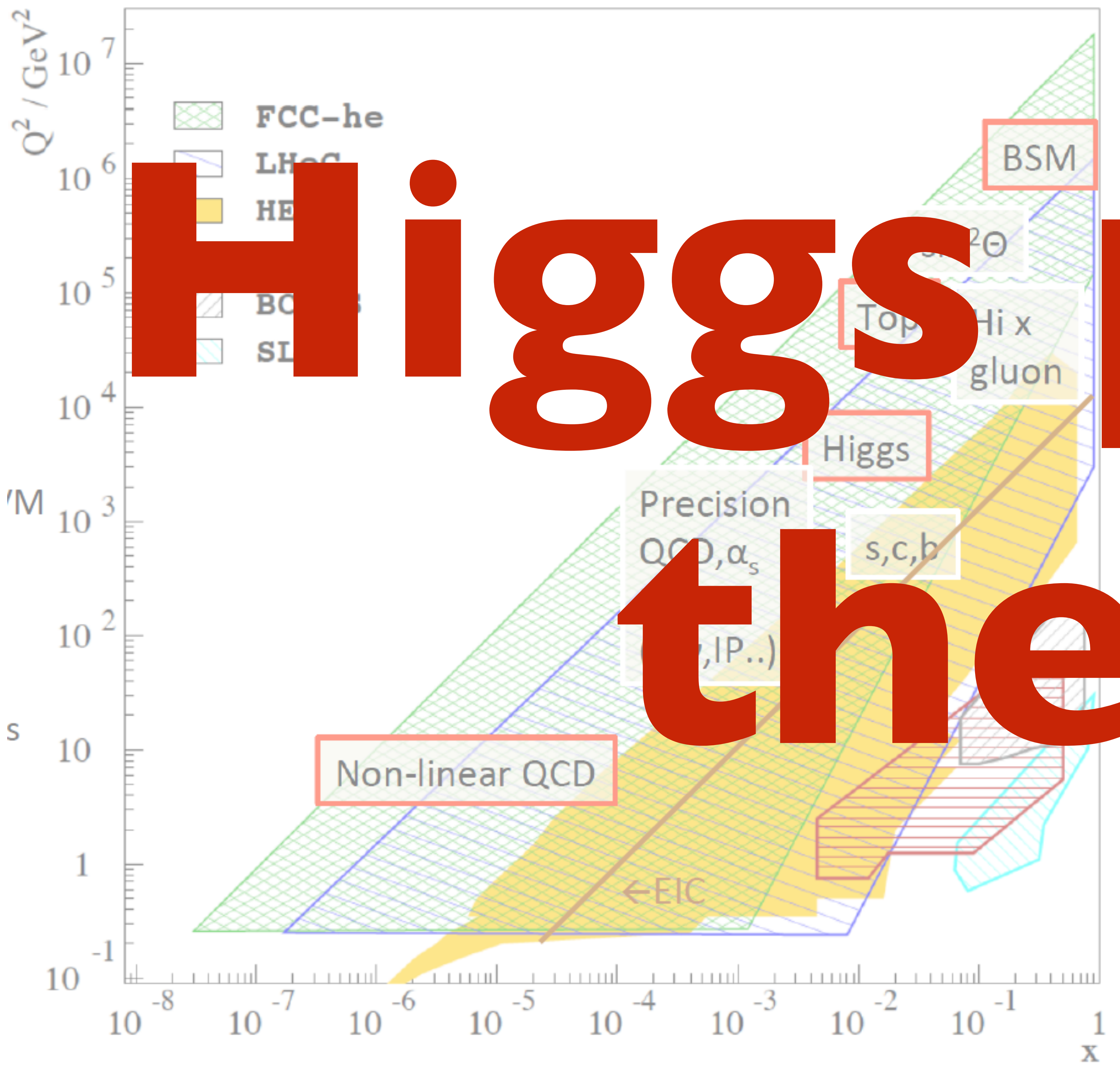
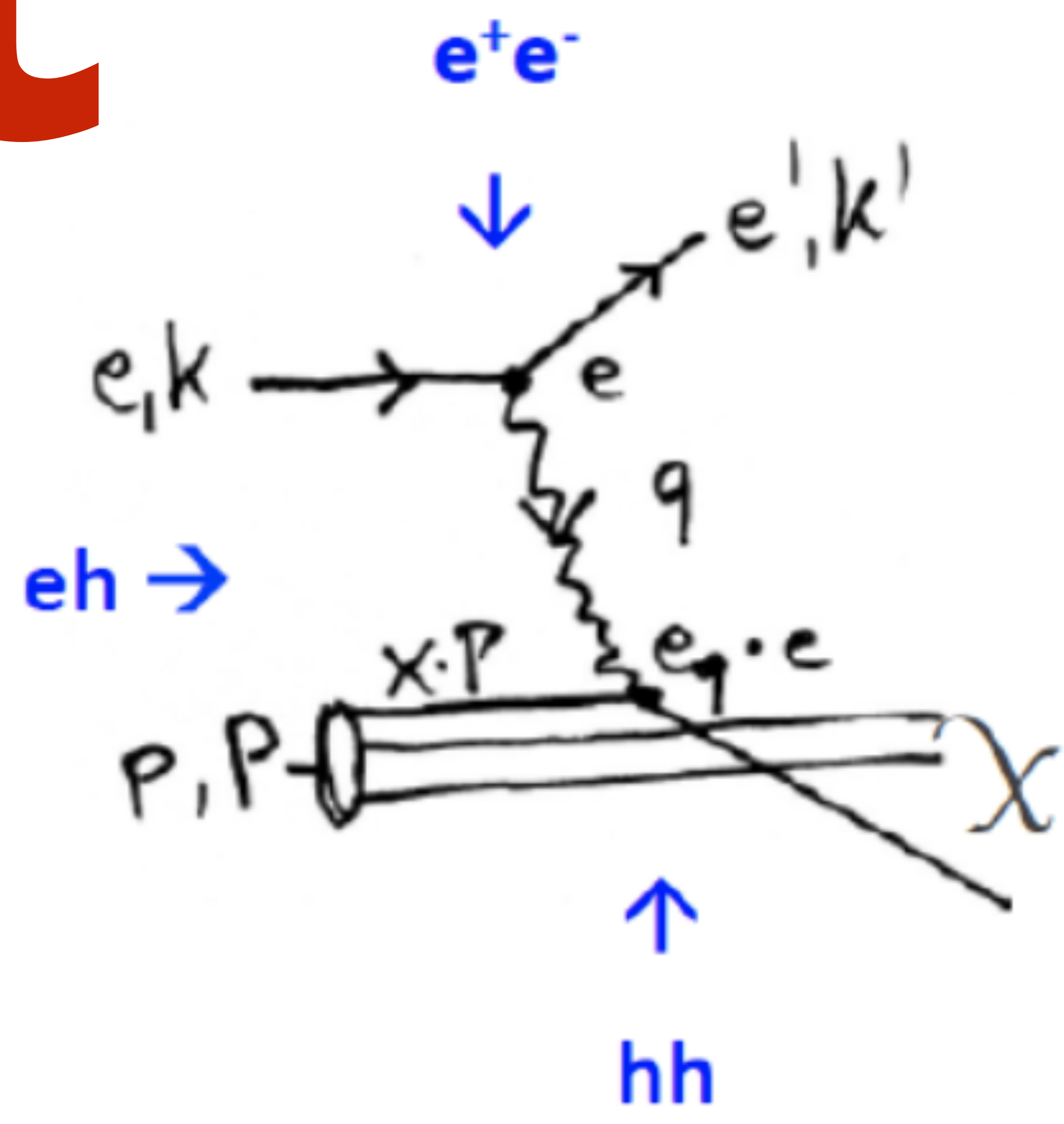
Higgs physics at the LHeC

2025 European Physical Society Conference on High Energy Physics
Marseille, July 11th 2025





Néstor Armesto

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

Contents:

1. Introduction.

2. Higgs physics:
   - ➜ Cross sections and yields.
   - ➜ Studies.
   - ➜ Couplings.
   - ➜ QCD effects on Higgs.

3. Summary.

Further talks at EPS-HEP 2025:

- BSM physics at the LHeC and the FCC-eh, 8 Jul 2025, 17:30, Christian Schwanenberger, T09.
- The LHeC collider as a bridge between major colliders at CERN, 9 Jul 2025, 08:30, Jorgen D'Hondt, T13.
- A detector for top energy DIS (poster), Laurent Forthomme, T11.
- Top and EW physics at the LHeC, 11 Jul 2025, 09:10, Christian Schwanenberger, T06.
- Two-photon processes in future electron-hadron facilities, 11/07/2025, 09:30, Laurent Forthomme, T06.
- QCD at the LHeC, 11 Jul 2025, 10:25, Néstor Armesto, T05.

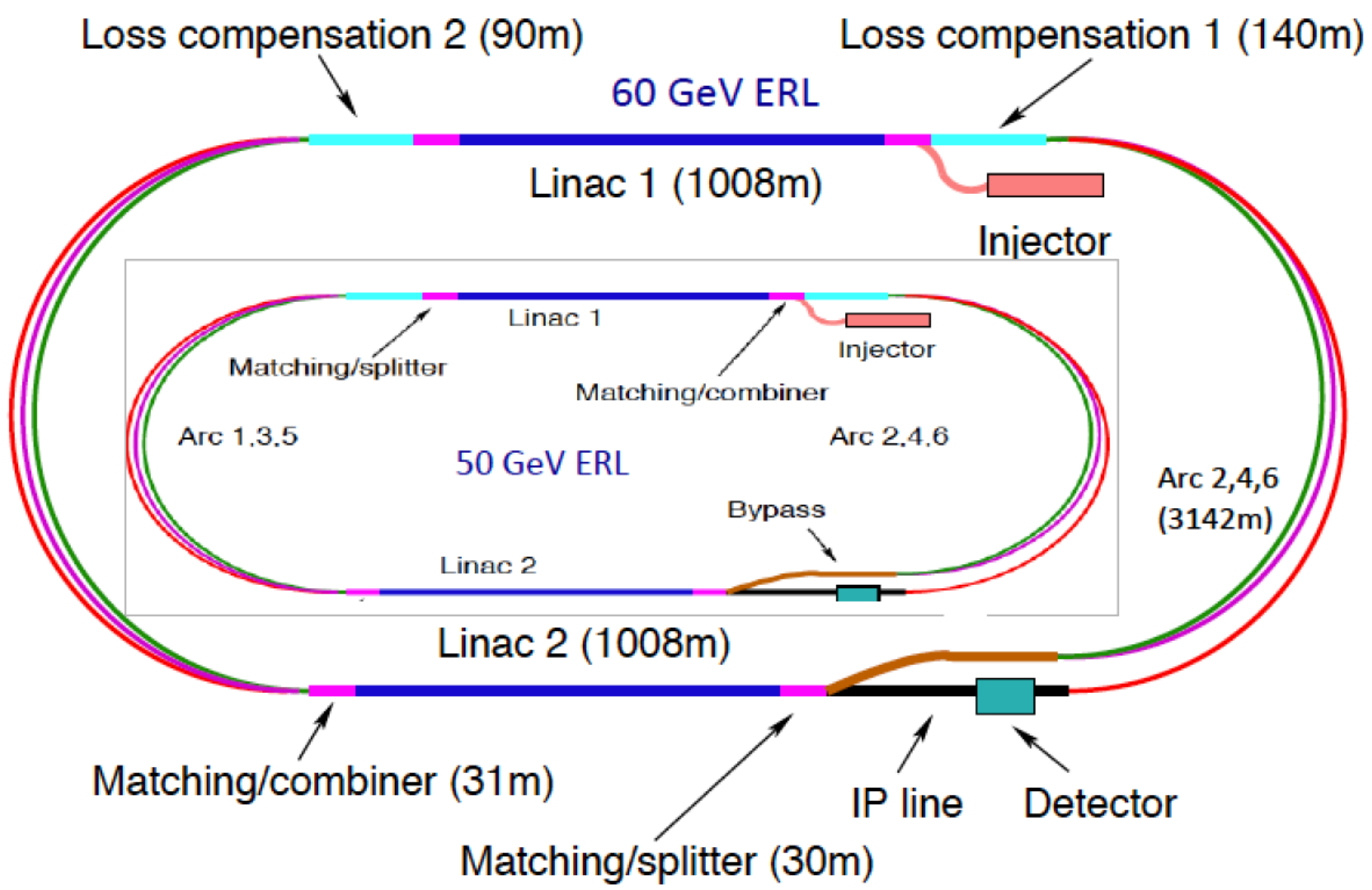
References:

- *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;*
- *European Strategy Update: Briefing Book, 1910.11775;*
- *Update of the 2012 LHeC CDR, 2007.14491;*
- *2201.02436;*
- *LHeC/FCC-eh talks at ICHEP2024, https://indico.cern.ch/event/1291157/, and DIS2025, https://indico.cern.ch/event/1436959/.*
- *Talks at the Synergy workshop between ep/eA and pp/pA/AA physics experiments, February 29th-March 1st 2024, https://indico.cern.ch/event/1367865/.*
- ***White paper: 2503.17727**, annex to the EPPS submission.*

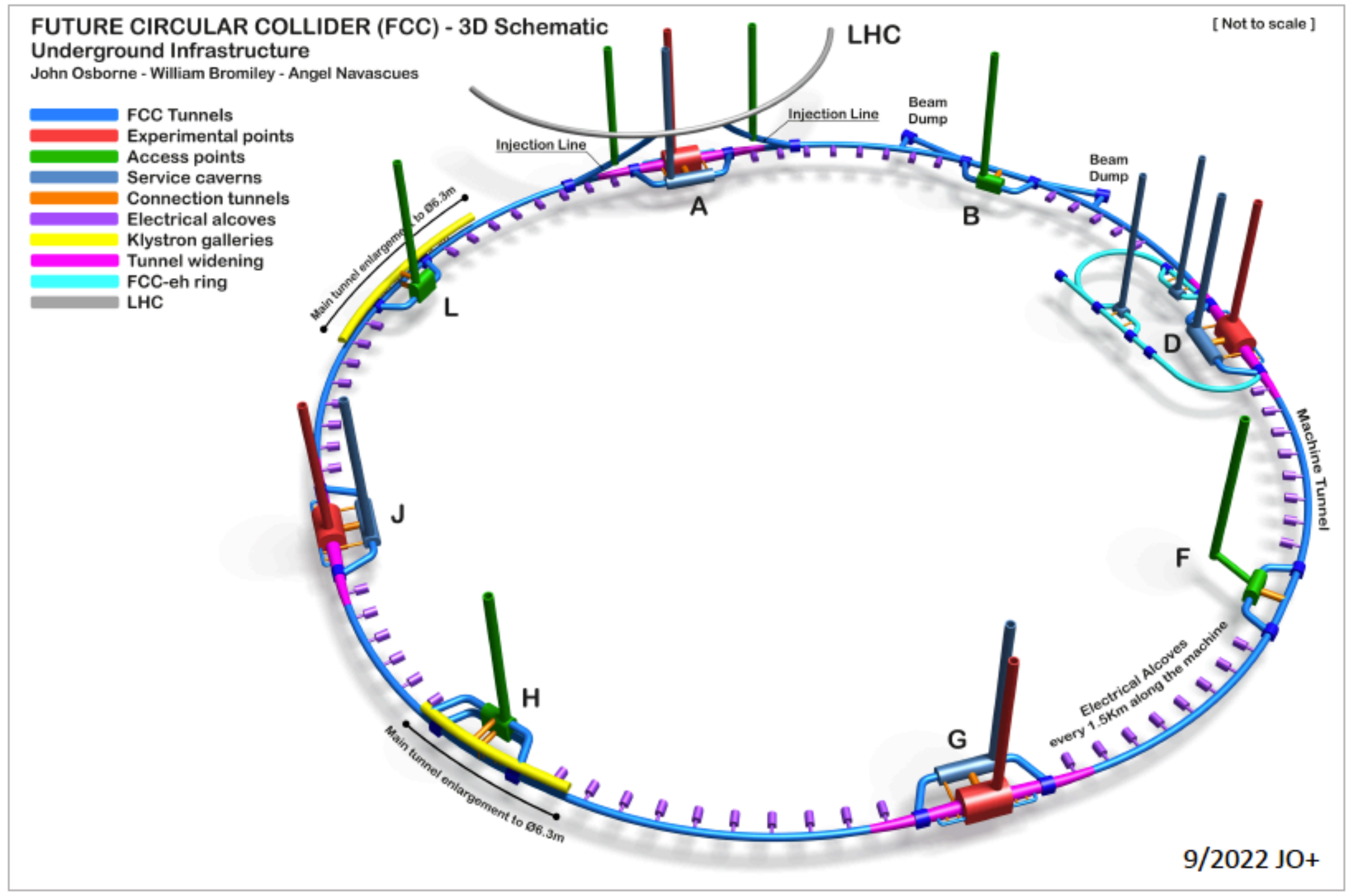
https://indico.cern.ch/event/lhecfcceh

Accelerators:

LHeC



FCC-eh



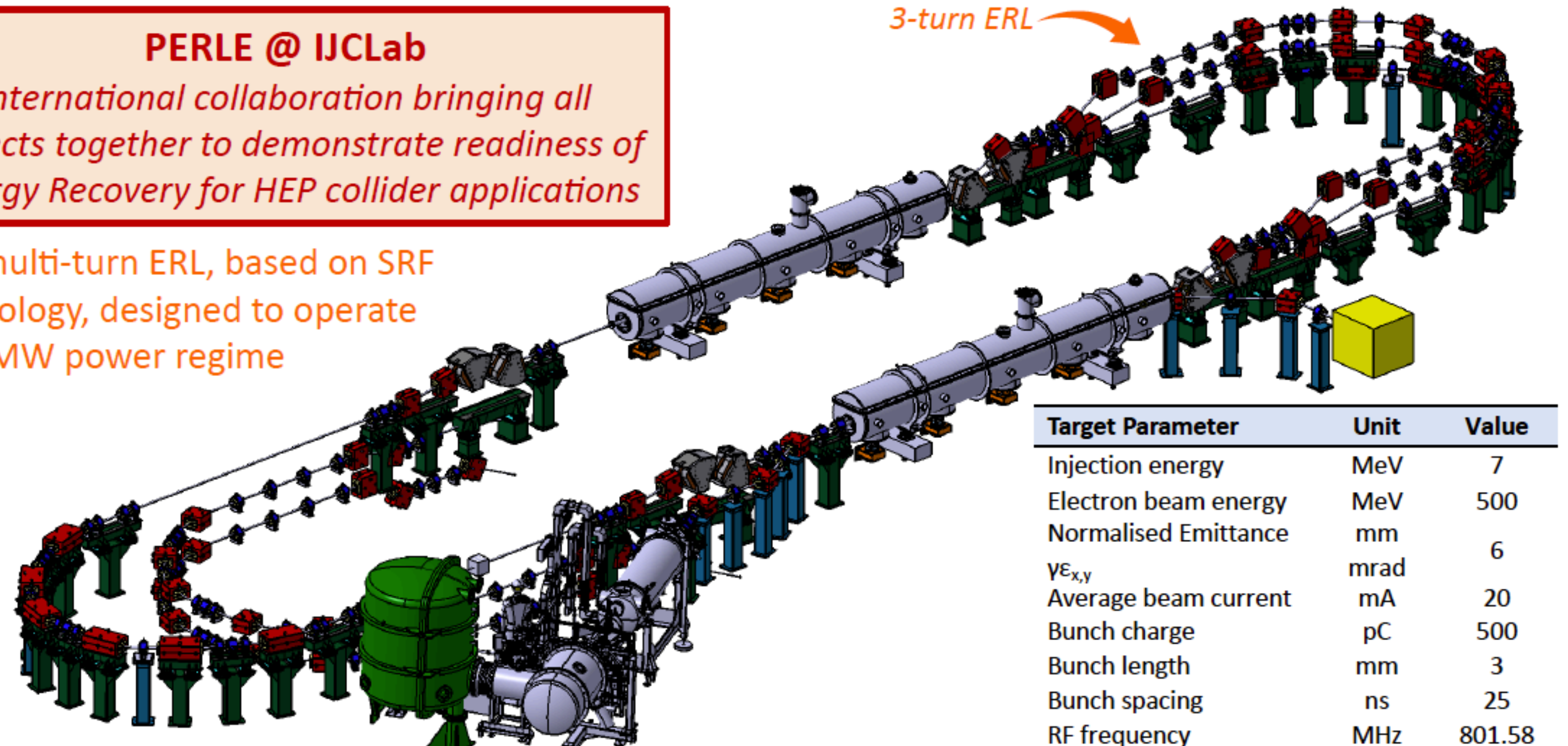
FCC-eh

$$\text{DIS at } \sqrt{s} \simeq 1.2/2.2/3.5 \ \ \text{TeV}, \quad \int \mathscr{L} dt \sim 1-2 \ \ \text{ab}^{-1} \sim 1000 \times \text{HERA}$$

PERLE

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



Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\epsilon_{x,y}$	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

