Highlighting the Importance of Theory to HEP Projects

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Why is theory important for HEP projects?

Theory has a dual role in the HEP program. It confronts profound issues at the core of our understanding of Nature and is therefore important in its own right, and it supports the experimental program in its search for new phenomena. I will focus on the second role here.

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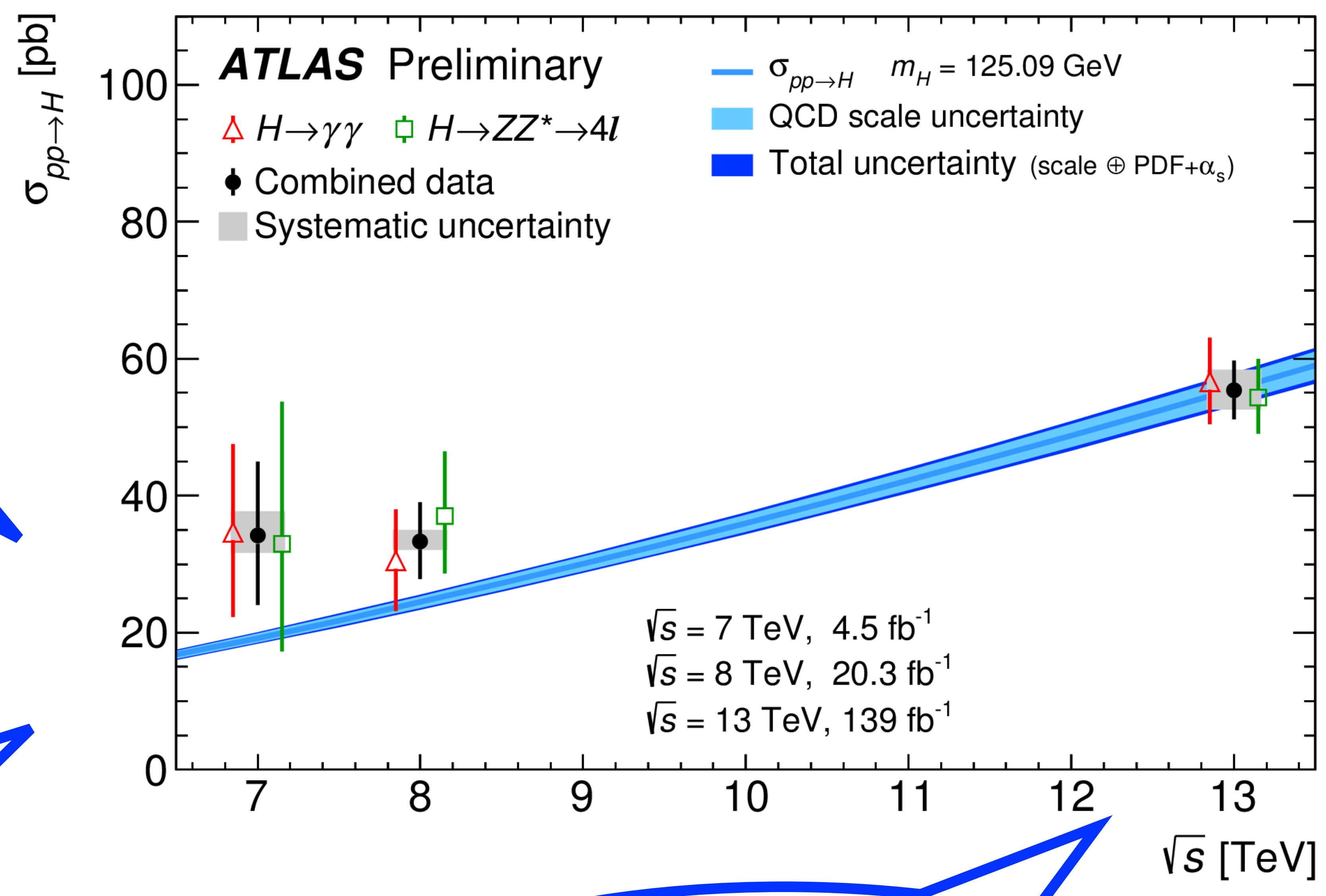
How does theory support the experimental program?

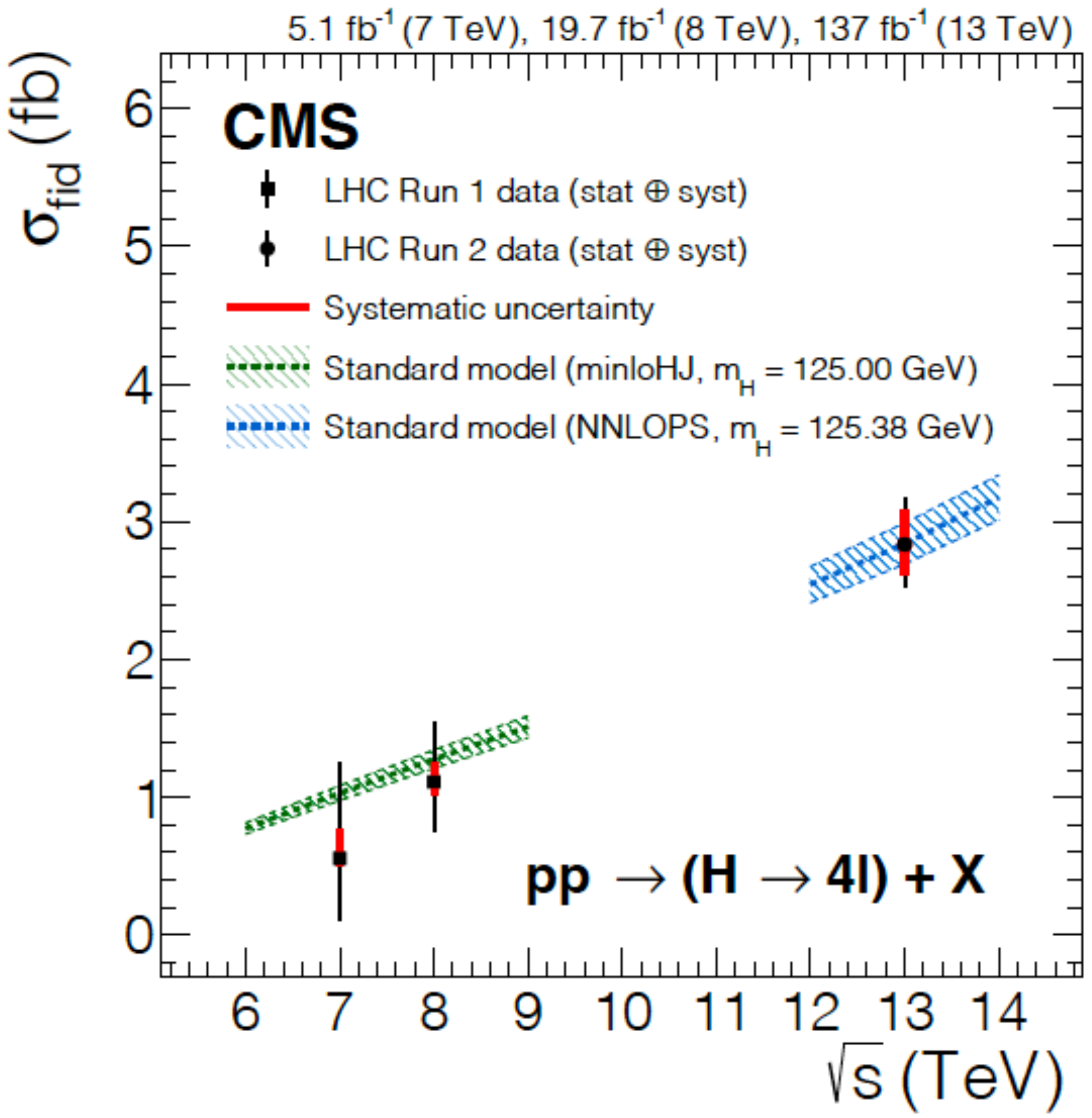
1. Precision calculations facilitate comparisons between experiment and the Standard Model, and make the identification of subtle discrepancies possible.
2. Theory invents models to solve outstanding problems that motivate experimental searches.
3. The development of effective field theories provides useful frameworks to compare results across experiments and energy scales.
4. Theory helps identify previously unrealized synergies between HEP and other areas of science.

Precision theory for HEP

- Precision theory is inherently multi-disciplinary. It ties together advances in mathematics and advanced computing with formal theory/amplitudes and experiment.
- The computation of the Higgs cross sections and decay modes is an excellent example that highlights all of the theoretical advances needed to maximize the potential of the LHC program.

Electroweak corrections at 2 loops





QCD@N^{3}LO

PDFs@NNLO

Precision determination of quark masses

Precision extraction of α_S

Precision theory for HEP

- We are on the path toward establishing the Standard Model at the N3LO in QCD perturbation theory. So far 2→1 processes such as gluon-fusion Higgs production and Drell-Yan are known. Going to more complicated processes will require insights from formal mathematics, new techniques for amplitude calculations, and harnessing high-performance computing.

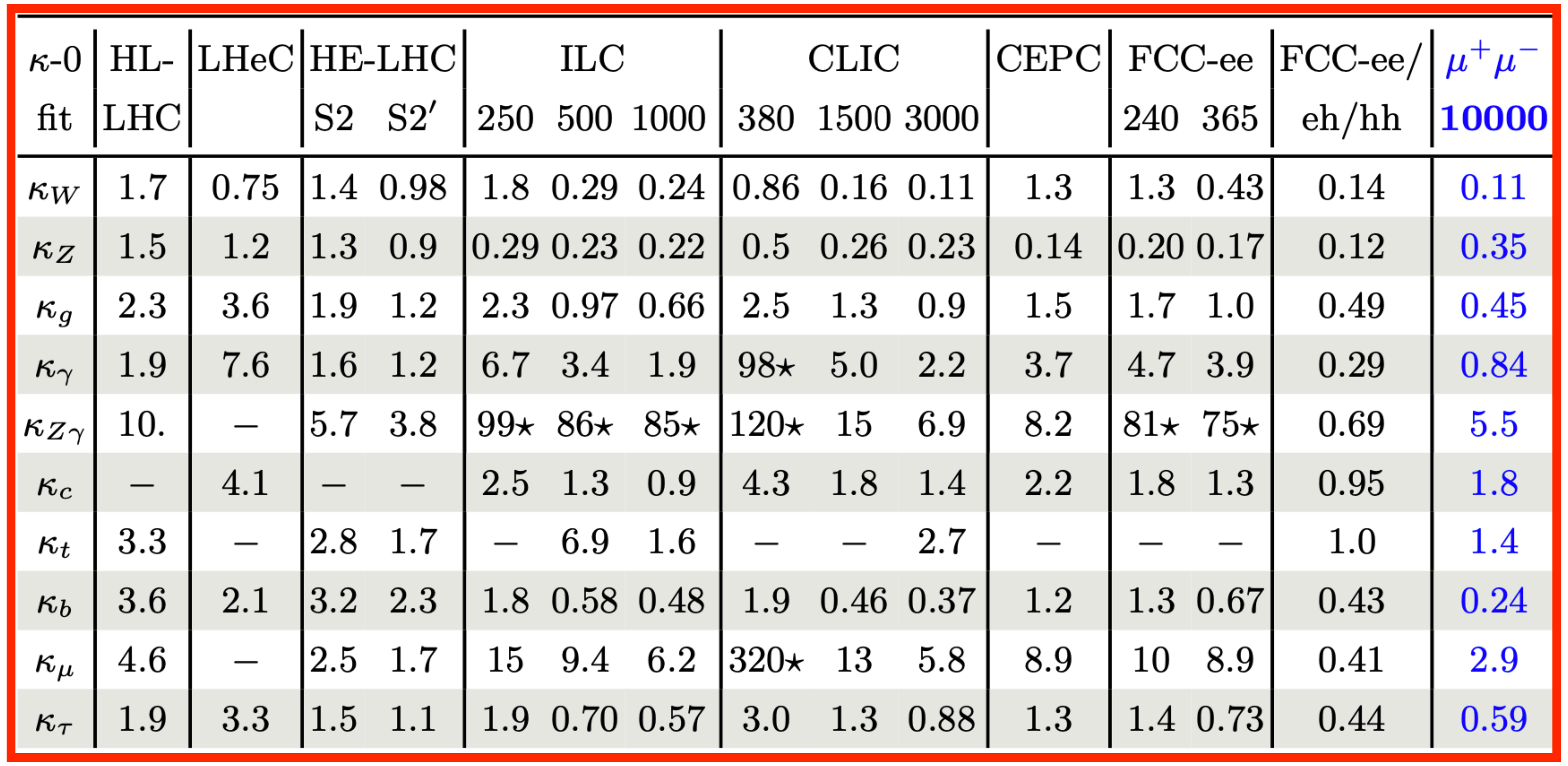
Many issues must be confronted to achieve this goal:

- Mathematical structure of iterated elliptic integrals
- 2-loop amplitude computations for 2→3 processes and beyond
- Efficient infrared subtraction schemes
- Robust uncertainty estimates
- Efficient numerical computation

Reviewed in *The Path Forward to N3LO*, Snowmass contribution

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2}$$

European Strategy Update, de Blas et al (2019); P. Meade, talk at ANL (2023)



κ-0	HL-	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/	$\mu^+\mu^-$
fit	LHC		S2	S2′	250	500	1000	380	1500	3000		240	365	eh/hh	**10000**
κ_W	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.11
κ_Z	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.35
κ_g	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.45
κ_γ	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.84
$\kappa_{Z\gamma}$	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	5.5
κ_c	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	1.8
κ_t	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	1.4
κ_b	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.24
κ_μ	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.9
κ_τ	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.59

Motivation: to support the exploration of the SM, especially the Higgs sector, at future colliders to the percent level

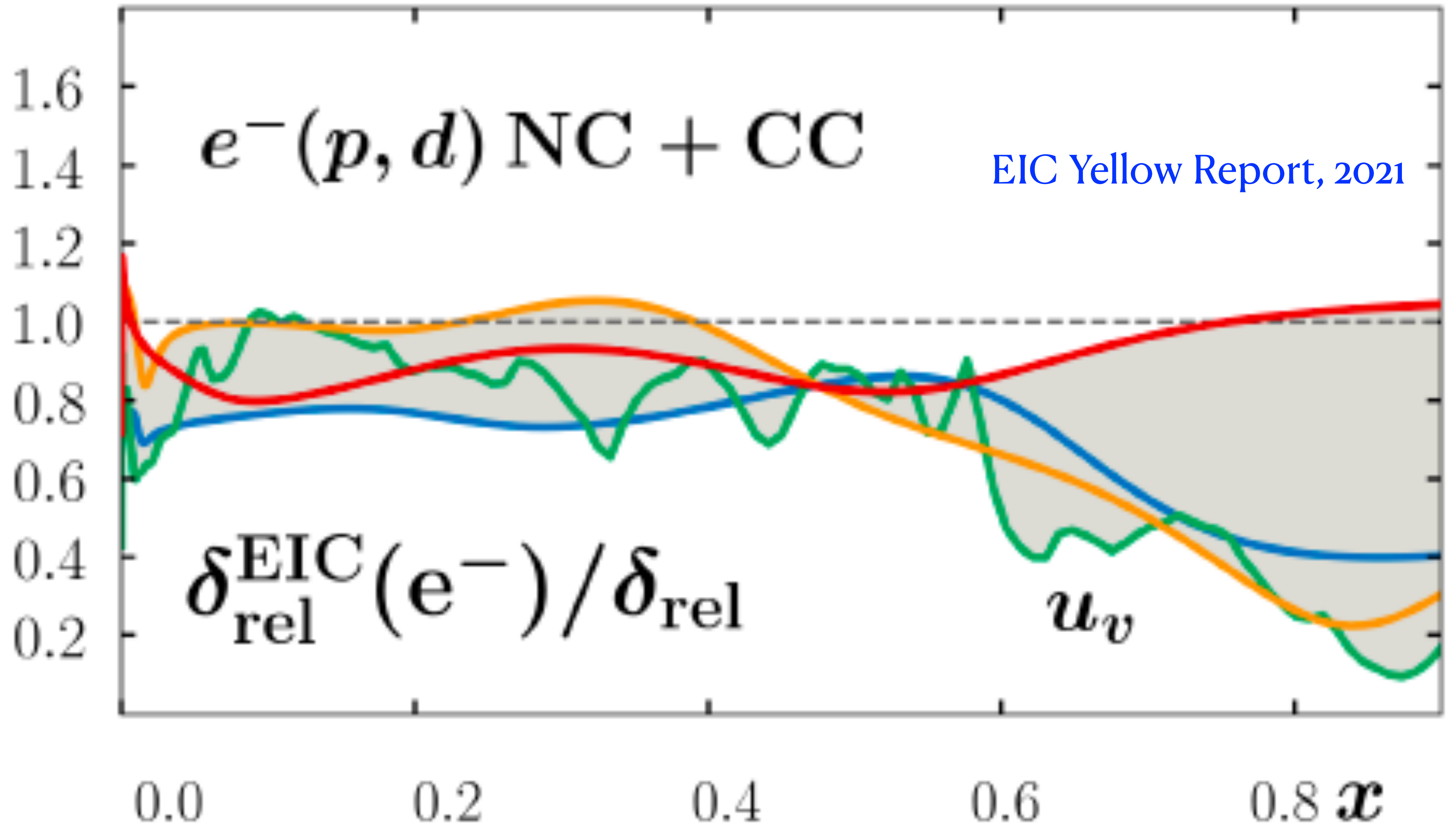
Precision theory for HEP

- Parton Distribution Functions tie together precision theory and experiment and are indispensable in all aspects of collider physics. The determination of PDFs at the same order as the scattering cross sections is an excellent example of synergy between HEP and other fields, since a future nuclear-physics Electron-Ion Collider is expected to play a vital role in this advance.

Fits with simulated EIC data:

Orange: CT fit
Green: NNPDF fit
Red: JAM fit
Blue: CJ fit

Reviewed in *Proton Structure at the Precision Frontier*, Snowmass contribution



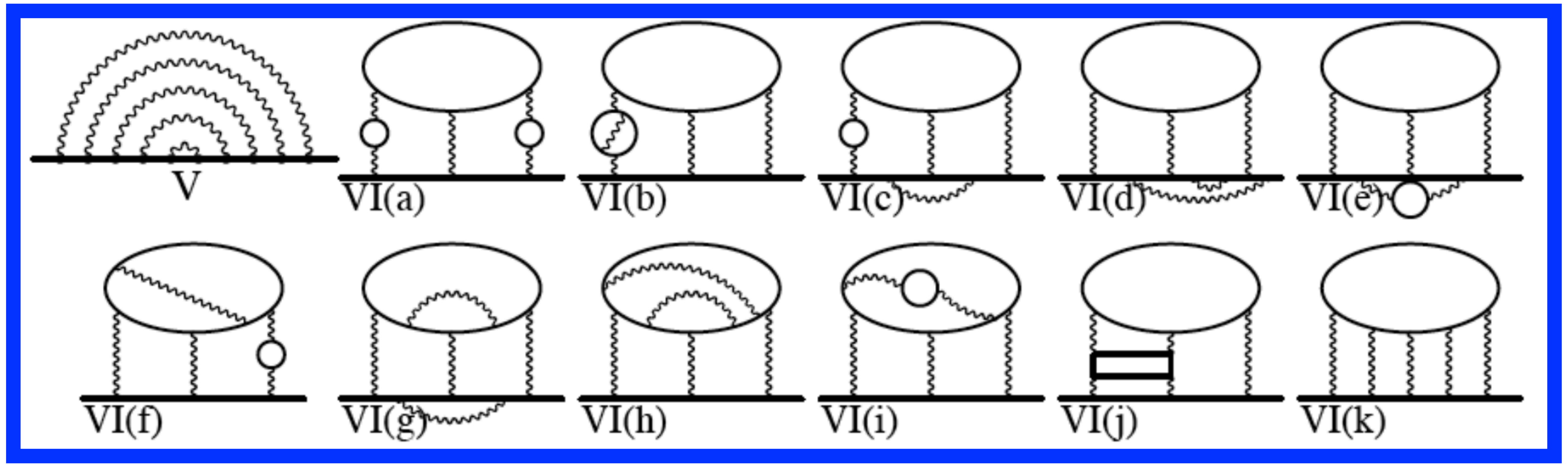
EIC Yellow Report, 2021

Gray band: uncertainty envelope after EIC data compared to pre-EIC

Up to an 80% reduction in valence quark distribution uncertainties with future EIC data!

