# Imprints of Electro-Weak Symmetry Breaking @ Particle Colliders

Andreas Papaefstathiou
Kennesaw State University, GA, USA

@ Wichita State University [May 1st 2024]

# Today's Plan:

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1 High Energy Physics

2 Open Questions,

3 ➜ the Breaking of Symmetry,

4 Extended Scalar Sectors.

# 1 What is High Energy Physics?

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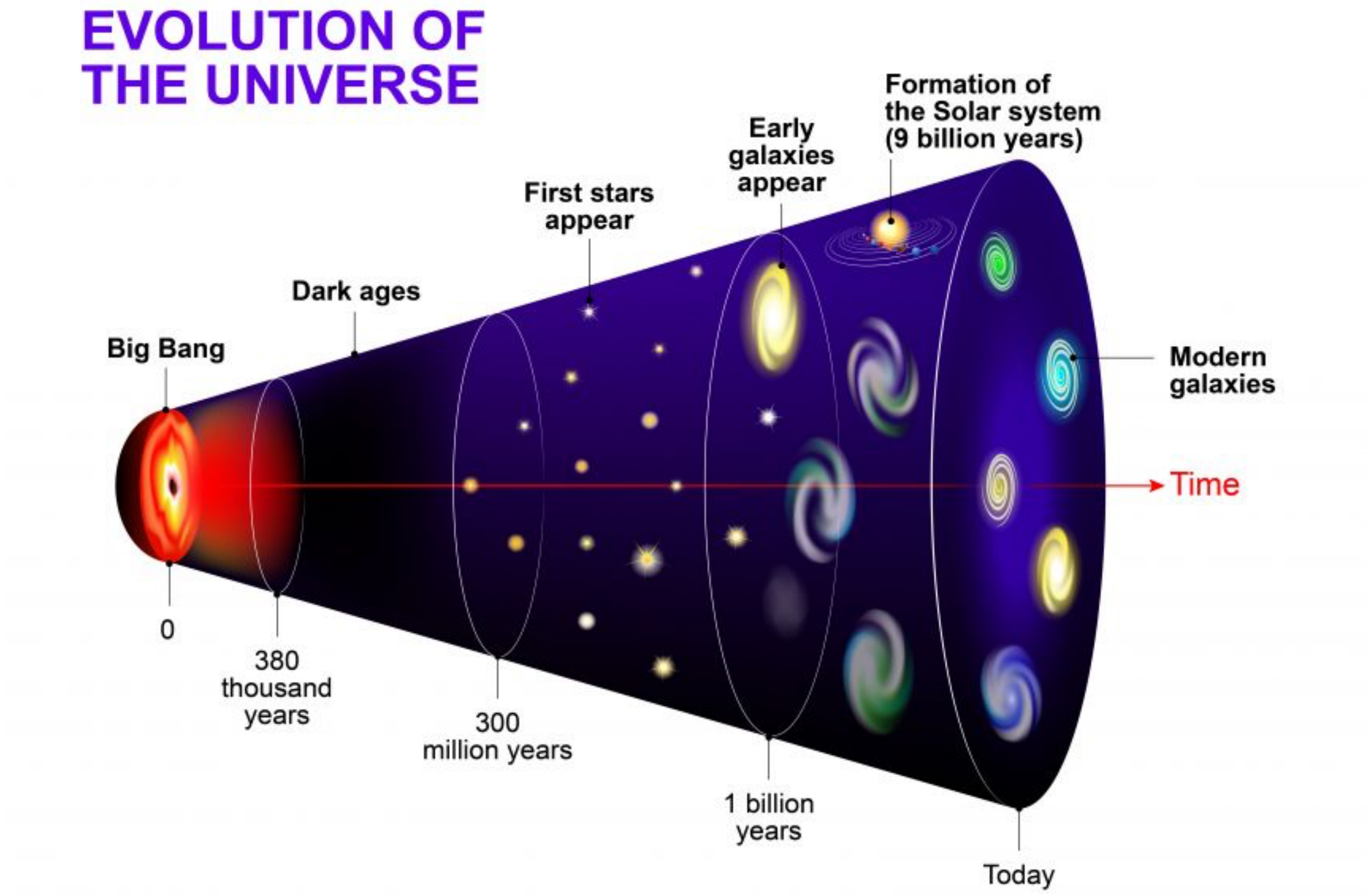
**Aim:** Smash particles together to “emulate” conditions <u>closer</u> to the Big Bang! (“Particle Archaeology”)




HIGHER ENERGY



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→ understand particle interactions:

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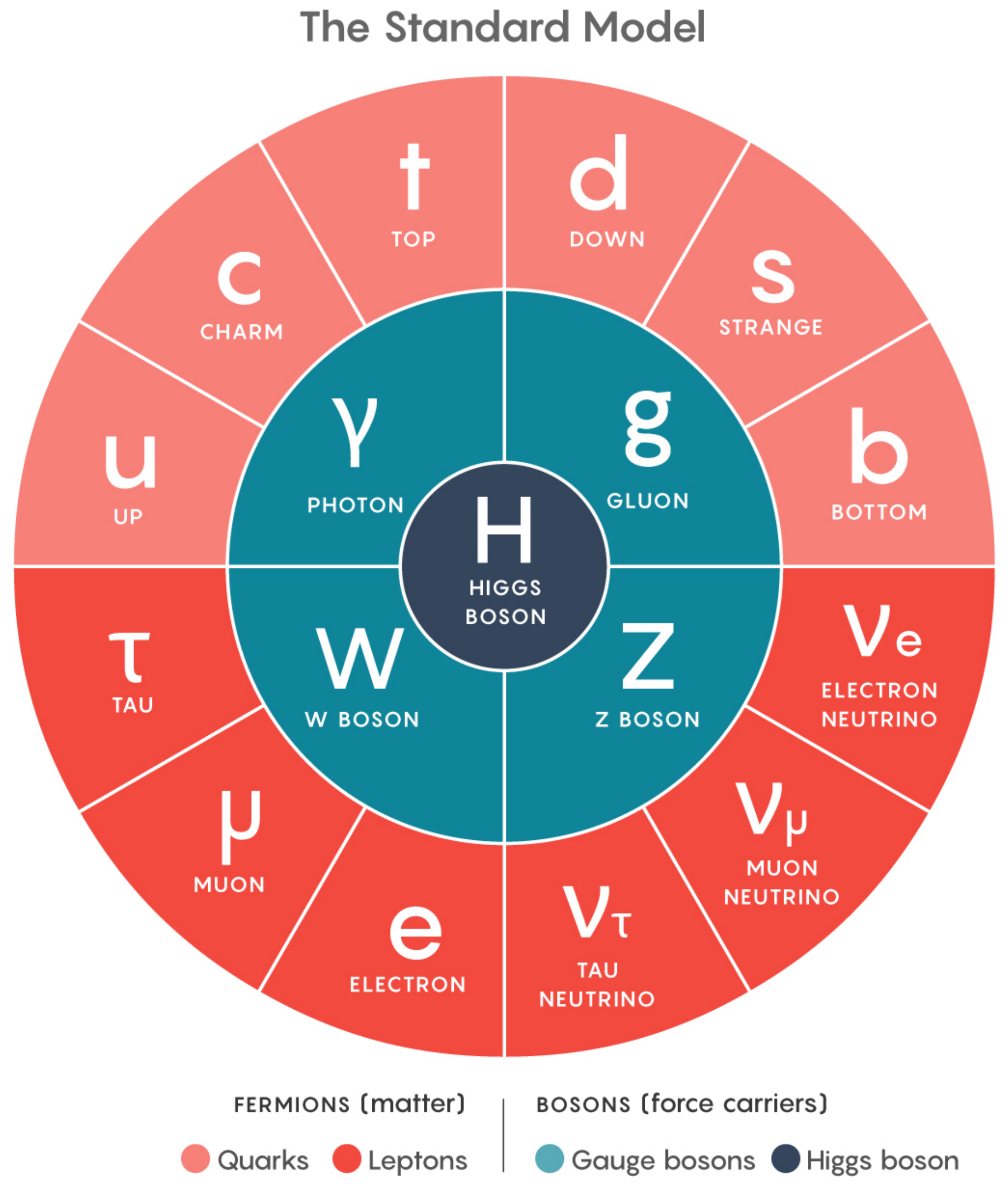


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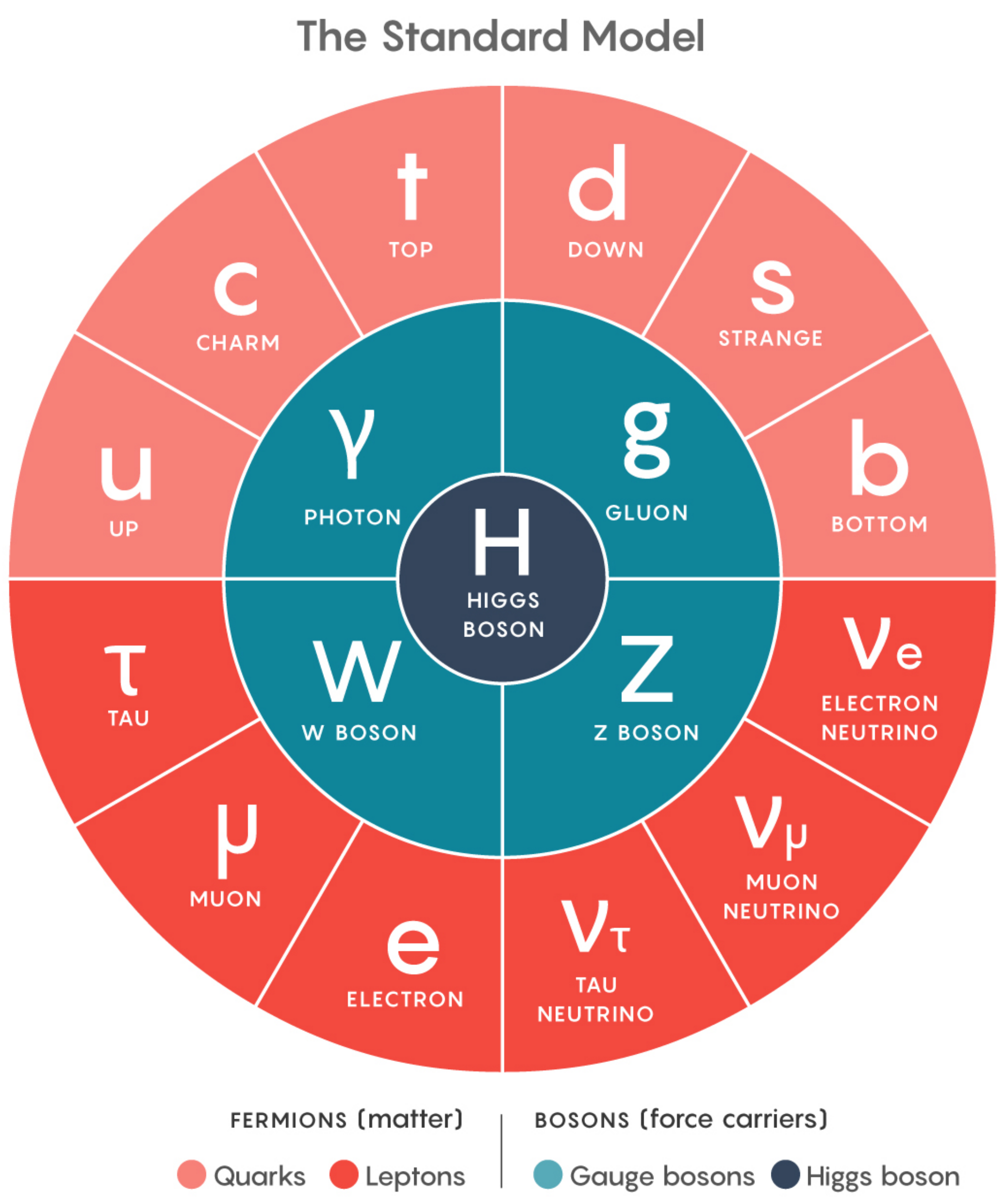
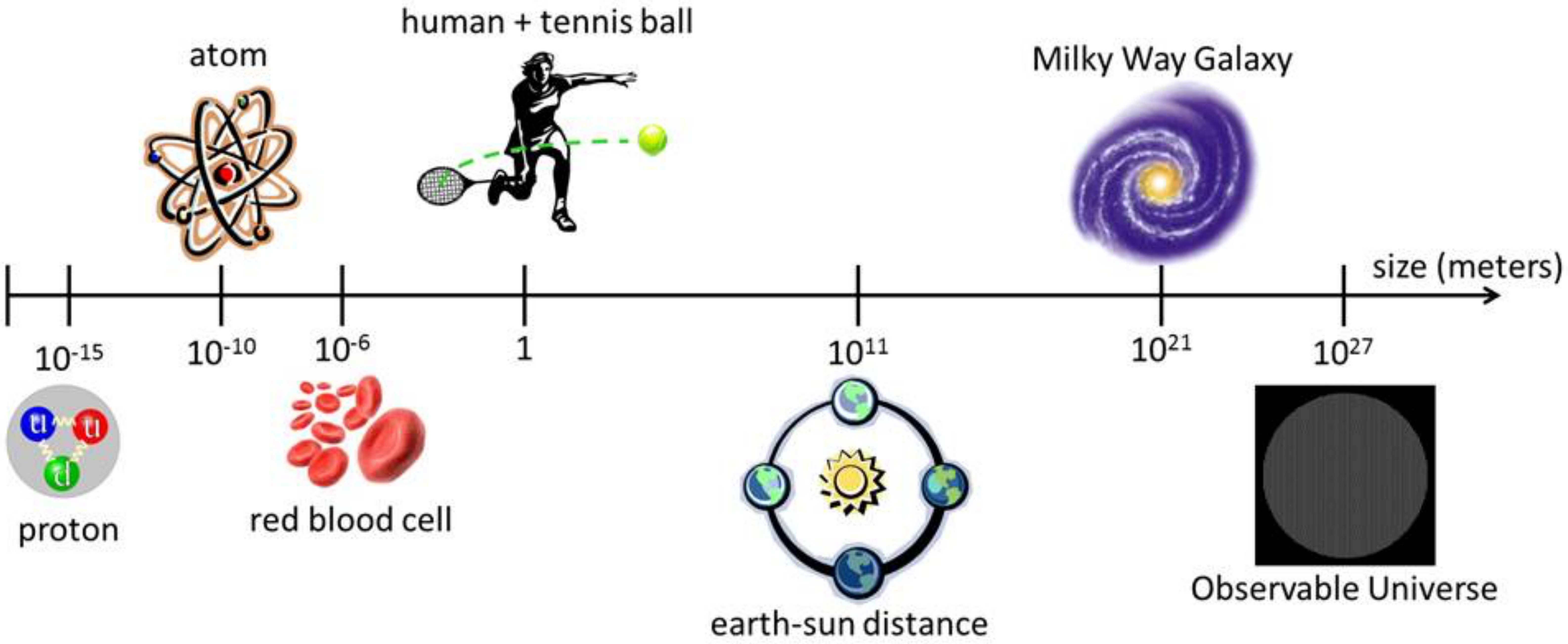



& discover **exotic** phenomena!

# What is High Energy Physics?

**Rule:** $E \propto 1/\lambda \Rightarrow$ **Higher Energy** $\Longleftrightarrow$ **Smaller Scales!**



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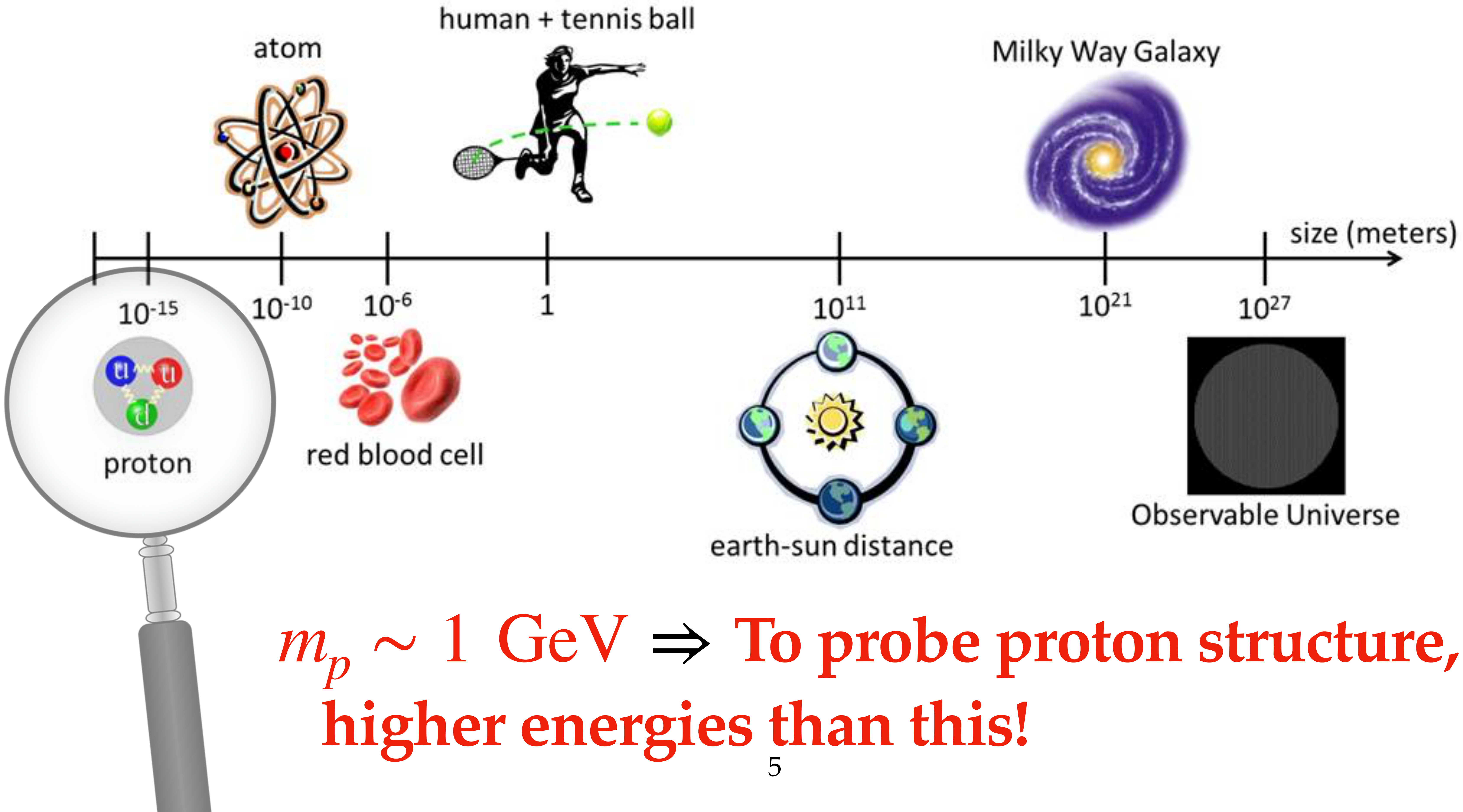


$m_p \sim 1$ GeV $\Rightarrow$ **To probe proton structure, go to higher energies than this!**





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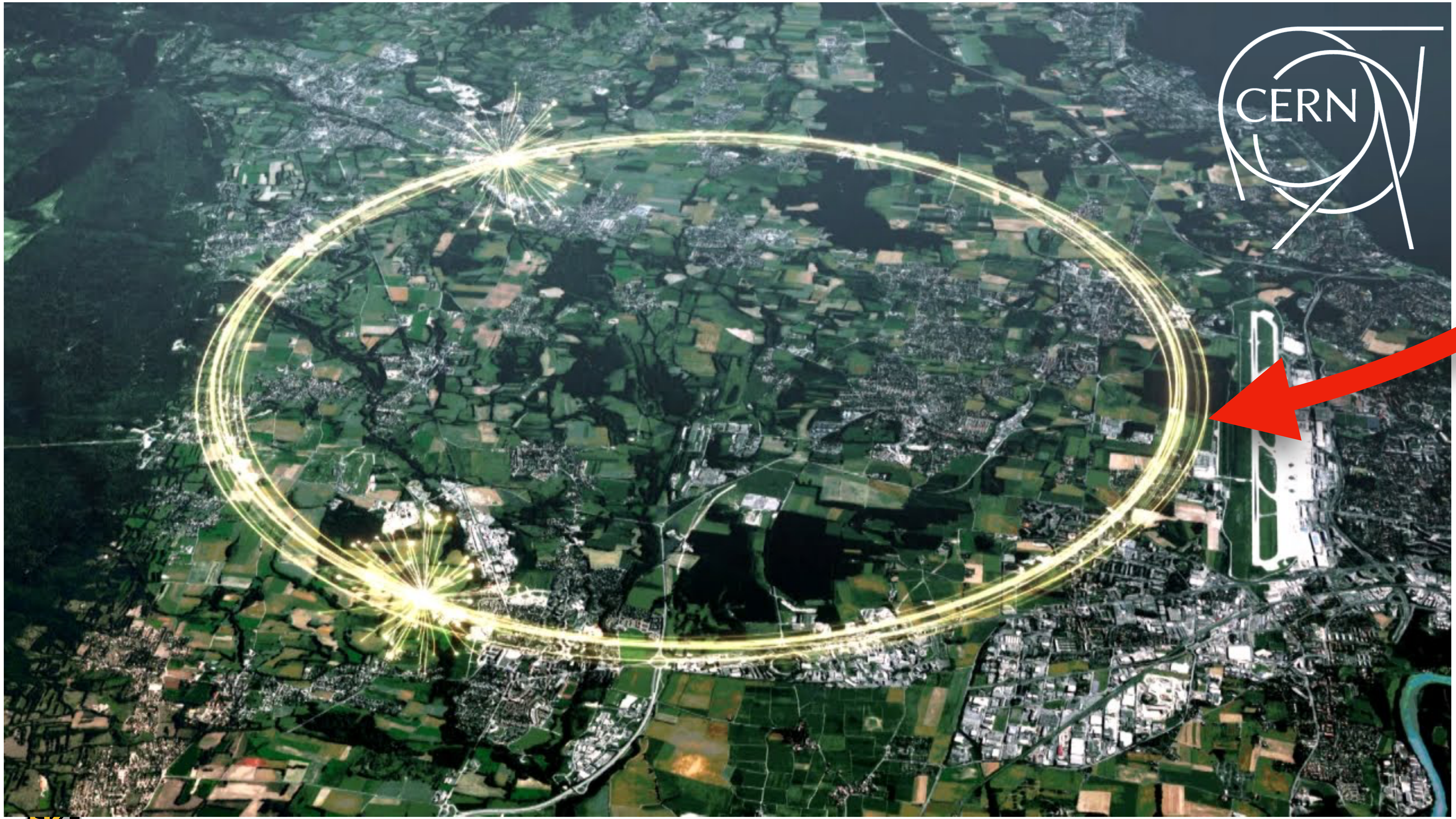
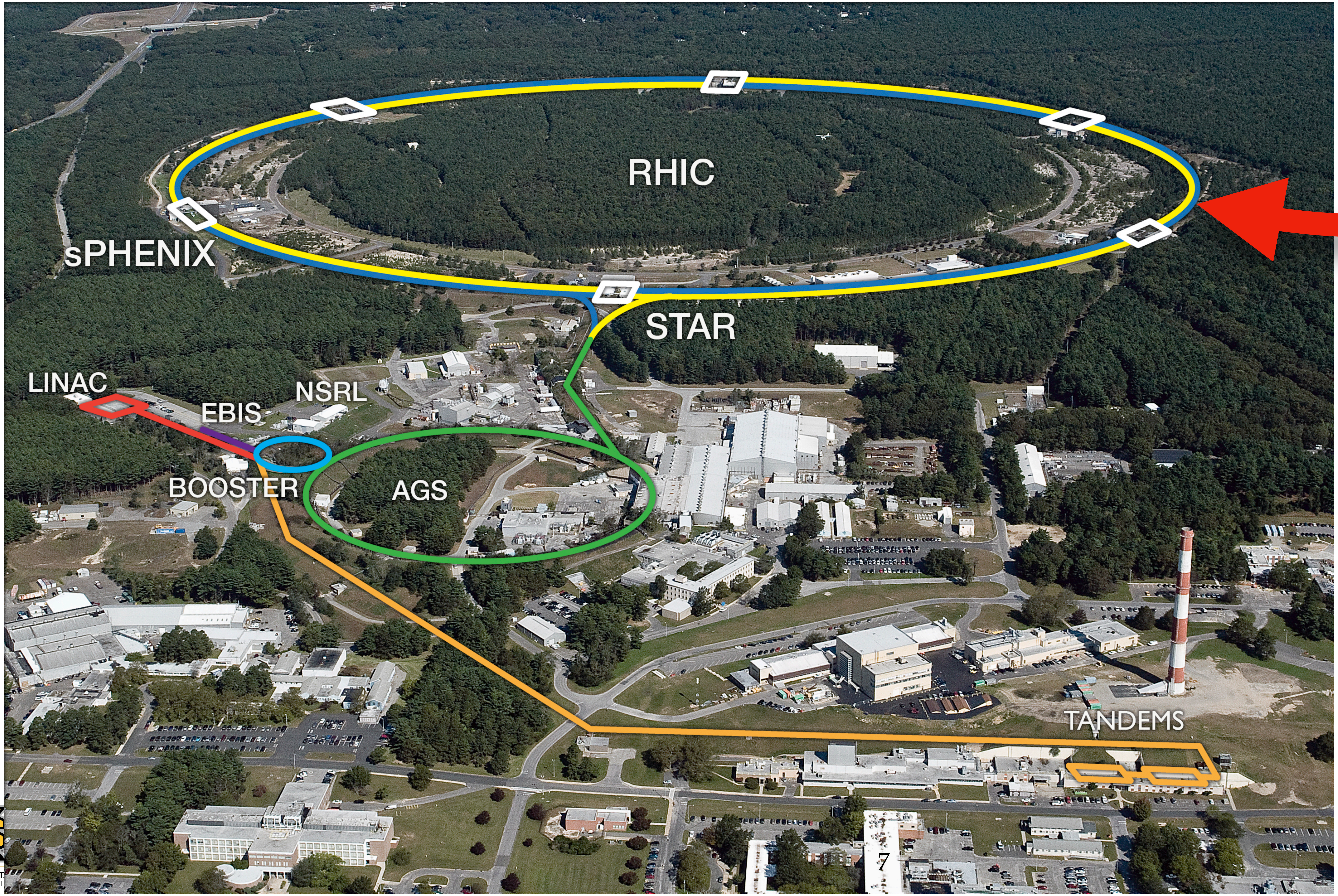
# High Energy Particle Colliders

**Large Hadron Collider (LHC)**
**@ CERN**
**in Geneva, Switzerland**




**Collides:** (primarily)
**Protons to Protons**
**Center-of-mass energy:**
**13,600 GeV = 13.6 TeV**

# High Energy Particle Colliders




**Relativistic Heavy Ion Collider**
@ Brookhaven National Lab
in Upton, NY

**Collides:** Heavy Ions

**+ Upcoming (2030s): Electron-Ion Collider,** will collide electrons and ions

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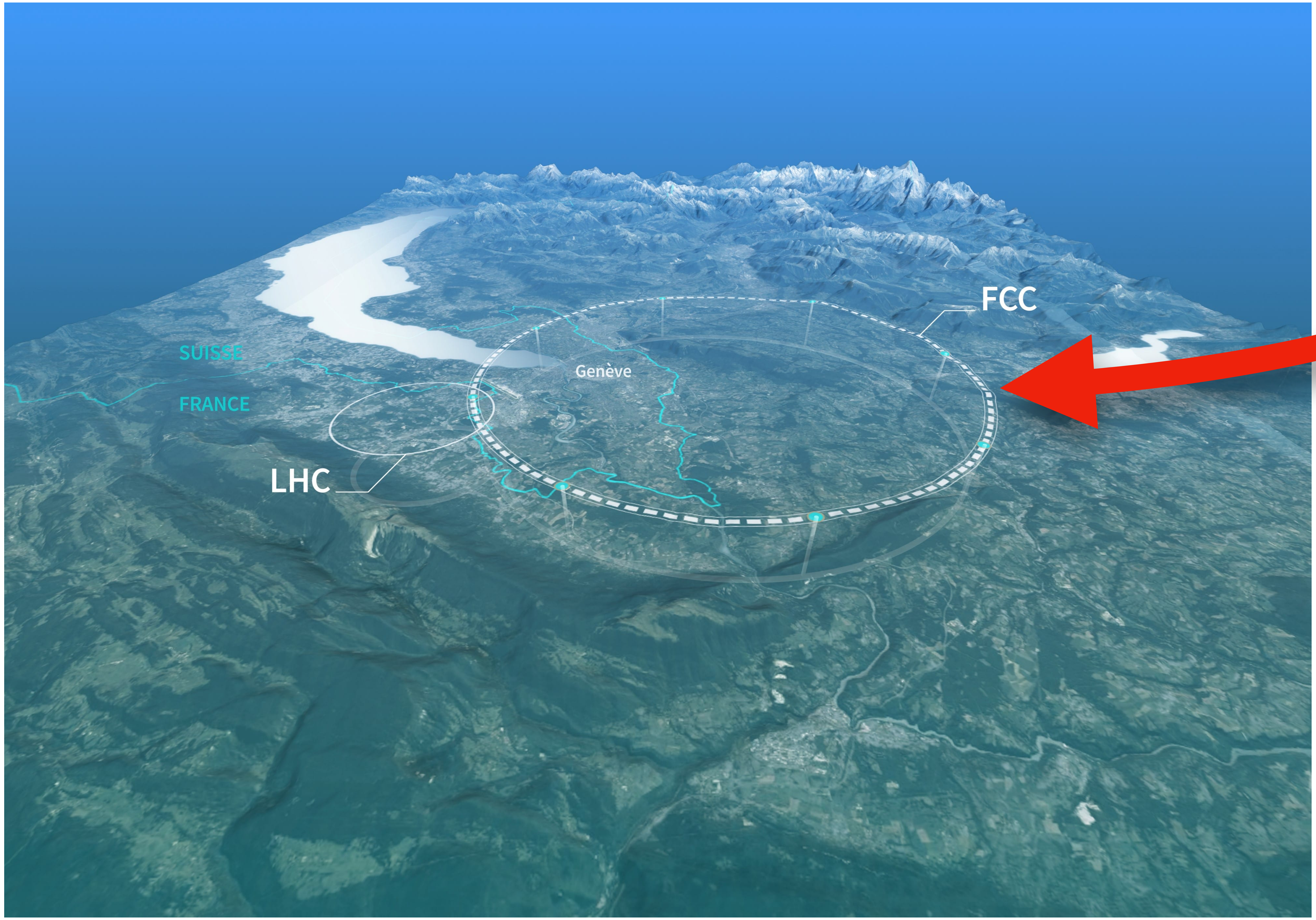
# High Energy Particle Colliders




"Future Circular Collider" @ CERN

Collides: electrons to positrons (2040s)

&

protons to protons (2070s) @ Center-of-mass energy: 100,000 GeV = 100 TeV

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# Happening Now: Particle Collisions at the LHC

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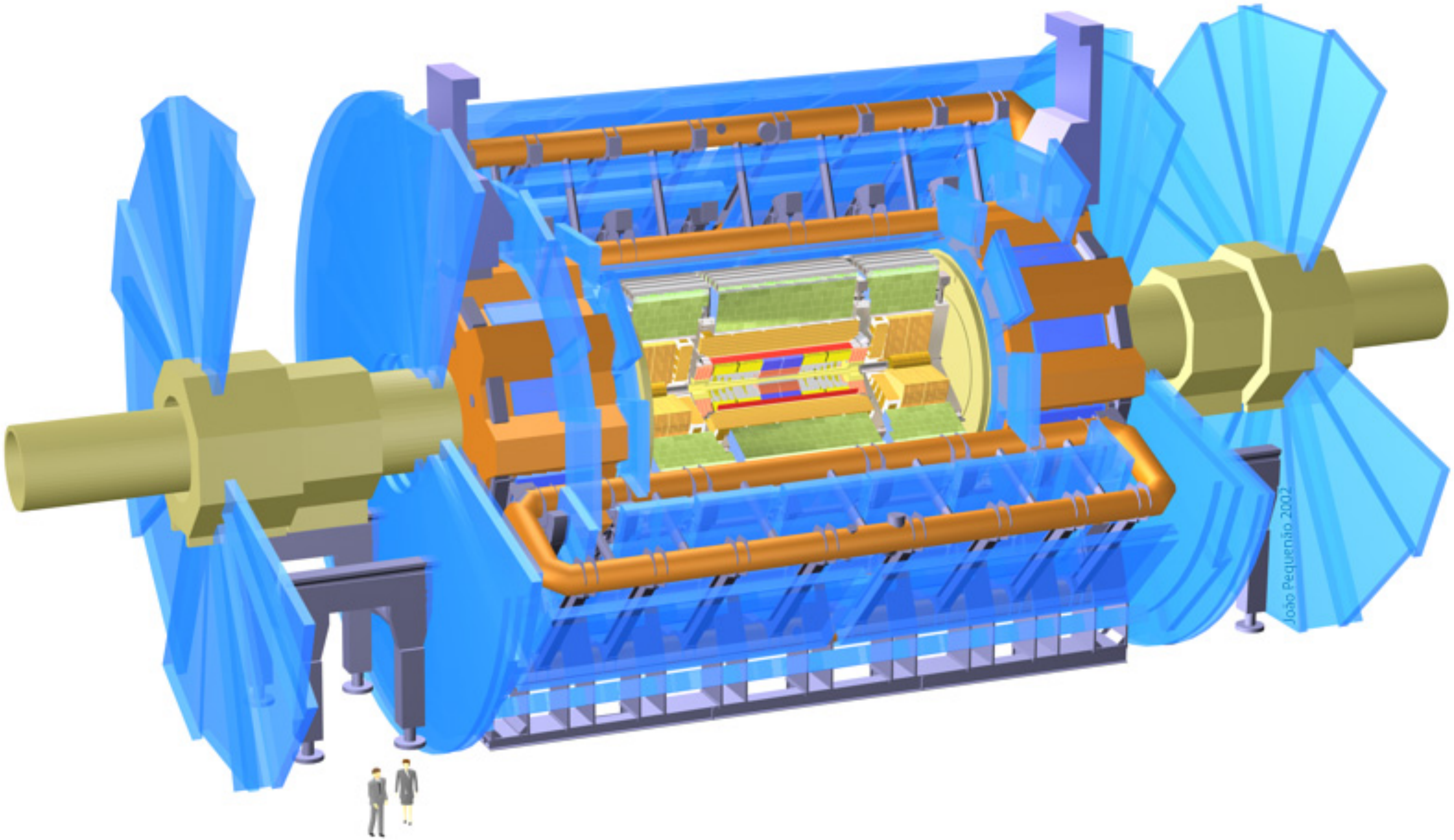



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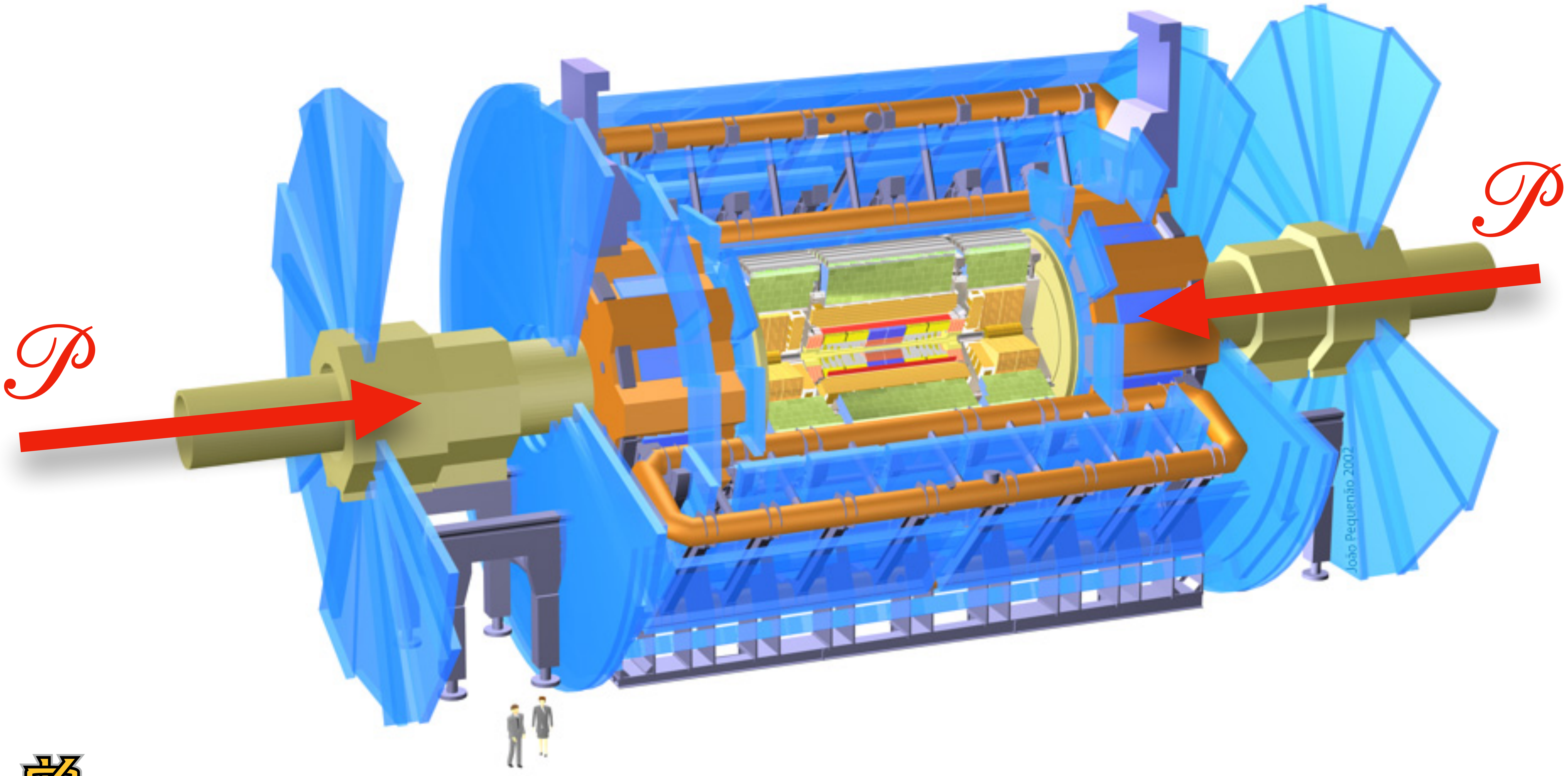

