LFC17

ECT*, Trento, 09/14/2017

LATTICE FIELD THEORY RESULTS ON NEW STRONG DYNAMICS

Enrico Rinaldi

BROOKHAVEN NATIONAL LABORATORY

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NEW STRONG DYNAMICS

Composite Higgs

Composite Dark Matter

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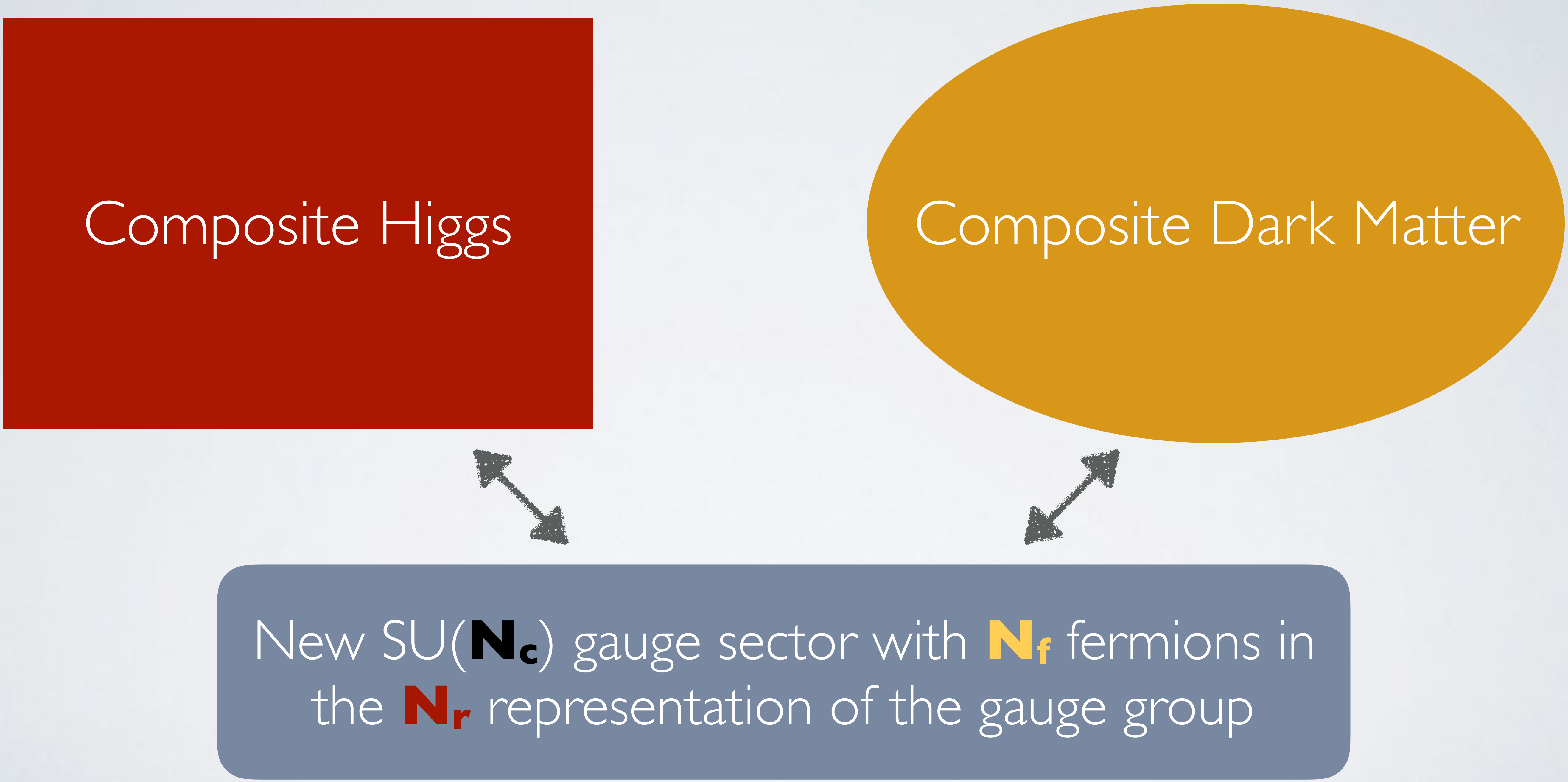


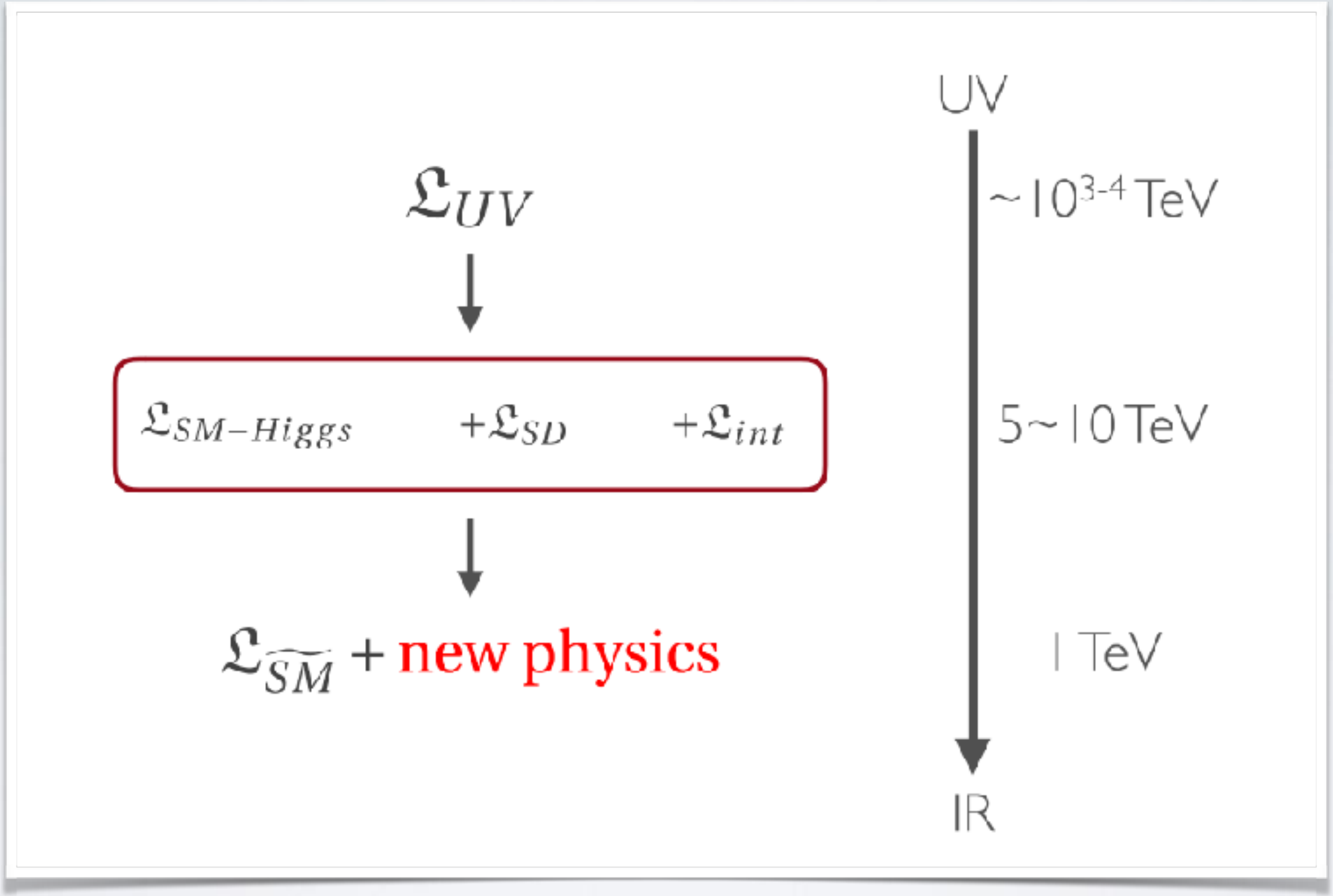
NEW STRONG DYNAMICS

Composite Higgs

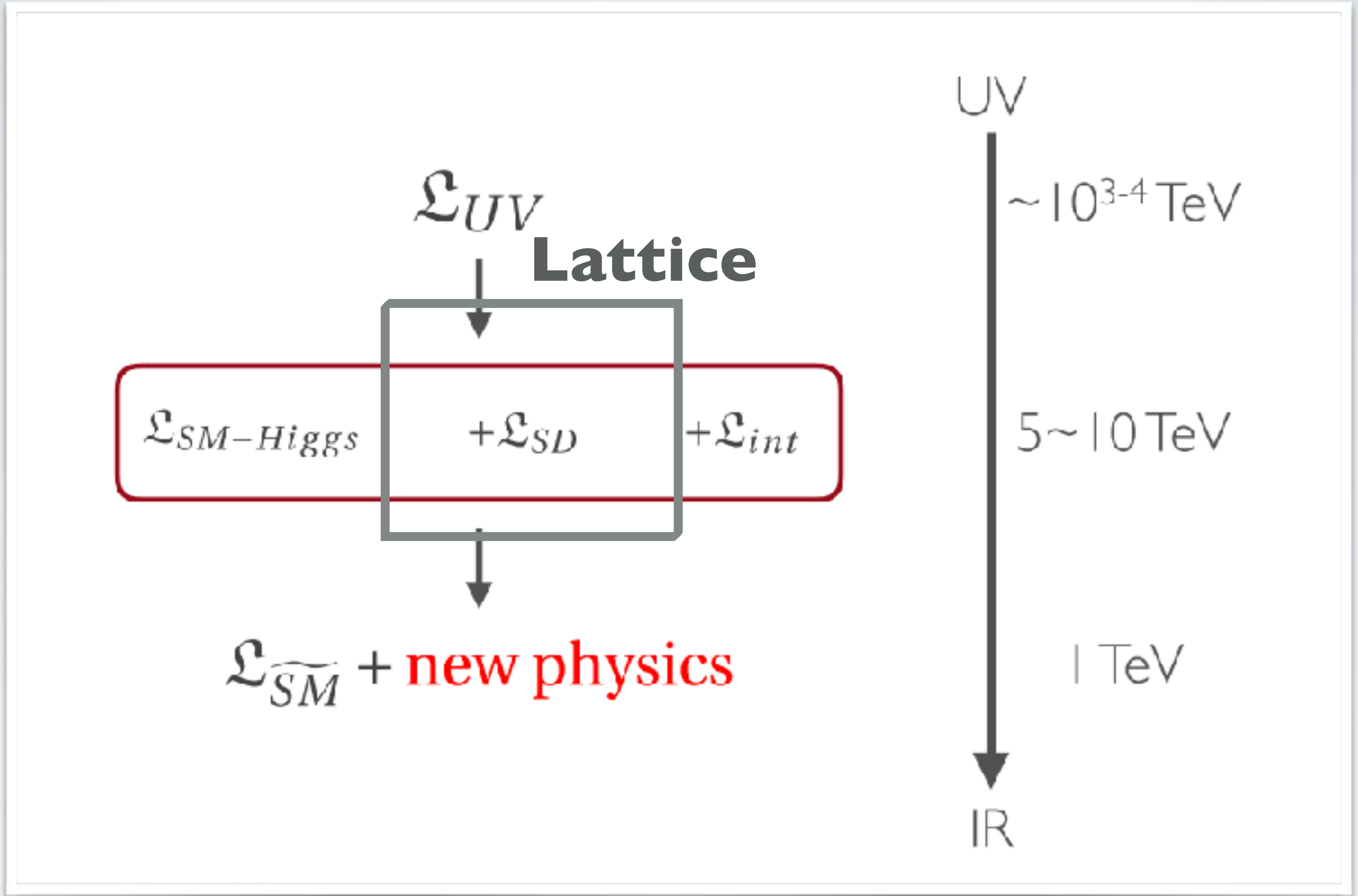
Composite Dark Matter

New SU(N_c) gauge sector with N_f fermions in the N_r representation of the gauge group

Most of the theory work is done using EFTs and there are only a handful of UV complete models



from Pica 1701.07782



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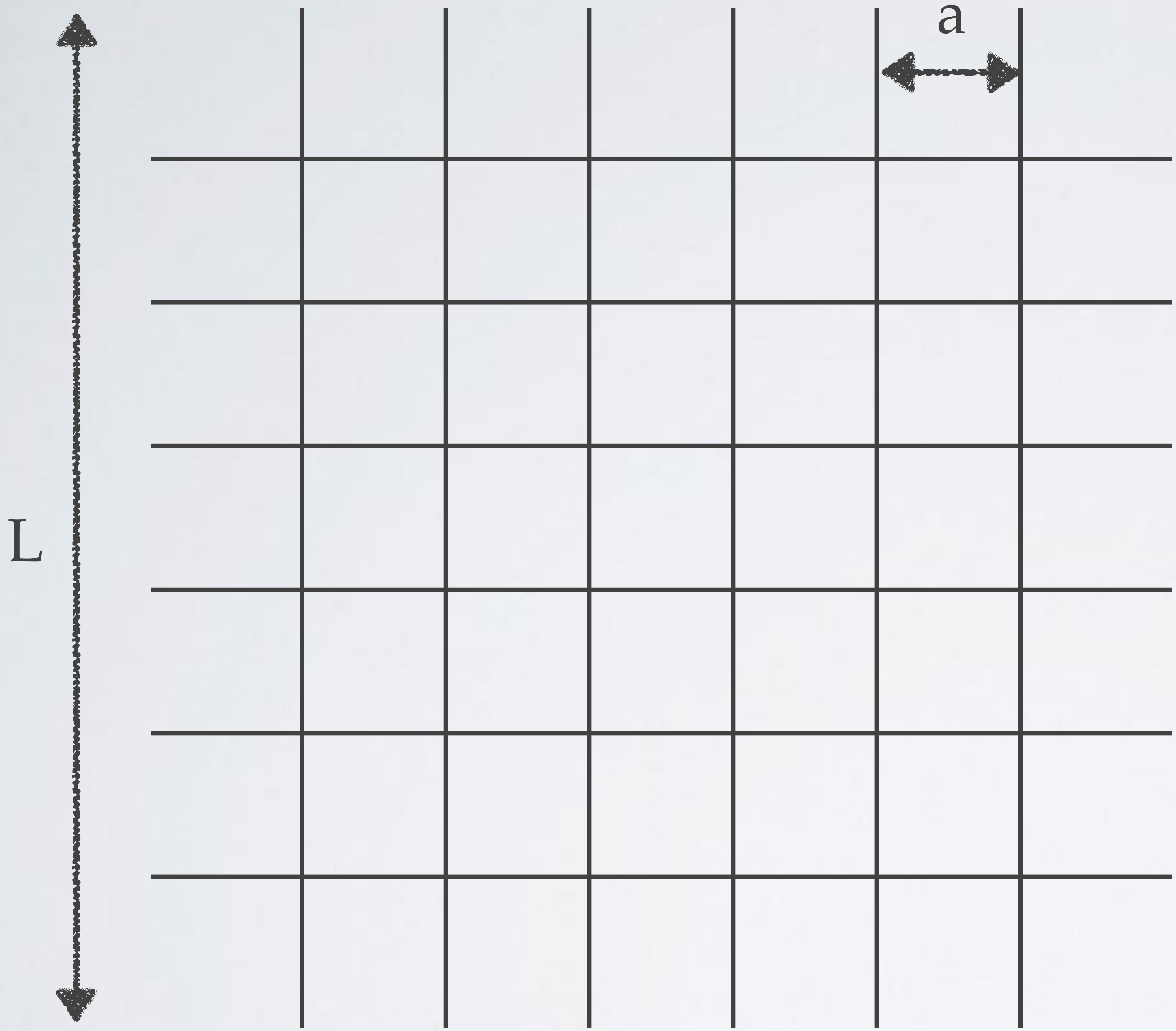
Lattice primer



- Discretize space and time
  - lattice spacing "a"
  - lattice size "L"
- Keep all d.o.f. of the theory
  - not a model!
  - no simplifications
- Amenable to numerical methods
  - Monte Carlo sampling
  - use supercomputers
- Precisely quantifiable and improvable errors
  - Systematic
  - Statistical

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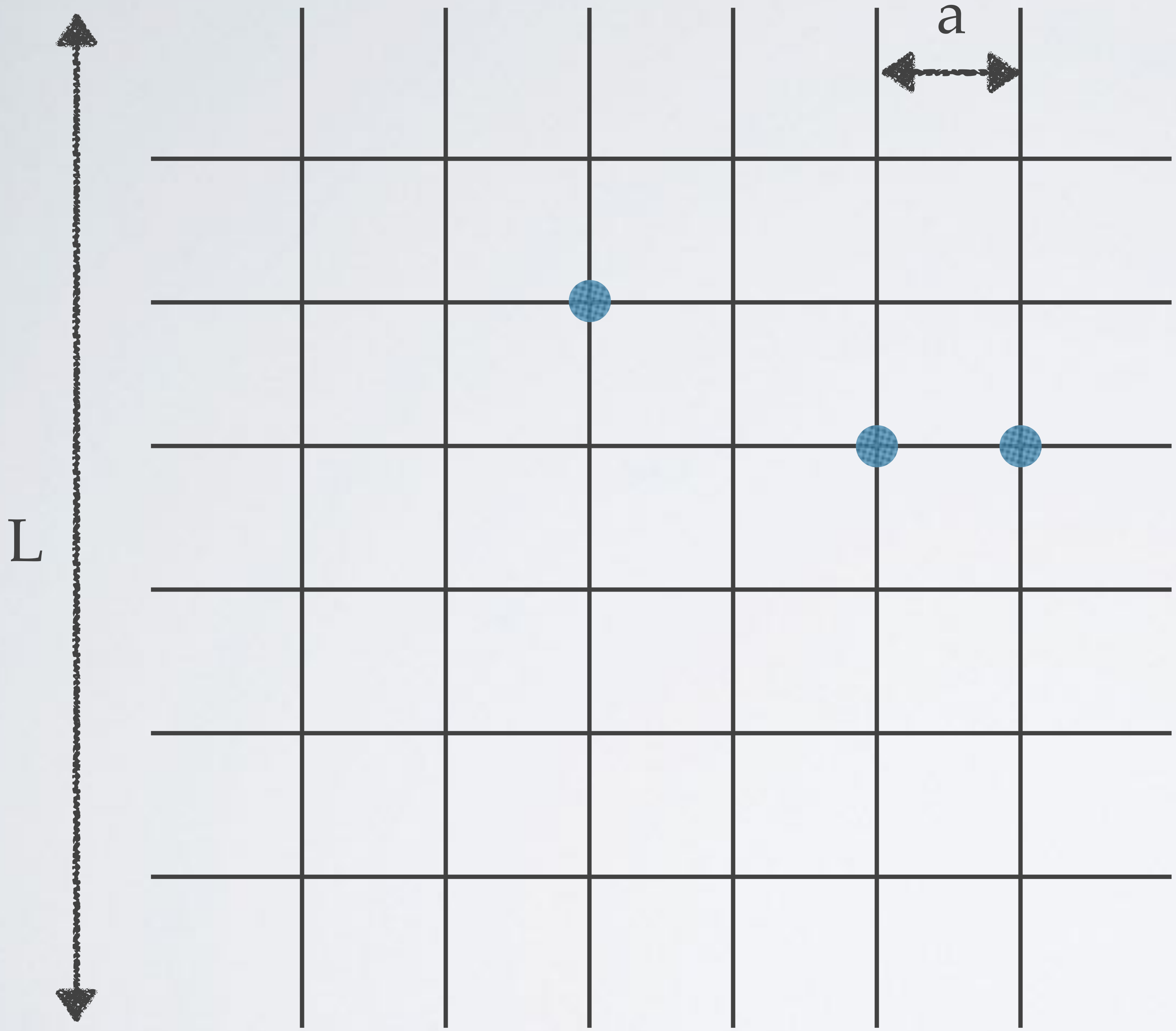

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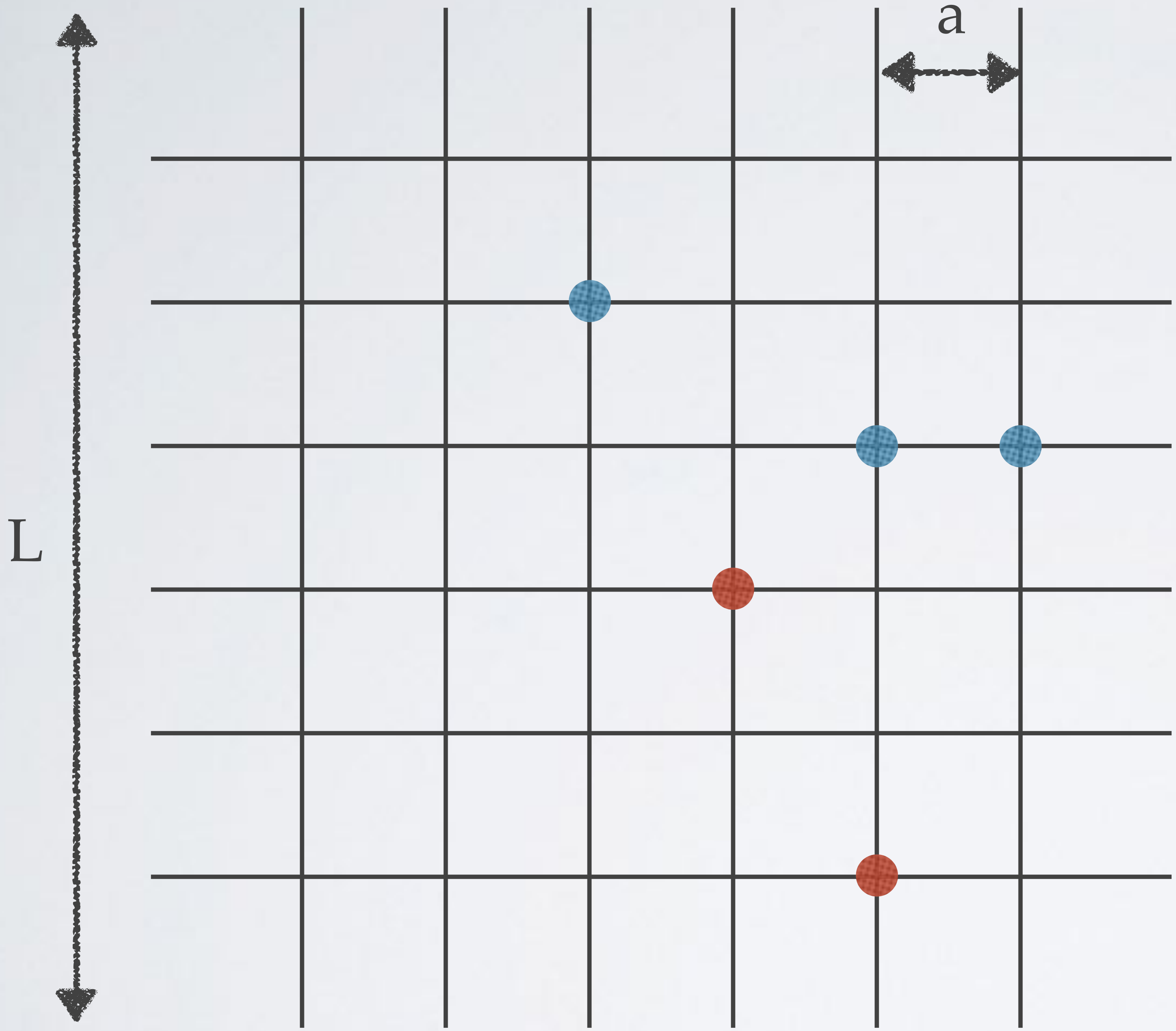

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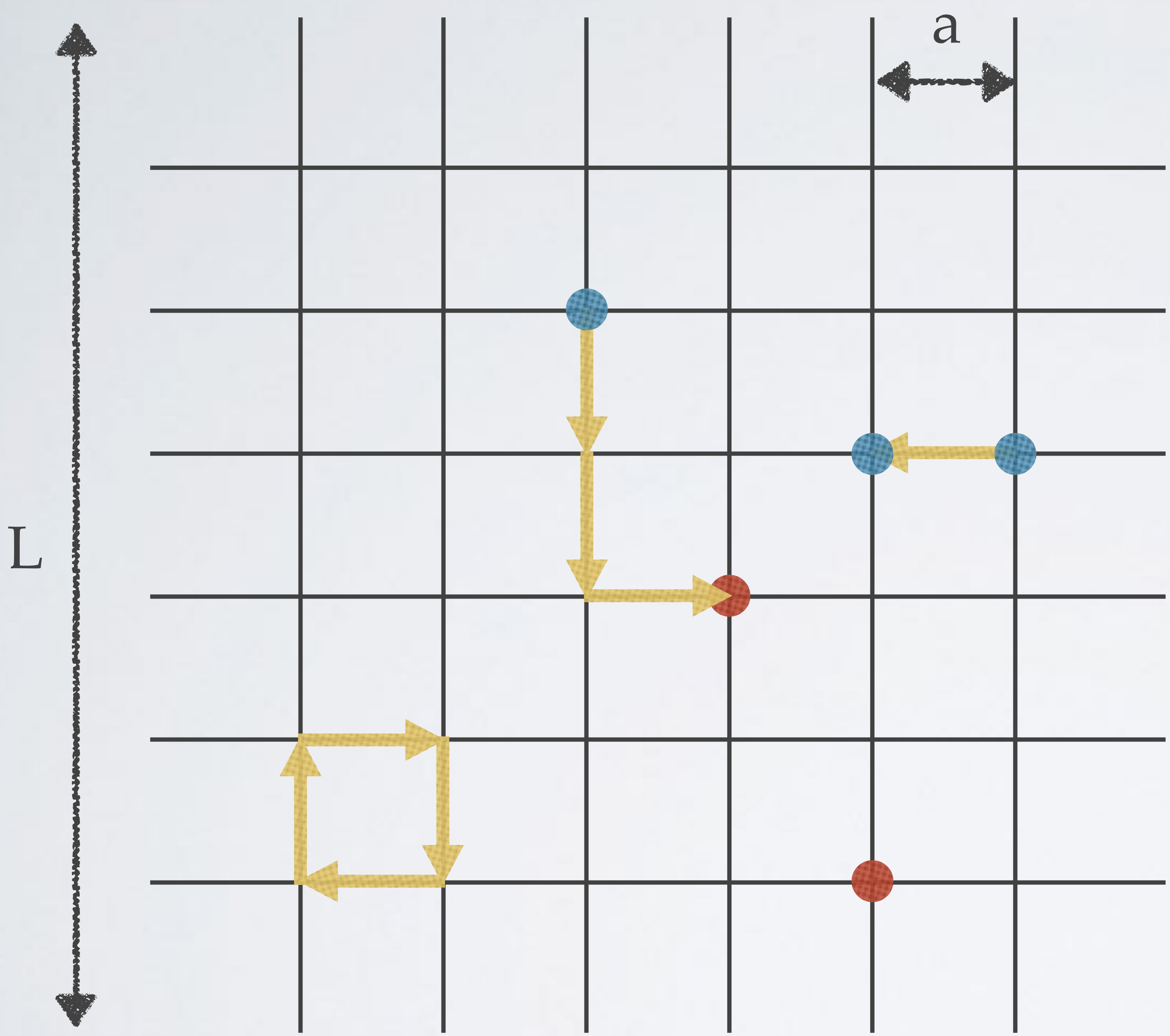

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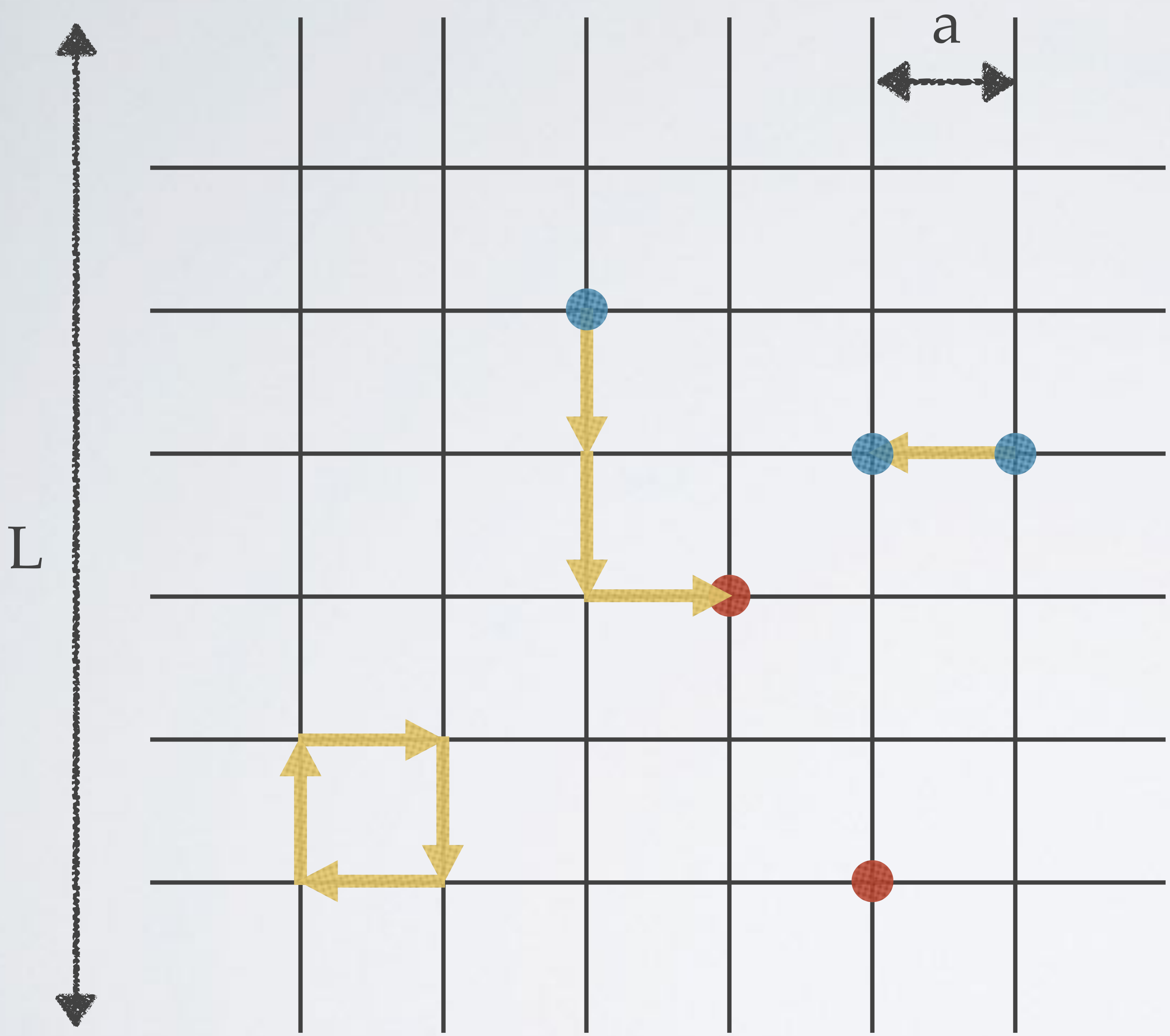

N_c N_f N_r parameters that can be easily changed

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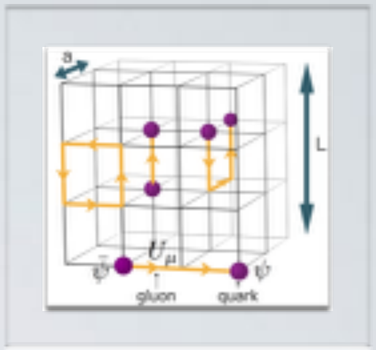
Importance of lattice simulations

[KEK-Japan]



- ★Lattice simulations are needed to numerically solve strong dynamics
- ★Controllable systematic errors and room for improvement
- ★Naive dimensional analysis and EFT approaches can miss important non-perturbative contributions
- ★EFTs inspired by QCD might not work when the dynamics is different
- ★Lattice studies can reliably point out similarities or differences as the parameter space (N_c,N_f,N_r) is scanned

[Pica 1701.07782] [Svetitsky 1708.04840]

MOTIVATIONS

- Strongly interacting quantum field theory with different N_c, N_f, and N_r
  - is the dynamics different from QCD?
  - what is the hierarchy in the spectrum?
  - is there a light scalar singlet?
- Phenomenology of physics beyond the Standard Model
  - light Higgs from composite dynamics (pNGB or dilatonic nature)
  - large anomalous dimensions
  - expected (near-)conformal dynamics for consistency with experiments

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in QCD there is a broad resonance $f_0(500)$

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LATTICE RESULTS

- This talk: SU(3) gauge theory with 8 degenerate fundamental fermions
  - focus on hierarchy of masses towards the chiral limit
  - focus on flavor-singlet states
    - scalar 0^{++} (also called "the sigma")
    - pseudoscalar 0^{-+} (also called "the eta prime")
  - focus on vector resonance (also called the ρ meson)

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Strong sector in isolation:
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Highlight differences and
similarities to QCD

in collaboration with

Lattice Strong Dynamics collaboration

LatKMI collaboration

Argonne: Jin, Osborn

Bern: Schaich

Boston: Brower, Rebbi, Weinberg

Colorado: Hasenfratz, Neil

Edinburgh: Witzel

LLNL: Vranas

UC Davis: Kiskis

Yale: Appelquist, Fleming, Gasbarro

KEK: Aoki, Kurachi, Shibata

Kyoto: Aoyama

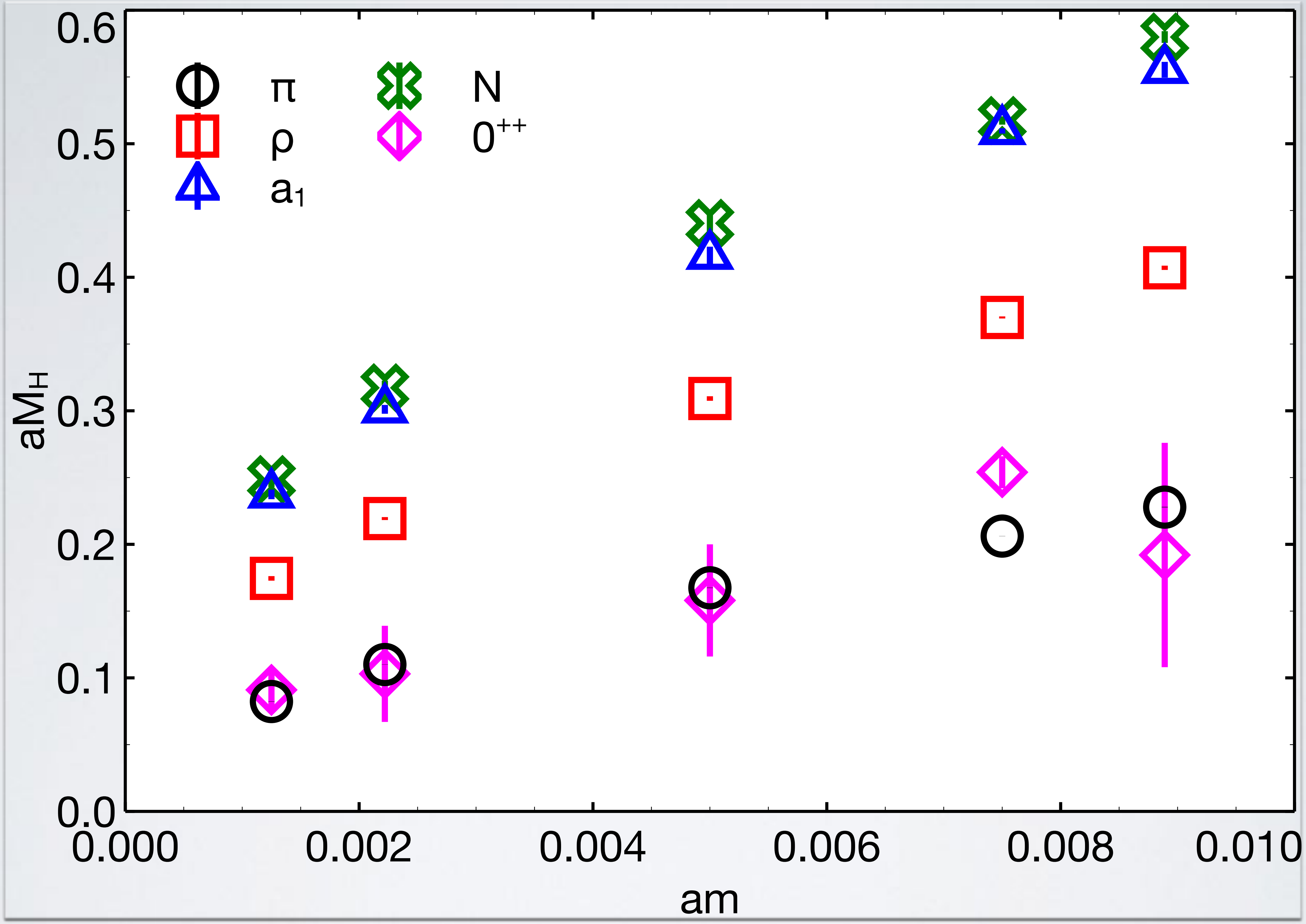
Nagoya: Maskawa, Yamawaki, Nagai

Nara: Ohki

Marseille: Miura

Swansea: Bennett

Tsukuba: Yamazaki



Lattice details: F+A Wilson plaquette action + nHYP smeared naive staggered quarks

