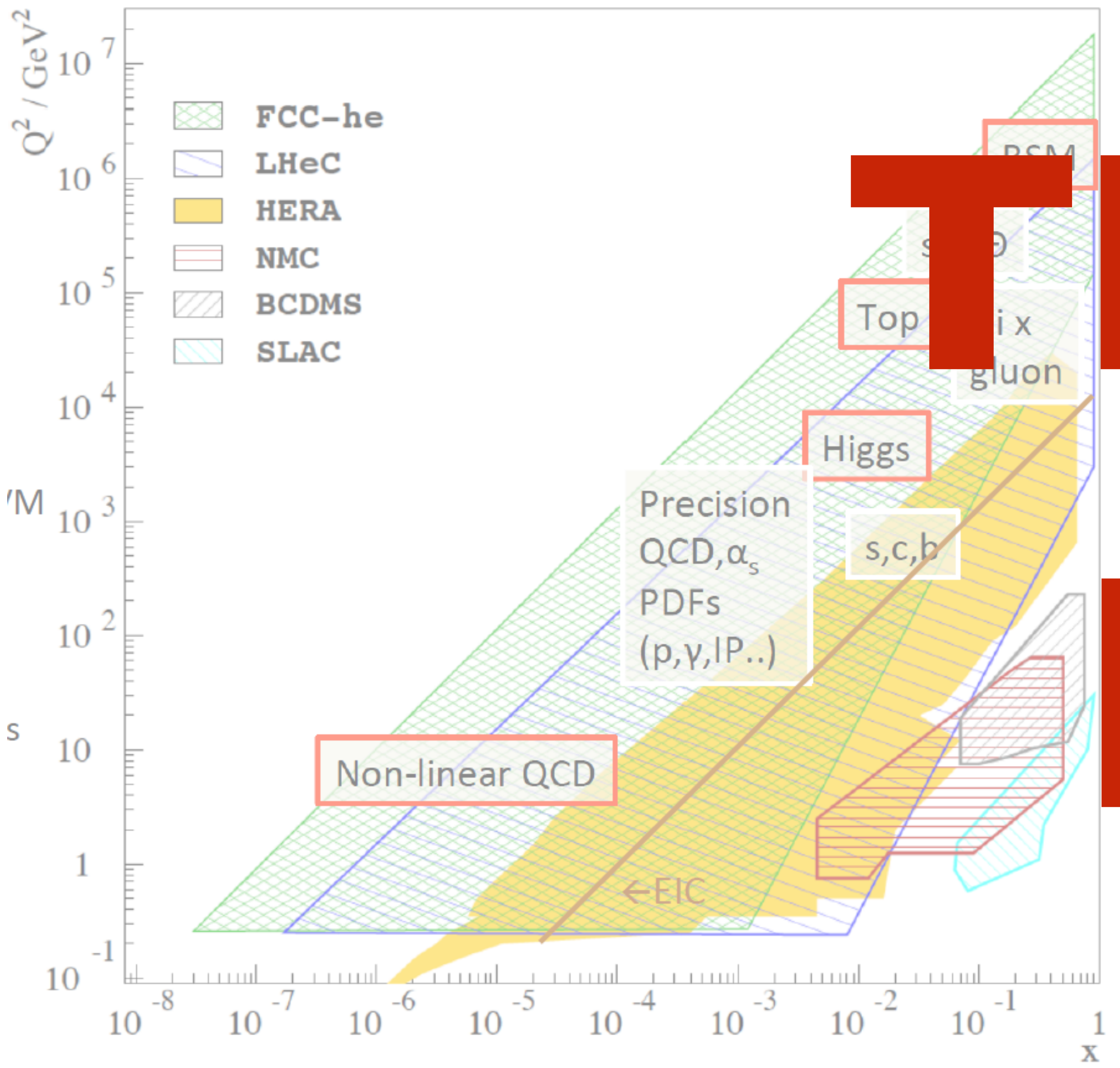
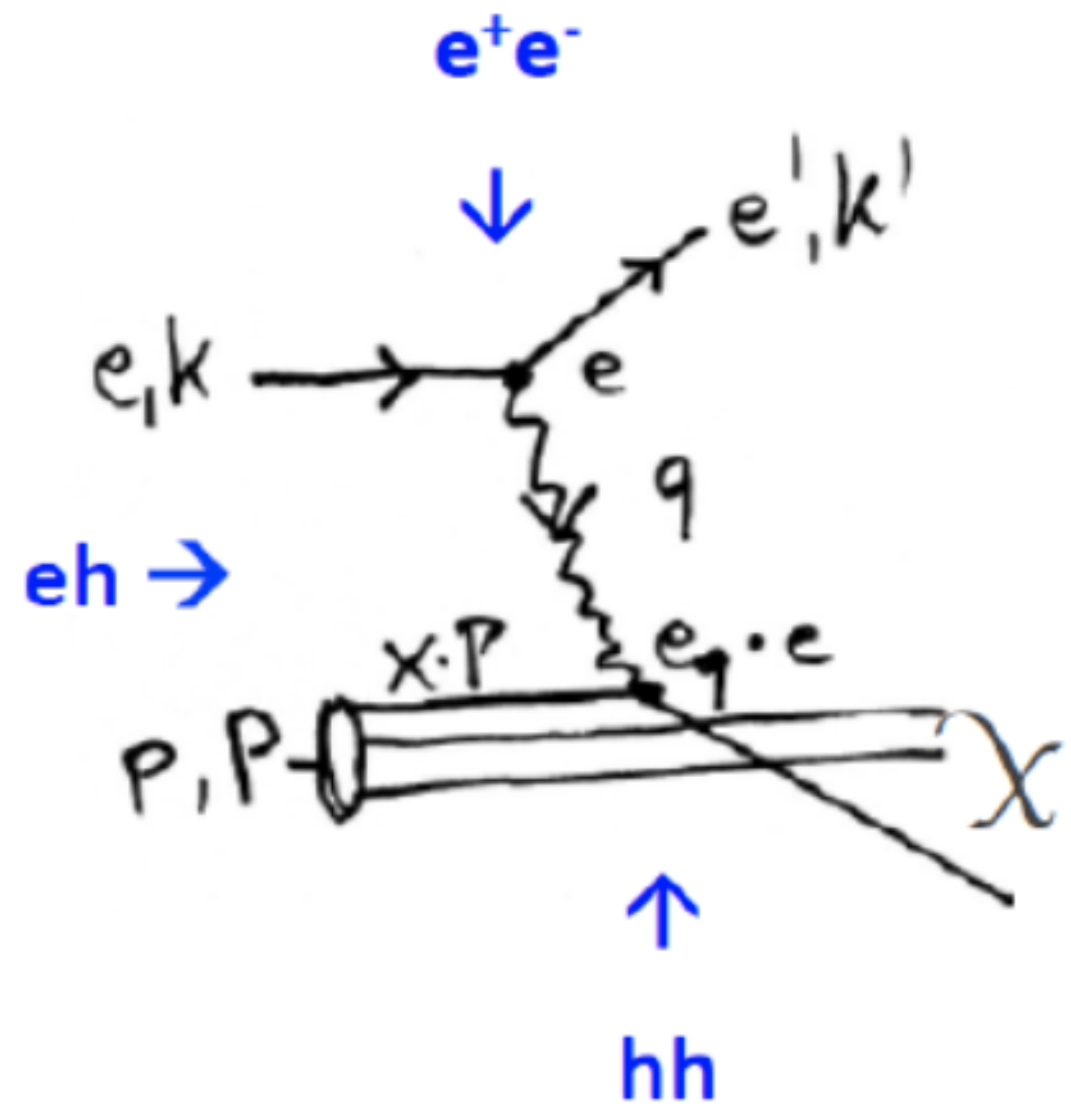
INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS IGFAE

IJCLab, Orsay, October 16th 2025



The LHeC project



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for the LHeC/FCC-eh Study Group, https://indico.cern.ch/event/lhecfcceh.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
AGENCIA ESTATAL DE INVESTIGACIÓN
EXCELENCIA MARÍA DE MAEZTU 2024-2030
Rede CIGUS Centros de investigación do Sistema Universitario de Galicia
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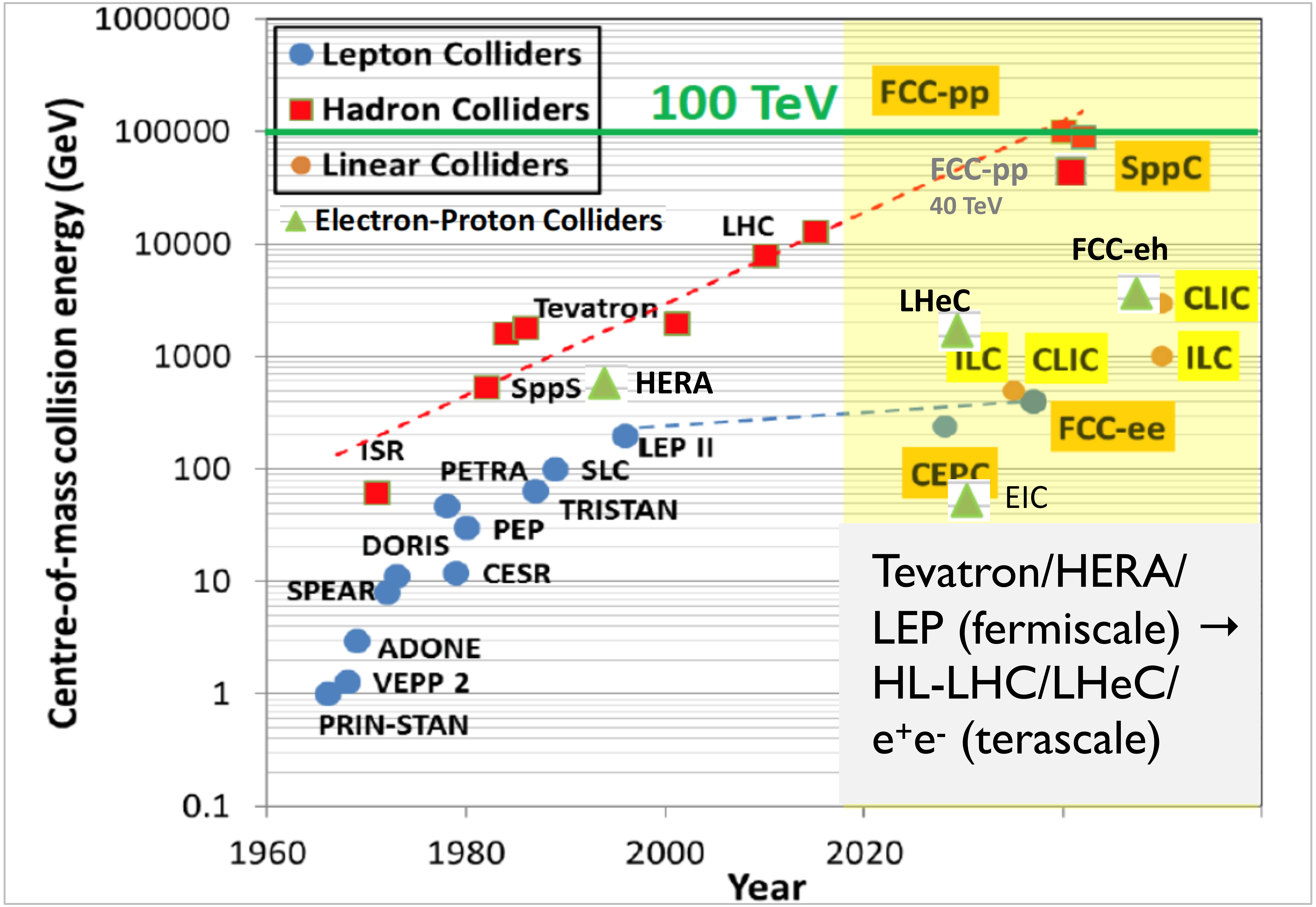
Introduction:

- Thoughts of combining LEP with LHC came from the start (1990's).

- LHeC idea born in 2005: upgrade of the (HL-)LHC to study DIS at the terascale.

- **It should be able to run concurrently with pp** (also FCC-eh), plus limitations on power consumption, high luminosity for Higgs studies,…⇒

Energy Recovery Linac as baseline.



Tevatron/HERA/LEP (fermiscale) → HL-LHC/LHeC/e^+e^- (terascale)

Contents:

1. Accelerator.

2. Detector.

3. Physics (some examples):
   - ➜ QCD.
   - ➜ Higgs.
   - ➜ EW.
   - ➜ Top.
   - ➜ BSM.

4. Status and plans.

5. Summary.

References:

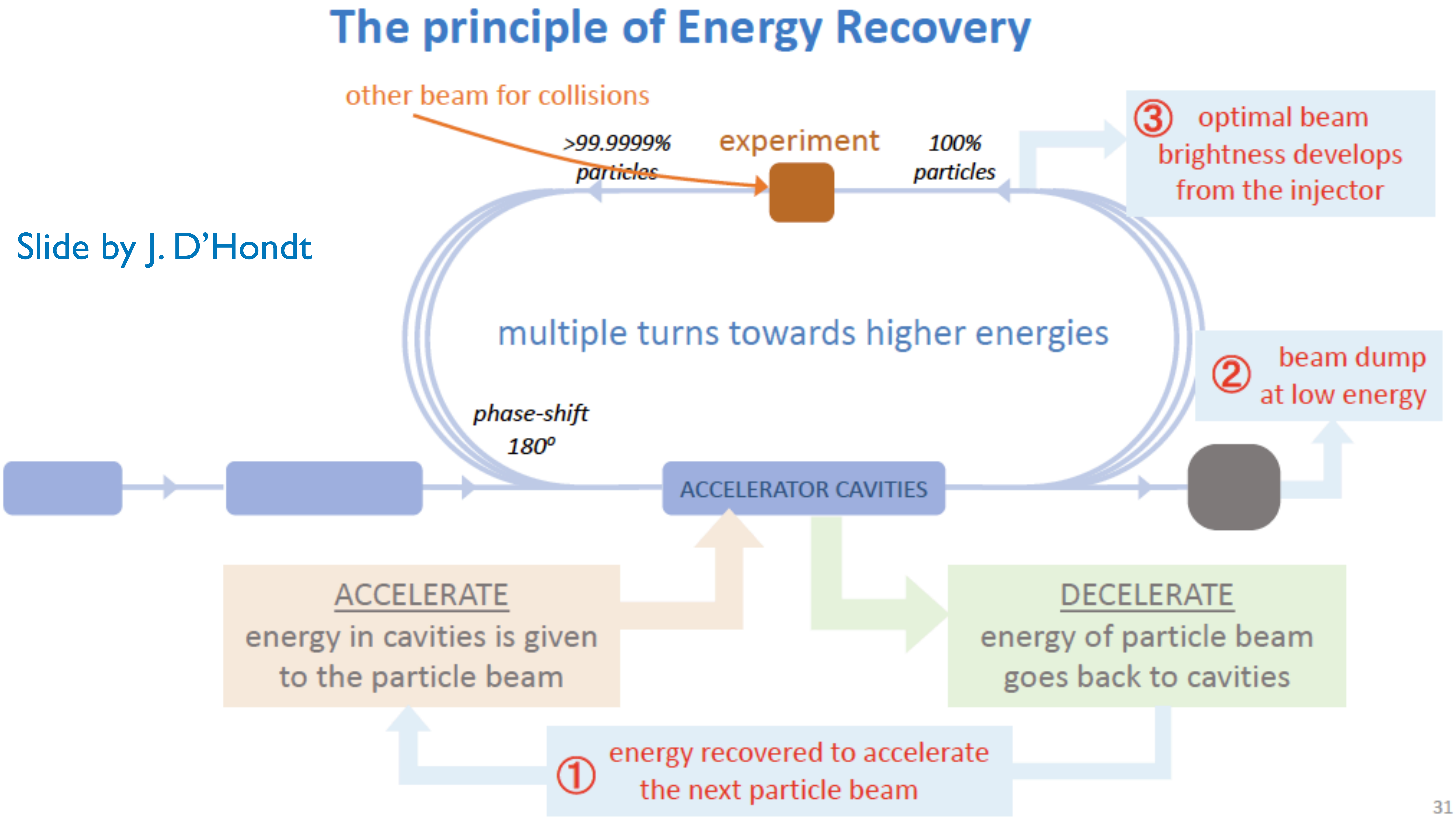
- *Future Circular Collider CDR: Vol. 1 Physics opportunities (Eur. Phys. J. C79 (2019) no.6, 474) and Vol. 3 FCC-hh: The Hadron Collider (Eur. Phys. J. ST 228 (2019) no.4, 755-1107);*
- *LHeC CDR, 1206.2913;*
- *ESPP 2020: Briefing Book, 1910.11775;*
- *Update of the 2012 LHeC CDR, 2007.14491;*
- *2201.02436;*
- *LHeC/FCC-eh talks at DIS2025, https://indico.cern.ch/event/1436959/, EPS-HEP 2025, https://indico.in2p3.fr/event/33627/, and the Open Symposium on the ESPP2026, https://agenda.infn.it/event/44943/;*
- ***White paper: 2503.17727**, annex to the EPPS submission.*

- *For comparisons, see the 2025 Briefing Book, https://cds.cern.ch/record/2944678.*

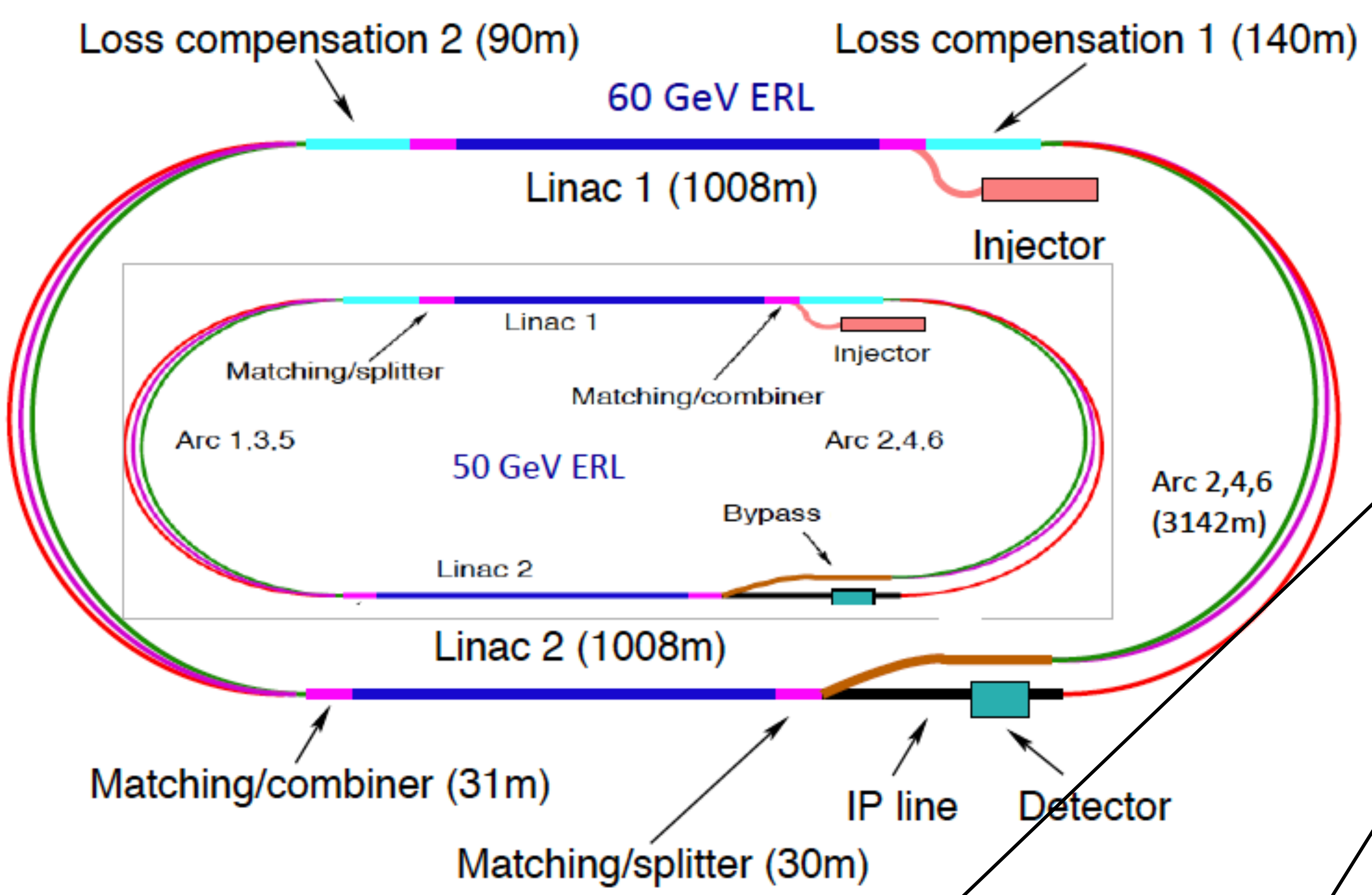
https://indico.cern.ch/event/lhecfcceh

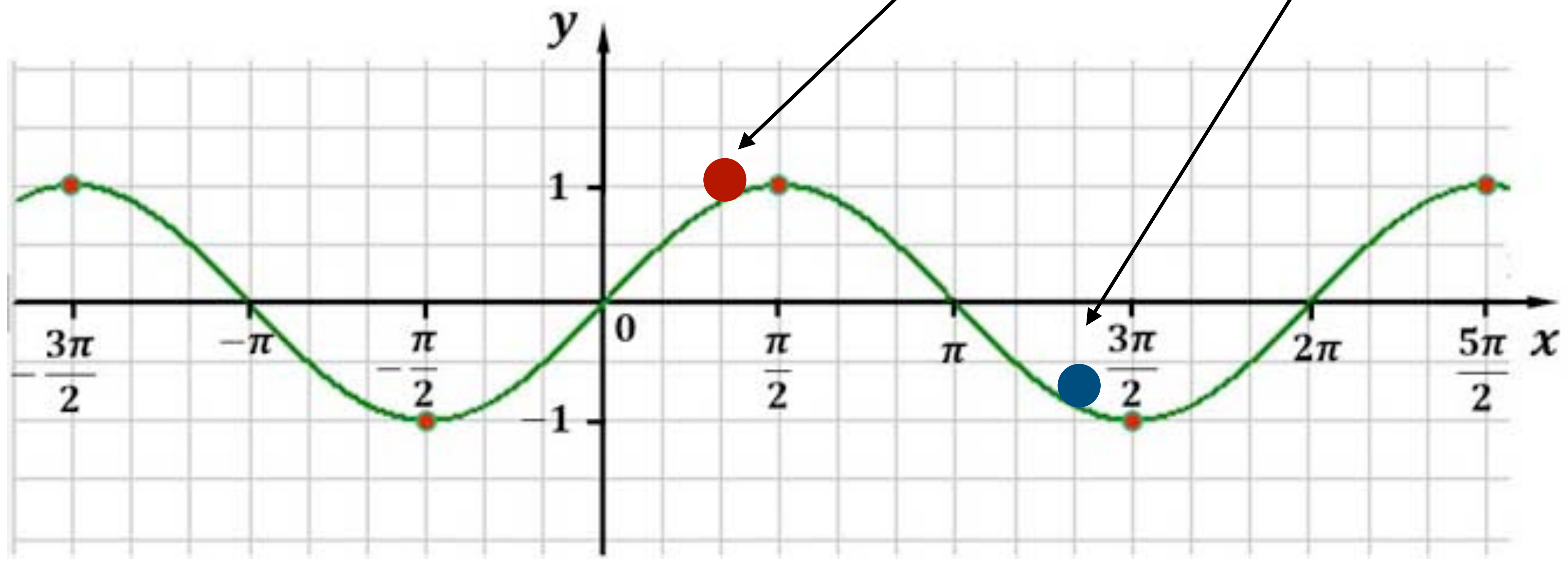
Accelerators: ER

Slide by J. D'Hondt

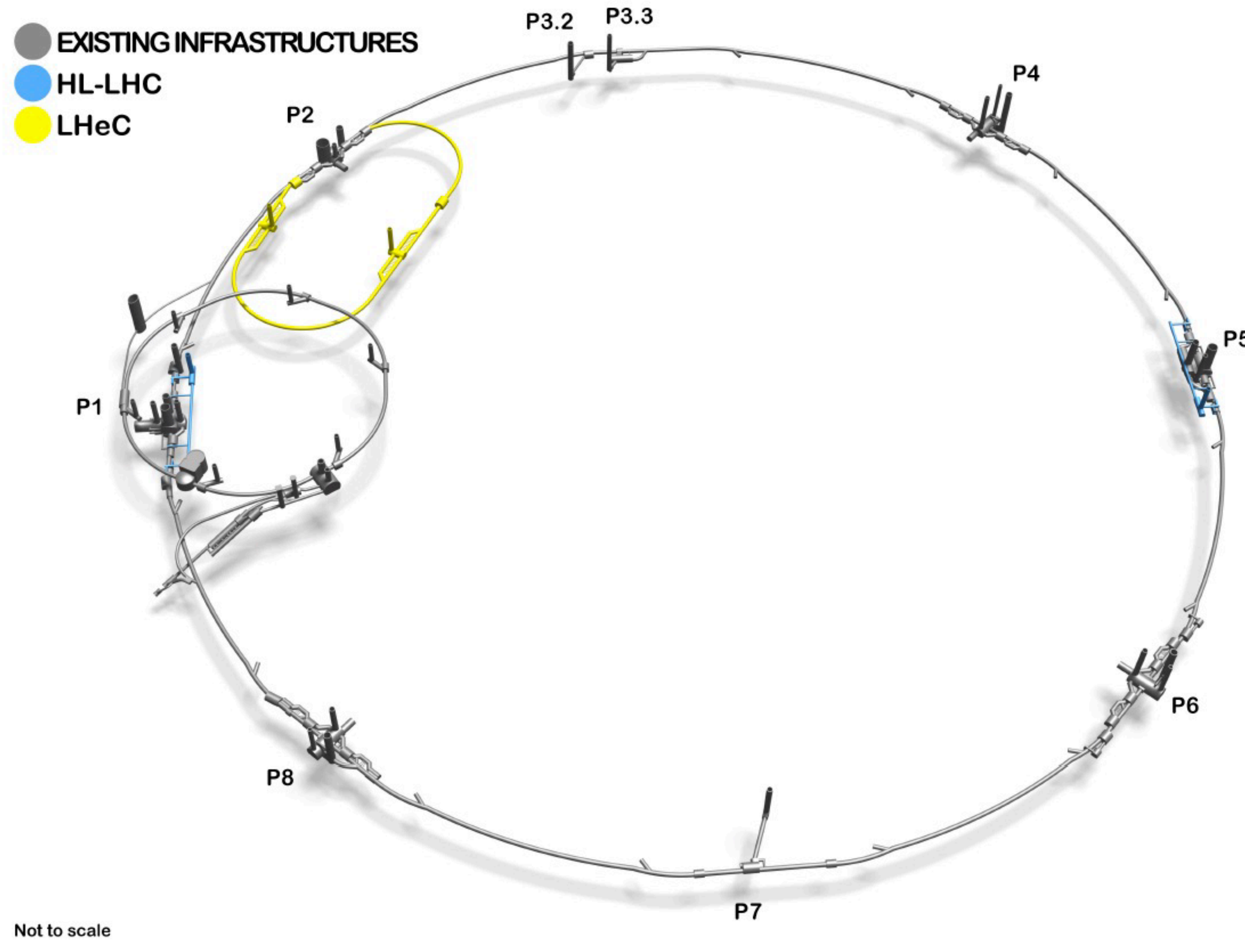


Accelerators: LHeC

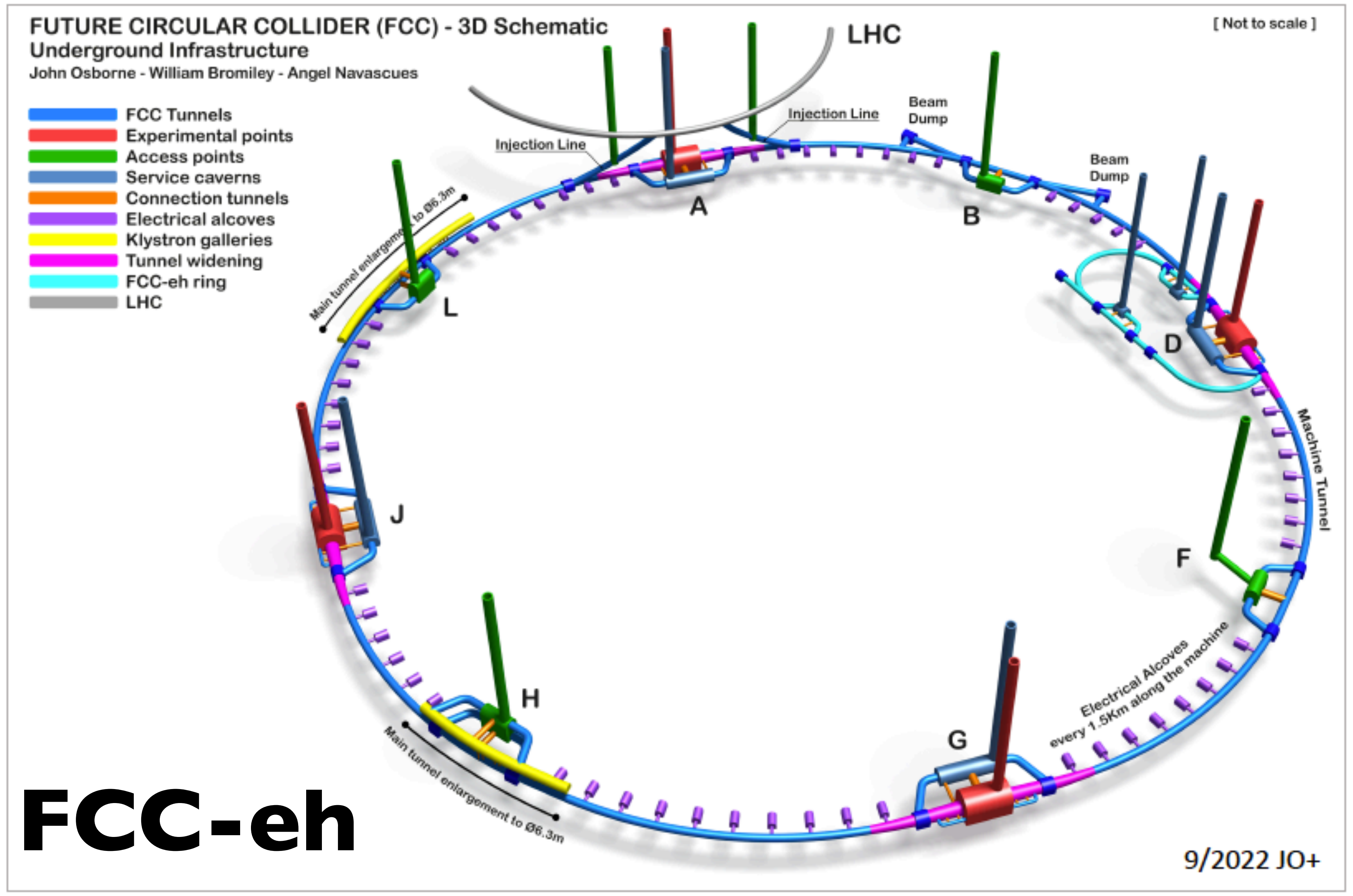




- Electron accelerator: Energy Recovery Linac in a racetrack configuration.
  - ➜ 3+3 turns.
  - ➜ Lengths from 1/3rd (60 GeV) to 1/5th (50 GeV) of the LHC.
  - ➜ ~98 % energy recovery, dump at injection energy.
- 1/3rd 50 GeV default choice for the LHeC, 60 GeV for FCC-eh.
- ep and eA modes.

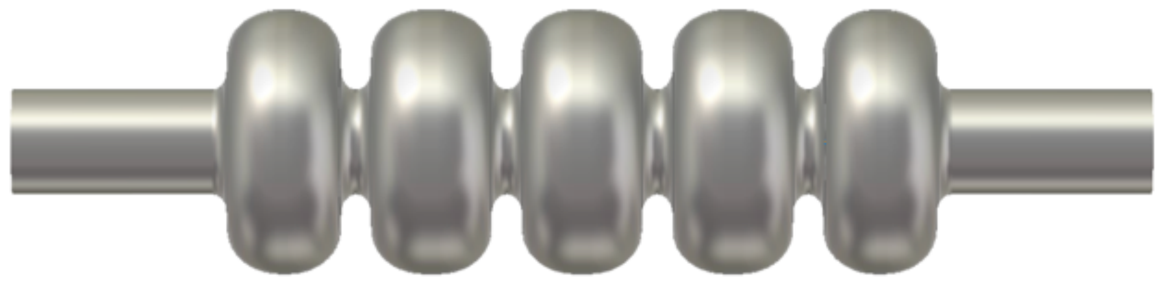


Accelerators: FCC-eh and PERLE



FCC-eh

- SRF choice 801.58 MHz (same as FCC-ee), $Q_0(2\ \mathrm{K}) \simeq 3 \cdot 10^{10}$ for 20 MV/m (5-cell JLab prototype).



- To be installed in a four cavity cryomodule for PERLE@IJCLab as demonstrator of 3-turn, high-current ERL; 1-turn/3-turn mode in 2029/2030.

$\sqrt{s} \simeq 1.2/2.2/3.5\,\mathrm{TeV},\ P = -0.8$

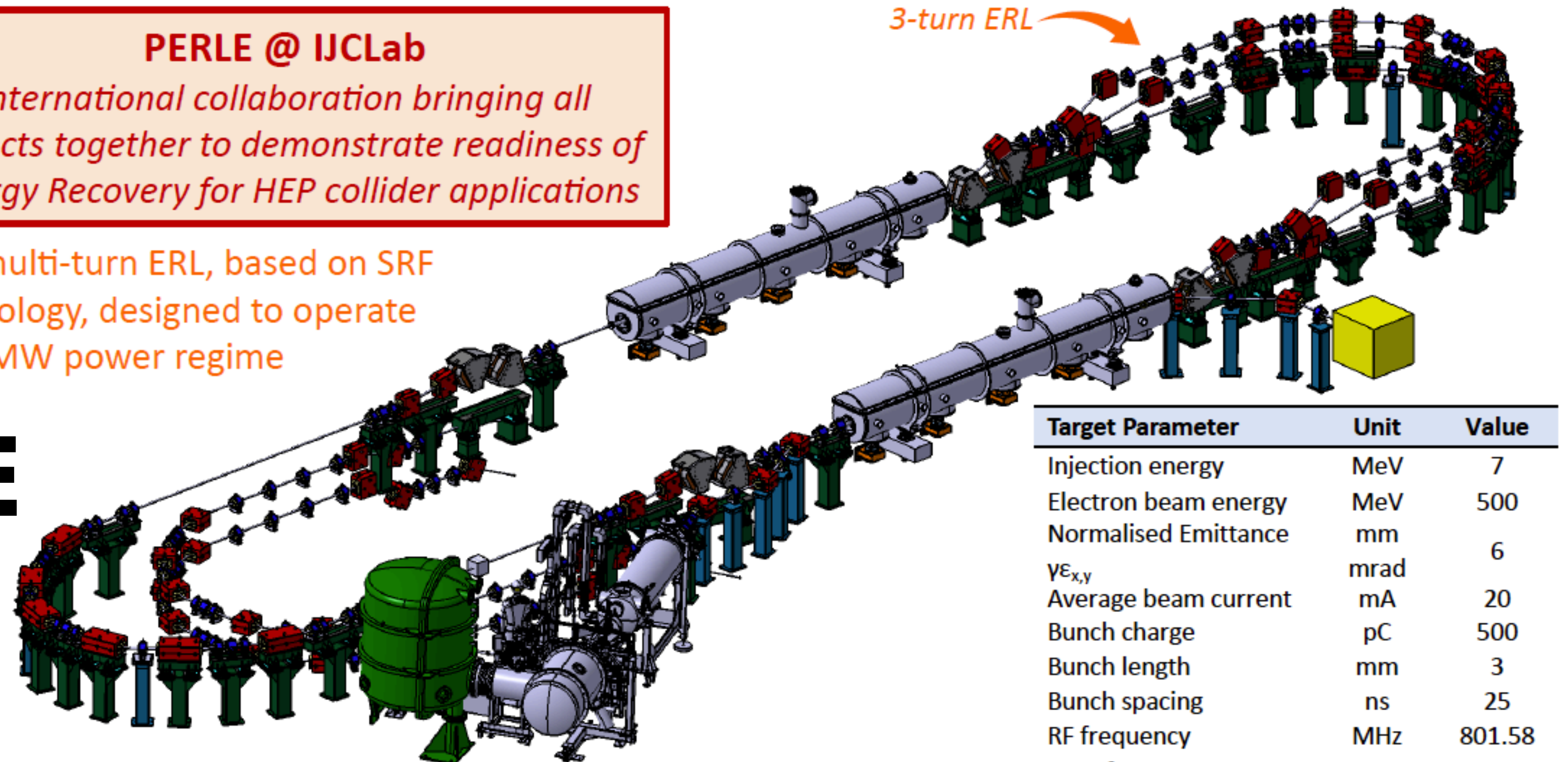
ep

Parameter	Unit	LHeC				FCC-eh	
		CDR	Run 5	Run 6	Dedicated	E_p=20 TeV	E_p=50 TeV
E_e	GeV	60	30	50	50	60	60
N_p	10^{11}	1.7	2.2	2.2	2.2	1	1
ϵ_p	μm	3.7	2.5	2.5	2.5	2.2	2.2
I_e	mA	6.4	15	20	50	20	20
N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
β^*	cm	10	10	7	7	12	15
Luminosity	$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	5	9	23	8	15

$\sim 1\ \mathrm{ab}^{-1}$ in 6 years

PERLE @ IJCLab
international collaboration bringing all aspects together to demonstrate readiness of Energy Recovery for HEP collider applications

first multi-turn ERL, based on SRF technology, designed to operate at 10MW power regime



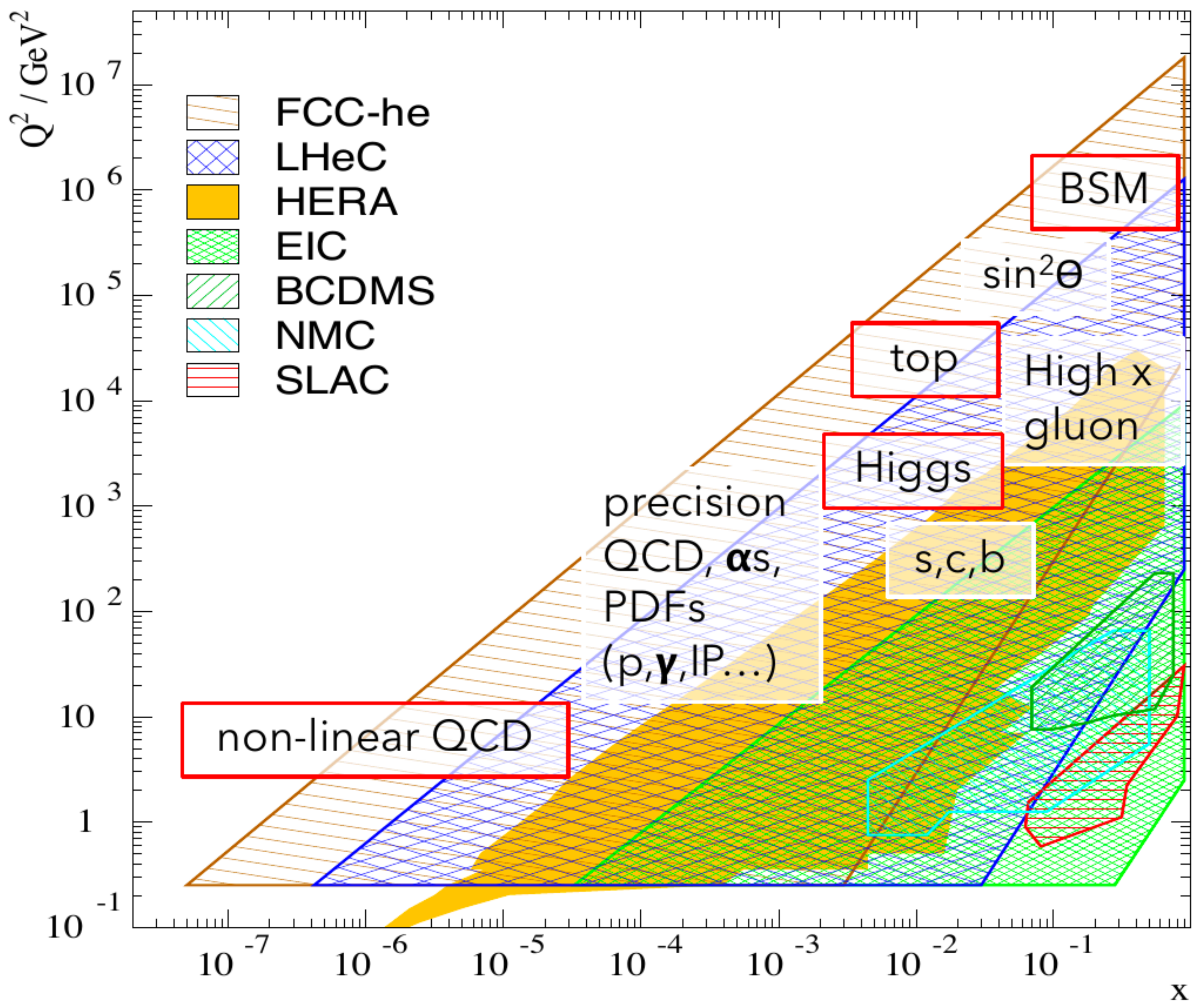
PERLE

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

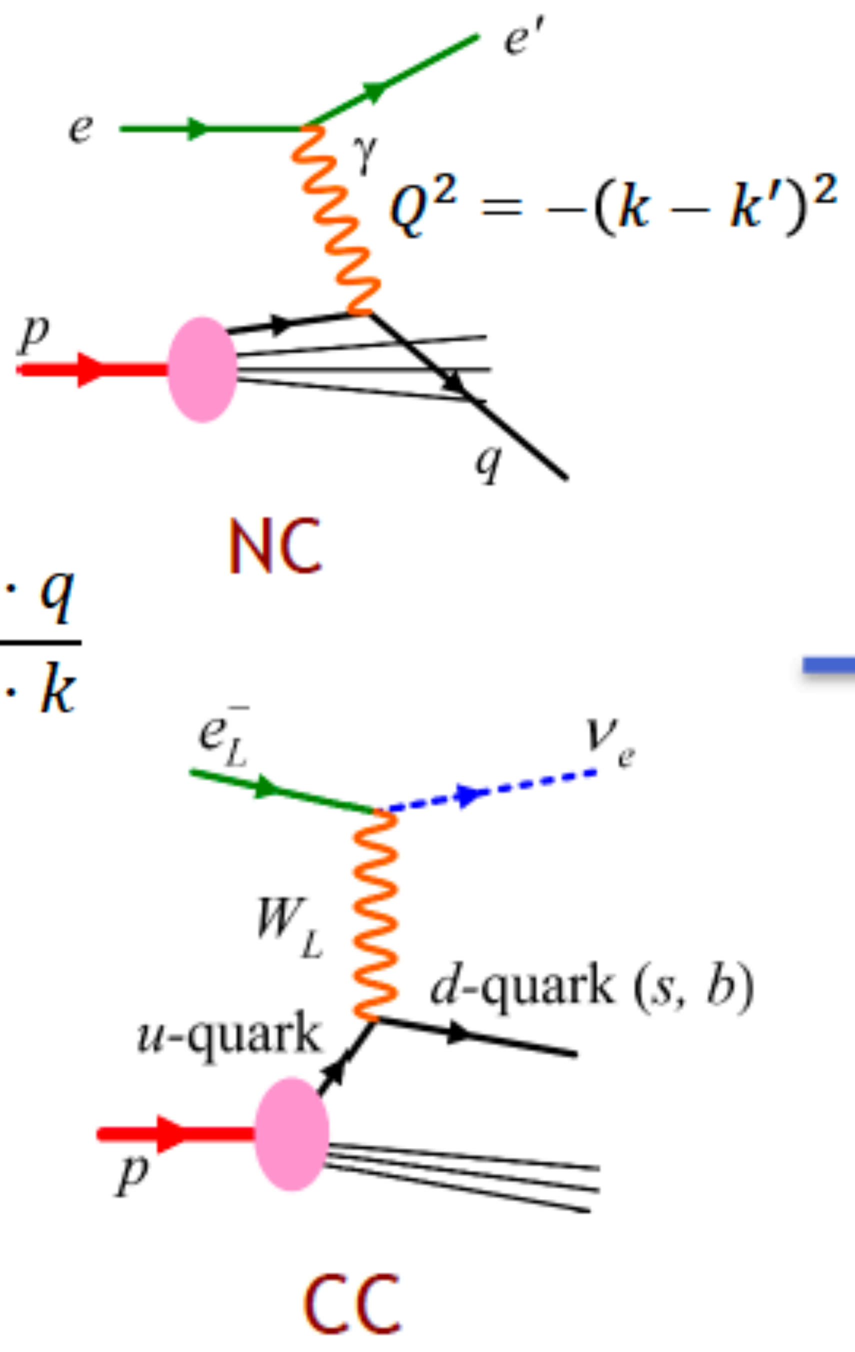
PERLE – Powerful Energy Recovery Linac for Experiments

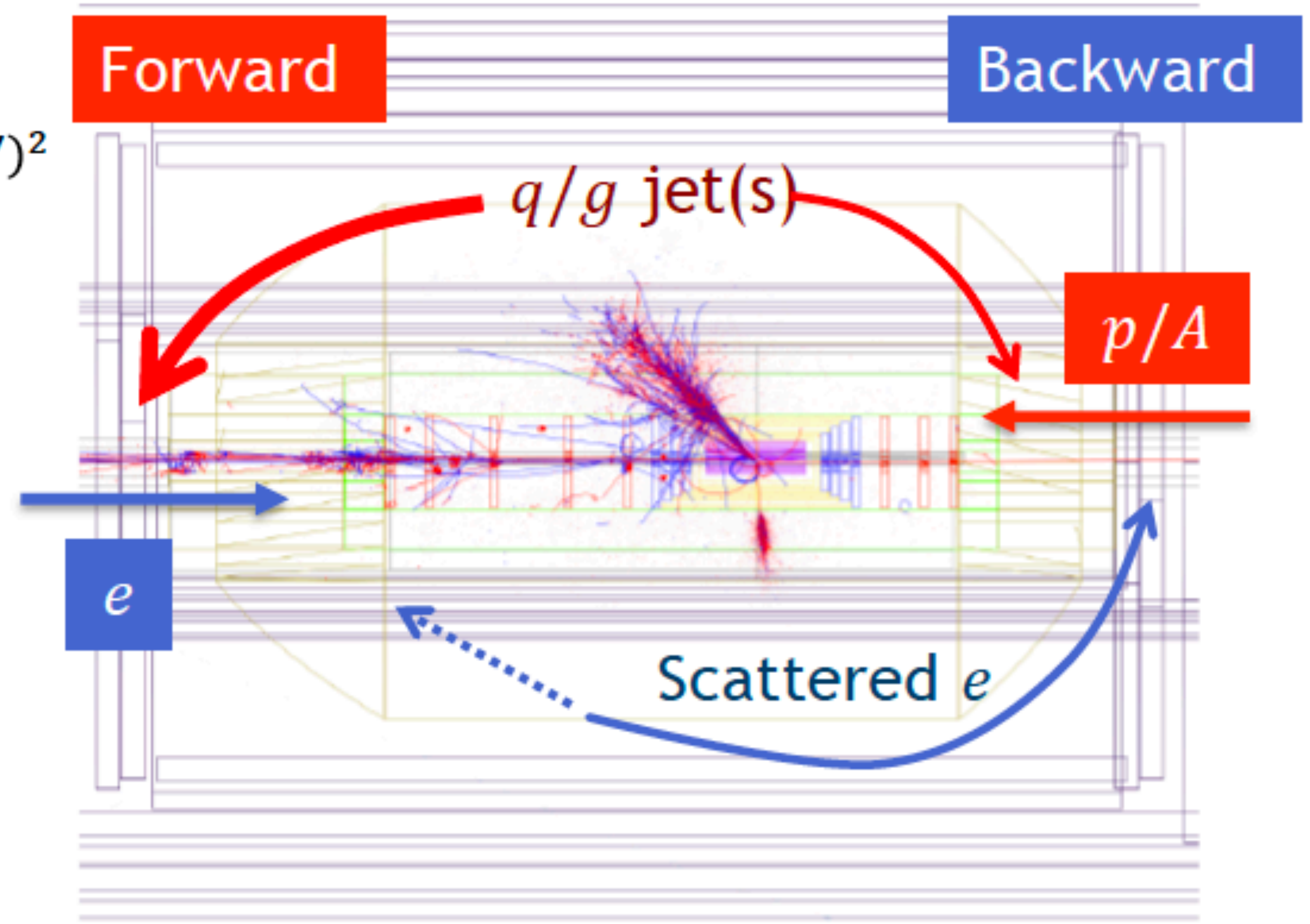
ePb: $\sqrt{s} = 0.74\,\mathrm{TeV/nucleon},\ \mathscr{L} = 0.7 \cdot 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

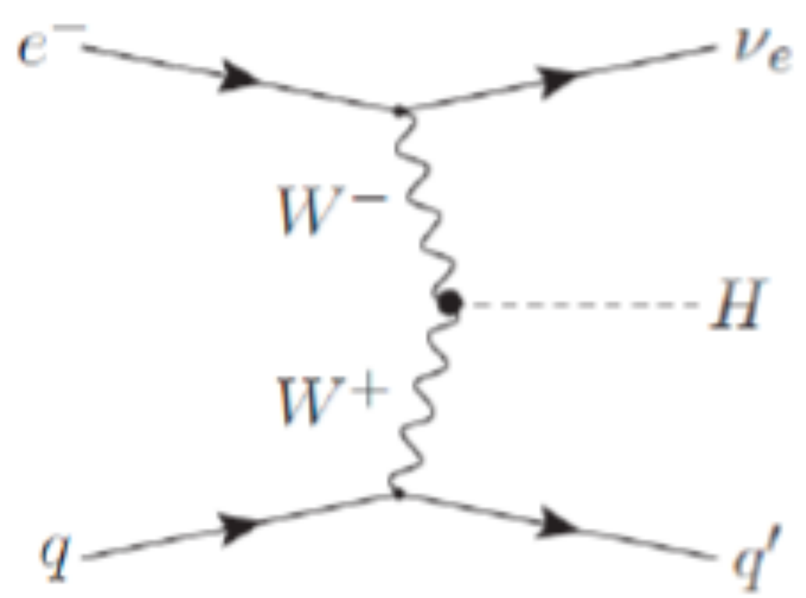
Detector: general considerations

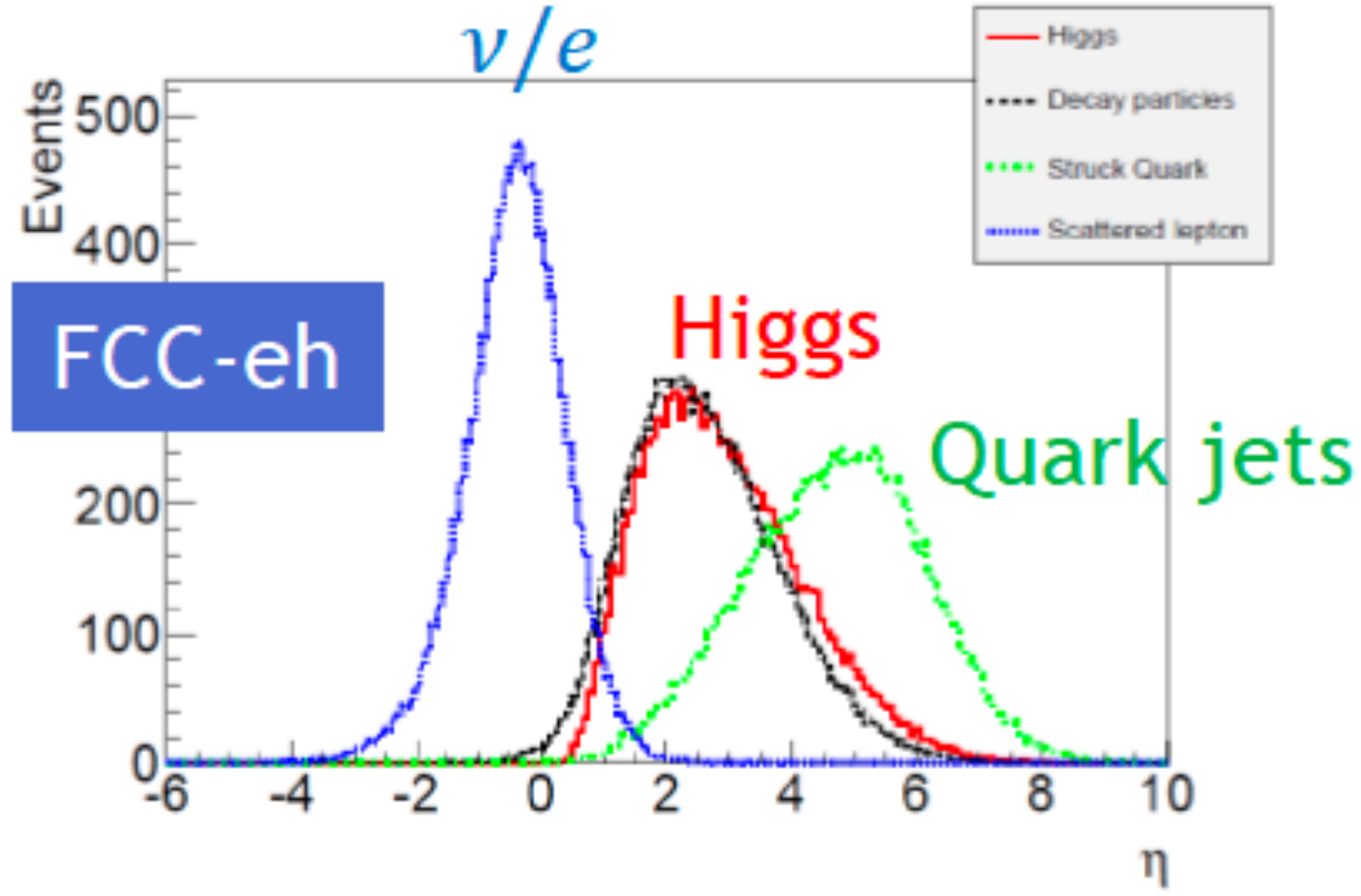


$$x = \frac{Q^2}{p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k}$$
$$sxy = Q^2$$



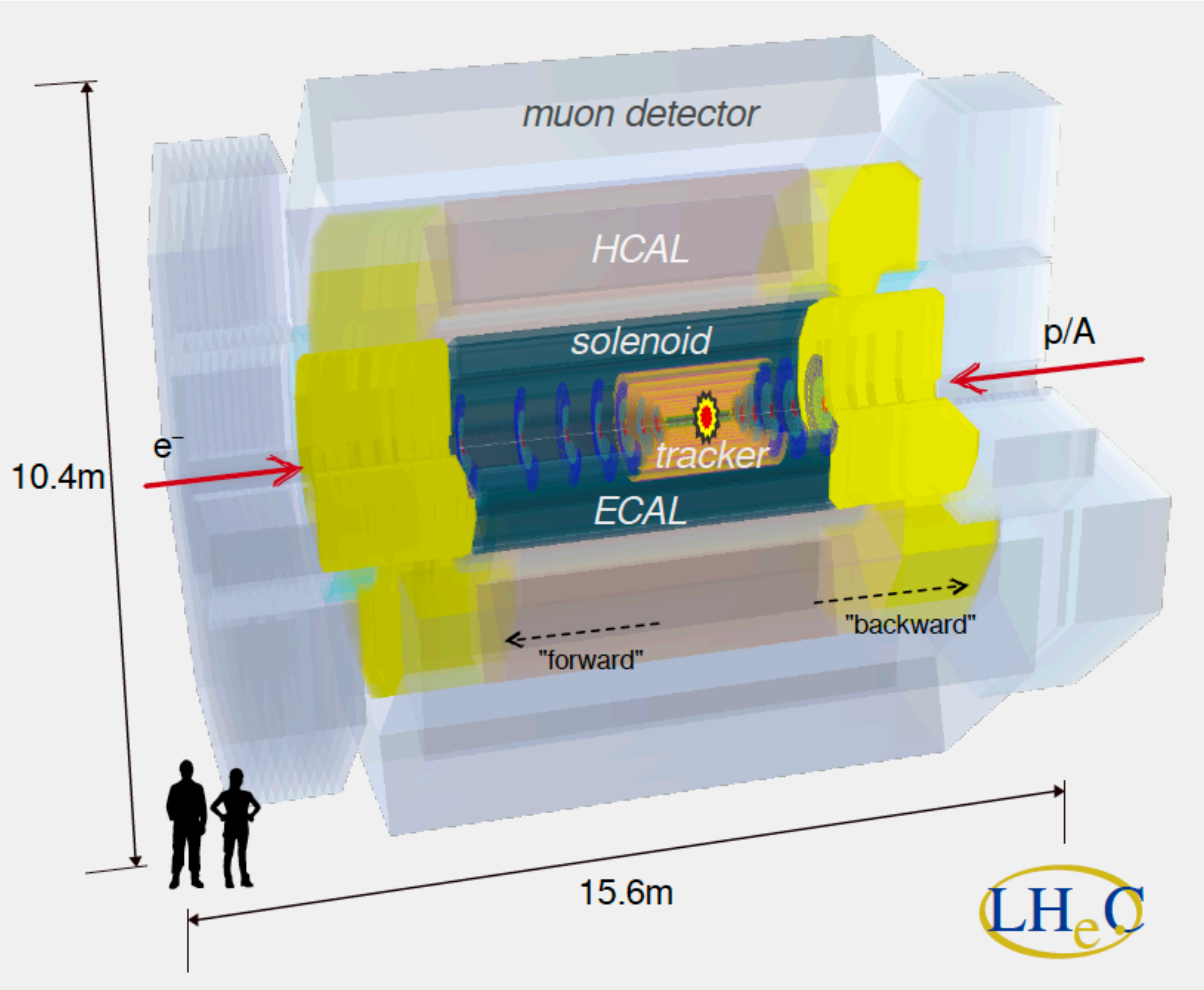






- Detector requirements;
  - ➜ Large acceptance (Higgs, small x).
  - ➜ High-resolution tracking for heavy flavour.
  - ➜ EMCAL/HCAL hermeticity (CC, Higgs), e/h separation.

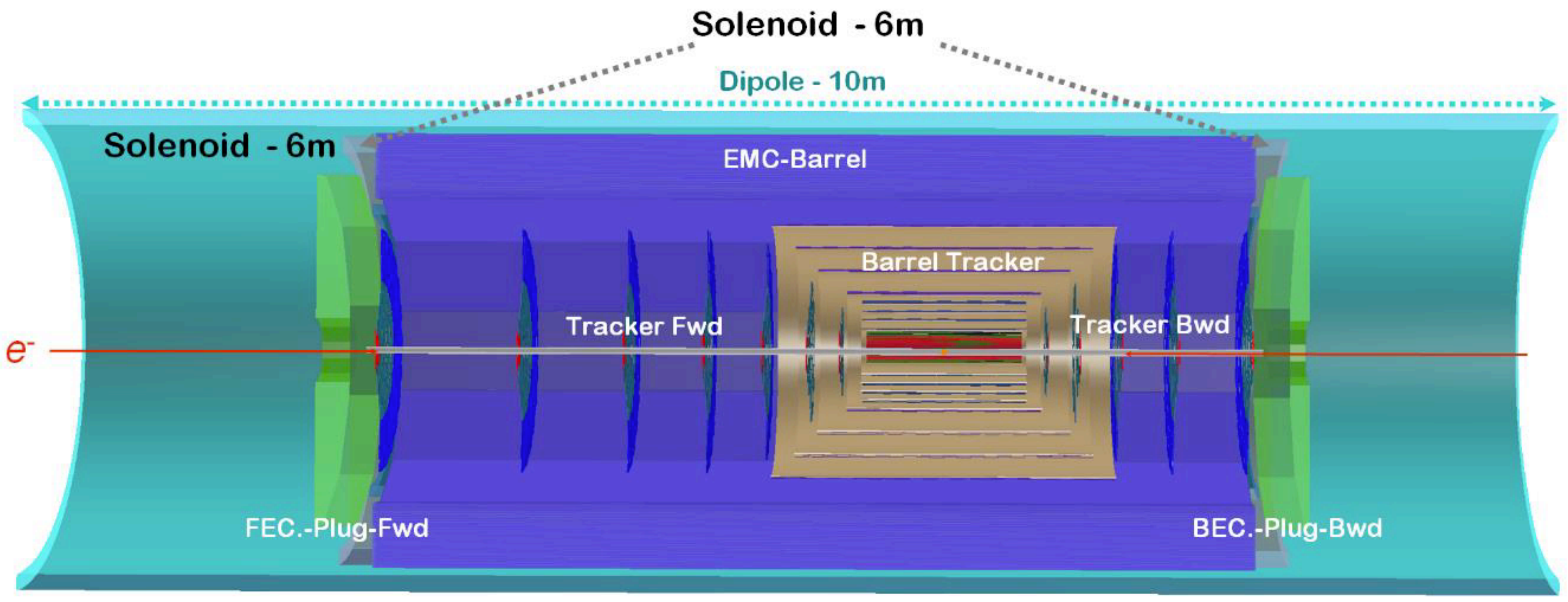
Detector: LHeC

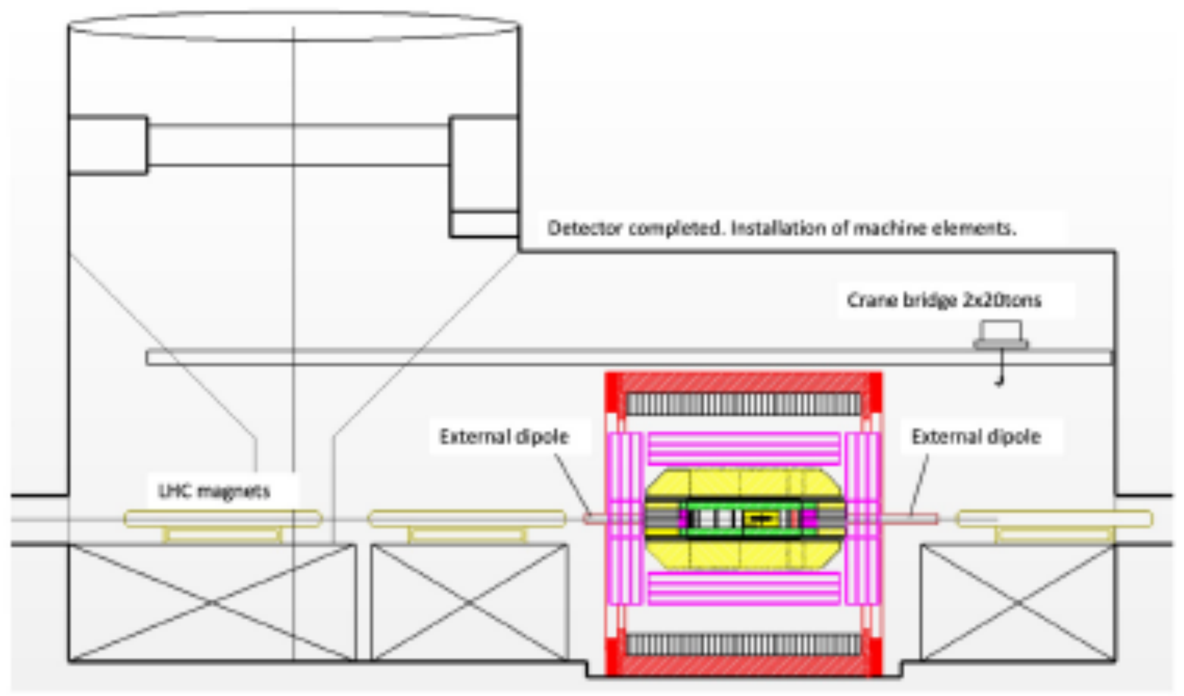


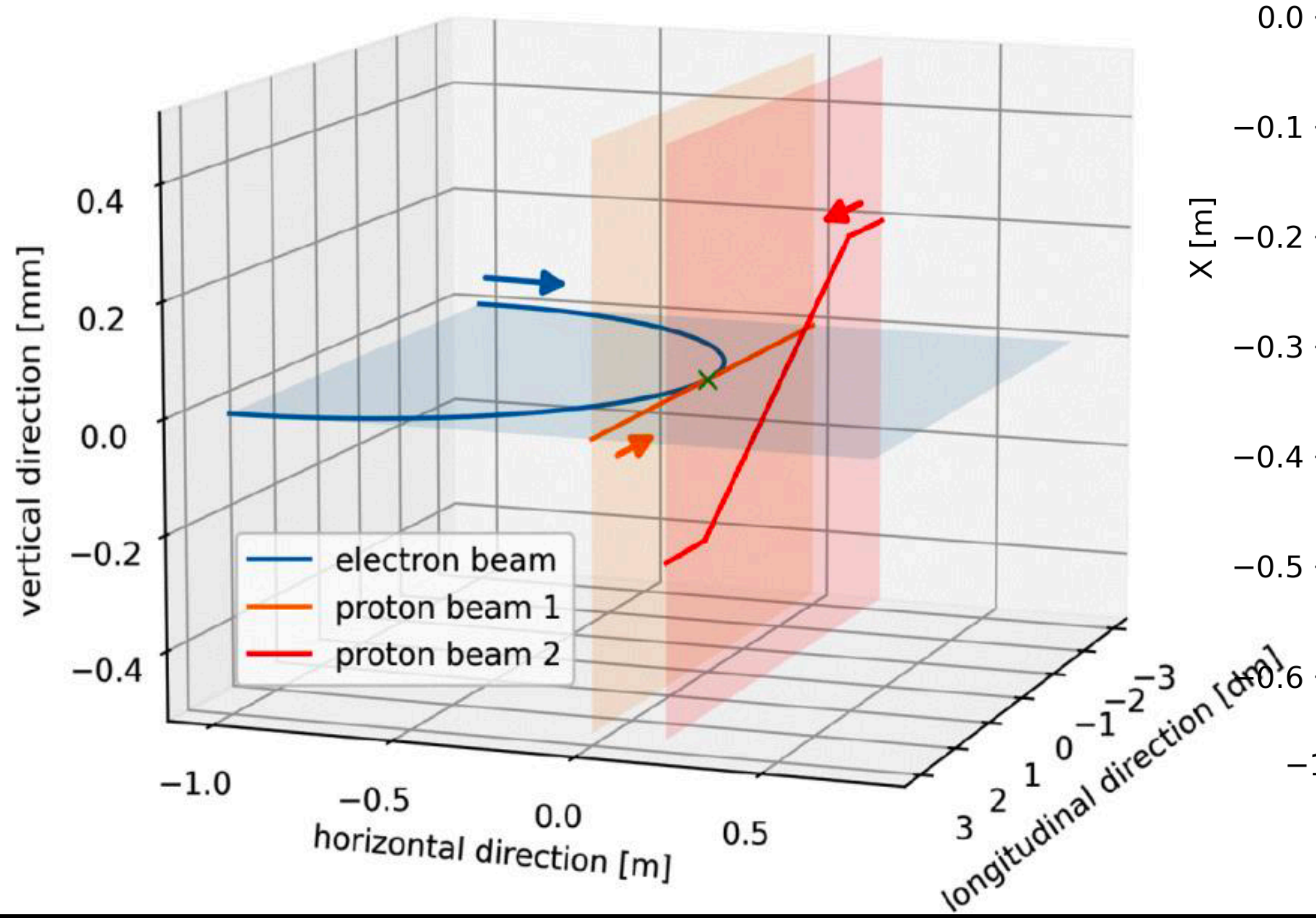
- Asymmetric detector concept, forward (proton) and backward (electron) subsections.
- From SR-optimised beam pipe outwards:
  ➜ Central silicon tracker (HV-CMOS MAPS, $0.2X_0$ up to $|\eta| \sim 4.5$).
    * Barrel: 6 layers of vertex locators (pixel), 4 layers of strips.
    * Endcaps: 7 layers (forward) + 5 layers (backward) of strips+(macro-)pixels, $1°$ tracking acceptance.
  ➜ "Accordion", ATLAS-like LAr ECAL barrel.
  ➜ Central 3.5 T solenoid + extended dipole ensuring head-on ep collisions.
  ➜ Plastic/scintillator HCAL.
  ➜ Muon RPC chambers.
  ➜ Forward/backward instrumentation (Roman pots, ZDC) for photoproduction, luminosity measurements and diffraction.