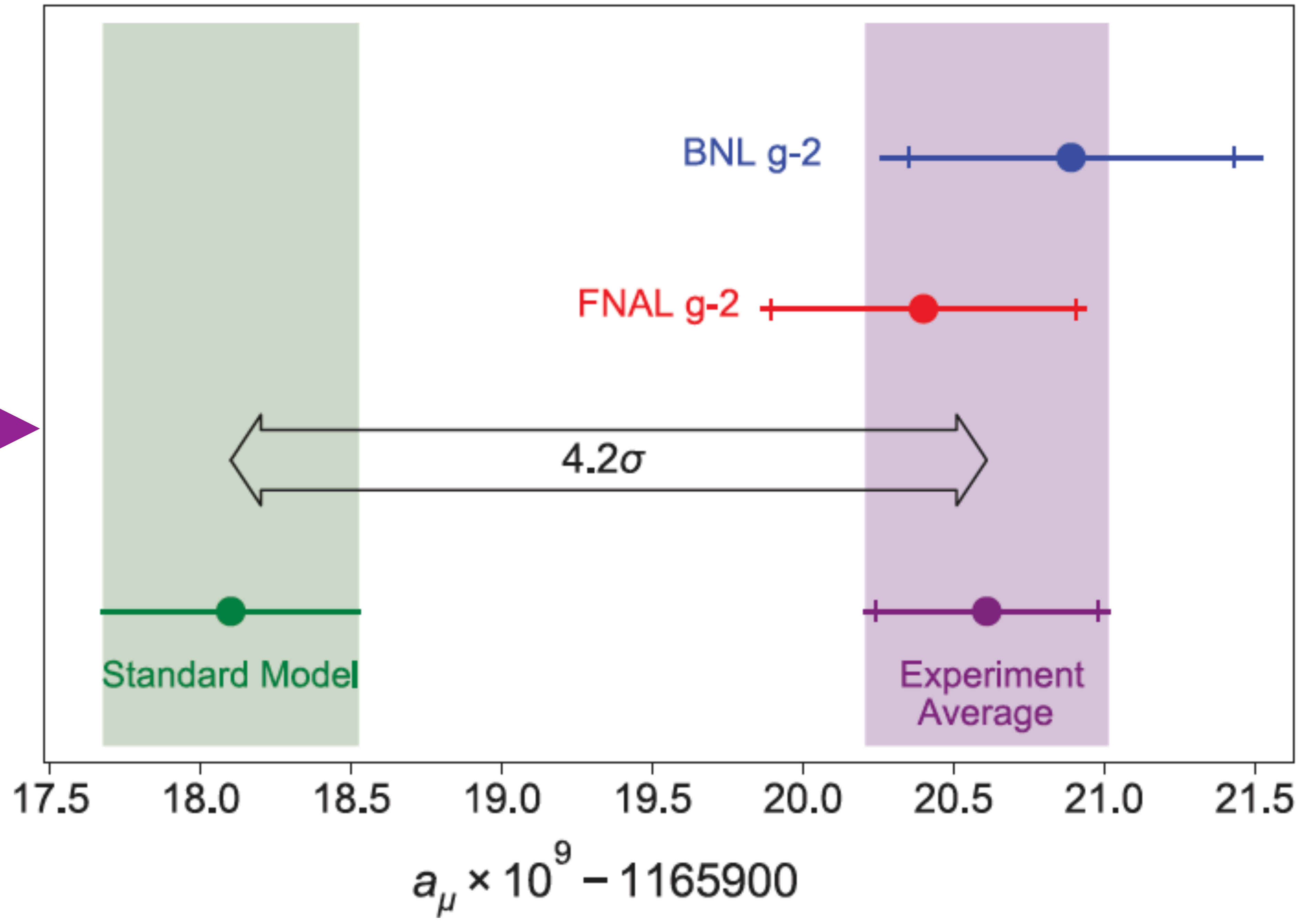
Precision theory for HEP

- The impact of precision theory spans the experimental frontiers. The heroic calculation of the 5-loop QED corrections to the muon g-2 is an indispensable part of the intensity frontier effort to improve the experimental measurement at Fermilab and to better understand the possible discrepancy between experiment and the Standard Model.



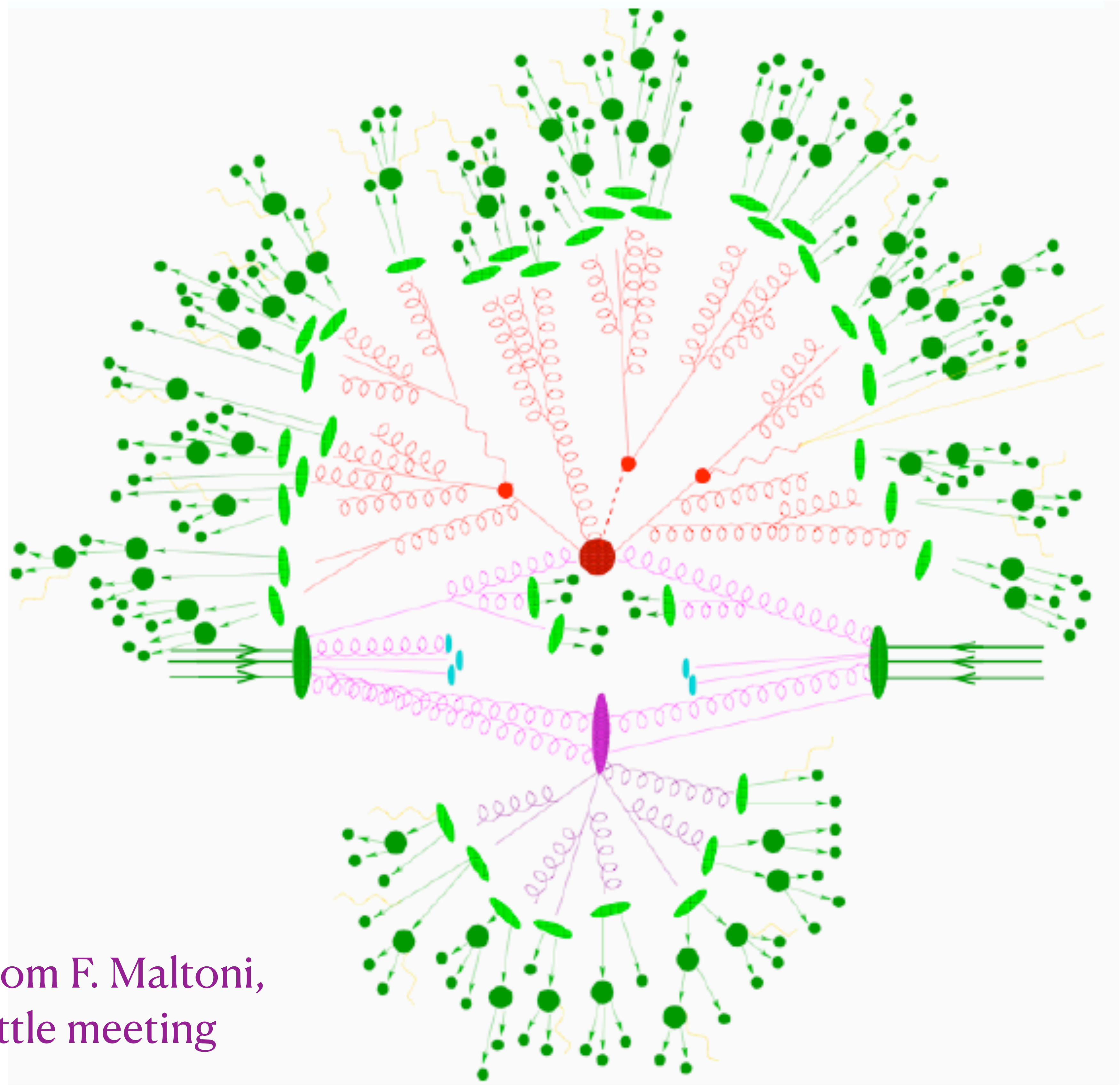
Without QED to this extraordinary order in perturbation theory, we would not have the theoretical resolution to distinguish between SM and experiment.

Muon g-2 collaboration, 2021



Event generation in HEP

- Monte Carlo event generators are an important component of the HEP infrastructure. They are how the QFT underlying the SM is turned into the actual events that can be compared to collider experiments. The past decade has seen enormous progress in improving the accuracy of parton shower event generators.



ttH at the LHC; from F. Maltoni, Snowmass Seattle meeting

A plethora of difficult issues must be brought under control for proper event generation:

- Fixed-order perturbation theory
- Matching/merging of fixed-order and parton shower evolution
- Logarithmic accuracy of the shower
- Hadronization models
- Underlying events

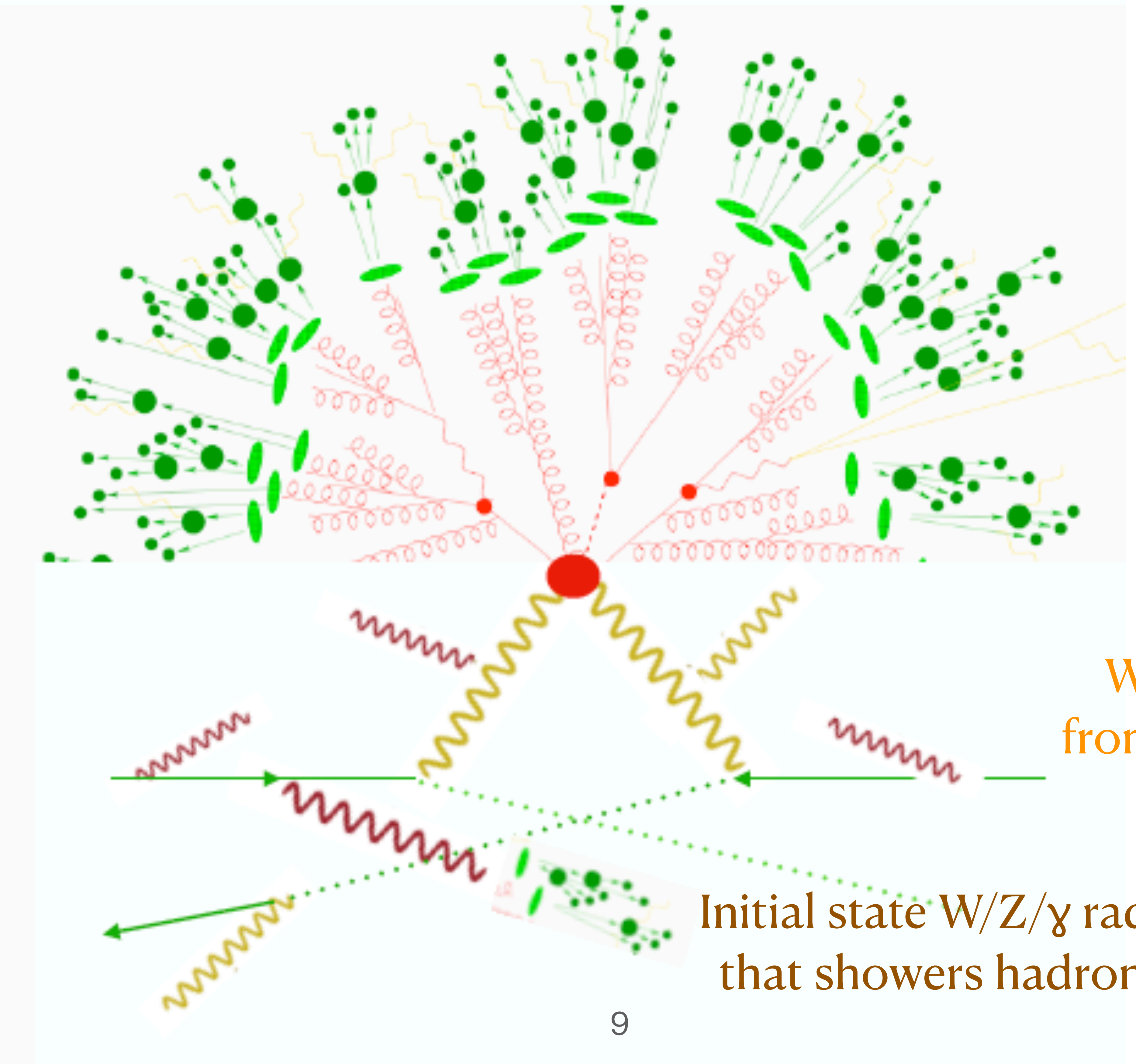
Reviewed in *Event generators for high energy physics; Future prospects for parton showers,* Snowmass contributions

Event generation in HEP

- Monte Carlo event generators will continue to be a vital part of the theory/experiment interface across the frontiers of HEP. Multi-TeV lepton colliders will require a parton-shower treatment of both electroweak and QCD radiation, while an improved description of neutrino event generation is needed for the future intensity frontier program.

