Challenges in lattice studies of models of new physics Beyond the Standard Model

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Acknowledgments

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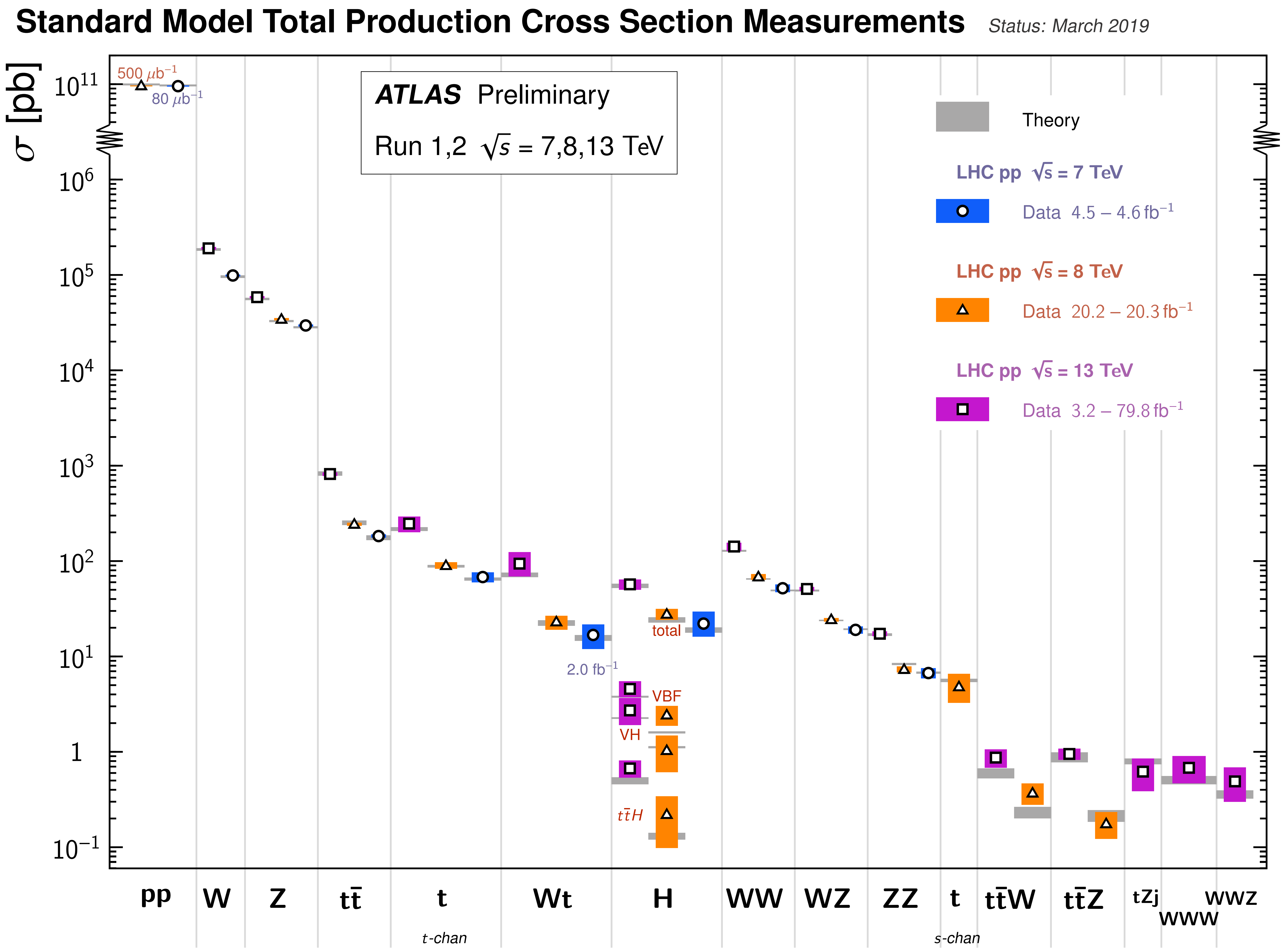
Outline

- Scientific objectives and challenges
- Computational tools
- Research highlights

Scientific objectives and challenges

The Standard Model …

- Describes experimental data for a wide range of processes.
- 2012: Discovery of the Standard Model last ingredient: “The Higgs Boson”.



[ATL-PHYS-PUB-2019-010]

The Standard Model … and beyond

- However: Experimental and theoretical evidence that require New Physics "beyond the Standard Model" (BSM):

  - Dark matter
  - Neutrino masses
  - Matter-antimatter asymmetry
  - Naturalness problem
  - …

Experimental program at CERN, but also on-board satellites, and other large experimental facilities: Hyper-Kamiokande, LUX-ZEPLIN, …

- Theoreticians develop models to address these issues: reliable predictions are needed to test their viability.

Composite Models

Extensions of the Standard Model

- Introduce a new interaction and a number of new fermions that confines them into bound states.
- Well-motivated framework to provide solution to some of the unexplained observational facts
- Exploit the phenomena of confinement of quarks into bound-states that occurs in Nature in QCD

Example of paradigms:

- Models where the Higgs boson is a Goldstone Boson: Pseudo-Nambu Goldstone Composite Higgs Models
- Models where the Higgs boson is a light scalar 0^{++} particle because of the dynamics of the new interaction
- Composite Dark Matter

Challenge:

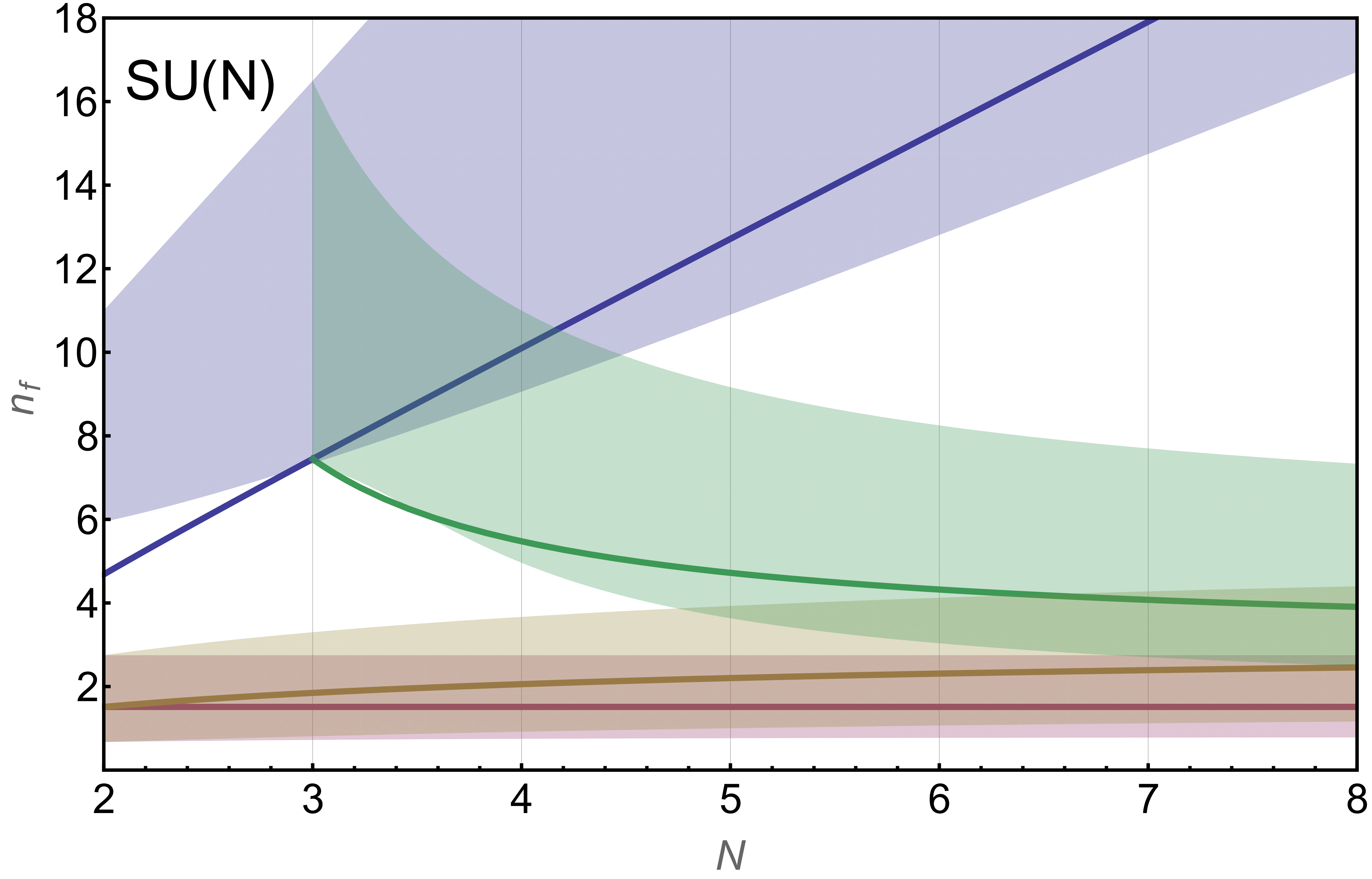
- The dynamics being non-perturbative, lattice simulations are the only tool to bring definite answer about the dynamics of such theories.

Lattice investigations

- In the UK: Edinburgh, Liverpool, Plymouth, Swansea
- In the EU: Denmark, Germany, Italy
- In the US: Many collaborations
- Also in Japan, Korea, Taiwan,…

Challenge 1: A large number of candidate theories

C. Pica and F. Sannino, Phys. Rev. D **83**, 035013 (2011), arXiv:1011.5917



- The parameters:
  - Gauge group : SU, Sp,…
  - Dimension of the Gauge group N
  - Number of fermions N_f
  - Fermions representation R

- The algorithms designed to study QCD are only a starting point of the investigation, they need to be adapted to the theory of interest.
- Fermion in multiple representation are interesting and add one dimension to an already large theory space.

Challenge 2: What to compute ?

- Interesting quantities:
  - Spectrum of low-lying states
  - Running coupling constant
  - Low energy constants
  - Properties of the scalar states : “Higgs candidates”
  - Properties of other states: width of resonances, couplings to Standard Model interactions.
  - Back reaction of the Standard Model
  - Simulations with Weyl fermions, often used by model builders [e.g partial compositness].

- Often the quantities of interest to the phenomenologists are very challenging for the lattice approach.

- Systematics difficult to control:
  - Conformal/Near-Conformal theories: large volumes needed
  - Near-Conformal theories: Low energy effective description less robust, very difficult to trust extrapolations.

- Lessons:
  - Tools must be flexible to allow to compute various observables and to adapt to the peculiar needs of “lattice BSM”

Example of current lattice projects

- Determination of the lower bound of the conformal window:
  - SU(3) + N_f =8,10 and 12 fundamental fermions [LatHC and Hasenfratz & Witzel]
  - …
- Investigations of near conformal theories for pseudo-dilaton Higgs model:
  - SU(3) + N_f =2 symmetric fermions [Kuti et al.]
  - SU(3) + 4light + 6 heavy fundamental fermions [LSD collaboration]
  - SU(3) + N_f =8 [LSD collaboration]
- Investigations of theories pseudo Nambu-Goldsone Composite Higgs model:
  - SU(2) = Sp(2) + N_f =2 [Drach et al]
  - Sp(4) + N_f = 2 [Lucini et al]
  - SU(4) with fermions in multiple representation [Del Debbio et al.and Ayyar et al.]
- Investigation of Composite Dark Matter models:
  - SU(4) + N_f =4 fundamental fermions [Schaich et al.]

What do to with an exascale system?

- Investigation of the effective Higgs potential of a minimal composite Higgs model:
  - Contribution from the EW sector
  - Contribution from the top quark

- Simulation of minimal partial compositeness with controlled systematics.
  - SU(4) with 5 massless Majorana fermions in the two-index antisymmetric representation and 3 Dirac fermions in the fundamental representation.

- Exploring the chiral limit of near-conformal theories
  - Large volume simulations with fermion masses an order of magnitude smaller.
  - Calculation of the scalar meson mass using a fully fledged scattering calculation

- Systematic calculation of key observables over a range of underlying theory:
  - Shedding light on the dependence on N_f and N_c to identify quantities sensitive to the underlying dynamics.

