Unified Composite Nature of Higgs and Dark Matter

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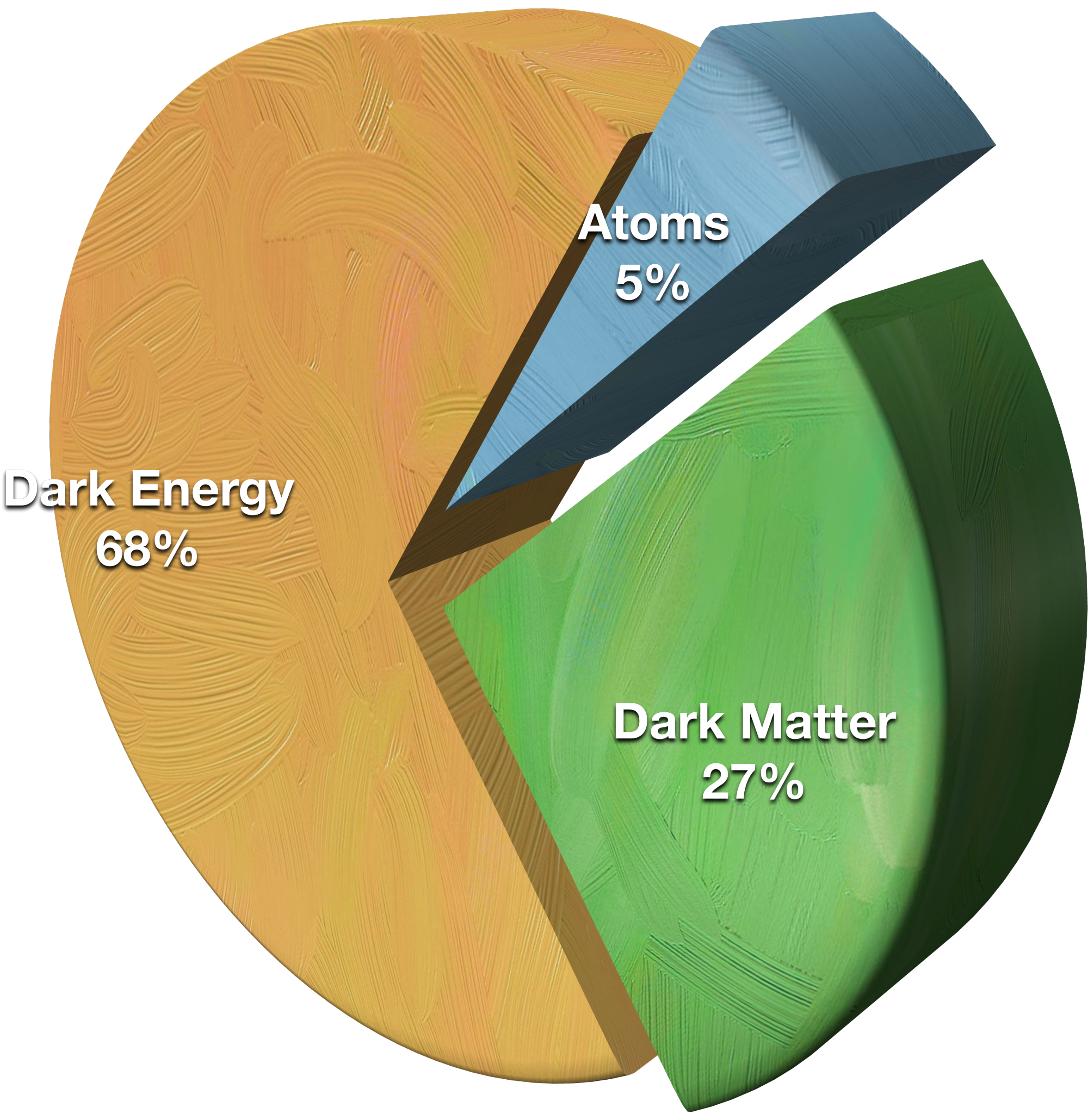
CP3 Origins
Cosmology & Particle Physics

Much ado for 5%



95% is unknown!

Richer than 5%? Most likely!

The Standard Model ado

Fields:

Gauge fields + fermions + scalars

Interactions:

Gauge: SU(3) x SU(2) x U(1) at EW scale

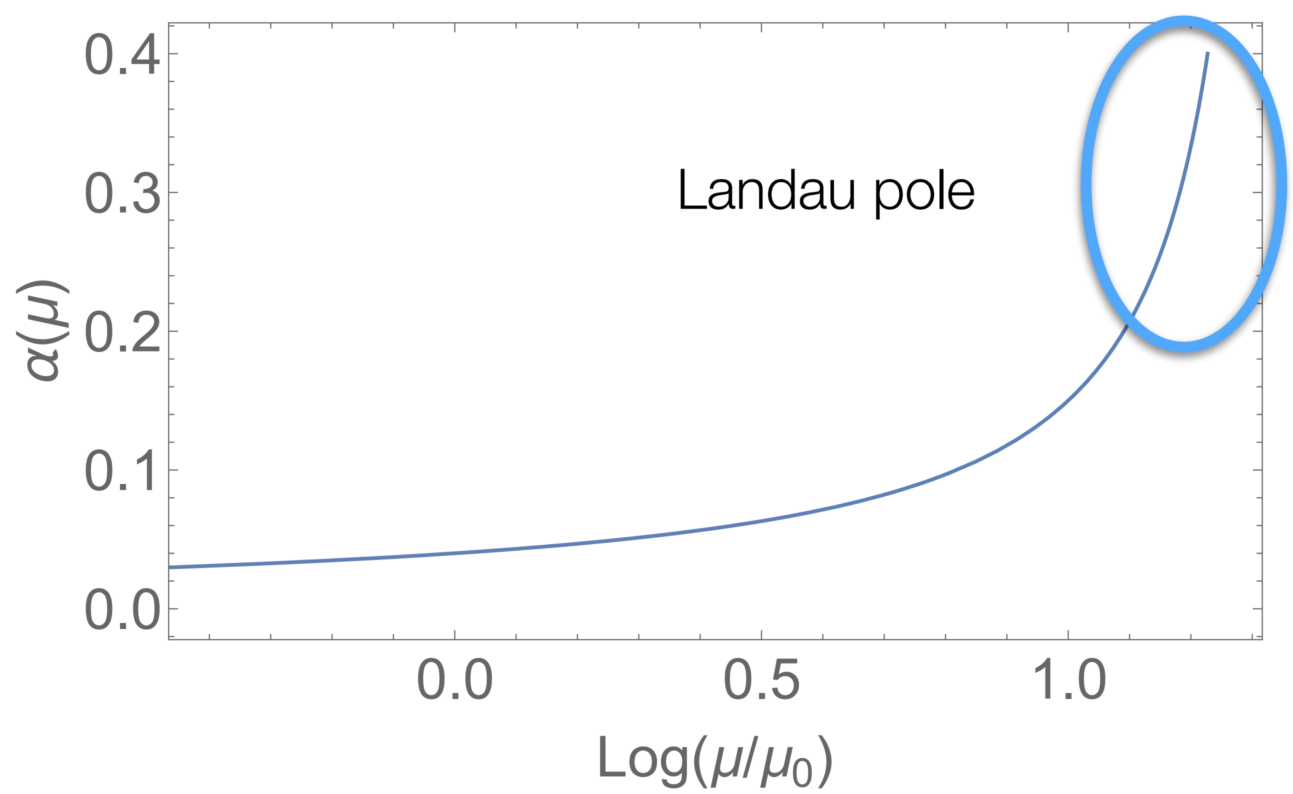
Yukawa: Fermion masses/Flavour

Culprit: Higgs

Scalar self-interaction

Two main issues

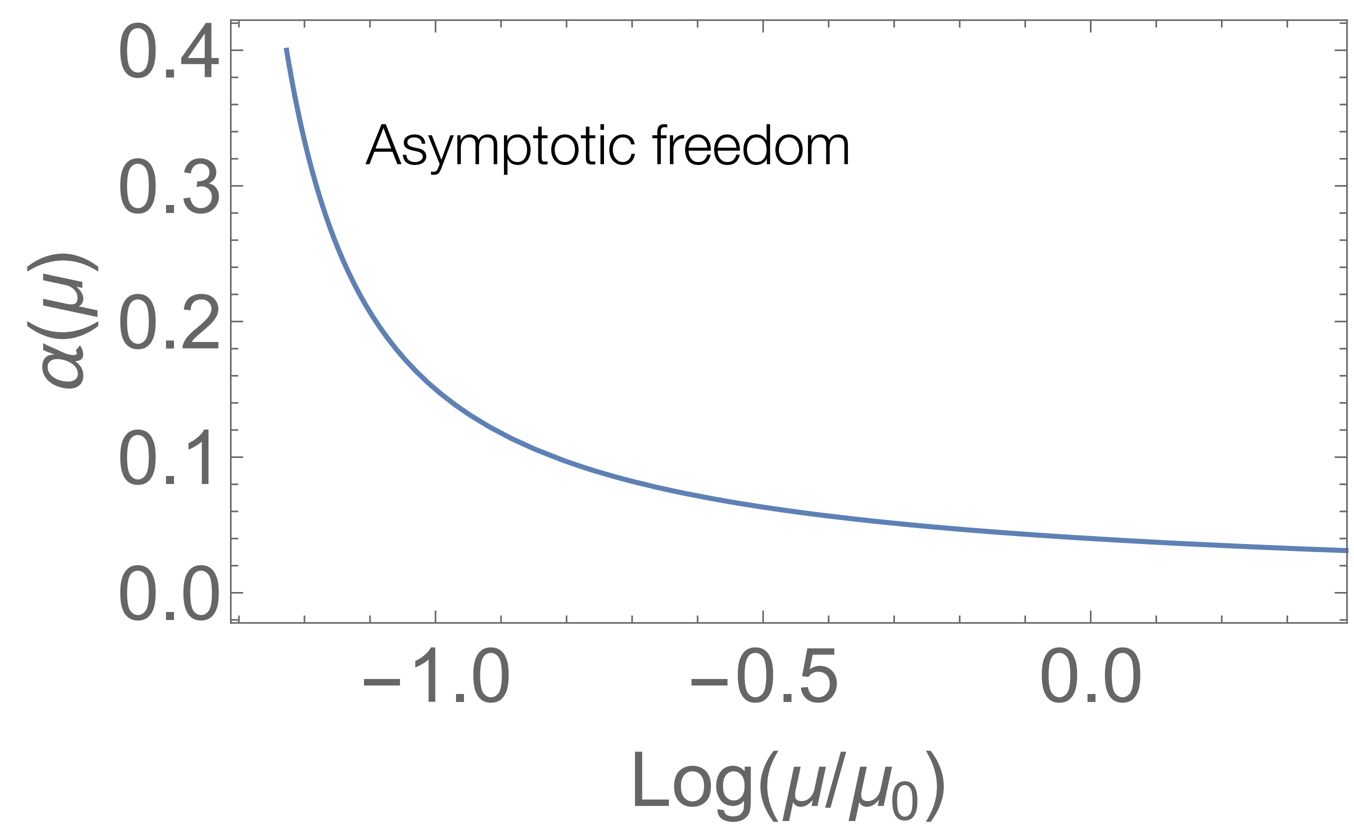
- EW scale stability
- UV triviality (Landau Pole)



The Compositeness Solution

- EW scale = Composite scale

- UV non trivial theories



Composite Higgs dynamics

$$DH^{\dagger}DH - V(H) + \overline{\Psi}_L H \psi_R$$

$$m_W^2 WW \qquad\qquad m_\psi \overline{\psi}_L \psi_R$$

TC ⟷ Extended TC

Technicolor

Higgs is the lightest scalar excitation of the condensate

Inside the box

- Break EW
- Theories available/unexplored
- Vacuum stable
- Natural

Outside the box

- Fermion masses vs FCNC
- Electroweak precision data
- Light Higgs

TC Higgs

TC - Higgs is the lightest spin-0 scalar made of TC-fermions

$$H \sim c_1 \bar{Q}Q + c_2 \bar{Q}Q\bar{Q}Q + \cdots$$

Will contain also a TC-glue component

QCD lightest scalar is $f_0(500)$ with mass ~ 400-550 MeV

Sannino & Schechter 95 PRD [‘t Hooft 1/N, crossing, chiral, pole mass]
Harada, Sannino & Schechter 95 PRD [$f_0(980)$], 96PRL
Pelaez - Confinement X - lecture

Narrow state in strong dynamics?

