Strongly interacting electroweak symmetry breaking models

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Lattice 19

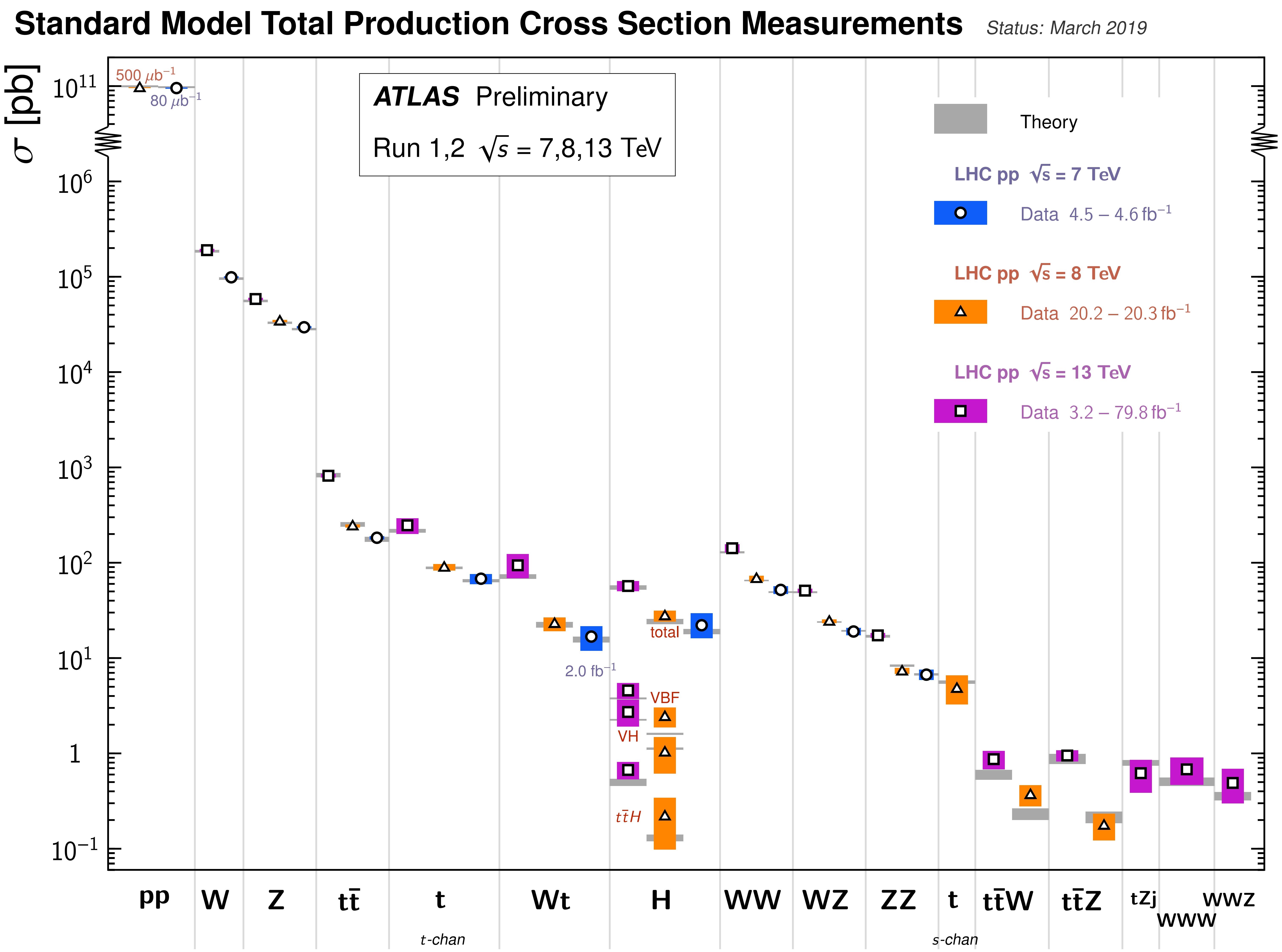
Wuhan·China | June 16-22

- I would like to thank the organisers for inviting me to review the lattice results concerning “*the recent developments of strong EW symmetry breaking models and simulation results*”.

- Thanks to everybody who sent details on their work.

The Standard Model and beyond

The success of the Standard Model



[ATL-PHYS-PUB-2019-010]

- Impressive overall agreement with the SM predictions.

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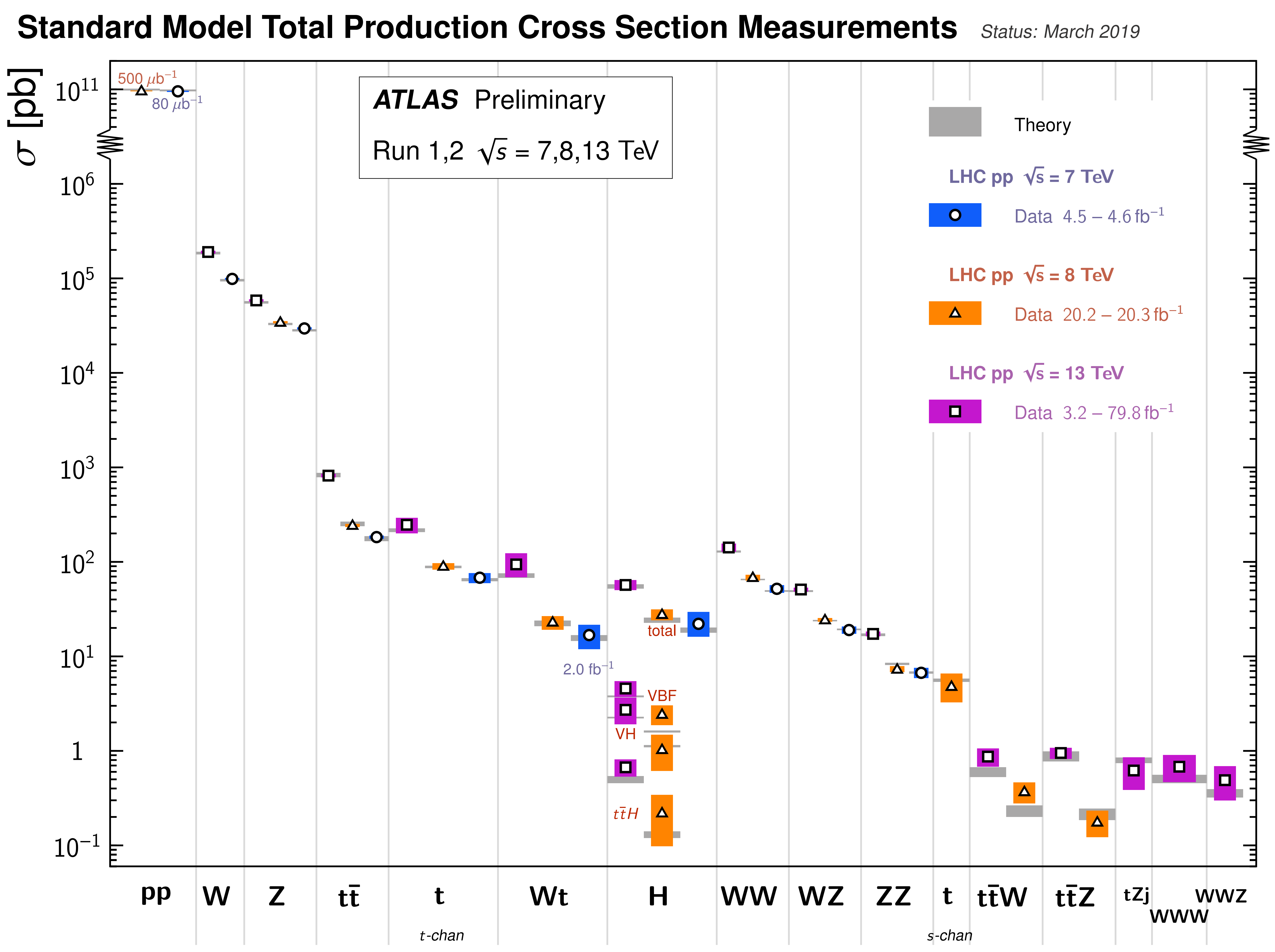

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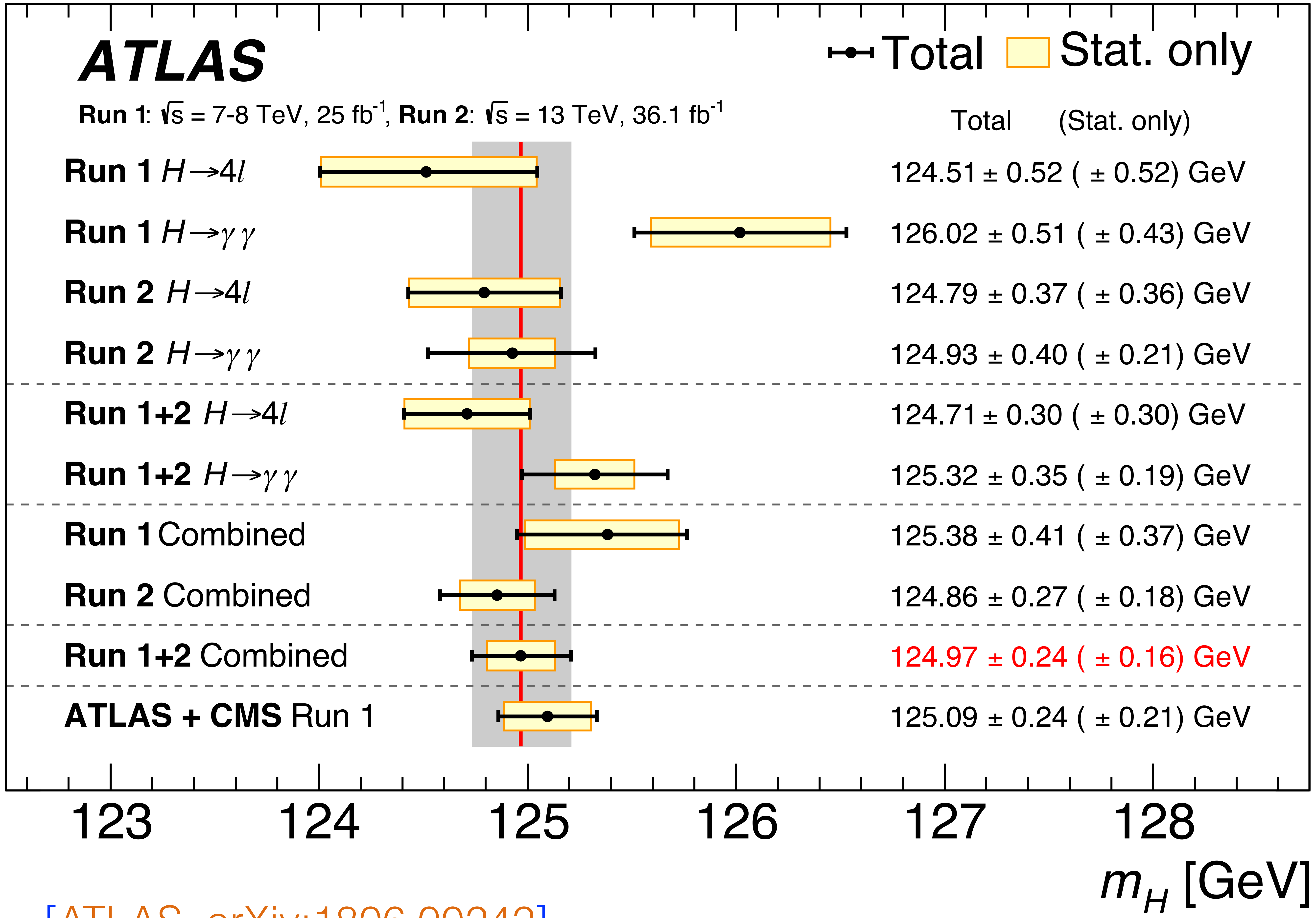

[ATLAS, arXiv:1806.00242]

- m_H known ~0.2% accuracy!
- m_H : EW precision observable ?
- Spin: highly constrained
- CP properties: much more challenging

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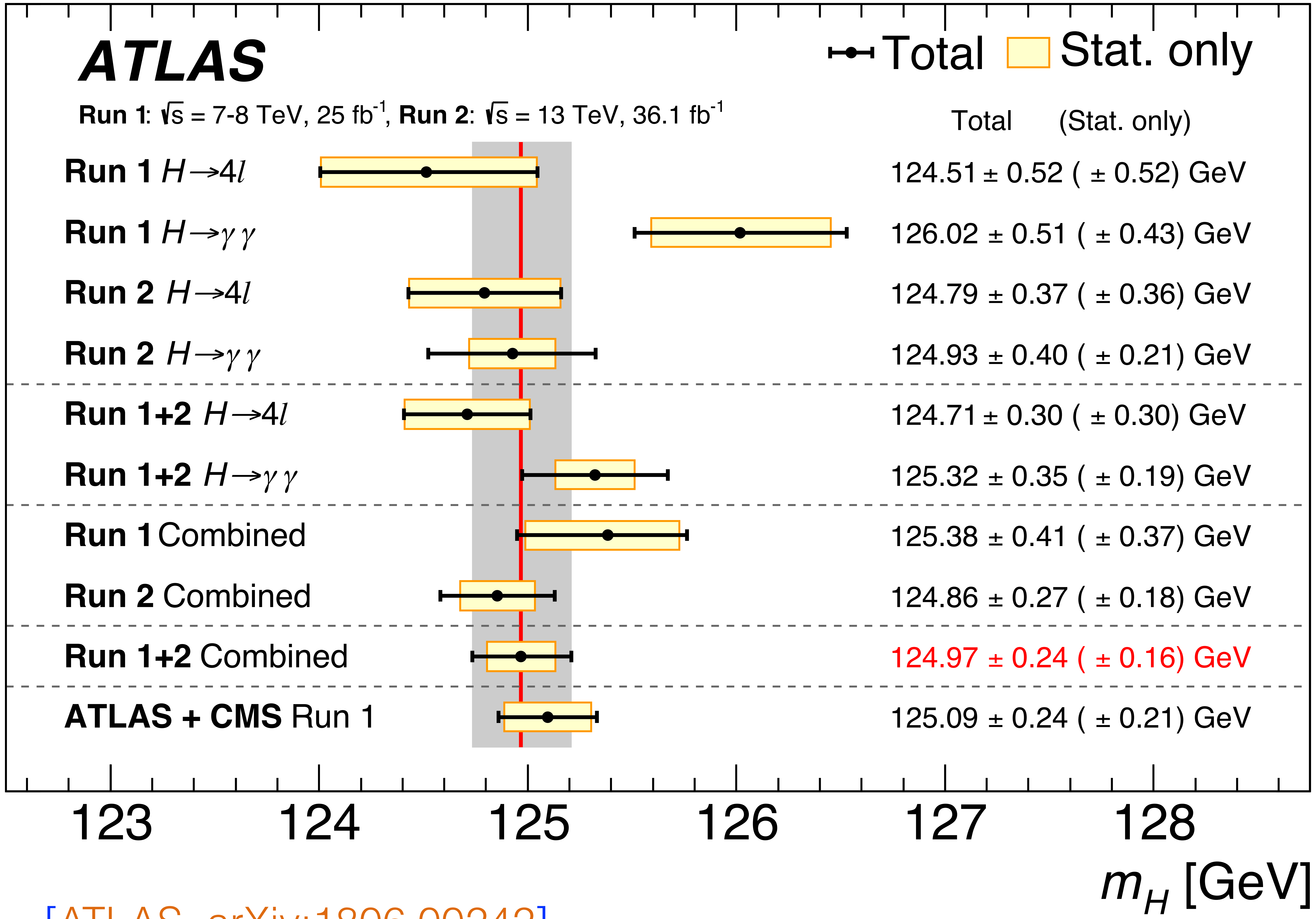

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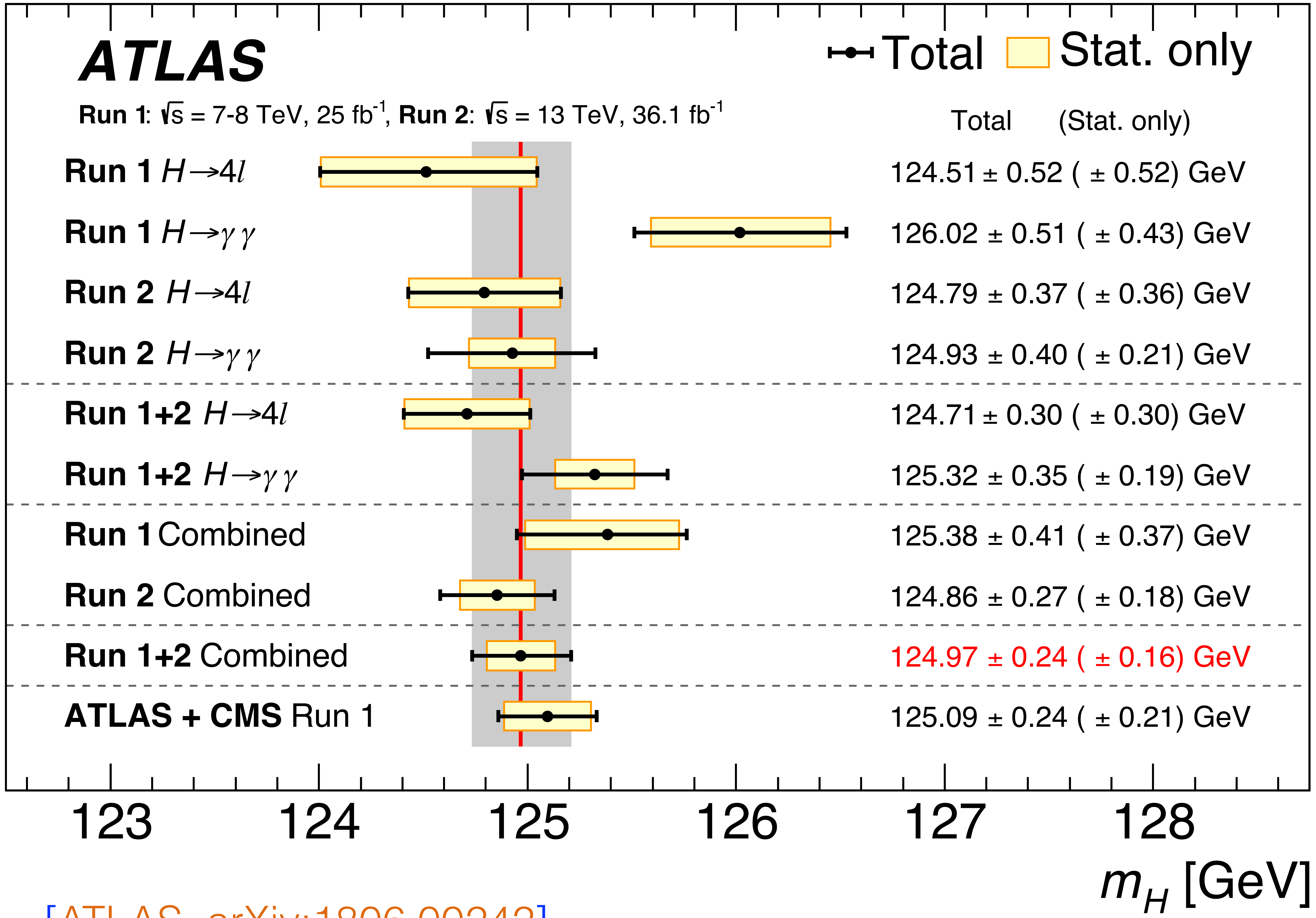

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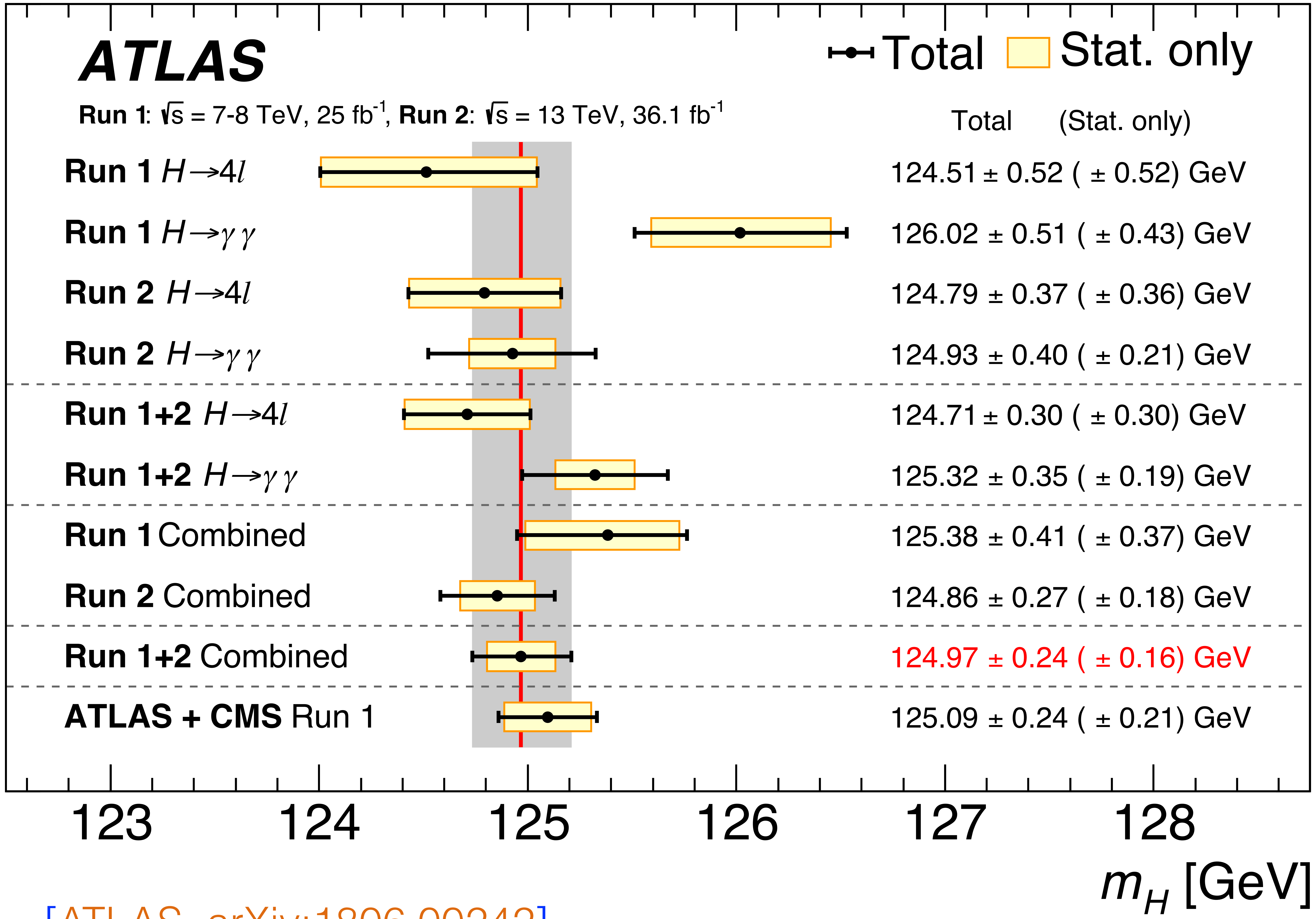

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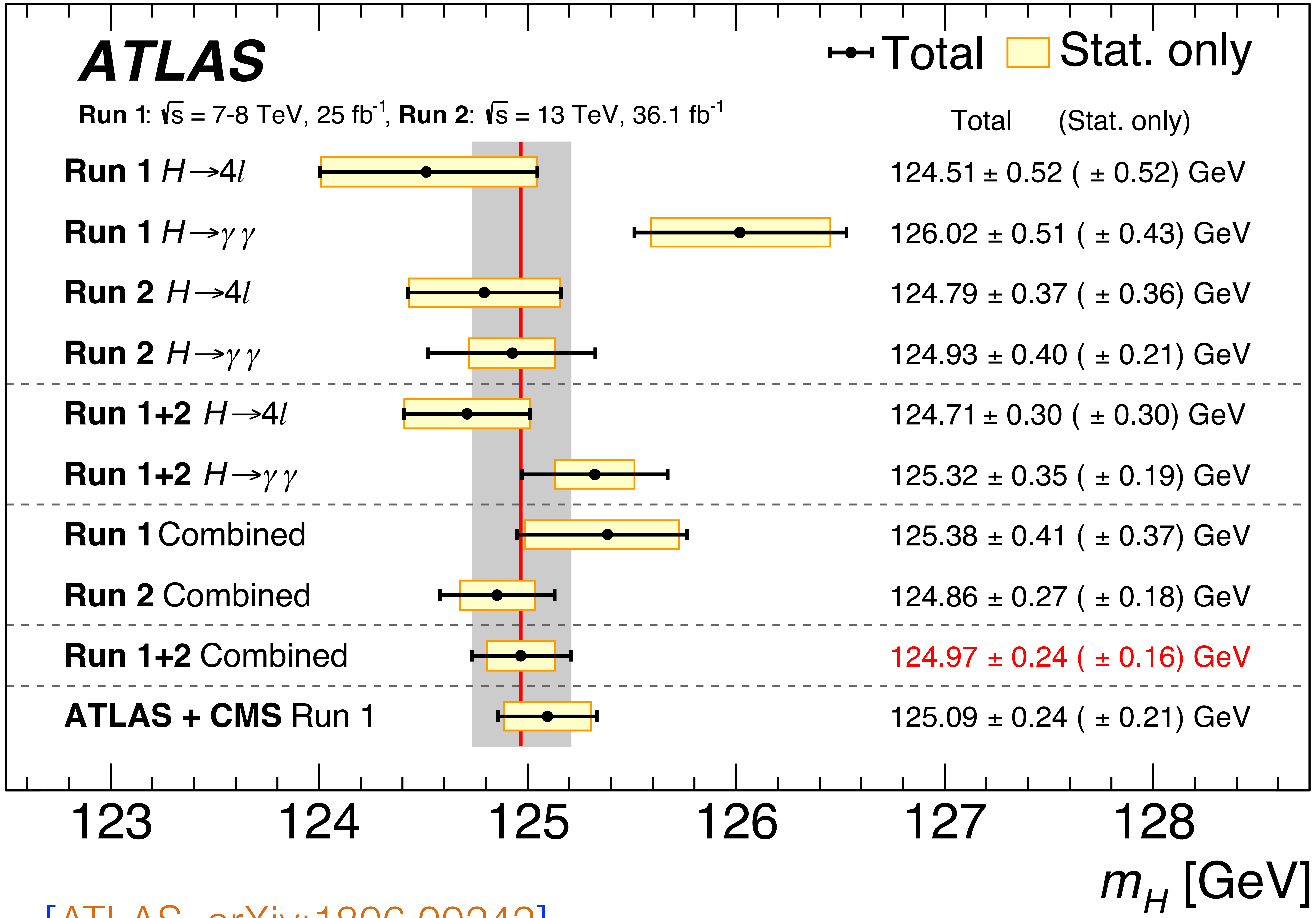