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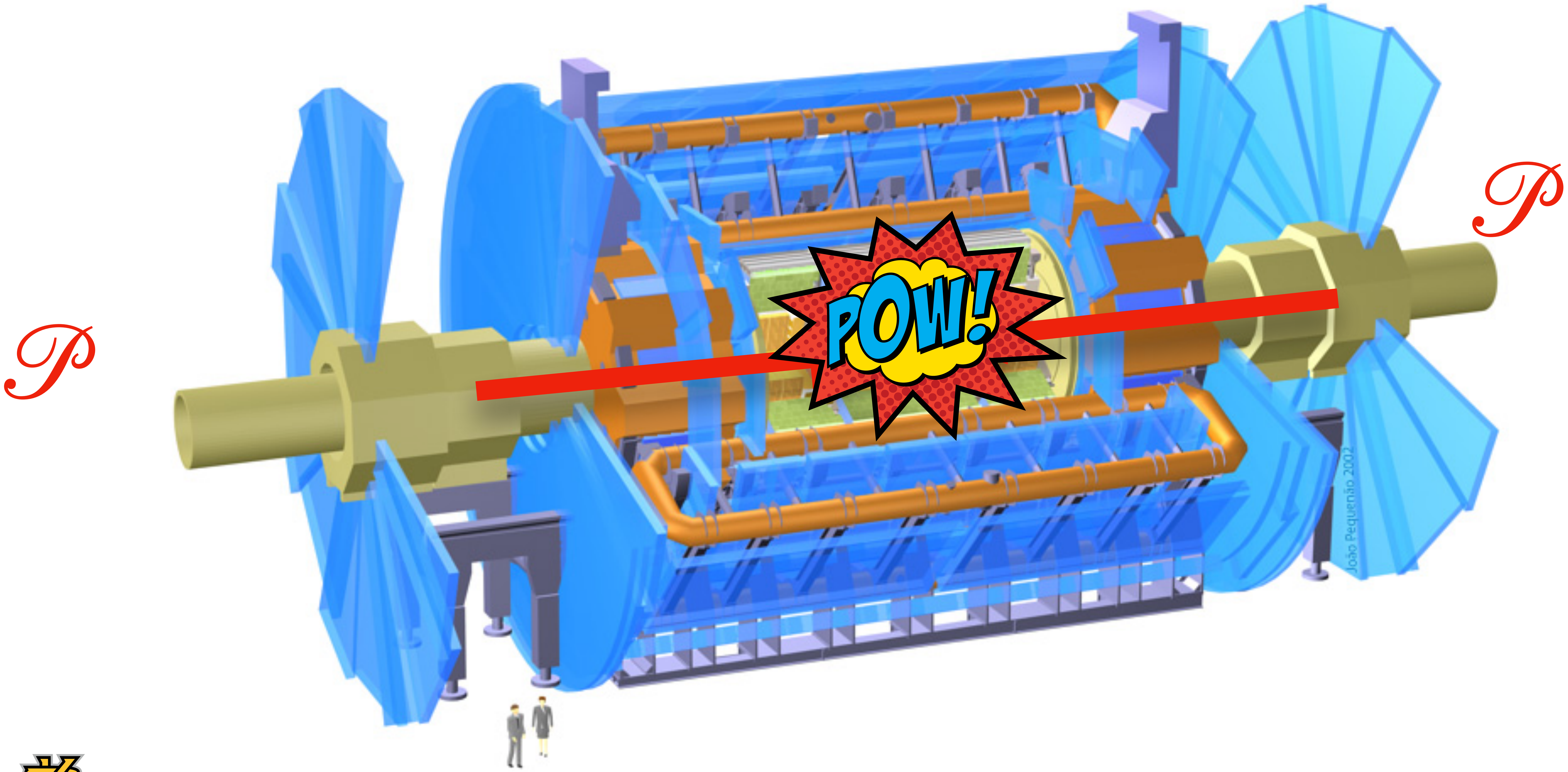
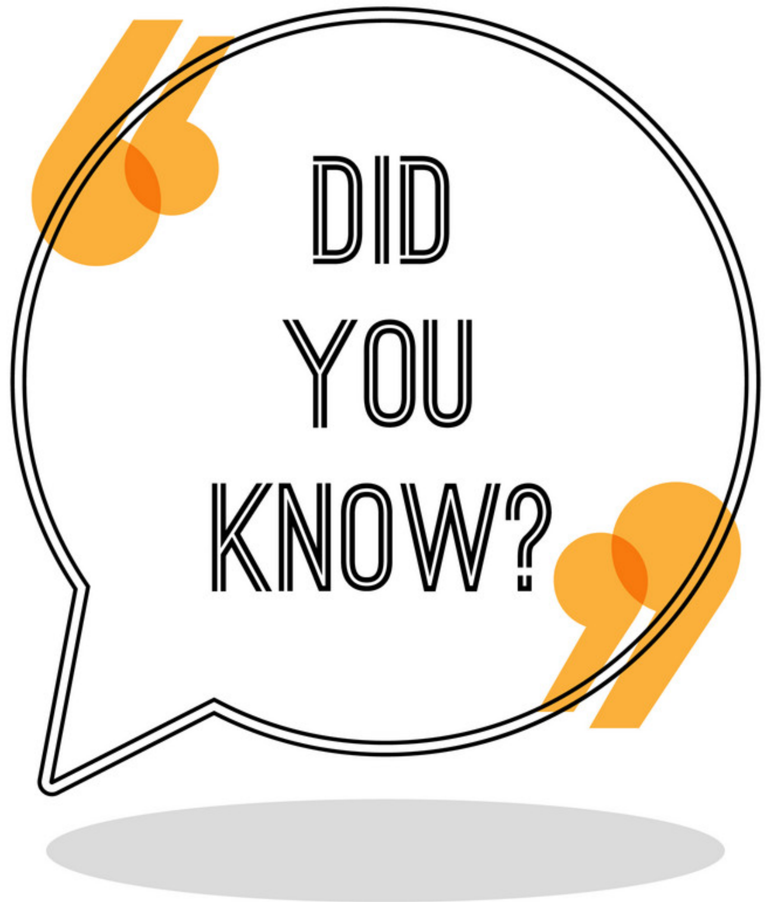
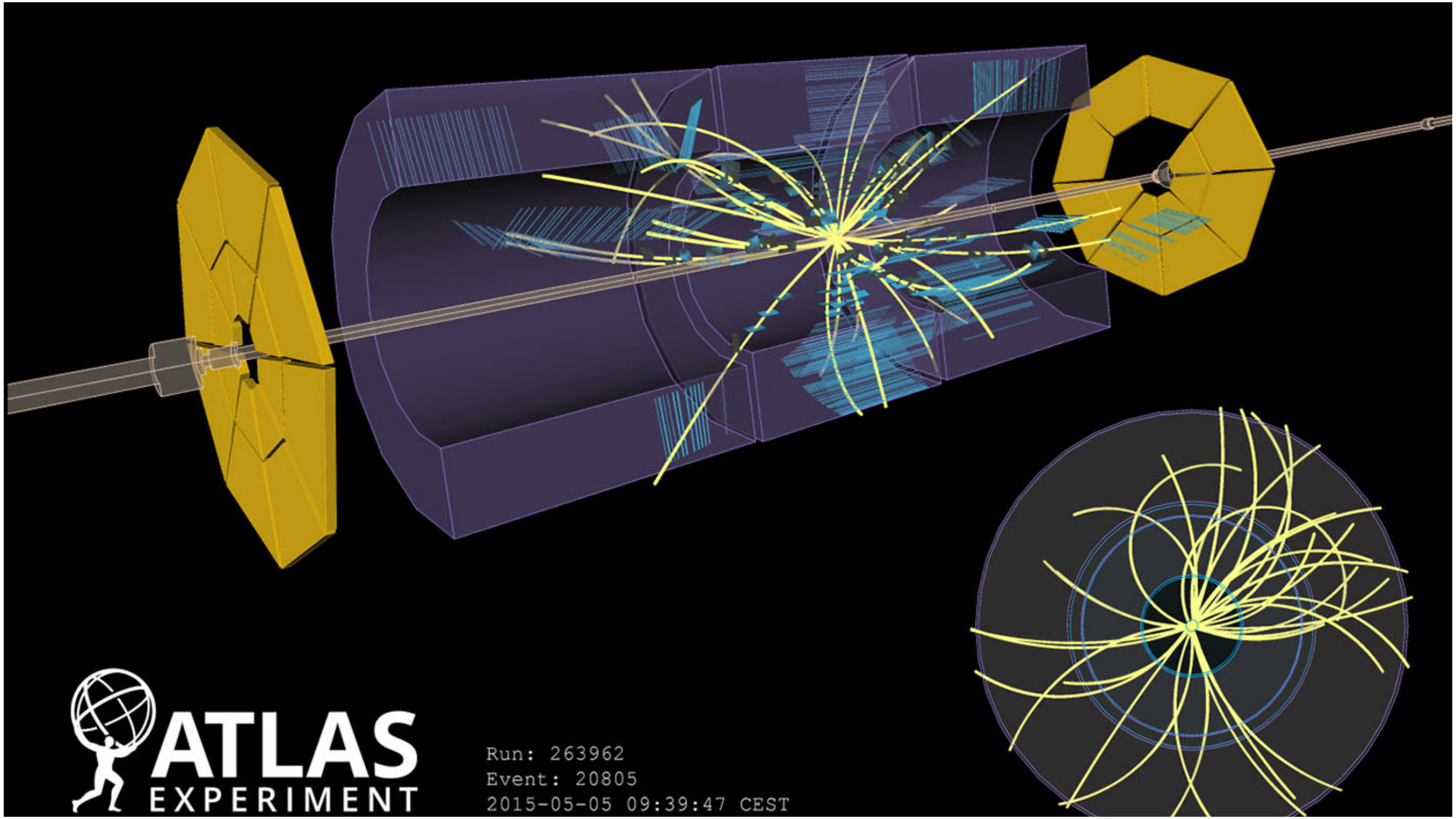


# LHC: Fun Facts




- Circumference of **27 km** (17 miles).
- Lies **100 m** (330 feet) underground.
- Produces **hundreds of millions of particle collisions/ second** (="events").
- **Energy stored** in particle beam = Energy of **1000 kg car @ 3000 km/h** (~1900 mph)!
- The data recorded can fill around **100,000 DVDs each year**!

# This is a real “event”!



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$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi$$
$$+ \Psi_i y_{ij} \Psi_j + \text{h.c.}$$
$$+ |D_\mu \Phi|^2 - V(\Phi)$$

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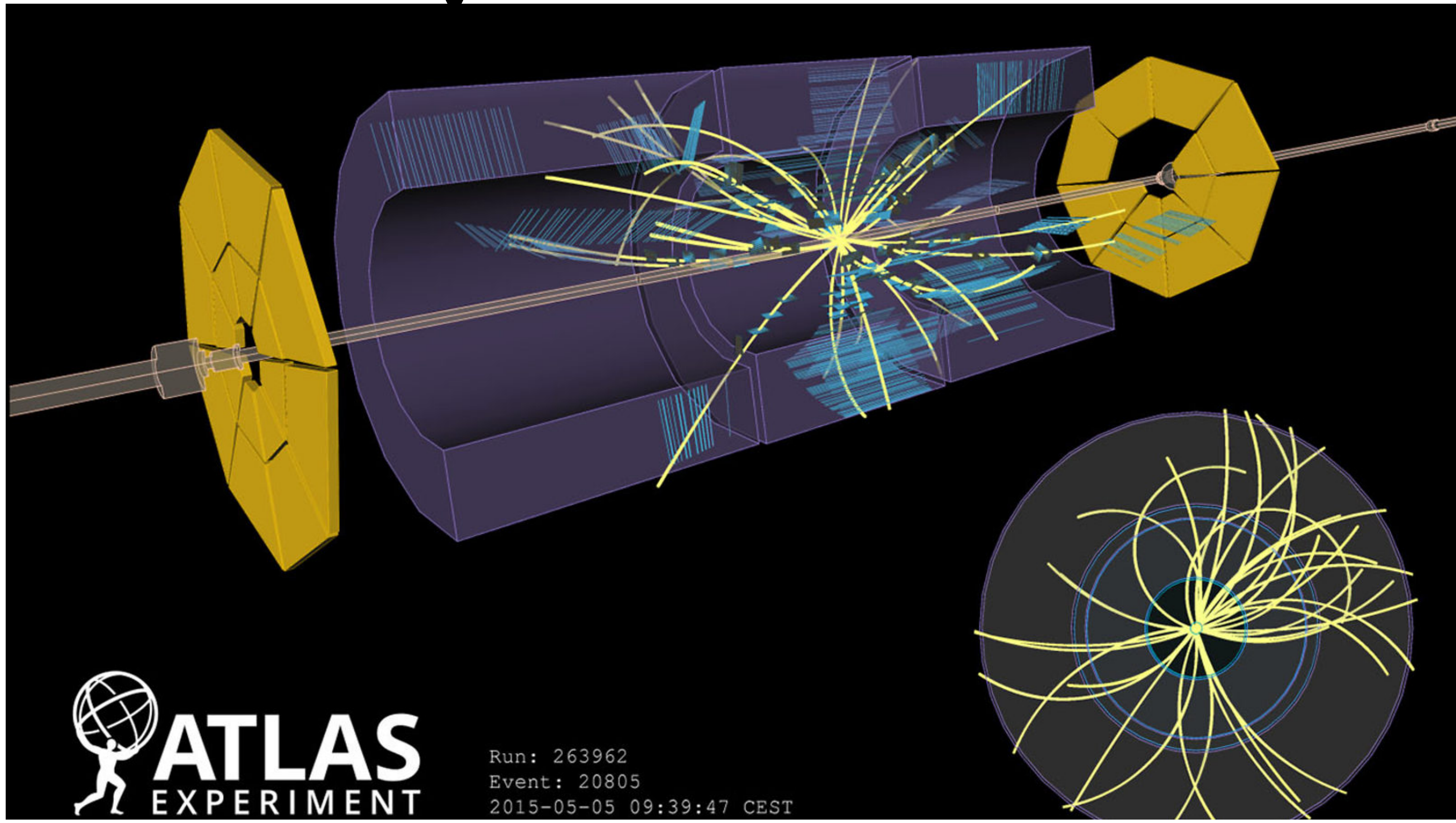
Experiment

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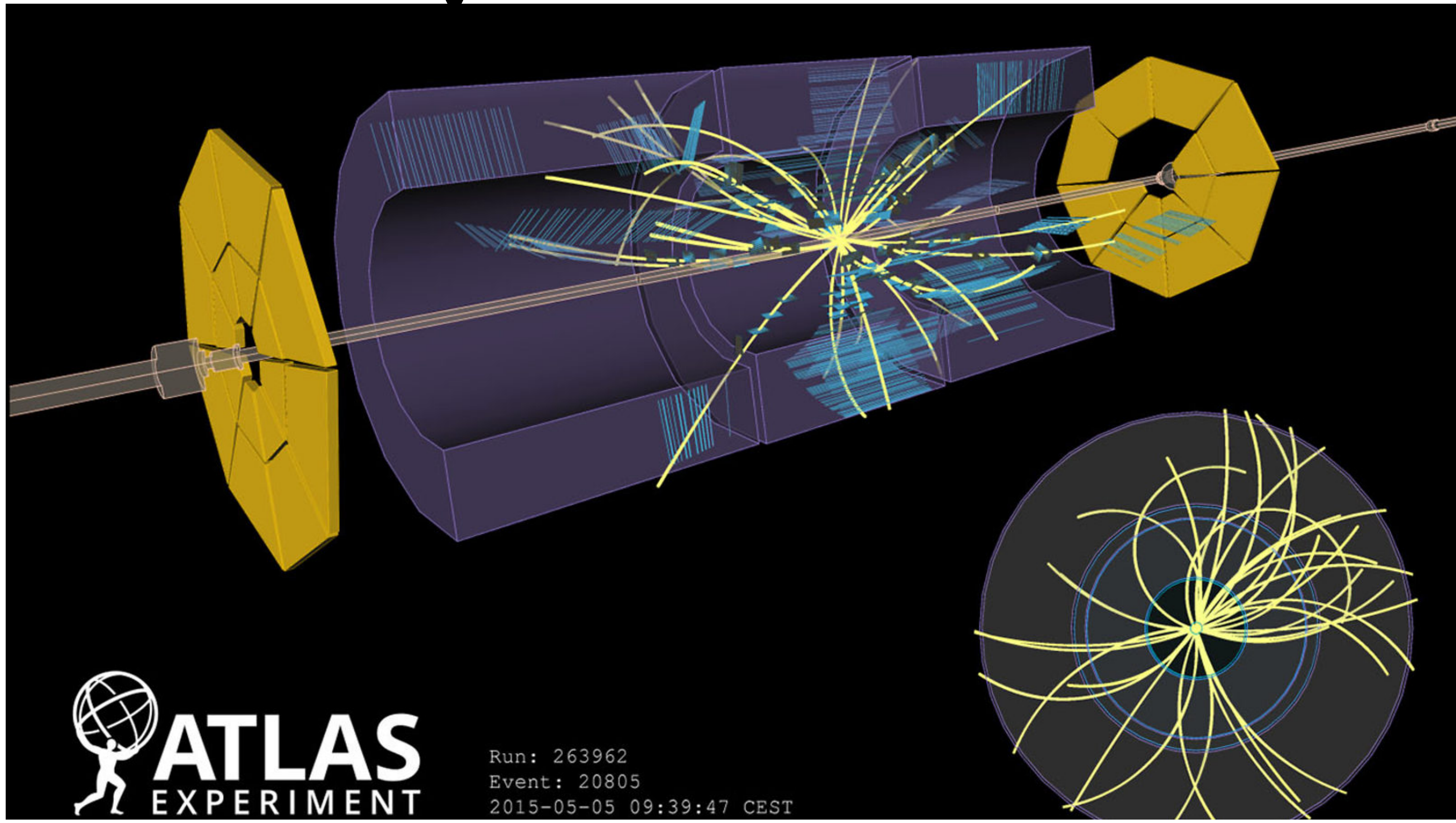


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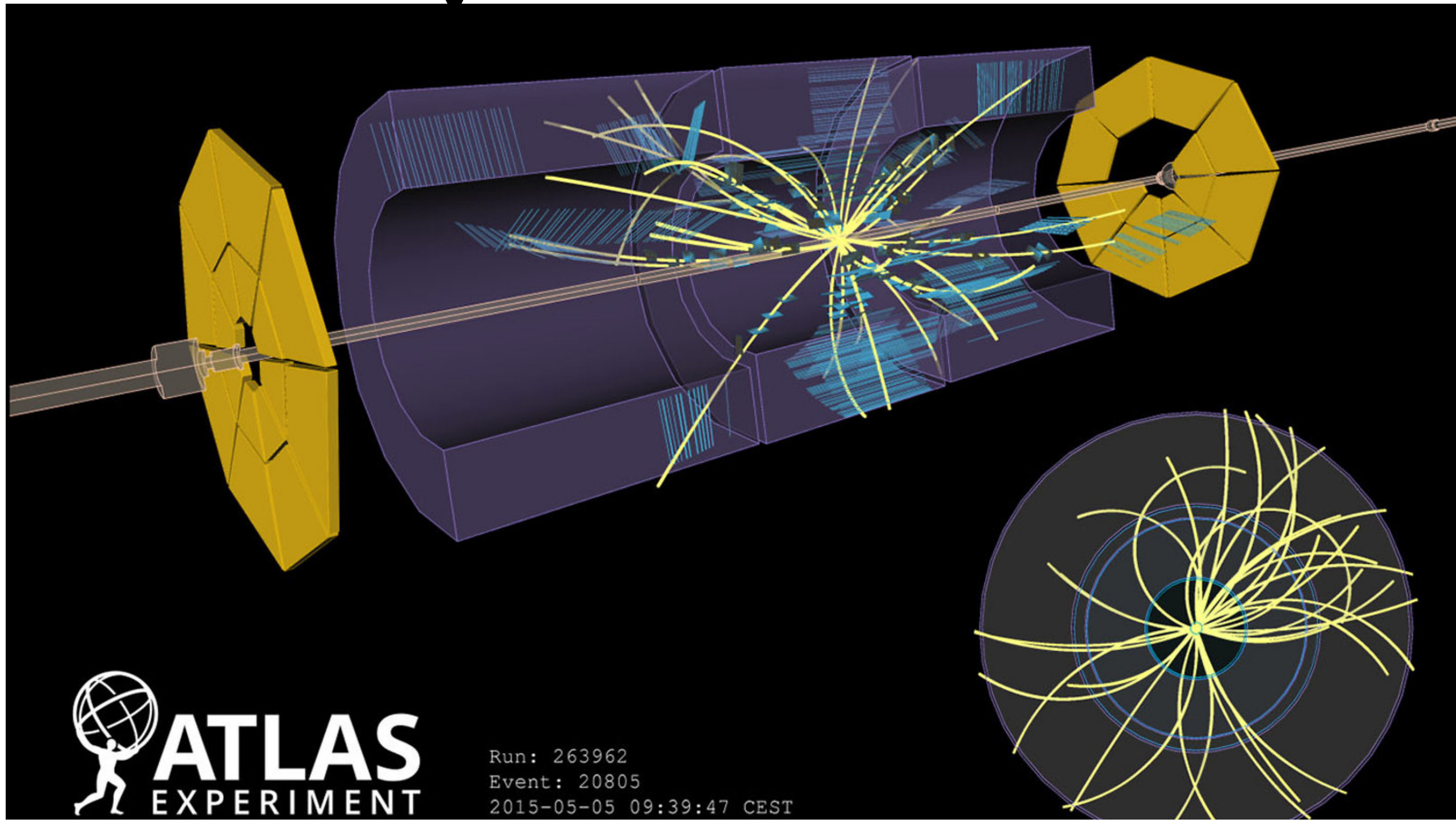
# How do we make sense of it all?

Shut up and Calculate!

???

Experiment

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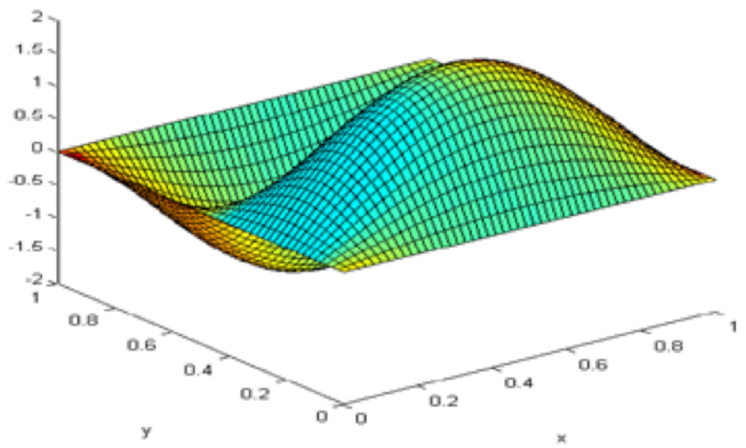
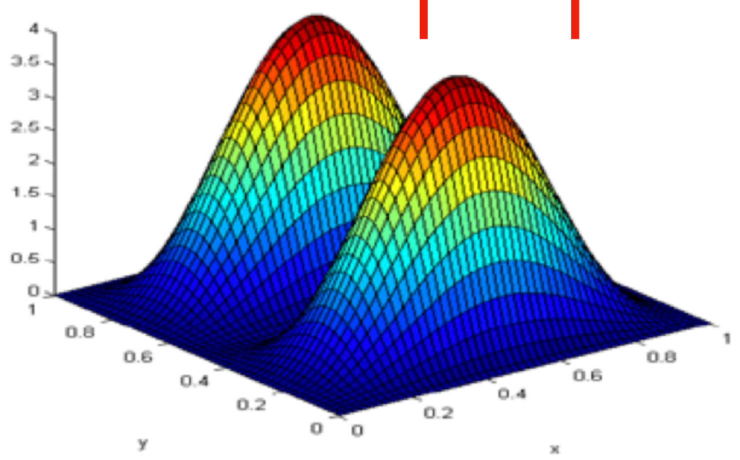


$\left|\Psi\right|^2$



→ Calculate $\Psi$,

⇒ Probability to find particle somewhere $\propto \left|\Psi\right|^2$

[$\Psi$ is called the "wave function"]

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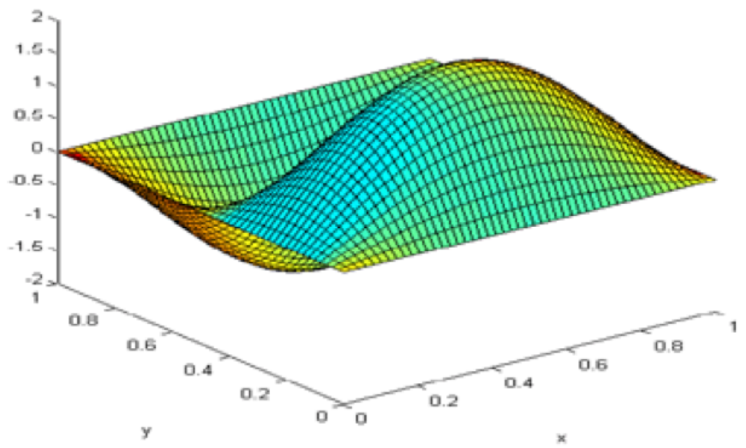

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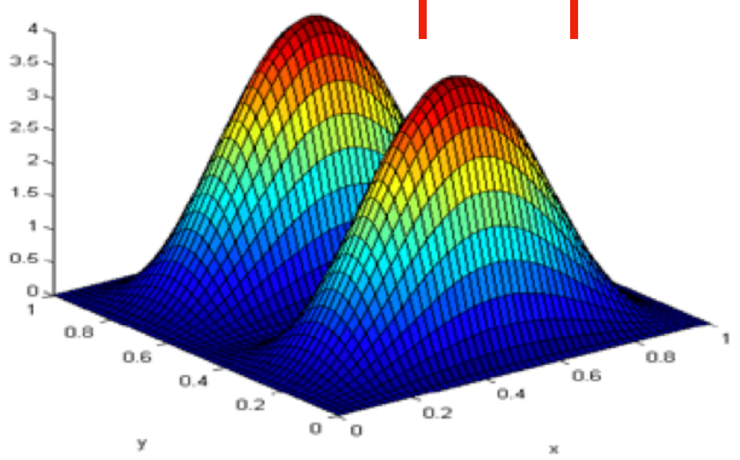

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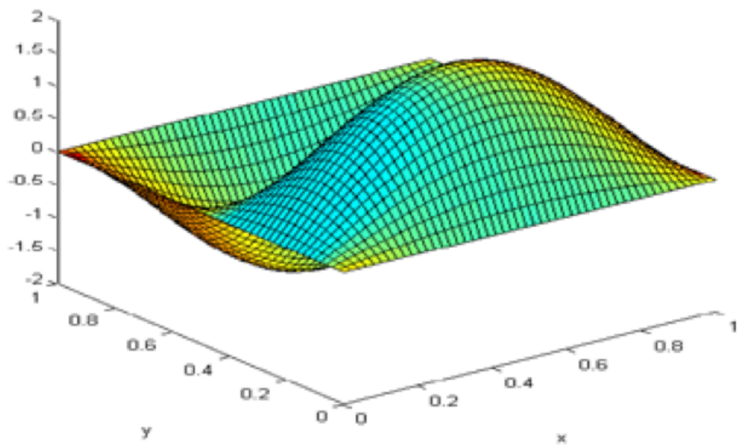
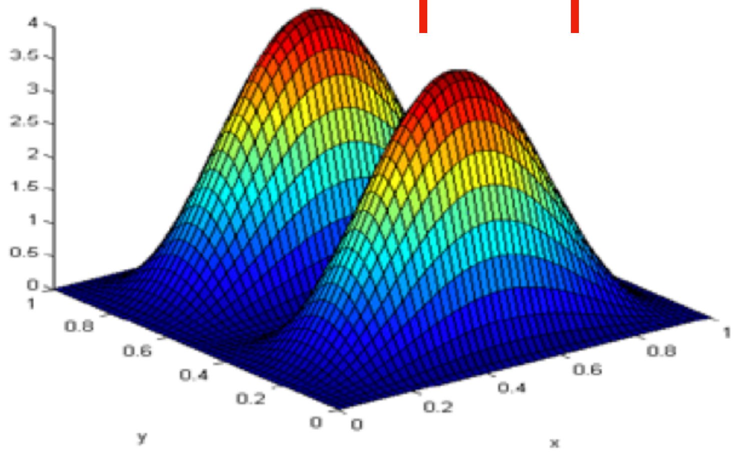
$\Psi$ 

$|\Psi|^2$ 

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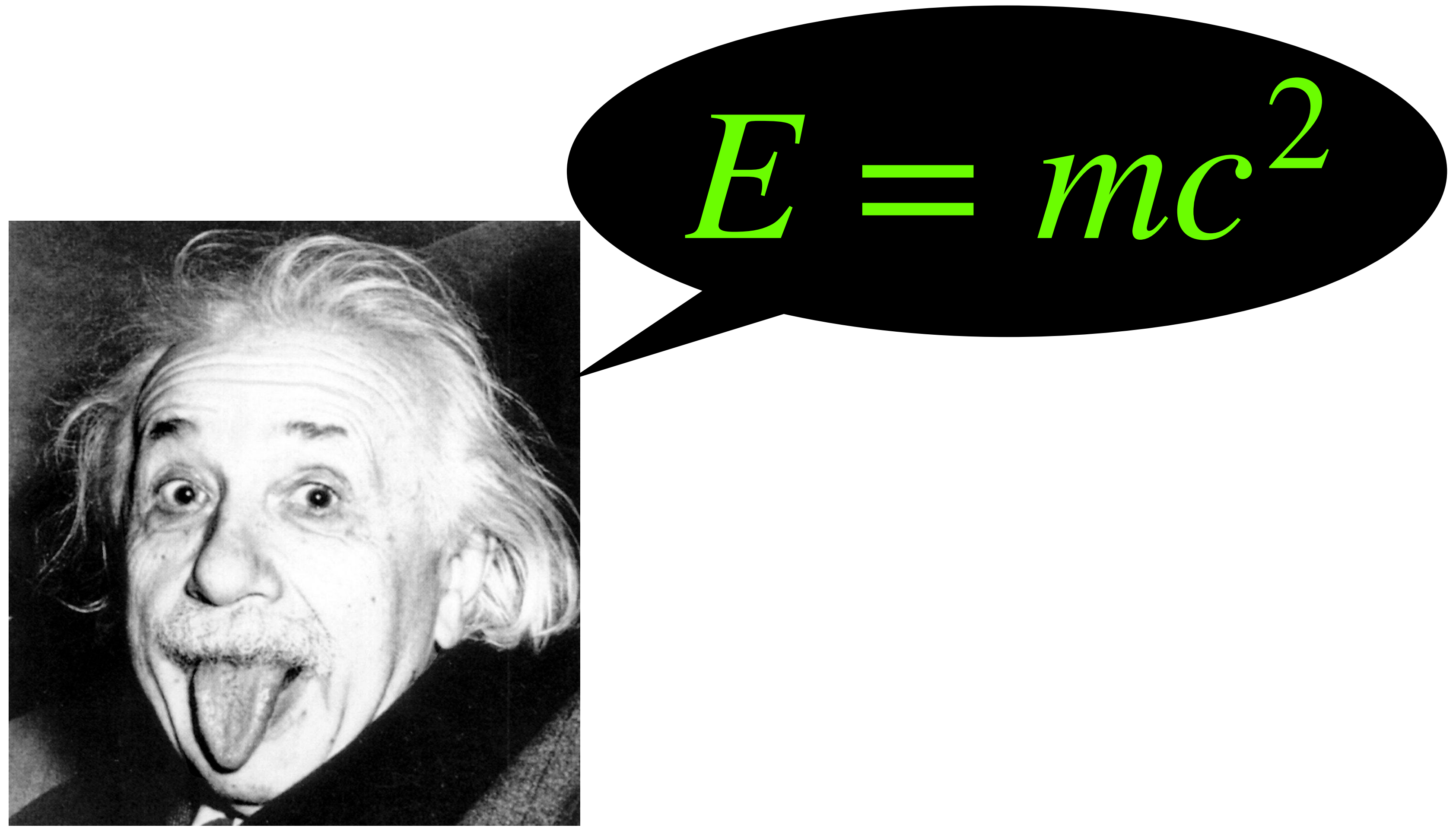

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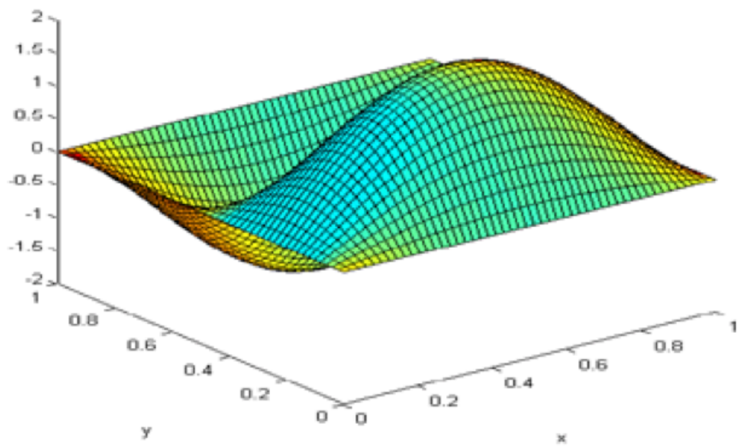

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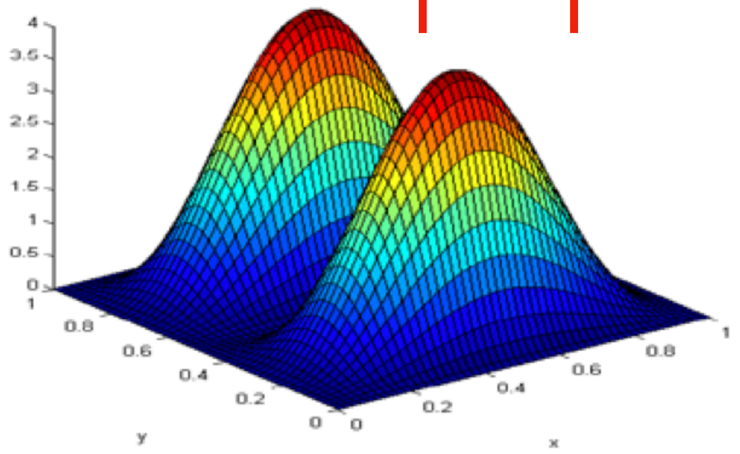

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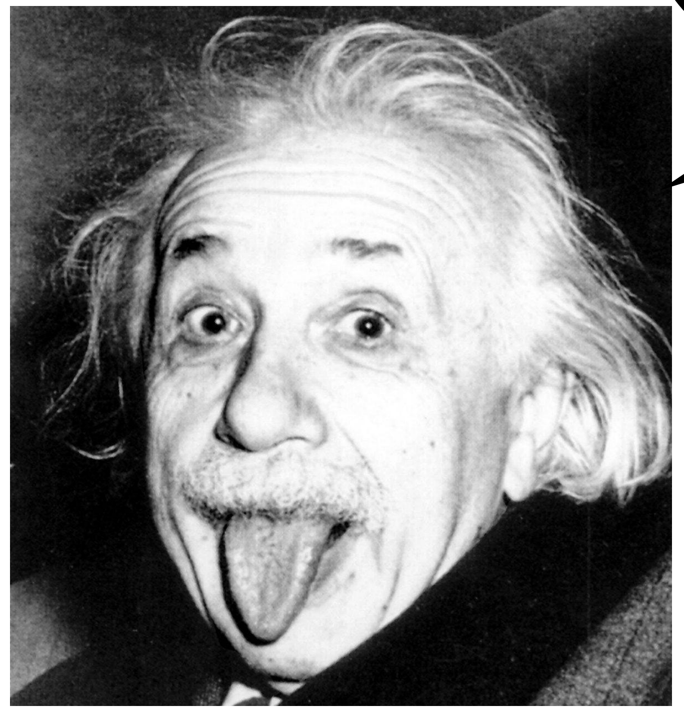


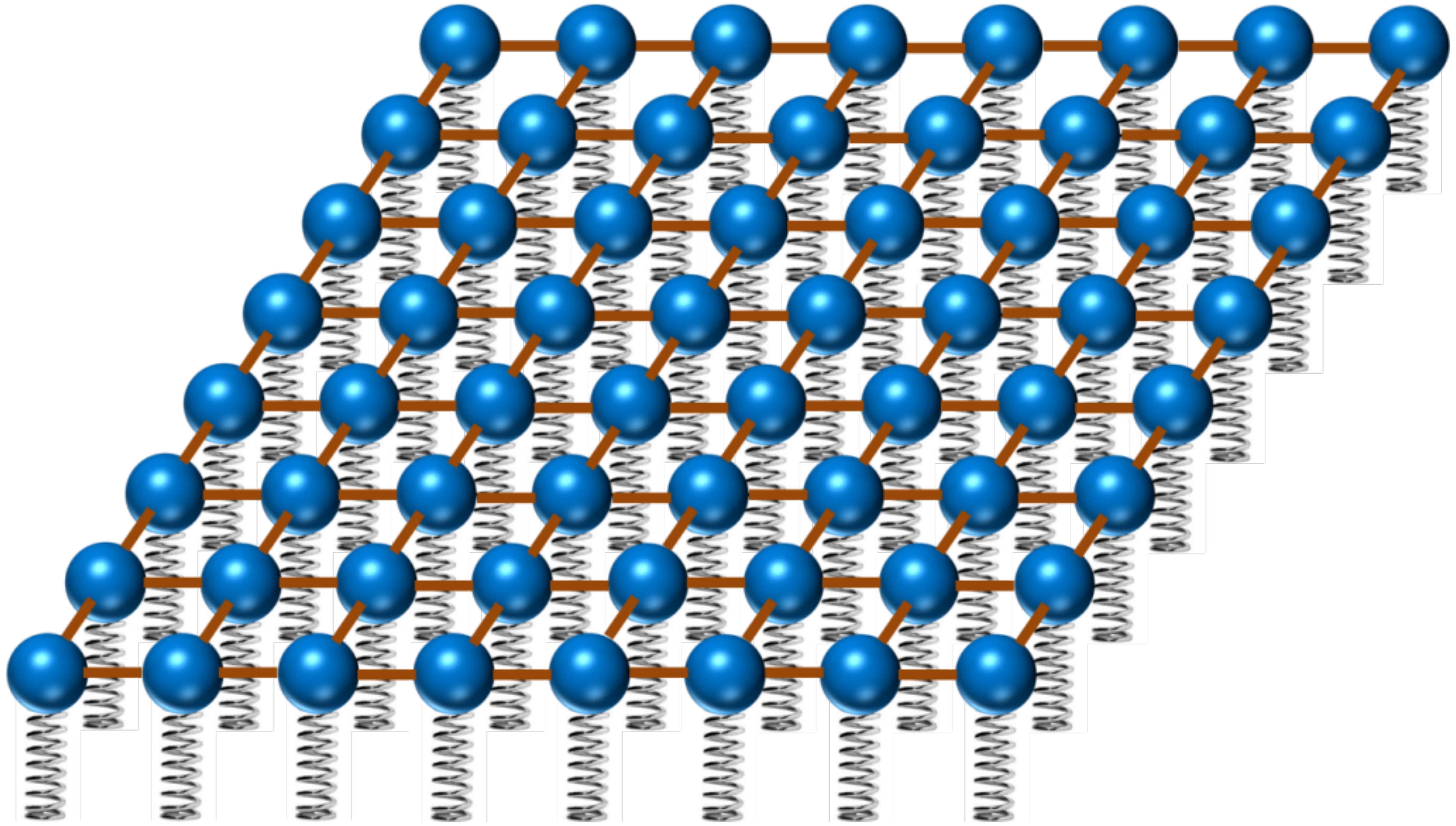
$$E = mc^2$$

→ Mass and Energy are equivalent!