Example $f_0(980)$

$$\Gamma = 40 - 100 \text{ MeV} \qquad\qquad m = 990 \pm 20 \text{ MeV}$$

Narrow because near/below 2 kaon threshold

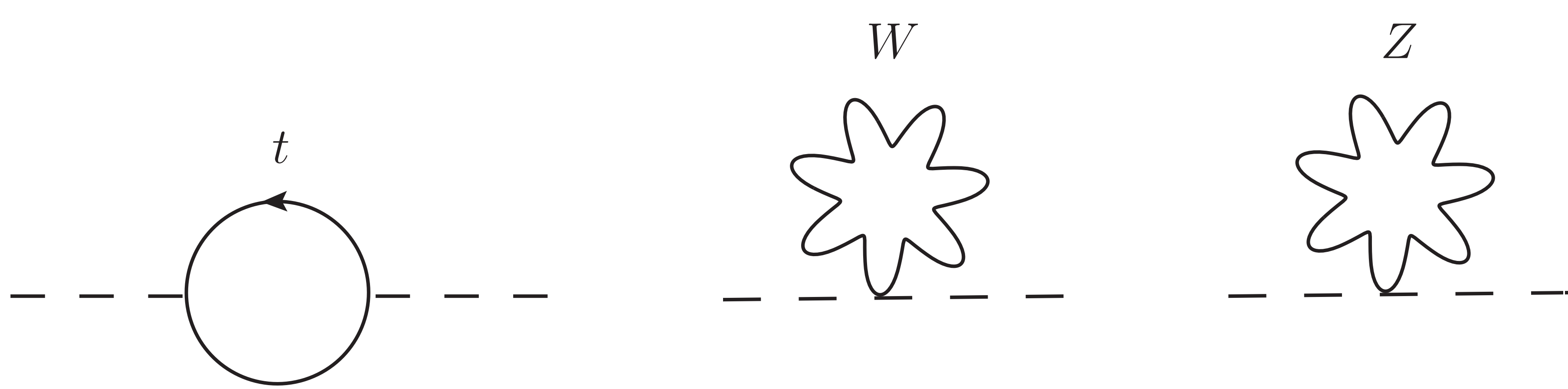
$$m_{2Kaons} \simeq 987.4 \text{ MeV}$$

Harada, Sannino & Schechter 95 PRD [$f_0(980)$], 96PRL [Large N apparent violation]

S. Weinberg 2013

Top - corrections

$$\mathcal{L}_H \supset \frac{2\, m_W^2\, r_\pi}{v} H\, W_\mu^+\, W^{-\mu} + \frac{m_Z^2\, r_\pi}{v} H\, Z_\mu\, Z^\mu - \frac{m_t\, r_t}{v} H\, \bar{t}\, t$$
$$+ \frac{m_W^2\, s_\pi}{v^2} H^2\, W_\mu^+\, W^{-\mu} + \frac{m_Z^2\, s_\pi}{2\, v^2} H^2\, Z_\mu\, Z^\mu$$



$$M_H^2 = (M_H^{\rm TC})^2 + \frac{3(4\pi\kappa F_\Pi)^2}{16\pi^2 v^2}\left[-4 r_t^2 m_t^2 + 2 s_\pi \left(m_W^2 + \frac{m_Z^2}{2}\right)\right] + \Delta_{M_H^2}(4\pi\kappa F_\Pi)$$

Foadi, Frandsen, Sannino, 1211.1083 PRD

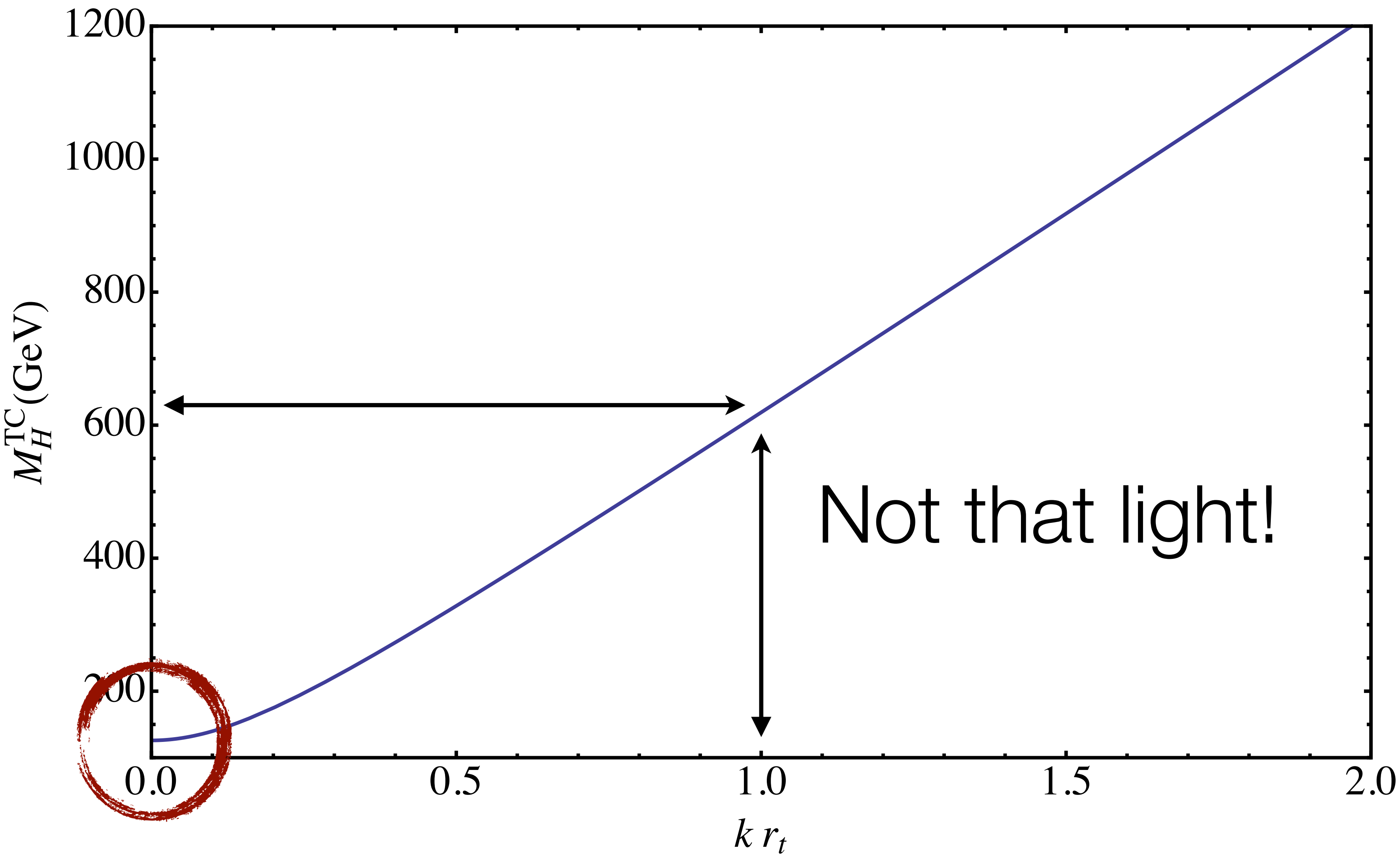
Cacciapaglia, Sannino 1402.0233 JHEP

How light is the TC-Higgs ?

$$(M_H^{\mathrm{TC}})^2 \simeq M_H^2 + 12\ \kappa^2 r_t^2 m_t^2$$

$\kappa\ r_t$ ~ TC x ETC

$$F_\Pi = v$$



Narrow due to kinematics [Similar to $f_0(980)$ in QCD]

(Lattice) $SU(3)_S$ MWT

Sannino & Tuominen hep-ph/0405209

Fodor, Holland, Kuti, Nogradi, Schroeder, Wong, 1209.0391 [LHC collaboration]

$$M_\rho \simeq 1754 \pm 104 \text{ GeV} \qquad M_{A_1} \simeq 2327 \pm 121 \text{ GeV}$$

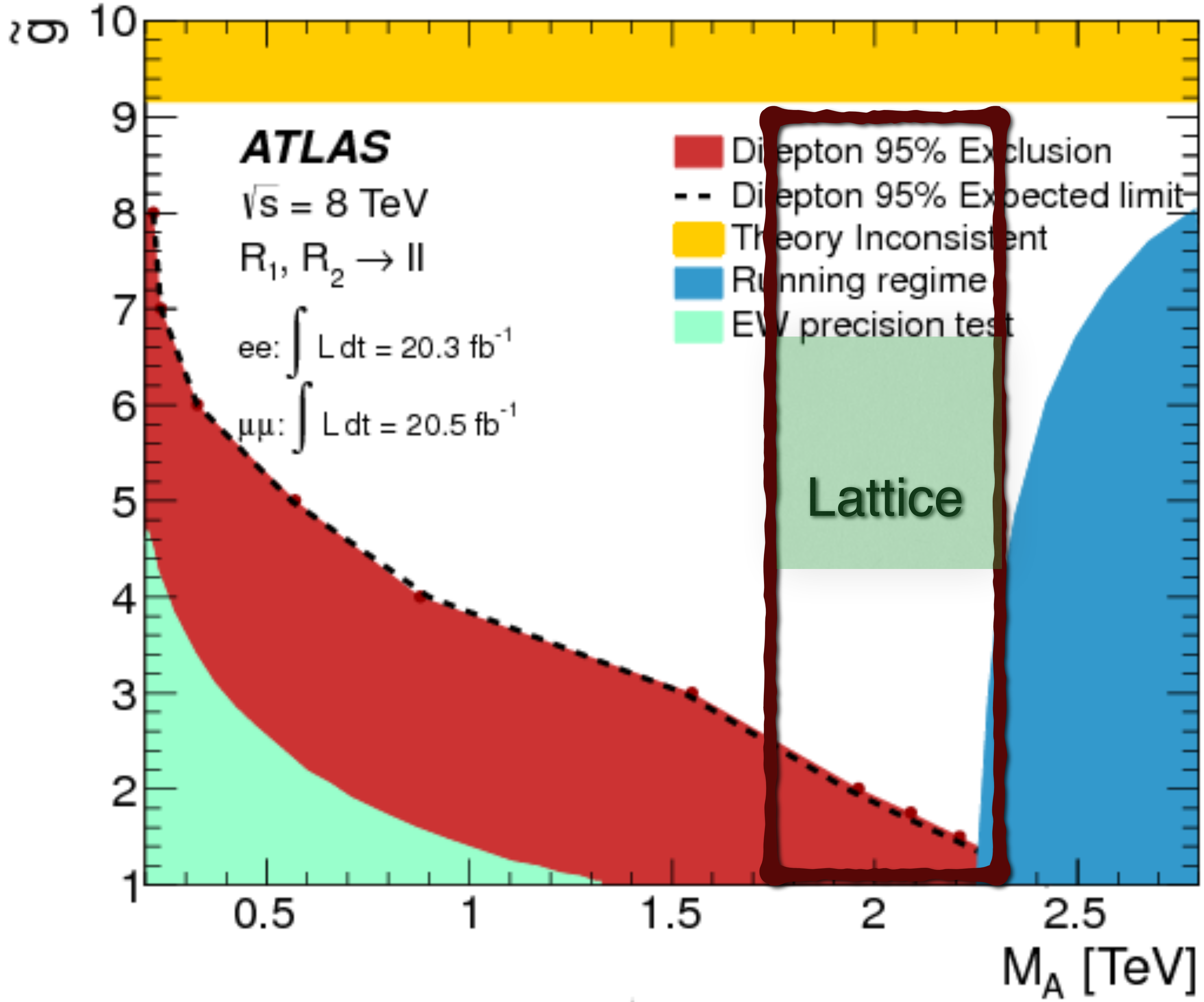
$$M_H^{TC} \approx 200 - 700 \text{ GeV}$$

