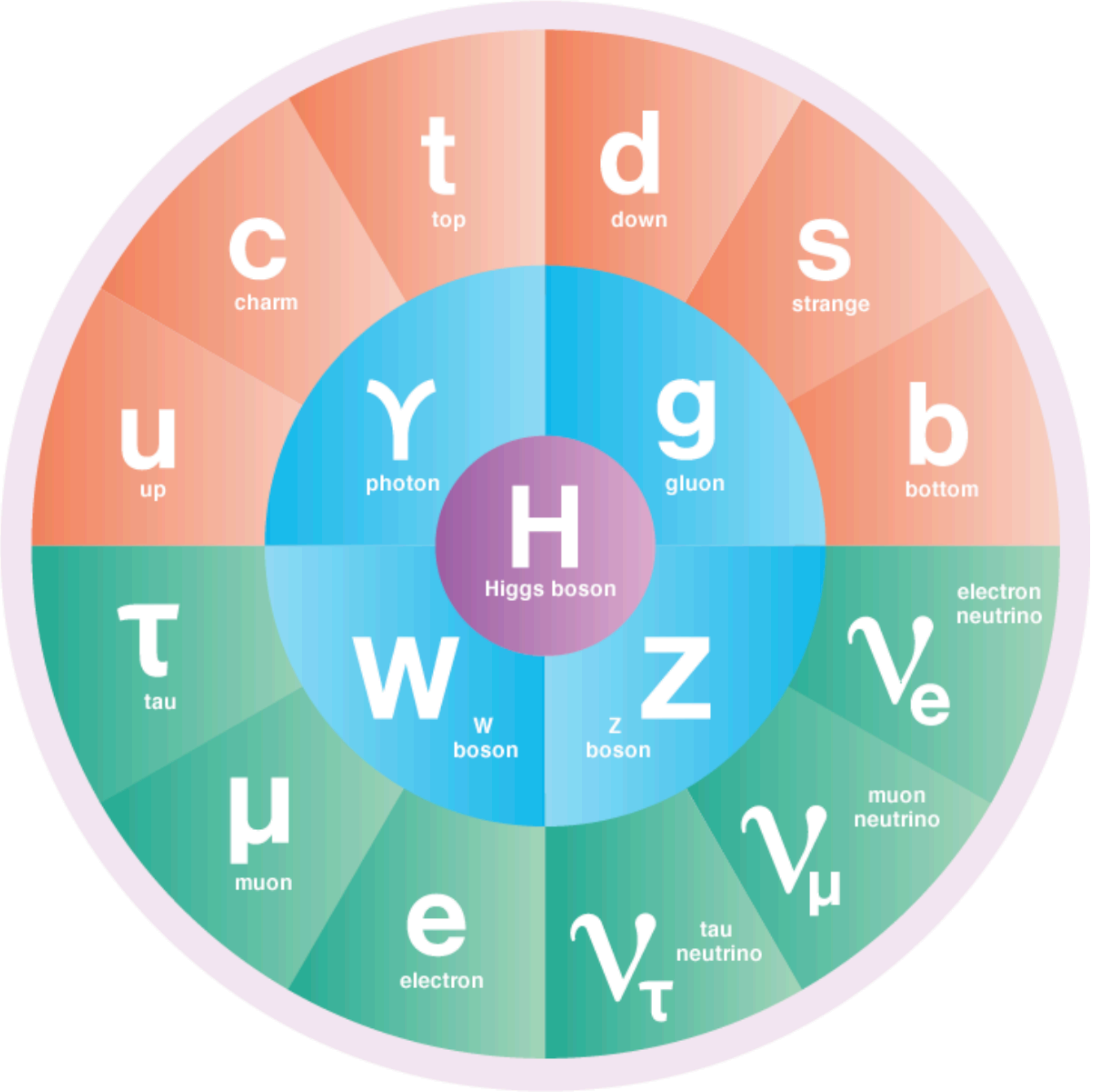
Quantum Algorithms for High-Energy Physics

Juan Rojo
VU Amsterdam & Theory group, Nikhef

AQA + CERN + QTI workshop on quantum algorithms for HEP
Leiden University, 20/02/2024

The Standard Model: a Success Story



- **Robust** and **predictive** mathematical framework describing **all known elementary particles** and their (non-gravitational) interactions

- **Matter particles**: three families of quarks and leptons

- **Force mediators**: photon (QED), gluon (strong interaction), W & Z bosons (electroweak force)

- The **Higgs field** and its excitation, the **Higgs boson**: a **completely new fundamental particle & interaction!**

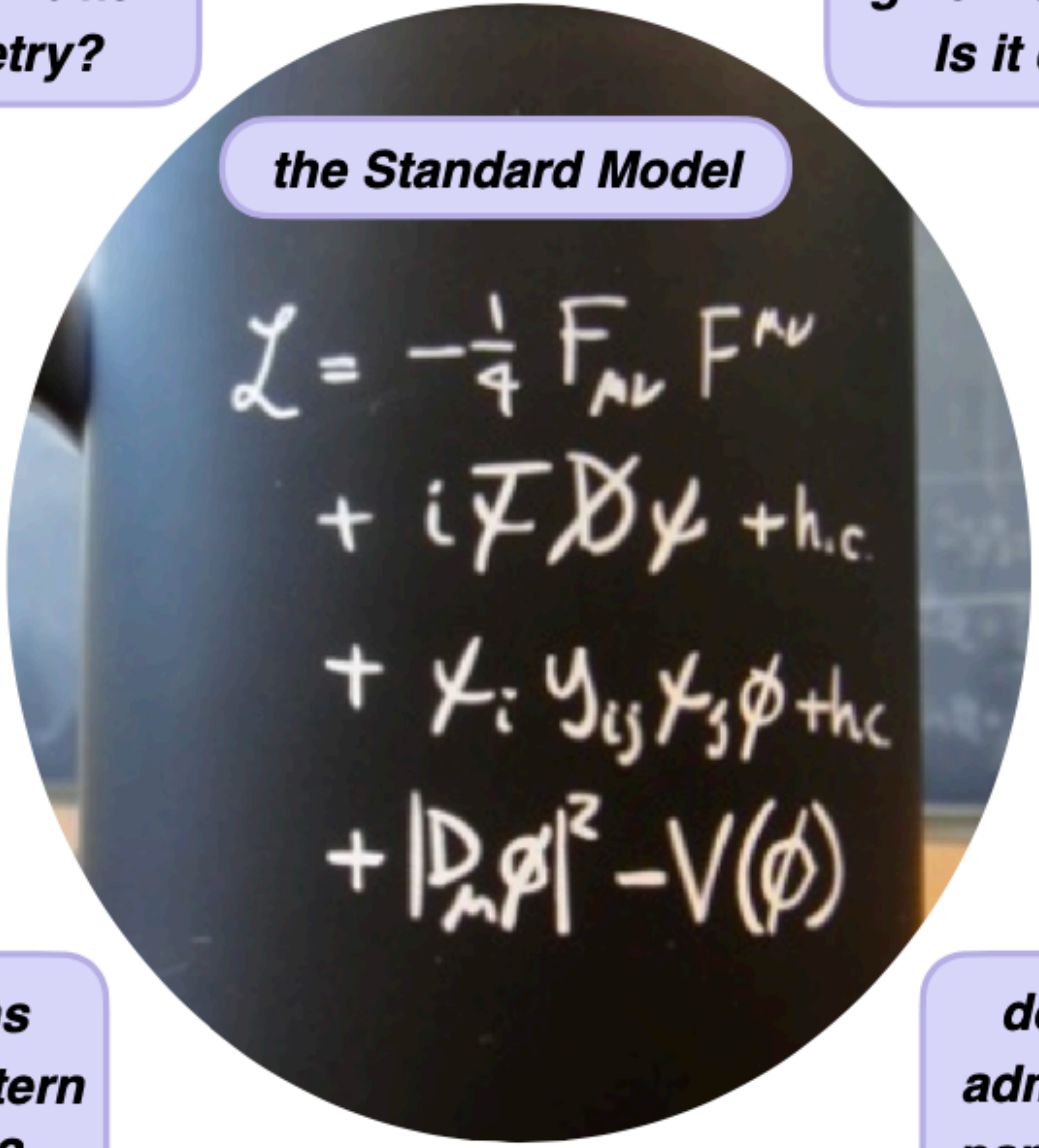
Discovered in 2012, now under intense scrutiny at the Large Hadron Collider at CERN

The Standard Model describes an incredibly wealth of measurements with astonishing precision: a major triumph of modern science

The Standard Model: not the Full Story!

why does our Universe exhibit such a strong matter/antimatter asymmetry?

why does the Higgs mechanism give mass to elementary particles? Is it effective or fundamental?



the Standard Model

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

what is the correct quantum mechanical description of gravity?

what sets the scale of neutrino masses? Do sterile neutrinos exist?

why do quarks and leptons exhibit such a disparate pattern of masses and couplings?

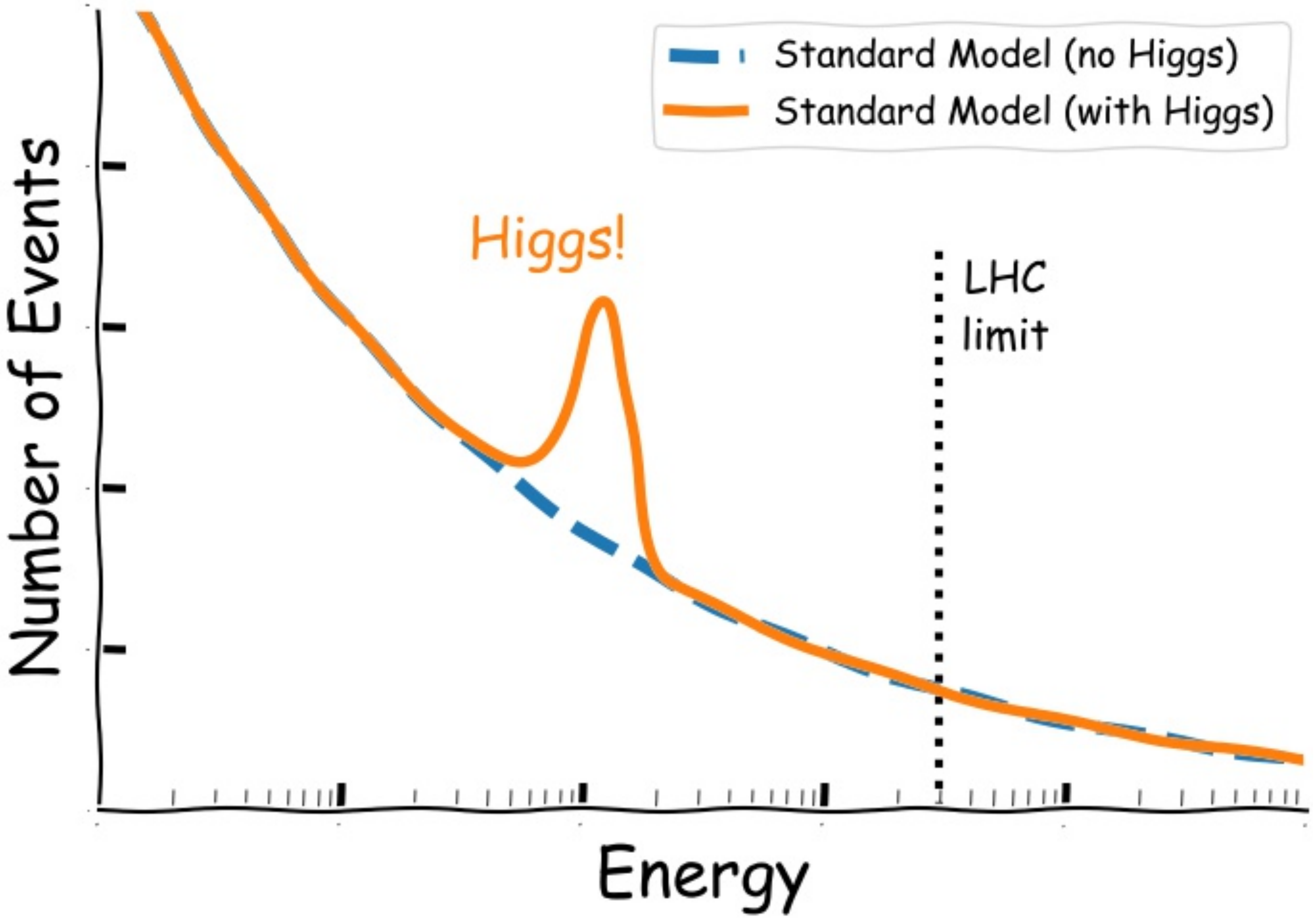
does Dark Matter admit an elementary particle description?

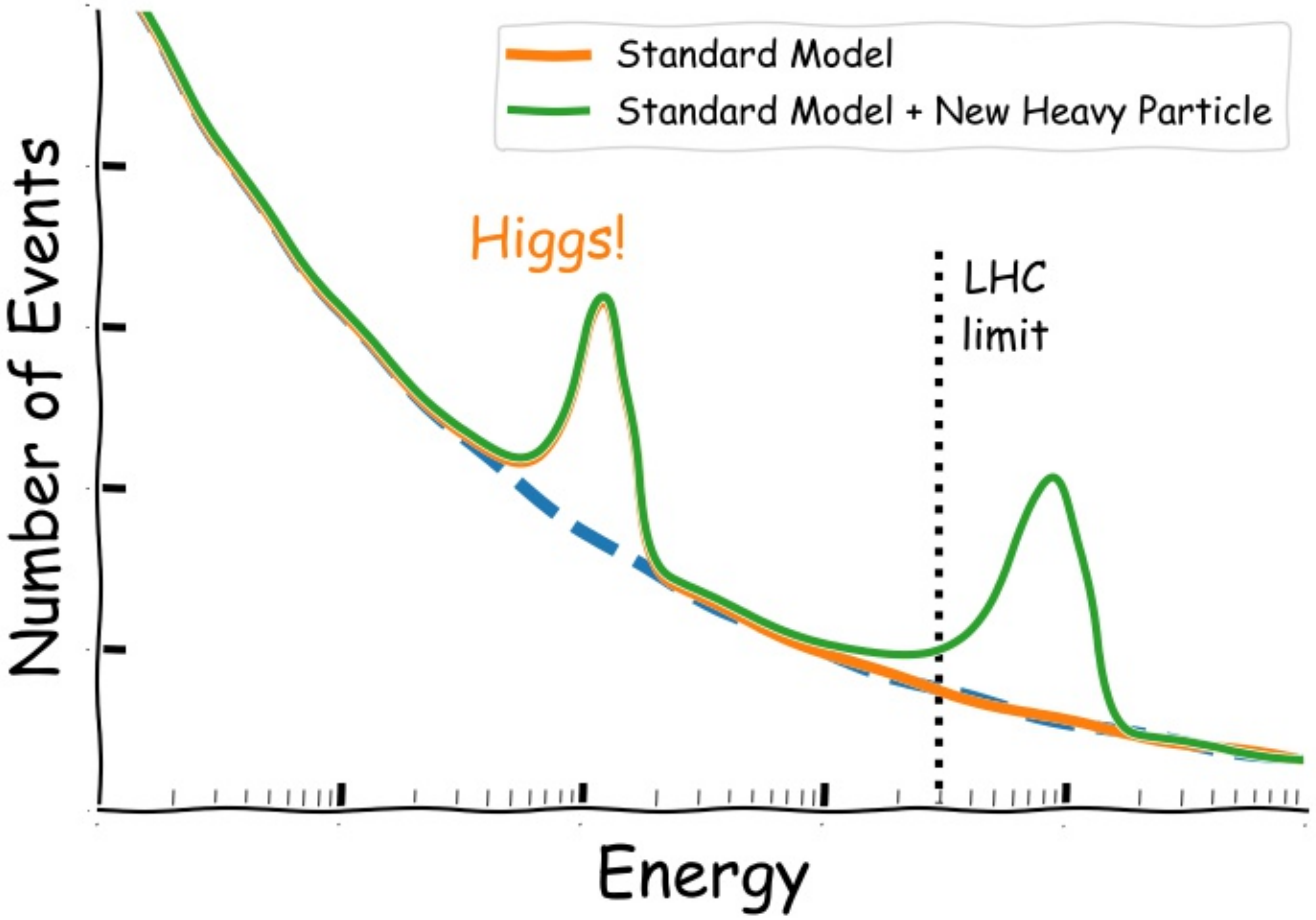
Innumerable extensions of the SM have been proposed. **None of them has been validated**

Towards a New Standard Model

Two main complementary strategies are being pursued to identify **the next layer of Nature** via a broad portfolio of experiments and theoretical investigations

- **Direct searches for new heavy or light particles**
- **Indirect searches through precision measurements**





How can **quantum science & algorithms & technologie**s assist HEP in this quest?

Quantum Info & Tech meet HEP

High-energy physics is of course nothing but **“applied” Quantum Field Theory**, hence **intrinsically quantum** in nature. What do we mean with “Quantum meets HEP” then?

Can ideas born of quantum information help to make **HEP analyses better & more sensitive**?
Can these ideas provide **new insights to guide e.g. model building**, BSM, searches for possible new heavy or light particles?

Can techniques born of quantum information & computing make some **HEP problems more efficient computationally**? Or eventually solve problems which are **classically intractable**?

Note that the two questions may be answered independently!

