5th South AFRICA - JINR SYMPOSIUM

Advances and Challenges in Physics by JINR and South Africa

Somerset West, South Africa

November 4-9, 2018

AT THE EDGE OF NEW DISCOVERIES IN PARTICLE PHYSICS

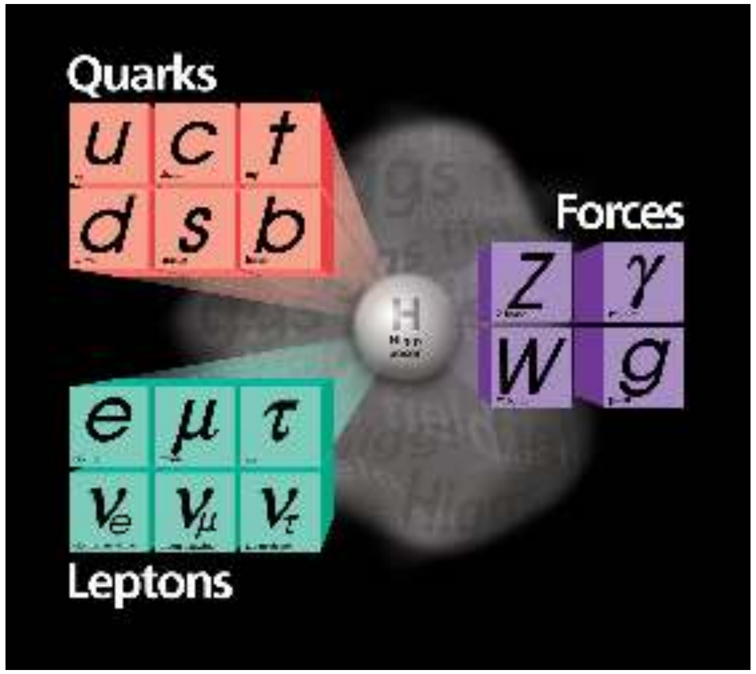
(WORLDWIDE AND WITH JINR PARTICIPATION)

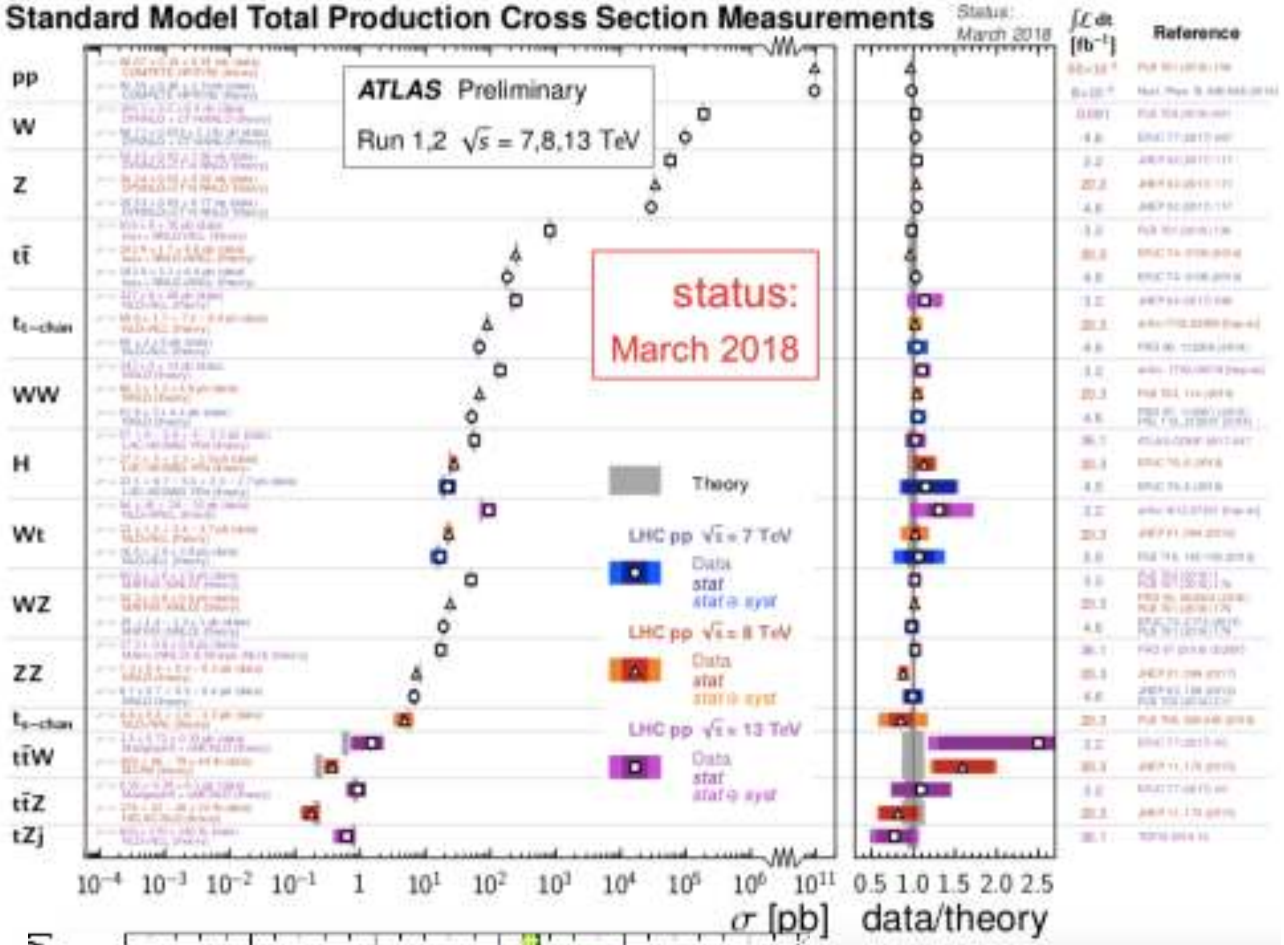
Dmitry Kazakov

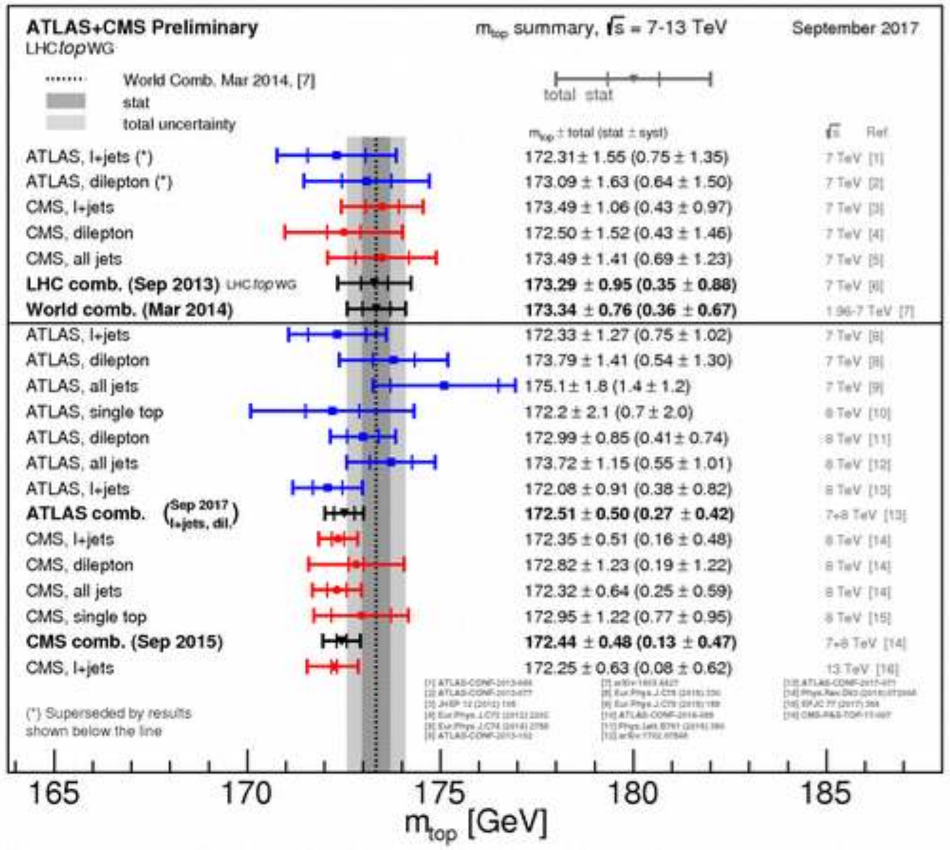
Bogoliubov Laboratory of Theoretical Physics

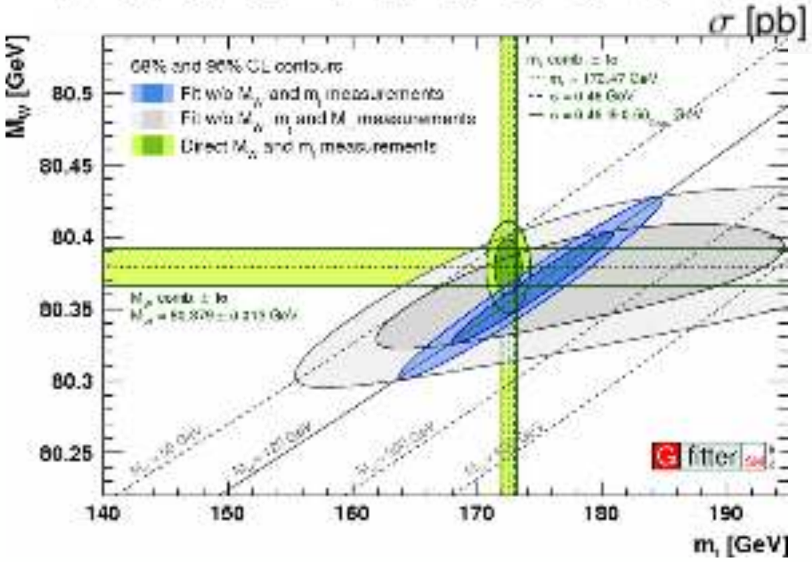
Joint Institute for Nuclear Research

The Standard Model









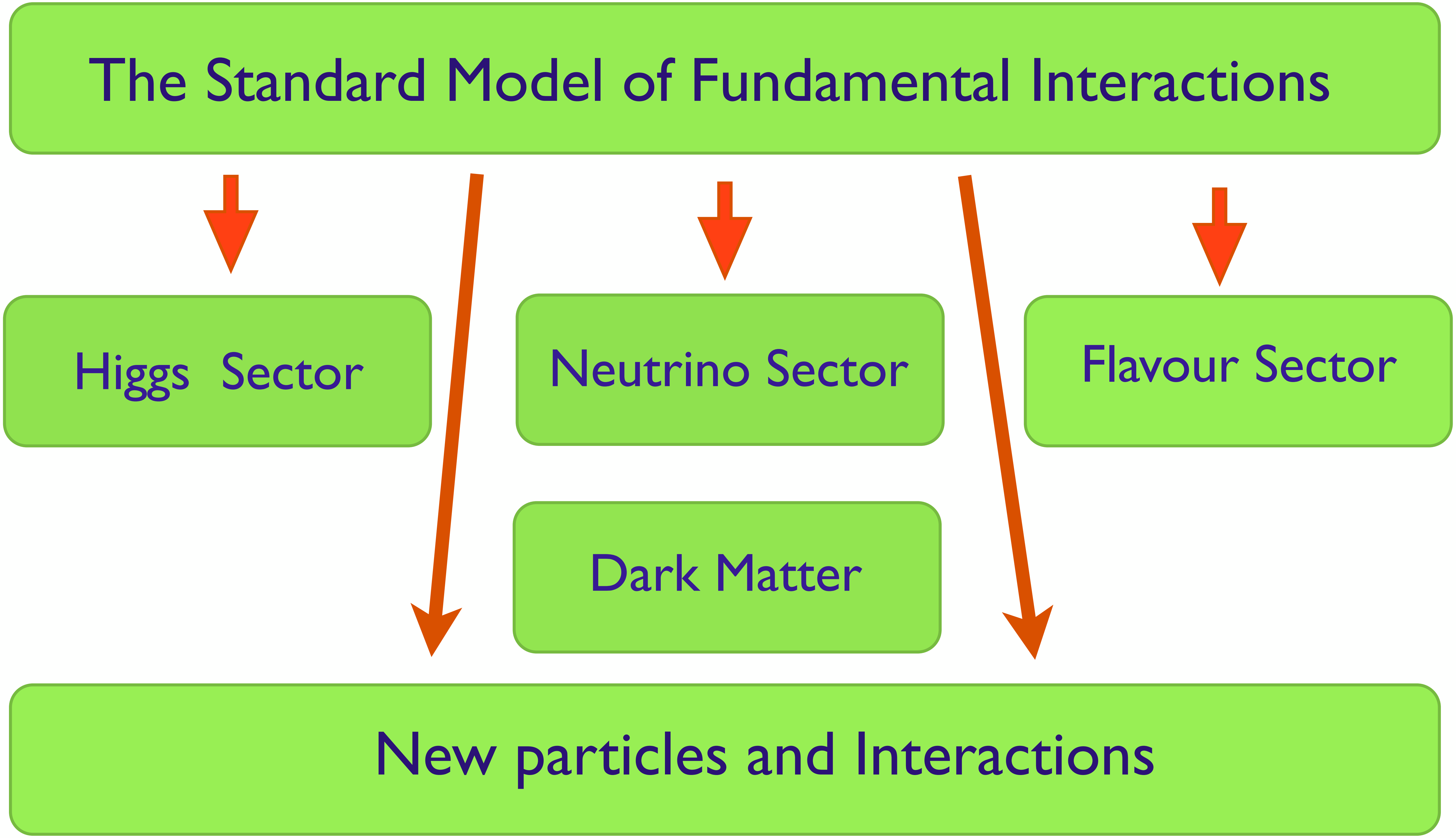
Extraordinary agreement between measurements and SM predictions

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

- With the Higgs Boson discovery the Standard Model is completed !
- Why are we not satisfied and think that new physics exists and new discoveries will come?