⇒ You can exchange one for the other!

⇒ Particle creation from Energy!

Quantum Mechanics + Special Relativity ≈ **Quantum Field Theory**



# From Theory to Experiment and Back Again

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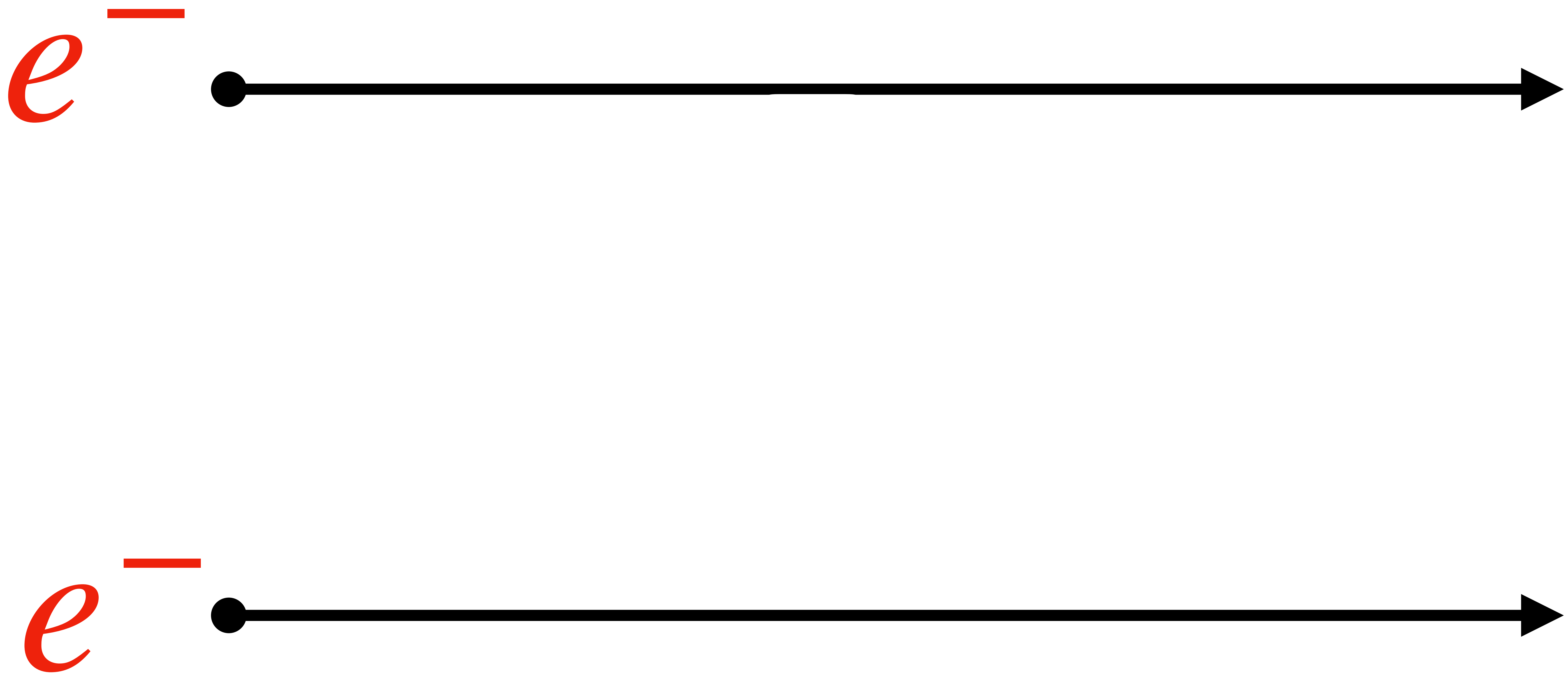

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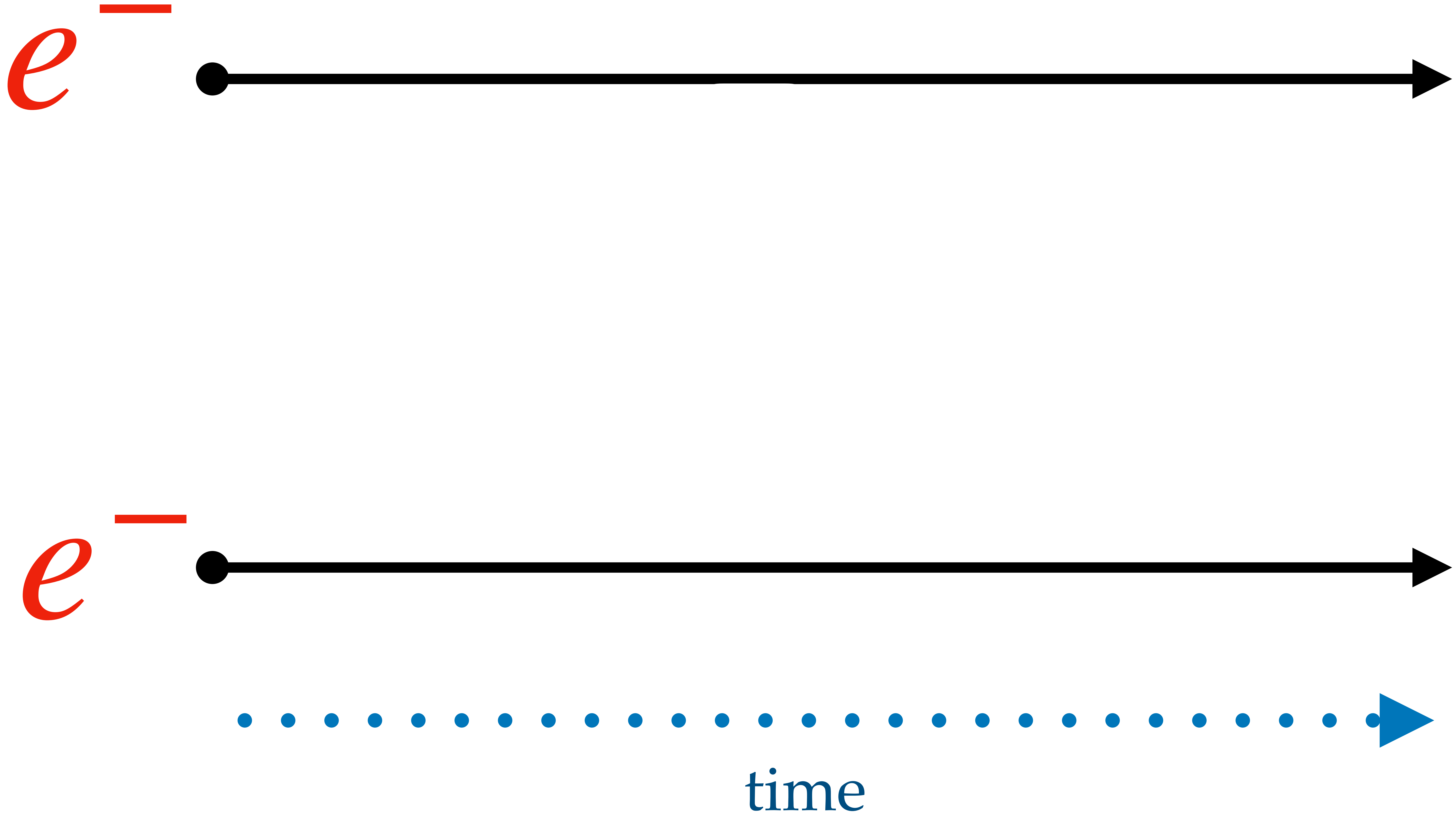

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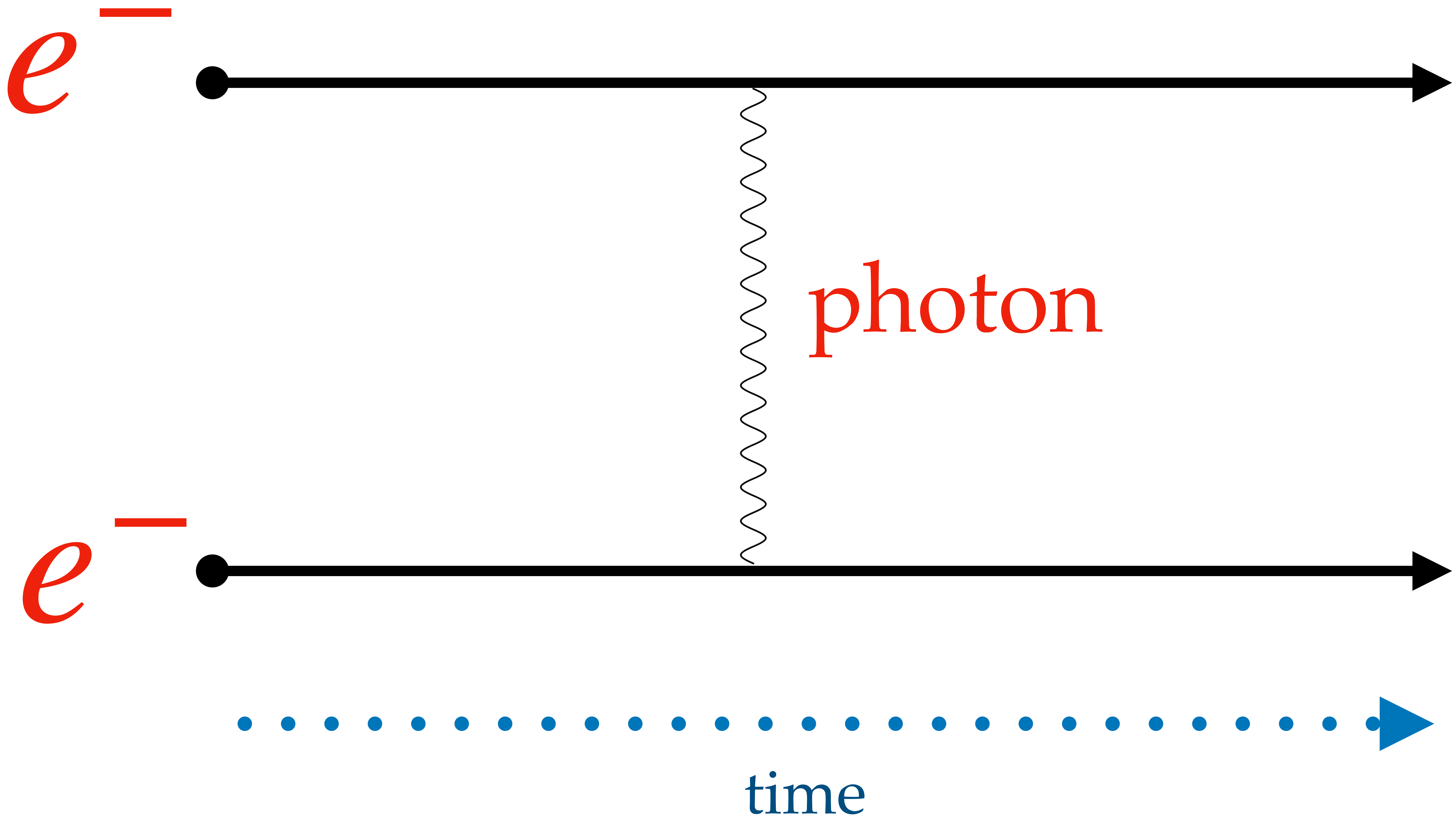




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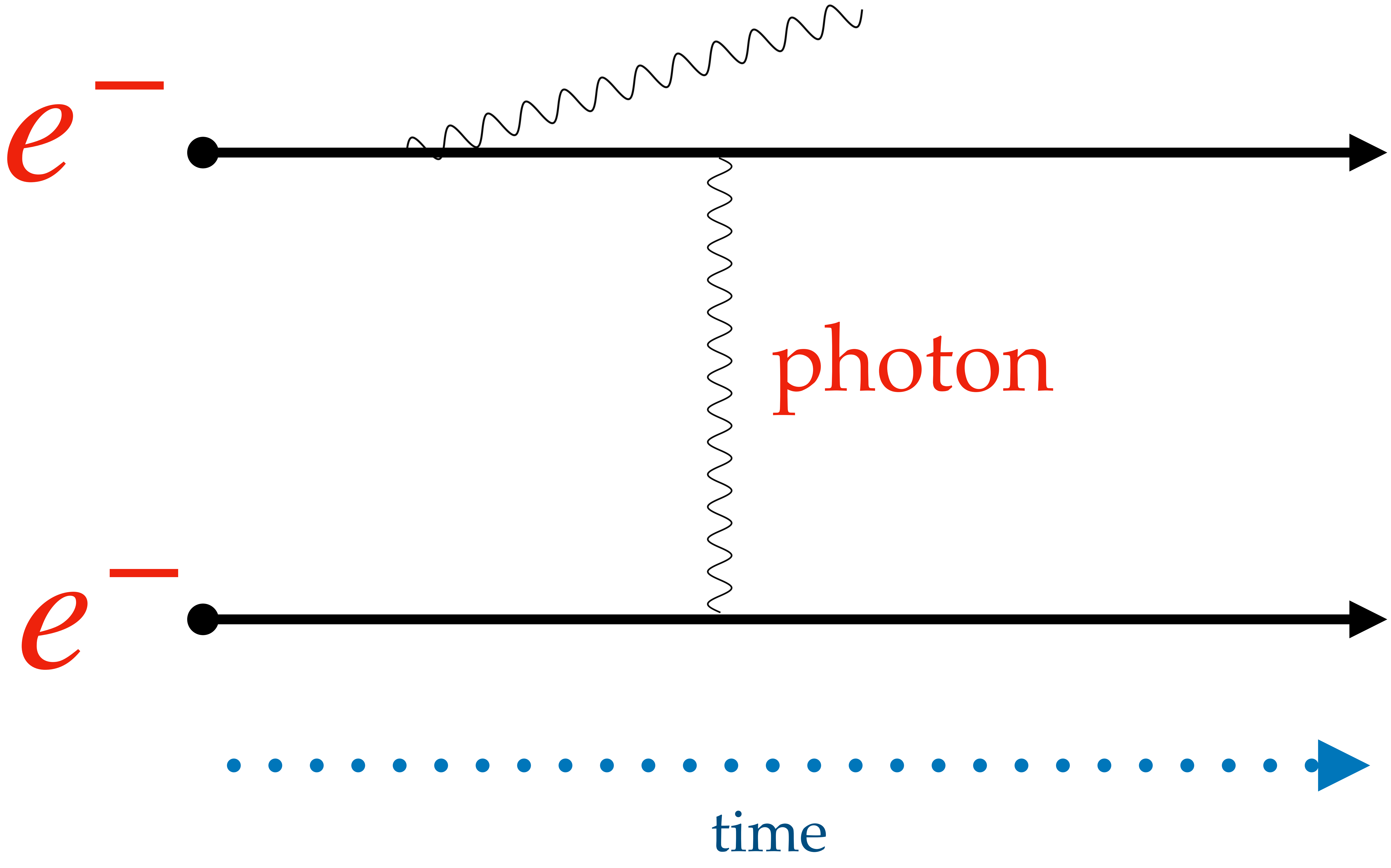




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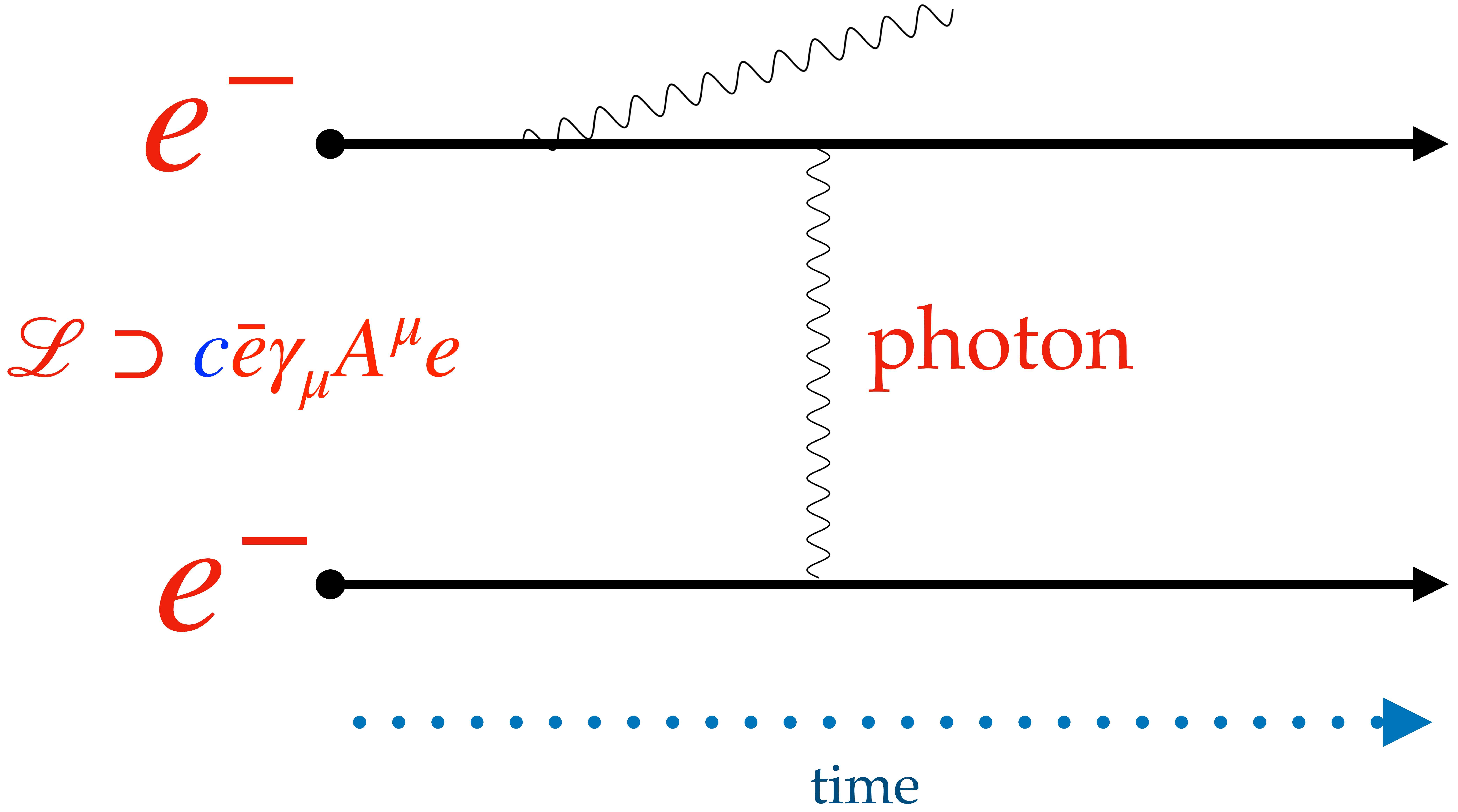




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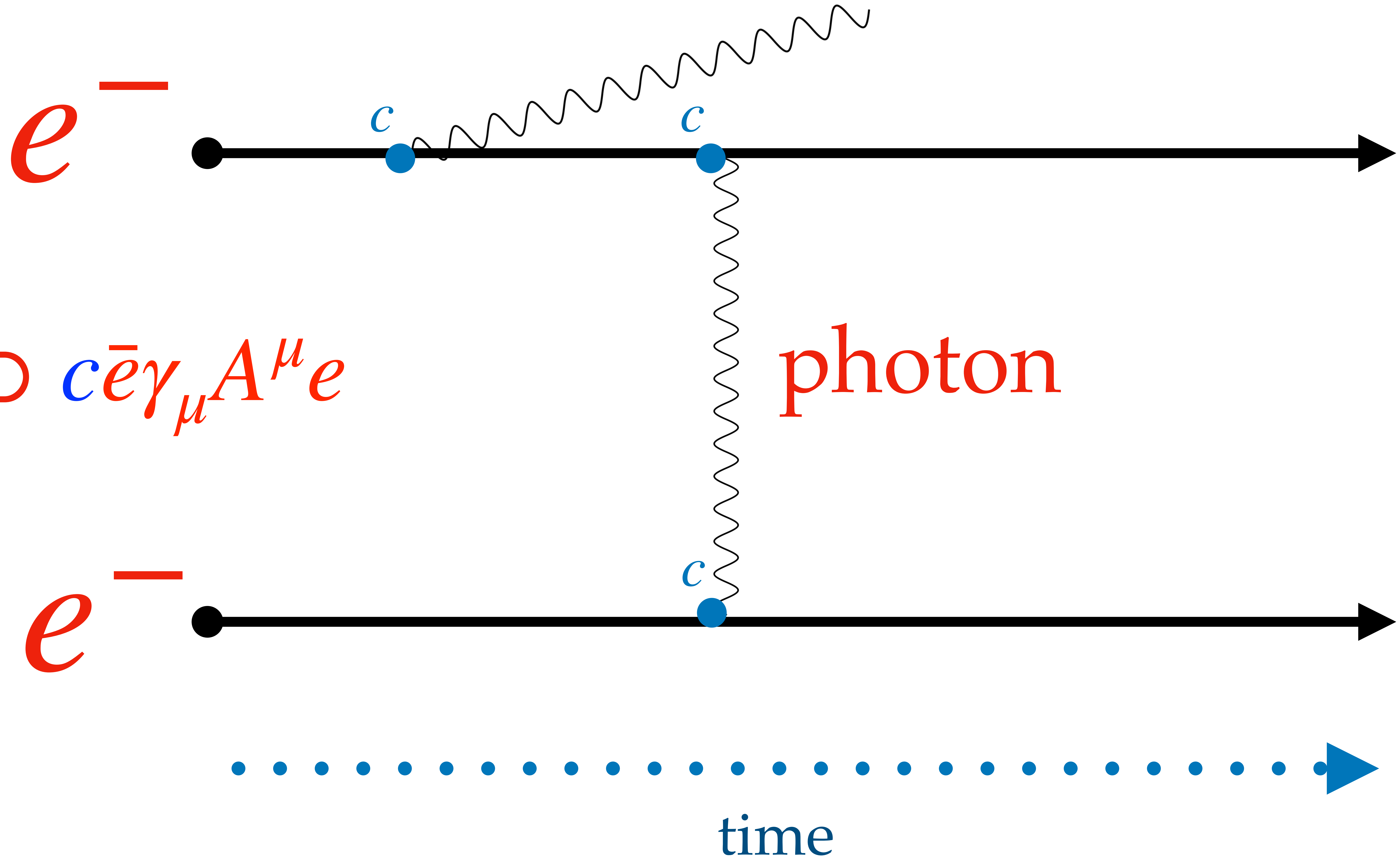


$$\mathscr{L} \supset c\bar{e}\gamma_\mu A^\mu e$$



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# From Theory to Experiment and Back Again

time

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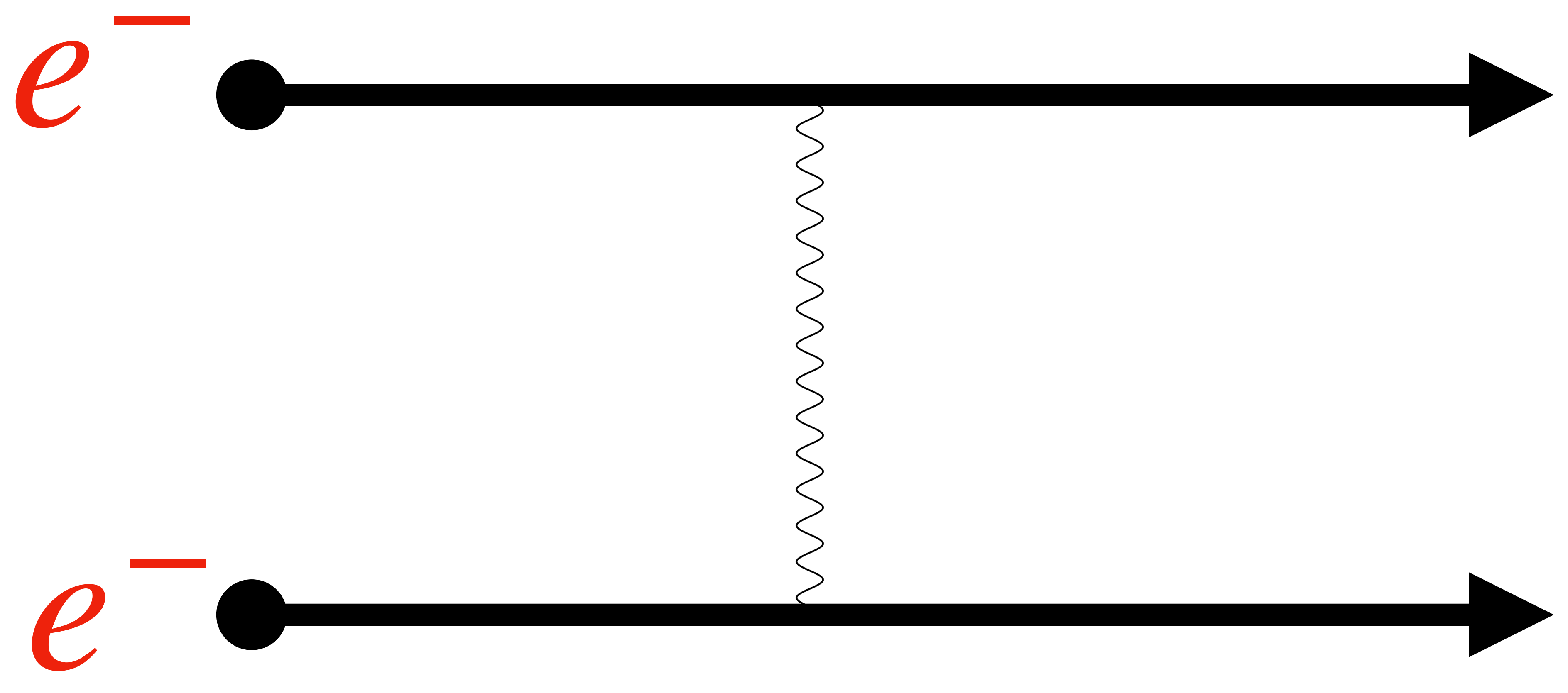


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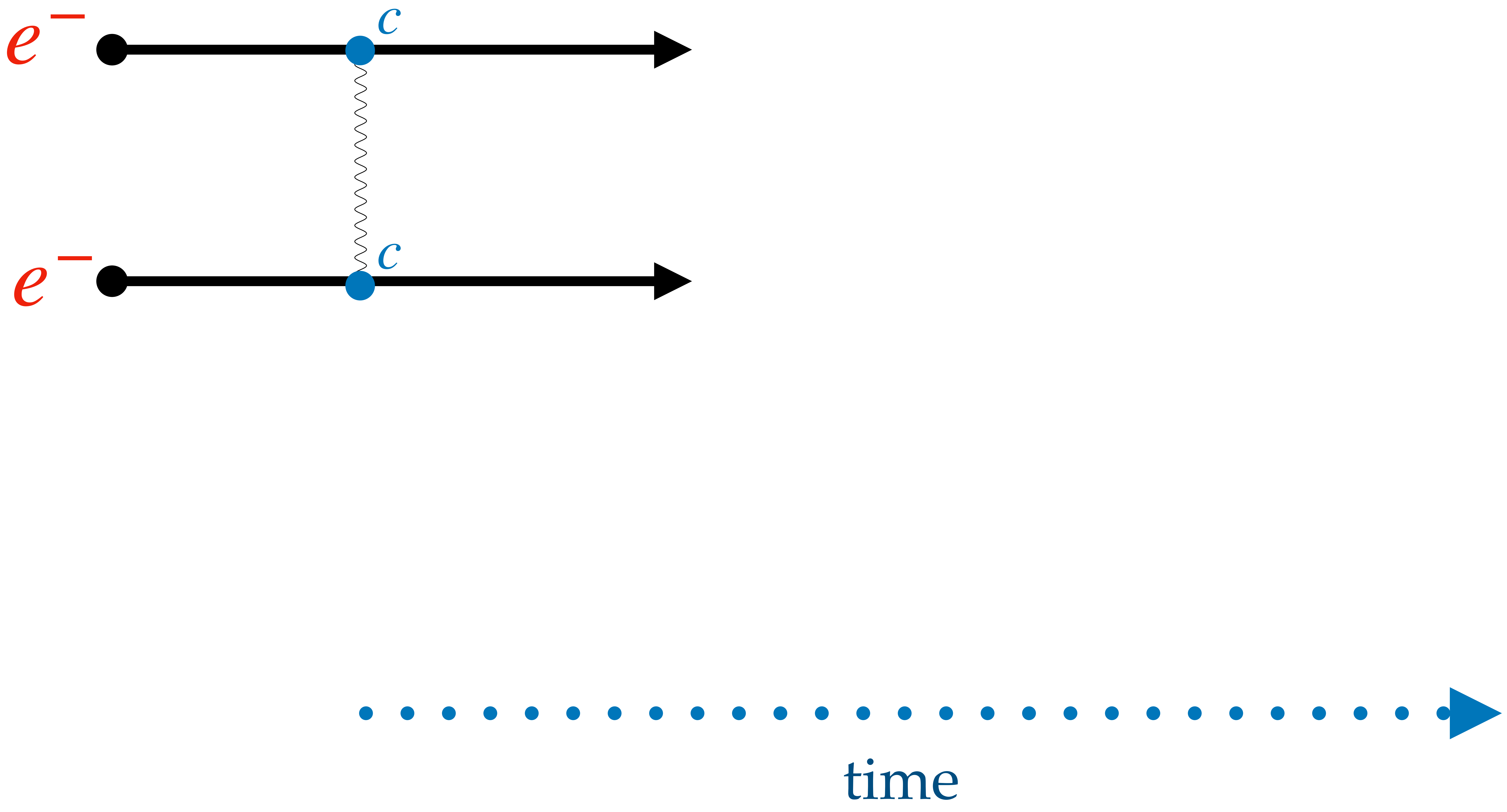

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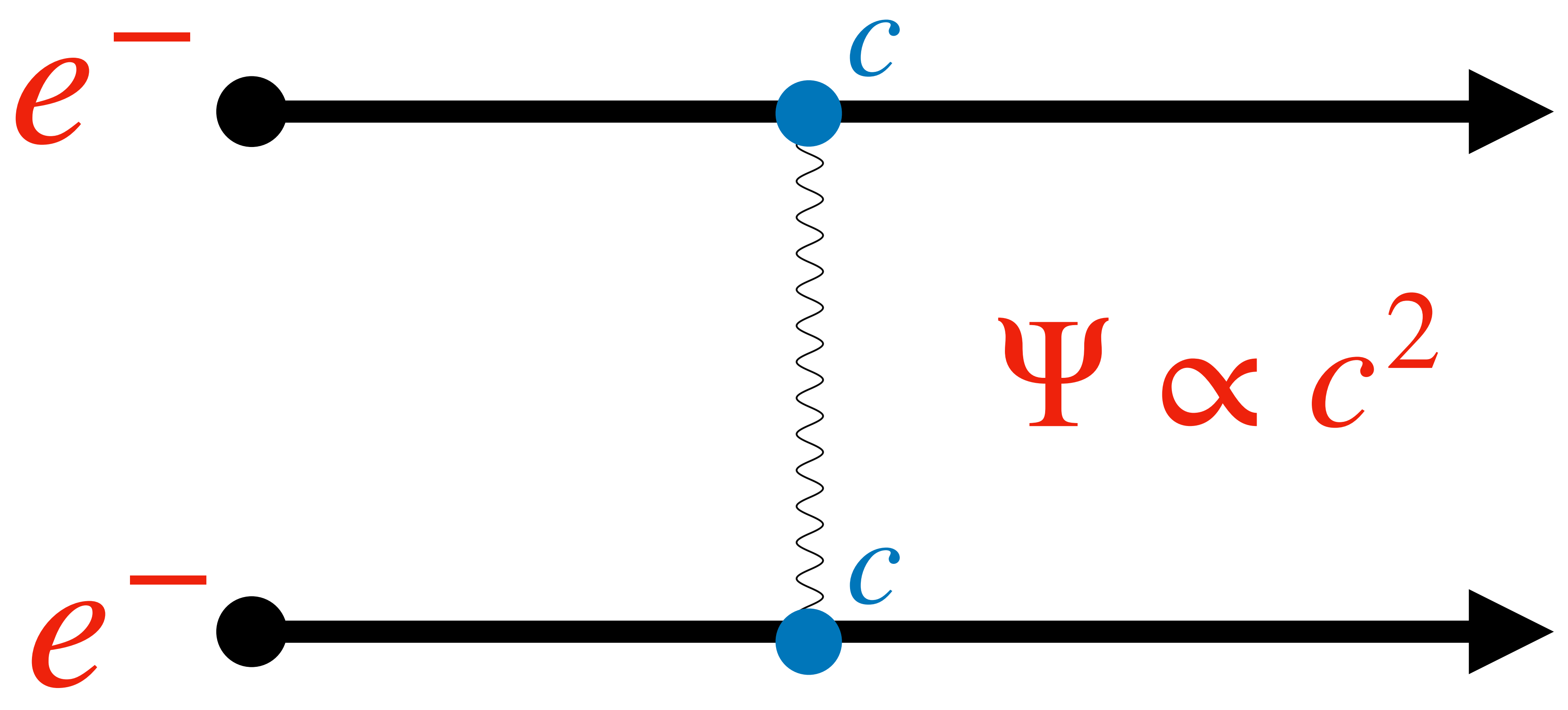


