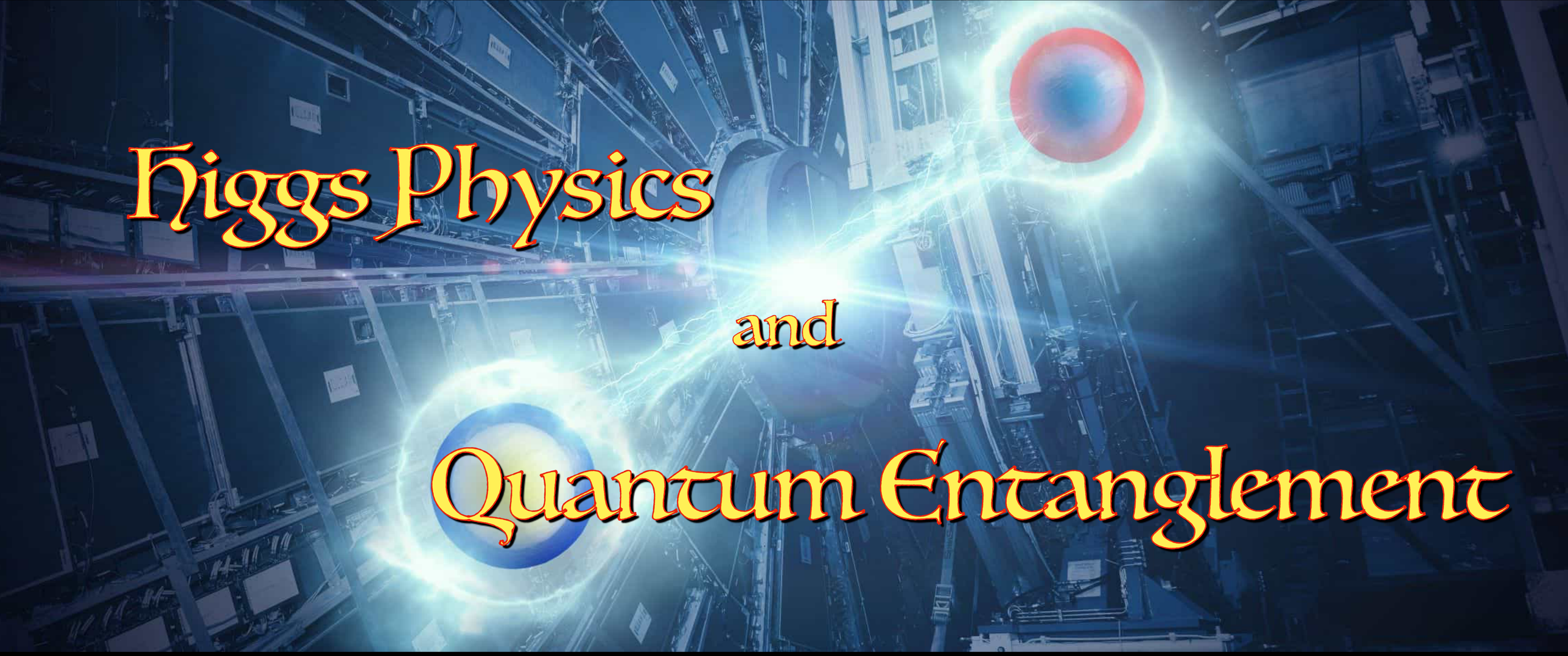


**Hao Zhang**

**Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences**
**For the 10th China LHC Physics Conference, Qingdao, Nov 16th, 2024**

# A Disclaimer

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- This talk will not be a
  - collection recent results which are easy to be found in papers published, or on arXiv;
  - paper list or author name list.

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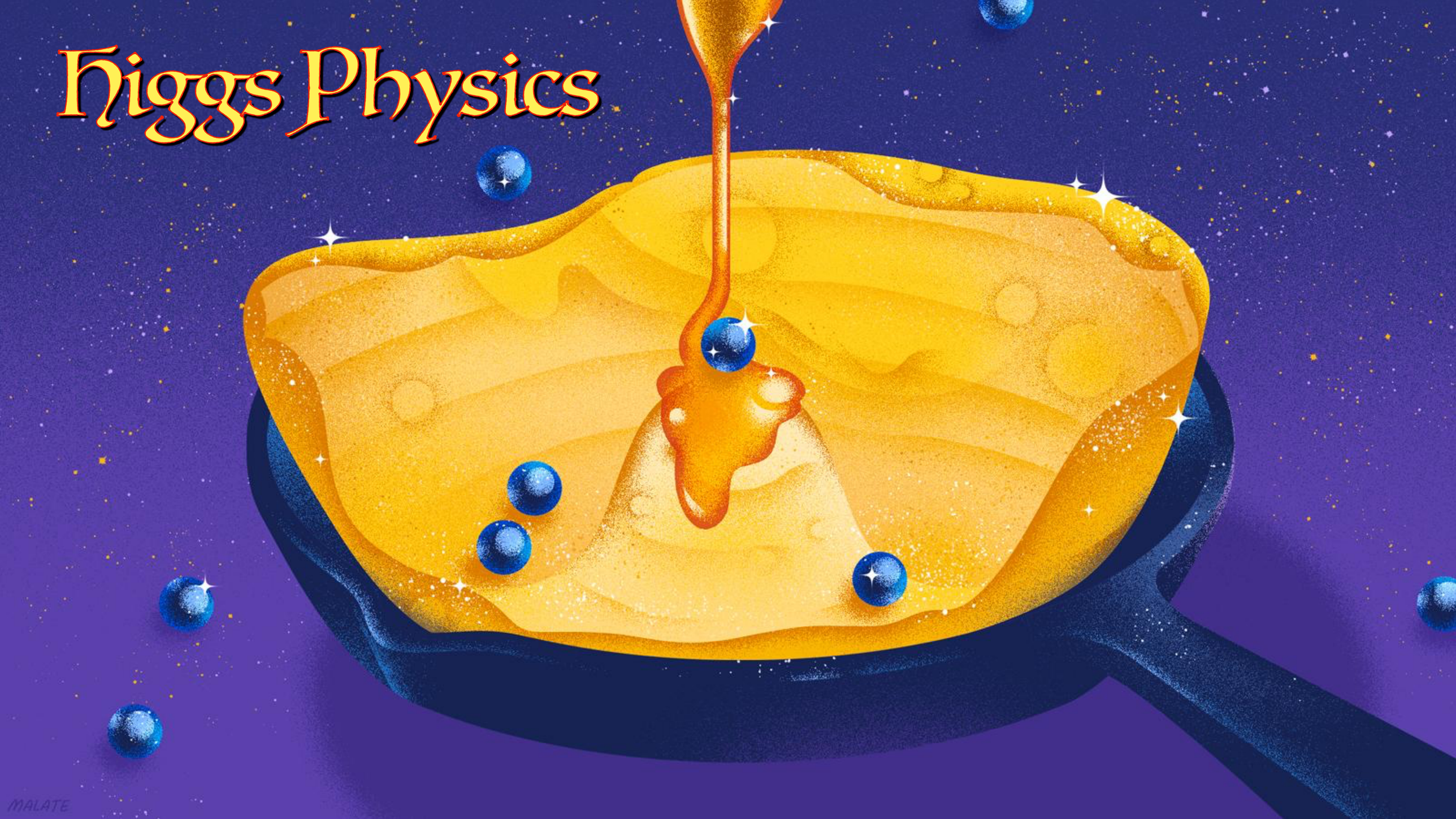
  - collection recent results which are easy to be found in papers published, or on arXiv;
  - paper list or author name list.

