Preliminary considerations on the NP sensitivity of low-energy μe scattering data

Giovanni Marco Pruna

Paul Scherrer Institut
Villigen, CH

μe scattering WS, Padova, 5 September 2017

Beyond-the-Standard-Model physics

The Standard Model of particle physics works, but fails to account for some remarkable exceptions:

- the neutrino oscillation;
- the abundance of matter;
- dark matter;
- gravity.

So far, no experimental hints.

This seems to indicate that any new physics should either:

- exist at our energy scales, but be rather weakly connected;
- exist at some energy scale that has not yet been reached;
- exist in a combination of both scenarios.

New Physics and μe scattering

μe scattering as a precision tool at (rather) high energy.

IMHO we shouldn't talk about top-down structured approaches.

New-physics studies can be approached by:

- exploiting effective-field-theory technologies;
- plugging 'dark portals'.

Effective interactions unconstrained by other experiments.
Dark particles surviving direct and indirect searches.

Extending the interactions of the SM

Assumptions: SM is merely an effective theory, valid up to some scale Λ. It can be extended to a field theory that satisfies the following requirements:

- its gauge group should contain $SU(3)_C \times SU(2)_L \times U(1)_Y$;
- all the SM degrees of freedom must be incorporated;
- at low energies (i.e. when $\Lambda \to \infty$), it should reduce to SM.

Assuming that such reduction proceeds via decoupling of New Physics (NP), the Appelquist-Carazzone theorem allows us to write such theory in the form:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right).$$

Dimension-six operators

2-leptons

$$\boxed{Q_{eW}} = (\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu};$$
$$\boxed{Q_{eB}} = (\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}.$$
$$\boxed{Q^{(1)}_{\varphi l}} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$$
$$\boxed{Q^{(3)}_{\varphi l}} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$$
$$\boxed{Q_{\varphi e}} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$$
$$\boxed{Q_{e\varphi}} = (\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$$

4-leptons

$$\boxed{Q_{ll}} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$$
$$\boxed{Q_{ee}} = (\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$$
$$\boxed{Q_{le}} = (\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$$

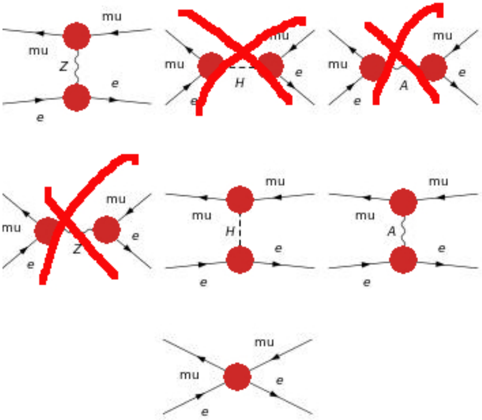
4-fermions

$$Q^{(1)}_{lq} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$
$$Q^{(3)}_{lq} = (\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$
$$Q_{eu} = (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$$
$$Q_{ed} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$
$$Q_{lu} = (\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$$
$$Q_{ld} = (\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$$
$$Q_{qe} = (\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$$
$$Q_{ledq} = (\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$$
$$Q^{(1)}_{lequ} = (\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$$
$$Q^{(3)}_{lequ} = (\bar{l}^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$$

Relevant coefficients for μe scattering at the tree-level

$C^{ii}_{e\gamma}$, with $i = 1, 2$
C^{ii}_{eZ}, with $i = 1, 2$
$C^{ii}_{e\varphi}$, with $i = 1, 2$
$C^{ii}_{\varphi e}$, with $i = 1, 2$
$C^{ii}_{\varphi l(1)}$, with $i = 1, 2$
$C^{ii}_{\varphi l(3)}$, with $i = 1, 2$

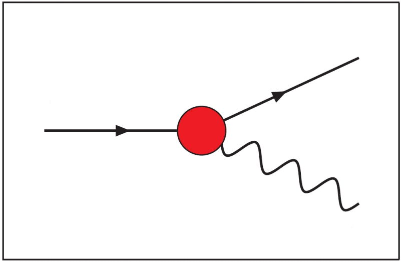
C^{1122}_{ee}
C^{1122}_{le}, C^{1221}_{le}, C^{2211}_{le}
C^{1122}_{ll}



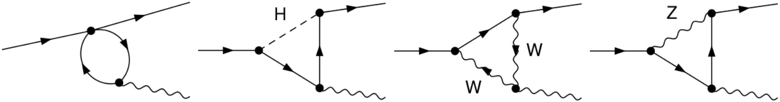
Severely constrained by low-energy experiments!

