Top and Electroweak physics at the LHeC

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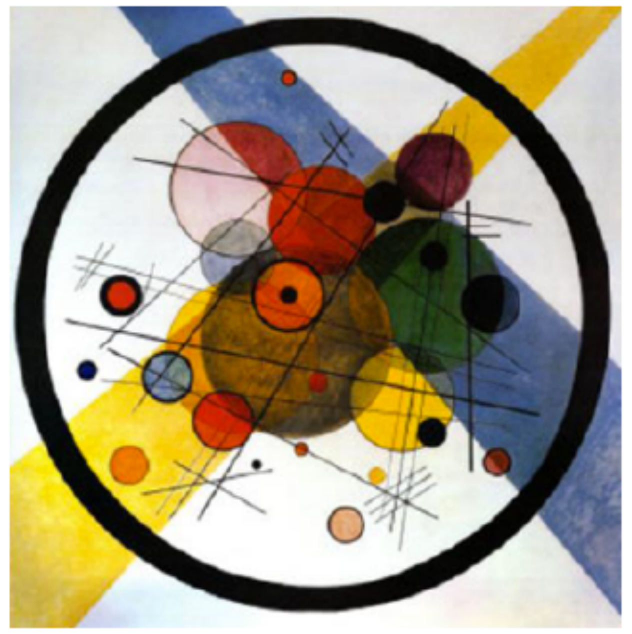
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

European Physical Society Conference on High Energy Physics
EPS-HEP 2025



Circles in a circle
W Kandinsky

LHeC

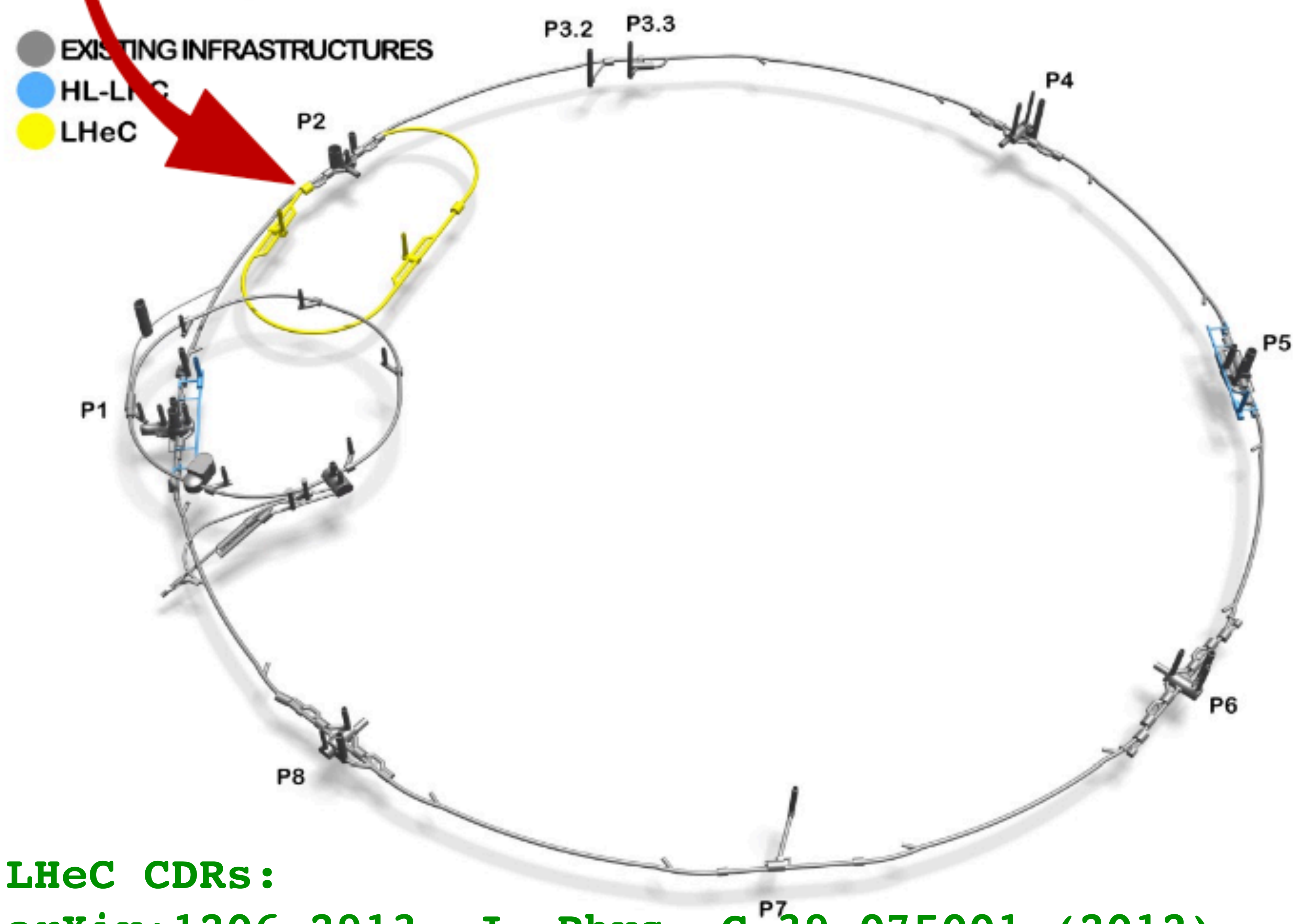
Marseille, France
11 July 2025

FCC
hh ee he

Linac-Ring Collider, LHeC and FCC-eh

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

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



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

arXiv:2503.17727

- **operated synchronously with FCC-hh**

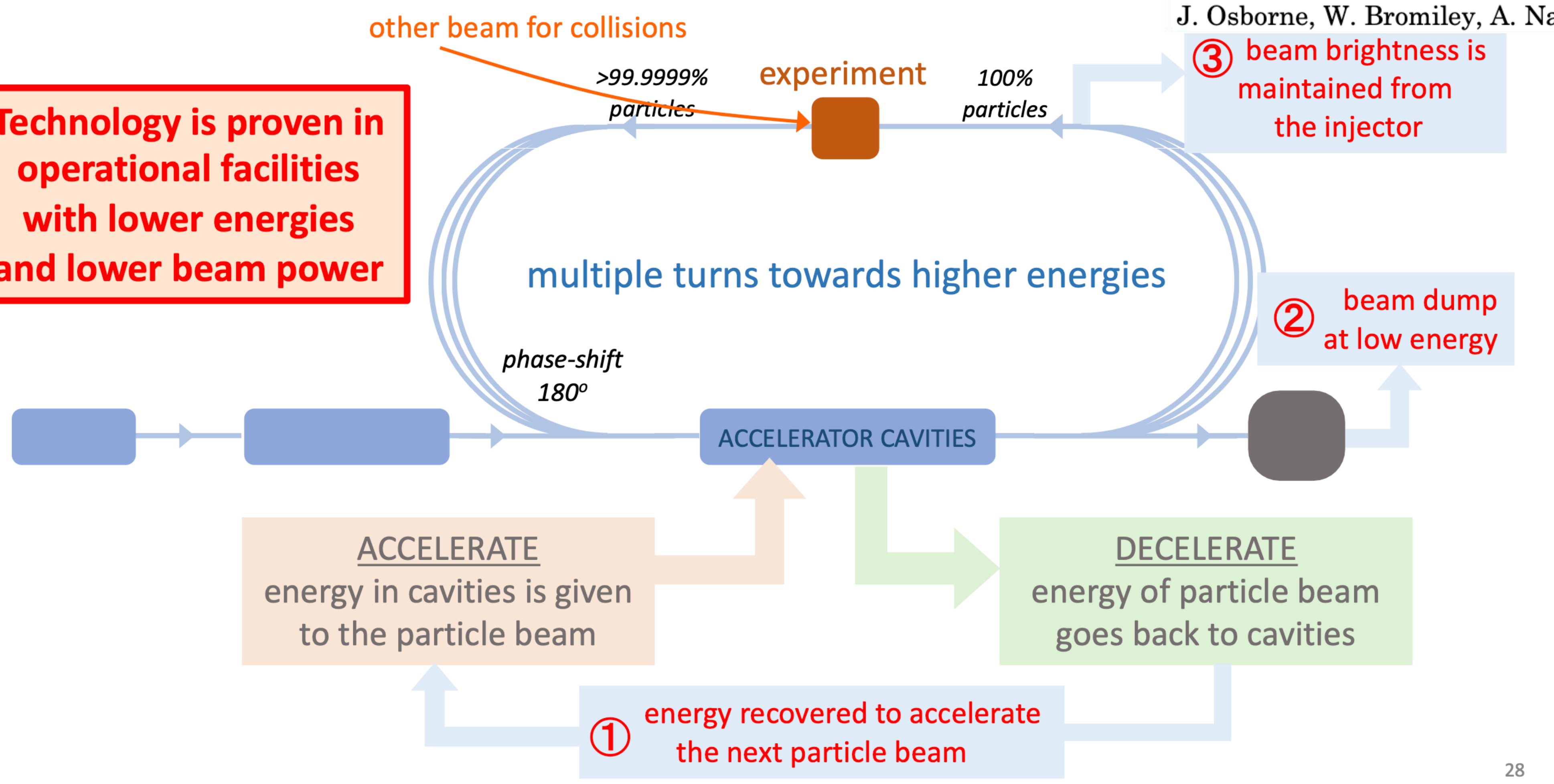
L_{int} = 1-2 ab^{-1} (1000×HERA!)
(integrated lumi of 180 fb^{-1} per year)

Energy Recovering Linac (ERL)

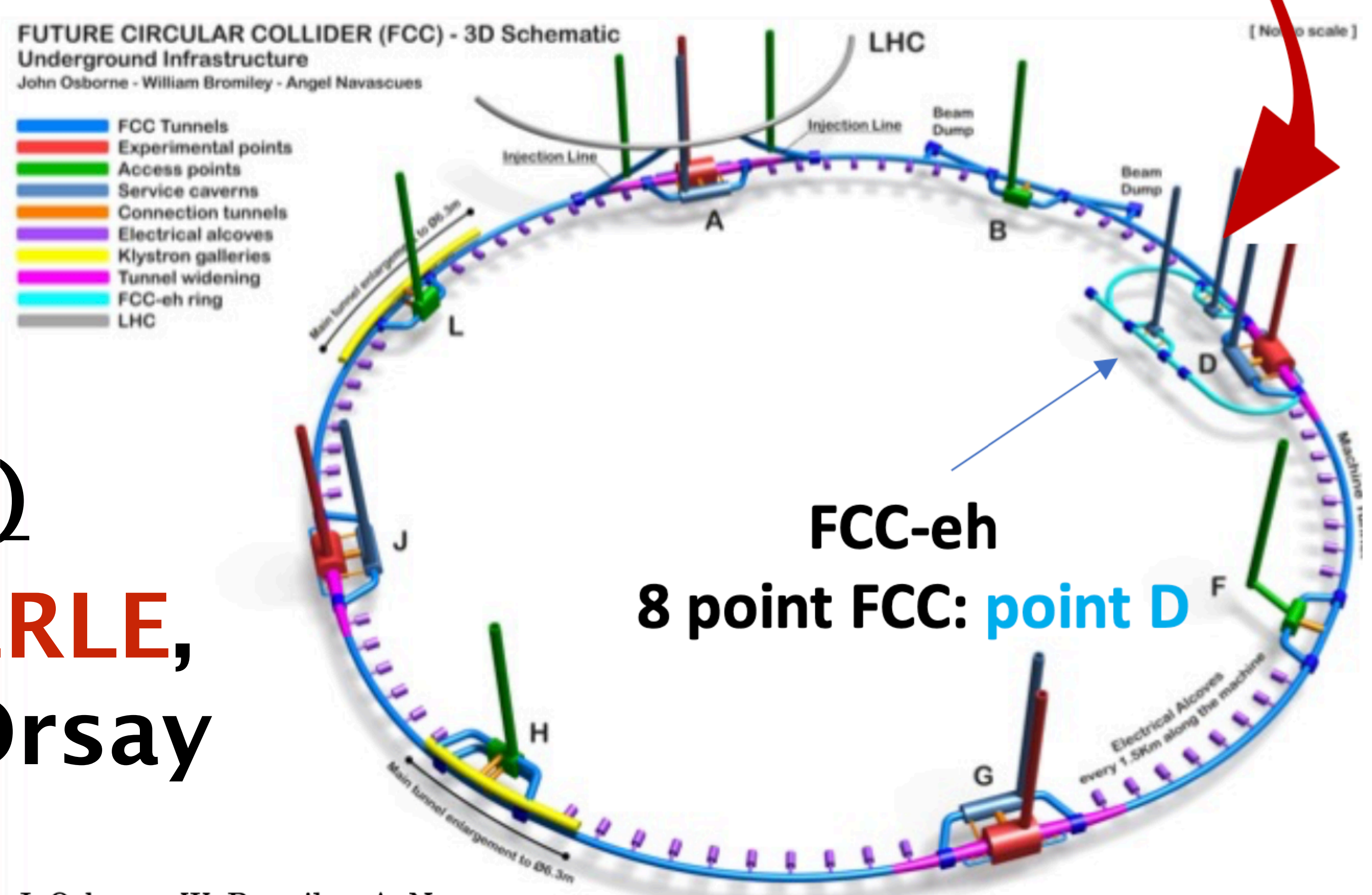
- **Technological innovation: PERLE, under construction@IJCLab, Orsay**

Technology is proven in operational facilities with lower energies and lower beam power

The principle of Energy Recovery



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



FCC-eh
8 point FCC: point D

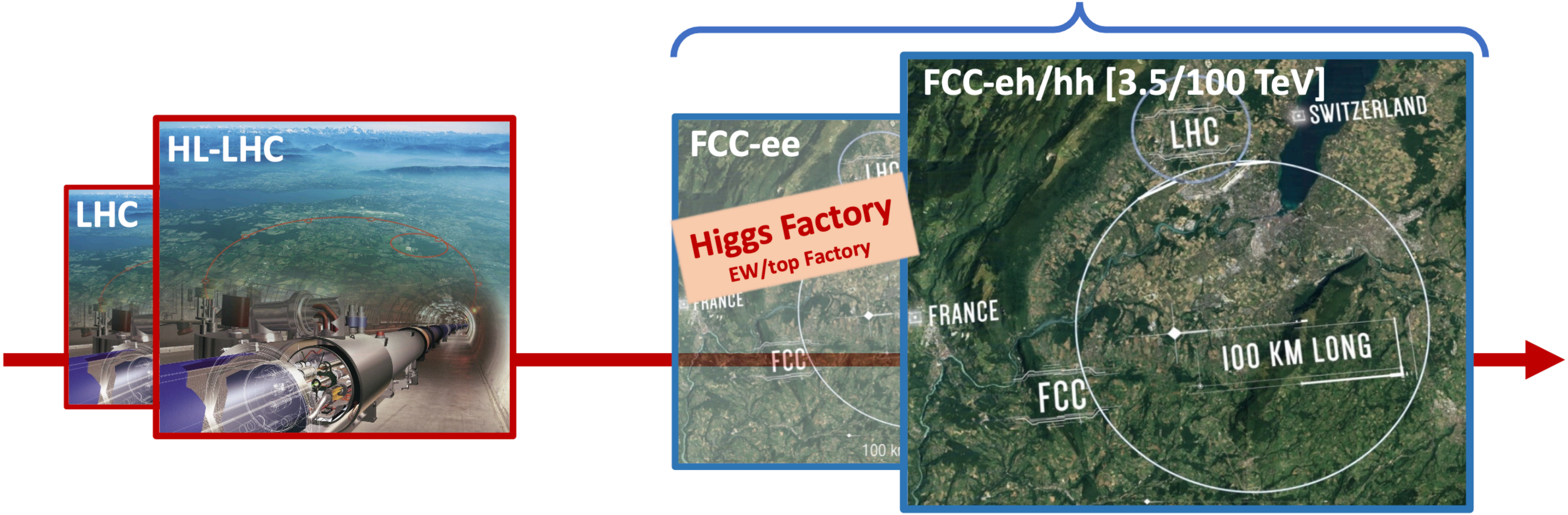
J. Osborne, W. Bromiley, A. Navascues

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

“Bridge” between current and future major collider @ CERN

Current flagship (27km)
impressive program up to 2041

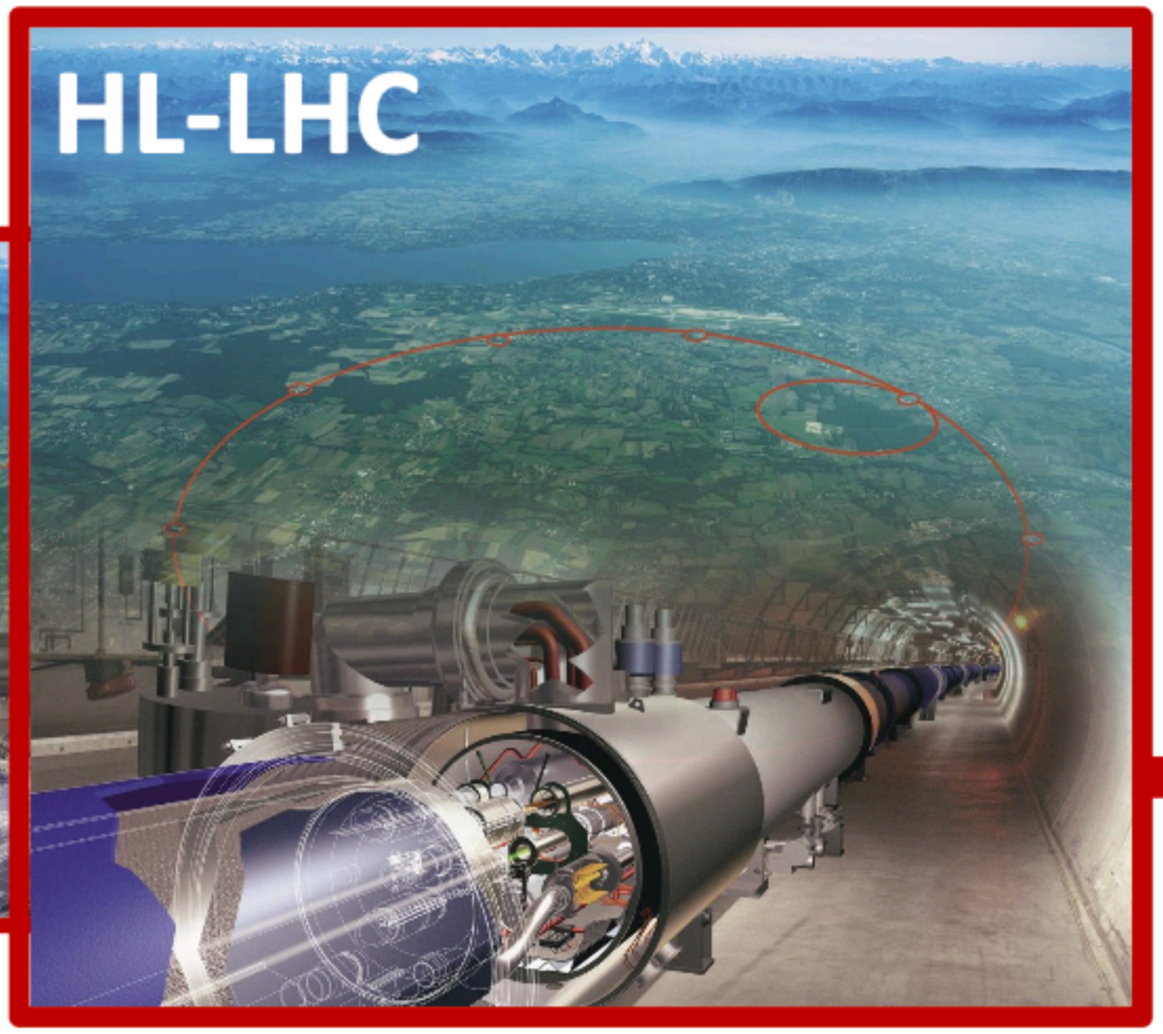
Future Circular Collider (FCC)
big sister future ambition (90km), beyond 2048



"Bridge" between current and future major collider @ CERN

Current flagship (27km)
impressive program up to 2041

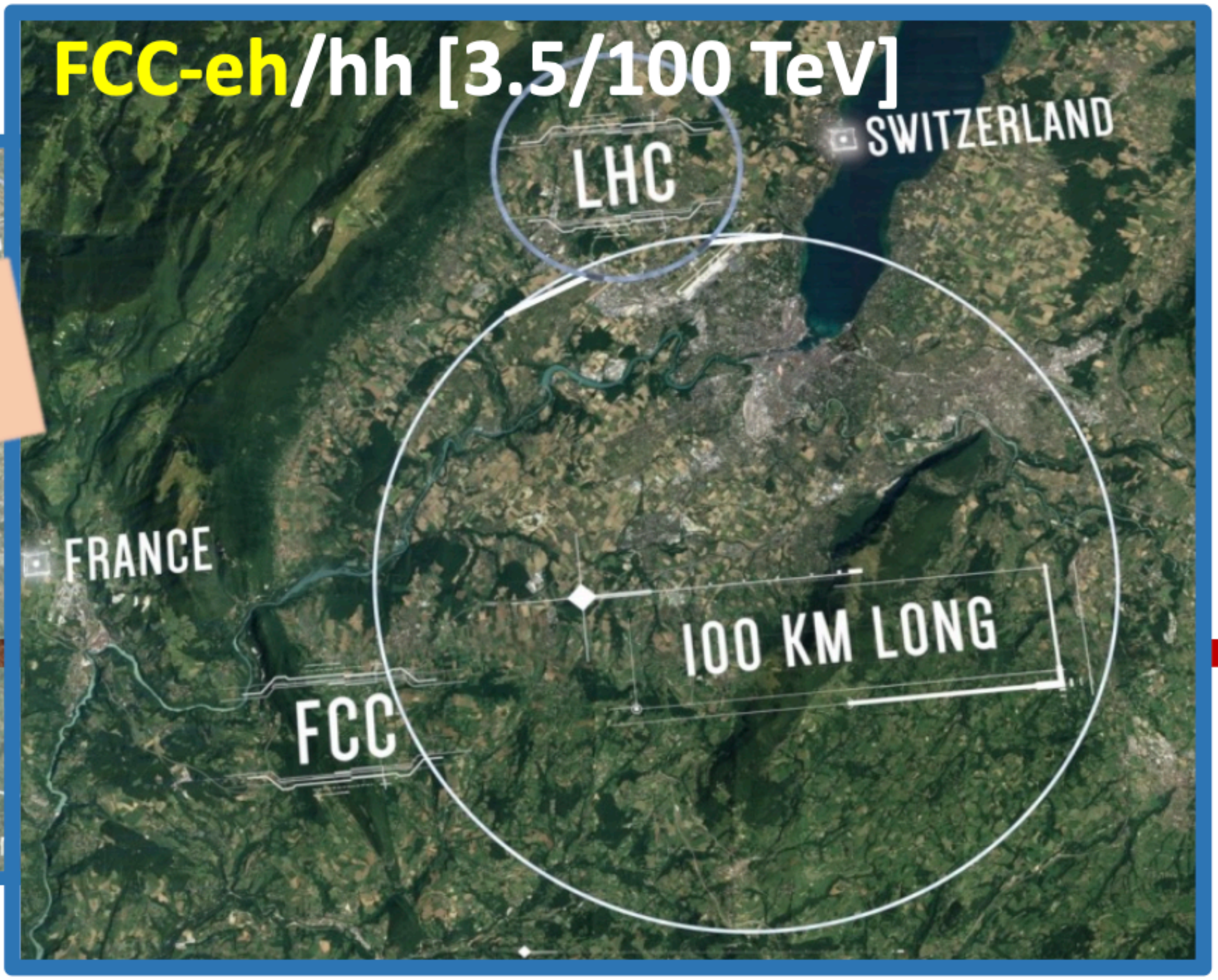
cost ~2 BCHF ⊕ one detector
operational cost similar to HL-LHC



LHeC

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

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



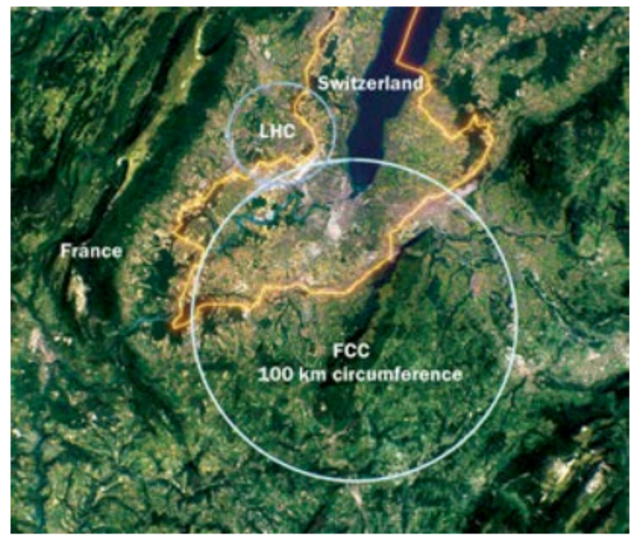
arXiv: 2503.17727 [hep-ex]

The LHeC in ECFA EPPSU

talk by
Karl Jakobs

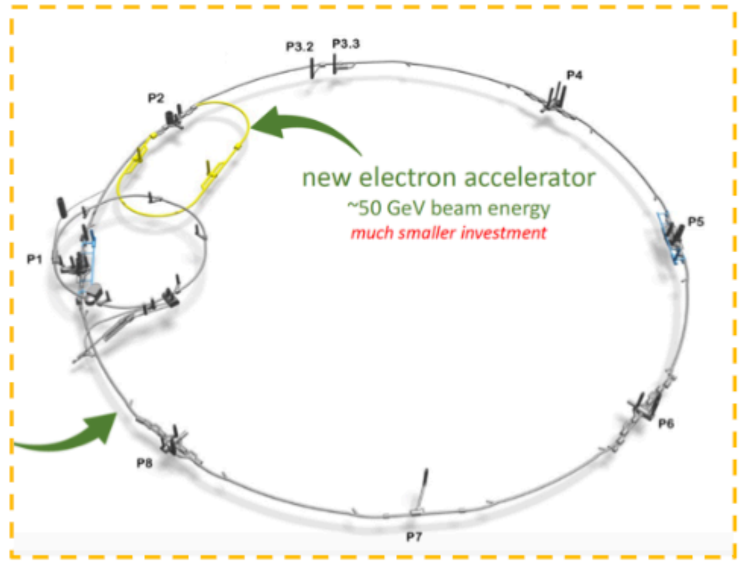
Potential for development: future 10 TeV parton-scale collider options

FCC-ee



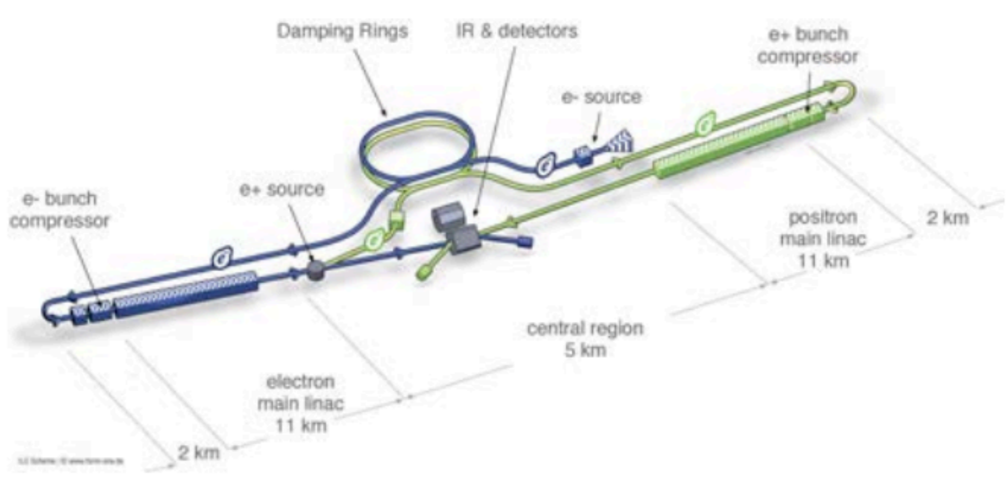
LEP3

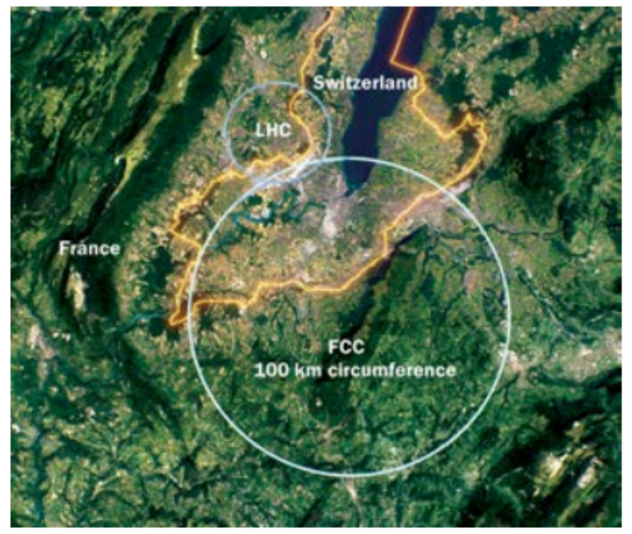
LHeC



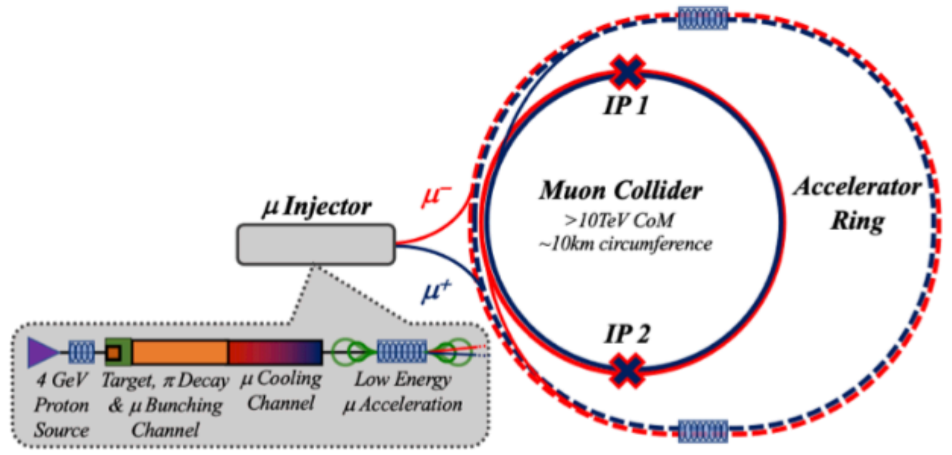
PERLE

LCF, CLIC





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



Muon Collider (3, 10 TeV)

R&D

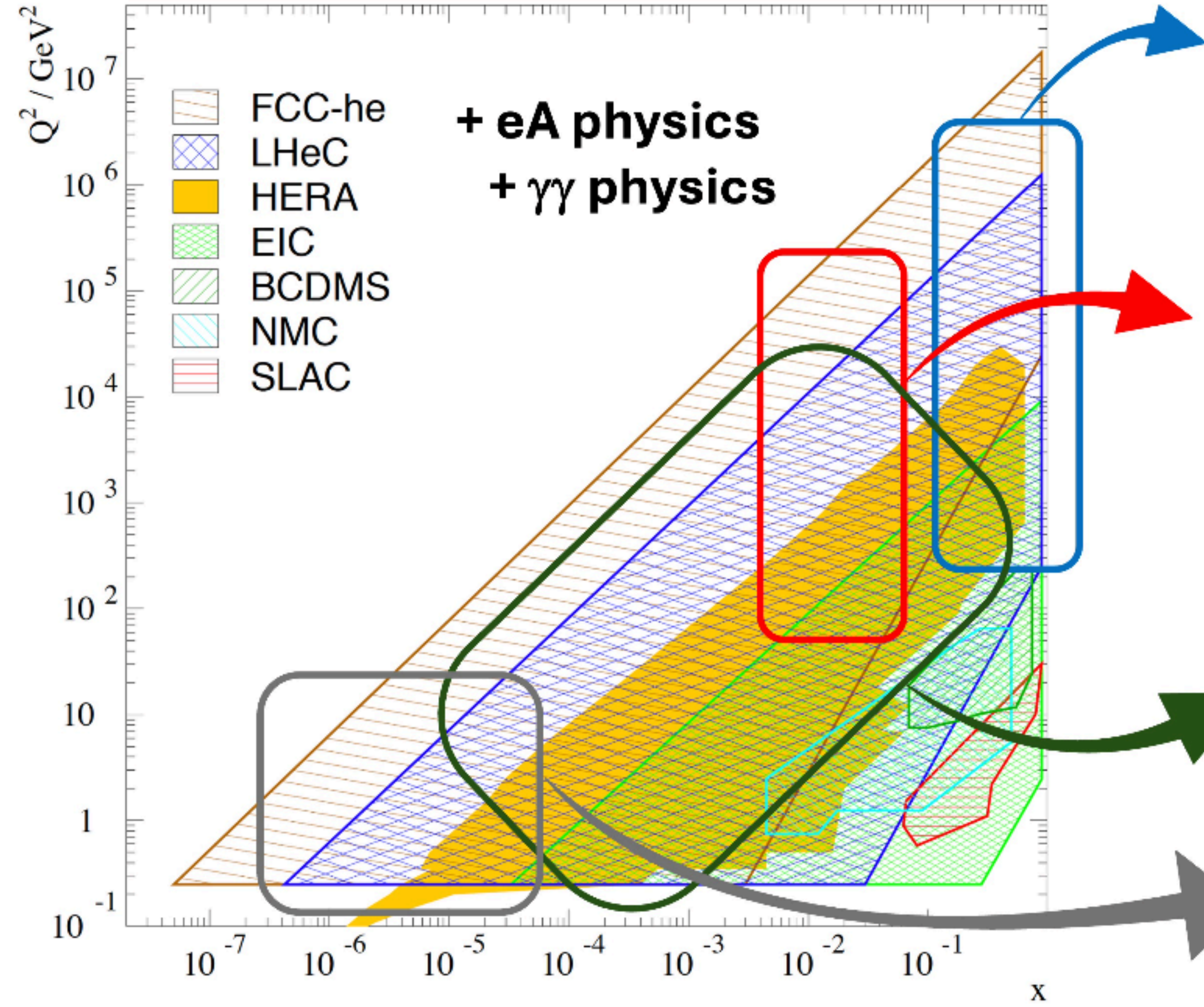
e^+e^- with improved acceleration technologies
LCF, C^3 (→ 1 TeV), CLIC (1.5 TeV), HALHF, …
→ plasma acceleration for higher energies
(can $\mathcal{O}(10)$ TeV be reached? on what timescale?)

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

8

Deep Inelastic Scattering at the Energy Frontier

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



direct searches for new physics

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

EW, Higgs and top quark physics

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

precision QCD physics

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

non-linear QCD physics

a new discovery frontier

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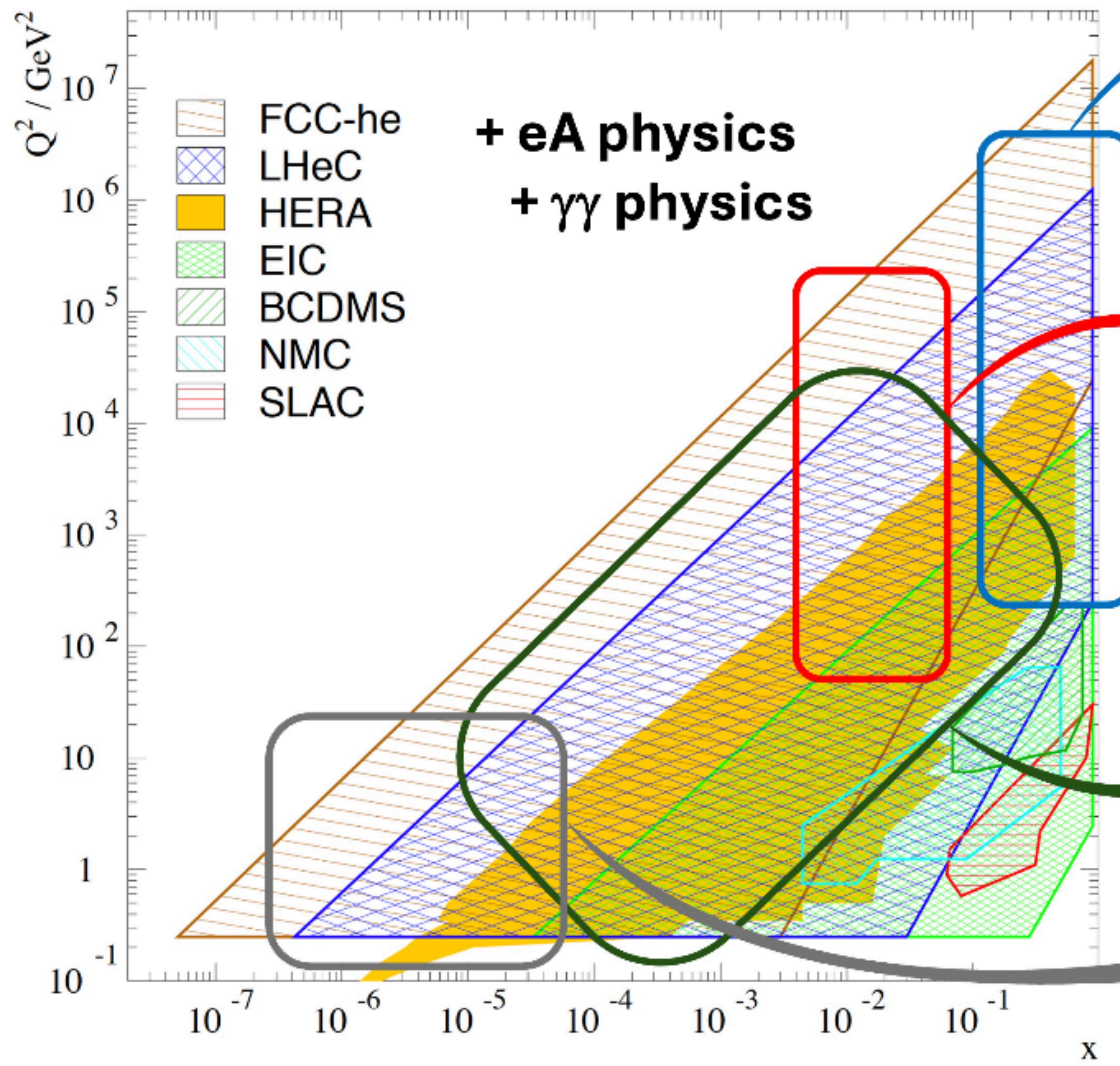

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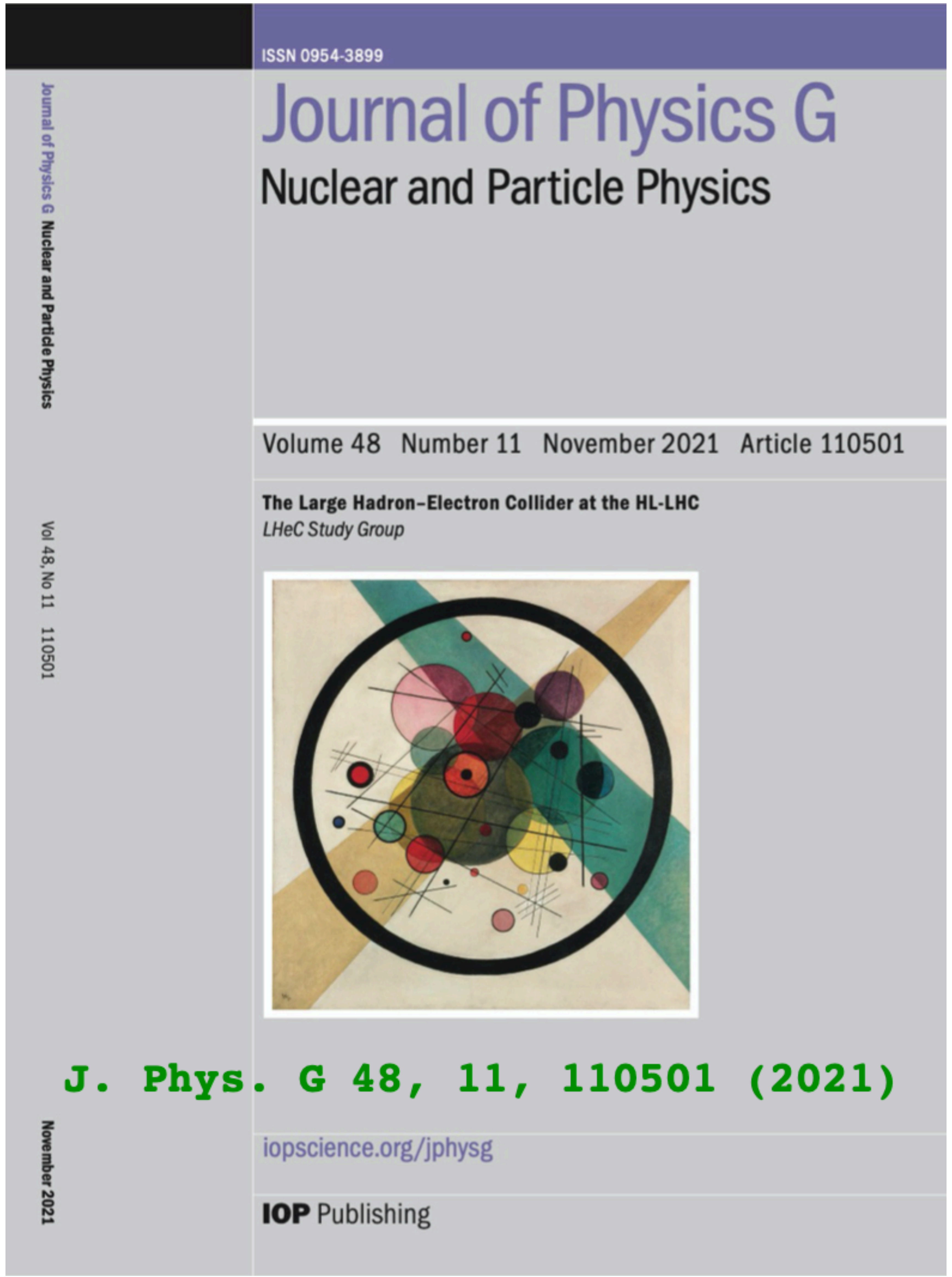
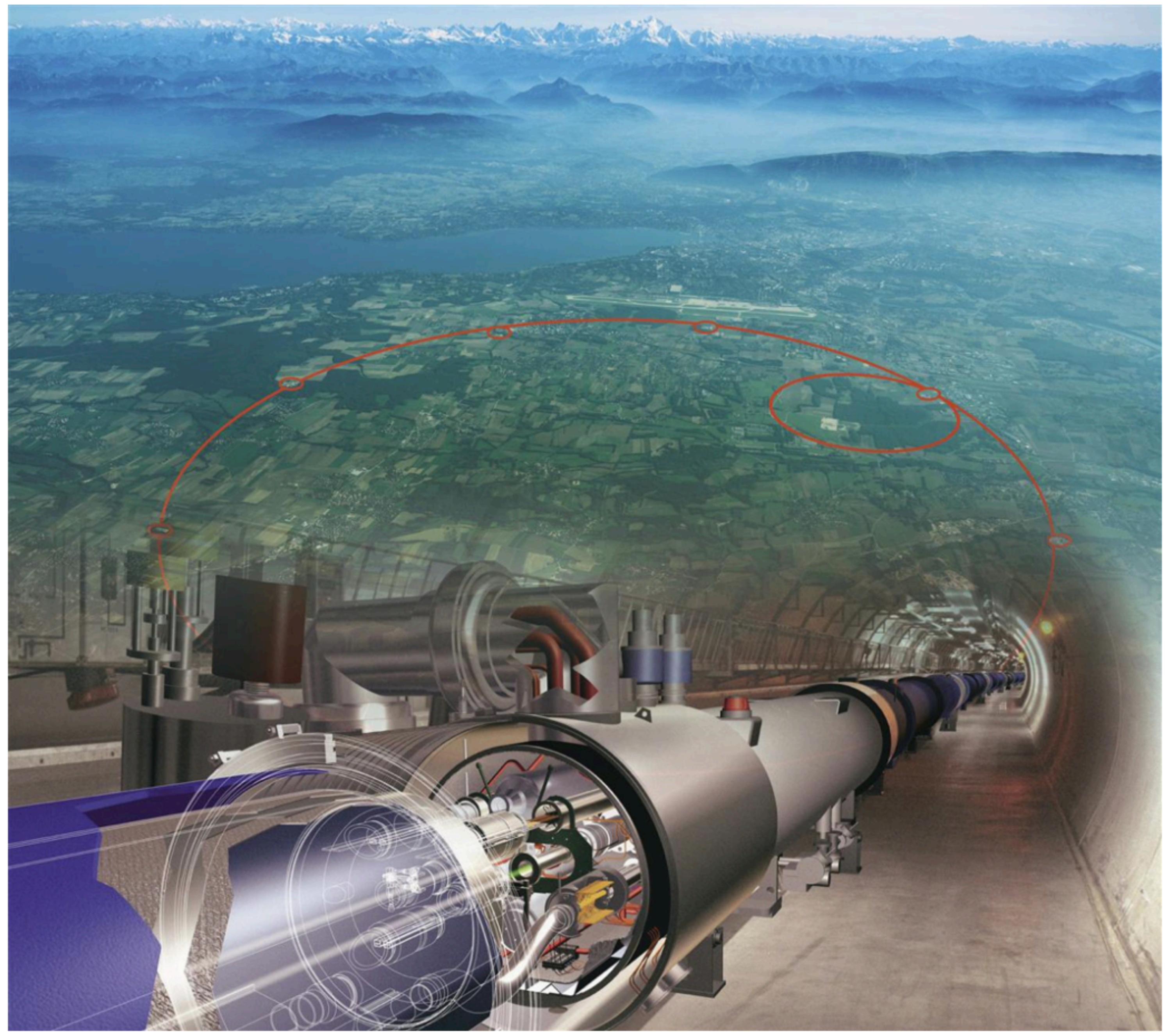
The Large Hadron-Electron Collider at the HL-LHC



