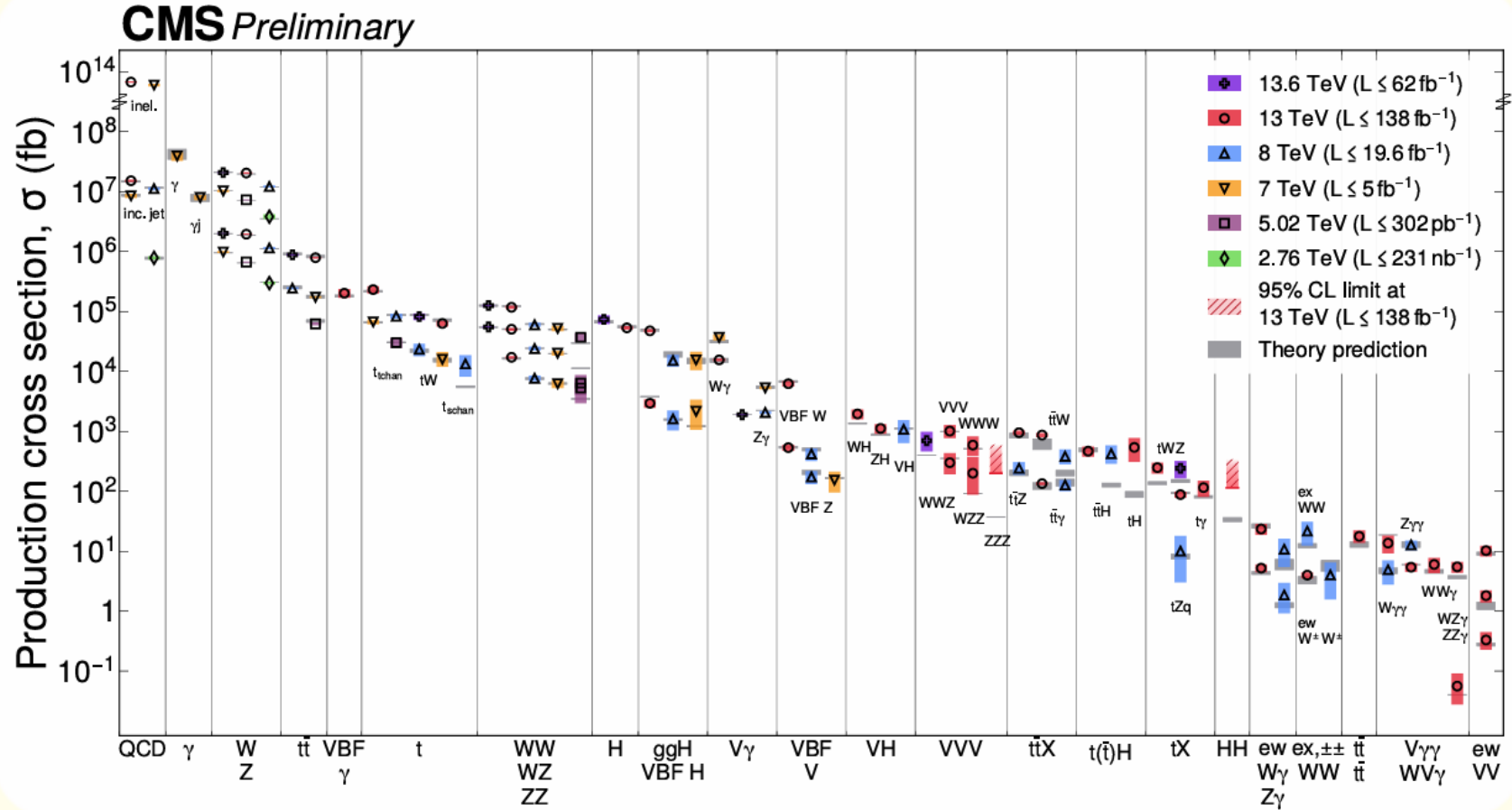
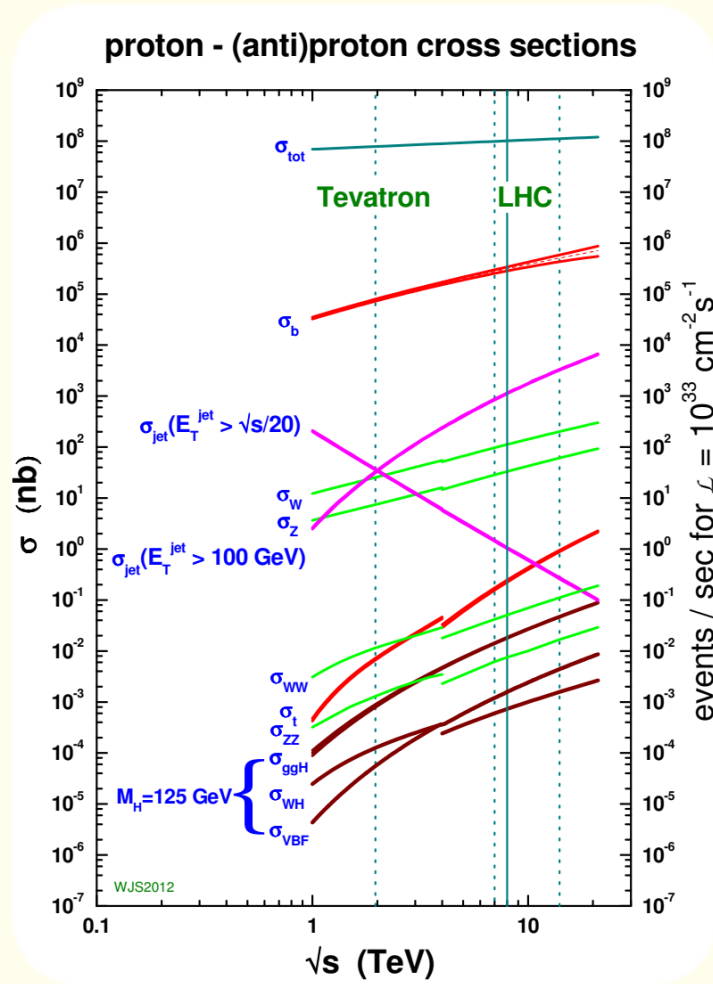


Searching for New Physics at the colliders

Qing-Hong Cao
Peking University

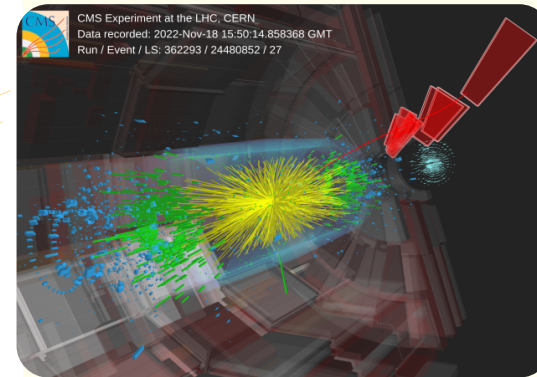
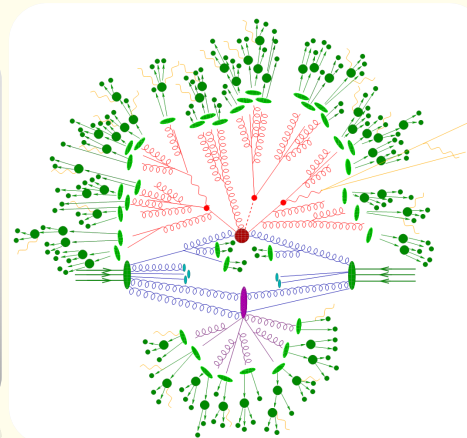
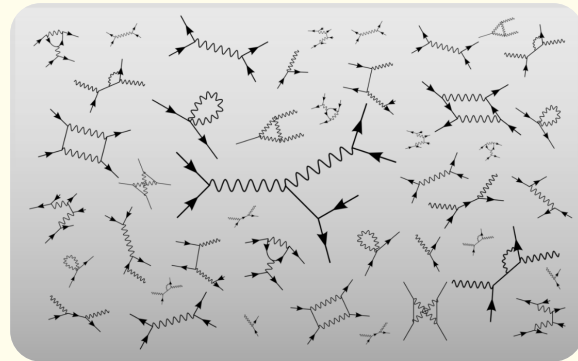
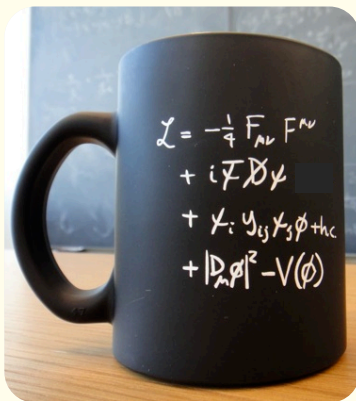
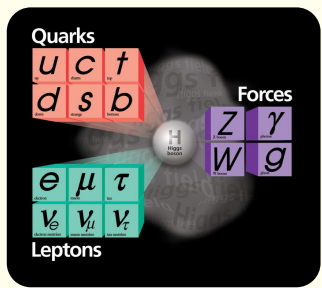
Long lived the Standard Model

From precision to exploration, precision test of SM at 15 orders !



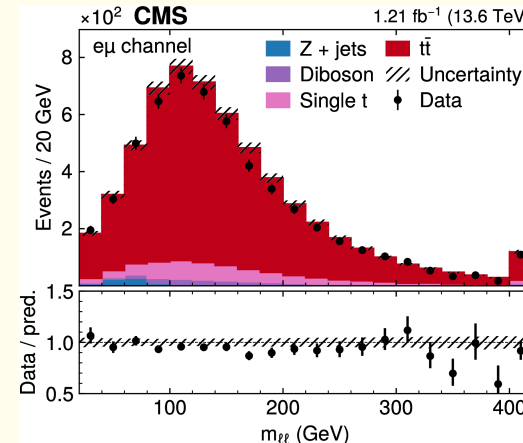
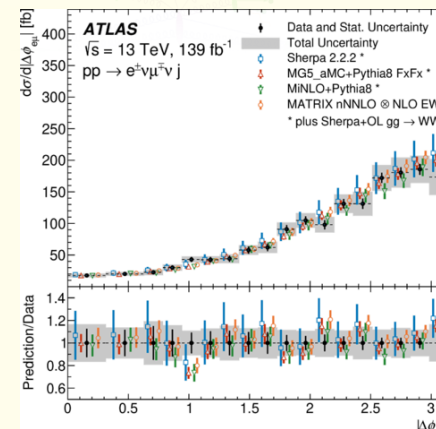
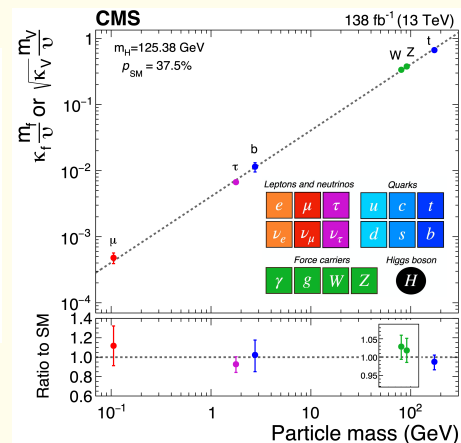
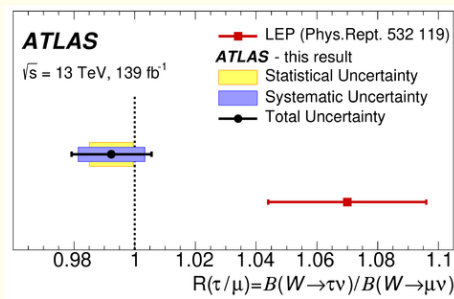
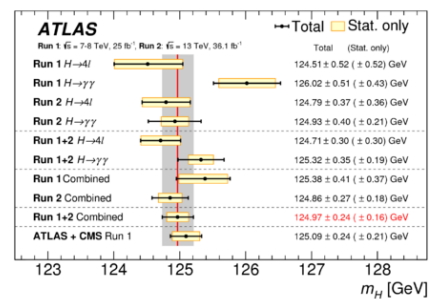
Triumphant, but with no joy — only despair!

Full Chain Efforts: Predictions and measurements



Predictions

Measurements



Quantum field structures, symmetries and intrinsic properties, model parameters

Couplings, interactions

Cross-sections

Detector observables

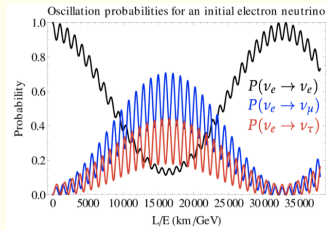
From the talk by Yusheng Wu: (Brief) Review of Standard Model Measurements at TeV

Motivation for new physics

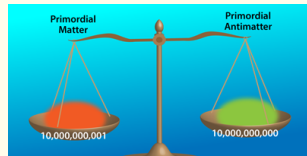
There are experimental challenges in the standard model and theoretical motivation for new physics

Experimental challenges

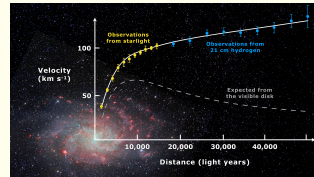
Neutrino masses



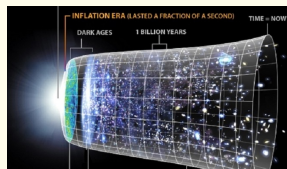
Baryon asymmetry



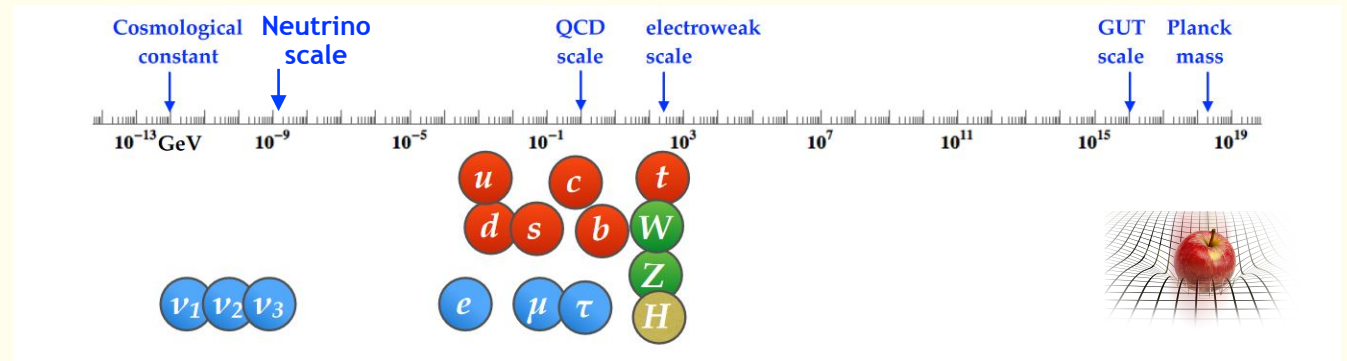
Dark matter



Inflation

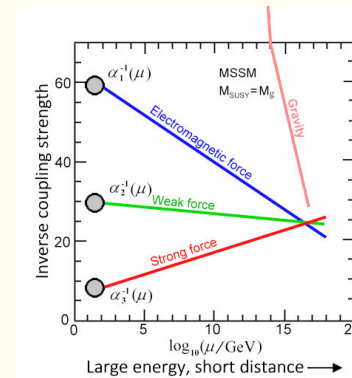


Theoretical motivations

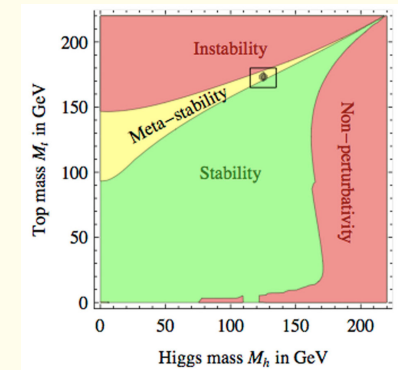


Fermion flavor hierarchy

Higgs hierarchy problem

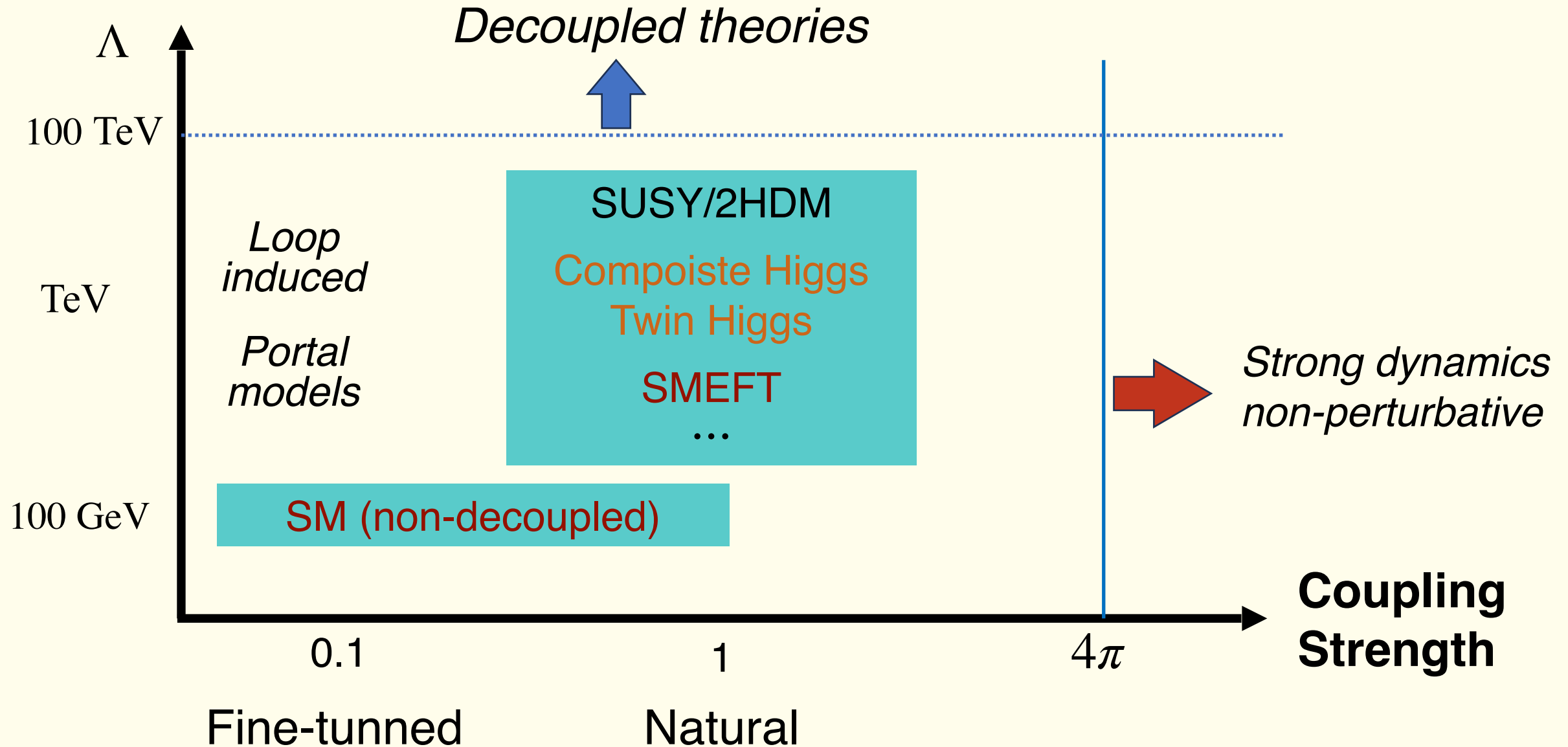


Gauge unification



Vacuum stability

New Physics beyond Standard Model



Precision measurements at the LHC

Purpose of precision measurements

$$\frac{\sigma_{\text{Data}} - \sigma_{\text{SM}}}{\sigma_{\text{SM}}} \sim 1\%$$

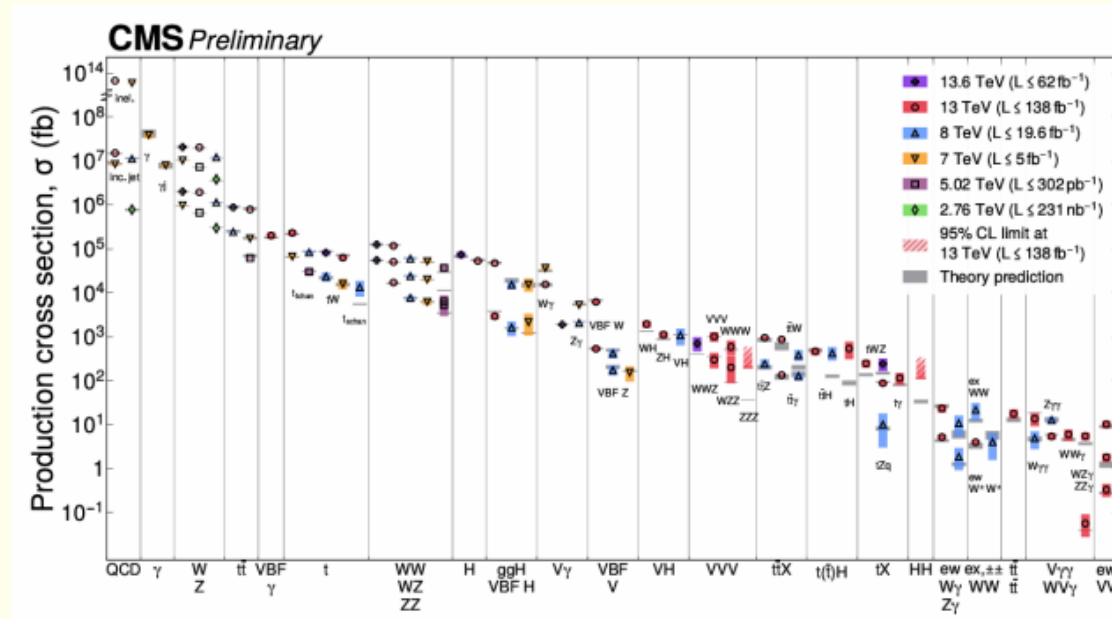
New symmetries

Effective couplings

$$U(1)_{\text{em}}$$

mass → charge → spin →	≈2.3 MeV/c ² 2/3 1/2	≈1.275 GeV/c ² 2/3 1/2	≈173.07 GeV/c ² 2/3 1/2	0 0 1	≈126 GeV/c ² 0 0
	u up	c charm	t top	g gluon	H Higgs boson
	≈4.8 MeV/c ² -1/3 1/2	≈95 MeV/c ² -1/3 1/2	≈4.18 GeV/c ² -1/3 1/2	0 0 1	0 0 1
QUARKS	d down	s strange	b bottom	γ photon	
	0.511 MeV/c ² -1 1/2	105.7 MeV/c ² -1 1/2	1.777 GeV/c ² -1 1/2	91.2 GeV/c ² 0 1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	<2.2 eV/c ² 0 1/2	<0.17 MeV/c ² 0 1/2	<15.5 MeV/c ² 0 1/2	80.4 GeV/c ² ±1 1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	GAUGE BOSONS

$$SU(2)_L \times U(1)_Y$$



Bump hunting

Effective Field Theory (Operators)

$$SU(2)_L \times U(1)_Y$$

New particles (D.o.F.)

Light quark Yukawa coupling

Directly measuring the light-quark Yukawa couplings is extremely challenging

➤ Tiny couplings

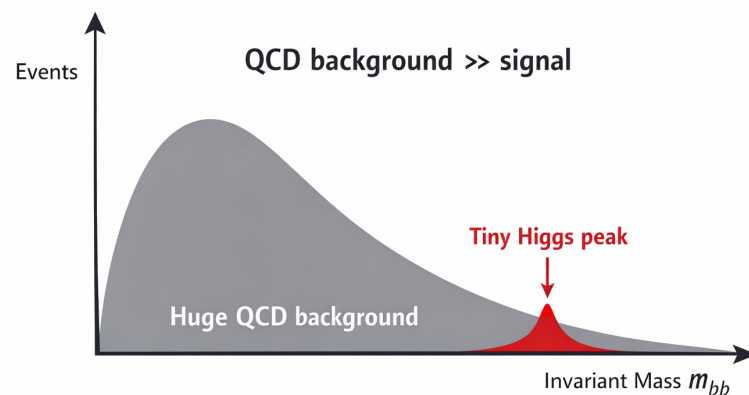
$$y_{u,d}^{\text{SM}} \sim \mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$$

➤ The cross sections or decay rates

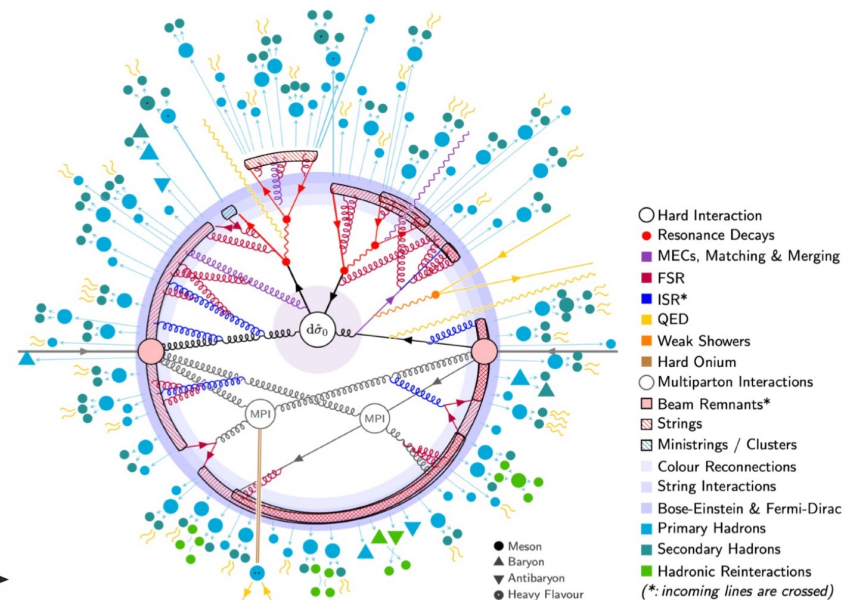
proportional to y_q^2 with $y_q \ll 1$

➤ Huge QCD backgrounds

➤ QCD confinement



Yukawa couplings flip chirality



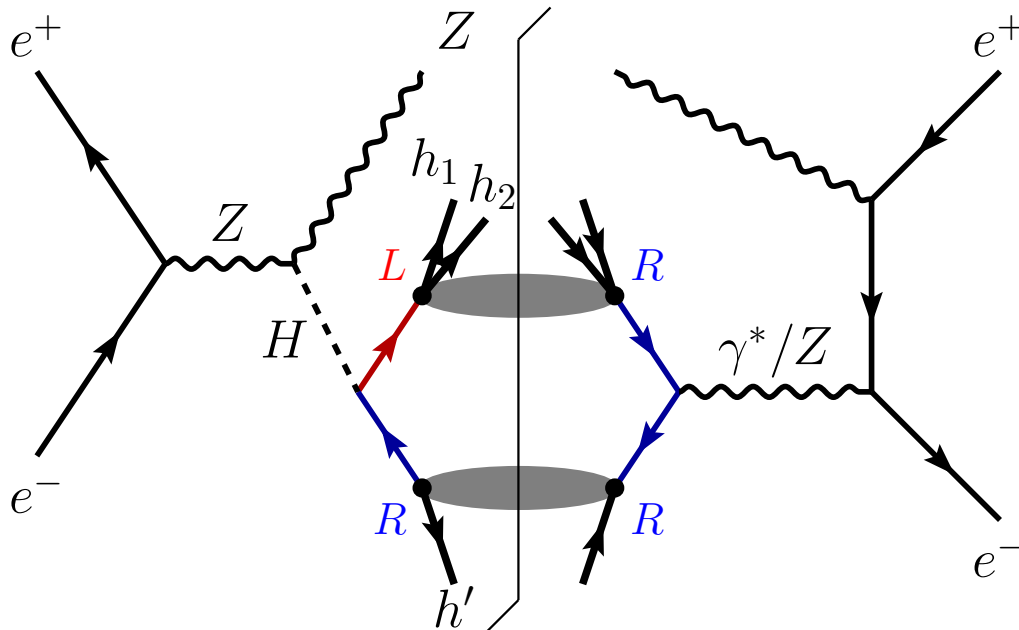
From PYTHIA 8.3

Light quark Yukawa coupling

- Tiny couplings → **Special and Unique Probe to “ZOOM IN”**
- Huge QCD backgrounds → **Lepton Collider, Spin Asymmetry**
- **The cross sections or decay rates: y_q^2 , ($y_q \ll 1$)**

✓ **Quark transverse spin** $\propto y_q$

Chiral-flipping Yukawa interactions generate **quark chiral-odd transverse spin** via the **interference between the different helicity** states of signal and background amplitudes



$$\rho = \frac{1}{2} (1 + \boldsymbol{\sigma} \cdot \mathbf{s}) = \frac{1}{2} \begin{pmatrix} 1 + \lambda & b_T e^{-i\phi_0} \\ b_T e^{i\phi_0} & 1 - \lambda \end{pmatrix}$$

$$\mathbf{s} = (b_1, b_2, \lambda) = (b_T \cos \phi_0, b_T \sin \phi_0, \lambda)$$

How to Measure ?

