Template Composite Dark Matter :

SU(2) gauge theory with N_f=2

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CP3 Origins

Outline

- Introduction
  - Motivations
  - The model : SU(2) Gauge theory + $N_f = 2$ fundamental fermions
- Polarizability
  - Definition
  - Chiral perturbation theory
  - Lattice techniques
- Results
  - Setup
  - Effective masses and analysis
  - Nucleon-DM scattering : Direct detection experiments

Introduction

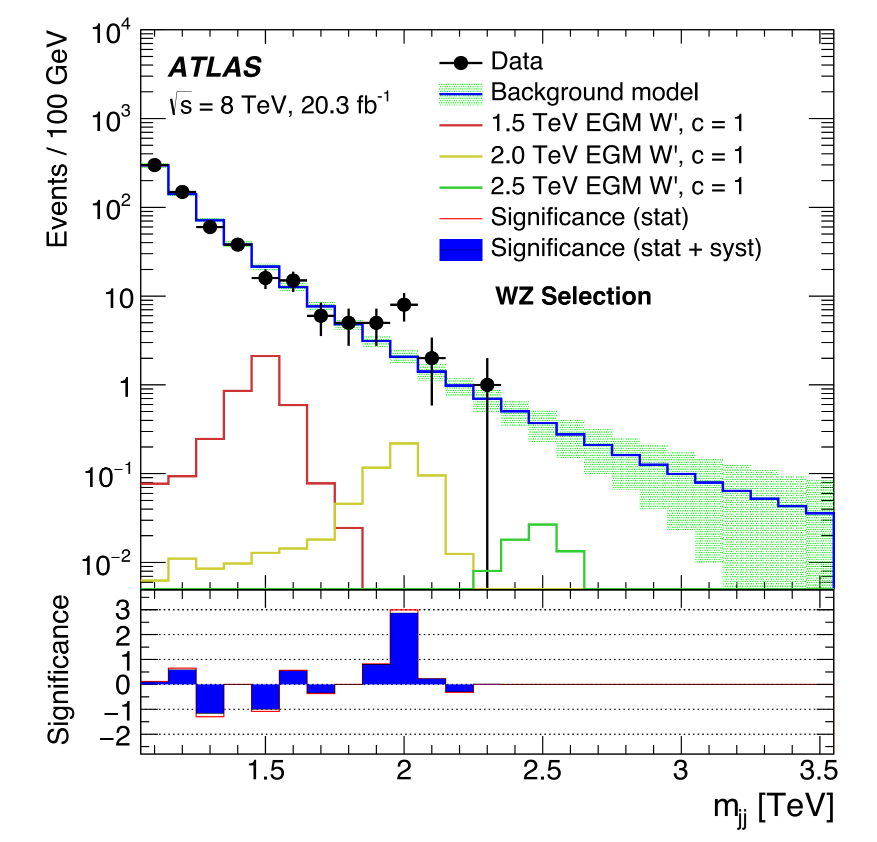
Composite Dark Matter

See F. Sannino (plenary session)
See E. Rinaldi (next talk)

- SU(2) gauge with 2 fermions in the fundamental representations have attracted a lot of attention to build composite DM model with self interactions.
- Several paradigms have been considered:
  - Unified composite Higgs / technicolor model.
  - SIMP(lest) Miracle
  - Dark atoms
- Alternative : Stealth Dark Matter

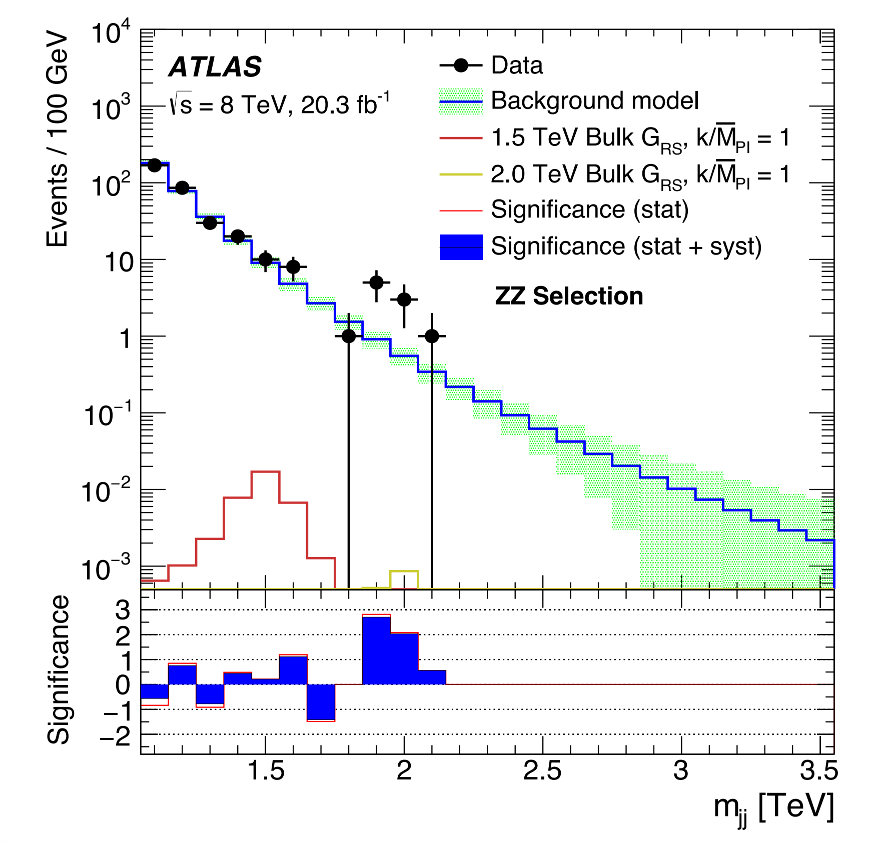
[Hietanen, Lewis, Pica and Sannino JHEP12(2014)]
[Appelquist *et al,* [1503.04203]]
[Appelquist *et al,* [1503.04205]]
[Detmold,McCullough, Pochinsky PRD90 (2014)]
[Hochberg, Kuflik, Volansky, Wacker PRL113(2014) & [1411.3727]]
[Hansen, Langaeble, Sannino [1507.01590]]

New resonances@LHC?