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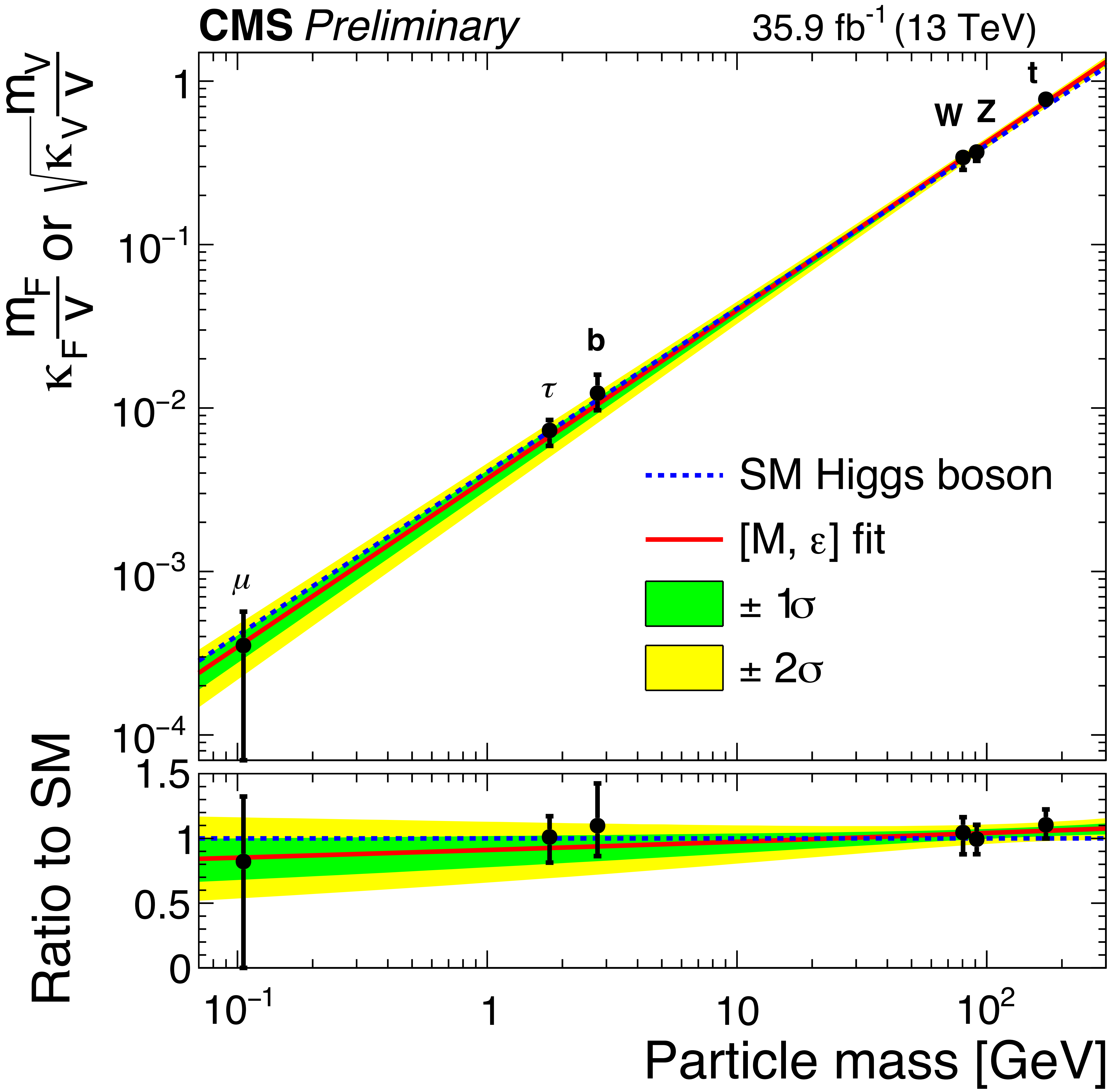
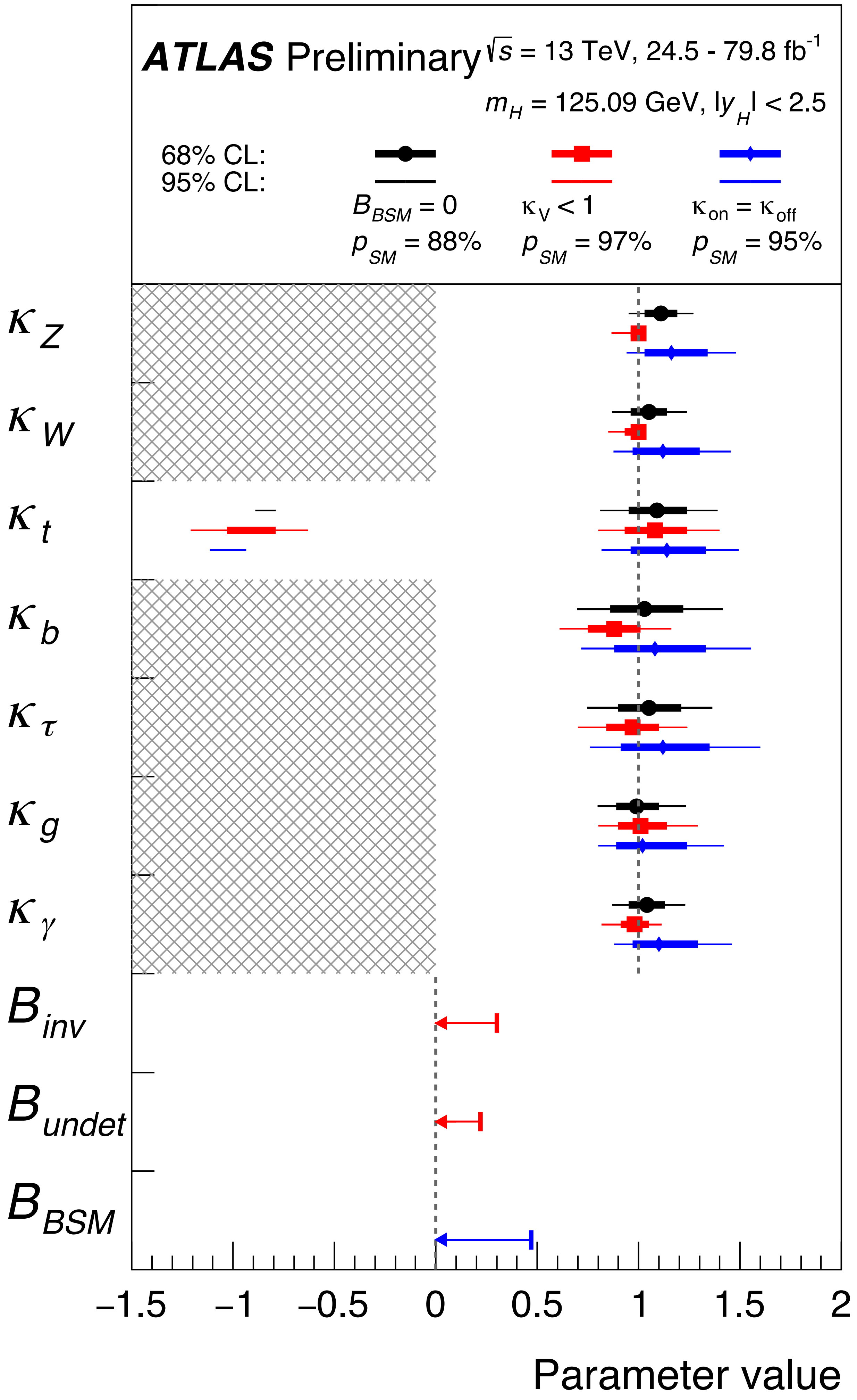


[CMS, arXiv:1809.10733]



[ATLAS-CONF-2019-005]

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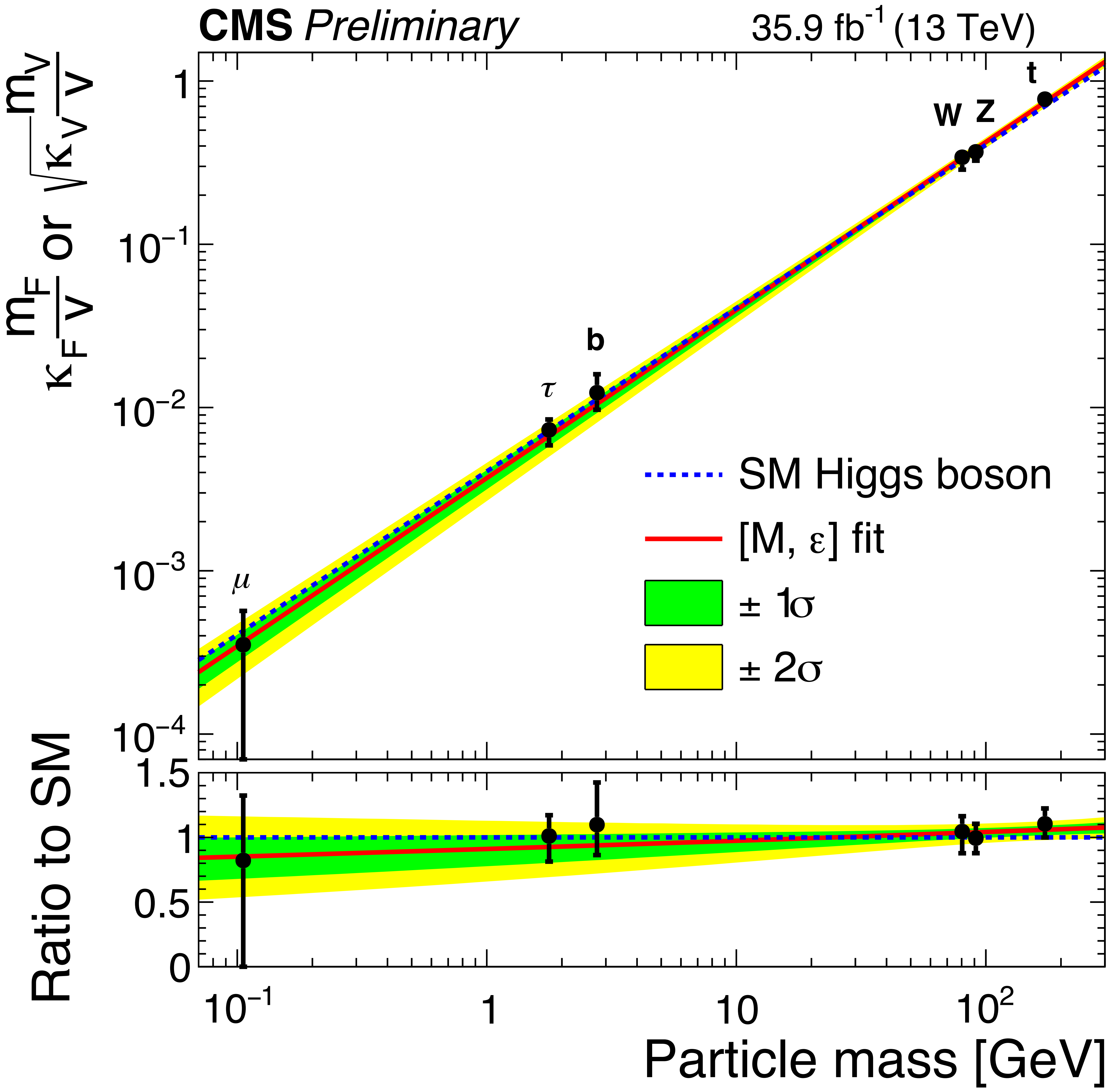

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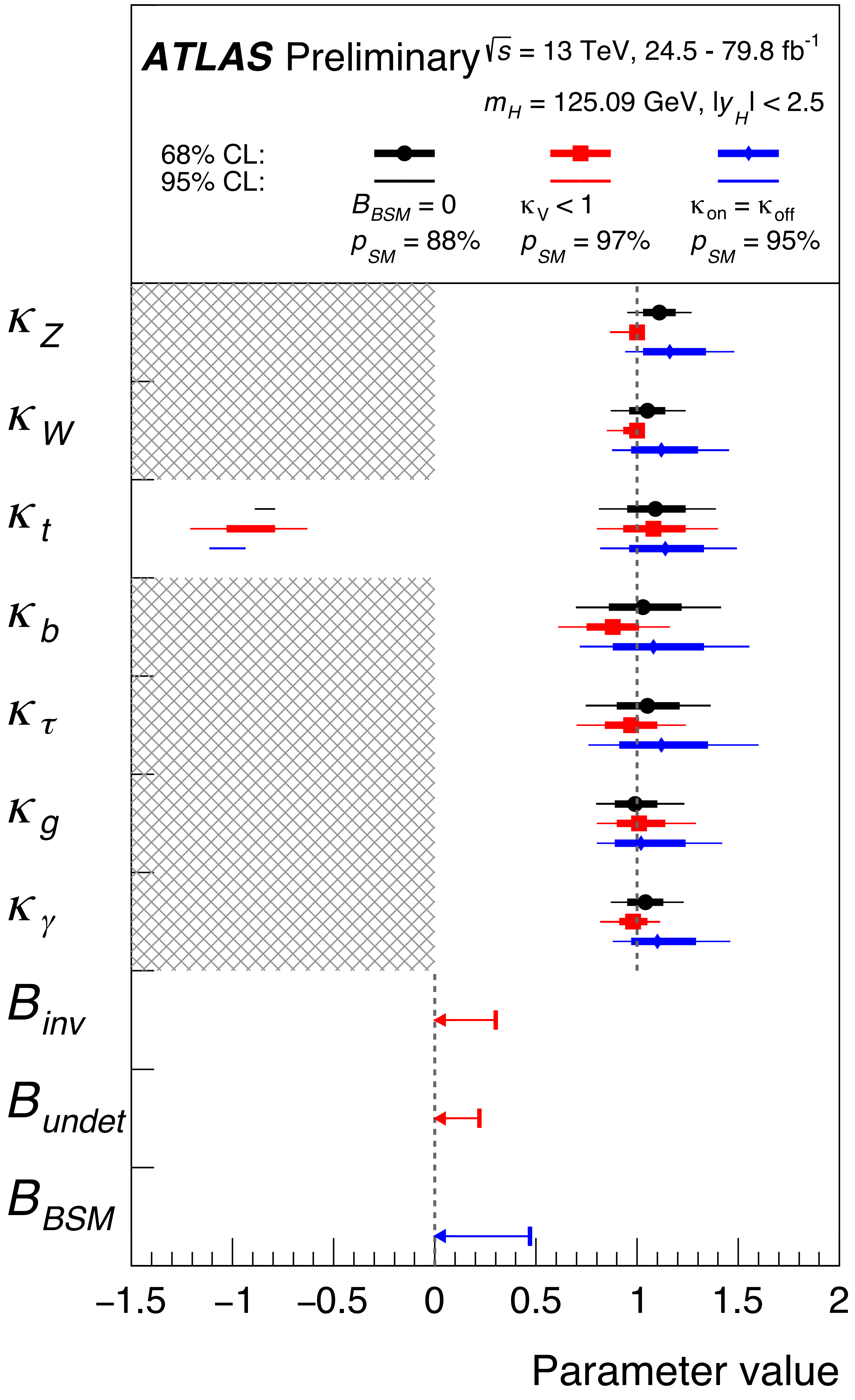

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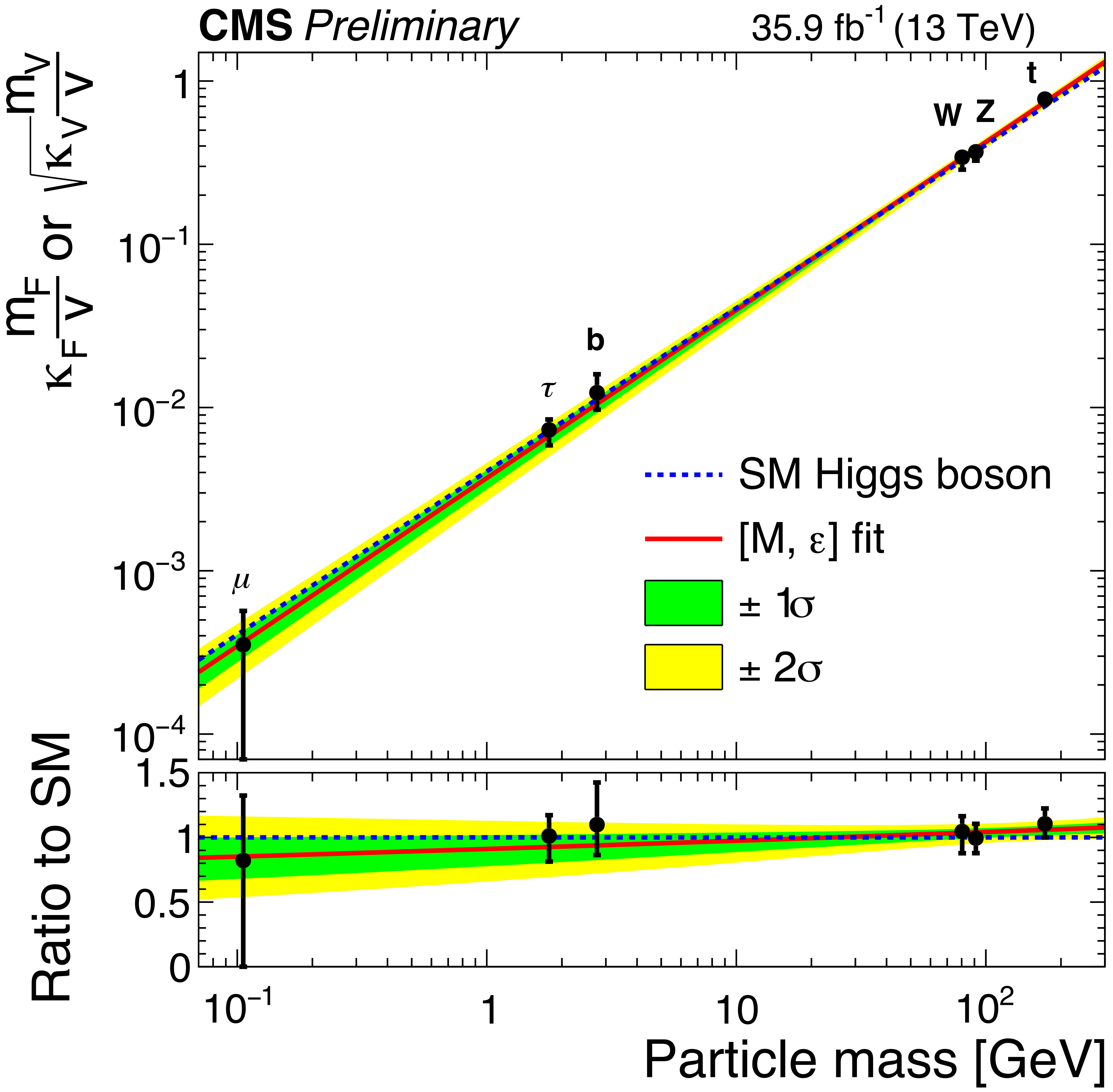

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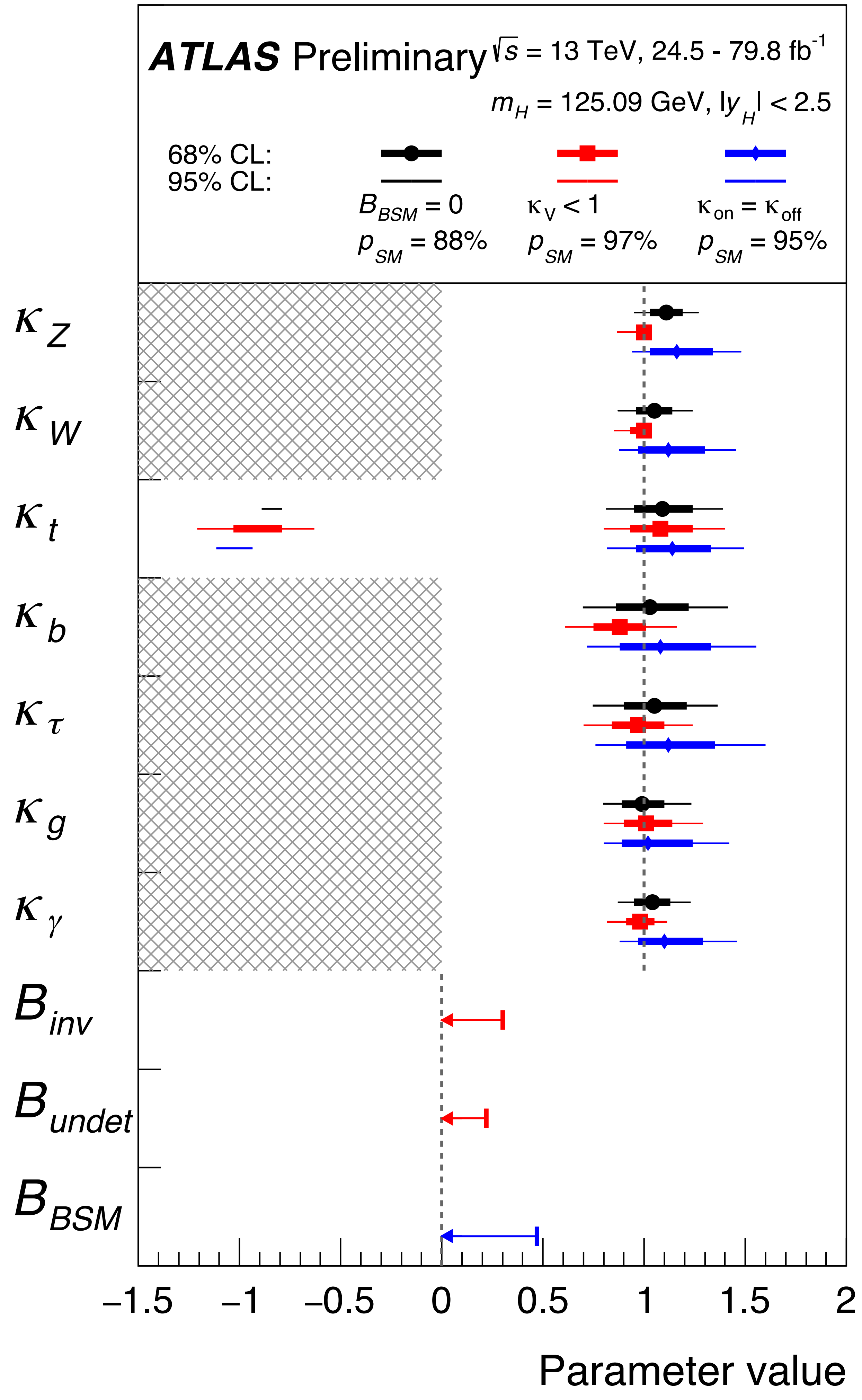

