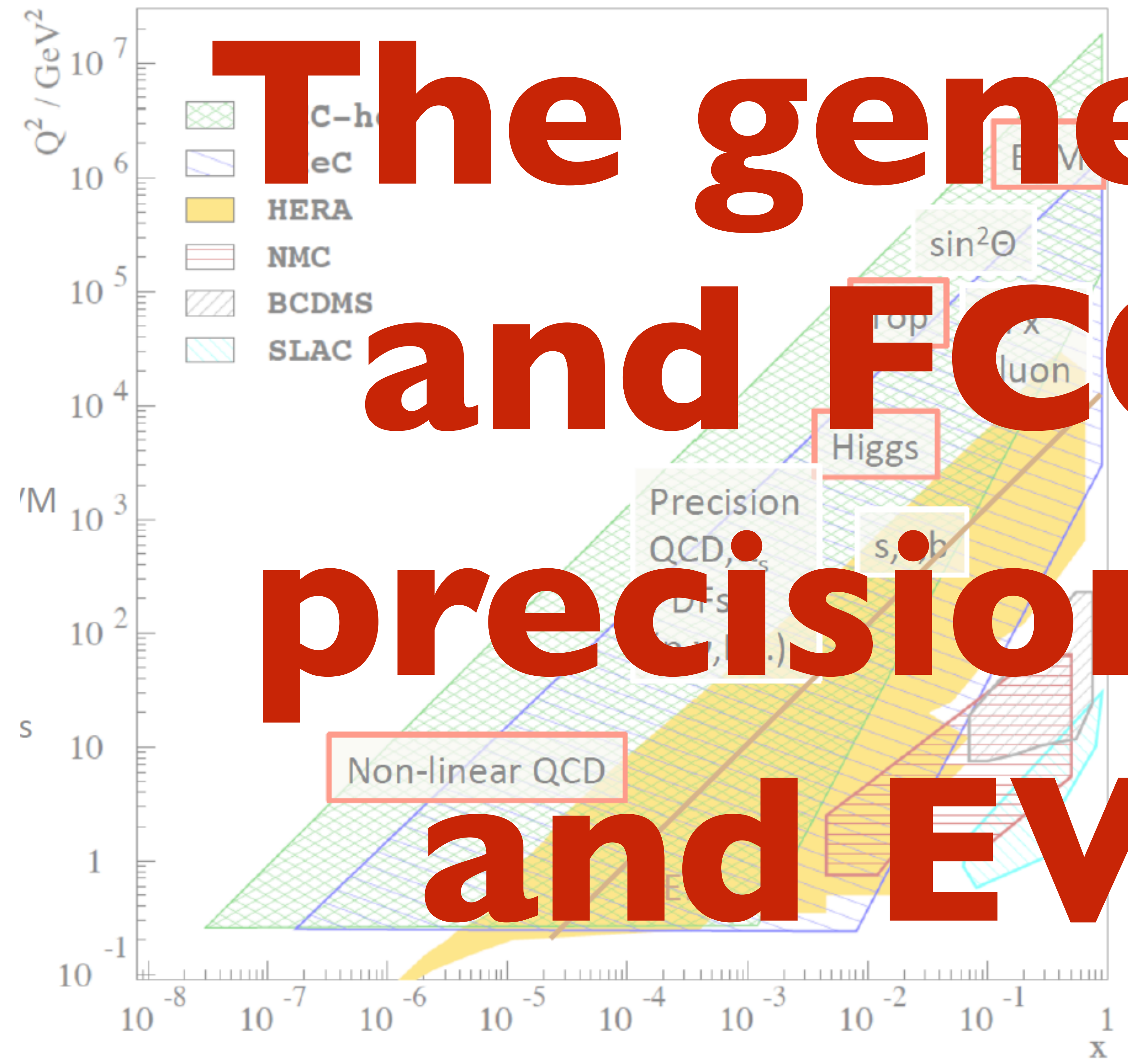
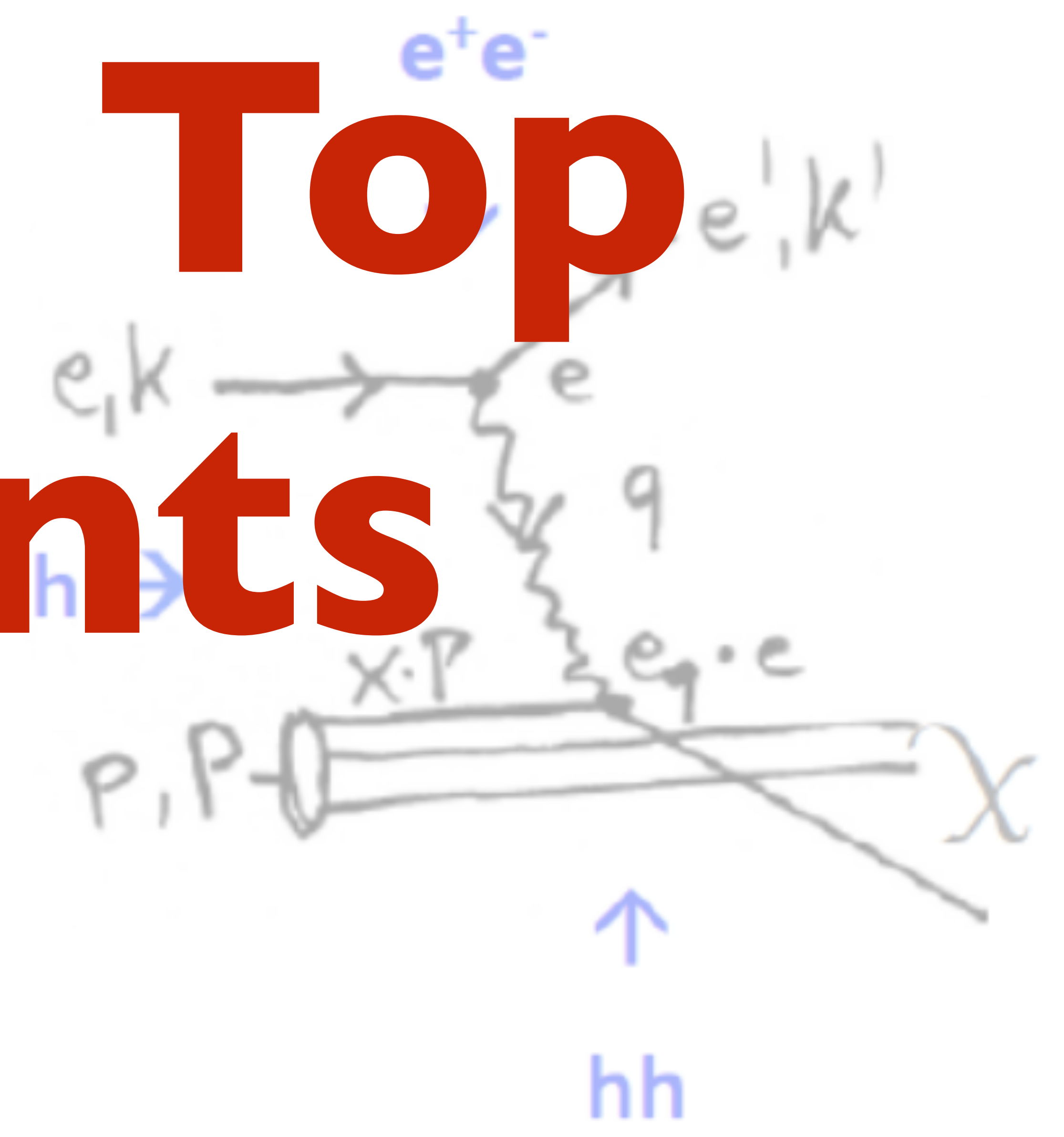
31st International Workshop on Deep Inelastic Scattering DIS2024
Maison MINATEC, Grenoble, April 10th 2024

The general-purpose LHeC and FCC-eh high-energy precision programme: Top and EW measurements





Néstor Armesto
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for the LHeC/FCC-eh Study Group

FONDO EUROPEO DE DESENVOLVEMENTO REXIONAL "Unha maneira de facer Europa"

Contents:

1. Introduction: accelerator, detector and physics.

2. EW physics and its impact on hh.

3. Top physics.

4. Summary.

References:

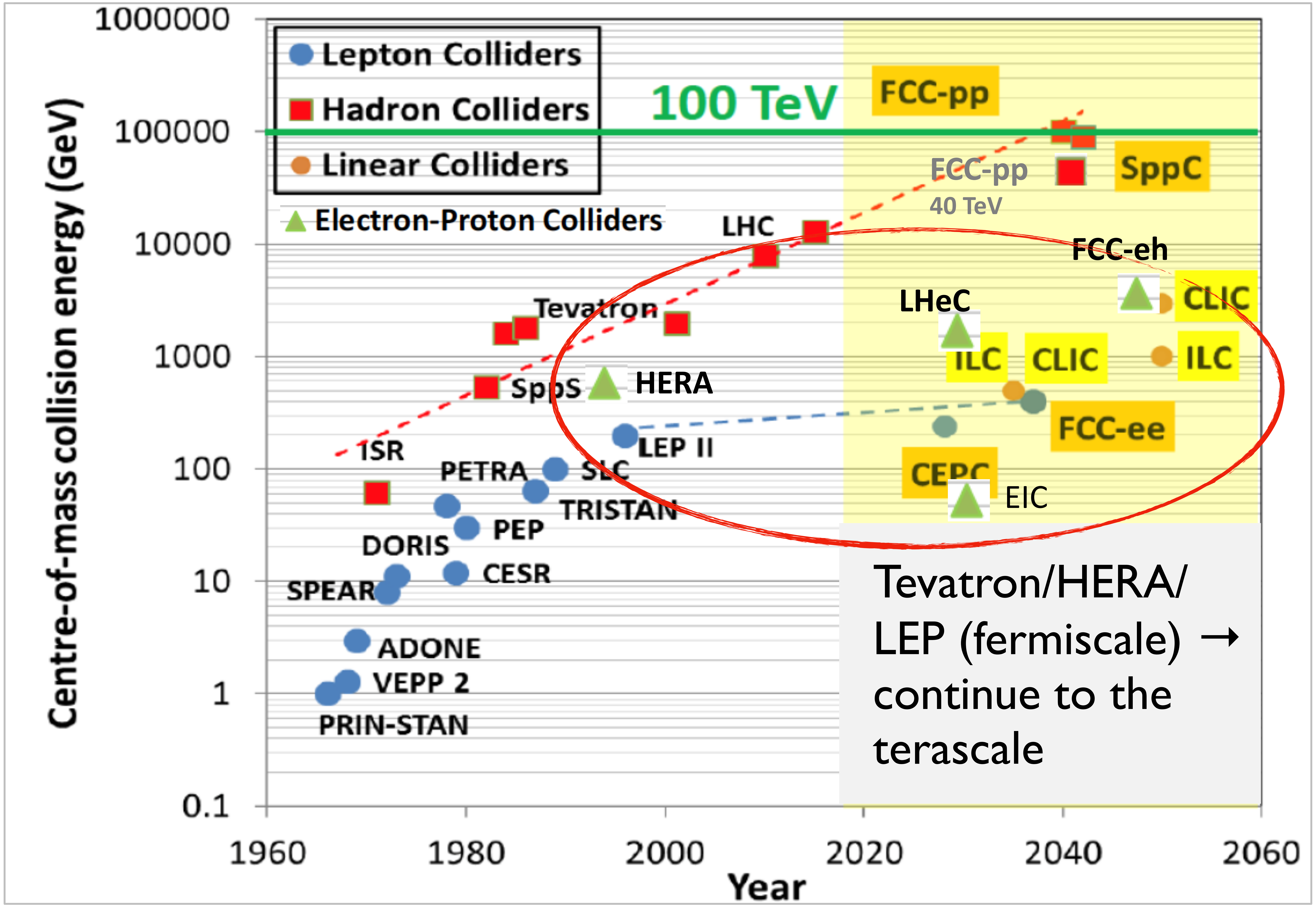
- *Future Circular Collider CDR: Vol. 1 Physics opportunities (Eur. Phys. J. C79 (2019) no.6, 474) and Vol. 3 FCC-hh: The Hadron Collider (Eur. Phys. J. ST 228 (2019) no.4, 755-1107);*
- *LHeC CDR, 1206.2913 and update 2007.14491;*
- *European Strategy Update: Briefing Book, 1910.11775;*
- *2201.02436;*
- *Talks at the LHeC/FCC-eh/PERLE workshop, October 26th-28th 2022, https://indico.ijclab.in2p3.fr/event/8623/;*
- *Talks at the Synergy workshop between ep/eA and pp/pA/AA physics and experiments, February 29th-March 1st 2024, https://indico.cern.ch/event/1367865/.*

See also the talks by Bruce Mellado (Higgs and BSM), Hamzeh Khanpour ($\gamma\gamma$ collisions), Amanda Cooper-Sarkar (PDFs and precision QCD) and Paul Newman (status and plans).

Accelerators:

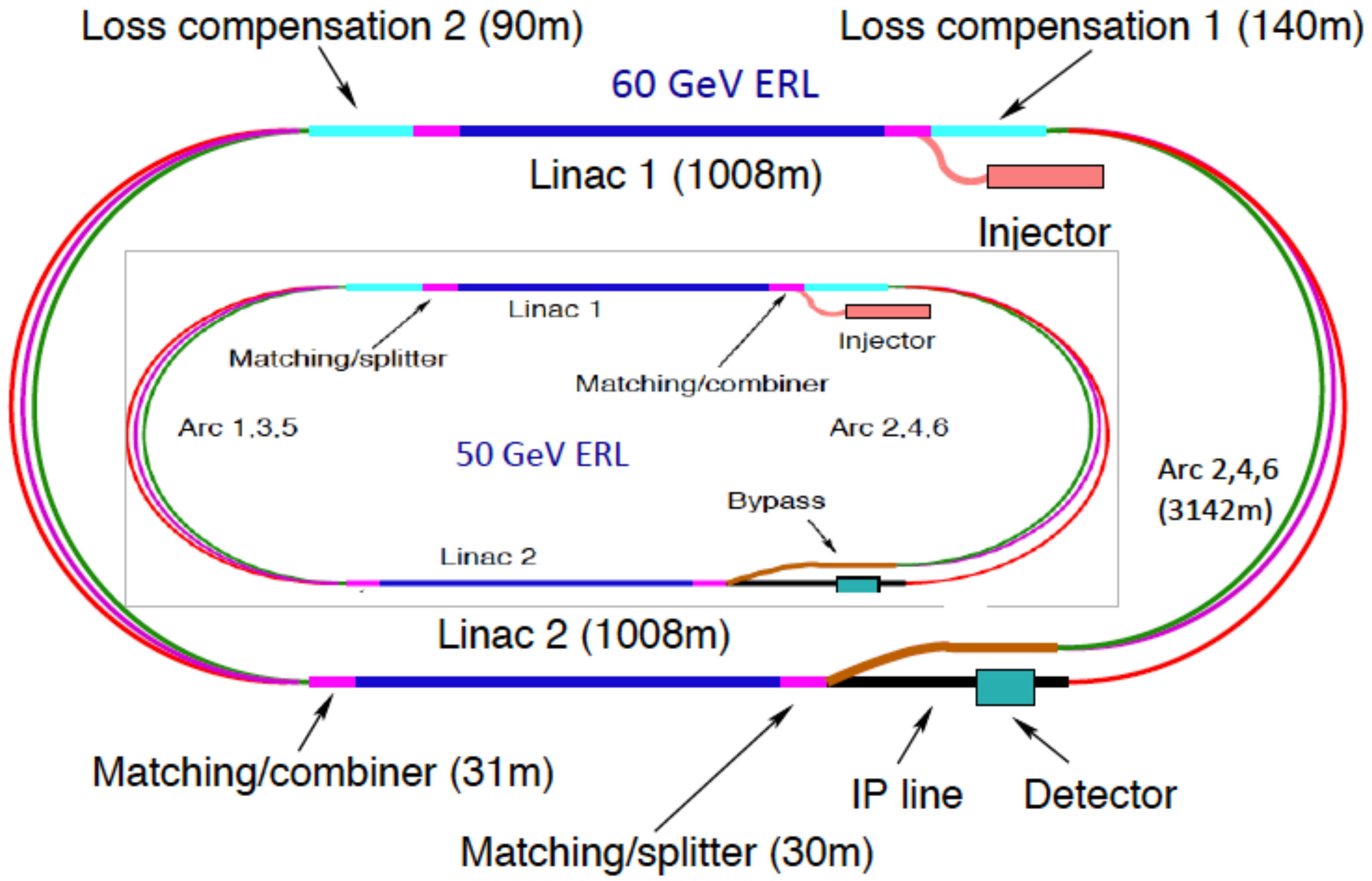
● LHeC idea born in 2005: upgrade of the HL-LHC to study DIS at the terascale.

● **It must 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.

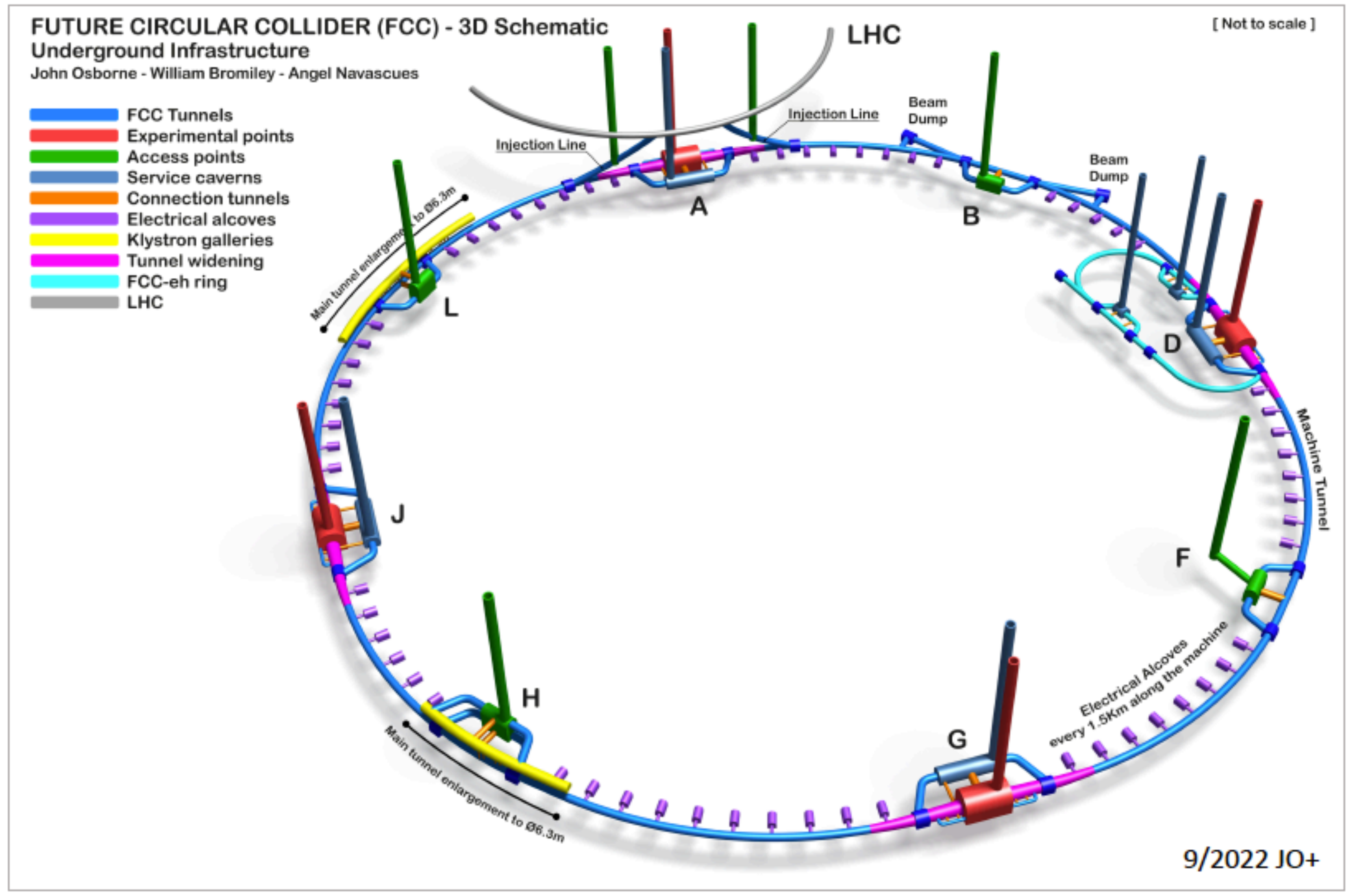


Accelerators:

LHeC



FCC-eh



FCC-eh

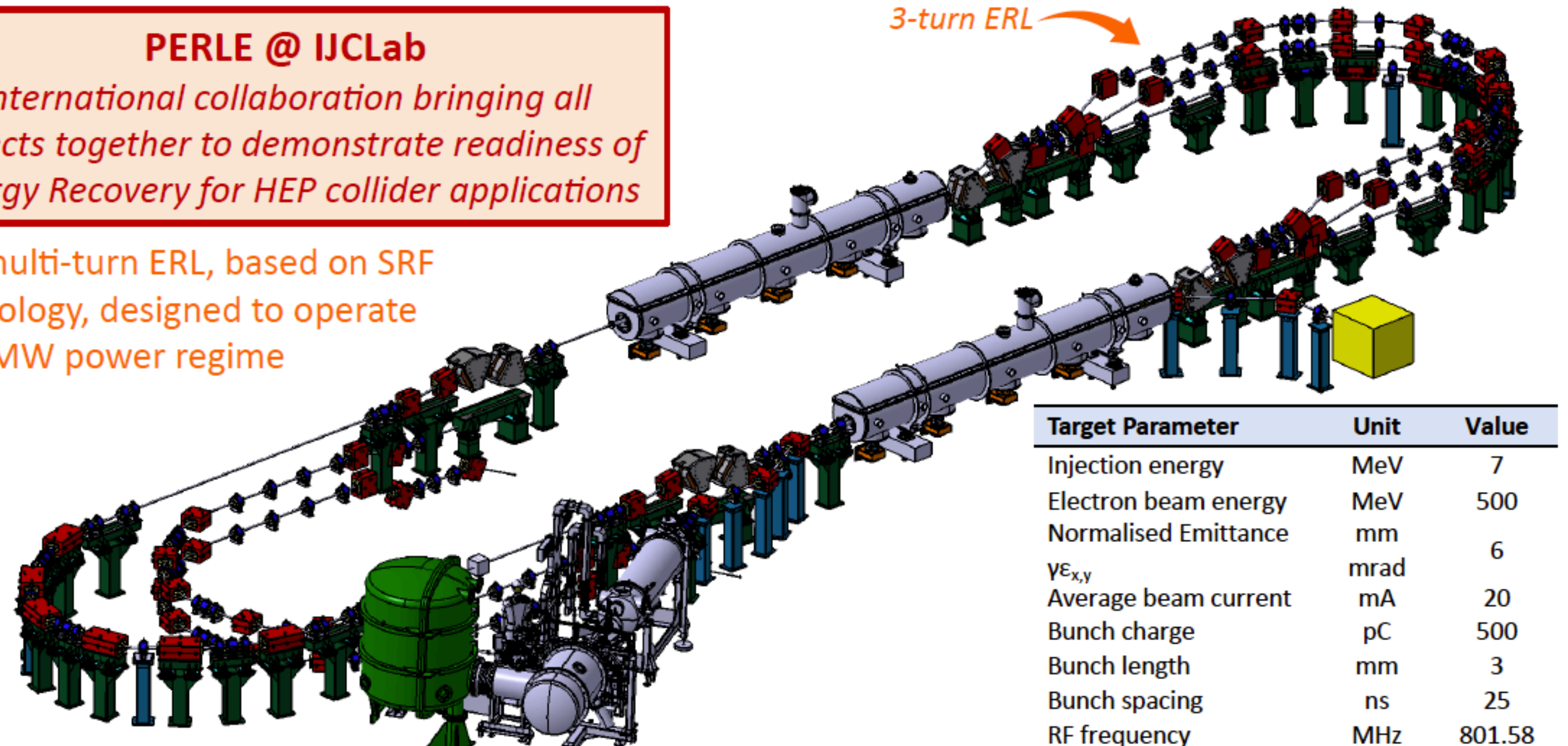
$$\text{DIS at } \sqrt{s} \simeq 1.3/2.2/3.5 \;\; \text{TeV}, \quad \int \mathscr{L} dt \sim 1-2 \;\; \text{ab}^{-1} \sim 1000 \times \text{HERA}$$

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 $\gamma\epsilon_{x,y}$	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

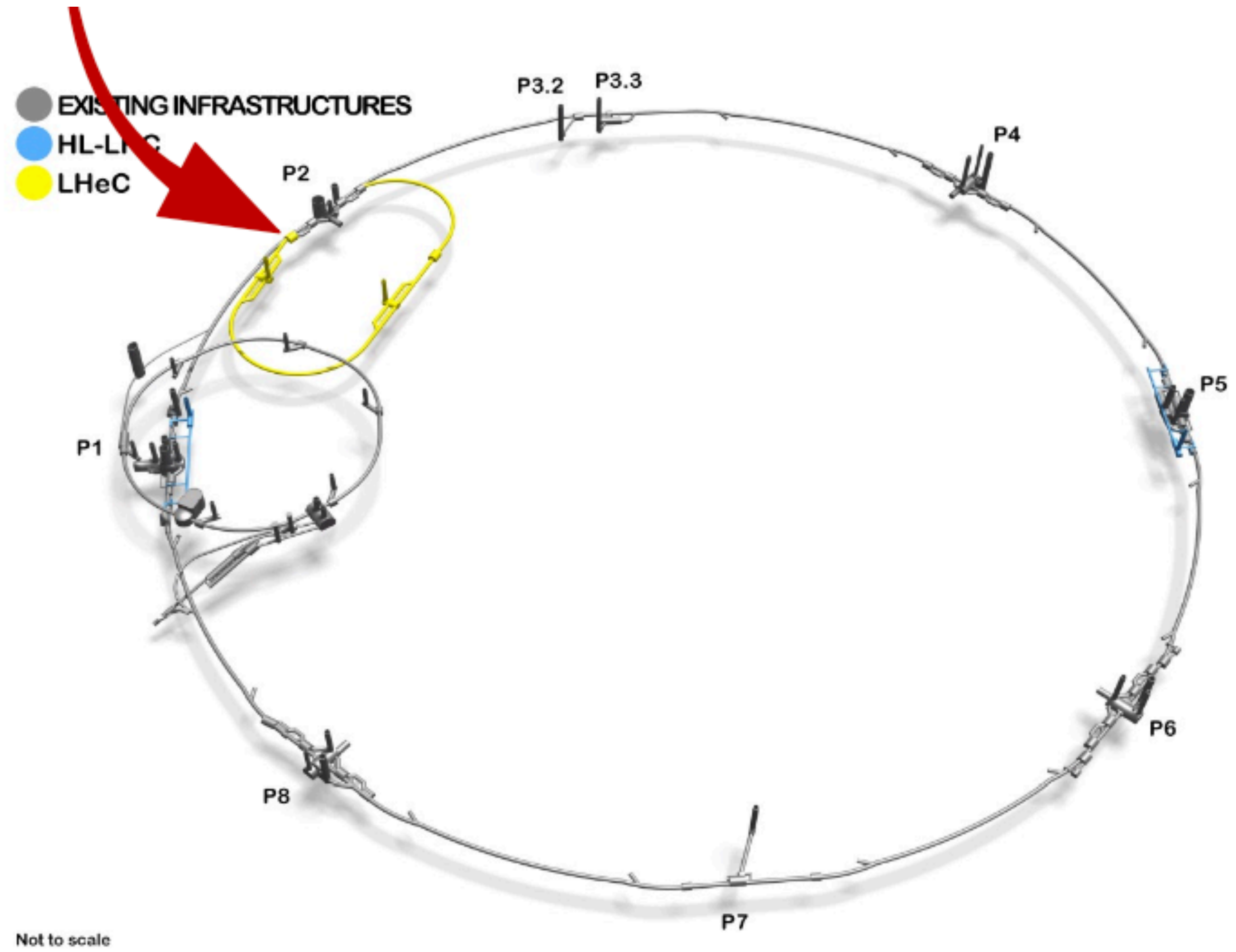
PERLE – Powerful Energy Recovery Linac for Experiments

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} cm^{-2}s^{-1}	1	5	9	23	8	15

1810.13022

Accelerators:

LHeC



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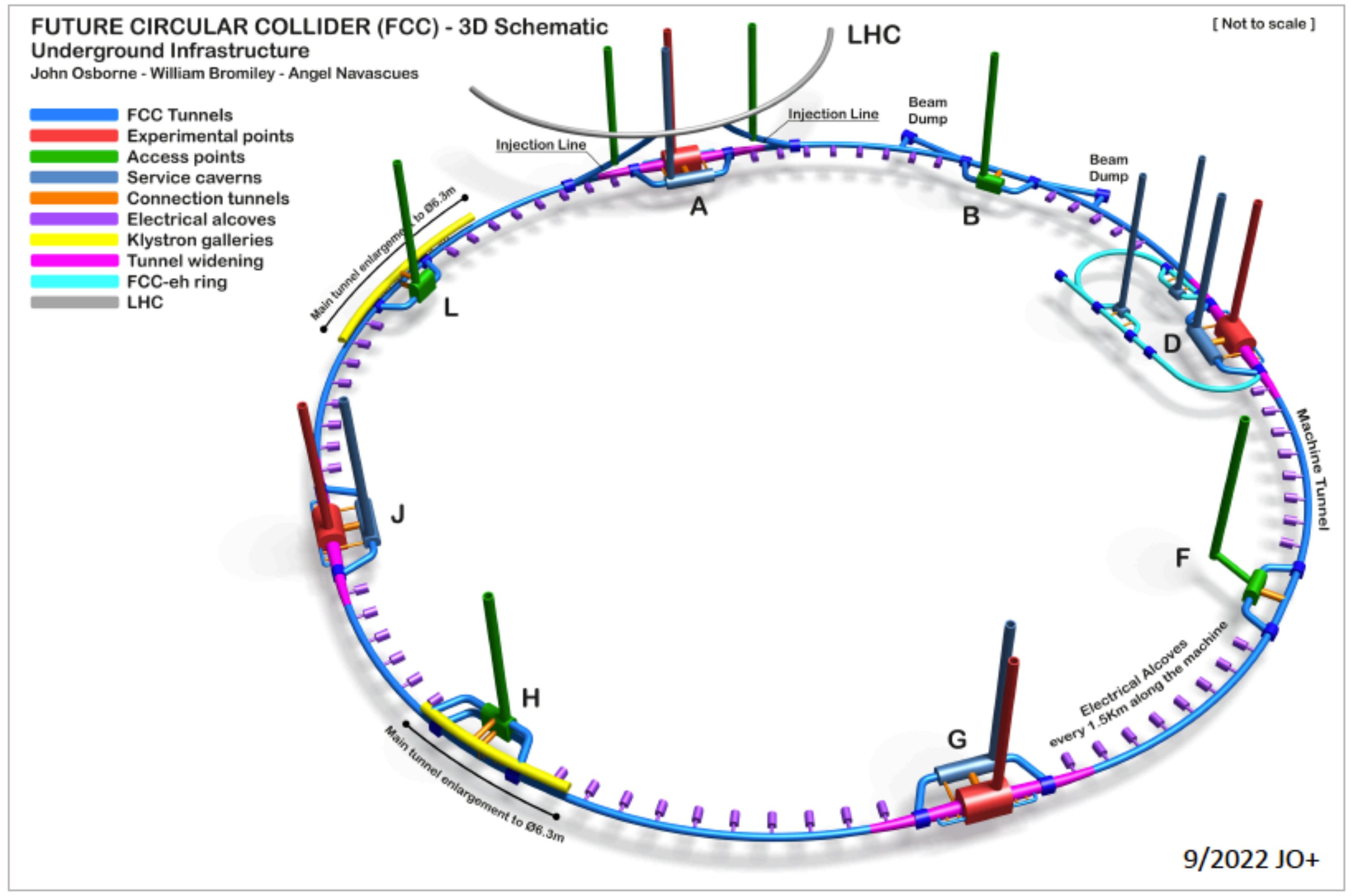