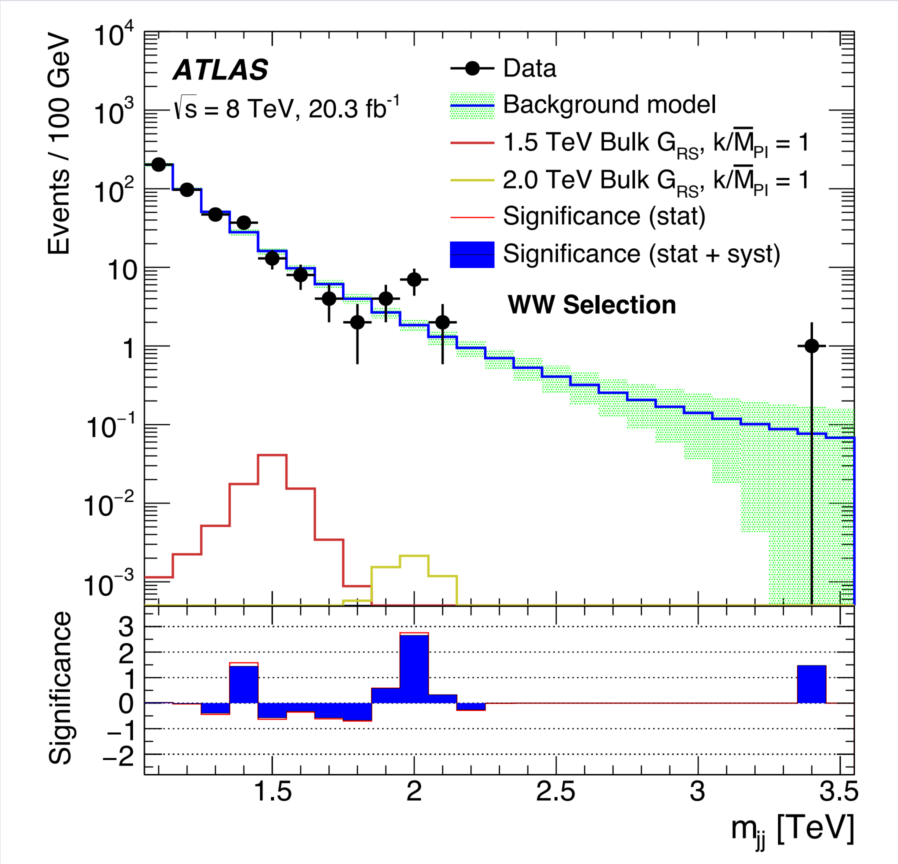
Fit of the dijet mass distribution with WZ channel

[ATLAS,1506.00962]



~3σ excess in each channel !

ZZ channel



WW channel

See Franzosi, Frandsen & Sannino [1506.04392]

for interpretation in the context of strong dynamics.

Unified Composite Higgs

[G. Cacciapaglia & F. Sannino, JHEP04(2014)III]

- SU(2) gauge theory with N_f = 2 Dirac fermions in the fundamental representation.

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\overline{U}\gamma^\mu D_\mu U + i\overline{D}\gamma^\mu D_\mu D + \frac{m}{2}Q^T(-i\sigma^2)C\,EQ + \frac{m}{2}\left(Q^T(-i\sigma^2)C\,EQ\right)^\dagger$$

- Pseudo-real irrep of SU(2): **global flavour symmetry is upgraded to SU(4)** :

$$Q \equiv \begin{pmatrix} U_L \\ D_L \\ \widetilde{U}_L \\ \widetilde{D}_L \end{pmatrix} \equiv \begin{pmatrix} U_L \\ D_L \\ -i\sigma_2 C\bar{u}_R^T \\ -i\sigma_2 C\bar{d}_R^T \end{pmatrix}, \quad E = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

- Infinitesimal SU(4) transformation $\quad Q \longrightarrow \left(1 + i\sum_{n=1}^{15}\alpha^n T^n\right)$
- Generators that leaves the Lagrangian invariant satisfy : $\quad ET^n + T^{nT}E = 0$
- Chiral symmetry breaking pattern : **SU(4) breaks to SP(4)** $\Longrightarrow$ 5 Goldstone Bosons

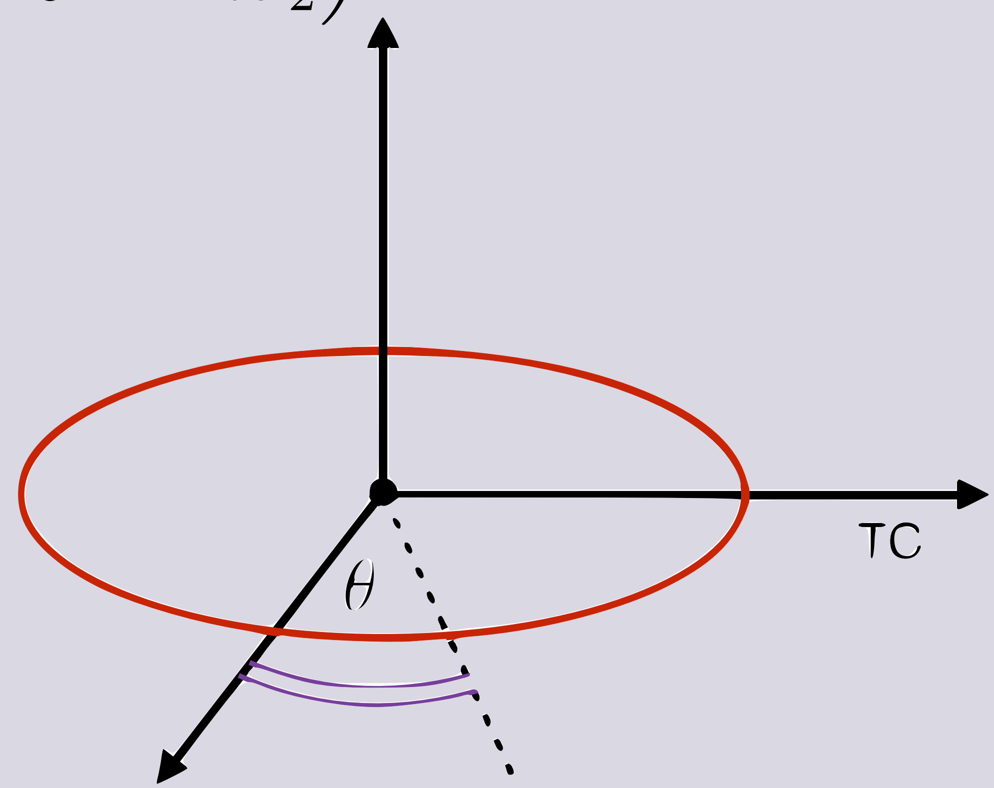
EW embedding

[G. Cacciapaglia & F. Sannino, JHEP04(2014)III]