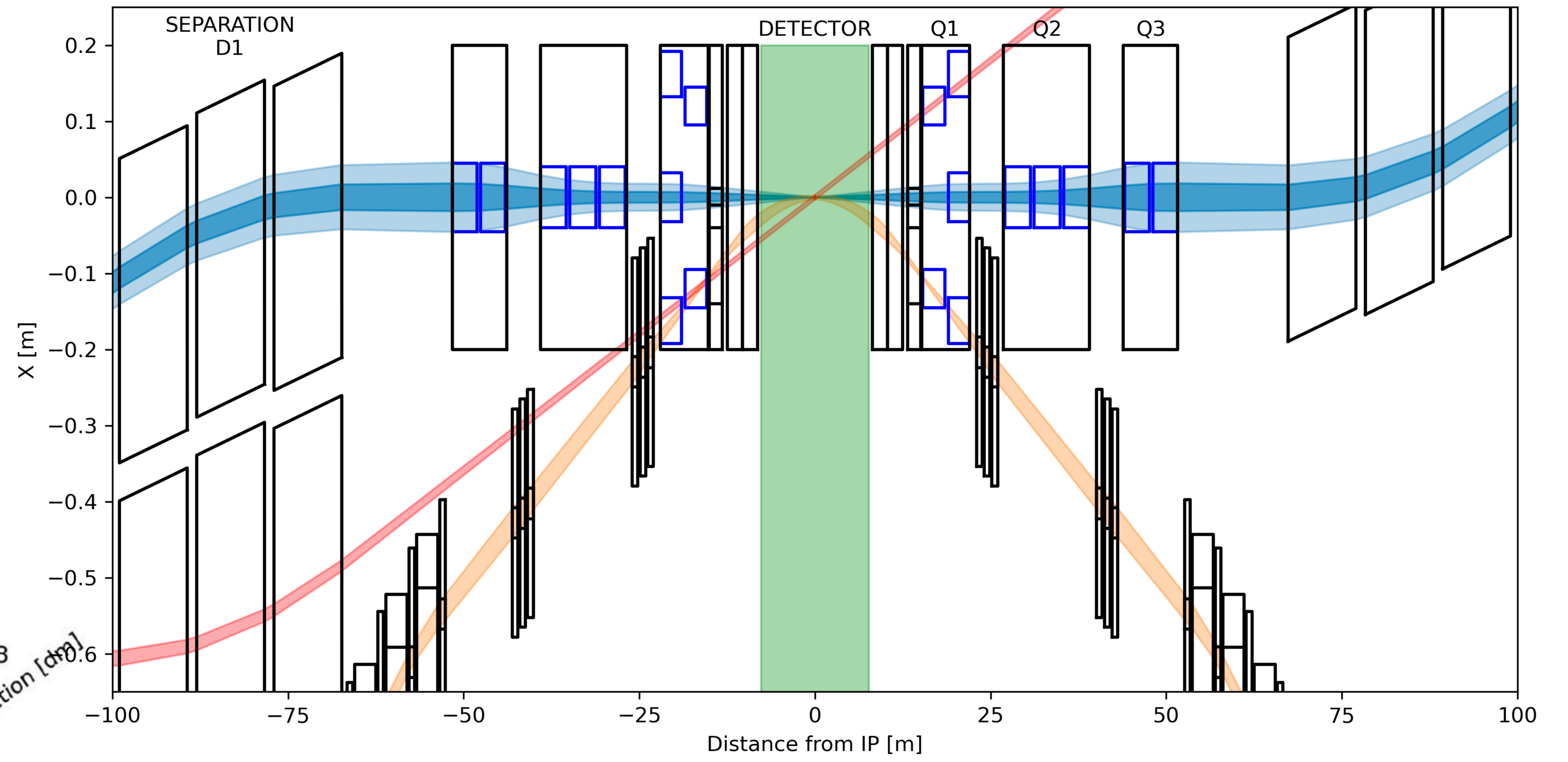
Detector: LHeC

- 1° acceptance ($|\eta| < 4.7$) required for small x and H (0.3° and 6 at the FCC-eh).
- Pileup negligible; less radiation hardness needed than at HL-LHC.
- Elliptical beam pipe to accommodate synchrotron radiation fan ($E_c = 114\,\mathrm{keV}$, $E_p = 6\,\mathrm{kW}$).
- 3 beams in IR: Q1 with large aperture, field-free region; less demanding in standalone mode.
- Can be installed in IP2 (inside L3 magnet) in 2 years.

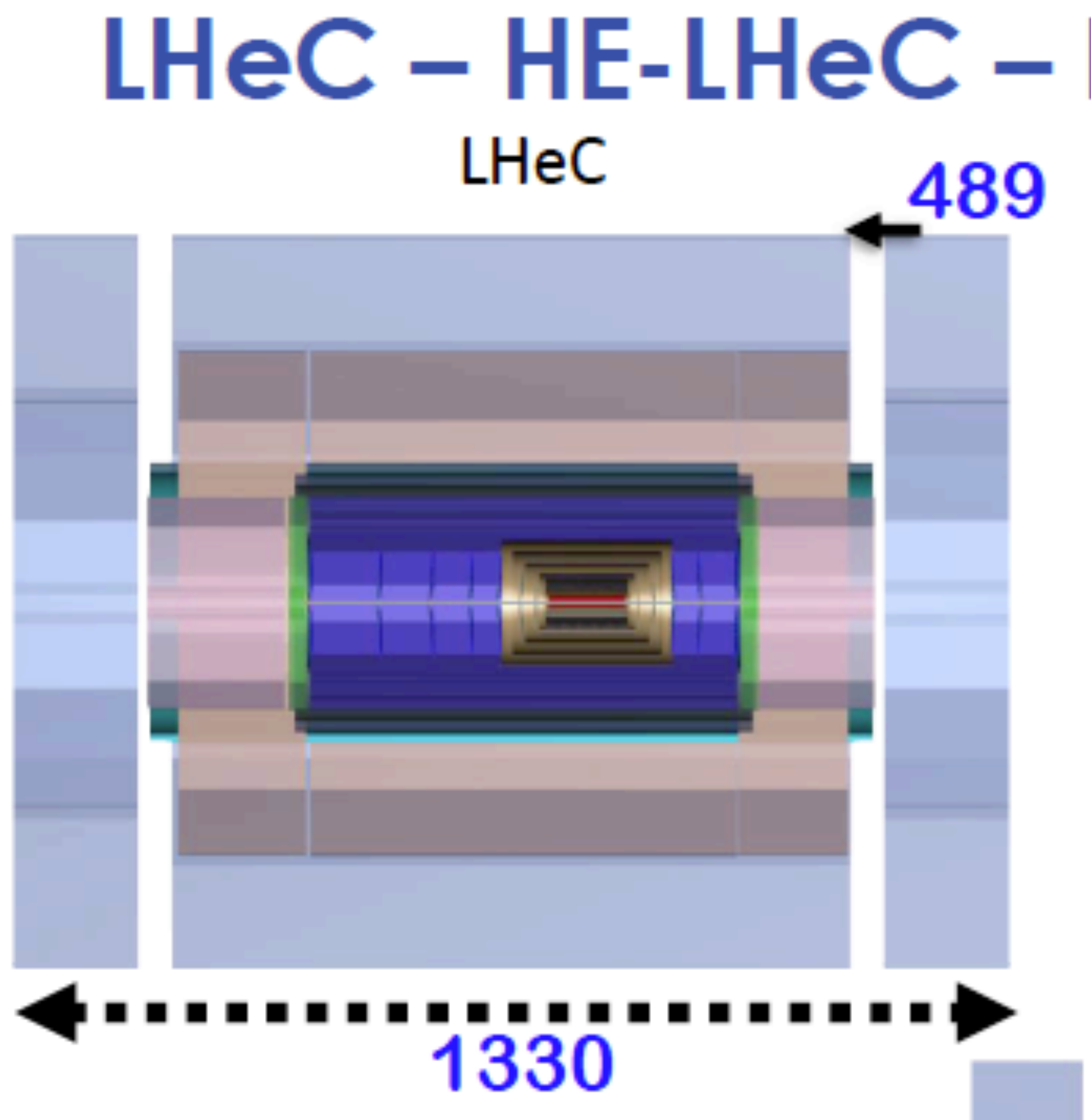


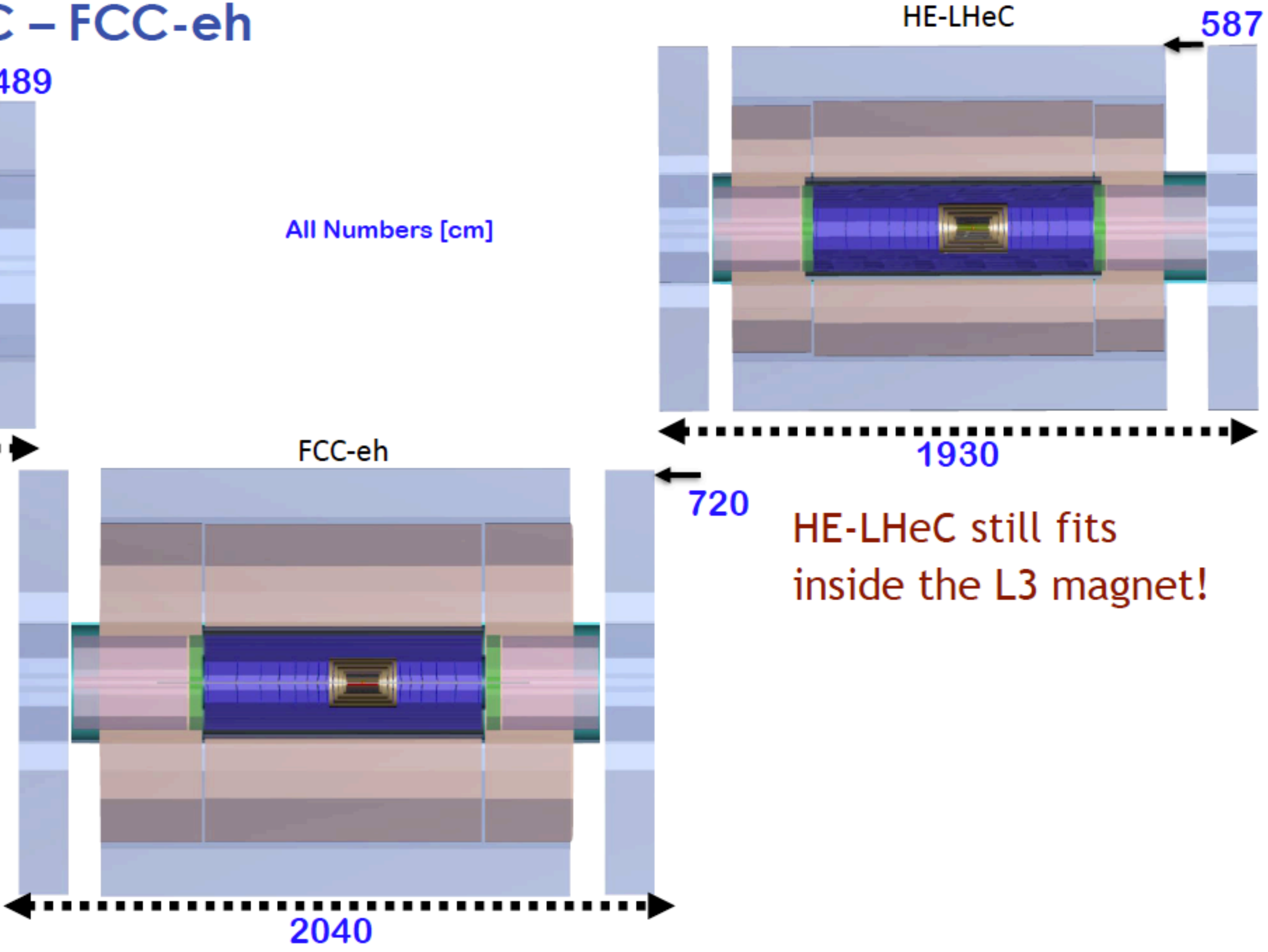






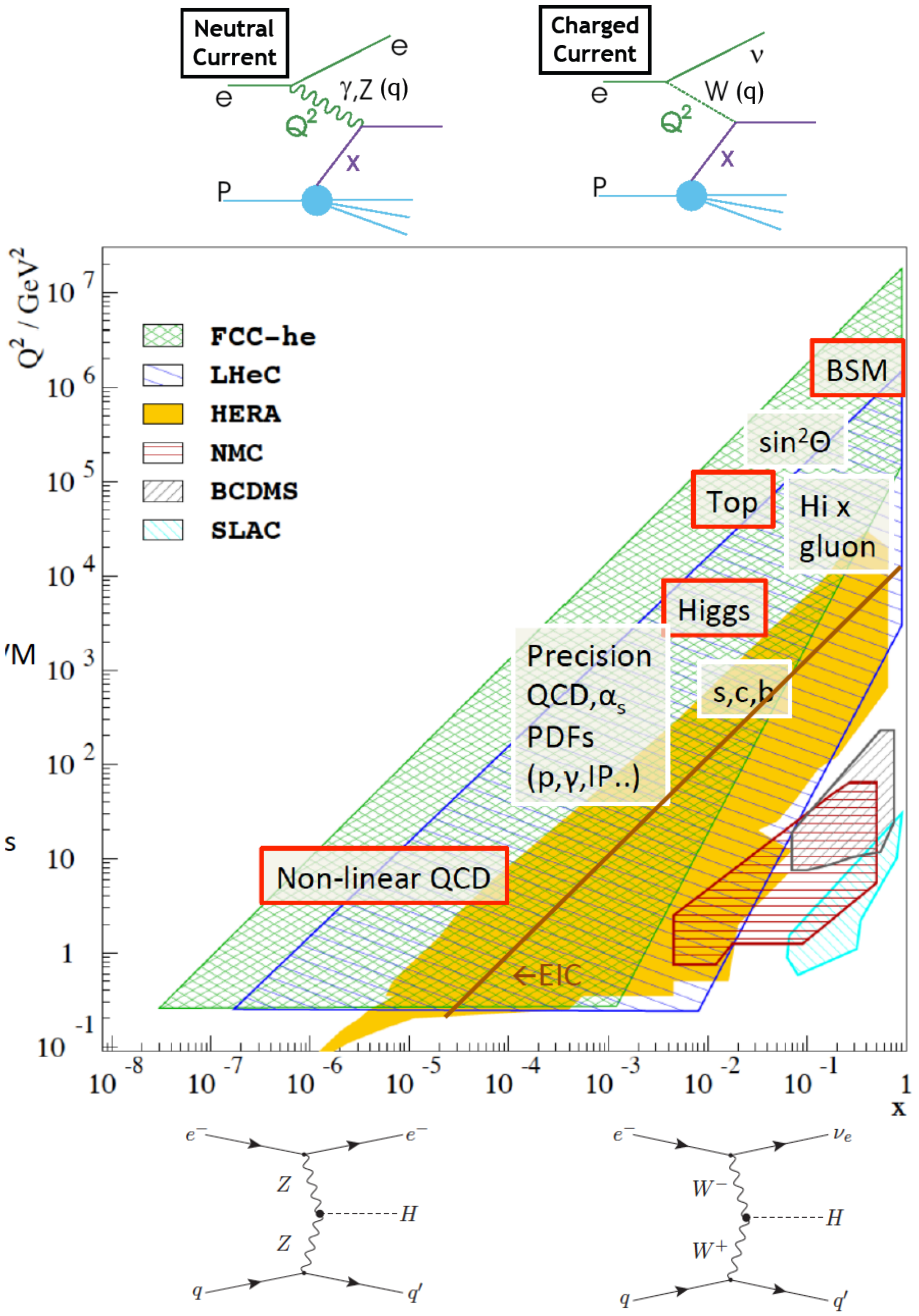
Detector: other energies





- <u>Disclaimer</u>: not most recent version, just to show the increase in scale.

Summary of physics:



- ep/eA colliders are the cleanest High Resolution Microscope:
  - ➜ Precision and discovery in QCD;
  - ➜ Study of EW / VBF production, LQ, multi-jet final states, forward objects,…

- Empower the LHC Search Programme (e.g., through PDFs, α_s, EW measurements).
- Transform the LHC into a precision Higgs facility.
- Has unique and complementary discovery potential of BSM particles (prompt and long-lived).

- It is also a $\gamma\gamma$ facility.

- **Overall: a unique Particle and Nuclear Physics Facility.**

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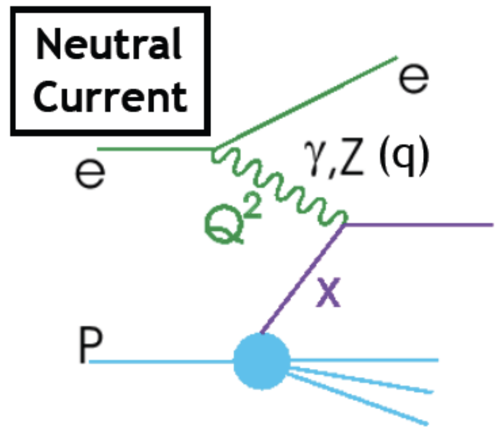
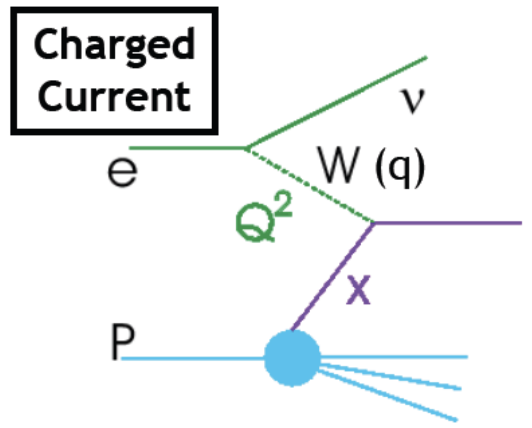
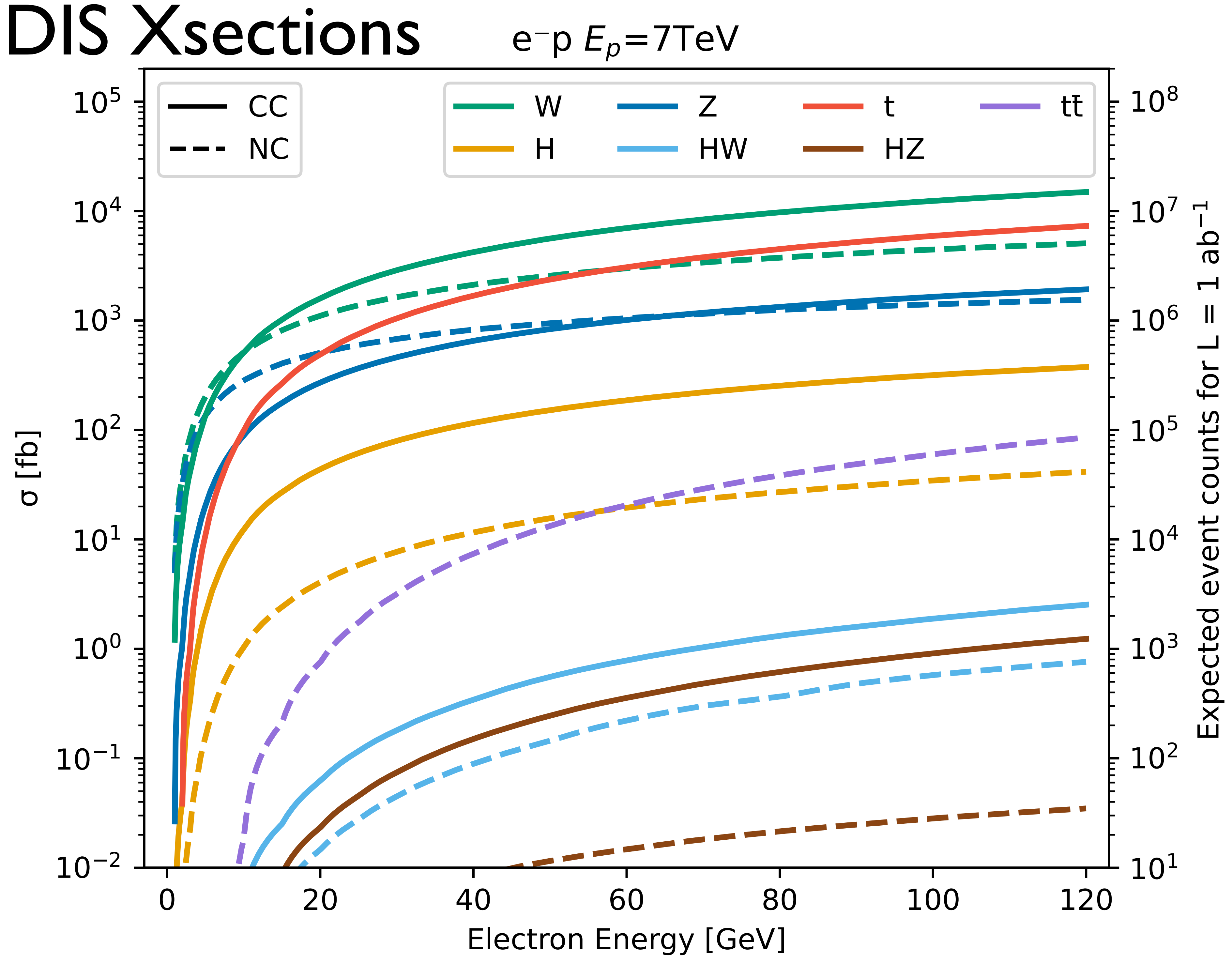
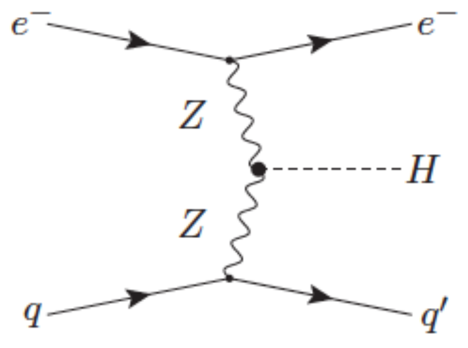
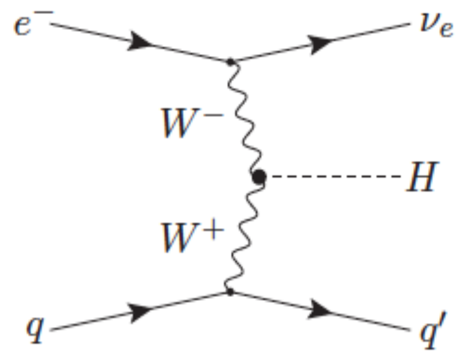




DIS Xsections







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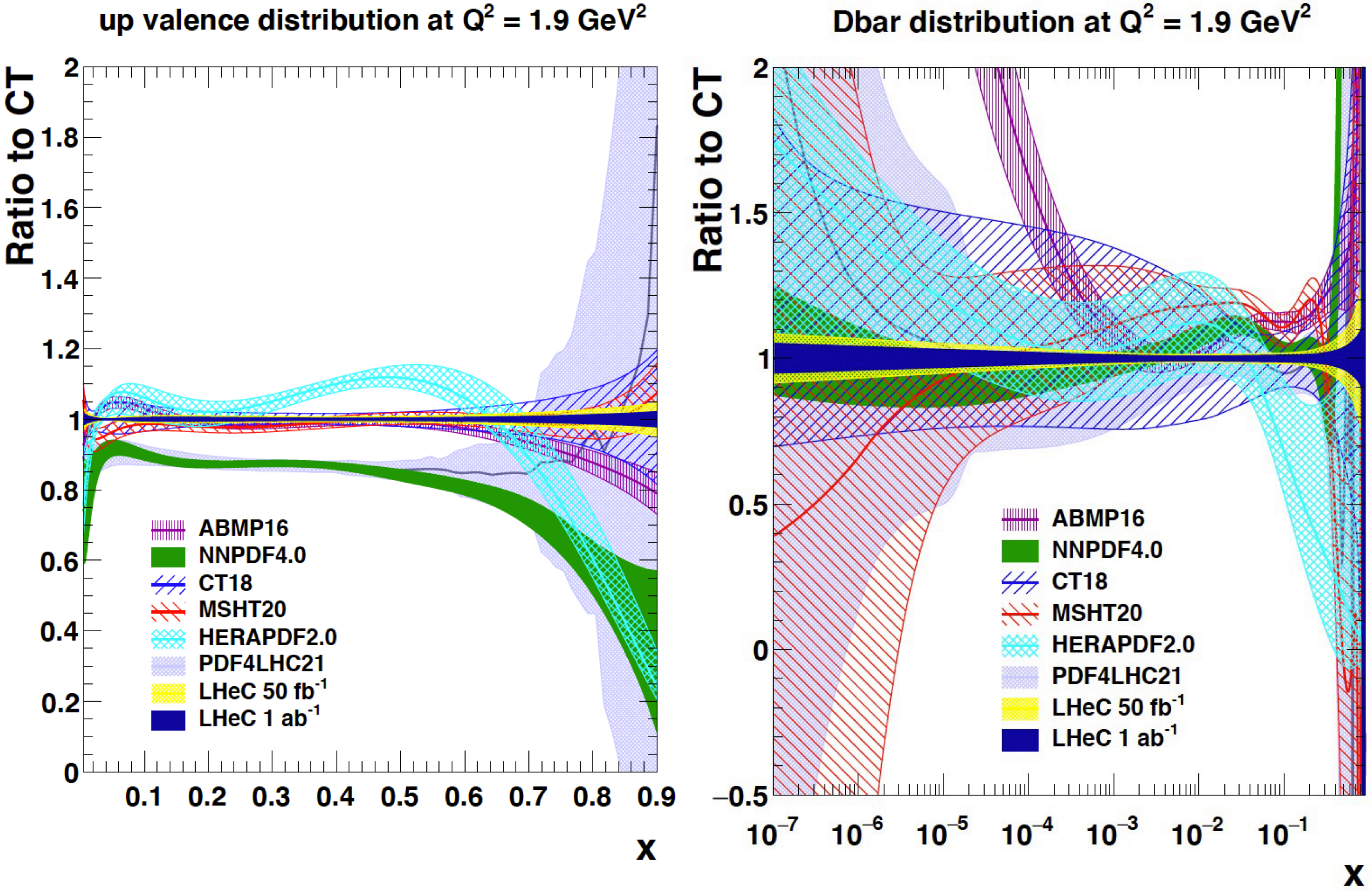
Parton luminosities:

- PDFs and α_s crucial for HL-LHC: high precision electro-weak, Higgs measurements (e.g., remove essential part of QCD uncertainties of gg→H), extension of high mass search range, non-linear parton evolution at low x: saturation.

- LHeC provides a complete resolution of flavour and gluon substructure in single system/experiment, in unprecedented kinematic range (no higher twists, no nuclear corrections,…): implications for hadron colliders.



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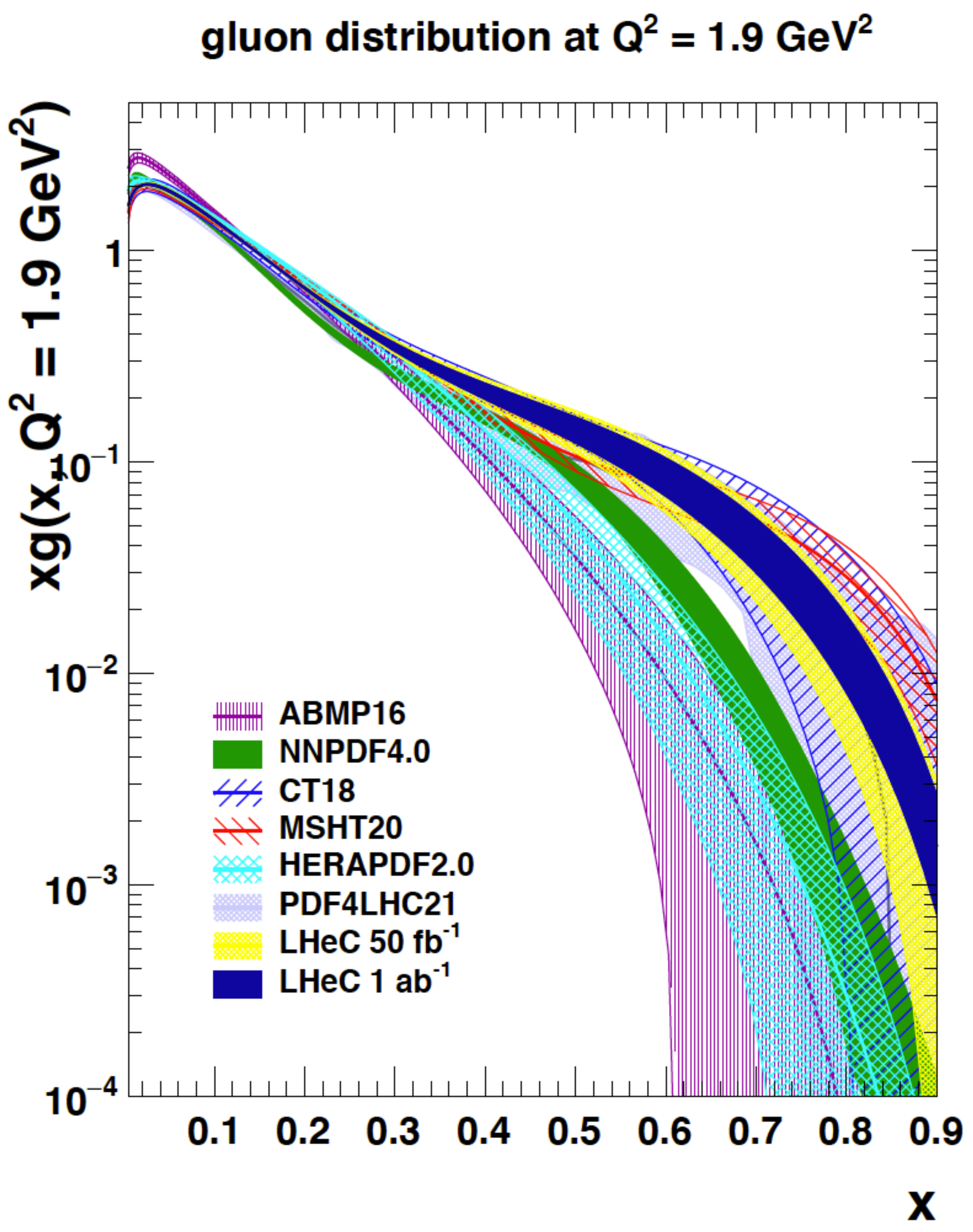

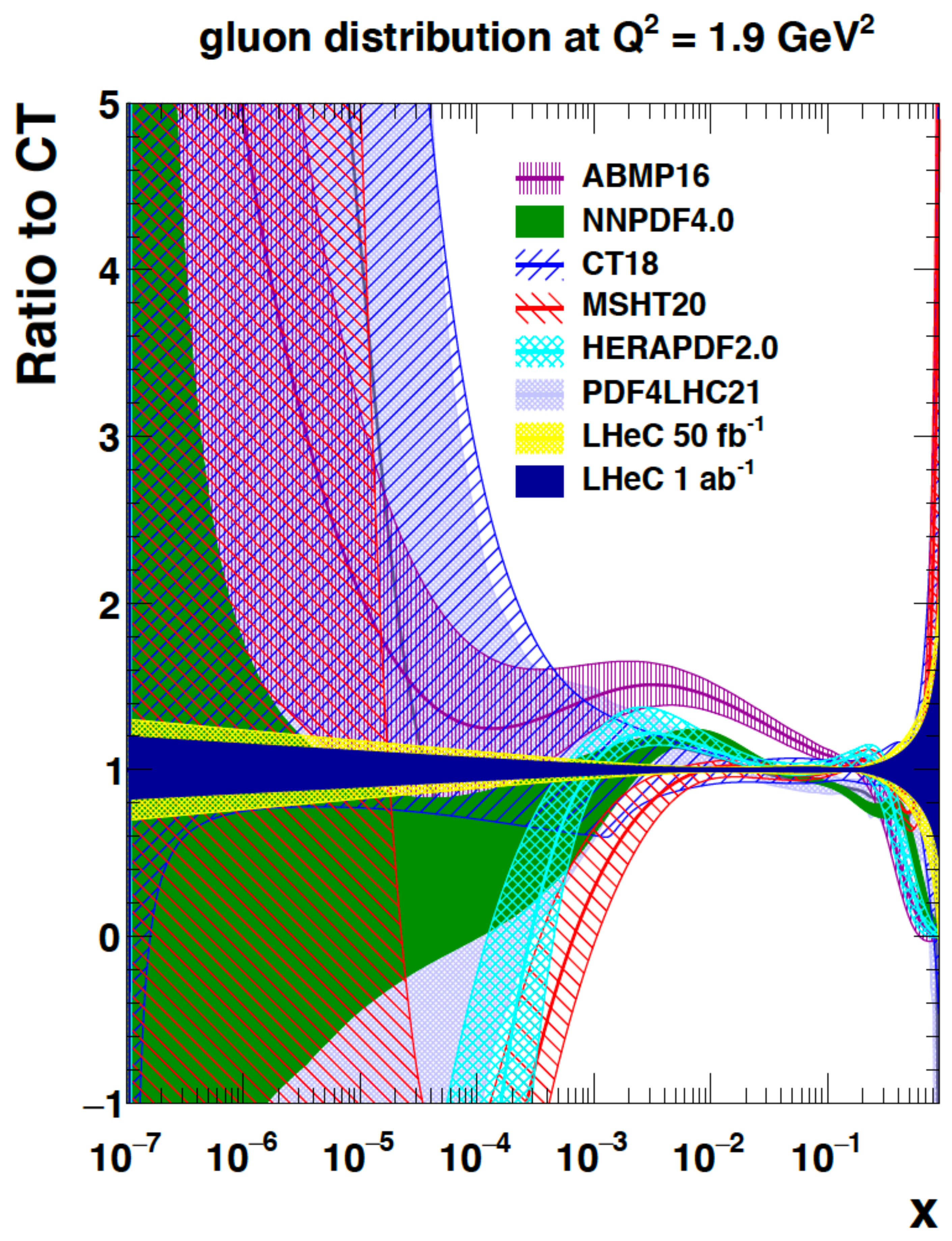

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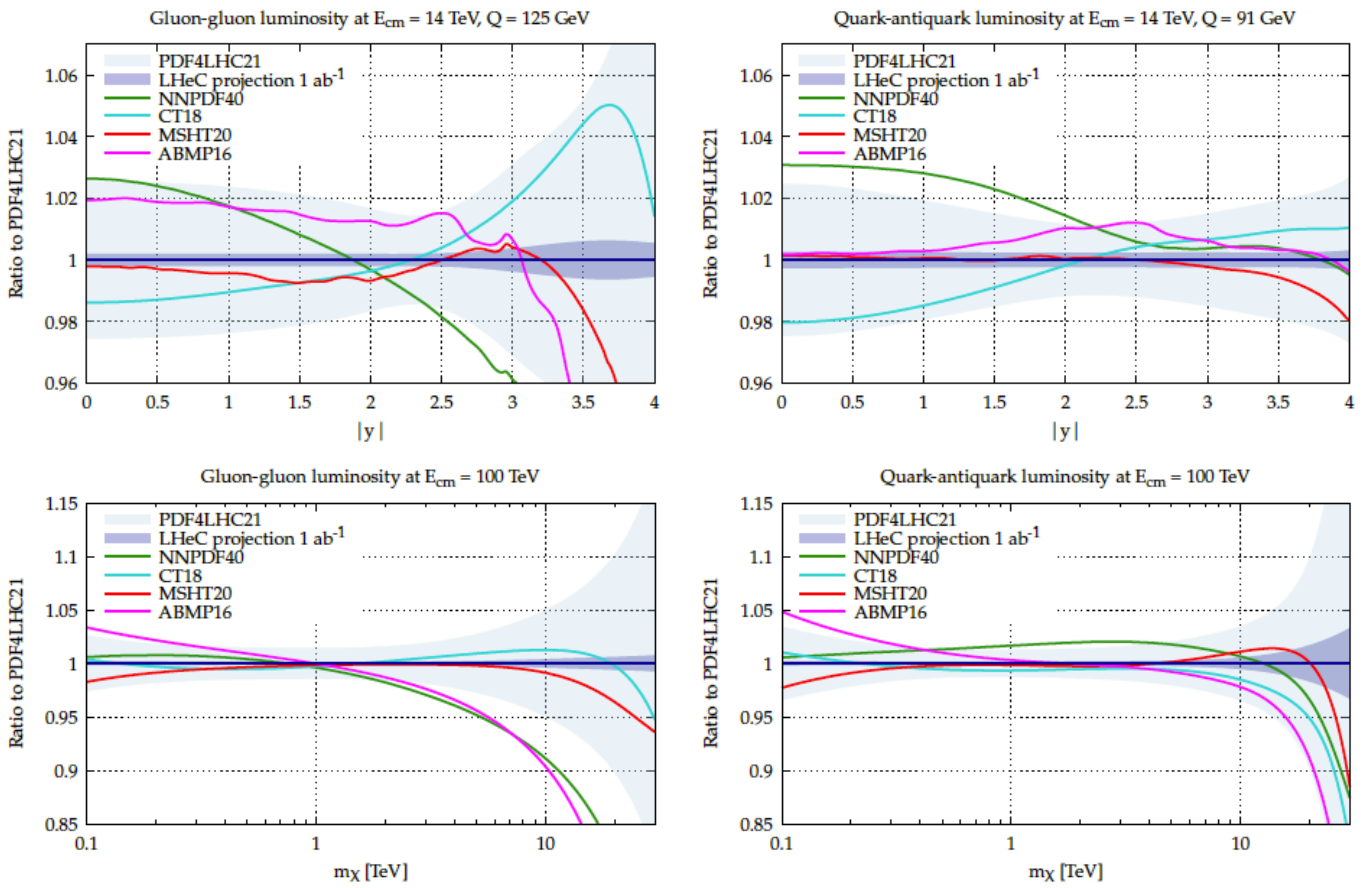
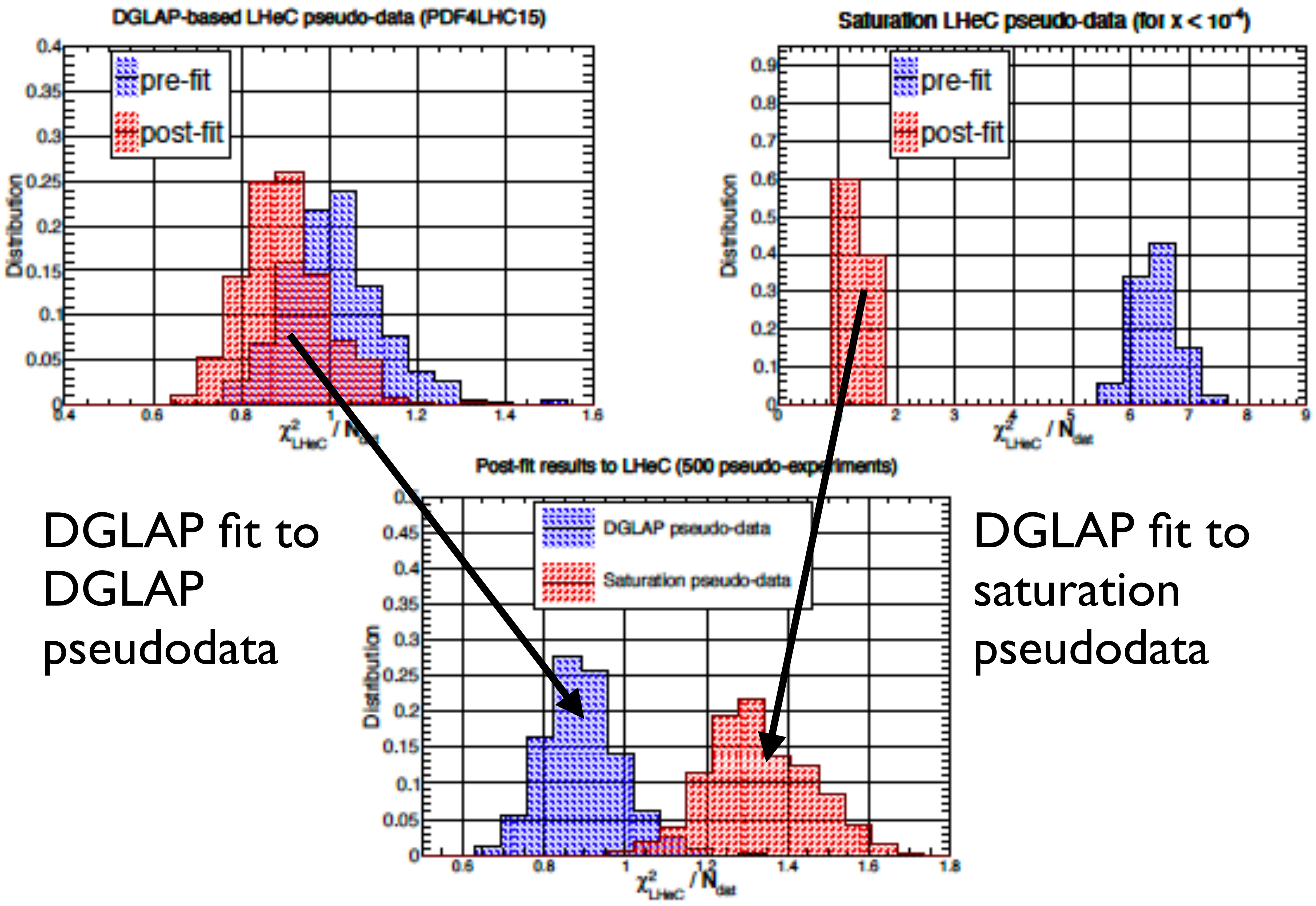


QCD: small x and α_s

- Breaking of *standard* factorisation: resummation and new non-linear regime of QCD, implications for FCC (e.g., gg→H).



- α_s to per mille accuracy (incl.+jets):

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

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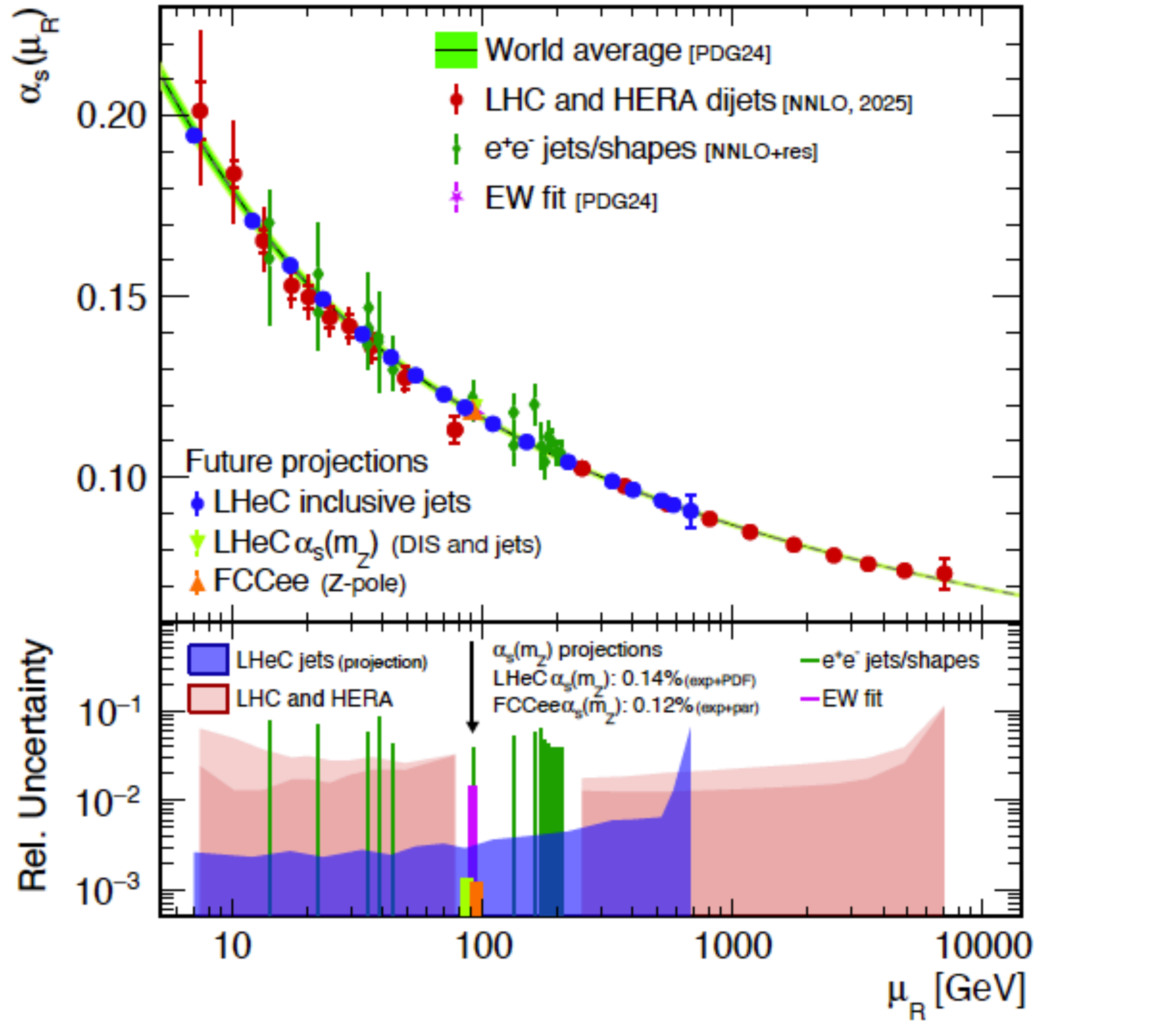

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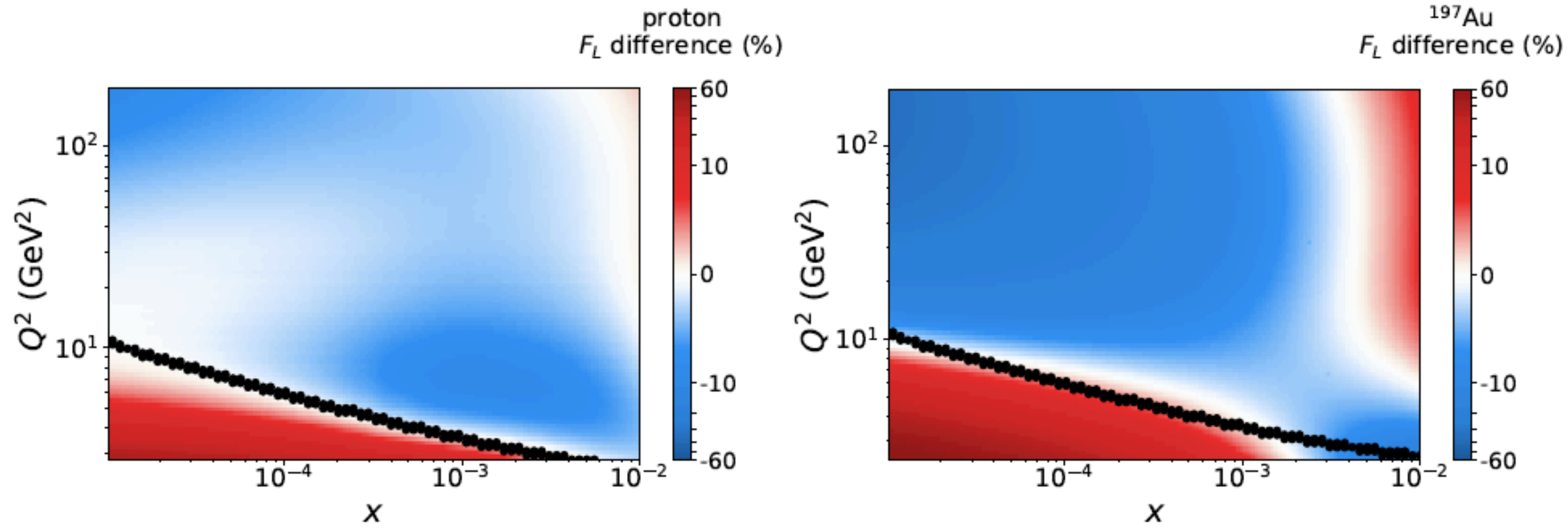

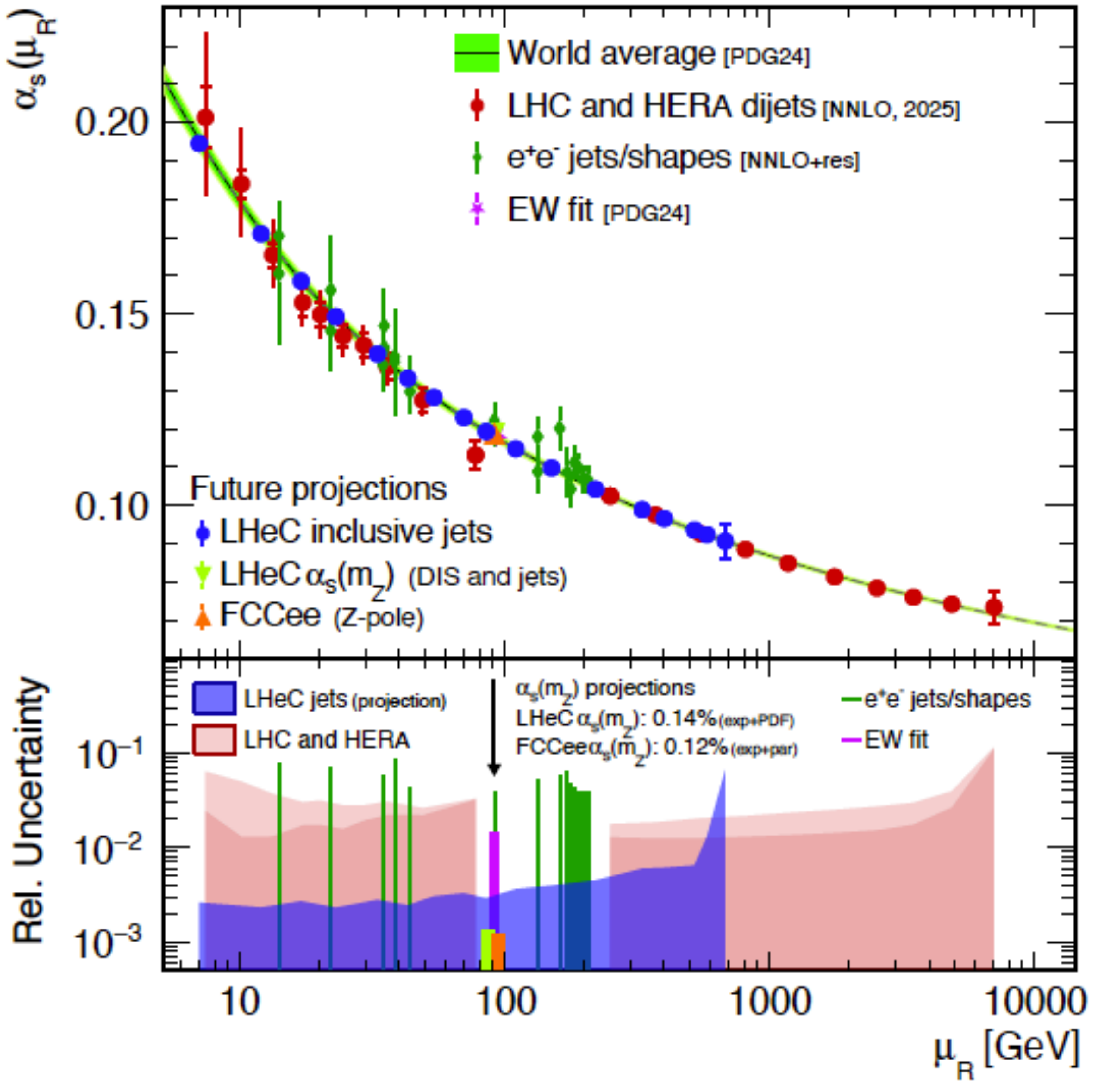

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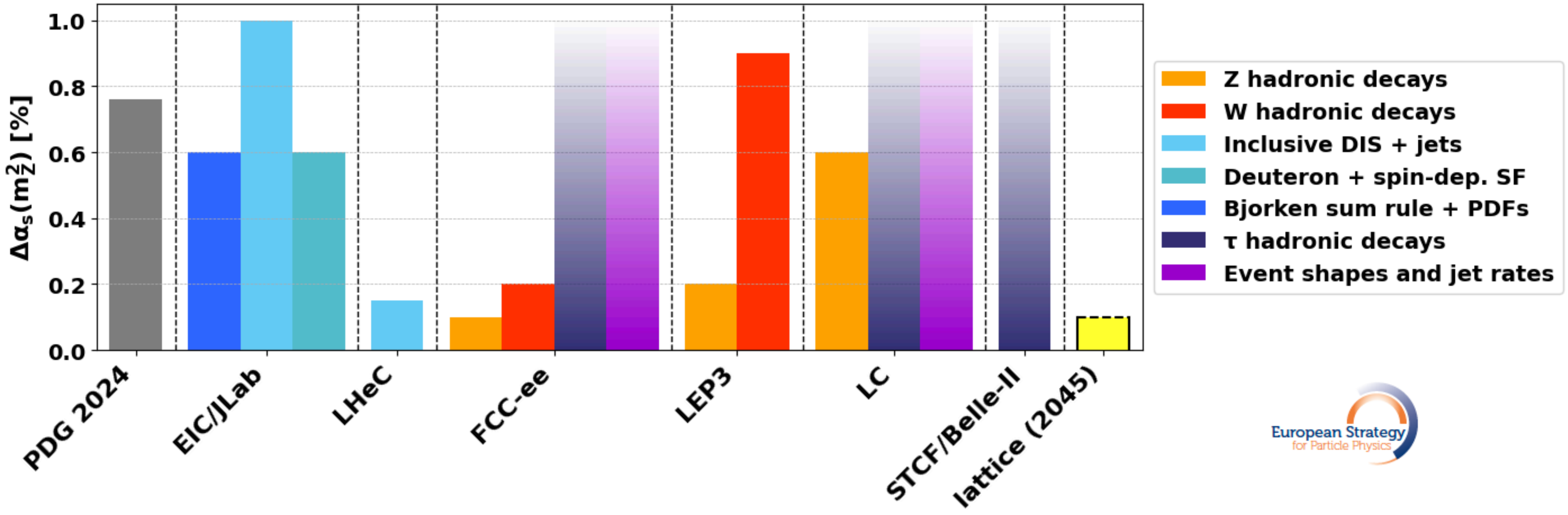
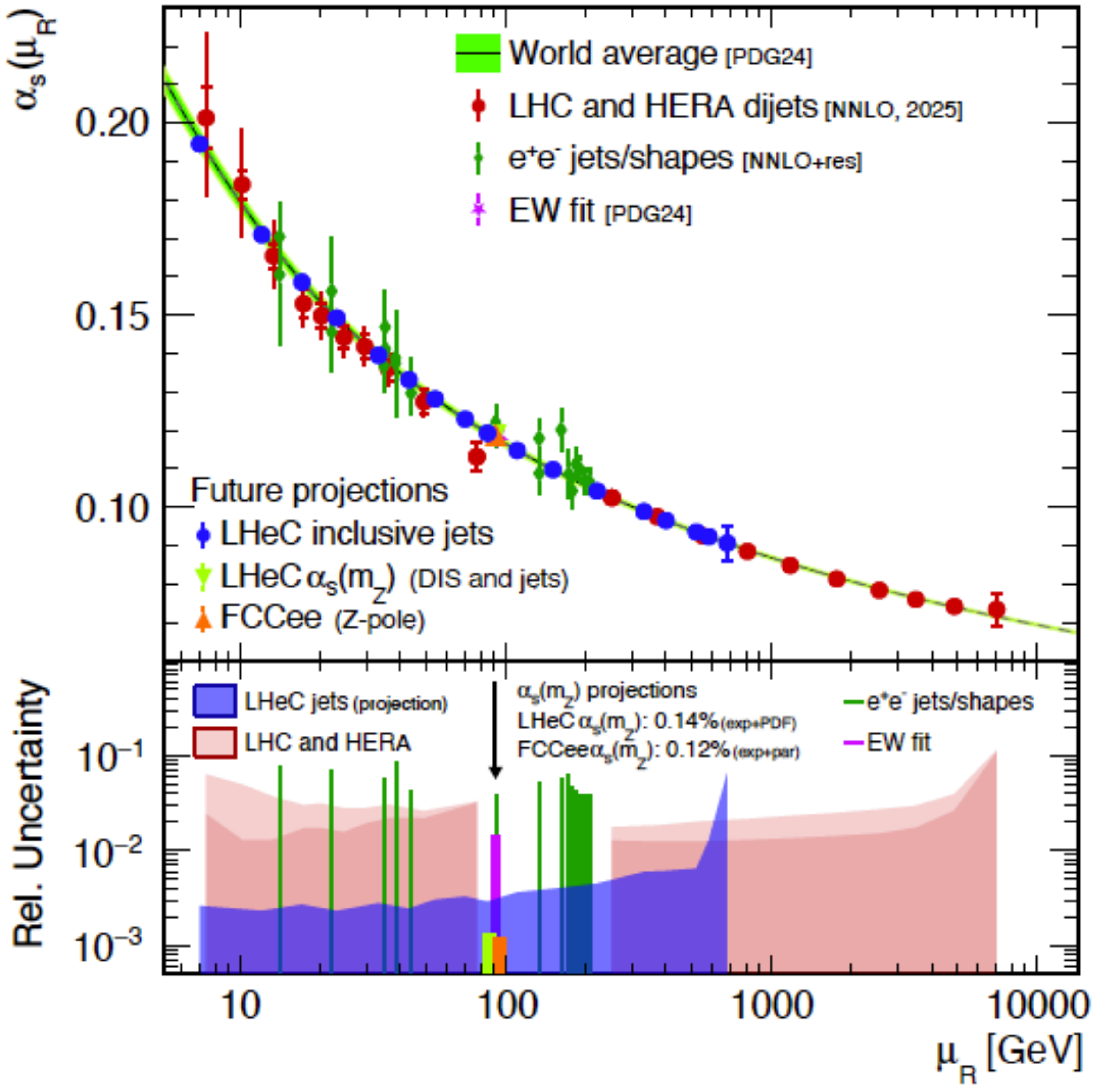
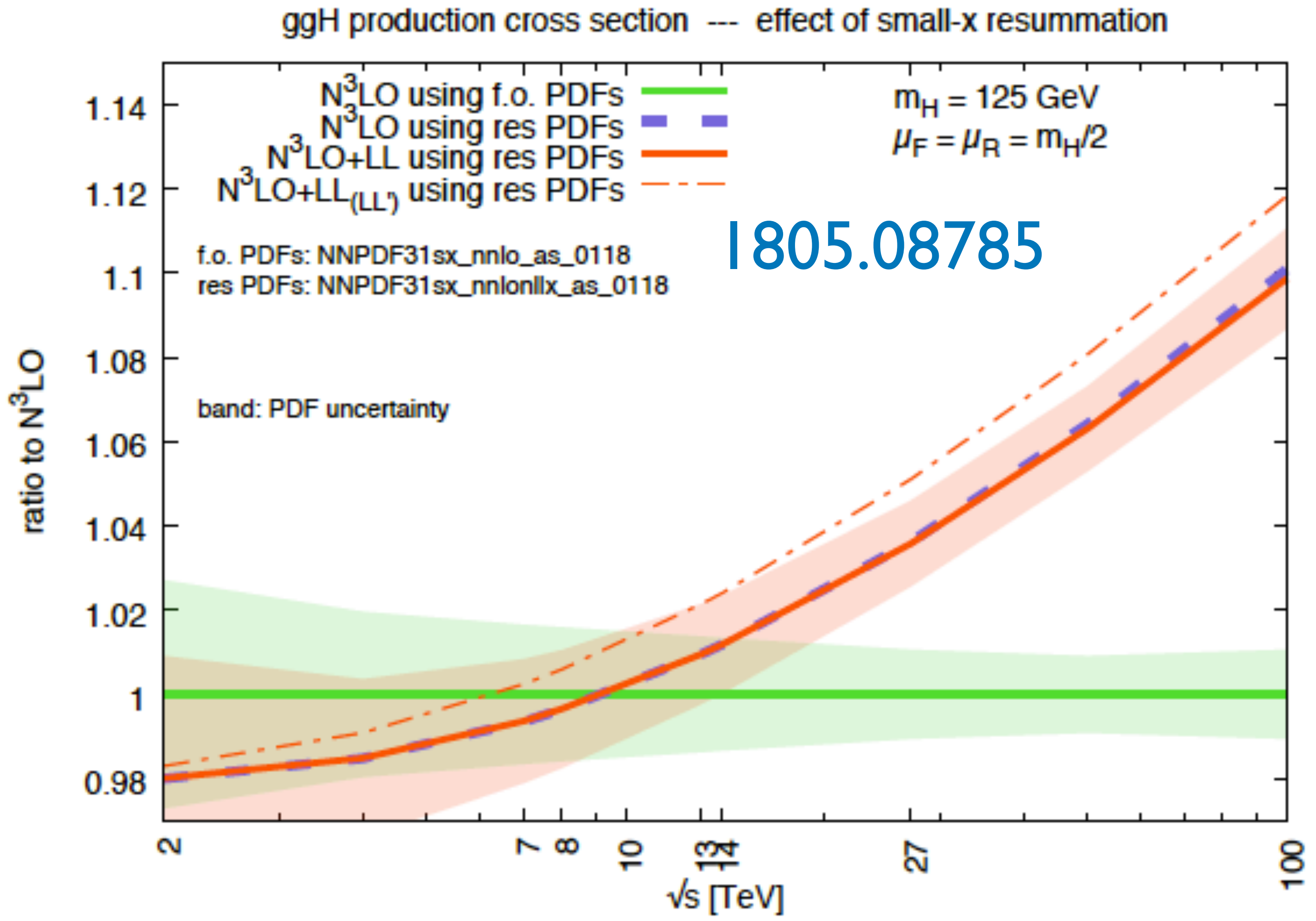




Implications on Higgs:

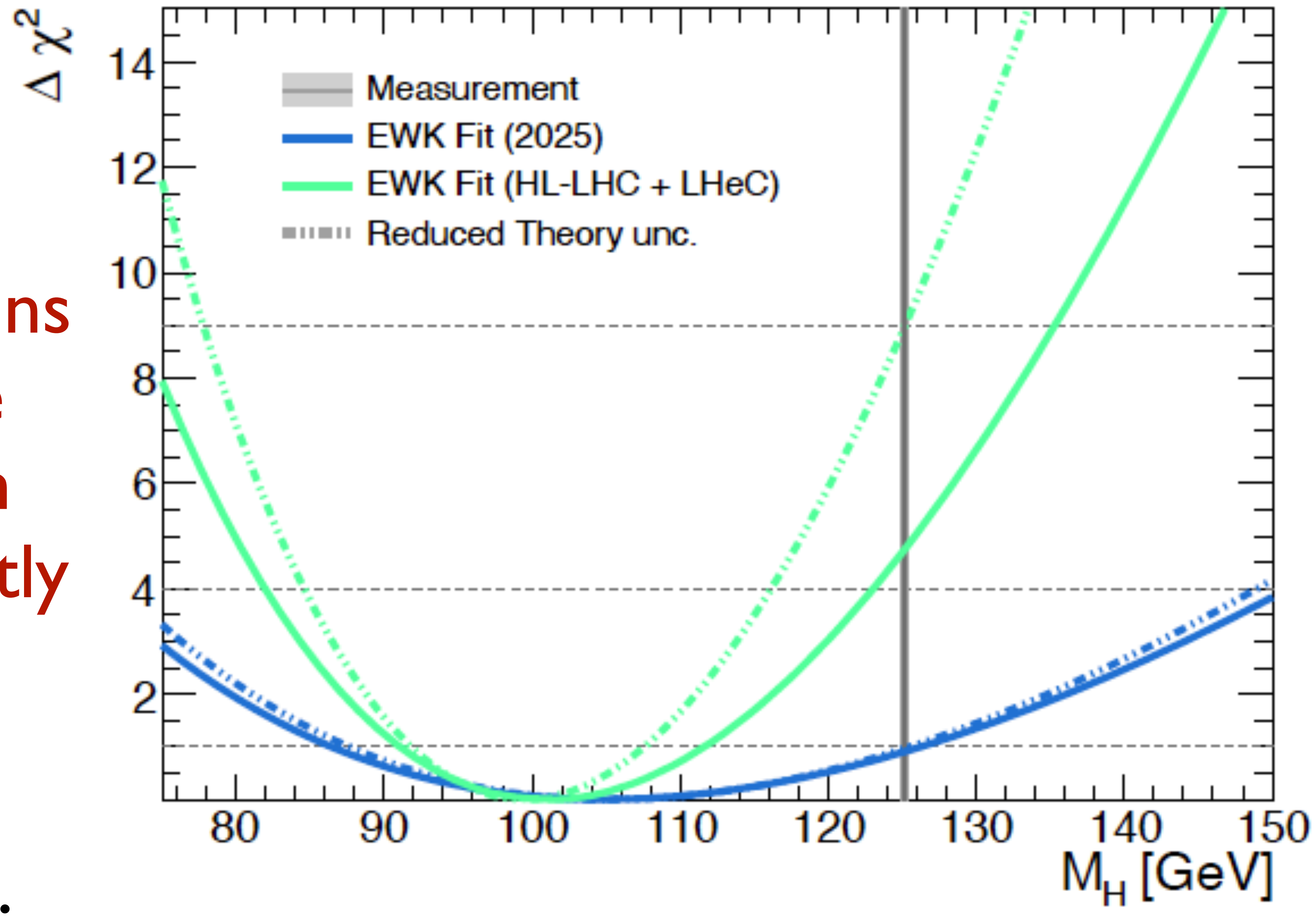
- PDFs+α_s measurements at the LHeC reduce very strongly the corresponding uncertainties in the Higgs cross section.

