New Physics

in the era of future colliders

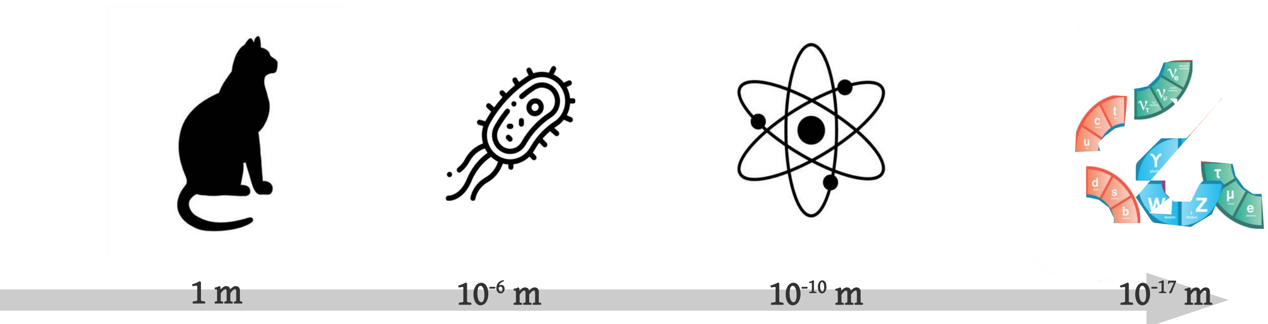
Marc Riembau
CERN

Corfu 2024
Workshop on Future Accelerators

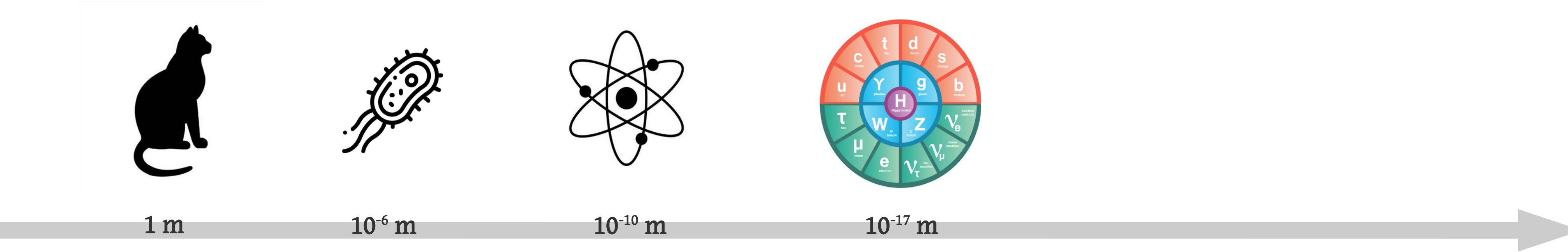
This is a personal, hence biased and time-dependent, view on what *“new physics”* means.

I do not claim any original thought, similar things have been said several times

Nature circa 2010:



Nature in 2024:



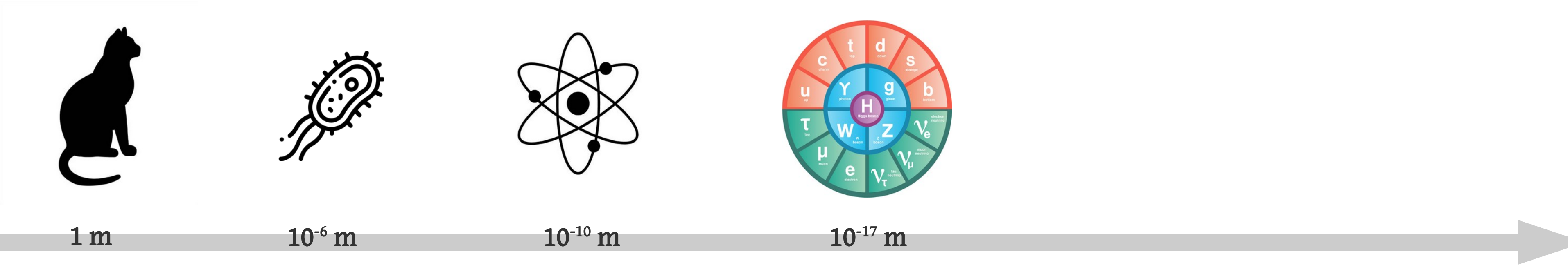
The LHC provided the **two** discoveries that transformed this picture:

The discovery of a scalar that can explain the origin of mass

The discovery of a mass gap above the electroweak scale

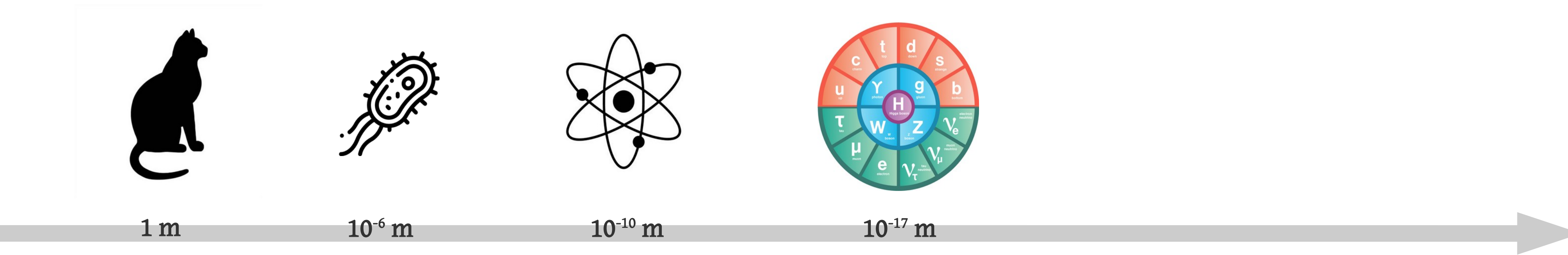
Both play an equally important role in our current description of Nature

Nature in 2024:



The Standard Model embodies *our* most fundamental understanding of Nature

Nature in 2024:



The Standard Model embodies *our* most fundamental understanding of Nature

It is ridiculous to think it is *the* fundamental description of Nature

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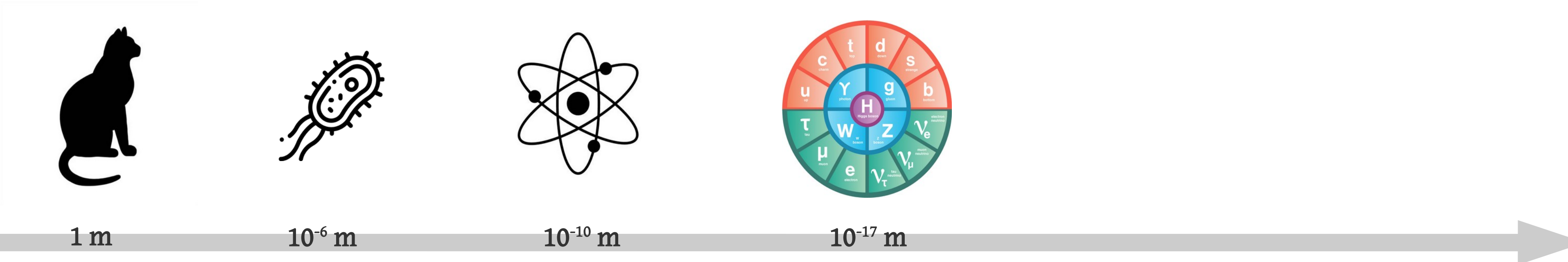

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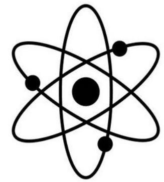
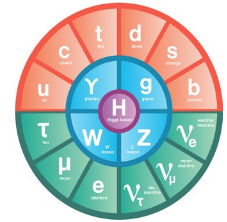




1 m

10^{-6} m

No explanation for flavor structure

Theta_QCD is compatible with zero without apparent reason

Higgs potential metastable

No explanation of matter-antimatter asymmetry

No dark matter candidate

No inflaton candidate

Unknown microscopic origin of neutrino masses

Large hierarchies

Dark energy???