Dimension-six operators: lepton current at one loop

From a point-like interaction. . .



. . . to quantum fluctuations!



No correlation: limits from muonic cLFV

GMP and A. Signer
JHEP **1410** (2014) 014

GMP and A. Signer
EPJWC **118** (2016) 01031

Similar limits for the flavour-conserving couplings from the $a_{e,\mu}$ and $d_{e,\mu}$

Coefficient	MEG ($\mu \to e\gamma$) $BR \le 5.7 \cdot 10^{-13}$	ATLAS ($Z \to e\mu$) $BR \le 7.5 \cdot 10^{-7}$	SINDRUM ($\mu \to 3e$) $BR \le 1.0 \cdot 10^{-12}$
$C_{eZ}^{\mu e}(m_Z)$	$1.4 \cdot 10^{-13} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$5.5 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$2.8 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{\varphi l}^{(1)}$	$2.5 \cdot 10^{-10} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$5.5 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$2.5 \cdot 10^{-11} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{\varphi l}^{(3)}$	$2.4 \cdot 10^{-10} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$5.5 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$2.5 \cdot 10^{-11} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{\varphi e}$	$2.4 \cdot 10^{-10} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$5.5 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$2.6 \cdot 10^{-11} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{e\varphi}^{\mu e}$	$2.7 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$		$6.1 \cdot 10^{-6} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{le}^{eee\mu}$	$4.2 \cdot 10^{-8} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$		$2.2 \cdot 10^{-11} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{le}^{e\mu\mu\mu}$	$2.0 \cdot 10^{-10} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$		
$C_{le}^{e\tau\tau\mu}$	$1.2 \cdot 10^{-11} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$		
$C_{ee}^{eee\mu}$			$7.7 \cdot 10^{-12} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{ll}^{eee\mu}$			$7.7 \cdot 10^{-12} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$

No correlation: limits from EDM

Coefficient	Contribution to d_l	Limits from d_e	Limits from d_μ
$C_{e\gamma}^{ii}$	$\frac{2\sqrt{2} m_W s_W}{e} \Im C_{e\gamma}^{ii}$	$5.8 \times 10^{-19} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$6.7 \times 10^{-10} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
C_{le}^{1ii1}	$\frac{e\, m_e}{8\pi^2} \Im C_{le}^{1ii1}$	N/A	N/A
C_{le}^{2ii2}	$\frac{e\, m_\mu}{8\pi^2} \Im C_{le}^{2ii2}$	$5.5 \times 10^{-13} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	N/A
C_{le}^{3ii3}	$\frac{e\, m_\tau}{8\pi^2} \Im C_{le}^{3ii3}$	$3.2 \times 10^{-14} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$3.7 \times 10^{-6} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$
$C_{e\varphi}^{ii}$	$\frac{m_i^2 m_W s_W}{8\sqrt{2} m_H^2 \pi^2} \left(-3 + 2\log\left[\frac{m_i^2}{m_H^2}\right]\right) \Im C_{e\varphi}^{ii}$	$3.8 \times 10^{-11} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	N/A
C_{eZ}^{ii}	$\frac{\alpha}{8\pi c_W s_W} \left(-3c_W^2 + 3s_W^2\right) \Im C_{eZ}^{ij}$	$5.5 \times 10^{-16} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$	$6.3 \times 10^{-7} \frac{\Lambda^2}{[\mathrm{GeV}]^2}$