Qing-Hong Cao, Xin-Kai Wen, Bin Yan, and Shu-Tao Zhang, arXiv: 2512.16492

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801, PRD112 (2025) 053004, 2408.07255

Dihadron FFs and Yukawa coupling

Yukawa interactions generate **transverse spin of quark** through interference between different helicity states of signal and backgrounds (**rising y_q^2 to y_q**)

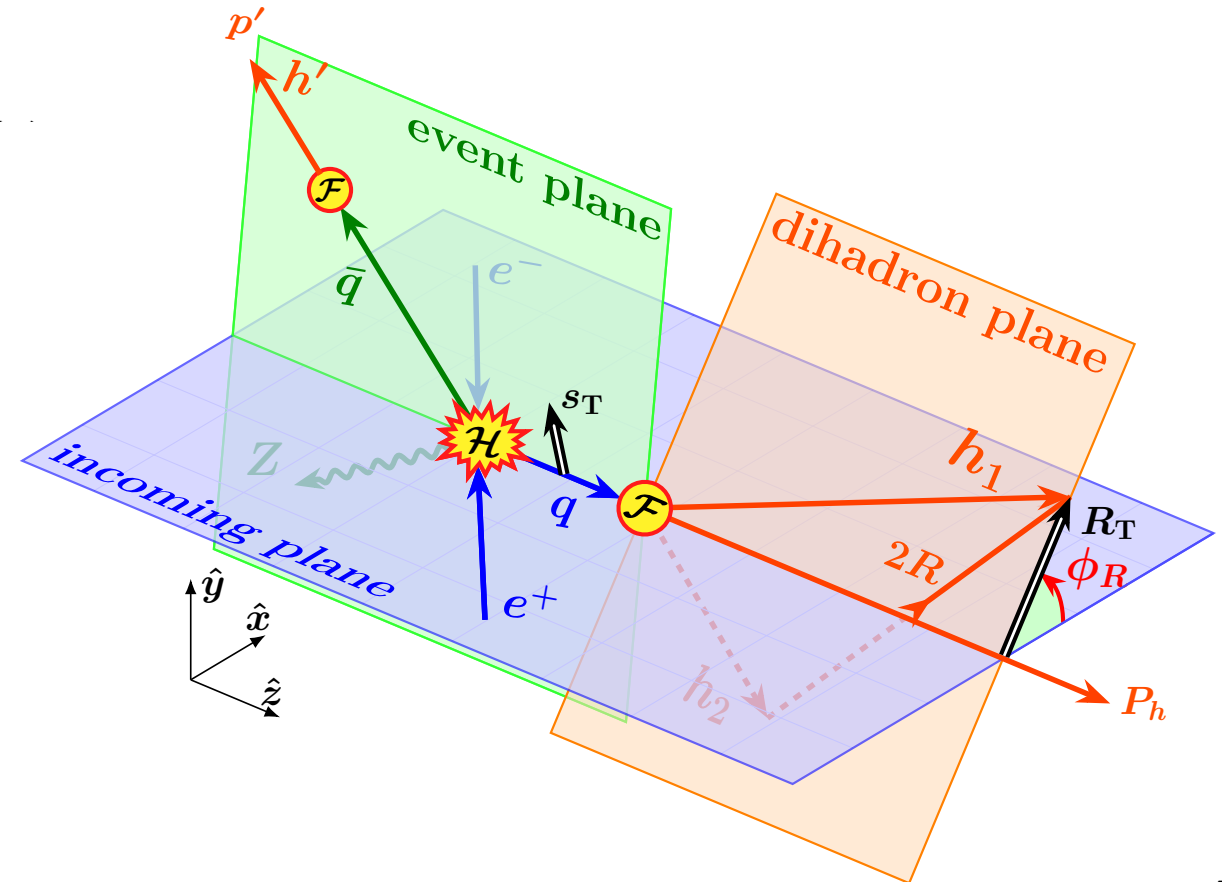
$$\frac{d\sigma}{dx_q dx_{\bar{q}} d\cos\theta d\phi dz d\bar{z} dM_h d\phi_R} = \frac{1}{64(2\pi)^5} \sum_{q, q \rightarrow \bar{q}} C_q D_q^{h'}(\bar{z})$$

$$\times \left[D_q^{h_1 h_2}(z, M_h) - (\mathbf{s}_{T,q} \times \hat{\mathbf{R}}_T)^z H_q^{h_1 h_2}(z, M_h) \right].$$

Unpolarized DiFFs Interference DiFFs (transverse spin)

$$e^+ e^- \rightarrow q \bar{q} Z$$

three-body kinematics



Different spin and CP dependence due to three-body nontrivial property

$$(\mathbf{s}_{T,q} \times \hat{\mathbf{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

$$s_q^x C_q = 2 \operatorname{Re} \mathcal{H}_{+-}^q = \omega_q y_q + \tilde{\omega}_q \tilde{y}_q$$

$$s_q^y C_q = 2 \operatorname{Im} \mathcal{H}_{+-}^q = \tilde{\omega}_q y_q - \omega_q \tilde{y}_q$$

Dihadron FFs and Yukawa coupling

Collinear and LO: the integration of the hard coefficients and FFs can be **factorized**

$$\langle \mathcal{O} \rangle \equiv \int dx_q dx_{\bar{q}} d \cos \theta d \phi \mathcal{O}_{\text{hard}}(x_q, x_{\bar{q}}, \cos \theta, \phi)$$

$$\langle \mathcal{O} \rangle \equiv \int dz d\bar{z} dM_h \mathcal{O}_{FF}(z, \bar{z}, M_h), \quad \sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 50 \text{ ab}^{-1}$$

$$2\pi \frac{d\sigma}{d\phi_R} = \sum_{q=u,d} \langle \mathcal{C}_q \rangle \langle D_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} + D_q^{h'} \rangle$$

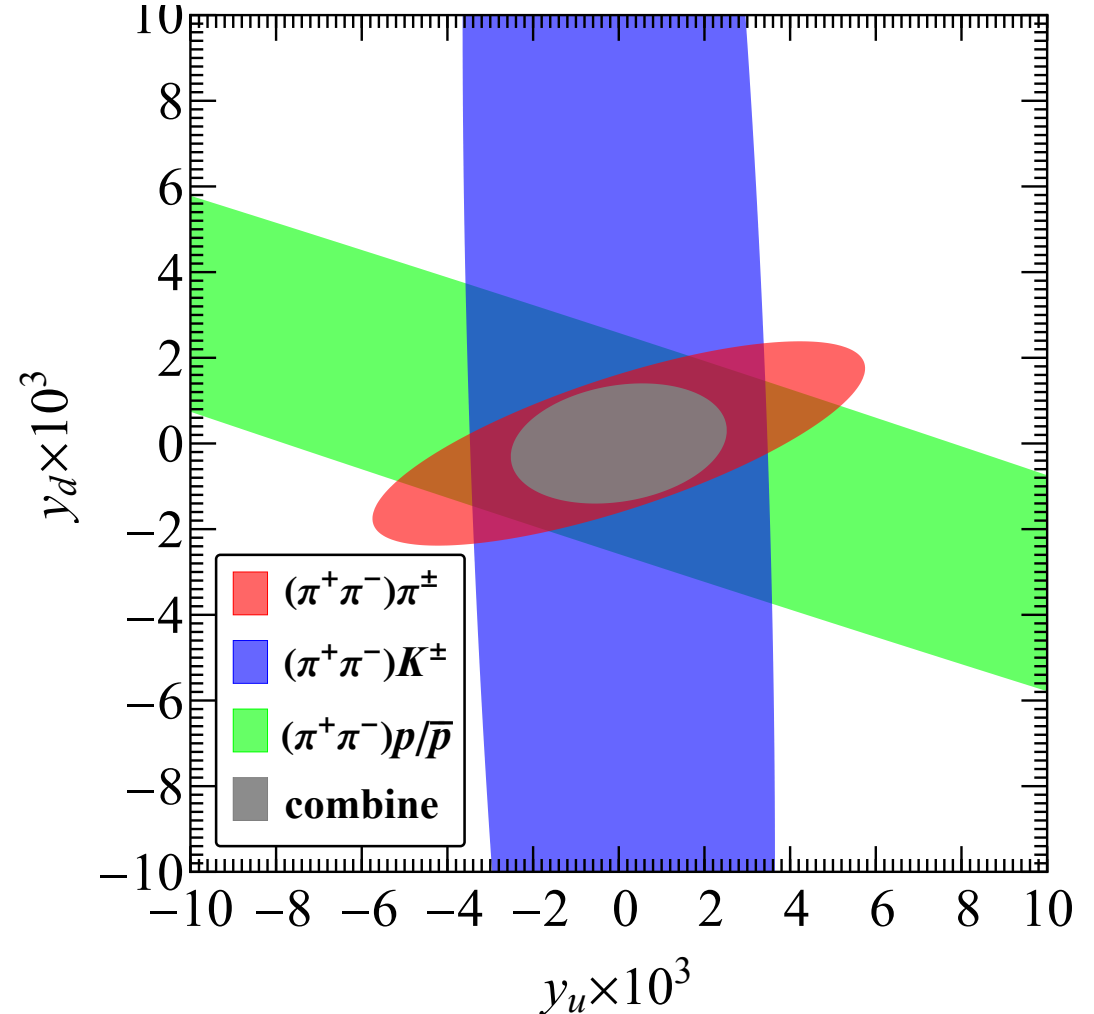
$$- [y_q \sin \phi_R + \tilde{y}_q \cos \phi_R] \langle \omega_q \rangle \langle H_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} - D_q^{h'} \rangle$$

$$- [\tilde{y}_q \sin \phi_R - y_q \cos \phi_R] \langle \tilde{\omega}_q \rangle \langle H_q^{h_1 h_2} \rangle \langle D_{\bar{q}}^{h'} + D_q^{h'} \rangle$$

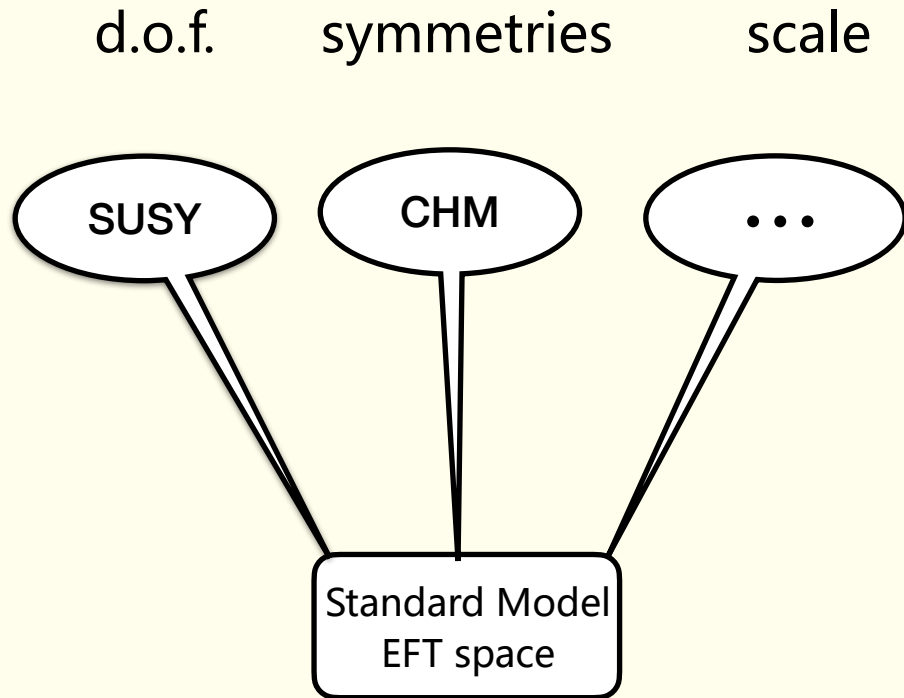
$$\frac{2\pi}{\sigma^{h'}} \frac{d\sigma^{h'}}{d\phi_R} = 1 + S_x^{h'} \sin \phi_R + S_y^{h'} \cos \phi_R$$

✓ The **single hadron as flavor tags** for up- and down-quarks, **enabling flavor separation**

✓ Yukawa couplings: $\mathcal{O}(10^{-4} - 10^{-3})$

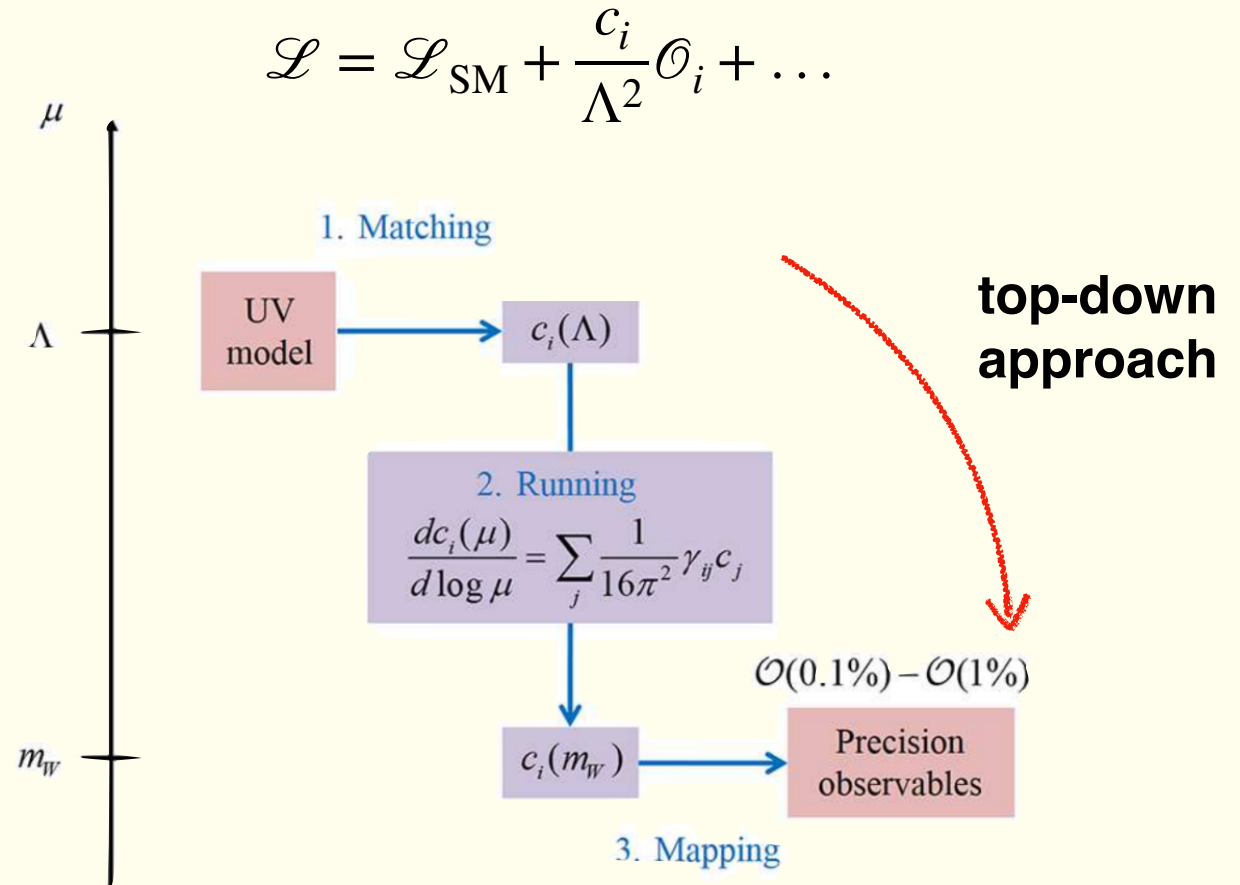


Example: NP and effective field theory



describes (infinitely) NP models by finite Wilson coefficients

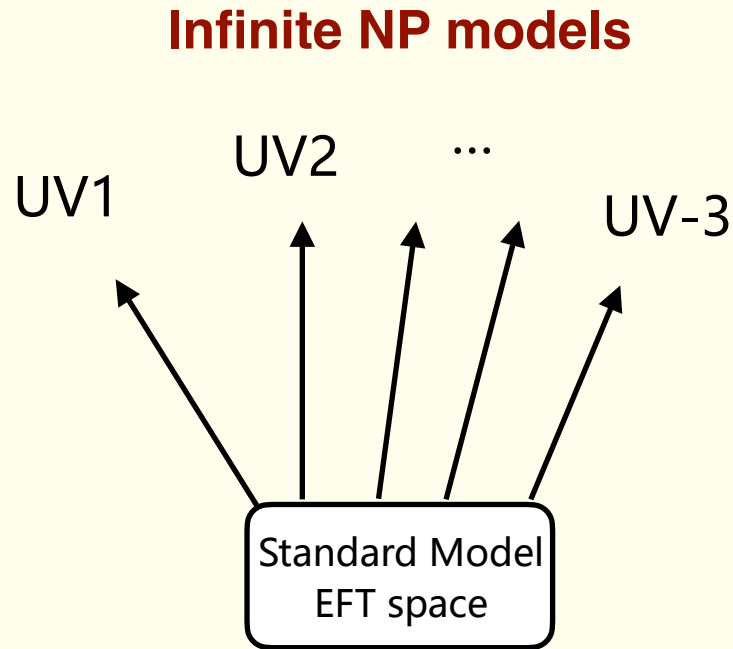
determined by global fit to LHC data



$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

Henning, Lu, Murayama,
1412.1837

Example: NP and effective field theory



$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

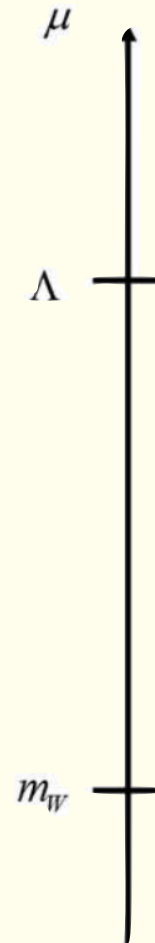
LHC inverse problem:

Once coefficients are known from LHC,
how and to what extent can we determine the models?

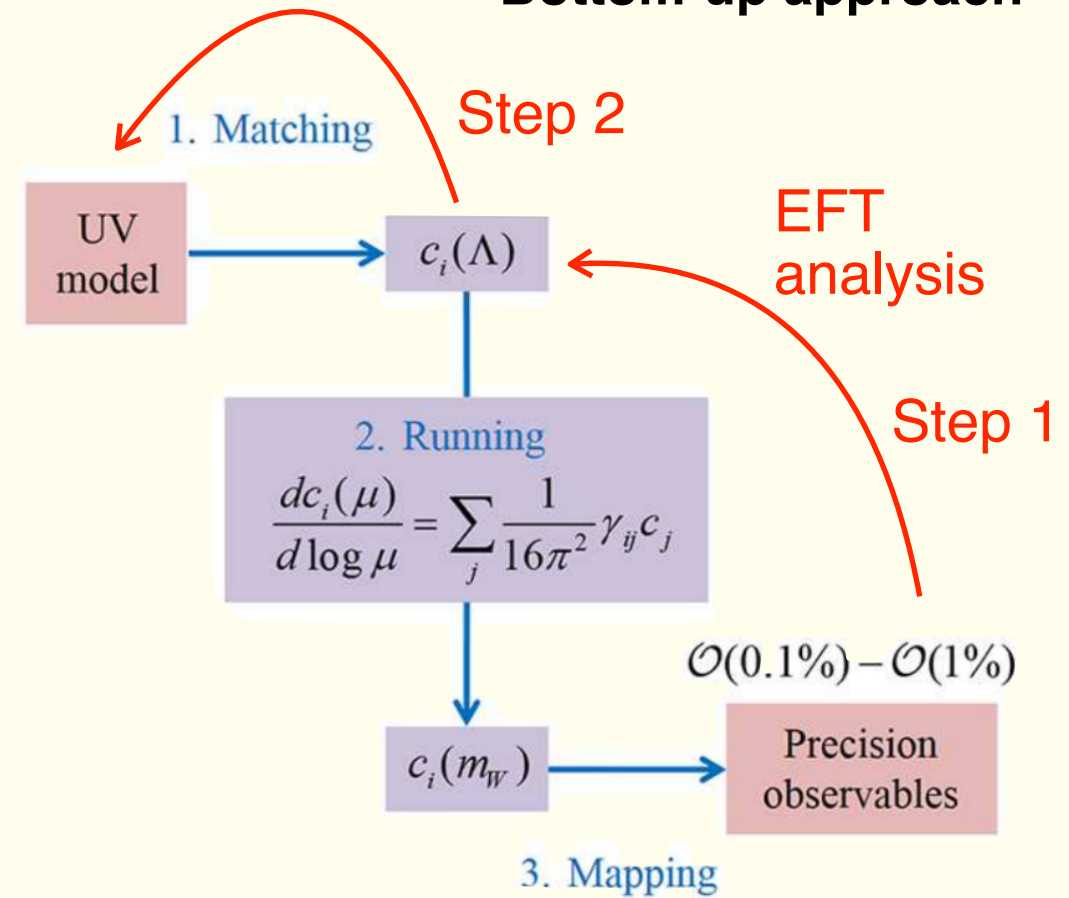
unknown
d.o.f

unknown
scale

unknown
Running



Bottom-up approach



Henning, Lu, Murayama,
1412.1837

Example: NP and effective field theory

Assumptions:

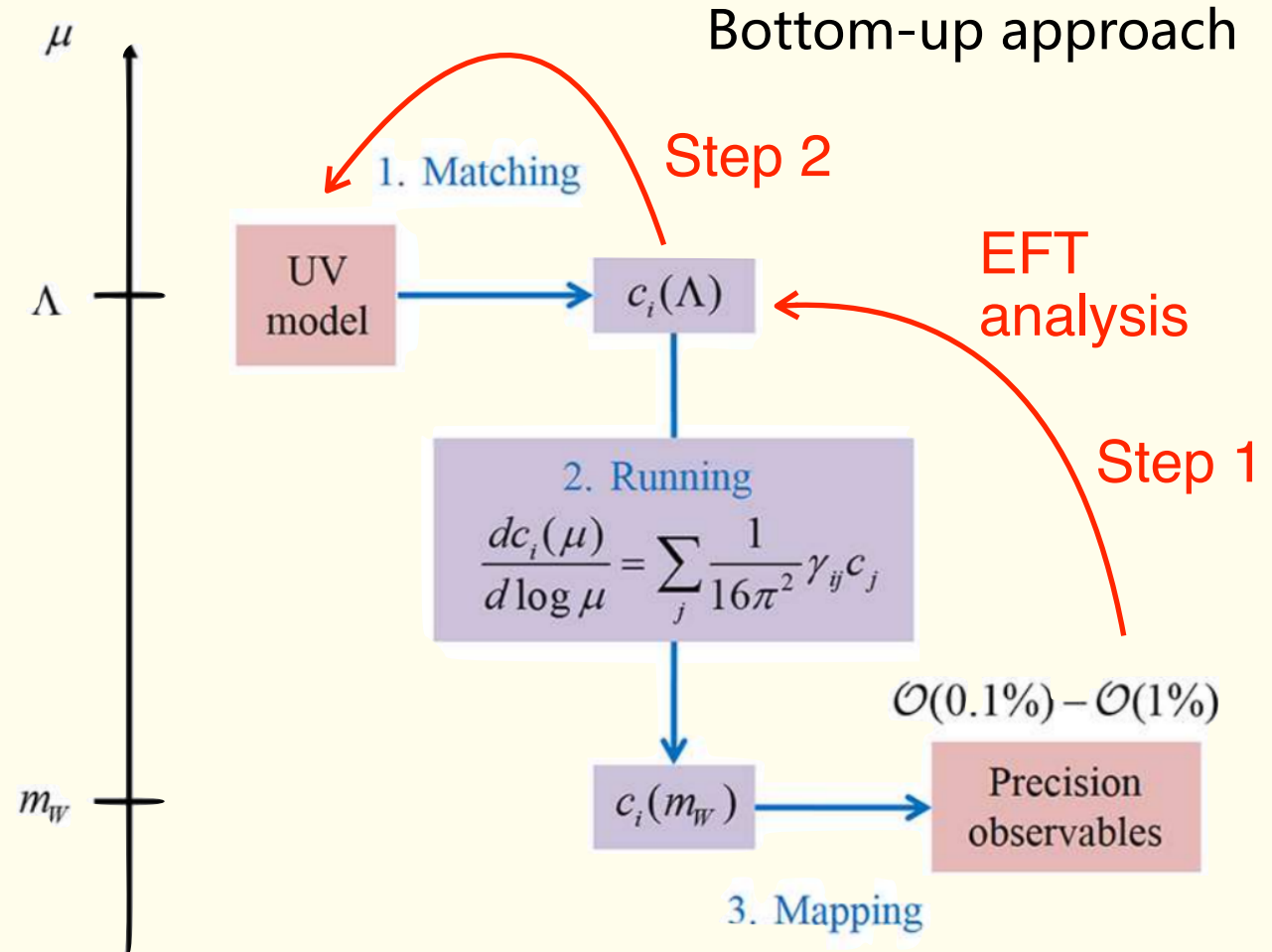
one and only one NP scale

SM running effects

Independent operator sets

{	dim - 5	$\frac{(LH)^2}{\Lambda}$
	dim - 6	59
	dim - 7	948 + 594
	⋮	

L. Lehman 1410.4193;
 Y. Liao .etc. 1607.07309;
 H.L.Li etc. 2005.00008
 B. Henning etc. 1512.03433,
 H.L. Li etc 2012.09188;



Henning, Lu, Murayama,
1412.1837

Inverse problem in SM EFT

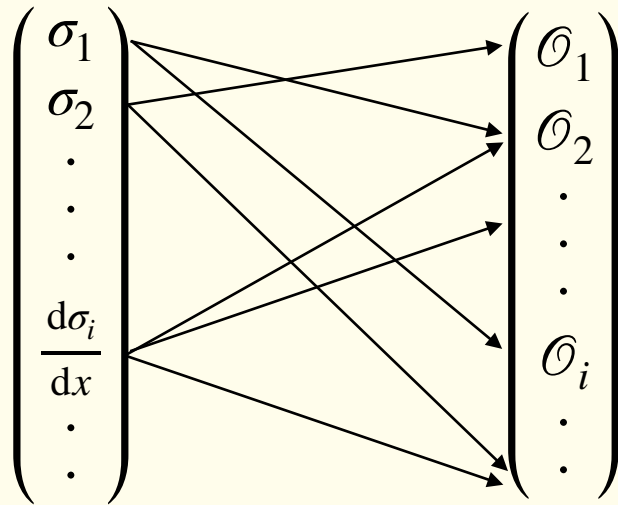
SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)} O_i^{(6)}}{\Lambda^2}$$

Measurements

$$O_n^{\text{EXP}} - O_n^{\text{SM}} = \sum_i \frac{a_{n,i}^{(6)}(\mu) c_i^{(6)}(\mu)}{\Lambda^2}$$

59 independent operators at dim-6 (flavor blind)



- 1) Which **operator basis**? Field and mass redefinitions?
- 2) **Linear** (interference) or **Quadratic** (operator squared)?
- 3) RG running effect?
- 4) QCD corrections? Operator mixings?