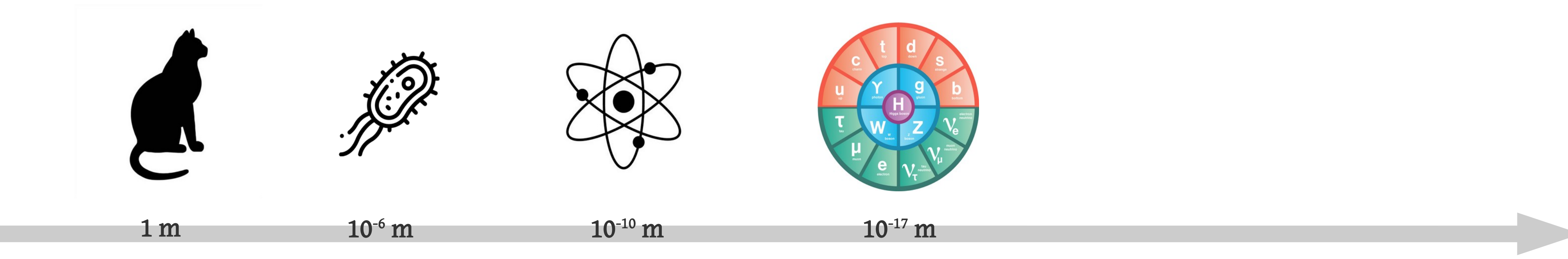
...

The Standard M … ding of Nature

It is ridicul … Nature

It is ridicu … ature

Nature in 2024:



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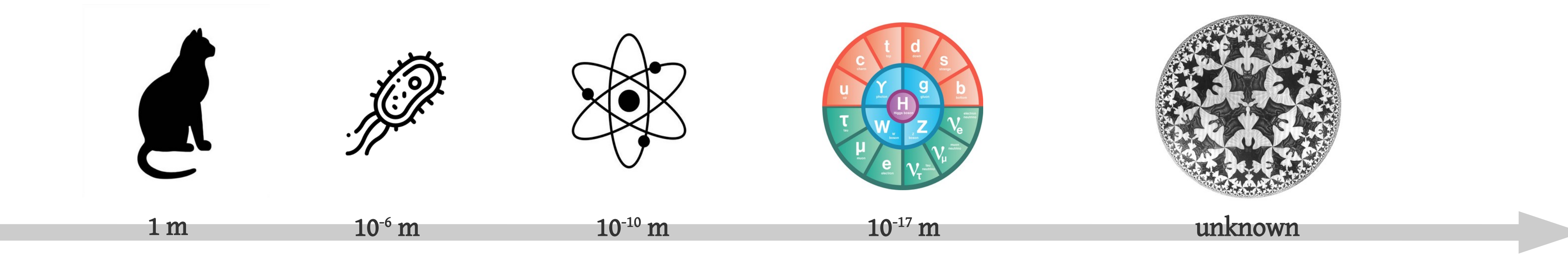
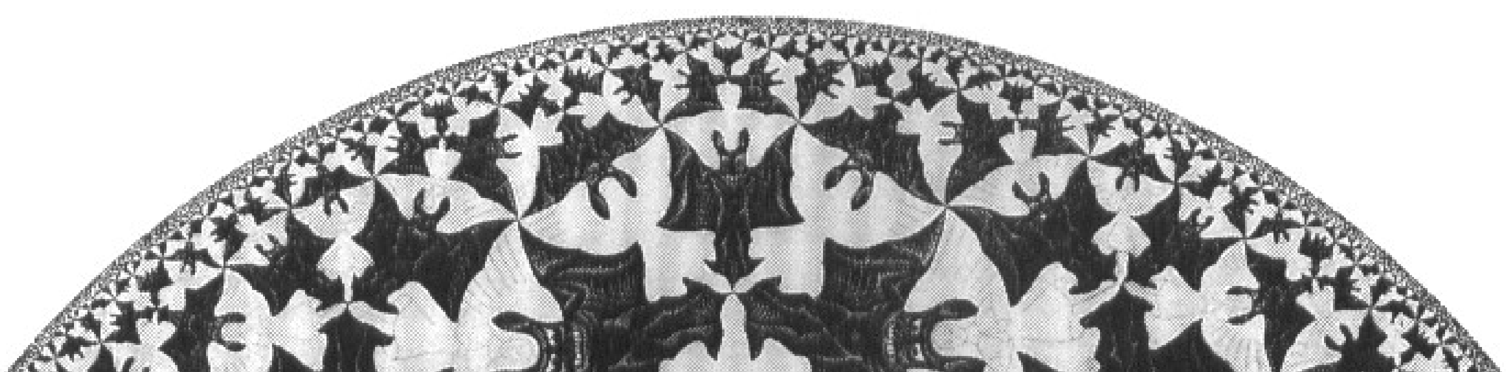
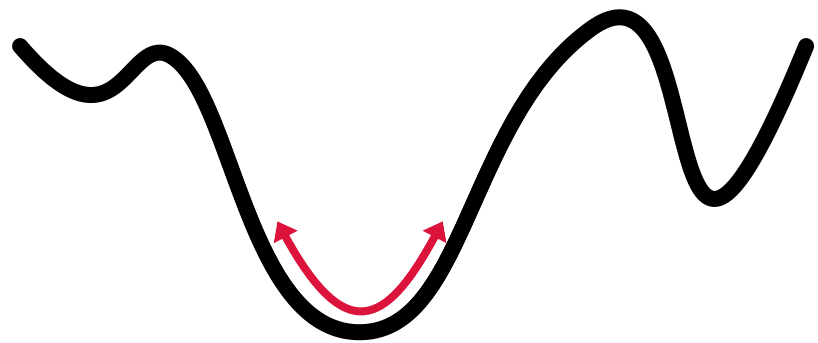
But it is *a* description


1 m
10-6 m
10-10 m
10-17 m
unknown

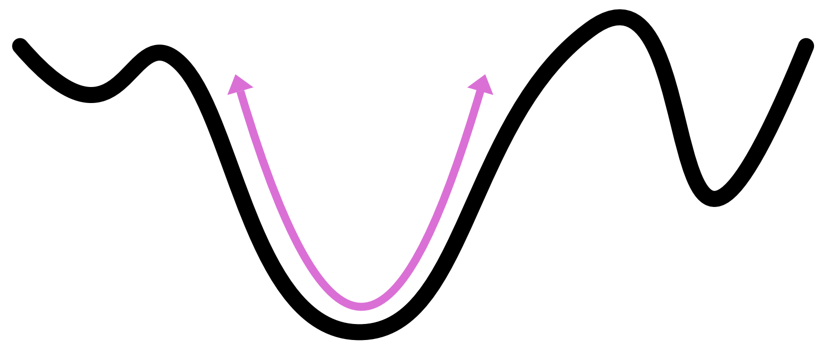
New Physics



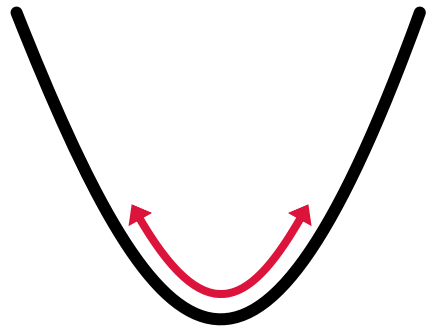
New Properties



$$\mathcal{L} = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}kx^2$$

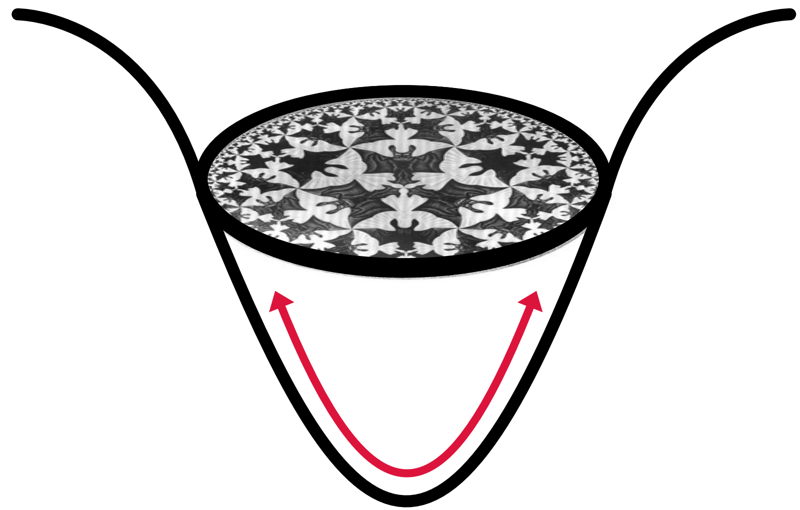


$$\mathcal{L} = \frac{1}{2}m\dot{x}^2 - \frac{1}{2}kx^2 + c_3x^3 + c_4x^4 + \ldots$$