$\sqrt{s}$ [TeV]	$\sigma_{gg\to H}$ [pb]	TH uncertainty		PDF+α_S uncertainty			Total		
		Ref.	S2	Ref.	S2	S2+LHeC	Ref.	S2	S2+LHeC
14	54.7	3.9%	2.0%	3.2%	1.6%	0.5%	5.1%	2.6%	2.0%
27	146.6	4.0%	2.0%	3.3%	1.7%	0.6%	5.2%	2.6%	2.1%
100	804.4	4.2%	2.1%	3.7%	1.9%	0.7%	5.6%	2.8%	2.2%



1805.08785

- Also constrains the mass in the SM indirectly in EWK fits (mostly effect of m_W):

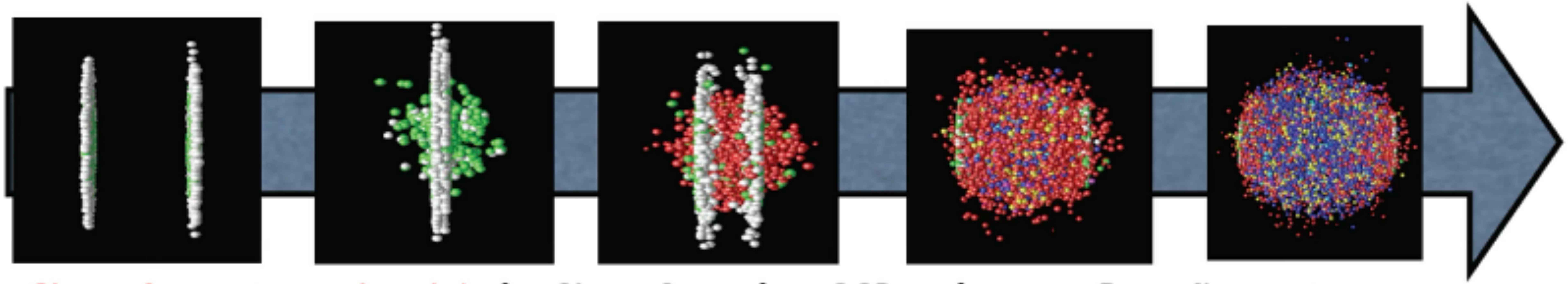


- Sizeable effect of the type of factorisation at small x.

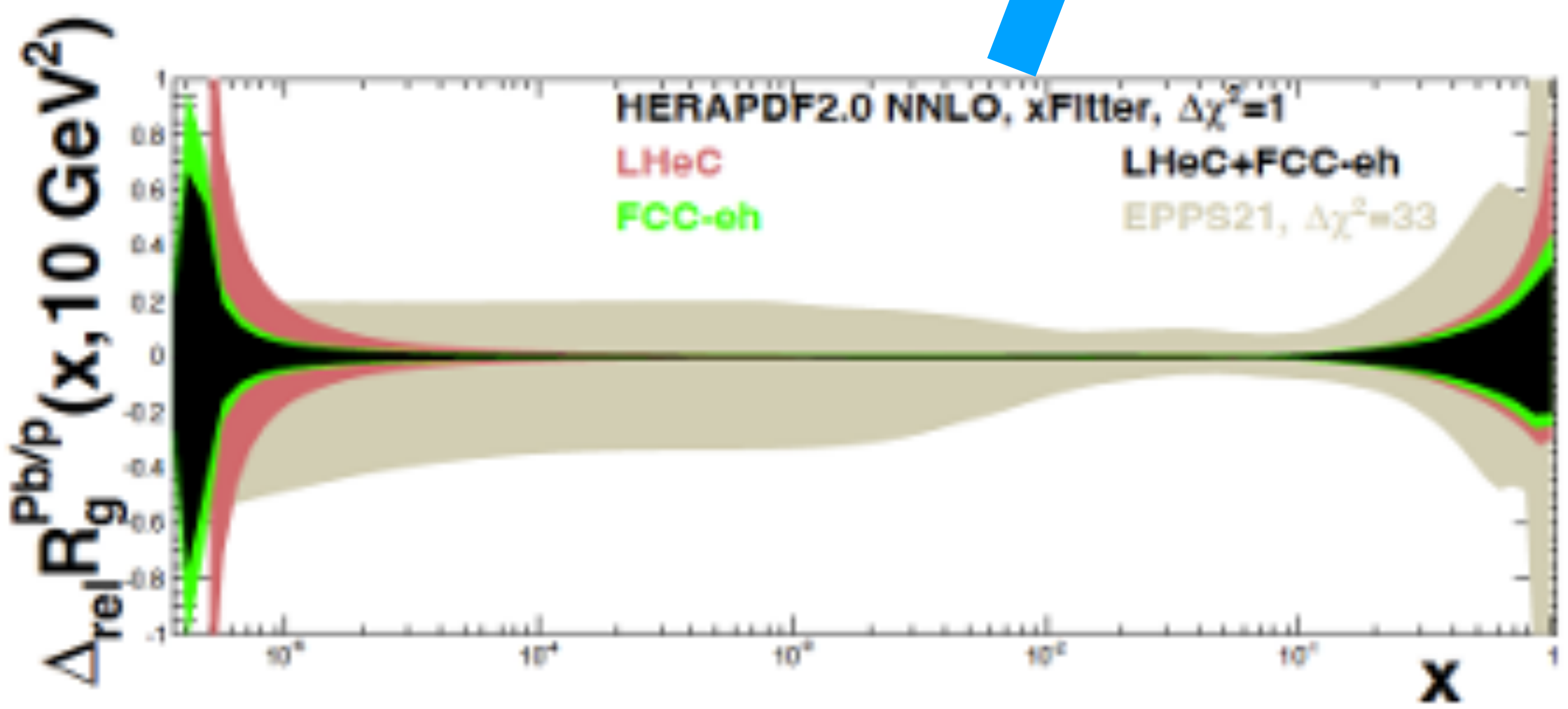
Implications of eA on pA/AA:

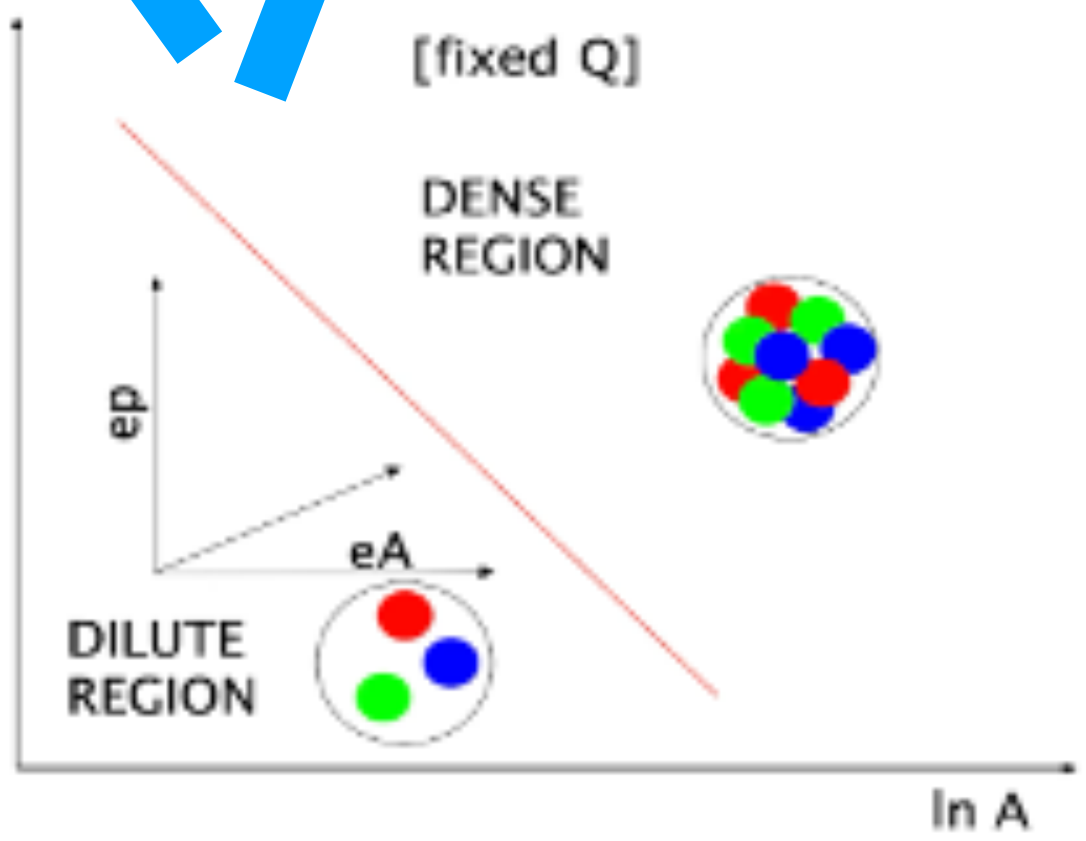
• eA collisions at the LHeC will provide precise information on the partonic structure of nuclei and the dynamics of dense partonic systems (a new non-linear regime of QCD which requires ep and eA), relevant for all stages of HICs.

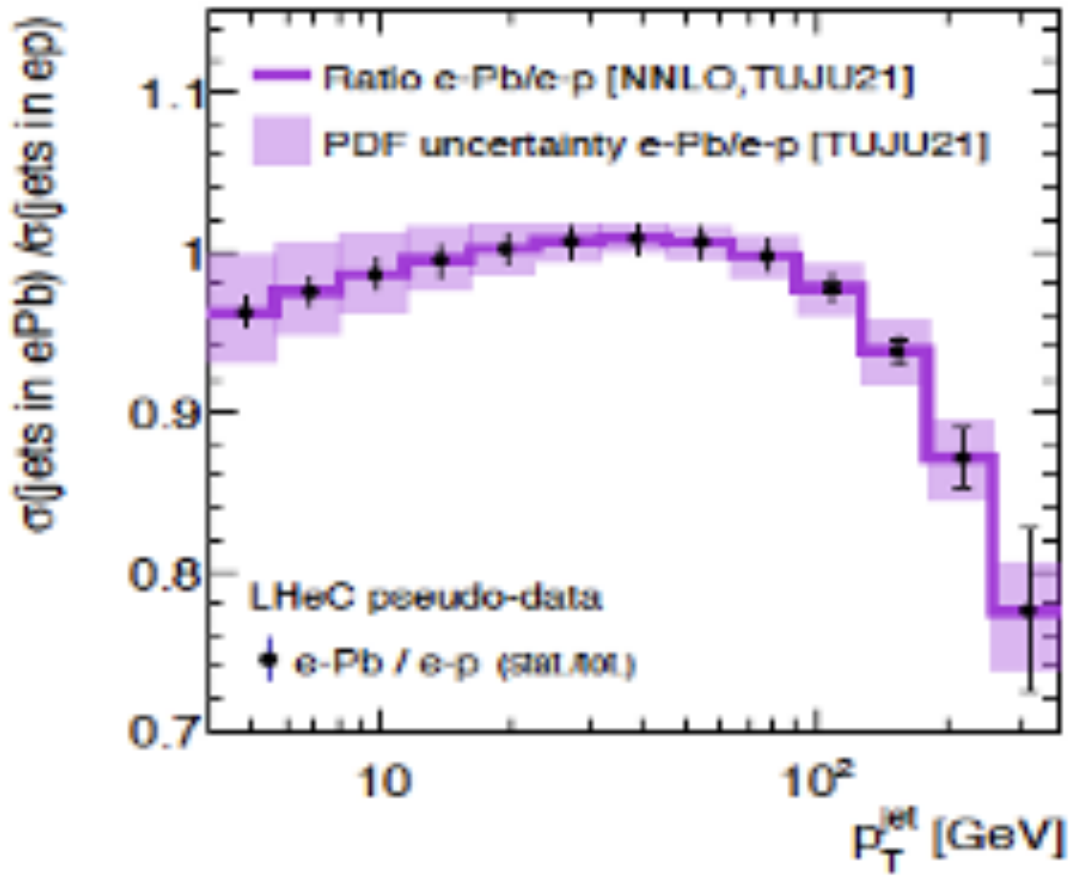
[B. Cole]



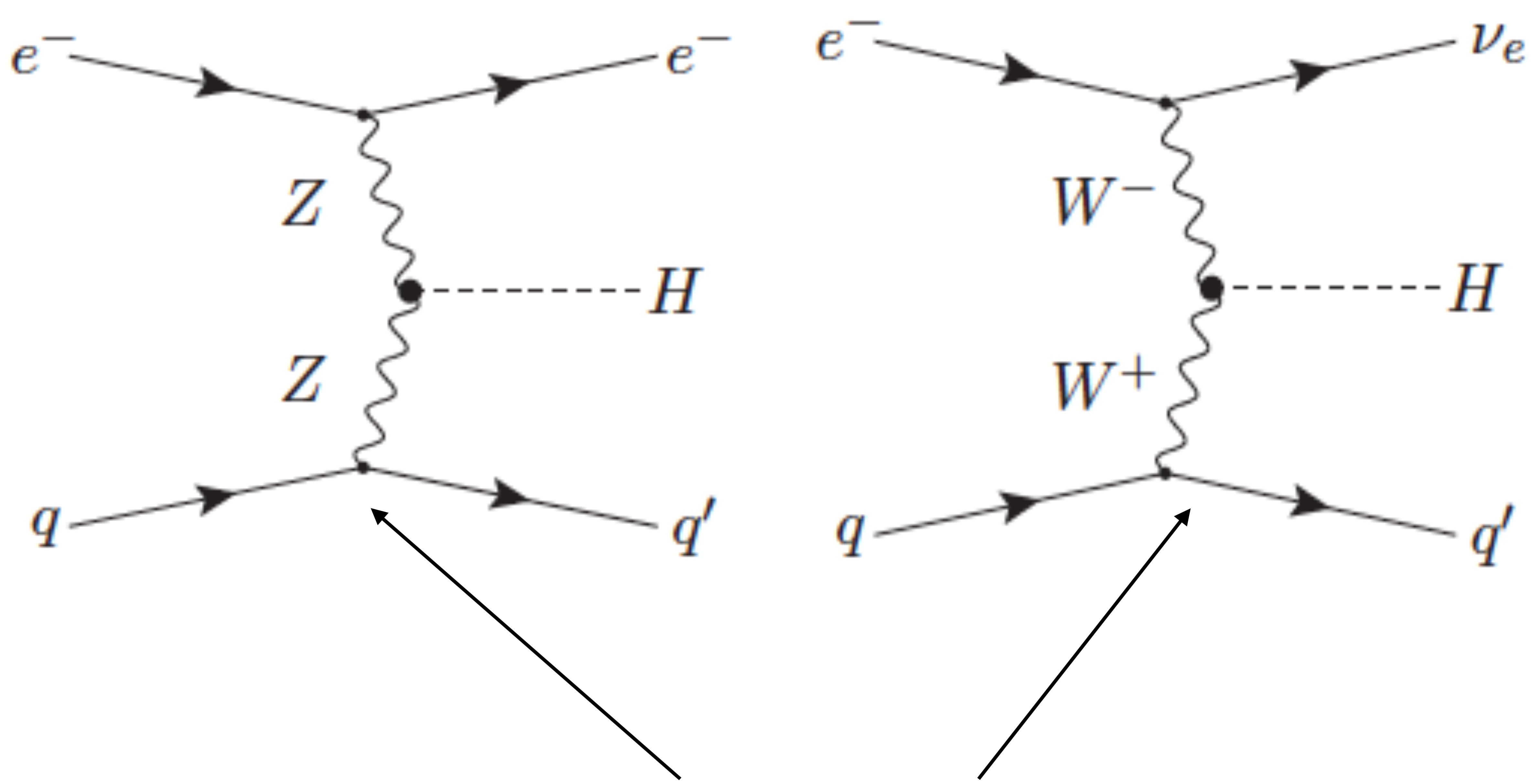
Gluons from saturated nuclei → Glasma? → QGP → Reconfinement







Higgs physics: cross sections



Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC} $(P=-0.8)$	fb	197	372	516	1038
σ_{NC} $(P=-0.8)$	fb	24	48	70	149
σ_{CC} $(P=0)$	fb	110	206	289	577
σ_{NC} $(P=0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46

		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	700	9 000
ZZ	0.026	5 100	54 000	620	7 900
$\gamma\gamma$	0.0023	450	5 000	55	700
$Z\gamma$	0.0015	300	3 100	35	450
$\mu^+\mu^-$	0.0002	40	410	5	70
σ [pb]		0.197	1.04	0.024	0.15

U. Klein at ICHEP2024

- Cross section for NC and CC Higgs production through VBF makes study possible with foreseen luminosities; initial estimate of g_{HHH} to 20 % accuracy at the FCC-eh.
- NLO contributions $\lesssim 20\,\%$ with shape distortions.
- Large Higgs dataset for precision measurements.

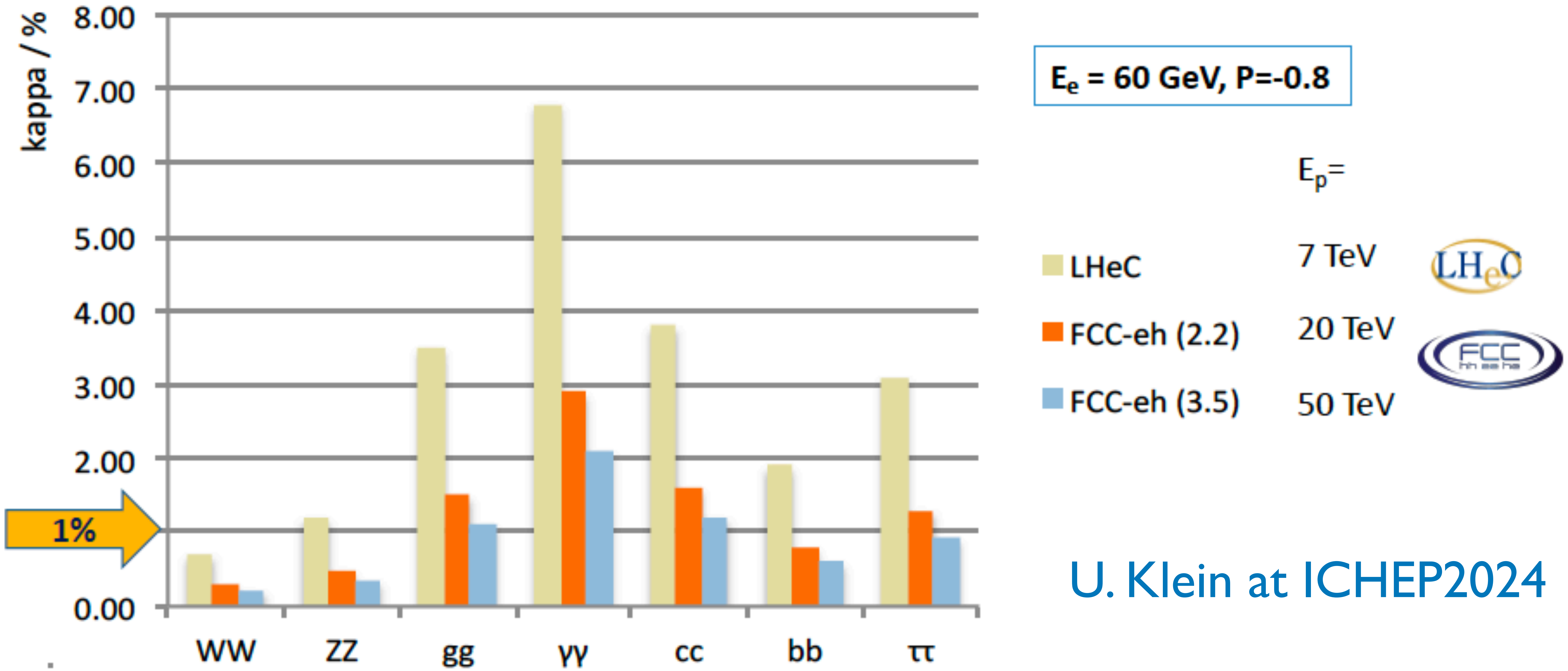
Higgs physics: κ-framework

- κ_i : coupling strength modified parameters, powerful method to parameterise possible deviations from SM couplings.

$$\sigma^i_{CC} = \sigma_{CC}\, br_i \cdot \kappa_W^2 \kappa_i^2 \frac{1}{\sum_j \kappa_j^2 br_j}$$

$$\sigma^i_{NC} = \sigma_{NC}\, br_i \cdot \kappa_Z^2 \kappa_i^2 \frac{1}{\sum_j \kappa_j^2 br_j}$$

- Standalone study yields few % uncertainties assuming SM branching fractions weighted by the measured κ values, and Γ_{md} (c.f. CLIC model-dependent method, 1608.07538).



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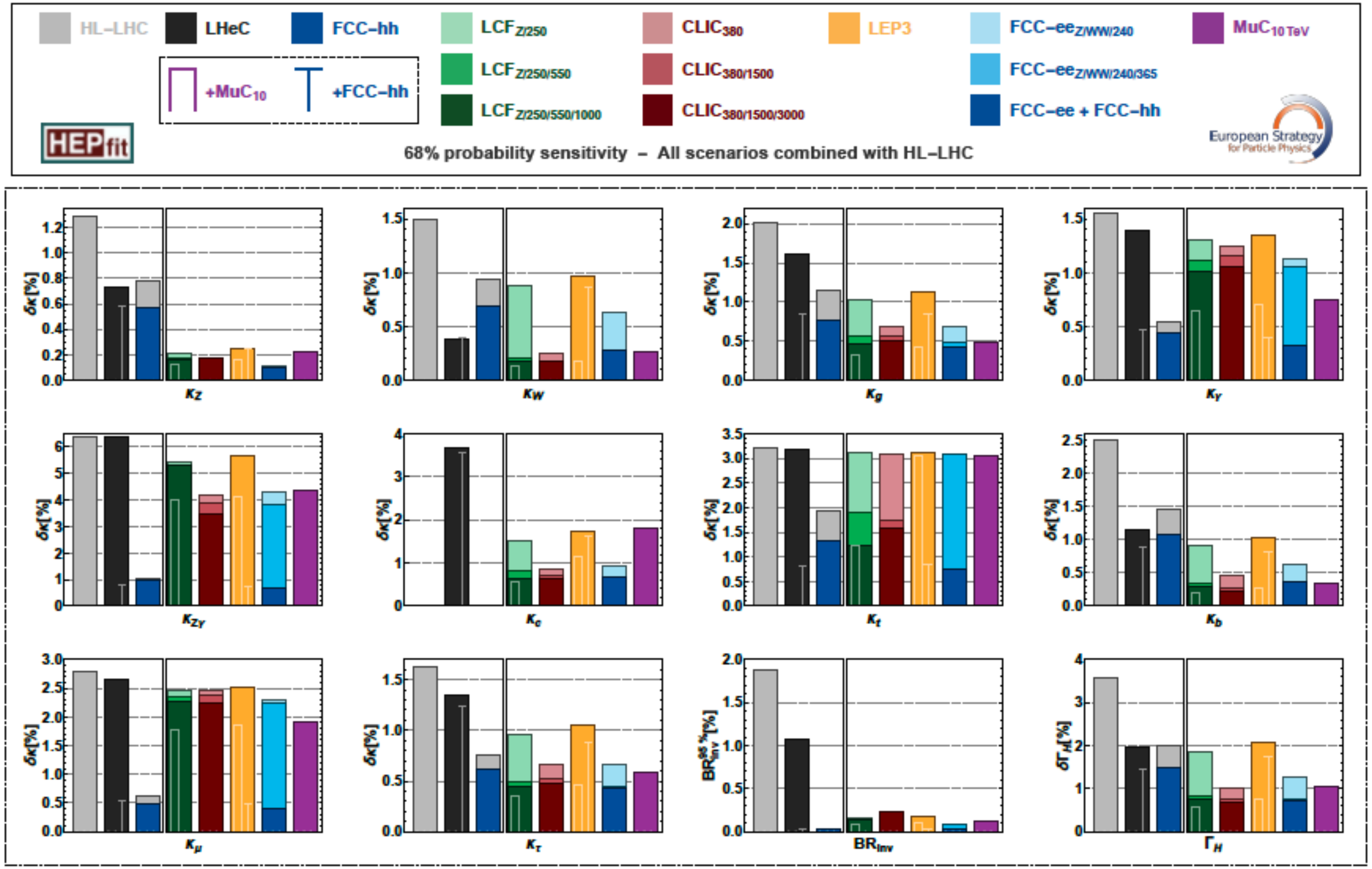
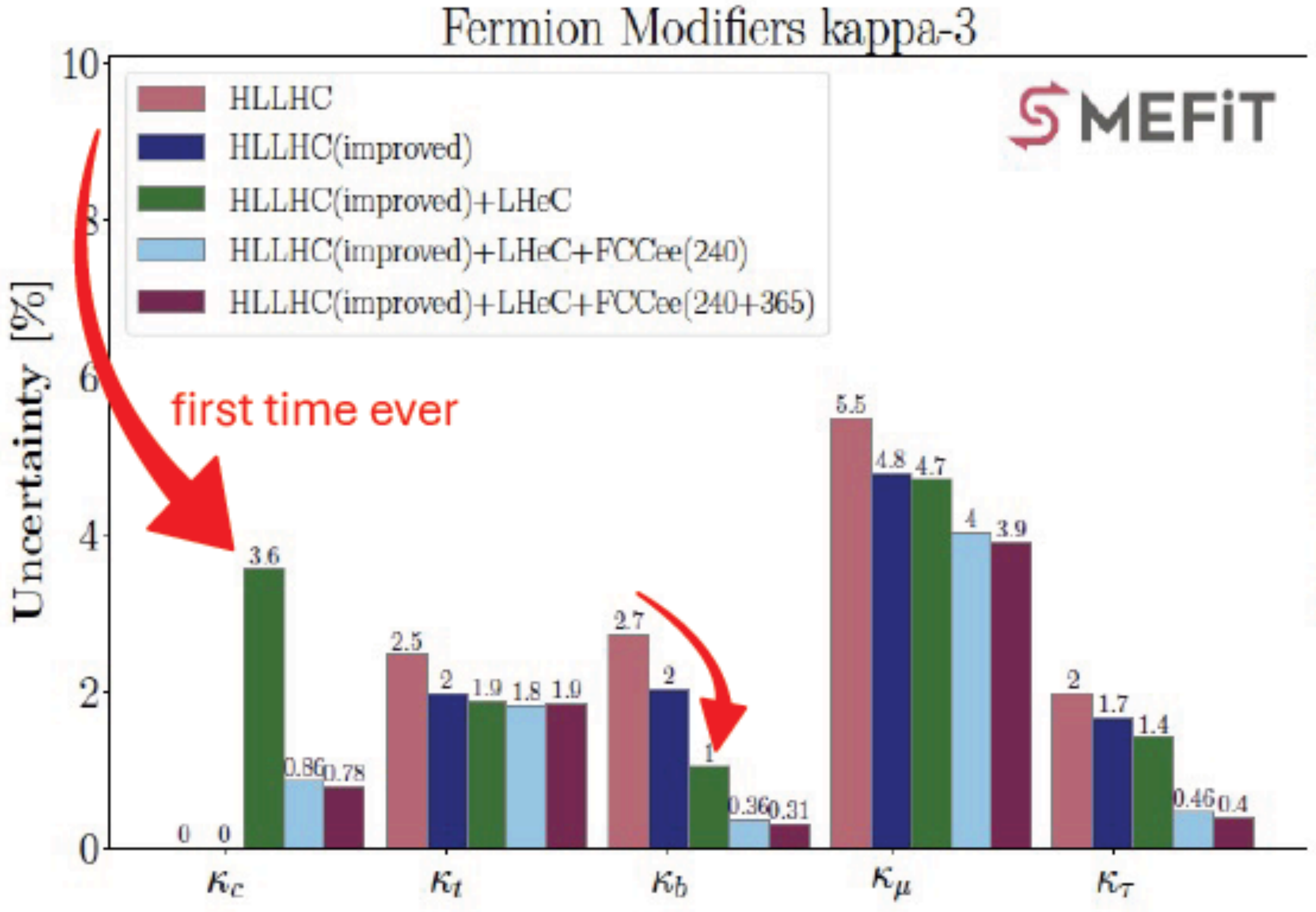
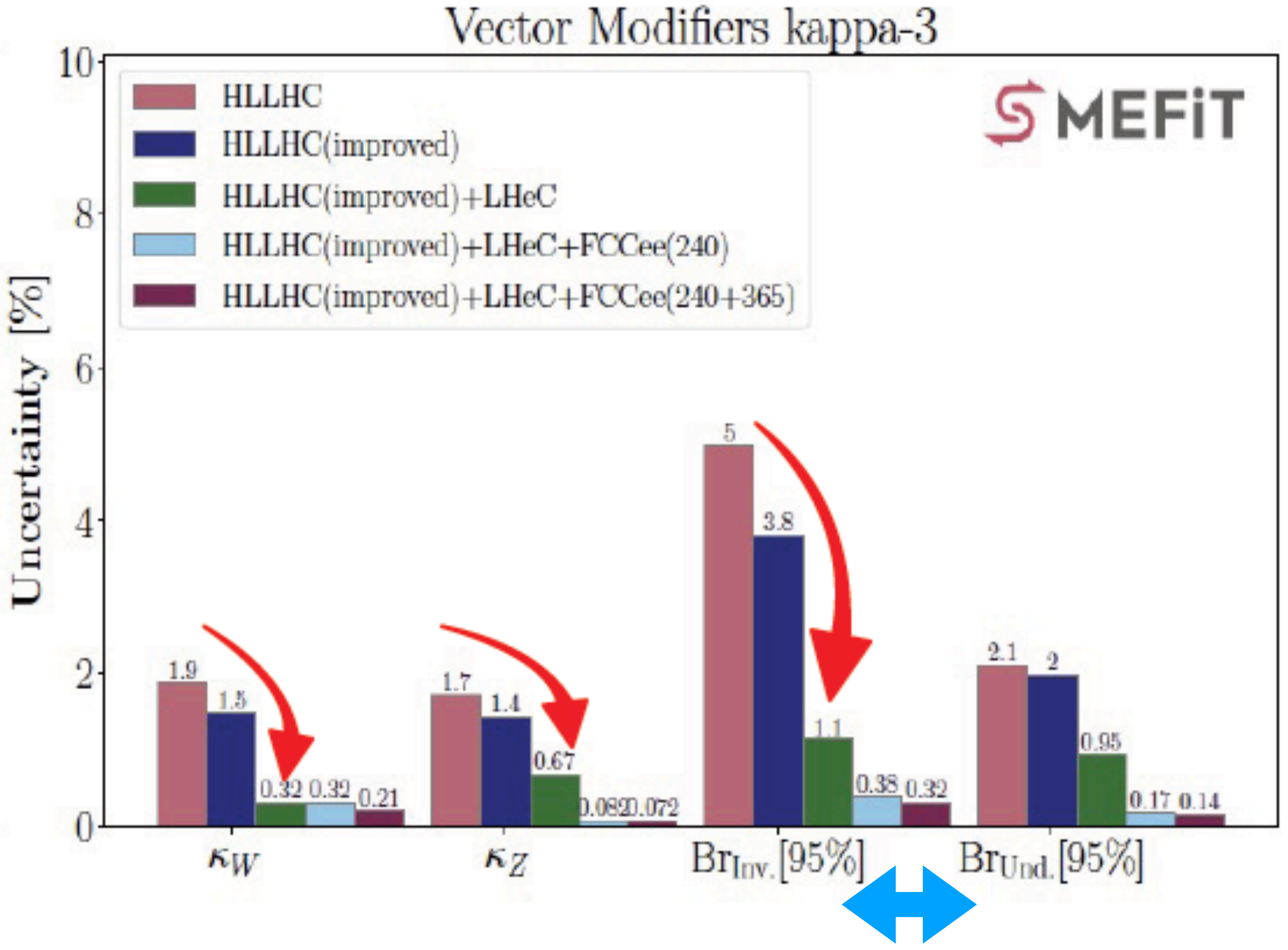


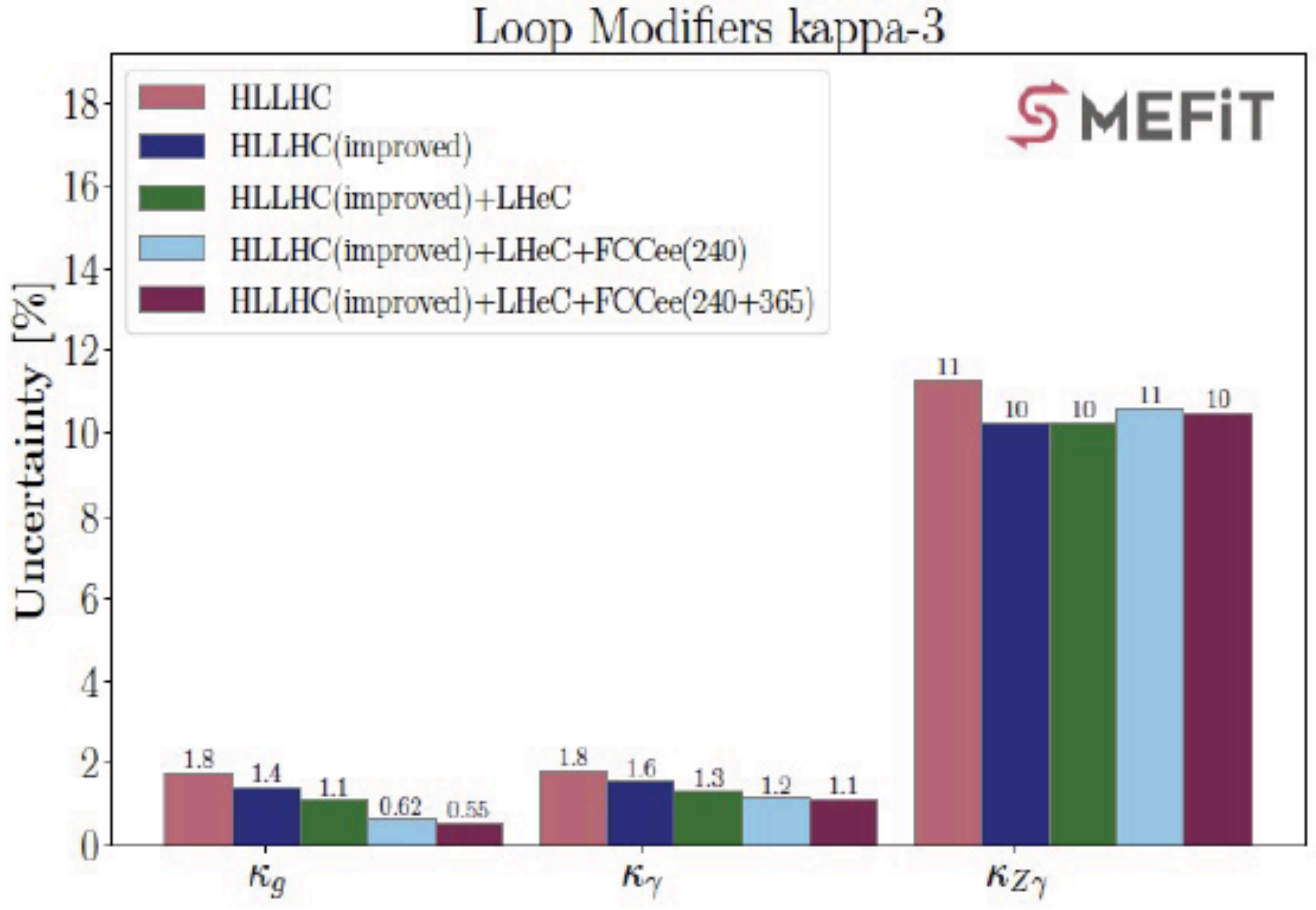
Higgs physics: κ-framework

- κ_i : coupling strength modified parameters, powerful method to parameterise possible deviations from SM couplings (SMEFiT, 2105.00006).

- LHeC PDFs+α_s improve all HL-LHC results:
  - ➜ Significantly $\kappa_t, \kappa_\tau, \kappa_g$.
  - ➜ Greatly $\kappa_b, \kappa_W, \kappa_Z$.
  - ➜ First time κ_c.



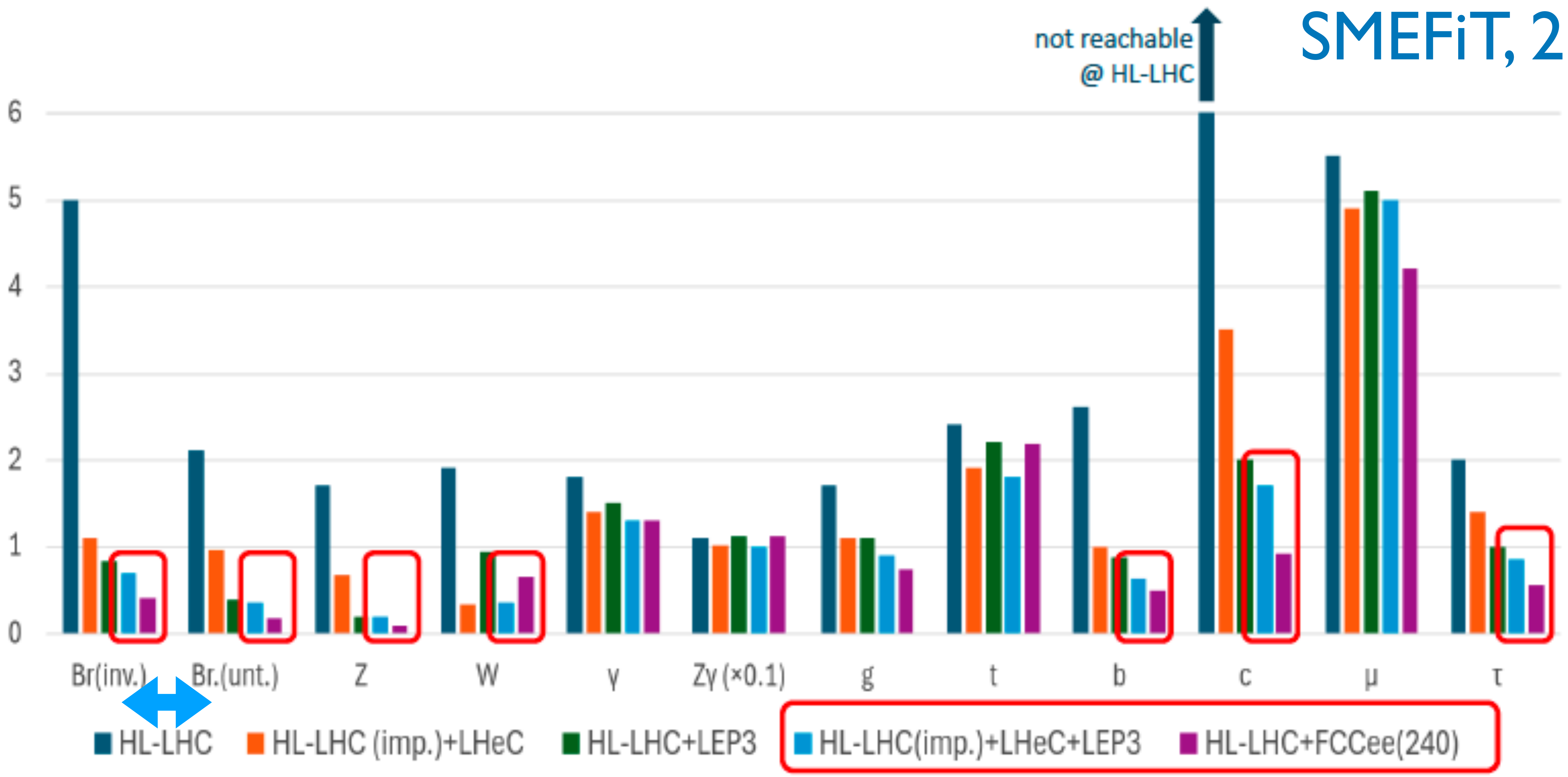




J. D'Hondt at the Open Symposium of the ESPP2026

Note: latest HL-LHC projections (2504.00672) only change sizeably κ_μ, $\kappa_{Z\gamma}$ wrt. 2020 ESPP ones.

Higgs physics: κ-framework



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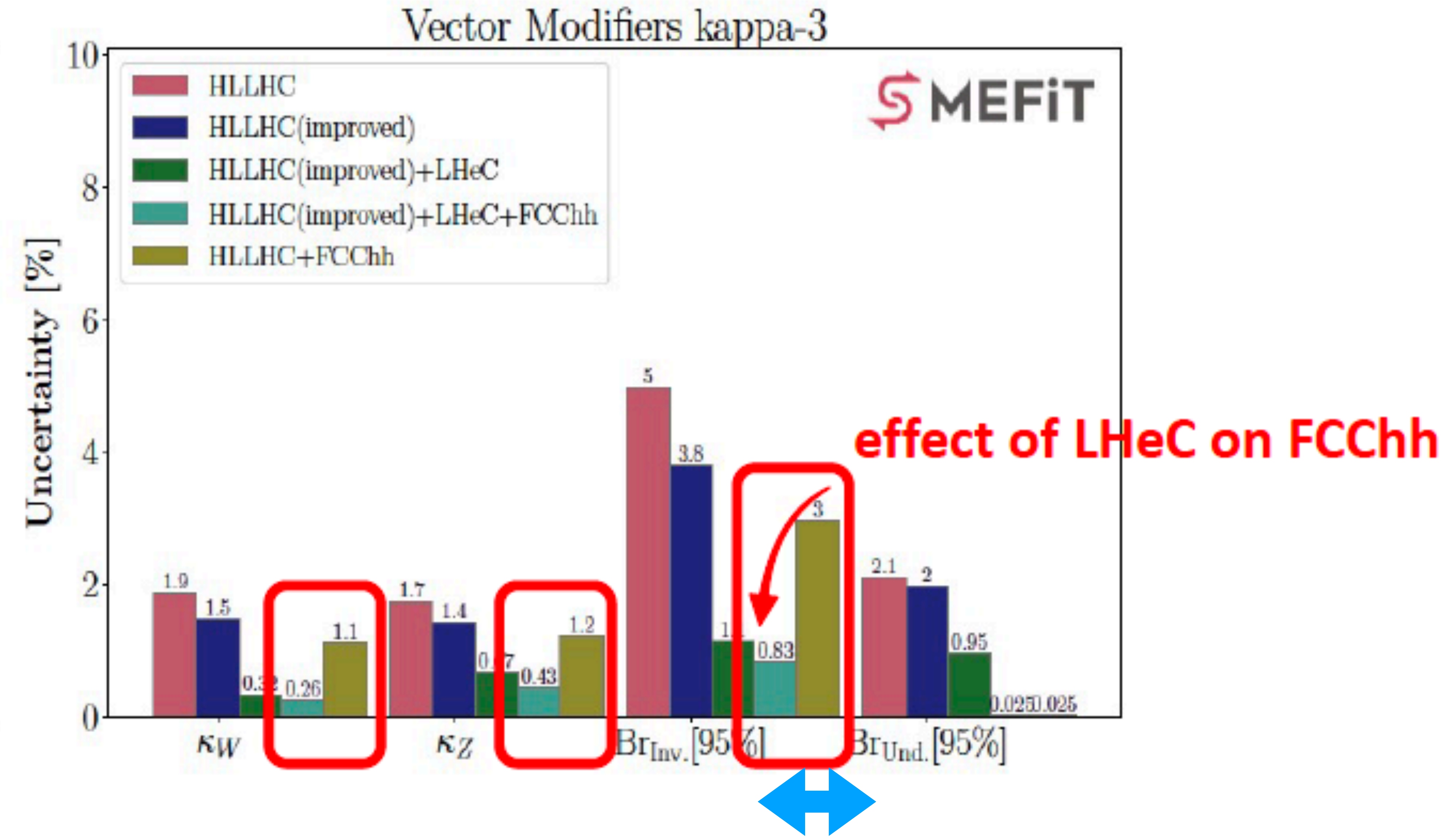

- LHeC combines well with LEP3 wrt. FCCee(240).

- LHeC needed to fully unlock the potential of FCC-hh.

J. D'Hondt at the Open Symposium of the ESPP2026

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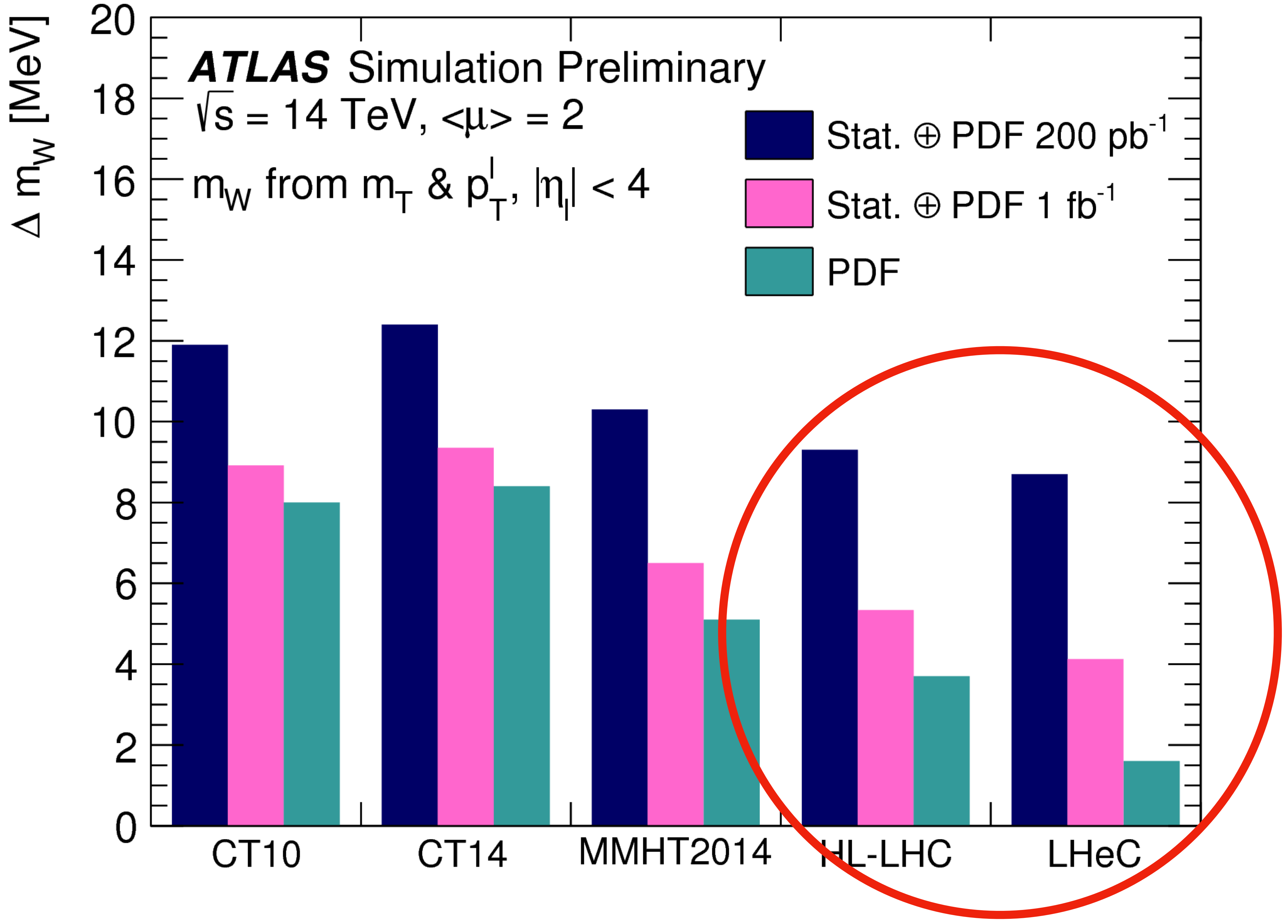
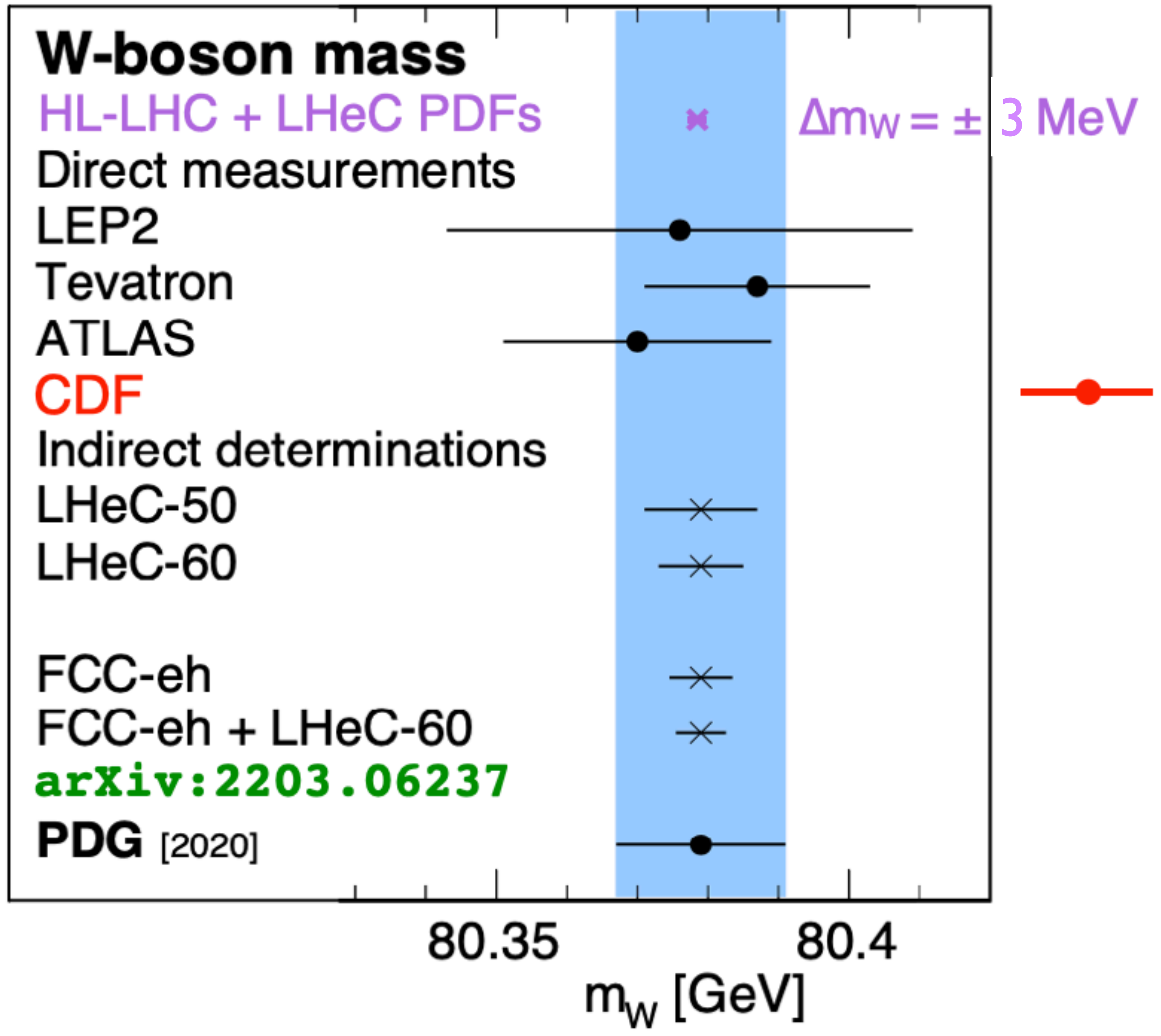
W mass:

- PDFs+α_s measurements at the LHeC reduce the corresponding uncertainties in the EWK parameters at the HL-LHC.

Parameter	Unit	Value	Uncertainty		
			Present	HL-LHC	HL-LHC+LHeC
m_Z	MeV	91187.6	2.1	< 2	< 2
m_W	MeV	80369.2	13.3	5–6	3
$\sin^2\theta^\ell_{\rm eff}$		0.23152	0.00016	0.00016	0.00008
$m_{\rm top}$	GeV	172.57	0.29	< 0.2	< 0.2
α_S		0.1179	0.0010	0.0008	0.00016



ΔM_W=±5-6 MeV (HL-LHC) → ±3 MeV (HL-LHC + LHeC PDFs)



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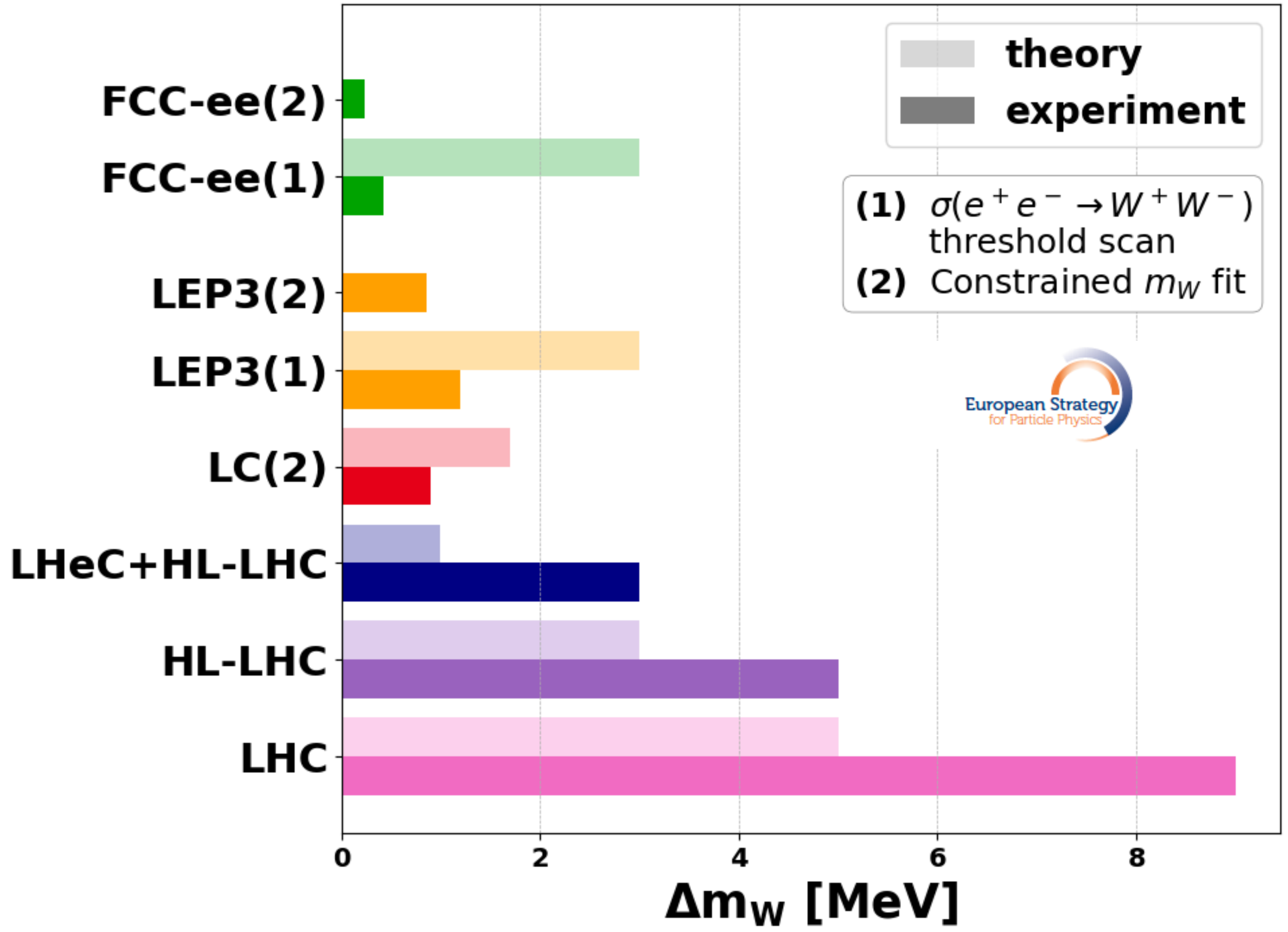
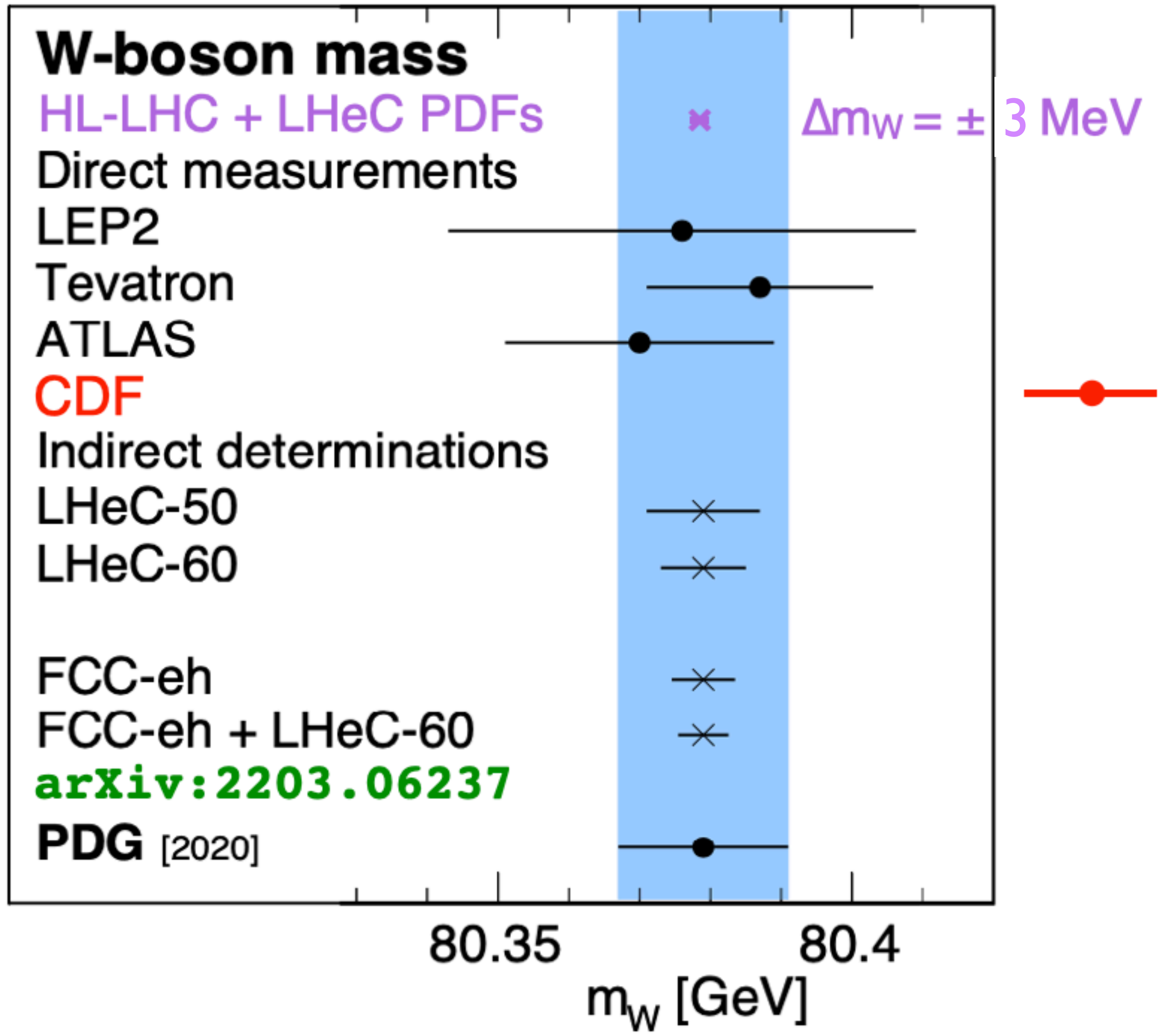
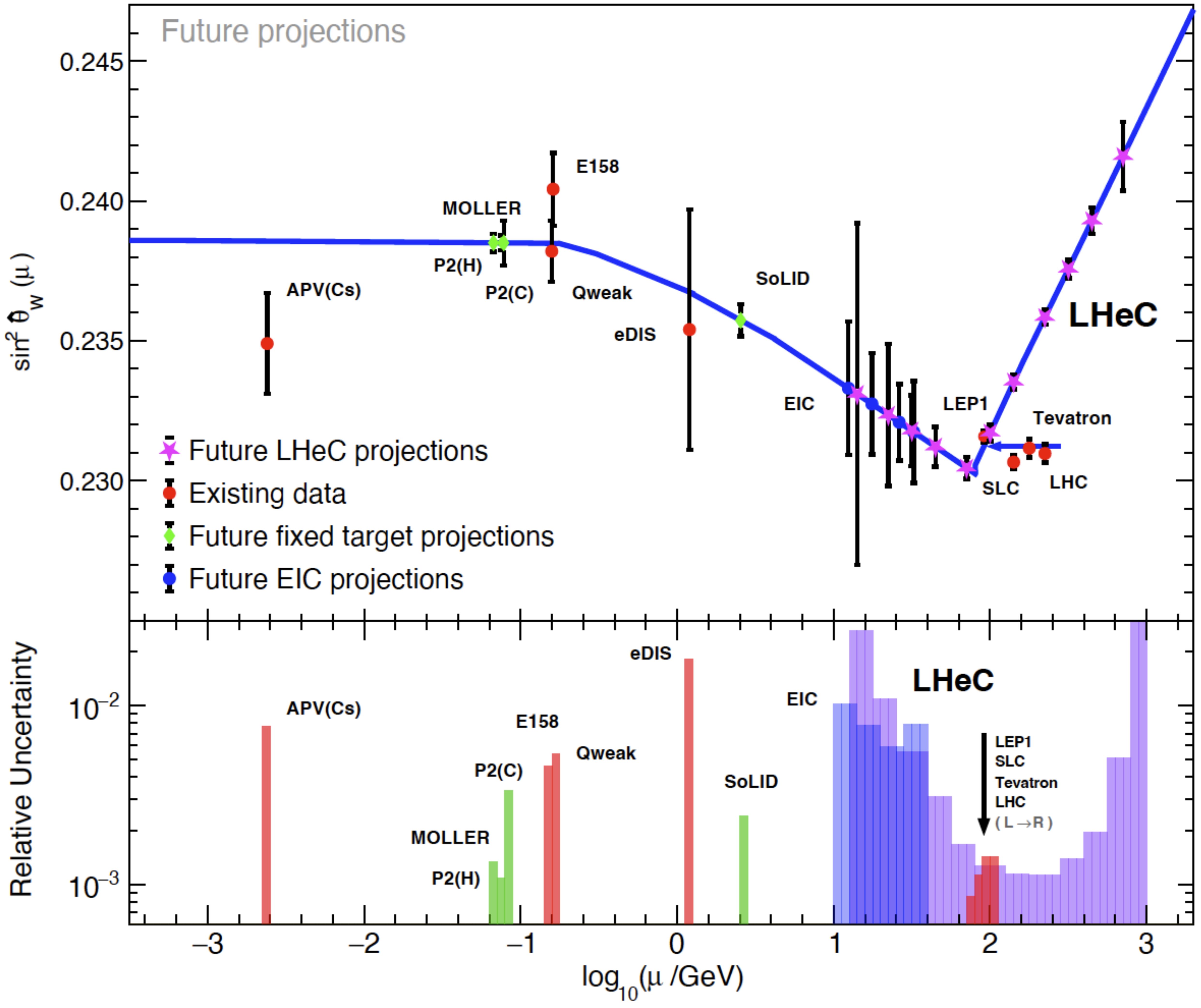




EW mixing angle:

- At the LHeC, many EW physics opportunities (spacelike vs. timelike in e^+e^- /pp) through PDF+EW fits: W&Z mass, $\sin^2\theta_W^{eff,l}$ and its running, V and A NC/CC couplings to light quarks, triple and quartic couplings,…



EW physics: couplings to light quarks

- Coupling of γ,Z,W to light flavours not accessible in other processes; also BSM contributions (e.g., in the SMEFT framework) and running are measurable.