\mathcal{O}_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$
$\mathcal{O}_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{l}_p \gamma^\mu l_r)$	$\mathcal{O}_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{e}_p \gamma^\mu e_r)$	$\mathcal{O}_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{q}_p \gamma^\mu q_r)$
$\mathcal{O}_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi) (\bar{q}_p \tau^I \gamma^\mu q_r)$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{u}_p \gamma^\mu u_r)$
$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi) (\bar{d}_p \gamma^\mu d_r)$	$\mathcal{O}_{\varphi ud}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi) (\bar{u}_p \gamma^\mu d_r)$
\mathcal{O}_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	\mathcal{O}_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$
\mathcal{O}_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	\mathcal{O}_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$
\mathcal{O}_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	\mathcal{O}_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$

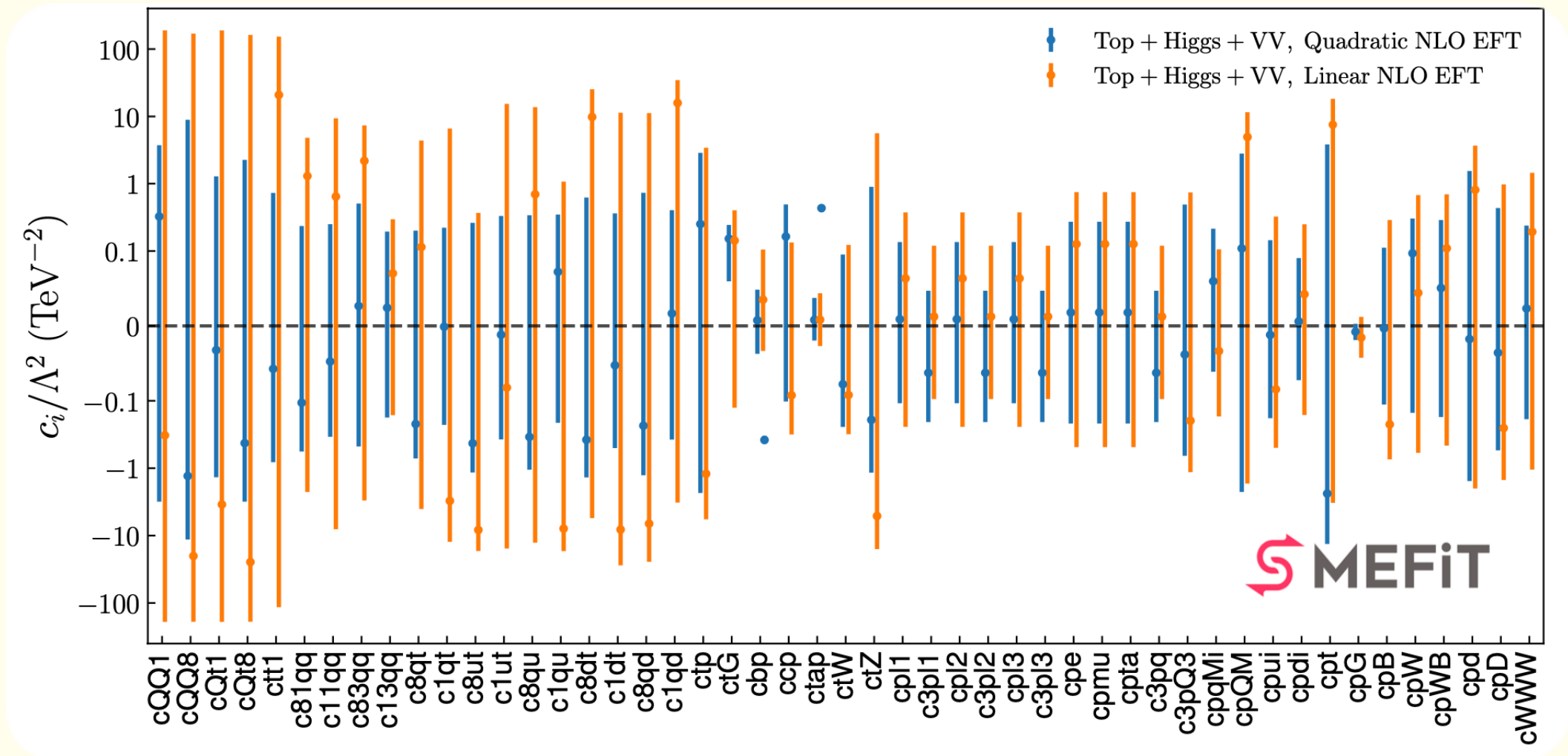
WARSAW basis

HISZ basis $(\mathcal{O}_{\varphi l}^{(1)}, \mathcal{O}_{\varphi l}^{(3)})$ $(\mathcal{O}_W^{\text{HISZ}}, \mathcal{O}_B^{\text{HISZ}})$

SILH basis $(\mathcal{O}_{\varphi W}, \mathcal{O}_{\varphi WB}, \mathcal{O}_{\varphi\Box}, \mathcal{O}_{\varphi D}, \mathcal{O}_{\varphi l}^{(1)}, \mathcal{O}_{\varphi l}^{(3)})$
 $(\mathcal{O}_W^{\text{HISZ}}, \mathcal{O}_B^{\text{HISZ}}, \mathcal{O}_{2W}, \mathcal{O}_{2B}, \mathcal{O}_W^{\text{SILH}}, \mathcal{O}_B^{\text{SILH}})$

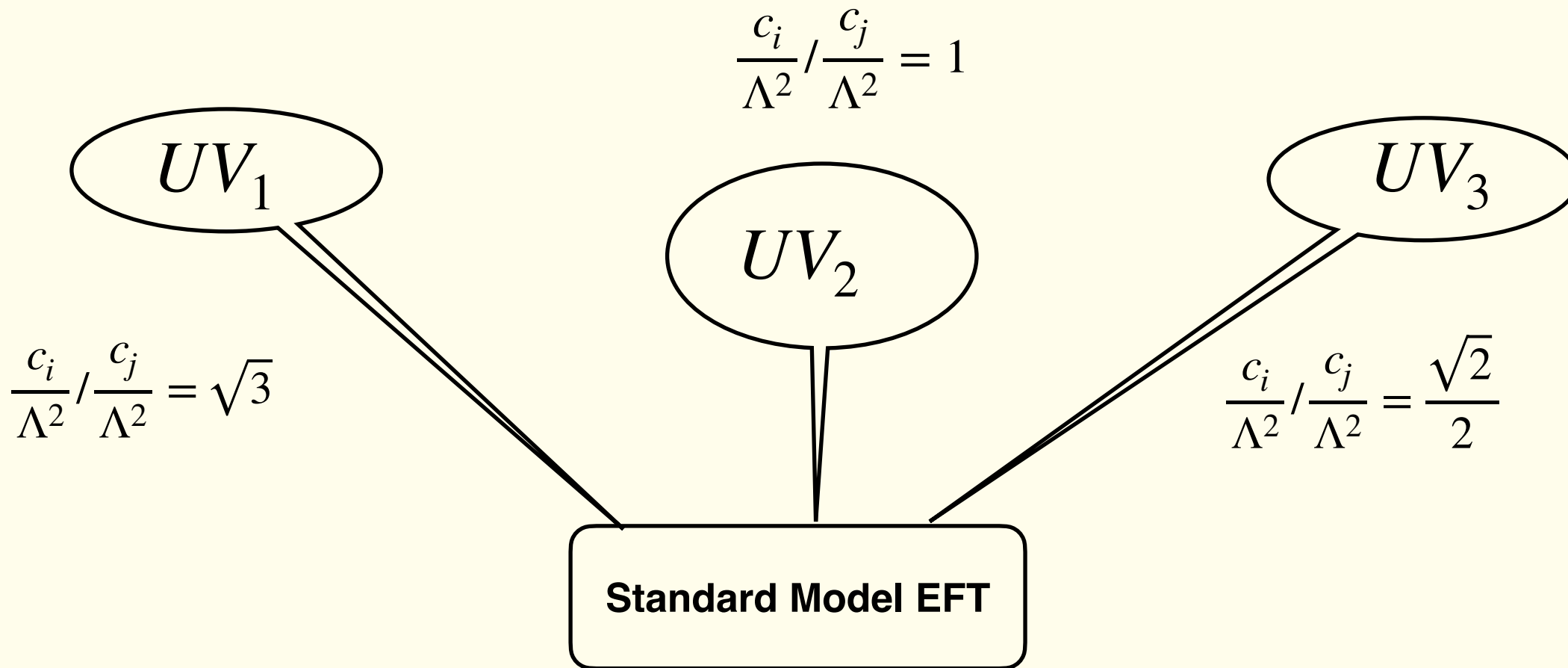
Equivalent by Equations of Motion

Global fit to the LHC data in dim-6 SMEFT



Hard to probe or rule out new physics, any other better way?

Operator correlation shedding lights on NP



Interference effects:

operator correlations independent of the NP scale as long as it is low enough to yield sizable quantum effects

Operator correlation: pictorial illustration

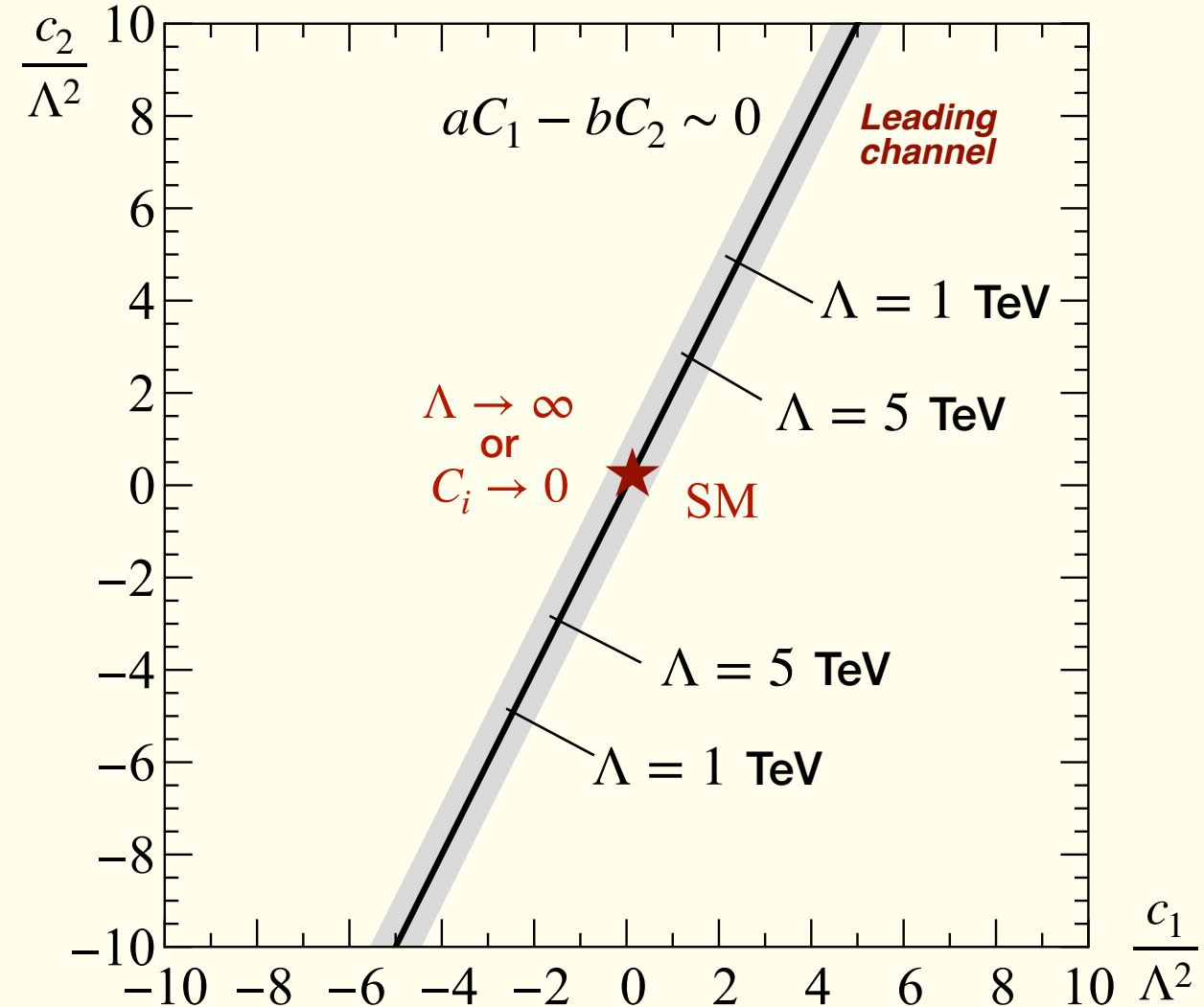
1) Find the correlated operators, e.g. O_1 and O_2 , in the *leading channel* (obs-1) of NP searches

2) Evaluate the operator correction

$$\begin{aligned} \delta\sigma^{\text{obs}_1} &\equiv \sigma^{\text{obs}_1}(O_1, O_2) - \sigma_{\text{SM}}^{\text{obs}_1} \\ &= (aC_1 - bC_2)/\Lambda^2 \end{aligned}$$

3) A blind direction is established if there is no deviation from the SM theory prediction.

$$aC_1 - bC_2 \sim 0$$



Operator correlation: pictorial illustration

1) Find the correlated operators, e.g. O_1 and O_2 , in the leading channel (obs-1) of NP searches

2) Evaluate the operator correction

$$\begin{aligned}\delta\sigma^{\text{obs}_1} &\equiv \sigma^{\text{obs}_1}(O_1, O_2) - \sigma_{\text{SM}}^{\text{obs}_1} \\ &= (aC_1 - bC_2)/\Lambda^2\end{aligned}$$

3) A blind direction is established if there is no deviation from the SM theory prediction.

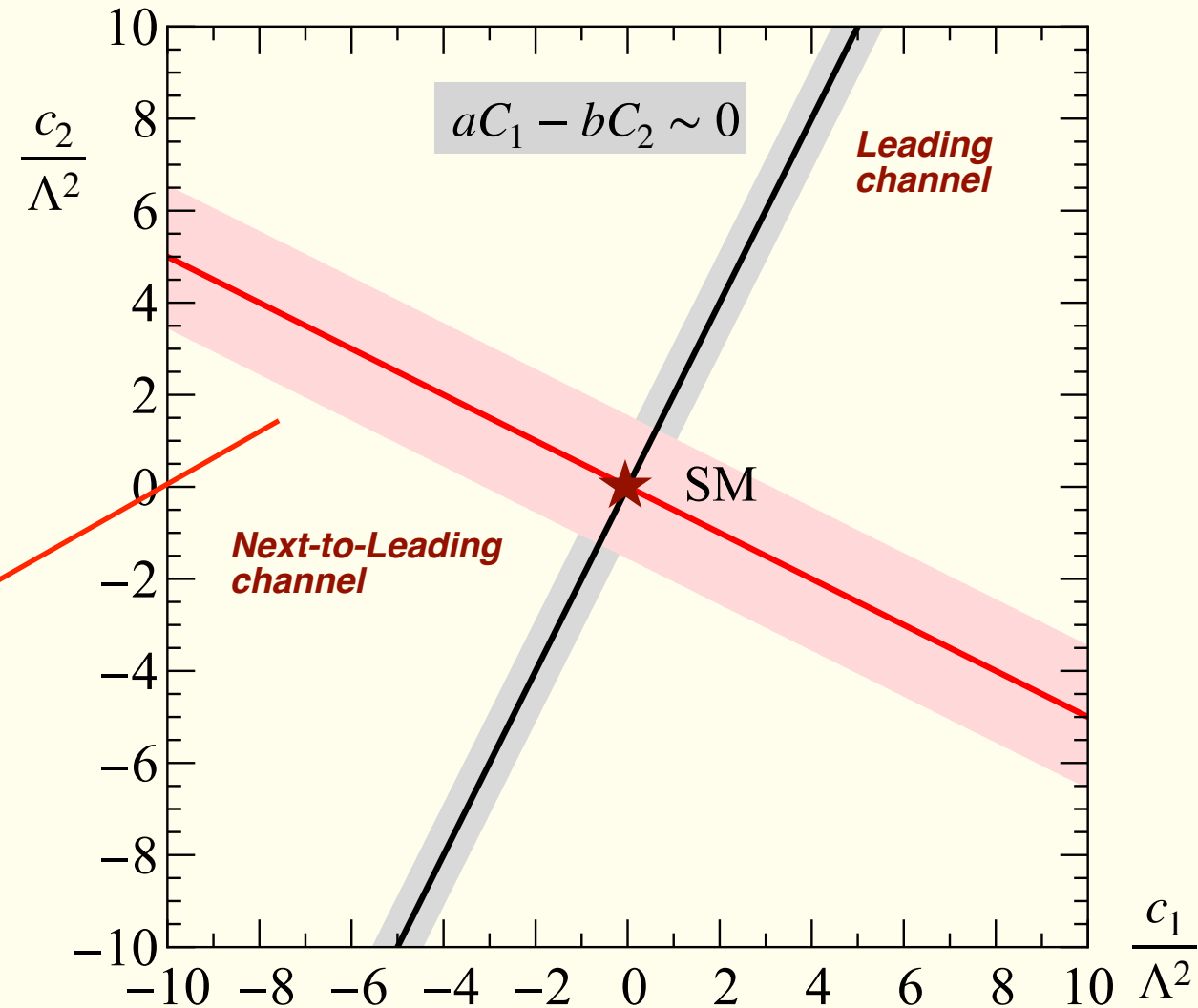
$$aC_1 - bC_2 \sim 0$$

4) Find the **next-to-leading** channel to probe the orthogonal direction.

$$\delta\sigma^{\text{obs}_2} = (mC_1 + nC_2)/\Lambda^2$$

It is now the most efficient channel to probe or rule out new physics.

5) If null results were found again, then the NP is far away from us, or it does not generate the operators.



Operator correlation: pictorial illustration

6) If we are lucky, a deviation was found in the *next-to-leading* channel

$$\delta\sigma^{\text{obs}_1} = \frac{aC_1 - bC_2}{\Lambda^2} = 0$$

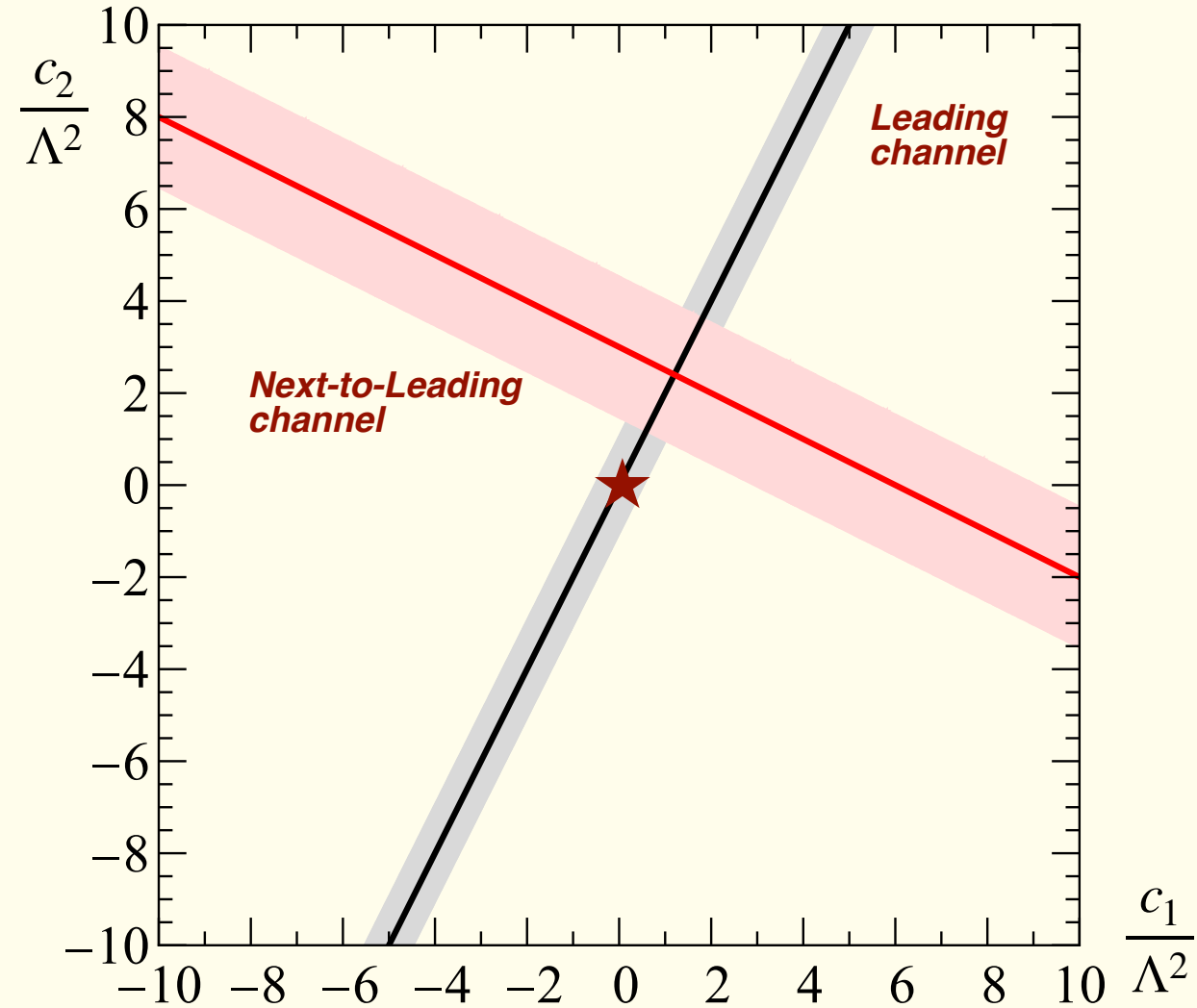
$$\delta\sigma^{\text{obs}_2} = \frac{mC_1 + nC_2}{\Lambda^2} \neq 0$$

then we might find NP and

it is along the direction of

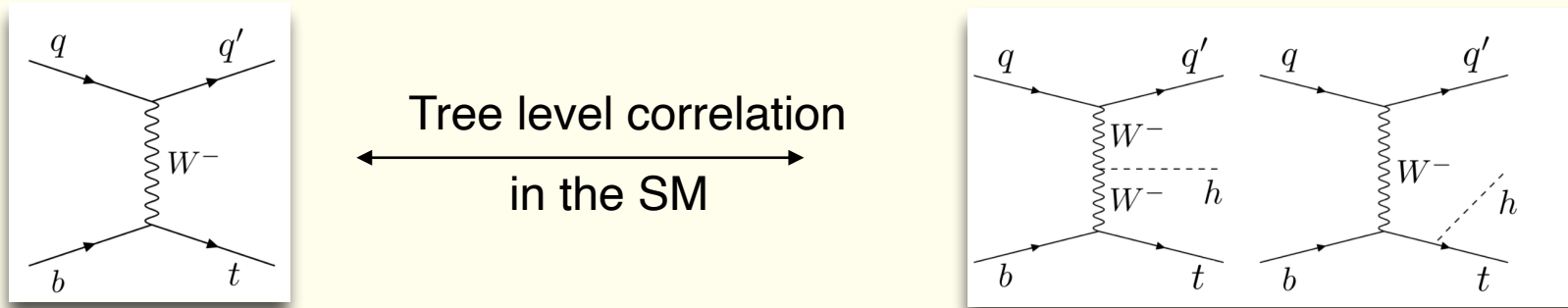
$$\frac{C_1}{C_2} = \frac{b}{a}$$

7) NP=?

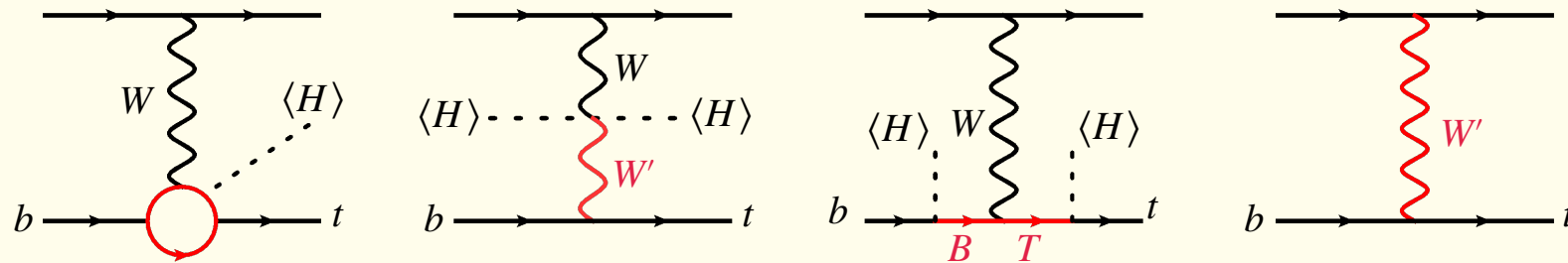


Demo: single top production w/ and w/o a Higgs boson

QHC, Jiang, Zeng
2105.04464



The correlation in the linear analysis in SMEFT



$$O_{uw} = (\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\phi} W_{\mu\nu}^I + h.c.,$$

$$O_{\phi q}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi) (\bar{q}_p \tau^I \gamma^\mu q_r) + h.c.,$$

$$O_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_r) (\bar{q}_s \gamma^\mu q_t) + h.c.,$$

$$O_{qq}^{(3)} = (\bar{q}_p \gamma_\mu \tau^I q_r) (\bar{q}_s \gamma^\mu \tau^I q_t) + h.c..$$

WMD

W-prime or Extra quarks

$$O_{3113}^{(1)} = (\bar{q}_3 \gamma_\mu q_1) (\bar{q}_1 \gamma^\mu q_3) + h.c.,$$

$$O_{3311}^{(3)} = (\bar{q}_3 \gamma_\mu \tau^I q_3) (\bar{q}_1 \gamma^\mu \tau^I q_1) + h.c..$$

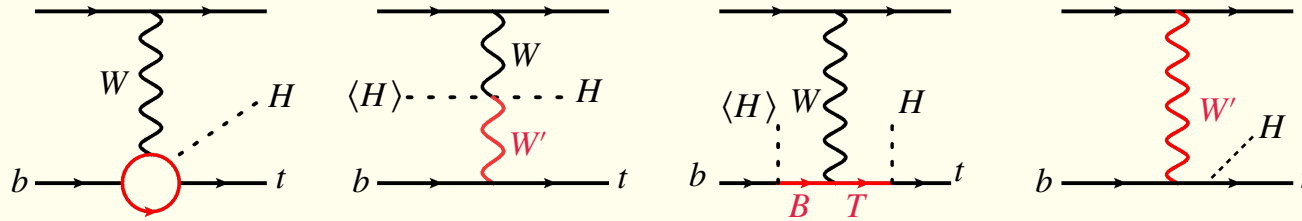
same
interference

$$O_{qq}^{(3)}$$

$$\sigma_t(\Lambda = 1\text{TeV}) = \left[214_{-1}^{+2} - 13_{-1}^{+2} C_{qq}^{(3)} + 16_{-3}^{+2} C_{uW} + 13_{-2}^{+1} C_{\phi q}^{(3)} \right] \text{pb}$$

Demo: single top production w/ and w/o a Higgs boson

Direct correlation induced by the three operators



More operators involved in tHq channel but bounded

Operators

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

$$O_{\phi \square} = (\phi^\dagger \phi) \square (\phi^\dagger \phi)$$

$$O_{u\phi} = (\phi^\dagger \phi) (\bar{q}_p u_r \tilde{\phi}) + h.c.$$

$$O_{\phi W} = \phi^\dagger \phi W_{\mu\nu}^I W^{I\mu\nu}$$

Measurements

EWPT at LEP

$$gg \rightarrow H$$

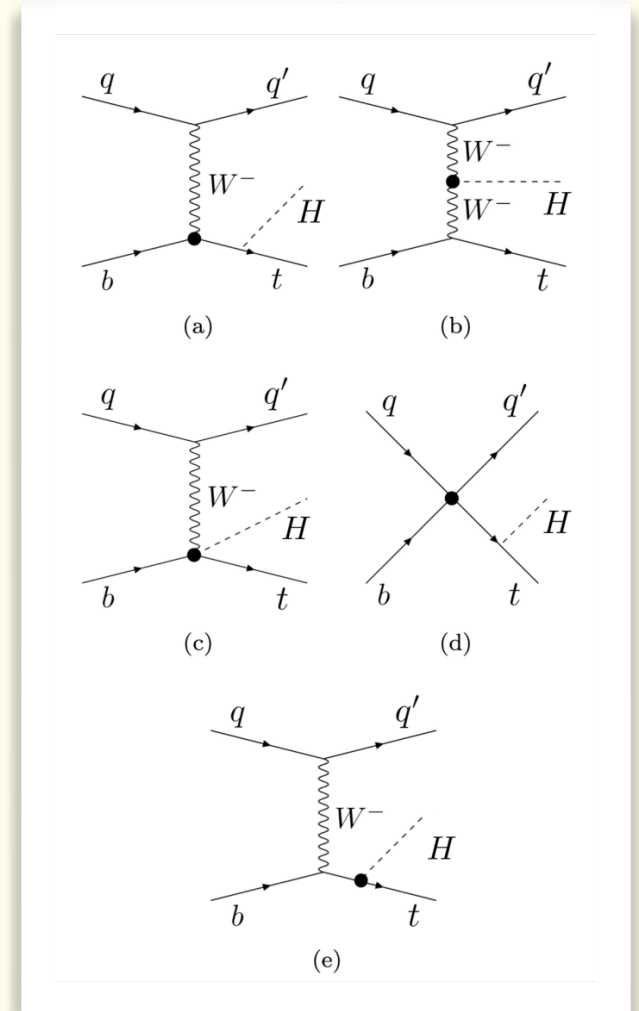
$$H \rightarrow b\bar{b}$$

$$gg \rightarrow H, \quad gg \rightarrow t\bar{t}H$$

$$H \rightarrow ZZ^*/Z\gamma/\gamma\gamma$$

The same three operators' contribution in the tHq channel

$$\sigma_{tHq}(\Lambda = 1\text{TeV}) = \left[70.0 - 11.3_{-0.3}^{+0.6} C_{qq}^{(3)} + 22_{-2}^{+1} C_{uW} - 2.6_{-0.2}^{+0.2} C_{\phi q}^{(3)} \right] \text{fb}$$



Demo: single top production w/ and w/o a Higgs boson

Three operators require at least three independent measurements; fortunately, single-top production provides richer info than expected.

$$\sigma_t = \sigma(tq) + \sigma(\bar{t}q) \longrightarrow O_{qq}^{(3)}, O_{uW}, O_{\varphi q}^{(3)}$$

$$R_t \equiv \frac{\sigma(tq)}{\sigma(\bar{t}q)} \longrightarrow O_{qq}^{(3)}, O_{uW}$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \longrightarrow O_{uW}$$

$$\sigma_{tHq} = \left[-95.1 - 44.0 \times \frac{\sigma_{t+\bar{t}}}{\sigma_{t+\bar{t}}^{\text{SM}}} - 266.0 \times \frac{A_{\text{FB}}}{A_{\text{FB}}^{\text{SM}}} + 479.4 \times \frac{R_t}{R_t^{\text{SM}}} \right] \text{ fb}$$

Current

$$\sigma_{tHq} = \left[106.8 \pm 64.8 \right] \text{ fb}$$

HL-LHC

$$\sigma_{tHq} = \left[74.3 \pm 45.4 \right] \text{ fb}$$

The relation serves for checking the consistency of SMEFT.

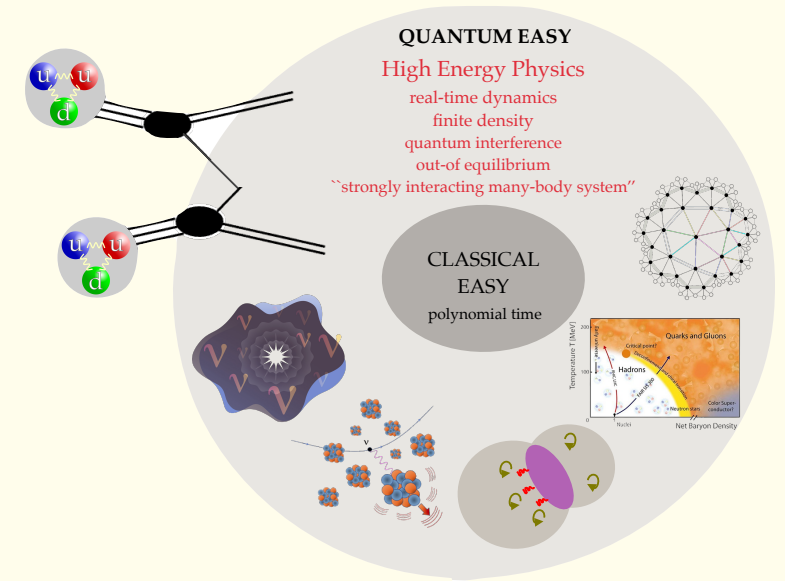
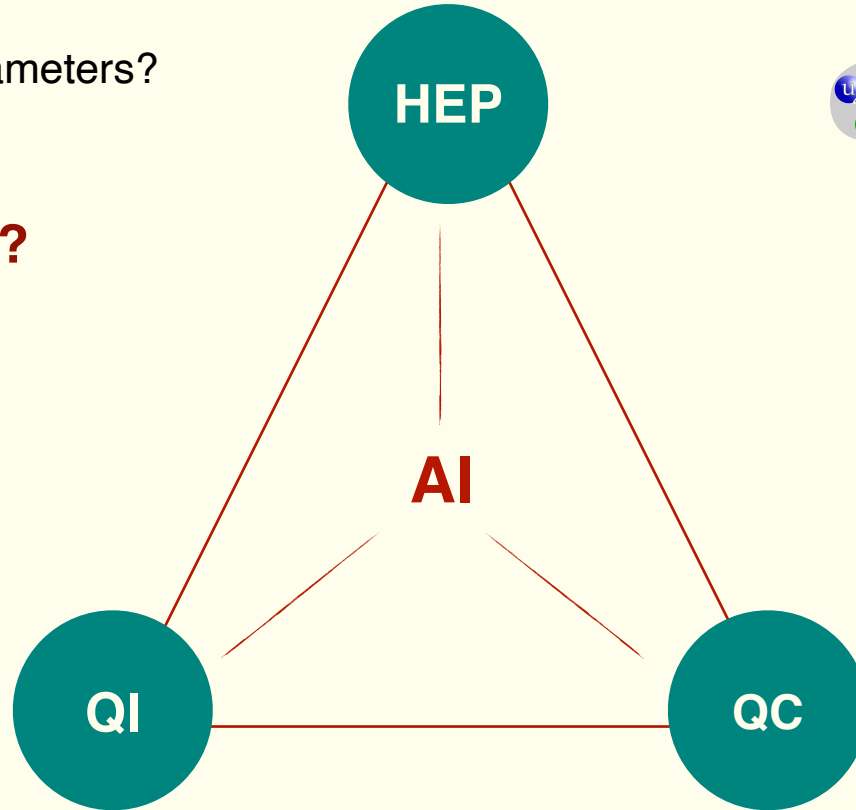
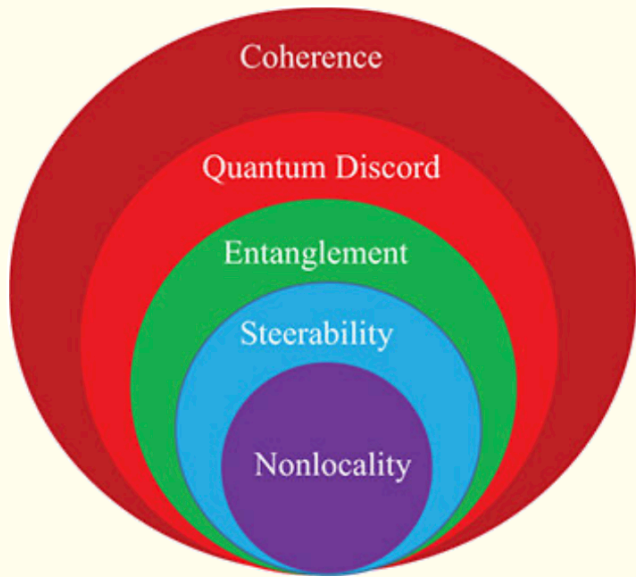
When HEP embraces Quantum Information, Quantum Computation, and Artificial Intelligence

HEP, Quantum informaton, and Quantum Computation

Symmetry determines the interaction form but not the strength.