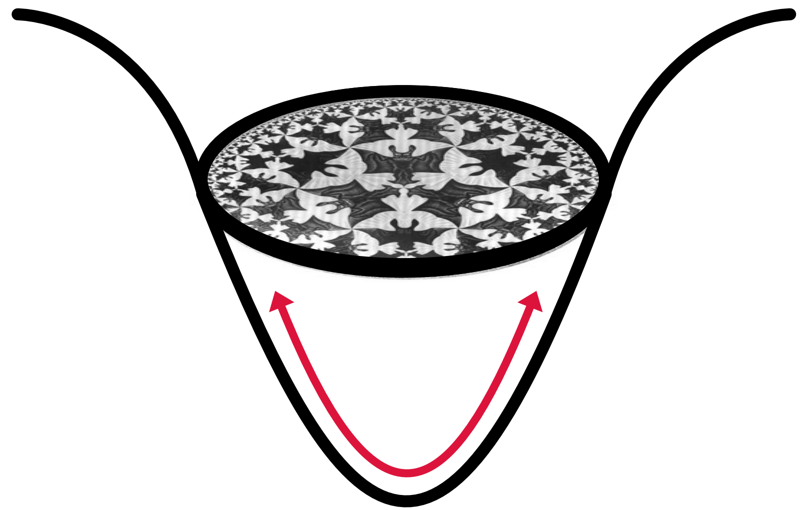
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + i\bar{\psi}\partial\psi + yH\bar{\psi}\psi + V(\phi)$$

Known matter dominated by simplest operators in the Lagrangian



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + i\bar{\psi}\partial\psi + yH\bar{\psi}\psi + V(\phi)$$
$$+\frac{1}{\Lambda}H\ell_L H\ell_L$$

That neutrinos should be massive is a remarkable prediction of the SM



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + i\bar{\psi}\partial\psi + yH\bar{\psi}\psi + V(\phi)$$

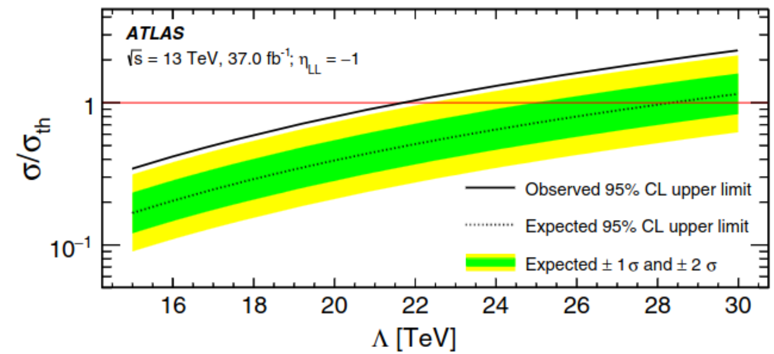
$$+\frac{1}{\Lambda}H\ell_L H\ell_L + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

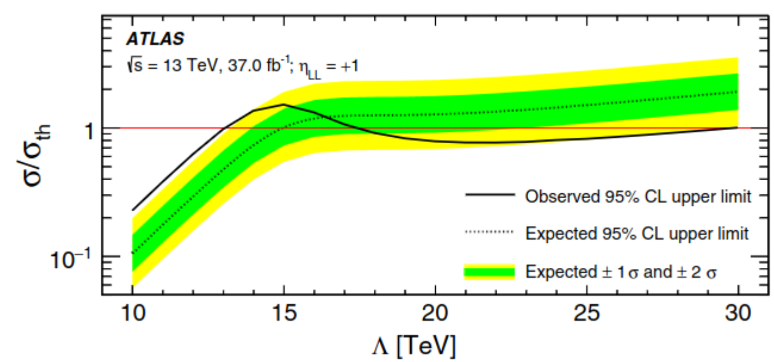
Many new properties at higher energies/precision from higher multipoles

Elementariness of elementary particles

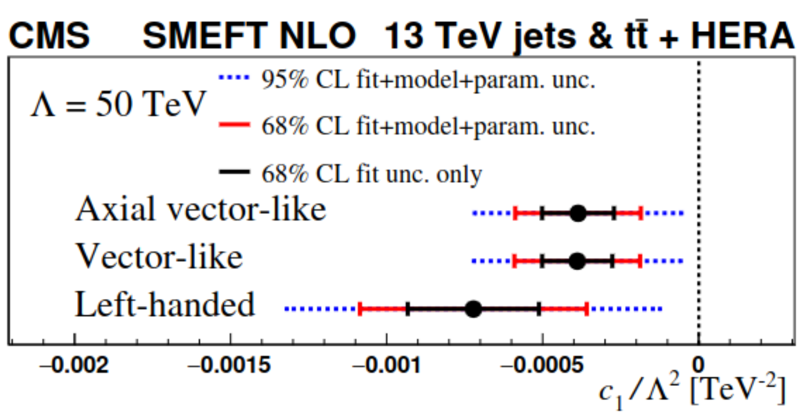
$$\mathcal{L} \supset \frac{c}{\Lambda^2}\bar{q}\gamma_\mu q\bar{q}\gamma_\mu q$$

PRD 96, 052004 (2017)





CMS-SMP-20-011

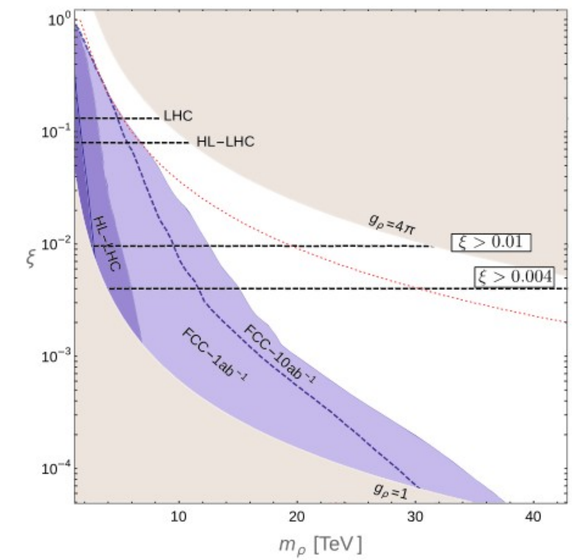


Higgs potential

Slide by Nathaniel Craig (and thanks, R. Petrossian-Byrne)

Higgs' size

	Large	Pion-ish	Point-like
size/λ_{Compton}	$\mathcal{O}(1)$	10^{-1}	
Proton	●		
Pion		●	
Electron			●
Higgs		● (current bound)	



see F. Riva's talk at 7th FCC Physics Workshop

How does the electroweak force propagate at high energies?

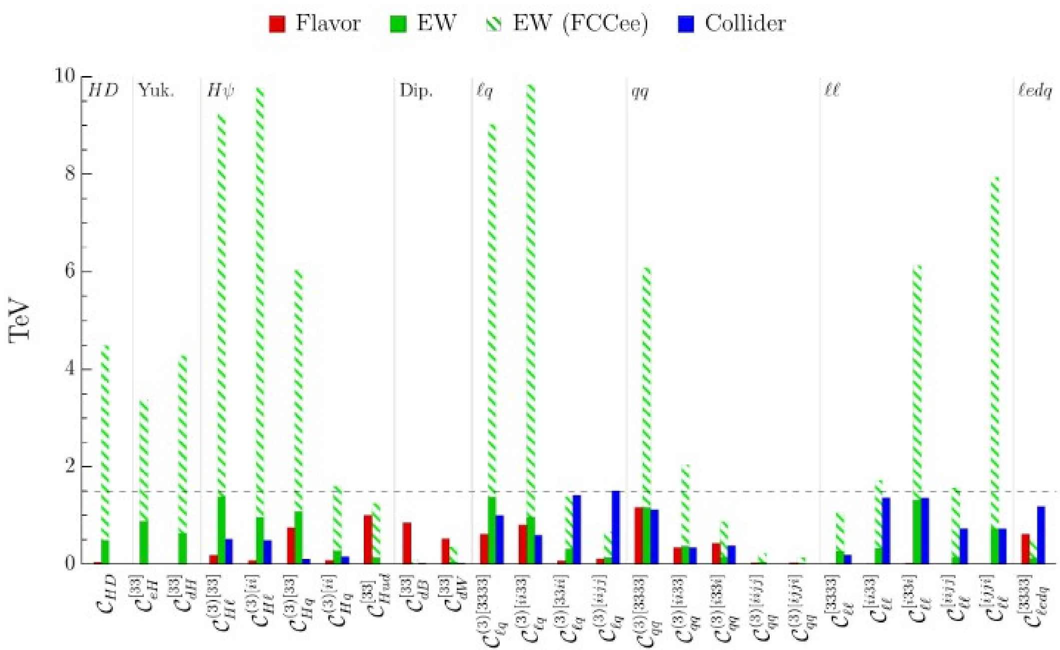
$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

Luminosity		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
		2×10^7 Z	19.7 fb^{-1}	20.3 fb^{-1}	0.3 ab^{-1}	3 ab^{-1}	10 ab^{-1}	10^{12} Z
NC	W $\times 10^4$	[− 19, 3]	[− 3, 15]	[− 5, 22]	± 1.5	± 0.8	± 0.04	± 1.2
	Y $\times 10^4$	[− 17, 4]	[− 4, 24]	[− 7, 41]	± 2.3	± 1.2	± 0.06	± 1.5
CC	W $\times 10^4$	–	± 3.9		± 0.7	± 0.45	± 0.02	–

Transitions among flavors

Tera-Z run at FCC-ee leads to per-million statistical precision.
Implications of such unprecedented precision is to be explored.