Rethinking the Role of Symmetry Principles

SciPost Phys. 3, 036 (2017)

Maximal entanglement in high energy physics

Alba Cervera-Lierta[1], José I. Latorre[1,2], Juan Rojo[3] and Luca Rottoli[4]

The Standard Model from the Bottom-Up

The Standard Model is **fully determined** by the following ingredients

- The **particle (matter) content**: three generations of quarks and leptons
- The **gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realised SU(2)$_L$ **electroweak symmetry breaking**
- Requiring **renormalizability**: predictions need to be valid up to **arbitrarily high scales**

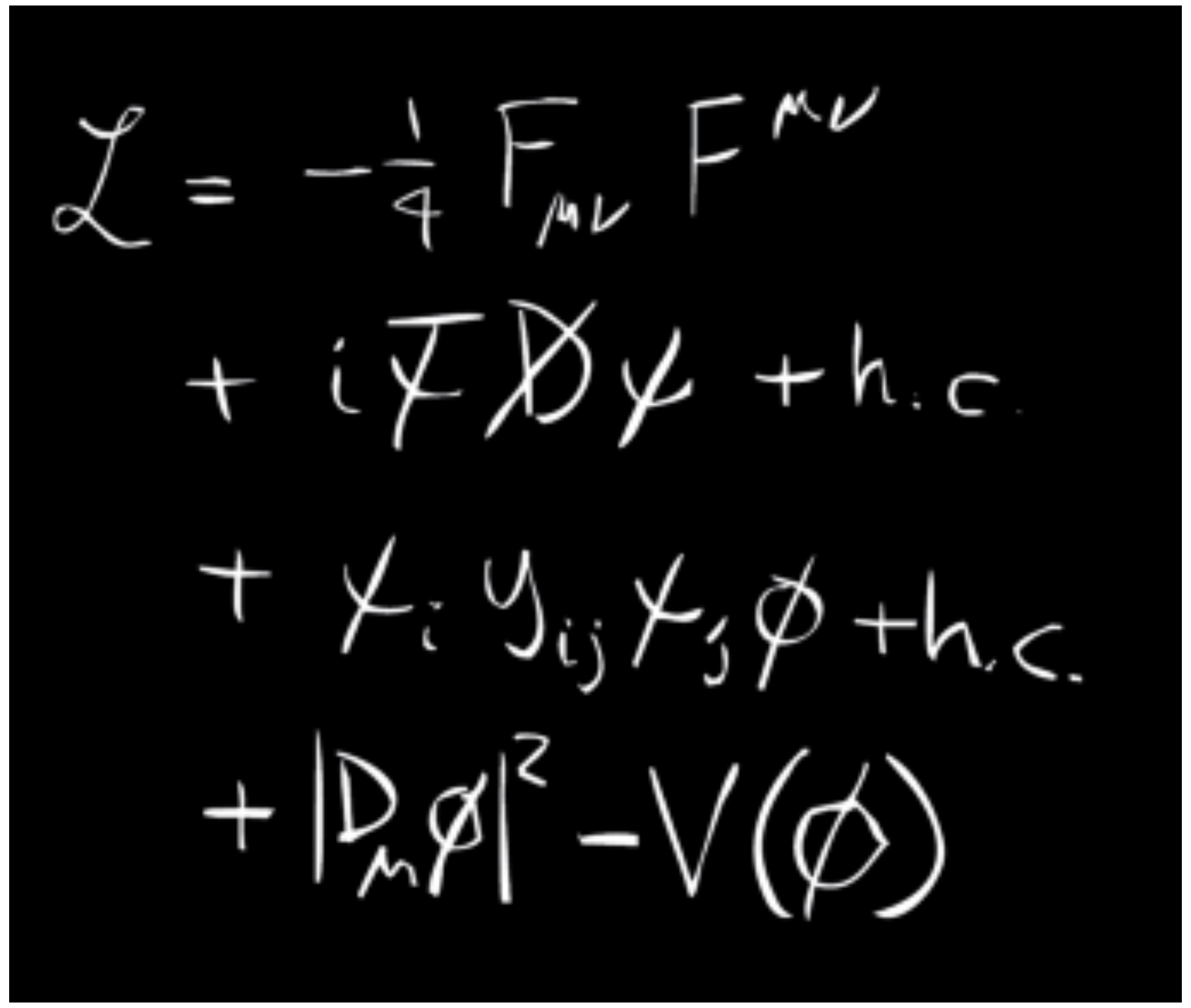
$$[F_{\mu\nu}] = 2\,,[\psi] = 3/2\,,[y] = 0\,,[\phi] = 1\ldots$$

$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathcal{O}_i^{(d=4)}$$

dimensionless couplings

All possible operators of **mass-dimension <=4** consistent with above requirements

extremely predictive and constrained framework



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

The Standard Model from the Bottom-Up

The Standard Model is **fully determined** by the following ingredients

- The **particle (matter) content**: three generations of quarks and leptons
- The **gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realised $SU(2)_L$ **electroweak symmetry breaking**
- Requiring **renormalizability**: predictions need to be valid up to **arbitrarily high scales**

Can we find an alternative derivation of the SM bypassing the gauge symmetry requirement?

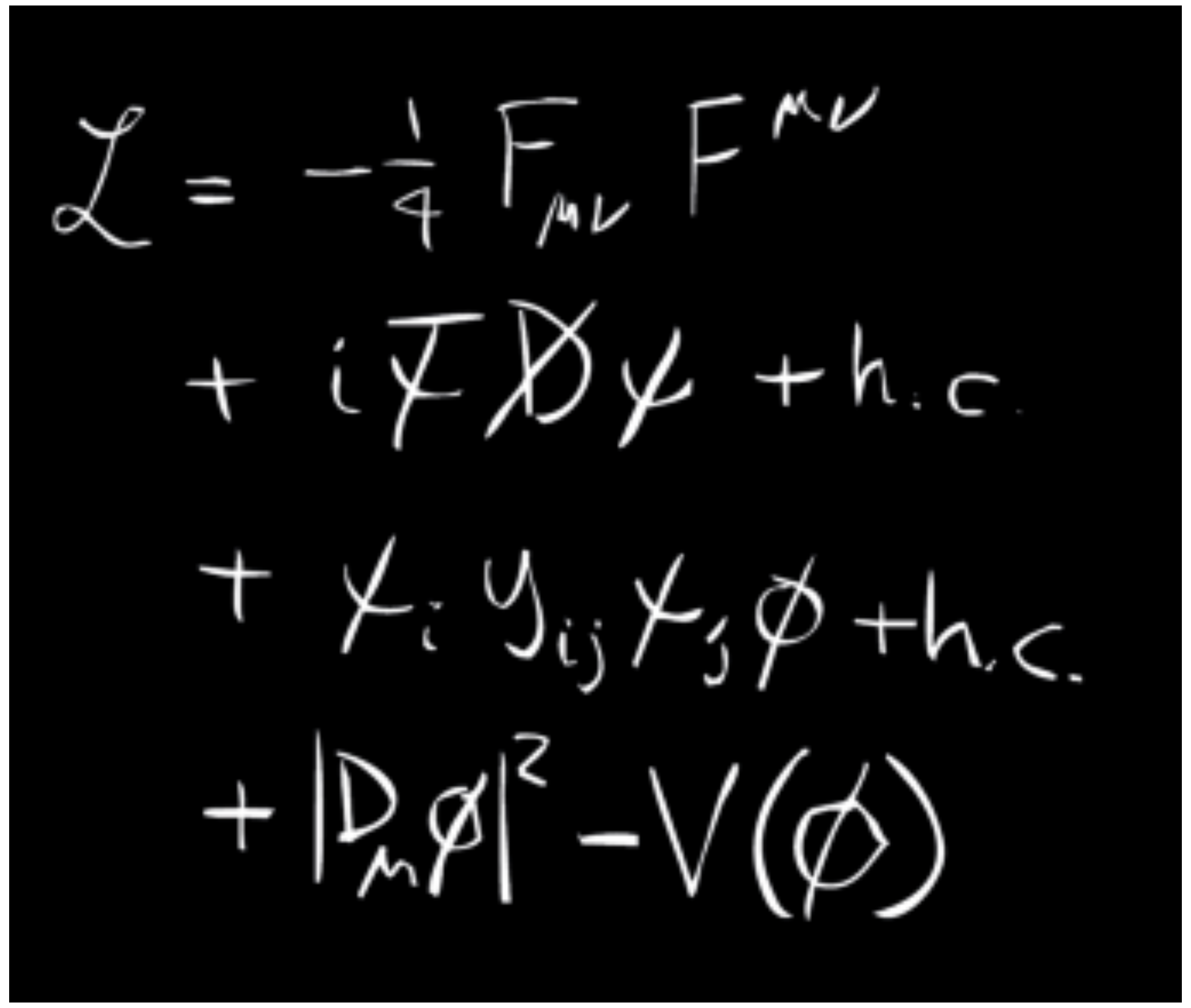
$$[F_{\mu\nu}] = 2\,,\ [\psi] = 3/2\,,\ [y] = 0\,,\ [\phi] = 1\,\ldots$$

$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathscr{O}_i^{(d=4)}$$

dimensionless couplings

All possible operators of **mass-dimension <=4** consistent with above requirements

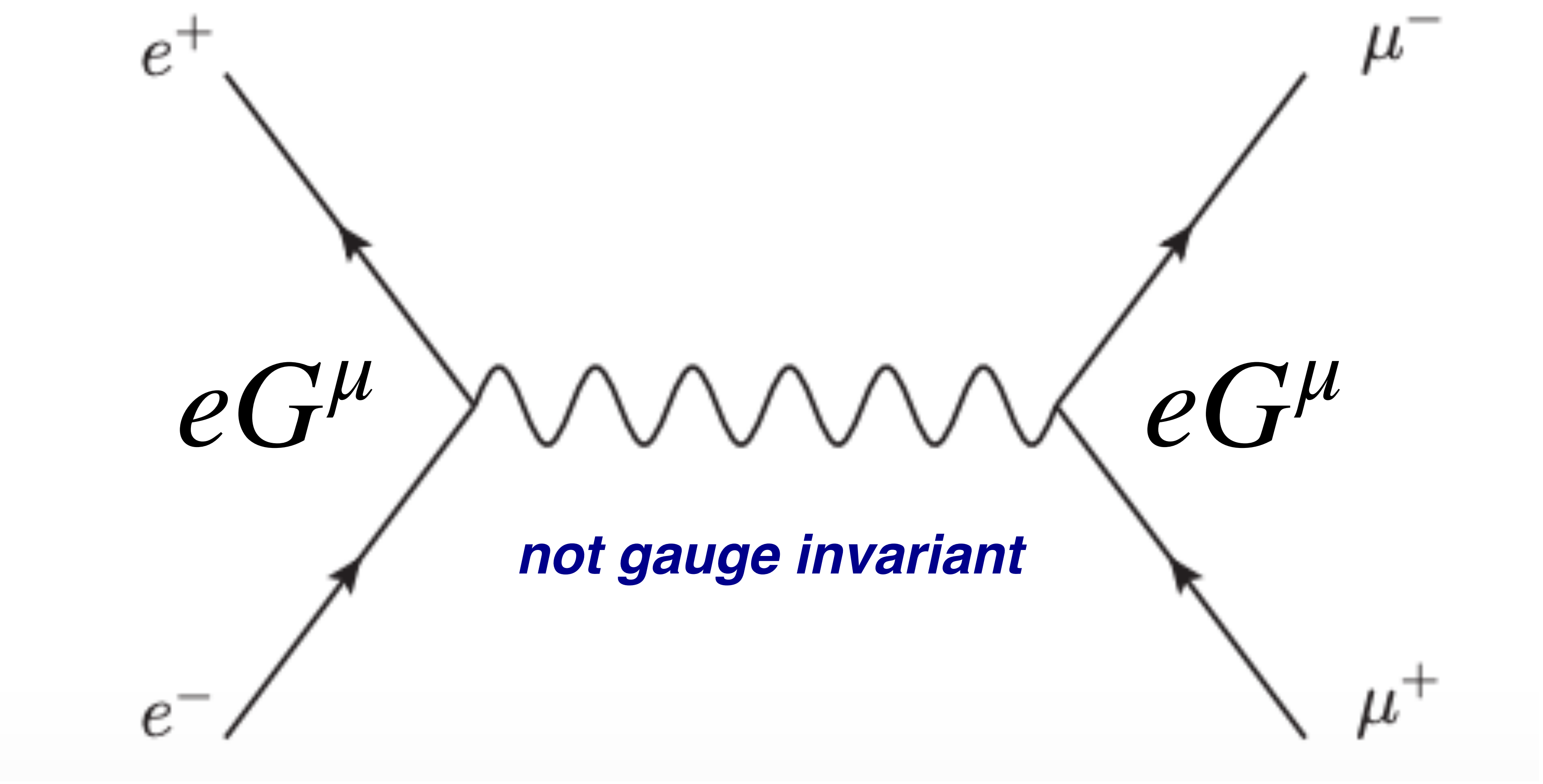
extremely predictive and constrained framework



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Maximal Entanglement as a Guiding Principle

- Consider **2=>2 scattering** processes involving **massless fermions and photons**. Quantify the entanglement involved in their helicities and polarisations (respectively) using the **concurrence metric**



$$|\phi\rangle = \alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$$

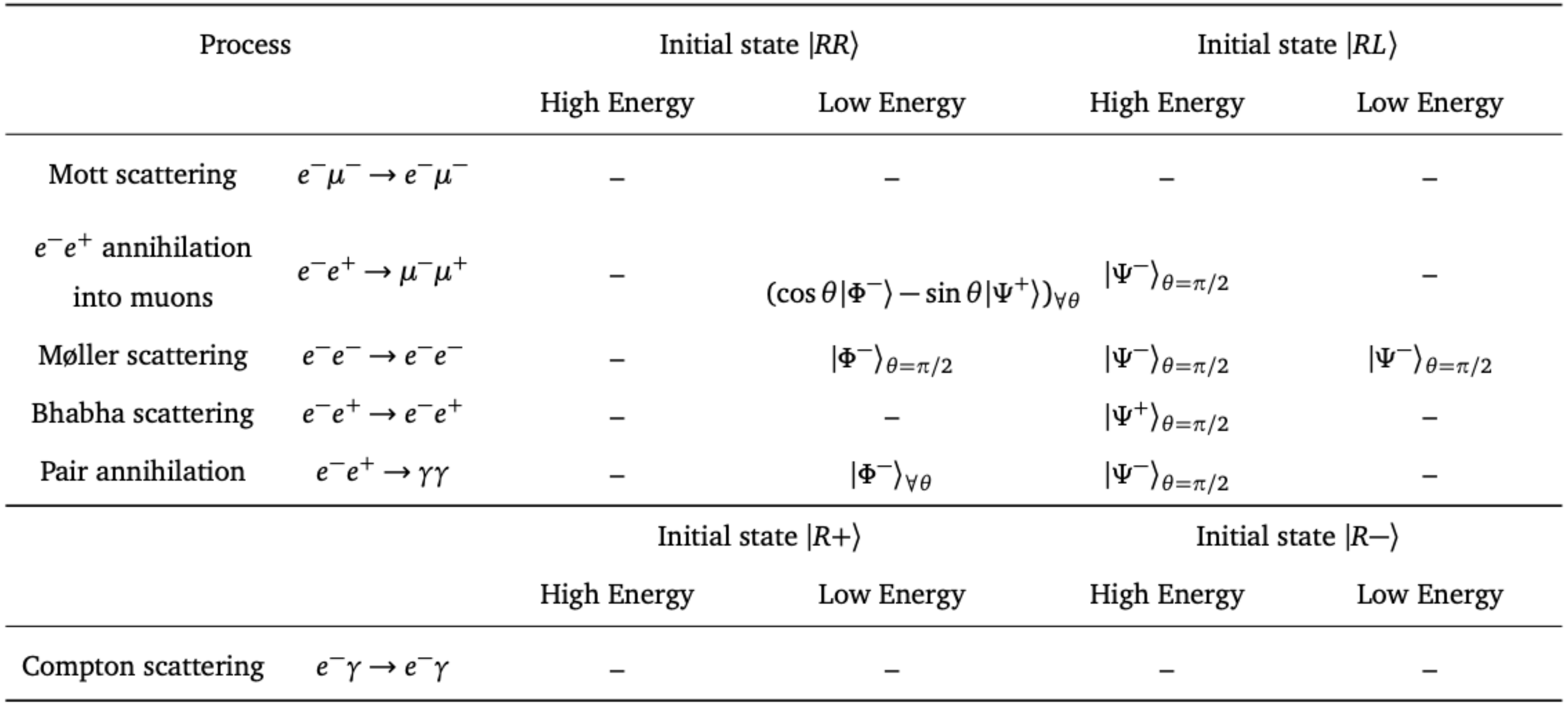
$$\Delta \equiv 2|\alpha\delta - \beta\gamma|$$

- Impose **maximal entanglement principle:** the laws of Nature generate **maximal entanglement (Δ=1)** even when initial state is unentangled
- Put aside gauge invariance: assume that the QED vertex is expressed in terms of **general matrices**. Can MaxEnt constrain them?

$$e\gamma^\mu \to eG^\mu$$

Maximal Entanglement as a Guiding Principle

- Global analysis of QED scattering process: to which extent are the **QED interactions constrained** if we impose the maximal entanglement principle?



