FCC WEEK 2016, Rome, April 11-15, 2016

Italian view on HEP beyond LHC

Antonio Masiero

INFN and Univ. of Padova

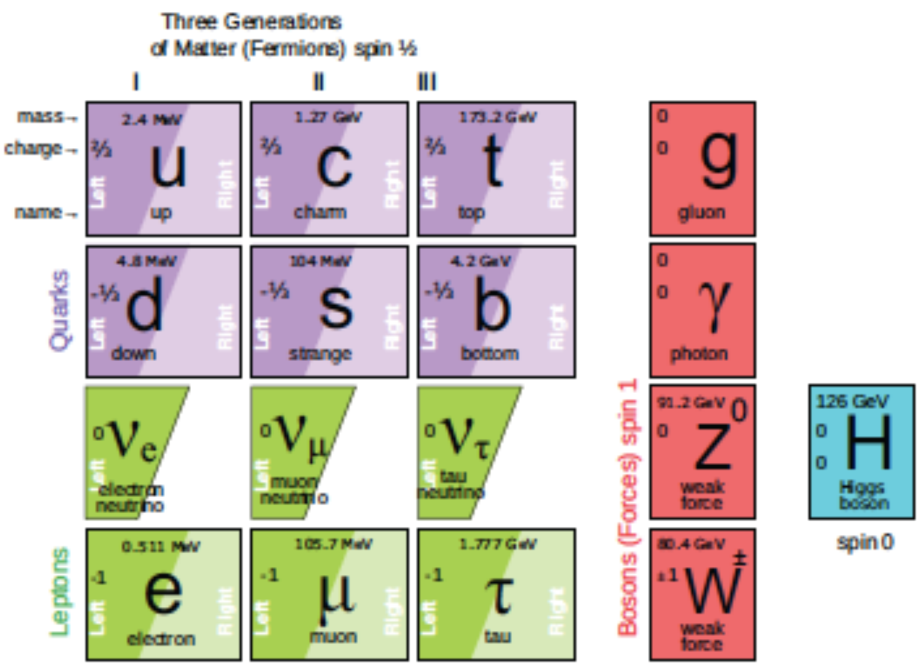
See also the talk "Italian & INFN activities towards future colliders" by A. Zoccoli on Monday

- By the end of the 20th century … **we have a comprehensive, fundamental theory of all observed forces of nature which has been tested and might be valid from the Planck length scale [10^{-33} cm.] to the edge of the universe [10^{+28} cm.]**

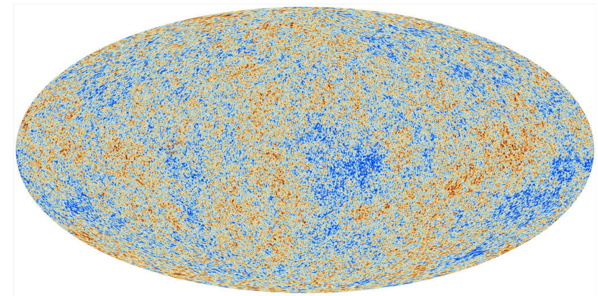
D. Gross 2007

2013 – 2016 : the triumph of the STANDARD

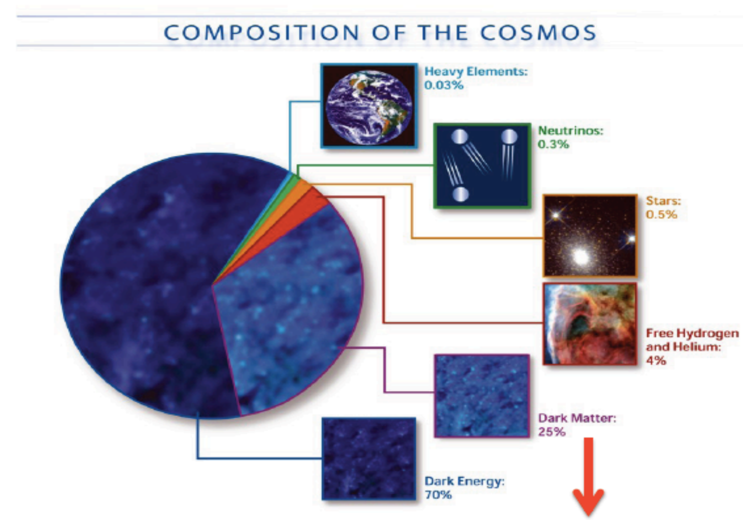
- **PARTICLE STANDARD MODEL**



- **COSMOLOGY STANDARD MODEL**



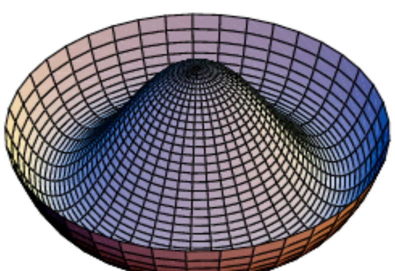
ΛCDM + "SIMPLE" INFLATION

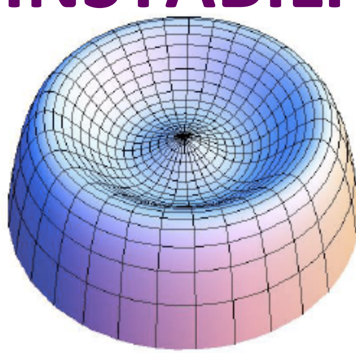


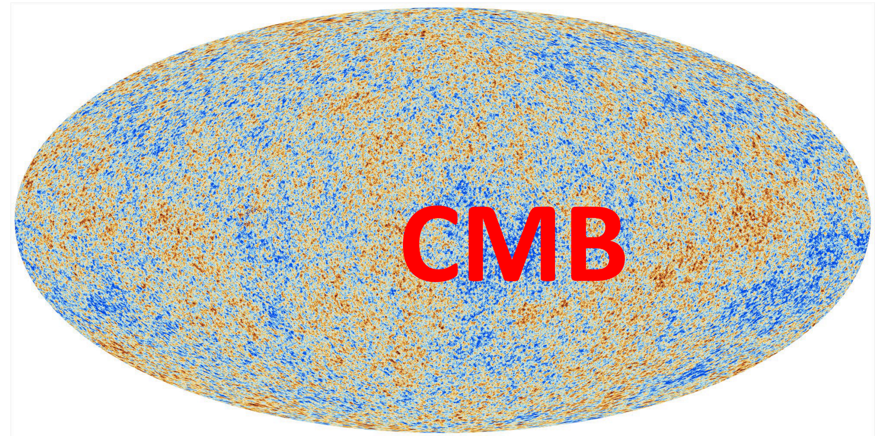
- PARTICLE **STANDARD** MODEL
- COSMOLOGY **STANDARD** MODEL

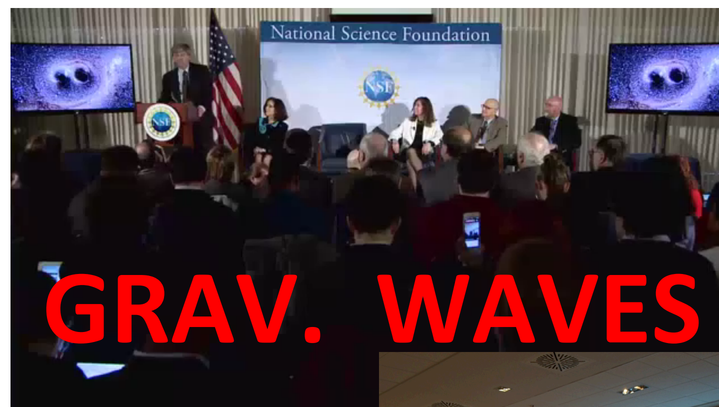
The Higgs boson and the destiny of the Universe

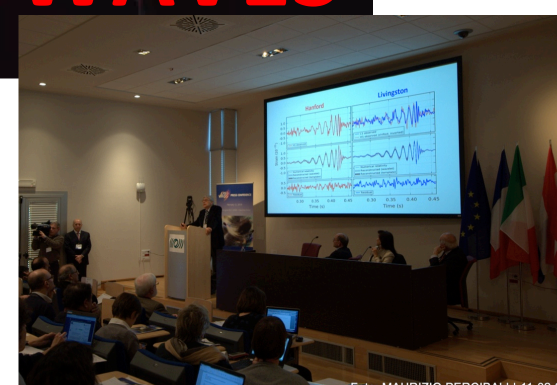
STABILITY ⟷ INSTABILITY

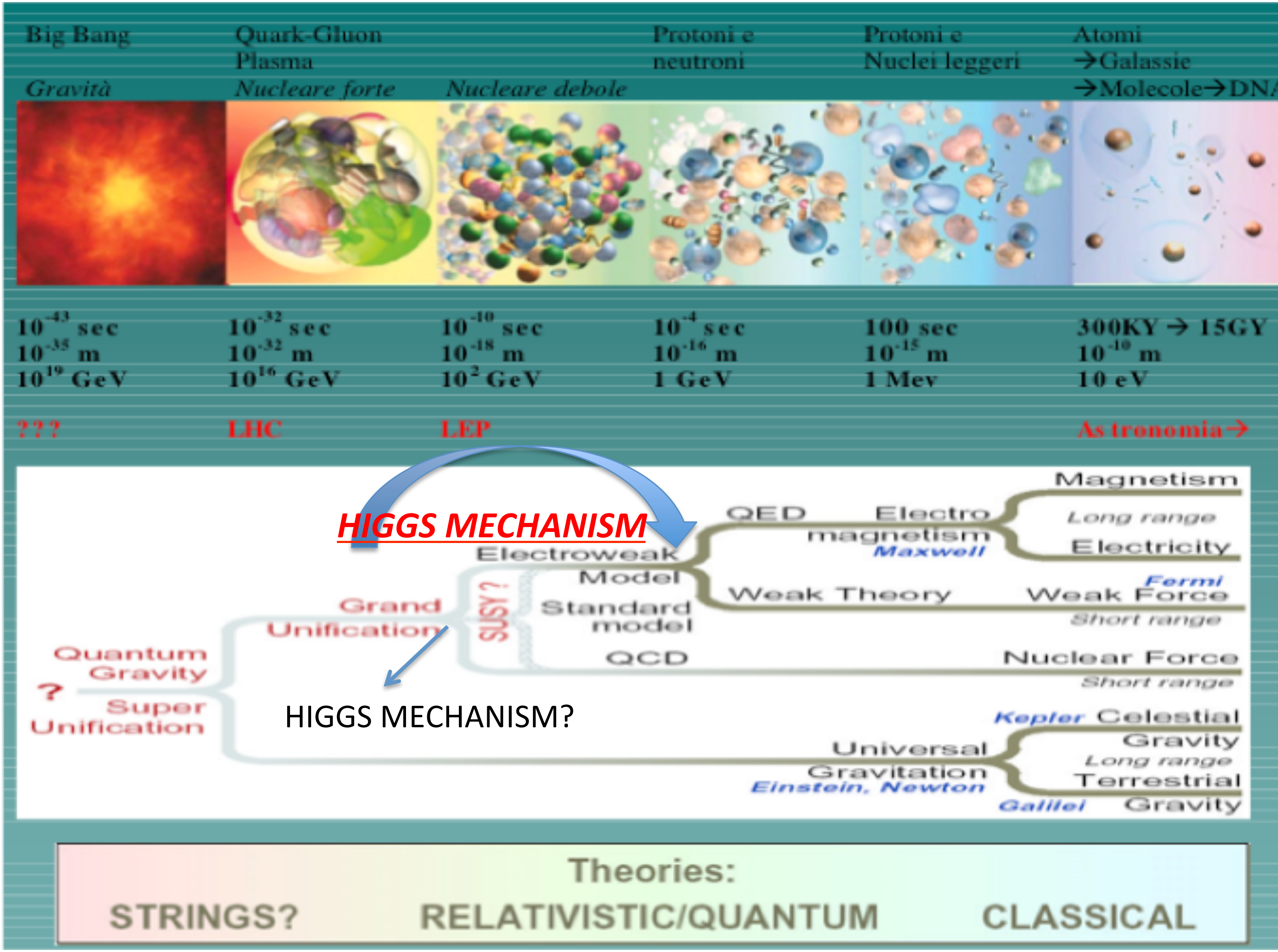











Big Bang
Gravità
Quark-Gluon Plasma
Nucleare forte
Nucleare debole
Protoni e neutroni
Protoni e Nuclei leggeri
Atomi →Galassie →Molecole→DNA
10^-43 sec 10^-35 m 10^19 GeV
10^-32 sec 10^-32 m 10^16 GeV
10^-10 sec 10^-18 m 10^2 GeV
10^-4 sec 10^-16 m 1 GeV
100 sec 10^-15 m 1 Mev
300KY → 15GY 10^-10 m 10 eV
???
LHC
LEP
As tronomia→
HIGGS MECHANISM
Magnetism
QED
Electro magnetism
Maxwell
Long range
Electricity
Electroweak
Model
Fermi
Weak Theory
Weak Force
Grand Unification
SUSY ?
Standard model
Short range
Quantum Gravity
QCD
Nuclear Force
Short range
?
Super Unification
HIGGS MECHANISM?
Kepler
Celestial Gravity
Universal Gravitation
Long range
Einstein, Newton
Terrestrial
Galilei
Gravity
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL

Are the SMs really STANDARD?