Why our mother Universe chooses such a symmetry?
Why 3 generations?
Any good reason for the SM parameters?

Can symmetry emerge from entropy extremum conditions?



Problems in HEP that are beyond classical easy but are "QUANTUM EASY"

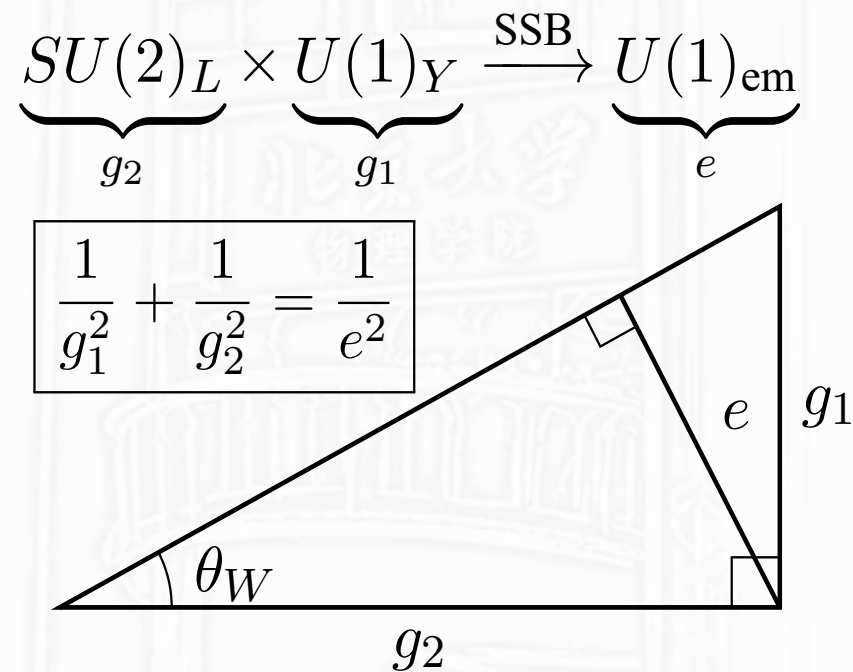
Entanglement measurements at colliders

粒子物理标准模型中的自由参数

规范对称性 G 体现为标准模型 Lagrangian 中的自由耦合常数 g_G ($\mathcal{L}_I = \mathcal{L}_I(g_G)$)。

相互作用理论 ($\mathcal{L}_I = \mathcal{L}_I(g_G)$)

$$\left\{ \begin{array}{l} \text{算符形式: } \mathcal{L}_I(g_G) = \sum_n \frac{c_n(g_G)}{\Lambda^n} \hat{\mathcal{O}}_n \\ \text{由 } G \text{ 约束 } (\hat{\mathcal{O}} \rightarrow g^{-1} \hat{\mathcal{O}} g, g \in G) \\ \text{具体数值: } c_n(g_G) \text{ 由实验输入无先验倾向} \end{array} \right.$$



量子场论框架无法自洽给出参数数值

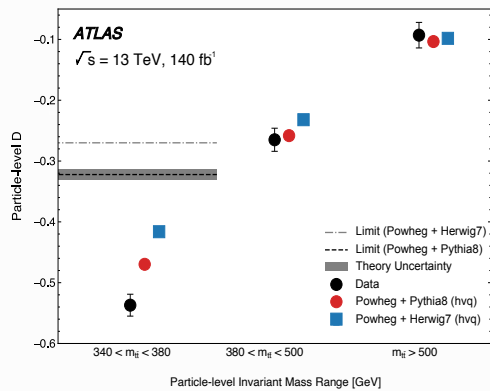
寻找超越量子场论的新范式 (量子信息)

$$s_W^2 = \frac{g_1^2}{g_1^2 + g_2^2}$$

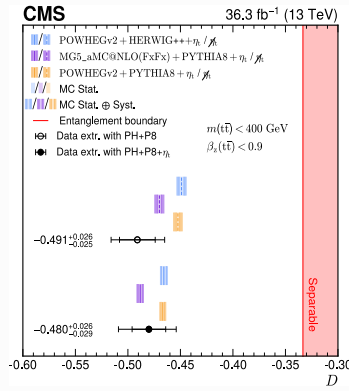
弱混合角决定破缺方向

“万物起源比特”：信息论视角下的高能物理

对撞机实验首次观测到顶夸克对纠缠



Nature 633(2024)



RPP 87(2024)

自旋关联重建末态密度矩阵

(K.Cheng & B.Yan, arXiv:2501.03321)

(K.Cheng & T.Han & M.Low, arXiv:2311.09166, 2407.01672)

$$\rho^{(f)} = \frac{1}{4} (\mathbb{1}_{4 \times 4} + B_i^A (\sigma_i \otimes \mathbb{1}_{2 \times 2}) + B_i^B (\mathbb{1}_{2 \times 2} \otimes \sigma_i) + C_{ij} (\sigma_i \otimes \sigma_j))$$

构造 Bell/CHSH 不等式: $|C_{xx} \pm C_{yy}| \geq \sqrt{2}$

纠缠熵正定性条件约束

(G.Elor et al., arXiv:2402.16956)

(Q.-H Cao & N.Kan & D.Ueda, arXiv:2211.08065)

- 么正性与解析性 $\text{Im}\{\mathcal{M}\} > 0$
- 限制有效算符 Wilson 系数的符号

纠缠熵极值条件演生对称性

(M.-L.Xiao et al., arXiv:2308.08112)

(A.C-Liarta et al., arXiv:2511.04358)

- 全局对称性 (势函数对场量的依赖)
- 规范对称性 (Non-Abelian 联络项)

纠缠熵极值条件确定破缺混合模式

(J.Thaler & S.Trifinopoulos, arXiv:2410.23343)

(Q.Liu & I.Low & Z.Yin, arXiv:2509.18251)

- 味道空间: CKM/PMNS 混合角, CP 相角
- 自旋空间: 弱混合角

1) Positivity bounds in dim-8 operators in SMEFT

Dim-8 operators in $SU(N)$ gauge theory

$$\mathcal{O}_1^{F^4} \quad (F^a F^a)(F^b F^b)$$

$$\mathcal{O}_2^{F^4} \quad (F^a \tilde{F}^a)(F^b \tilde{F}^b)$$

$$\mathcal{O}_3^{F^4} \quad (F^a F^b)(F^a F^b)$$

$$\mathcal{O}_4^{F^4} \quad (F^a \tilde{F}^b)(F^a \tilde{F}^b)$$

$$\mathcal{O}_5^{F^4} \quad d^{abe} d^{cde} (F^a F^b)(F^c F^d)$$

$$\mathcal{O}_6^{F^4} \quad d^{abe} d^{cde} (F^a \tilde{F}^b)(F^c \tilde{F}^d)$$

$$\mathcal{O}_7^{F^4} \quad d^{ace} d^{bde} (F^a F^b)(F^c F^d)$$

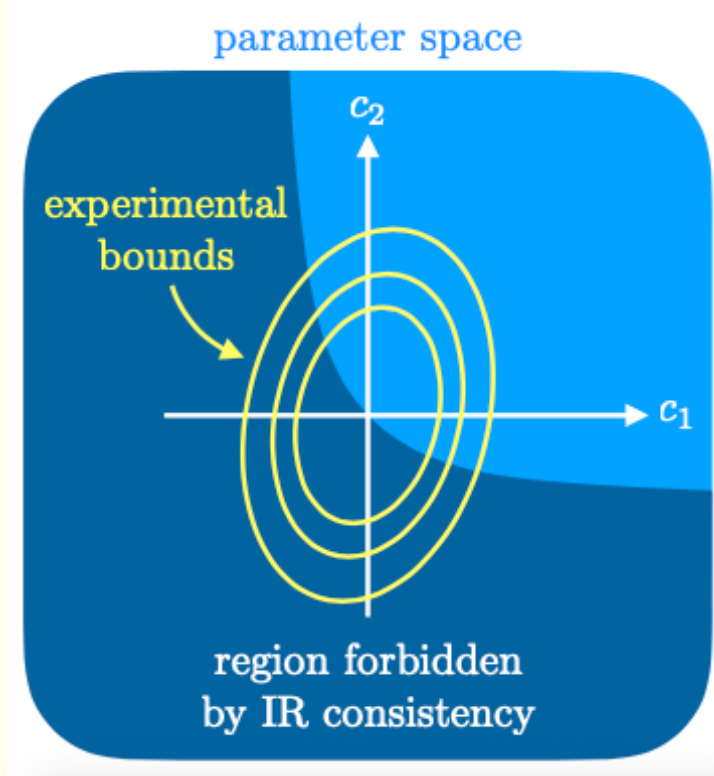
$$\mathcal{O}_8^{F^4} \quad d^{ace} d^{bde} (F^a \tilde{F}^b)(F^c \tilde{F}^d)$$

$$\tilde{\mathcal{O}}_1^{F^4} \quad (F^a F^a)(F^b \tilde{F}^b)$$

$$\tilde{\mathcal{O}}_2^{F^4} \quad (F^a F^b)(F^a \tilde{F}^b)$$

$$\tilde{\mathcal{O}}_3^{F^4} \quad d^{abe} d^{cde} (F^a F^b)(F^c \tilde{F}^d)$$

$$\tilde{\mathcal{O}}_4^{F^4} \quad d^{ace} d^{bde} (F^a F^b)(F^c \tilde{F}^d)$$



Remmen, Rodd
1908.09845

Analyticity

Unitarity+Locality

$$3c_1^{G^4} + 3c_3^{G^4} + c_5^{G^4} > 0$$

$$3c_3^{G^4} + 2c_5^{G^4} > 0$$

$$3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4} > 0$$

$$3c_4^{G^4} + 2c_6^{G^4} > 0$$

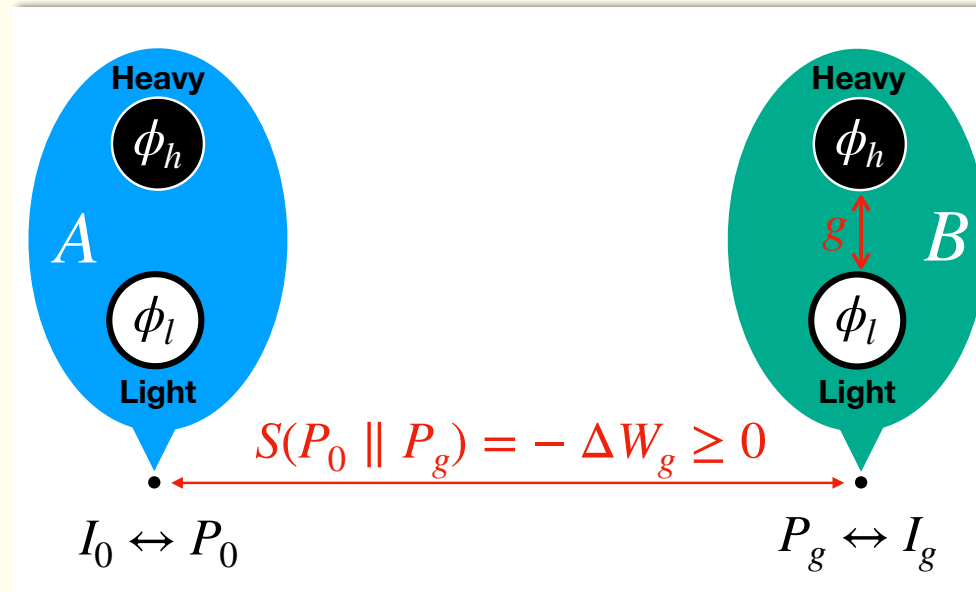
$$(3\tilde{c}_1^{G^4} + 3\tilde{c}_2^{G^4} + \tilde{c}_3^{G^4})^2 < 4(3c_1^{G^4} + 3c_3^{G^4} + c_5^{G^4})(3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4})$$

$$(3\tilde{c}_2^{G^4} + 2\tilde{c}_3^{G^4})^2 < 4(3c_3^{G^4} + 2c_5^{G^4})(3c_4^{G^4} + 2c_6^{G^4}).$$

For SU(3) gauge theory

Positivity constraints from the relative entropy

Defined a **distance** between two different theories in the approach of information theory



QHC, Kan, and Ueda
2201.00931, 2211.08065

I_0 without interaction b/w heavy and light

$I_g = I_0 + g \cdot I_I$ with the interaction

Distance defined by relative entropy

$$S(P_0 \parallel P_g) = \int d[\phi_h] \left(P_0 \ln P_0 - P_0 \ln P_g \right) \geq 0$$

$$P_0 = e^{-I_0/Z_0} \quad P_g = e^{-I_g/Z_g}$$

Positivity bounds on SMEFT $SU(N)$ gauge bosonic operators

- Relative entropy when dim-8 operators are generated by **interaction** b/w **heavy** and **light** fields:

$$S(P_A || P_B) = W_0 - W_g + g \cdot (dW_g/dg)_{g=0} = \int (d^4x)_E \frac{1}{\Lambda^4} \sum_i c_i \mathcal{O}_i \geq 0$$

assume the interaction does not involve higher-derivative terms

- Classical solution of $\partial^\mu F_{\mu\nu}^a + g f^{abc} A^{\mu,b} F_{\mu\nu}^c = 0$: $A_\mu^a = u_1^a \epsilon_{1\mu} w_1 + u_2^a \epsilon_{2\mu} w_2$ with $f^{abc} u_1^a u_2^b = 0$, $\partial_\mu w_1 = l_\mu$, and $\partial_\mu w_2 = k_\mu$

- $U(1)_Y$: $c_1^{B^4} \geq 0$, $c_2^{B^4} \geq 0$, $4c_1^{B^4} c_2^{B^4} \geq (\tilde{c}_1^{B^4})^2$, * l_μ, k_μ : constant vectors
- $SU(2)_L$: $c_1^{W^4} + c_3^{W^4} \geq 0$, $c_2^{W^4} + c_4^{W^4} \geq 0$, $4(c_1^{W^4} + c_3^{W^4})(c_2^{W^4} + c_4^{W^4}) \geq (\tilde{c}_1^{W^4} + \tilde{c}_2^{W^4})^2$,

U(1) and SU(2) bounds are the same as positivity bounds from unitarity and causality

[G.N. Remmen, and N.L. Rodd, arXiv:1908.09845]

- $SU(3)_C$: $2c_1^{G^4} + c_3^{G^4} \geq 0$, $3c_2^{G^4} + 2c_5^{G^4} \geq 0$, $3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4} \geq 0$, $3c_4^{G^4} + 2c_6^{G^4} \geq 0$,
 $4(3c_1^{G^4} + 3c_3^{G^4} + c_5^{G^4})(3c_2^{G^4} + 3c_4^{G^4} + c_6^{G^4}) \geq (3\tilde{c}_1^{G^4} + 3\tilde{c}_2^{G^4} + \tilde{c}_3^{G^4})^2$
 $4(3c_3^{G^4} + 2c_5^{G^4})(3c_4^{G^4} + 2c_6^{G^4}) \geq (3\tilde{c}_2^{G^4} + 2\tilde{c}_3^{G^4})^2$

SU(3) bounds are stronger than positivity bounds from unitarity and causality

2) Weak mixing angle from Stabilizer Rényi Entropy

Liu, Low, Yin, 2509.18251

The stabilizer Rényi entropy (SRE) of order α quantifies the non-stabilizerness: the magic of any pure state.

$$\Xi_P(|\psi\rangle) = \frac{1}{d} \langle \psi | P | \psi \rangle^2 = \frac{1}{d} \text{Tr}(\rho P)^2$$

The stabilizer α -Rényi entropy of a state $|\psi\rangle$ defined as

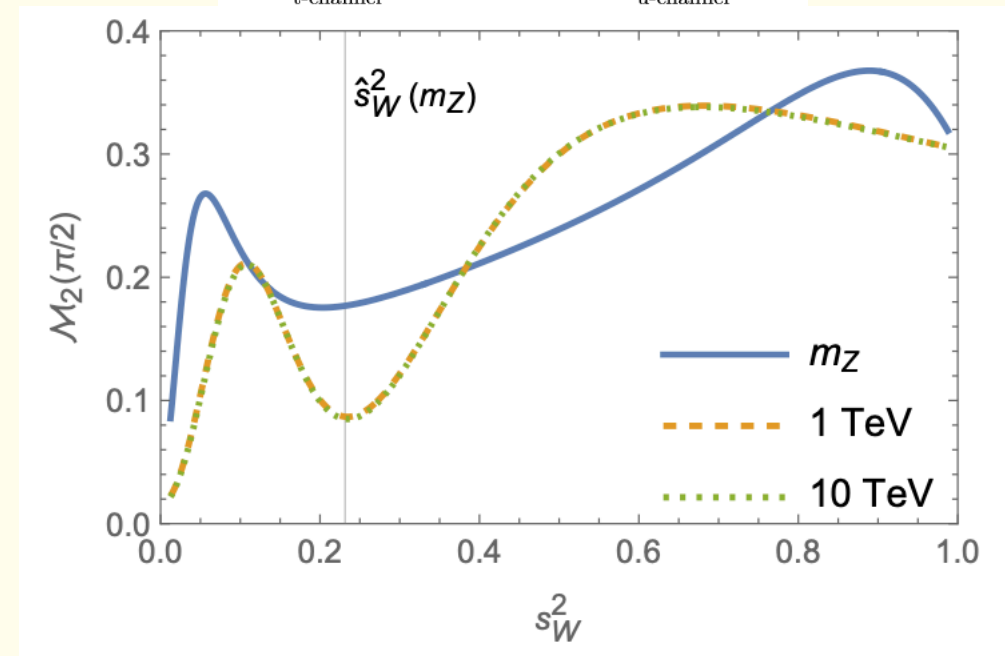
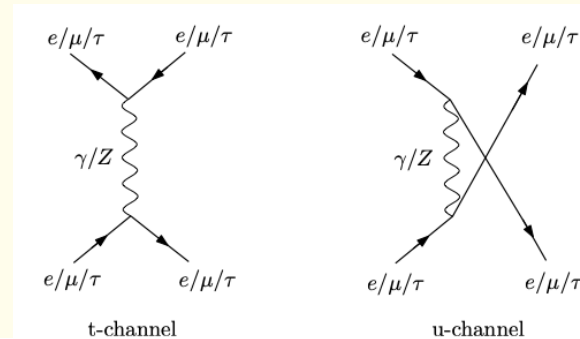
$$\begin{aligned} M_\alpha(|\psi\rangle) &= \frac{1}{1-\alpha} \log \sum_{P \in \mathcal{P}_n} \Xi_P^\alpha(|\psi\rangle) - \log d \\ &= \frac{1}{1-\alpha} \log \sum_{P \in \mathcal{P}_n} \frac{1}{d} \langle \psi | P | \psi \rangle^{2\alpha} \end{aligned}$$

\mathcal{P}_n : the set of n -qubits Pauli strings with phase +1

$$\mathcal{P}_n = \{P_1 \otimes P_2 \otimes \dots \otimes P_n\}$$

$$P_i \in \{I, X, Y, Z\}$$

Magic production in Møller scattering $e^-e^- \rightarrow e^-e^-$ as a function of the weak mixing angle s_W^2

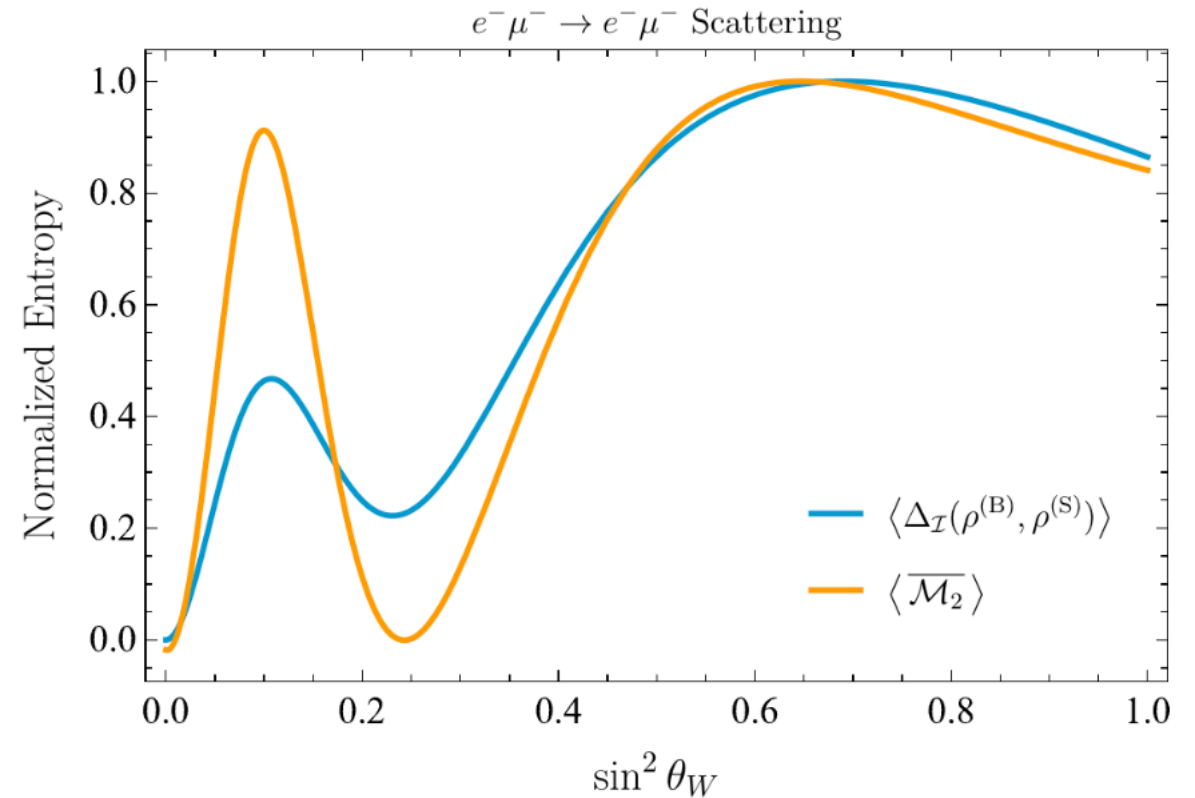
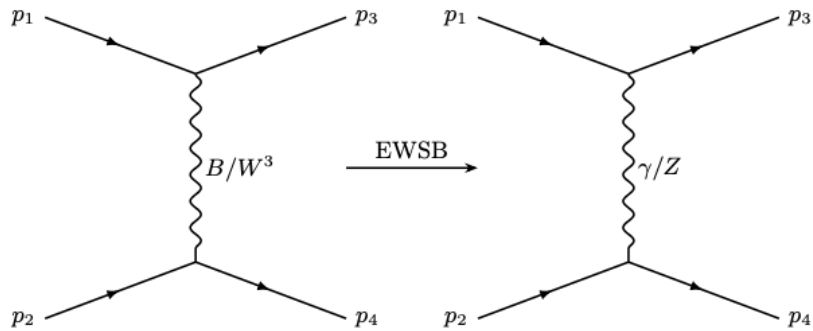


Symmetry Breaking as Quantum Gate: Entropy and Weak Mixing Angle

Qing-Hong Cao,^{1,2,3,*} Yandong Liu,^{4,5,†} Haotian Qi,^{1,‡} Hao Zhang,^{6,7,3,§} and Haoran Zhao^{1,¶}

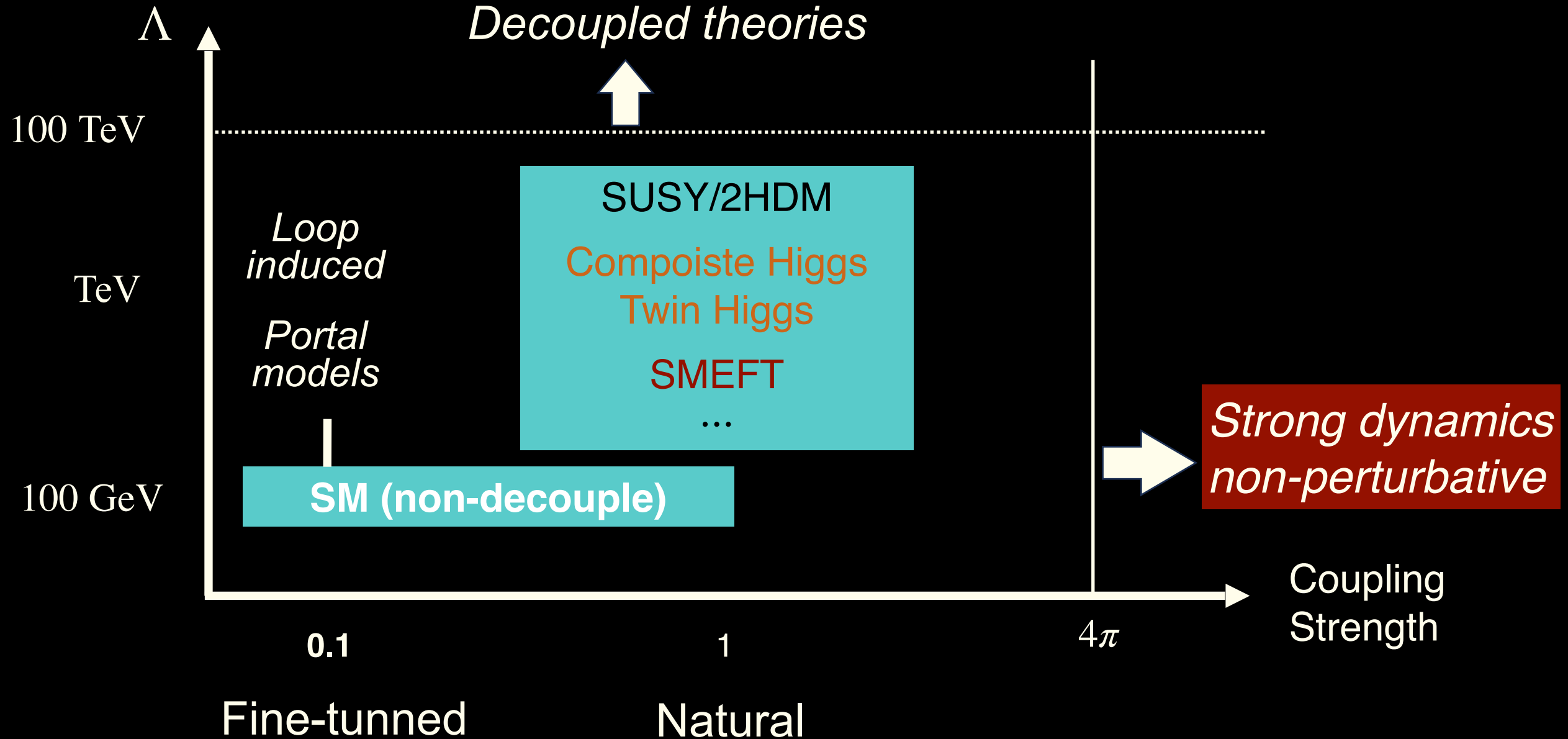
Quantum Rényi mutual information (RMI)

$$\Delta_I(\rho^{(B)}, \rho^{(S)}) = \left| I^{(B)}(A : B) - I^{(S)}(A : B) \right|$$



The fermion mass, generated by Yukawa interaction after EWSB, is a quantum gate Υ .