- There are conceptional problems which require a critical view beyond the SM
- There are small discrepancies which might grow up to become a problem for the SM
- It is hard to believe that the quest for the miracle of Nature is over

THE STANDARD MODEL: THE WAYS BEYOND



The Standard Model of Fundamental Interactions

Higgs Sector

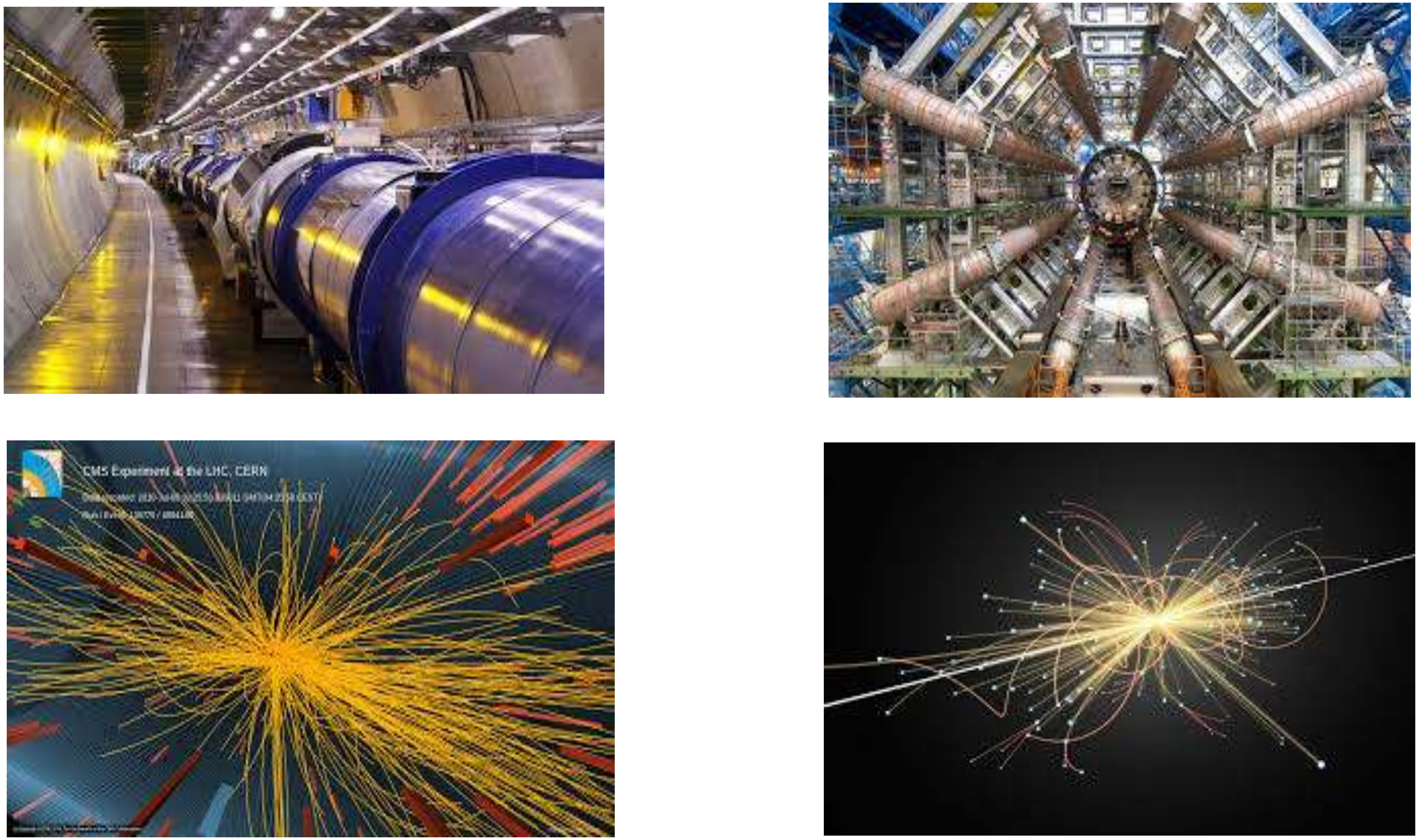
Neutrino Sector

Flavour Sector

Dark Matter

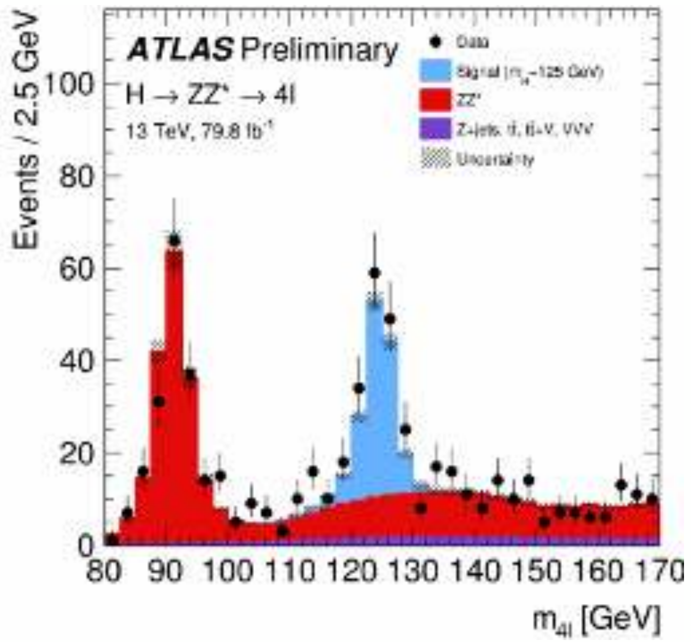
New particles and Interactions

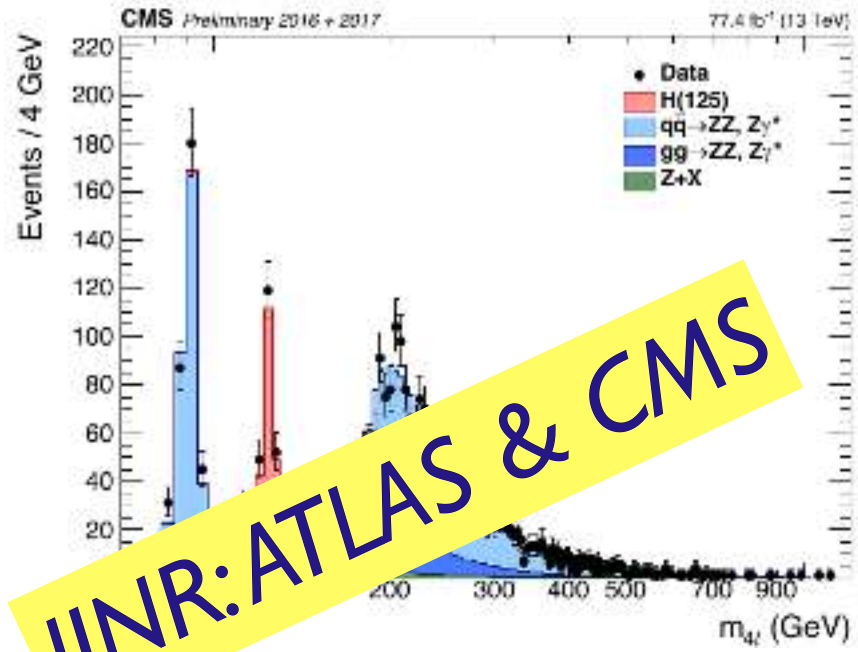
Accelerator Physics



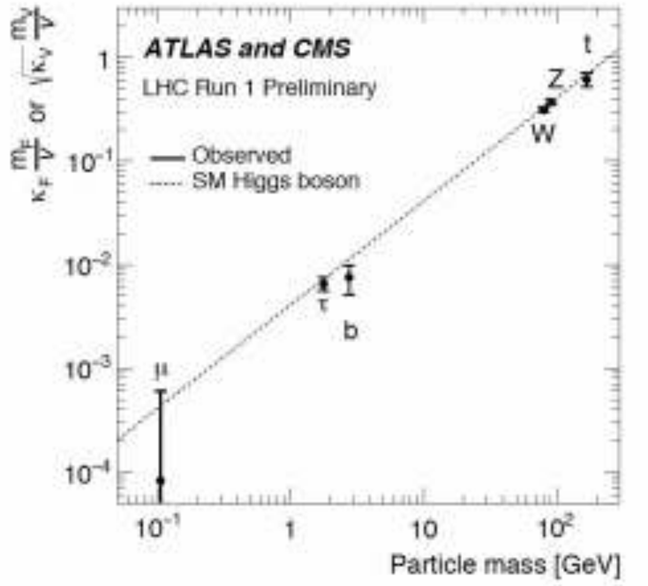
Higgs bosons - entering precision era

Run-2 analyses with 80 fb^{-1} for the first time – higher precision is coming!