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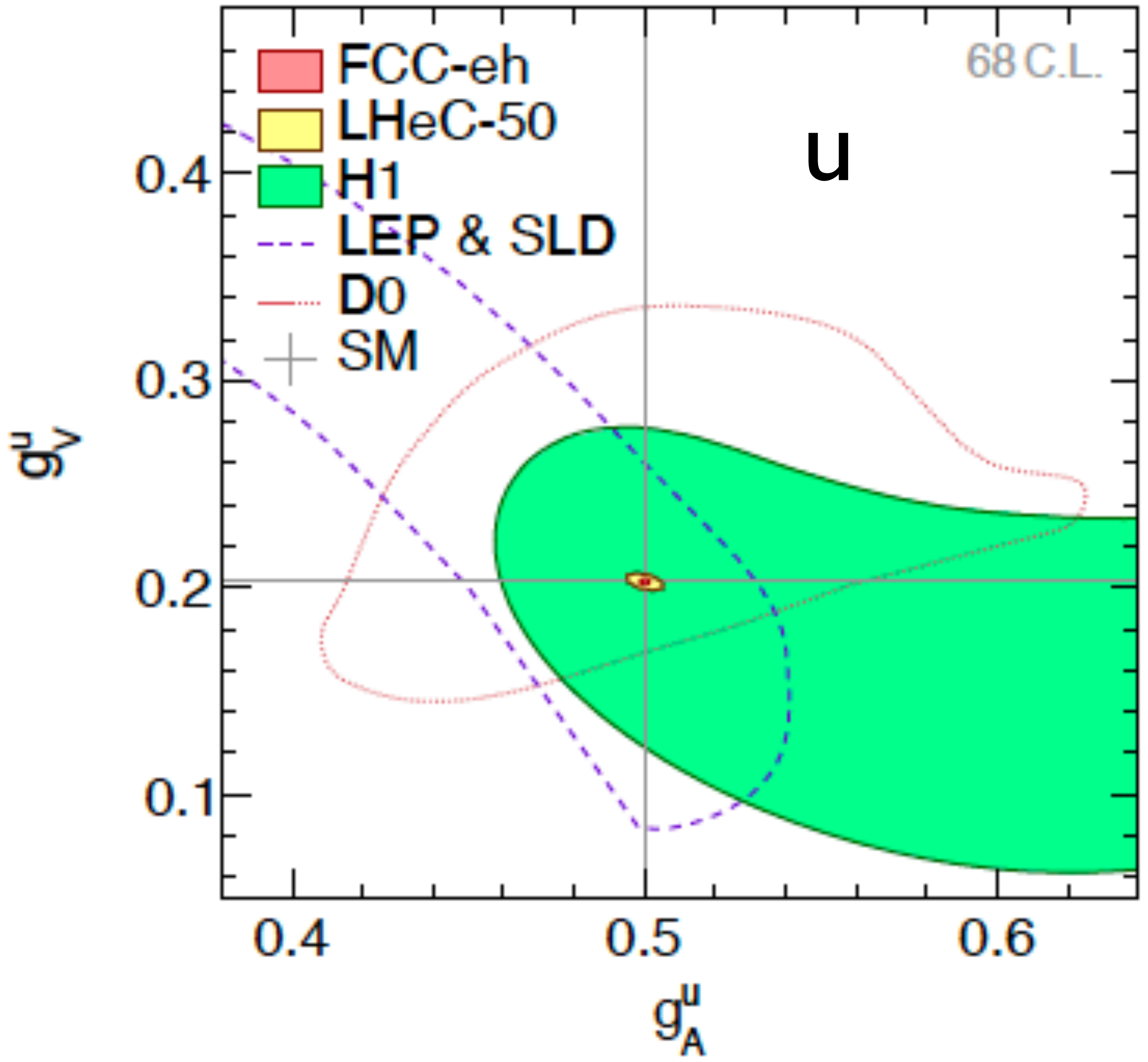

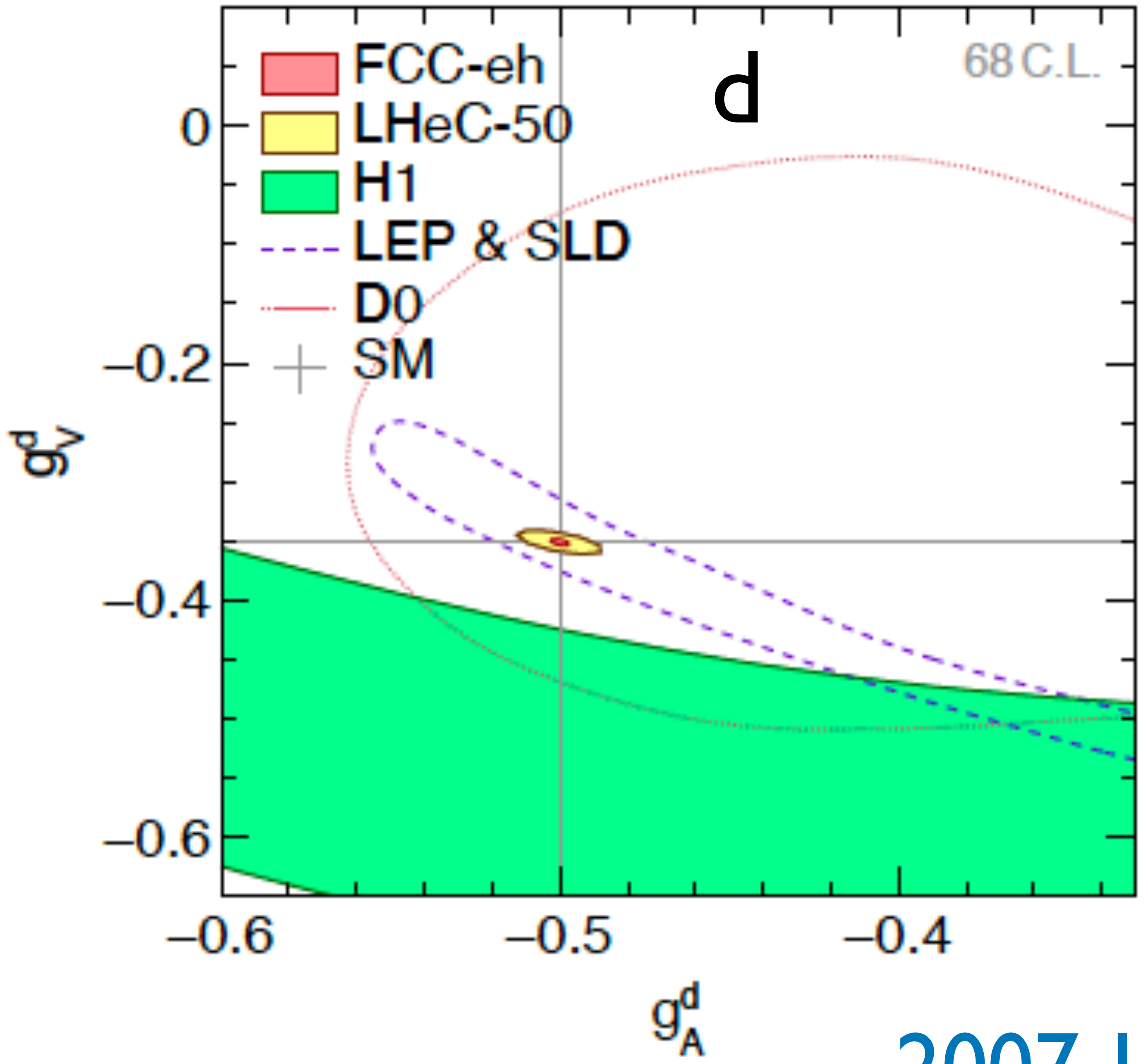

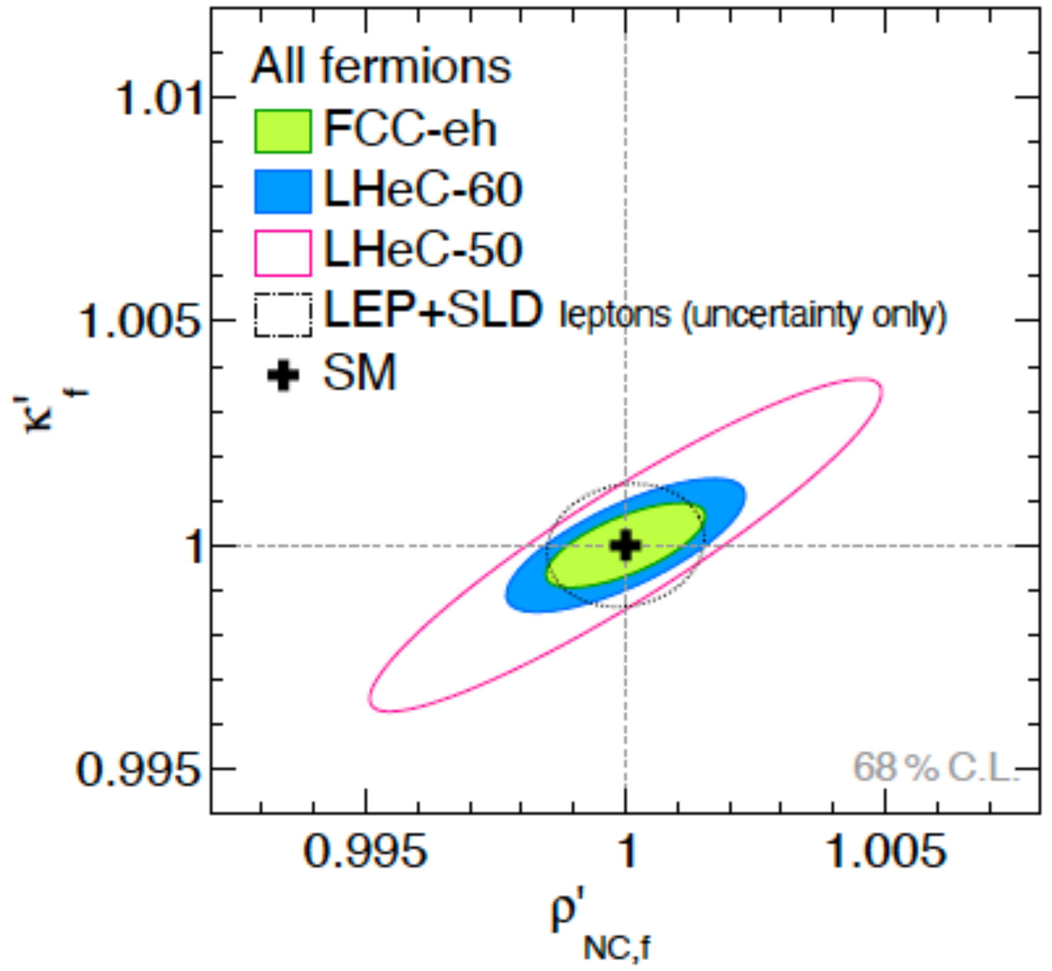

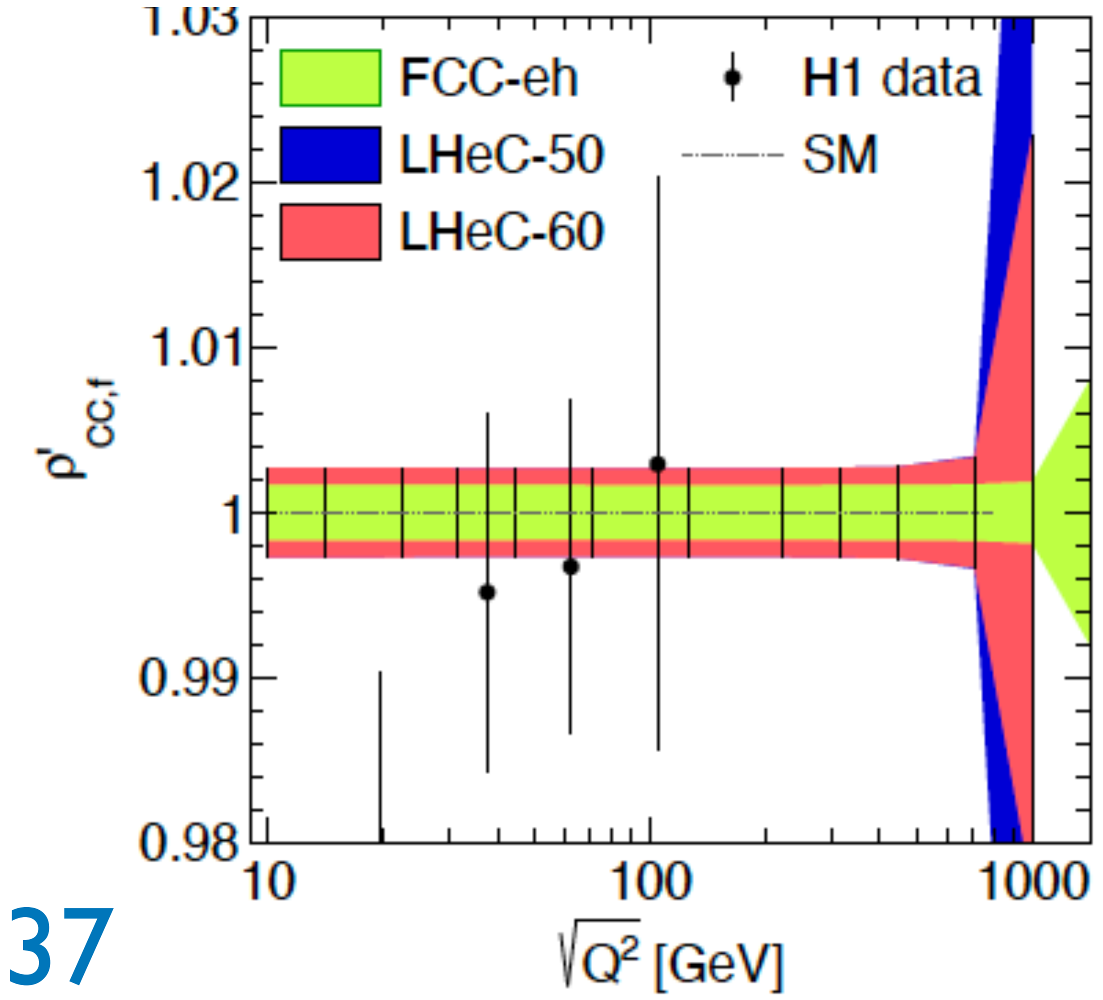

2007.11799, 2203.06237

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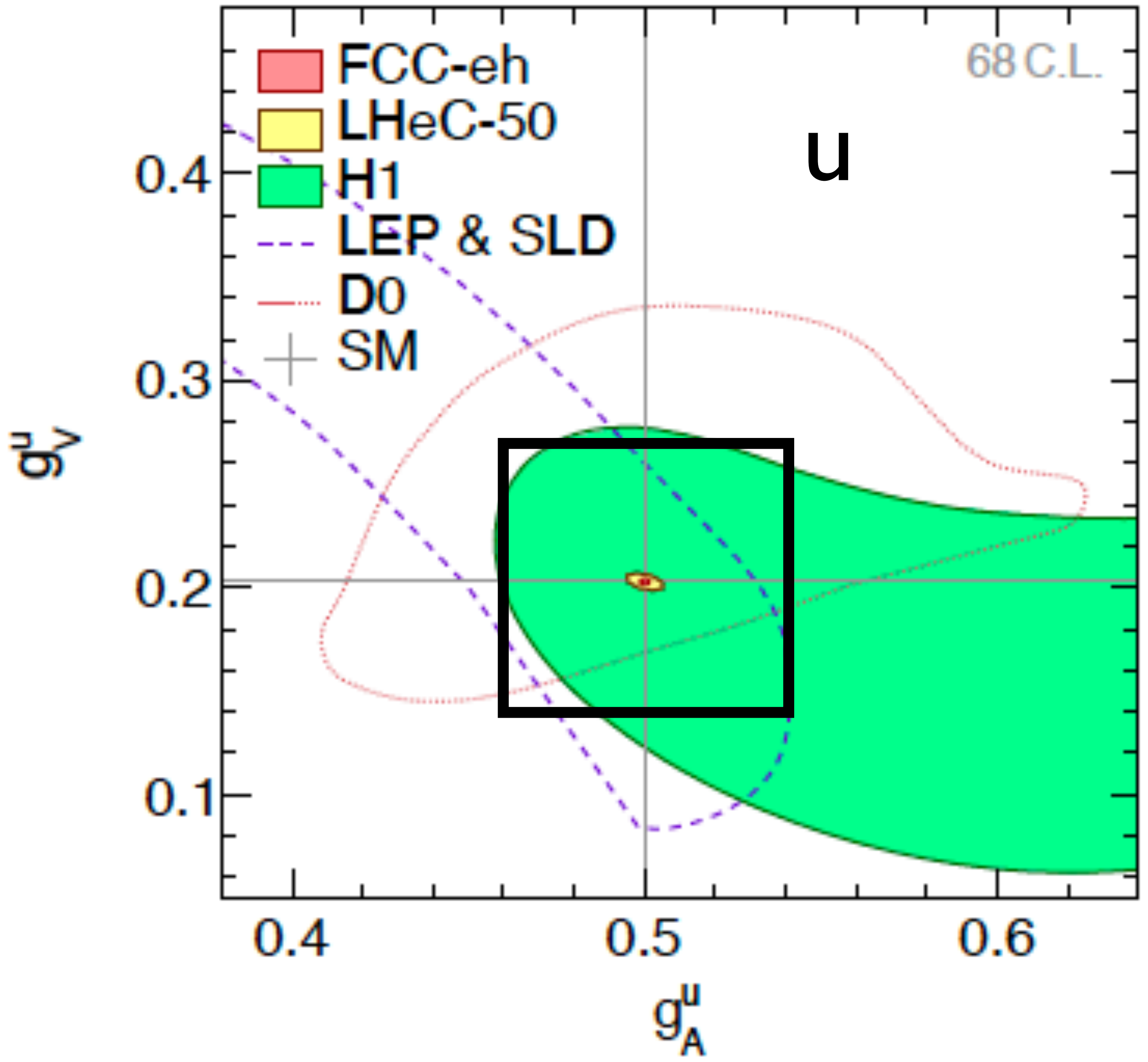

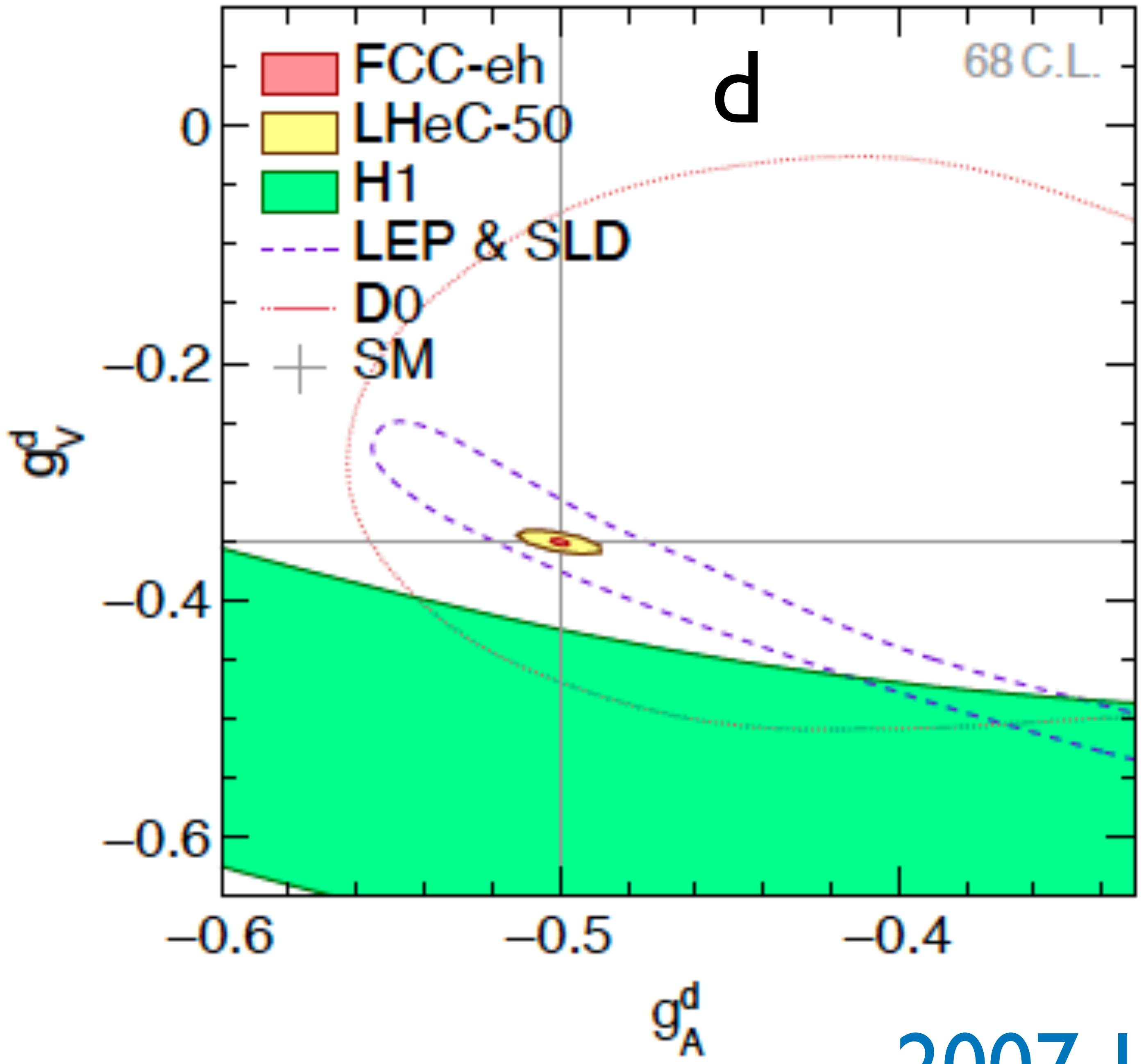

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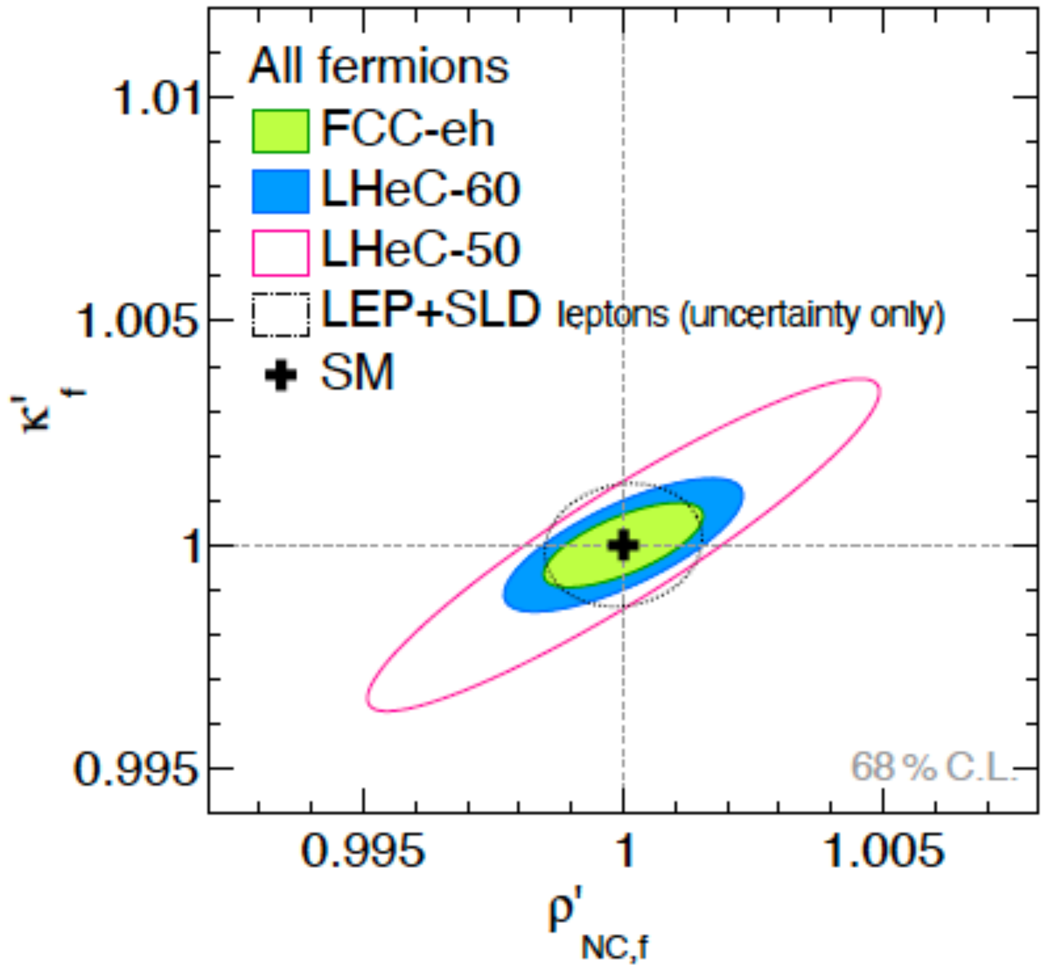

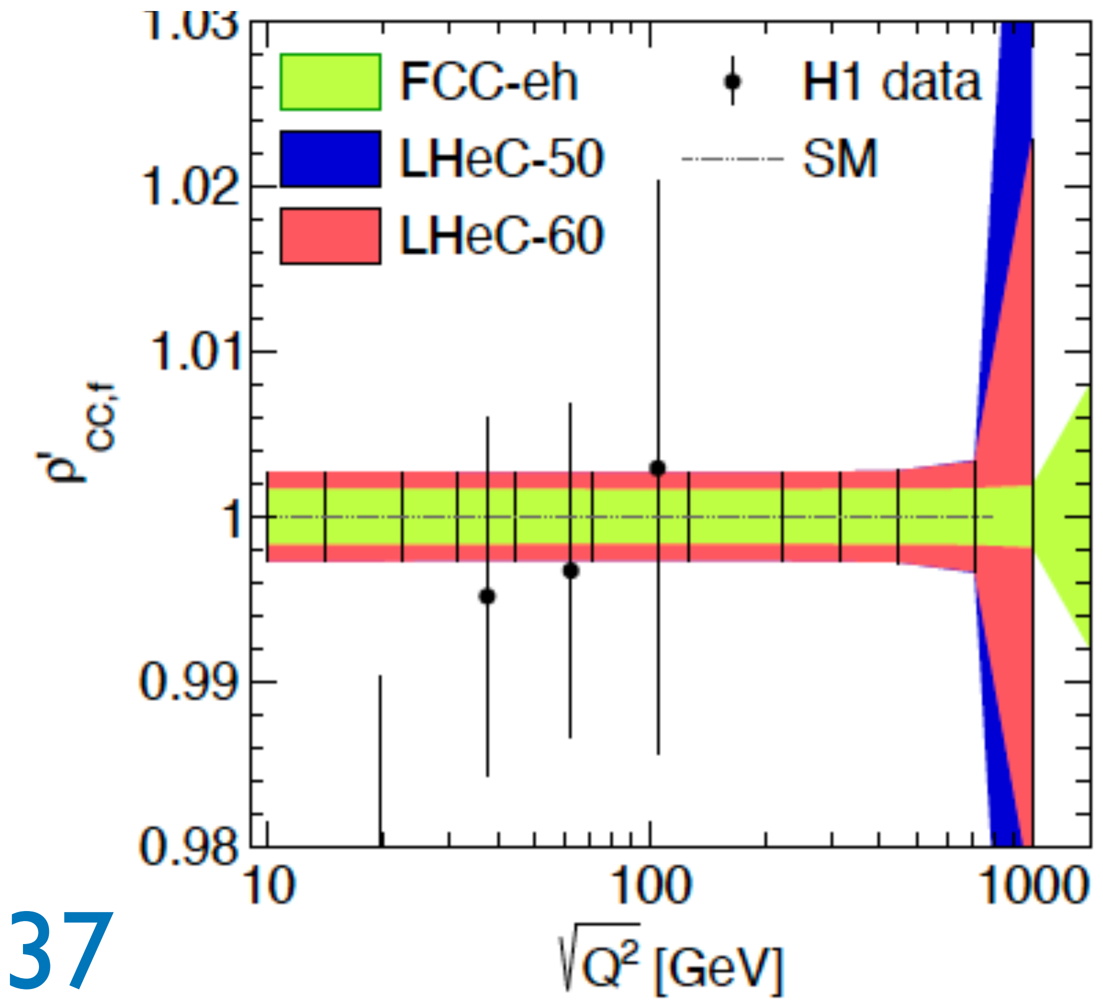

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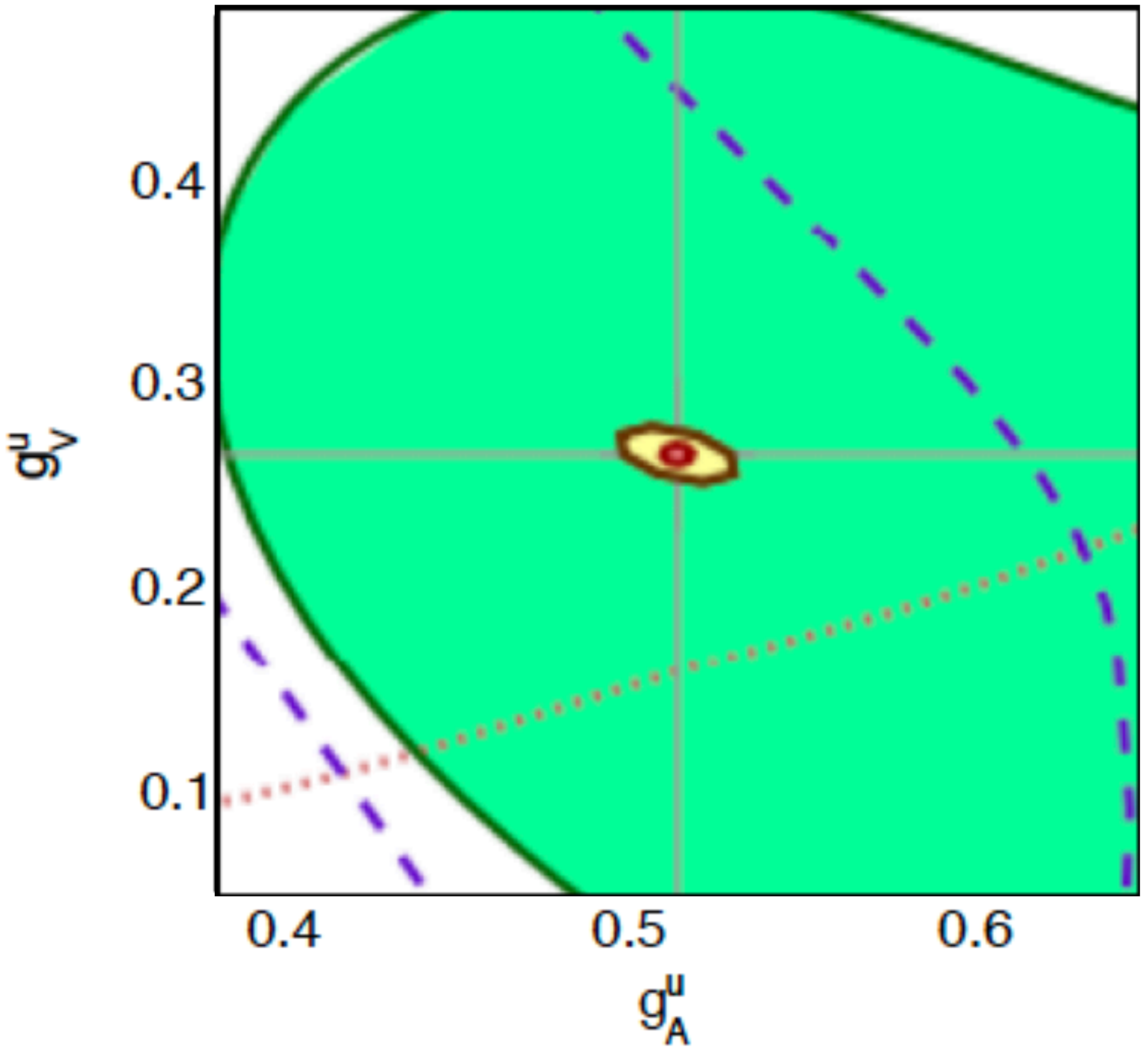

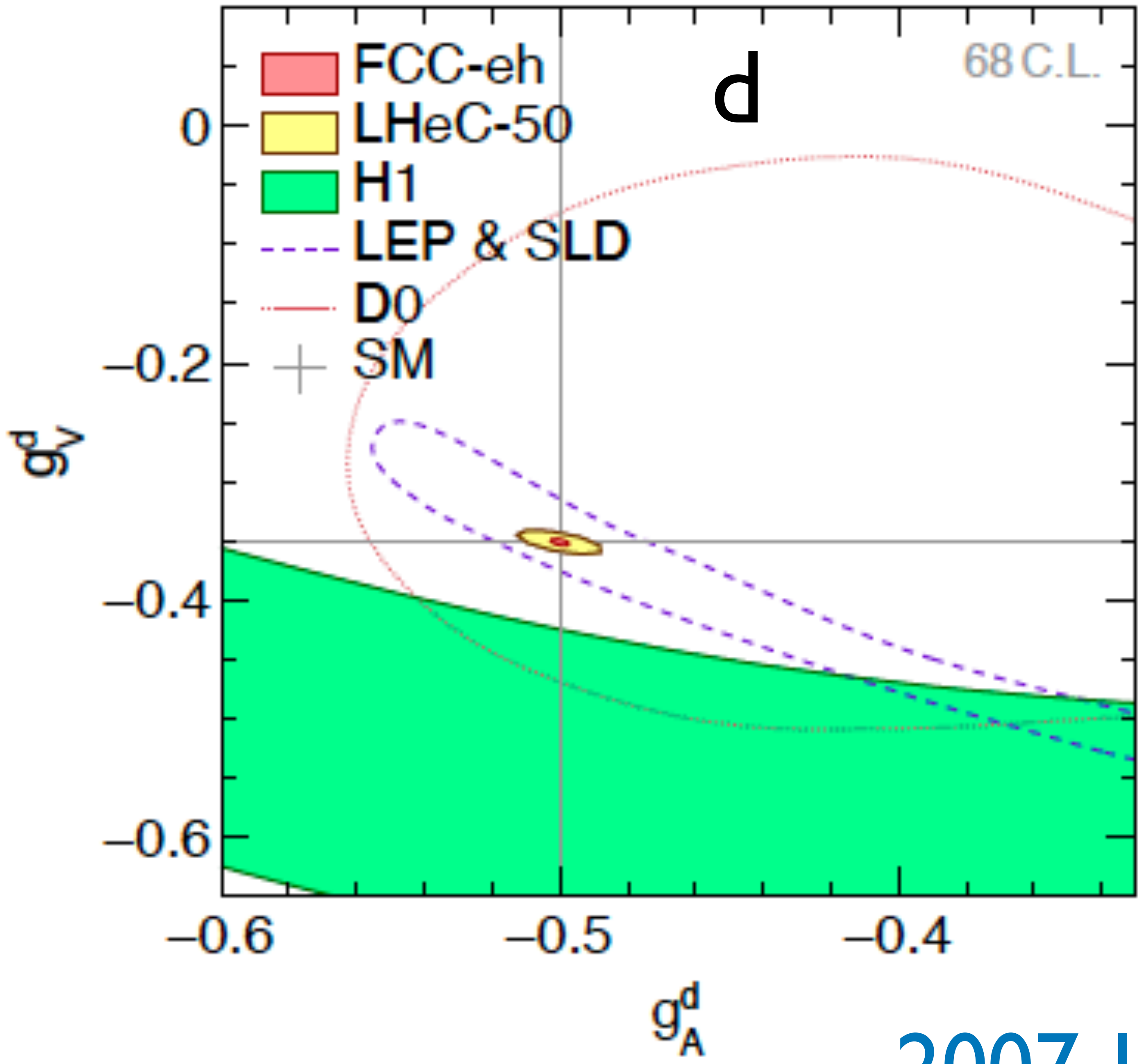

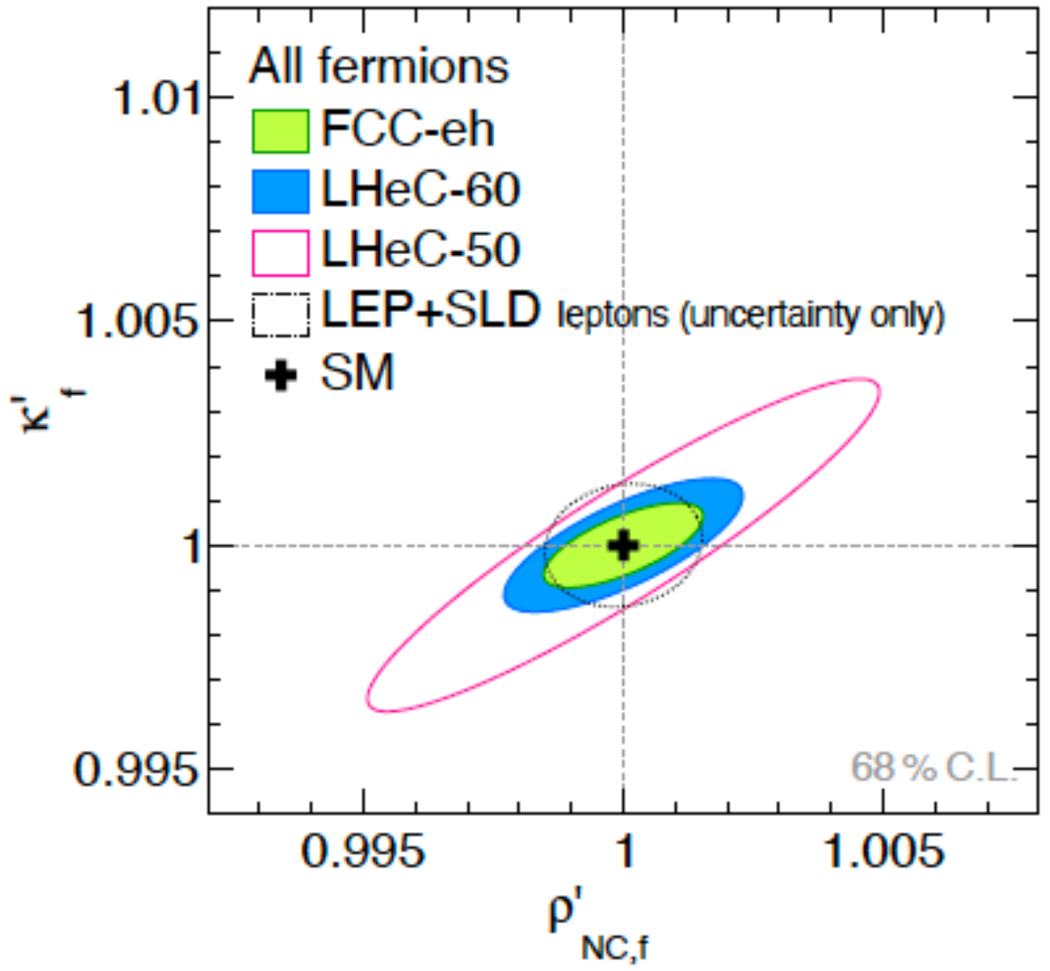

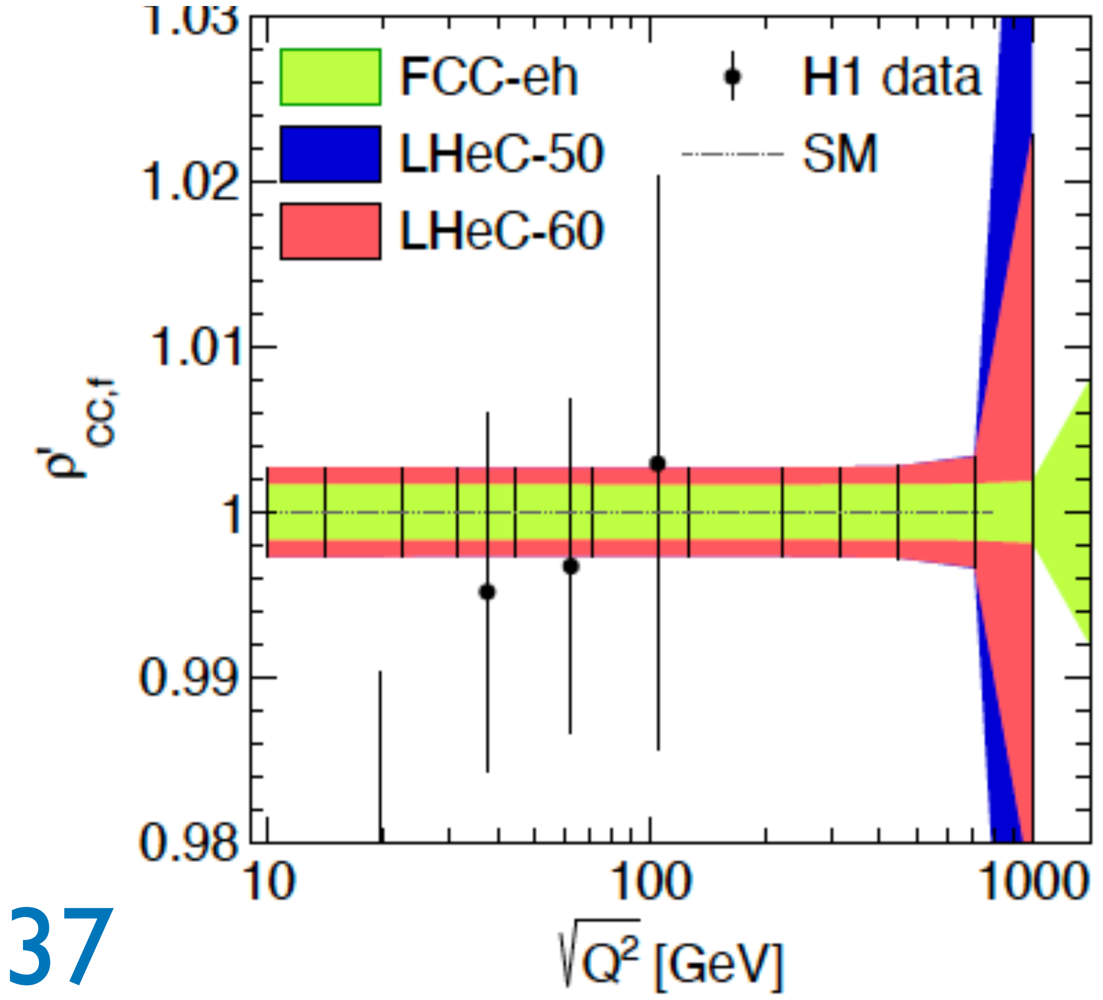

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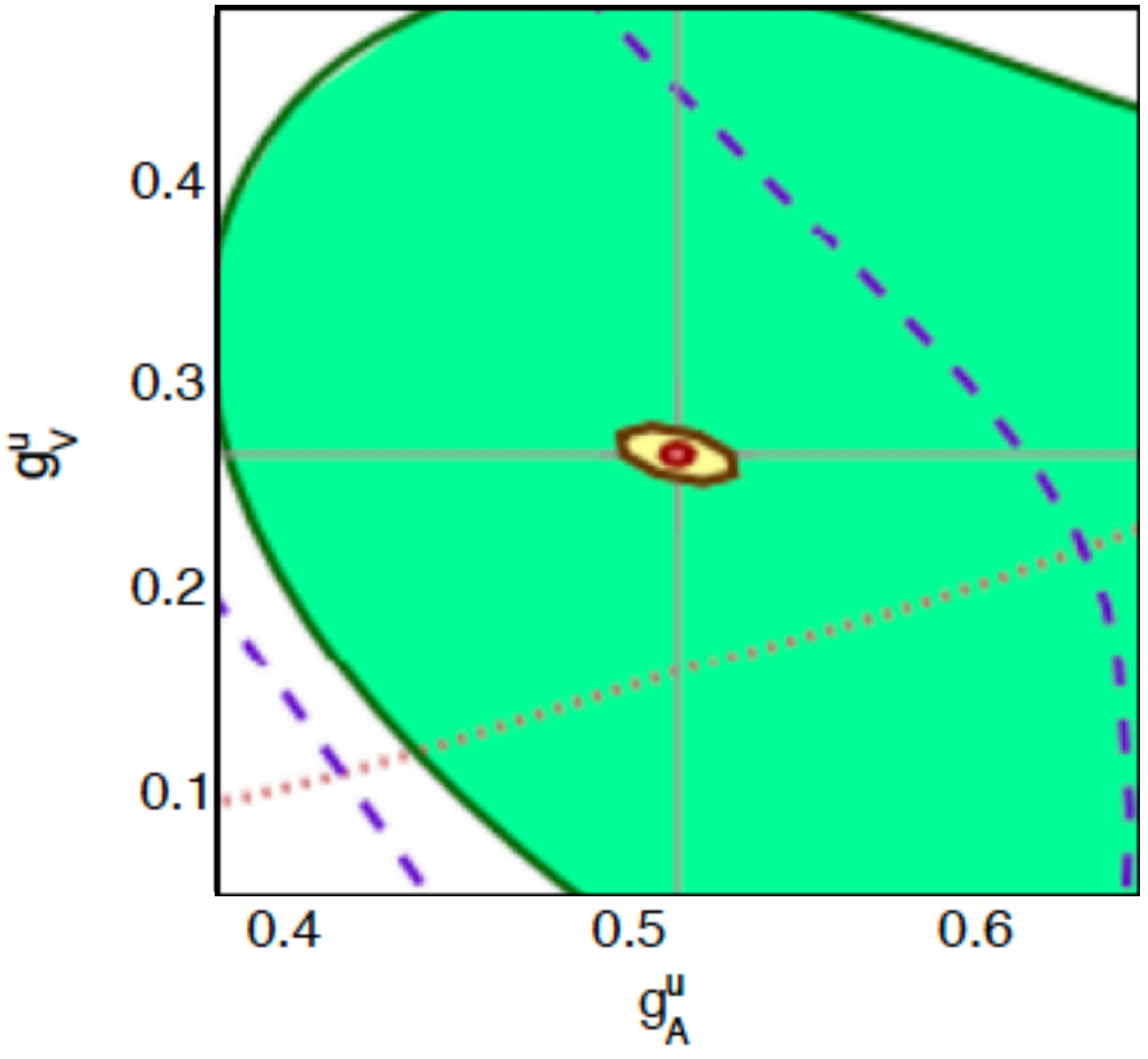
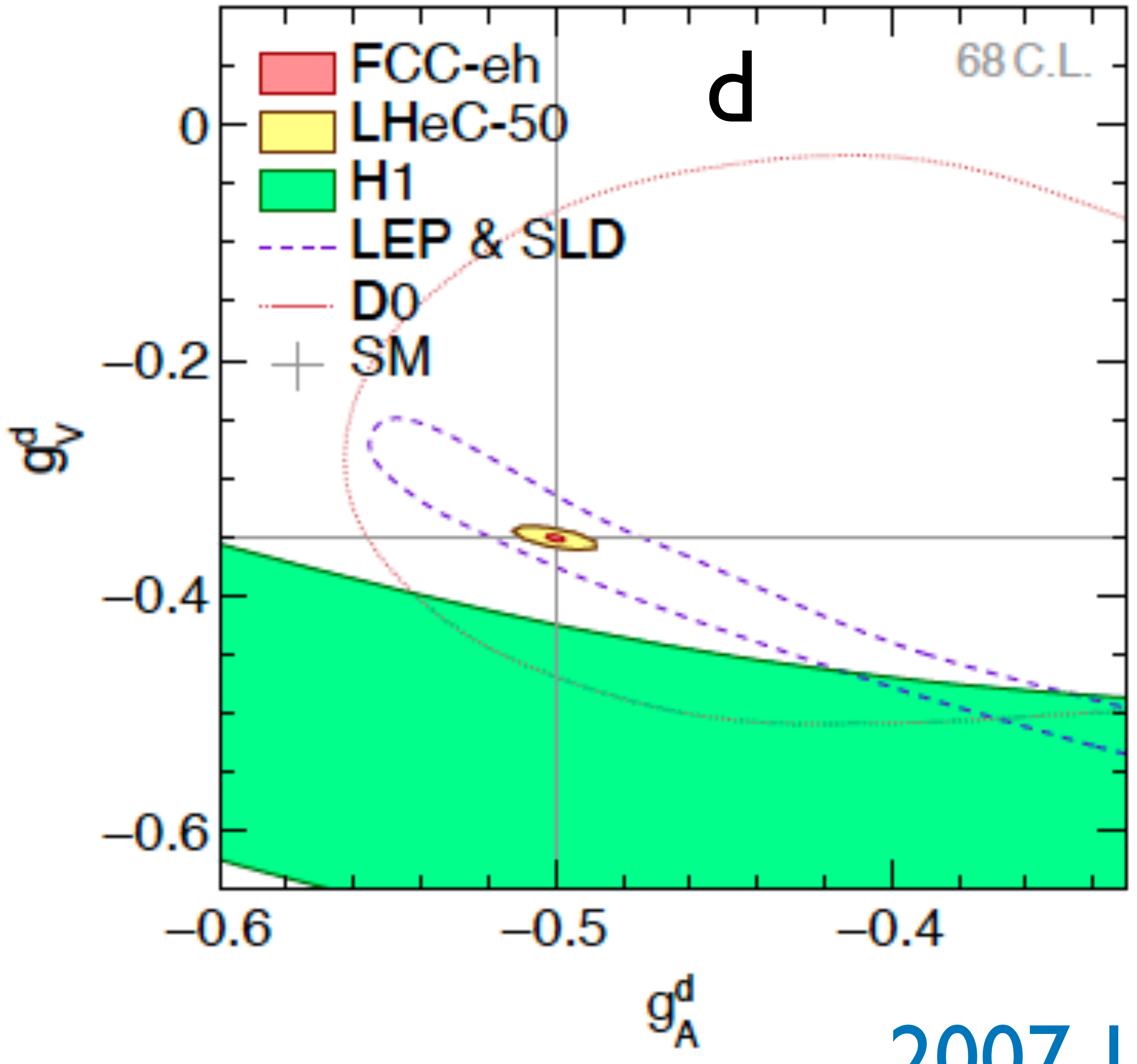
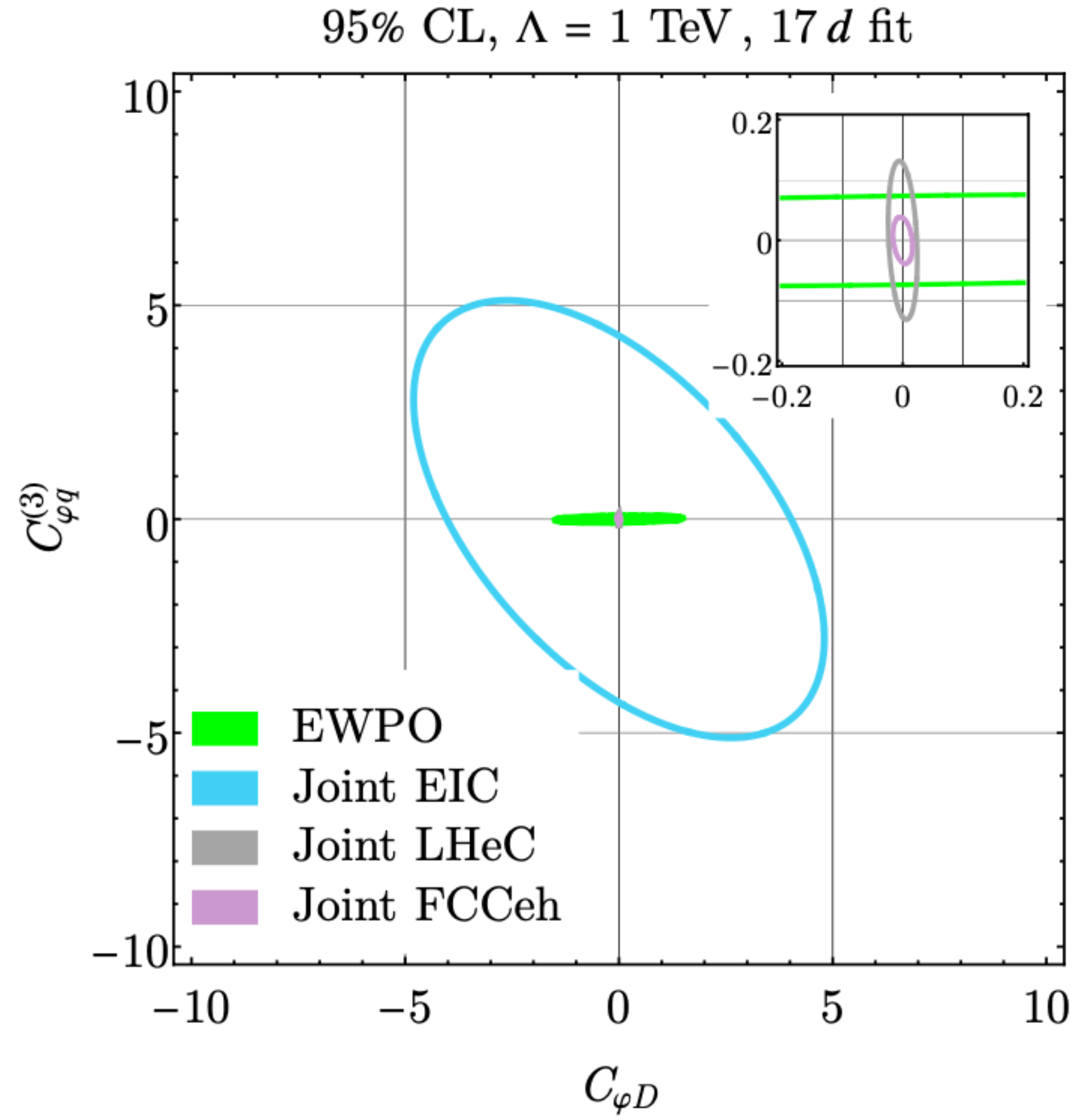
2306.05564

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







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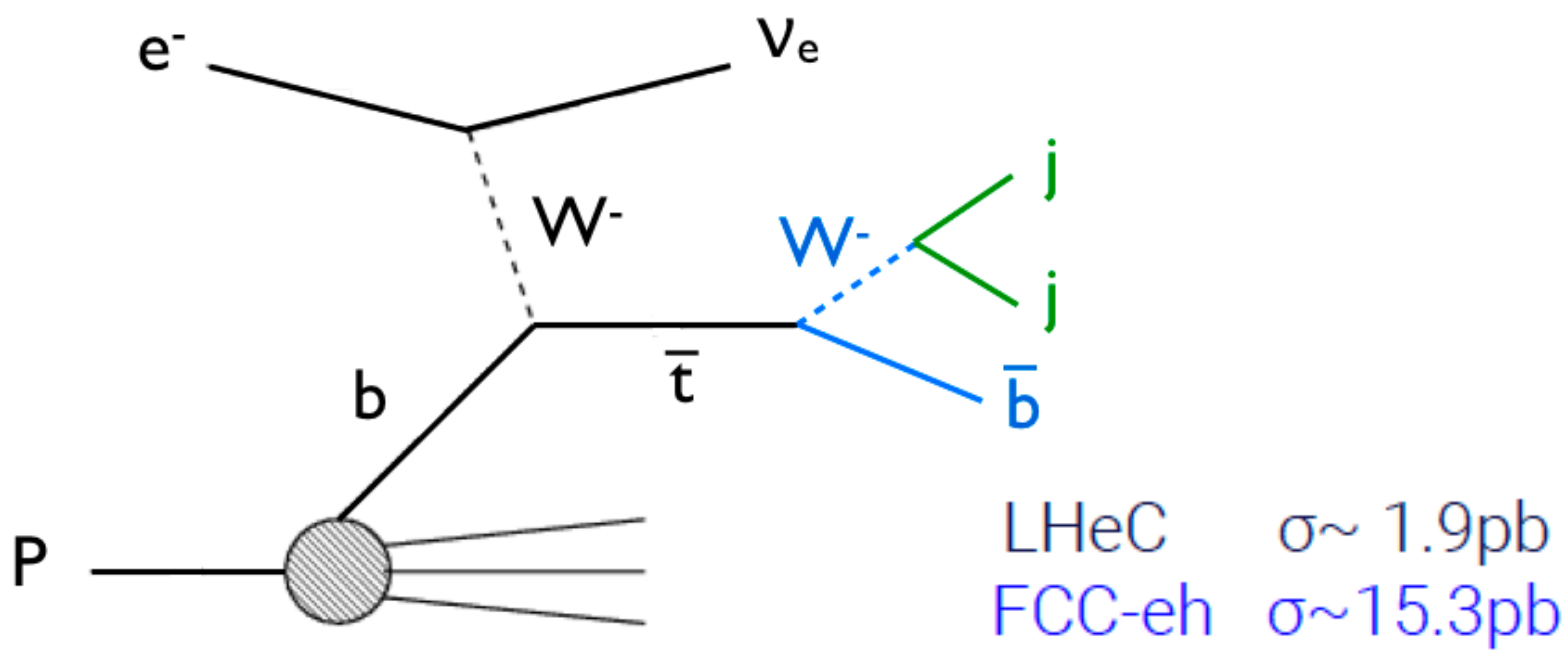
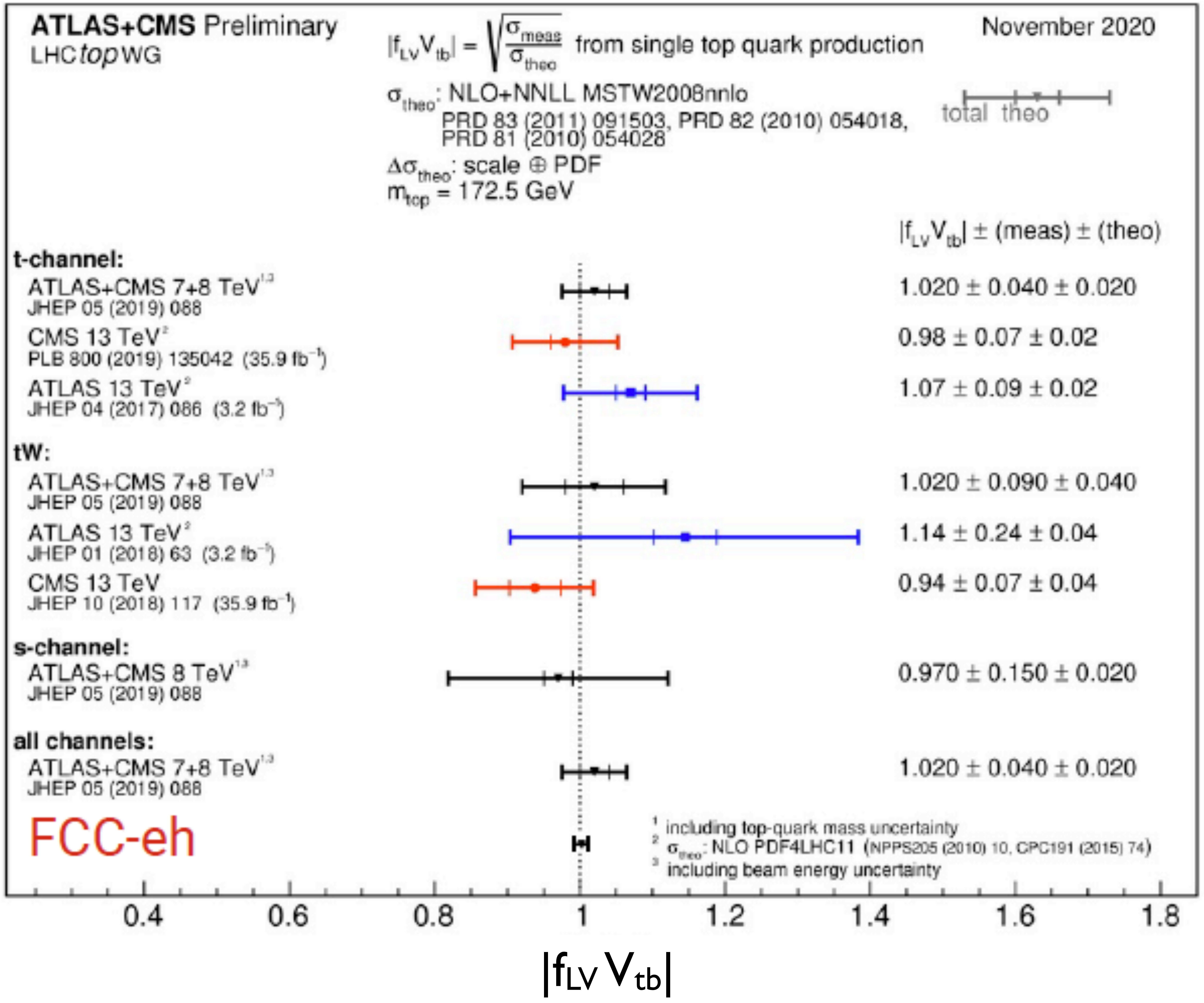
Top physics: CKM

- At the LHeC, limits on several CKM matrix elements can be set using single top production (V_{tb} to 1% at the LHeC): polarisation essential.