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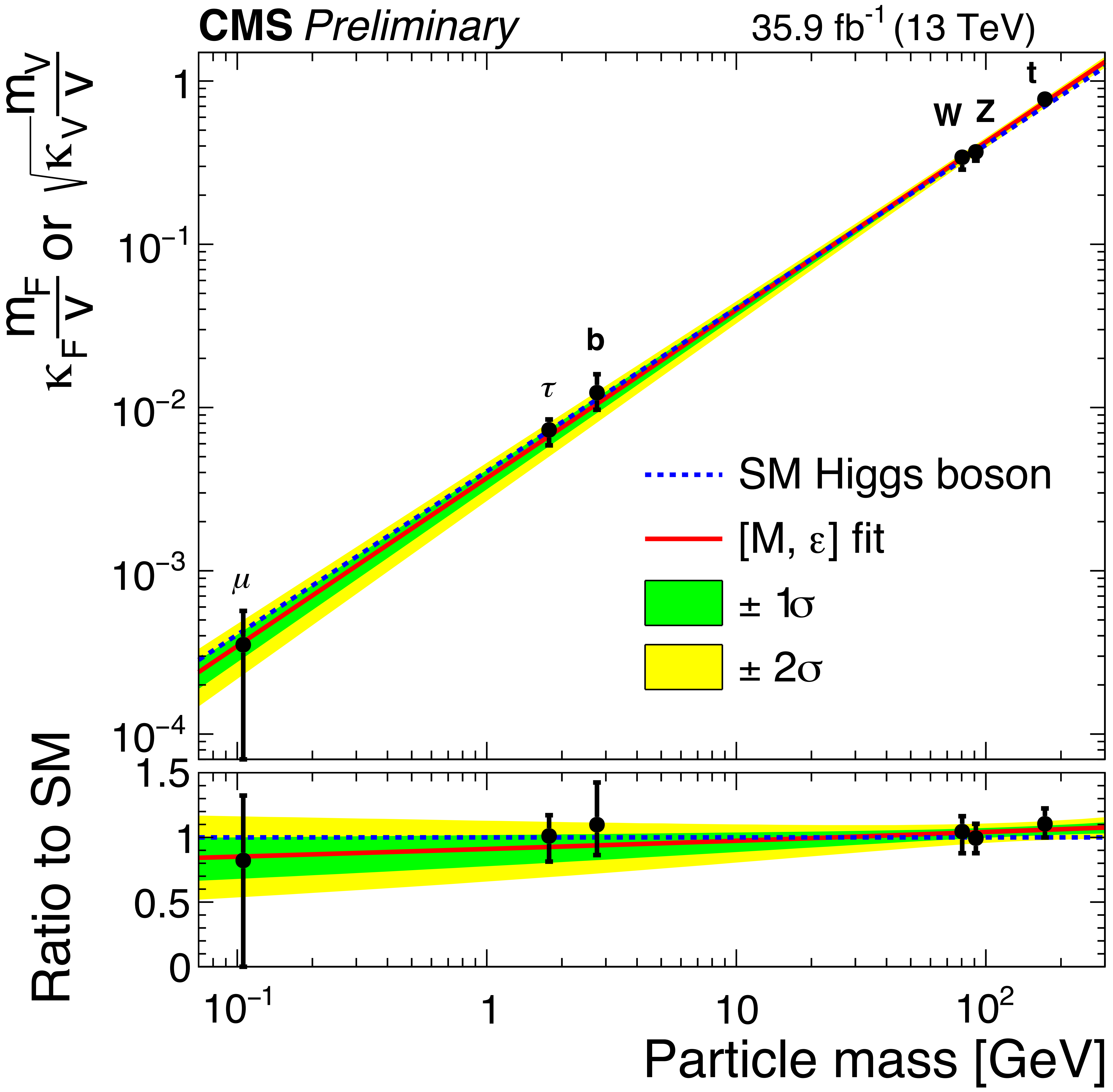

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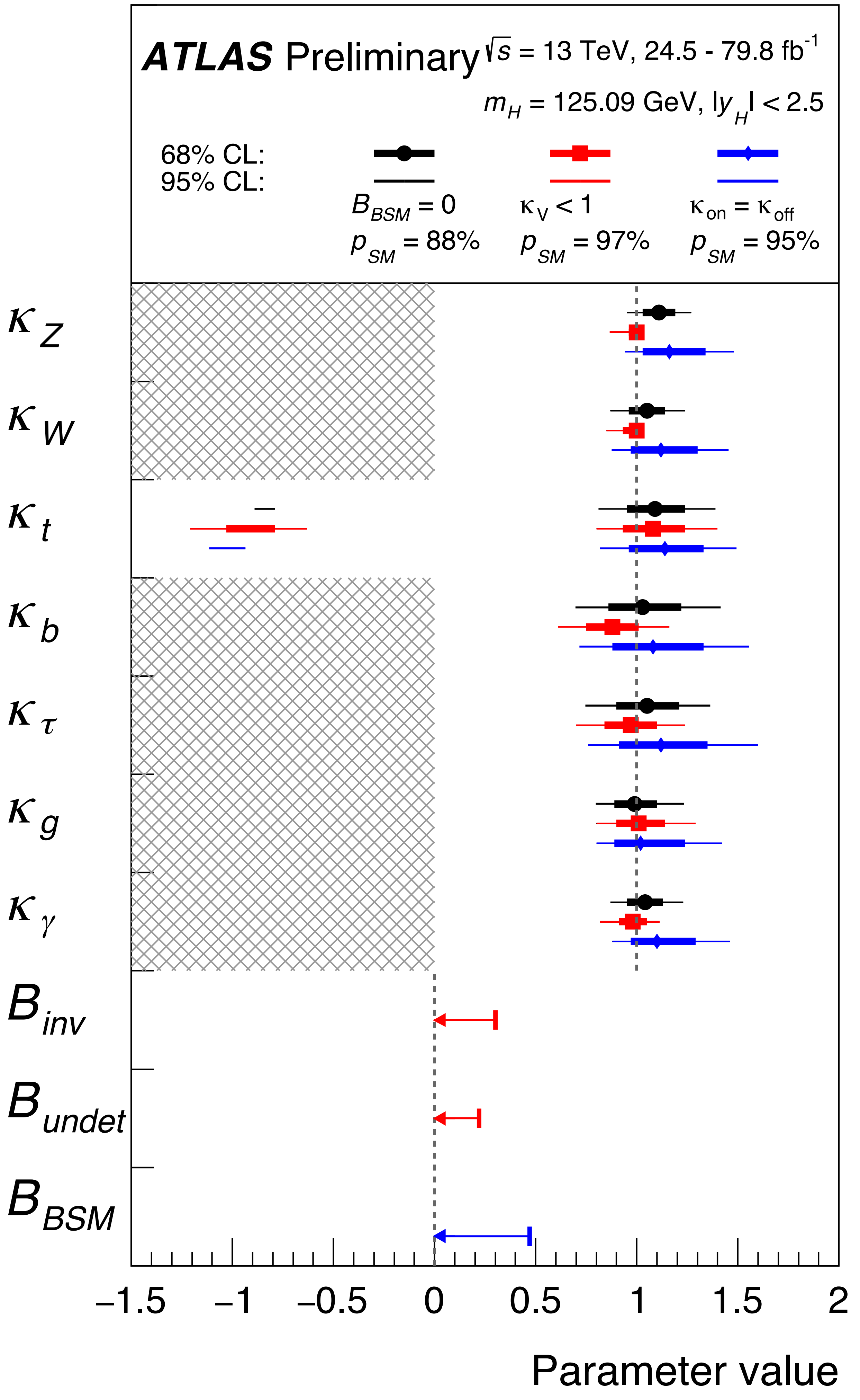

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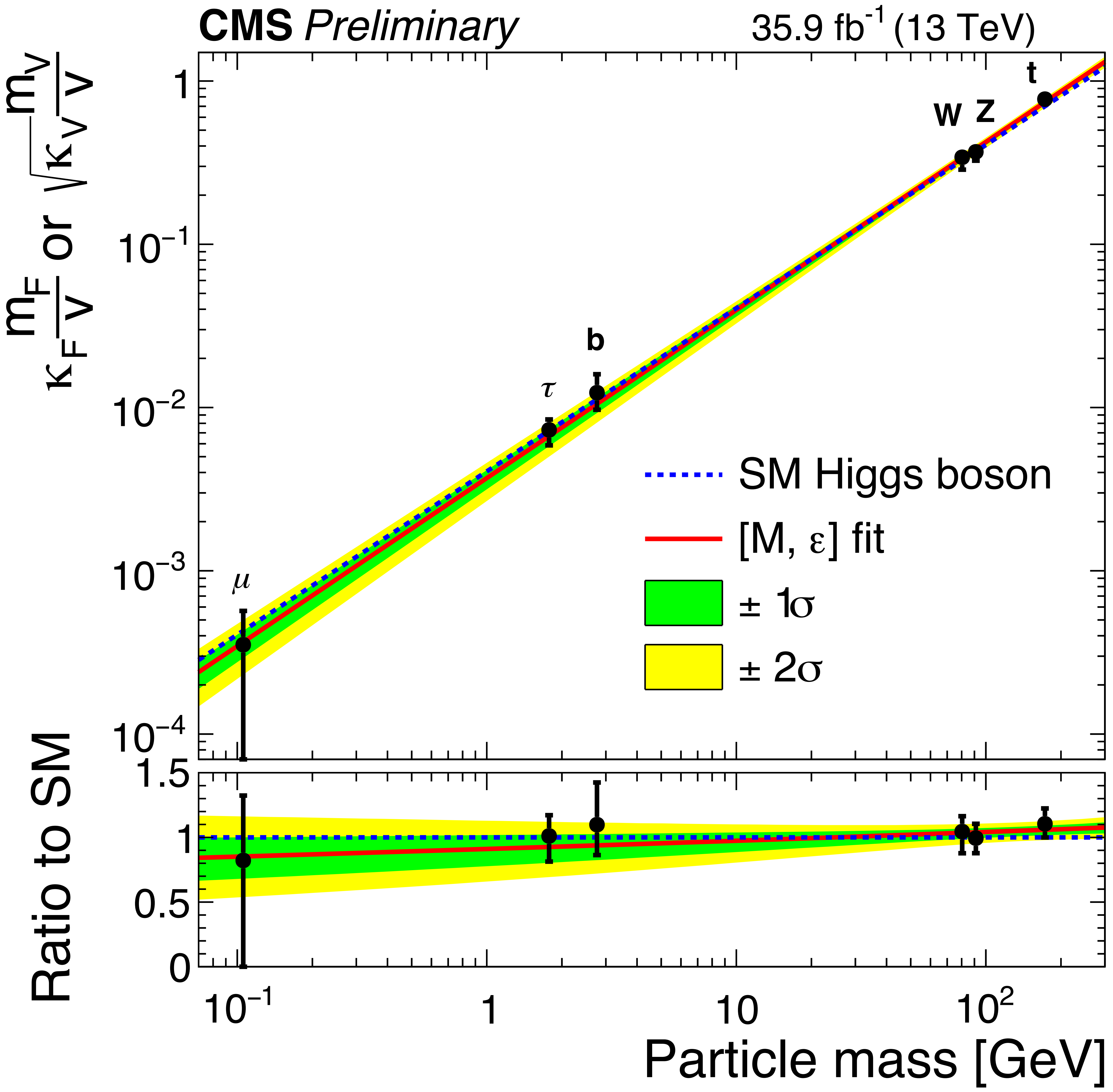

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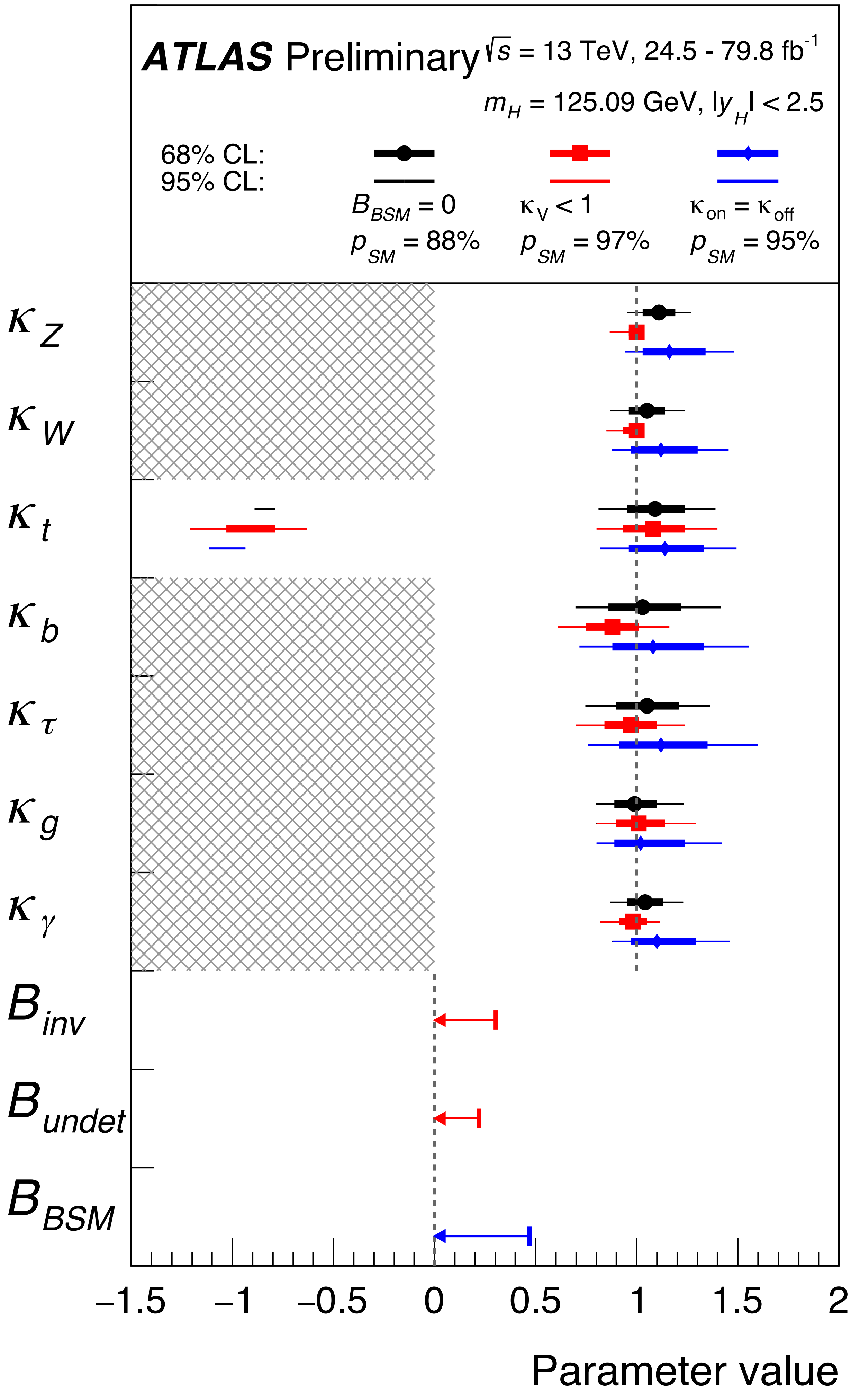

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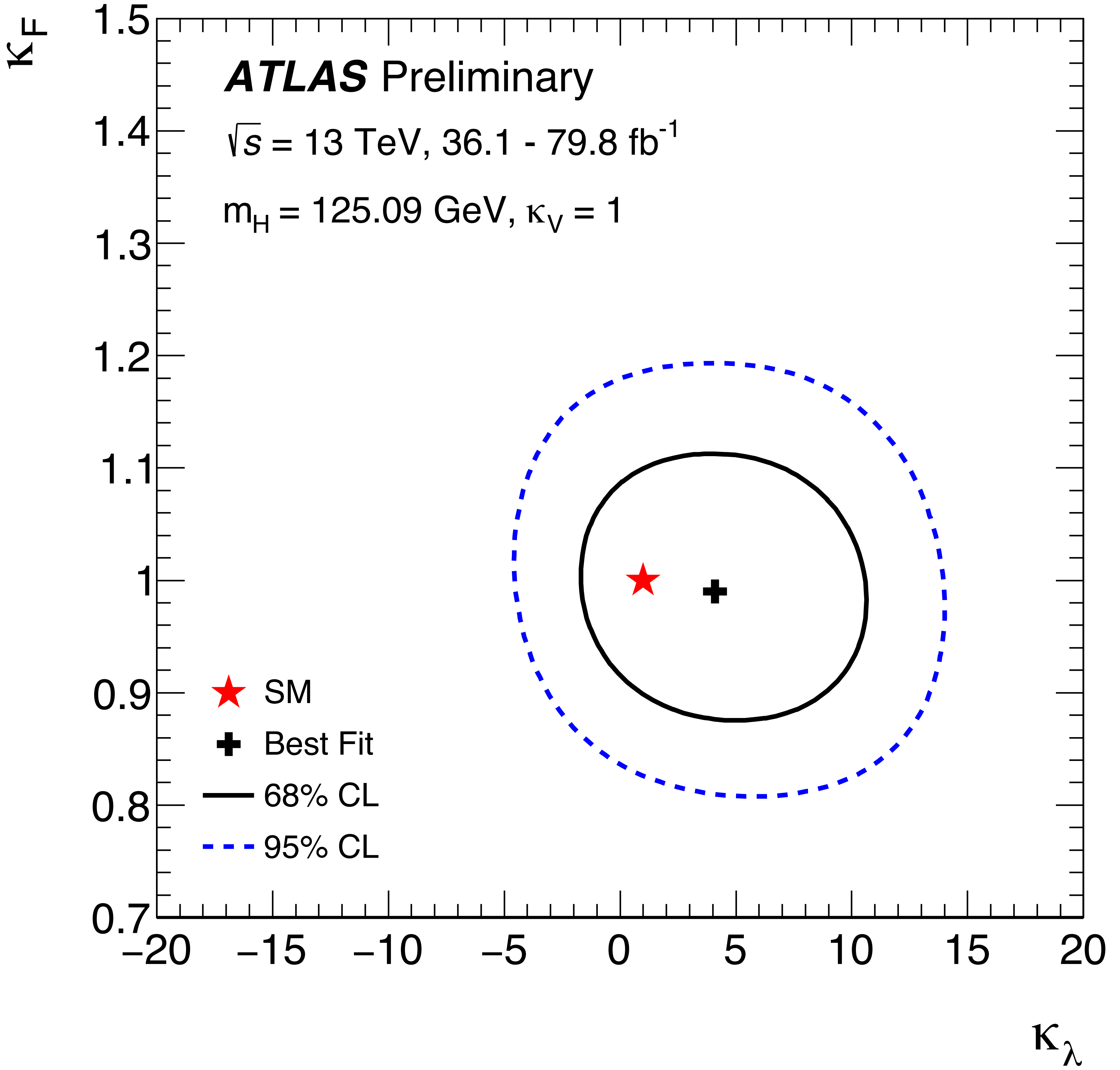
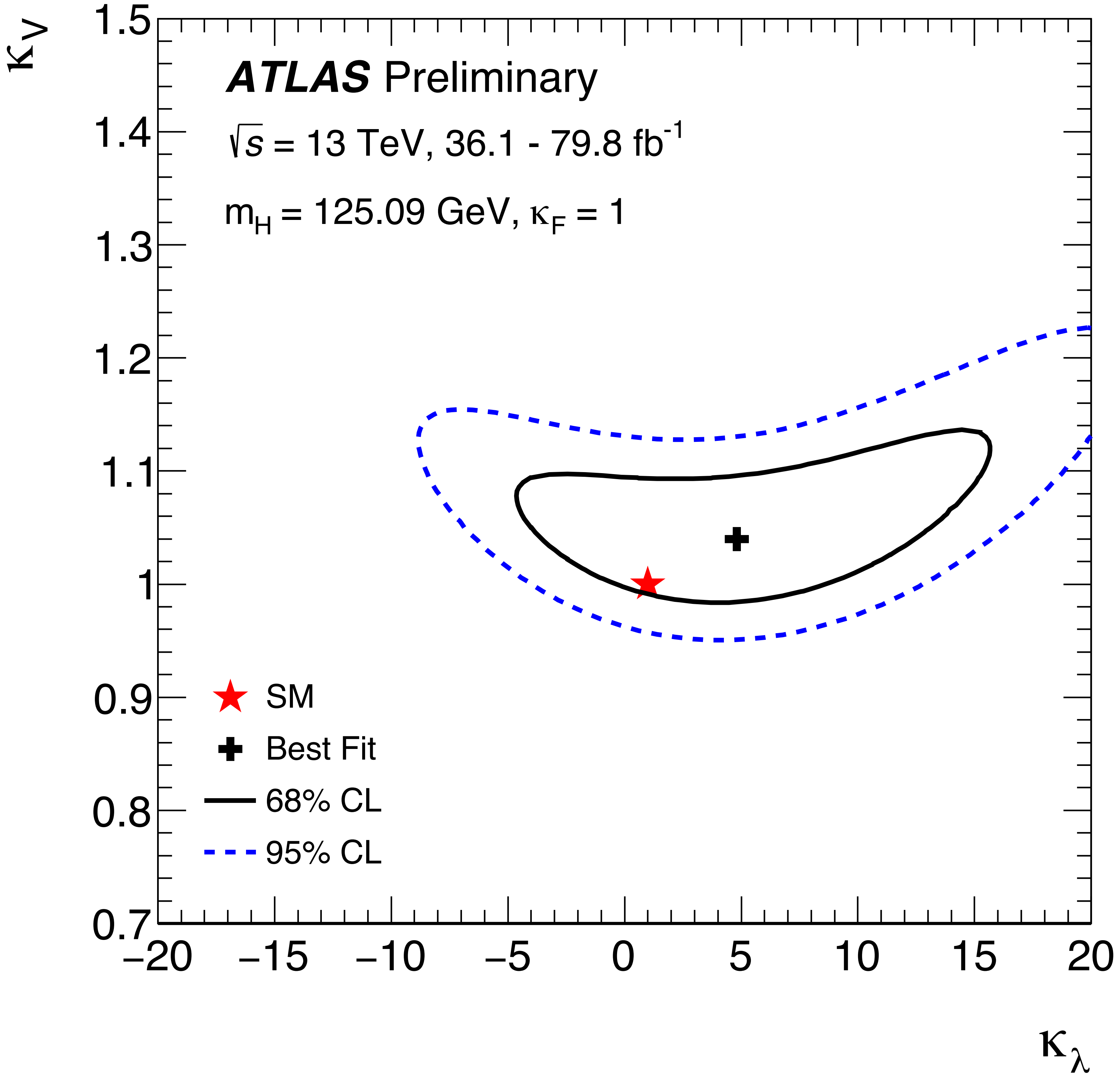
Bounds on Higgs cubic self-coupling

[ATLAS-CONF-2019-009]



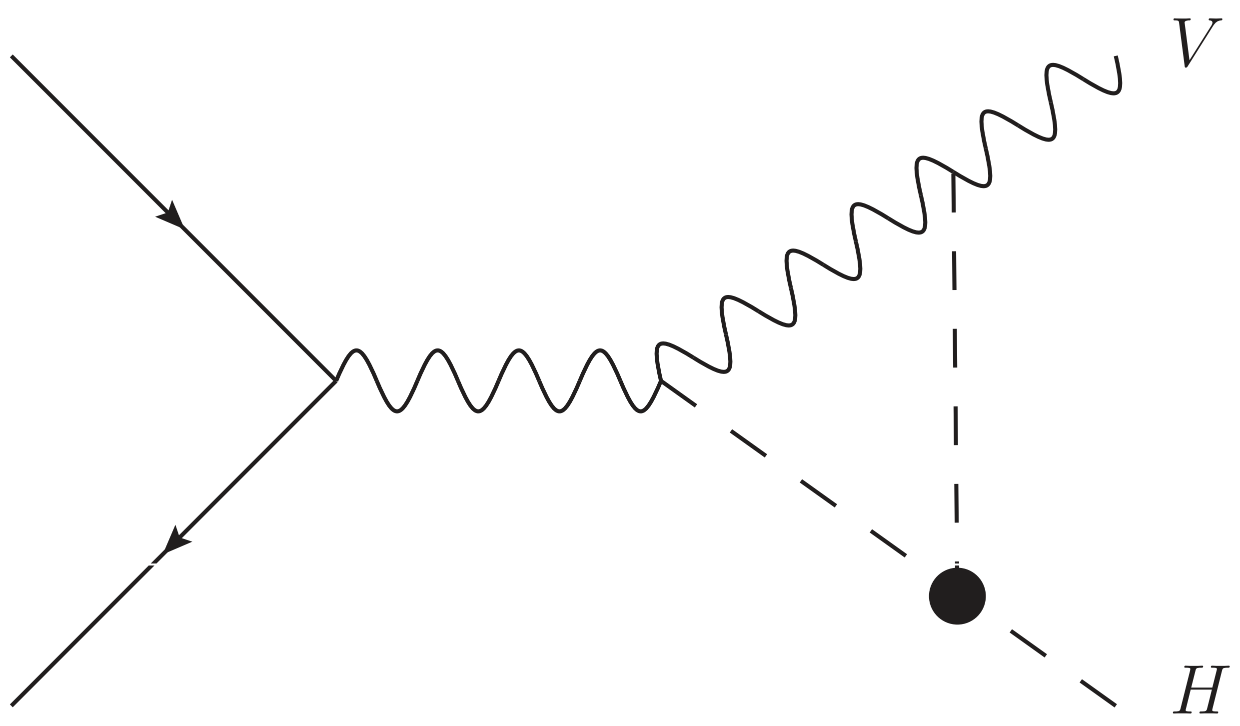


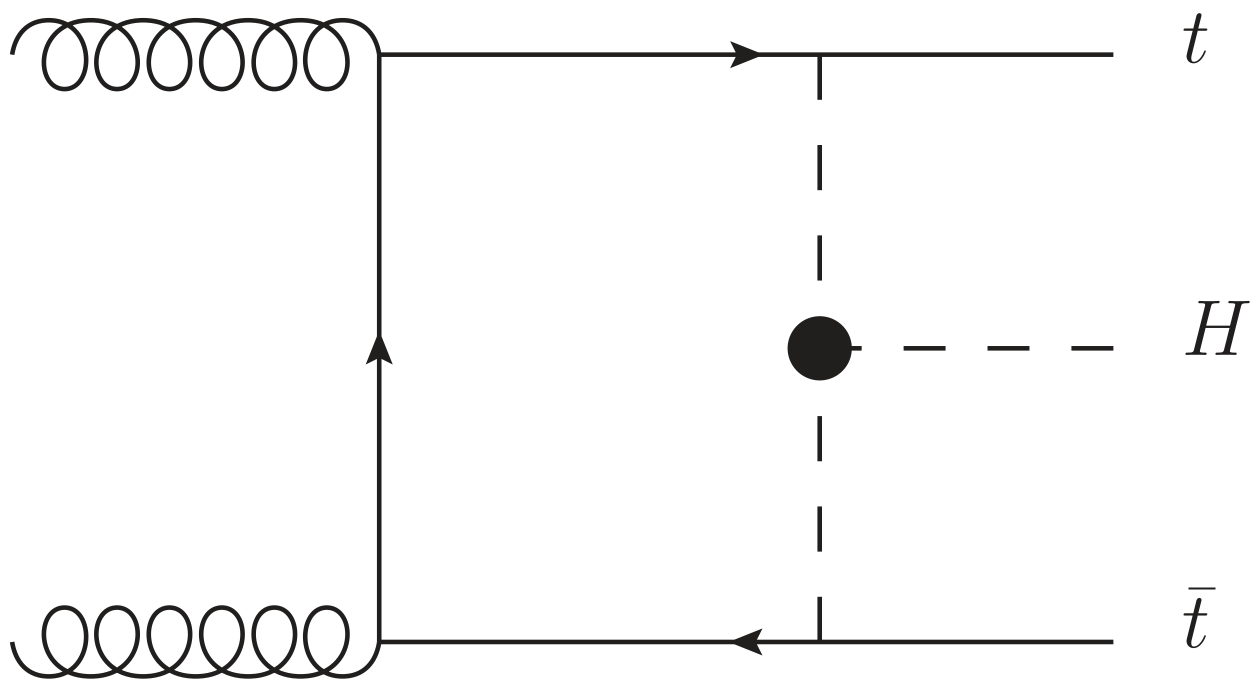
- ✦λ_{HHH} contributes at NLO EW
- ✦Coupling strength:

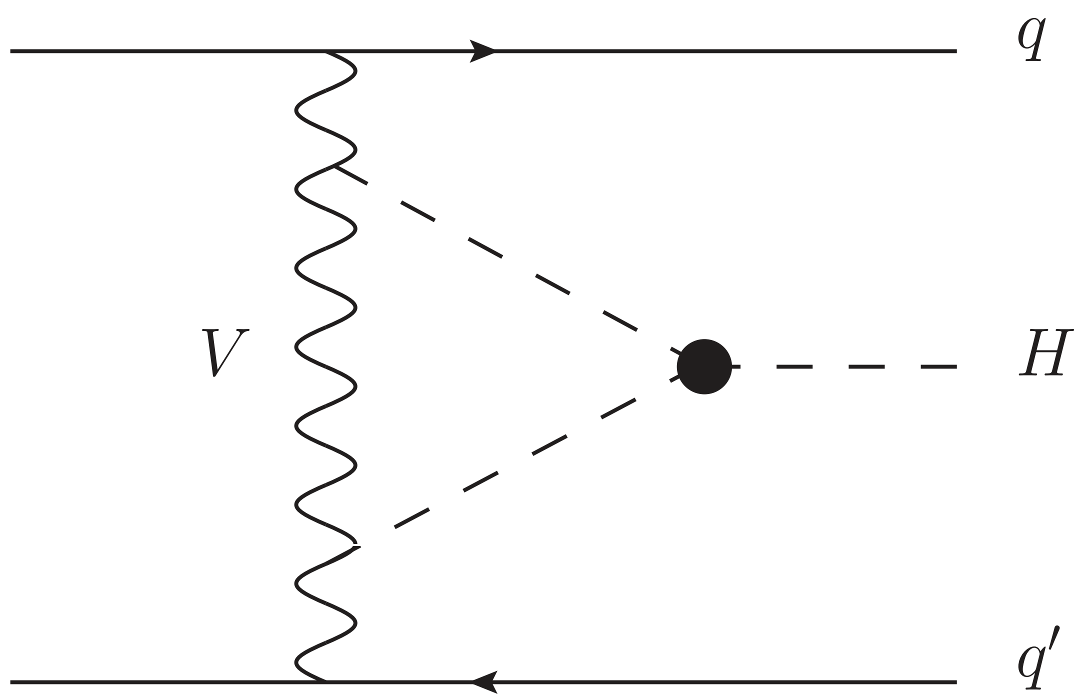
$$\kappa_\lambda = \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$$

- ✦Result:

$$-3.2 < \kappa_\lambda < 11.9 \quad (95\%\ \mathrm{C.L})$$







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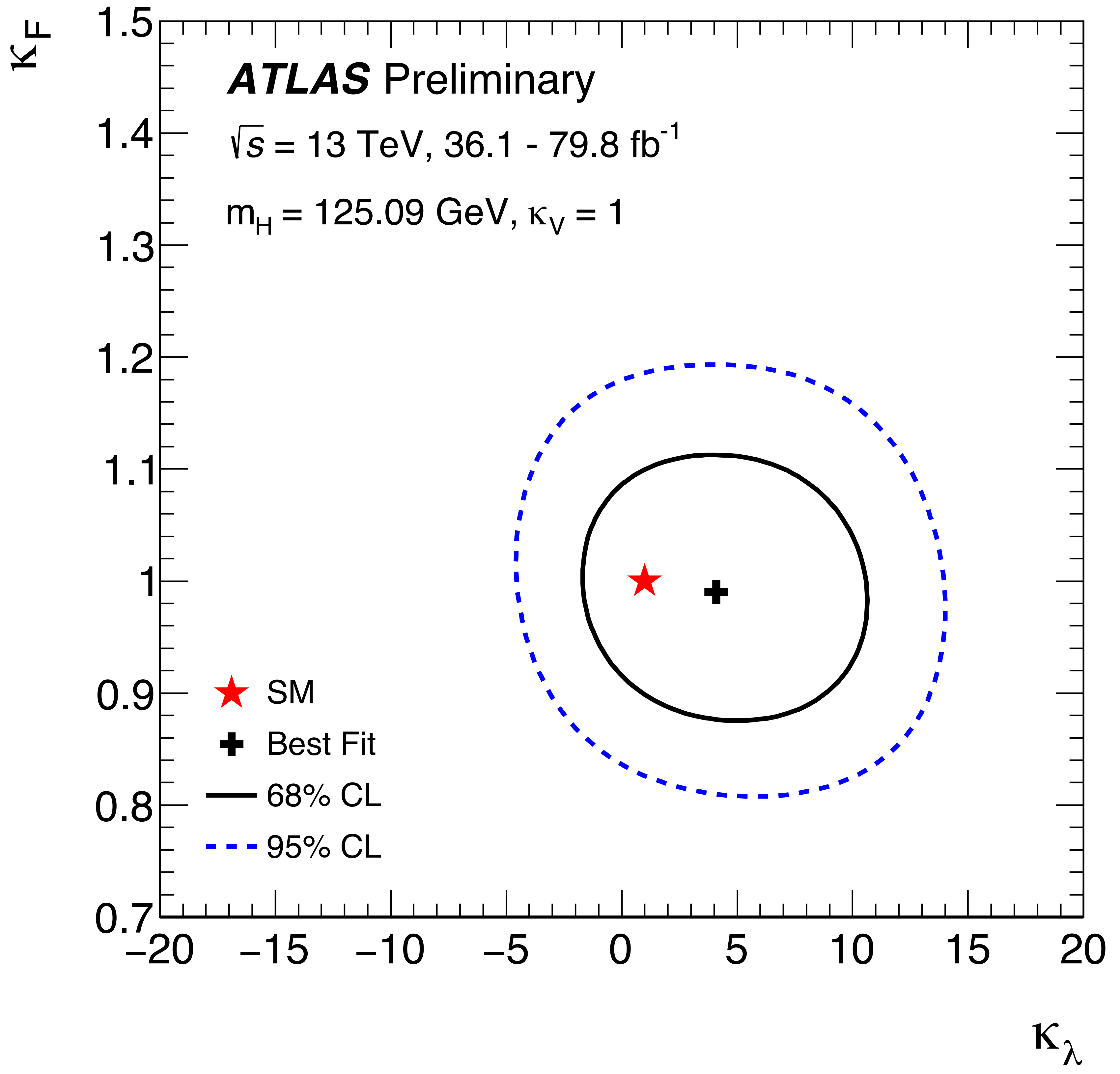

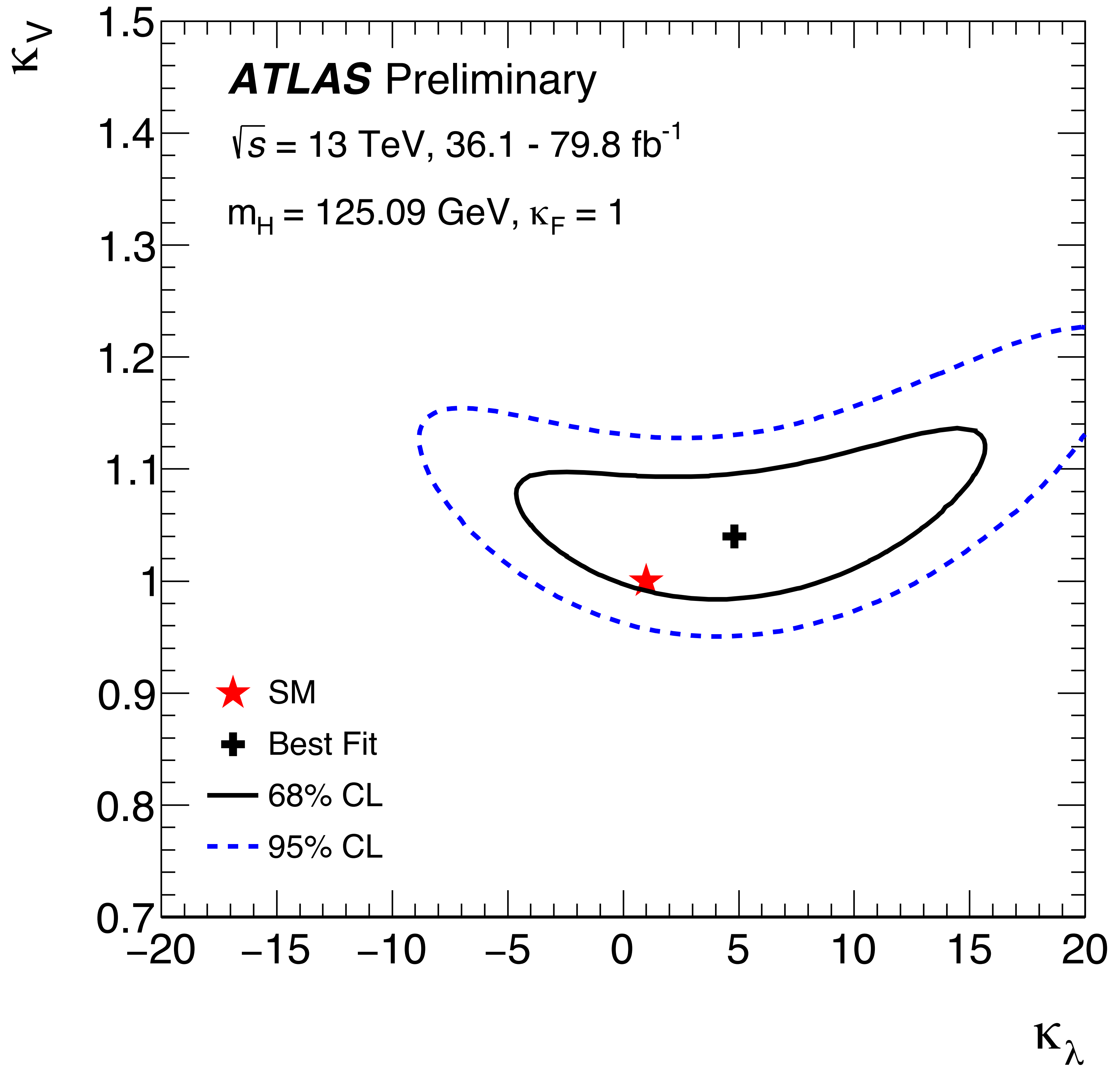

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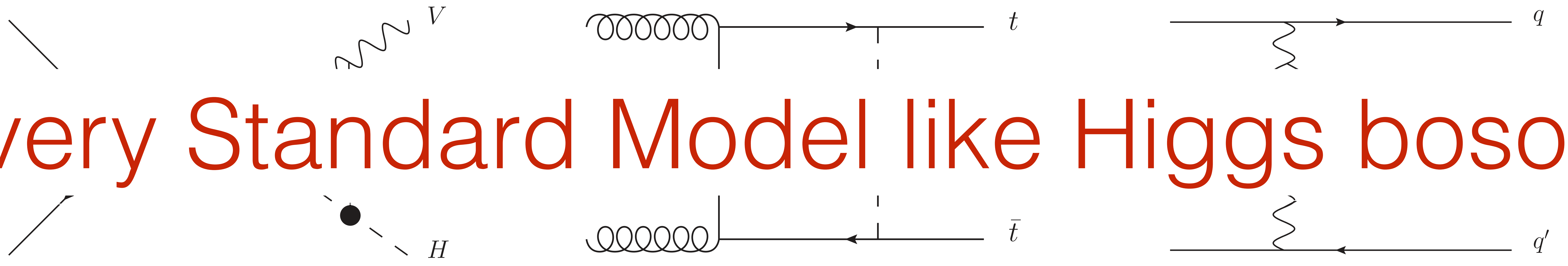

A very Standard Model like Higgs boson.

The Standard Model flaws

- Theoretical:
    - naturalness
    - hierarchy
    - Fermion masses

- Unexplained phenomena:
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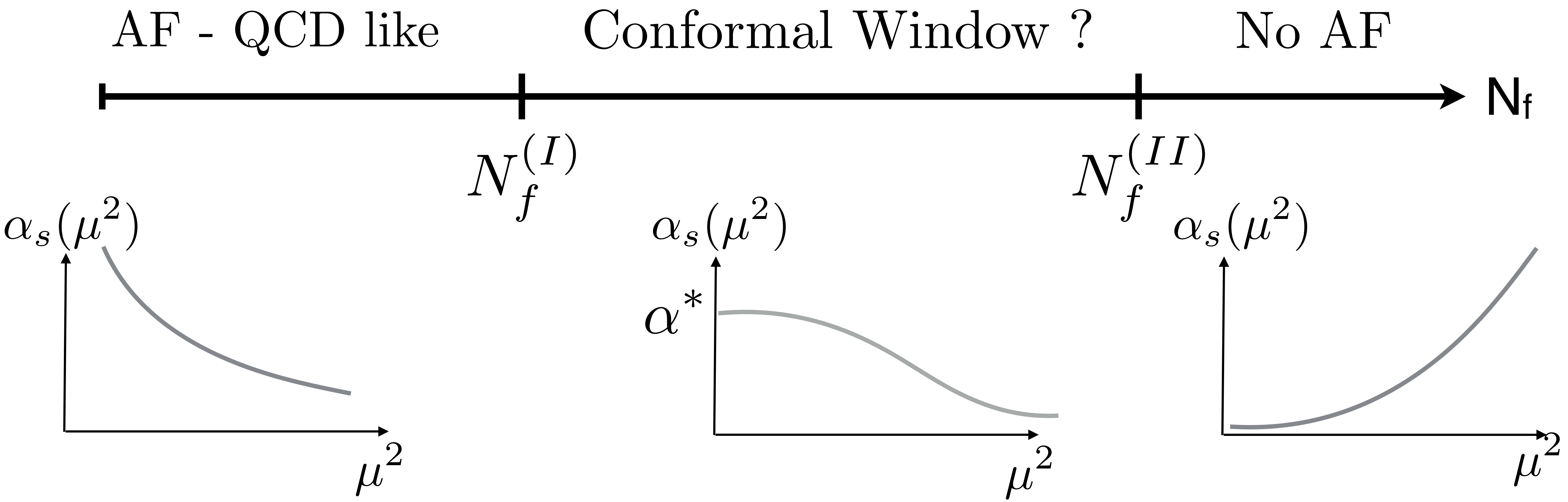
→ Calls for a more quantitative understanding of the non-perturbative dynamics of gauge theories

→ Lattice calculations can provide guidance to model builders and to BSM searches

The theory landscape



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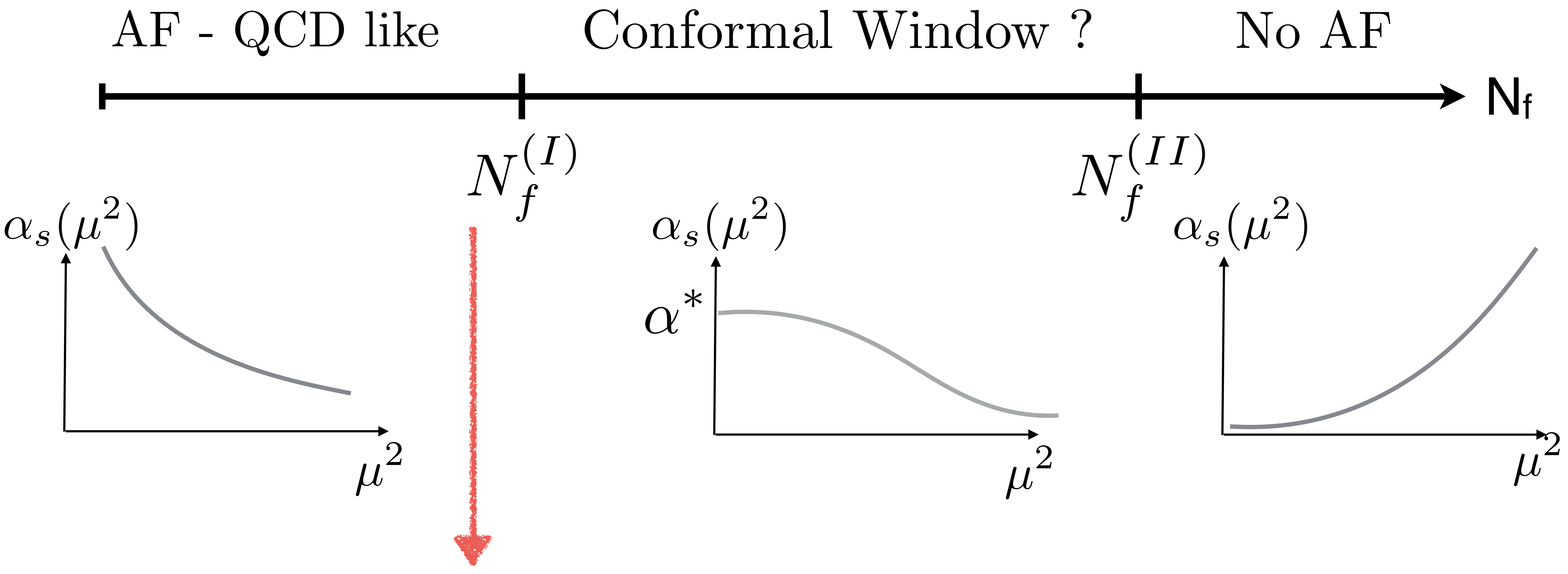

Near-conformal ?

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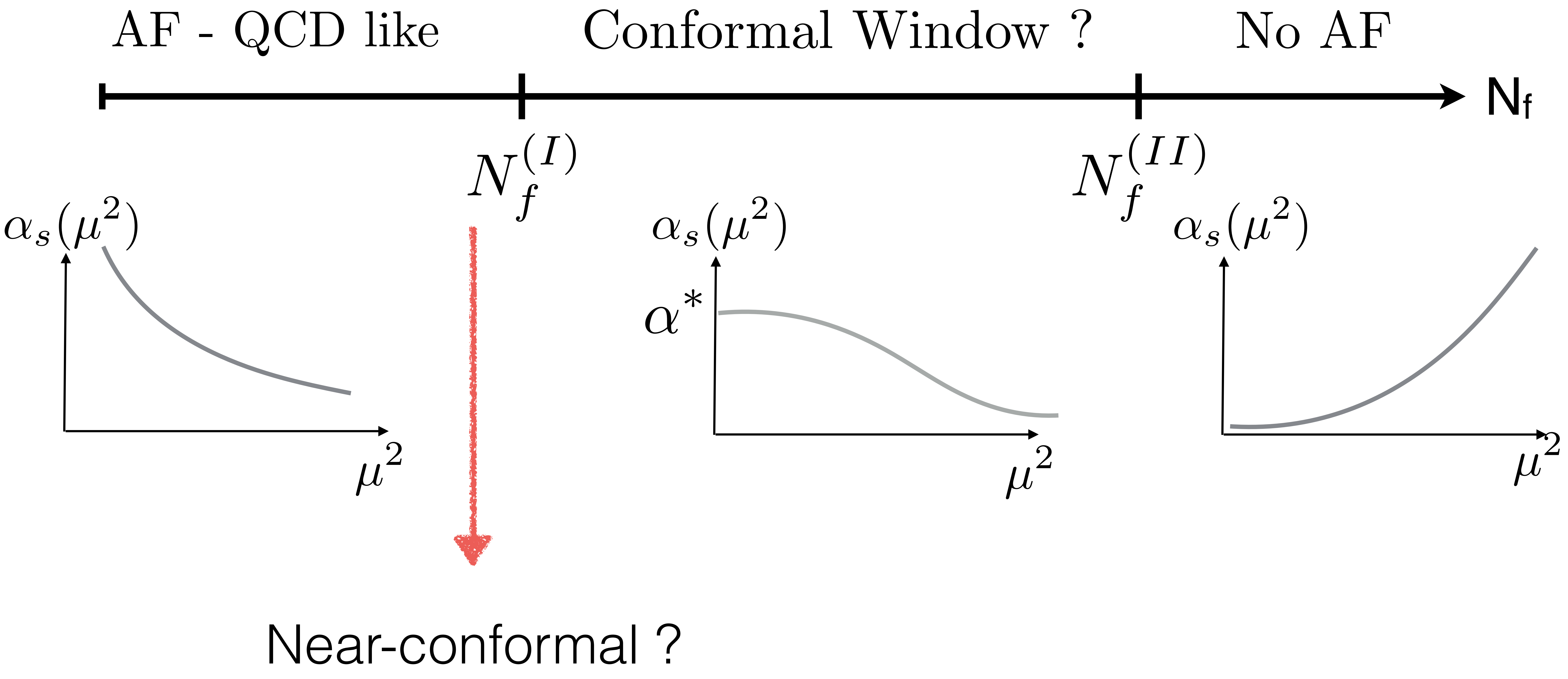

Parameters :

- Gauge group : **SU**, **SO**, **Sp**, **E**,…
- Matter representation : **R**
- # of flavors : $\mathbf{N_f}$

Strongly interacting electroweak symmetry breaking models

$$\begin{array}{lll} \Lambda_{\rm NP}: & \mathcal{L}^{\rm (SM-Higgs)}_{\rm massless} & + \quad \mathcal{L}_{\rm SCT} \\ \Big\downarrow & & \\ \Lambda_{\rm EW}: & \mathcal{L}^{\rm (SM)}_{\rm massless} & + \, \mathcal{O}\left(\dfrac{1}{\Lambda_{\rm NP}}\right) \end{array}$$

$\longrightarrow$ the flavor sector requires new interactions at the New Physics scale.

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Near-conformal - dilaton-like scenario

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Pseudo-Nambu-Goldstone bosons scenario

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- W and Z: Standard Model like.
- Using $\xi = v_{EW}$^2/f_{PS}^2 ; $\kappa_V = 1-\xi/2 + O(\xi^2)$

Outline

* Near-conformal dynamics.
* Pseudo-Nambu-Goldstone bosons.
* Progress in the theory landscape & alternative mechanisms.

Near-conformal dynamics on the lattice

Evidence for a light scalar

- increasing evidence that near-conformal dynamics give rise to a light scalar state:

  - SU(3) with N_f=8 fundamental fermions.

    [Lattice Strong Dynamics Collaboration arXiv:1807.08411]

  - SU(3) with Nf=2 sextet fermions.

    [Fodor, Holland, Kuti, Wong arXiv:1901.06324]
    [LatKMI Collaboration arXiv:1610.07011]

  - SU(3) 4 light + 8 heavy fundamental flavors.

    [Brower, Hasenfratz, Rebbi, Weinberg, Witzel arXiv:1609.01401]

  - SU(2) with Nf=1 or 2 adjoint.