- Two interesting alignments of the condensate :

$$\Sigma_H \equiv E = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$: break EW symmetry

$$\Sigma_B \equiv \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}$$: does not break EW



- General superposition : $\Sigma_0 = \cos\theta \; \Sigma_B + \sin\theta \; \Sigma_H$

- $Q_L = (U_L, D_L)$: $SU(2)_L$ doublet with hypercharge 0
- $\tilde{U}_L, \tilde{D}_L$: $SU(2)_L$ singlet with hypercharge $\pm 1/2$
- Electric charge matrix :

$$Q = \mathrm{diag}\left(\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}\right)$$

- Two limit cases :
  - θ = 0 : EW does not break : composite Higgs limit
  - θ = π/2 : EW breaks + DM candidate : technicolor limit

(DM mass generated via top and EW corrections)

- Mixed case is natural : 0 < θ < π/2

$\Longrightarrow$ the model interpolate between TC and CH

Polarizability

Generalities

[Hu, Jiang & Tiburzi PRD77 (2008) and reference therein]

[Tiburzi NPB745 (2006)]

- Neutral particles can be polarized by an external electric field.
- Polarisability $\alpha_E^{(X)}$([fm^3]) of X appears in X $\gamma \longrightarrow$ X γ
- Equivalent definition: change of mass of the hadron in presence of a classical constant electric field.
- **QCD** ($N_f = 2$) : $\alpha_E^{(\pi^0)} \propto Q_u^2 - Q_d^2$ (@NLO in chiPT)
- **Here** : $Q_u^2 = Q_d^2$ one expect no contribution at NLO.
- Polarizability appears in the EFT at O(E^6)

$$\mathcal{L} \supset m\phi^2 F_{\mu\nu}F^{\mu\nu} \quad (+F_{\mu\nu}F^{\mu\nu}\partial_\rho\phi\partial^\rho\phi)$$

Generalities

[Detmold, Tiburzi & Walker-Loud PRD81 (2010)]

['t Hooft NPB153 (1979)]

- Electric field dependence of the mass :

$$M(E) = M + \frac{1}{2} 4\pi\alpha_E \mathcal{E}^2 + \mathcal{O}(\mathcal{E}^4)$$

- Finite volume : electric field needs to be quantised (**'t Hooft condition**)

$$\mathcal{E} = (ea^2)^{-1} \frac{2\pi n}{Q N_t N_L} \equiv (ea^2)^{-1} E$$

- Background U(1) field only in the valence :

$$U_\mu(x) \longrightarrow U_\mu(x) U_\mu^{(\mathcal{E})}(x), \text{ where } U^{(\mathcal{E})}(x) \in U(1)$$

- Electric field breaks SP(4) symmetry in the valence

Two-points function

- DM candidate : is a diquark GB $\phi = u^T C\gamma_5\sigma_2 d$

- Two points function :

$$C^{\mathcal{E}}_{2\mathrm{pt}}(t) = \sum_{\vec{x}} \langle \phi(x)\phi^\dagger(0)\rangle$$

- For $\mathcal{E} = 0$: $C^{\mathcal{E}=0}_{2\mathrm{pt}}(t) = C^{\mathcal{E}=0,\pi^+}_{2\mathrm{pt}}(t)$

- For $\mathcal{E} \neq 0$: $C^{\mathcal{E}}_{2\mathrm{pt}}(t) = C^{\mathcal{E},\pi^0}_{2\mathrm{pt,conn.}}(t)$

Results

Simulation details

R. Lewis, C. Pica, F. Sannino, Phys.Rev. D85 (2012) 014504 [arXiv:1109.3513]

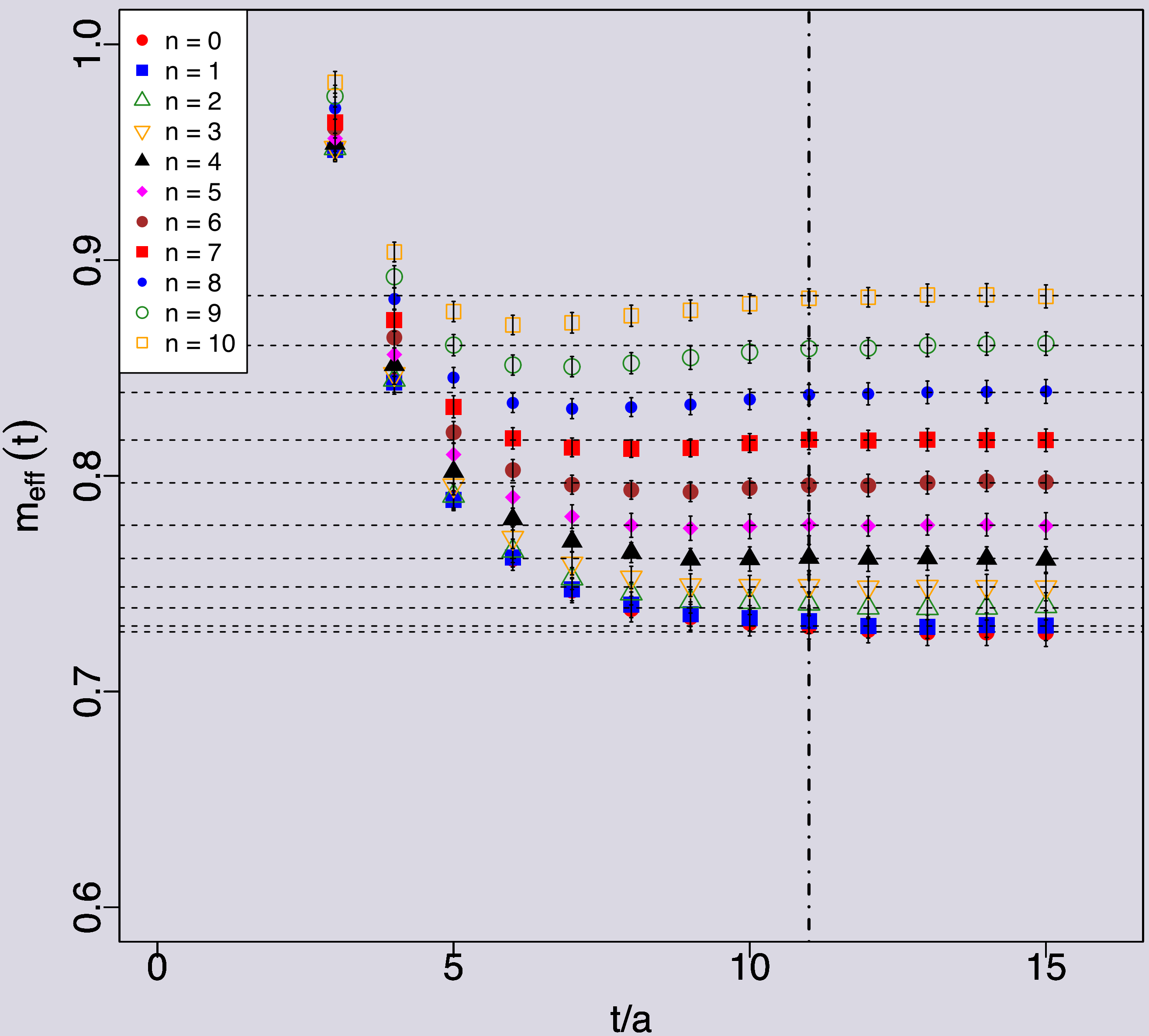
A. Hietanen, C. Pica, R. Lewis, F. Sannino, JHEP 1407 (2014) 116 [arXiv:1404.2794]