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

5 pages summary:

ECFA Newsletter #5



O. Brüning, M. Klein

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

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

An Experiment for Electron-Hadron Scattering at the LHC

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

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[3]Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, 22769 Hamburg, Germany
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[5]JLab, Newport News, Virginia, USA
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[8]Bursa Uludag University, Bursa, Turkey
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[12]LIP, Av. Prof. Gama Pinto, 2, P-1649-003 Lisboa , Portugal
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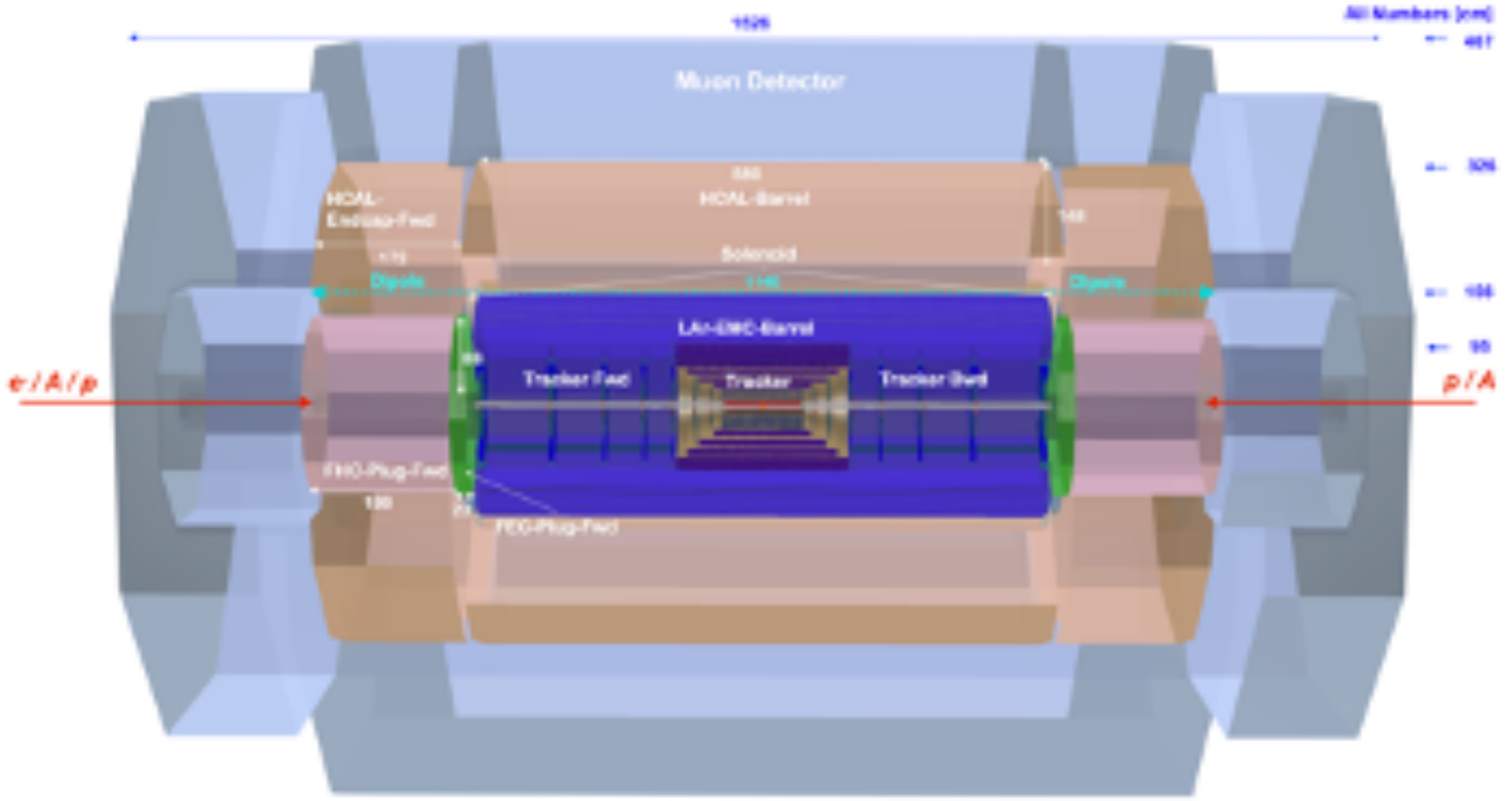
[14]Université Catholique de Louvain, Centre for Cosmology, Particle Physics and Phenomenology, 1348 Louvain-la-Neuve, Belgium
[15]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Bologna, Bologna, Italy
[16]Graduate School of Science, Kobe University, Rokkodai-cho 1-1, Nada, 657-8501 Kobe, Japan

Received: date / Accepted: date

v1 [hep-ex] 7 Jan 2022

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

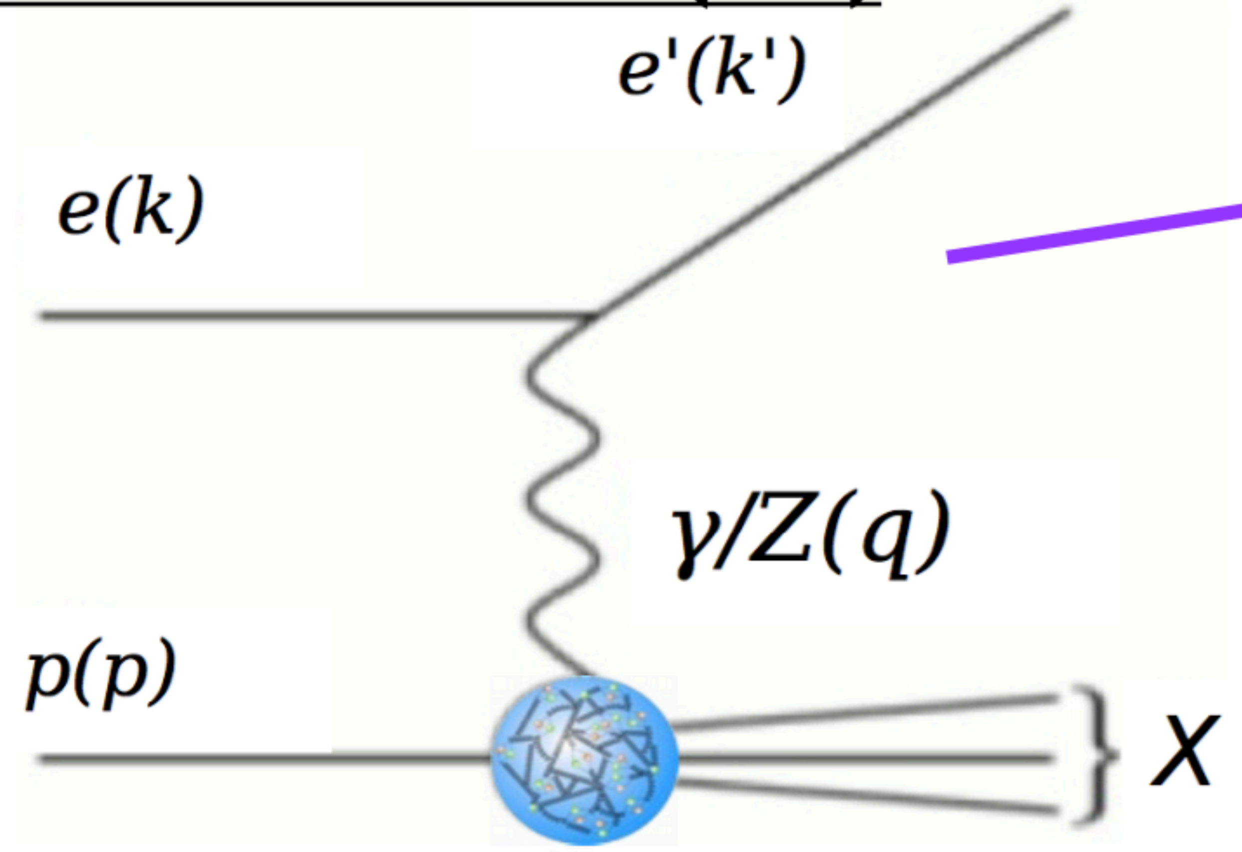


novel concept of a detector to alternately serve eh and hh collisions/physics

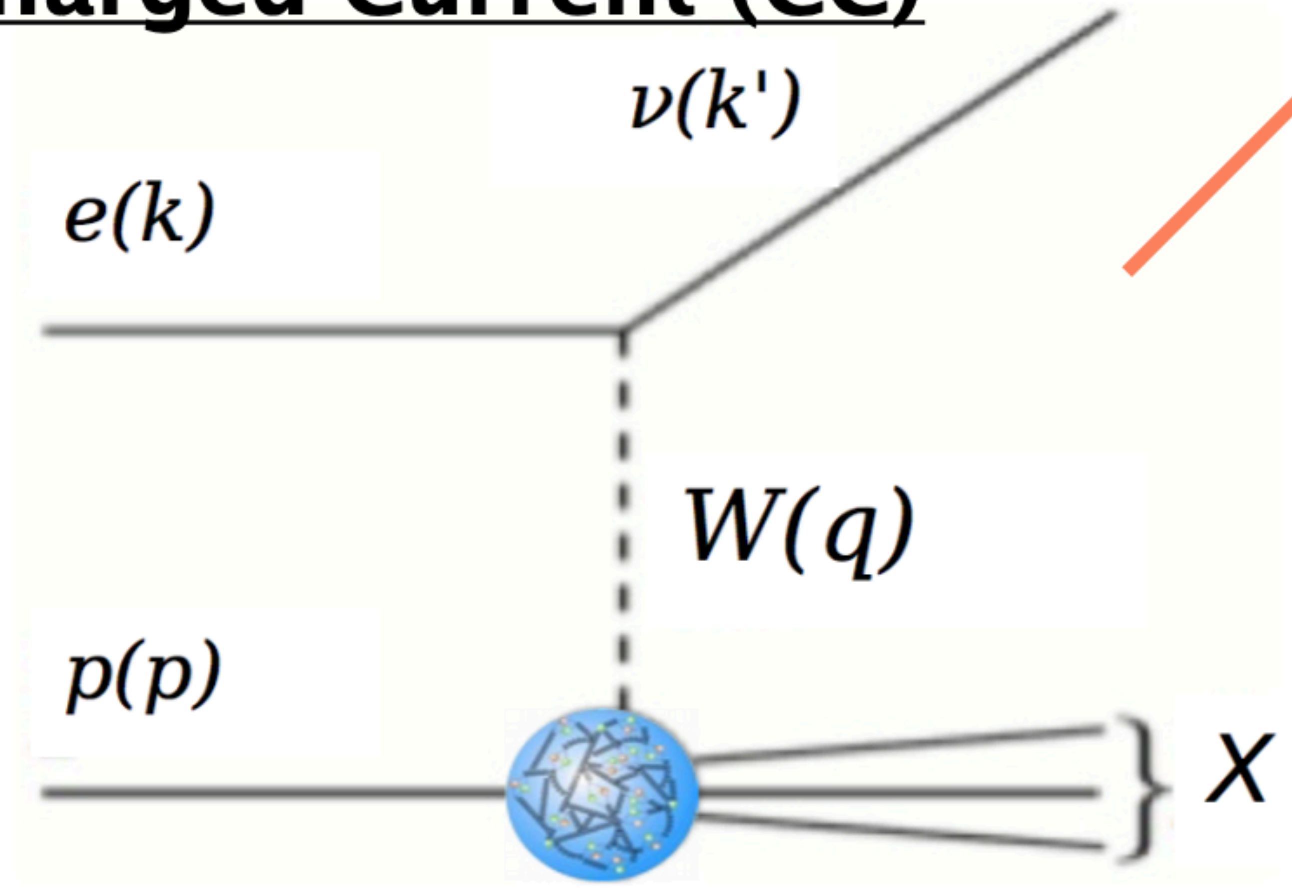
Bridge project: 2503.17727 [hep-ex]

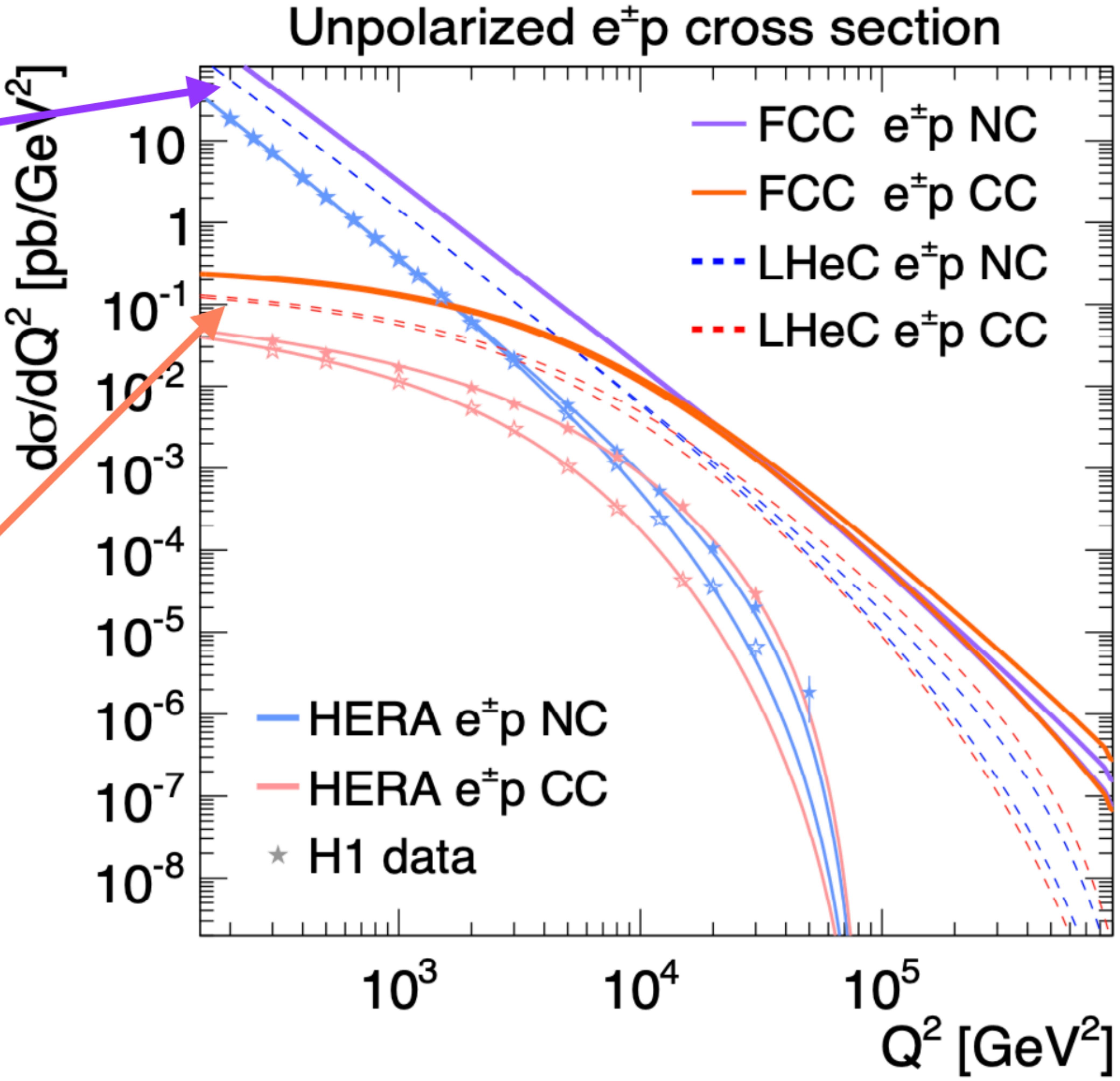
Deep Inelastic Scattering and EKW observables

Neutral Current (NC)



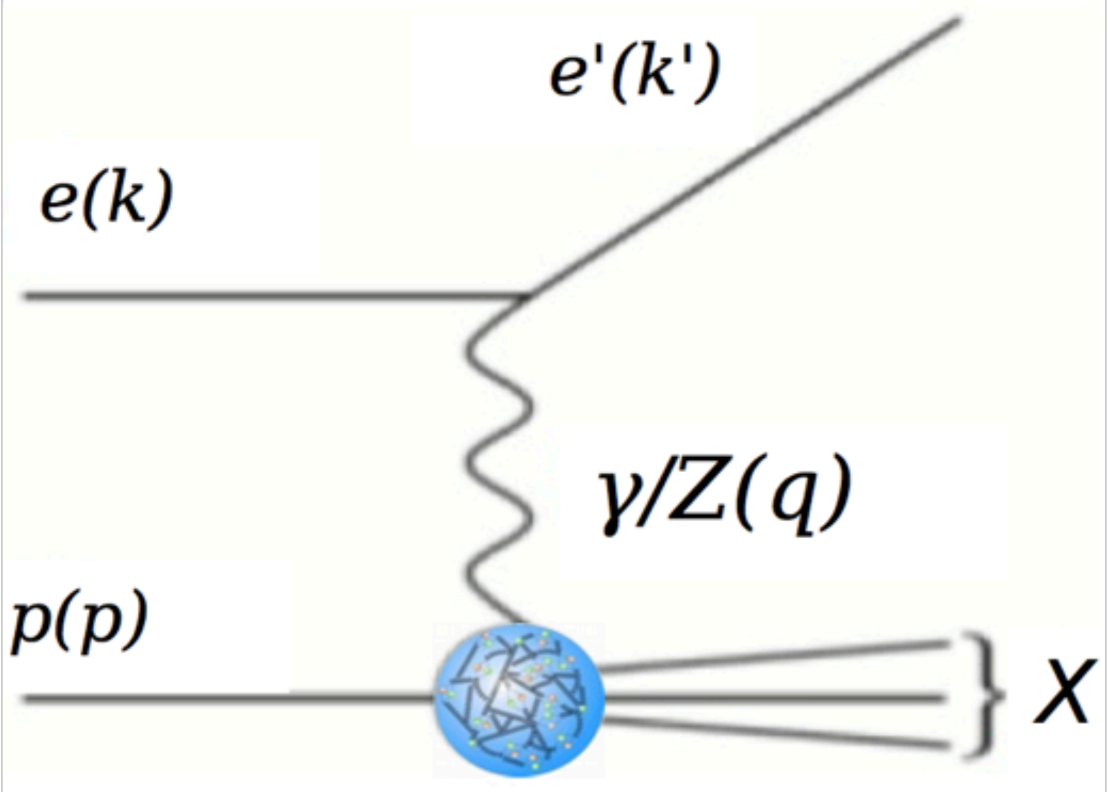
Charged Current (CC)





→ **LHeC/FCC-eh are unique facilities for testing EW theory:**
NC+CC, two e-beam charge and polarisation states, p or isoscalar targets

Electroweak Fermion Couplings and SMEFT couplings



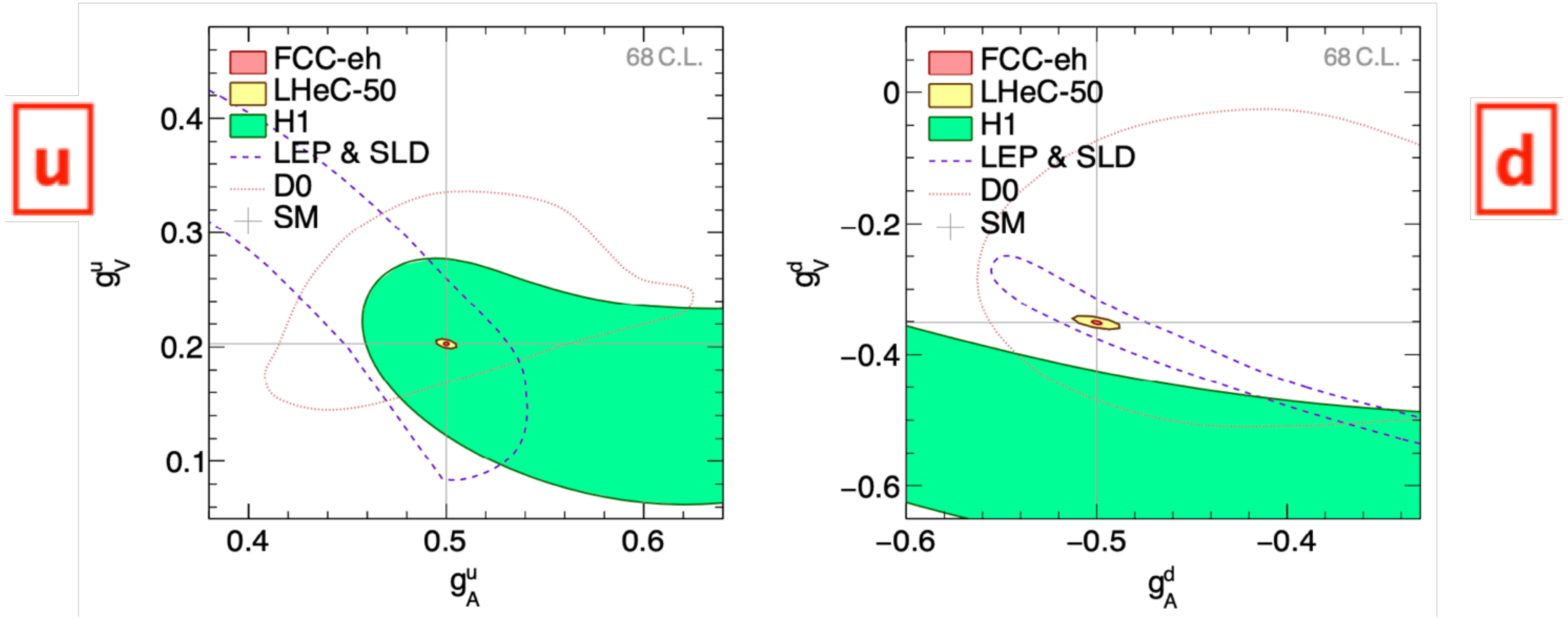
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}\rho'_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}\,,$$

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

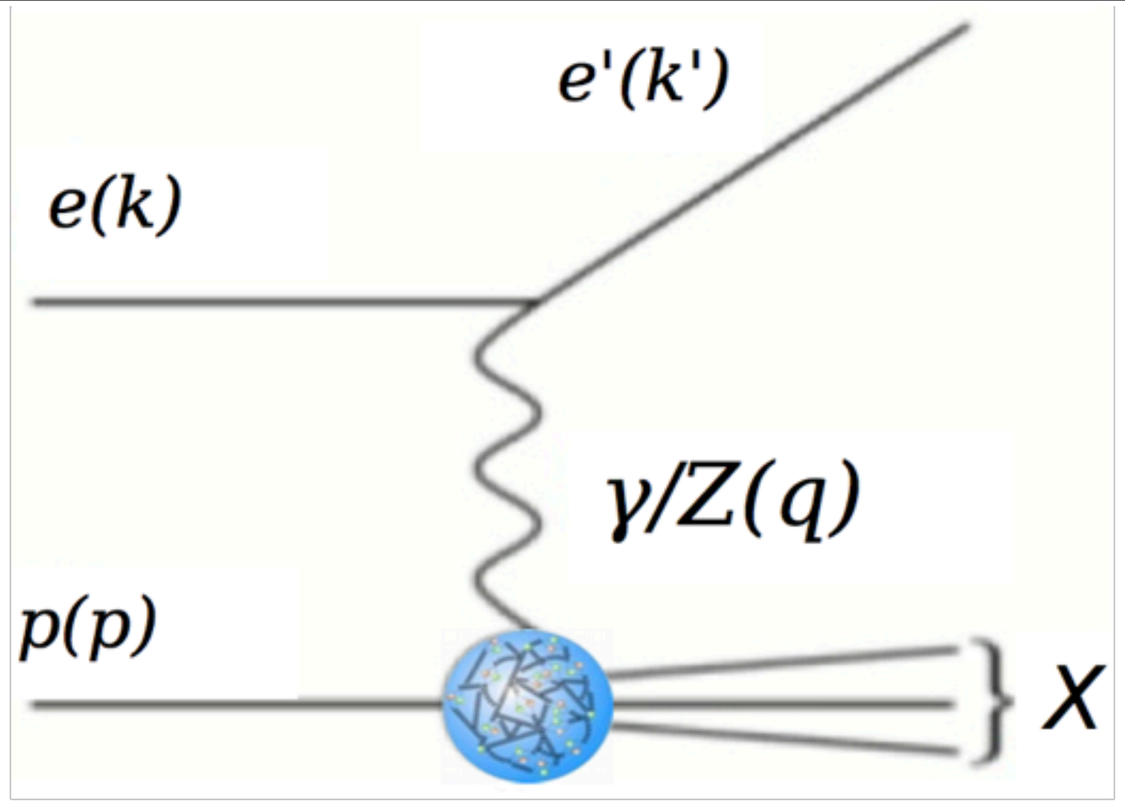
Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

→ **precision on per mille level**

(largely unaccessible in e+e-)



Electroweak Fermion Couplings and SMEFT couplings



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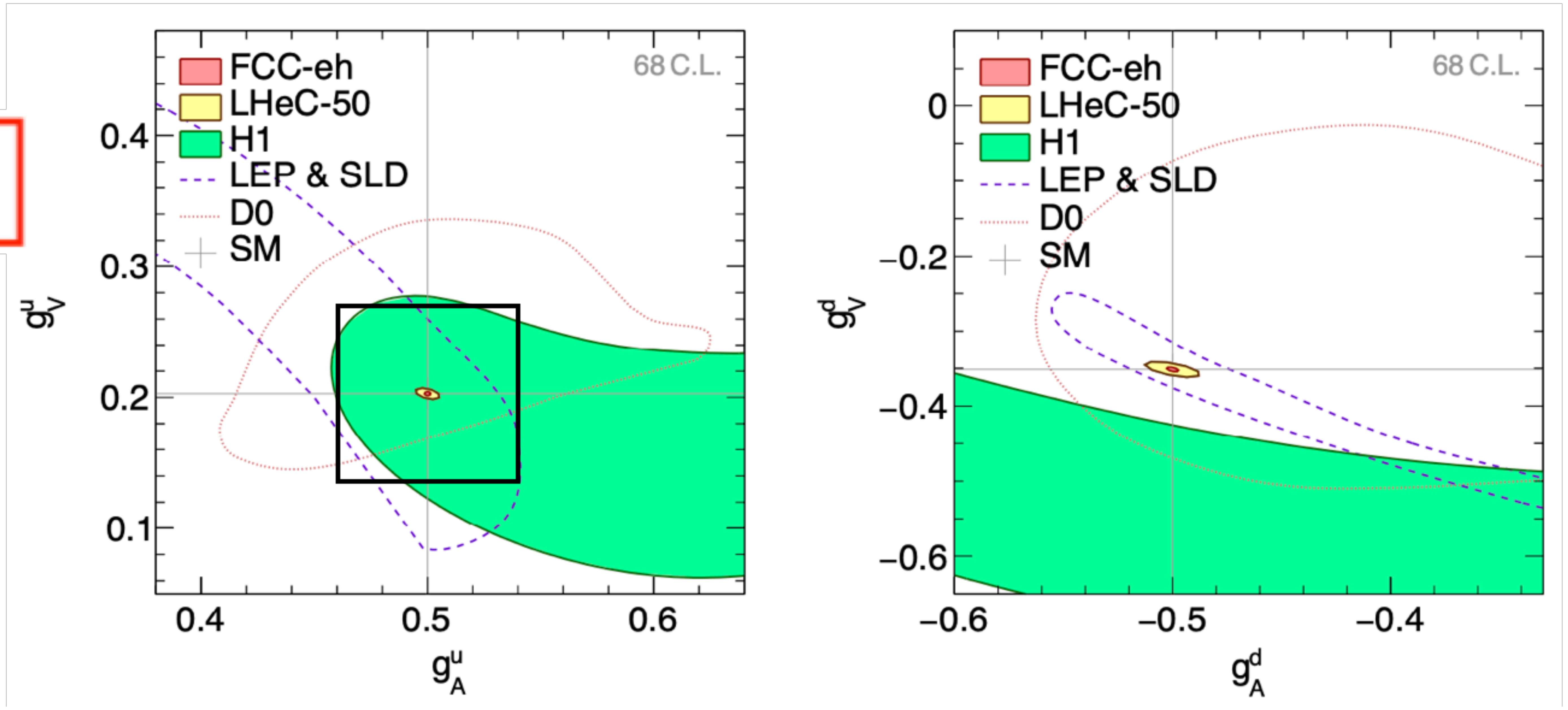

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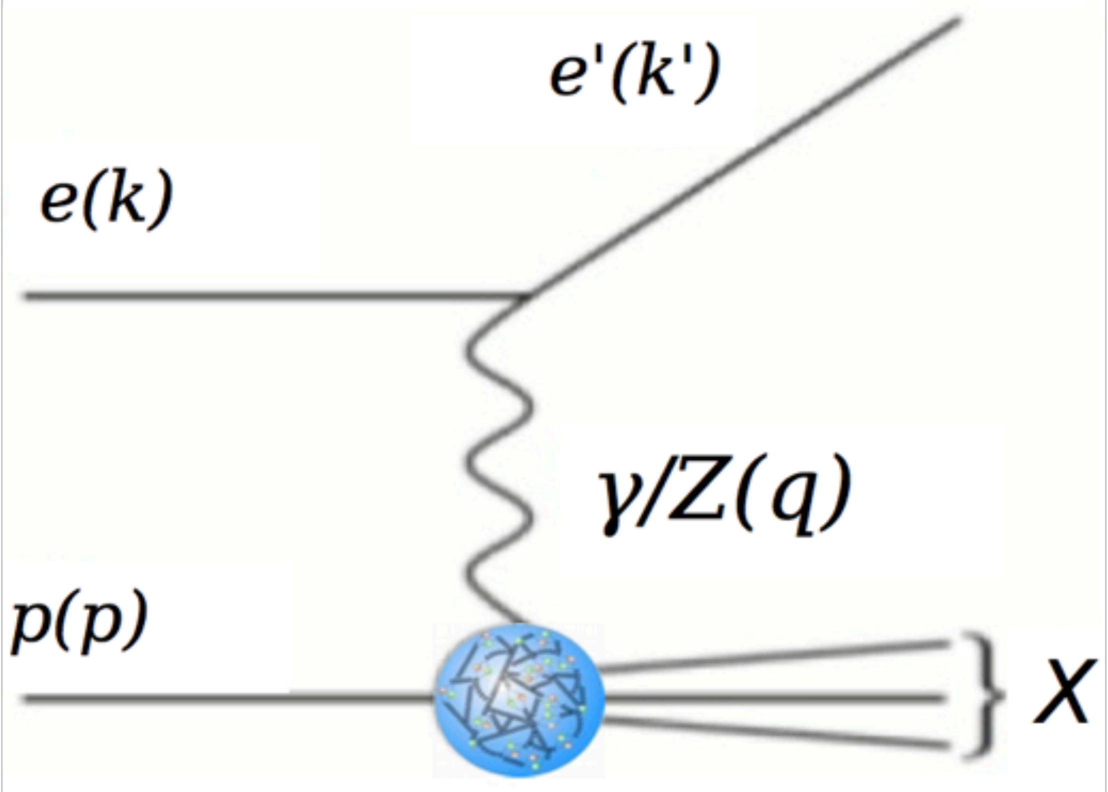
Electroweak Fermion Couplings and SMEFT couplings



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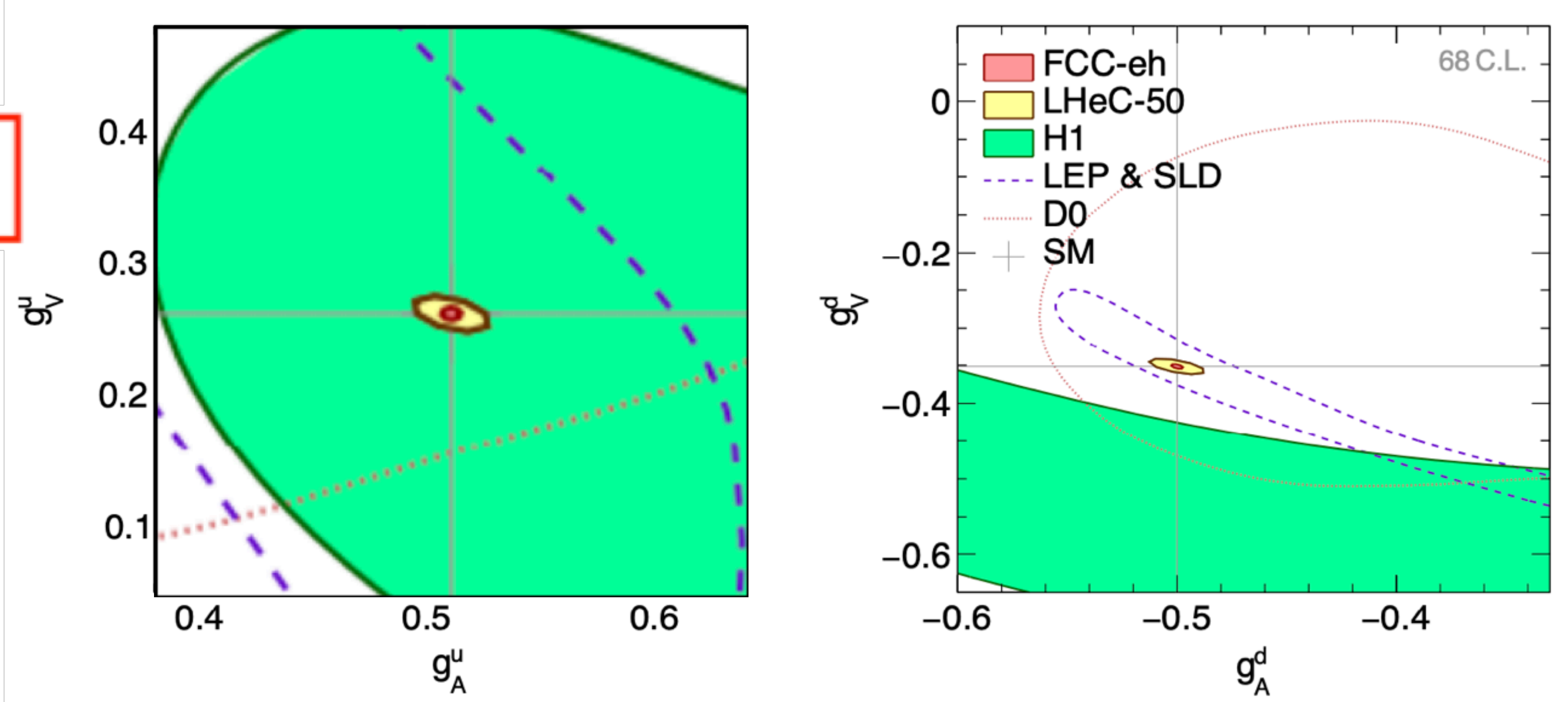

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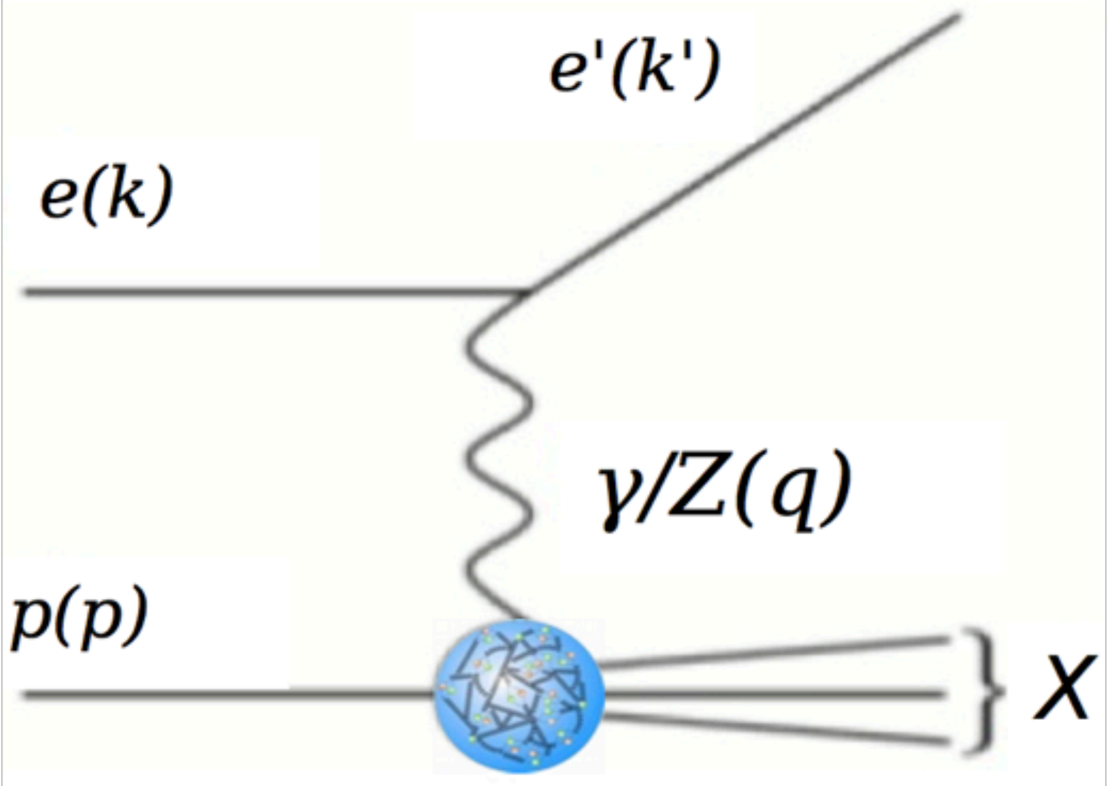
Electroweak physics of 1st generation quarks are largely inaccessible in other colliders

Electroweak Fermion Couplings and SMEFT couplings



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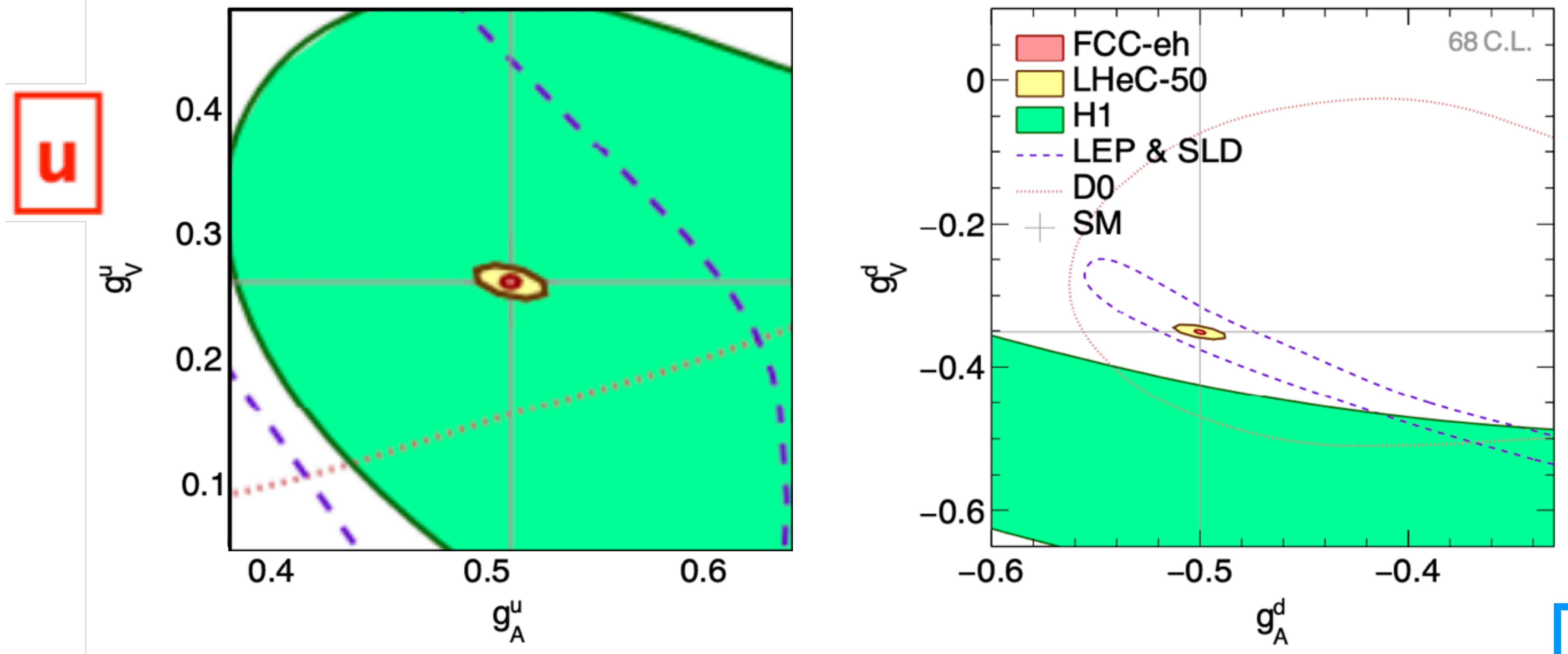
Britzger, Klein, Spiesberger, Eur.Phys.J.C 80 (2020) 831

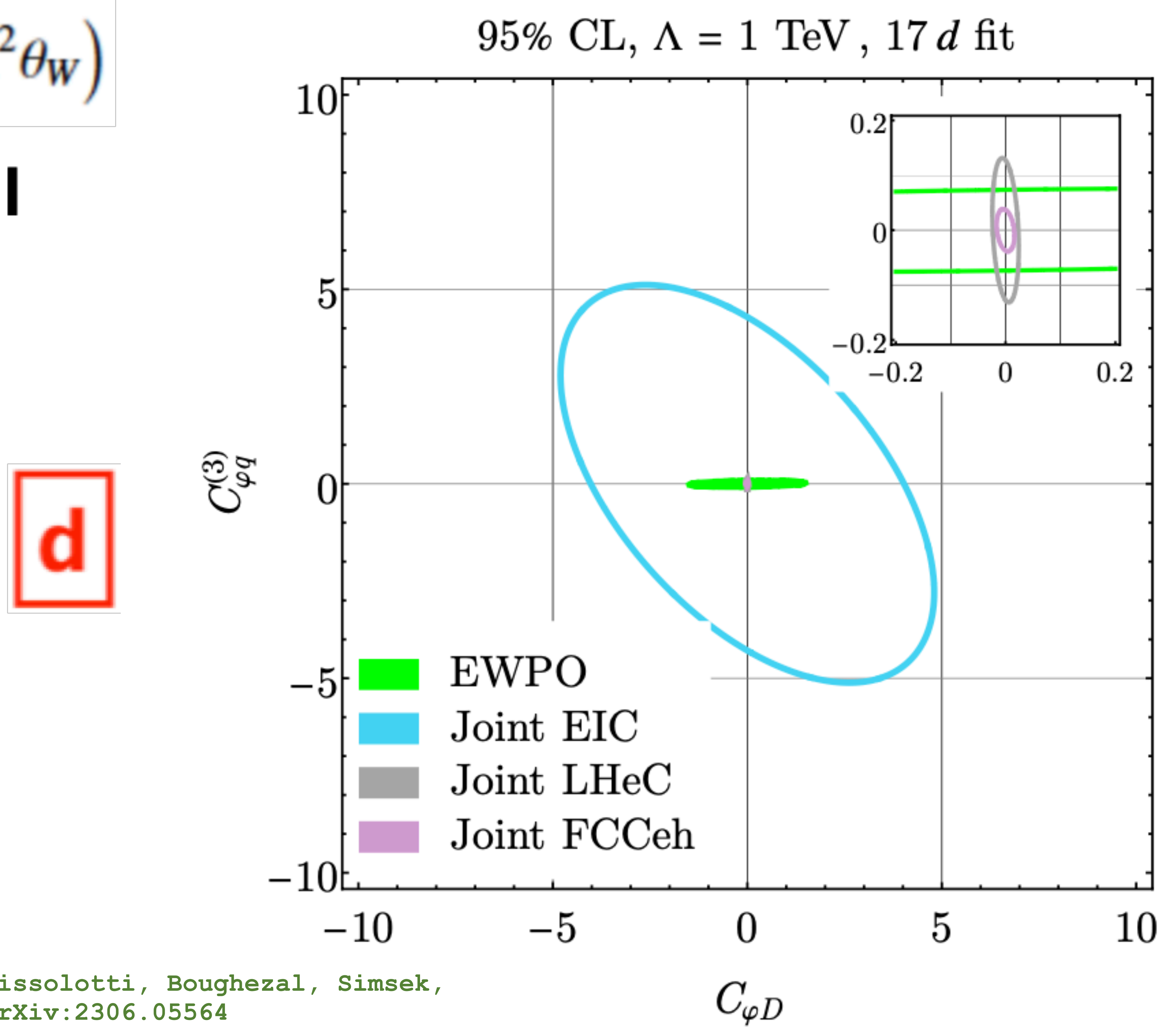
→ **precision on per mille level**

(largely unaccessible in e+e-)

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

$$O_{\varphi D} = (\varphi^\dagger D_\mu \varphi)^*(\varphi^\dagger D^\mu \varphi)$$