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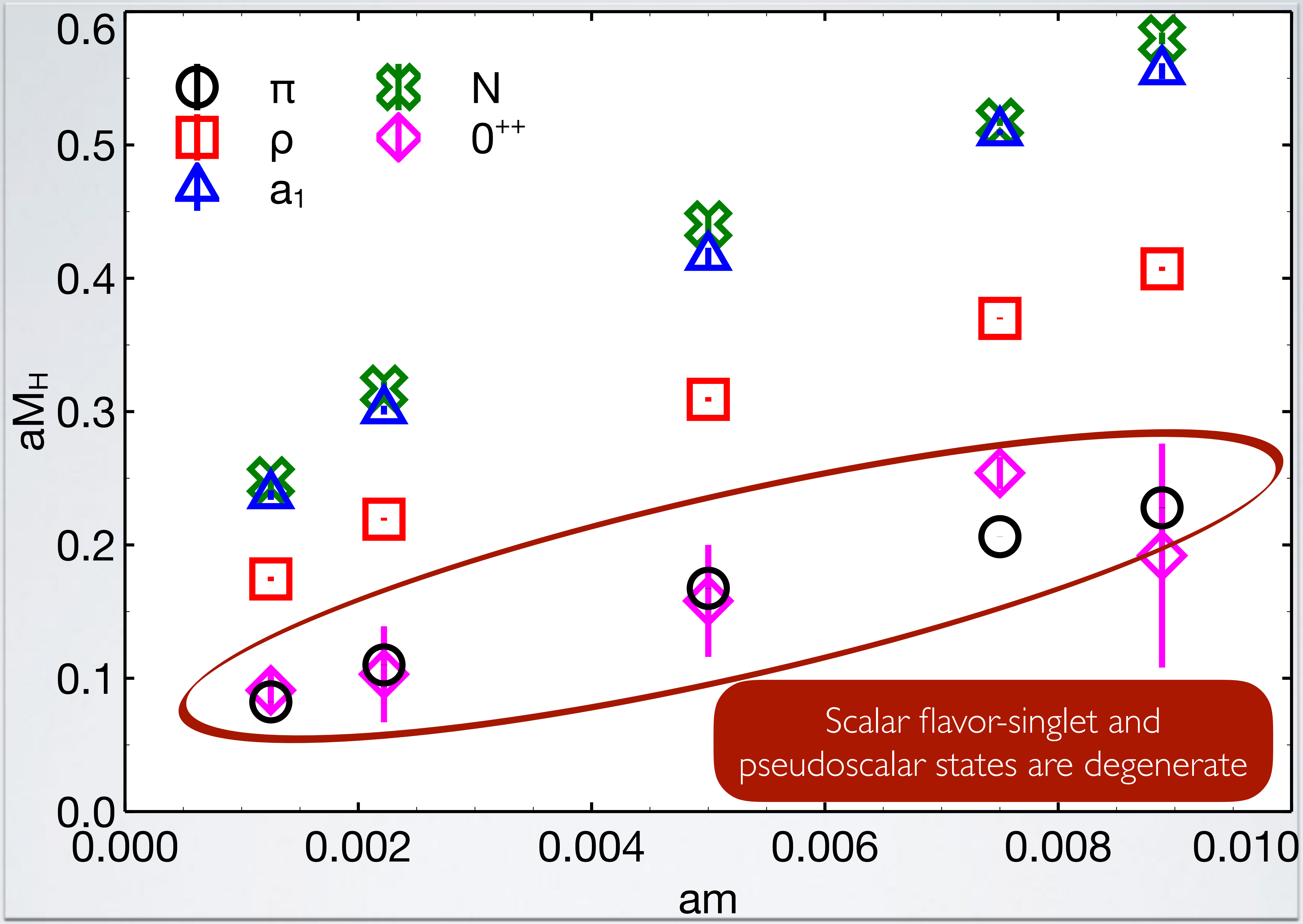

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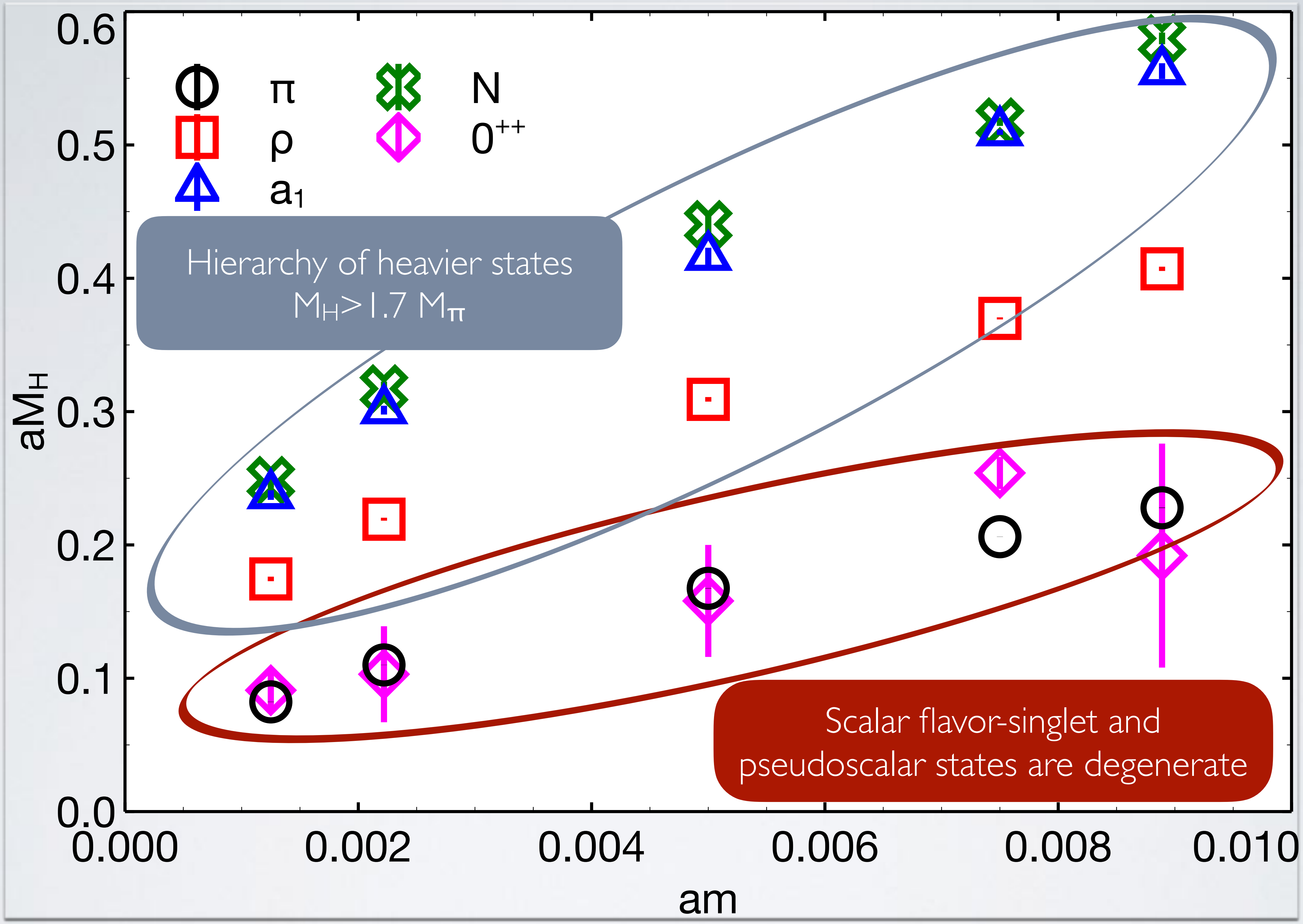

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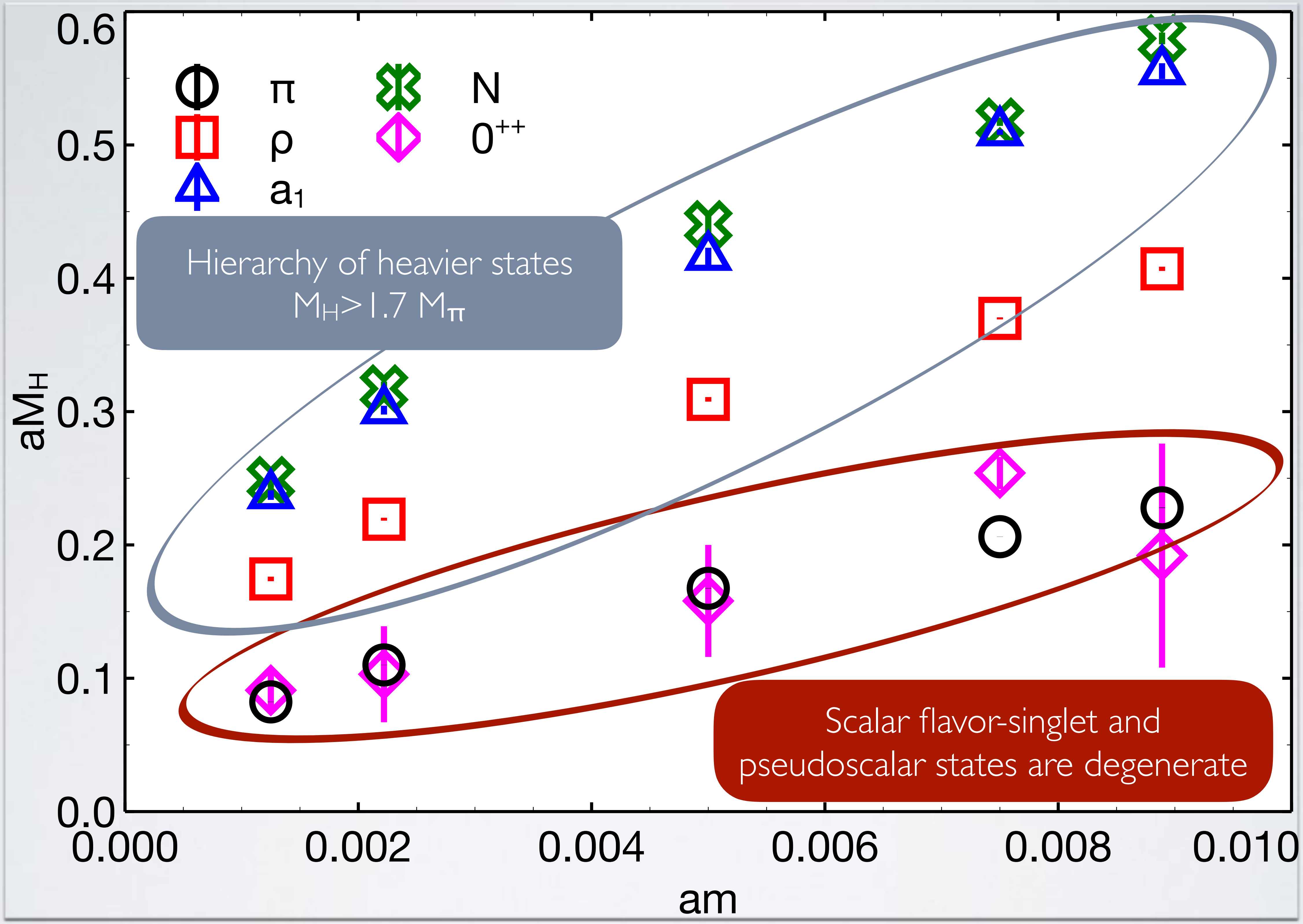

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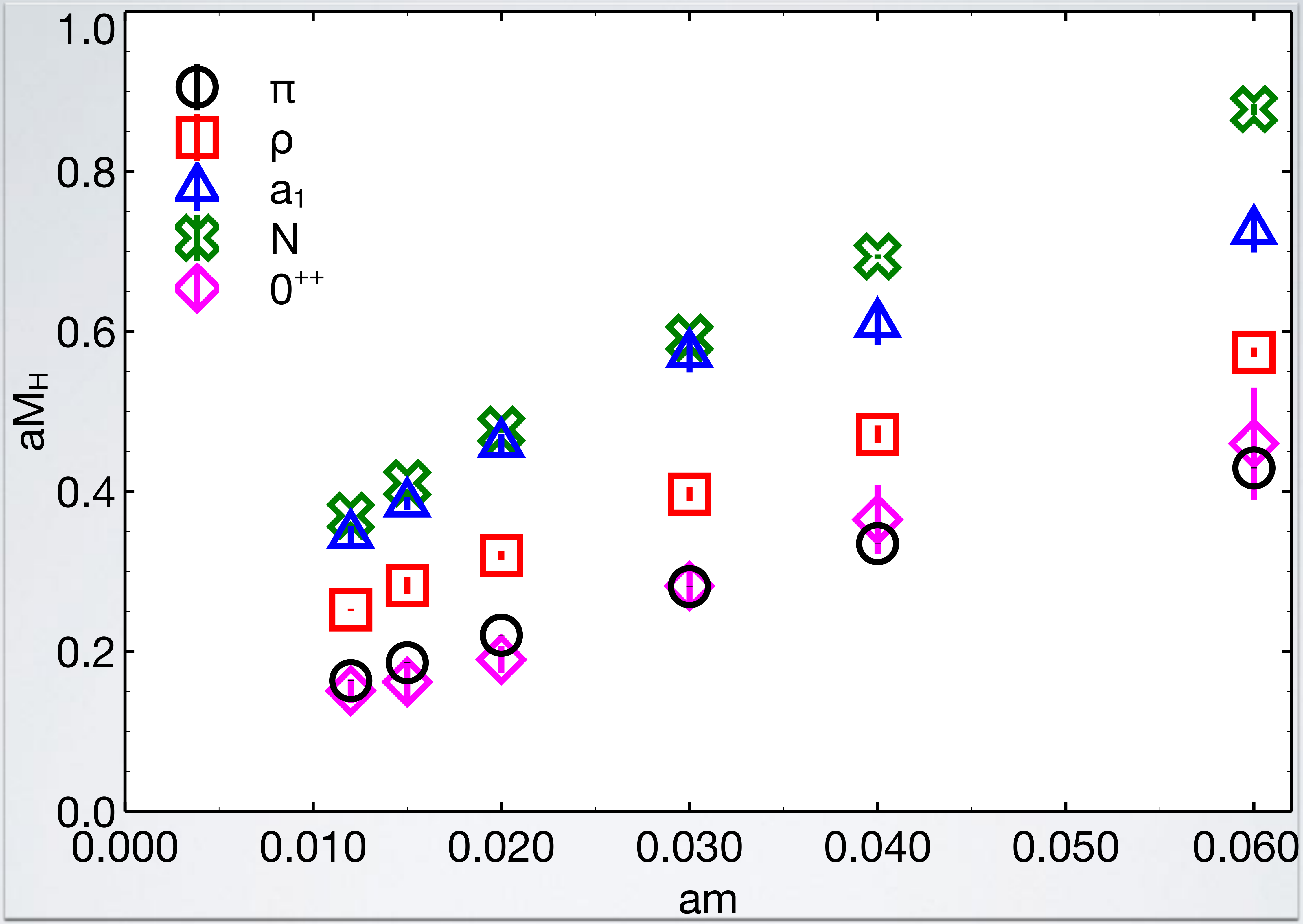

Lattice details: tree-level Symanzik gauge action + HISQ staggered quarks

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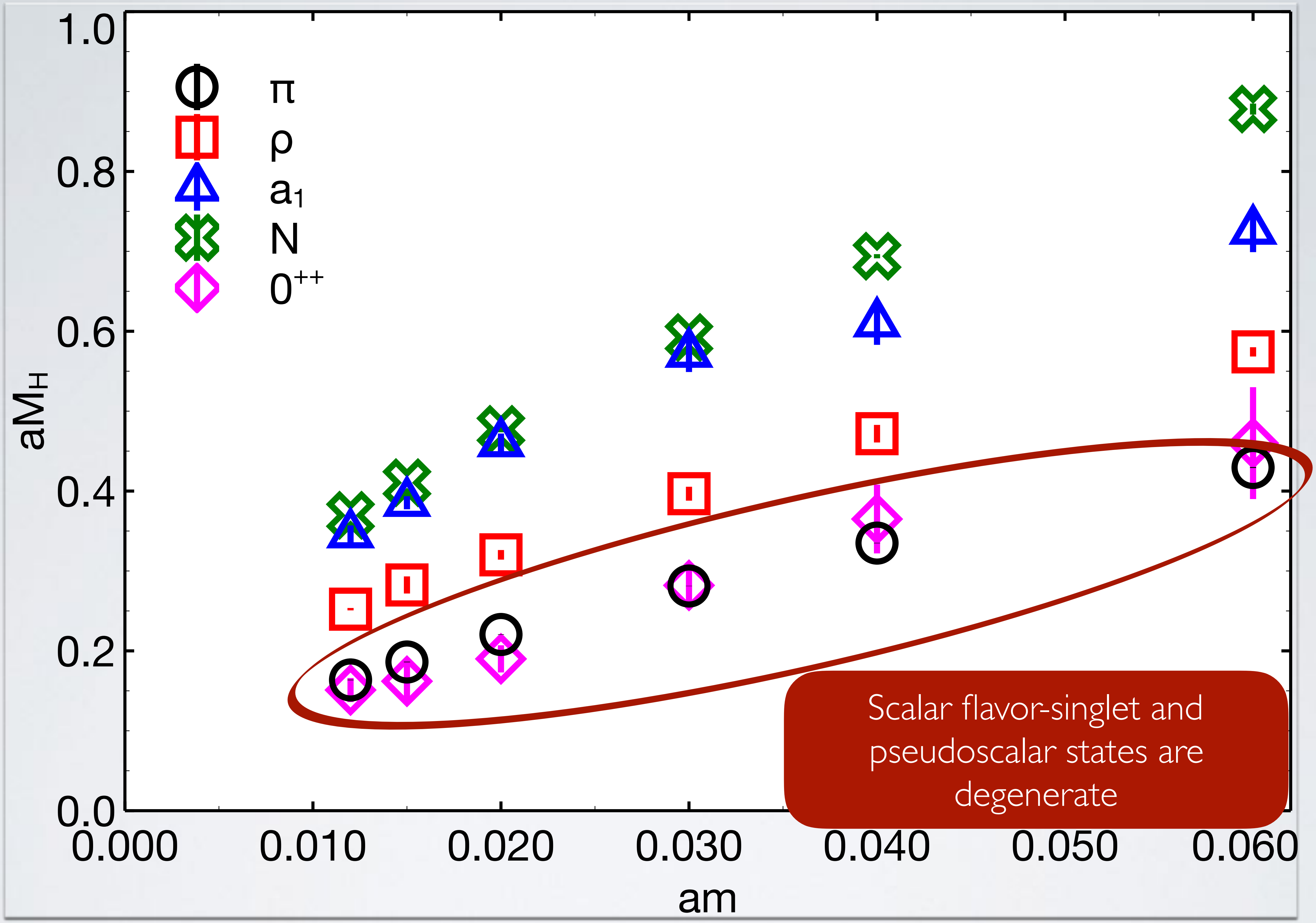

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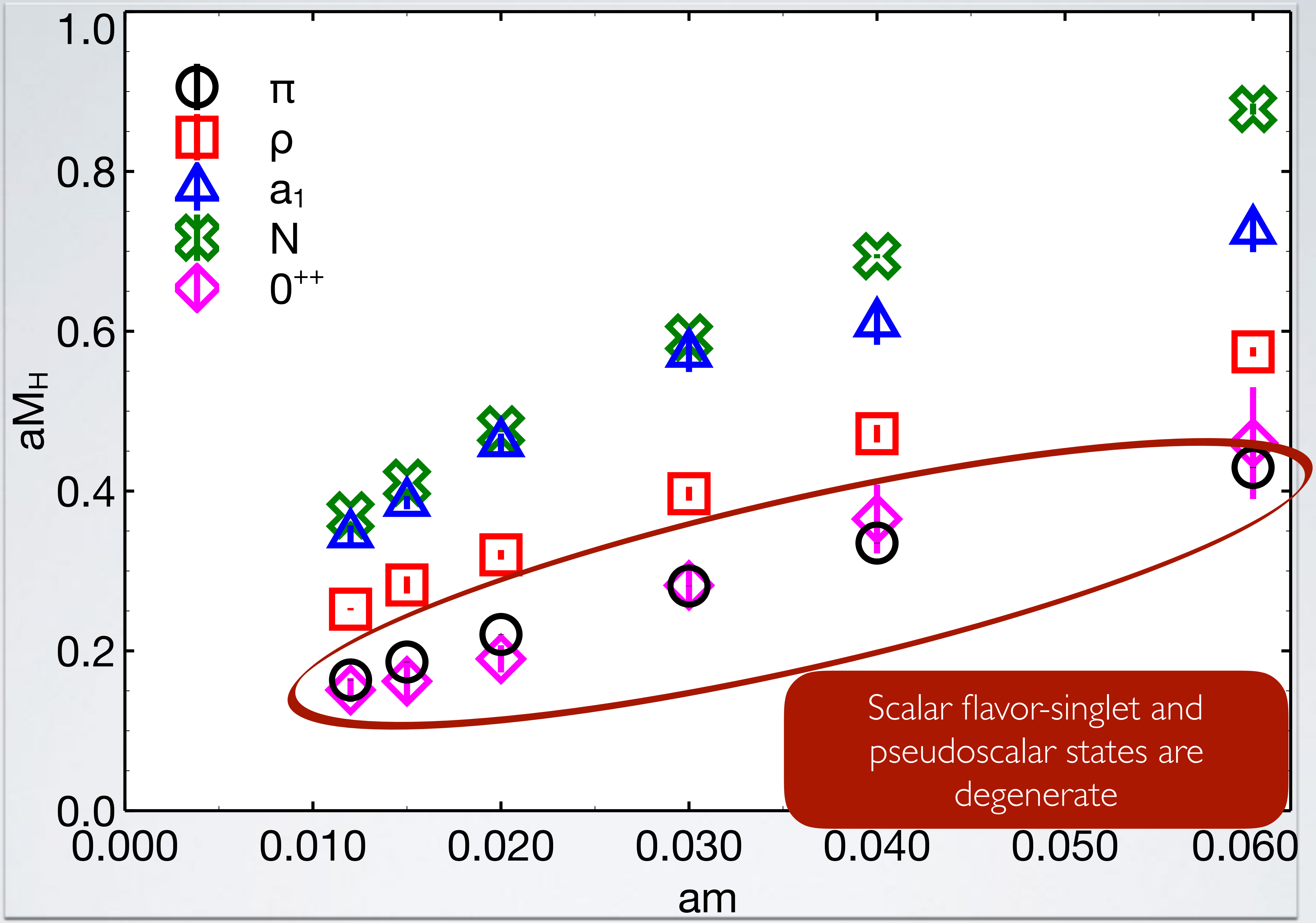

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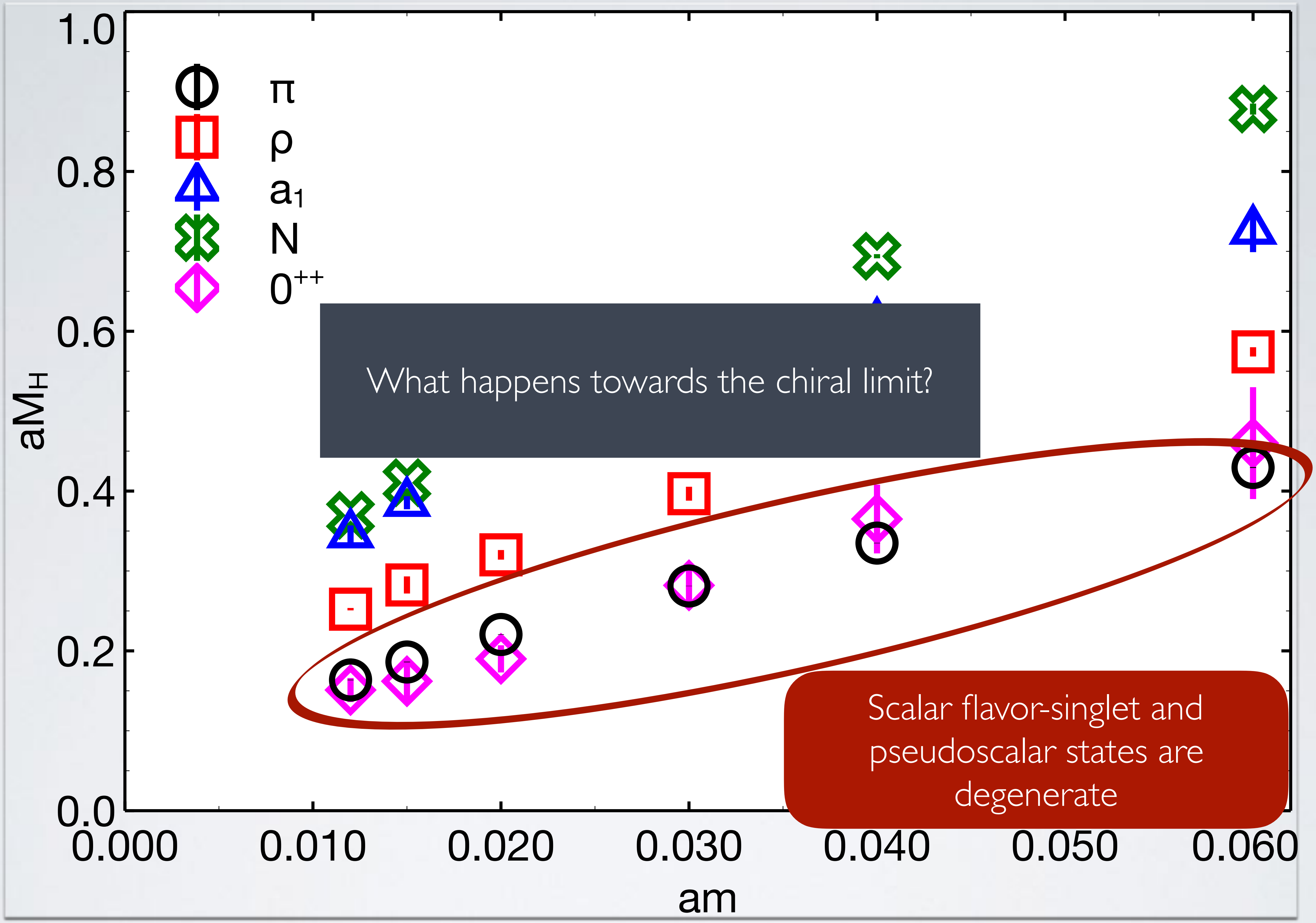

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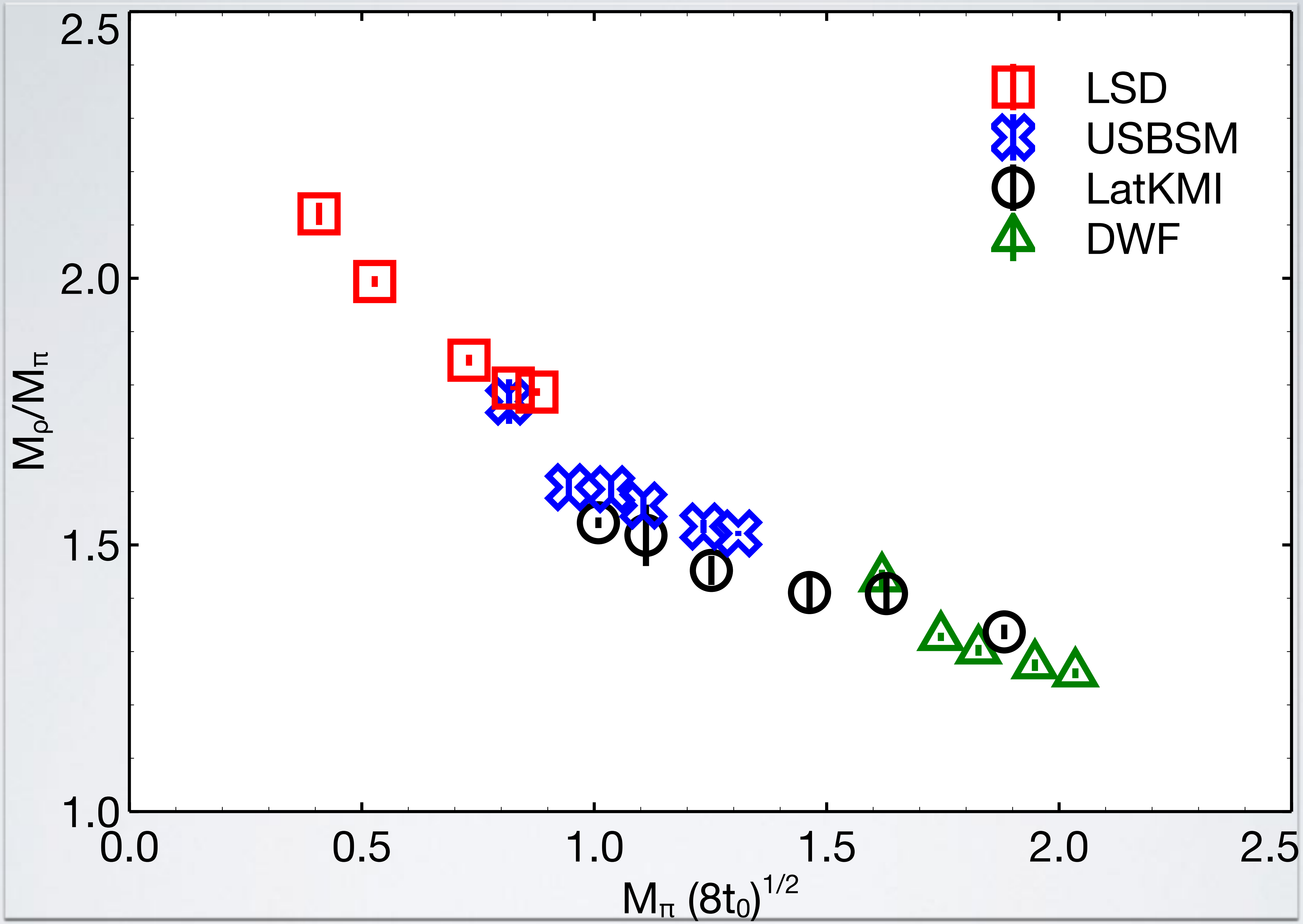

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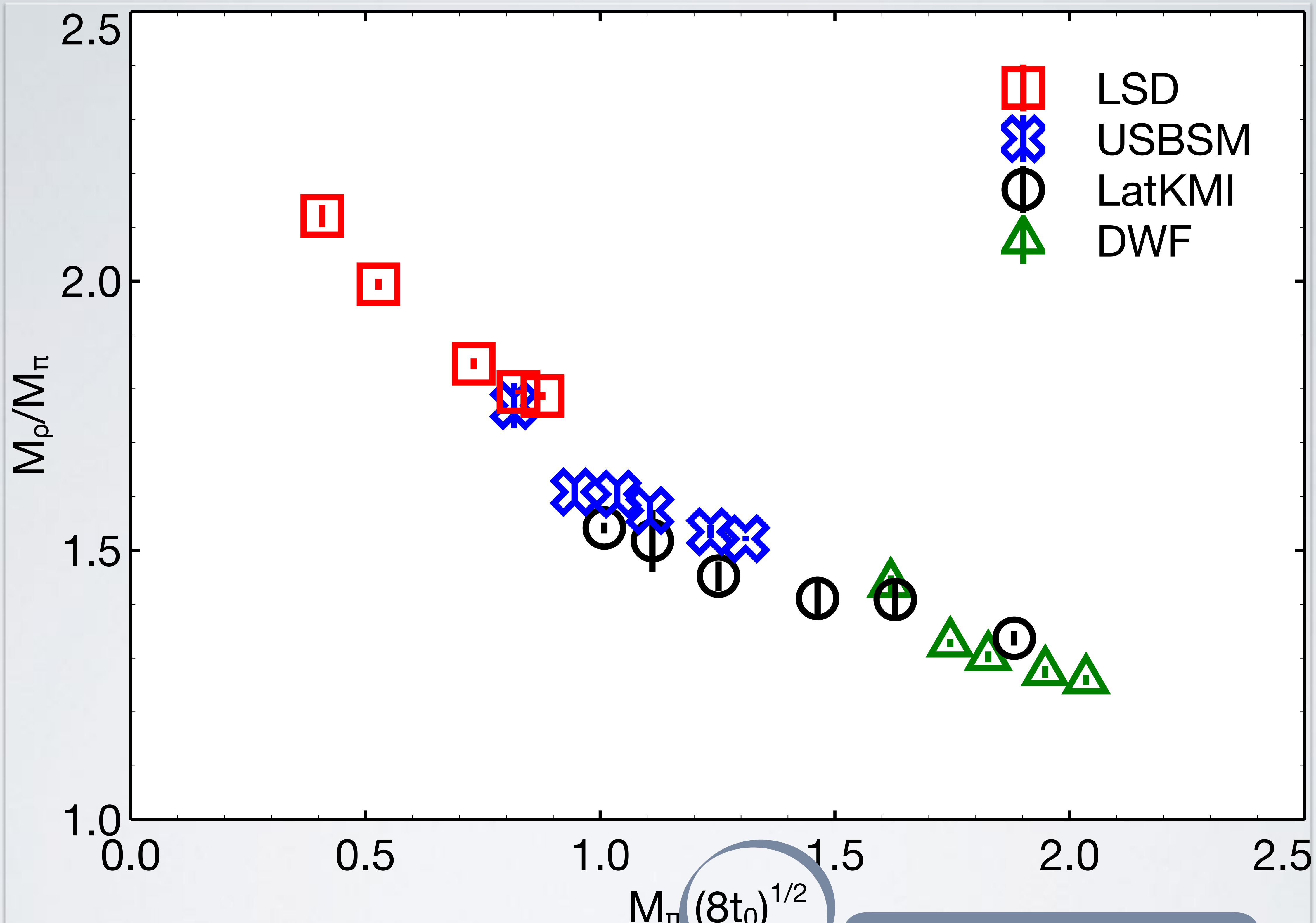

Wilson flow scale:
common reference

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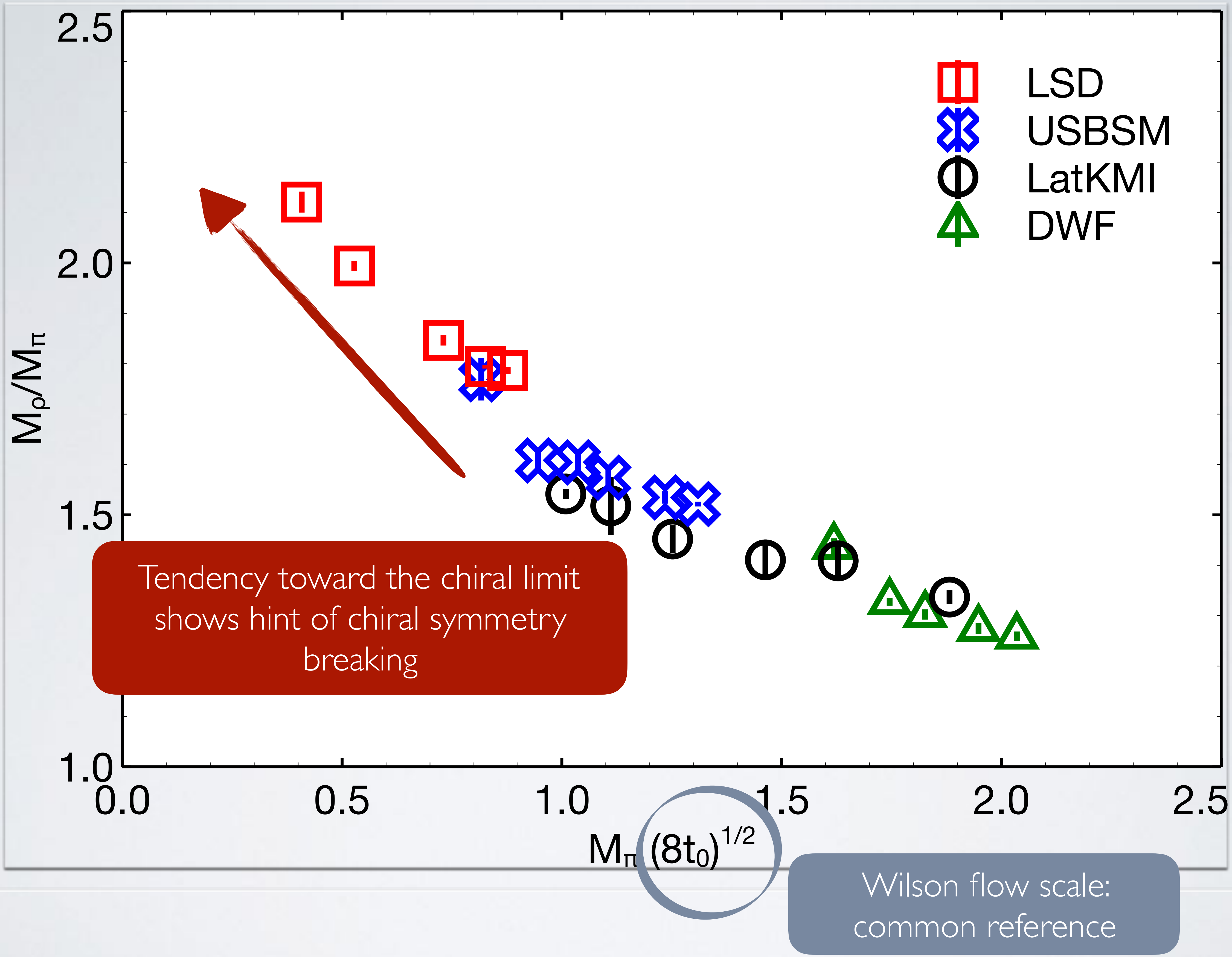