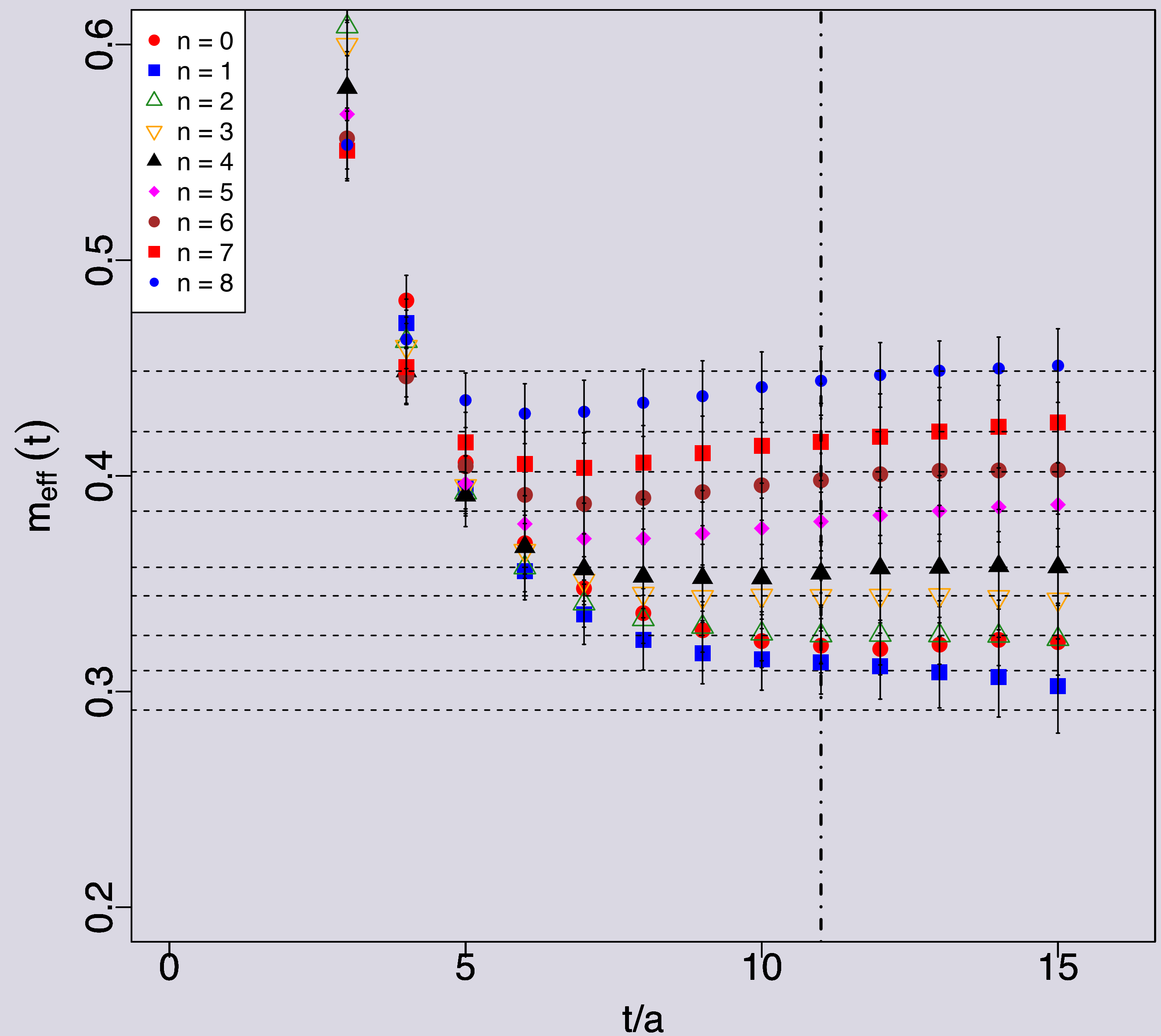
A. Hietanen, C. Pica, R. Lewis, F. Sannino [arXiv:1308.4130]

- Plaquette action + Wilson Fermion
- Several volumes and quark masses
- 2 lattice spacing
- Scale setting : **F_π = 246 GeV** (technicolor limit)
- Perturbative renormalisation : $Z_A = 1 - \frac{g_0^2}{16\pi^2}\frac{N^2-1}{2N} \overset{N=2}{=} 1 - 0.2983/\beta$
- Electric field : (smallest quark mass) $\frac{(e\mathcal{E})^2}{m_{\mathrm{PS}^4}} \sim 0.03n^2$

