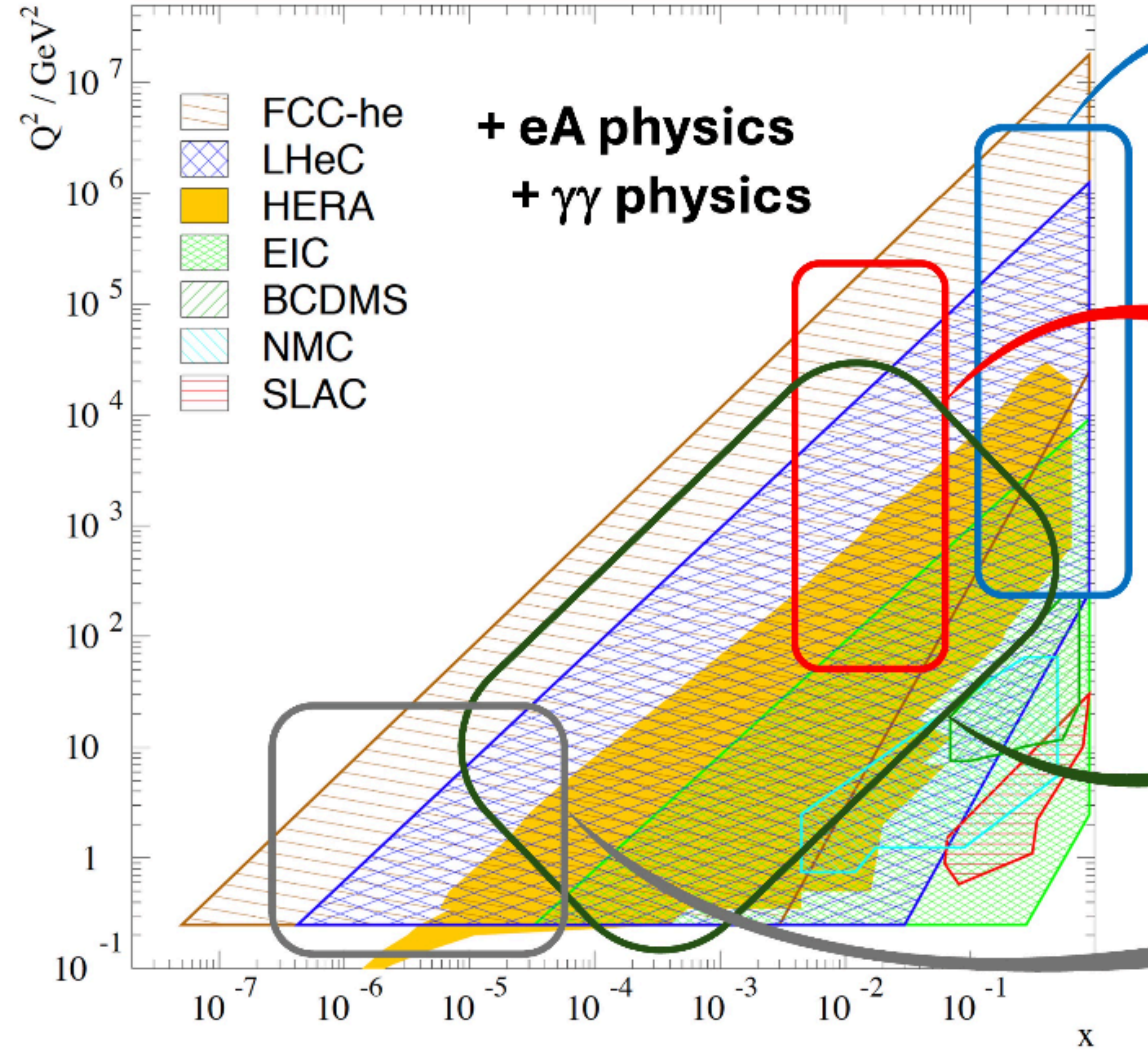


ep-option after HL-LHC: ***LHeC***
6y @ 1.2 TeV (1ab^{-1})

arXiv: 2503.17727 [hep-ex]

Deep Inelastic Scattering at the Energy Frontier

1.2 TeV ep collisions cover the (Q^2,x) plane → General Purpose Experiment



direct searches for new physics

unique environment: eq only EW interactions
e.g. heavy ν, dark γ, axion-like particles

EW, Higgs and top quark physics

$\Delta m_W \sim 3$ MeV, $\Delta|V_{tb}| \sim 1\%$, top-quark FCNC
$\Delta \sin^2\theta_W^{eff} \sim 0.0002$ (full scale-dependency)
weak neutral couplings to light quarks ~ 1%
Higgs couplings largely improved wrt HL-LHC
improved SMEFT fits (accuracy & degeneracy)

precision QCD physics

$\Delta\alpha_s \sim 0.14\%$ & running of α_s
PDFs covering a vast kinematic range

non-linear QCD physics

a new discovery frontier

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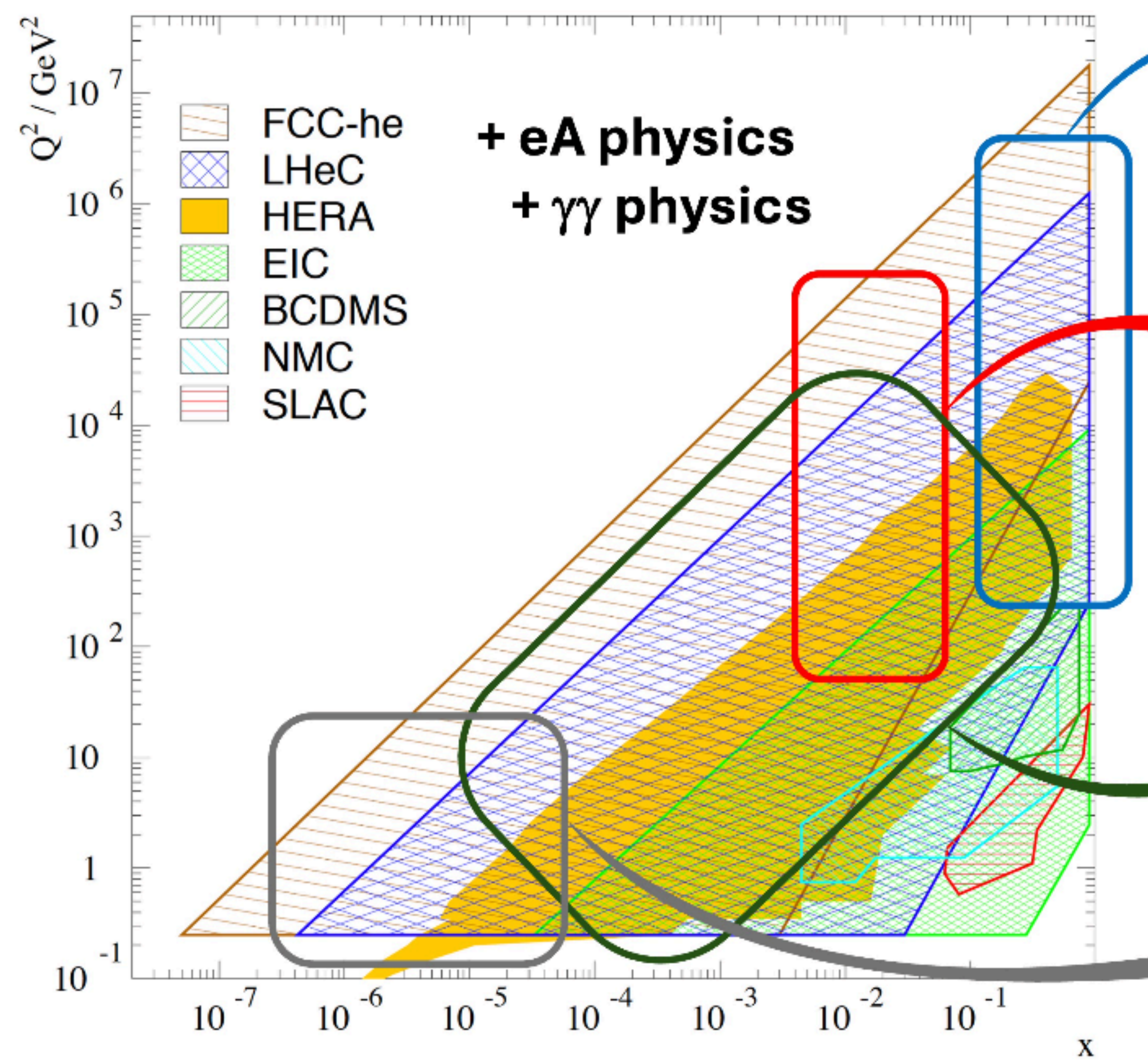

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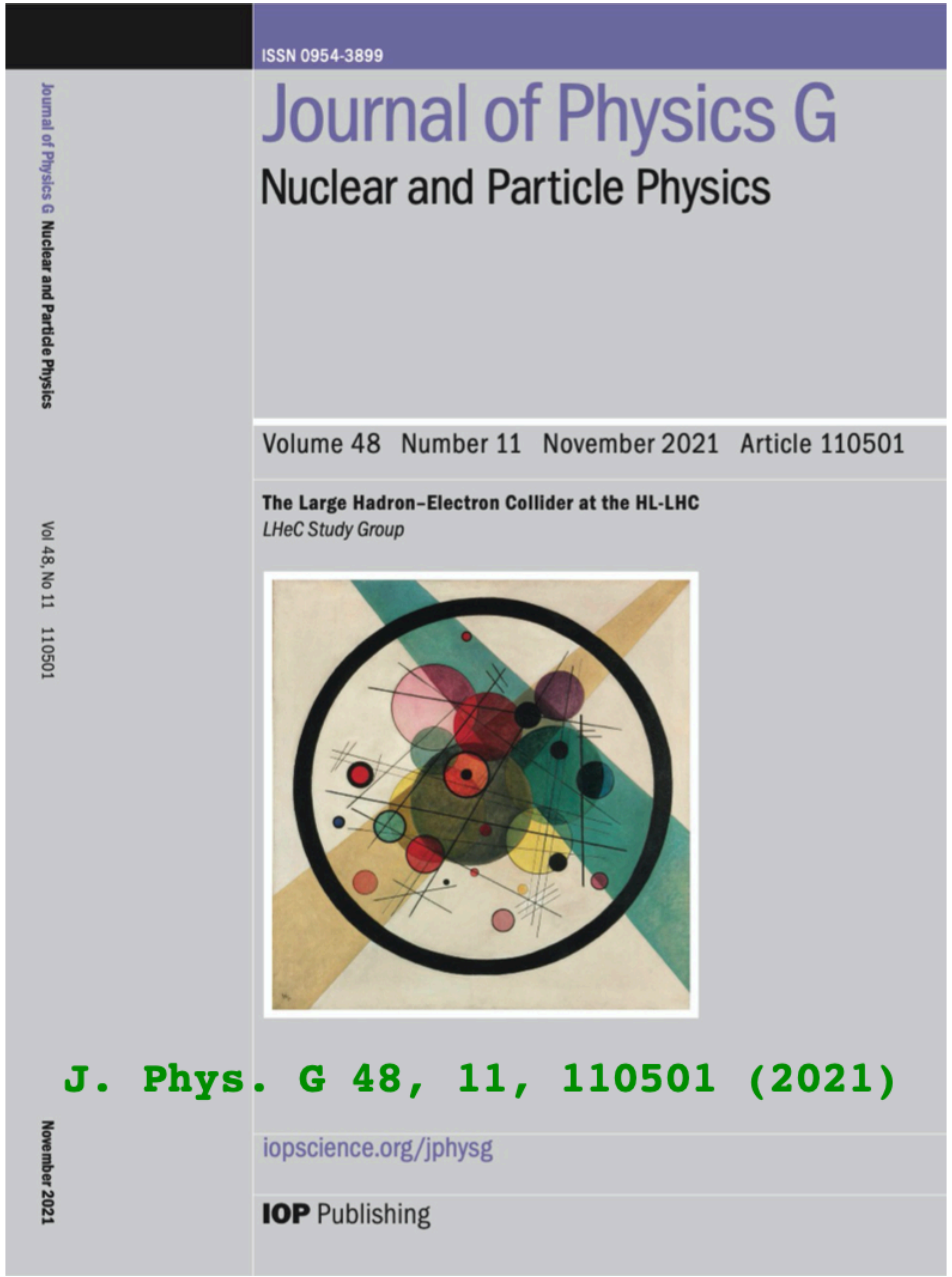
The Large Hadron-Electron Collider at the HL-LHC

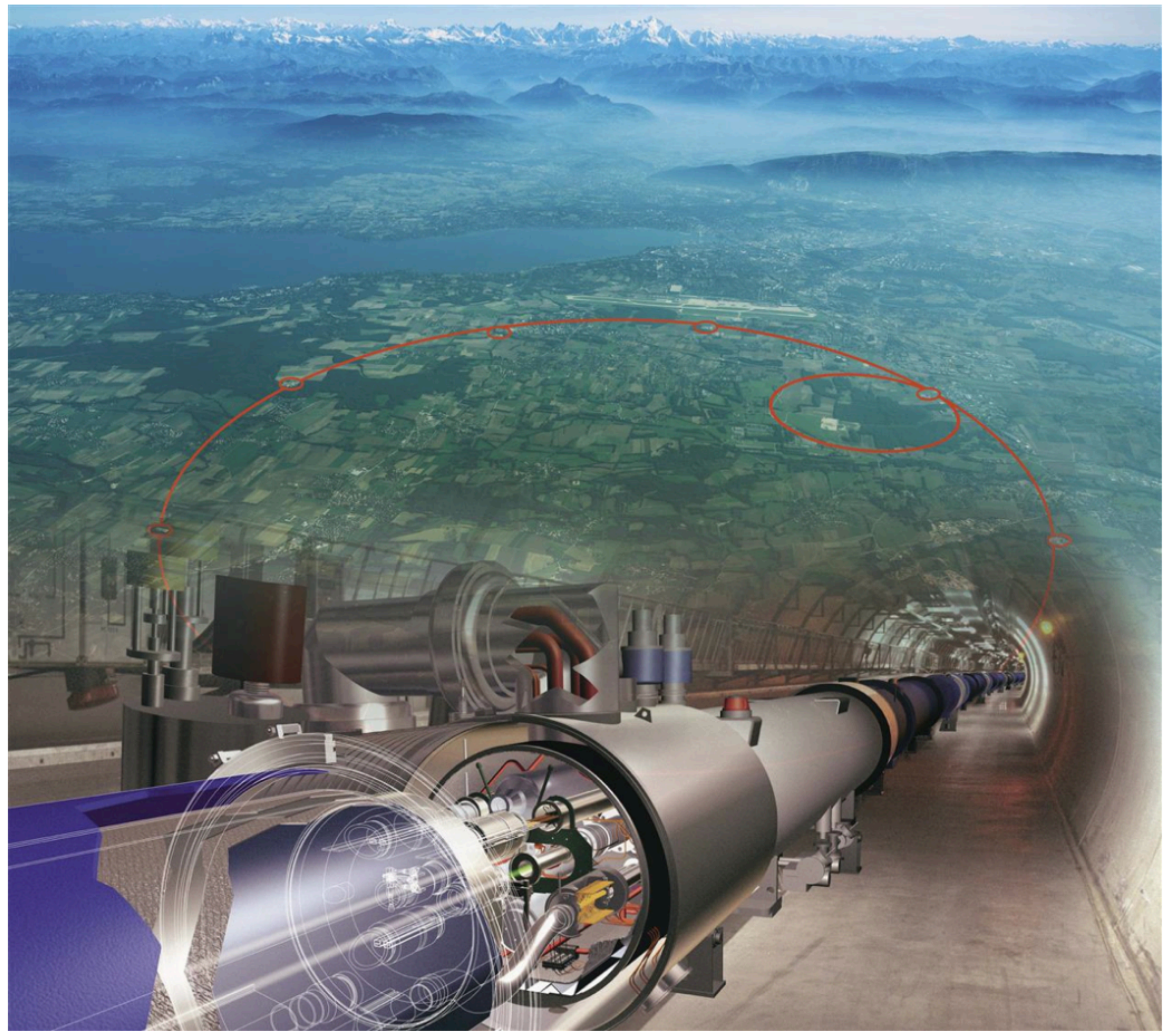


J. Phys. G 48, 11, 110501 (2021)

5 pages summary:

ECFA
European Committee for Future Accelerators

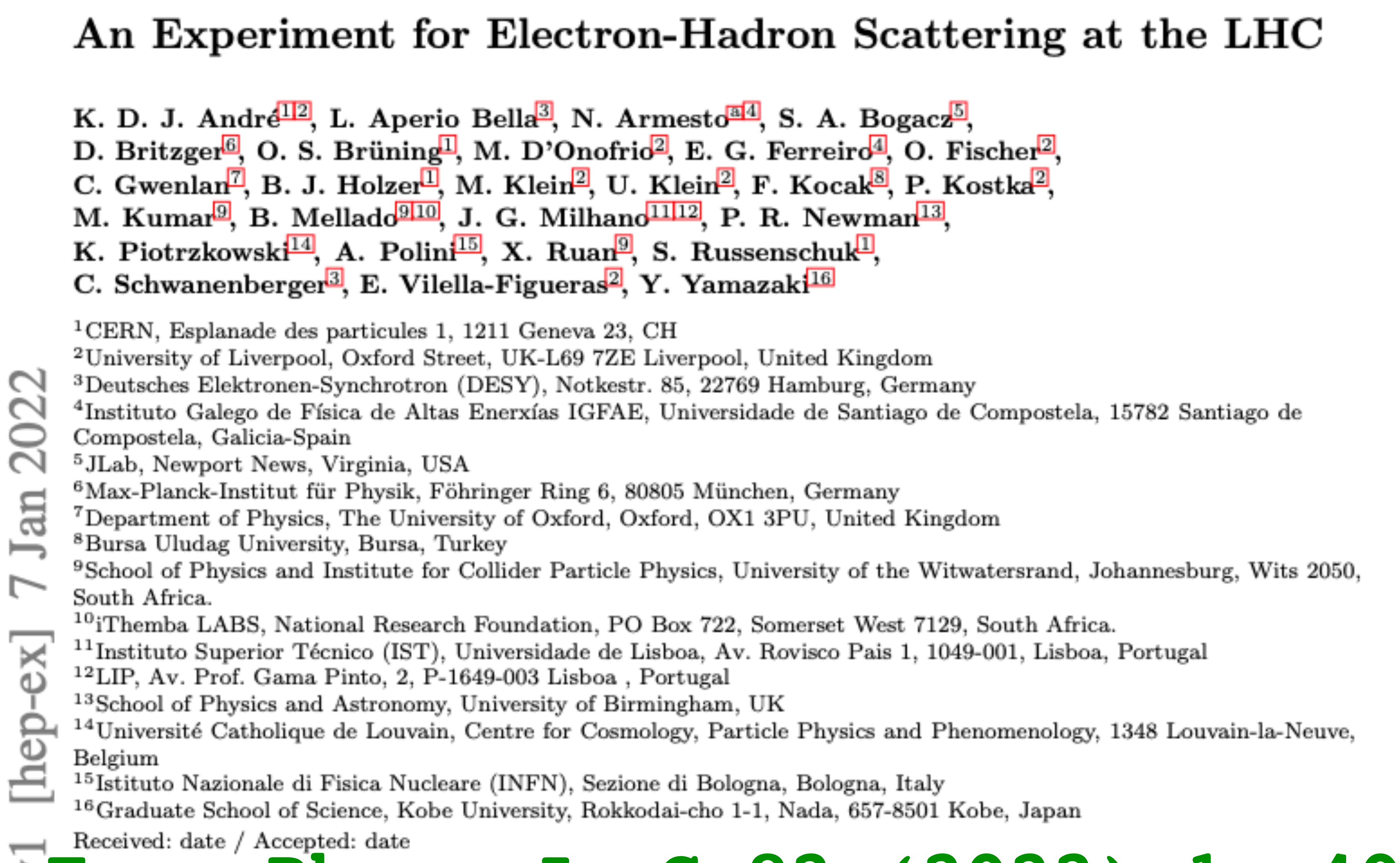
ECFA Newsletter #5



O. Brüning, M. Klein

Following the Plenary ECFA meeting, 13 July 2020
https://indico.cern.ch/event/933318/
Summer 2020

https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf



An Experiment for Electron-Hadron Scattering at the LHC

K. D. J. André[1,12], L. Aperio Bella[3], N. Armesto[4], S. A. Bogacz[5], D. Britzger[6], O. S. Brüning[1], M. D'Onofrio[2], E. G. Ferreiro[4], O. Fischer[2], C. Gwenlan[7], B. J. Holzer[1], M. Klein[2], U. Klein[2], F. Kocak[8], P. Kostka[2], M. Kumar[9], B. Mellado[9,10], J. G. Milhano[11,12], P. R. Newman[13], K. Piotrzkowski[14], A. Polini[15], X. Ruan[9], S. Russenschuk[1], C. Schwanenberger[3], E. Vilella-Figueras[2], Y. Yamazaki[16]

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[4]Instituto Galego de Física de Altas Enerxías IGFAE, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia-Spain
[5]JLab, Newport News, Virginia, USA
[6]Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
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[10]iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa.
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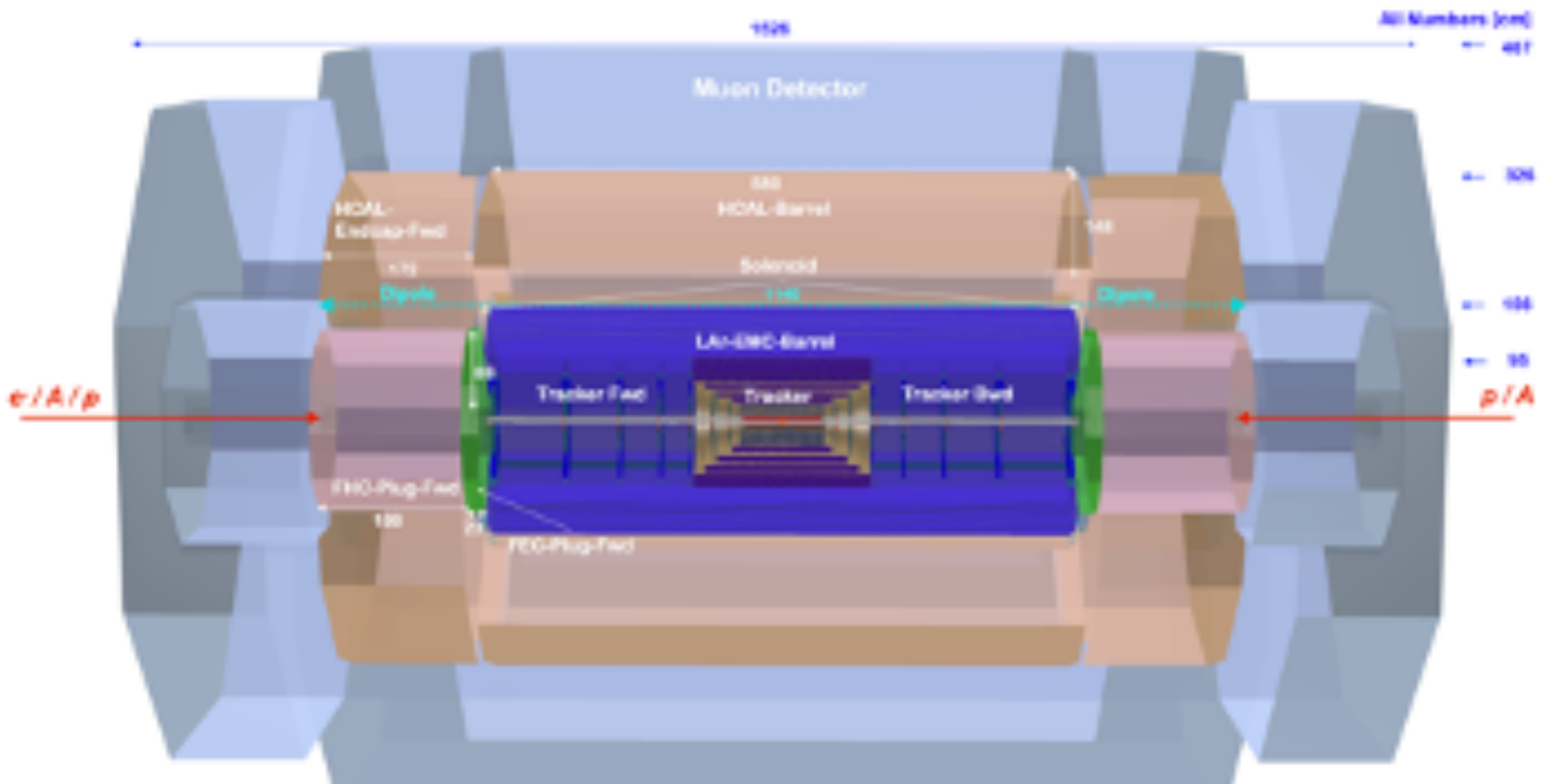
[13]School of Physics and Astronomy, University of Birmingham, UK
[14]Université Catholique de Louvain, Centre for Cosmology, Particle Physics and Phenomenology, 1348 Louvain-la-Neuve, Belgium
[15]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bologna, Bologna, Italy
[16]Graduate School of Science, Kobe University, Rokkodai-cho 1-1, Nada, 657-8501 Kobe, Japan

Received: date / Accepted: date

v1 [hep-ex] 7 Jan 2022

Eur. Phys. J. C 82 (2022) 1, 40



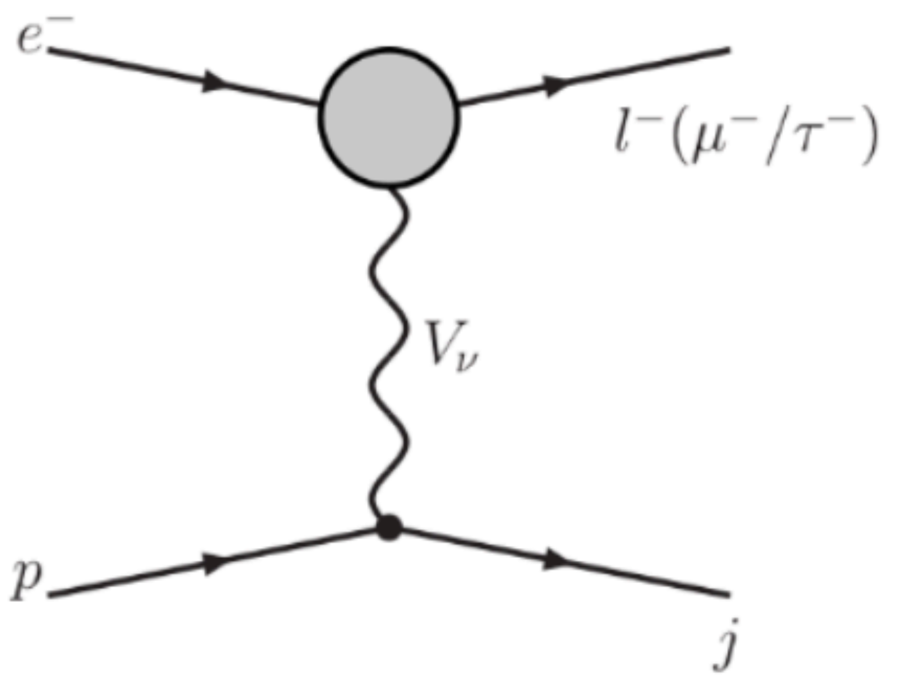
novel concept of a detector to alternately serve eh and hh collisions/physics

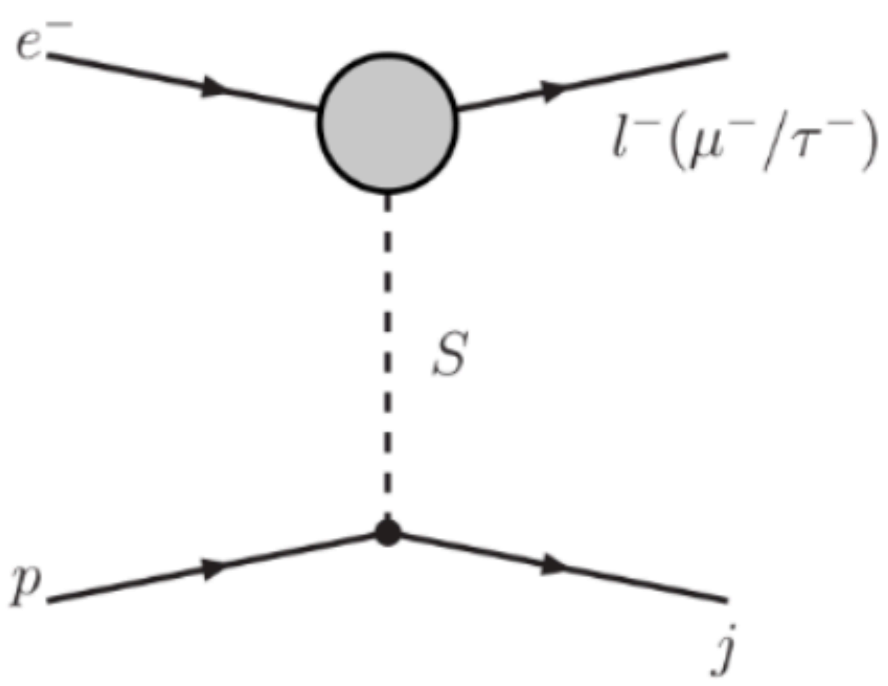
Bridge project: 2503.17727 [hep-ex]

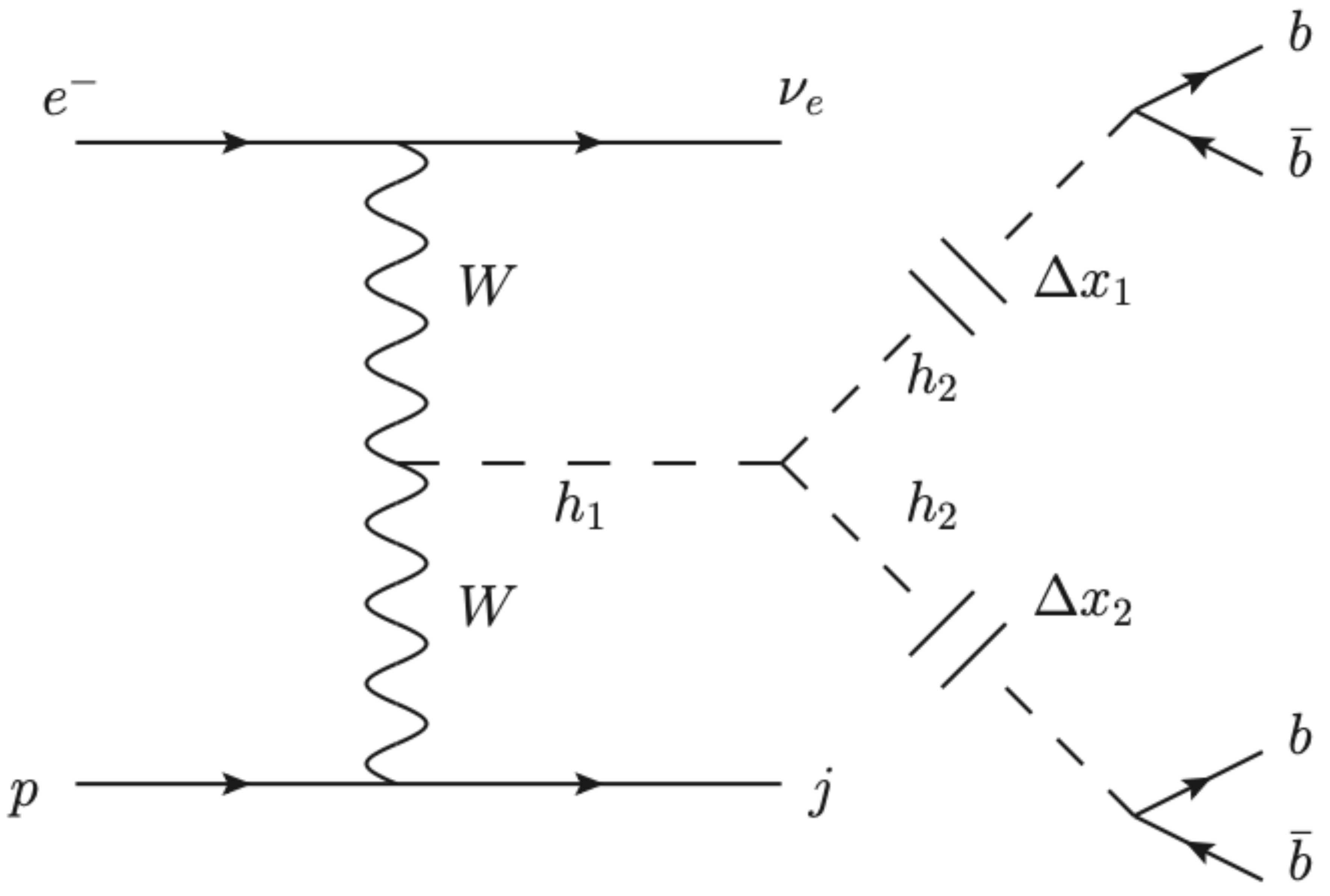
Complementary searches for new phenomena

+others published afterwords
leptophilic DM, non-resonant BSM
di-Higgs, heavy majorana neutrino,
exotics higgs ...