Scalar mass in line with theory expectations: 1401.2176

US - Germany - Hungary collaboration



Di-leptons -predictions for $SU(3)_S$ MWT



ATLAS arXiv:1405.4123

LHC can discover/rule-out MWT

Composite Goldstone Higgs

D.B. Kaplan & H. Georgi, 84

Higgs is a pseudo goldstone boson

Inside the box

- Higgs is massless
- Gauge boson couplings

Work in 4 dimensions

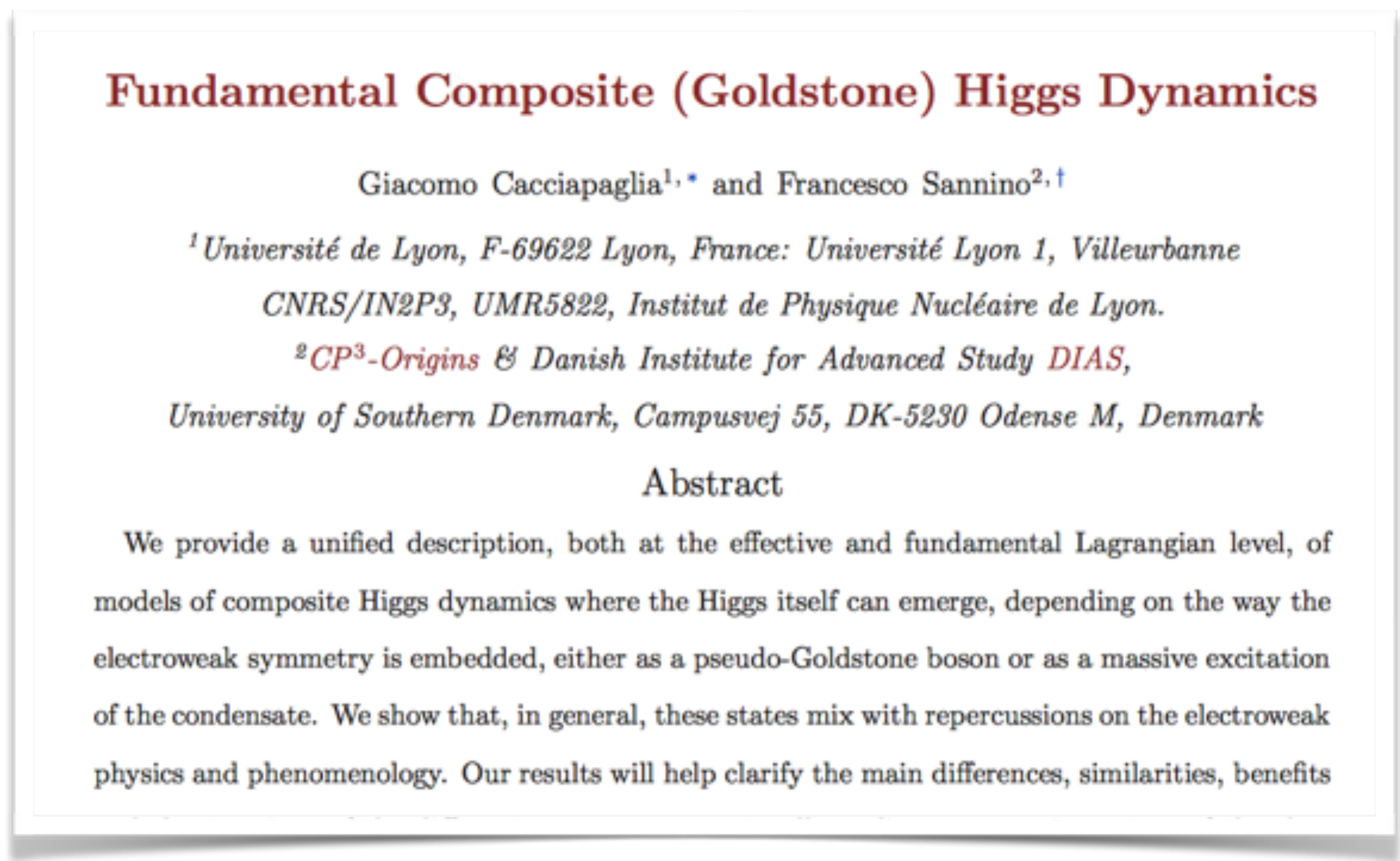
Outside the box

- Underlying theory
- Higgs mass
- Fermion masses/couplings
- EW vacuum alignment

Composite Dynamics 2014$^+$

Cacciapaglia and Sannino arXiv:1402.0233 JHEP

- Unified TC and CH framework
- Fund 4D underlying theory
- Spectrum via lattice



Fundamental Composite (Goldstone) Higgs Dynamics

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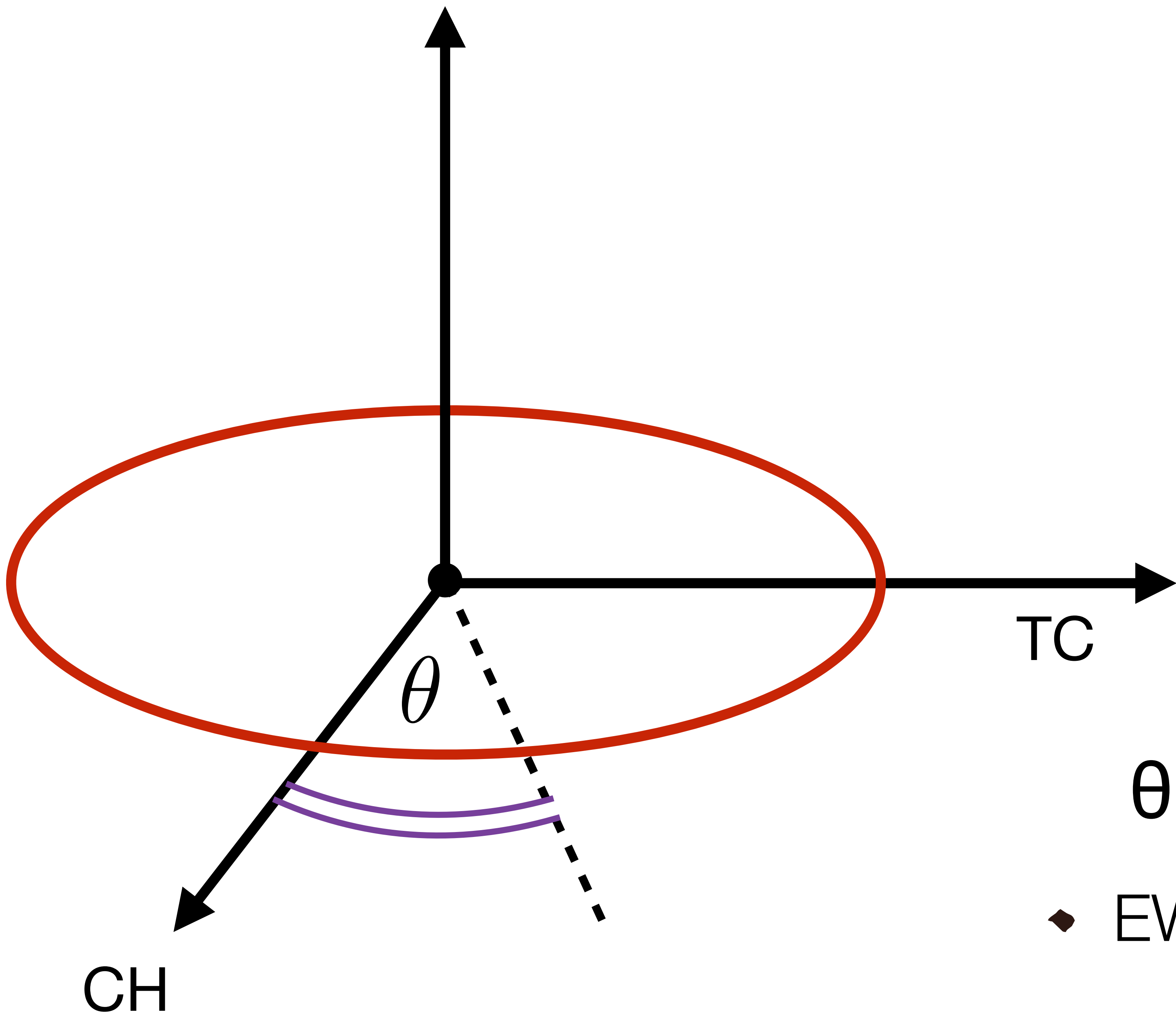
[2] *CP^3-Origins & Danish Institute for Advanced Study DIAS, University of Southern Denmark, Campusvej 55, DK-5230 Odense M, Denmark*

Abstract

We provide a unified description, both at the effective and fundamental Lagrangian level, of models of composite Higgs dynamics where the Higgs itself can emerge, depending on the way the electroweak symmetry is embedded, either as a pseudo-Goldstone boson or as a massive excitation of the condensate. We show that, in general, these states mix with repercussions on the electroweak physics and phenomenology. Our results will help clarify the main differences, similarities, benefits

CoDyCE project: Unified pheno + Lattice @ LHC13.5 underway

How does it work?



$\theta = 0$

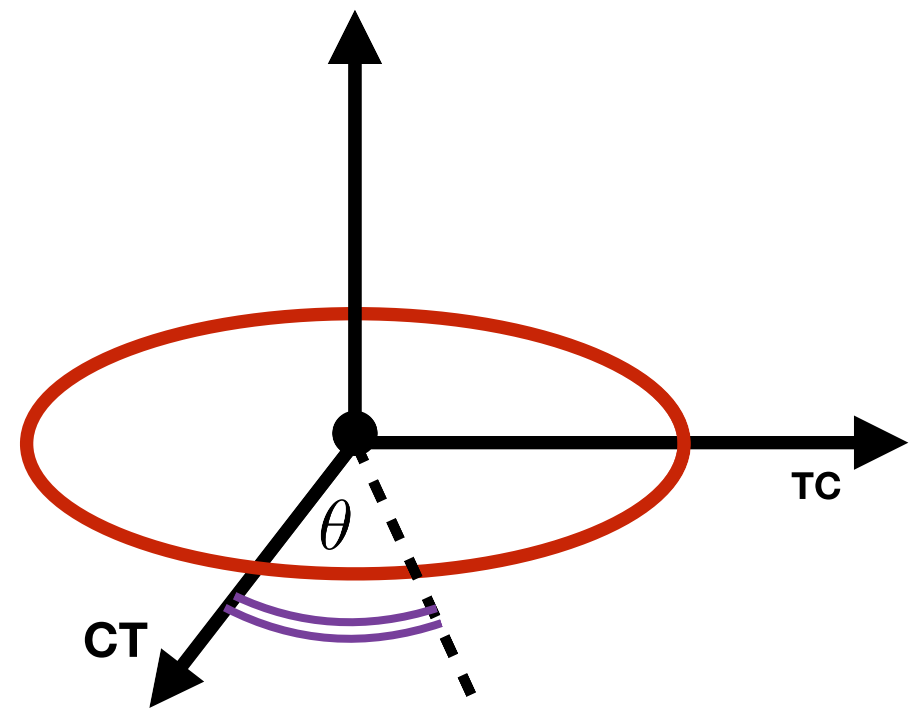
- EW does not break
- Higgs is exact GB

$\theta = \pi/2$

- EW breaks
- Higgs is massive excitation

What fixes θ ?

- Gauge bosons quantum corrections
- Top corrections
- Explicit breaking of global symmetry

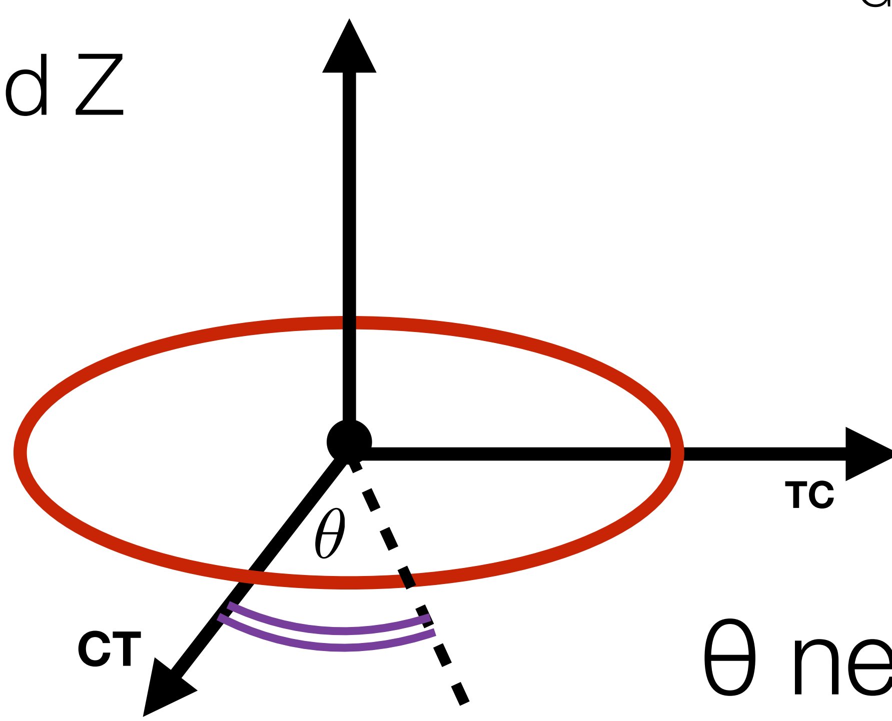


Mixed case is natural: $0 < \theta < \pi/2$

A pattern SU(4) →Sp(4)~SO(5)

- Fundam. underlying 4d dynamics
- 5 Goldstone Bosons
- 3 eaten by W^+, W^- and Z