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

Effective masses

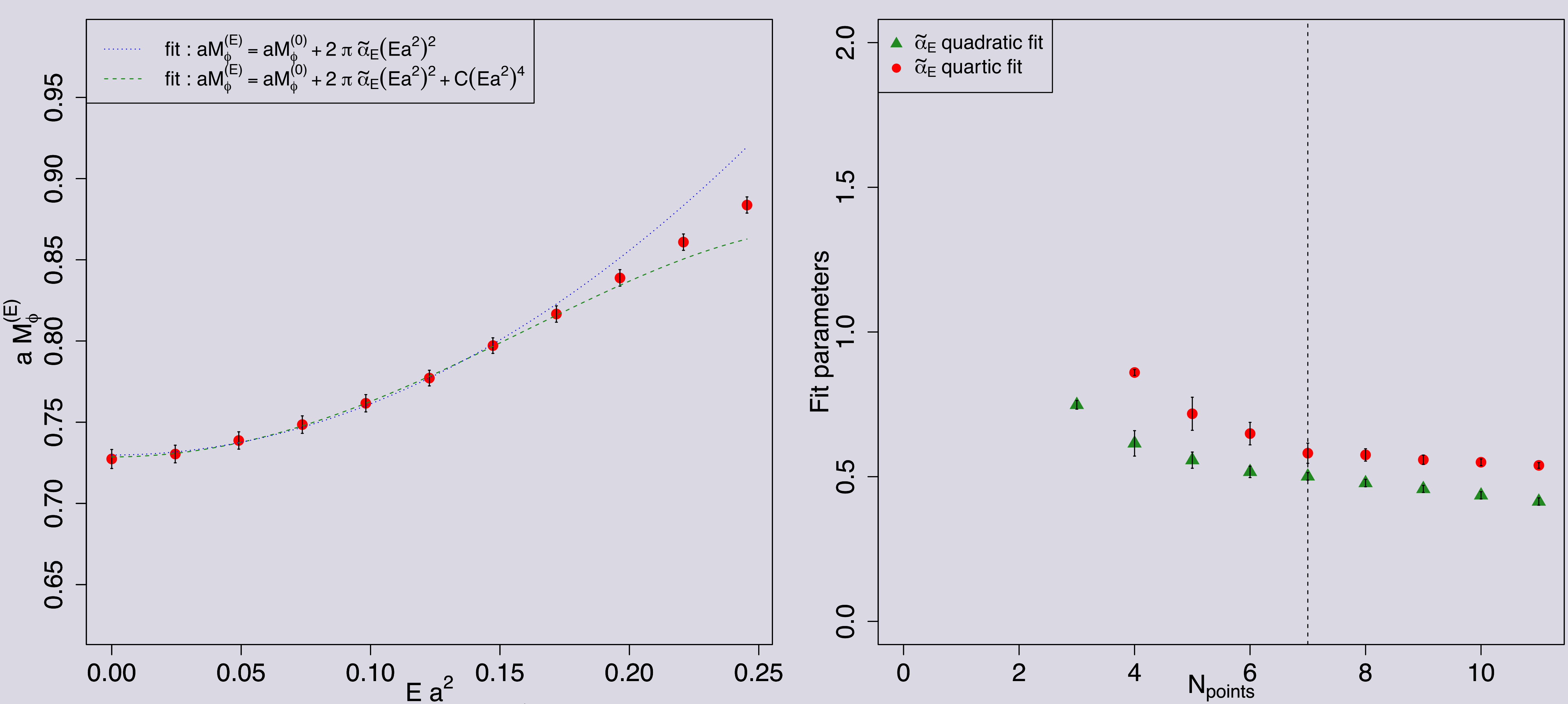




- L=16a, T=32a , β=2.2, m_0=-0.65 (left) and m_0= -0.75 (right)
- $m_{PS}L > 4.8$
- effective mass :

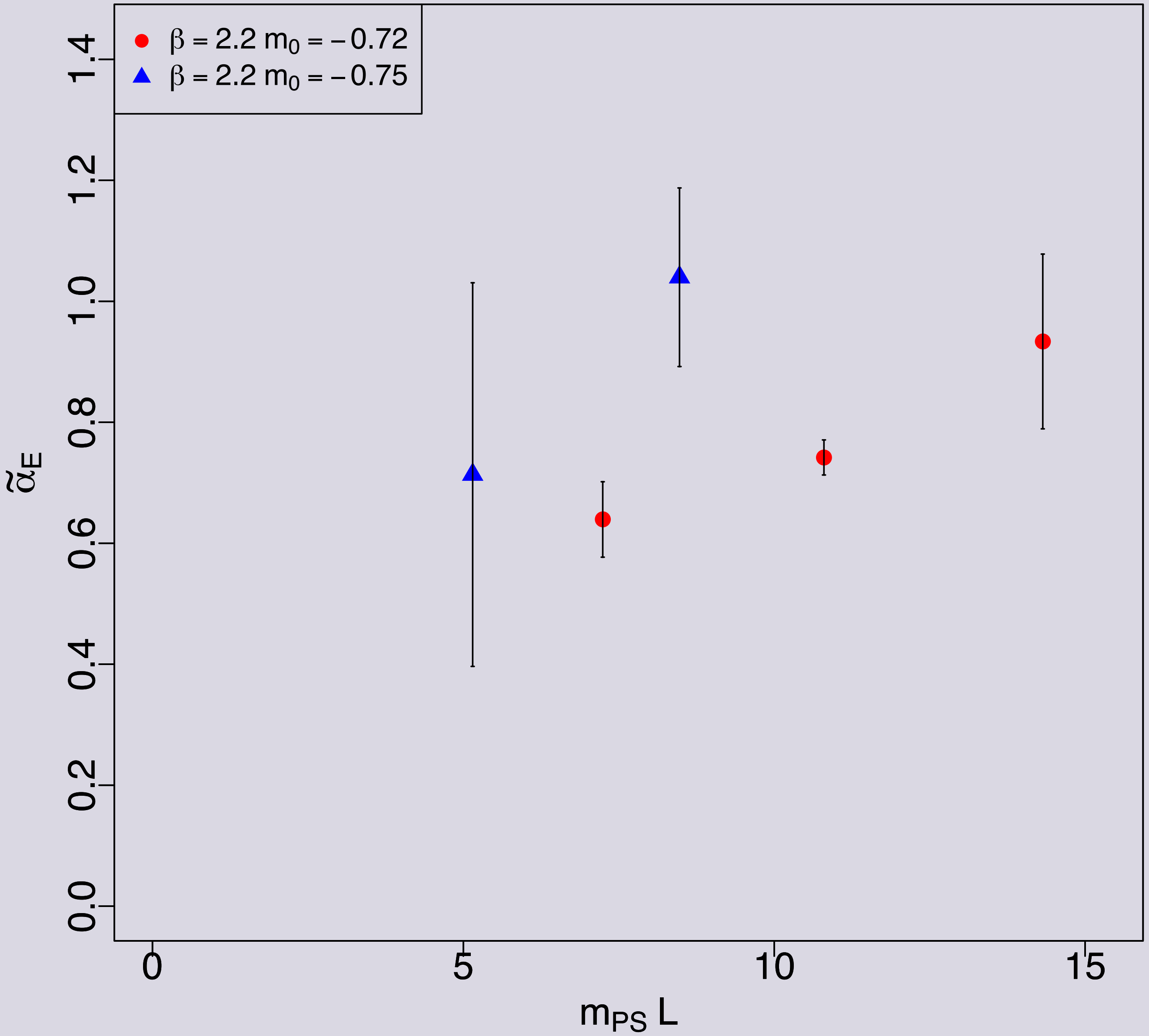
$$\frac{C(t-a)}{C(t)} = \frac{e^{-m_{\text{eff}}(t)(t-a)} + e^{-m_{\text{eff}}(t)(T-(t-a))}}{e^{-m_{\text{eff}}(t)t} + e^{-m_{\text{eff}}(t)(T-t)}}$$