G-W-S SM

- **All the experimental results** of both **high-energy particle physics** and **high-intensity flavor physics** are surprisingly (and embarrassingly) in **very good agreement** with the predictions of the GSW SM

- Only (possible) exceptions:

-- **the anomalous magnetic moment of the muon (3.6 σ discrepancy w.r.t. the SM prediction);**

- **diphoton peak at 750 GeV**

ΛCDM SM

- **All the cosmic observations are in agreement** with the ~25% CDM, ~70% cosmological constant **Λ** , ~5% ordinary matter of the **ΛCDM SM**

- (Possible) exception: **troubles with pure Cold DM** from absence proto-galaxies, non-existence of spikes in DM density at the centre of the galaxies

…

THE FLAVOUR PROBLEMS

FERMION MASSES

What is the rationale hiding behind the spectrum of fermion masses and mixing angles (our "**Balmer lines**" problem)

→ **LACK OF A FLAVOUR "THEORY"**

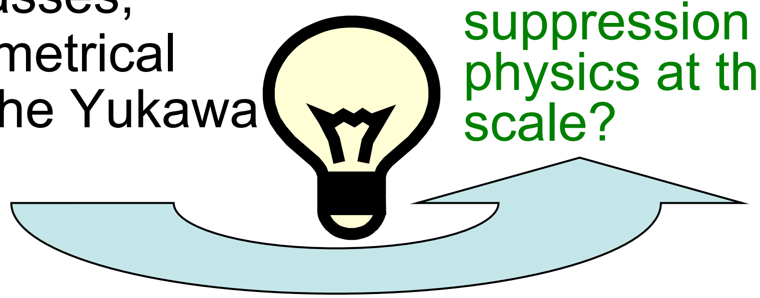
(new flavour – horizontal symmetry, radiatively induced lighter fermion masses, dynamical or geometrical determination of the Yukawa couplings, …?)

FCNC

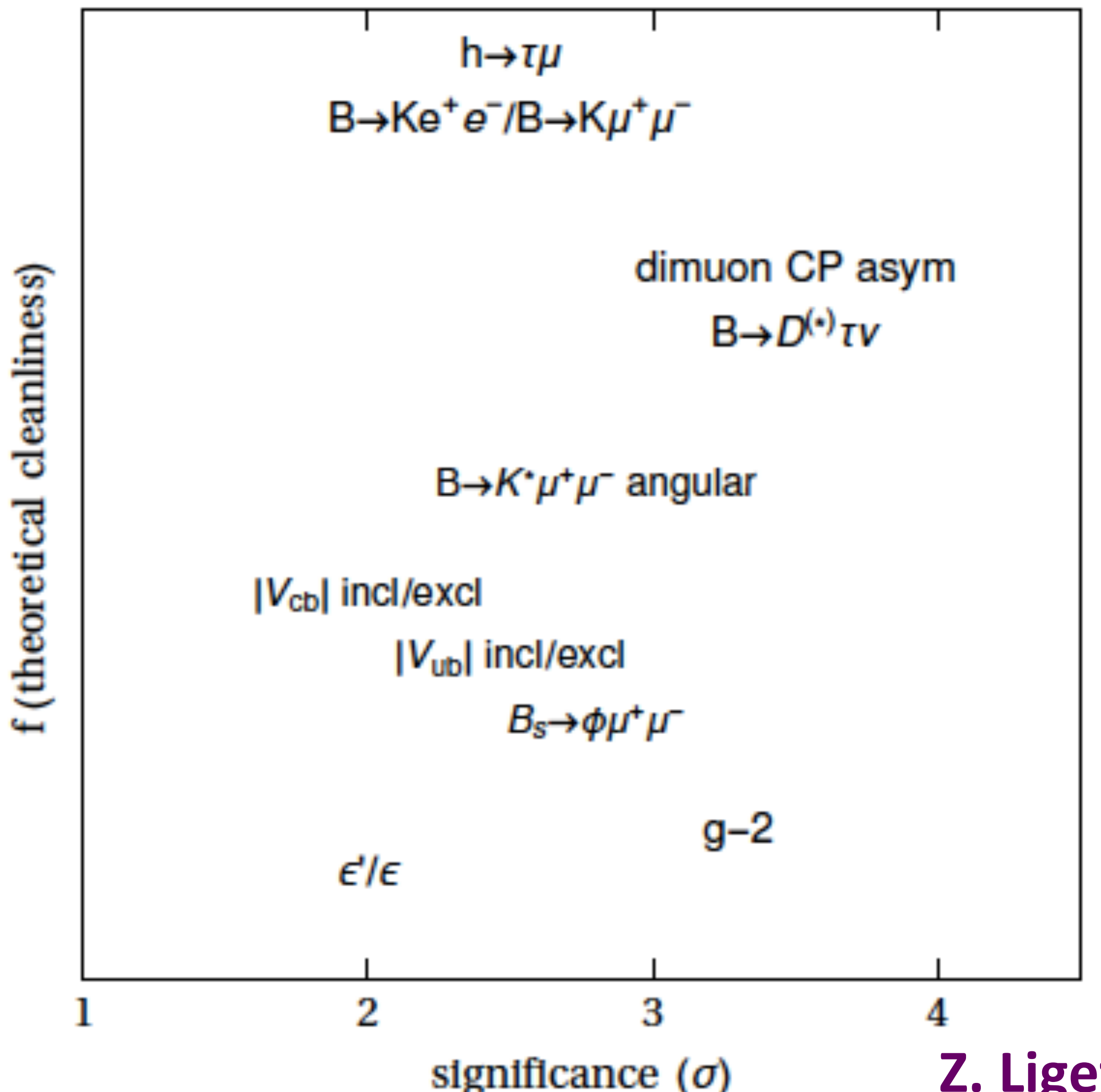
Flavour changing neutral current (FCNC) processes are suppressed.

In the SM two nice mechanisms are at work: the **GIM mechanism** and the structure of the **CKM mixing matrix.**

How to cope with such delicate suppression if the there is new physics at the electroweak scale?



Deviations from the SM expectations: significance of such deviations vs. their theoretical cleanliness



Z. Ligeti, LP 2015

MICRO

GWS STANDARD MODEL

MACRO

HOT BIG BANG STANDARD MODEL

UNIVERSE EXPANSION + WEAK INTERACTIONS

1 sec. after BB

NUCLEOYINTHESIS

NUMBER OF BARYONS and **OF NEUTRINO SPECIES** → CONFIRMED FROM CMB **350000 YEARS** AFTER BB

Independent confirmation from the study of the CMB

BUT ALSO

FRICTION POINTS

-COSMIC MATTER-ANTIMATTER ASYMMETRY

-INFLATION ???

- DARK MATTER + DARK ENERGY

OBSERVATIONAL EVIDENCE OF NEW PHYSICS

BEYOND THE STANDARD

What the SM does not account for…

- neutrino masses
- dark matter
- baryogenesis
- inflation

→ OBSERVATIONAL REASONS

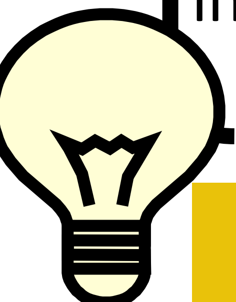
- $M_{HIGGS} / M_{PLANCK} \sim 10^{-16}$
- $E_{VACUUM} (DE) / M_{HIGGS} \sim 10^{-14}$
- $\Theta_{CPV \text{ in STRONG INTERAC.}} < 10^{-9}$

→ THEOR. REASONS

The Energy Scale from the "Observational" New Physics

- neutrino masses
- dark matter
- baryogenesis
- inflation

NO NEED FOR THE NP SCALE TO BE CLOSE TO THE ELW. SCALE



The Energy Scale from the "Theoretical" New Physics

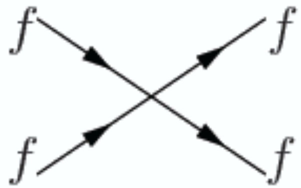
★ ★ ★ **Stabilization of the electroweak symmetry breaking at M_W calls for an ULTRAVIOLET COMPLETION of the SM already at the TeV scale** +

★ **CORRECT GRAND UNIFICATION "CALLS" FOR NEW PARTICLES AT THE ELW. SCALE**

No-Lose Theorems

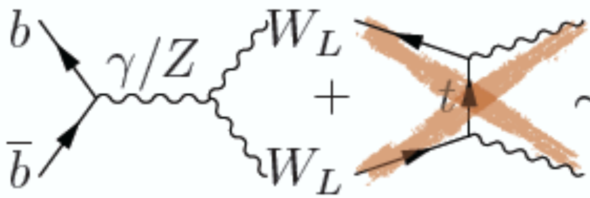
A number of **guaranteed** discoveries in the history of HEP

Beyond the Fermi Theory:



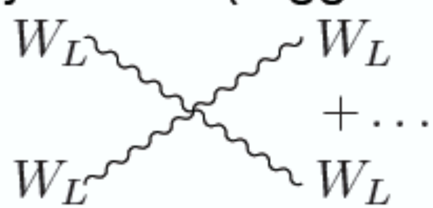
$$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \Rightarrow m_W < 4\pi v$$

Beyond the Bottom Quark:



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \Rightarrow m_t < 4\pi v$$

Beyond the (Higgsless) EW Theory:



$$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \Rightarrow m_H < 4\pi v$$

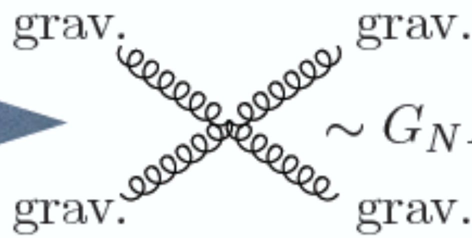
Each (secretly) due to d=6 non-renormalizable operators, signalling nearby new physics.

A. Wulzer 2015

No-Lose Theorems

A. Wulzer

Only one d>4 is left after Higgs discovery …

$\frac{1}{G_N}\sqrt{g}R$ ⟶ 

$\sim G_N E^2 \simeq E^2/{M_\mathrm{P}}^2 < 16\pi^2$ ⟶ $\Lambda_\mathrm{SM} \lesssim M_\mathrm{P}$

… the last, impractical, No-Lose Theorem is Q.G. at M_P !

We do have exp. evidences of BSM, but none necessarily pointing to light/strongly-coupled enough new physics:

"No guaranteed discoveries" = "post-Higgs depression"

However, one **d<4** comes with the Higgs discovery:

$\frac{m_H^2}{2}H^\dagger H$ ⟶

The **Naturalness Problem:**

Why $m_H \ll \Lambda_\mathrm{SM}$?

THE "COMPREHENSION" OF THE ELECTROWEAK SCALE

$$V = \mu^2|H|^2 + \lambda|H|^4$$

μ ~ 10^2 GeV

Romanino

- M = O(10^{16} GeV)

	SU(3)	SU(2)	U(1)		SO(10)
L	1	2	-1/2		
e	1	1	1		
Q	3	2	1/6	⇒	16
u	3*	1	-2/3		
d	3*	1	1/3		

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

ONLY FOR SCALARS; SM FERMIONS AND GAUGE BOSON MASSES ARE PROTECTED BY THE SU(2) × U(1) SYMMETRY !