    [Del Debbio, Lucini, Patella, Pica, Rago arXiv:1512.08242]
    [Athenodorou, Bennett, Bergner, Elander, Lin, Lucini, Piai arXiv:1702.06452]

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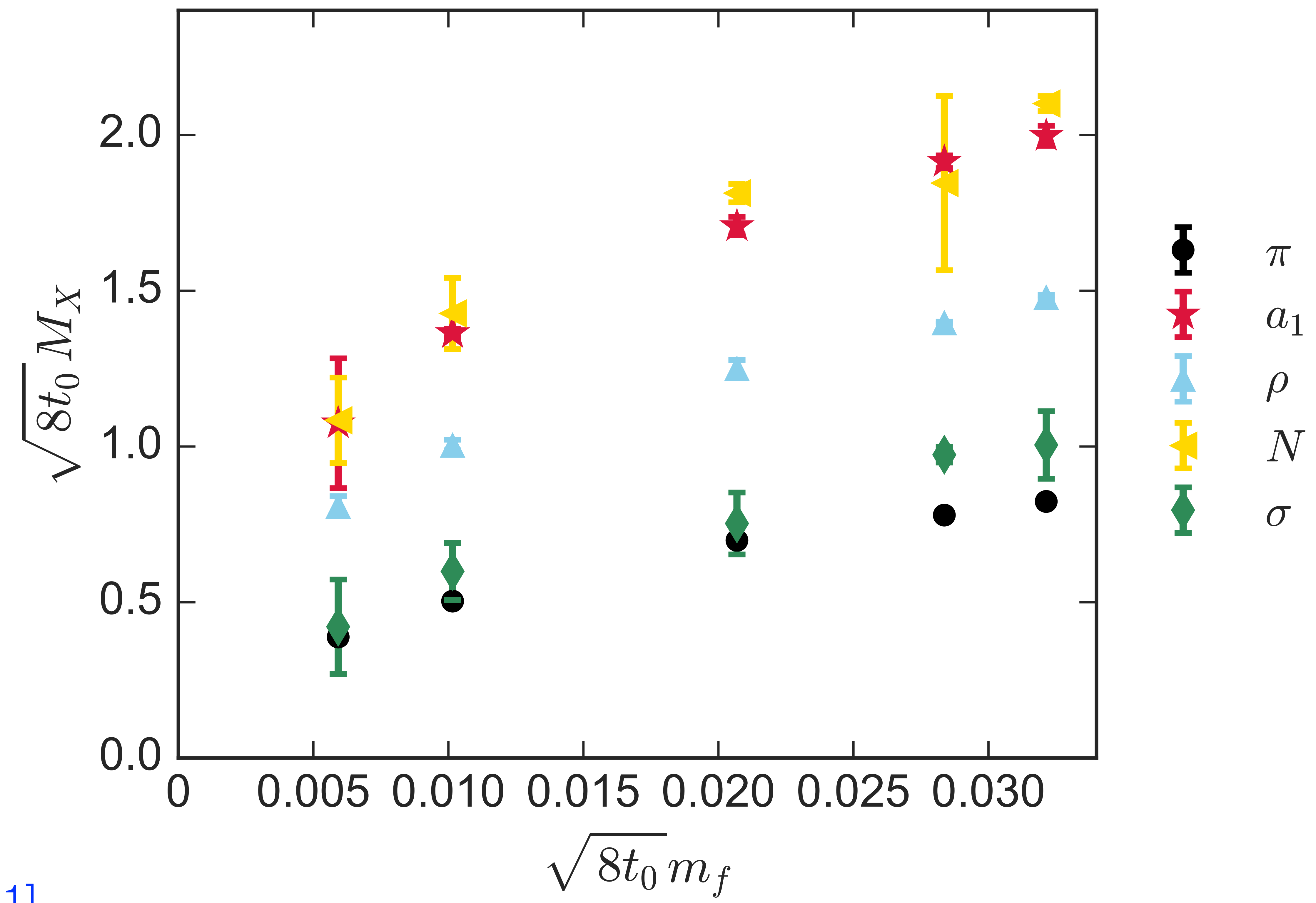

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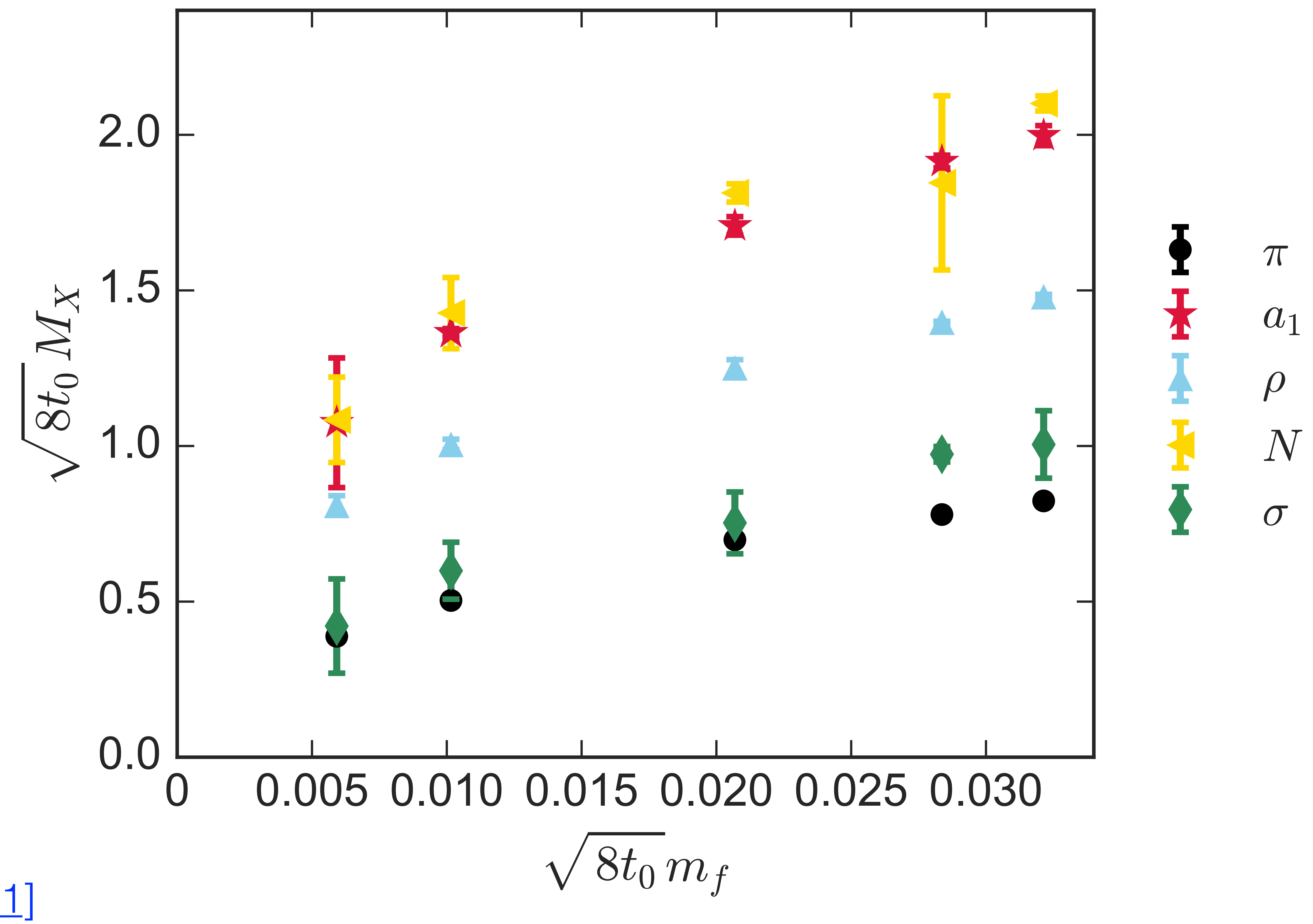


What is the effective field theory description?

Effective Field theories for near-conformal dynamics.

- Several candidate EFTs :
  - A bound state model for a light scalar

    [Holdom&Koniuk arXiv:1704.05893]

  - Chiral perturbation theory with a dilatonic meson

    [Goldberger, Grinstein, Skiba arXiv:0708.1463]
    [Matsuzaki, Yamawaki arXiv:1311.3784]
    [Golterman, Shamir arXiv:1603.04575]
    [Appelquist, Ingoldby, Piai, arXiv:1702.04410]

  - Linear Sigma EFT for Nearly Conformal Gauge Theories

    [Lattice Strong Dynamics collaboration arXiv:1809.02624]

  - The large-mass regime of the dilaton-pion low-energy effective theory

    [Golterman, Shamir arXiv:1805.00198 arXiv:1810.05353]

  - Linear sigma model for multiflavor gauge theories

    [De Floor, Gustafson, Meurice arXiv:1807.05047]

  - Proposition of an alternative paradigm: complex CFT

[J. Kuti, Thu 14:20]

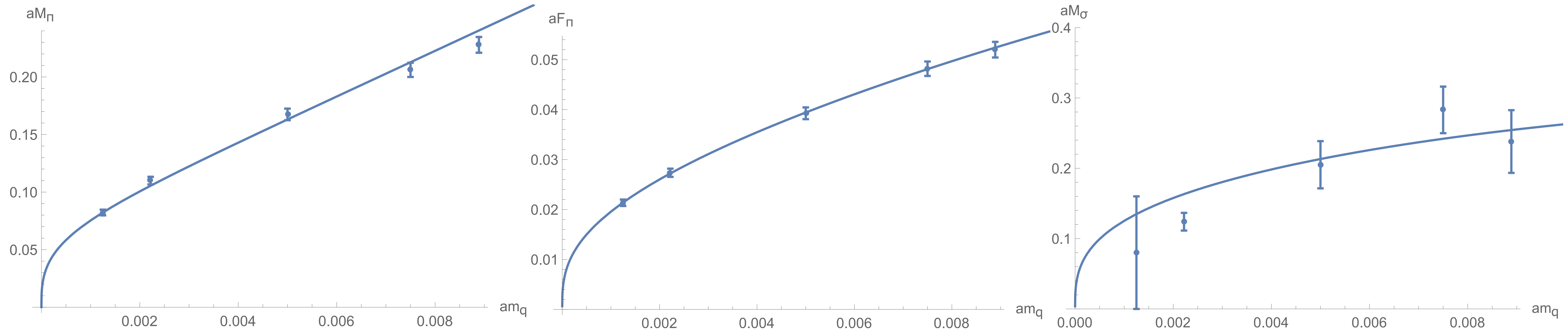
Near-conformal dynamics: SU(3) with Nf=8 fundamental fermions

[G. Fleming (LSD collaboration), Thu 16:30]

- Linear Sigma Model fits : good description of the data.

Preliminary

Lattice units
χ^2/dof=1.30



- Linear Sigma Model EFT expressions for pi-pi scattering lengths and effective ranges, scalar decay constants have been derived: lattice calculations underway.

Near-conformal dynamics: SU(3) with N_f=8 fundamental fermions

[M. Golterman, Thu 16:30]

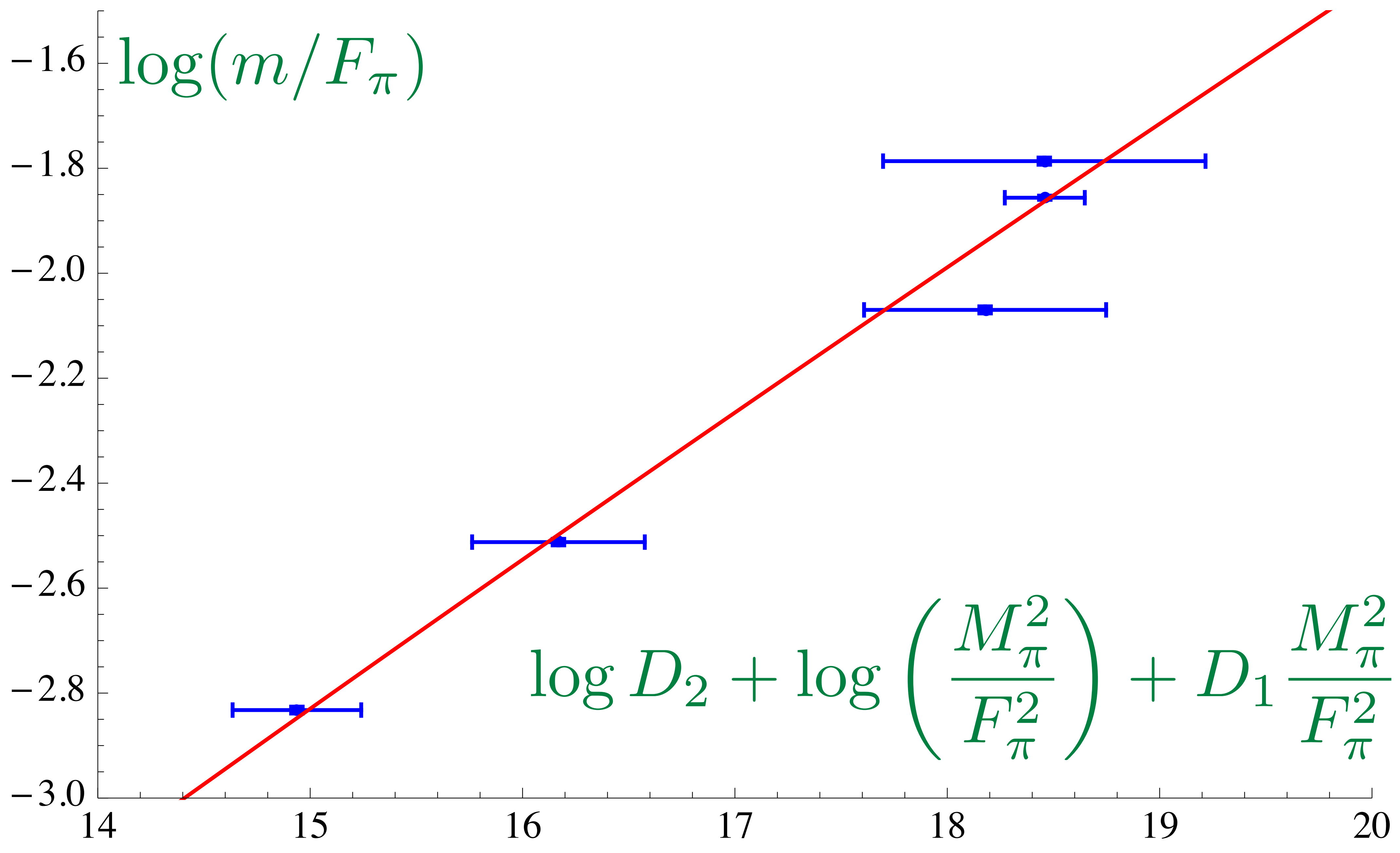
- Dilaton-EFT has a "large mass" regime : systematic expansion when mass is not small relative to the confinement scale.

[M. Golterman and Y. Shamir arXiv:1805.00198 arXiv:1810.05353]

- In that regime physical quantities exhibit hyperscaling relations to leading order.

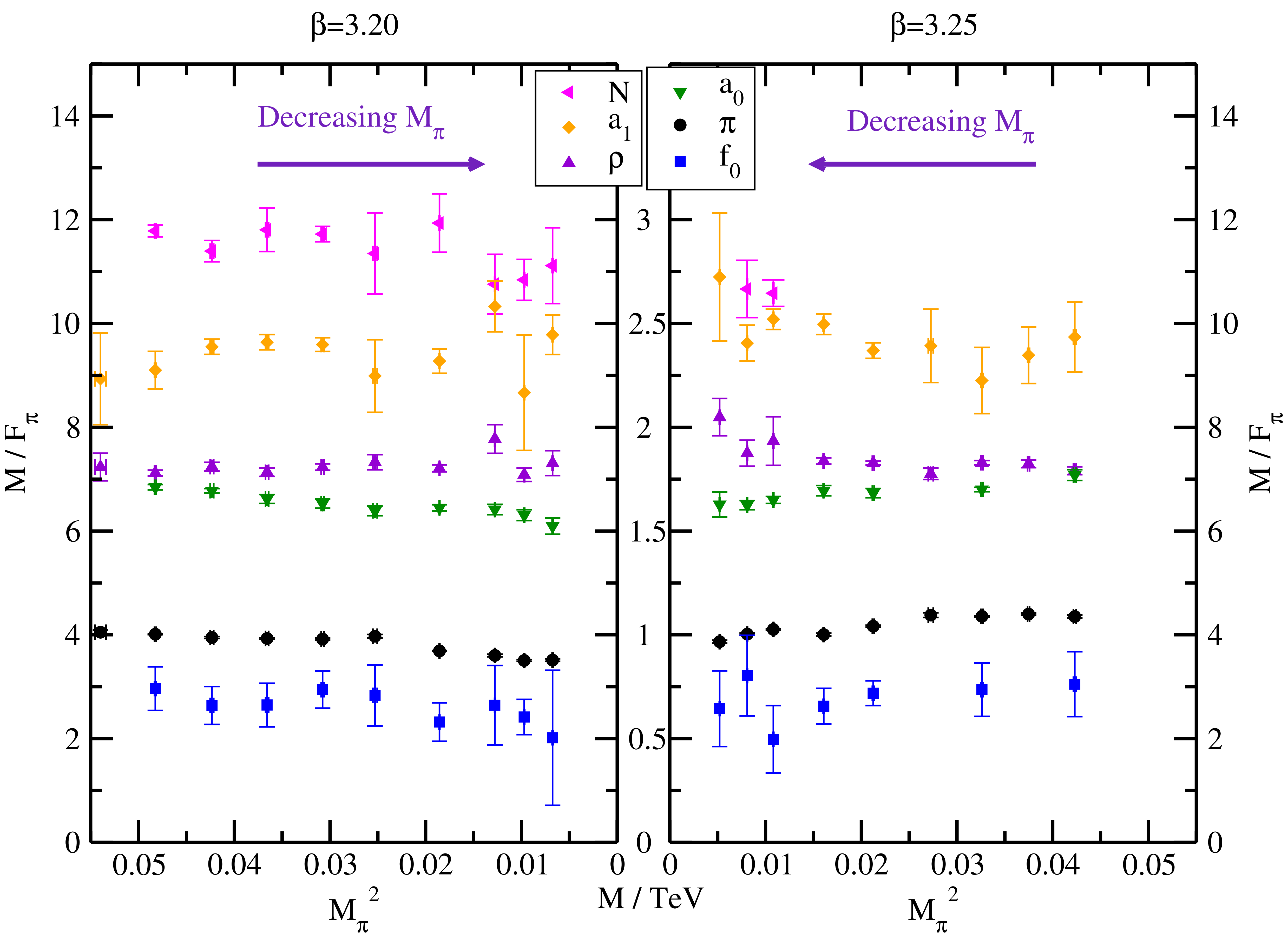
- Quantitative tests of the LO Dilaton-EFT.

- Confirms that the LSD data are in the large-mass regime of the Dilaton-EFT.



SU(3) with N_f=2 fermions in the symmetric representation

- Dilaton hypothesis with two typical dilaton potentials.
- Infinite volume extrapolation of m_{PS} and f_{PS}.
- f_d/f_{PS} and m_d/m_{PS} are very sensitive to the noisy 0^{++}.



[R. Wong (LatHC), Thu 14:40]

Mass-split model: 4 light + 6 heavy fundamental flavors of SU(3)

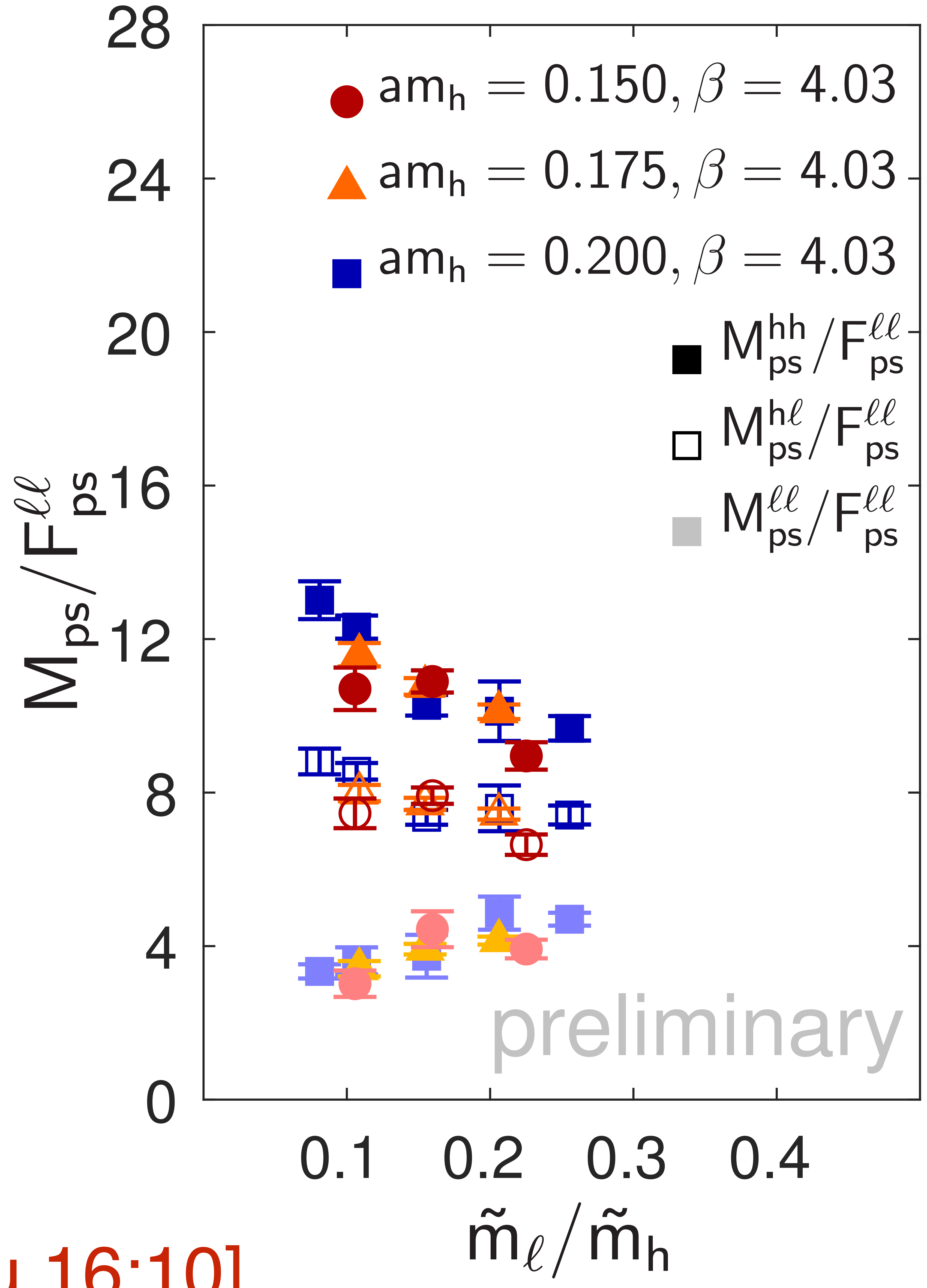
- Large separation of scale needed for composite models.
- Promising composite Higgs model are chirally broken in the IR but conformal in the UV.
- Mass-split models can feature a light dilaton or a PNGB scenarios.

[Luty,Okui arXiv:0409274]
[Dietrich Sannino arXiv:0611341]
[Vecchi arXiv:1506.00623]
[Ferretti, Karateev arXiv:1312.5330]

- UV: driven by IRFP.
- IR: 6 heavy flavors decouple → χSB.
- Hyperscaling: dimensionless ratio = $f(m_l/m_h)$.

[Hasenfratz, Rebbi, Witzel arXiv:1609.01401]

- Spectrum: light-light, light-heavy, heavy-heavy states.