Allwicher, Cornella, Isidori, Stefanek 2311.00020



10^{-12}Z bosons

10^{-6} stat.

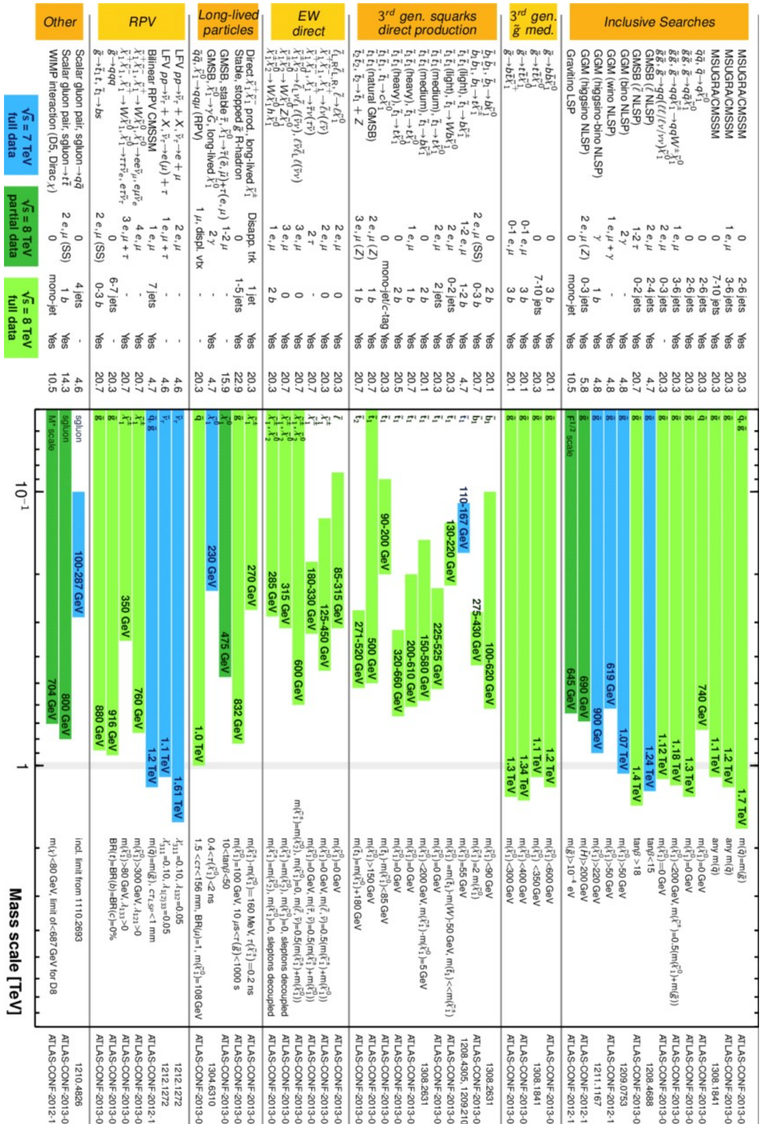
$$\delta_{obs} \sim \frac{m_Z^2}{\Lambda^2} \rightarrow \Lambda \sim 100\text{TeV}$$

$$\delta_{obs} \sim \frac{g^2}{16\pi^2} \log(\frac{m_Z^2}{\Lambda^2})\frac{m_Z^2}{\Lambda^2} \rightarrow \Lambda \sim 10\text{TeV}$$

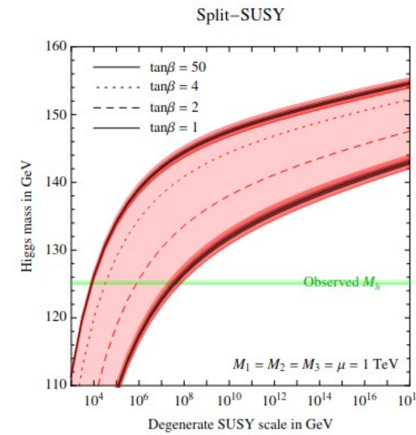
$$\delta_{obs} \sim \left(\frac{g^2}{16\pi^2}\right)^2 \log(\frac{m_Z^2}{\Lambda^2})\frac{m_Z^2}{\Lambda^2} \rightarrow \Lambda \sim 1\text{TeV}$$