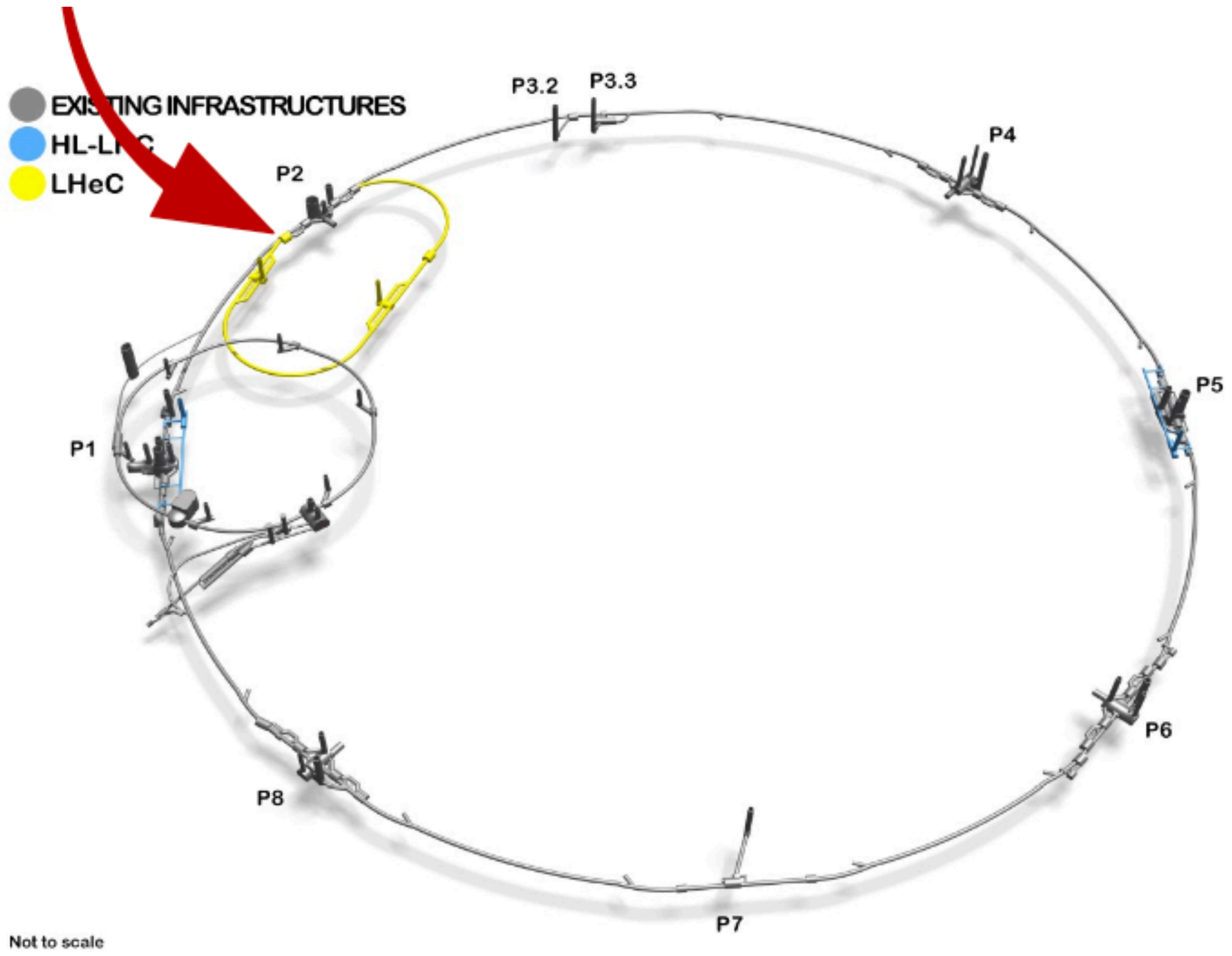
PERLE – Powerful Energy Recovery Linac for Experiments

Parameter	Unit	LHeC				FCC-eh	
ep	P=±0.8 (e^-)	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	$10^{33}\,\text{cm}^{-2}\text{s}^{-1}$	1	5	9	23	8	15

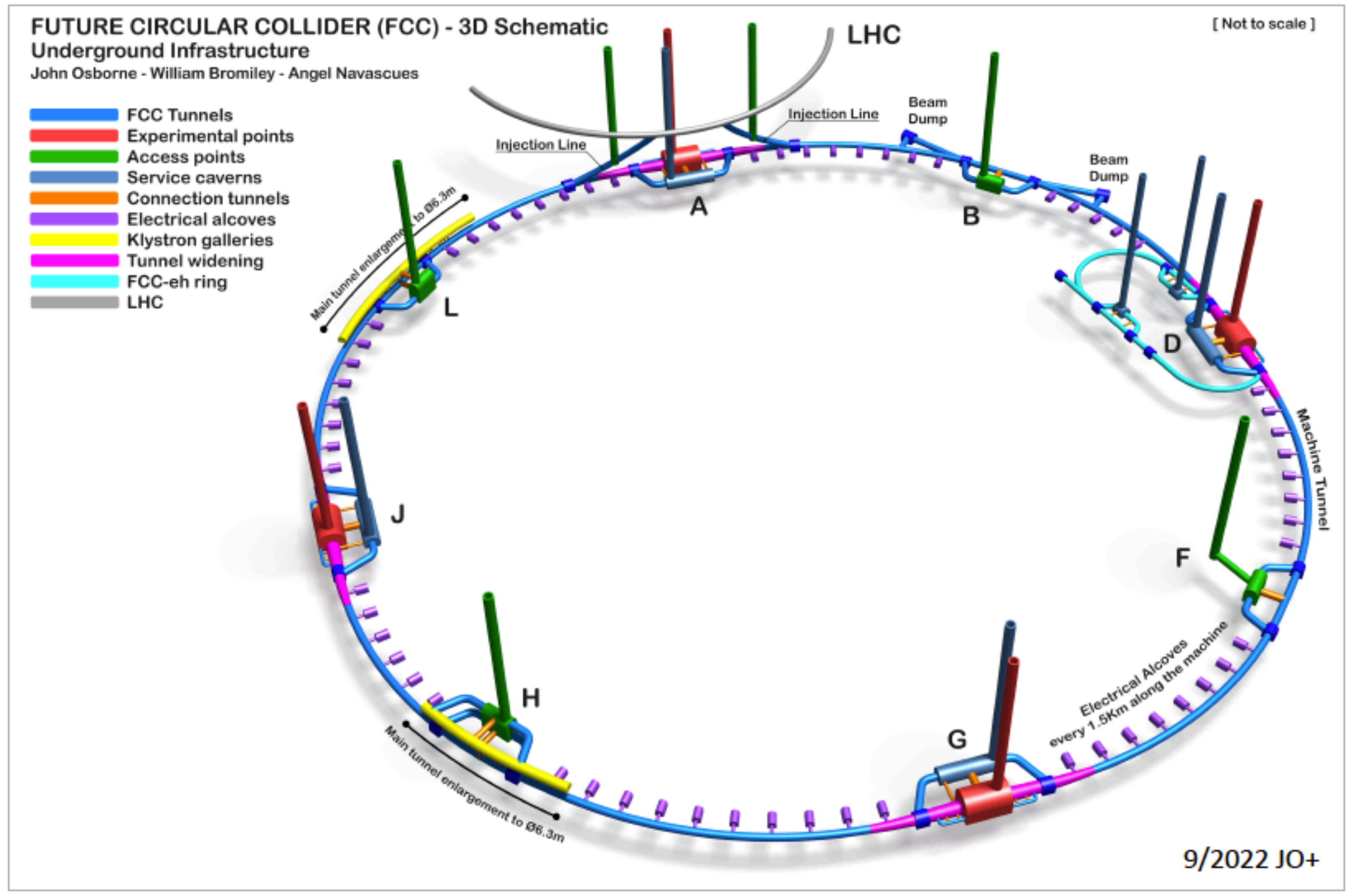
1810.13022

Accelerators:

LHeC



FCC-eh



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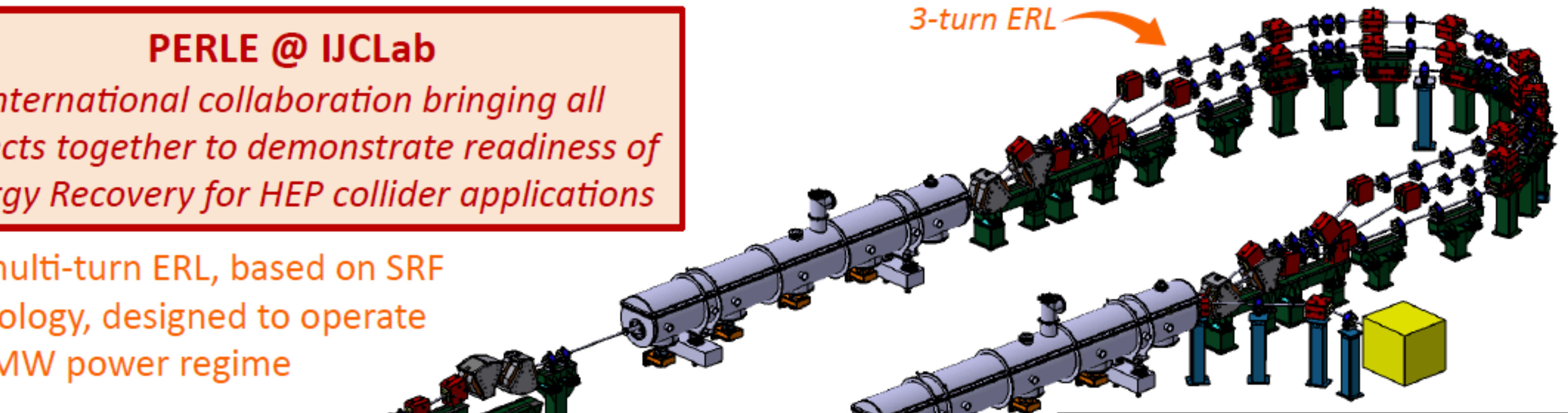

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N_e	10^9	1	2.3	3.1	7.8	3.1	3.1
$\beta*$	cm	10	10	7	7	12	15
Luminosity	10^{33} cm^{-2}s^{-1}	1	5	9	23	8	15

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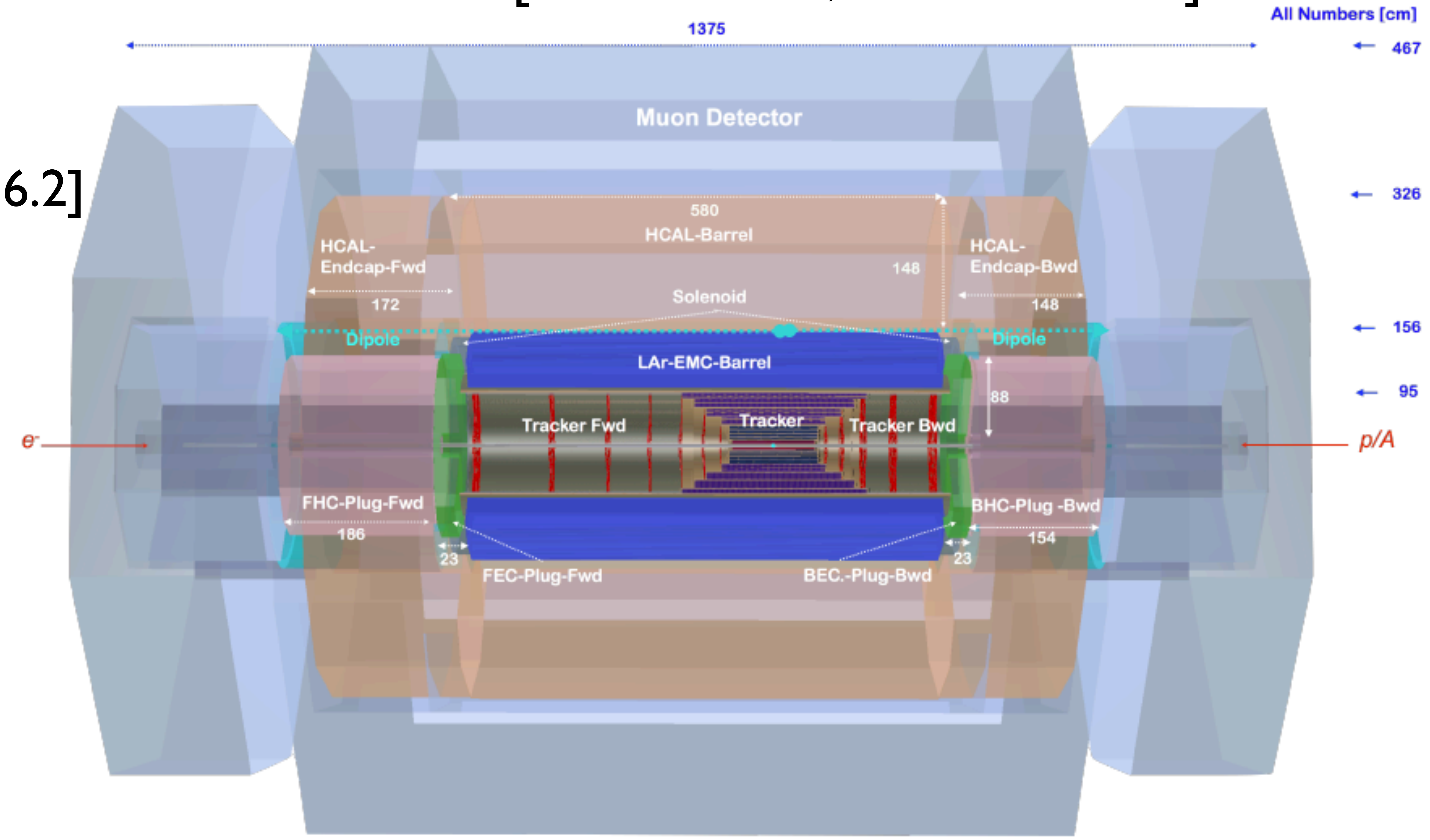
Detectors:

L=13.2 m [FCC-eh: 19.3, about CMS size]

R=4.8 m
[FCC-eh: 6.2]



➜ Large acceptance, precision device: design determined by kinematics ($H \rightarrow b\bar{b}$ in CC).

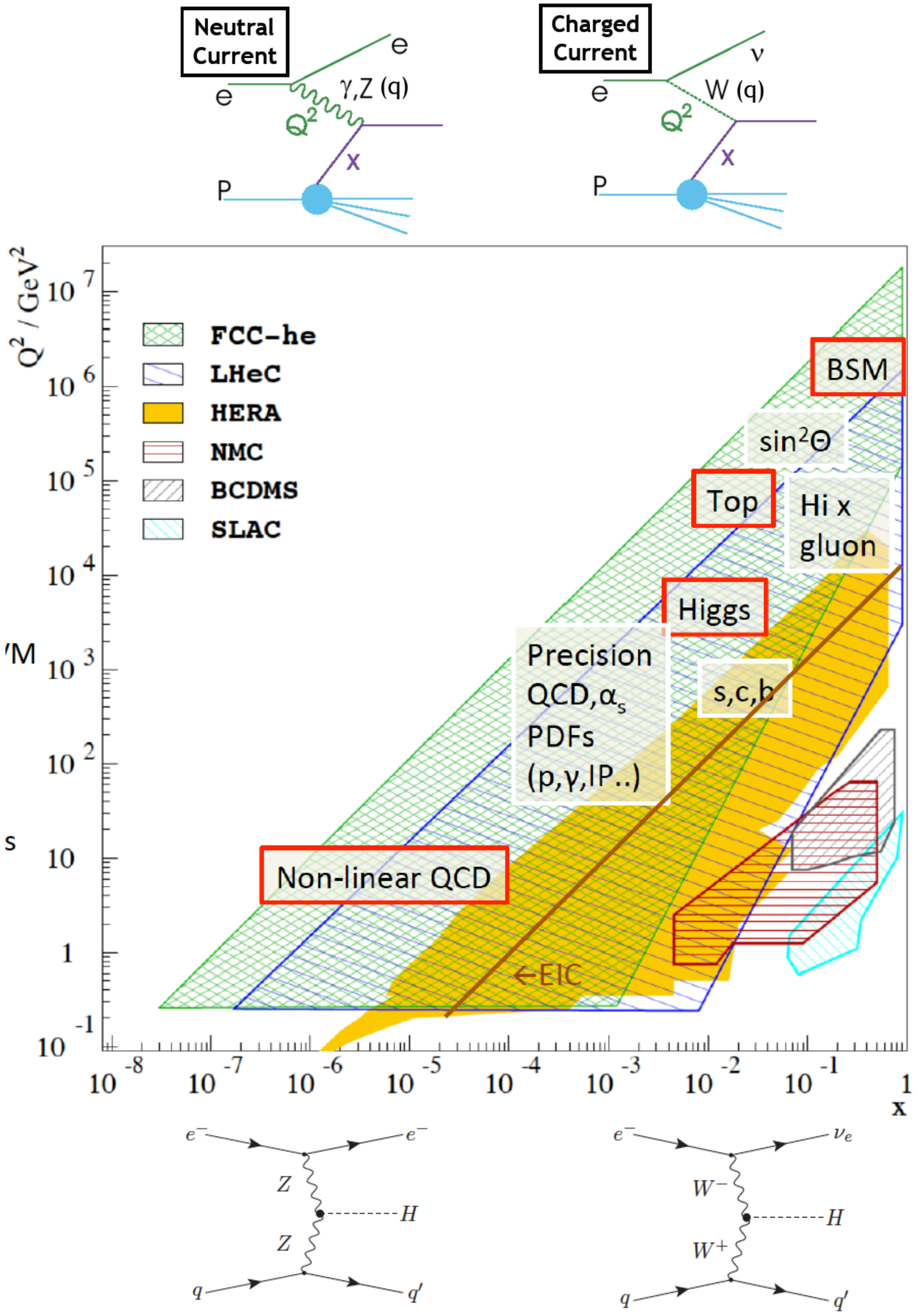
➜ Low radiation (1/100 that of pp) enables sensitive technology such as HV CMOS to be used.

➜ Low field dipole inserted before the HCAL to ensure head-on ep collision; conventional solenoid.

➜ Forward (p,n) and backward (e, γ) tagging detectors.

➜ Modular structure for fast installation, fitting inside the L3 magnet in IP2.
➜ Forward-backward symmetrised version would allow eh and hh collisions in the same IP (2201.02436).

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., PDFs, EW measurements).
- Transform the LHC into a precision Higgs facility.
- 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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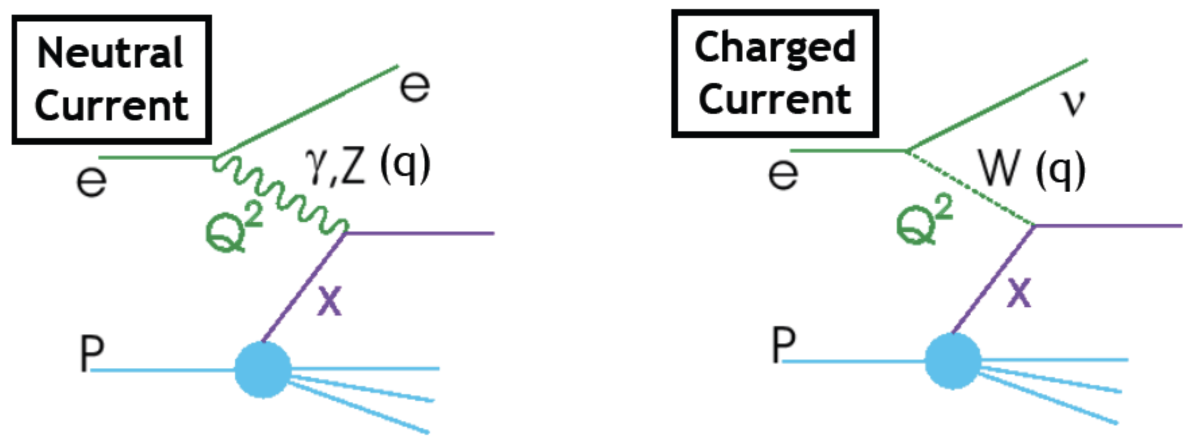