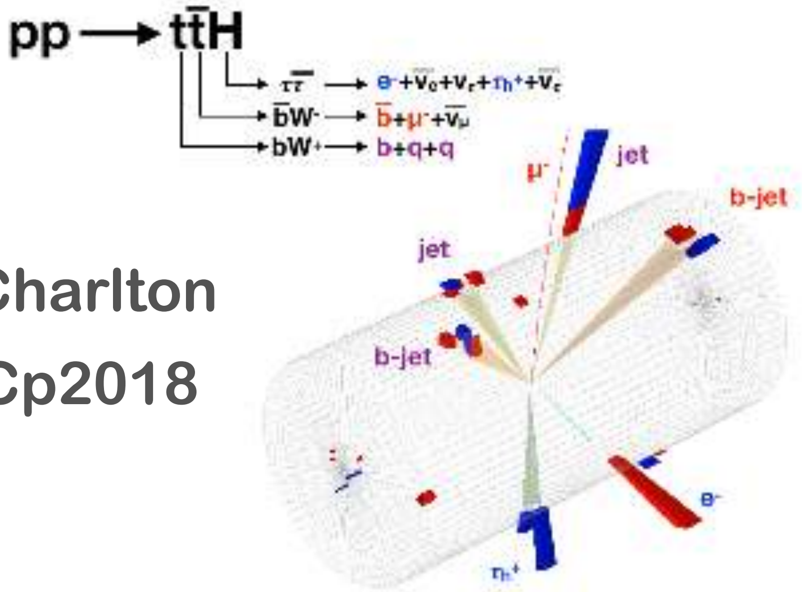


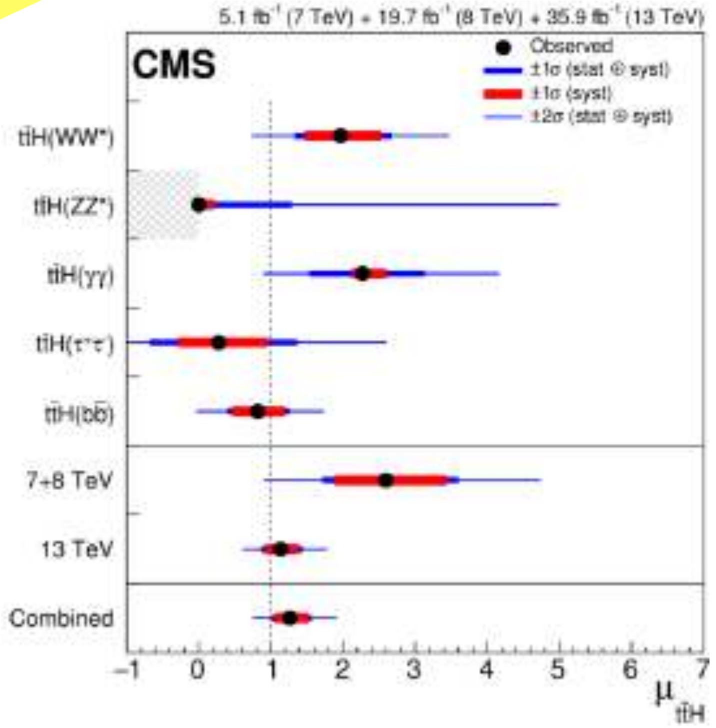


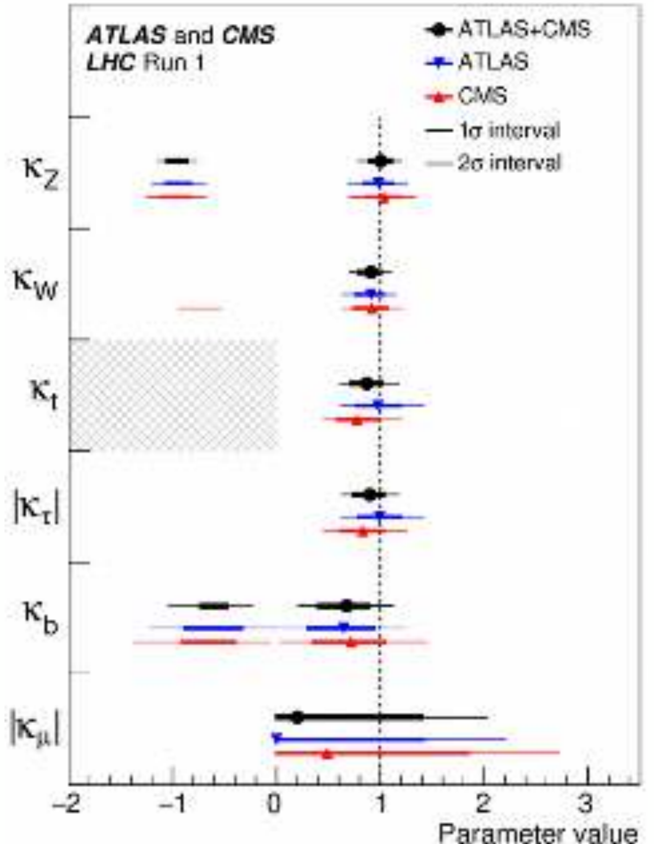
JINR:ATLAS & CMS



ttH observation





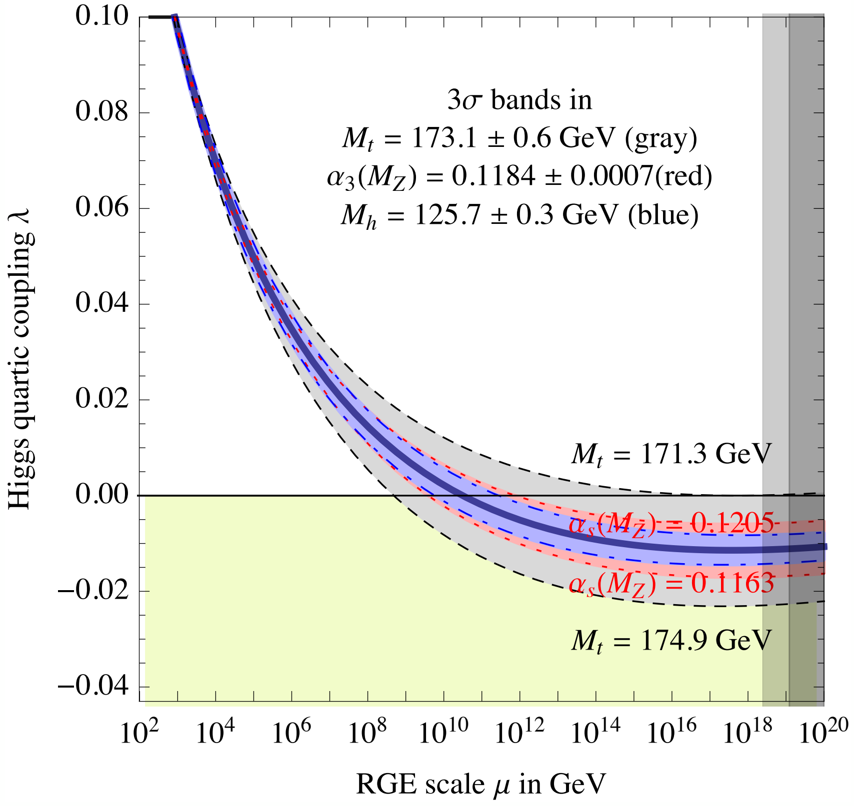


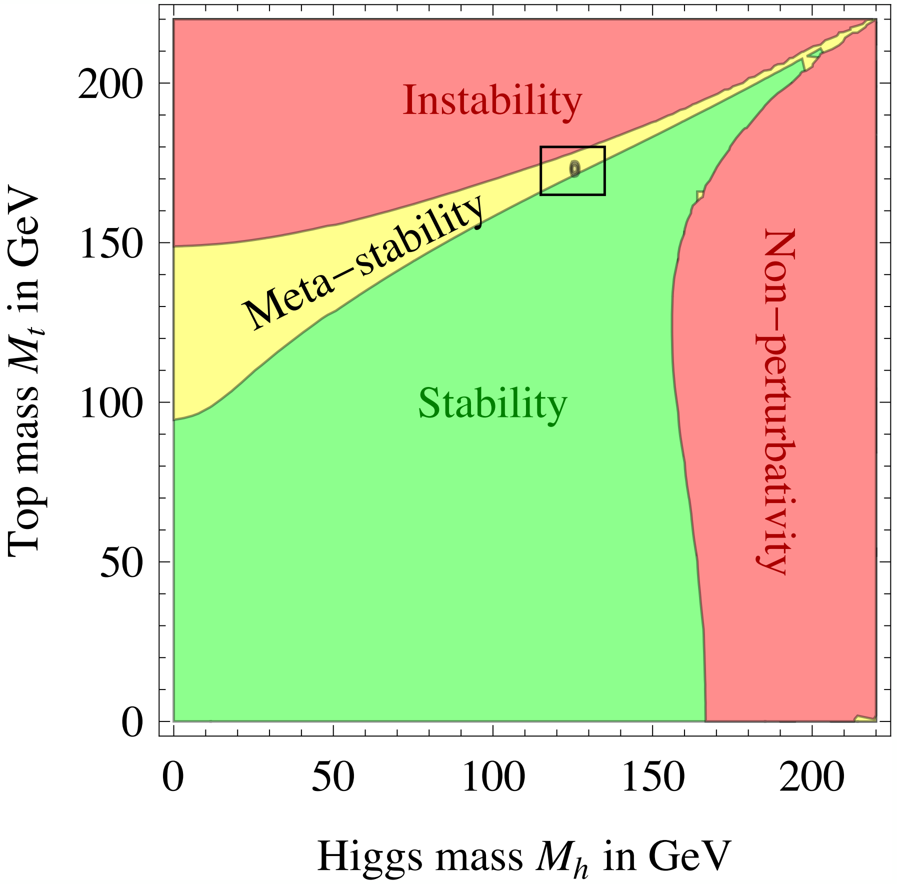
D. Charlton
LHCp2018

THE STANDARD MODEL: THE STATUS REPORT AND OPEN QUESTIONS

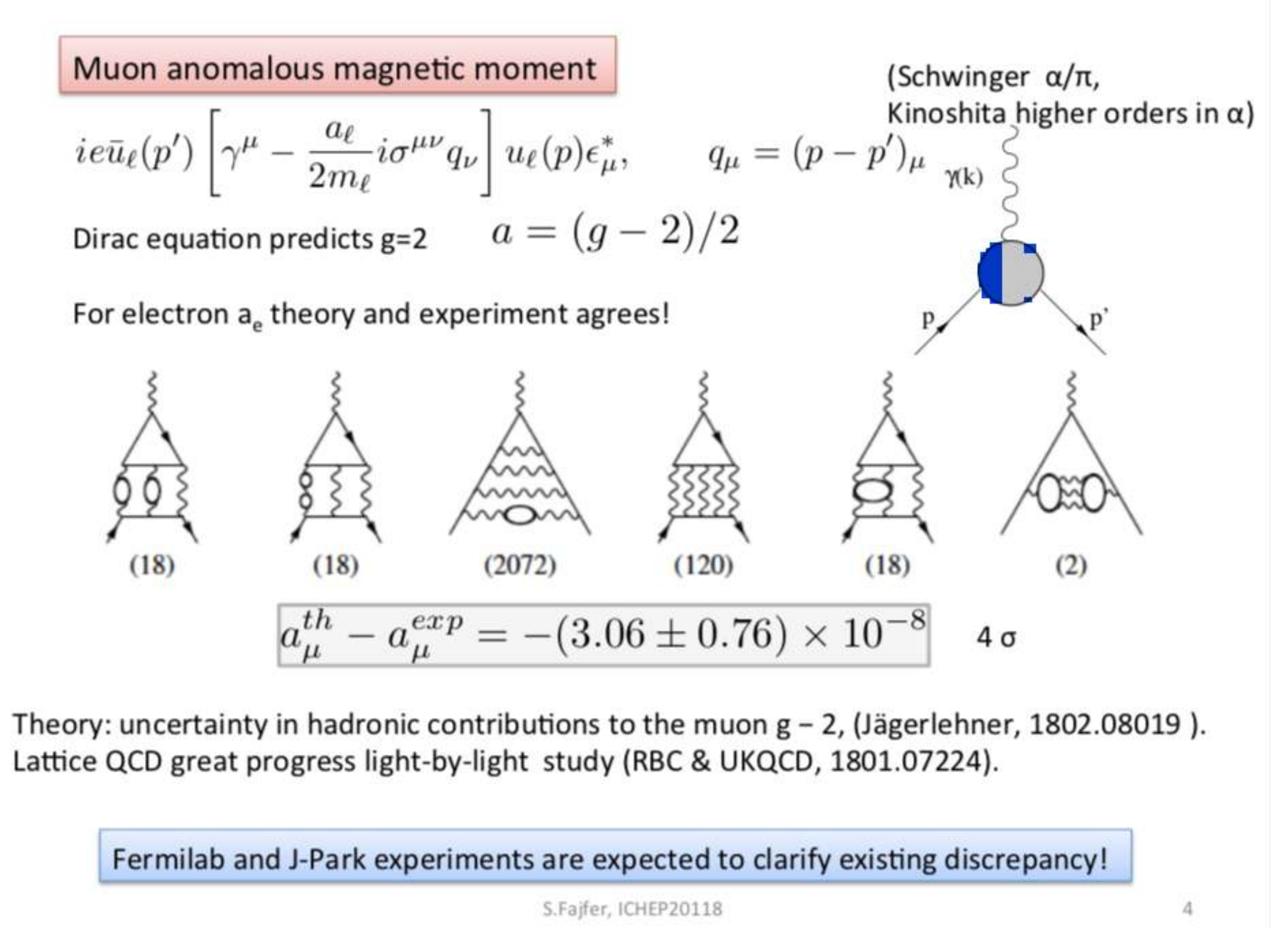
- The electroweak vacuum is unstable under radiative corrections

- The whole construction of the SM may be in trouble being metastable or even unstable





- the situation crucially depends on the top and Higgs mass values and requires severe fine-tuning and high accuracy of calculations (3 loops)



Muon anomalous magnetic moment

$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu\right] u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$

(Schwinger α/π,
Kinoshita higher orders in α)

Dirac equation predicts g=2 $\quad a = (g-2)/2$

For electron a_e theory and experiment agrees!

$$\boxed{a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}}$$ 4 σ

Theory: uncertainty in hadronic contributions to the muon g – 2, (Jägerlehner, 1802.08019).
Lattice QCD great progress light-by-light study (RBC & UKQCD, 1801.07224).

Fermilab and J-Park experiments are expected to clarify existing discrepancy!

B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

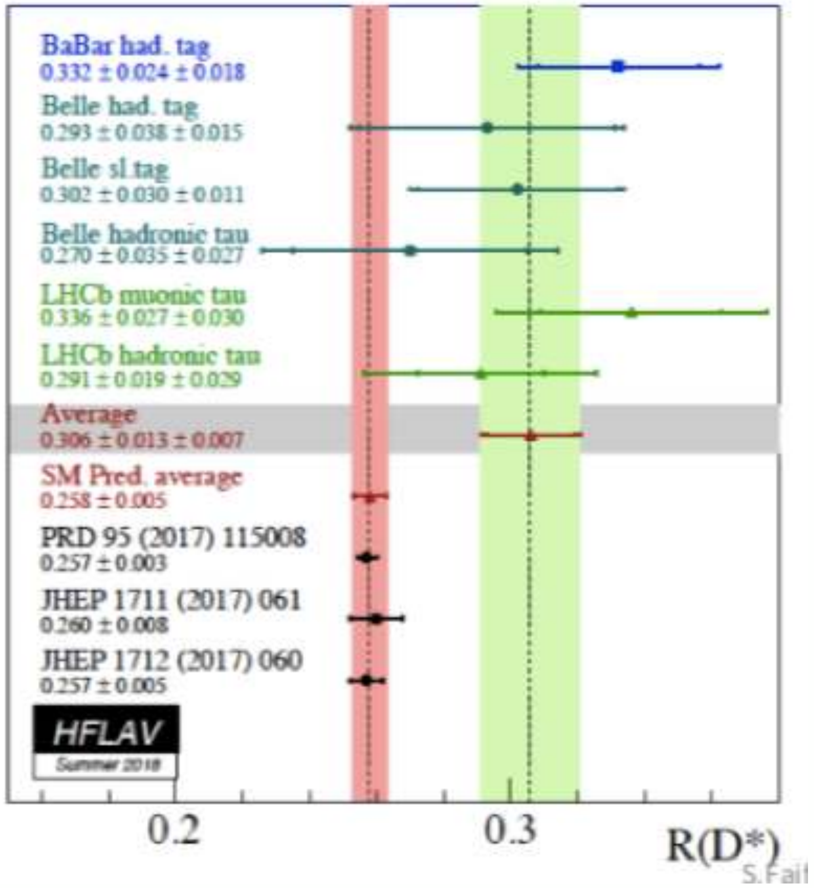
FCNC - SM loop process: $R_{K(*)}$ anomaly