[O. Witzel (LSD collaboration), Thu 16:10]

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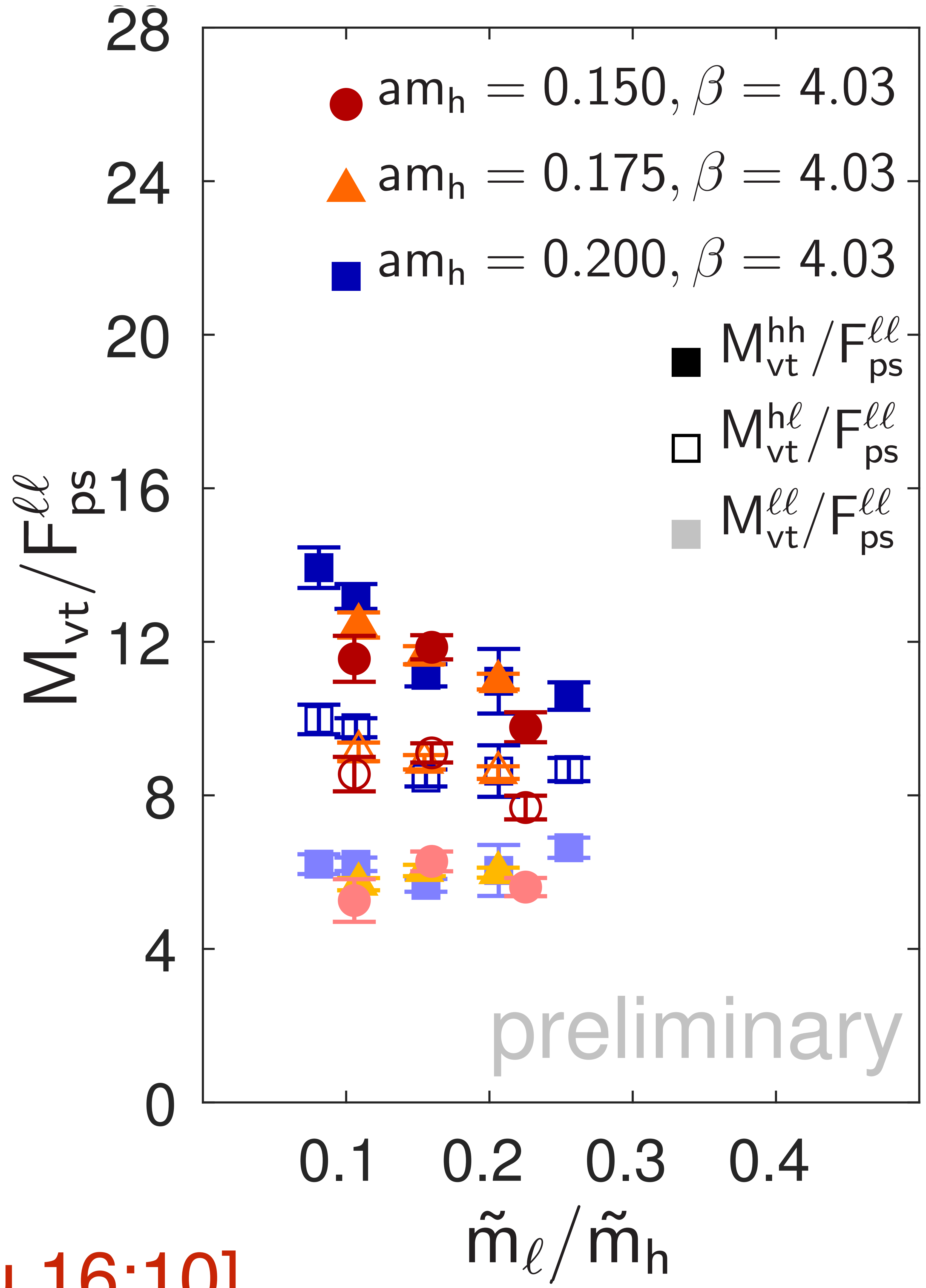

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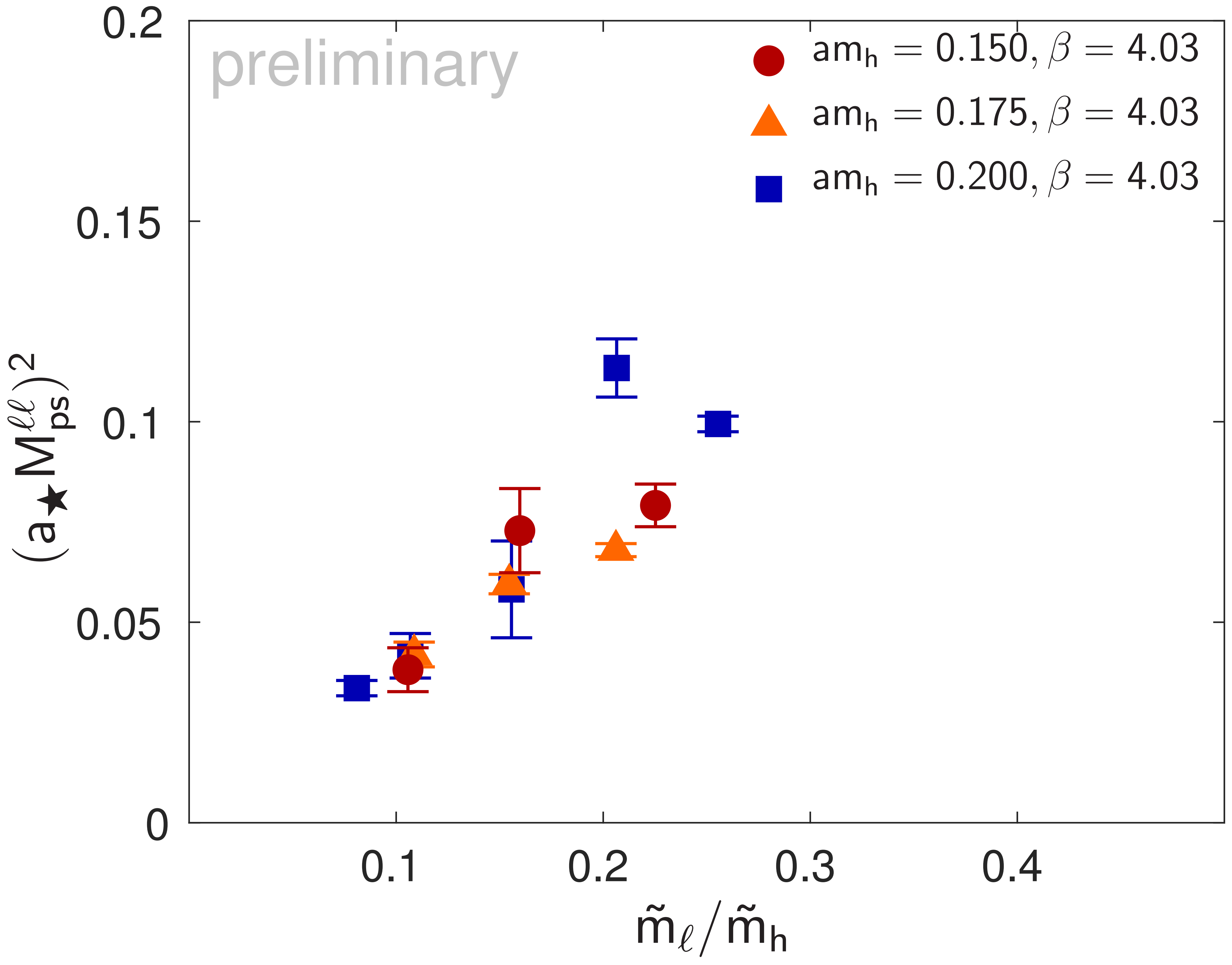

[O. Witzel (LSD collaboration), Thu 16:10]

Pseudo-Nambu-Goldstone Boson Higgs

Pseudo-Nambu-Goldsone Higgs “framework”

[D. B. Kaplan and H. Georgi, Phys. Lett. B 136, 183 (1984)]
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- Strongly coupled gauge theory featuring χSB pattern $G \to H$
- Gauge the new fermions Q under $SU(3)_C \times SU(2)_L \times U(1)_Y$: 4 of the PNGBs are interpreted as the Higgs doublet.
- Write down the EFT: ξ parametrises the hierarchy between the weak scale and the strong sector spontaneous symmetry breaking scale.
- Deal with the top: next slide.

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Pseudo-Nambu-Goldstone Higgs: adding the top

Need an another sector at a scale Λ_{UV}.

- Approach 1:
  - At Λ_{NP} add $\frac{1}{\Lambda_{UV}^{d_O-1}}\bar{q}qO_{SCT}$

- Approach 2: "Partial Compositeness" [Kaplan, Nucl. Phys. B365, 259 (1991)]
  - At Λ_{NP} add $\frac{1}{\Lambda_{UV}^{d_O-5/2}}\bar{q}^a O^a_{SCT}$

- Generic couplings: $\kappa_V = 1 + \mathcal{O}(\xi)$

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  - Requires fermionic bound states charged under $SU(3)_c$.

- Generic couplings:

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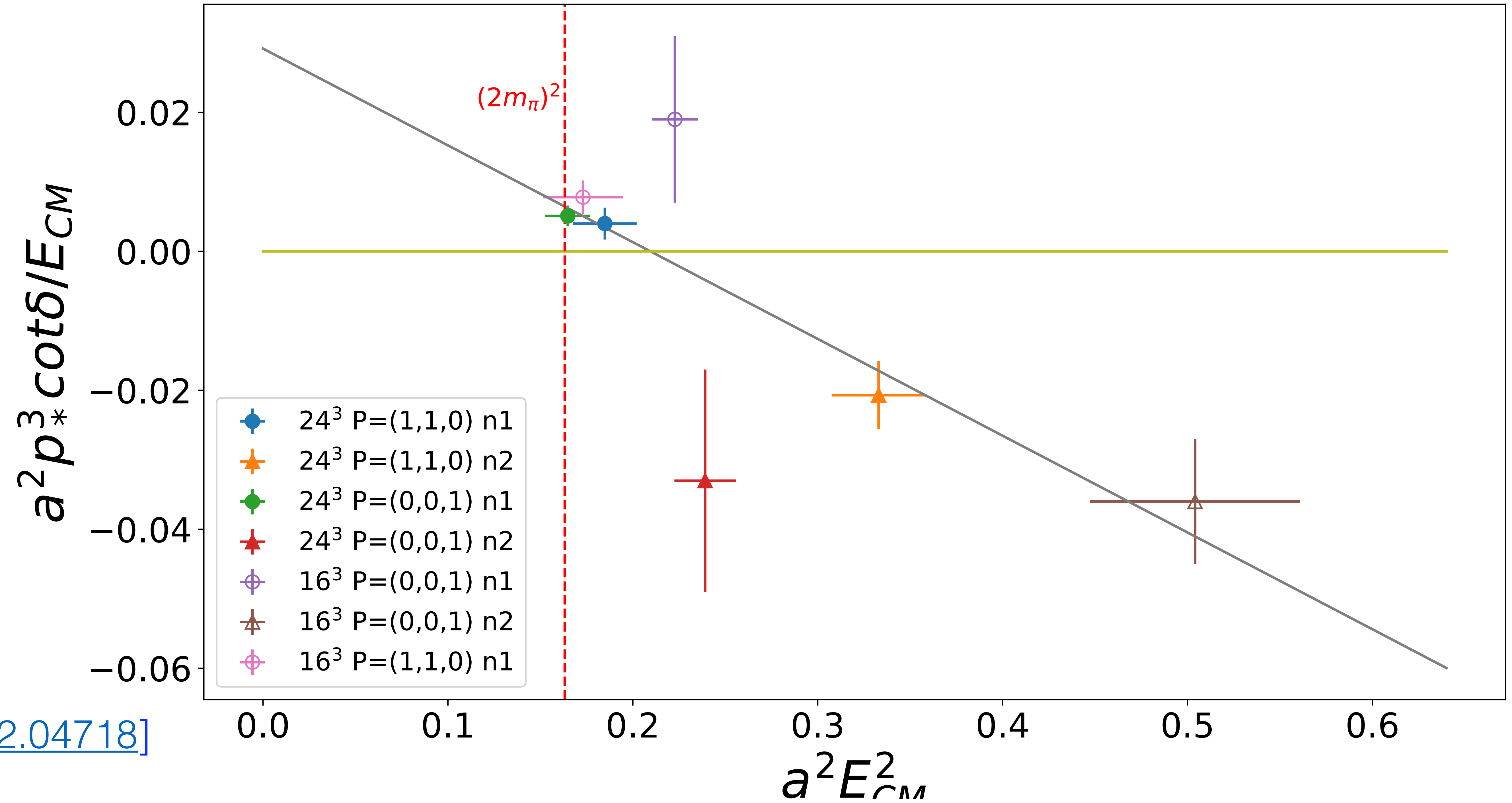
Minimal composite Higgs: SU(2) with N_f=2 fundamental fermions

[Arthur, Hietanen, Pica, Sannino, VD arXiv:1607.06654]
[Arthur, Hansen, Hietanen, Pica, Sannino, VD arXiv:1602.06559]

- Flavor symmetry upgraded to SU(4).
- Chiral symmetry breaking SU(4)→Sp(4) [5 GBs]
- Electroweak embedding and EFT.
  [Sannino, Cacciapaglia: arXiv:1402.0233, arXiv:1508.00016]
- Phenomenologically viable.
  [Arbey, Cacciapaglia, Cai, Deandrea, Le Corre, Sannino arXiv:1502.04718]
- Vector meson phase shift and **g** coupling: control cross section production.
- Wilson-clover, Luscher formalism: 2 moving frames + Breit-Wigner parametrisation of the resonance



[T. Janowski, Friday 14:00]

$\longrightarrow \quad g_{\rho\pi\pi} \sim 11(2)$

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[Arthur, Hansen, Hietanen, Pica, Sannino, VD arXiv:1602.06559]

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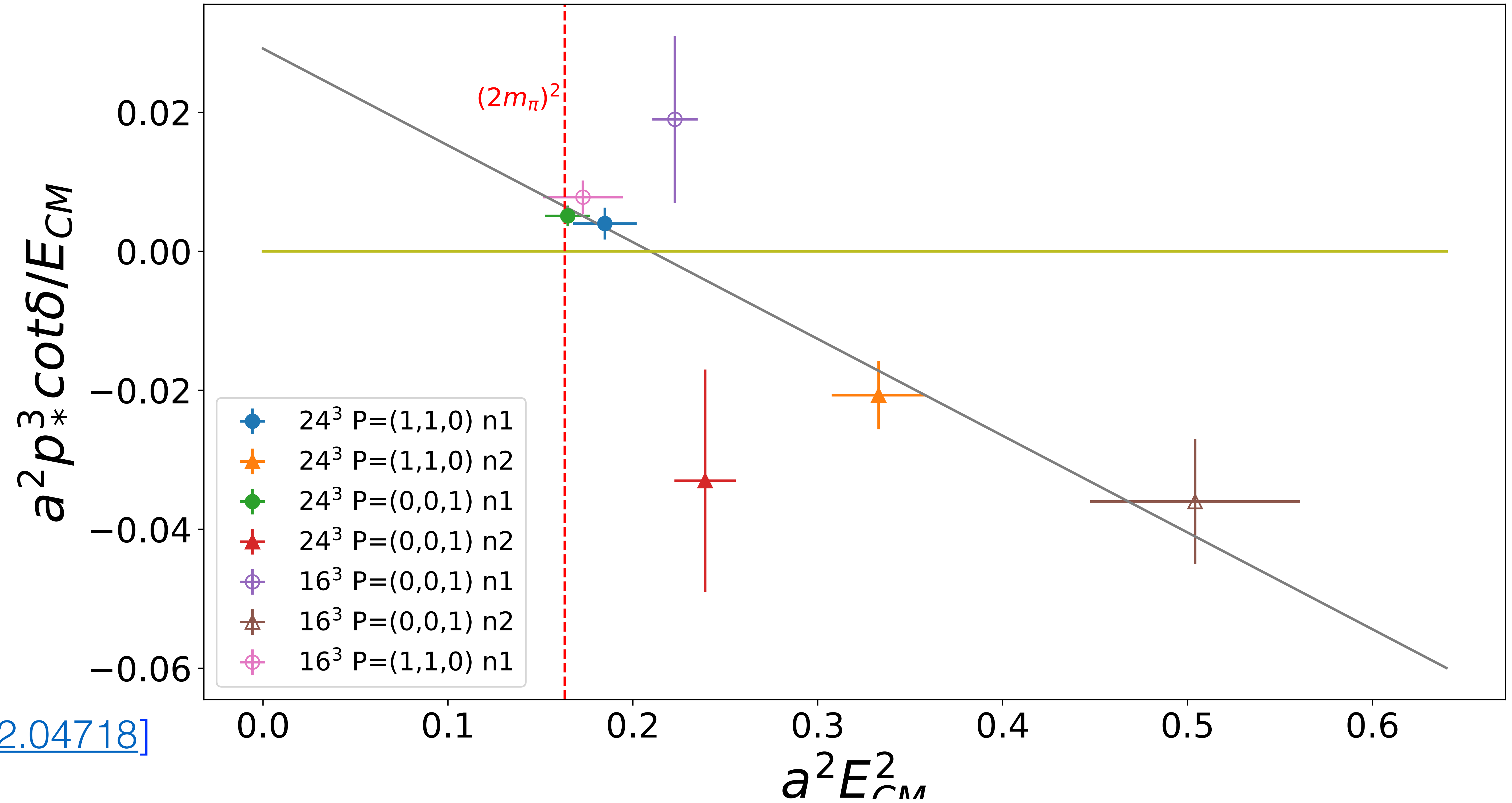

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[T. Janowski, Friday 14:00]

- Wil
+ B

Phenomenogical impact to be worked out.

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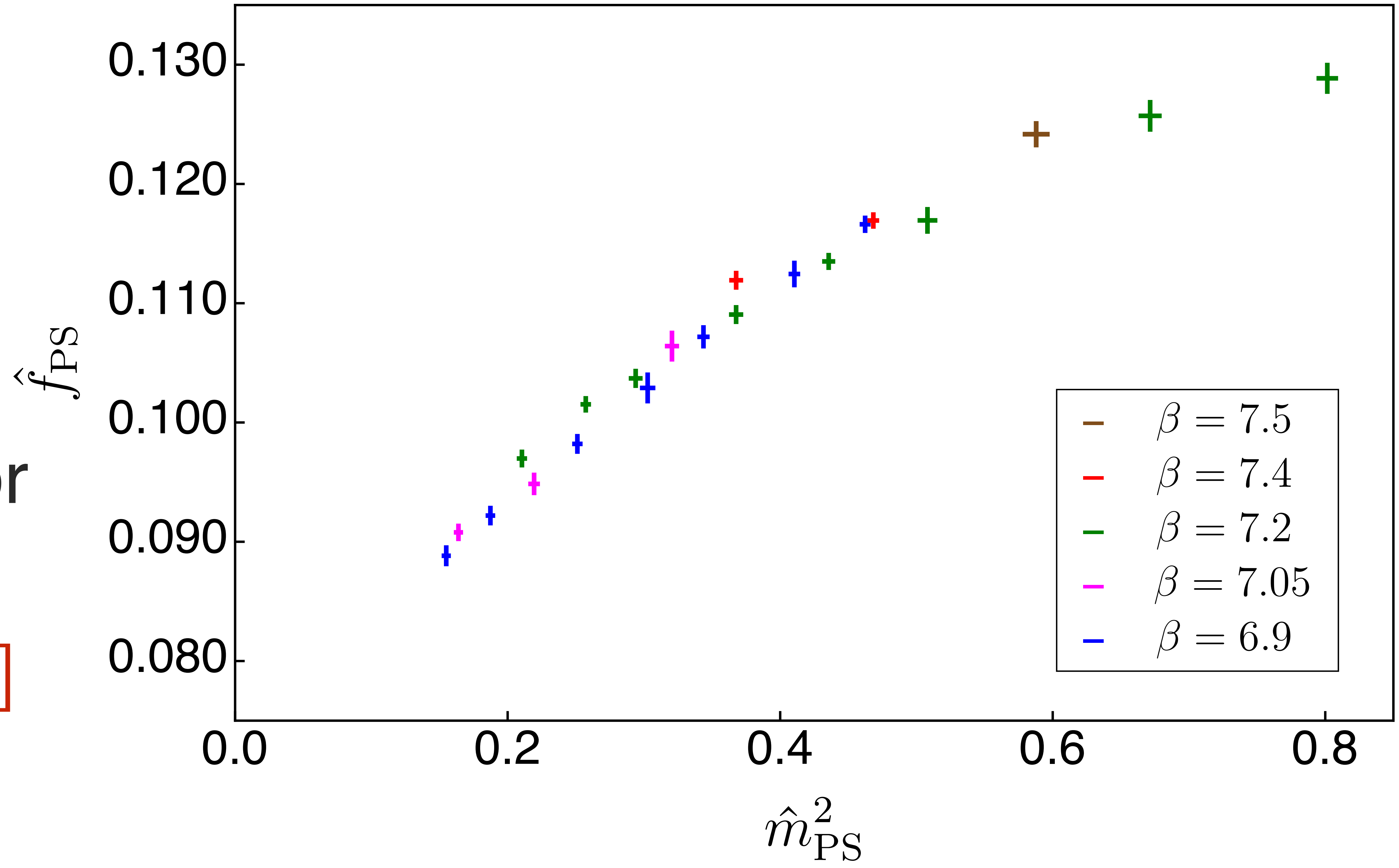
Sp(4) with N_f = 2 fundamental fermions

[Lee, Bennett, Hong, Lin, Lucini, Piai, Vadacchino ,arXiv:1811.00276.]
[Bennett, Hong,Lee,Lin, Lucini, Piai, Vadacchino, arXiv:1712.04220]

- χSB pattern SU(4)→Sp(4) [5 GBs]
- Same χSB has SU(2)=Sp(2)
- Wilson fermions
- Spectrum extensive study:chiral behavior and discretisation error

[J.-W. Lee, Friday 14:20]



- Comparison with SU(2) + N_f = 2 fundamental fermions ?

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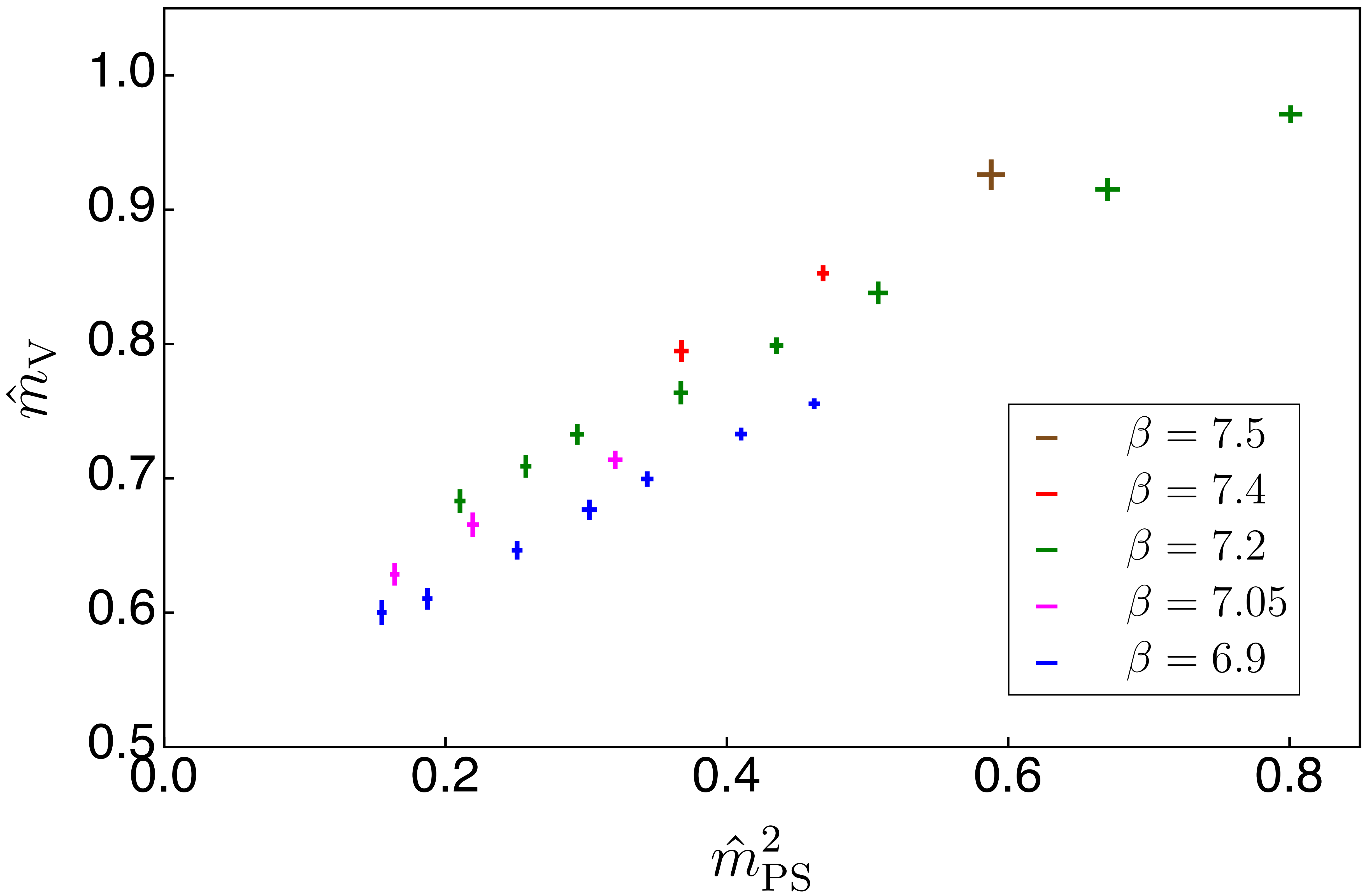

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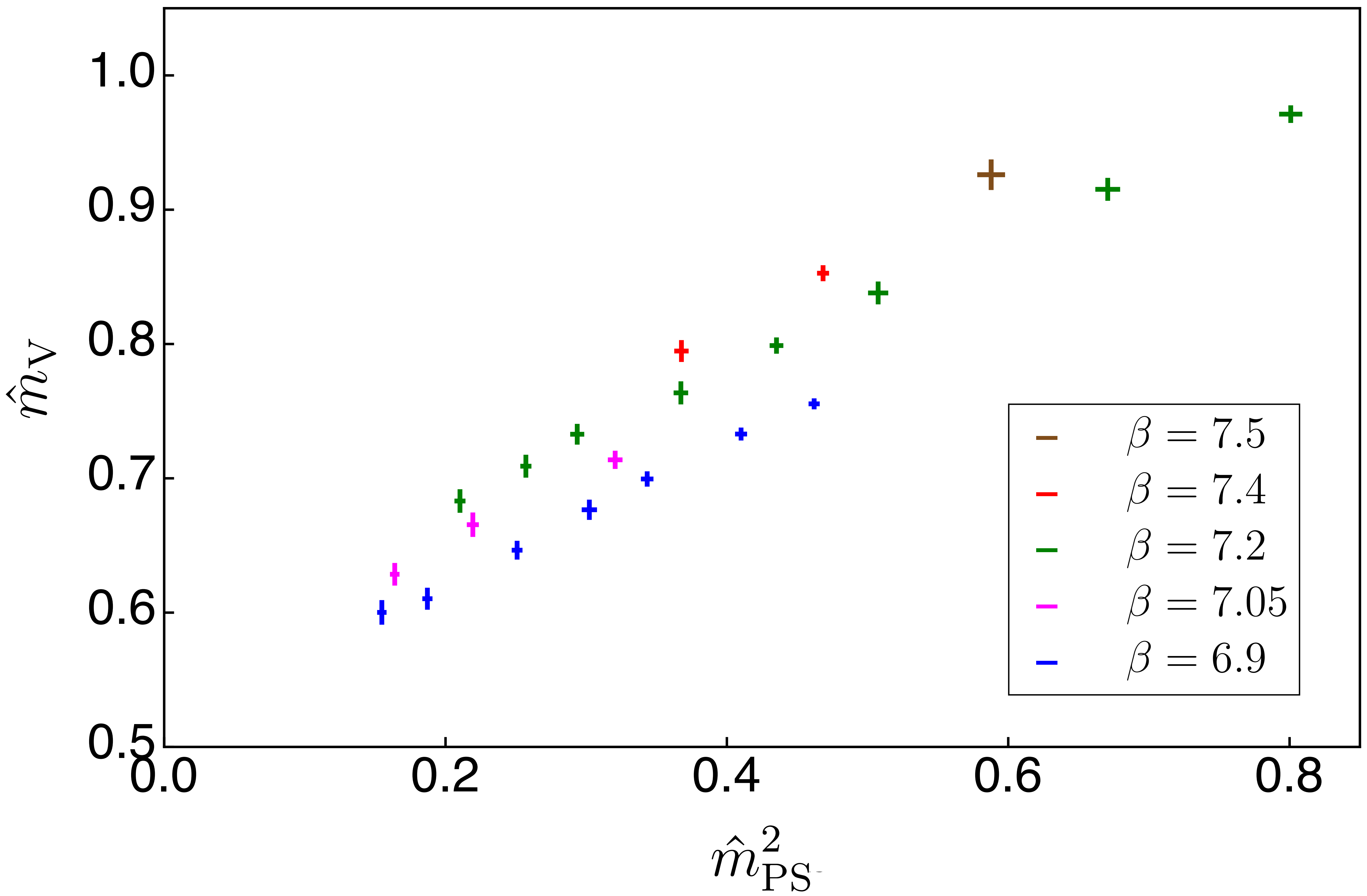

- Comparison with SU(2) + $N_f = 2$ fundamental fermions ?