- This talk would contain some
  - (probably) open questions;
  - a lot of personal bias.

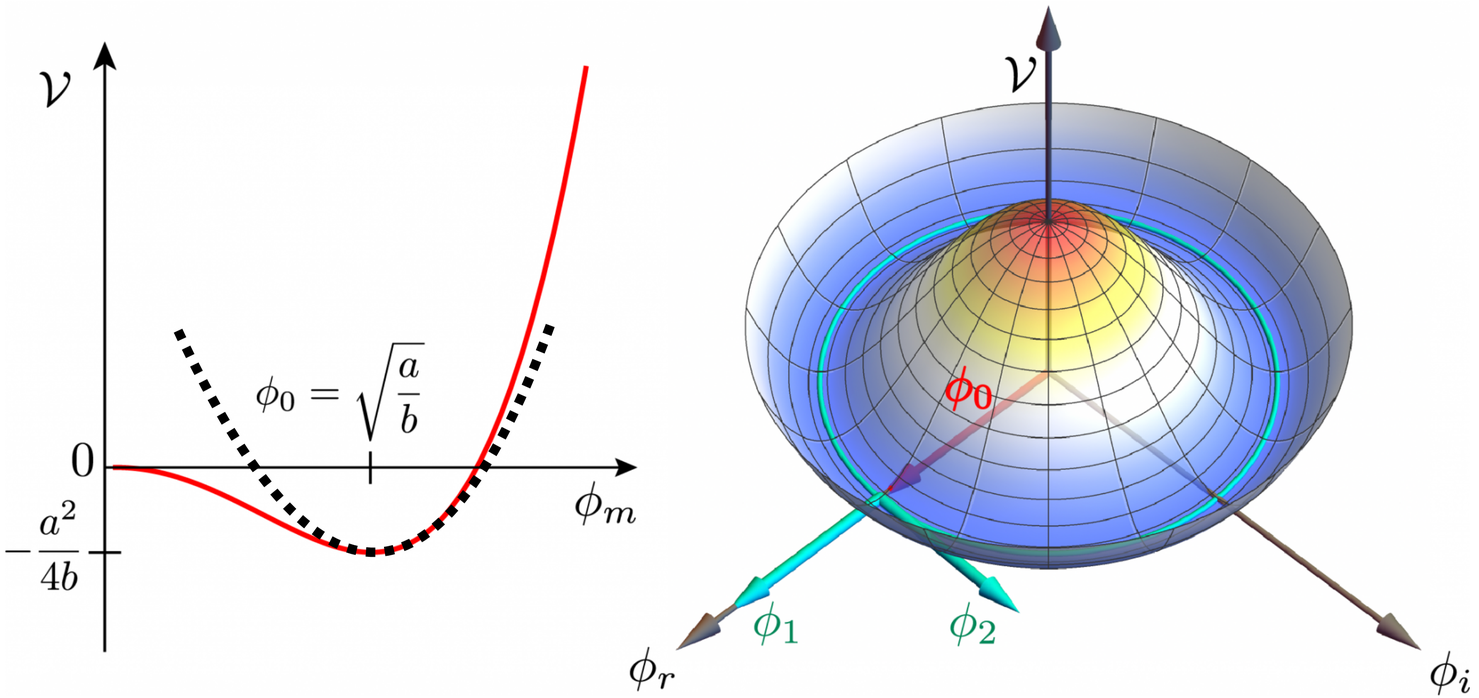
# Higgs Physics



# What are we doing,
# and going to do for a long time?

# Higgs Potential

- Higgs pair productions.
- Test the mass generation mechanism in the SM.
- From two Higgs to multi-Higgs?



# Other Important Topics

- Yukawa interactions with light fermions.
- Gauge interactions in Higgs pair processes.
- Inclusive measurement of the width of the Higgs boson.
- CP property of the Higgs boson.
- …

# New Physics with Higgs Boson

- For experimentalists: model independent methods, popular models.

  SMEFT, HEFT, 2HDM, 3HDM, XHDM, MSSM, Composite Higgs model…

# New Physics with Higgs Boson

- For experimentalists: model independent methods, popular models.

  SMEFT, HEFT, 2HDM, 3HDM, XHDM, MSSM, Composite Higgs model…

- For phenomenologists: new observables, physical meanings, what do we miss?

  UNDERSTAND physics without AI, faked SM signals…

# New Physics with Higgs Boson

- For experimentalists: model independent methods, popular models.

  SMEFT, HEFT, 2HDM, 3HDM, XHDM, MSSM, Composite Higgs model…

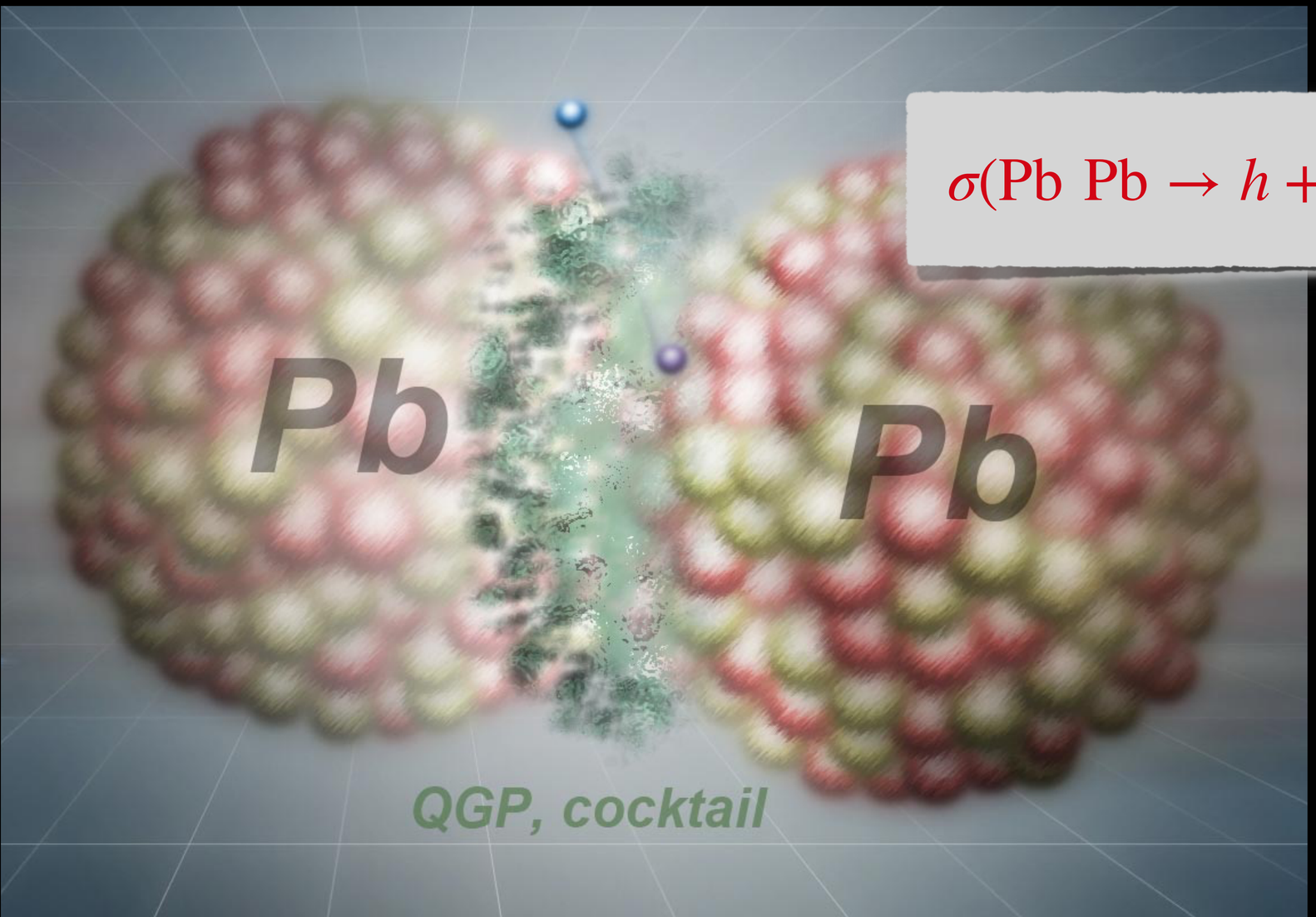
- For phenomenologists: new observables, physical meanings, what do we miss?