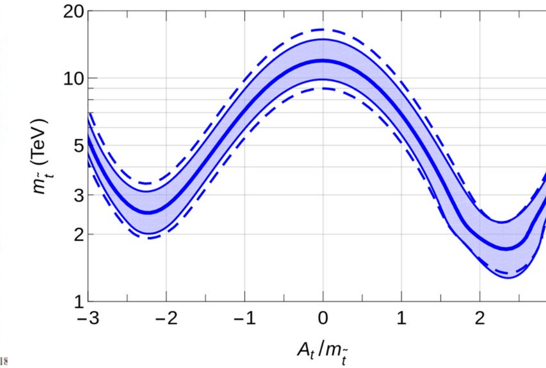
New Particles

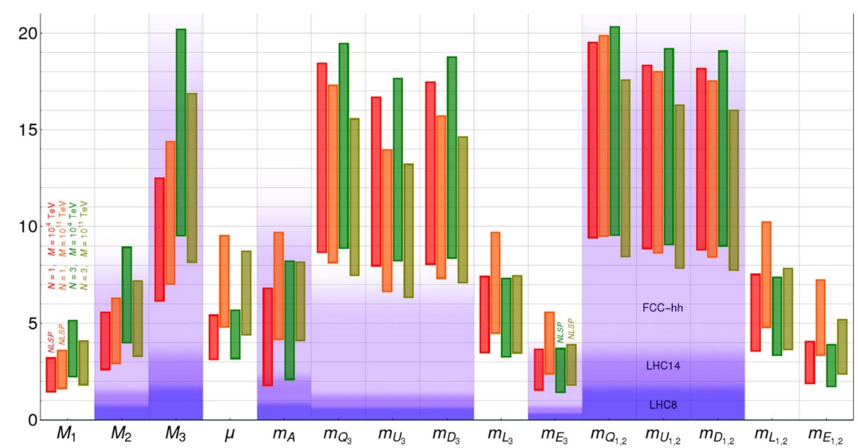
New Particles



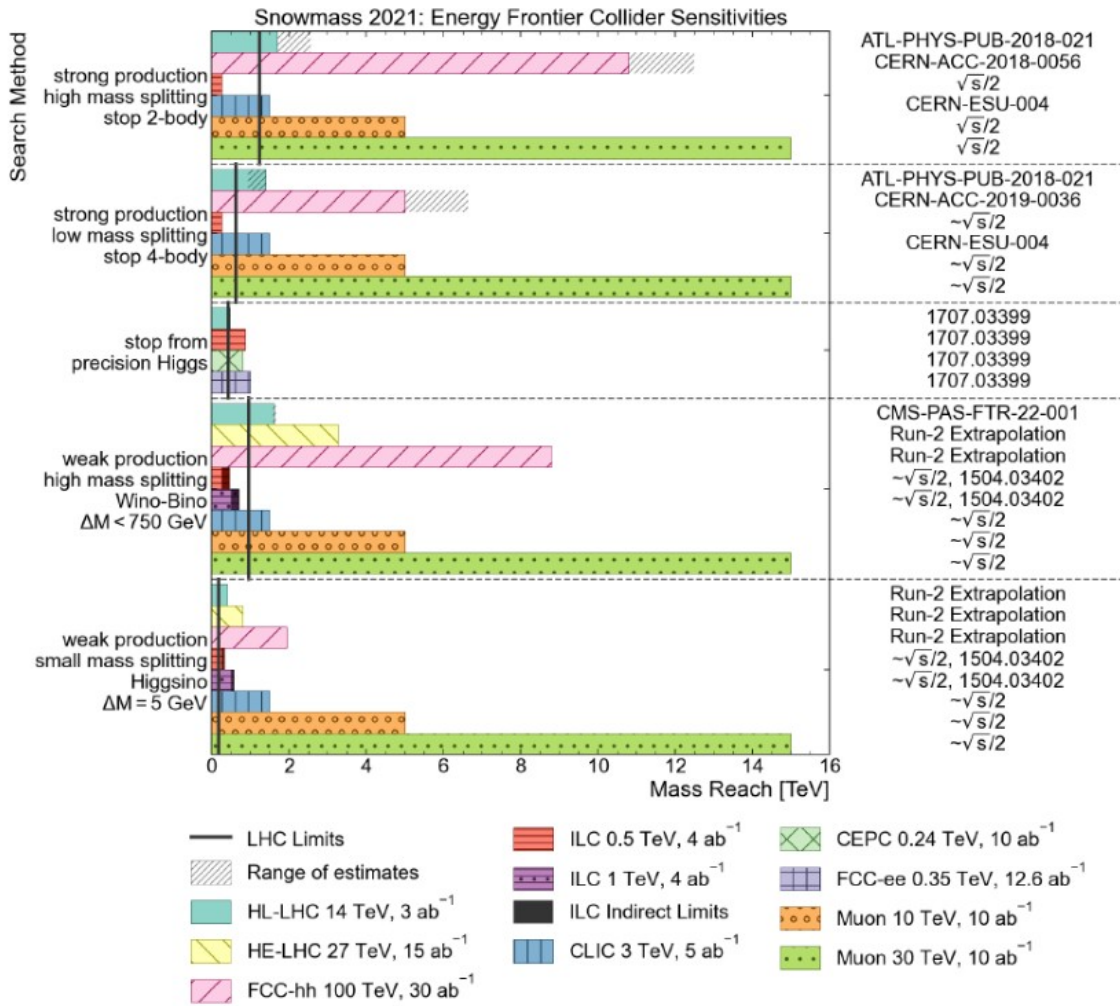
Bagnaschi, Giudice, Slavich, Strumia ‘14
Prado Vega, Villadoro ‘15





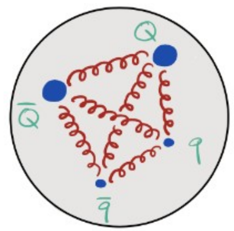


Order-of-magnitude estimate for future reach:



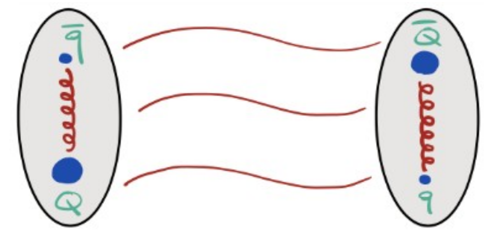
The LHC has found plenty of new resonances compatible with multiquark states

Both competing explanations have issues:



Apparent per mille fine tunning

Missing partners



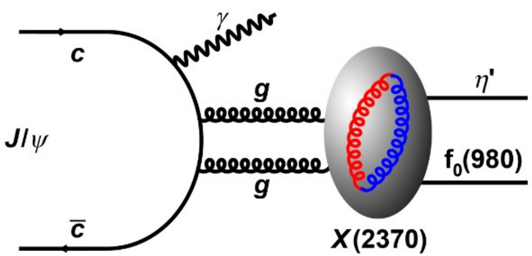
Cannot explain prompt production

Not in SU(3) of flavor

Esposito, Pilloni, Polosa Phys.Rept. (2017), 1611.07920
Lebed, Mitchell, Swanson Prog.Part.Nucl.Phys. (2017), 1610.04528
Guo, Hanhart, Meißner, Wang, Zhao Rev.Mod.Phys. (2018), 1705.00141
Esposito, Germani, Glioti, Polosa, Rattazzi Phys.Lett.B 847 (2023), 2307.11400
Germani, Niliani, Polosa 2403.04068

This morning:
[https://indico.cern.ch/event/1418383/]

Discovery of a Glueball-like particle X(2370) @ BESIII

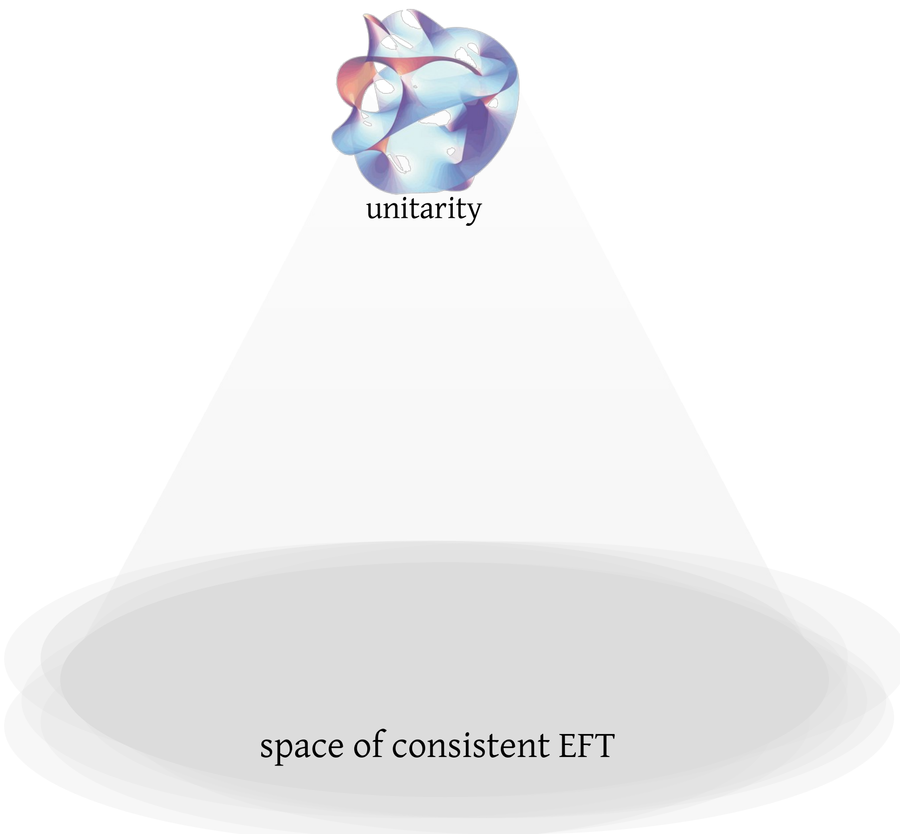


Yanping Huang
Institute of High Energy Physics, CAS
(On behalf of the BESIII Collaboration)