LHeC and FCC CDRs: and several dedicated publications



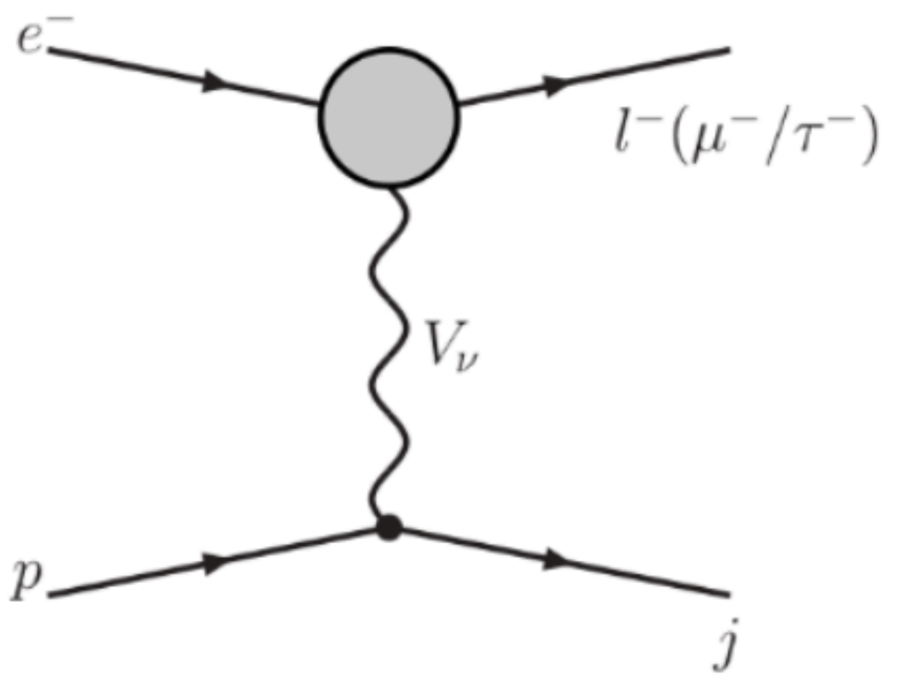


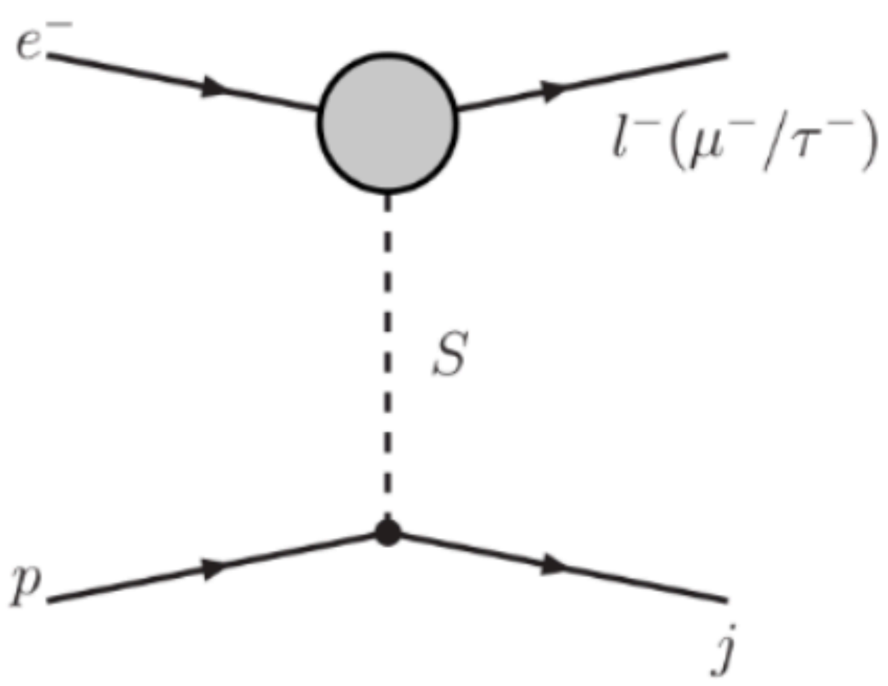


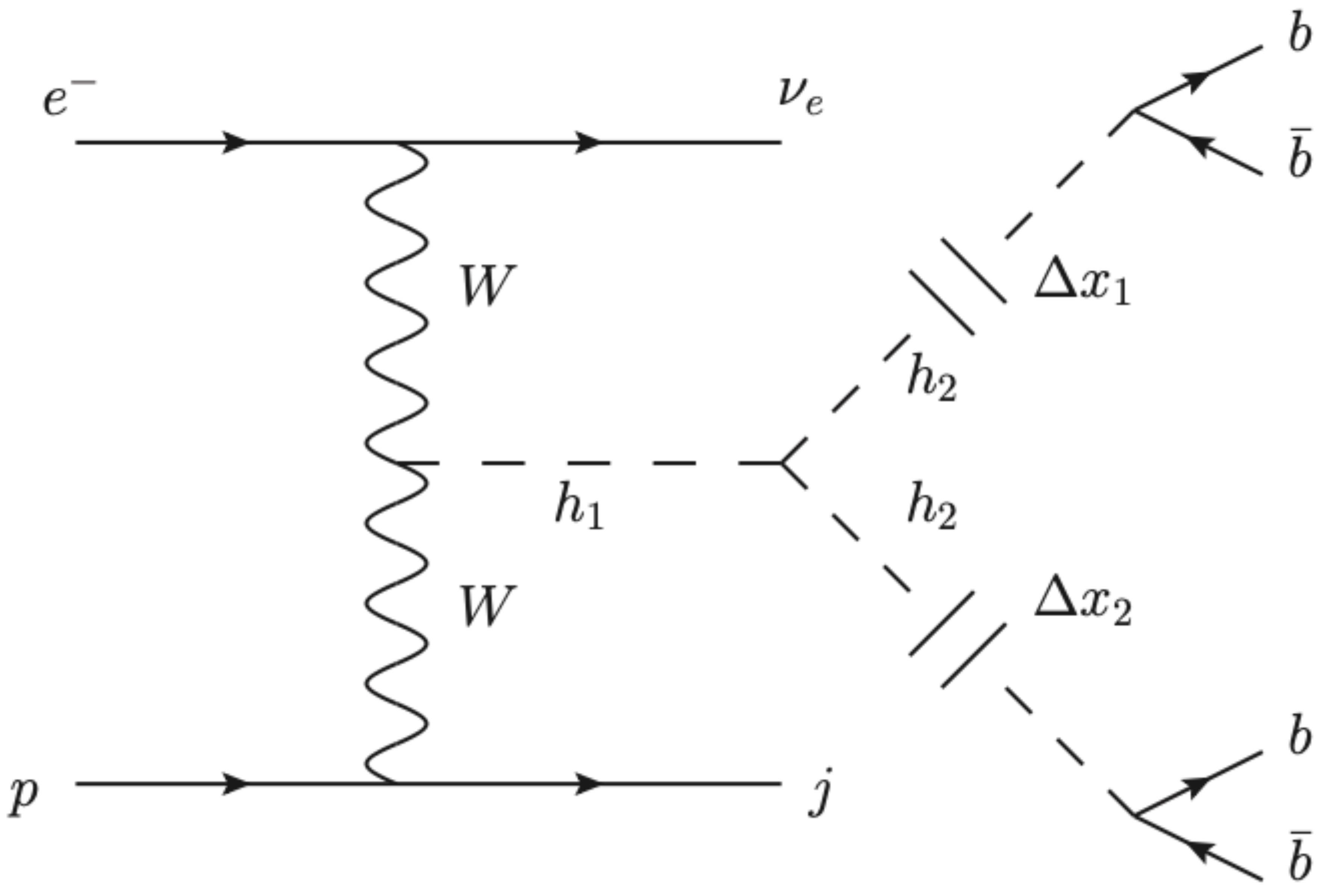
... and much more

Complementary searches for new phenomena

- ep collider is ideal to study common features of electrons and quarks with
  - Electroweak / Vector Boson Fusion production, Leptoquarks, forward objects, long-lived particles, Dark Matter
- Differences and complementarities with pp colliders
- Some promising aspects:
  - small background due to absence of QCD interaction between e and p
  - very low pileup
- Some difficult aspects:
  low production rate for NP processes due to small center of mass energy







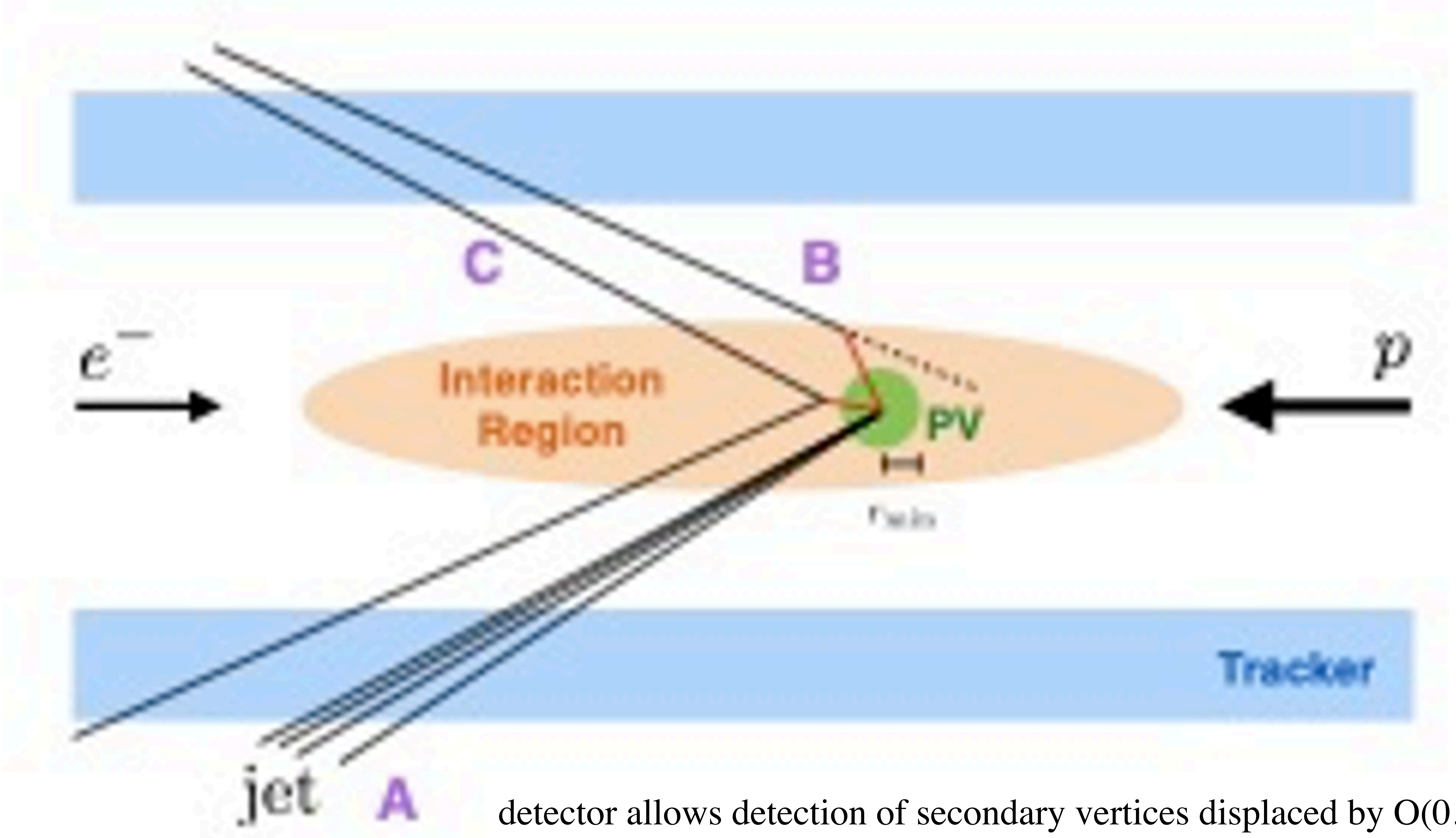
→ only a few specific examples given here

Hidden, Dark Sectors

- New physics models predicting long-lived particles gained lot of attention in the past few years
  - Hidden, dark sector
  - populated by feebly interacting particles
- Might be difficult in certain regions at hh
  - Large backgrounds and high pileup
  - detector dimensions and geometrical acceptance
    - [e.g. short-distances are hard to cover for hh]

Portal	Coupling
Vector (Dark Vector, A_μ)	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS} S^2) H^\dagger H$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi}\gamma^\mu\gamma^5\psi$
Fermion (Sterile Neutrino, N)	$y_N L H N$

→ At LHeC (and FCC-eh), one can reconstruct displaced vertices and as such be sensitive to non-promptly decaying, light new particles

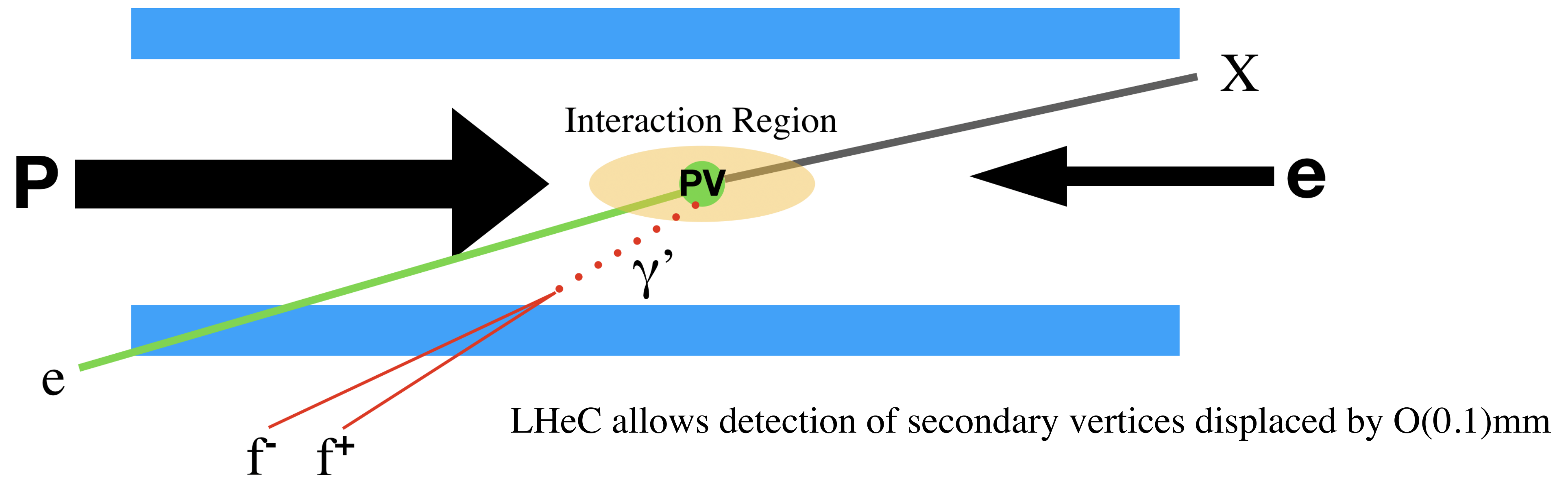


benchmark value is r_{min} = 40μm (~ 5 nominal detector resolutions); p_T threshold for reconstruction of a single charged particle is chosen as 100 MeV

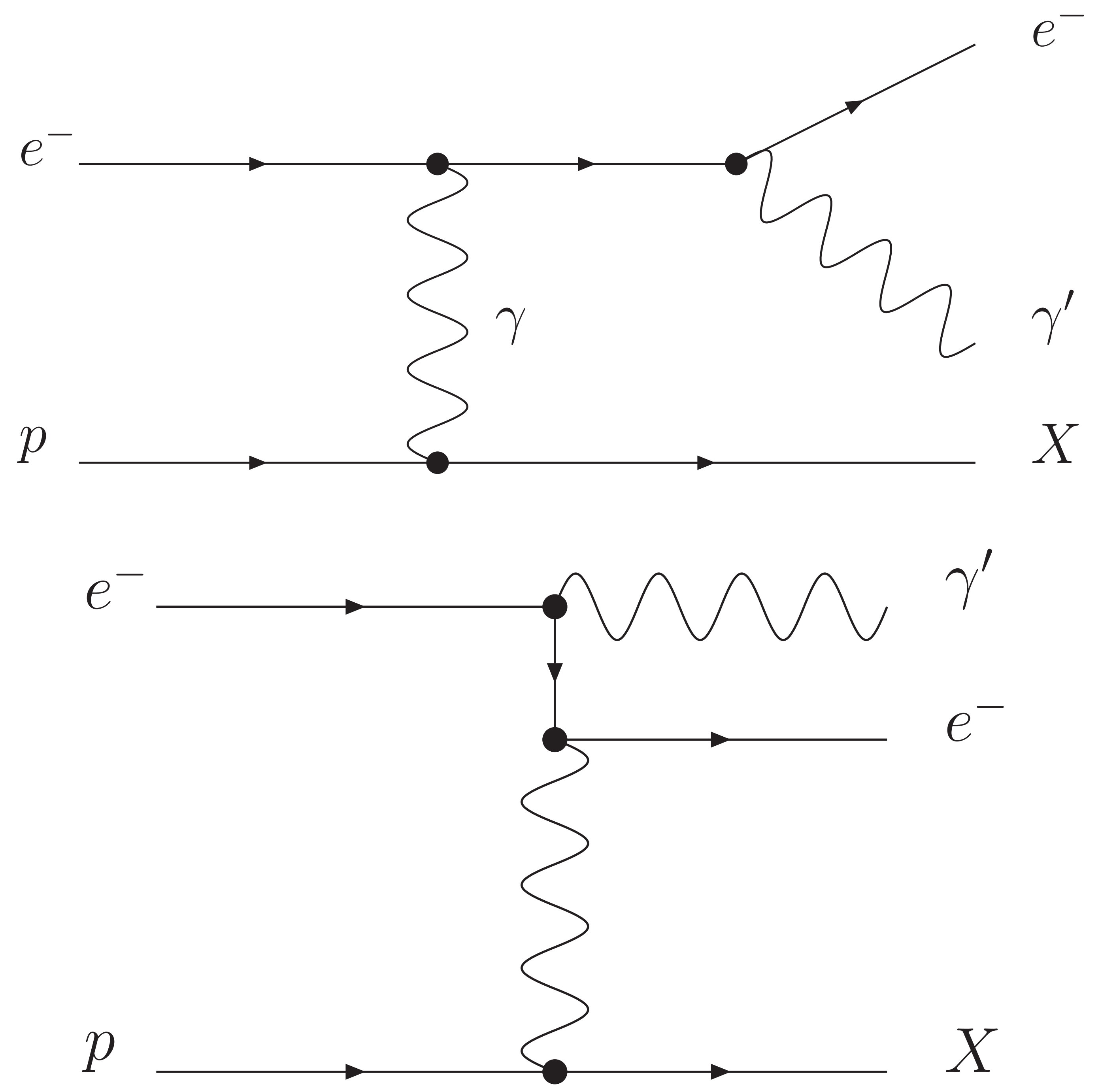
detector allows detection of secondary vertices displaced by O(0.1)mm

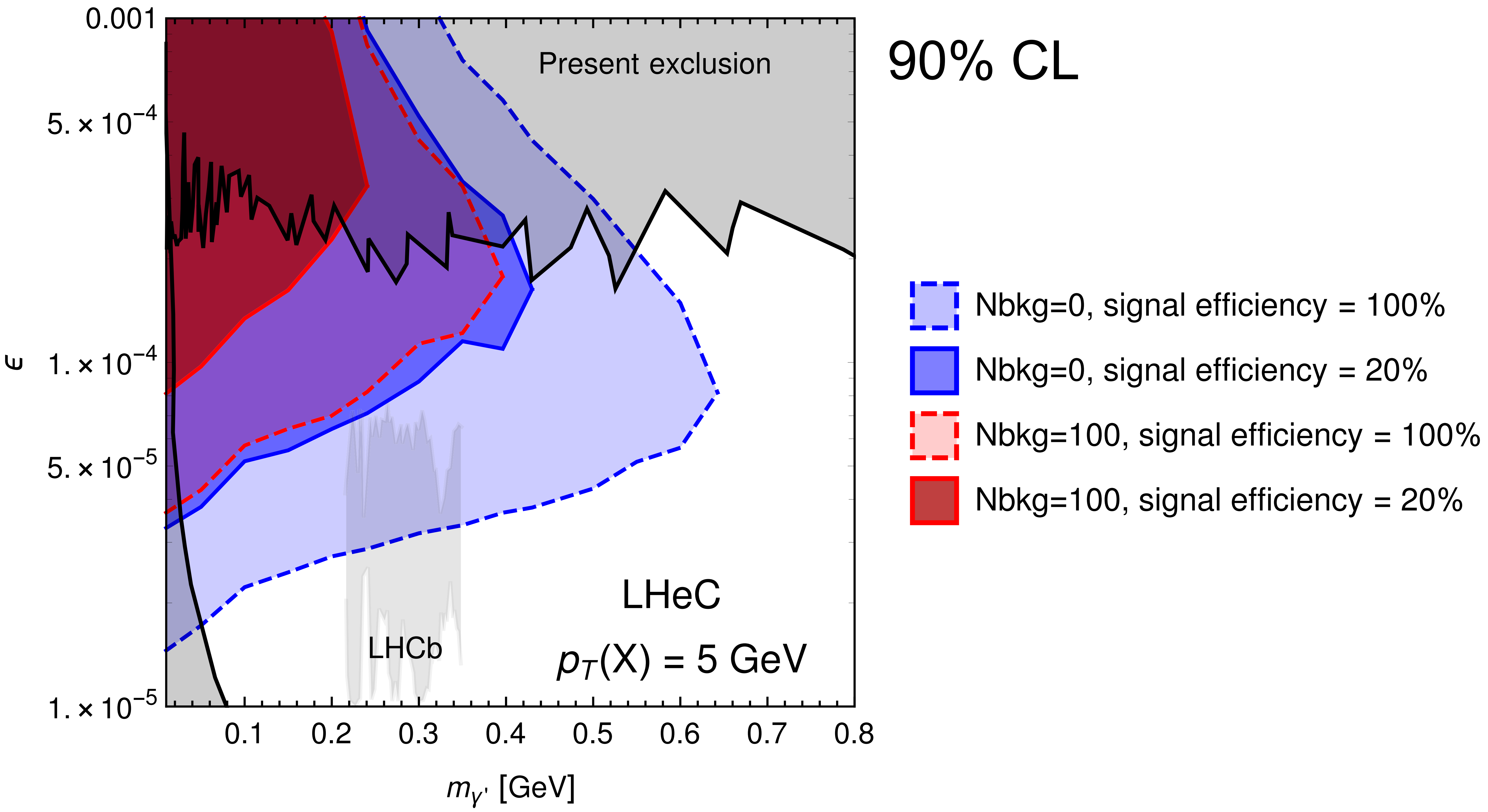
Search for Dark Photons

- have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε



$$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$$





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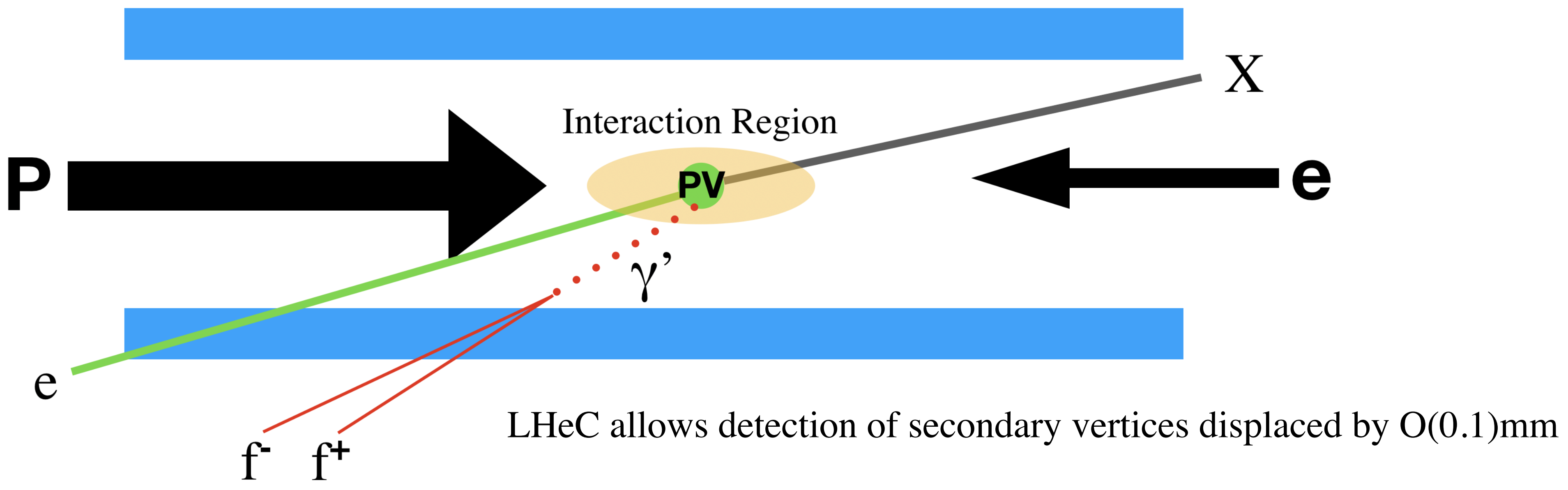

