How *strange* is the nucleon ? -Hadronic uncertainties in direct Dark Matter detection -

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in collaboration with

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Institute for Theoretical Physics , Münster, Germany, 13th June 2016

Outline

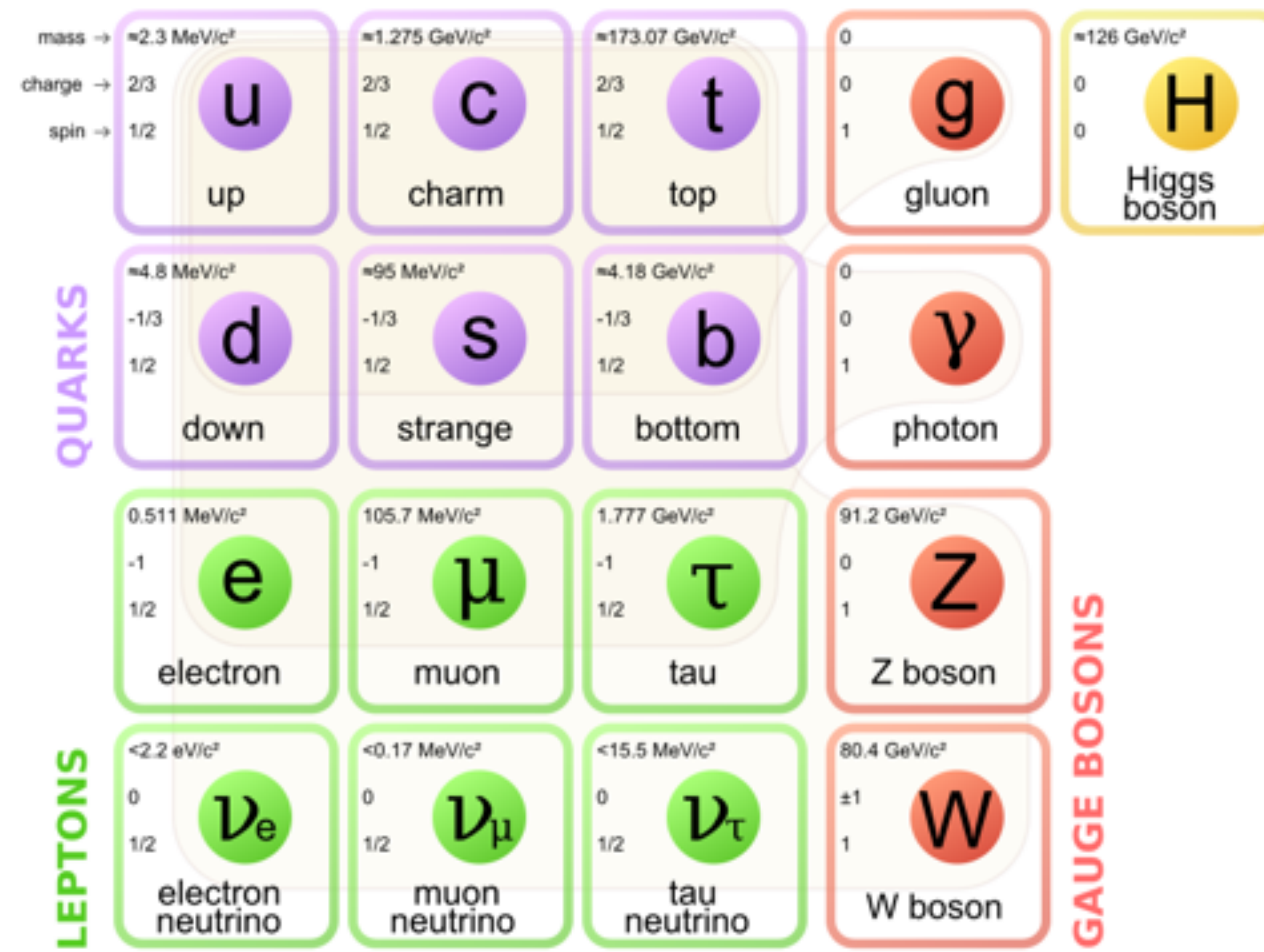
- Introduction
  - ★ Why DM ?
  - ★ How to detect DM ?
  - ★ Main assumptions
- Nucleon mass origins :
  - ★ Energy momentum tensor
  - ★ Heavy quark contribution
  - ★ Effective theory and phenomenological results
- Lattice techniques :
  - ★ Setup
  - ★ Indirect approach
  - ★ Challenges of *disconnected* diagrams
- Lattice results :
  - ★ Our setup
  - ★ New Results
  - ★ Comparison with other methods and collaborations
- Summary/Outlook

Standard Model and beyond…

- Standard Model successful « Gauge Yukawa theory »

BUT

- Theoretical Issues :
  - ★ Naturalness/Fine-tuning
  - ★ Hierarchy
- Experimental evidences :
  - ★ Dark Matter
  - ★ Neutrino masses
  - ★ Not enough CP violation
  - ★ Hint(s) @ CERN …



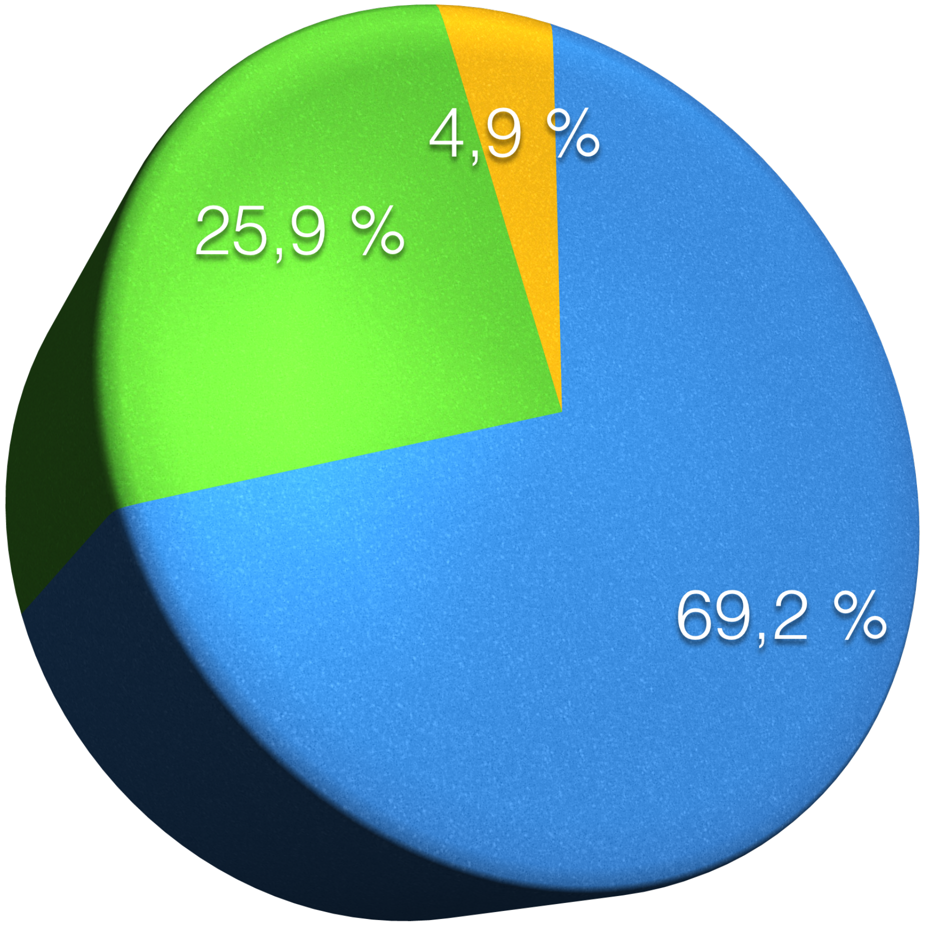
Dark matter in a nutshell

Planck 2015 results. XIII. Cosmological parameters [1502.01589]

- Consistent and accumulating evidences for a large amount of Dark Matter component in the Universe
  - ★ Cosmology
  - ★ Astrophysics (Rotation of spiral galaxies, velocity dispersion of Galaxies, Galaxy clusters and gravitational lensing)

- What do we know :
  - ★ Gravitationally interacts
  - ★ Electrically neutral

- Questions :
  - ★ Relation with EW scale ?
  - ★ Cold or Warm ?
  - ★ size of the self interaction ?
  - ★ Coupled to Higgs boson?
  - ★ Spin ?
  - ★ Is it only one state ?
  - ★ Can it be composite ?