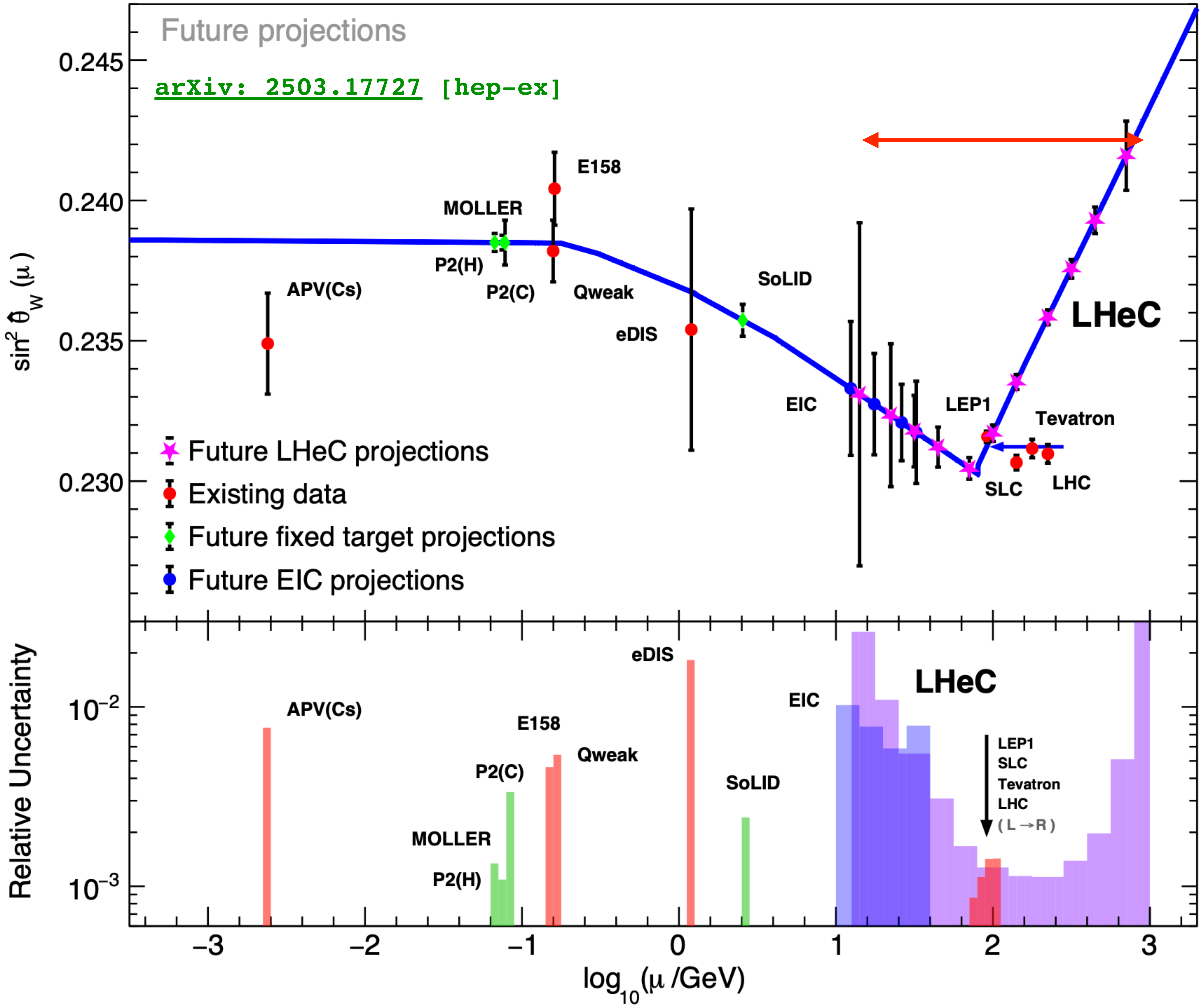


Bissolotti, Boughezal, Simsek, arXiv:2306.05564

Electroweak physics of 1st generation quarks are largely inaccessible in other colliders

FCC-eh and LHeC will improve upon existing precision electroweak bounds in SMEFT parameter space in many cases, also for correlations

Scale Dependence of $\sin^2\theta_W$



→ **probe large range of scale dependence**

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\,\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\sin^2\theta_{\mathrm{W}}\right)$$

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

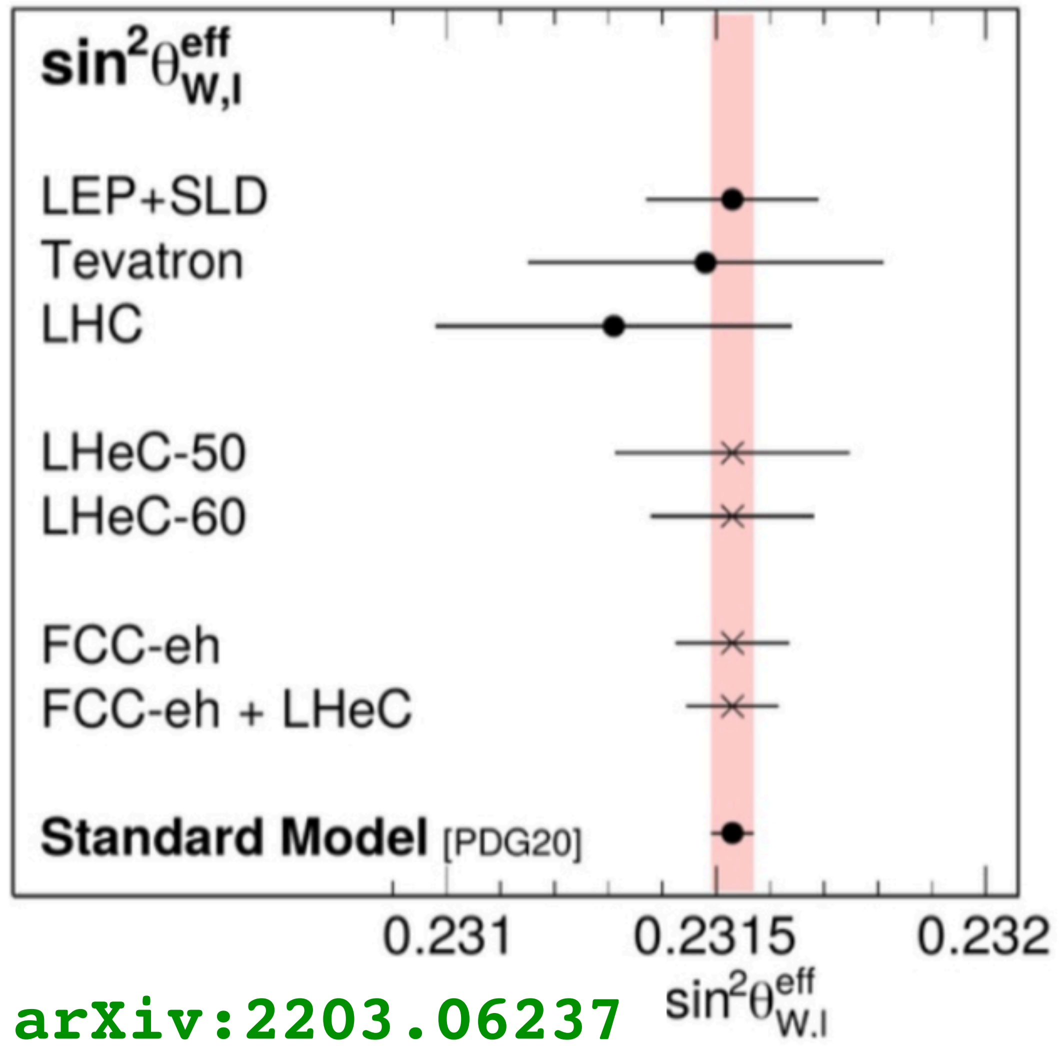
→ **precision per mille level**

→ **scale dependence**

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

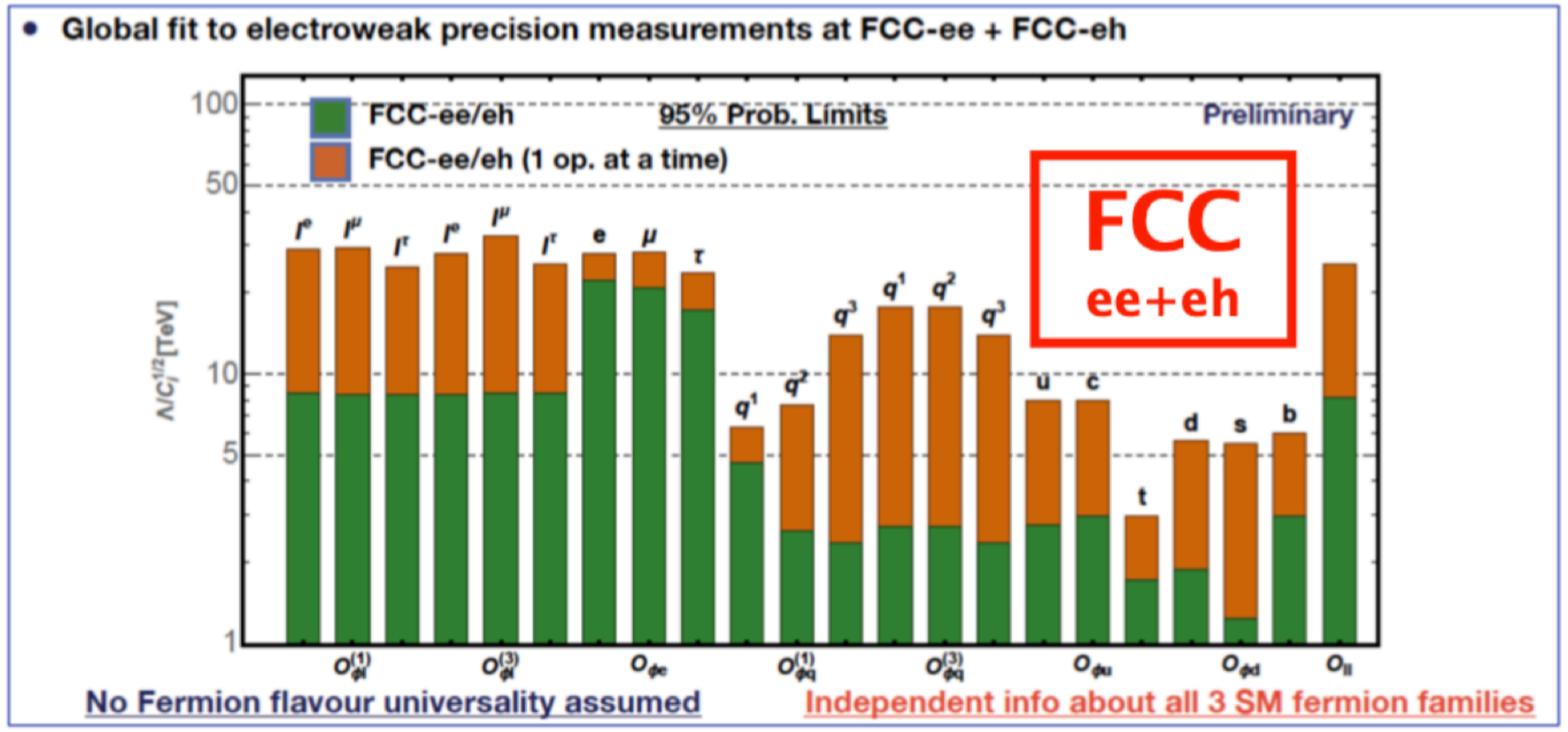
$\Delta m_W = \pm$ 4.5 MeV

(includes PDF uncertainty of about ±3.6 MeV)



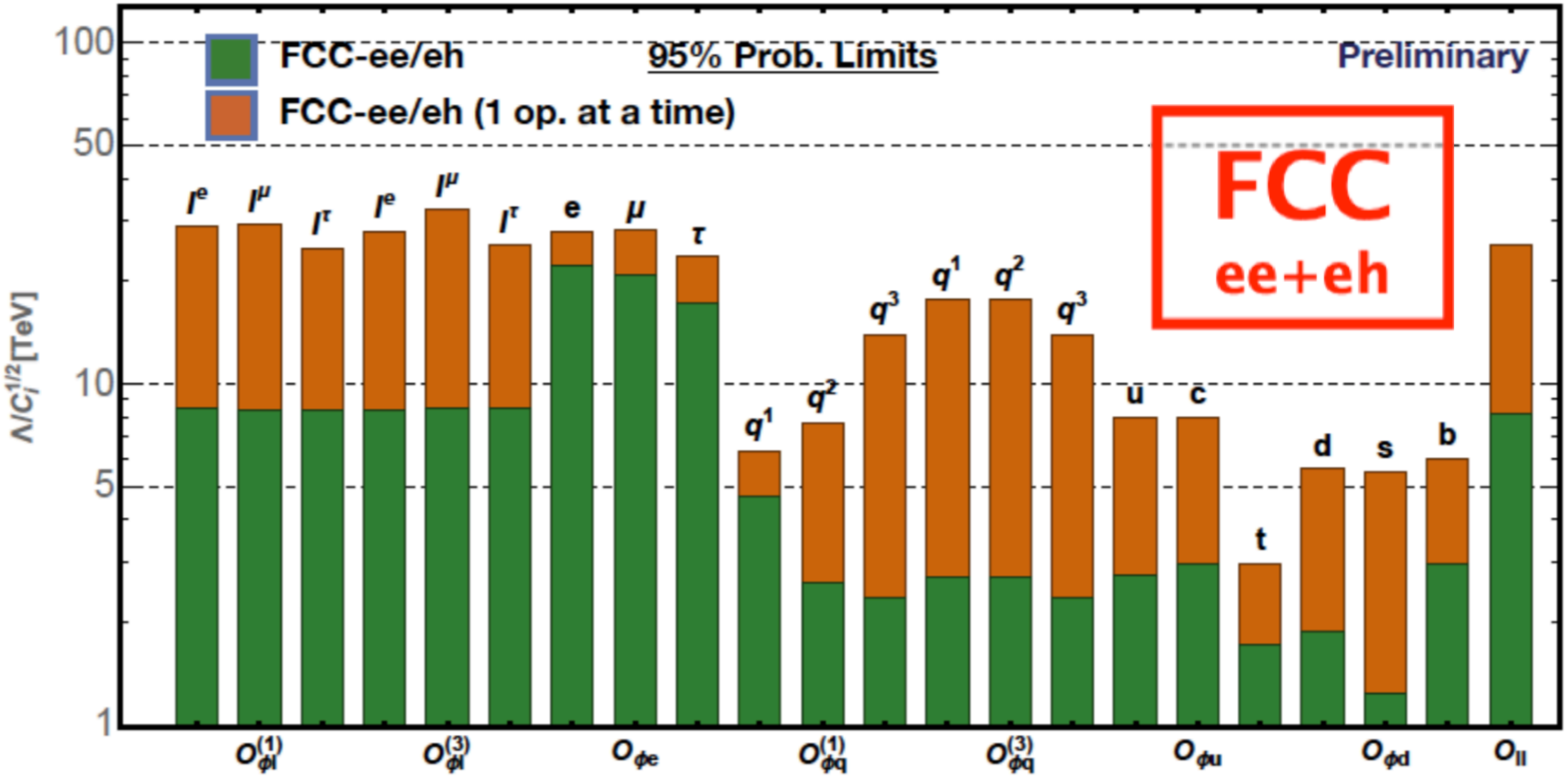
arXiv:2203.06237

→ **high sensitivity to NP**



Constraints on New Physics: EFT operators

- Global fit to electroweak precision measurements at FCC-ee + FCC-eh



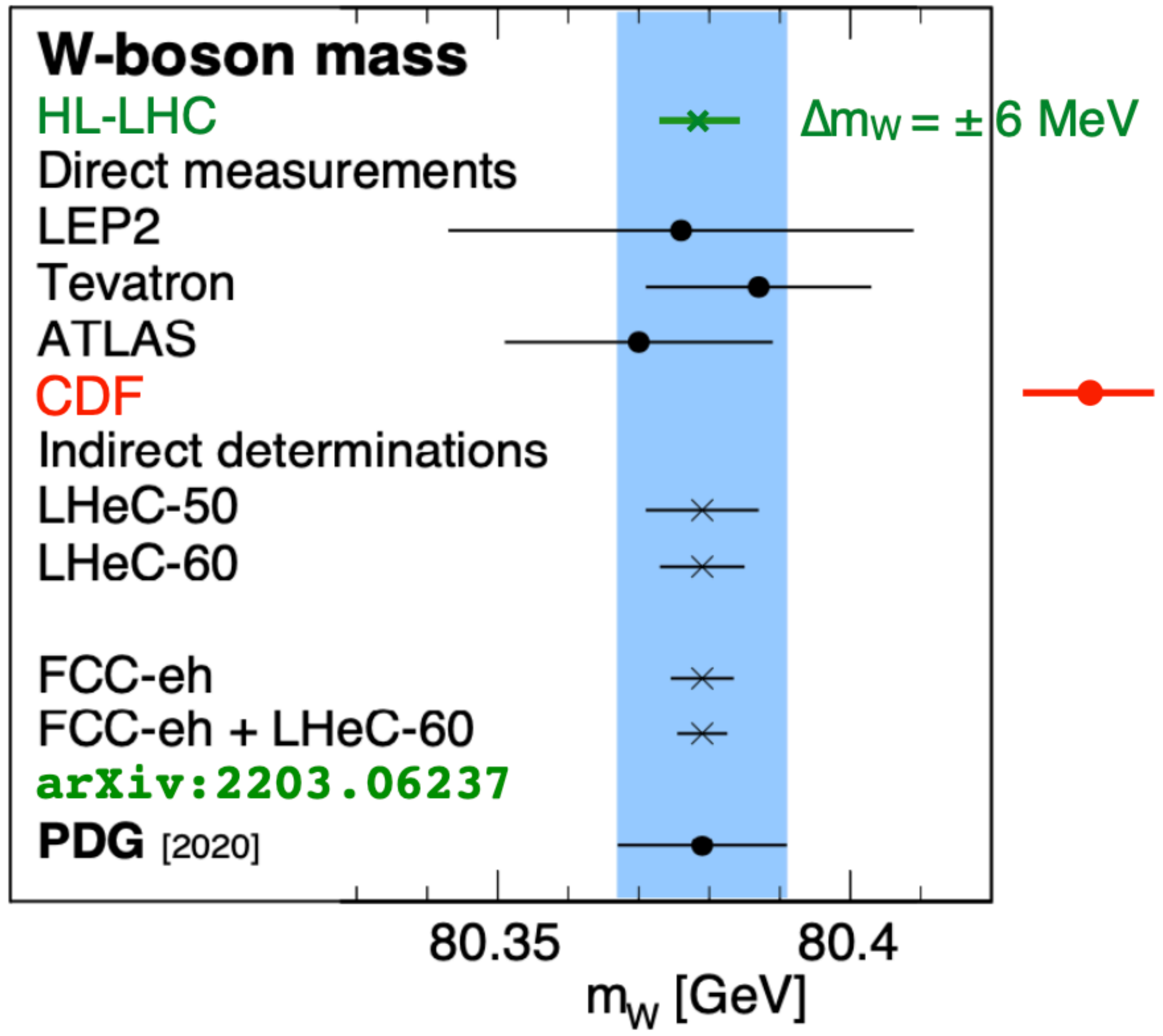
No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

→ high sensitivity to NP

Impact on W mass and effective EWK mixing angle @ HL-LHC

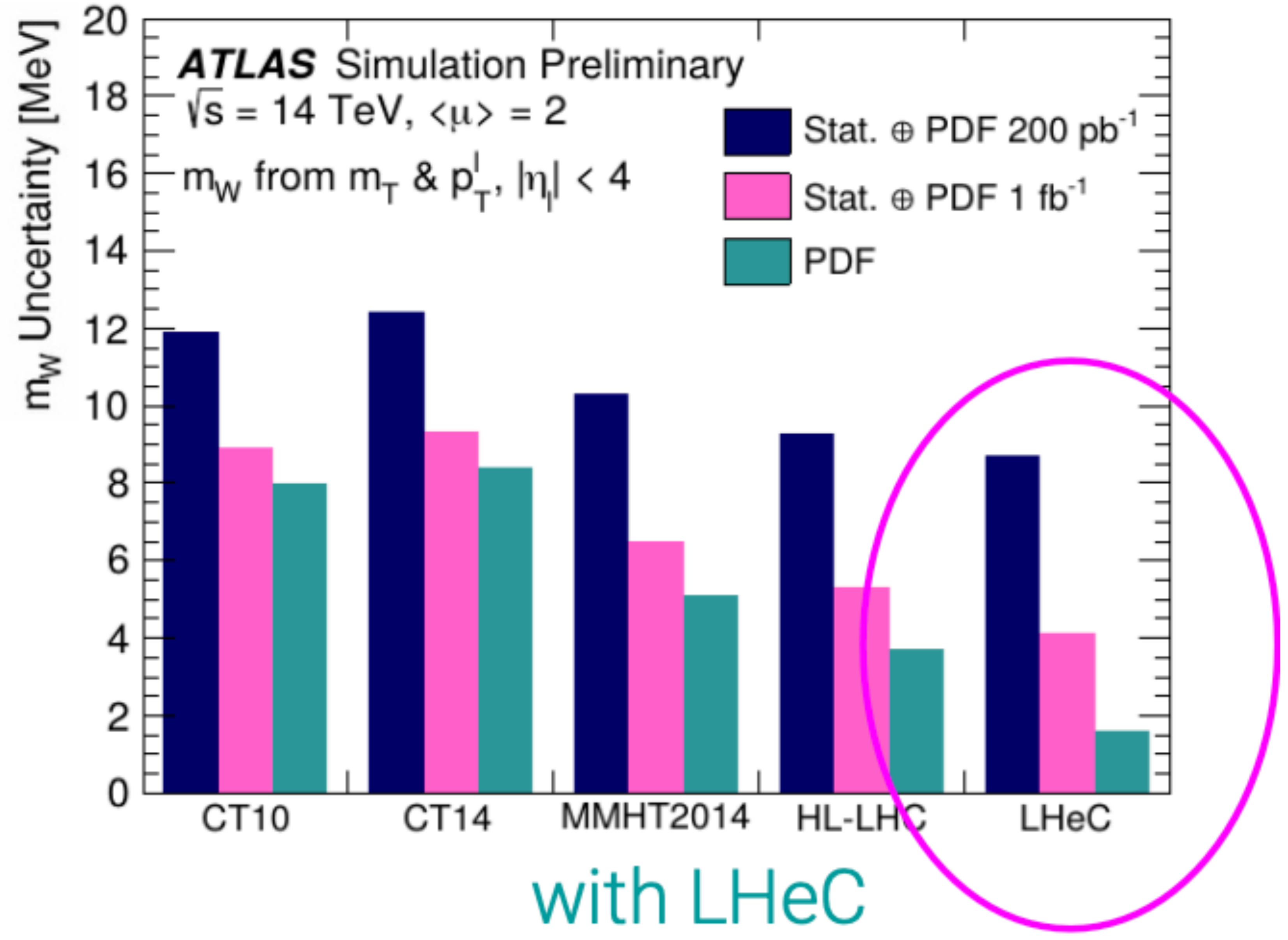
W mass uncertainty prospects @ HL-LHC

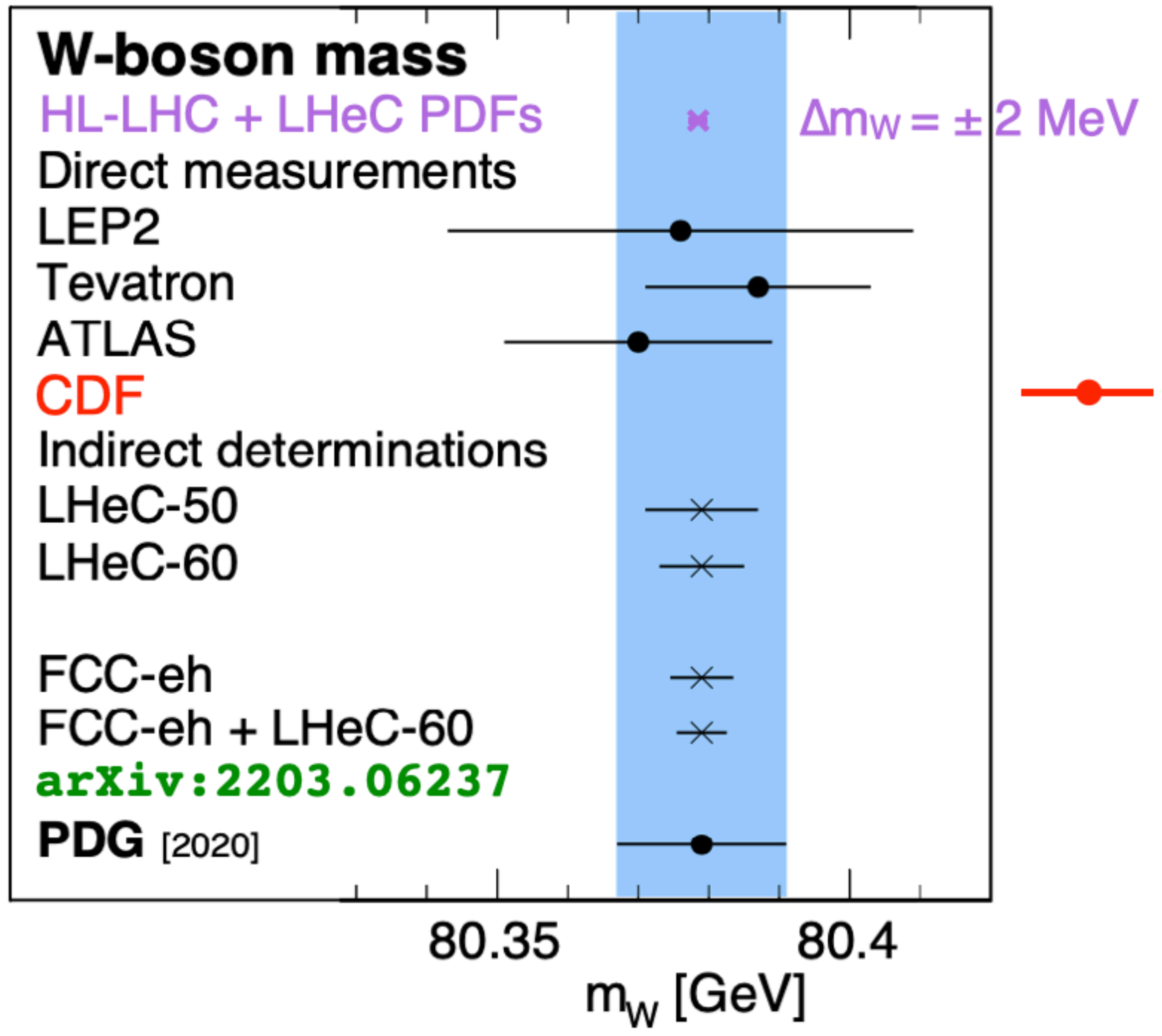


Impact on W mass and effective EWK mixing angle @ HL-LHC

W mass uncertainty prospects @ HL-LHC

ATLAS low-<μ> HL-LHC prospects





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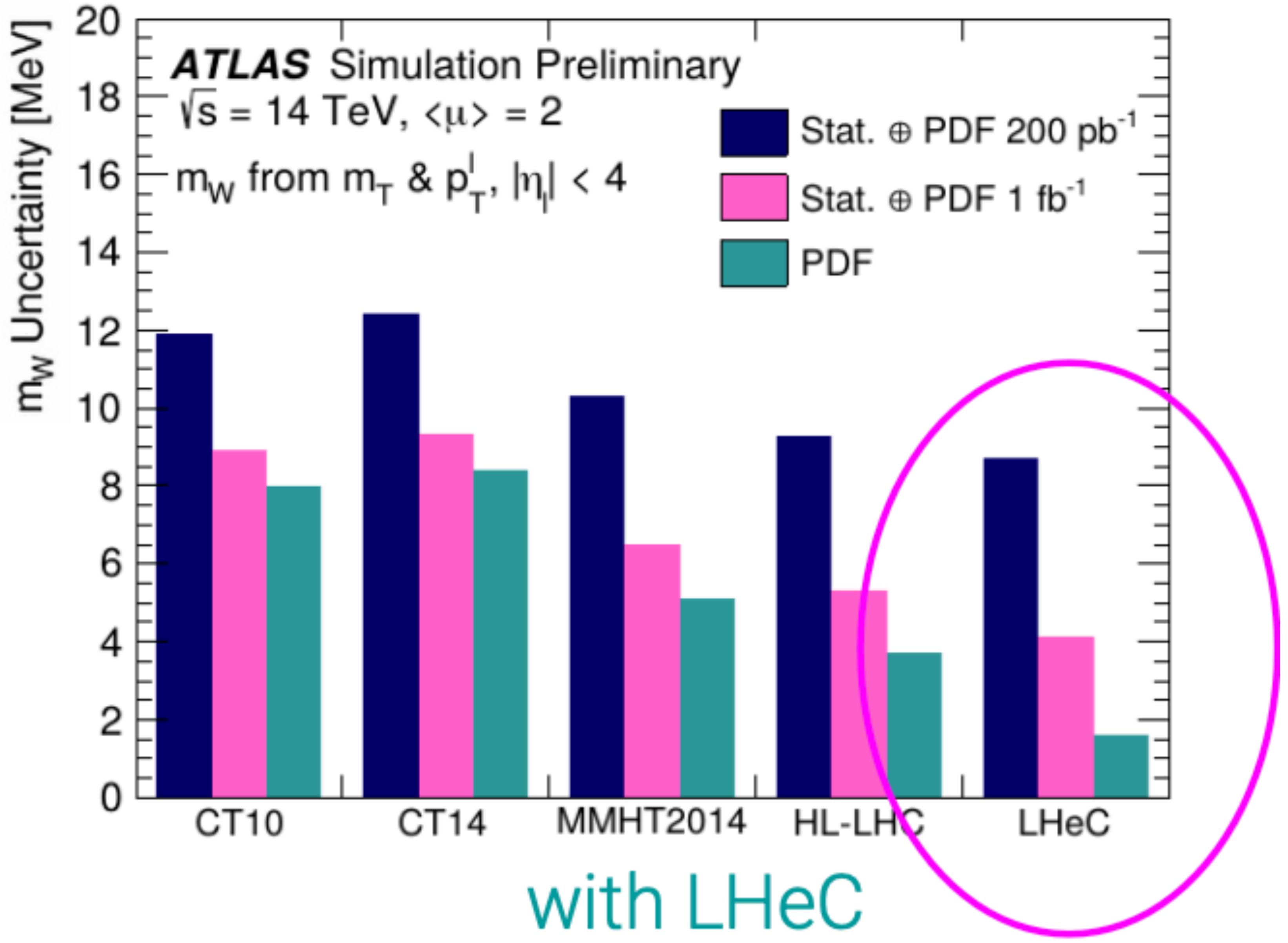
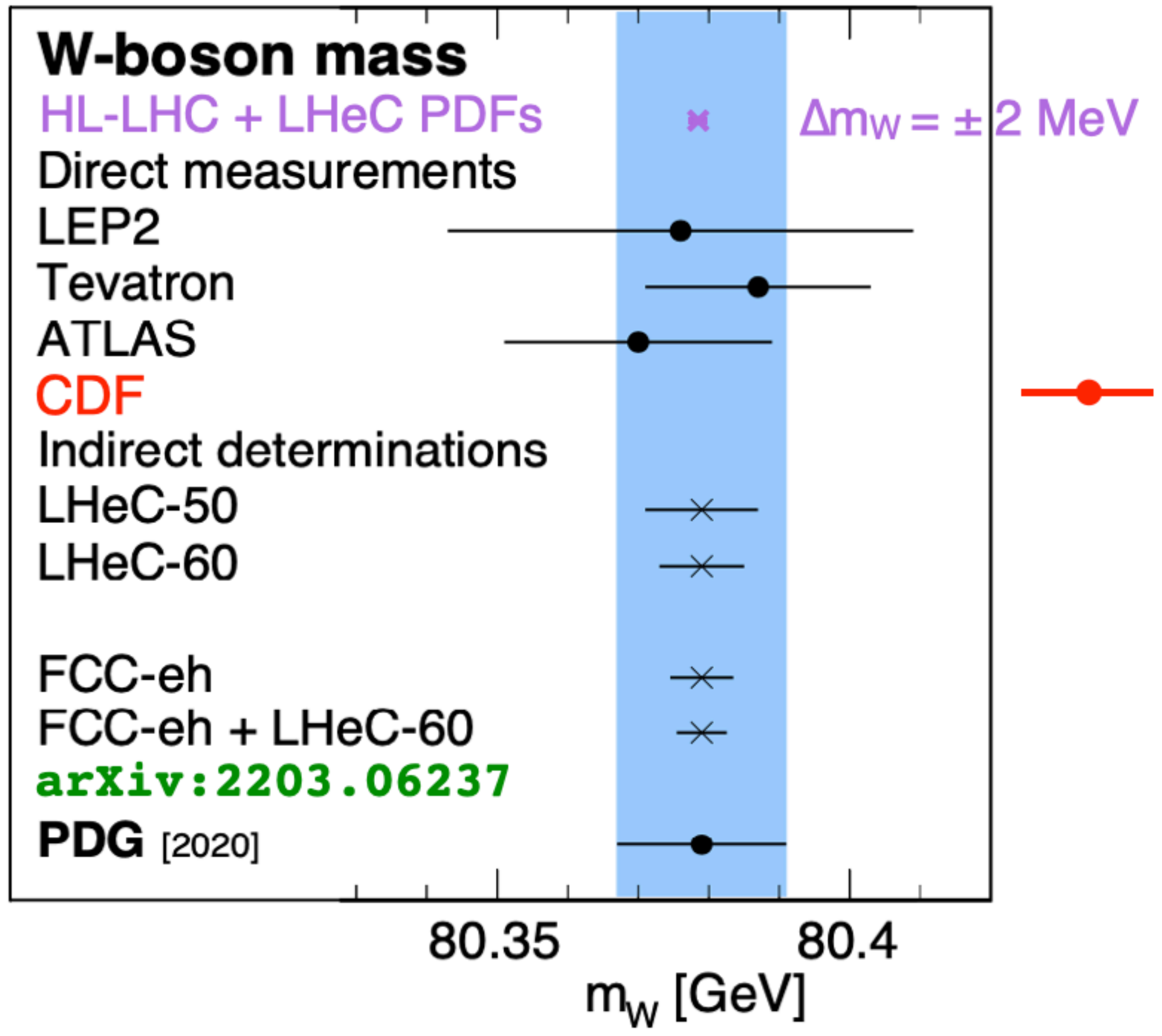
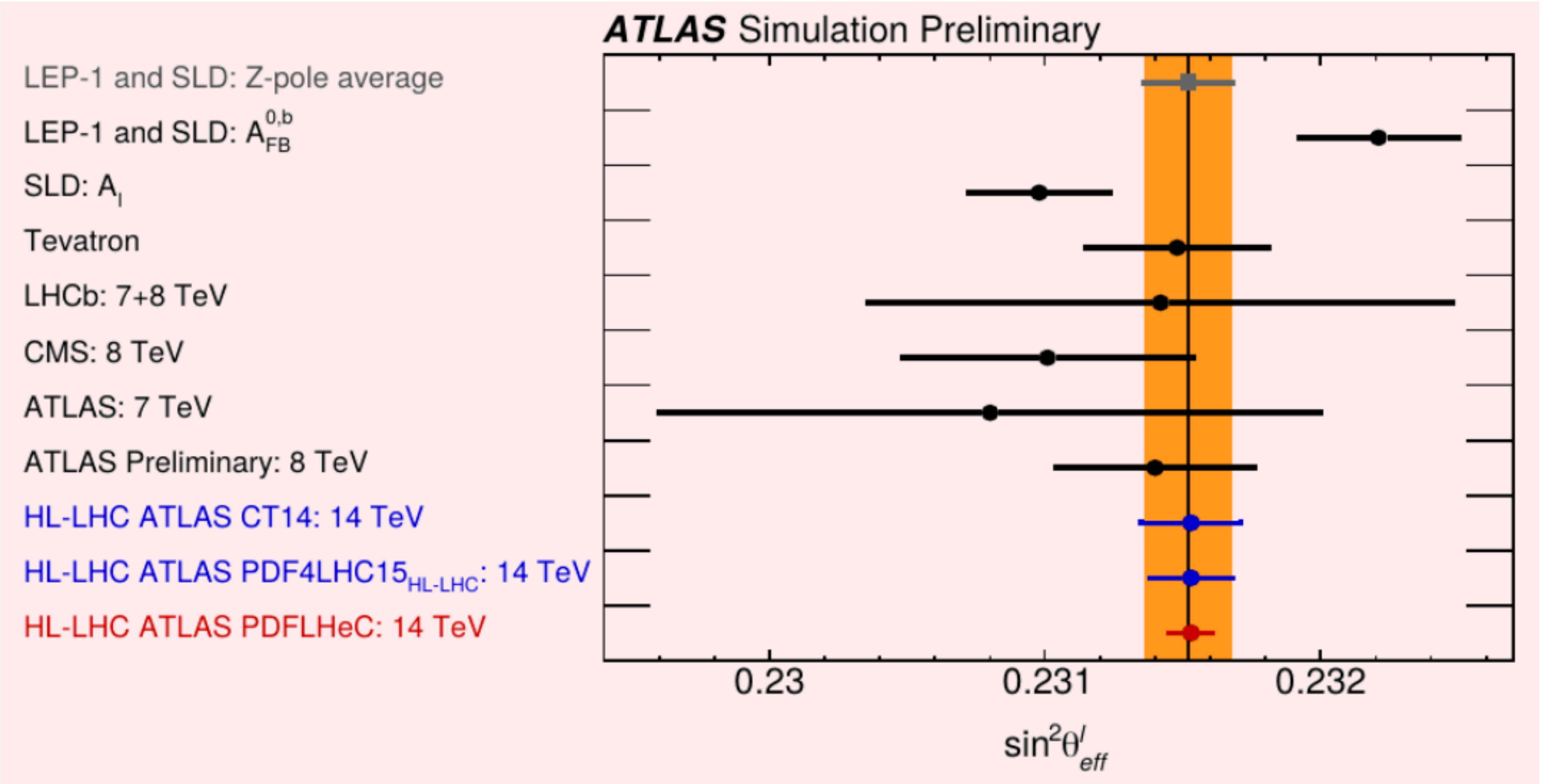




$\sin^2\Theta_W$ prospects @ HL-LHC

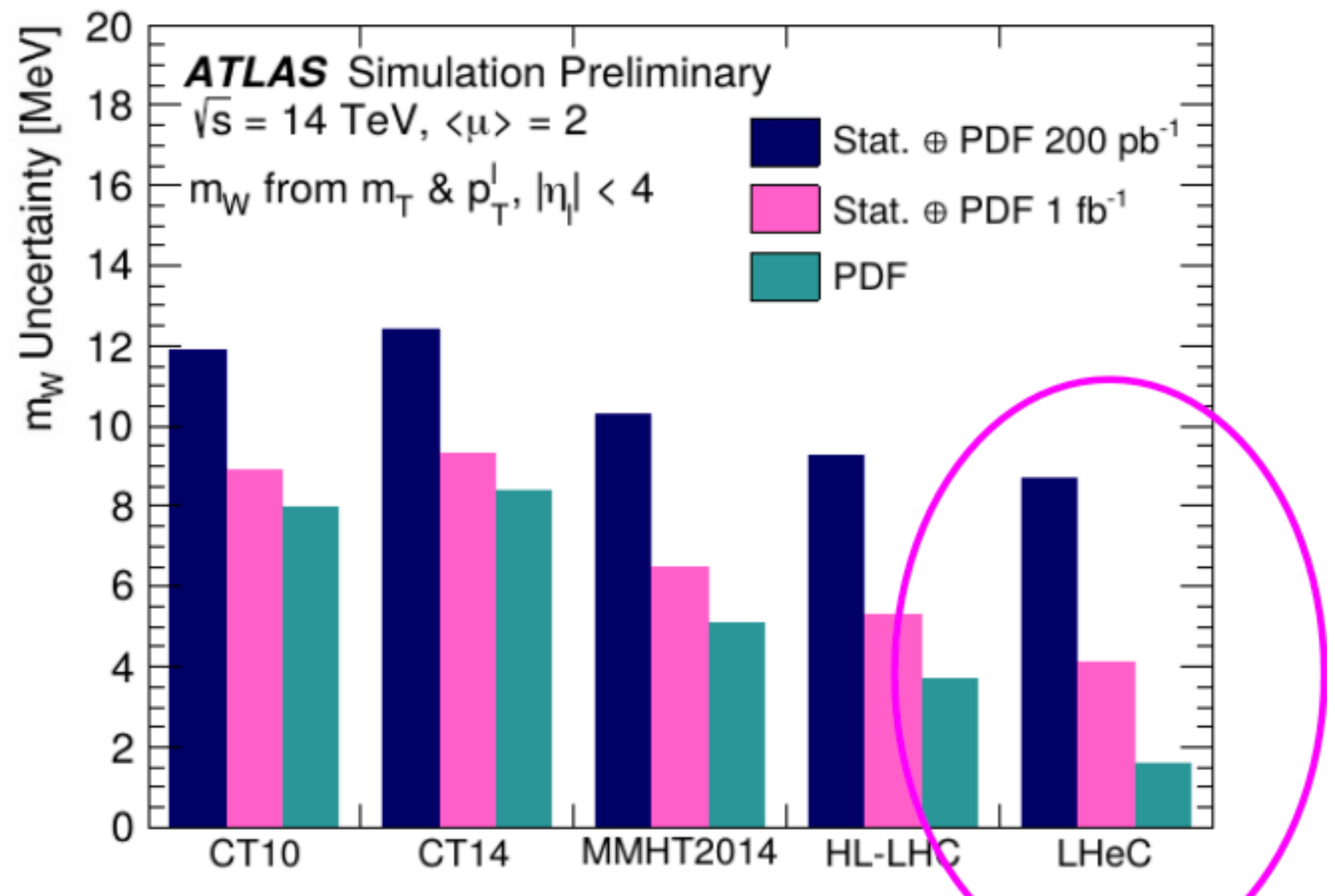


Precision of W mass and effective electroweak mixing angle

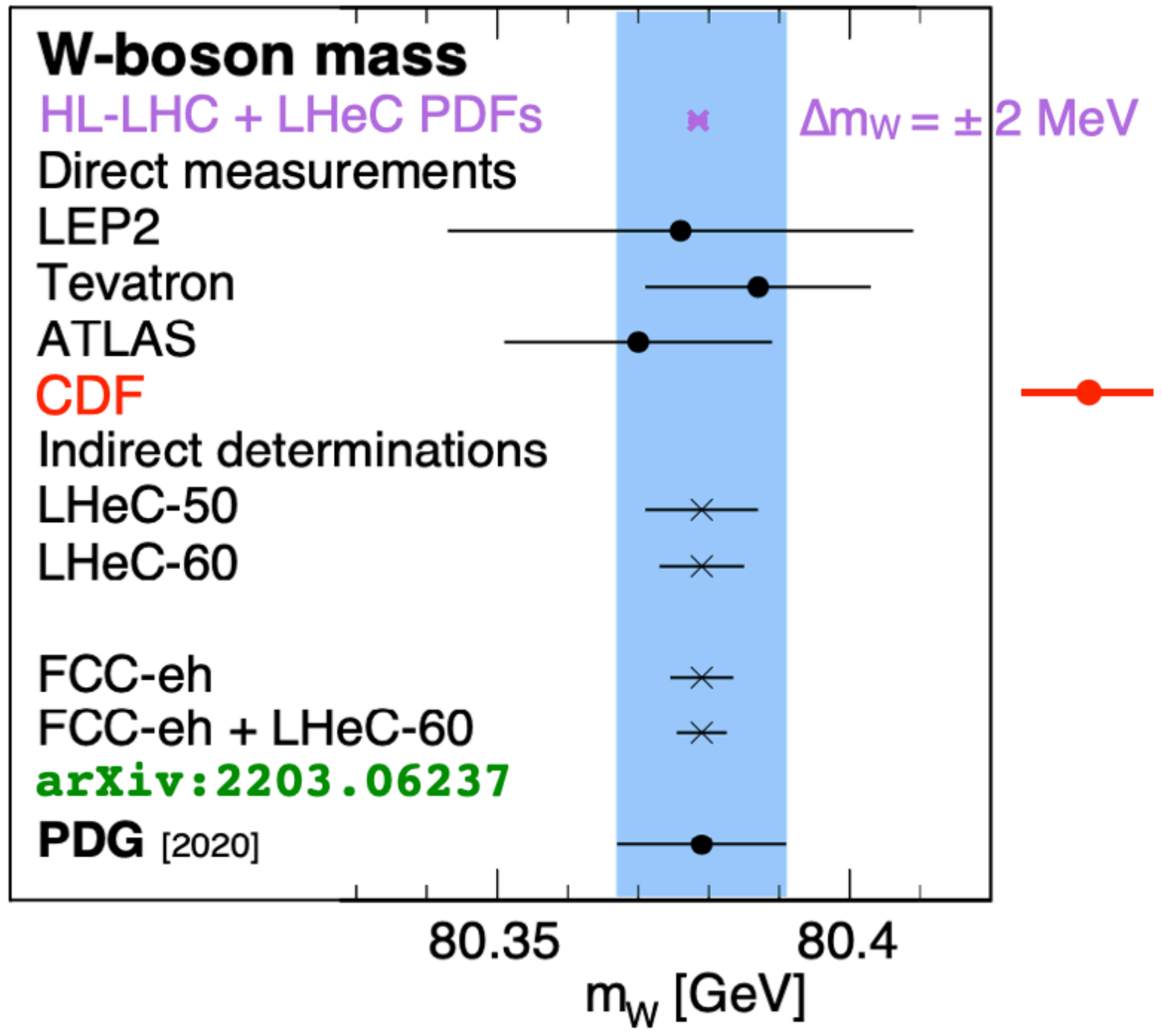
W mass uncertainty prospects @ HL-LHC

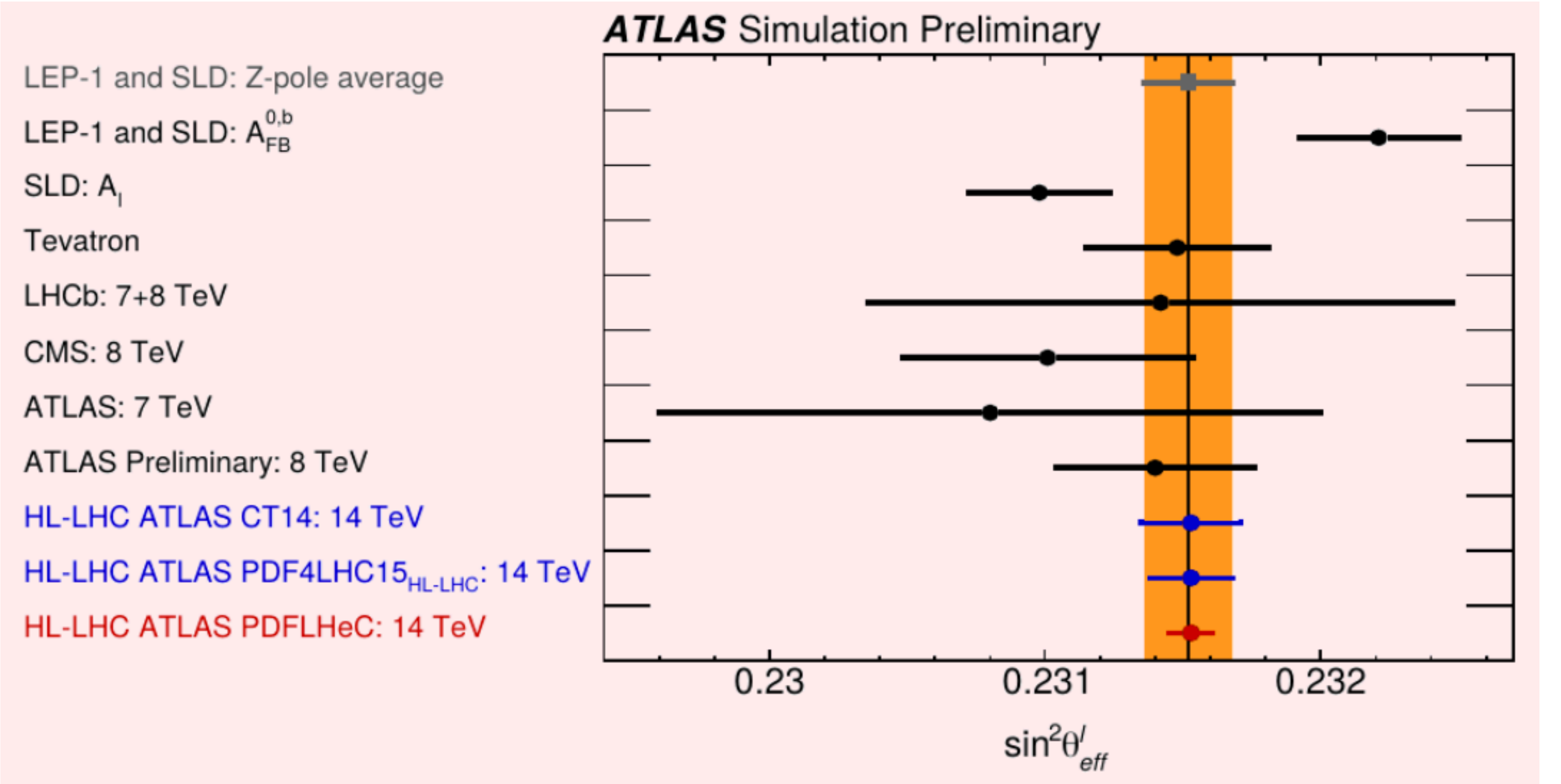
$\sin^2\Theta_W$ prospects @ HL-LHC

ATLAS low-<μ> HL-LHC prospects



with LHeC





LHeC PDFs will shrink uncertainties in HL-LHC measurements of many (not only electroweak) parameters dramatically