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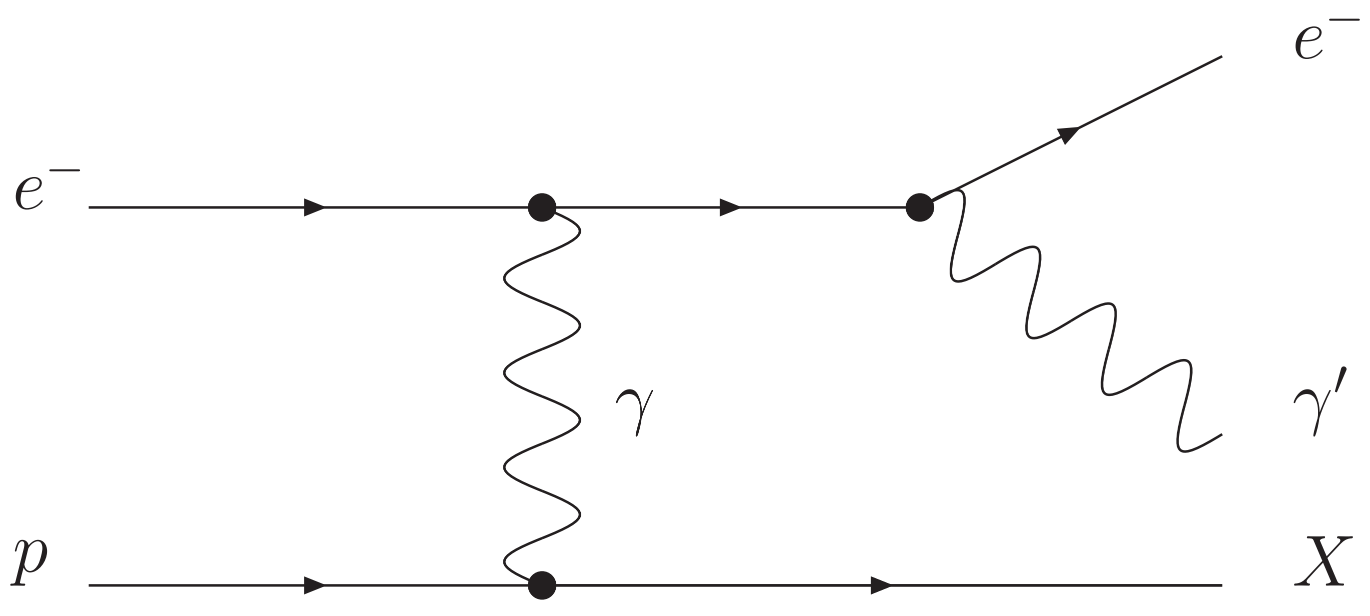
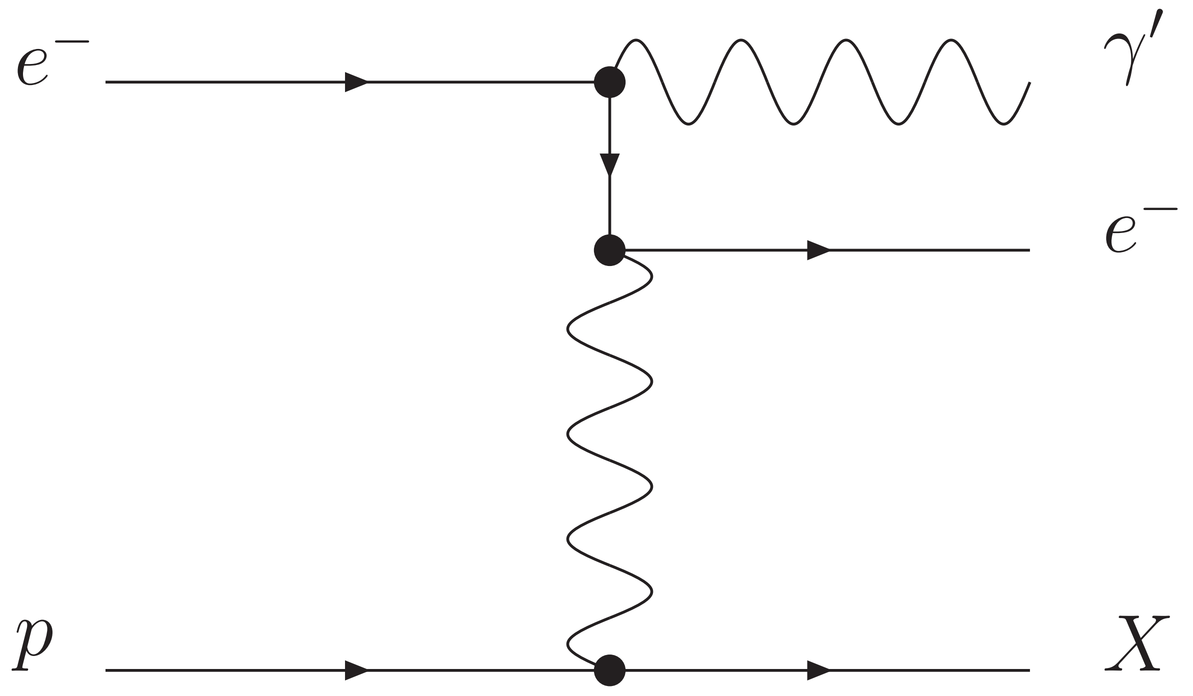
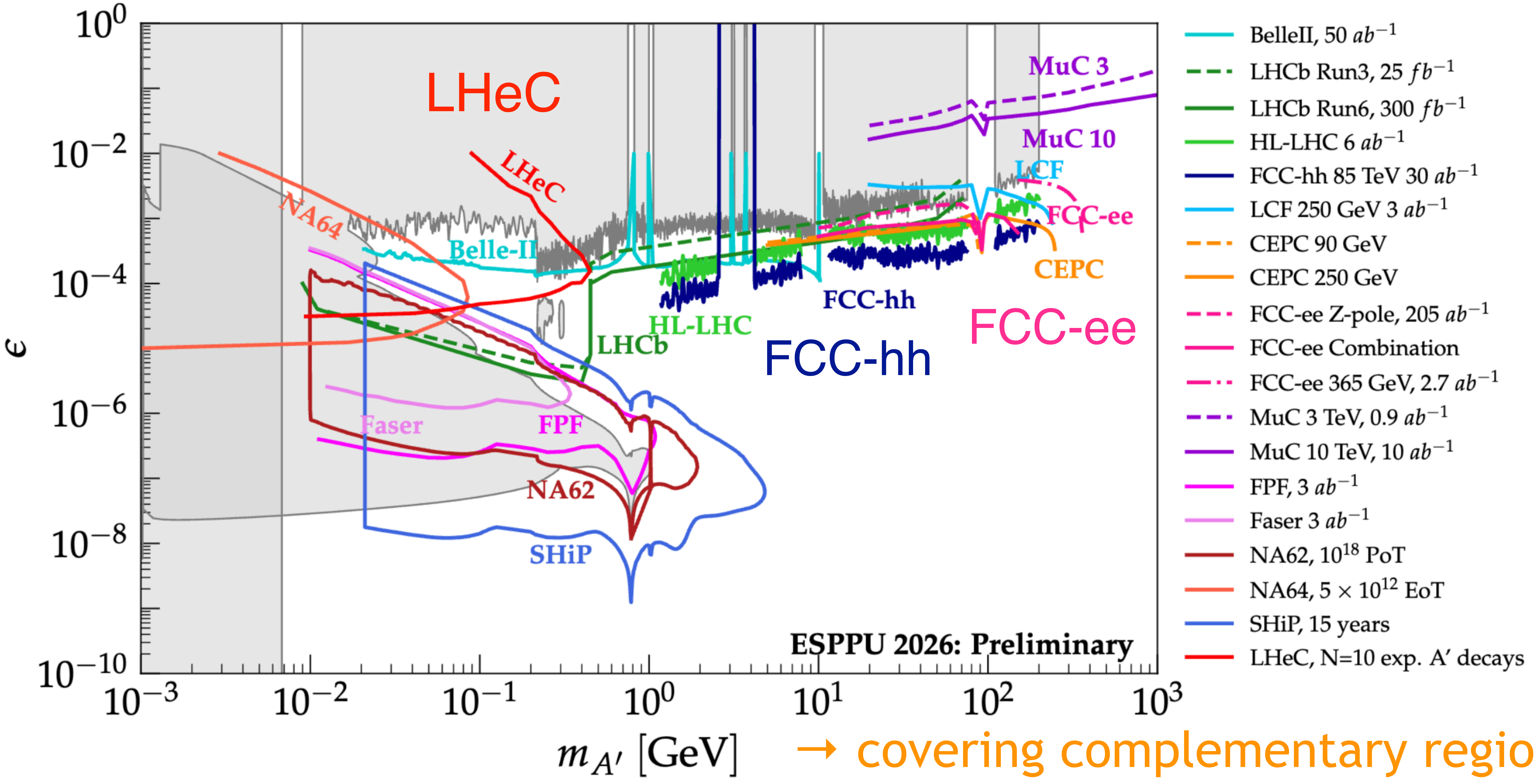
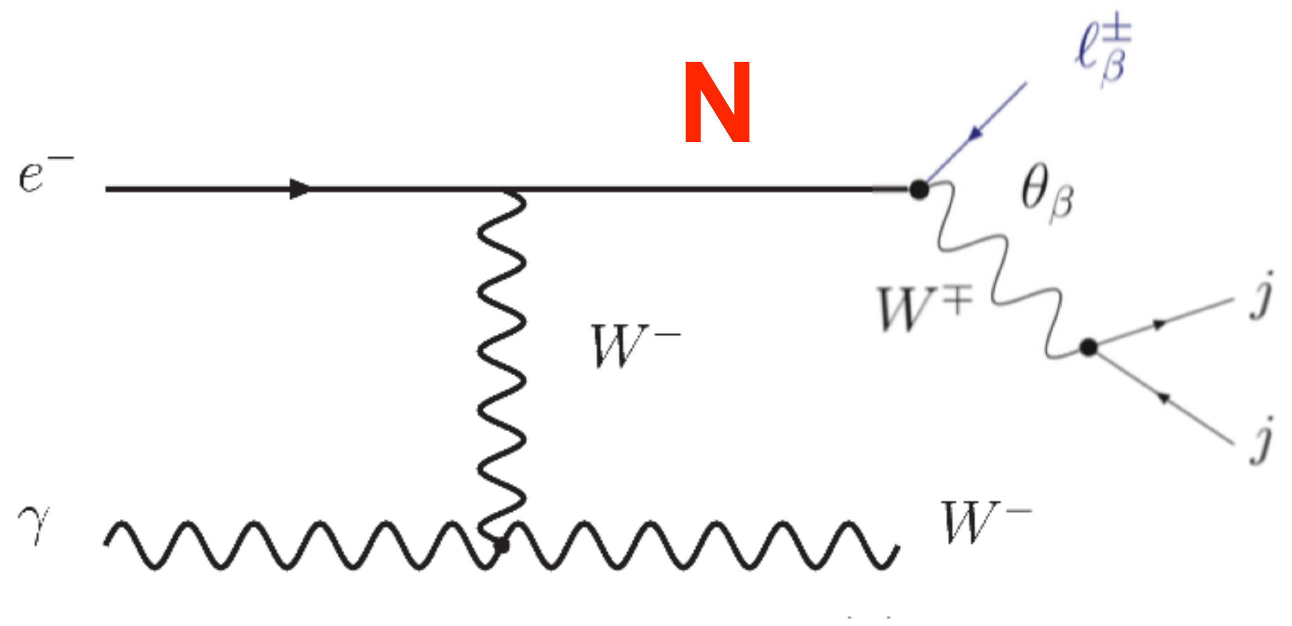




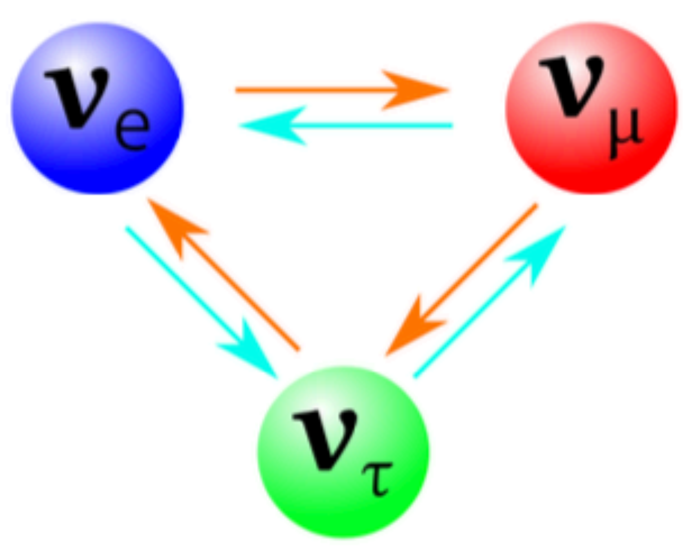


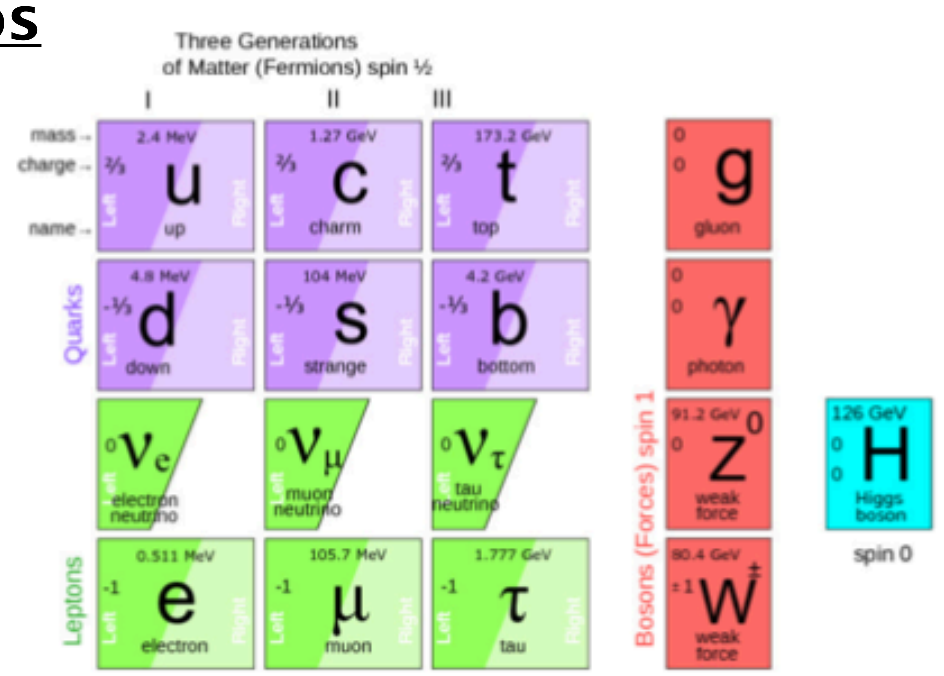
→ covering complementary region

Search for heavy neutrinos

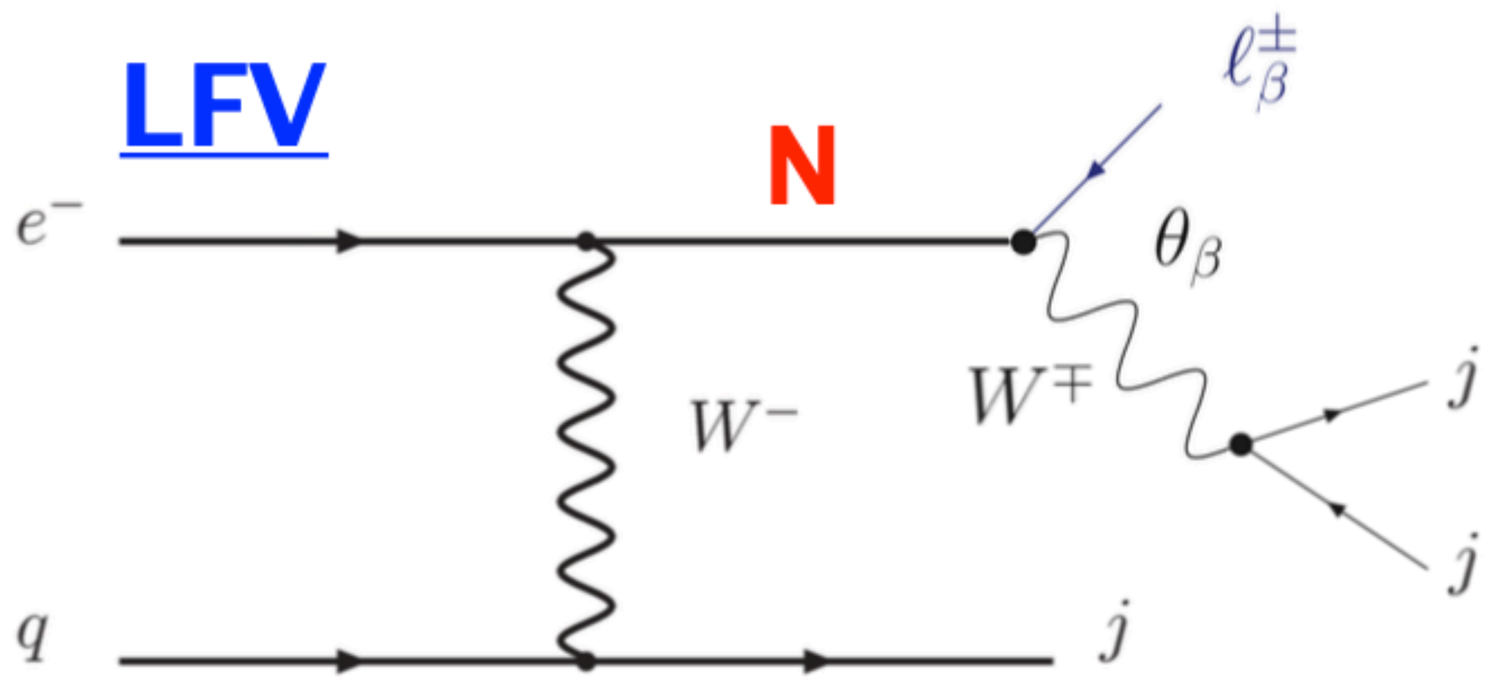


Heavy sterile neutrinos



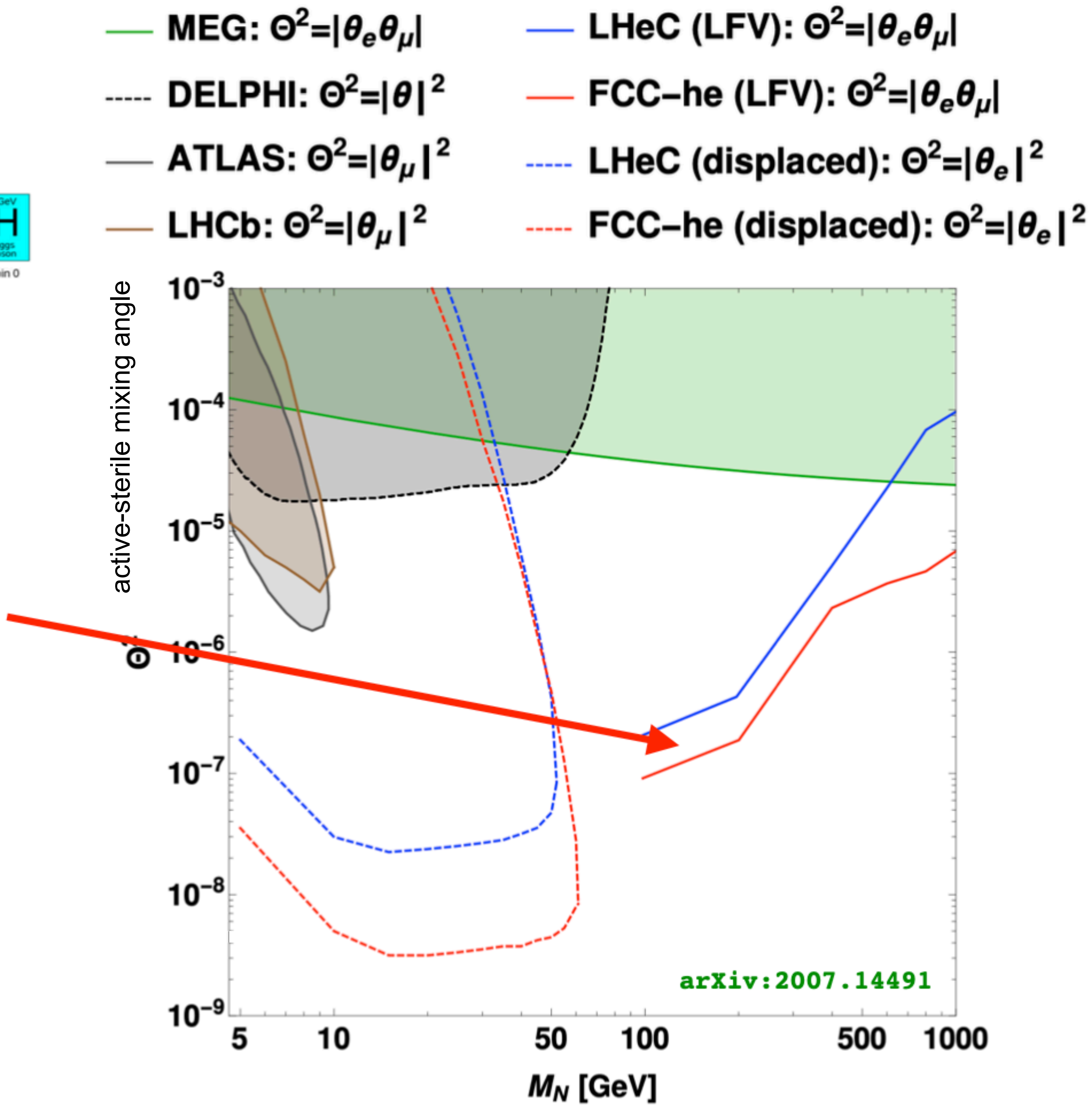


LFV



+ many backgrounds included

arXiv:1908.02852



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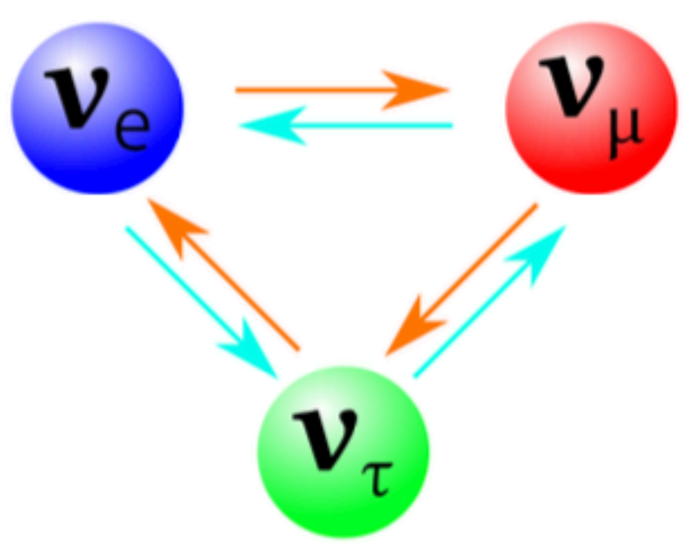
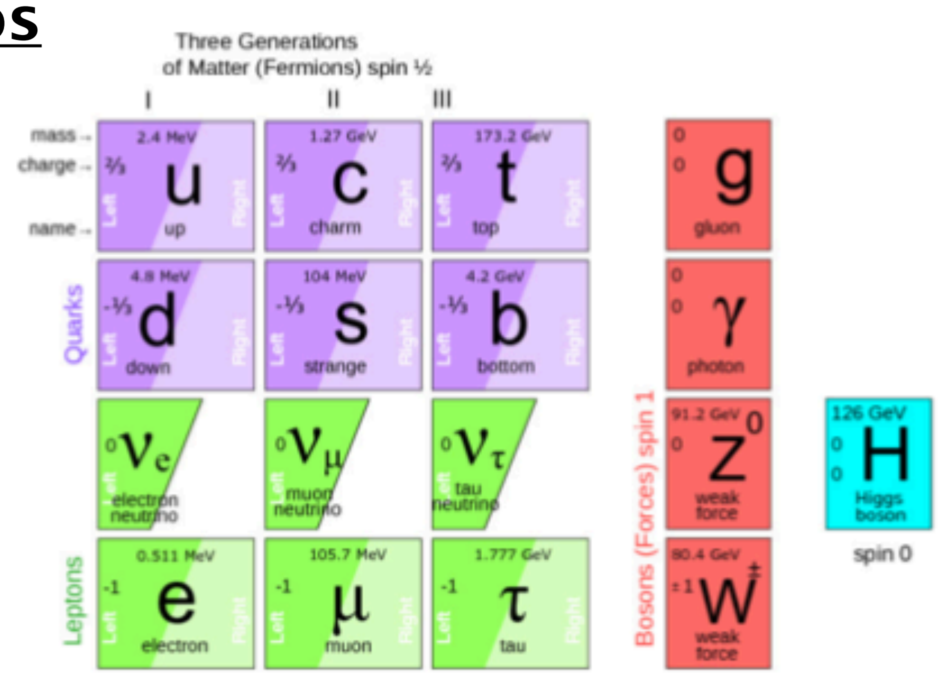
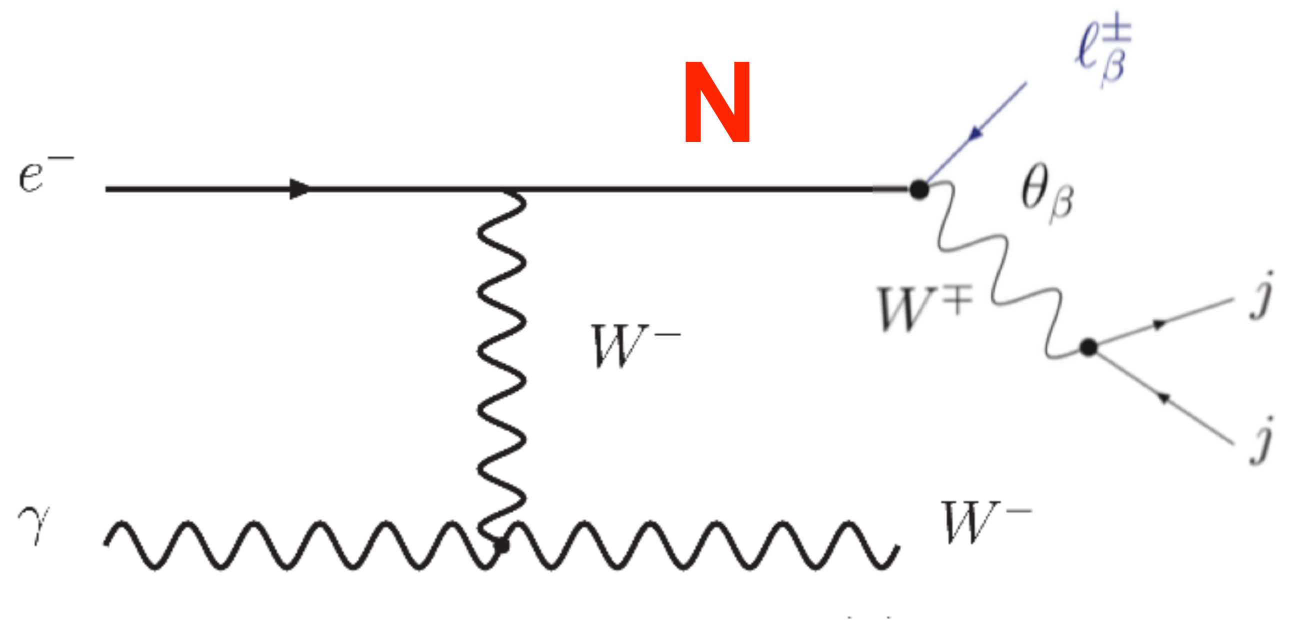
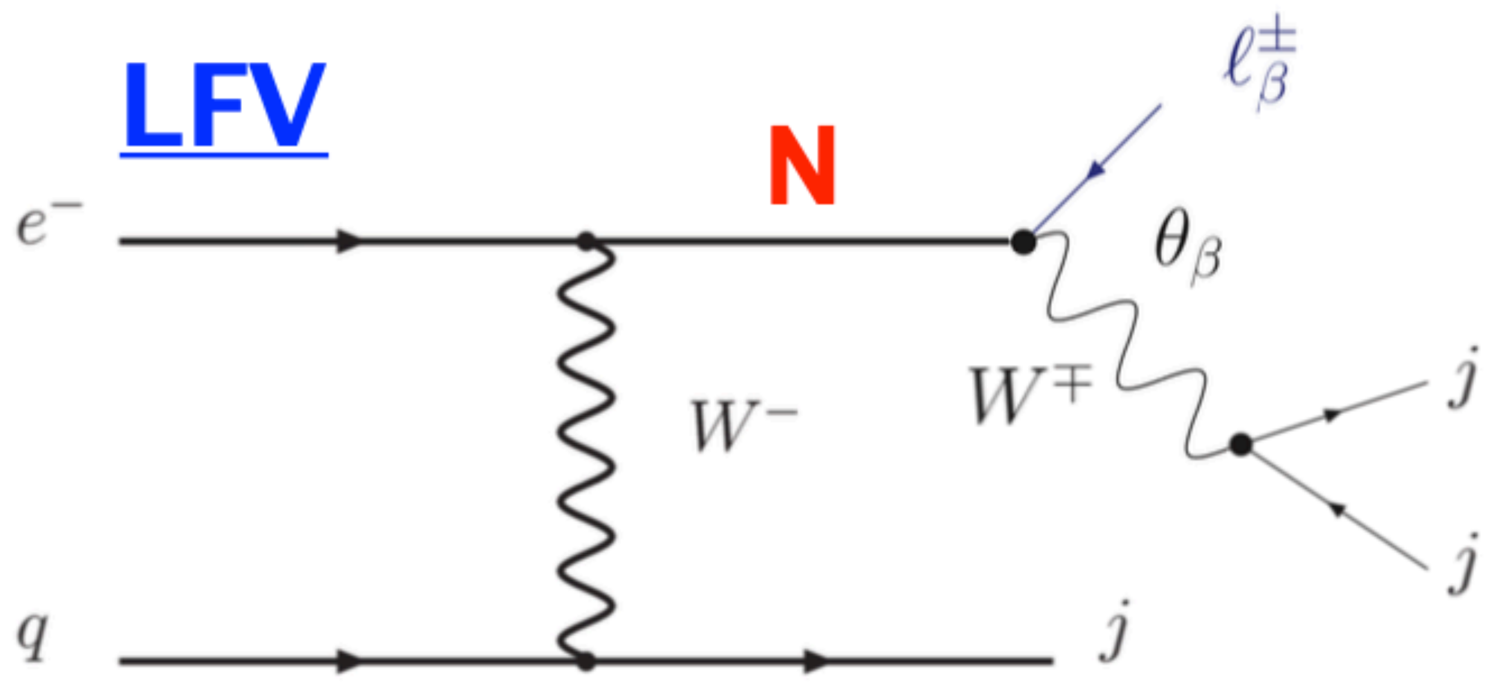