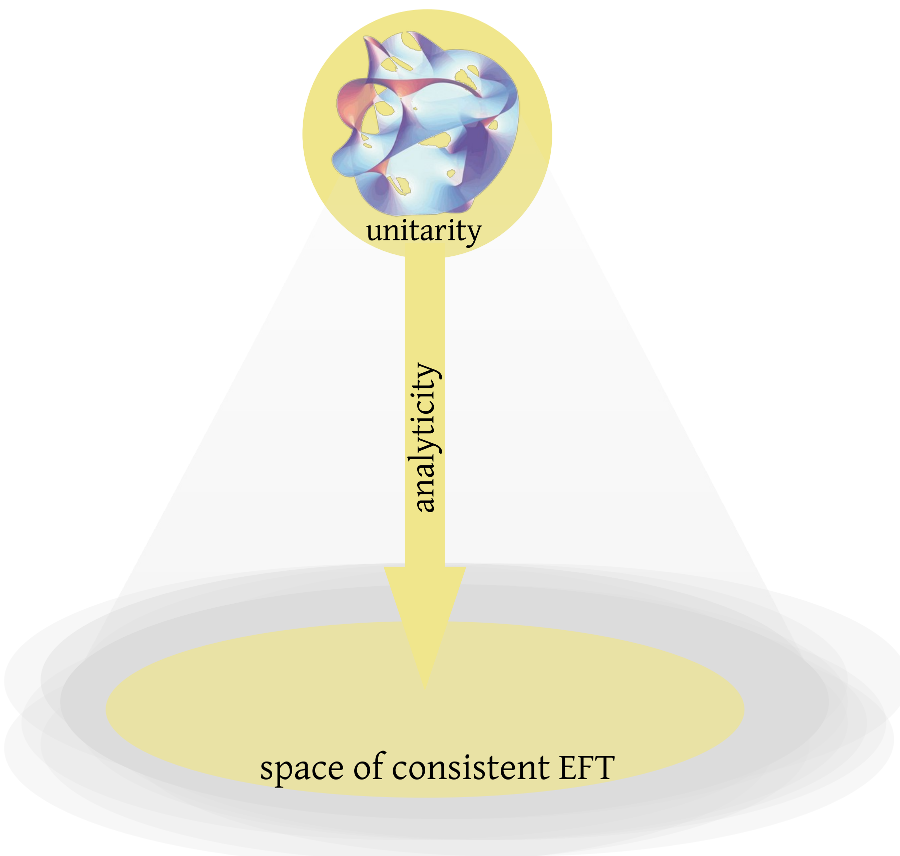
CERN Seminar, May 21st, 2024

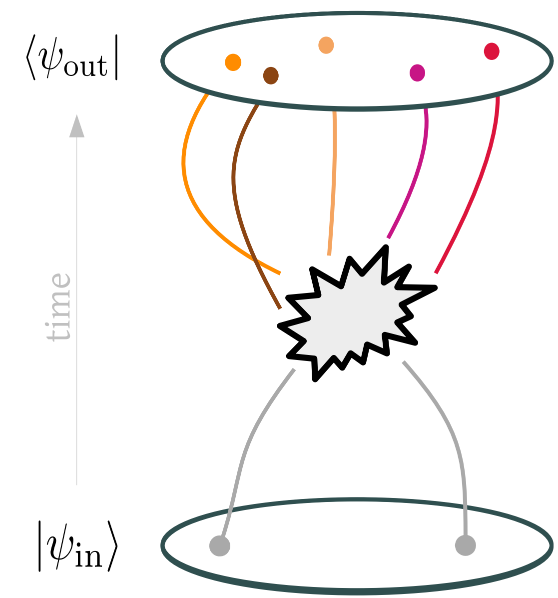
New Principles

space of microscopic theories



space of microscopic theories





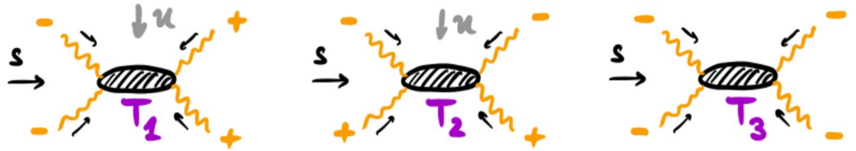
Nontrivial long-distance consequences of short-distance unitarity due to analyticity of S-matrix

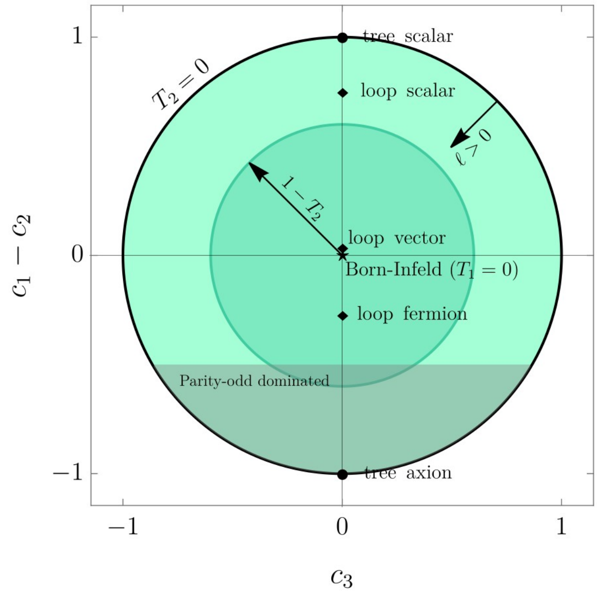
Precise implementation in recent years

Space of light-by-light scattering:

$$\mathcal{L} = -(FF) + c_1(FF)^2 + c_2(F\widetilde{F})^2 + c_3(FF)(F\widetilde{F}) + \dots$$

Li, Xu, Yang, Zhang, Zhou '21
Haring, Hebbar, Karateev, Meineri, Penedones '22
Bertucci, Henriksson, McPeak, Ricossa, Riva, Vichi '24
Durieux, Remmen, **MR**, Rodd; WIP



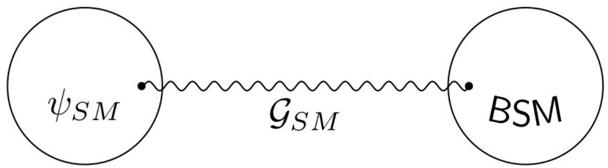


Different operators must be correlated

Map between IR and nonperturbative UV properties

McCullough, **MR**, Ricci '23

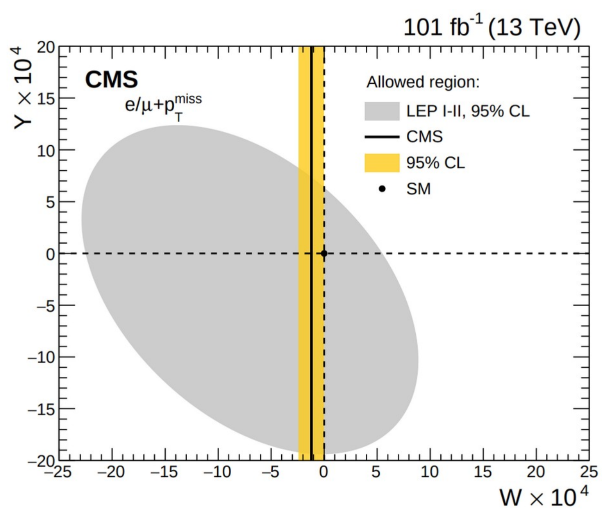
In *universal theories*, electroweak force cannot propagate arbitrarily



$$\begin{pmatrix} W & X \\ X & Y \end{pmatrix} \succ 0$$

$$W > 0\,, \quad Y > 0\,, \quad WY - X^2 > 0$$

Best determination of W parameter is from CMS, [CMS collab. 2202.06075]

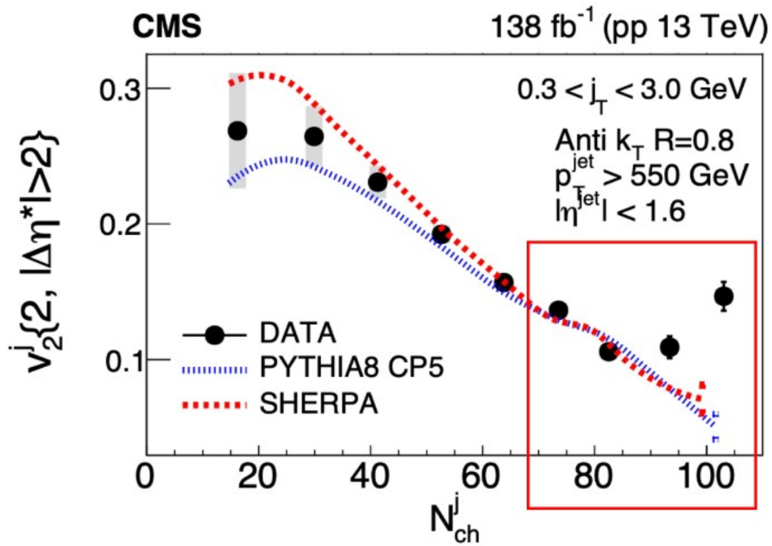


$$W = -1.2^{+0.5}_{-0.6} \times 10^{-4} \;\; !$$

New Phenomena

LHC has revealed many surprising, poorly understood phenomena.
A particularly fascinating one is the long-range correlation in high-multiplicity jets

$$\frac{1}{N_{ch}^{j}}\frac{dN^{pair}}{d\Delta\phi^*} \propto \sum_{n=1}^{\infty} V_{n\Delta}\cos(n\Delta\phi^*)$$



Collectivity?

Multiparton interactions?

String dynamics?