Anatomy of a muon collider event:

Similar to the LHC, except the EW gauge bosons now play an important role in the shower due to the expected high energy



ttH at a μC; from F. Maltoni, Snowmass Seattle meeting

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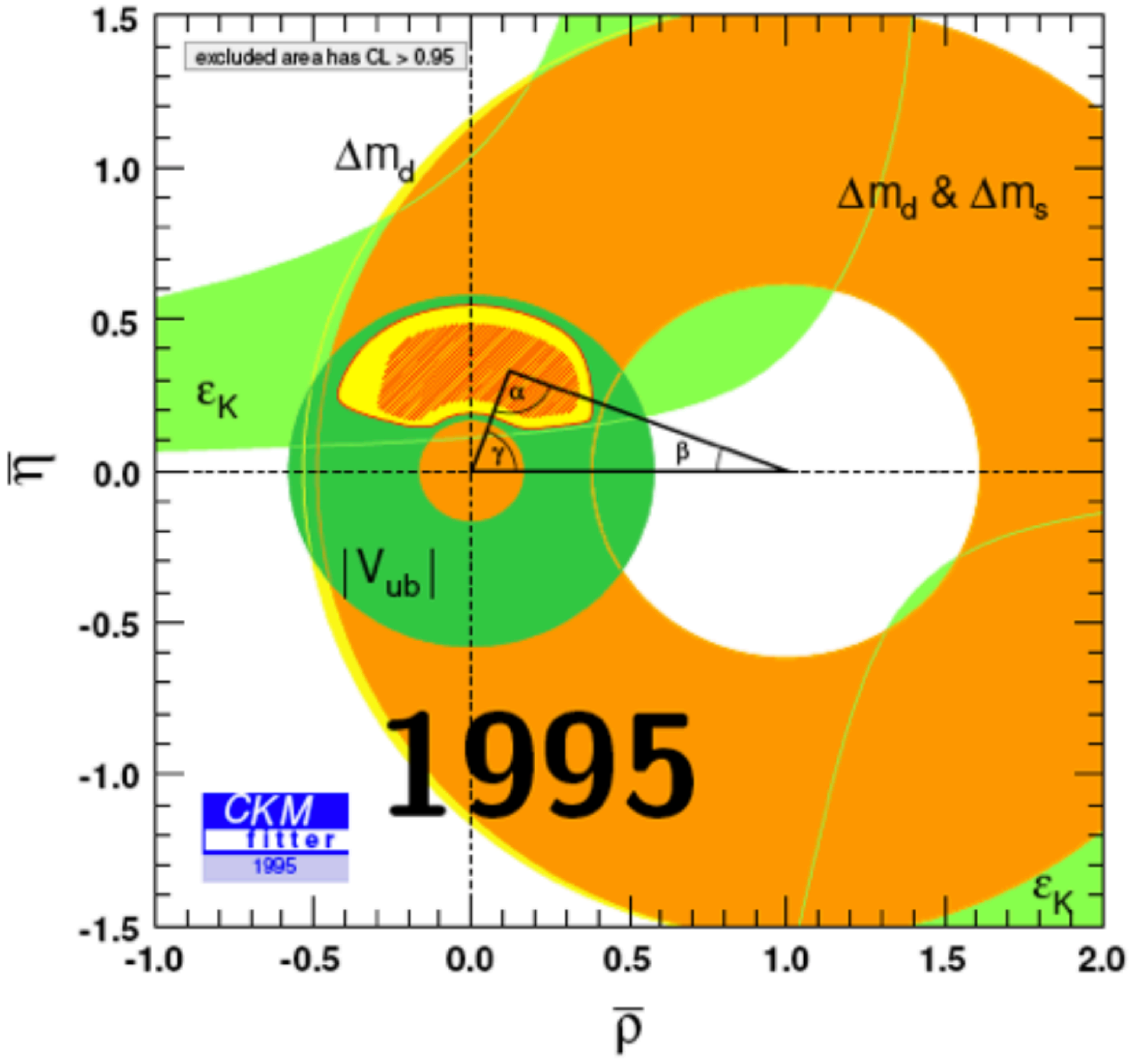
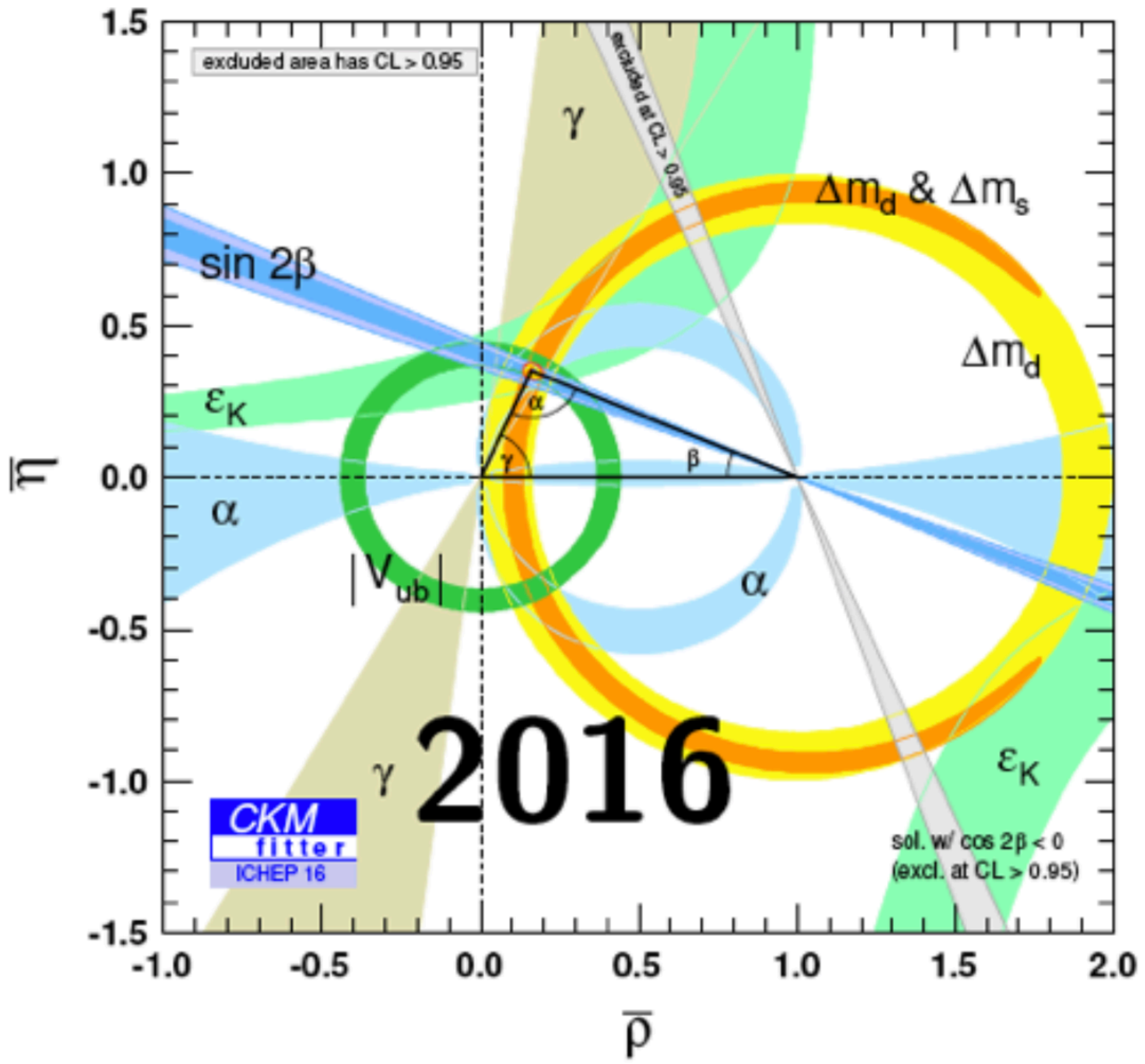
Precision flavor physics

- Precision flavor physics unlocks scales far beyond the direct energy reach of colliders. The desire to understand the results of Babar and Belle led to the development of Soft-Collinear Effective Theory, which has applications ranging from from the LHC to dark matter physics. Progress in flavor physics has spurred the development of new techniques and algorithms for multi-loop calculations that have crossed over into LHC physics.

Progress in both experimental measurements and theory has sharpened our image of the quark flavor sector in the SM.





Reviewed in *Theory techniques for precision physics,* Snowmass topical group report

Precision flavor physics

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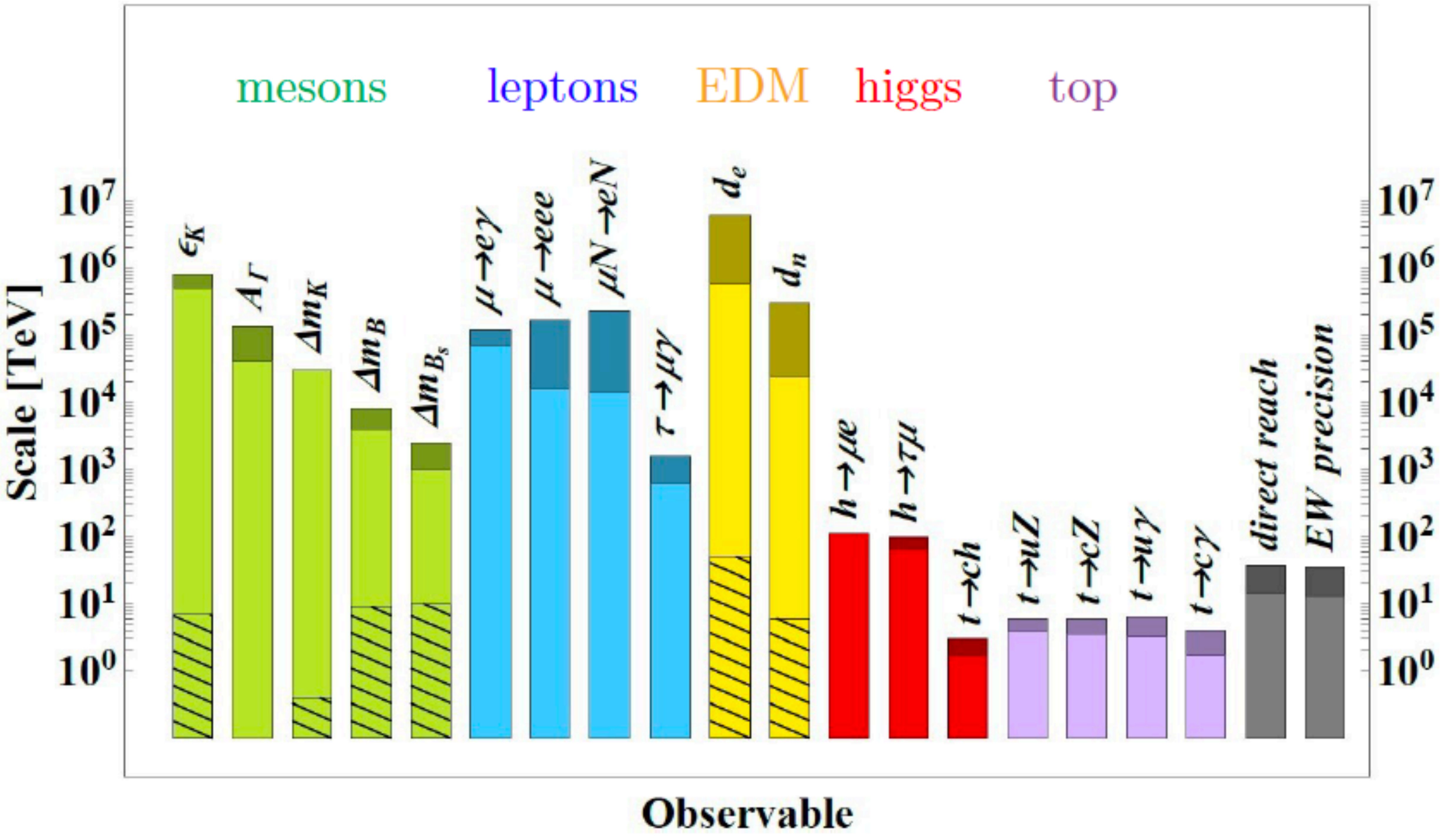
Precision measurements in the kaon and B-meson systems can probe scales for flavor-violating new physics far beyond the direct reach of experiments.