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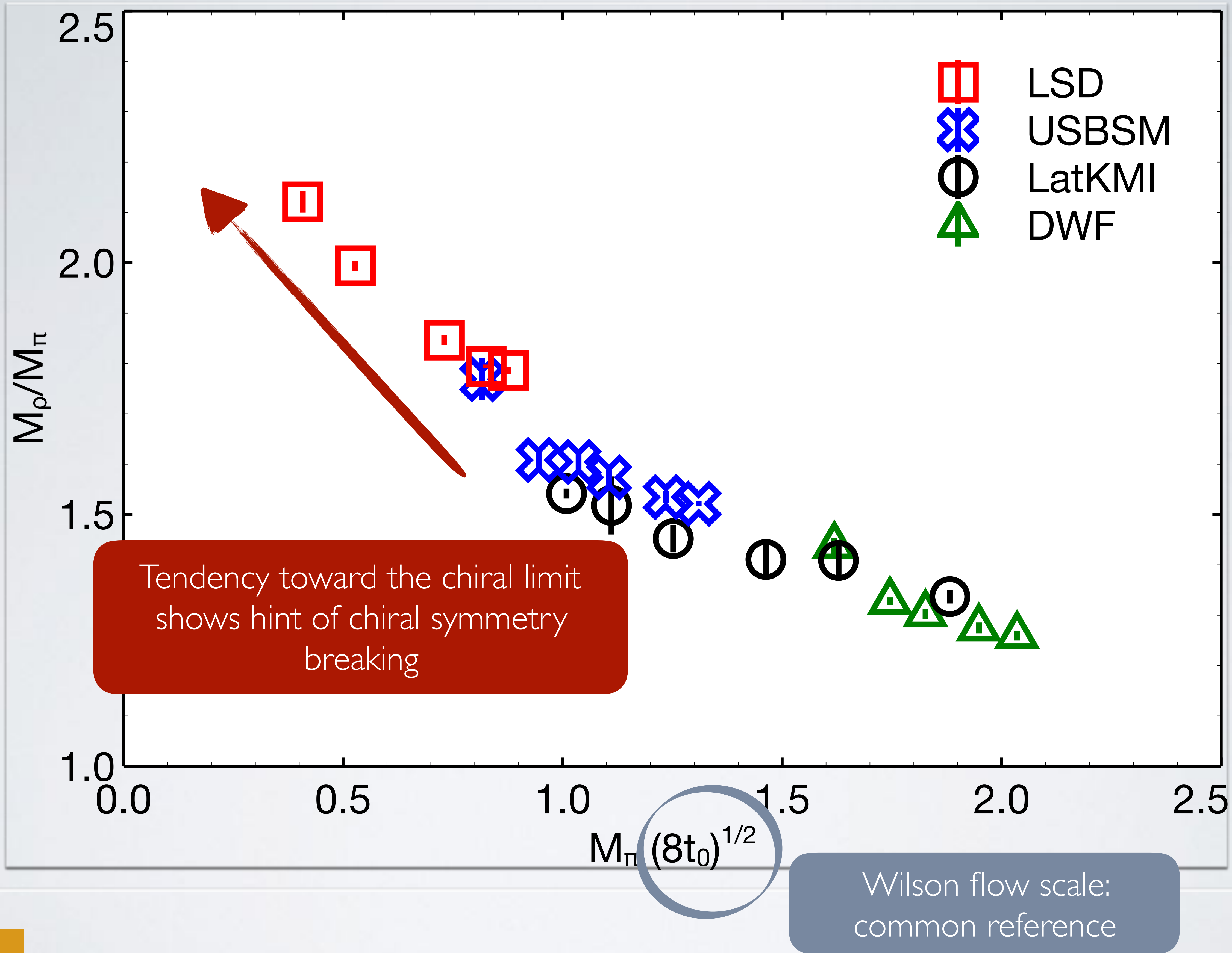

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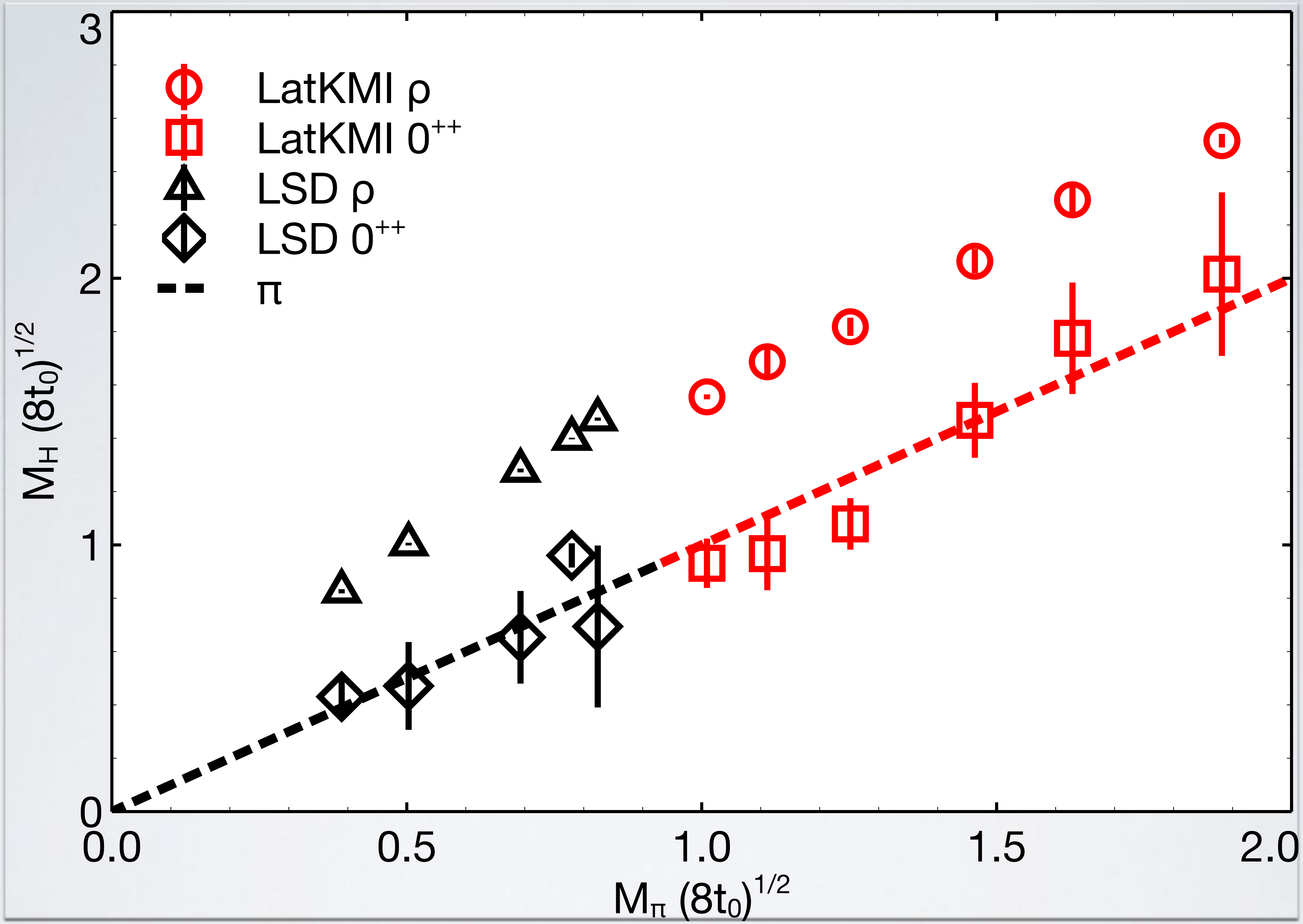

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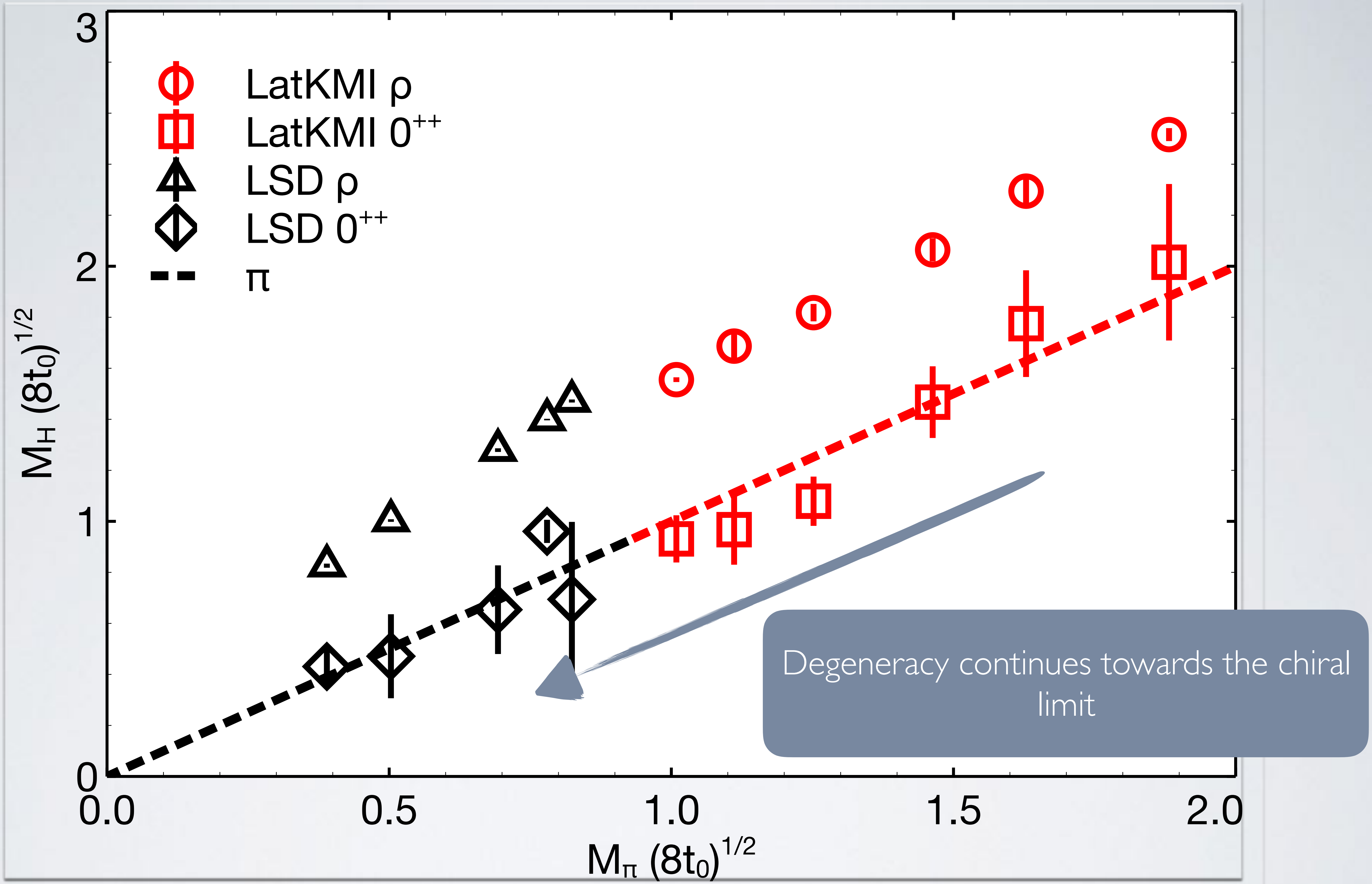

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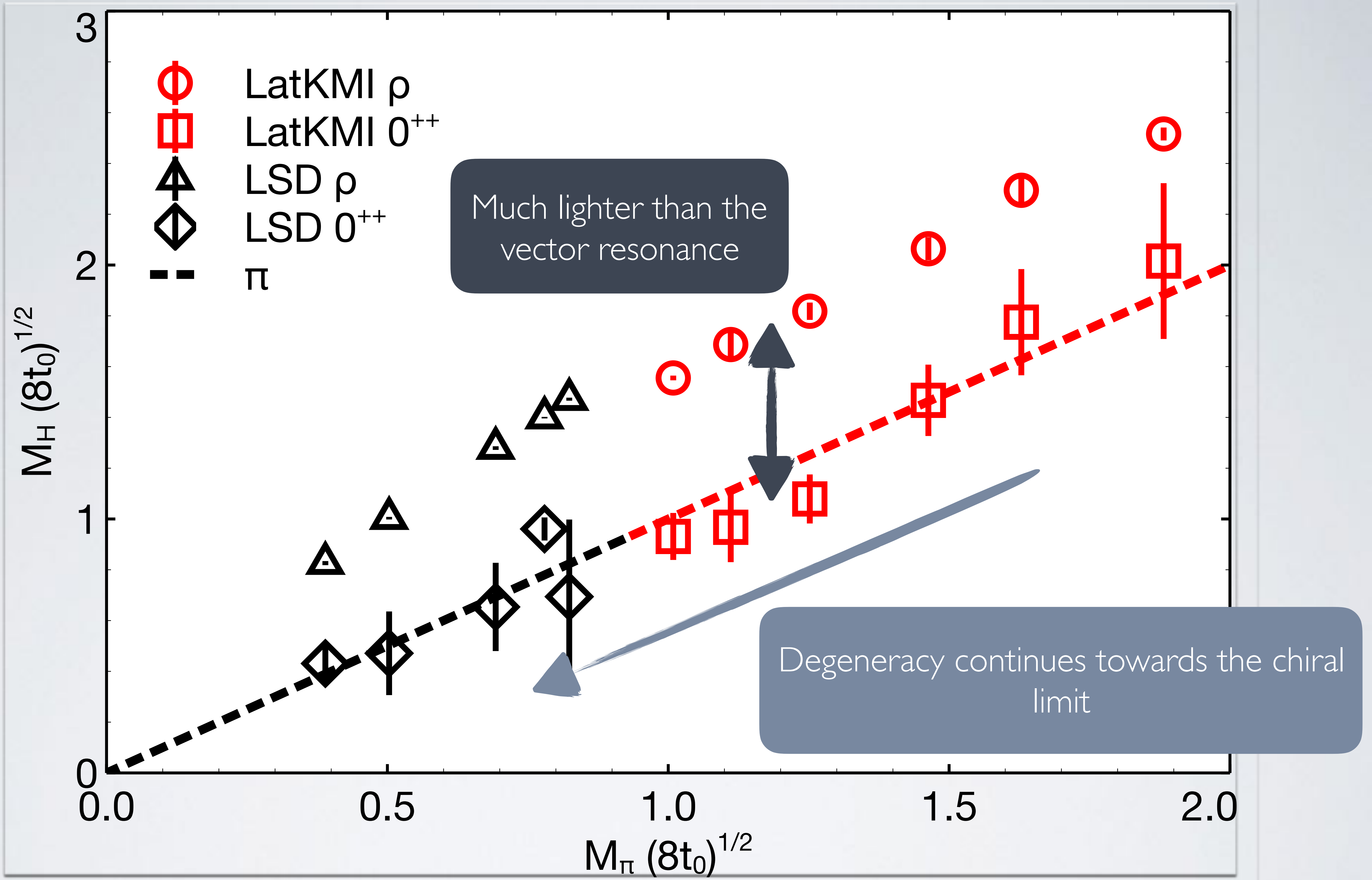

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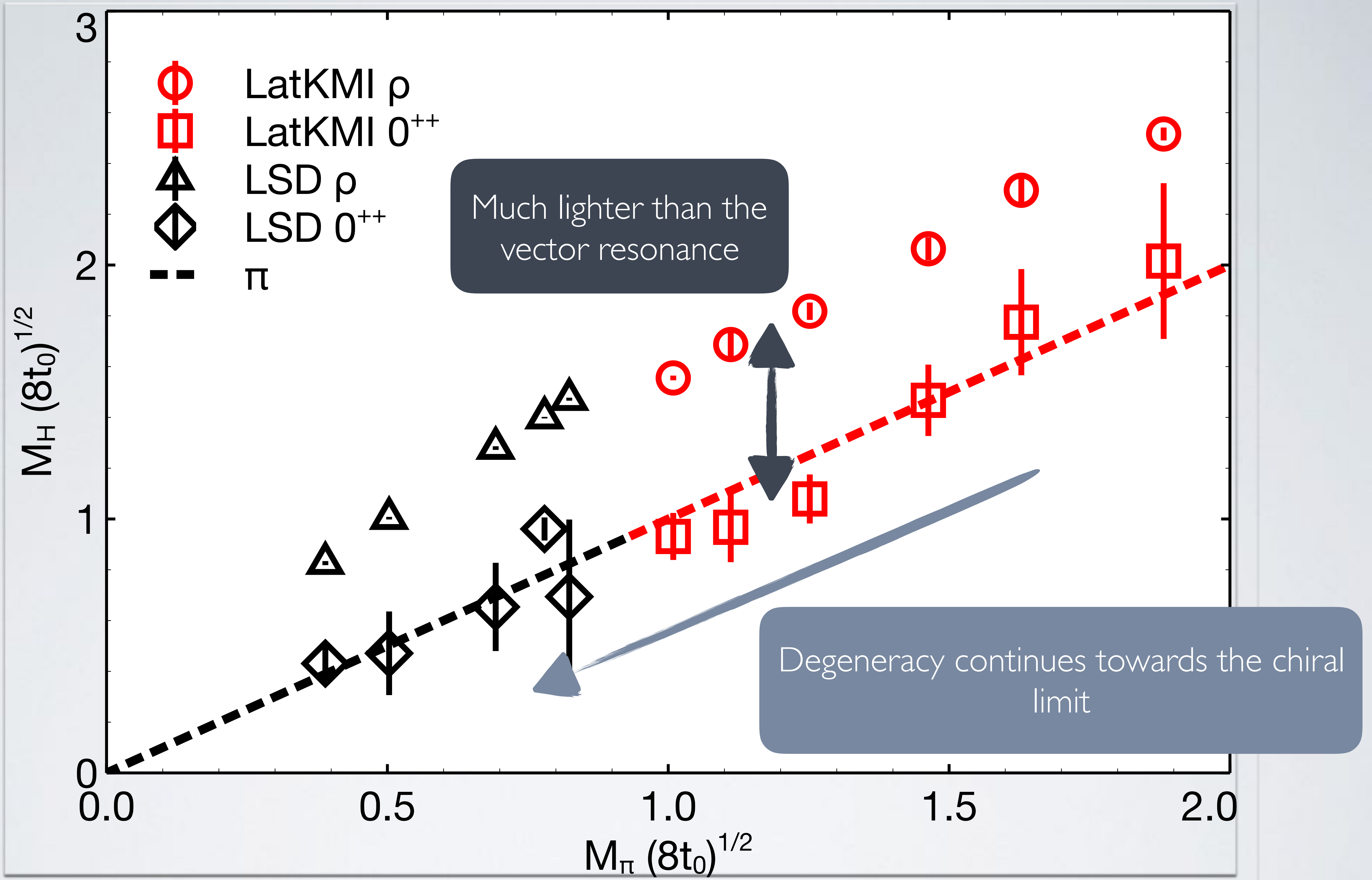

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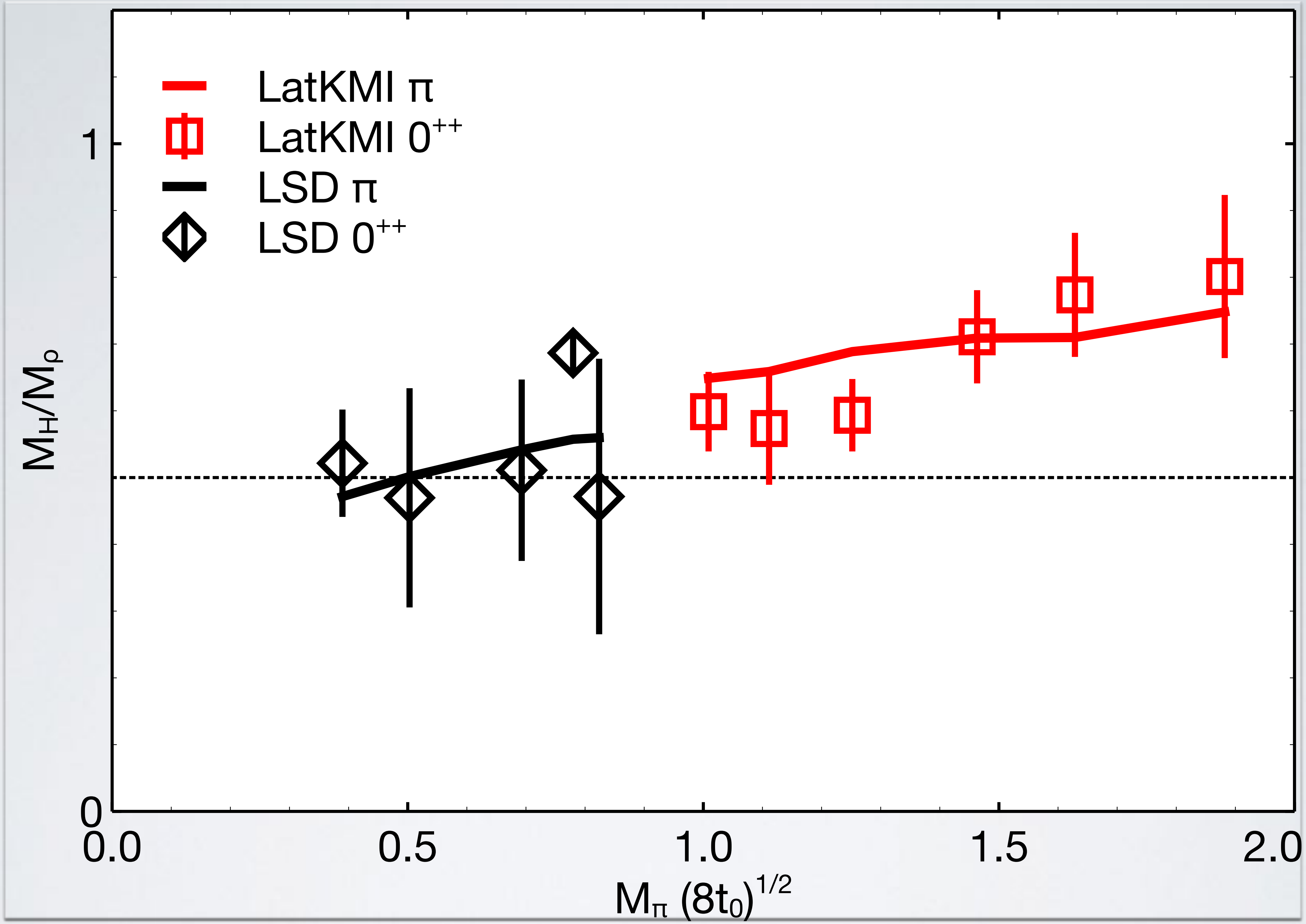

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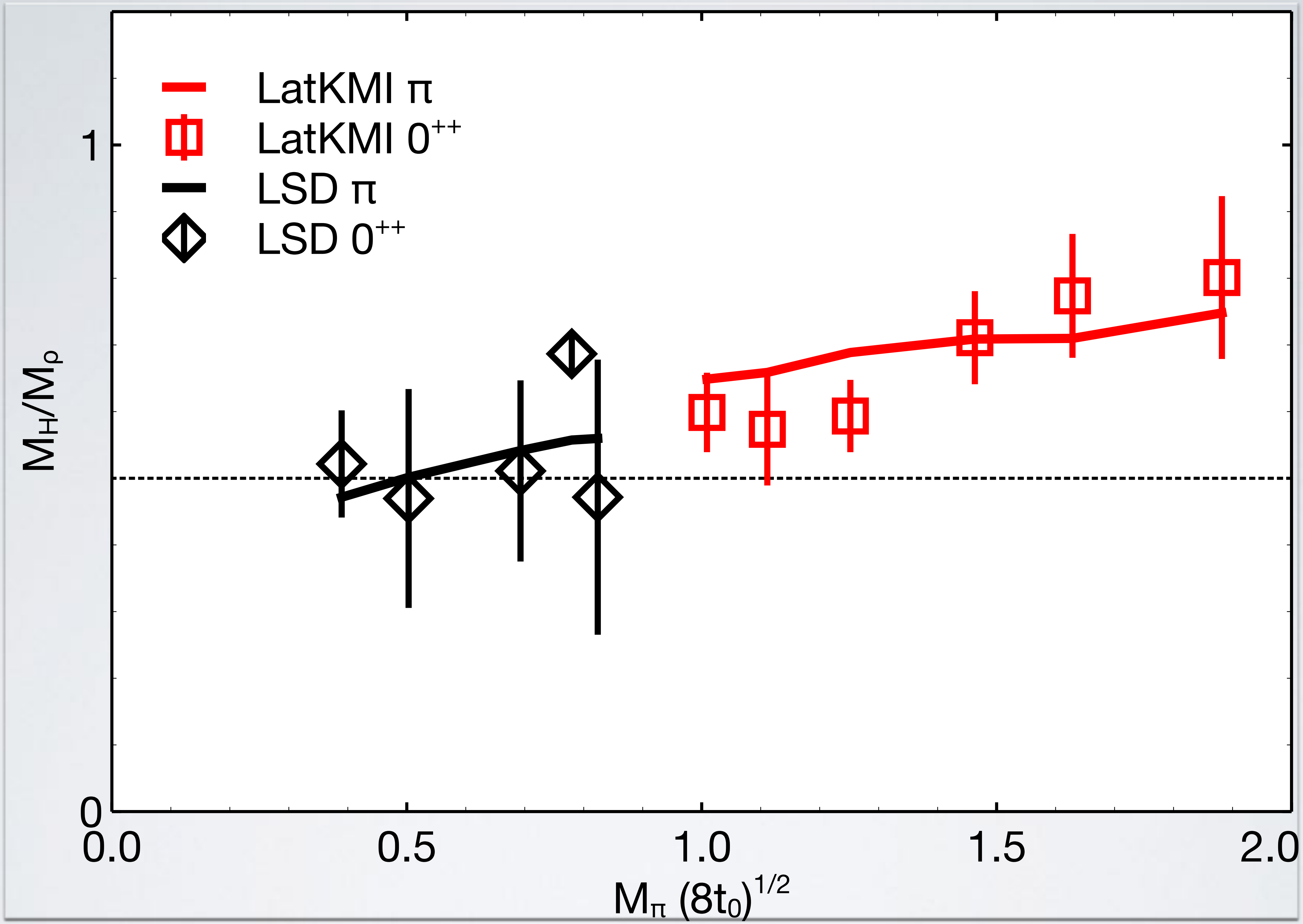

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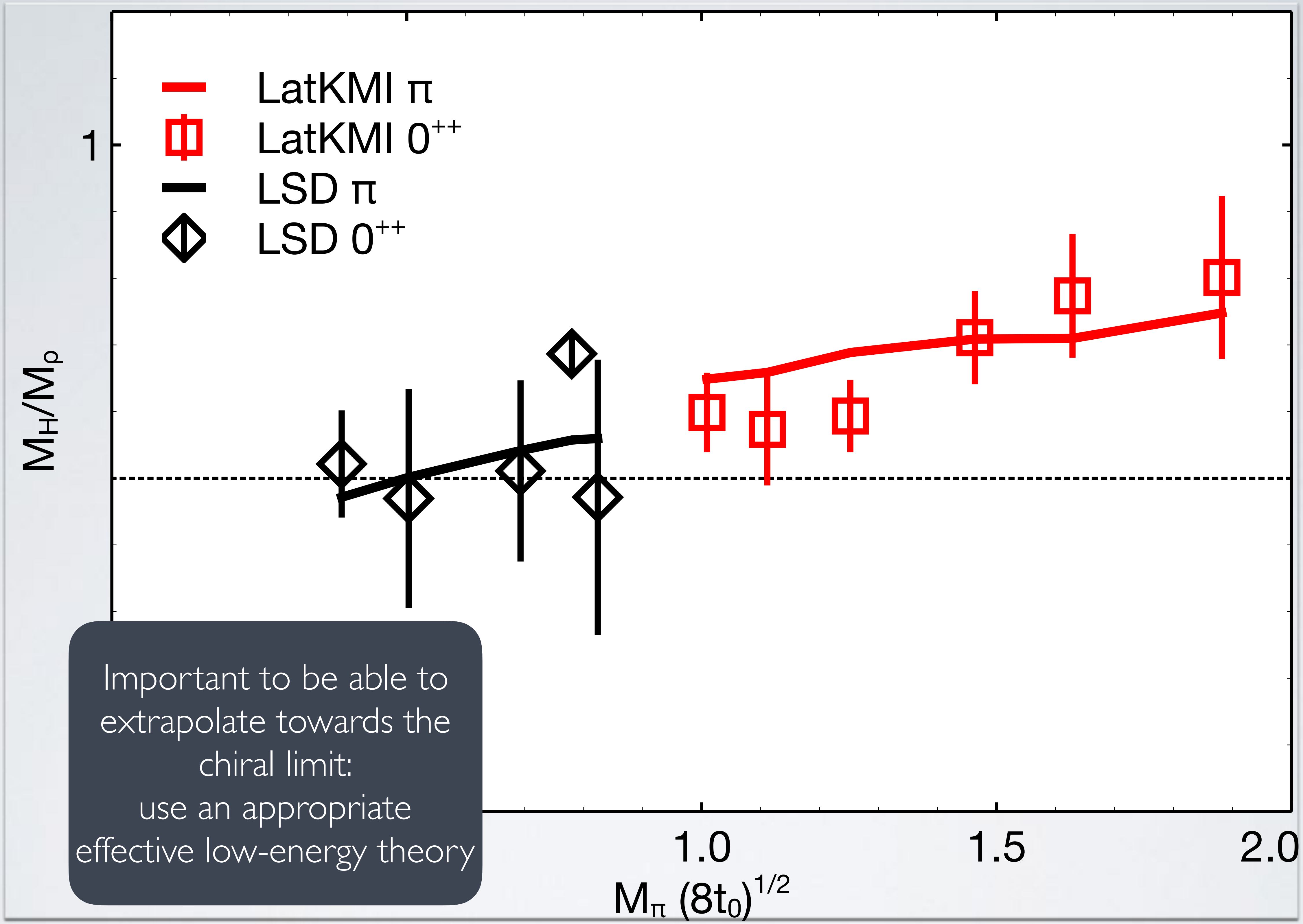

Important to be able to extrapolate towards the chiral limit:
use an appropriate effective low-energy theory

Different from QCD

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  - Different forms of the Effective potential for the scalar and pseudoscalar can be directly tested against Lattice data **[Appelquist,Ingoldby&Piai:1702.04410]**

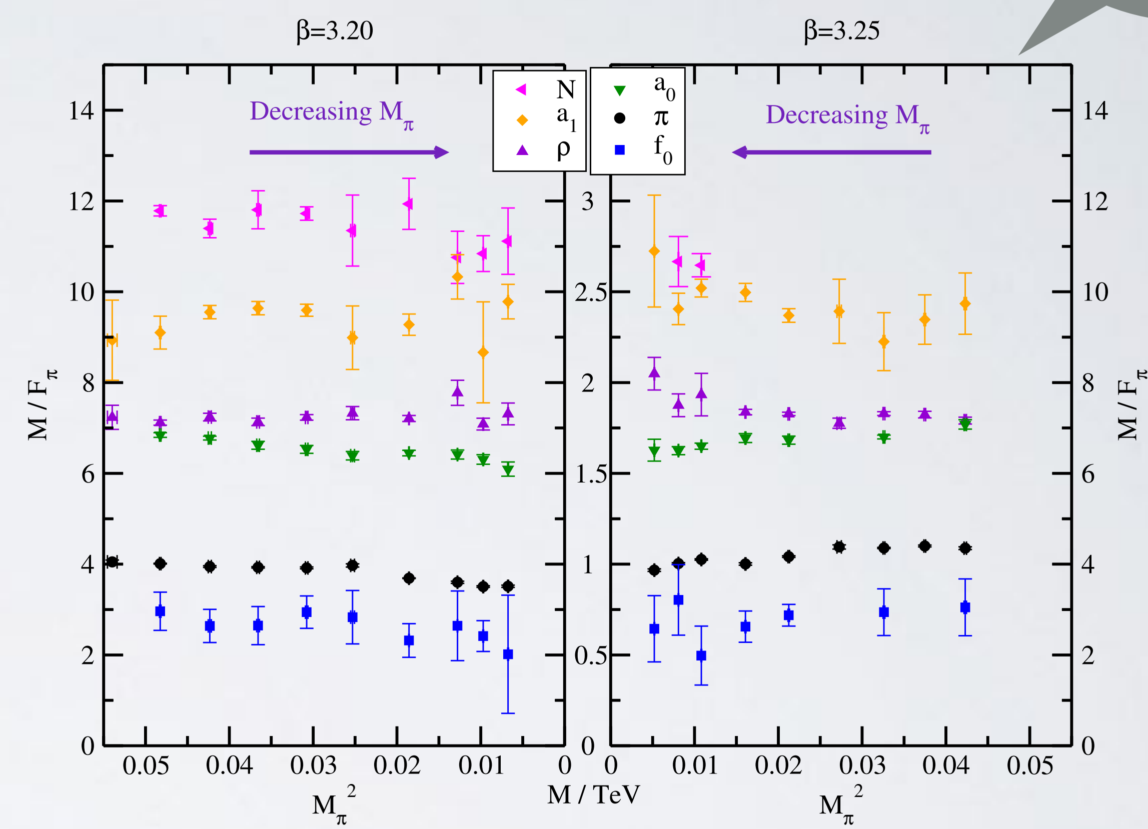
[latest results in Pica arxiv:1701.07782 and Svetitsky arxiv:1708.04840]

★ light
■ heavy

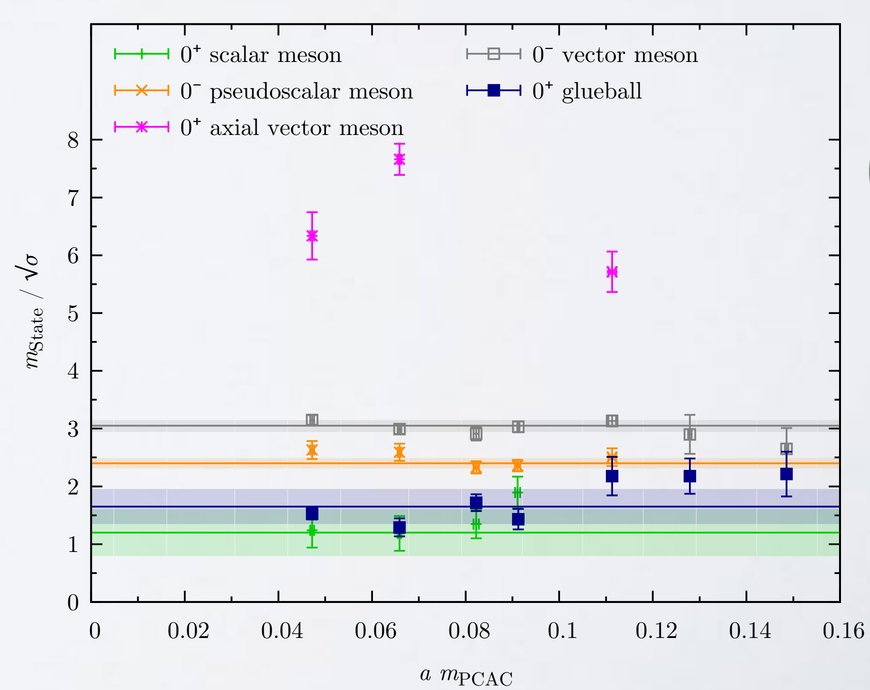
SUMMARY RESULTS

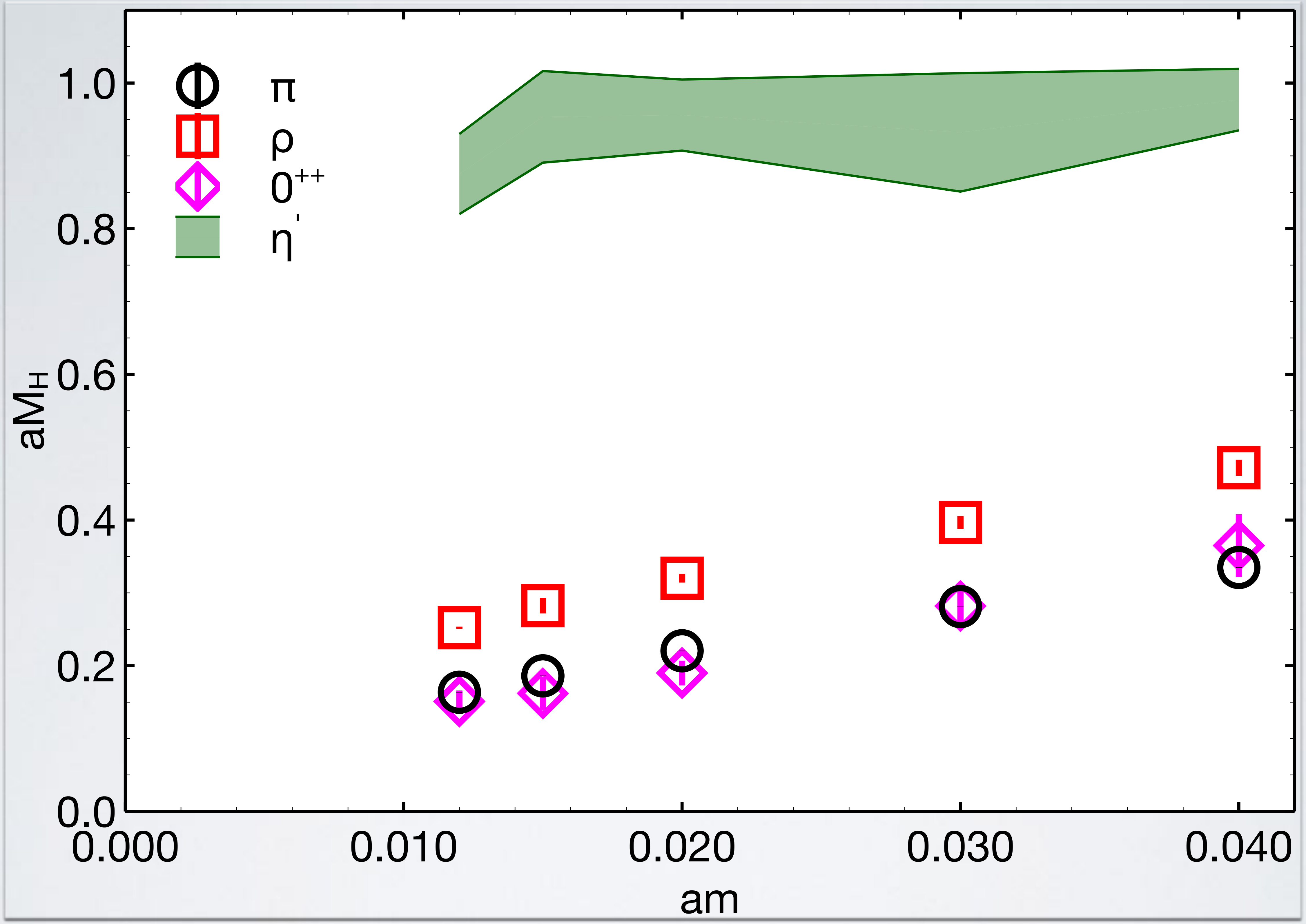
Template Models	Scalar
SU(2) N_f=2 (F)	■
SU(2) N_f=2 (A)	★
SU(2) N_f=1 (A)	★
SU(3) N_f=12 (F)	★
SU(3) N_f=8 (F)	★
SU(3) N_f=4 (F)	■
SU(3) N_f=2 (S)	★