To comprehend (i.e. stabilize) the elw. scale need NEW PHYSICS (NP) to be operative at a scale $m_{NP} \ll M$

Naturalness or Un-naturalness?

Naturalness

- **New SYMMETRY** giving rise to a cut-off at

$$m_{NP} \ll M$$

Low-energy **SuperSymmetry**

- **Space-time modification (extra-dim., warped space)**

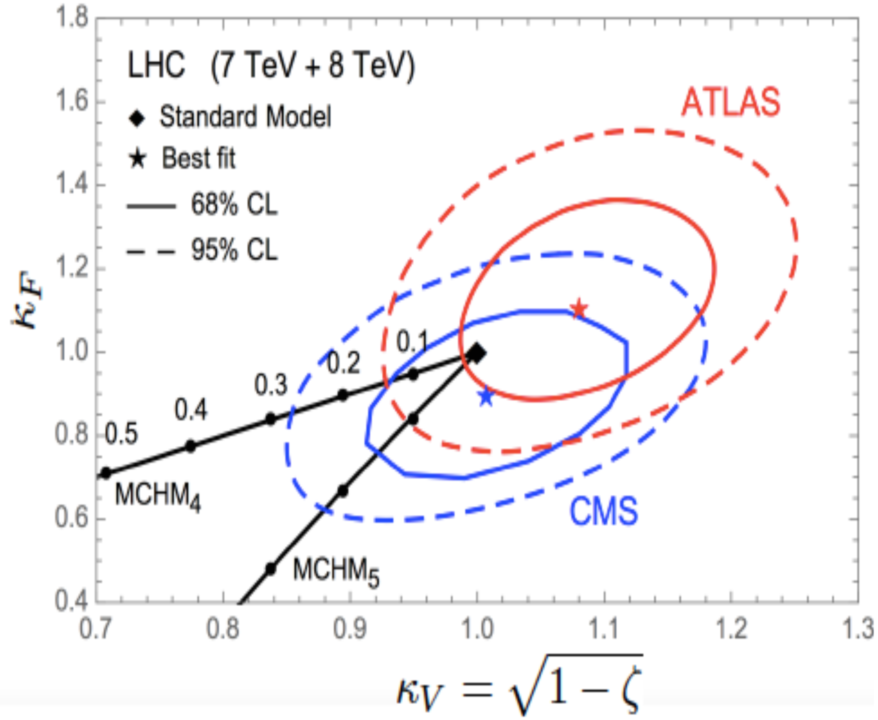
- **COMPOSITE HIGGS** : the Higgs is a pseudo-Goldstone boson (pion-like) → new interaction getting strong at $m_{NP} \ll M$

Un-naturalness

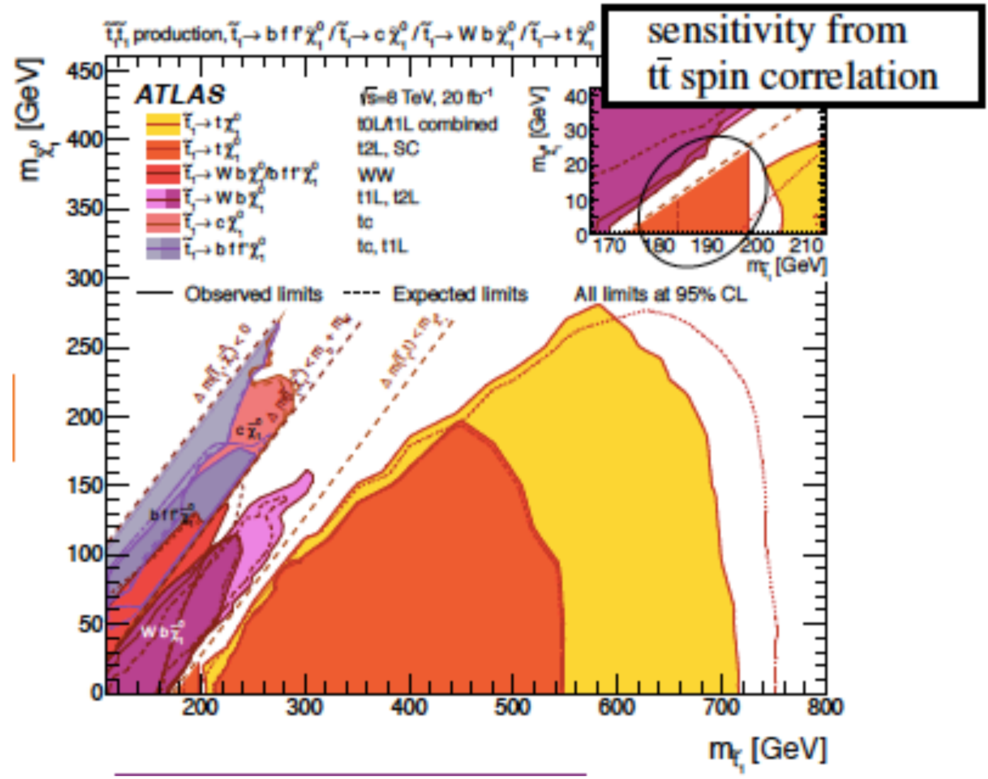
- **The scale at which the electroweak symmetry is spontaneously broken by <H> results from COSMOLOGICAL EVOLUTION**

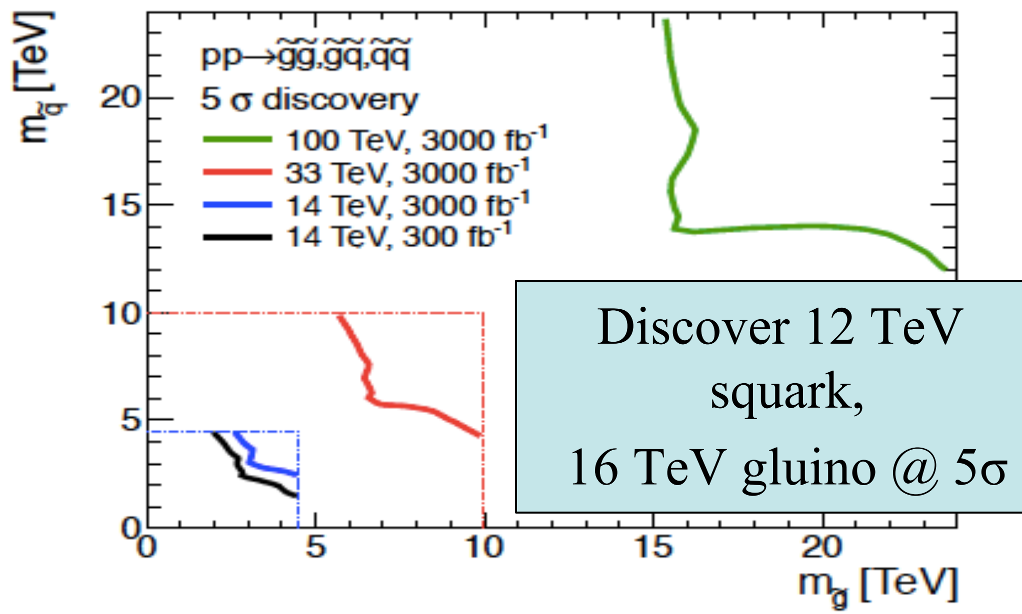
- **H is a fundamental (elementary) particle → we live in a universe where the fine-tuning at M arises (anthropic solution, multiverse, Landscape of string theory)**

Higgs boson: elementary or composite?



Current bound ζ < 0.12 → already some tuning on the **composite** models to look like SM





What remains to be learnt on the SM from LHC and future accelerators

- **Higgs boson couplings to bosons and fermions**: precisions ≤ 10% attainable with 300 fb^{-1} ;

  precisions 2% - 5% in the High Luminosity phase

  uncertainties O(1%) at ILC and <1% at FCC-ee

- **Higgs total width**: too narrow (~4 MeV) to be measured at LHC – at HL-LHC try using the interference of a specific mode with the continuum; at ILC/FCC-ee through HZ

- **Higgs boson rare production and rare decay modes**: HH production important → related to Higgs self-couplings → need full HL-LHC phase

Units are %

Coupling $\sqrt{s}$ (TeV) → L (fb^{-1}) →	LHC 14 3000(1 expt)	CepC 0.24 5000	FCC-ee 0.24 +0.35 13000	ILC 0.25+0.5 6000	CLIC 0.38+1.4+3 4000	FCC-hh 100 40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Few preliminary estimates available
SppC : similar reach

from K_γ/K_Z, using K_Z from FCC-ee

rare decays → pp competitive/better

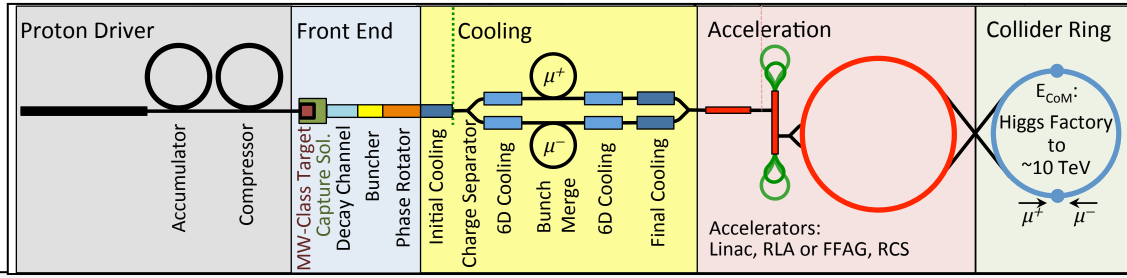
from ttH/ttZ, using ttZ and H BR from FCC-ee

- LHC: ~20% today → ~ 10% by 2023 (14 TeV, 300 fb^{-1}) → ~ 5% HL-LHC
- HL-LHC: -- first direct observation of couplings to 2nd generation (H→ μμ)
  -- model-independent ratios of couplings to 2-5%
- Best precision (few 0.1%) at FCC-ee (luminosity !), except for heavy states (ttH and HH) where high energy needed → linear colliders, high-E pp colliders
- Complementarity/synergies between ee and pp

F. Gianotti, EPS '15

Theory uncertainties (presently few percent e.g. on BR) need to be improved to match expected superb experimental precision

Muon colliders



Synergies with neutrino factories

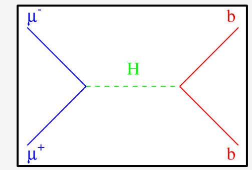
F. Gianotti, EPS '15

Main advantage compared to e^+e^- colliders: $m_\mu \sim 200\, m_e$

→ negligible SR → can reach multi-TeV with (compact !) circular colliders: 300 m ring for $\sqrt{s}$ = 125 GeV, 4.5 km for $\sqrt{s}$ = 3 TeV

→ negligible beamstrahlung → much smaller E spread

→ σ (μμ → H) ~ 20 pb (s-channel resonant production) → H factory

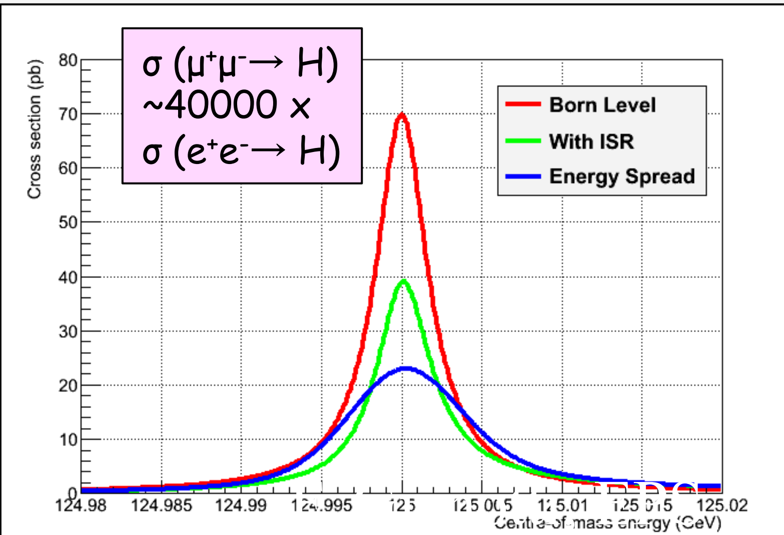


Main challenge: produce high-intensity, low E-spread beams:

- ❑ $m_\mu \sim 200\, m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of ~ 3×10^{-5} (for precise line shape studies) and high L
- ❑ $\tau_\mu \sim 2.2$ μs → production, collection, cooling, acceleration, collisions within ~ ms

Beam spread of ~ 3×10^{-5} would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances

However, with currently projected L (~10^{32}): ~ 20000 H/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)

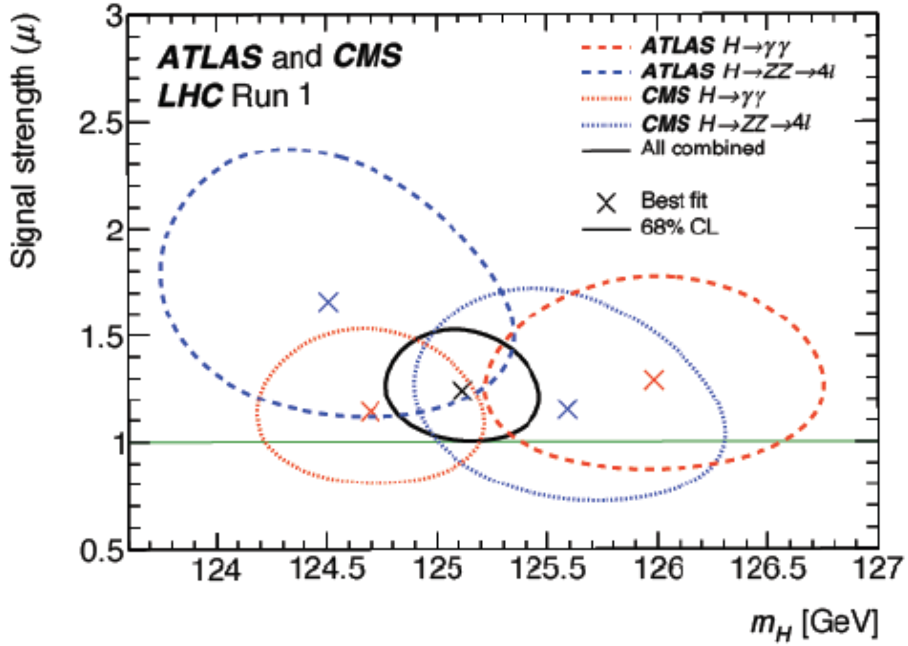


More R&D needed to demonstrated feasibility, in particular cooling:

linear systems (MICE at RAL), rings (recently re-ignited by C.Rubbi

Higgs Mass measurements

ATLAS + CMS ZZ* and γγ final states



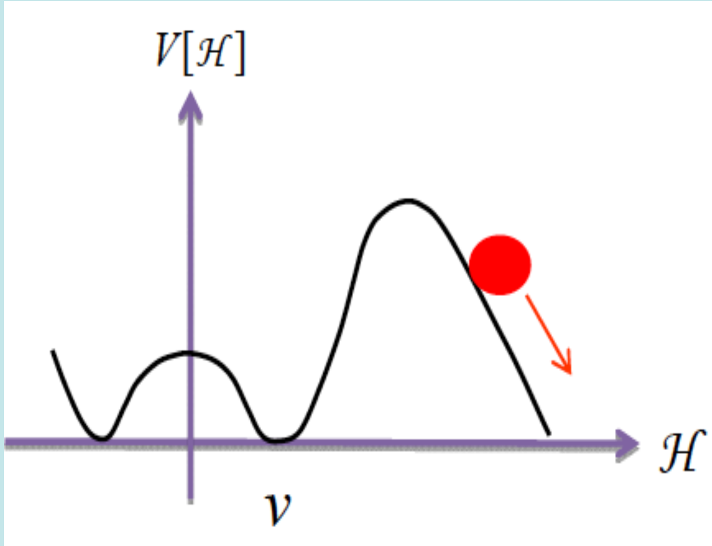
$$125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$$

The values of the **TOP and HIGGS masses** are crucial to establish the stability of the

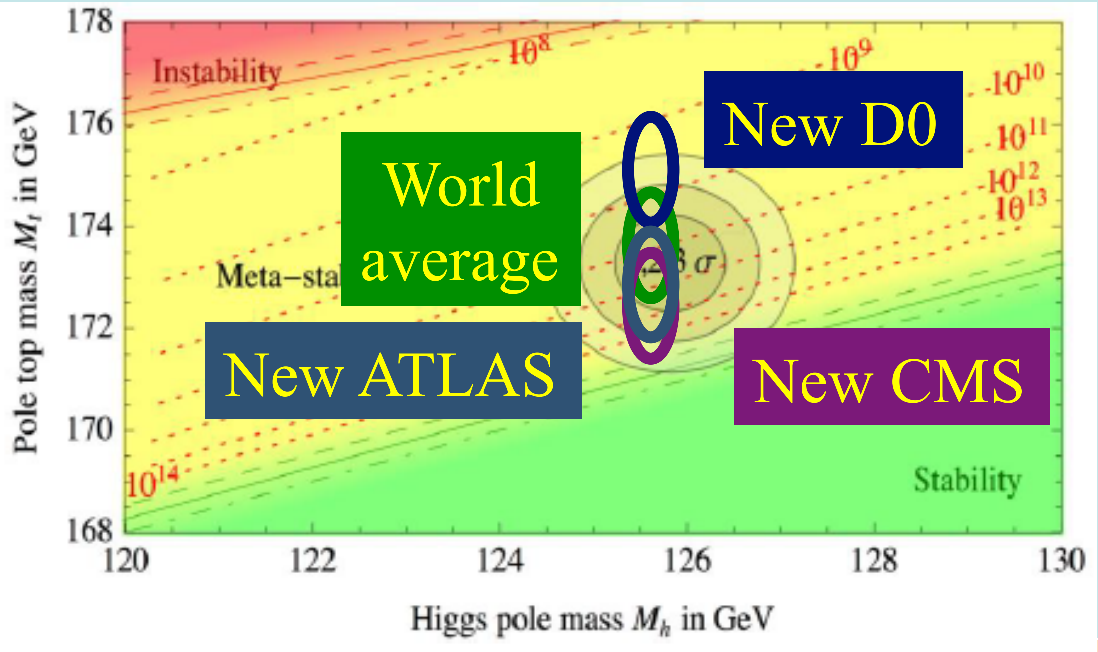
ELECTROWEAK VACUUM

Vacuum Instability in the Standard Model

- Very sensitive to m_t as well as M_H



J. Ellis, LP 2015



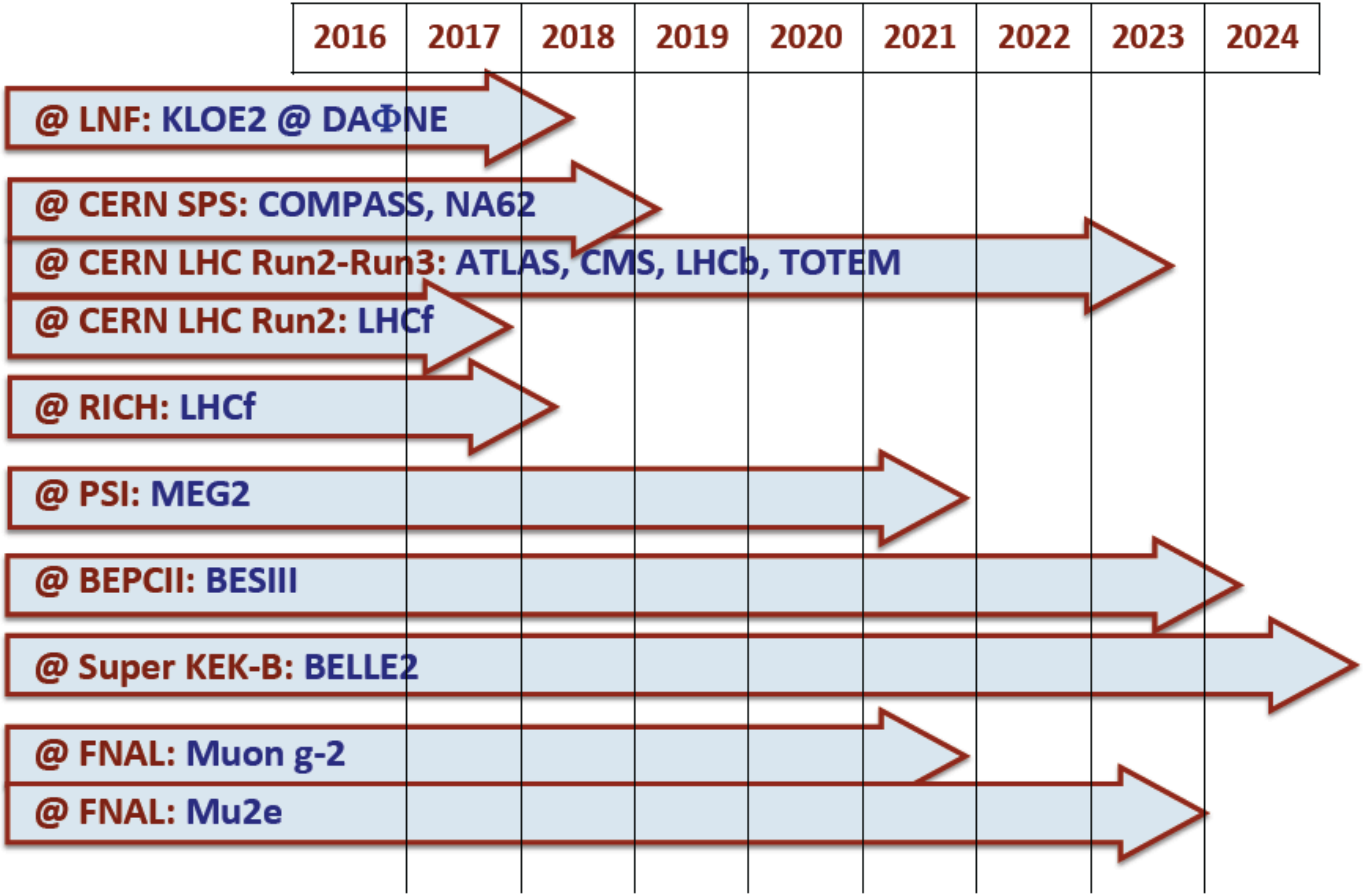
Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio & Strumia, arXiv:1307.3536

- Instability scale:

$$\log_{10}\frac{\Lambda_I}{\text{GeV}} = 11.3 + 1.0\left(\frac{M_h}{\text{GeV}} - 125.66\right) - 1.2\left(\frac{M_t}{\text{GeV}} - 173.10\right) + 0.4\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007}$$

$m_t = 173.3 \pm 1.0$ GeV → $\log_{10}(\Lambda/\text{GeV}) = 11.1 \pm 1.3$

Complete data taking plans with approved detectors



Full exploitation of our ability of 'understanding' the SM

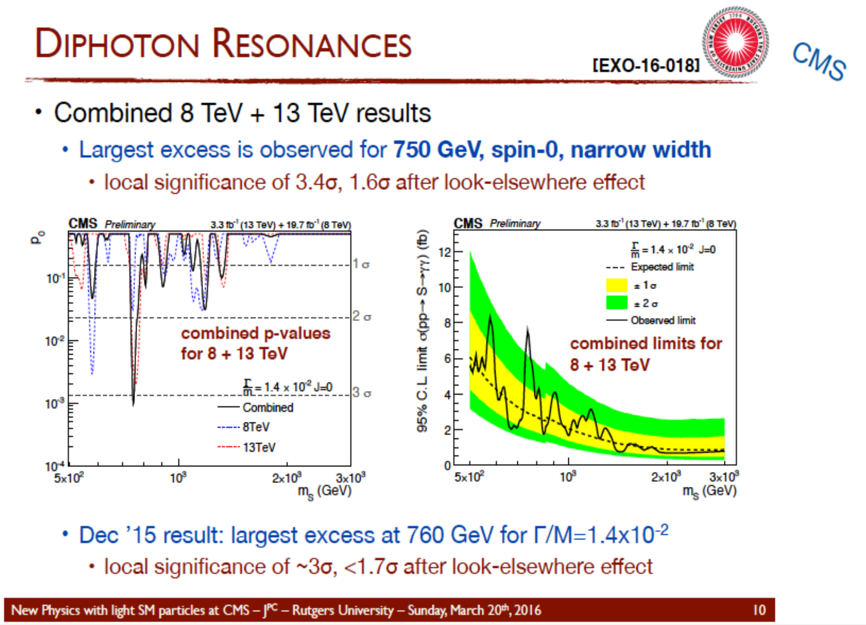
- Still relevant investigations on the SM importance of the SM precision physics for
  i) a **better and deeper understanding of the SM**,
  ii) indirect hints of **new physics**