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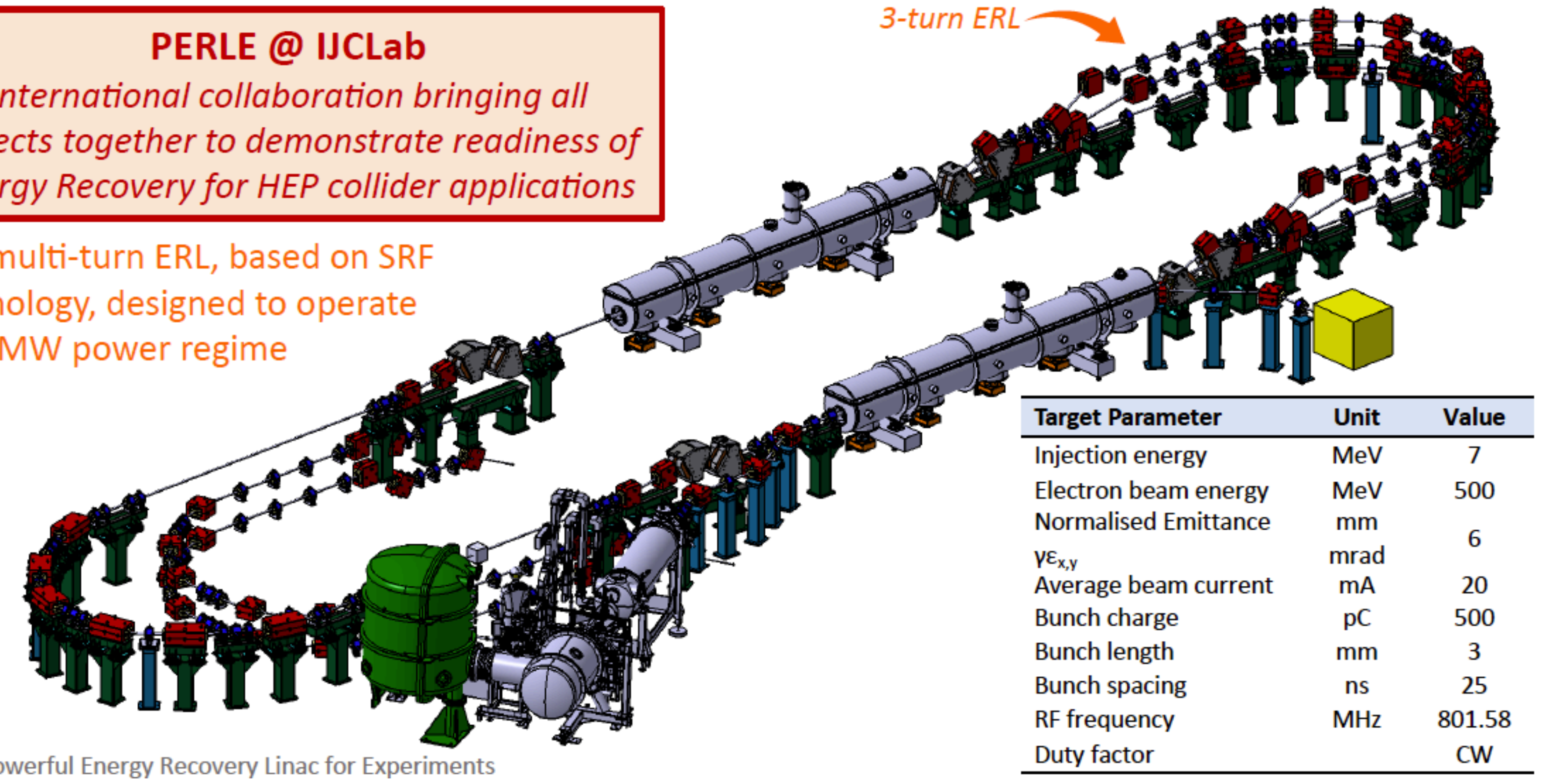

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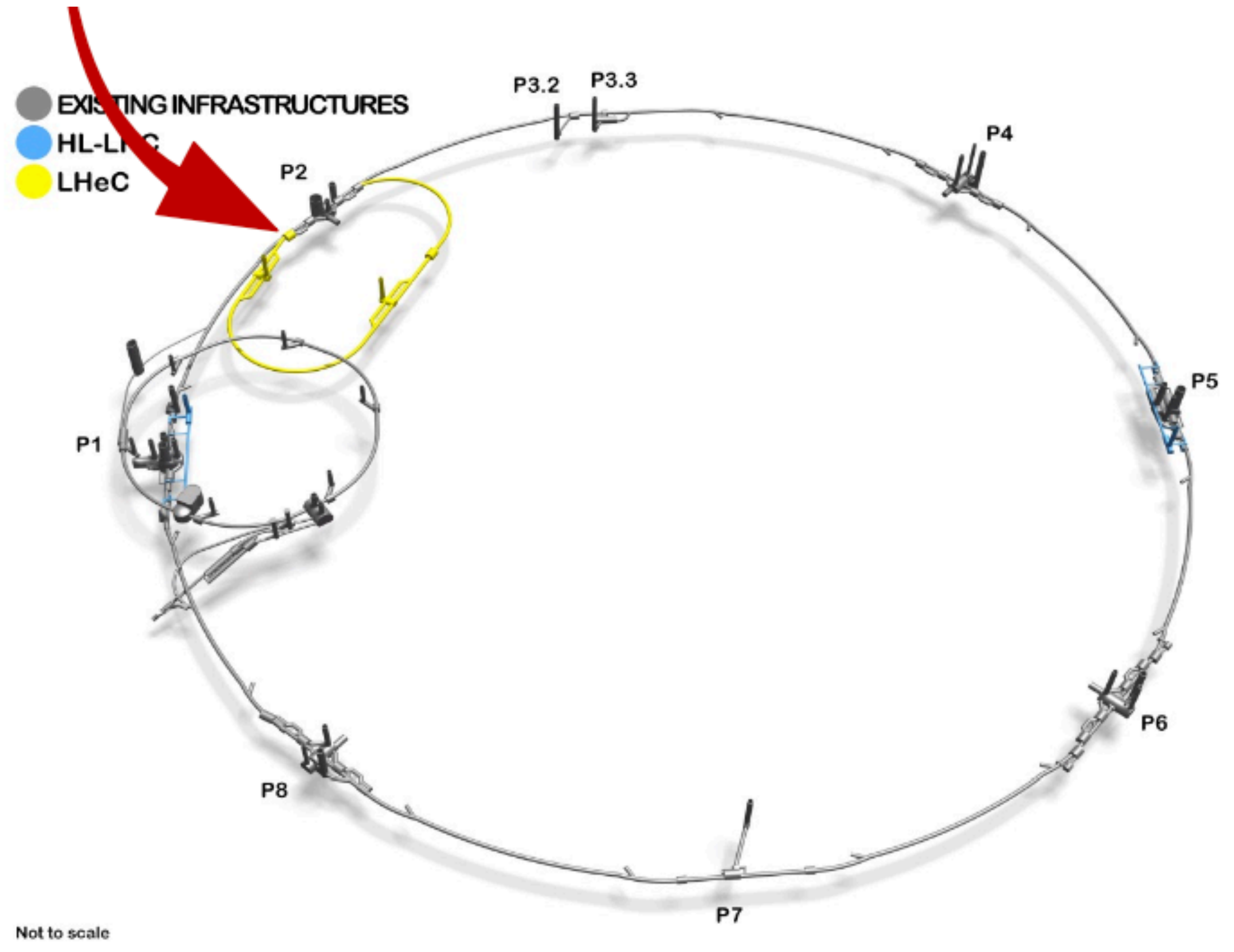

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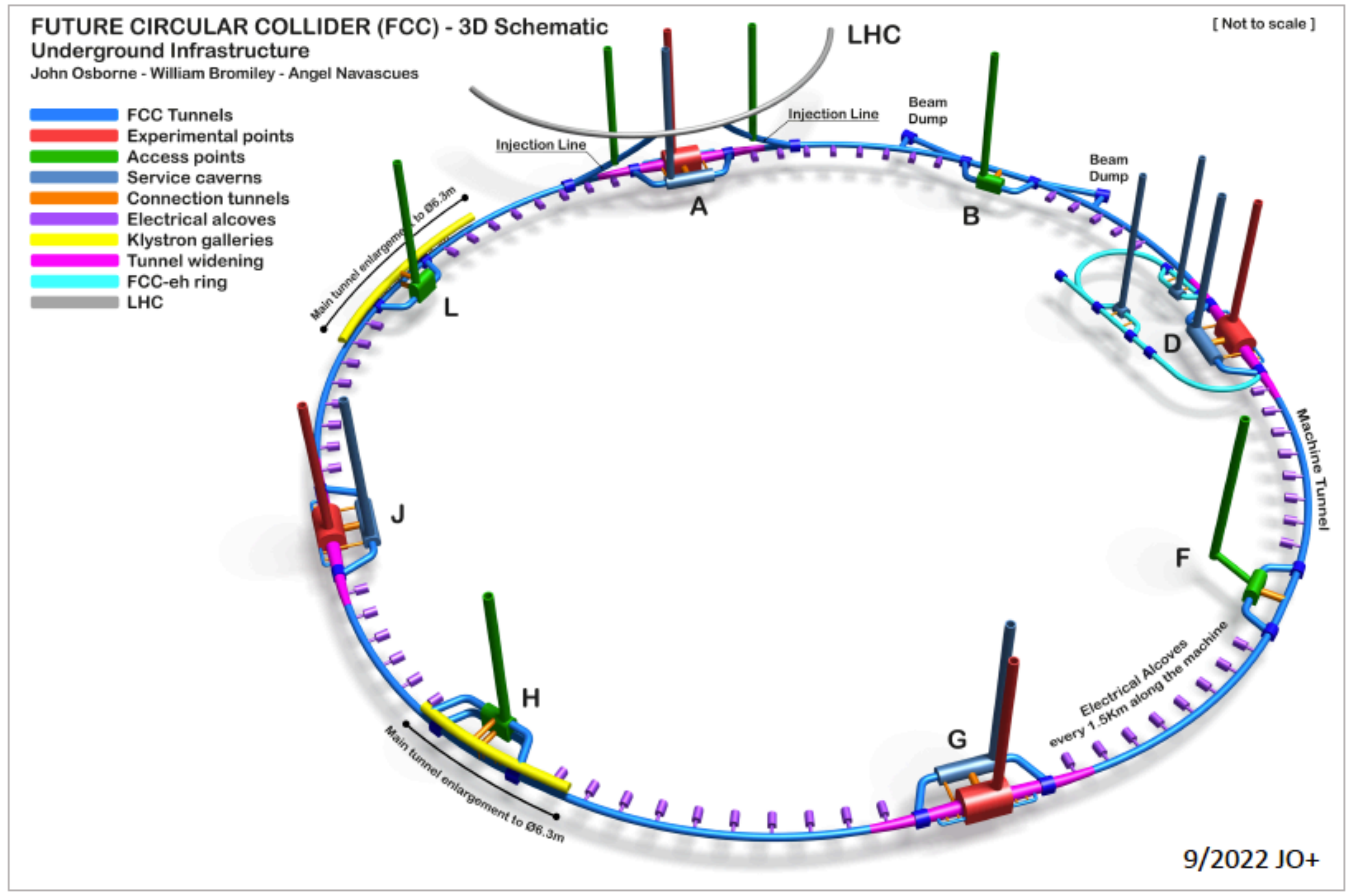

FCC-eh

ePb

Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β_A^*	cm	10	10	15
e-N Luminosity	$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7	14	35

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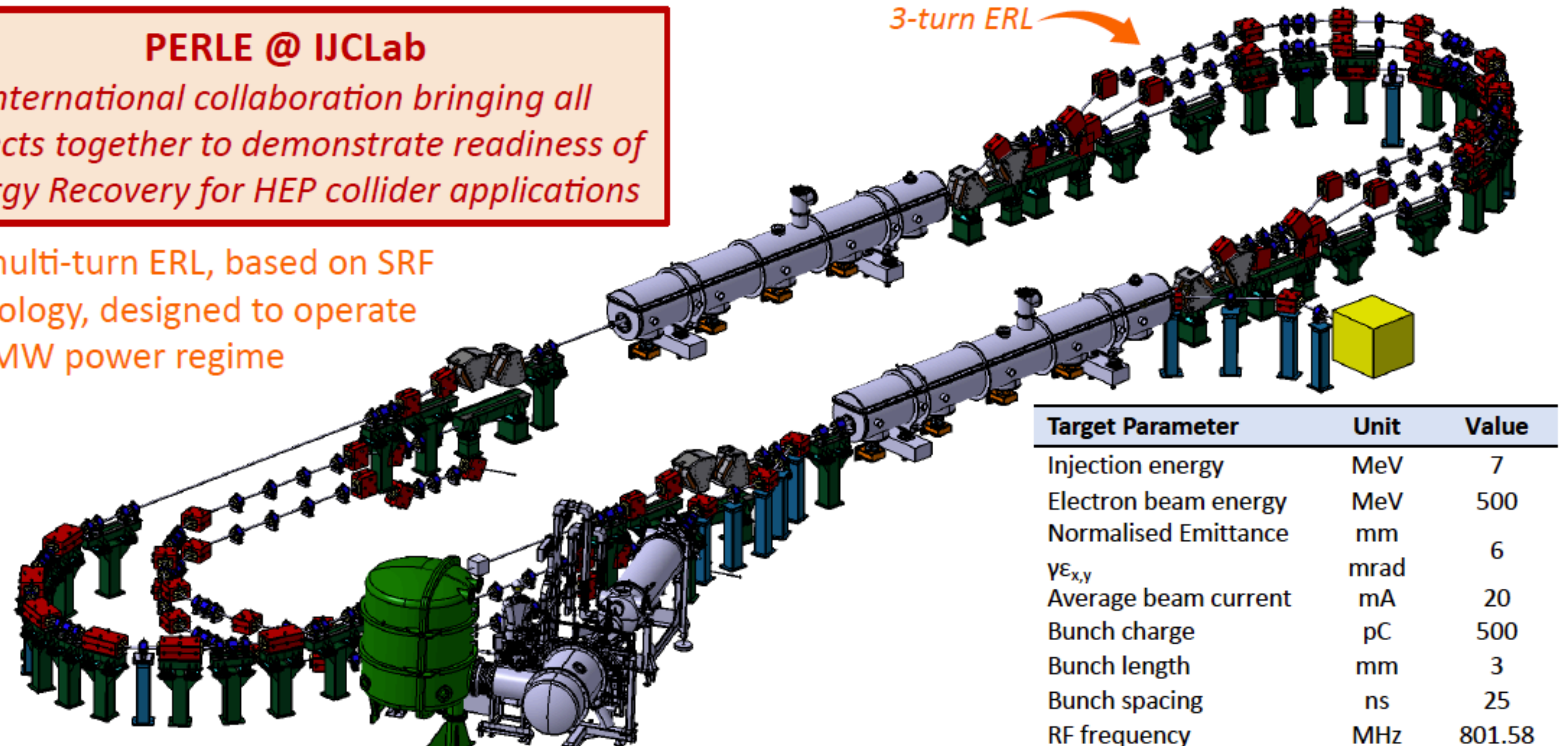

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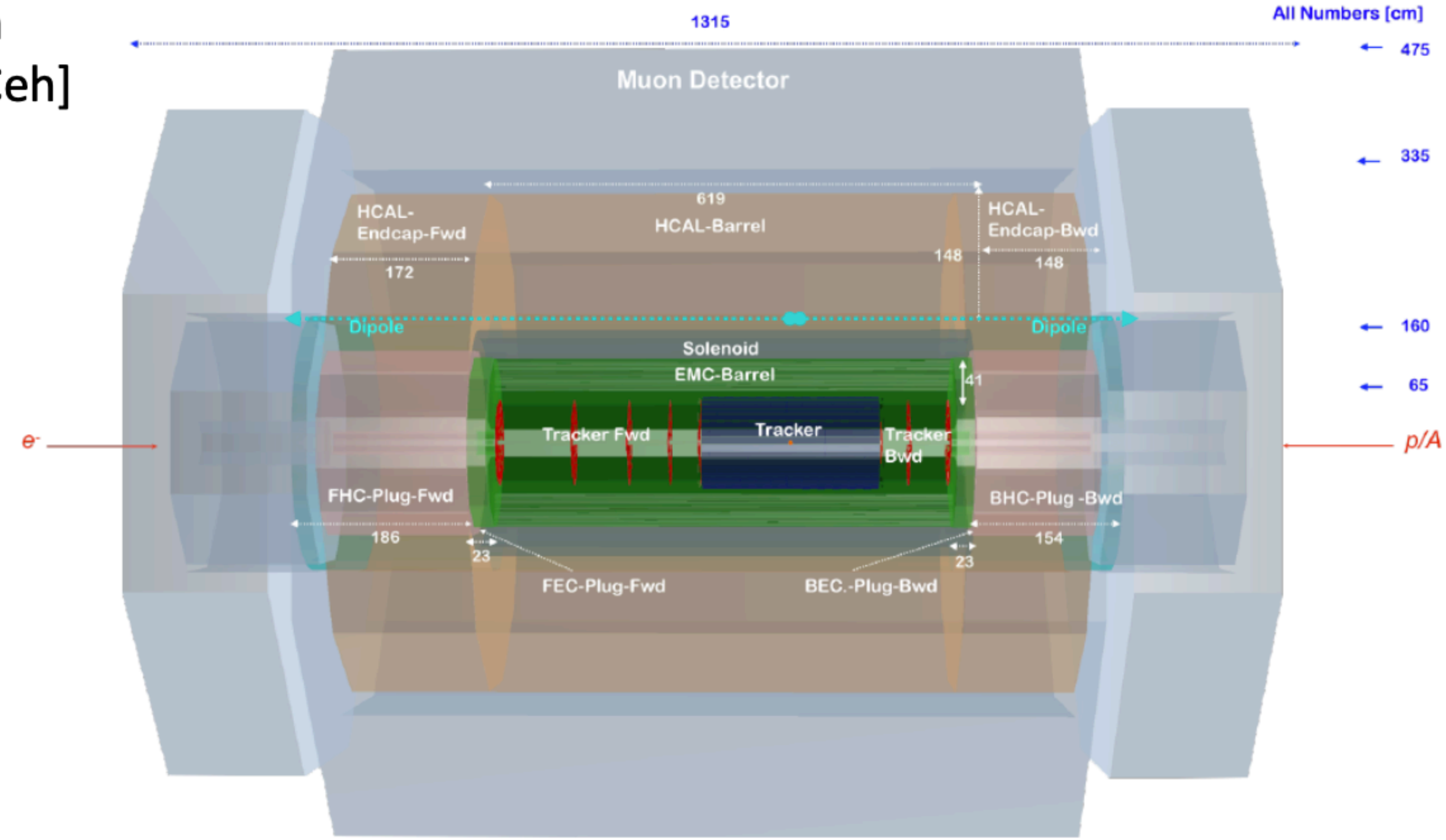
Detectors:

L=13.2 m [FCCeh:19.3 about CMS size]

R=4.8 m
[6.2 FCCeh]



➜ Large acceptance, precision device: design determined by kinematics and high precision (H→bb in CC).

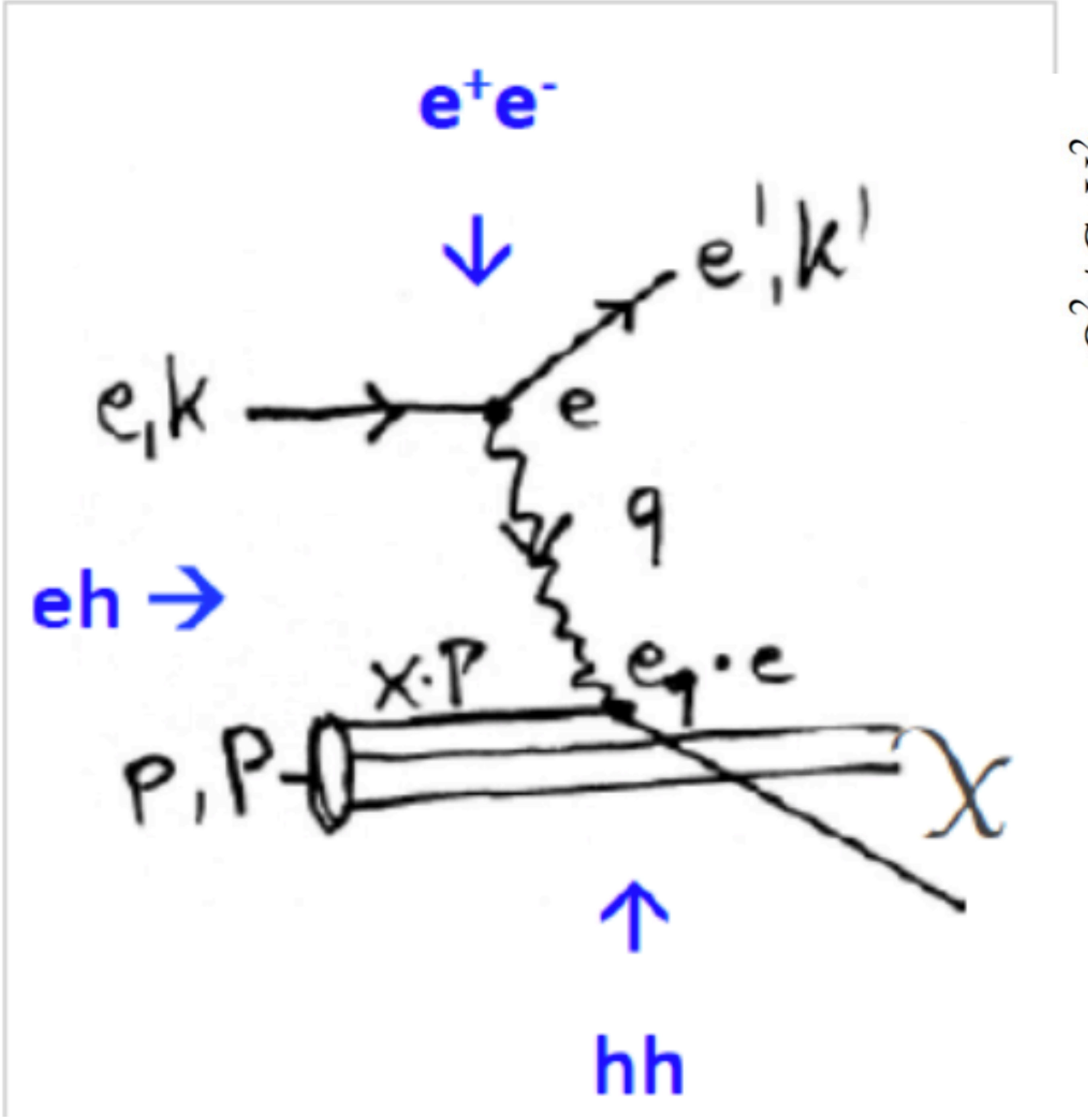
➜ Low radiation (1/100 that of pp) enables sensitive technology such as HV CMOS to be used.

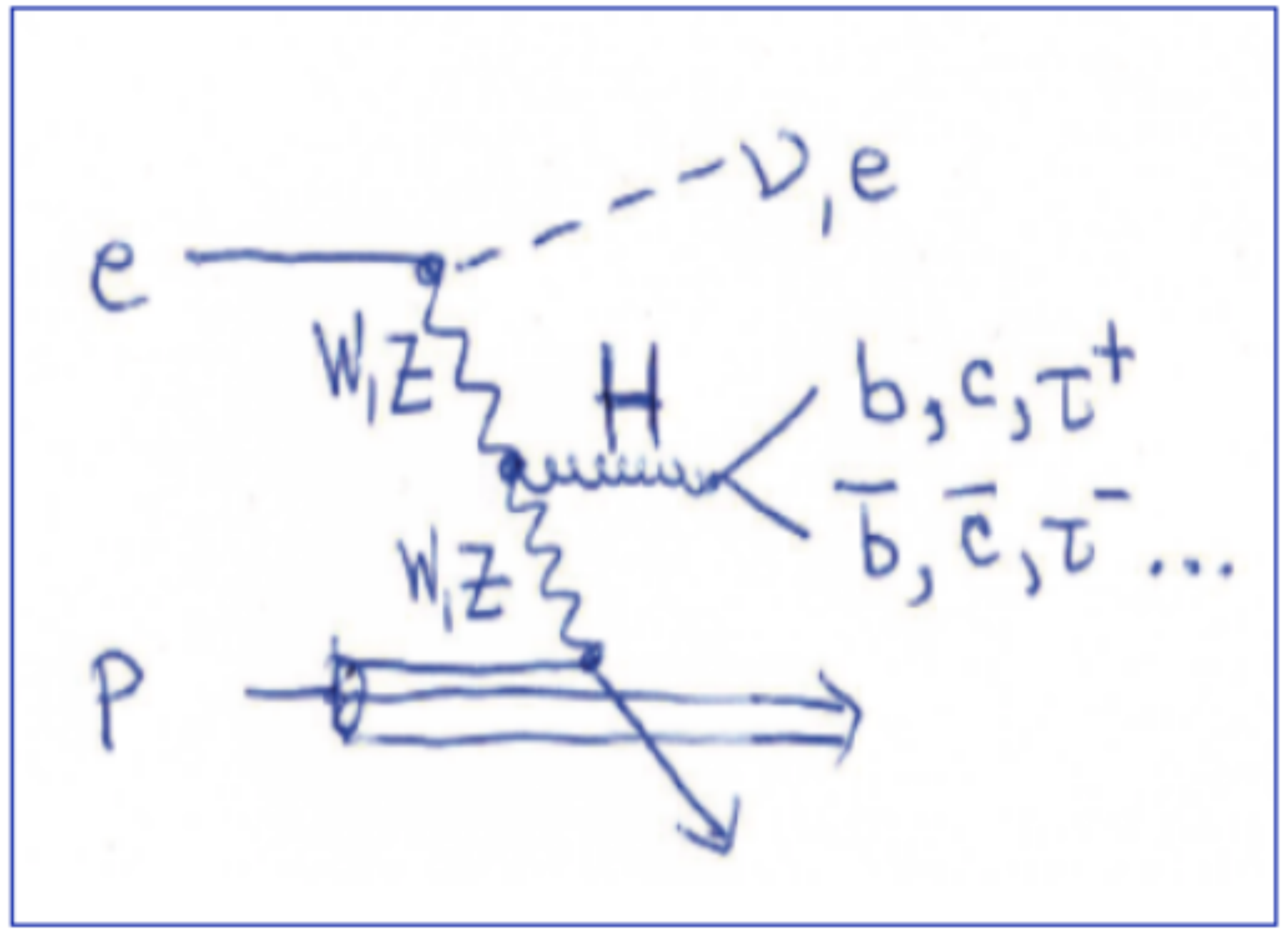
➜ Low field dipole inserted before the HCAL to ensure head-on ep collision; conventional solenoid.

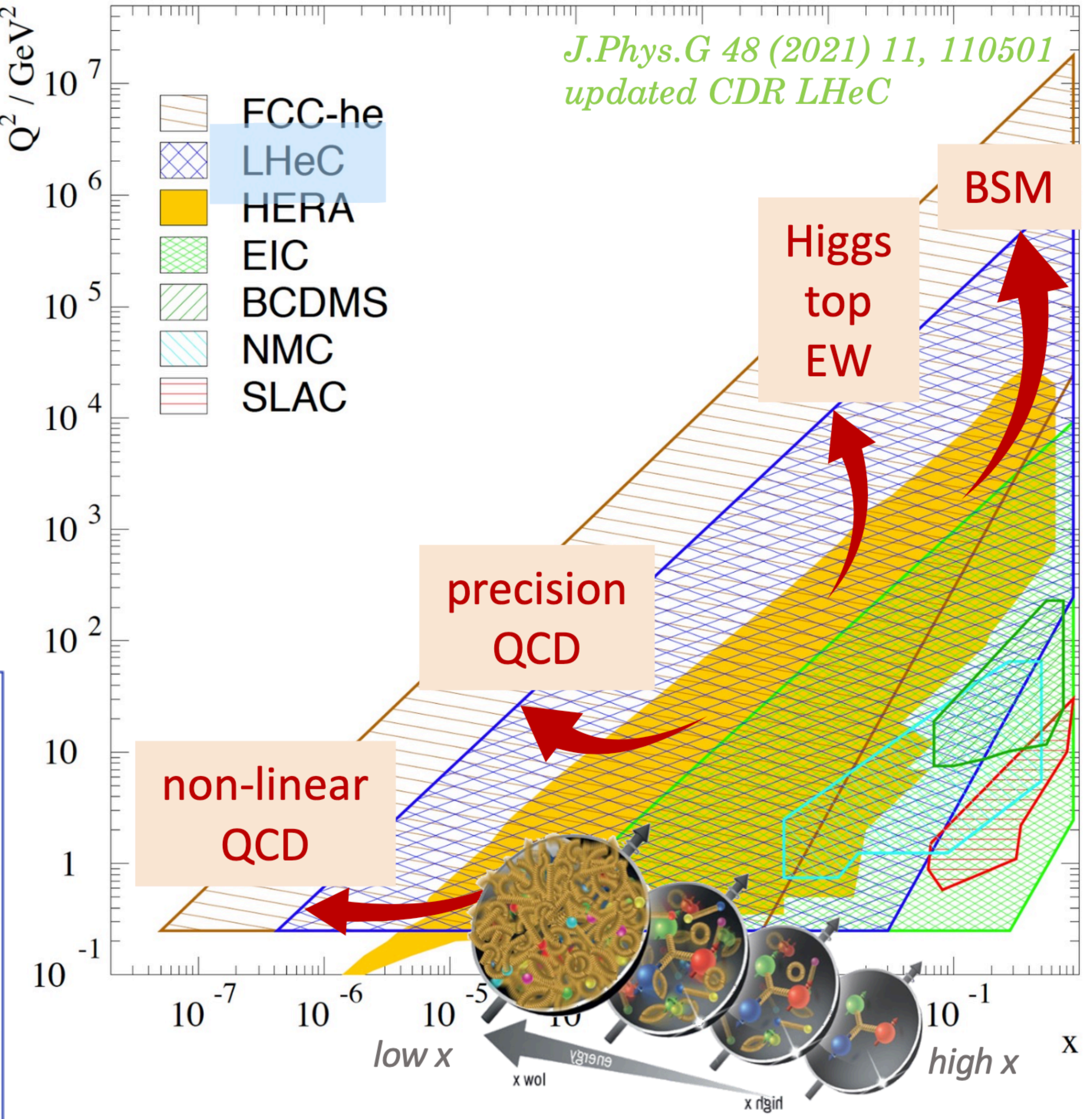
➜ Forward (p,n) and backward (e, γ) tagging detectors.

➜ 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).

DIS at the energy frontier:







● **Deliverables of ep/eA:**

➜ Highest resolution microscope: discovery in QCD.

➜ Empowering the LHC/FCC programmes.

➜ Precision Higgs facility together with HL-LHC/FCC-hh.

➜ Precision and discovery facility (top, EW, BSM).

➜ Unique nuclear physics facility.

● **Contribution to LHC/FCC:**

➜ Improve SM measurements.

➜ Searches for BSM.

➜ Flavor physics of heavy quarks and leptons.

➜ Higgs properties.

➜ QCD at high density/temperature.