Appelquist, Sannino, 98, 99
Ryttov, Sannino, 2008
Katz, Nelson Walker, 2005
Gripaios, Pomarol, Riva, Serra, 2009
Galloway, Evans, Luty, Tacchi, 2010



θ near zero

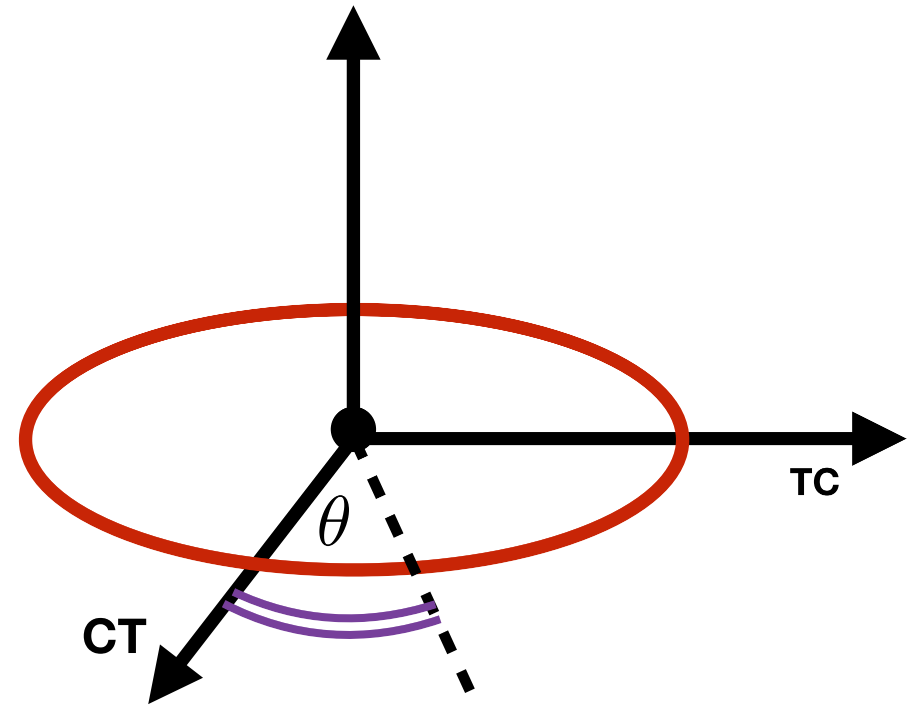
- One GB is Higgs-like
- Other GB is SM neutral

θ near π/2

- Complex GB, SM-neutral
- Natural DM candidate*

Generic properties

- TC-Higgs and PGB Higgs mix
- Top reduces TC-Higgs mass
- Top contributes PGB Higgs mass



@ θ near zero

$$\frac{g_{WWh_1}}{g^{SM}_{WWh}} = 1 + C_{h_2 h_1}\,\theta + \mathcal{O}(\theta^2)$$

$$\frac{g_{t\bar{t}h_1}}{g^{SM}_{t\bar{t}h}} = 1 + D_{h_2 h_1}\,\theta + \mathcal{O}(\theta^2)$$

- h_1 and h_2 are eigenstates
- C & D vanish for large m_{h2} mass
- Modified higgs phenomenology
- A new TeV scalar before vectors?

Spin one resonances

- Simply rescale TC limit by sinθ
- Small coupling to SM fermions via GB mixing

$$m_\rho = \frac{m_\rho^{TC}}{\sin\theta} \qquad m_A = \frac{m_A^{TC}}{\sin\theta}$$

Minimal Fund. Gauge Theory

SU(2) = Sp(2) - Template

Appelquist, Sannino, 98, 99

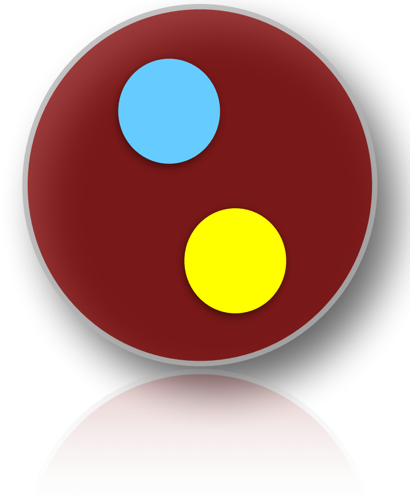
Ryttov, Sannino, 2008

Järvinen, Ryttov, Sannino, 2009

Lewis, Pica, Sannino 2012

Hietanen, Lewis, Pica, Sannino 2013, 2014

Sp(2)



$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \overline{Q}(i\gamma^\mu D_\mu) Q$$

$$Q = \begin{pmatrix} U_L \\ D_L \\ -i\sigma^2 C \overline{U}_R^T \\ -i\sigma^2 C \overline{D}_R^T \end{pmatrix}$$

- Act. invariant under SU(4) transf.

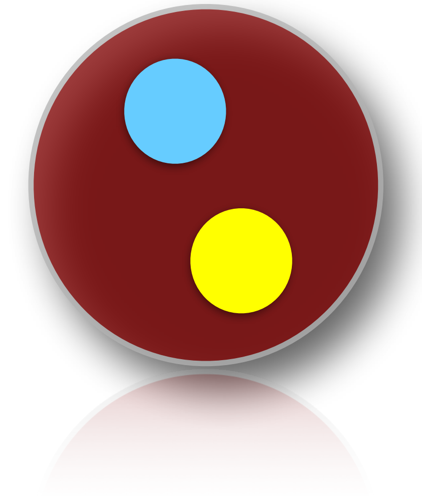
$$Q \to \left(1 + i \sum_{k=1}^{15} \alpha^k T^k\right) Q$$

- Mass term respects Sp(4) with 10 generators

$$\delta\mathcal{L} = \frac{m}{2} Q^T (-i\sigma^2) C\, E Q + \text{h.c.}$$

$$E = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

Theoretical expectations

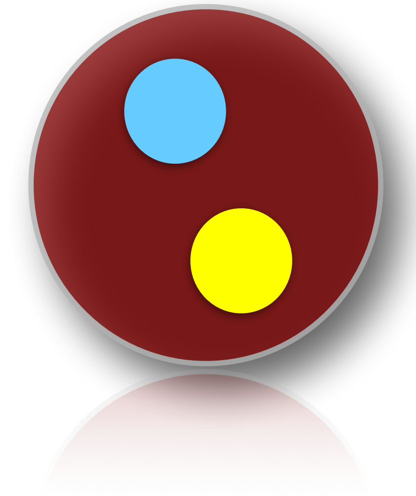


- @ m=0

$$\langle Q^T(-i\sigma^2)C\,EQ\rangle = \langle \bar{U}U + \bar{D}D\rangle = \Lambda^3 \neq 0$$

- SU(4) can break spontaneously to Sp(4)
- Composite spectrum are representations of Sp(4)
- 5 Goldstones

Hadronic operators



- Mesons

$$\mathcal{O}^{(\Gamma)}_{\overline{U}D} \equiv \overline{U}(x)\Gamma D(x) \ ,$$
$$\mathcal{O}^{(\Gamma)}_{\overline{D}U} \equiv \overline{D}(x)\Gamma U(x) \ ,$$
$$\mathcal{O}^{(\Gamma)}_{\overline{U}U\pm\overline{D}D} \equiv \frac{1}{\sqrt{2}}\left(\overline{U}(x)\Gamma U(x) \pm \overline{D}(x)\Gamma D(x)\right)$$

- Baryons (diquarks)

$$\mathcal{O}^{(\Gamma)}_{UD} \equiv U^T(x)(-i\sigma^2)C\Gamma D(x) \ ,$$
$$\mathcal{O}^{(\Gamma)}_{DU} \equiv D^T(x)(-i\sigma^2)C\Gamma U(x) \ ,$$
$$\mathcal{O}^{(\Gamma)}_{UU\pm DD} \equiv \frac{1}{\sqrt{2}}\left(U^T(x)(-i\sigma^2 C)\Gamma U(x) \pm D^T(x)(-i\sigma^2 C)\Gamma D(x)\right)$$

$$\Gamma = 1, \gamma^5, \gamma^\mu, ...$$

Facts

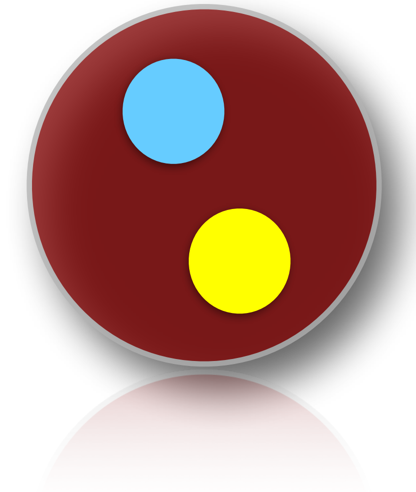
- Mesons and baryons are mass-degenerate
- Equal angular momentum & opposite parity

$$
\begin{aligned}
J\left(\mathcal{O}^{(\Gamma)}_{UD}\right) &= J\left(\mathcal{O}^{(\Gamma)}_{\bar{U}D}\right), \\
P\left(\mathcal{O}^{(\Gamma)}_{UD}\right) &= -P\left(\mathcal{O}^{(\Gamma)}_{\bar{U}D}\right)
\end{aligned}
$$

- 5 Goldstones

pseudoscalar	Π^+	Π^-	Π^0
scalar baryon	Π_{UD}	$\Pi_{\overline{UD}}$	

Minimal TC Model & DM



$$\theta = \frac{\pi}{2}$$

Appelquist, Sannino, 98, 99

Ryttov, Sannino, 2008

Järvinen, Ryttov, Sannino, 2009

- Gauge $SU_L(2)xU_Y(1)$ in SU(4)

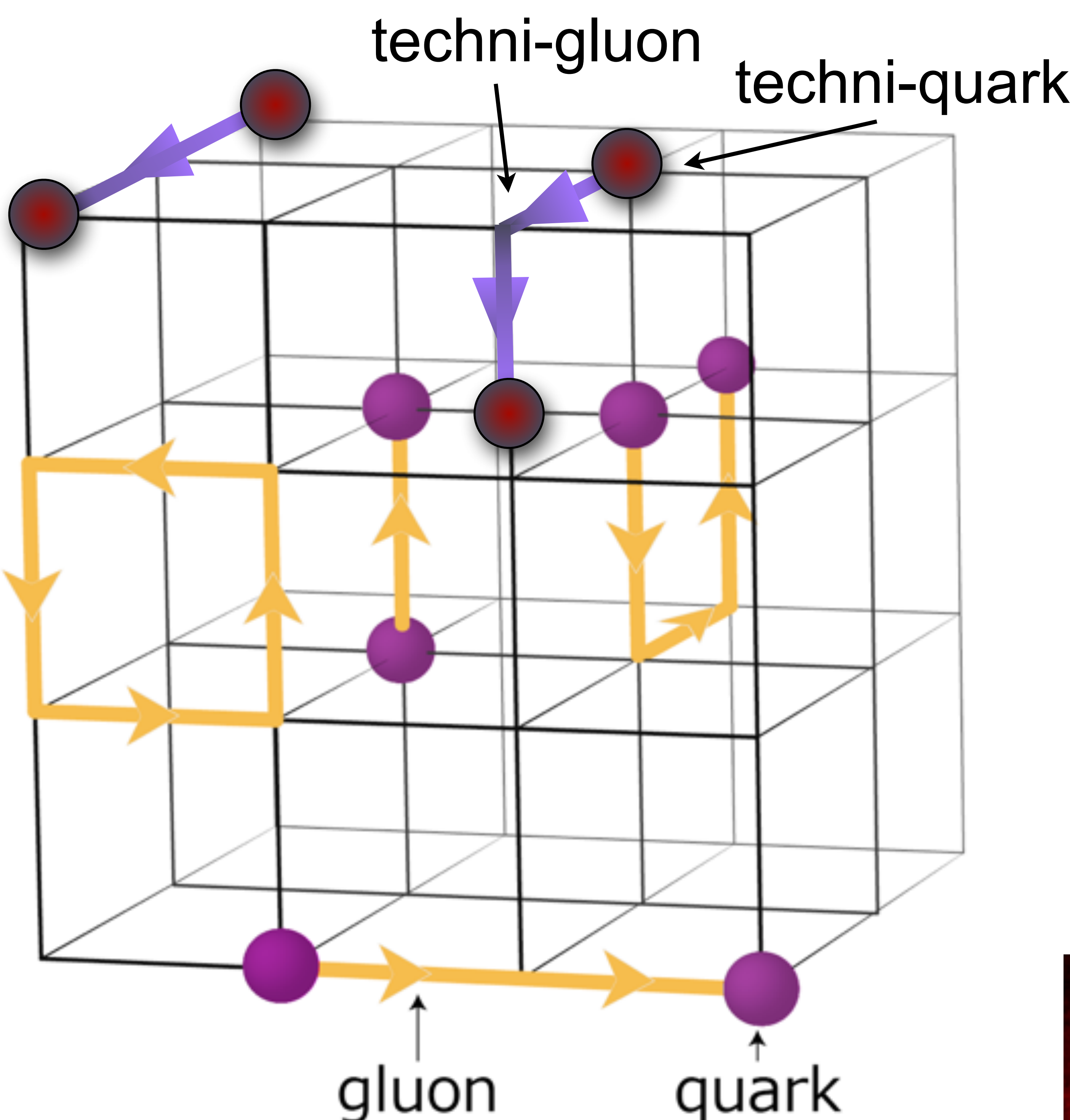
$$f_\Pi \simeq 246 \text{ GeV}$$

- Such that

Π^+	Π^-	Π^0	Longitudinal W and Z
Π_{UD}	$\Pi_{\overline{UD}}$		Goldstone DM & anti-DM, SM singlet