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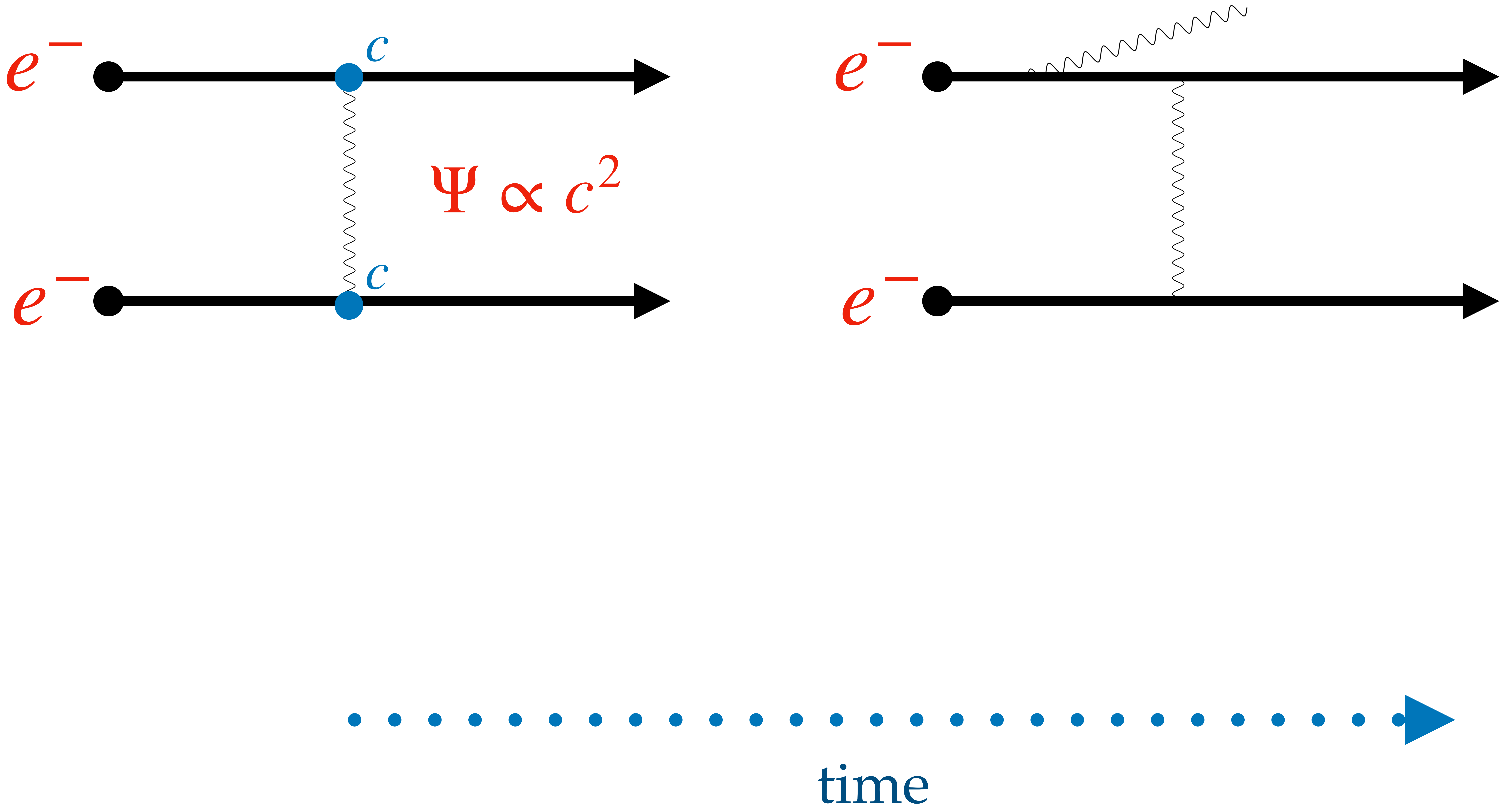

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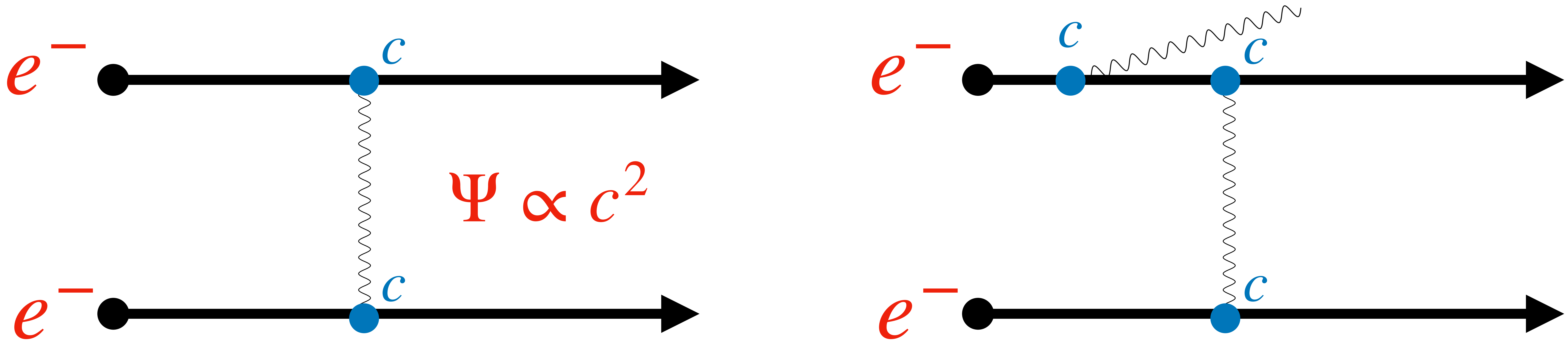


$$\Psi \propto c^2$$

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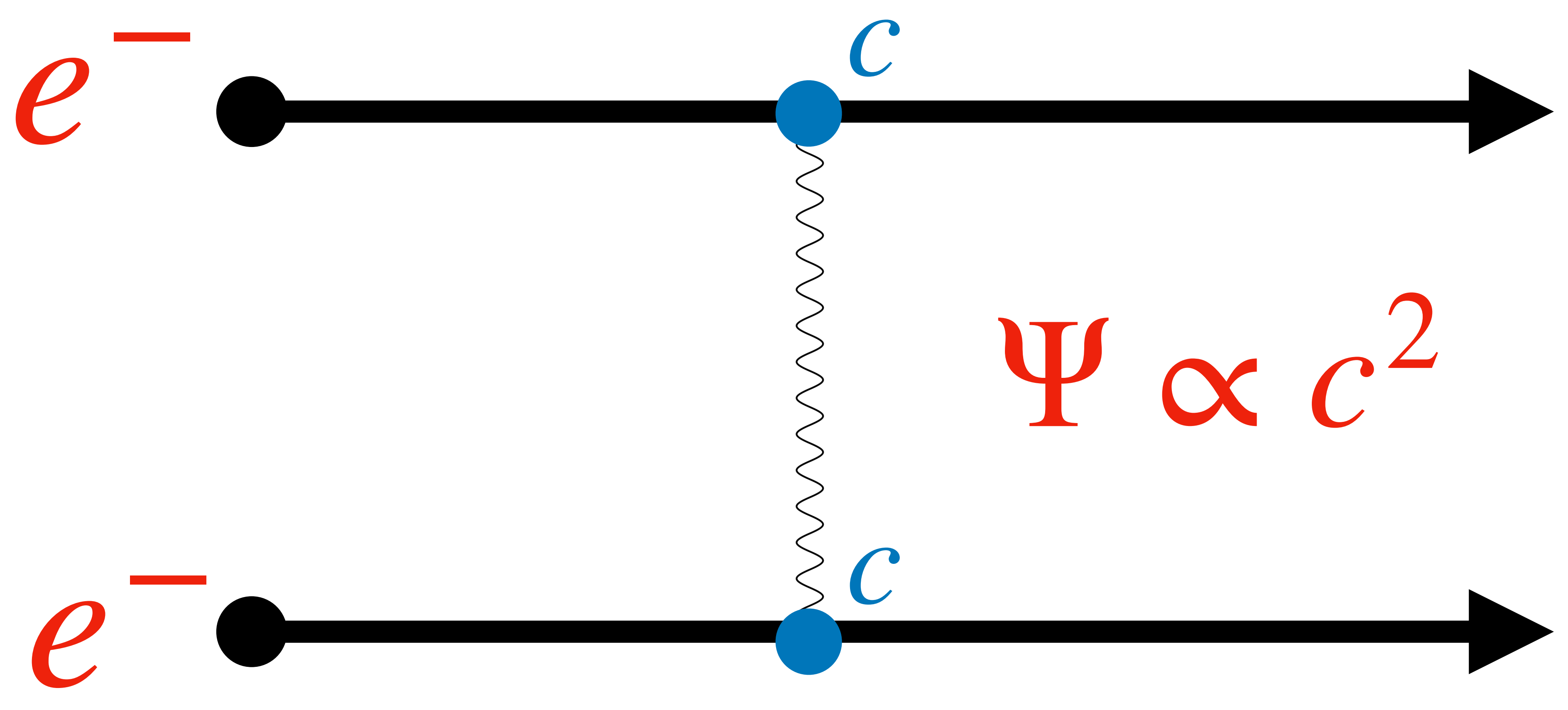


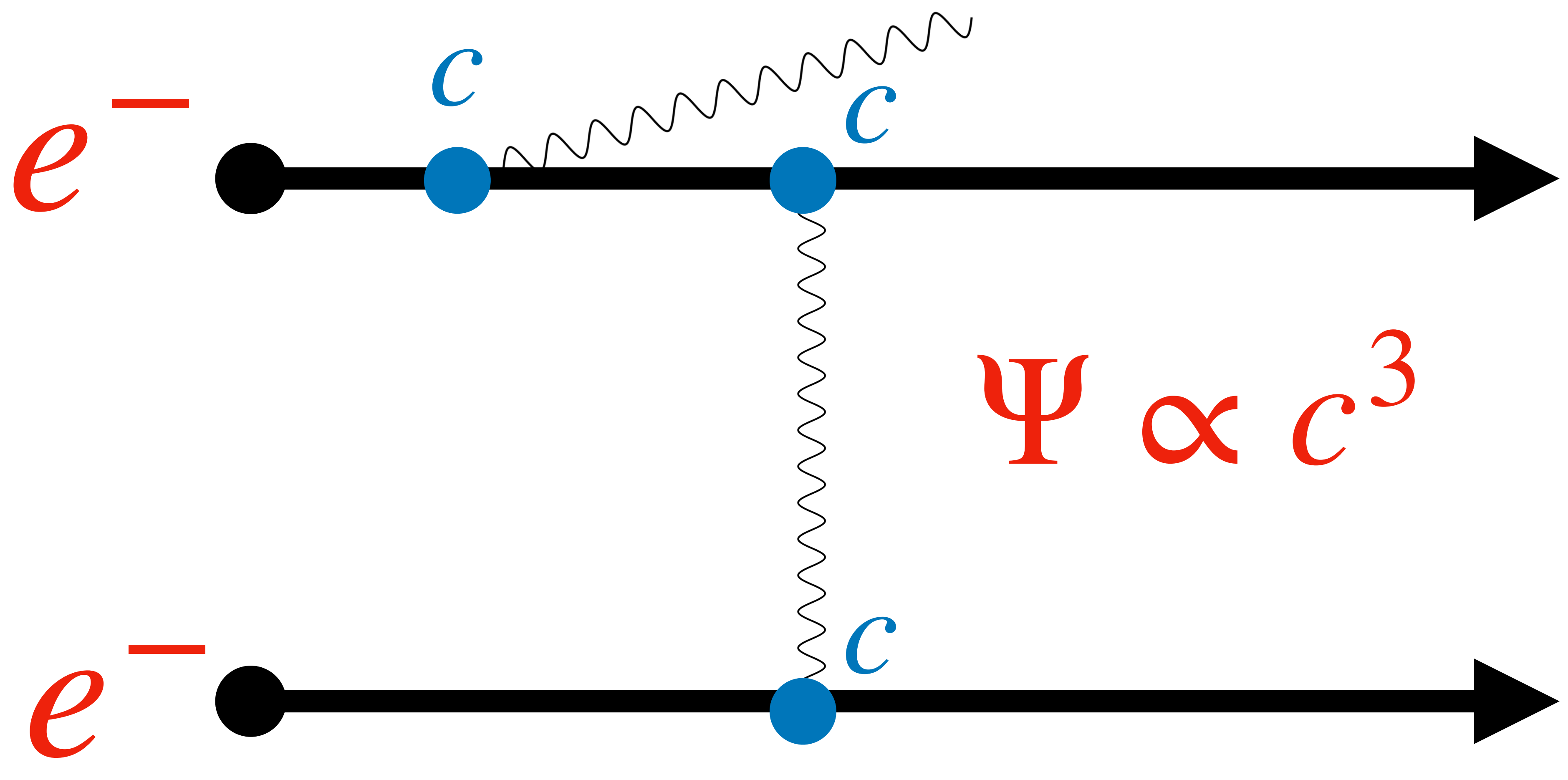


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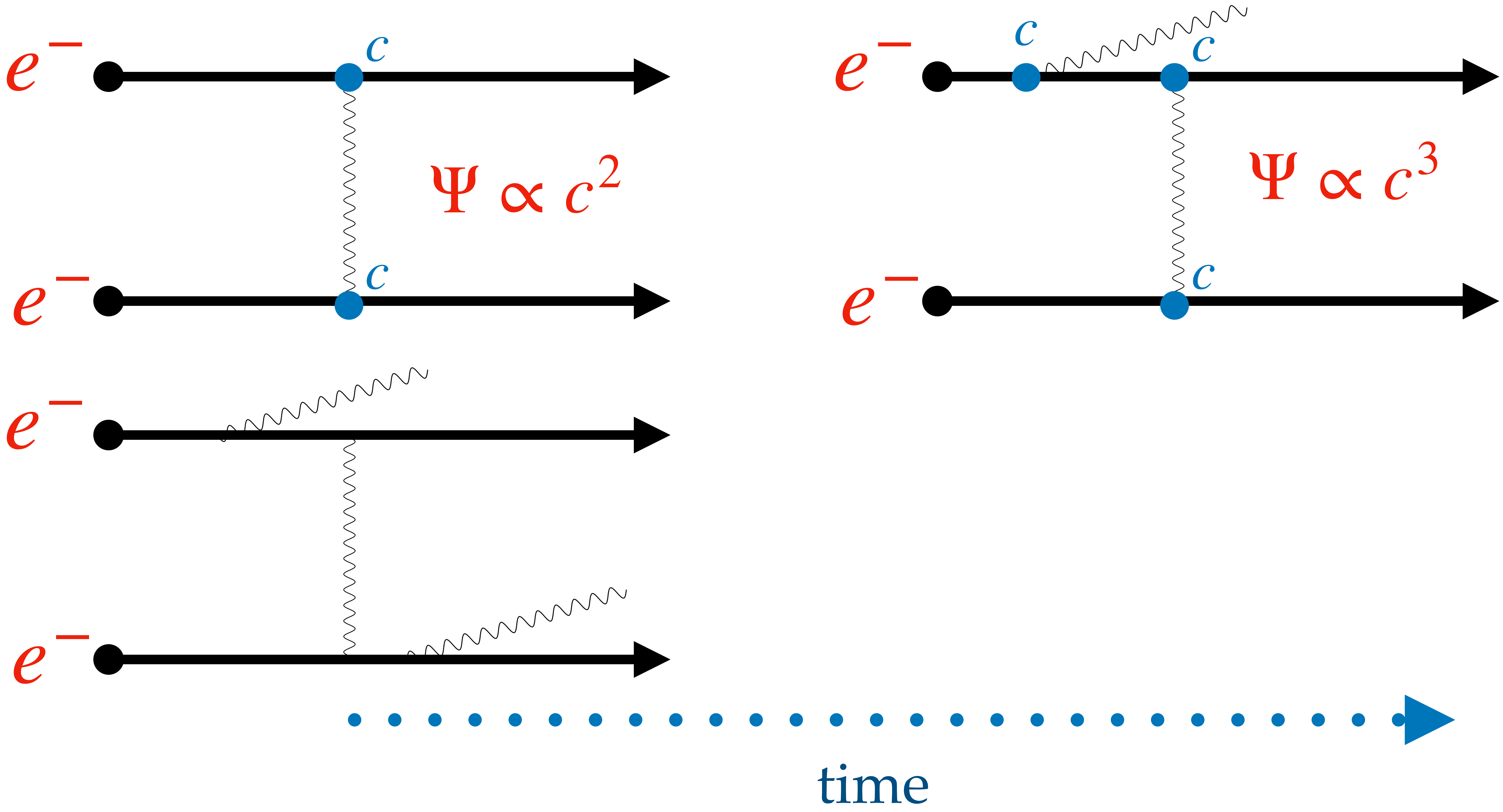




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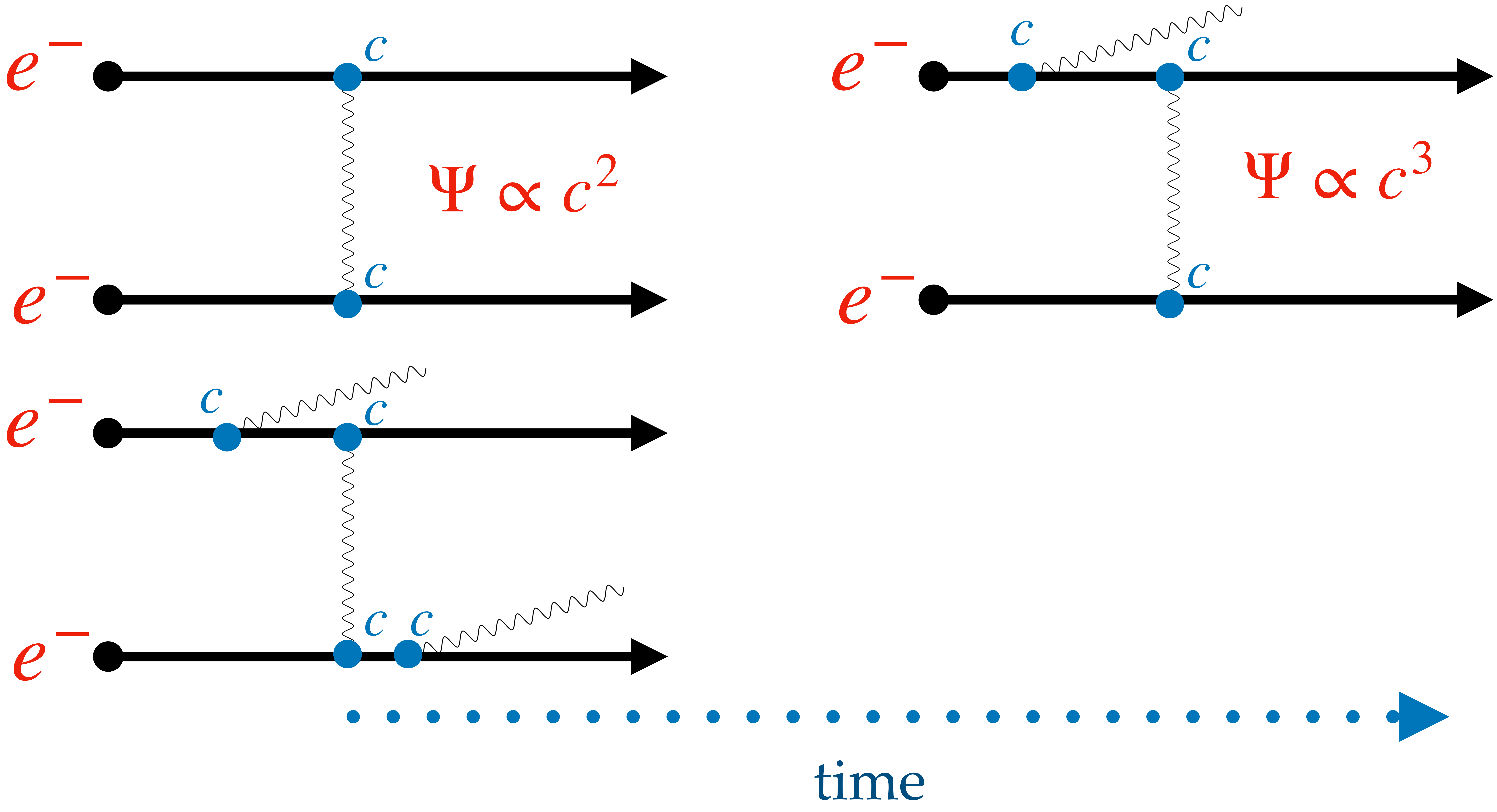

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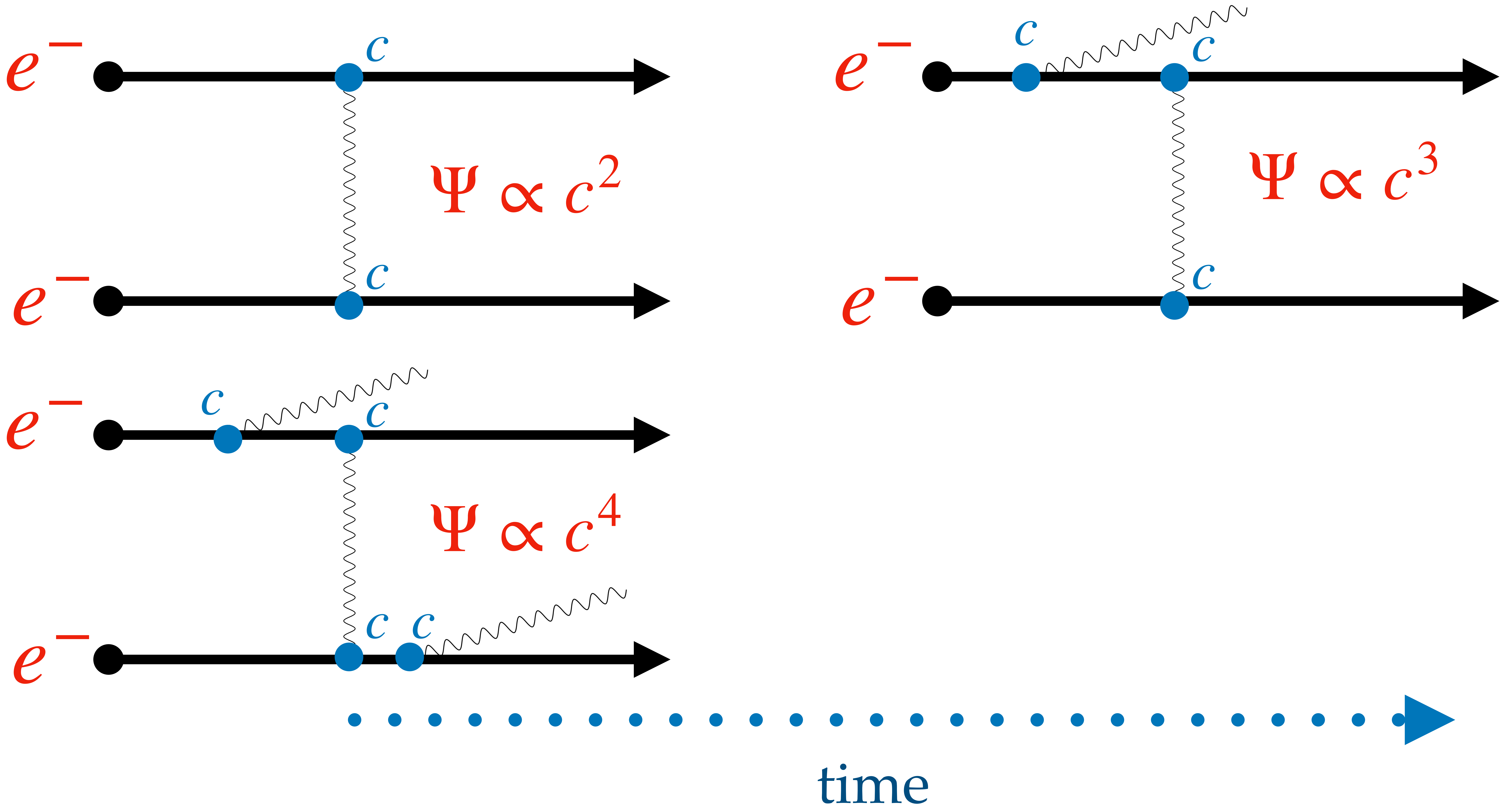

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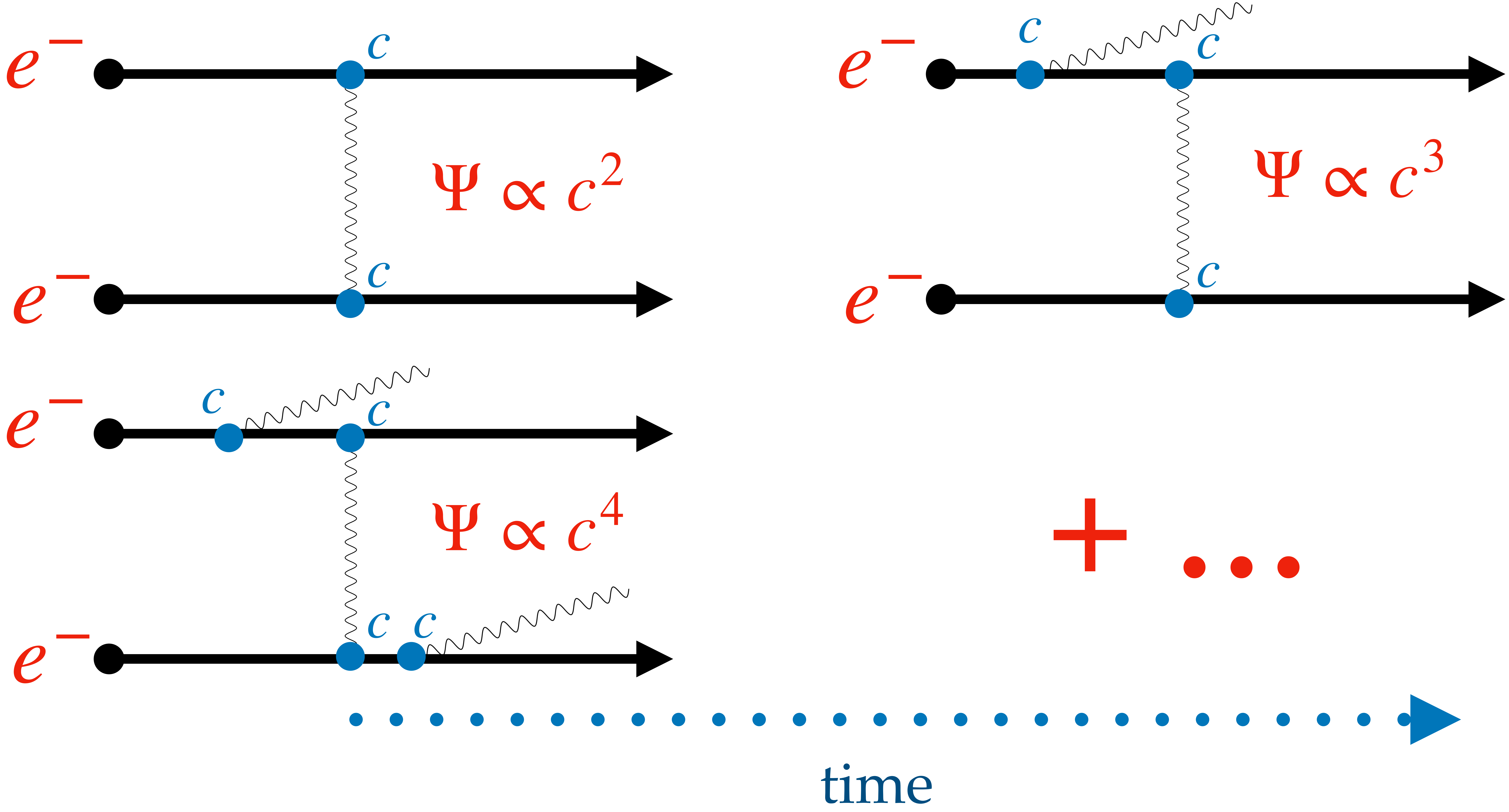

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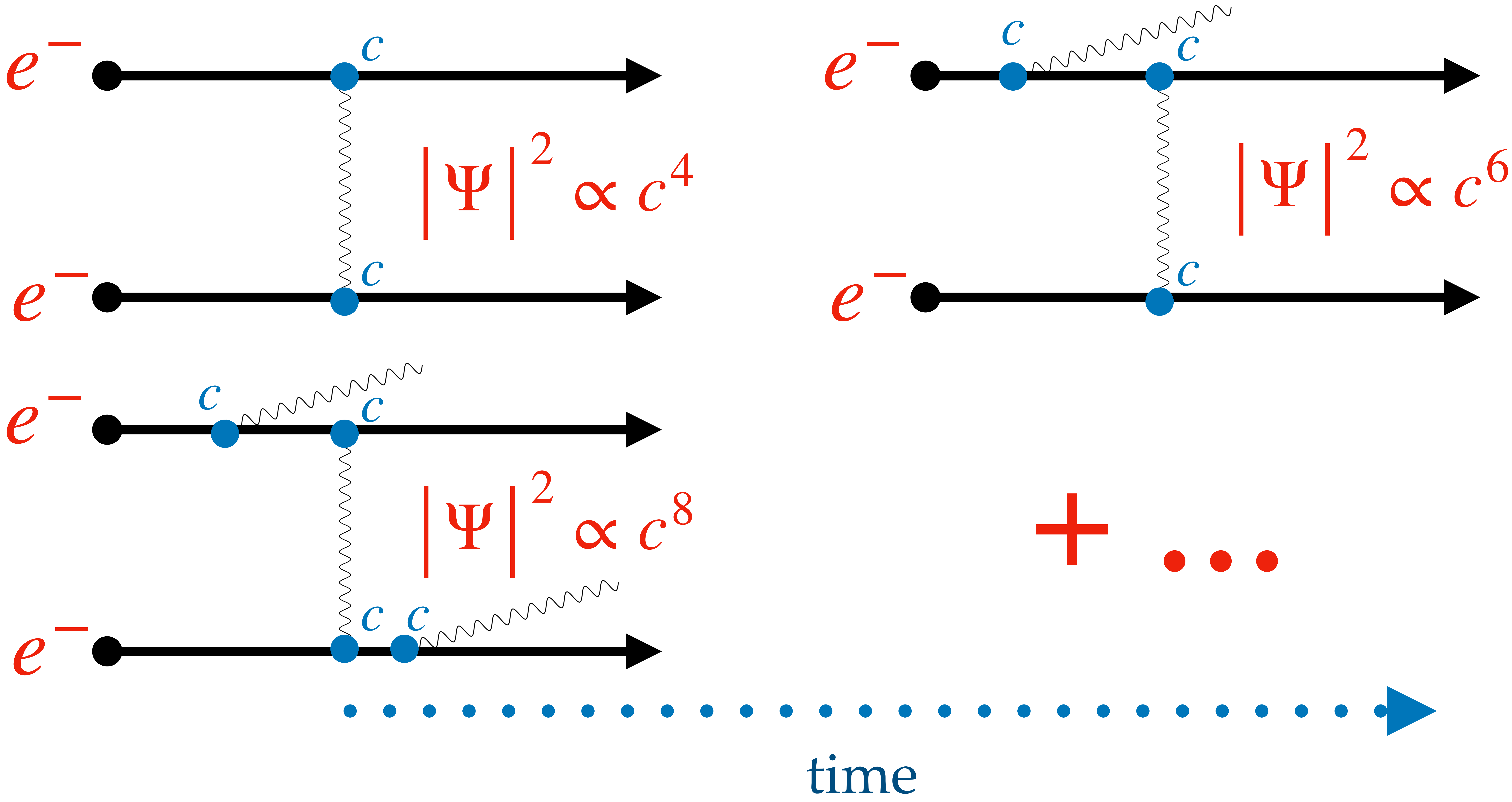

# From Theory to Experiment and Back Again

We now know how to calculate **probabilities** in Quantum Field Theory!

$$|\Psi|^2 \propto \alpha c^4 + \beta c^6 + \gamma c^8 + \dots$$

If $c^2 < 1$ then we can simply add terms for increased precision!

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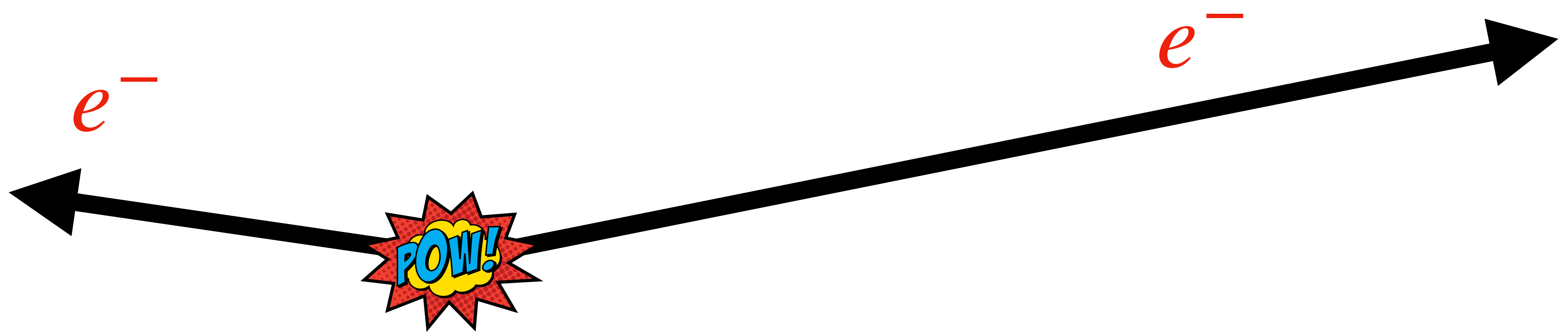

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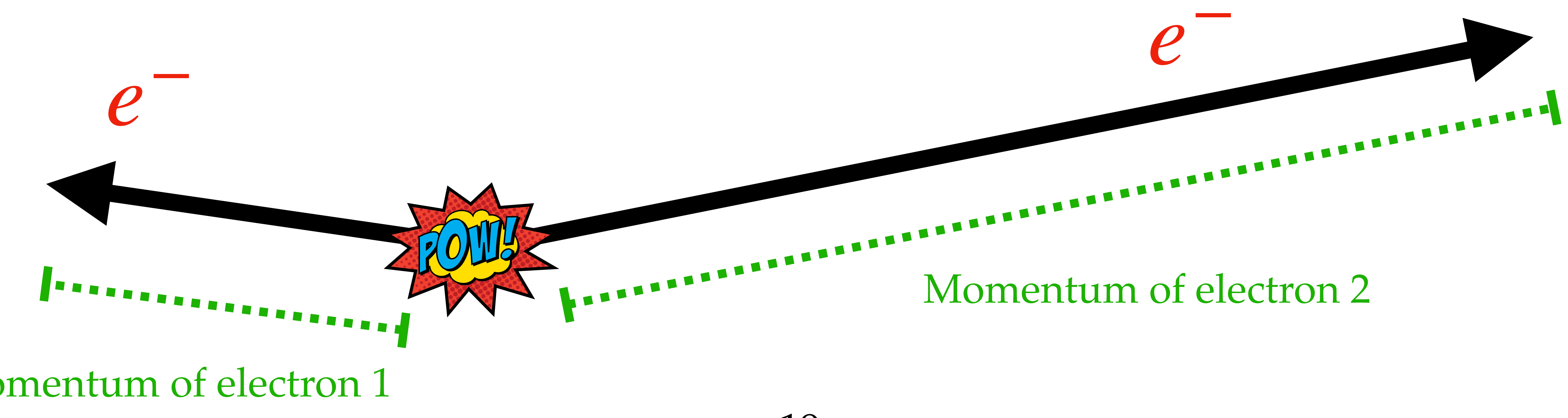




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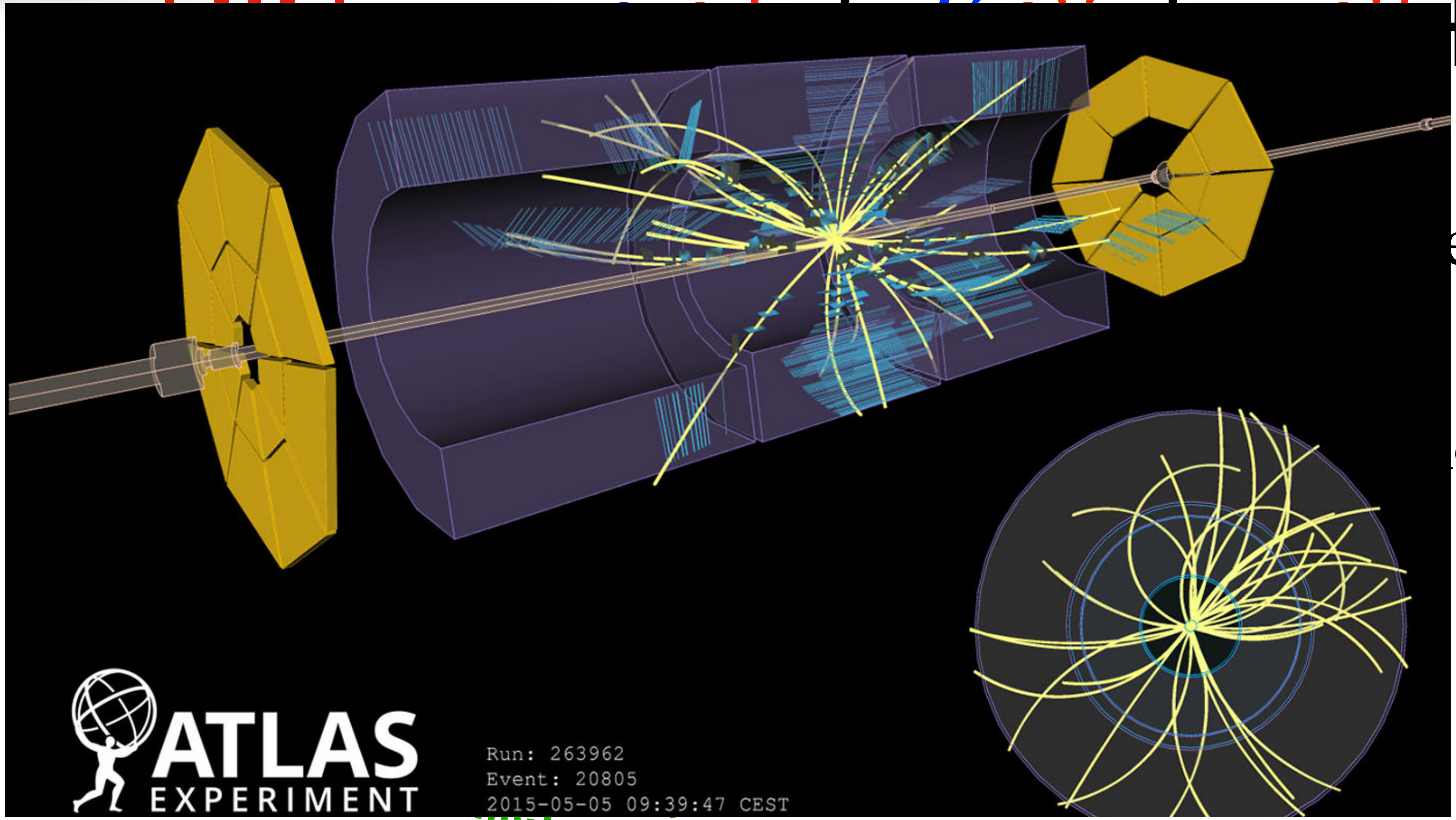
**We have a way to describe what we observe at experiments!**

$+ \ldots$




If $c^2 < 1$ … ecision!