Improving on d_τ: M. Fael *et al.*, JHEP **1603** (2016) 140

Below the EWSB scale

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{QCD}} + \frac{1}{\Lambda^2} \sum_i C_i Q_i,$$

and the explicit structure of the operators is given by

Dipole			
$Q_{e\gamma}$	$e m_r (\bar{l}_p \sigma^{\mu\nu} P_L l_r) F_{\mu\nu} + \text{H.c.}$		
Scalar/Tensorial		**Vectorial**	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \text{H.c.}$	Q_{VLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_L l_t)$
		Q_{VLR}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
		Q_{VRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{l}_s \gamma_\mu P_R l_t)$
$Q_{Slq(1)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \text{H.c.}$	Q_{VlqLL}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \text{H.c.}$	Q_{VlqLR}	$(\bar{l}_p \gamma^\mu P_L l_r)(\bar{q}_s \gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p \sigma^{\mu\nu} P_L l_r)(\bar{q}_s \sigma_{\mu\nu} P_L q_t) + \text{H.c.}$	Q_{VlqRL}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p \gamma^\mu P_R l_r)(\bar{q}_s \gamma_\mu P_R q_t)$

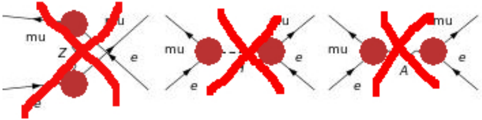
In absence of interplay at the EWSB scale

	$\mathrm{Br}(\mu^+ \to e^+\gamma)$		$\mathrm{Br}(\mu^+ \to e^+e^-e^+)$		$\mathrm{Br}^{\mathrm{Au/Al}}_{\mu\to e}$	
	$4.2\cdot 10^{-13}$	$4.0\cdot 10^{-14}$	$1.0\cdot 10^{-12}$	$5.0\cdot 10^{-15}$	$7.0\cdot 10^{-13}$	$1.0\cdot 10^{-16}$
C_L^D	$1.0\cdot 10^{-8}$	$3.1\cdot 10^{-9}$	$2.0\cdot 10^{-7}$	$1.4\cdot 10^{-8}$	$2.0\cdot 10^{-7}$	$2.9\cdot 10^{-9}$
$C_{ee}^{S\,LL}$	$4.8\cdot 10^{-5}$	$1.5\cdot 10^{-5}$	$8.1\cdot 10^{-7}$	$5.8\cdot 10^{-8}$	$1.4\cdot 10^{-3}$	$2.1\cdot 10^{-5}$
$C_{\mu\mu}^{S\,LL}$	$2.3\cdot 10^{-7}$	$7.2\cdot 10^{-8}$	$4.6\cdot 10^{-6}$	$3.3\cdot 10^{-7}$	$7.1\cdot 10^{-6}$	$1.0\cdot 10^{-7}$
$C_{\tau\tau}^{S\,LL}$	$1.2\cdot 10^{-6}$	$3.7\cdot 10^{-7}$	$2.4\cdot 10^{-5}$	$1.7\cdot 10^{-6}$	$2.4\cdot 10^{-5}$	$3.5\cdot 10^{-7}$
$C_{\tau\tau}^{T\,LL}$	$2.9\cdot 10^{-9}$	$9.0\cdot 10^{-10}$	$5.7\cdot 10^{-8}$	$4.1\cdot 10^{-9}$	$5.9\cdot 10^{-8}$	$8.5\cdot 10^{-10}$
$C_{bb}^{S\,LL}$	$2.8\cdot 10^{-6}$	$8.6\cdot 10^{-7}$	$5.4\cdot 10^{-5}$	$3.8\cdot 10^{-6}$	$9.0\cdot 10^{-7}$	$1.2\cdot 10^{-8}$
$C_{bb}^{T\,LL}$	$2.1\cdot 10^{-9}$	$6.4\cdot 10^{-10}$	$4.1\cdot 10^{-8}$	$2.9\cdot 10^{-9}$	$4.2\cdot 10^{-8}$	$6.0\cdot 10^{-10}$
$C_{ee}^{V\,RR}$	$3.0\cdot 10^{-5}$	$9.4\cdot 10^{-6}$	$2.1\cdot 10^{-7}$	$1.5\cdot 10^{-8}$	$2.1\cdot 10^{-6}$	$3.5\cdot 10^{-8}$
$C_{\mu\mu}^{V\,RR}$	$3.0\cdot 10^{-5}$	$9.4\cdot 10^{-6}$	$1.6\cdot 10^{-5}$	$1.1\cdot 10^{-6}$	$2.1\cdot 10^{-6}$	$3.5\cdot 10^{-8}$
$C_{\tau\tau}^{V\,RR}$	$1.0\cdot 10^{-4}$	$3.2\cdot 10^{-5}$	$5.3\cdot 10^{-5}$	$3.8\cdot 10^{-6}$	$4.8\cdot 10^{-6}$	$7.9\cdot 10^{-8}$
$C_{bb}^{V\,RR}$	$3.5\cdot 10^{-4}$	$1.1\cdot 10^{-4}$	$6.7\cdot 10^{-5}$	$4.8\cdot 10^{-6}$	$6.0\cdot 10^{-6}$	$1.0\cdot 10^{-7}$
C_{bb}^{RA}	$4.2\cdot 10^{-4}$	$1.3\cdot 10^{-4}$	$6.5\cdot 10^{-3}$	$4.6\cdot 10^{-4}$	$1.3\cdot 10^{-3}$	$2.2\cdot 10^{-5}$
C_{bb}^{RV}	$2.1\cdot 10^{-3}$	$6.4\cdot 10^{-4}$	$6.7\cdot 10^{-5}$	$4.7\cdot 10^{-6}$	$6.0\cdot 10^{-6}$	$1.0\cdot 10^{-7}$