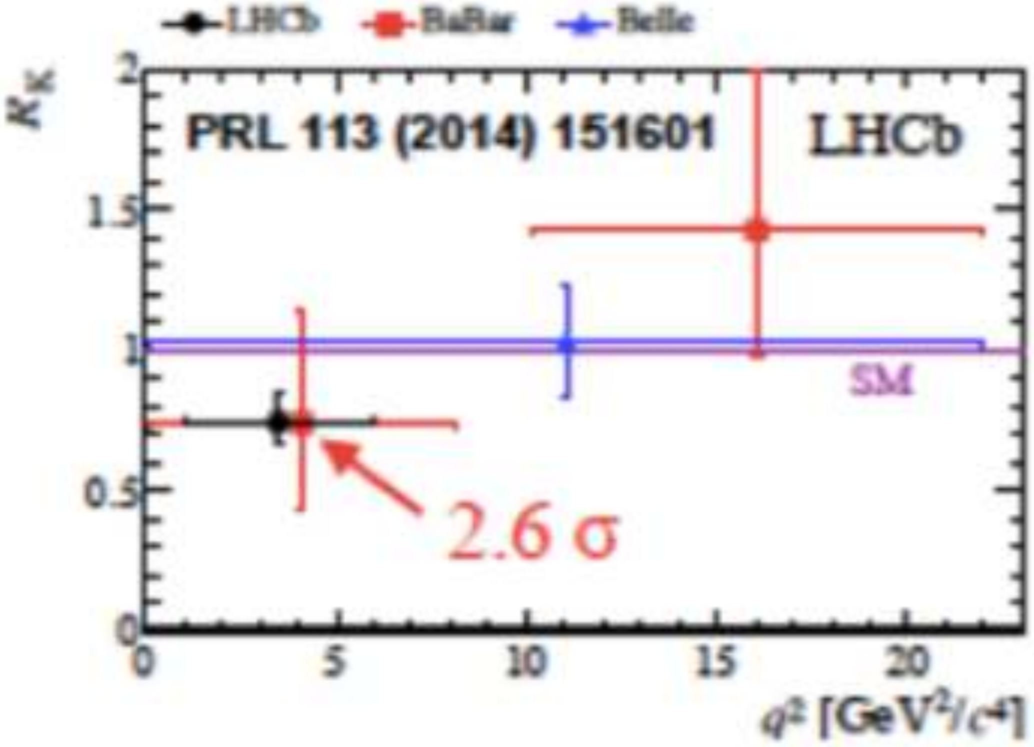
$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\mu\nu_\mu)}$$

3.8σ

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

3σ

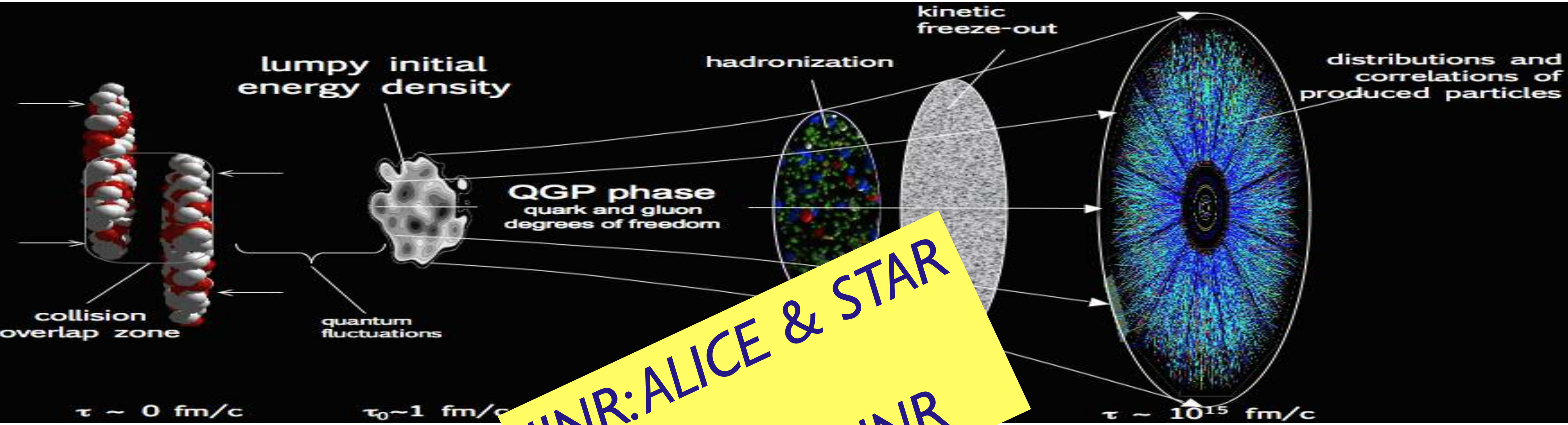




LHCb: the discrepancy present in $B_s \to \phi\mu\mu$ and $\Lambda_b \to \Lambda\mu\mu$

Discrepancy might dissolve and might as well grow up

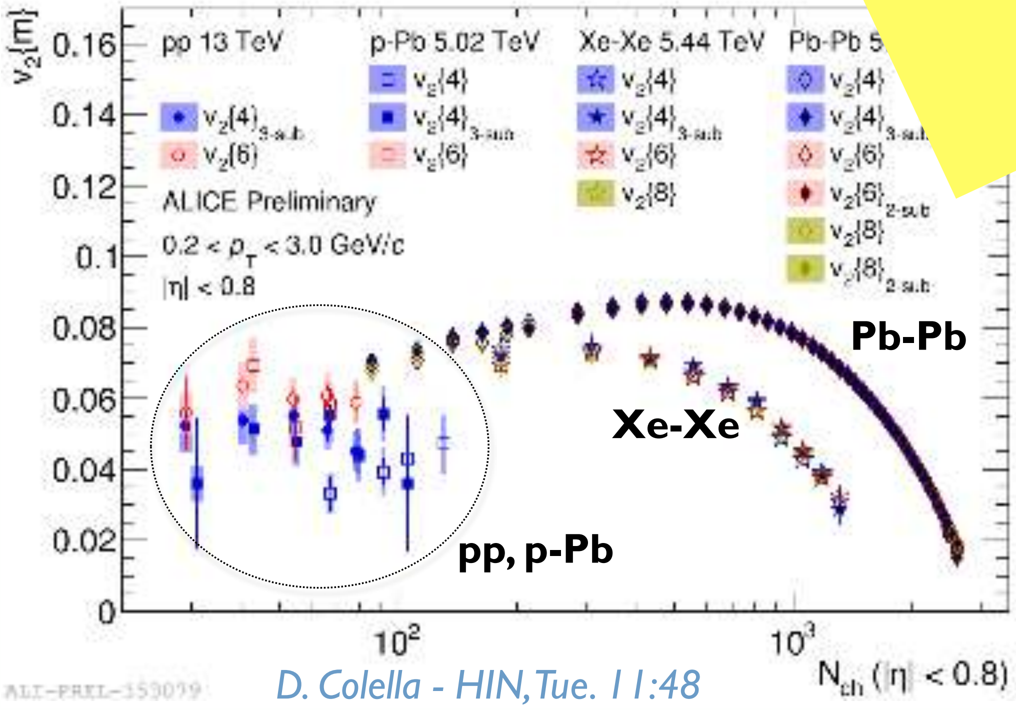
Heavy Ion Collisions: new State of Matter and new Phenomena at Density Frontier



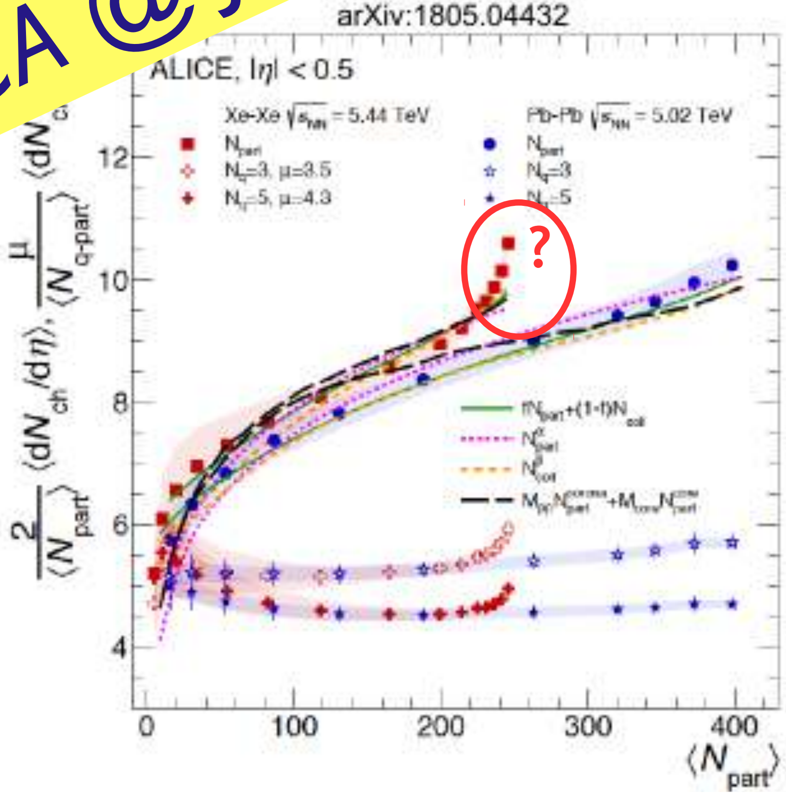
JINR: ALICE & STAR

NICA @ JINR

Collectivity in small system



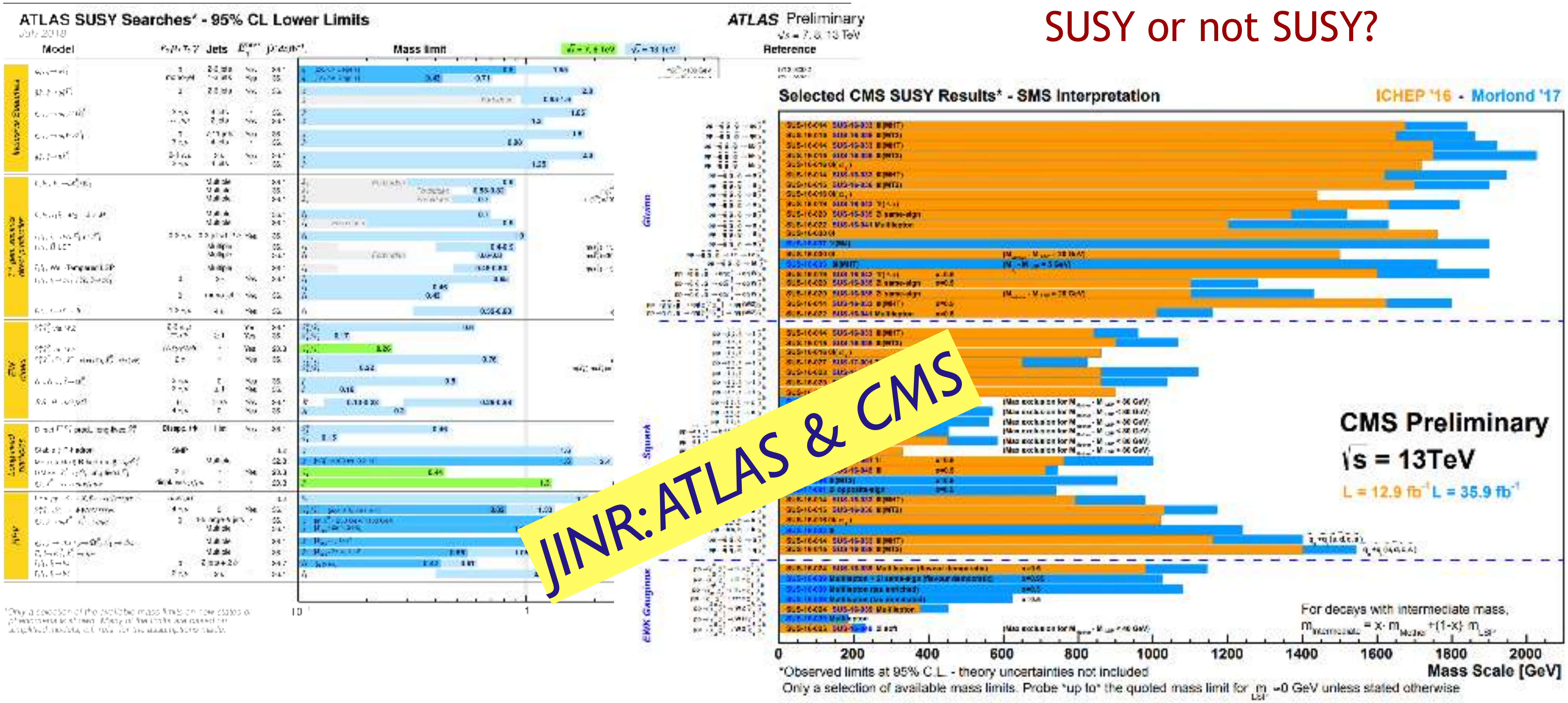
D. Colella - HIN, Tue. 11:48



Sharp increase in multiplicity at high centrality in XeXe – not seen in PbPb

BEYOND THE STANDARD MODEL: SEARCH FOR NEW PARTICLES

SUSY or not SUSY?



- No evidence for SUSY yet → strong message from the LHC.