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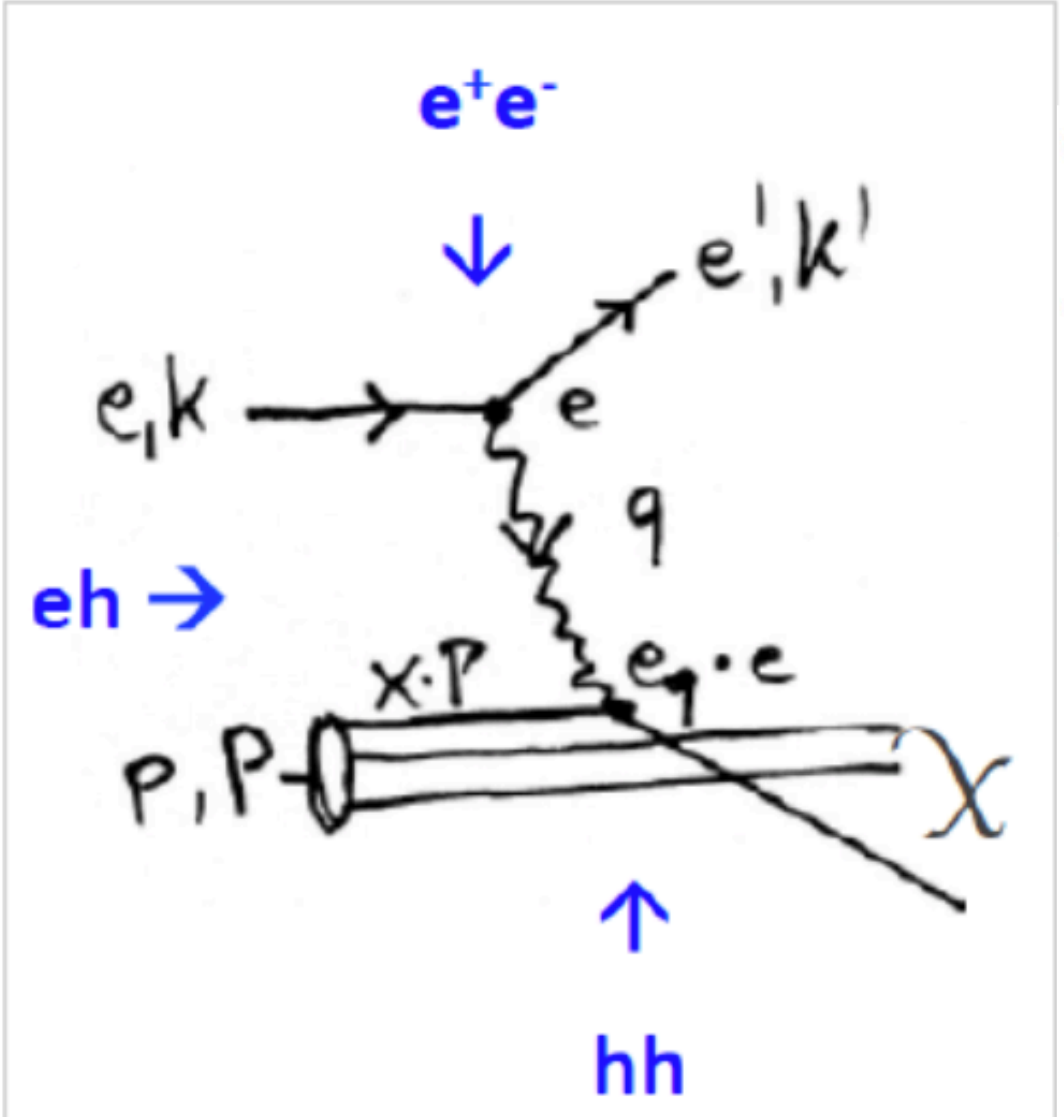

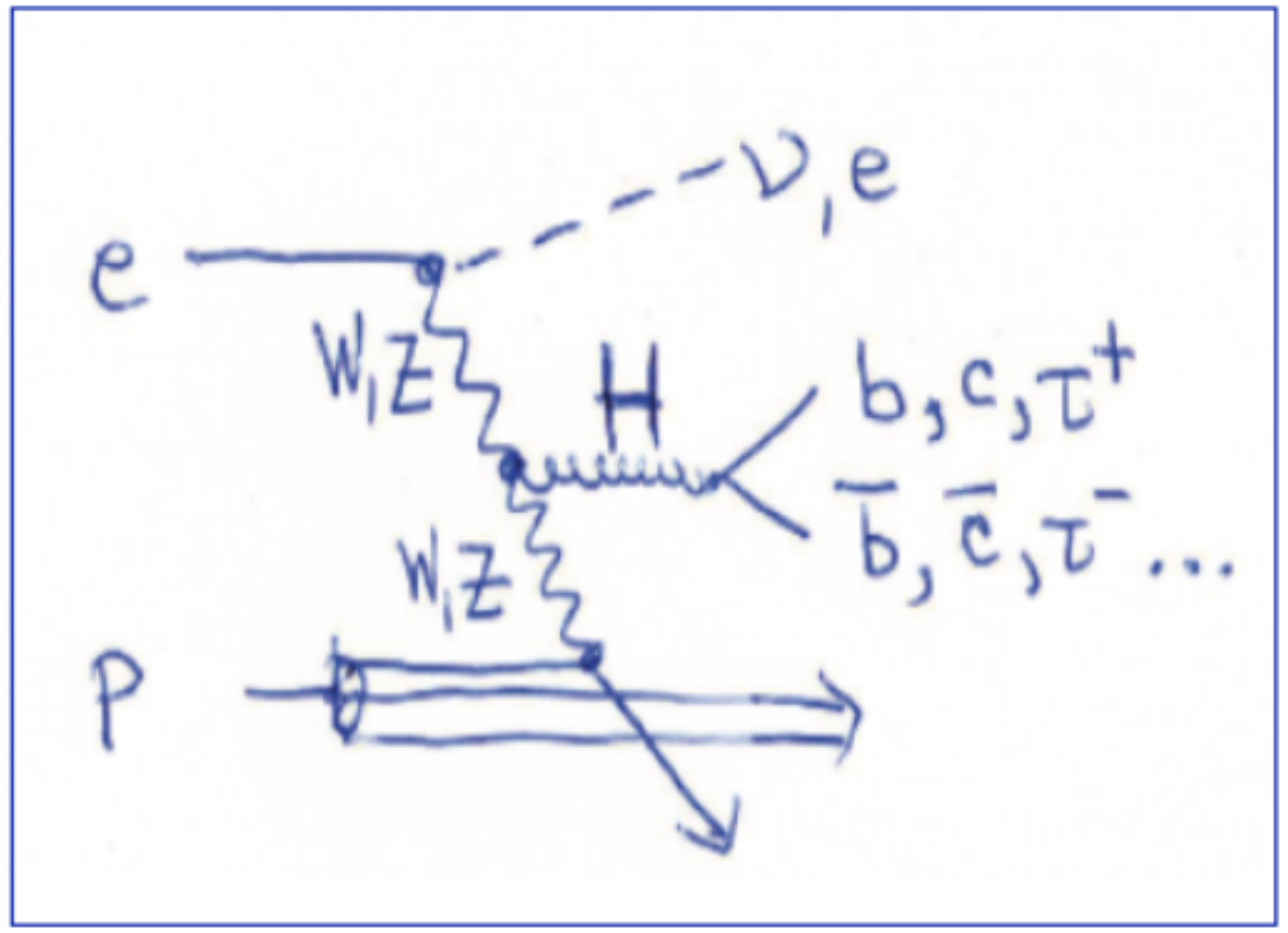

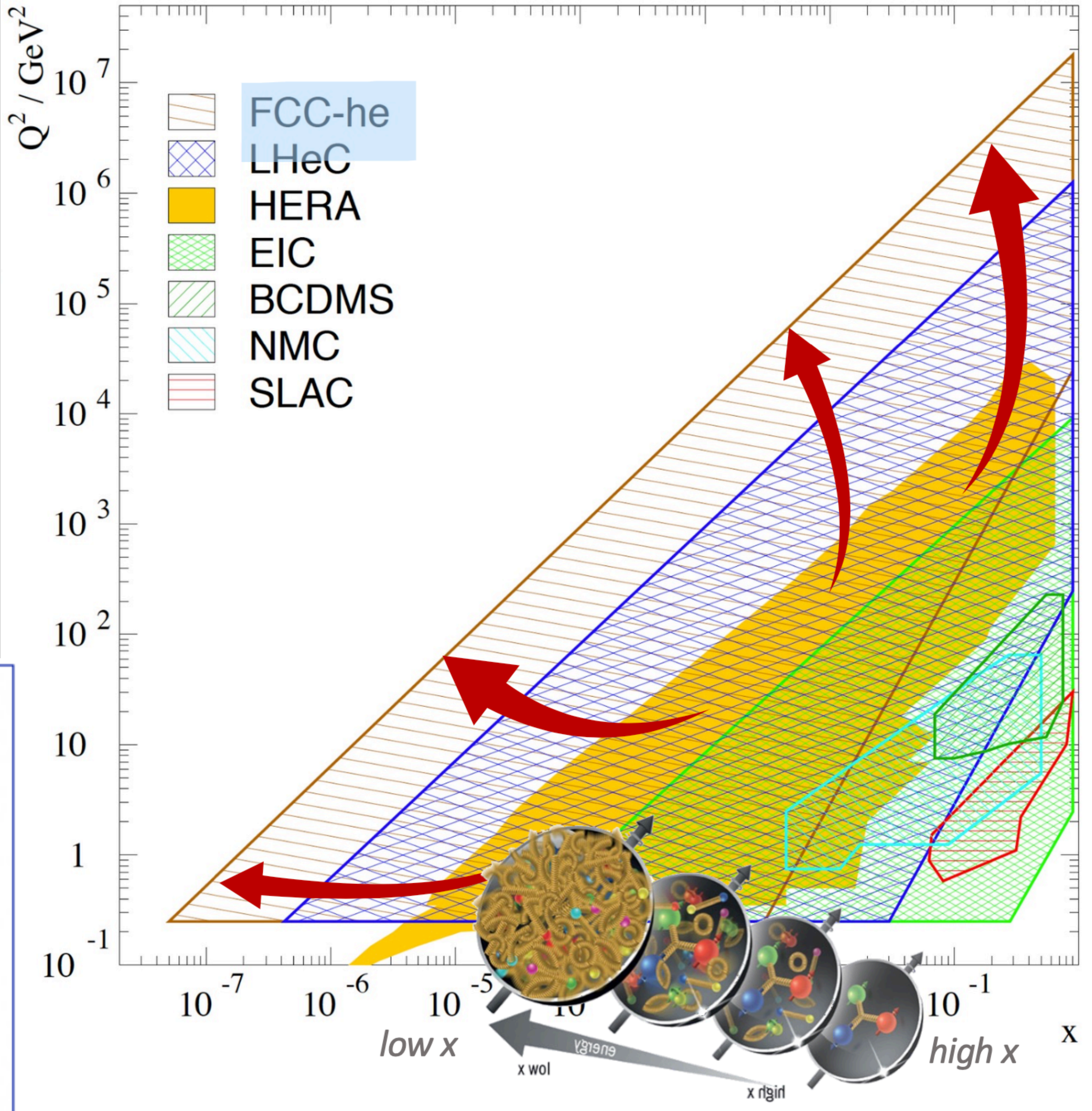

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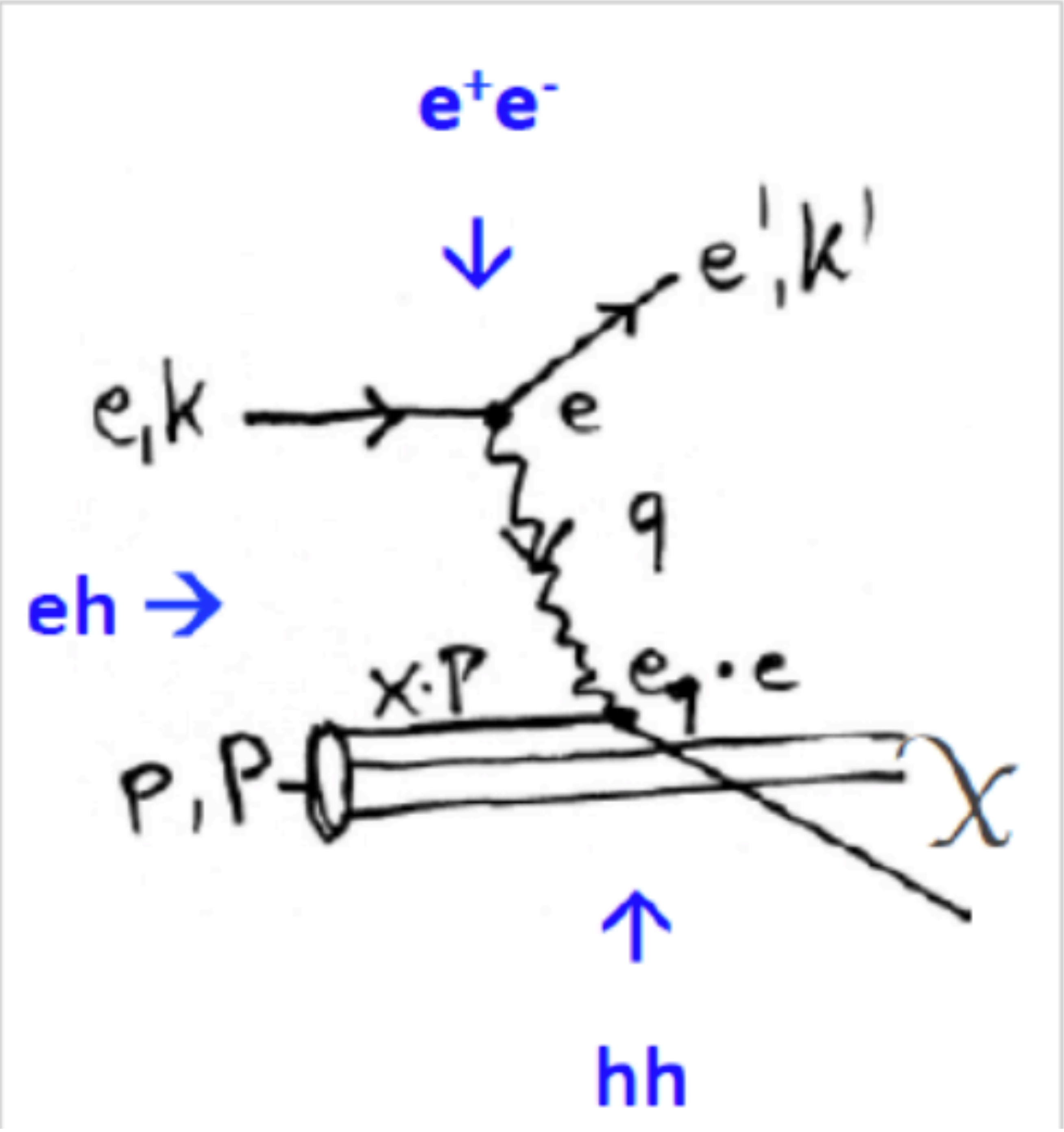

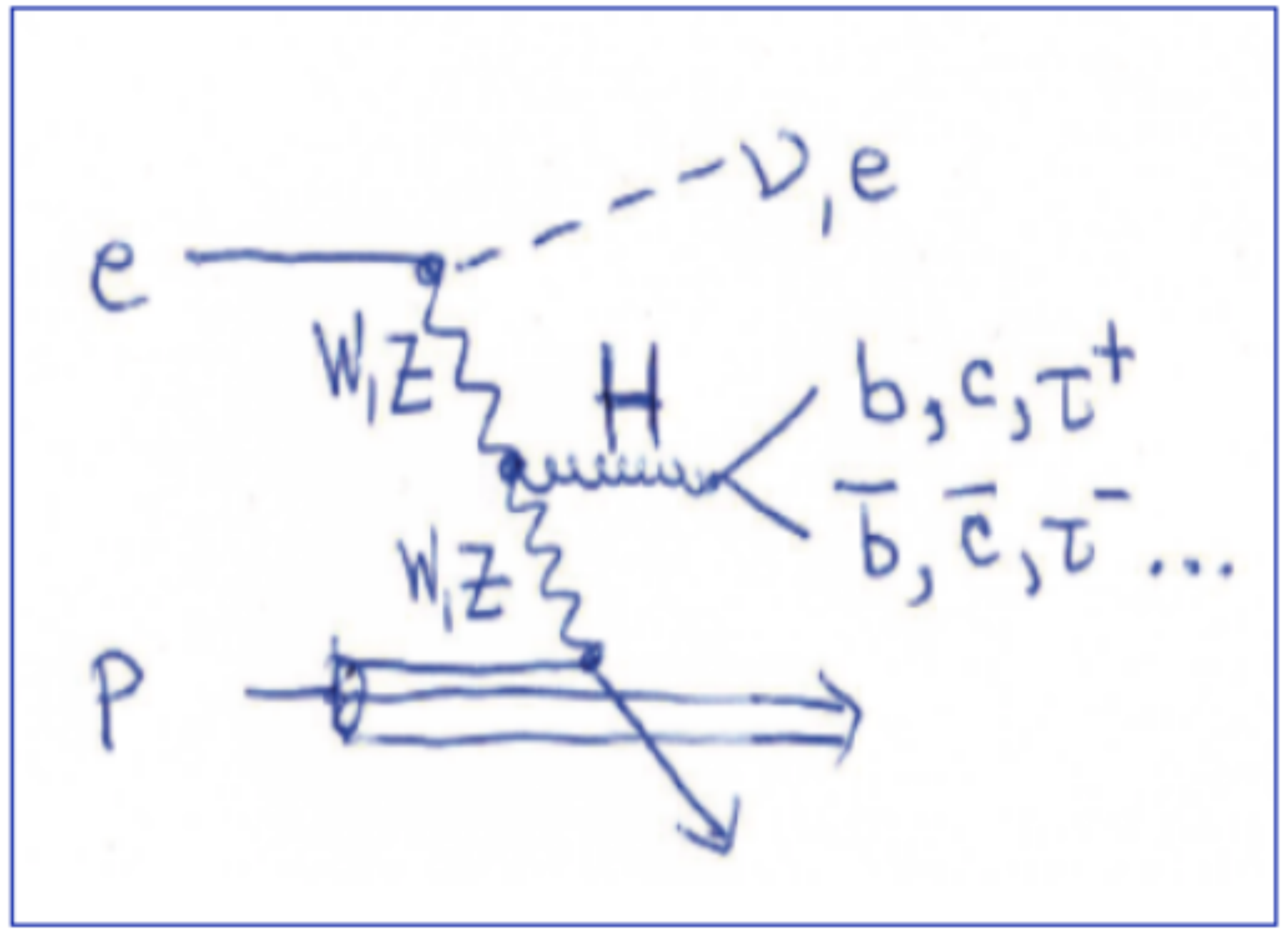

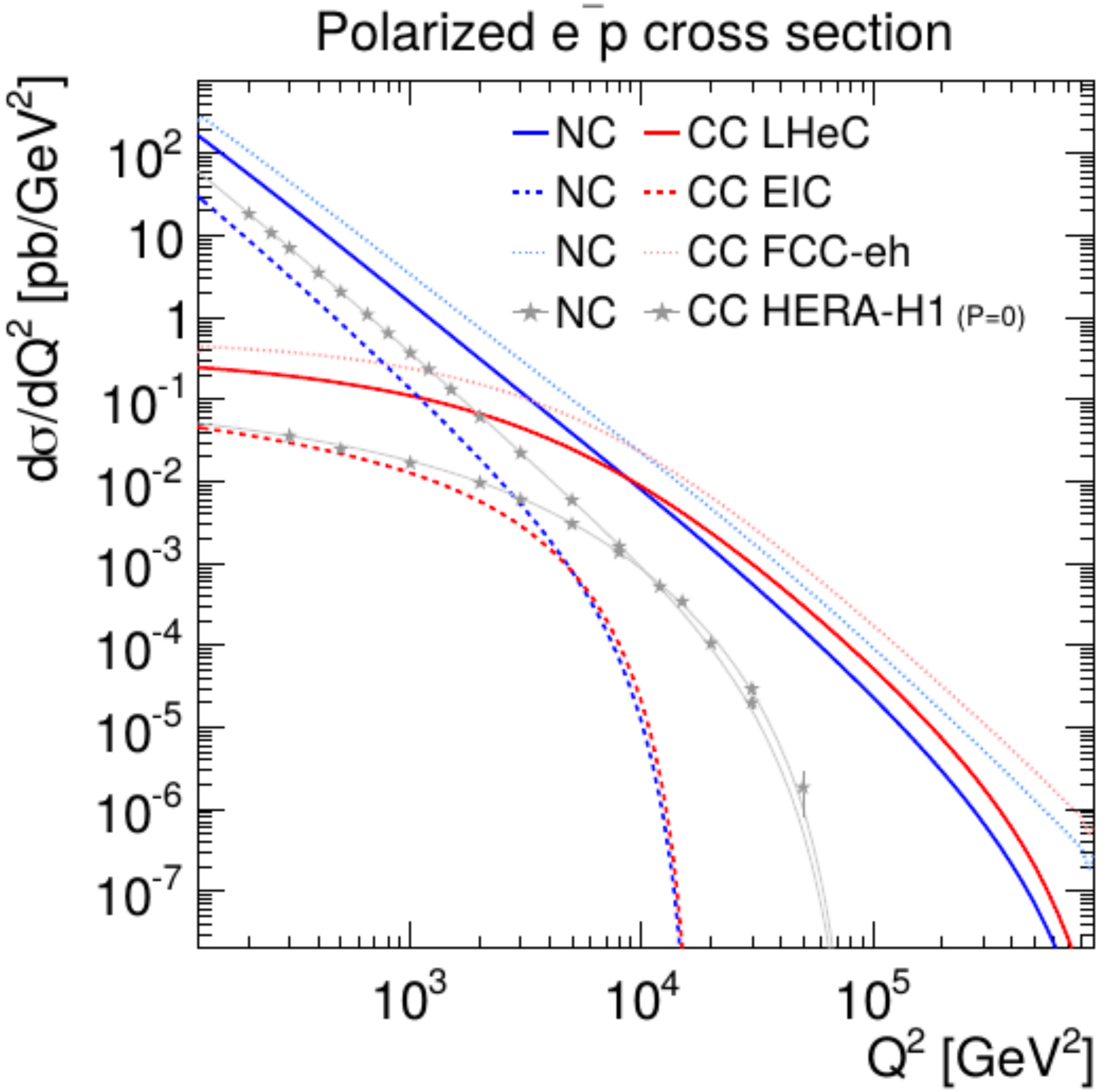

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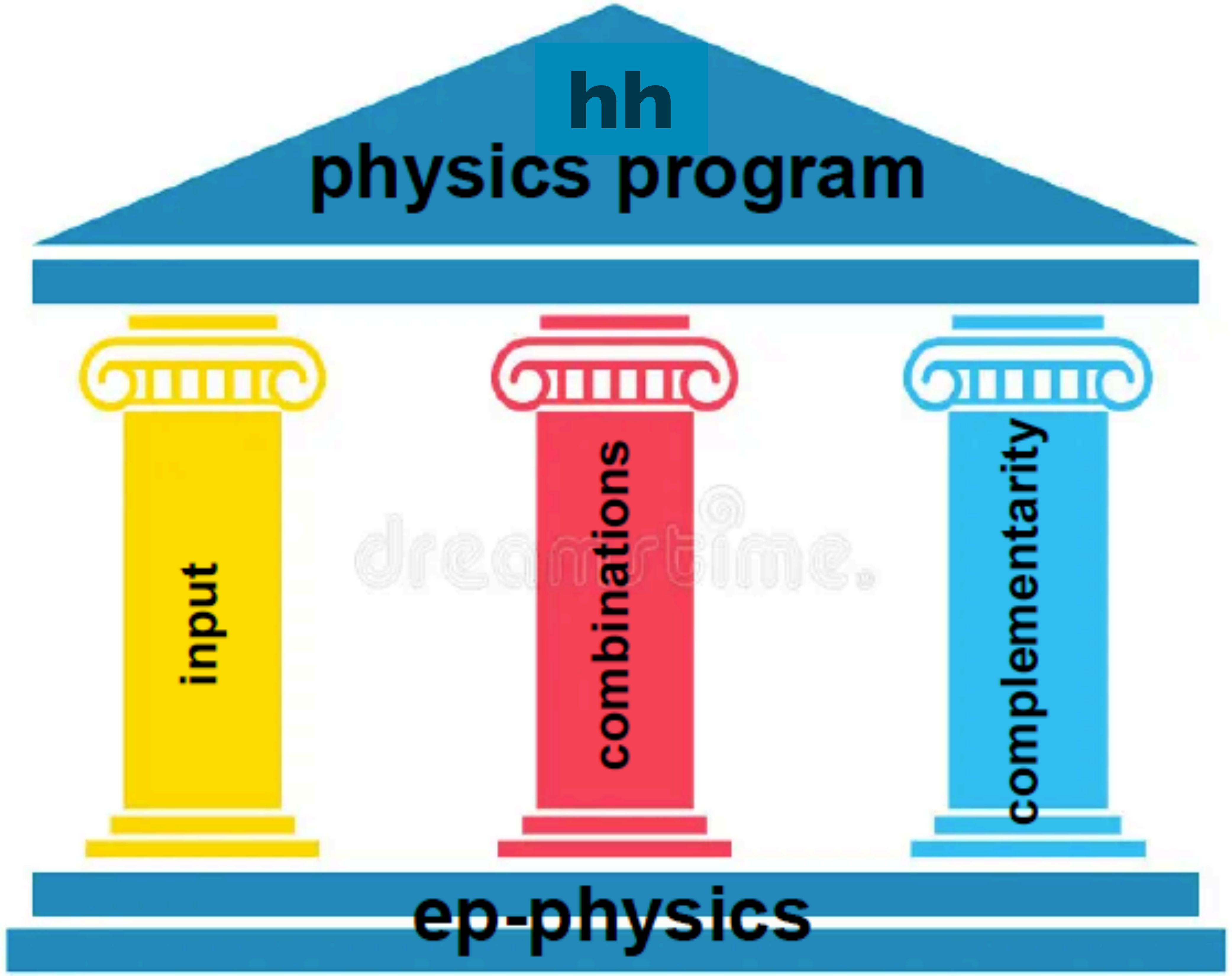
Synergies between eh and hh programes:

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

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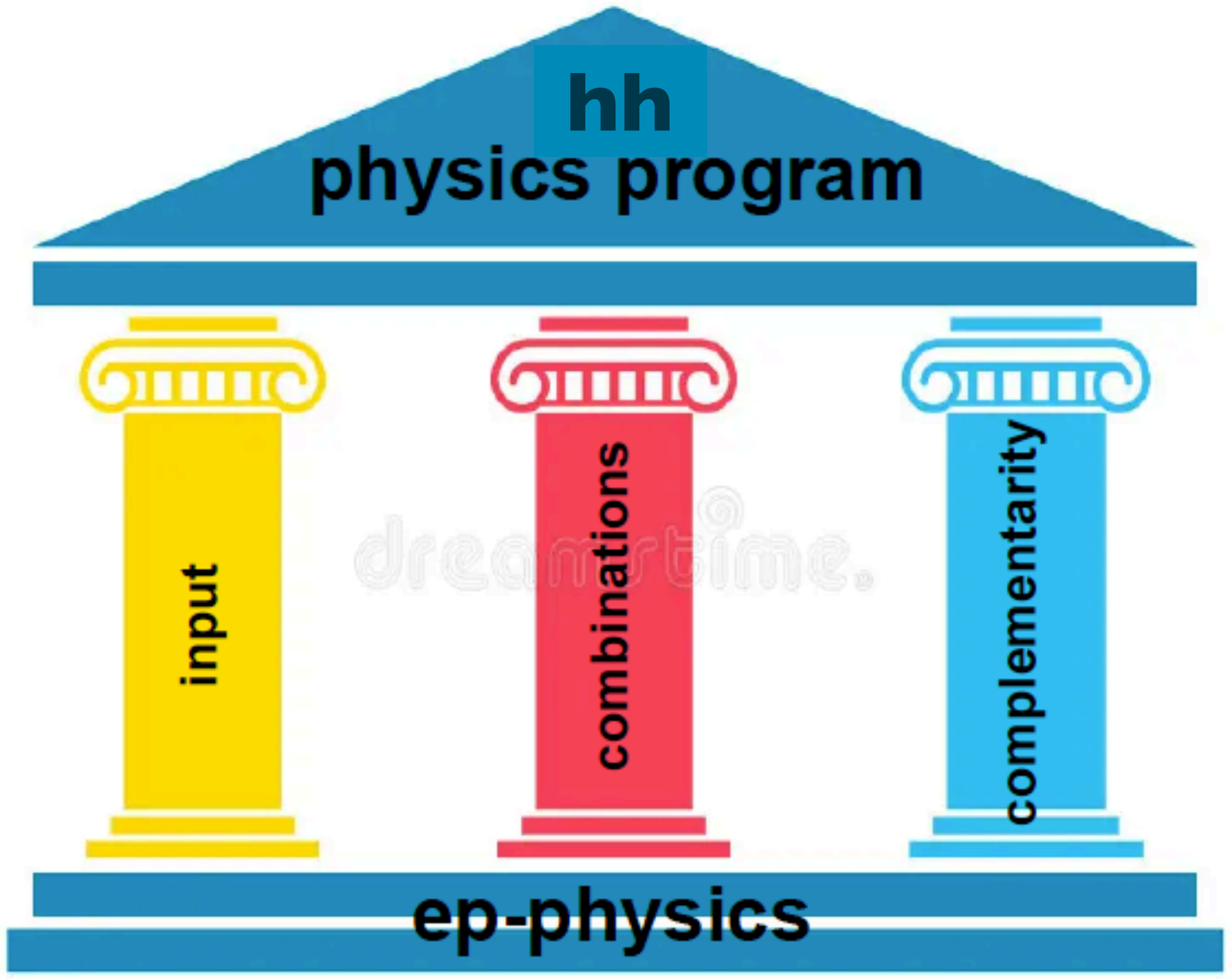
→ Empowerment of hh program.
→ Input to pp physics analyses improving sizable uncertainties and limitations.