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



- Also sensitivity to anomalous top couplings and top FCNC.

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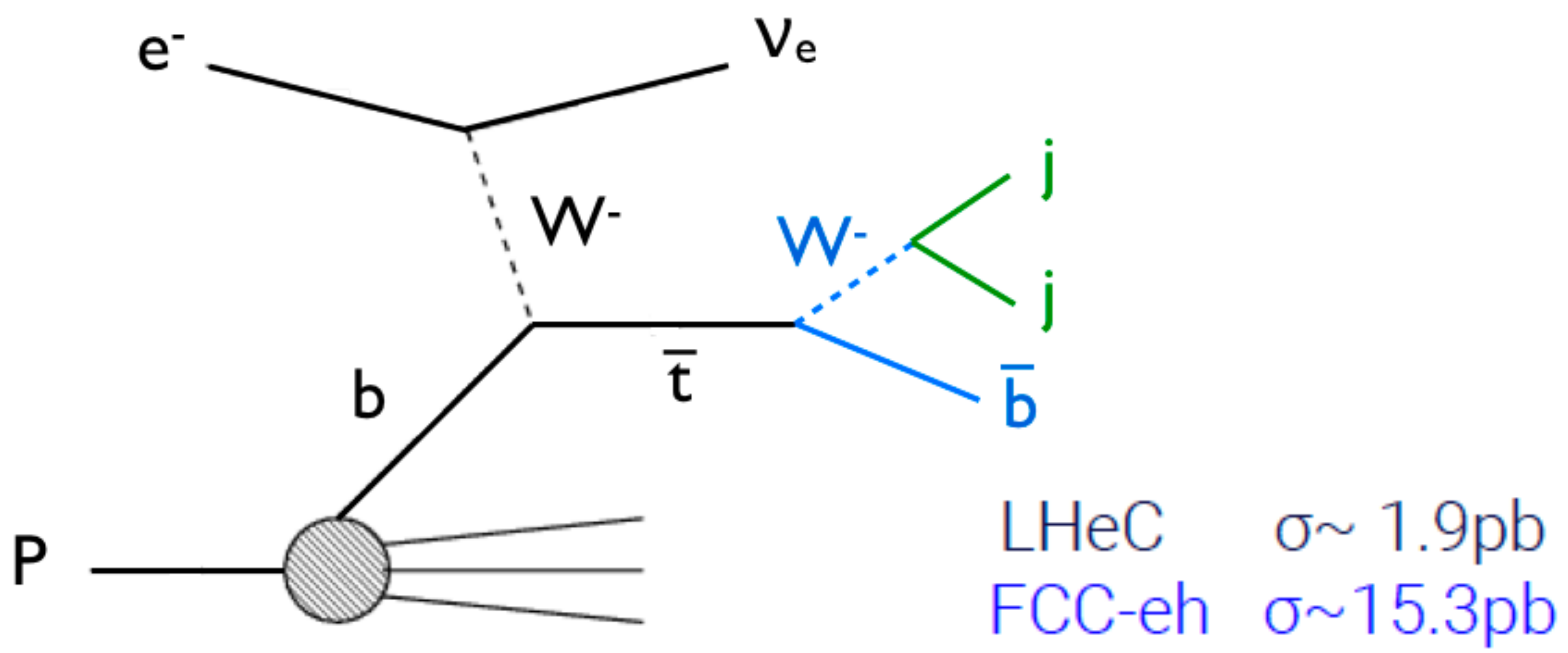

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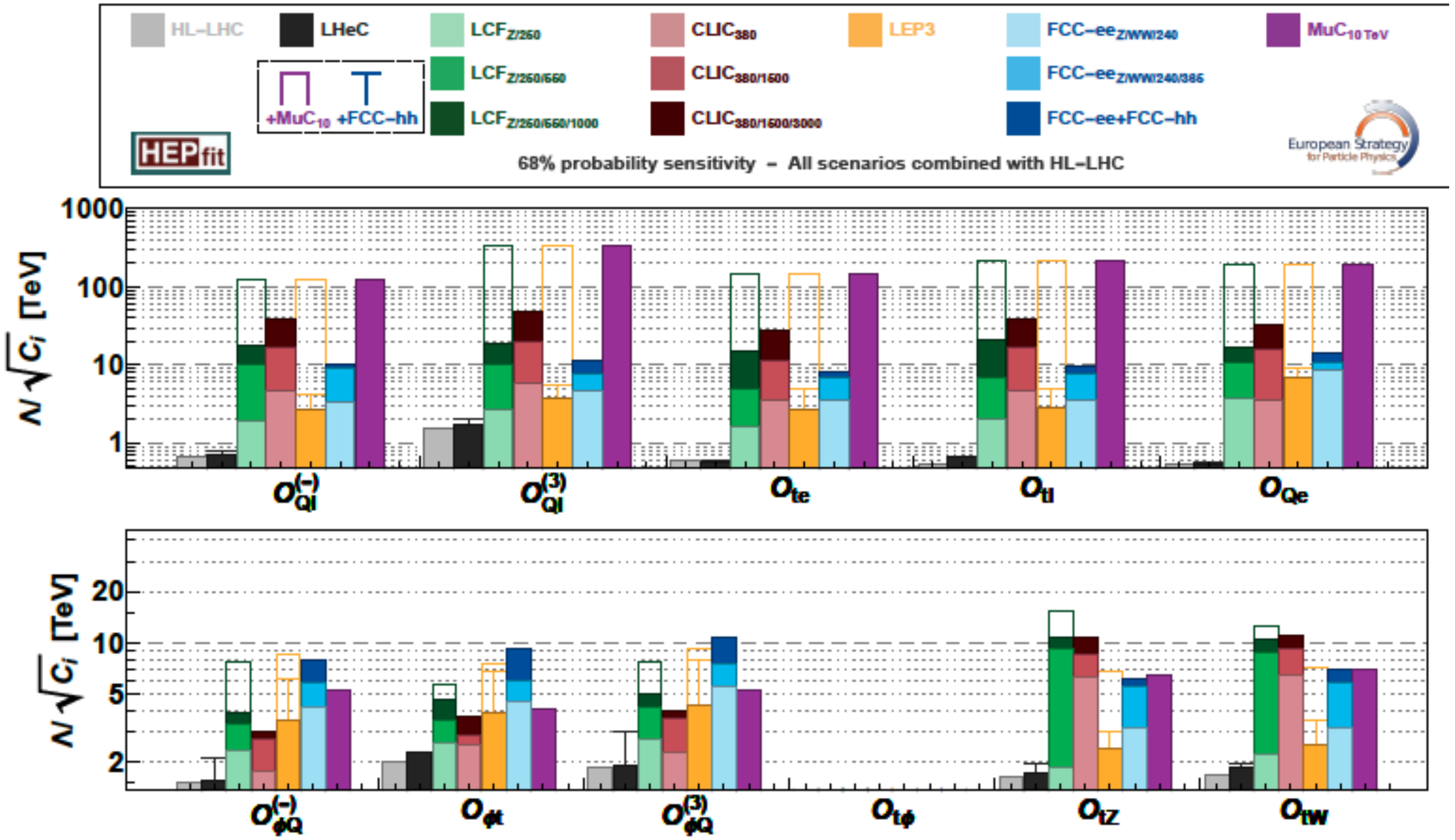
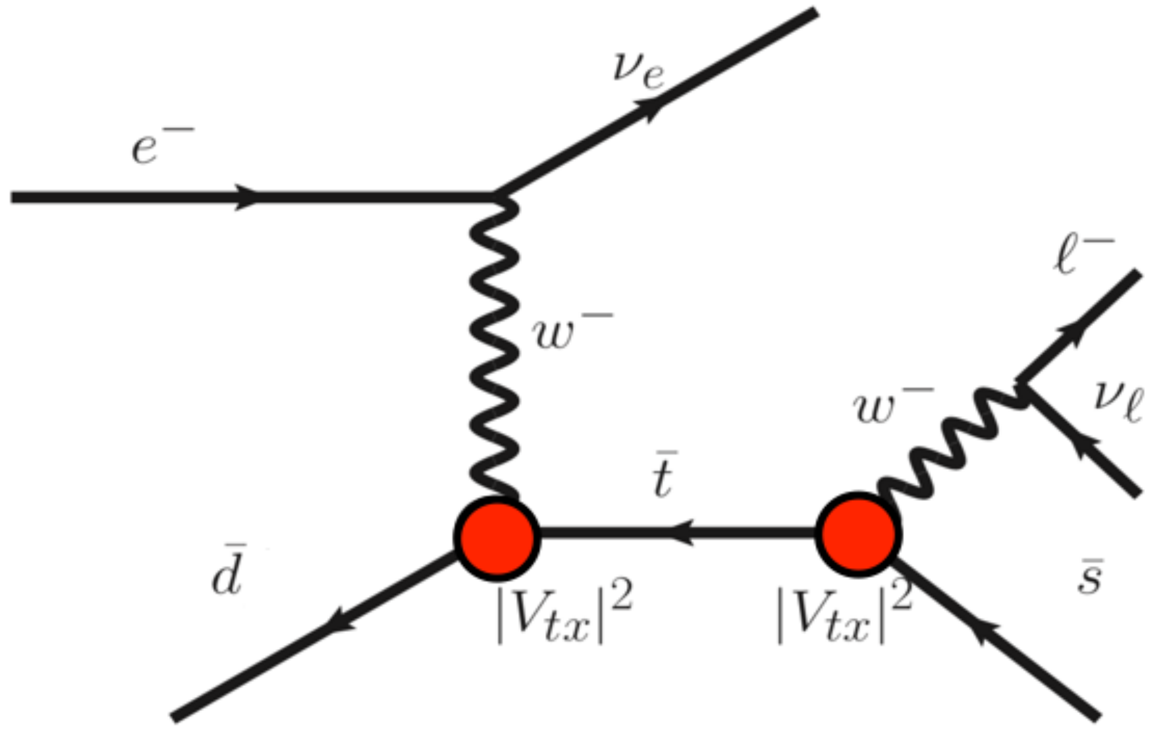


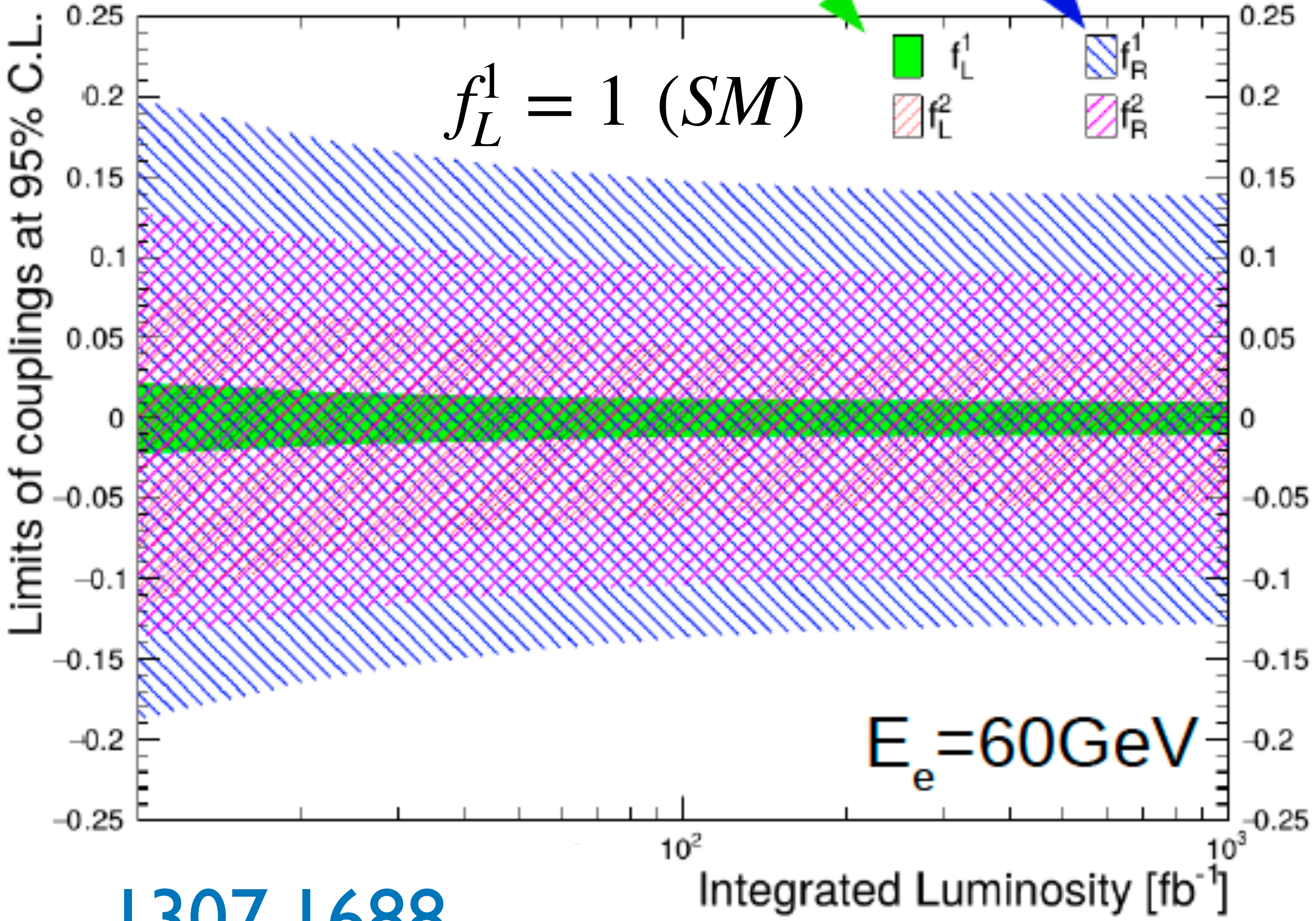
- Also sensitivity to anomalous top couplings and top FCNC.

Top physics: anomalous couplings

- Anomalous couplings can be probed, limits competitive with HL-LHC, plus FCNC and CP violation.
- Checks of SM predictions.



$$\mathscr{L}_{Wtb} = \frac{g}{\sqrt{2}}\Big[W_\mu \bar{t}\gamma^\mu (V_{tb}\, f_1^L P_L + f_1^R P_R) b - \frac{1}{2\,m_W} W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_2^L P_L + f_2^R P_R) b\Big] + h.c.$$



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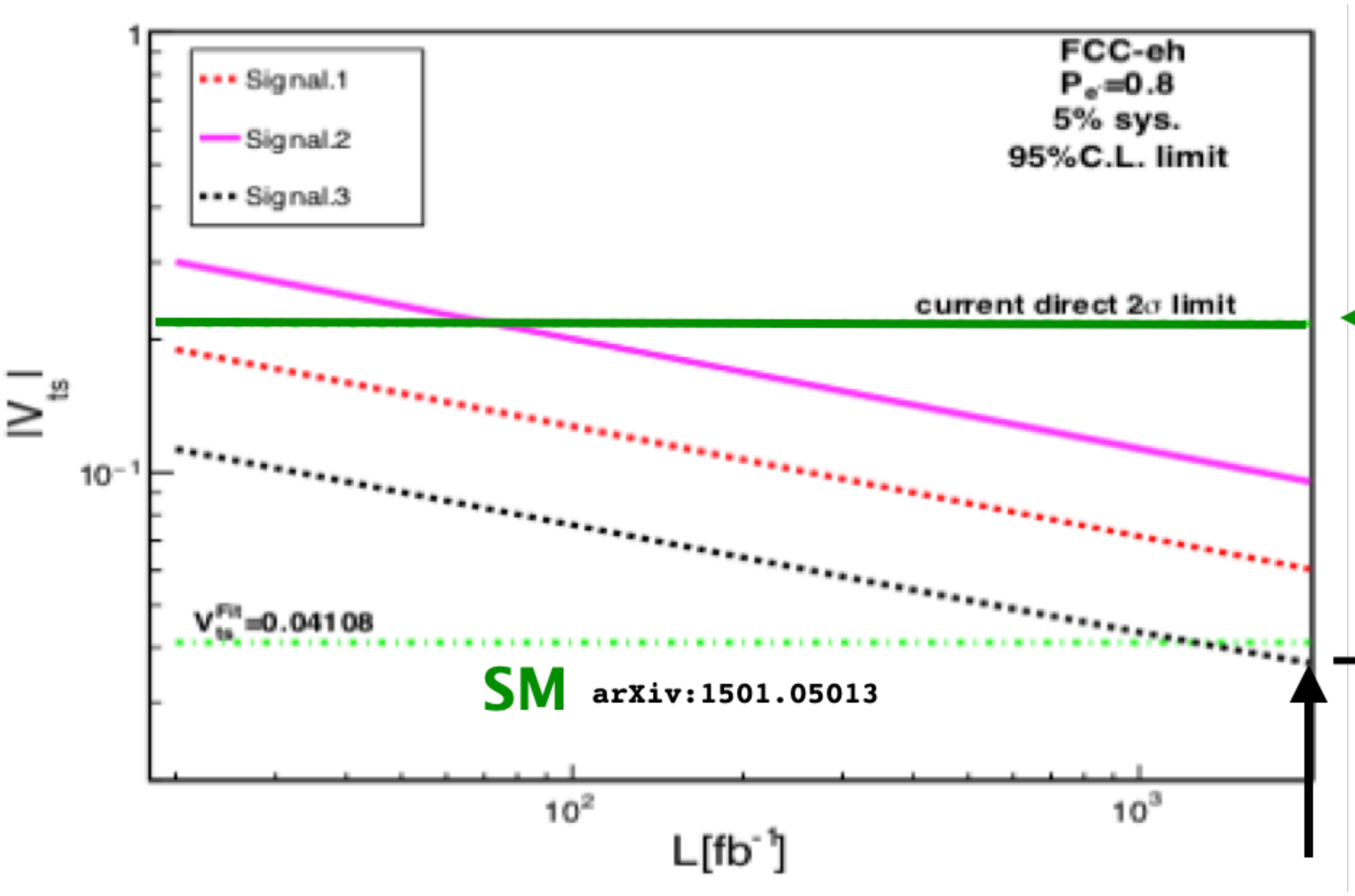


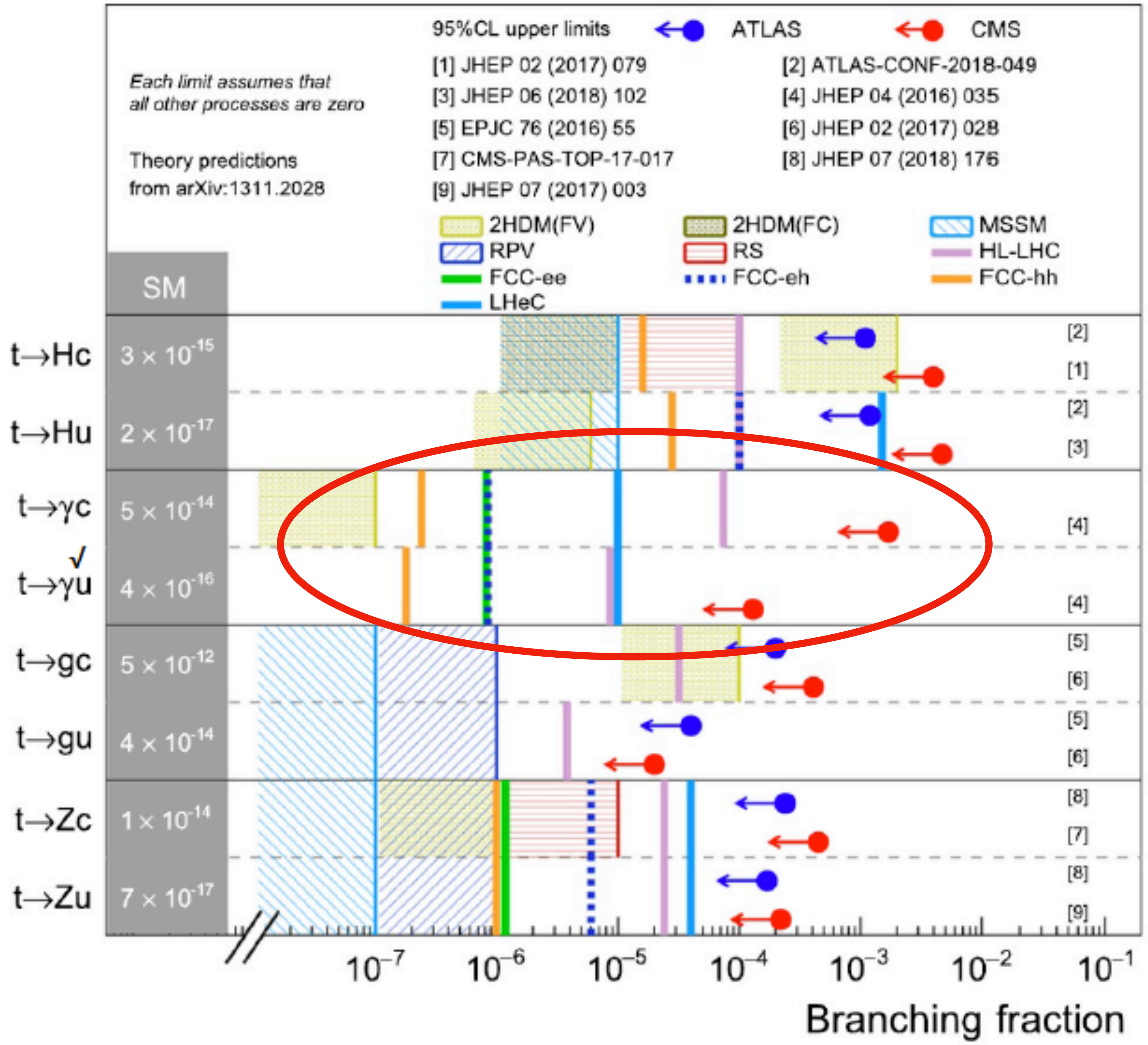
arXiv:1709.07887

LHC

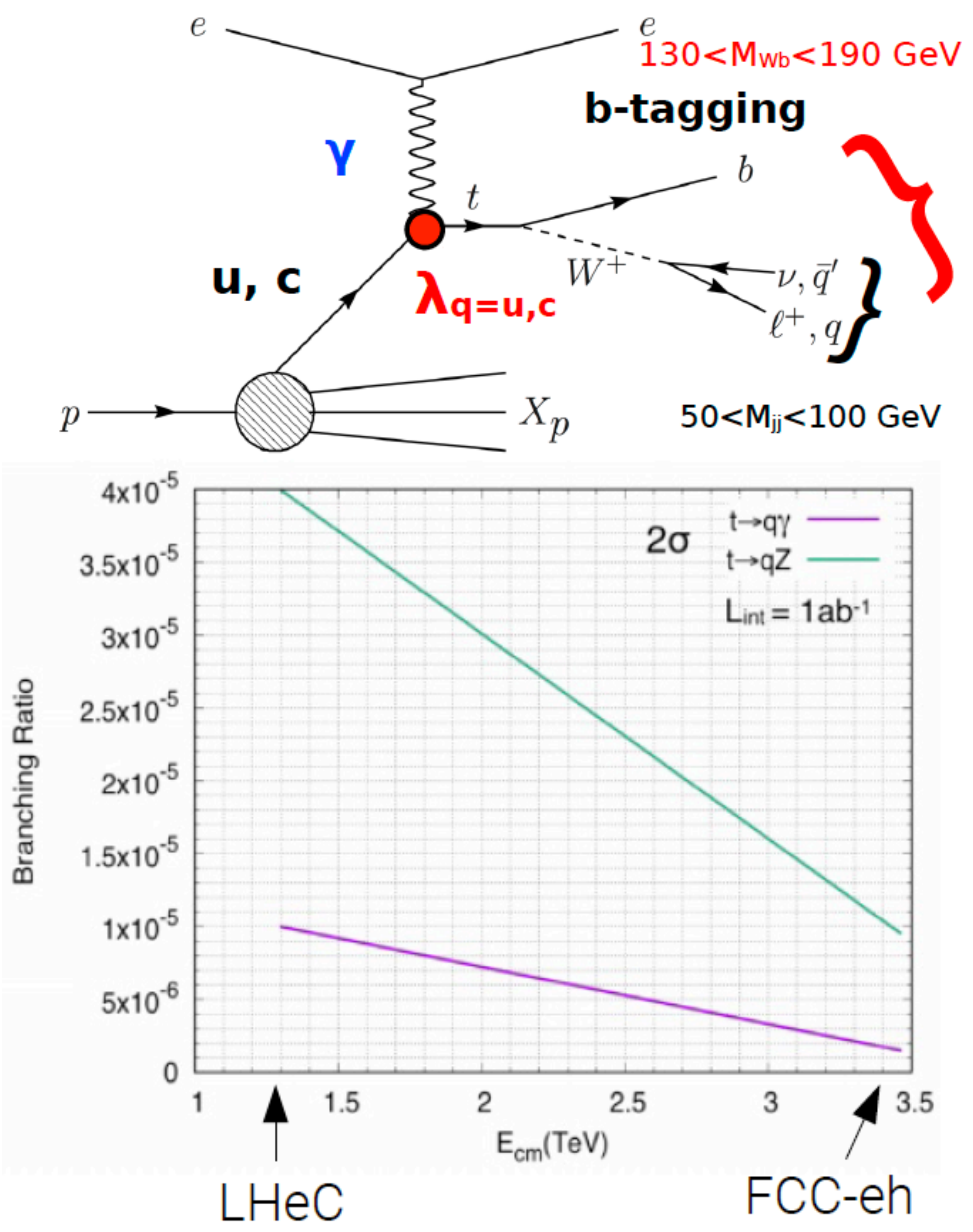
→ $|V_{ts}|<0.037$

Top physics: FCNC

- Also top FCNC (suppressed in the SM and enhanced through BSM) or CP violation in top Yukawa couplings: competitive/complementary with other machines.



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



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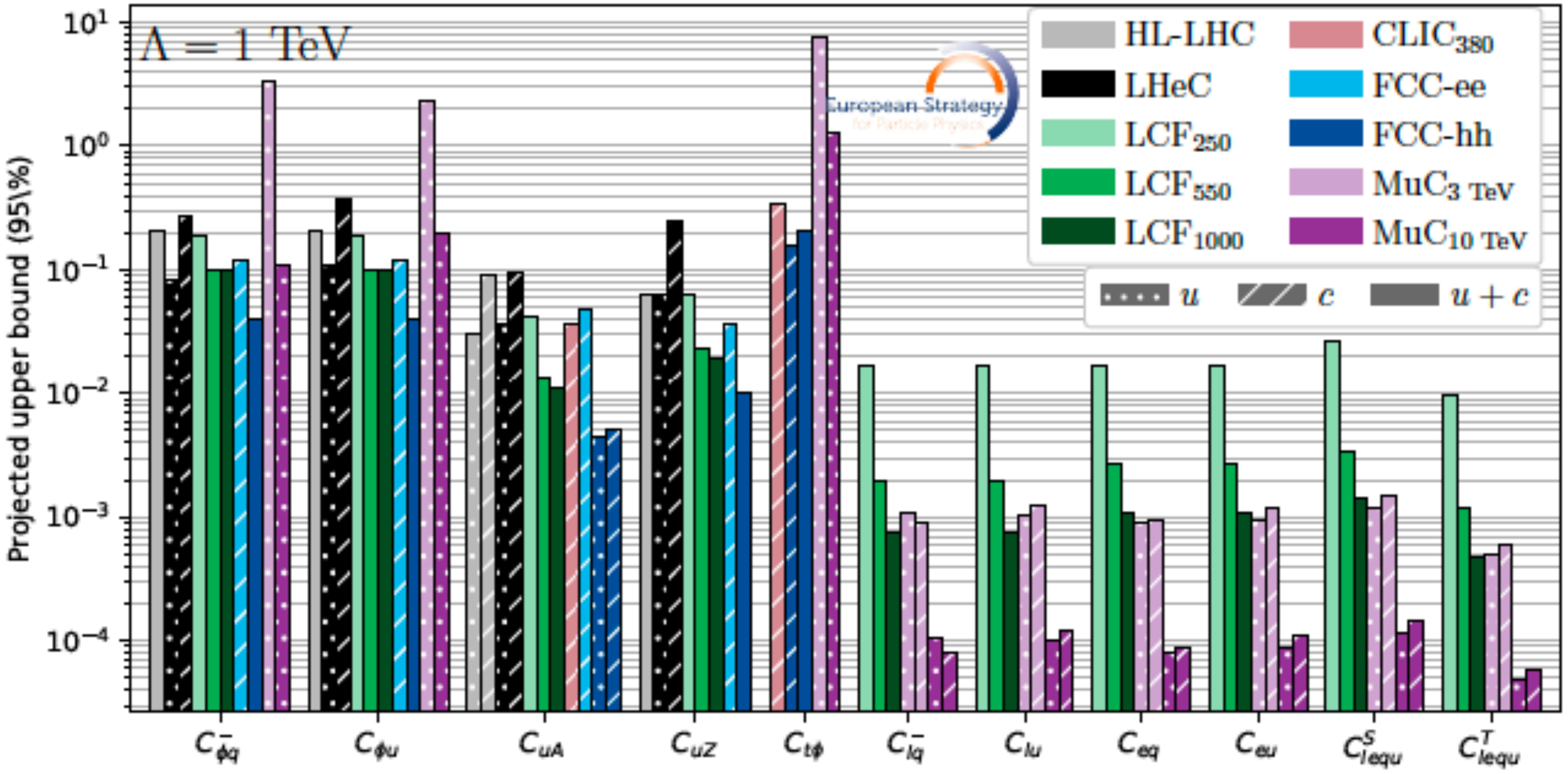

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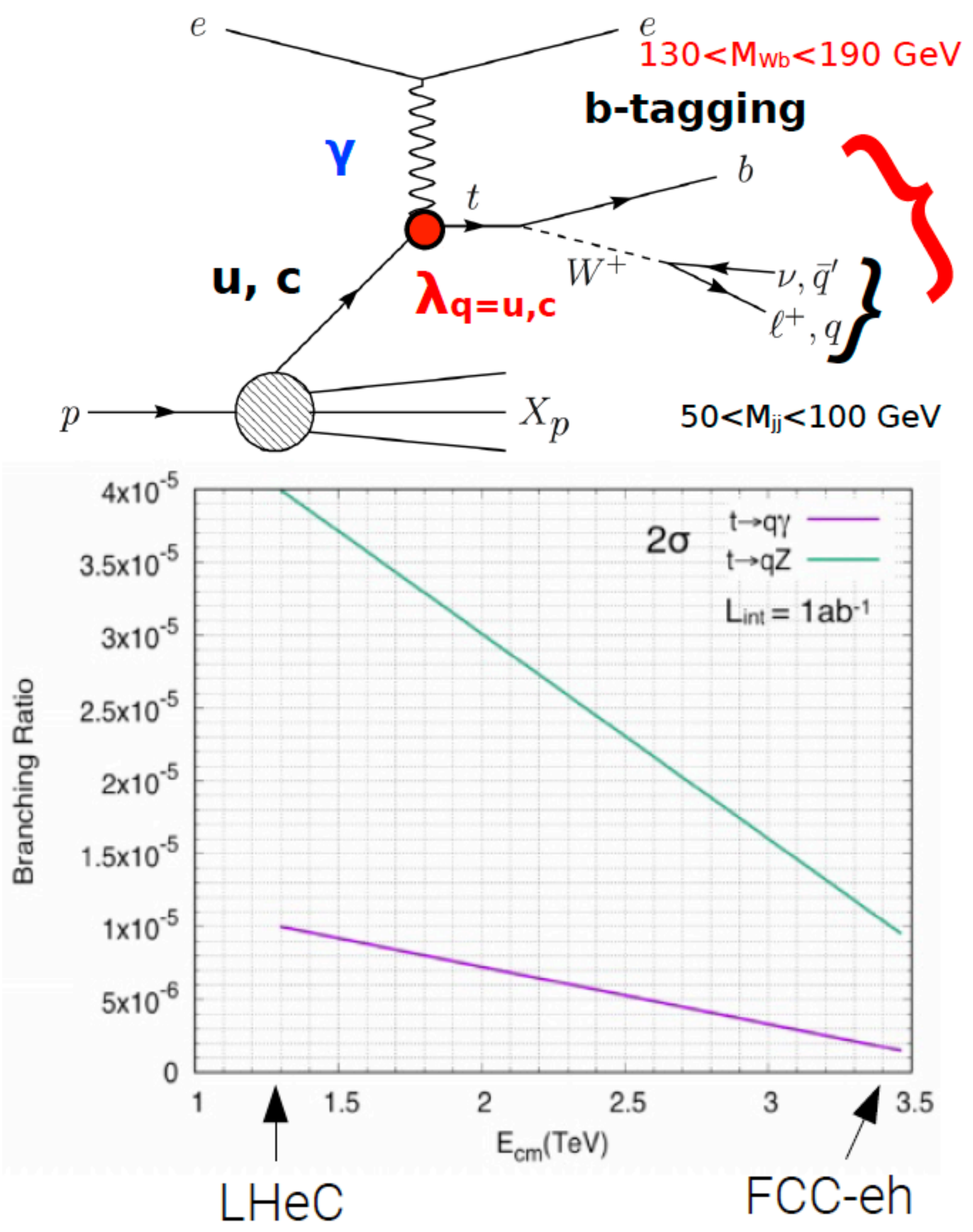


BSM physics:

- ep collider is ideal to study common features of electrons and quarks with EW / VBF production, LQ, forward objects, long-lived particles.

- BSM programme at ep aims to:
  - ➜ Explore new and/or challenging scenarios.
  - ➜ Characterize hints for new physics if some excess or deviations from the SM are found at pp colliders.

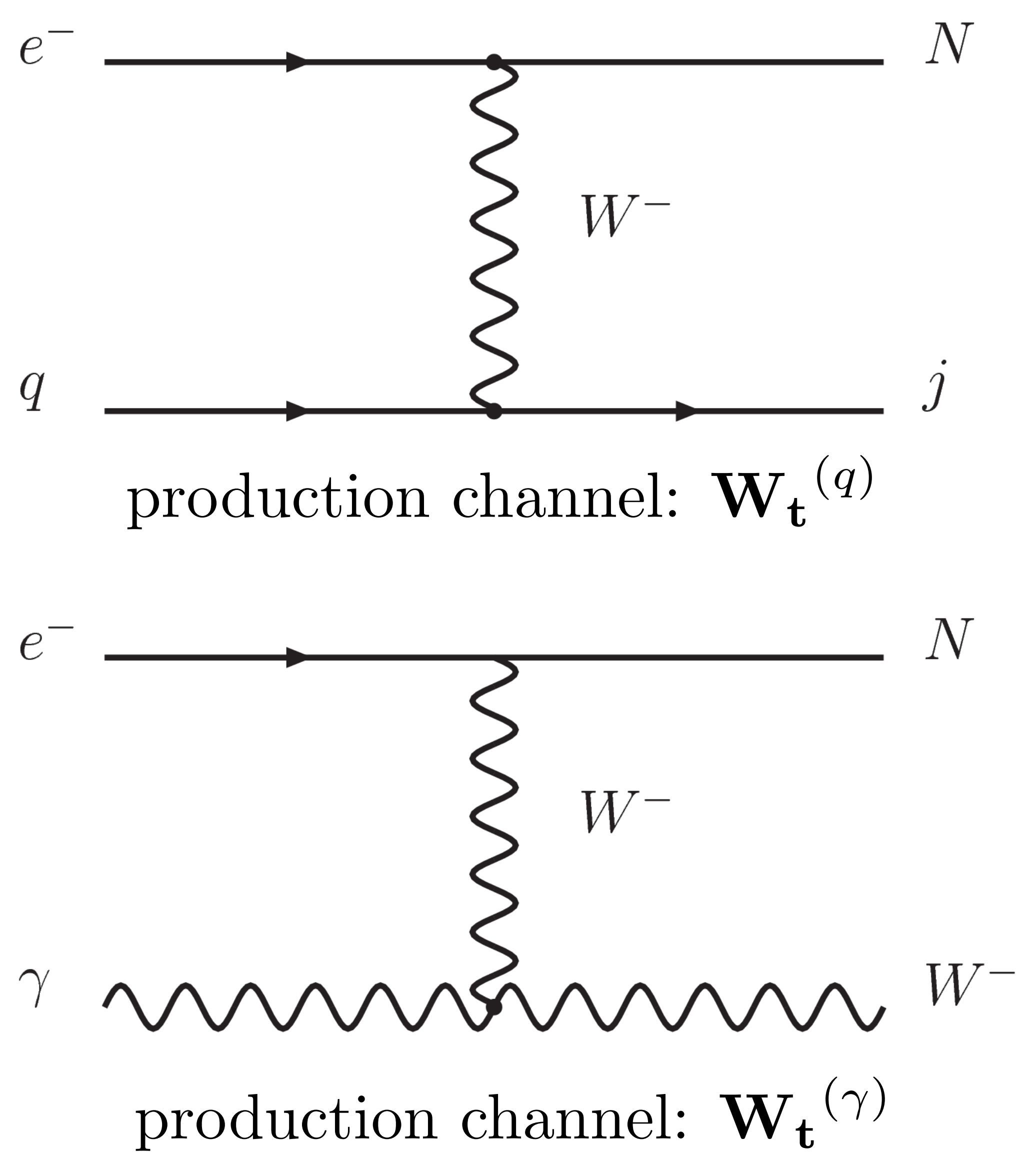
- Differences and complementarities with pp colliders.

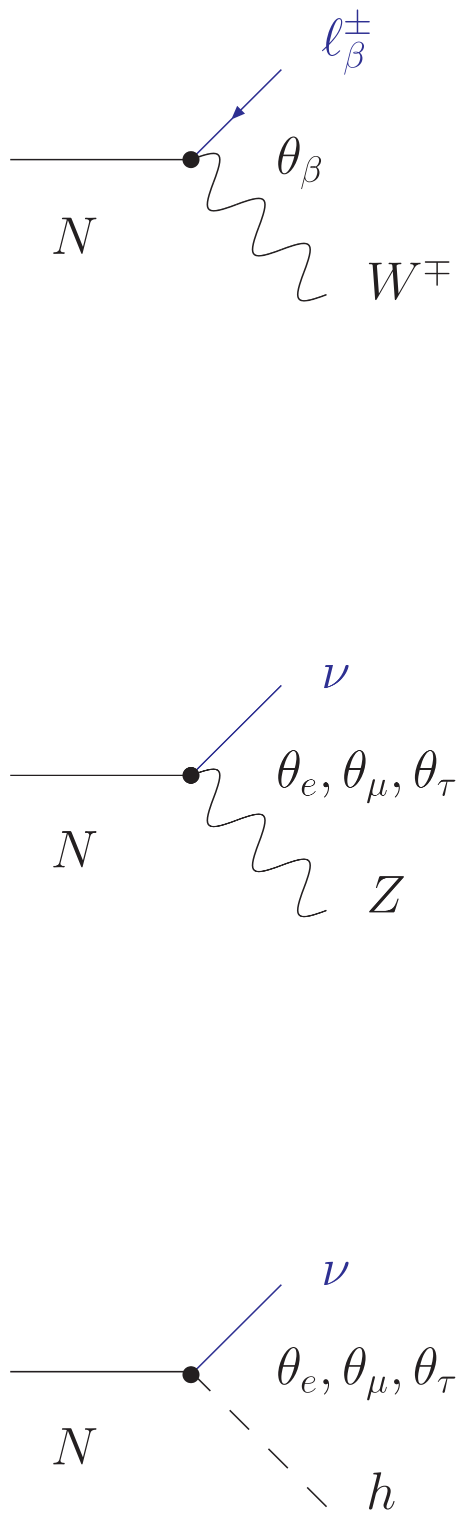
- Some promising aspects:
  - ➜ small background due to absence of QCD interaction between e and p;
  - ➜ very low pileup.

- Some difficult aspects: low production rate for NP processes due to small E_{cm}.

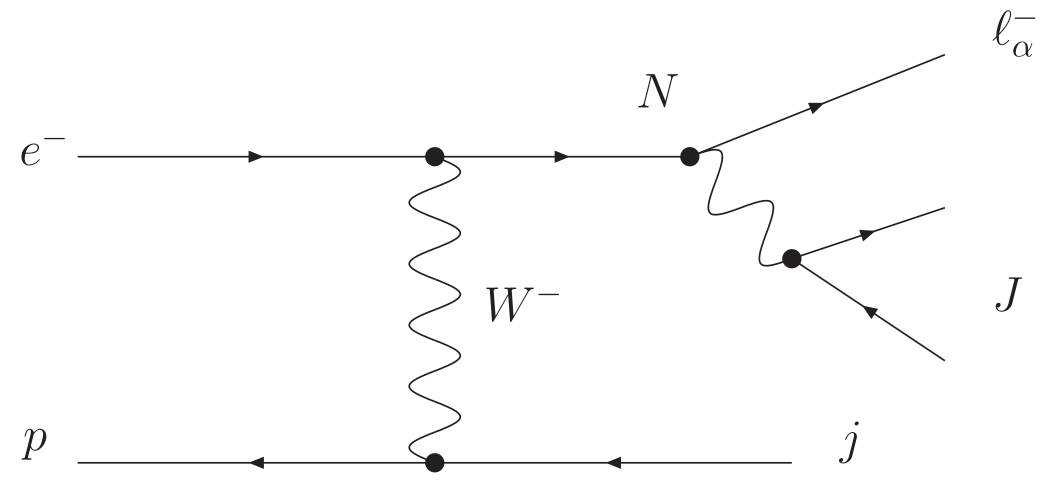
- In general, weakly produced and/or non-promptly decaying particles very challenging at pp and e^+e^- colliders: good complementarity with ep colliders, similarly to the case of the Higgs exotics decays, sterile neutrinos.

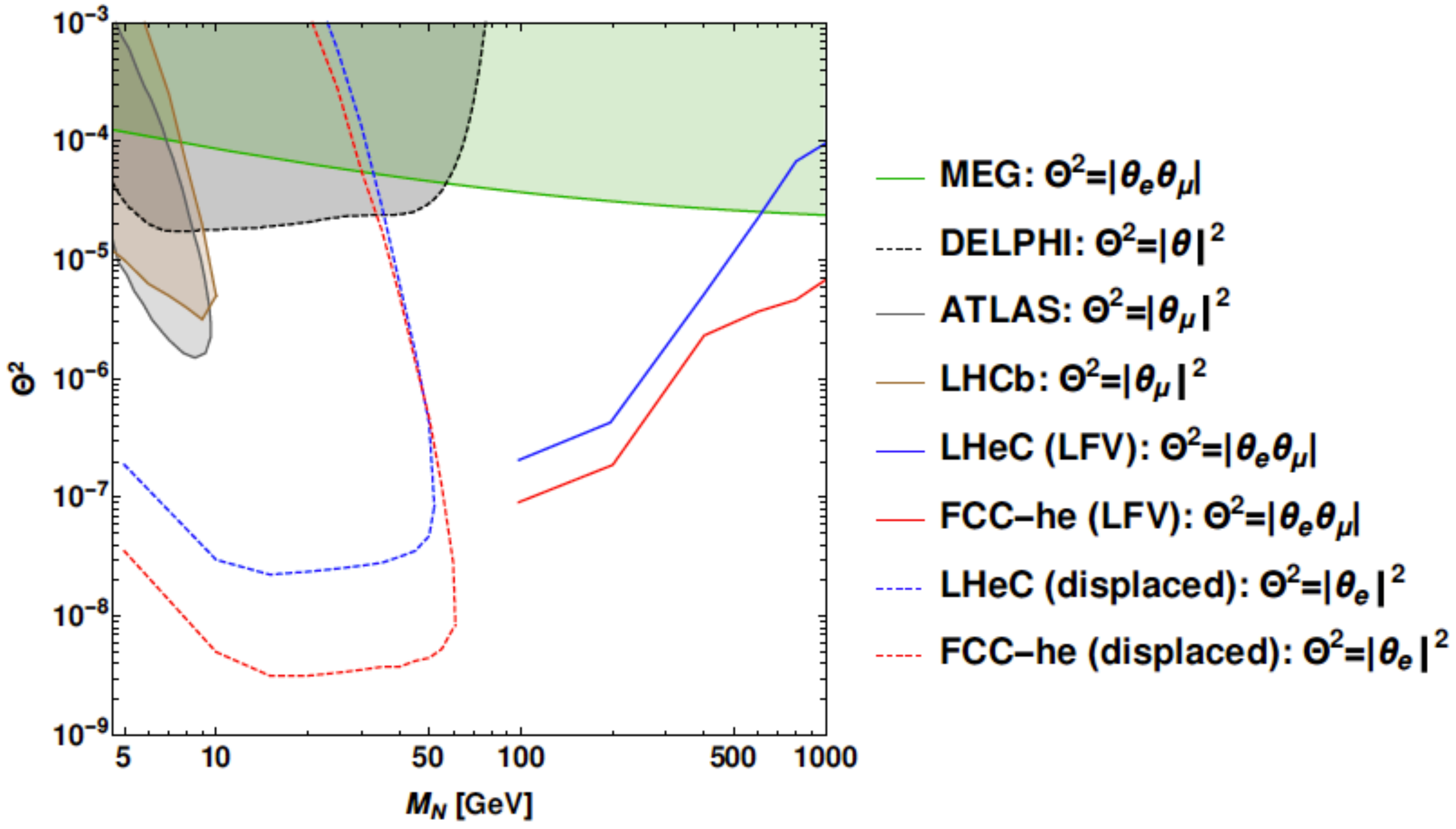
active-sterile neutrino mixing with the electron flavour → $|\theta_e|^2$





Sensitivity of the LFV lepton-trijet searches (at 95 % C.L.) and of the DV one





BSM physics: heavy neutrinos

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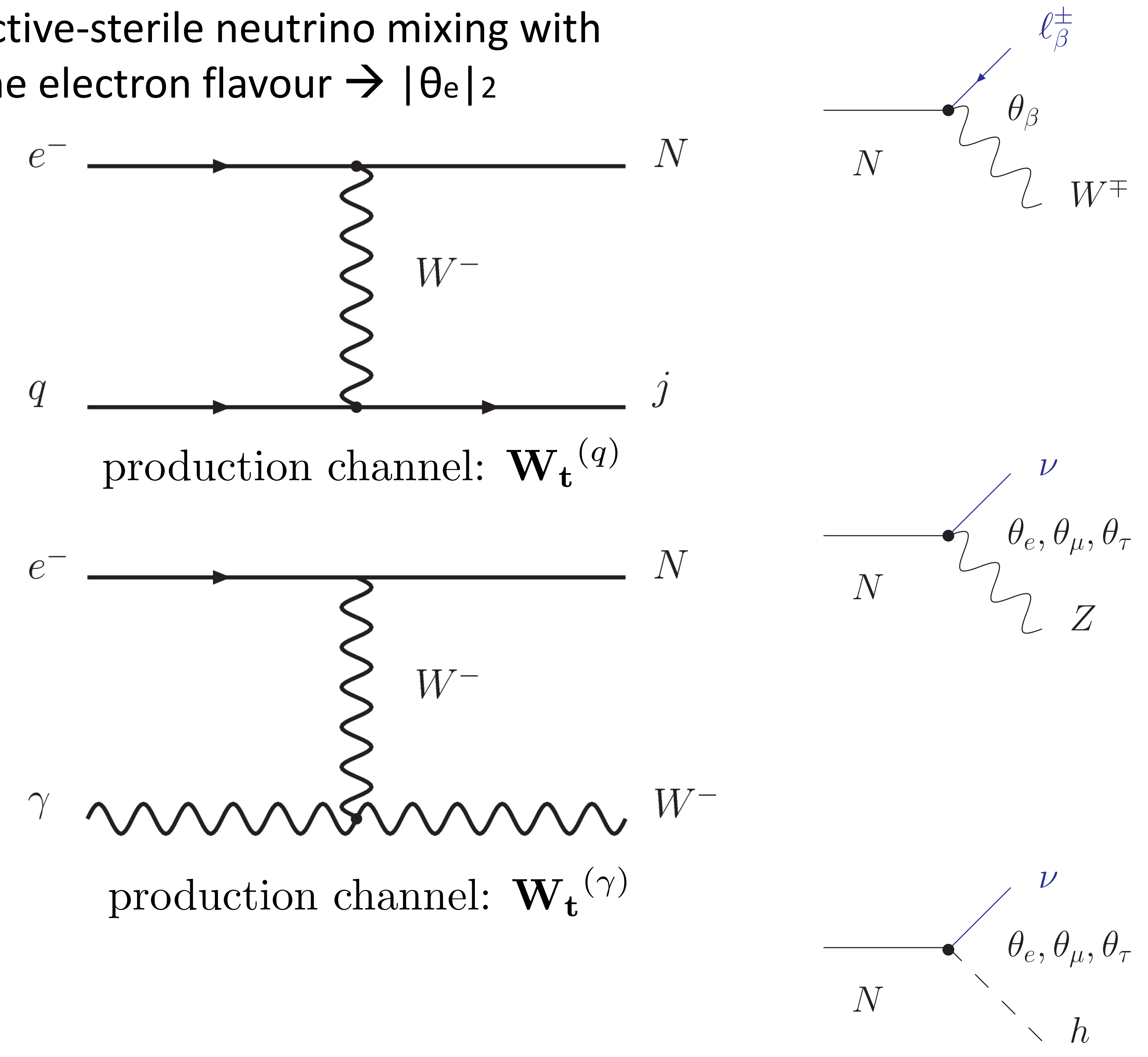
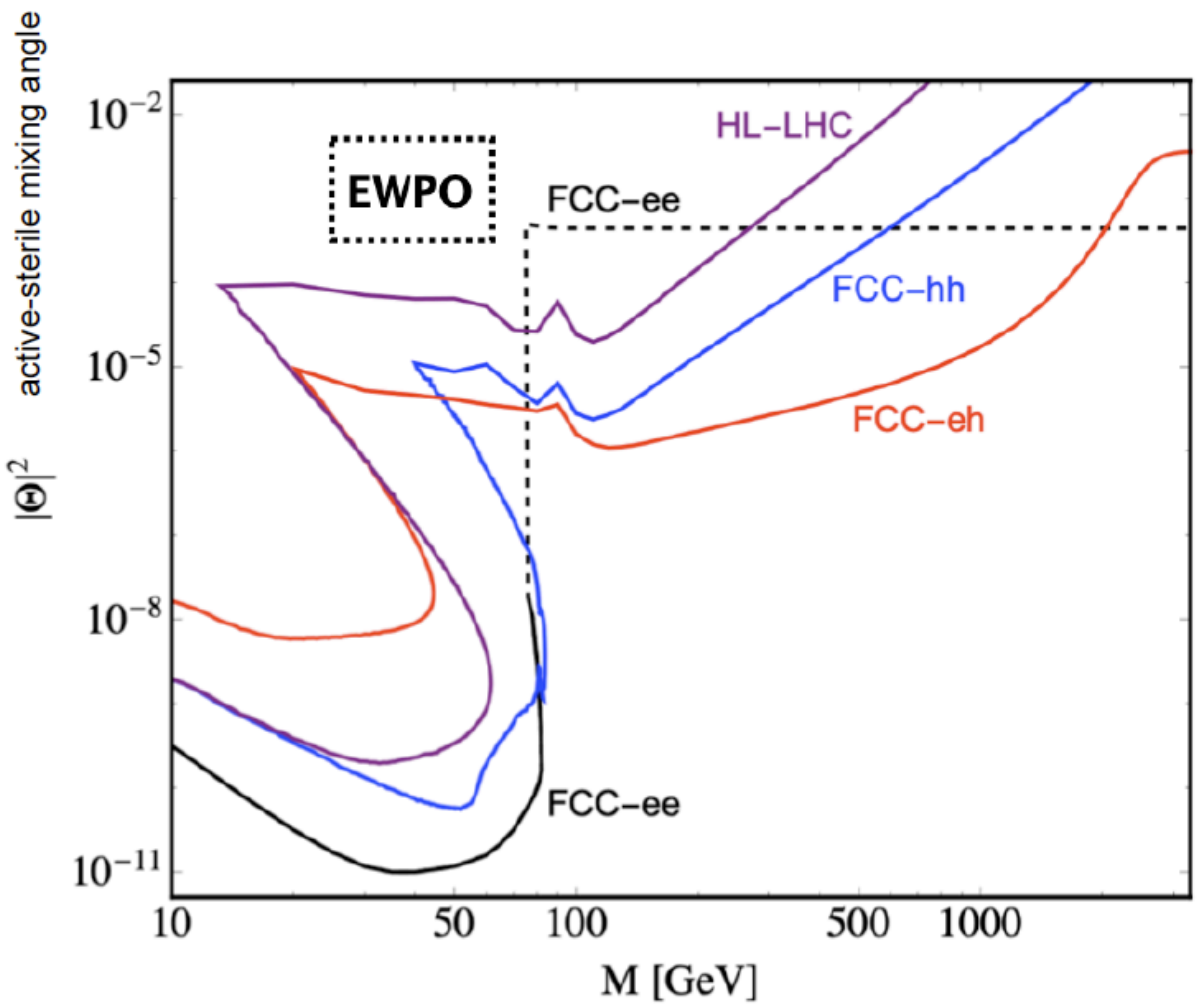
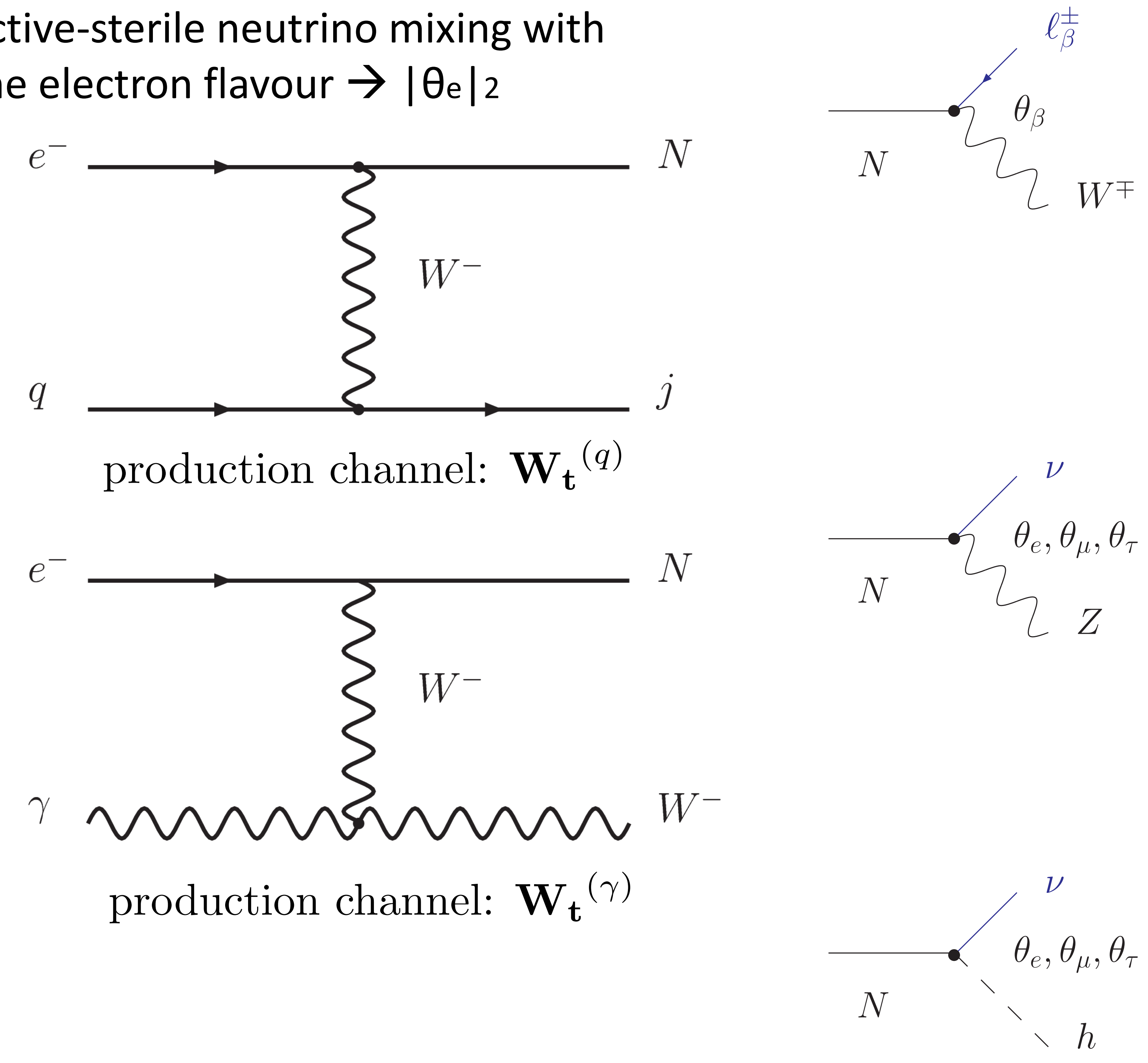


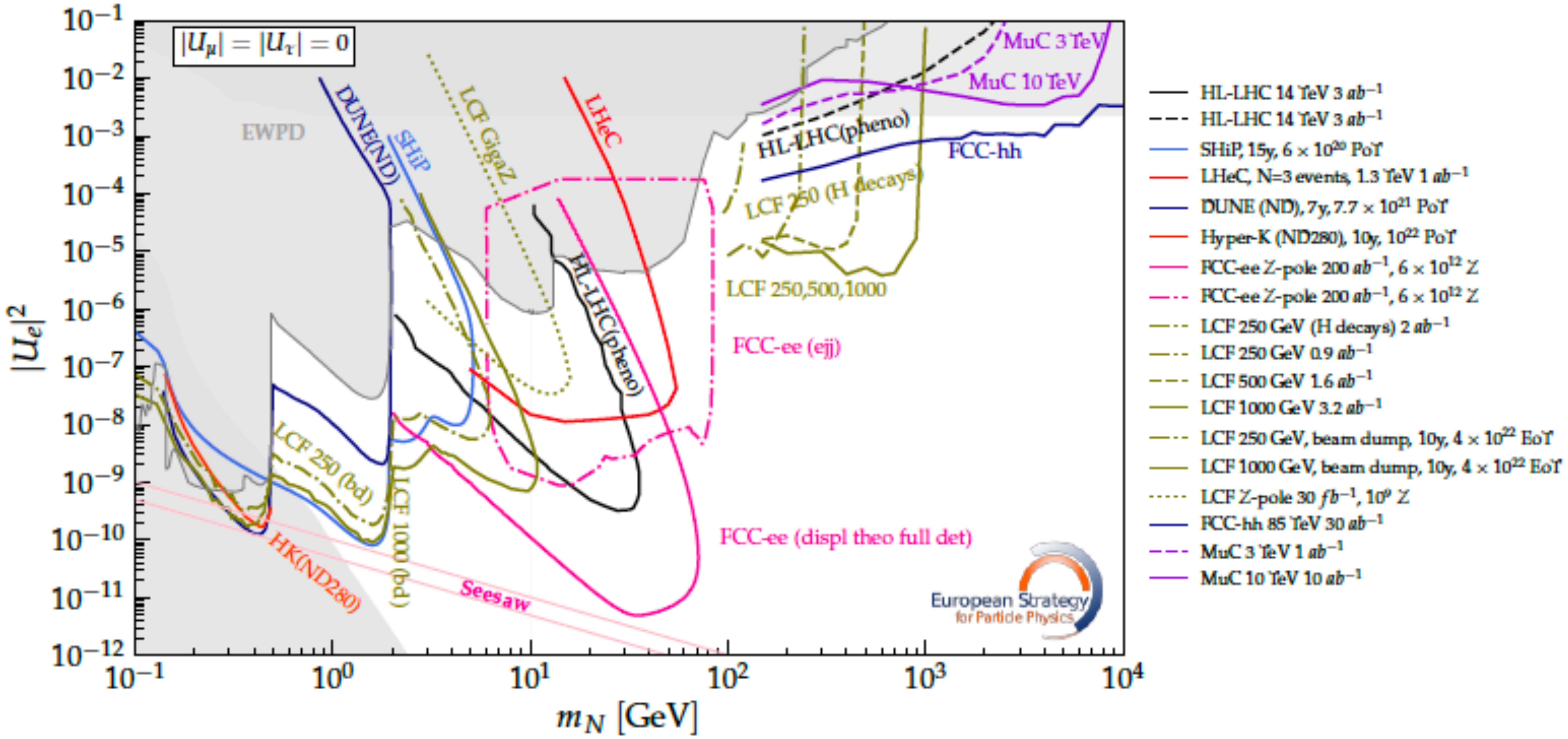


BSM physics: heavy neutrinos

- In general, weakly produced and/or non-promptly decaying particles very challenging at pp and e^+e^- colliders: good complementarity with ep colliders, similarly to the case of the Higgs exotics decays, sterile neutrinos.