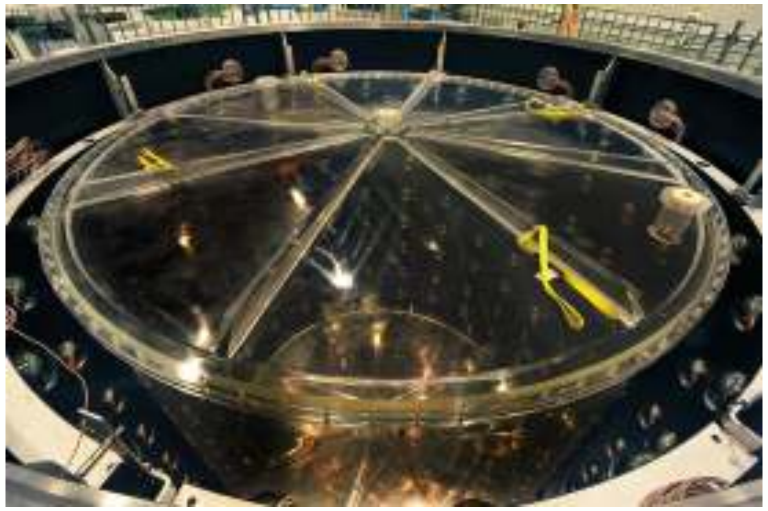
- In most favourable / challenging scenarios we exclude
gluinos up to O(2) / O(1) TeV.
squarks up to O(1.5) / O(0.5) TeV.
stops and sbottoms up to O(1) / O(0.7) TeV.
EW produced sparticles up to O(0.5-1) / O(0.1) TeV.

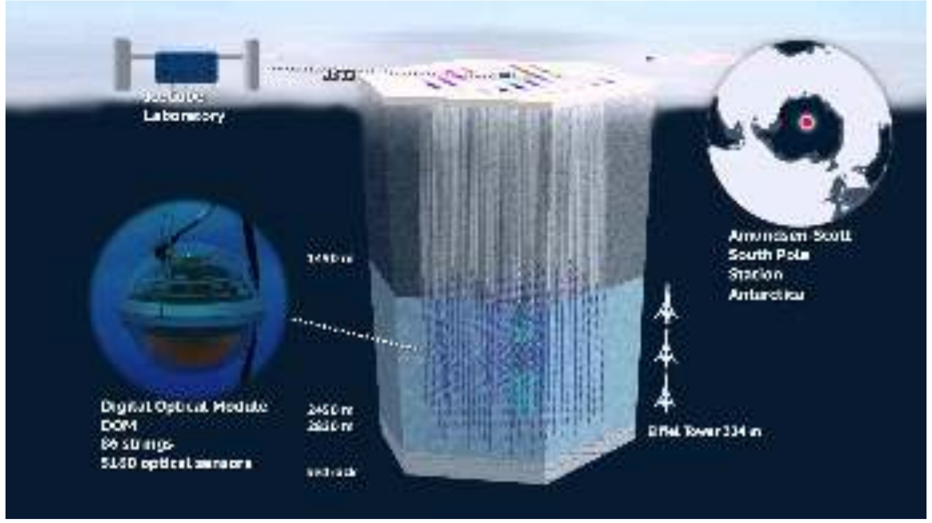
- Regions of parameter space still not well covered.

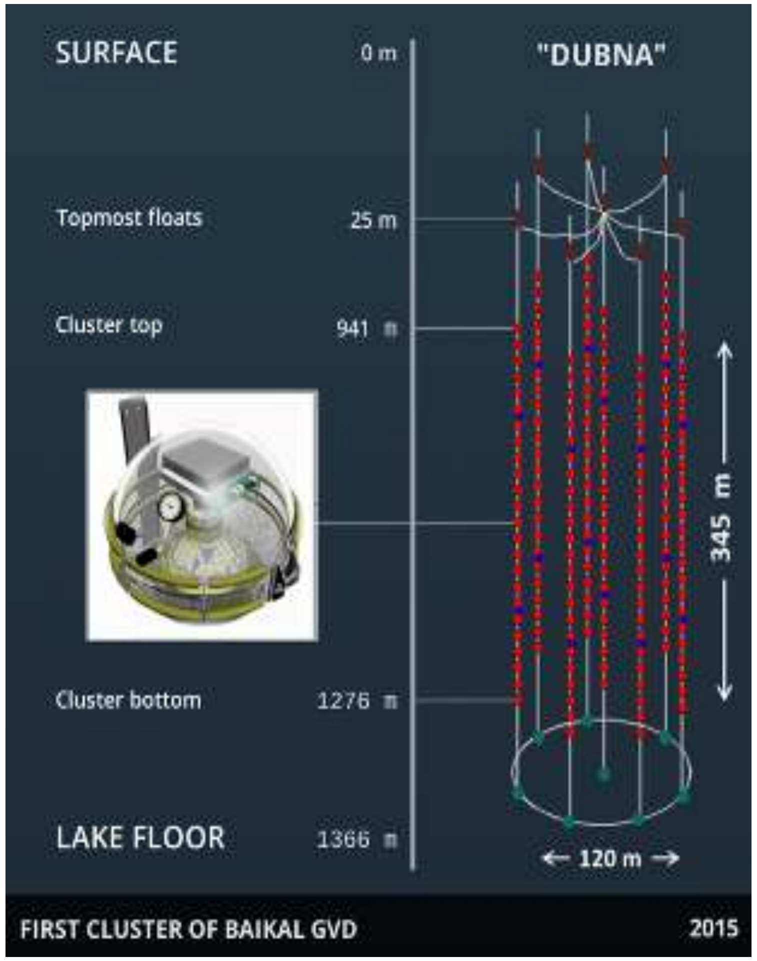
- Next step is to complete the program with the full Run 2 dataset (150 fb^{-1} expected).

- Ensure we cover all signatures within our reach.

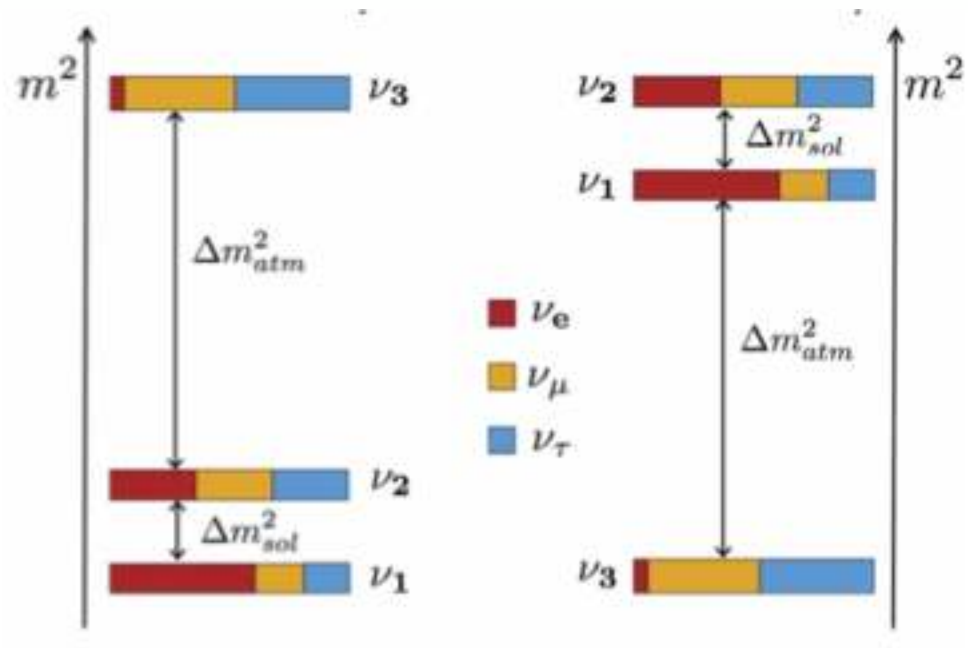
Neutrino Physics

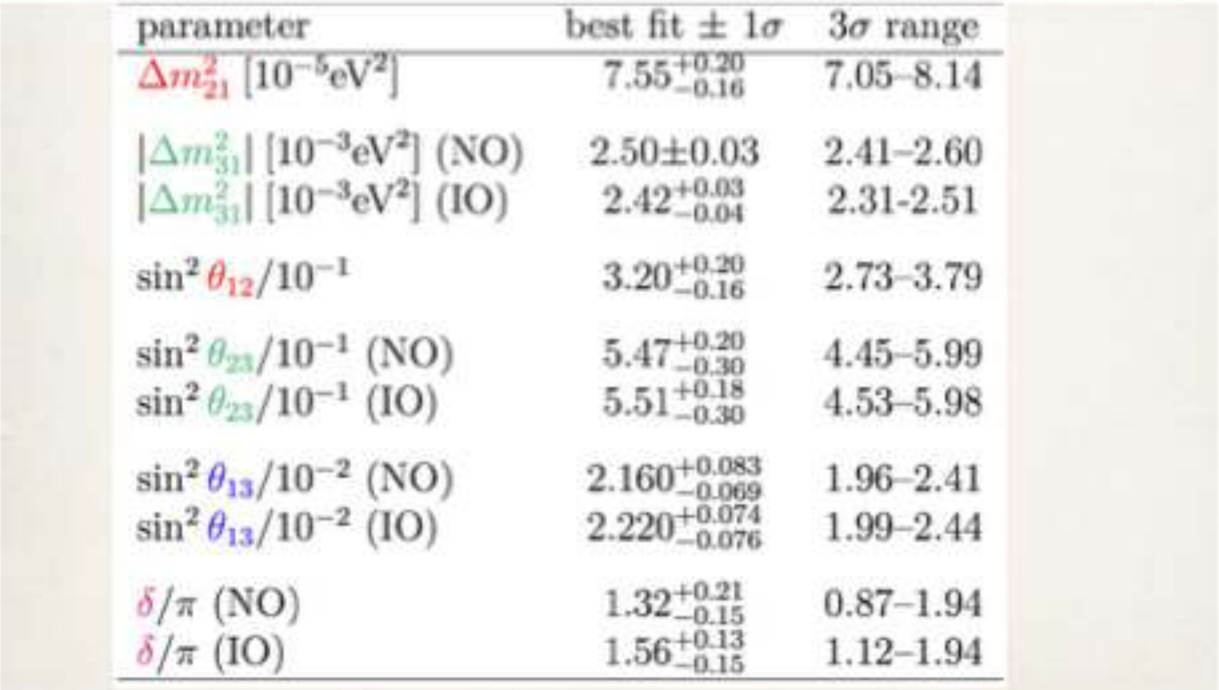






Neutrino Physics





parameter	best fit ± 1σ	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.50 ± 0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

de Salas et al, 1708.01186

- Absolute value of neutrino masses ?
- Mass hierarchy?
- Dirac or Majorana?
- Fourth sterile neutrino?
- Neutrino dark matter?

$$\boxed{0.06\ eV < \sum m_\nu < 0.12\ eV}$$

ν-osc

CMB

PMNS-matrix parameters are measured with high accuracy of few %

- Normal hierarchy favoured at 3.1 σ
- Nonzero CP phase favoured
- Upper octant favoured

Is it just the SM or requires New physics?

Three Types of Seesaw Mechanisms

Require the existence of new degrees of freedom (particle) beyond those present in the SM

Type I seesaw mechanism: ν_{lR} - RH νs' (he

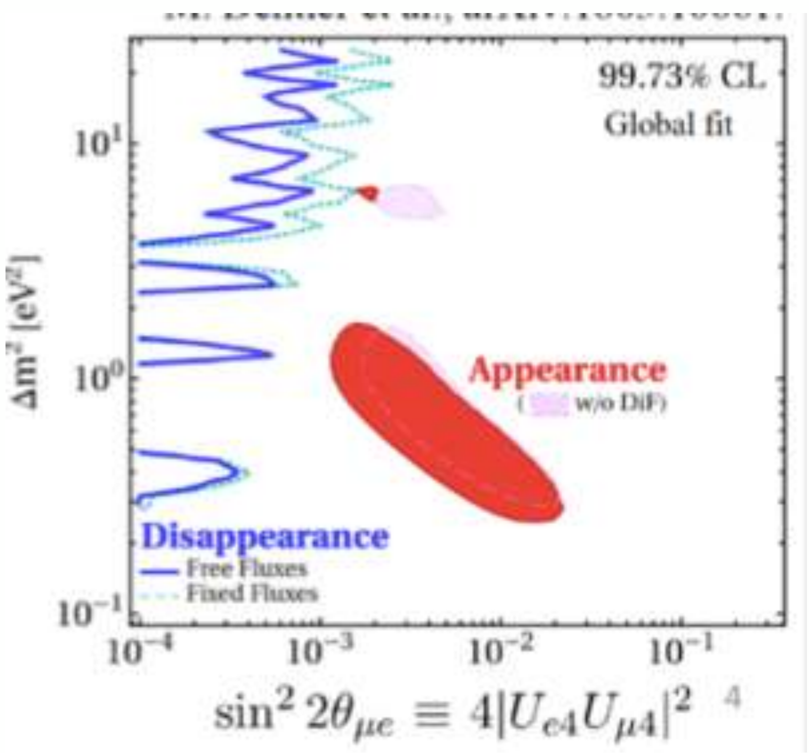
Type II seesaw mechanism: H(x) - ,H^{--} Higgs fields.

Type III seesaw mechanism: fermion fields.