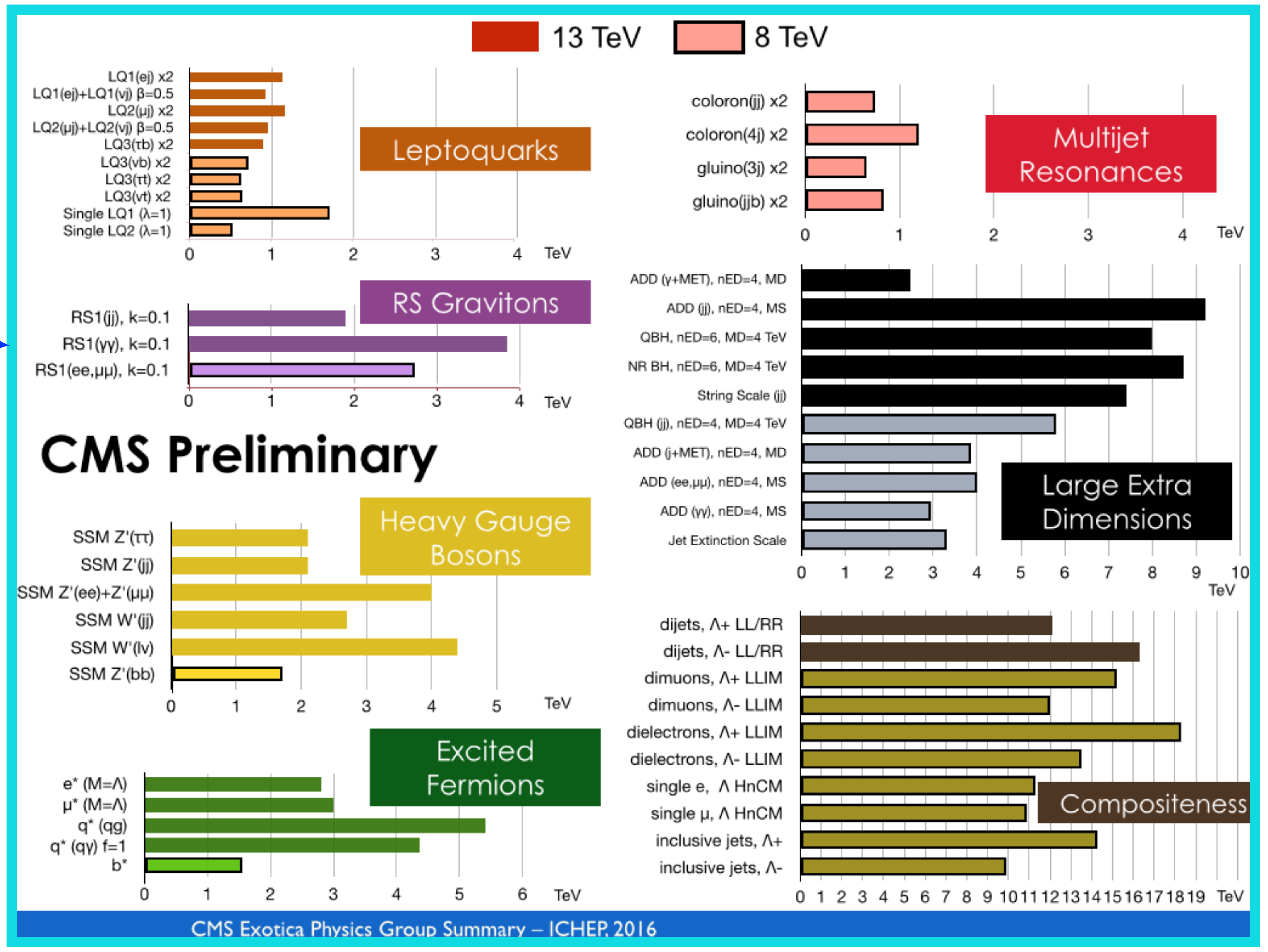
Reviewed in *Theory techniques for precision physics,* Snowmass topical group report

Novel signatures for experiment

- The theory community has a long history of motivating new experimental searches. Many of the new phenomena searches at high-energy colliders, and elsewhere, are motivated by theoretical models that attempt to solve outstanding issues in Nature.

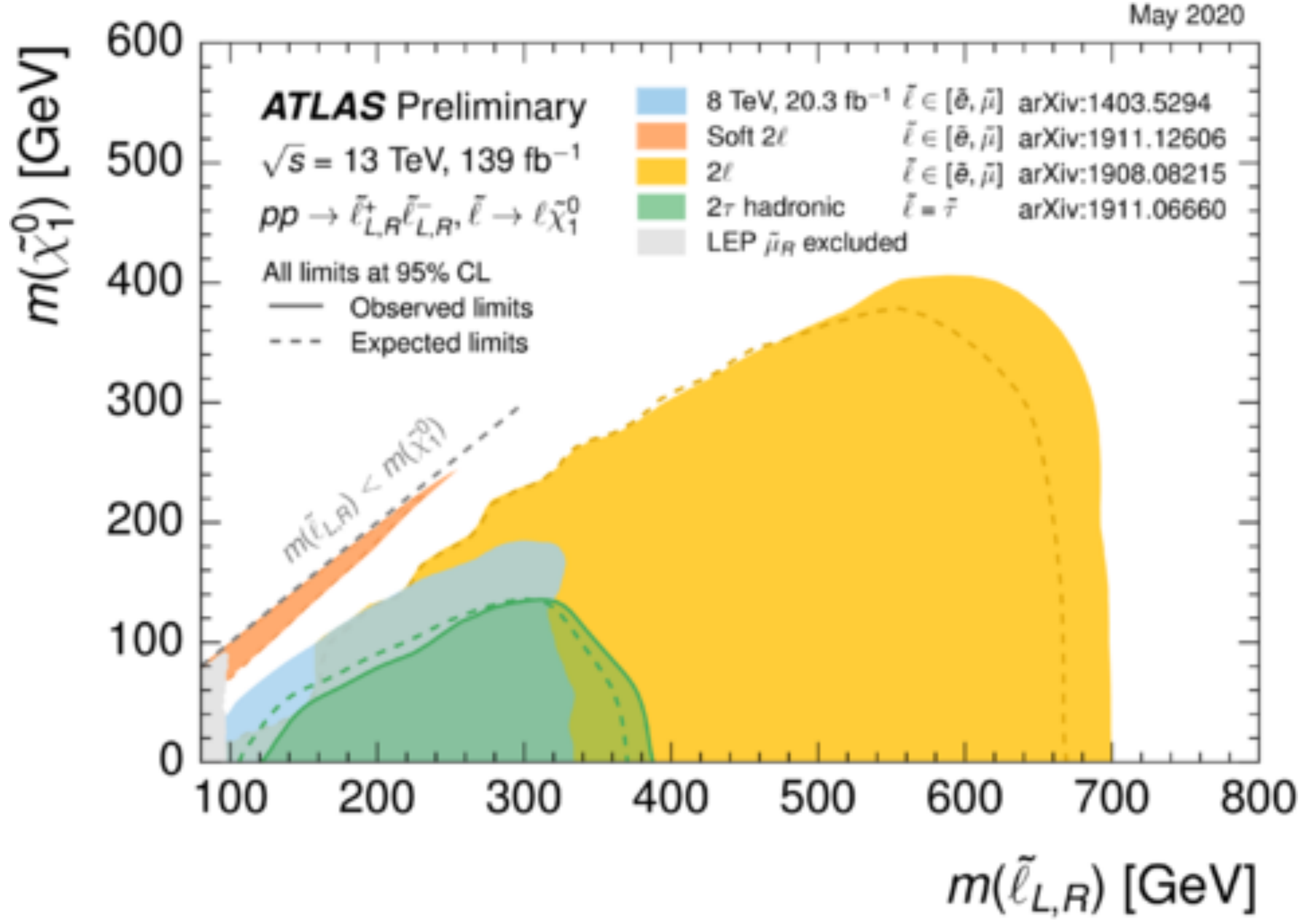
TeV-scale gravity with warped geometries: hierarchy problem and fermion Yukawa puzzle