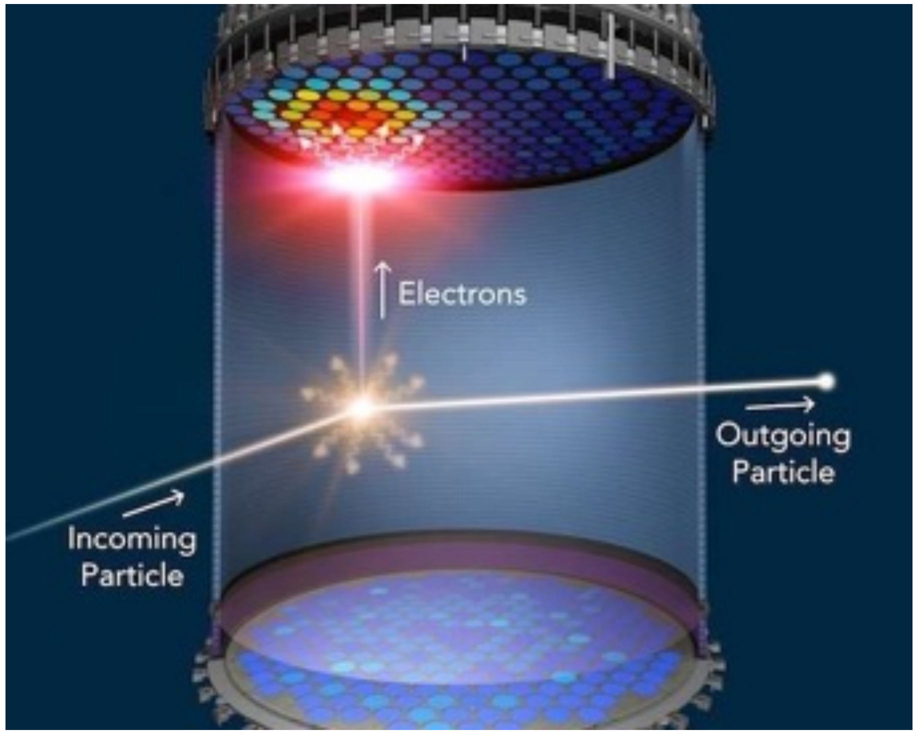


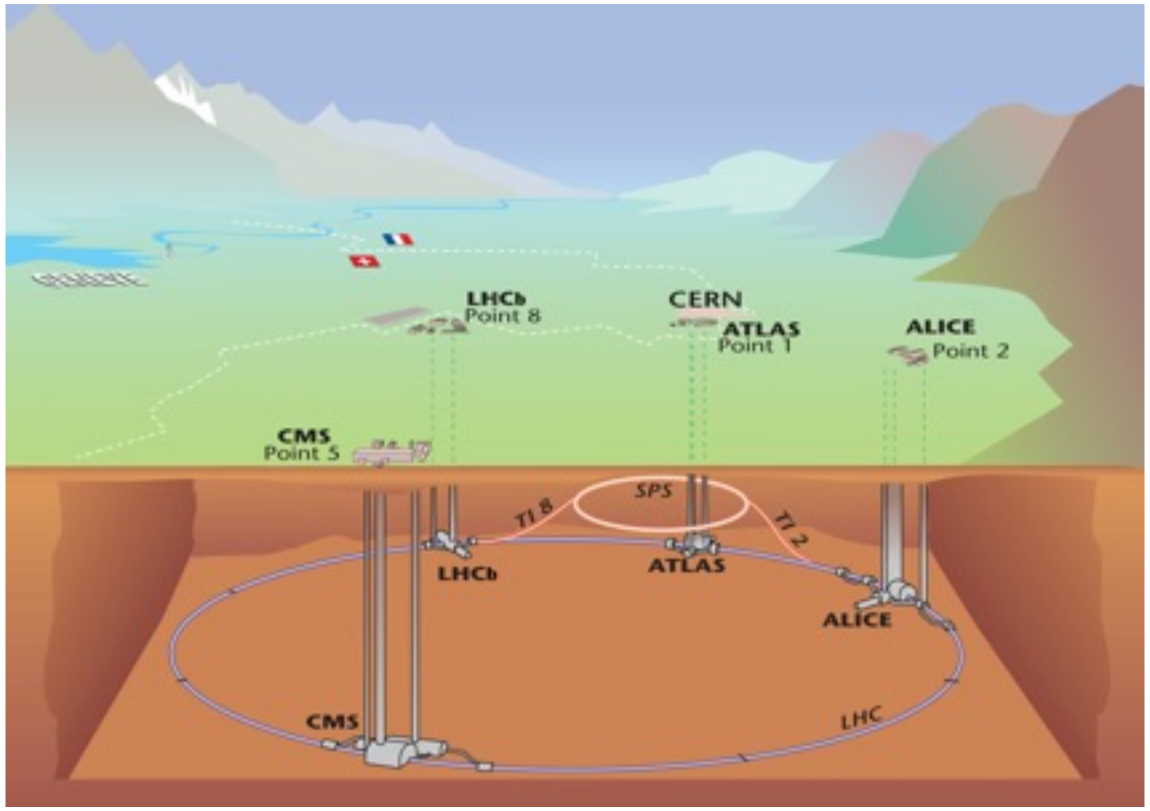
Energy budget of the universe (Planck)

Dark Matter searches

- Types of searches:
  - Indirect detection
  - Direct searches
  - Colliders

credit NASA

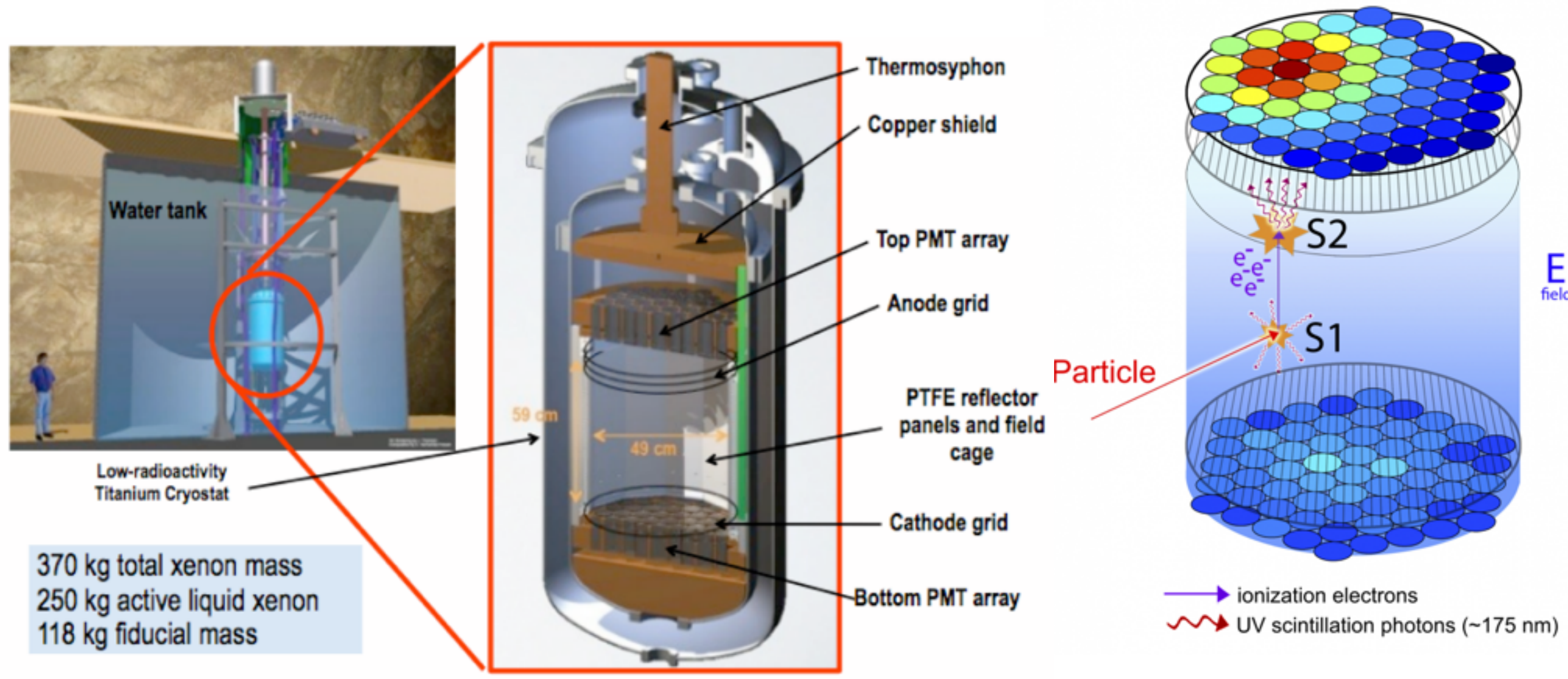




Complementary searches

Direct detection - the LUX experiment

LUX Collaboration, Phys.Rev.Lett. 116 (2016) no.16



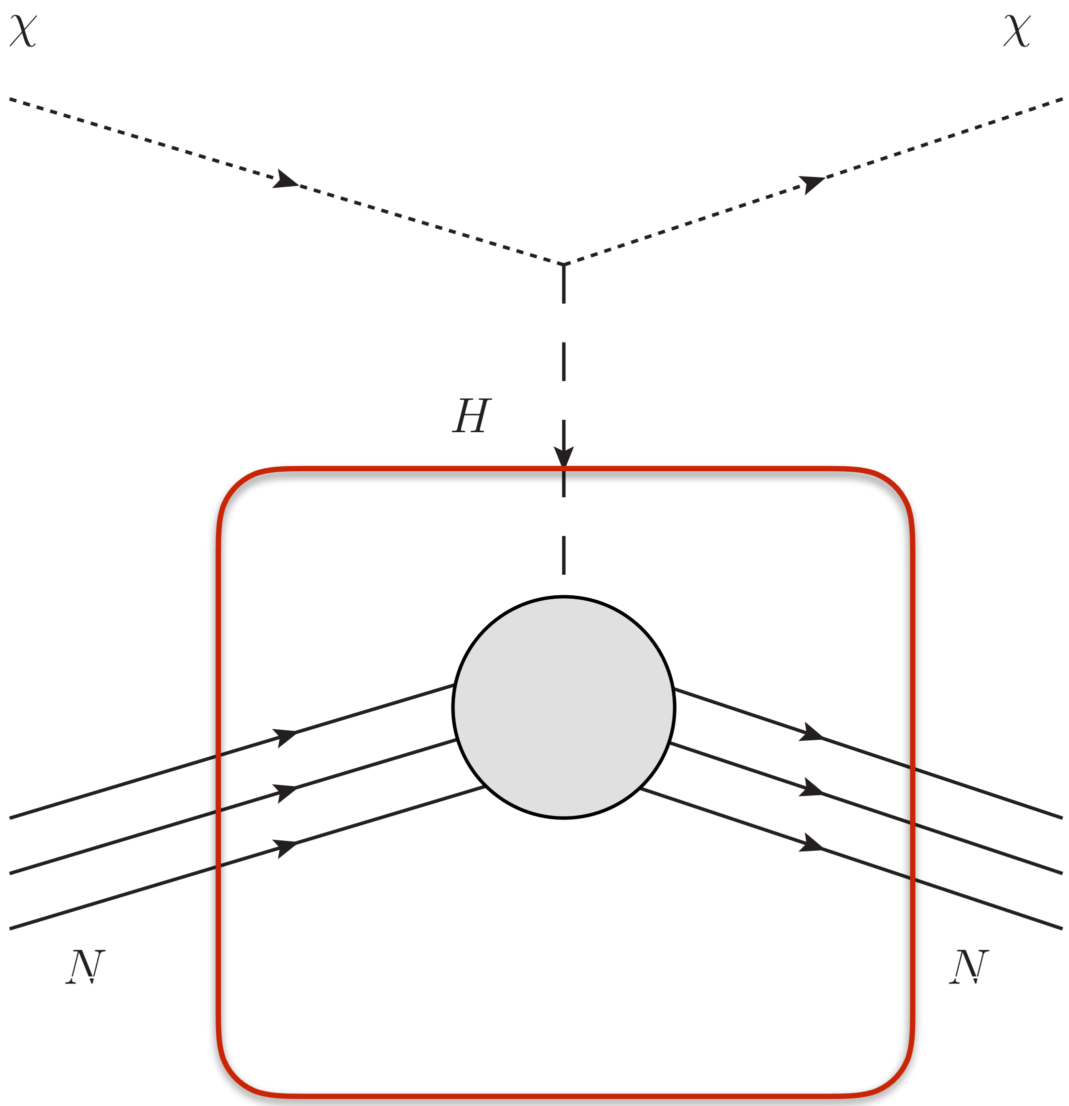
Direct detection experiments constrain the nuclei-DM cross section

Direct detection

- Assumptions:
  - Interaction through Higgs exchange
  - zero momentum transfer limit
  - Collective effects in the nuclei are neglected
  - Here : spin-independent