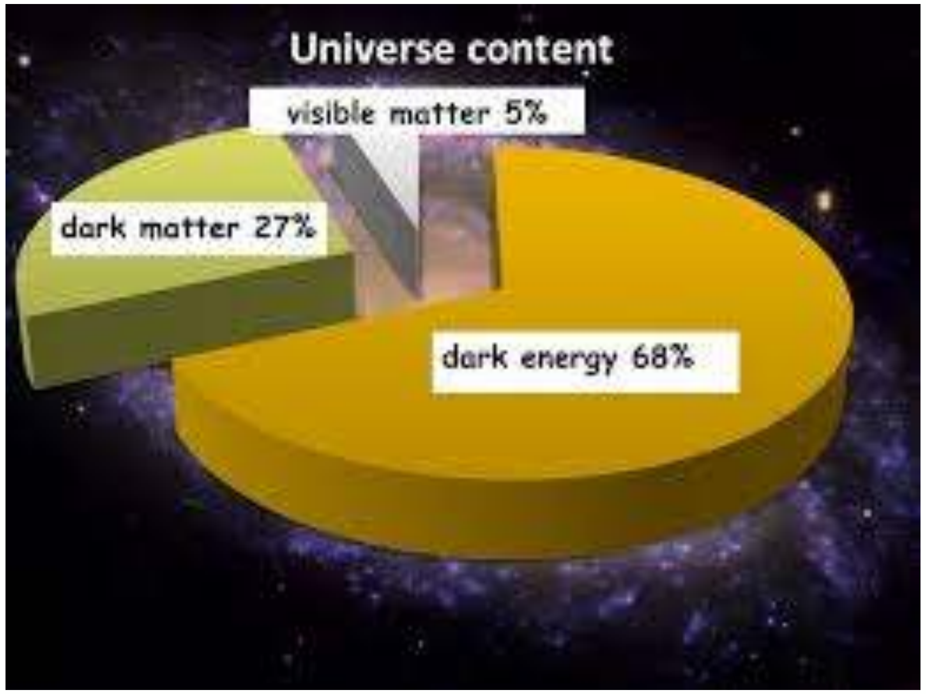
JINR: BAIKAL GVD, JUNO, Daya Bay, Borexino
NOνA, GERDA, SupeNemo

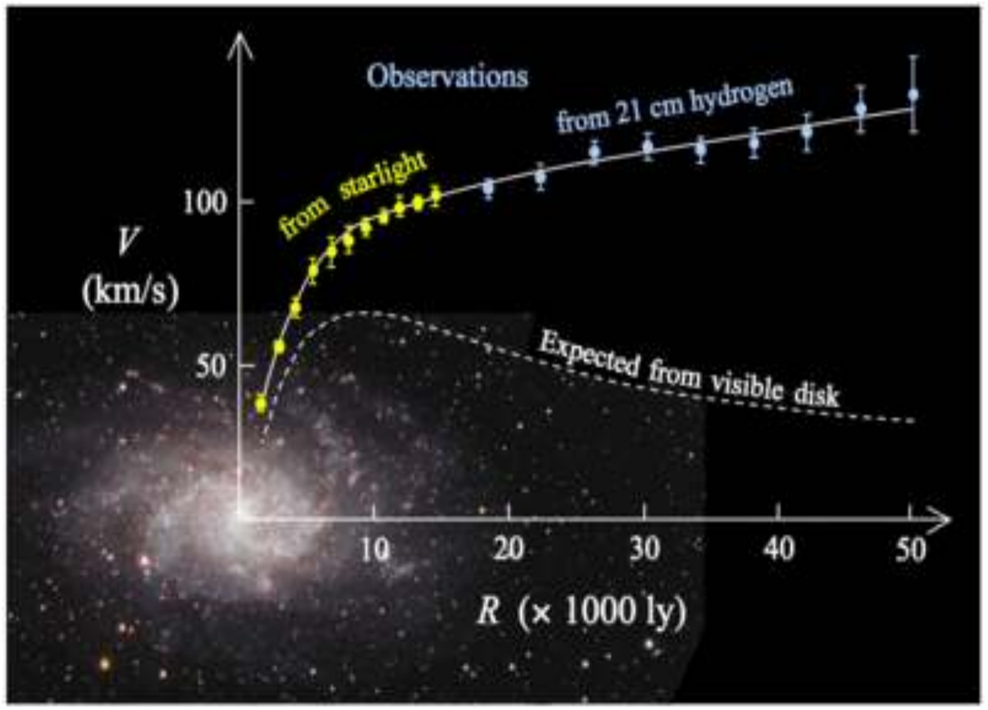
M. Weber ICHEP2018

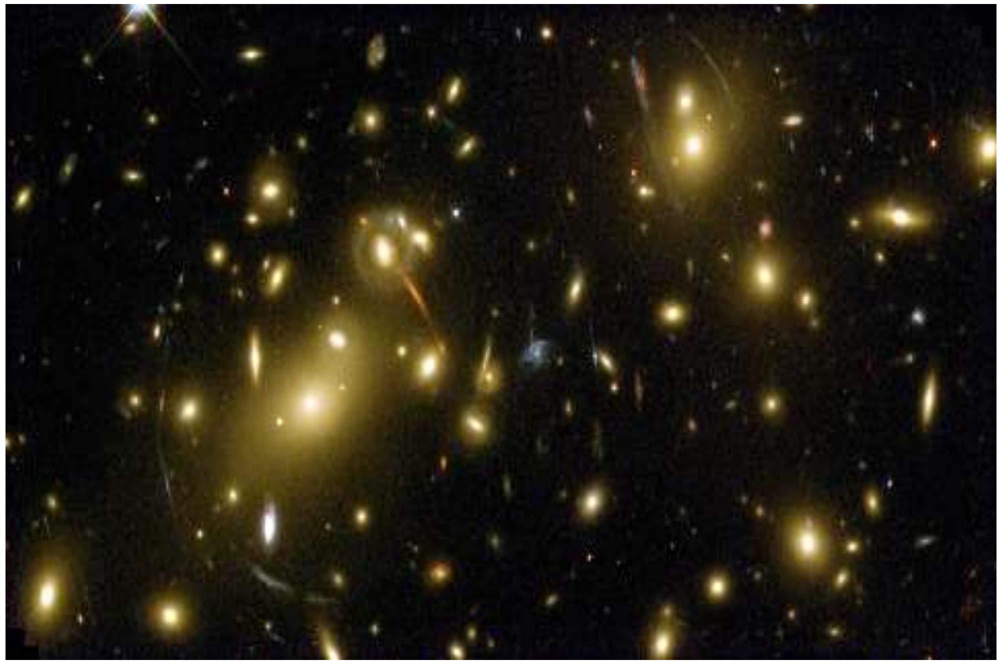
- **Possible St**
  - **New Mi tent with LSND** **(but low e ess?)**
  - **Reactor anomaly questioned by Daya Bay/RENO time dependence**
  - **New SBL and source experiments**
  - **Conflict with ν_μ disappearance**



Dark Matter


Universe content
visible matter 5%
dark matter 27%
dark energy 68%


Observations
from 21 cm hydrogen
from starlight
100
50
V
(km/s)
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)



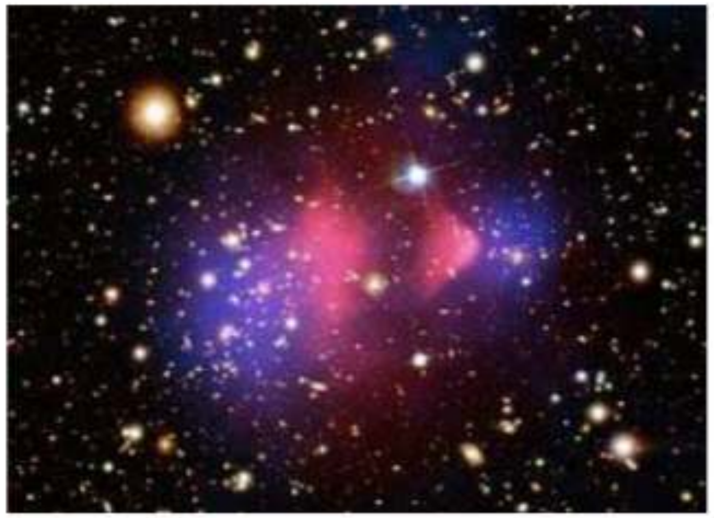
BEYOND THE STANDARD MODEL: DARK MATTER

Major problem: 85% of matter is dark and remains invisible!

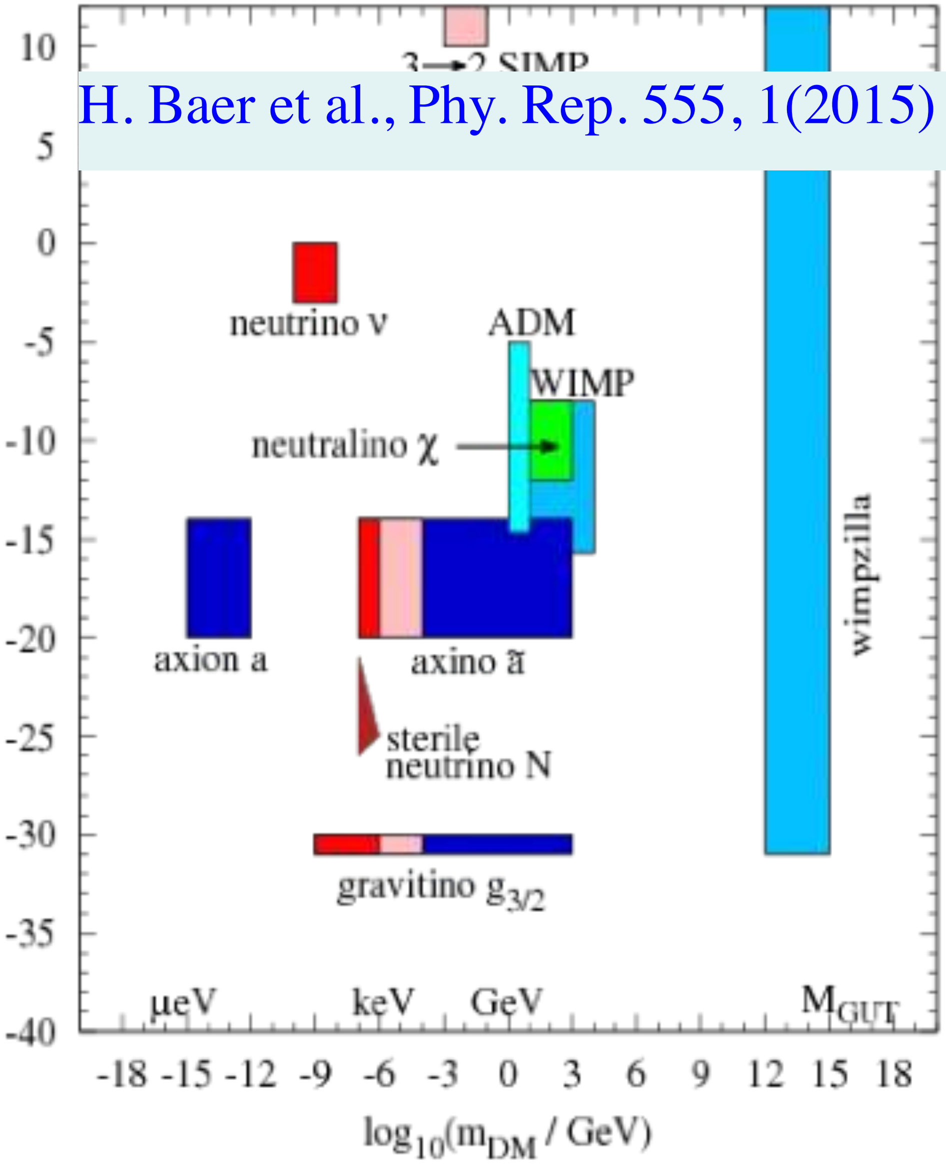
Is this compatible with the SM?

Does it requires modification of the SM or addition of gravity?