Grand Unified Theories: gauge coupling unification



Kaluza-Klein extra dimensions at the TeV scale: hierarchy problem

SUSY: dark matter, hierarchy problem

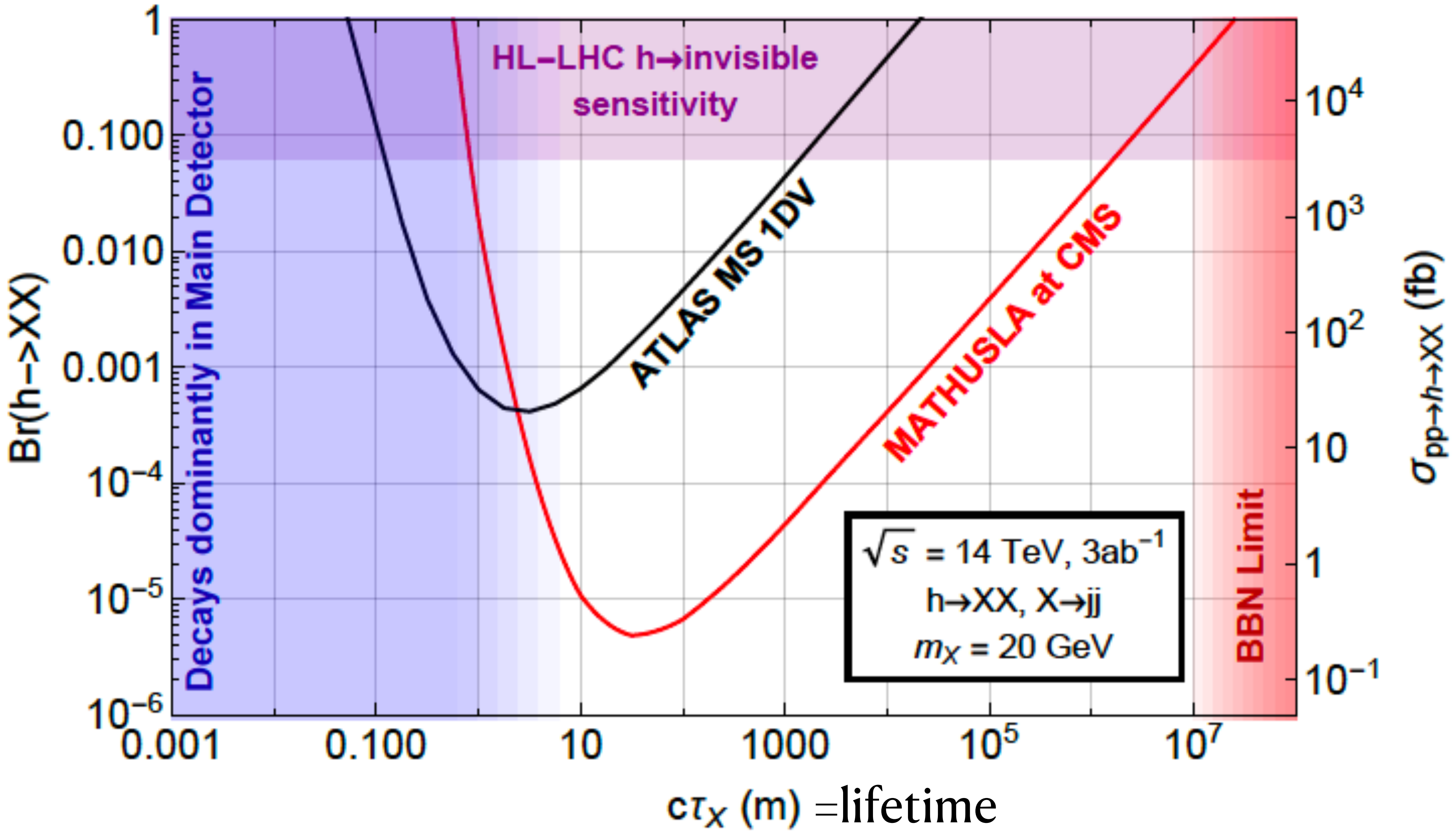


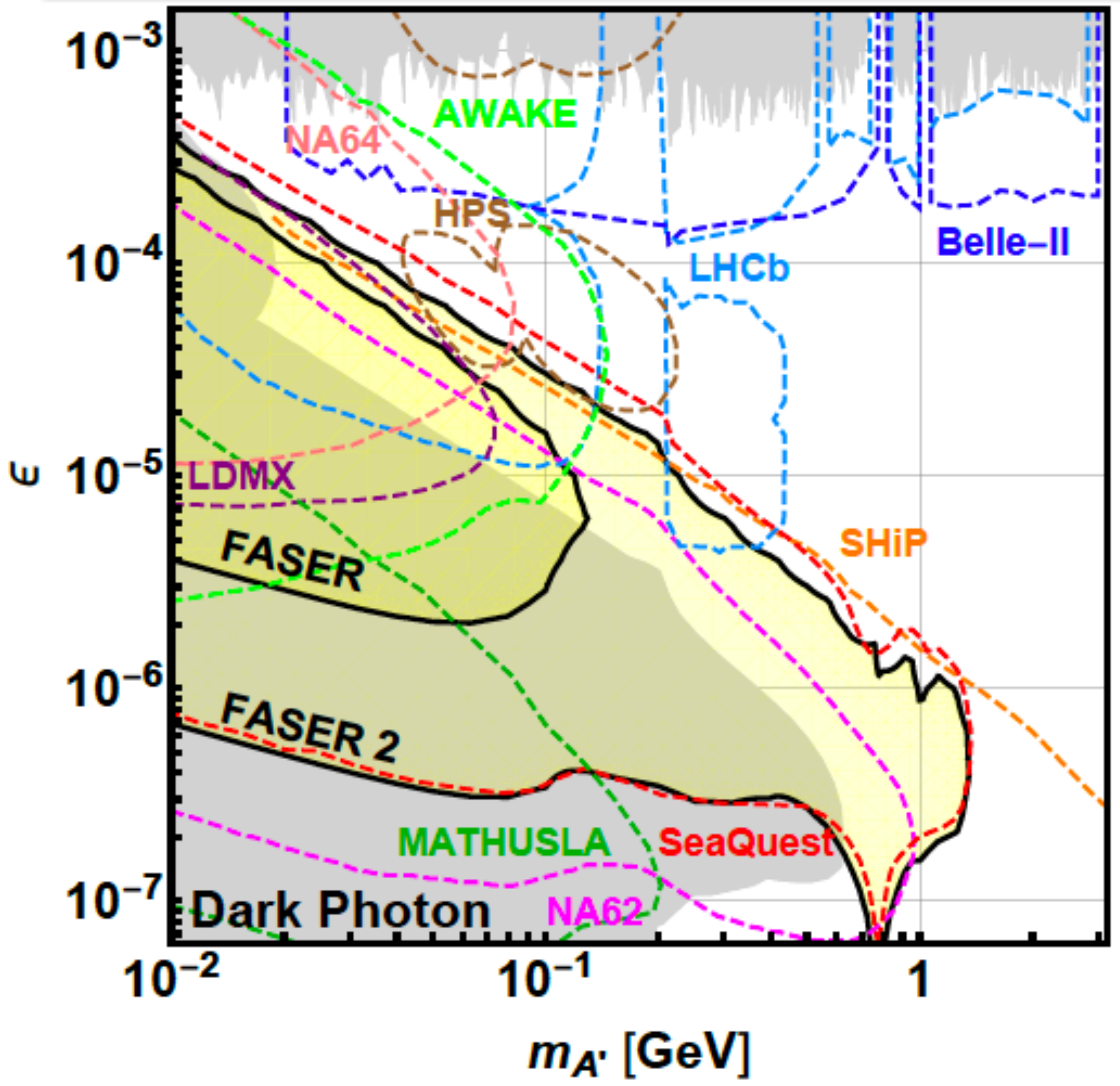
Novel signatures for experiment

- The past few years have seen a flurry of activity on developing models of ultra-light dark matter, long-lived particles, axions, and a host of other particles leading to novel signatures that in many cases have led to the proposal of new experiments.

Reviewed in *Theory of Collider Phenomena*, Snowmass contribution

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f$$





MATHLUSA: searches for long-lived particles mediating exotic Higgs decays. Can extend the reach of the HL-LHC for these states.

FASER: searches for dark photon and other long-lived or weakly-interacting particles. Probes parameter space complementary to Belle and LHCb.

EFT frameworks for new physics searches

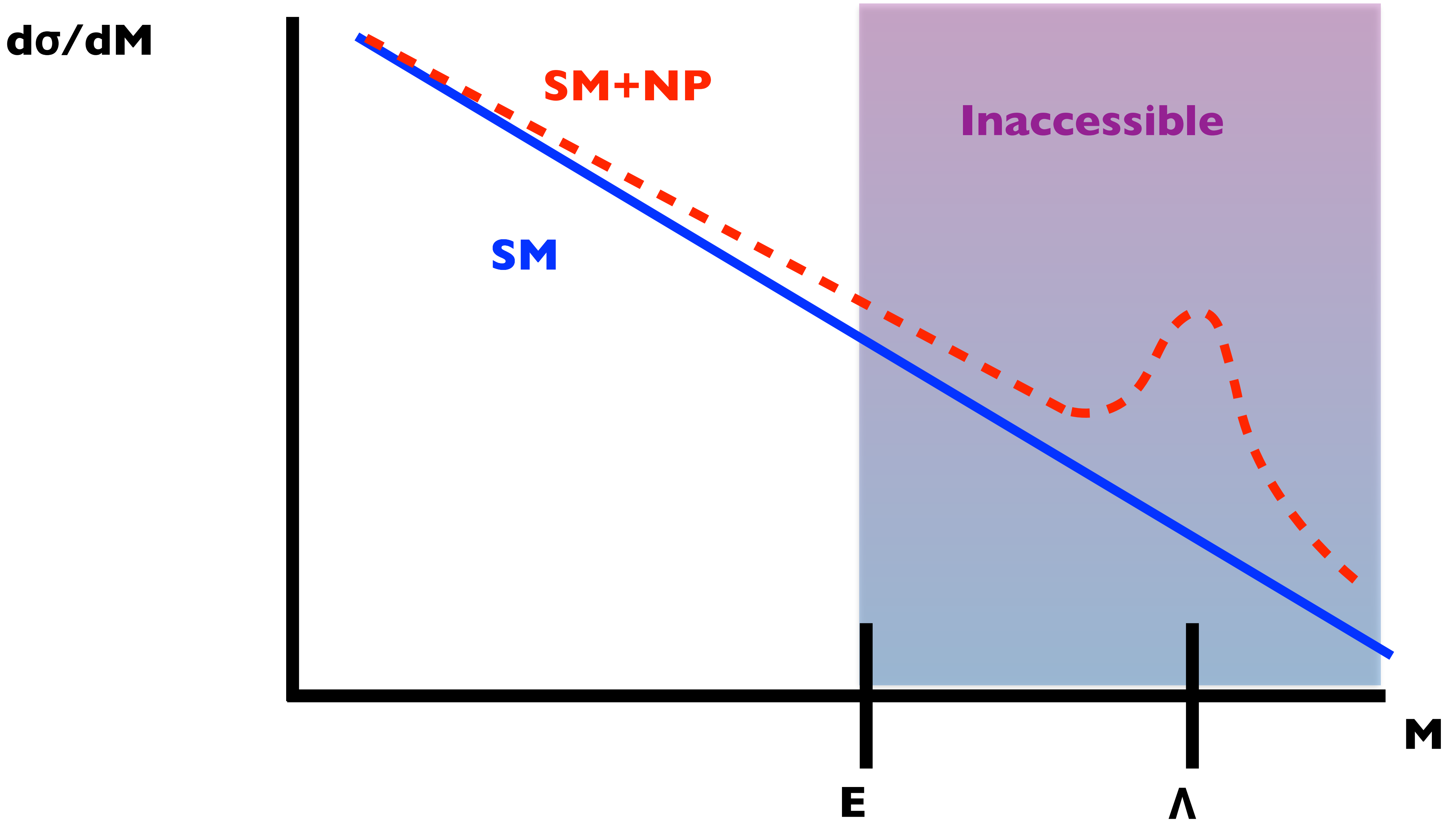
- There is no definitive evidence of new physics beyond the Standard Model. The search reach in many channels at the LHC has reached several TeV, motivating a mass gap between the SM and any new states. The Standard Model Effective Field Theory is an EFT framework that encapsulates this picture and provides a well-defined framework for current and future studies.