New Physics beyond Standard Model

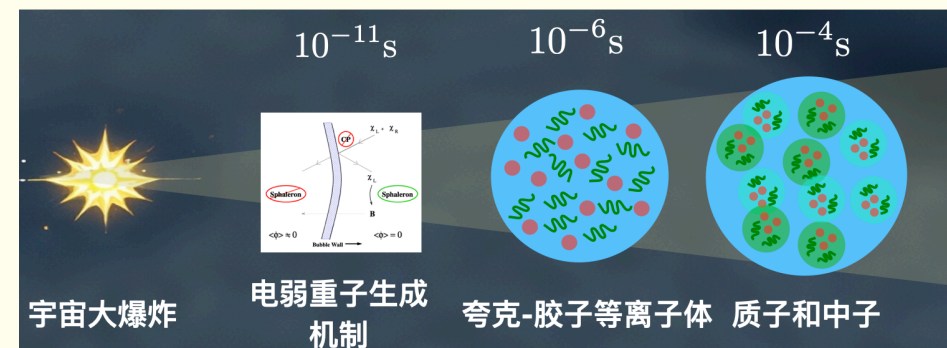


Quantum Simulation

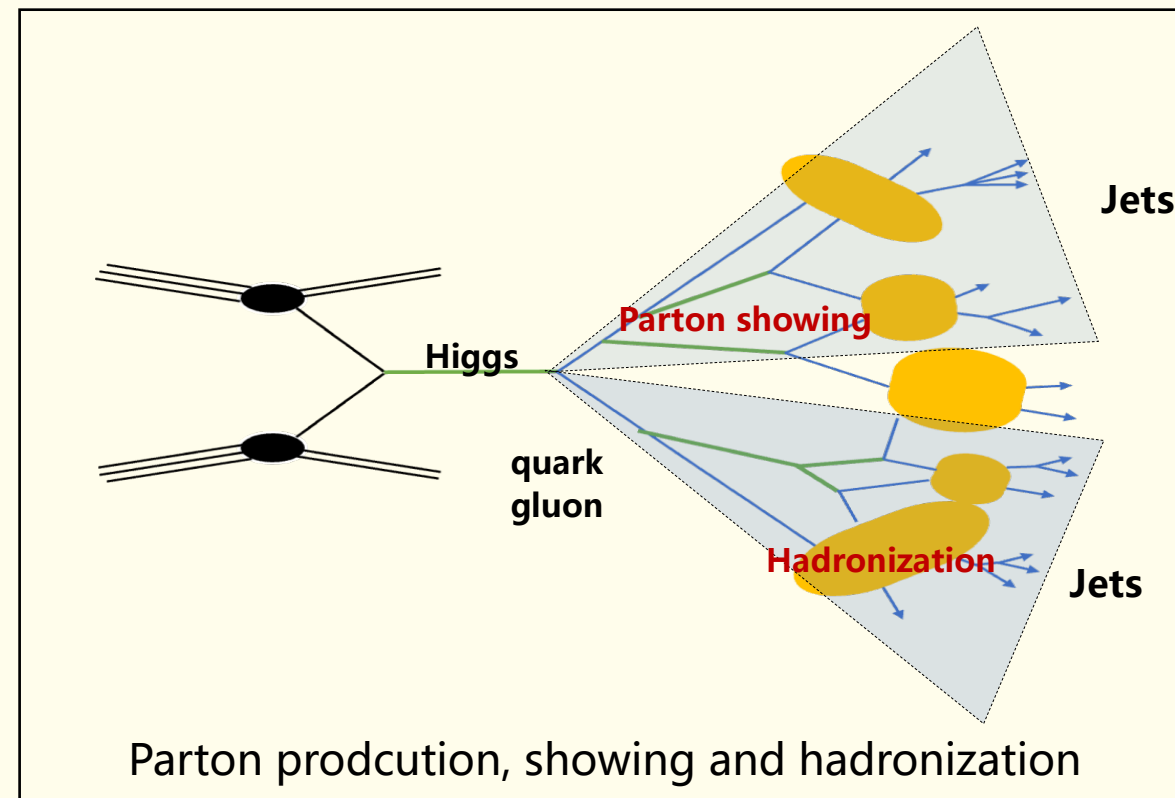
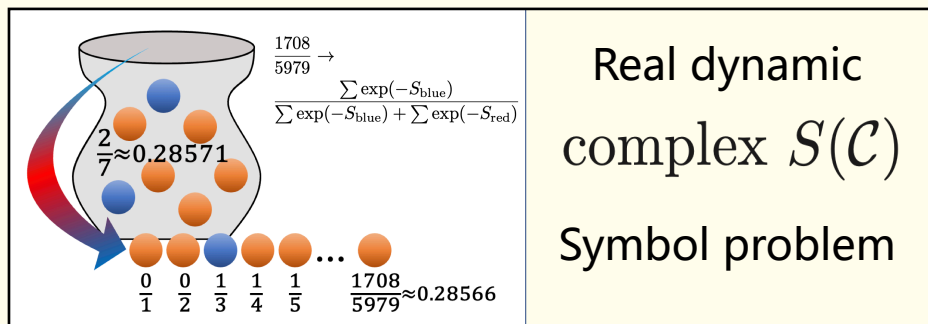
The hadronization mechanism and the baryogenesis mechanism are crucial for understanding the origin of matter in the universe.

The evolution process of partons (quarks/gluons) is an important subject for studying the hadronization mechanism.

Parton evolution is a non-perturbative, real-time dynamical process — a non-equilibrium physical phenomenon — and its description from first principles is difficult to achieve using classical methods.



Classical method: Monte Carlo



Quantum Simulation



Simulating Physics with Computers

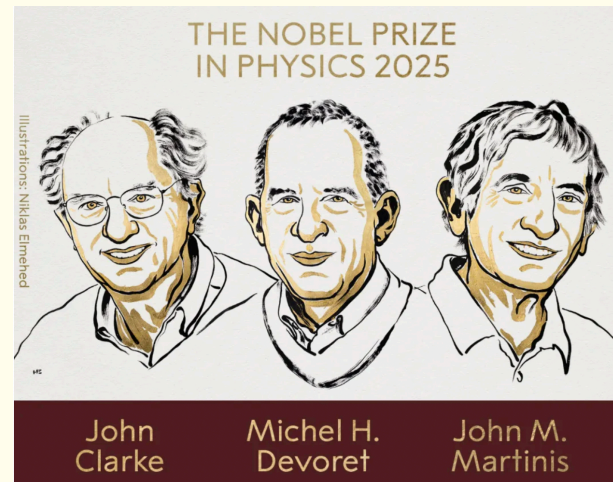
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

...nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy...

量子算法和技术的发展



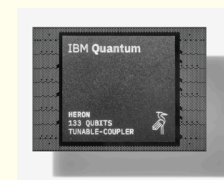
David Deutsch, 通用量子计算机, 1985



Peter Shor, 因数分解量子算法, 1994



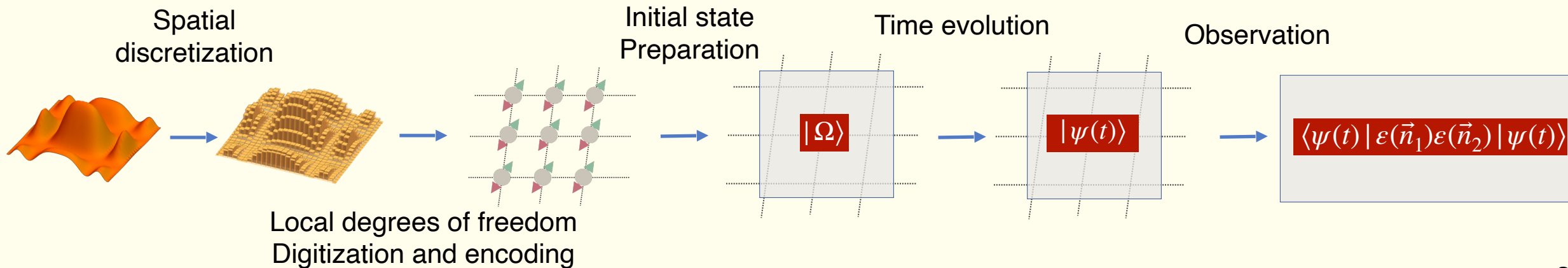
Seth Lloyd, 量子模拟器, 1996



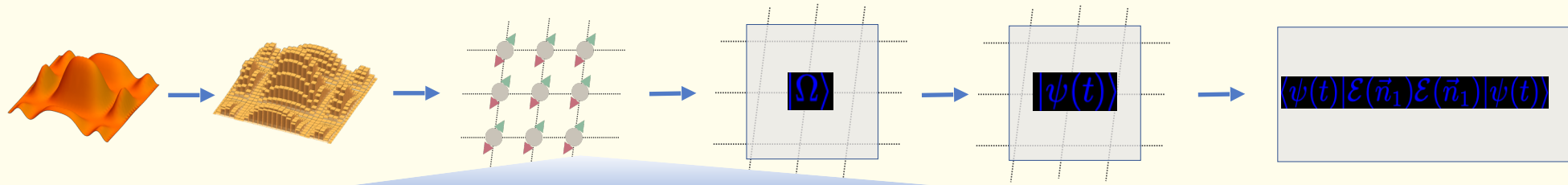
1121 qubits

First-principles calculation of nonequilibrium processes in many-body systems: Quantum computational methods

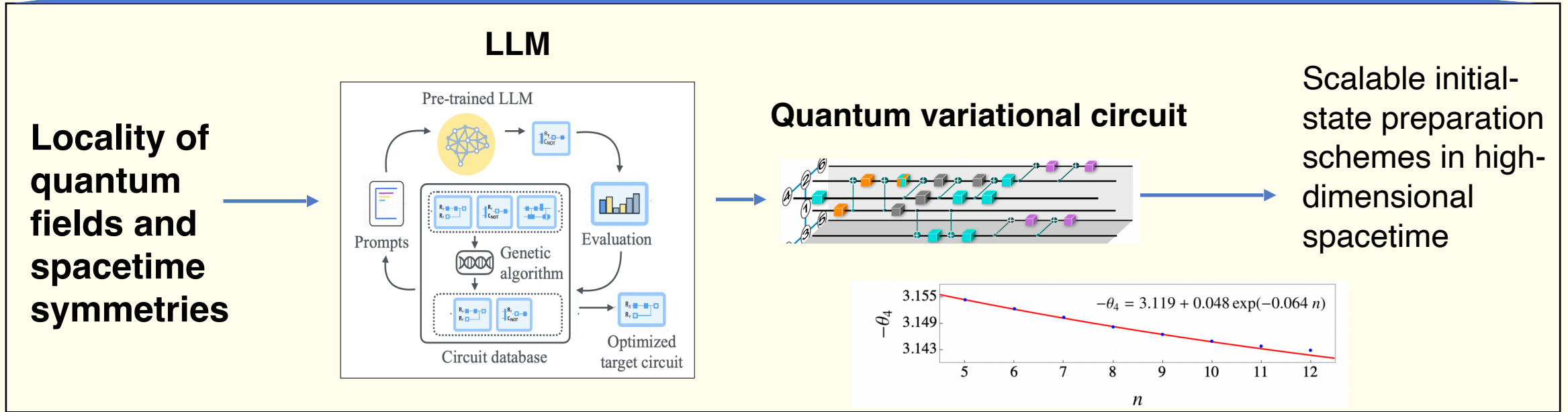
Jordan-Lee-Preskill framework



Scalable initial-state preparation schemes for large systems



Initial-state preparation scheme



QHC, Zong-Yue Hou, Ying-Ying Li, Xiaohui Liu, Zhuo-Yang Song,
 Liang-Qi Zhang, Shutao Zhang, Ke Zhao,
 arXiv:2505.06347

Scalable initial-state preparation schemes for large systems

arXiv > quant-ph > arXiv:2505.06347

Quantum Physics

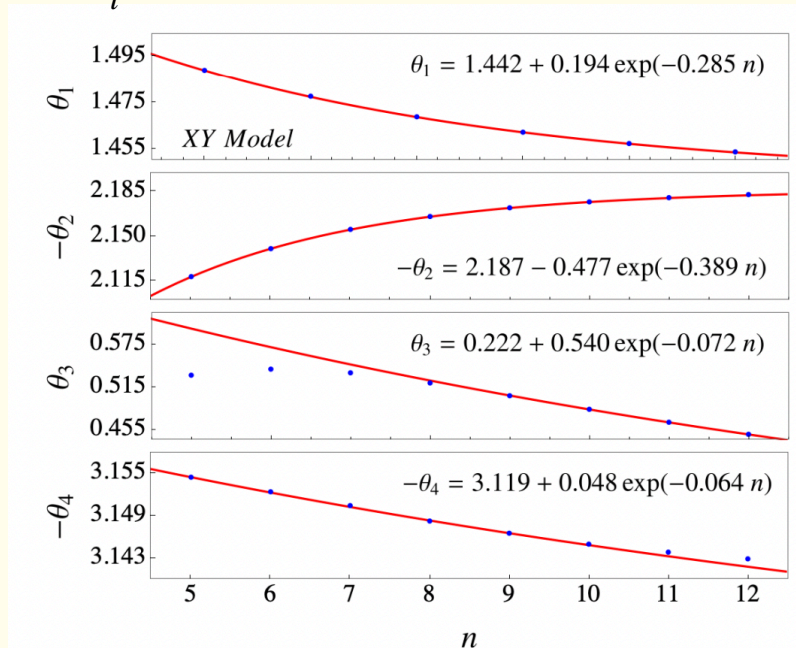
[Submitted on 9 May 2025]

Quantum State Preparation via Large-Language-Model-Driven Evolution

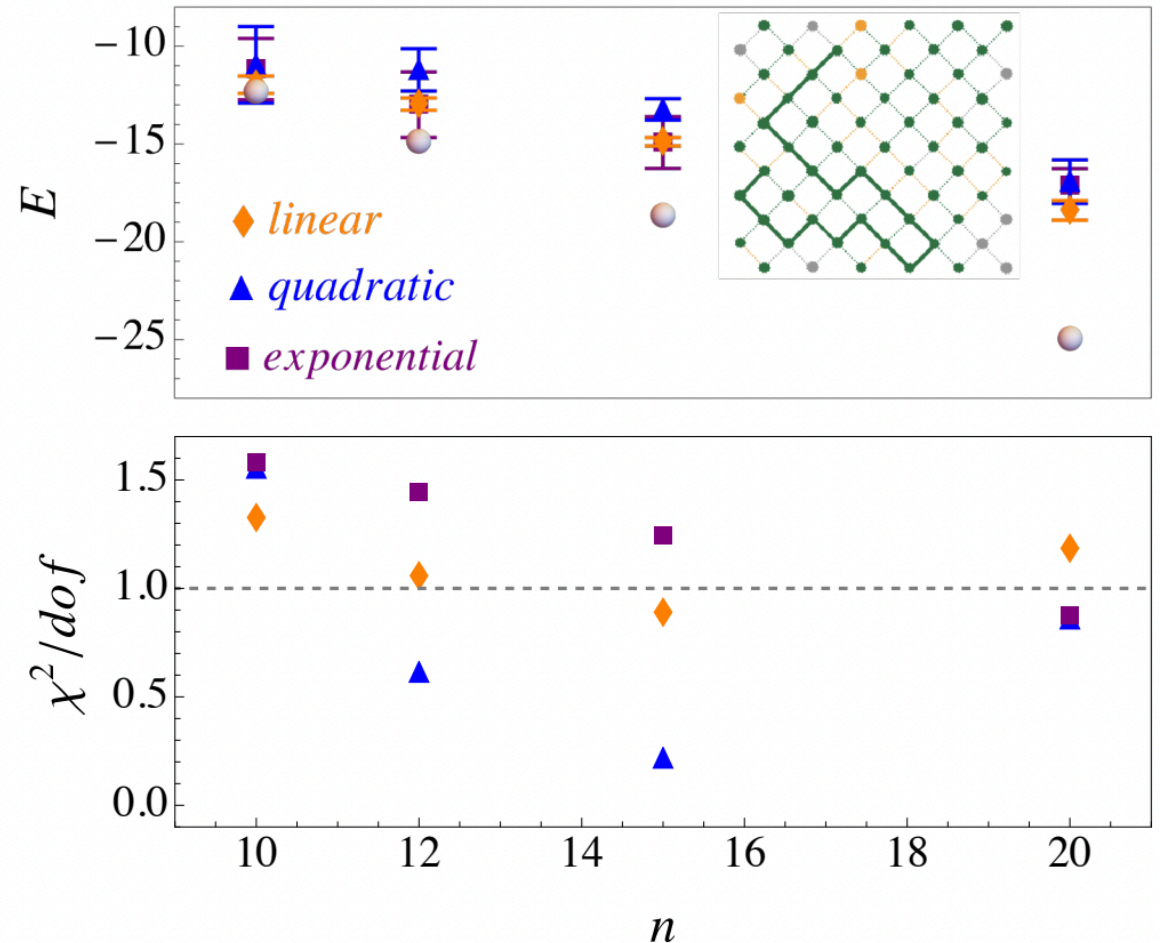
Qing-Hong Cao, Zong-Yue Hou, Ying-Ying Li, Xiaohui Liu, Zhuo-Yang Song, Liang-Qi Zhang, Shutao Zhang, Ke Zhao

1+1d Ising model

$$H_{XY} = \sum_i^{n-1} \left(\frac{1+\gamma}{2} \sigma_i^x \sigma_{i+1}^x + \frac{1-\gamma}{2} \sigma_i^y \sigma_{i+1}^y \right) + g_z \sum_i^n \sigma_i^z$$



Performance at the *Zucongzhi* quantum computer



Scalable initial-state preparation schemes for large systems

2+1d scalar field

$$\mathcal{H} = \frac{1}{2}\Pi^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4$$



Spatial discretization

$$H = a^d \sum_{\mathbf{x}} \frac{1}{2}\Pi^2 - \frac{1}{2}\phi \nabla_a^2 \phi + \frac{1}{2}m_0^2\phi^2 + \frac{\lambda_0}{4!}\phi^4$$



Second quantization of field operators
& Digitization of scalar field (JLP)

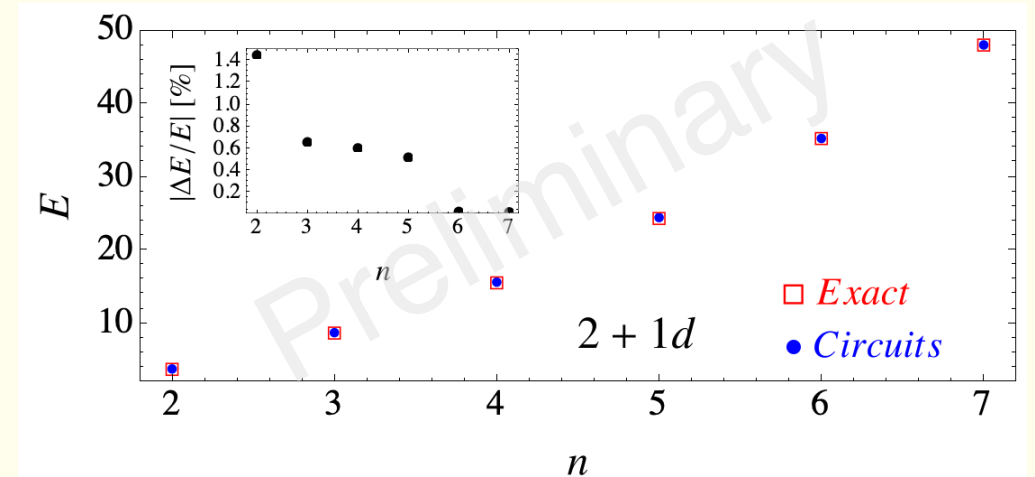
$$\hat{\phi}_i = \sum_{j=0}^{n_Q-1} 2^j \hat{\sigma}_{z,i}^{(j)} \quad [\hat{\phi}(i), \hat{\Pi}(j)] = \frac{i}{a^d} \delta_{i,j} \hat{I}$$

the operator representation of the canonical momentum obtained through the quantum Fourier transform

Interaction term ϕ^3

	depth	energy	parameter number	could extrapolate
IdeaSearch	24	3.5	3	True
adiabatic	72	3.5	6	False

The LLM-generated circuit has better depth, number of parameters, and extrapolability compared to the adiabatic circuit ansatz.



A new method of digitizing the scalar field

2+1d scalar field

$$\mathcal{H} = \frac{1}{2}\Pi^2 + \frac{1}{2}(\nabla\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4$$



Spatial discretization

$$H = a^d \sum_{\mathbf{x}} \frac{1}{2}\Pi^2 - \frac{1}{2}\phi \nabla_a^2 \phi + \frac{1}{2}m_0^2\phi^2 + \frac{\lambda_0}{4!}\phi^4$$



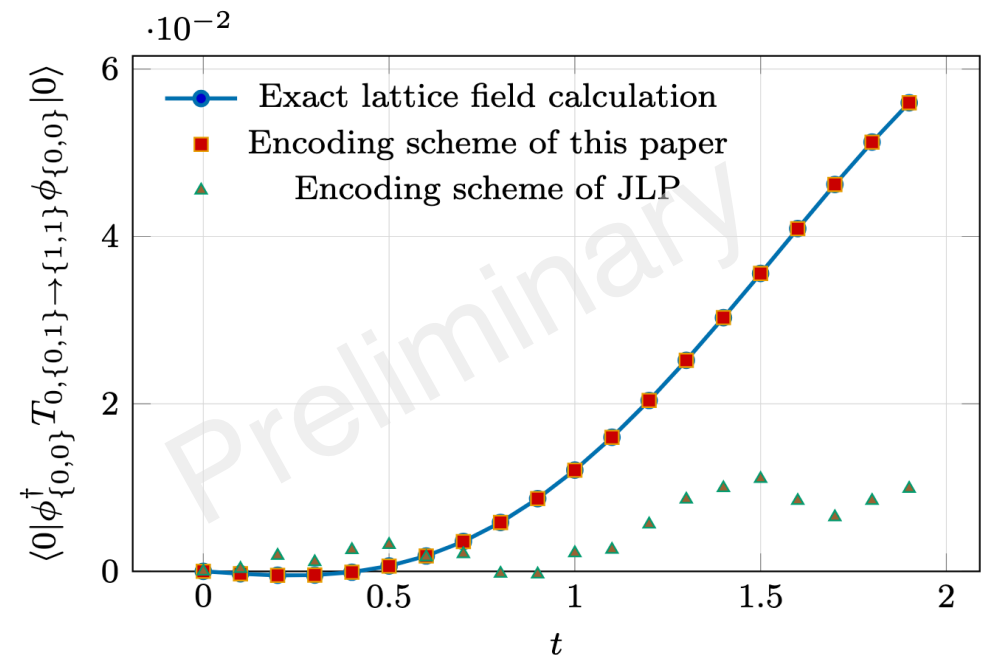
Second quantization of field operators
& Digitization of scalar field (JLP)

$$\hat{\phi}_i = \sum_{j=0}^{n_Q-1} 2^j \hat{\sigma}_{z,i}^{(j)} \quad [\hat{\phi}(i), \hat{\Pi}(j)] = \frac{i}{a^d} \delta_{i,j} \hat{I}$$

the operator representation of the canonical momentum obtained through the quantum Fourier transform

Truncations in the occupation number representation

$$\tilde{a} = \sum_{n=1}^{2^{n_Q}-1} \sqrt{n} |n-1\rangle \langle n|, \quad \tilde{a}^\dagger = \sum_{n=1}^{2^{n_Q}-1} \sqrt{n} |n\rangle \langle n-1|.$$



When HEP embraces Quantum Information, Quantum Computation, and **Artificial Intelligence**

LLM驱动搜索与生成

FunSearch

DeepMind : Nature 2024

LLM + 进化搜索 -> 发现新数学定理

Cap set问题: 超越数十年人类最优解



AlphaProof

DeepMind : 2024 IMO

RL引导证明搜索 -> IMO银牌 (28/42)

Problem 6: 仅5/609人类选手解出



Test-Time Compute Scaling

UC Berkeley : 2024

小模型 + 推理搜索 > 大模型 + 直接输

o1/o3/o4范式的理论基础



o3 on ARC-AGI

OpenAI : December 2024

87.5% (高算力) vs 人类基线85%

但每道题花费数千美元

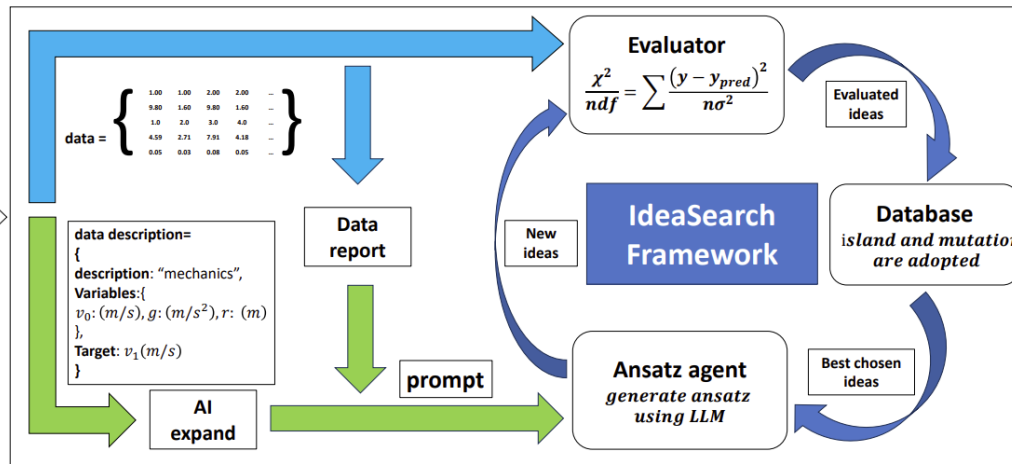
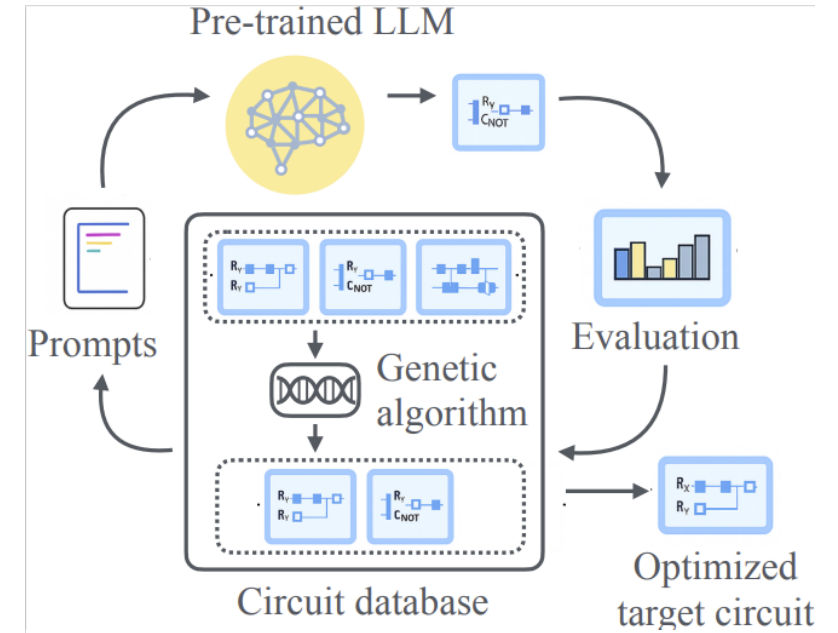
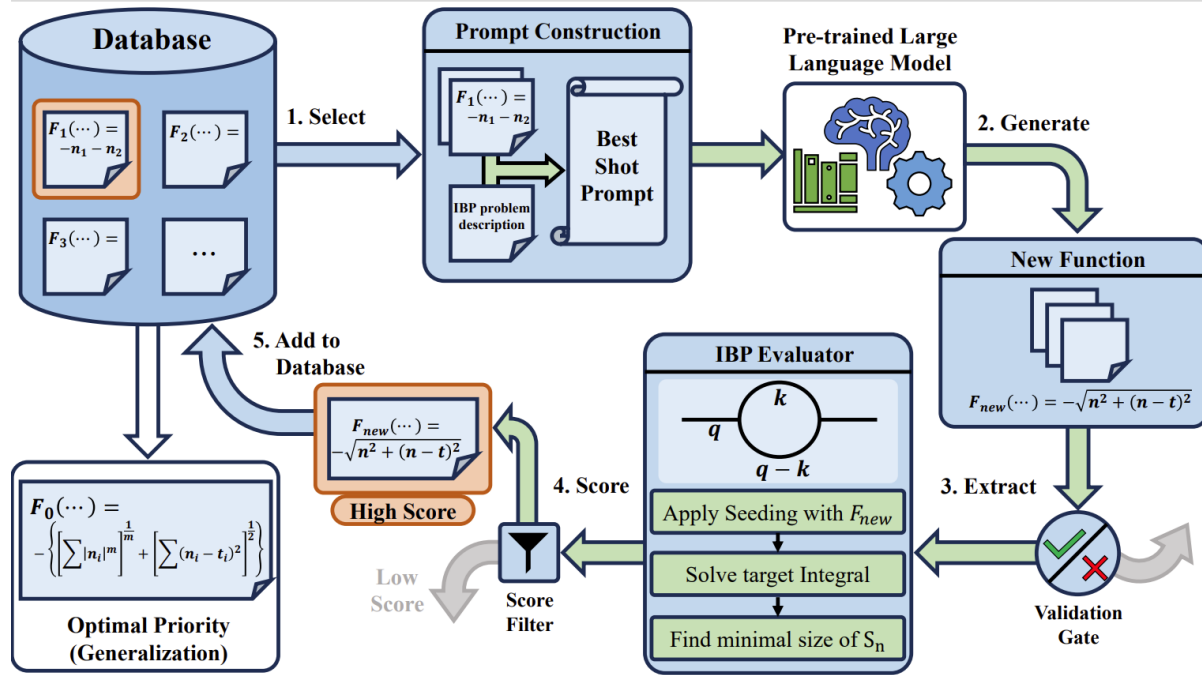
搜索的热力学代价



LLM解决难题的能力往往依赖于搜索——理解搜索的物理规律至关重要

Romera-Paredes Nature 2024; Snell arXiv:2408.03314; ARC Prize Foundation arxiv:2501.07458

How Far can we go?