Check the workshop *On the theory interpretation of multi-particle correlations in small collision systems,*
In particular Wei Li's talk [https://indico.cern.ch/event/1380096/]

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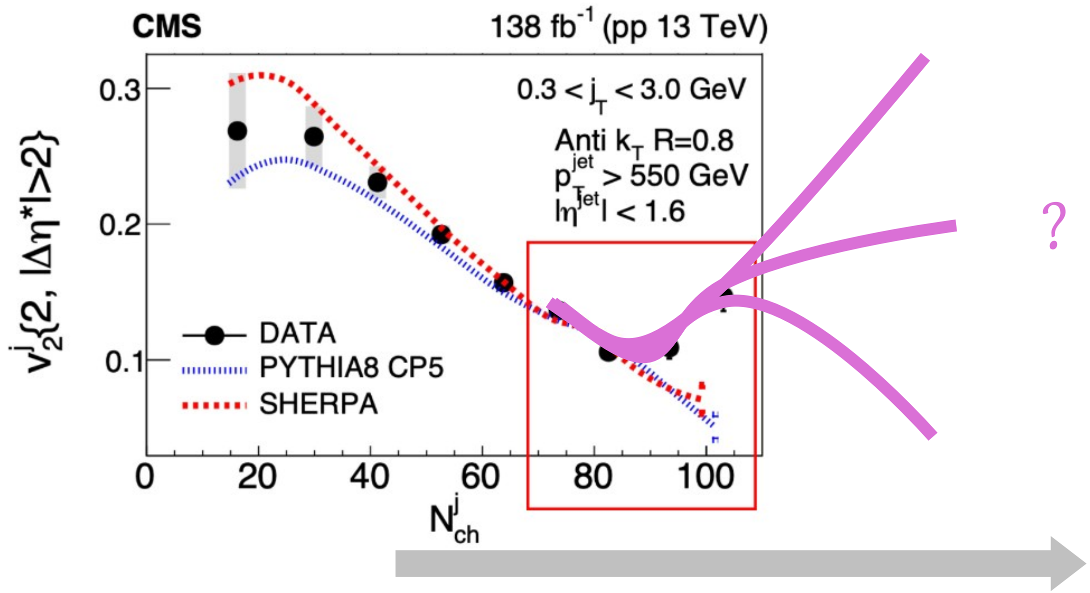

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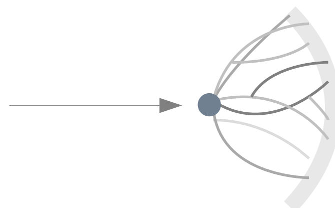
New Perspectives

Cross sections: rate at which a given state is produced.



$$\sigma(i \to j) \propto \langle i|\mathcal{M}^\dagger|j\rangle\langle j|\mathcal{M}|i\rangle$$

Can be a very hard question!

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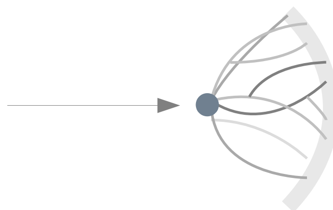

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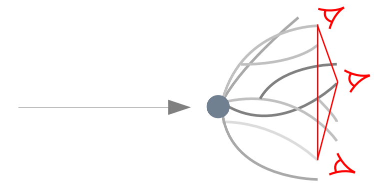
Recent resurgence of an old idea:

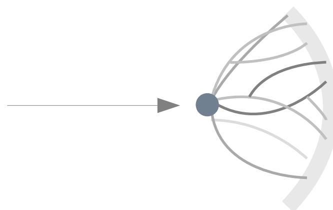
What is the correlation between energy fluxes at different directions?



$$\langle \mathcal{E}_1\mathcal{E}_2\rangle_\chi \propto \sum_\beta \int d\sigma(\alpha \to \beta) \sum_{i,j\in\beta} E_i E_j \delta(\cos\theta_{ij} - \chi)$$

Theoretically (and experimentally) more robust (e.g. defined in CFTs)

Cross sections: rate at which a given state is produced.



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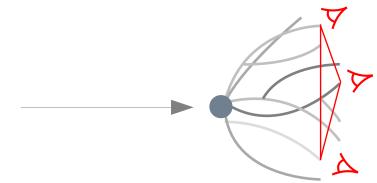

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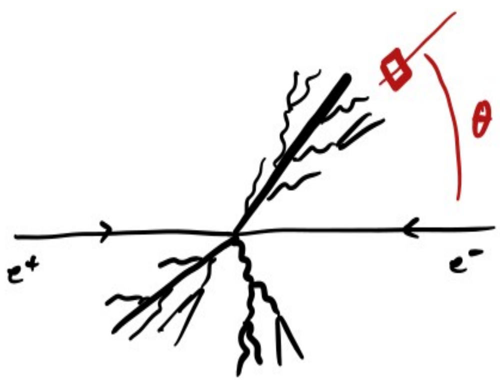
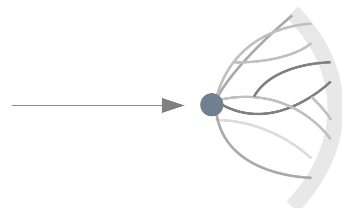


Basham, Brown, Ellis, Love '78

An experimental measure is presented for a precise test of quantum chromodynamics. This measure involves the asymmetry in the energy-weighted opening angles of the jets of hadrons produced in the process $e^+e^- \to$ hadrons at energy W. It is special for several reasons: It is reliably calculable in asymptotically free perturbation theory; it has rapidly vanishing (order $1/W^2$) corrections due to nonperturbative confinement effects; and it is straightforward to determine experimentally.

$$\frac{d\langle E\rangle}{d\chi} = \sum_i \int d\Omega |\mathcal{A}|^2 E_i \delta(\cos\theta_i - \chi)$$

Cross sections: rate at which a given state is produced.



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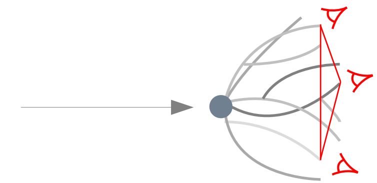

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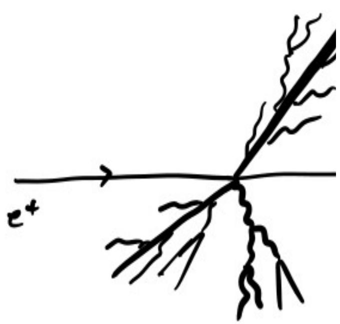

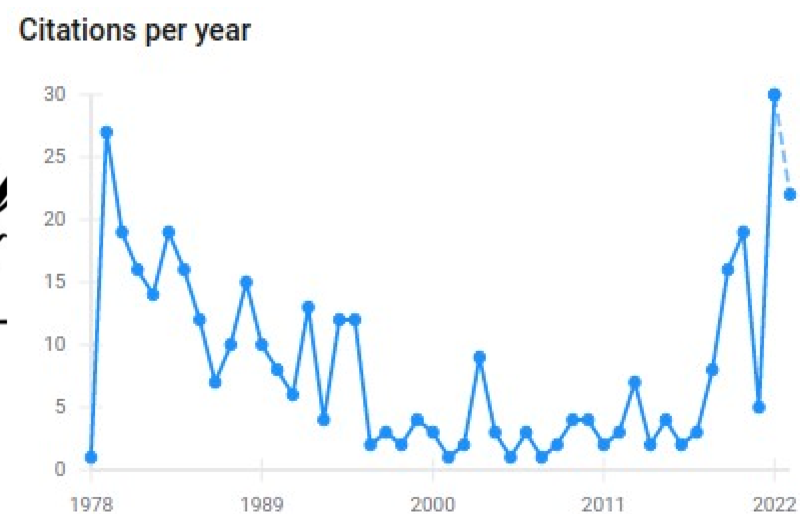

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perturbative confinement effects; and

$$\delta(\cos\theta_i - \chi)$$

Sveshnikov, Tkachov '95

Energy weights have an operatorial definition

$$\mathcal{O}_{\hat{n}_i}|\alpha\rangle = \sum_i E_i \delta(\hat{p}_i - \hat{n}_i)|\alpha\rangle$$

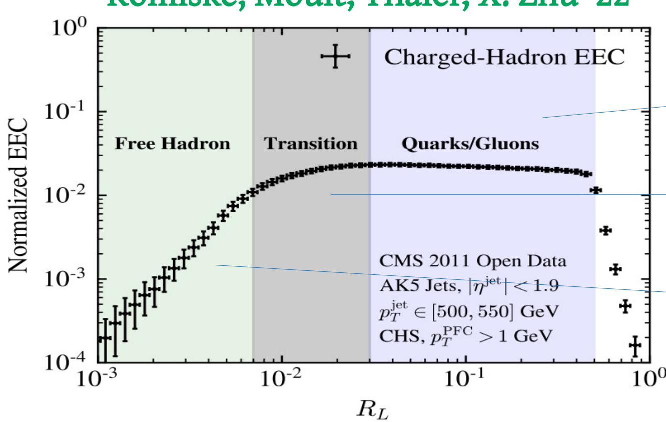
$$\mathcal{O}_n = \lim_{r\to\infty} \int dt r^2 n_i T_{i0}(t, r\hat{n}) \quad \rightarrow \quad \frac{d\langle E\rangle}{d\chi} = L_{\mu\nu} \int d^4x \langle 0|j^\mu(x)\mathcal{O}_{\hat{n}} j^\nu(0)|0\rangle$$