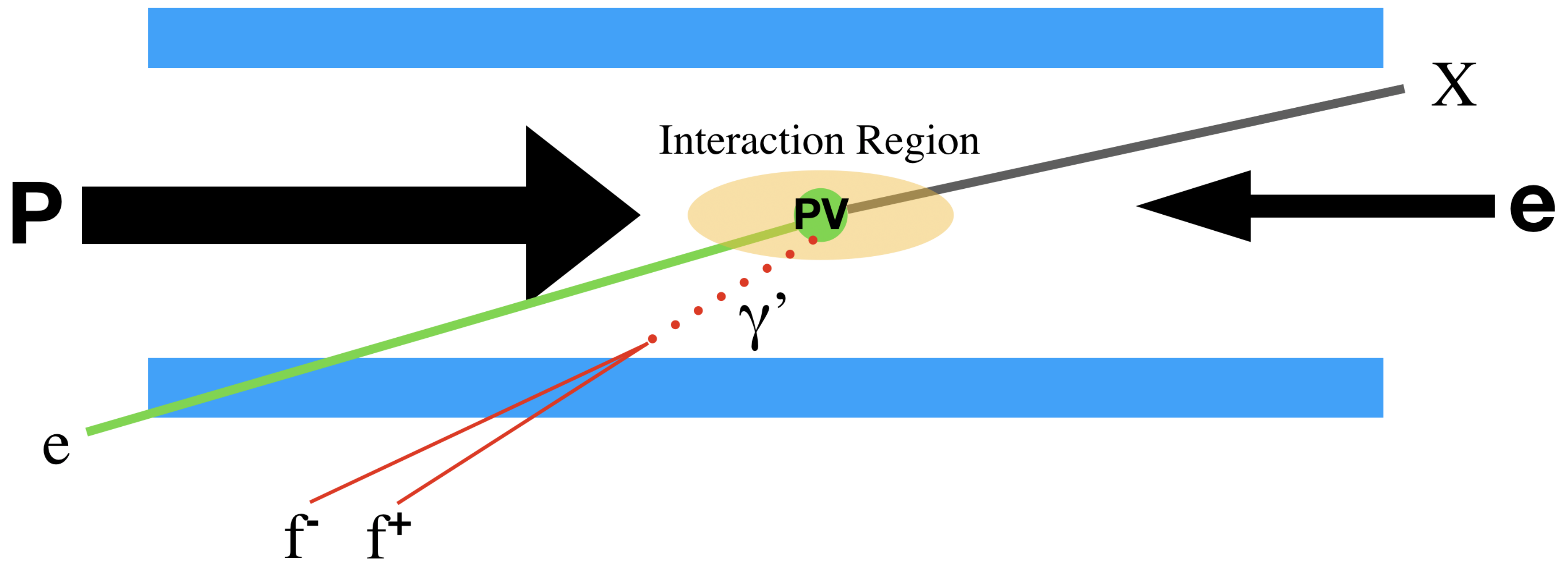
active-sterile neutrino mixing with the electron flavour → $|\theta_e|^2$

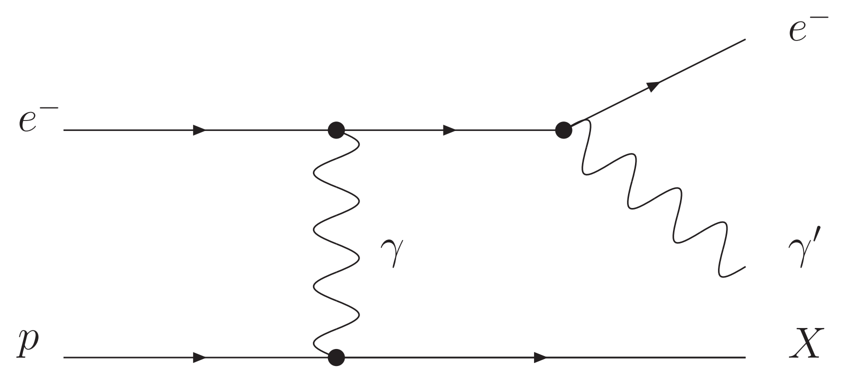


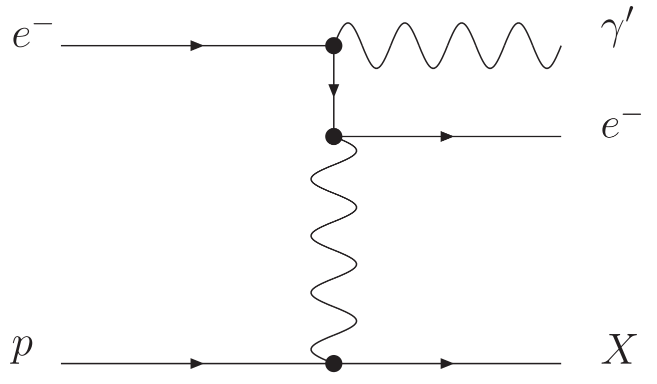


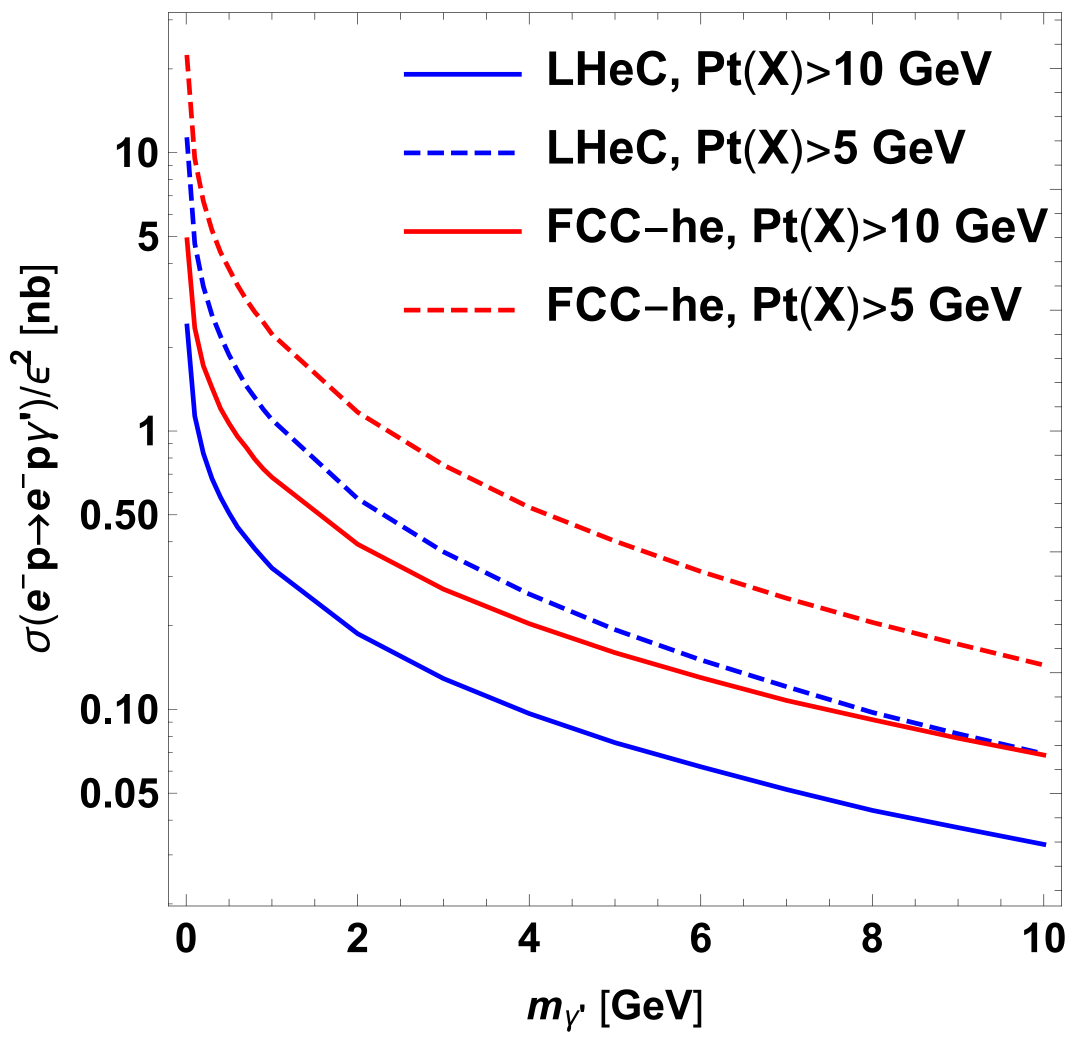
BSM physics: dark photons

- Additional gauge boson mixed with the $U(1)_Y$ SM factor kinetically.
- Masses $\mathcal{O}(1)$ GeV, QED-like interactions, small mixing ε.
- Decay to pairs of leptons, hadrons, or quarks, which can give rise to a displaced vertex.



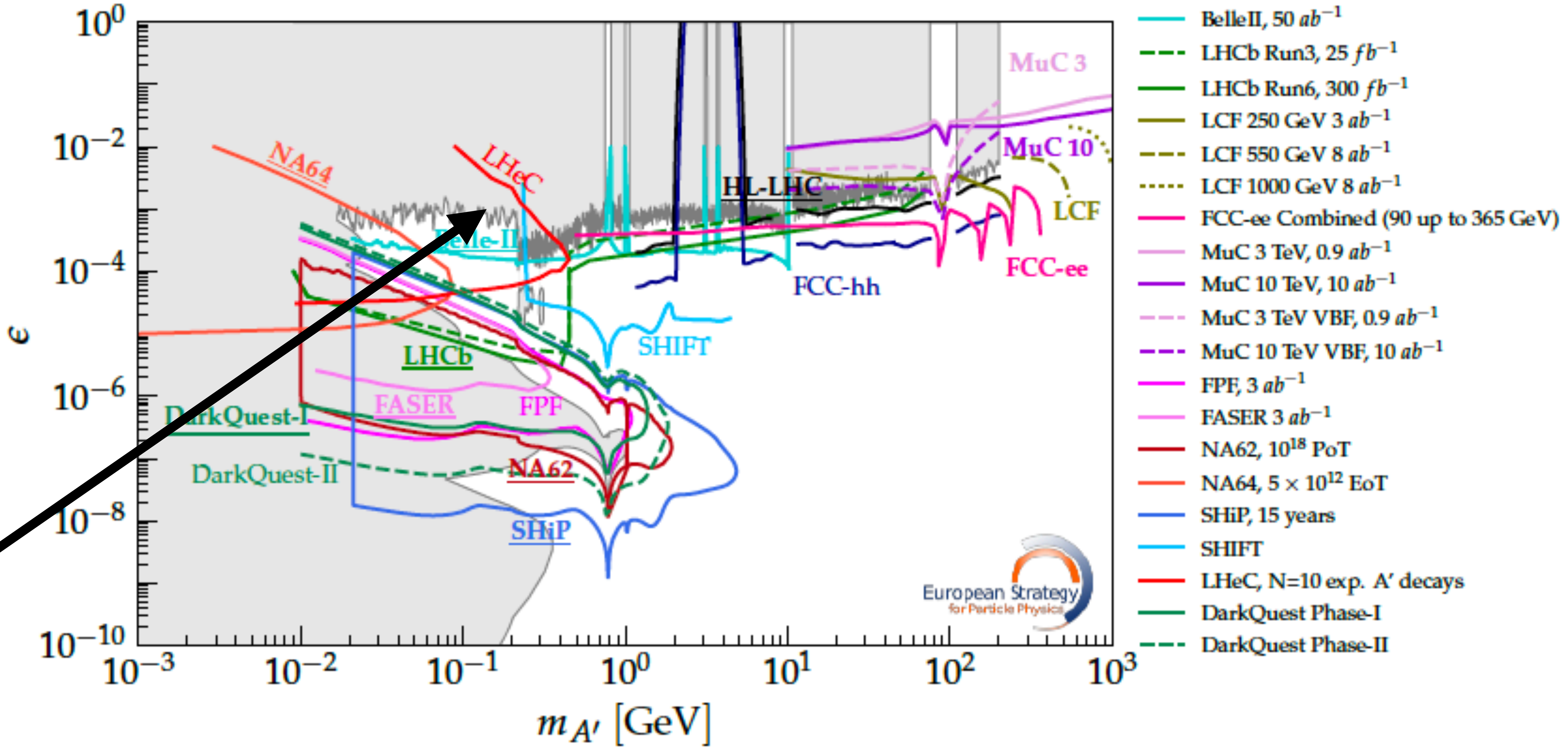






$$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$

Covering regions between pp and e^+e^- / low energy experiments



Components, cost, sustainability:

Section	Horizontal Dipoles			Vertical Dipoles			Quadrupoles			RF Cavities		
	Number	Field	Mag. Length	Number	Field	Mag. Length	Number	Gradient	Mag. Length	Number	Frequency/Cell	RF Gradient
LINAC 1							29	1.9	1.0	448	802/5	20.0
LINAC 2							29	1.9	1.0	448	802/5	20.0
Arc 1	344	0.039	4.0	8	0.51	4.0	158	9.3	1.0			
Arc 2	294	0.077	4.0	6	0.74	4.0	138	17.7	1.0			
Arc 3	344	0.123	4.0	6	0.92	4.0	158	24.3	1.0	6	1604/9	30.0
Arc 4	294	0.181	4.0	6	1.23	4.0	138	27.2	1.0	6	1604/9	30.0
Arc 5	344	0.189	4.0	4	0.77	4.0	156	33.9	1.0	18	1604/9	30.0
Arc 6	344	0.226	4.0	4	1.49	4.0	156	40.8	1.0	30	1604/9	30.0
Total	1964			34			962			956		

Units: meter (m), Tesla (T), T/m, MHz, MV/m

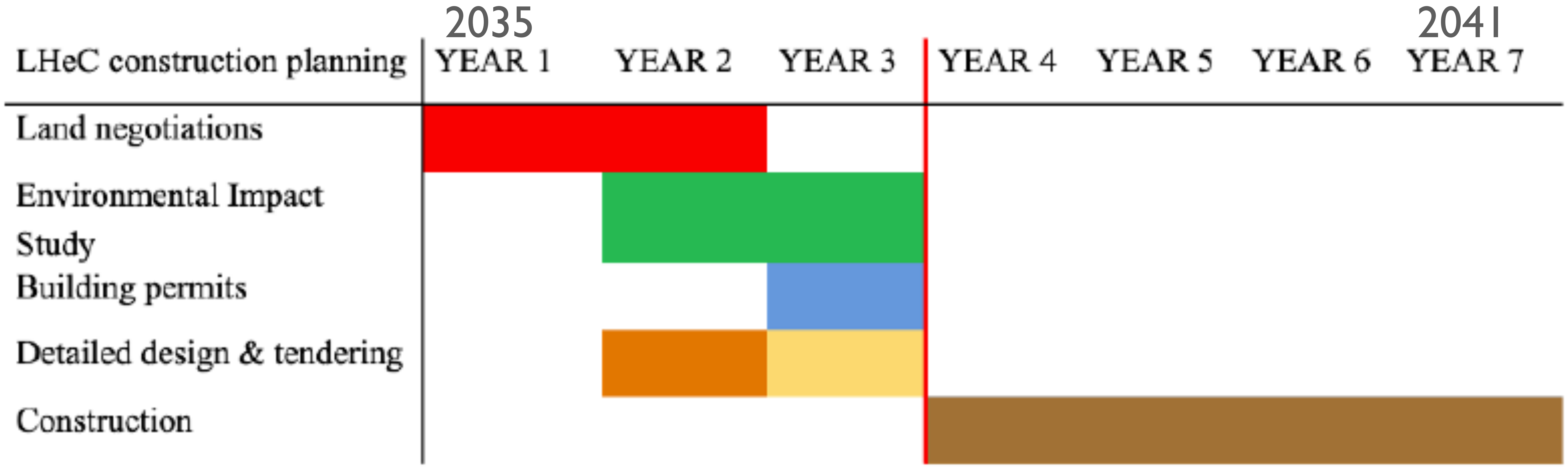
A. Bogacz, full lattice simulation for ERL at 50 GeV

Budget Item	Cost
SRF System	671 MCHF
SRF R&D and Proto Typing	31MCHF
Injector	40MCHF
Magnet and Vacuum System	215MCHF
SC IR magnets	105MCHF
Dump System and Source	5MCHF
Cryogenic Infrastructure	100MCHF
General Infrastructure and installation	69MCHF
Civil Engineering	386MCHF
Total	1622MCHF

- Cost estimate for 1/3rd of the LHC, 50 GeV racetrack: 1.6 BCHF (2018 cost, CERN-ACC-2018-0061), 46% corresponding to the SRF ERL accelerator and 24% to civil engineering; detector: 360 MCHF (75% calorimetry).

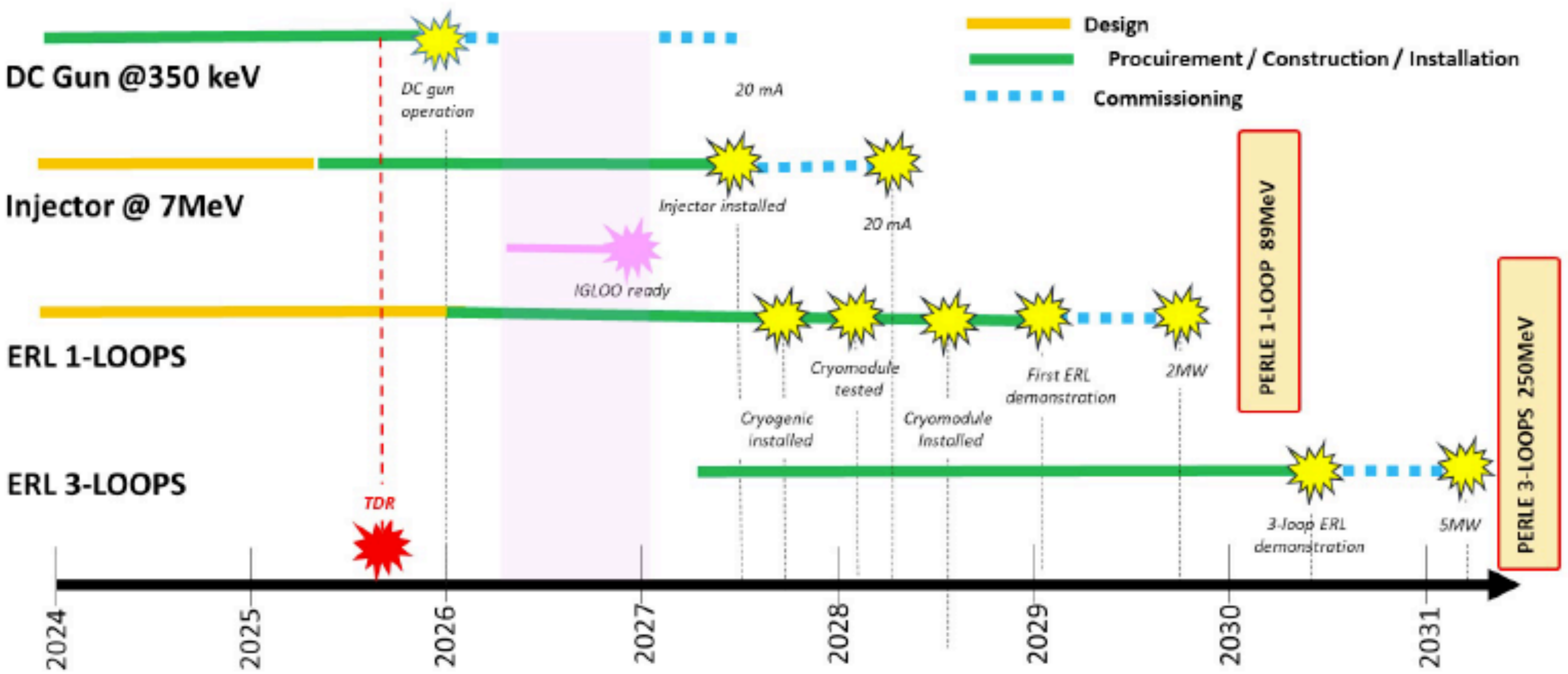
- Power consumption for this option: 220 MW including the ERL, the single-beam HL-LHC and the detector ⟶ +60 MW w.r.t. HL-LHC and +75 MW w.r.t. nominal LHC operation.

Feasibility:



- Target ep luminosity of $\sim 1\,\mathrm{ab}^{-1}$ can be achieved in 6 years: two years for installation and commissioning plus one year LS leads to completion in 2050.

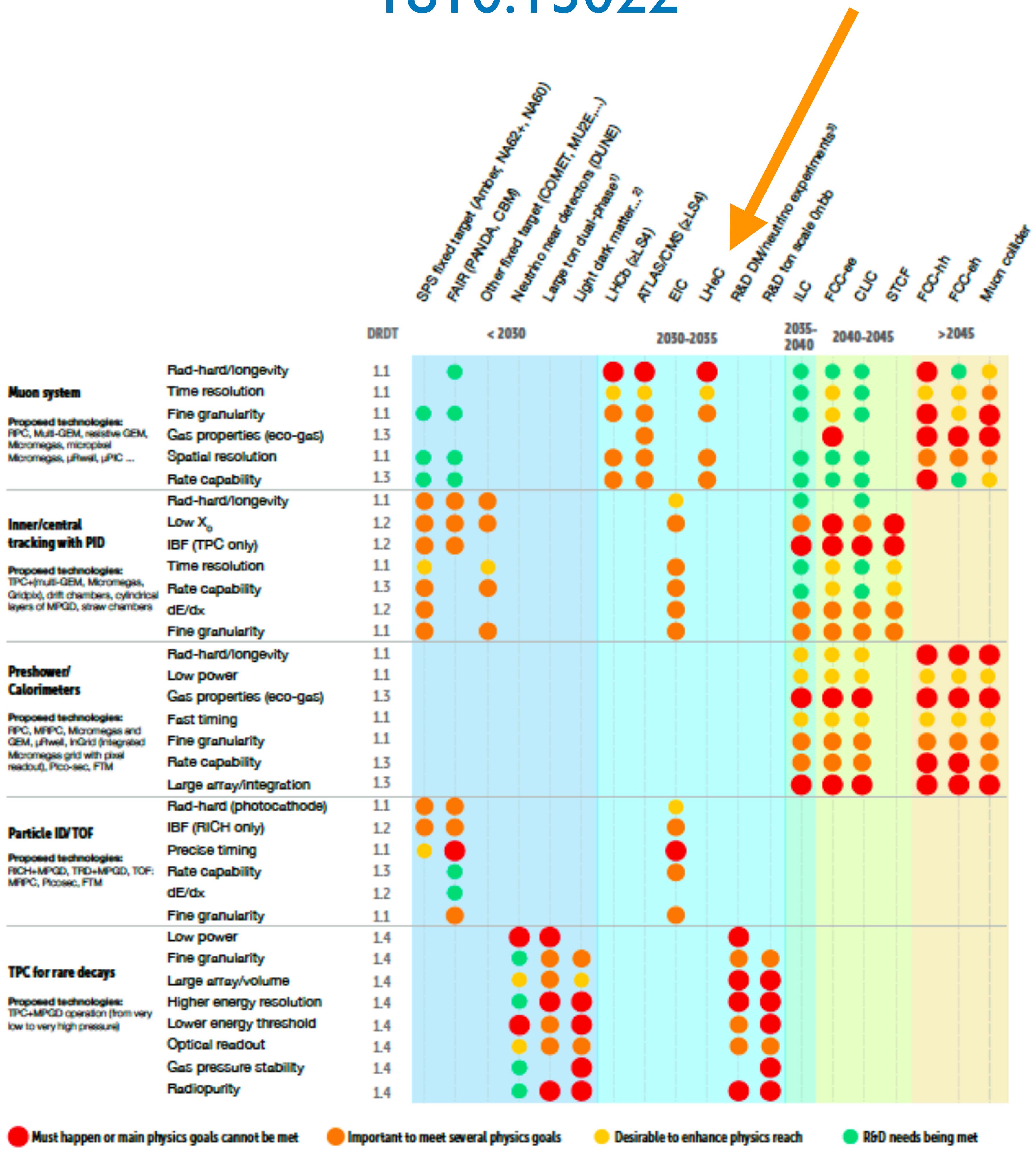
- Demonstration of multi-turn high-current ERL in PERLE in 2029/2030:



Challenges:

- Accelerator (ERL in the ECFA Accelerator Roadmap and in the 2020 strategy):
  - ➜ High quality SRF cavities integrated in the cryomodule: PERLE (iSAS).
  - ➜ High-current, multi-pass ERL → PERLE as demonstrator (2029 1-turn, 2030 3-turn).
  - ➜ Synchrotron radiation in arcs: simulation, CEBAF?
- Detector (in the ECFA Detector Roadmap):
  - ➜ Keep material budget in the forward direction low (MAPS) → synergies with ALICE(3) and ePIC.
  - ➜ Choose between more conservative or more aggressive proposal: particle ID, EMCAL? → synergies with EIC.
  - ➜ Further develop an ep/pp option and the possibility of reusing existing detectors.
- Machine-detector interface:
  - ➜ Synchrotron radiation protection: beam pipe and inner tracking.
  - ➜ 3-beam IR: high aperture, field-free region Q1 (HL-LHC complexity). 2-beam configuration simpler.

1810.13022



From Karl Jakobs:

Remit of the European Strategy Group (ESG)

- *The aim of the Strategy update should be to develop a* ***visionary and concrete plan*** *that greatly advances human knowledge in fundamental physics through the* ***realisation of the next flagship project at CERN****. This plan should attract and value* ***international collaboration*** *and should* ***allow Europe to continue to play a leading role in the field.”***

- The ESG should take into consideration:
  - Input of the particle physics community;
  - Status of implementation of the 2020 Strategy update;
  - Accomplishments over recent years

    (Results from the LHC and other experiments and facilities worldwide, progress in the construction of the High-Luminosity LHC, outcome of the FCC Feasibility Study, recent technological developments in accelerator, detector and computing areas)
  - International landscape of the field

- *The Strategy update should include the* ***preferred option for the next collider at CERN*** *and* ***prioritised alternative options*** *to be pursued if the chosen preferred plan turns out not to be feasible or competitive.*

- *The Strategy update should also* ***indicate areas of priority for exploration complementary to colliders*** *and for other experiments to be considered at CERN and at other laboratories in Europe, as well as for participation in projects outside Europe.*

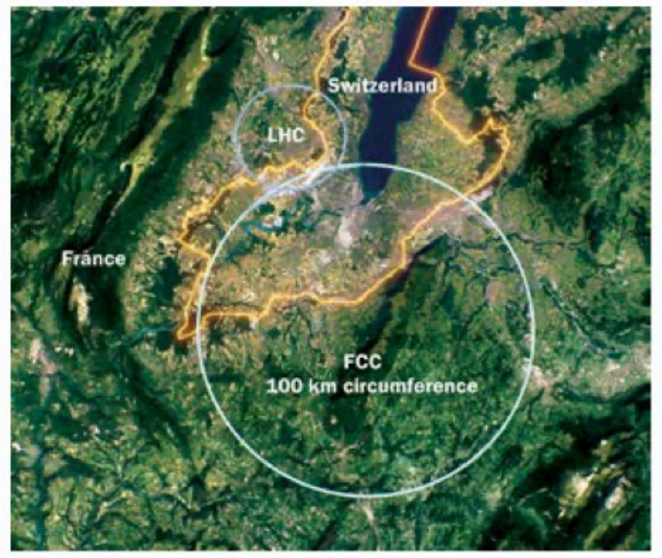
K. Jakobs, EPS-HEP Conference, Marseille, 10th July 2025

3

From Karl Jakobs:

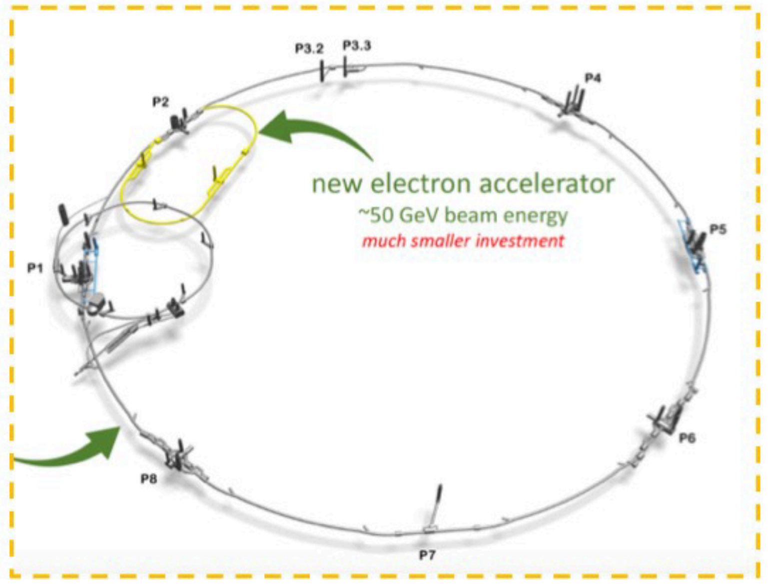
Potential for development: future 10 TeV parton-scale collider options

FCC-ee



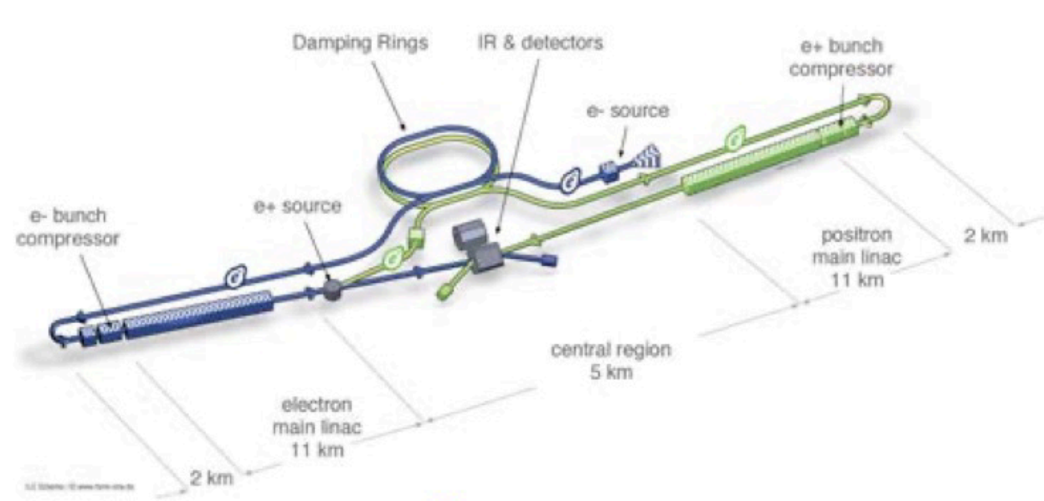
LEP3

LHeC



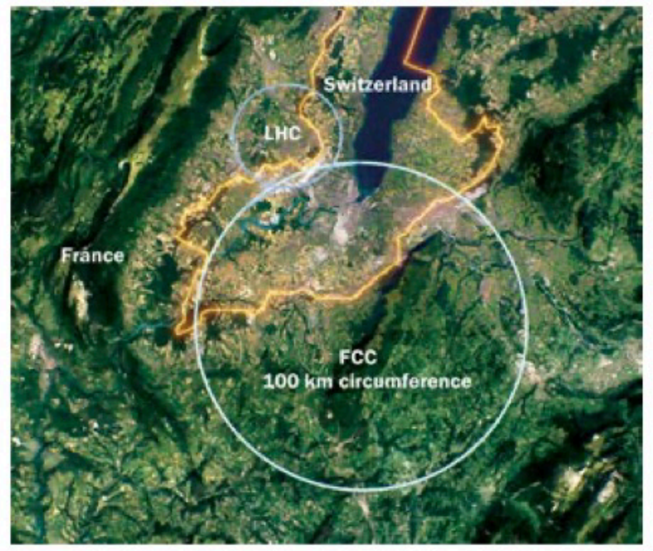
PERLE

LCF, CLIC

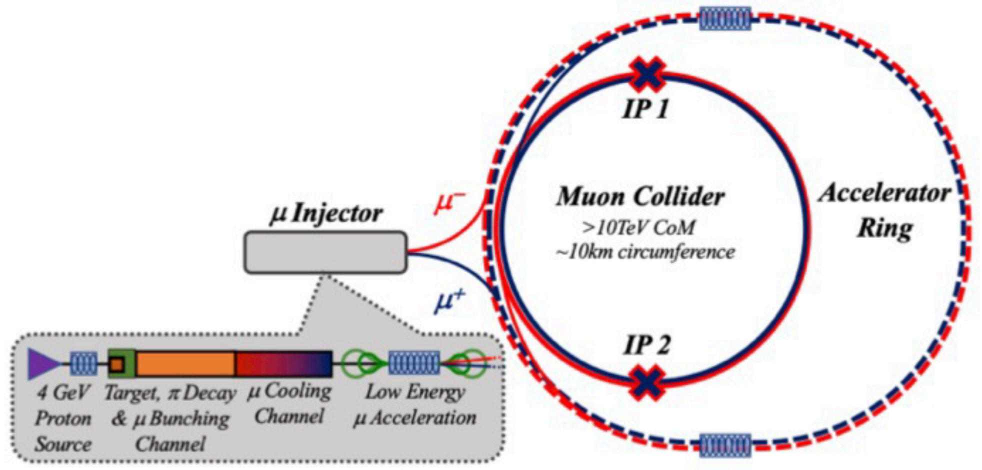


$\mathcal{O}(1)$ TeV parton-parton scattering

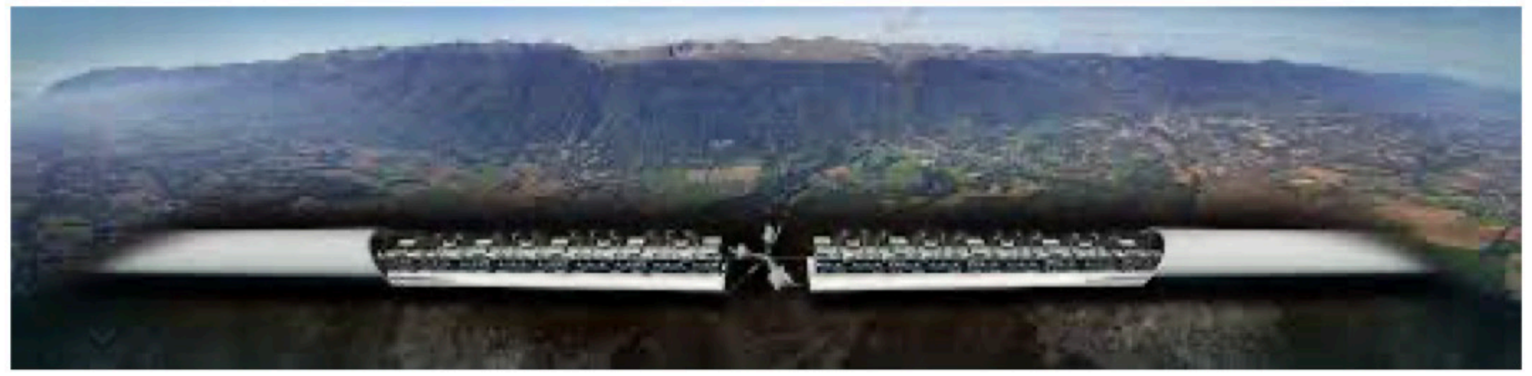
R&D



FCC-hh,
baseline 85 TeV (→ 120 TeV)
+ possibility for HI collisions



Muon Collider (3, 10 TeV)



e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

$\mathcal{O}(10)$ TeV parton-parton scattering

K. Jakobs, ESPP Open Symposium, 27th June 2025

4

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Potential for development: future 10 TeV parton-scale collider options

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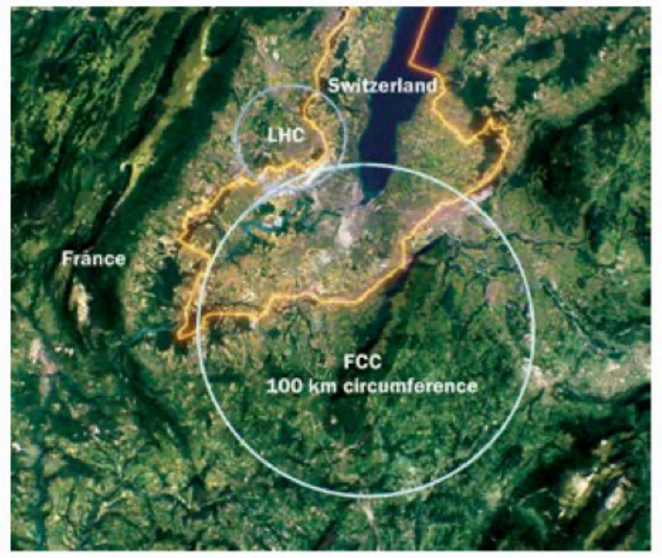
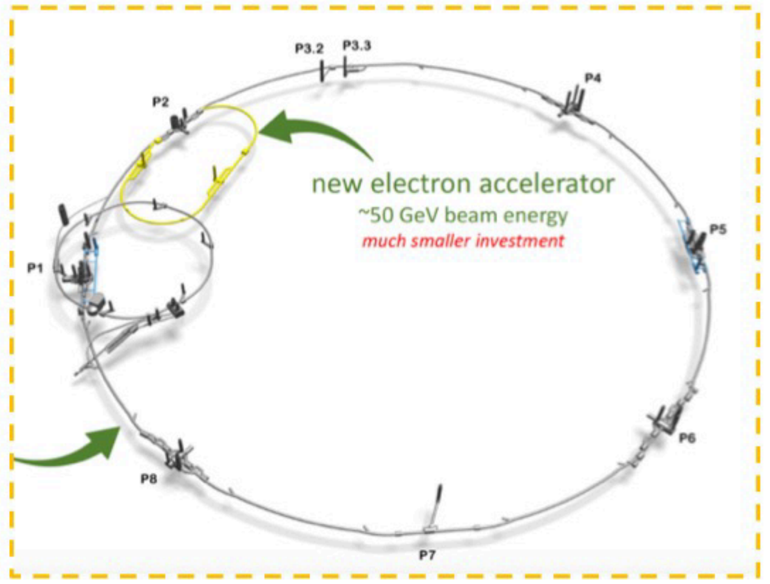


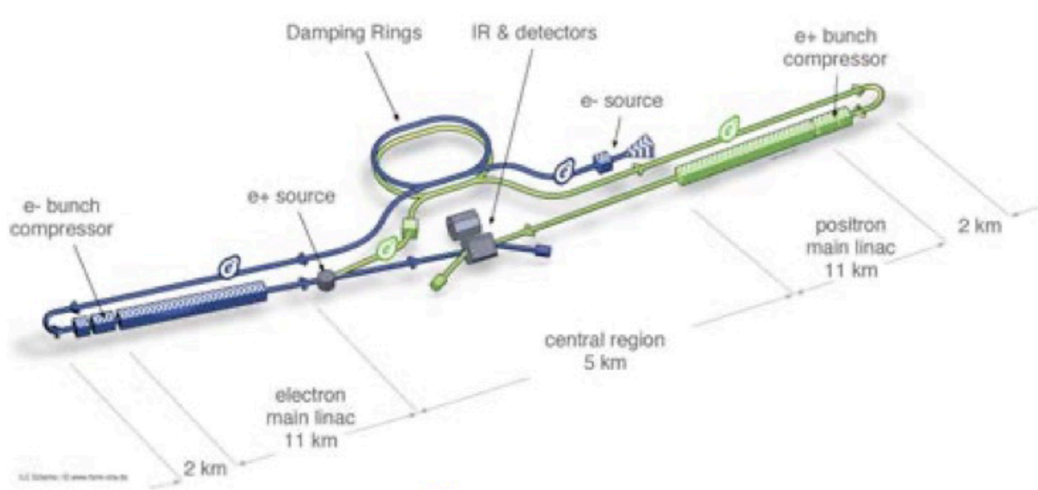
LEP3

LHeC



PERLE

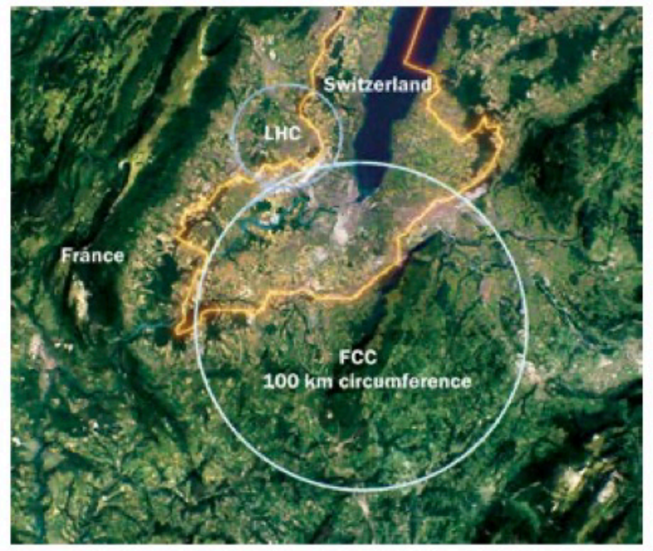
LCF, CLIC



$\mathcal{O}(1)$ TeV parton-parton scattering

Plan A

R&D



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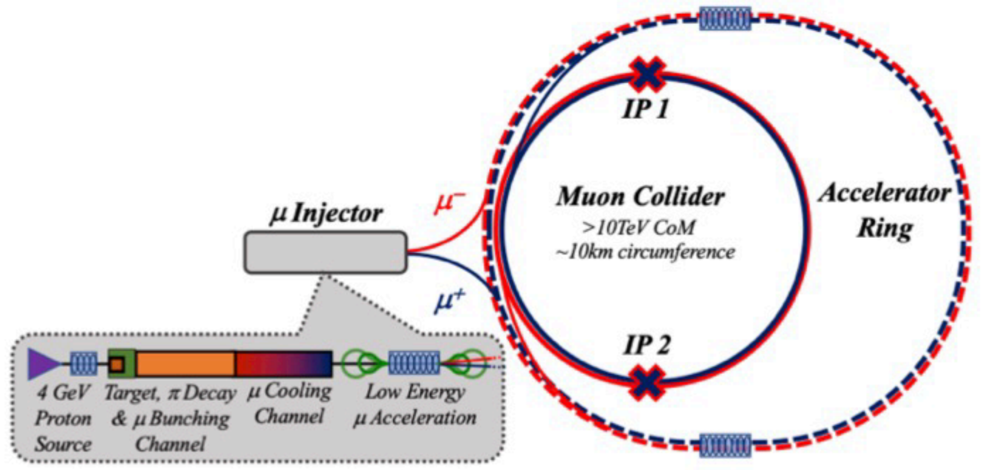

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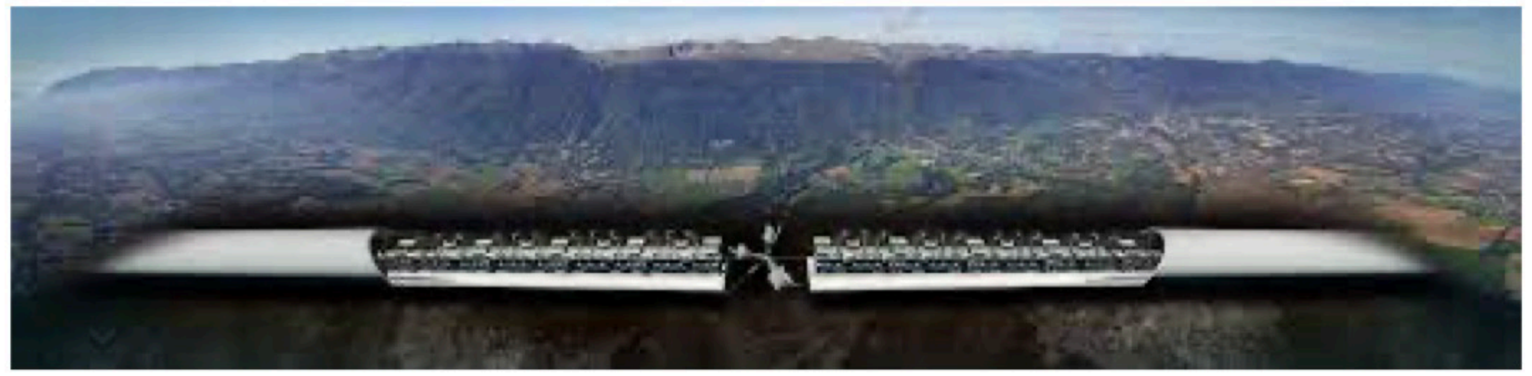

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$\mathcal{O}(10)$ TeV parton-parton scattering

K. Jakobs, ESPP Open Symposium, 27th June 2025

4

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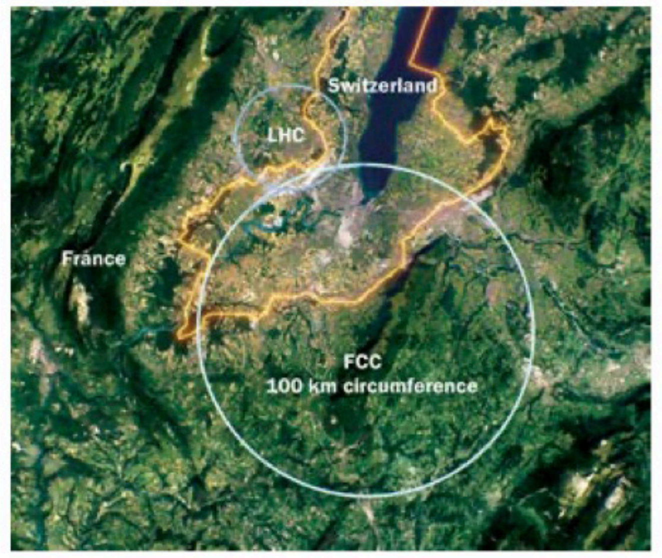

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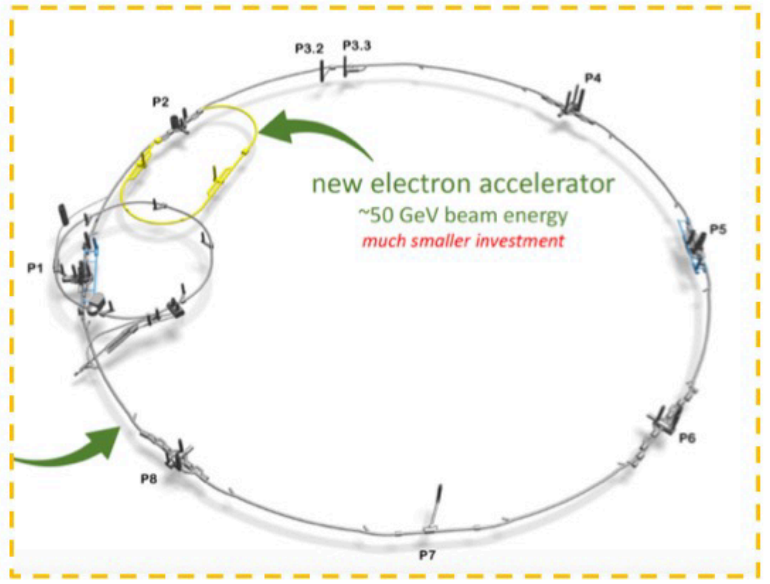
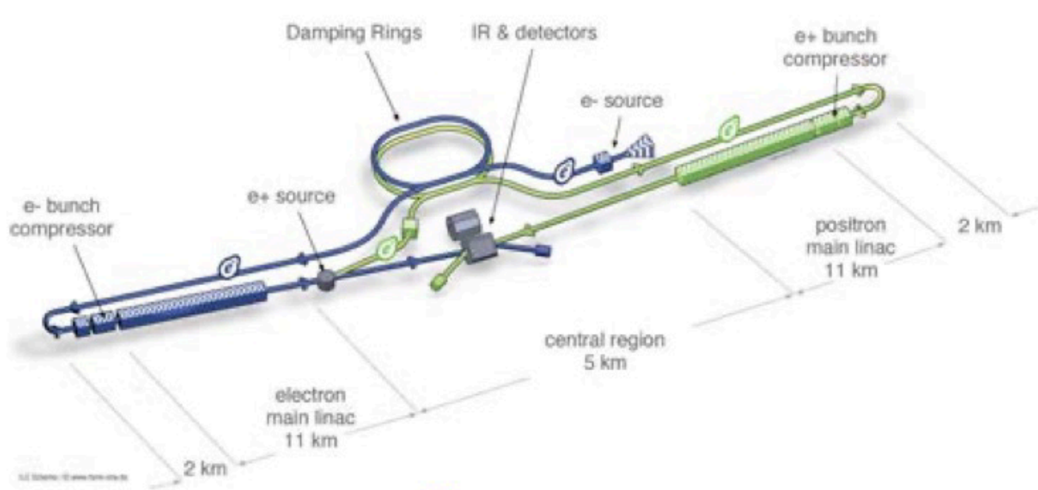
LHeC



PERLE

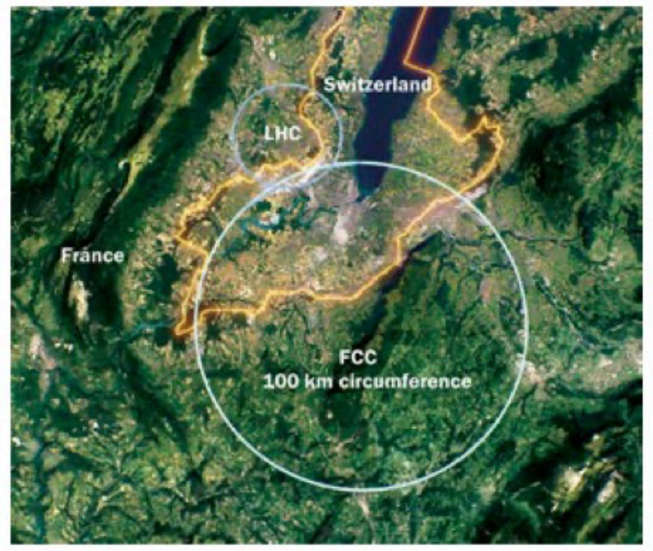
LCF, CLIC



$\mathcal{O}(1)$ TeV parton-parton scattering

Reusing the LEP/LHC tunnel

R&D



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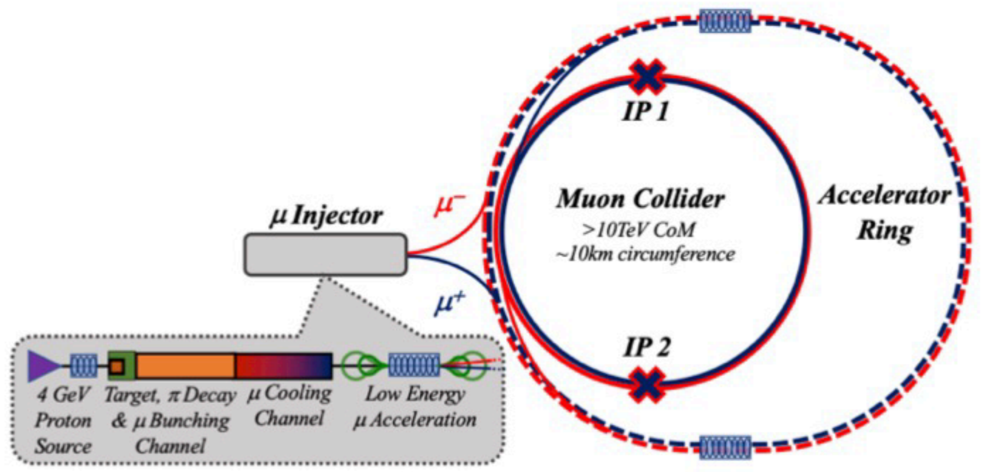

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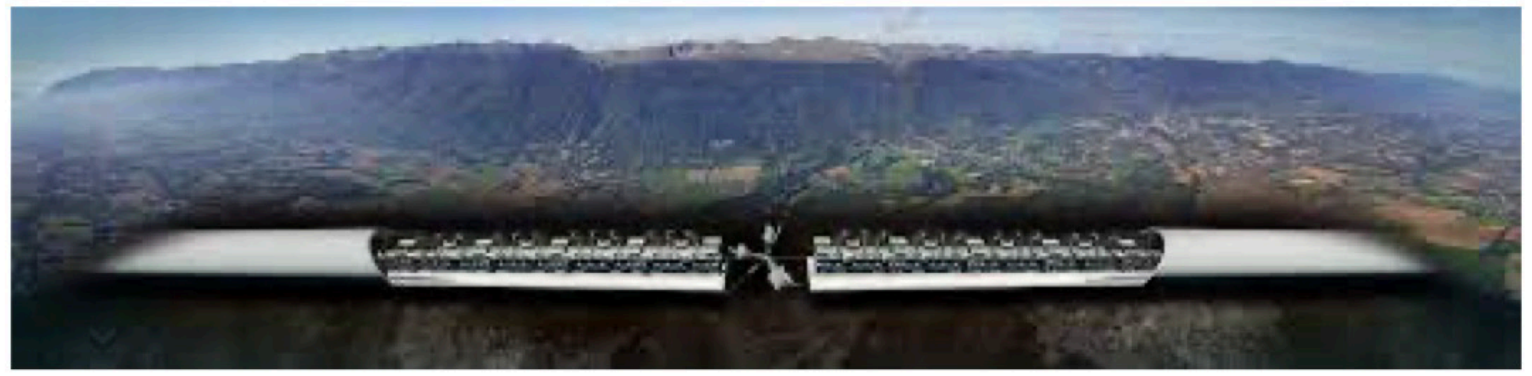

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$\mathcal{O}(10)$ TeV parton-parton scattering

K. Jakobs, ESPP Open Symposium, 27th June 2025

4

LHeC as a bridge:

● In standalone mode (ep/eA only), LHeC may be a bridge between major colliders at CERN, between the end of the HL-LHC (2041) and the next flagship CERN collider.

Slide by J. D'Hondt

LHC

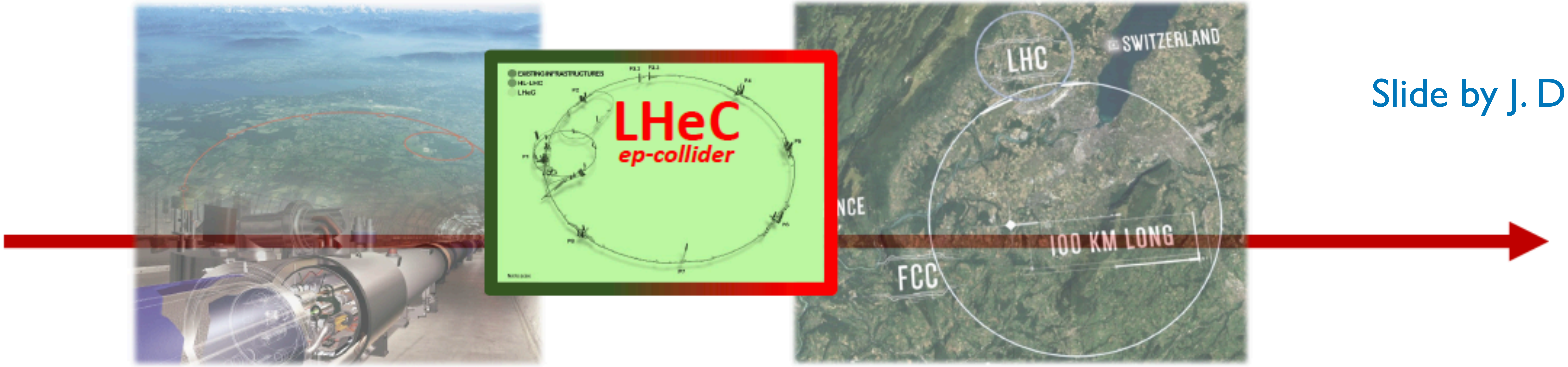
FCC (ee or hh)

13

LHeC as a bridge:

● In standalone mode (ep/eA only), LHeC may be a bridge between major colliders at CERN, between the end of the HL-LHC (2041) and the next flagship CERN collider.

ep-option with HL-LHC: LHeC
updated CDR: J.Phys.G 48 (2021) 11, 110501
10y @ 1.2 TeV (1ab^{-1}) = Run-6 + 5y ep-only@LHC
6y ep-only@LHC > 1 ab^{-1}



Slide by J. D'Hondt

14

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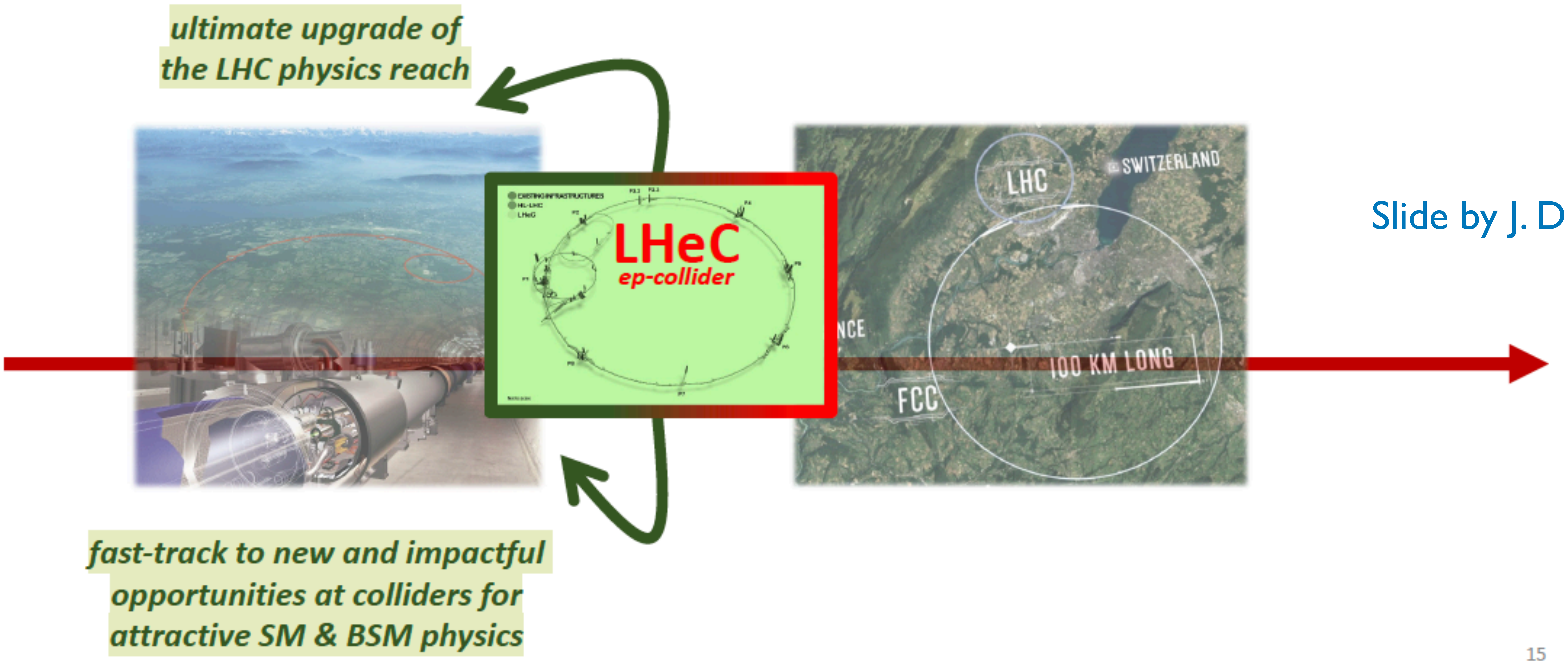

Slide by J. D'Hondt

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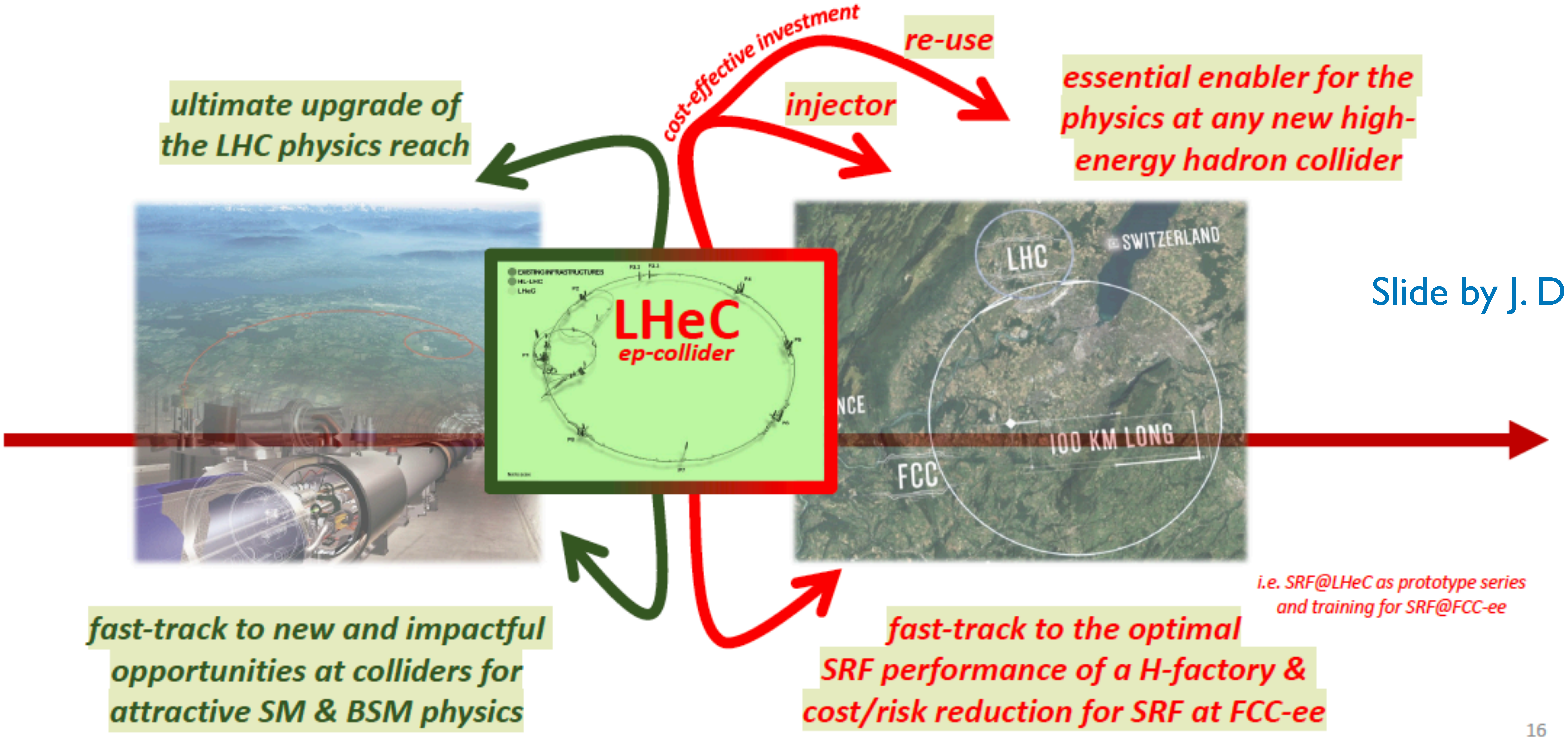