Process		Initial state $\|RR\rangle$		Initial state $\|RL\rangle$	
		High Energy	Low Energy	High Energy	Low Energy
Mott scattering	$e^-\mu^- \to e^-\mu^-$	–	–	–	–
e^-e^+ annihilation into muons	$e^-e^+ \to \mu^-\mu^+$	–	$(\cos\theta\|\Phi^-\rangle - \sin\theta\|\Psi^+\rangle)_{\forall\theta}$	$\|\Psi^-\rangle_{\theta=\pi/2}$	–
Møller scattering	$e^-e^- \to e^-e^-$	–	$\|\Phi^-\rangle_{\theta=\pi/2}$	$\|\Psi^-\rangle_{\theta=\pi/2}$	$\|\Psi^-\rangle_{\theta=\pi/2}$
Bhabha scattering	$e^-e^+ \to e^-e^+$	–	–	$\|\Psi^+\rangle_{\theta=\pi/2}$	–
Pair annihilation	$e^-e^+ \to \gamma\gamma$	–	$\|\Phi^-\rangle_{\forall\theta}$	$\|\Psi^-\rangle_{\theta=\pi/2}$	–
		Initial state $\|R+\rangle$		Initial state $\|R-\rangle$	
		High Energy	Low Energy	High Energy	Low Energy
Compton scattering	$e^-\gamma \to e^-\gamma$	–	–	–	–

- The gauge-invariant QED vertex is **recovered up to a sign!** Deep connection between **quantum-theoretic ideas** and **gauge symmetry principles**

$$\left(G^0, G^1, G^2, G^3\right) = \left(\pm\gamma^0, \pm\gamma^1, \pm\gamma^2, \pm\gamma^3\right)$$

Quantum-Theoretic Probes of New Physics

The Standard Model from the Bottom-Up

The Standard Model is **fully determined** by the following ingredients

- The **particle (matter) content**: three generations of quarks and leptons
- The **gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realised SU(2)$_L$ **electroweak symmetry breaking**
- Requiring **renormalizability**: predictions need to be valid up to **arbitrarily high scales**

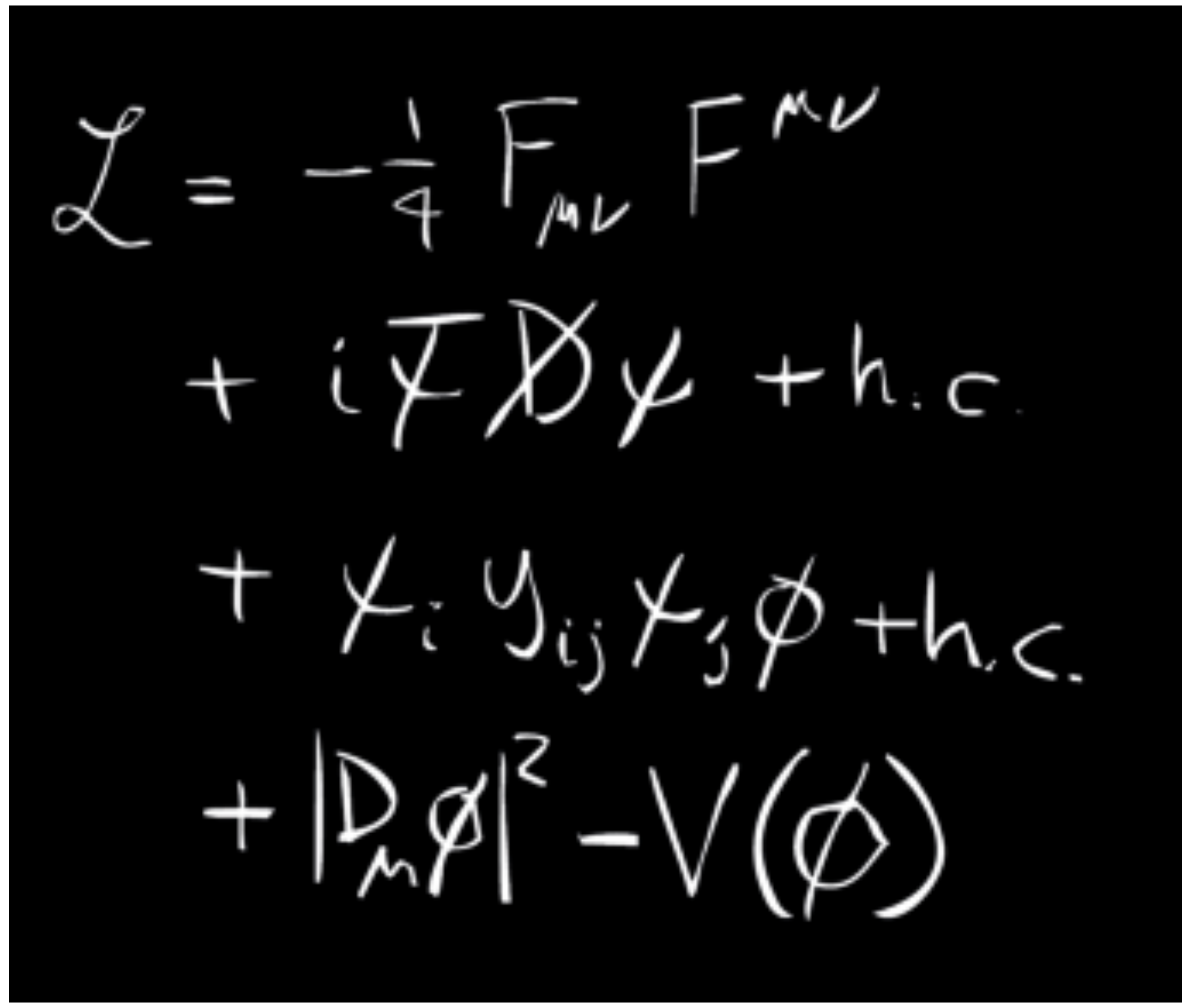
$$[F_{\mu\nu}] = 2\,,[\psi] = 3/2\,,[y] = 0\,,[\phi] = 1\dots$$

$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathscr{O}_i^{(d=4)}$$

dimensionless couplings

All possible operators of **mass-dimension <=4** consistent with above requirements

extremely predictive and constrained framework



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

The Standard Model from the Bottom-Up

The Standard Model is **fully determined** by the following ingredients

- The **particle (matter) content**: three generations of quarks and leptons
- The **gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realised SU(2)$_L$ **electroweak symmetry breaking**

how essential is this condition?

- Requiring **renormalizability**: predictions need to be valid up to **arbitrarily high scales**

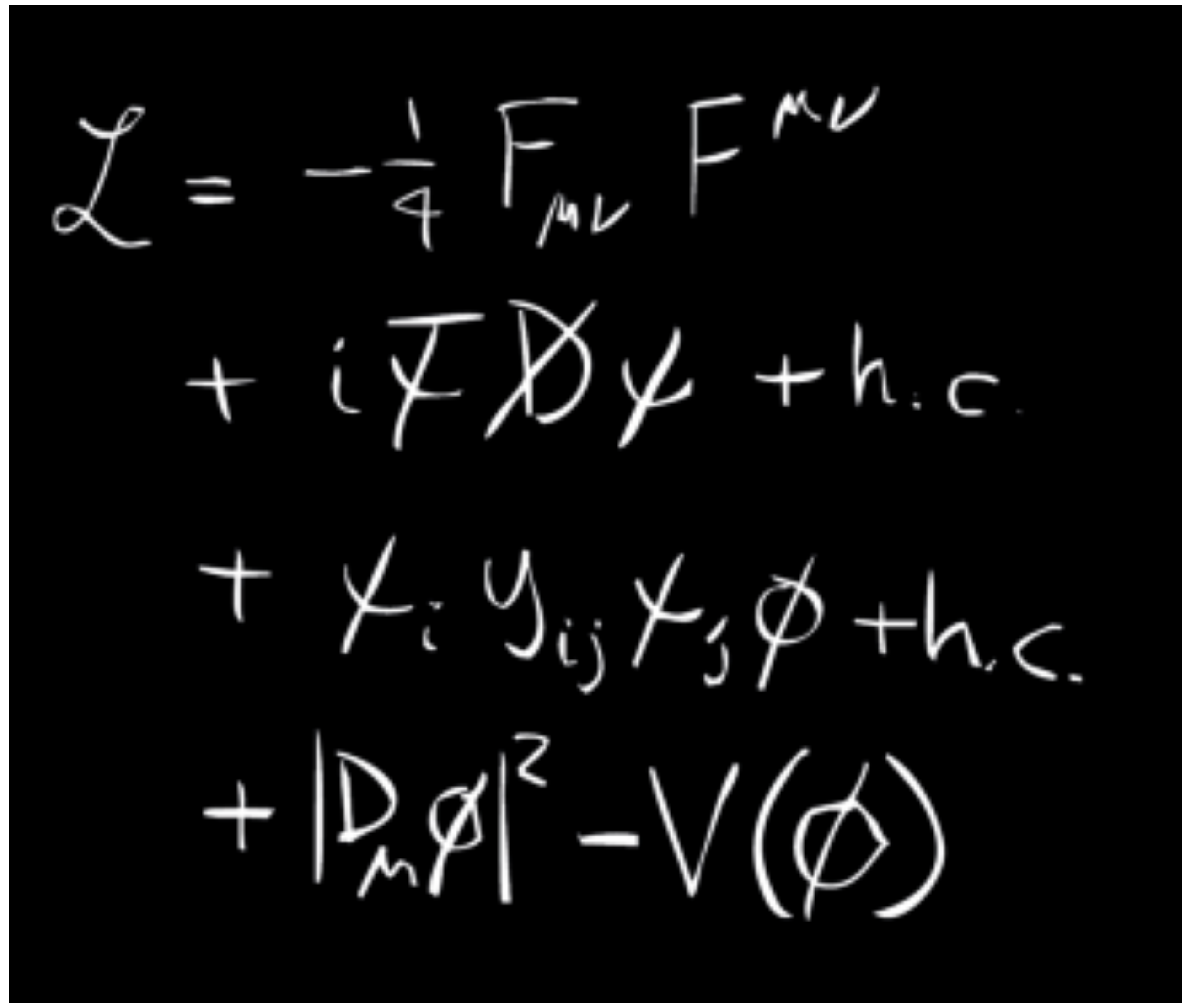
$$[F_{\mu\nu}] = 2\,,\, [\psi] = 3/2\,,\, [y] = 0\,,\, [\phi] = 1\ldots$$

$$\mathscr{L}_{\rm SM} = \sum_i c_i \mathcal{O}_i^{(d=4)}$$

dimensionless couplings

All possible operators of **mass-dimension <=4** consistent with above requirements

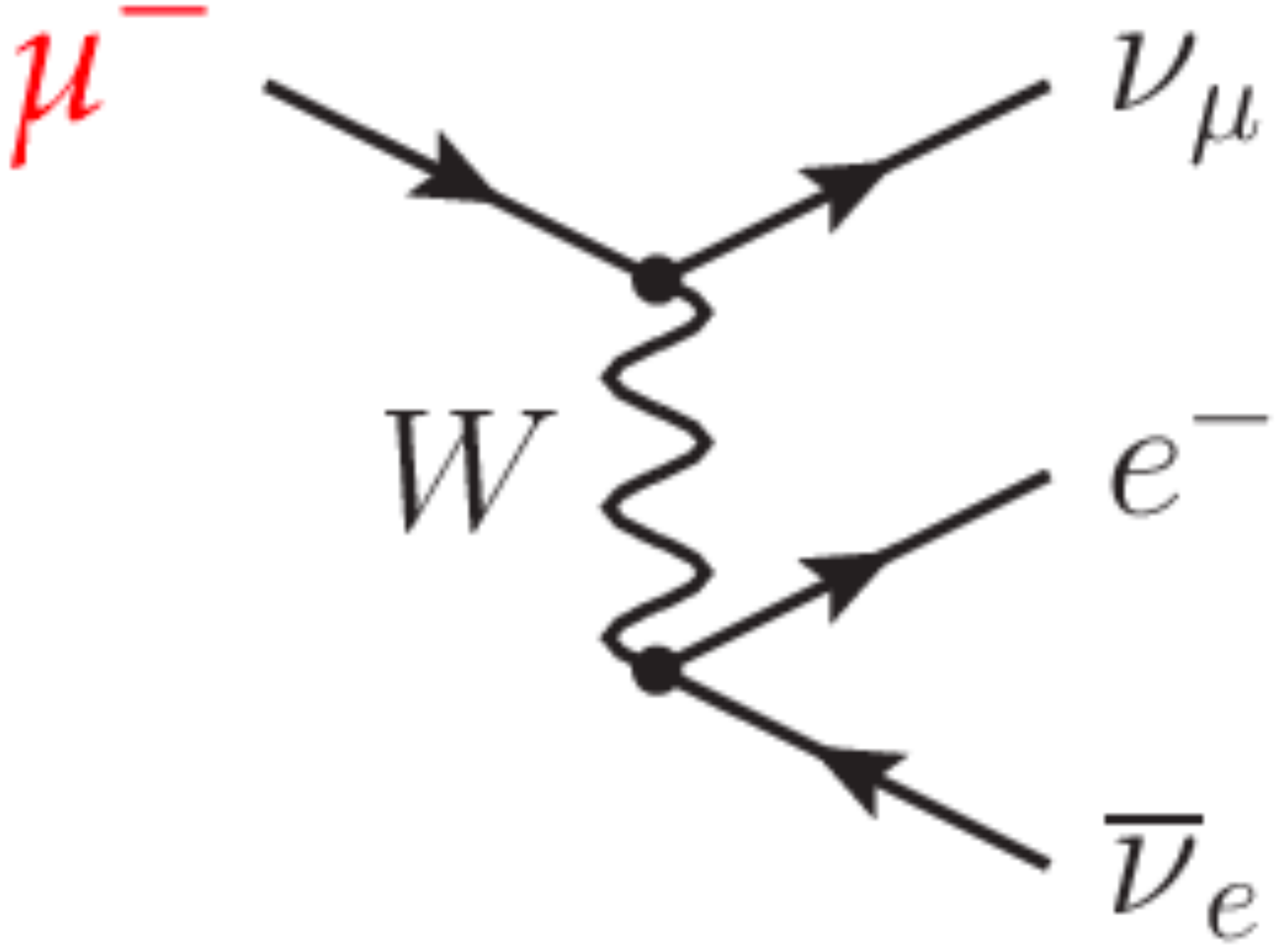
extremely predictive and constrained framework

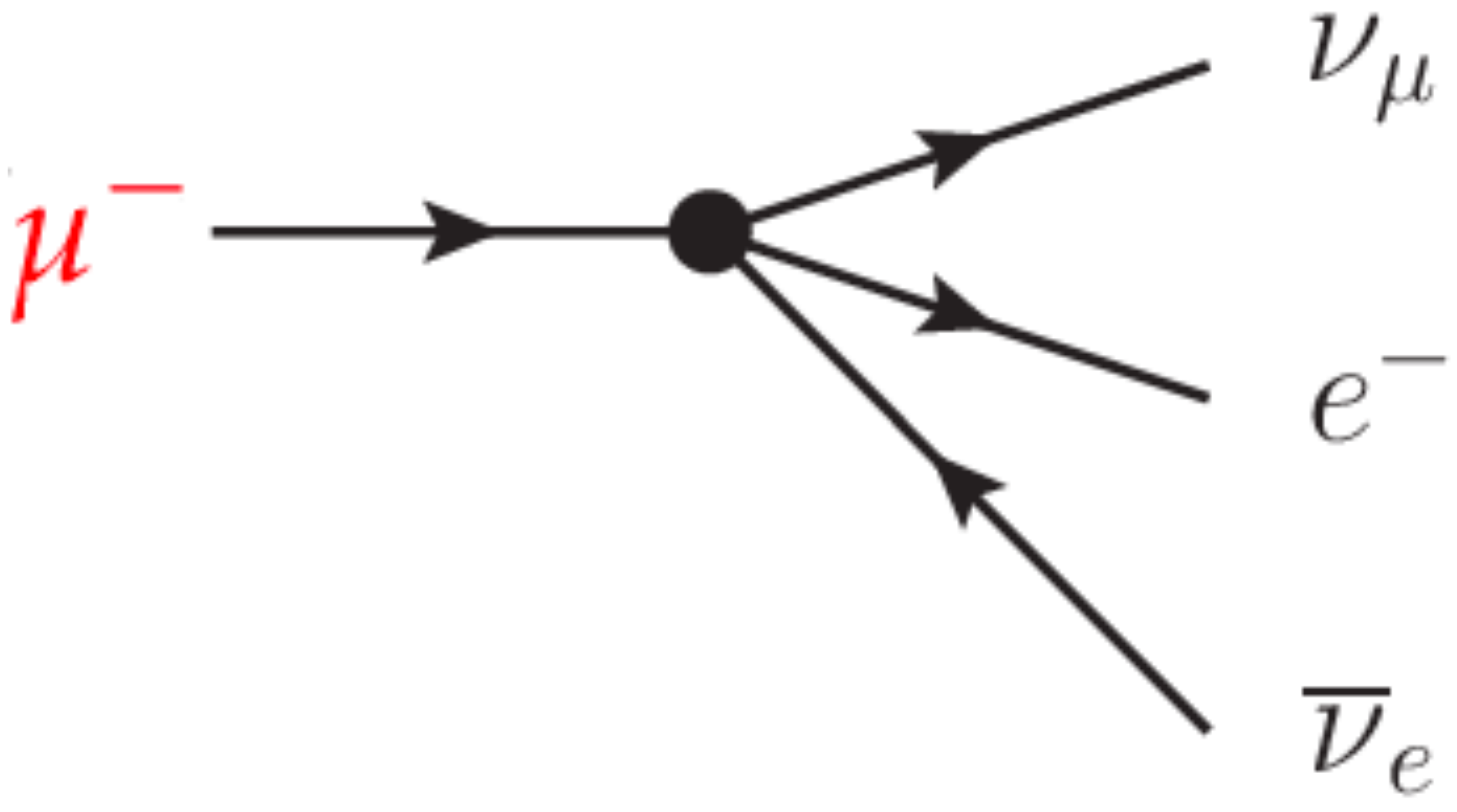


$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Effective vs Fundamental QFTs

For a sensible QFT, must its predictions be valid to **arbitrarily high scales? No!**