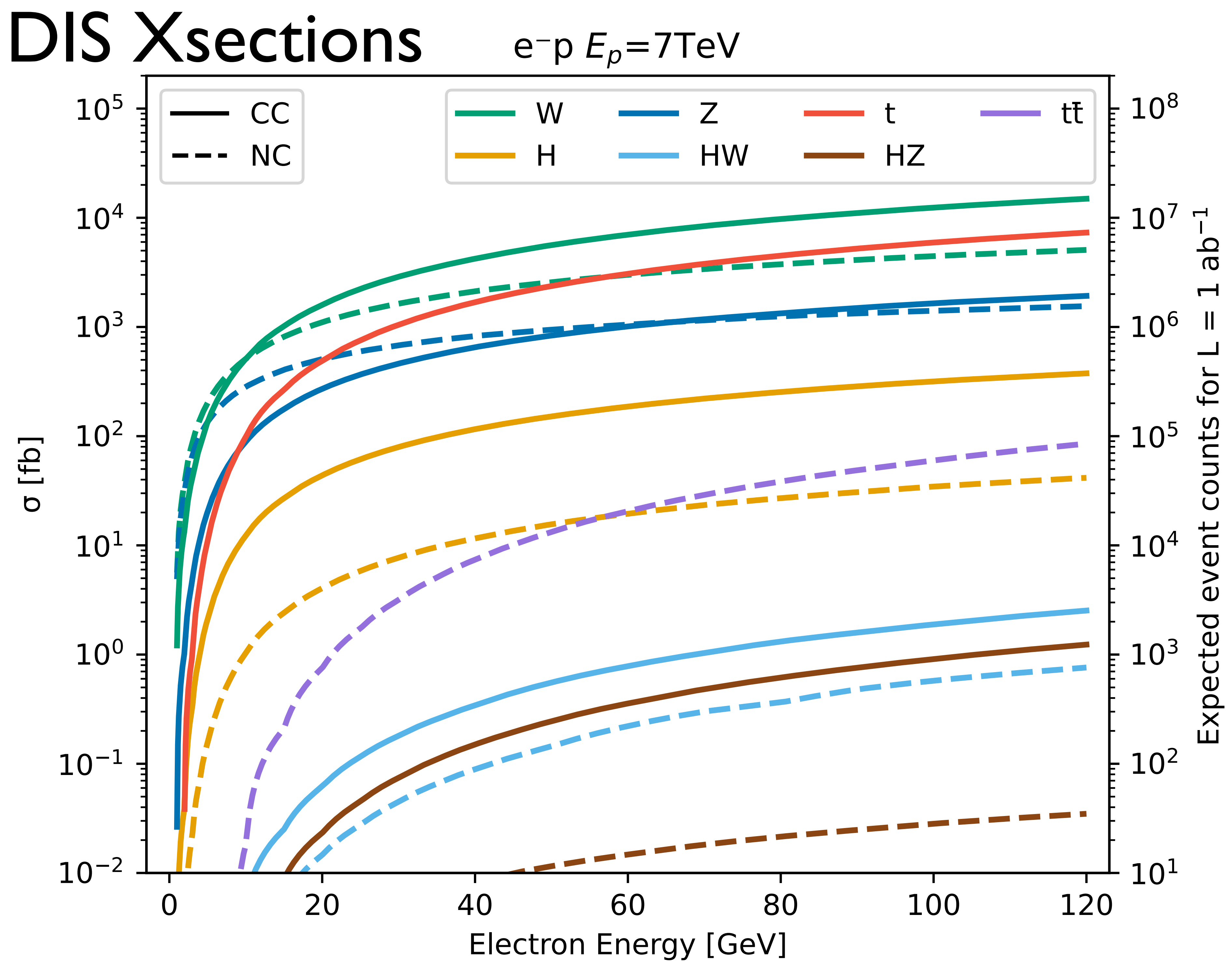

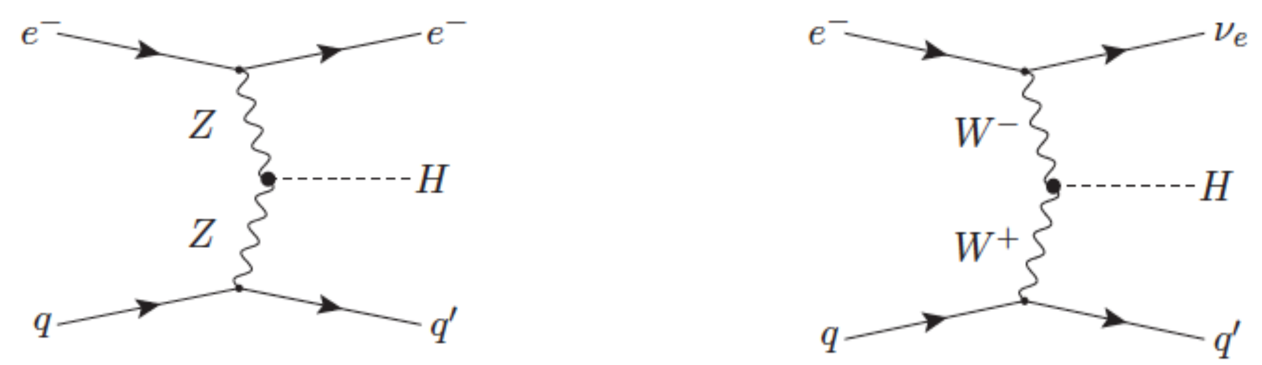

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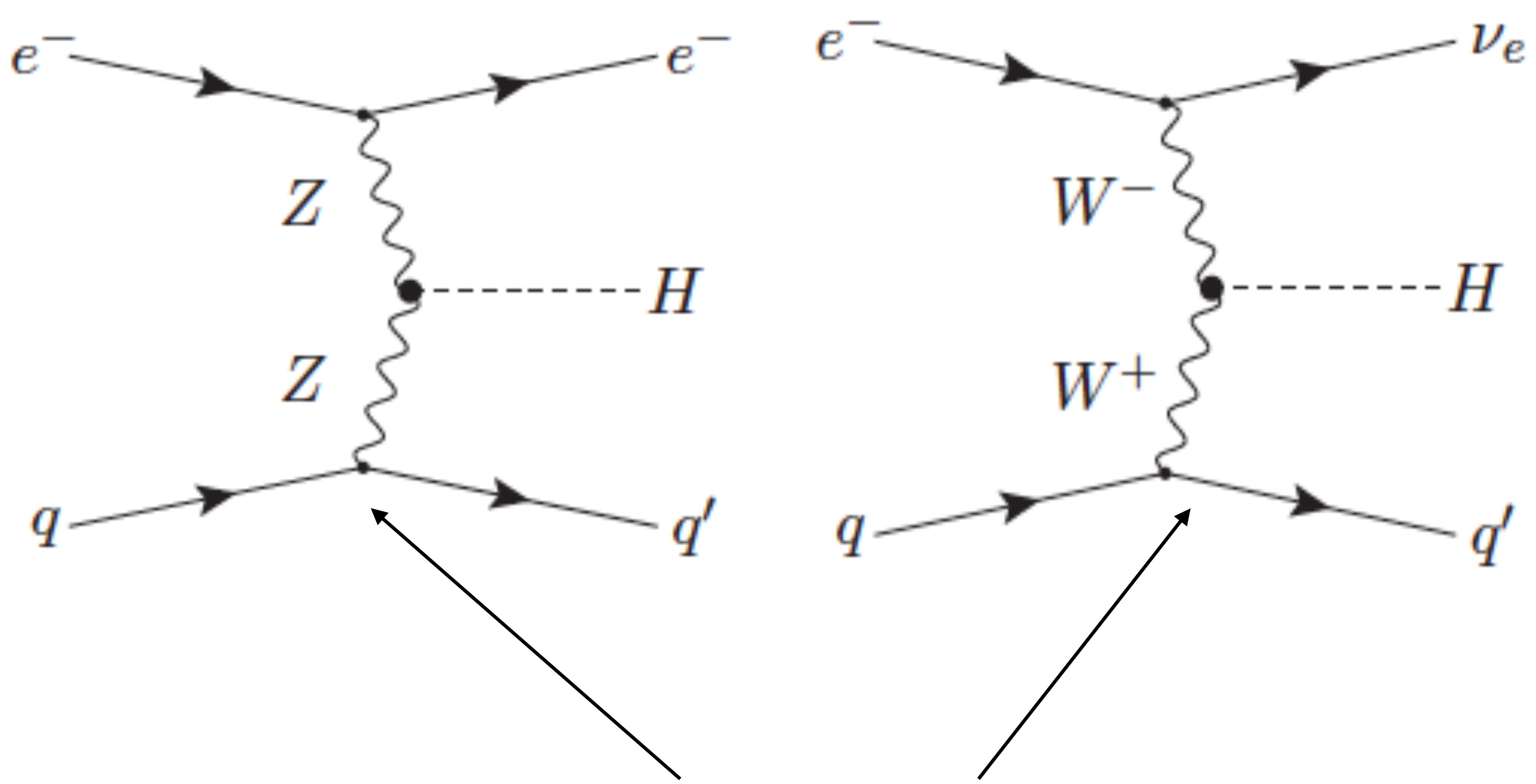
Higgs physics: cross sections



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

- 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.

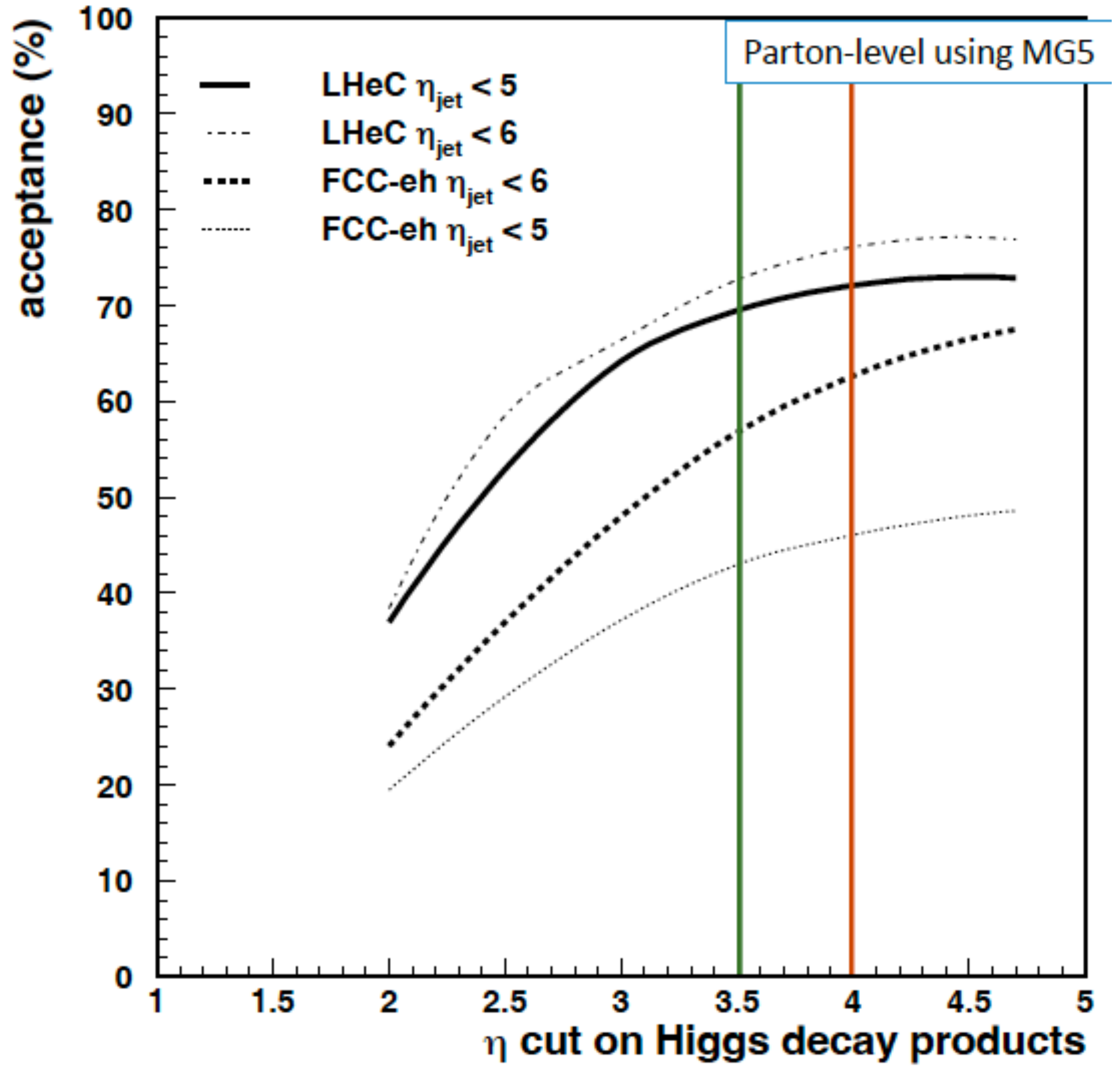
		Number of Events			
		Charged Current		Neutral Current	
Channel	Fraction	LHeC	FCC-eh	LHeC	FCC-eh
$b\bar{b}$	0.581	114 500	1 208 000	14 000	175 000
W^+W^-	0.215	42 300	447 000	5 160	64 000
gg	0.082	16 150	171 000	2000	25 000
$\tau^+\tau^-$	0.063	12 400	131 000	1 500	20 000
$c\bar{c}$	0.029	5700	60 000	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

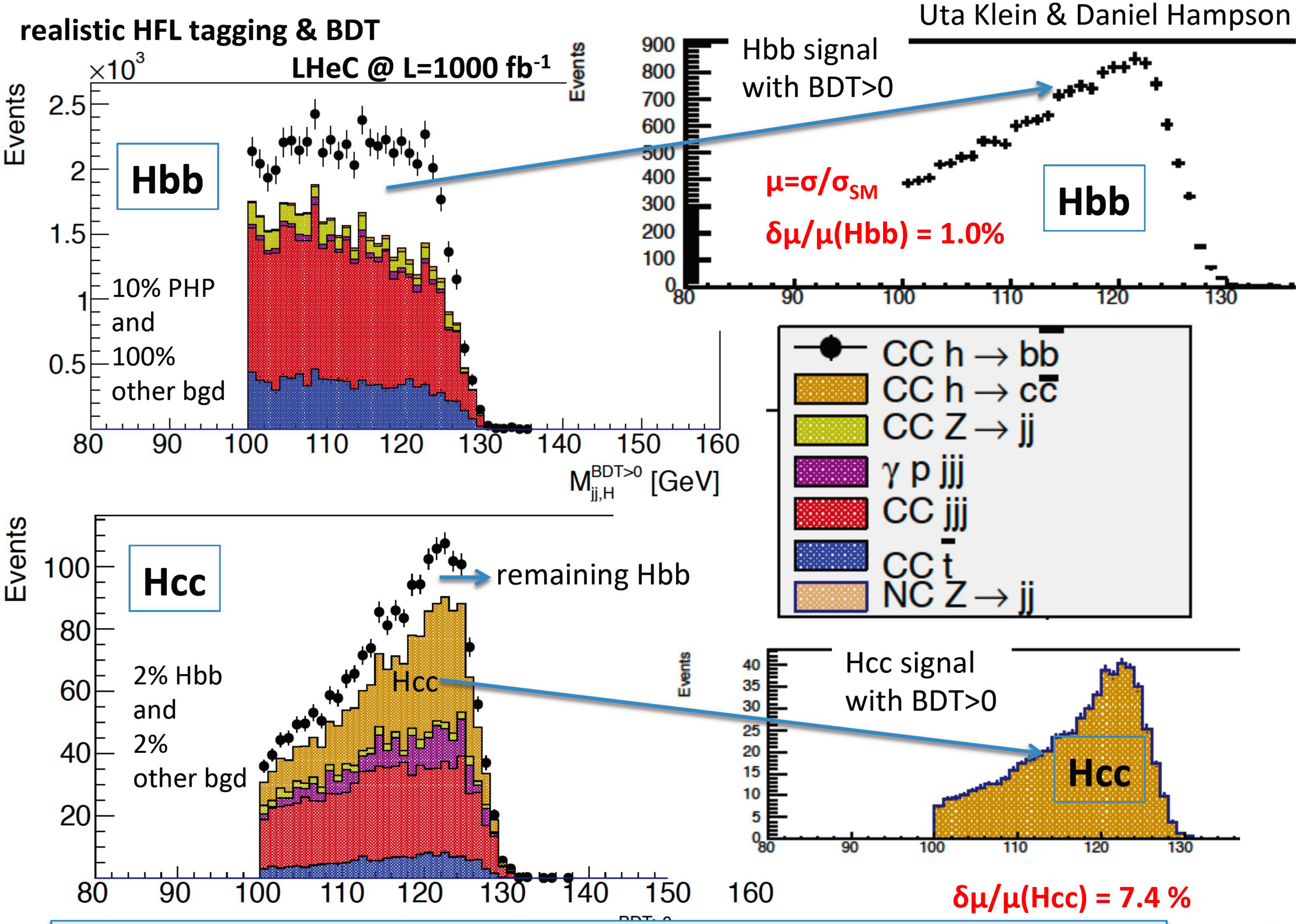
Higgs physics: analyses

- 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



$\delta\mu/\mu$(Hcc) = 7.4 %

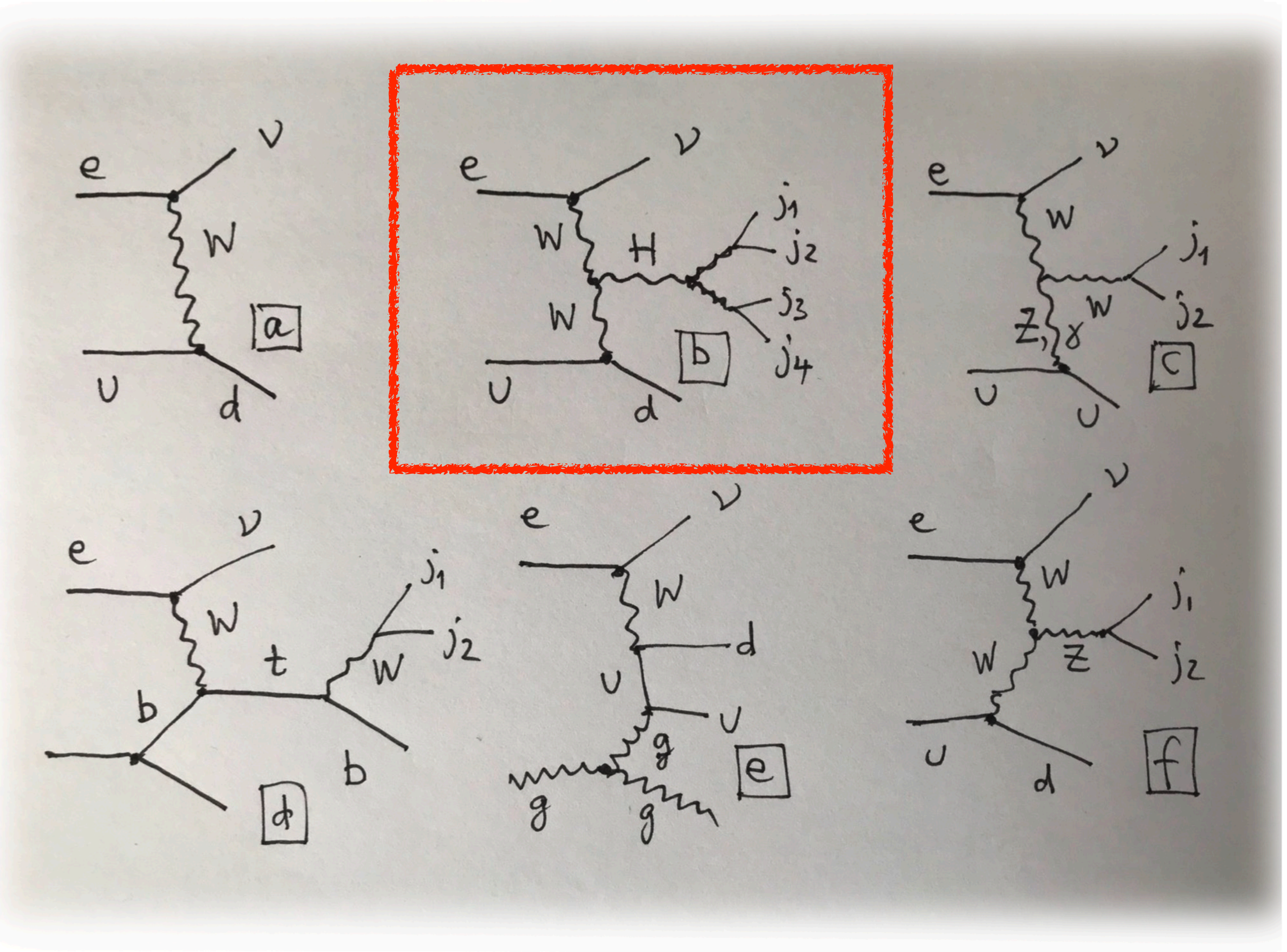
→ Main systematic checks: variations of background contribution and tagging efficiencies

8

Higgs physics: analyses

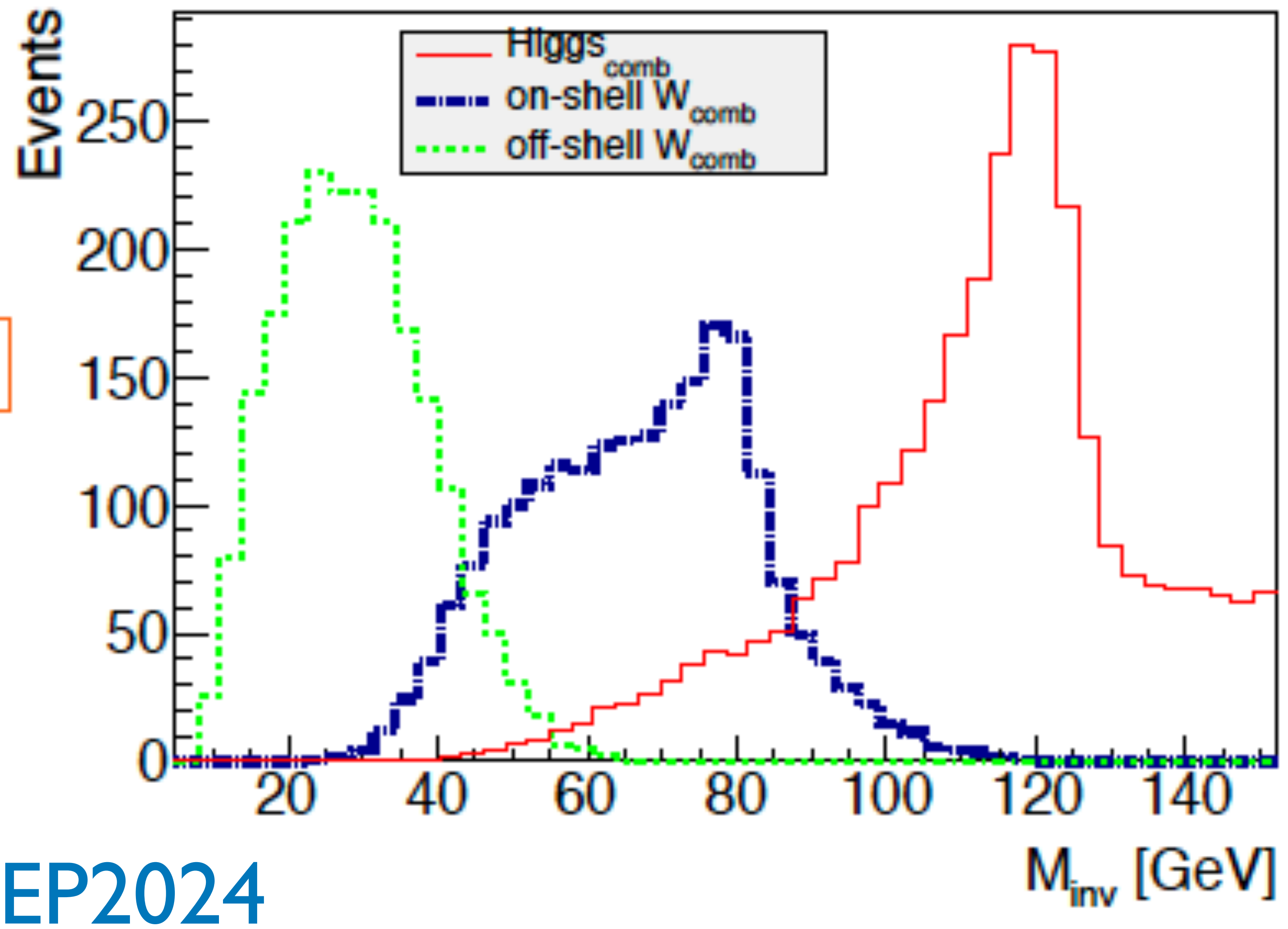
- HWW from 4+1 jets + ν configurations, CC cross section $\propto g_{HWW}^4$ in SM.

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



At Delphes detector level

NO mass requirements in combinatorics!