Detmold *et al.* Phys.Rev. D89 (2014) 074505

- Many on-going experiments:
  - LUX
  - Xenon
  - CREST
  - …



Hadronic uncertainties

From nuclear to nucleon σ-terms

Ellis *et al.* Phys.Rev. D77 (2008) 065026

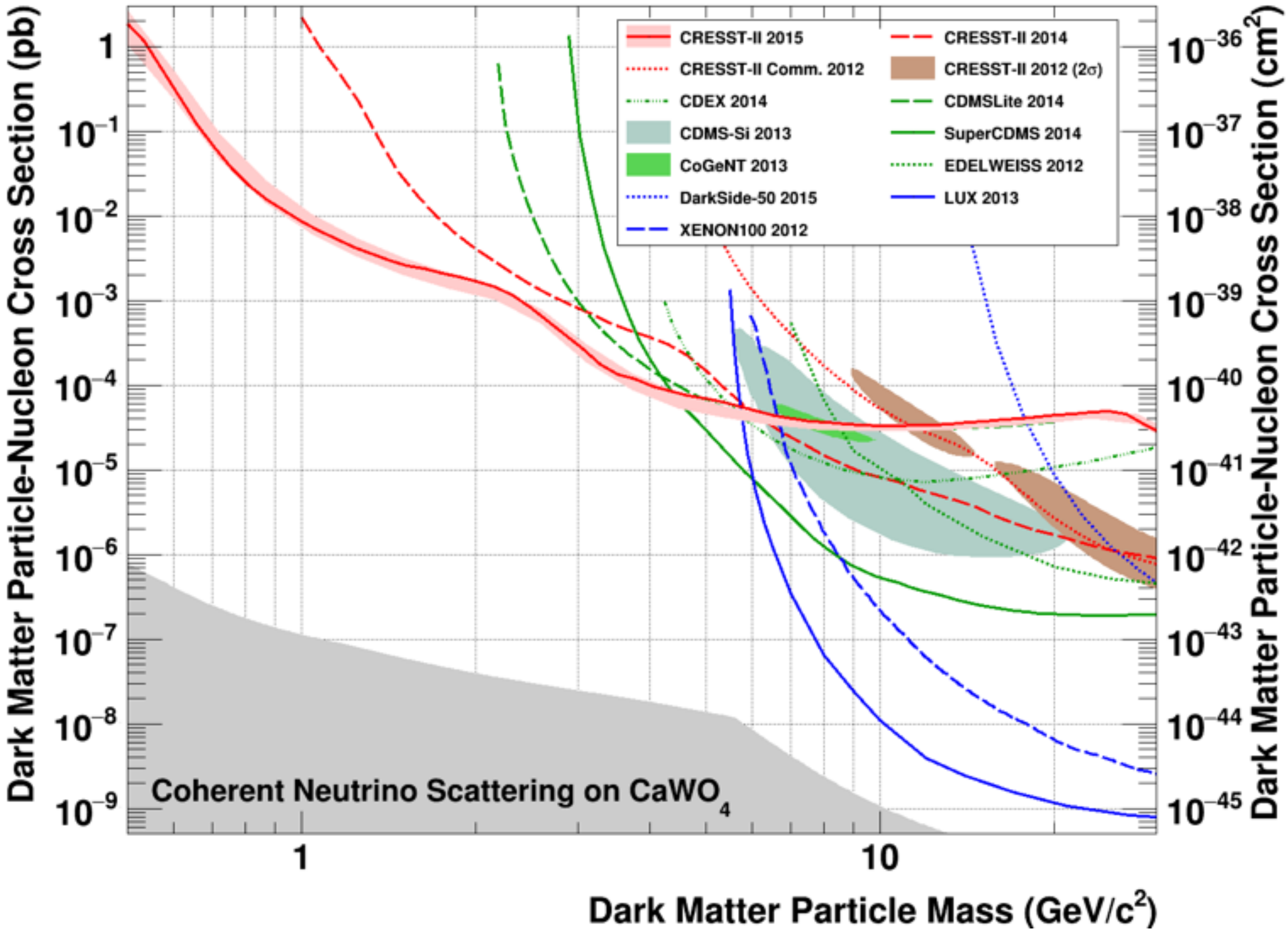
- Assumptions:
  - Interaction through scalar mediator
  - zero momentum transfer limit
  - Collective effects in the nuclei are neglected
  - Here : spin-independent
- Cross section: $$\sigma_{\rm SI} = \frac{4m_r^2}{\pi}\left(Zf_p + (A-Z)f_n\right)^2\,, \qquad m_r = \frac{m_{\rm DM}m_{\rm at.}}{m_{\rm DM}+m_{\rm at.}}$$
  - Characterized by atomic and mass number of the nuclei
  - ***f_{Tq}*** : scalar coupling of individual nucleons with flavor q
  - ***a_q*** : depends on underlying DM model and on the EW scale

$$\frac{f_{N=n,p}}{m_N} = \sum_{q=u,d,s,c,b,t} f_{T_q}\frac{\alpha_q}{m_q}, \qquad f_{T_q} = \frac{m_q\langle N|\bar{q}q|N\rangle}{m_N}$$

Non perturbative property of the Nucleon

Spin independent case

CREST collaboration, Eur.Phys.J. C76 (2016) no.1, 25



Input to constrain New Physics

Origin of the Nucleon mass

Neglect isospin breaking effect $m_u=m_d=m_l$

- The energy momentum tensor :
  - Rigorous decomposition of the Nucleon mass

X.-D. Ji, Phys.Rev.Lett. 74 (1995) 1071-107479

$$m_X = \langle X,\vec{0}|T^0{}_0|X,\vec{0}\rangle = \sum_q \underbrace{m_q\langle X,\vec{0}|\bar{q}q|X,\vec{0}\rangle}_{\sigma_q^X} + \text{gauge contribution}$$

- Feynman-Hellman theorem :
  - $\sigma_q^X \equiv m_q \dfrac{\partial}{\partial m_q} m_X$

Indirect method to compute the σ-terms !

  - Equivalent to $f_{T_q} = \dfrac{\sigma_q^X}{m_N}$

- Other quantities of interests :

$$\sigma_{\pi N} = \sigma_l = m_l\langle N|\bar{u}u + \bar{d}d|N\rangle, \quad m_l = \frac{m_u+m_d}{2}$$

$$\sigma_0 = m_l\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

$$y_N = \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

the « strangeness » of the nucleon

Origin of the Nucleon mass : heavy quarks

Shifman, Vainshtein and Zakharov, Phys.Lett. B78 (1978) 443-446

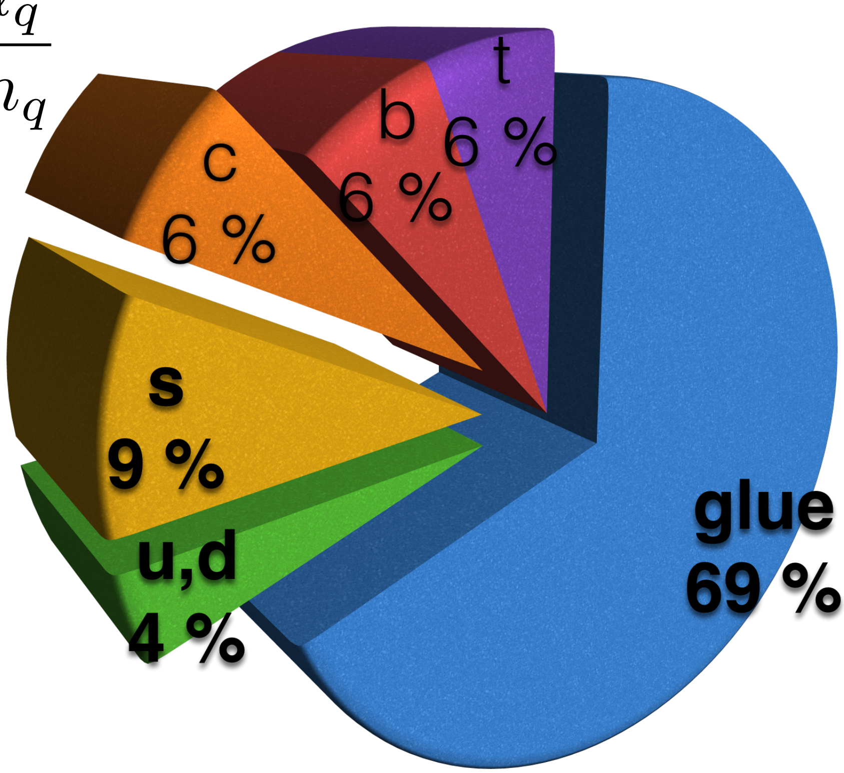
- In the static limit :

  - σ_h in terms of the sum of the σ-terms for which $m_q < m_h$

$$\sigma_h^X = \frac{2}{27}\left(m_X - \sum_{q=u,d,s} \sigma_q^X\right)$$

  - gluon contribution and heavy quark contributions are related !
  - Radiative corrections — Hill and Solon, Phys.Rev. D91 (2015) 043505; Vecchi [1312.5695]
  - Explain why $\frac{f_N}{m_N} \approx \sum_{q=u,d,s} f_{T_q}\frac{\alpha_q}{m_q} + \frac{2}{27} f_{T_G} \sum_{q=c,b,t} \frac{\alpha_q}{m_q}$

- Cross section proportional to $\mathbf{f_N}^2$
- Assuming σ_l ~38 MeV, σ_s ~87 MeV, σ_h ~60 MeV



Heavy quark contribution should confirmed by a lattice calculation

Phenomenological estimates

- σ_l determination :
  - π-N scattering data
  - extrapolation at the unphysical Cheng-Dashen point

- σ_s determination :
  - SU(3) breaking in the spectrum : σ_0

$$\sigma_s = \frac{1}{2}\frac{m_s}{m_l}(\sigma_l - \sigma_0) \qquad y_N = 1 - \frac{\sigma_0}{\sigma_l}$$

- Examples:
  - GLS : σ_l = 45(8) MeV J. Gasser, H. Leutwyler, and M. Sainio, Phys. Lett. B 253, 252 (1991)
  - GWU : σ_l = 64(7) MeV M. M. Pavan *et al*, PiN Newsl. 16, 110 (2002).
  - AMO : σ_l = 59(7) MeV J. Alarcon, J. Martin Camalich, and J. Oller, Phys. Rev. D85, 051503 (2012)
  - σ_0 = 36(7) MeV B. Borasoy and U.-G. Meissner, Ann. Phys. (Berlin) 254, 192 (1997).
  - σ_0 = 58(8) MeV J. M. Alarcon, *et al*, Phys. Lett. B 730, 342 (2014)