  UNDERSTAND physics without AI, faked SM signals…

- For theorists: new physical motivations, accurate calculations.

# More Ideas?

# Higgs boson in medium?




$$\sigma(\mathrm{Pb\ Pb} \to h + X)\big|_{\sqrt{s_{NN}}=5.5\mathrm{TeV}} \sim 0.5\mathrm{nb}$$

2.2~2.8nb$^{-1}$/month for Run3 and Run4 for ATLAS, CMS and ALICE.

# From Higgs particle to Higgs Field?

# From Higgs particle to Higgs Field?

SM B+L violation process

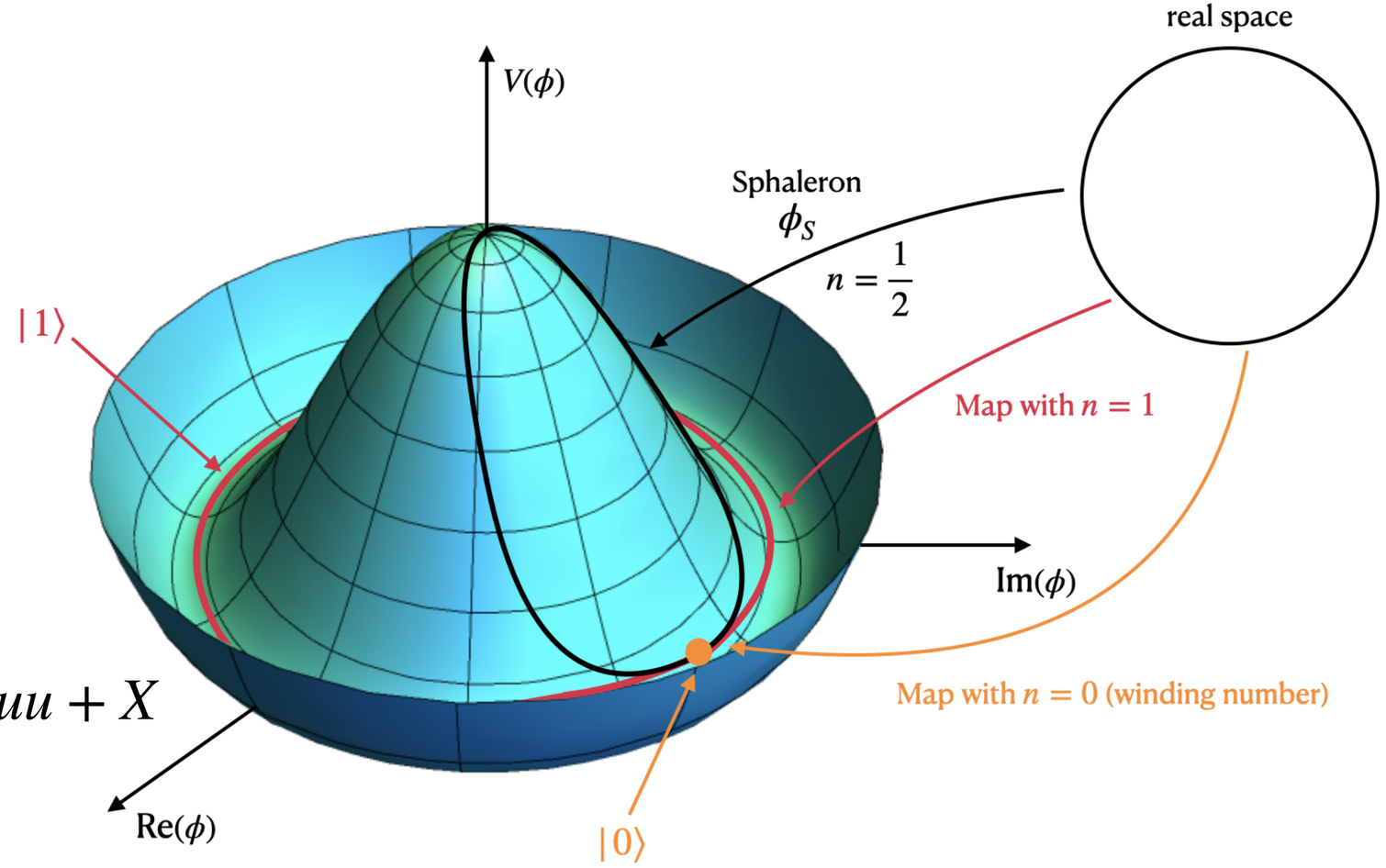
and sphaleron?

Mass of the sphaleron?