LFV



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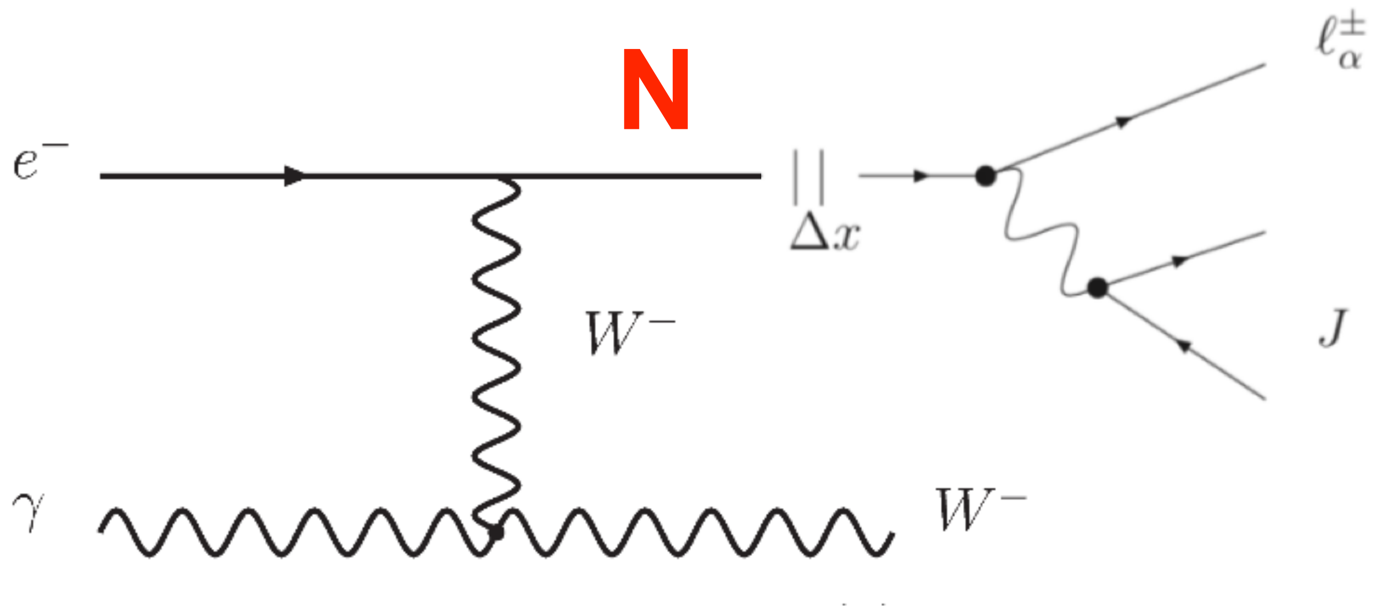

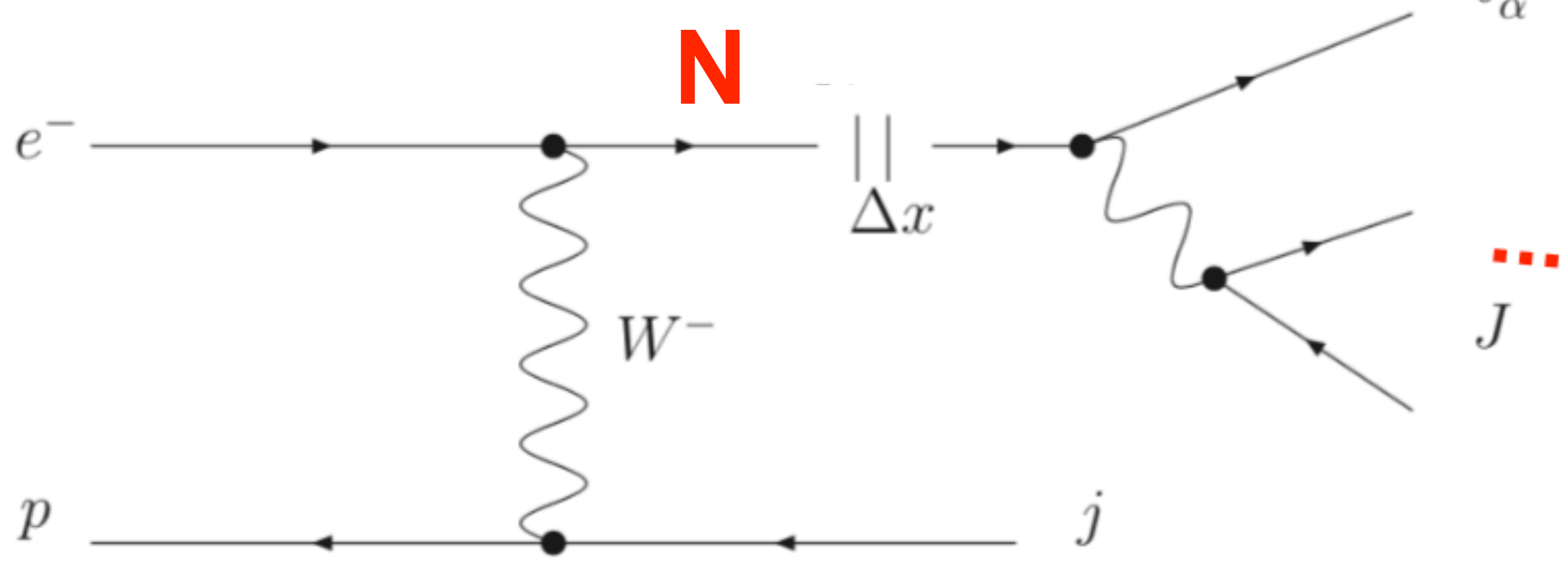

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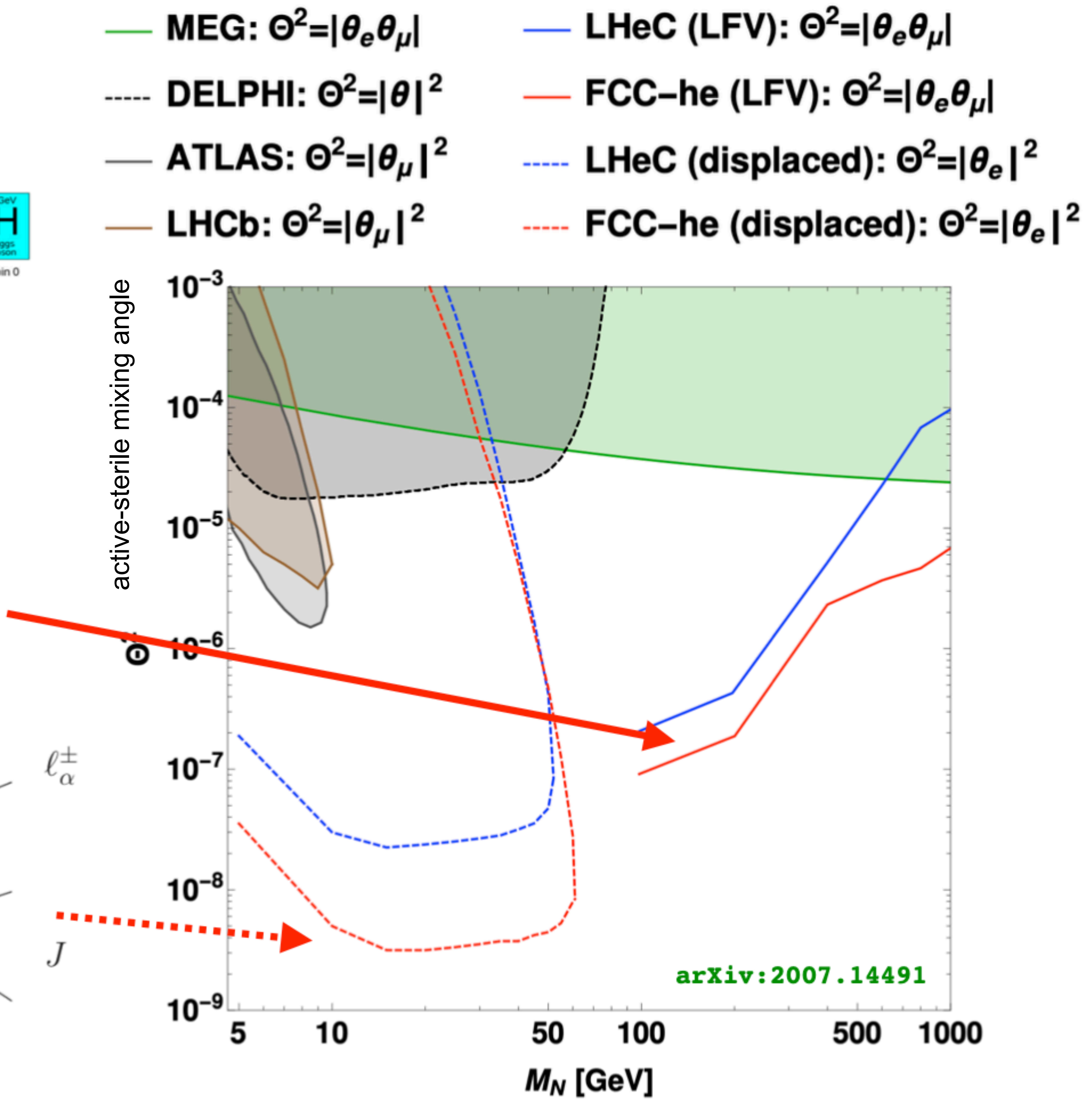
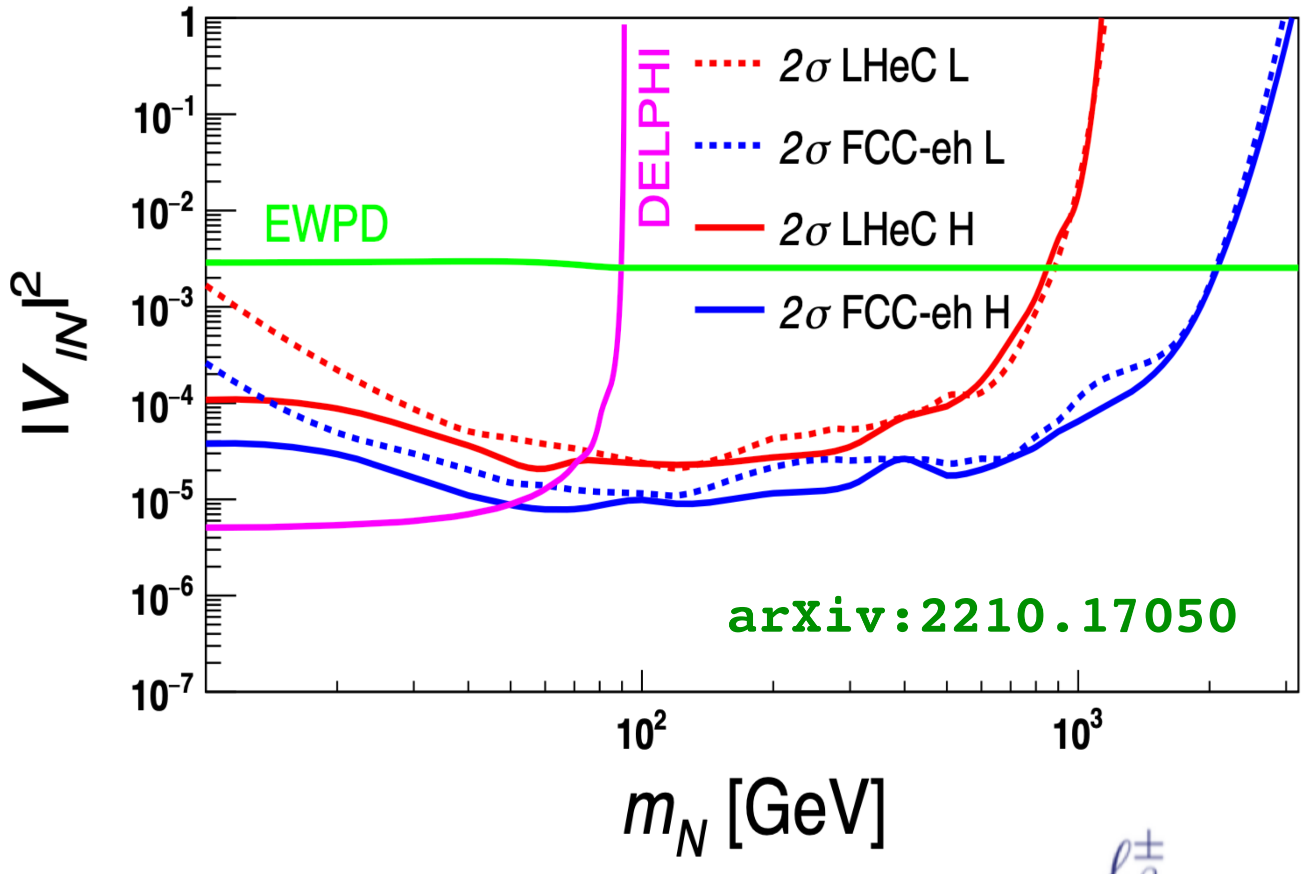
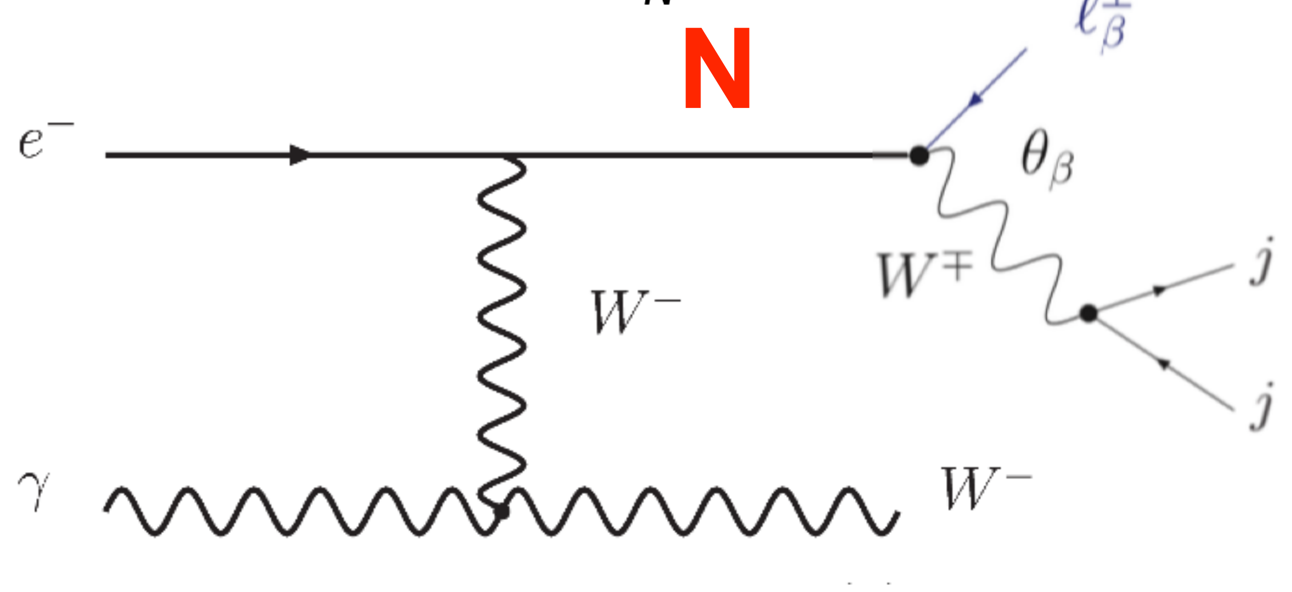
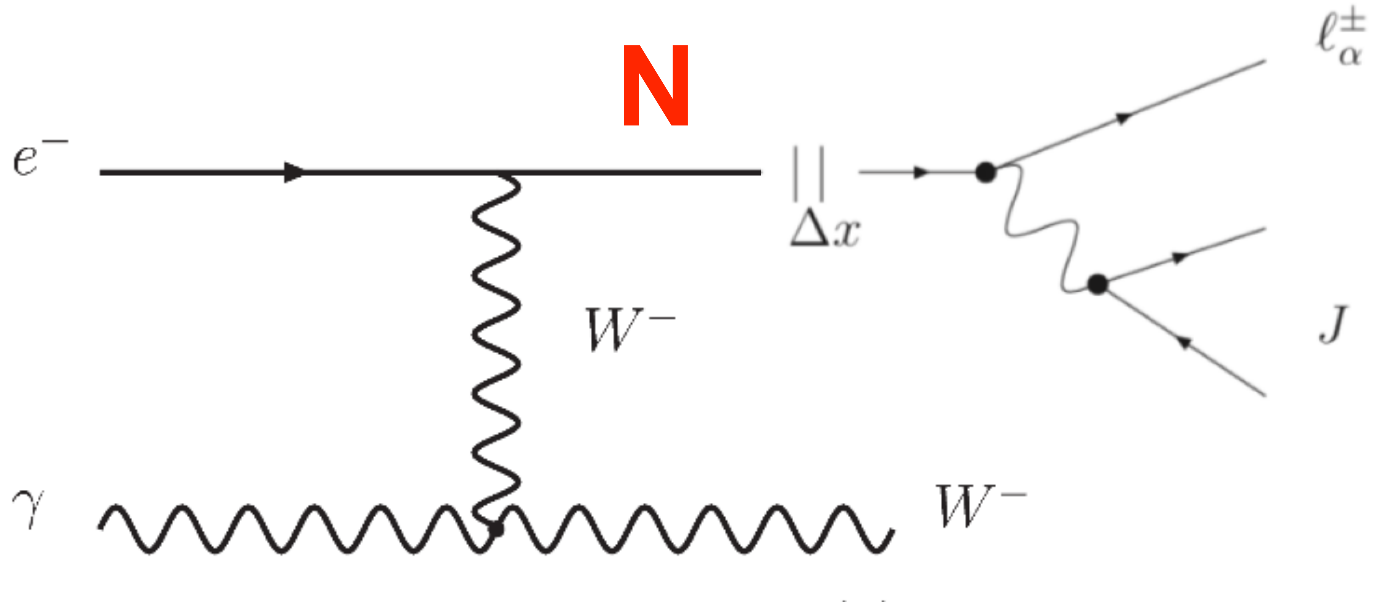


Search for heavy neutrinos

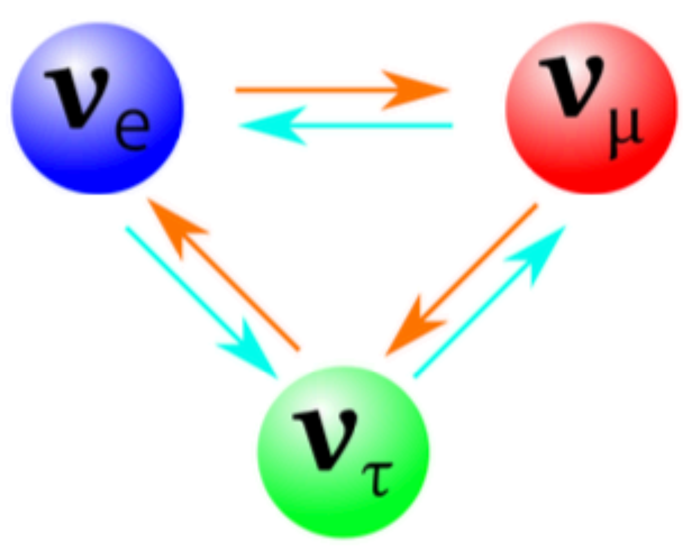
Heavy Majorana neutrinos in τ final states