SU(3) Nf=2 (S)

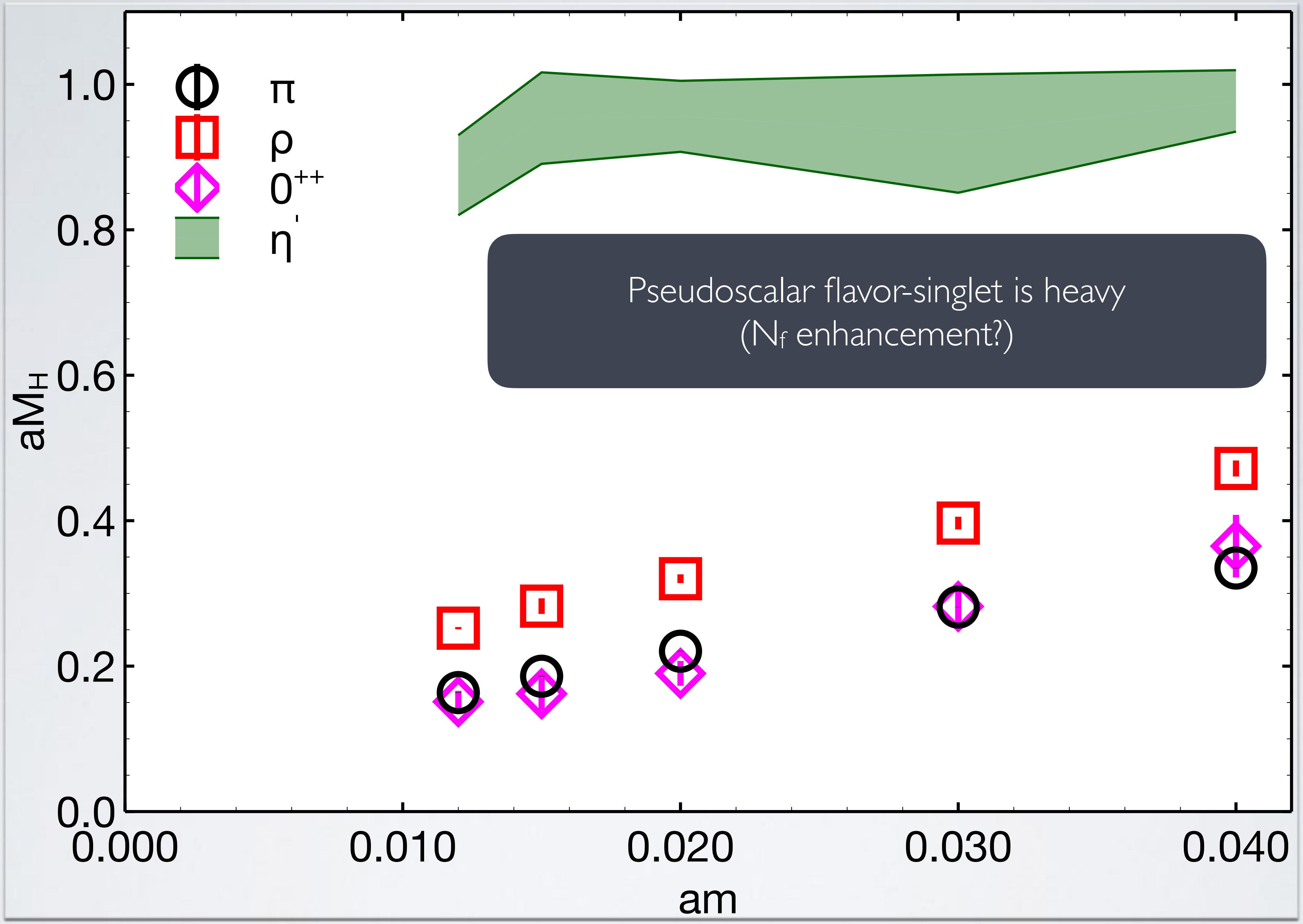


SU(2) Nf=1 (A)





LatKMI arxiv:1610.07011 [+ in preparation]



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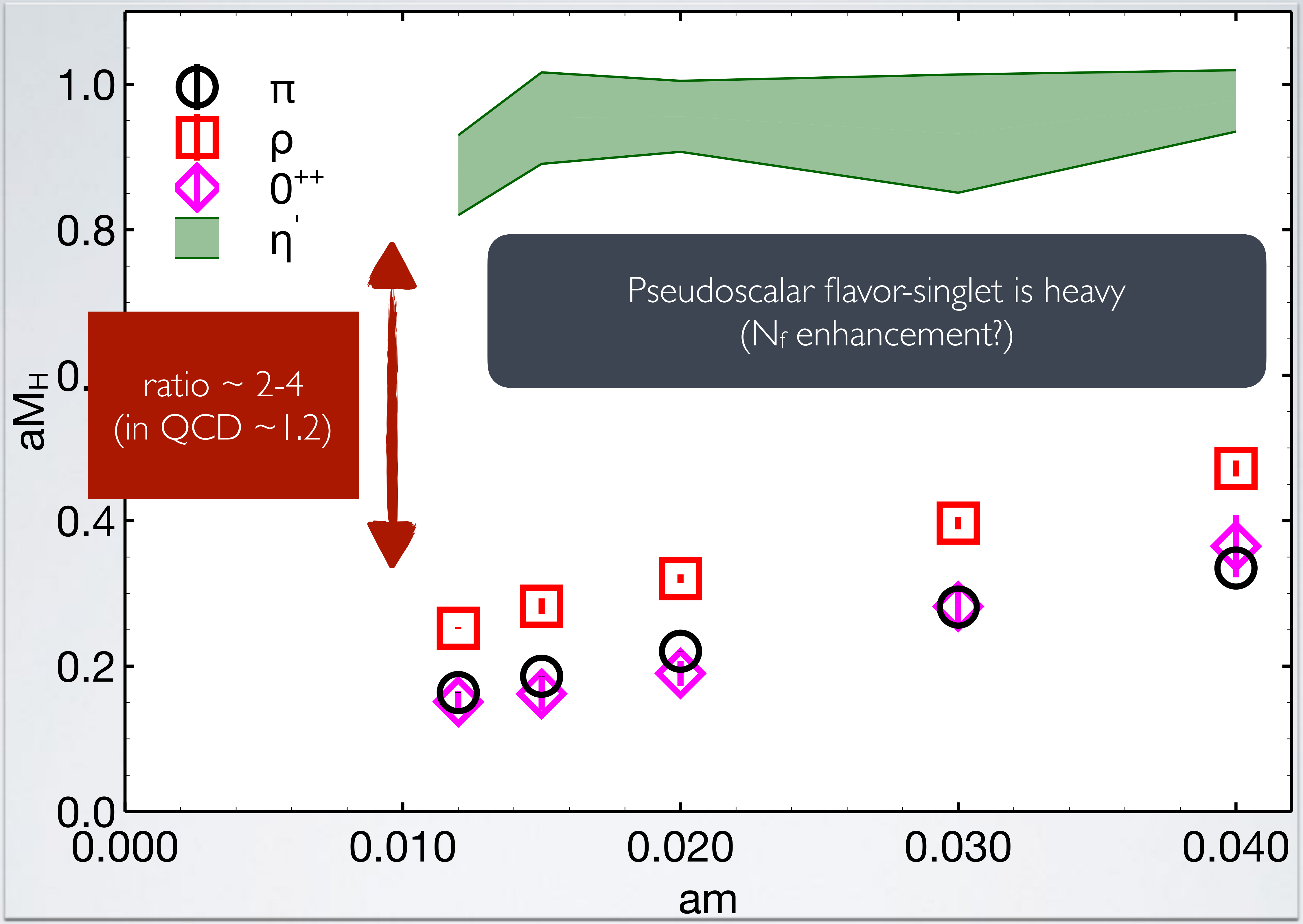

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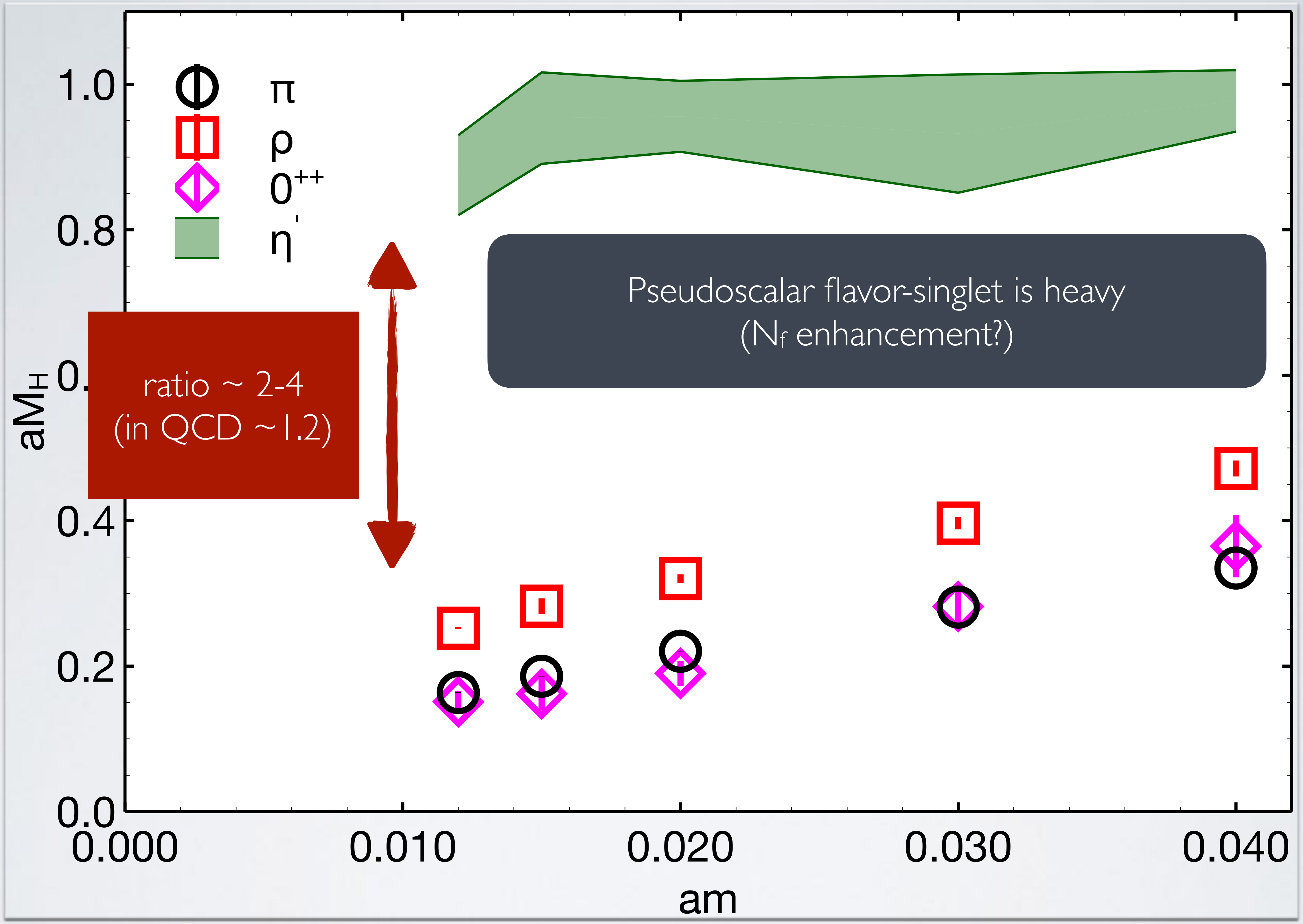

Different from QCD

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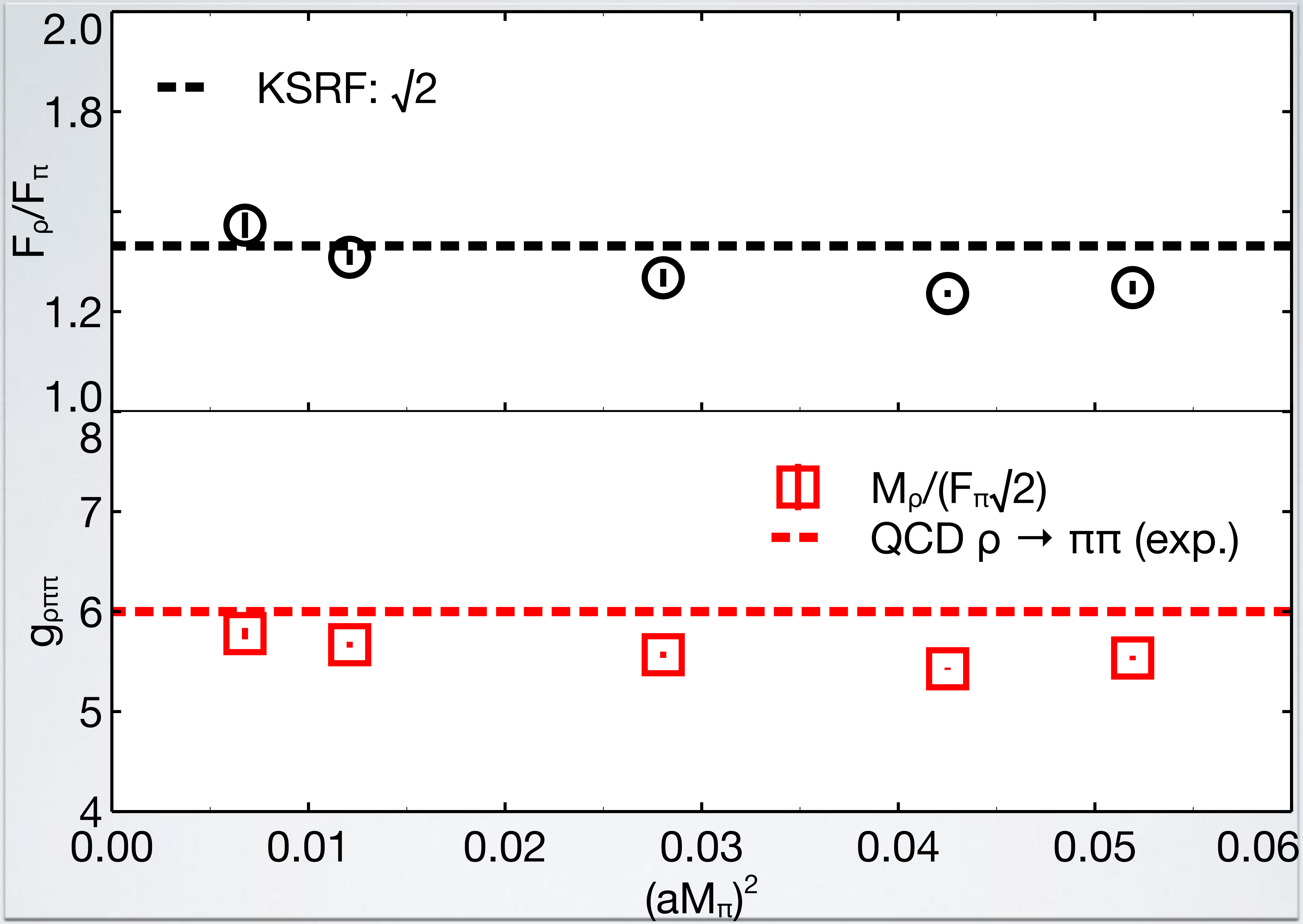
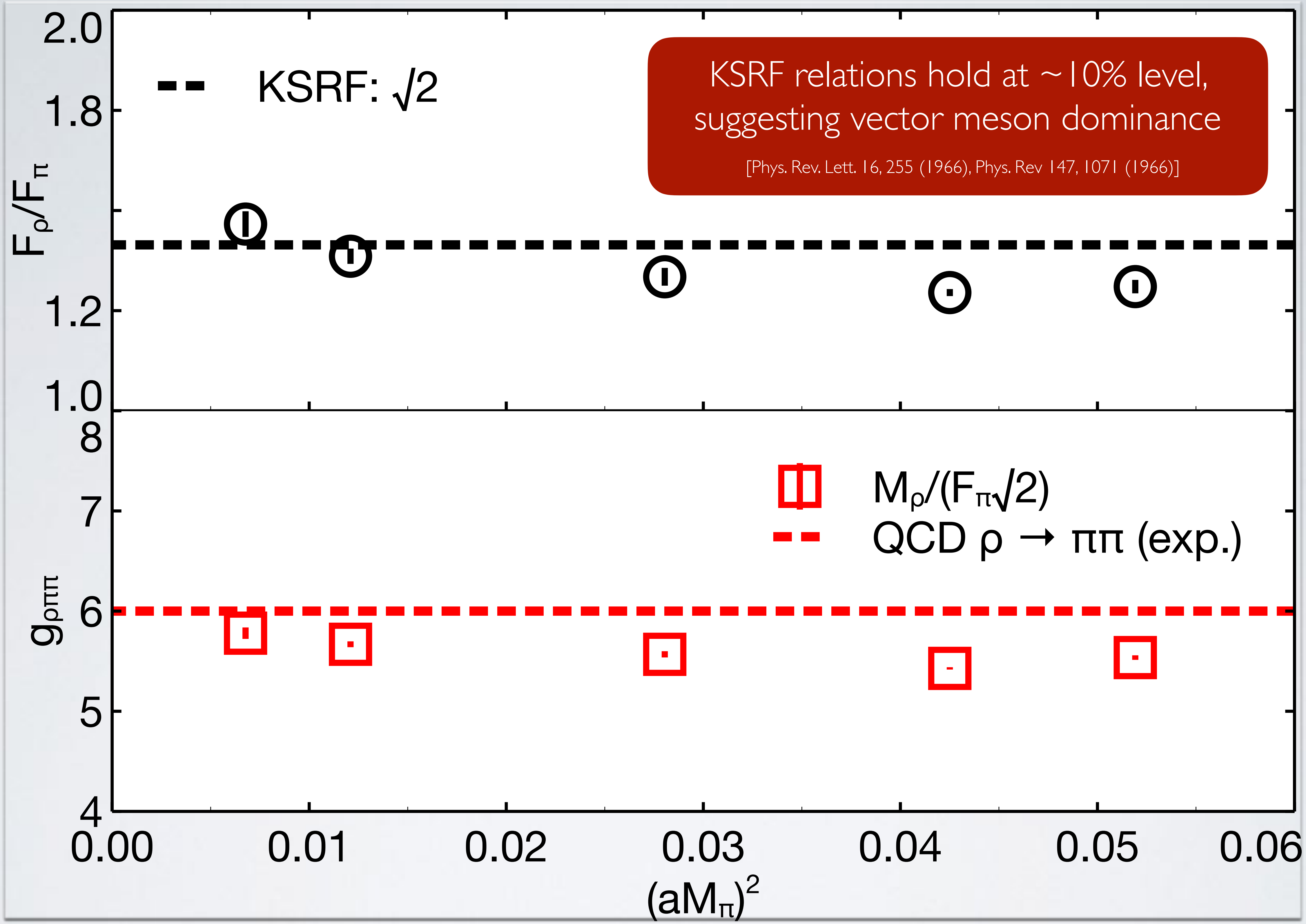


LSD arxiv:1601.04027



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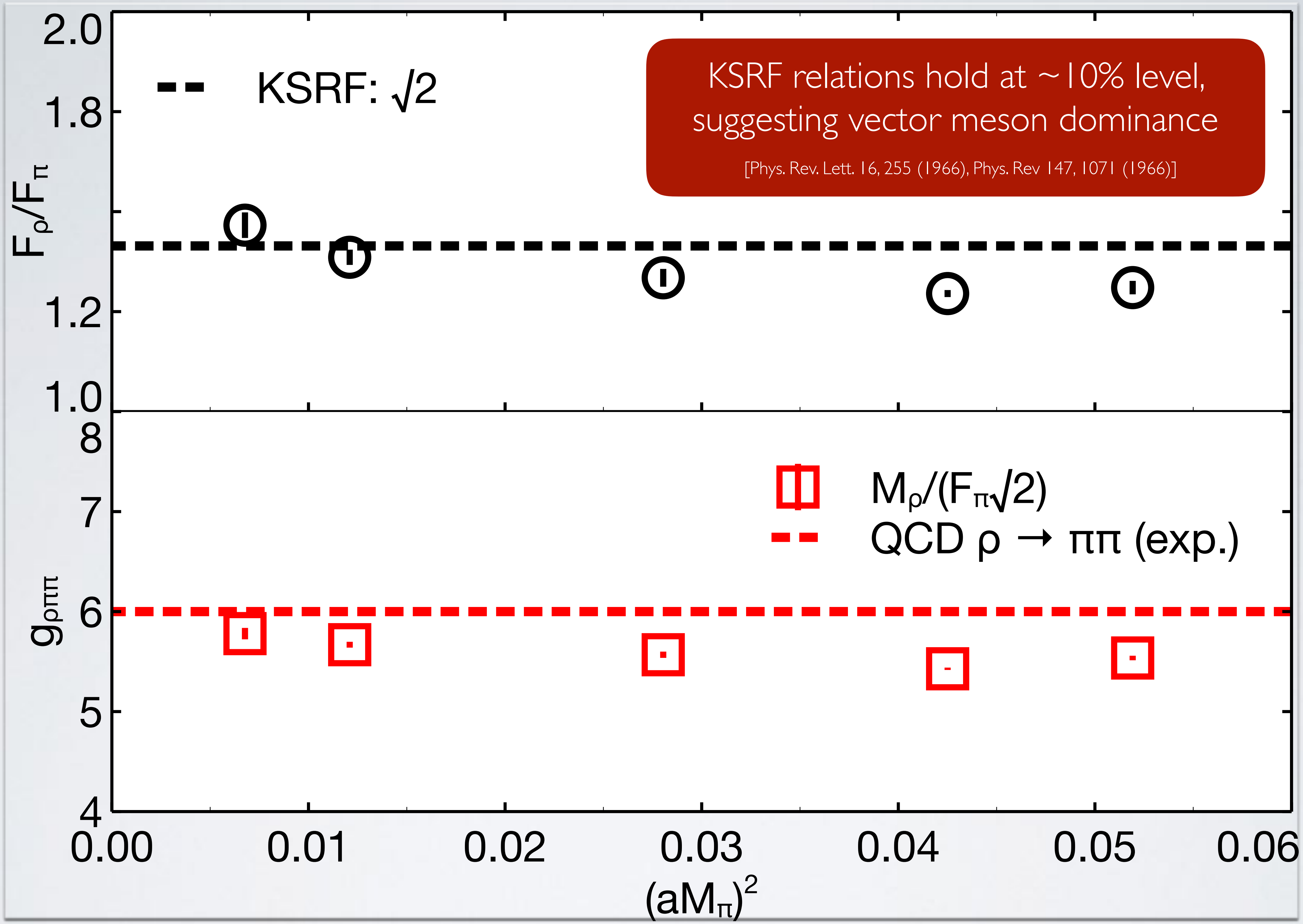

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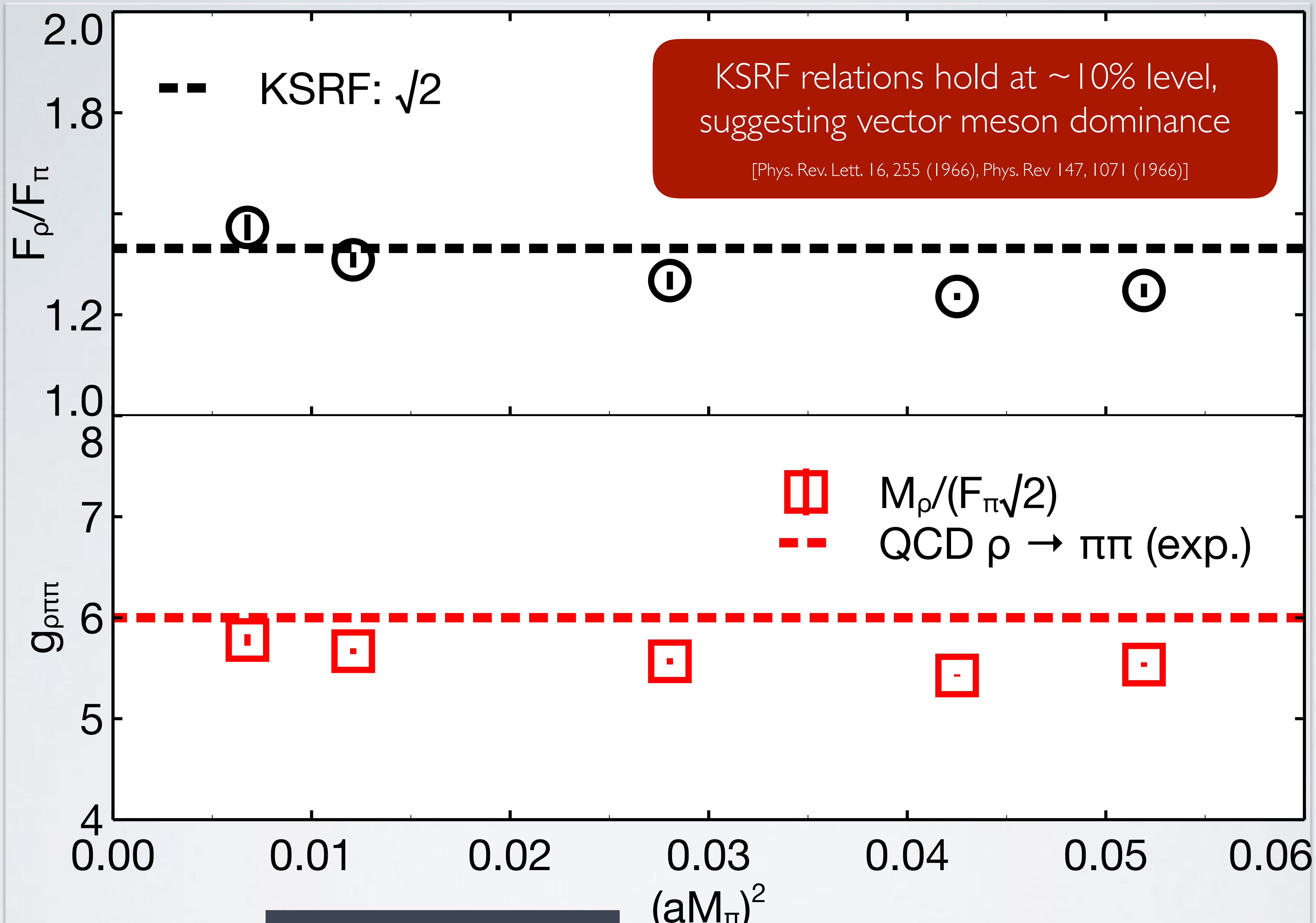

$$\Gamma_\rho \approx \frac{g_{\rho\pi\pi}^2 M_\rho}{48\pi}$$

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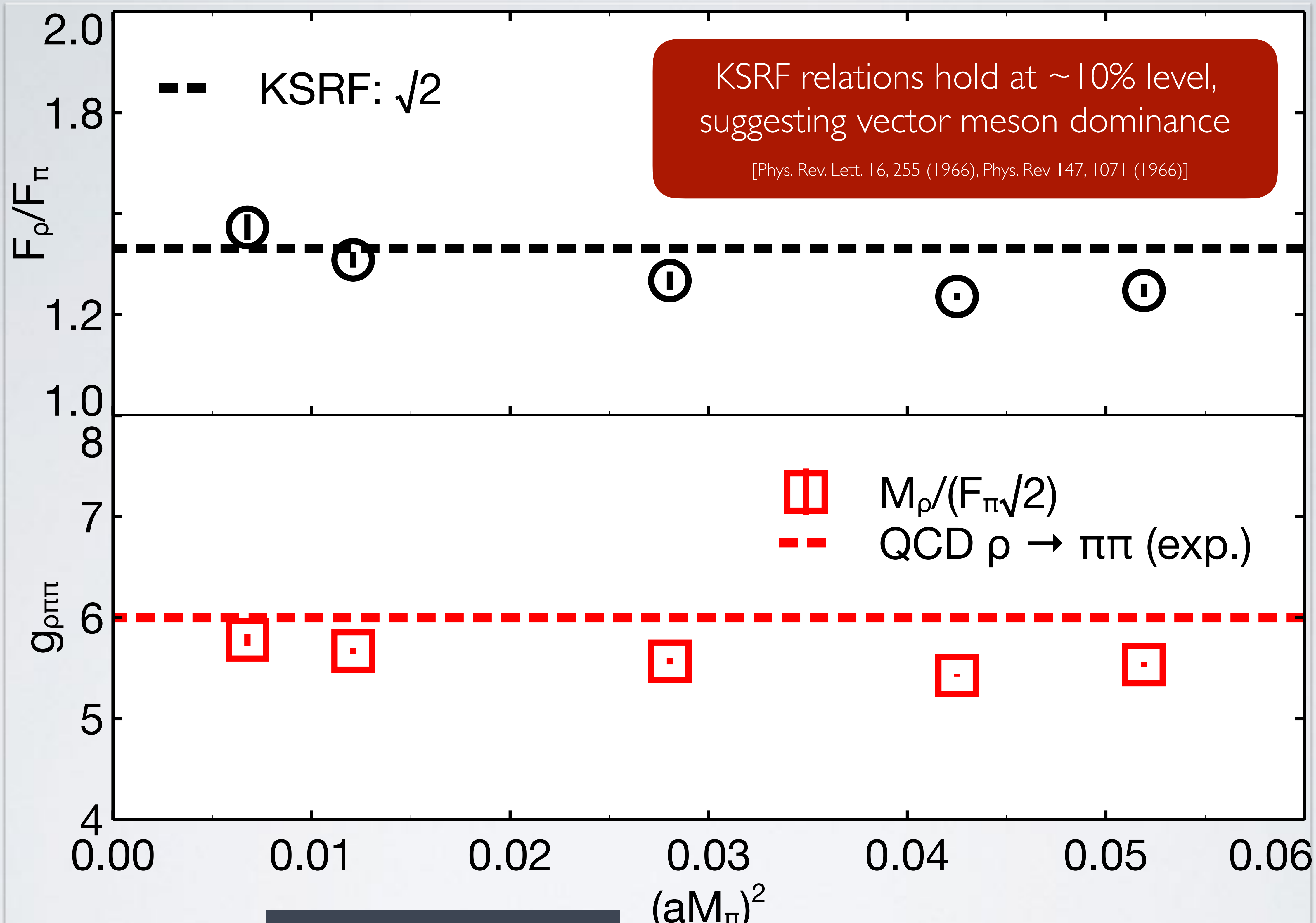

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M_ρ~2TeV and Γ_ρ~450GeV

Similar to QCD

LSD arxiv:1601.04027

CONCLUSIONS

- Lattice results for the SU(3) N_f=8 theory using different discretizations are painting a consistent picture: there is a light scalar flavor-singlet state, the dynamics is different form QCD, but other heavier resonances behave similarly to QCD

- A light scalar has been observed in other systems that are very *close or inside the conformal window*

- Lattice studies can give information about other hadronic quantities:

    - S-parameter **[LSD arxiv:1405.4752, LatKMI arxiv:1602.00796]**

    - couplings between flavor-singlet scalar and pseudoscalars, e.g. $\pi\pi$ scattering in the scalar channel **[LSD arXiv:1702.00480 + in prep.]**

    - Higgs coupling to SM fermions, e.g. dilaton decay constant **[LatKMI arxiv:1610.07011]**

    - anomalous dimensions **[LSD arxiv:1405.4752, LatKMI arxiv:1610.07011]**

Caveat: infinite volume limit, continuum limit and chiral limit need to be worked on!