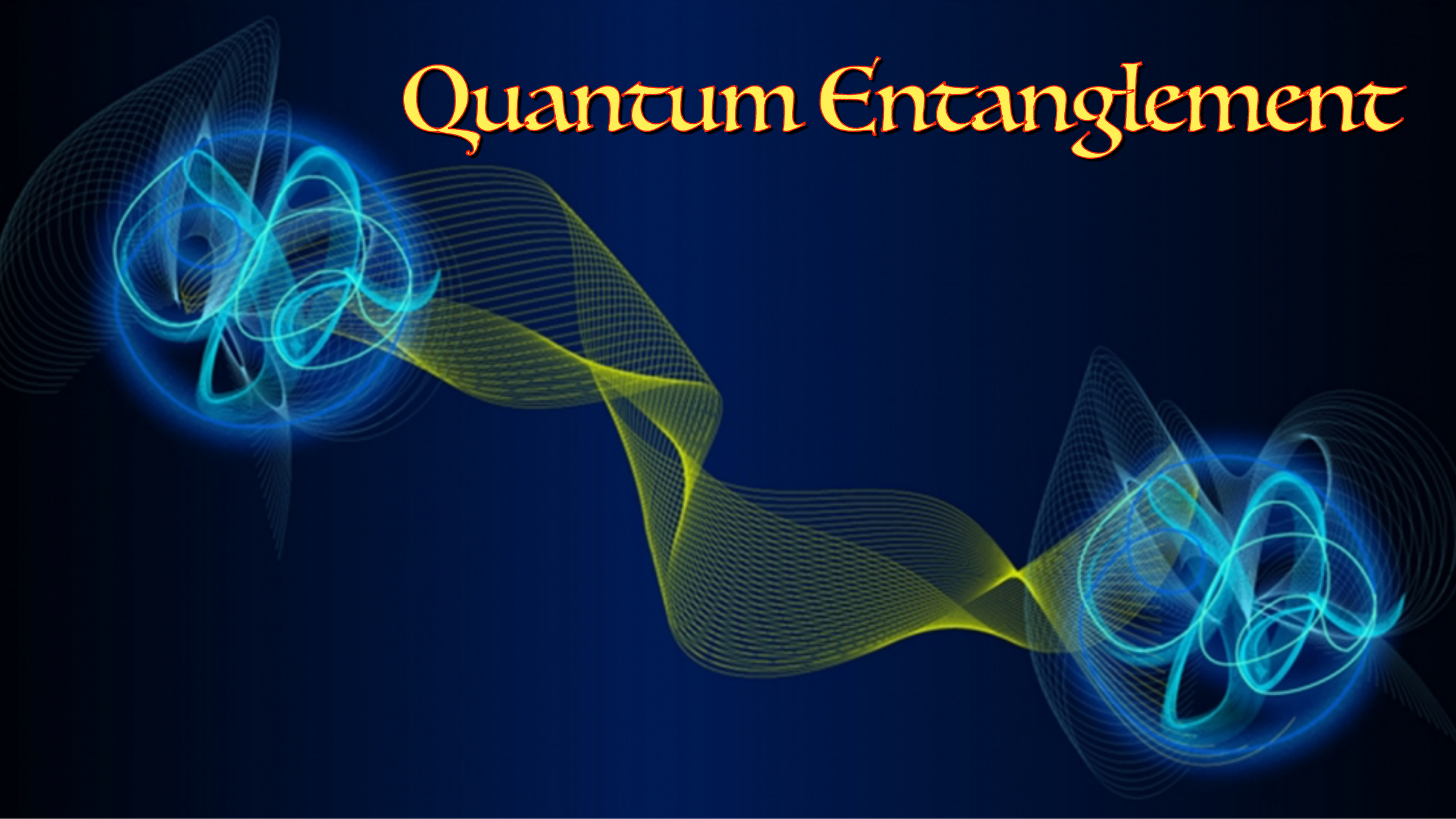
Typical signals?

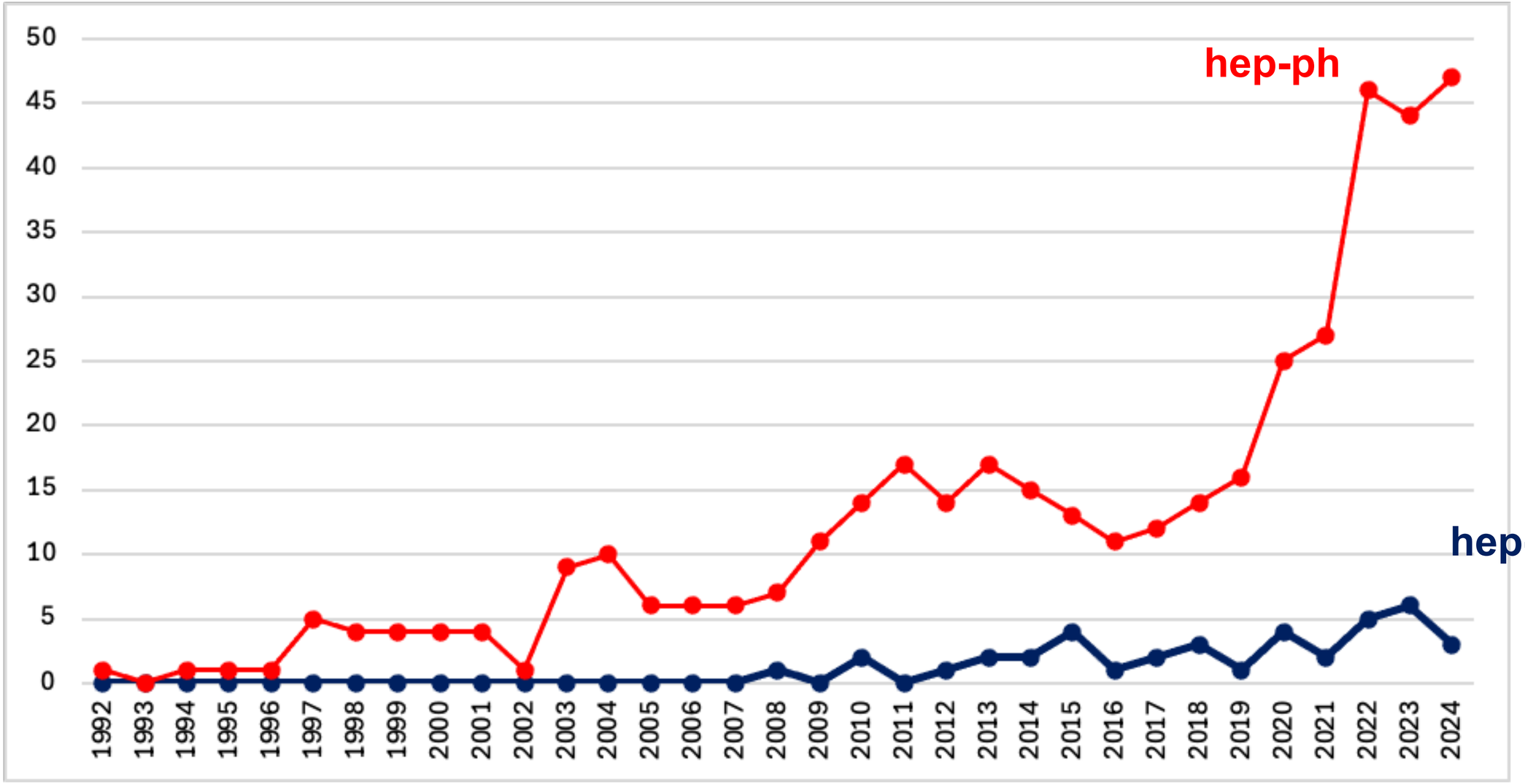
Production rate?