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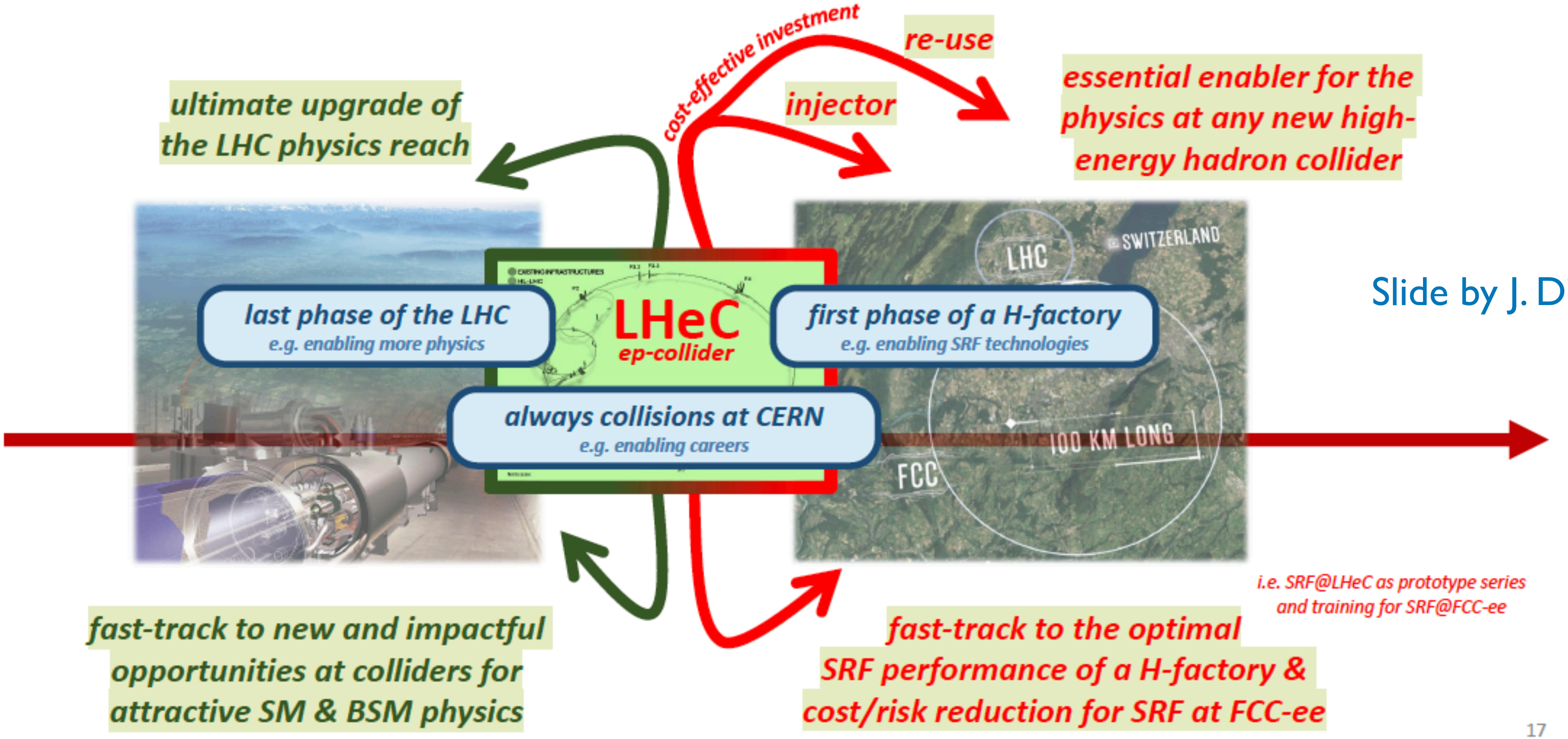
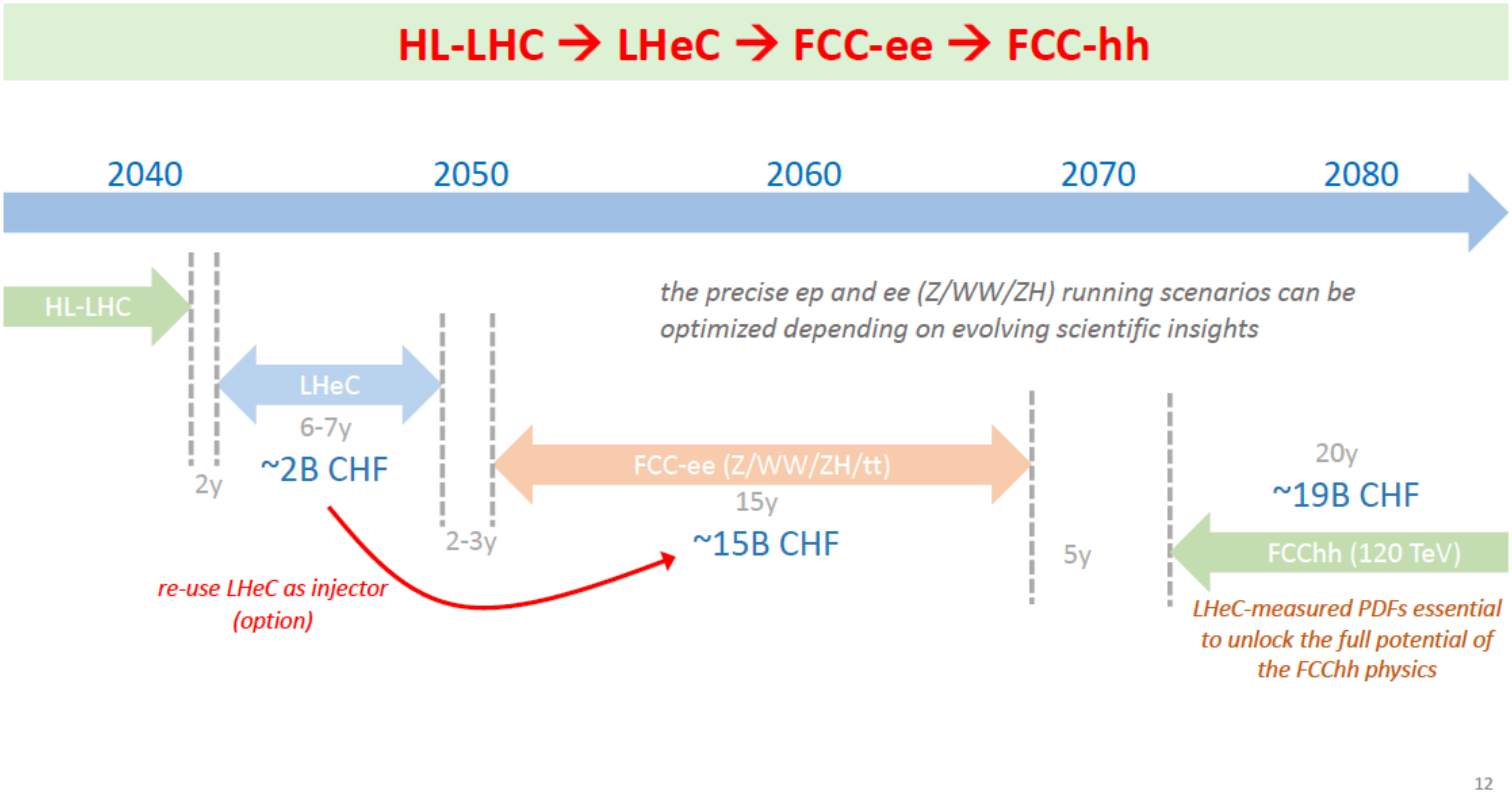


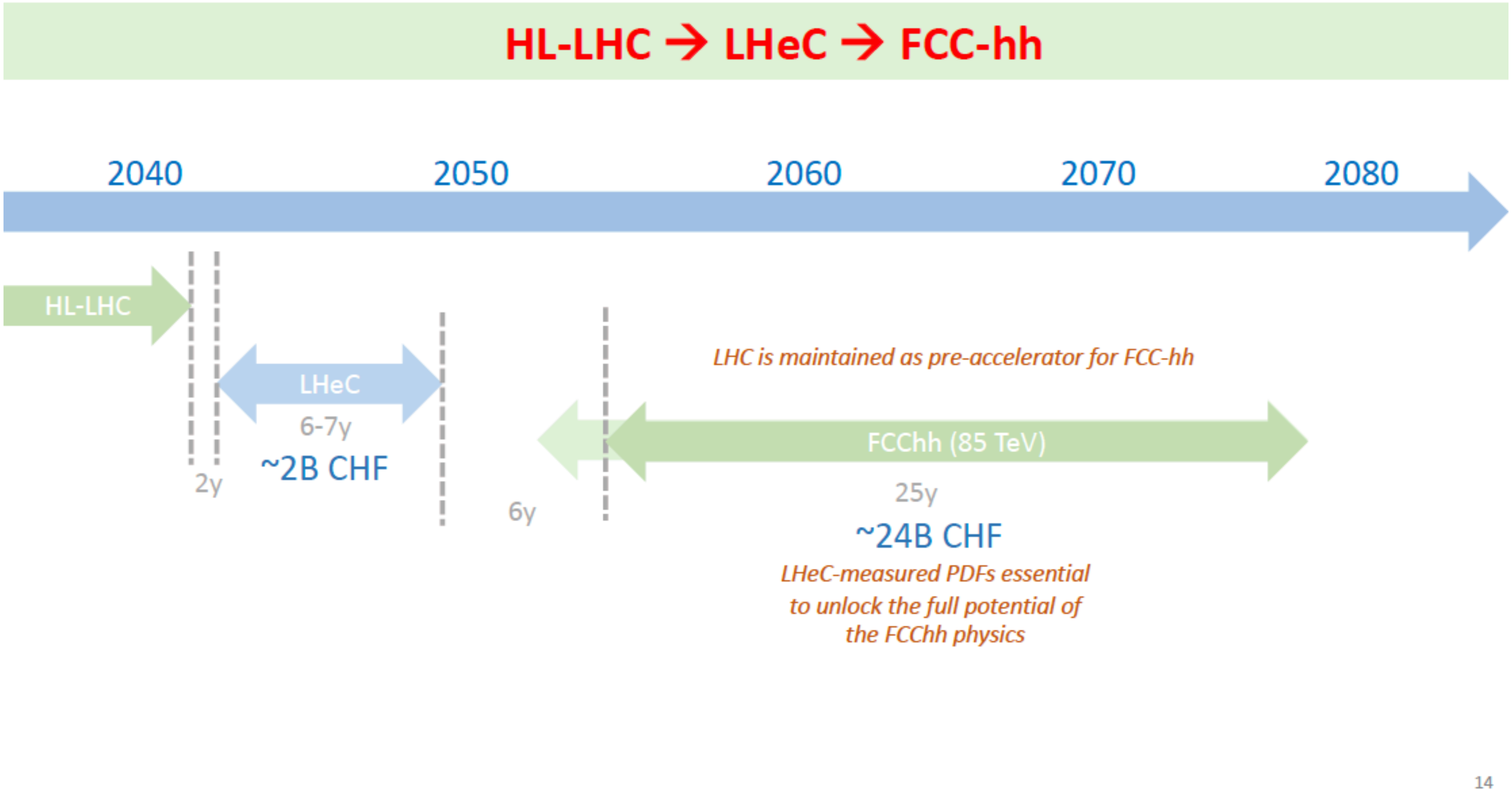
Slide by J. D'Hondt

LHeC as a bridge:



Slide by J. D'Hondt; similar schemes with MuCol

LHeC as a bridge:



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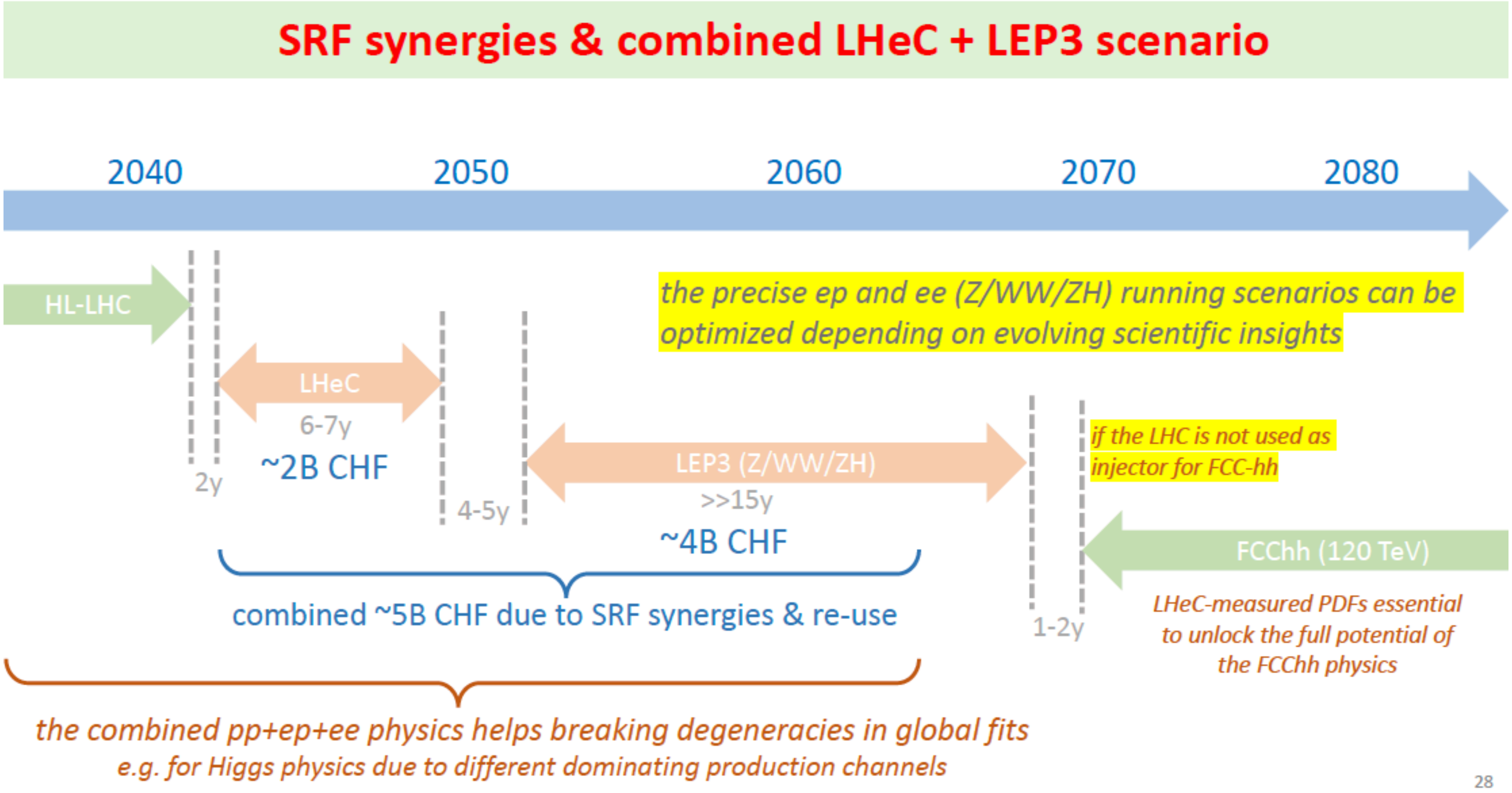
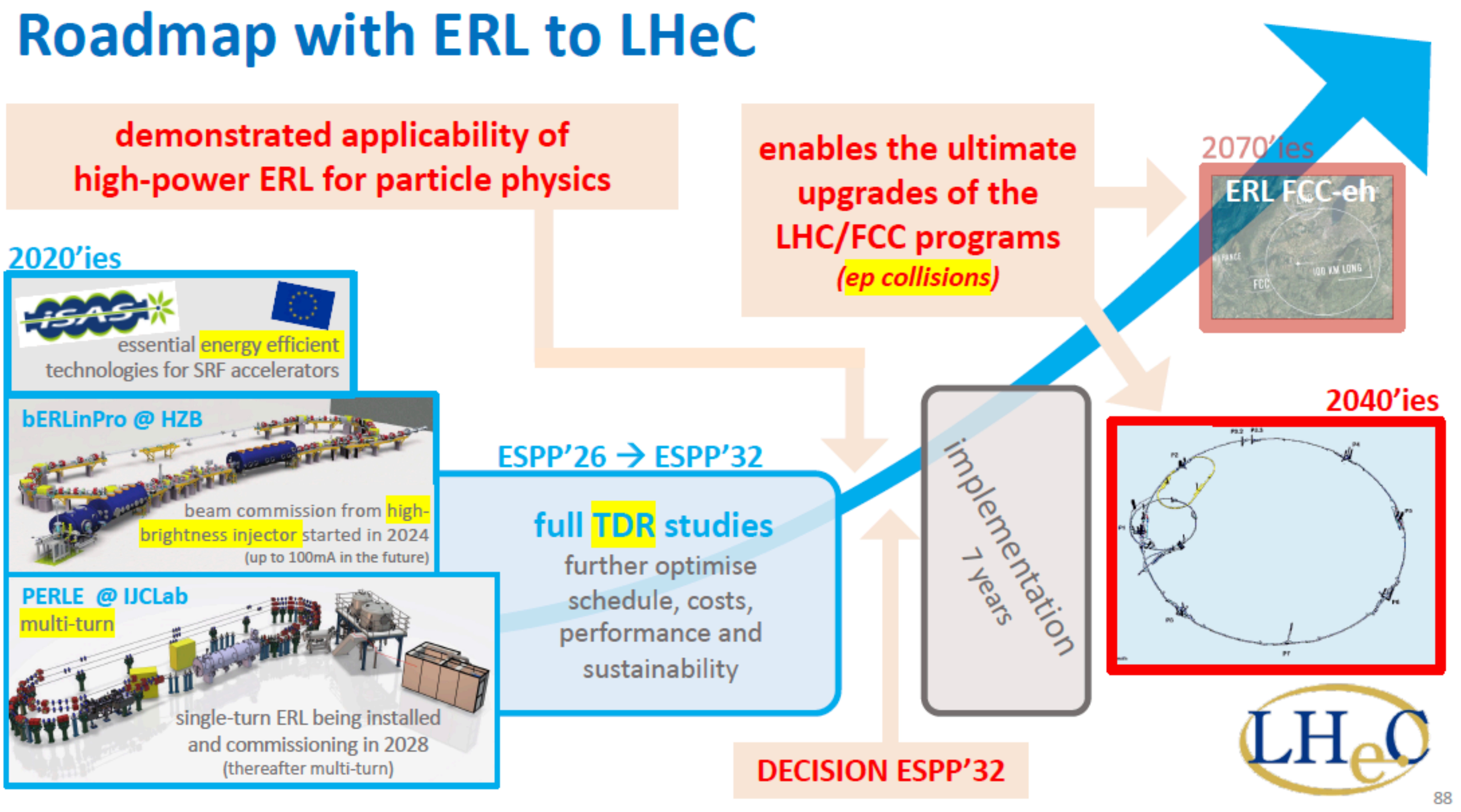


Slide by J. D'Hondt; similar schemes with MuCol

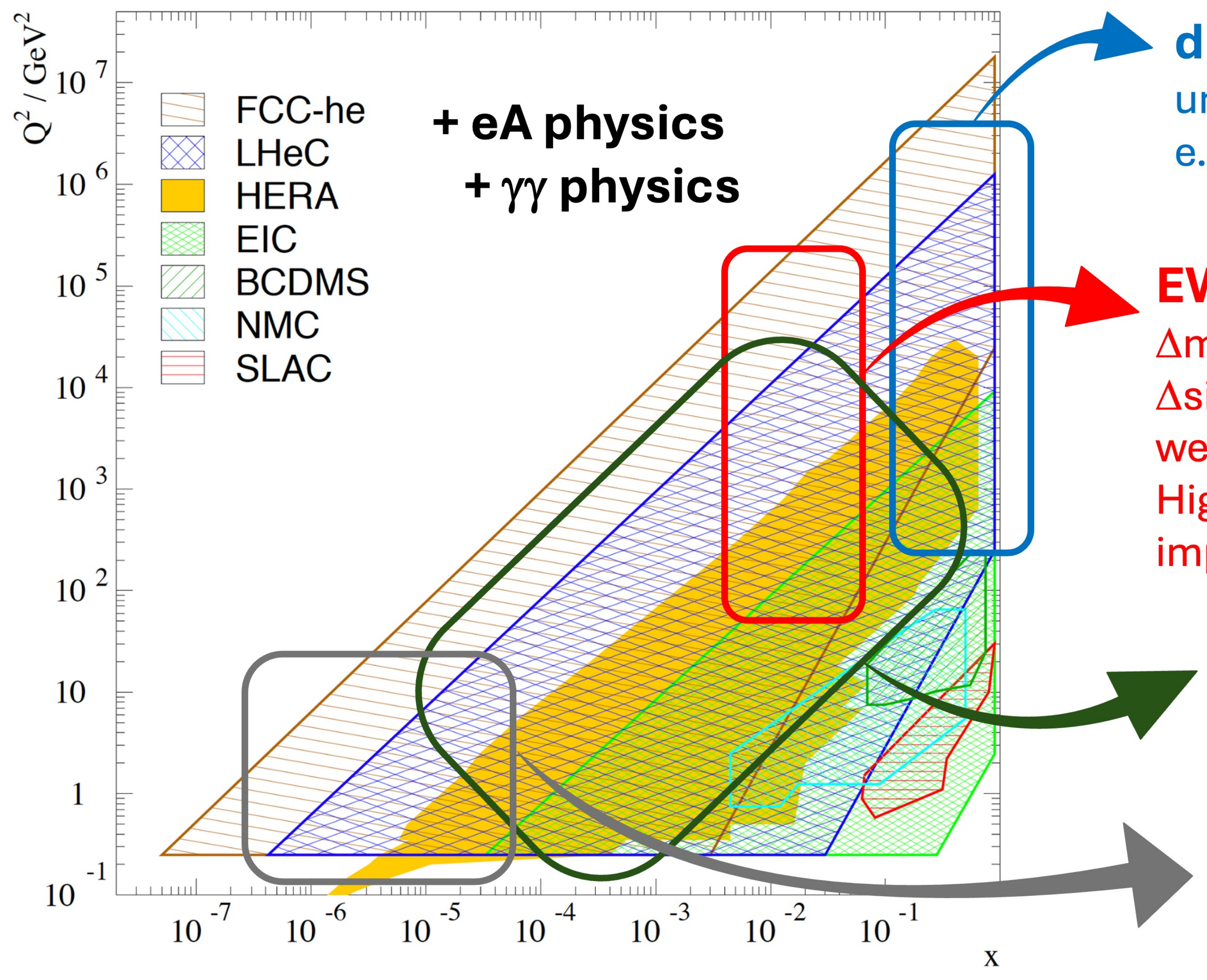
Roadmap:



Slide by J. D'Hondt

Summary:

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



- **The LHeC project:**
  ➜ Physics case on their own: QCD (precision and discovery in ep & eA), EW, top, Higgs, BSM.
  ➜ Enlarge the reach of hadronic colliders into (higher) precision, both for pp and for AA.
  ➜ Complementarities/synergies with hh & e^+e^-.

- **LHeC is not the next flagship project at CERN but it may serve as bridge between HL-LHC and a new major project at CERN (2503.17727):**
  ➜ Ultimate exploitation of the results of the LHC (e.g., m_W, Higgs couplings).
  ➜ Physics program on its own: proton/nuclear structure and dynamics, EW, top, Higgs, BSM.
  ➜ It facilitates technology (SRF, ERL, detector) and physics (e.g., PDFs for pp and AA, combinations of Higgs couplings, complementary regions on searches) for future projects.

The end:

Max Klein, 1951-2024
Spokesperson 2005-2022

Rohini Godbole, 1952-2024
Member of the IAC

Herwig Schopper, 1924-2025
Chair of the IAC

Thanks to the organisers for the invitation and to you for your attention!!!

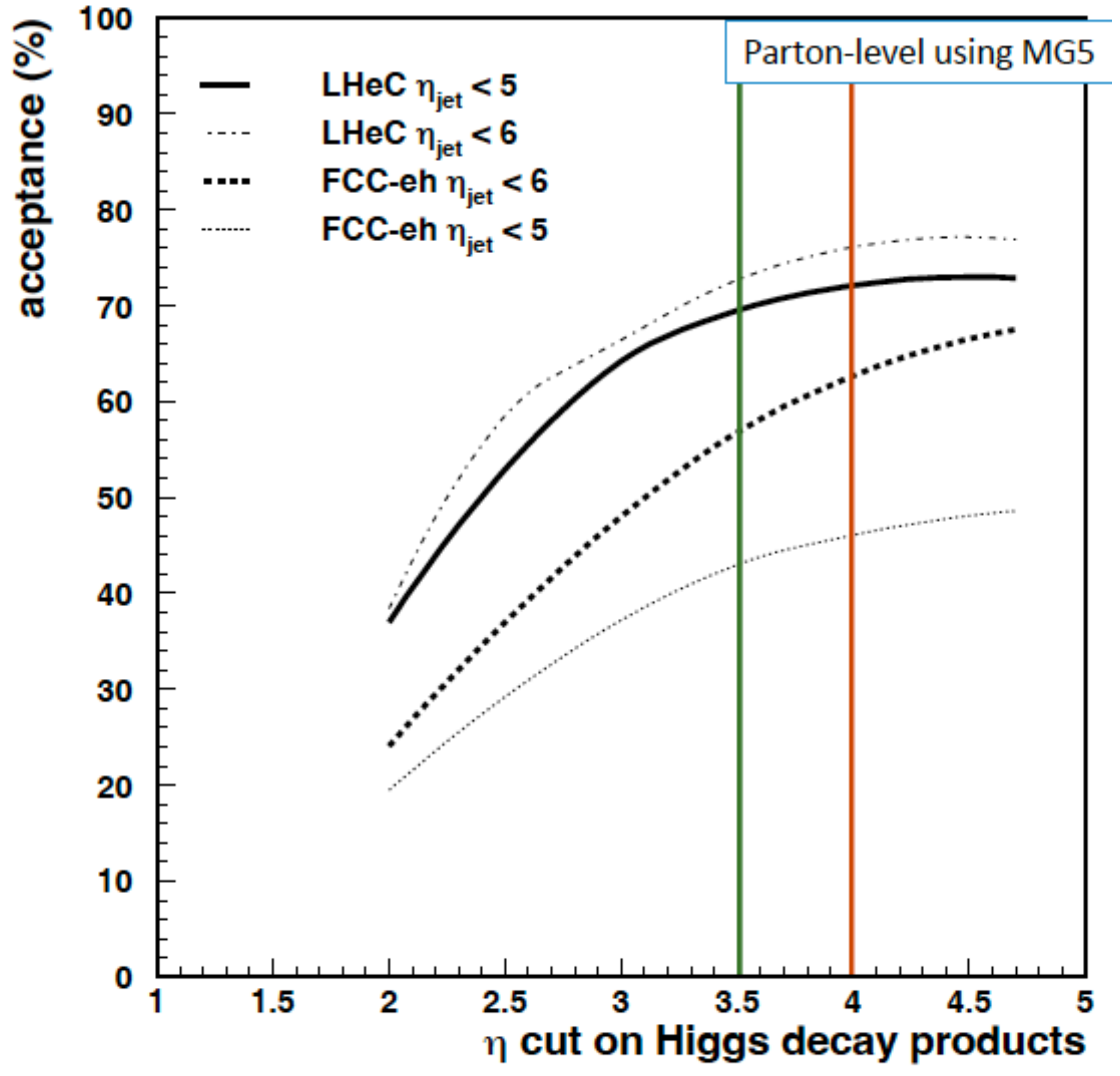
https://indico.cern.ch/event/lhecfcceh

Backup:

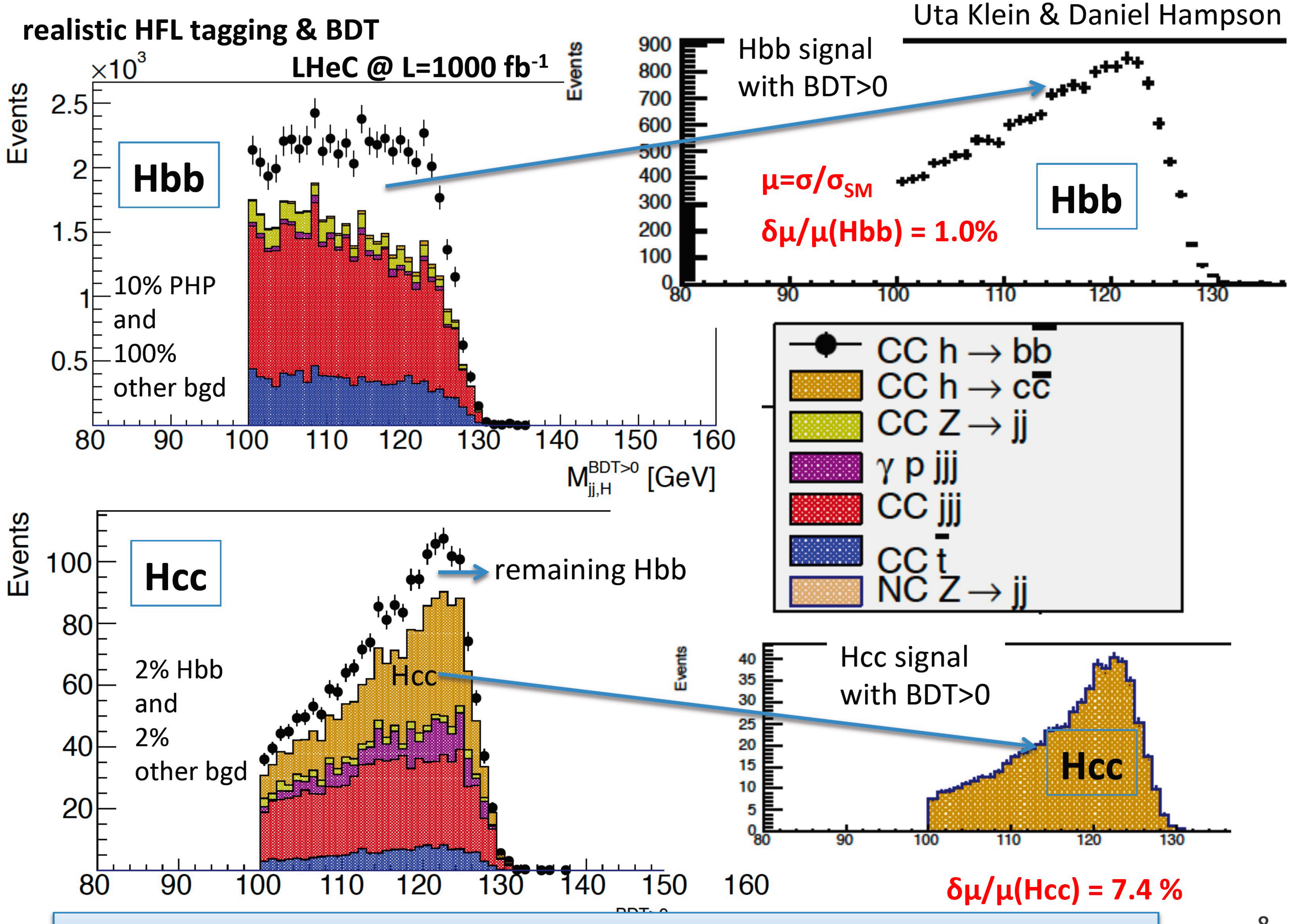
Higgs physics: analyses

- Large acceptance for jets and Higgs decay products crucial.
- Delphes cut- and BDT-based analyses performed, conservative HF tagging: b 60%, c 10%, udsg 1% (see also 2201.04037).

U. Klein at ICHEP2024



Uta Klein & Daniel Hampson



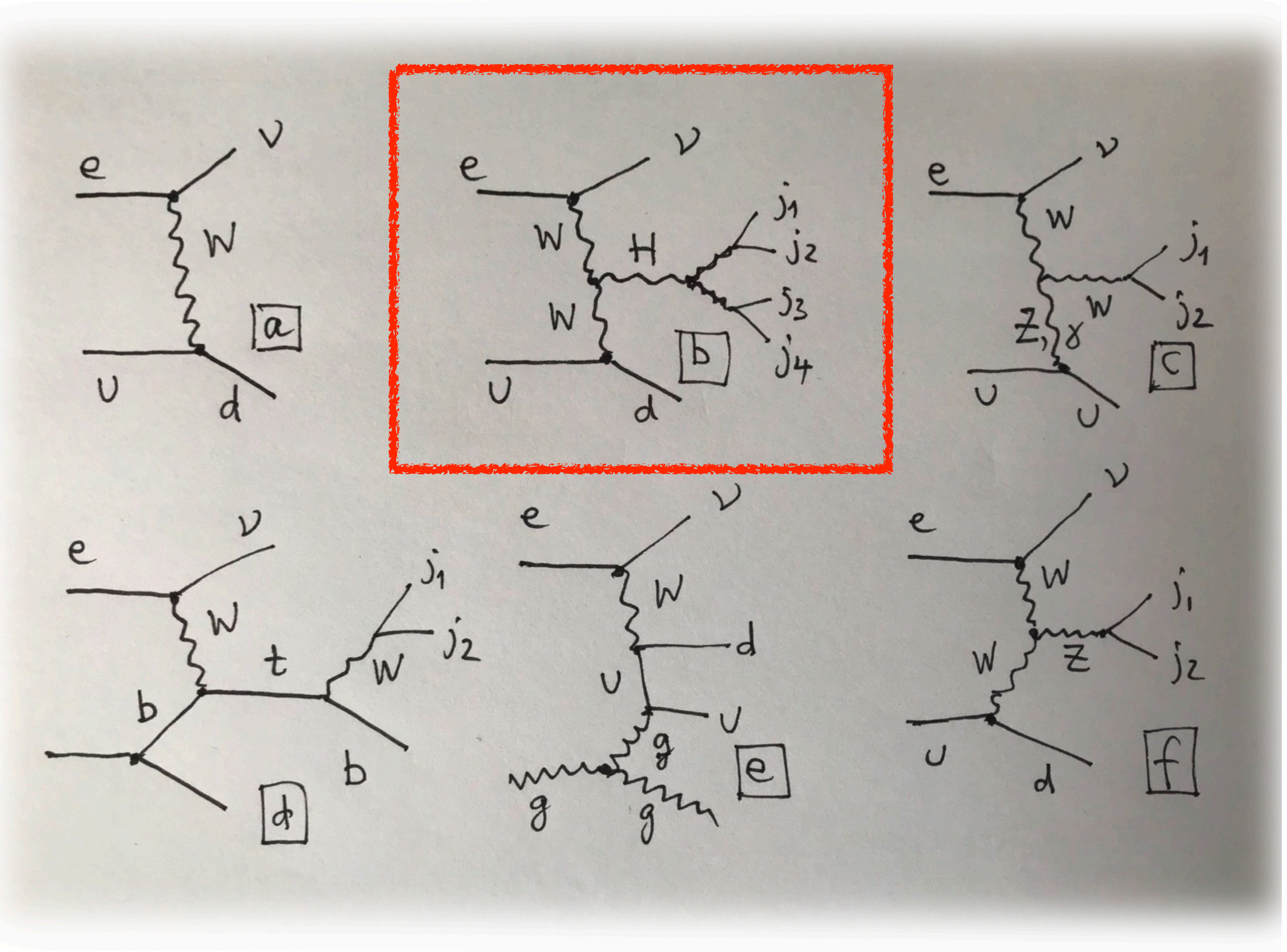
→ Main systematic checks: variations of background contribution and tagging efficiencies

8

Higgs physics: analyses

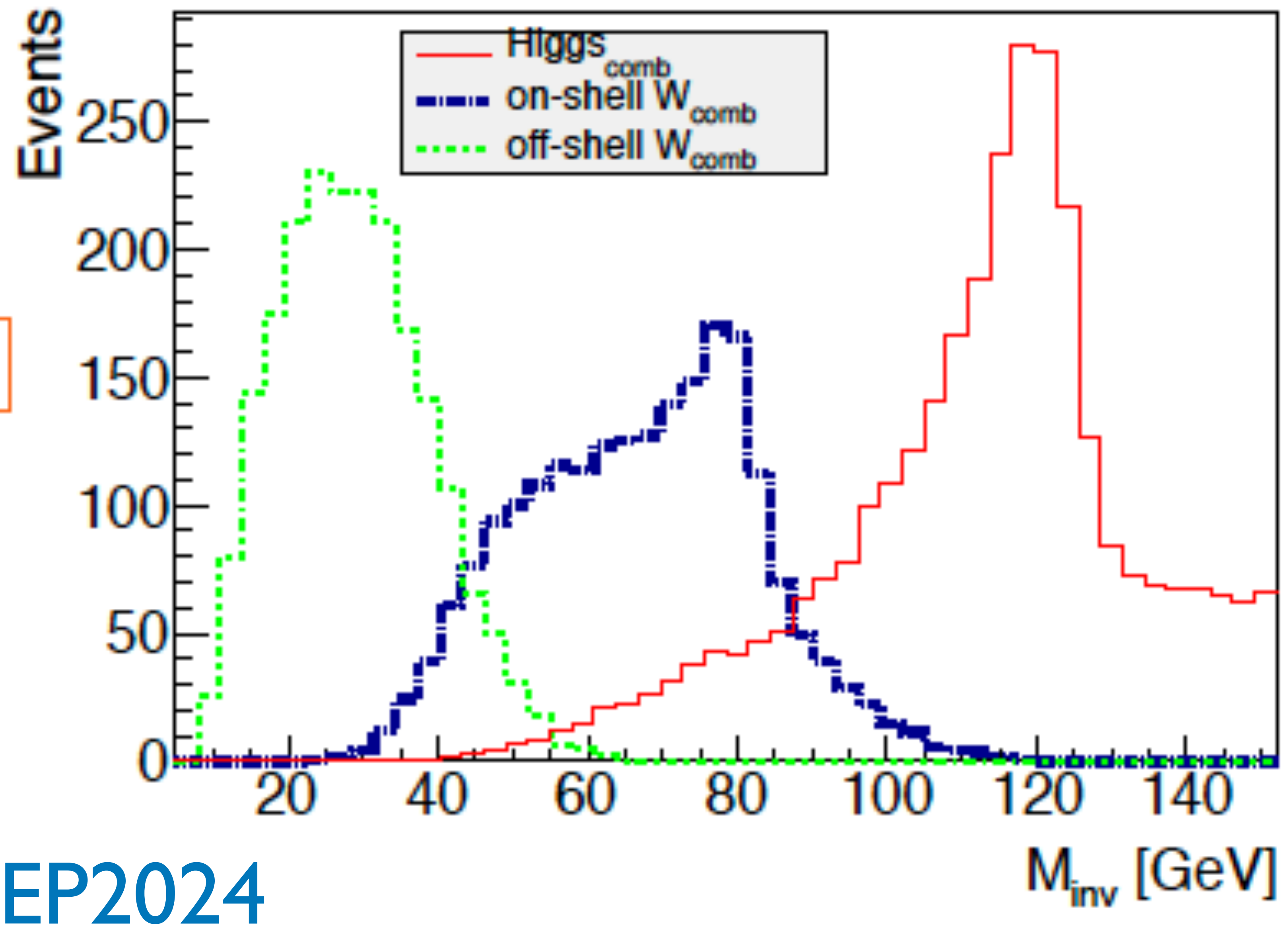
- HWW from 4+1 jets + ν configurations, CC cross section $\propto g^4_{HWW}$ in SM.

- $\delta\mu/\mu(HWW) \simeq 2\,\%$ for FCC-eh.



At Delphes detector level

NO mass requirements in combinatorics!



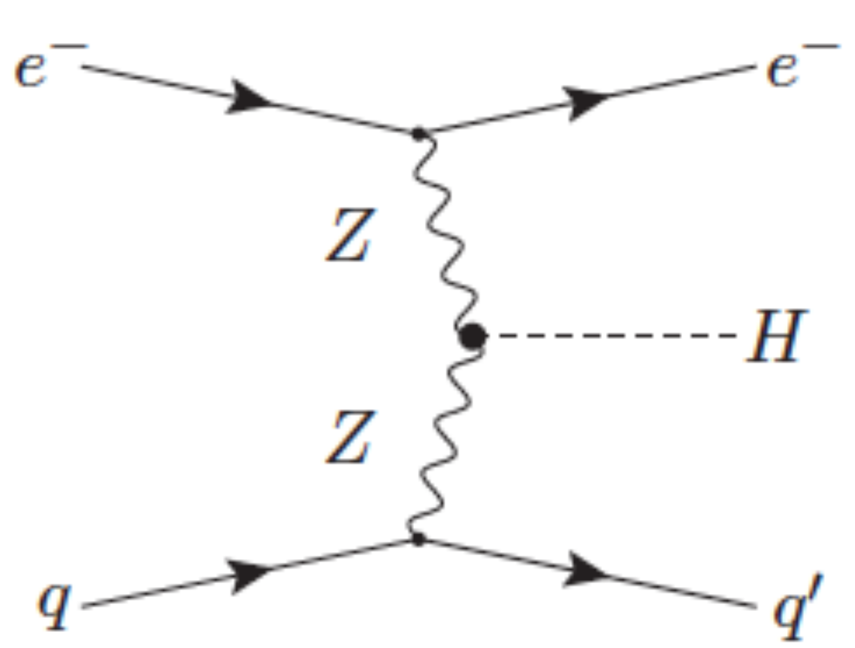
U. Klein at ICHEP2024

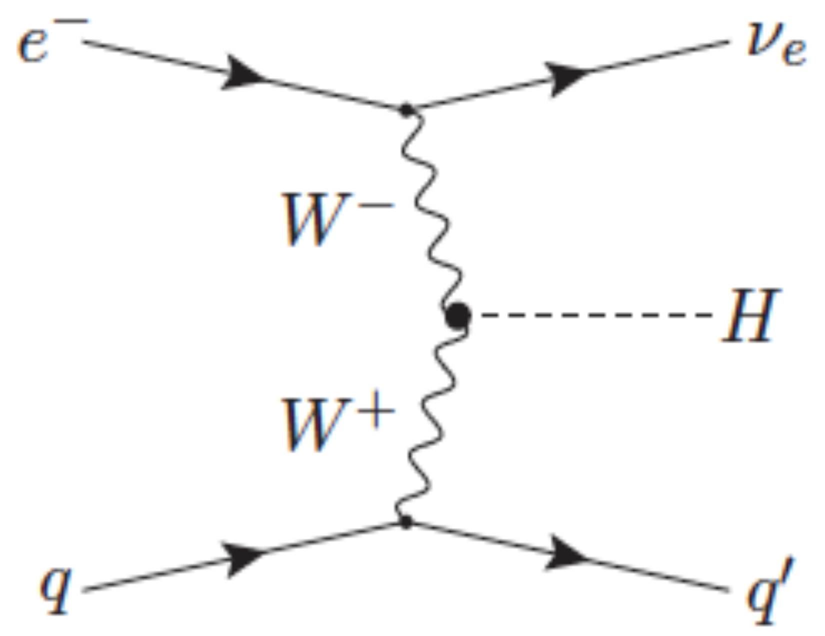
Reconstructed W*, W and Higgs, after jet combinatorics based on selecting at **least 5 jets** with **p_T> 6 GeV** and finding the Higgs candidate which has two jet pairs with min **Δη**; max **Δη** between Higgs candidate and fwd jet; max **Δϕ** between Higgs candidate and E_T^{miss} or Higgs candidate and fwd jet ➔ then *passed to BDT for S/N optimisation*

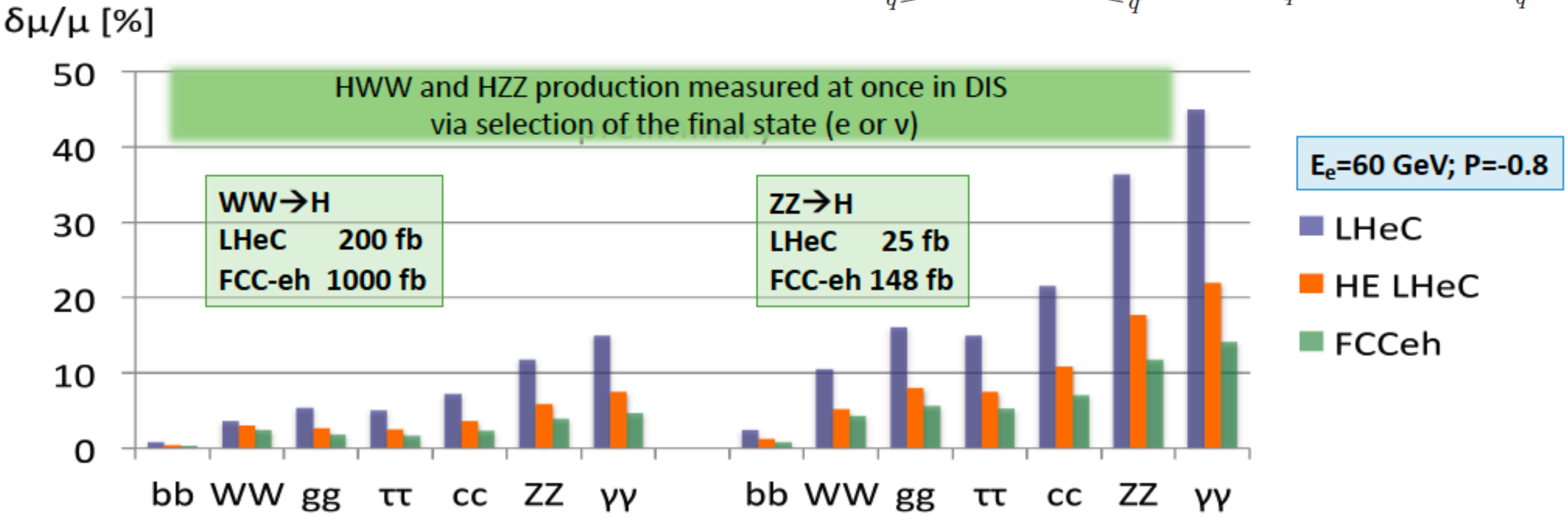
Higgs physics: signal strengths

- Few % level measurement of several couplings.

- CC and NC over-constrain Higgs couplings in combined SM fits.



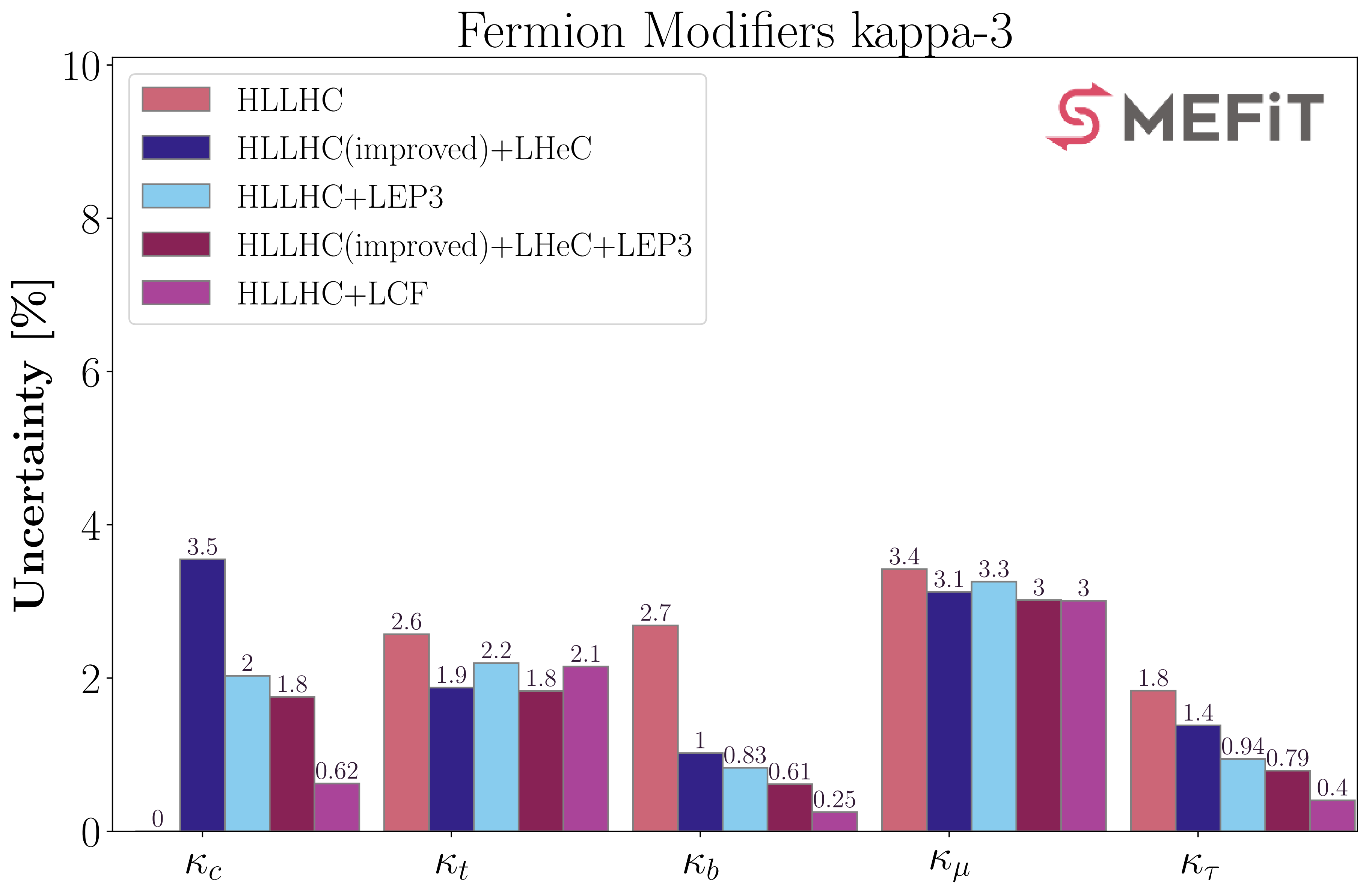


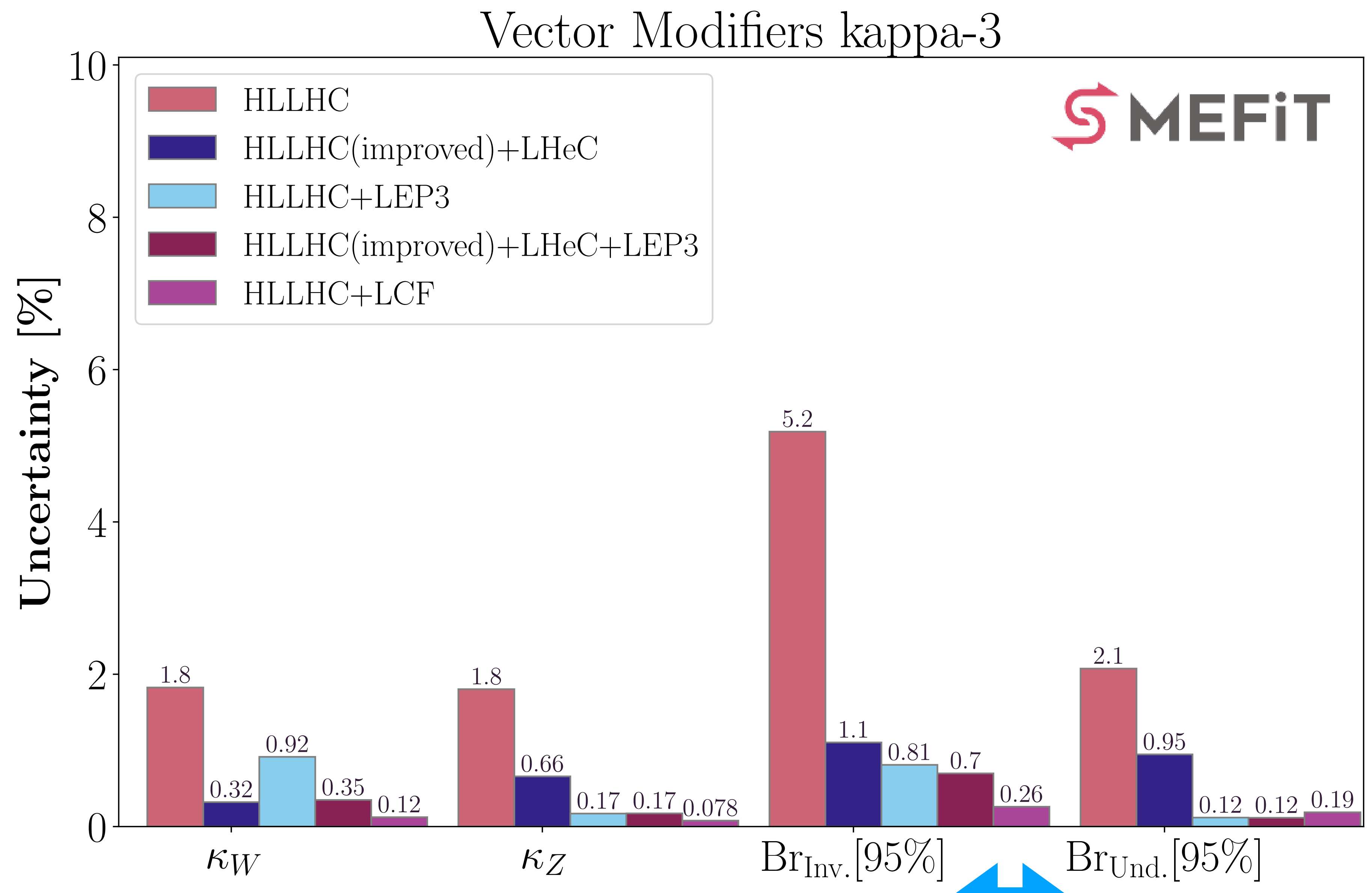


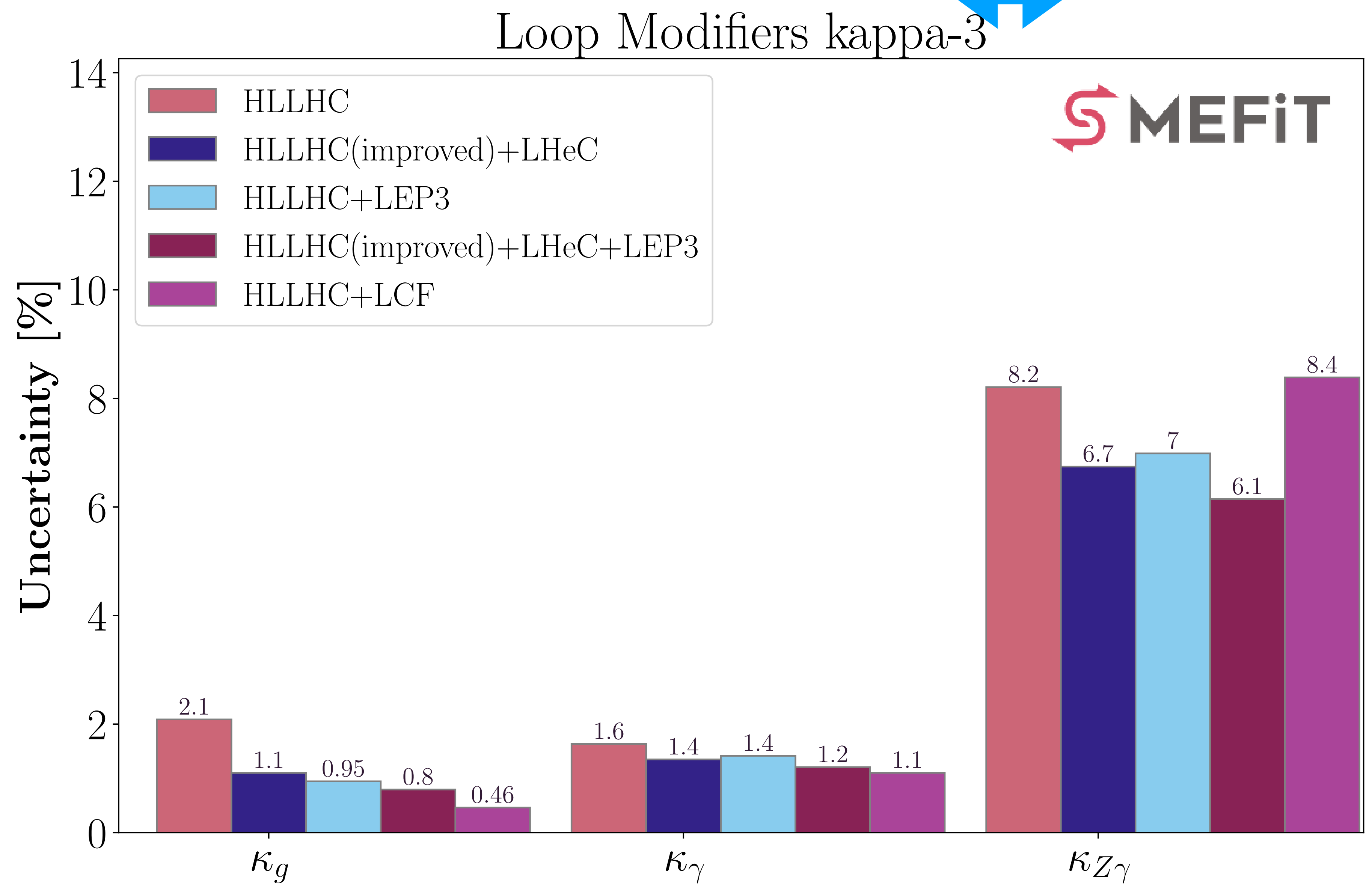
U. Klein at ICHEP2024

Higgs physics: κ-framework

SMEFiT, 2105.00006





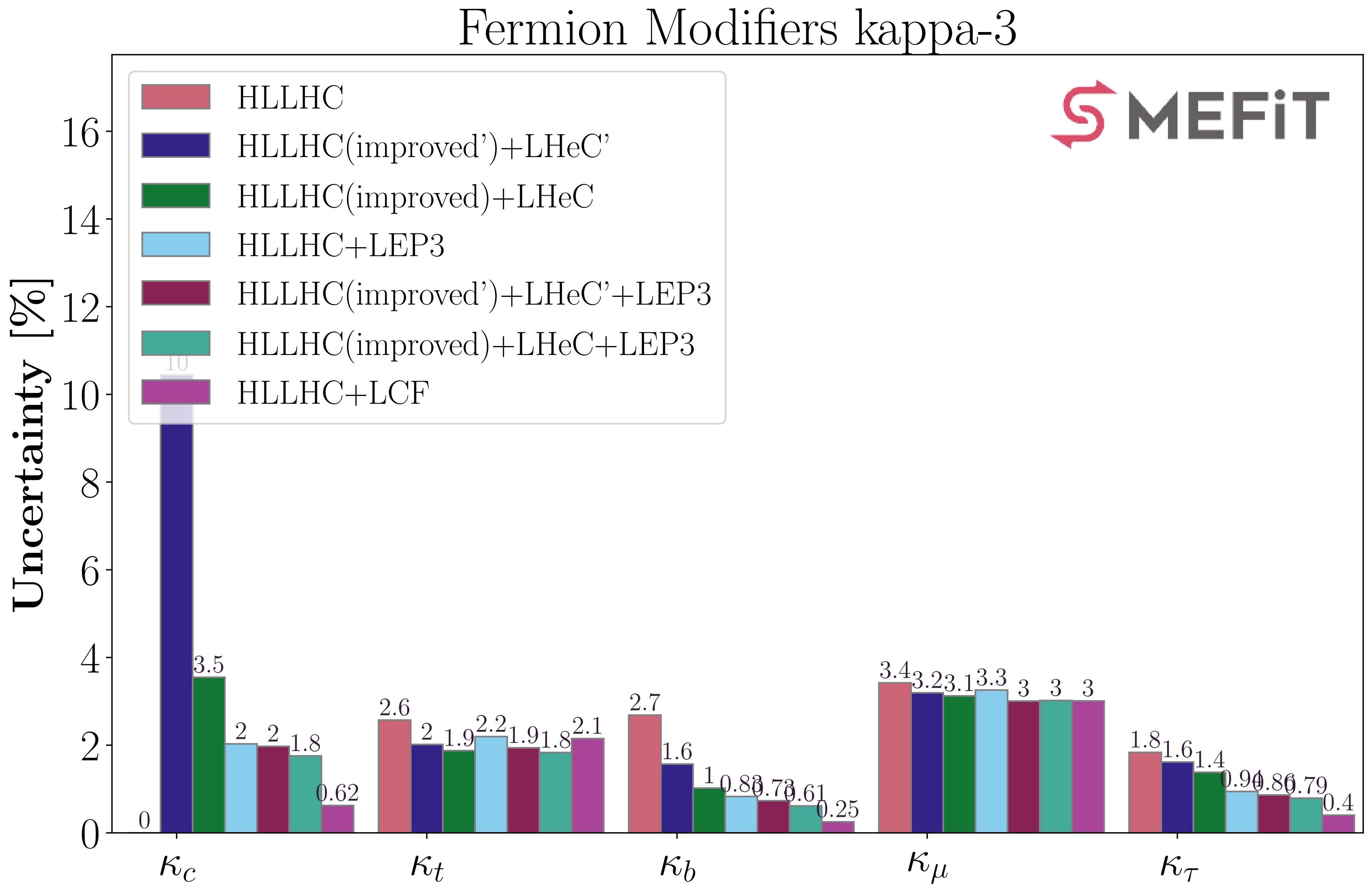


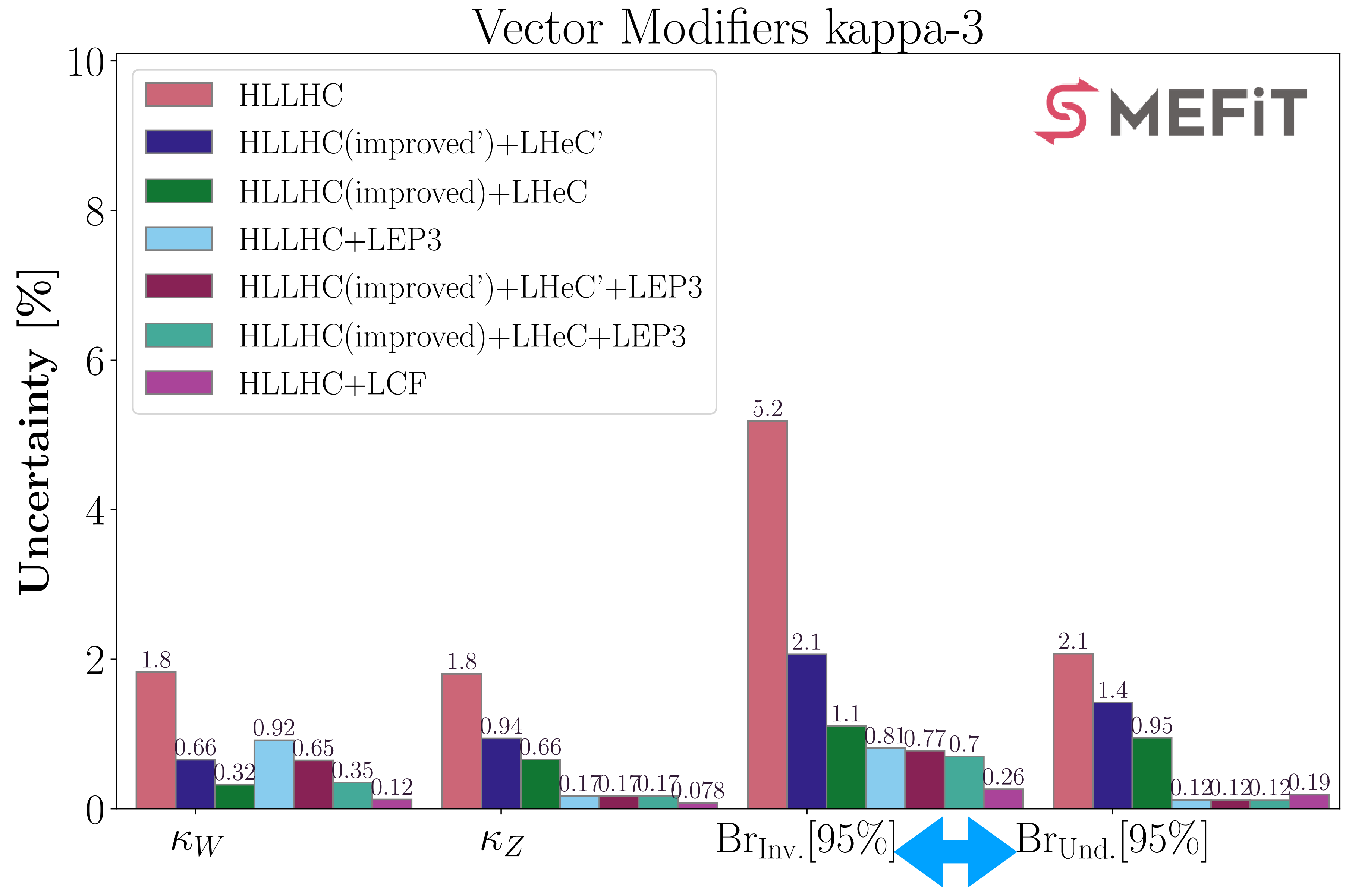
- LHeC combined with LEP3 versus LCF(all).

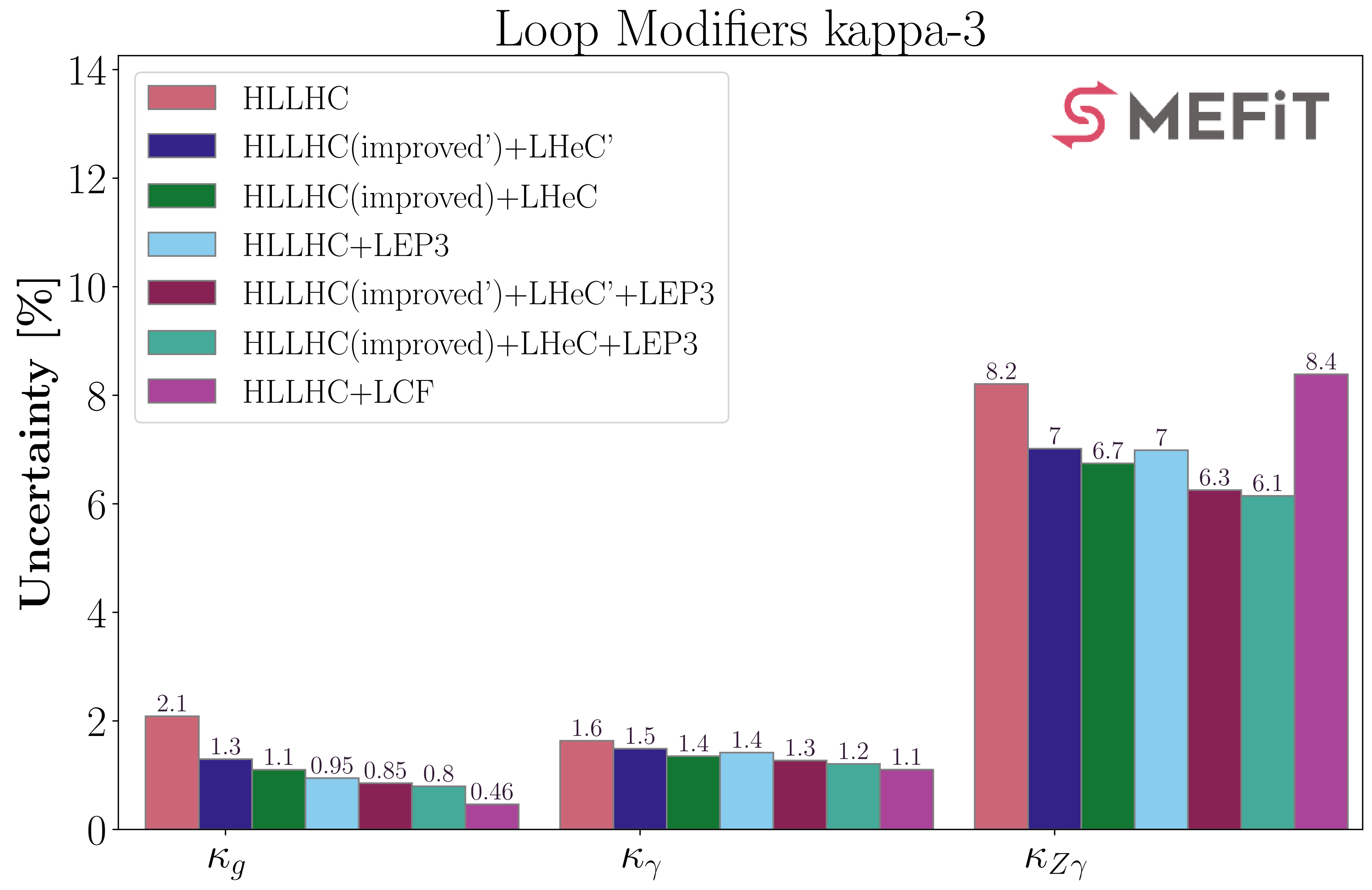
Note: latest HL-LHC projections (2504.00672) only change sizeably κ_μ, $\kappa_{Z\gamma}$ wrt. 2020 ESPP ones.