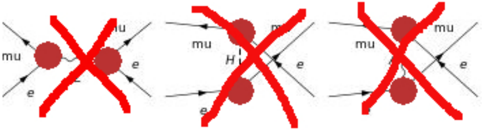
Limits on the various coefficients $C_i(m_W)$ from current and future experimental constraints, assuming that (at the high scale m_W) only one coefficient at a time is non-vanishing and not including operator-dependent efficiency corrections.

Relevant coefficients for $\mu^+e^- \to \mu^-e^+$ at the tree-level

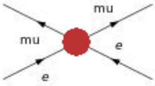
No three-point operators!



No three-point operators!



C_{ee}^{1212}, C_{le}^{1212}, C_{ll}^{1212}



Interesting rearrangement of the flavour indexes!

Same interaction in muon-antimuon conversion

Effective Hamiltonian:

$$\begin{aligned}
\mathcal{H}_1 &= \frac{G_{M\overline{M}}}{\sqrt{2}}\left[\overline{u}\gamma^{\lambda}\left(1+\gamma_5\right)e\right]^2 + h.c. \\
\mathcal{H}_2 &= \frac{G'_{M\overline{M}}}{\sqrt{2}}\left[\overline{u}\gamma^{\lambda}\left(1-\gamma_5\right)e\right]^2 + h.c. \\
\mathcal{H}_3 &= \frac{G''_{M\overline{M}}}{\sqrt{2}}\left[\overline{u}\gamma^{\lambda}\left(1+\gamma_5\right)e\right]\left[\overline{u}\gamma^{\lambda}\left(1-\gamma_5\right)e\right] + h.c.
\end{aligned}$$

For example, $\mathcal{H}_1$ produces a transition described by

$$\mathcal{P}\left(\overline{M}\right) = 64^3\left(\frac{3\pi^2\alpha^3}{G_F m_\mu^2}\right)^2\left(\frac{m_e}{m_\mu}\right)^6\left(\frac{G_{M\overline{M}}}{G_F}\right)^2 \leq \frac{8.3\times 10^{-11}}{S_B}$$

An explicit BSM realisation

The doubly charged scalar ($SU(2)_L$-singlet) is a perfect candidate for the neutrino mass generation mechanism.