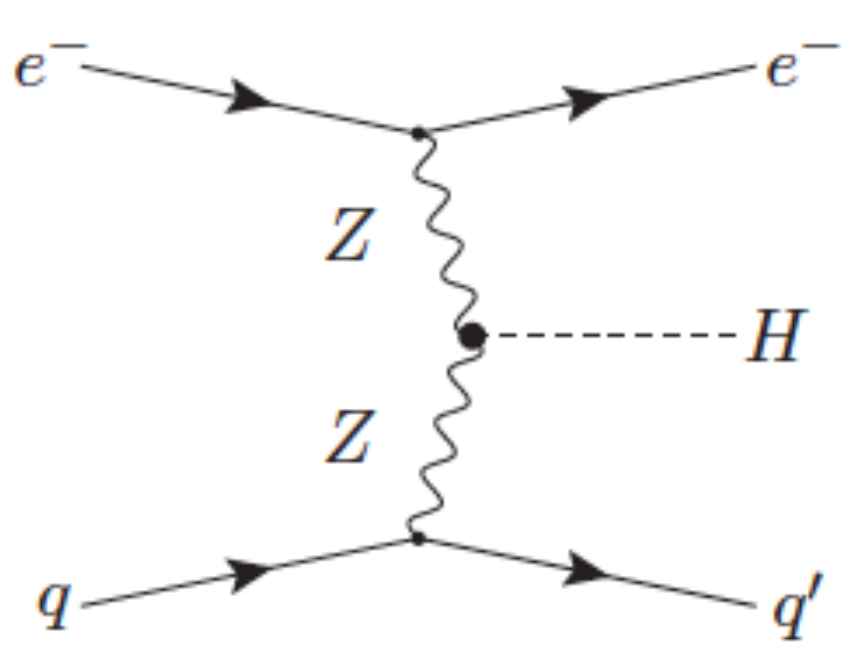


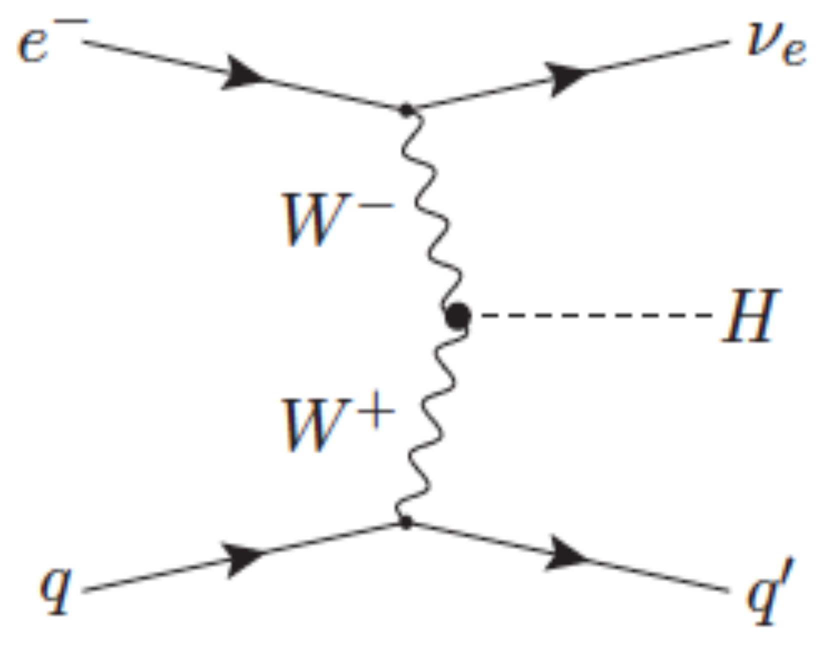
U. Klein at ICHEP2024

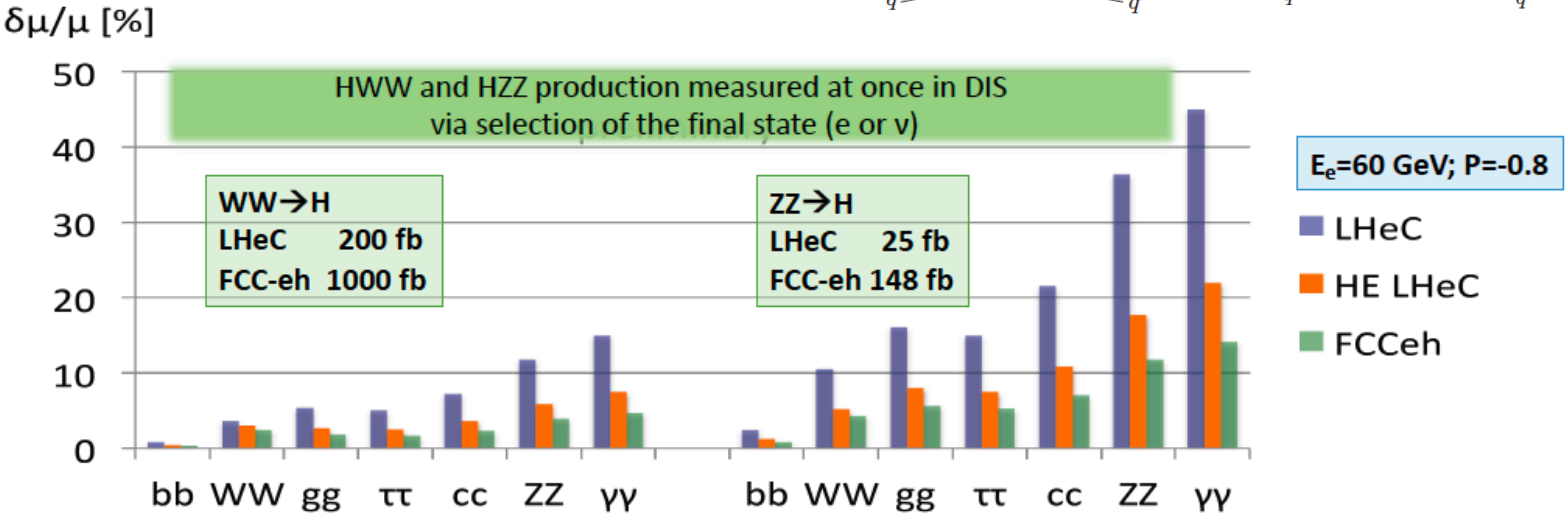
Reconstructed W*, W and Higgs, after jet combinatorics based on selecting at **least 5 jets** with **p_T> 6 GeV** and finding the Higgs candidate which has two jet pairs with min **Δη**; max **Δη** between Higgs candidate and fwd jet; max **Δϕ** between Higgs candidate and E_T^{miss} or Higgs candidate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

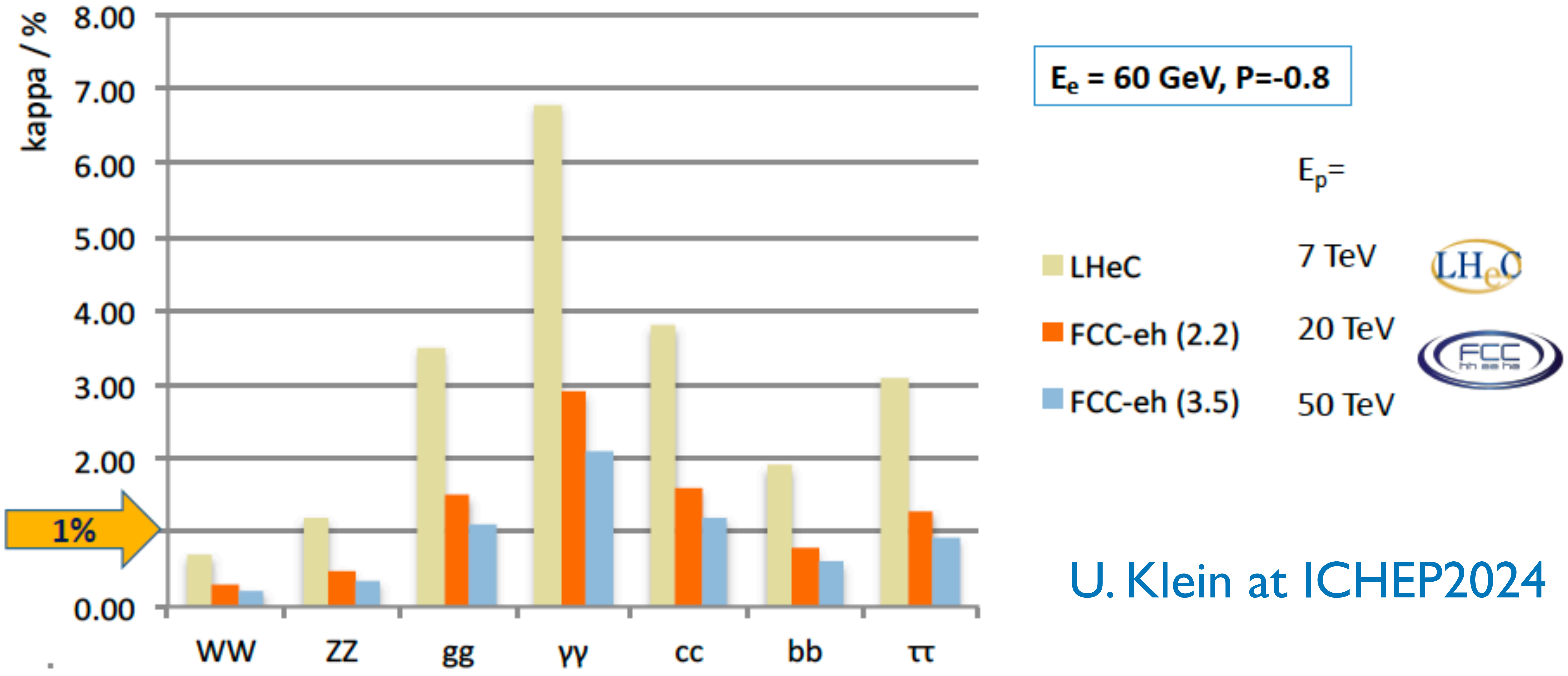
Higgs physics: κ-framework

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

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

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

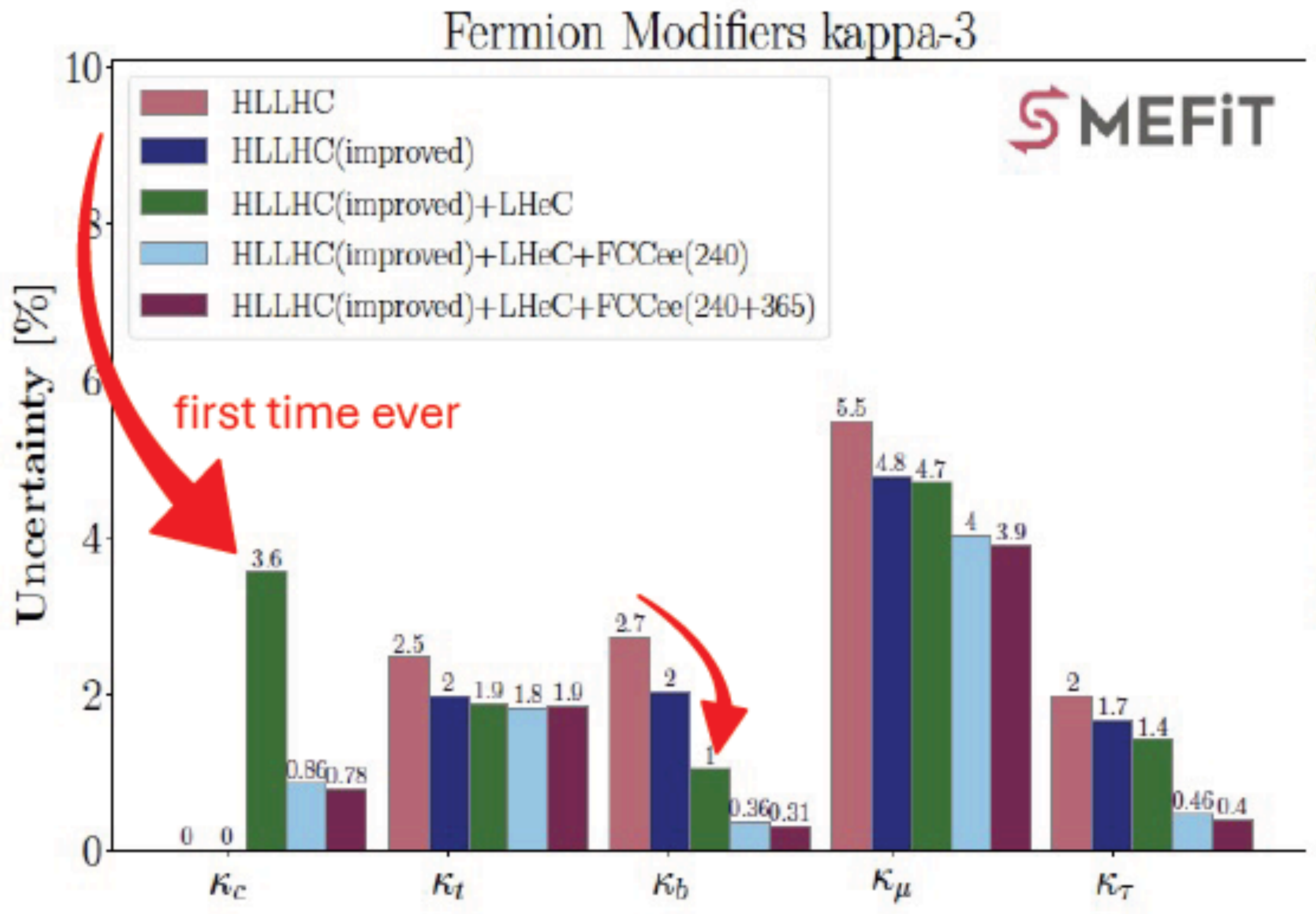
- Standalone study yields few % uncertainties assuming SM branching fractions weighted by the measured κ values, and Γ_{md} (c.f. CLIC model-dependent method, 1608.07538).

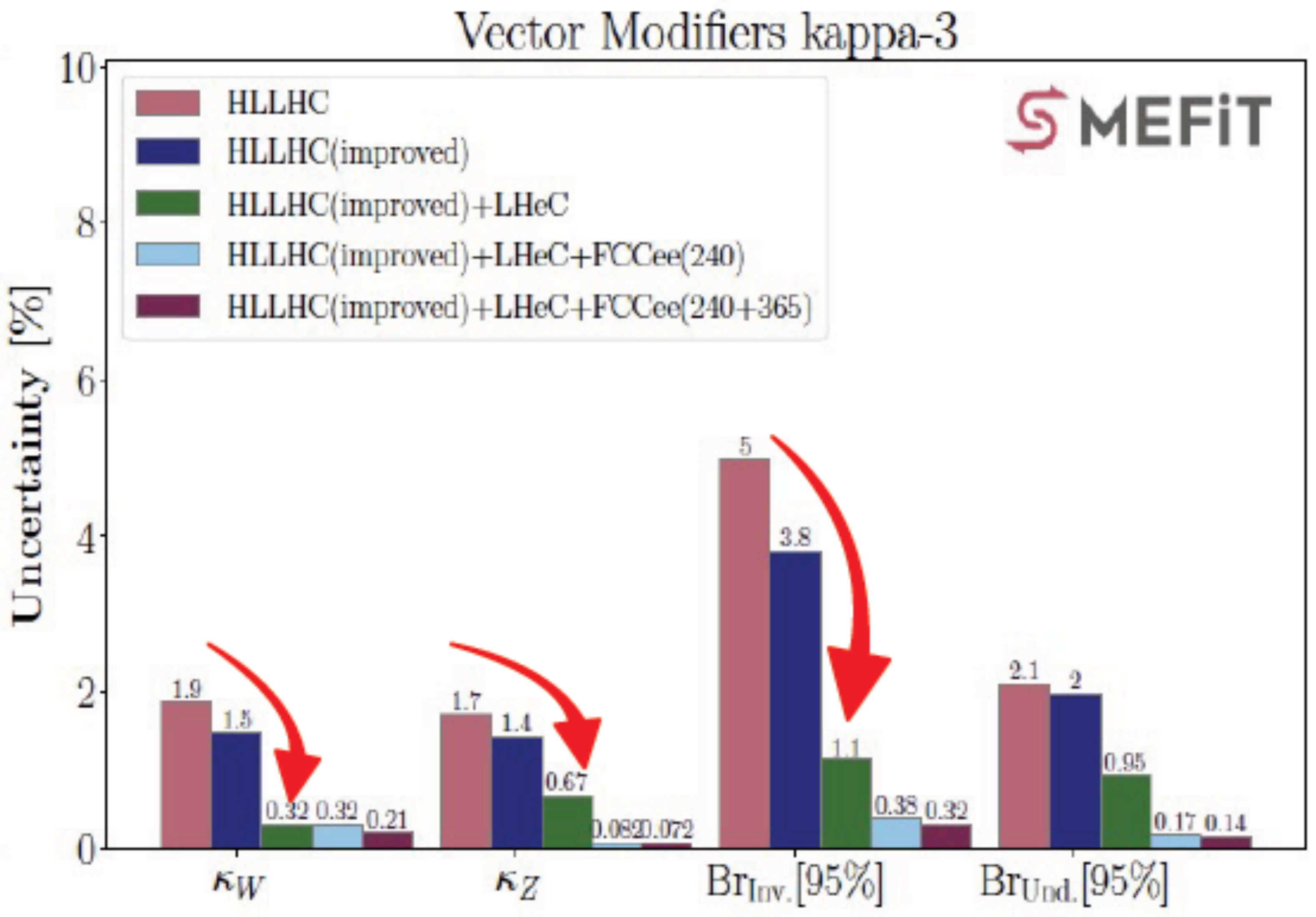


U. Klein at ICHEP2024

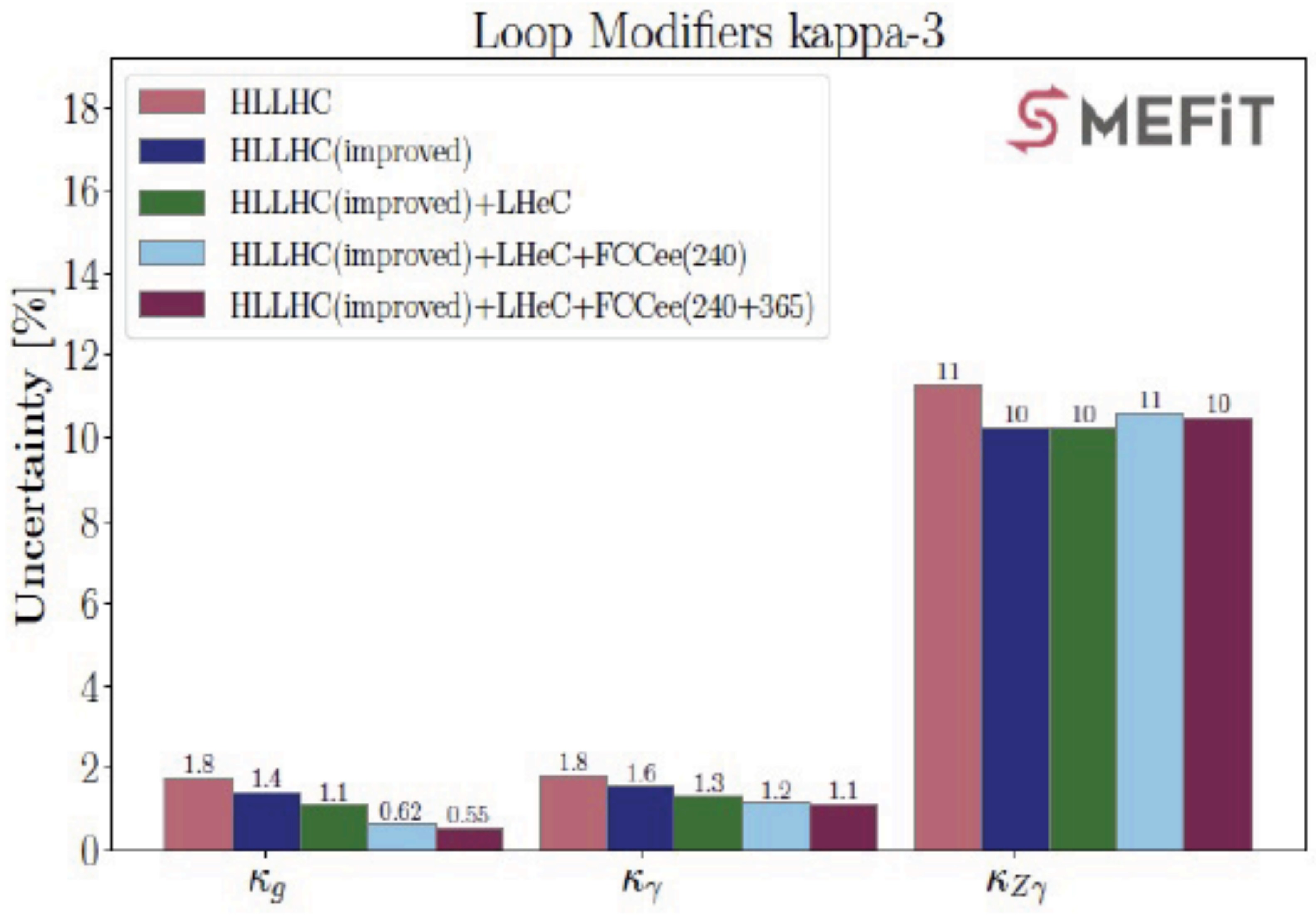
Higgs physics: κ-framework

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





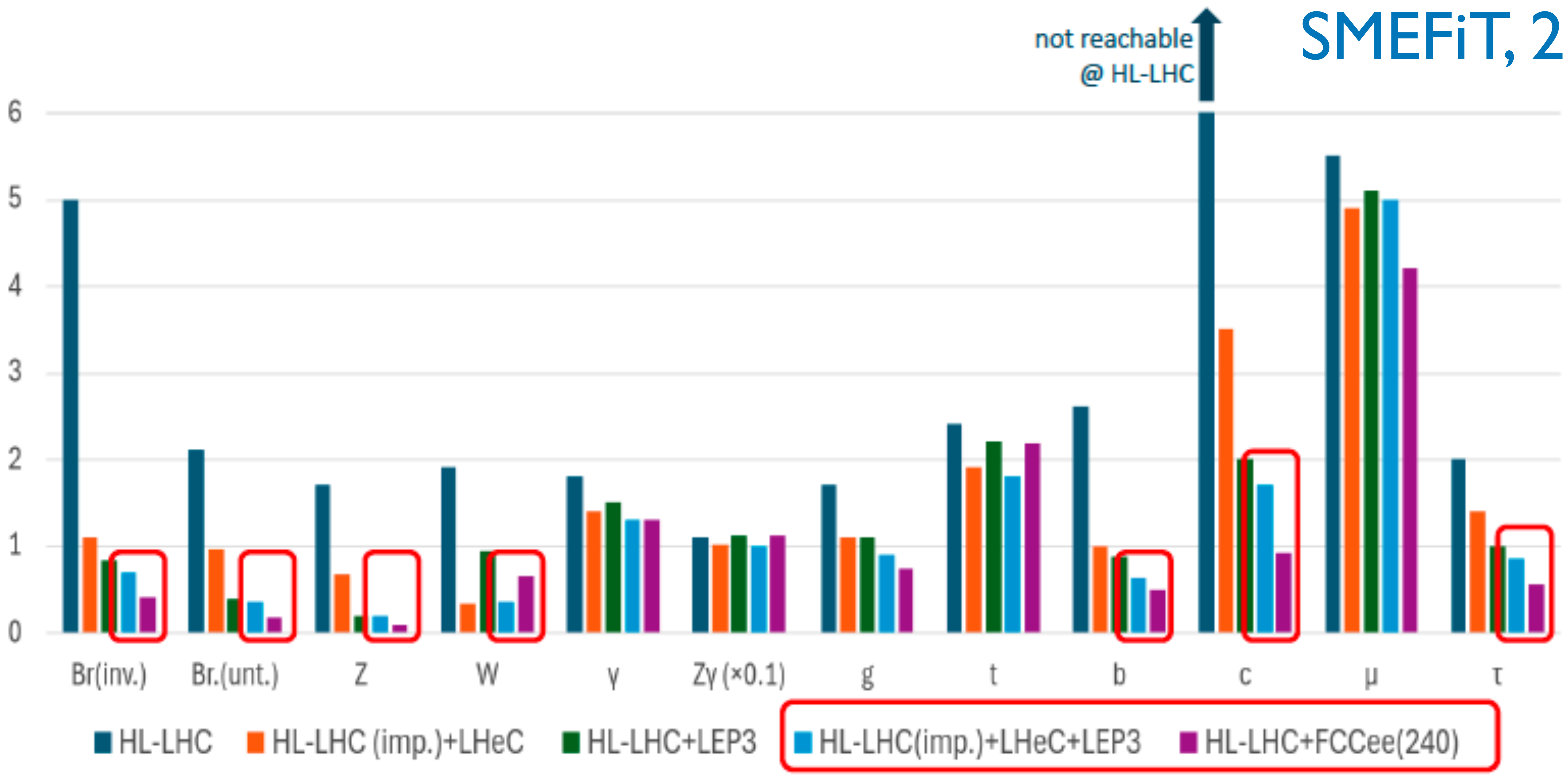
- LHeC PDFs+α_s improve all HL-LHC results:
  - ➜ Significantly κ_t, κ_τ, κ_g.
  - ➜ Greatly κ_b, κ_W, κ_Z.
  - ➜ First time κ_c.