- **Many candidates in many orders of magnitude of mass:**
  - **MOND** (Problems: large scales, Bullet cluster)
  - **Primordial black holes** (LIGO, but constraints)
  - **Fuzzy** (very light bosons)
  - **Warm** (KeV sterile)
  - **WIMP**
  - **Axions/ALPs**
  - **Dark sector**
  - **Gravitinos**
  - **Moduli**
  - **Wimpzillas**



M. Drees

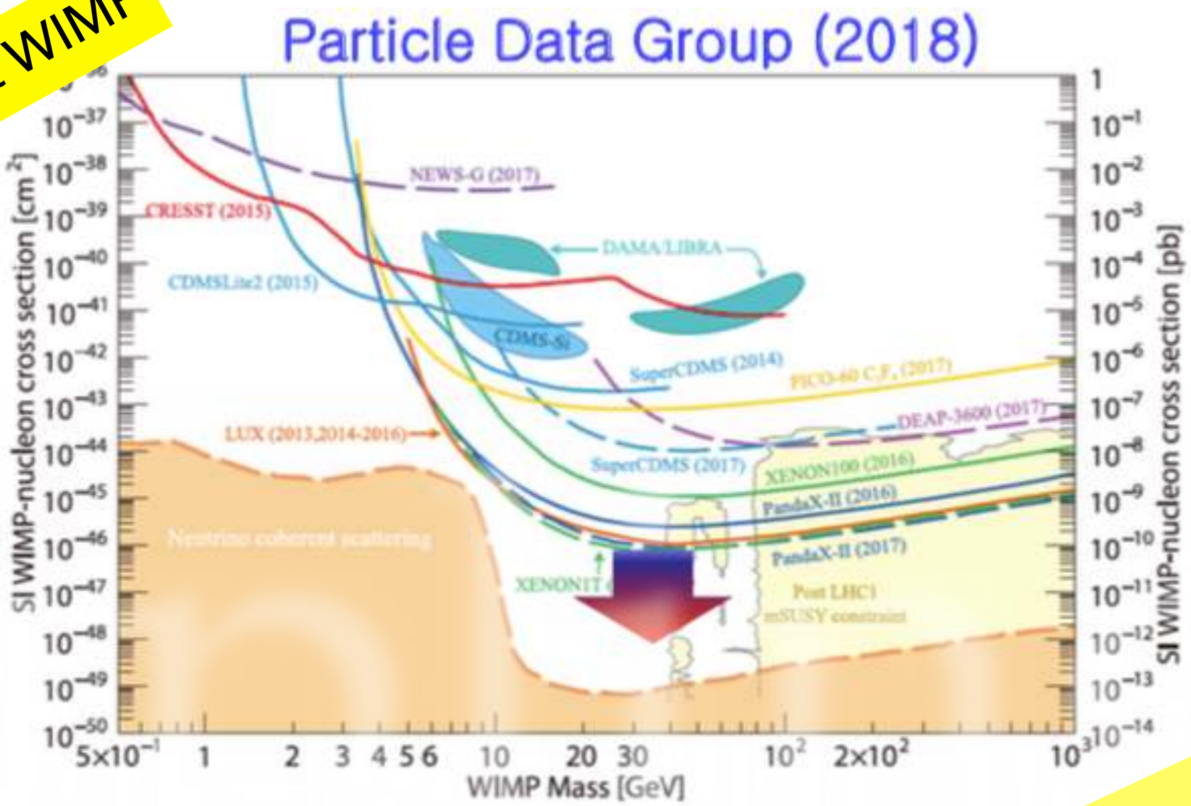


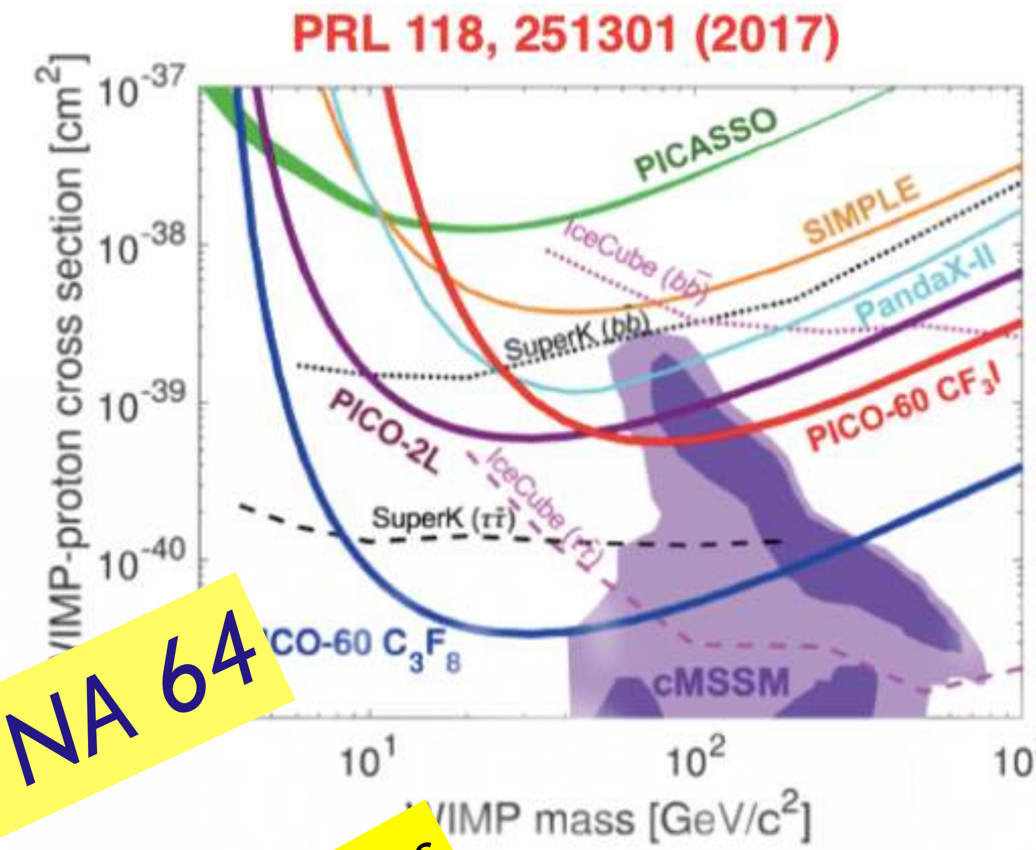
H. Baer et al., Phy. Rep. 555, 1(2015)

- **Direct, indirect, collider**

BEYOND THE STANDARD MODEL: DARK MATTER SEARCHES

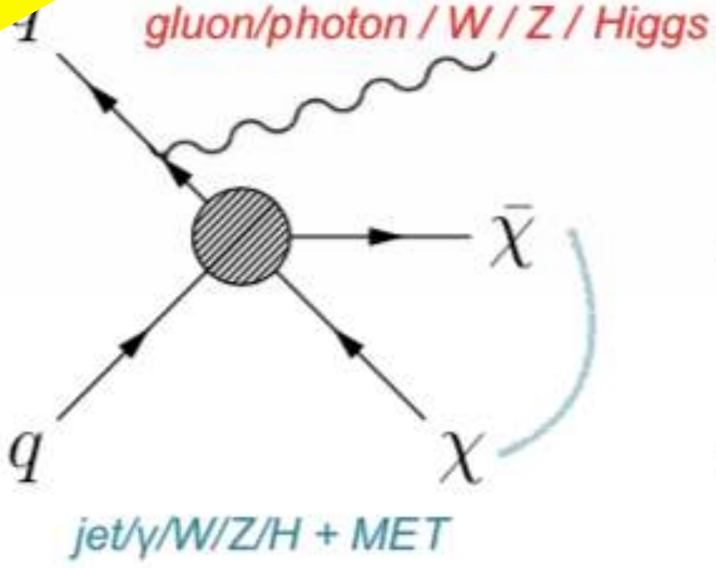
Direct WIMP


Particle Data Group (2018)


PRL 118, 251301 (2017)

JINR: Edelweiss, NA 64

Colliders WIMP

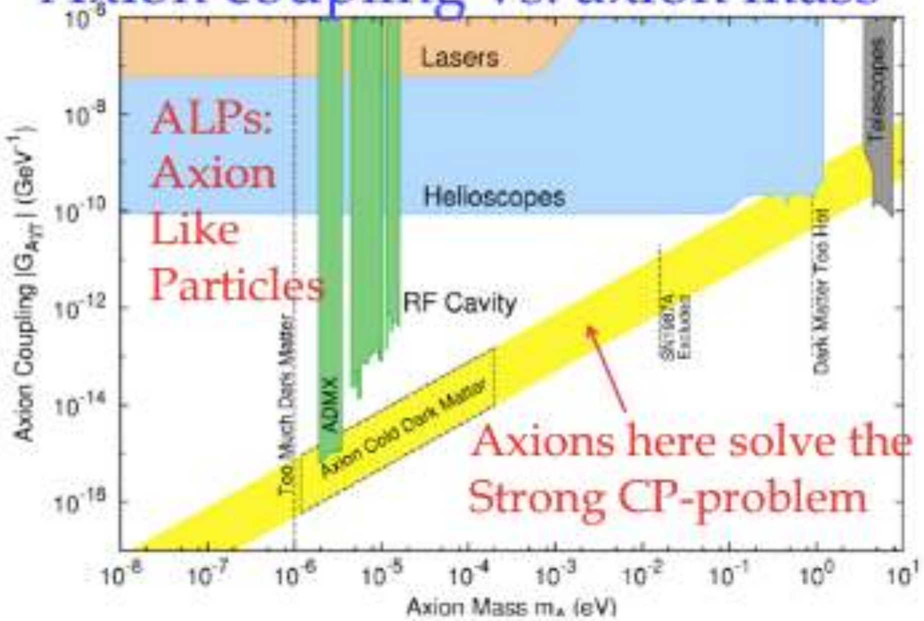


- [illegible]
  - signature, constraints on many mode
- photon
  - more challenging for background estimation
  - less powerful: EW vs. strong interaction
- mono-W/Z leptonic
  - clean signature and simple trigger
  - penalized by W/Z branching fraction
- mono-W/Z hadronic
  - larger statistics with larger background
- tt+MET/bb+MET and mono-top
  - more complicated experimentally
  - powerful in some scenarios
- mono-Higgs
  - powerful in some scenarios

D. del Re

Axion-likes

Axion coupling vs. axion mass



Y. Semertzidis

Flavour Sector

BEYOND THE STANDARD MODEL: THE MASS SPECTRUM AND MIXINGS

- Mass spectrum?

$$m_{quark} = y_{quark} \cdot v$$

$$m_{lepton} = y_{lepton} \cdot v$$

$$m_W = g/\sqrt{2} \cdot v$$

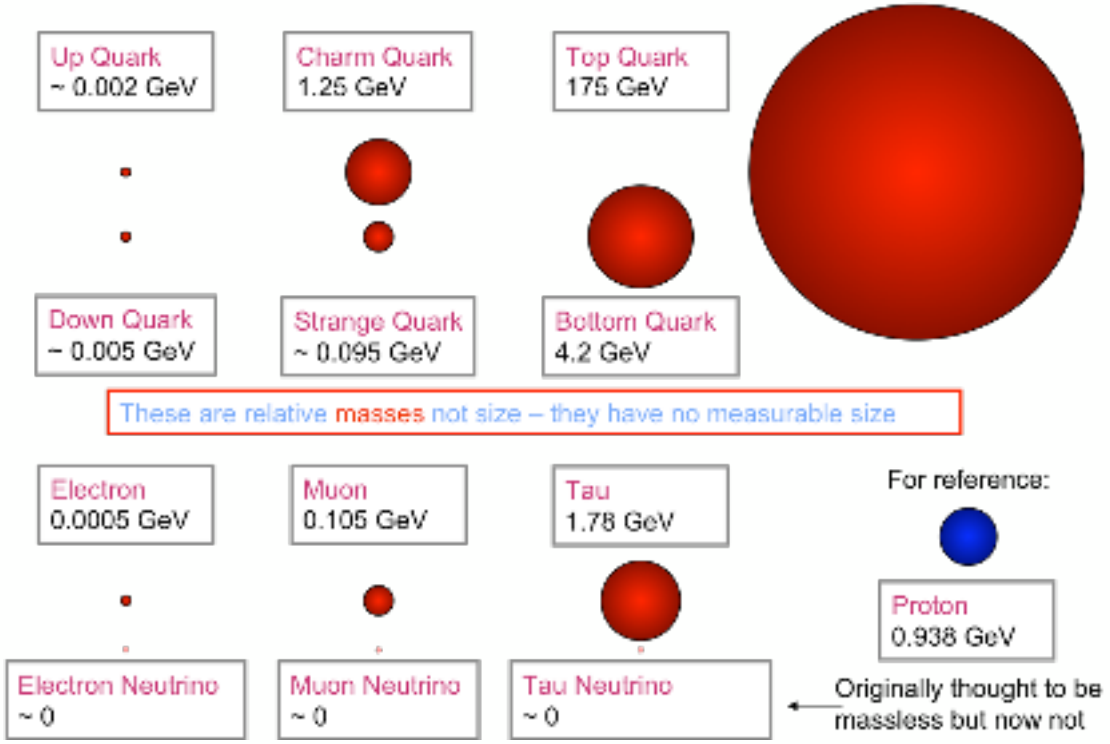
$$m_Z = \sqrt{g^2 + g'^2}/\sqrt{2} \cdot v$$

$$m_H = \sqrt{\lambda} \cdot v$$

$$m_\gamma = 0$$

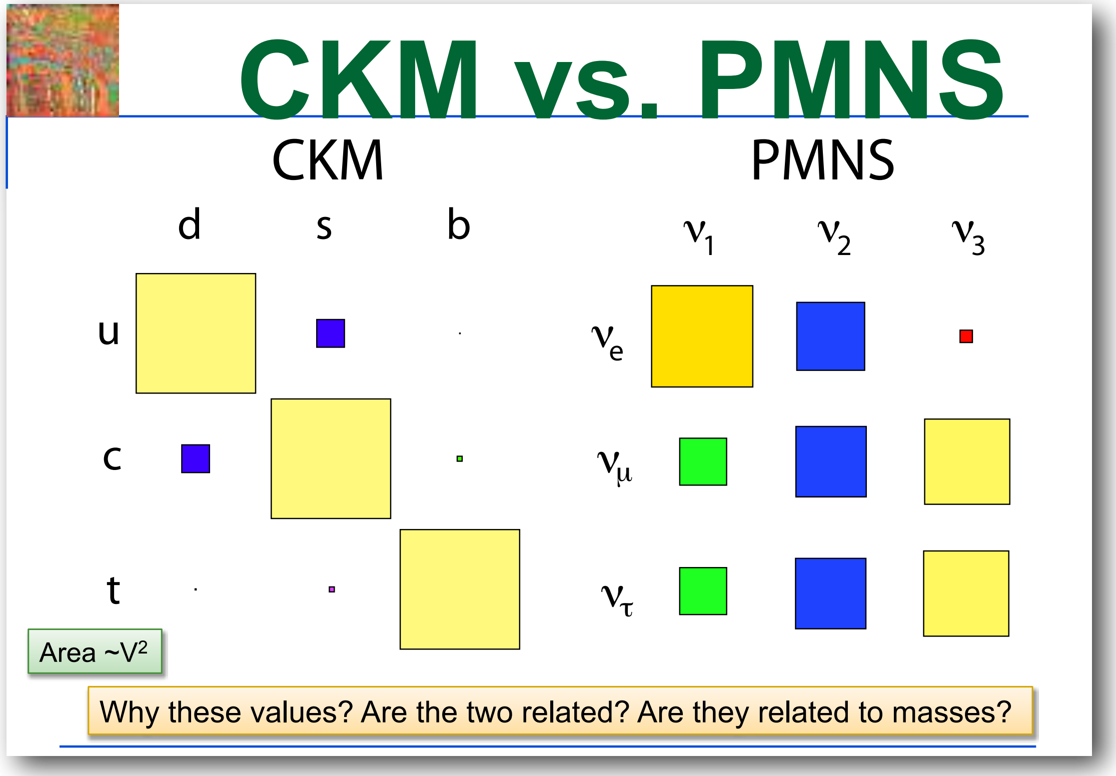
$$m_{gluon} = 0$$

SM



- Mixing Matrices?