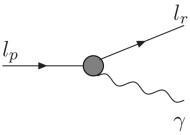
Effective Majorana mass term at the tree-loop level.

$$\begin{aligned}\mathcal{L}_{UV} &= \mathcal{L}_{\rm SM} + \left(D_\mu S^{++}\right)^\dagger \left(D^\mu S^{++}\right) \\ &\quad + \left(\lambda_{ab}\, \overline{(\ell_R)^c_a} \ell_{Rb}\, S^{++} + \text{h.c.}\right).\end{aligned}$$

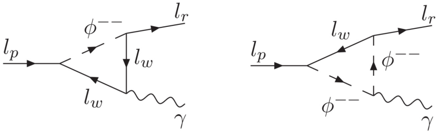
7 new parameters: the mass of the doubly charged scalar m_ϕ, and the 6 complex parameters λ_{ab}.

What happens to the muon-antimuon oscillation?

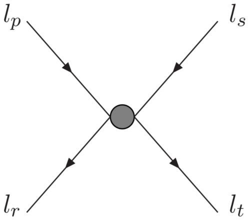
Matching BSM physics to the EFT



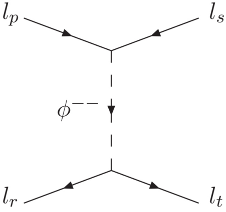
(a)



(b)



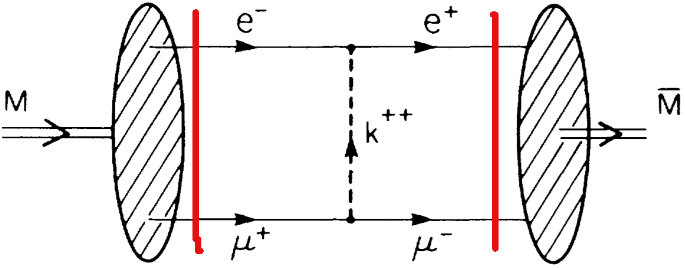
(c)



(d)

$$C_{e\gamma}^{pr}\left(m_W\right) = \frac{1}{24 m_\phi^2 \pi^2} \sum_{w=1}^{3} (\lambda_{rw}\lambda_{pw}^*) \qquad C_{VRR}^{prst}\left(m_W\right) = -\frac{\lambda_{rt}\lambda_{ps}^*}{2m_\phi^2}$$

Phenomenology at lower scales

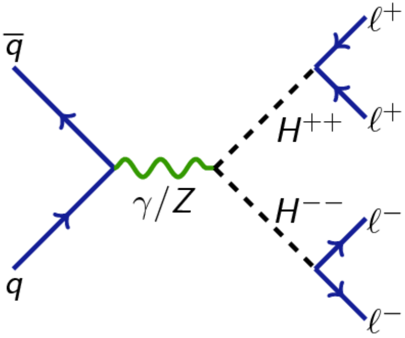


This is the only observable constraining such combination of couplings:

$$\mathcal{P}\left(\overline{M}\right) = \frac{18(8\pi)^4\alpha^6 m_e^6 \left|\lambda_{11}\right|^2 \left|\lambda_{22}\right|^2}{G_F^4 m_\mu^{10} m_\phi^4} \leq 10^{-10}$$

Exploring the high energy scale at colliders

Same-charge e pair final states in pp collisions at the LHC.



ATLAS & CMS (7-13 TeV)

Right-handed coupling:

$m_\phi > 460$ GeV

Left-handed coupling:

$m_\phi > 570$ GeV

BR$(\phi^\pm \to e^\pm e^\pm) \simeq 100\%$

Conclusion

√ More questions than answers

- light New Physics in the μe scattering?
- light/heavy New Physics associated to different final states?

√ Thinking about a different set-up for BSM searches

- spin-off experimental project?
- maybe a joint pheno effort with atomic physics and the muon-antimuon oscillation guys?
- complementarity with searches at present and future colliders?

√ Our theoretical set-up is (basically) ready.

Acknowledgements

"Lepton flavour violation in an effective-field-theory approach with dimension 6 operators"

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giovanni-marco.pruna(at)psi.ch