Muon decay in the SM

Muon decay in Fermi Theory $m_\mu \ll m_W$

Mediated by ``heavy" W-boson, m_W = 80 GeV

No explicit force mediator

Involves **dimension-4** interactions with **dimensionless couplings**

dimension-6 interactions with **dimensionfull couplings**

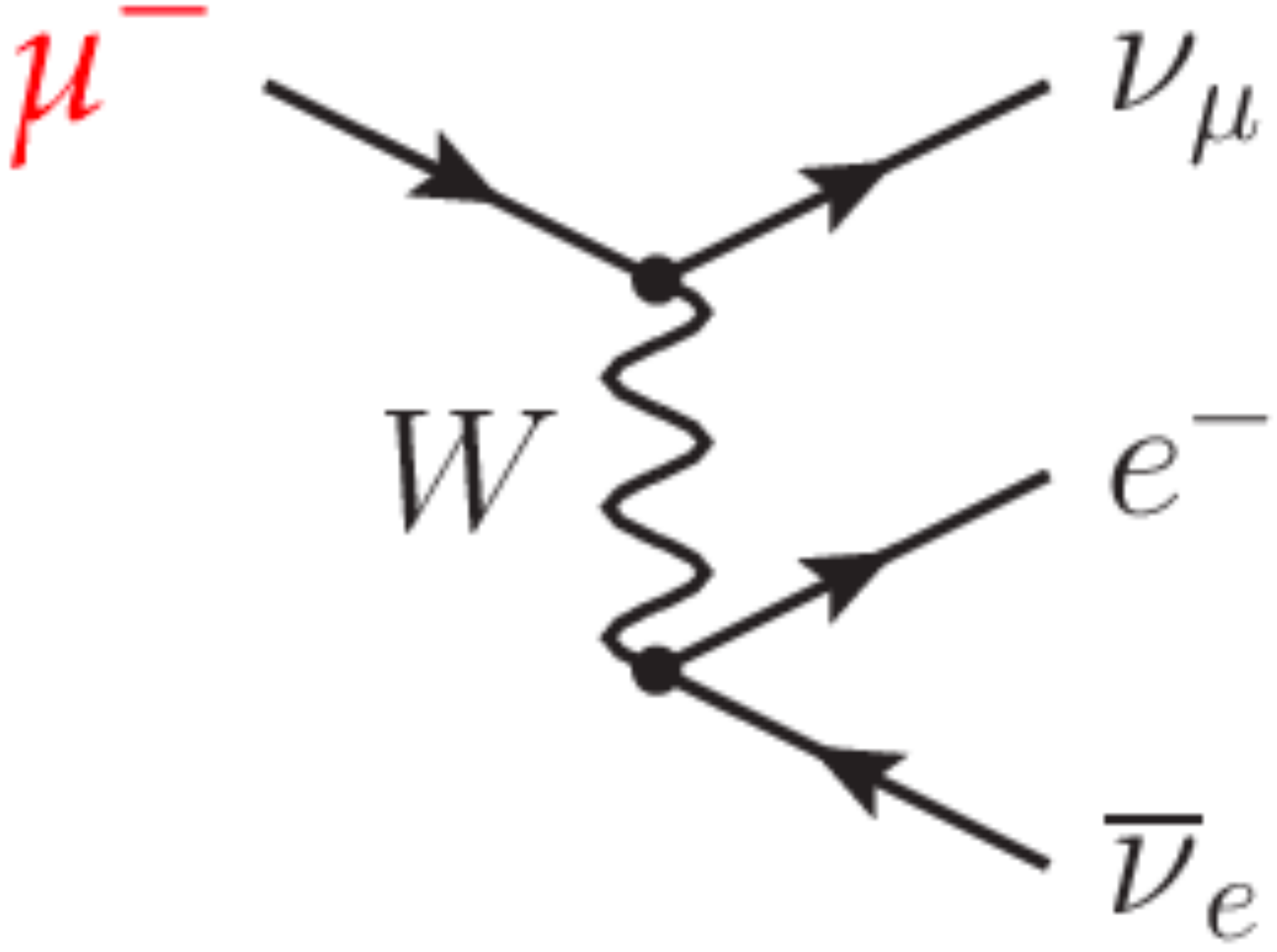
$$\mathscr{L}_{\text{SM}} \supset g\bar{\psi}_\ell \gamma^\mu W_\mu \psi_\nu$$

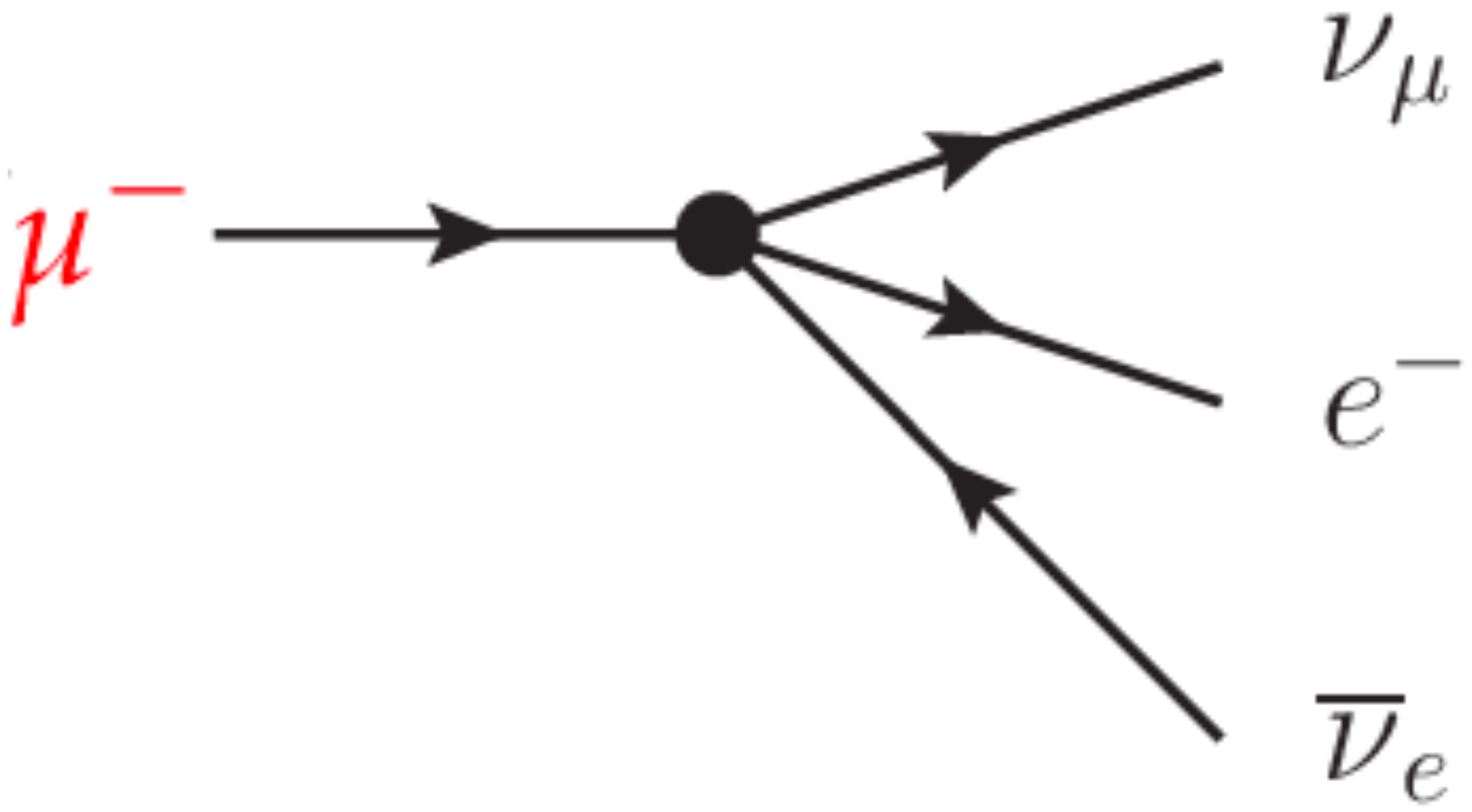
$$\mathscr{L}_{\text{EFT}} \supset G_F \bar{\psi}_\ell \psi_\nu \bar{\psi}_{\ell'} \psi_{\nu'}$$

$$G_F = 1.2 \times 10^{-5}\,\text{GeV}^{-2}$$

Effective vs Fundamental QFTs

For a sensible QFT, must its predictions be valid to **arbitrarily high scales? No!**





Muon decay in the SM

$$\mathscr{L}_{\text{SM}} \supset g\bar{\psi}_\ell \gamma^\mu W_\mu \psi_\nu$$

Muon decay in Fermi Theory

$$\mathscr{L}_{\text{EFT}} \supset G_F \bar{\psi}_\ell \psi_\nu \bar{\psi}_{\ell'} \psi_{\nu'}$$

The SM and its low-energy EFT result in identical predictions for energies well below the W mass

knowledge of SM Lagrangian irrelevant to precisely compute muon lifetime

The (New) Standard Model from the Bottom-Up

The **Standard Model EFT** is **fully determined** by the following ingredients:

- The **particle (matter) content**: three generations of quarks and leptons
- The **gauge** (local) symmetries and their eventual breaking mechanisms
- **Lorentz** invariance and other global symmetries
- Linearly realised SU(2)$_L$ **electroweak symmetry breaking**
- Predictions **valid only up to a cutoff scale Λ**, above which a new fundamental UV-completion takes over

Requiring the SM to be prediction up the Plank scale is not a necessary condition to describe physics at the scales accessible by experiments!

Wilson coefficients

higher-dimensional operators built upon SM fields & satisfying all its symmetries

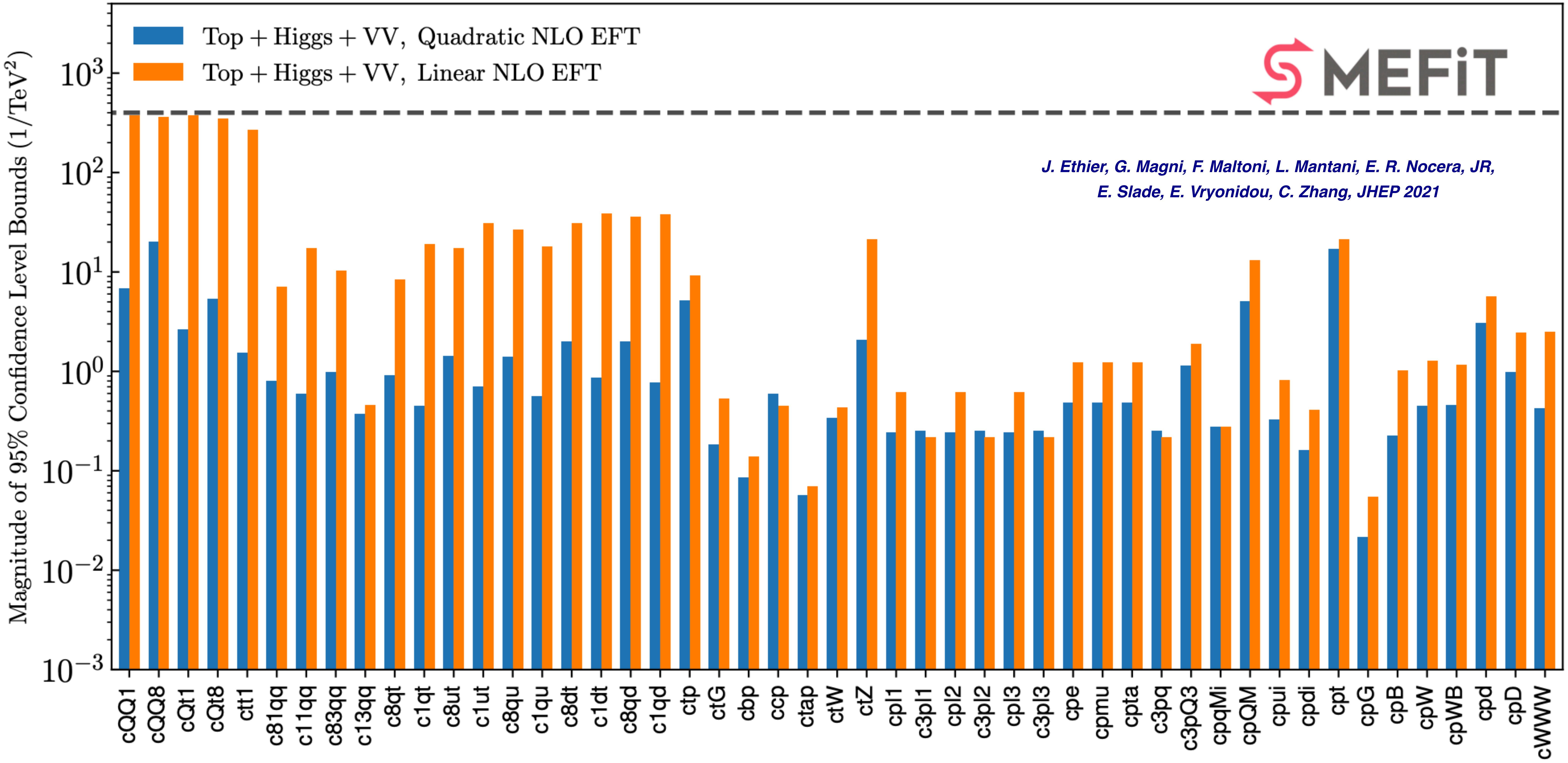
$$\mathscr{L}_{\rm SM} \to \mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{d=5}^{\infty} \sum_{i=1}^{N_d} c_i^{(d)} \frac{\mathscr{O}_i^{(d)}}{\Lambda^{d-4}}$$

well-defined power counting

when cutoff >> accessible energy scales: recover SM

cutoff scale

Global SMEFT analyses: state-of-the-art



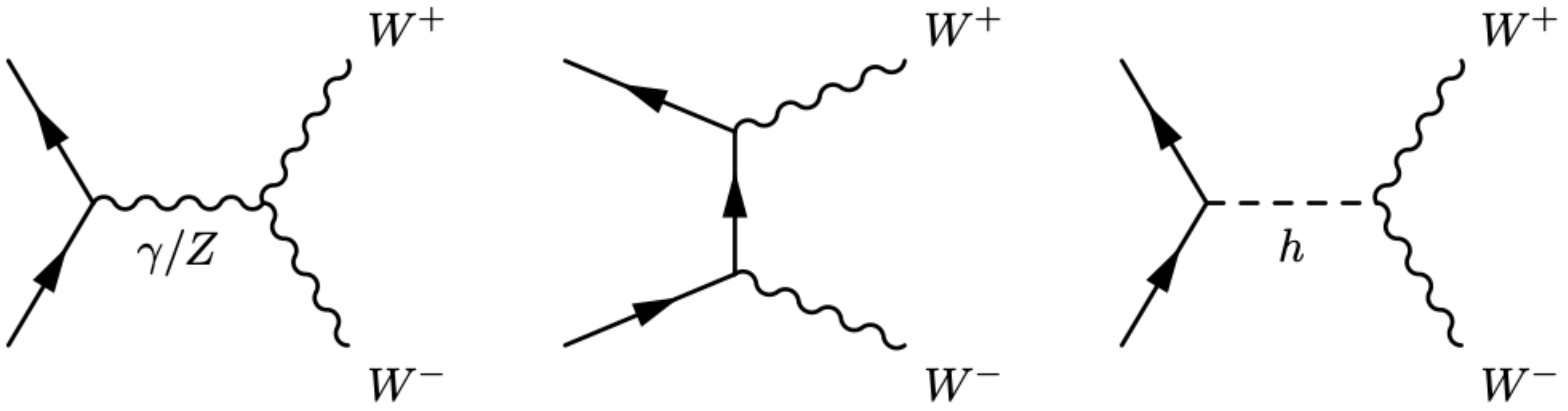
J. Ethier, G. Magni, F. Maltoni, L. Mantani, E. R. Nocera, JR,
E. Slade, E. Vryonidou, C. Zhang, JHEP 2021

EFT fits include data on **top quark, Higgs, and gauge boson production**, both inclusive and differential measurements & the constraints from LEP EWPOs

Global search for new fundamental interactions: quantum imprints of unobserved particles

New physics searches via entanglement

- Electroweak boson pair production is sensitive to new interactions. Higher-dimensional EFT operators in particular modify the possible helicity patterns and hence the **generation of entanglement**



Entanglement patterns quantified by **concurrence**

$$\mathcal{C}(\rho) = \inf\left[\sum_i p_i c(|\psi_i\rangle)\right]$$

$(\lambda_1\lambda_2\|\alpha\,\beta)$	SM	EFT Λ^{-2} : c_{WWW}
$+-00$	$-2\sqrt{2}G_F m_Z^2 \sin\theta$	-
$+--+$	$2\sqrt{2}G_F m_W^2 \sin\theta$	-
$+-+-$	$-\frac{1}{\sqrt{2}}G_F m_W^2 \sin^3\theta\csc^4(\theta/2)$	-
$+-\pm\pm$	-	$3\cdot 2^{1/4}\sqrt{G_F}m_W \sin\theta\,(4m_W^2x^2 - m_Z^2)$
$+-0\pm$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\pm 1 + \cos\theta)\,x$
$+-\pm 0$	-	$-3\cdot 2^{3/4}\sqrt{G_F}m_W^3(\mp 1 + \cos\theta)\,x$
$-+00$	$2\sqrt{2}G_F(m_Z^2 - m_W^2)\sin\theta$	-
$-+\pm\pm$	-	$6\cdot 2^{1/4}\sqrt{G_F}m_W(m_Z^2 - m_W^2)\sin\theta$

Lower and upper bounds on the concurrence can be derived, **different in SM and in SMEFT**

quantum-theoretic ideas used to derive optimised observables for SMEFT searches

Probing new physics through entanglement in diboson production

---

Rafael Aoude,[a] Eric Madge,[b] Fabio Maltoni,[a,c] and Luca Mantani[d]

New physics searches via entanglement

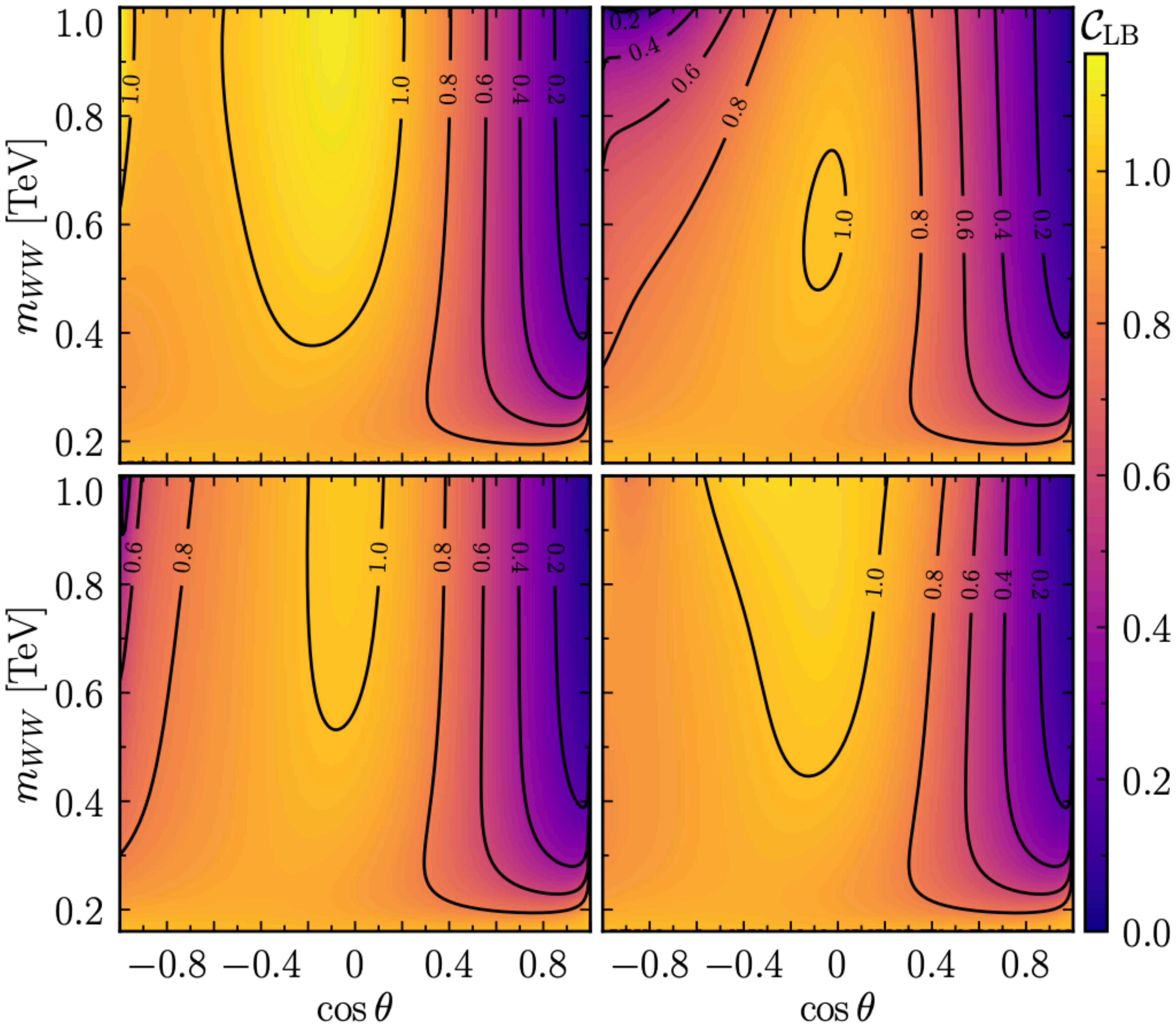


Figure 6: The changes in the marker $\mathcal{C}_{\rm LB}$ is shown for a selection of operators and benchmark Wilson coefficient values for the production of W^+W^- at a lepton collider. Only one operator at the time is switched on. Top left: $c_{\varphi e} = 0.1\,\text{TeV}^{-2}$, top right: $c_{\varphi l}^{(1)} = 0.1\,\text{TeV}^{-2}$, bottom left: $c_{\varphi WB} = 0.25\,\text{TeV}^{-2}$, bottom right: $c_W = 0.25\,\text{TeV}^{-2}$.