$$q_L + q_L \to e^- \mu^- \tau^- bbbccccddduu + X$$



# Quantum Entanglement




hep-ph
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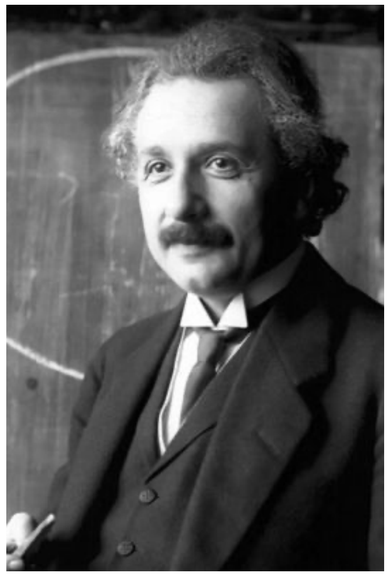
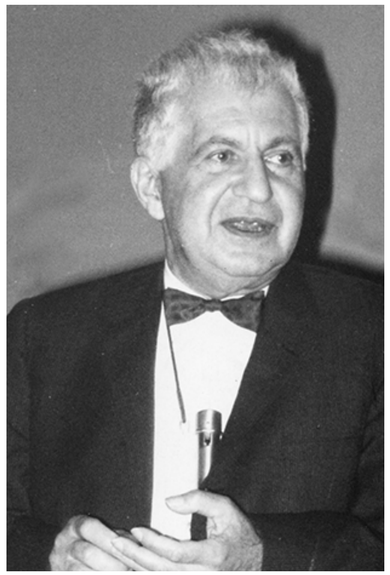
# Quantum Reality?

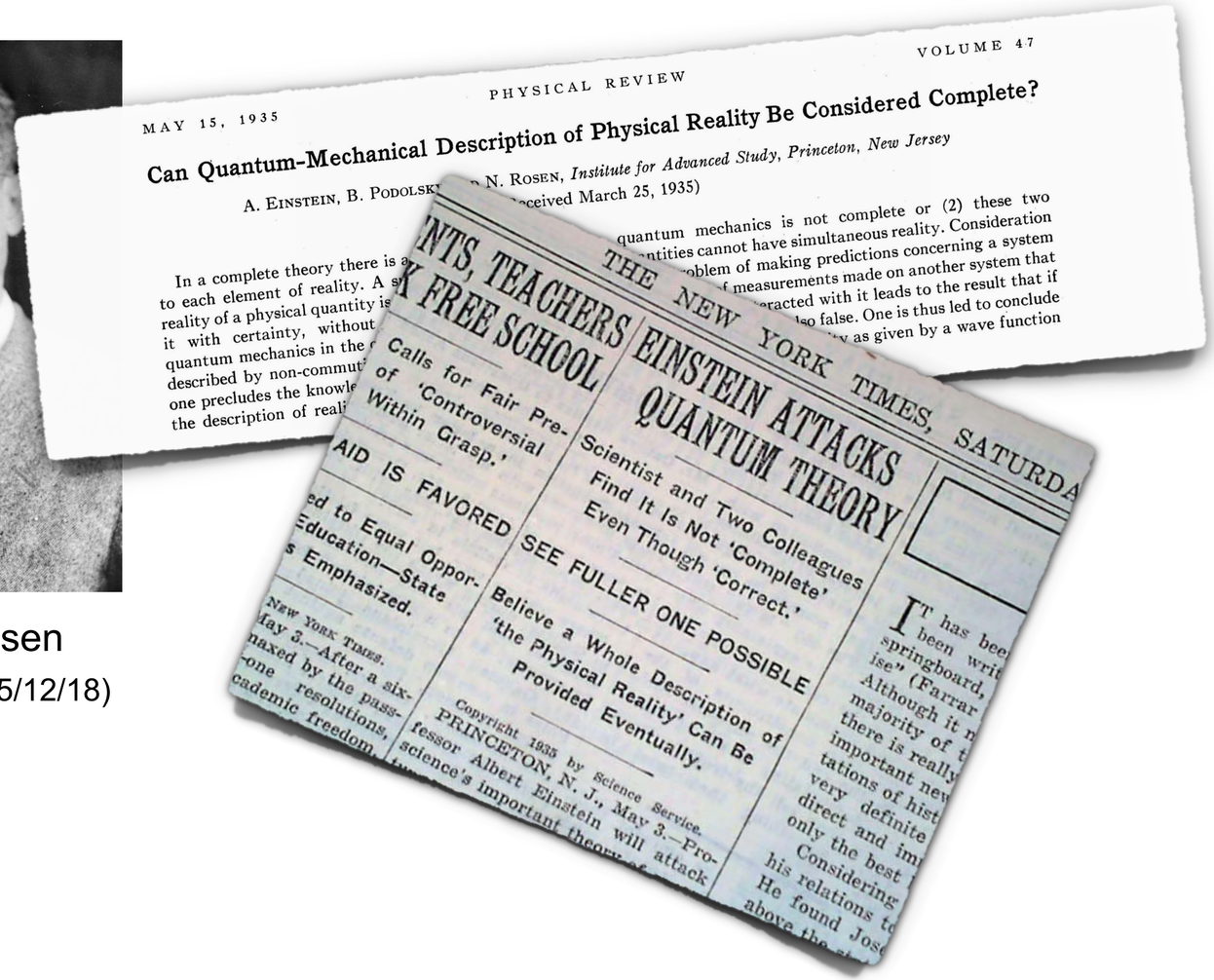


Albert Einstein
(1879/03/14-1955/04/18)



Boris Yakovlevich Podolsky
(1896/06/29-1966/11/28)

Nathan Rosen
(1909/03/22-1995/12/18)



PHYSICAL REVIEW VOLUME 47

MAY 15, 1935

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY, N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is a... to each element of reality. A s... reality of a physical quantity is... it with certainty, without... quantum mechanics in the... described by non-commut... one precludes the knowle... the description of reali...

quantum mechanics is not complete or (2) these two ...ntities cannot have simultaneous reality. Consideration ...oblem of making predictions concerning a system ...f measurements made on another system that ...eracted with it leads to the result that if ...so false. One is thus led to conclude ...y as given by a wave function

THE NEW YORK TIMES, SATURDA...

EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not 'Complete' Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of 'the Physical Reality' Can Be Provided Eventually.

Copyright 1935 by Science Service.

PRINCETON, N. J., May 3.—Professor Albert Einstein will attack science's important theory...

...NTS, TEACHERS ...K FREE SCHOOL

Calls for Fair Pre... of 'Controversial Within Grasp.'

AID IS FAVORED

...ed to Equal Oppor... Education—State ...s Emphasized.

NEW YORK TIMES. May 3.—After a six... naxed by the pass... one resolutions, ...cademic freedom...

It has bee... been writ... springboard, ...ise" (Farrar... Although it n... majority of t... there is really... important new... tations of hist... very definite... direct and im... only the best... Considering... his relations t... He found Jos... above the...