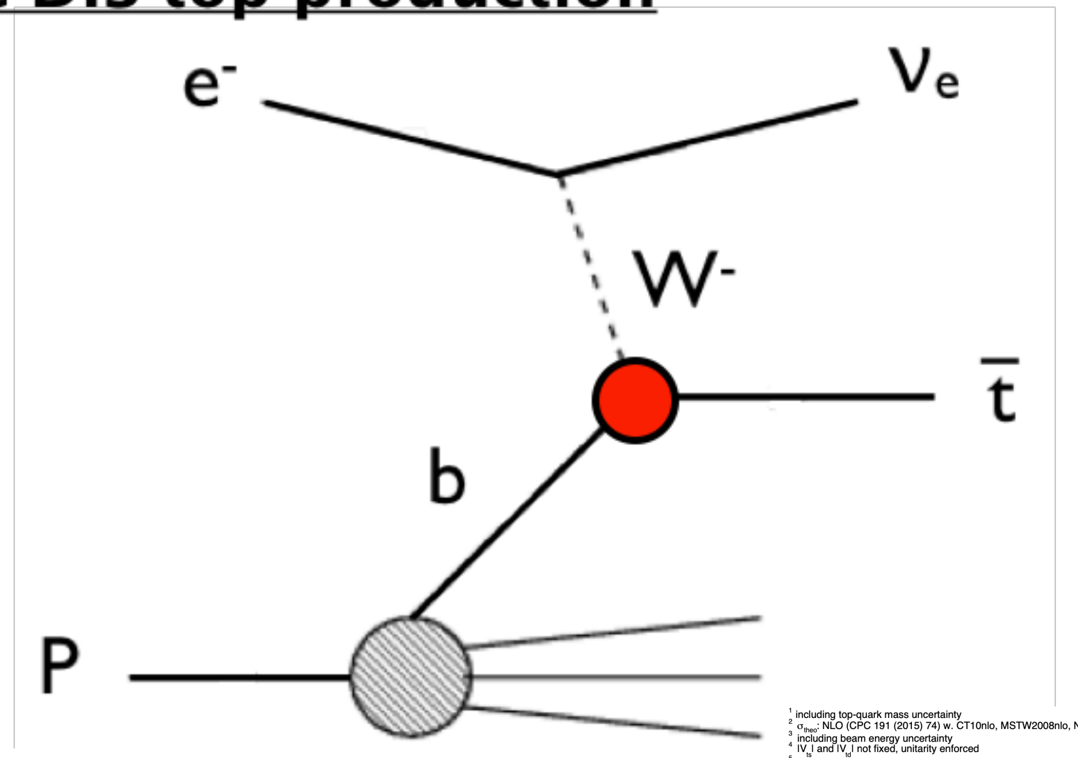
Expected measurements of Wtb couplings

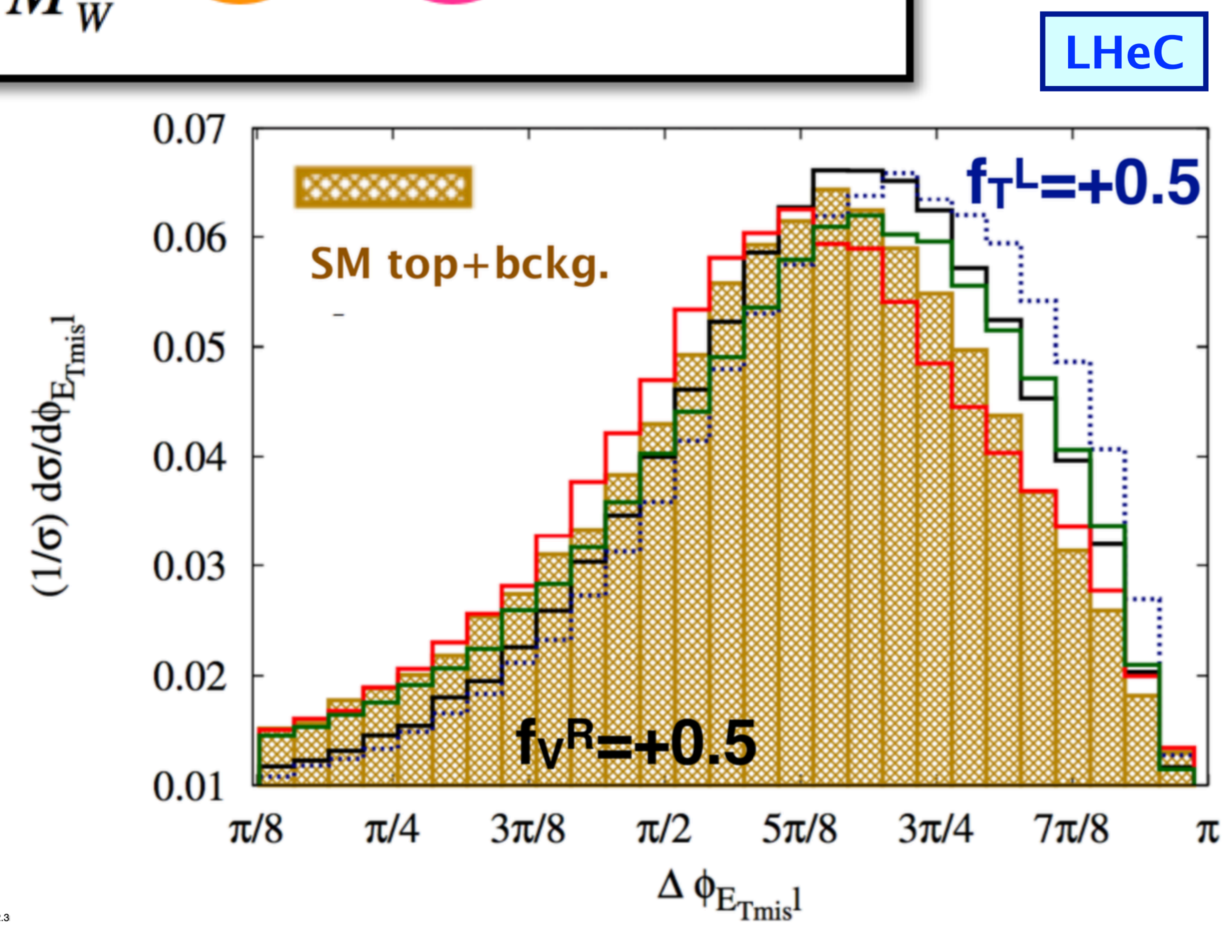
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

= 1 in SM

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688
Kumar, Ruan, to be publ.

CC DIS top production





+ other variables sensitive on W helicity

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

Expected measurements of Wtb couplings

$$L = -\frac{g}{\sqrt{2}} \bar{b}\gamma^\mu V_{tb}\left(f_V^L P_L + f_V^R P_R\right) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} \left(f_T^L P_L + f_T^R P_R\right) t W_\mu^- + h.c.$$

= 1 in SM

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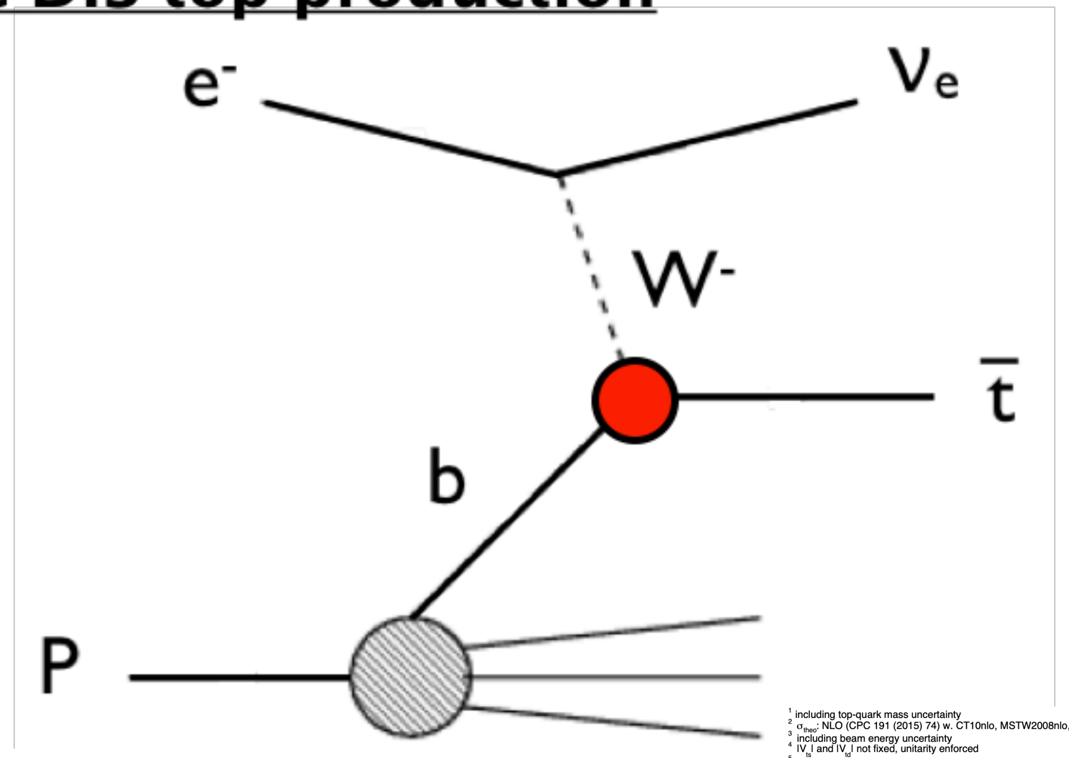
arXiv:1307.1688
Kumar, Ruan, to be publ.

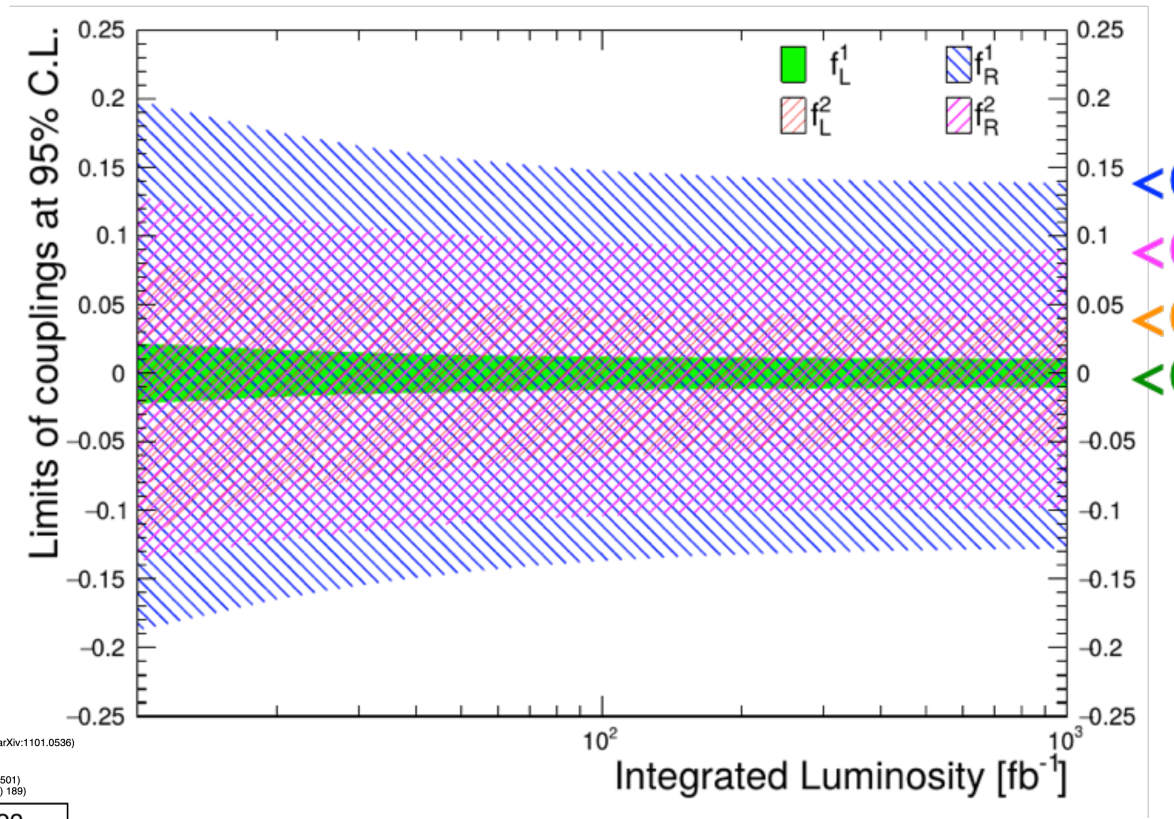
Anomalous Wtb Coupling	f_R^1	f_L^2	f_R^2
HL-LHC, 3000 fb^{-1} ($\mathcal{R}e$)	[-0.28,0.32]	[-0.17,0.19]	[-0.05,0.02]
HL-LHC, 3000 fb^{-1} ($\mathcal{I}m$)	[-0.30,0.32]	[-0.19,0.18]	[0.11,0.10]
LHeC, 1000 fb^{-1} ($\mathcal{R}e$)	[-0.13,0.14]	[-0.05,0.04]	[-0.10,0.09]

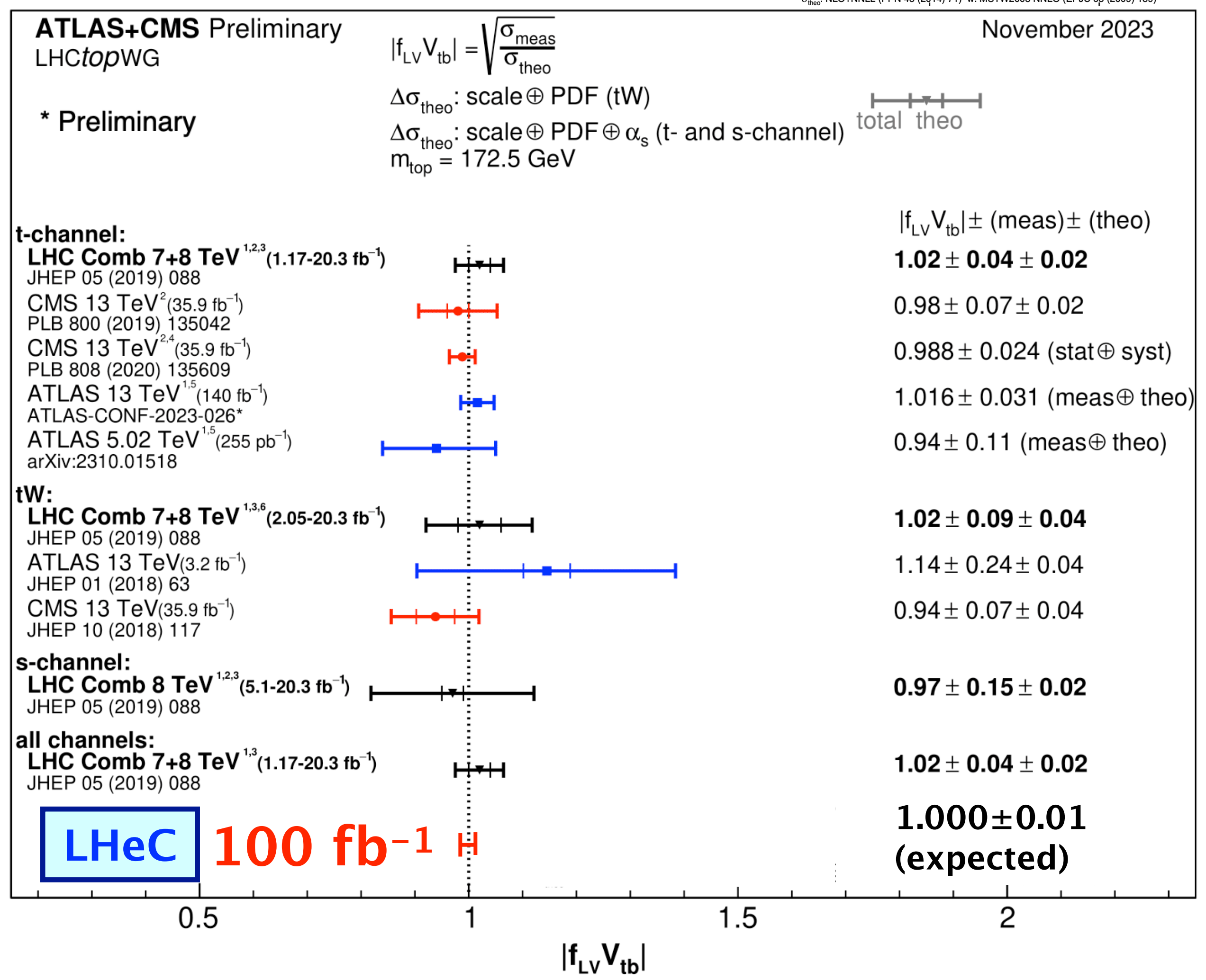
CC DIS top production



LHeC

hadronic channel:





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Unprecedented precision < 1%

Expected measurements of Wtb couplings

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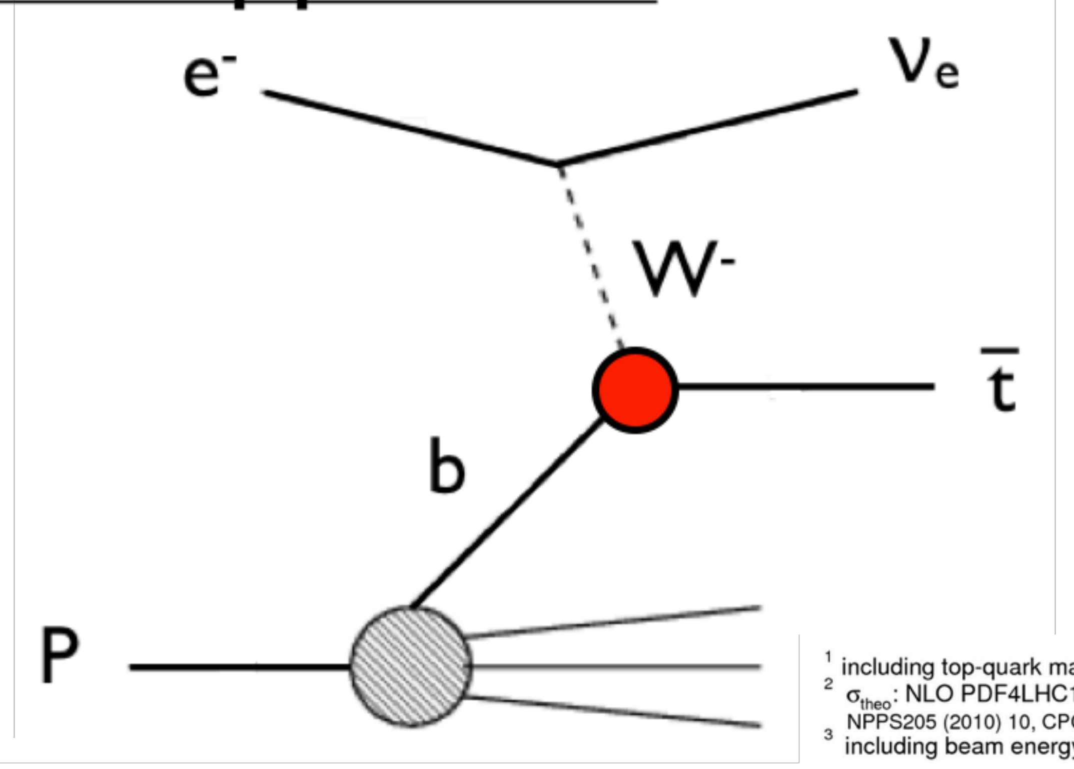
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_{\mu}^{-} + h.c.$$

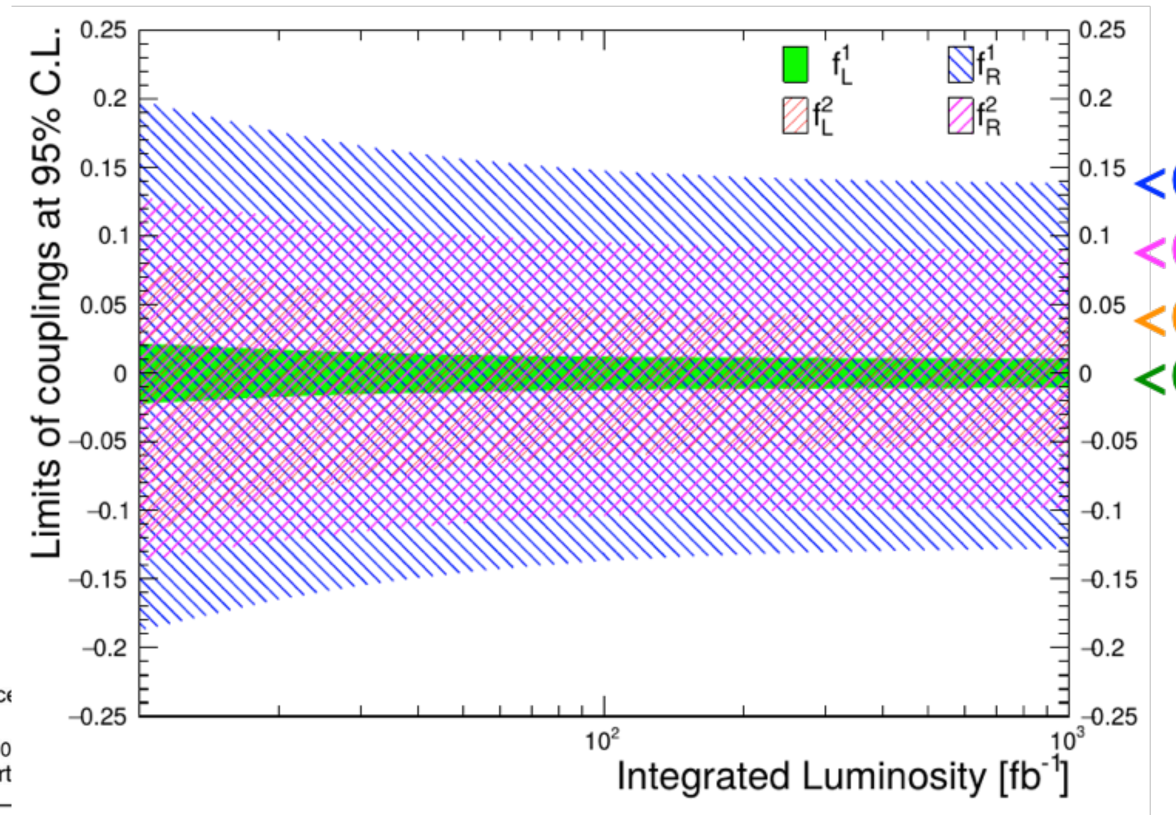
= 1 in SM

Dutta, Goyal, Kumar, Mellado, arXiv:1307.1688
Kumar, Ruan, to be publ.

CC DIS top production



hadronic channel:



LHeC

<0.14
<0.09
<0.04
<0.01

Anomalous Wtb Coupling	f_R^1	f_L^2	f_R^2
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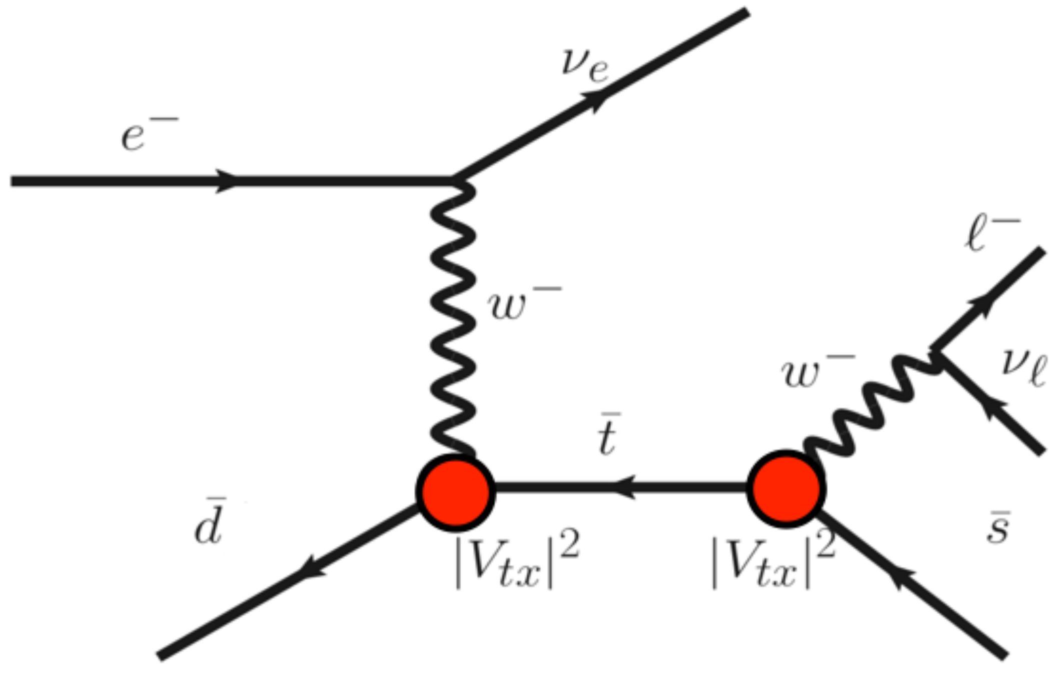
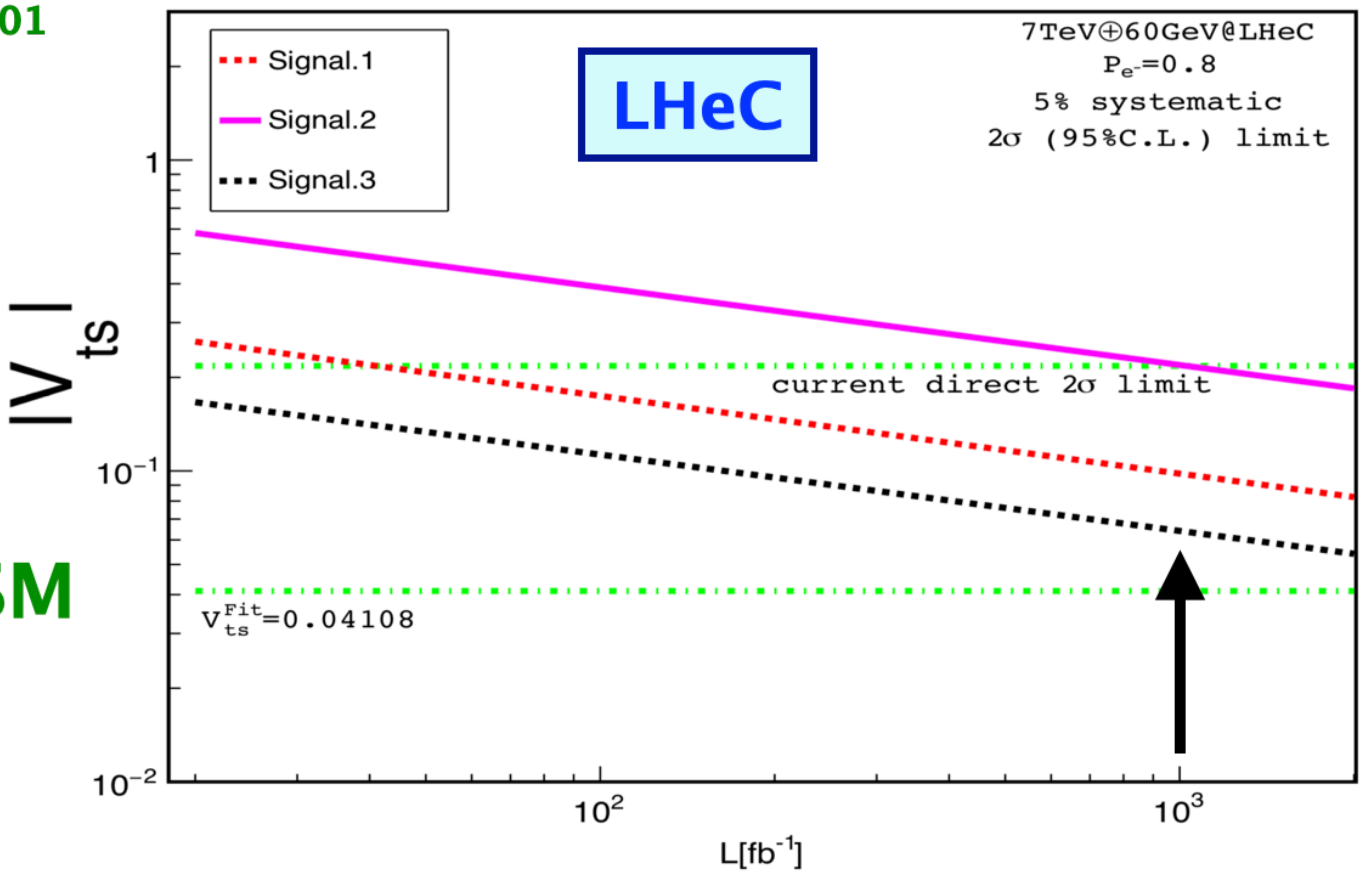
HL-LHC, 3000 fb^{-1} ($\mathcal{I}m$)	[-0.30,0.32]	[-0.19,0.18]	[0.11,0.10]
LHeC, 1000 fb^{-1} ($\mathcal{R}e$)	[-0.13,0.14]	[-0.05,0.04]	[-0.10,0.09]

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



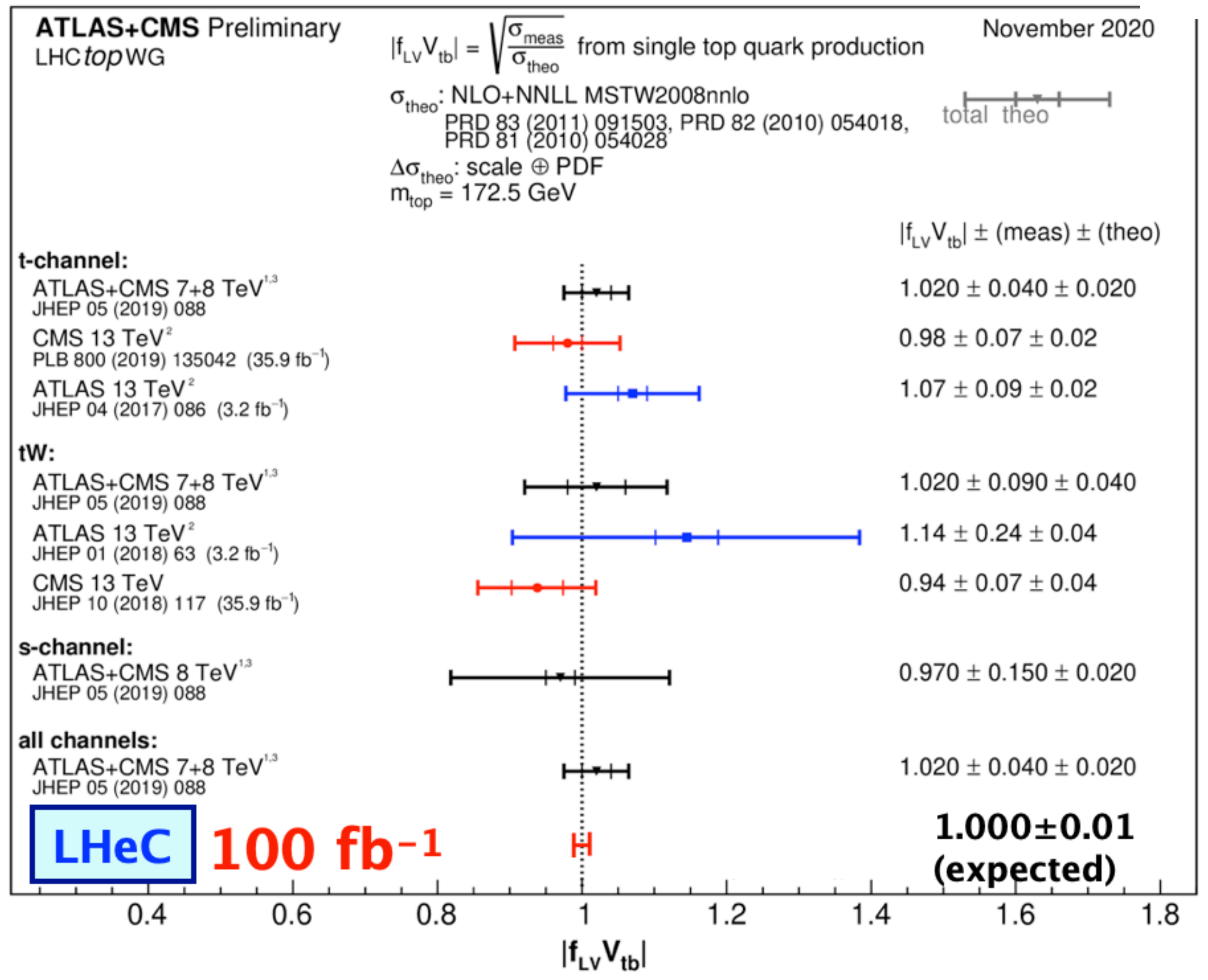
H. Sun PoS DIS 2018, 167 (2018)



2σ

LHC

→ $|V_{ts}|<0.06$



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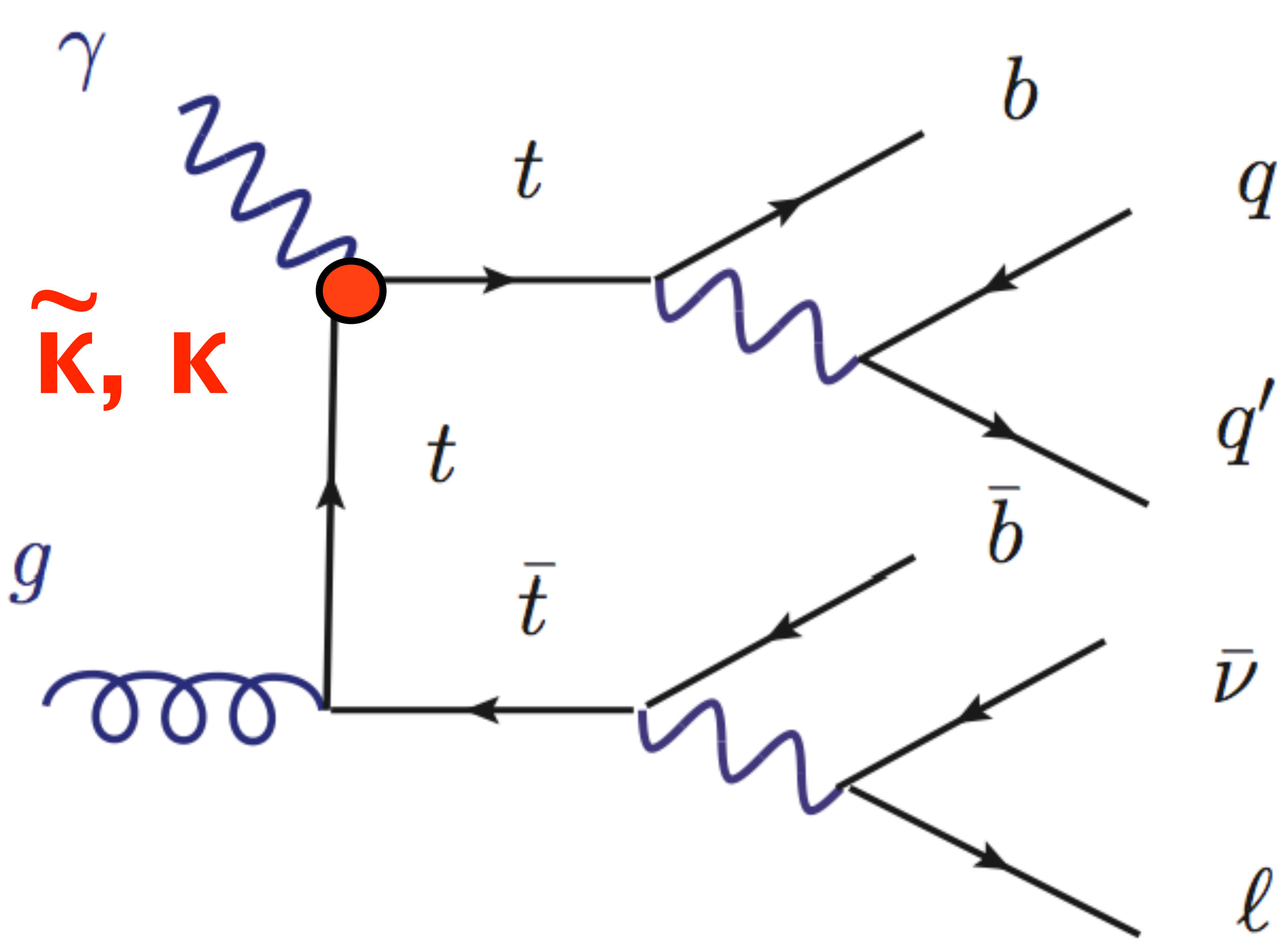
SM

Unprecedented precision < 1%

Probing SM prediction directly for the first time

Search for Anomalous $t\bar{t}\gamma$ Couplings



$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

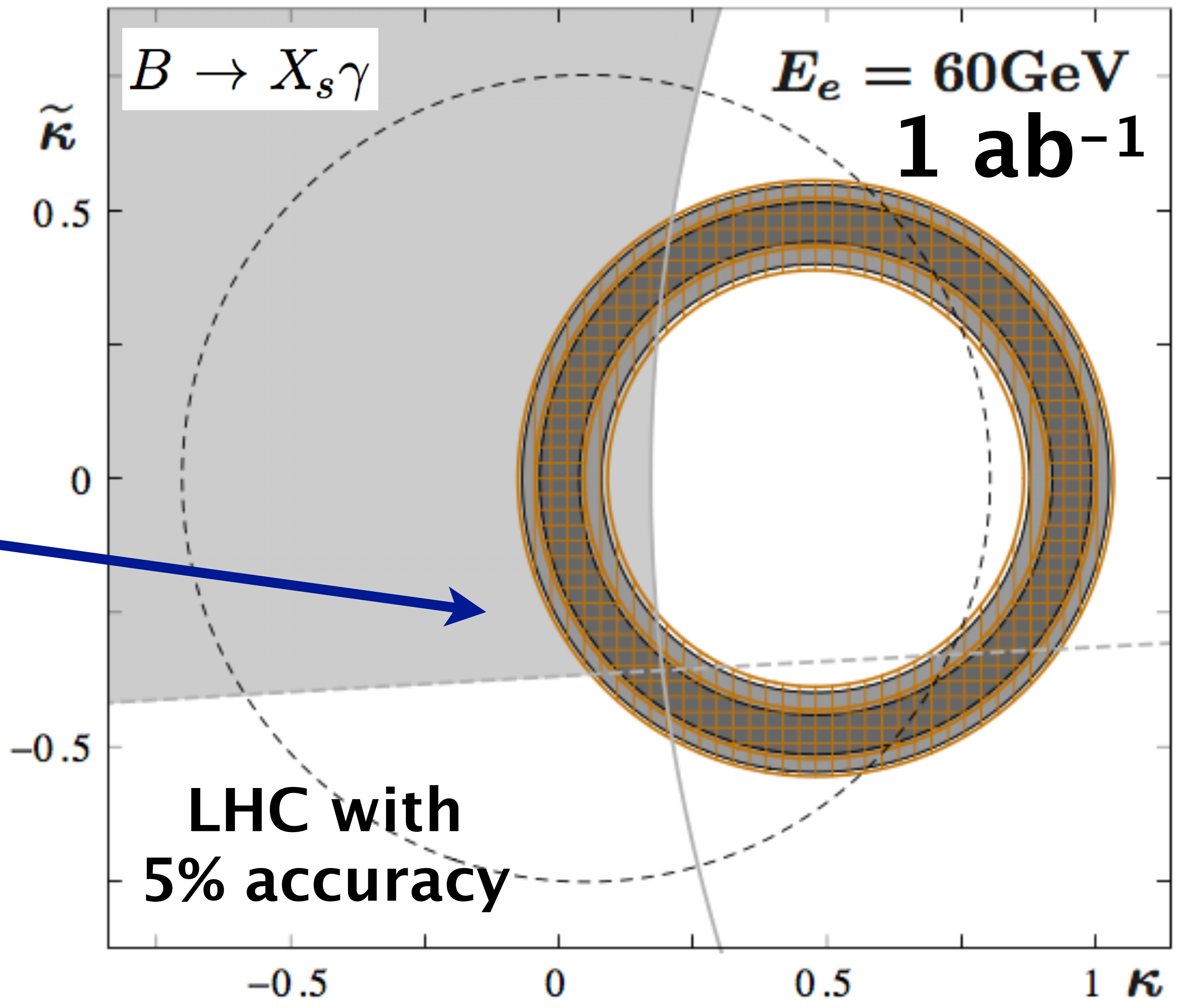
electric dipole moment: $\tilde{\kappa}$

