How to discover a new Standard Model

Oleg Ruchayskiy

International school "Standard Model, Quantum Chromodynamics, Heavy Ion Collisions"

. . . and a major headache for theorists

We know that new particles exist

- Neutrino masses and oscillations

  Scale of new physics: from 10^{-9} GeV to 10^{15} GeV
- Dark matter

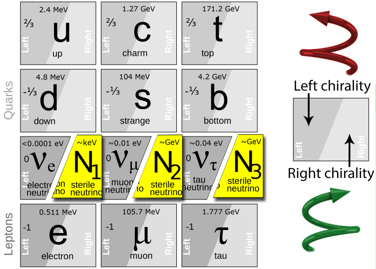
  Scale of new physics: from 10^{-30} GeV to 10^{64} GeV
- Baryon asymmetry of the Universe

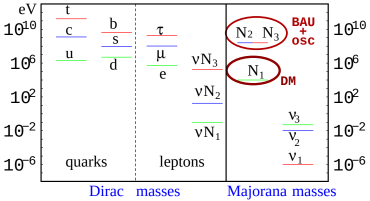
  Scale of new physics: from 10^{-3} GeV to 10^{15} GeV

Two possibilities

1. New particles are **heavy** ☹
2. New particles are **light** ☺ but **superweakly** interacting ☹

How many light particles are needed to solve all BSM problems?





HNL can explain ...

- ...neutrino oscillations

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

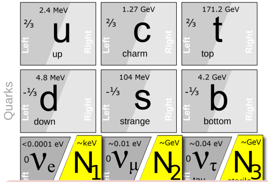
- ...Baryon asymmetry

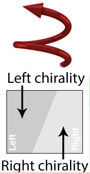
  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

- ...Dark matter

  Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –

How many light particles are needed to solve all BSM problems?





HNL can explain ...

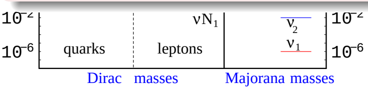
- ... neutrino oscillations

Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79;

HNL can explain all of it

- Neutrino Minimal Standard Model (νMSM)

  Asaka & Shaposhnikov'05 + ... hundreds of subsequent works
- Masses of HNL are of the order of masses of other leptons
- Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]



Neutrino Majorana mass

- Neutrino carries no electric charge, but it is **not** neutral
- …neutrino is part of the SU(2) doublet $L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$
- …and carries **hypercharge** $Y_L = -1$
- What we call **neutrino** is actually $\nu = (L \cdot \tilde{H})$ (where $\tilde{H}_a = \varepsilon_{ab} H_b^*$)
- Therefore neutrino Majorana mass term is

$$\text{Neutrino Majorana mass} = \frac{\boldsymbol{c}(\bar{L} \cdot \tilde{H}^\dagger)(L^c \cdot \tilde{H})}{\boldsymbol{\Lambda}}$$

- Notice that this operator violates **lepton number**
- Assuming $\boldsymbol{c} \sim \mathcal{O}(1)$ one gets

$$\boldsymbol{\Lambda} \sim \frac{v^2}{m_{\text{atm}}} \sim 10^{15}\ \text{GeV}$$

- This is **Weinberg operator** or "dimension-5 operator"

Neutrino oscillations and conservation laws

- Lepton sector: 3 conserved quantities **lepton flavour number**

Particle	L_e	L_μ	L_τ	L_{tot}
e^-	1	0	0	1
ν_e	1	0	0	1
μ^-	0	1	0	1
ν_μ	0	1	0	1
τ^-	0	0	1	1
ν_τ	0	0	1	1

Prohibited decays based on these conservation laws

- $\mu \to e\gamma$
- $\mu \to e\bar{e}e$
- $\tau \to \mu\bar{\mu}\mu$

Exercise 1: *What conservation law makes stable electron? Proton? What decay modes would be available for these particles if the corresponding conservation laws were gone?*

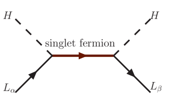
- Neutrino oscillations violate L_e, L_μ, L_τ **but preserve total lepton number**
- Weinberg operator (neutrino Majorana mass) violates the **total lepton number**

$$\frac{(\bar{L}\cdot\tilde{H}^\dagger)(L^c\cdot\tilde{H})}{\Lambda}$$

- This has not yet been confirmed experimentally!