# Quantum Entanglement

- Non-factorizable state.

$$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}} \neq (a_1|\uparrow\rangle + b_1|\downarrow\rangle) \otimes (a_2|\uparrow\rangle + b_2|\downarrow\rangle)$$

# Quantum Entanglement

- Non-factorizable state.

$$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}} \neq (a_1|\uparrow\rangle + b_1|\downarrow\rangle) \otimes (a_2|\uparrow\rangle + b_2|\downarrow\rangle)$$

$$\neq \uparrow\downarrow \text{ or } \downarrow\uparrow$$

# Quantum Entanglement

- Non-factorizable state.

$$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$$

$$\neq (a_1|\uparrow\rangle + b_1|\downarrow\rangle) \otimes (a_2|\uparrow\rangle + b_2|\downarrow\rangle)$$

$$\neq \uparrow\downarrow \quad \text{or} \quad \downarrow\uparrow$$

$$= \frac{|\leftarrow\rightarrow\rangle - |\rightarrow\leftarrow\rangle}{\sqrt{2}}$$

# Quantum Entanglement

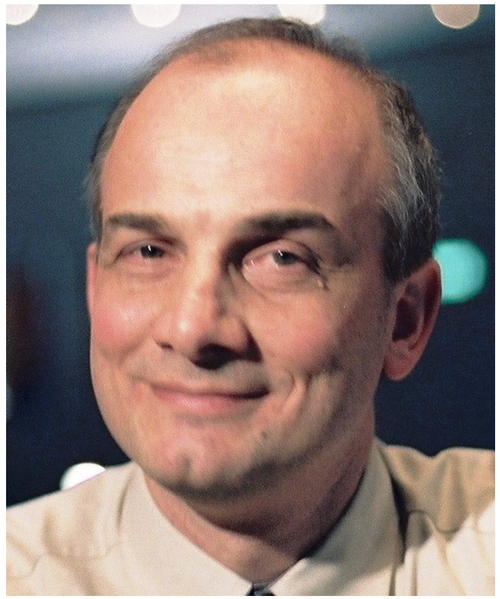
- From pure state to mixed state.

***"A quantitatively characterization of the degree of the entanglement between the subsystems of a system in a mixed state, is not unique! "***

$$\rho_{AB} \overset{?}{=} \sum_{i=1}^{N} p_i \rho_A^{(i)} \otimes \rho_B^{(i)}, \quad \left( \sum_i^N p_i = 1, \, p_i > 0 \right)$$

"Finally, we prove that the weak membership problem for the convex set of separable normalized bipartite density matrices is ***NP-HARD***. "

——Leonid Gurvits



# Quantum Entanglement

- For $2 \times 2$ and $2 \times 3$ system, it is solved by Peres, and Horodeckis 1996 (Peres-Horodecki criterion, concurrence).

Asher Peres
(1934/01/30-2005/01/01)

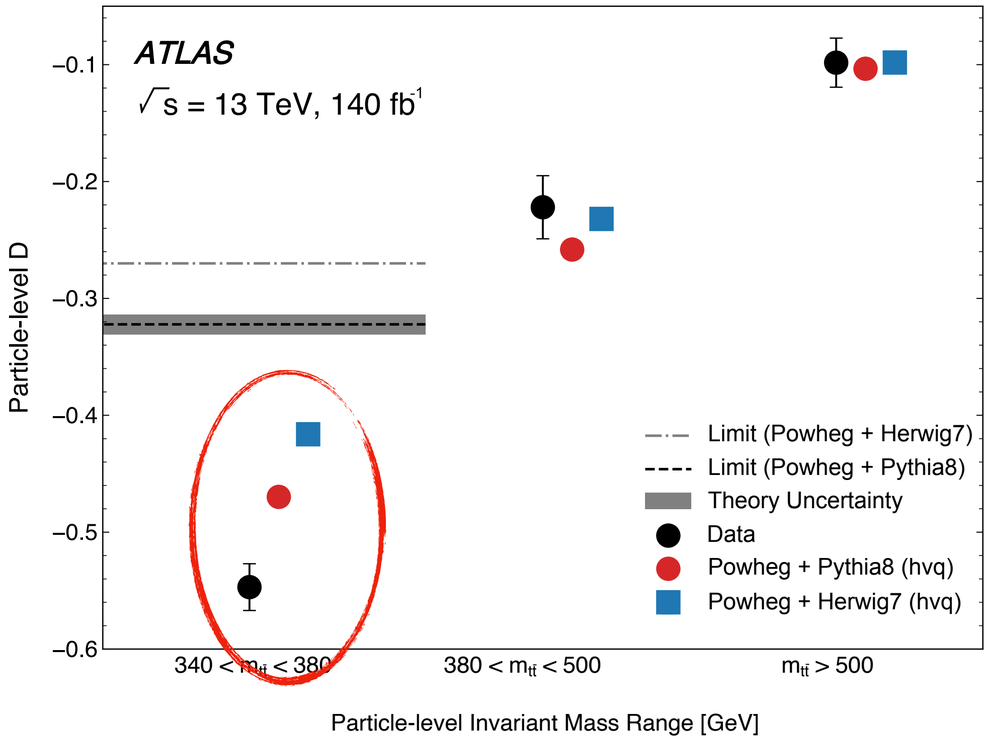
Ryszard Horodecki
(1943/09/30-)

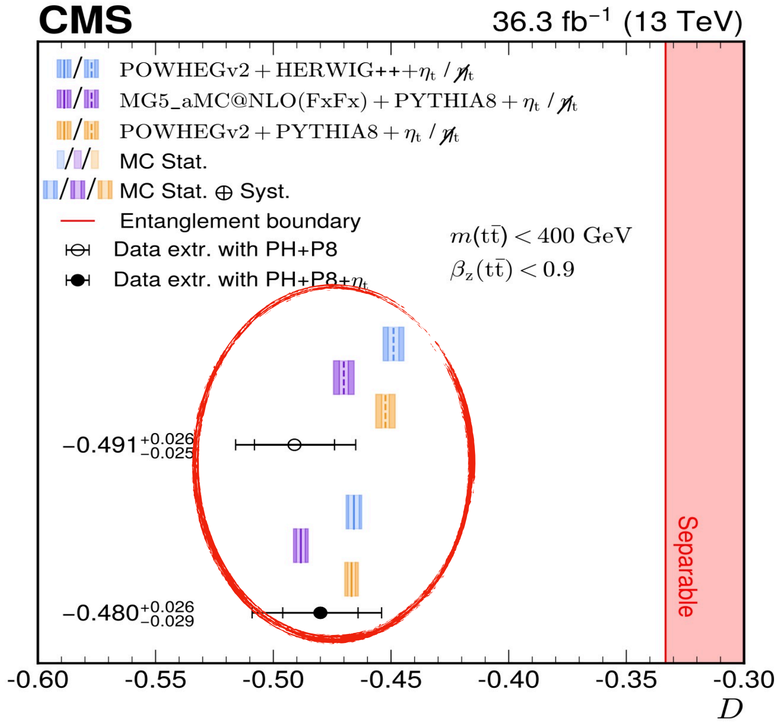
Paweł Horodecki
(1971-)

Michał Horodecki
(1973-)

# Quantum Entanglement

- Testing quantum entanglement at TeV scale (for more details, see Prof. Hongbo Liao's talk).