LHeC

8% and 16% accuracy

10% 18%

→ systematically limited

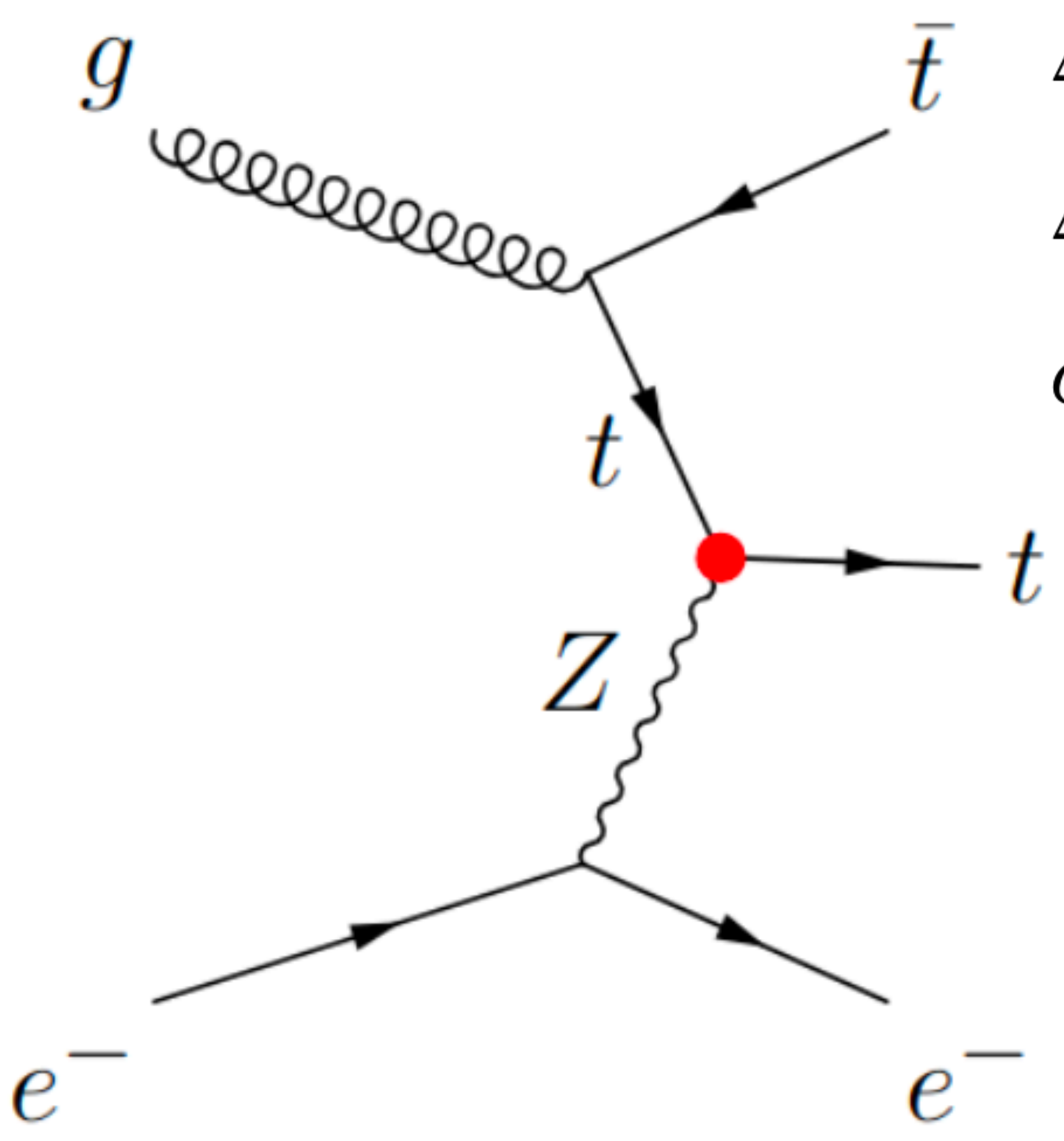


magnetic dipole moment: κ

ATLAS 27% accuracy (4.59fb^{-1}, 7 TeV)

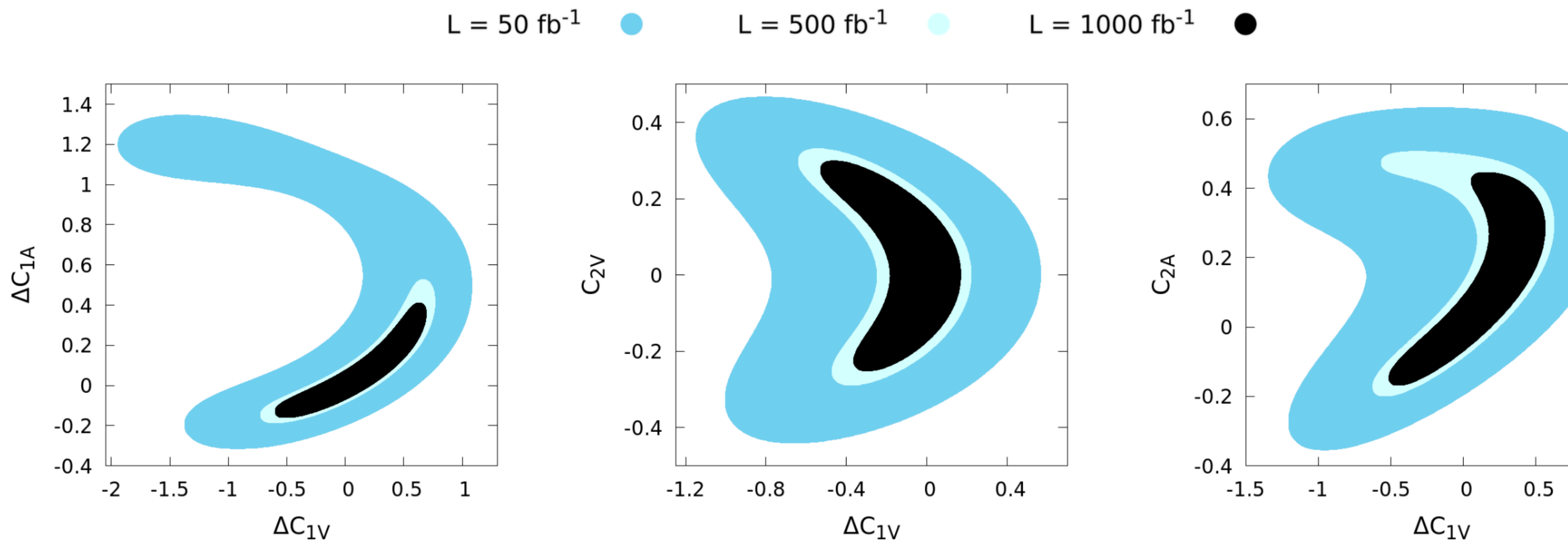
Bouzas, Larios,
Physical Review D 88, 094007 (2013)

Search for Anomalous $t\bar{t}Z$ Couplings



$$\Delta C_{1V} = \frac{v^2}{\Lambda^2}\mathfrak{Re}\left[-c_{\phi t} - c^-_{\phi Q}\right],$$
$$\Delta C_{1A} = \frac{v^2}{\Lambda^2}\mathfrak{Re}\left[-c_{\phi t} + c^-_{\phi Q}\right],$$
$$C_{2V} = \frac{\sqrt{2}\,v^2}{\Lambda^2}c_{tZ}, \quad C_{2A} = \frac{\sqrt{2}\,v^2}{\Lambda^2}c^I_{tZ}$$

Improve LHC sensitivity

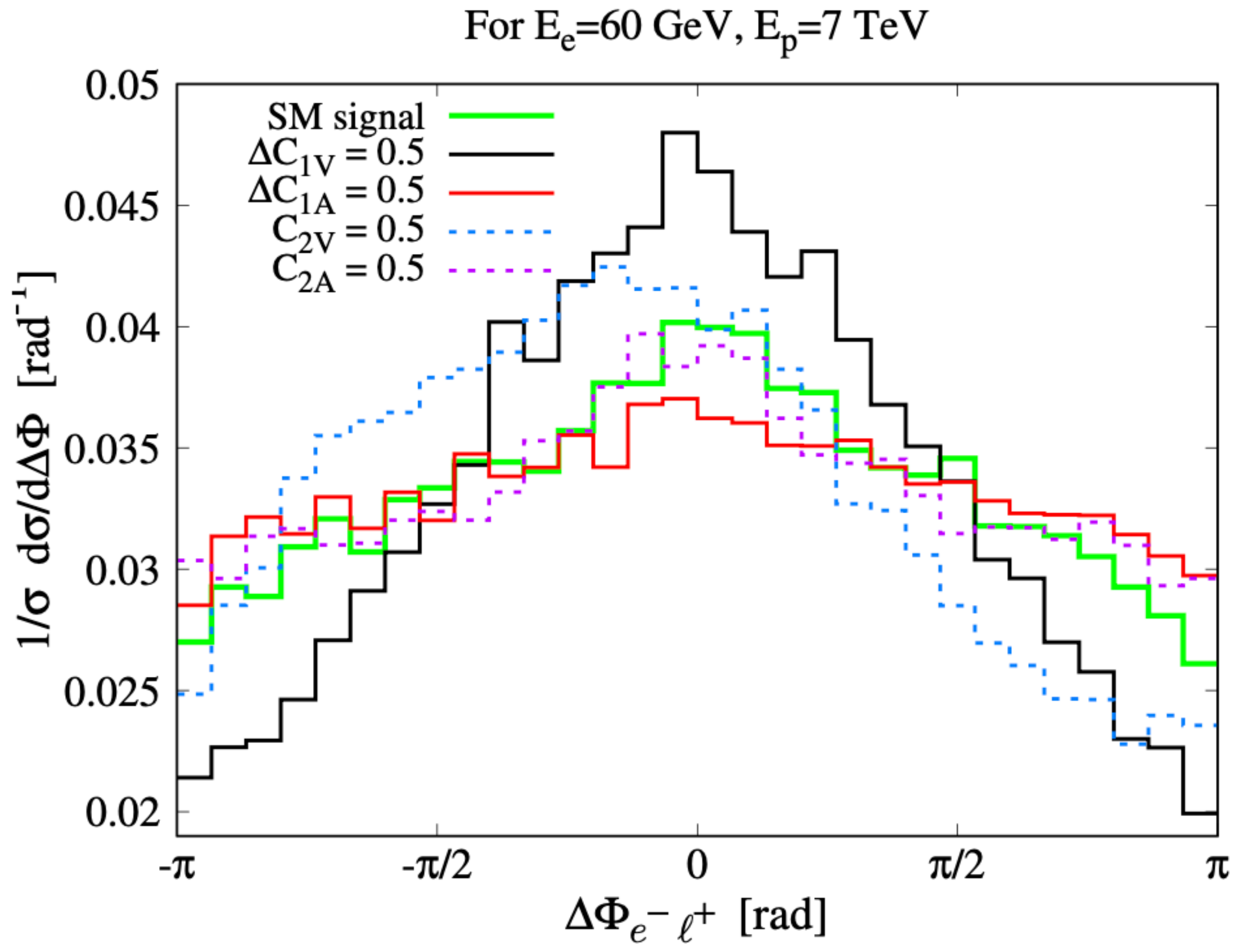


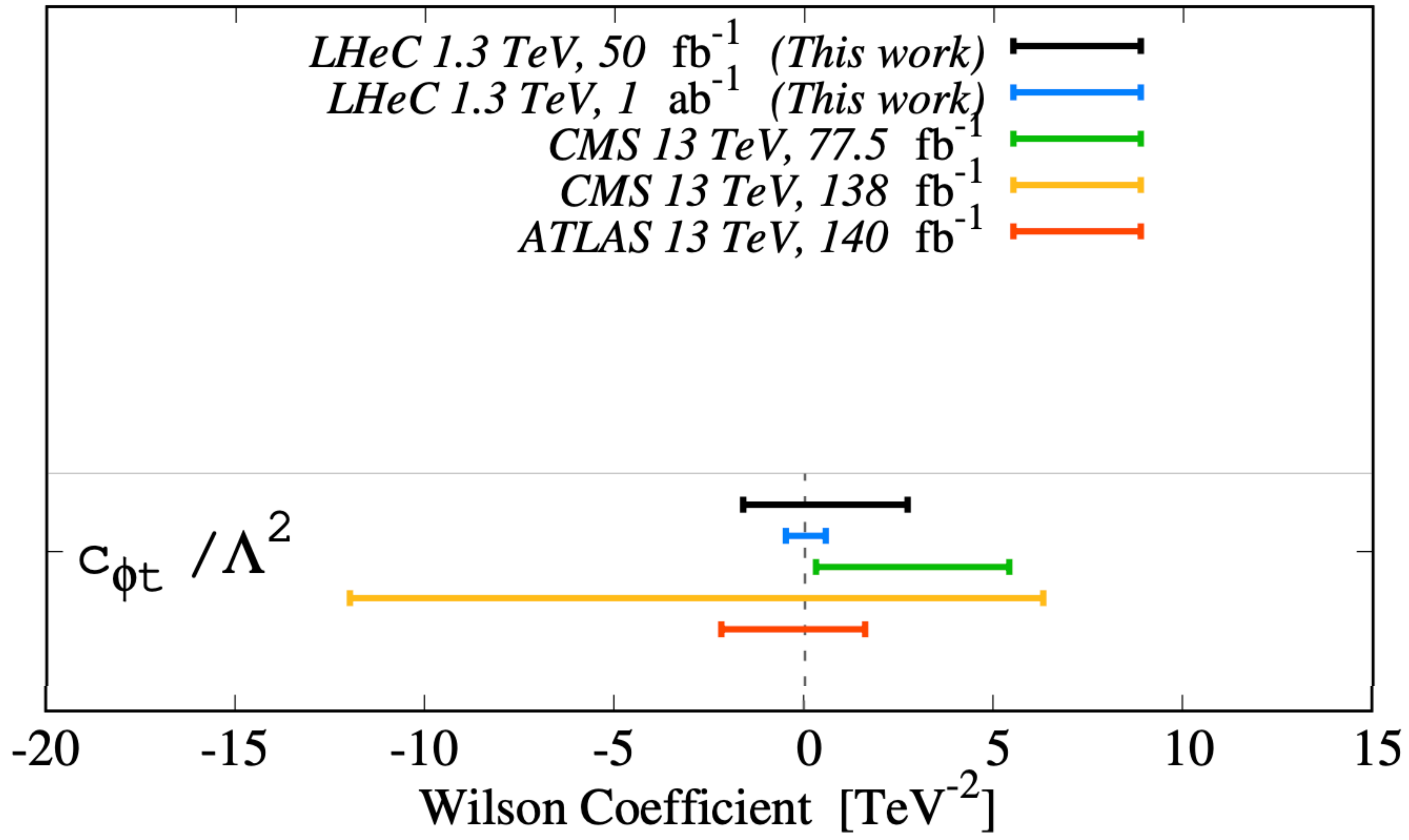
arXiv:2507.02267 [hep-ph]

95% C.L. Intervals for Wilson coefficient

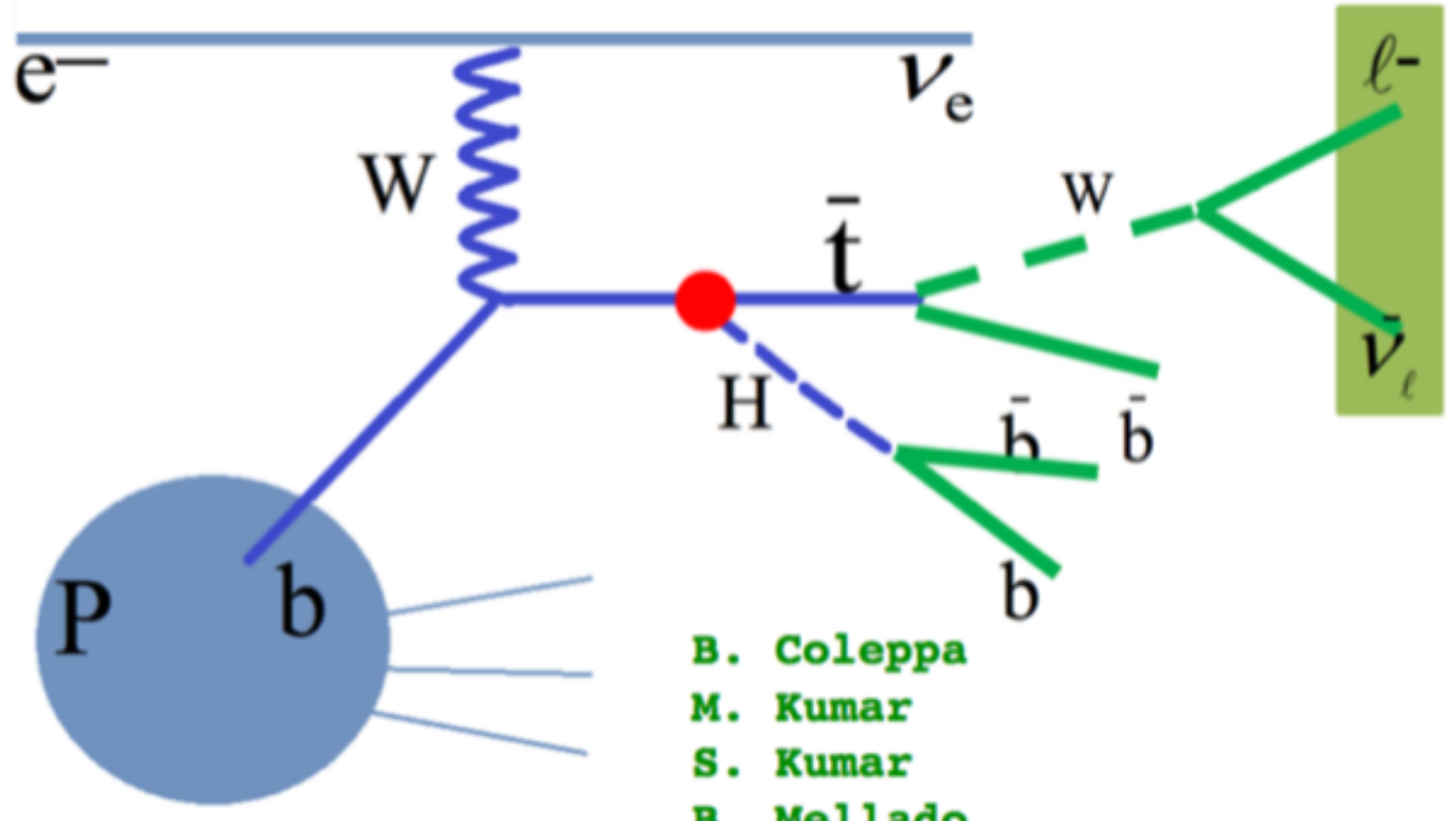
$$\mathcal{L}_{t\bar{t}Z} \supset \frac{g}{2\cos\theta_W}\bar{t}\Big[\gamma^\mu\left(\Delta C_{1V} - \Delta C_{1A}\gamma^5\right) + \frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C_{2V} - iC_{2A}\gamma^5\right)\Big]t\,Z_\mu$$

$$\mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\bar{\phi}B_{\mu\nu},$$
$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\bar{\phi}W^I_{\mu\nu},$$
$$\mathcal{O}_{\phi t} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{t}\gamma^\mu t),$$
$$\mathcal{O}^{(1)}_{\phi Q} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{Q}\gamma^\mu Q),$$
$$\mathcal{O}^{(3)}_{\phi Q} = (\phi^\dagger i\overleftrightarrow{D}_\mu\tau^I\phi)(\bar{Q}\gamma^\mu\tau^I Q)$$





Top Quark Yukawa Coupling and CP Nature

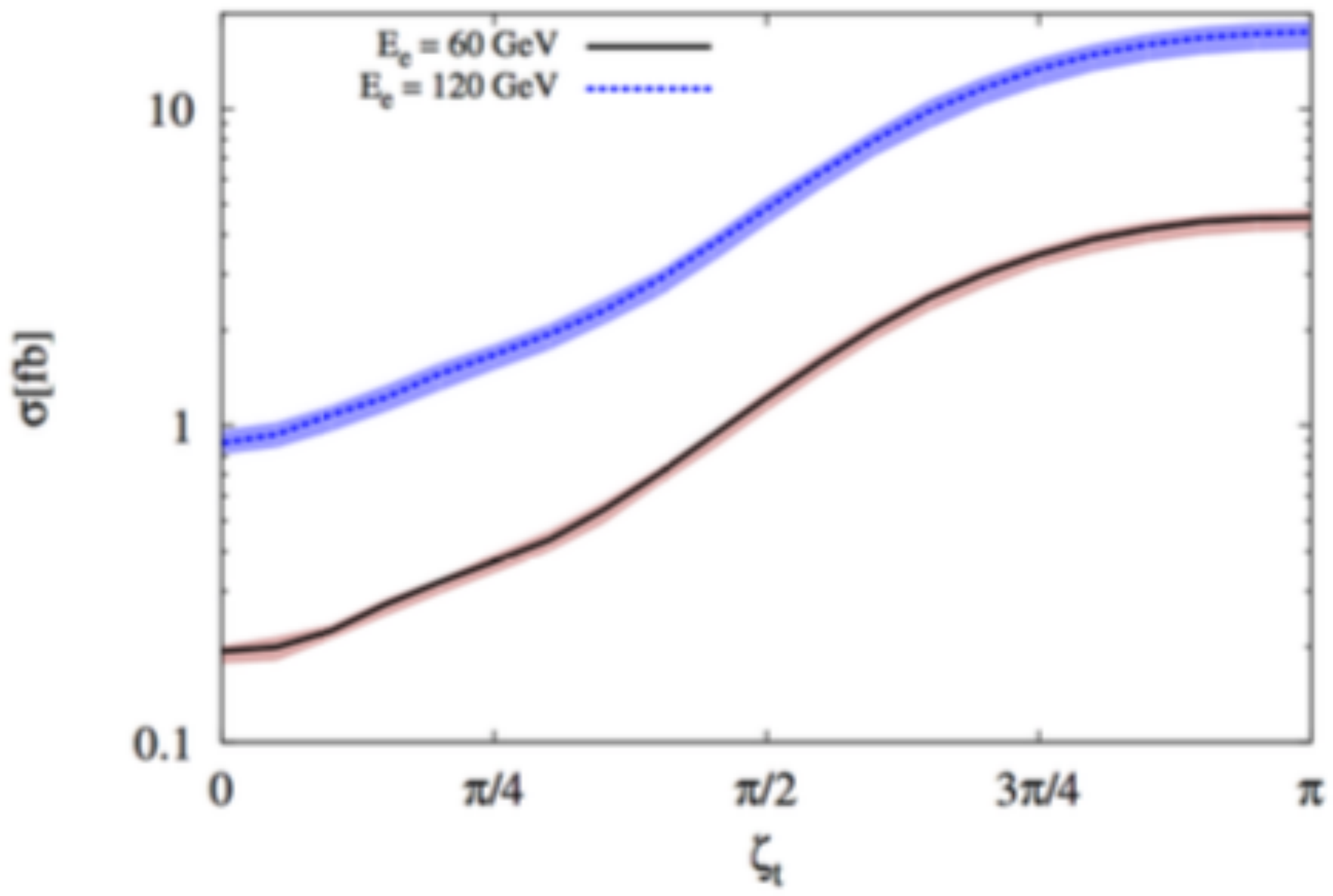


parton level

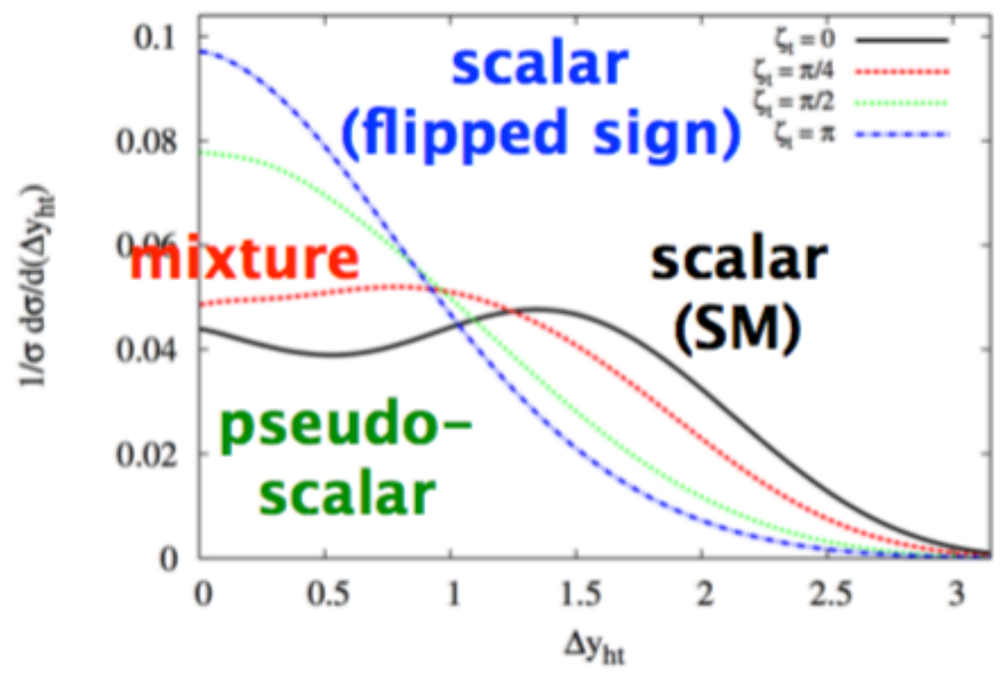
B. Coleppa
M. Kumar
S. Kumar
B. Mellado

Phys. Lett. B770 (2017) 335

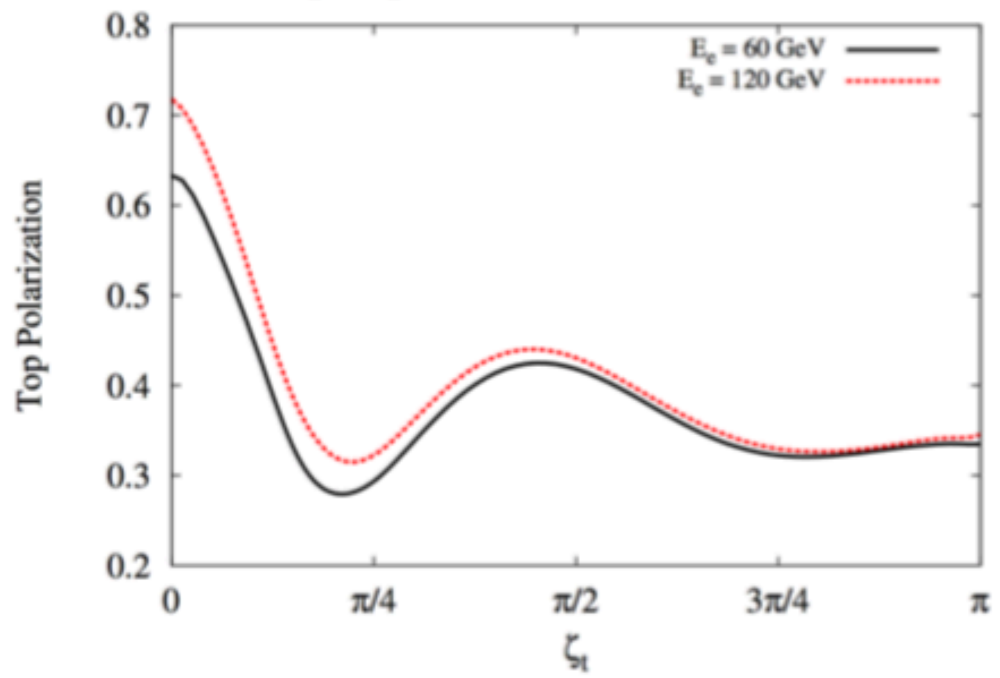
fiducial incl. cross-section



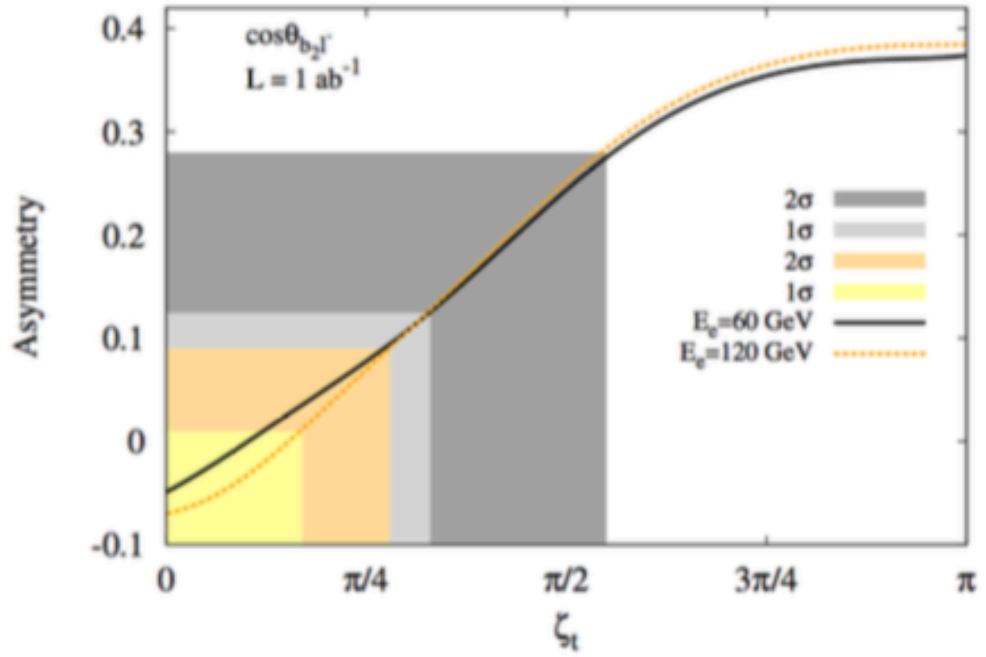
rapidity difference (H,$\bar{t}$)



top polarisation



angular asymmetries (b_2,l^-)



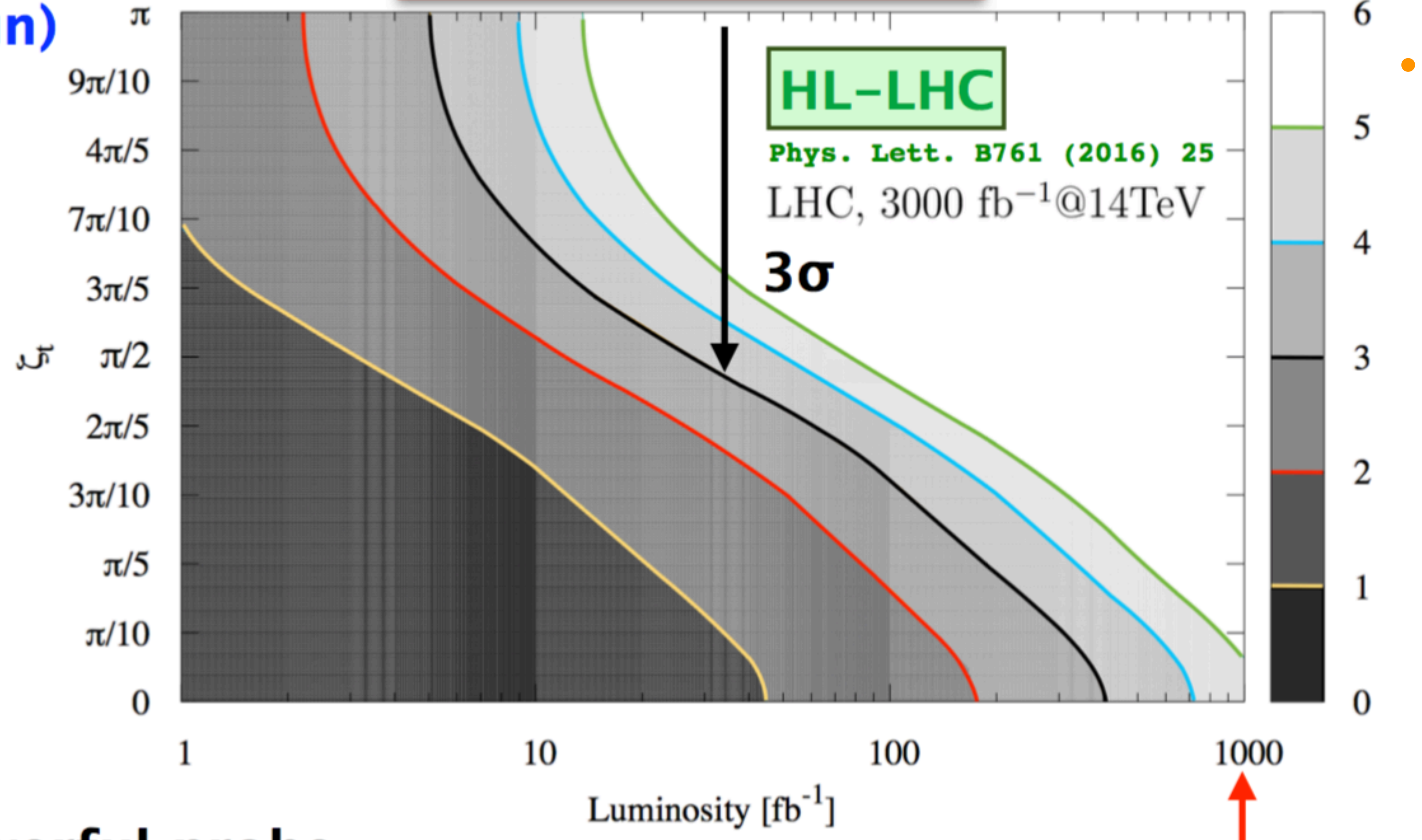
LHeC

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

CP-even
(flipped sign)

CP-odd

CP-even
(SM)



→ powerful probe of ttH coupling

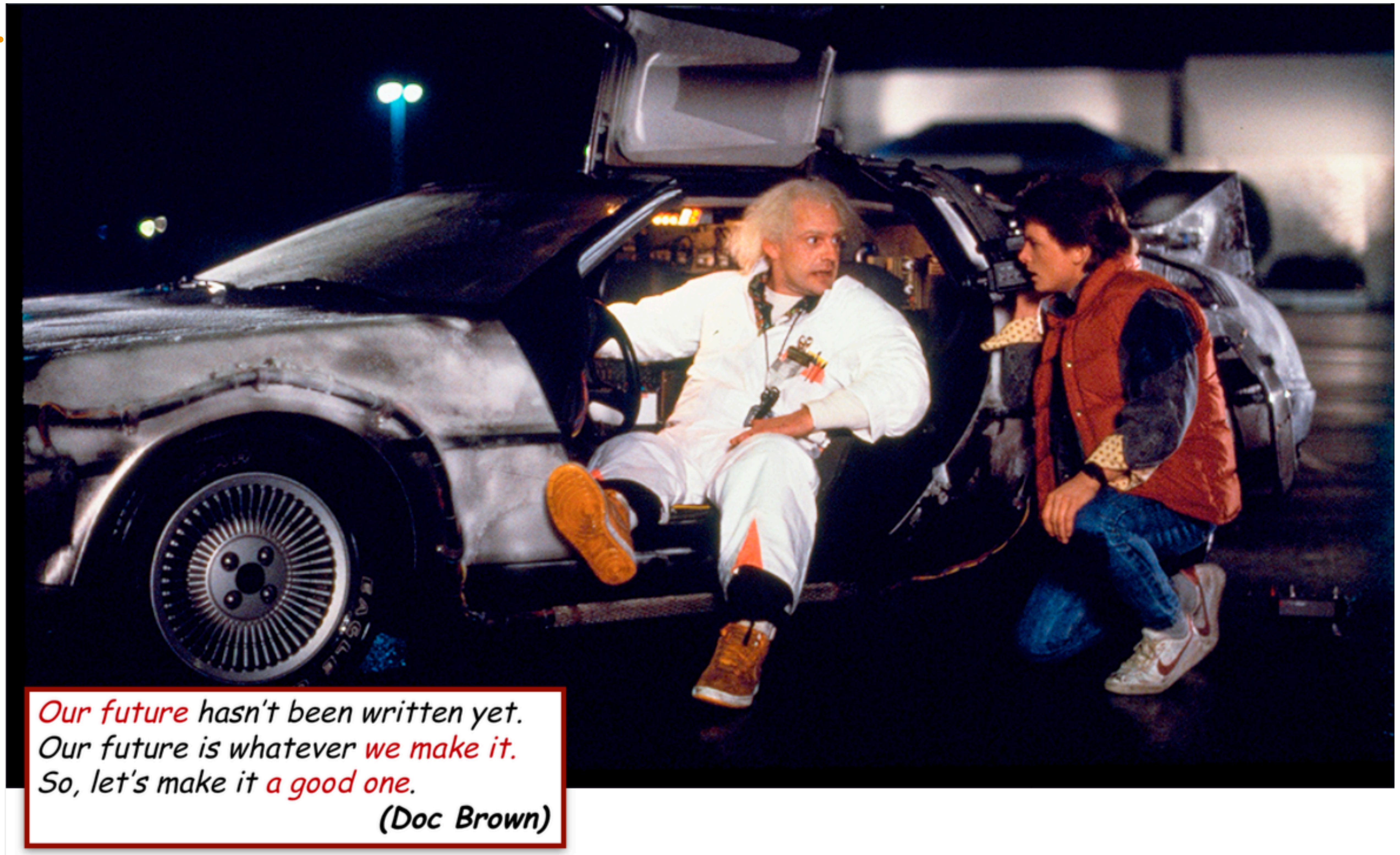
10% uncertainty on background yields

$\kappa = 1.00 \pm 0.17$

- LC: analysis of CP nature profits from direct production at high energies

Conclusions

- **LHeC** great potential for a compelling and competitive physics programme
- This includes electroweak and top quark measurements
- An electron-proton facility represents a seminal opportunity on its own but also in particular in combination of pp with ep
- here only some examples of the studies carried out are presented



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

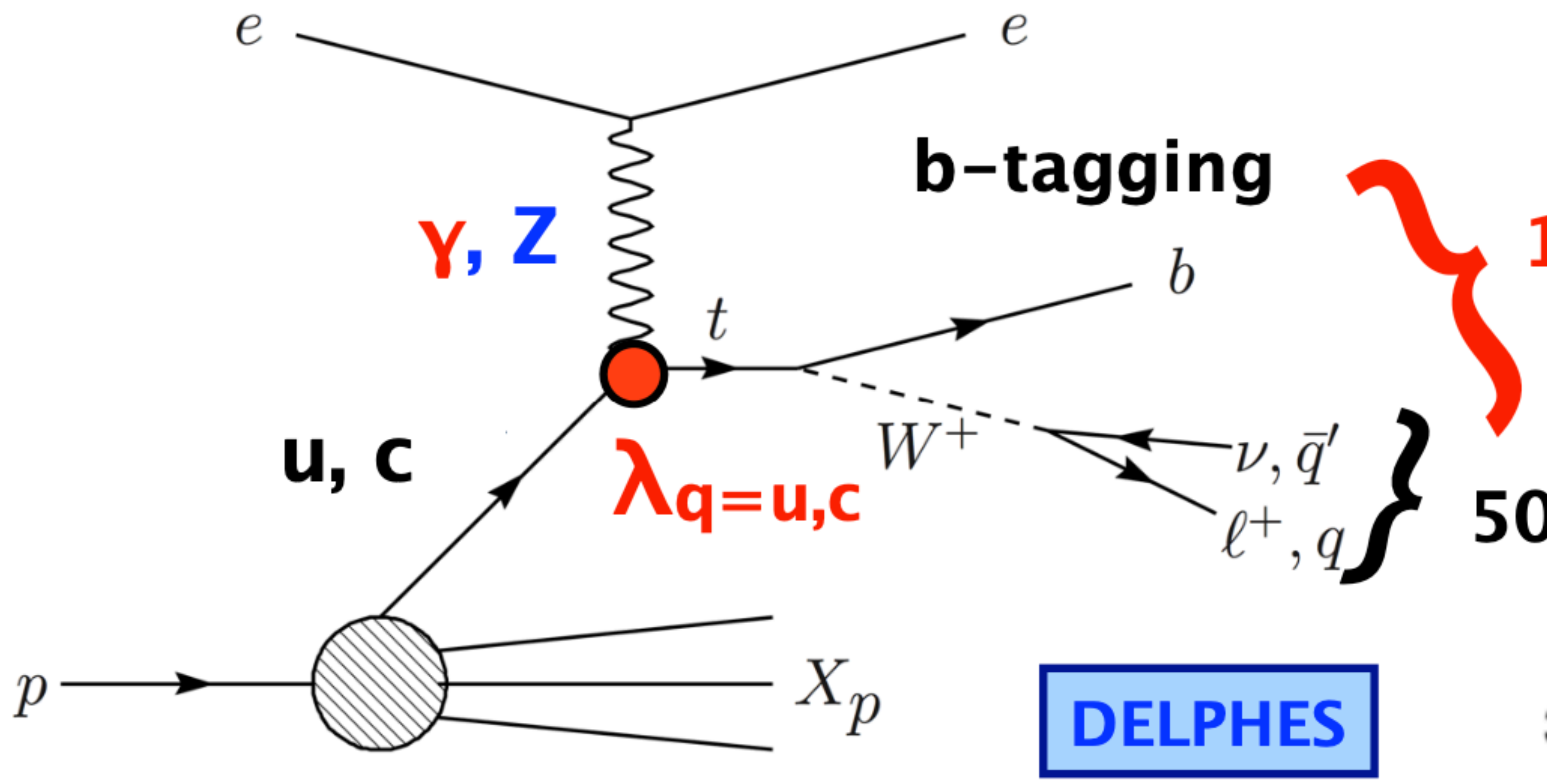
Backup

Anomalous FCNC tuγ, tuZ Couplings

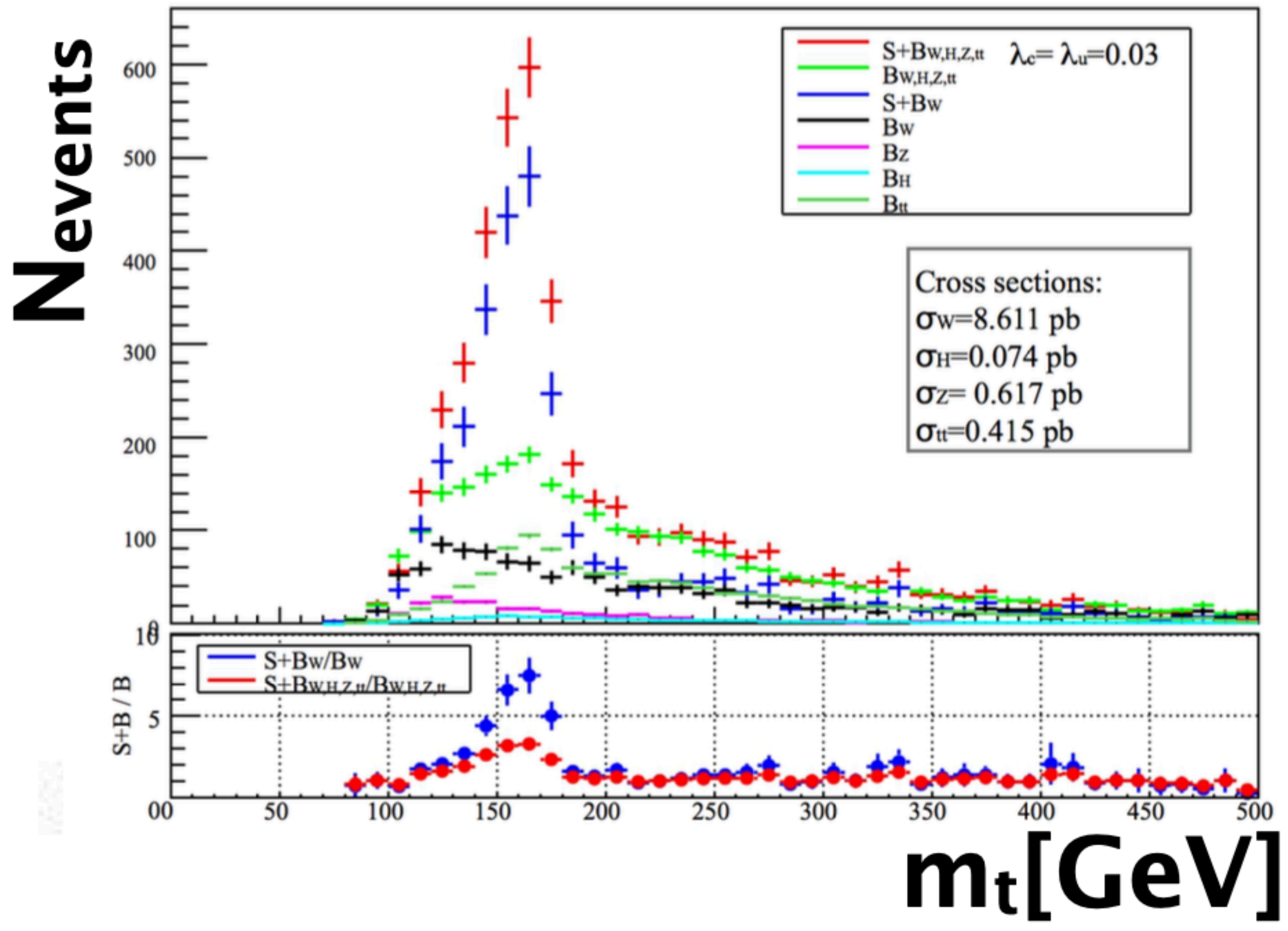
signal

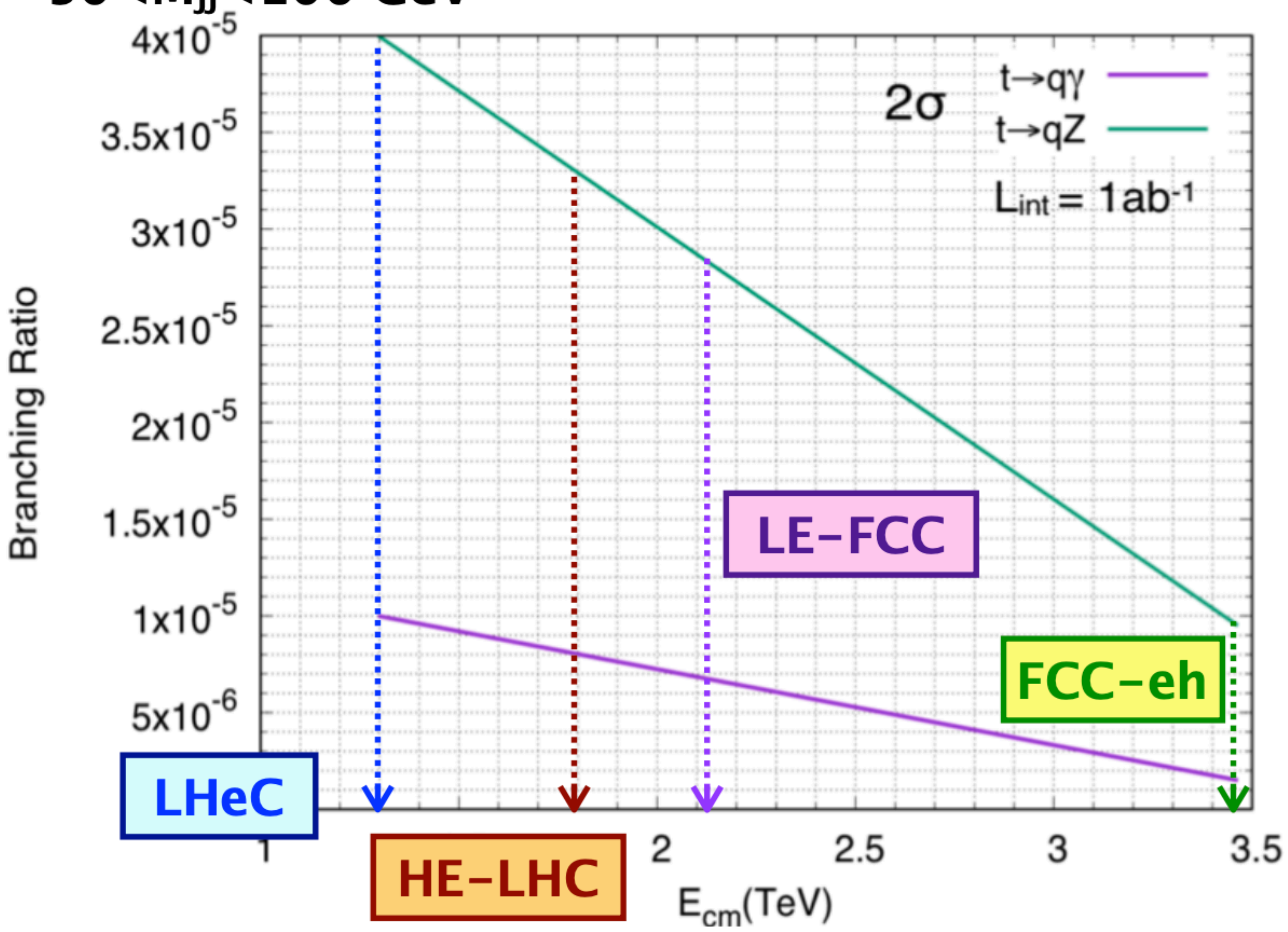
I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