Higgs physics: κ-framework

SMEFiT, 2105.00006





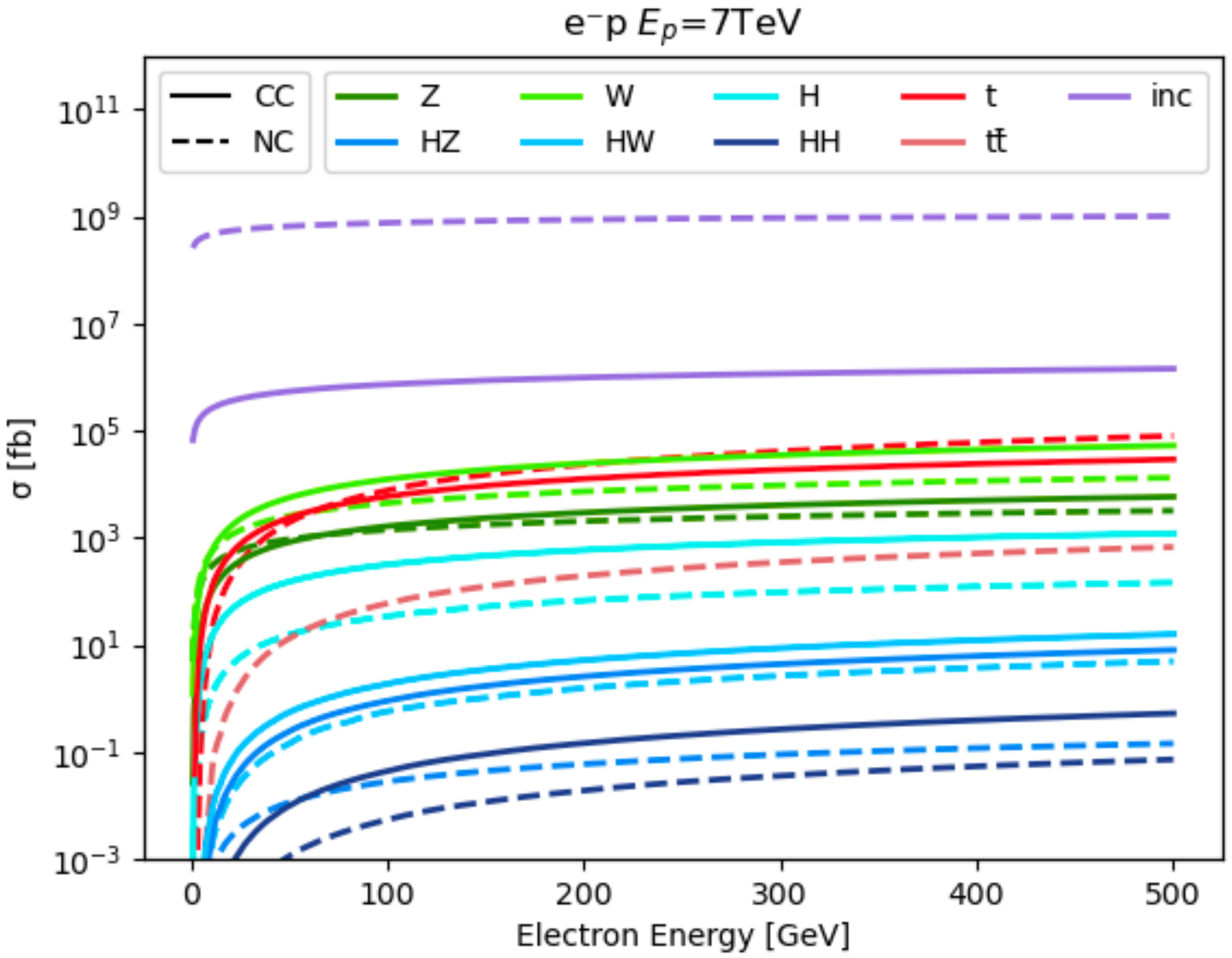


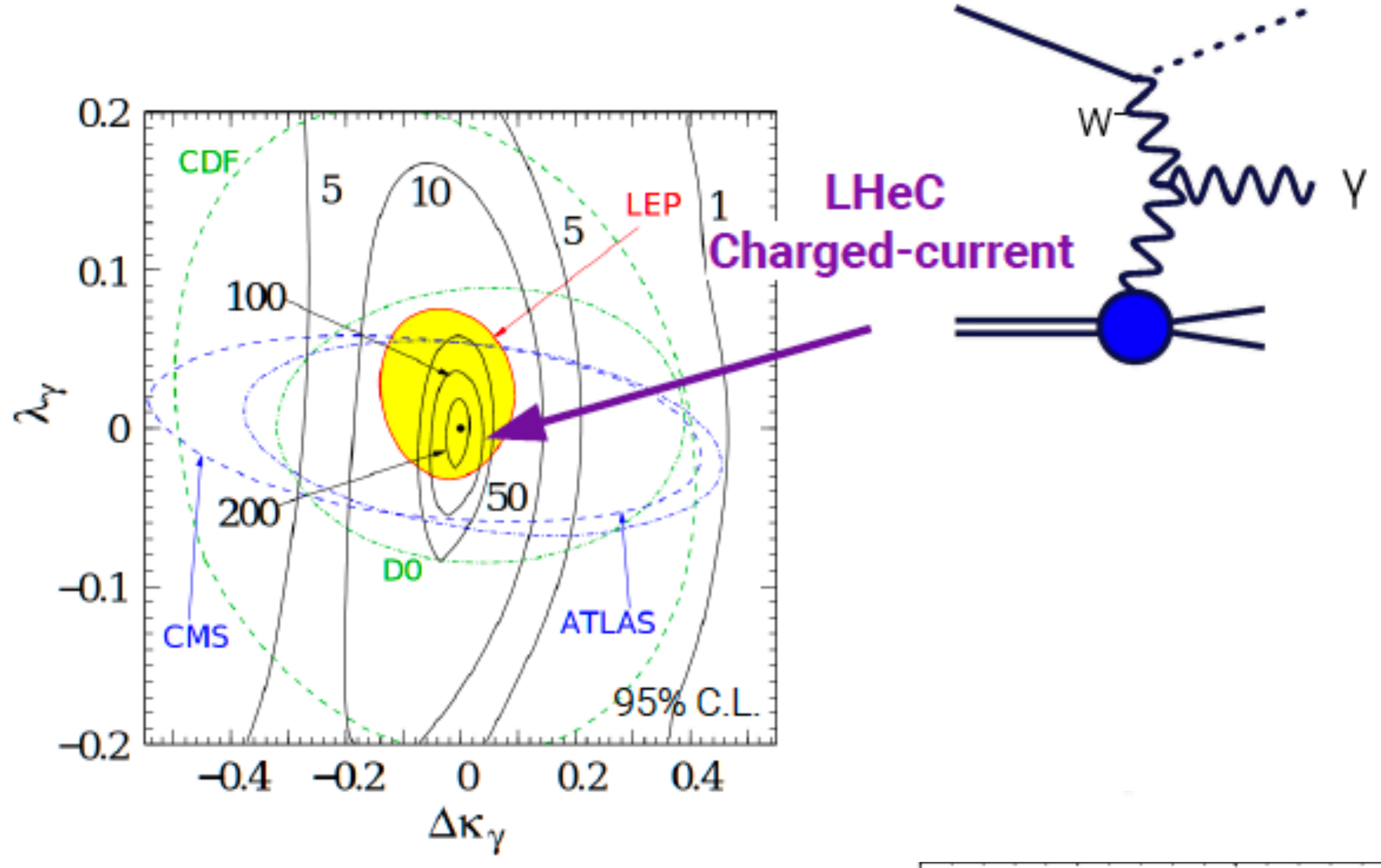
- LHeC': statistics reduced by a factor 10.

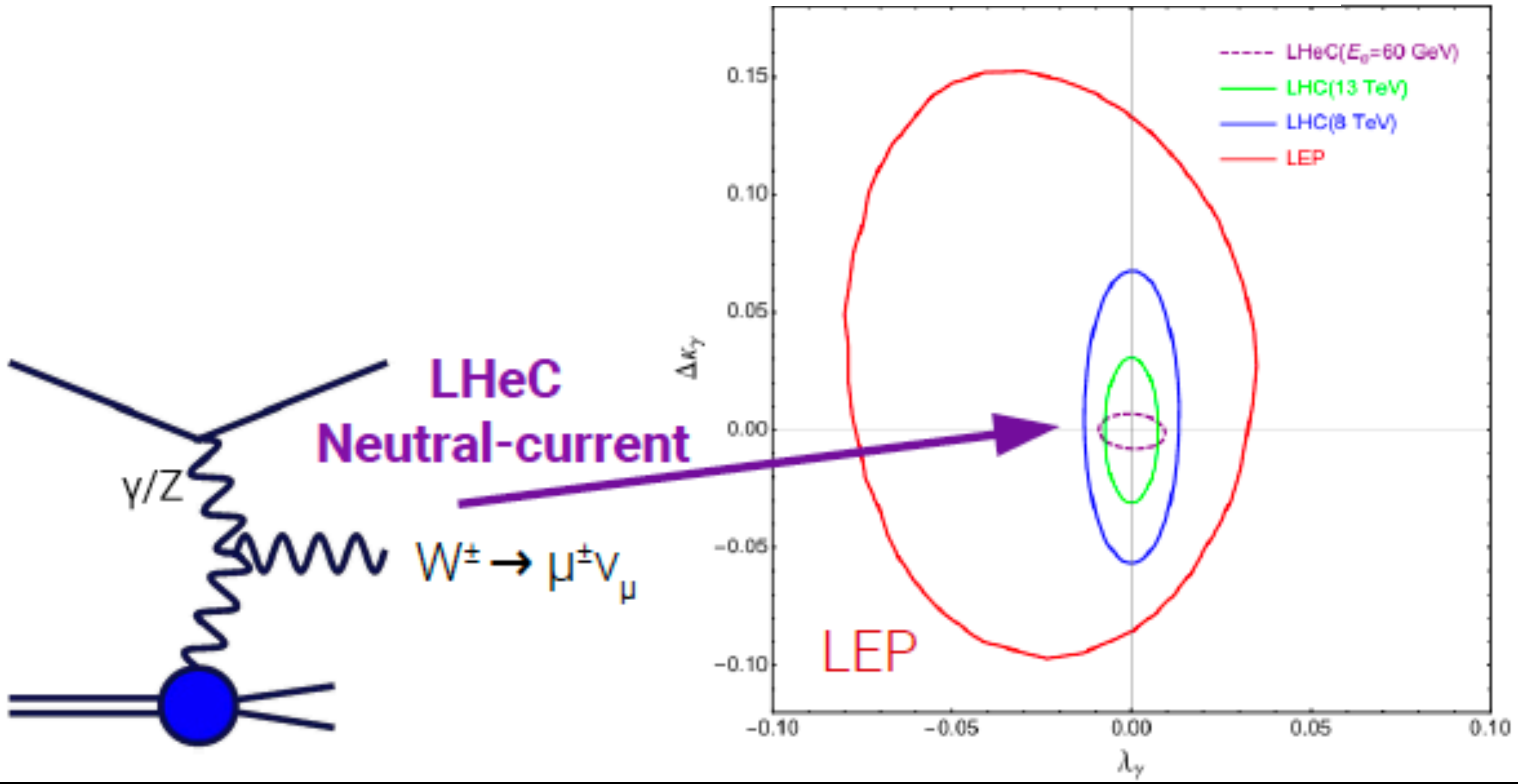
Note: latest HL-LHC projections (2504.00672) only change sizeably κ_μ, $\kappa_{Z\gamma}$ wrt. 2020 ESPP ones.

EW physics: triple and quartic gauge couplings

- Triple and quartic gauge couplings can be probed (D. Britzger, EPS-HEP2023) (also in $\gamma\gamma$ mode).







BSM physics: invisible Higgs

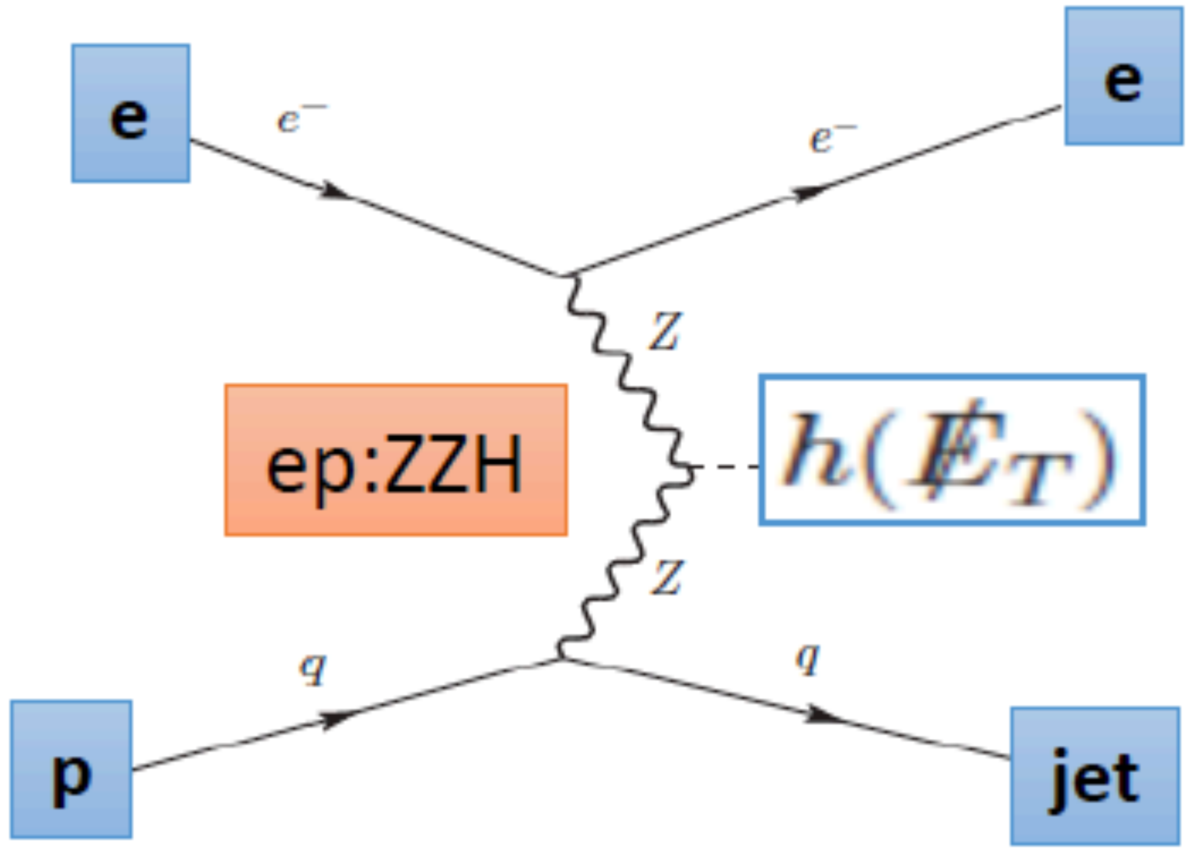
Stand alone Branching for invisible Higgs

Satoshi Kawaguchi,
Masahiro Kuze
Tokyo Tech

Values given in case of 2σ and L=1 ab^{-1}

Delphes detectors	LHeC [HE-LHeC] 1.3 [1.8 TeV]	FCC-eh 3.5 TeV
LHC-style	4.7% [3.2%]	1.9%
First 'ep-style'	5.7%	2.6%
+BDT Optimisation	5.5% (4.5%*)	1.7% (2.1%*)

LHeC parton-level, cut based <6% [Y.-L.Tang et al. arXiv: 1508.01095]



PORTAL to Dark Matter ?

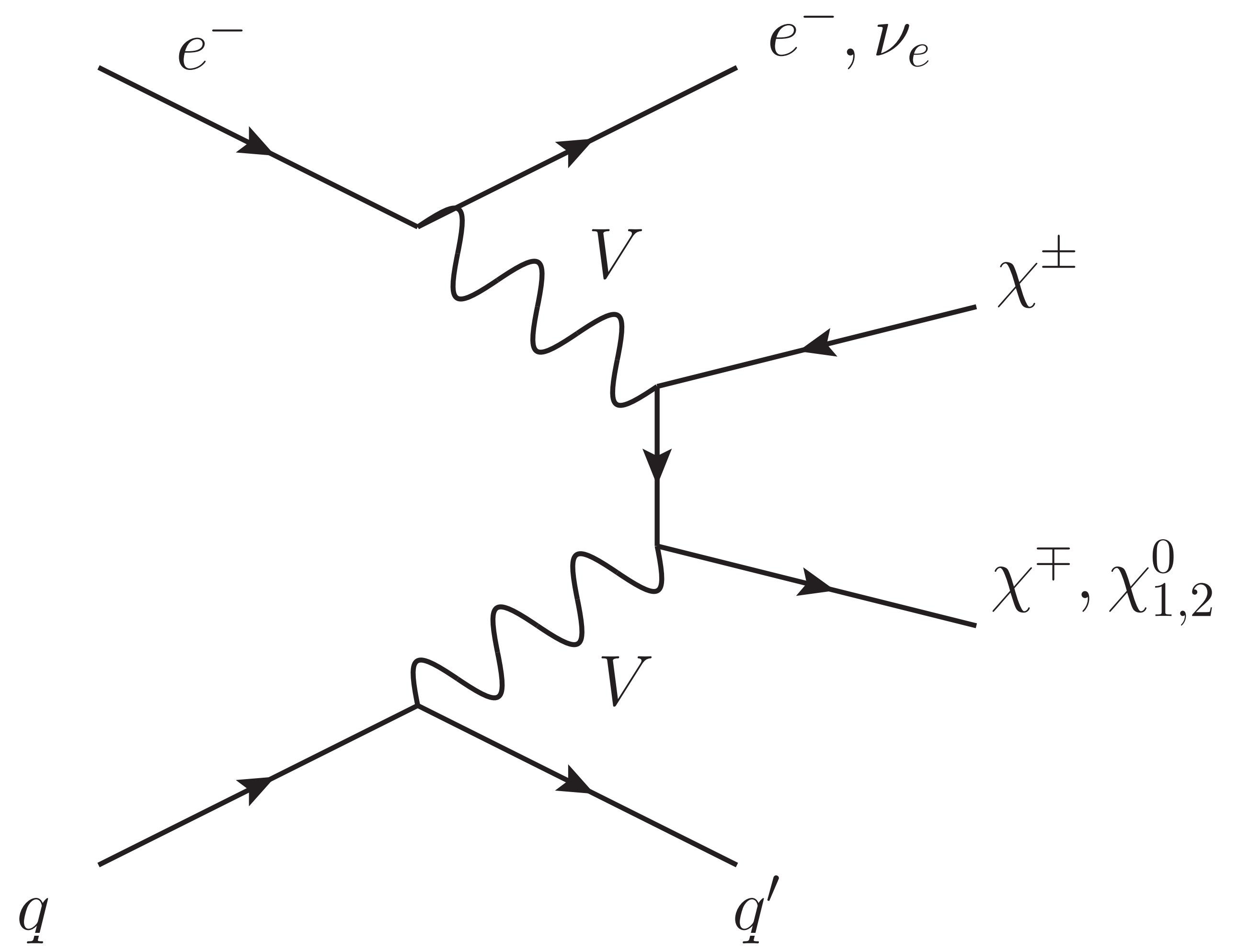
Uta Klein at LHeC/FCC-eh/PERLE workshop 2022

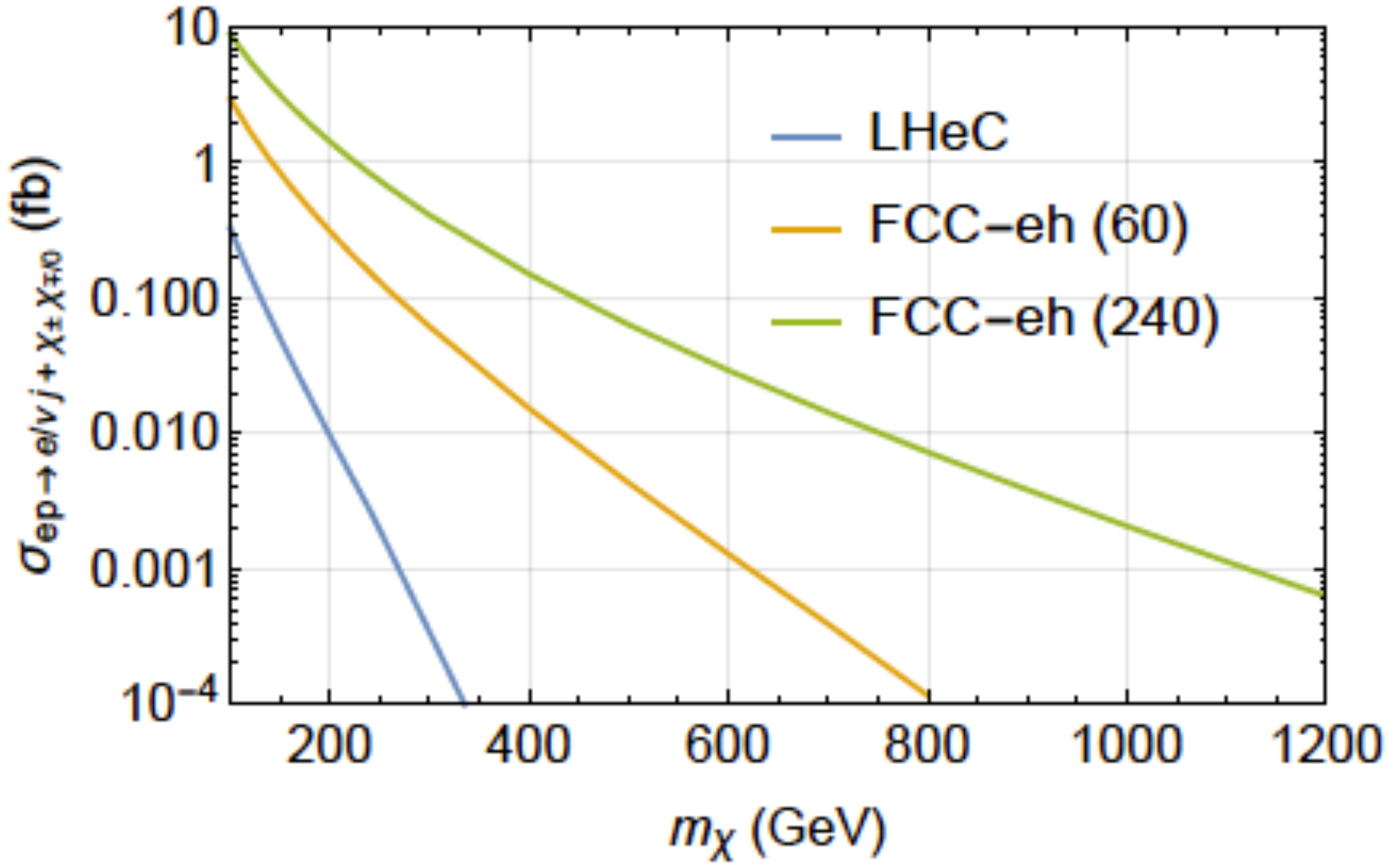
- ✓ **Uses ZZH fusion process to estimate prospects of Higgs to invisible decay using *standard cut/BDT analysis techniques focused on a stand alone determination***
- ✓ **Full MG5+Delphes analyses, done for 3 c.m.s. energies → very encouraging for a measurement of the branching of Higgs to invisible in ep down to 5%** [1.2%] **for 1** [2] **ab^{-1} for LHeC** [FCC-eh]

- Sub-percent branching ratios H → 2 scalar LLP can be tested (2008.09614).

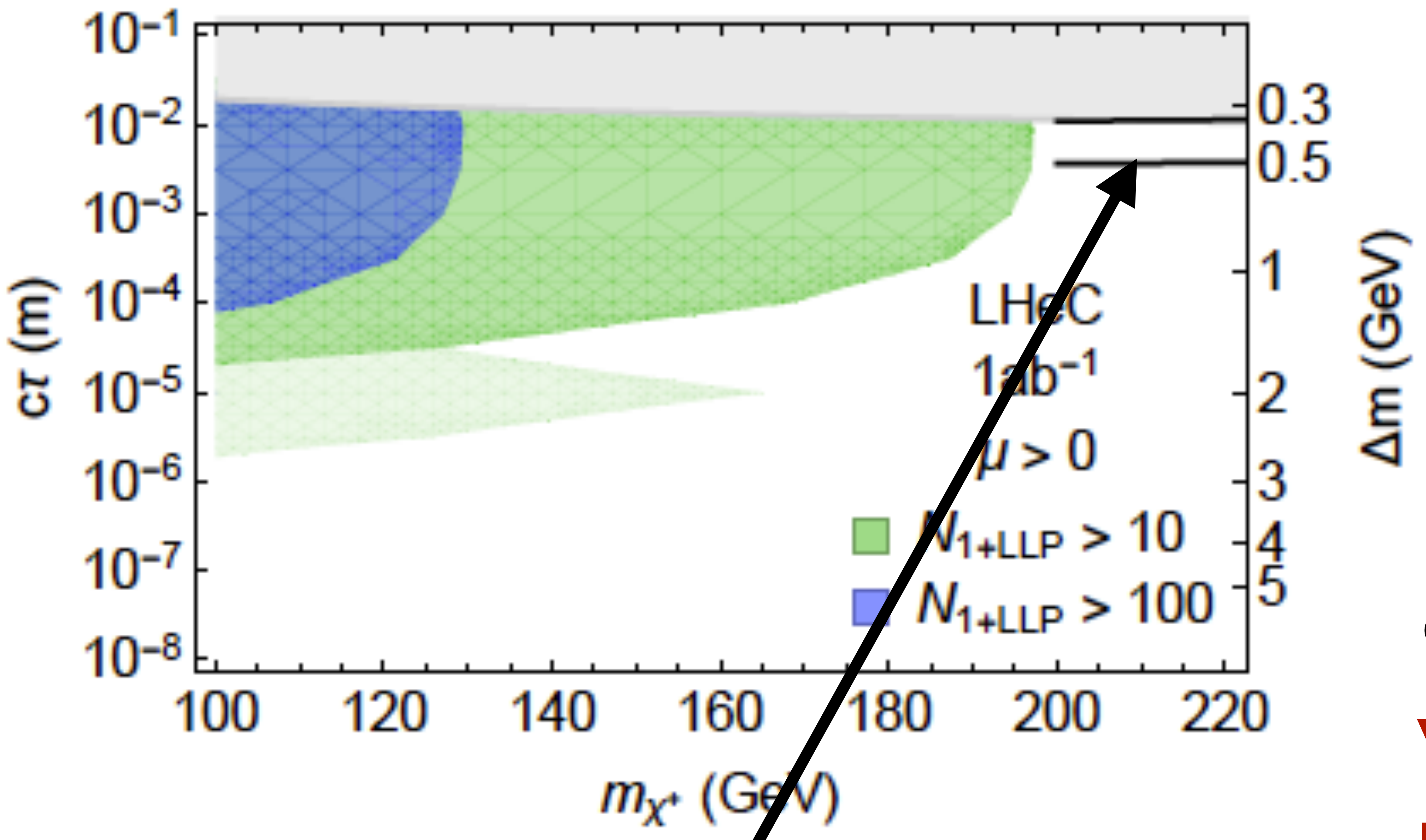
BSM physics: disappearing tracks

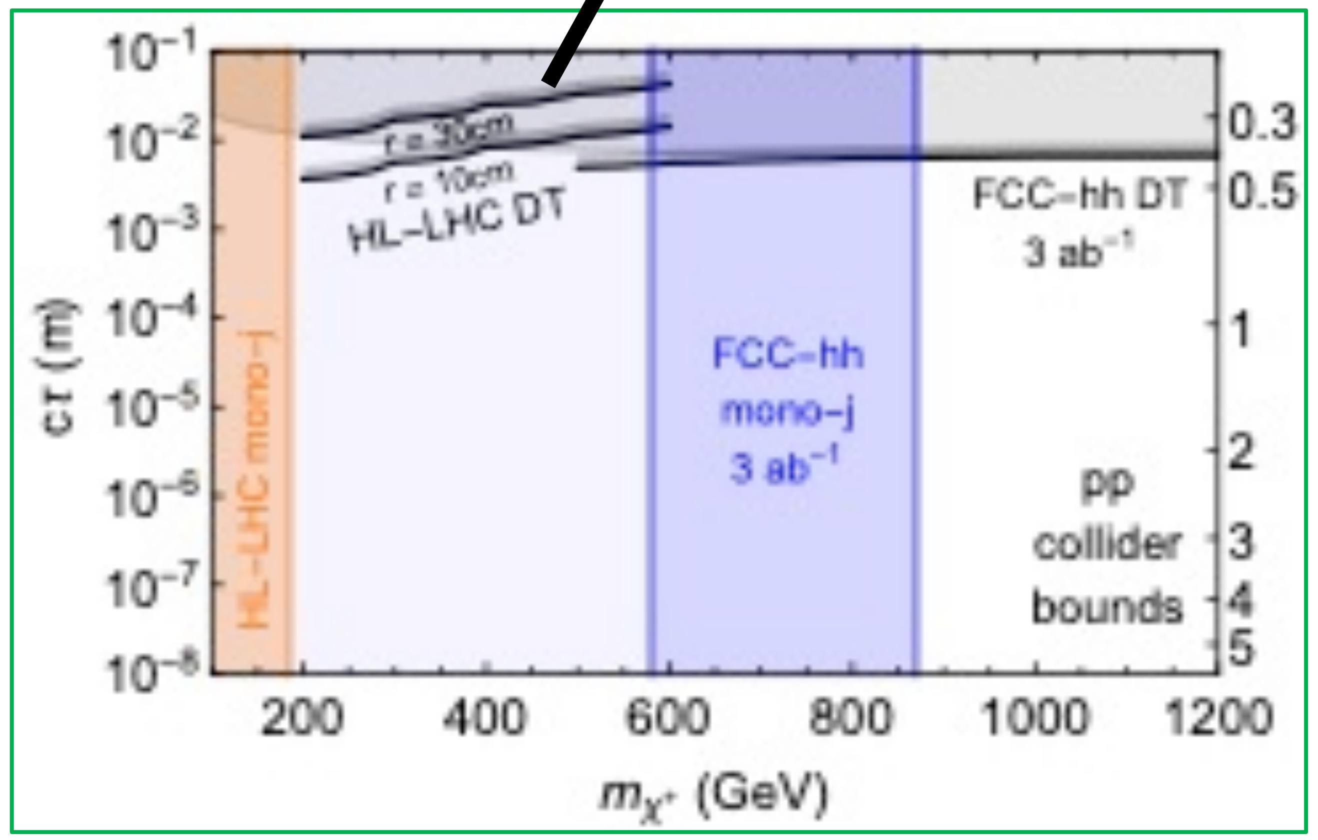
- Searches for Higgsinos with masses $\mathcal{O}(100)$ GeV appearing in natural SUSY theories, through disappearing tracks.





1712.07135





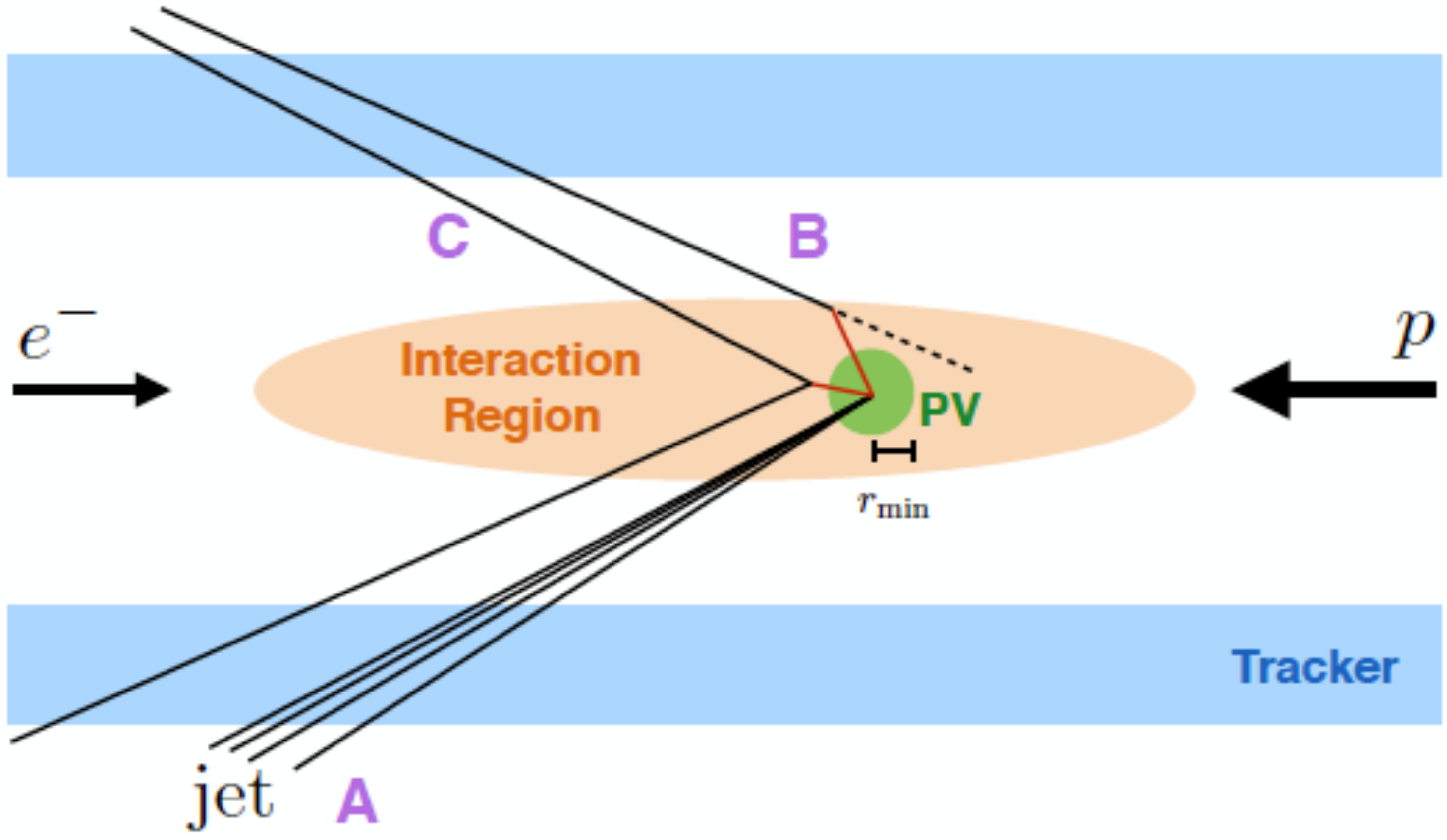
green (blue) region: 2σ sensitivity estimate in the presence of τ backgrounds; 10 (100) events with LLP observed.

- Larger sensitivity to very short lifetimes than pp colliders.

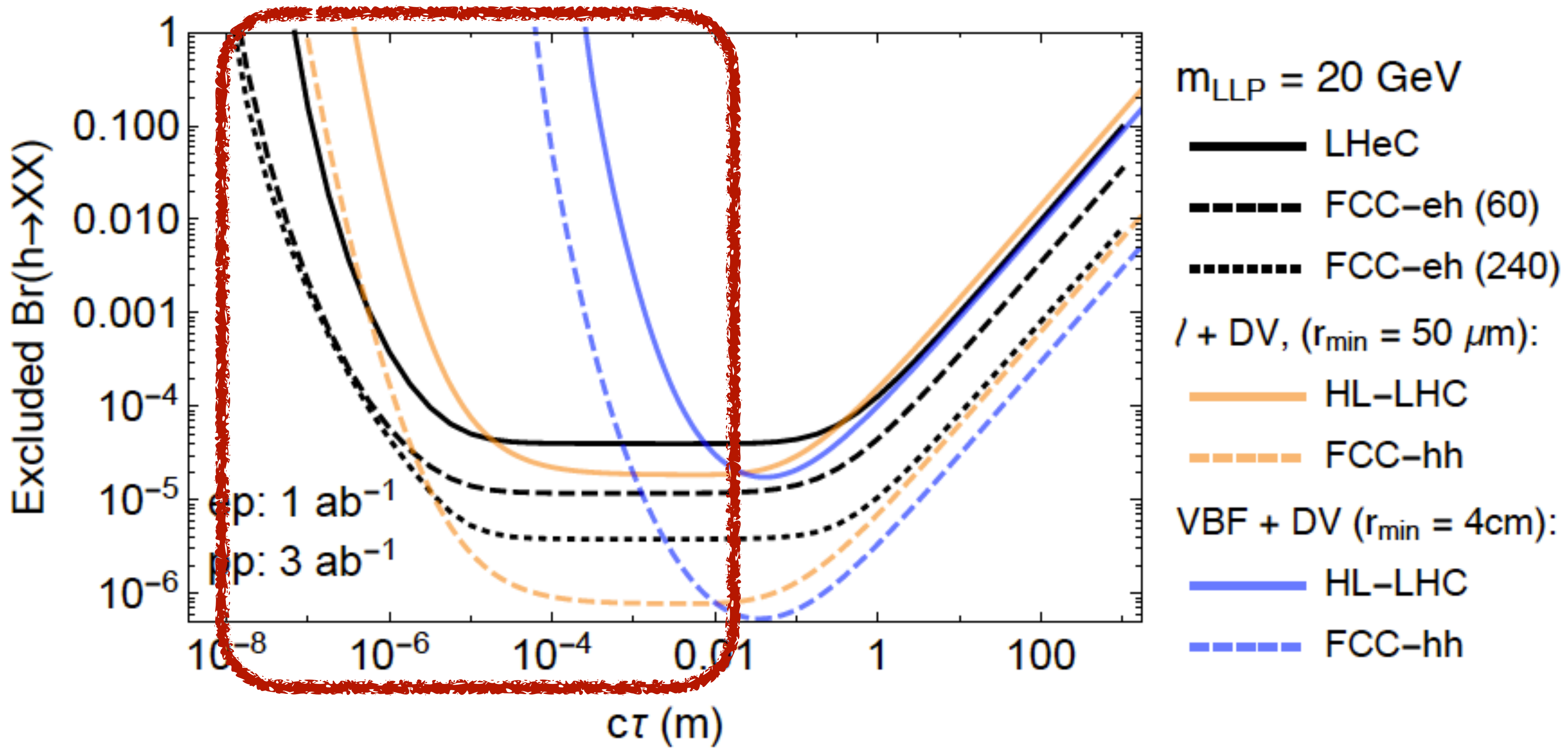
black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic)

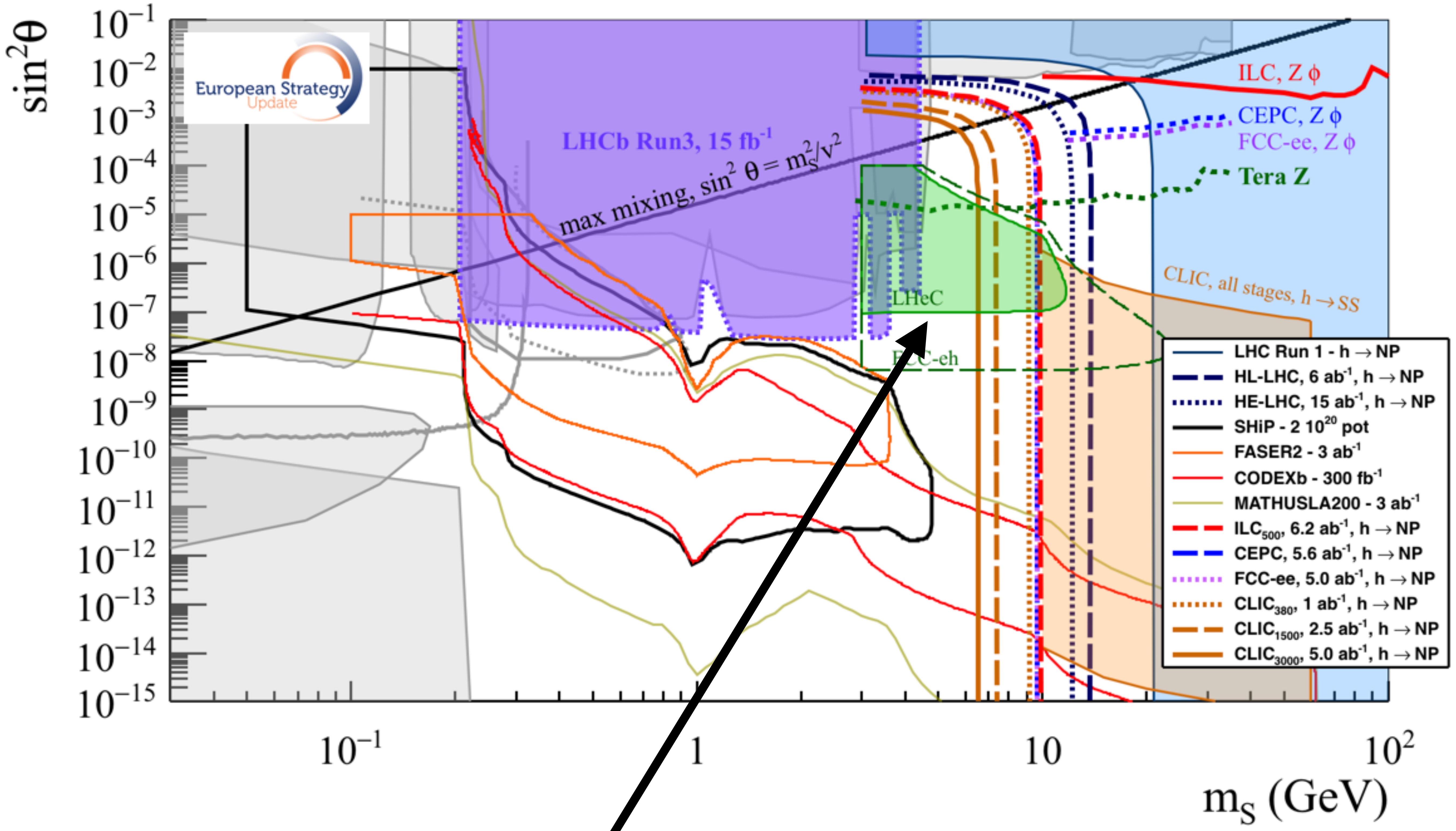
BSM physics: new scalars from Higgs

- New exotic scalars (X) from Higgs decay: displaced signatures if long-lived.
- X → 2+ charged particles above p_T threshold to identify DV and $r > r_{min}$ from PV: LLP.



Improvements wrt HL-LHC

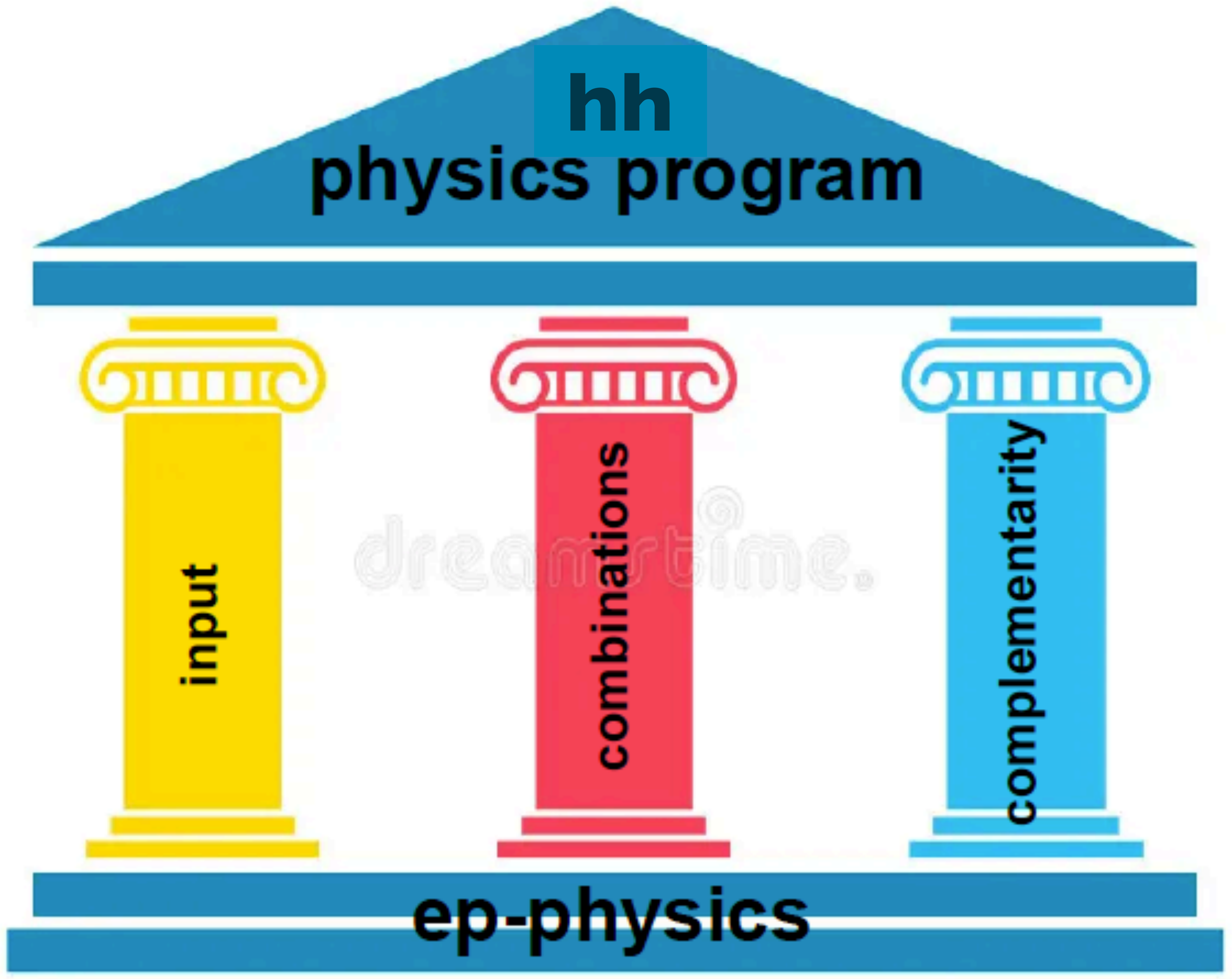




Covering regions between pp and e^+e^- / low energy experiments (2020 ESPP plot)

Synergies between eh and hh programes:

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



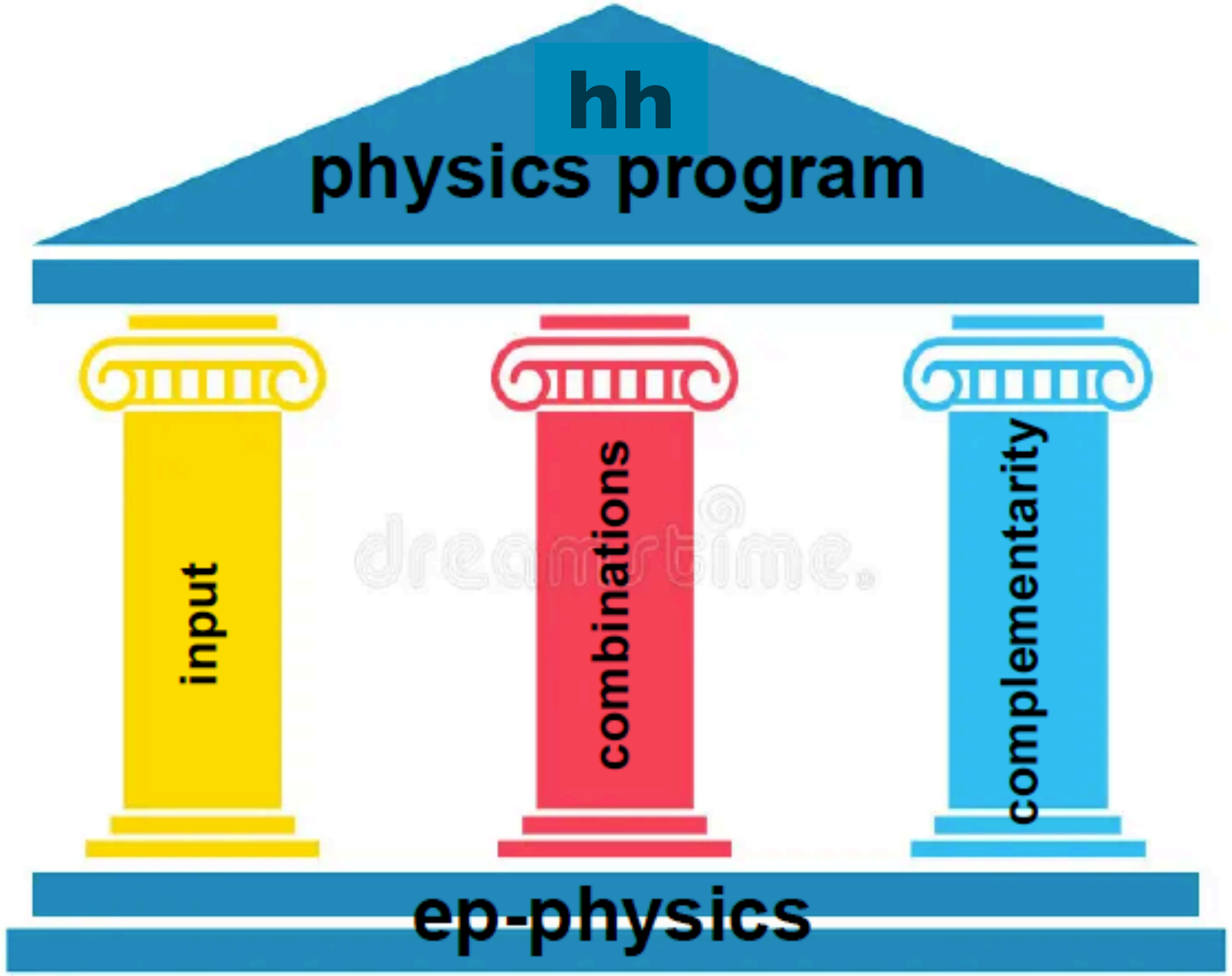
ep analyses with sensitivity complementary to hh analyses to complete the overall hh physics program

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

Synergies between eh and hh programes:

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

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



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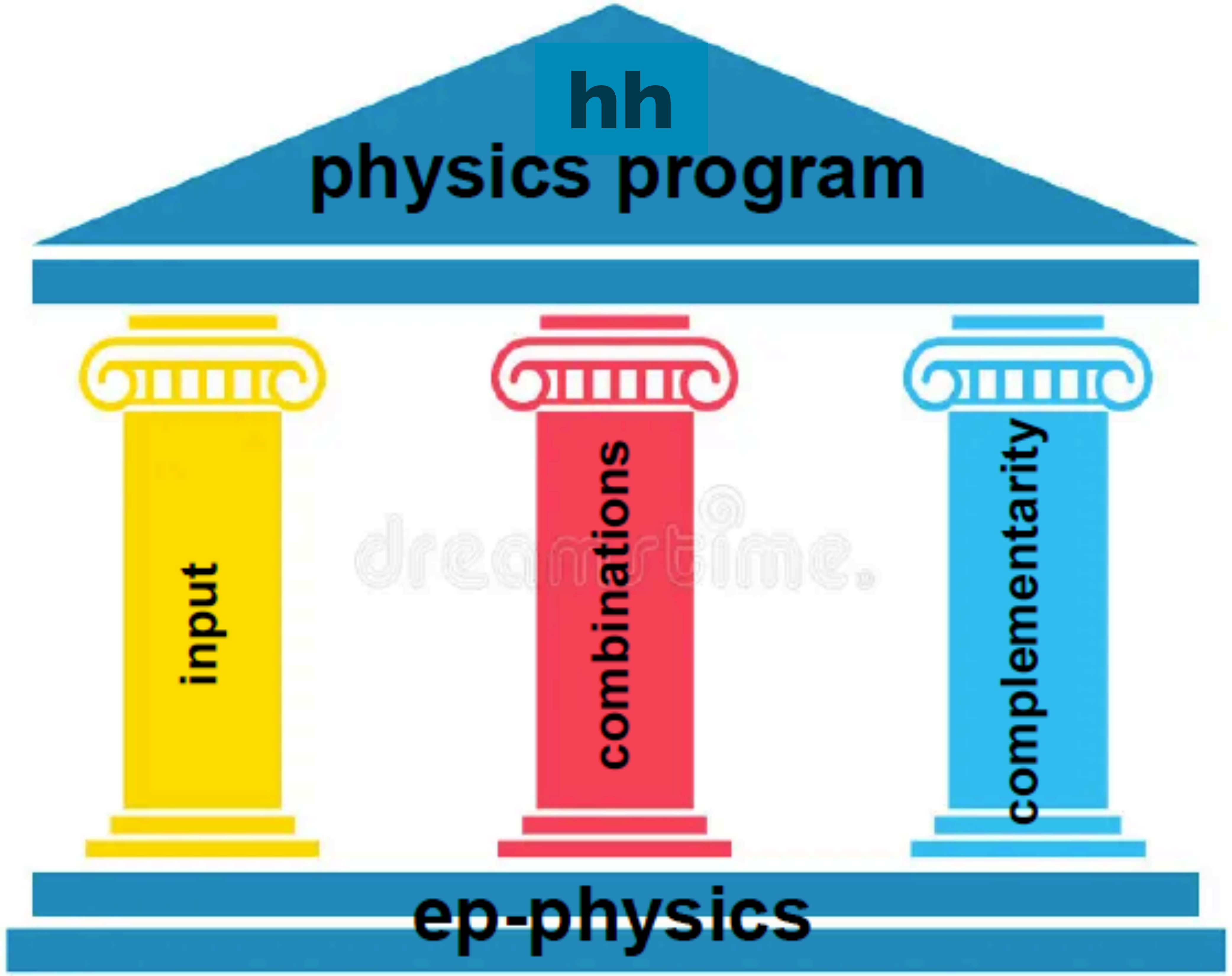

ep analyses with sensitivity complementary to hh analyses to complete the overall hh physics program

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

→ Competitive measurements and combination of results.
→ Uncorrelated uncertainties.
→ Resolve common/correlated expt. uncertainties.
→ Resolve correlations in parameters of interest.
→ Empowers global fits.

Synergies between eh and hh programes:

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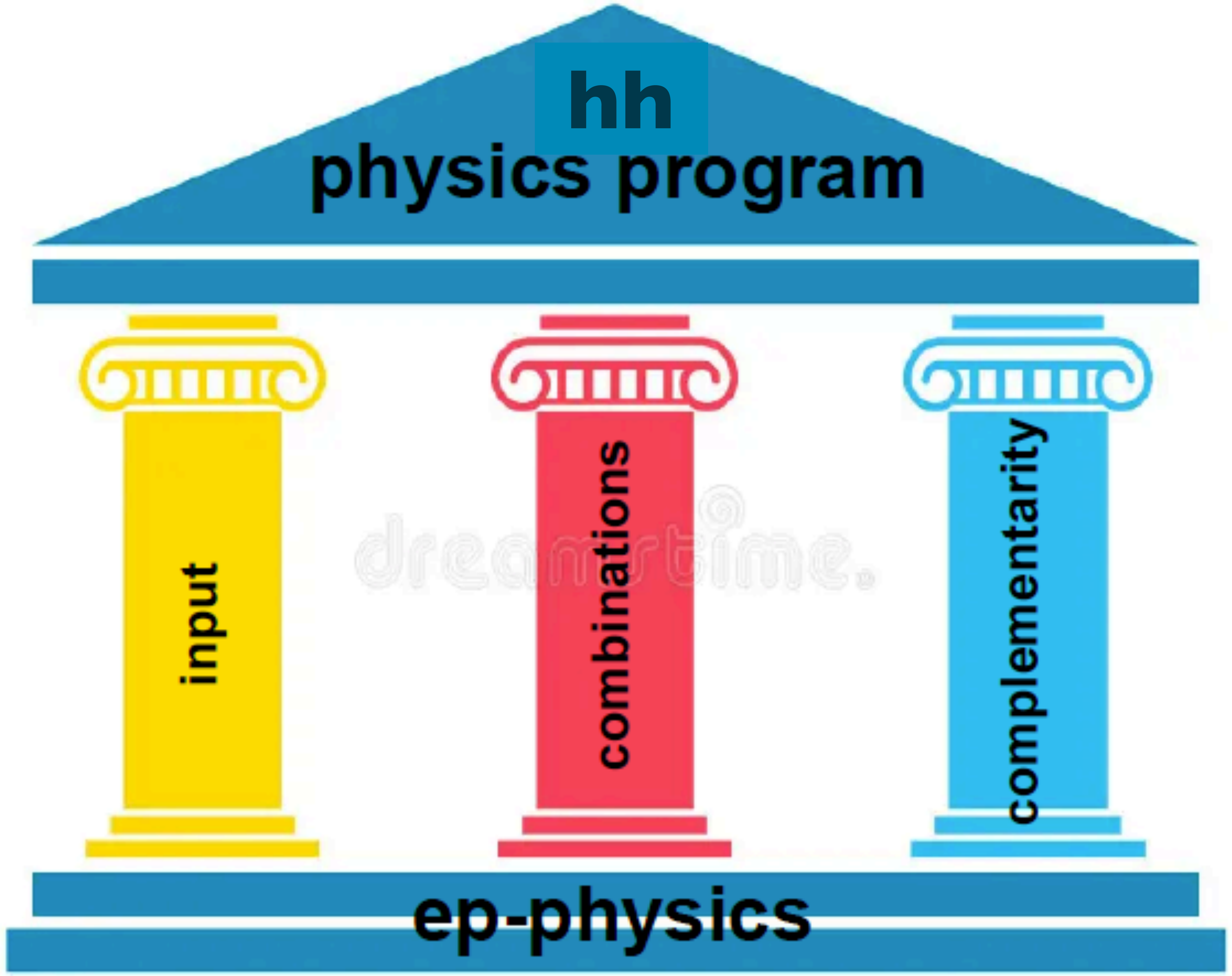


ep analyses with sensitivity complementary to hh analyses to complete the overall hh physics program

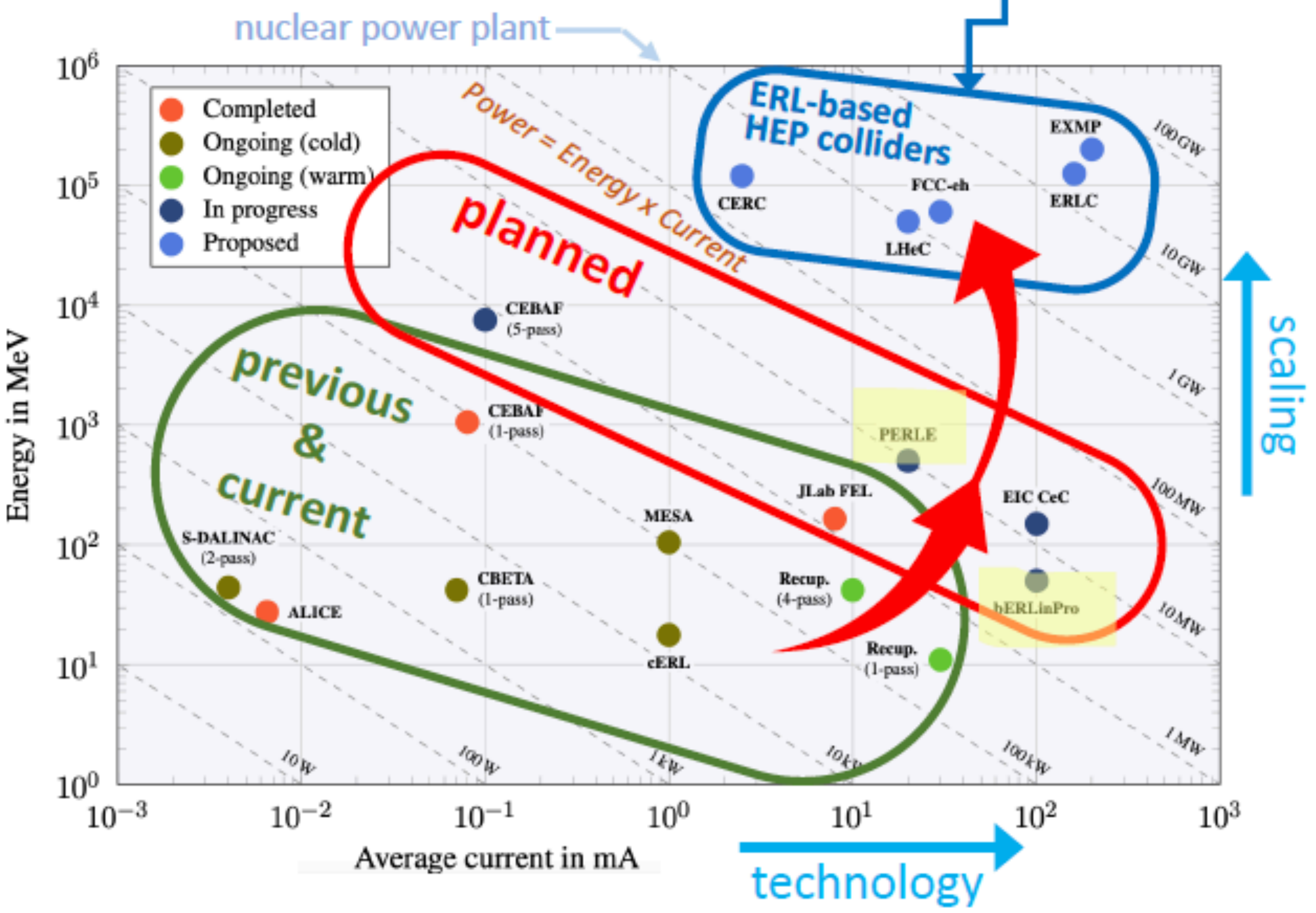
→ High precision QCD analyses.
→ High precision measurements of specific parameters.
→ Searches in complementary phase space regions.

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

→ Competitive measurements and combination of results.
→ Uncorrelated uncertainties.
→ Resolve common/correlated expt. uncertainties.
→ Resolve correlations in parameters of interest.
→ Empowers global fits.

ERL:

ERL to enable high-power beams that would otherwise require one or more nuclear power plants



Future ERL-based Colliders

H, HH, ep/eA, muons, …

bERLinPro & PERLE

essential accelerator R&D labs with ambitions overlapping with those of the particle physics community

towards high power

Energy Recovery demonstrated

great achievements on all aspects and large research infrastructures based on Energy Recovery systems have been operated successfully

Slide by J. D'Hondt

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