- Quark-Lepton Symmetry
- Strong difference in parameters



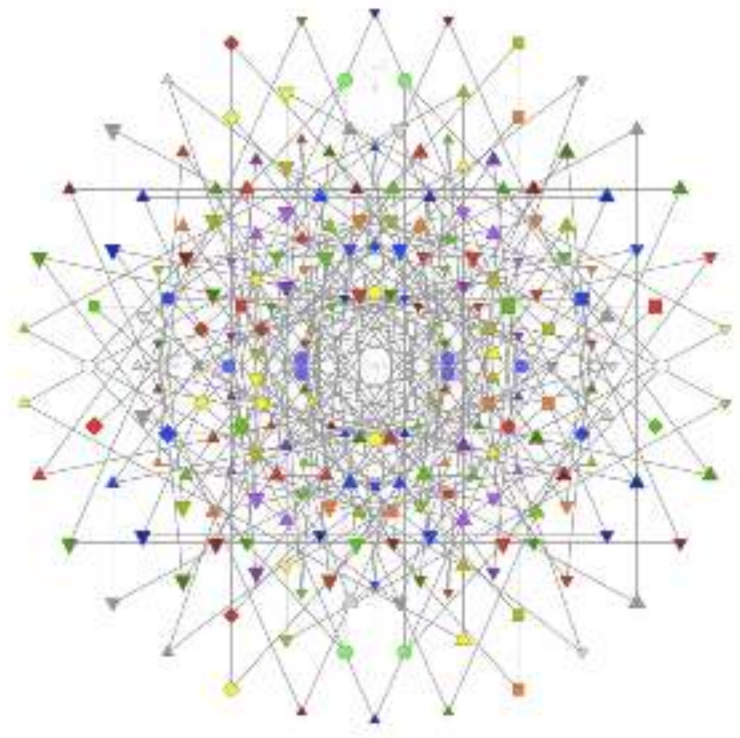
Why these values? Are the two related? Are they related to masses?

- What are the CKM and PMNS phases?
- Where lies the source of CP violation: in quark or lepton sector?

$$J_{CP} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

BEYOND THE STANDARD MODEL: QUEST FOR SYMMETRY

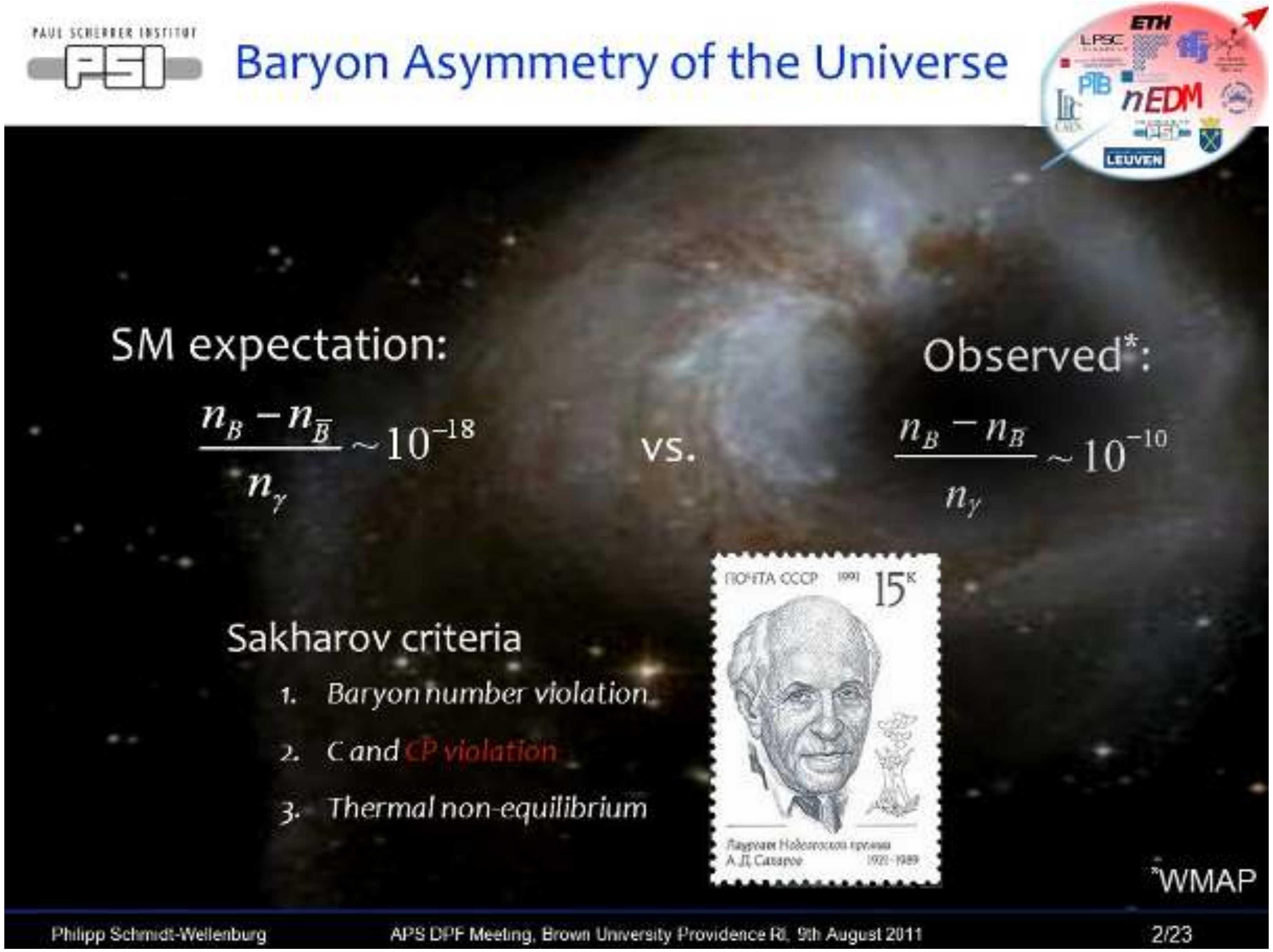
Looking for new physics we are looking for new Symmetry of Nature!



E8 roots

Symmetry might be tricky

THE STANDARD MODEL: CONCEPTUAL PROBLEMS



Baryon Asymmetry of the Universe

SM expectation:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$$

vs.

Observed*:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

Sakharov criteria

1. Baryon number violation
2. C and CP violation
3. Thermal non-equilibrium

ПОЧТА СССР 1991 15к

Лауреат Нобелевской премии А.Д. Сахаров 1921–1989

*WMAP

Philipp Schmidt-Wellenburg APS DPF Meeting, Brown University Providence RI, 9th August 2011 2/23

- Baryon number is conserved in the SM with exponential accuracy

- Violation of baryon number occur in Grand Unified Theories and in Lepton=fourth color models (Pati-Salam model)

New particles = Leptoquarks, Extended Highs sector

$$B = \frac{N_q - N_{\bar{q}}}{3} \qquad \cancel{B}$$

- Violation of CP invariance in the SM achieved via phase factors in the CKM and PMNS mixing matrices $\longleftrightarrow$ $\cancel{CP}$

BAU requires larger CP than in the SM Possible Baryogeneses via Leptogeneses

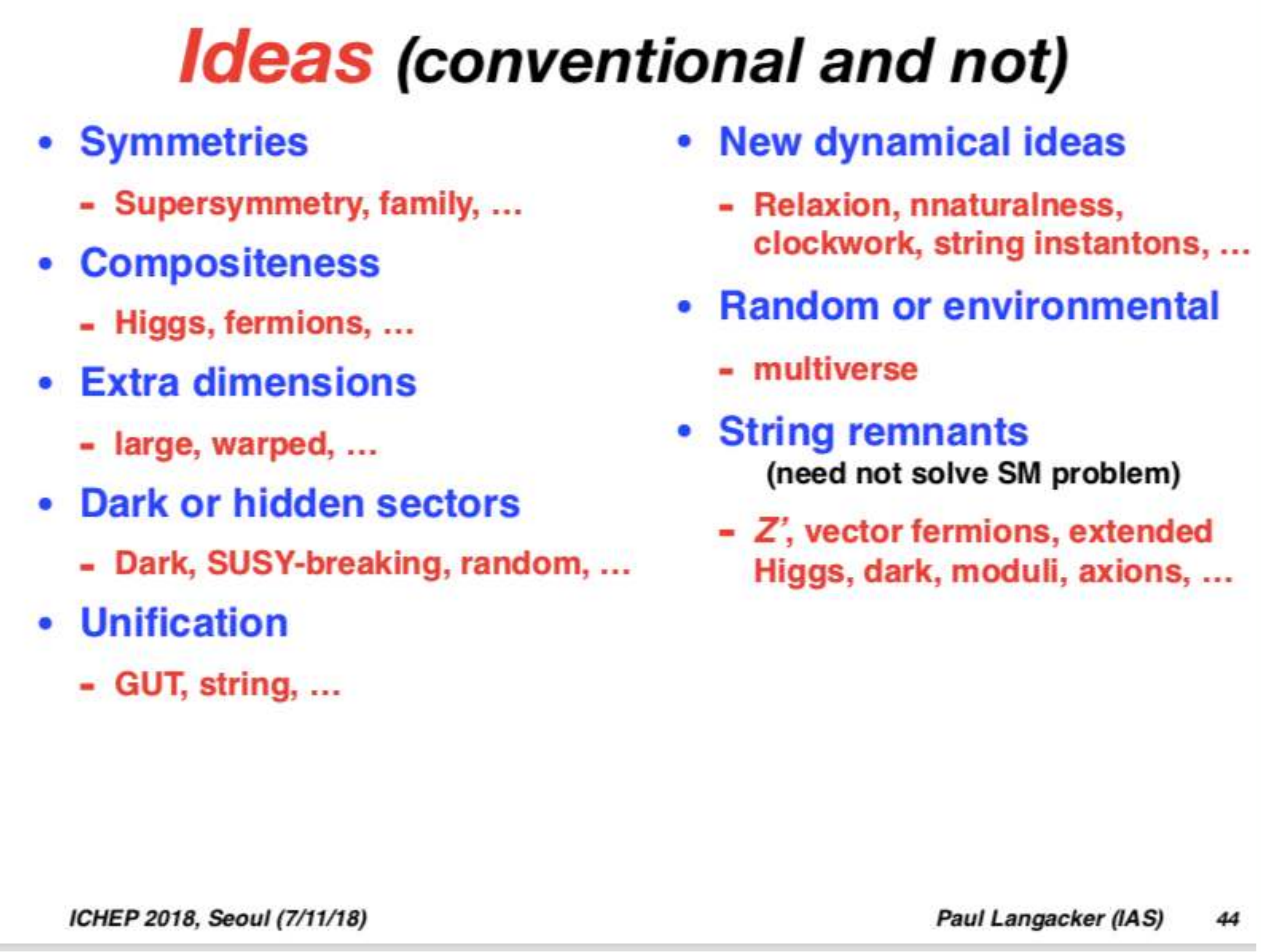
The presence of new phase factors in extended models (2HDM, SUSY, etc)

BEYOND THE STANDARD MODEL: CONCLUSIONS

WHAT MAKES US THINK THAT THERE IS PHYSICS BEYOND THE STANDARD MODEL?

- Small discrepancy with experimental data
- Possible new ingredients in neutrino sector (majorana neutrino)
- Instability of electroweak vacuum
- Inability to describe the Dark matter (unless it has pure gravitational nature)
- Baryon asymmetry of the Universe is a fundamental problem (Baryon and Lepton genesis might require new ingredients)
- Lack of understanding of flavor structure of the SM calls for explanation at higher level
- New era in gravity due to discovery of gravitational waves and black holes might change the landscape

BEYOND THE STANDARD MODEL: CONCLUSIONS



Ideas (conventional and not)

- **Symmetries**
  - Supersymmetry, family, …
- **Compositeness**
  - Higgs, fermions, …
- **Extra dimensions**
  - large, warped, …
- **Dark or hidden sectors**
  - Dark, SUSY-breaking, random, …
- **Unification**
  - GUT, string, …
- **New dynamical ideas**
  - Relaxion, nnaturalness, clockwork, string instantons, …
- **Random or environmental**
  - multiverse
- **String remnants** (need not solve SM problem)
  - *Z'*, vector fermions, extended Higgs, dark, moduli, axions, …

ICHEP 2018, Seoul (7/11/18) *Paul Langacker (IAS)* 44

Which way to go ?

How Will We Make Progress?

- **The energy frontier**
- **The precision frontier and neutrinos**
- **Cosmology and astrophysics**