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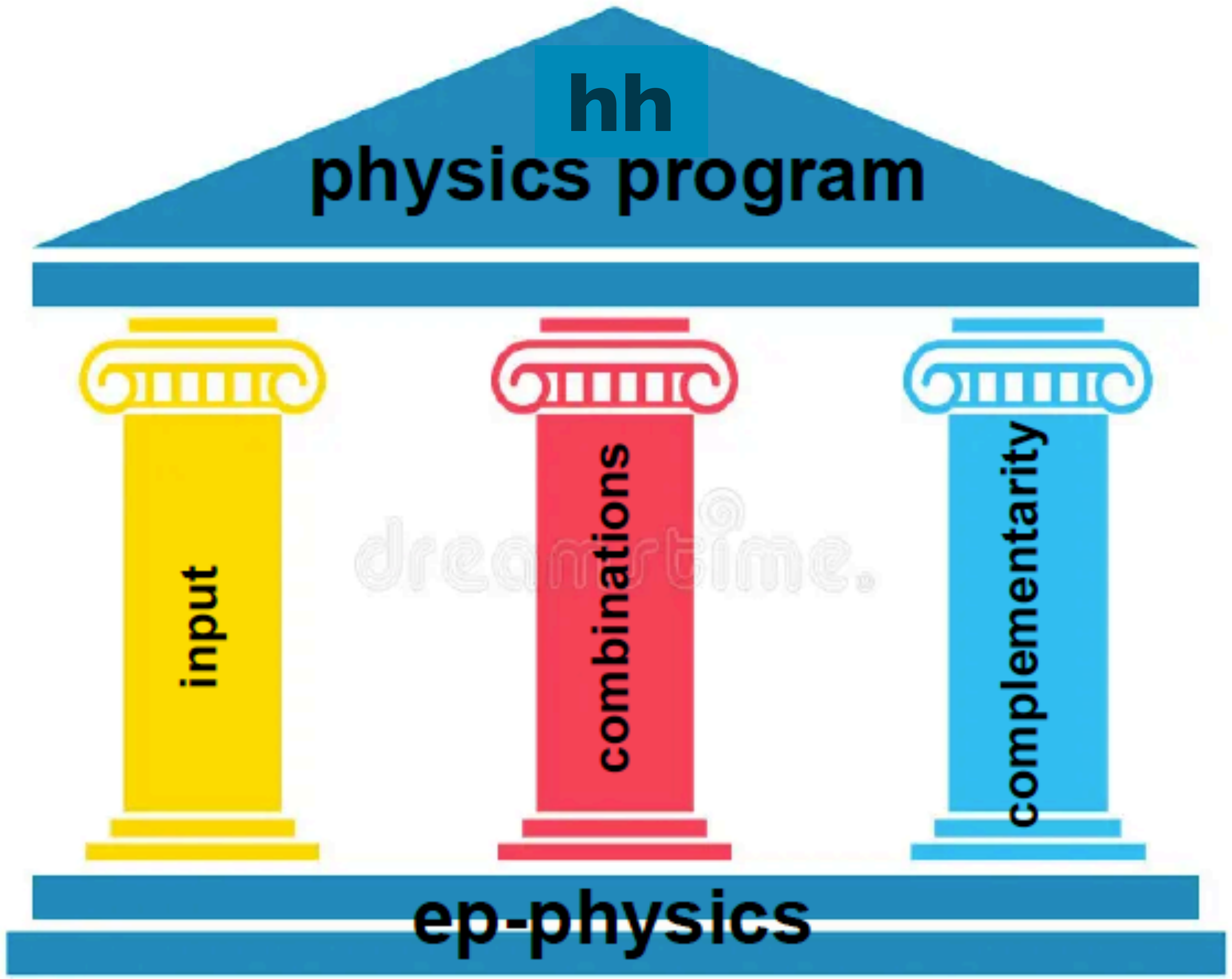

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ep measurements to considerably improve hh physics output, e.g., in final combinations

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

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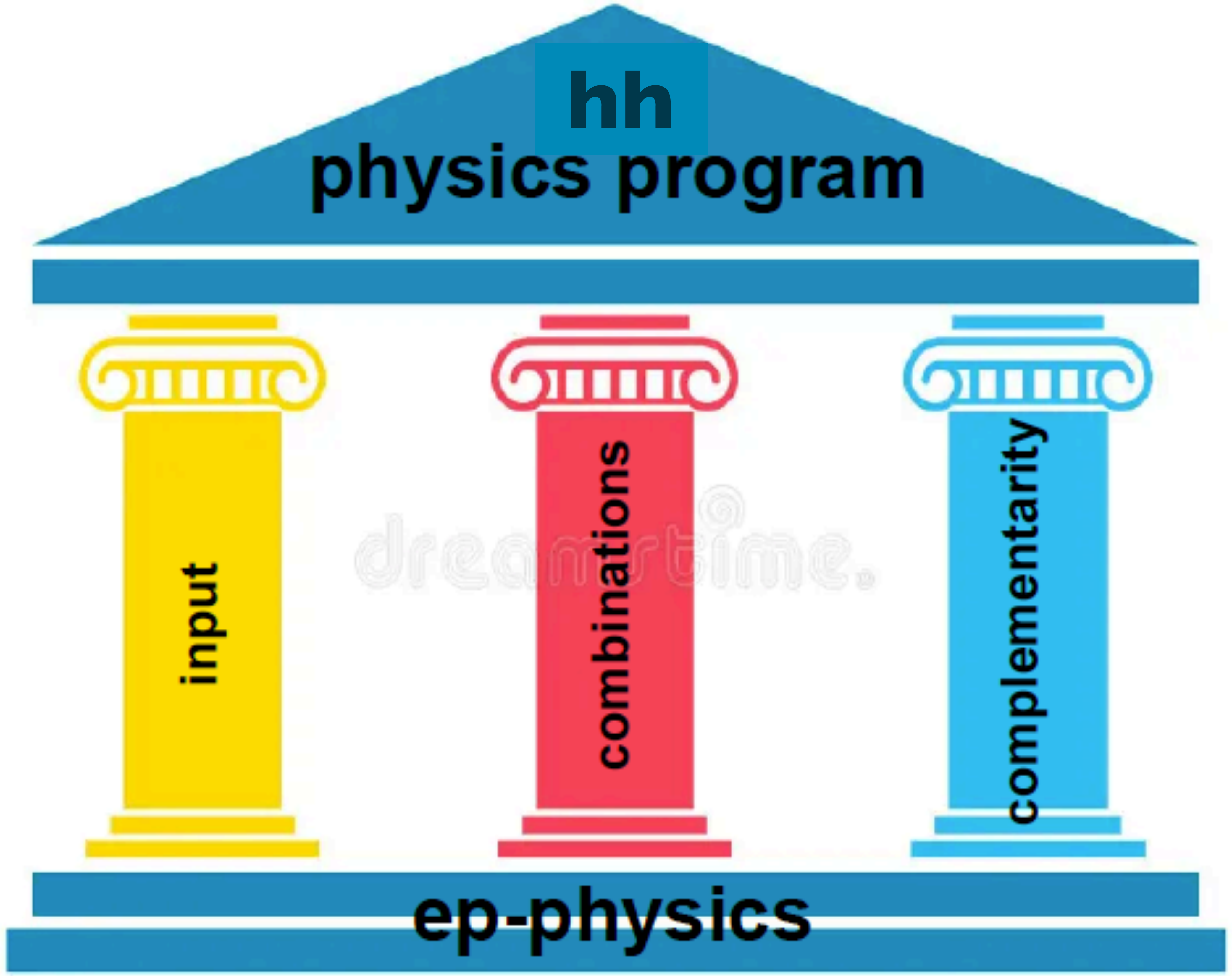

ep analyses with sensitivity complementary to hh analyses to complete the overall hh physics program

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

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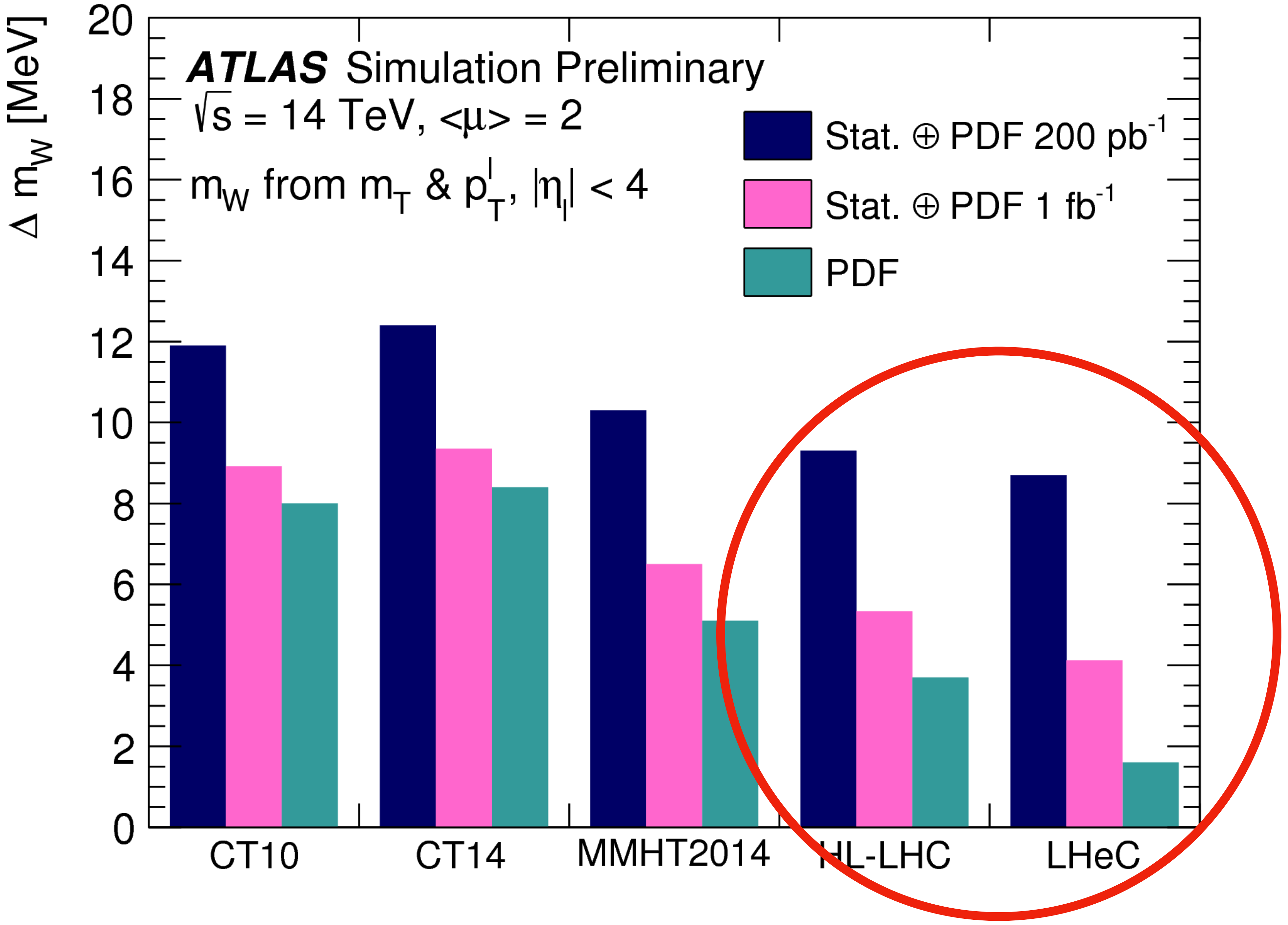
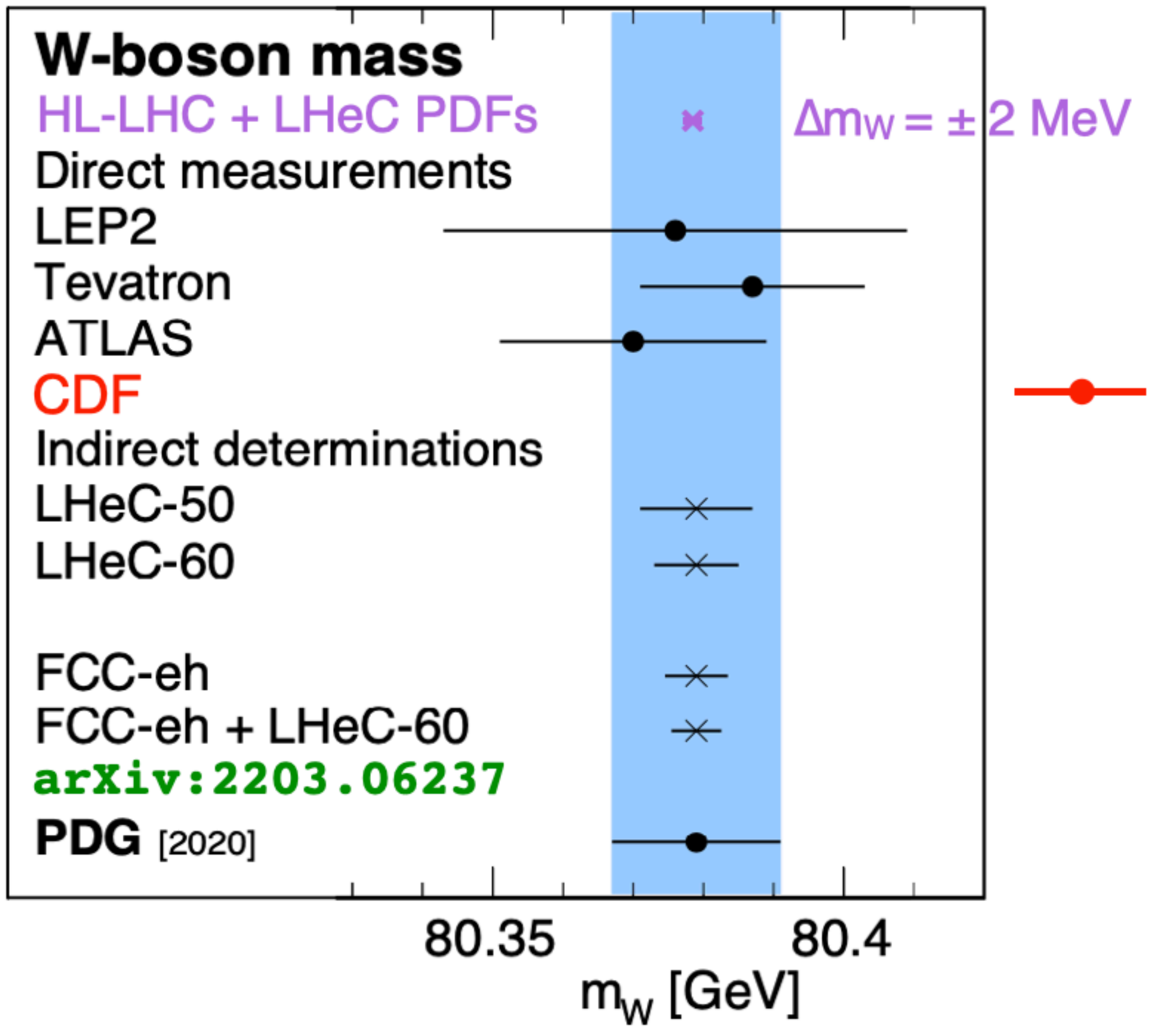
EW physics: W mass

- Many EW physics opportunities (spacelike vs. timelike in e^+e^- /pp) through PDF+EW fits: W&Z mass, $\sin^2\theta_W^{eff,l}$, V and A NC/CC couplings to light quarks,…
- LHeC will provide additional precision, though PDFs, to the determination of M_W at HL-LHC.



$\Delta M_W = \pm 6$ MeV (HL-LHC) → ±2 MeV (HL-LHC + LHeC PDFs)



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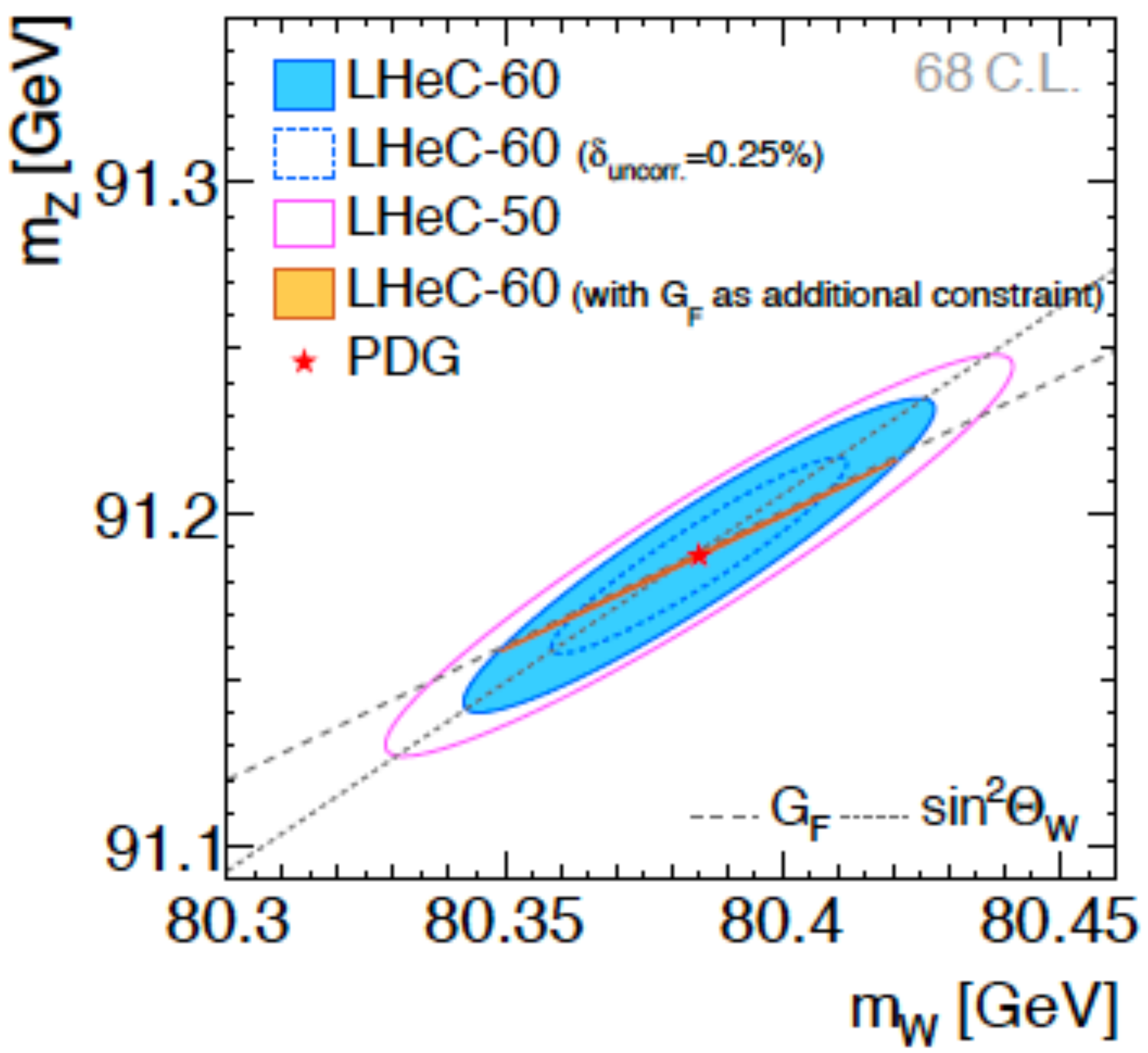
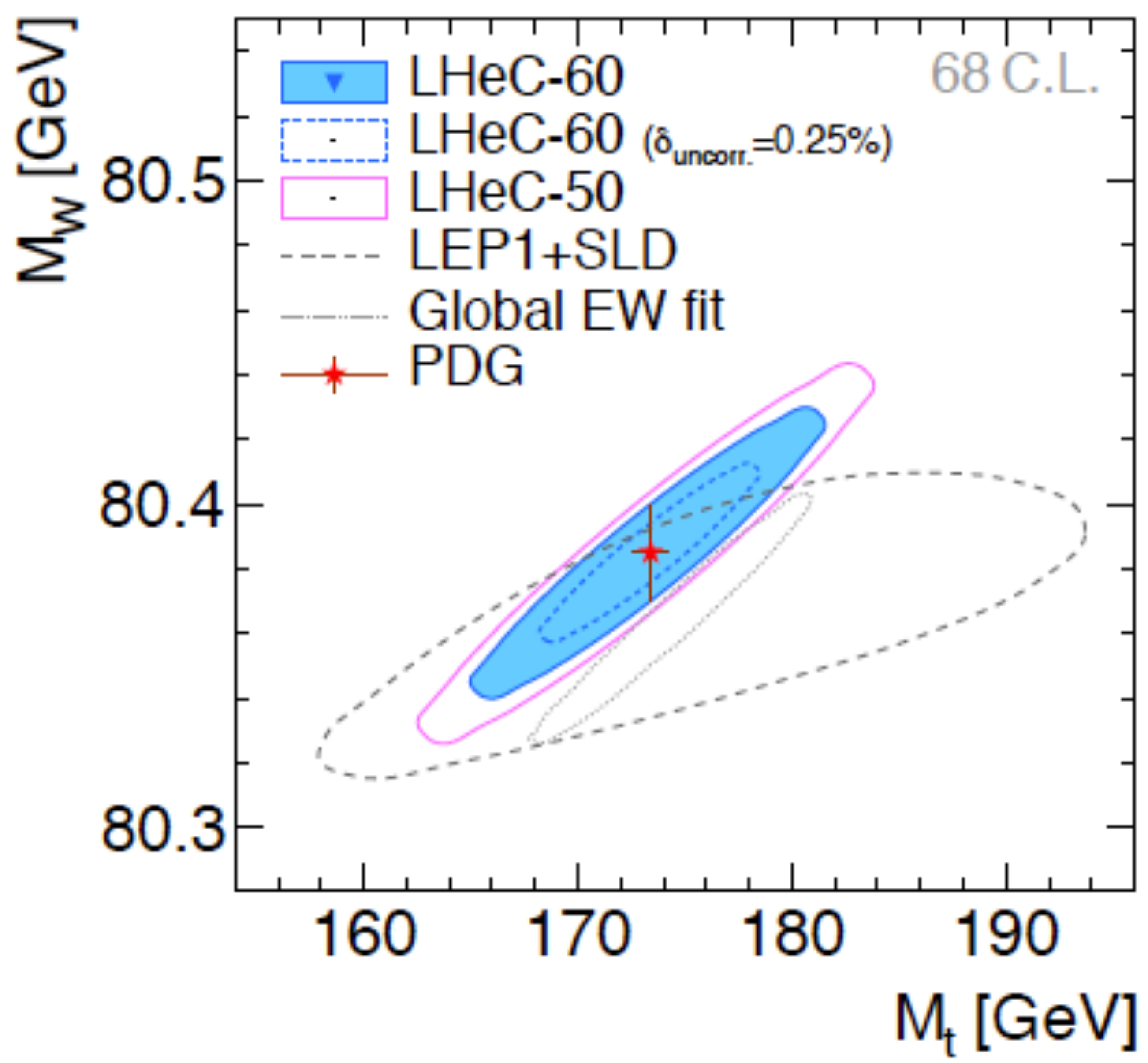
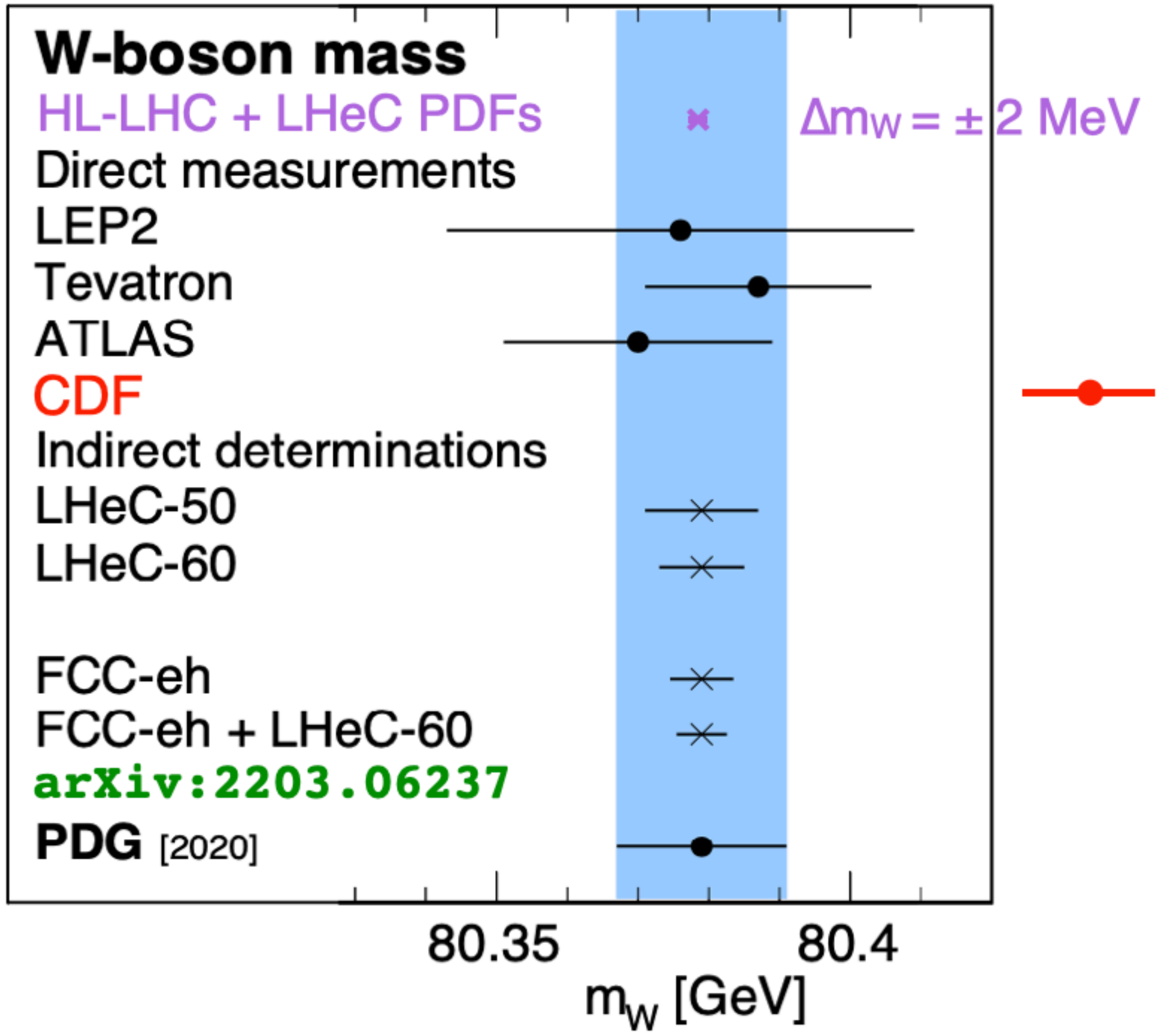






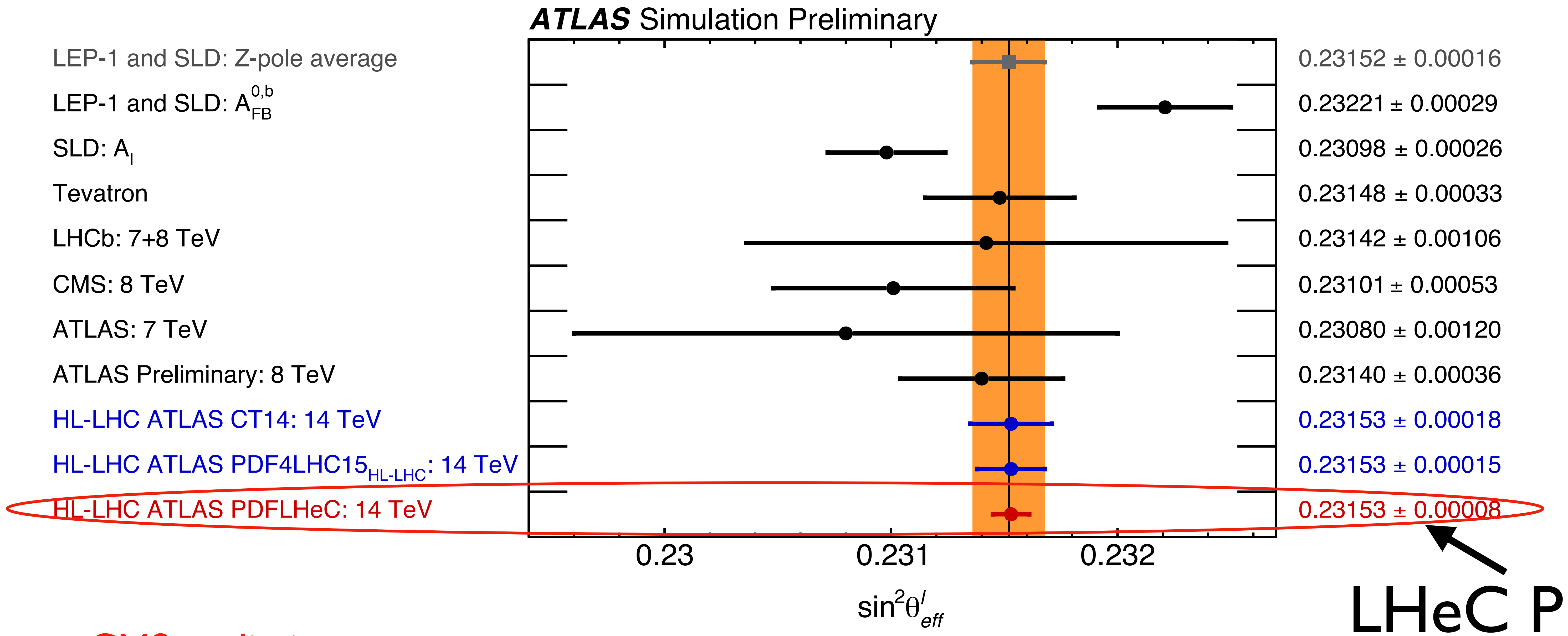
EW physics: $\sin^2\theta_W$

- **Direct constraints on** $\sin^2\theta_W^{eff,l}$, higher order corrections included: $\sin^2\theta_W^{\text{eff},\ell}(\mu^2) = \kappa_{\text{NC},\ell}(\mu^2)\sin^2\theta_W$

- Scale dependence through simultaneous fits with PDFs.
- Indirect determination through improving LHC measurements (FB asymmetries).

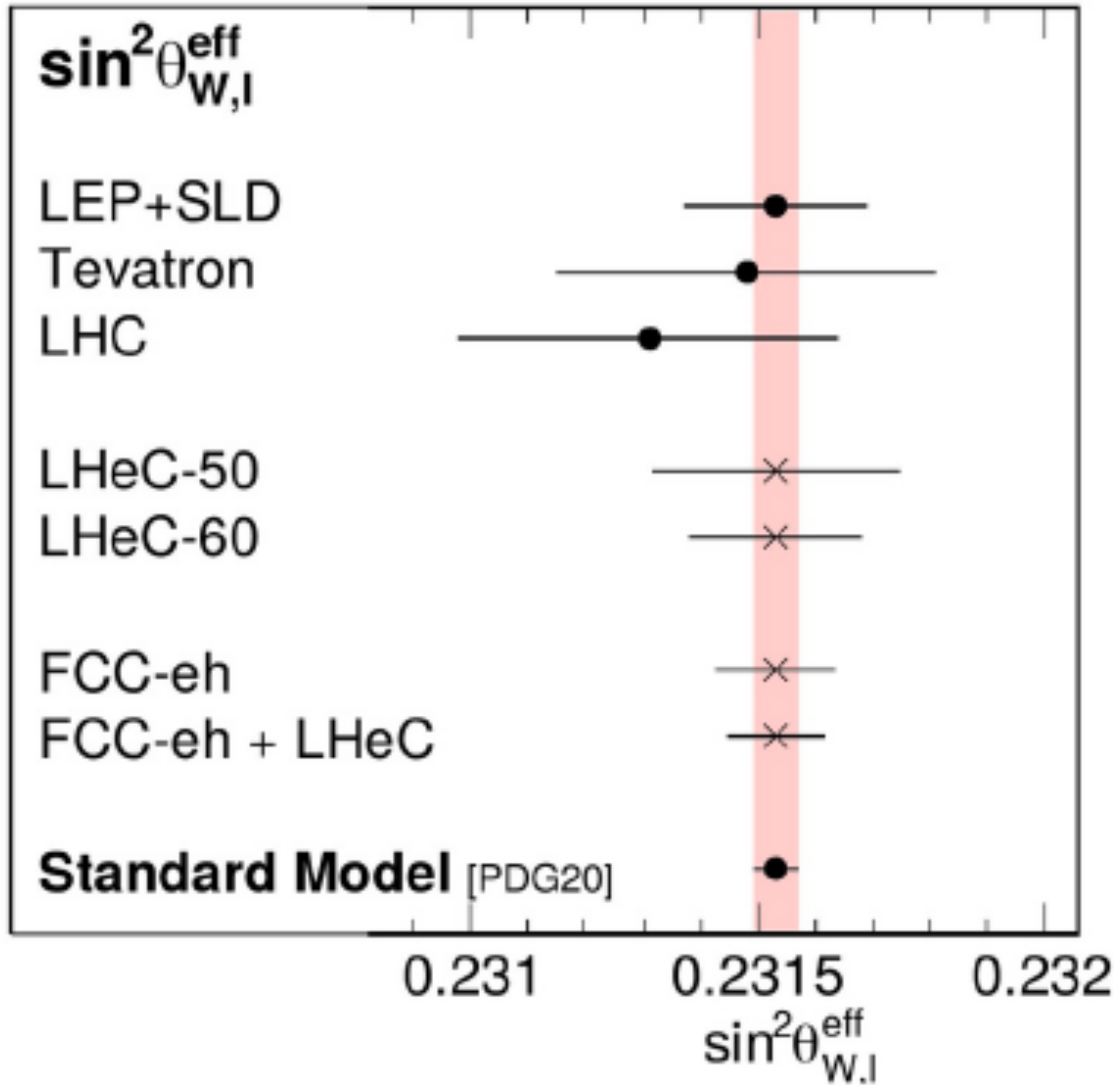
$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= ±0.00010$_{(exp)}$ ±0.00004$_{(PDF)}$

$\Delta\sin^2\theta_w$ (LHeC-50) = ±0.00021
$\Delta\sin^2\theta_w$ (LHeC-60) = ±0.00015
$\Delta\sin^2\theta_w$ (FCC-eh+LHeC) = ±0.000086