CONCLUSIONS

- Lattice results for the SU(3) N_f=8 theory using different discretizations are painting a consistent picture: there is a light scalar flavor-singlet state, the dynamics is different form QCD, but other heavier resonances behave similarly to QCD

- A light scalar has been observed in other systems that are very *close or inside the conformal window*

- Lattice studies can give information about other hadronic quantities:
    - S-parameter **[LSD arxiv:1405.4752, LatKMI arxiv:1602.00796]**
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extra slides

[list of references focused on lattice results when possible]

[review by Kribs & Neil, 1604.04627]

COMPOSITE DARK MATTER

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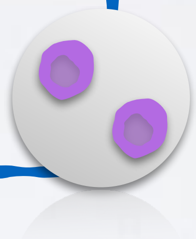
- ★ Pion-like (dark quark-antiquark)
  - ✦ pNGB DM *[Hietanen et al.,1308.4130]*
  - ✦ Quirky DM *[Kribs et al.,0909.2034]*
  - ✦ Ectocolor DM *[Buckley&Neil,1209.6054]*
  - ✦ SIMP *[Hochberg et al.,1411.3727]*
  - ✦ Minimal SU(2) *[Francis et al.,1610.10068]*



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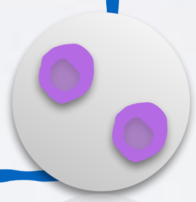
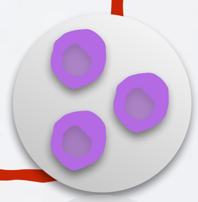


★ Baryon-like (multiple quarks)

- ✦ "Technibaryons" *[LSD, 1301.1693]*
- ✦ Stealth DM *[LSD, 1503.04203-1503.04205]*
- ✦ One-family TC *[LatKMI, 1510.07373]*
- ✦ Sextet CH *[LatHC, 1601.03302]*



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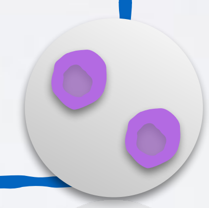
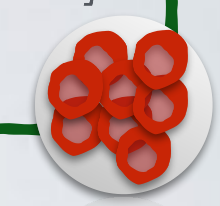


★ Glueball-like (only gluons)

- ✦ SUNonia *[Boddy et al.,1402.3629]*



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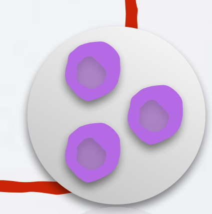

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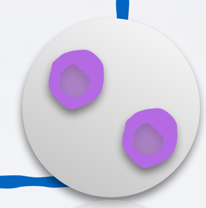

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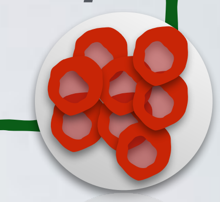

★ Dark Nuclei *[Detmold et al.,1406.2276-1406.4116]*

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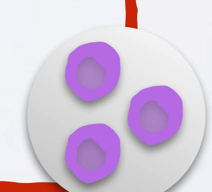

[references in Kribs & Neil, 1604.04627]

★ lattice
★ estimate
■ forbidden

LATTICE RESULTS

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) $N_f=1$	★ (lattice)				
SU(2) $N_f=2$	★ (lattice)	★ (estimate)		★ (estimate)	★ (lattice)
SU(3) $N_f=2,6$	★ (lattice)		★ (lattice)	★ (lattice)	
SU(3) $N_f=8$	★ (lattice)	★ (estimate)			
SU(3) $N_f=2$ (S)	★ (lattice)				
SU(4) $N_f=4$	★ (lattice)	★ (lattice)			★ (lattice)
SO(4) $N_f=2$ (V)	★ (lattice)				
SU(N) $N_f=0$	★ (lattice)				

[references in Kribs & Neil, 1604.04627]

- lattice
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- forbidden

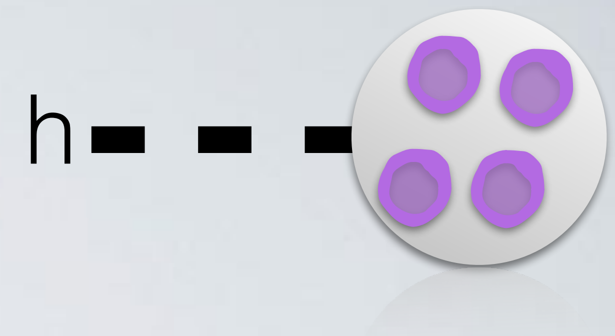
LATTICE RESULTS

Template Models	Spectrum	Higgs	Mag. Dip.	Charge r.	Polariz.
SU(2) N_f=1	lattice				
SU(2) N_f=2	lattice	estimate	forbidden (forbidden in pNGB DM)	estimate	lattice
SU(3) N_f=2,6	lattice		lattice	lattice	
SU(3) N_f=8	lattice	estimate			
SU(3) N_f=2 (S)	lattice				
SU(4) N_f=4	lattice	lattice	forbidden	forbidden	lattice
SO(4) N_f=2 (V)	lattice				
SU(N) N_f=0	lattice	forbidden	forbidden	forbidden	forbidden

forbidden in Stealth DM

forbidden in SUNonia

Bounds from Higgs exchange

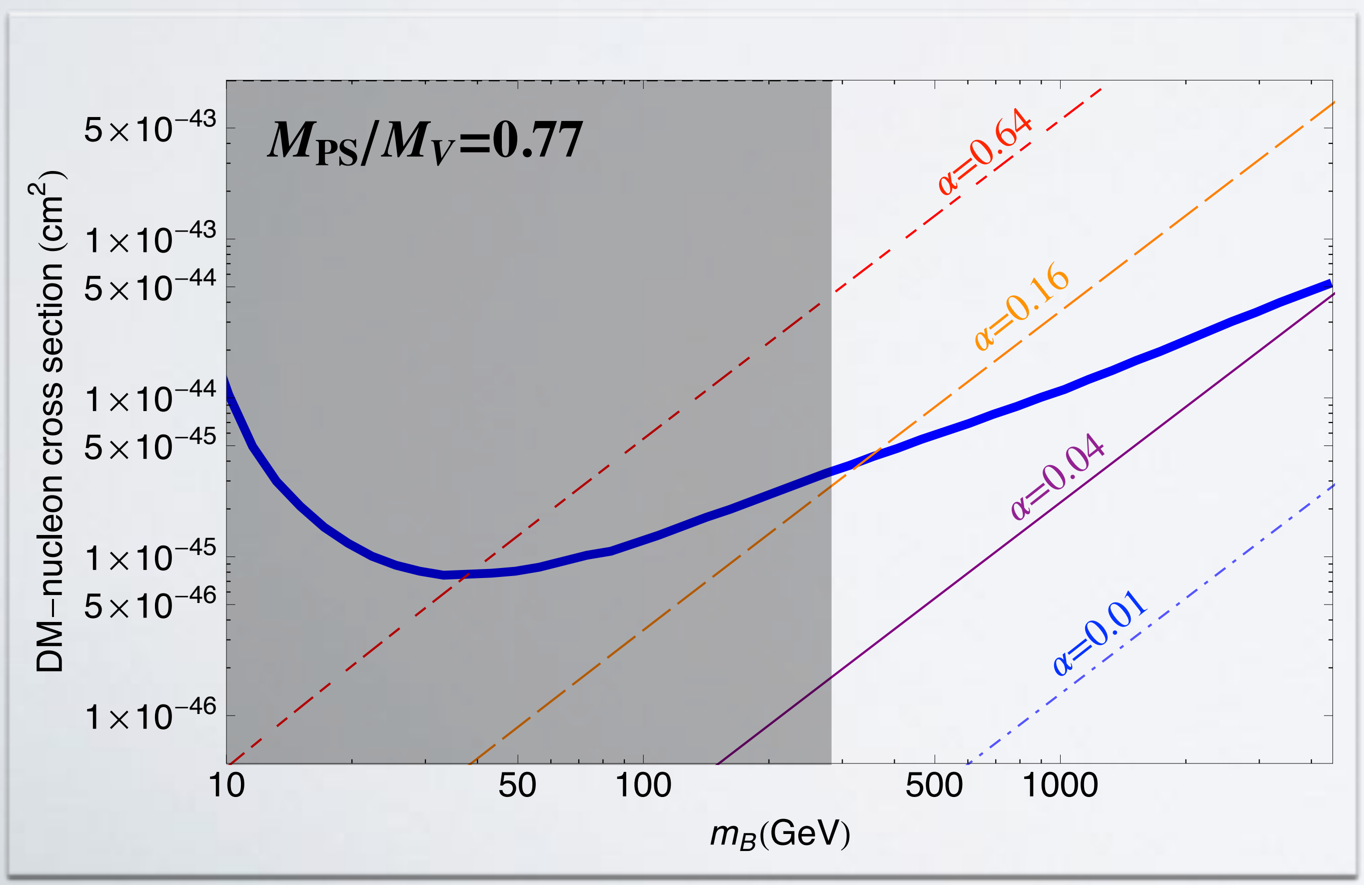


✦Lattice results for the cross-section are compared to **experimental** bounds

✦Coupling space in specific models can be vastly constrained

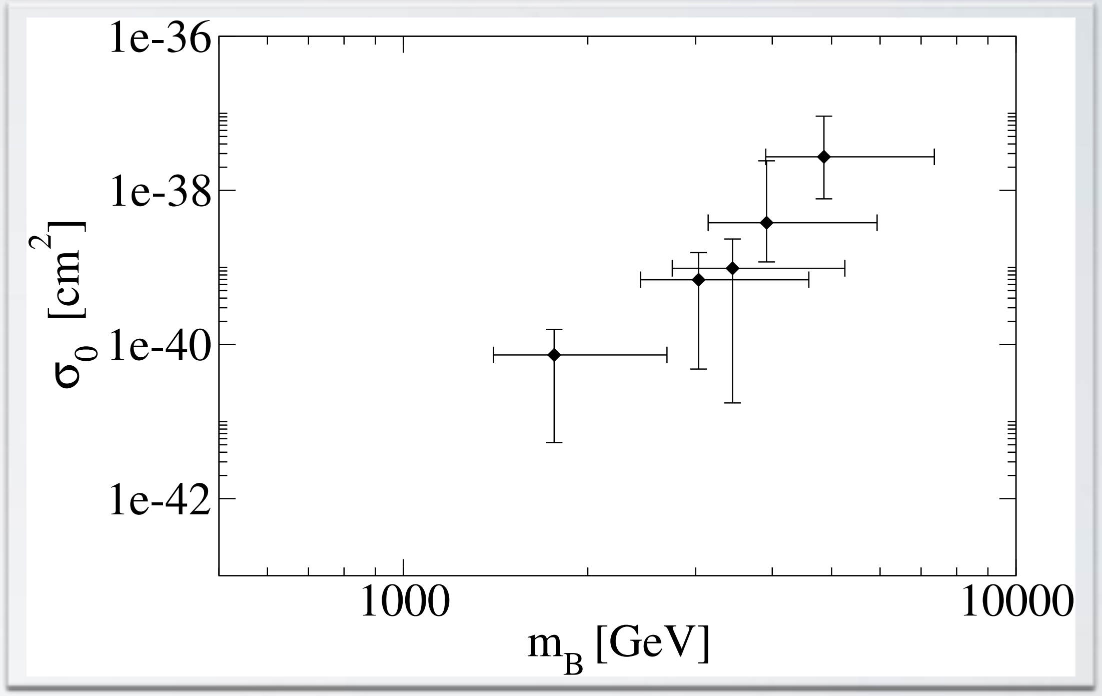
SU(4) N_f=4 Stealth DM

[LSD, 1402.6656-1503.04203]



SU(3) N_f=8 "technibaryon"

[LatKMI, 1510.07373]

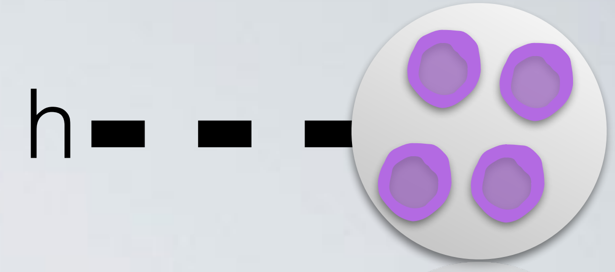


✦Some candidates can be excluded as dominant sources of dark matter

✦There is lattice evidence for universality of dark scalar form factors

[DeGrand et al., 1501.05665]

Bounds from Higgs exchange



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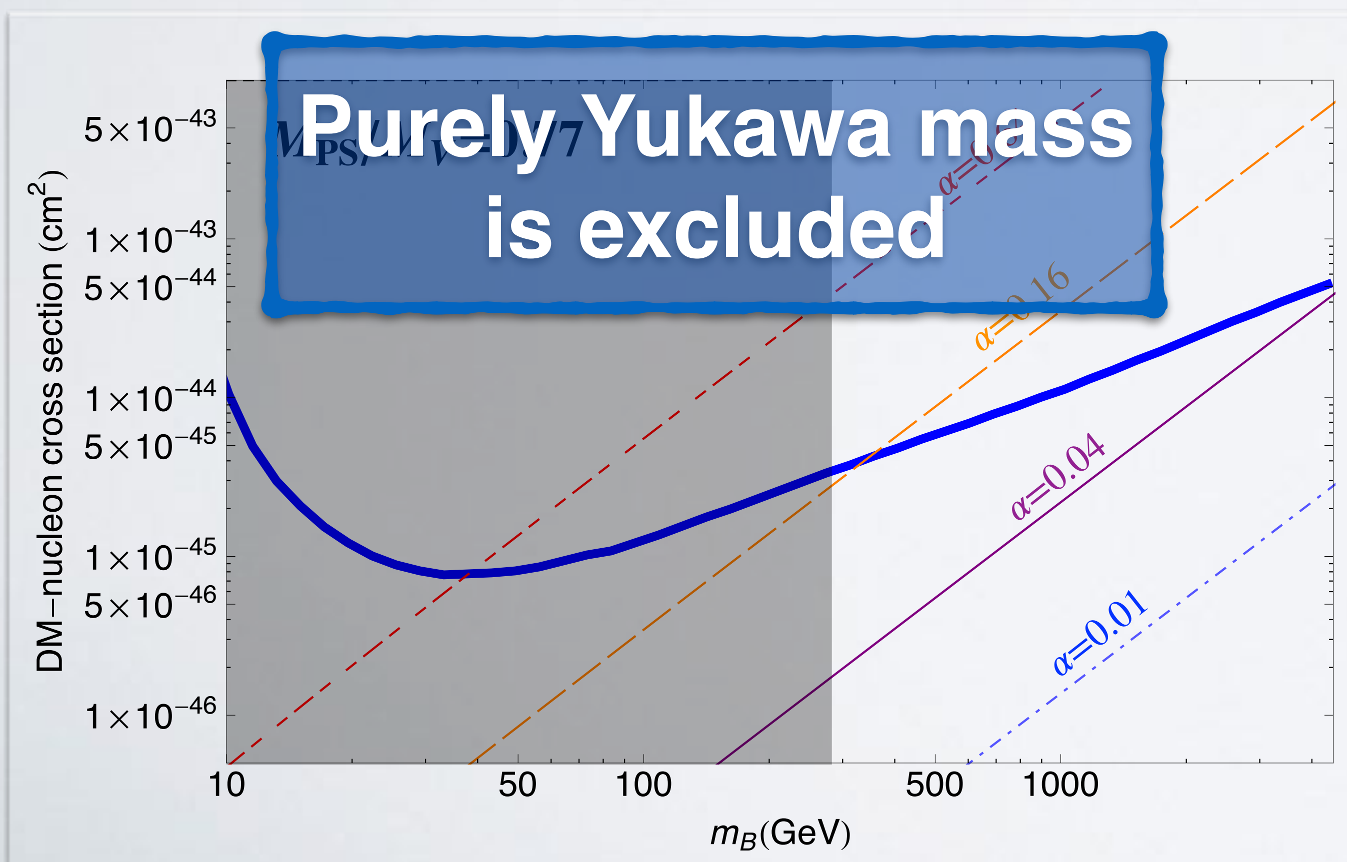

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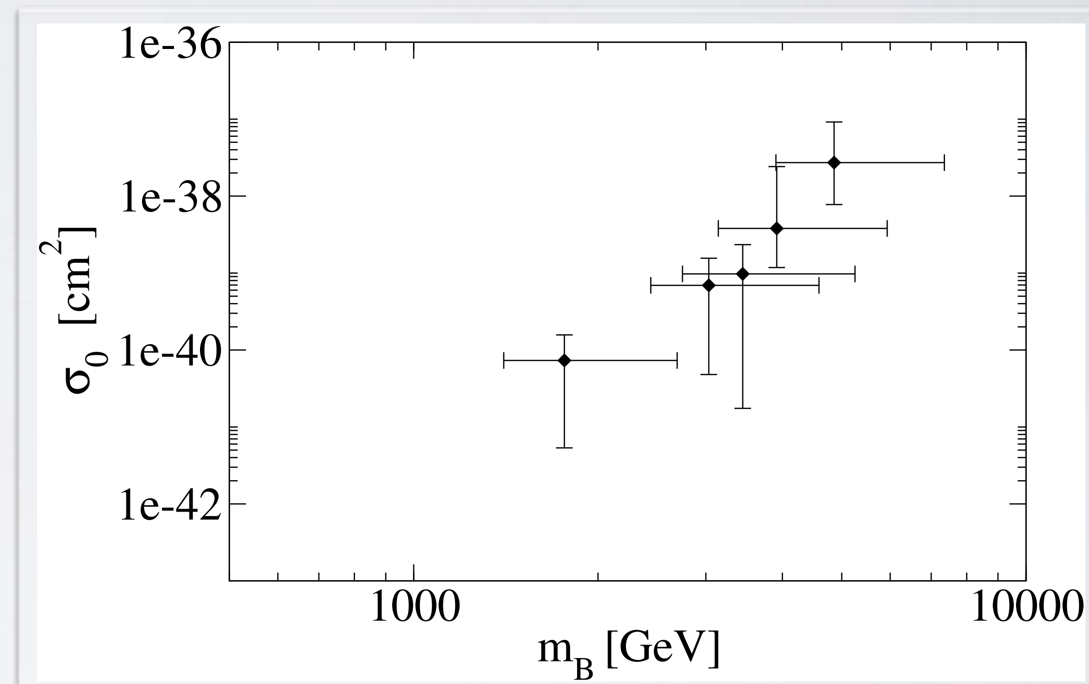

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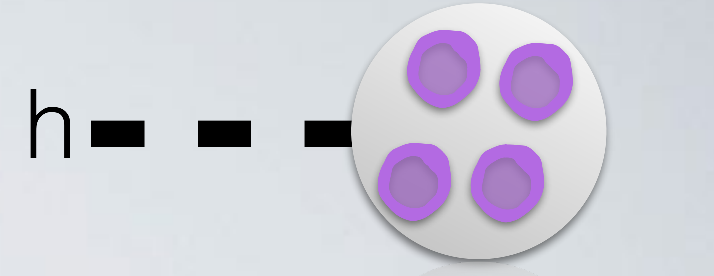

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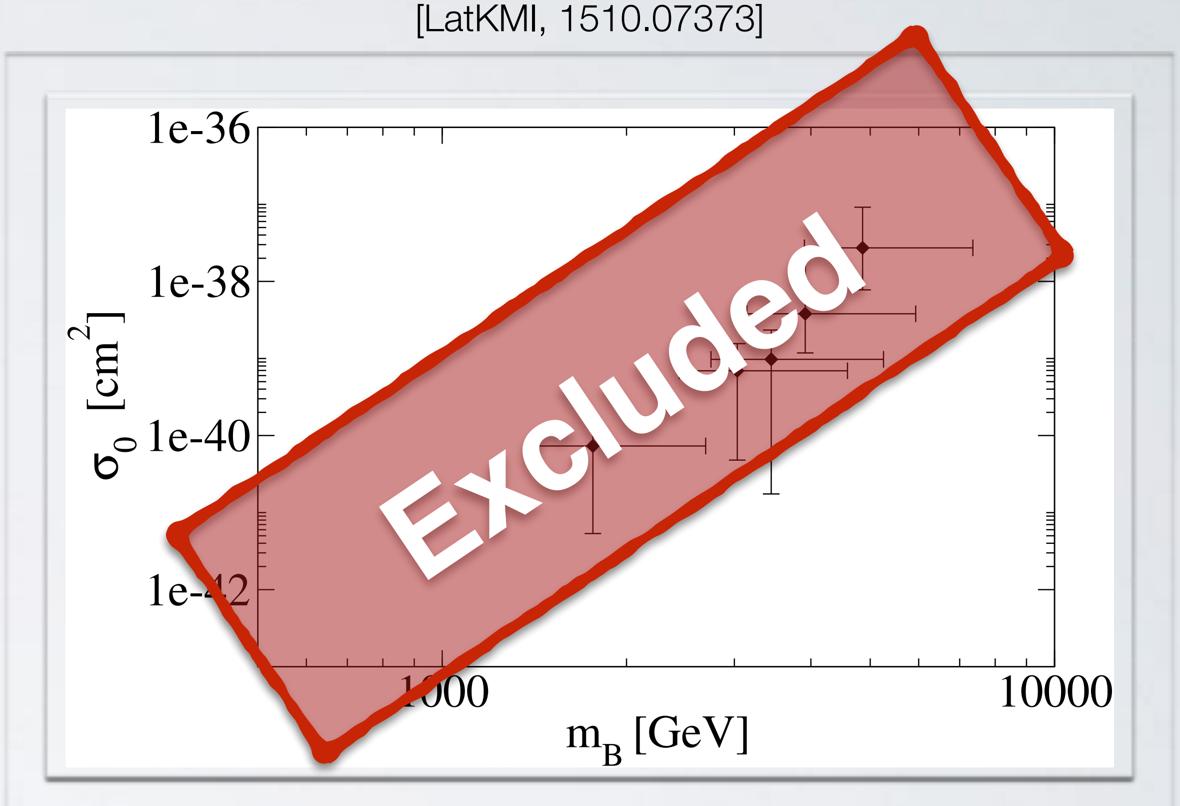

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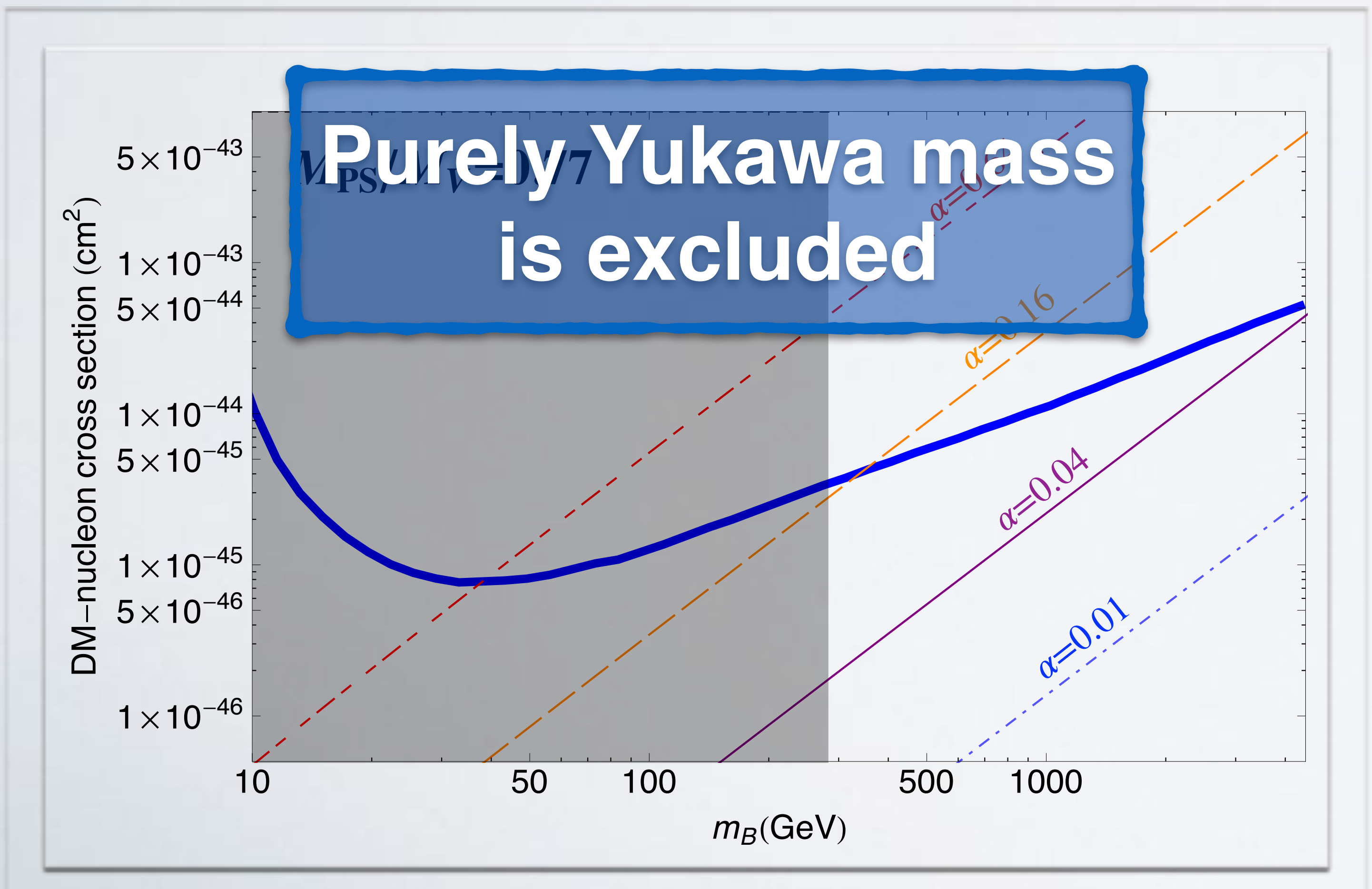

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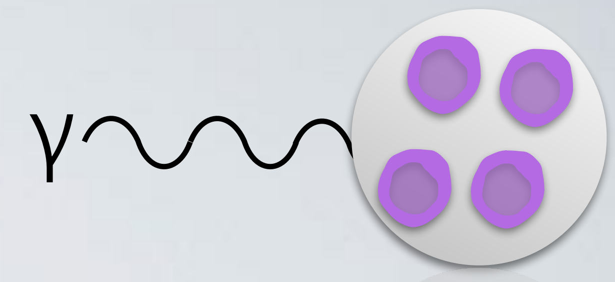
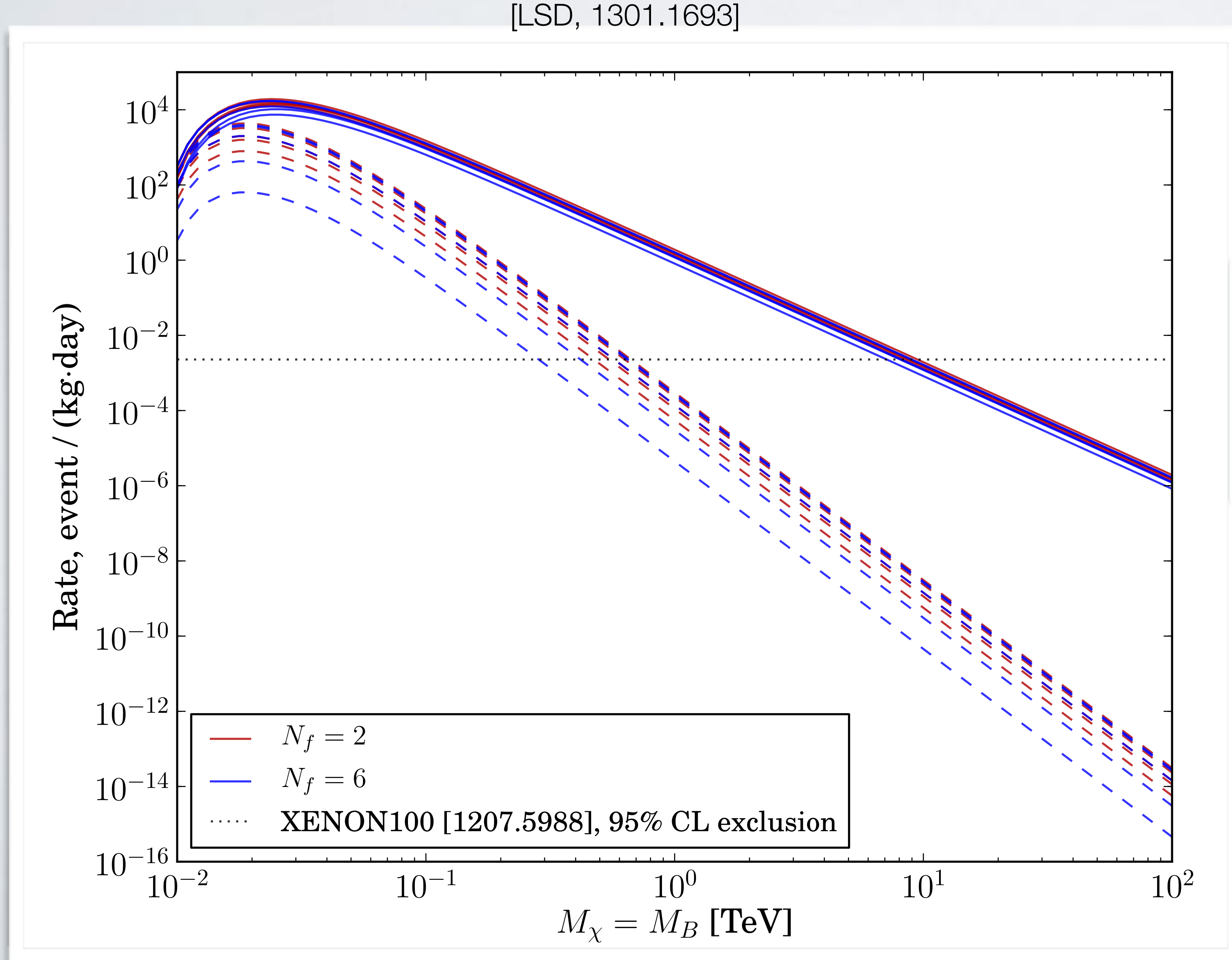
Bounds from EM moments



Mesonic and Baryonic EM form factors directly from lattice simulations

SU(3) N_f=2,6 dark fermionic baryon

[LSD, 1301.1693]



- ★ baryon similar to QCD neutron
- ★ dark quarks with Q=Y
- ★ calculate connected 3pt
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- ★ magnetic moment dominates
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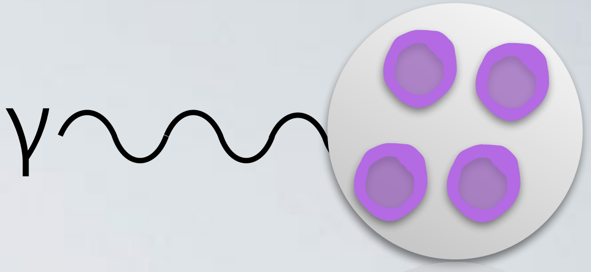

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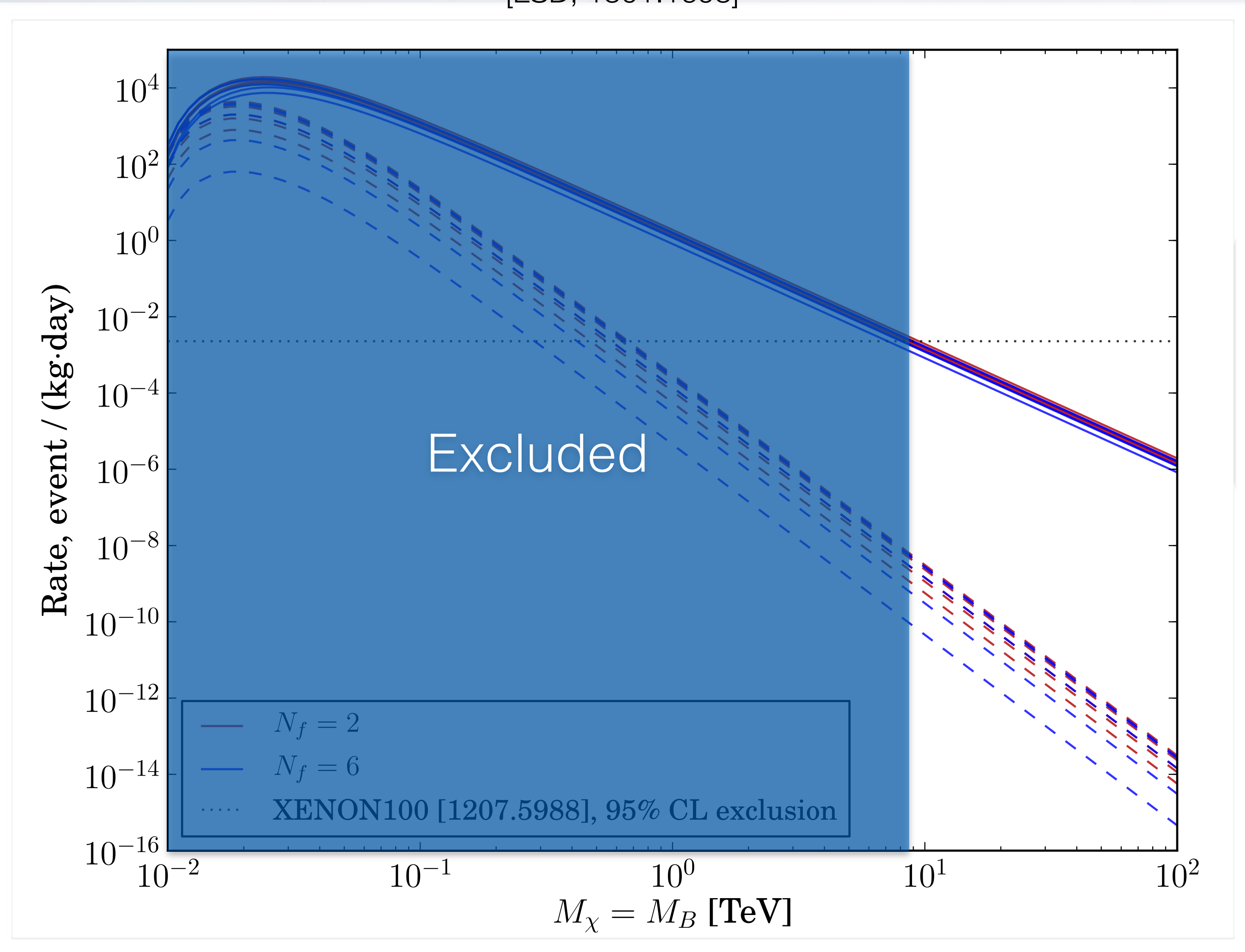

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M_B >~ 10 TeV

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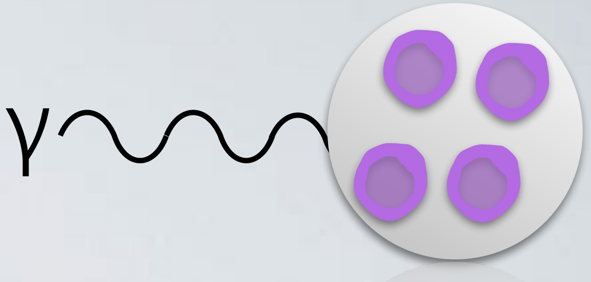

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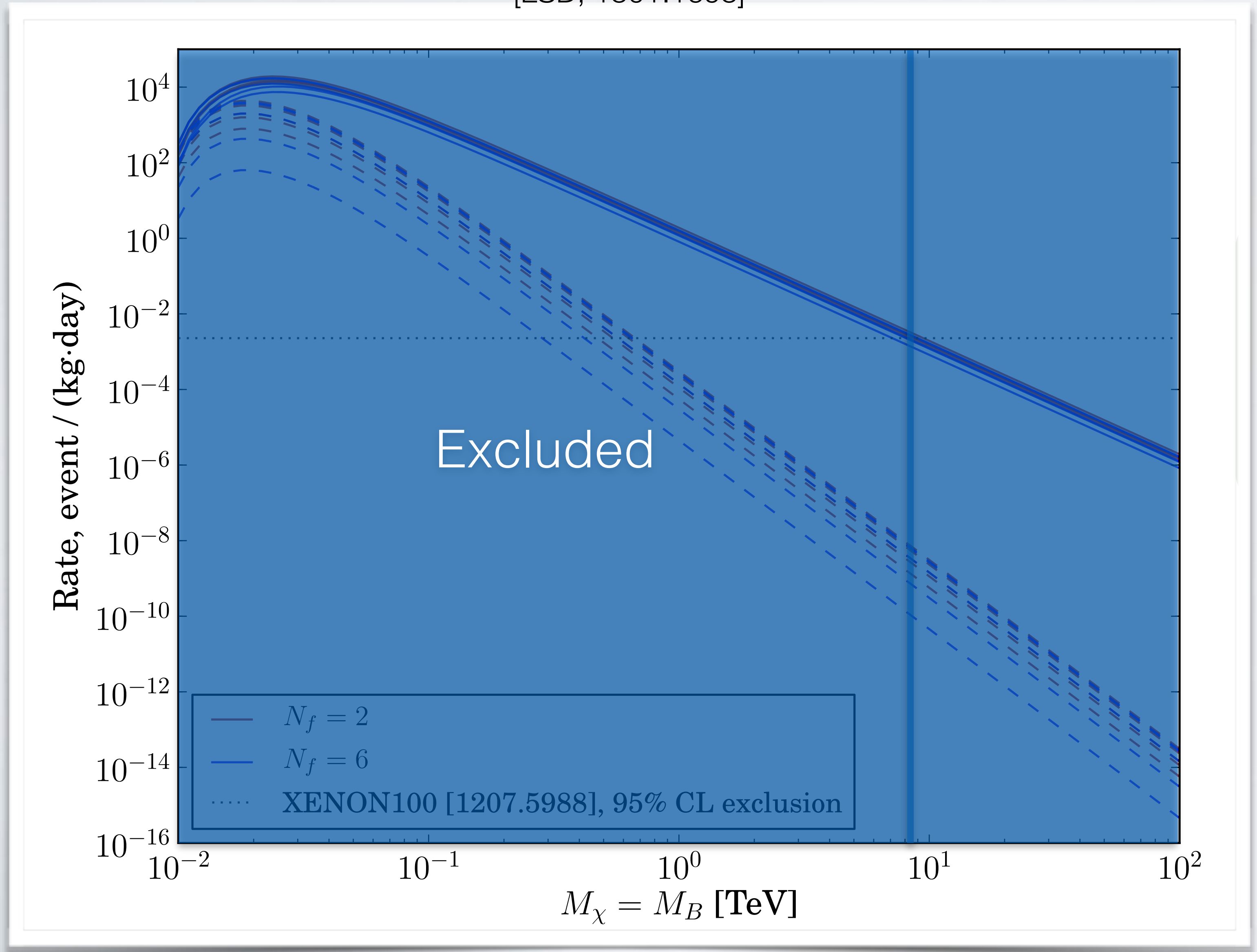

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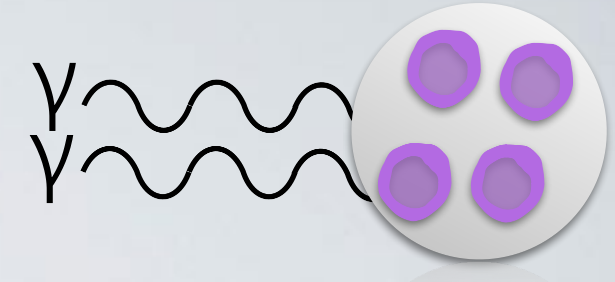
M_B >~ 10 TeV