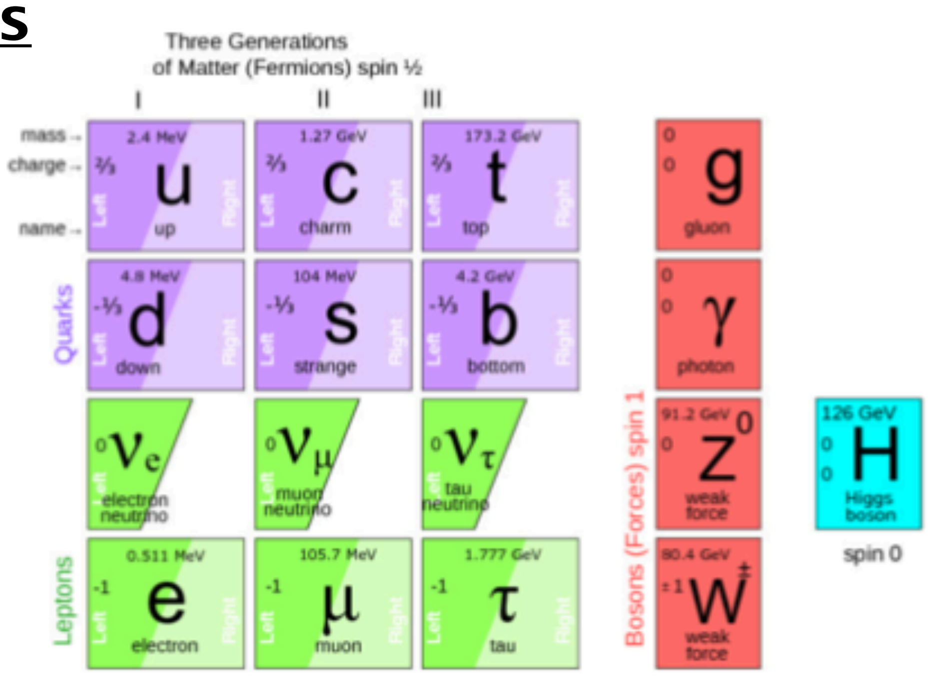


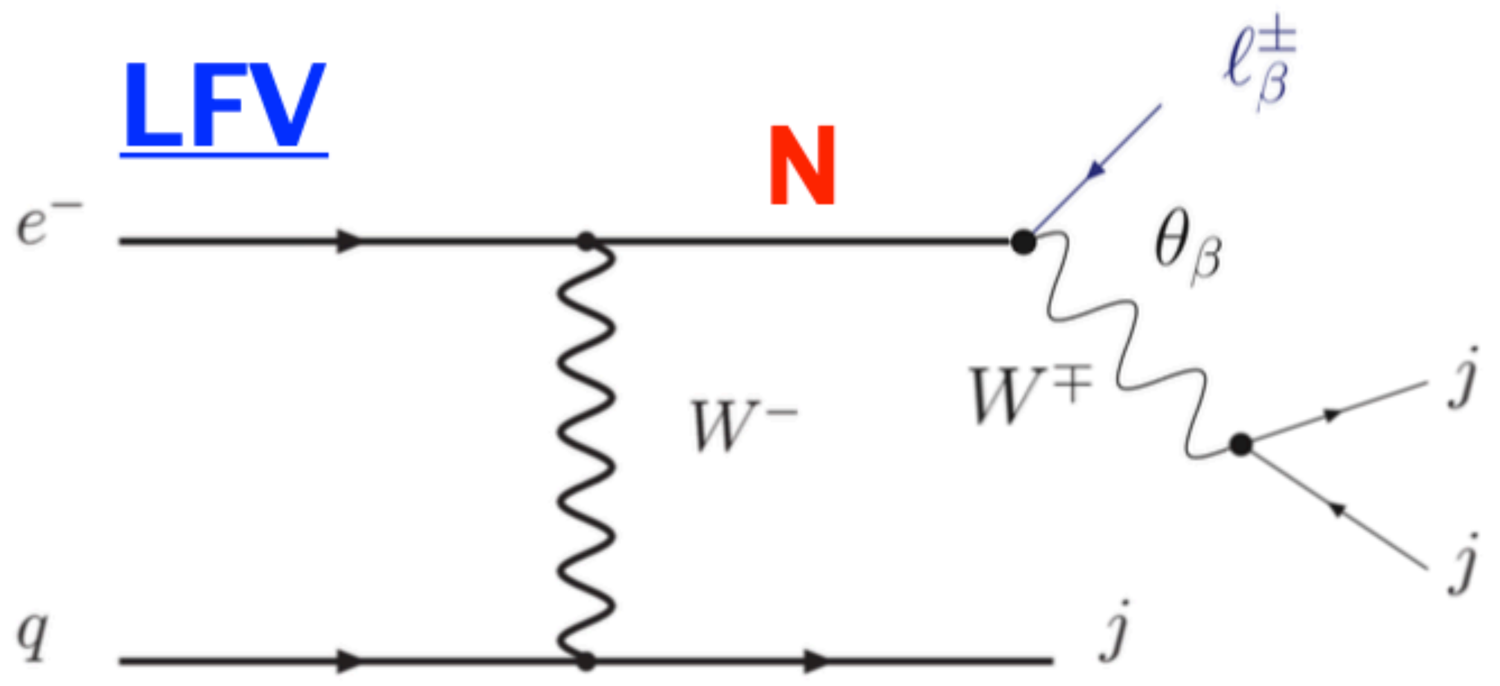




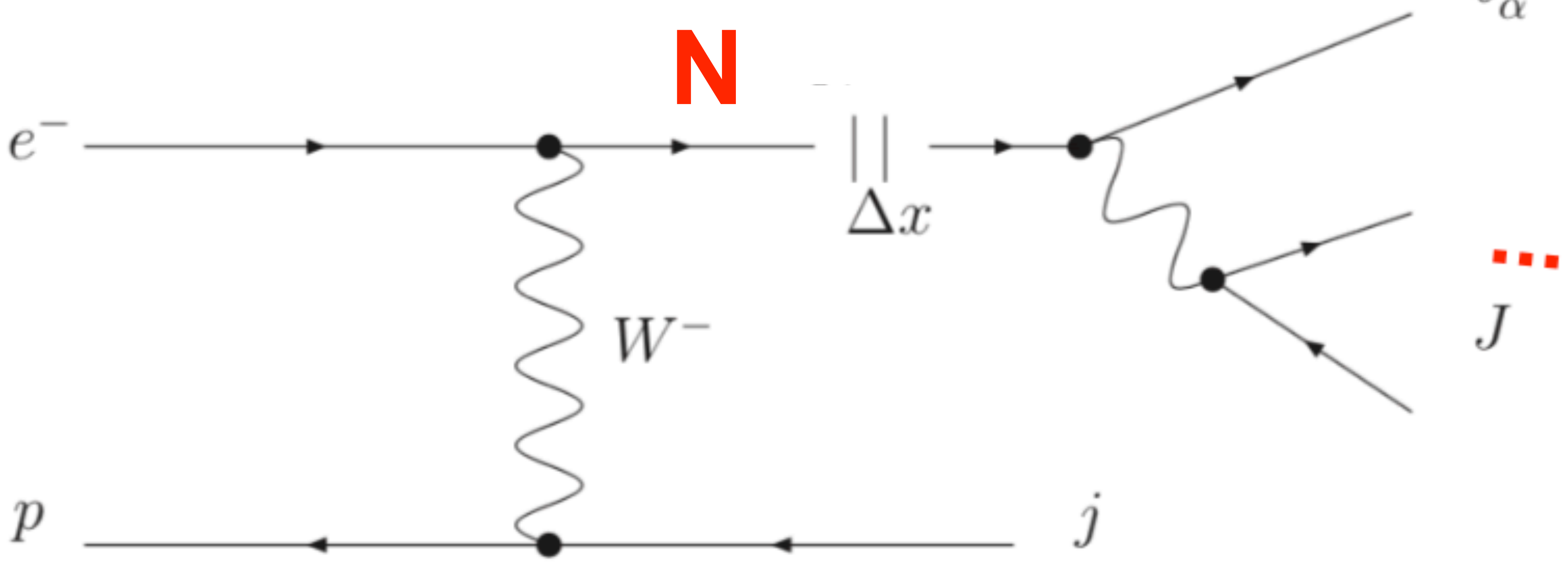
Heavy sterile neutrinos







+ many backgrounds included



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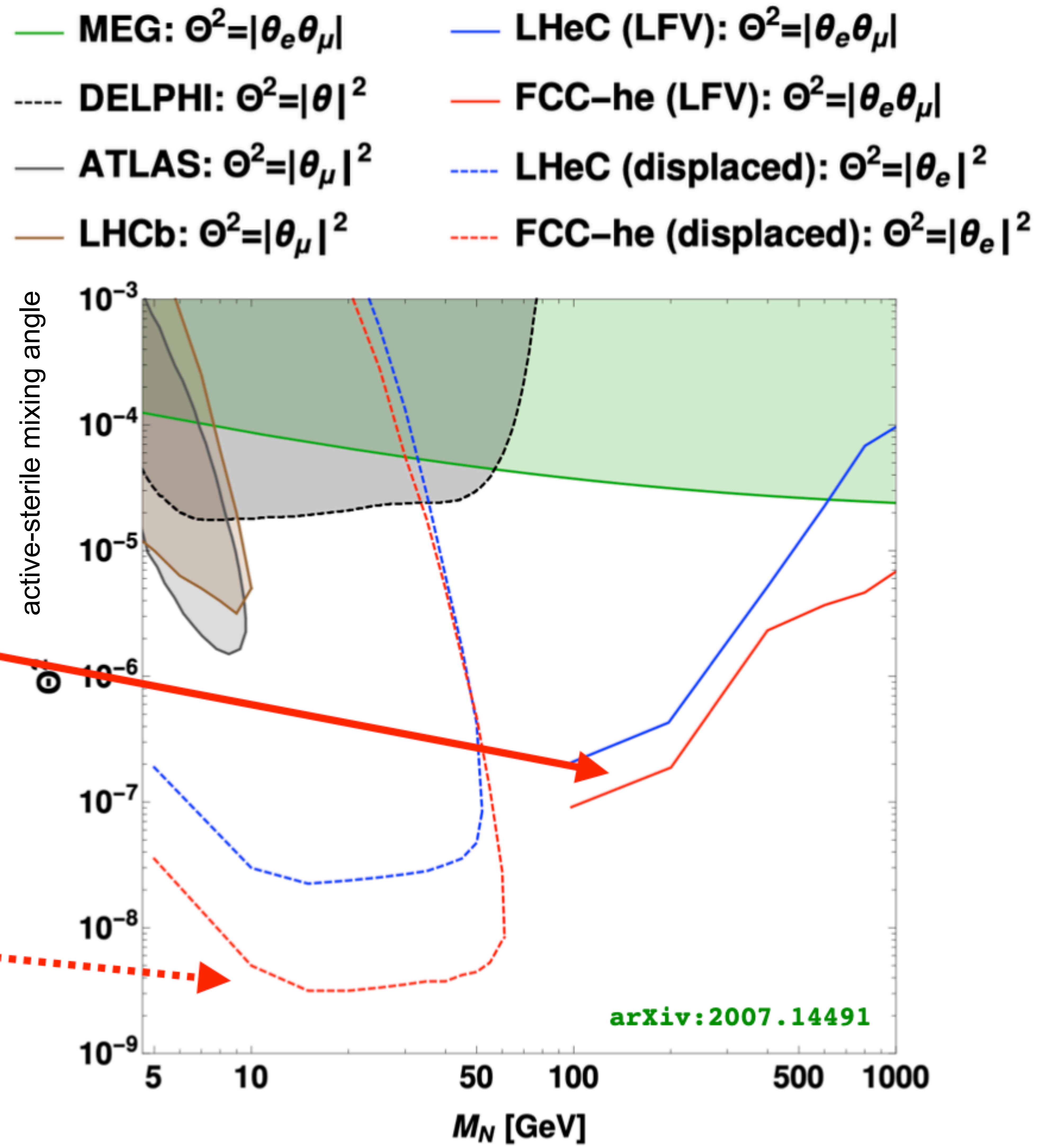
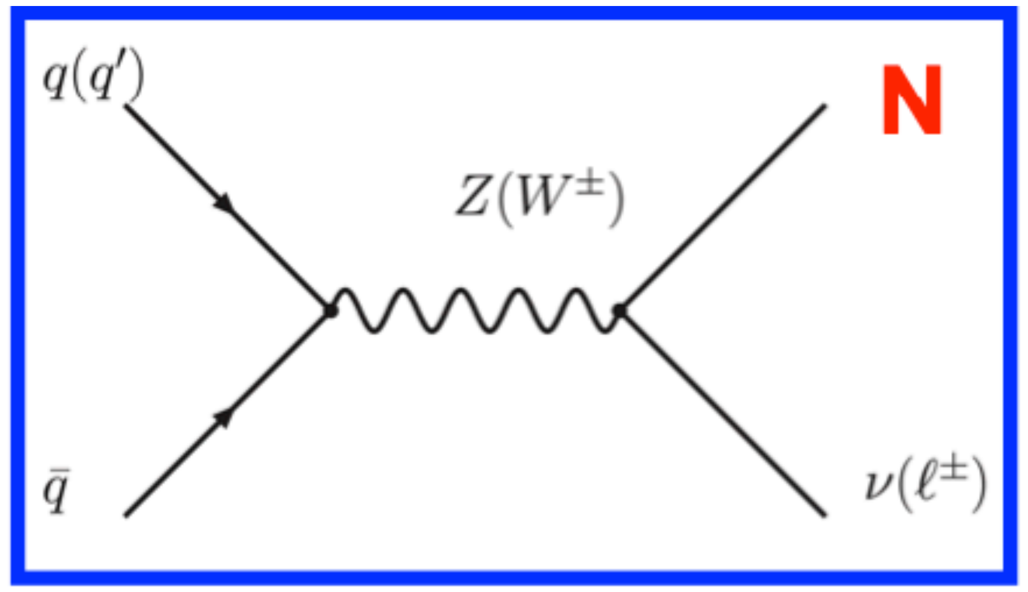
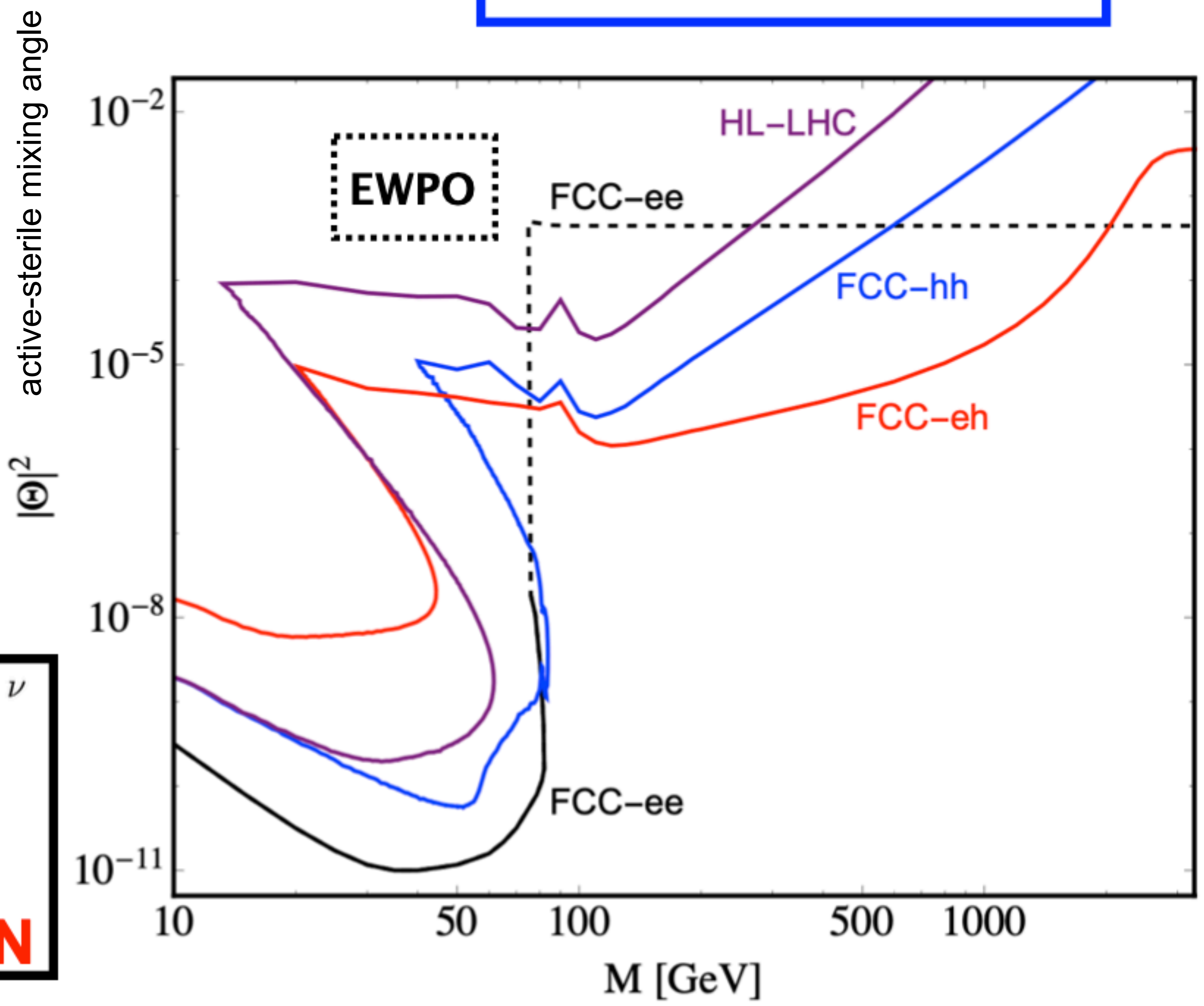
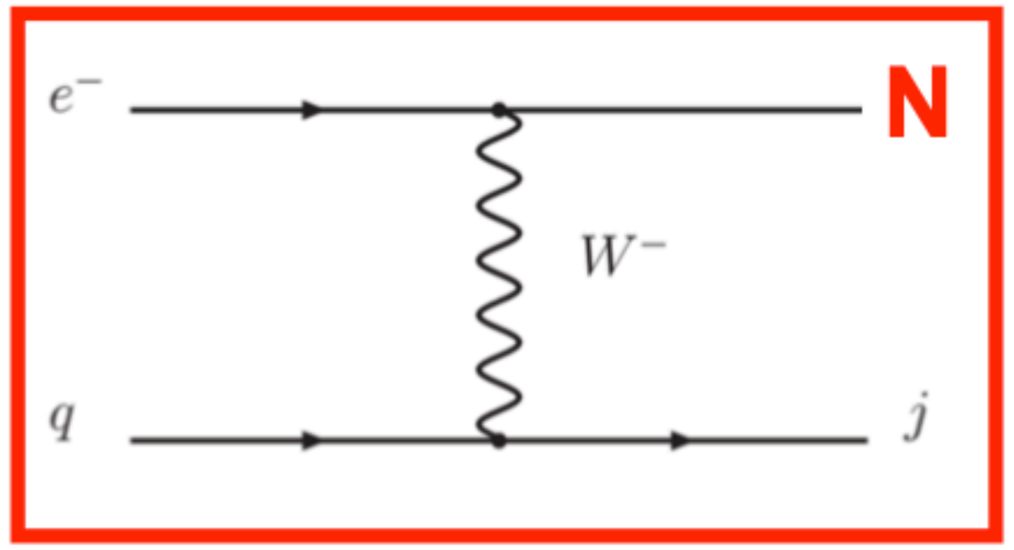


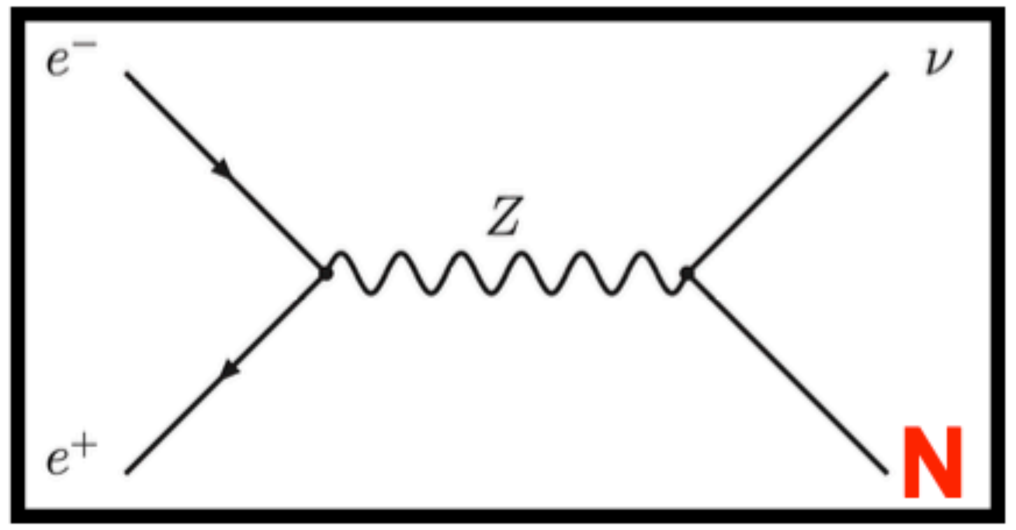
Search for heavy sterile neutrinos

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





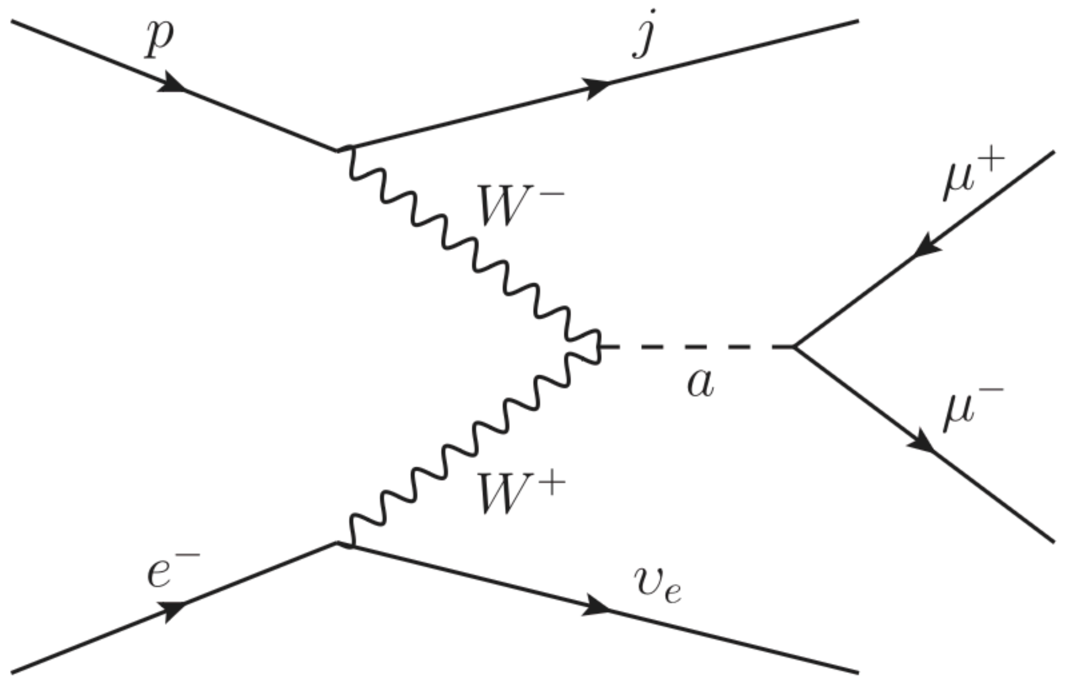


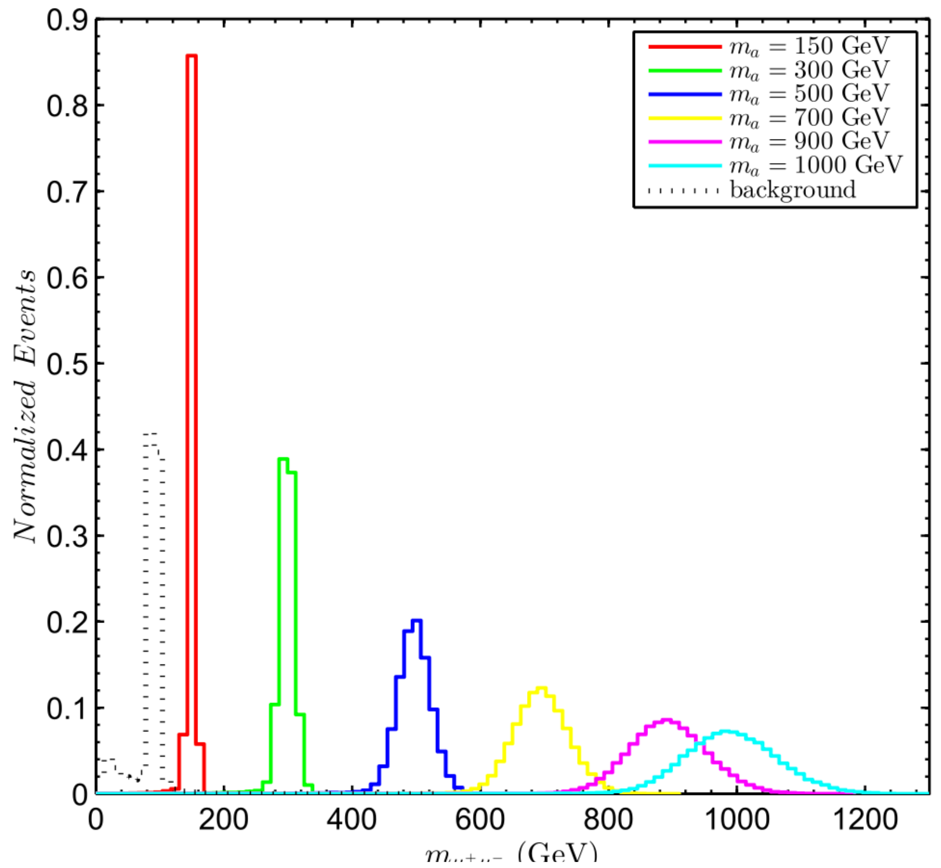


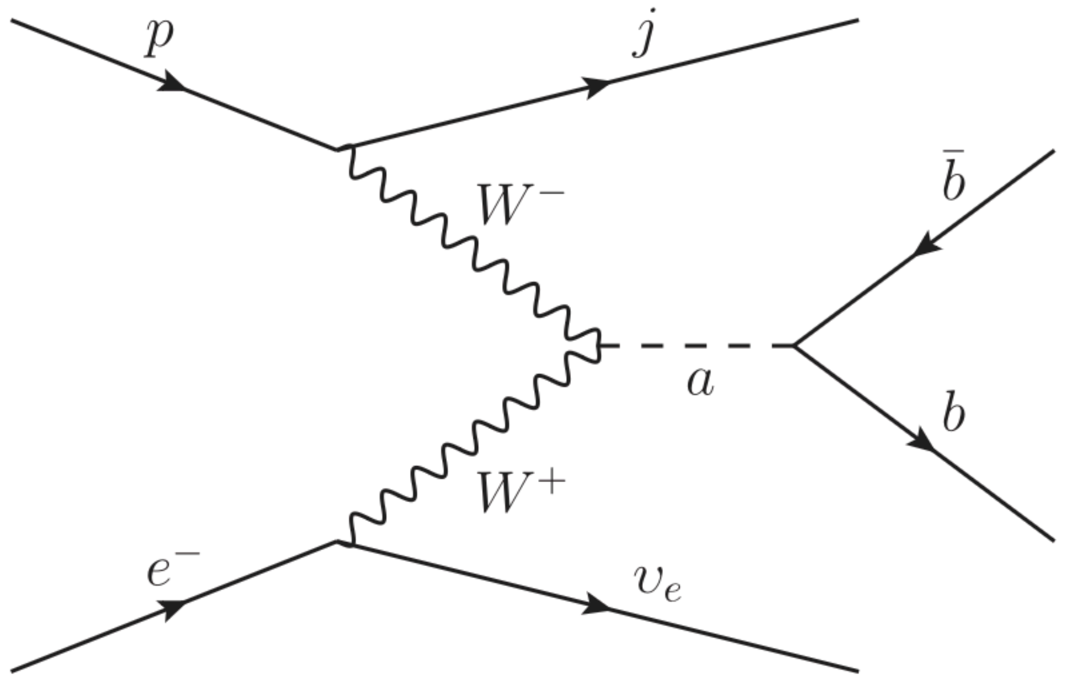
→ **complementary prospects for discovery in ee, ep and pp**

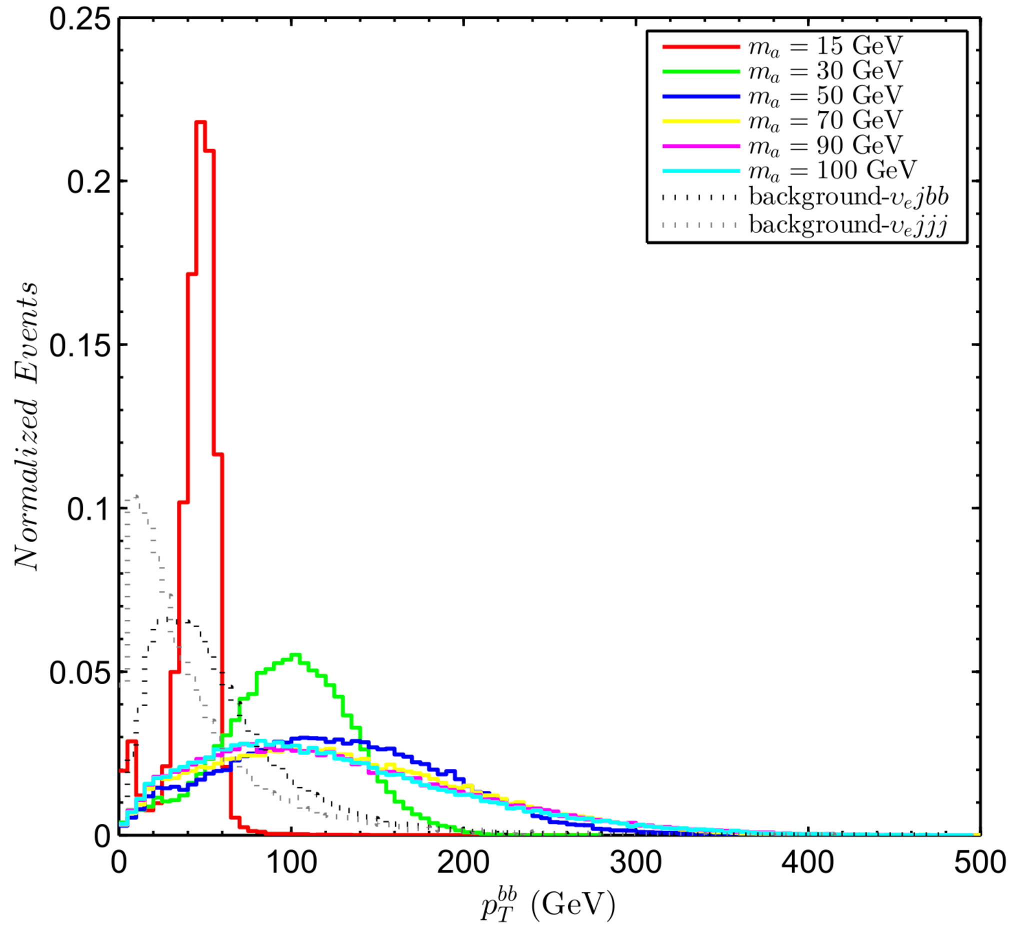
Search for axion-like particles (ALPs)

$$\mathcal{L}_{\text{eff}} \supset i g_{a\psi} a \sum_{\psi=Q,L} m_\psi^{\text{diag}} \bar{\psi}\gamma_5\psi - \frac{1}{4} g_{aWW} a W_{\mu\nu} \tilde{W}^{\mu\nu},$$