LHeC PDFs

CMS preliminary



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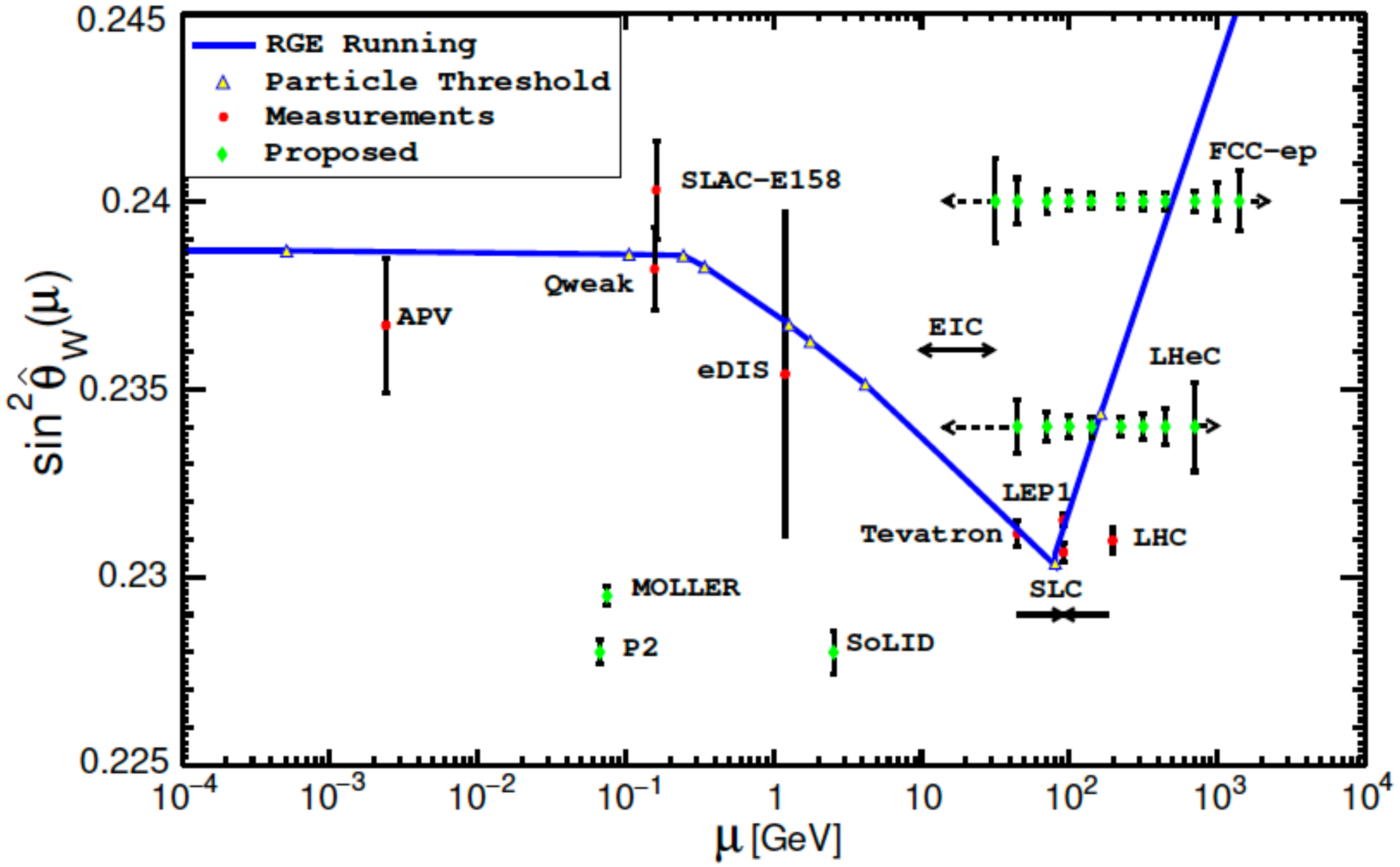

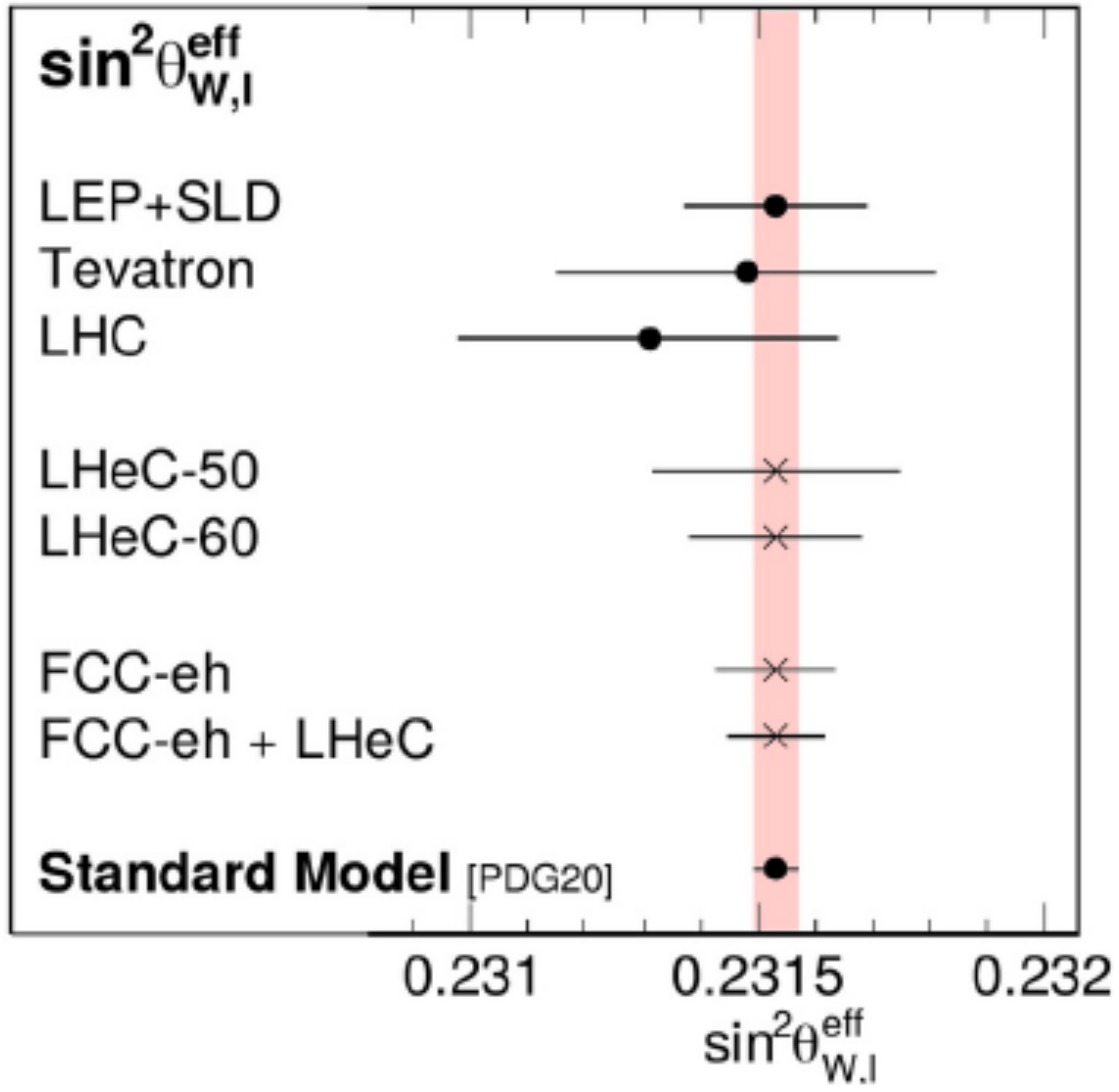

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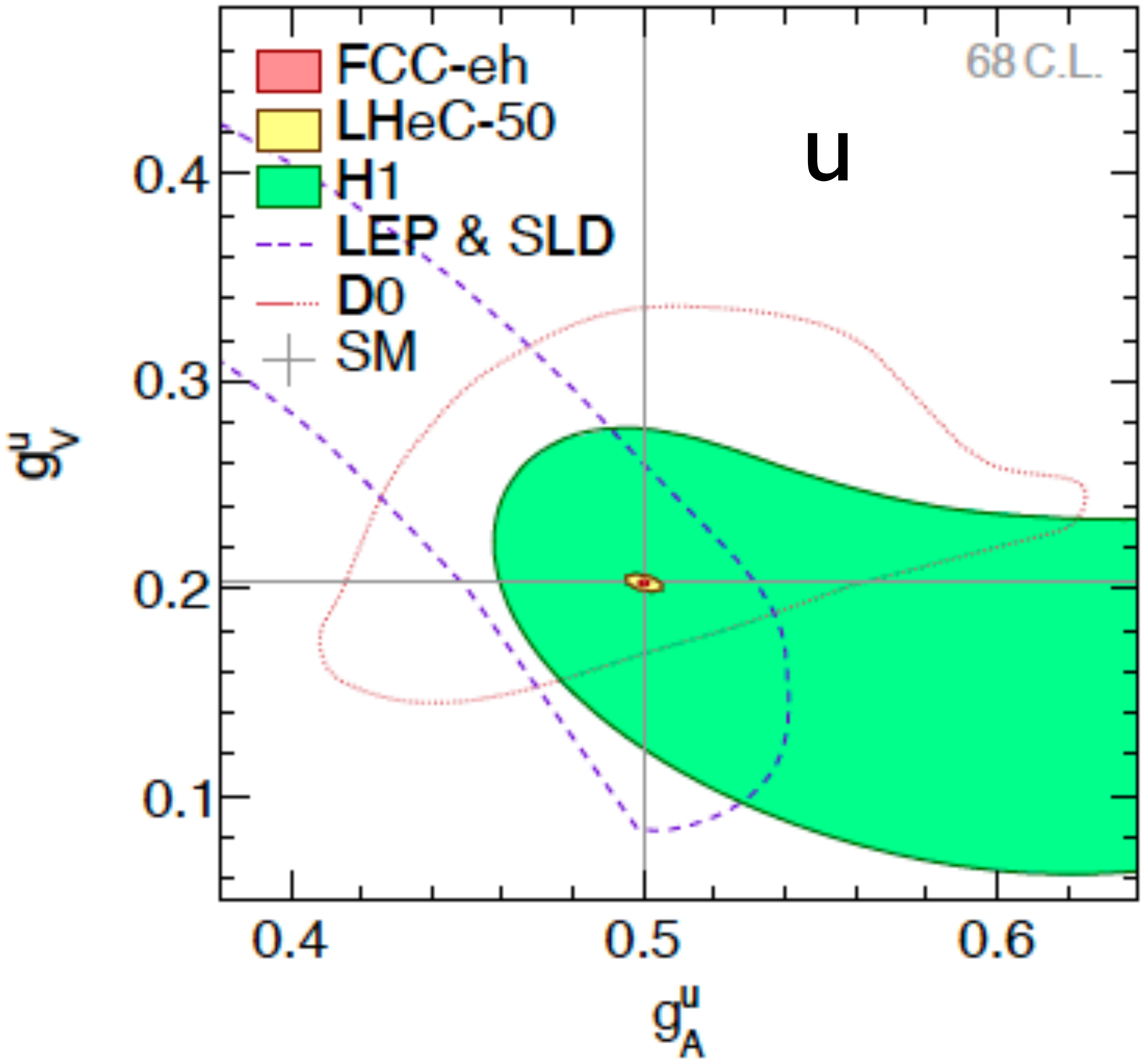
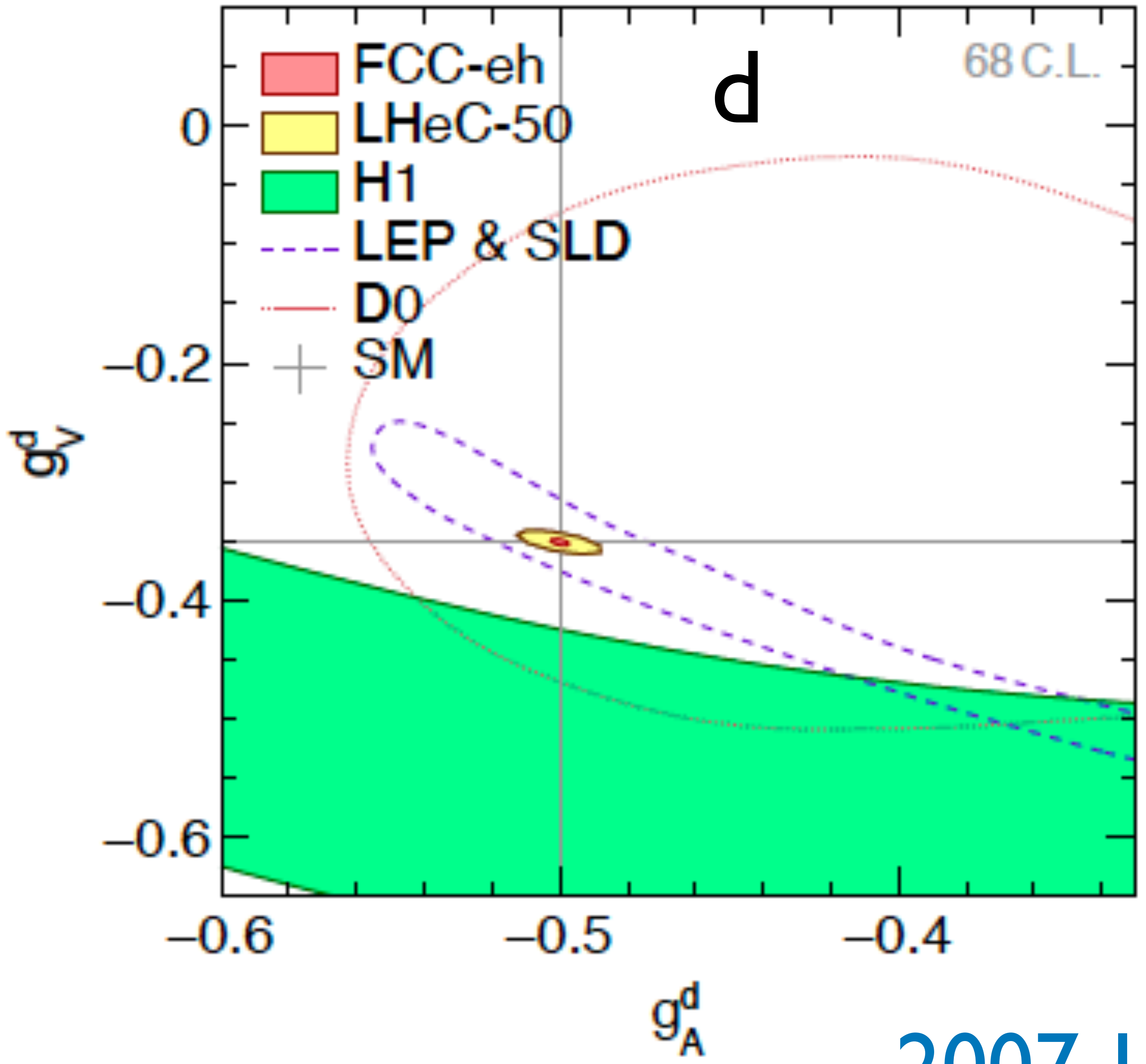
EW physics: couplings to light quarks

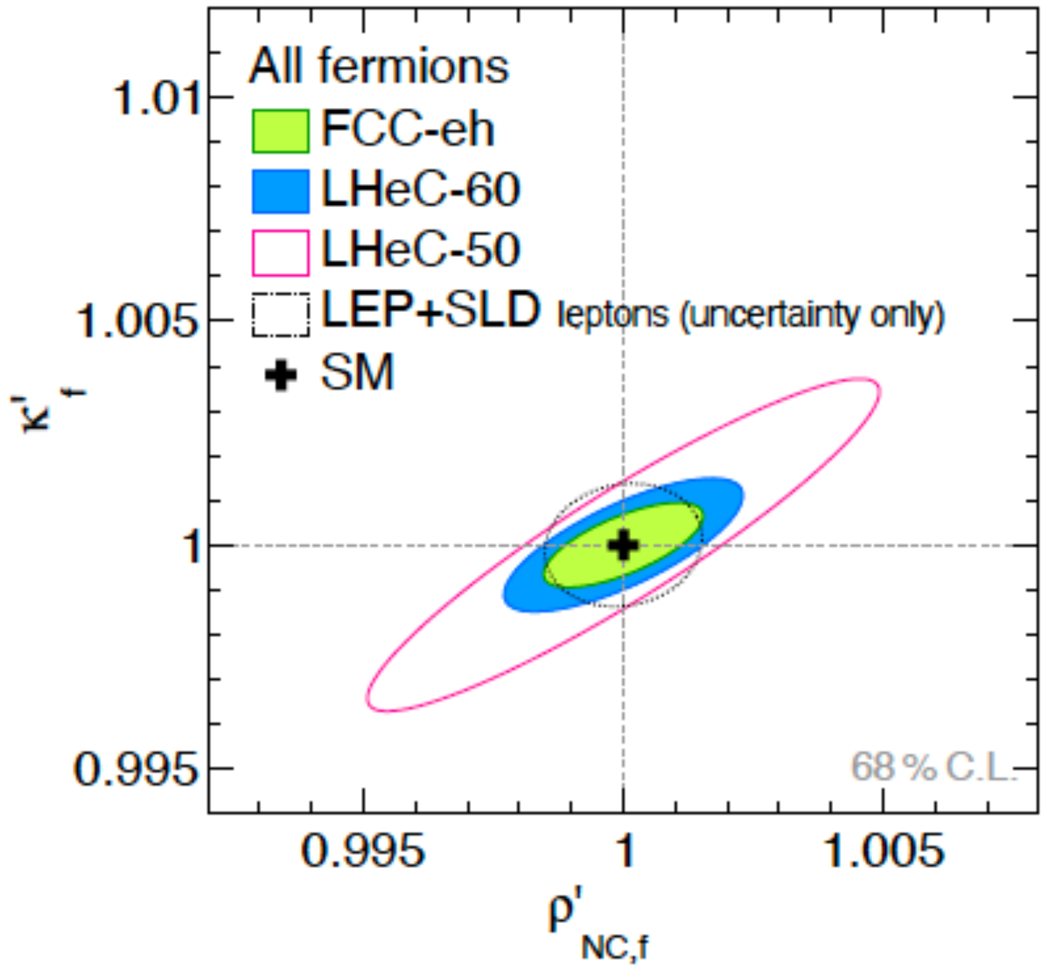
- Coupling of γ,Z,W to light flavours not accessible in other processes; also BSM contributions (e.g., in the SMEFT framework) and running are measurable.

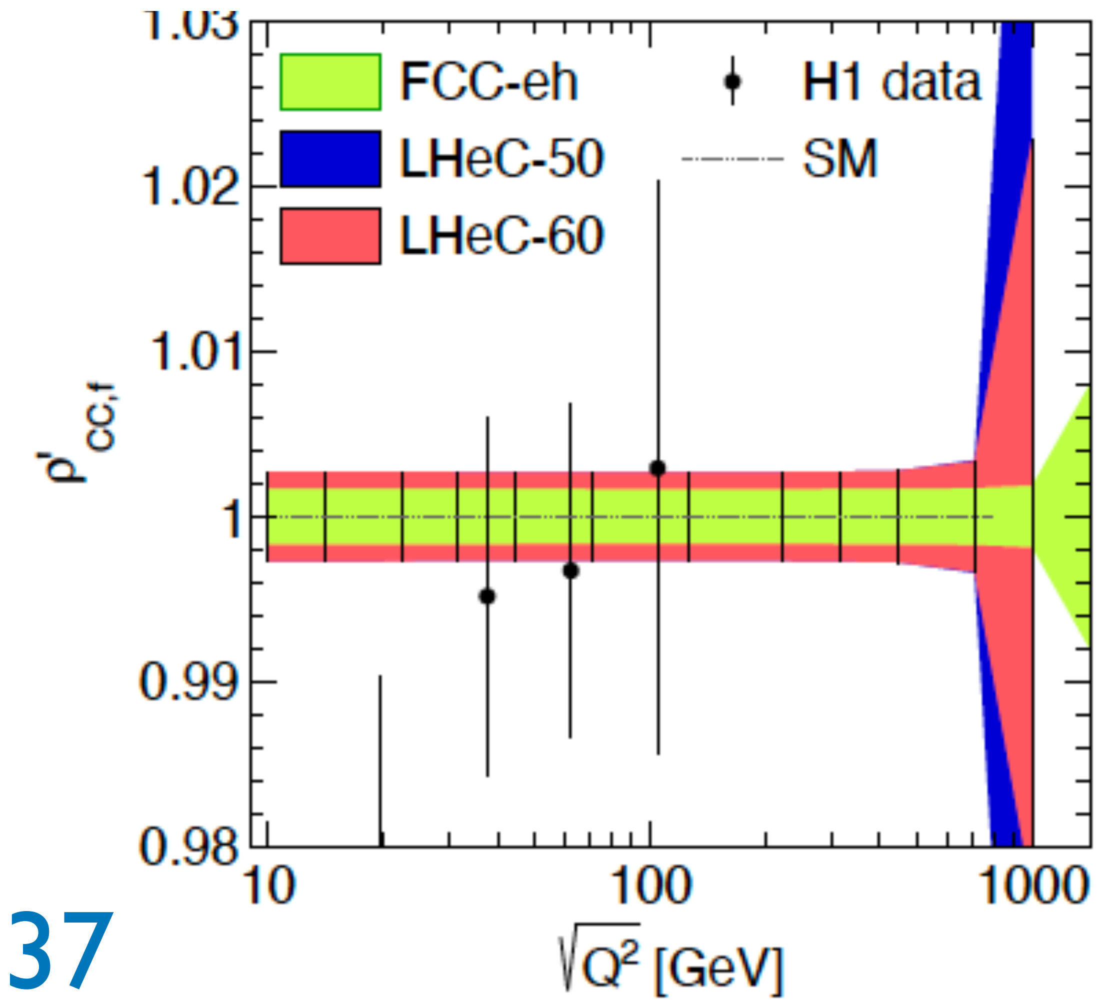
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\, I_{\mathrm{L},f}^3\,,$$
$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\, \left(I_{\mathrm{L},f}^3 - 2Q_f\,\kappa_f\,\sin^2\theta_W\right)$$

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









2007.11799, 2203.06237

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.

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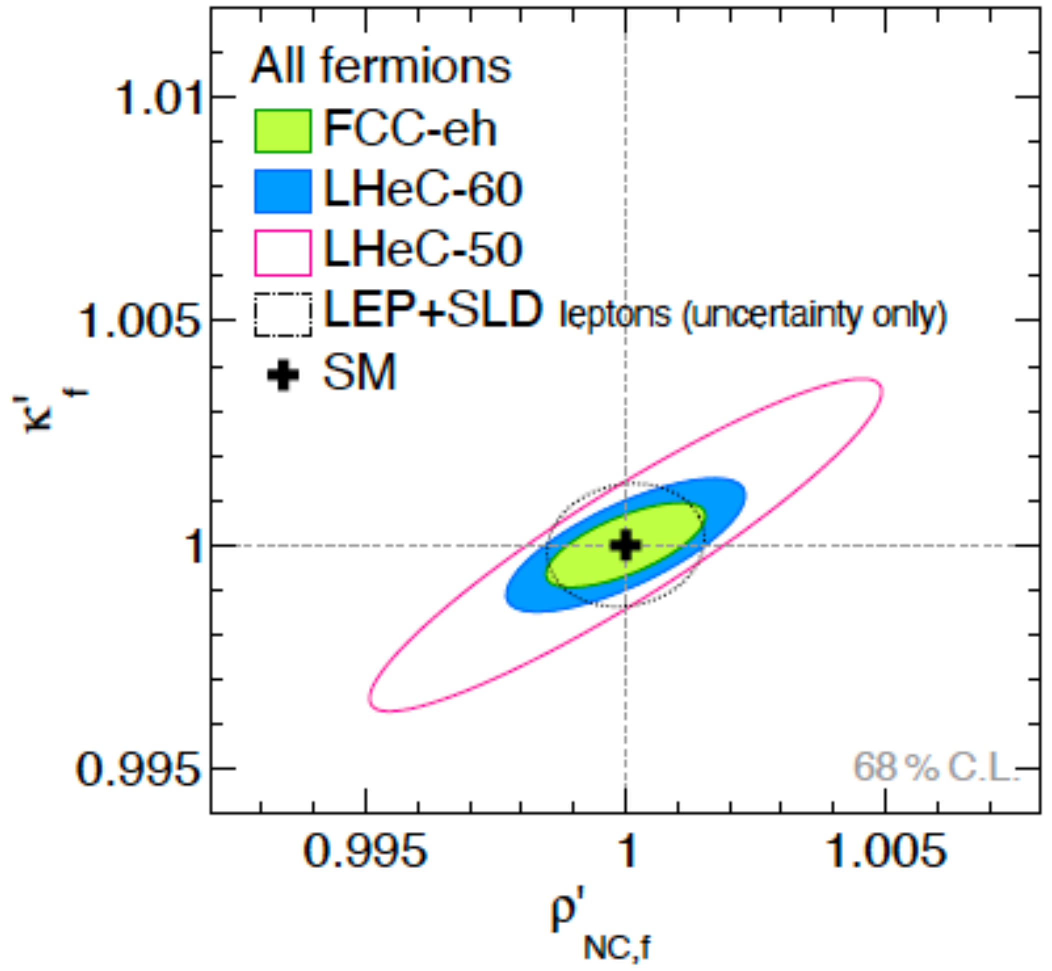