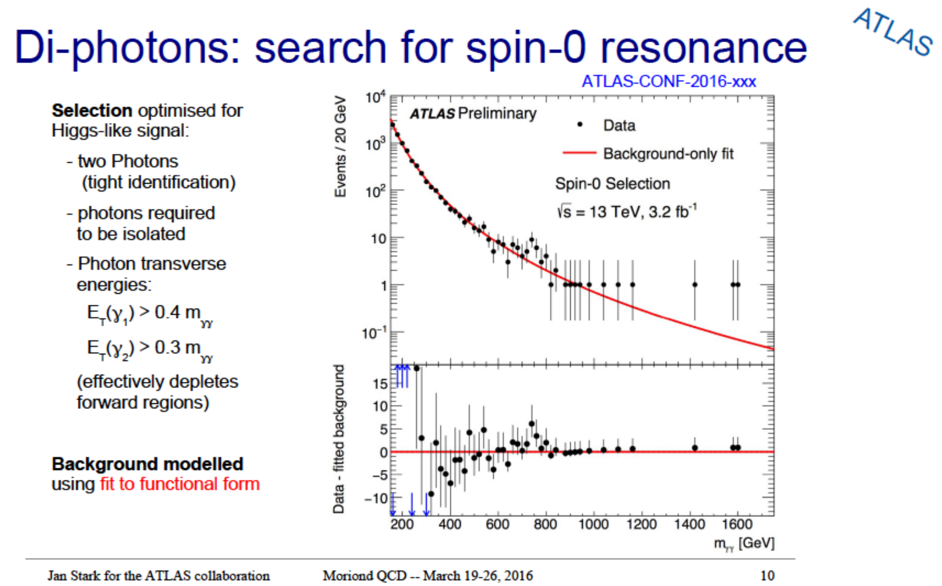
- 'Sociological' remark: it may be difficult **to attract and keep young people** with the horizon of performing precious SM precision physics

much depends on the next 5 years …

- **LHC14** (high energy: ATLAS, CMS; flavor: LHCb; quark-hadron phase transition: ALICE)
- **Flavor**: NA62; upgraded MEG, Mu-e; BELLEII; EDMs; g-2
- **DM** 1-ton exps. → $10^{-10} – 10^{-11}$ pb
- **Neutrinoless double β** → ν mass degenerate region; enter IH region
- **SBN** → sterile ν ?
- **Gravitational waves** → discovery to pave the way to gravitational wave astronomy
- **DE**: BOSS →DESI; DES → LSST
- **CMB**: final PLANCK; B-modes of the polariz.+ black-body spectrum : EU exps. QUBIC, LSPE, QIJOTE + many others on ground and balloons in US, Japan

if…



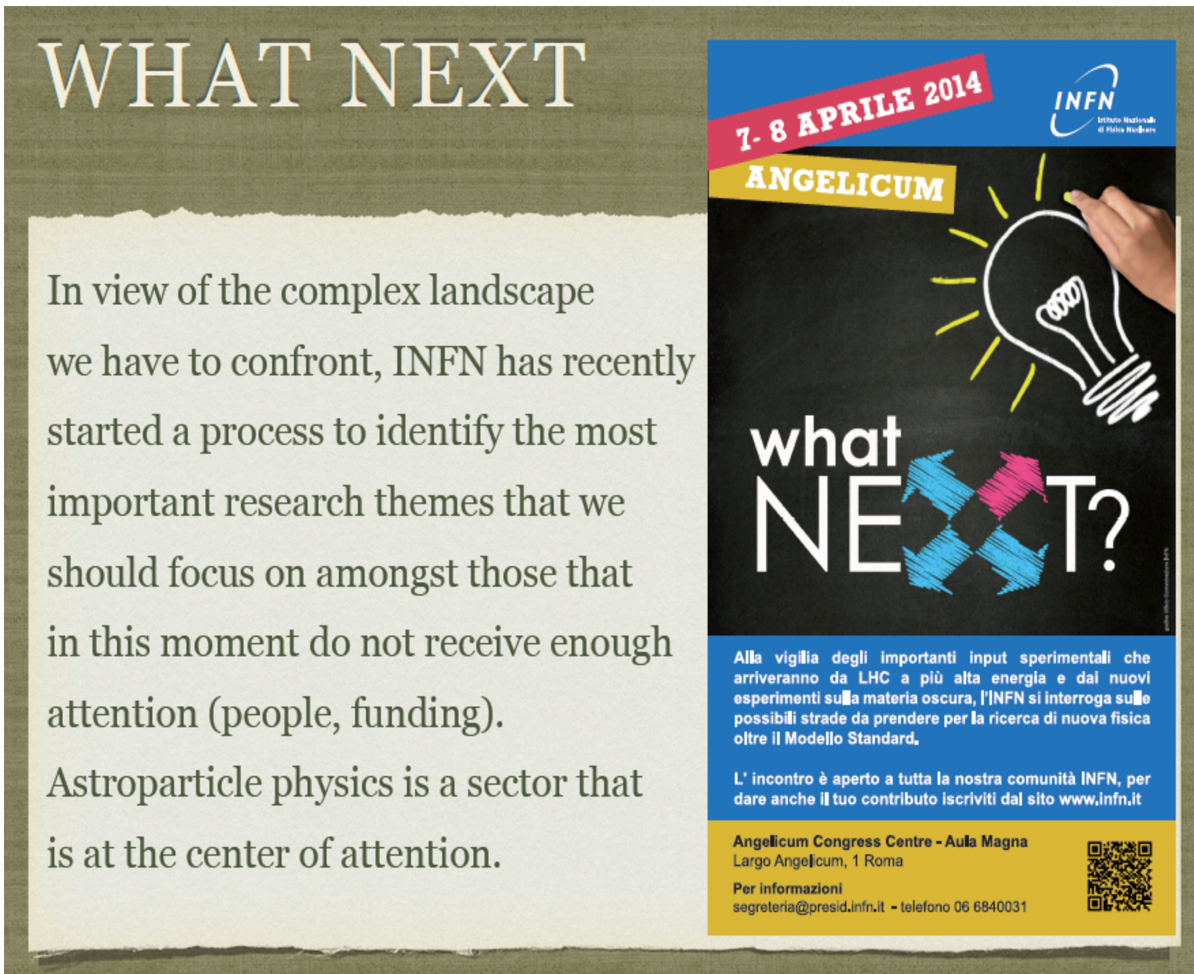


or some other NP signal shows up at LHC14, then, obviously, "**jump**" into such NP area → for instance if the Diphoton peak proves to be real, then **doubling LHC energy** may become an attractive option

if…

- **No** new NP signal shows up at LHC14 and at the new generation astroparticle projects → vigorous study of the various post-LHC options, while

s

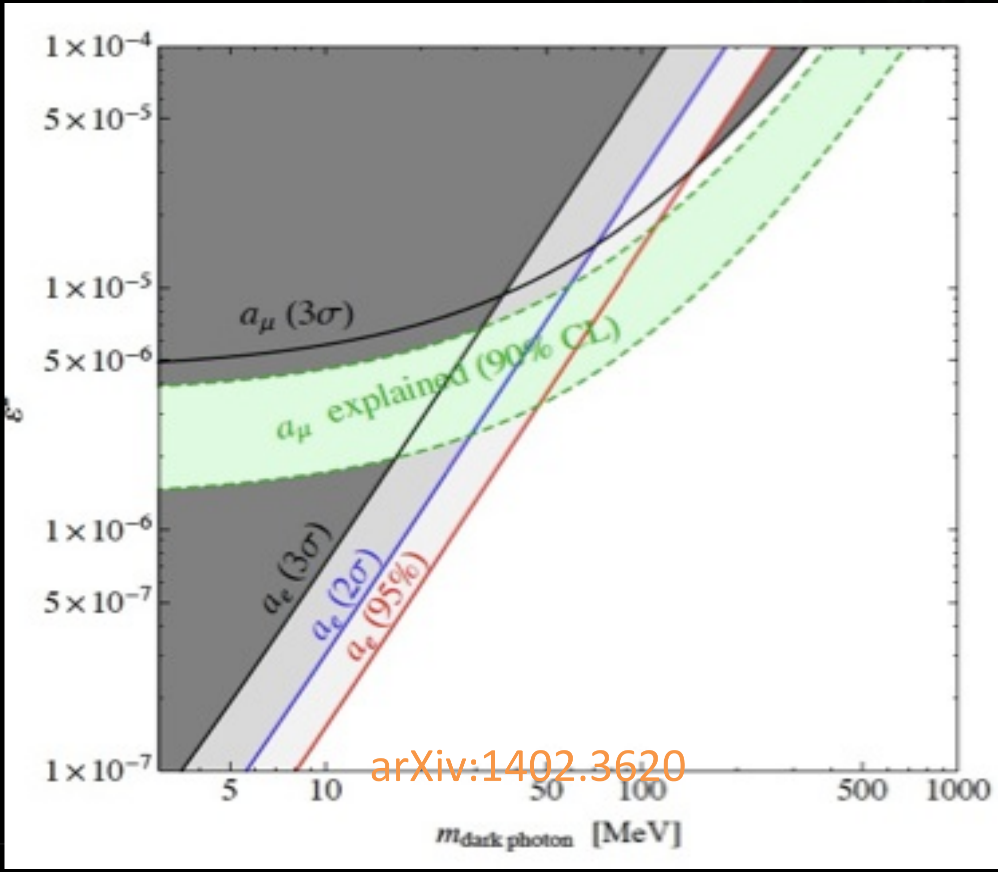


HIGH ENERGY, HIGH-INTENSITY, ASTROPARTICLE PHYSICS → COMPLEMENTARY ATTACK TO THE NEW PHYSICS FORTRESS

PADME at Frascati

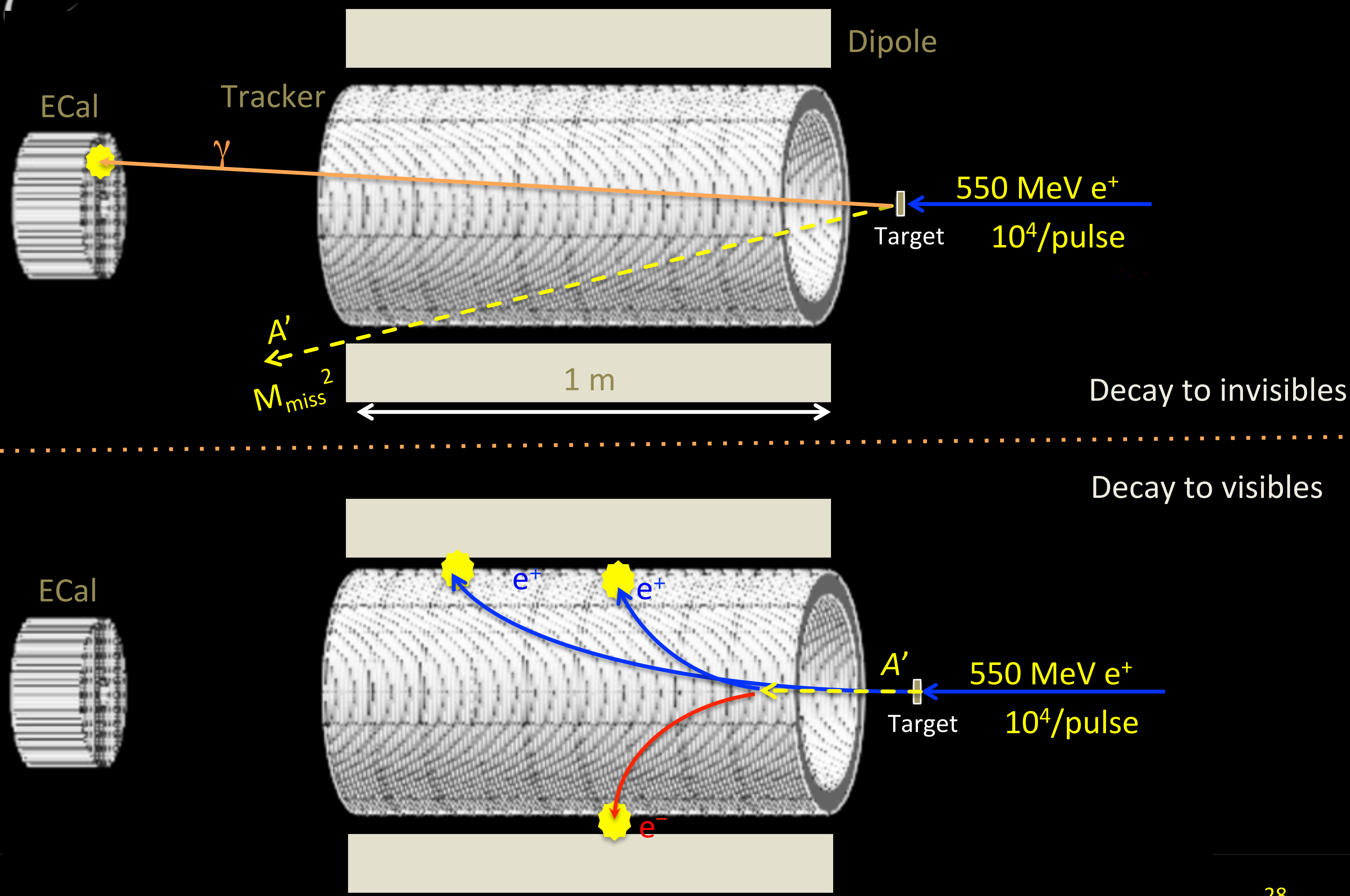
PADME aims to detect U boson produced in e^+e^- annihilation and decaying into invisibles
- No assumption on the U decays products and coupling to quarks
- Only minimal assumption: U bosons couples to leptons