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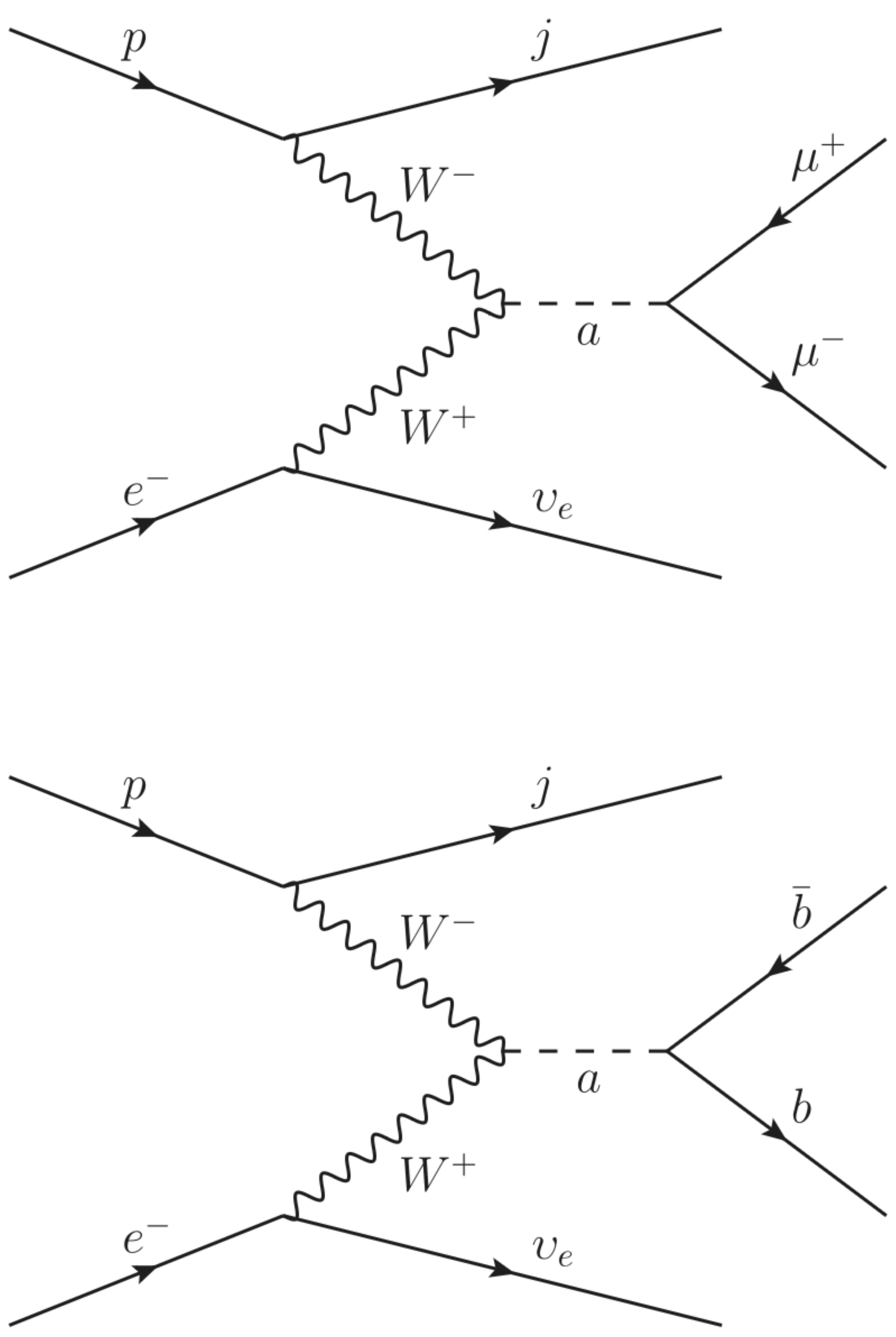
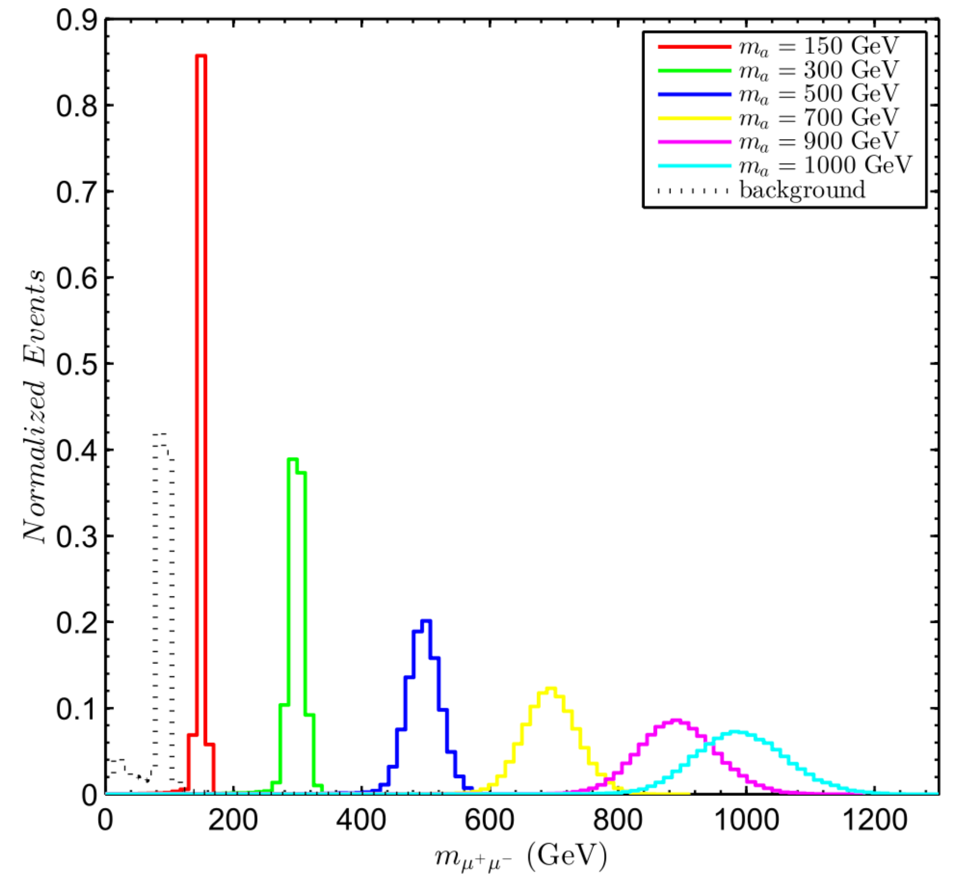
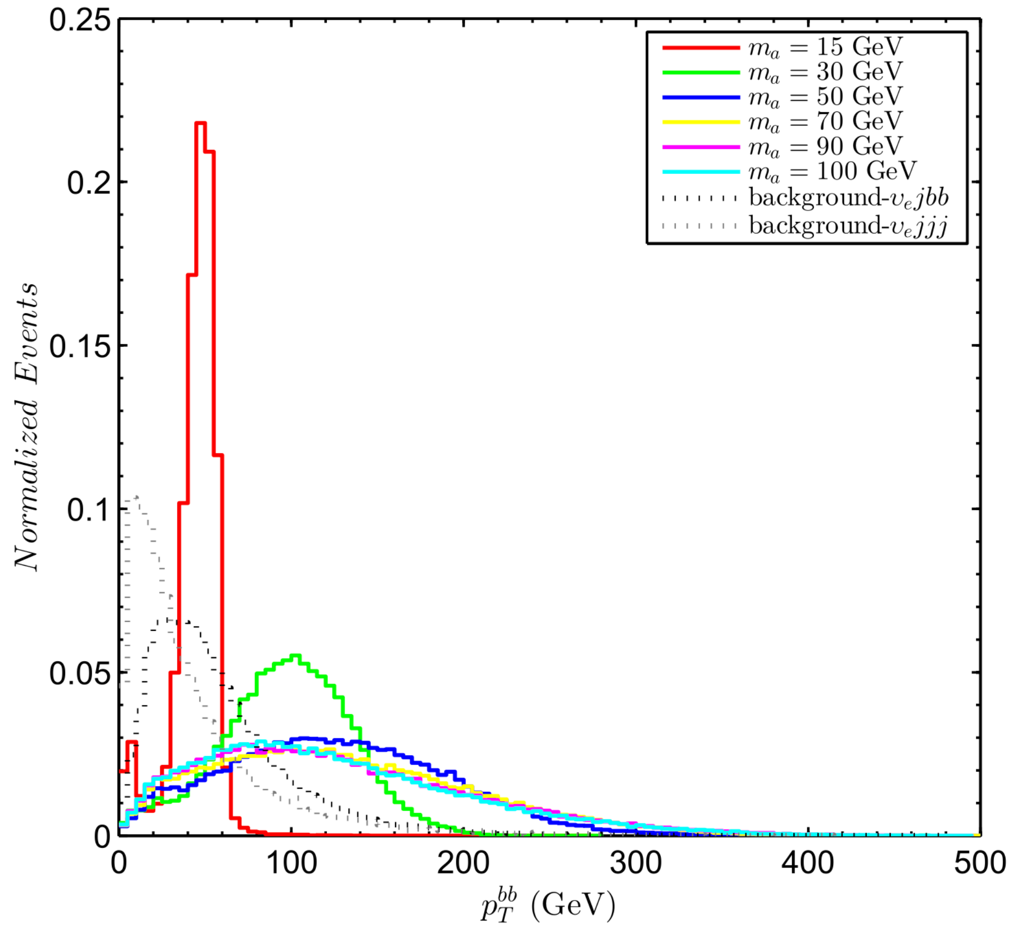
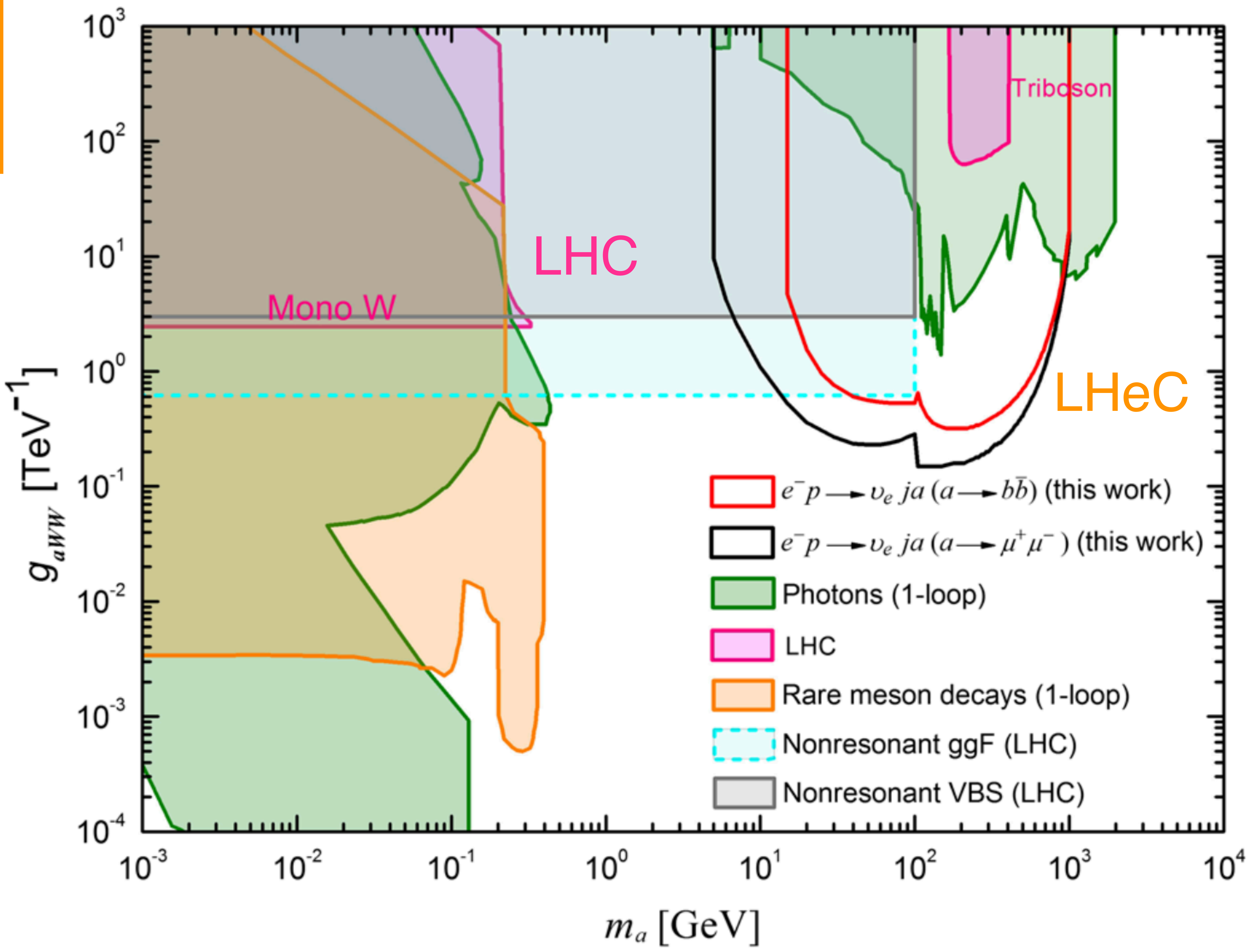






Phys. Rev. D 107, 115025 (2023)



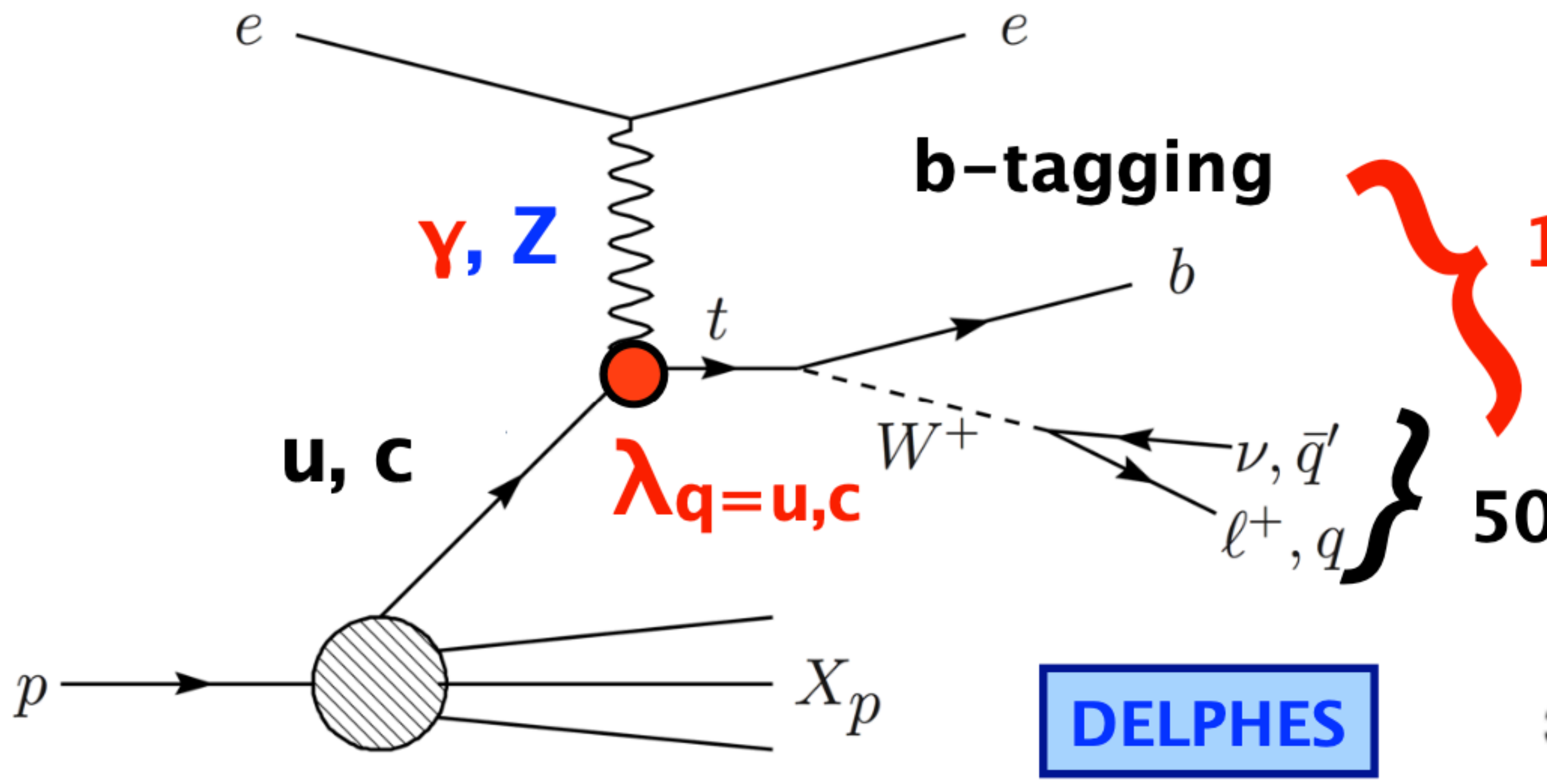
→ promising sensitivity beyond LHC reach

Anomalous FCNC tuγ, tuZ Couplings

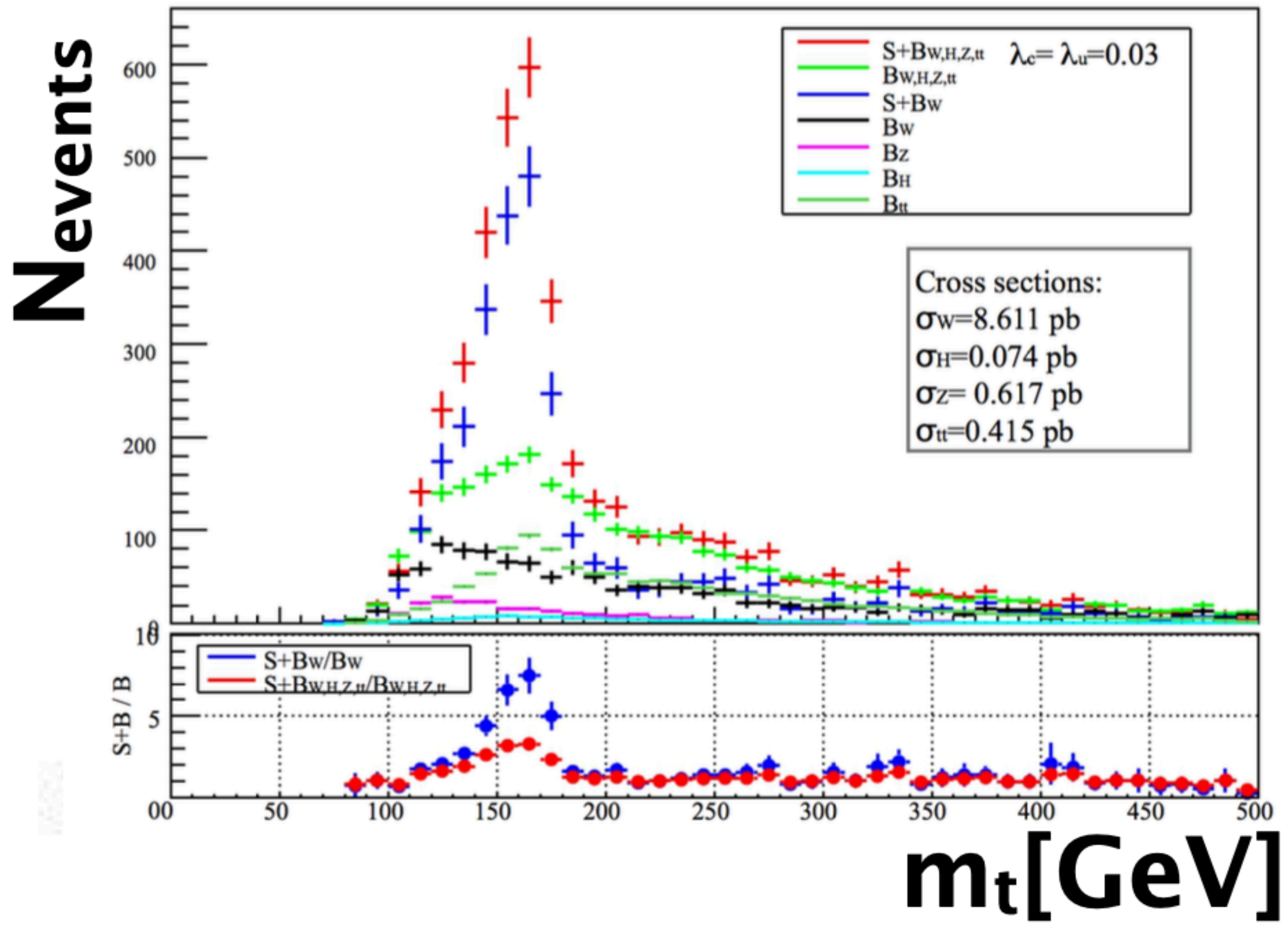
signal

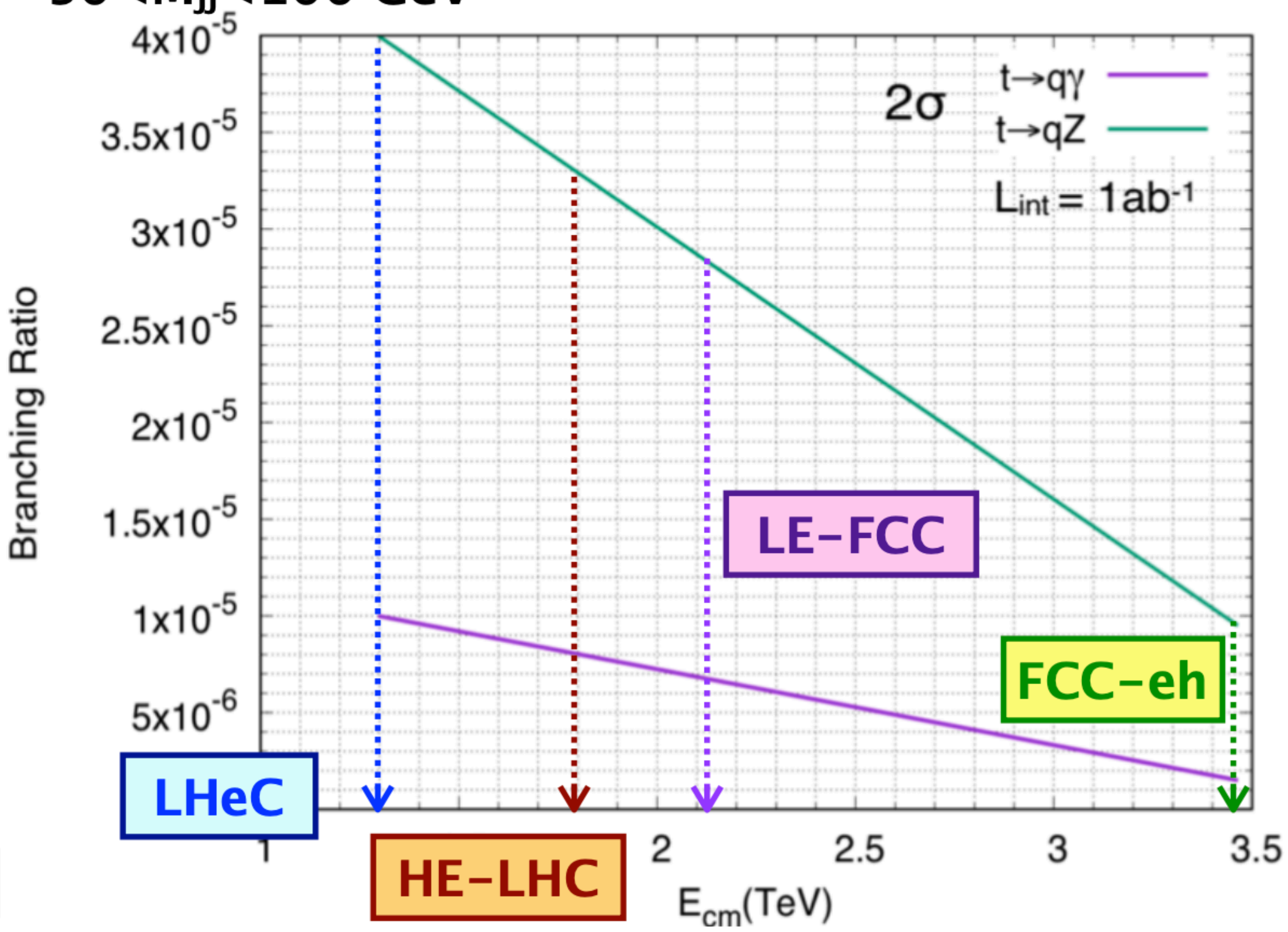
I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

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



DELPHES

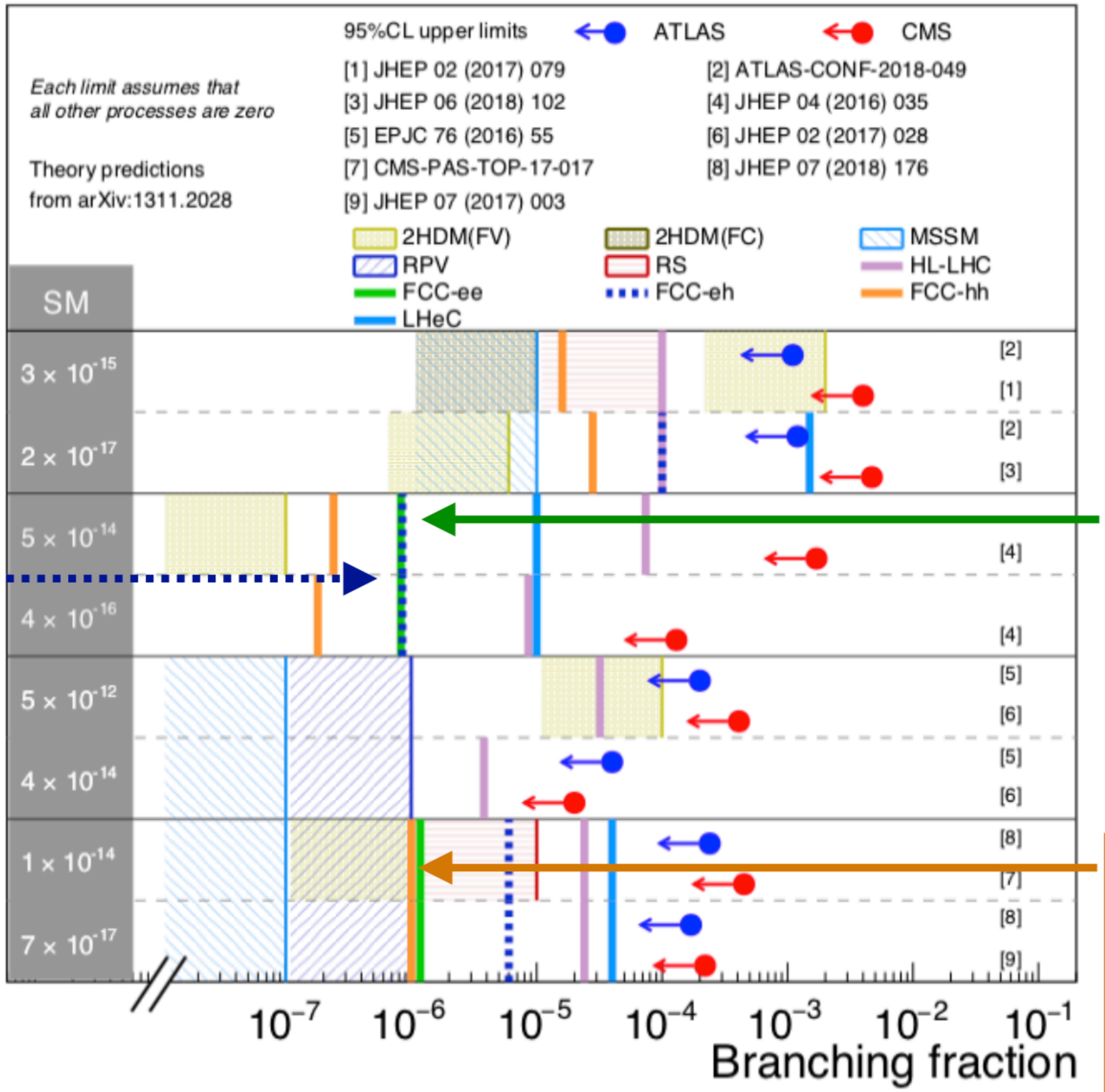




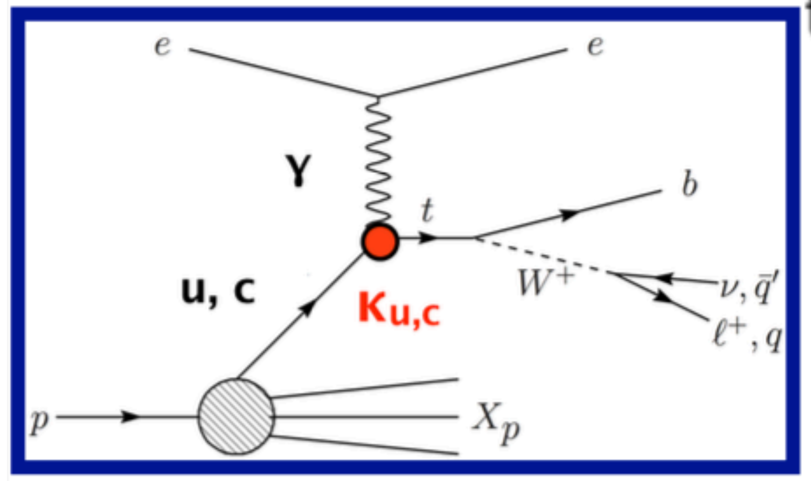
test exotic models leading to FCNC

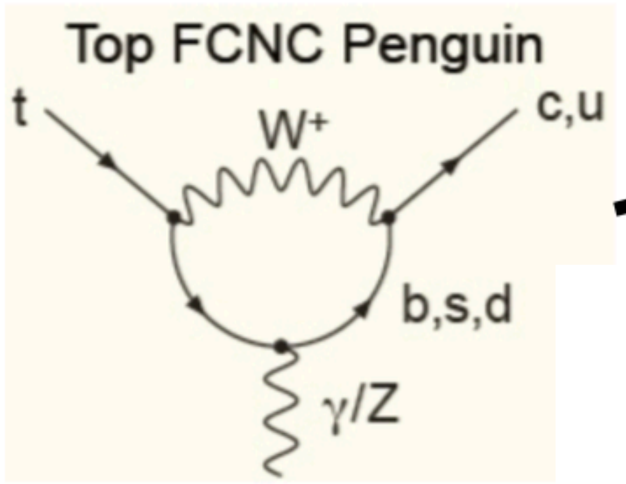
FCNC Top Quark Couplings

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)