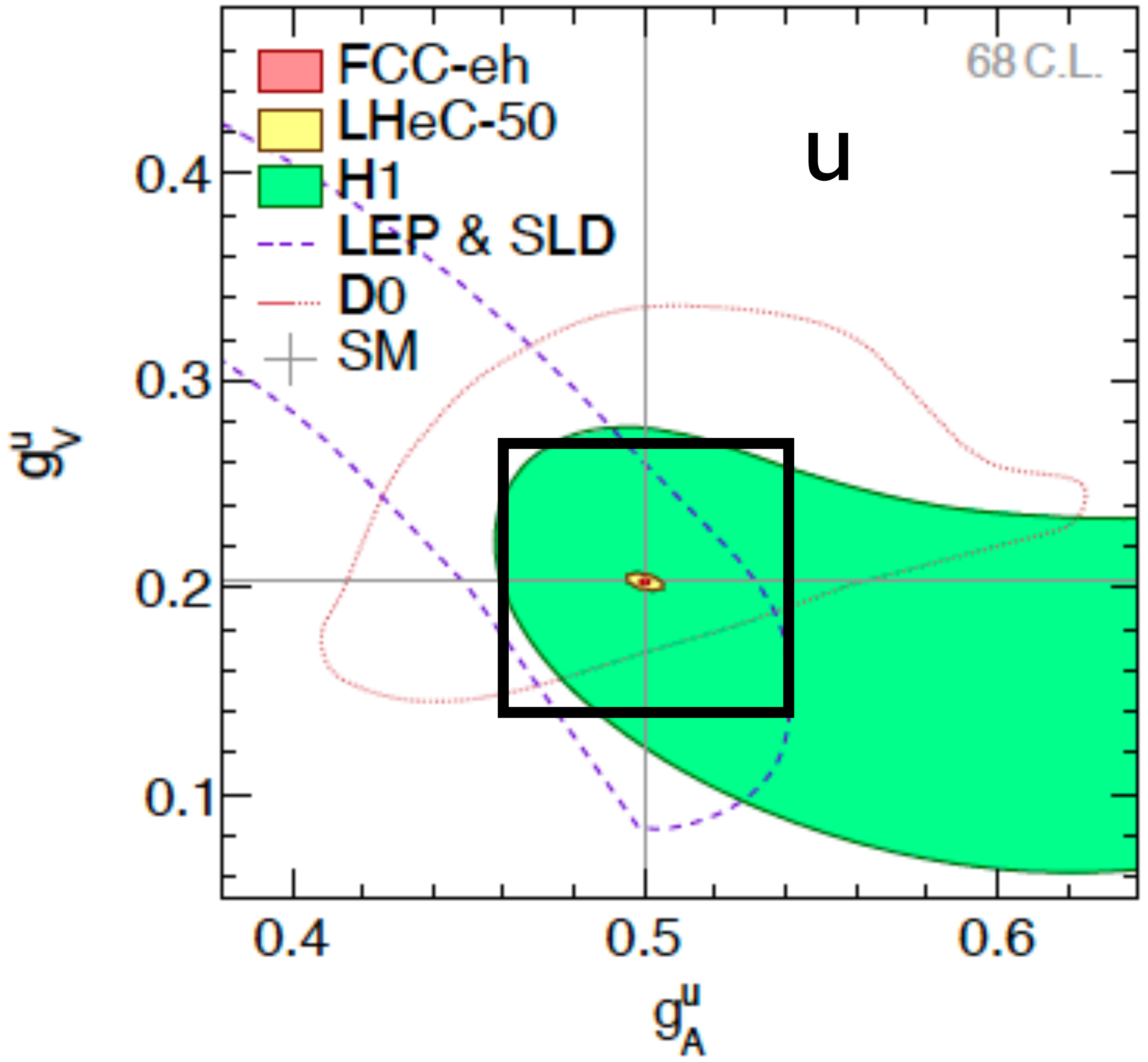

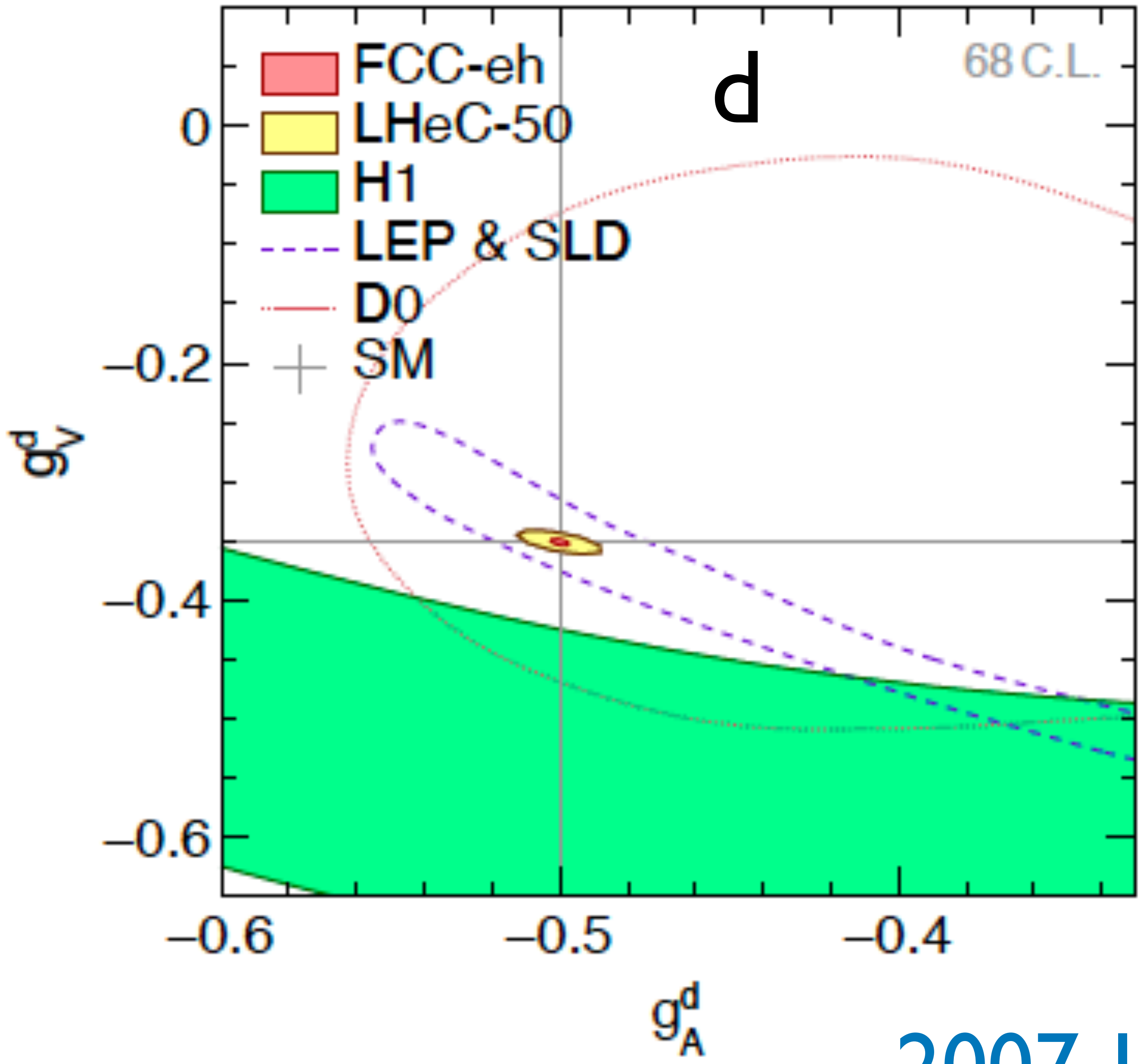

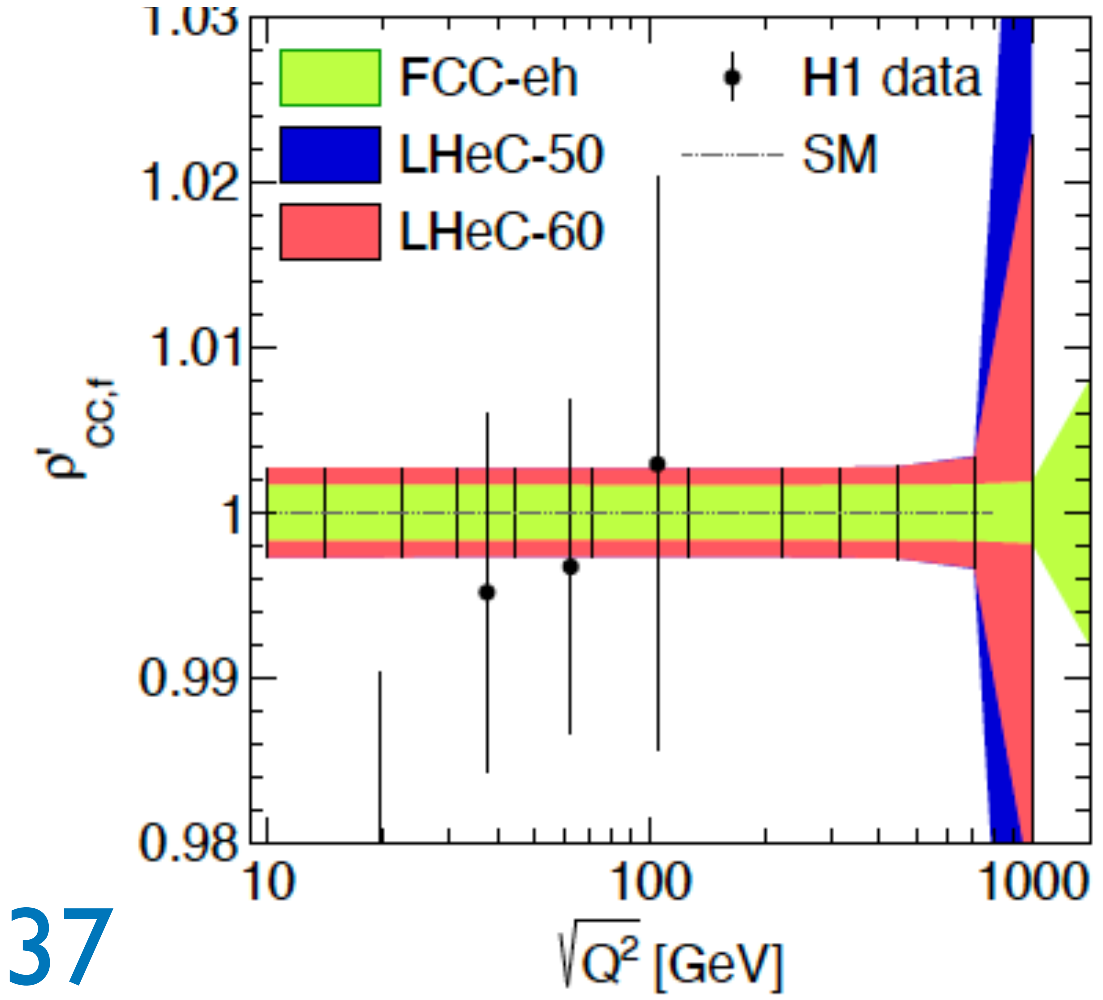

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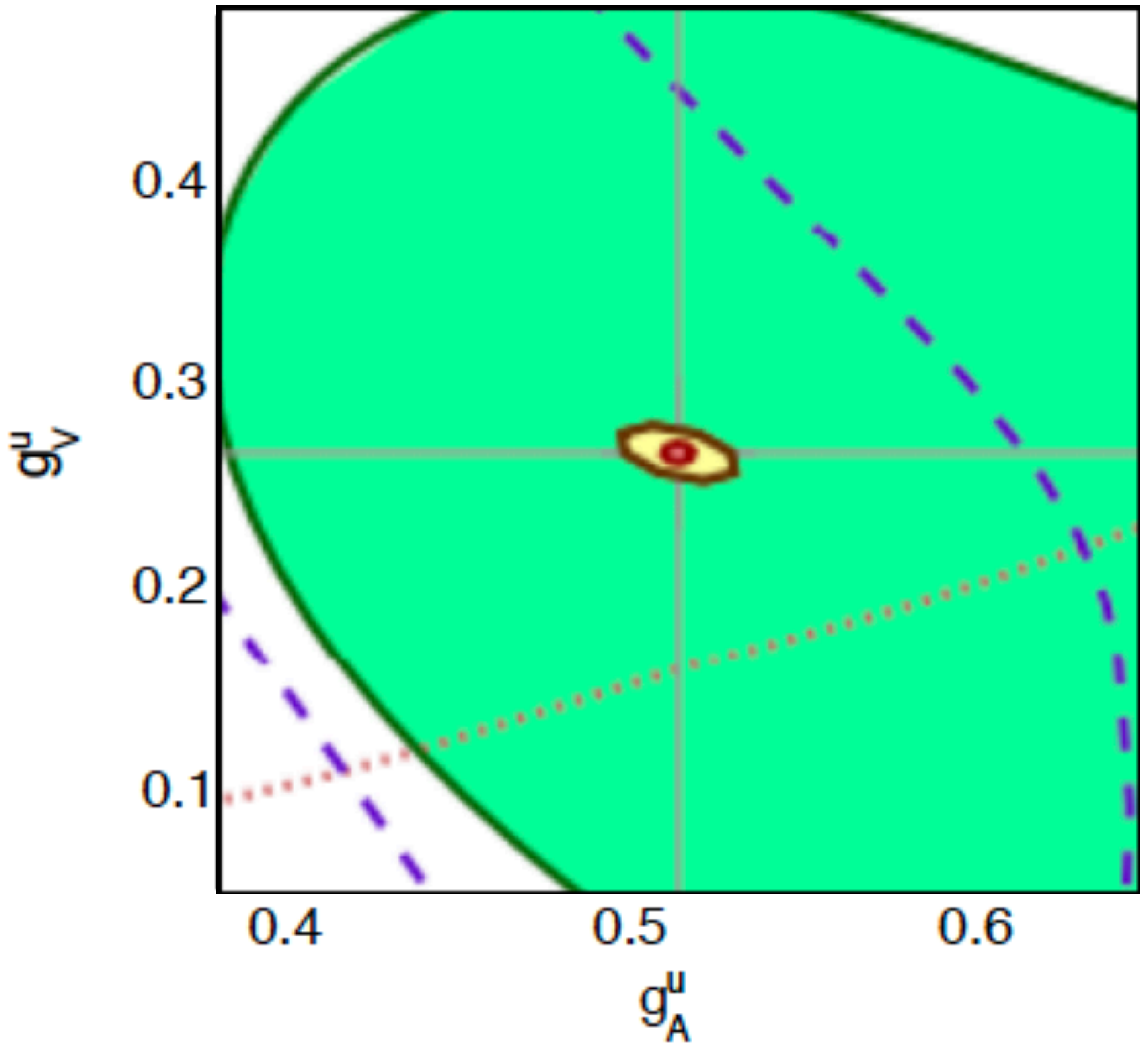

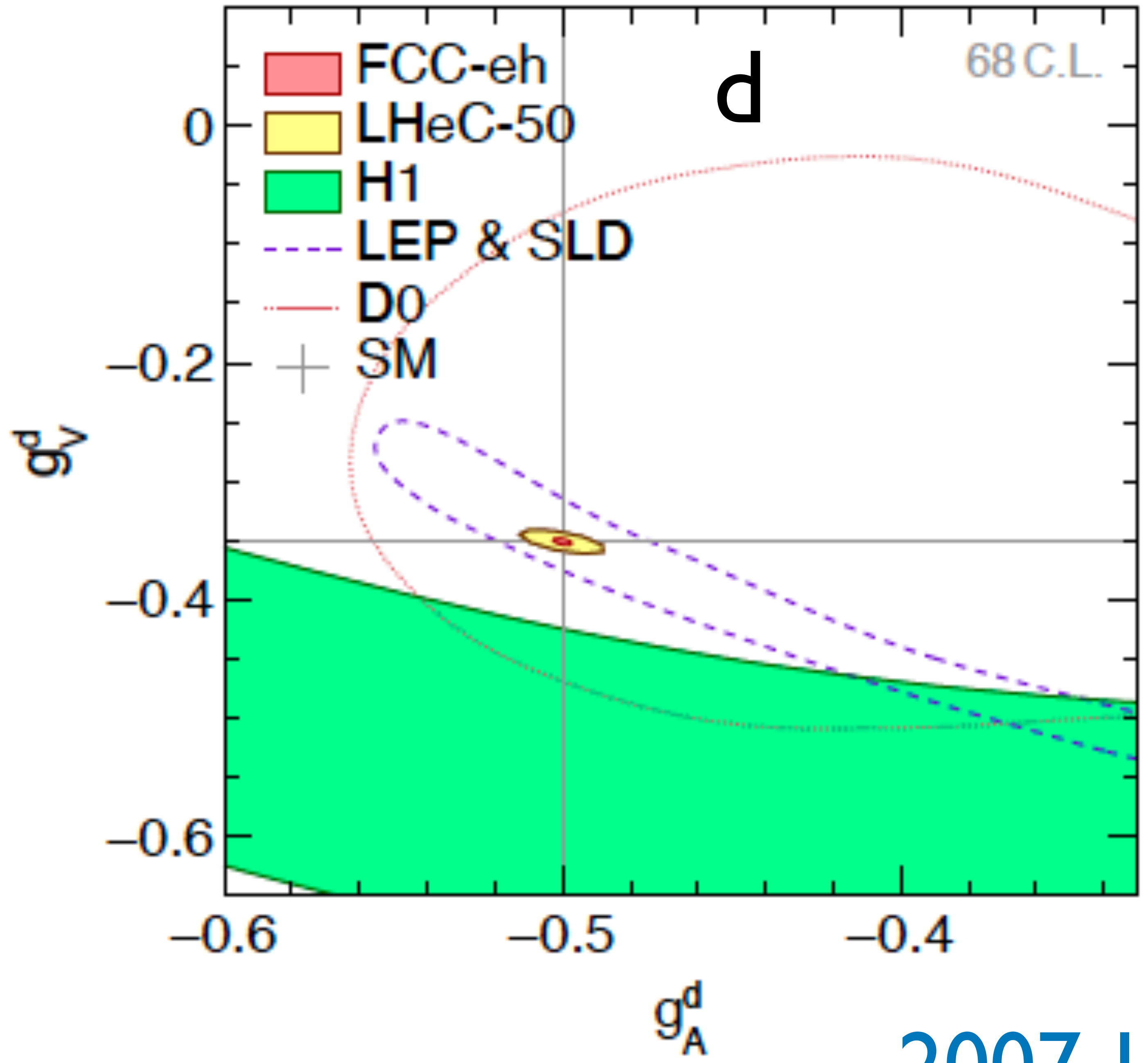

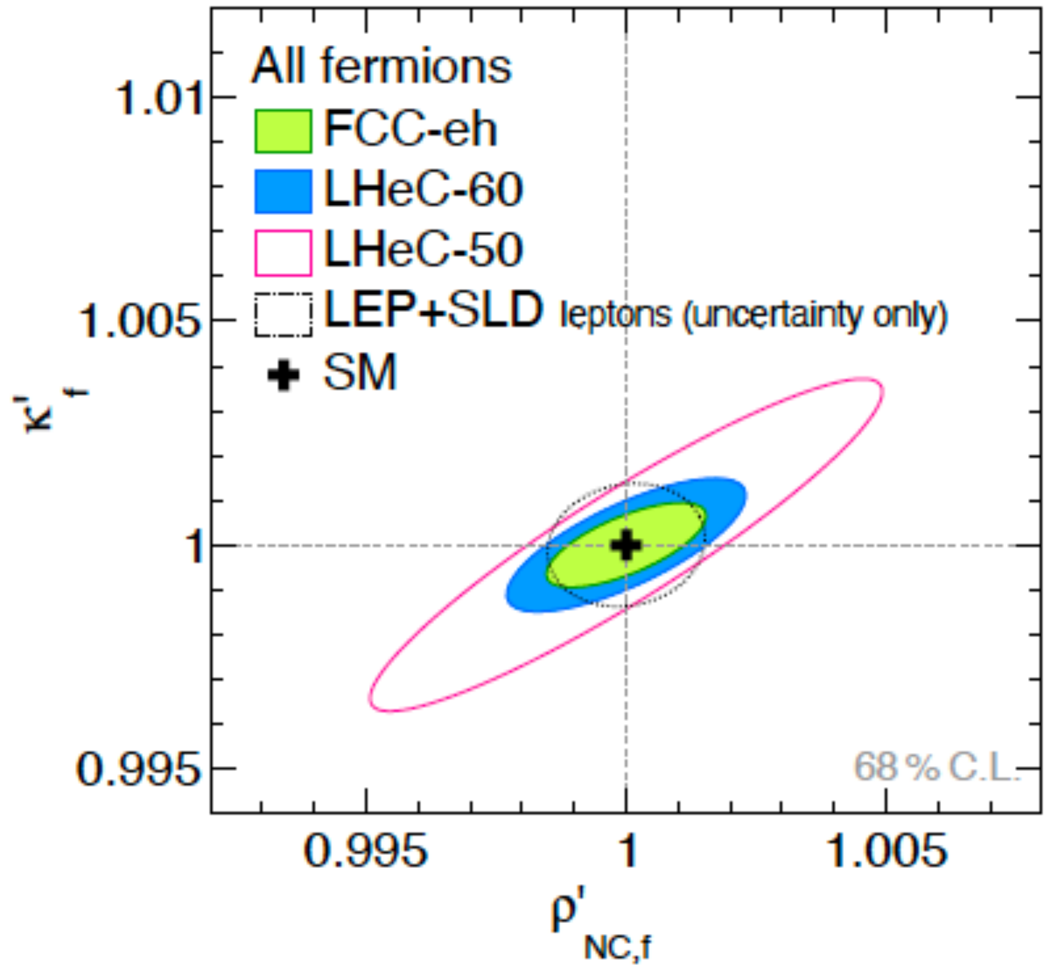

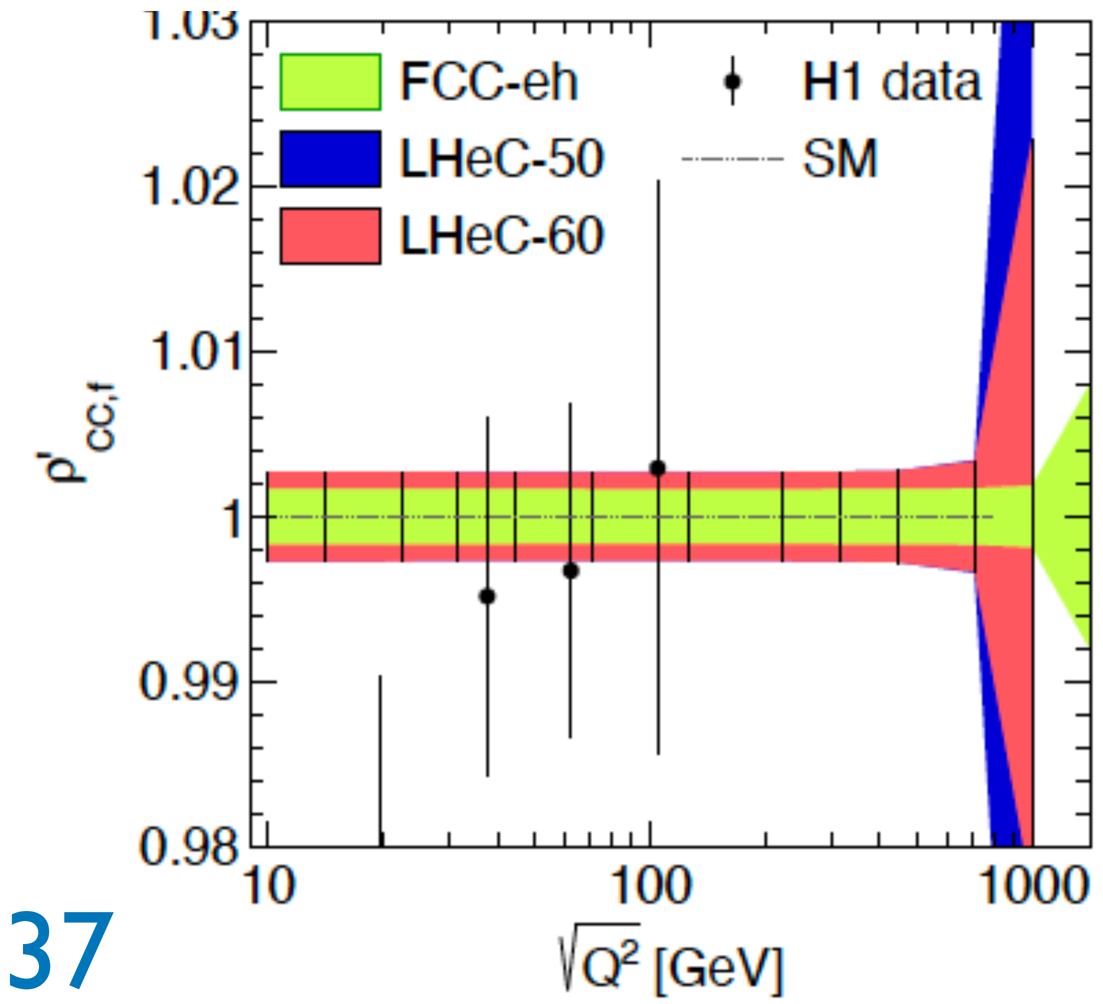

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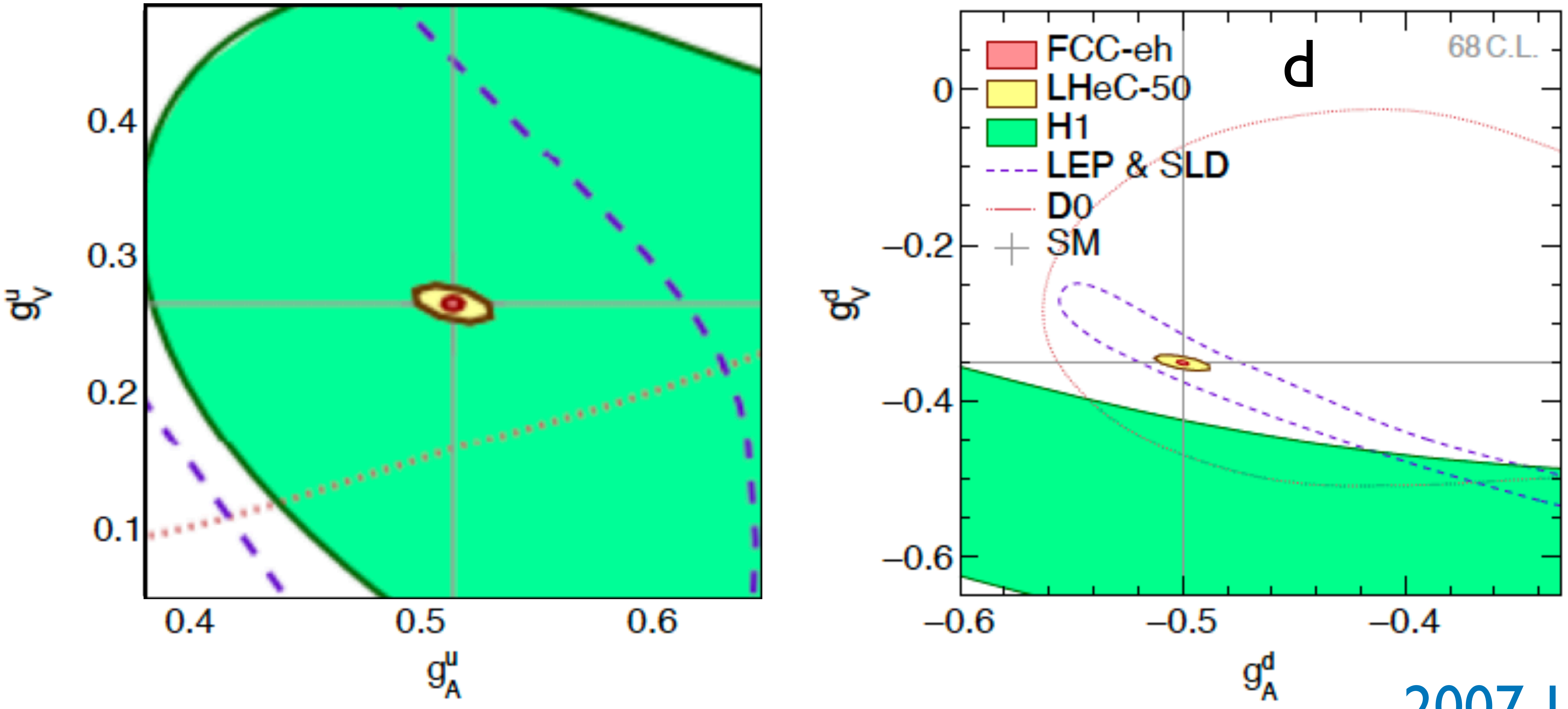
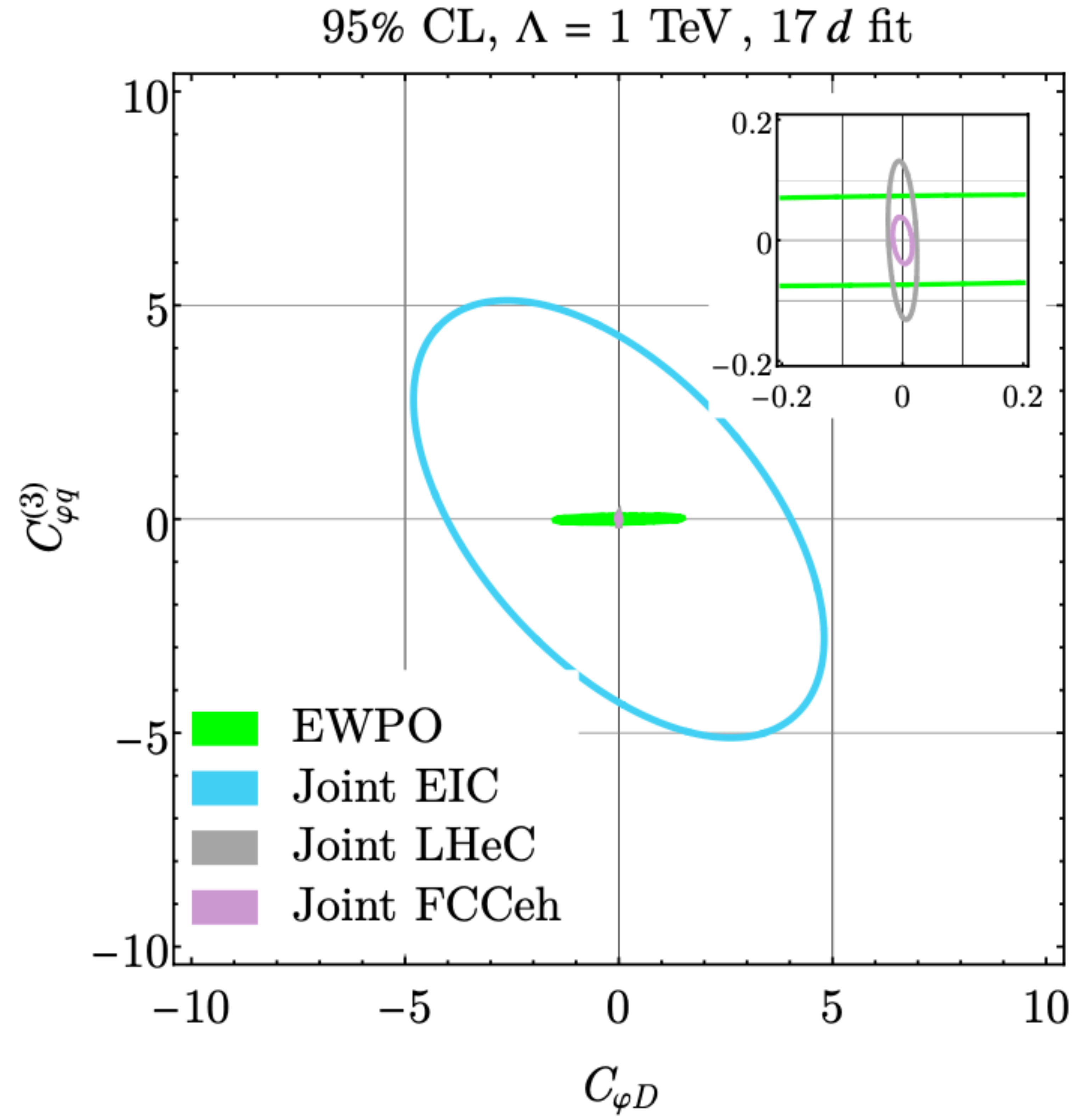
2306.05564

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





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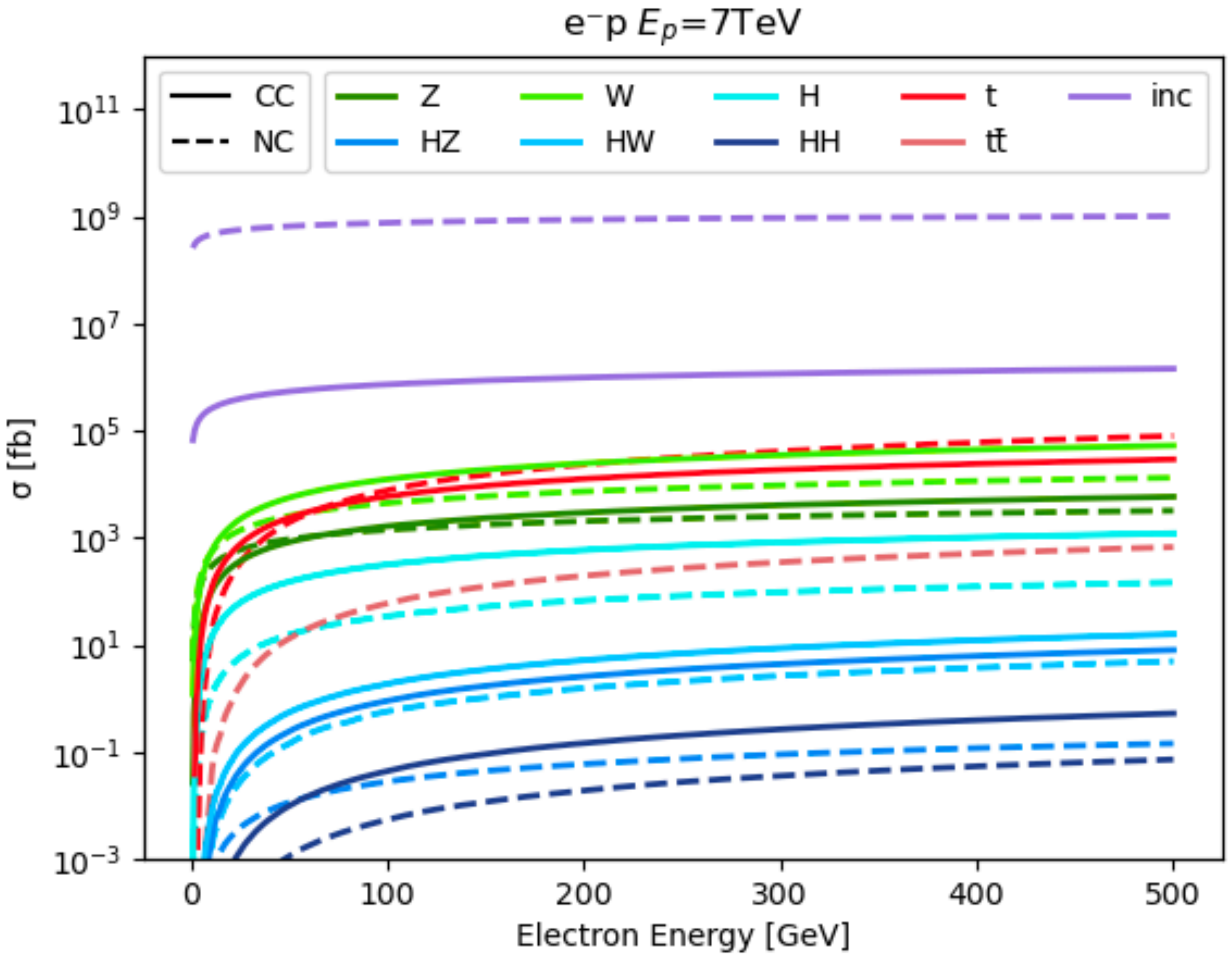
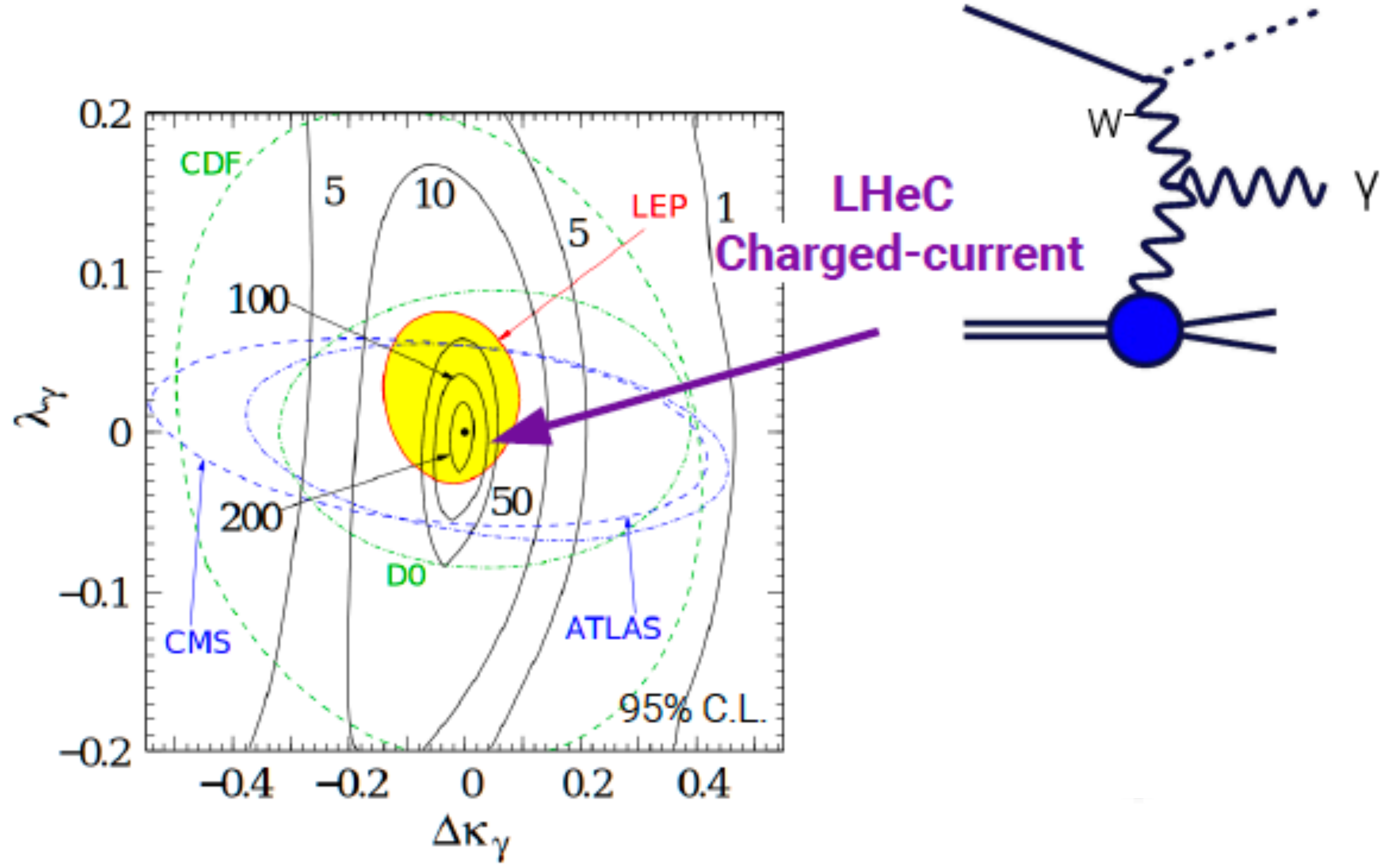
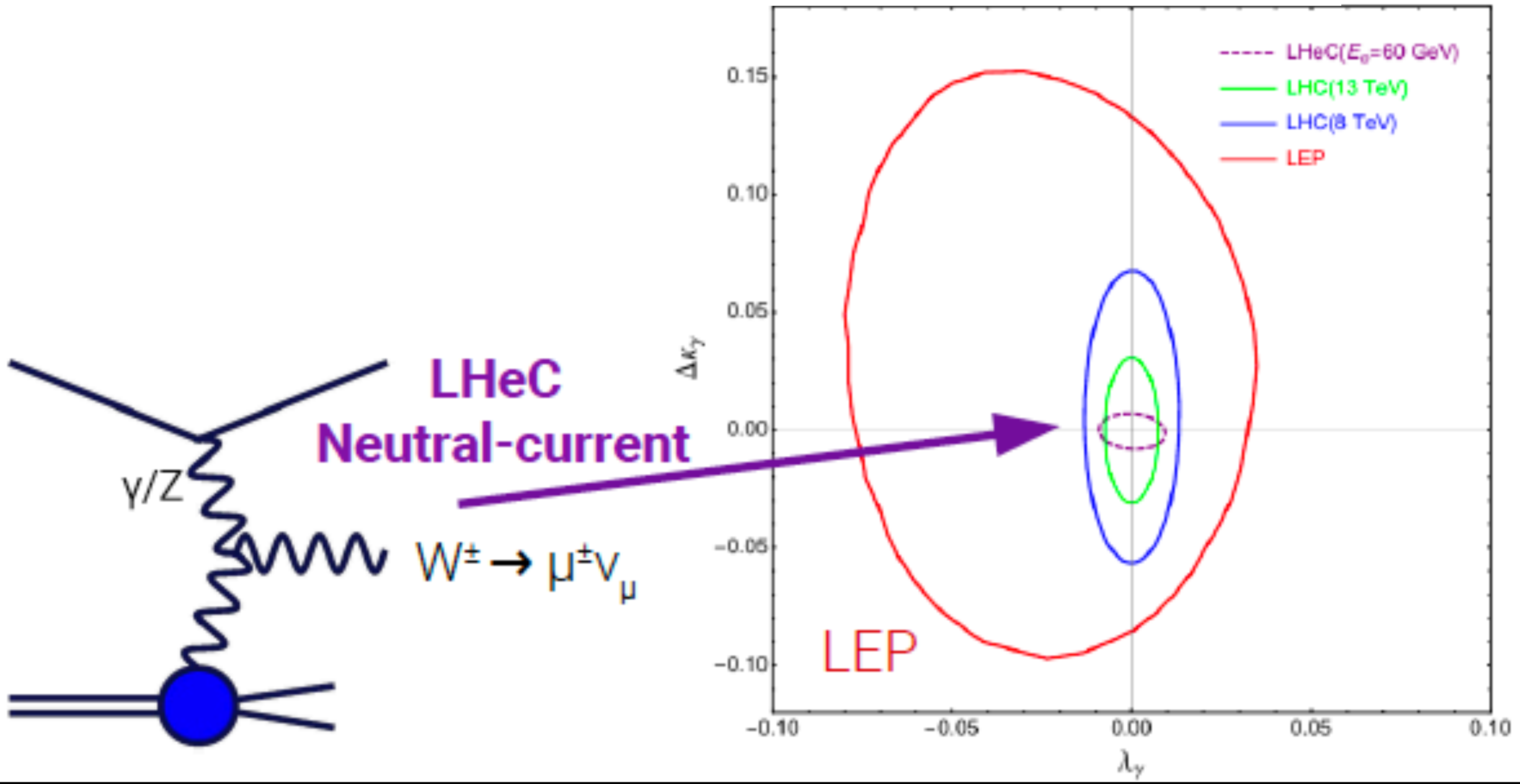
EW physics: triple and quartic gauge couplings