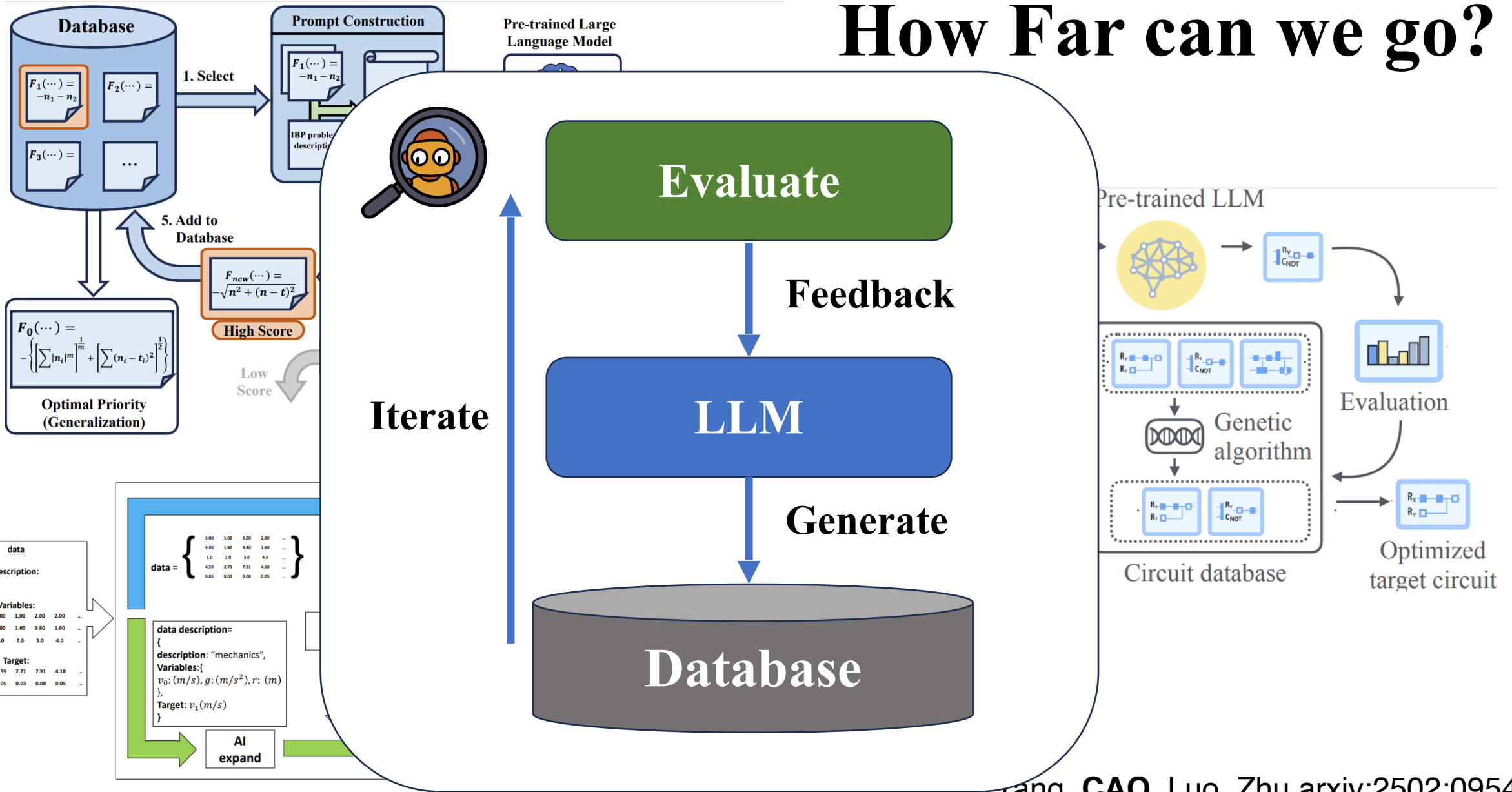
Pareto Frontier			
formula	χ^2/ndf	complexity	Is true
$v_1 = \sqrt{v_0^2 + 2.0 \times gr}$	9.6×10^{-1}	7	True
$v_1 = 1.0 \times v_0 + \sqrt{gr}$	4.4×10^1	5	False
$v_1 = 3.0 \times v_0$	3.0×10^1	2	False

Song, Yang, **CAO**, Luo, Zhu arxiv:2502:09544

CAO, Hou, Li, Liu, Song, Zhang, Zhang, Zhao arxiv:2505:06347

Song, Cai, Zhang, Wei, Pan, Qiu, **CAO**, Hou, Liu, Luo, Zhu arxiv: 2510.08317

How Far can we go?

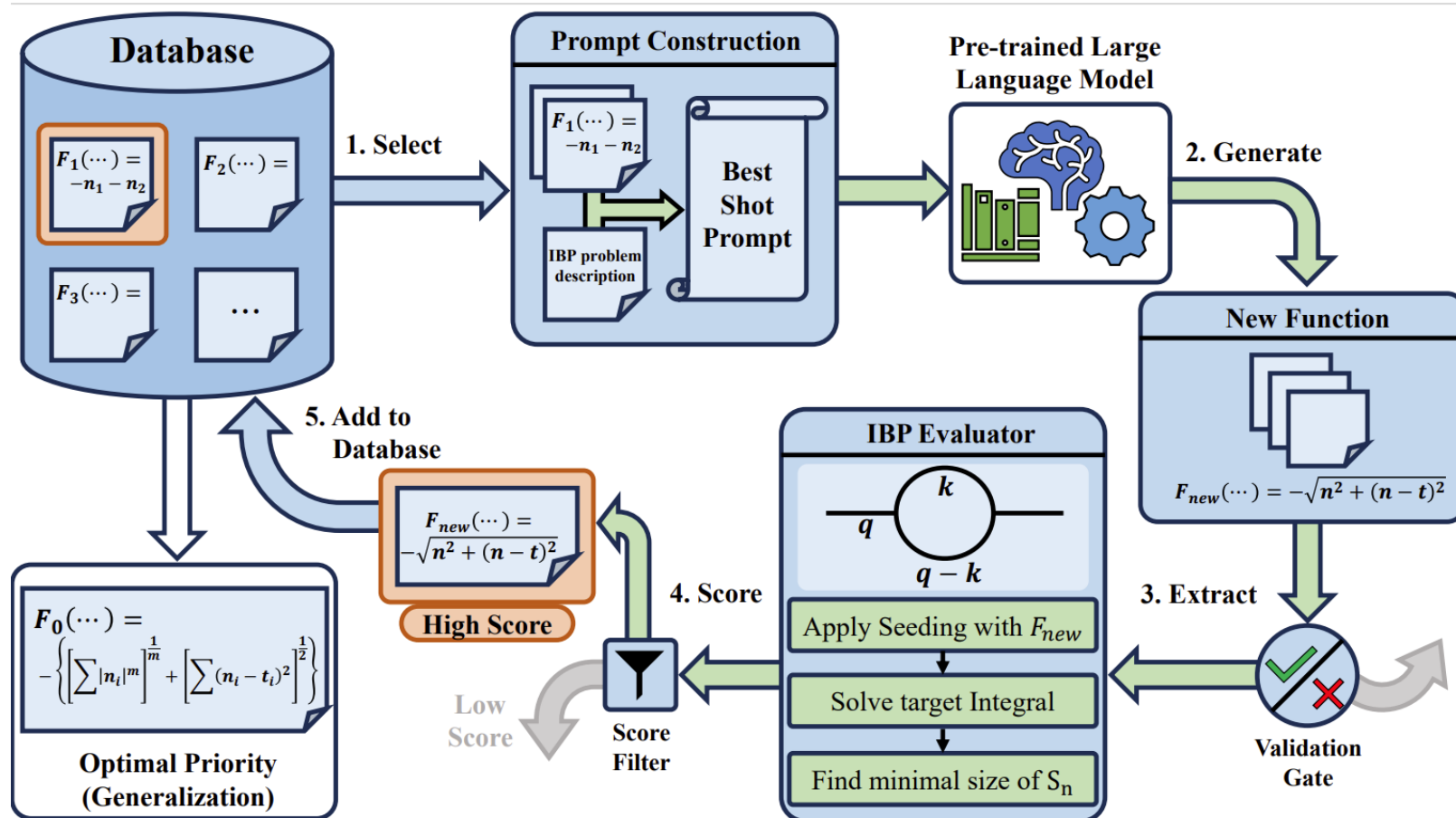


Song, Tang, **CAO**, Luo, Zhu arxiv:2502:09544

CAO, Hou, Li, Liu, Song, Zhang, Zhang, Zhao arxiv:2505:06347

Song, Cai, Zhang, Wei, Pan, Qiu, **CAO**, Hou, Liu, Luo, Zhu arxiv: 2510.08317

用LLM设计IBP约化的算法



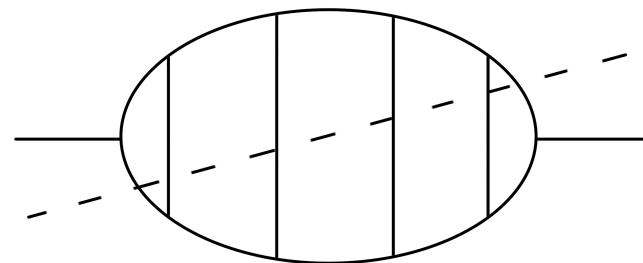
在单圈图上评估IBP算法的效率

在高圈图上做外推性测试

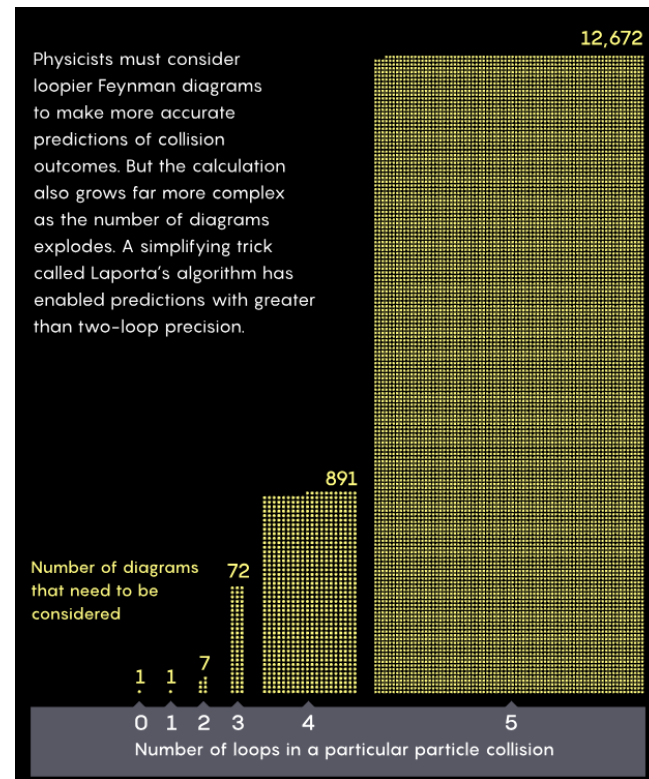
在5圈图上提速1000倍

用LLM设计IBP约化的算法

$$I(n_1, \dots, n_m) = \int \prod_{i=1}^L \frac{d^d k_i}{(2\pi)^d} \frac{1}{D_1^{n_1} \dots D_m^{n_m}}$$



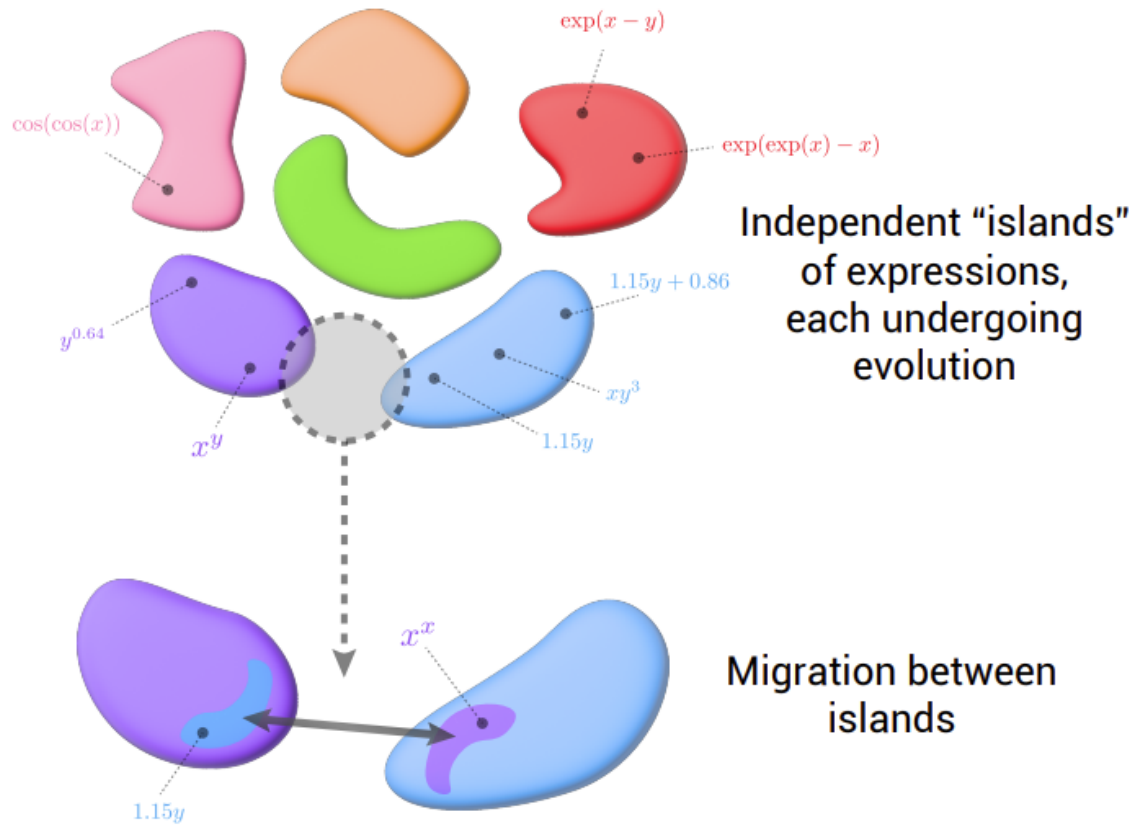
Integrals	Laporta	Improved	Priority	Ratio
s2	1 299 923	3061	2985	1.03
s3	7 276 962	4125	3708	1.11
s4	20 549 627	10 803	7144	1.51
s5	81 359 547	35 065	19 052	1.84
s6	237 961 845	108 215	46 390	2.33
s8	-	791 164	101 549	7.79
s10	-	4 388 968	268 909	16.32
s12	-	19 901 220	802 488	24.8
d1	523 596	154 700	1791	86.38
d3	2 940 855	2 775 780	3466	800.9
d5	11 654 385	21 740 796	7109	3058



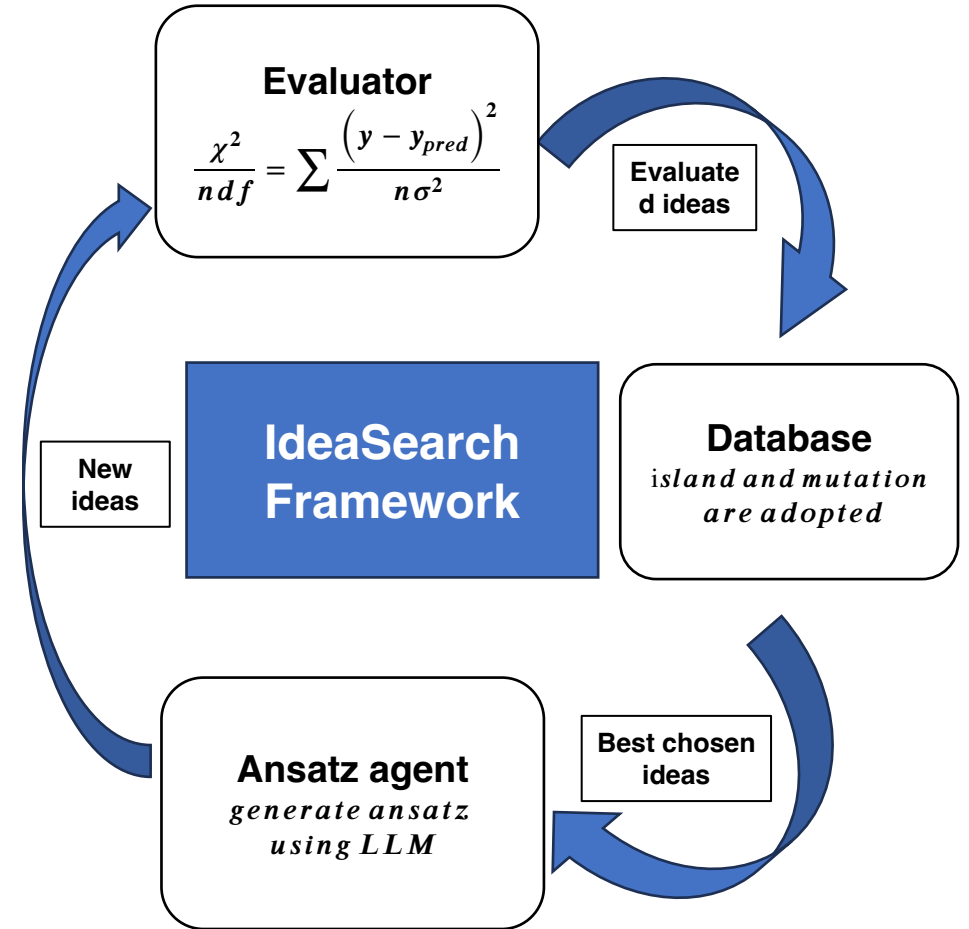
S. Laporta. hep-ph/0102033

Song, Yang, Cao, Luo, Zhu arxiv:2502:09544

用LLM做符号回归



Cranmer. PySR 2024
Udrescu, Tegmark. Sci. Adv. 2020
Burlacu, Kronberger, Kommenda. GECCO 2020



Song, Cai, Zhang, Wei, Pan, Qiu, **CAO**, Hou, Liu, Luo, Zhu
arxiv: 2510.08317

LLMsPDF: application to CT18 Global Analysis

Preliminary

CT18 global analysis uses 6 parton flavors, i.e., g, u_v, d_v, u, b, s , with 29 free parameters. The Standard CT18 functional form} at $Q_0 = 1.3 \text{ GeV}$:

$$f_i(x, Q_0) = a_0 x^{a_1-1} (1-x)^{a_2} P_i(x; a_3, a_4, \dots)$$

Regge Theory

quark counting rule

Bernstein polynomials

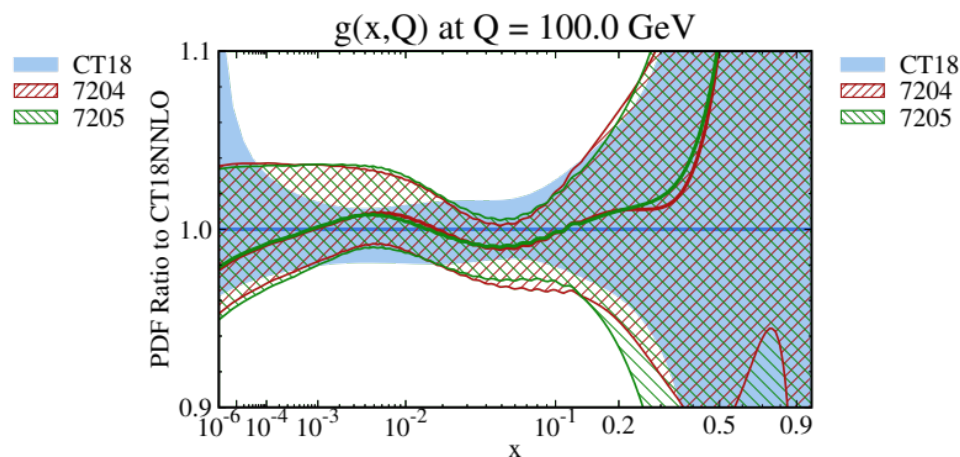
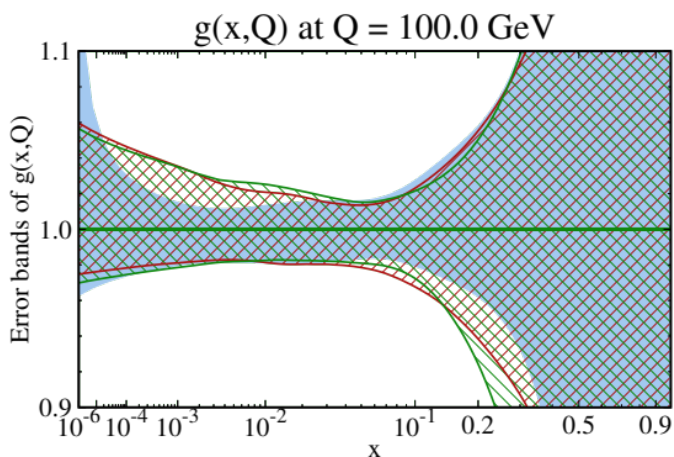
- Fix the power-law envelope $x^{(a_1-1)}(1-x)^{a_2}$
- Replace $P_i(x; a_3, a_4, \dots)$ with an **IdeaSearchFitter**-discovered ansatz
- Evaluate χ^2 against the full CT18 experimental dataset
- One flavor at a time
- 66 candidates obtained from IdeaSearchFitter are used to perform the global analysis, with **34 (51%)** achieving good fits without any human intervention.

IdeaSearchFitter
models

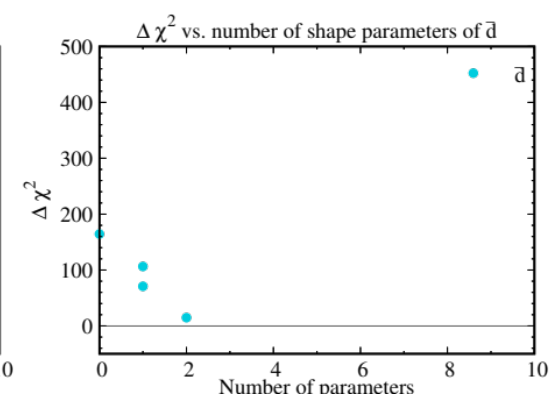
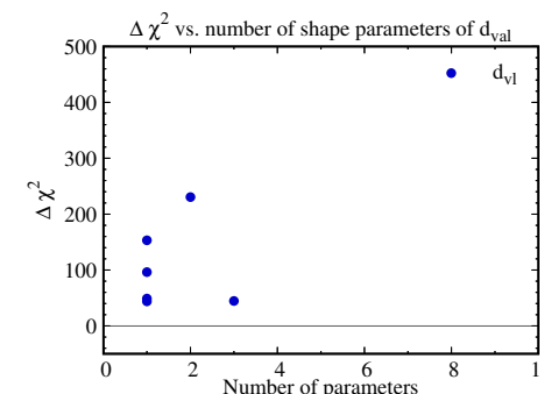
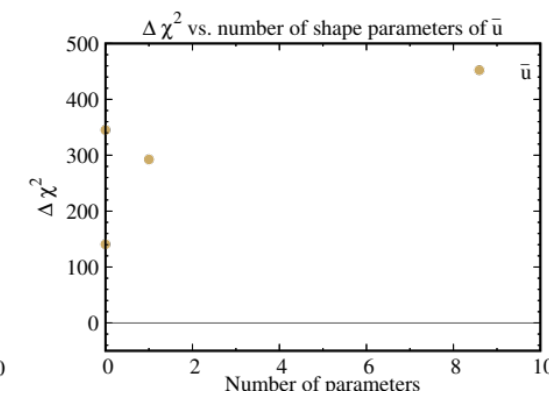
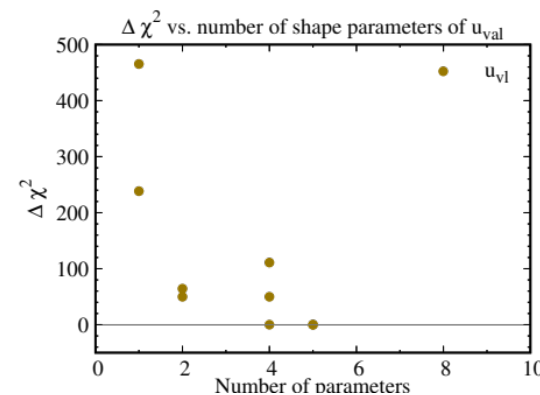
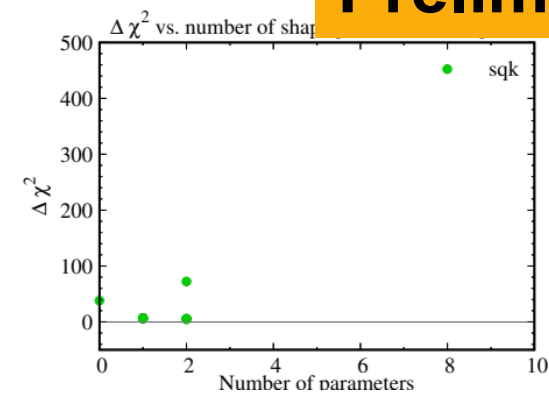
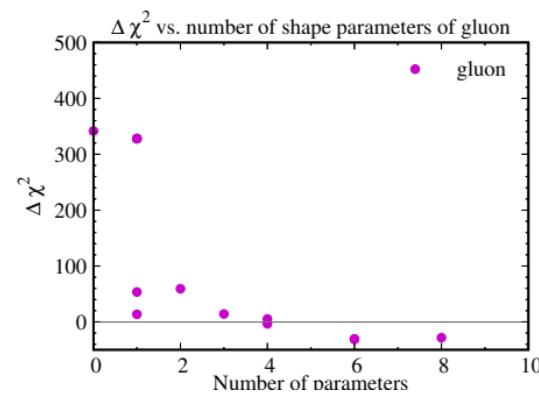
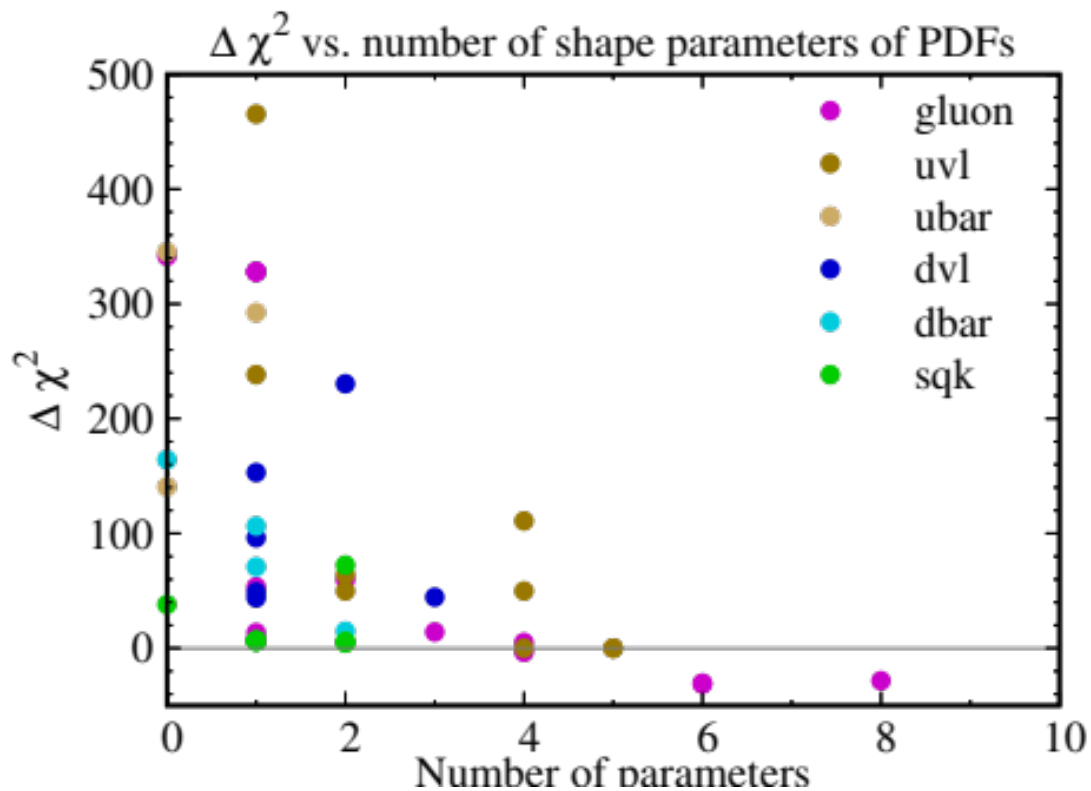
Category	$\Delta\chi^2$ range	Count
Improved	$\Delta\chi^2 \leq 0.0$	5
Compatible (68% CL)	$0.0 < \Delta\chi^2 \leq 36.96$	15
Compatible (90% CL)	$36.96 < \Delta\chi^2 \leq 100.0$	14
Marginal	$100.0 < \Delta\chi^2 \leq 500.0$	16
Divergent	$500.0 < \Delta\chi^2$	16
Total		66

$$P_{7204} = (a_3 e^{a_4 x} + a_5 \sin(x)) / (a_6 + x^{a_7}) - a_8$$

$$P_{7205} = (a_3 e^{a_4 x} + a_5 \sin(x)) / (a_6 + x^{a_7}) - a_8 e^{-x}$$



- $\Delta\chi^2 = 100$ is concerned as 90% C.L in CT18
- **5** of the models from IdeaSearchFitter provide better $\Delta\chi^2$ then that of CT18
- **68%** of converged models (34/50) are good (Improved or Compatible)
- **51%** of all candidates (34/66) achieve good fits without human intervention
- IdeaSearchFitter gluon models with better χ^2 use significantly more parameters than CT18.
- The larger number of parameters leads to larger uncertainties in these models.



- A clear inverse trend between $\Delta\chi^2$ and N_{par} is observed. This validates IdeaSearchFitter, confirming the results are semantically coherent rather than random noise.