First principles answers are needed

Lattice techniques

Lattice calculations in a nutshell

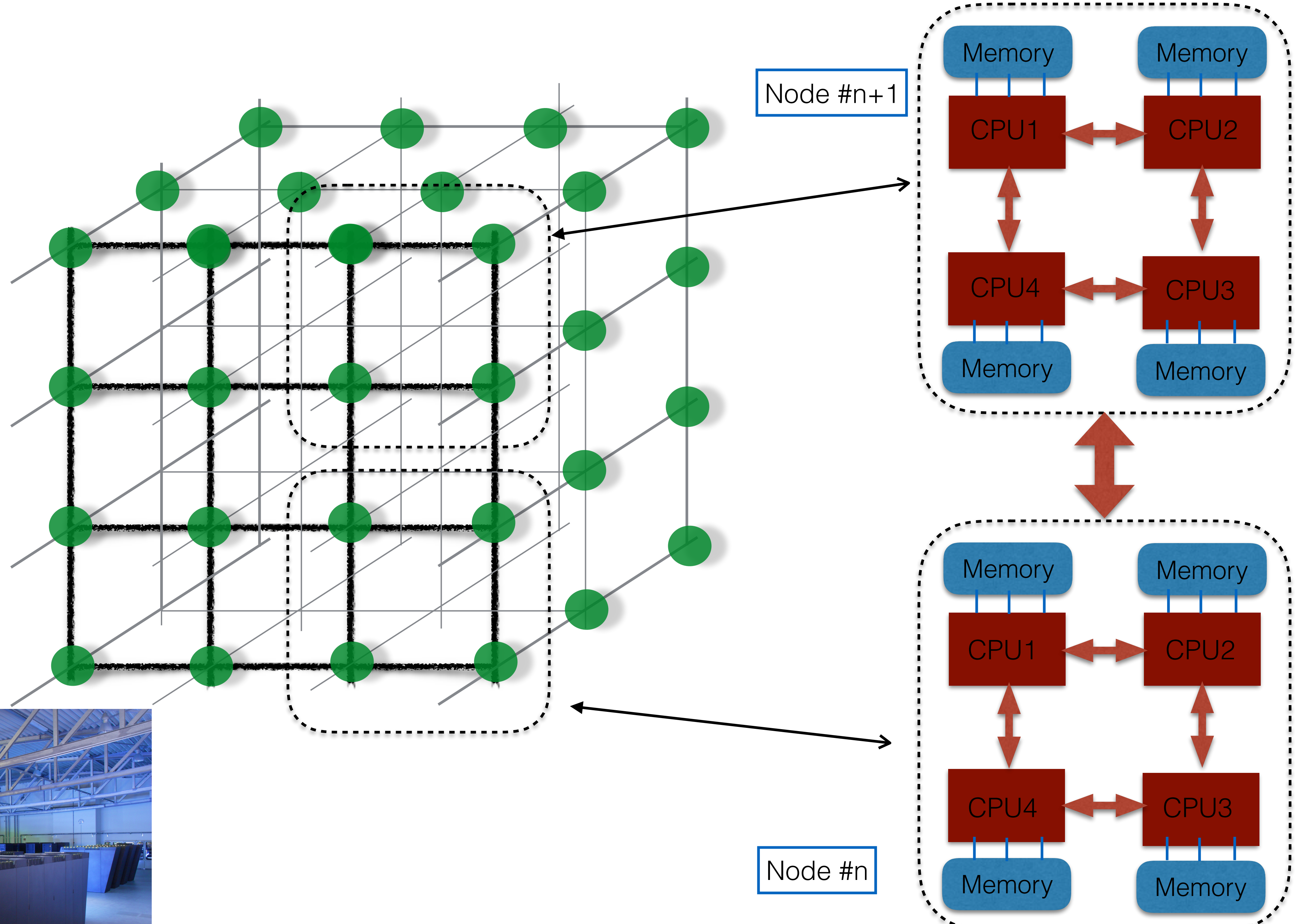
- LGT : Compute non perturbatively euclidean correlation functions:

$$\langle O[\bar{\psi}, \psi, A_\mu] \rangle = \frac{\int D[\bar{\psi}]D[\psi]D[A_\mu]e^{-S[\bar{\psi},\psi,A_\mu]}O[\bar{\psi}, \psi, A_\mu]}{Z}$$

- Strategy :
  - Discretize : lattice spacing a, volume V, mass m_f,
  - Boltzmann weight: probability distribution
  - Sample : HMC algorithm
  - Compute correlations functions at finite V, a, and m_f.
  - Renormalize if needed
  - Extrapolate to $V=\infty$, $a=0$ and $m_f=0$

Theoretically well defined framework !
Errors can be systematically controlled

Lattice calculations in a nutshell



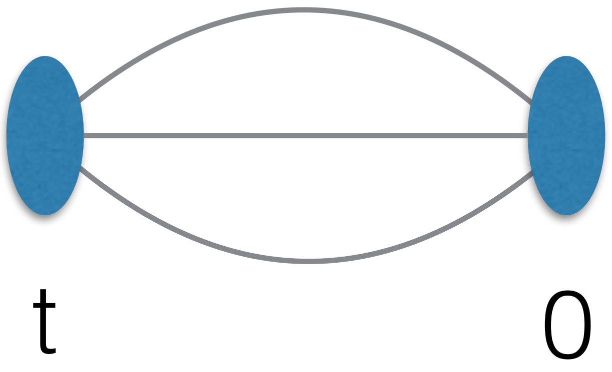
Gauge configuration generation typically run on ~ 10 000 cores !

Extracting masses

- Compute non perturbatively euclidean correlation functions:

$$C^X_{\rm 2pts}(t) = \sum_{\vec{x}} \mathcal{P}\langle J(x) J^\dagger(0)\rangle \propto e^{-M_X t} + \mathcal{O}(e^{-M_{X^*} t}), \quad M_{X^*} > M_X$$

- Sketch of the strategy :
  - Choose J : to give the right quantum numbers,
  - Study the asymptotic behavior



No assumptions on the quark and glue content.

Extracting (bare) Matrix elements

- Compute non perturbatively euclidean correlation functions:

$$R(t,t_s) = \frac{\sum_{\vec{x},\vec{y}} \mathrm{Tr}\left\{\Lambda\langle J(x)O(y)J^\dagger(0)\rangle\right\}}{C^X_{\mathrm{opts}}(t_s)} = \langle X|O(0)|X\rangle + \mathcal{O}(e^{-\Delta M_X(t-t_s)}) + \mathcal{O}(e^{-\Delta M_X t_s})$$

- Sketch of the strategy :
    - Choose O, Λ
    - Extract the asymptotic behavior in a 2D plane (t,t_s)
    - Obtain the bare matrix element

Asymptotically exact

Disconnected contributions

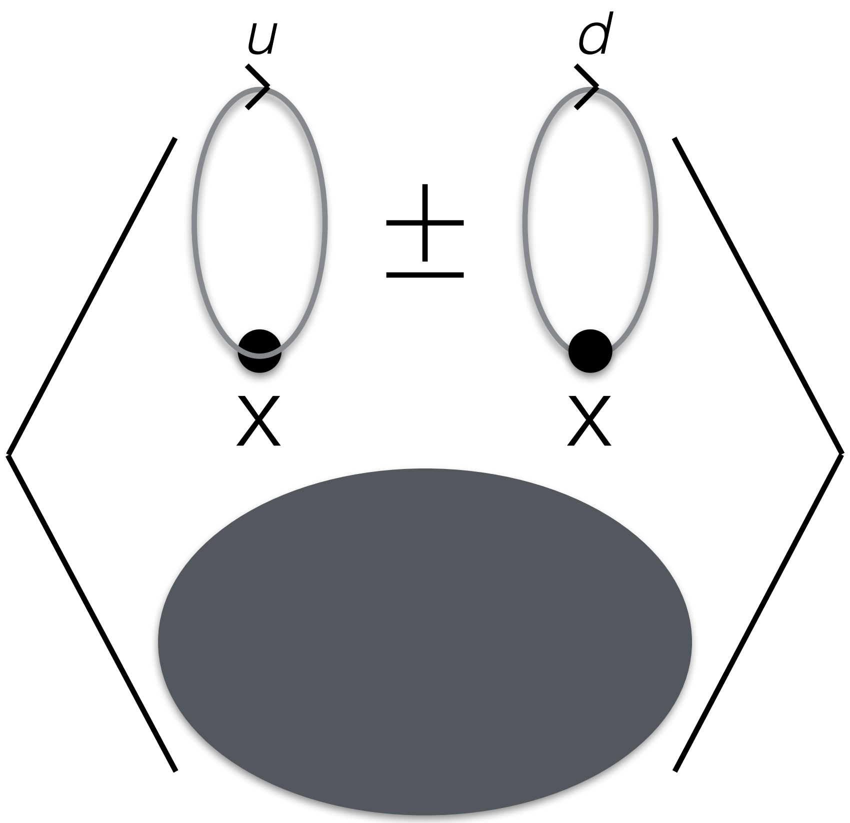
- Jargon :
  - «Connected» correlation functions only involve quark propagator from different space time points.
  - «Disconnected» correlation functions involve quark propagators from the same space time point.

- Examples
  - Connected :

$$\langle \ldots \left[\bar{u}\Gamma u - \bar{d}\Gamma d \right](x) \ldots \rangle$$

  - Disconnected :

$$\langle \ldots \left[\bar{u}\Gamma u + \bar{d}\Gamma d \right](x) \ldots \rangle$$



Why are they fundamental ?

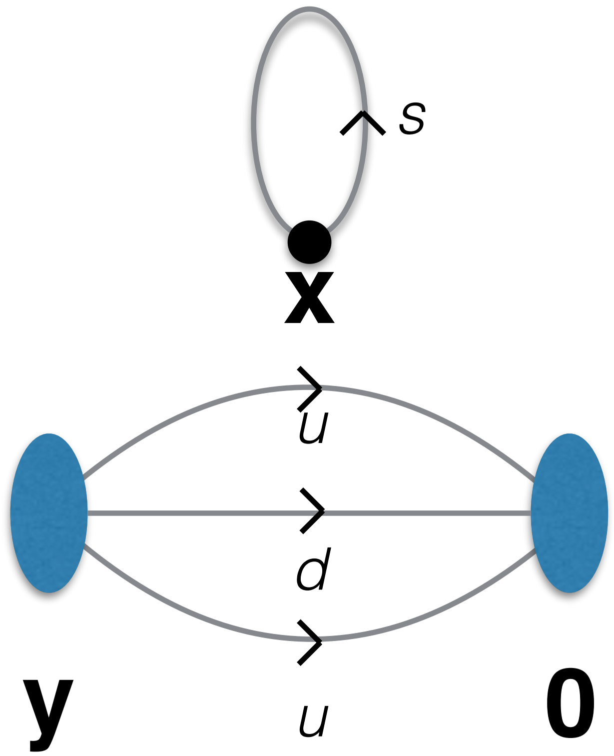
- Some relevant observables:
  - Hadronic contribution to the vacuum polarization
  - η, η', σ fermionic operators
  - flavour singlet quantities
  - Isospin breaking quantities (from QED or from mass difference)
  - matrix elements of operator containing only one flavor

- Remark :
  - they are an issue both to compute masses and matrix element

Why are they difficult to estimate?

- Example:
    - Strange σ-term of the Nucleon

$$\langle \bar{N}(y)\ \bar{s}s(x)\ N(0)\rangle, \quad N = \epsilon^{abc}(u^{a,T}C\gamma_5 d^b)u^c$$



$$\sim D_s^{-1}[U](x \to x)$$

Large fluctuations !

$$\sim C_{2\text{pt}}(0 \to y)$$

$$\sim \langle C_{2\text{pt}}(0 \to y) D_s^{-1}[U](x \to x)\rangle$$

Measures correlations between one object and a UV sensitive quantity !