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



DELPHES

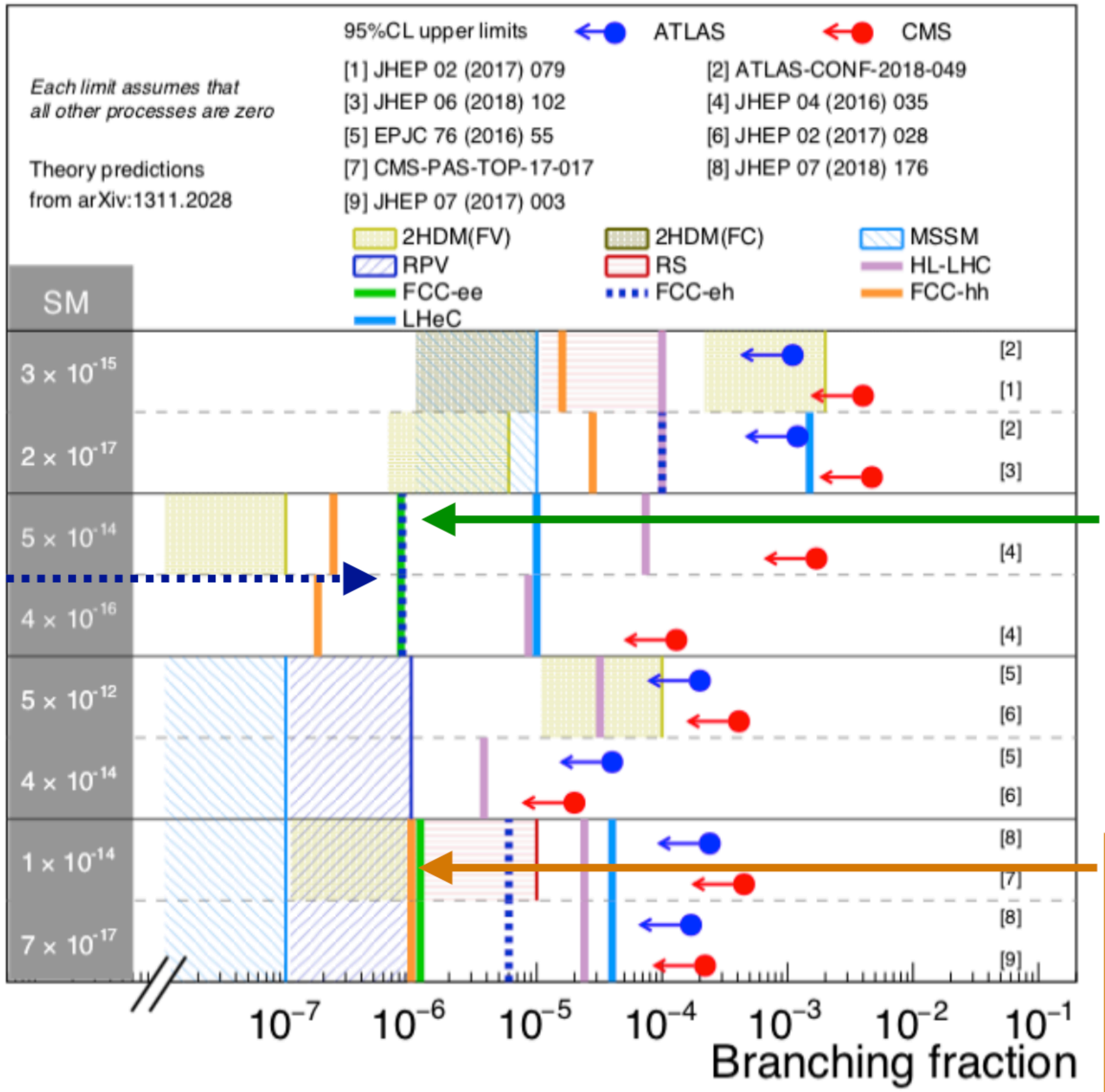




test exotic models leading to FCNC

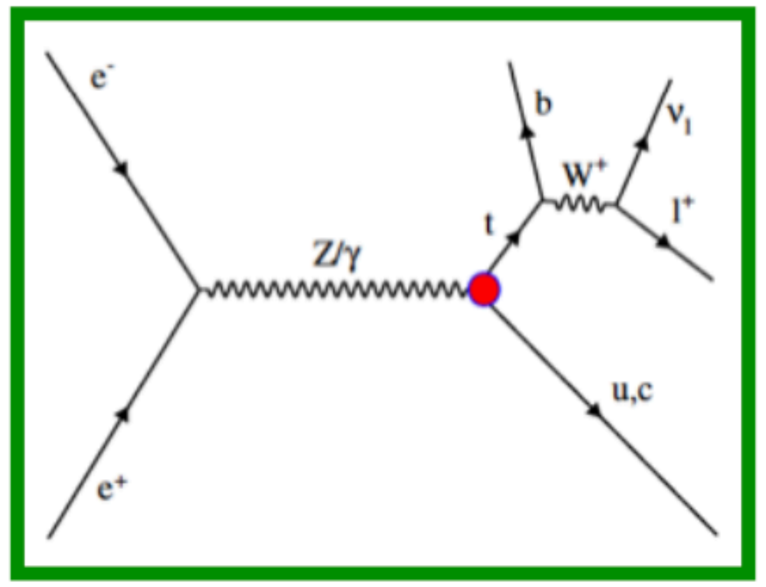
FCNC Top Quark Couplings

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

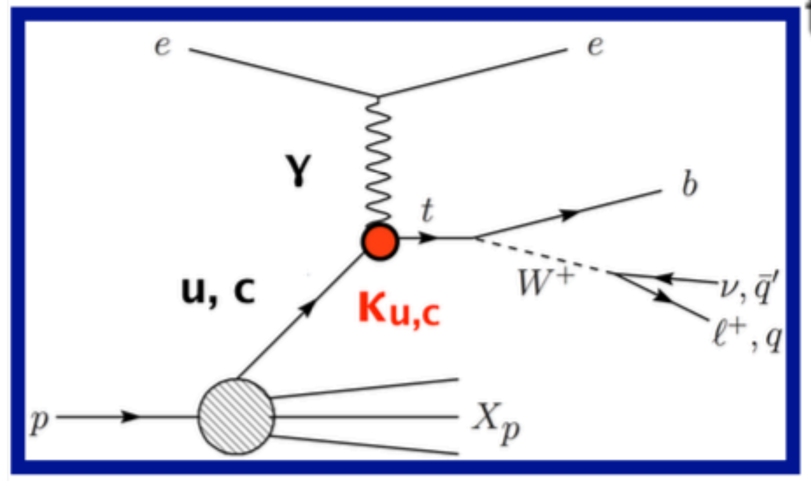


complementarity of colliders

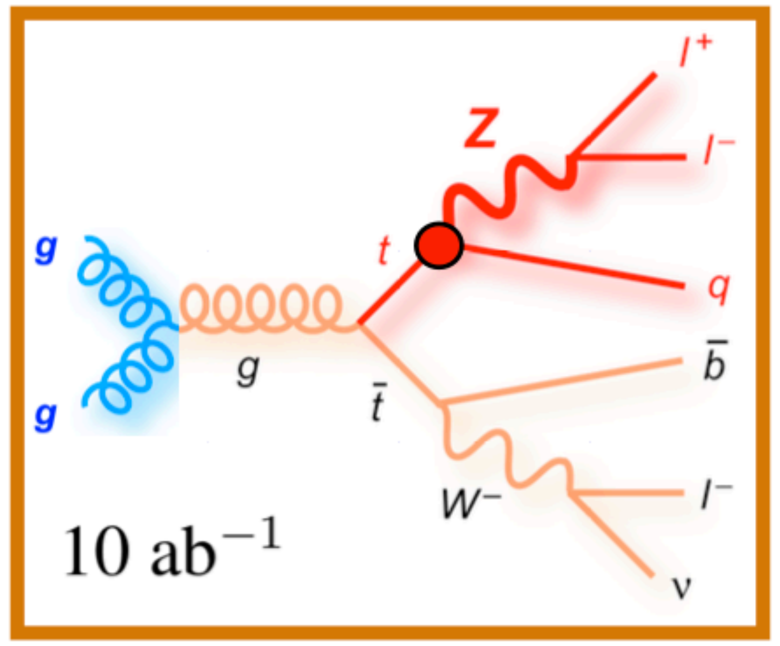
FCC-ee

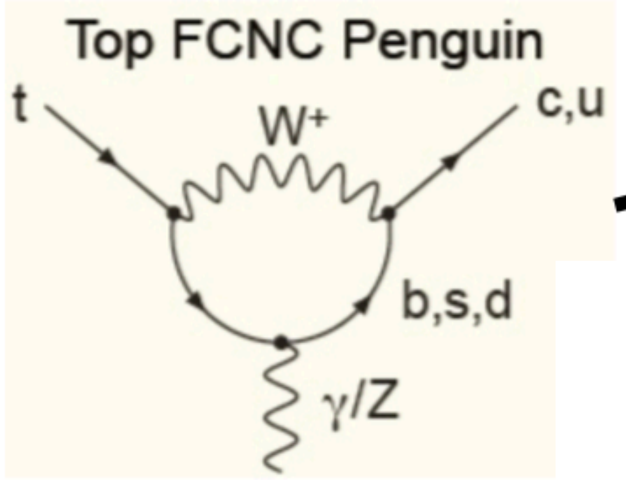


FCC-eh



FCC-pp

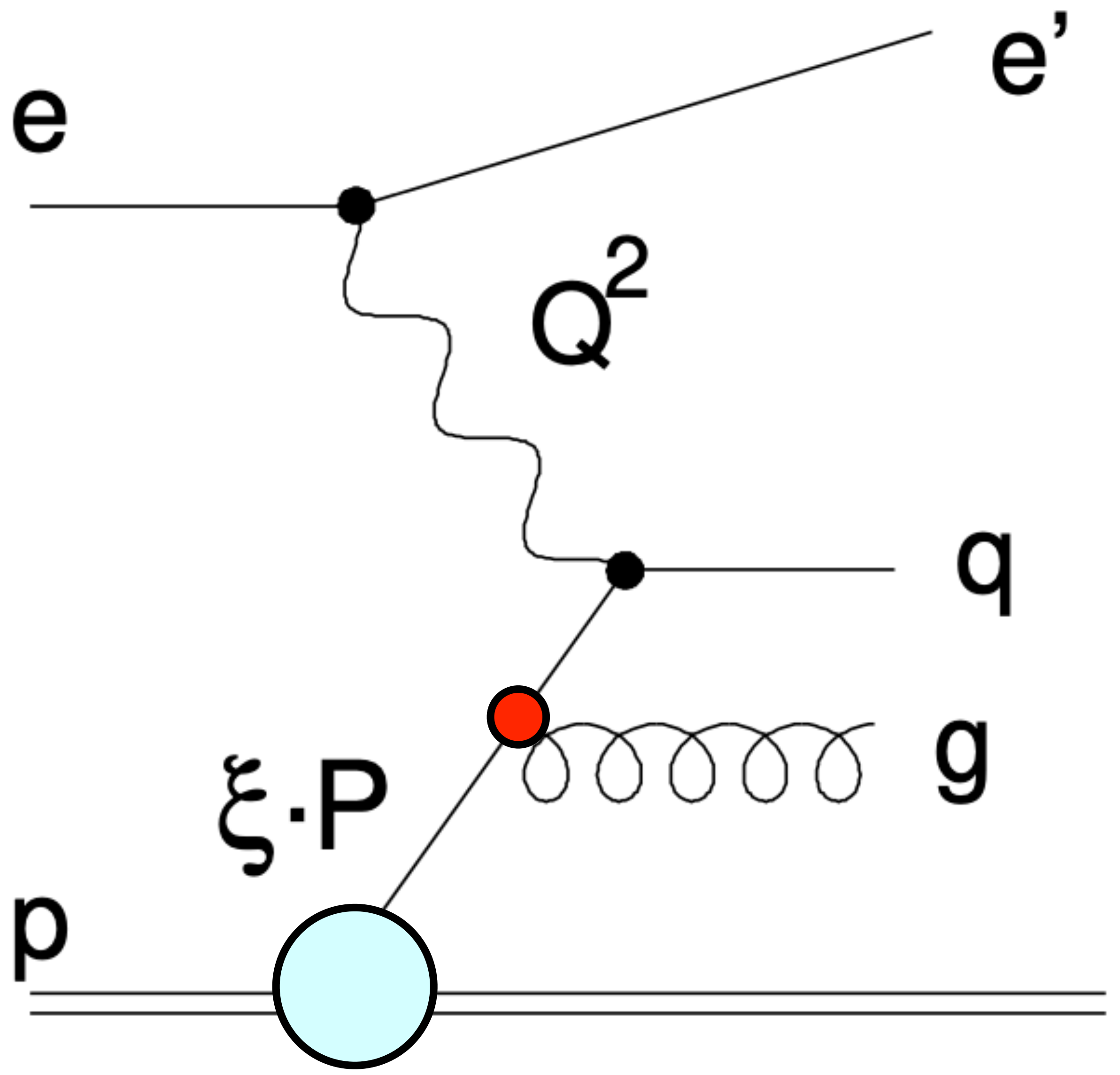


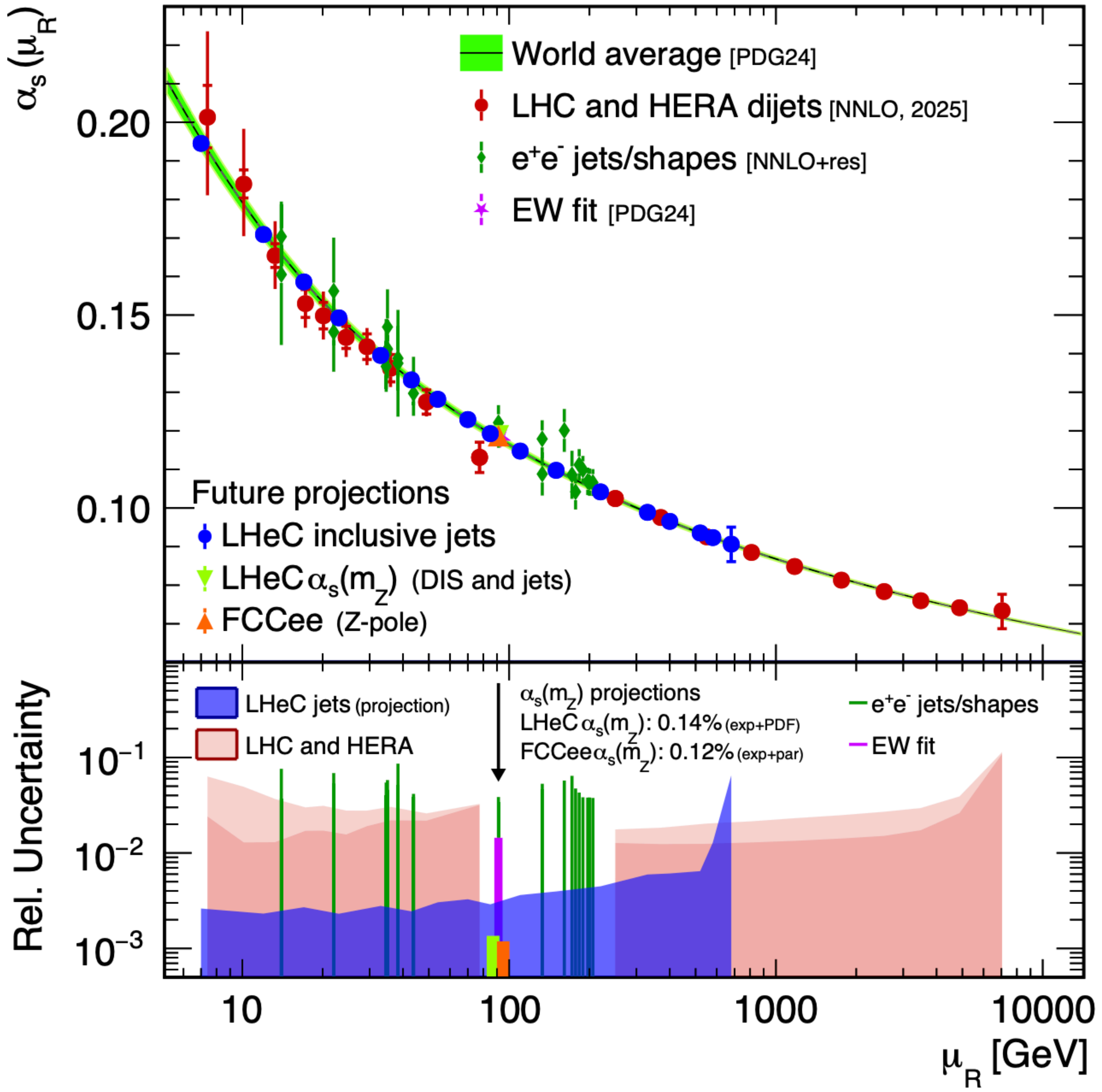


test little Higgs, SUSY, technicolor, …

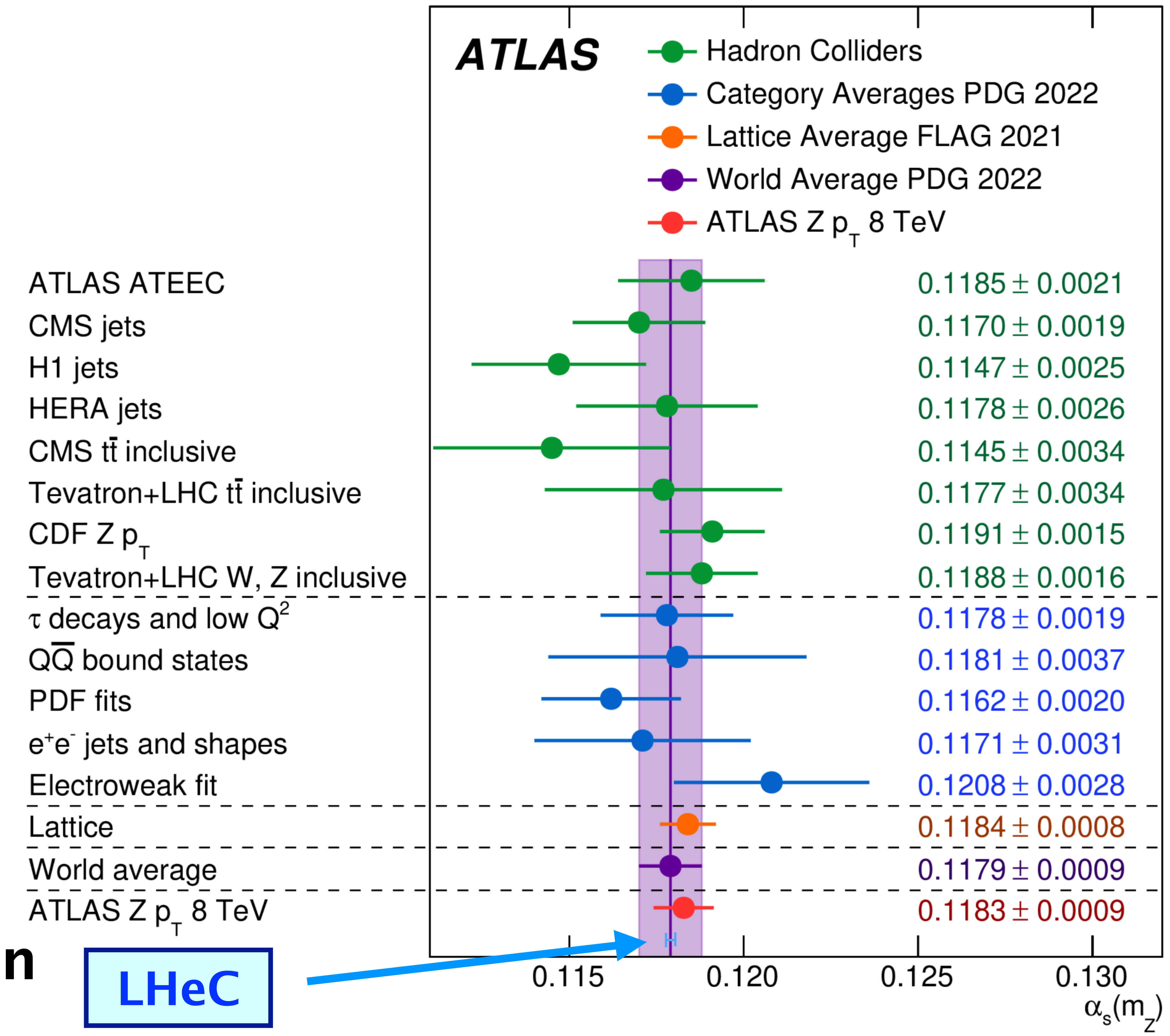
Determination of the strong coupling

- α_s is least known coupling constant





- α_s from fits to ep jet production



LHeC simultaneous PDF+α_s fit:

- $\Delta\alpha_S(m_Z) = \pm 0.00022_{\text{(exp.+PDF)}}$
- $\Delta\alpha_S(m_Z) = \pm 0.00018$ (with ep jets)

LHeC CDRs and arXiv:2203.08271

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

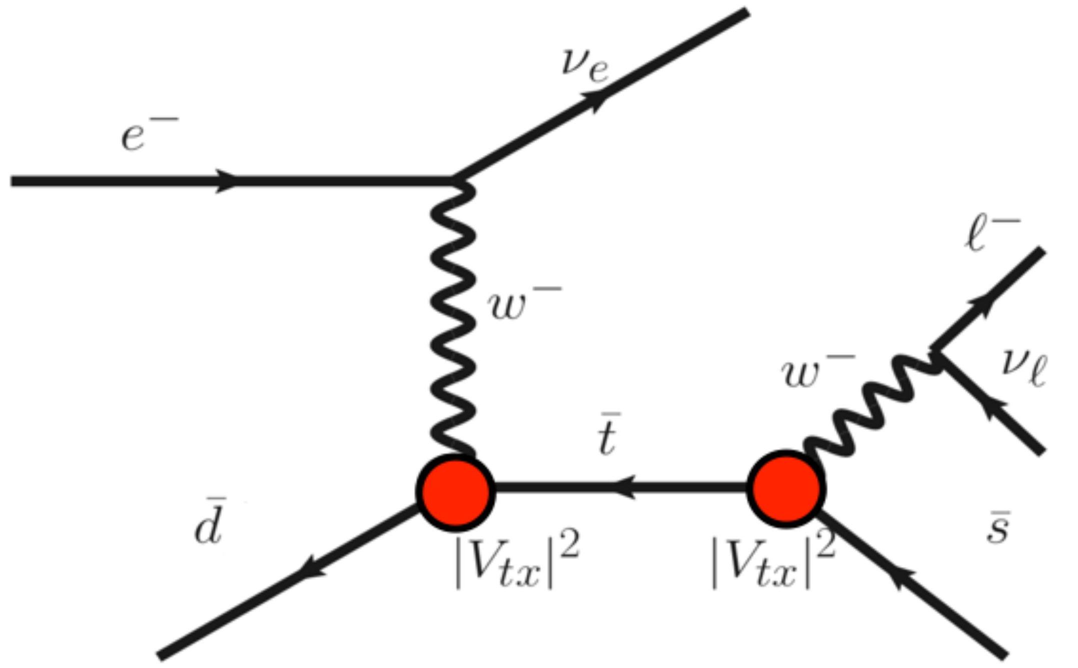
→ considerable improvement of world average

Expected measurements of Wtb couplings

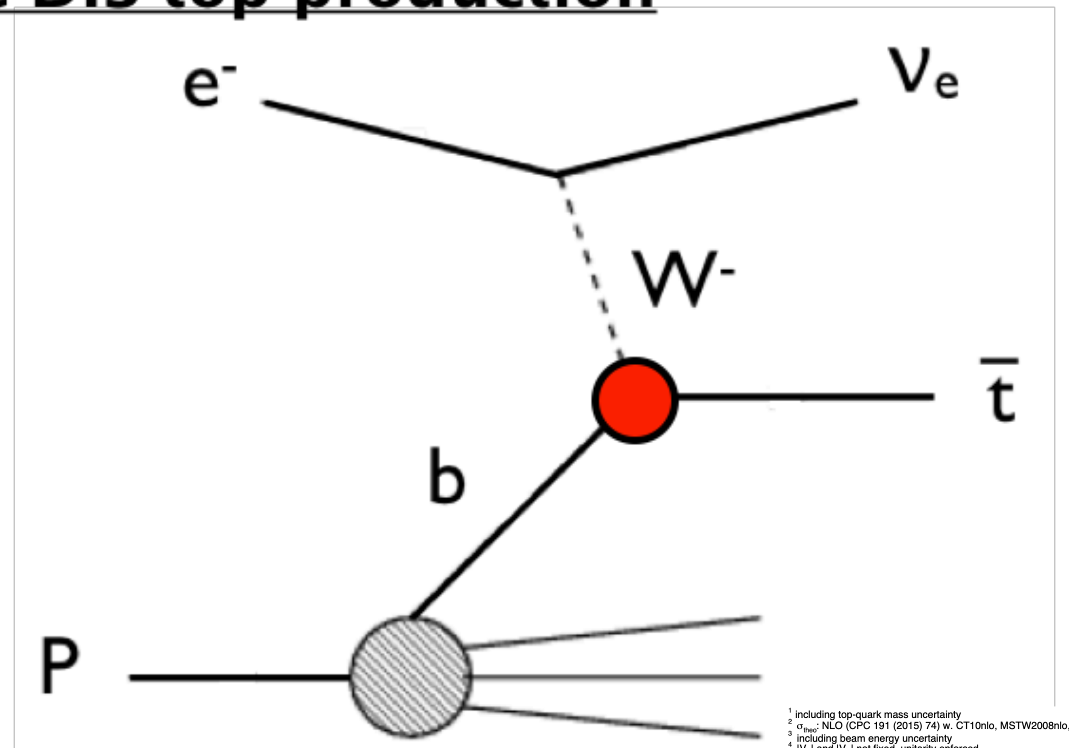
$$L = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}\left(f_V^L P_L + f_V^R P_R\right)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(f_T^L P_L + f_T^R P_R\right)tW_\mu^- + h.c.$$

= 1 in SM

Dutta, Goyal, Kumar, Mellado,
arXiv:1307.1688
Kumar, Ruan, to be publ.

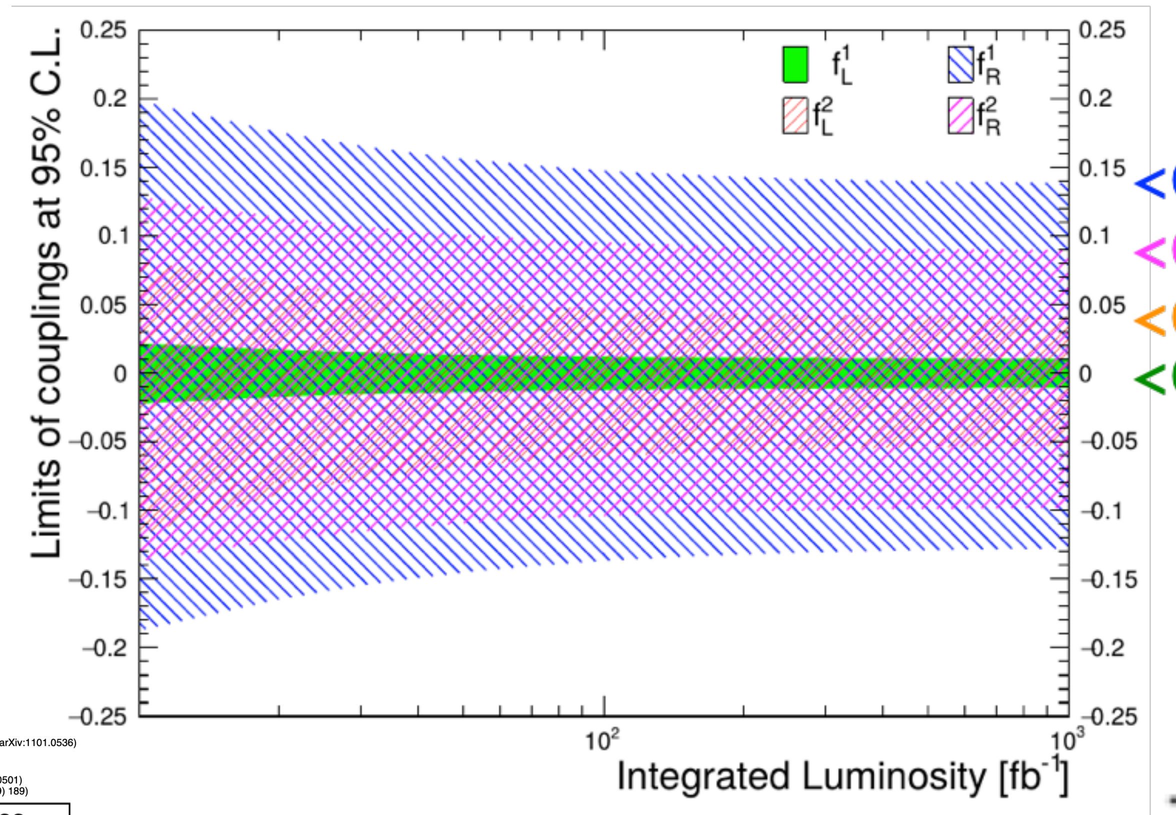


CC DIS top production



hadronic channel:

LHeC



<0.14
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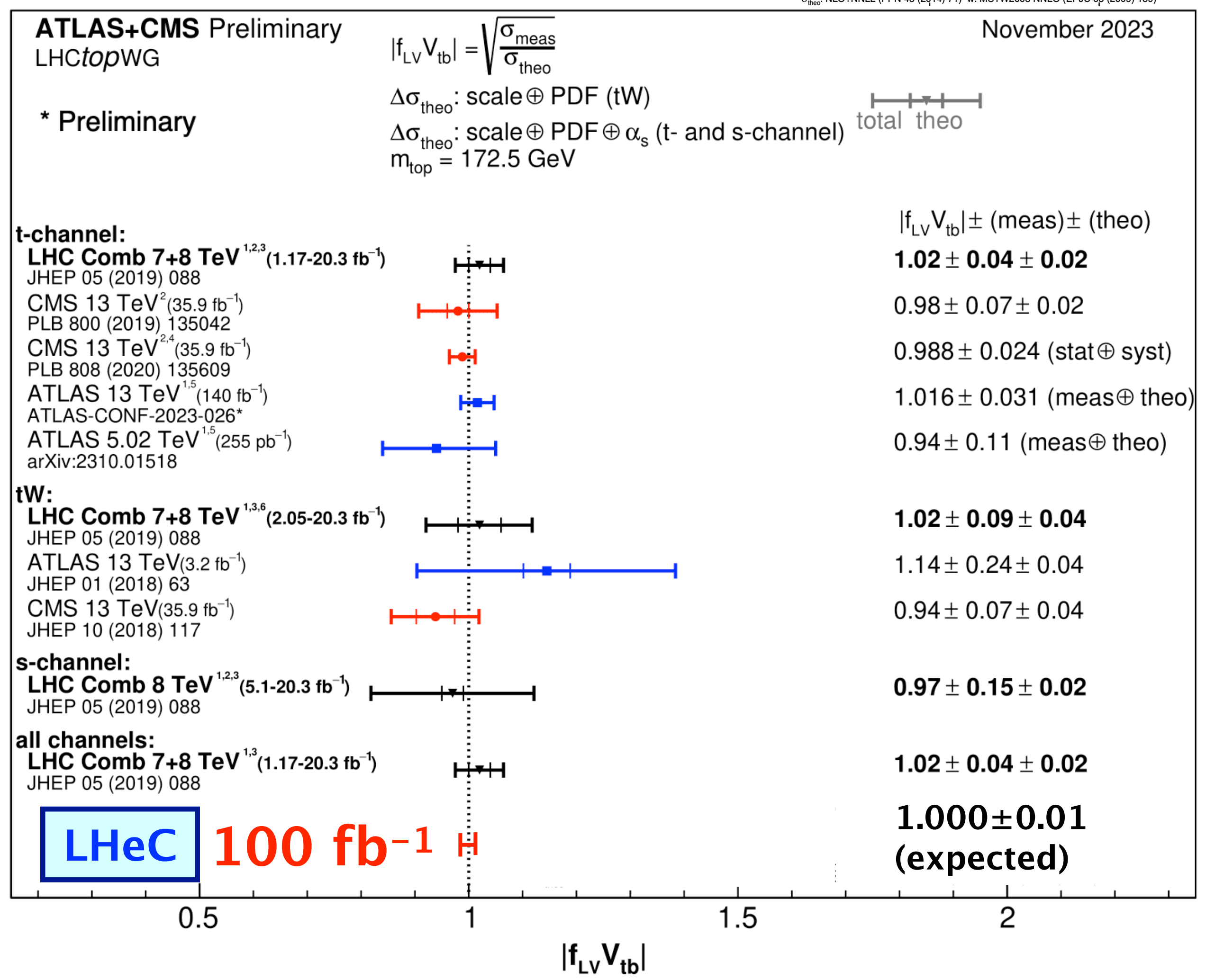

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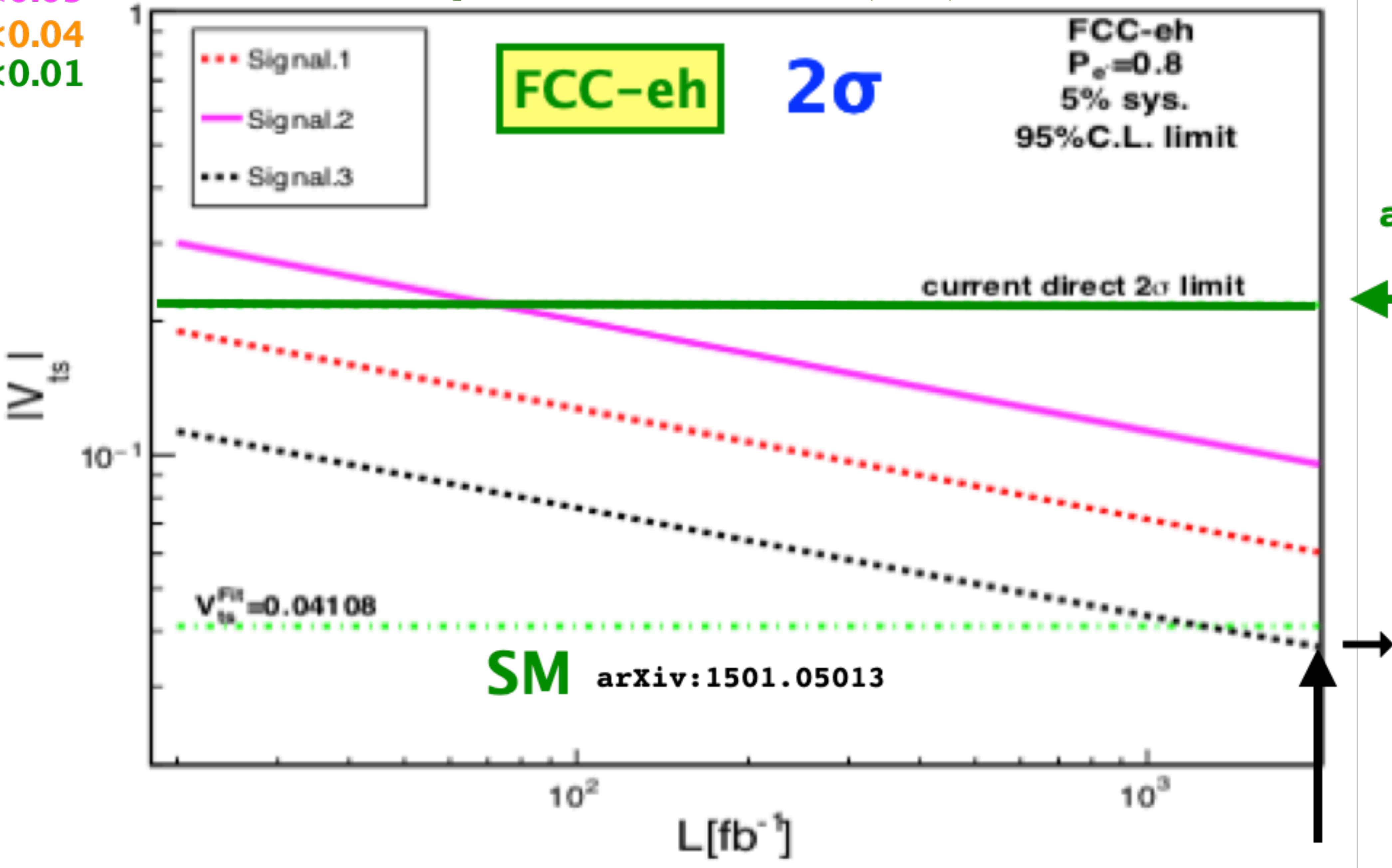
Unprecedented precision < 1%

FCC CDR, Eur. Phys. J. C 79, no. 6, 474 (2019)   H. Sun PoS DIS 2018, 167 (2018)



arXiv:1709.07887

LHC

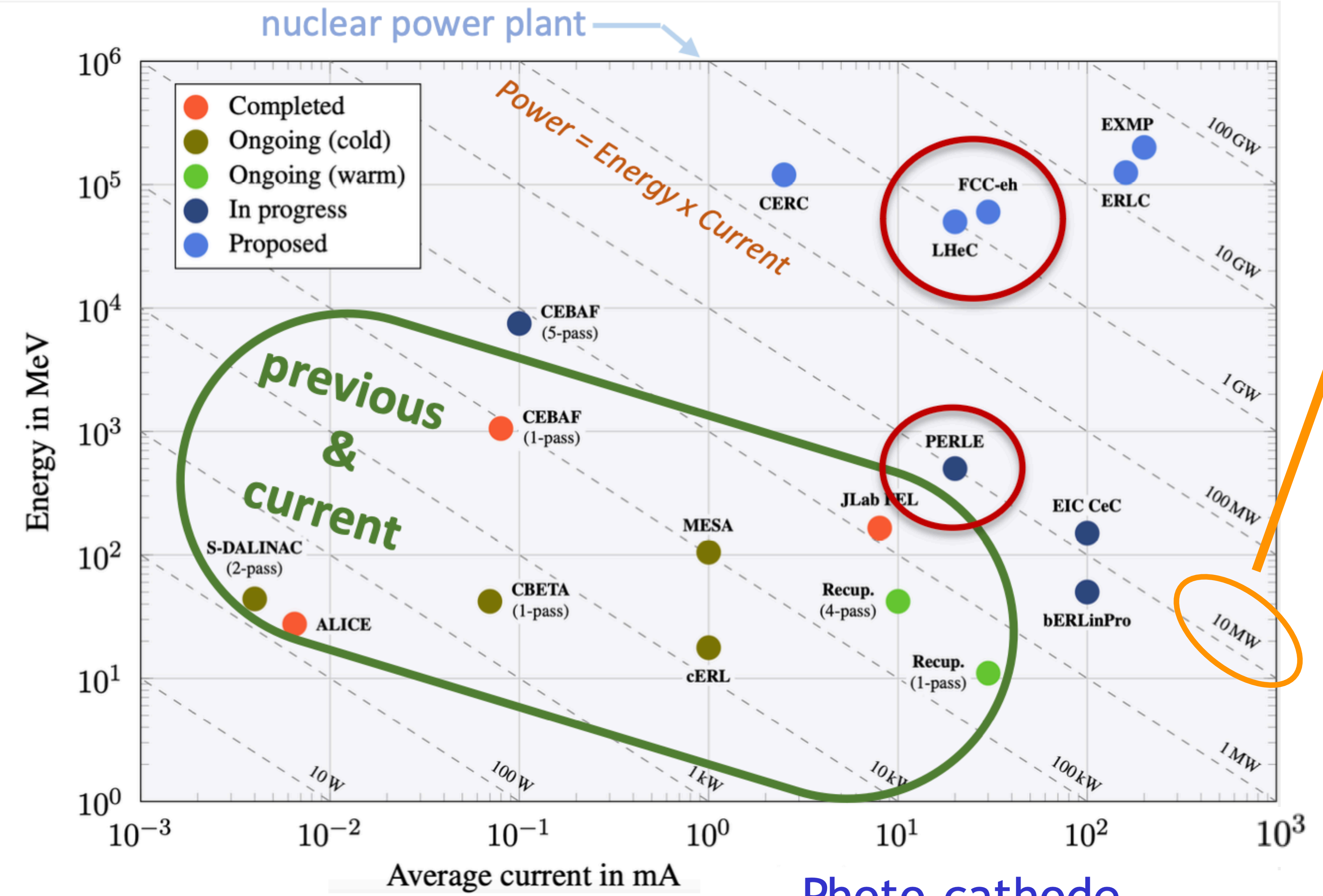
→ $|V_{ts}|$<0.037

Probing SM prediction directly for the first time

Status of the facility: Energy Recovery Linacs (ERL)

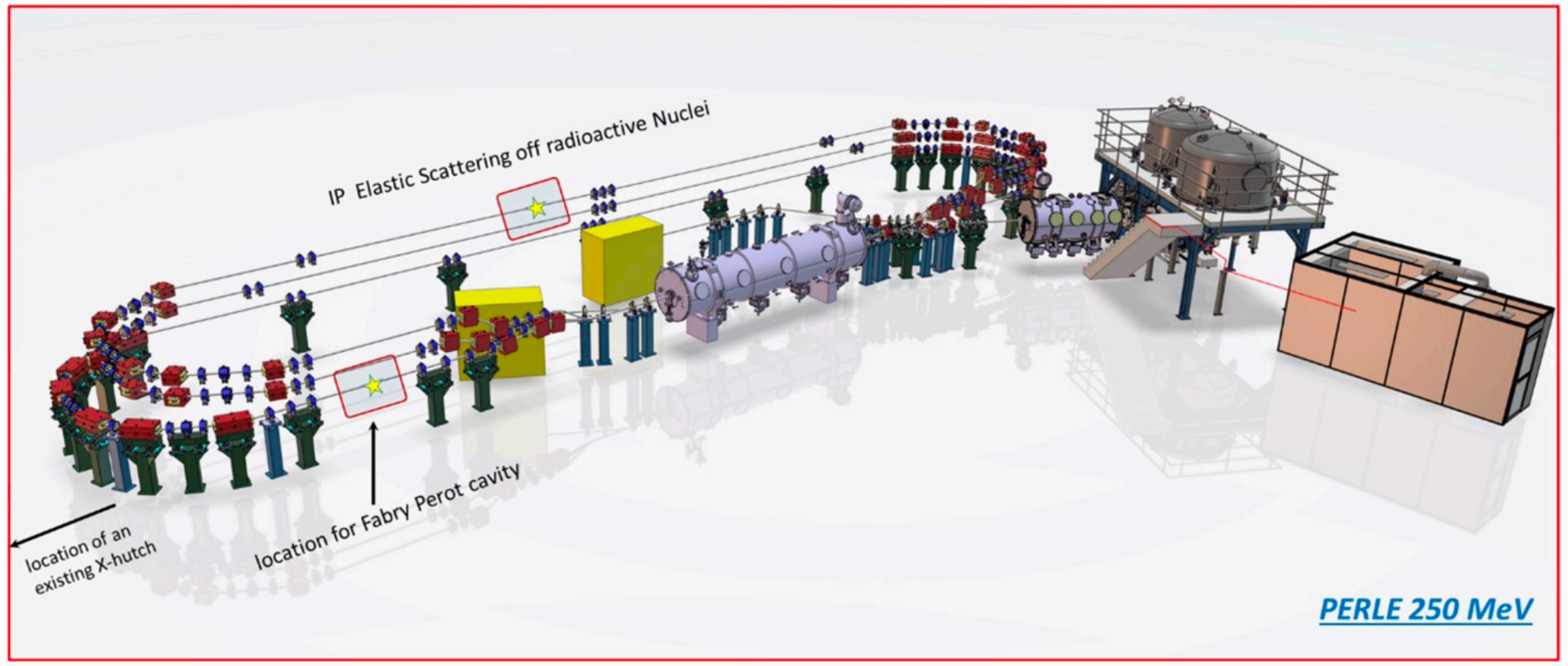
- Demonstrating ERL: scalability is critical path
- Prototype (PERLE @ IJCLab / Orsay) implementation started
- First stage (one turn) by 2028, 3 turns in 2029