Electric polarizability

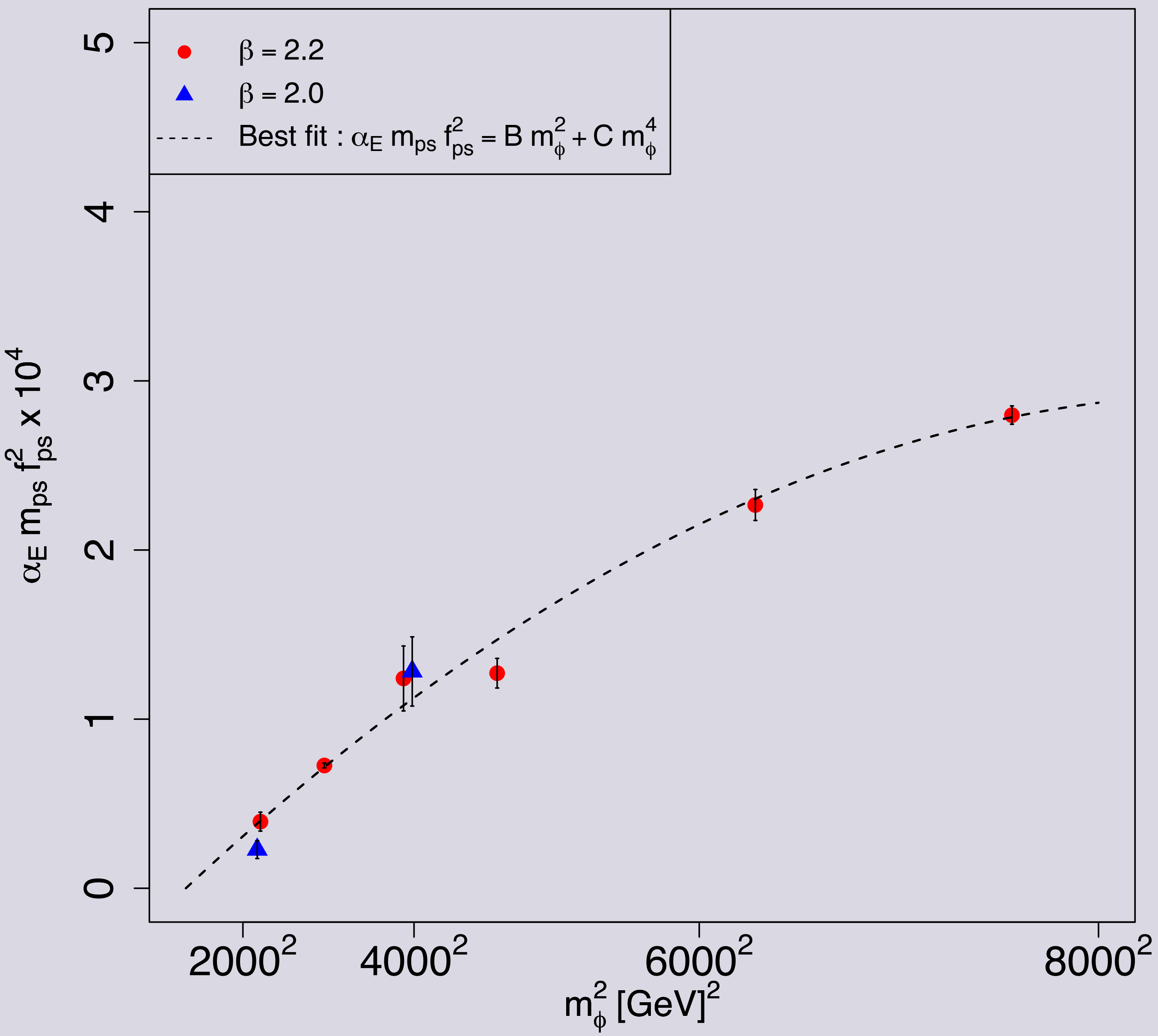


- $aE(E) = aM + \frac{1}{2}4\pi\tilde{\alpha}_E E^2 + CE^4$ with $\tilde{\alpha}_E = \frac{\alpha_E}{4\pi\alpha a^3}$
- L=16a, T=32a, β=2.2, m_0=-0.65
- Quartic and quadratic agree reasonably well.

FV effects-Chiral behaviour



Finite Volume effects



Chiral behaviour

- L=16a,24a,32a & T=32a , β=2.2, m_0=-0.72
- small upward trend ?

- 2 lattice spacings
- Polynomial fit (only β=2.2)