Type I seesaw mechanism I

- Assume one extra fermion N
- It couples to the "neutrino" combination $\nu = (\tilde{H} \cdot L)$
- This combination is $SU(3) \times SU(2) \times U(1)$ gauge singlet
- **N carries no Standard Model gauge charges!**



$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + F\bar{N}(\tilde{H} \cdot L) + \mathscr{L}_{\text{Majorana}}(N) \qquad (1)$$

- Majorana mass term $\mathscr{L}_{\text{Majorana}}(N) = \frac{1}{2}\bar{N}\boldsymbol{M}N^c + \text{h.c}$ is possible for N
- In terms of ν and N we get ($m_{\text{Dirac}} = F\nu$ – Dirac mass)

$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + \frac{1}{2}\begin{pmatrix}\bar{\nu} \\ \bar{N}^c\end{pmatrix}\begin{pmatrix}0 & m_{\text{Dirac}} \\ m_{\text{Dirac}} & \boldsymbol{M}\end{pmatrix}\begin{pmatrix}\nu^c \\ N\end{pmatrix} \qquad (2)$$

Type I seesaw mechanism II

Particle content

- If $M \gg m_{\text{Dirac}}$ this theory describes two particles:
  - Light **neutrino** with mass $\boxed{m_\nu \simeq m_{\text{Dirac}} \frac{m_{\text{Dirac}}}{M}}$ — **seesaw formula**
  - Heavier particle with mass $\approx M$
- Neutrinos are light because $m_{\text{Dirac}} \ll M$
- Mixture between states ν and N (difference between weak eigenstate ν and massive state $\tilde{\nu}$) is parametrized by **active-sterile mixing angle**

$$\boxed{\sin U \approx U = \frac{m_{\text{Dirac}}}{M} \ll 1} \tag{3}$$

Type I seesaw mechanism III

We call this new particle

"Sterile neutrino" or "heavy neutral lepton" or **HNL**

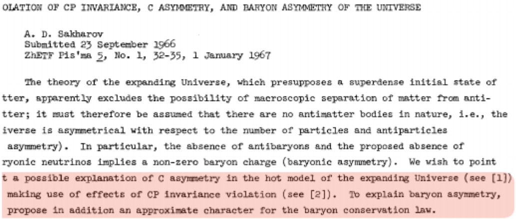
also "Majorana fermion", "heavy Majorana neutrino", "right-handed neutrino", etc.

Can we discover these particles at the LHC / at CERN / in the near future?

Matter-antimatter imbalance of the Universe

- Matte-antimatter asymmetry of the Universe.
- Space around us consists of matter and there is no evidence of primordial antimatter
- This contradicts the standard cosmological scenario that predicts symmetrical initial conditions
- Particle physics predicts many billion times smaller asymmetry

Sakharov's conditions on the Big Bang


OLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of tter, apparently excludes the possibility of macroscopic separation of matter from anti-tter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the iverse is asymmetrical with respect to the number of particles and antiparticles asymmetry). In particular, the absence of antibaryons and the proposed absence of ryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point t a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, propose in addition an approximate character for the baryon conservation law.