Twisted mass fermions

Frezzotti, Grassi, Sint, Weisz 1999

- Action:

$$S^{\rm tm}_{(m_0,\mu)} = a^4 \sum_x \bar{\chi}(x)\left[\gamma_\mu \tilde{\nabla}_\mu + m_0 - r\frac{a}{2}\nabla^*_\mu \nabla_\mu + i\mu\gamma_5\tau_3\right]\chi(x)$$

  - m_0 : bare Wilson mass, μ : bare twisted mass
  - χ : doublet of Dirac spinors
  - τ_3: Pauli Matrix
  - Wilson fermions : $\mu=0$

- Properties:
  - Break flavor symmetry and parity at finite lattice spacing
  - automatic O(a) improvement if m_0 is properly tuned
  - non degenerate doublet can be added

Theoretically well defined framework !

Errors can be systematically controlled

Twisted mass variance reduction: idea

S. Dinter, VD, R. Frezzotti, G. Herdoiza, K. Jansen, G. Rossi JHEP 1208 (2012) 037

- Twisted Mass doublet Dirac operator :

$$D[U] = \begin{pmatrix} D_+[U] & 0 \\ 0 & D_-[U] \end{pmatrix}$$

$$D_\pm[U] = D_\mathrm{W}[U] + am_0 \pm ia\mu_q\gamma_5$$

- Properties :

$$\frac{1}{D_-} - \frac{1}{D_+} = 2ia\mu_q \frac{1}{D_-}\gamma_5\frac{1}{D_+}$$

Algebric property

$$i\bar{\chi}\gamma_5\tau_3\chi \to \bar{u}u + \bar{d}d$$

Transformation to the « physical » basis

- We have shown that

Bare mass **Bare matrix element**

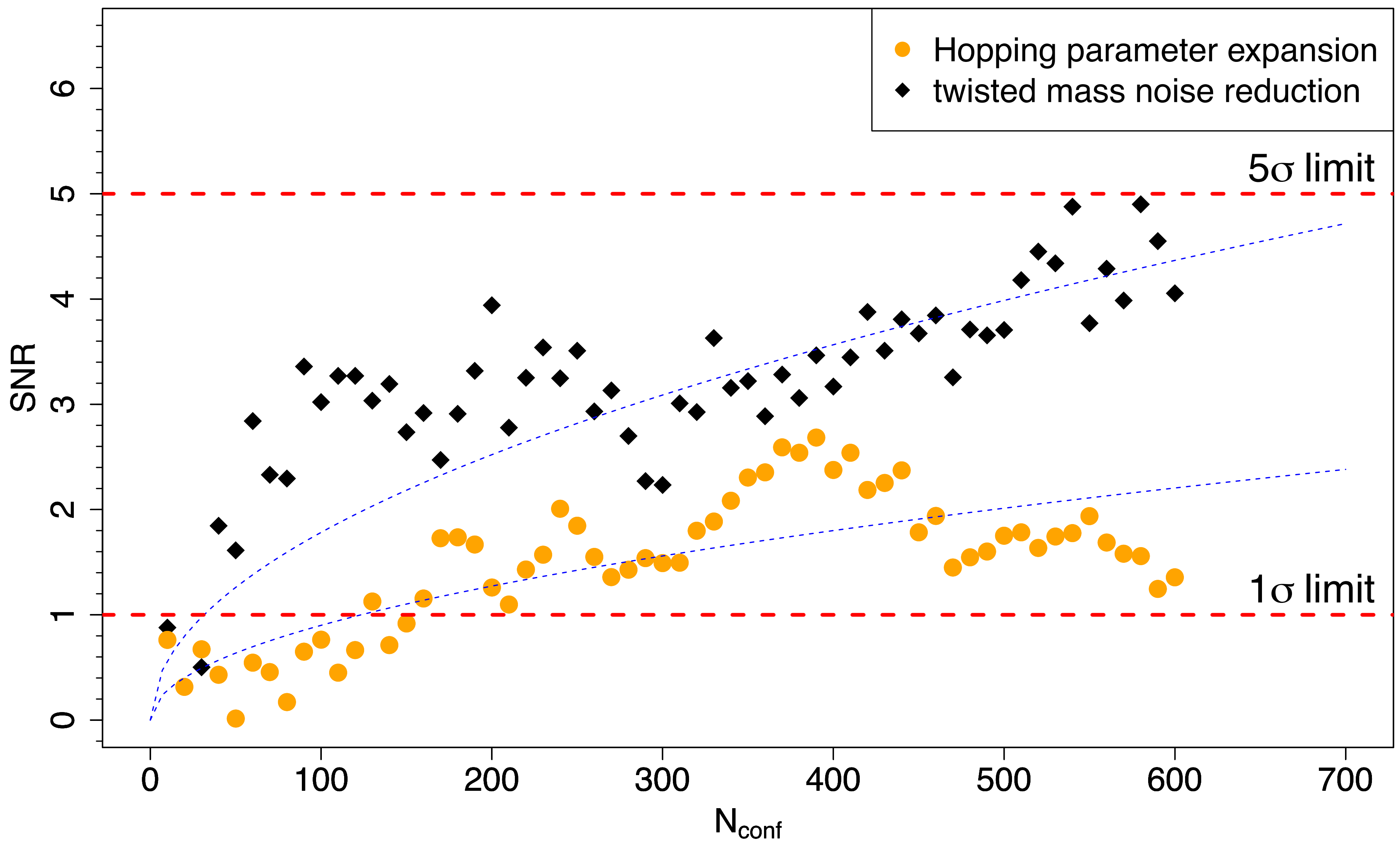
$$\mu_q\langle N,\vec{0}|\bar{\chi}\gamma_5\tau_3\chi|N,\vec{0}\rangle = \sigma_{\pi N}$$

Renormalization group invariant!

- Numerically : exploit the fact that the difference is proportional to the product

twisted mass variance reduction: performances

S. Dinter, VD, R. Frezzotti, G. Herdoiza, K. Jansen, G. Rossi JHEP 1208 (2012) 037



$$\frac{R(t_{\rm op}) = 6a, t_s = 12a)}{dR(t_{\rm op} = 6a, t_s = 12a)}(N_{\rm conf})$$

Huge improvement at fixed numerical cost with twisted mass fermions !

Generalisation to the strange sector

- Trick : introduce at the *valence* level a doublet of strange quark !

They differ by O(a) effects

- The proof goes through
- Recipe :
  - Tune mass (μ_s) such that $m_K^{\text{valence}} = m_K^{\text{sea}}$
  - Write the corresponding Ward-Identities to proof renormalizability
  - Deduce that

$$\frac{\mu_s}{2}\langle N,\vec{0}\left|\bar{\chi}_s i\gamma_5\tau_3\chi_s\right|N,\vec{0}\rangle = \sigma_s$$

Idem for σ_c !

ETMC setup (old)

Frezzotti, Grassi, Sint, Weisz, 1999

- Properties :
  - N_f=2+1+1 simulations : degenerate light flavors (u,d), strange (s) and charm(c) bare Wilson mass, μ : bare twisted mass
  - Lightest pion mass : 230 MeV
  - 3 lattice spacings
  - multiple volumes

- Many results :
  - baryon spectrum and structure
  - flavour physics
  - Hadronic contribution to the g-2
  - ….

ETMC setup (new)

Frezzotti, Grassi, Sint, Weisz 1999

- Properties :
  - N_f=2 simulations : degenerate light flavors (u,d) (with clover term)
  - Physical pion mass : ~140 MeV
  - One lattice spacing
  - One volume

- Many results :
  - baryon spectrum and structure
  - flavour physics
  - Hadronic contribution to the g-2
  - ….

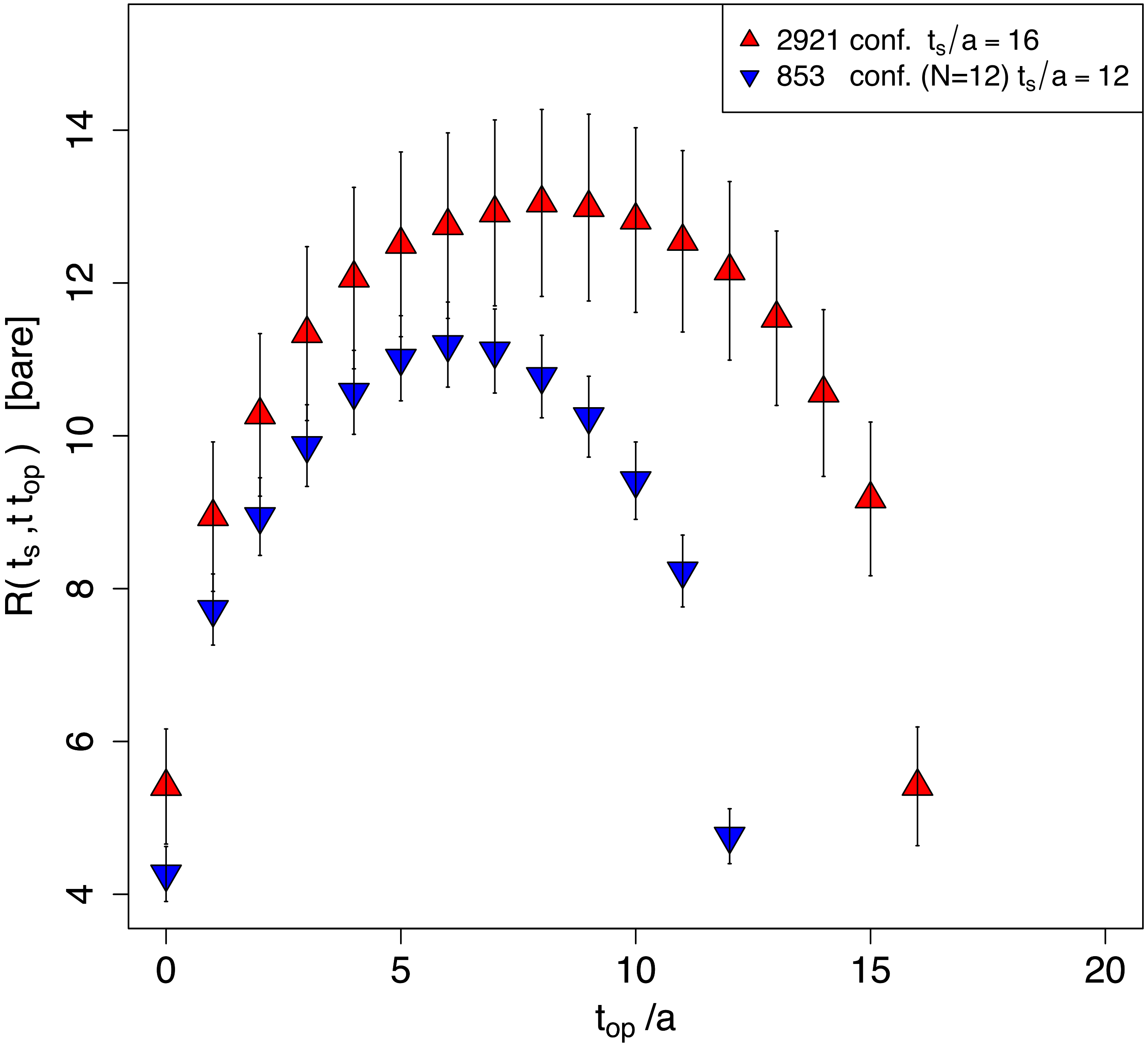
N_f=2+1+1 simulations at the physical pion mass are underway !