In reality: … e particles involved!

Momentum of electron 1



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# Monte Carlo Simulations

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- **Solutions**: **1**. Use **approximate** $c^n$ for $n$ large & **2**. **model** situations where $c^2 \geq 1$!

# Monte Carlo Simulations

- So, can we calculate everything using pen and paper? **Not really…**

$$|\Psi|^2 \propto \alpha c^4 + \beta c^6 + \gamma c^8 + \ldots$$

**1**. Adding more & more terms is extremely challenging!

& **2**. if $c^2 \geq 1 \Rightarrow$ Series becomes invalid!

- **Solutions**: **1**. Use **approximate** $c^n$ for $n$ large & **2**. **model** situations where $c^2 \geq 1$!

- **Monte Carlo Simulations accomplish this!**

Based on randomness and probability.
Just like Quantum Mechanics!

Pictured: Casino Monte Carlo, Monaco.

# How do we make sense of it all?

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$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi$$
$$+ \Psi_i y_{ij} \Psi_j + \text{h.c.}$$
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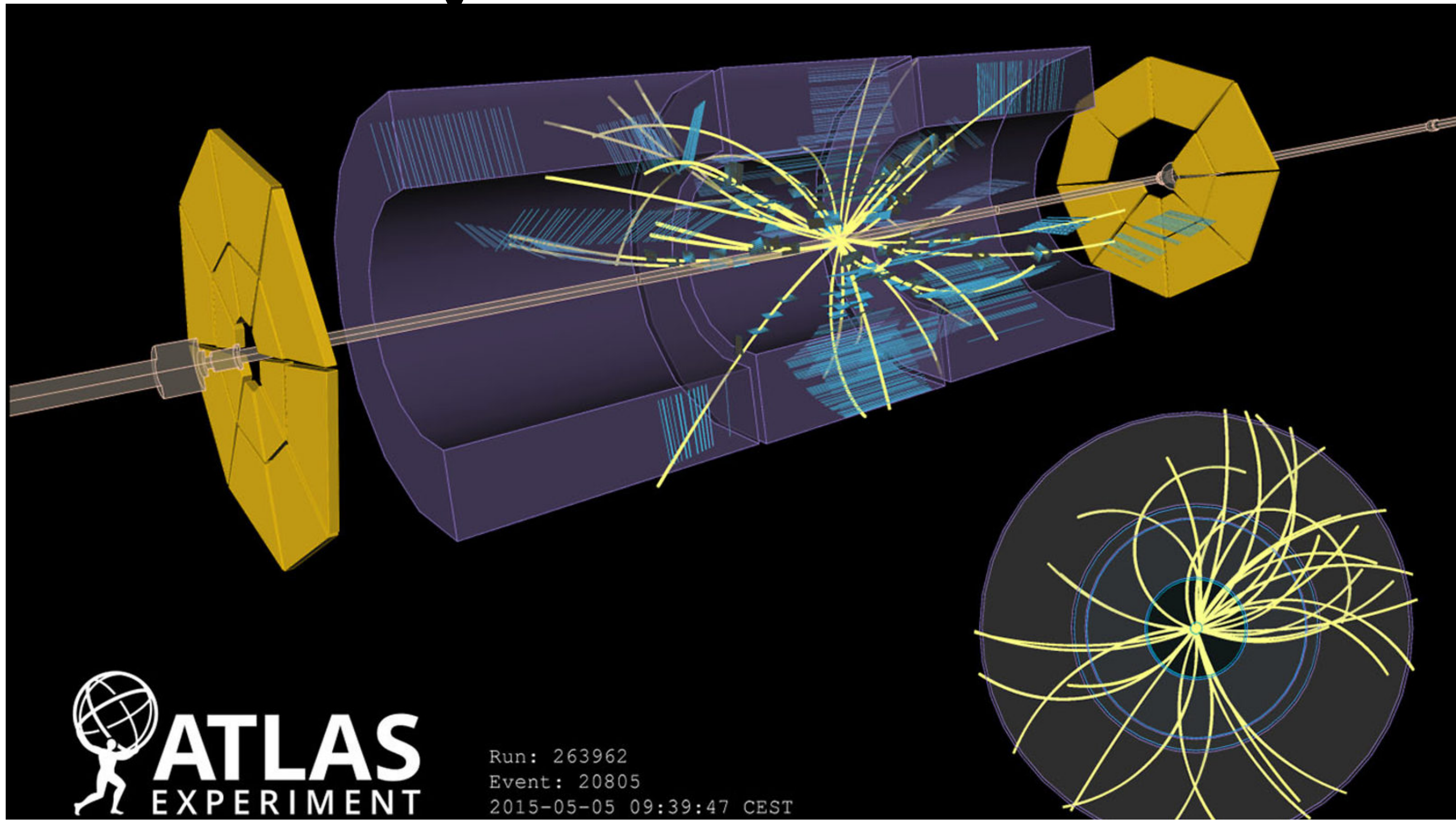
Experiment



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**Simulations**

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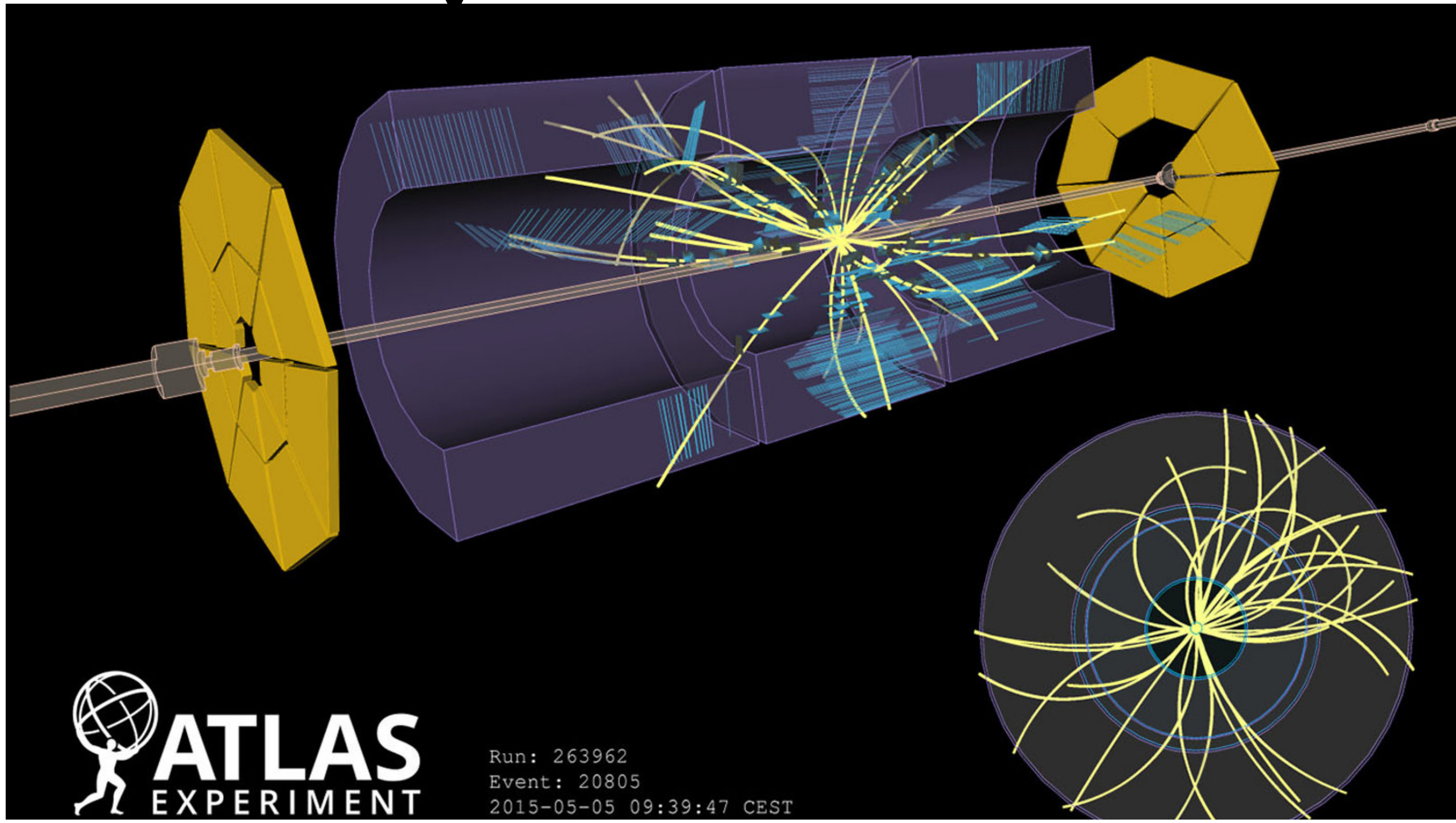


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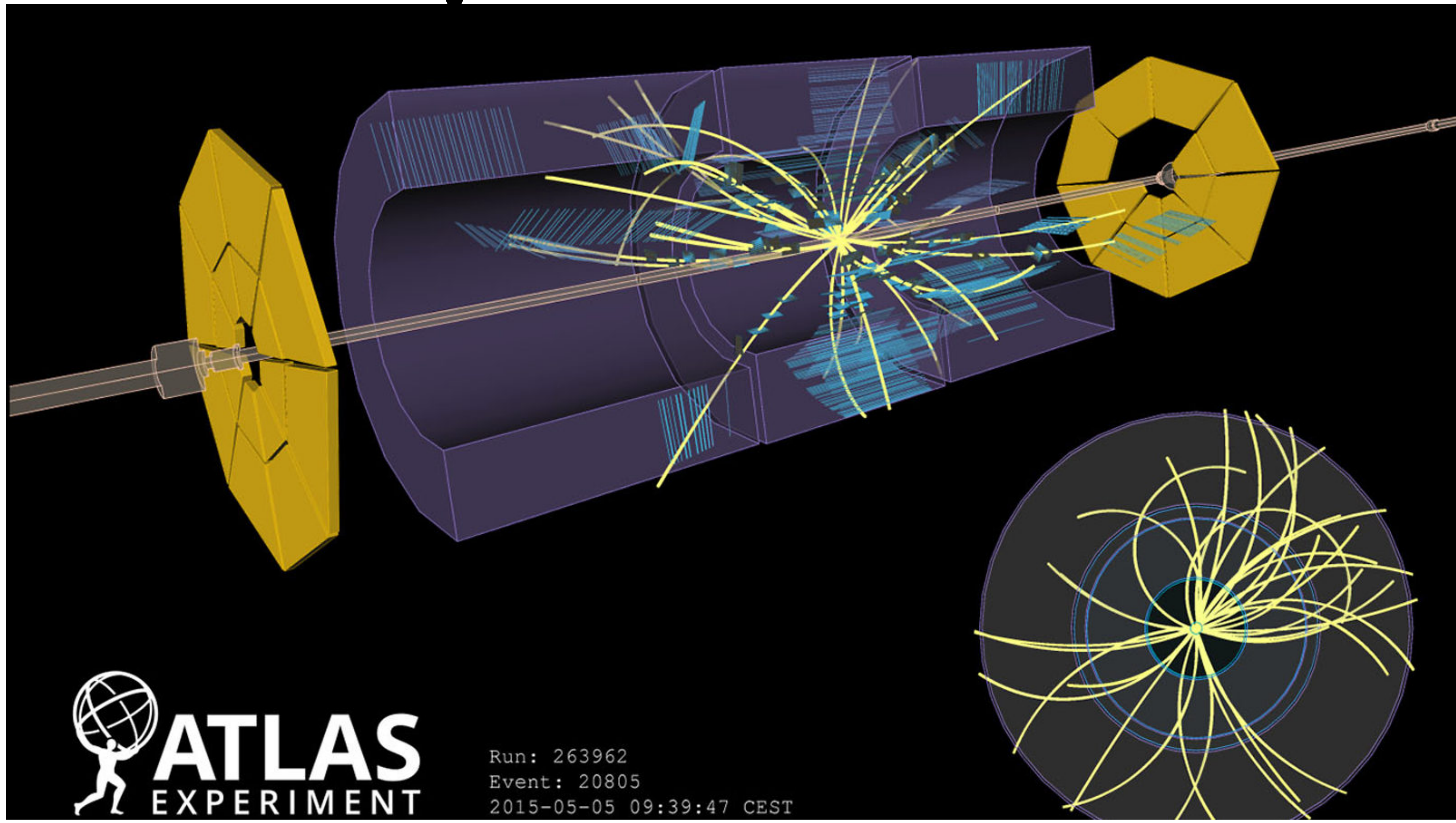
# How do we make sense of it all?

Simulations

Shut up and Simulate!

Experiment



# Simulations via the Monte Carlo method: Calculate π!

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- "Theory":
  - Area of a circle: $A = \pi r^2$.
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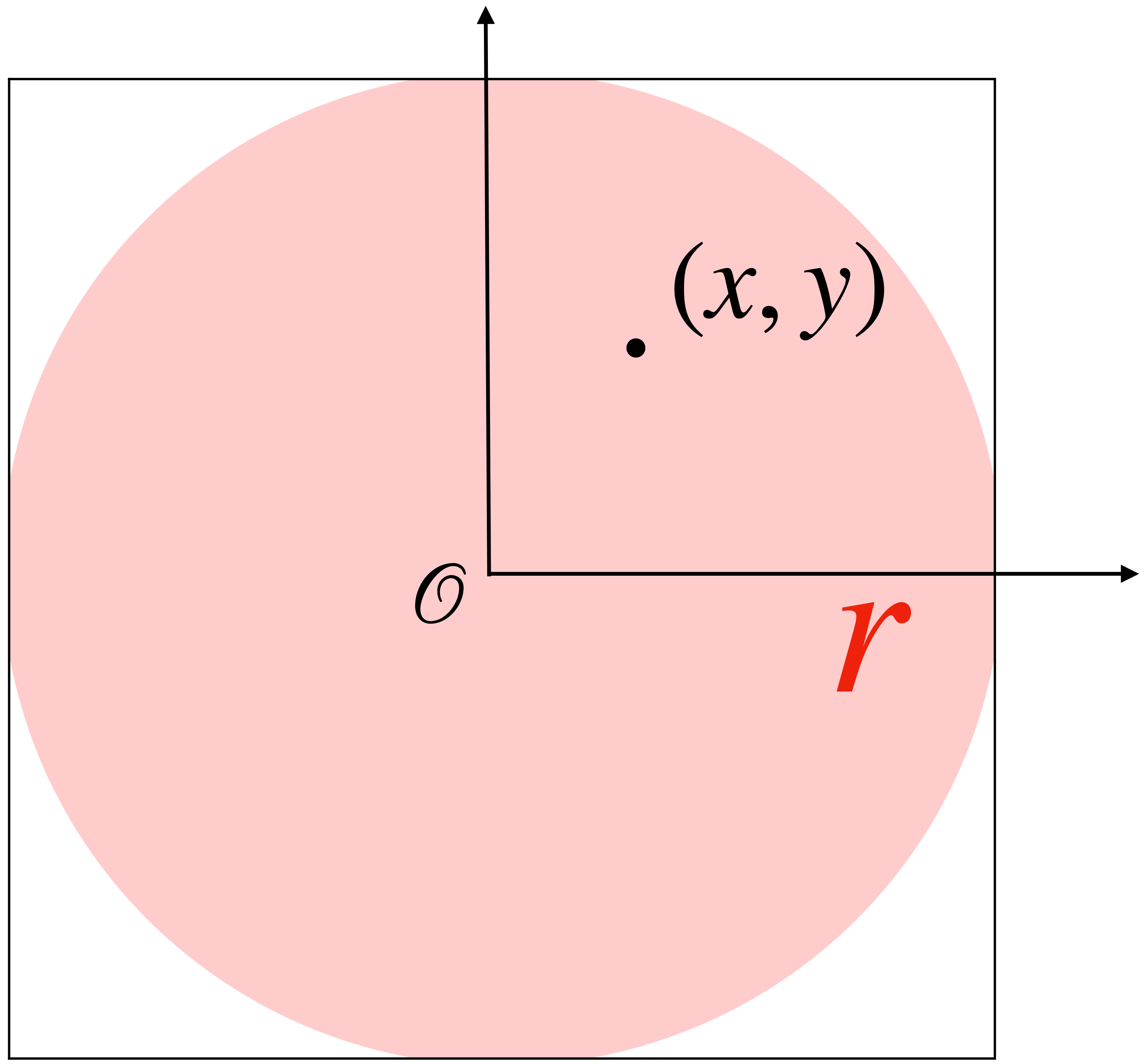

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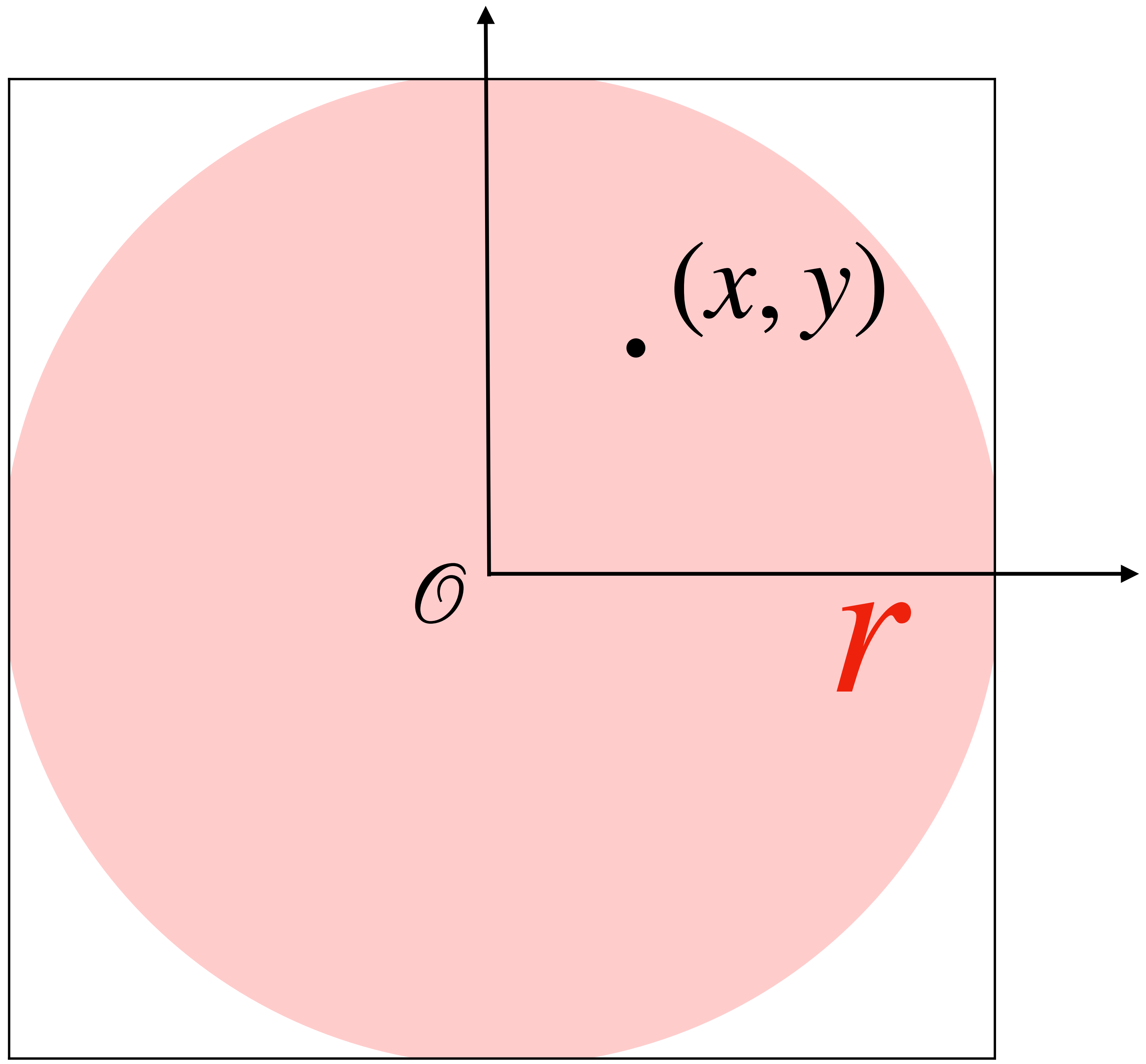




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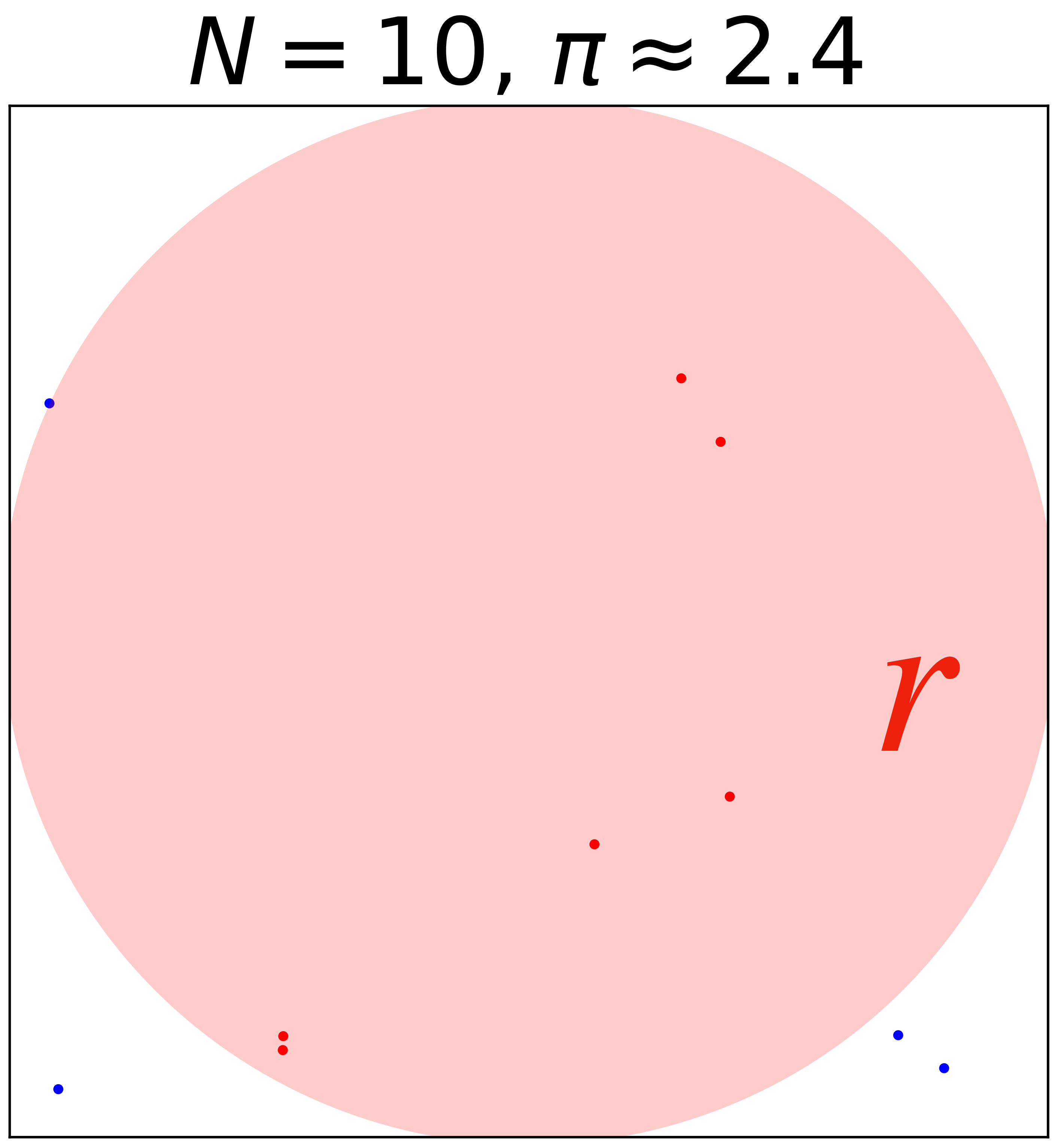

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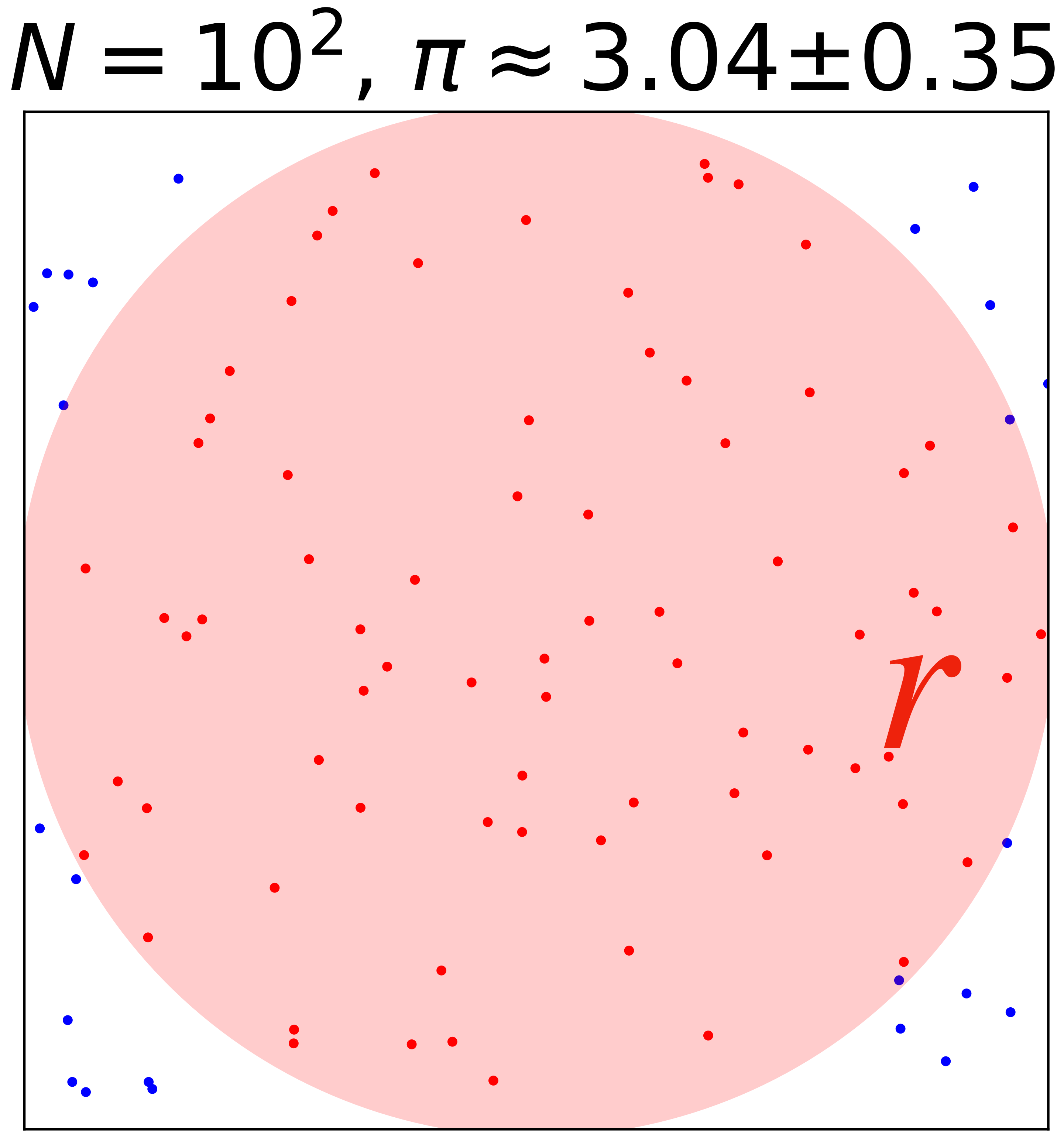


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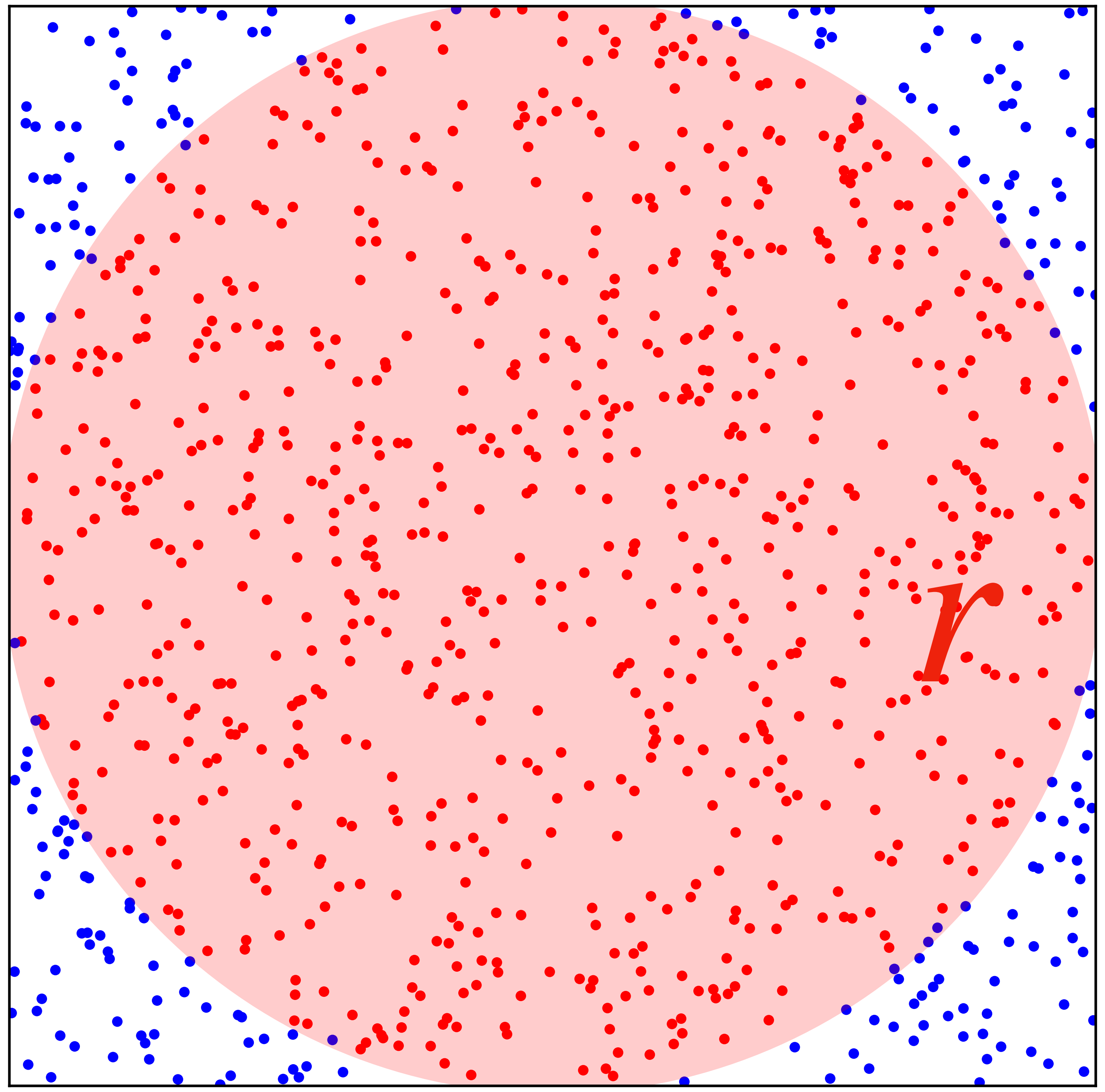
$N = 10^3$, $\pi \approx 3.08 \pm 0.11$



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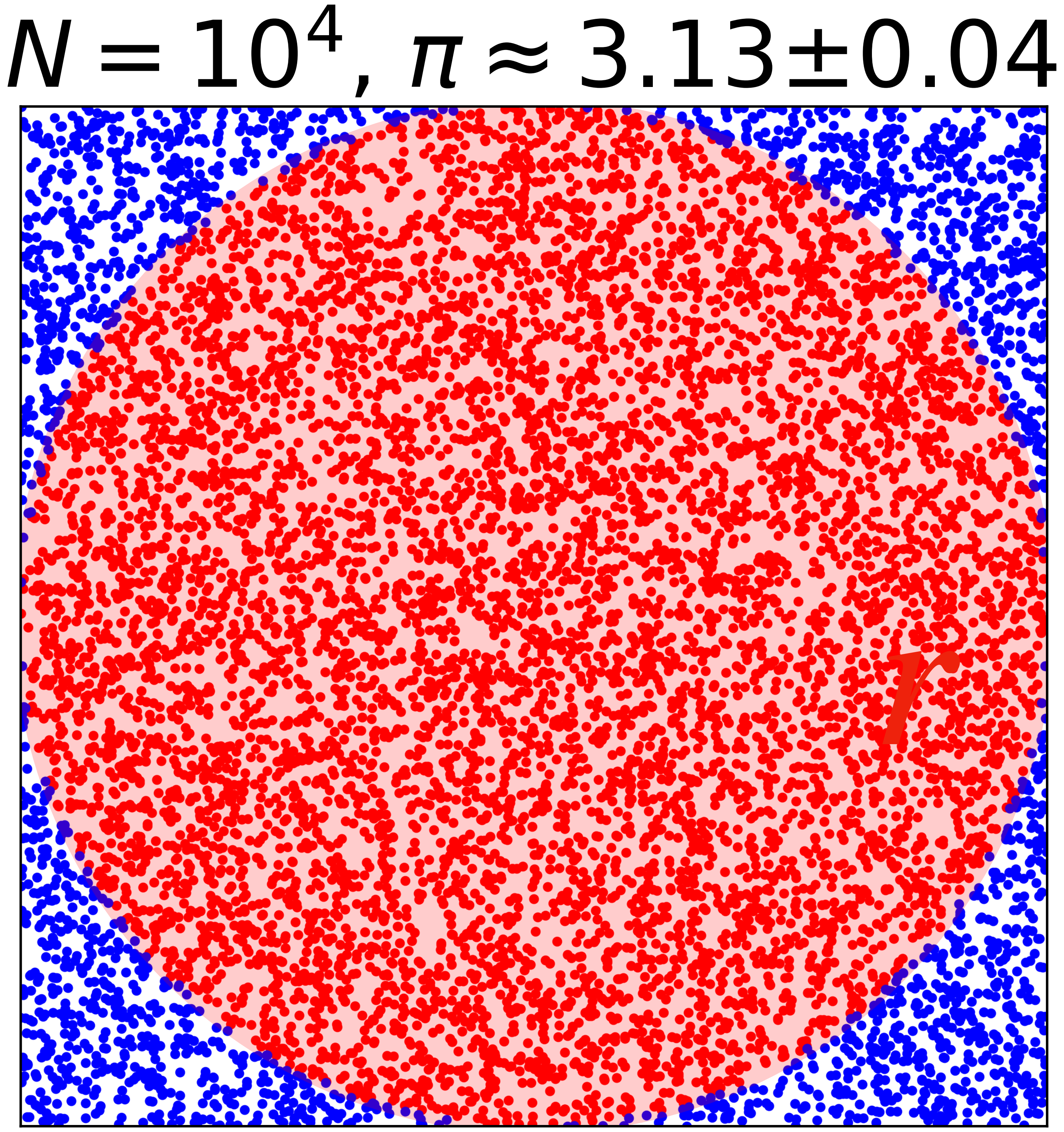

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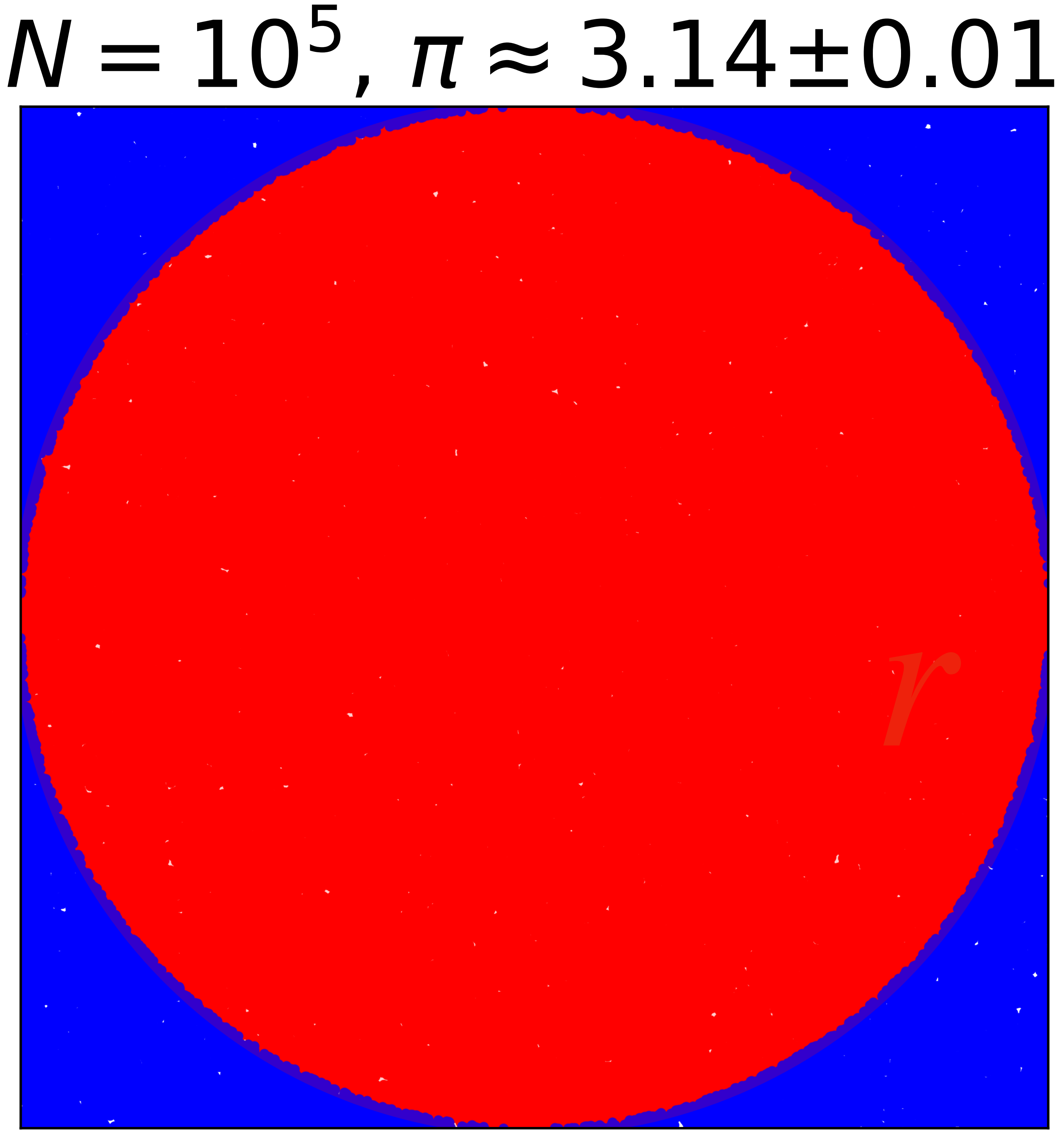

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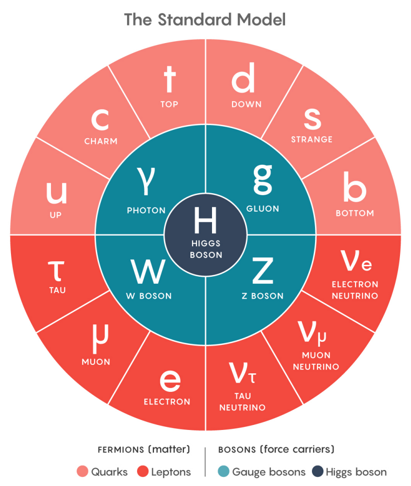


  - Calculate **probabilities** via Quantum Field Theory → actually $|\mathscr{M}|^2$ (the matrix element).