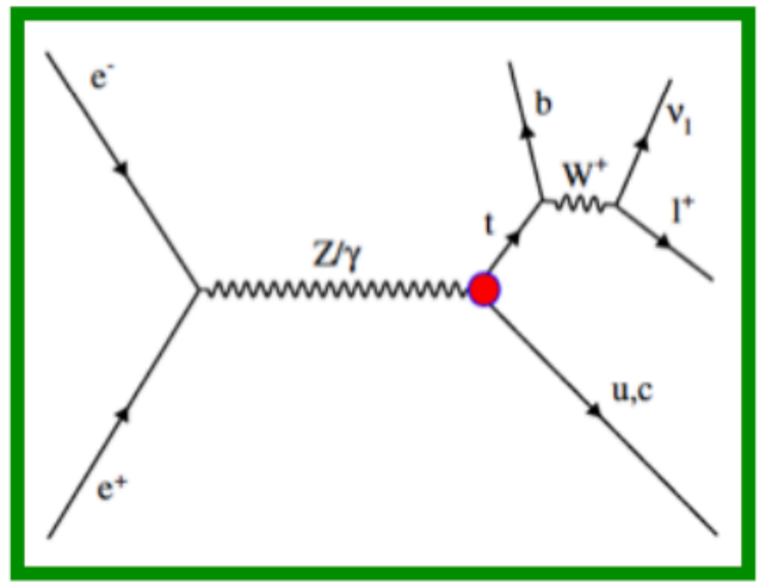
FCC-eh



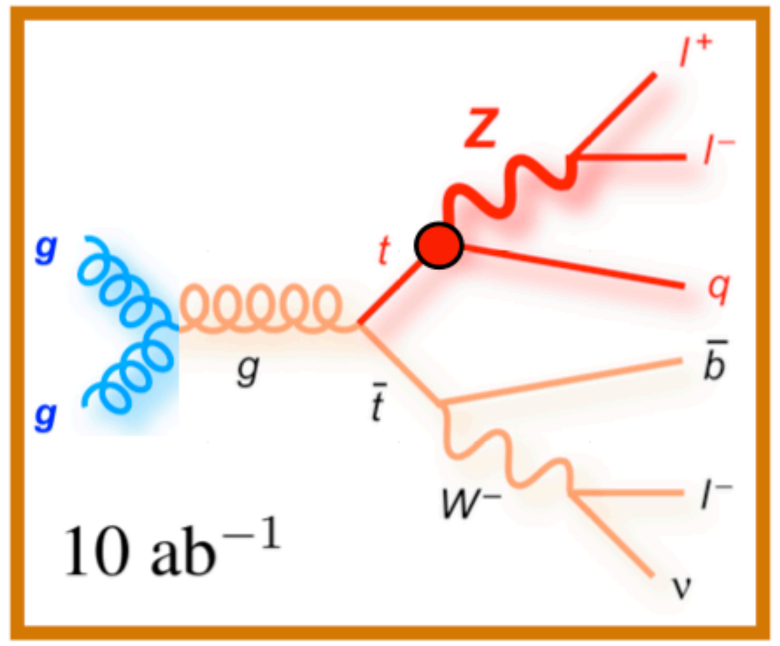


complementarity of colliders

FCC-ee



FCC-pp



test little Higgs, SUSY, technicolor, …

High Mass Searches at the LHC via EFT

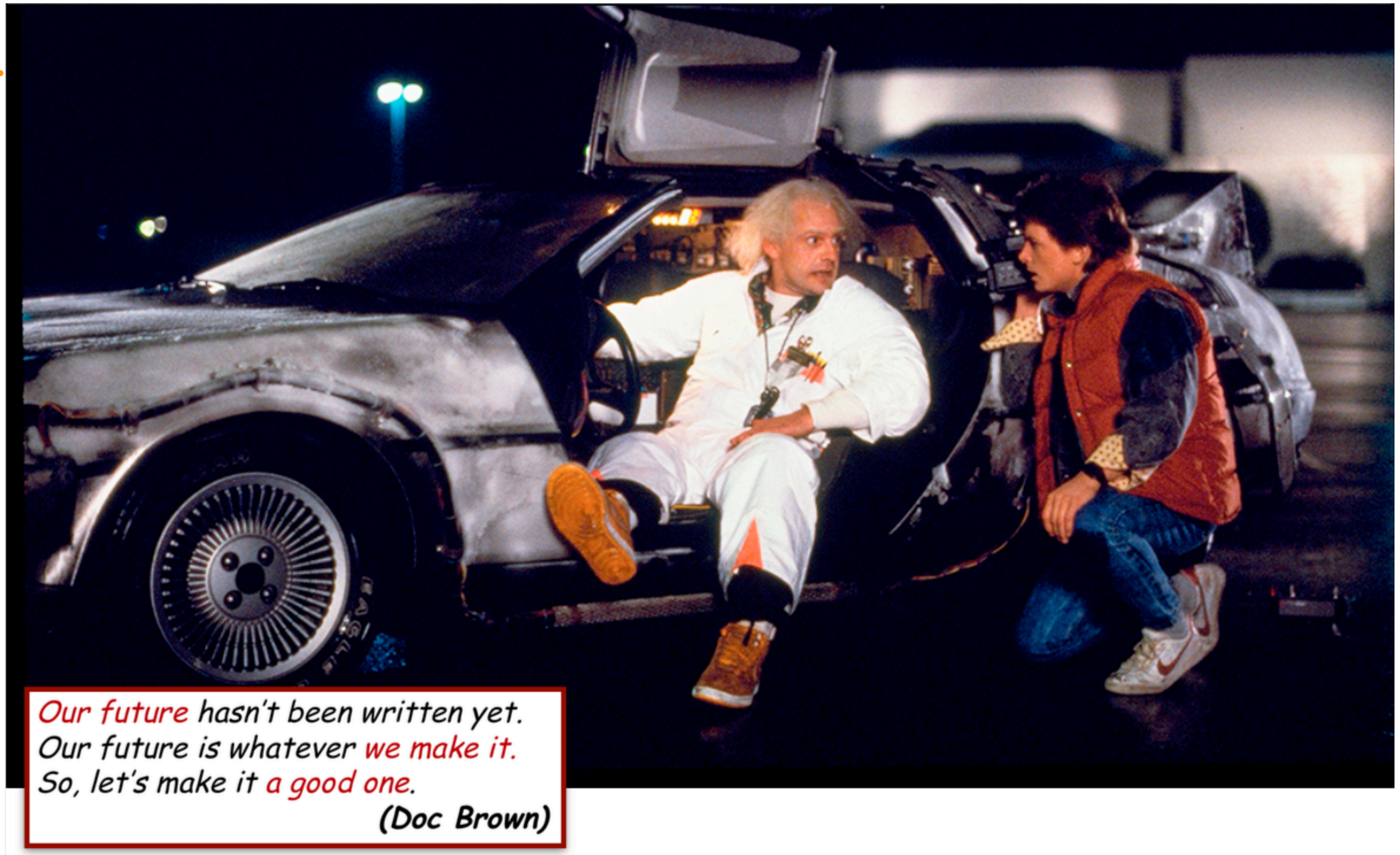
$$\mathcal{L}_{\rm CI} = \frac{g^2}{\Lambda^2}\eta_{ij}(\bar{q}_i\gamma_\mu q_i)(\bar{\ell}_i\gamma^\mu\ell_i),$$

Model	ATLAS (Ref. [702])	HL-LHC	
	$\mathcal{L} = 36\,\mathrm{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\mathrm{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

→ **considerable improvement (up to factor 1.7) in reach of new physics mass scale using LHeC PDFs and α_s**

Conclusions

- **LHeC** great potential for a compelling and competitive physics programme
- This includes direct and indirct searches for new physics
- An electron-proton facility represents a seminal opportunity on its own but also in particular in combination of pp with ep
- here some examples of the studies carried out are presented, more could be done



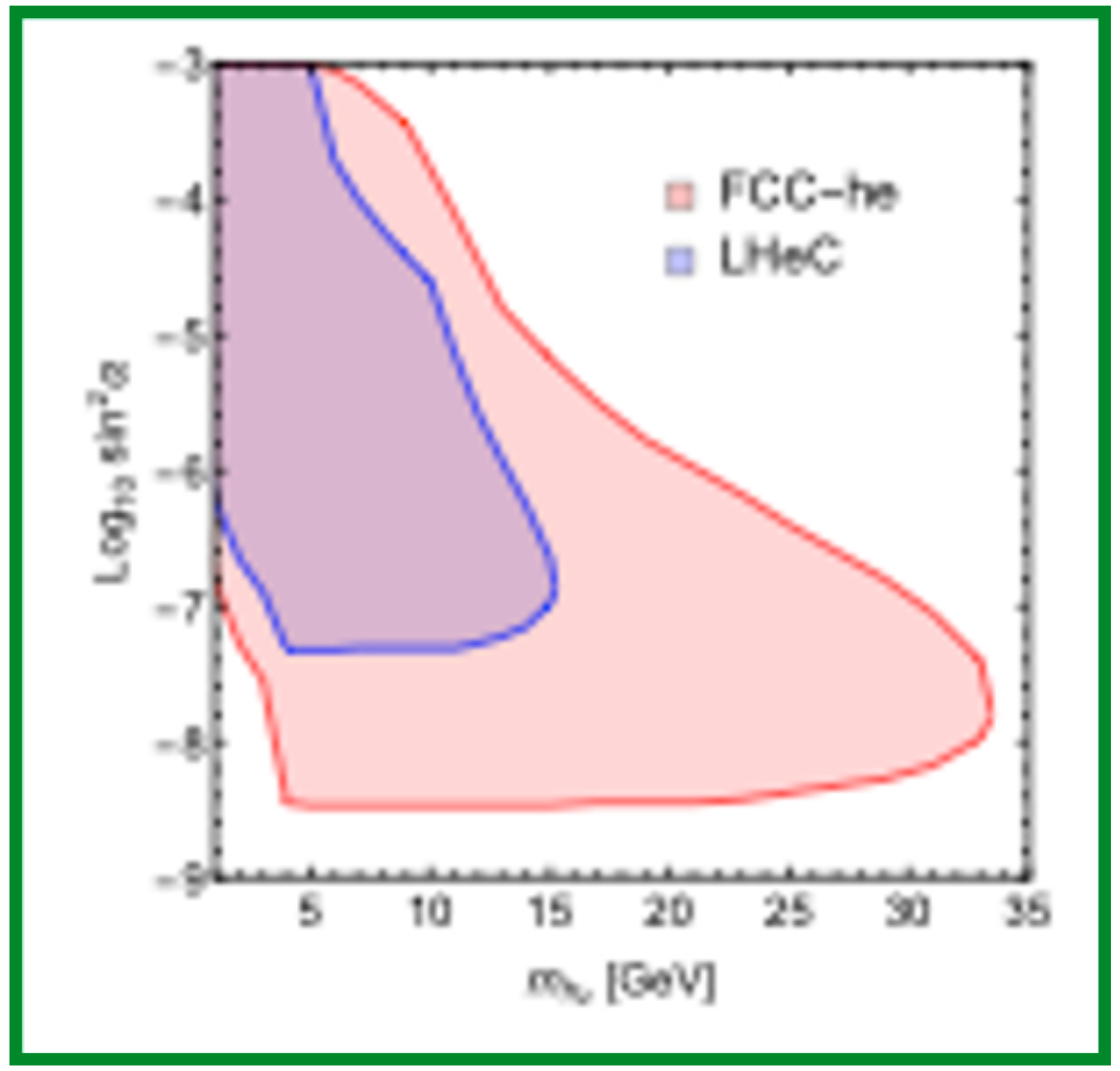
The **LHeC** offers an achievable bridging project for CERN, with an impactful physics programme, including further empowerment of the HL-LHC

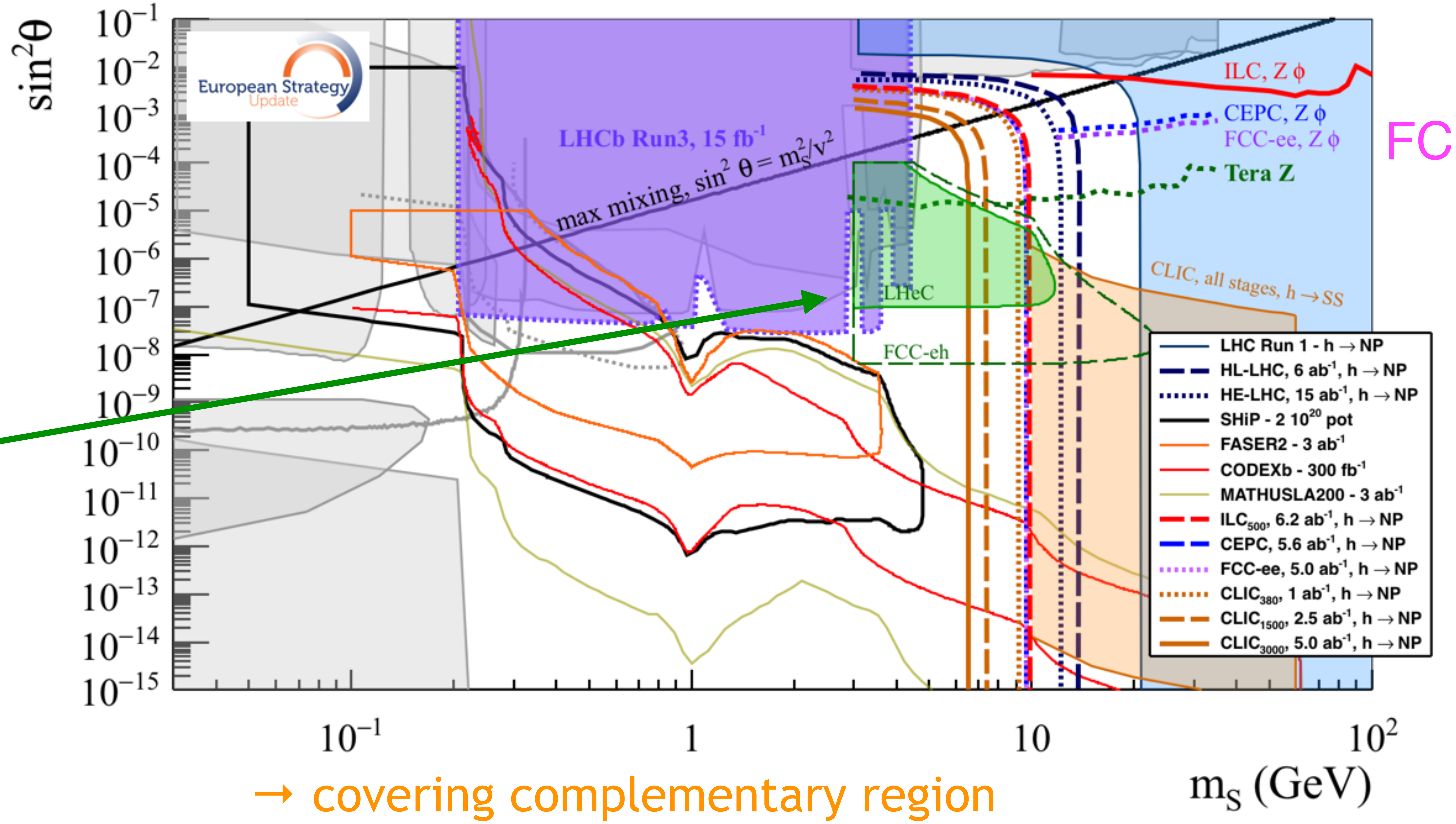
Backup

Search for new scalars

- Interpreting the results for a specific model, where lifetime and production rate of the LLP are governed by the scalar mixing angle
- The contours are for 3 events and consider displacements larger than 50 µm to be free of background.

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$



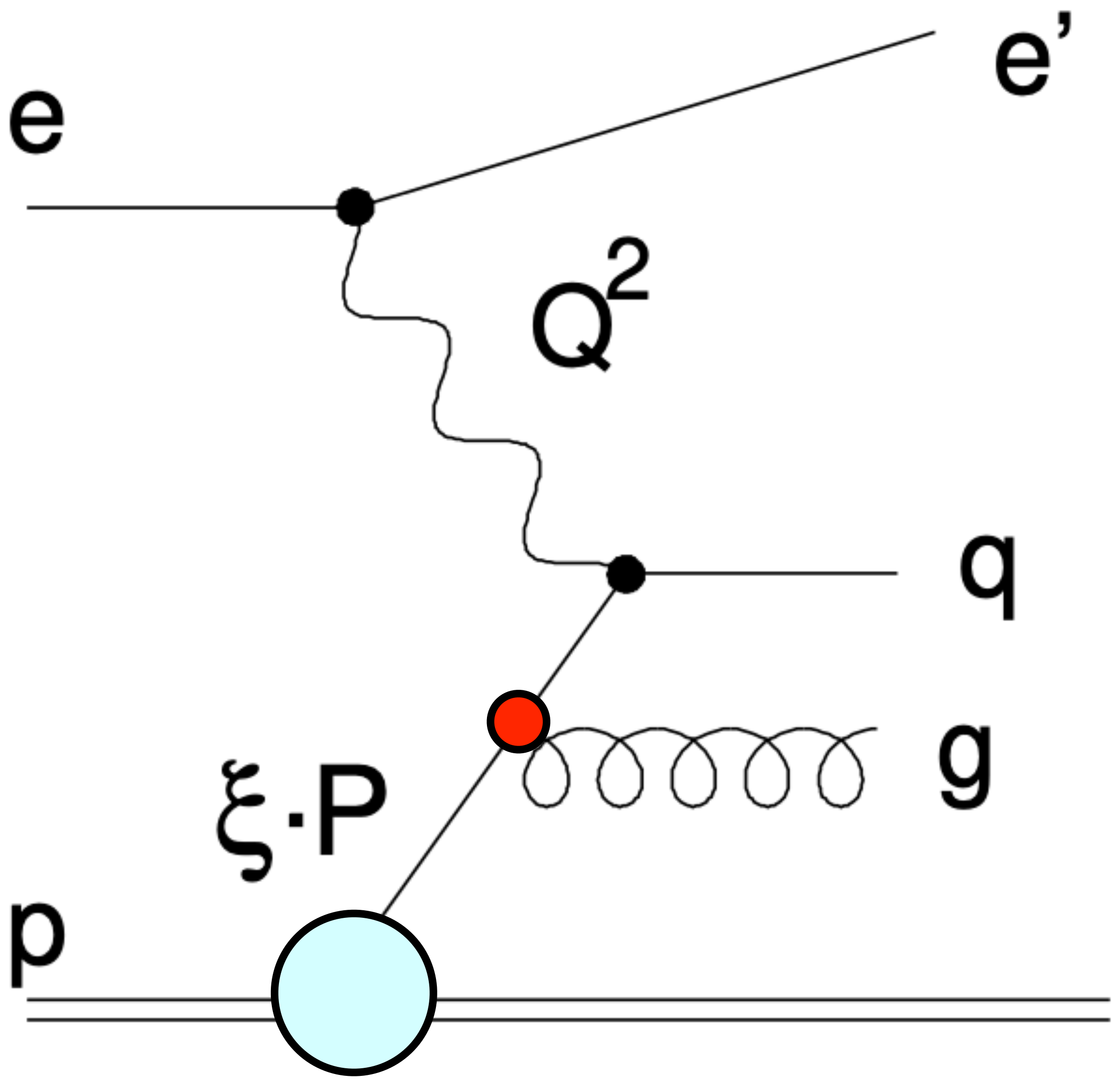


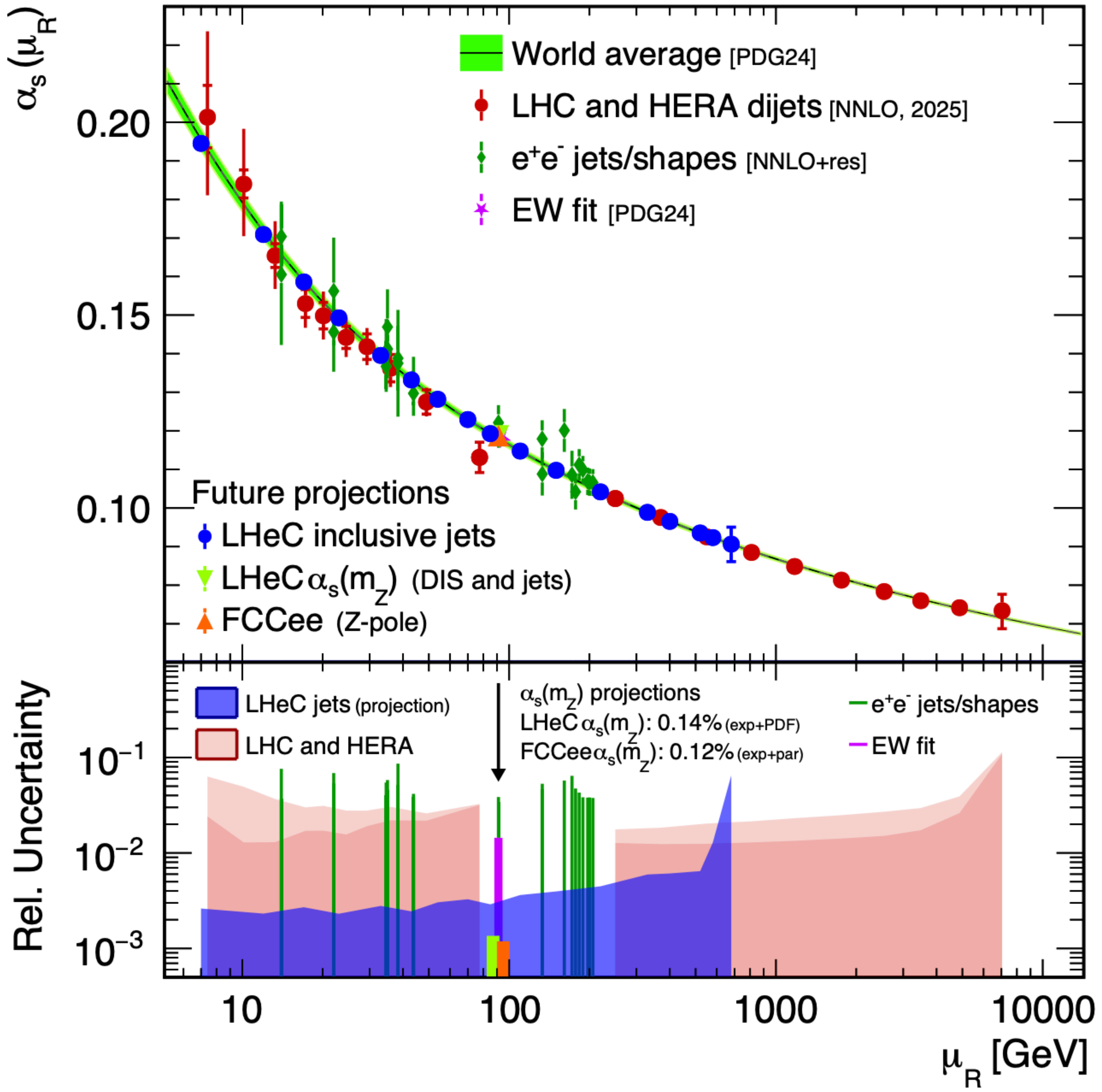
FCC-ee

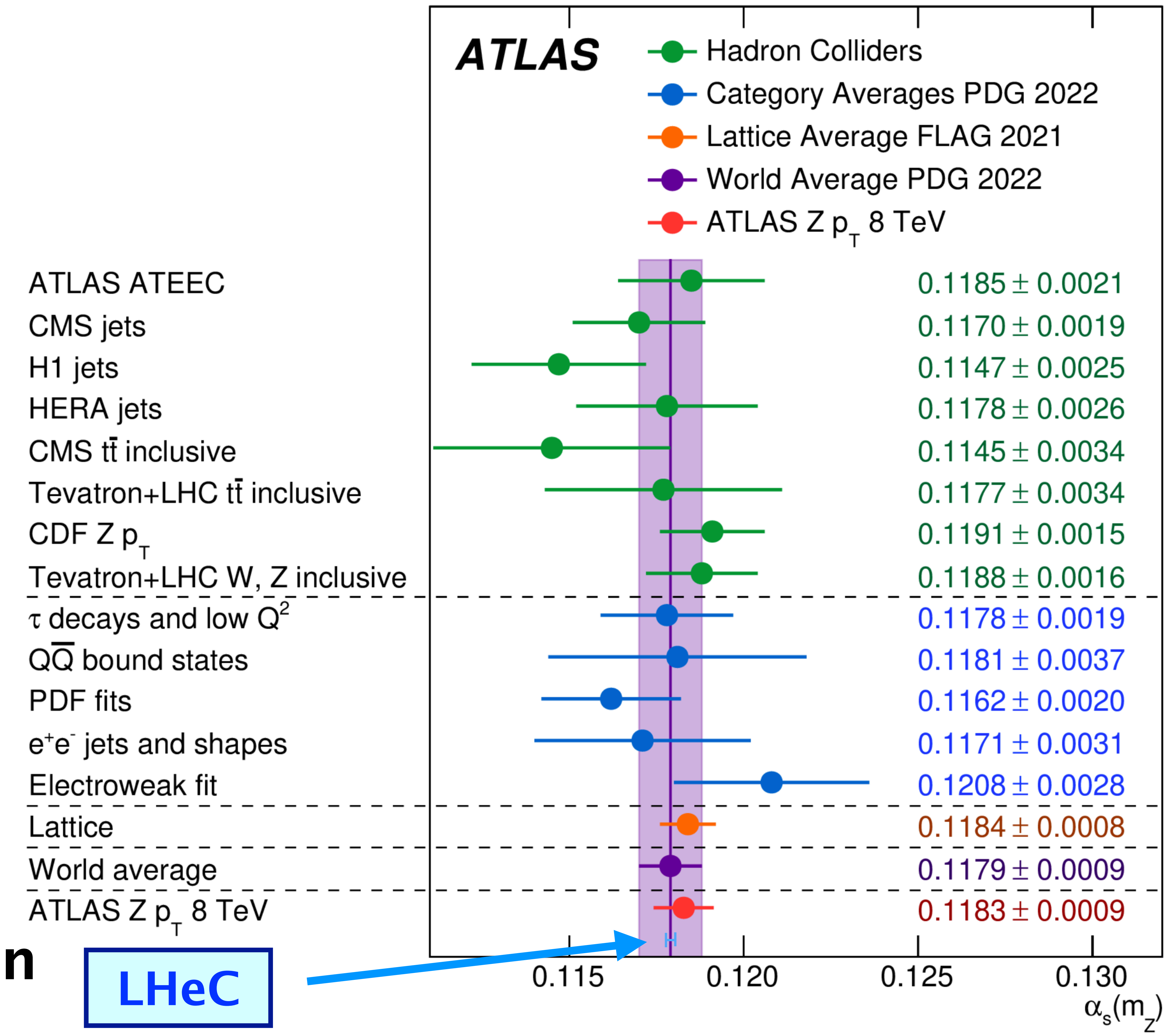
→ covering complementary region

Determination of the strong coupling

- 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

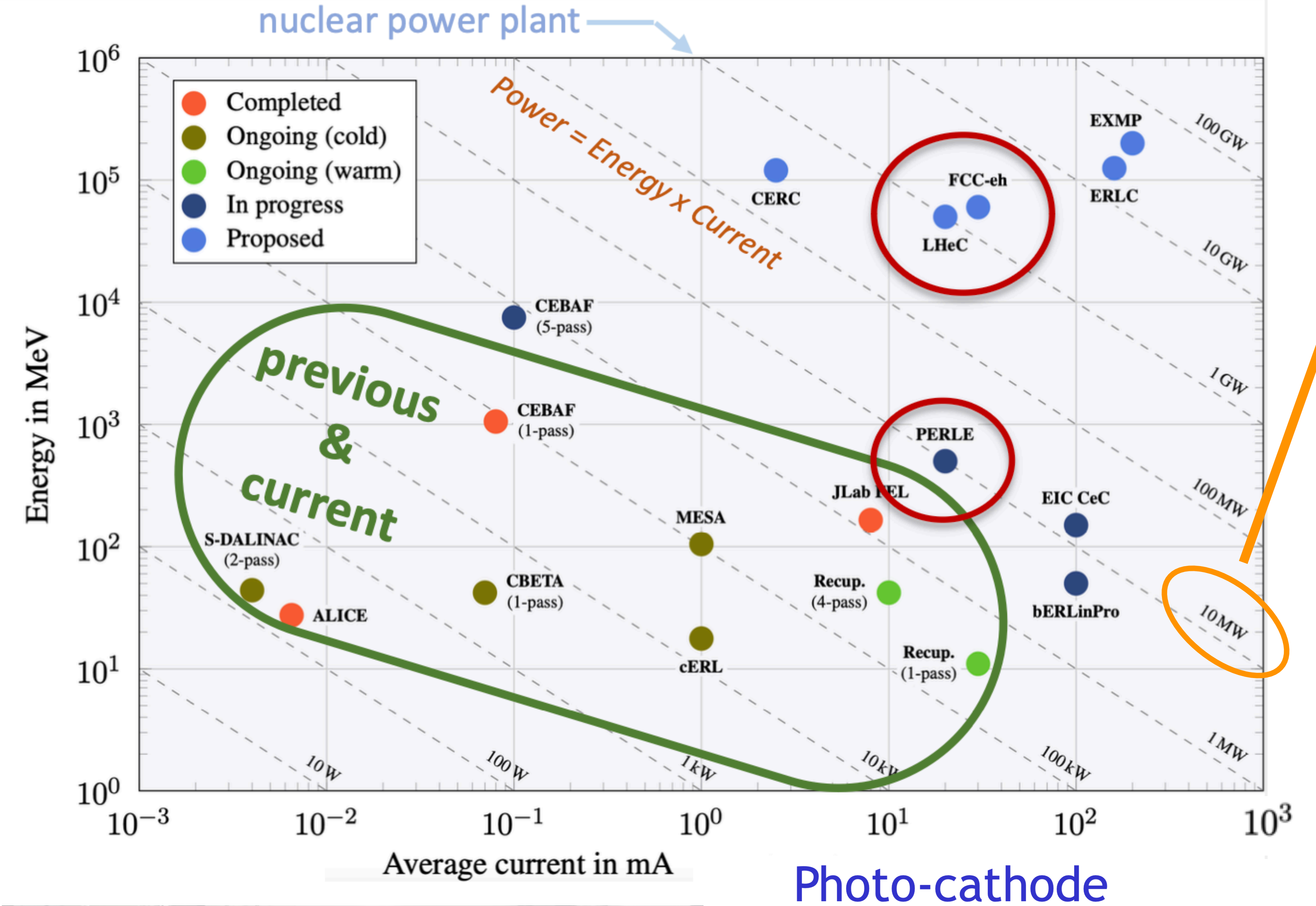
Achievable precision: $\mathcal{O}(0.1\%)$ - **x5-10** better than today

→ considerable improvement of world average

Status of the facility: Energy Recovery Linacs (ERL)

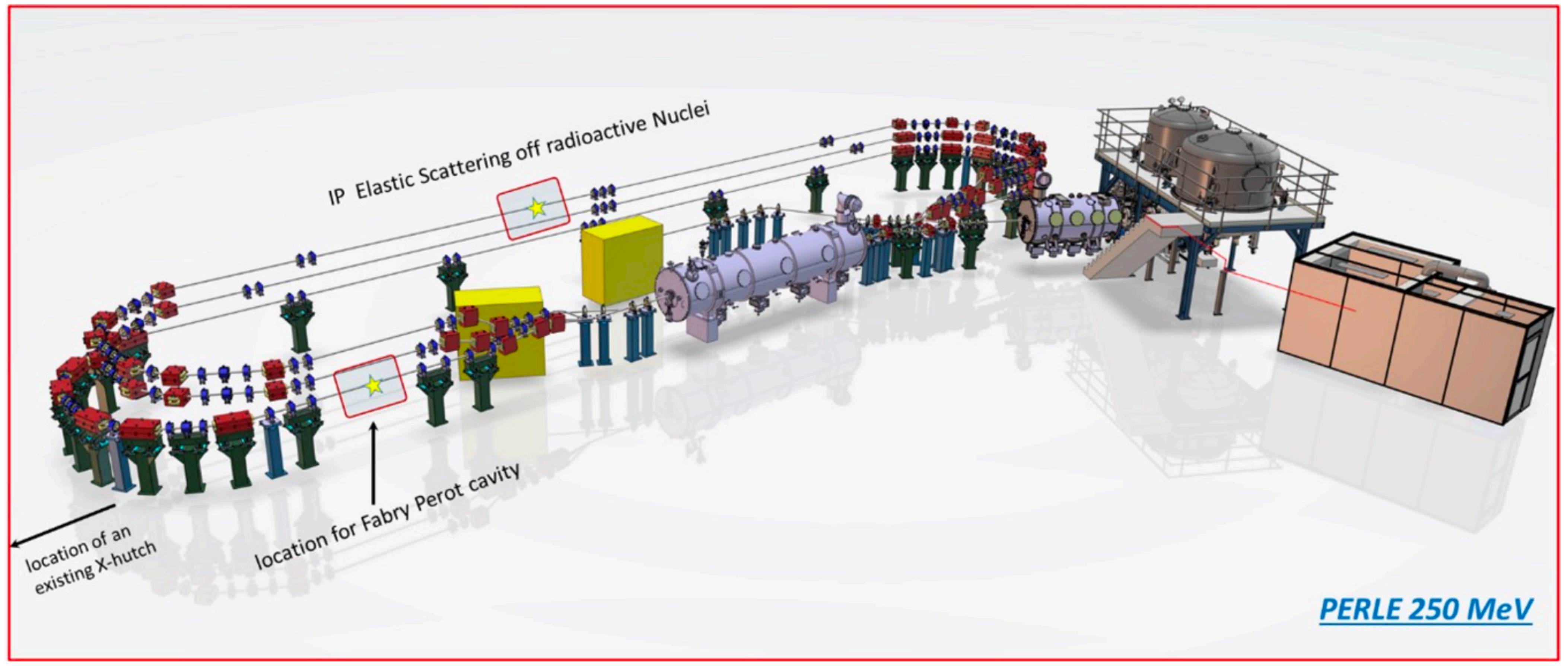
- Demonstrating ERL: scalability is critical path
- Prototype (PERLE @ IJCLab / Orsay) implementation started
- First stage (one turn) by 2028, 3 turns in 2029

multi–turn ERL based on SRF technology
(3–turns, 500 MeV, 20 mA)