→ Require at least 2 orders of magnitude more computing time

State of the art computational tools

Computational tools: simulation software for BSM

Some software used by the lattice BSM community

- Grid & Hadron
- HiRep
- USQCD and in particular QHMC (FUEL) and QEX + QUDA

HiRep:

- DiL (Leicester, UK) : Intel Xeon Skylake, 100Gb/s EDR 2:1 blocking Infiniband network in a fat-tree topology, 3.0PB Intel Lustre file system.
- Peta4 (Cambridge, UK) : Intel Xeon Skylake, Intel OmniPath in 2:1 Blocking
- MareNostrum4 (BSC, Spain) : Intel Xeon Scalable Platinum (Skylake)
- Abacus 2.0 (Denmark): Intel E5-2680v3 Haswell, InfiniBand
- Piz Daint (CSCS,Switzerland): Cray XC30, Broadwell, Aries routing, Dragonfly network topology
- Swansea Sunbird (Swansea, UK) system Intel(R) Xeon(R) Gold 6148 (Skylake) @ 2.40GHz with 20 cores each
- Spark (Taiwan): intel xeon phi 7250 (KNL)
- Korea: Intel Xeon Gold 6140 (Skylake), Intel Omni-path
- BlueGene L & P & Q

Grid:

- Peta4 (Cambridge, UK) : Intel Xeon Skylake, Intel OmniPath in 2:1 Blocking
- Tesseract (Edinburgh,UK) : Intel Xeon Silver (Skylake), Intel OPA Interconnect,3 PB Lustre Filesystem
- In the US: intel KNL, Skylake, Haswell, Broadwell systems and also partly on IBM+Nvidia Tesla GPUs

Computational tools: HiRep

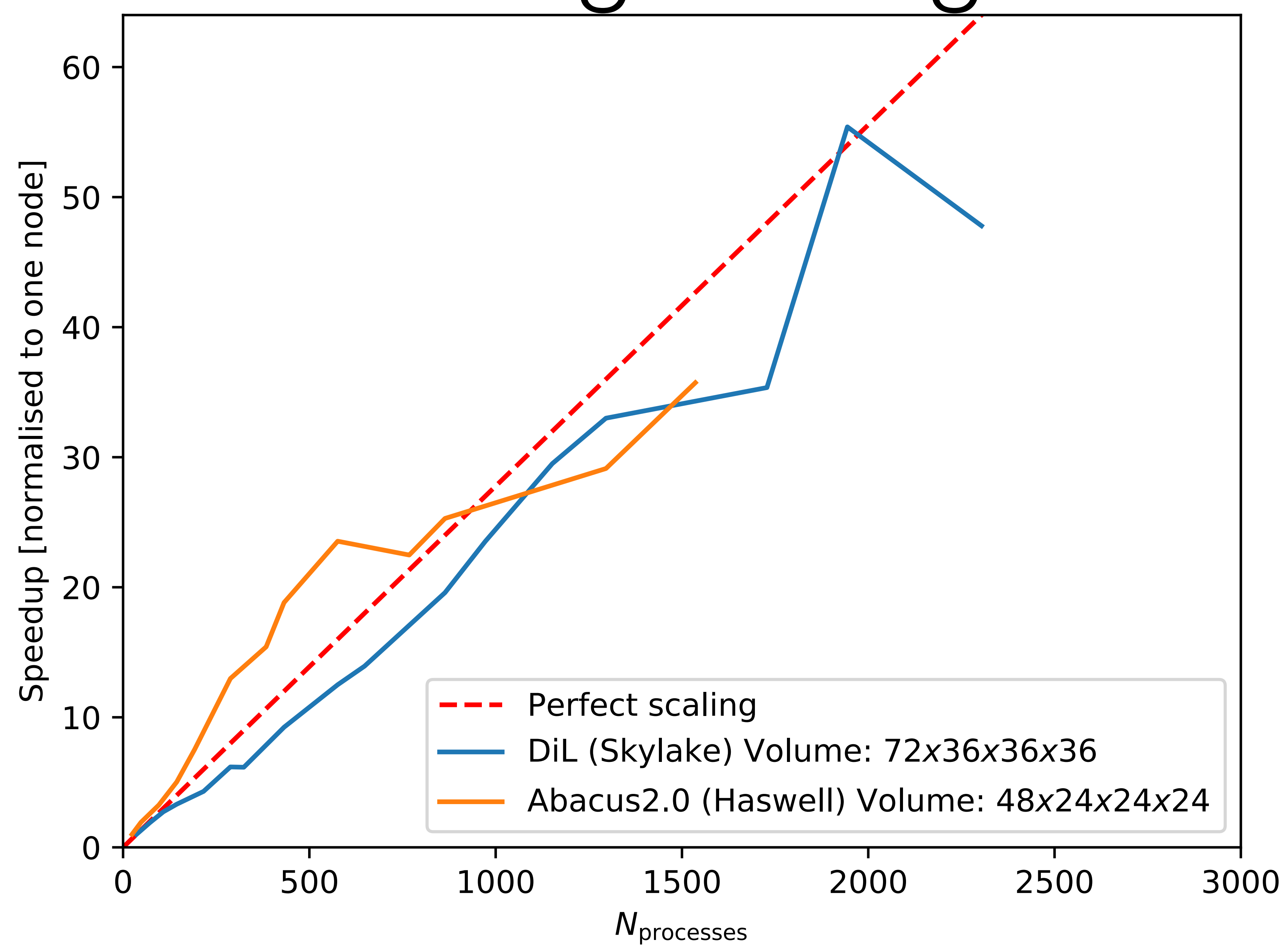
HiRep:

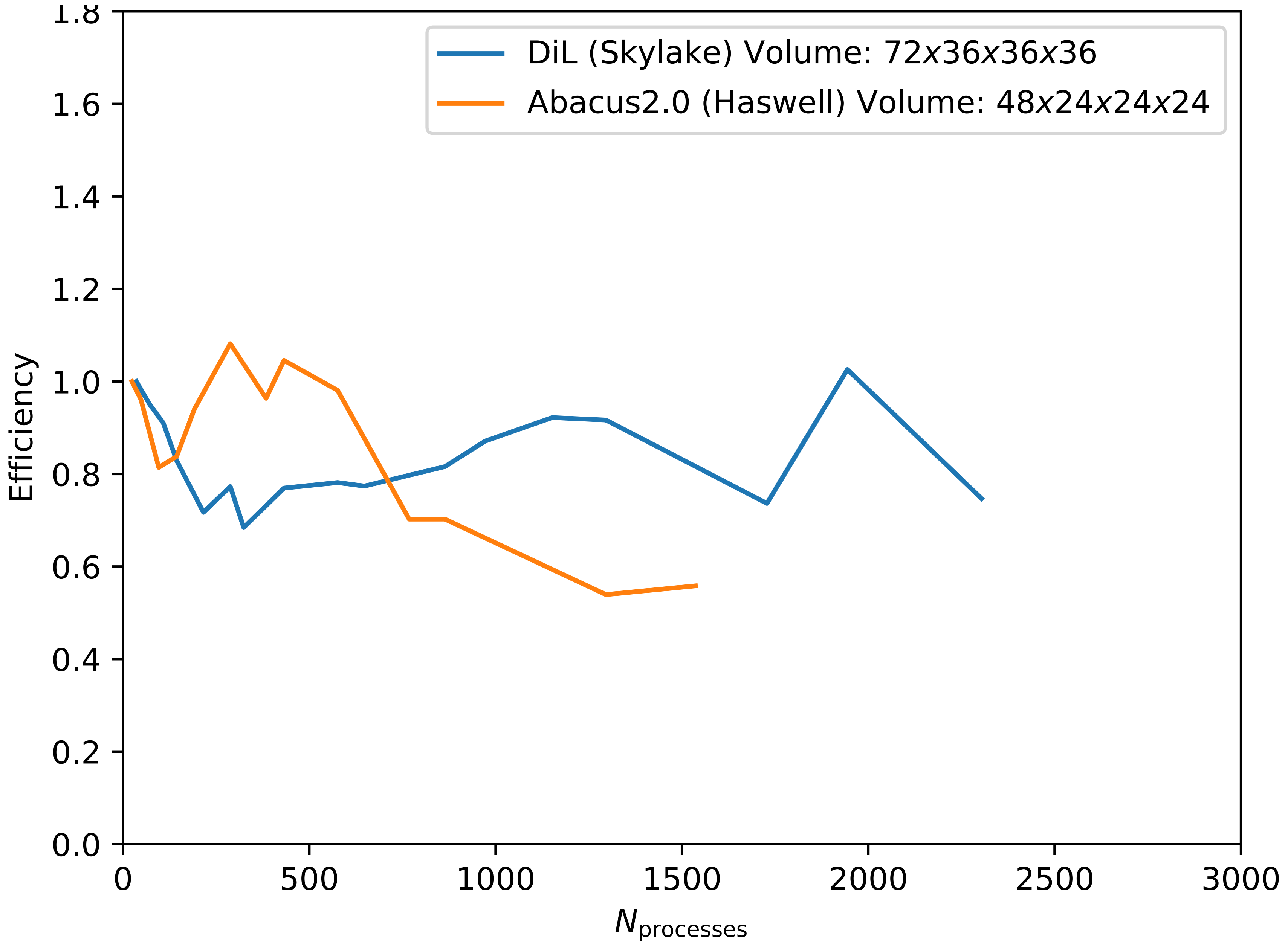
- Free (GPLv2) standard c99 https://github.com/claudiopica/HiRep
- Designed to be flexible: Gauge group, fermion representation
- Implement HMC/RHMC
- Wilson-like fermions only (unimproved, clover, exp-clover).
- Open BCs/ SF BCs
- Standard preconditonners,
- Hasenbusch acceleration
- Non-blocking communications
- openMP support
- Various solvers
- GPU branch obsolete and need a revamp.
- Also contains tools to compute many observables: spectrum, disconnected contributions, Goldstone boson scattering,….
- Continuous Integration in place.
- Efficient & portable: tested on many current supercomputing facilities. Efficiencies typically > 70% for ~1000 MPI processes.

[A. Francis, P. Fritzsch, M. Lüscher and A. Rago Comput. Phys. Commun. **255**, 107355 (2020),arXiv:1911.04533]