$\Lambda \gg$vev, E

$$\boxed{\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \underbrace{C_{6,i}\mathcal{O}_{6,i}}_{\text{Dimension-6}} + \frac{1}{\Lambda^4}\sum_i \underbrace{C_{8,i}\mathcal{O}_{8,i}}_{\text{Dimension-8}}}$$

The theory contains all operators consistent with the SM gauge symmetries. It is a consistent and predictive QFT: it is renormalizable order-by-order in Λ.

What the SMEFT is designed to handle:

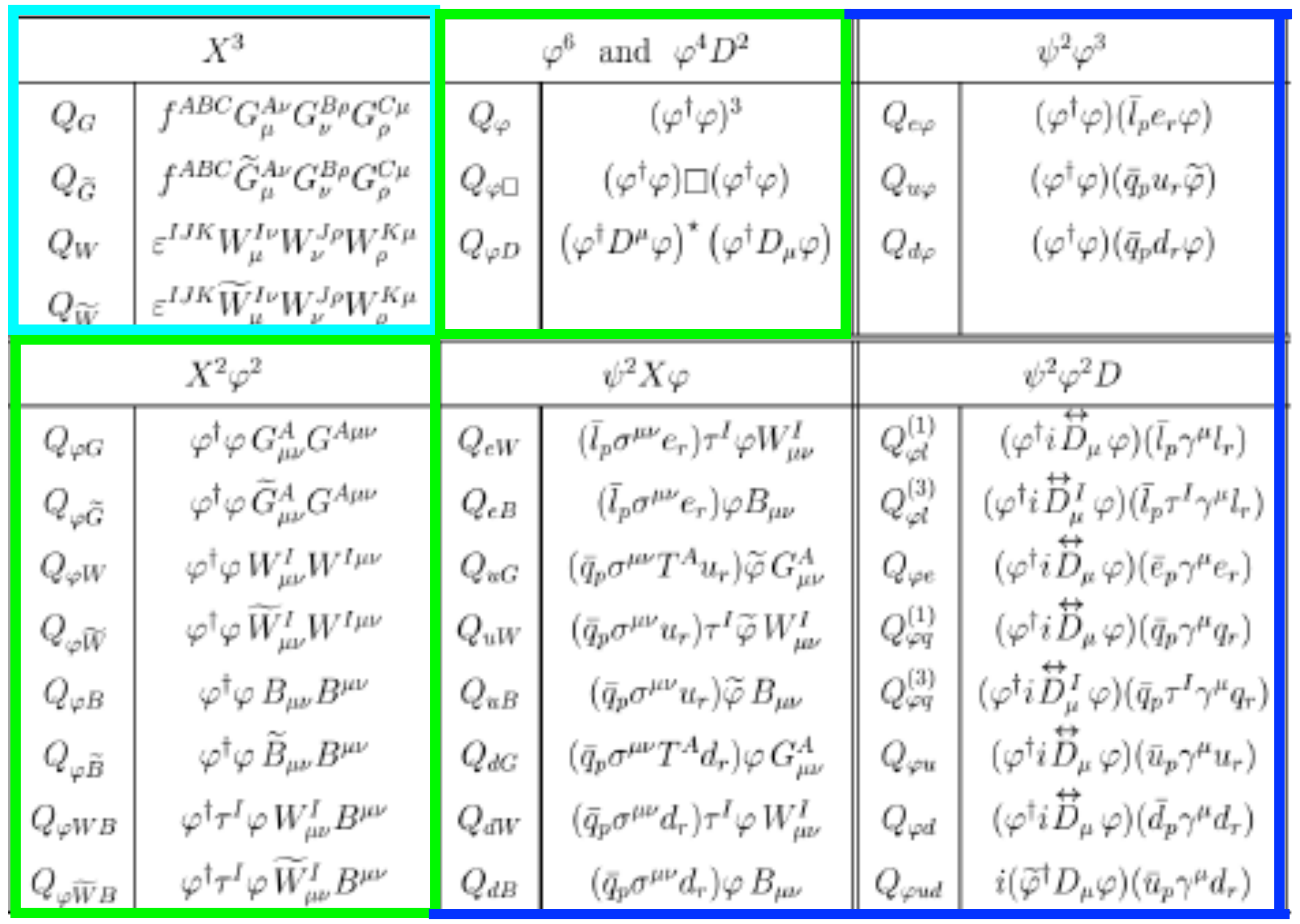


EFT frameworks for new physics searches

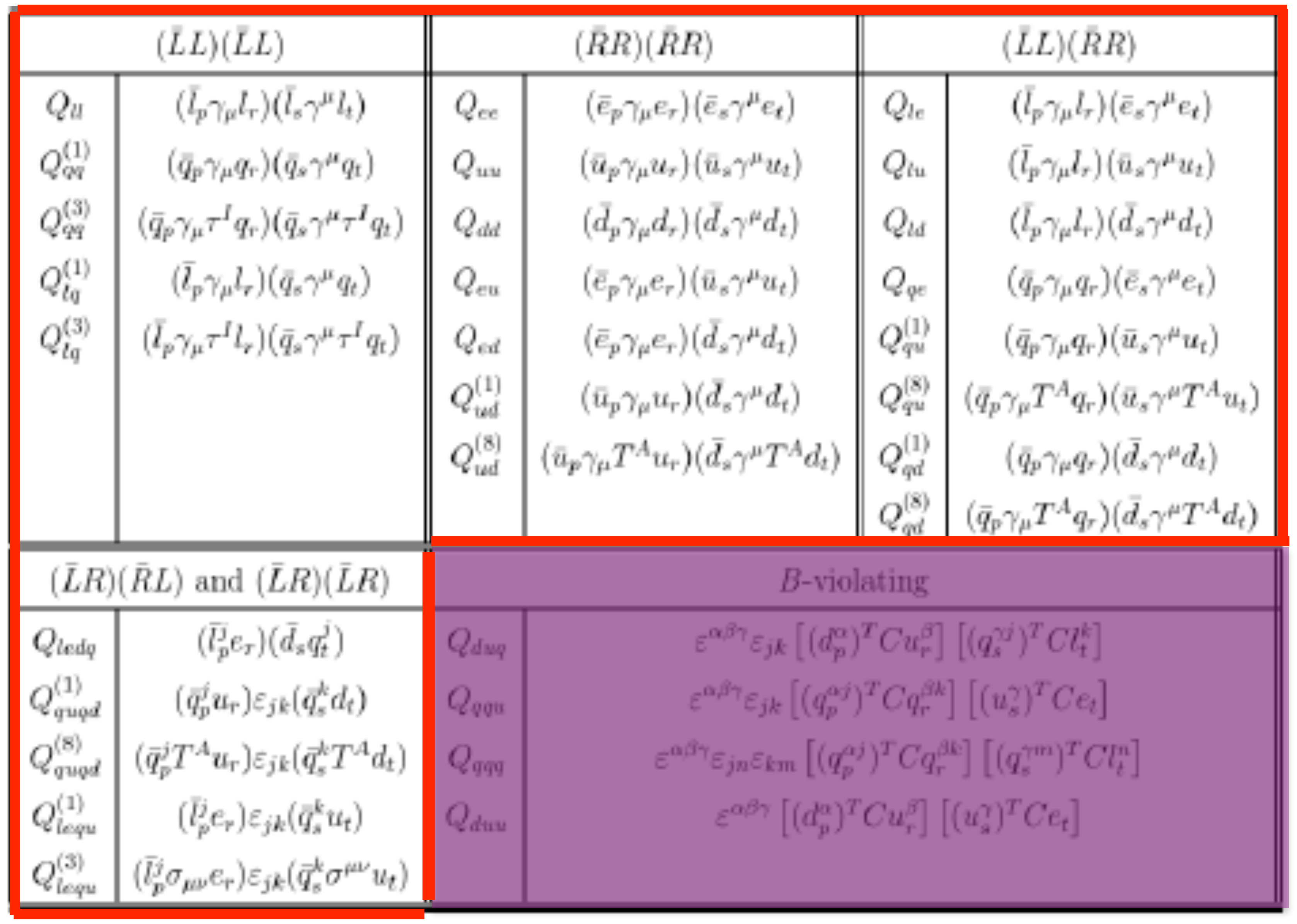
- The development of the SMEFT as a fully consistent QFT ready for comparison with experiment, with higher-order corrections and renormalization-group effects incorporated, has been a great success of the theory community over the past decade.

Pure Gauge interactions

Accommodates a rich phenomenology in all sectors



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$				

Gauge-Higgs interactions

Fermion-Higgs-gauge interactions

Four-fermion interactions

Baryon-number violating interactions

Dimension-6 basis:

Buchmuller, Wyler (1986);

Grzadkowski et al (2010)

Dimension-6 RG running:

Alonso, Jenkins, Manojar, Trott (2013-2014)

Dimension-8 basis:

Murphy (2020)

Li et al (2020)

Future directions in the theoretical development of the SMEFT reviewed in *Theoretical developments in the SMEFT at dimension-8 and beyond*, Snowmass contribution

EFT frameworks for new physics searches

- An increasingly important effort in the community is the incorporation of available data into global fits within the SMEFT framework. This is a very active area that spans both the theoretical and experimental communities, and overlaps with the development of machine learning and other advanced computational techniques.