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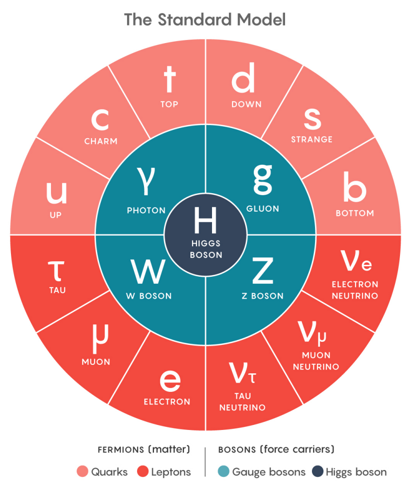
  - A set of particles and their interactions! e.g.: 

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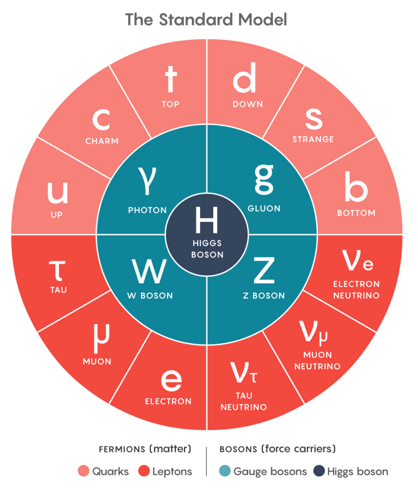


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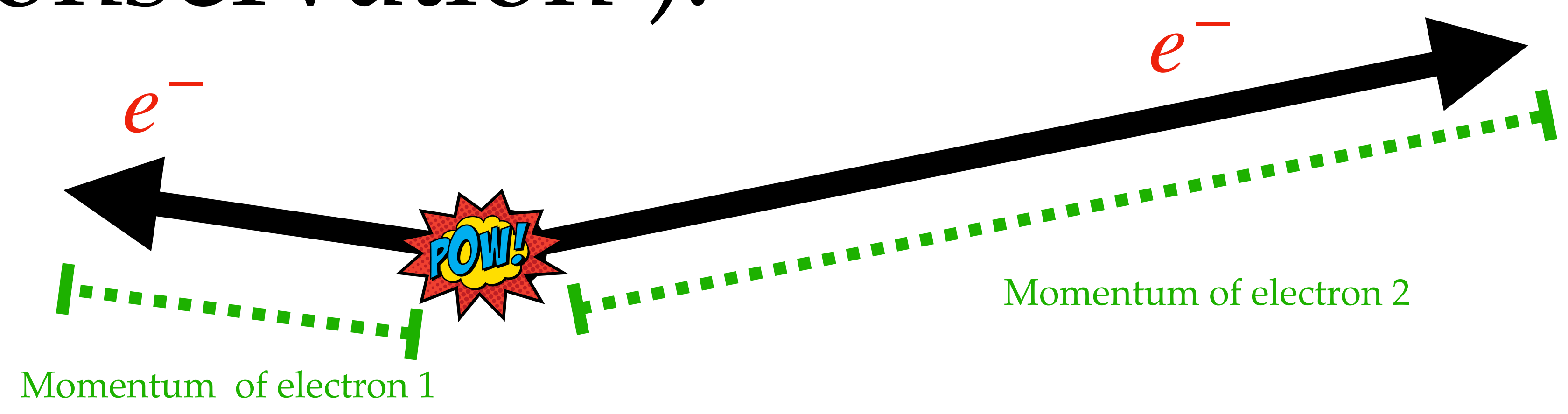


**probability** $\sim |\mathscr{M}|^2(p_1, p_2, \ldots)$

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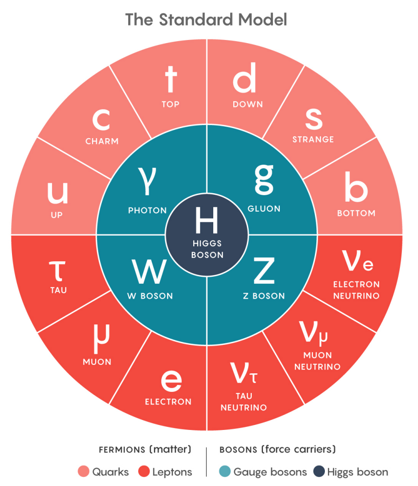


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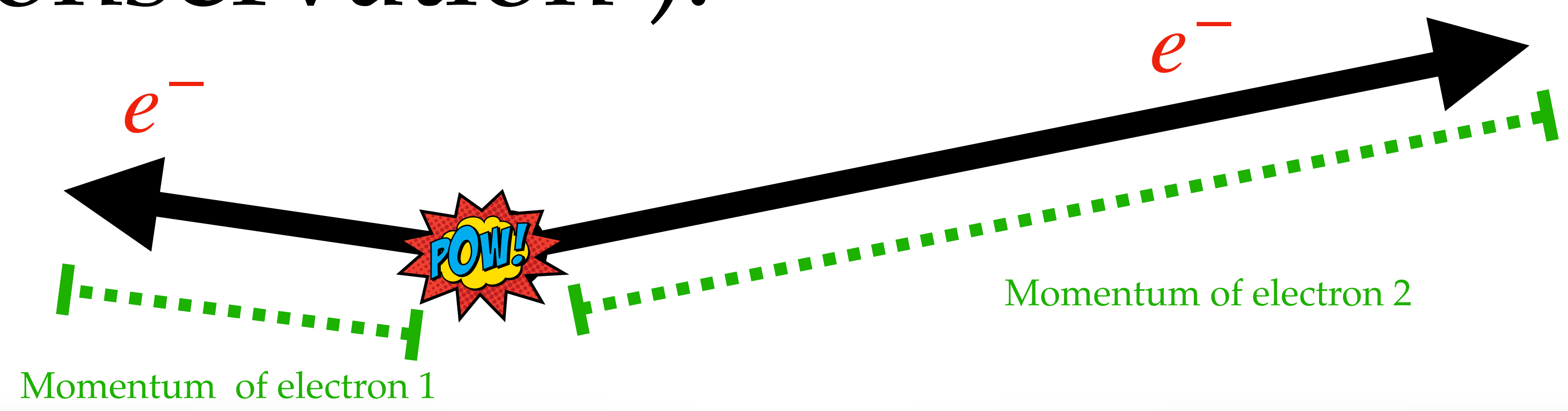


**probability ~** $|\mathscr{M}|^2(p_1, p_2, \ldots)$

⇒ Get lists of particles that look like real events!

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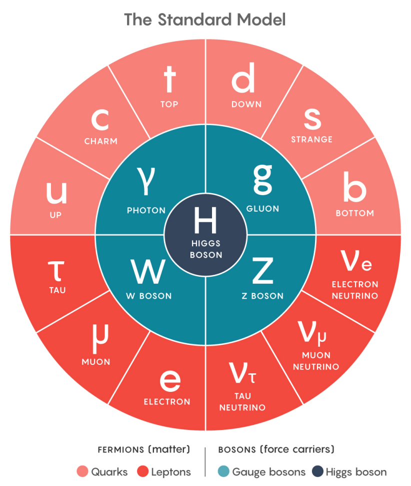


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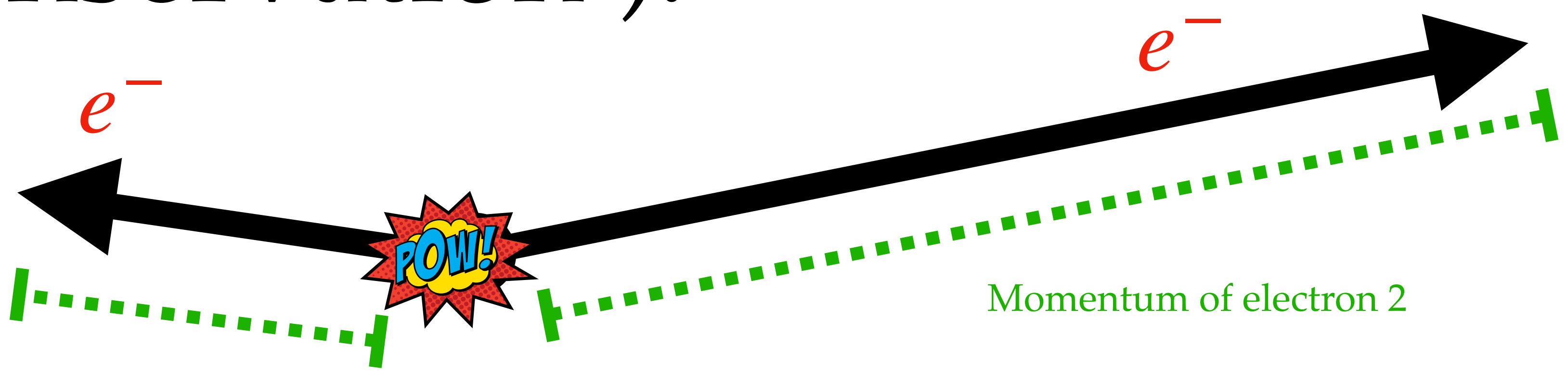


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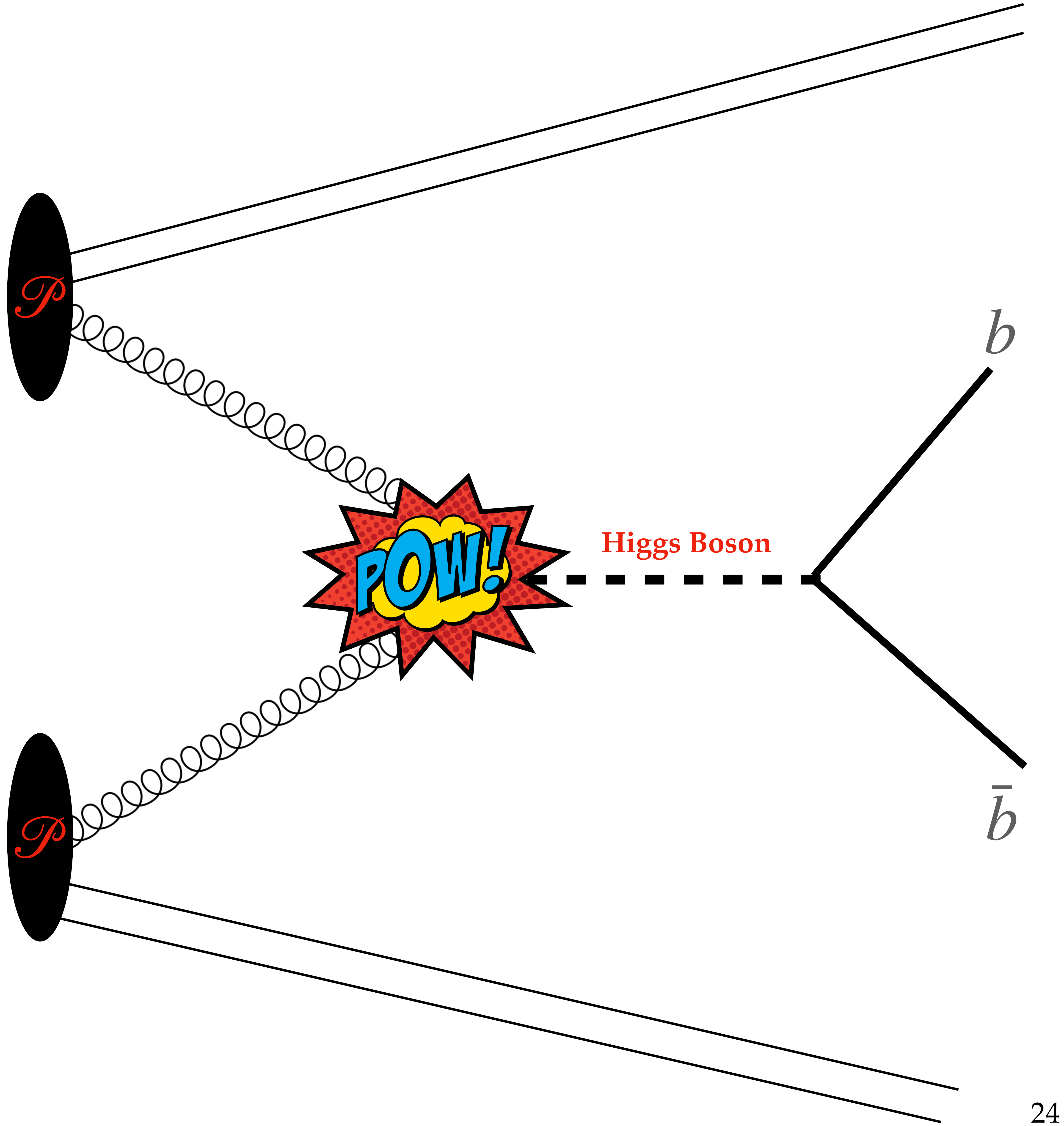
## ⇒ Get lists of particles that look like real events!

[e.g. "How-to: write a parton-level Monte Carlo particle physics event generator", **AP**, arXiv:1412.4677]

# An Example of a Monte Carlo Event




```
Event number 2 (id: LHC) performed by EventHandler
Weight: 1
================================================================================

--- Colliding particles:
  1         p+     2212  (3,6)
                                 0.000      0.000  6500.000  6500.000      0.938
  2         p+     2212  (4,7)
                                 0.000      0.000 -6500.000  6500.000      0.938
--------------------------------------------------------------------------------
Primary sub-process performed by MEHiggs
--- incoming:
  3          g       21 [1] (5)    {+1,-2}
                                -0.000      0.000   150.729   150.729      0.000
  4          g       21 [2] (5)    {+2,-1}
                                 0.000     -0.000   -26.206    26.206      0.000
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  6     Rem:p+       82 [1]    7>>7 {+2,-1}
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--------------------------------------------------------------------------------
     Sum of momenta:                     0  3.08e-46          0   1.3e+04    1.3e+04
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Generated using the Herwig 7 Monte Carlo Event Generator [https://herwig.hepforge.org/]



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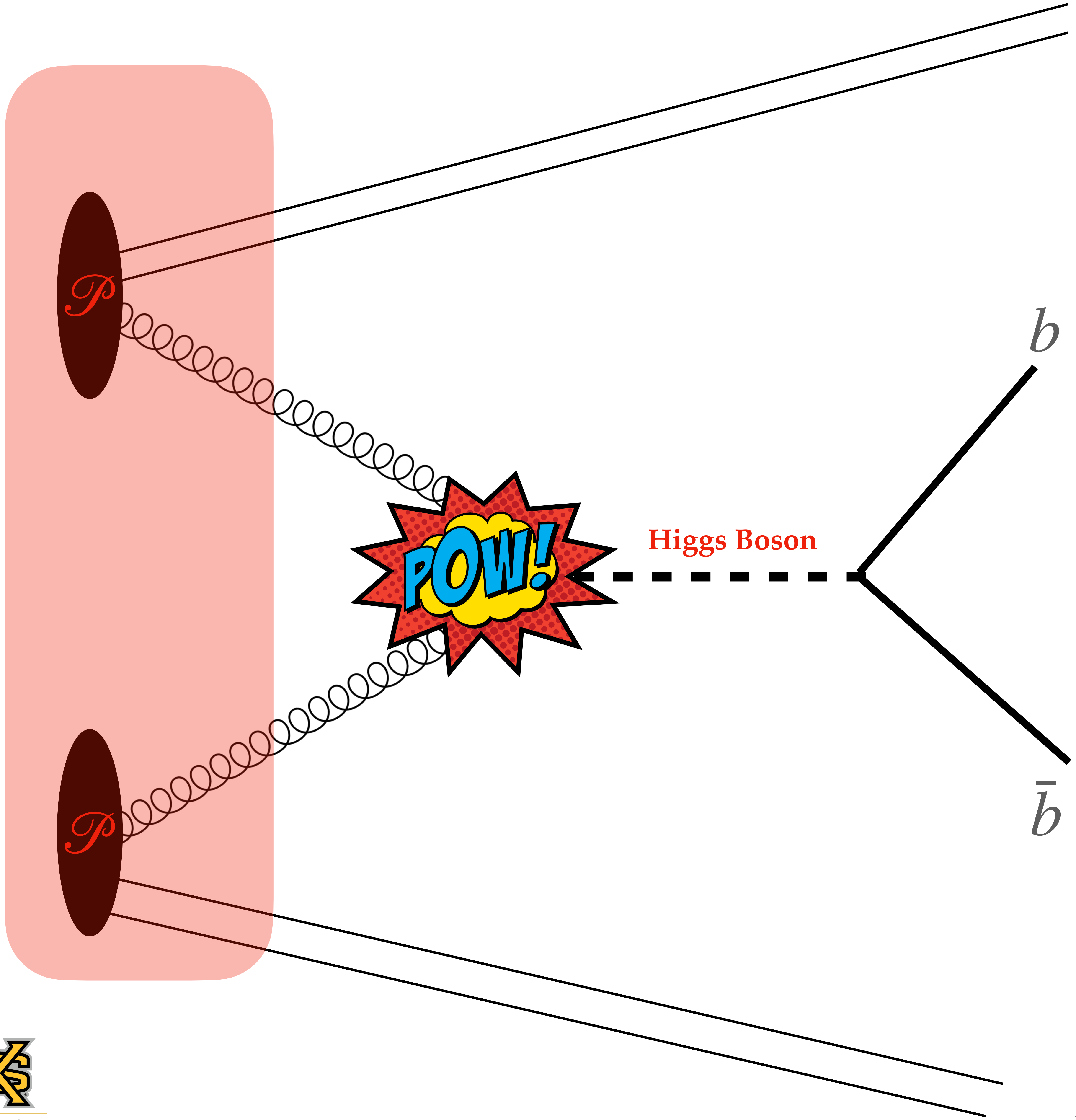


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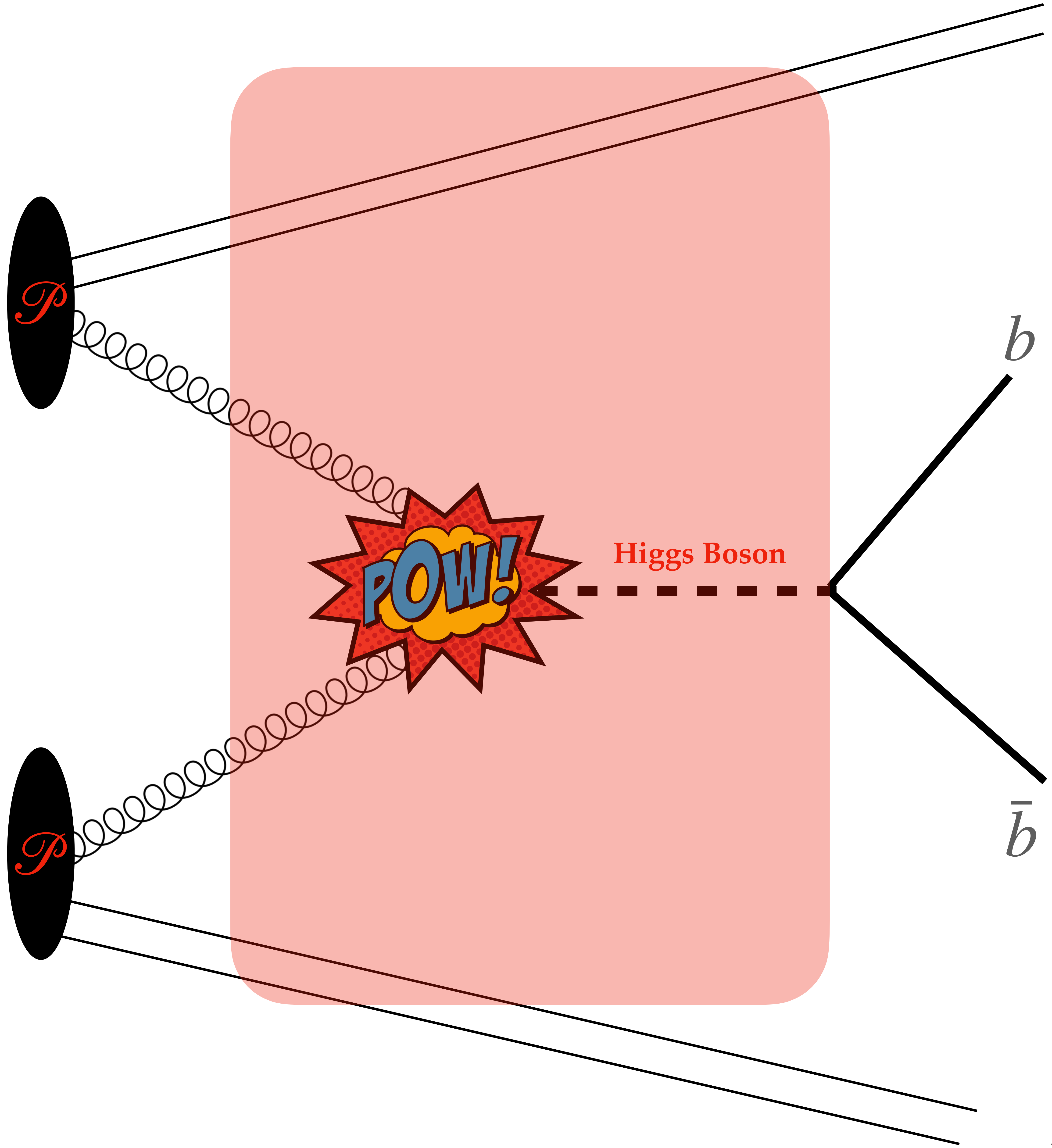


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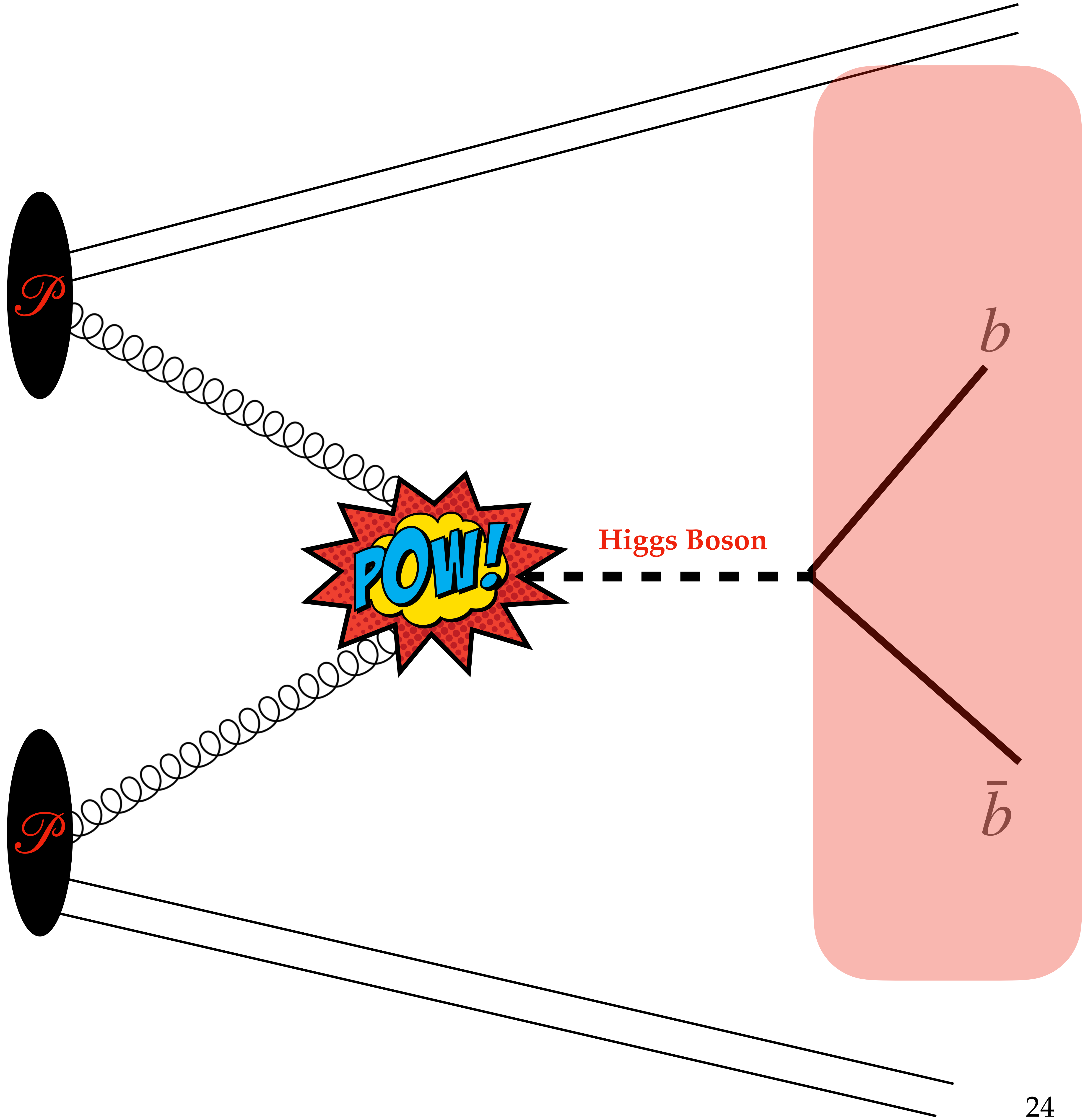


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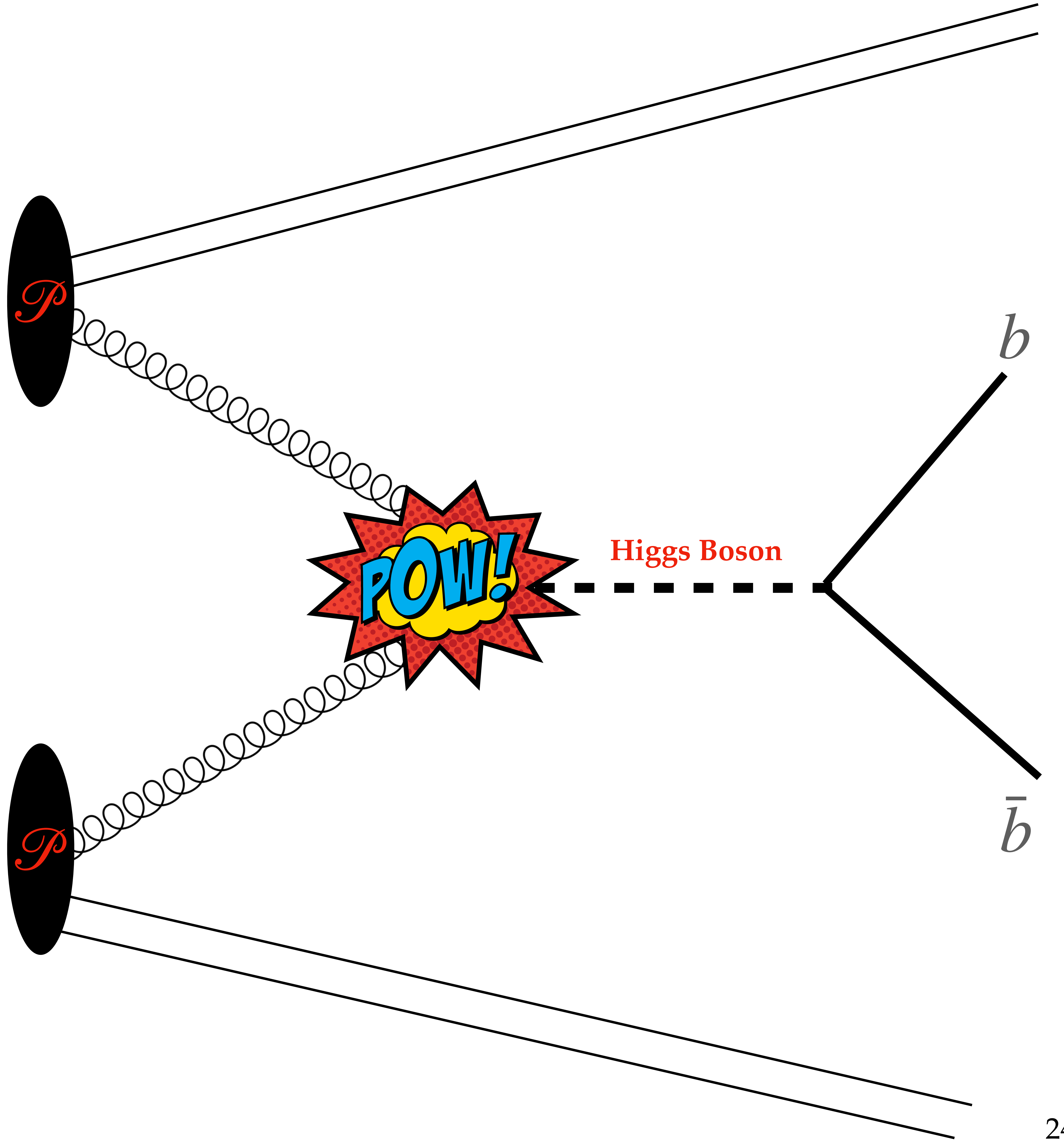
Generated using the Herwig 7 Monte Carlo Event Generator [https://herwig.hepforge.org/]

# An Example of a Monte Carlo Event




```
Event number 2 (id: LHC) performed by EventHandler
Weight: 1
==============================================================================