Entanglement patterns in HEP processes sensitive to New Physics, potentially improving the reach of ``traditional'' observables

Proton Structure with Quantum Algorithms

Why Proton Structure?

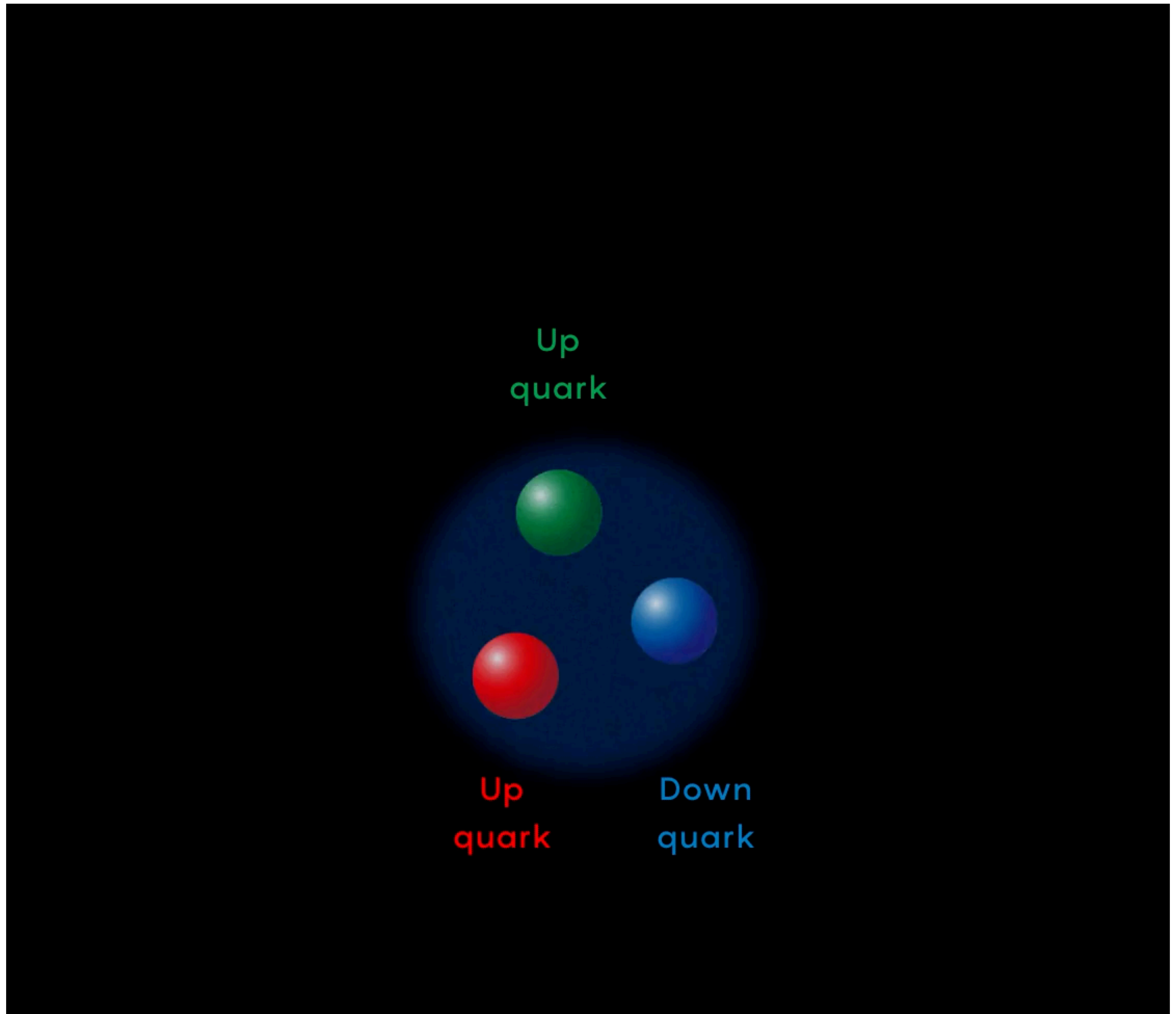
Knowledge of proton structure crucial for collider physics, astroparticle physics, nuclear physics

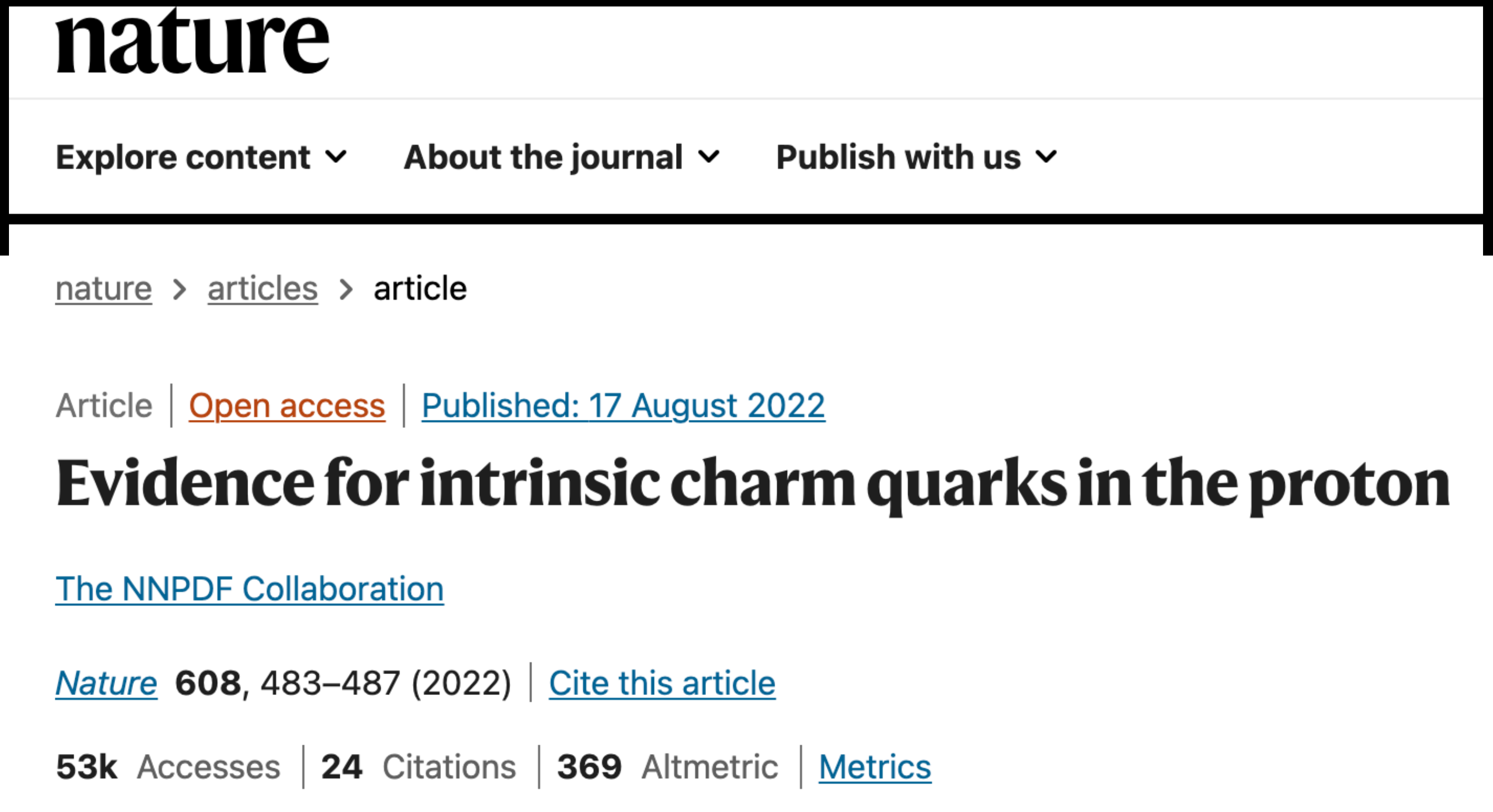
Why Proton Structure?

credit: *visualising the proton*, Arts at MIT (https://arts.mit.edu/visualizing-the-proton/)

Bjorken-x: fraction of the proton energy carried by a quark or gluon

Novel phenomena within the SM accessible through mapping proton substructure





Article | Open access | Published: 17 August 2022

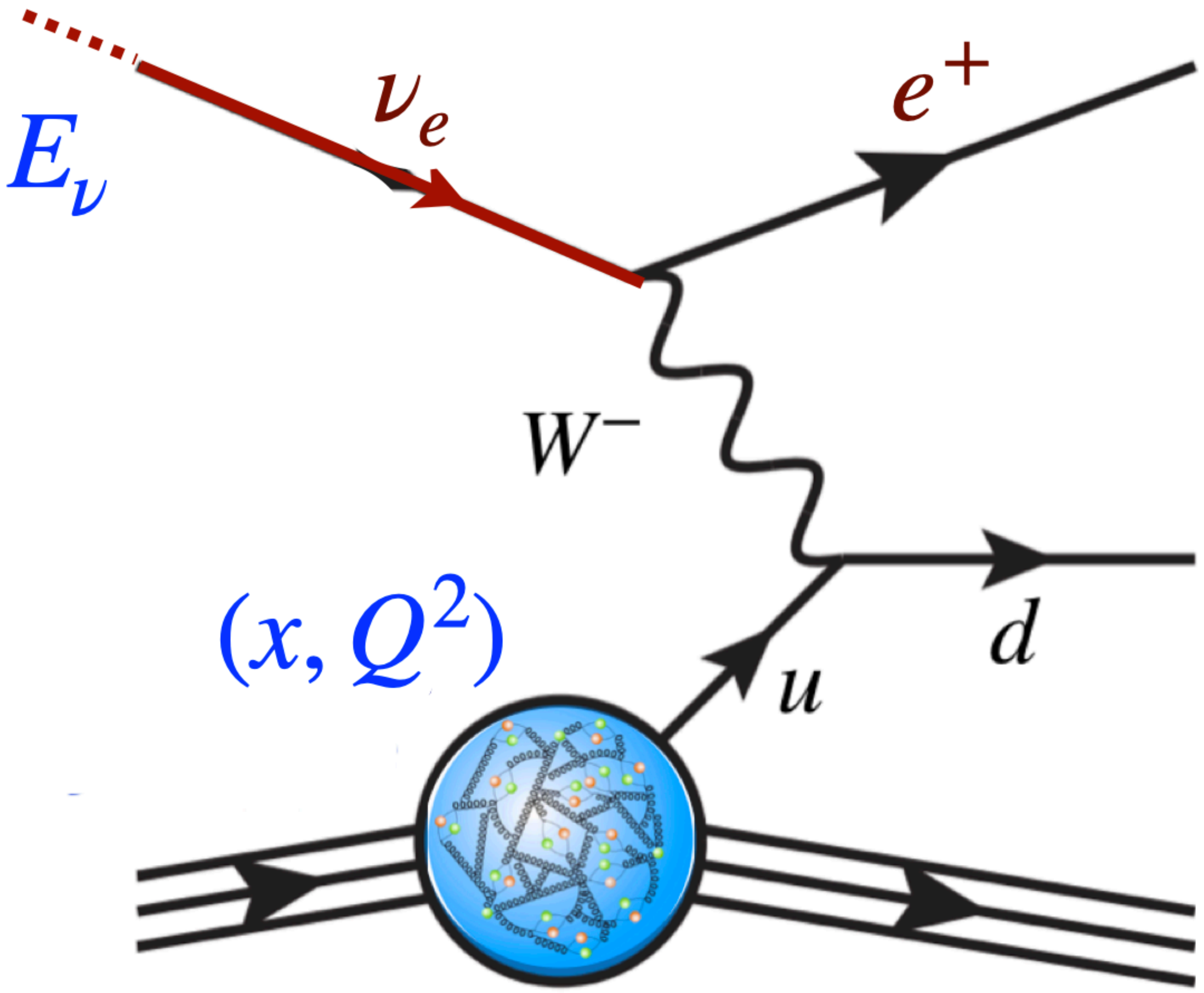
Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

Nature **608**, 483–487 (2022) | Cite this article

53k Accesses | **24** Citations | **369** Altmetric | Metrics

Fitting Parton Distributions



$$\sigma_{\nu p \to e^+ X}(E_\nu) = \tilde{\sigma}_{\nu u \to d} \otimes u(x, Q^2)$$

neutrino-proton scattering rate

partonic cross-section

up-quark content the proton

$$u(x, Q^2)$$

Probability of **finding an up quark inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

$$u(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

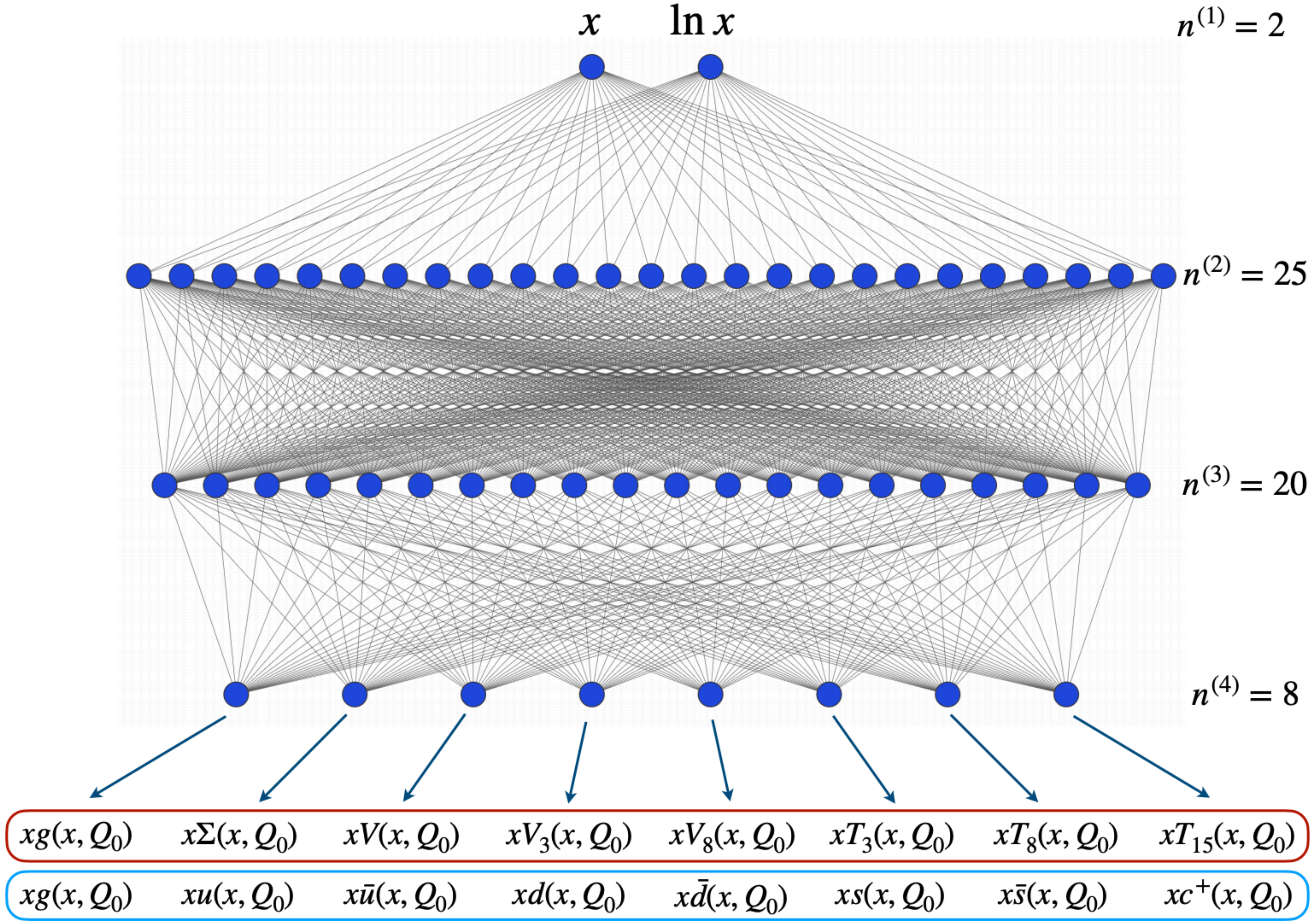
constrain from global fit to high-p_T data