Numerical results & systematics

More problems….

- Example σ_l:
  - N_f=2+1+1 simulations
  - pion mass : 380 MeV
  - Large statistics

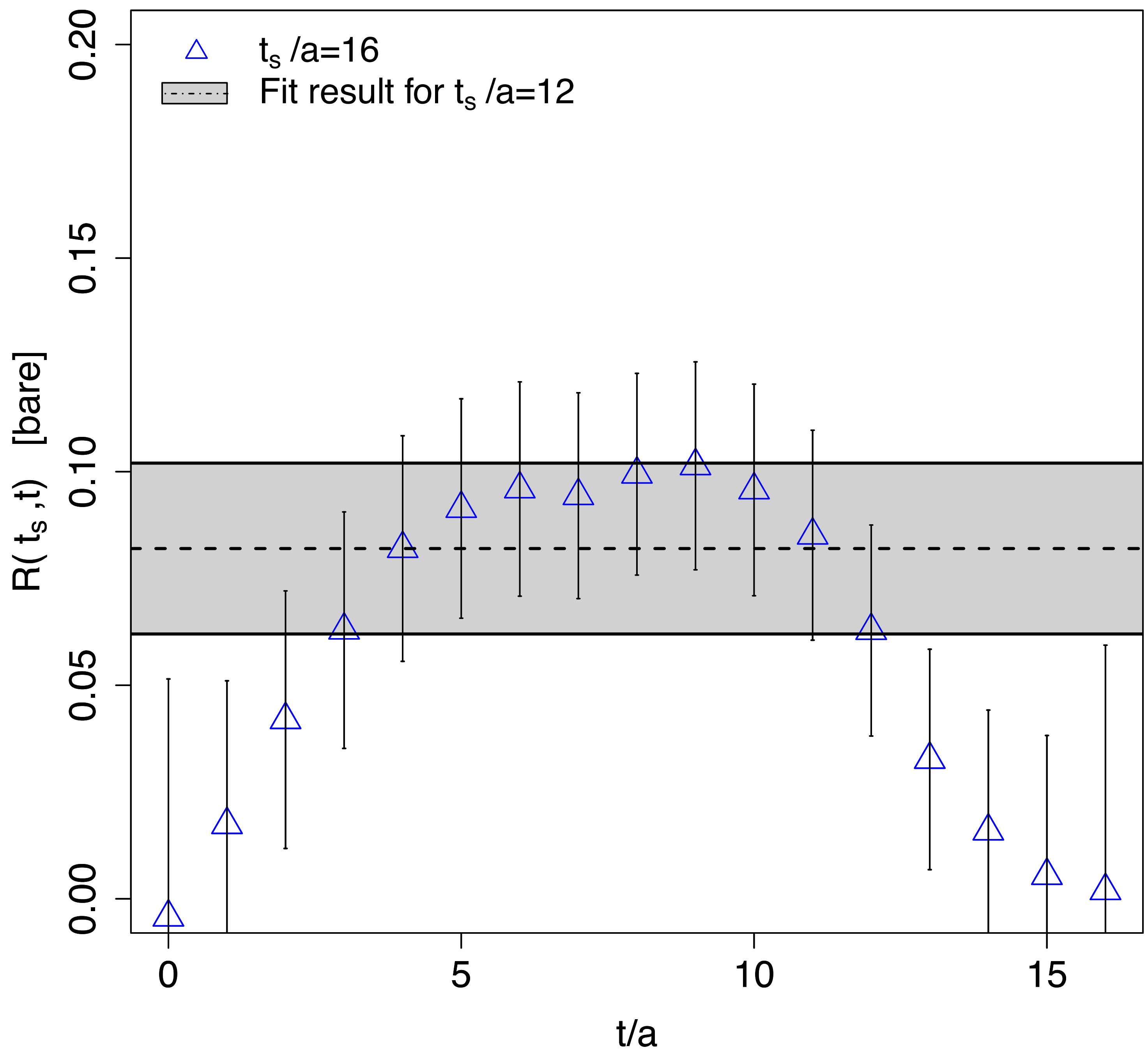
- Technicalities$_l$:
  - Both connected and disconnected contributions
  - large excited states contamination !!!
  - similar in the strange sector



Alternative : the strangeness

S. Dinter, VD, R. Frezzotti, G. Herdoiza, K. Jansen, G. Rossi JHEP 1208 (2012) 037

- Example y_N:
  - N_f=2+1+1 simulations
  - pion mass : 380 MeV
  - Large statistics
- Technicalities:
  - Both connected and disconnected contributions
  - Excited states contamination cancels out
  - First 5σ away from 0 results for y_N



Excited states under control ! But what about the other systematics ?

Heavy Baryon Chiral Perturbation Theory

- Chiral perturbation theory :

$$m_{\rm PS}^2 = 2Bm_l + \mathcal{O}(m_l^2)$$

- Heavy baryon χPT:
  - EFT describing interactions of nucleons and pions
  - Expansion in $m_{\rm pions} / m_B$
  - LO in $m_{\rm pions} / m_B$

$$m_N(m_{\rm PS}) = m_N^{(0)} - 4c^{(1)} m_{\rm PS}^2 - \frac{3g_A^2}{32\pi f_\pi^2} m_{\rm PS}^3 + \mathcal{O}(m_{\rm PS}^4)$$

- FH theorem :
  - $\sigma_q^X \equiv m_q \dfrac{\partial}{\partial m_q} m_X$
  - Chiral expansion of σ_l :

$$\sigma_l(m_{\rm PS}) = m_{\rm PS}^2 \left(-4c^{(1)} - \frac{3}{2} \frac{3g_A^2}{16\pi f_\pi^2} m_{\rm PS} + \mathcal{O}(m_{\rm PS}^2) \right)$$

-4 $c^{(1)}$ must be strictly positive

What about the strangeness ?

- Chiral perturbation theory : $$m_{\rm PS}^2 = 2Bm_l + \mathcal{O}(m_l^2)$$

- Heavy baryon χPT:

$$m_N(m_{\rm PS}) = m_N^{(0)} - 4c^{(1)}m_{\rm PS}^2 - \frac{3g_A^2}{32\pi f_\pi^2} m_{\rm PS}^3 + \mathcal{O}(m_{\rm PS}^4)$$

- σ_s ansatz :

$$\sigma_s(m_{\rm PS}) = m_s\left(d_0 + d_1 m_{\rm PS}^2 + \mathcal{O}(m_{\rm PS}^3)\right)$$

- y_N expansion : (neglecting the strange quark mass depend of m_{PS})

$$y_N = 2\frac{\partial m_N}{\partial m_s}\left(\frac{\partial m_{\rm PS}^2}{\partial m_l}\frac{\partial m_N}{\partial m_{\rm PS}^2}\right)^{-1}$$

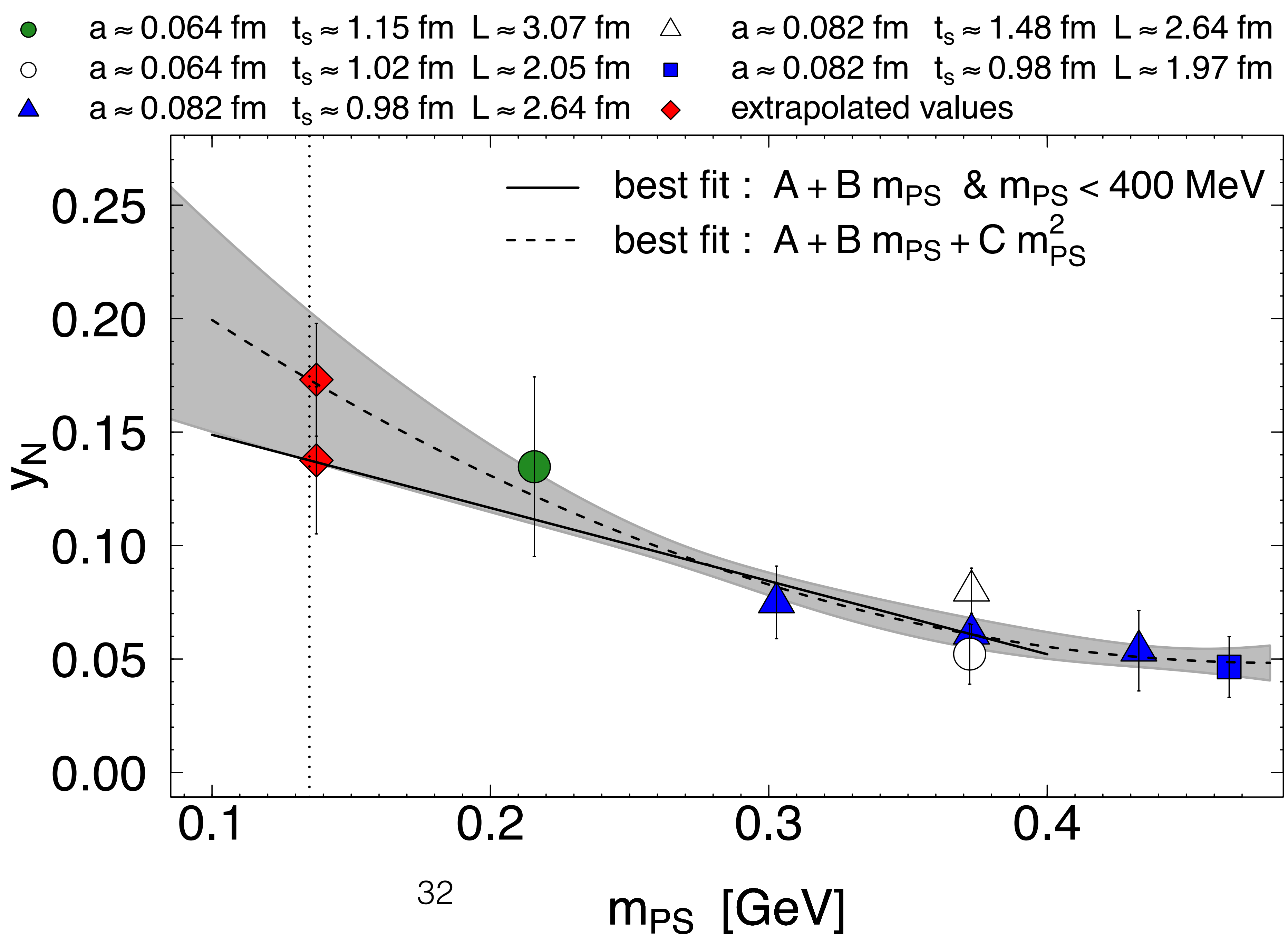
$$y_N = y_N^{(0)} + y_N^{(1)} m_{\rm PS} + \mathcal{O}(m_{\rm PS}^2), \text{ with } y_N^{(0)} = \frac{d_0}{-4Bc^{(1)}}, \quad y_N^{(1)} = \frac{9d_0 g_A^2}{64\pi B(4c^{(1)})^2 f_{\rm PS}^2}$$

y_N should be an increasing function of m_{PS}!