Baryon asymmetry of the Universe (Sakharov conditions)

Sakharov (1967)

To generate baryon asymmetry of the Universe **3 conditions** should be satisfied

I. Baryon number should not be conserved

II. C-symmetry and CP-symmetry must be broken

III. Deviation from thermal equilibrium in the Universe expansion

Baryon asymmetry tells us:

- At early times the Universe is so hot and dense that Neutrinos are deep in equilibrium with other particles
- Need "something like neutrino", but even weaker interacting (not to enter thermal equilibrium in the early Universe)

Baryogenesis with HNLs

Heavy neutral leptons provide

- Out-of-equilibrium conditions (**small Yukawas**)
- Additional sources of CP-violation (**CP-phases in active-sterile mixing**)
- Violation of the lepton number and $B - L$ (**Majorana mass**)

Wide class of scenarios known as leptogenesis

Thermal leptogenesis: $M_N \sim 10^9 - 10^{12}$ GeV

Fukugita & Yanagida'86

Resonant leptogenesis: $M_{N_1} \approx M_{N_2} \sim \mathrm{TeV}$ and $|M_{N_\mathrm{I}} - M_{N_\mathrm{J}}| \ll M_N$

Pilaftsis, Underwood'04–'05

Leptogenesis via oscillations: 2 or 3 HNLs, $M_N < M_W$ and $|M_{N_1} - M_{N_2}| \ll M_{N_1,N_2}$

Akhmedov, Smirnov & Rubakov'98

Asaka & Shaposhnikov'05

...

About 50 different variations of these ideas ☺

What do we have and what do we need ?

Theoretical predictions of the minimal LLP

Taking νMSM as a minimal model where LLPs solve all BSM problems we have as predictions

1. Two HNLs of GeV scale
2. Nearly degenerate in mass
3. Possibly CP violation in the active-steirle mixing

Experimental program

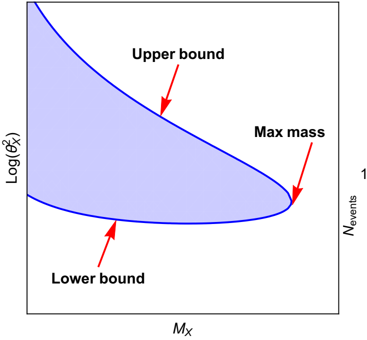
1. Discover new particle
2. Measure its properties (Mass, spin, branching fractions, flavour structures)
3. Confront with theoretical predictions (from seesaw, BAU, etc)

Discover new particles I

Dependence on experimental design

- Feebly interacting particles are easily **long-lived** (LLPs)
- Typical sensitivity region is cigar-shaped
- Number of events inside the shaded region

$$N_{events} = N_{produced} \times P_{decay}$$



- **Lower boundary** – too few decays in the decay volume:

$$P_{decay} \sim \frac{L_{det}}{c\tau_{decay}\gamma} \qquad (4)$$

– large detectors (L_{det}) allow to probe wider parameter space

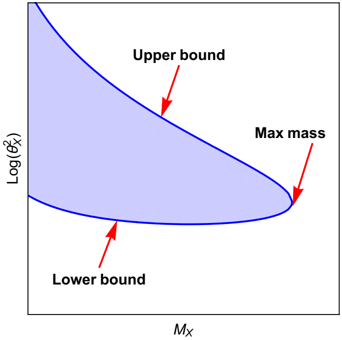
Discover new particles II

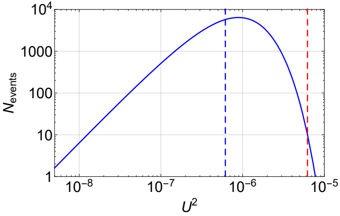
Dependence on experimental design

- **Upper boundary** – decay too fast, do not reach the decay vessel

$$P_{decay} \propto e^{-\frac{L_{to-det}}{c\tau_{decay}\gamma}} \quad (5)$$

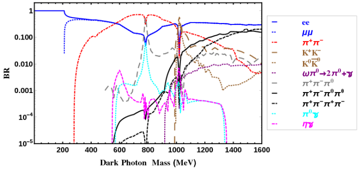
  where distance between FIP production and decay vessel L_{to-det} as well as **distribution** in γ-factors, etc play the main role
- Maximal mass – intersection of the above or kinematics
- Most of these things can be estimated analytically [1902.06240]

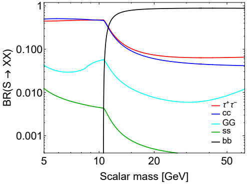


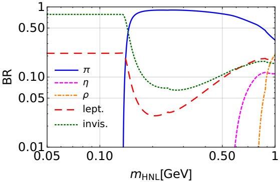


What did we discover?