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to aN³LO

$$\frac{\partial}{\partial \ln Q^2} q_i(x, Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) q_j(z, Q^2)$$

Fitting Parton Distributions

``Classical” option: parametrise PDFs with **deep learning models** trained to the data



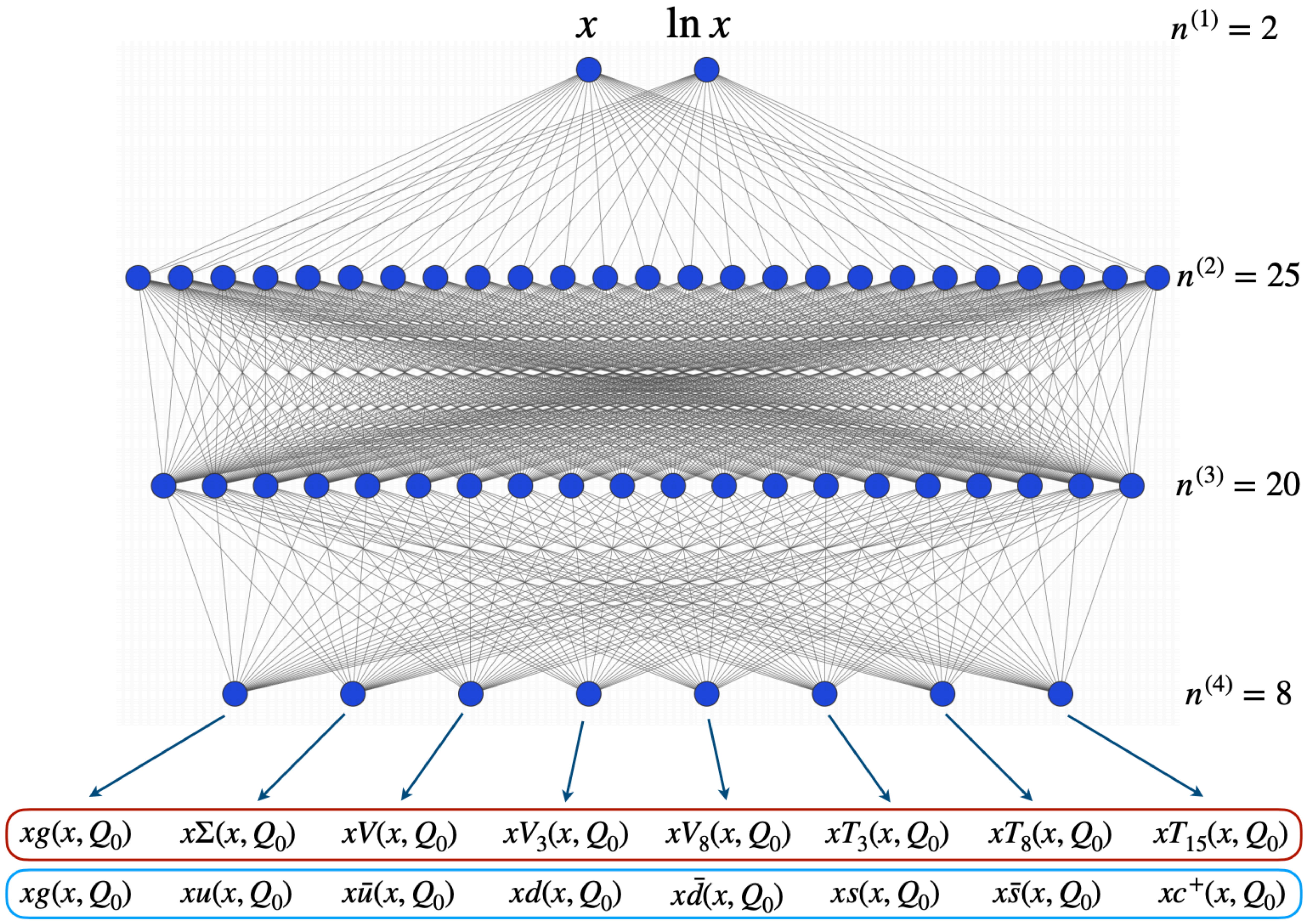
$xg(x,Q_0)$ $x\Sigma(x,Q_0)$ $xV(x,Q_0)$ $xV_3(x,Q_0)$ $xV_8(x,Q_0)$ $xT_3(x,Q_0)$ $xT_8(x,Q_0)$ $xT_{15}(x,Q_0)$

$xg(x,Q_0)$ $xu(x,Q_0)$ $x\bar{u}(x,Q_0)$ $xd(x,Q_0)$ $x\bar{d}(x,Q_0)$ $xs(x,Q_0)$ $x\bar{s}(x,Q_0)$ $xc^+(x,Q_0)$

(Machine Learning & AI techniques ubiquitous in HEP…)

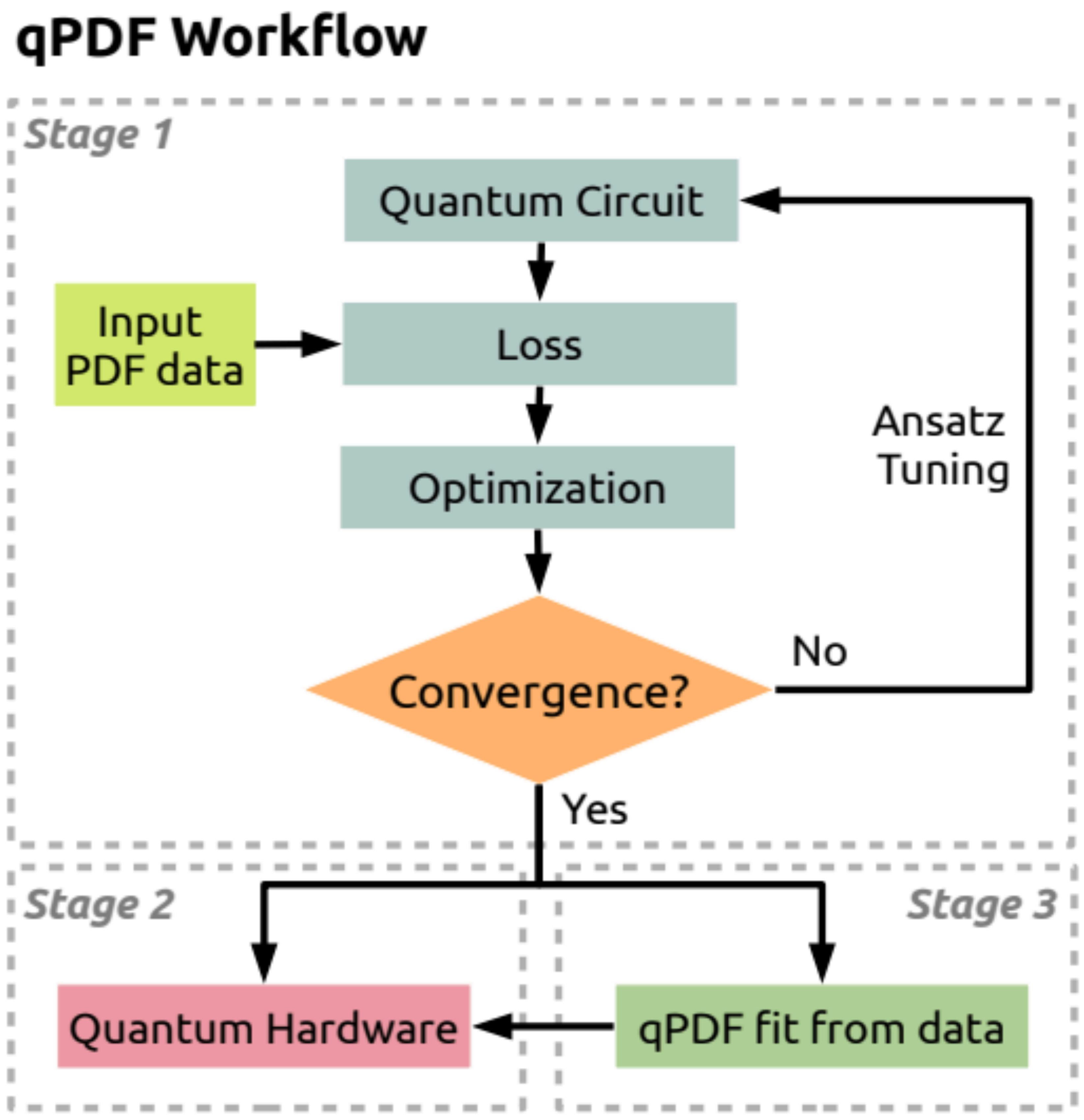
Fitting Parton Distributions

``Classical” option: parametrise PDFs with **deep learning models** trained to the data



Constrain the quantum nature of the proton using quantum software and hardware!

``Quantum” option: parametrise PDFs with **variational quantum circuits** trained to the data



Determining the proton content with a quantum computer

Adrián Pérez-Salinas,[1,2] Juan Cruz-Martinez,[3] Abdulla A. Alhajri,[4] and Stefano Carrazza[3,5,4]

Evaluating Parton Distributions

Were we able to solve Quantum Chromodynamics in its non-perturbative, strong coupling limit, we could **compute PDFs from first principles**

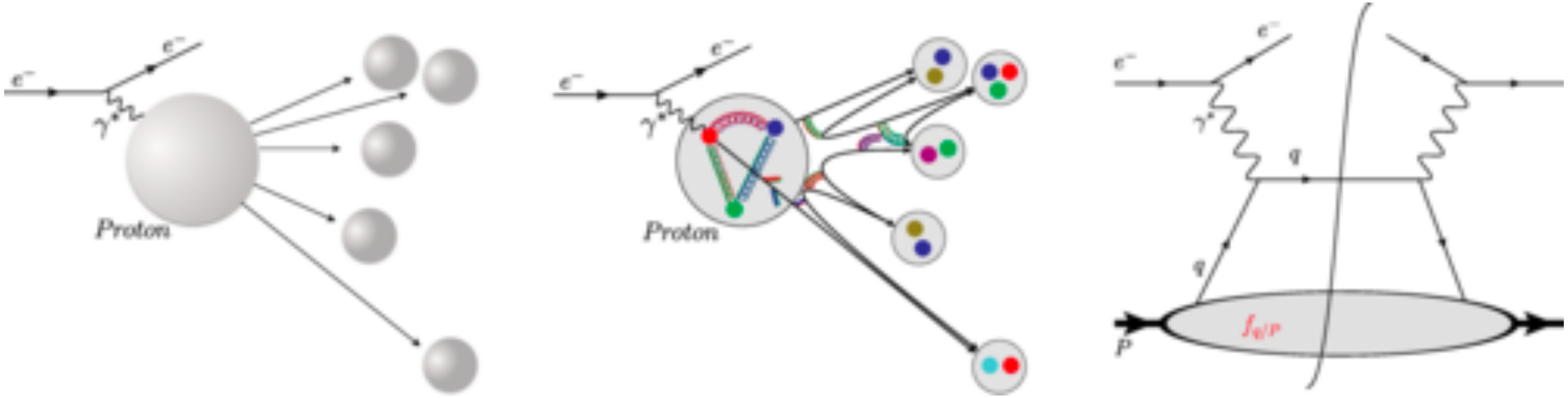
$$q(x) = \frac{1}{4\pi}\int dy^- e^{-iy^- xp^+}\langle p|\bar{\psi}(0,y^-,\mathbf{0}_\perp)\gamma^+\mathcal{G}\psi(0,0,\mathbf{0})|p\rangle$$

a lot of recent progress in lattice QCD calculations!

quark PDF

proton wave function

quark field

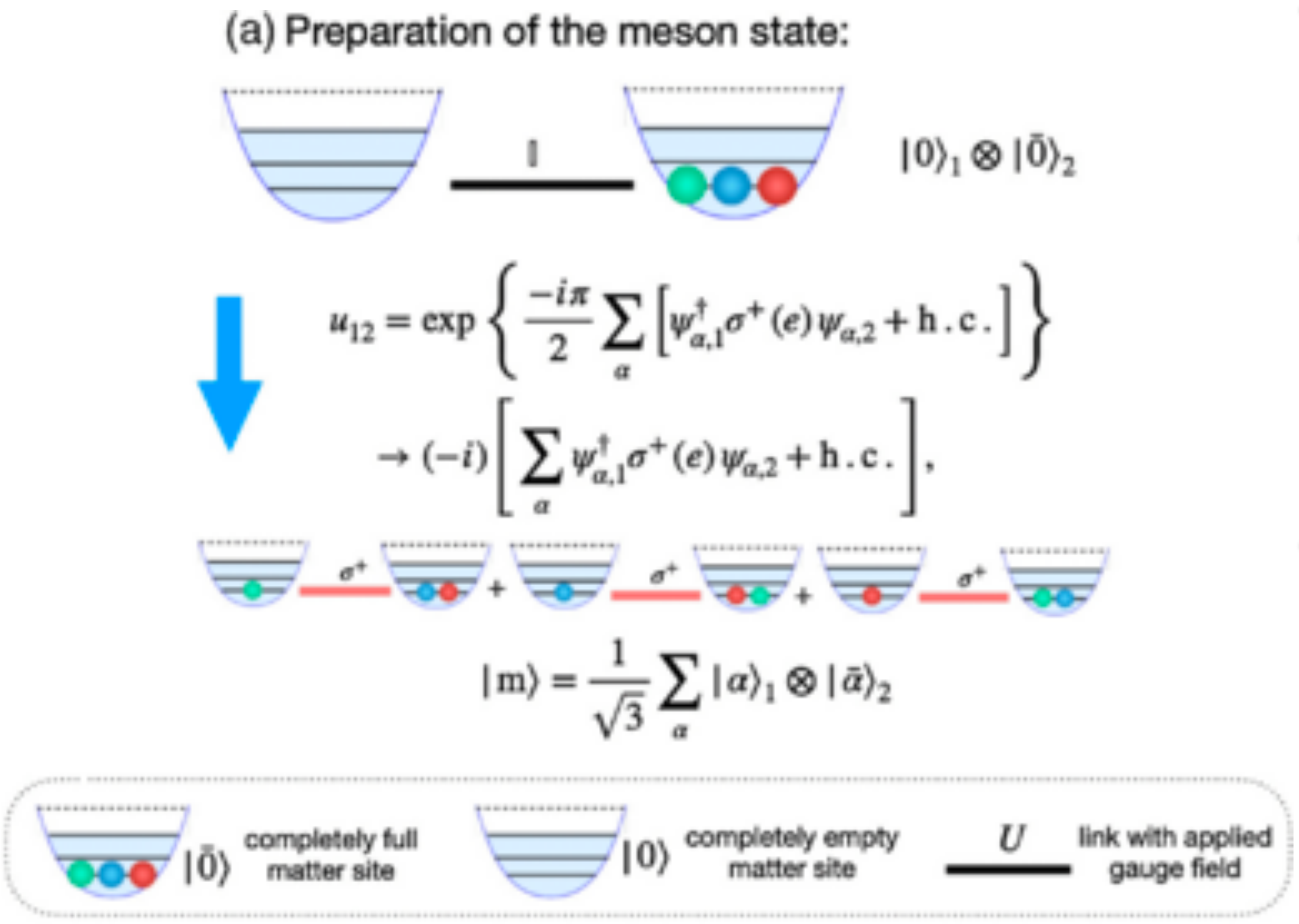


Can we use **quantum information & computing ideas** to enhance these first-principle QCD calculations?

Evaluating Parton Distributions

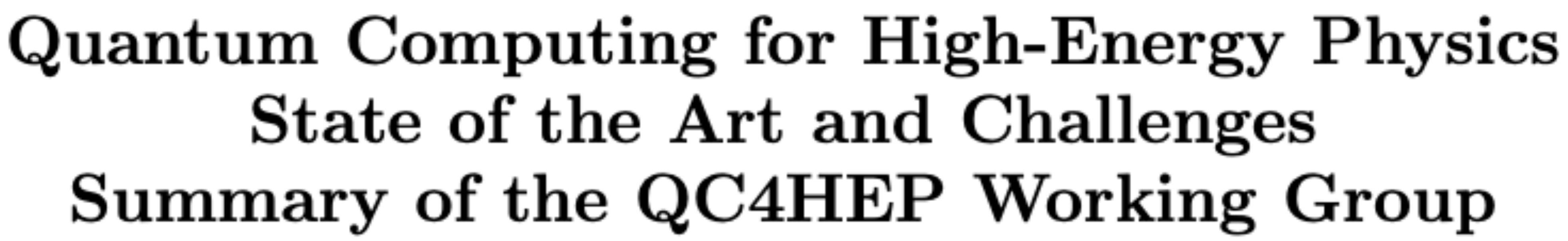
Quantum simulation of light-front parton correlators

M. G. Echevarria, I. L. Egusquiza, E. Rico, and G. Schnell
Phys. Rev. D **104**, 014512 – Published 30 July 2021



- Quantum algorithm can perform a **quantum simulation of partonic correlators** entering PDF calculations.
- Can be implementated using quantum gates that are accessible within **actual quantum technologies** (cold atoms setups, trapped ions, superconducting circuits).
- Eventually complement (or replace?) **existing first-principle (classical) lattice QCD calculations**?