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



→ first 10 MW ERL facility

HV tanks



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

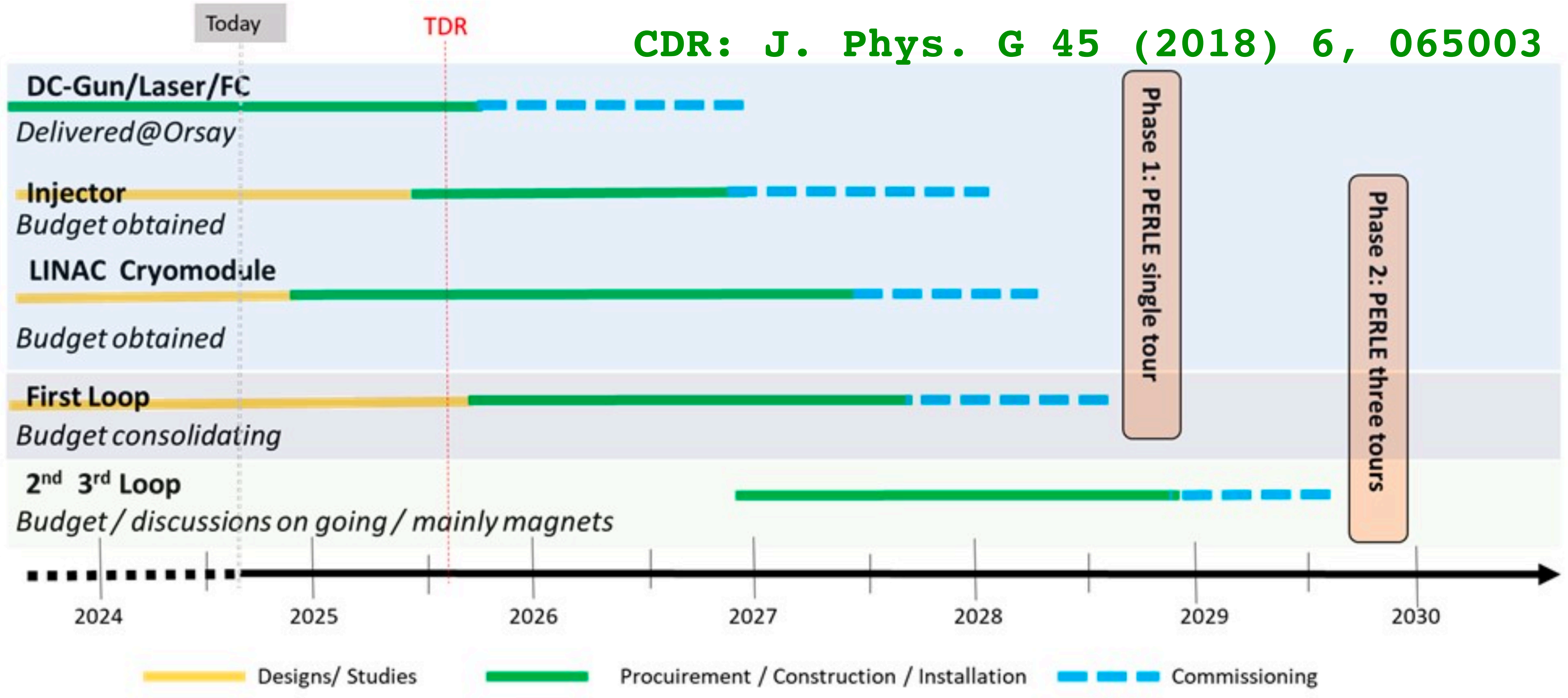


Photo-cathode

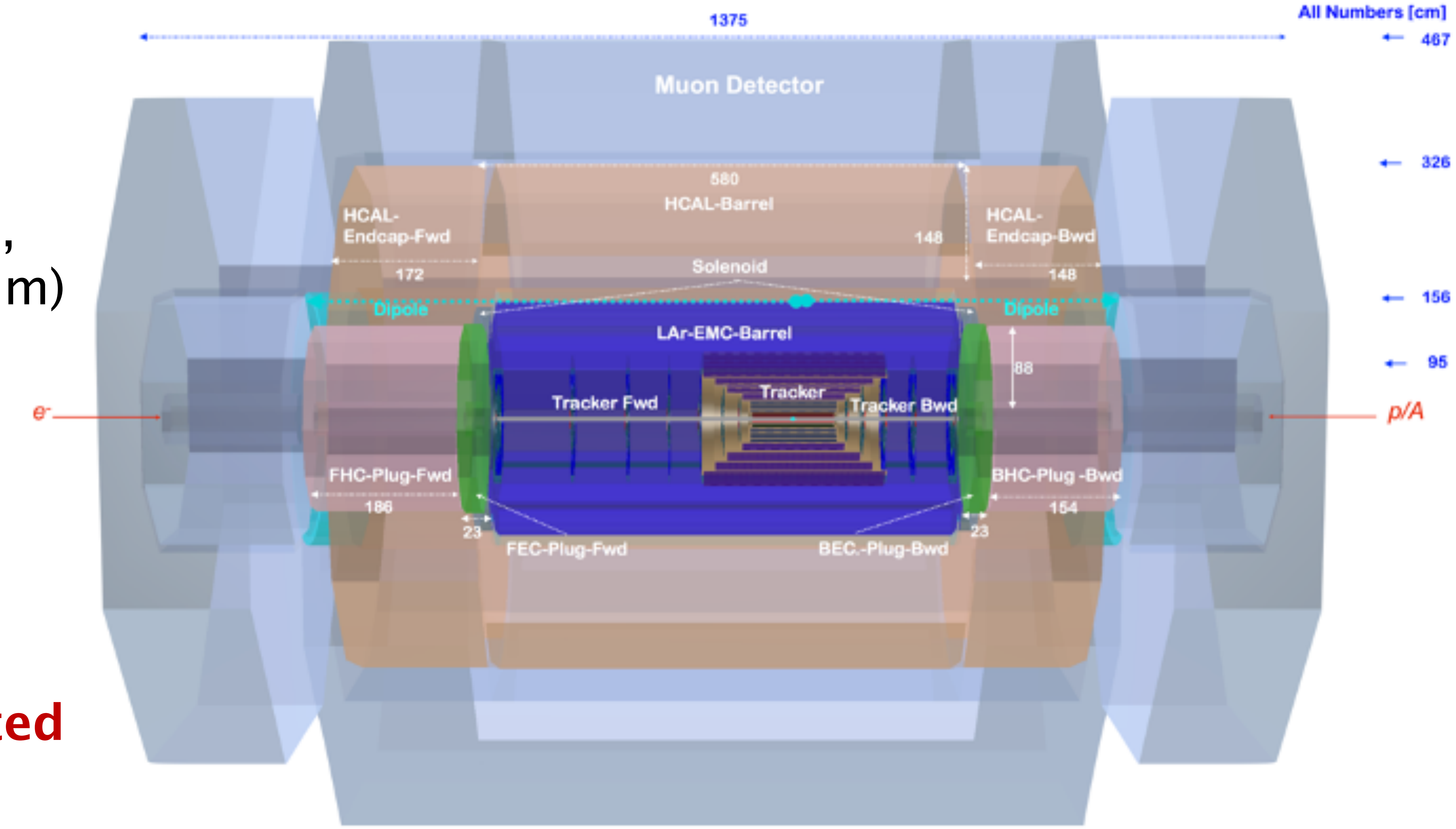
Electron DC-gun

R&D Need: Detector Design

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

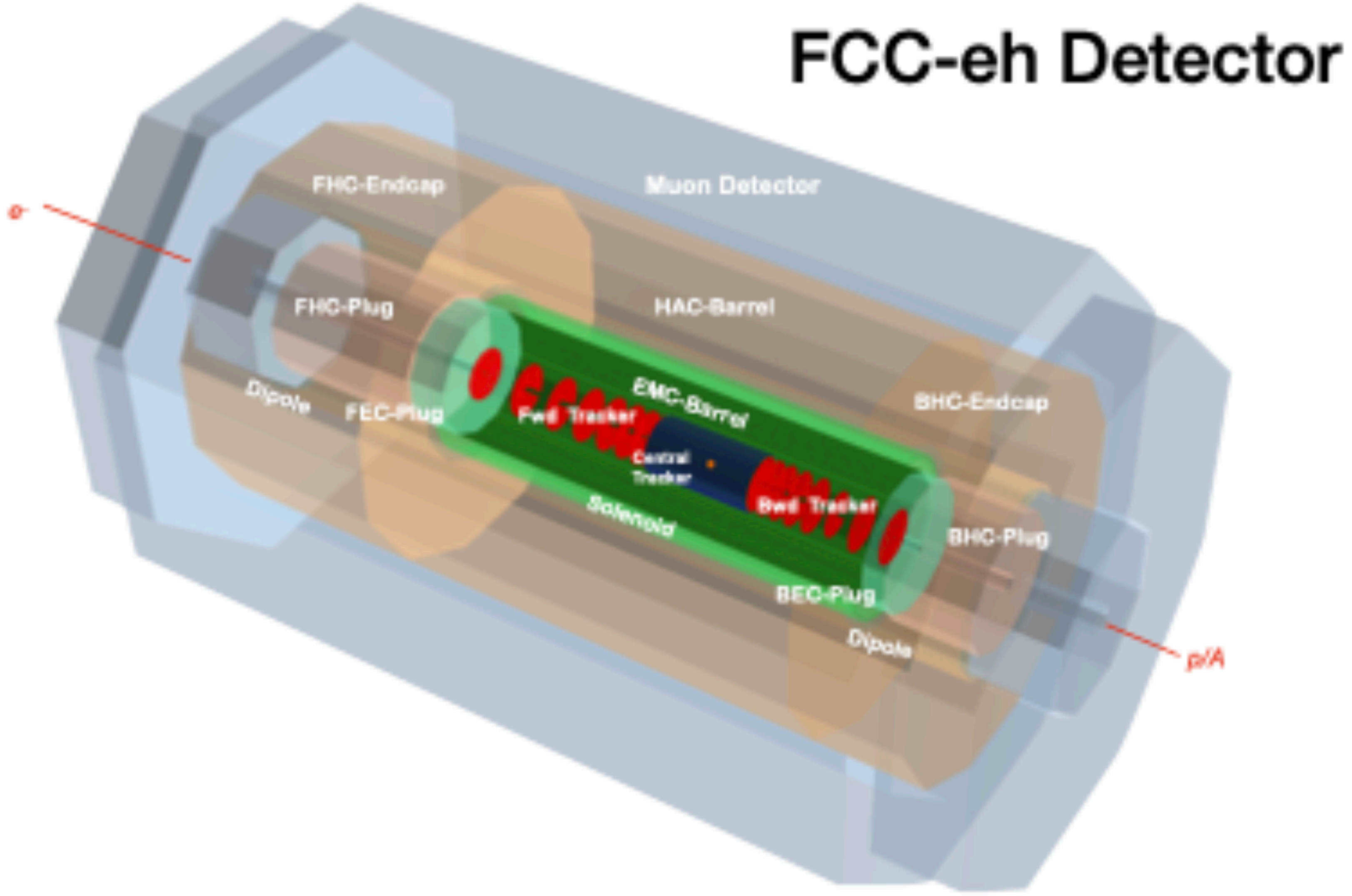
Hermetic
– 1° tracking acceptance forward & backward

Beamline also well instrumented



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

FCC-eh: 19m x 12m



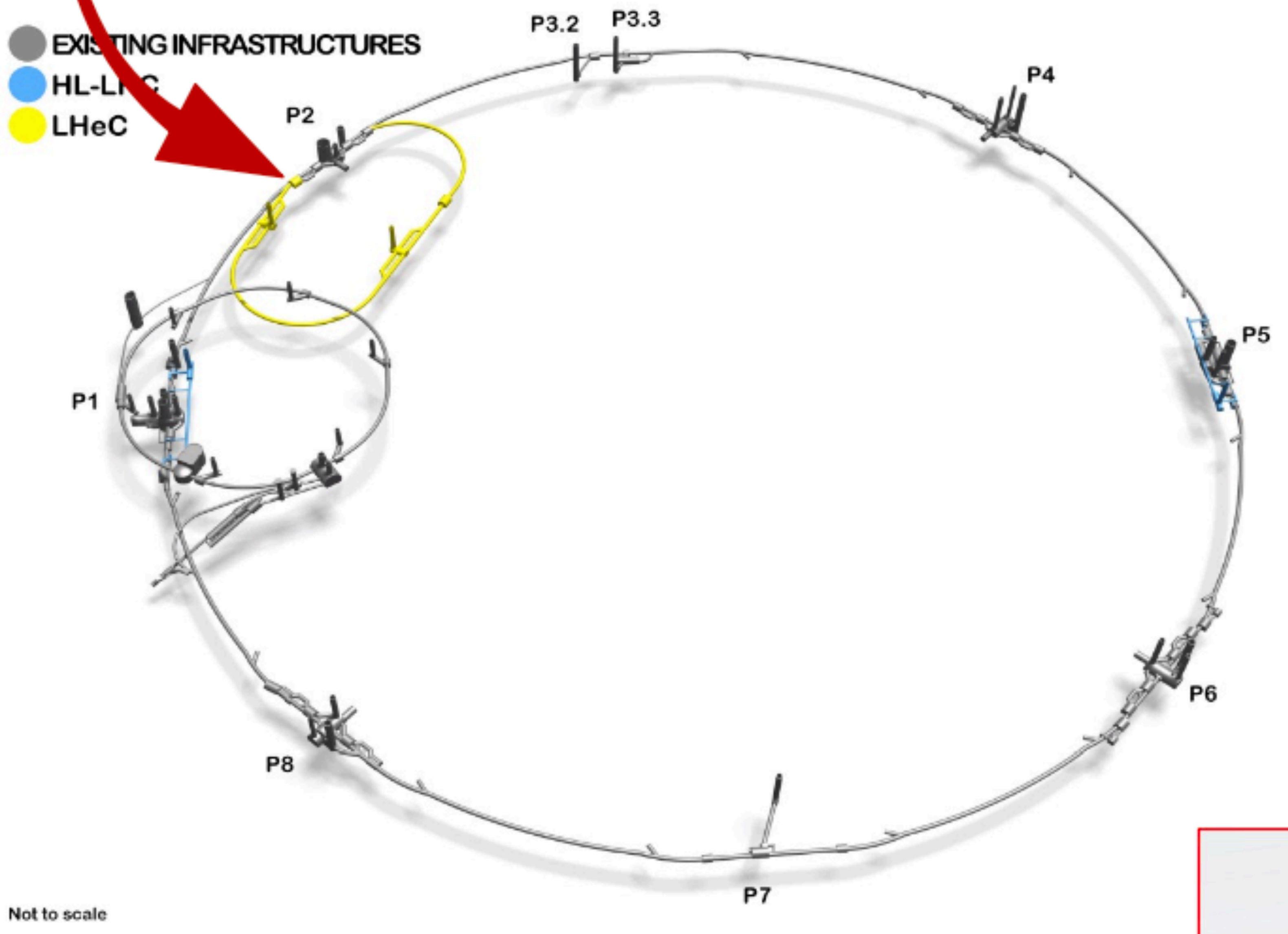
Could be built now, but many open questions:

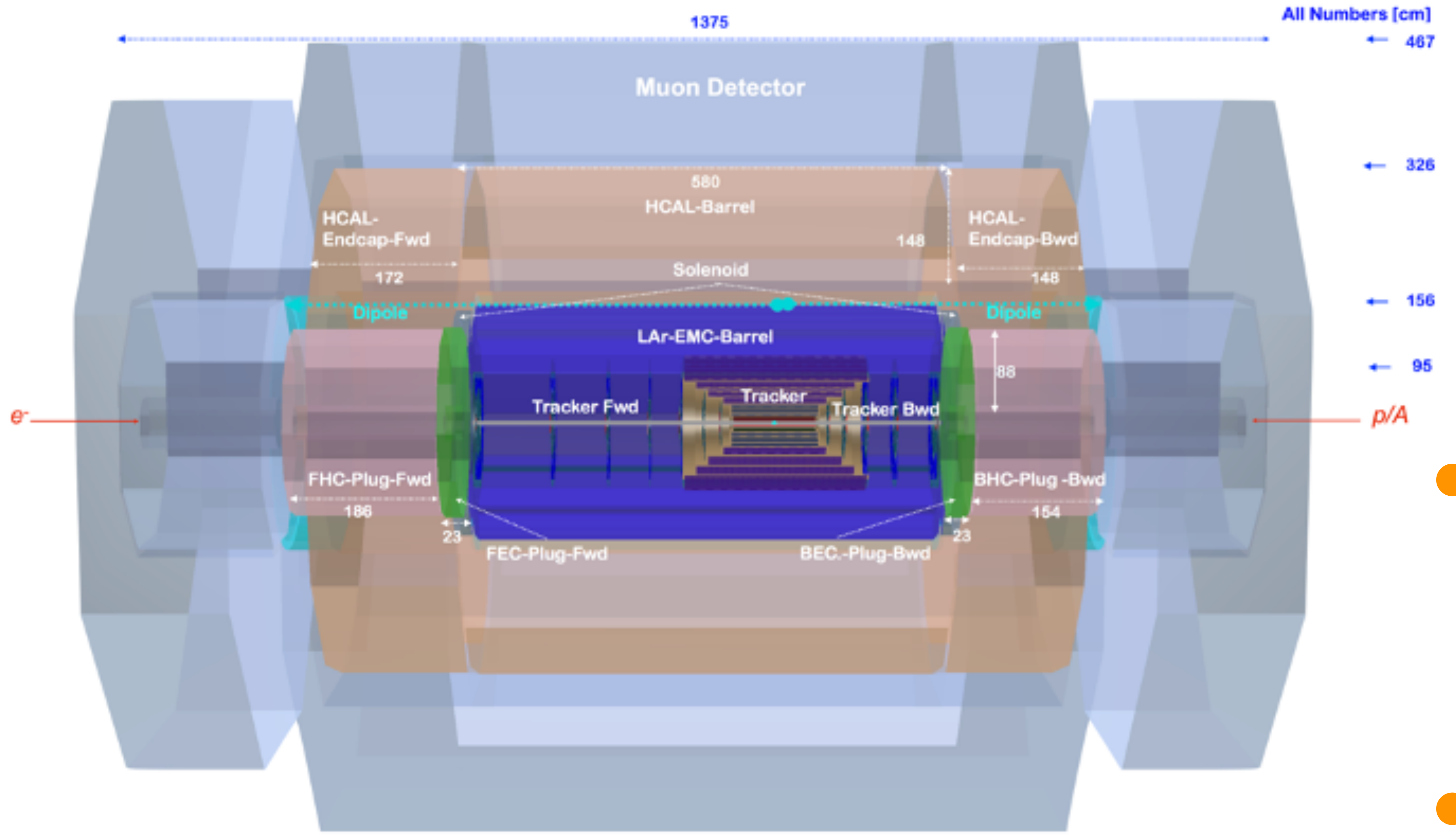
– a snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
– possibly lacking components for some ep/eA physics (e.g. Particle ID)
– not particularly well integrated or optimized

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

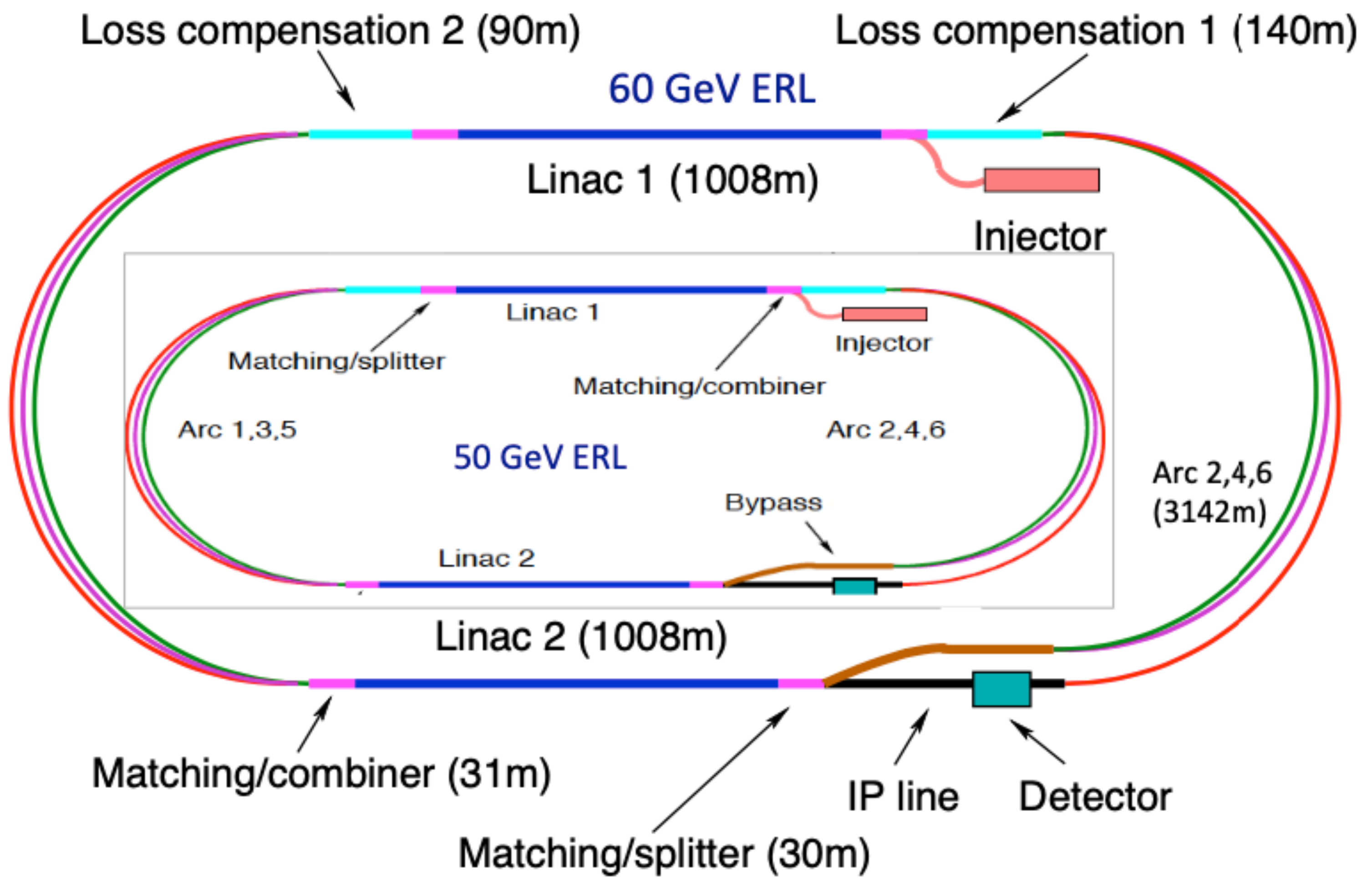
Estimates of sustainability

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

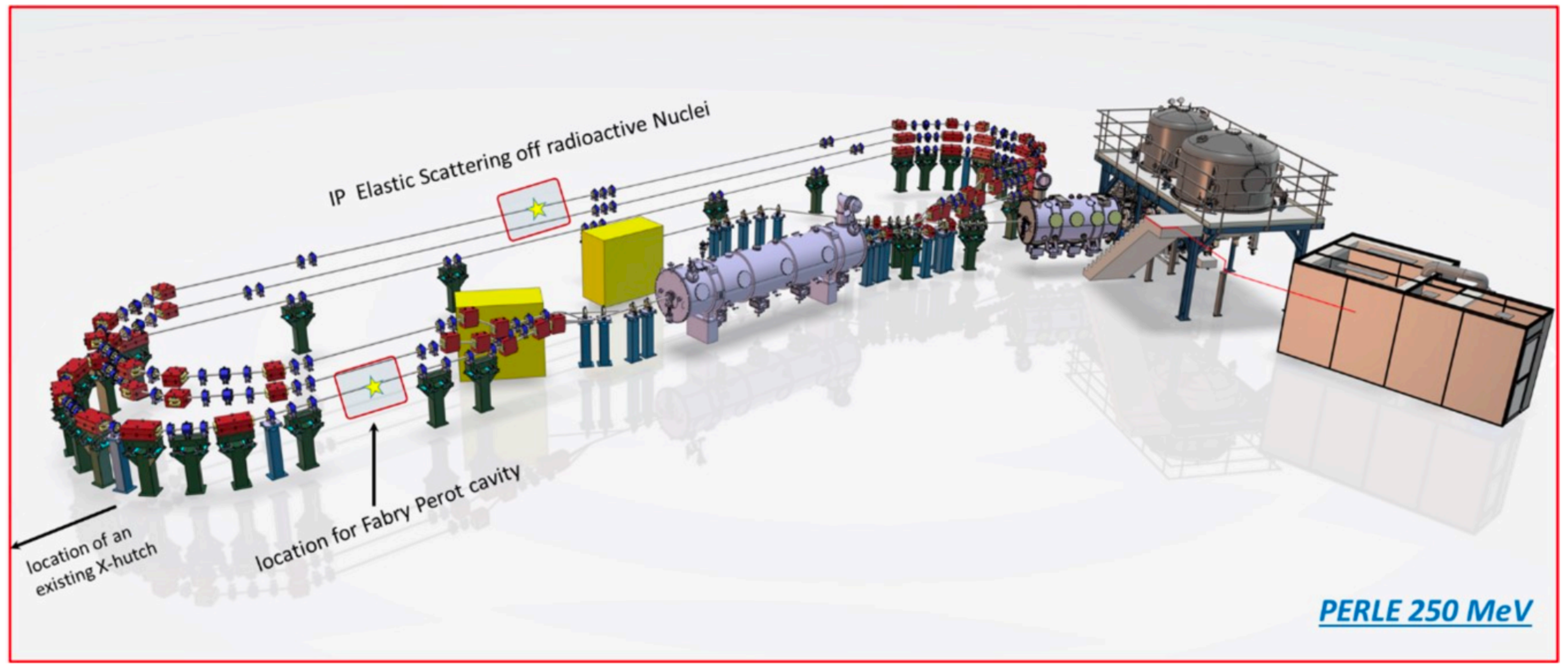




- ‘sustainable’ acceleration:
  ~100 MW (similar to LHC today)
- green technology



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



Costs and personpower

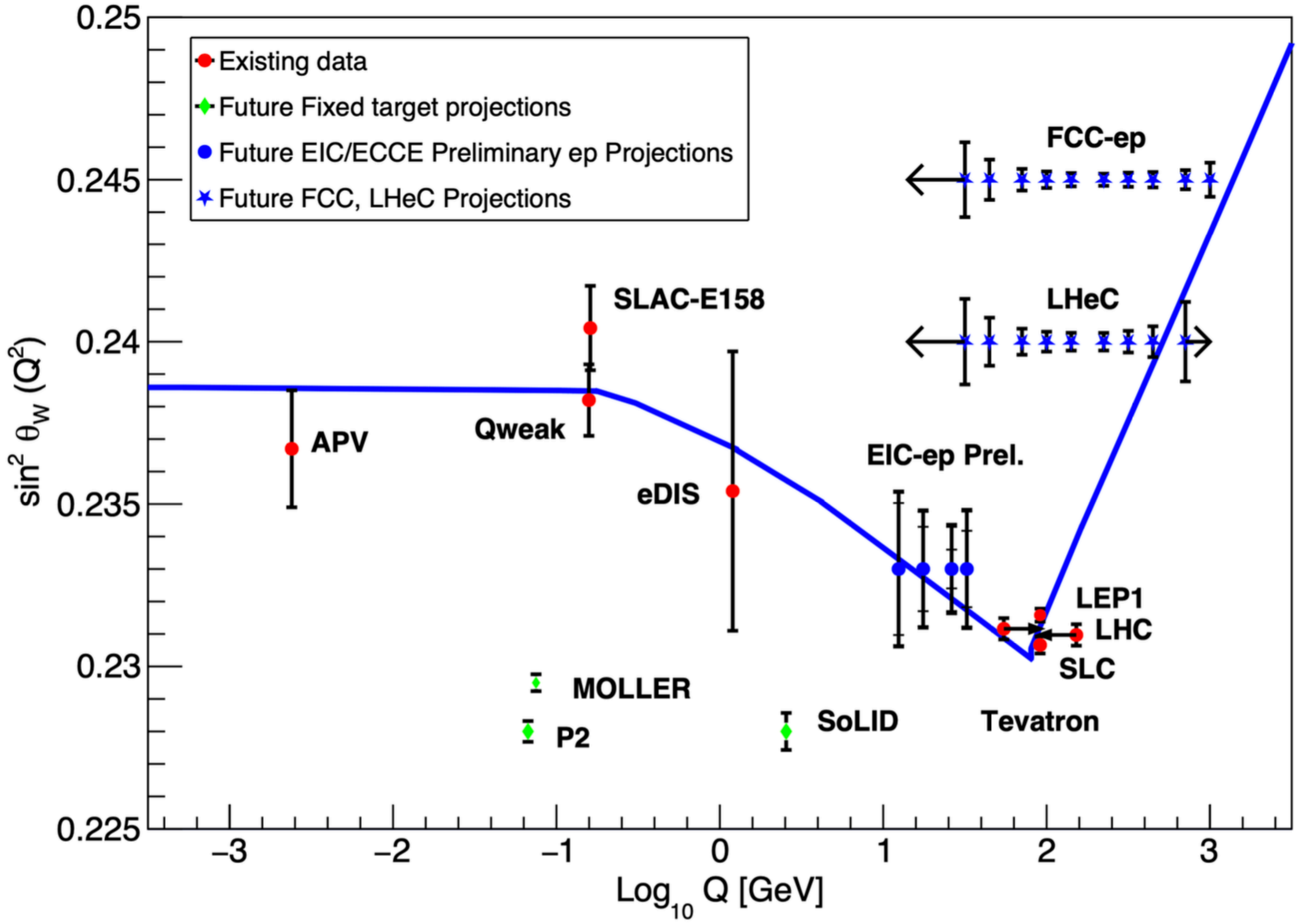
CERN-ACC-2018-0061, ATS report approved by director of accelerators, Frederick Bordry

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

costs: 2018

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

Effective electroweak mixing angle



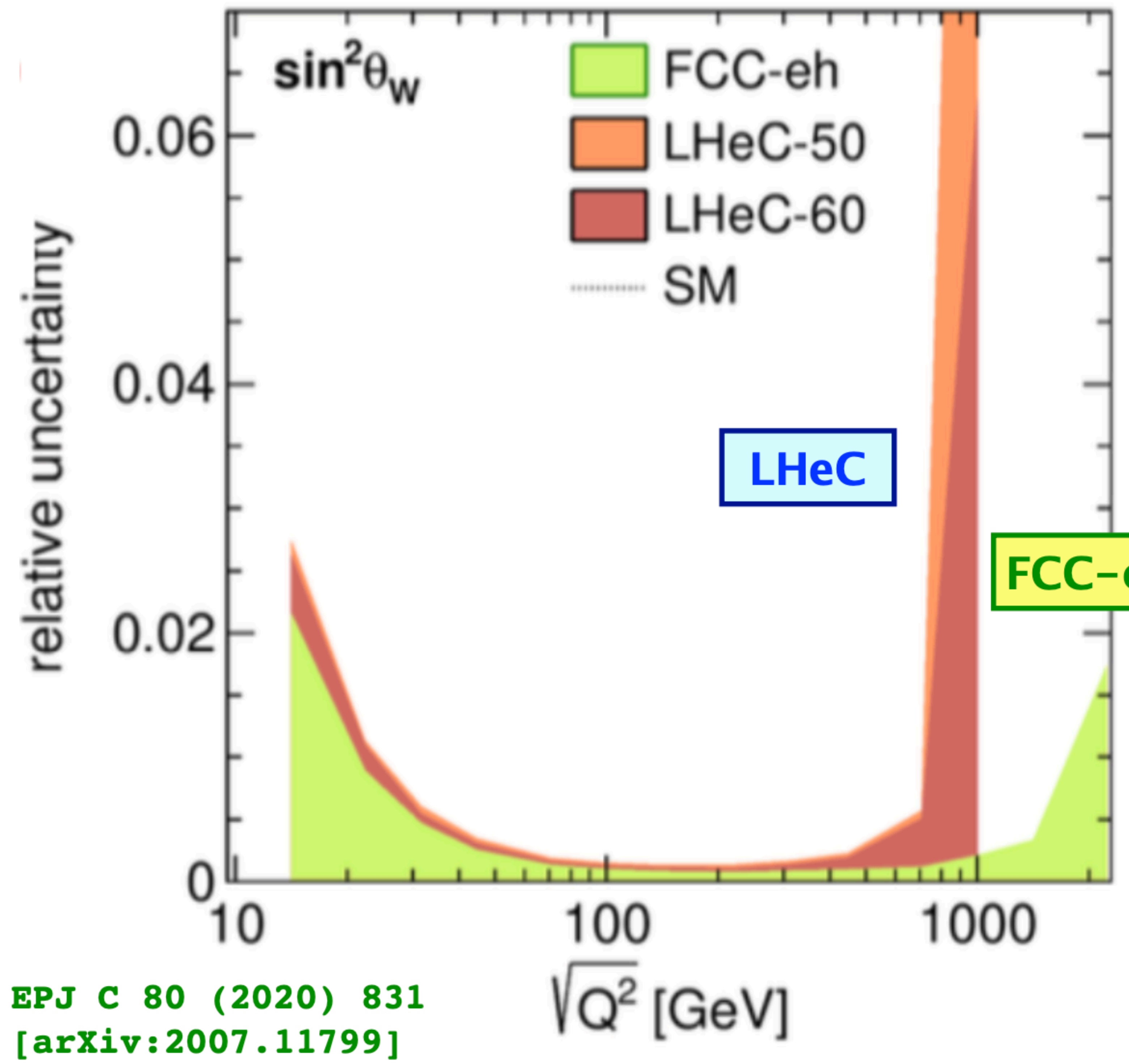
FCC-eh

LHeC

→ **probe large range of scale dependence**

arXiv:2203.06237

NC+CC DIS

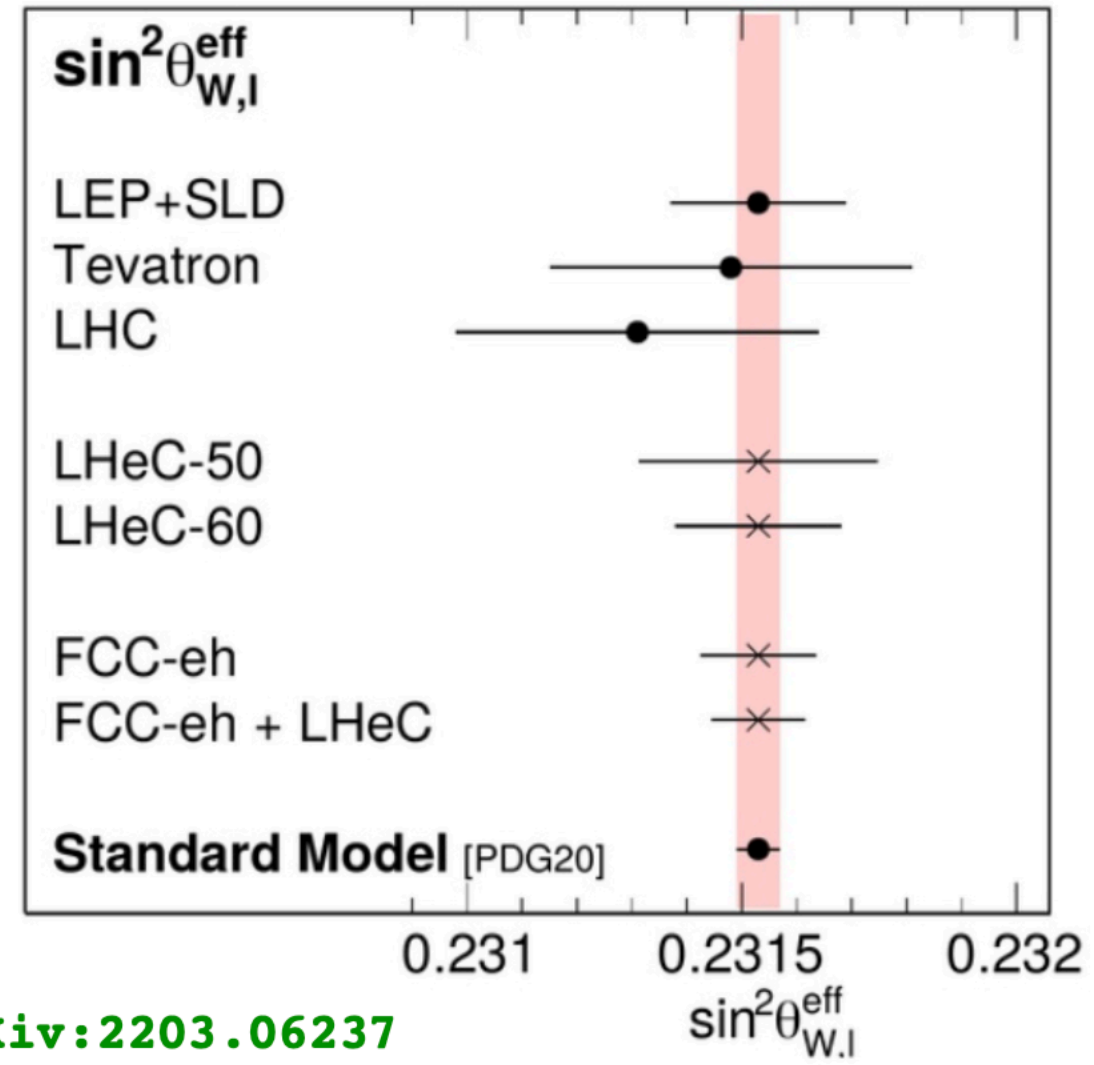


EPJ C 80 (2020) 831 [arXiv:2007.11799]

→ **probe large range of scale dependence**

$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= $\pm0.00010_{(exp)}$ $\pm0.00004_{(PDF)}$

→ **precision per mille level**



arXiv:2203.06237

on-shell definition $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$

$\Delta m_W = \pm\,4.5$ MeV

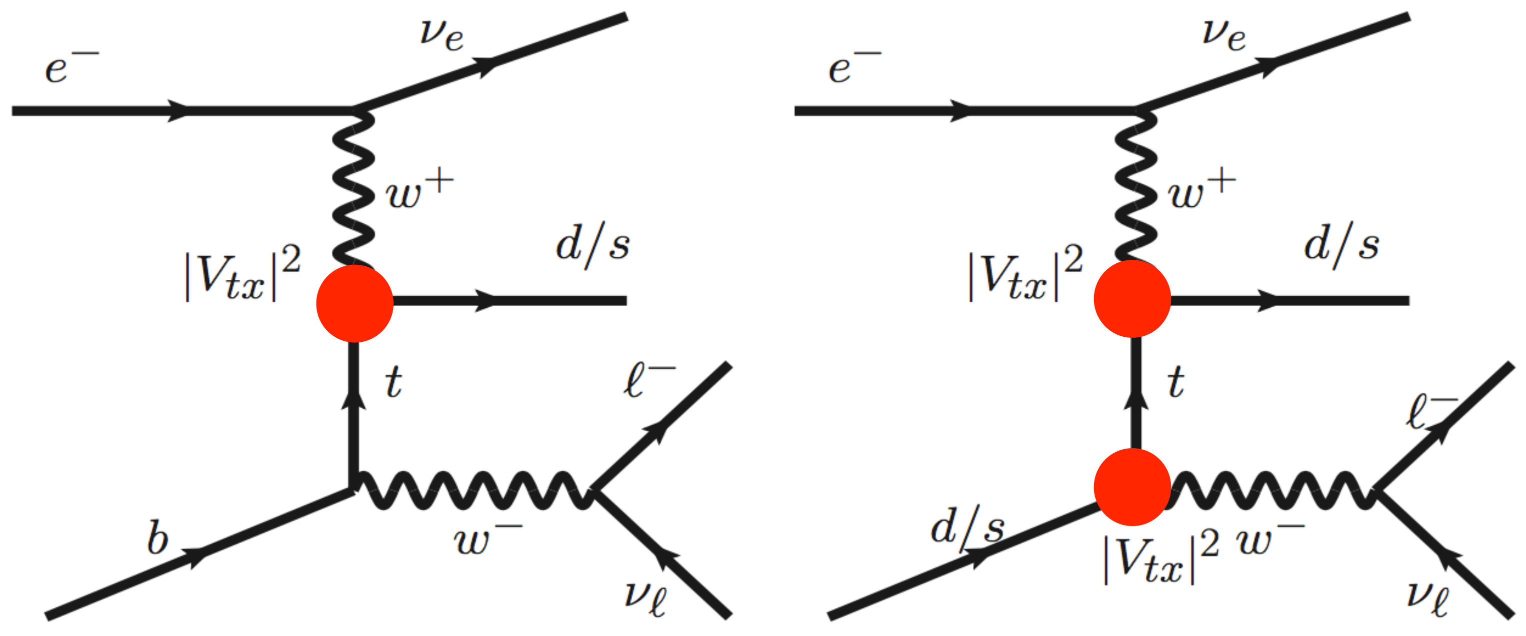
(includes PDF uncertainty of about ±3.6 MeV)

Measurement of $|V_{td}|$

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

similar

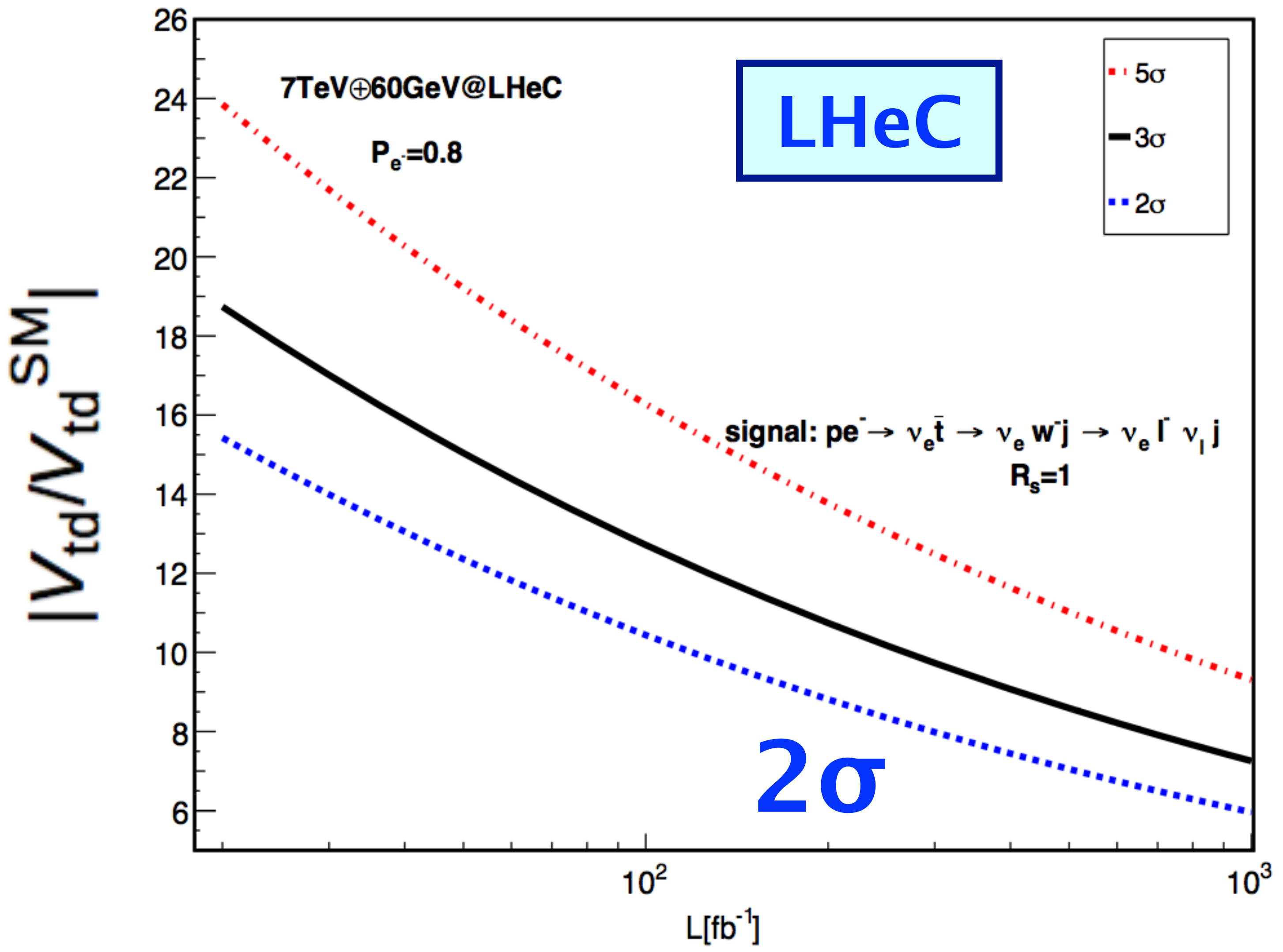
$$|V_{td}^{\mathrm{SM}}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$



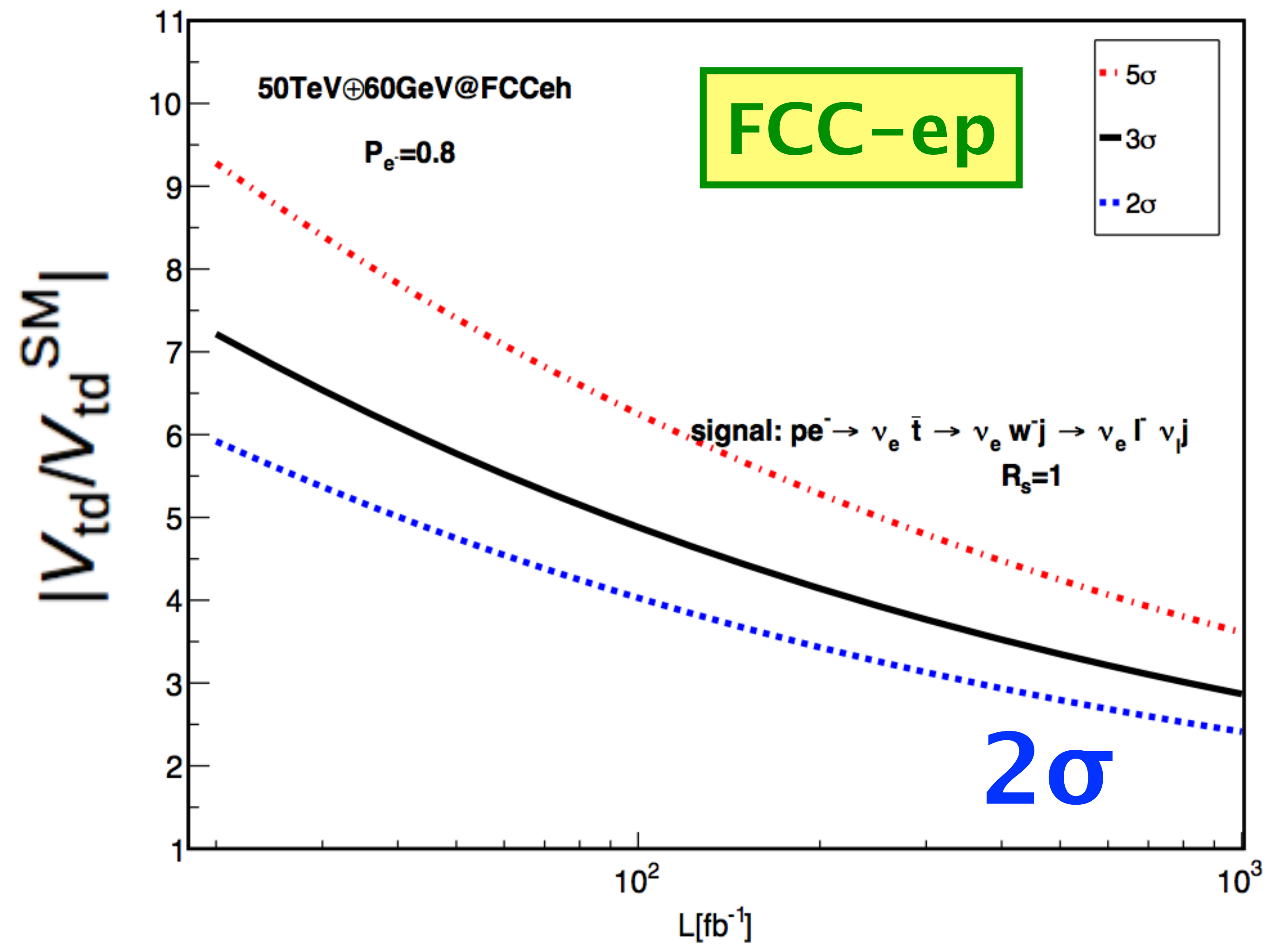
DELPHES

Hao Sun to be publ.