# Quantum Entanglement

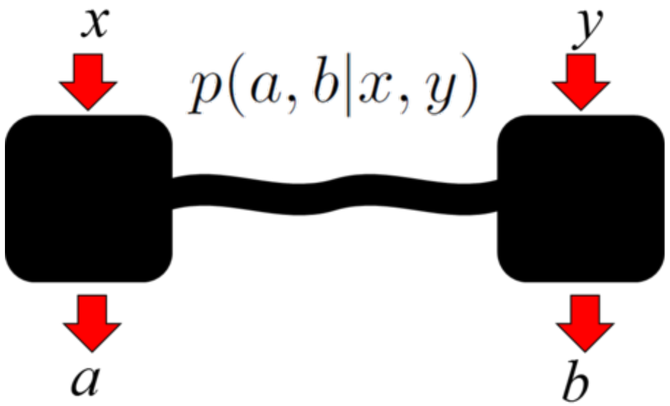
- Beyond “simple” repetition of the measurement of entanglement did by our condensed matter colleagues?
- Entanglement in Quantum Field Theory?
- A lot of works need to be done.

# STAYING TRUE TO OUR ORIGINAL ASPIRATION AND FOUNDING MISSION

# Quantum Non-Locality

- The different correlations.

“Alice”



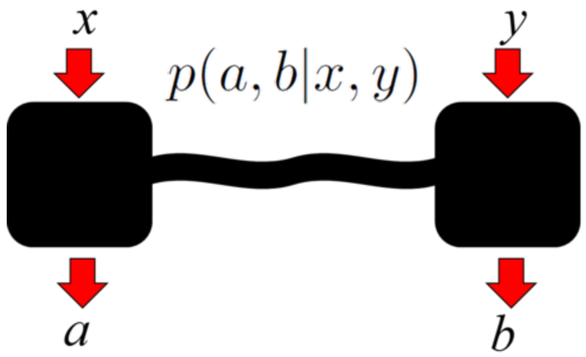

“Bob”

| Local correlations | Quantum correlations | No-signaling correlations |
|---|---|---|

# Quantum Non-Locality

## Local correlations

“Alice”



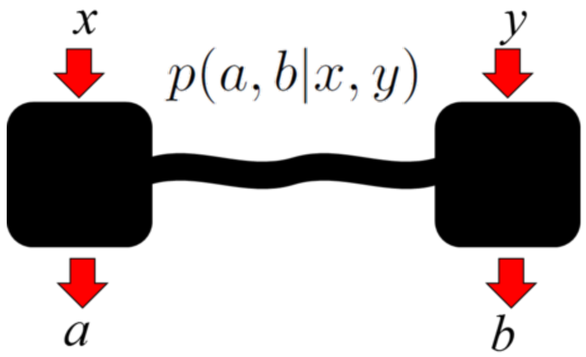

“Bob”

$$p(ab|xy) = \int_{\Lambda} d\lambda q(\lambda) p(a|x,\lambda) p(b|y,\lambda),$$

# Quantum Non-Locality

## Local correlations

“Alice”




“Bob”

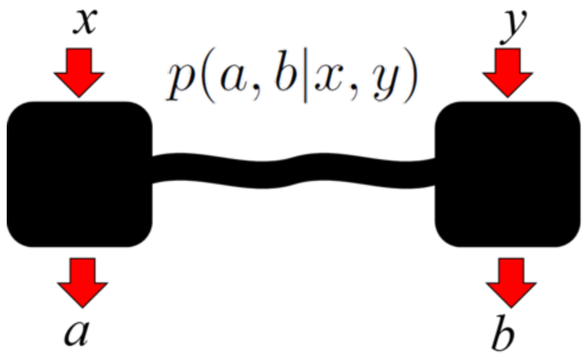
$$p(ab|xy) = \int_{\Lambda} d\lambda q(\lambda) p(a|x,\lambda) p(b|y,\lambda),$$

$\lambda$-“Hidden variable(s)”

# Quantum Non-Locality

## Quantum correlations-I

“Alice”



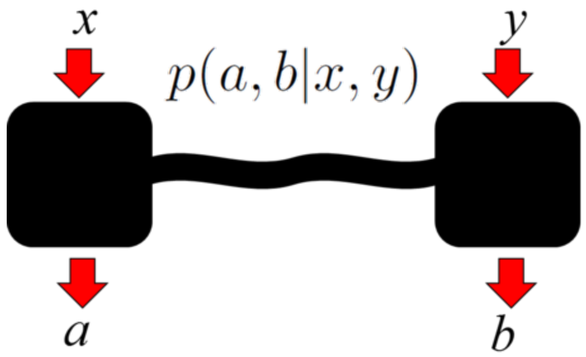

“Bob”

$$p(ab|xy) = \mathrm{tr}\,(\rho_{AB} M_{a|x} \otimes M_{b|y}),$$

# Quantum Non-Locality

## Quantum correlations-II

“Alice”



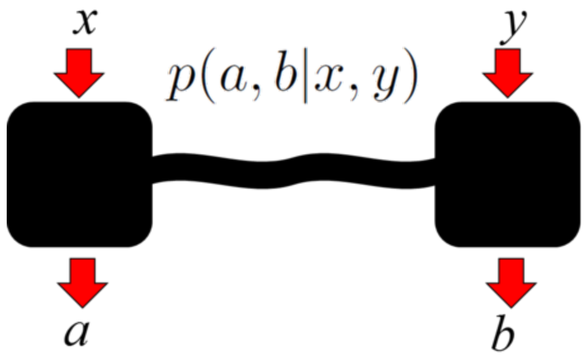

“Bob”

$$p(ab\,|\,xy) = \rho_{AB}(M_{a|x}M_{b|y}),\ [M_{a|x}, M_{b|y}] = 0$$

# Quantum Non-Locality and Beyond

## No-signaling correlations

“Alice”




“Bob”

$$\sum_{b=1}^{\Delta} p(ab|xy) = \sum_{b=1}^{\Delta} p(ab|xy'), \quad \text{for all } a, x, y, y',$$

$$\sum_{a=1}^{\Delta} p(ab|xy) = \sum_{a=1}^{\Delta} p(ab|x'y), \quad \text{for all } b, y, x, x'.$$