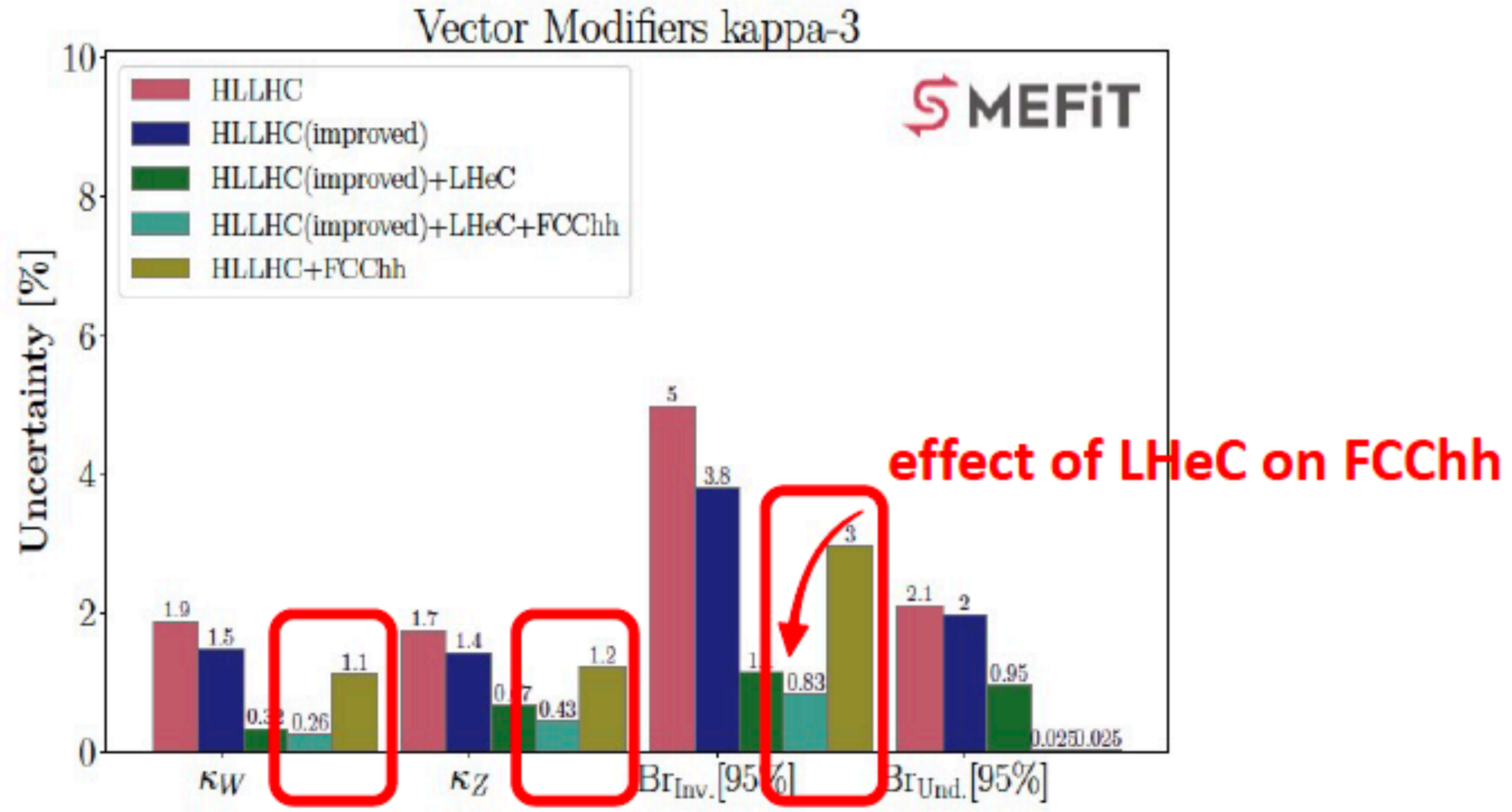


J. D'Hondt at the Open Symposium of the ESPP2026

Higgs physics: κ-framework

SMEFiT, 2105.00006





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

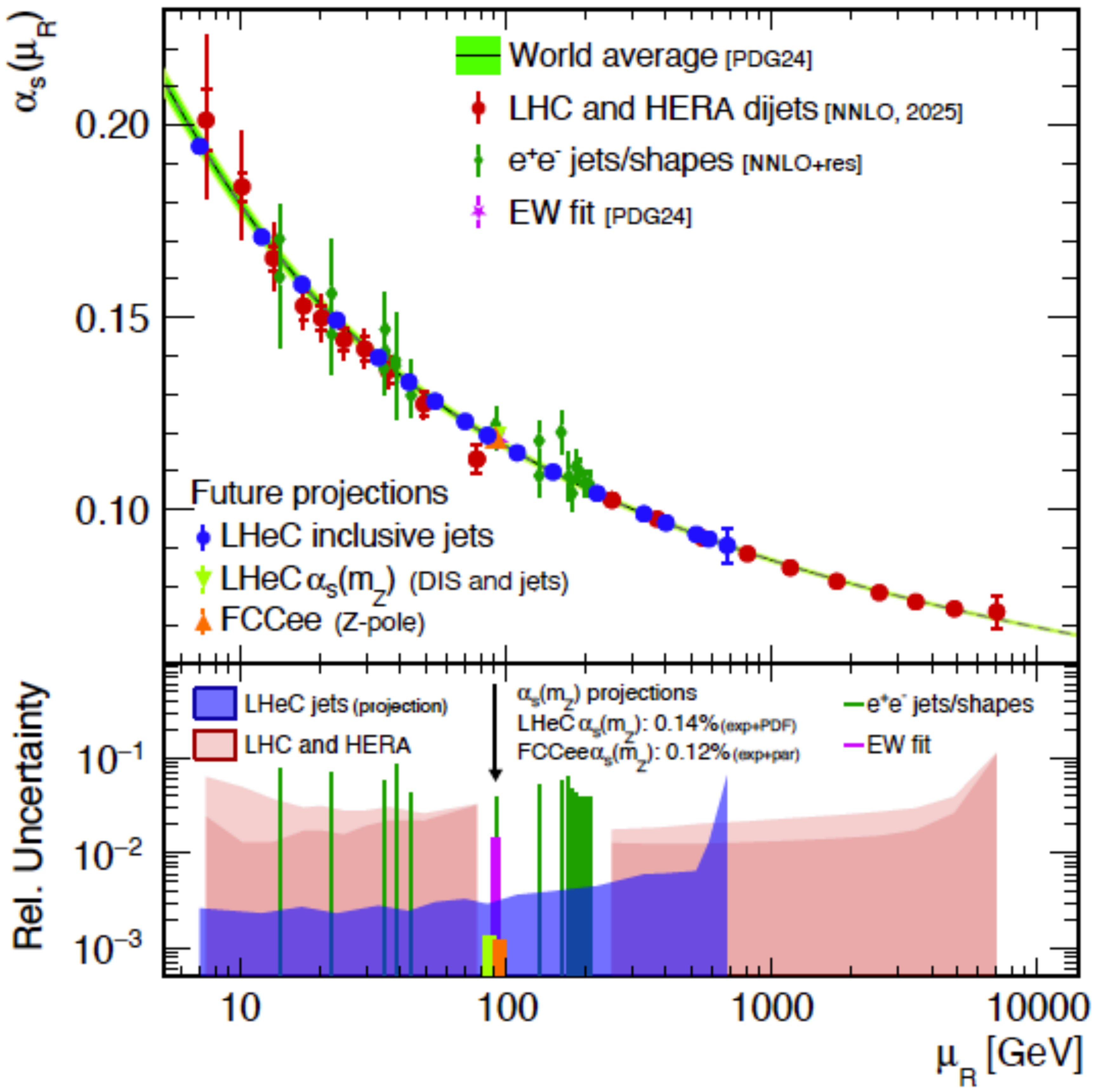
• LHeC needed to fully unlock the potential of FCC-hh.

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

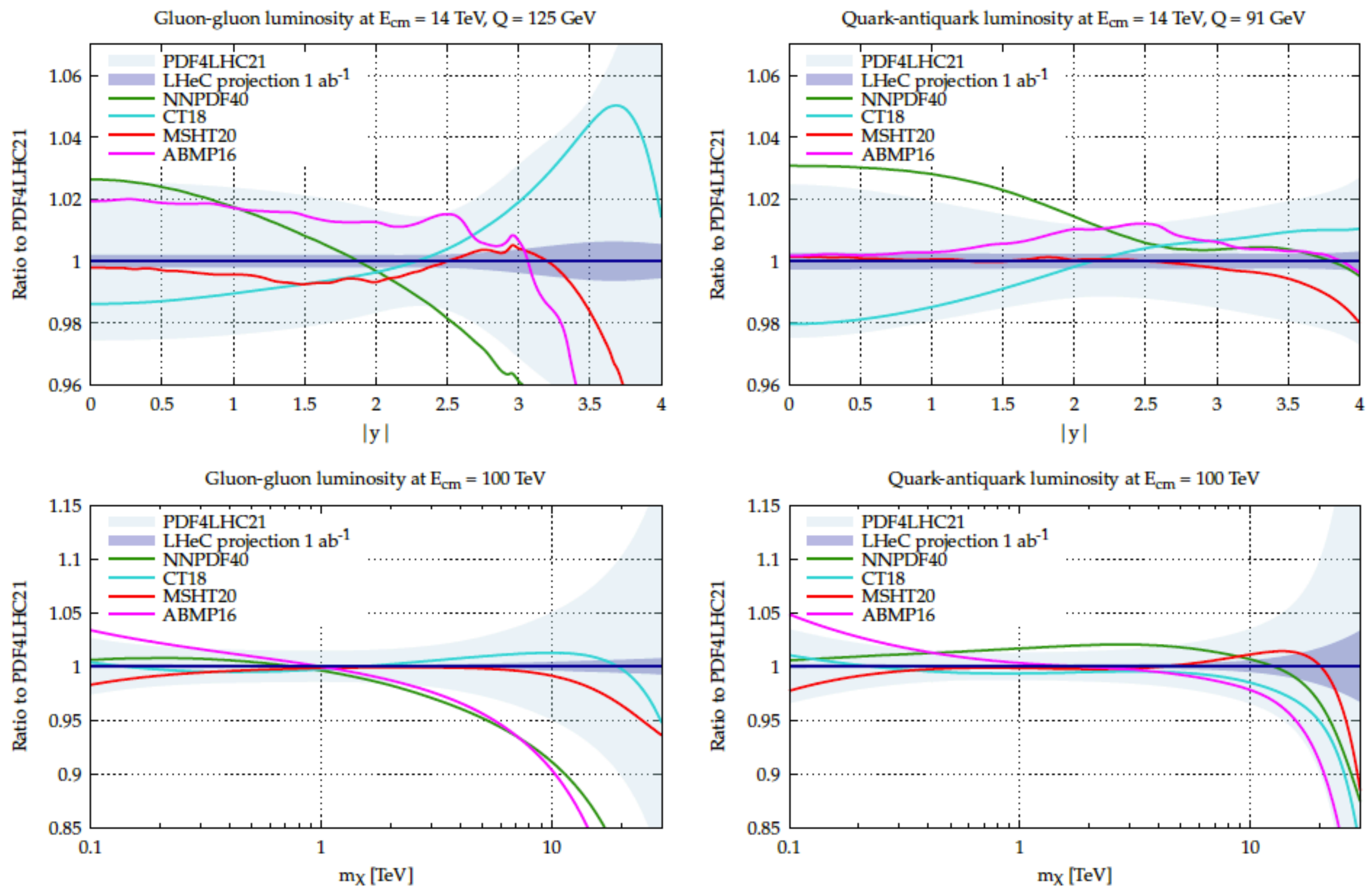
QCD input:

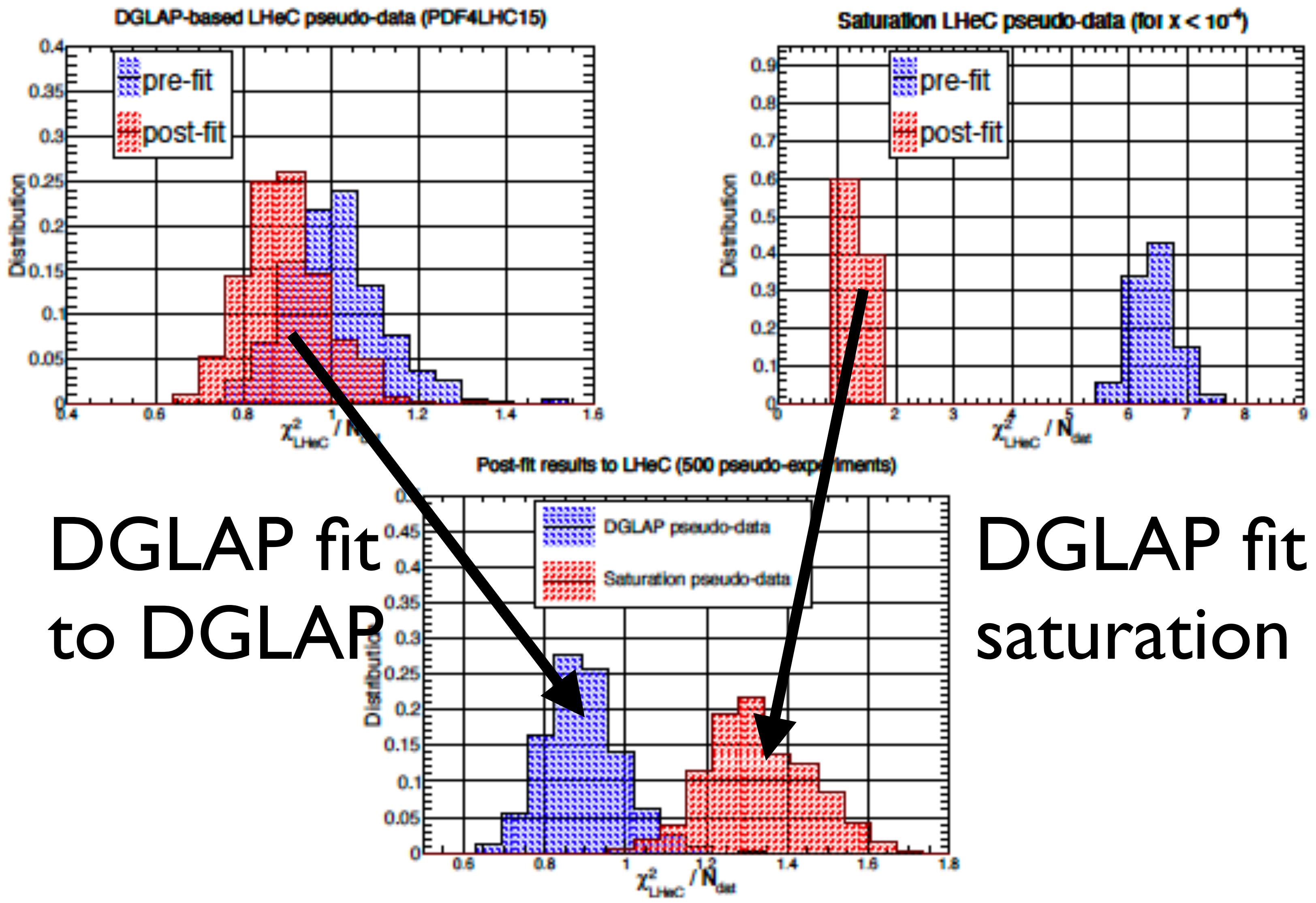
$$\Delta\alpha_s(M_Z)\ (\text{incl. DIS}) = \pm\, 0.00022_{(\text{exp+PDF})}$$

$$\Delta\alpha_s(M_Z)\ (\text{incl. DIS \& jets}) = \pm\, 0.00016_{(\text{exp+PDF})}$$



- PDFs and α_s crucial for HL-LHC: high precision EW, Higgs (e.g., remove essential part of QCD uncertainties of gg→H), extension of high-mass search range, new dynamics at small x:
  - ➜ Precise PDFs.
  - ➜ Per mille-level α_s.
  - ➜ Breaking of standard factorisation.