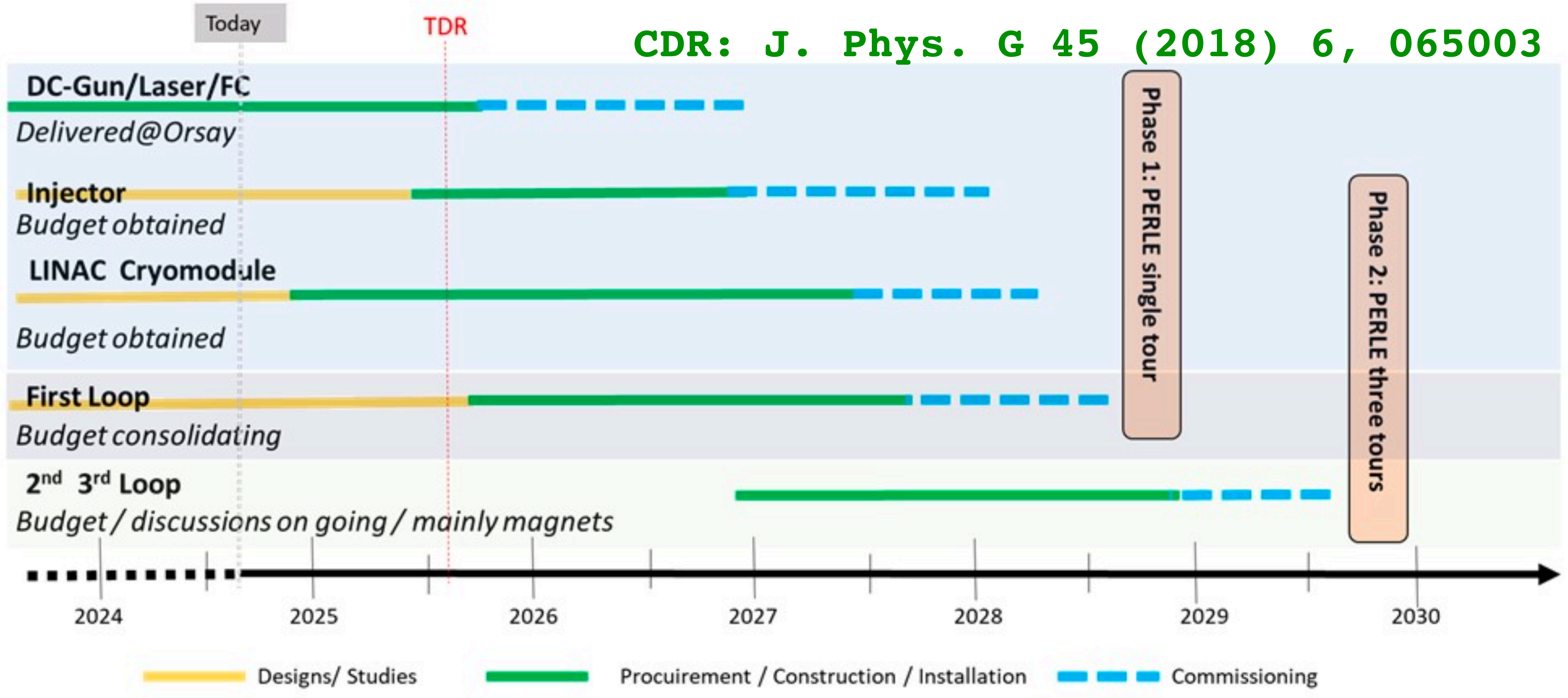


→ first 10 MW ERL facility

HV tanks



CDR: J. Phys. G 45 (2018) 6, 065003



Electron DC-gun

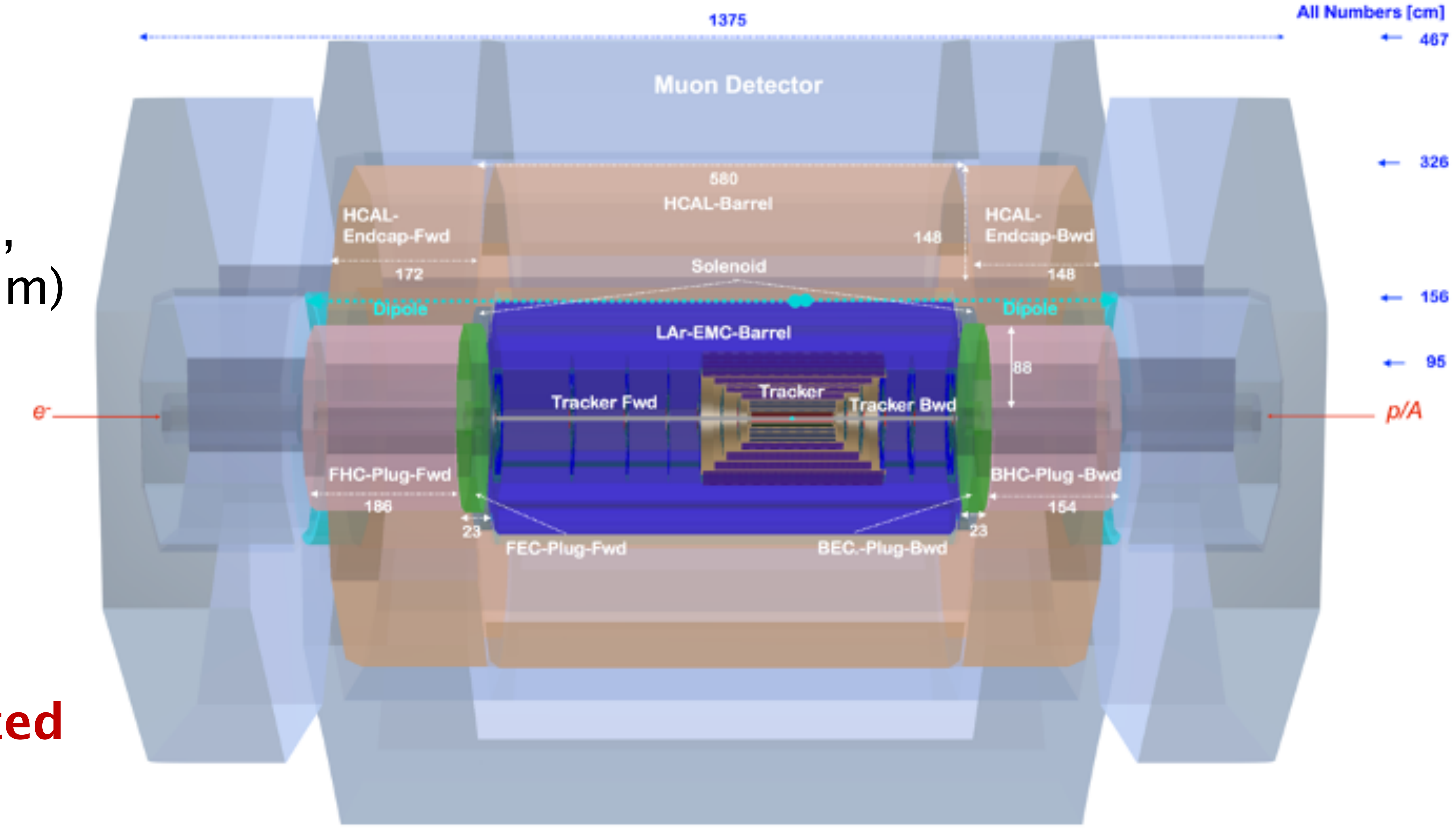
Photo-cathode

R&D Need: Detector Design

Compact
13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

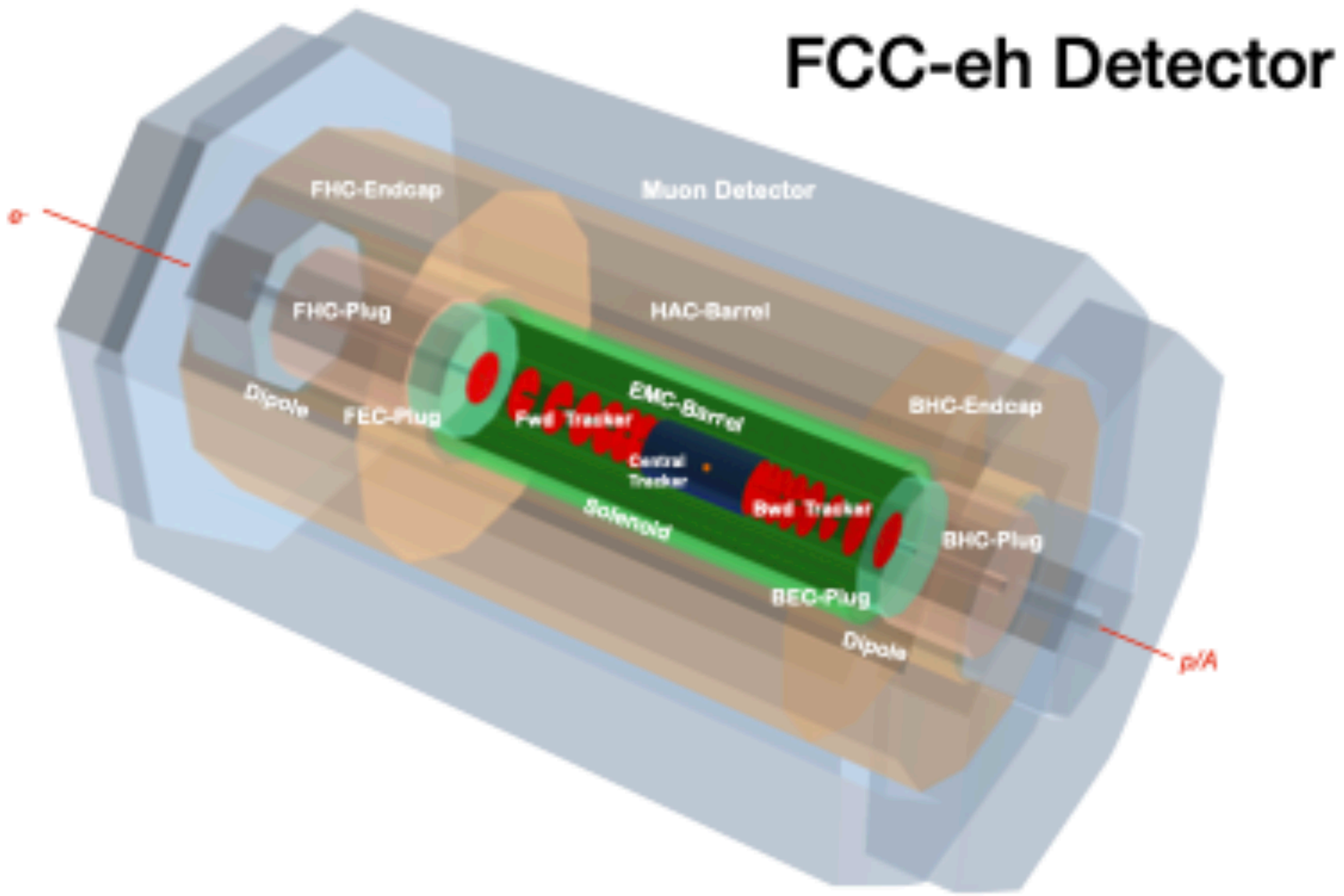
Hermetic
– 1° tracking acceptance forward & backward

Beamline also well instrumented



Eur. Phys. J. C 82 (2022) 1, 40

FCC-eh: 19m x 12m



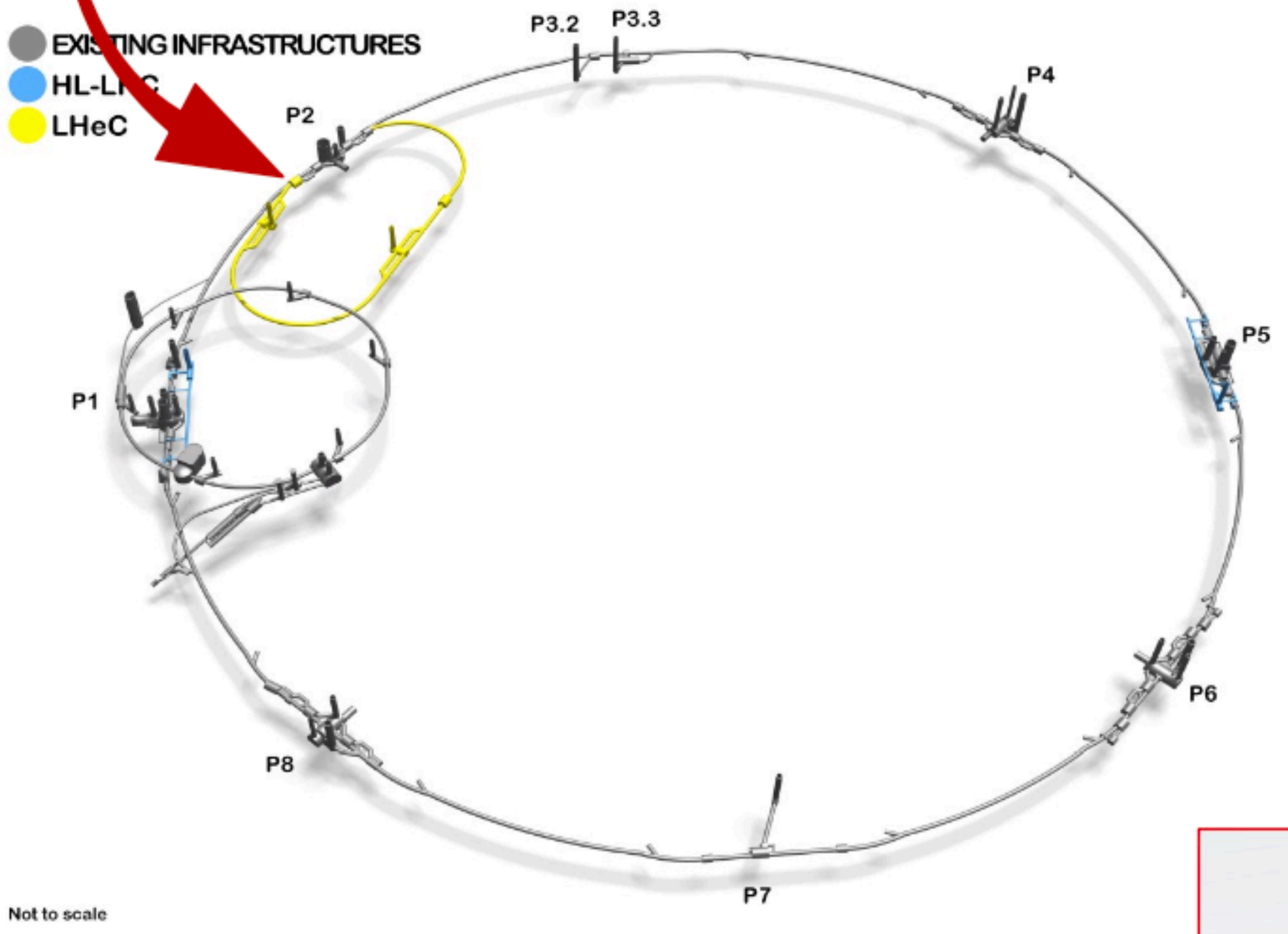
Could be built now, but many open questions:

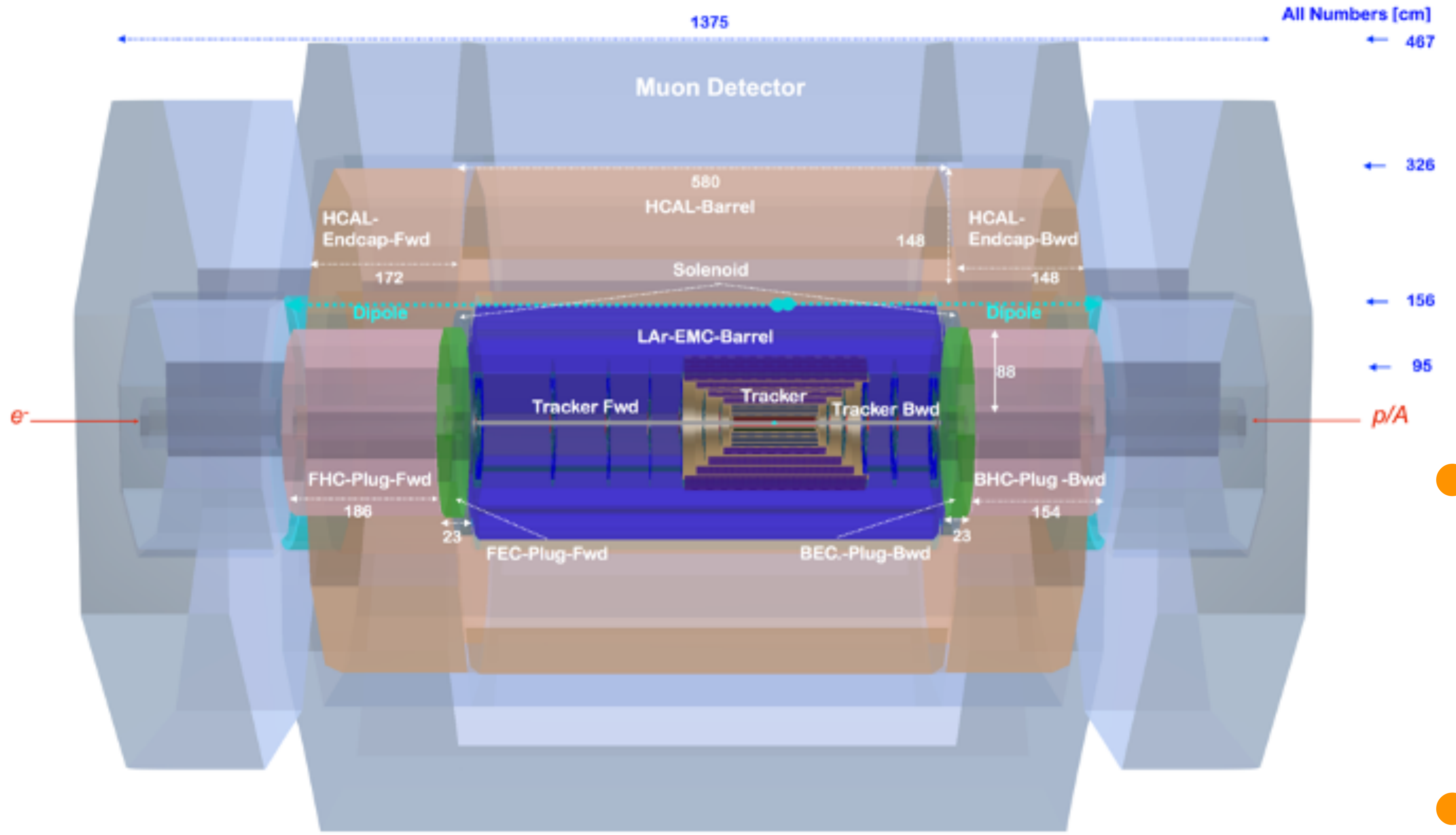
- a snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- possibly lacking components for some ep/eA physics (e.g. Particle ID)
- not particularly well integrated or optimized

… synergies with EIC, LHCb, ALICE3, future lepton colliders still to be explored

Estimates of sustainability

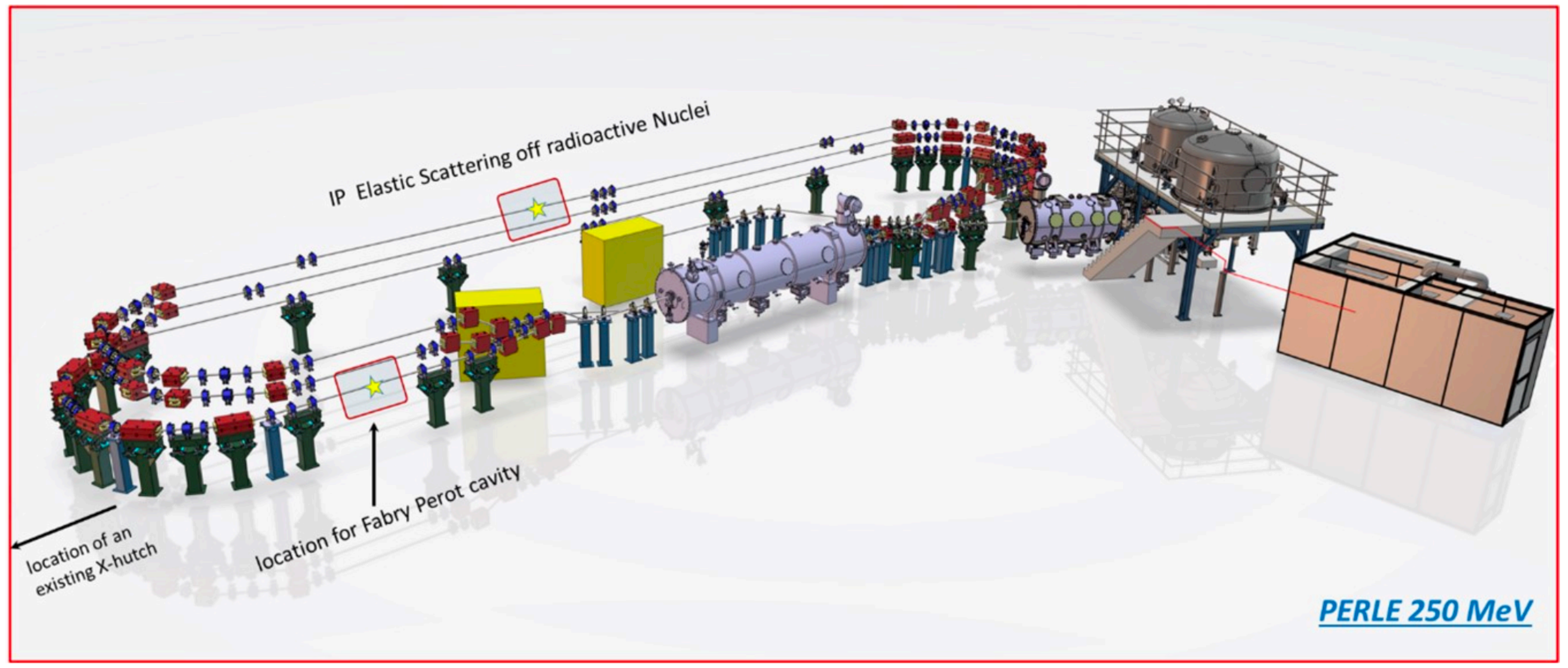
LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC ($\gtrsim$ Run5)

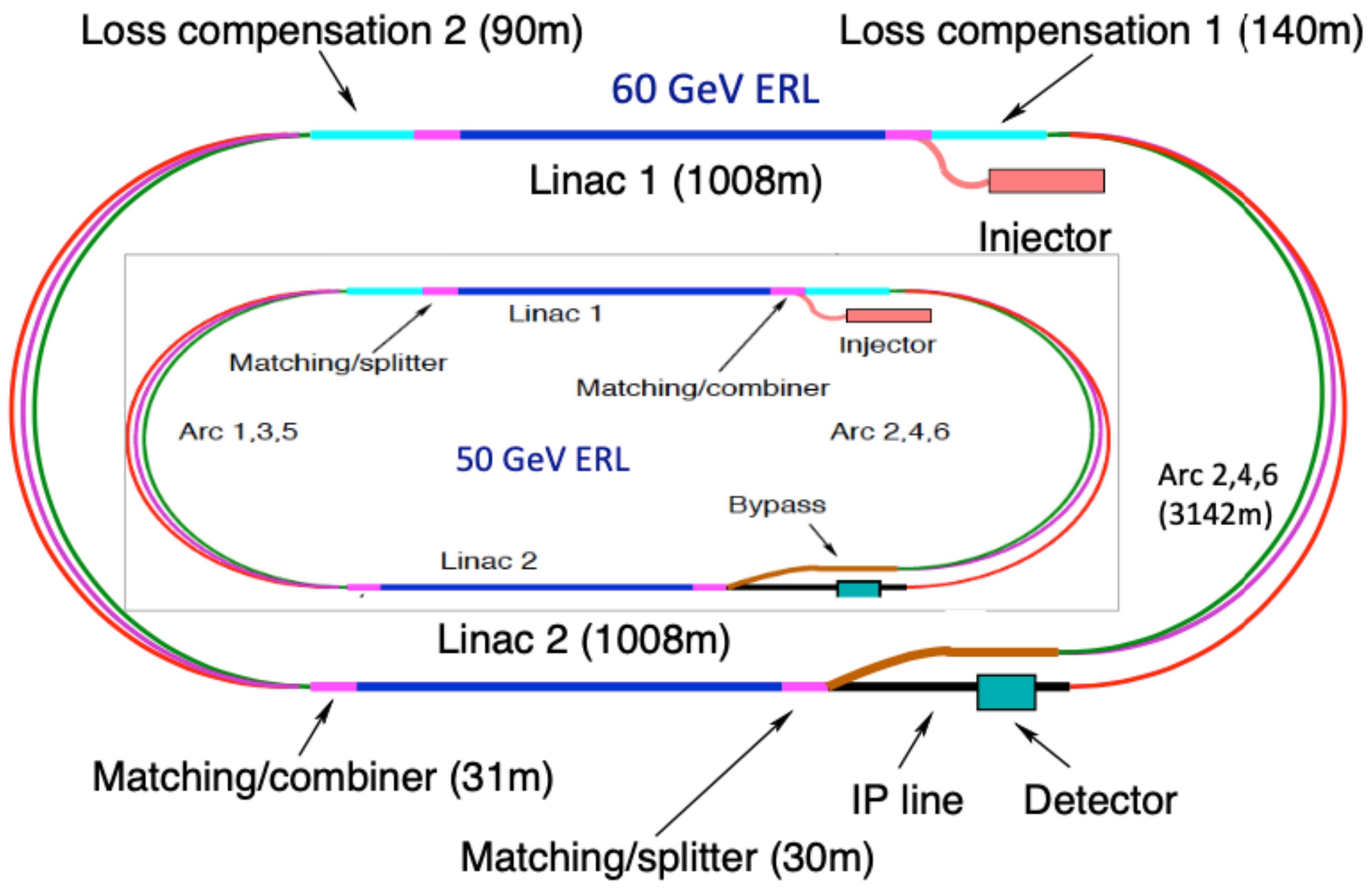




- ‘sustainable’ acceleration: ~100 MW (similar to LHC today)
- green technology

→ aspects of sustainability are being collected and reviewed by a dedicated working group of the LDG (Lab Directors Group), in due time this report will become public





Costs and personpower

CERN-ACC-2018-0061, ATS report approved by director of accelerators, Frederick Bordry

Budget Item	Cost 30GeV	➔ 50GeV
SRF System	402MCHF	+268MCHF
SRF R&D and Proto Typing	31MCHF	
Injector	40MCHF	
Magnet and Vacuum System	103MCHF	
SC IR magnets	105MCHF	
Dump System and Source	5MCHF	
Cryogenic Infrastructure	41.5MCHF	+28MCHF
General Infrastructure and installation	58MCHF	
Civil Engineering	289MCHF	
Total	1075MCHF	➔ 1371MCHF

costs: 2018

- 1-1.8 BCHF: in 10 years means ~8-14% of the CERN annual budget
- detector: ~few x 100 MCHF, presumably mostly coming from contributions via an experimental collaboration, so not core CERN funds
- Considering electricity price of 0.1CHF/kWh: additional operation cost for the LHeC at around 15MCHF to 30MCHF per year (similar to LHC)
- accelerator implementation: total personpower need of ca. 2500 Person Years (2300 of CERN staff plus personpower from international collaborations)
- operating the LHeC: with only one experimental insertion of one proton beam and ERL facility is comparable to the needs of to HL-LHC with two proton beams and 4 experimental insertions