- In experiments that can do PID and measure mass – you can roughly guess whether this is boson or fermion
- Does invariant mass $m_{\mu\mu}$ or even M_{jj} has a peak – boson – or is broadly distributed (HNL)
  $\gamma' \to \ell^+\ell^-$ vs. $N \to \mu^+\mu^-\nu$ or $N \to \ell^+ + \pi^-$, etc







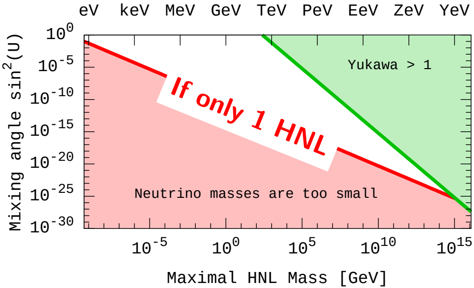
Plots from [1608.08632; 1805.08567; 1908.04635]

How many of them?

- We discovered HNLs  How many of them?
- If you discovered an HNL signal – you actually discovered **two or more particles** ☺
- Naive seesaw formula

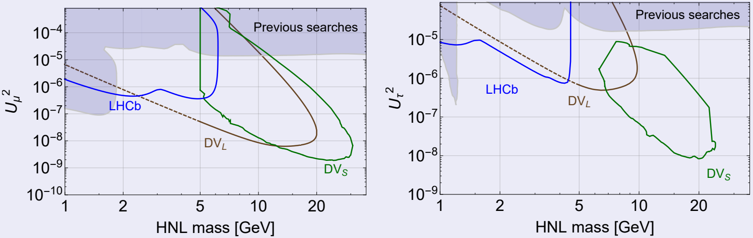
$$U^2_{bottom} \sim \frac{m_{atm}}{M} \sim 10^{-11}\frac{10\,\mathrm{GeV}}{M}$$

- In order to have HNLs with mixings $U^2 \gg U^2_{bottom}$ you need several HNLs that "**conspire**" to cancel each other's contribution to neutrino masses

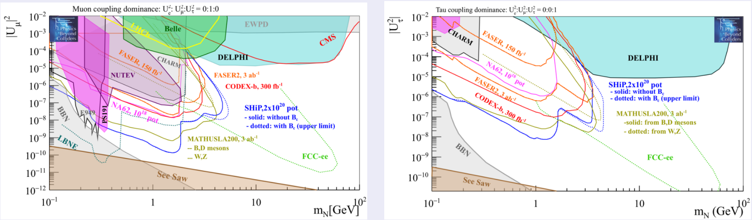


Shaposhnikov'06; Kersten & Smirnov'07

Flavour structures can be measured



LHC displaced vertex searches (Boiarska+ [1902.04535])



PBC report

Do they fit predictions?

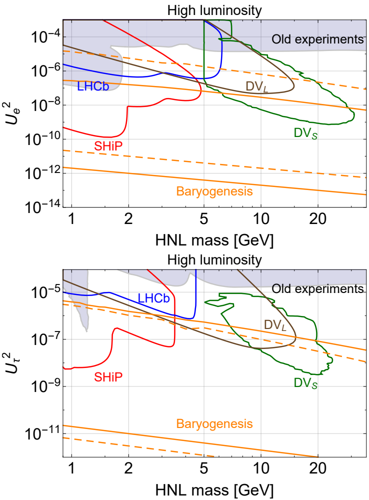
- Once HNL parameters are determined, you can check whether they fall into the theory predictions
- And whether different measurements agree with each other

Boiarska+ [1902.04535]

BAU contours: Eijima+ [1808.10833];

Short DV: Cottin+ [1806.05191];

Long DV: Bondarenko+ [1903.11918]