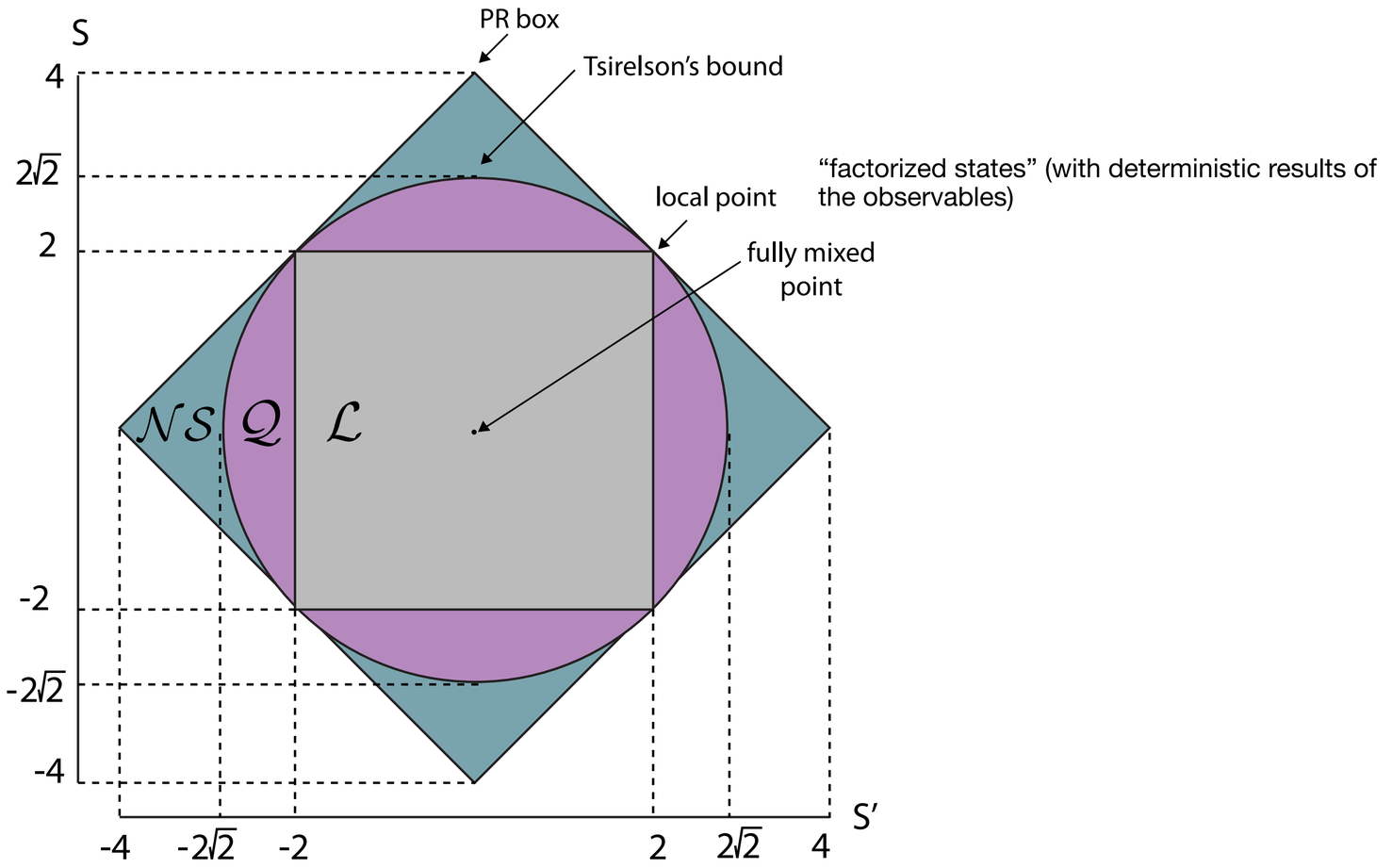
# Quantum Non-Locality and Beyond

**Local correlations**

⊂ **Quantum correlations-I**

⊂ **Quantum correlations-II**

⊂ **No-signaling correlations**

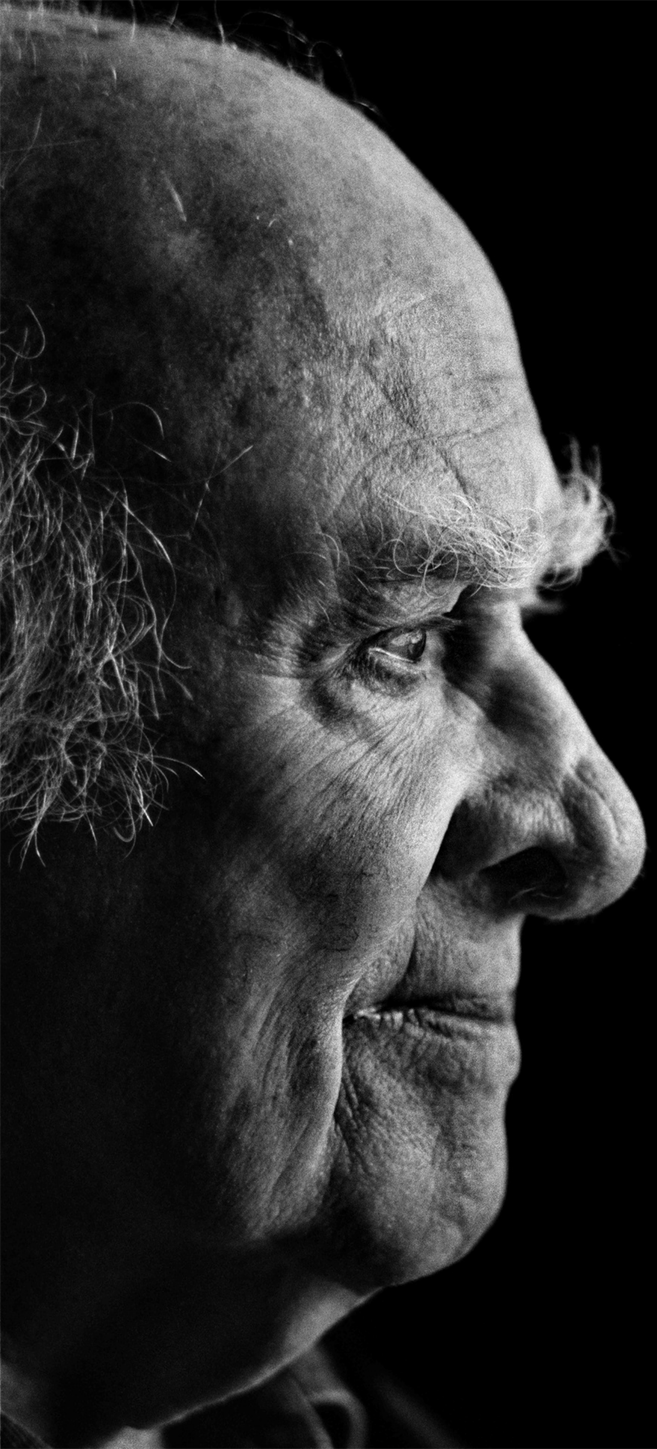


# Quantum Non-Locality

- Testing Bell inequality violation at TeV scale.
- There have been several works.
- The advantages and problems.

# Quantum Physics at Colliders

- Quantum entanglement
- Bell inequality and Tsirelson inequality
- Quantum Steering
- Quantum Discord
- Measurement Theory in QFT
- Non-perturbative objects in QFT
- Quantum Energy Teleportation and beyond
- …



# High Energy Physics in Quantum Era


Thank you!