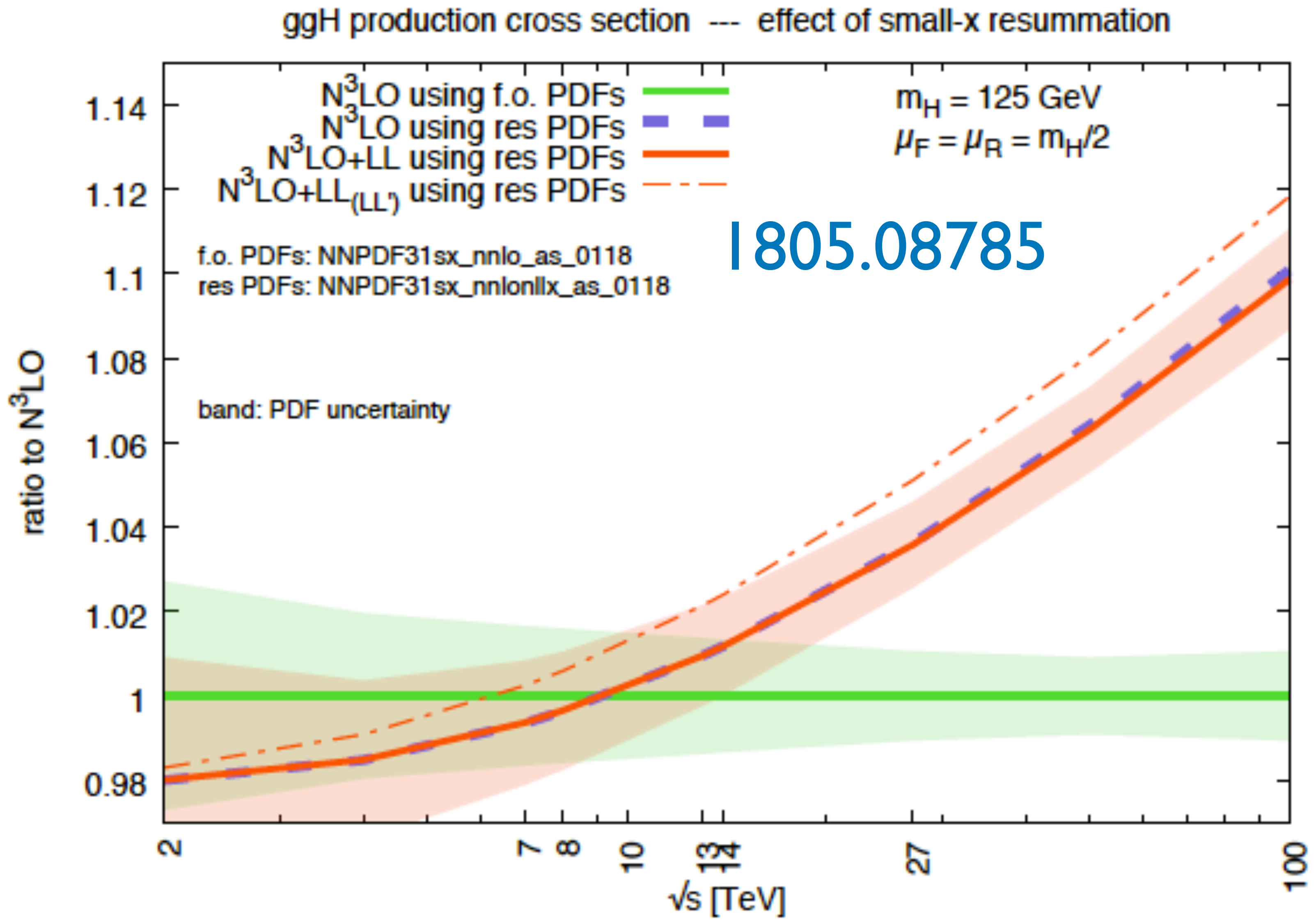
DGLAP fit to DGLAP

DGLAP fit to saturation

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%



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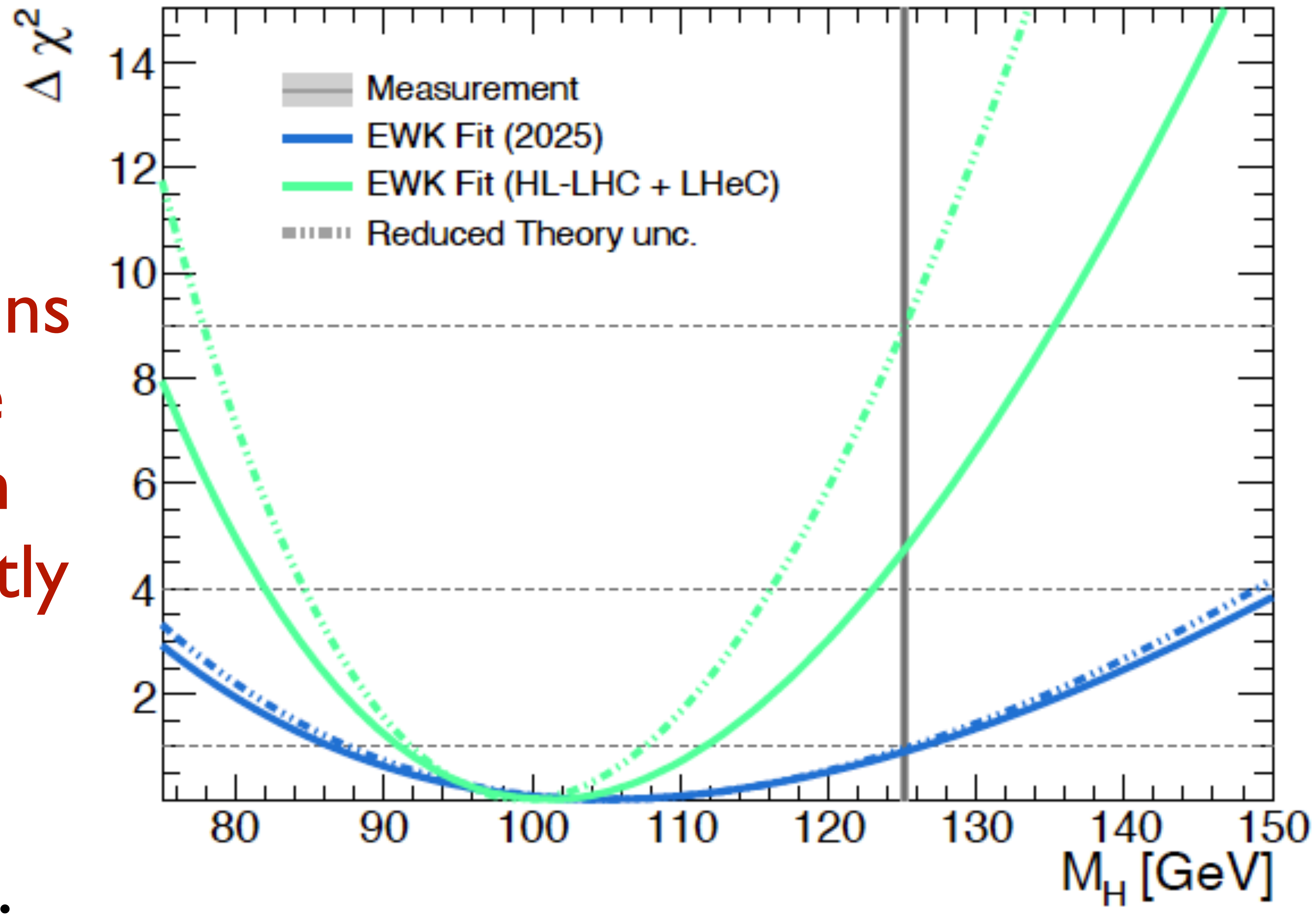
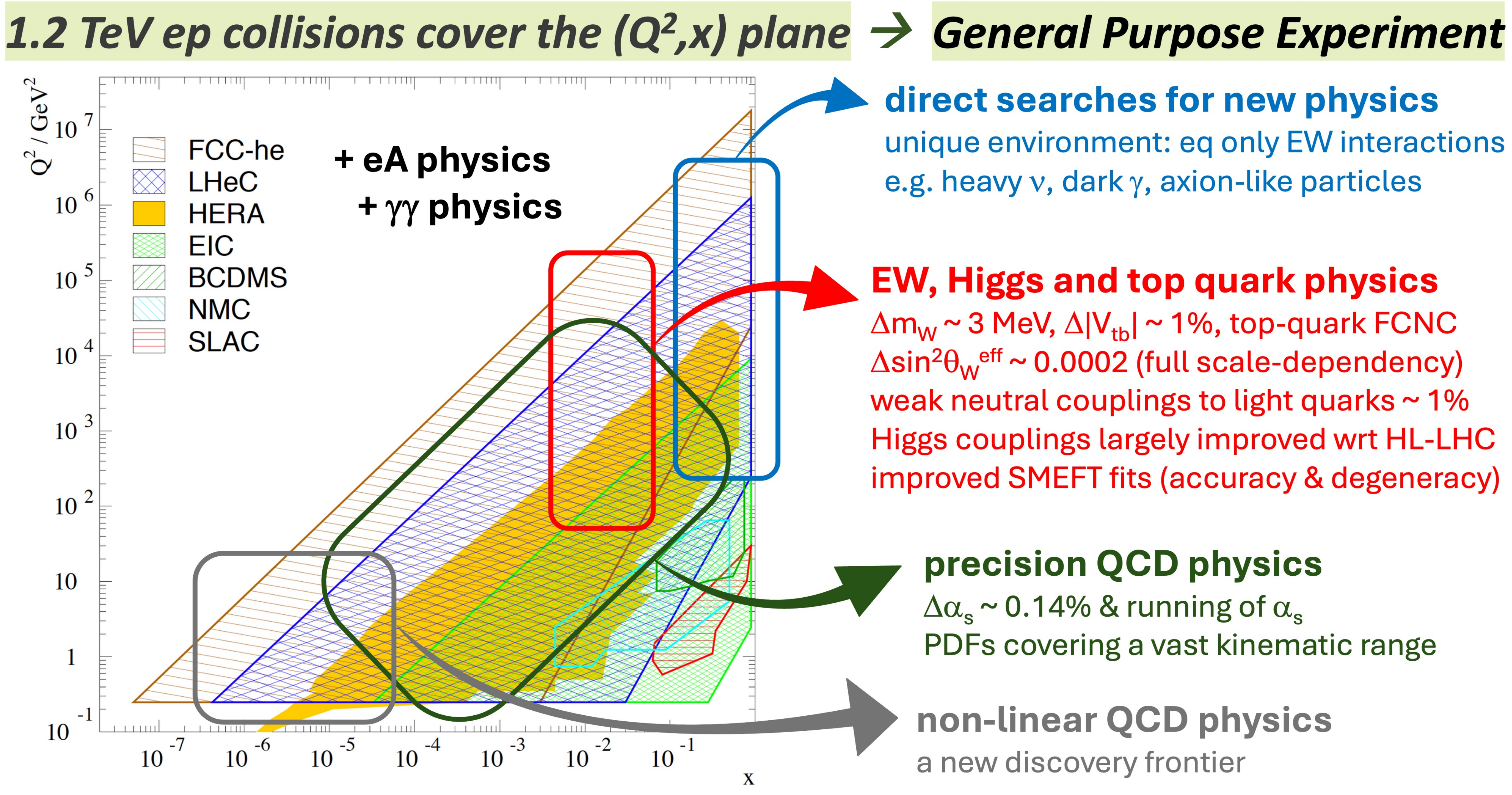
- Also constrains the mass in the SM indirectly in EWK fits (mostly effect of m_W).



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

Summary:

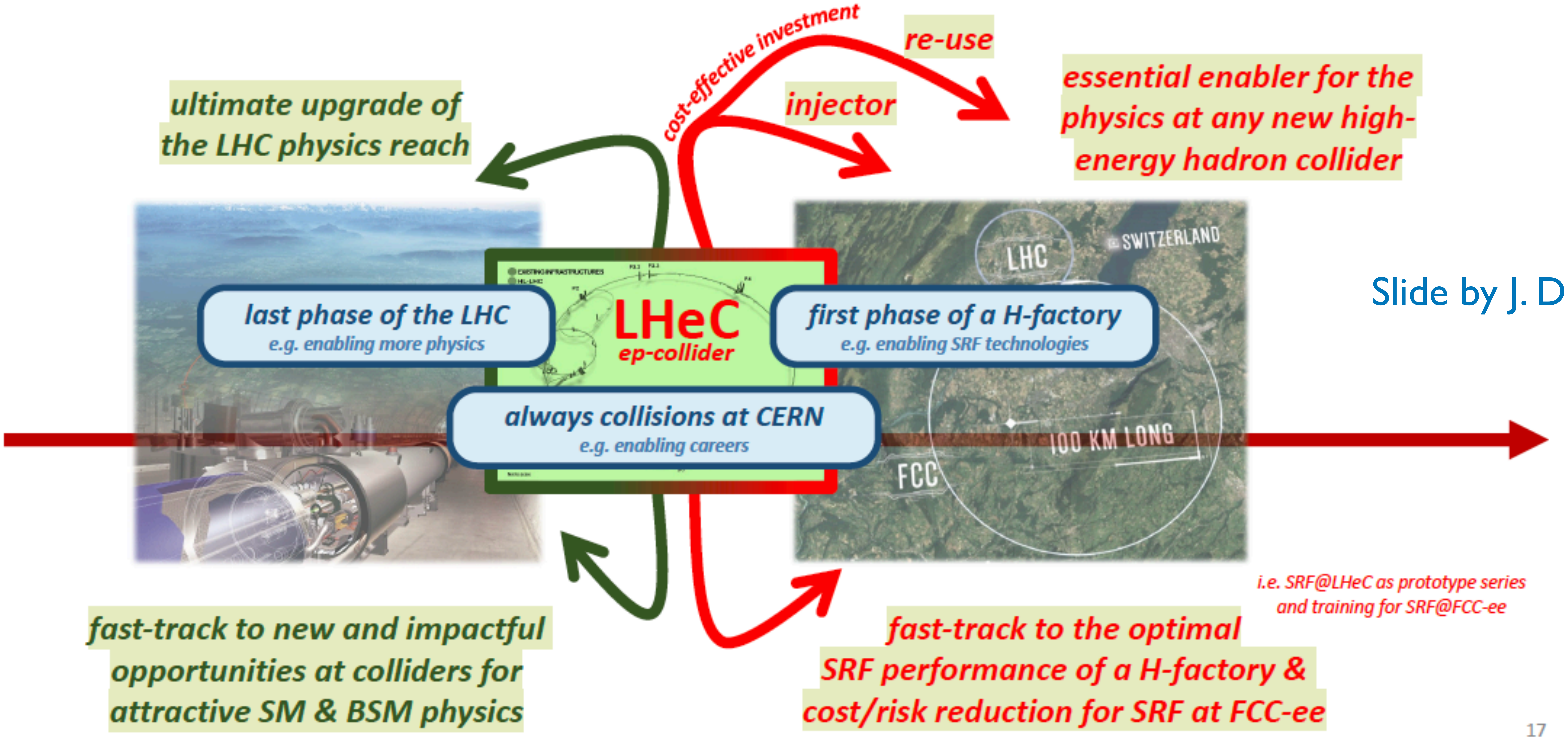


- **LHeC in the landscape of particle physics colliders:**
  ➜ Physics case on their own: QCD (precision and discovery in ep & eA), EW, top, Higgs, BSM.
  ➜ Enlarge the reach of hadronic colliders into (higher) precision, both for pp and for AA.
  ➜ Complementarities/synergies with hh & e^+e^-.

- **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.

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

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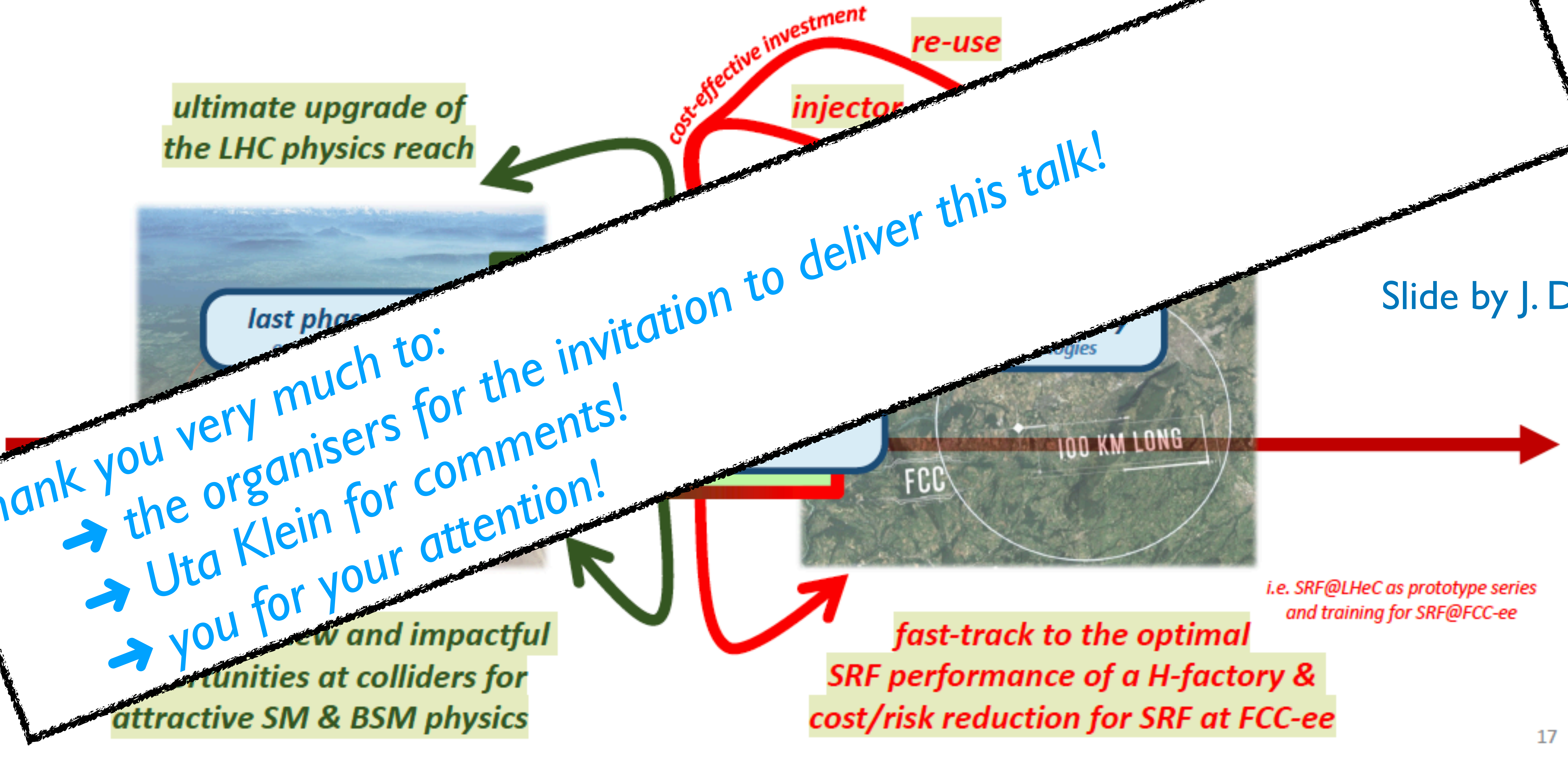


Slide by J. D'Hondt

Thank you very much to:
→ the organisers for the invitation to deliver this talk!
→ Uta Klein for comments!
→ you for your attention!

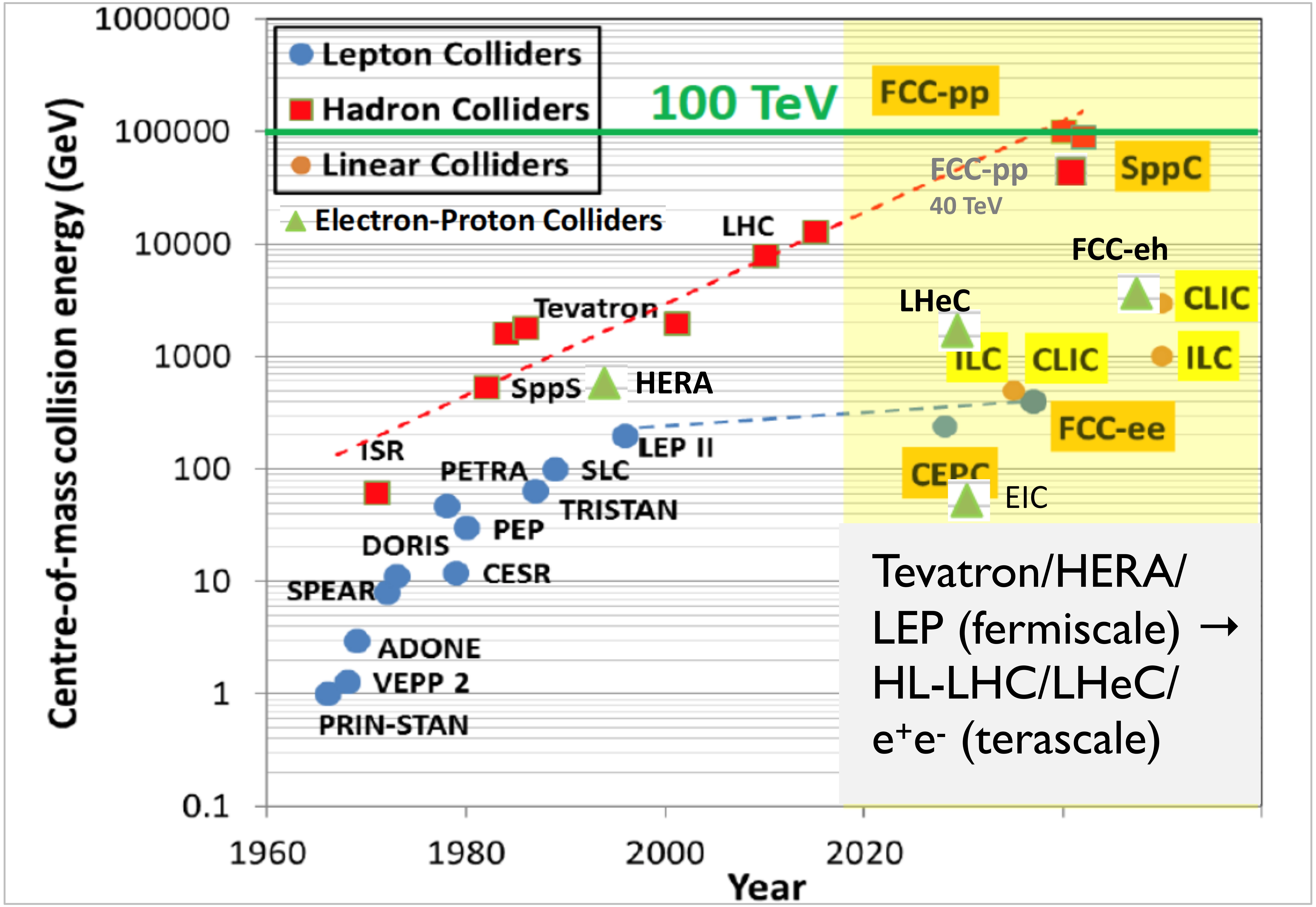
Backup:

Accelerators:

- 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.

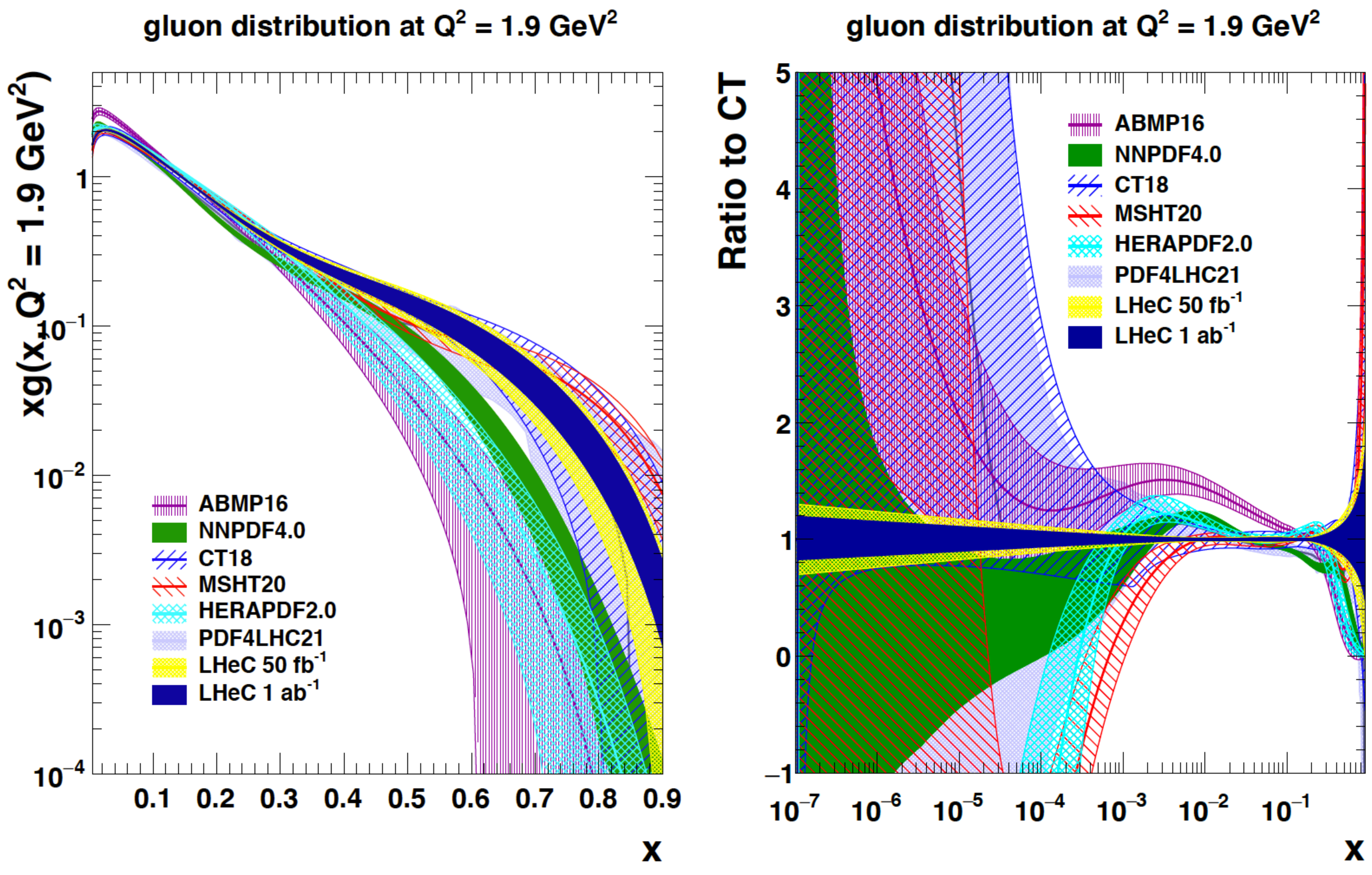
- **It should be able to run concurrently with pp** (also FCC-eh), plus limitations on power consumption, high luminosity for Higgs studies,… ⇒ energy recovery linac as baseline.