Hoffman, Maldacena '08

Energy weights have an OPE

$$\langle 0|j^\mu(x)\mathcal{O}_{\hat{n}}\mathcal{O}_{\hat{n}'} j^\nu(0)|0\rangle \sim \frac{1}{\theta^\gamma}\langle 0|j^\mu(x)\widetilde{\mathcal{O}}_{\hat{n}} j^\nu(0)|0\rangle + \ldots, \quad \cos\theta = \hat{n}\cdot\hat{n}'$$

Komiske, Moult, Thaler, X. Zhu '22



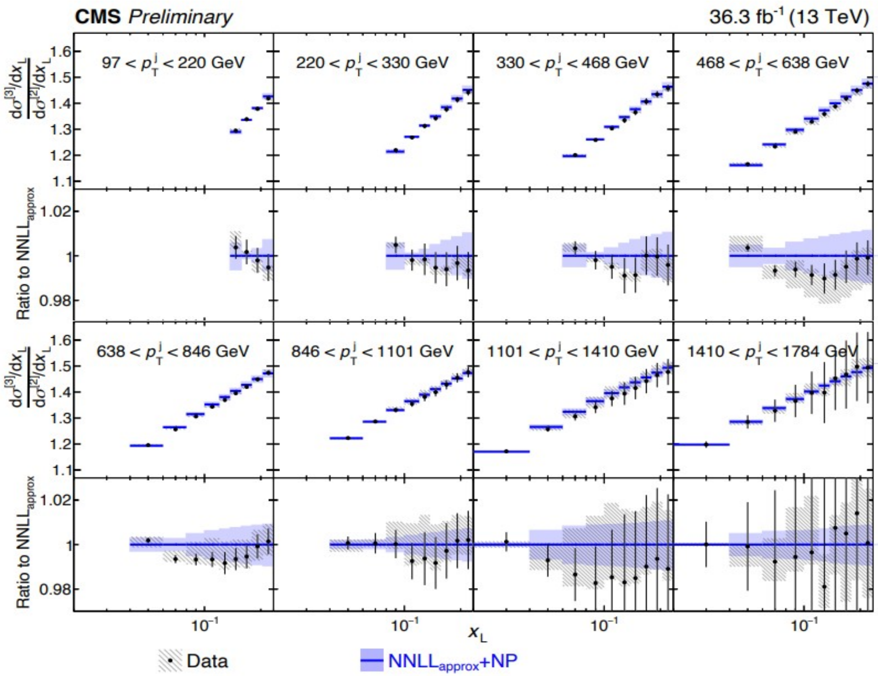
$$1 \gg \theta \gg \Lambda_{QCD}/E_{jet}$$

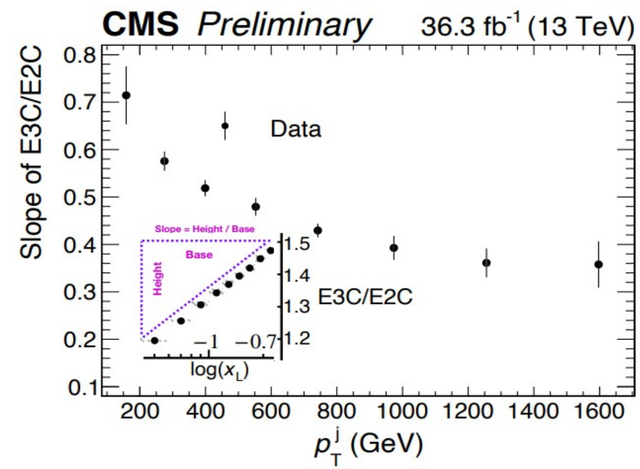
$$\theta \sim \Lambda_{QCD}/E_{jet}$$

$$\Lambda_{QCD}/E_{jet} \gg \theta$$

Strong coupling measurement inside jets

Chen, Gao, Li, Xu, Zhang, X. Zhu ‘23
CMS-PAS-SMP-22-015 ‘23





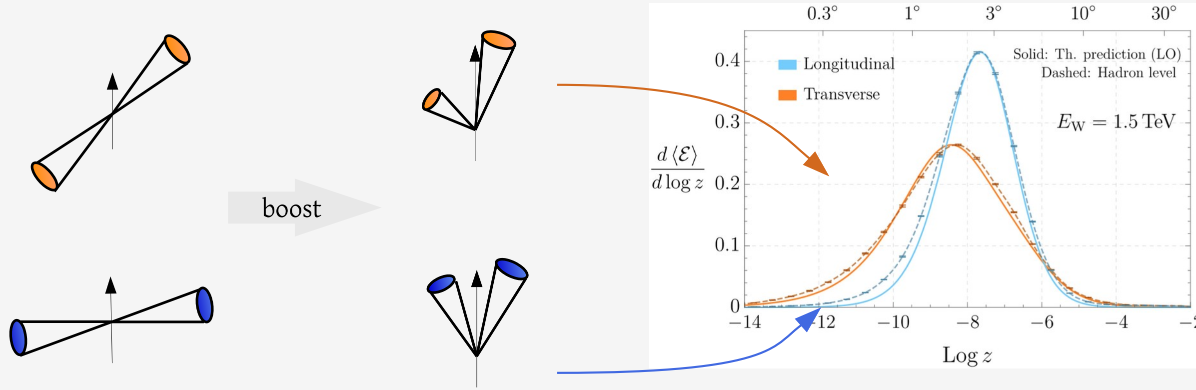
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

Certain questions are ideally phrased in terms of correlators

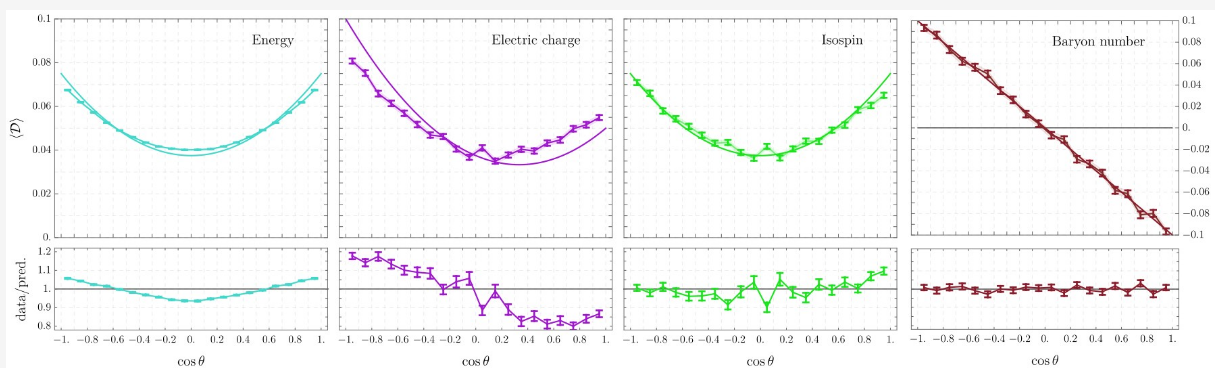
Ricci, **MR** Phys.Rev.D 106 (2022)

Density matrix of electroweak bosons:



Son, **MR** ‘24

Densities of conserved charges



A very short list of the multiple explorations in the recent years:

Top physics: Procura, Holguin, Moult, Pathak ‘22
Holguin, Moult, Pathak, Procura, Schofbeck, Schwarz ‘23

High precision: Yang, Zhang ‘22

QGP: Andres, Dominguez, Kunnawalkam, Raghav, Holguin, Marquet, Moult ‘22
Barata, Caucal, Soto-Ontoso ‘23

Nuclear physics: Liu, Liu, Pan, Yuan, Zhu ‘23
Devereaux, Fan, Ke, Lee, Moult ‘23

Theoretical: Chicherin, Korchemsky, Sokatchev, Zhiboedov ‘23
Firat, Monin, Rattazzi, Walters ‘24

Summary

New physics is a multifaceted concept, it lies between the known and the unknown

P henomena
P articles
P rinciples
N ew P ysics
P erspectives
P roperties
…

"As long as a branch of science offers an
abundance of problems, so long is it alive;
a lack of problems foreshadows extinction
or the cessation of independent development."

David Hilbert, 1900 *Mathematical problems*
during the Second International Congress of Mathematicians in Paris

New physics is within each of us

in our ability to ask good, relevant questions

when explaining what we see