No experimental results yet with this approach (VEPP3 planned experiment)

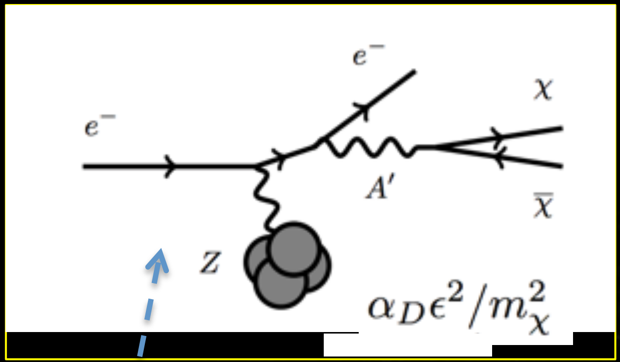


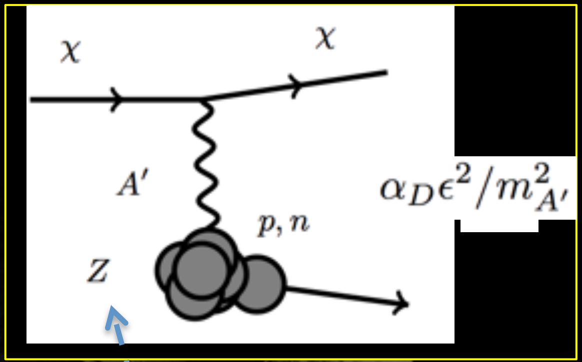
arXiv:1402.3620

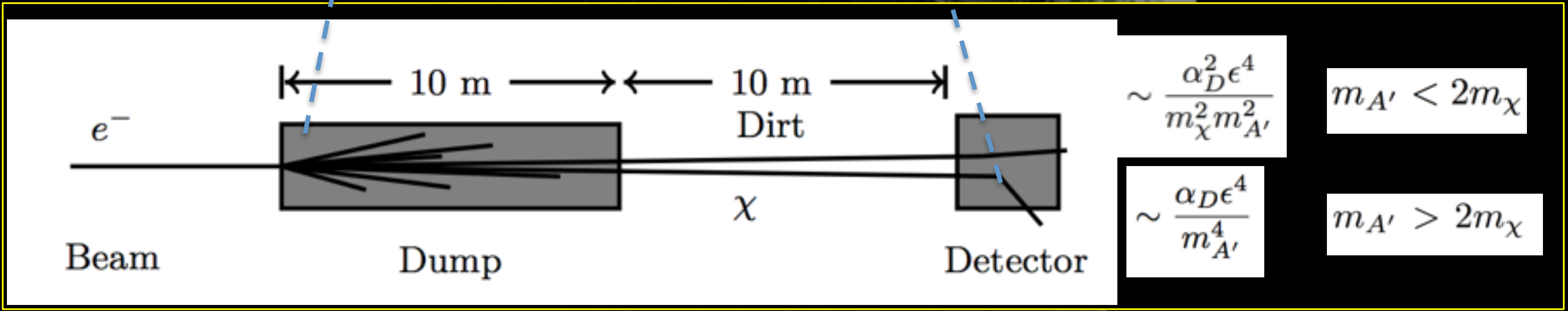
PADME at Frascati



New ideas for dump experiment: BDX at JLAB







Scintillator 1 m^3

1 MeV/10 MeV e^+e^- detection threshold

Backgrounds:

- Neutrino production
- Cosmogenic muons and neutrons

LOI presented to PAC

BDX at Frascati?

χ production and detection

- 1.5 GeV electron beam
- 7 10^{19} EOT/year
- 1 year run (50% efficiency)
- Repetition rate: 50 Hz, (0.7A in 10 ns bunch)
- **Negligible cosmogenic BG with timing cut**
- Expected ~20 counts in $1m^3$ plastic scintillator detector (1 MeVee threshold)
- **Significant sensitivity to low mass (A'/χ) region**

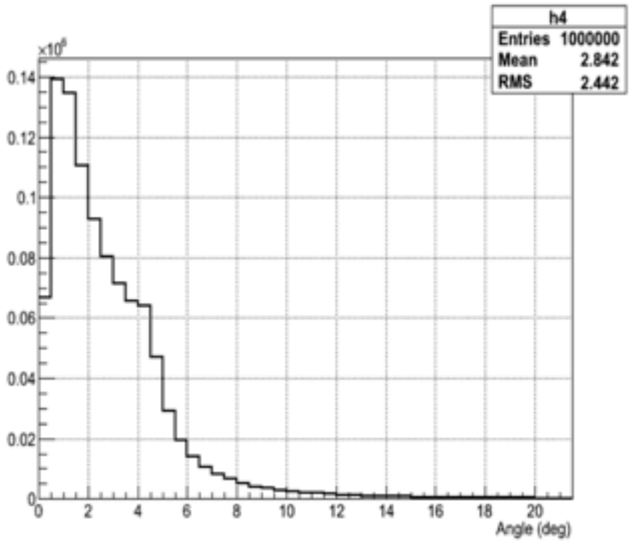
Parameters:

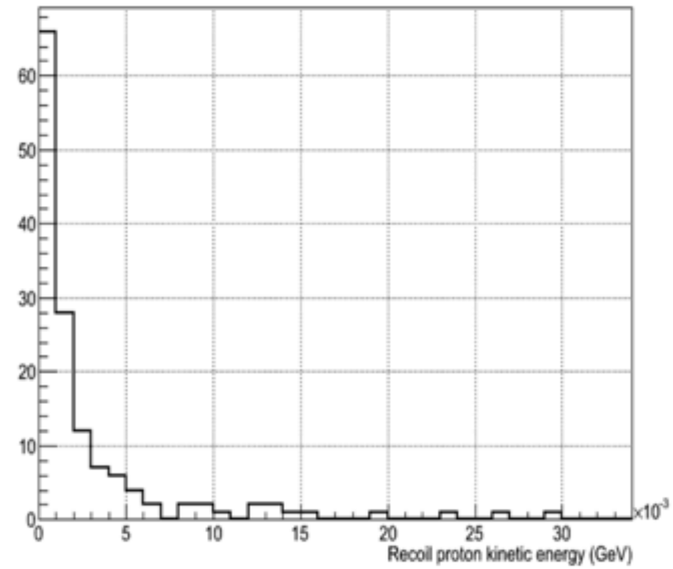
M_A' = 50 MeV

M_Chi = 10 MeV

Alpha_dark = 0.1

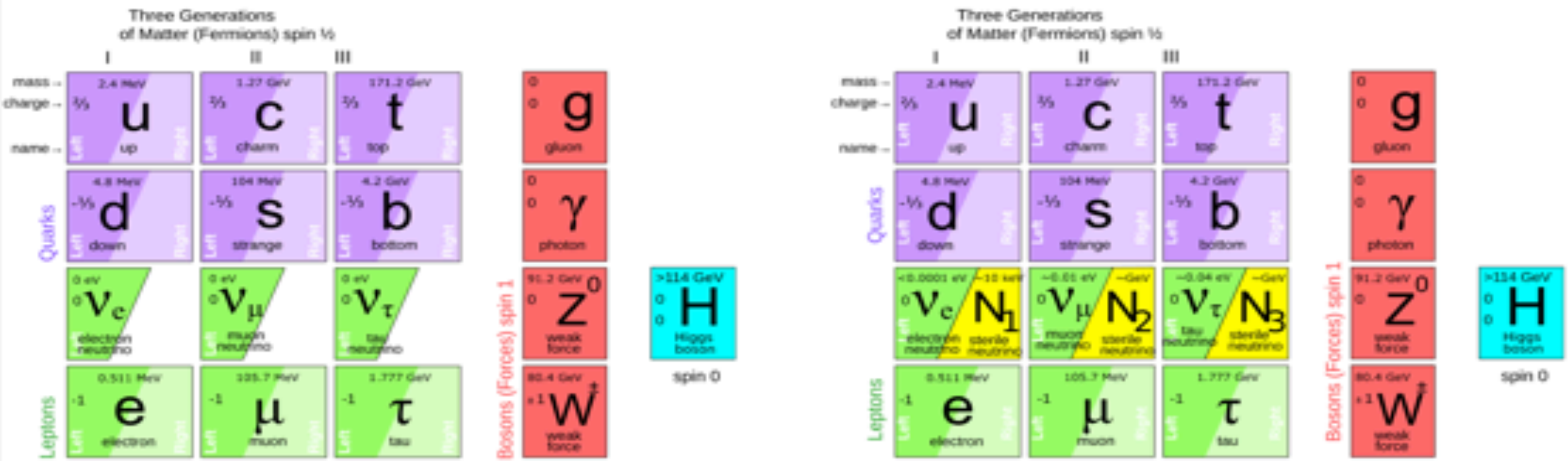
Epsilon = 10^-3





Very preliminary study. Results look very promising and should be investigated further.

quale **minima estensione del SM** posso fare per “curare” le sue tre malattie “osservative”:**dar massa ai neutrini, avere materia oscura e produrre una asimmetria materia-antimateria** **Modello di Shaposhnikov et al. con 3 neutrini right-handed “leggeri”**



Role of N_1 with mass in keV region: dark matter

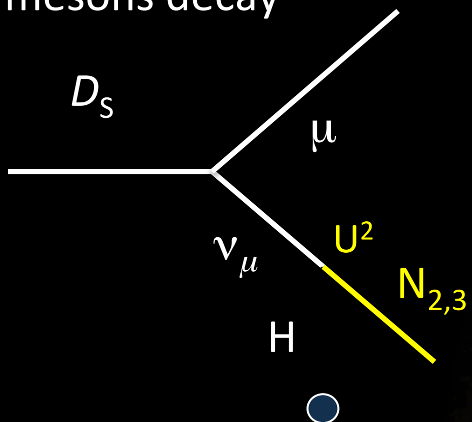
Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

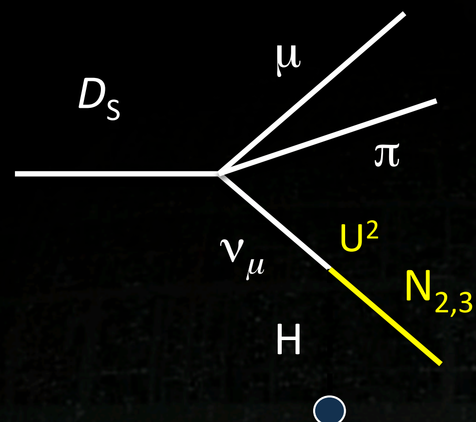
Role of the Higgs: give masses to quarks, leptons, Z and W and inflate the Universe.