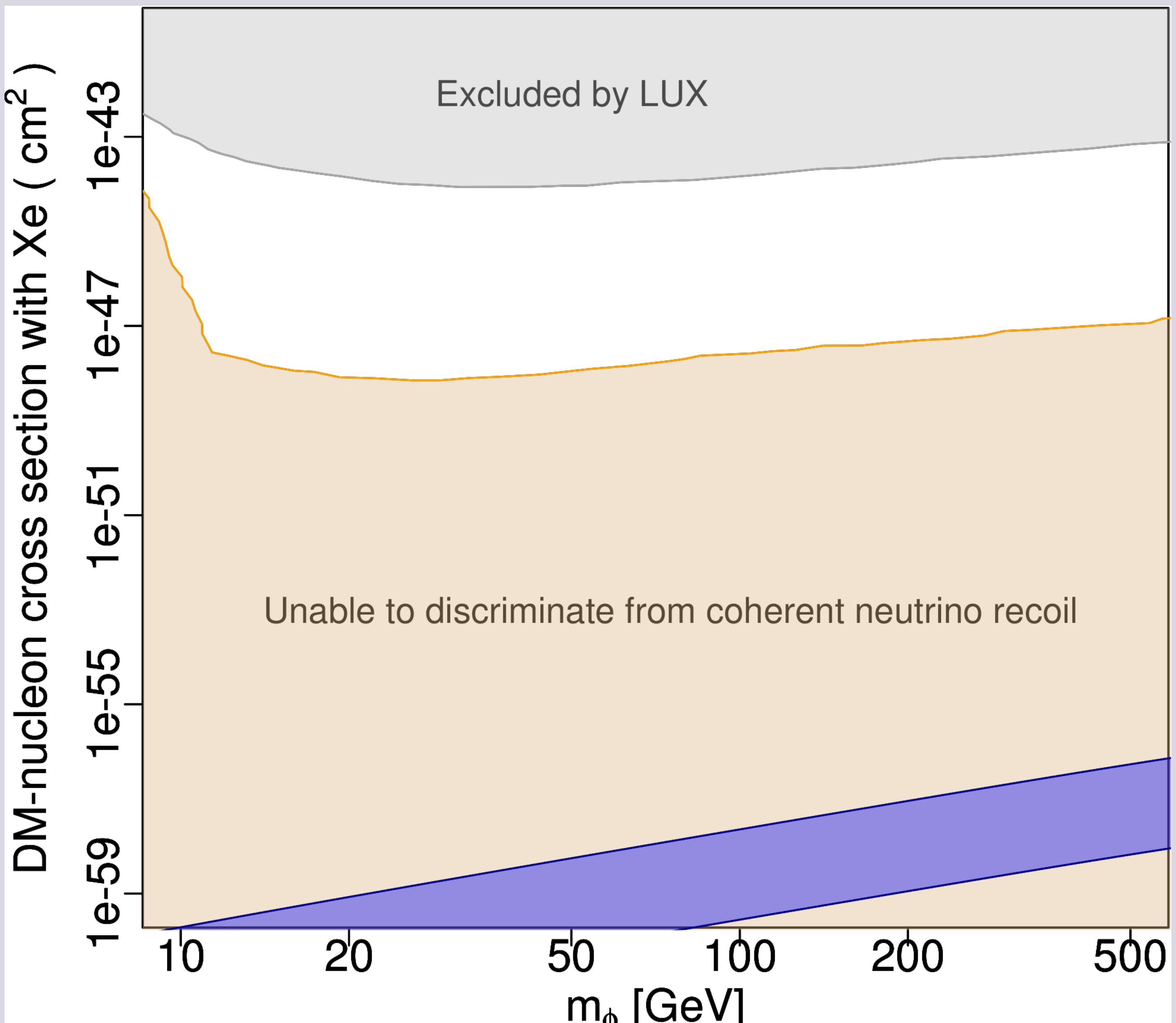
Polarizability and direct detection

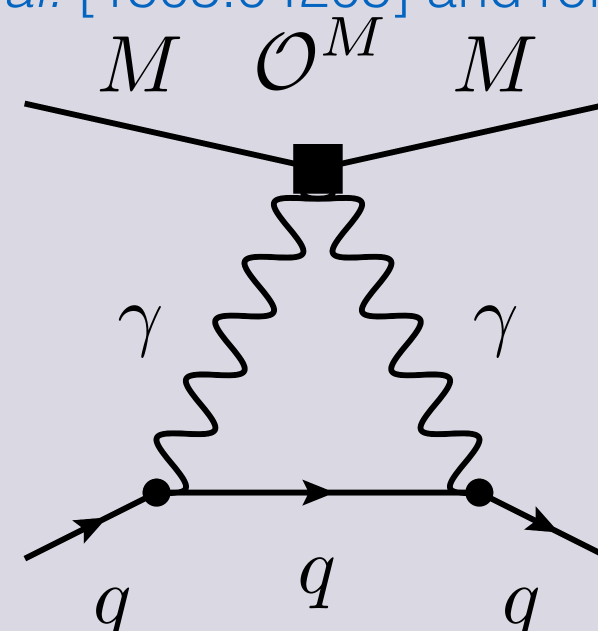
See E. Rinaldi (next talk)

[Appelquist *et al.* [1503.04205] and reference therein]

- Assuming $\mathcal{L} = \pi\alpha_E F_{\mu\nu}F^{\mu\nu}\phi^*\phi$:

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{9\pi\alpha^2\mu_{n\phi}^2(M_F^A)^2}{R^2}\alpha_E^2$$





- (Z,A) : atomic and mass number of the target
- $\mu_{n\phi}$ is the reduced mass
- $R = 1.2\ A^{1/3}$ fm
- M_A^F : nuclear matrix element
- α is the EM coupling constant
- α_E is related to "lattice" polarisability by $\tilde{\alpha}_E = \frac{\alpha_E}{4\pi\alpha a^3}$

$\Rightarrow$ DM candidate cannot be detected via direct detection experiments

Conclusion & Outlook

- One interesting framework :