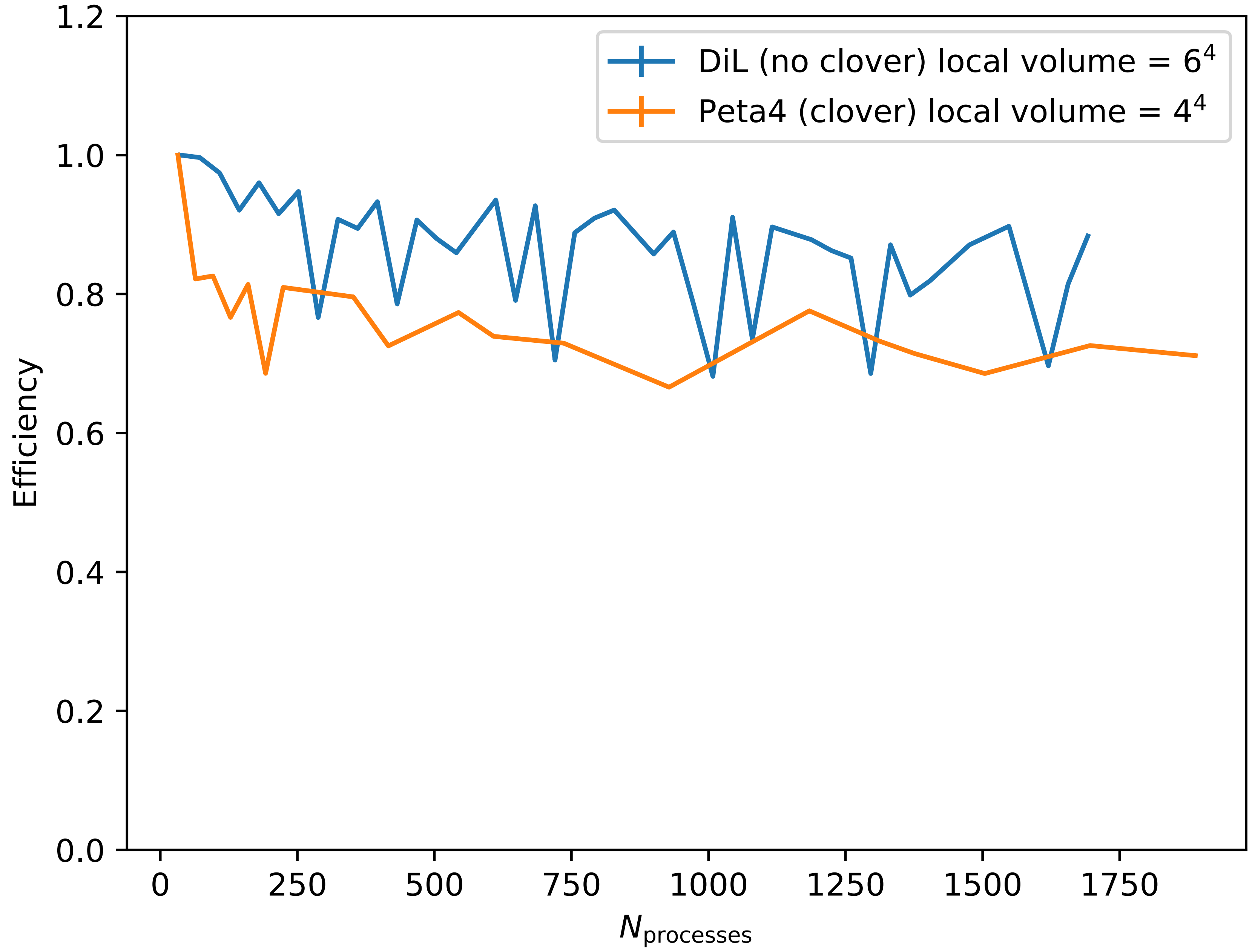
Computational tools: Scaling HiRep

Strong scaling





Application of Dslash
SU(2) with N_f = 2 fundamental fermions



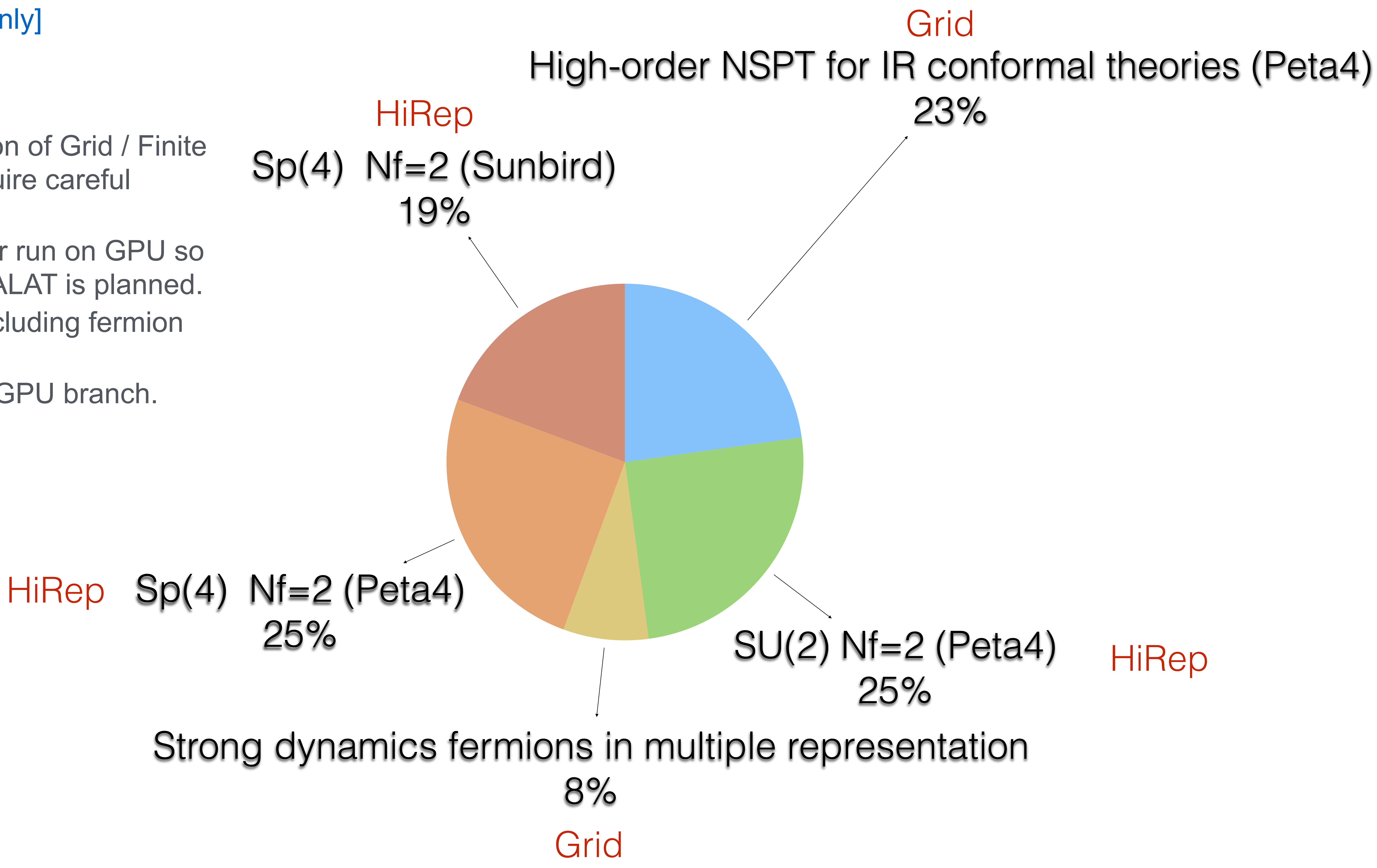
Weak scaling

Overall UK computing ressources (2019-2020).

Number of core-hours : 26 M core-hours [UK only]

Ongoing development:

- NSPT project based on an older version of Grid / Finite Volume effects are significant and require careful investigations.
- Multiple fermion representations: never run on GPU so far. Benchmark on GPU as part of EXALAT is planned.
- Sp(4) simulations: ongoing work on including fermion in mixed representation.
- SU(2) simulations: plan to refresh the GPU branch.



Software usage in the US

- SU(3), many flavours beta-functions, anomalous dimension MDWF fermion [Hasenfratz, Rebbi, Witzel]: Grid on intel KNL, Skylake, Haswell, Broadwell, …

- SU(3) mass-split 4+6 model MDWF [LSD collaboration]: Grid on intel KNL, Skylake, Haswell, Broadwell

- SU(3), 8 flavors staggered [LSD collaboration]: QHMC/FUEL on intel CPUs & QEX+QUDA on IBM+Nvidia Tesla GPUs
- Möbius DWF with gauge group SU(3) and N_f=10 [LSD collaboration]:: Grid & Hadrons mostly on KNL clusters and pre-exascale GPU-based "Lassen" system at Livermore.

- Two-representations simulation SU(4) inspired by Ferretti's model [Neil, Shamir, Svetitsky et al.]: MILC fork on CPU cluster

- SU(4) dark matter [LSD collaboration] QHMC/FUEL on intel CPUs

- Supersymmetric systems [Schaich, Catterall, Giedt et al.] MILC fork on CPU cluster