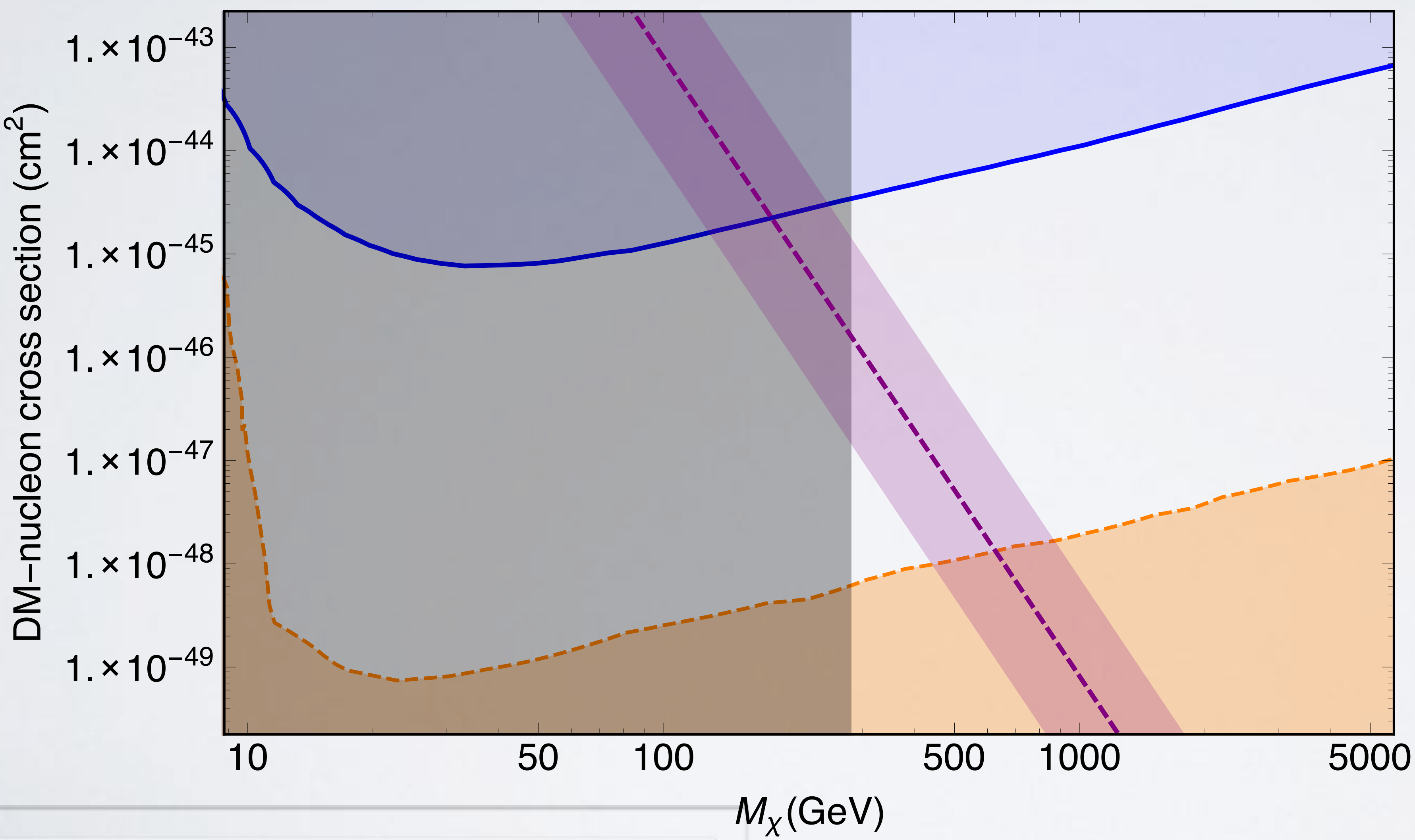
pushed to ~100 TeV with new LUX

Lowest bound from EM polarizability

[see also Drach et al.,1511.04370 for SU(2) N_f=2]



Electric polarizability from lattice simulations with background fields



SU(4) N_f=4 Stealth DM

[LSD, 1503.04205]

$$\sigma_{\text{nucleon}}(Z,A) = \frac{Z^4}{A^2}\frac{144\pi\alpha^4\mu_{n\chi}^2 (M_F^A)^2}{m_\chi^6 R^2}[c_F]^2$$

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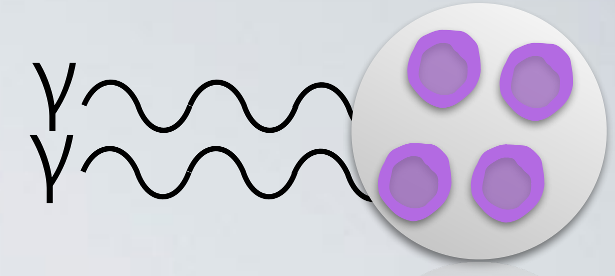
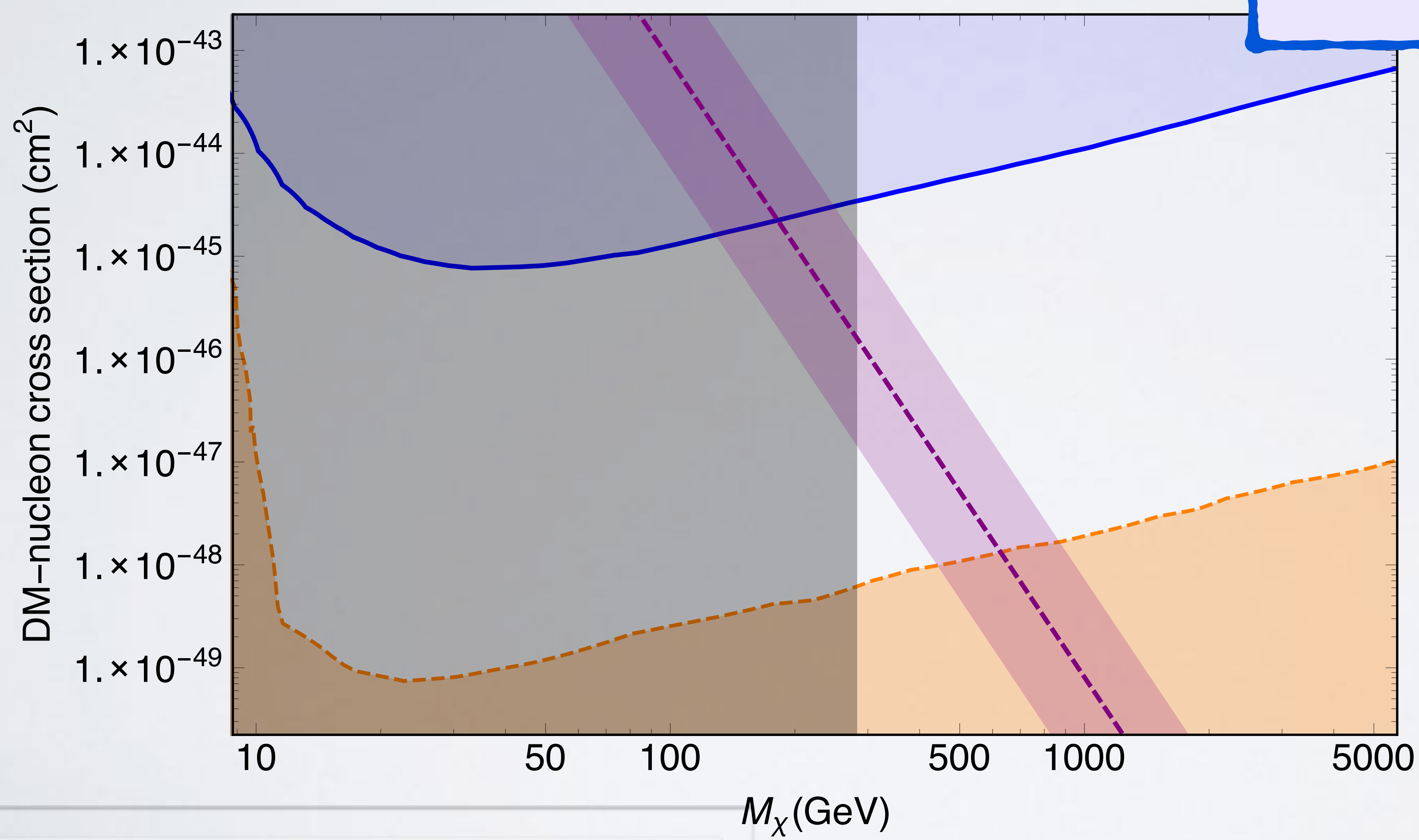


Electric polarizability from lattice simulations with background fields

LUX exclusion bound for spin-independent cross section



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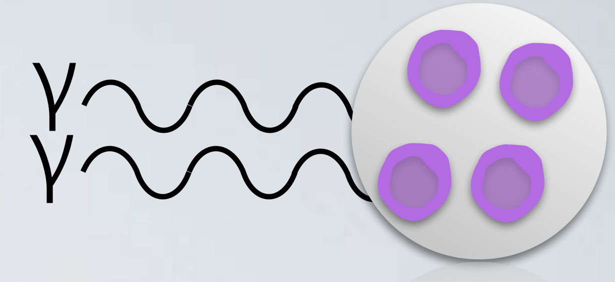

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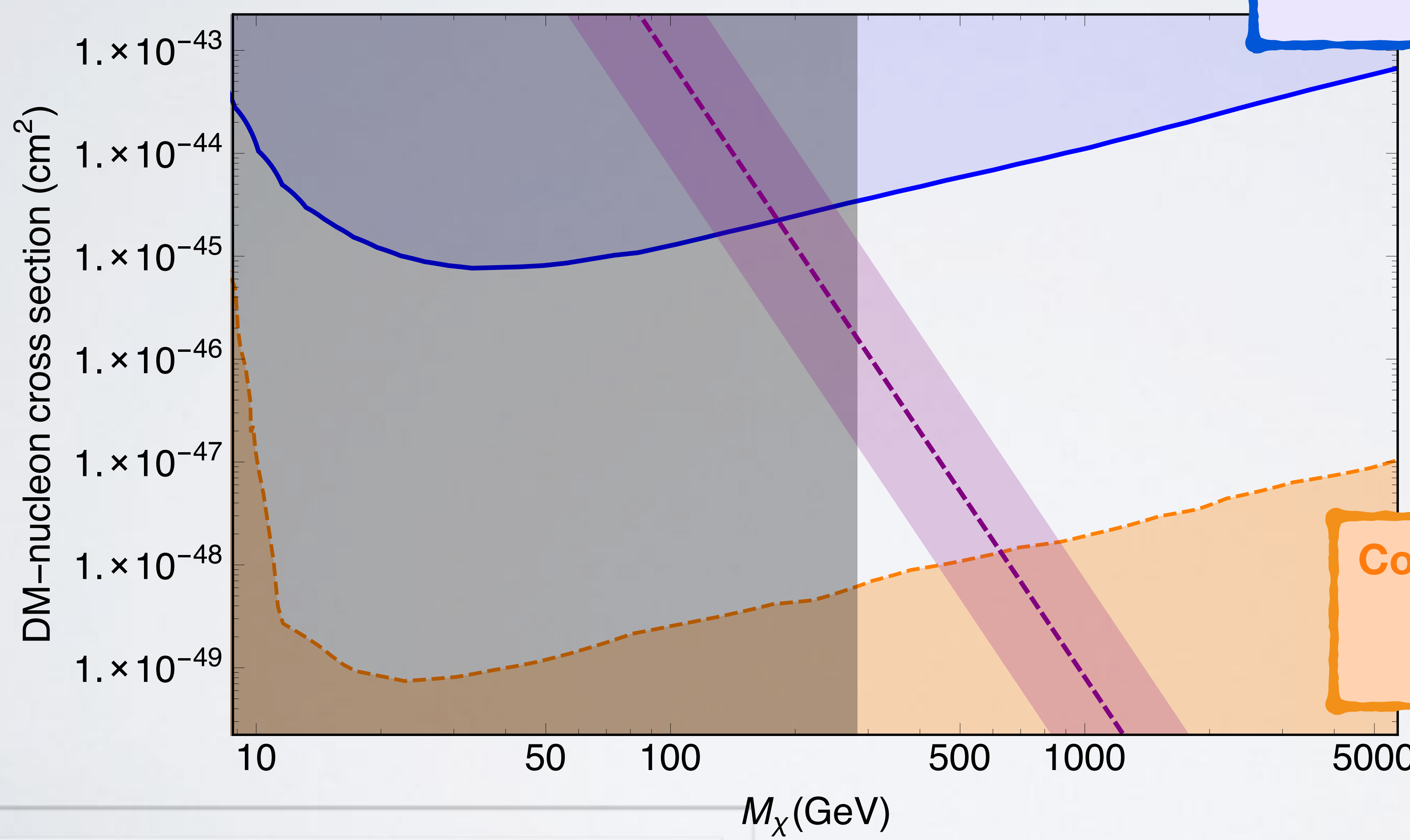

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Coherent neutrino scattering background

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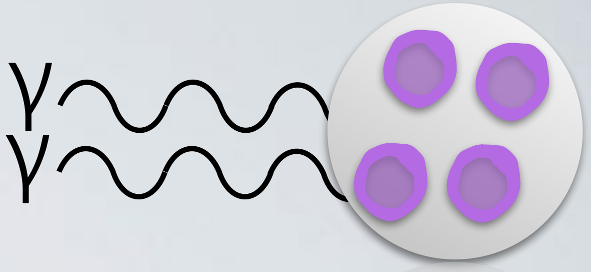

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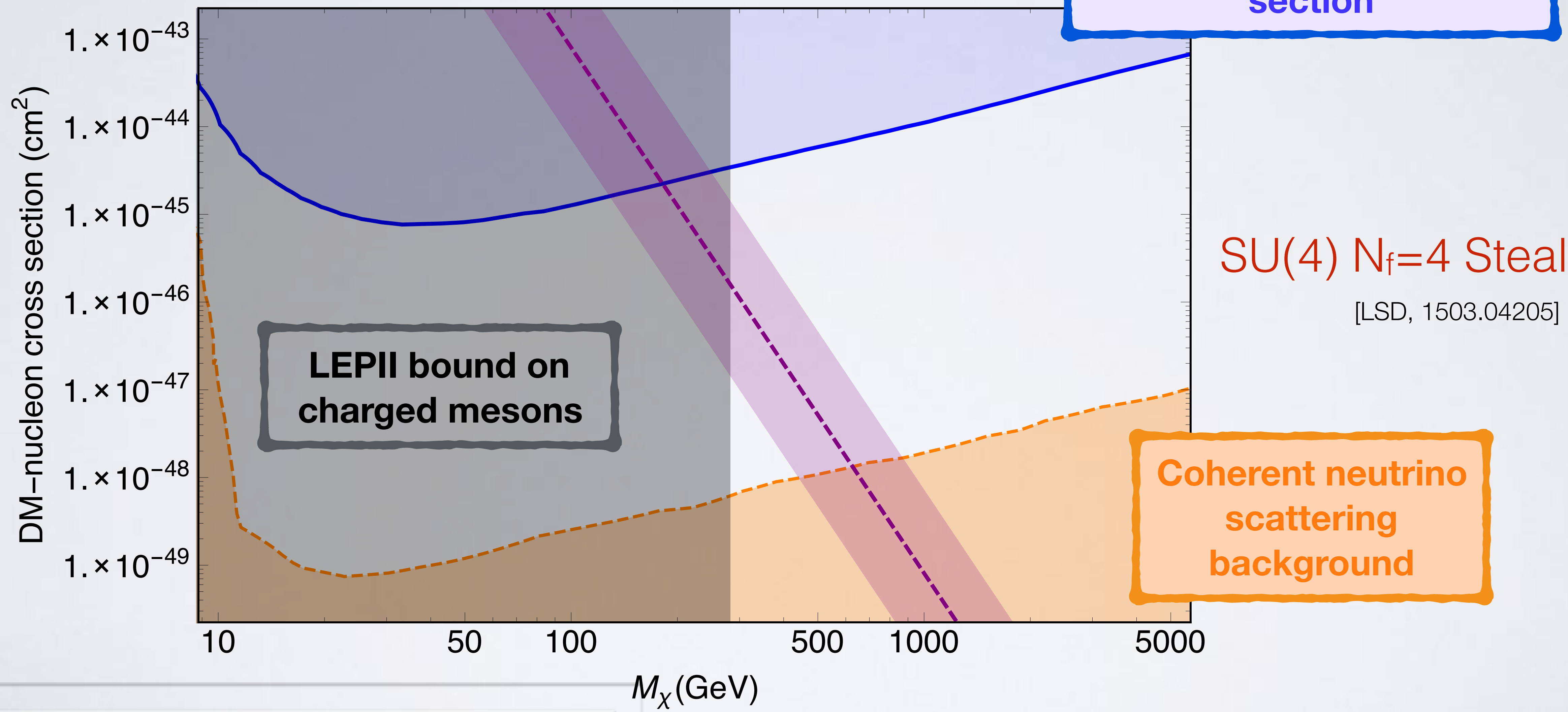

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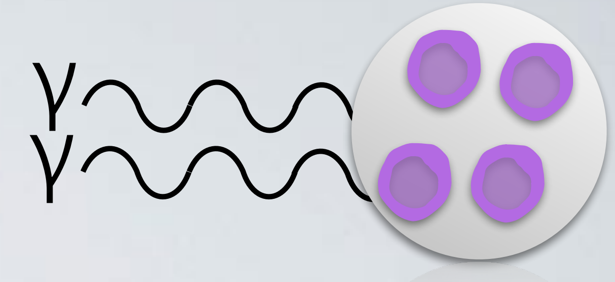

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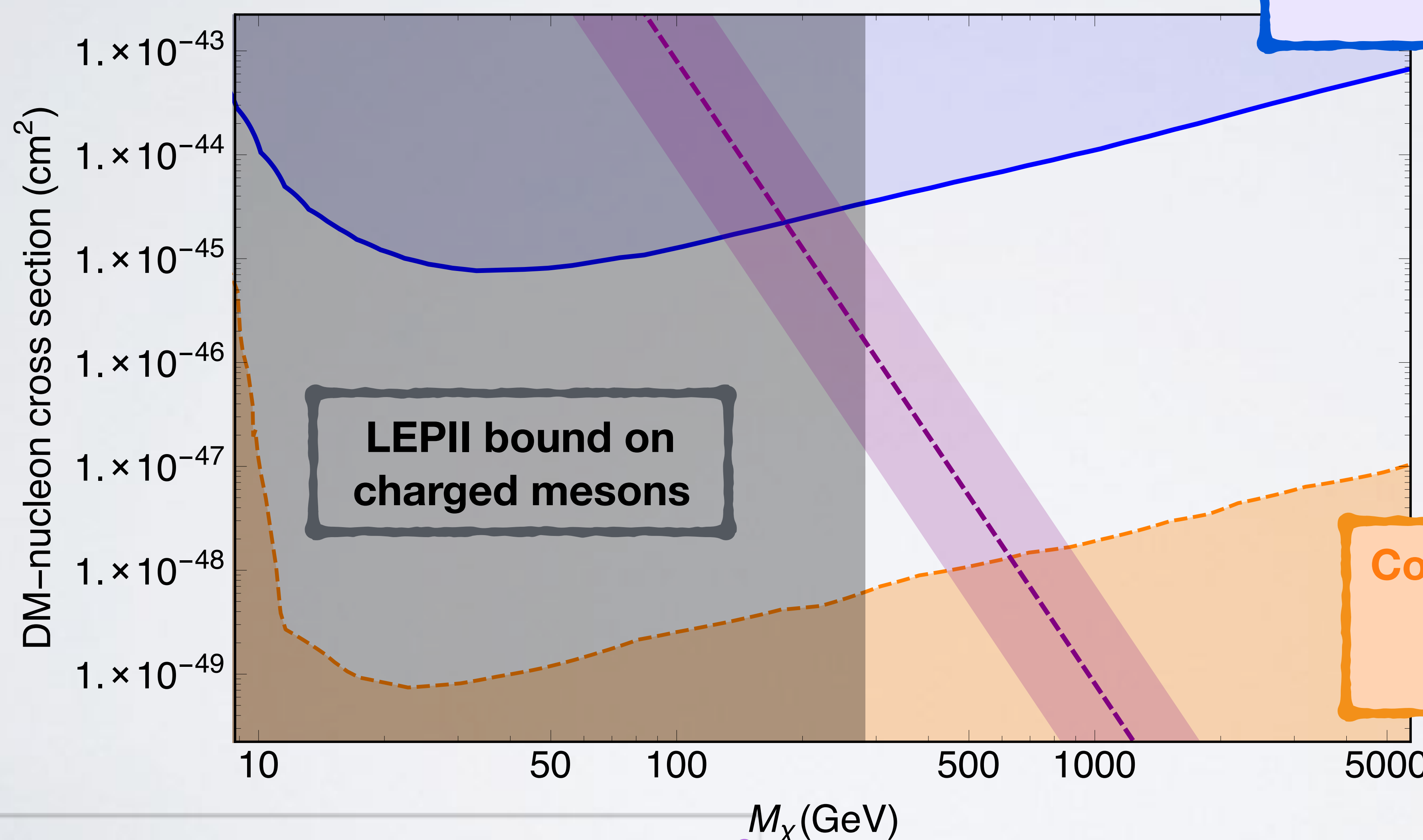

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lowest allowed direct detection cross-section for composite dark matter theories with EW charged constituents

"Stealth Dark Matter" model

[LSD collab., Phys. Rev. D92 (2015) 075030]

- The field content of the model consists in *8 Weyl fermions*
- Dark fermions interact with the SM Higgs and obtain current/chiral masses
- Introduce vector-like masses for dark fermions that do not break EW symmetry
- Diagonalizing in the mass eigenbasis gives *4 Dirac fermions*
- Assume custodial SU(2) symmetry arising when ***u*** ↔ ***d***

Field	$\mathrm{SU}(N)_D$	$(\mathrm{SU}(2)_L, Y)$	Q
$F_1 = \begin{pmatrix} F_1^u \\ F_1^d \end{pmatrix}$	$\mathbf{N}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
$F_2 = \begin{pmatrix} F_2^u \\ F_2^d \end{pmatrix}$	$\overline{\mathbf{N}}$	$(\mathbf{2}, 0)$	$\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$
F_3^u	$\mathbf{N}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_3^d	$\mathbf{N}$	$(\mathbf{1}, -1/2)$	$-1/2$
F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

$$\mathcal{L} \supset + y^u_{14}\epsilon_{ij} F_1^i H^j F_4^d + y^d_{14} F_1 \cdot H^\dagger F_4^u - y^d_{23}\epsilon_{ij} F_2^i H^j F_3^d - y^u_{23} F_2 \cdot H^\dagger F_3^u + h.c.$$

$$\mathcal{L} \supset M_{12}\epsilon_{ij} F_1^i F_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^u + h.c.$$

$$y^u_{14} = y^d_{14} \qquad y^u_{23} = y^d_{23} \qquad M^u_{34} = M^d_{34}$$

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EW interactions

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F_4^u	$\overline{\mathbf{N}}$	$(\mathbf{1}, +1/2)$	$+1/2$
F_4^d	$\overline{\mathbf{N}}$	$(\mathbf{1}, -1/2)$	$-1/2$

$$\mathcal{L} \supset + y_{14}^u \epsilon_{ij} F_1^i H^j F_4^d + y_{14}^d F_1 \cdot H^\dagger F_4^u - y_{23}^d \epsilon_{ij} F_2^i H^j F_3^d - y_{23}^u F_2 \cdot H^\dagger F_3^u + h.c.$$

$$\mathcal{L} \supset M_{12} \epsilon_{ij} F_1^i F_2^j - M_{34}^u F_3^u F_4^d + M_{34}^d F_3^d F_4^u + h.c.$$

$$y_{14}^u = y_{14}^d \qquad y_{23}^u = y_{23}^d \qquad M_{34}^u = M_{34}^d$$

http://www.media.inaf.it/2015/09/25/materia-oscura-stealth/

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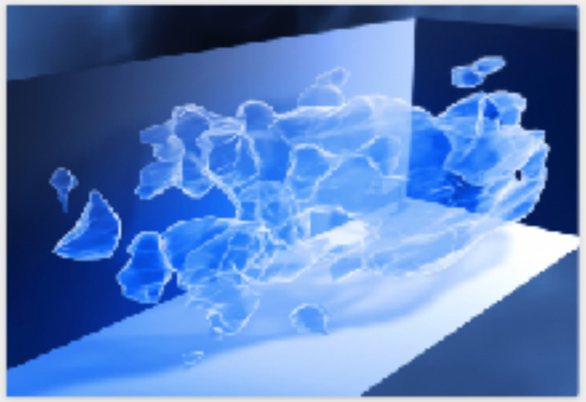
Materia oscura "stealth"

Quark oscuri tenuti insieme da un'interazione forte a sua volta oscura. Ecco come la dark matter riuscirebbe a eludere a ogni tentativo d'incastrarla. Enrico Rinaldi (LLNL): «Esiste la possibilità che questo "mondo oscuro", con le sue nuove particelle, possa essere rivelato dagli esperimenti in corso al Large Hadron Collider al CERN di Ginevra»

di Marco Malaspina | Segui @malamino | venerdì 25 settembre 2015 @ 16:15

Stealth come furtiva. *Stealth* come imprendibile. *Stealth* come quei minacciosi aerei da guerra dal profilo sagomato così da essere invisibili al radar. Da quanto emerge dai calcoli dei fisici dell'LLNL, il Lawrence Livermore National Laboratory californiano, e dai modelli dati in pasto a Vulcan (un supercomputer per il calcolo parallelo in grado masticare numeri al ritmo del *petaflop*), sarebbe questa la natura della materia oscura: *stealthy*, appunto. Per forza non c'è ancora esperimento che sia riuscito a incastrarla.



Mappa 3D della distribuzione su larga scala della materia oscura ricostruita da misure di lente gravitazionale debole utilizzando il telescopio spaziale Hubble

https://www.llnl.gov/news/new-stealth-dark-matter-theory-may-explain-mystery-universes-missing-mass

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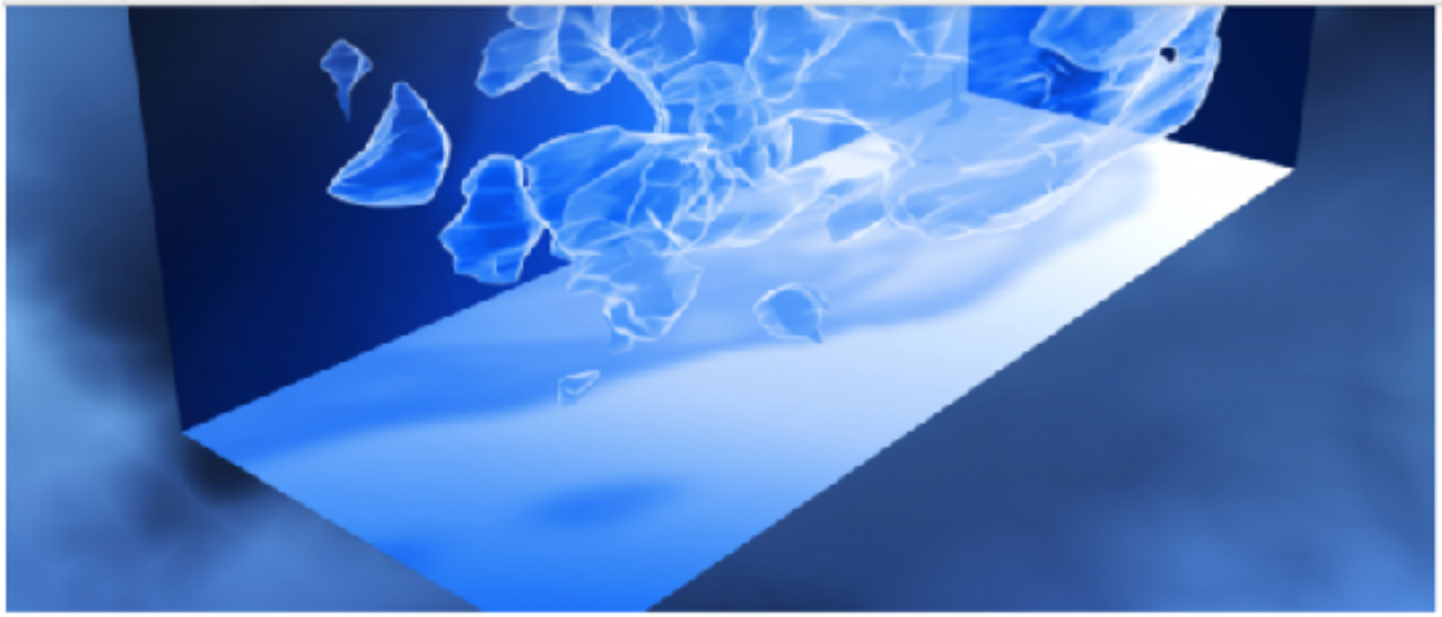

This 3D map illustrates the large-scale distribution of dark matter, reconstructed from measurements of weak gravitational lensing by using the Hubble Space Telescope. (Download Image)

New 'stealth dark matter' theory may explain mystery of the universe's missing mass

Lawrence Livermore National Laboratory (LLNL) scientists have come up with a new theory that may identify why dark matter has evaded direct detection in Earth-based experiments.

Anne M Stark
stark8@llnl.gov
925-422-9799

Detecting Stealth Dark Matter Directly through Electromagnetic Polarizability.

Overview of attention for article published in Physical Review Letters, October 2015

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Title	Detecting Stealth Dark Matter Directly through Electromagnetic Polarizability.
Published in	Physical Review Letters, October 2015
DOI	10.1103/physrevlett.115.171803
Pubmed ID	26551103
Authors	T. Appelquist, E. Berkowitz, R.C. Brower, M.I. Buchoff, G.T. Fleming, X.-Y. Jin, J. Kiskis, G.D... [show]
Abstract	We calculate the spin-independent scattering cross section for direct detection that results from... [show]

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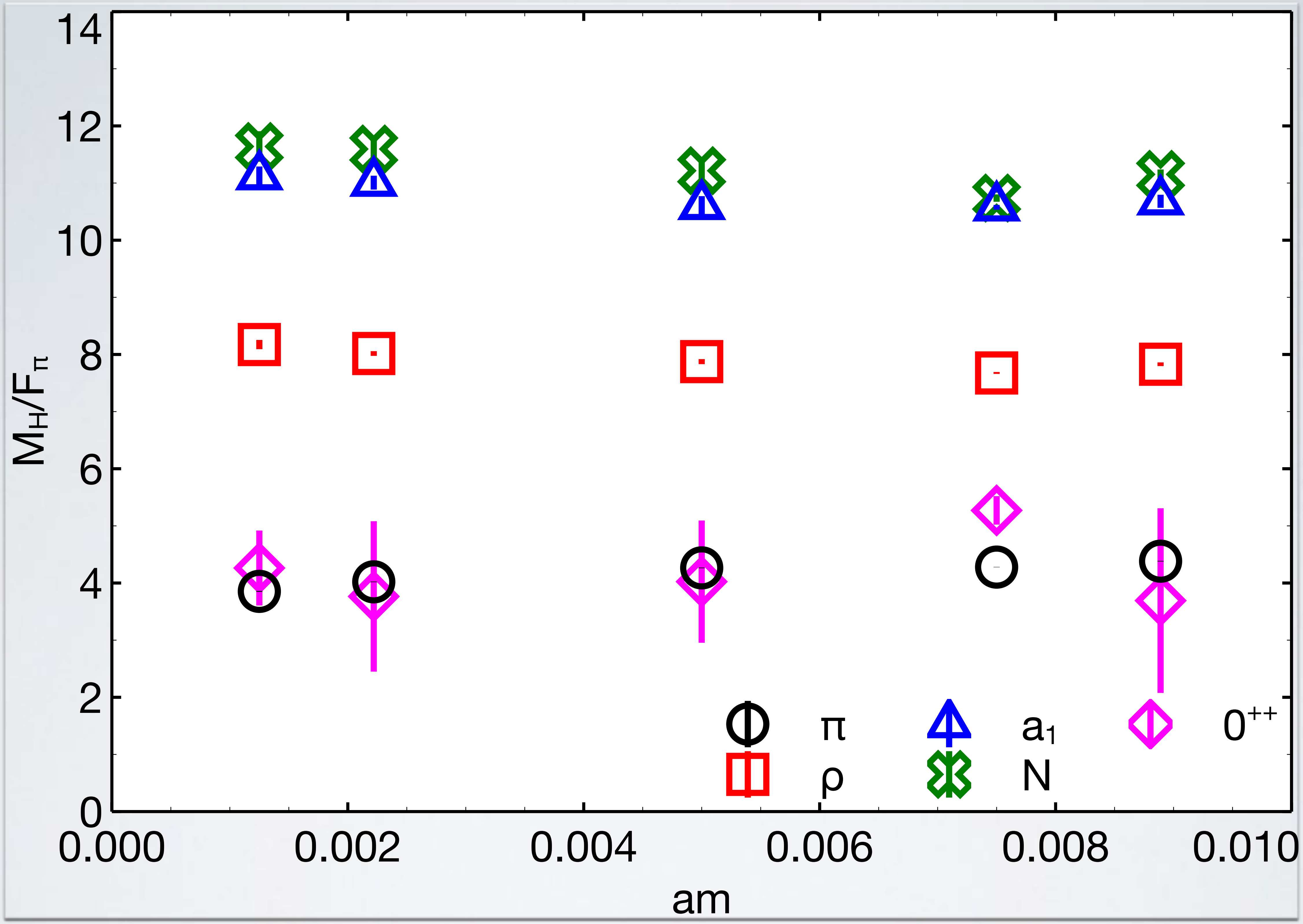
28 settembre 2015

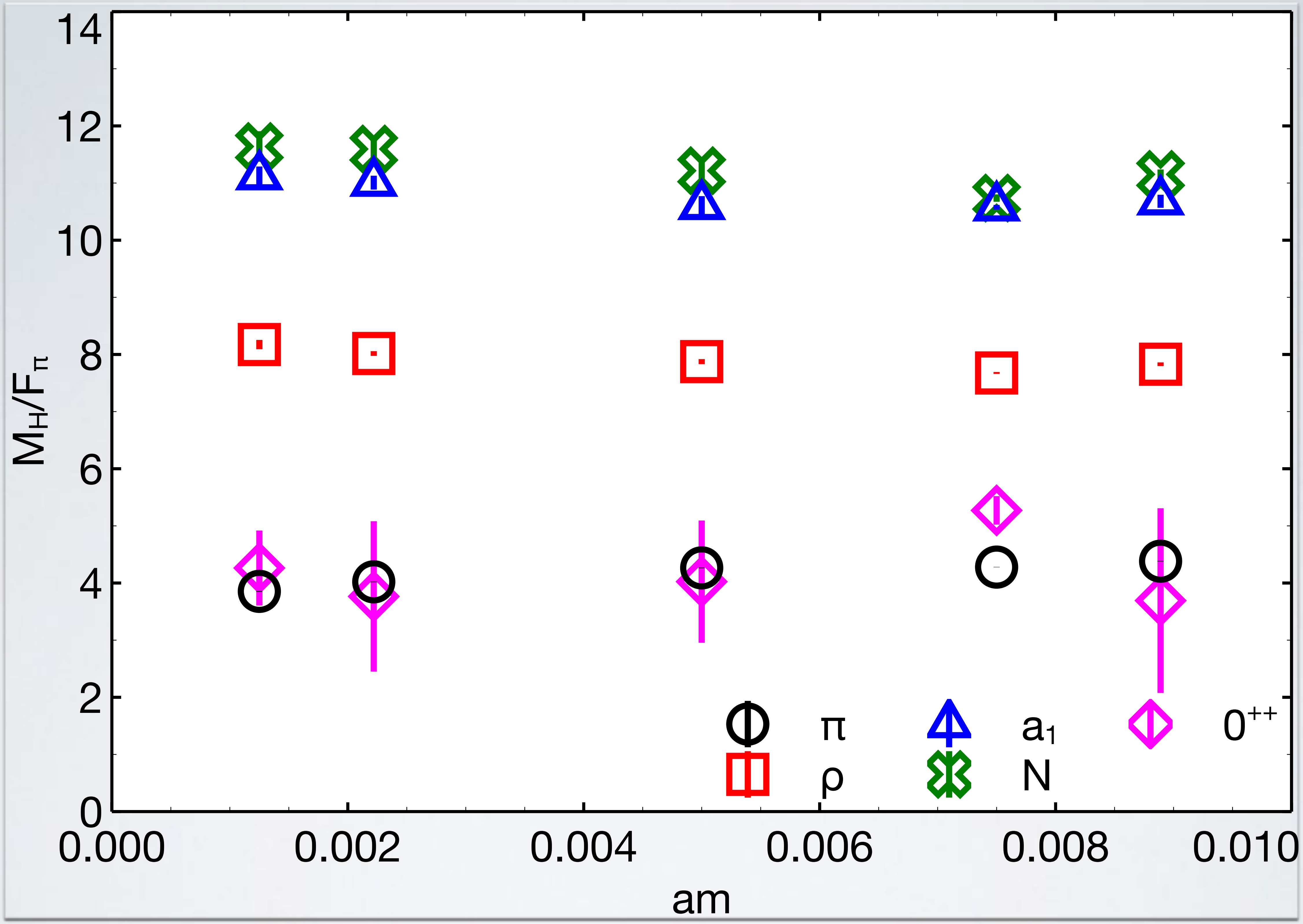
Un nuovo modello per la materia oscura

Cortesia Lawrence Livermore National Laboratory

Questa forma misteriosa di materia potrebbe avere una struttura composita come la materia ordinaria, con "quark oscuri" aggregati e tenuti insieme da un analogo della forza che permette ai normali nuclei di rimanere stabili. I componenti di questo tipo di materia oscura, definita stealth matter, potrebbero essere studiati in modo indiretto dal collisore Large Hadron Collider del CERN di Ginevra *(red)*

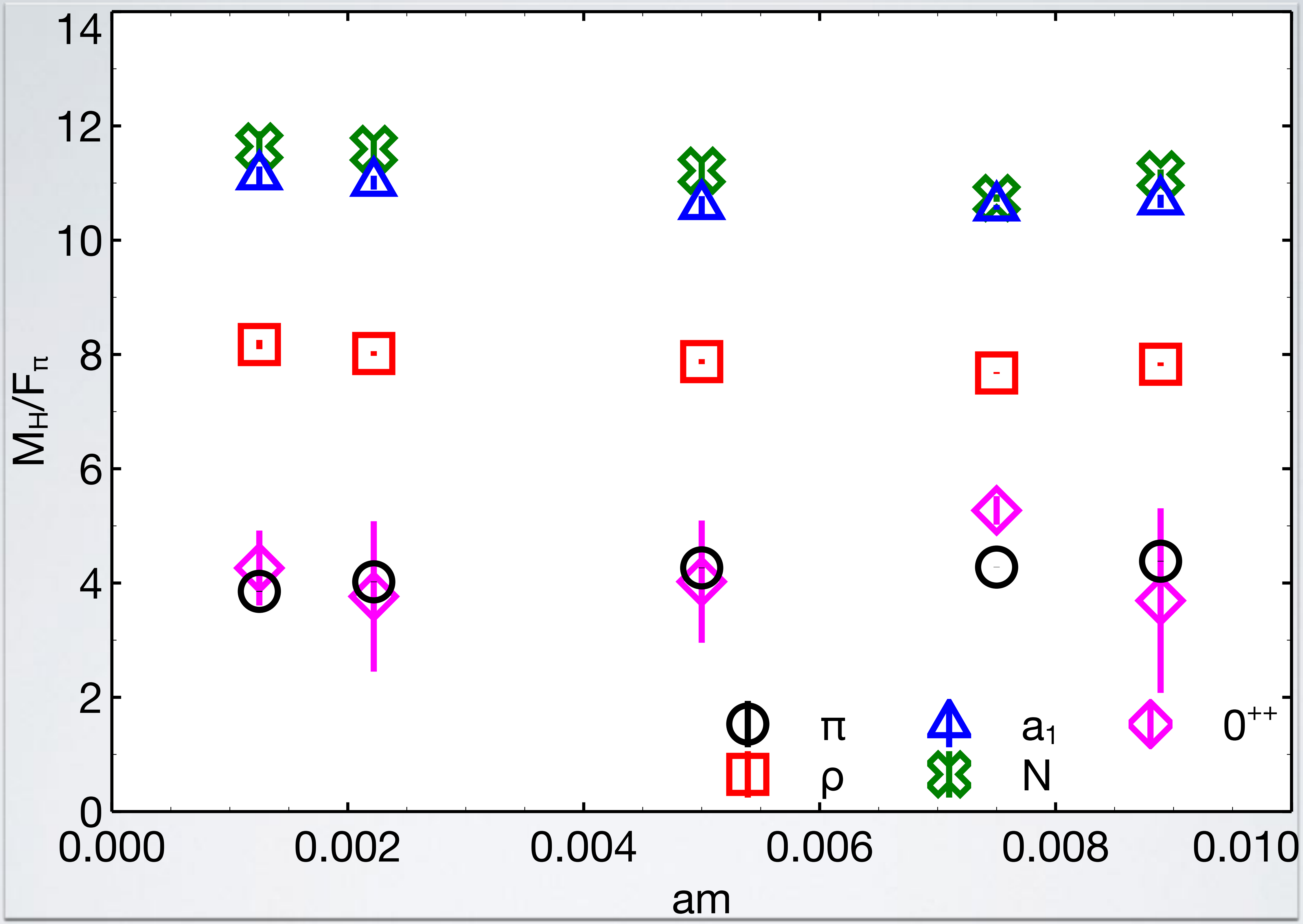


LSD arxiv:1601.04027 [scalar update, preliminary]



Similar to QCD?