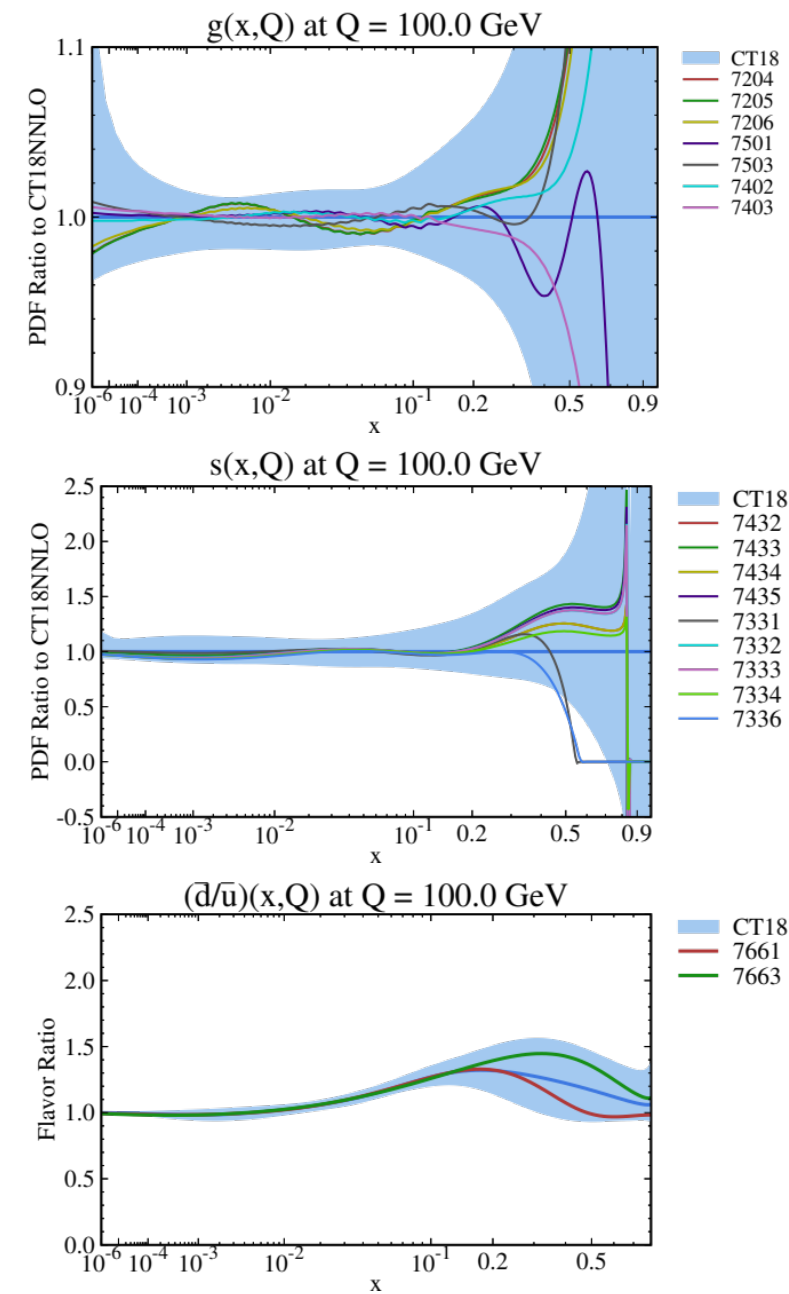
LLMsPDF: application to CT18 Global Analysis

Preliminary

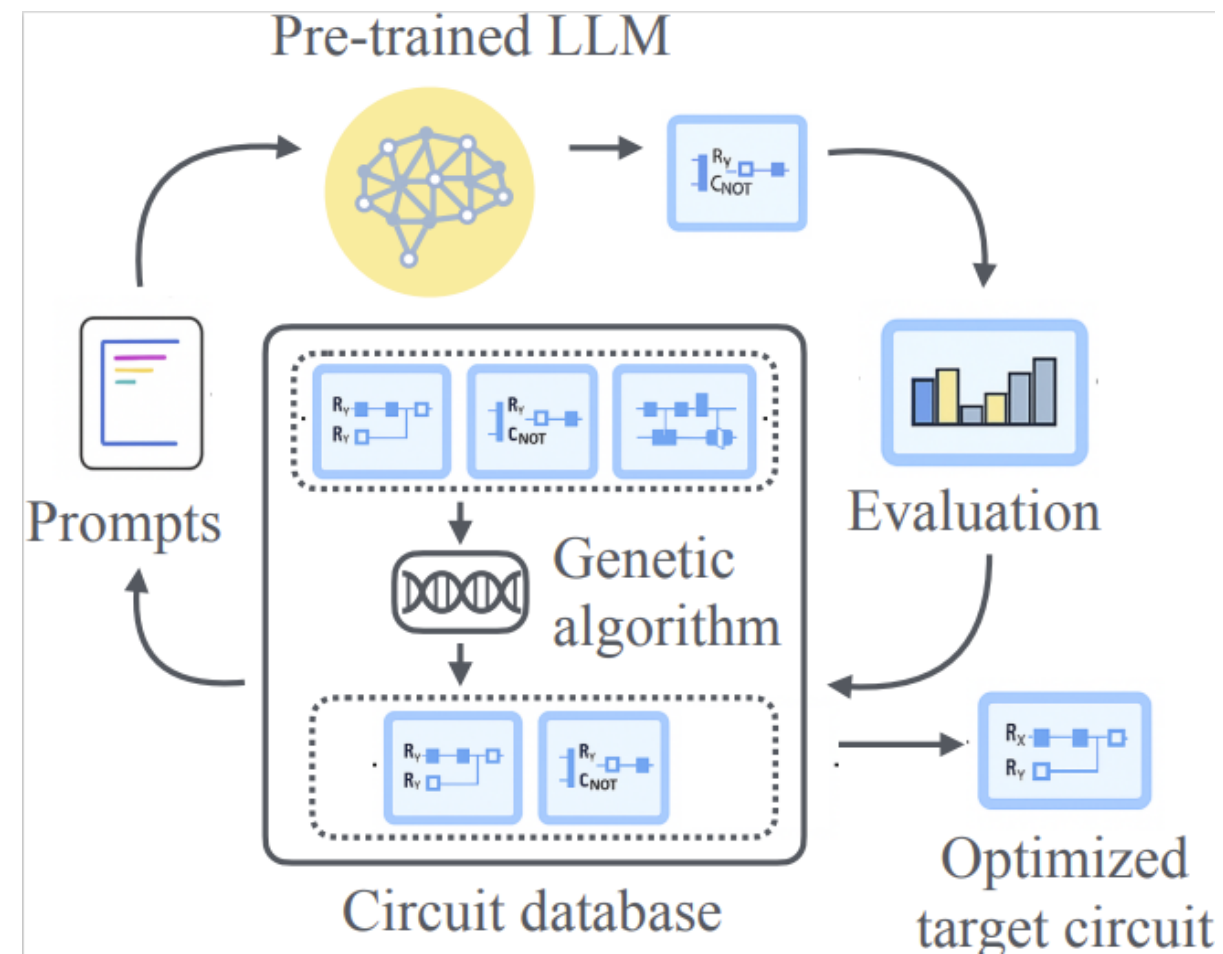
Functional Family	Good	Total	Success Rate
Trigonometric	4	5	80%
Power-law compound	10	15	67%
Exponential	9	16	56%
Logarithmic	3	6	50%
Rational	7	14	50%
Hyperbolic	2	4	50%
Linear / Polynomial	2	12	17%

Analysis of functional forms from IdeaSearchFitter

- **Trigonometric** and **power-law compound** forms perform best
- Simple polynomials (linear/quadratic) rarely succeed (17%)
- Power-law compounds at $N_{\text{par}} \geq 2$ are remarkably robust (67%)
- Strange quark achieves 82% success regardless of functional form
- Anti-up quark achieves 0% success regardless of functional form



用LLM设计量子线路



在小尺度Ising模型/格点QCD优化能量

在不同尺度Ising模型/格点QCD上测试保真度，在真机上测试

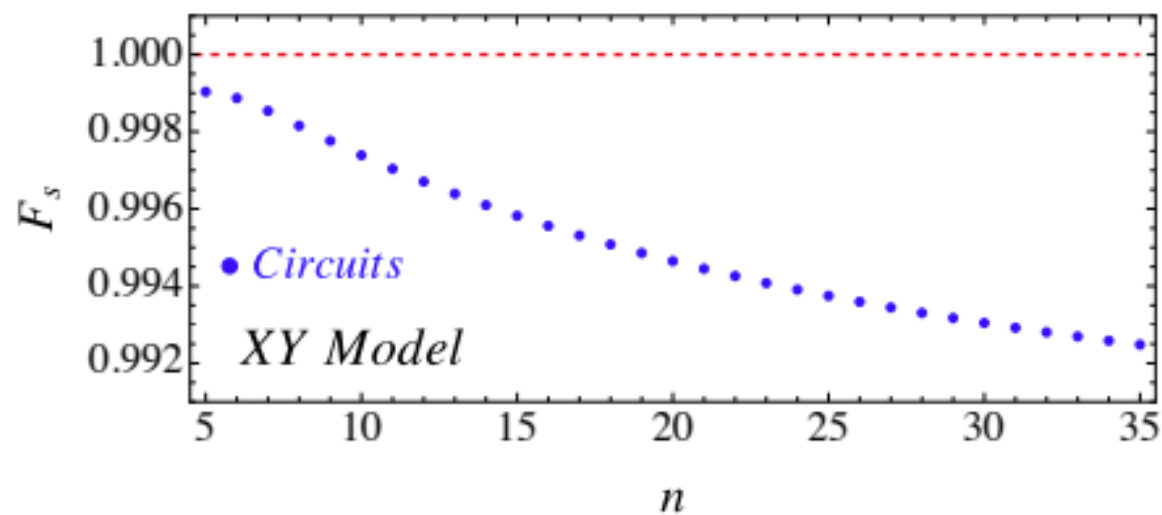
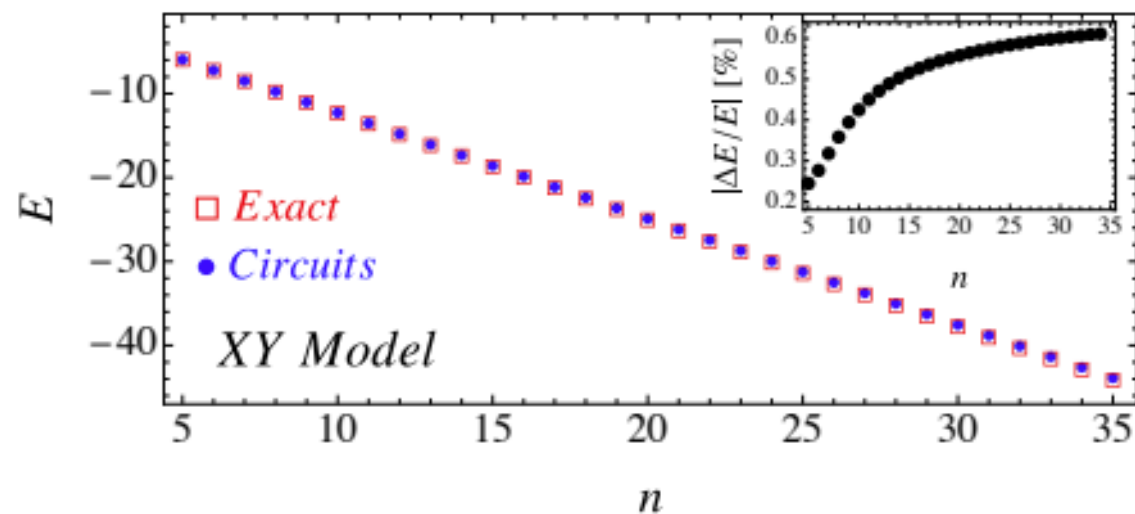
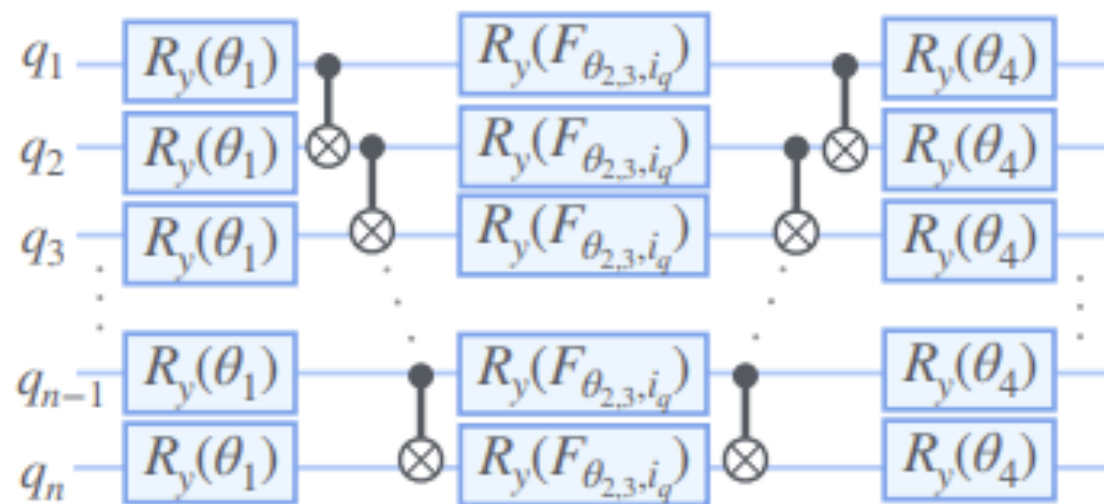
AI自动设计的线路可扩展可使用

Z. Davoudi, et al., Quantum 8, 1520 (2024)

Y. Atas, et al., Nat Commun 12, 6499 (2021)

M. Cerezo et al., Nature Rev. Phys. 3, 625 (2021).

用LLM设计量子线路



ColliderAgent:

AI 智能体驱动的自动化对撞机唯象研究

arXiv: 2603.14553

RISE-AGI-2026-001
CPTNP-2026-012

An End-to-end Architecture for Collider Physics and Beyond

仇是 蔡则宇 卫家燊 李泽宇 殷艺轩

Shi Qiu,¹ Zeyu Cai,¹ Jiashen Wei,¹ Zeyu Li,^{1,2} Yixuan Yin,¹ Qing-Hong
Cao,^{1,3,2} Chang Liu,^{1,4} Ming-xing Luo,⁵ Xing-Bo Yuan,⁶ and Hua Xing Zhu^{1,2}
曹庆宏 刘畅 罗民兴 袁兴博 朱华星

¹*School of Physics, Peking University, Beijing 100871, China*

²*Center for High Energy Physics, Peking University, Beijing 100871, China*

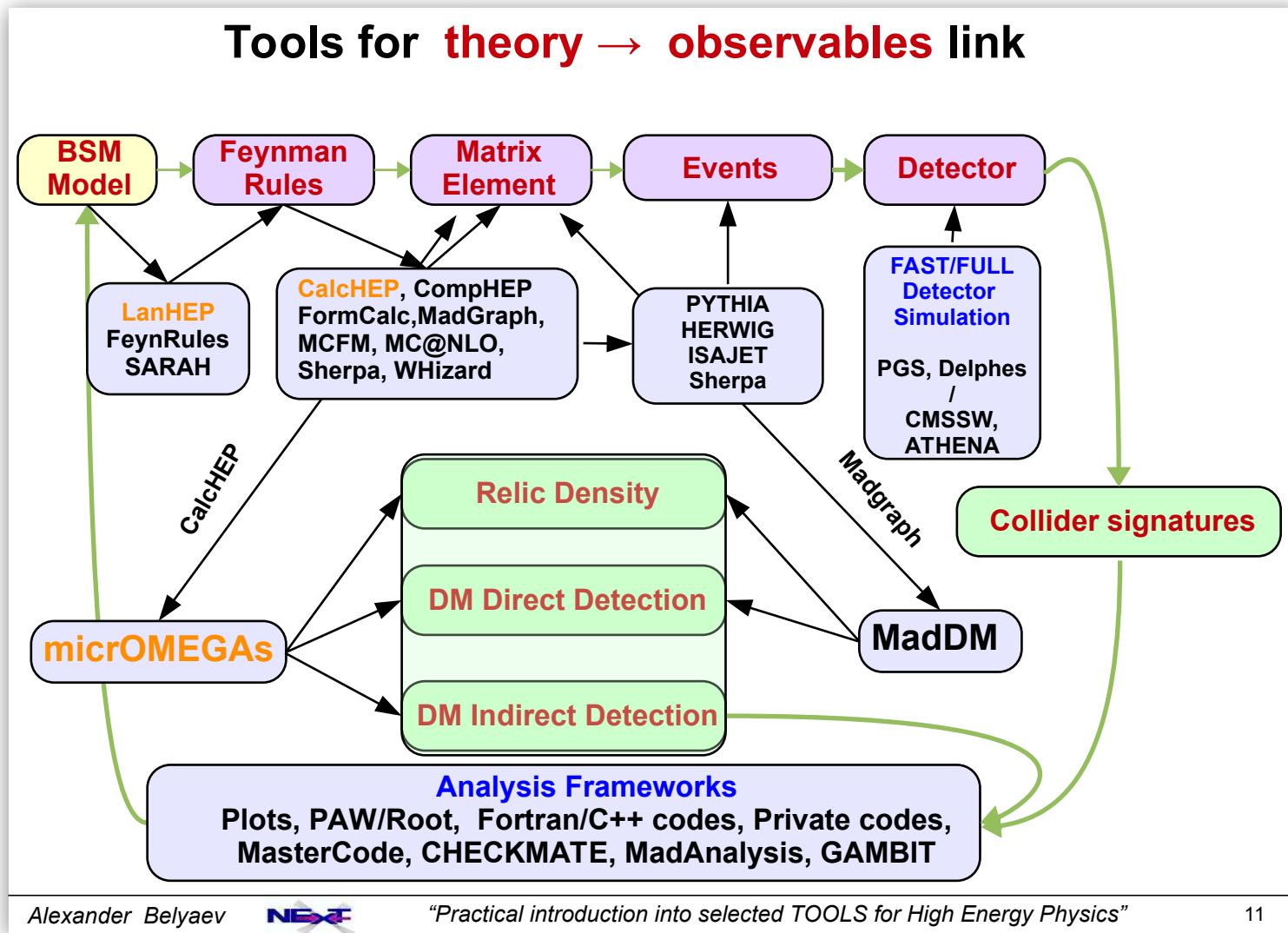
³*School of Physics, Zhengzhou University, Zhengzhou 450001, China*

⁴*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

⁵*Beijing Computational Science Research Center, Beijing 100193, China*

⁶*Institute of Particle Physics and Key Laboratory of Quark and Lepton Physics
(MOE), Central China Normal University, Wuhan, Hubei 430079, China*

高能物理唯象领域的软件生态



- ▶ 高能物理领域有很多非常优秀的程序包 😊
- ▶ 形成了相对稳定的 workflow 😊
- ▶ 不同程序包的代码约定/风格不一样，学起来很难 😭
- ▶ 安装时配置各类环境很烦。使用手册比较粗糙 😭

一线科研人员要花费大量时间学习相关程序包的功能和用法，而要知道程序包内部的运作方式、甚至隐藏的技巧更是难上加难) 😭

能否自动化的运行整个 workflow?
能否减少学习成本?

一些程序尝试自动化 workflow 的部分阶段、或针对特定唯象任务进行自动化: Checkmate, SARAH/SPheno, GAMBIT GUM

在 AI 时代，我们能不能做的更好？如何去做？

实现 workflow 的自动化
降低软件的学习成本
实现物理结果的可复现性

对撞机物理、暗物质、新物理领域的程序包

AI与高能物理软件生态的结合

现状：HEP程序包的差异极大，编程语言涵盖C、Fortran、Python、Mathematica，各程序的约定、输入输出的格式也各不相同

问题：如何用AI解决这些问题，并进一步的实现工作流的自动化？

我们发现HEP各类程序包有一个共性：可以通过少量的配置程序，或轻量级的代码来控制

MadGraph
脚本示例

```
import model sm
define l+ = e+ mu+
define l- = e- mu-
generate p p > l+ l-
output events/pp_ll_14tev
launch events/pp_ll_14tev
done
set nevents 50000
set ebeam1 6500
set ebeam2 6500
```

FeynRules 模型文件示例

```
LALP := Block[{mu, nu, rho, sigma},
- gaZA * (1/2) * Eps[mu, nu, rho, sigma] * FS[Z, mu, nu] * FS[A, rho, sigma] *
alp
- gaZZ * (1/4) * Eps[mu, nu, rho, sigma] * FS[Z, mu, nu] * FS[Z, rho, sigma] *
alp
- gaWW * (1/2) * Eps[mu, nu, rho, sigma] * FS[W, mu, nu] * FS[Wbar, rho, sigma]
* alp
];
```

解决方案：如果可以让LLM来写这些配置程序或轻量级代码，并调用相关程序来执行，就实现了我们的目的

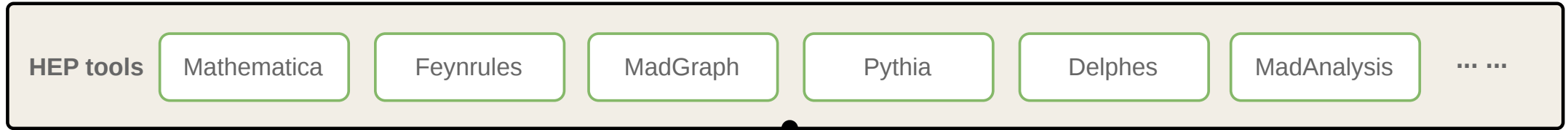
如何告诉LLM各类HEP程序包的使用方法？

1. 当前LLM已经具备了足够的编程能力
2. LLM的训练集中已经包含了部分HEP程序的手册和文档
3. 通过上下文工程来告诉LLM程序的执行步骤，关键的约定

Agent Skills

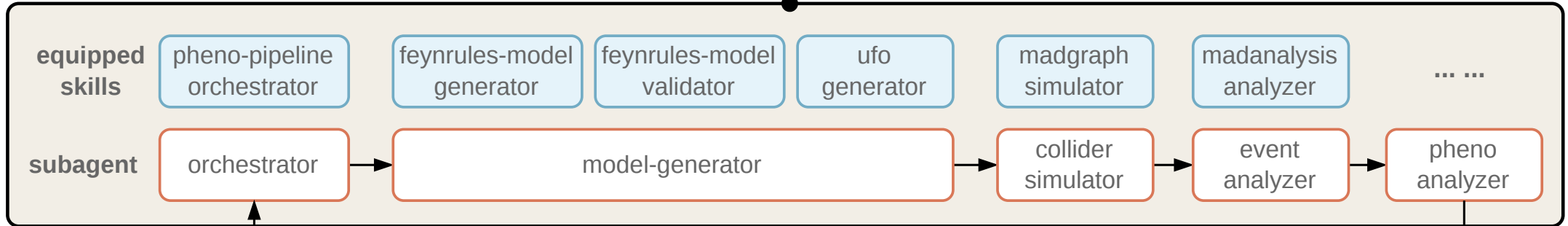
智能体架构

Execution Backend: Magnus



CLI

Cognitive Reasoning Engine



User Layer



基于Agent Skills

多智能体

认知-执行解耦

1. Single LQ production at the LHC

PHYSICAL REVIEW LETTERS **125**, 231804 (2020)

Lepton-Quark Collisions at the Large Hadron Collider

Luca Buonocore^{1,2,*}, Ulrich Haisch^{3,†}, Paolo Nason^{4,‡}, Francesco Tramontano^{1,§} and Giulia Zanderighi^{3,||}

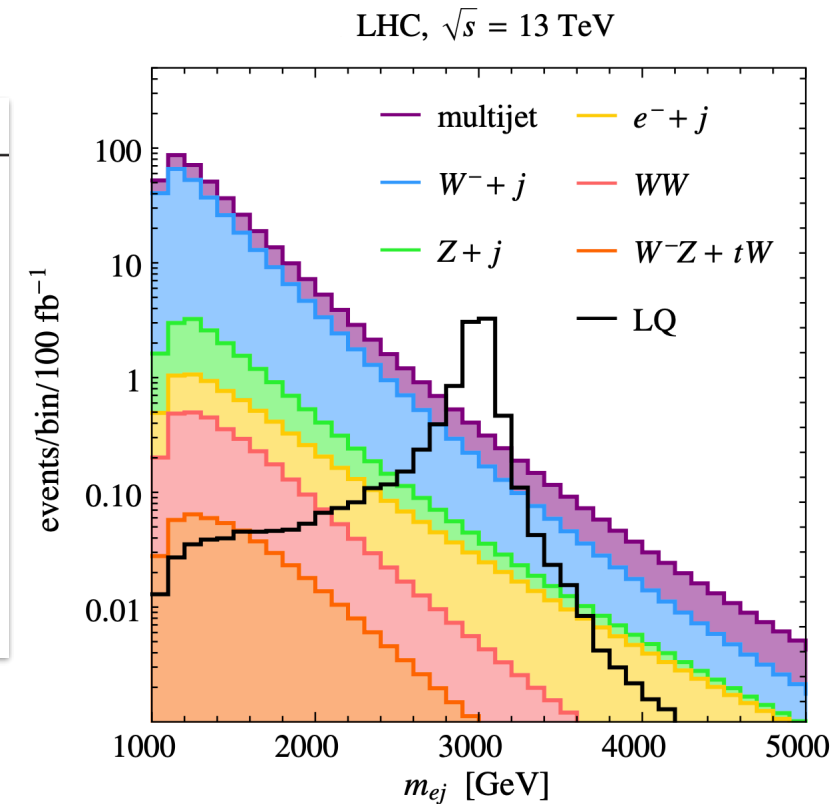
¹*Dipartimento di Fisica, Università di Napoli Federico II and INFN, Sezione di Napoli, I-80126 Napoli, Italy*

²*Physik Institut, Universität Zürich, CH-8057 Zürich, Switzerland*

³*Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany*

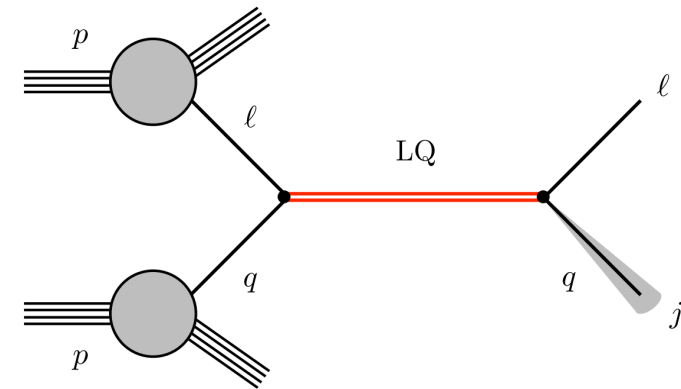
⁴*Università di Milano-Bicocca and INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*

(Received 29 May 2020; revised 29 September 2020; accepted 9 November 2020; published 2 December 2020)



- ▶ single leptoquark production by picking a lepton from one beam and a quark from the other beam
- ▶ requiring the correct use of the LUXlep PDF set to account for leptons inside the proton.

Since Pythia cannot handle incoming leptonic partons, the initial-state leptons in the LHE events should be replaced by photons before showering. The parton shower backward evolution of PYTHIA then produces only quarks from photon splitting, so after showering the simulation includes initial-state quarks instead of leptons.



1. Single LQ production at the LHC

1. Target

3. Collider Simulation

4. Numerical Analysis

4.1 Event selection

Read the reconstructed events from the Delphes output and apply the following selection cuts:

1. Electron: $p_T > 500$ GeV, $|\eta| < 2.5$
2. Jet: $p_T > 500$ GeV, $|\eta| < 2.5$ (anti- k_T , $R = 0.4$)
3. Missing transverse energy: $E_T^{\text{miss}} < 50$ GeV
4. Lepton veto: veto events with additional leptons ($|\eta| < 2.5$, $p_{T,\ell} > 7$ GeV)
5. Jet veto: veto events with additional subleading jets ($|\eta| < 2.5$, $p_{T,j} > 30$ GeV)

4.2 Signal histogram

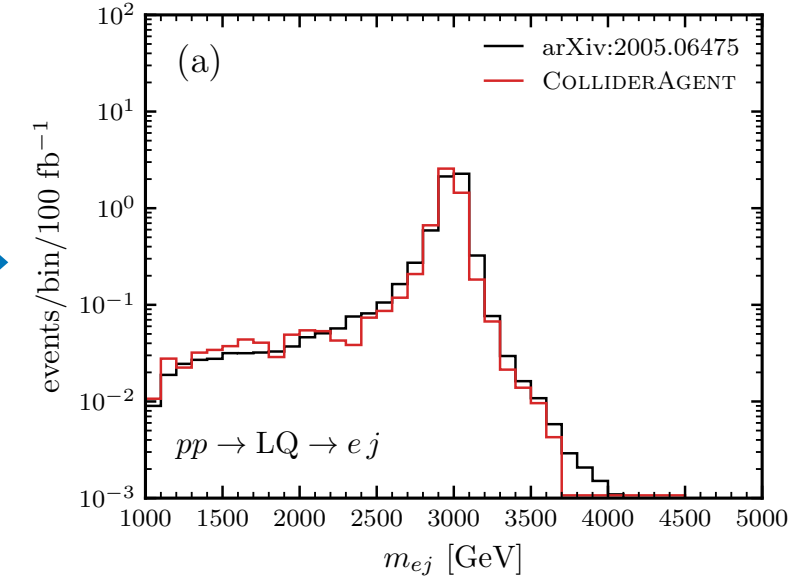
Compute the invariant mass m_{ej} of the leading electron and leading jet for events passing all cuts.

- Bin the m_{ej} distribution in 100 GeV bins from 0 to 5000 GeV.
- Weight each event by $w = \sigma \times \mathcal{L} / N_{\text{gen}}$, where σ is the cross section, $\mathcal{L} = 100 \text{ fb}^{-1}$, and N_{gen} is the total number of generated events.

5. Plot Figure

Plot the signal m_{ej} distribution with solid black line.

1. After MadGraph generates the LHE file, replace all initial-state leptons with photons in the LHE file.
2. Disable Pythia8's built-in event validity checks (charge/momentum conservation) so it accepts and showers the manually modified LHE file without rejecting it.
3. Perform shower and detector simulation.