Role of scale invariance and unimodular gravity: dilaton gives mass to the Higgs and $N_{1,2,3}$ and provides dynamical dark energy

SHiP at CERN SPS

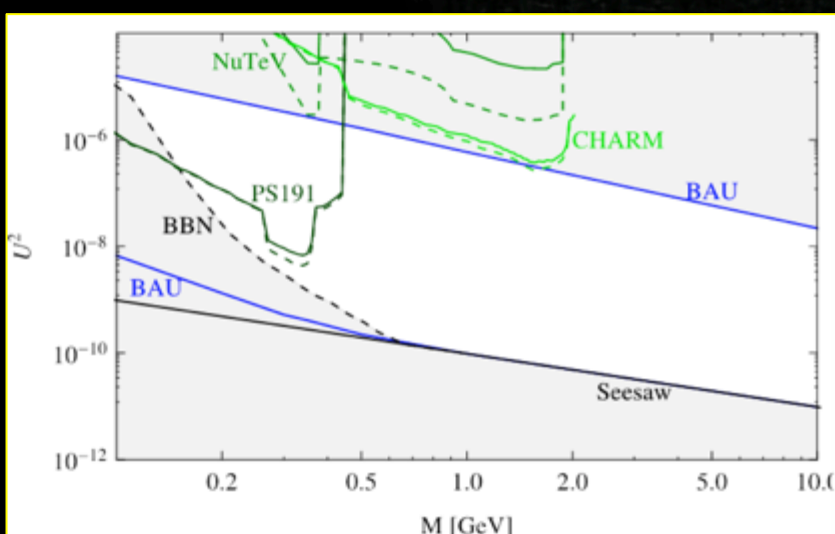
Look for HNL through the only possible interaction (Yukawa coupling to the Higgs) in the D mesons decay





- Small couplings, long decay length (km!)
- Decay channels in μ/e π, μ/e ρ, ν μ e

Coupling

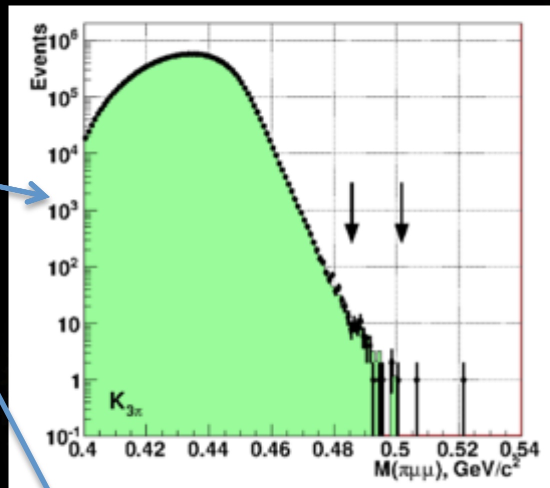


Mass

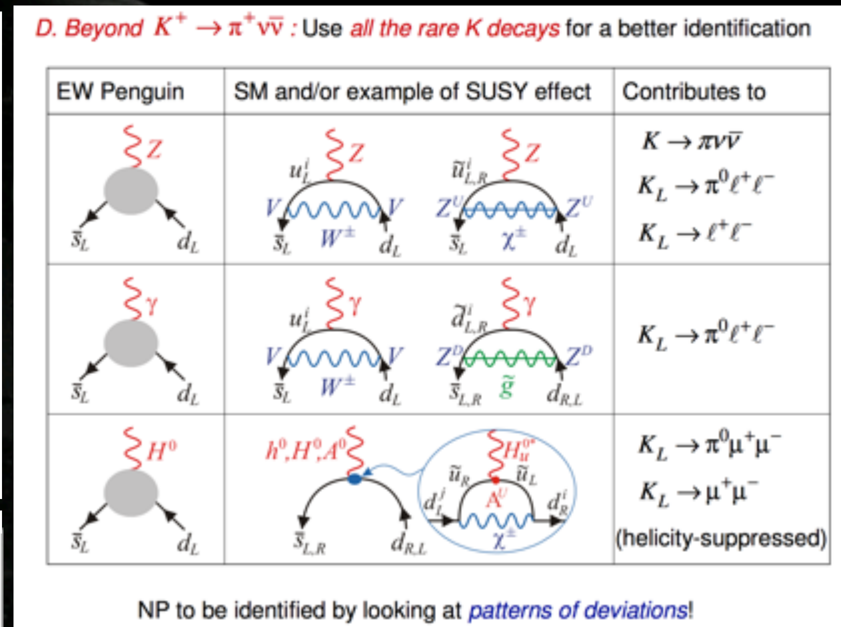
NA62

- Of course NA62 main goal is already searching for BSM effects
- What can be done with 10^{13} *K* decay and $2.5 \cdot 10^{12}$ π^0 decays?

- Search for LFV modes
- Dark photon
- Majorana neutrino
- Right-handed neutrino



$$B(\pi^0 \to \nu\nu) \sim 3 \cdot 10^{-8} k \left(\frac{m_\nu}{m_\pi}\right)^2 \sqrt{1 - 4\left(\frac{m_\nu}{m_\pi}\right)^2}$$



A) **Multimessenger astronomy**,
B) **neutrino properties**,
C) **dark side of the Universe and CMB**

- A) **Photon**, **cosmic ray**, **neutrino** , **gravitational** astronomies (some in their maturity, some in their youth, some just baby or even at the embryonic level
- B) **Neutrino mass** and its relation to the global symmetry of the SM, **Lepton number** (Dirac vs. Majorana natur of the neutrinos); measuring the full **neutrino mass parameters** (neutrino mass hierarchy, CP violation)
- C) **Dark Matter**; **Dark Energy** and **their role in the evolution of the Universe**; **CMB** (primordial inflation, elw. Phase transition, quark-hadron phase transition, nucleosynthesis, matter-antimatter cosmic asymmetry) -

A memorable past decade for astroparticle physics…

- **Multimessenger astronomy**: 2 new entries, i.e. **2 new cosmic messengers are DISCOVERED**, **HE cosmic neutrinos and gravitational waves**. Important progress in gamma- and charged cosmic ray – astronomy
- Impressive progress in our knowledge of **neutrino properties** through a combined action of **astroparticle physics and cosmology**
- **CMB**: extraordinary achievements by the Planck satellite on our knowledge of CMB temperature fluctuations as well as the CMB polarization modes
- The **dark side of the Universe**: amazing progress in our bounds especially on **WIMP DM**, but **the DM mystery** still remains. In spite of our better knowledge of some **DE** properties, still **its nature remains completely obscure**.

… and a thrilling decade in front of us

- **Multi-Messenger Astronomy** (advent of the cosmic HE neutrino and gravitational waves astronomies, the CTA tremendous leap in gamma astronomy, the new horizon in charged cosmic ray astronomy with the upgrade of AUGER);

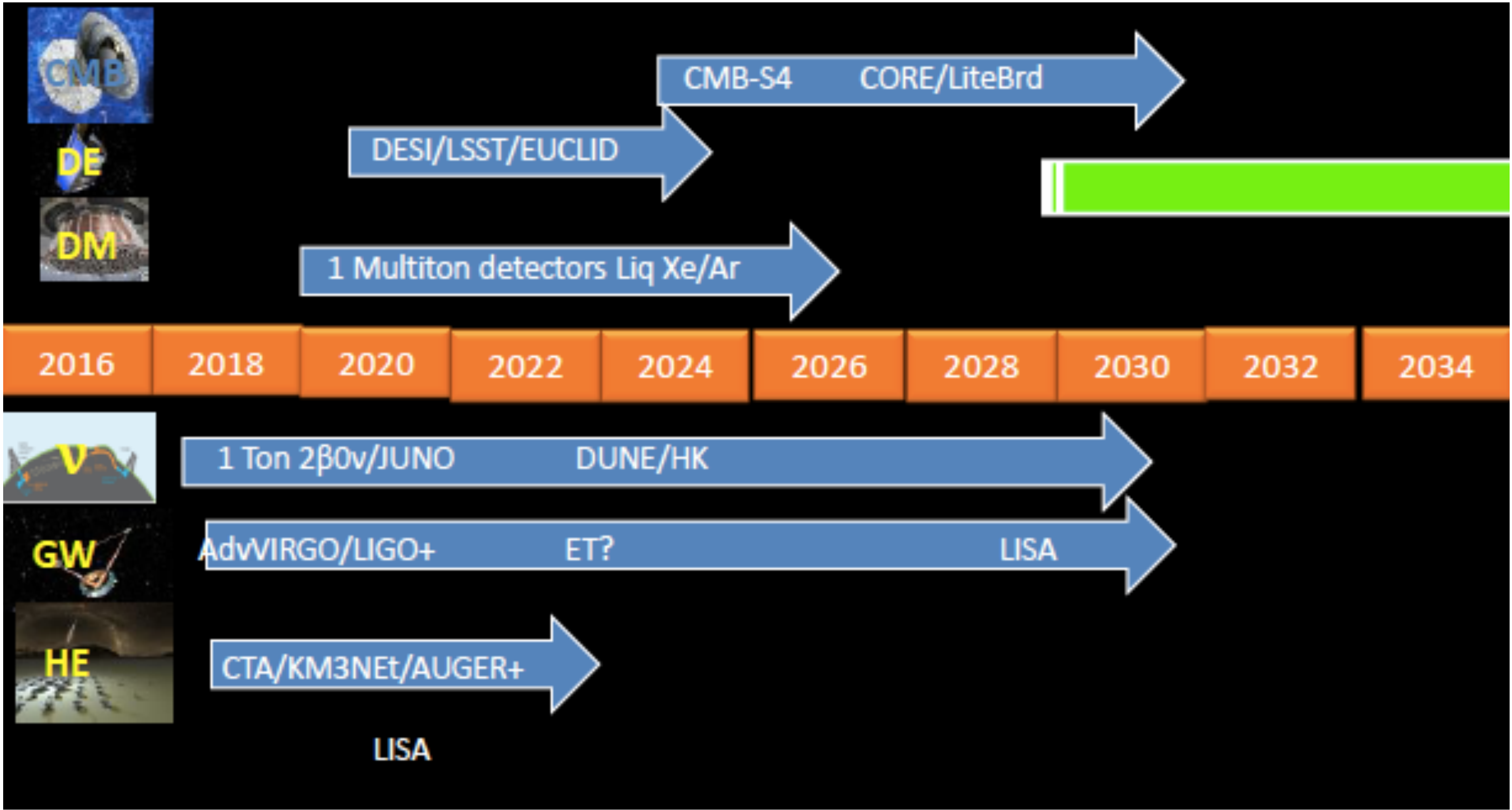
- Impressive progress in unveiling (some of) the **neutrino mysteries**: **Dirac vs. Majorana** (1-ton $(\beta\beta)_{0\nu\nu}$ exps.); **ν mass hierarchy** (the race: see fig.); ν CP violation (new long baseline ν exps.); **ν masses** (direct exps., amazing input from cosmology)