LSD arxiv:1601.04027 [scalar update, preliminary]



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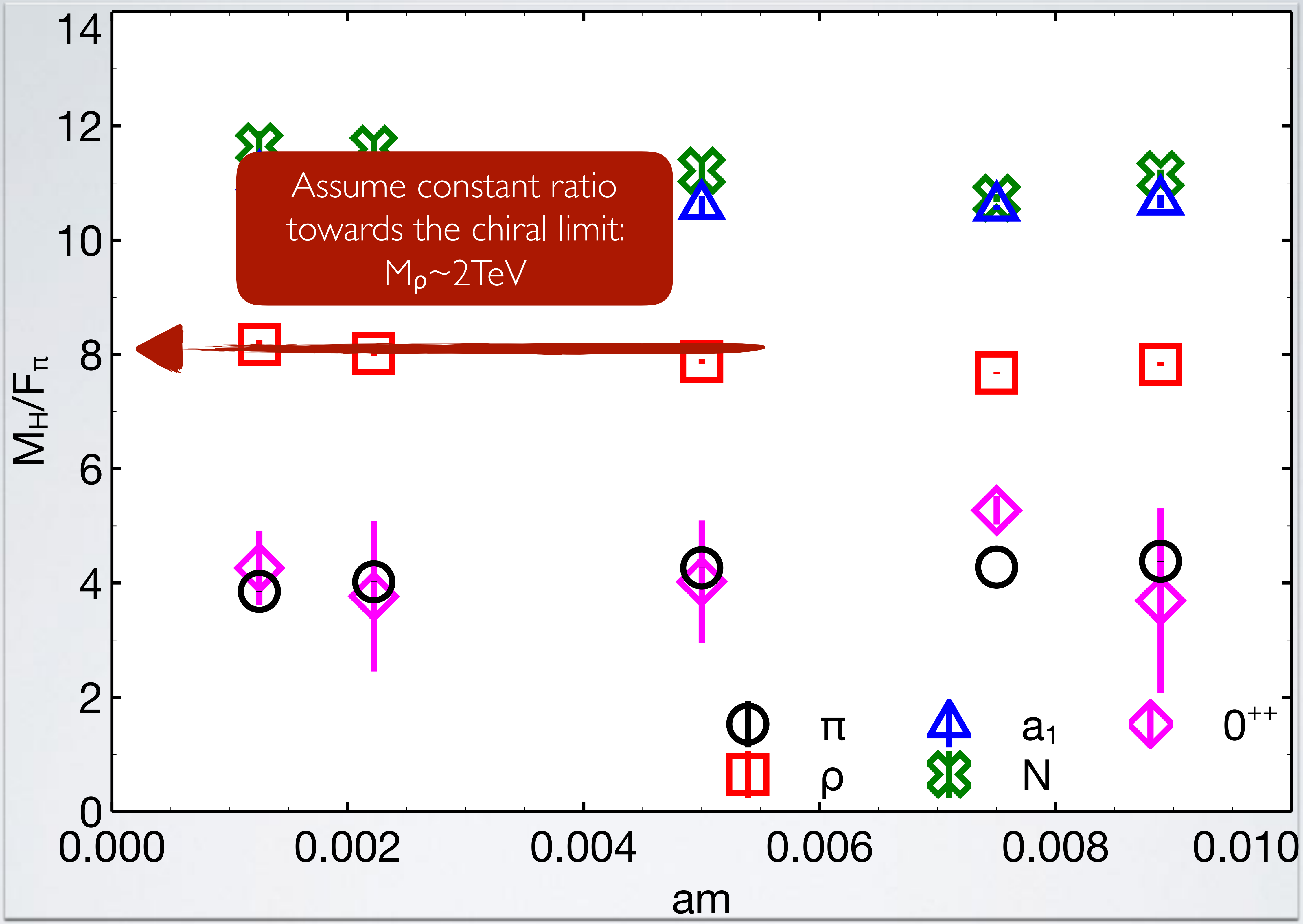
Assume $F_\pi \sim 246$GeV



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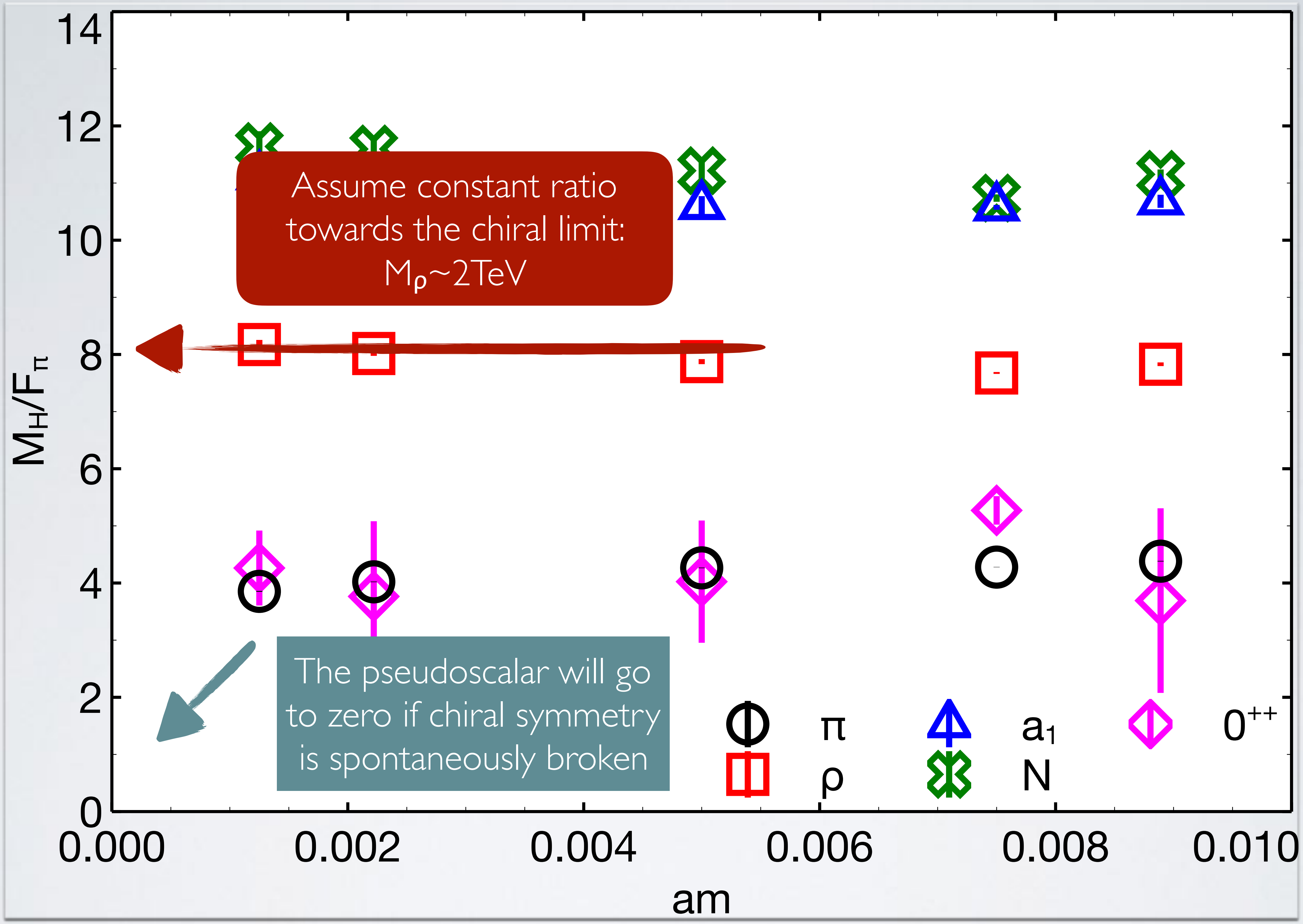

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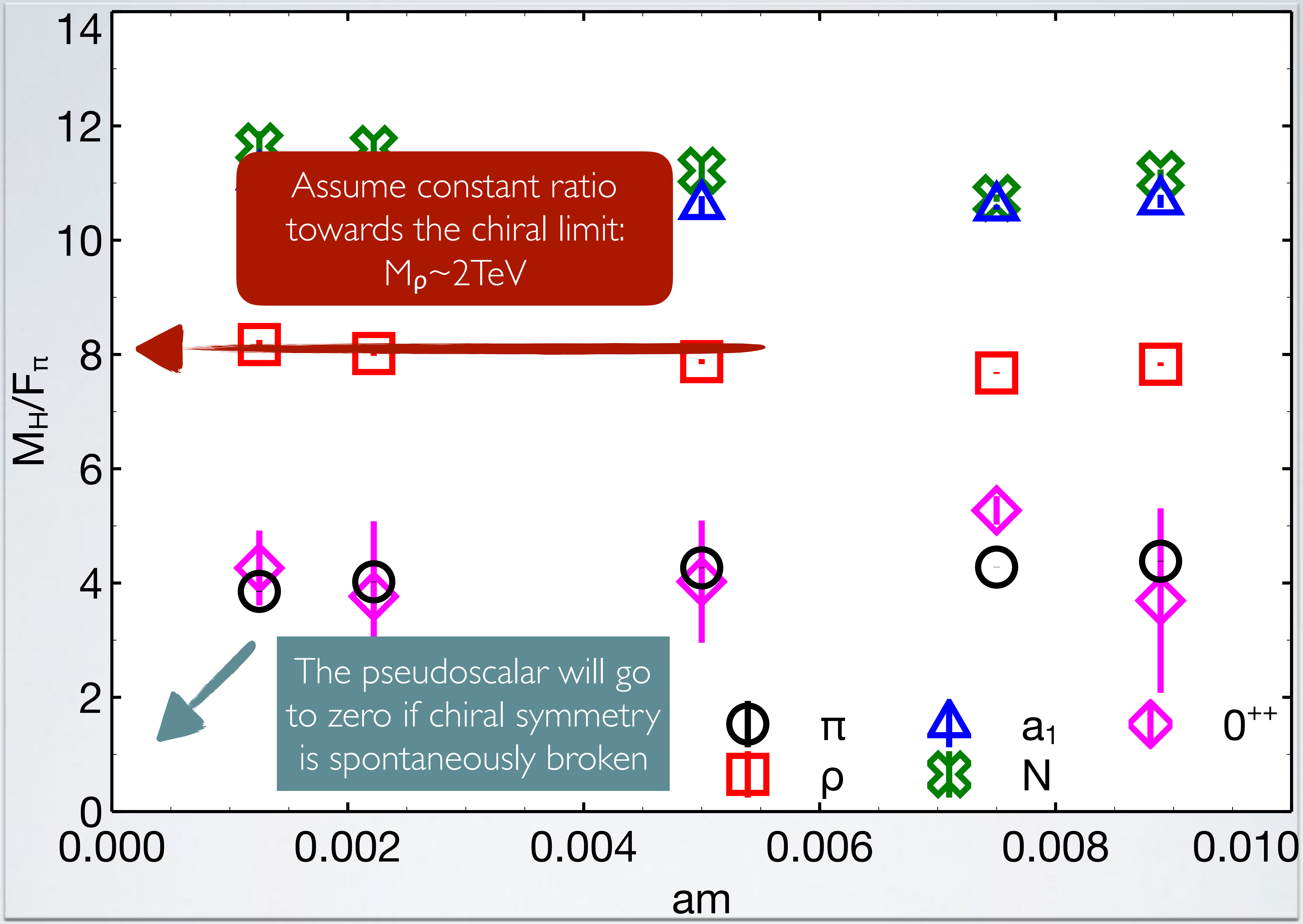
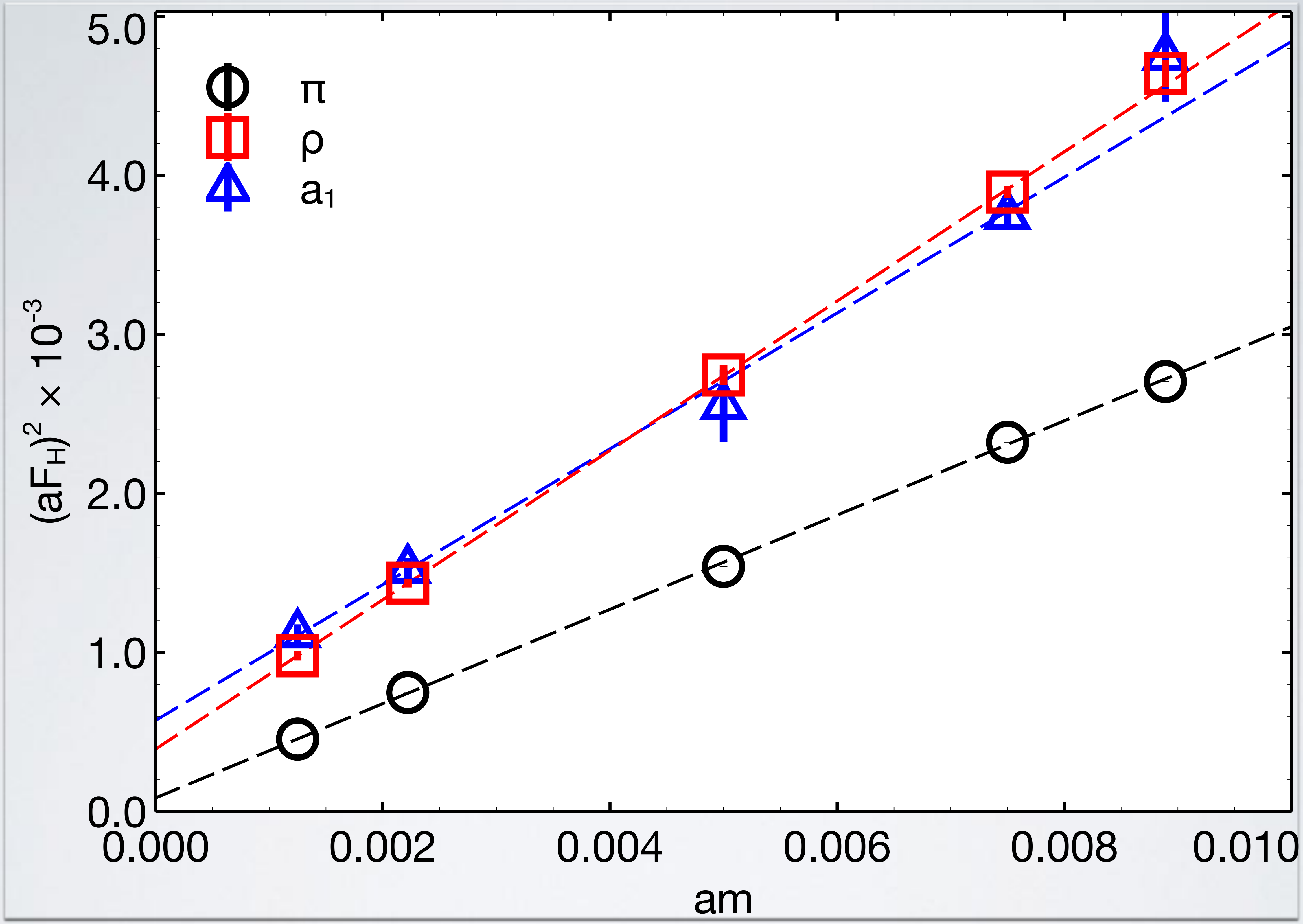


Similar to QCD?

Important again: extrapolate towards the chiral limit using an appropriate effective low-energy theory

LSD arxiv:1601.04027 [scalar update, preliminary]

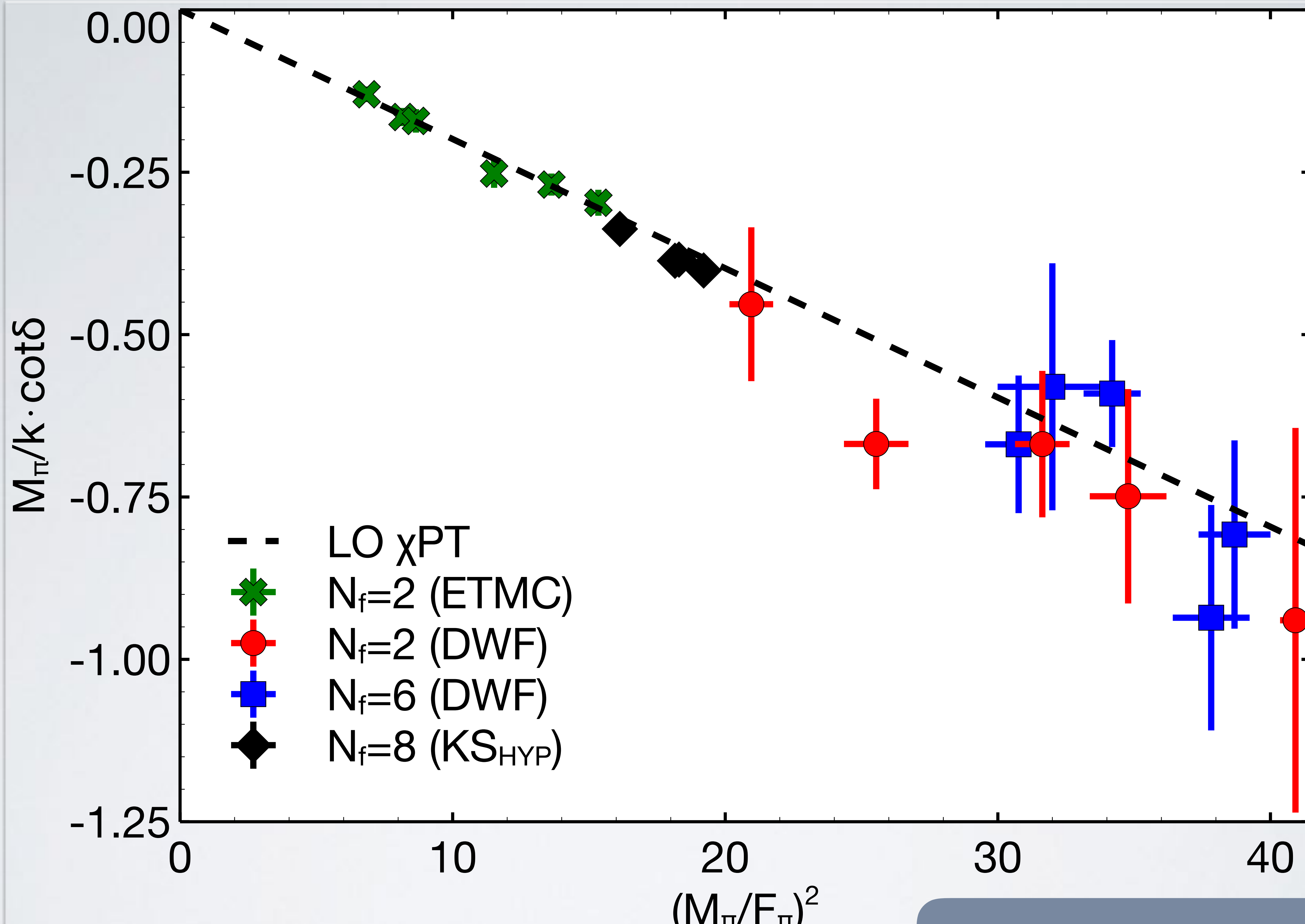
Assume F_π~246GeV



Useful to study vector meson width in the VMD picture

LSD arxiv:1601.04027

Useful to study EFT predictions [Appelquist et al. 1702.04410]

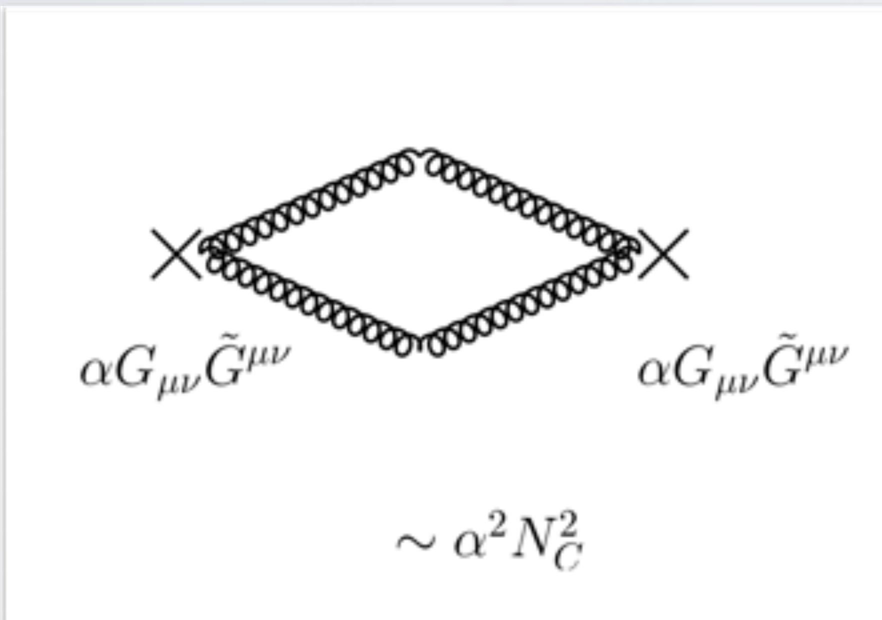


Scattering observables are useful to constrain EFT terms

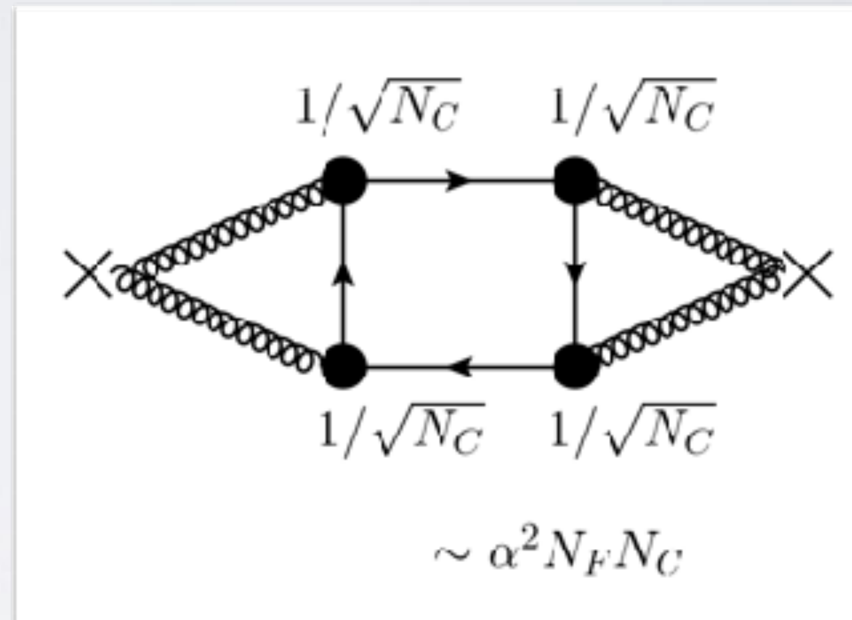
Gasbarro and Fleming (LSD collaboration) 1702.00480

[based on ladder SD and WTI: Matsuzaki, Yamawaki arxiv:1508.07688]

WITTEN-VENEZIANO



gluon loop



fermion loop

Regular Witten-Veneziano $\quad \dfrac{N_f}{N_c} \ll 1$

"anti-"Witten-Veneziano $\quad \dfrac{N_f}{N_c} \gg 1$

$$\lambda = N_c g^2 = \text{fixed} \qquad N_c \to \infty$$

[based on ladder SD and WTI: Matsuzaki, Yamawaki arxiv:1508.07688]

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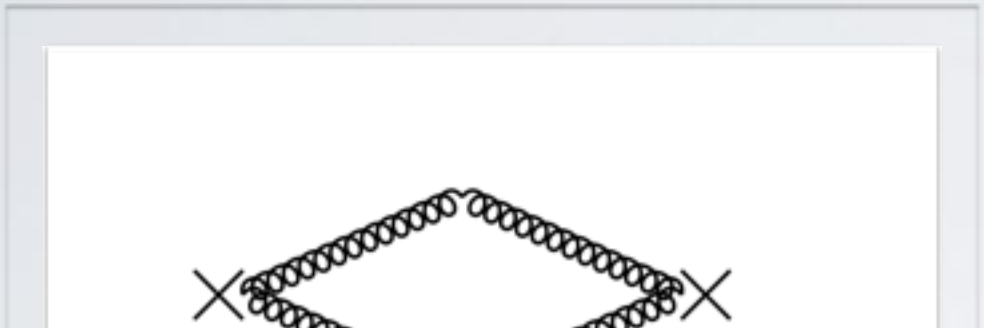

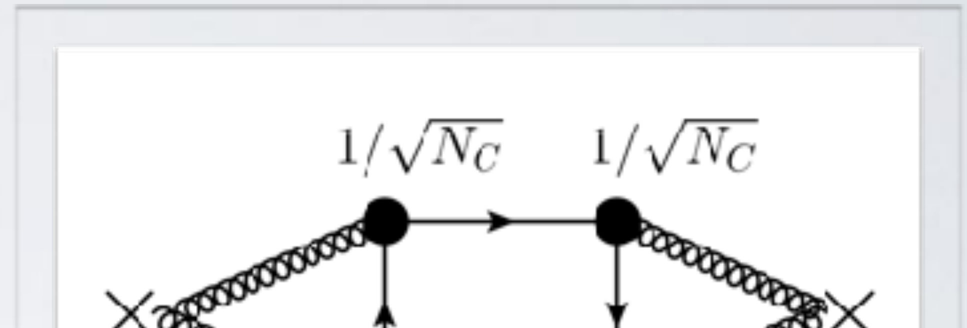

lattice results seem to align with expectations from ladder-SD analyses [arxiv:1508.07688]: a flavor-singlet scalar in a near conformal theory is light similarly to a flavor-singlet pseudoscalar in the Witten-Veneziano limit, but a flavor-singlet pseudoscalar is heavier in the "anti"-Witten-Veneziano limit (large N_f/N_c)

Regular Witten-Veneziano $\frac{N_f}{N_c} \ll 1$

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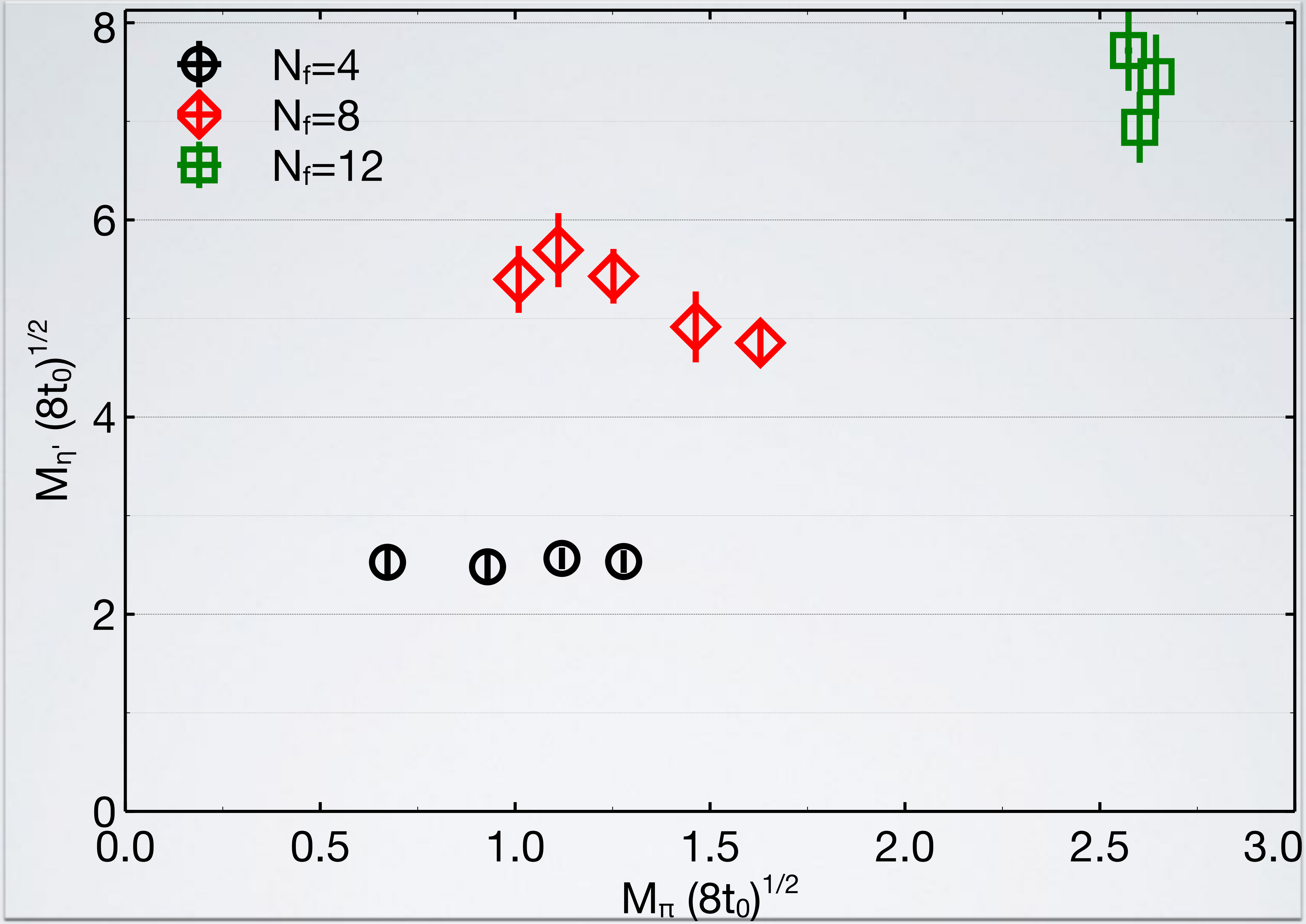
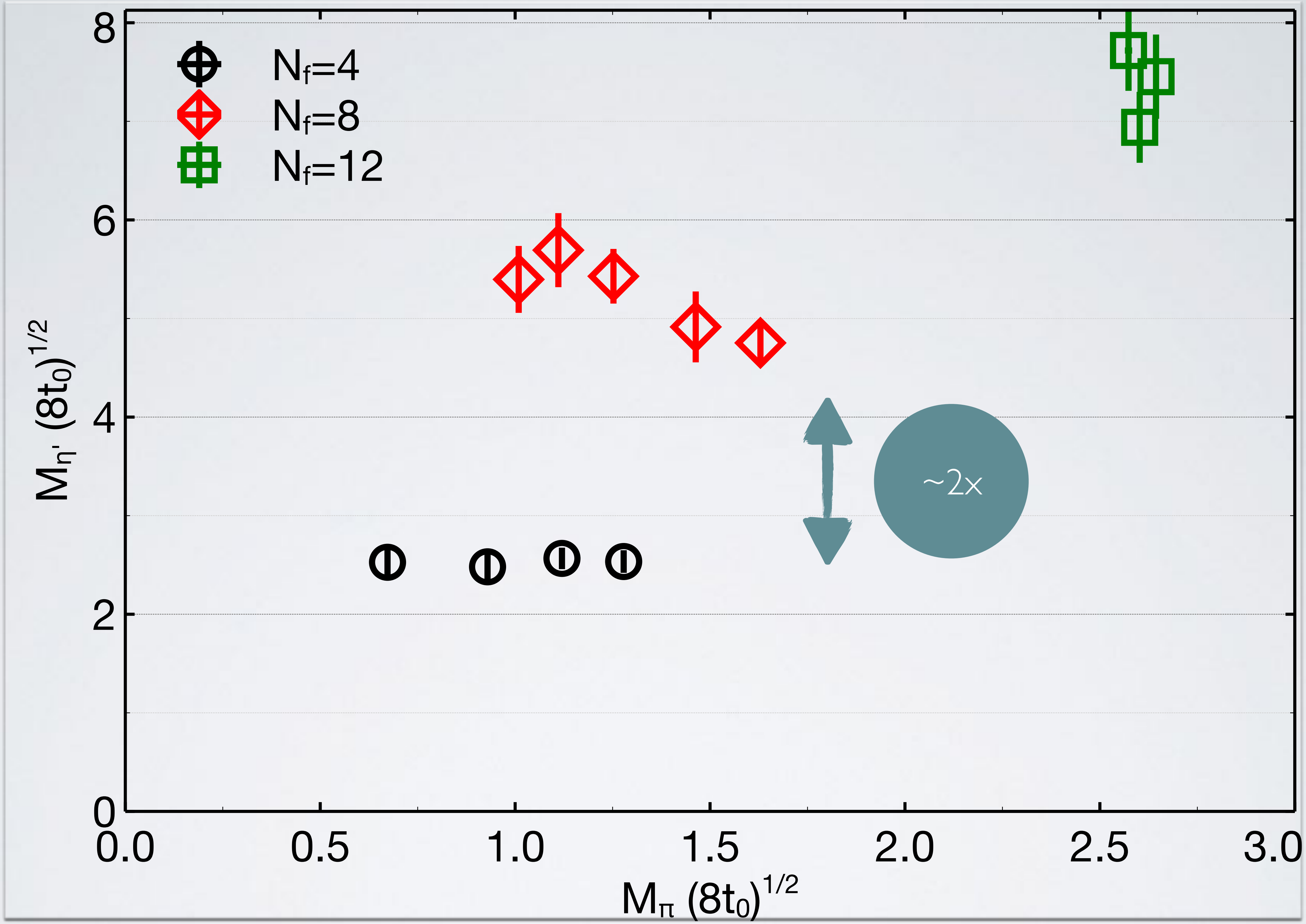


LatKMI [in preparation]