Chiral behavior y_N

- Setup:
  - N_f=2+1+1 simulations
  - Several lattice spacings
  - Several volumes
  - Chiral extrapolation challenging

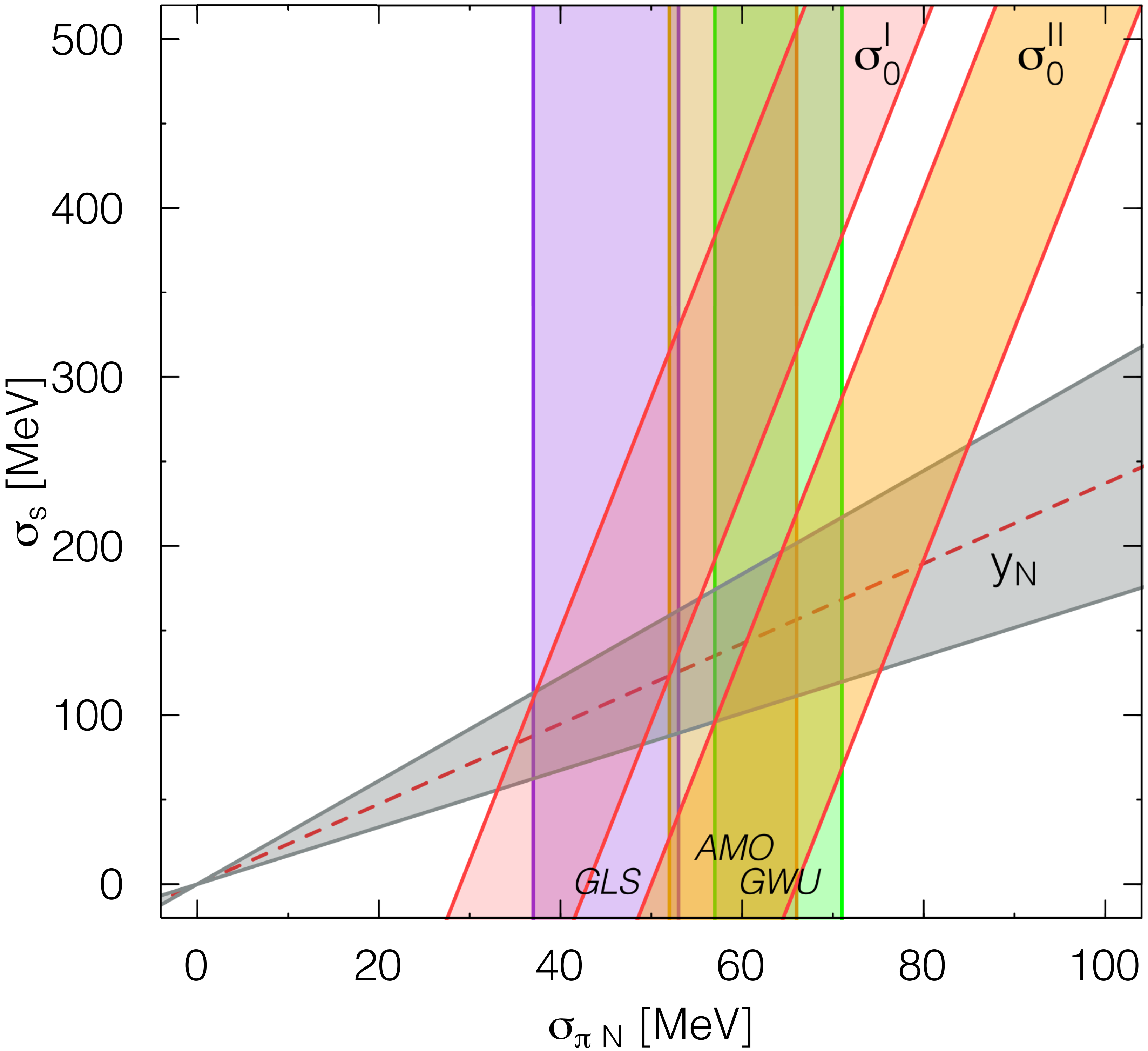
ETM Collaboration, Phys.Rev. D91 (2015) no.9, 094503



Chiral behavior y_N

- Setup:
  - N_f=2+1+1 simulations
  - Several lattice spacings
  - Several volumes
  - y_N=0.17(5)

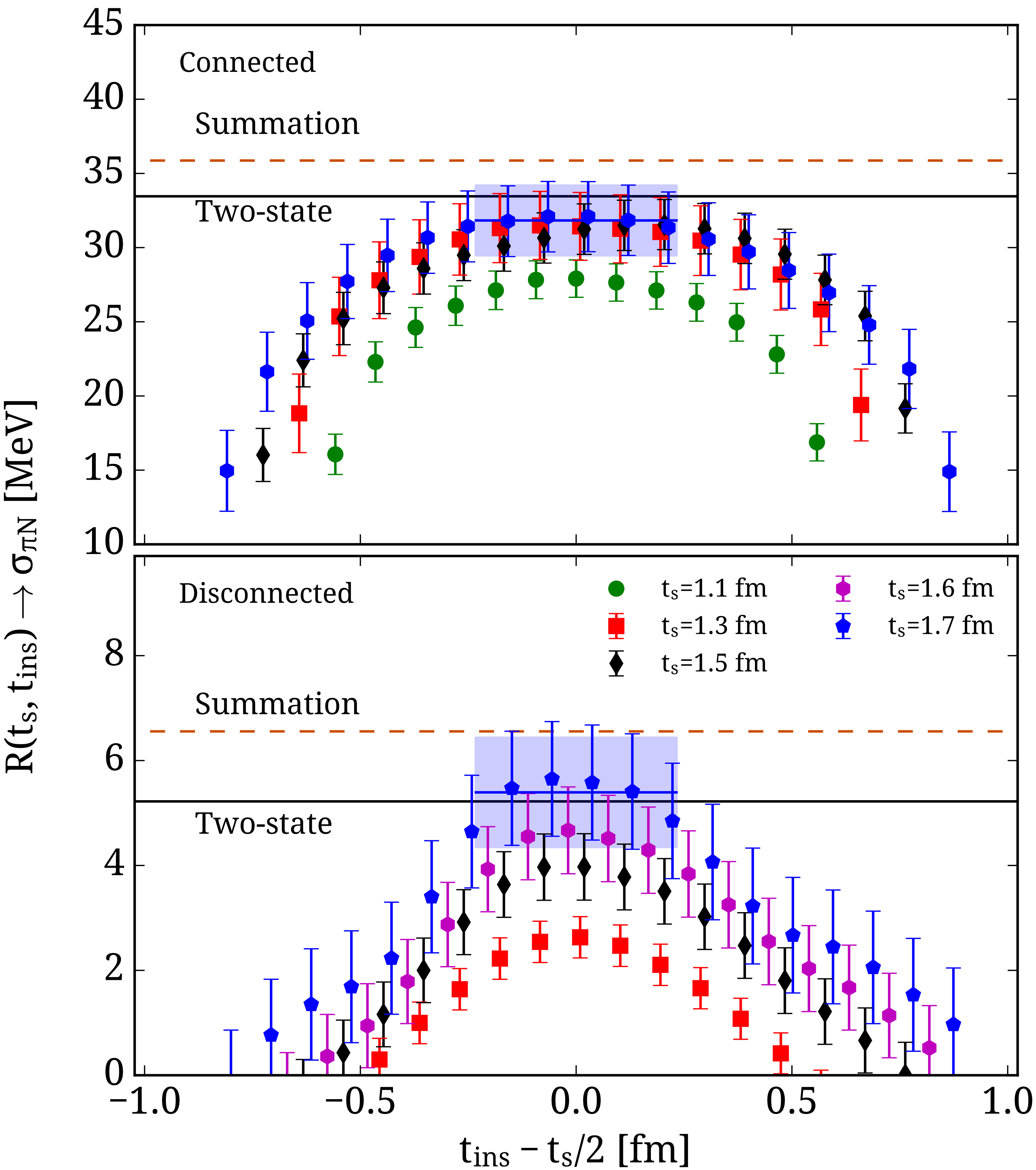
ETM Collaboration, Phys.Rev. D91 (2015) no.9, 094503



New setup :

- Setup:
  - $N_f=2$ simulations
  - Physical pion mass
  - s and c are «quenched»
  - $\sigma_l=37(3)(10)$ MeV
  - $\sigma_s=41(8)(10)$ MeV
  - $\sigma_c=79(21)(2)$ MeV