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

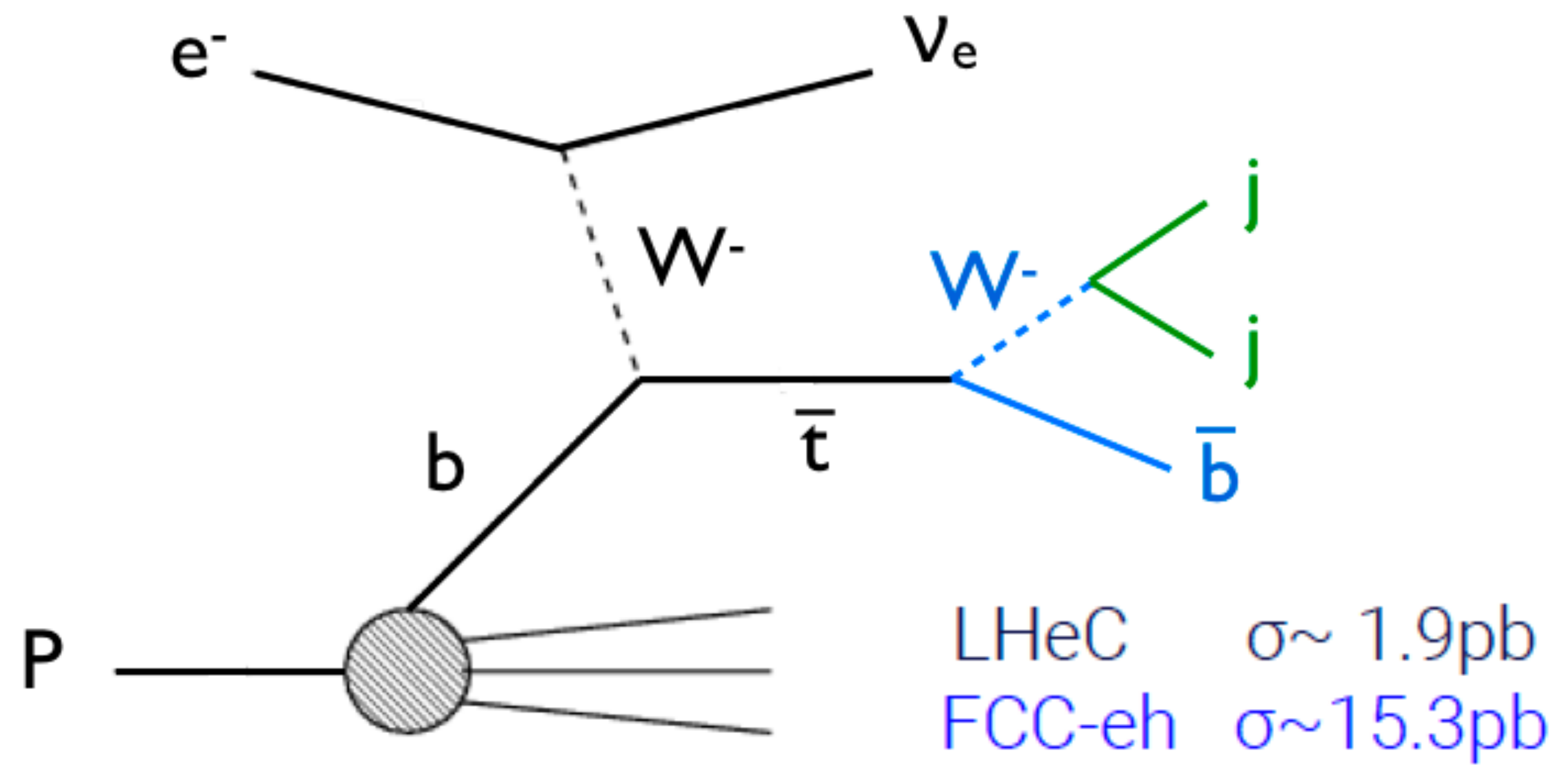




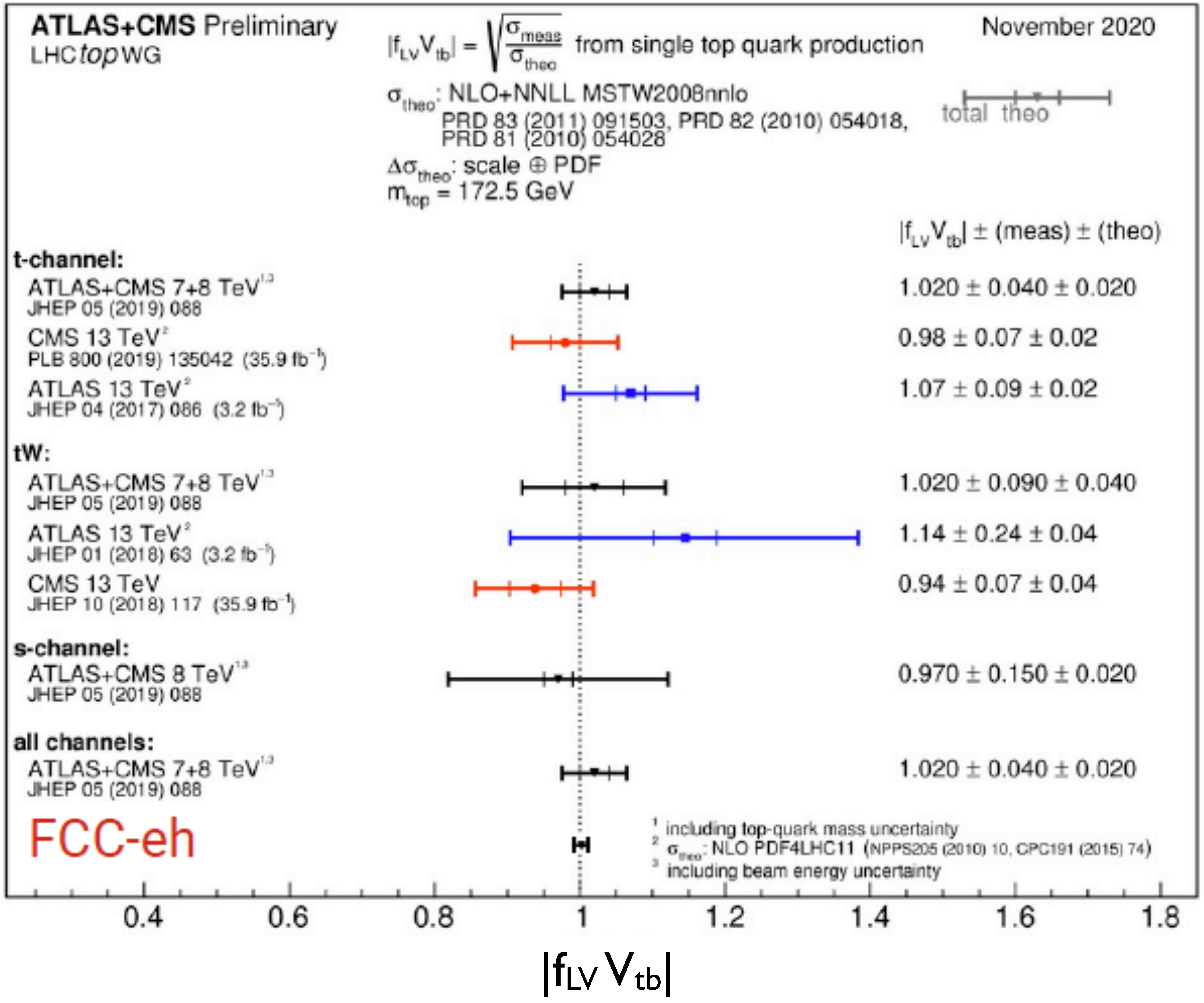


Top physics: CKM

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



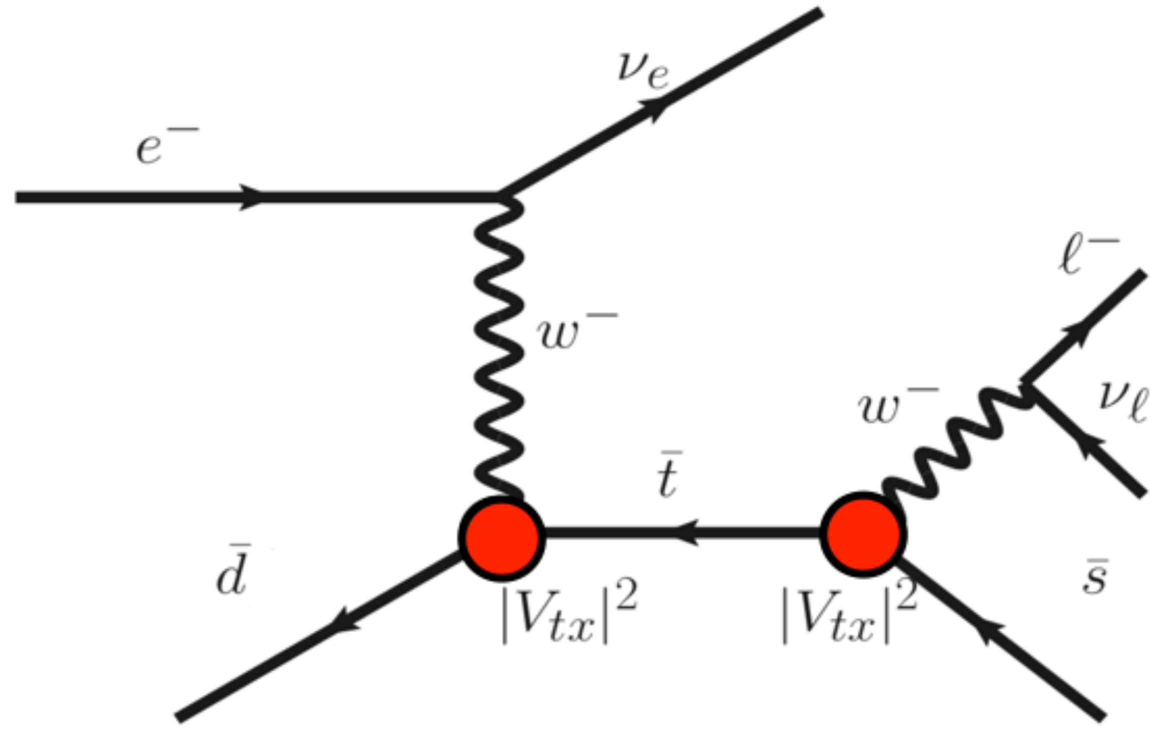
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

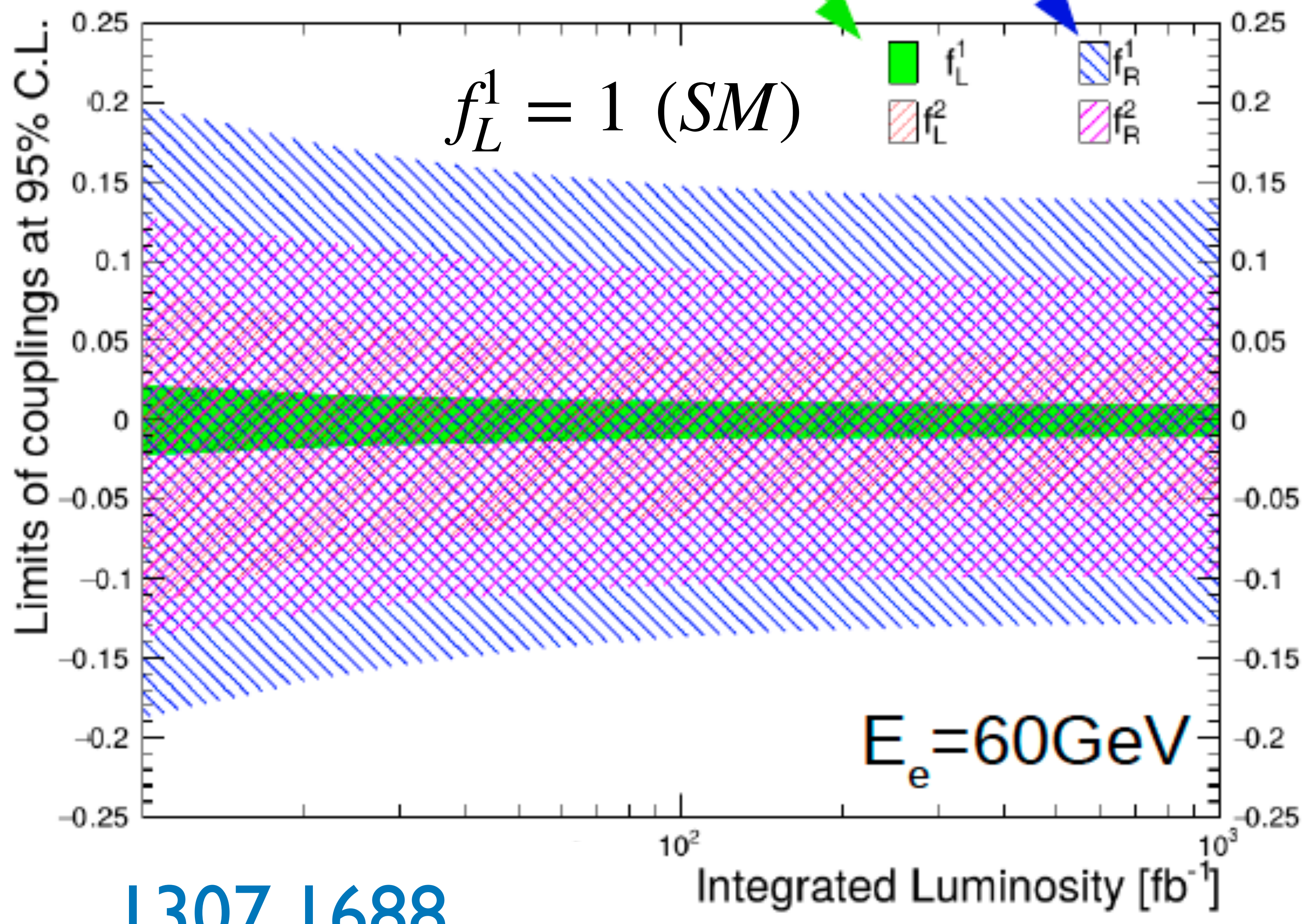


Top physics: anomalous couplings

- Anomalous couplings can be probed, limits competitive with HL-LHC.
- Checks of SM predictions.

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





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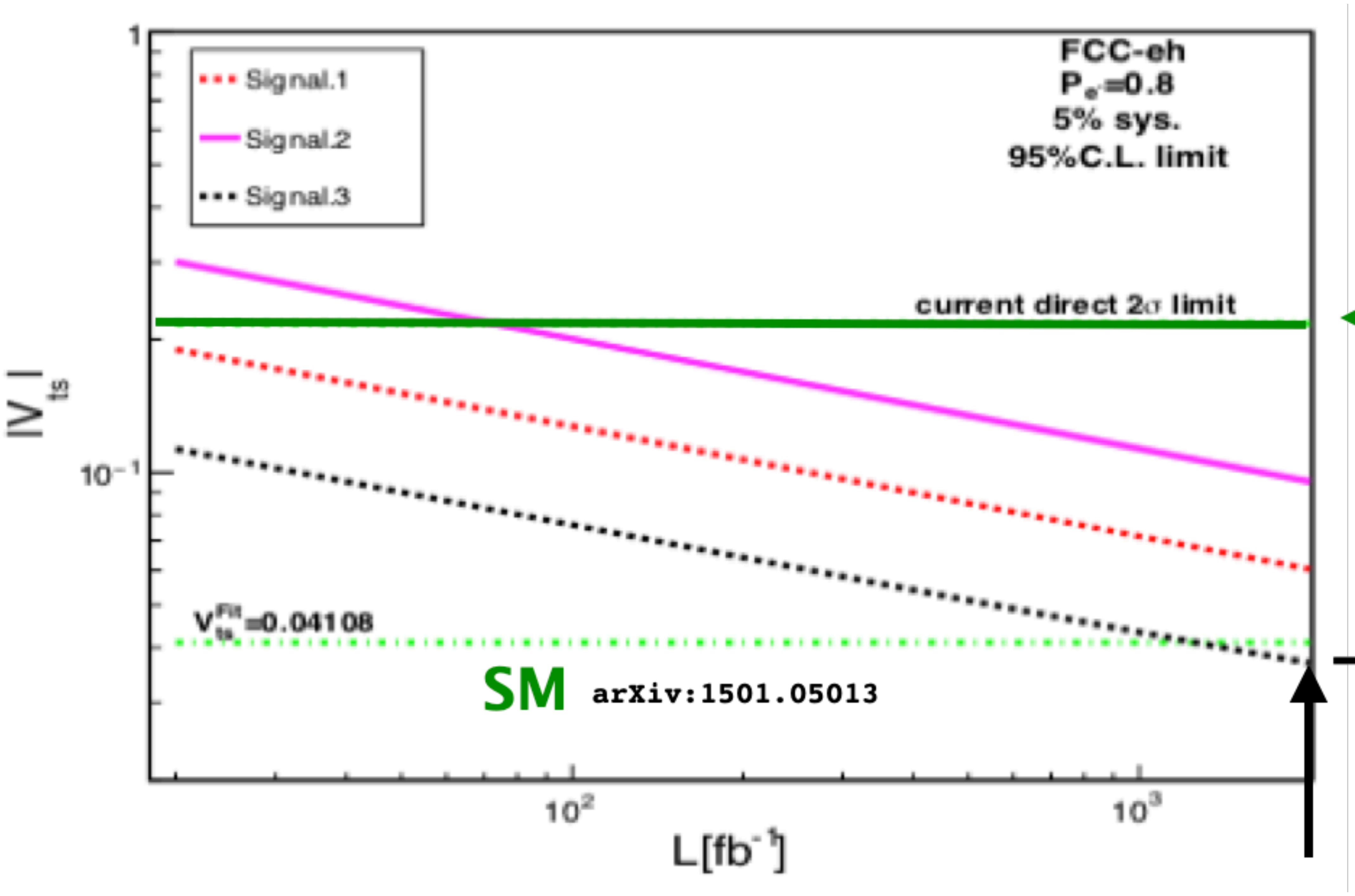
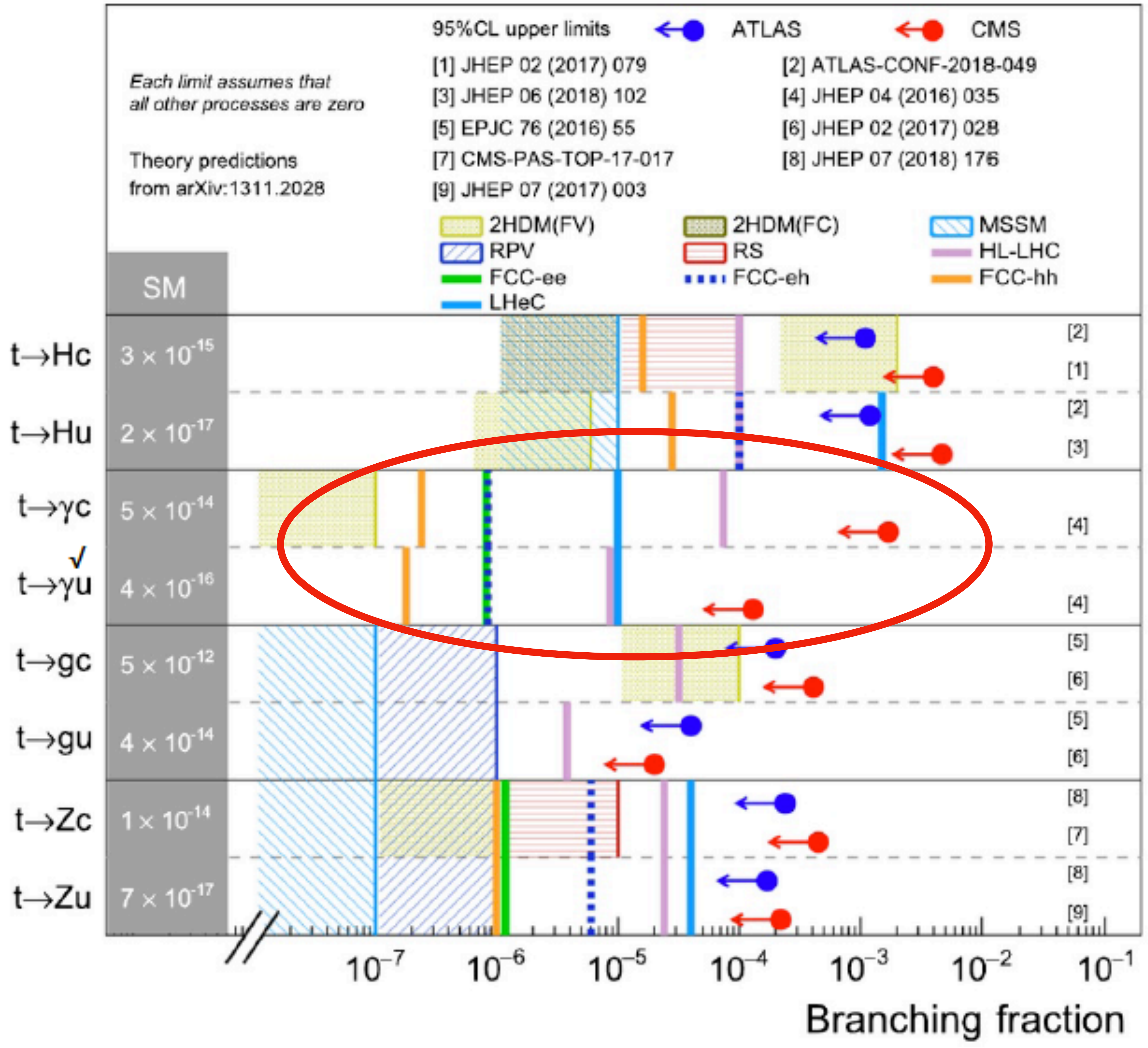
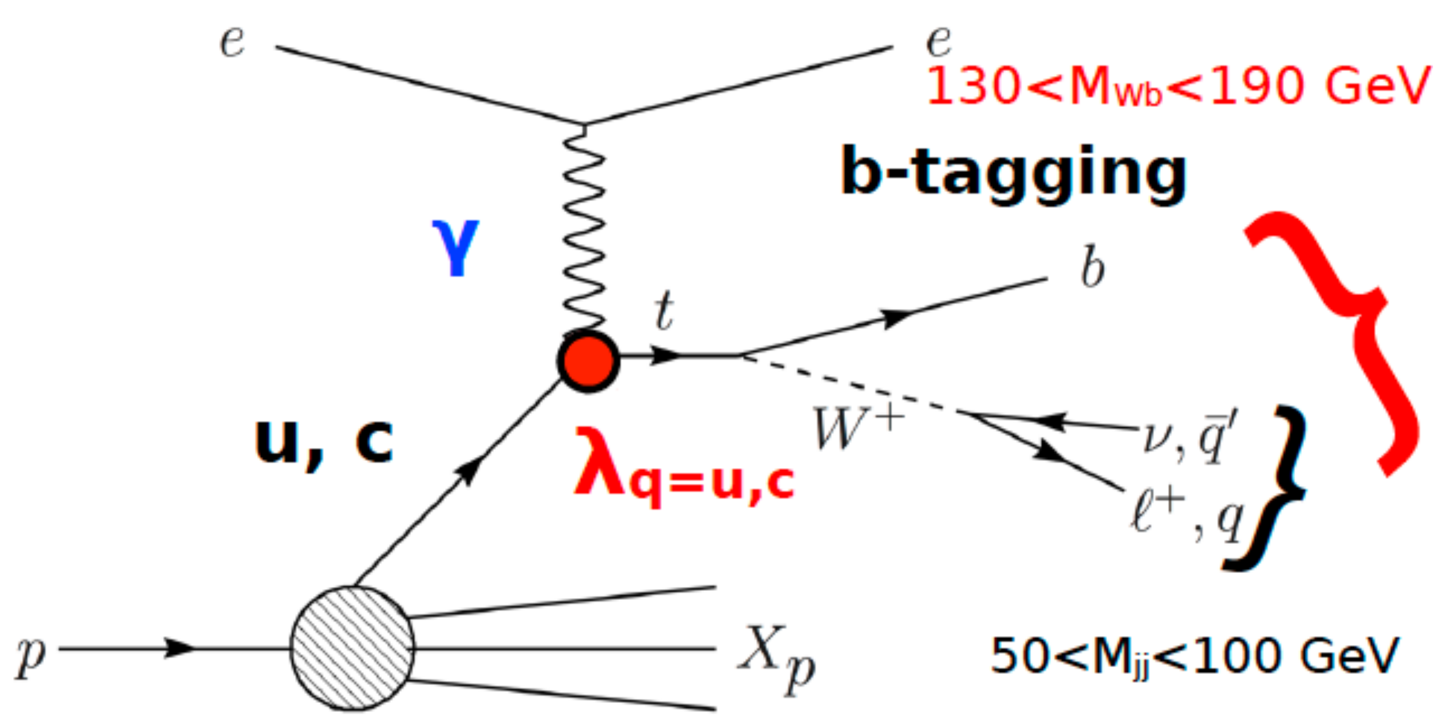


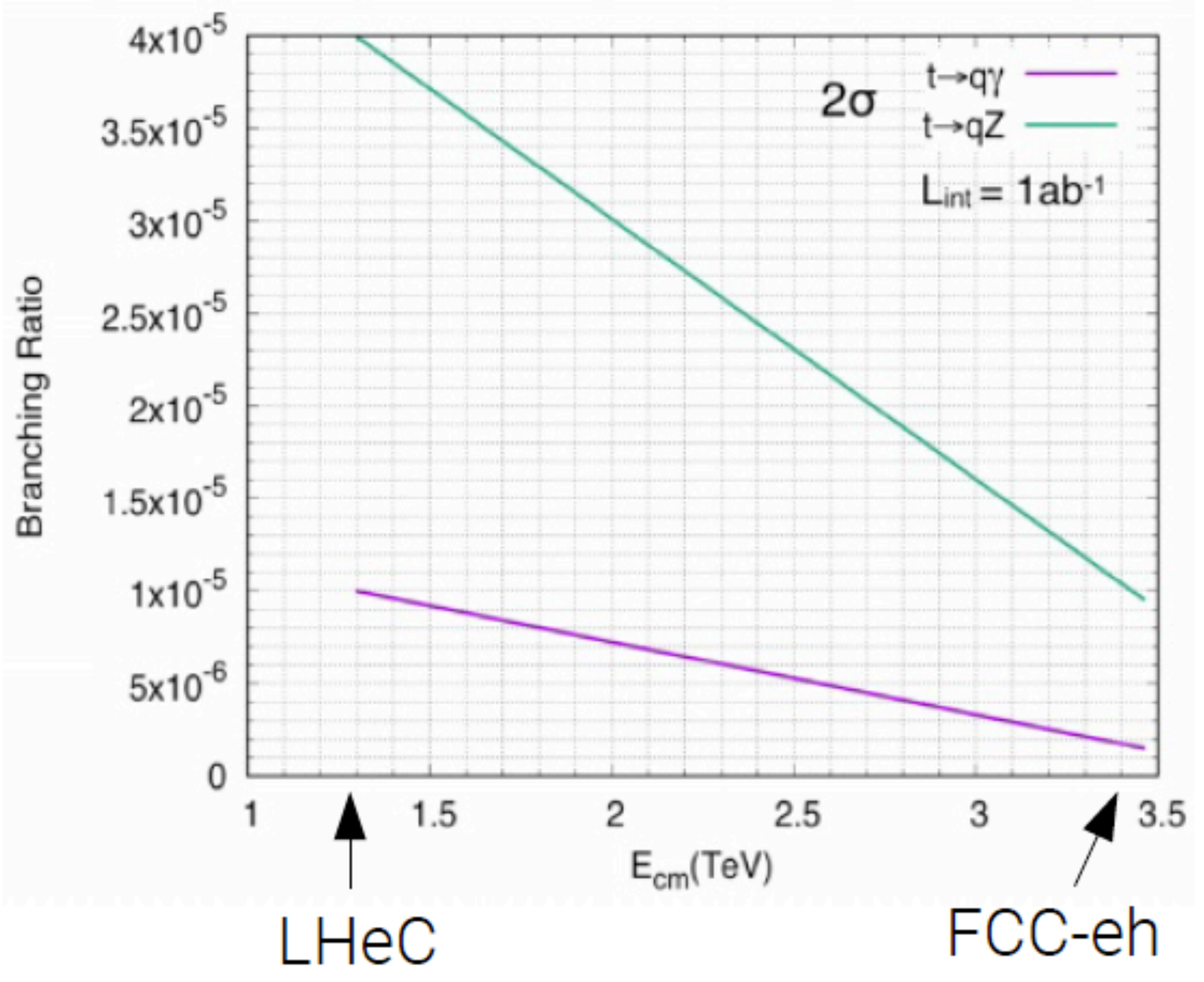
Top physics: FCNC

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

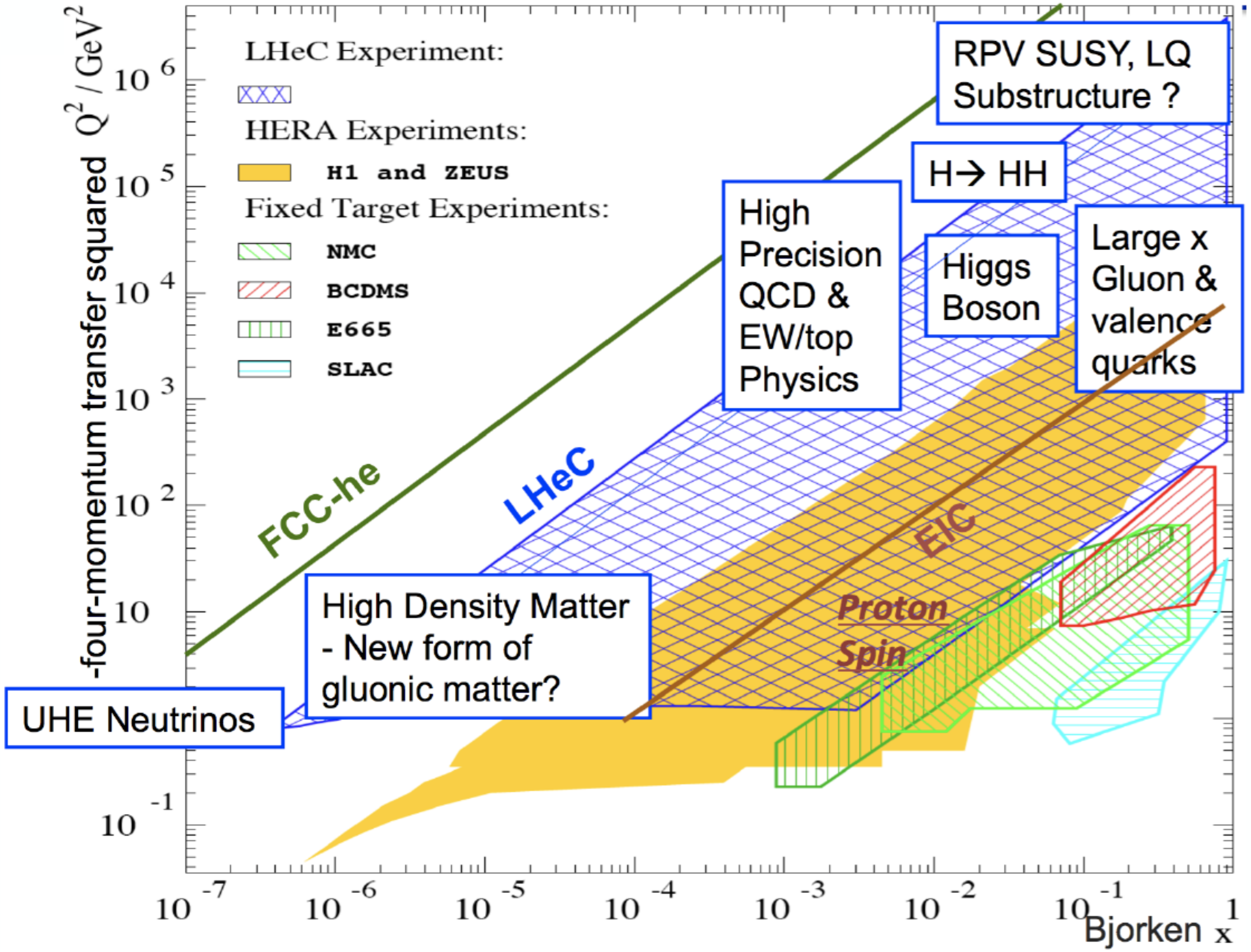


I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)





Summary:



- **LHeC and FCC-eh:**

  ➜ Have a physics case on their own: obviously QCD (both precision and discovery in ep and eA), but also EW, top, Higgs, BSM.