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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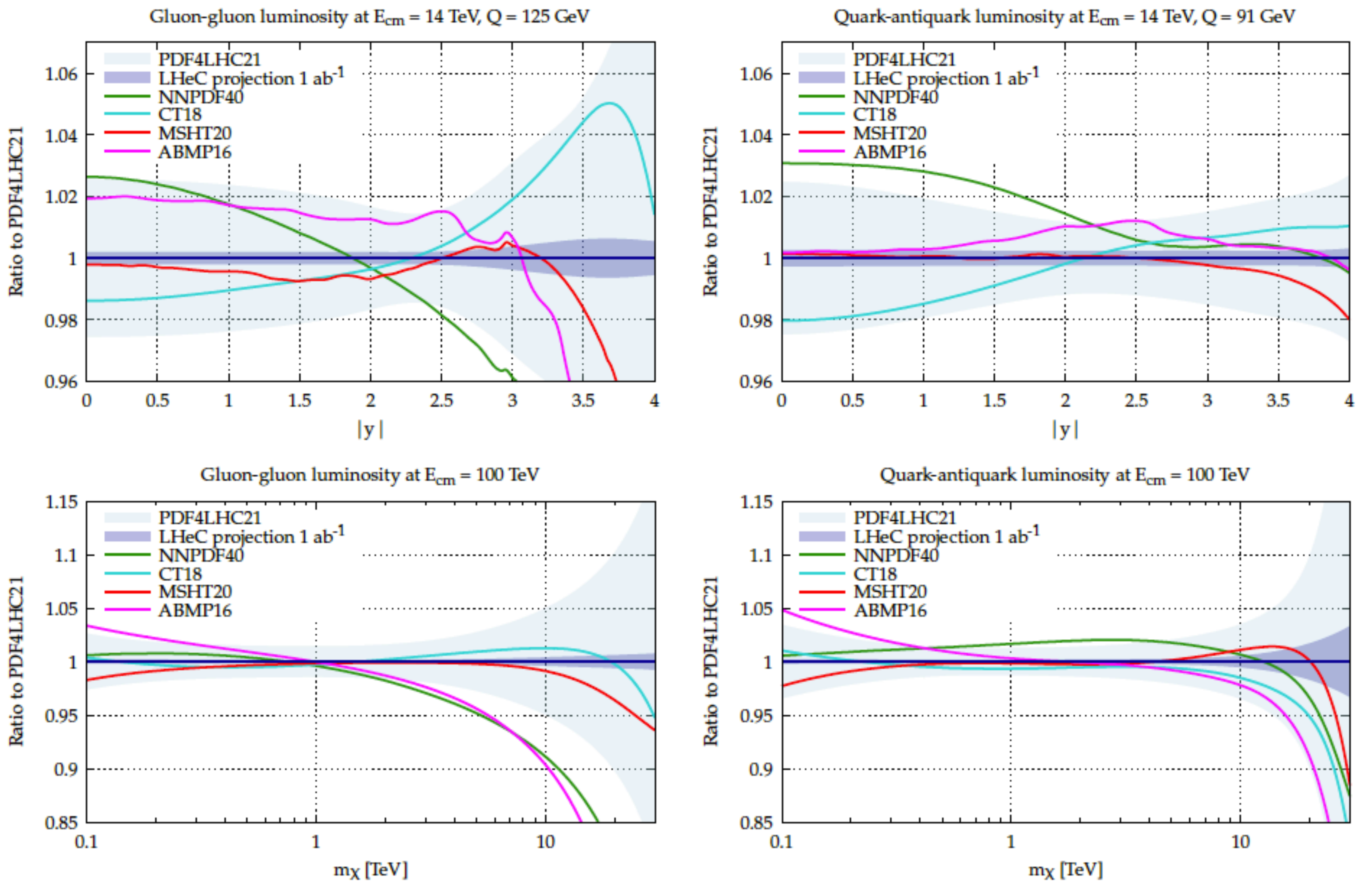
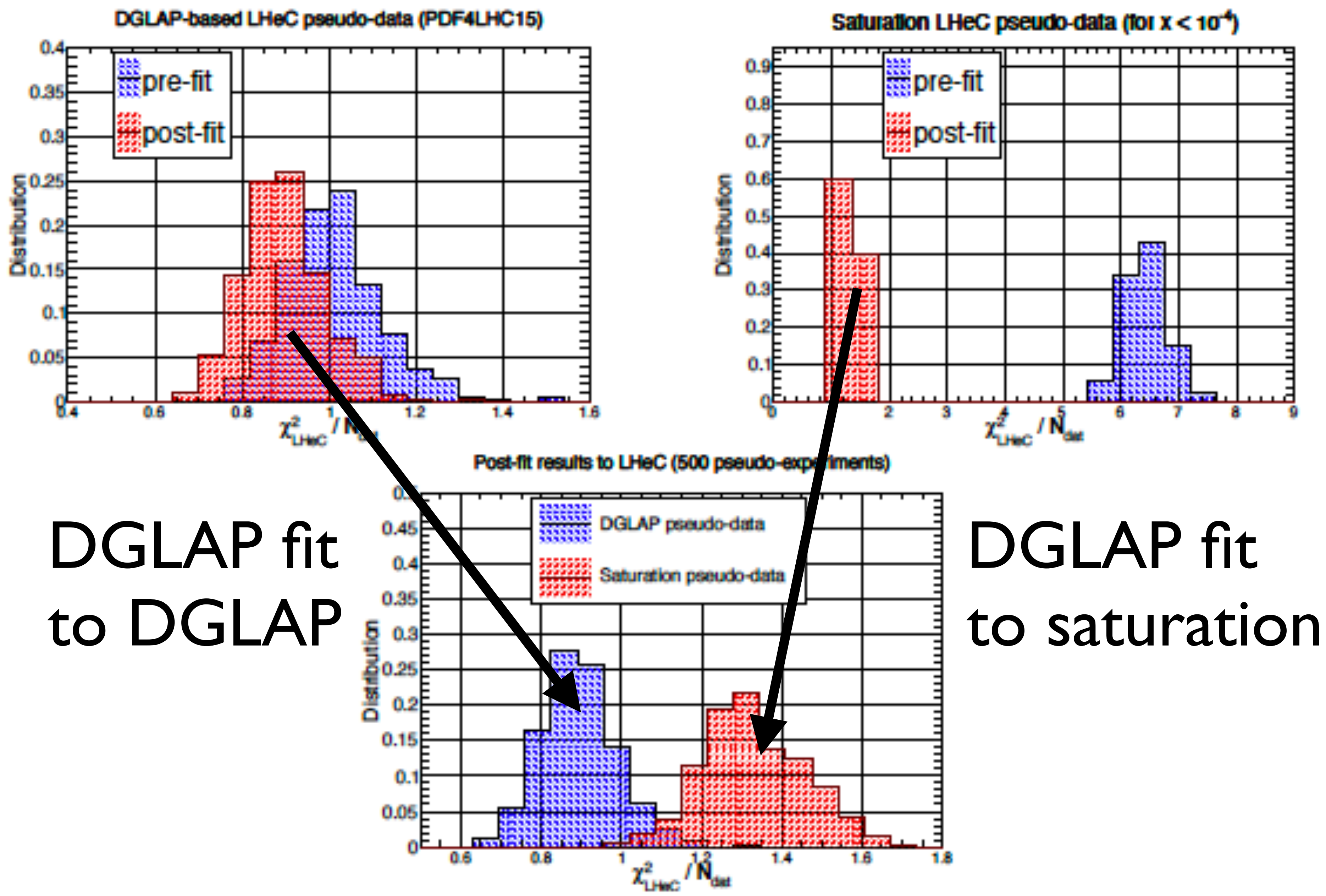
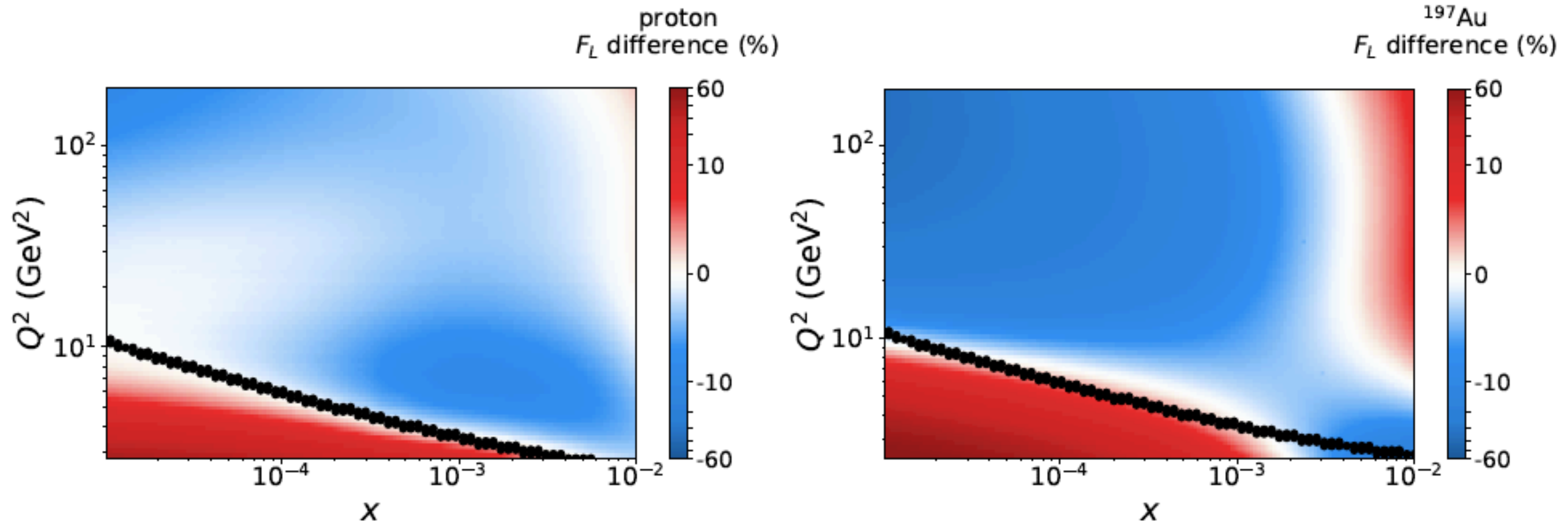


QCD: small x and α_s

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

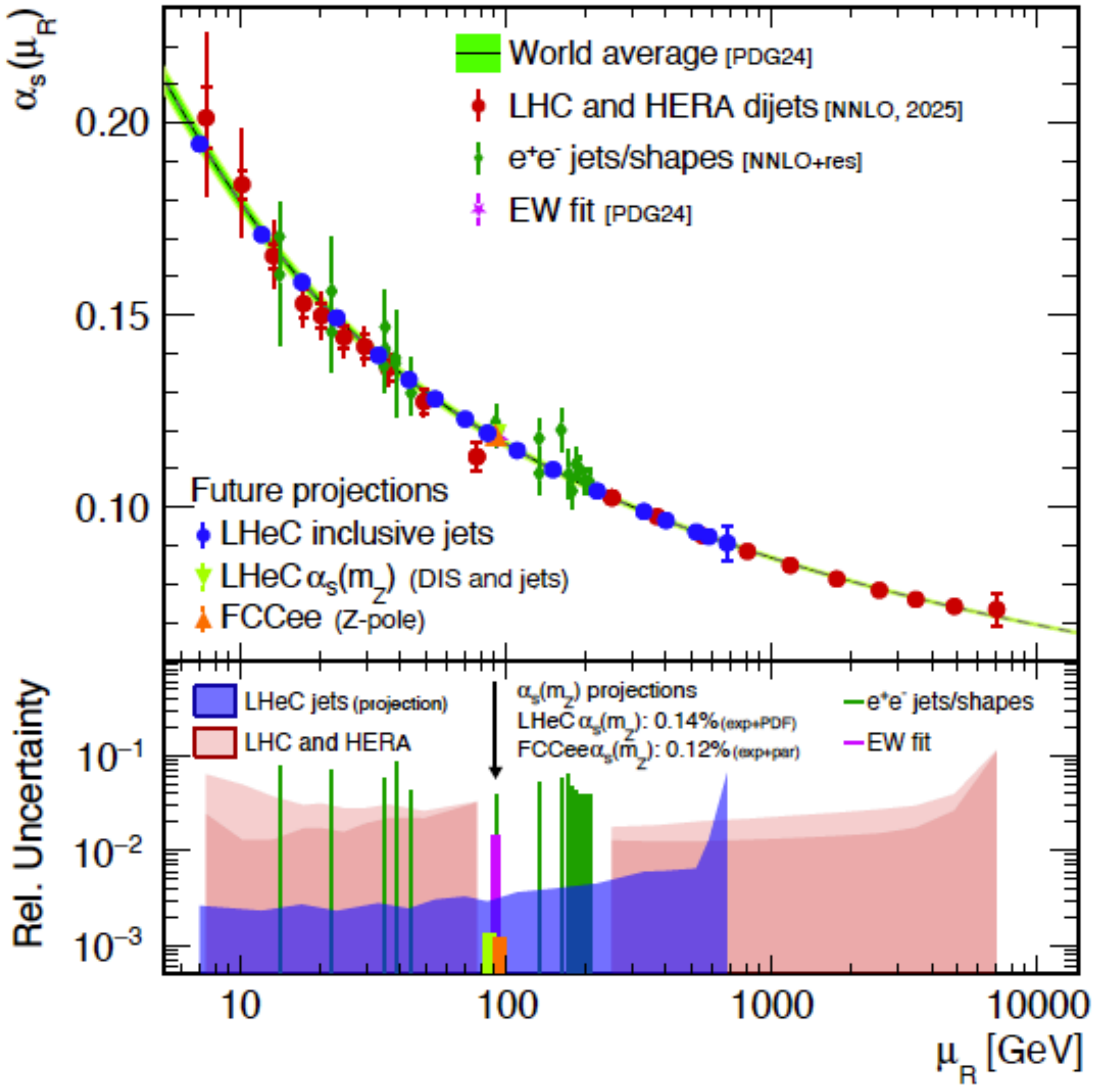




- α_s to per mille accuracy (incl.+jets):

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

$$\Delta\alpha_s(M_Z)\ (\text{incl. DIS \& jets}) = \pm\, 0.00016_{(\text{exp+PDF})}$$



BSM physics: invisible Higgs

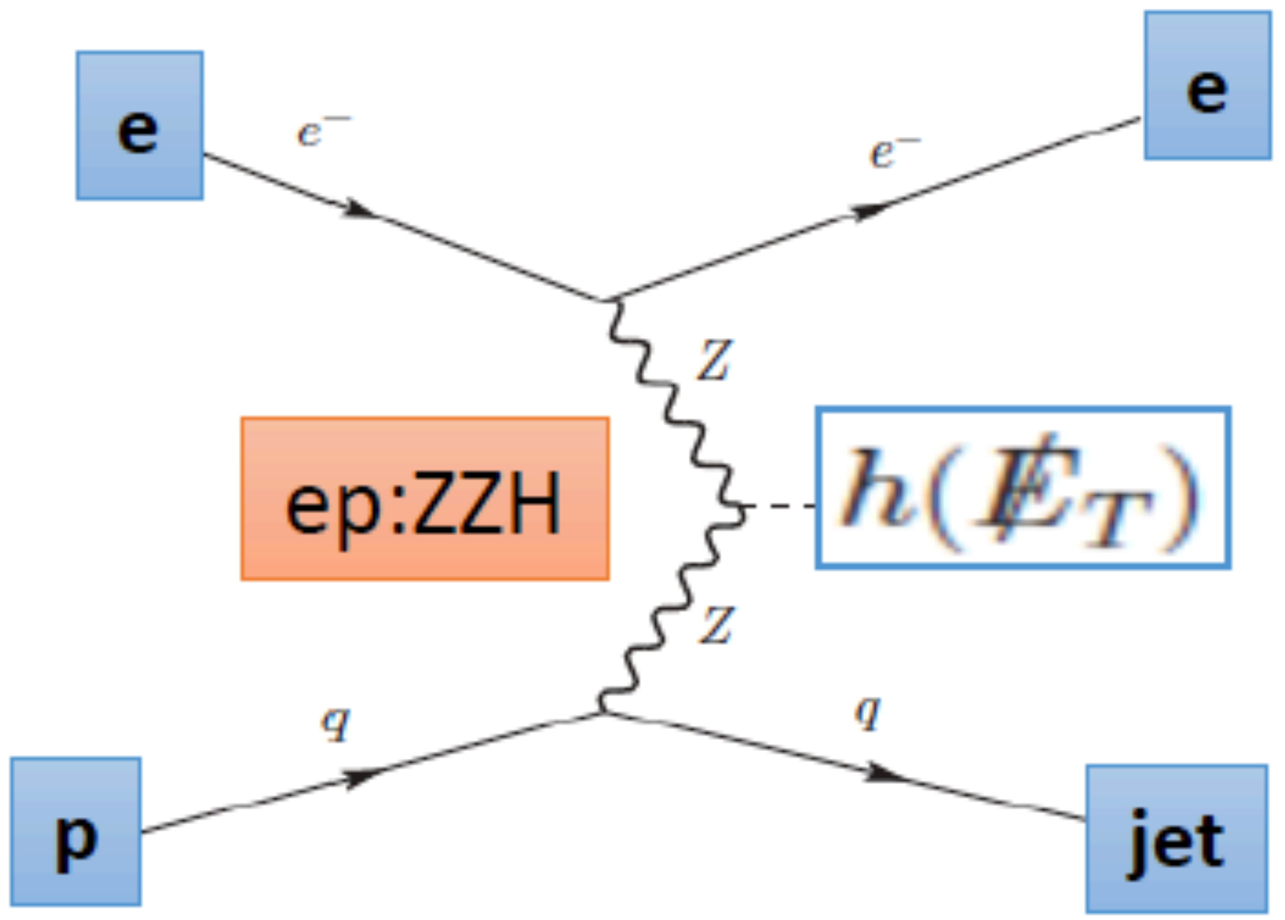
Stand alone Branching for invisible Higgs

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]



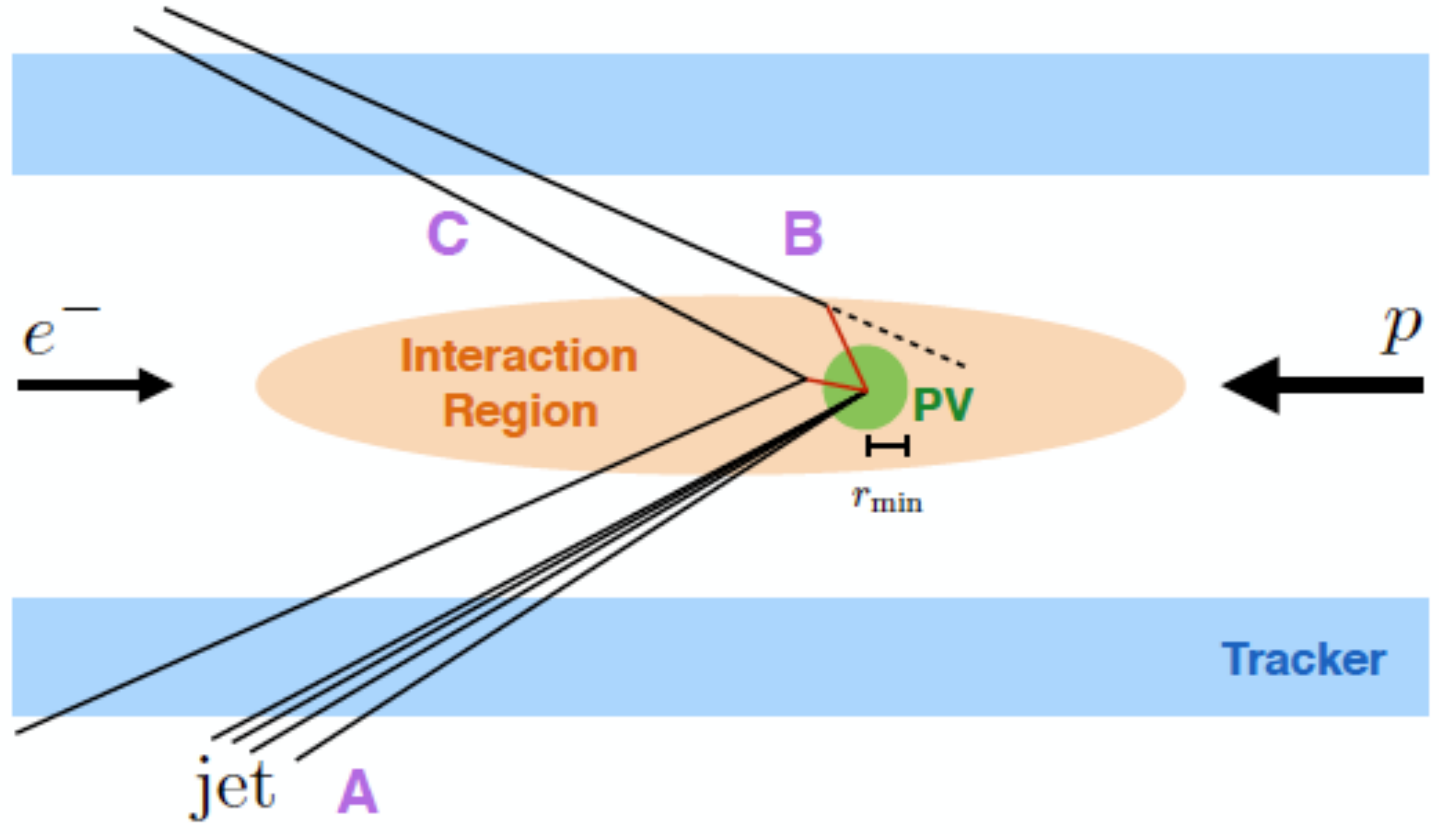
PORTAL to Dark Matter ?