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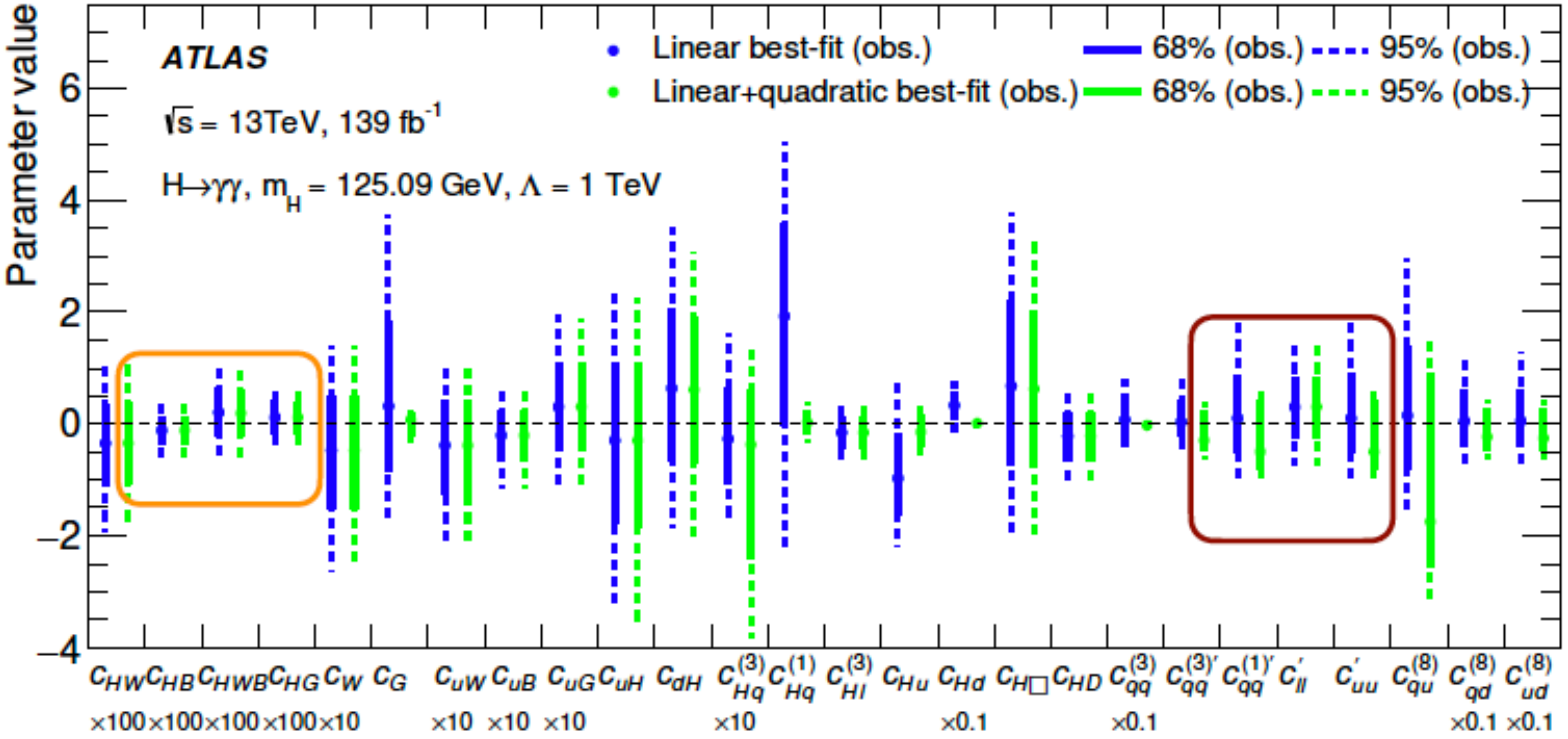
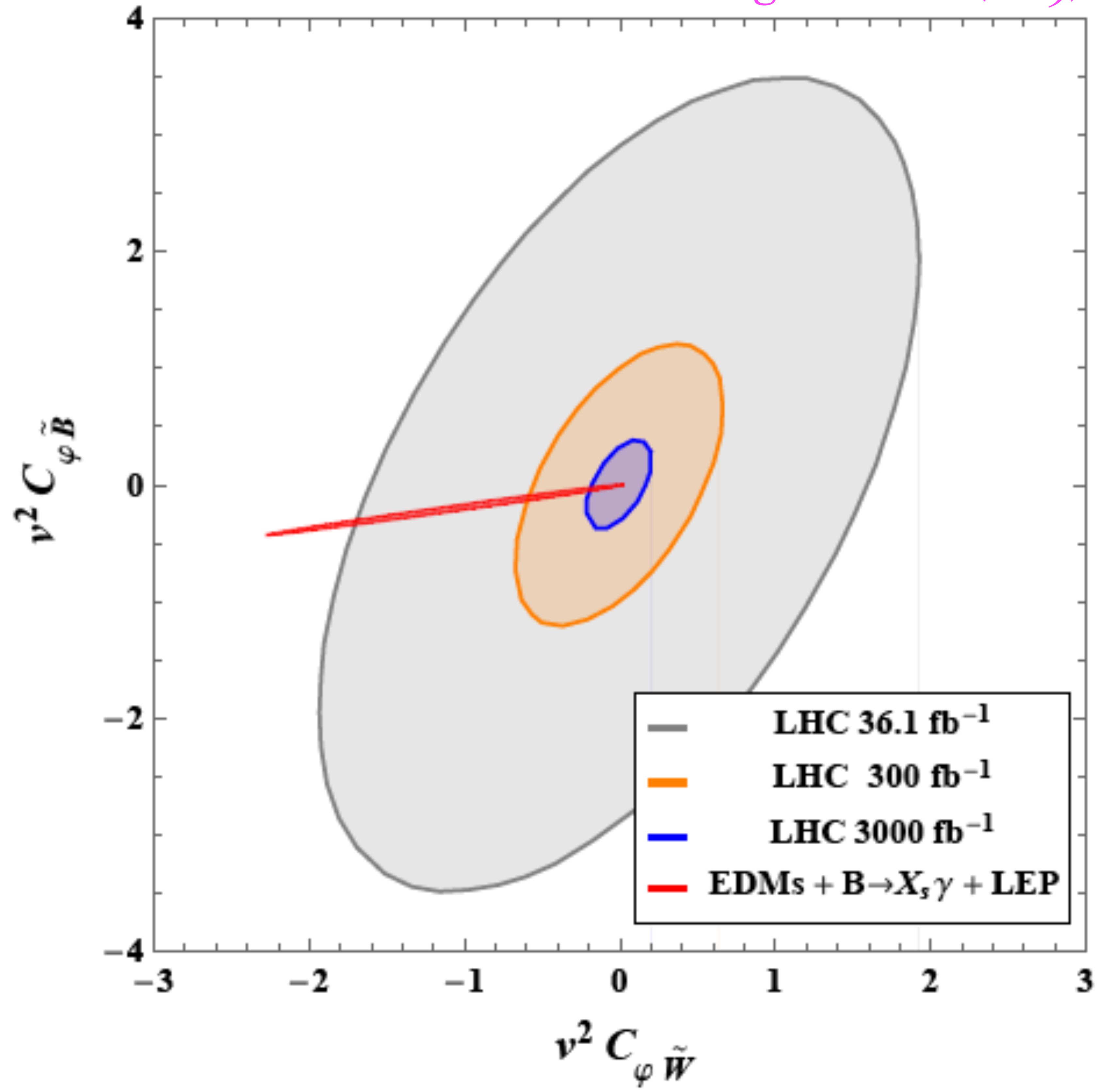


Current LHC data increasingly probes a large spectrum of operators at or beyond the TeV scale

EFT frameworks for new physics searches

- The EFT framework makes manifest the strong synergies between searches at high-energy HEP facilities and those in other fields. They may feature different energies and may have been designed for other purposes, but they are revealing different aspects of the same physics.

Cirigliano et al (2019)



$C_{\phi\tilde{B}}$: $\phi^\dagger \phi B_{\mu\nu} \tilde{B}^{\mu\nu}$

$C_{\phi\tilde{W}}$: $\phi^\dagger \phi W_{\mu\nu} \tilde{W}^{\mu\nu}$

The LHC removes an approximate flat direction that appears in low-energy EDM probes of CP-violating Higgs interactions

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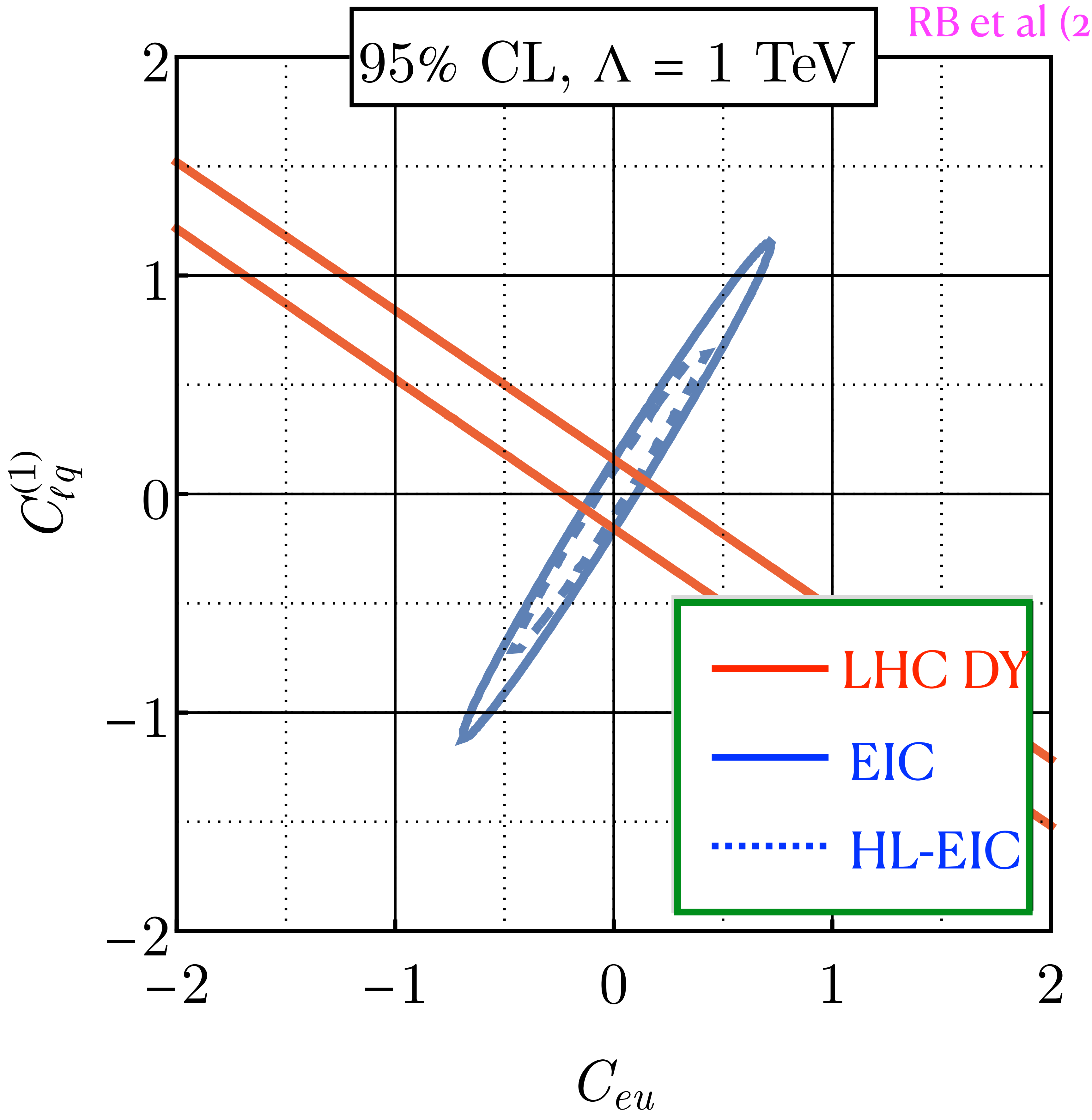

RB et al (2022)

C_{eu}: $(\bar{e}\gamma^{\mu}e)(\bar{u}\gamma_{\mu}u)$

$C^{(1)}_{lq}$: $(\bar{l}\gamma^{\mu}l)(\bar{q}\gamma_{\mu}q)$

Conversely, a future Electron-Ion Collider can remove degeneracies that appear in LHC Drell-Yan probes of four-fermion operators.

Conclusions

Theory provides the structure that underlies the experimental program, motivates new directions for explorations, and ties together the different research thrusts of HEP.

Theory is, and will remain, a vital part of the HEP research program!