- Fermion mass generation sectors can yield mass to DM

Composite EW on Lattice



Lewis, Pica, Sannino 2012

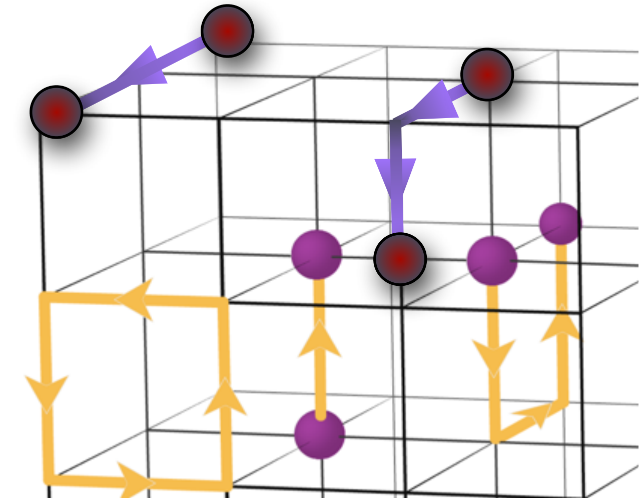
Hietanen, Pica, Sannino, Søndergaard 2013

Hietanen, Lewis, Pica, Sannino 2013

Hietanen, Lewis, Pica, Sannino 2014

Canadian-Danish collaboration

Wilson action



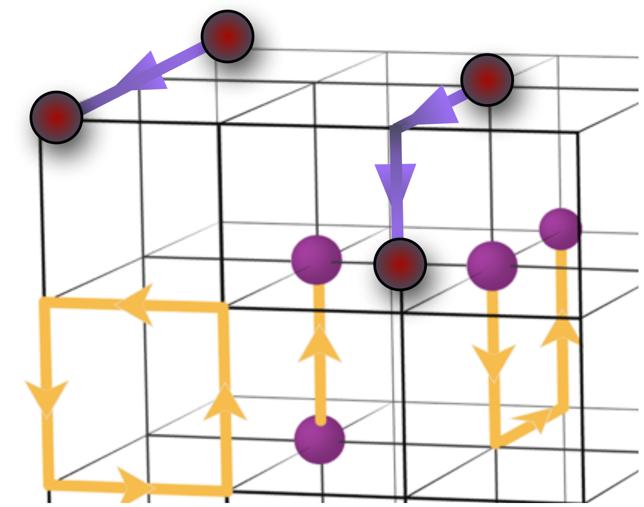
$$S_W = \frac{\beta}{2}\sum_{x,\mu,\nu}\left(1-\frac{1}{2}\mathrm{ReTr}U_\mu(x)U_\nu(x+\hat{\mu})U_\mu^\dagger(x+\hat{\nu})U_\nu^\dagger(x)\right)$$
$$+ (4+m_0)\sum_x \bar{\psi}(x)\psi(x)$$
$$-\frac{1}{2}\sum_{x,\mu}\left(\bar{\psi}(x)(1-\gamma_\mu)U_\mu(x)\psi(x+\hat{\mu})+\bar{\psi}(x+\hat{\mu})(1+\gamma_\mu)U_\mu^\dagger(x)\psi(x)\right)$$

β	Volume	m_0	Therm.	Conf.
2.0	$16^3 \times 32$	-0.85, -0.9, -0.94, -0.945, -0.947, -0.949	320	680
2.0	32^4	-0.947	500	680
2.2	$16^3 \times 32$	-0.60, -0.65, -0.68, -0.70, -0.72, -0.75	320	680
2.2	$24^3 \times 32$	-0.75	500	~2000
2.2	32^4	-0.72,-0.735, -0.75	500	~2000

Therm. = # of discarded configurations

Conf. = # of independent conf. used

- Fermion mass via PCAC



$$m_{\rm q} = \lim_{t\to\infty} \frac{1}{2}\frac{\partial_t V_\Pi}{V_{\rm PP}}$$

$$V_\Pi(t_i - t_f) = a^3 \sum_{x_1,x_2,x_3} \langle \overline{u}(t_i)\gamma_0\gamma_5 d(t_i)\overline{u}(t_f)\gamma_5 d(t_f)\rangle$$

$$V_{\rm PP}(t_i - t_f) = a^3 \sum_{x_1,x_2,x_3} \langle \overline{u}(t_i)\gamma_5 d(t_i)\overline{u}_1(t_f)\gamma_5 d(t_f)\rangle$$

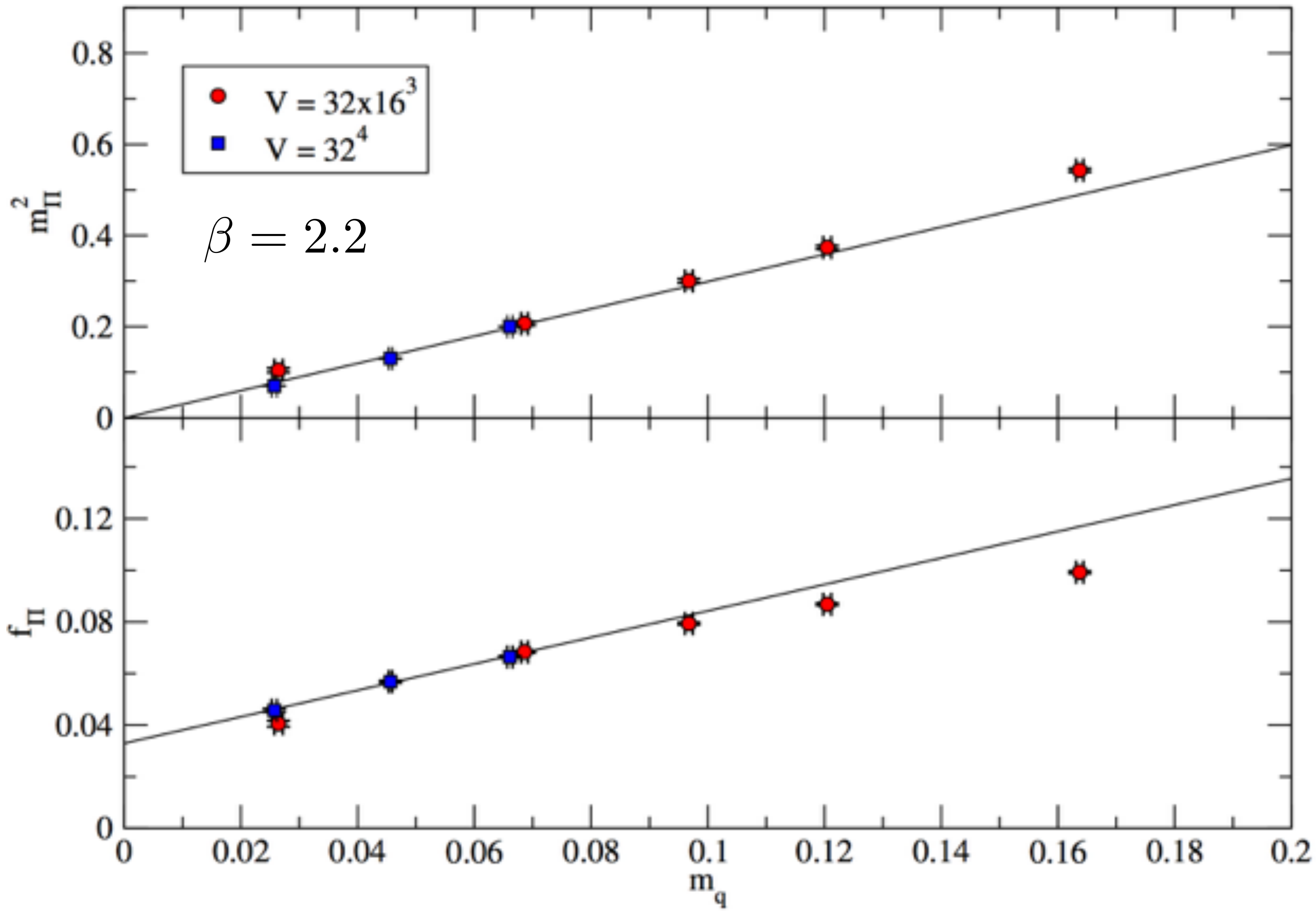
- Decay constant

$$f_\Pi = \frac{m_{\rm q}}{m_\Pi^2} G_\Pi \qquad V_{\rm PP}(t_i - t_f) = -\frac{G_\Pi^2}{m_\Pi} \exp\left[-m_\Pi(t_i - t_f)\right]$$

- 2 point functions

$$C^{(\Gamma)}_{\overline{u}d}(t_i - t_f) = \sum_{\vec{x}_i,\vec{x}_f} \left\langle \mathcal{O}^{(\Gamma)}_{ud}(x_f)\mathcal{O}^{(\Gamma)\dagger}_{ud}(x_i)\right\rangle = \sum_{\vec{x}_i,\vec{x}_f} {\rm Tr}\Gamma S_{d\overline{d}}(x_f,x_i)\gamma^0\Gamma^\dagger\gamma^0 S_{u\overline{u}}(x_i,x_f)$$