- Glueball spectrum for pure Sp(2N) Yang-Mills in the large-N limit

[J. Holligan, Friday 14:40]

Partial compositeness: Ferretti's model

[Ferretti, Karateev: arXiv:1312.5330]

[Ferretti arXiv:1404.7137]

- UV completion: SU(4) gauge theory:
  - 5 Weyl in AS irrep (**6**)
  - 3 Dirac in the fundamental irrep (**4**).
- Feature baryons charged under $SU(3)_c$

	G_{HC}	G_{F}				
	$\mathrm{SU}(4)$	$\mathrm{SU}(5)$	$\mathrm{SU}(3)$	$\mathrm{SU}(3)'$	$\mathrm{U}(1)_X$	$\mathrm{U}(1)'$
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χ	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$5/3$
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[Ayyar, DeGrand, Hackett, Jay, Neil, Shamir, Svetitsky arXiv:1812.02727]

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[Cossu, Del Debbio, Panero, Preti arXiv:1904.08885]

→ This is not a UV completion of a PNGB Higgs model but a first approximation

Partial compositeness on the lattice

[Ayyar, DeGrand, Hackett, Jay, Neil, Shamir, Svetitsky arXiv:1812.02727]

- What are the mixing matrix elements for the top quark?

- At Λ_{EW}

$$y_t \approx G_L G_R \frac{Z_L Z_R}{M_B F_{P6}}$$

[B. Svetitsky (TACO Collaboration), Friday 15:00]

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Effective "Fermi" constant from the unknown UV theory

[B. Svetitsky (TACO Collaboration), Friday 15:00]

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$Z_L Z_R$ → New !

$M_B F_{P6}$ → Already computed on the lattice

$G_L G_R$ → Effective "Fermi" constant from the unknown UV theory

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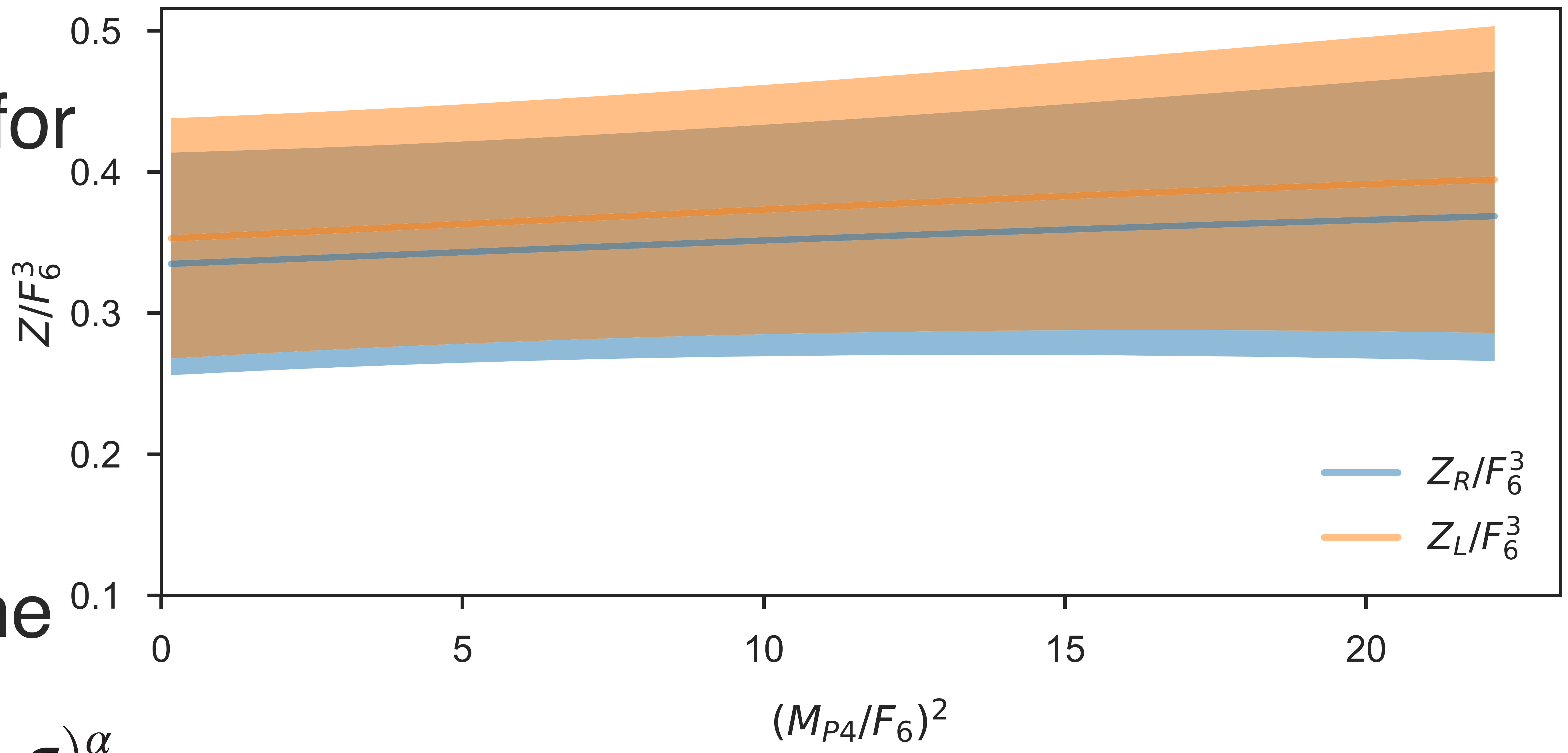


- What are the mixing matrix elements for the top quark?

- At Λ_{EW} $\quad y_t \approx G_L G_R \dfrac{Z_L Z_R}{M_B F_{P6}}$

- $Z_{L,R}$: mixing of "chimera" states with the top quark: $\langle 0|\mathcal{O}^{\alpha}_{L,R}(\mathbf{0},0)|\Lambda,\mathbf{0},\sigma\rangle = Z_{L,R}u(\mathbf{0},\sigma)^{\alpha},$

- Assuming $G \sim g^2_{\mathrm{EHC}}/\Lambda^2_{\mathrm{EHC}}$ and imposing $y_t \sim 1$:

$$\frac{g_{EHC}F_6}{\Lambda_{EHC}} \approx 3 \longrightarrow \text{Incompatible with } \Lambda_{EHC} \gg F_6$$

[B. Svetitsky (TACO Collaboration), Friday 15:00]

Partial compositeness on the lattice: the Higgs potential

[Ayyar, Golterman, Hackett, Jay, Neil, Shamir, Svetitsky arXiv:1903.02535]

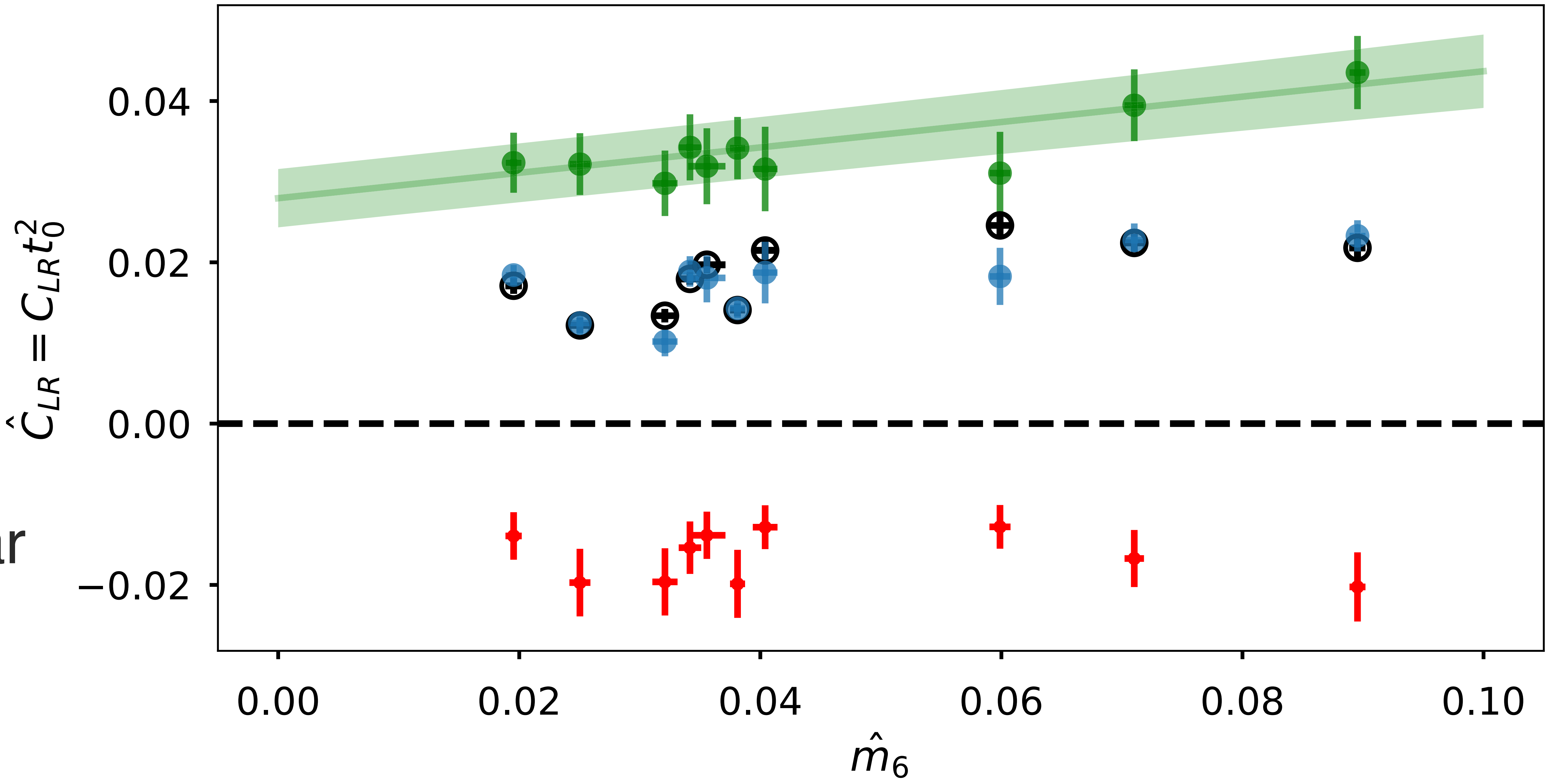
- The Higgs potential is not guaranteed to trigger EWSB: the potential is induced by loops of gauge bosons and top quarks.
- The top contribution requires to estimate a 4-point function. [L. Del Debbio, C. Englert, R. Zwicky arXiv:1703.06064]
- Vector boson contribution is controlled by a LEC, similar to the one that controls the pion mass spitting in QCD:

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 \propto \alpha \frac{C_{LR}}{f_\pi^2}$$

- Staggered over Wilson-clover action, with normalized hypercubic (nHYP) smeared gauge links.

- Compute : $C_{LR} = 16\pi^2 \int \frac{d^4q}{2\pi^4}\, \Pi_{LR}(q_\mu)$

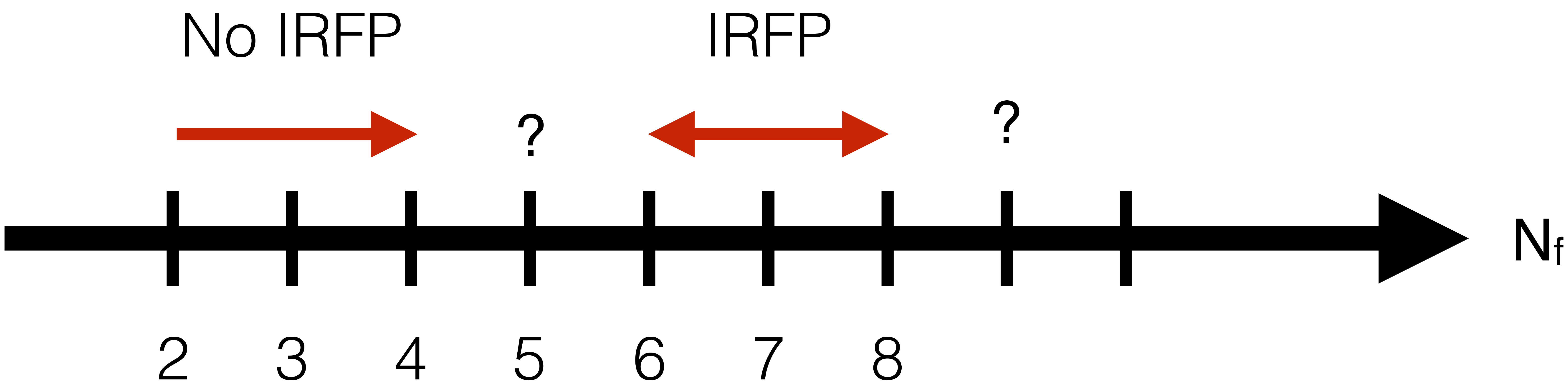
- After continuum extrapolation $C_{LR}/f_{P6}^4 = 29(8)(5)$



The theory landscape

Conformal window

SU(2) with N_f fundamental:



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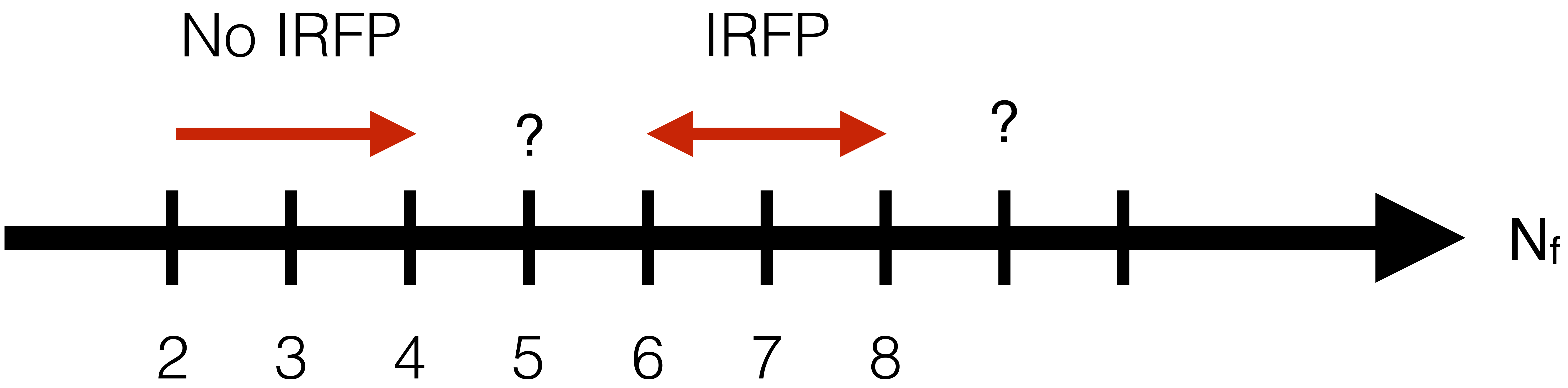

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SU(2) with N_f adjoint: IRFP evidence for N_f = 1,3/2,2

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[C. Lopez, Thu 17:10]
[A. Grebe, Fri 16:10]

Conformal window

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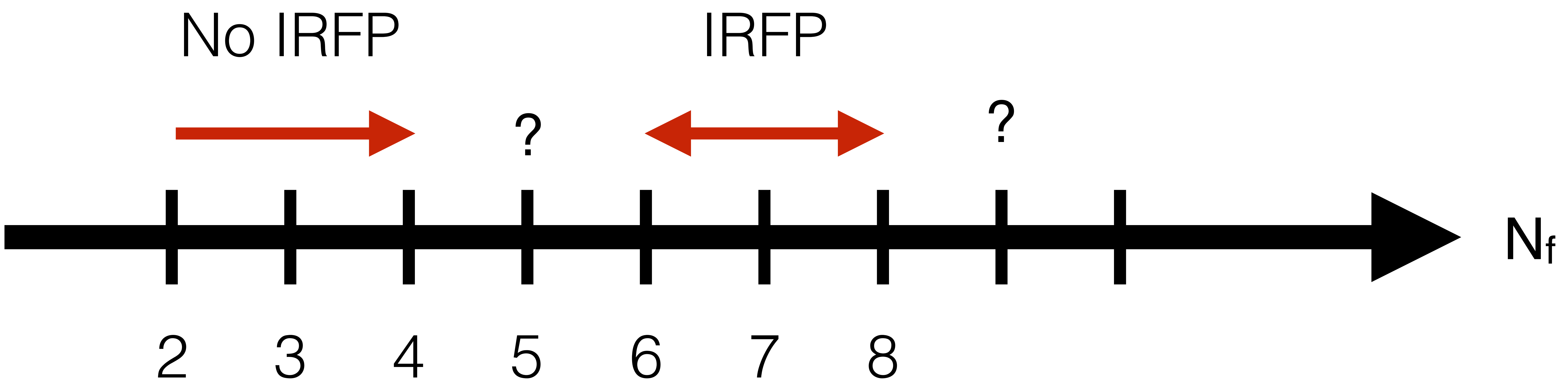

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SU(3) with N_f fundamental: Controversial

SU(3) Conformal window: new results @Lattice2019

- Case studies of near-conformal and conformal betas functions for SU(3) with Nf=10, 12 and 13 fundamental fermions and with Nf=2 in the sextet [K. Holland (LatHC), Thurs. 15:00]

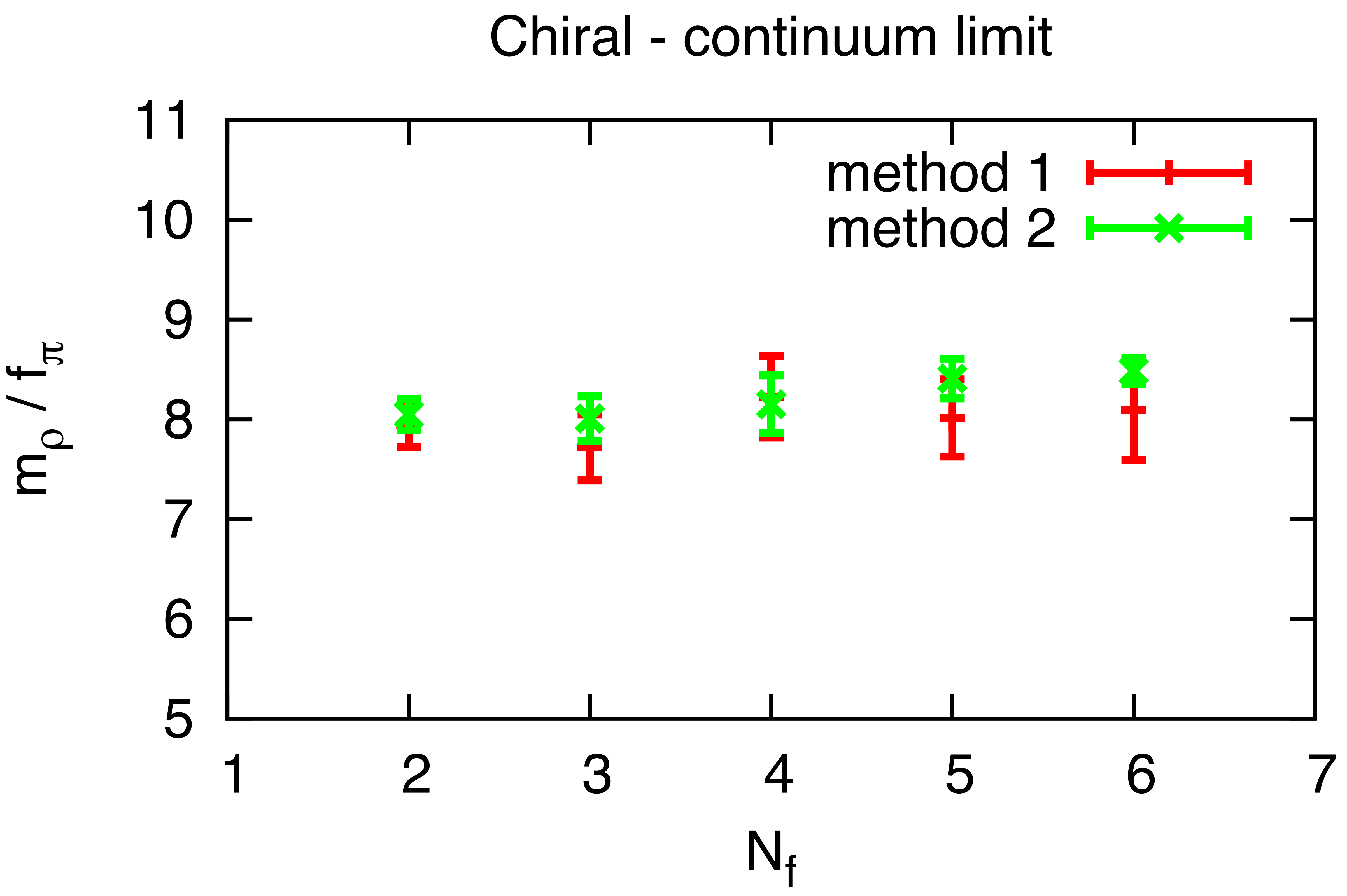
- SU(3) gauge theory with 10 massless, fundamental flavors with gradient flow step-scaling calculation [O. Witzel, Thu 16:10]

- SU(3) gauge system with twelve fundamental flavors [A. Hasenfratz, poster]

Flavor dependence of m_ρ / f_π (QCD-like phase)

[Nogradi, Szikszai arXiv:1905.01909]

- SU(3) with Nf= 2,3,4,5,6 fundamental fermions.
- Careful analysis of the finite volume effects.
- Chiral and continuum extrapolation performed from the stable ρ regime ($m_\rho < 2\, m_\pi$).
- Assuming KSRF-relations: estimation of $g_{\rho\pi\pi}$
- *Motivation*: Vector resonance is an experimental signature of an underlying strong dynamics.
- Scale $f_\pi = 246$ GeV, first resonance ~ 2 TeV independently of the the number of underlying flavors.