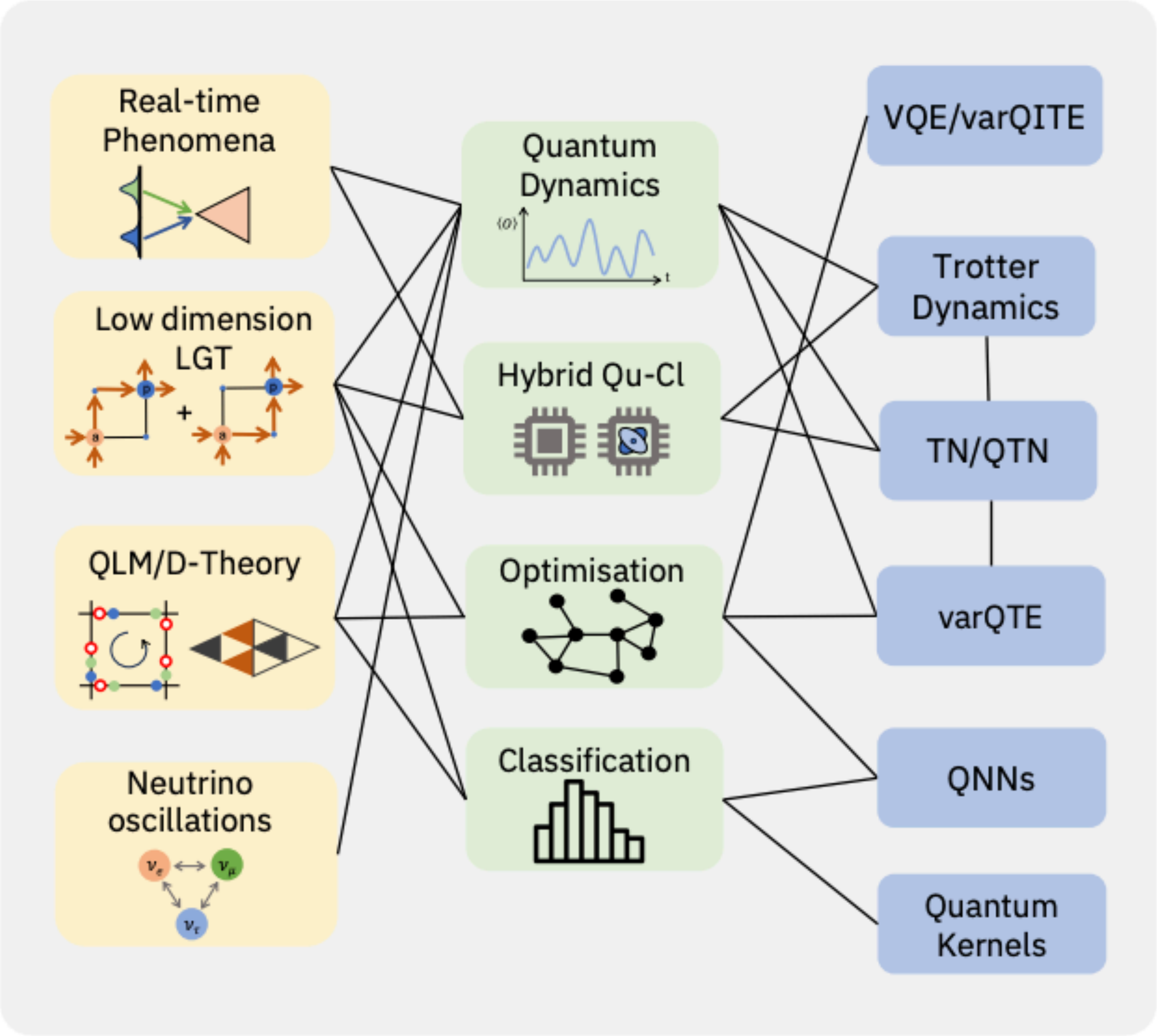
Yet More Quantum Algorithms for HEP


Quantum Computing for High-Energy Physics
State of the Art and Challenges
Summary of the QC4HEP Working Group

https://arxiv.org/pdf/2307.03236.pdf

Quantum Computing for HEP

Theory



Real-time Phenomena

Low dimension LGT

QLM/D-Theory

Neutrino oscillations

Quantum Dynamics

Hybrid Qu-Cl

Optimisation

Classification

VQE/varQITE

Trotter Dynamics

TN/QTN

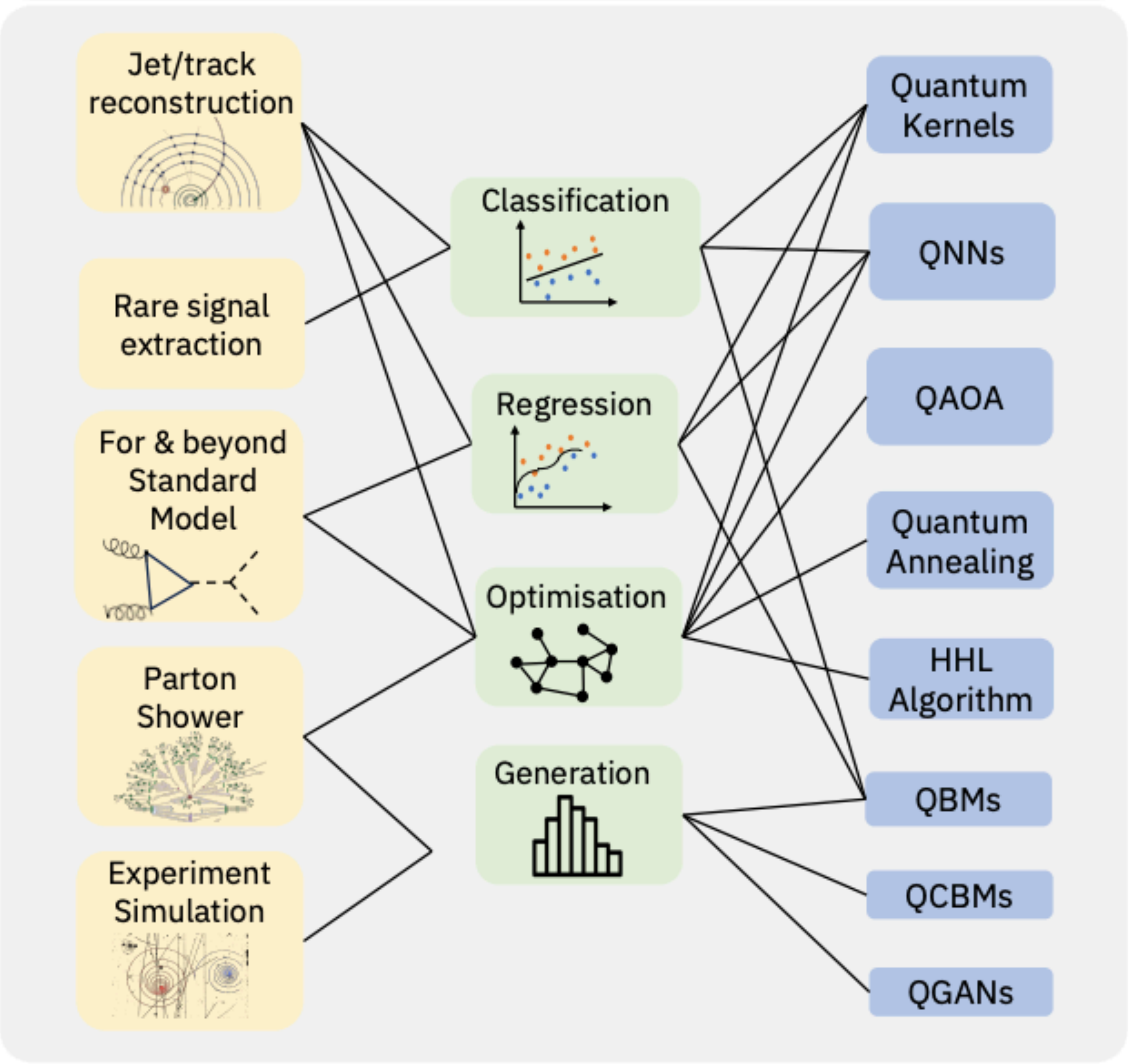
varQTE

QNNs

Quantum Kernels

problem approach QAlg

Phenomenology & Experiment



Jet/track reconstruction

Rare signal extraction

For & beyond Standard Model

Parton Shower

Experiment Simulation

Classification

Regression

Optimisation

Generation

Quantum Kernels

QNNs

QAOA

Quantum Annealing

HHL Algorithm

QBMs

QCBMs

QGANs

problem approach QAlg

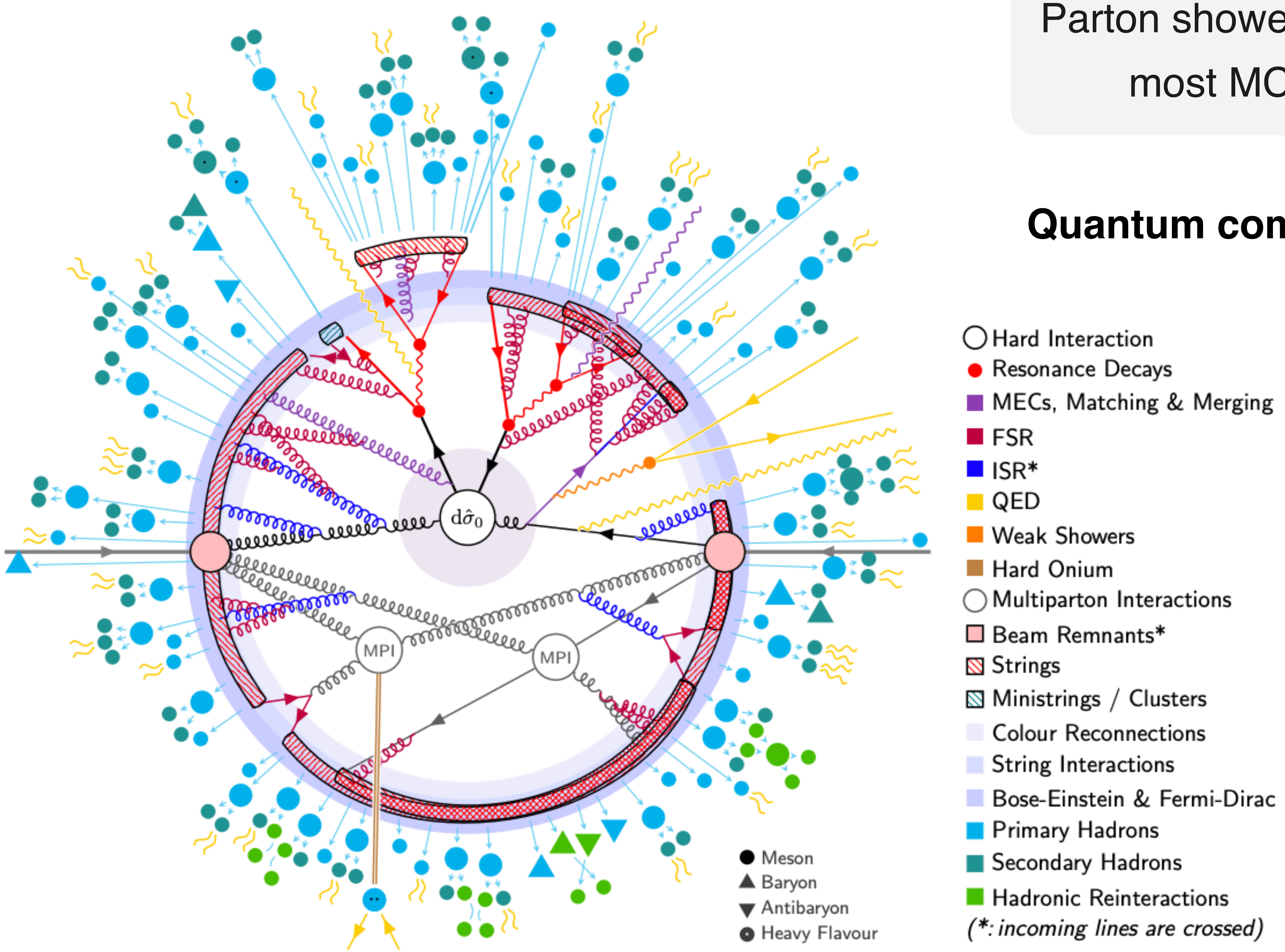
To be relevant for HEP, quantum algorithms should (eventually) **outperform classical algorithms (including ML/AI/HPC)** for the same task

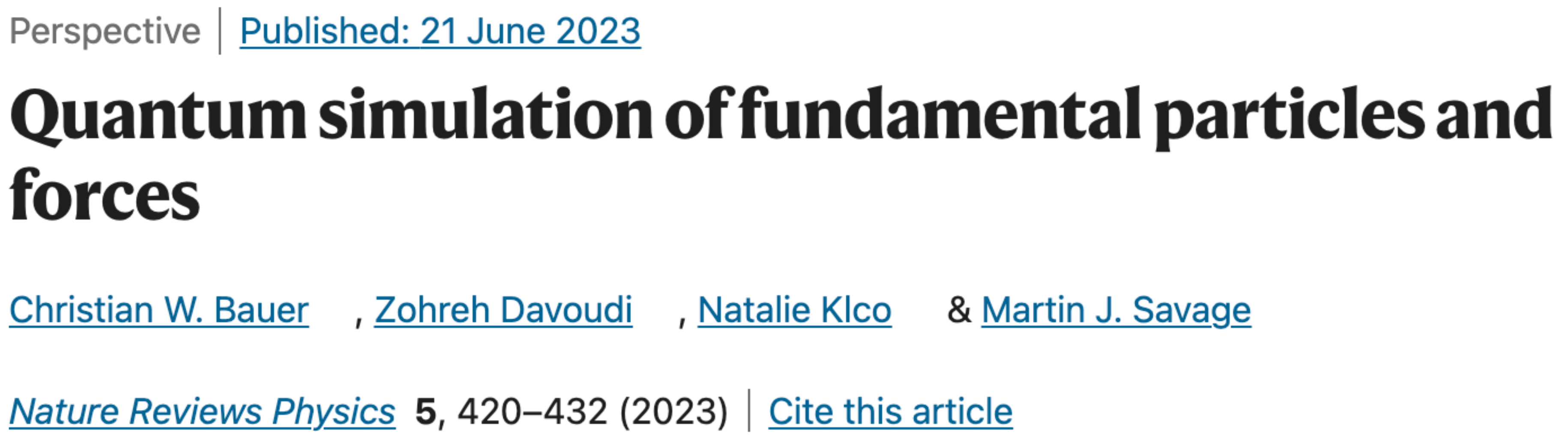
Quantum Simulations of Quantum Collisions

Key to all HEP studies are **Monte Carlo event generators** which simulate particle collisions

Parton shower and hadronisation are **intrinsically quantum**, but in most MCs are treated in the semi-classical approximation

Quantum computers have the potential to more accurate and higher performance MC generators





Perspective | Published: 21 June 2023

Quantum simulation of fundamental particles and forces

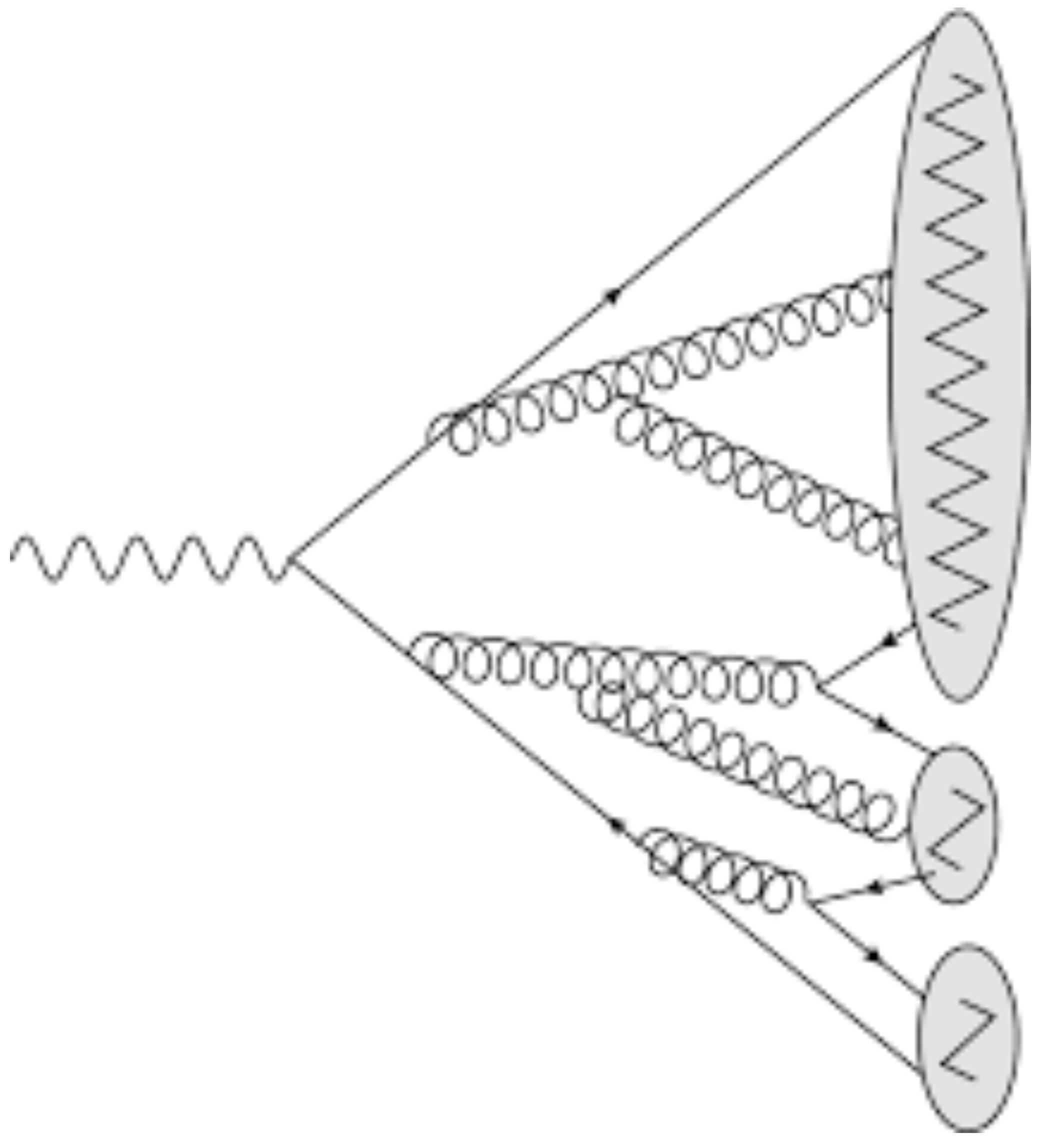
Christian W. Bauer, Zohreh Davoudi, Natalie Klco & Martin J. Savage