$$S_{u\overline{u}}(x,y) = \langle u(x)\overline{u}(y)\rangle$$



- Chiral symmetry breaks

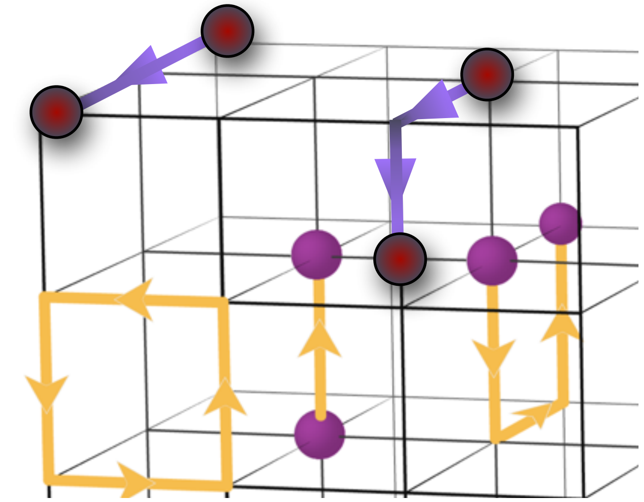
$$m_\Pi^2 \propto m_q$$

- Nonzero decay constant

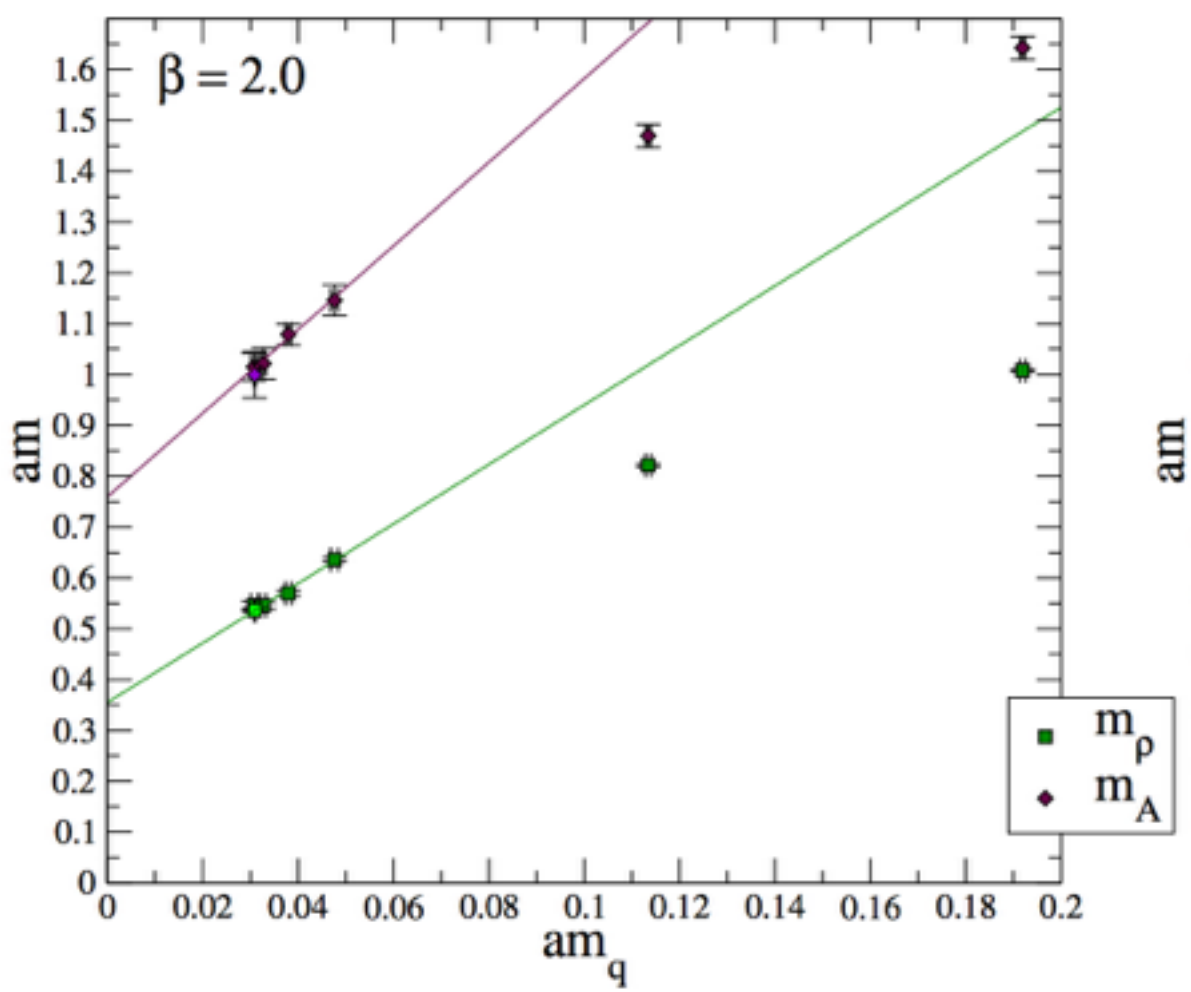
- Perturbative estimate of Z_a

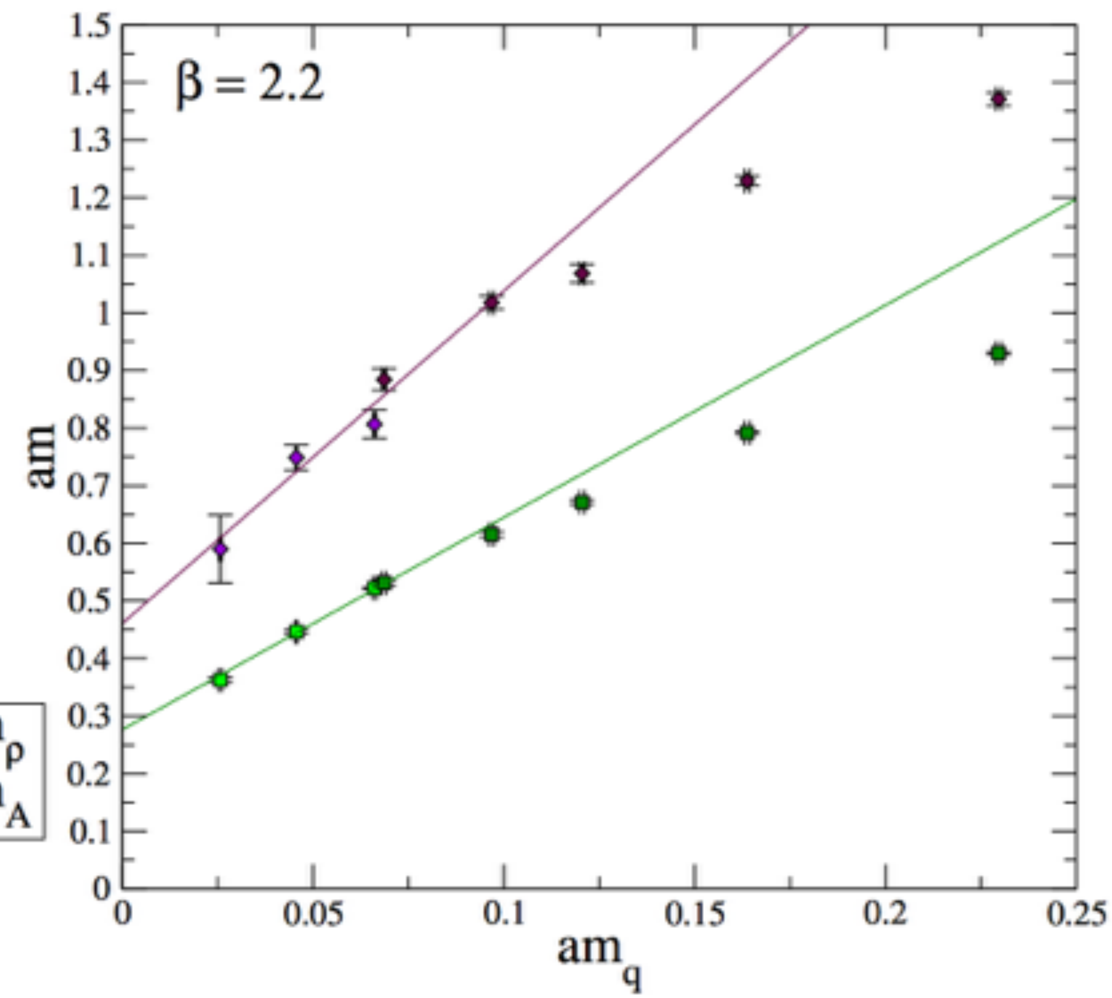
$$Z_a = 1 - \frac{g_0^2}{16\pi^2}\frac{N^2-1}{2N}15.7 \overset{N=2}{=} 1 - 0.2983/\beta$$

Spin one spectrum

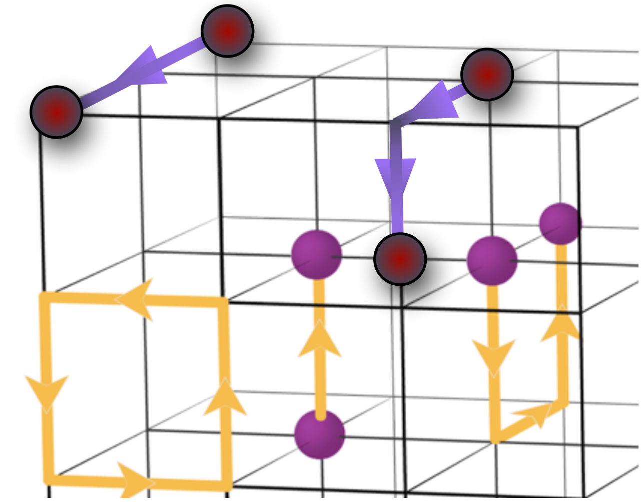


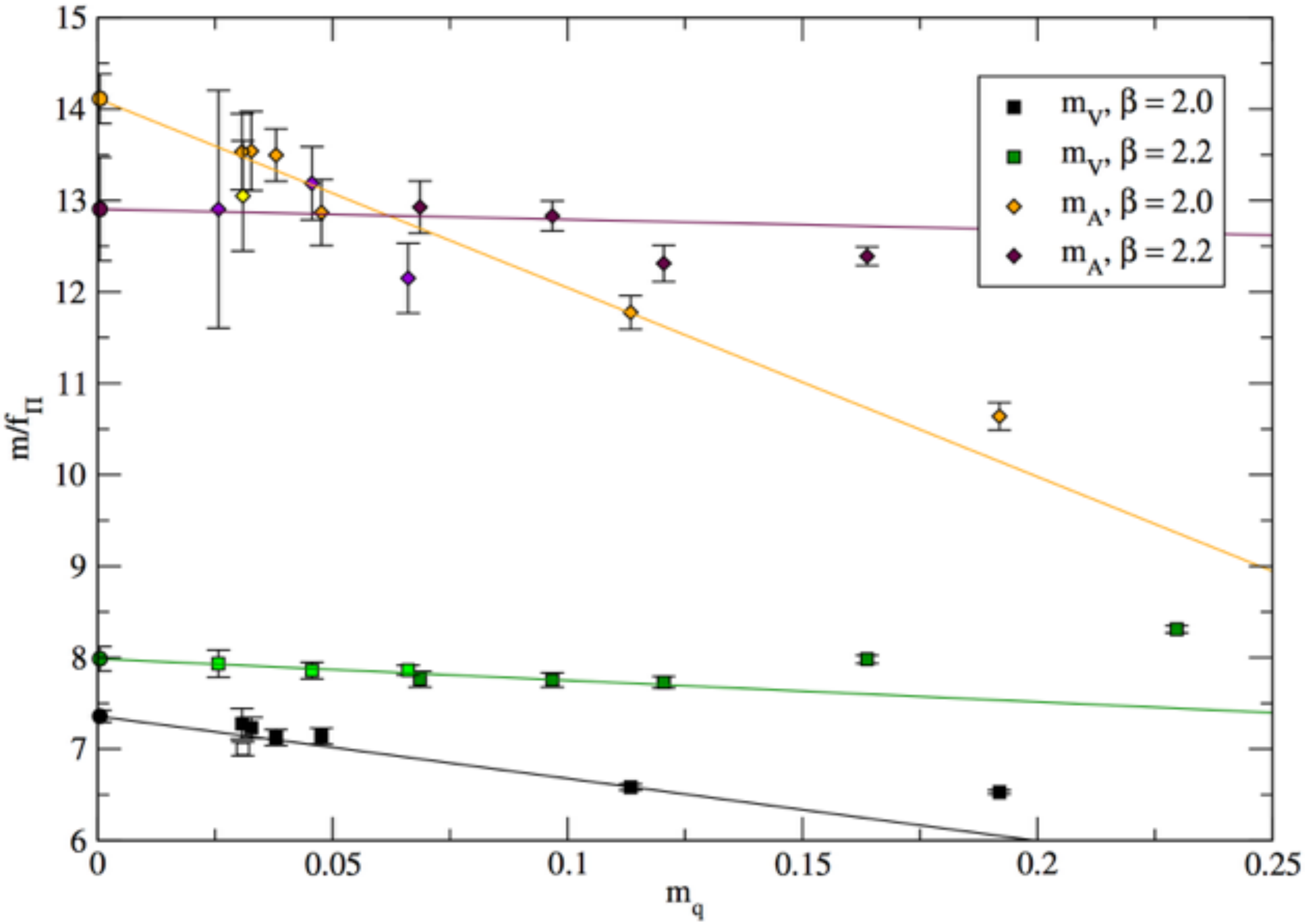
- 2 Volumes: $16^3 \times 32$ and 32^4 in lighter colors
- Smaller volume effects for beta = 2.0
- Larger volume effects for the most chiral points for beta = 2.2
- Volume corrections for lighter masses





Continuum estimates



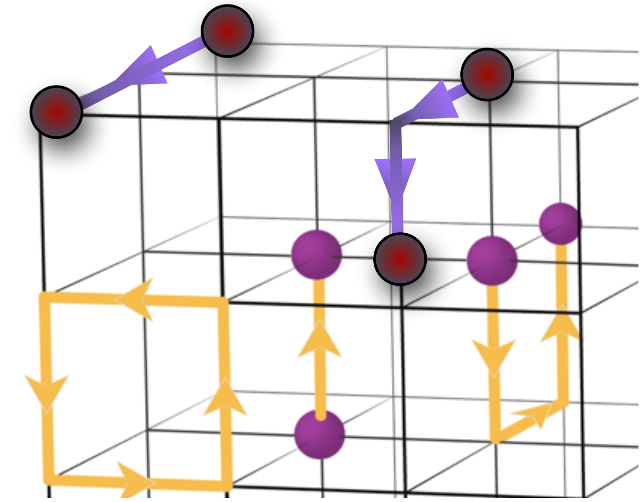


$$m_\rho \simeq 2510(40)(280)(300)\ \text{GeV}$$

$$f_\Pi \simeq 246\ \text{GeV} \qquad m_A \simeq 3270(130)(370)(370)\ \text{GeV}$$

(stat.) (continuum) (Z_a)