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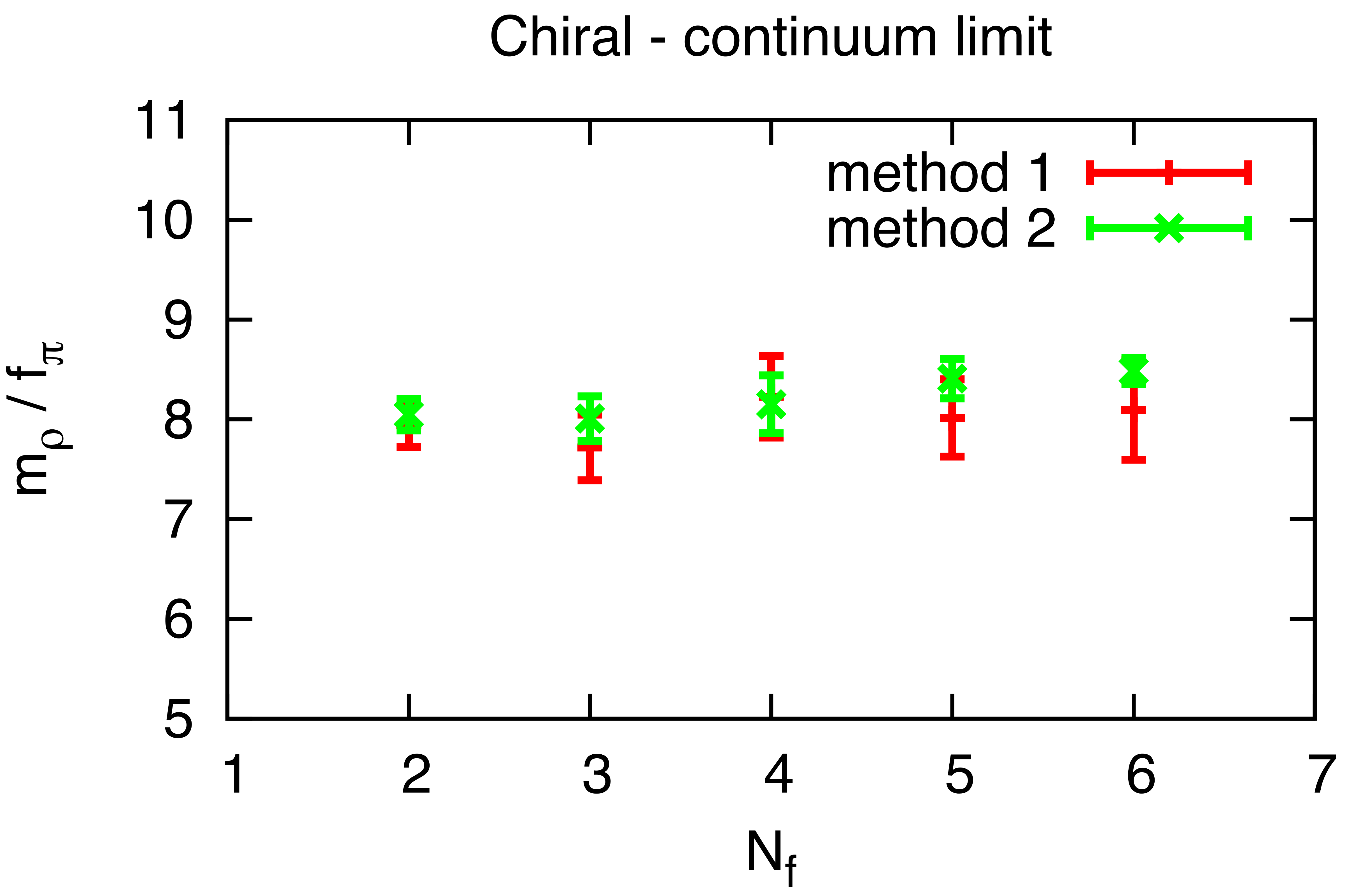

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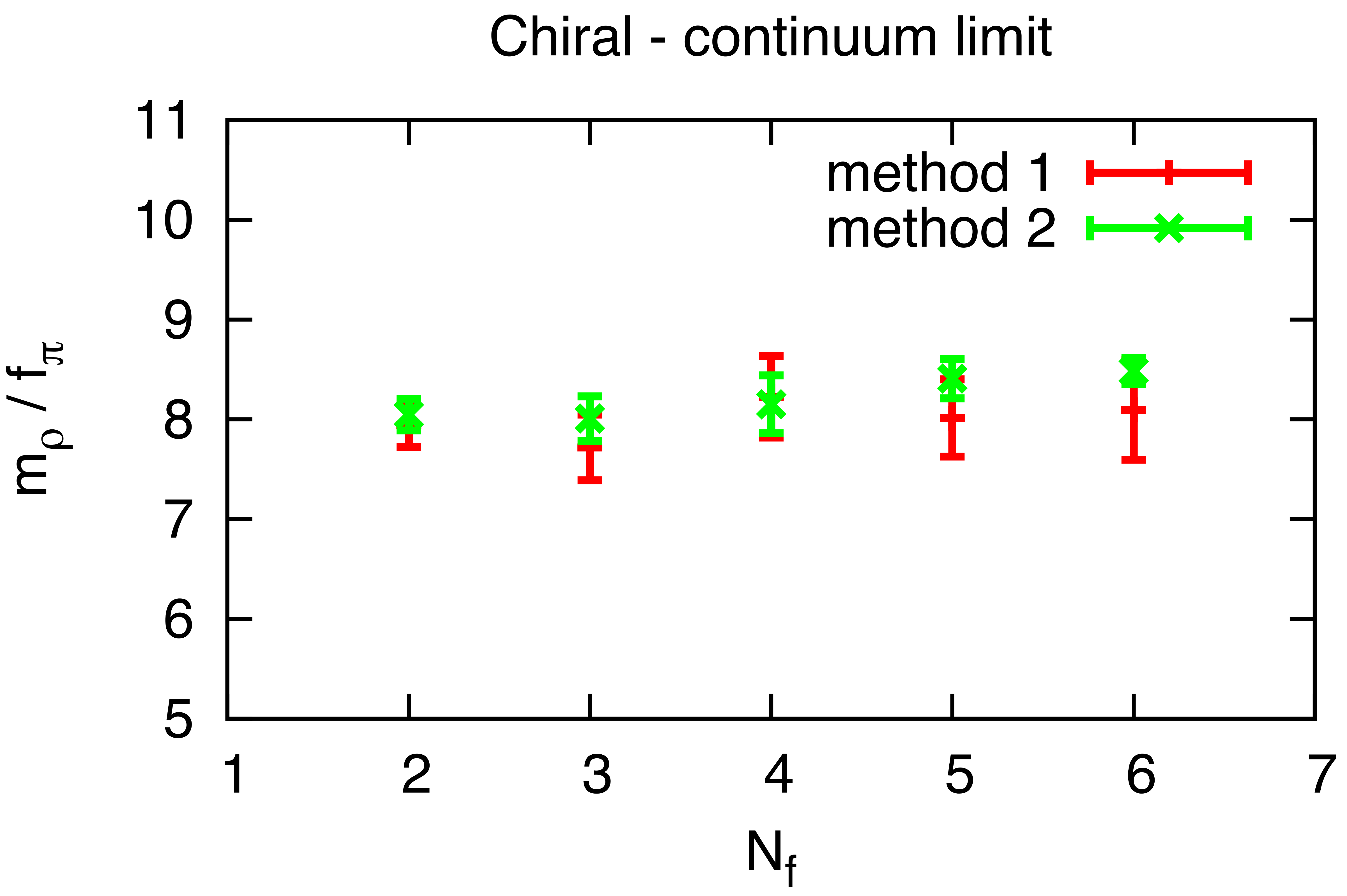

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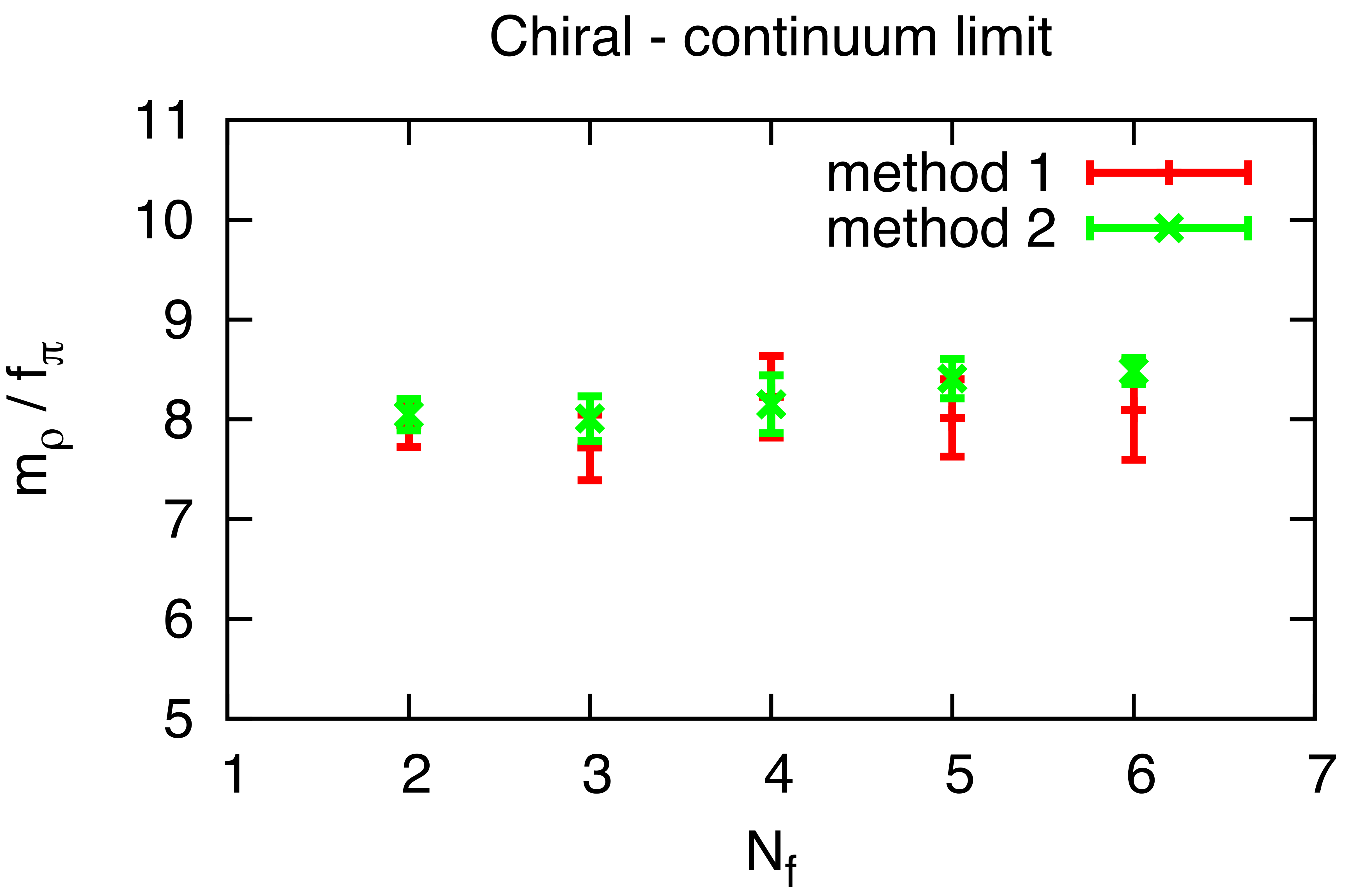

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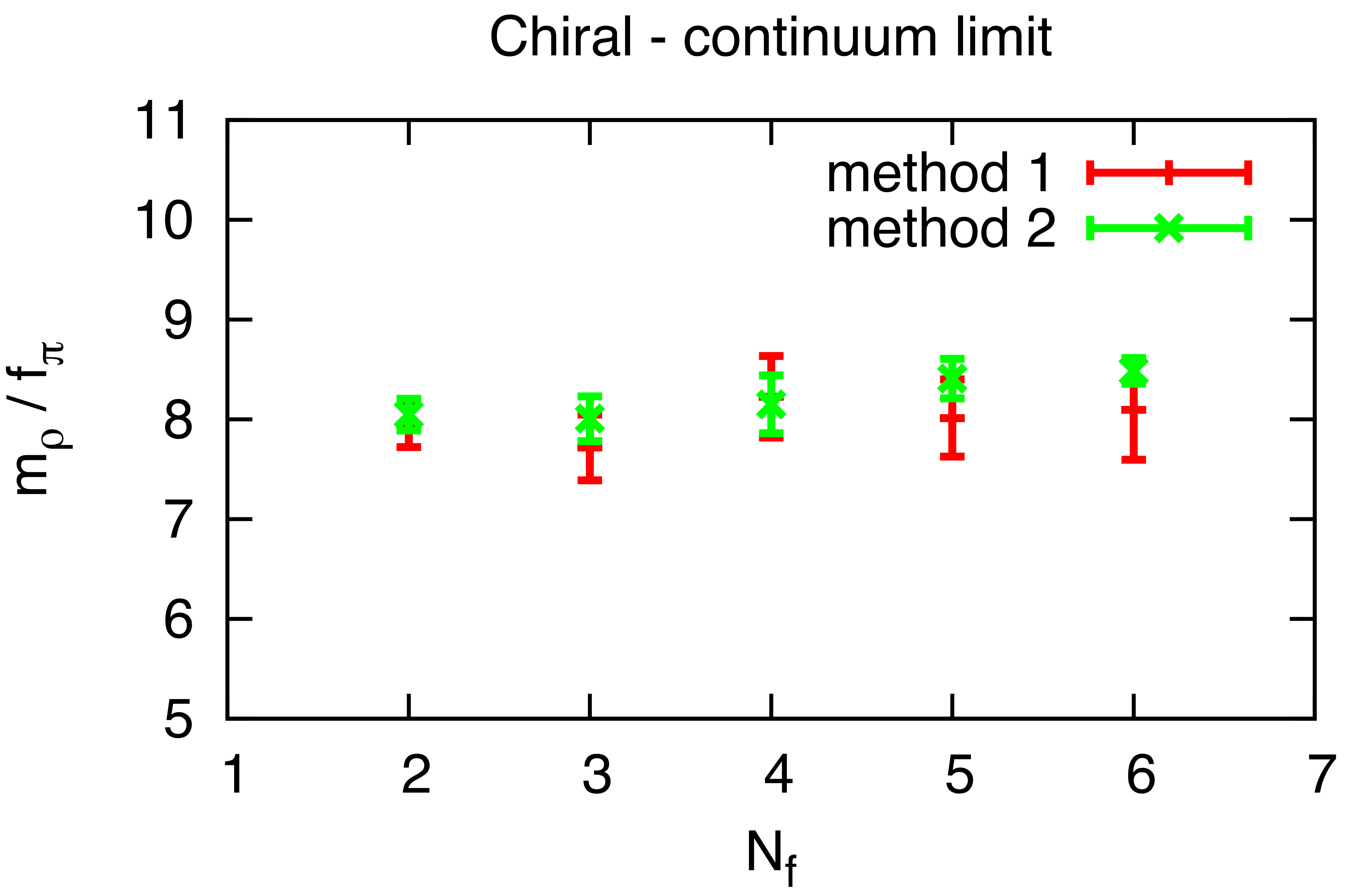

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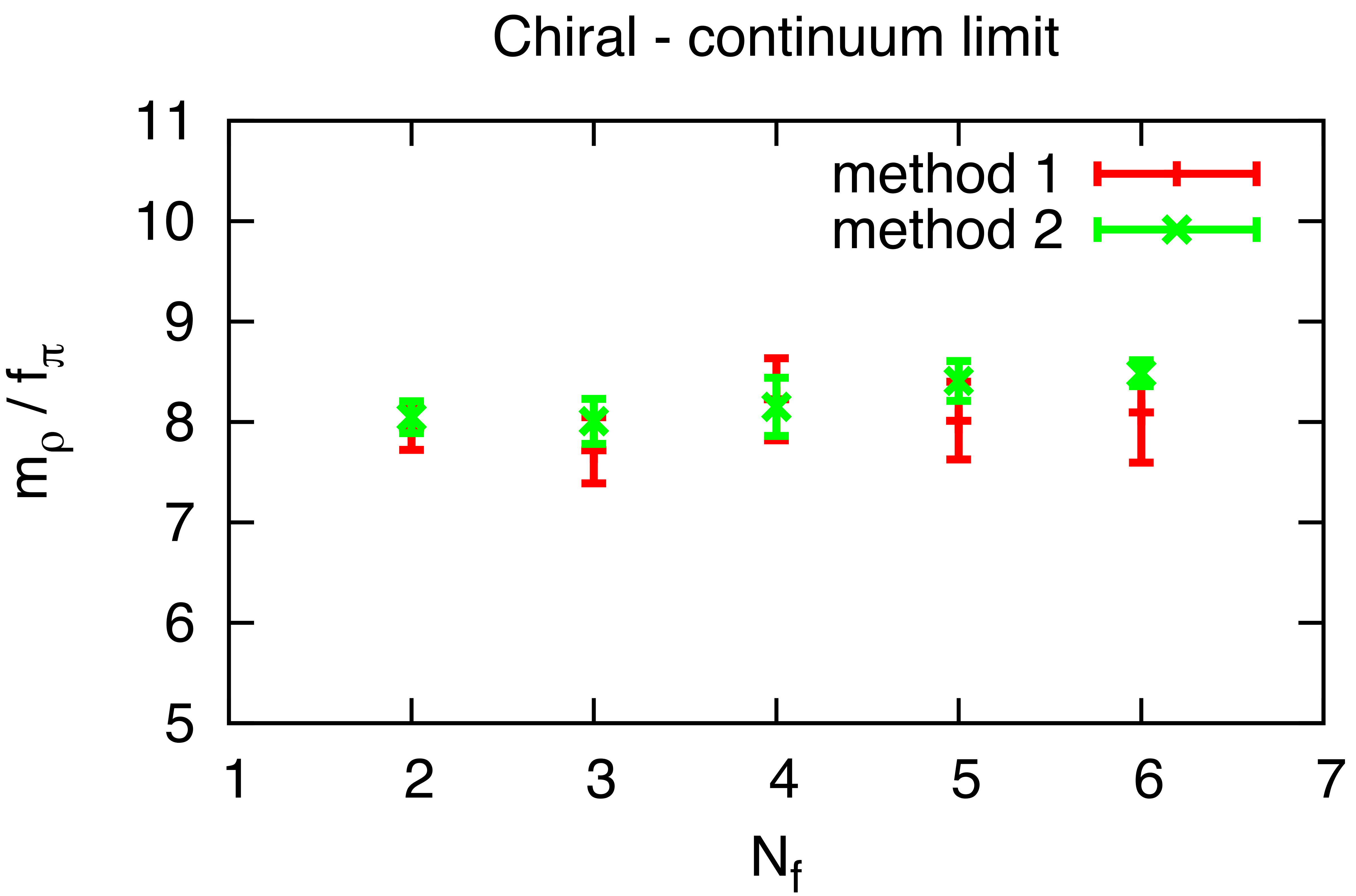

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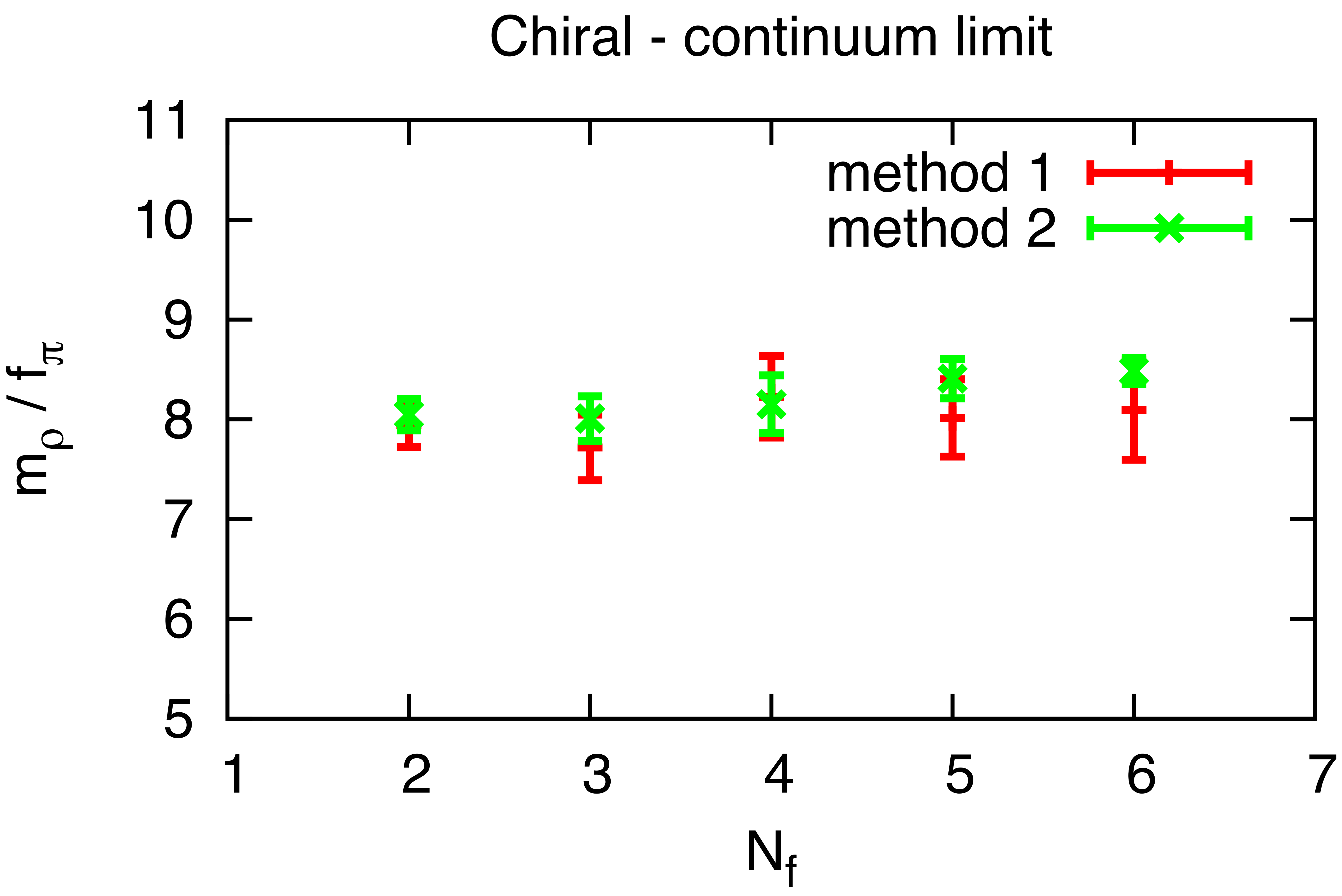

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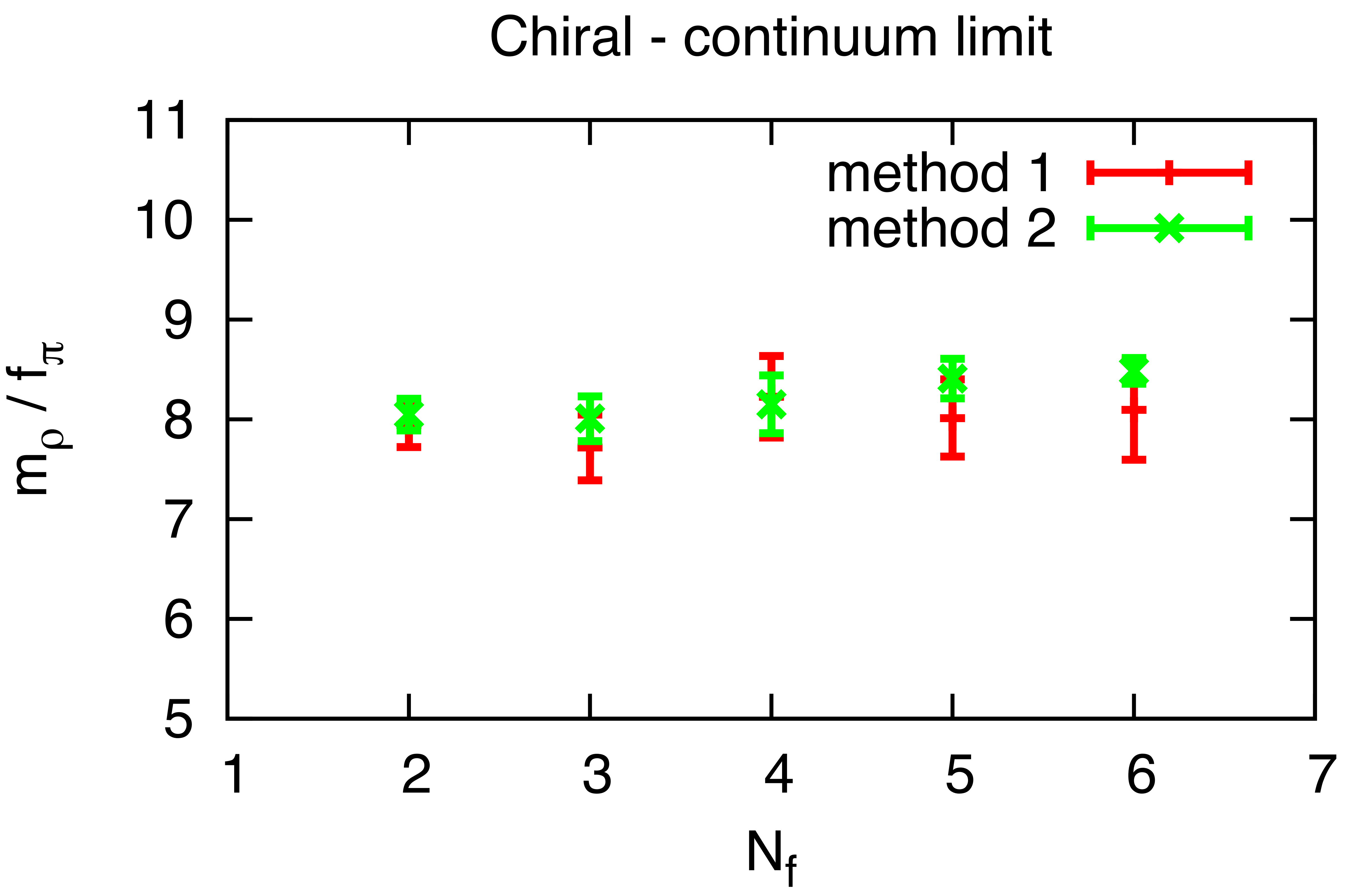

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Alternative mechanisms

- ✦Gauge-invariant perturbation theory can lead to unexpected physical spectrum.

[Mass arXiv:1712.04721]
[Maas, Sondenheimer, Törek arXiv:1709.07477]
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→ Consequence for composite models ?

✦Dynamical generation of particle masses: natural alternative to the Higgs mechanism

[Frezzotti, Rossi arXiv:1402.0389 and arXiv:1811.10326]

SU(3) + N_f=2 + a colourless complex scalar doublet + Yukawa + Wilson-like term:

- Left-over breaking of fermionic chiral symmetry at cutoff scale polarizes vacuum
- SSB dynamically generates PCAC fermion mass

✦Lattice simulations with continuum extrapolations support the proposed mechanism.

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→ Higgs a composite state in WW+ZZ channel ?

Conclusion

- No sign of new physics at the LHC: strong constraints on BSM

- Lattice simulations can test/explore mechanisms that can guide phenomenologists and BSM searches.

- Near-conformal dynamics:
  - Several attempts to test EFT in a regime with a light scalar.
  - Explorative study of a mass-split model

- PNGBs Composite Higgs models:
  - First calculation of vector meson resonance parameter
  - Investigation of partial compositeness and of the Higgs potential