  ➜ Enlarge the reach of hadronic colliders into (higher) precision (PDFs, factorisation), both for pp and for AA.

  ➜ Have complementarities and synergies with the other collision modes: hh and e^+e^-.

Plans:

Adapted from Jorgen d'Hondt

The ep/eA study at the LHC and FCC – new impactful goals for the community

2023 | WS | 2024 | WS | 2025 | TWS | *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces

general-purpose high-energy physics programme: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions

ep/eA-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics programme

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics

developing a sustainable LHeC and FCC-eh collider programme
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

- typically 2-3 conveners per theme
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)
- inform the community with regular ep/eA Newsletters
- everybody is welcome to join

Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

Plans:

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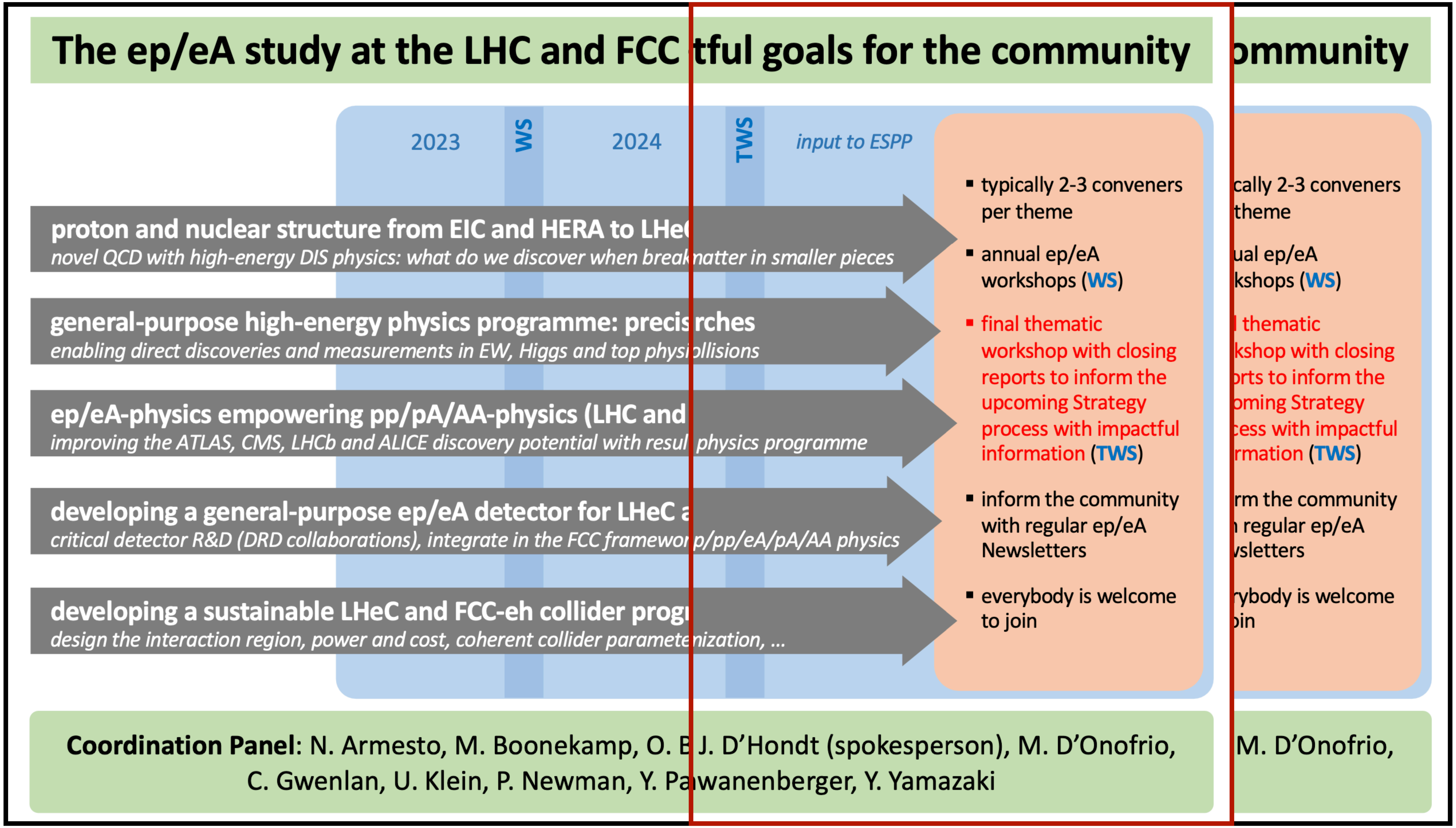

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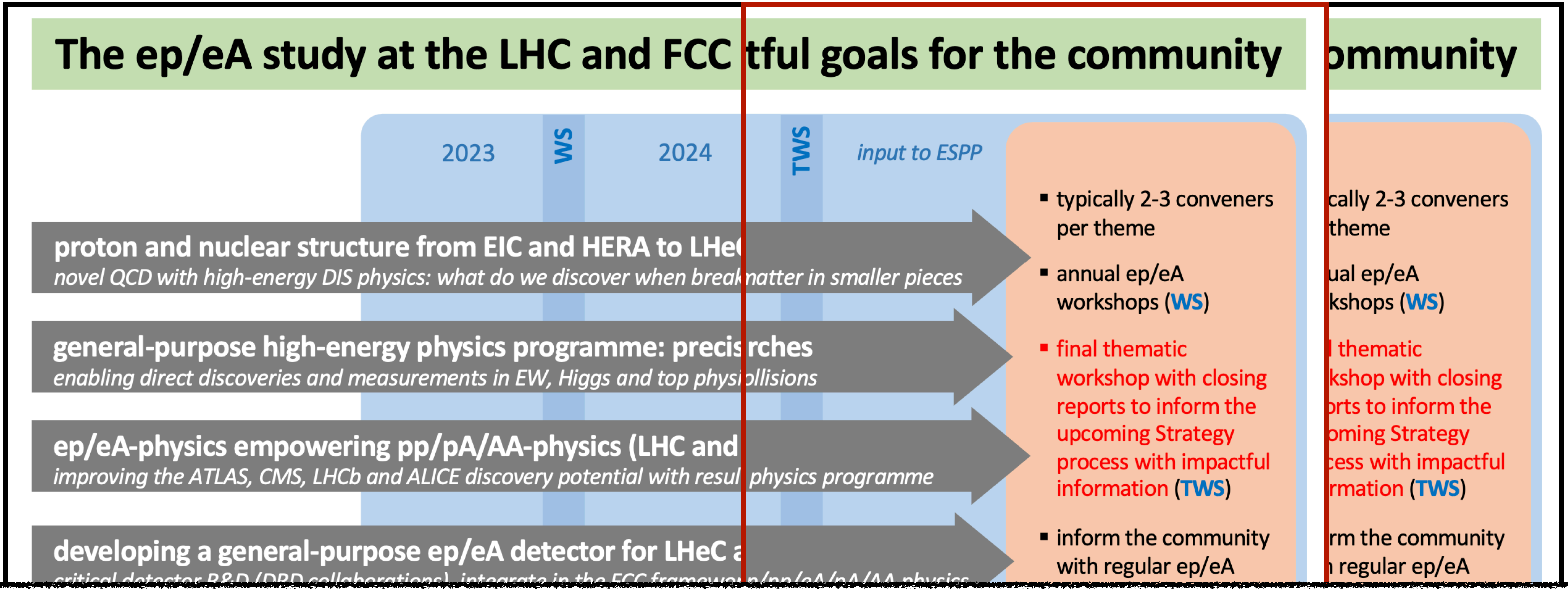


from Jorgen d'Hondt

- ***Thank you very much to:***

  ➜ *The organisers for the invitation to deliver this talk.*

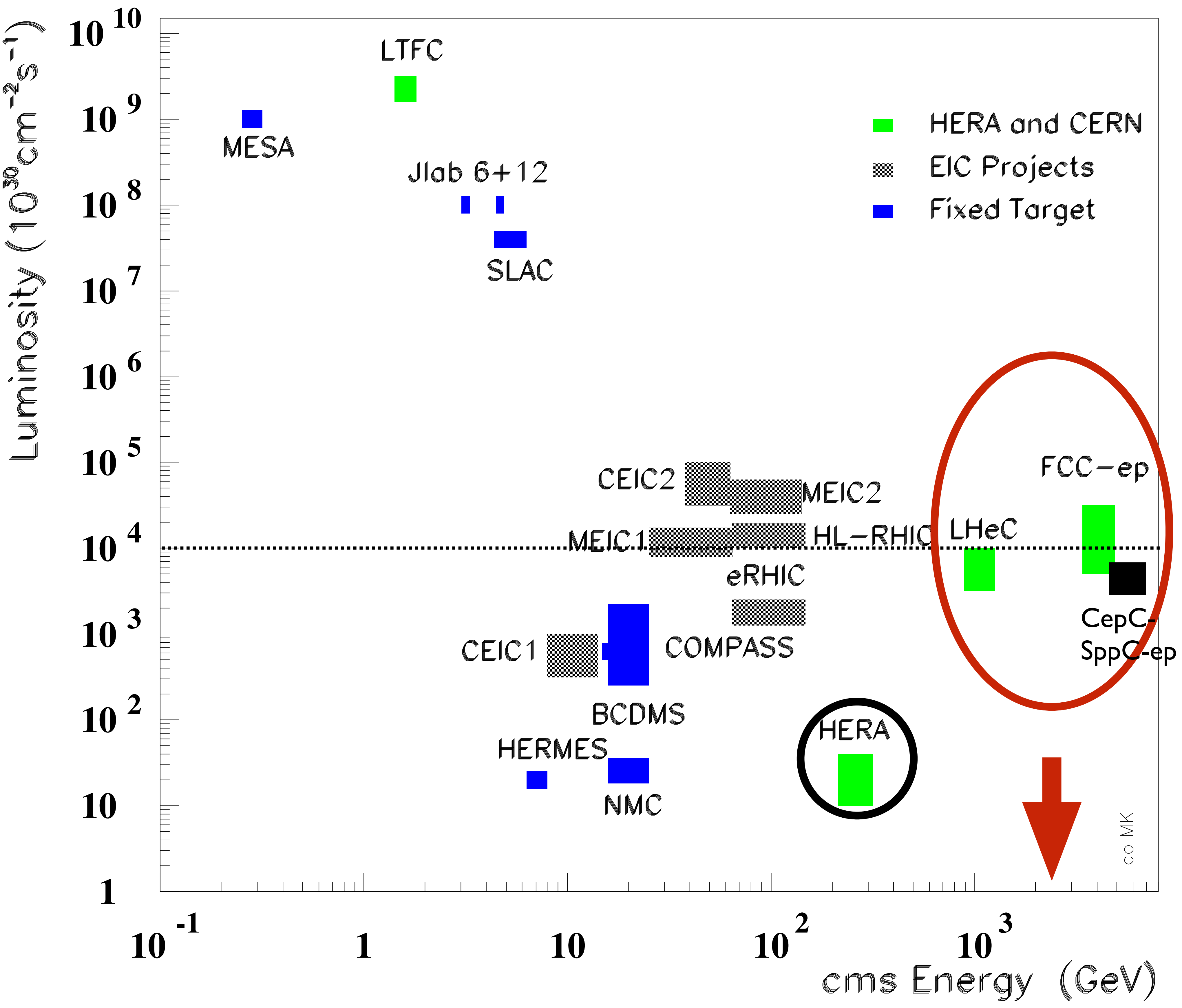
  ➜ *Maarten Boonekamp, Daniel Britzger and Christian Schwanenberger for material and feedback.*

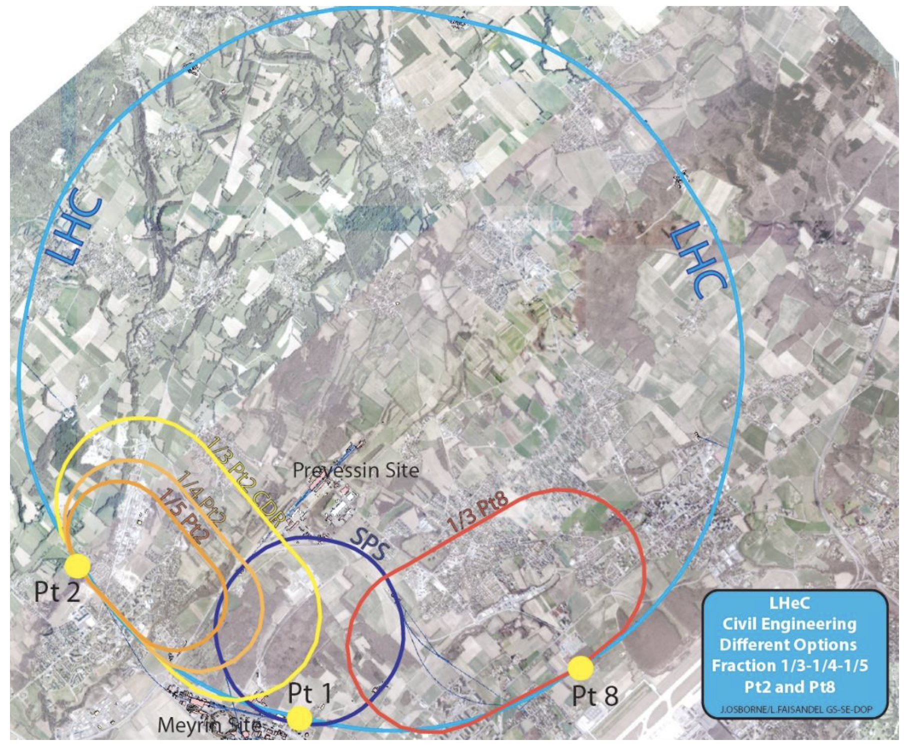
  ➜ *You for your attention!*

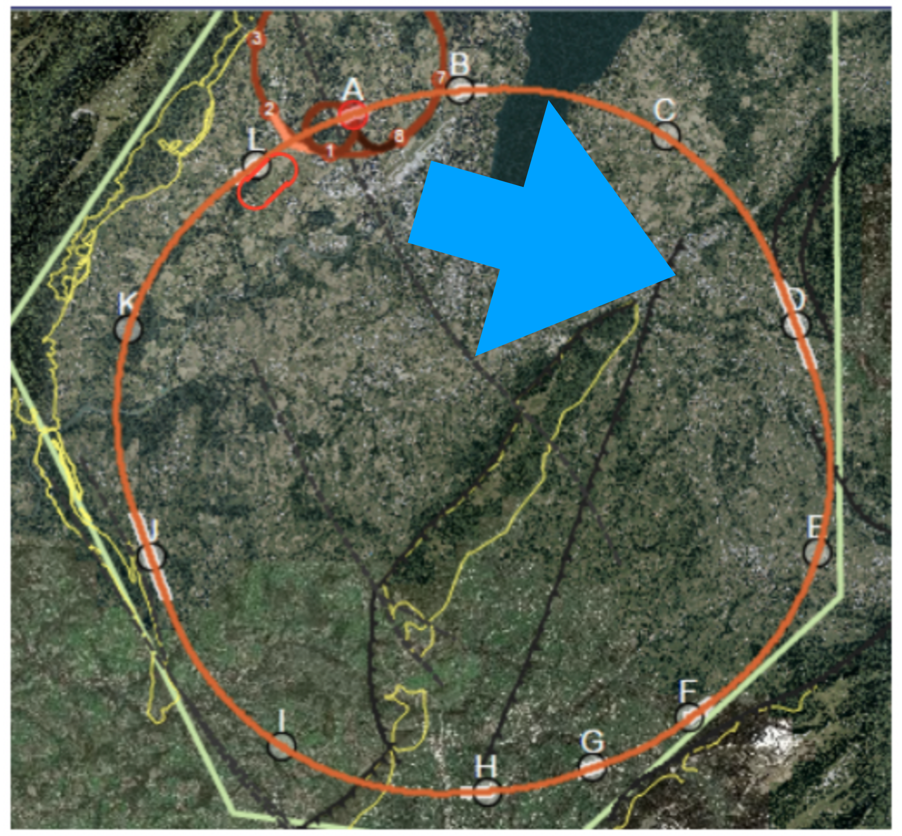
Backup:

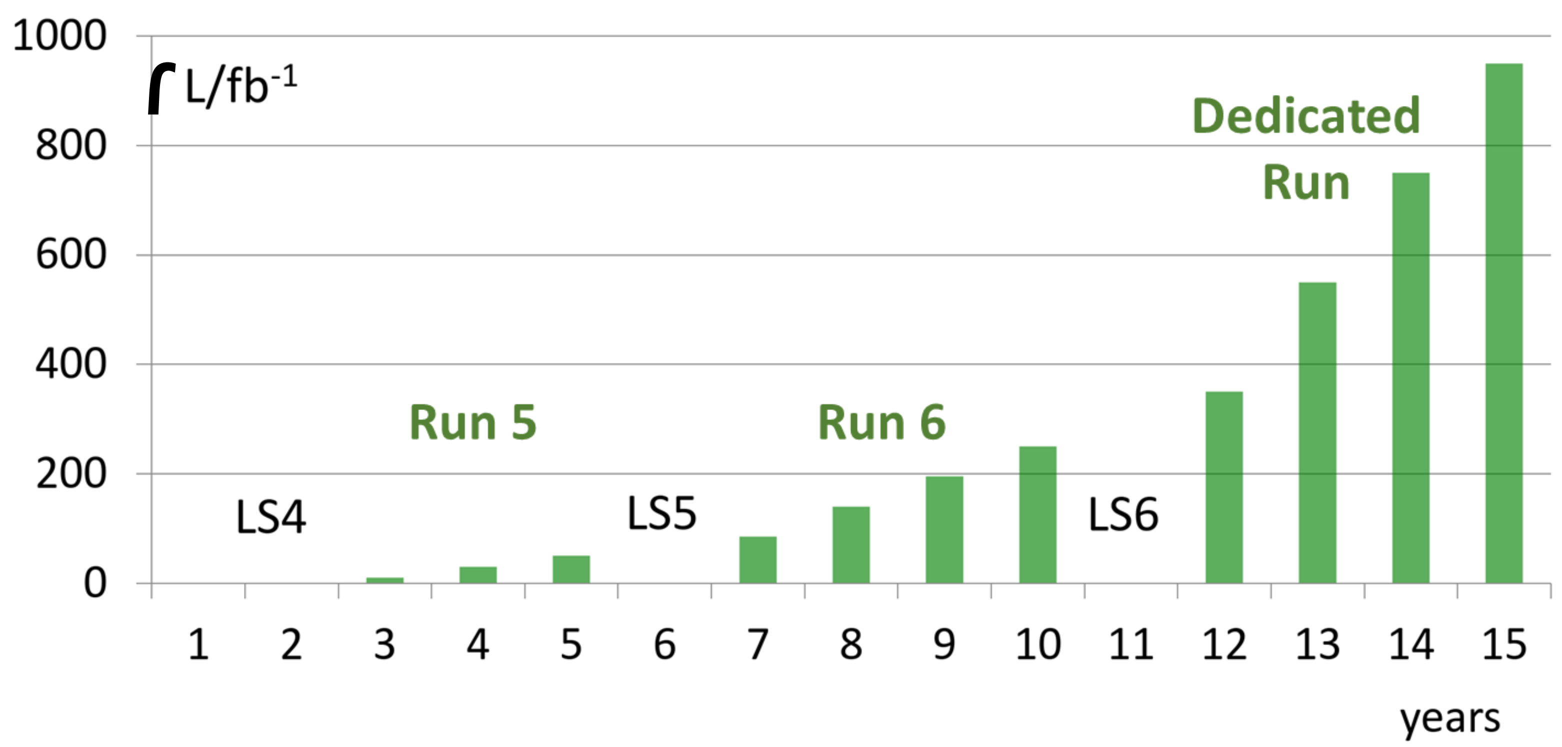
Accelerators:

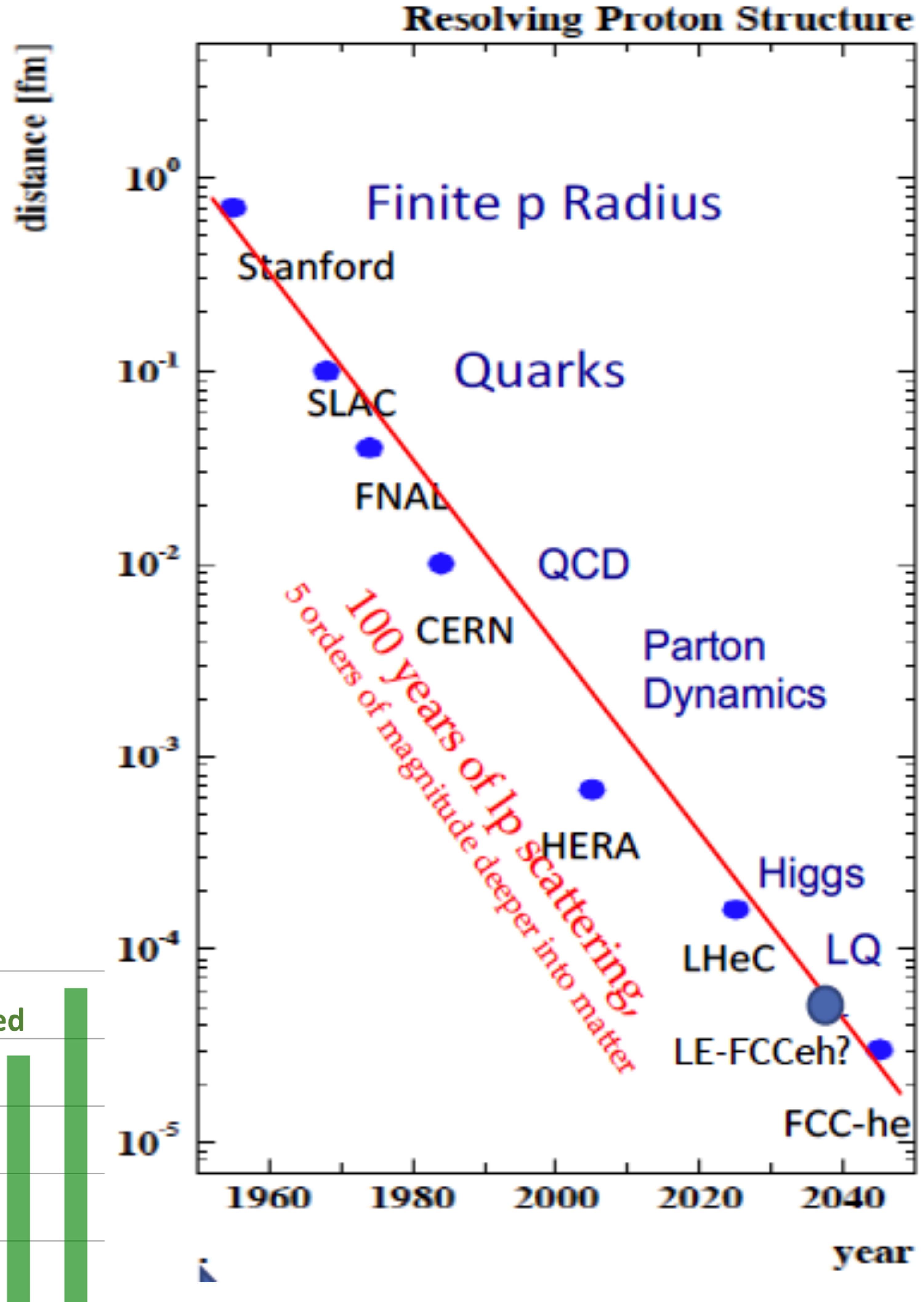
Lepton-proton/nucleus scattering facilities











1810.13022

Luminosities: ~10^{34} (10^{33}) cm^{-2}s^{-1} in ep (ePb) (details in backup).

Luminosities:

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} cm^{-2}s^{-1}	1	5	9	23	8	15

ePb

Parameter	Unit	LHeC	FCC-eh (E_p=20 TeV)	FCC-eh (E_p=50 TeV)
Ion energy E_{Pb}	PeV	0.574	1.64	4.1
Ion energy/nucleon E_{Pb}/A	TeV	2.76	7.88	19.7
Electron beam energy E_e	GeV	50	60	60
Electron-nucleon CMS $\sqrt{s_{eN}}$	TeV	0.74	1.4	2.2
Bunch spacing	ns	50	100	100
Number of bunches		1200	2072	2072
Ions per bunch	10^8	1.8	1.8	1.8
Normalised emittance ϵ_n	μm	1.5	1.5	1.5
Electrons per bunch	10^9	6.2	6.2	6.2
Electron current	mA	20	20	20
IP beta function β^*_A	cm	10	10	15
e-N Luminosity	10^{32}cm^{-2}s^{-1}	7	14	35

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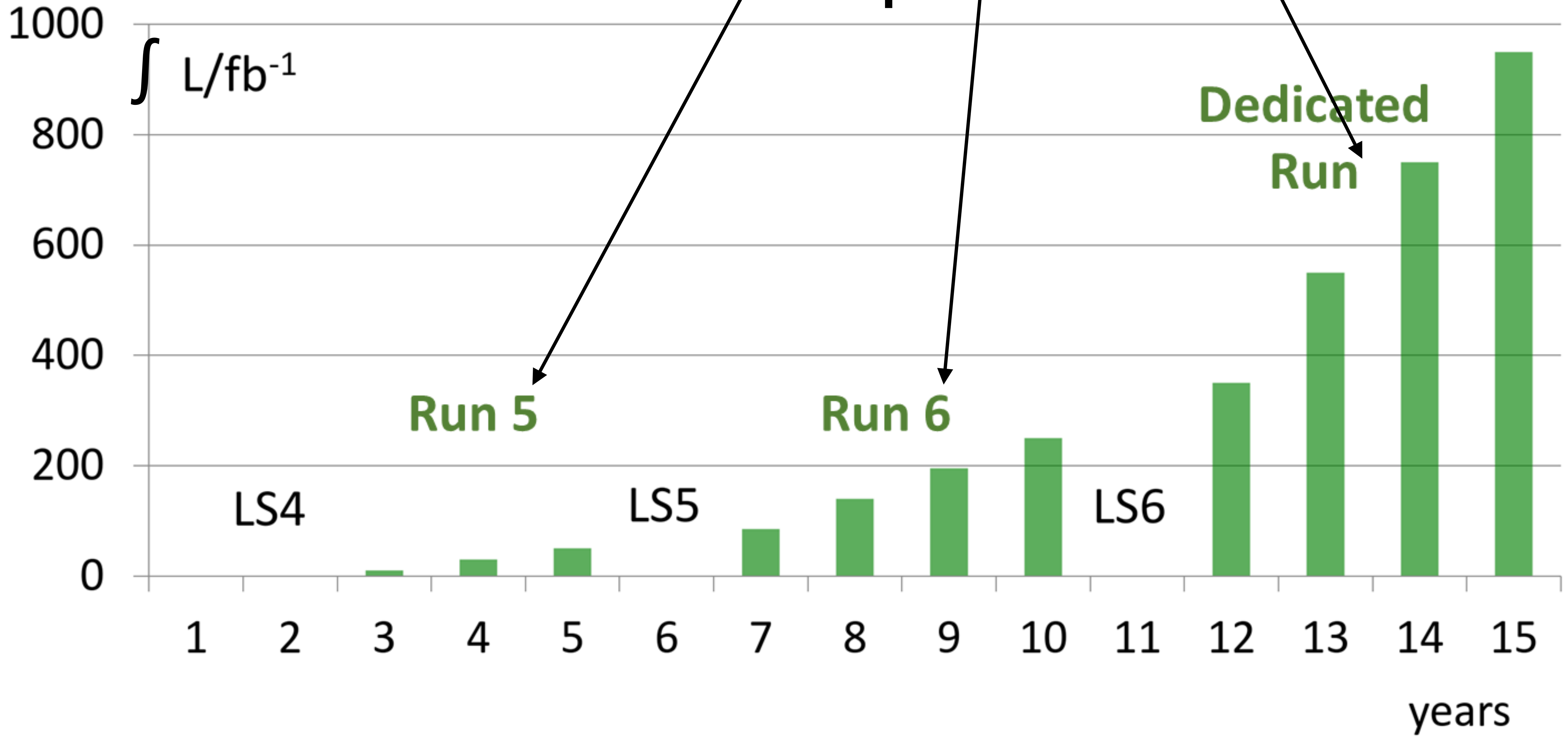
ep



- P=±0.8 (electrons): important for Higgs, not used in BSM.
- Positrons: P=0, ~1/1000 luminosity.
- FCC-eh could deliver ~2 ab^{-1}.
- ePb integrated luminosities can be estimated 1/100 those in ep (10 times smaller luminosity times 10 times smaller running time).