LHC



→ $|V_{td}| < 0.05$



→ $|V_{td}| < 0.02$

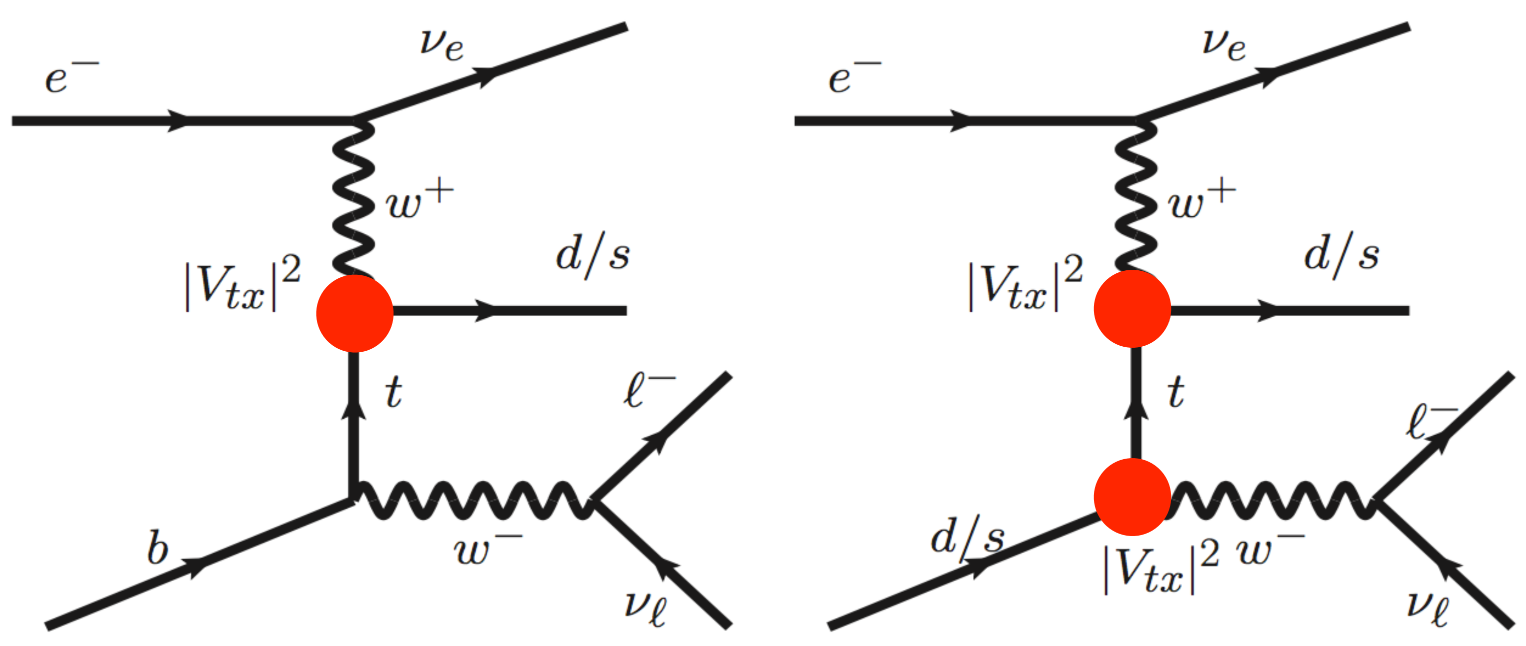
at 2σ C.L.

Measurement of $|V_{td}|$

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

similar

$$|V_{td}^{SM}| = 8.575^{+0.076}_{-0.098} \times 10^{-3}$$

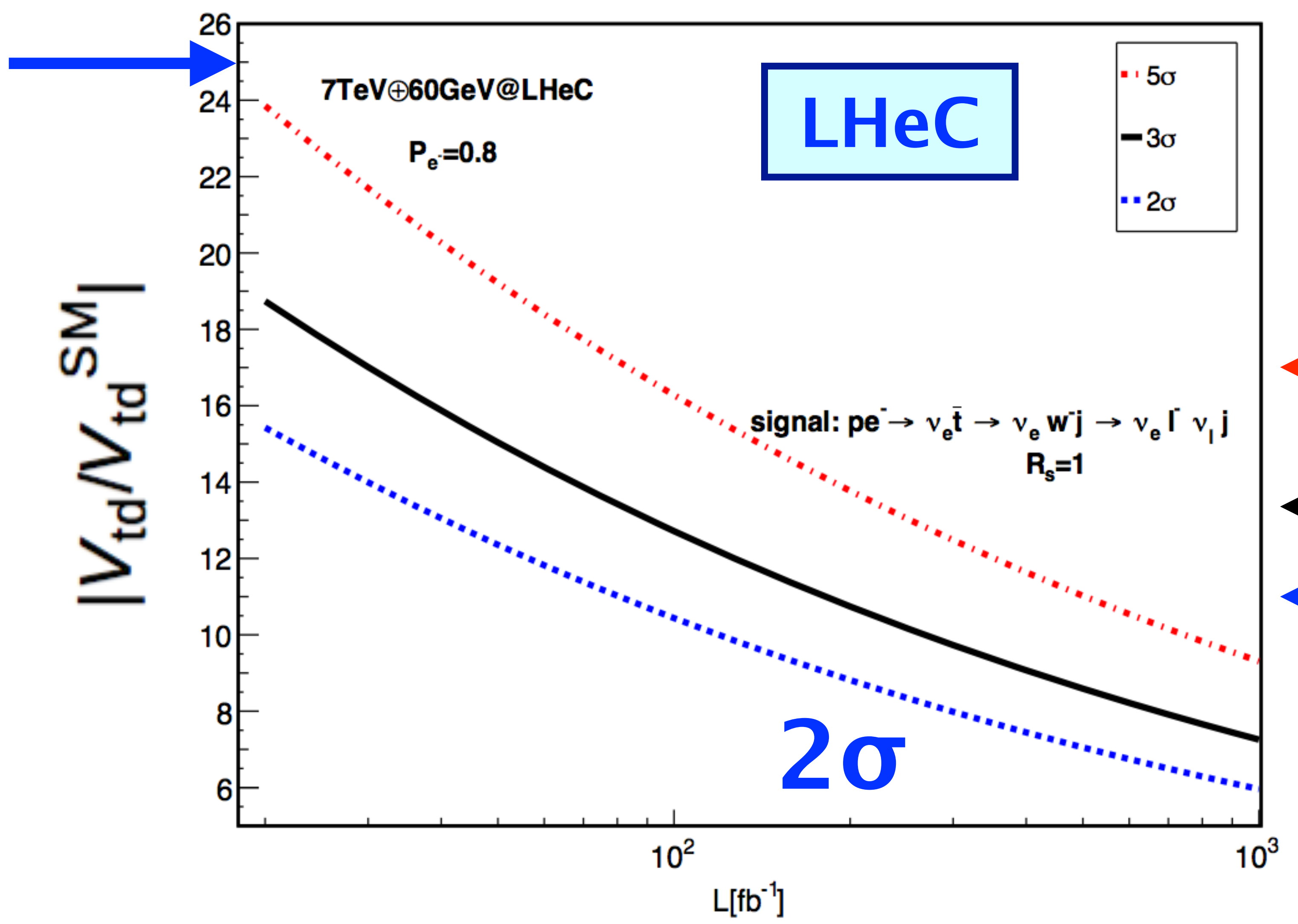


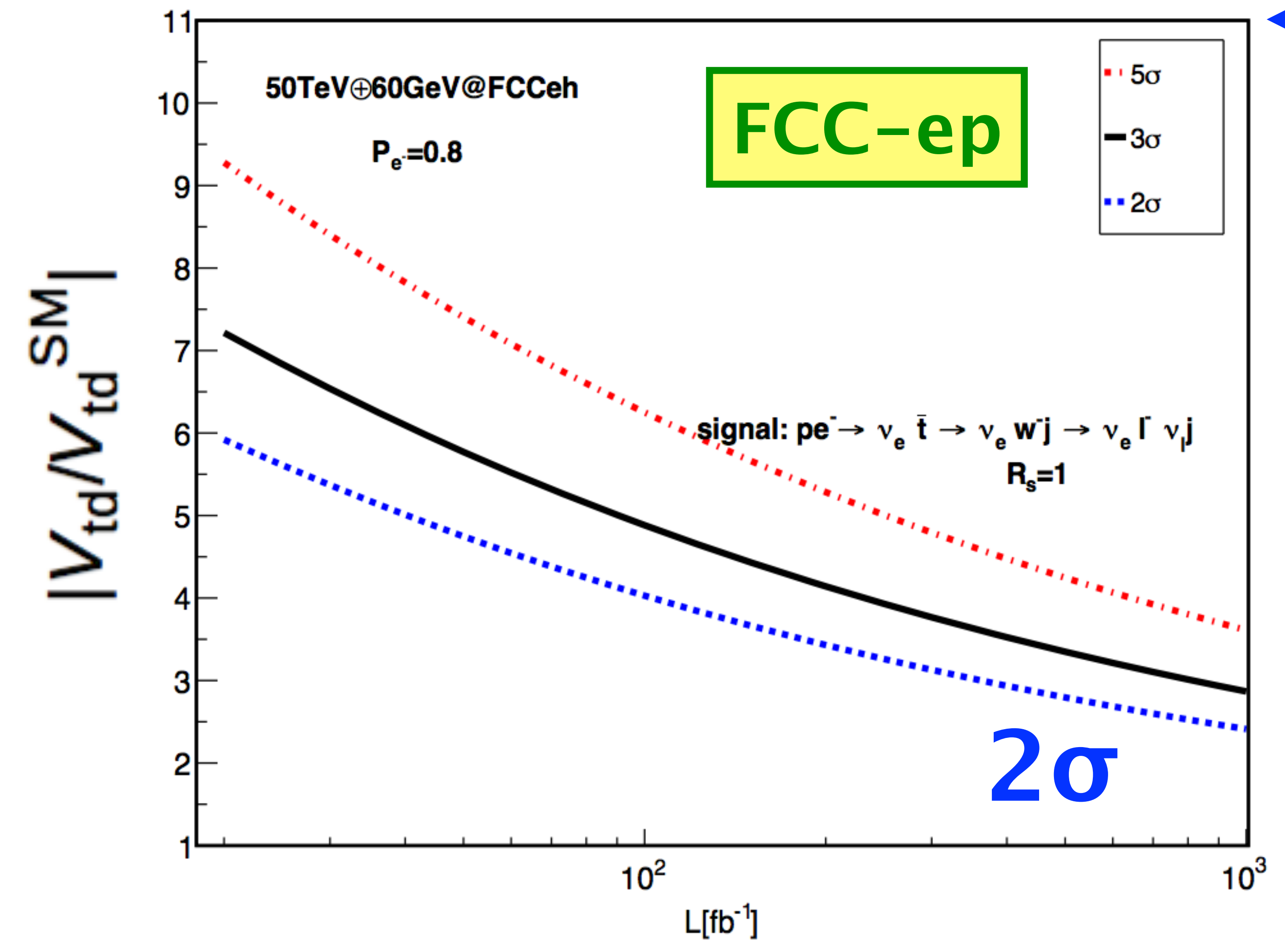
DELPHES

Hao Sun to be publ.

→ extend HL-LHC limits

LHC





LHC, 3000 fb^{-1}@14TeV

HL-LHC

arXiv:1709.07887

5σ

3σ

2σ

→ $|V_{td}| < 0.05$

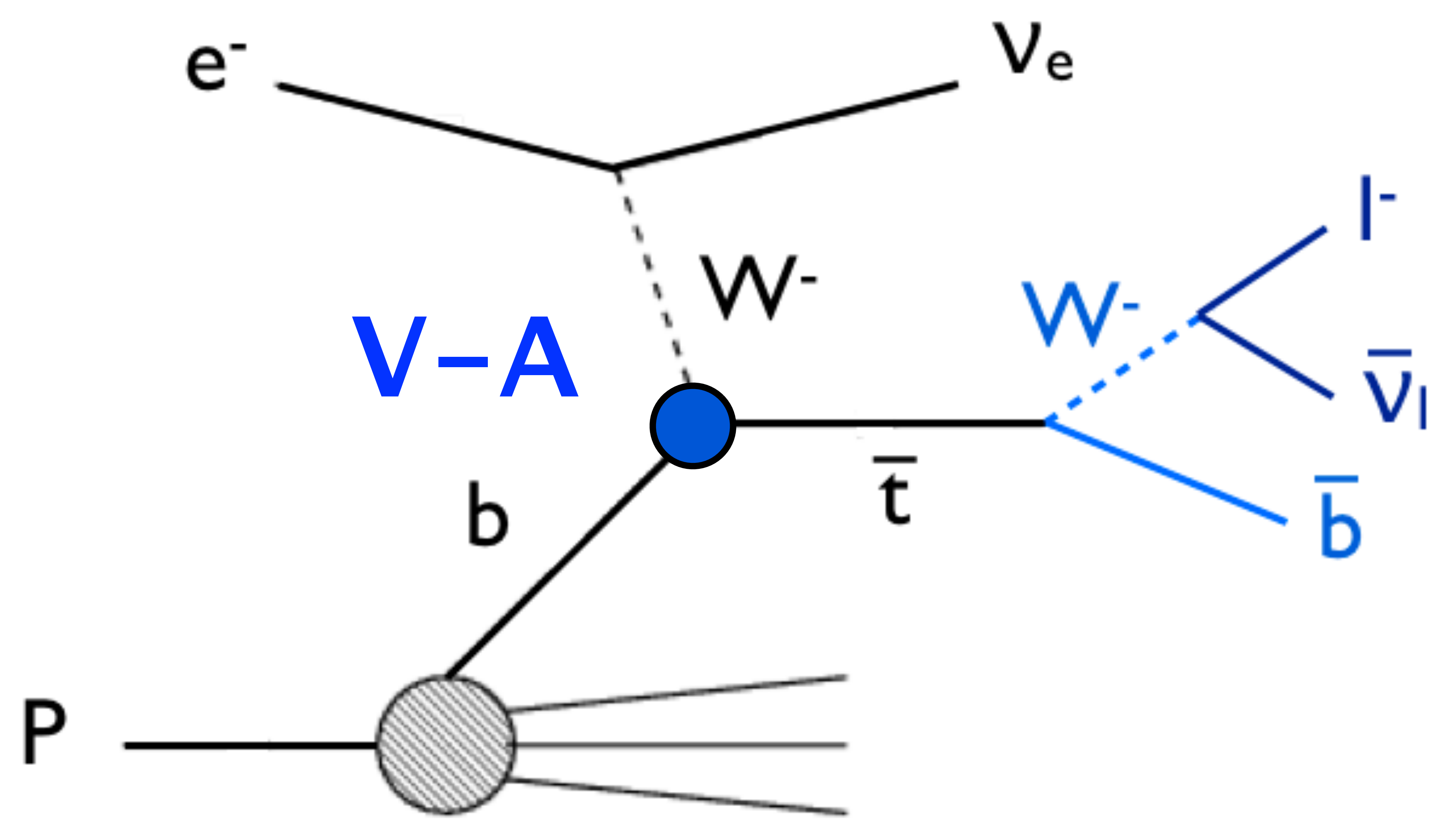
2σ

→ $|V_{td}| < 0.02$

at 2σ C.L.

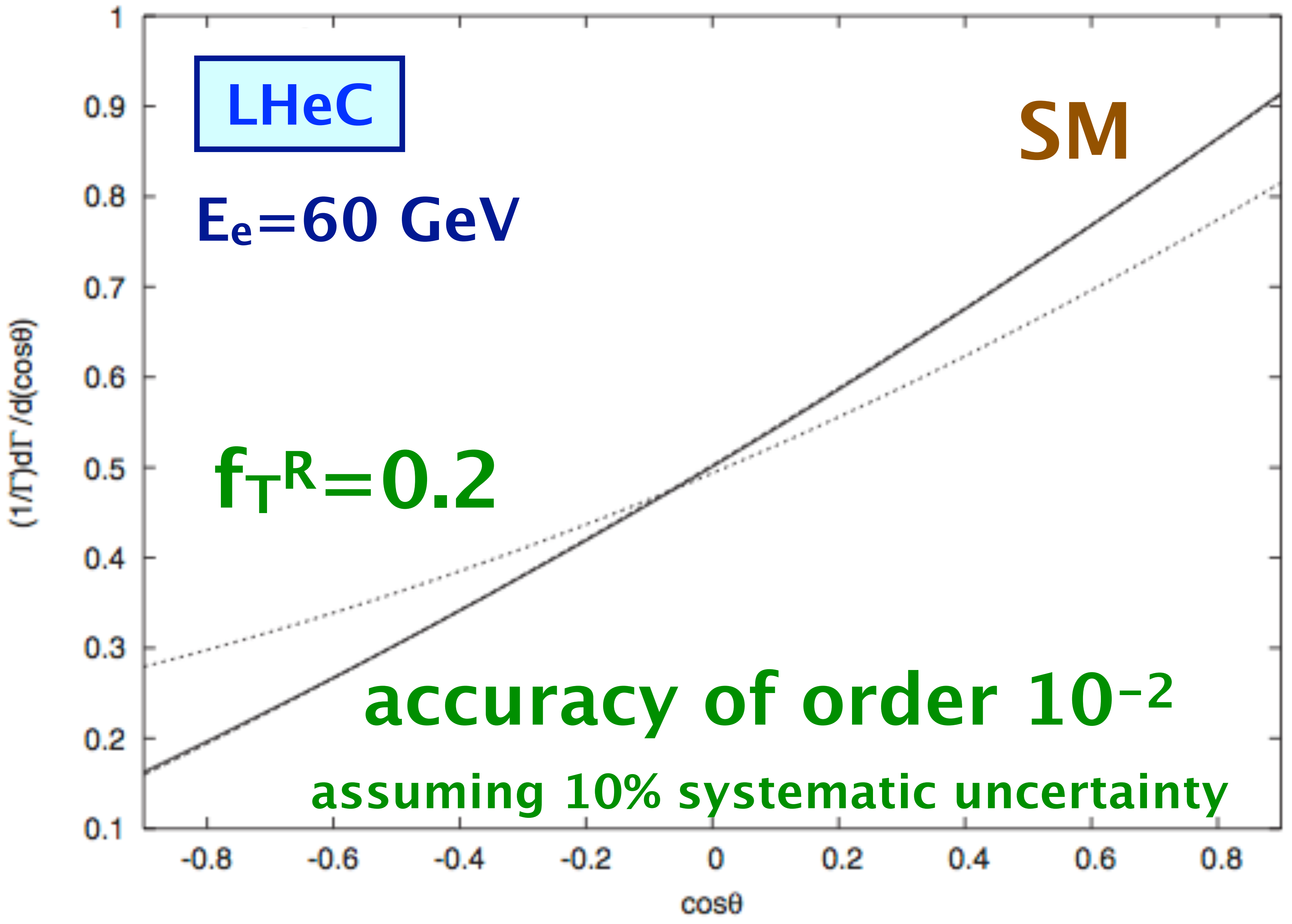
Top Quark Polarisation

Atag, Sahin,
PRD 73, 074001 (2006)



cosθ: angle between charged lepton and spin quantisation axis in top rest frame

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}(1 + A_{\uparrow\downarrow}\alpha\cos\theta) \qquad A_{\uparrow\downarrow} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



using simply e−beam axis:
polarisation: P_t = 96%

TESLA+HERAp:

$\sqrt{s}$=1.6 TeV
L_{int}=20 fb^{-1}

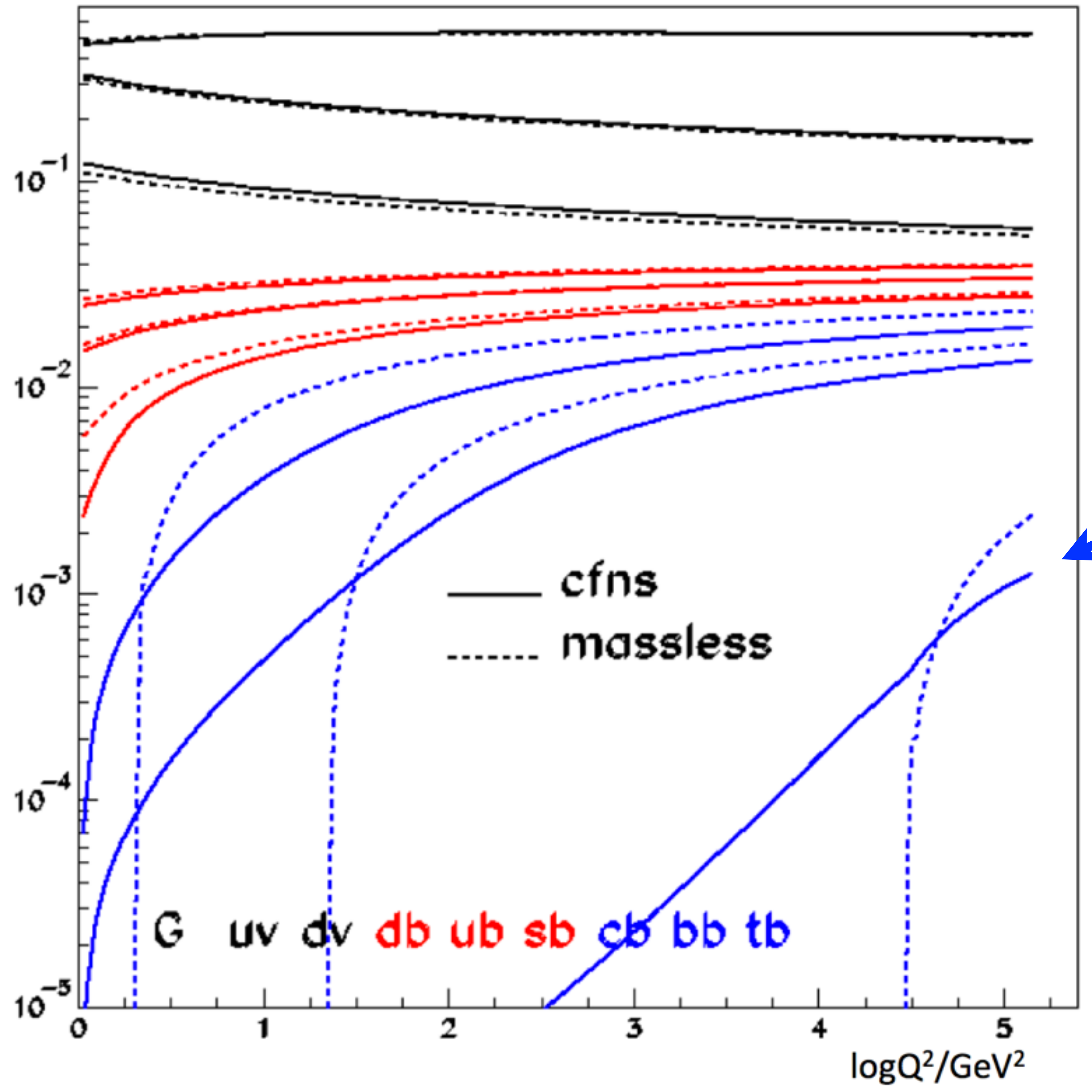
CMS 19.7 fb^{-1}: $A_{\uparrow\downarrow} = 0.26 \pm 0.11$

JHEP 04 (2016) 073

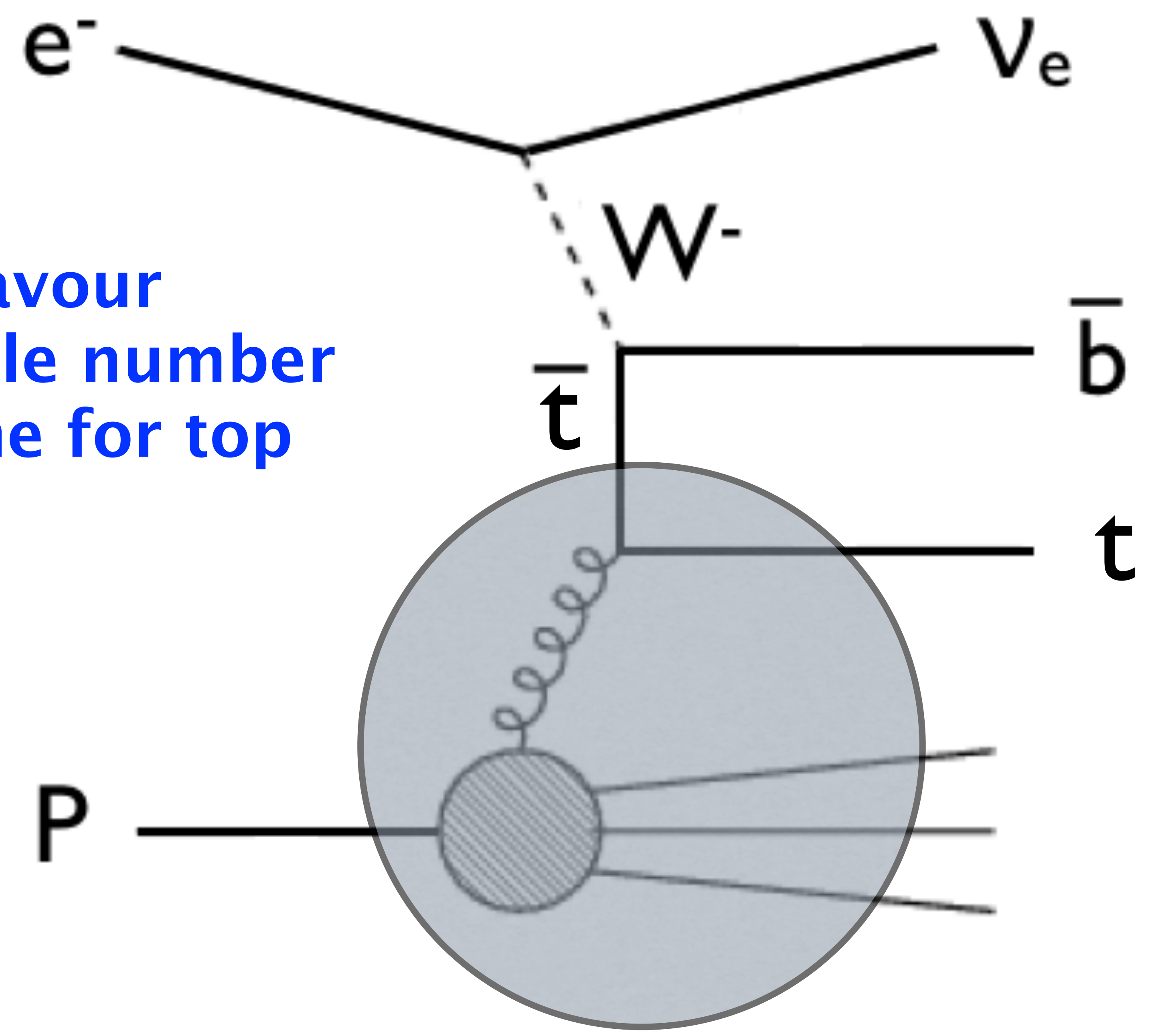
Top Quark Parton Density Function

LHeC CDR, J.Phys. G39, 075001 (2012)

parton momentum fraction



six-flavour variable number scheme for top quark



- in 6 flavour number scheme, top receives at $Q^2 \sim m_t^2$ certain fraction of the proton's momentum
- need to understand what a "top PDF" is in the framework of parton model

→ LHeC offers new field of research for top quark PDF

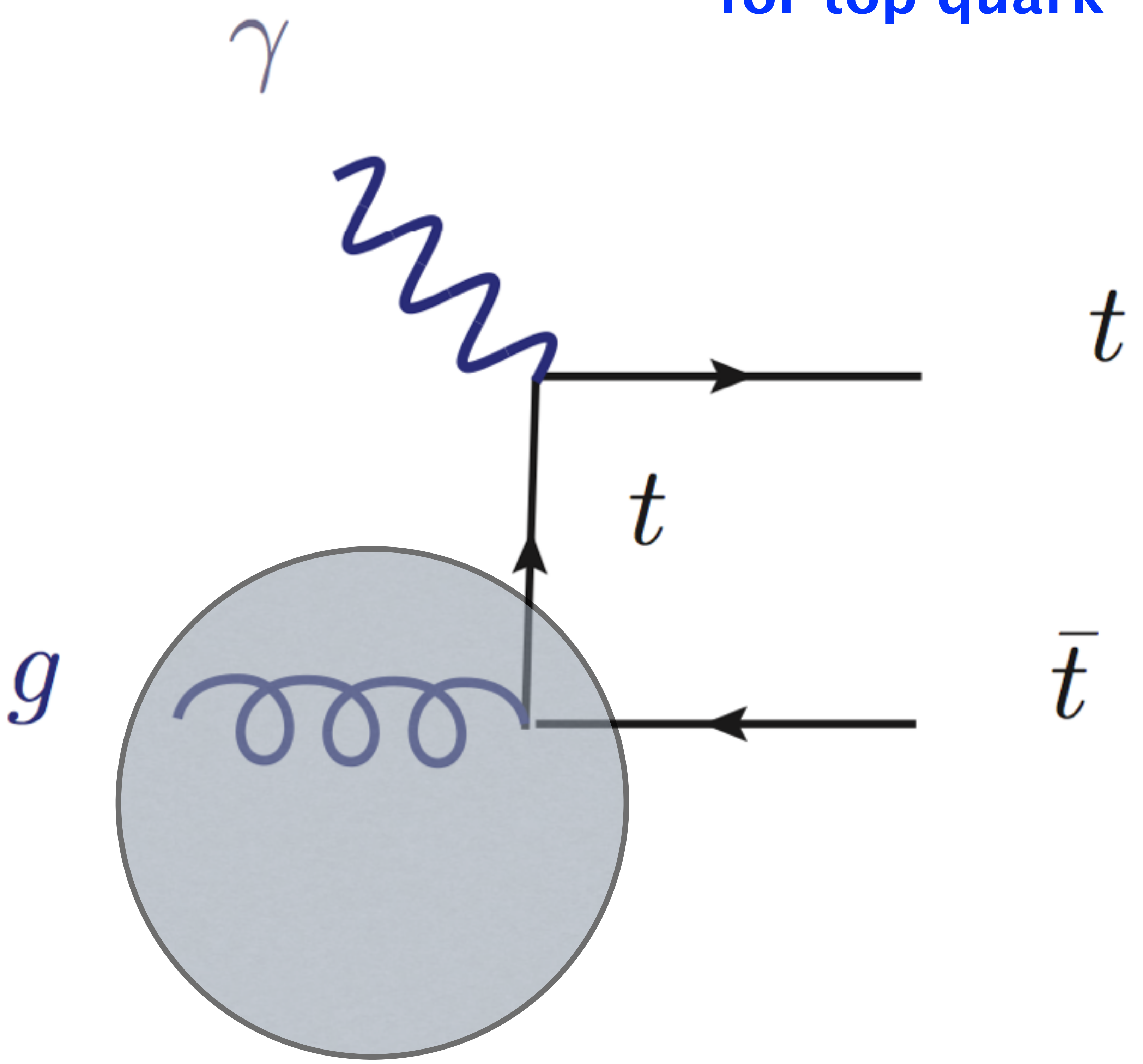
Top Quark Structure Function

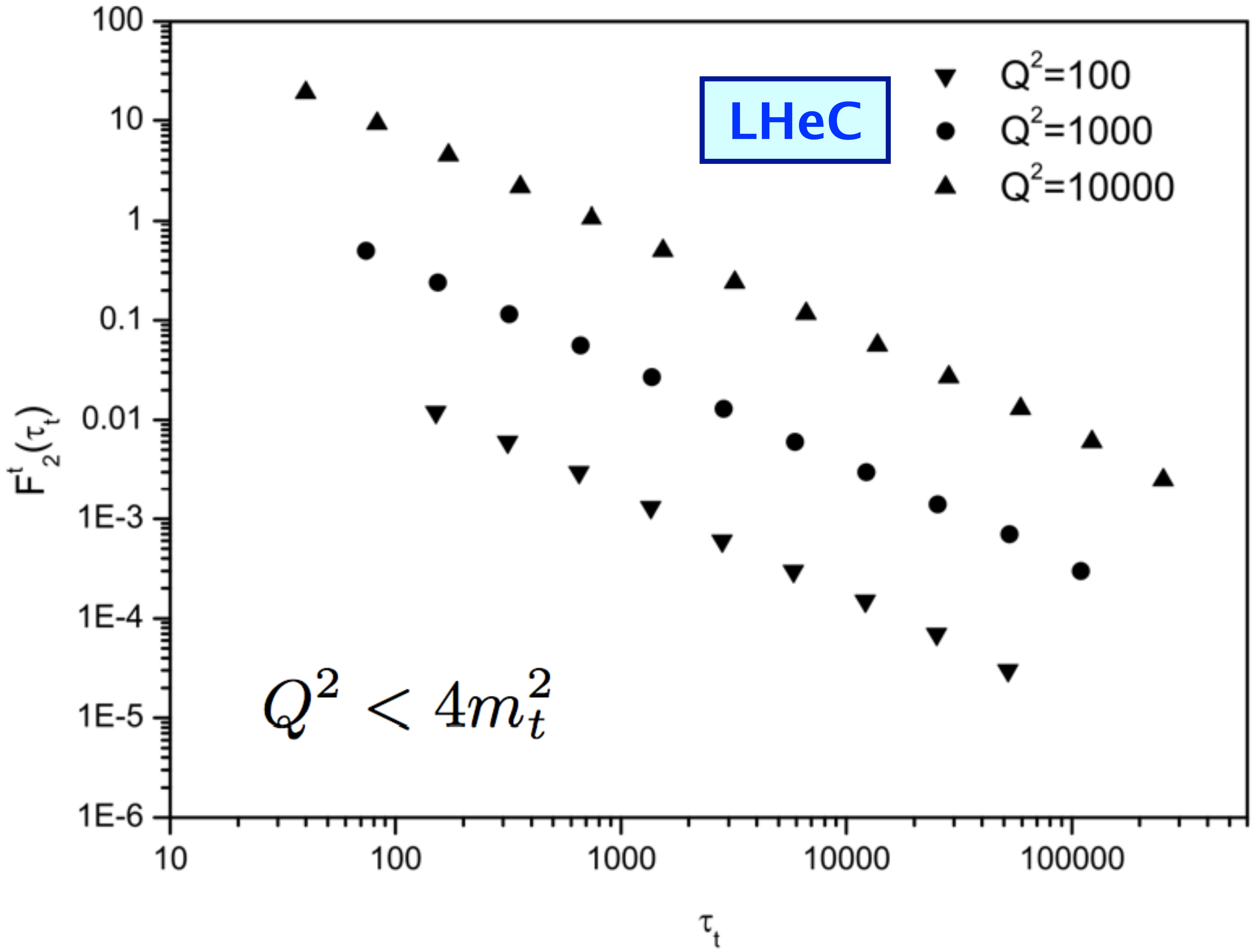
Boroun, Phys. Lett. B744, 142 (2015)

L_{int}=10 fb^{-1}

E_e=60 GeV

variable flavour number scheme for top quark





$$\tau_t = (1 + \frac{4m_t^2}{Q^2})^{1+\lambda} \frac{Q^2}{Q_0^2} (\frac{x_B}{x_0})^\lambda$$

$$x = x_B (1 + \frac{4m_t^2}{Q^2})$$

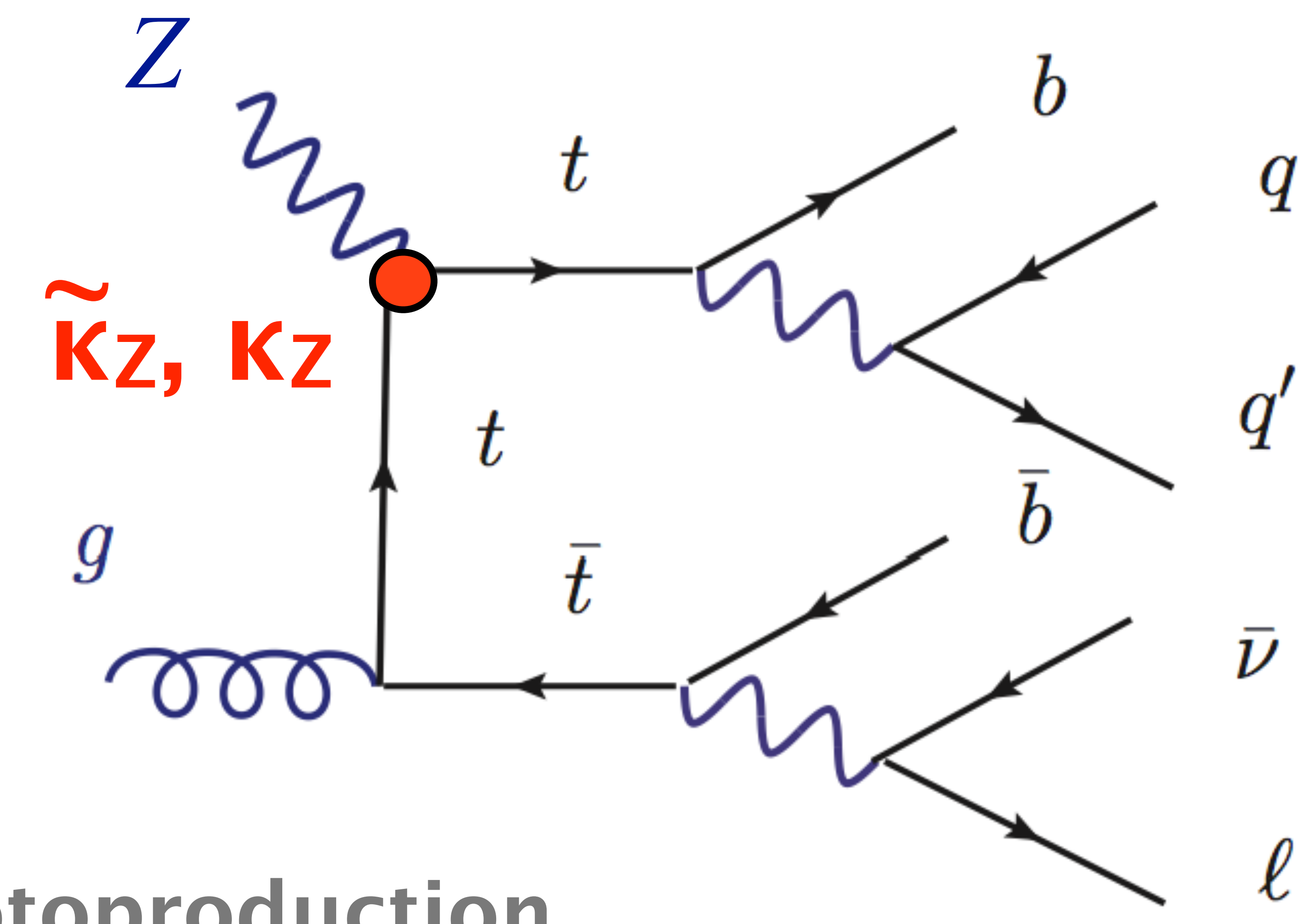
→ **LHeC/FCC-ep opens up a new field of top quark PDFs and to unveil the complete flavour structure of the proton**

Search for Anomalous $t\bar{t}Z$ Couplings

$\tilde{\kappa} = 2m_t d_t$

$\kappa = 2m_t \mu_t$

Bouzas, Larios,
Physical Review D 88, 094007 (2013)

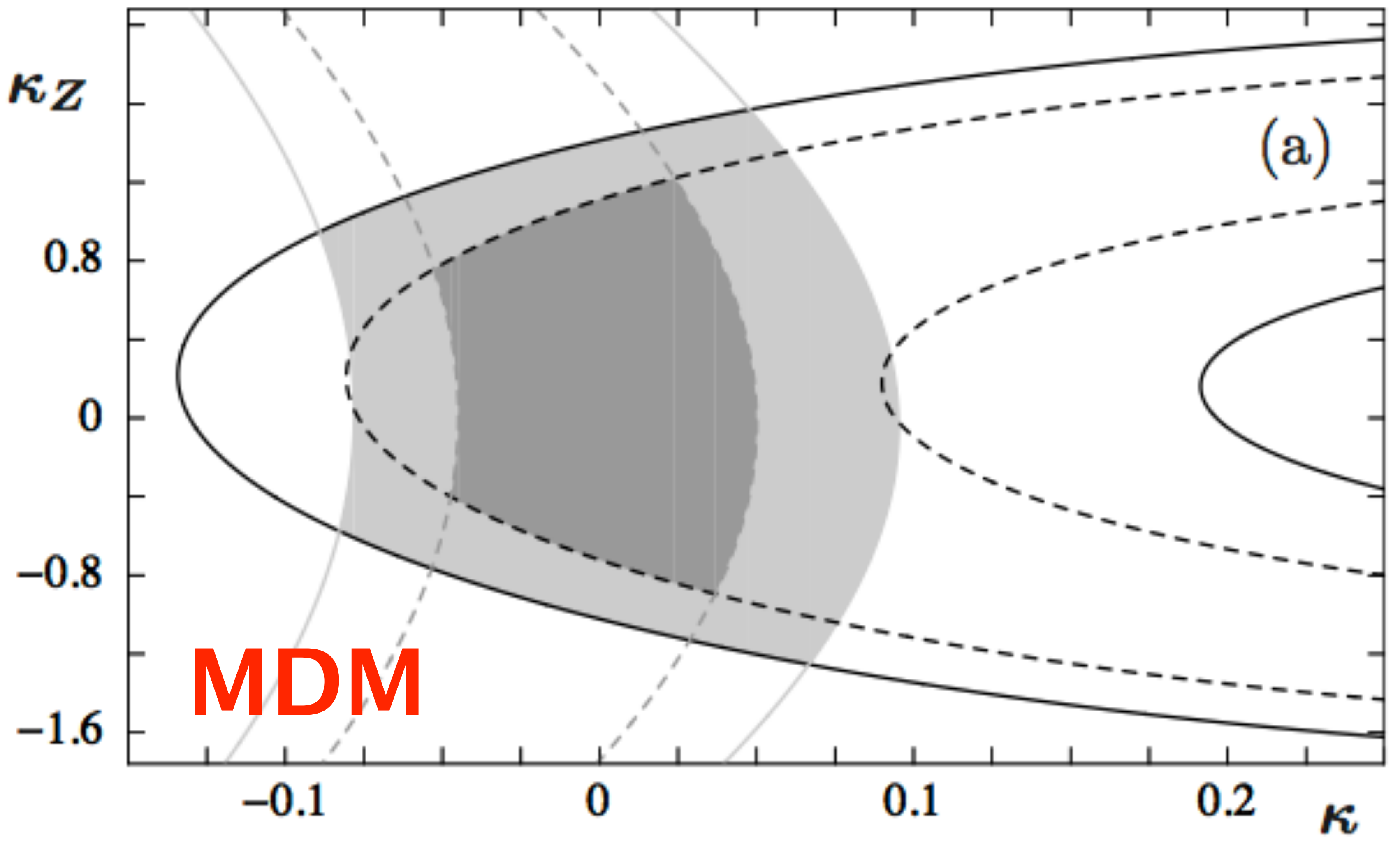


$t\bar{t}$ photoproduction

property	precision
EDM: $\tilde{\kappa}$ / $\tilde{\kappa}_Z$	0.20-0.28/0.6-0.8
MDM: κ / κ_Z	0.05-0.09/0.9-1.3

LHeC E_e=60 GeV

10% and 18% accuracy assumed



$t\bar{t}$ DIS