- ✓ 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]

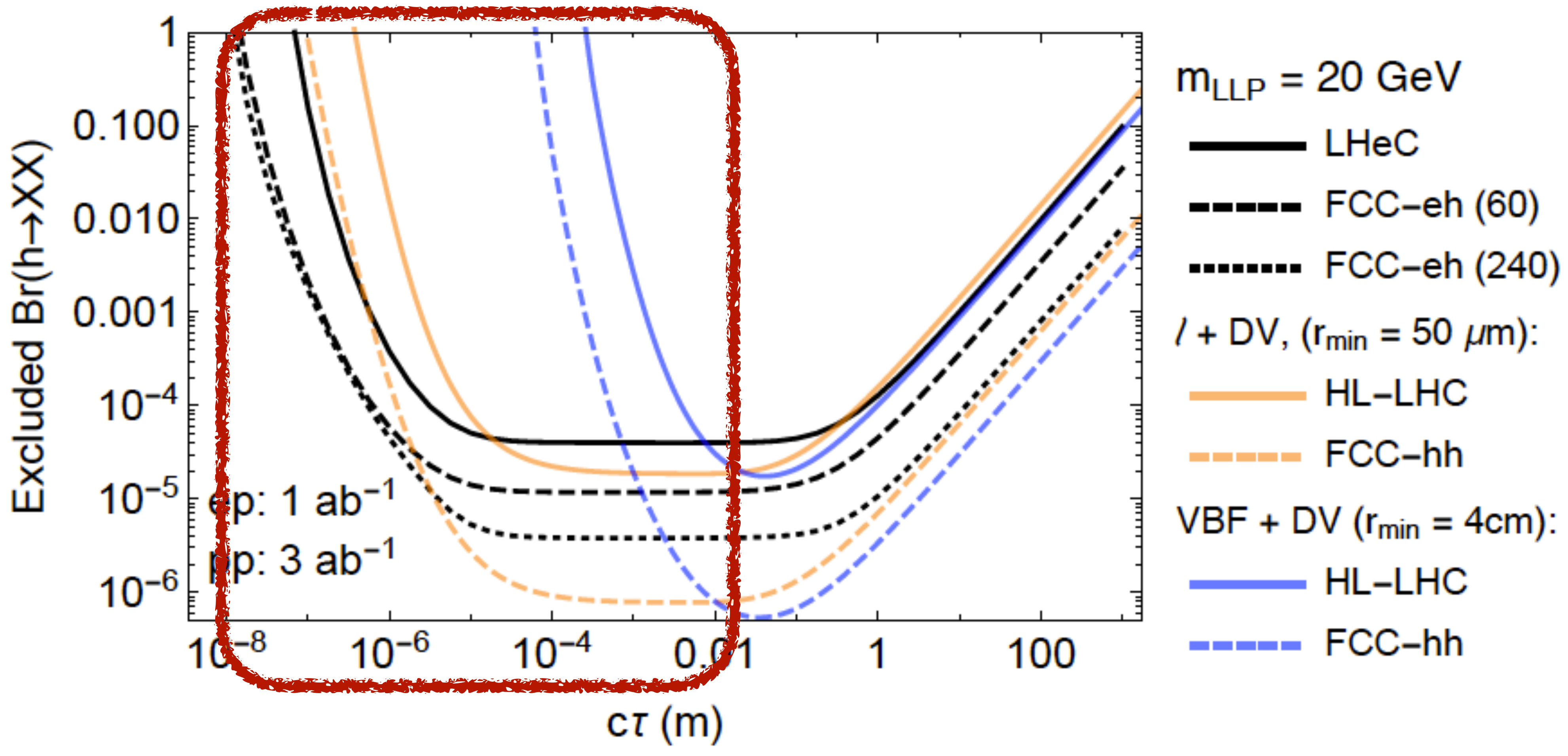
U. Klein at ICHEP2024

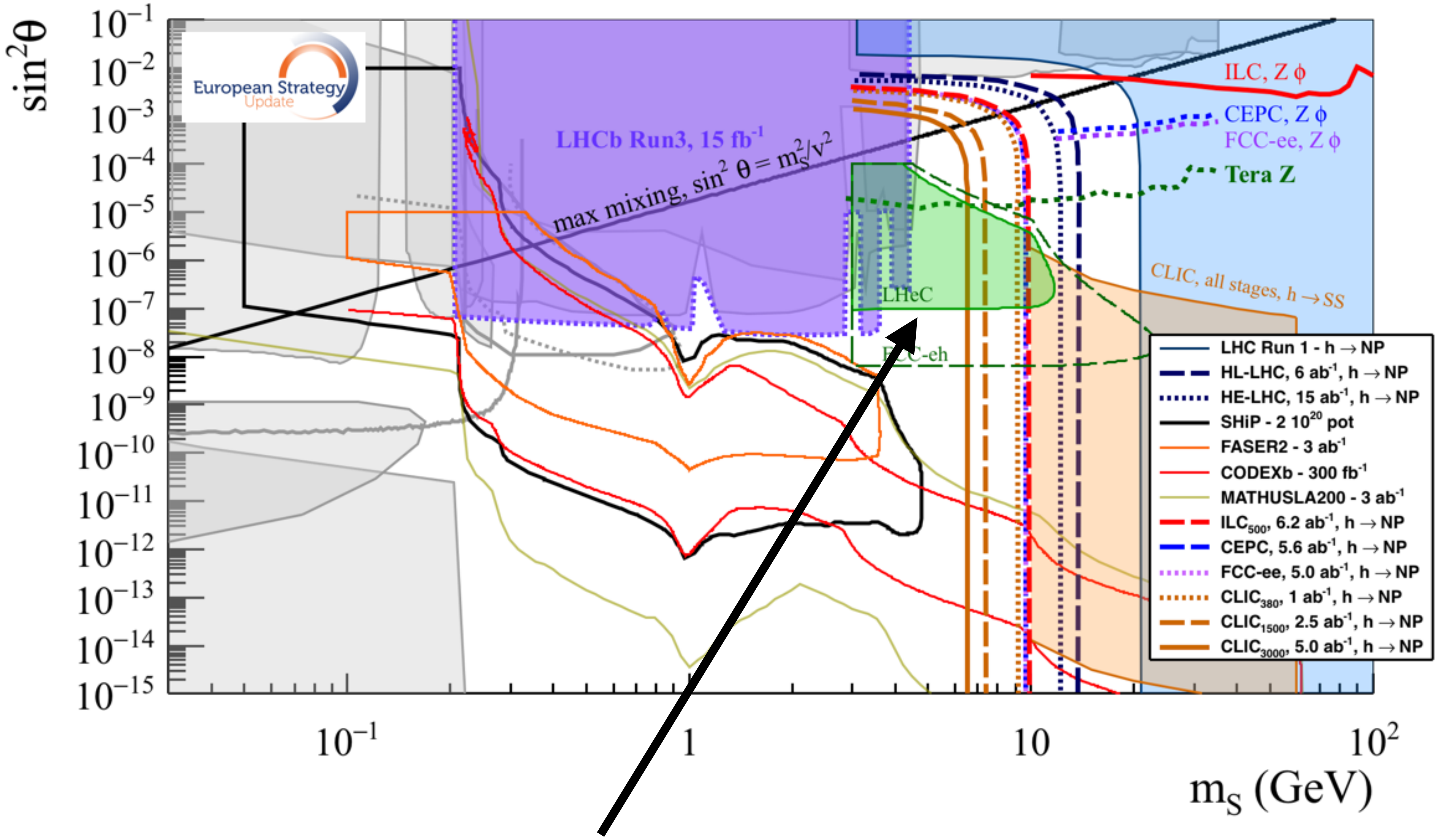
BSM physics: new scalars from Higgs

- 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

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

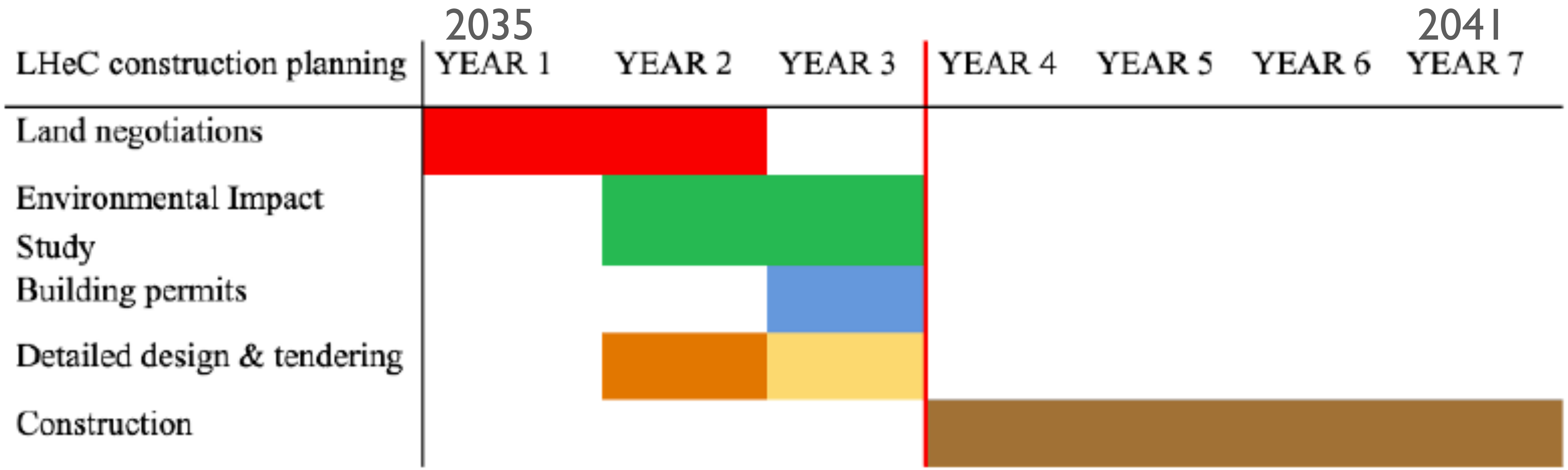
A. Bogacz, full lattice simulation for ERL at 50 GeV

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	1622 MCHF

- 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).

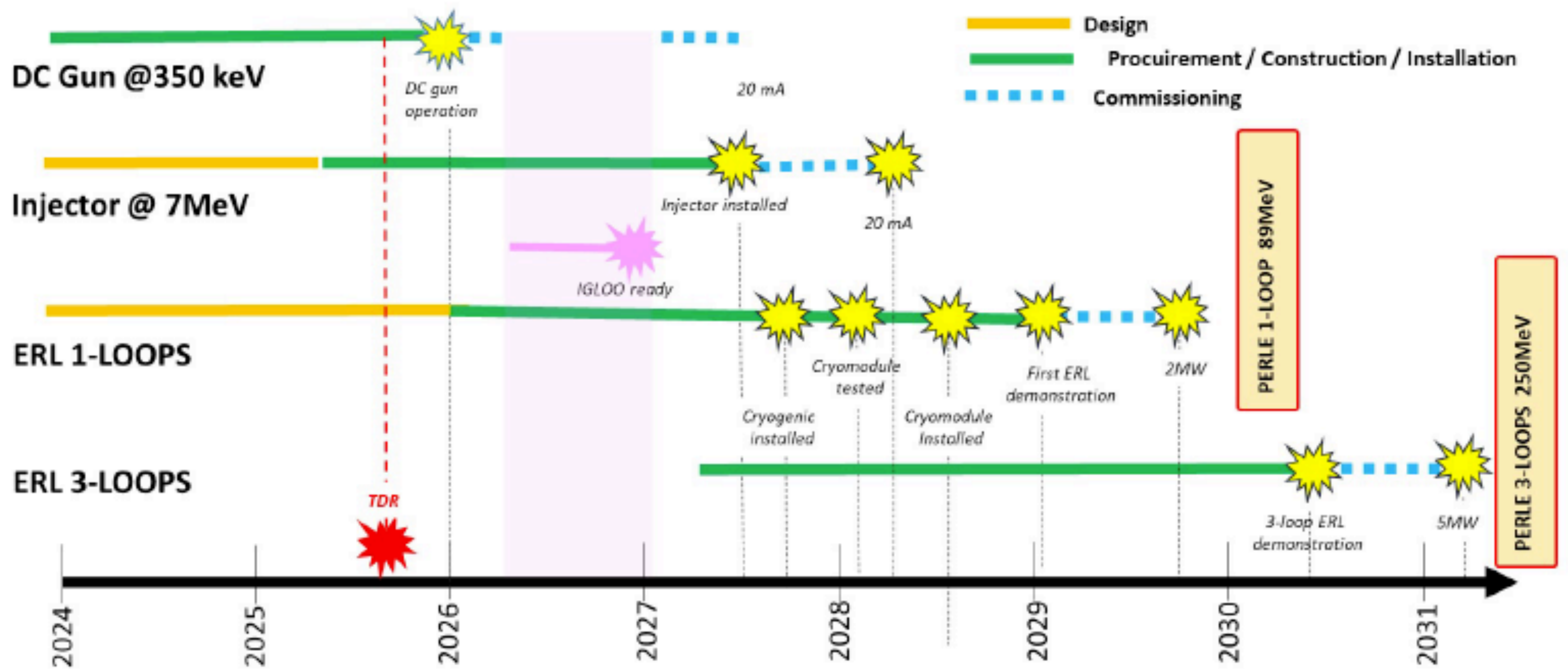
- Power consumption for this option: 220 MW including the ERL, the single-beam HL-LHC and the detector ⟶ +60 MW w.r.t. HL-LHC and +75 MW w.r.t. nominal LHC operation.

Feasibility:



- Target ep luminosity of $1\ \mathrm{ab}^{-1}$ 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).
- 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.

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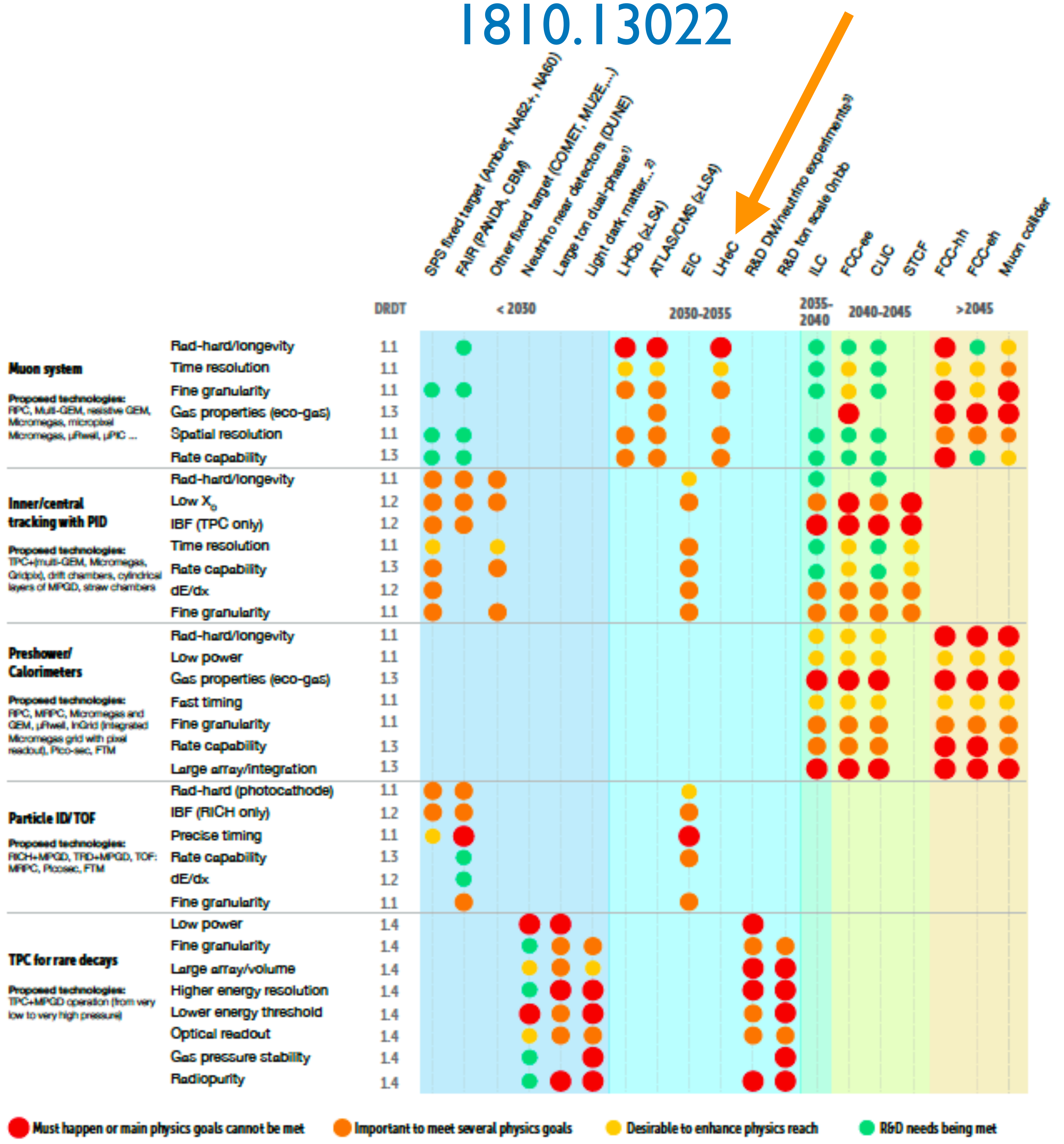
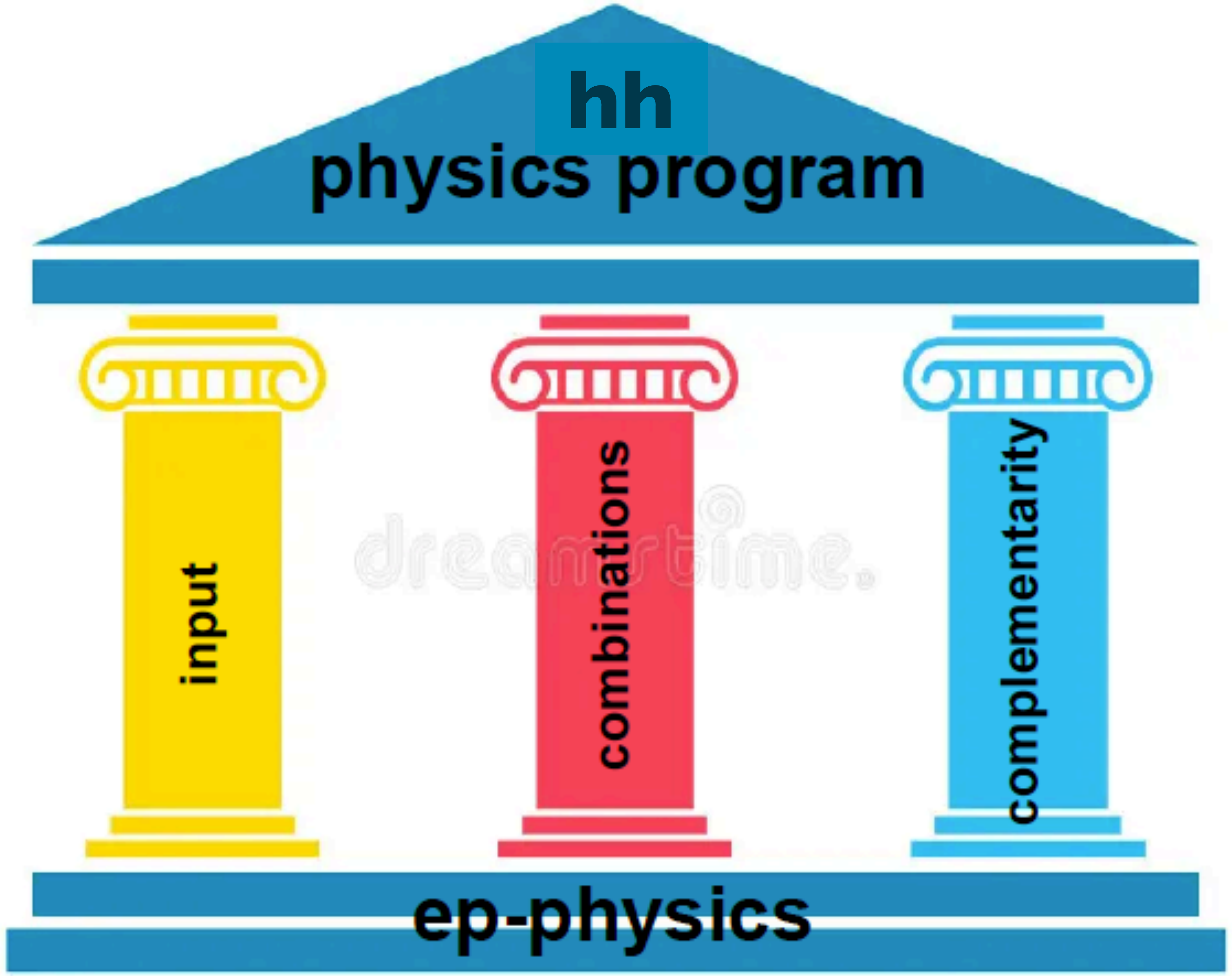


Synergies between eh and hh programes:

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.



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.