  Unified Composite Higgs and Technicolor model

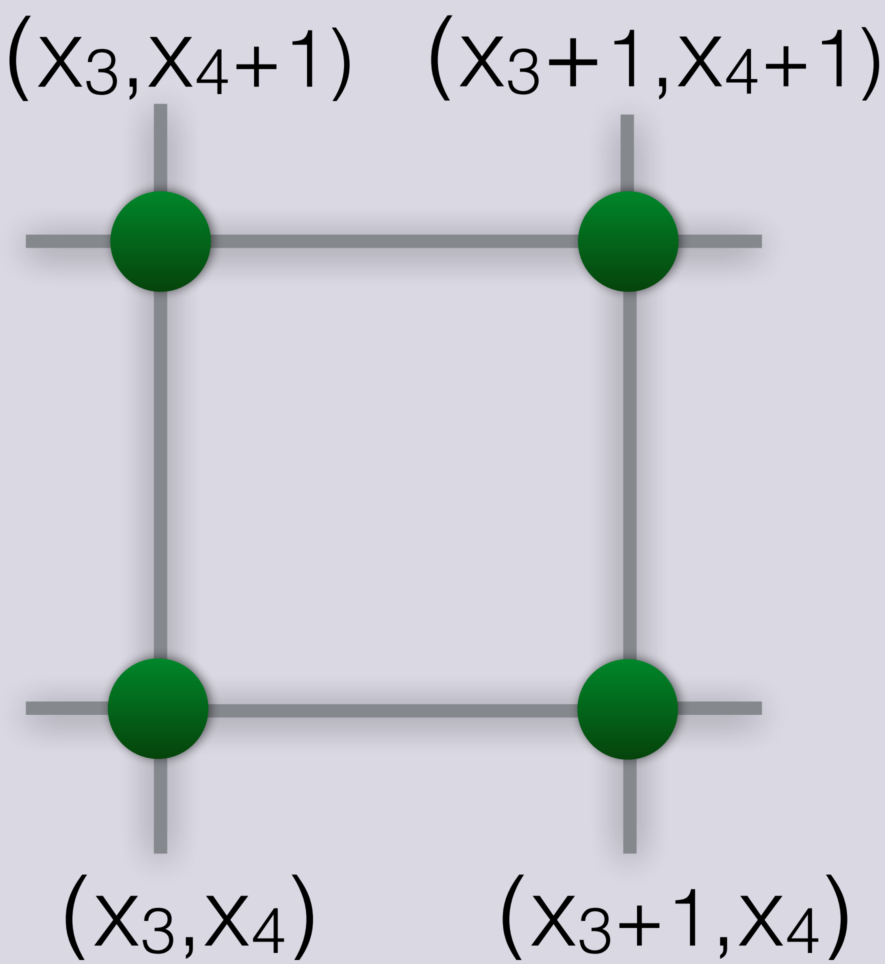
- In the technicolor limit : effective electromagnetic interaction of the DM with the nucleon controlled by the polarizability.
- DM Polarizability estimated using background field method.
- Cross section *not* accessible via direct detection experiments (and much smaller than the expected contribution of the edm).
- Outlook :
  - Weak corrections ?
  - What happens beyond the technicolor limit ?

Backup

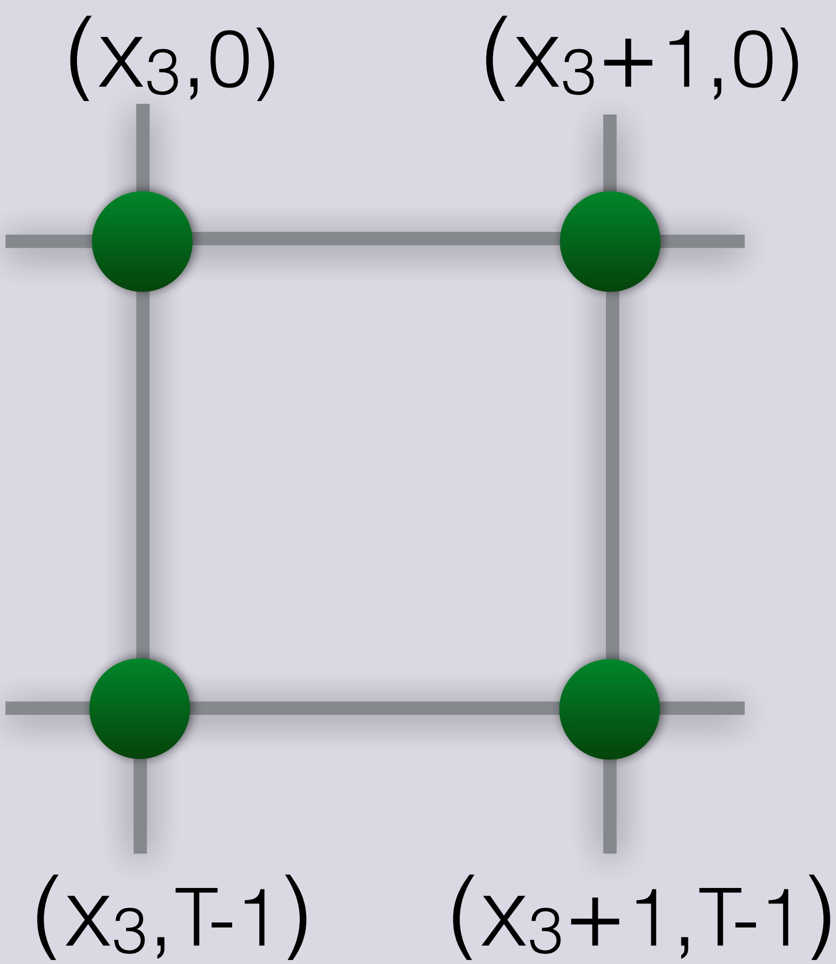
Background field method

$A_\mu = (0, 0, -Ex_4, 0)$ [Detmold, Tiburzi & Walker-Loud PRD81 (2010)]

$$U_\mu^{(E)} = e^{iQA_\mu(x)} e^{iQEN_t x_3 \delta_{\mu,4} \delta_{x_4, N_t - 1}}$$



Bulk

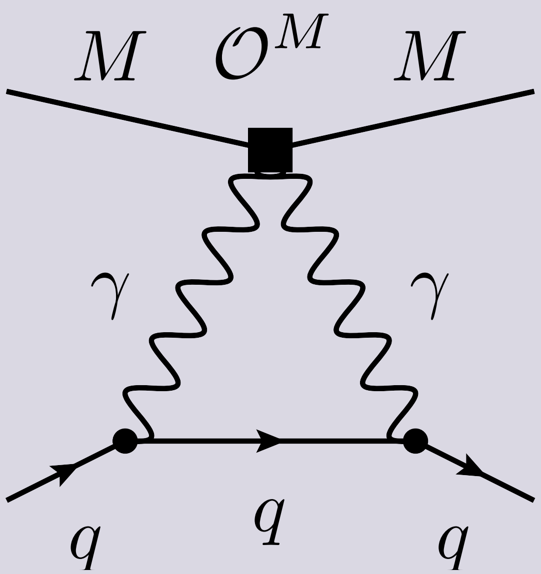


Time boundary

$\longleftrightarrow \quad \forall x \in \Lambda,\ P(x) = e^{iQE(1-TL)}$ (if ’t Hooft condition is satisfied)

Polarizability and direct detection

[Appelquist *et al.* [1503.04205] and reference therein]



- Assuming $\mathcal{L} = \pi\alpha_E F_{\mu\nu}F^{\mu\nu}\phi^*\phi$
- cross section per nucleon

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{9\pi\alpha^2\mu_{n\phi}^2(M_F^A)^2}{R^2}\alpha_E^2$$

- where (Z,A) are the atomic and mass number of the target
- $\mu_{n\phi}$ is the reduced mass
- $R = 1.2\ A^{1/3}$ fm
- M_A^F : nuclear matrix element
- α is the EM coupling constant
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