… and a thrilling decade in front of us

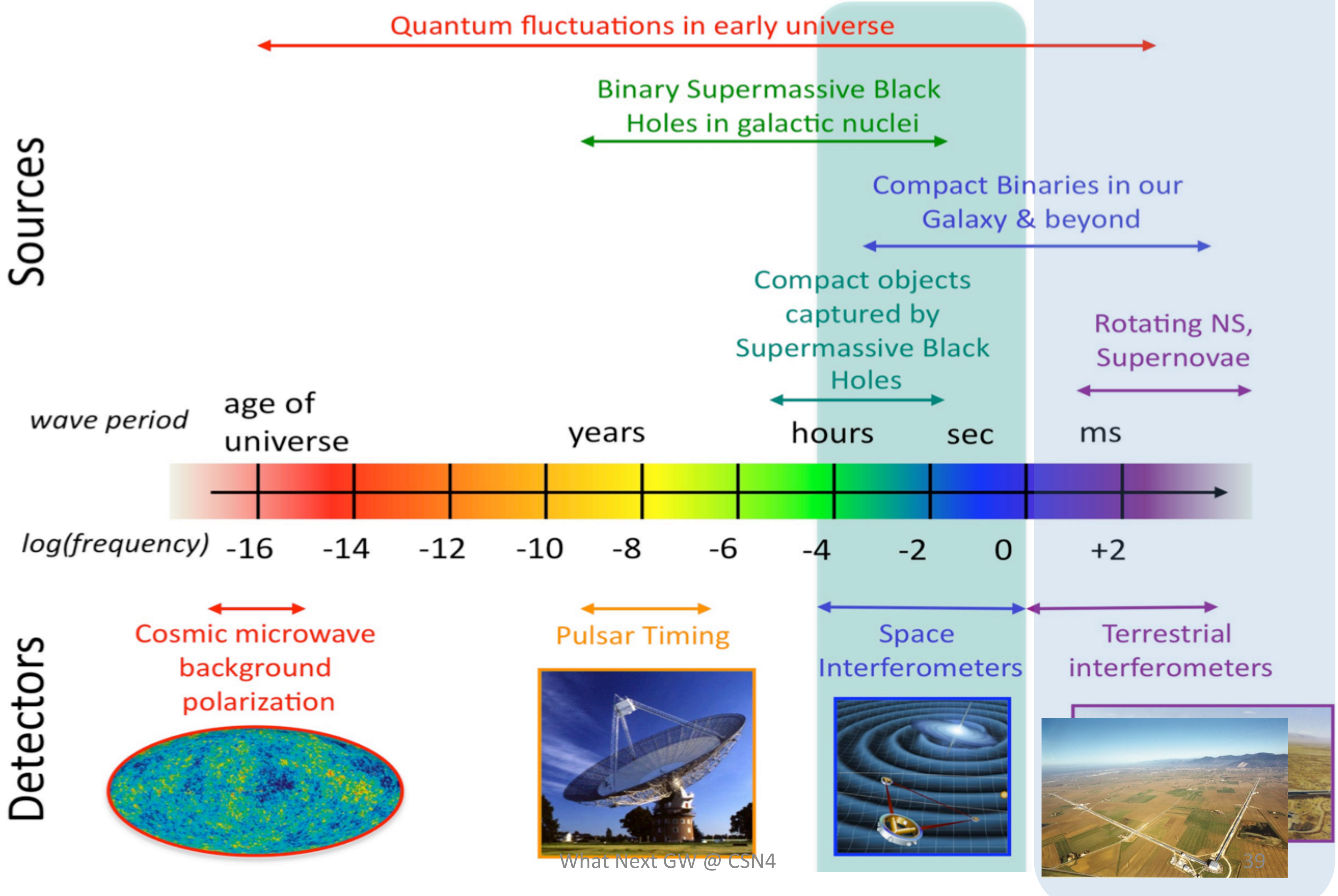
- **CMB** in the post-Planck (satellite) era → tremendous progress in ground, balloon and space exps.

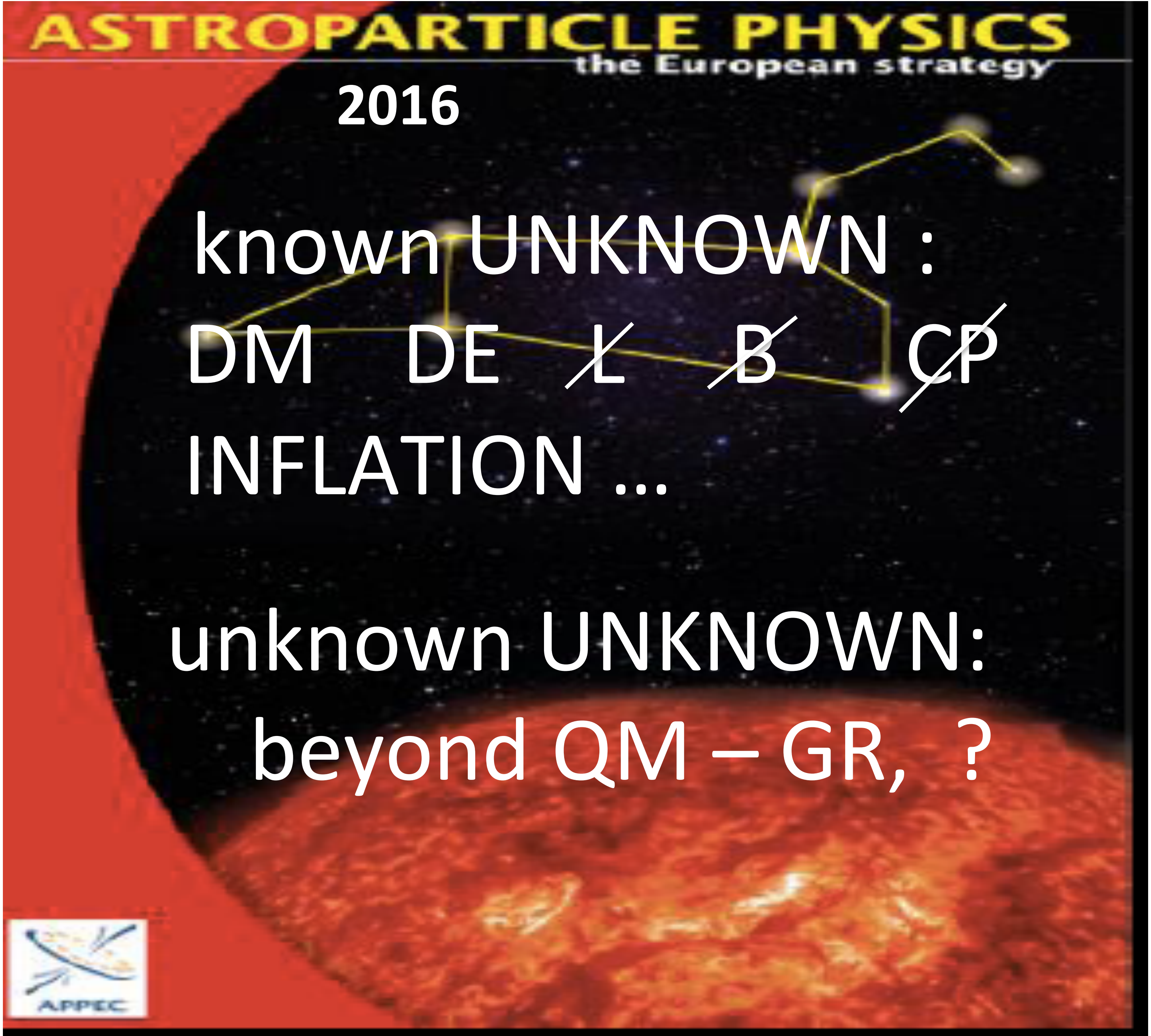
- Shedding (an impressive amount of) light on the **dark side of the Universe**: **DM** → multi-ton exps. towards the ultimate ν background (attempting to even overcome it); **DE**: remarkable leap in our knowledge of the history of the expansion rate of the Universe and the rate of growth of the cosmic structures through new ground and space exps

The magnificent 9 of astroparticle physics and cosmology in the next 20 years



The Gravitational Wave Spectrum




ASTROPARTICLE PHYSICS
the European strategy
2016
known UNKNOWN :
DM DE ~~L~~ ~~B~~ C~~P~~
INFLATION ...
unknown UNKNOWN:
beyond QM – GR, ?
APPEC

The importance of being SMALL

My recommendation: beware the temptation of going ONLY for LARGE enterprises

The protective shield of large, Big Science: too big to fail!

Richness of small, “unorthodox” projects based more on clever ideas than on muscular, managerial strength!

the two Standard Models are an extraordinary step forward in our knowledge of the Universe:

but, beware, Nature is rich of "unknown unknown"

→ after all Physics had already produced a "comprehensive, fundamental theory of all observed forces of nature" at the end of the XIX century…

Maybe the DM and the DE mysteries could represent the XXI century black-body and photoelectric problems

Puzzling deviations: $R(D^{(*)}) = BR(\bar{B} \to D^{(*)}\tau\bar{\nu})/BR(\bar{B} \to D^{(*)}l\bar{\nu})$

New HFAG average of $R(D^*)$ and $R(D)$:

HFAG averages:

$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

$R(D) = 0.391 \pm 0.041 \pm 0.028$

Correlation $(D,D^*) = -0.29$

SM predictions:

$R(D^*) = 0.252 \pm 0.003$

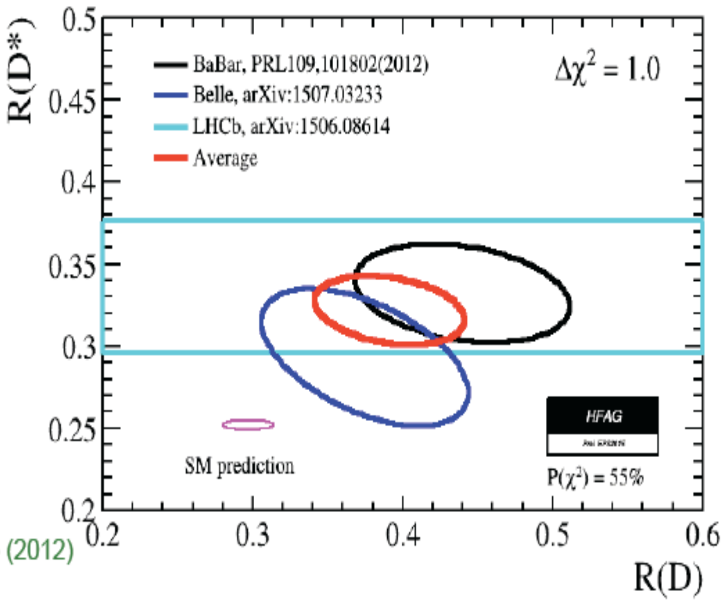
PRD 85 (2012) 094025

$R(D) = 0.300 \pm 0.010$

FNAL/MILC, arXiv:1503.07237

H. Na at al., arXiv:1505.03925

S. Fajfer et al., PRD 85, 094025 (2012)



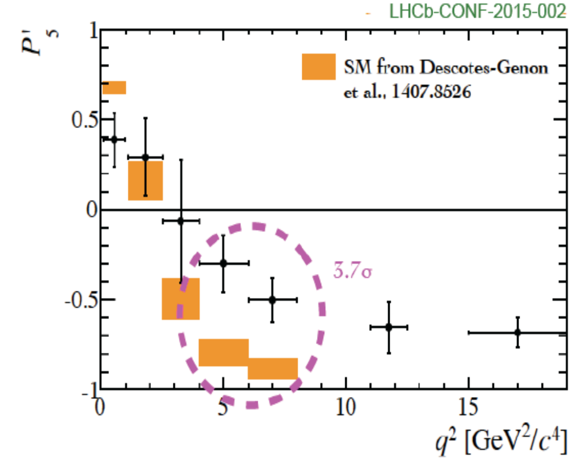
Difference with SM predictions at 3.9 σ level.

G. Lanfranchi, LP 2015

Puzzling deviations: P'_5 in $B^0 \to K^{*0} \mu^+ \mu^-$

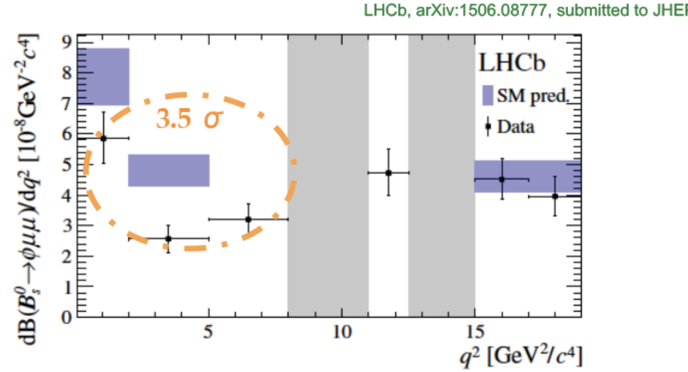
Recently confirmed by LHCb with the full Run I dataset (3 fb^{-1})

LHCb-CONF-2015-002



..and recently also in the differential BR of $B^0_s \to \phi \mu^+\mu^-$ with full Run I dataset (3 fb^{-1})

LHCb, arXiv:1506.08777, submitted to JHEP



SM predictions based on W. Altmannshofer and D. Straub, arXiv:1411.3161

A. Bharucha, D. Straub, R. Zwicky: arXiv:1503.05534