--- Colliding particles:
  1         p+    2212  (3,6)
                               0.000      0.000  6500.000  6500.000      0.938
  2         p+    2212  (4,7)
                               0.000      0.000 -6500.000  6500.000      0.938
------------------------------------------------------------------------------
Primary sub-process performed by MEHiggs
--- incoming:
  3          g      21 [1] (5)   {+1,-2}
                              -0.000      0.000   150.729   150.729      0.000
  4          g      21 [2] (5)   {+2,-1}
                               0.000     -0.000   -26.206    26.206      0.000
--- outgoing:
  5         h0      25 [3,4] (8,9)
                               0.000      0.000   124.524   176.935    125.698
------------------------------------------------------------------------------
Step 1
--- intermediates:
  3          g      21 [1] (5)   {+1,-2}
                              -0.000      0.000   150.729   150.729      0.000
  4          g      21 [2] (5)   {+2,-1}
                               0.000     -0.000   -26.206    26.206      0.000
--- final:
  5         h0      25 [3,4] (8,9)
                               0.000      0.000   124.524   176.935    125.698
  6     Rem:p+      82 [1]   7>>7 {+2,-1}
                               0.000      0.000  6349.270  6349.271      0.927
  7     Rem:p+      82 [2]   6>>6 {+1,-2}
                              -0.000      0.000 -6473.794  6473.794      0.936
------------------------------------------------------------------------------
     Sum of momenta:                   0  3.08e-46         0   1.3e+04    1.3e+04
------------------------------------------------------------------------------
Step 2 performed by DecayHandler
--- final:
  6     Rem:p+      82 [1]   7>>7 {+2,-1}
                               0.000      0.000  6349.270  6349.271      0.927
  7     Rem:p+      82 [2]   6>>6 {+1,-2}
                              -0.000      0.000 -6473.794  6473.794      0.936
  8          b       5 [5]   >9 {+3}
                              43.874    -21.517     6.943    49.535      4.200
  9       bbar      -5 [5]   8> {-3}
                             -43.874     21.517   117.581   127.400      4.200
------------------------------------------------------------------------------
     Sum of momenta:                   0         0         0   1.3e+04    1.3e+04
******************************************************************************
```

Generated using the Herwig 7 Monte Carlo Event Generator [https://herwig.hepforge.org/]

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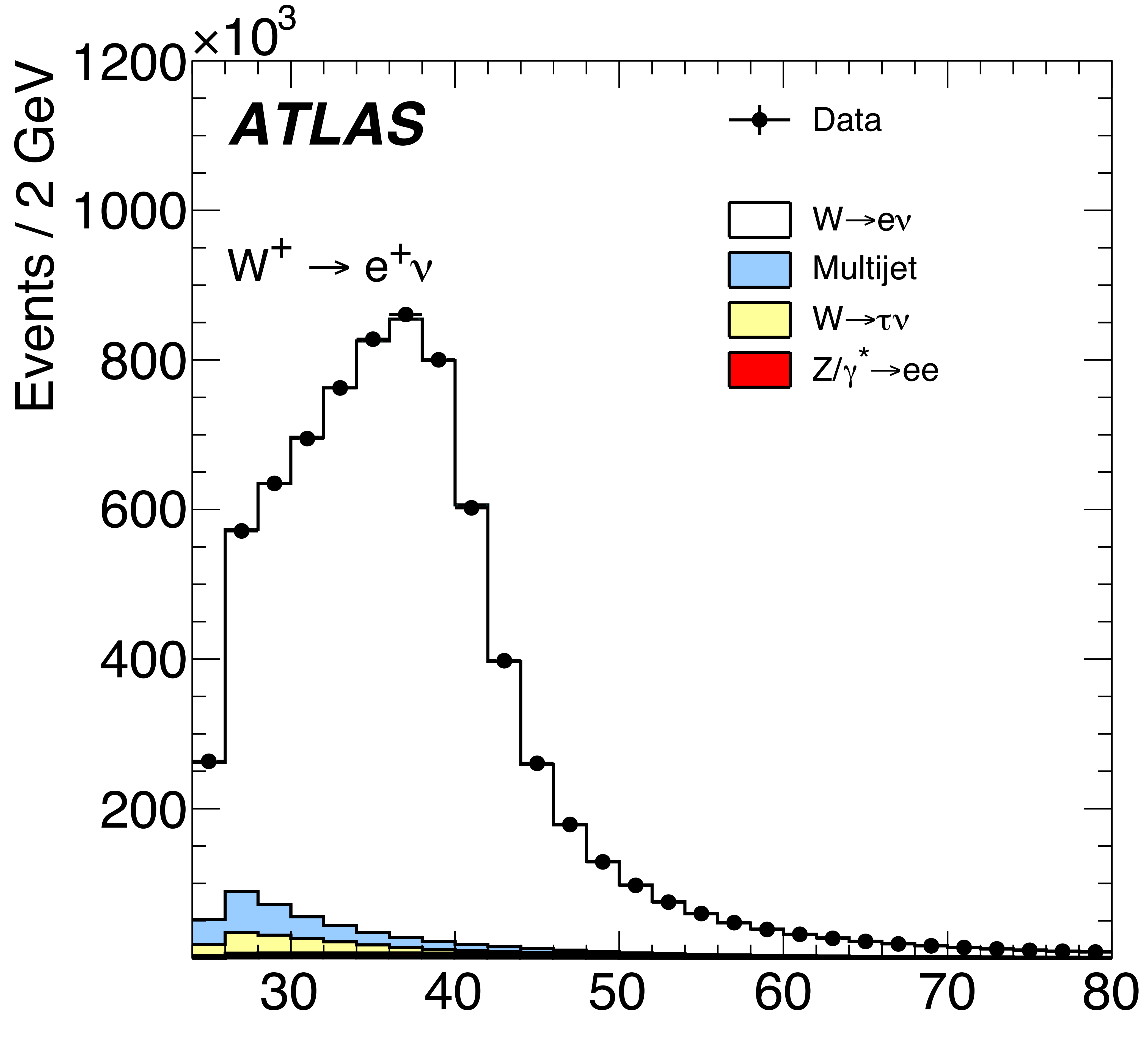
# Theory VS Experiments

⇒ Construct histograms &
Compare to real data!
e.g.:




~ Electron energy



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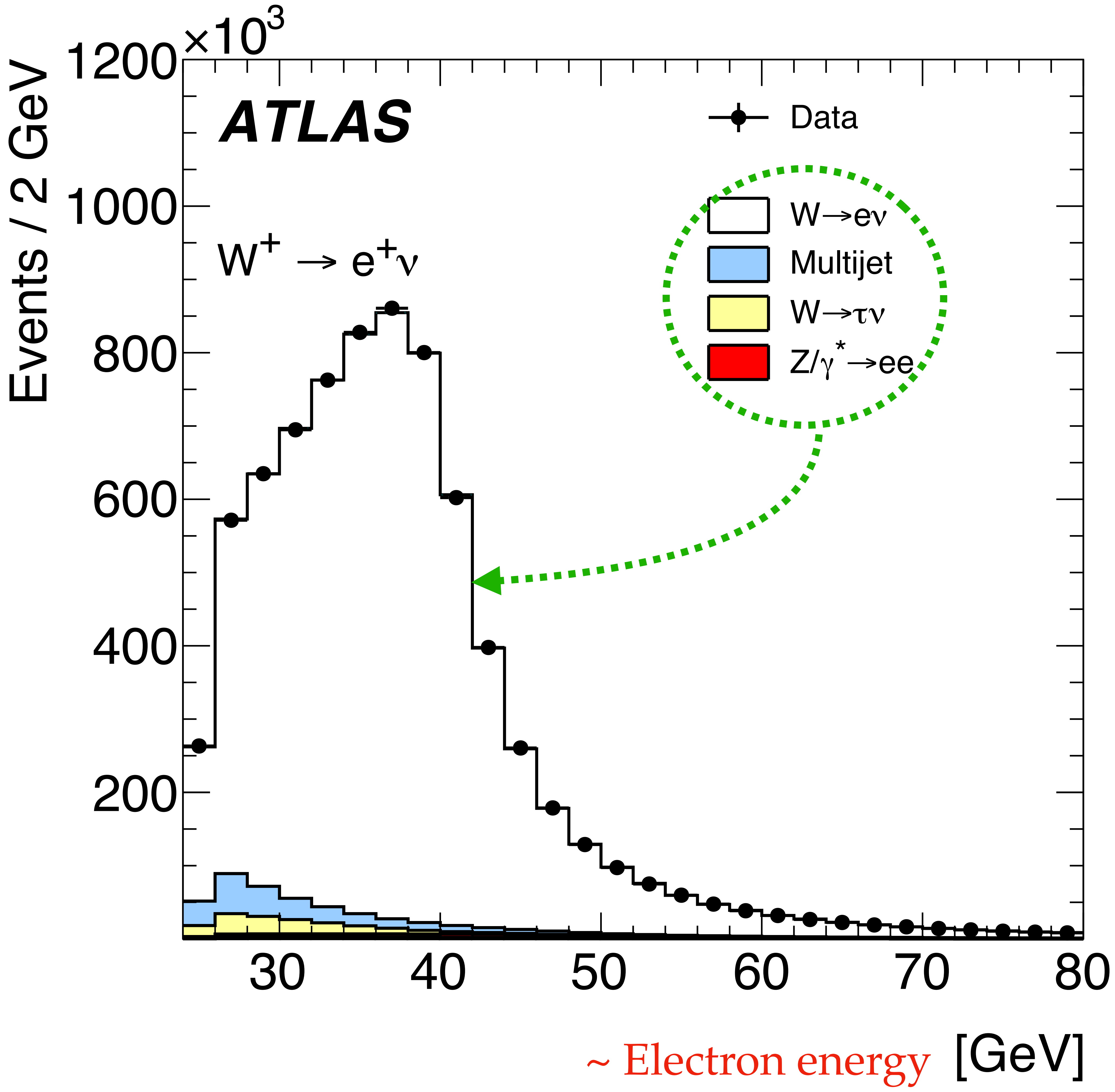




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# Searching for New Phenomena

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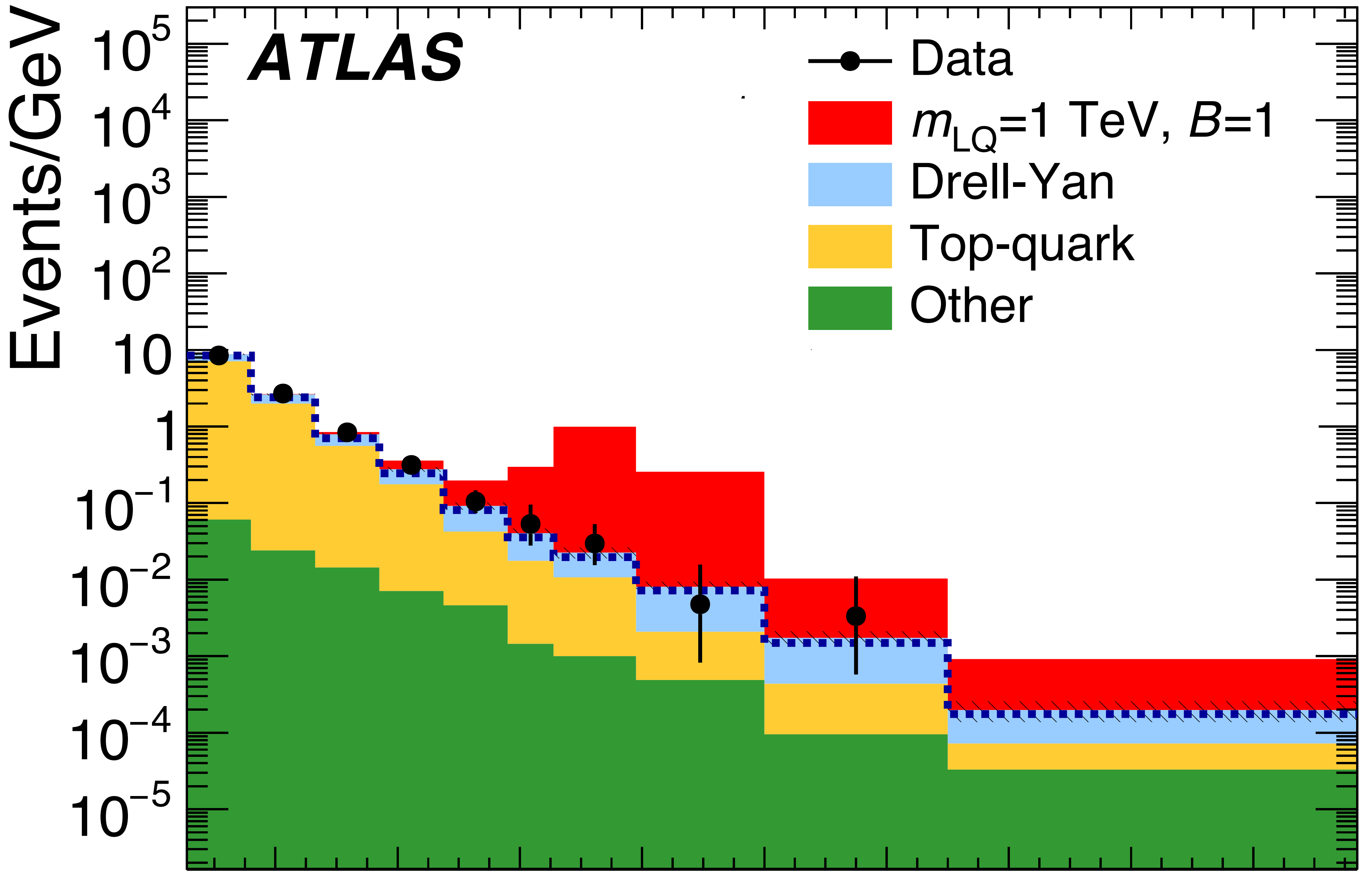


Some Observable Quantity [GeV]

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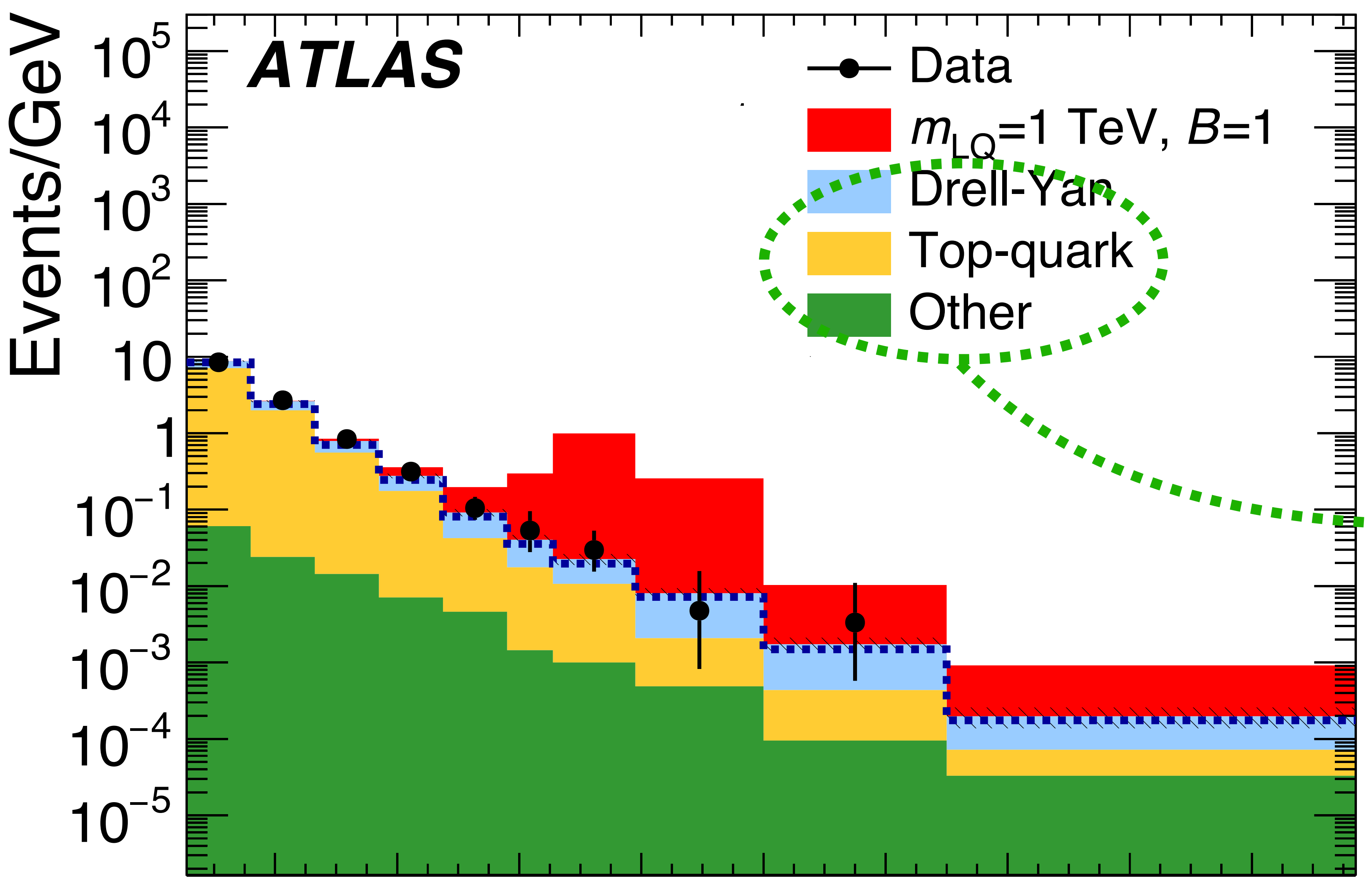


Some Observable Quantity [GeV]

Simulation of stuff that we know exist!