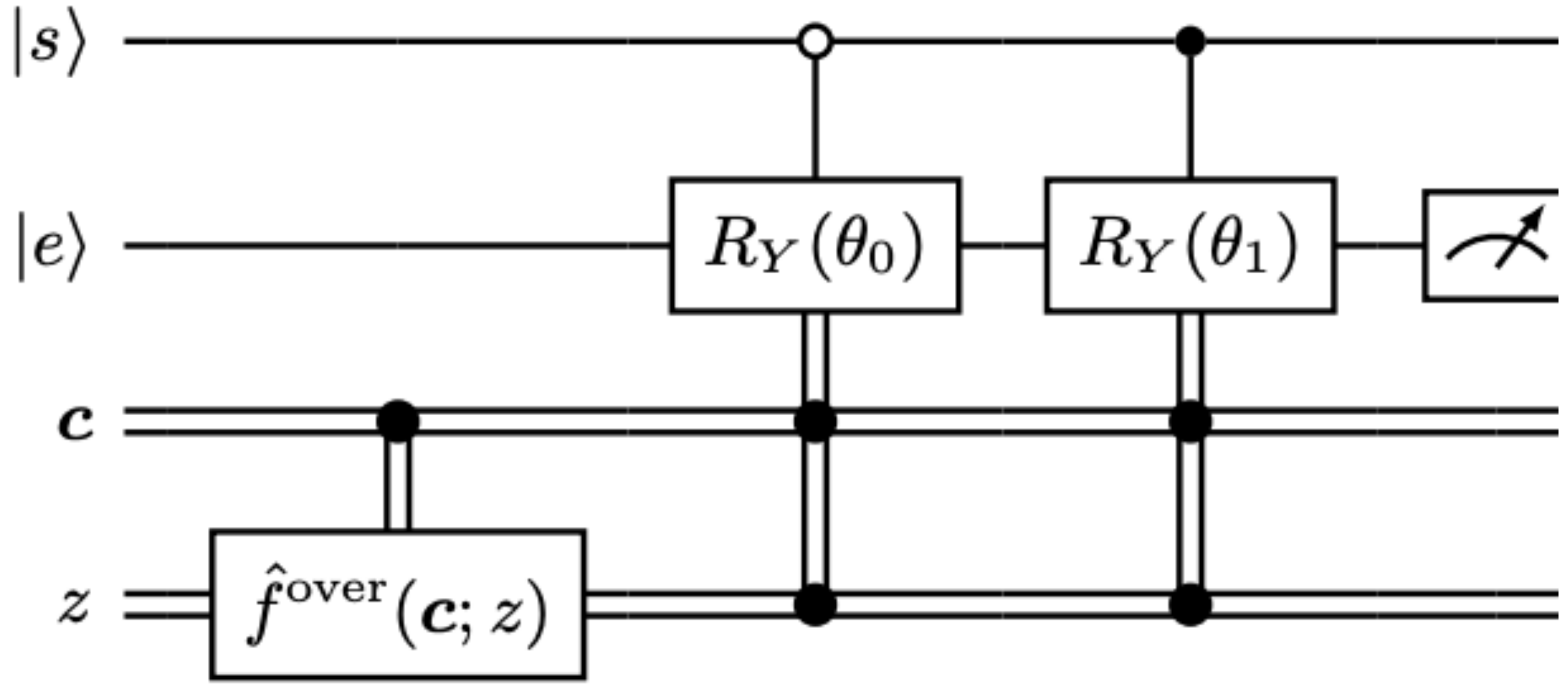
Nature Reviews Physics **5**, 420–432 (2023) | Cite this article

Can we use quantum computing to realise improved event generators for HEP?

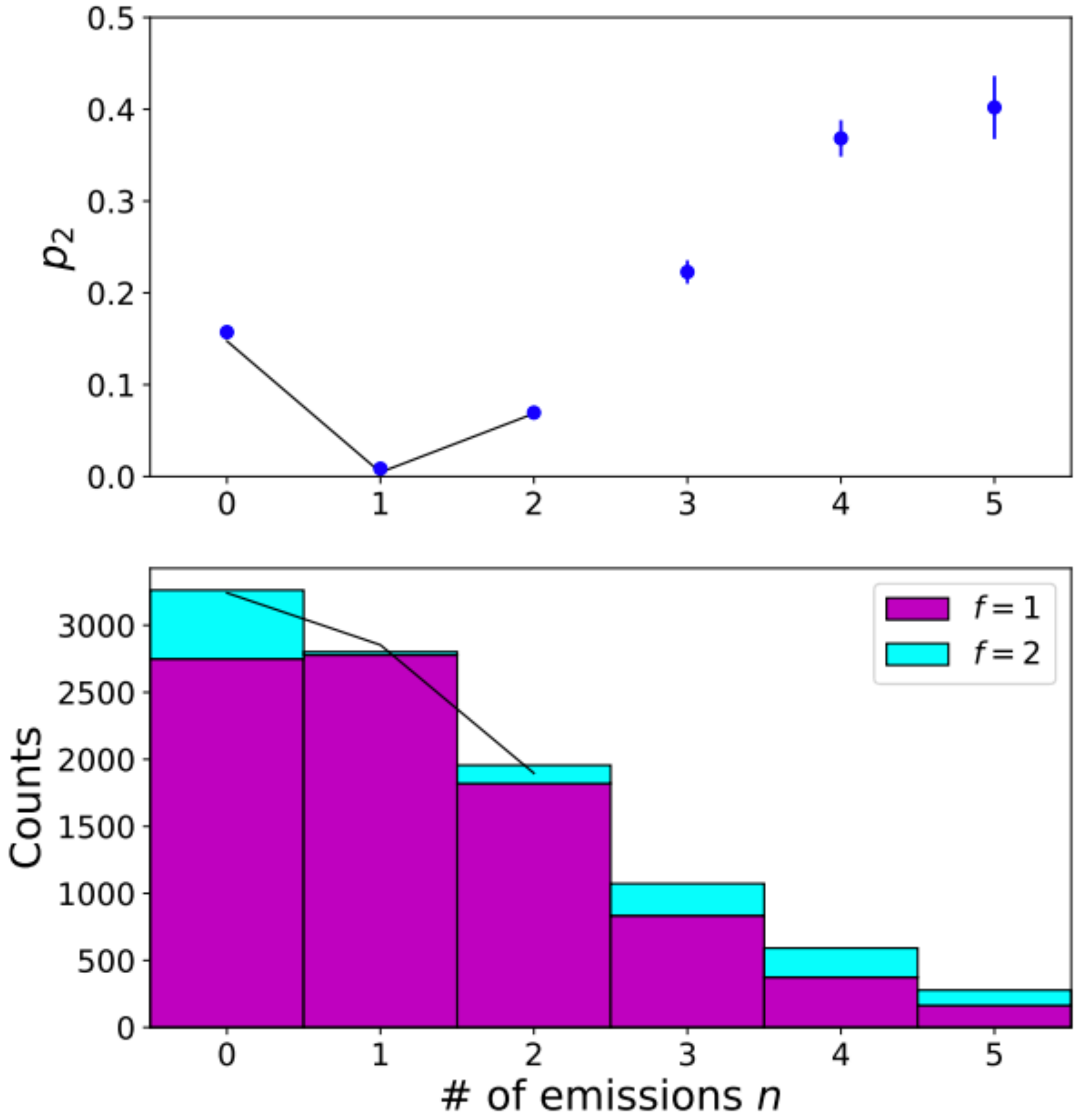
Quantum Simulations of Quantum Collisions

In parton showers, one has to determine when a **quark or gluon should radiate** more partons





quantum circuit implementing emission procedure

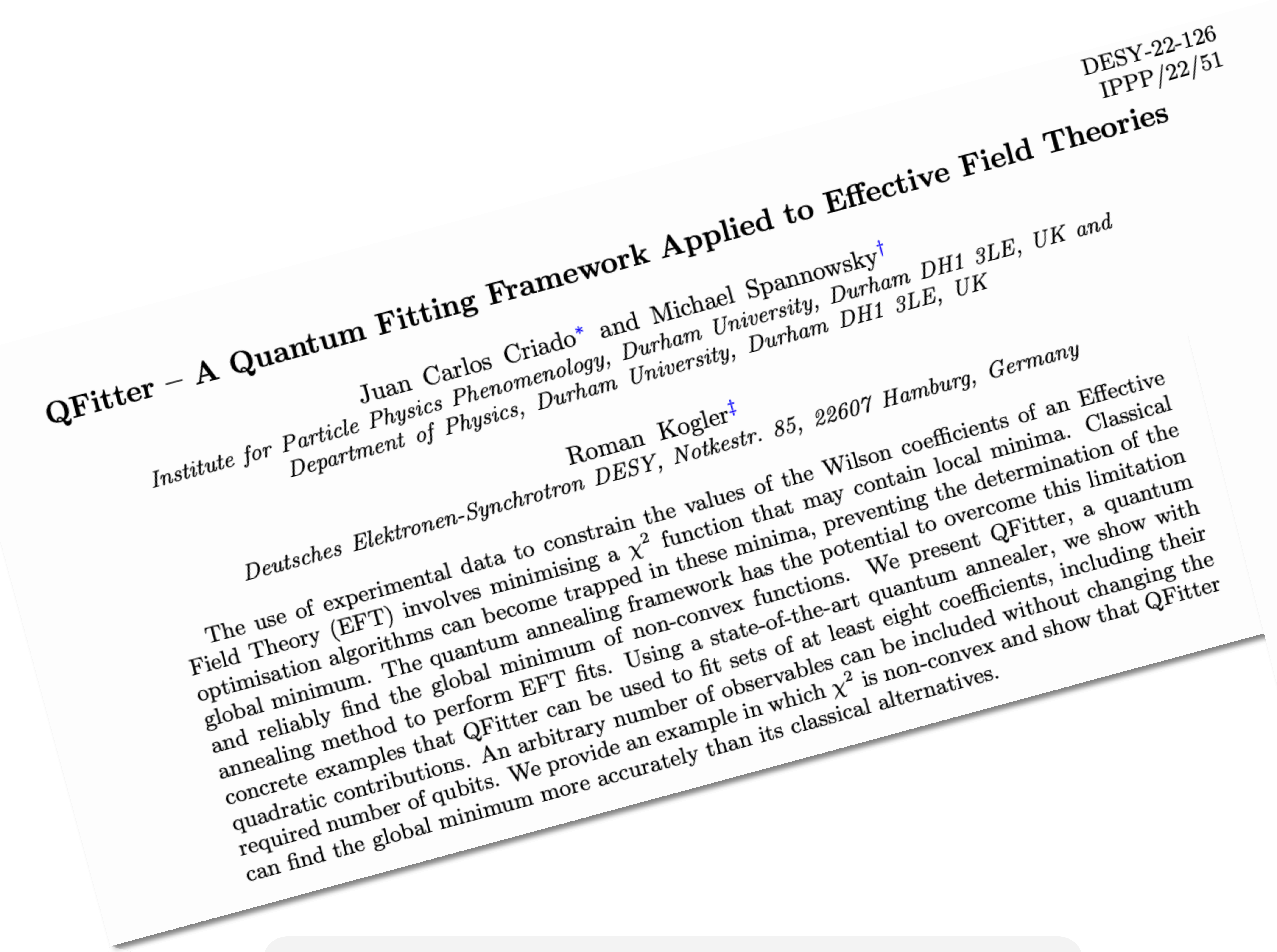


Several proof-of-concept studies of **quantum parton showers** & MC generators, still far from full-fledged implementation

Quantum Parton Shower with Kinematics

Christian W. Bauer[1,2] So Chigusa[1,2] and Masahito Yamazaki[3,4,5]

Quantum Simulations of Quantum Collisions



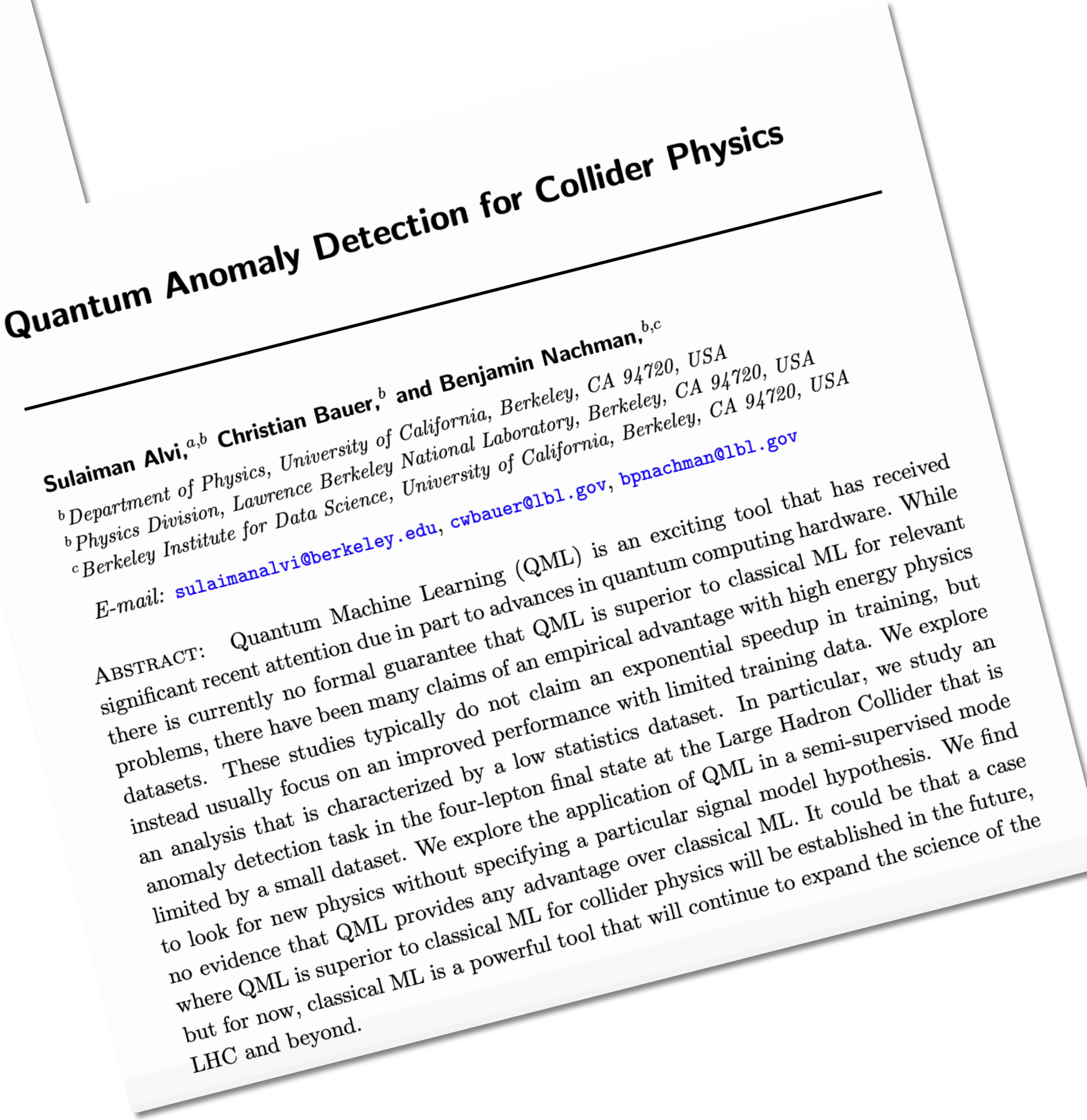
DESY-22-126
IPPP/22/51

QFitter – A Quantum Fitting Framework Applied to Effective Field Theories

Juan Carlos Criado[*] and Michael Spannowsky[†]
Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, UK and
Department of Physics, Durham University, Durham DH1 3LE, UK

Roman Kogler[‡]
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

The use of experimental data to constrain the values of the Wilson coefficients of an Effective Field Theory (EFT) involves minimising a χ^2 function that may contain local minima. Classical optimisation algorithms can become trapped in these minima, preventing the determination of the global minimum. The quantum annealing framework has the potential to overcome this limitation and reliably find the global minimum of non-convex functions. We present QFitter, a quantum annealing method to perform EFT fits. Using a state-of-the-art quantum annealer, we show with concrete examples that QFitter can be used to fit sets of at least eight coefficients, including their quadratic contributions. An arbitrary number of observables can be included without changing the required number of qubits. We provide an example in which χ^2 is non-convex and show that QFitter can find the global minimum more accurately than its classical alternatives.



Quantum Anomaly Detection for Collider Physics

Sulaiman Alvi,[a,b] **Christian Bauer,**[b] **and Benjamin Nachman,**[b,c]
[a] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[b] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[c] *Berkeley Institute for Data Science, University of California, Berkeley, CA 94720, USA*

E-mail: sulaimanalvi@berkeley.edu, cwbauer@lbl.gov, bpnachman@lbl.gov

ABSTRACT: Quantum Machine Learning (QML) is an exciting tool that has received significant recent attention due in part to advances in quantum computing hardware. While there is currently no formal guarantee that QML is superior to classical ML for relevant problems, there have been many claims of an empirical advantage with high energy physics datasets. These studies typically do not claim an exponential speedup in training, but instead usually focus on an improved performance with limited training data. We explore an analysis that is characterized by a low statistics dataset. In particular, we study an anomaly detection task in the four-lepton final state at the Large Hadron Collider that is limited by a small dataset. We explore the application of QML in a semi-supervised mode to look for new physics without specifying a particular signal model hypothesis. We find no evidence that QML provides any advantage over classical ML. It could be that a case where QML is superior to classical ML for collider physics will be established in the future, but for now, classical ML is a powerful tool that will continue to expand the science of the LHC and beyond.

QAlgs also relevant for SMEFT studies, anomaly detection, neutrino physics, … - an ever growing list of exiting applications!

Quantum Algorithms for HEP

- Ideas and techniques from quantum algorithms & information & computing exhibit **ample potential for breakthroughs in HEP,** from theory to phenomenology and experiment

- **Case studies** highlighted here: new insights for model-building, searches for quantum imprints of heavy particles using EFTs, proton structure, Monte Carlo event generators, …..

- Main challenge is to identify **relevant projects** where Qalgs can make a real difference as compare to ``classical" methods (including ML/AI/HPC): exploit **unique quantum advantages**

- This requires **dedicated person-power** to kick-start joint projects between HEP and Qalg groups. Getting funding for this from HEP side is challenging, more Qalg side seems more promising

- Ideas and suggestions to move forwards welcome!