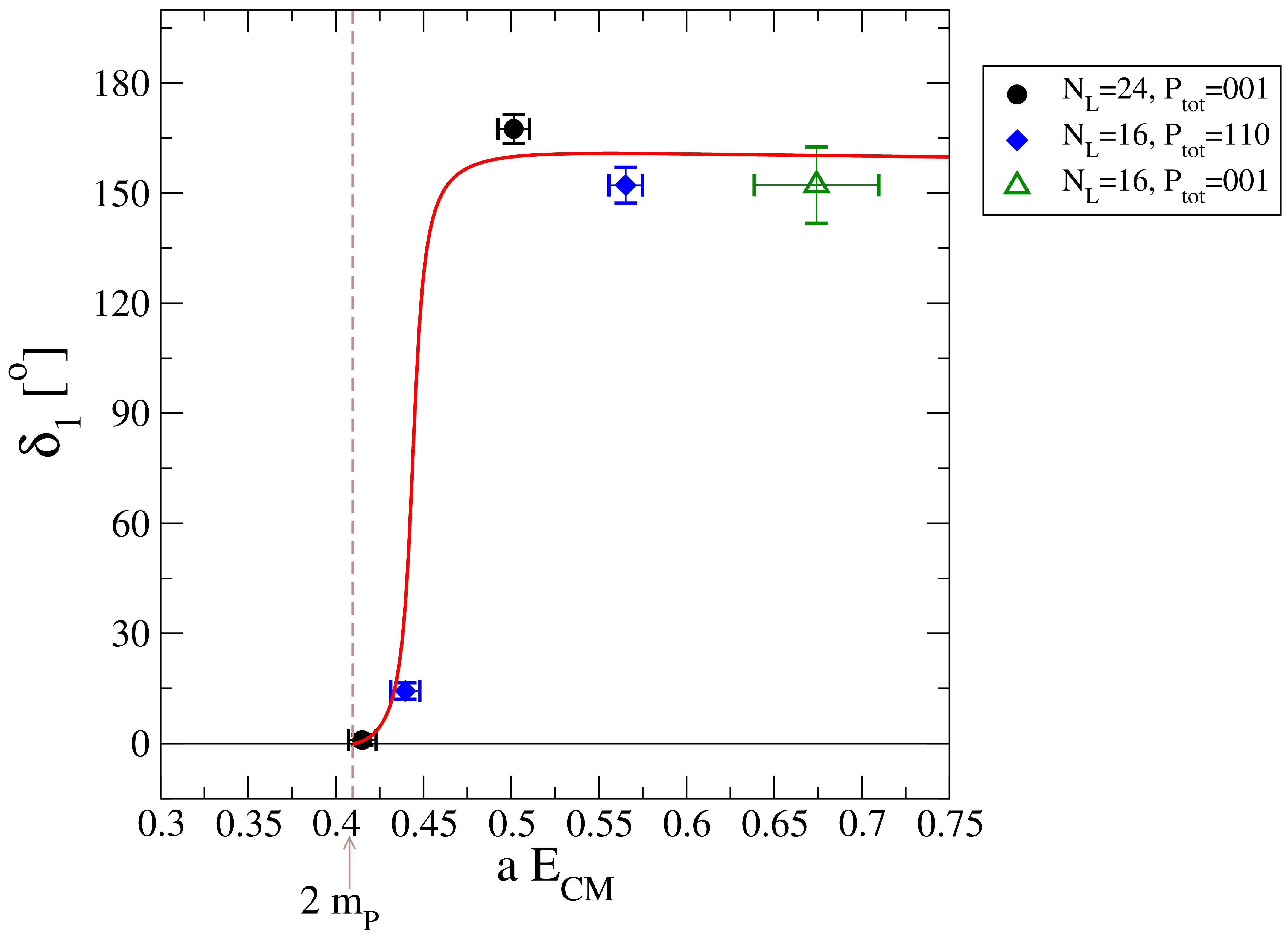
Research Highlights

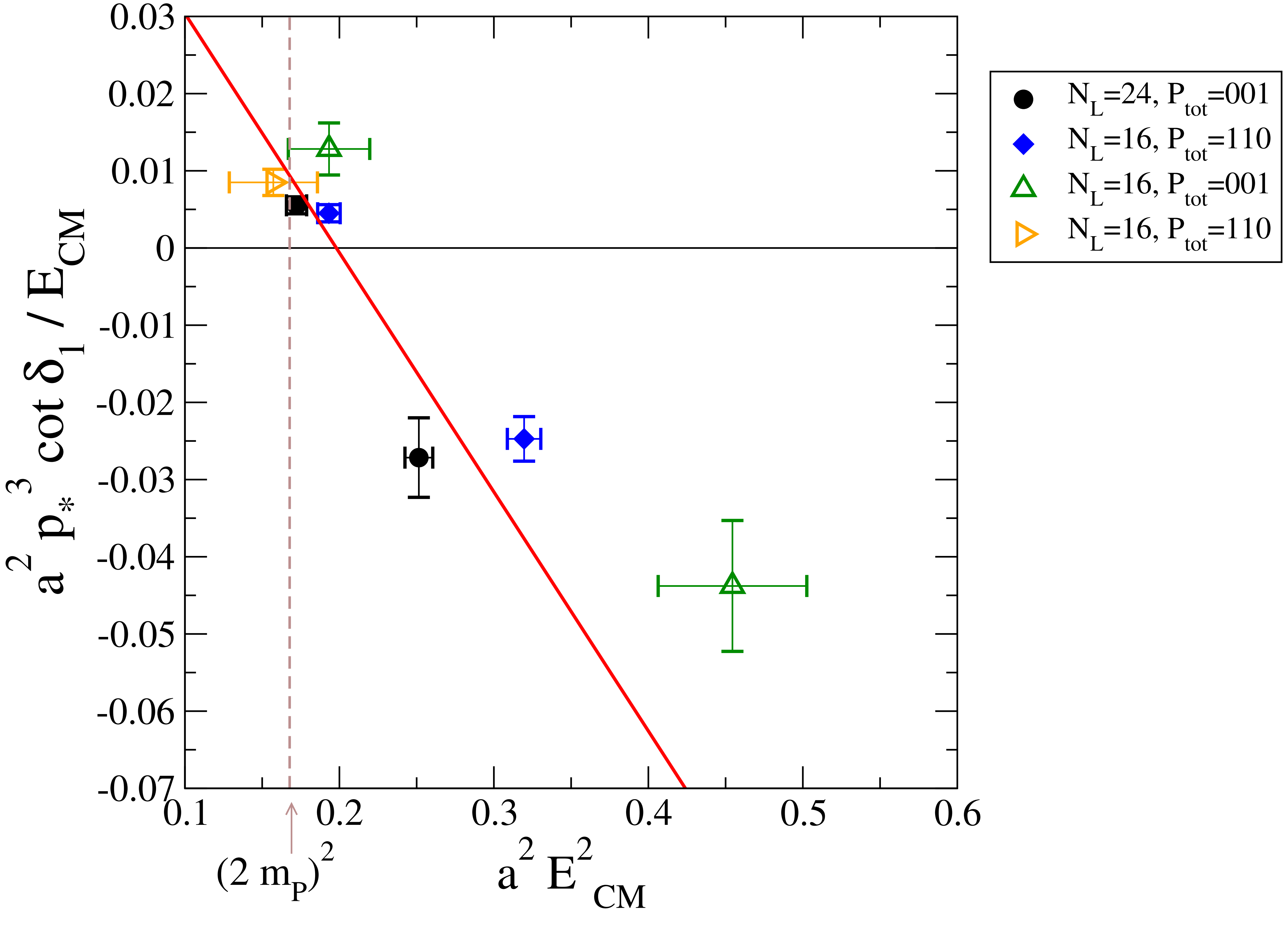
Minimal composite Higgs - First scattering calculation

[Drach, Janowski Prelovsek in preparation]

SU(2) with N_f=2 fundamental fermions:

- First study of the decay width of a vector meson in a viable Composite Higgs model
- The coupling of the vector meson to 2 Goldstone bosons controls the production cross section at the LHC of the resonance in this model.
- Wilson-clover, two pion scattering in 2 moving frames + Breit-Wigner parametrisation of the resonance



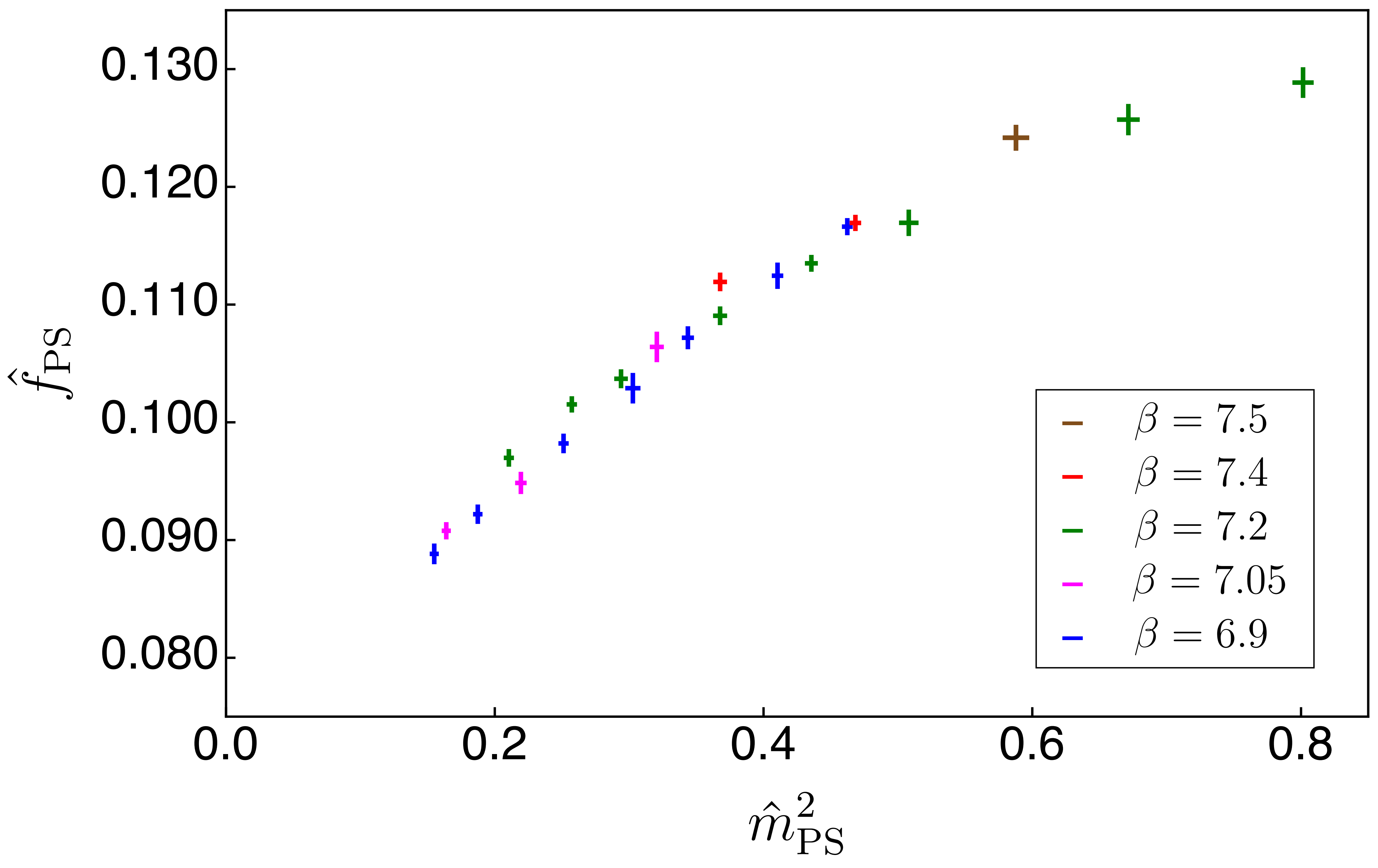


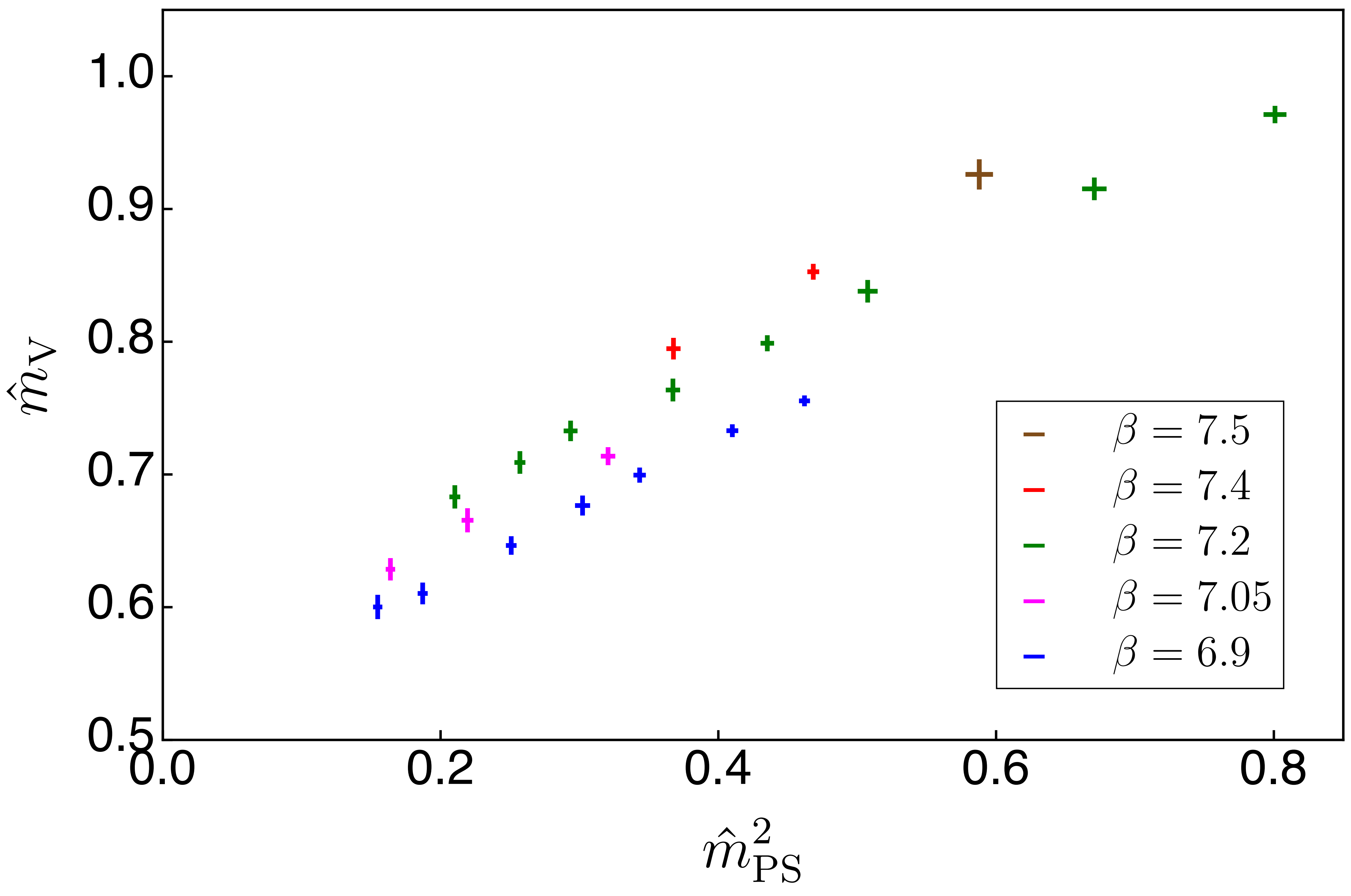
SP(4) with Nf = 2 fundamental fermions

[Ed Bennett, Deog Ki Hong, Jong-Wan Lee, C.-J. David Lin, Biagio Lucini, Maurizio Piai, Davide Vadacchino, Proceedings of Science arxiv:1911.00437]

- First study of the spectrum including chiral extrapolations and discretisation errors.
- Same chiral symmetry breaking pattern an SU(2) with N_f=2 fundamental but different gauge dynamics
- Pave the way to investigate Sp(4) with N_f=2 fundamental and N_f=2 Antisymmetric fermion a Composite Higgs models featuring top partners candidates
- Preliminary quenched study:

[See *Phys.Rev.D* 101 (2020) 7, 074516, arxiv:1912.06505]



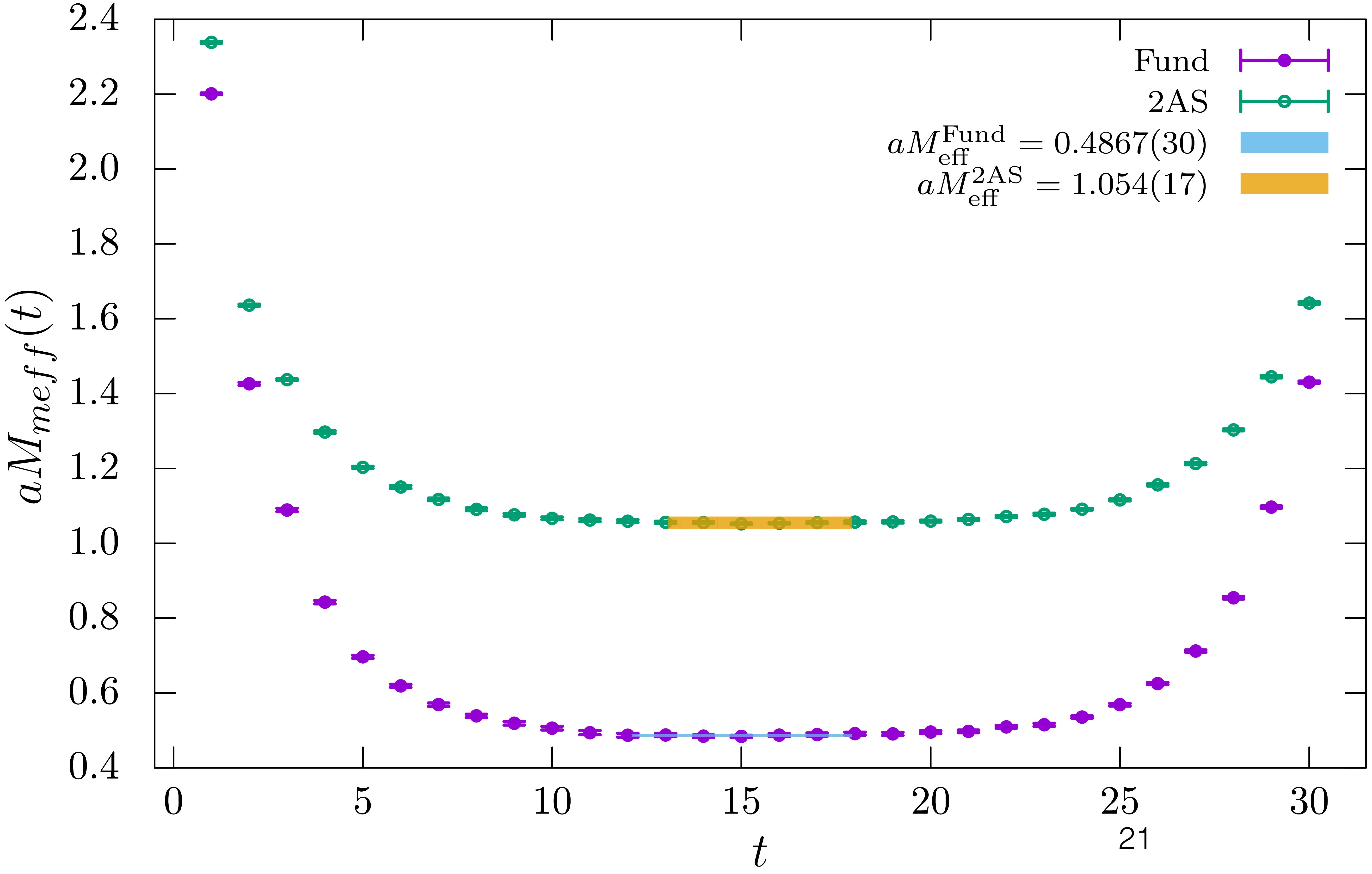


Strong dynamics with matter in multiple representations:

SU(4) gauge theory with two fundamental and two sextet fermions:

- A theory closely related to minimal partial compositness model proposed by Ferretti
- Flexible implementation discussed in detail
- Implemented in Grid
- Wilson Dirac operator with clover improvement

[G. Cossu, L. Del Debbio, M. Panero and D. Preti, *Eur.Phys.J.C* 79 (2019) 8, 638 arxiv:1904.08885]



Outlook

- Search for beyond the Standard Model is a key motivation for current and future particle physics experiments.
- Composite scenarios are appealing to address a number of issues: Higgs naturalness, Dark Matter,…
- Lattice calculations inform phenomenologists and provide reliable tests of the viability of models of composite dynamics.
- Growing interest for the lattice approach to composite models
- Exploring various theories, observables and mechanisms require flexible software