Lattice for LHC



- SU(4) breaks to Sp(4)
- 5 Goldstone bosons
- Goldstone form factors

Lewis, Pica, Sannino 2012

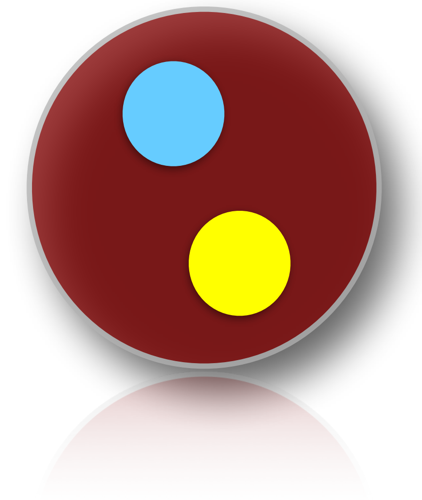
Hietanen, Lewis, Pica, Sannino 2013, 2014

Unified spin one spectrum predictions:

$$m_\rho = 2.5 \pm 0.5 \ \text{TeV}/\sin\theta \qquad m_A = 3.3 \pm 0.7 \ \text{TeV}/\sin\theta$$

Canadian-Danish

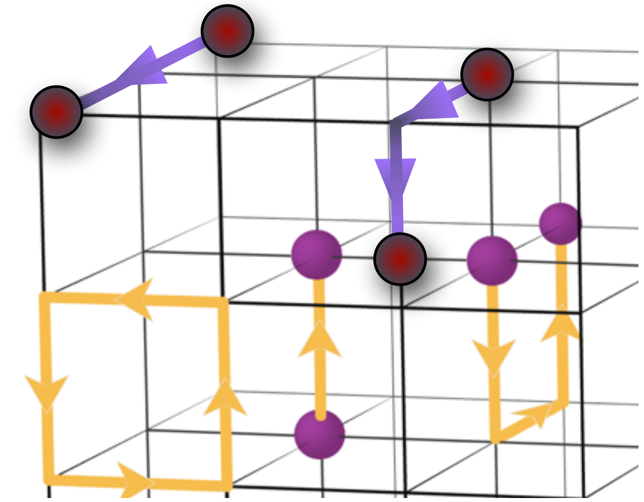
Hietanen, Lewis, Pica, Sannino 1404.2794



Composite (Goldstone) Dark Matter

$$\theta = \frac{\pi}{2}$$

DM-photon interaction



- U_L and D_L form a weak doublet
- U_R and D_R fields are weak singlets
- U (D) have 1/2 (-1/2) *electric charge*
- No gauge and Witten anomalies

Dark coupling to photon via charge radius

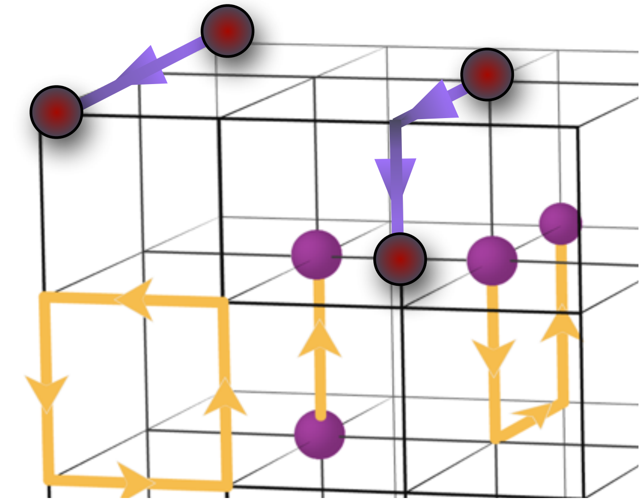
$$\phi \equiv \Pi_{UD}$$

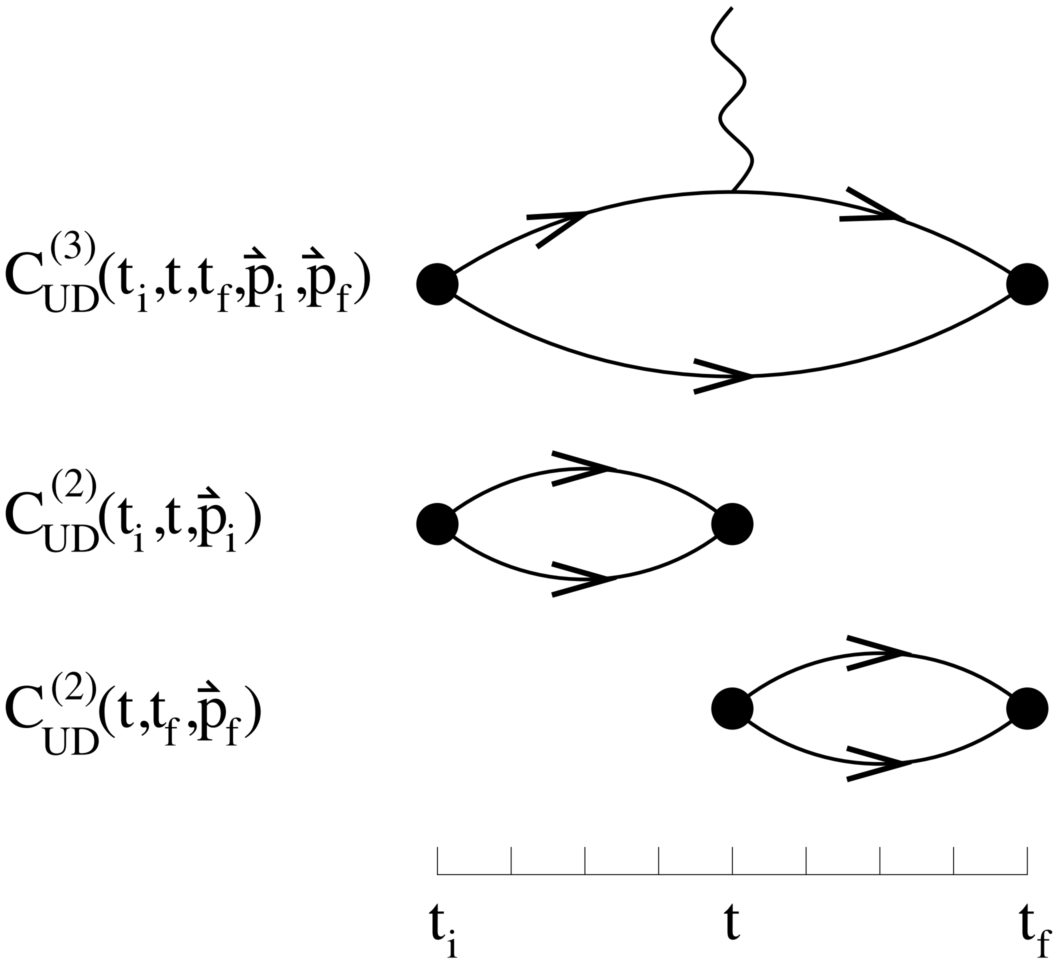
$$\mathcal{L}_\gamma = ie\frac{d_B}{\Lambda^2}\phi^* \overleftrightarrow{\partial_\mu}\phi\,\partial_\nu F^{\mu\nu}$$

$$\frac{d_B}{\Lambda^2} = ?$$

- Need to determine 3-point functions (GBs form factors)

GBs vector form factors



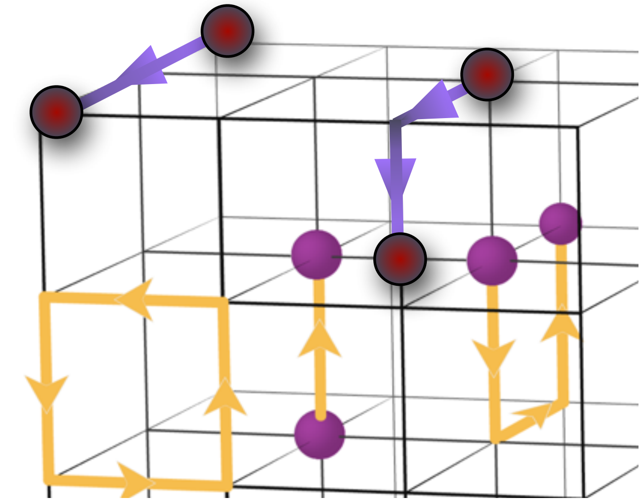


- Lattice electromagnetic current

$$
\begin{aligned}
V_\mu(x) &= \frac{1}{2}V_\mu^U(x) - \frac{1}{2}V_\mu^D(x) \\
V_\mu^X(x) &= \frac{1}{2}\overline{X}(x+\hat{\mu})(1+\gamma_\mu)U_\mu^\dagger(x)X(x) \\
&- \frac{1}{2}\overline{X}(x)(1-\gamma_\mu)U_\mu(x)X(x+\hat{\mu})
\end{aligned}
$$

$$
F_\Pi(Q^2) = \frac{C_{ud}^{(3)}(t_i,t,t_f,\vec{p}_i,\vec{p}_f)C_{ud}^{(2)}(t_i,t,\vec{p}_f)}{C_{ud}^{(2)}(t_i,t,\vec{p}_i)C_{ud}^{(2)}(t_i,t_f,\vec{p}_f)}\left(\frac{2E_\Pi(\vec{p}_f)}{E_\Pi(\vec{p}_i)+E_\Pi(\vec{p}_f)}\right)
$$

Avoiding disconnected diagrams

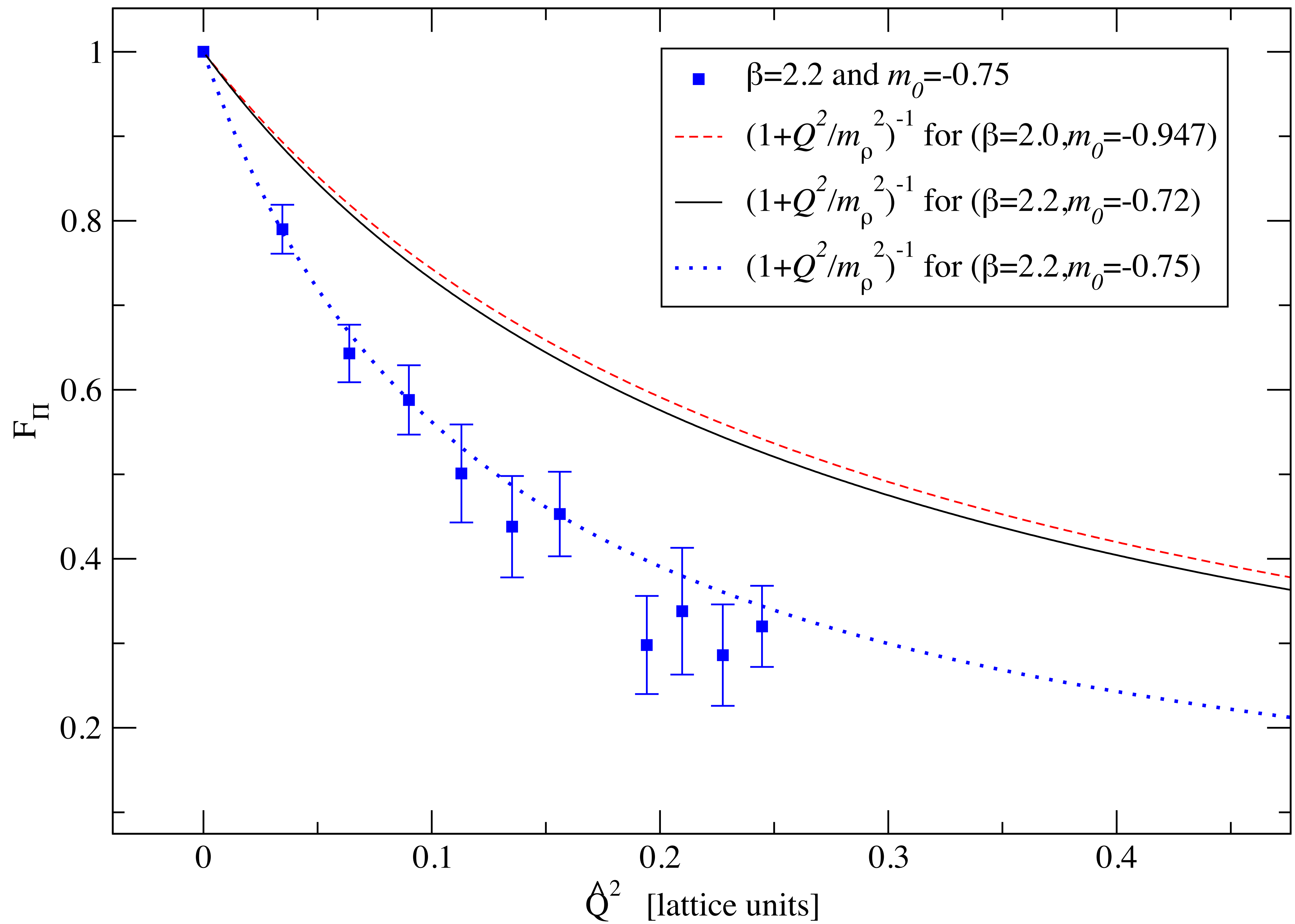


- Lattice simulation expensive for different fermion masses
- But for $m_U = m_D$ form factors vanish
- Up and Down are related in QCD at large N [works for N=3]