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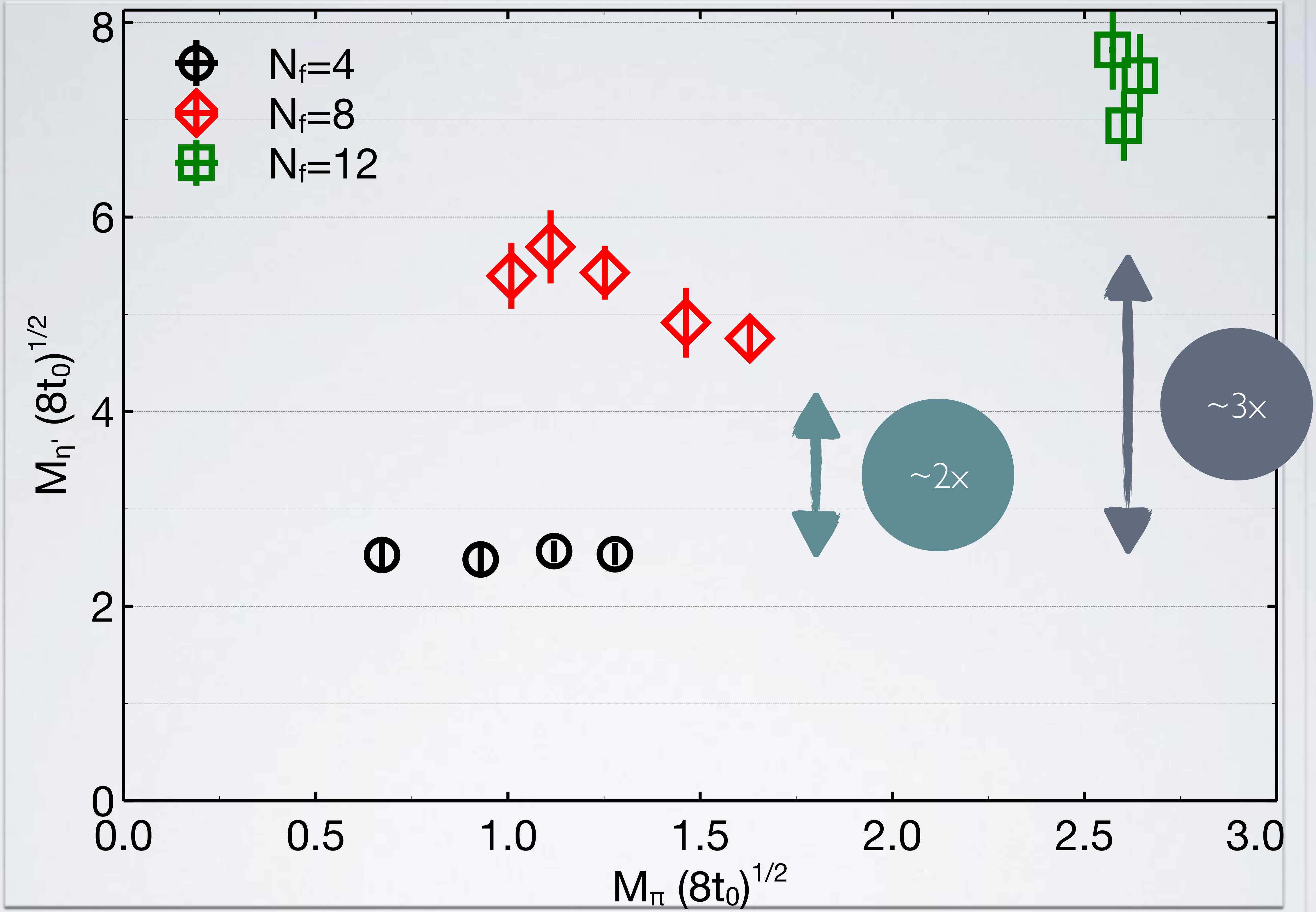
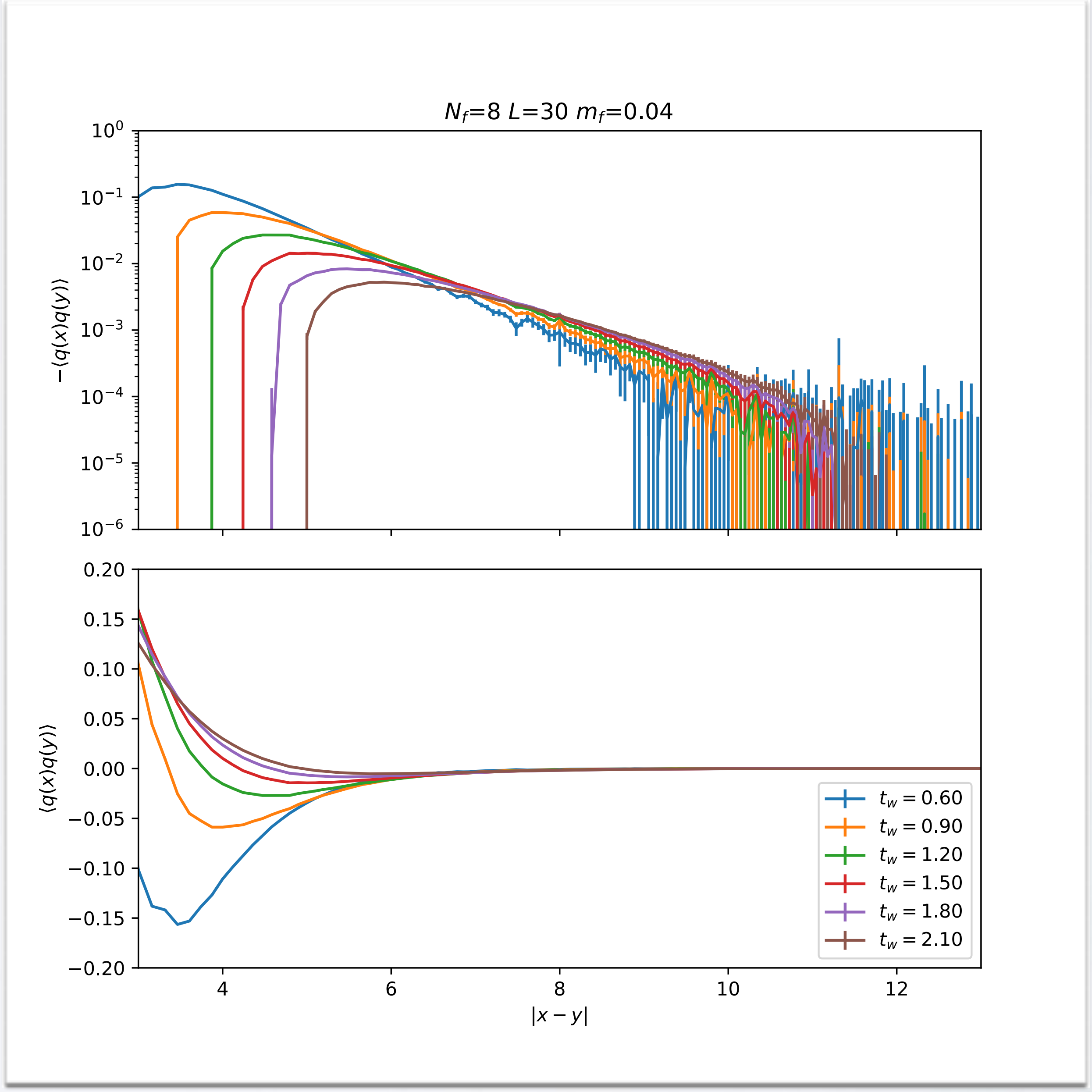


LatKMI [in preparation]

METHODOLOGY FOR 0^{-+}

- Use a gluonic operator with 0^{-+} quantum numbers: topological charge density
- Use Wilson flow smearing as a technique to ameliorate the signal-to-noise problem
- Entirely similar to previous studies in SU(3) YM [arxiv: 1409.6459] and QCD [arxiv: 1509.00944]
- Main difficulty is estimating the systematics due to smearing and excited states



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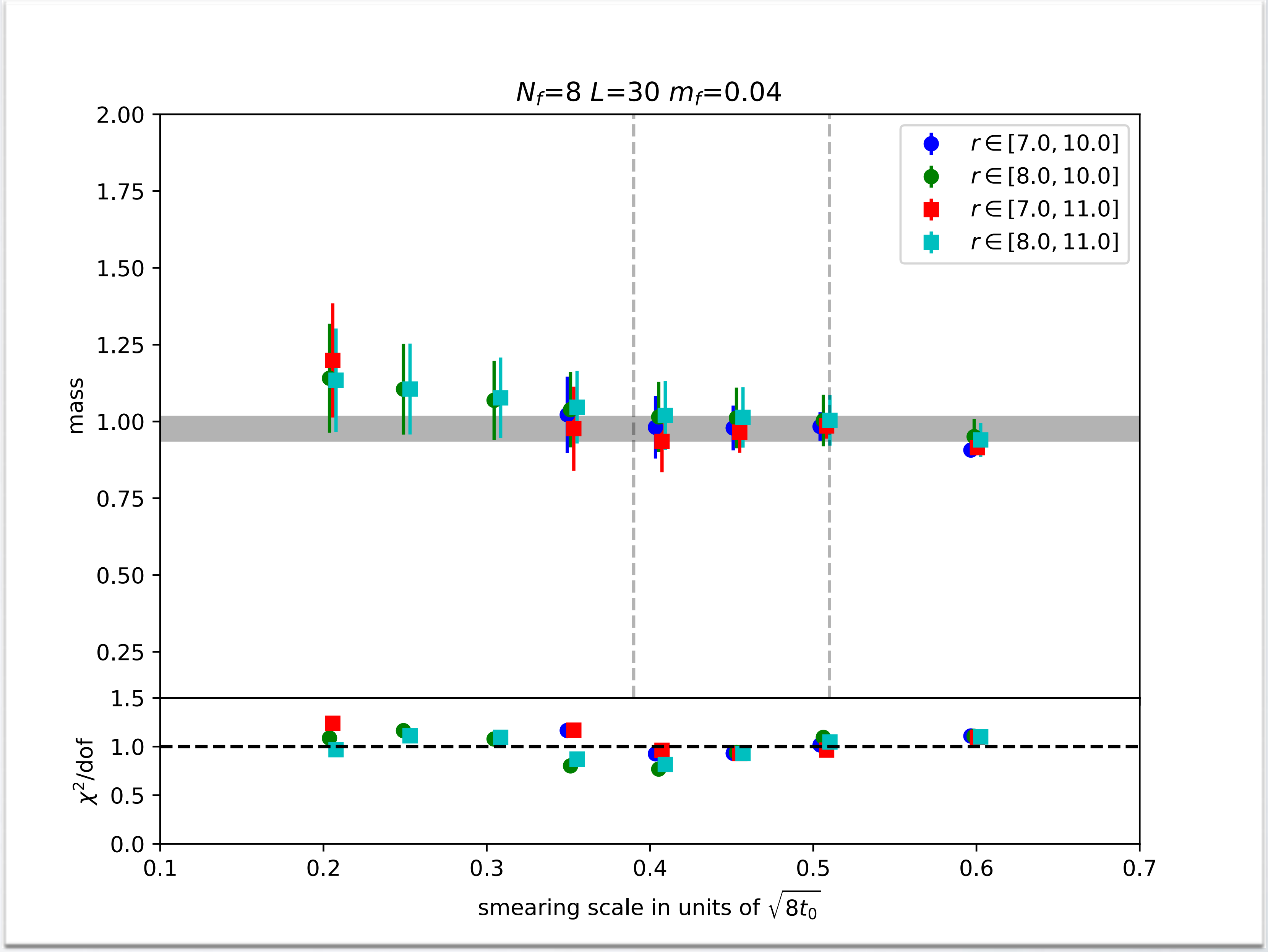
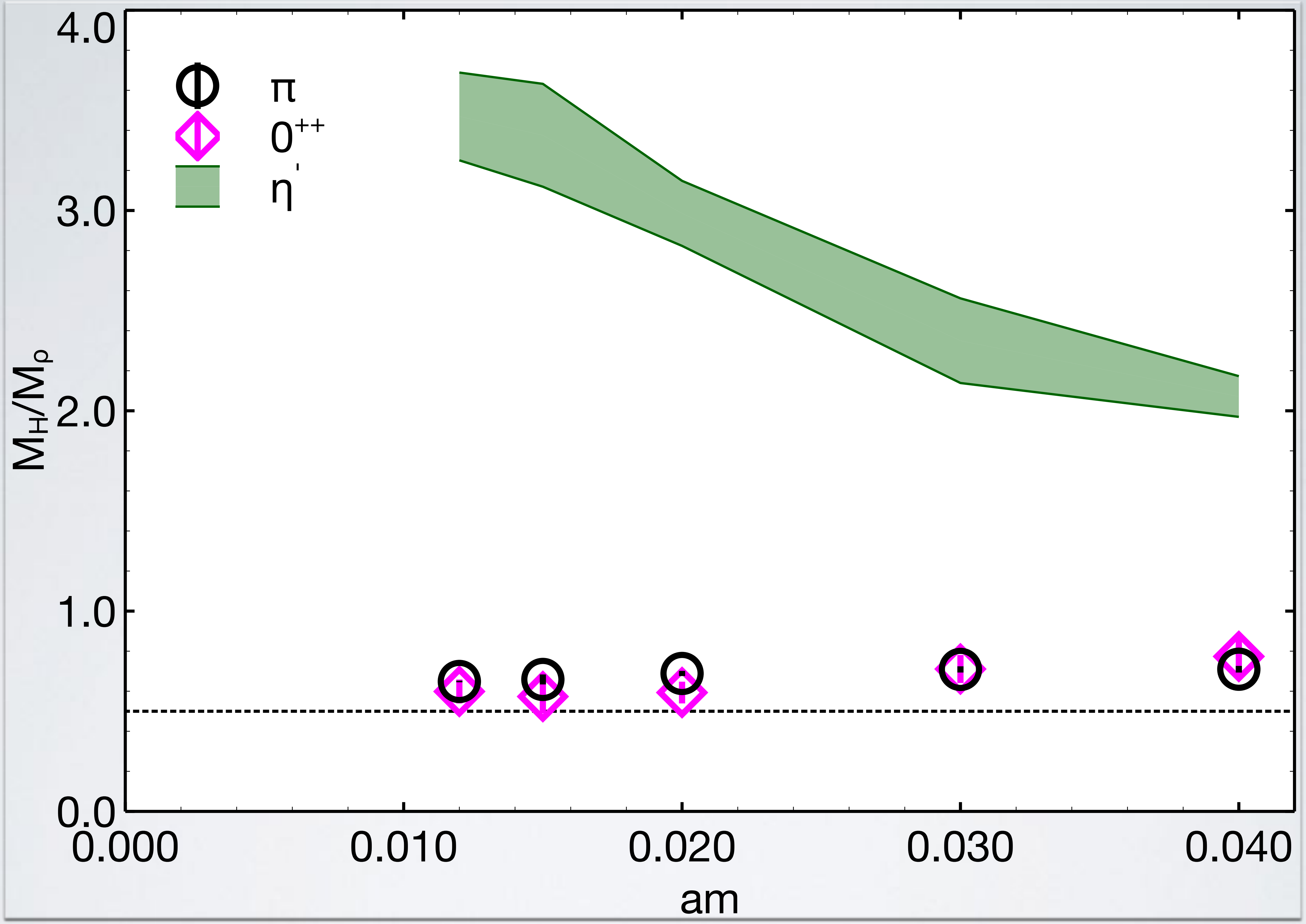
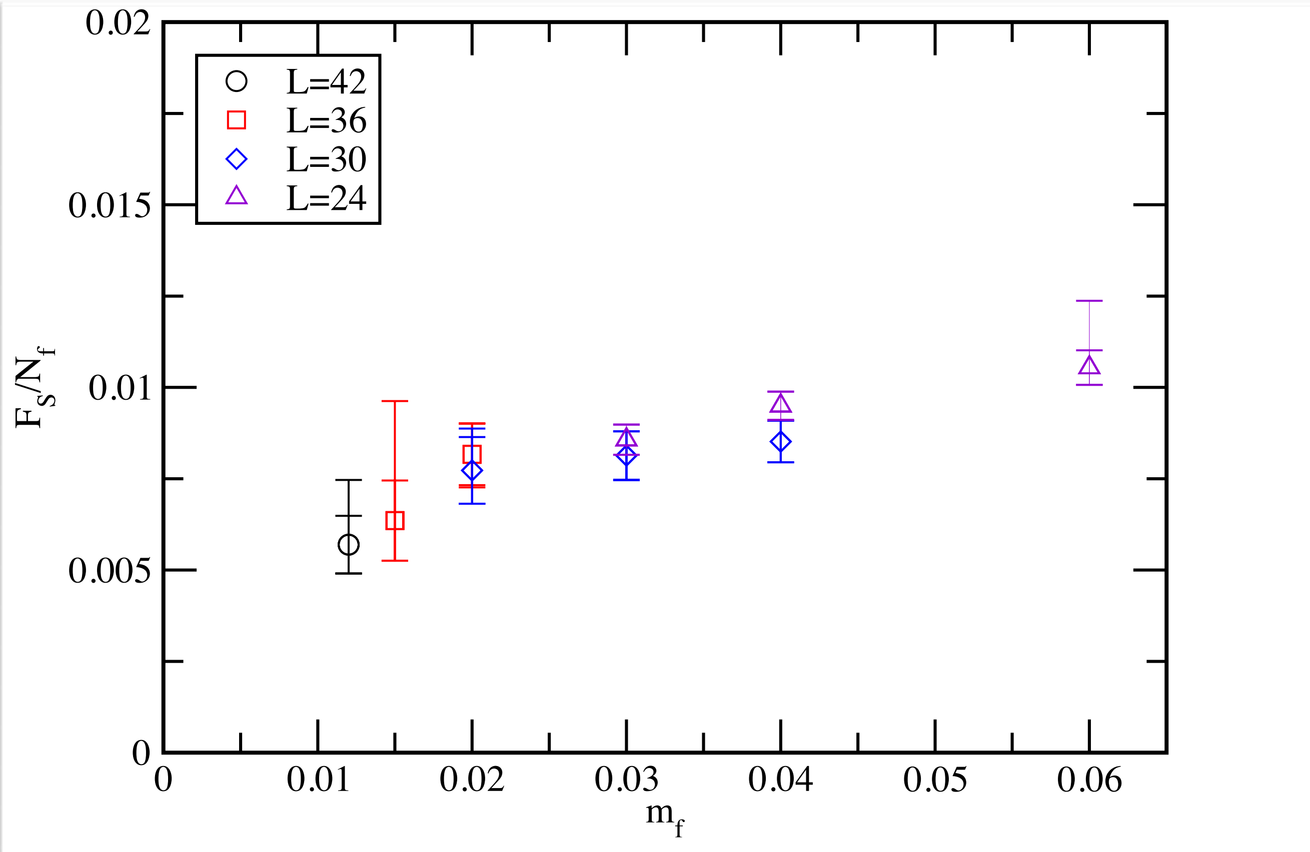


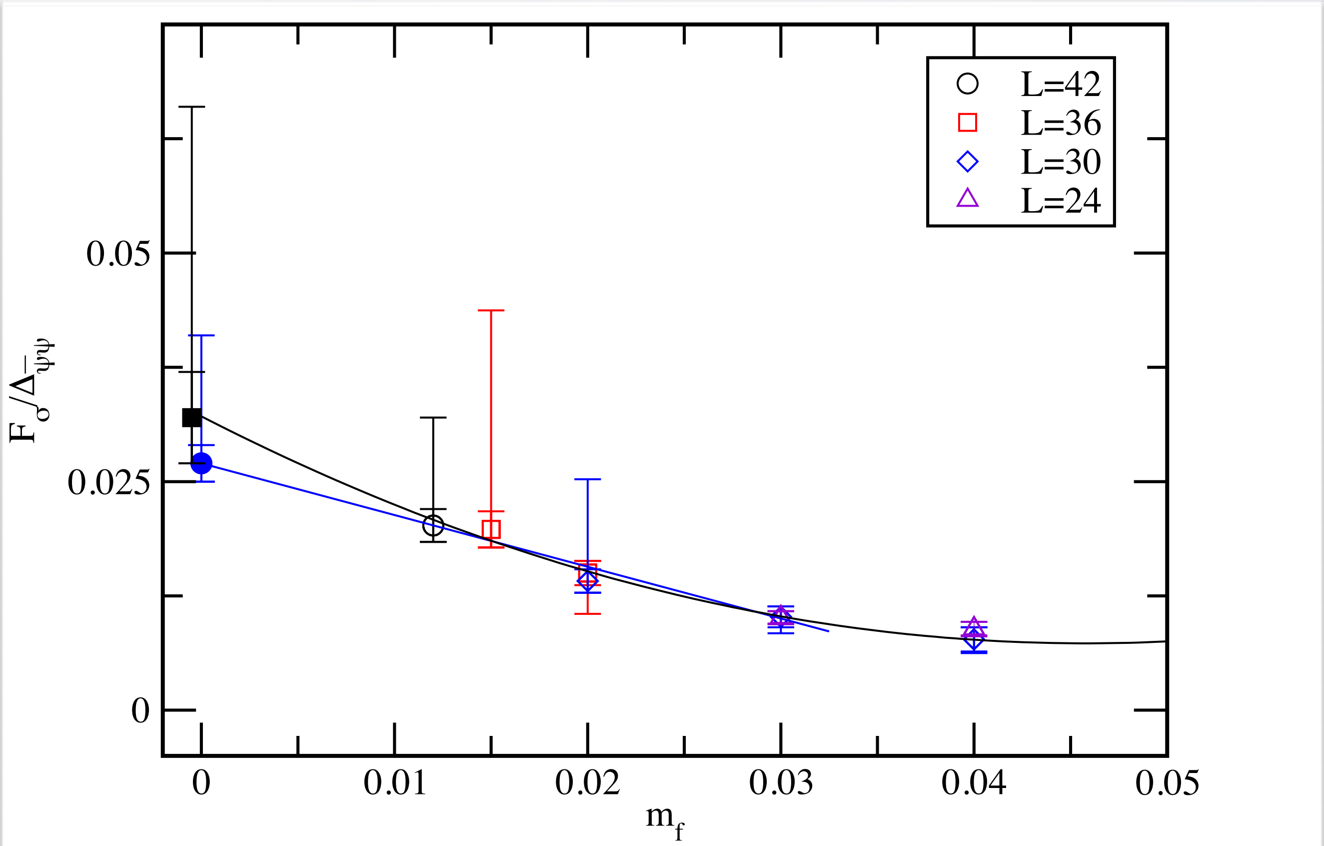


LatKMI [in preparation]

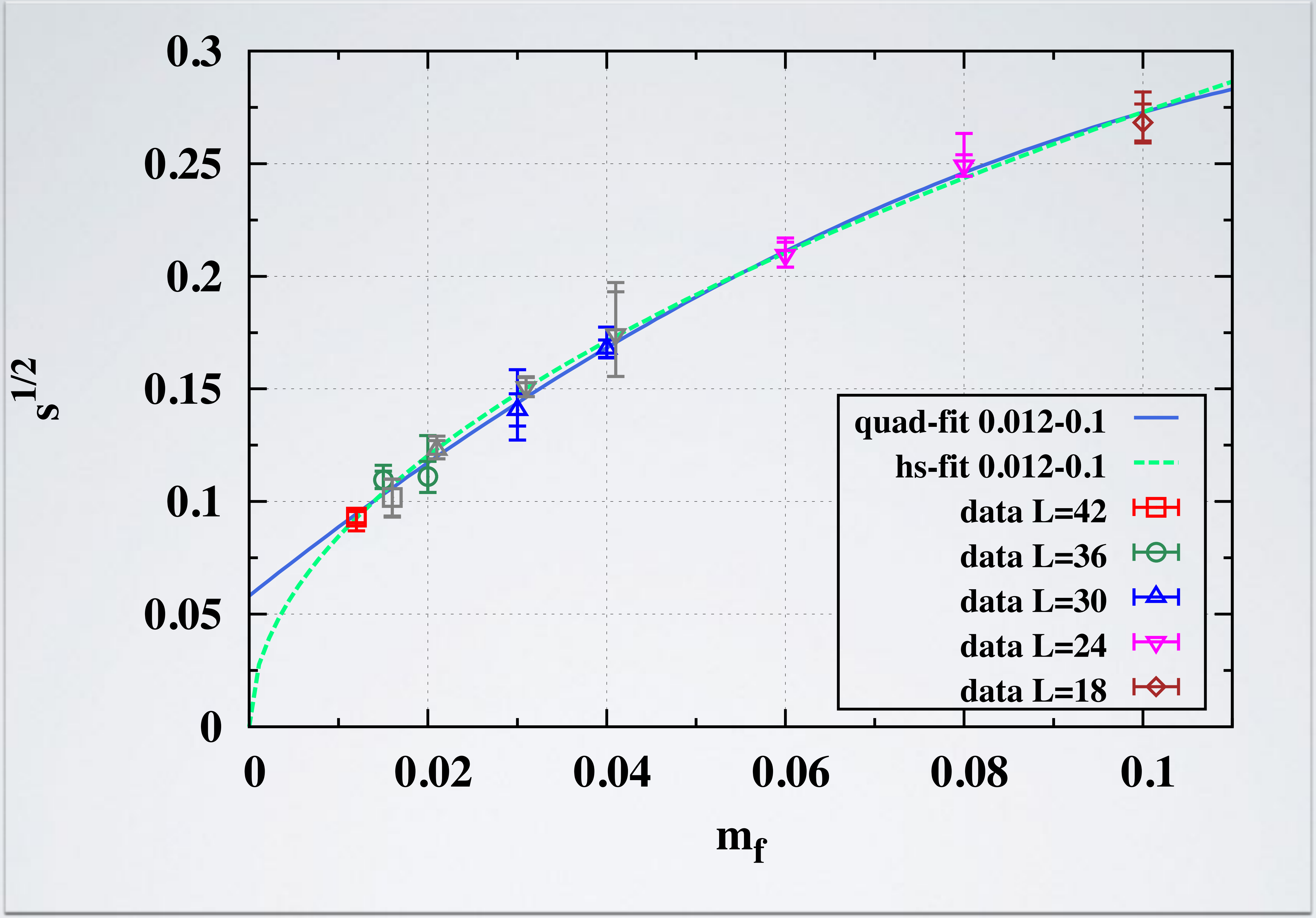


$$\langle 0|m_f O_S(0,0)|\sigma(0)\rangle = F_S M_\sigma^2$$

$$F_S F_\sigma M_\sigma^2 = -\Delta_{\overline{\psi}\psi} m_f \sum_i^{N_f} \langle \overline{\psi}_i \psi_i \rangle$$



LatKMI arxiv:1610.07011



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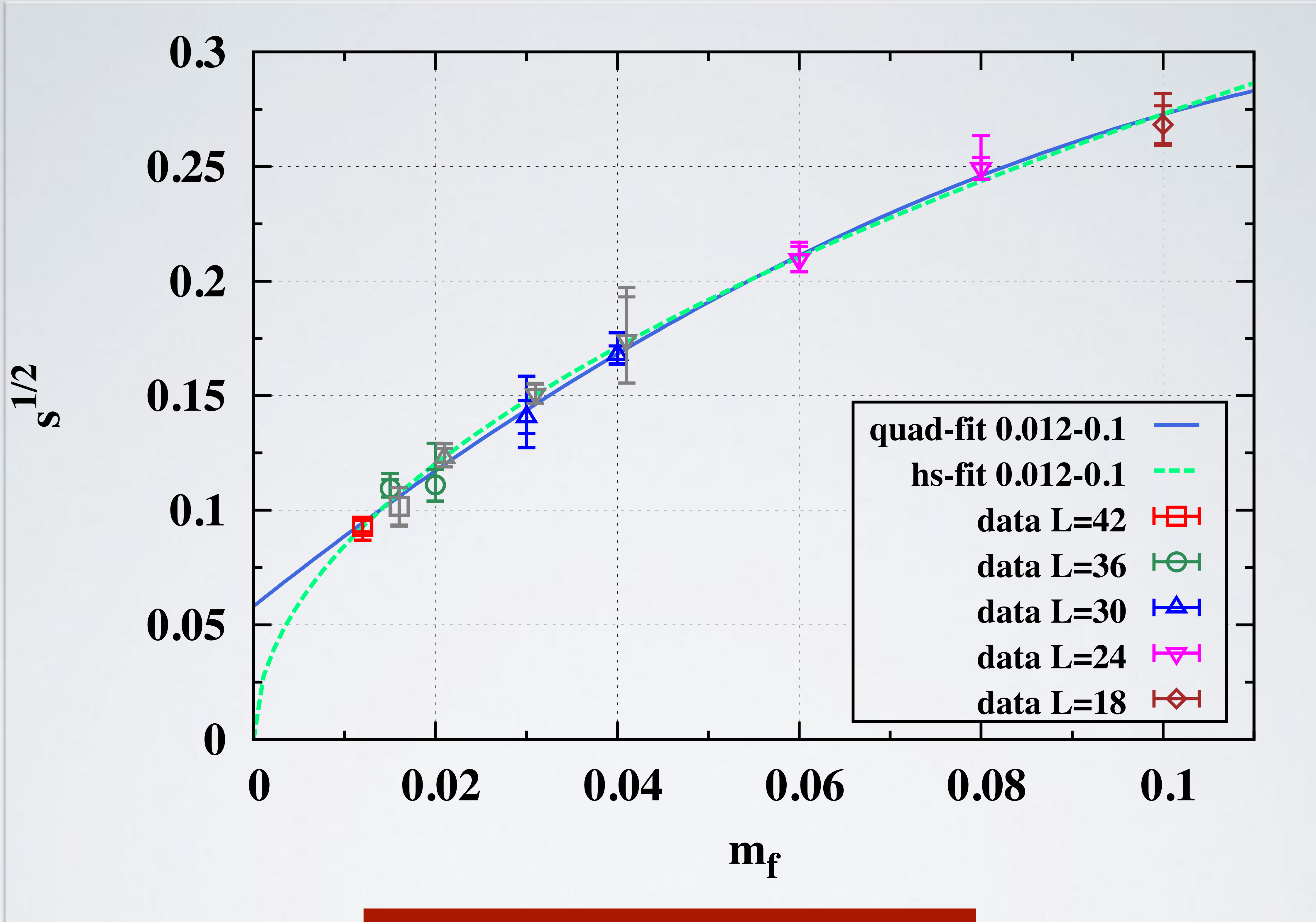
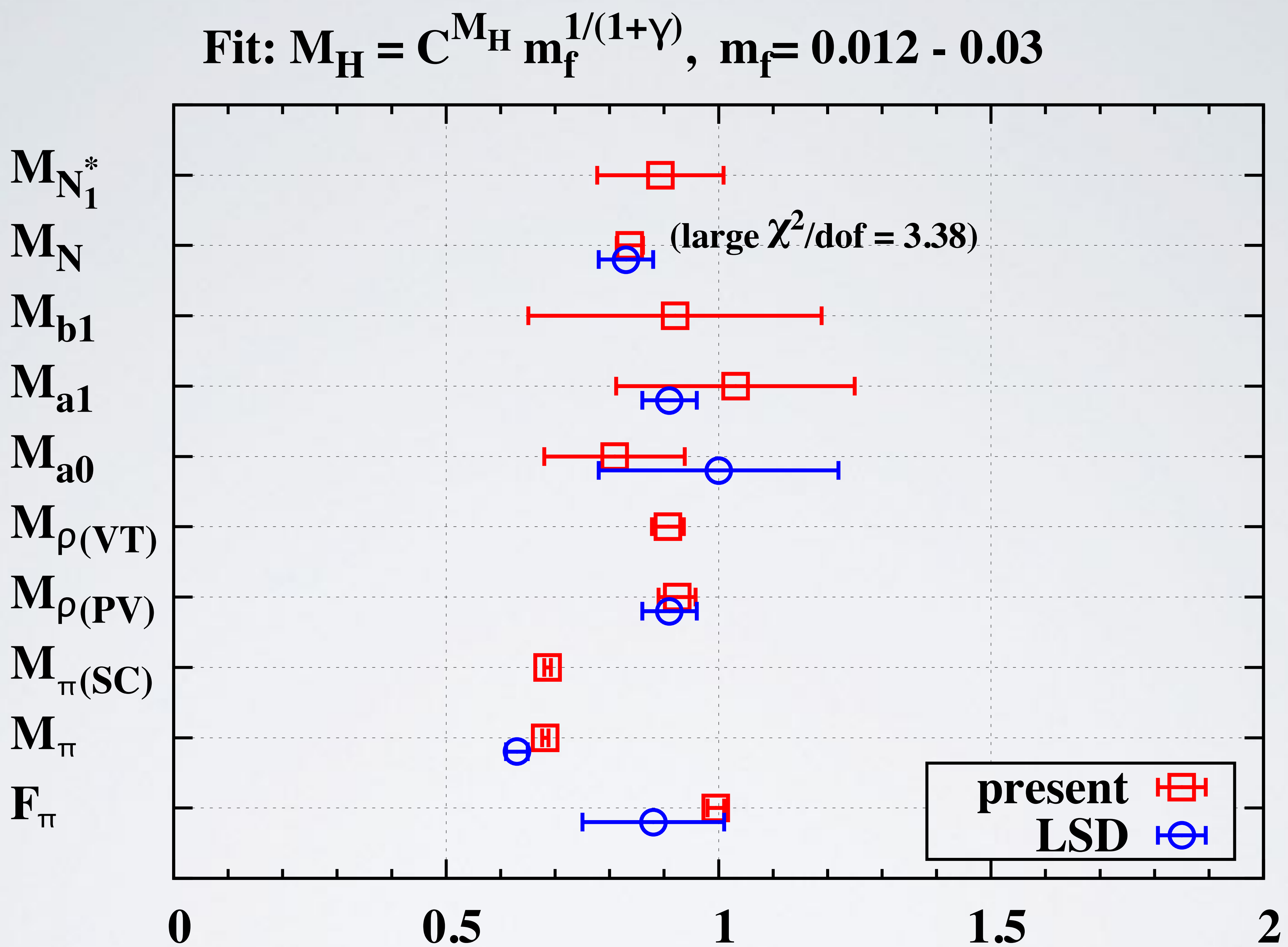
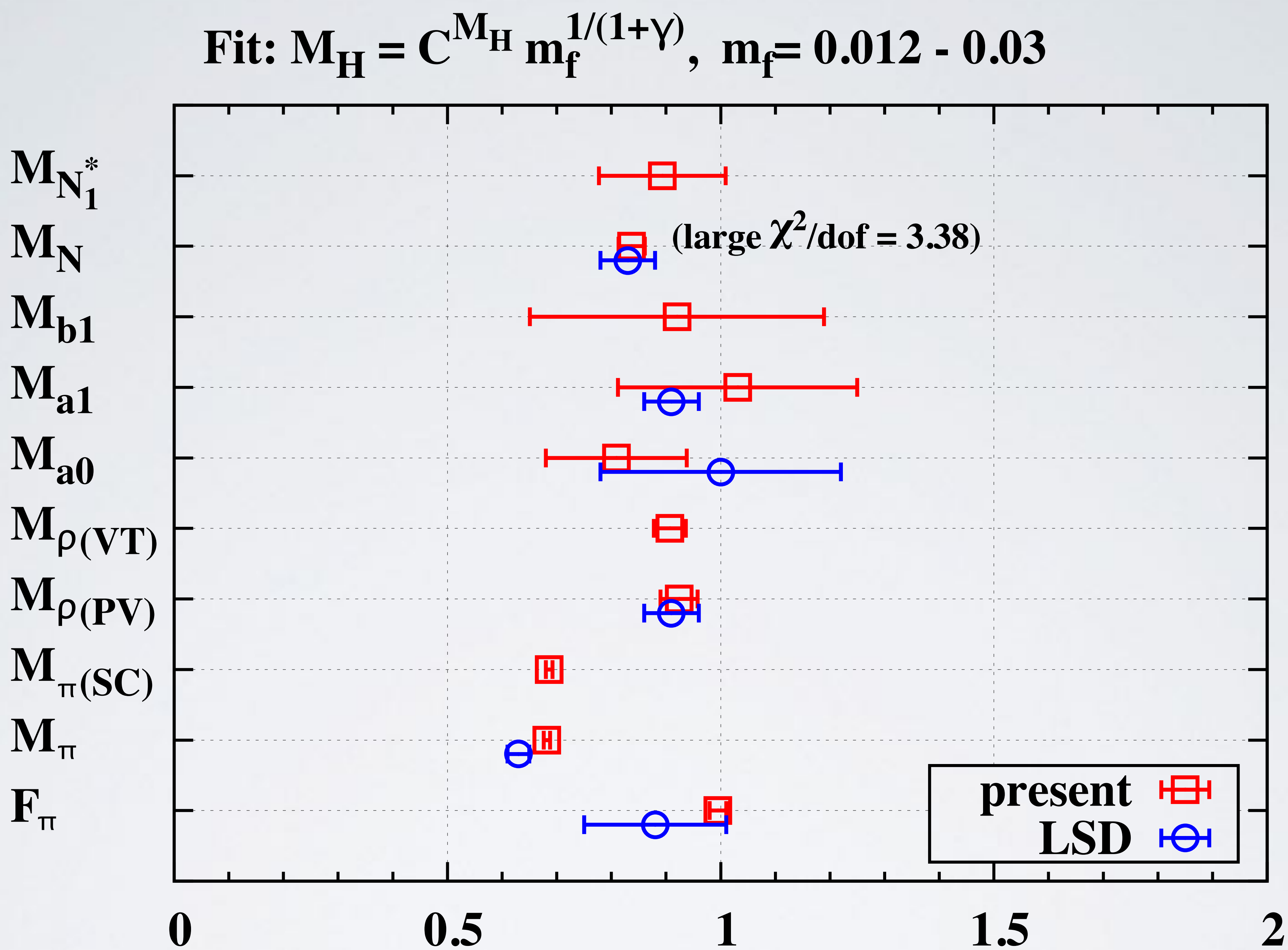


Not able to distinguish between
hyper scaling fit with γ~ 0.96(6)
and quadratic fit with finite intercept ≠0

LatKMI arxiv:1610.07011



LatKMI arxiv:1610.07011 | LSD arxiv:1405.4752



All the states studied in the spectrum have $\gamma \sim 1$ except for the pseudoscalar.
Comparison with different lattice discretizations: staggered and domain wall fermions

LatKMI arxiv:1610.07011 | LSD arxiv:1405.4752