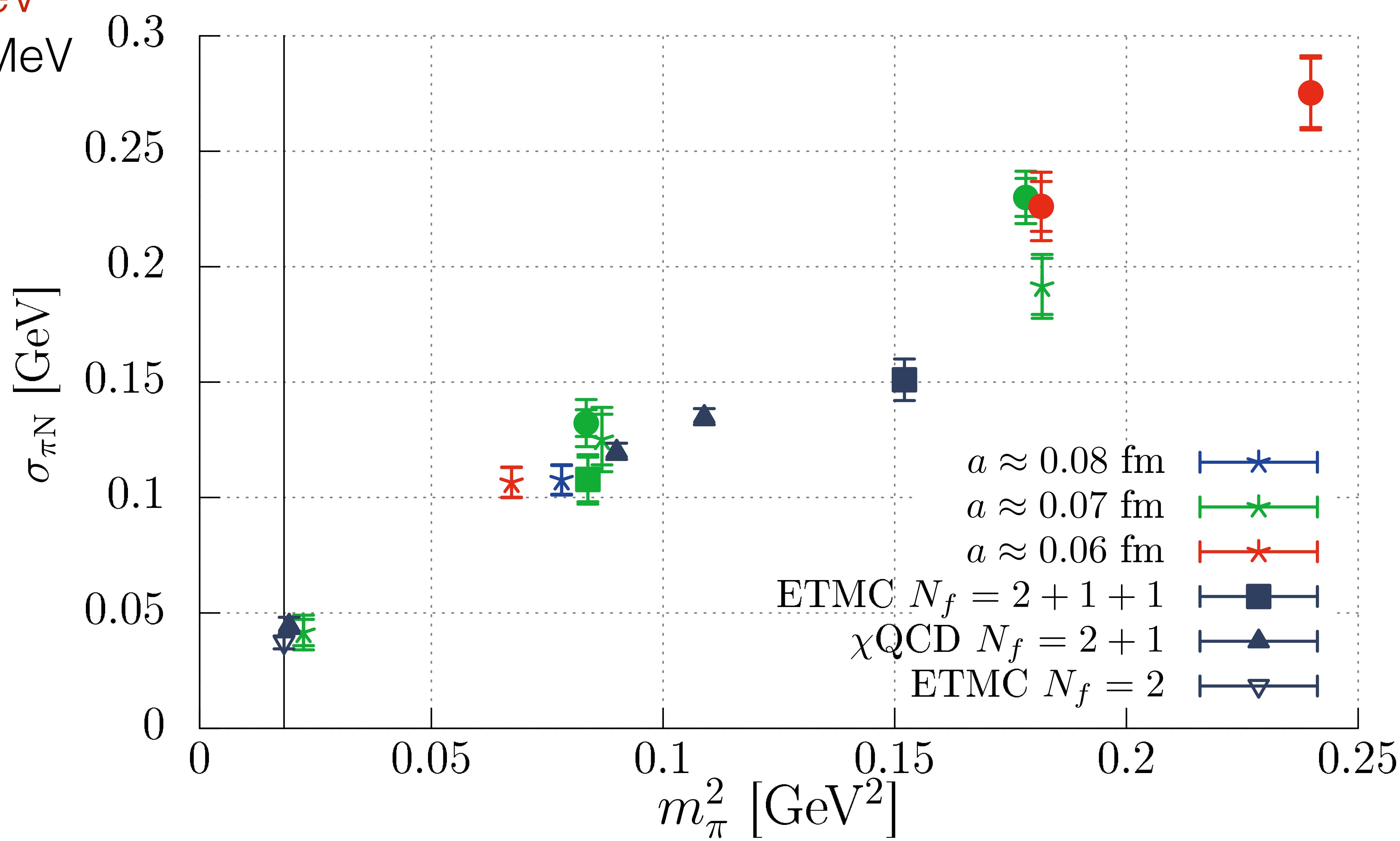
ETM Collaboration, [1601.01624]



RQCD collaboration

- Setup:
  - N_f=2 simulations
  - Physical pion mass
  - ME approach
  - σ_l=35(6) MeV
  - σ_s=35(12) MeV

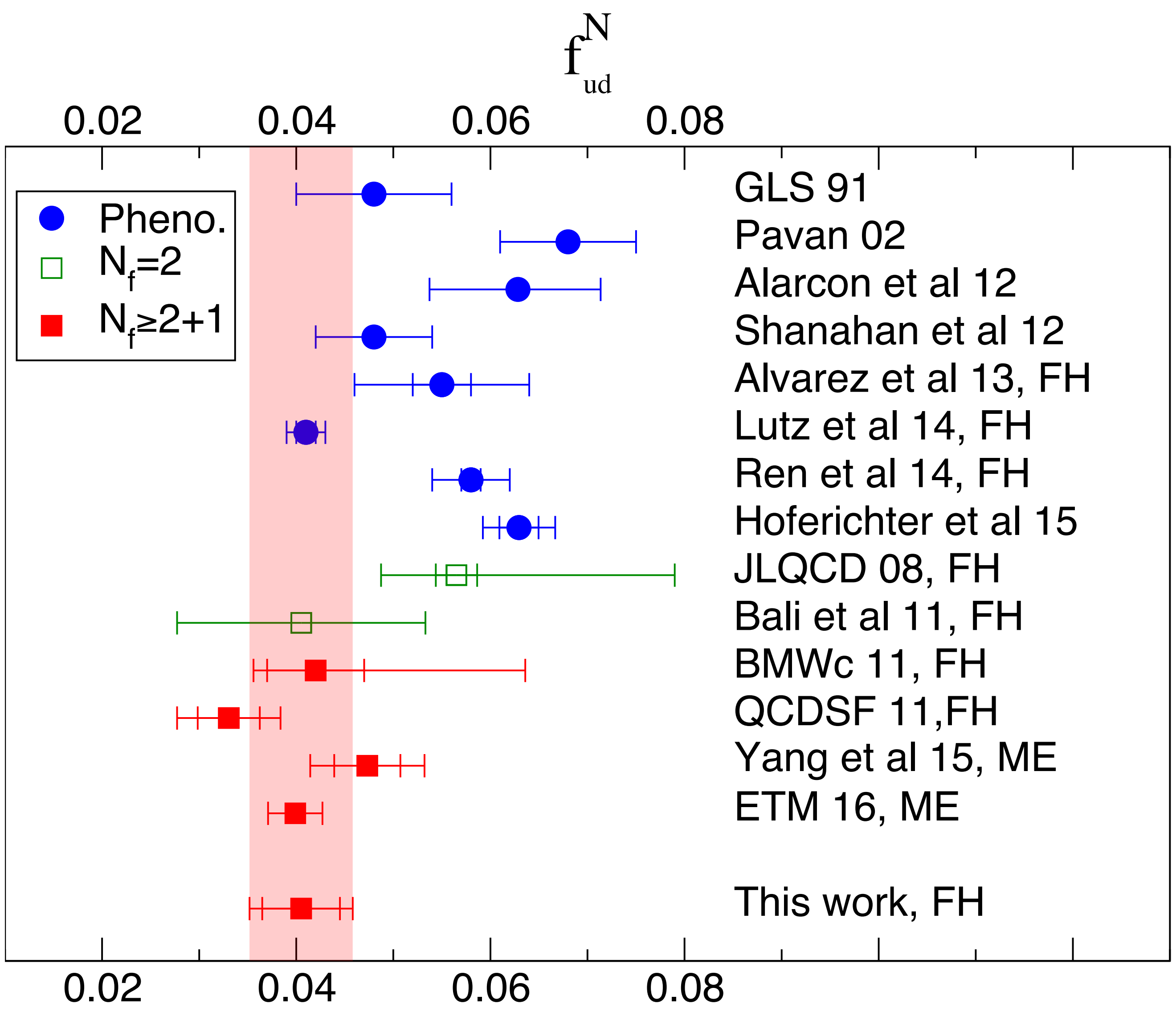
RQCD Collaboration, Phys.Rev. D93 (2016) no.9, 094504

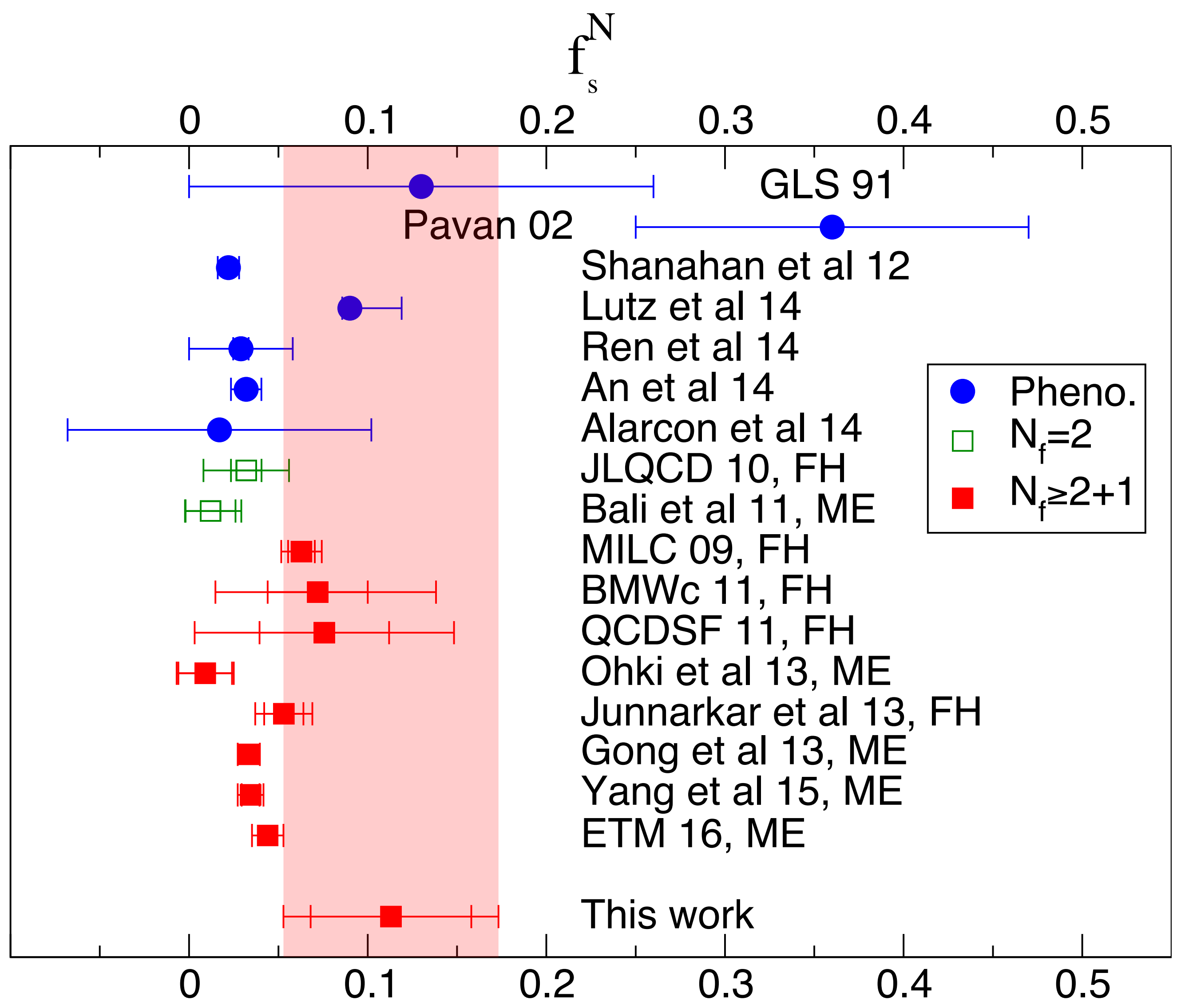


BMW collaboration

- Setup:
  - N_f=2+1 simulations
  - Physical pion mass
  - FH approach
  - σ_l=38(3)(3) MeV
  - σ_s=105(41)(37) MeV
  - y_N=0.20(8)(8)

BMW Collaboration, [PRL 116 (2016) no. 17, 172001]





Conclusions & Outlook (I)

- Hadronic uncertainties to interpret direct detection constraints
- Cross section controlled by the *σ-terms* for each quark flavors
- Theoretical interest : Dynamical origin of the nucleon's mass
- Lattice calculations are challenging :
  - ✦ Disconnected diagrams
  - ✦ Systematics are difficult to control
  - ✦ Heavy quark content should be addressed…

Conclusions & Outlook (II)

- ETM Collaboration :
  - ✦ First results of a direct calculation of y_N
  - ✦ Results for σ_l encouraging @ the physical point (N_f=2)
  - ✦ Looking forward for N_f=2+1+1 simulations
- Other group :
  - ✦ light sector : $\sigma_l \sim 38$ MeV
  - ✦ strange sector : 35 MeV $< \sigma_s <$ 150 MeV