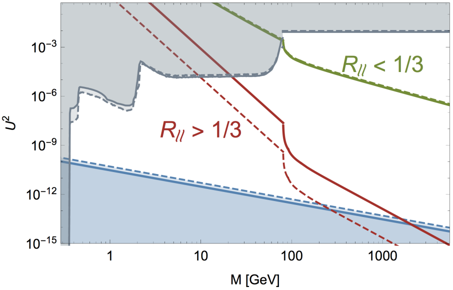
Can we measure HNL mass splitting

- If we measure both LNV and LNC events as well as the total lifetime - we can hope to determine the **mass splitting**:

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}.$$

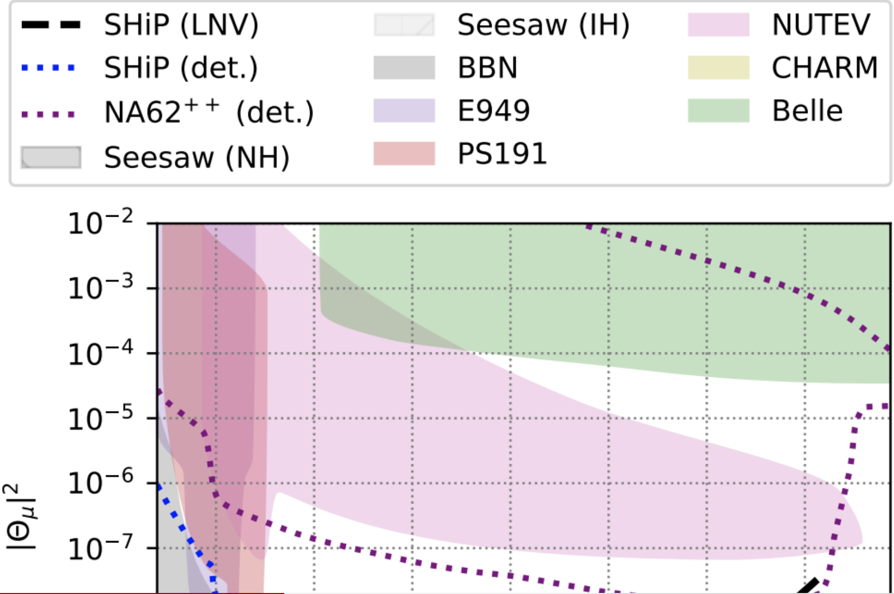
  R_{ll} — ratio of same-sign to opposite-sign leptons **Anamiati+ [1607.05641]**

- ΔM can also be measured in SHiP **[To appear]**



Drewes+ [1907.13034]

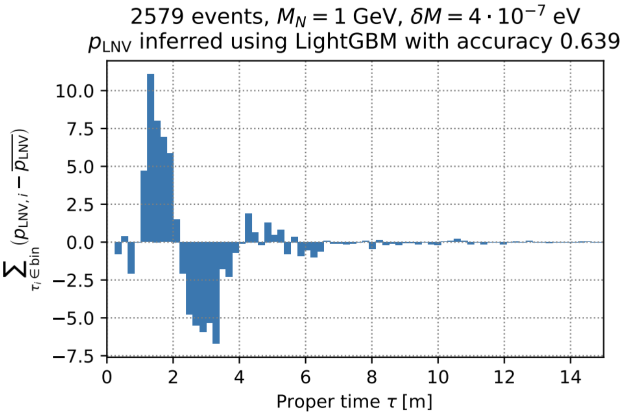
LNV nature of HNLs at SHiP



Mass splitting at SHiP

From [1912.05520]

- In some region of parameter space it is even possible to measure δM
- Binning events in proper time τ we can determine δM via $\delta M \tau = 2\pi$



Holistic view

Finally, LHC measurements can be confronted with results of other experiments

An unidentified spectral line at ~ 3.5 keV I

Boyarsky, Ruchayskiy+ (PRL 2014); Bulbul+ (ApJ 2014); Review “Sterile Neutrino Dark Matter ” [1807.07938]