如果不放心的话，还可以
“请帮我验证arXiv: 2006.06477中的table 1”

user prompt \approx research note or paper

SM cross section for lepton-lepton scattering at the LHC

	$e^+\mu^-$	$e^+\tau^-$	$\mu^+\tau^-$	e^+e^+	$\mu^+\mu^+$	$\tau^+\tau^+$
$\sigma_{13\text{TeV}}$ [fb]	$0.29^{+0.13}_{-0.10}$	$0.18^{+0.11}_{-0.08}$	$0.16^{+0.10}_{-0.07}$	$0.24^{+0.10}_{-0.08}$	$0.19^{+0.09}_{-0.07}$	$0.08^{+0.06}_{-0.04}$
$\sigma_{27\text{TeV}}$ [fb]	$0.53^{+0.25}_{-0.18}$	$0.34^{+0.21}_{-0.15}$	$0.30^{+0.19}_{-0.14}$	$0.440^{+0.19}_{-0.14}$	$0.34^{+0.16}_{-0.12}$	$0.14^{+0.12}_{-0.07}$

Buonocore, Nason, Tramontano, Zanderighi, 2005.06477

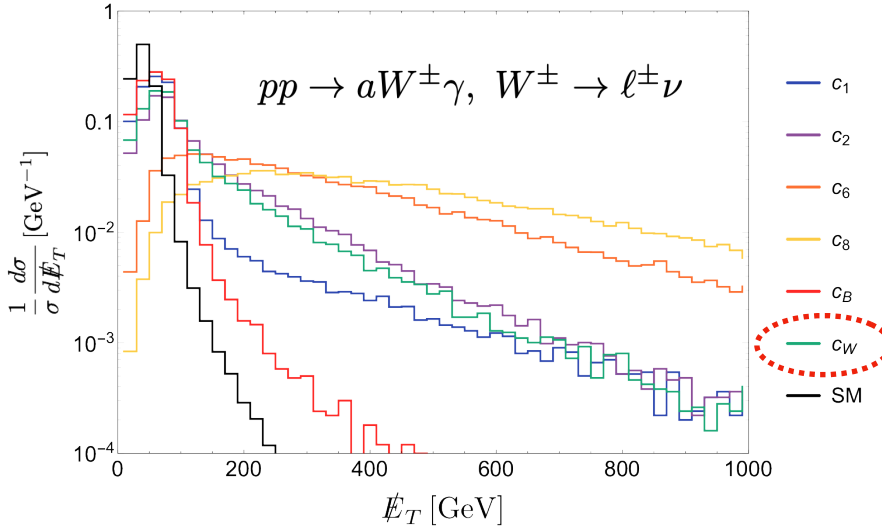
2. ALP production at the LHC in EFT

ALPs Effective Field Theory and Collider Signatures #1

I. Brivio (Bohr Inst. and Madrid, Autonoma U. and Madrid, IFT), M.B. Gavela (Madrid, Autonoma U. and Madrid, IFT), L. Merlo (Madrid, Autonoma U. and Madrid, IFT), K. Mimasu (Louvain U., CP3 and Sussex U.), J.M. No (King's Coll. London and Sussex U.) et al. (Jan 19, 2017)

Published in: *Eur.Phys.J.C* 77 (2017) 8, 572 • e-Print: 1701.05379 [hep-ph]

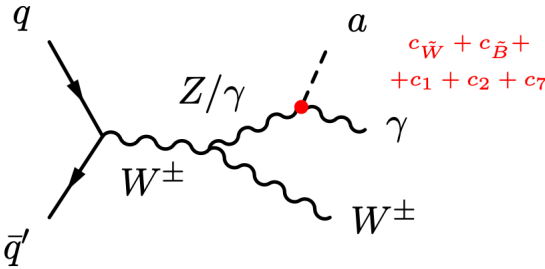
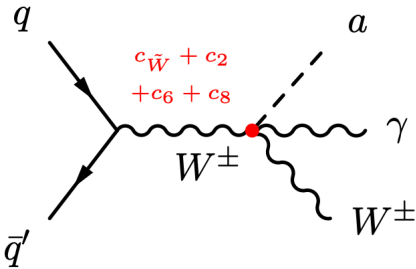
pdf DOI cite claim reference search 324 citations



EW vertices induced by ALP EFT operators

$$\mathcal{A}_{\tilde{B}} = -B_{\mu\nu} \tilde{B}^{\mu\nu} \frac{a}{f_a} \quad \mathcal{A}_{\tilde{W}} = -W_{\mu\nu}^a \tilde{W}^{a\mu\nu} \frac{a}{f_a}$$

$$c_{\tilde{B}} = -\tan^2 \theta_W c_{\tilde{W}} \text{ so that } g_{a\gamma\gamma} = 0$$



2. ALP production at the LHC in EFT

1. Target

3. Collider Simulation

3.1 Process

$$pp \rightarrow a W^\pm \gamma, \quad W^\pm \rightarrow \ell^\pm \nu$$

3.2 Collider Simulation Settings

- Collider: 13 TeV LHC
- Event number: 500,000
- Analysis level: Parton-level (no parton shower or detector simulation)
- PDF: nn23lo1
- $f_a = 1000$ GeV, $m_a = 0.001$ GeV, and $c_{\bar{W}} = 1$

4. Numerical Analysis

4.1 Event Selection

Read the LHE events and apply the following selection cuts:

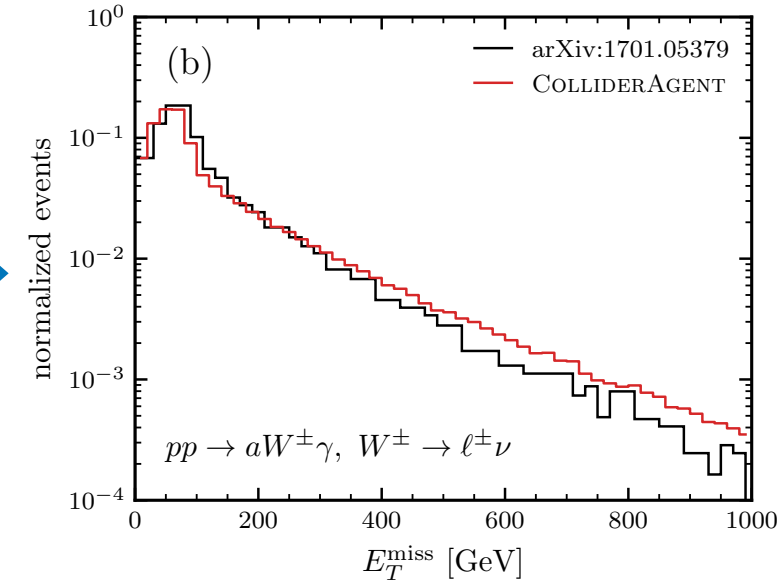
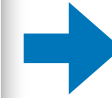
- photon: $p_T > 20$ GeV, $\eta < 2.5$
- lepton: $p_T > 20$ GeV, $\eta < 2.5$

4.2 Histogram and Normalization

- Histogram: $E_T^{\text{miss}} = |\vec{p}_T^a + \vec{p}_T^\nu|$, the vector sum of the transverse momenta of all invisible particles (ALP + neutrino).
- Binning: 50 bins, 0–1000 GeV

4.3 Plot Figure

Plot the histogram. The height of the histogram is the normalized events, which are defined as the ratio of the number of events in the bin to the total number of events.



3. Constraints on U_1 LQ from LHC mono- τ search

Mono- τ Signatures at the LHC Constrain Explanations of B -decay Anomalies

Admir Greljo (CERN), Jorge Martin Camalich (CERN and IAC, La Laguna and Laguna U., Tenerife), José David Ruiz-Álvarez (Antioquia U.)

Nov 19, 2018

7 pages

Published in: *Phys.Rev.Lett.* 122 (2019) 13, 131803

Published: Apr 6, 2019

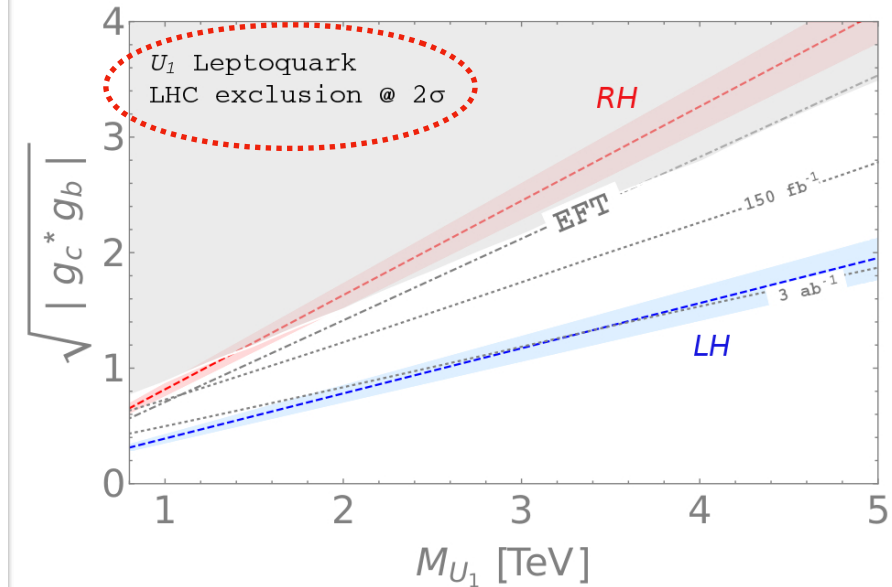
e-Print: 1811.07920 [hep-ph]

DOI: 10.1103/PhysRevLett.122.131803

View in: [CERN Document Server](#), [ADS Abstract Service](#)

[pdf](#) [cite](#) [claim](#)

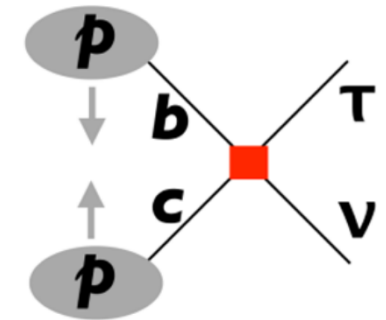
[reference search](#) [135 citations](#)



► U_1 leptoquark model

$$\mathcal{L}_{U_1} = -(D_\mu U_{1\nu} - D_\nu U_{1\mu})^\dagger (D^\mu U_1^\nu - D^\nu U_1^\mu) + M_{U_1}^2 U_{1\mu}^\dagger U_1^\mu + [g_c(\bar{c}\gamma^\mu P_L \nu_\tau)U_{1\mu}^\dagger + g_b(\bar{b}\gamma^\mu P_L \tau)U_{1\mu}^\dagger + \text{h.c.}]$$

- full workflow, including event generation for the signal process $pp \rightarrow \tau\nu$, showering and hadronization, detector simulation with ATLAS and CMS configurations, experiment-specific event selection, and the extraction of the exclusion contour by comparing the resulting signal templates with published LHC data in a profile-likelihood analysis.



3. Constraints on U_1 LQ from LHC mono- τ search

1. Target

3. Collider Simulation

4 Numerical Analysis

step 2: signal template construction

For events passing selection, histogram m_T into ATLAS or CMS bins.

$$s_i^{(g=1)} = \frac{N_i^{\text{pass}}}{N_{\text{gen}}} \times \sigma(g=1) \times \mathcal{L}$$

where

- N_{gen} is the number of reconstructed events
- $\sigma(g=1)$ is the cross section at coupling $g=1$
- \mathcal{L} is the luminosity (36.1 fb^{-1} ATLAS, 35.9 fb^{-1} CMS)

Signal scaling: $s_i(g) = g^4 s_i^{(g=1)}$

3.3 Profile likelihood analysis

For each bin,

$$-\ln L_i(\theta_i) = -[n_i \ln \mu_i - \mu_i] + \frac{1}{2} \frac{\theta_i^2}{(\delta_i/b_i)^2}$$

where

- n_i observed events
- b_i expected SM background
- δ_i systematic uncertainty
- θ_i nuisance parameter
- $s_i(g) = g^4 s_i^{(g=1)}$
- $\mu_i = b_i(1 + \theta_i) + s_i$

Procedure to find the 2σ exclusion contour

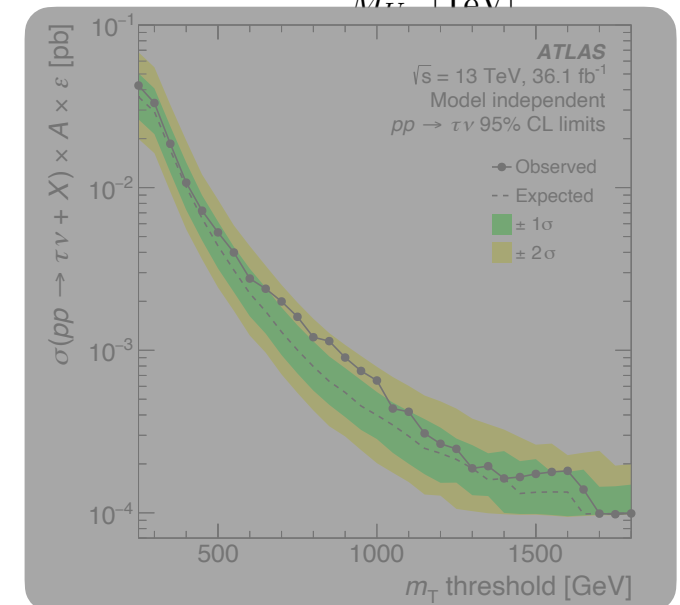
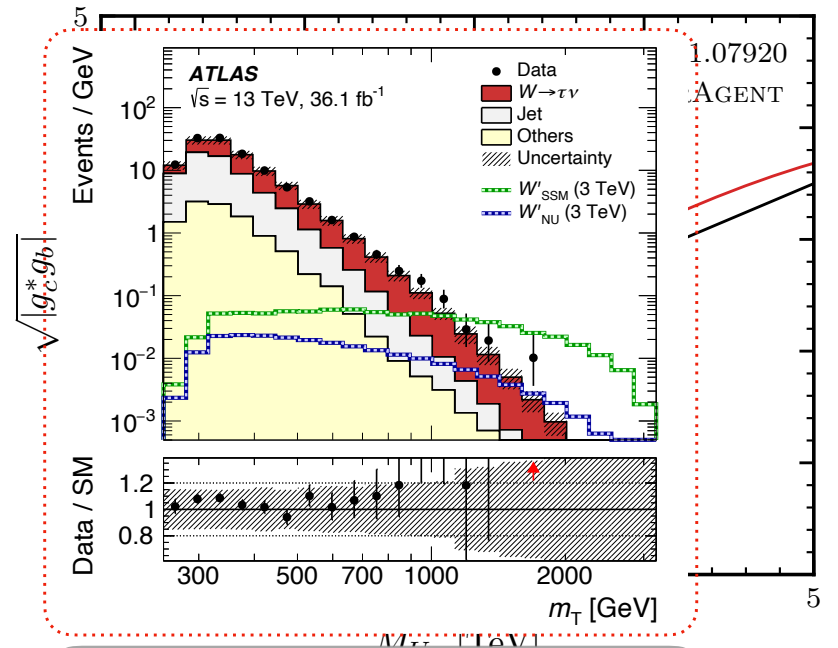
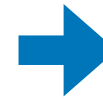
step 1 profiling: Minimize $-\ln L_i(\theta_i)$ numerically with constraint $\mu_i > 0$.

step 2 combine ATLAS + CMS Likelihood: $\ln \mathcal{L}_{\text{comb}} = \ln \mathcal{L}_{\text{ATLAS}} + \ln \mathcal{L}_{\text{CMS}}$

step 3 extract exclusion region:

1. Find best-fit \hat{g}
2. Find the exclusion curve by considering g_{excl} satisfying $-2[\ln \mathcal{L}(g_{\text{excl}}) - \ln \mathcal{L}(\hat{g})] = 4$

3.4 Plot Figure



4. Parameter scan in a minimal $U(1)_{B-L}$ model



PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: May 14, 2016

ACCEPTED: July 1, 2016

PUBLISHED: July 18, 2016

Z' , Higgses and heavy neutrinos in $U(1)'$ models: from the LHC to the GUT scale

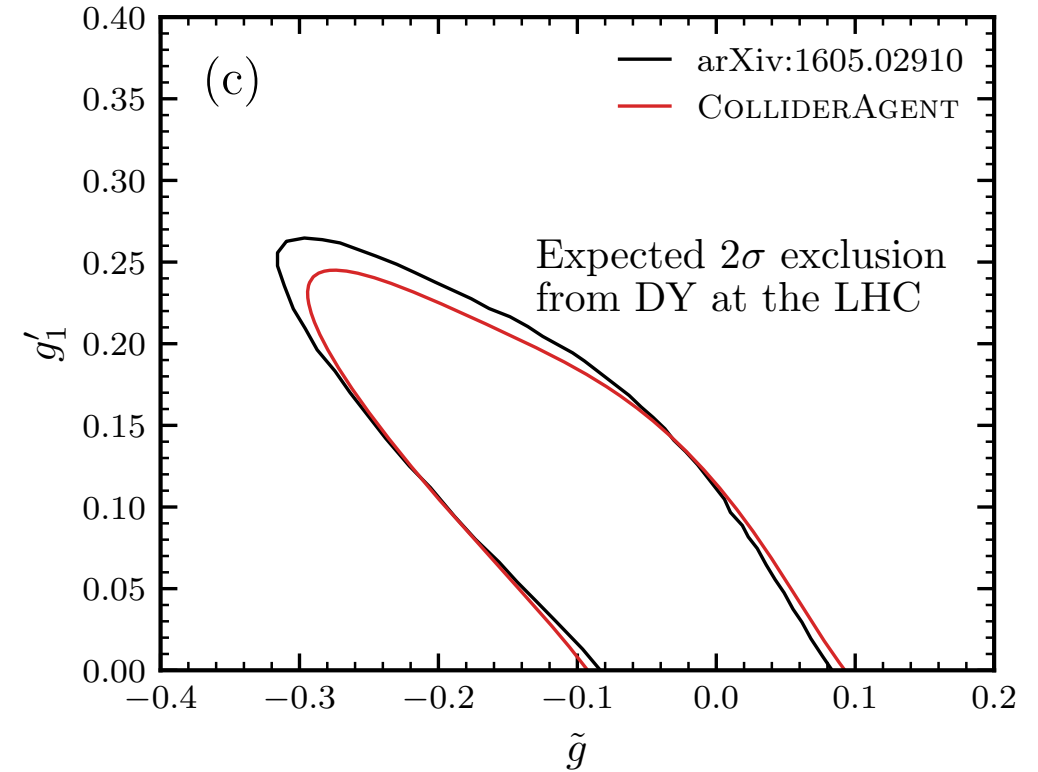
Elena Accomando,^a Claudio Corianò,^{b,c} Luigi Delle Rose,^a Juri Fiaschi,^a Carlo Marzo^c
and Stefano Moretti^a

Part of the Lagrangian

$$\mathcal{L}_{Z'ff} = \sum_f Z'_\mu \bar{f} \gamma^\mu (C_{f,L} P_L + C_{f,R} P_R) f$$

$$C_{f,L} = -e \frac{\sin \theta'}{\sin \theta_W \cos \theta_W} (T_f^3 - \sin^2 \theta_W Q_f) + (\tilde{g} Y_{f,L} + g'_1 z_f) \cos \theta'$$

$$C_{f,R} = e \frac{\sin \theta_W \sin \theta'}{\cos \theta_W} Q_f + (\tilde{g} Y_{f,R} + g'_1 z_f) \cos \theta'$$



Parameter Scan

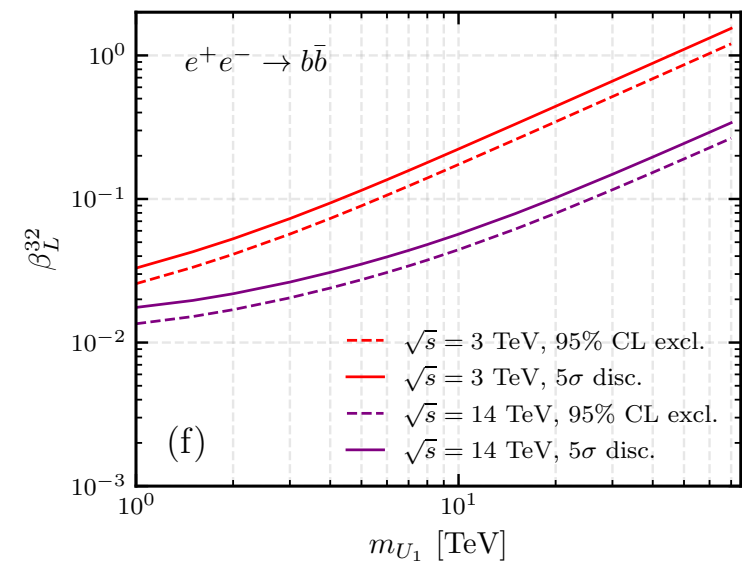
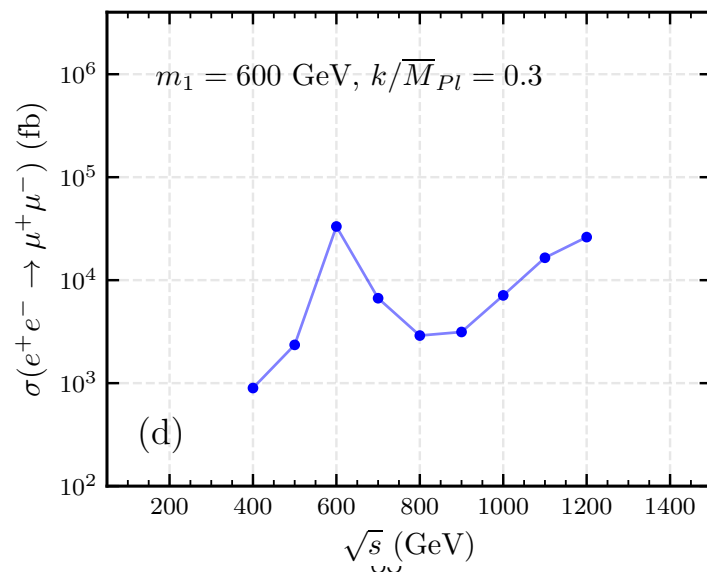
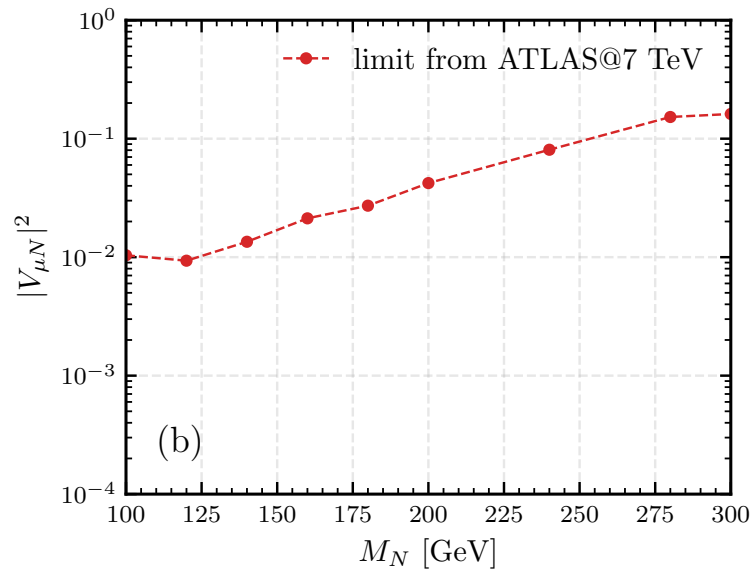
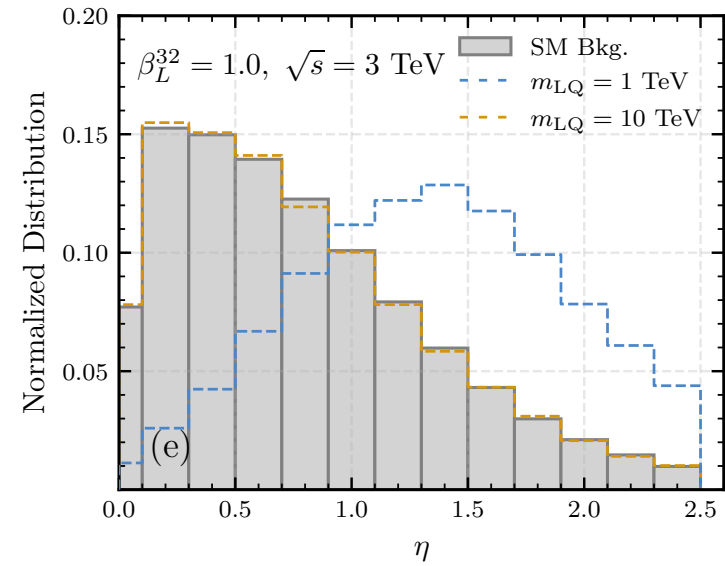
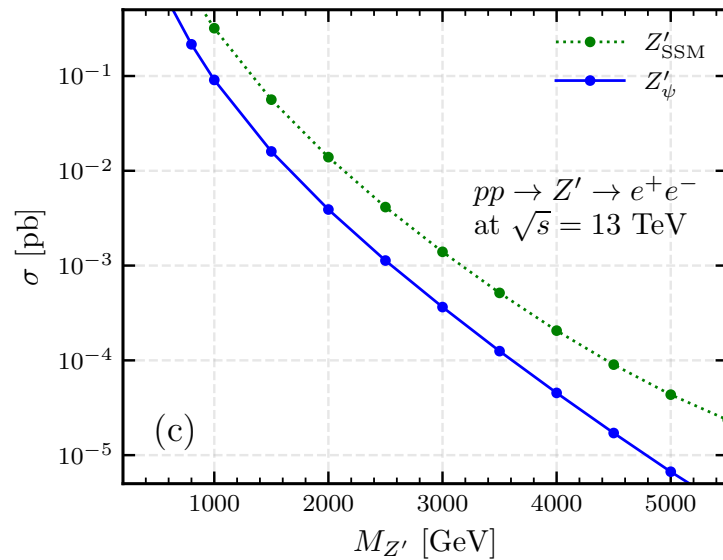
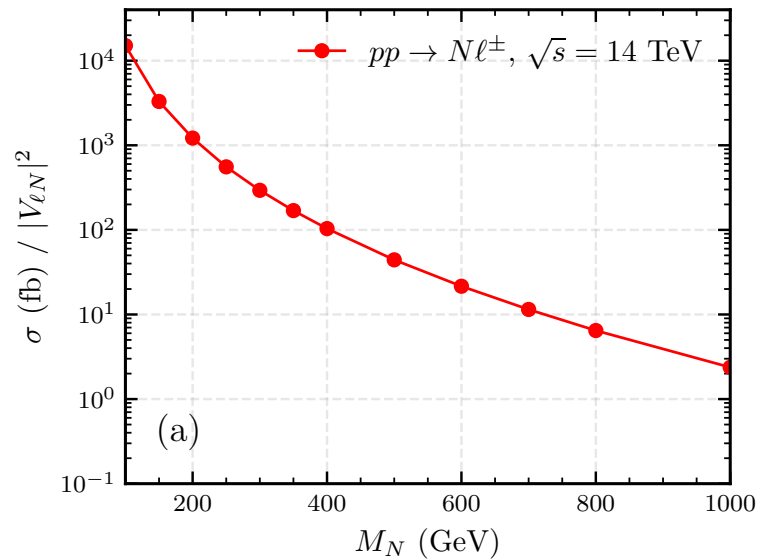
Other examples

(a, b) P. S. B. Dev, A. Pilaftsis, and U.-k. Yang, arXiv: 1308.2209

(c) CMS, arXiv: 2103.02708

(d) H. Davoudiasl, J. L. Hewett, and T. G. Rizzo, hep-ph/9909255

(e, f) P. Asadi, R. Capdevilla, C. Cesarotti, and S. Homiller, arXiv: 2104.05720



广告： ColliderAgent

项目地址：<https://github.com/HET-AGI/ColliderAgent>

(安装方法, 使用说明)

Multi-Agent + Skills: **Claude Code**

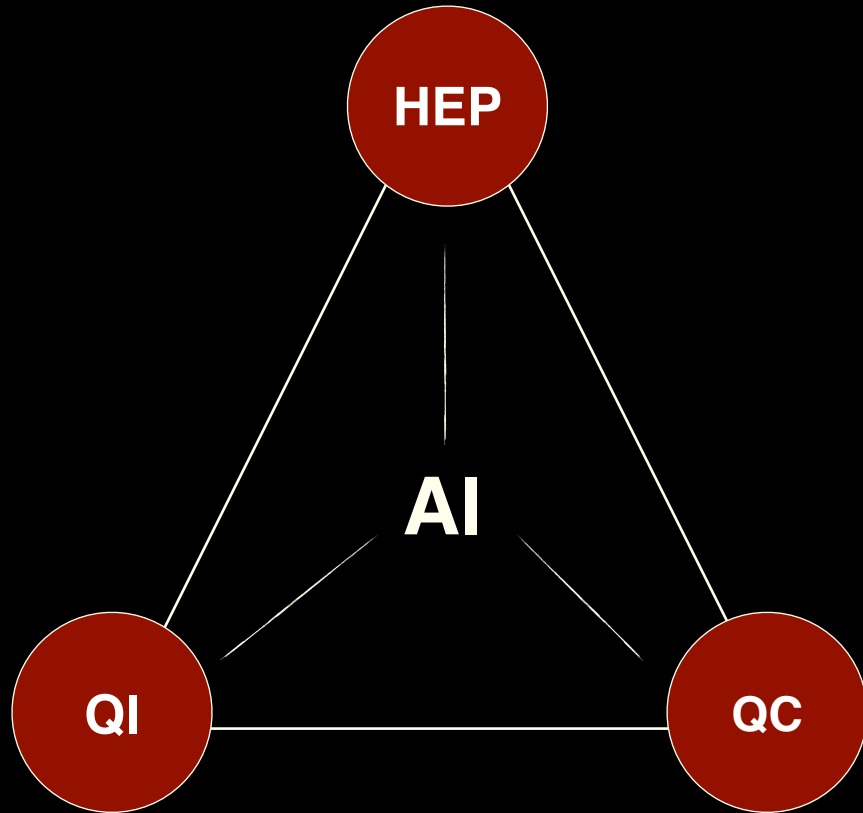
Skills: **Cursor, CodeX, OpenCode, GitHub Copilot**

群聊: ColliderAgent 交流群



Summary

Thirty years passed, and the **questions** that drive me crazy have not yet been answered.



Why is the Higgs boson mass 125 GeV?
What is the origin of the Standard Model parameters?
Do fermions and bosons have the same origin of mass?
What is the mechanism behind large CP violation?
Why are there only three generations of quarks and leptons?
Could there be a fourth generation of matter field particles?
Can all the fundamental forces in nature be unified?
Are there new types of interactions?
Do quarks and leptons have internal structure?
What are the intrinsic properties of dark matter, and how does it interact?
What is dark energy?
Are there extra spatial dimensions?
...

The LHC may no longer be able to answer the above question.

We are in the era of AI, and it might be able to help us. Keep our fingers crossed.

Thank You !