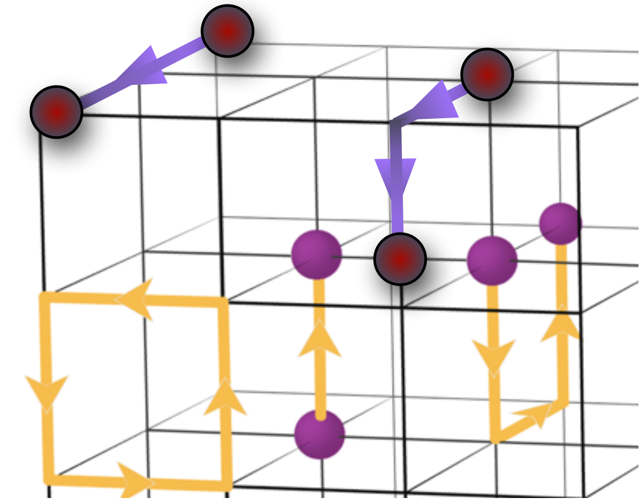
$$
\begin{aligned}
F_{\pi^+}(Q^2) &\approx \frac{2}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)+\frac{1}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)\\
F_{K^+}(Q^2) &\approx \frac{2}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)+\frac{1}{3}\left(\frac{m_\phi^2}{m_\phi^2+Q^2}\right)\\
F_{K^0}(Q^2) &\approx -\frac{1}{3}\left(\frac{m_\rho^2}{m_\rho^2+Q^2}\right)+\frac{1}{3}\left(\frac{m_\phi^2}{m_\phi^2+Q^2}\right)
\end{aligned}
$$

We will test VMD for SU(2)

GB form factor vs vector pole



Lattice prediction



- Form factor requires isospin breaking from ETC

Lattice determines

$$\Lambda = m_\rho \,, \quad d_B = \frac{m_{\rho_U} - m_{\rho_D}}{m_\rho}$$

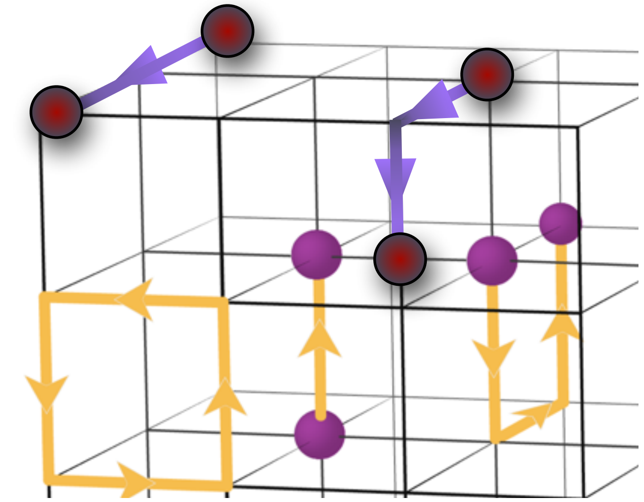
- EM cross section with proton

$$\sigma_p^\gamma = \frac{\mu^2}{4\pi} \left(\frac{8\pi\alpha d_B}{\Lambda^2} \right)^2 \quad \mu = \frac{m_\phi m_N}{m_\phi + m_N} \qquad |d_B| < 1 \quad m_\phi > m_p$$

$$\sigma_p^\gamma < 2.3 \times 10^{-44} \text{ cm}^2$$

First principle !

DM inter. with Higgs ?



Basic interactions

$$\mathcal{L}_h = \frac{d_1}{\Lambda} h\, \partial_\mu \phi^* \partial^\mu \phi + \frac{d_2}{\Lambda} m_\phi^2 h\, \phi^* \phi$$

$d_1 \approx d_2 \approx \mathcal{O}(1)$

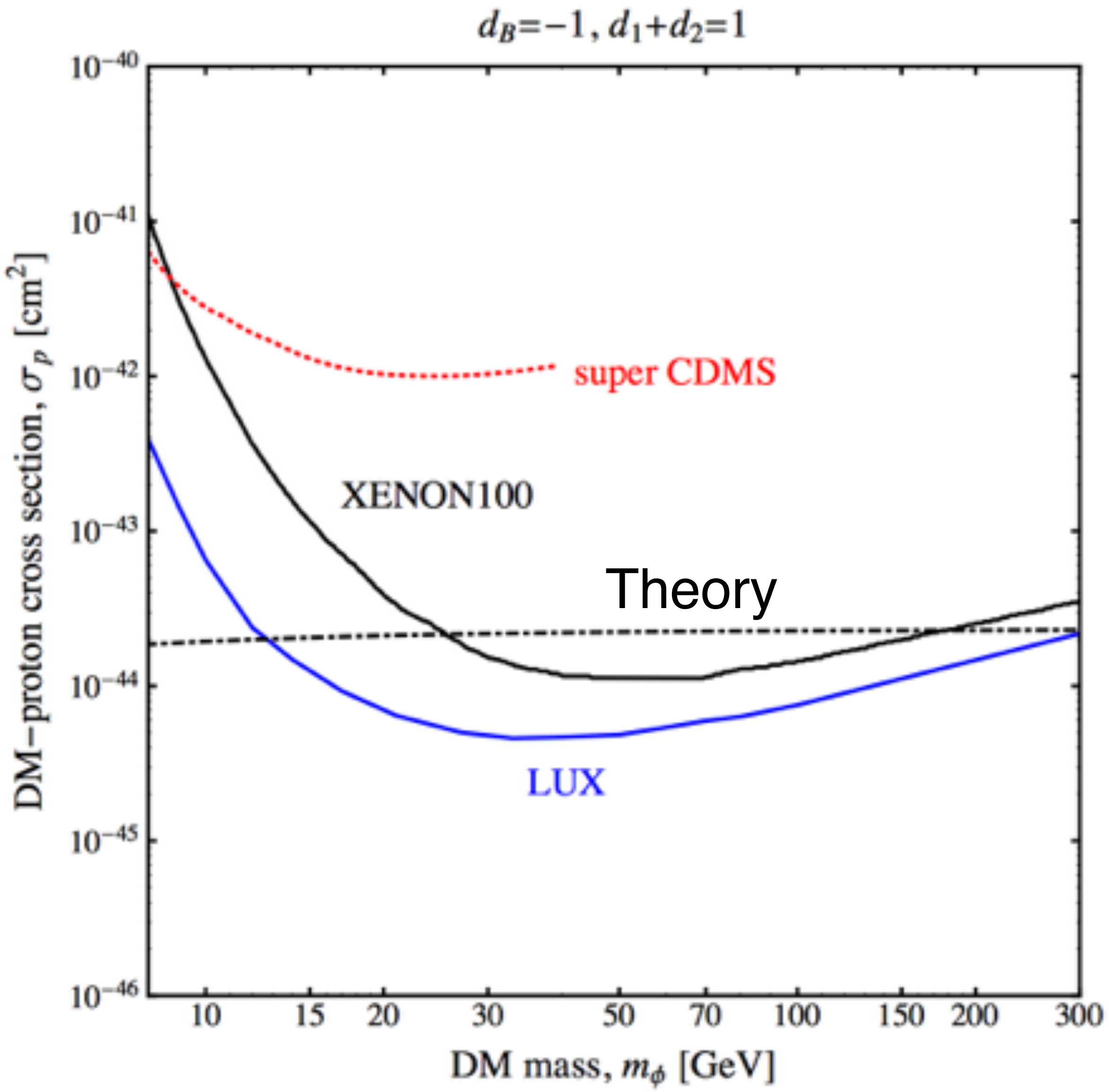
DM is a GB

Cross section with the proton

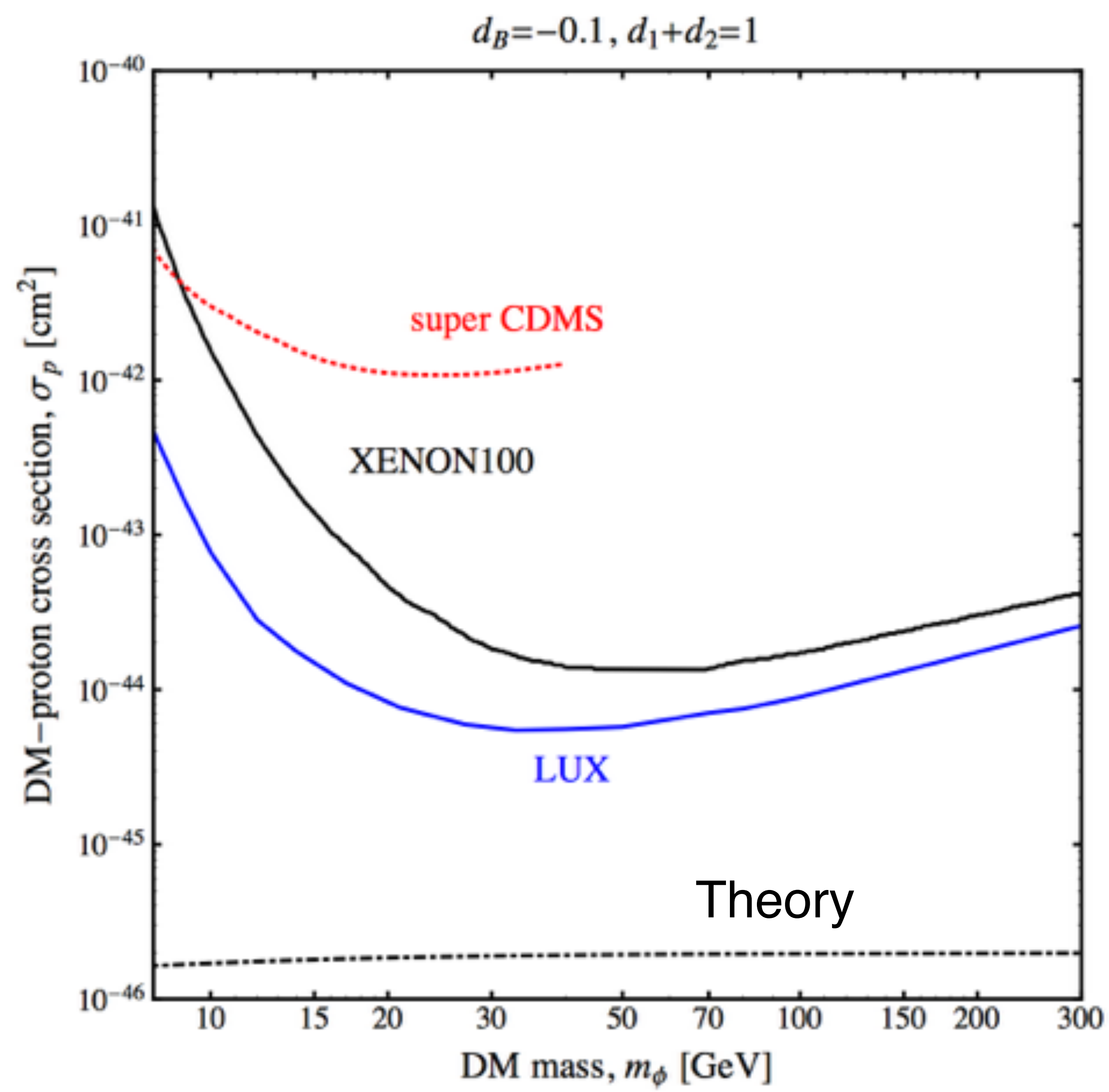
$$\sigma_p = \frac{\mu^2}{4\pi} \left[\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} + 8\pi\alpha \frac{d_B}{\Lambda^2} \right]^2$$

$f \simeq 0.3$

$$f_n = -\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} \qquad f_p = -\frac{(d_1 + d_2) f m_N m_\phi^2}{m_H^2 m_\phi v_{EW} \Lambda} - 8\pi\alpha \frac{d_B}{\Lambda^2}$$



Experiments



Lattice

Summary

A natural avenue: Compositeness

Relevance of Top corrections for Technicolor

Unified TC and Comp (Goldstone) Higgs description

SU(2): Univ. fund. template

First principle lattice predictions for LHC and DM