- Many detections – **not statistical fluctuations**

  Milky way & Andromeda galaxies, Perseus cluster, Draco dSph, distant clusters. COSMOS & Chandra deep fields

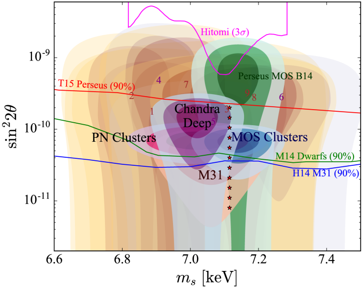
- Detections with many telescopes – **not systematics**

  XMM MOS and PN cameras, Chandra, Suzaku, NuStar

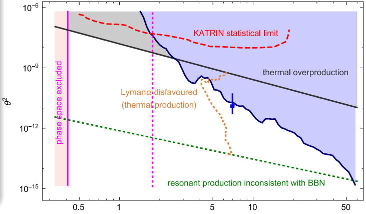
- Has not been seen by Hitomi – **not astronomical line**

  Hitomi observation of the Perseus galaxy cluster ruled out the interpretation as Potassium or any other narrow atomic line.

  Sulphur ion charge exchange? (Gu+ 2015 & 2017; Shah+ 2016)



[1705.01837]

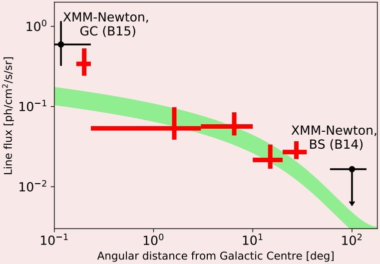


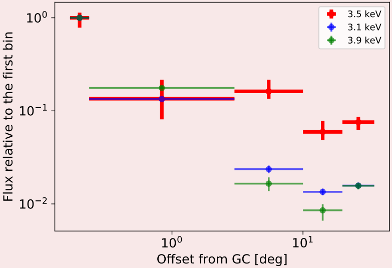
Recent result: Surface brightness profile in the Galaxy

Recent result: Boyarsky, Ruchayskiy et al. [1812.10488]

Surface brightness profile in the Galaxy

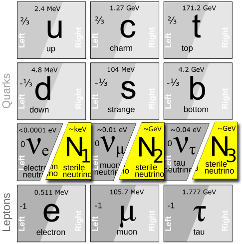
- Detected with 7σ significance in 5 spatial bins off Galactic Center

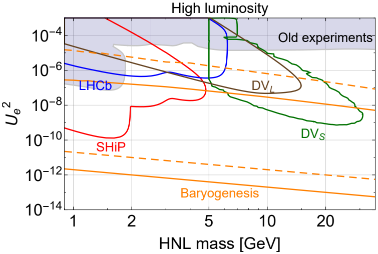




- Radial profile consistent with DM density profile
- Different from astrophysical lines

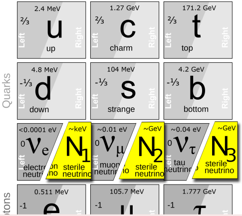
Conclusion

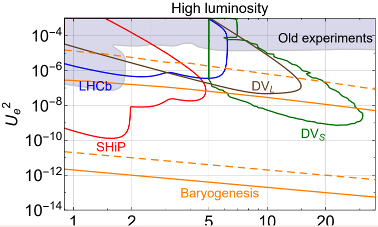




- It took many years of measurements and cross-checks to promote a model of particle physics to the **Standard** model
- Discovering **any signal** would be great. . .
- . . . but we can aim at much more!
- We may discover HNLs and **show** that they are responsible for BSM problems
- Cross-checks between different measurements and between different experiments at LHC and beyond are essential and should be planned today

Conclusion





Thank you for your attention!

- It took many years of measurements and cross-checks to promote a model of particle physics to the **Standard** model
- Discovering **any signal** would be great...
- ...but we can aim at much more!
- We may discover HNLs and **show** that they are responsible for BSM problems
- Cross-checks between different measurements and between different experiments at LHC and beyond are essential and should be planned today