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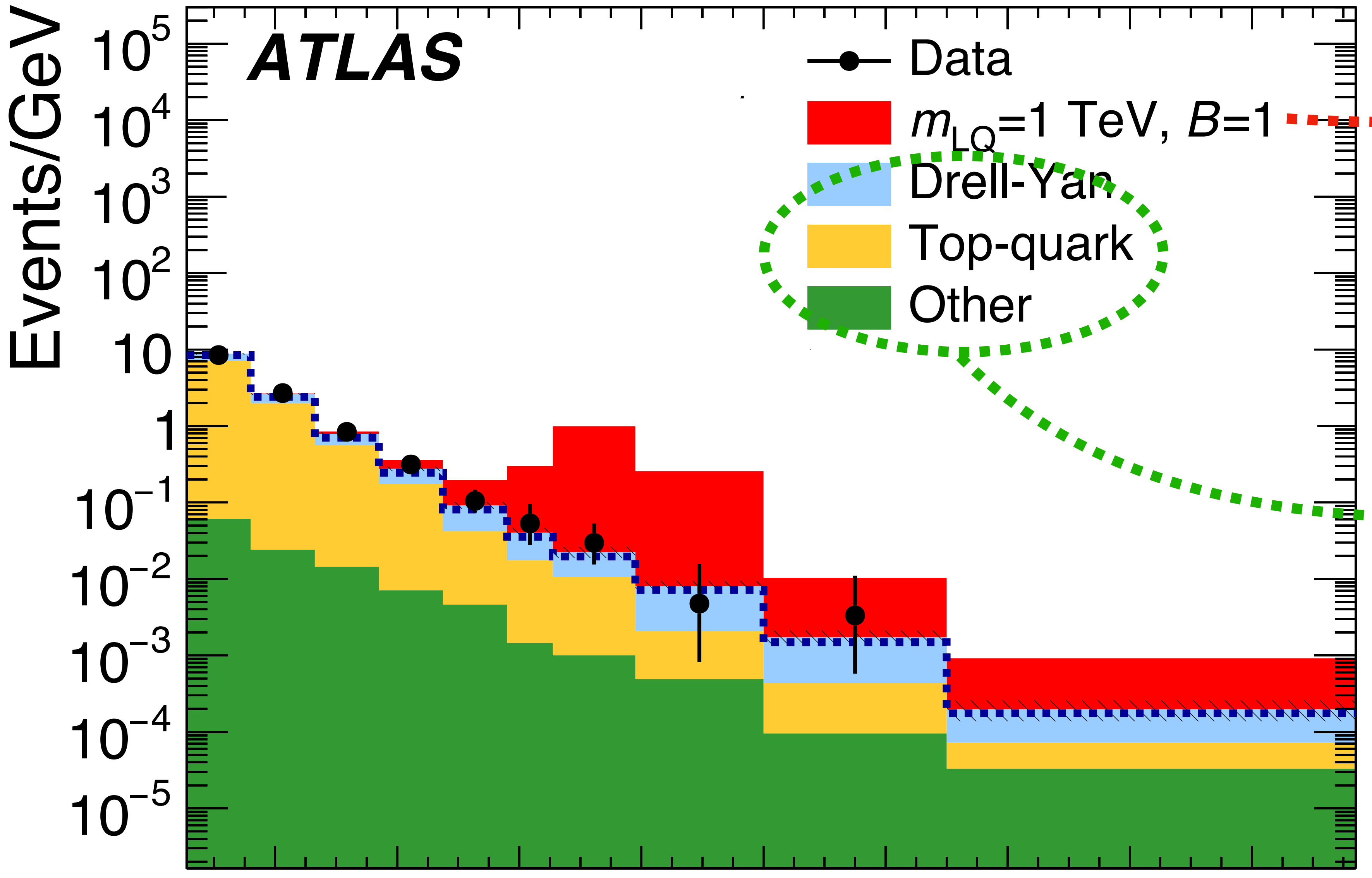
# Searching for New Phenomena

NEW!

⇒ Construct histograms & Compare to real data!

e.g.:




Some Observable Quantity [GeV]

Hypothetical particle

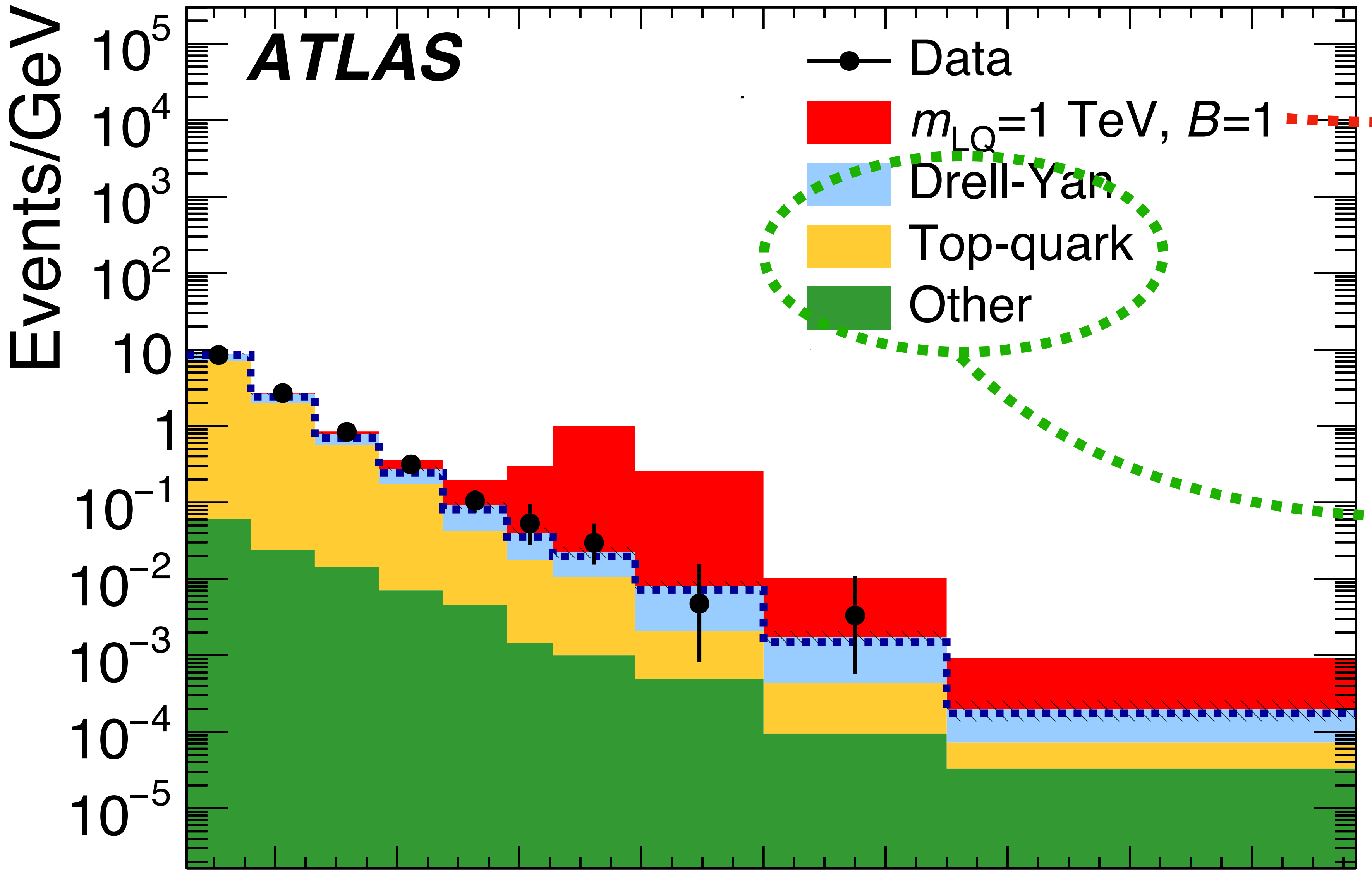
Simulation of stuff that we know exist!

# Searching for New Phenomena

NEW!

Hypothetical particle

⇒ Construct histograms & Compare to real data! e.g.:




Some Observable Quantity [GeV]

Simulation of stuff that we know exist!

⇒ Determine whether a hypothetical particle is compatible with data!

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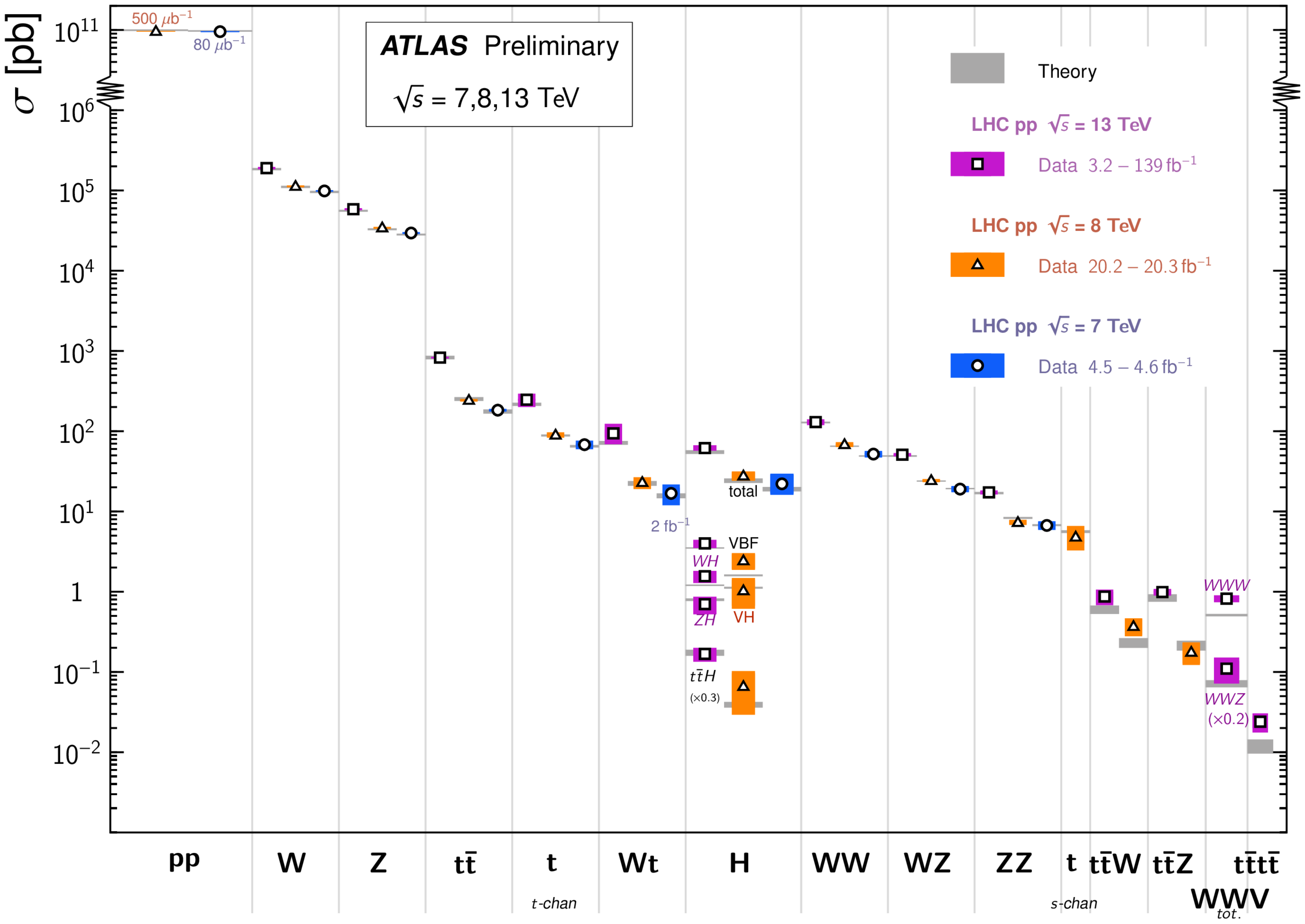
# Experiment VS Theory

Standard Model Total Production Cross Section Measurements

Status: February 2022




Cross Section [pb]

~ Frequency of type of event

Process Type



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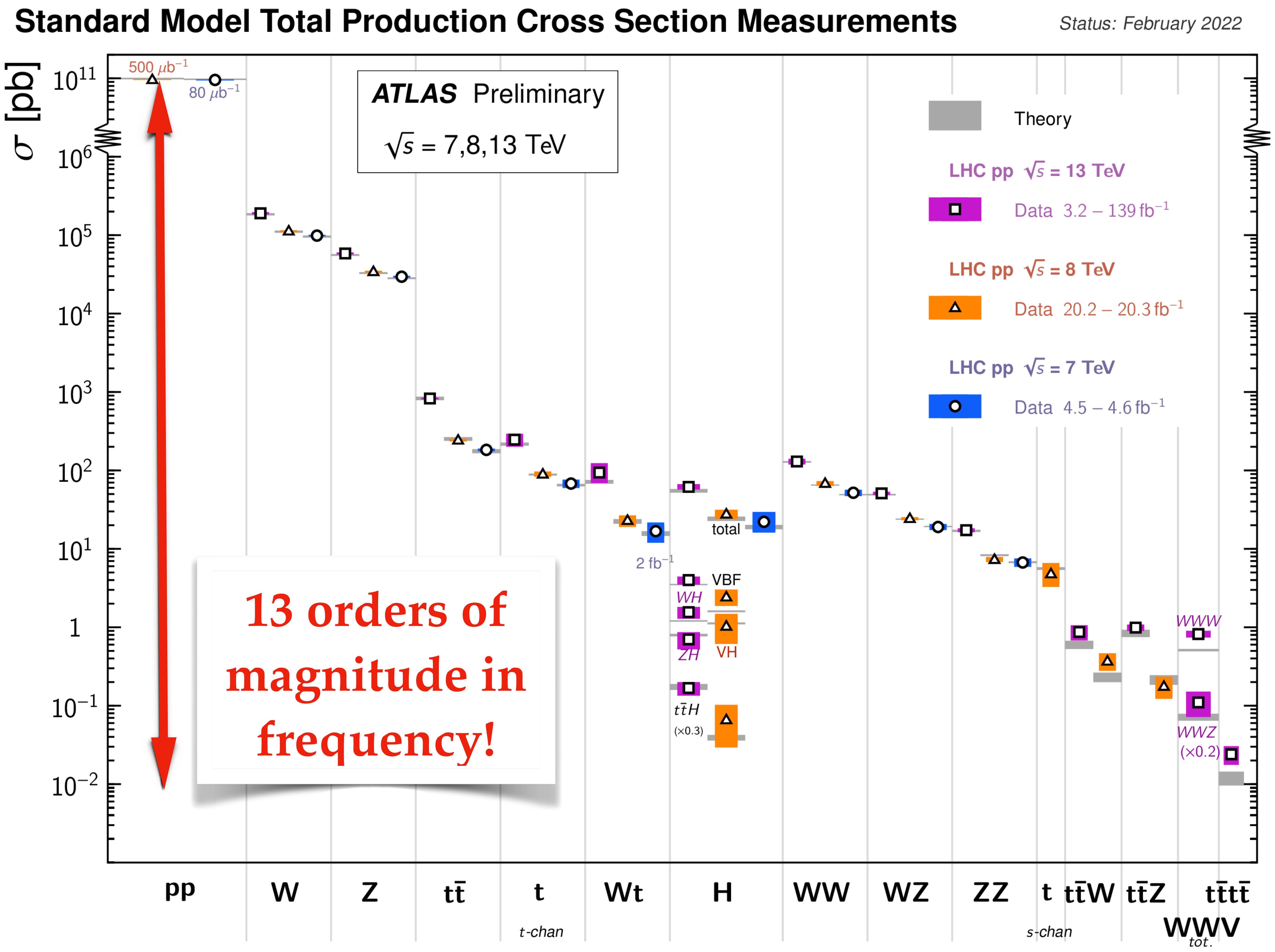
# Experiment VS Theory

Cross Section [pb]

~ Frequency of type of event




Process Type



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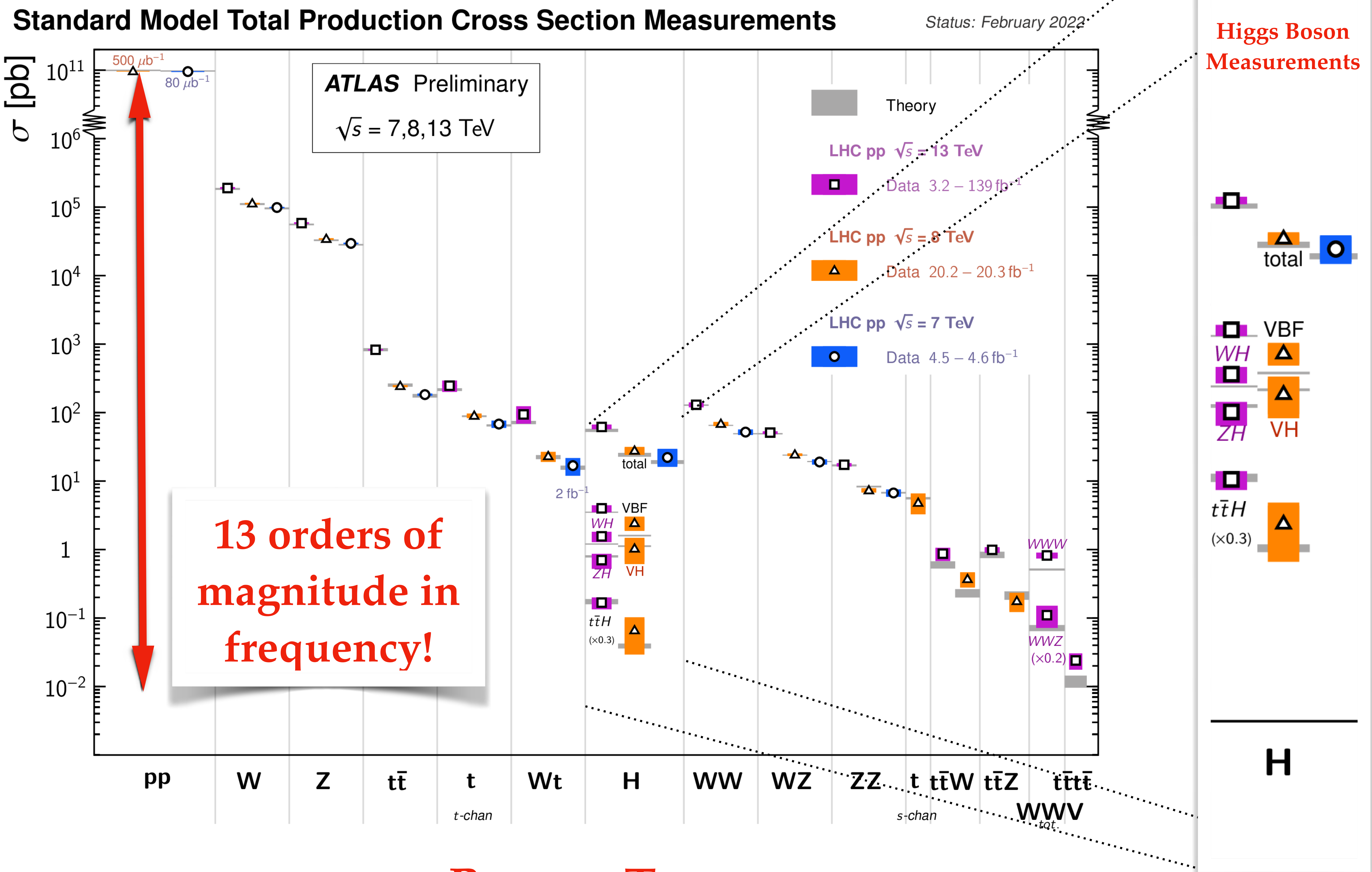


Cross Section [pb]

~ Frequency of type of event

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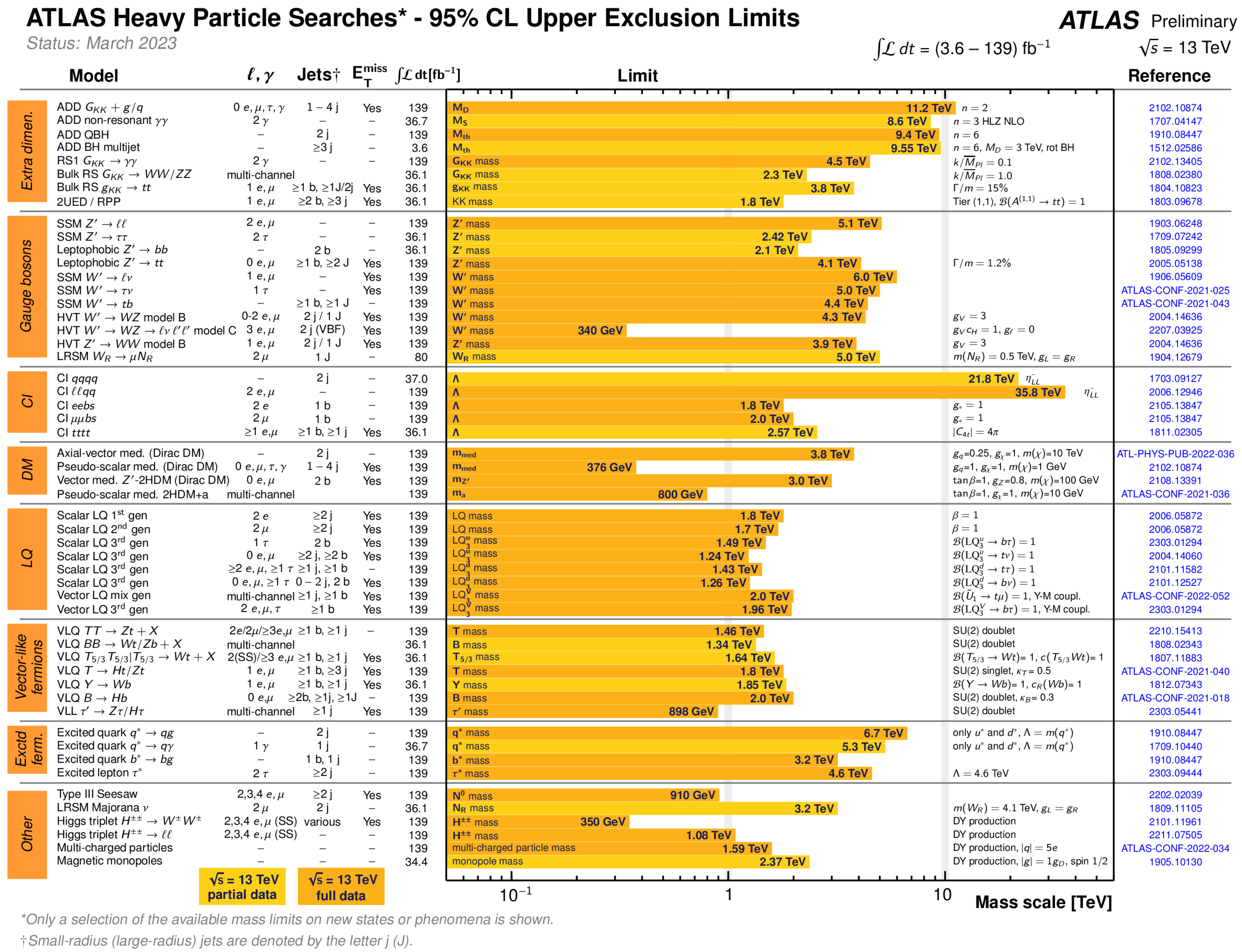
# Experiment VS New Phenomena



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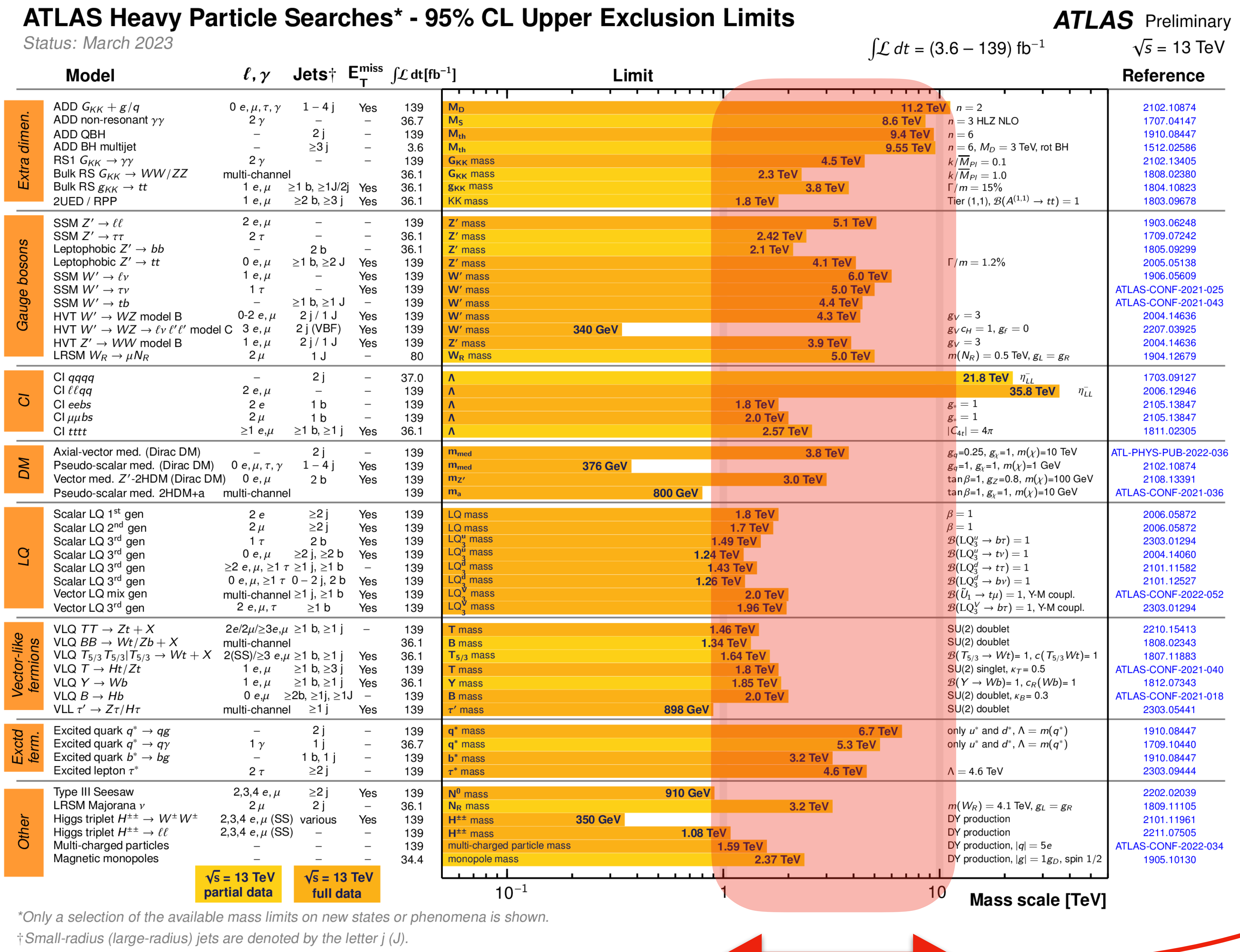


**Mass Scale limits: 1-10 TeV**



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# STANDARD MODEL WINS!

⇒ ***No*** **new phenomena!?**


[credit: Alvaro Rujula, Found in a CERN TH office]

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# STANDARD MODEL WINS!

⇒ *No* new phenomena!?


[credit: Alvaro Rujula, Found in a CERN TH office]

# Is that all folks?

# Questions


PHOTOGRAPHY
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Provence

# Questions


# Answers

# Questions

# Answers



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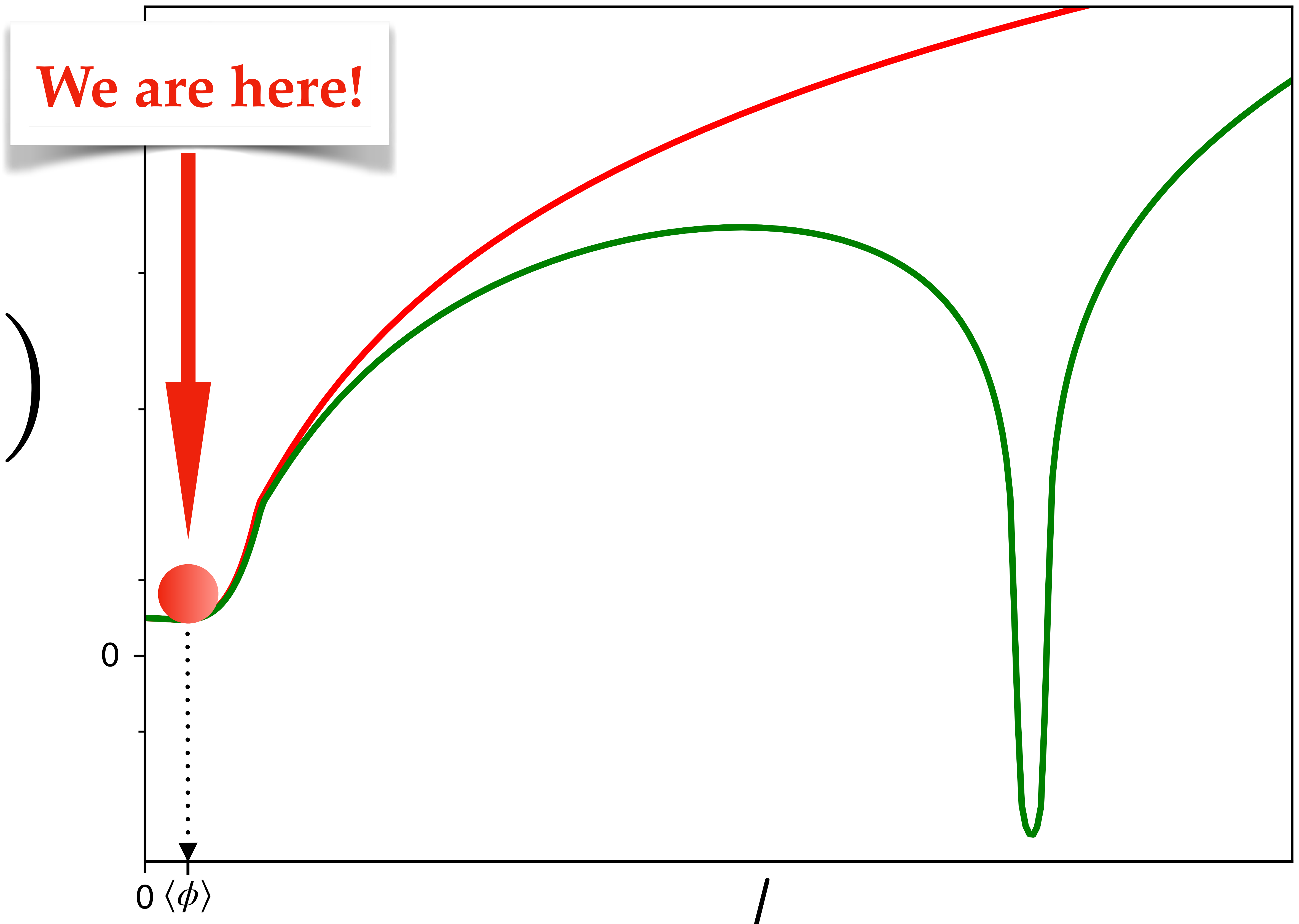
# Questions

# Answers

# 2 Q: What is the ultimate fate of our Universe?

Higgs Potential: $\mathcal{V}(\phi)$




Higgs Field: $\phi$

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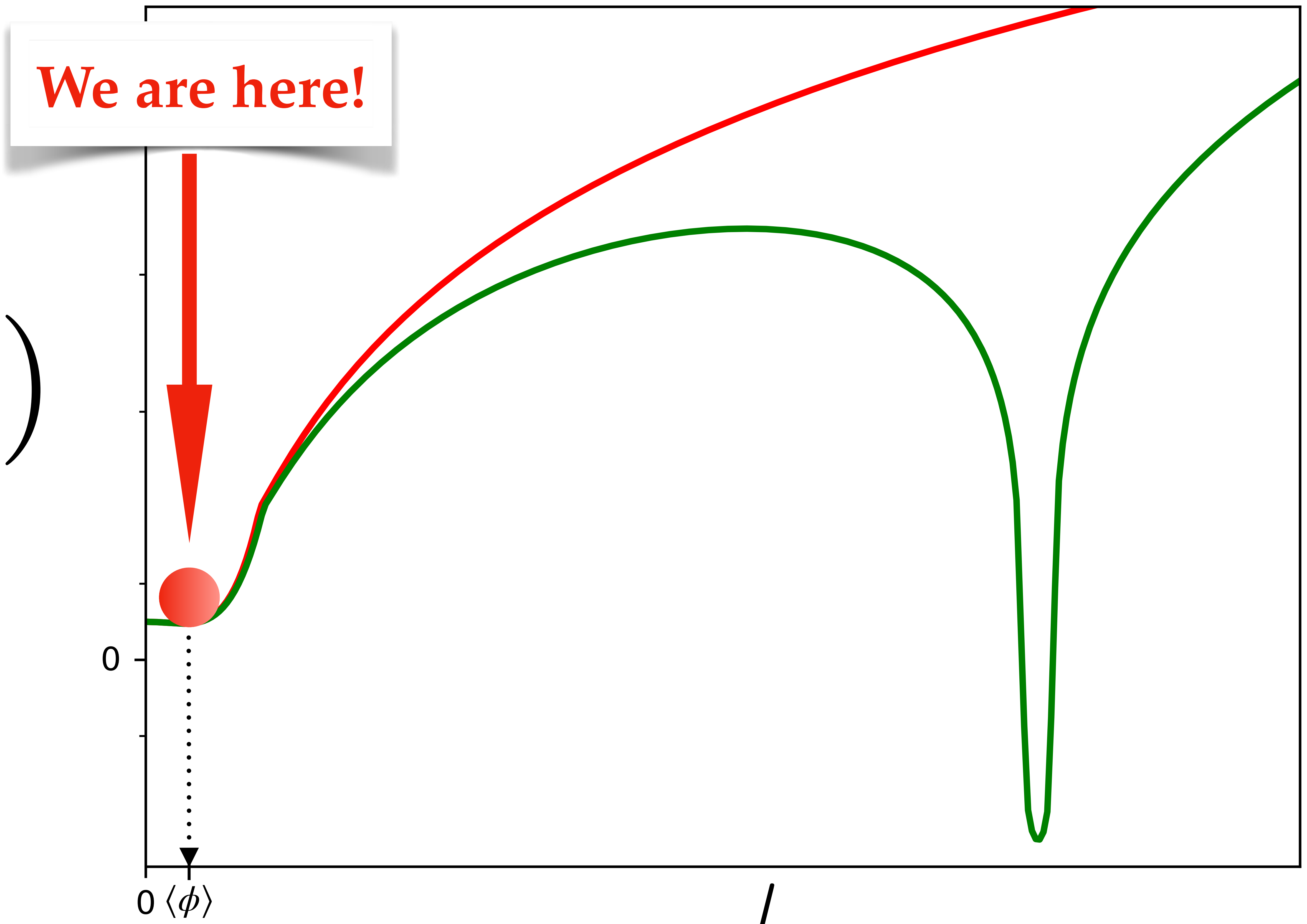


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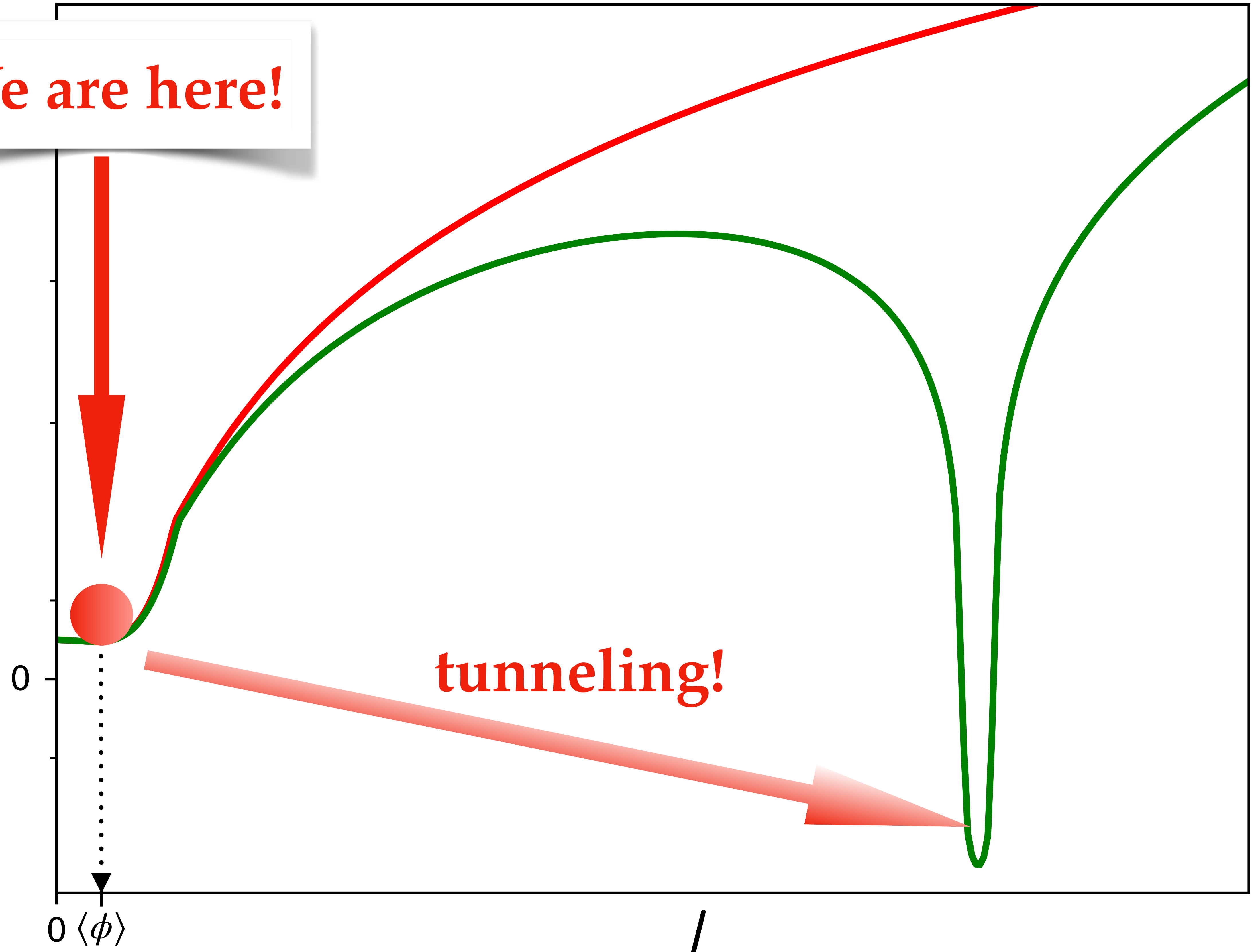


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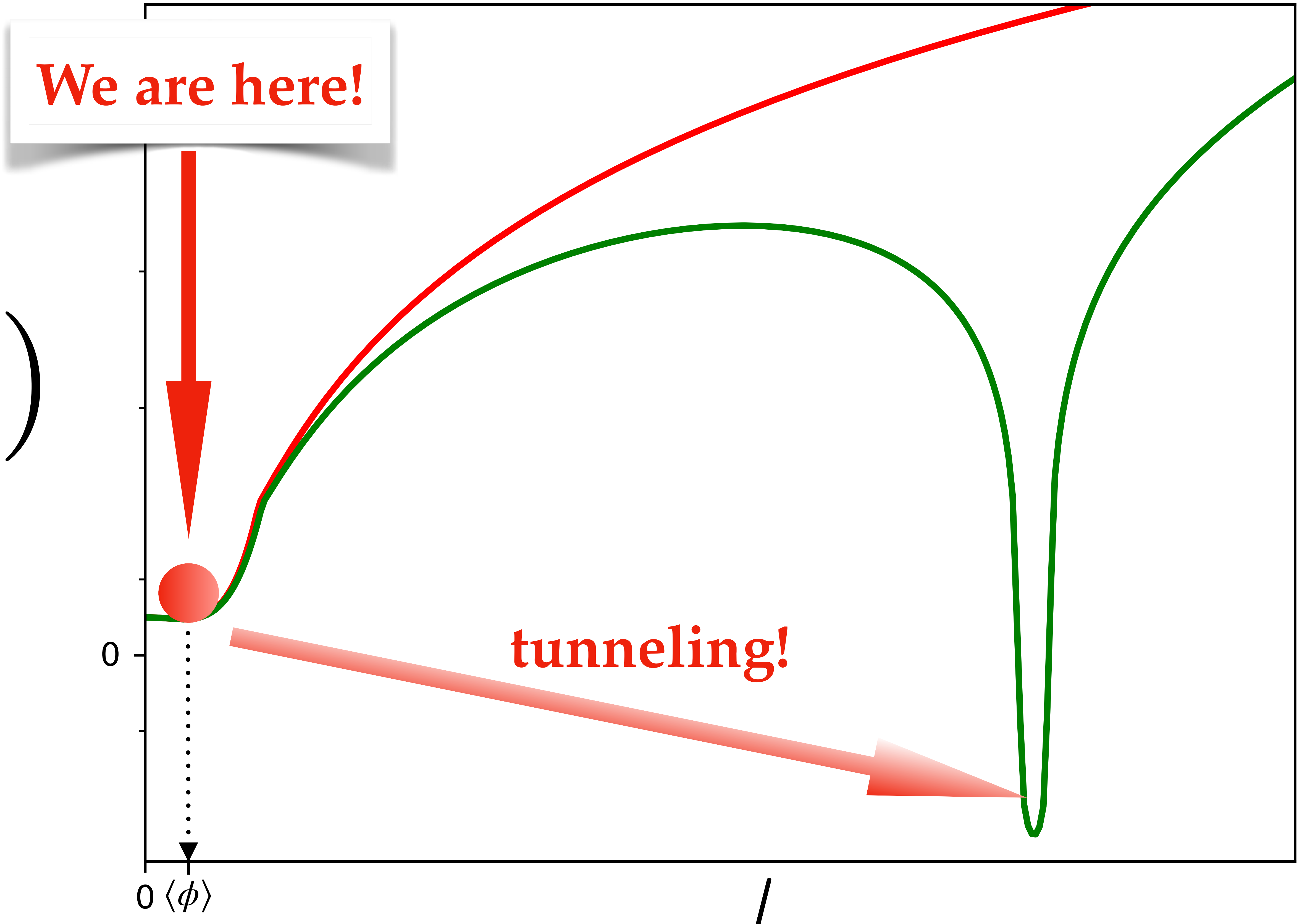


Higgs Field: $\phi$

➜ the **"Vacuum Stability Problem"**.



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# Q: Why does the matter we are made of exist?

**[or: Why is there so much more matter than anti-matter?]**

[credit: QuantaMagazine]



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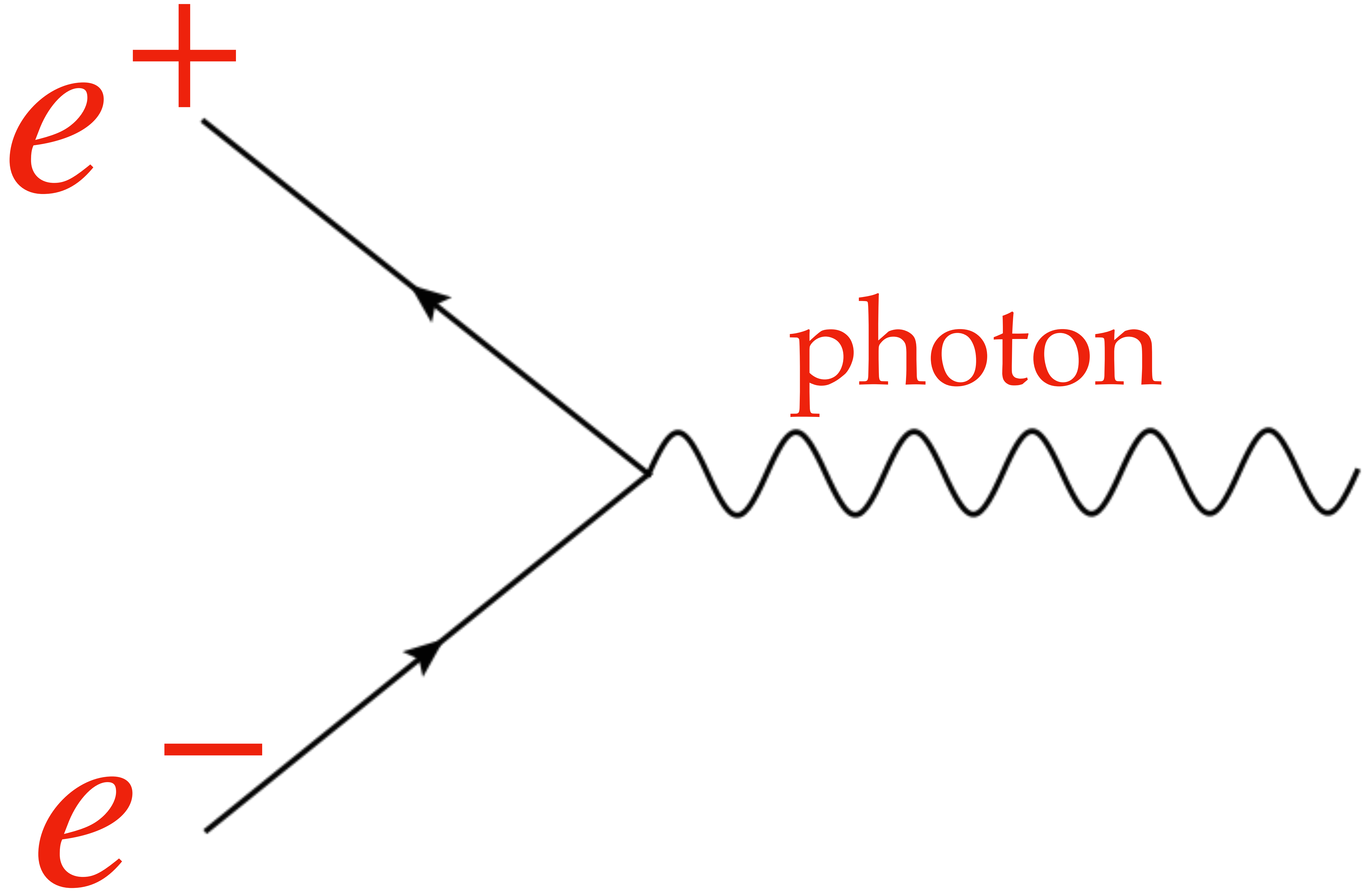

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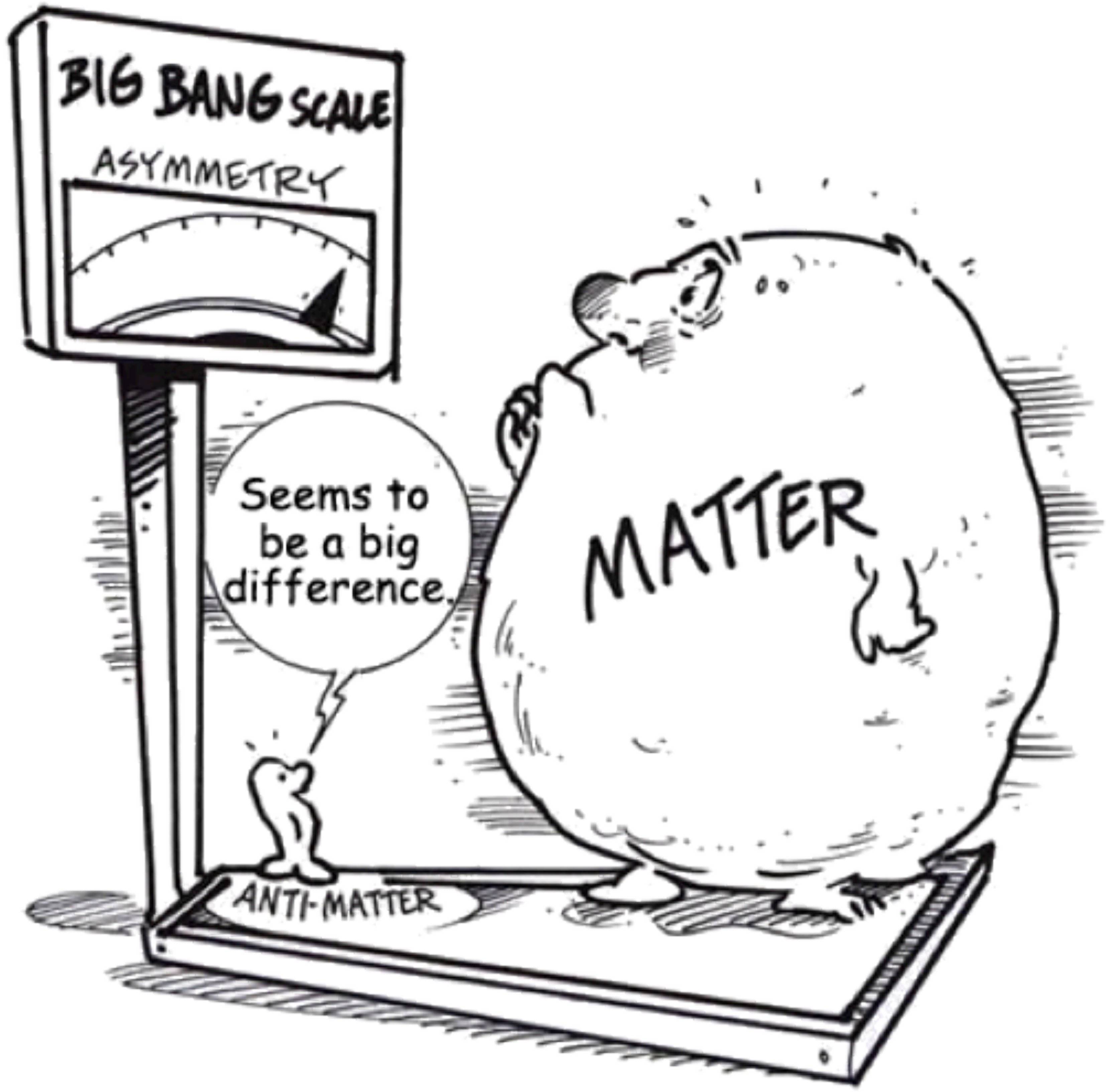

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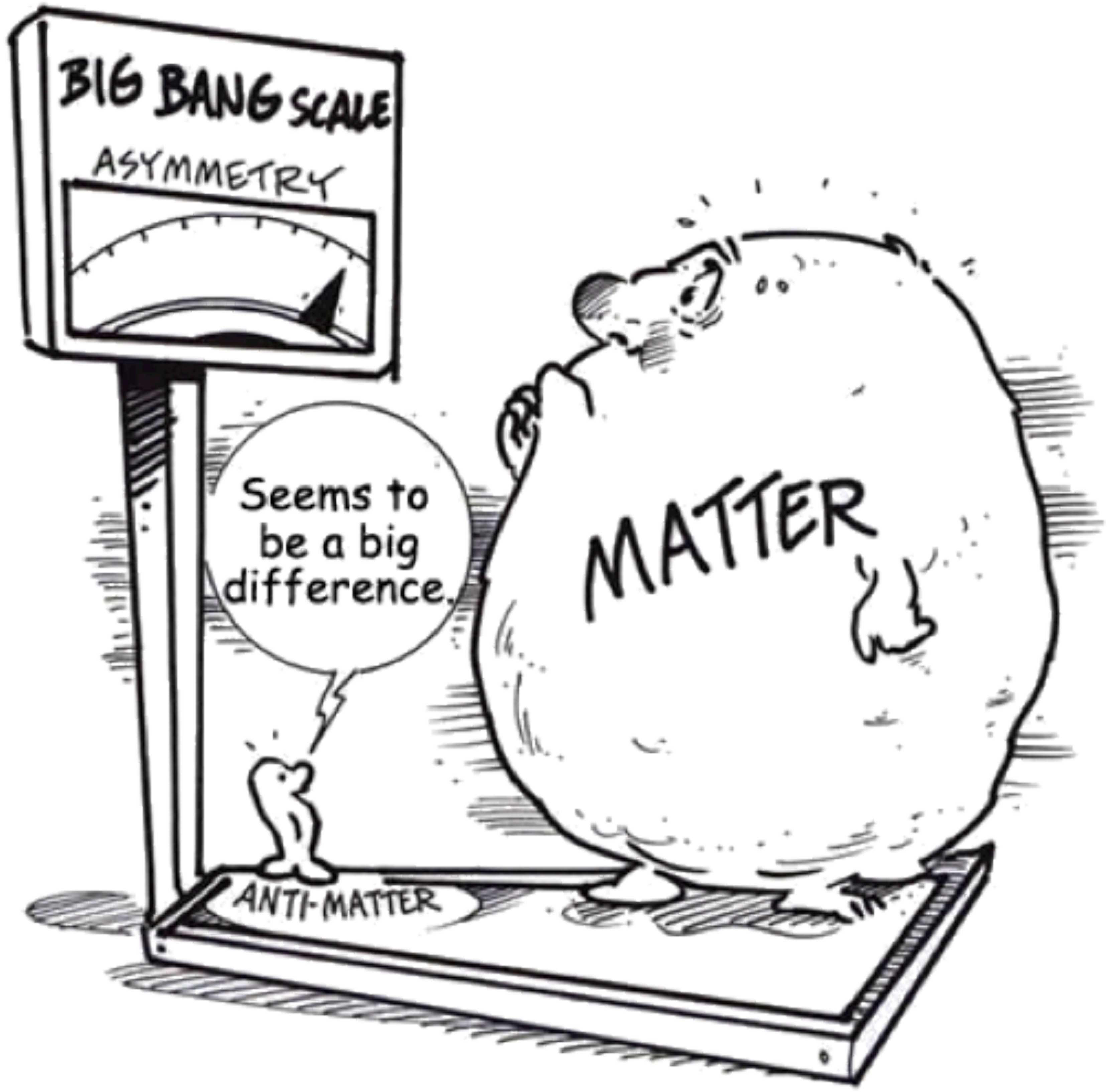
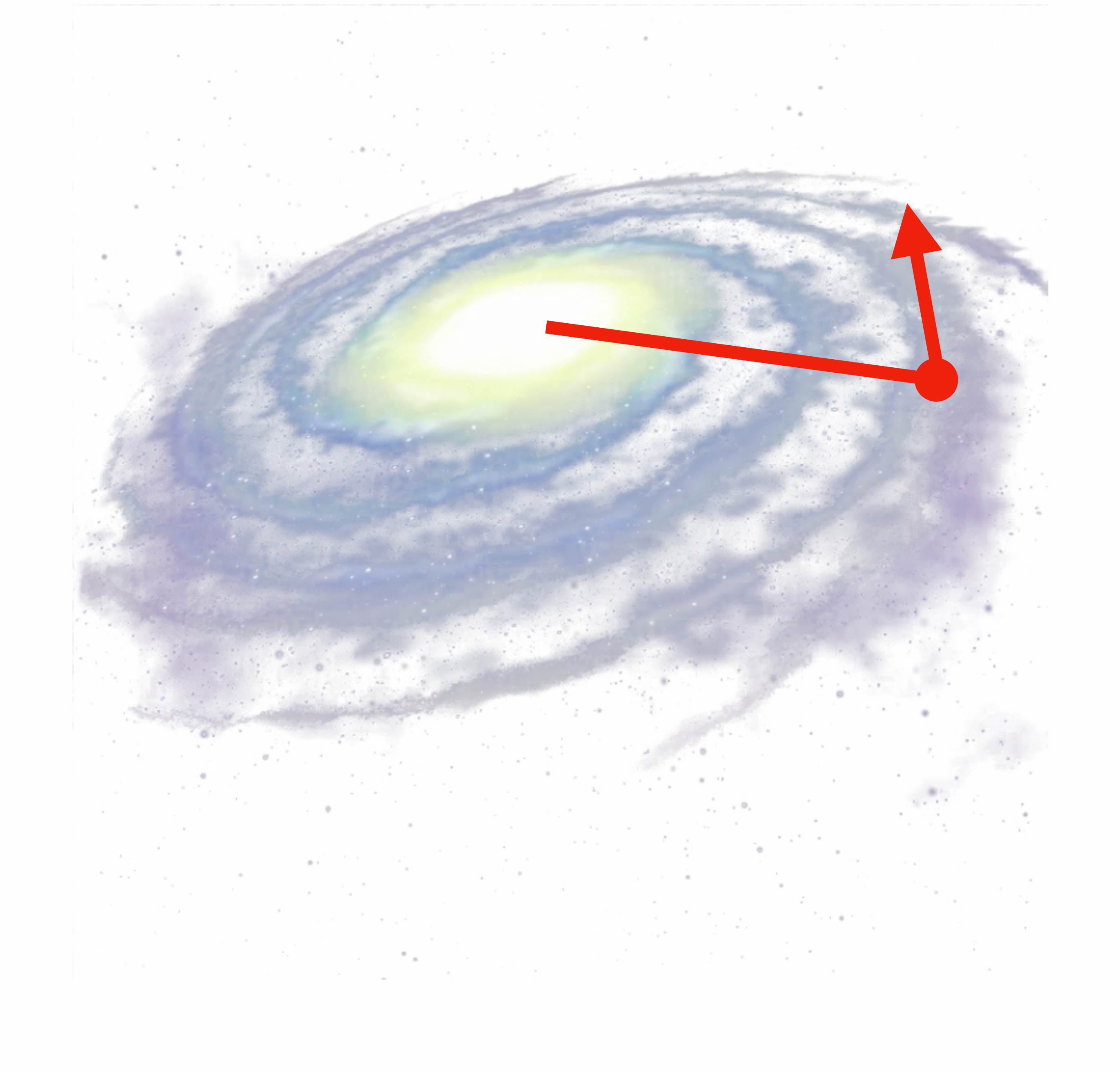
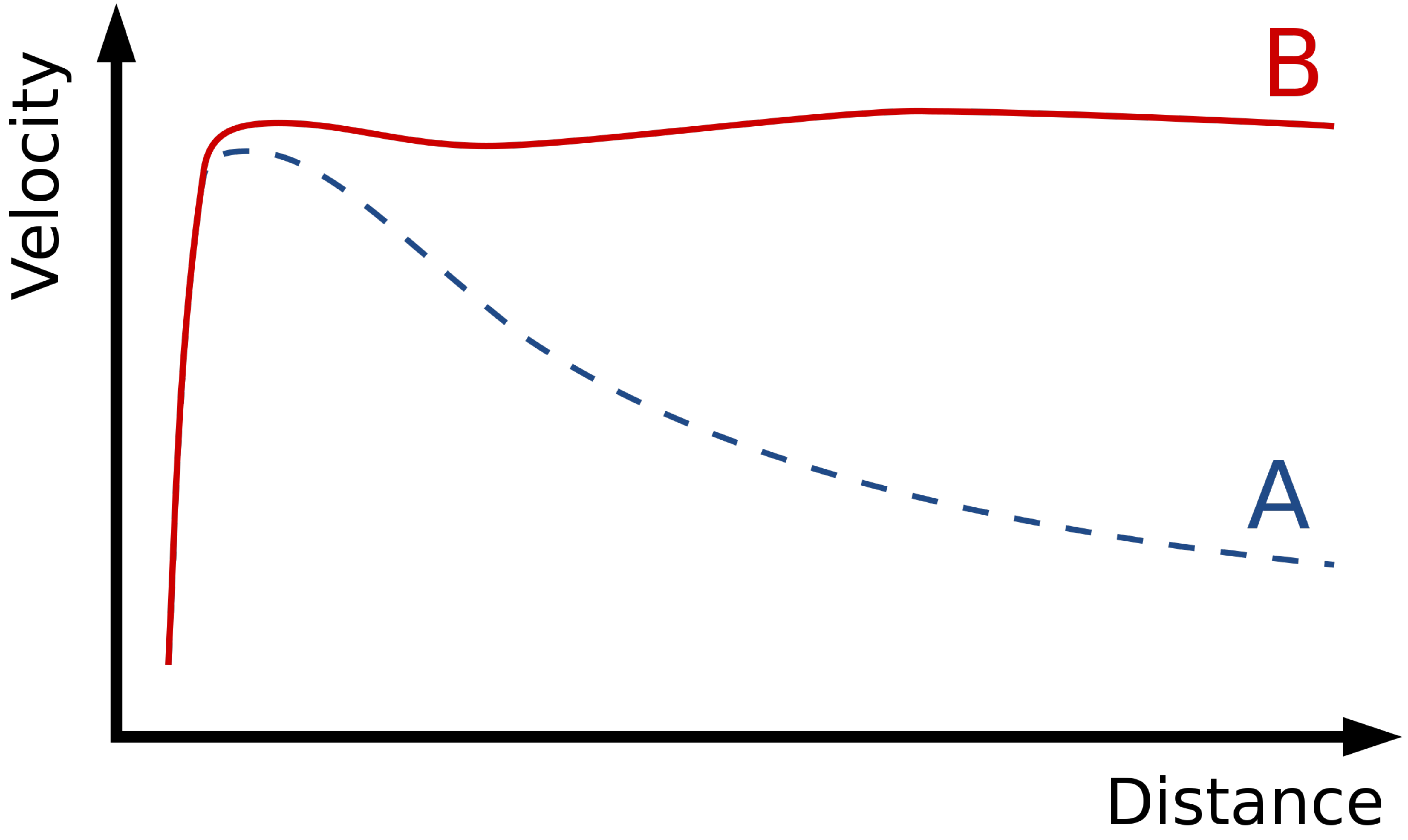



➜ the **"Matter-Anti-Matter Asymmetry"**.

# Q: What is the nature of Dark Matter?

**Rotation curve of a typical spiral galaxy: predicted (A) and observed (B).**





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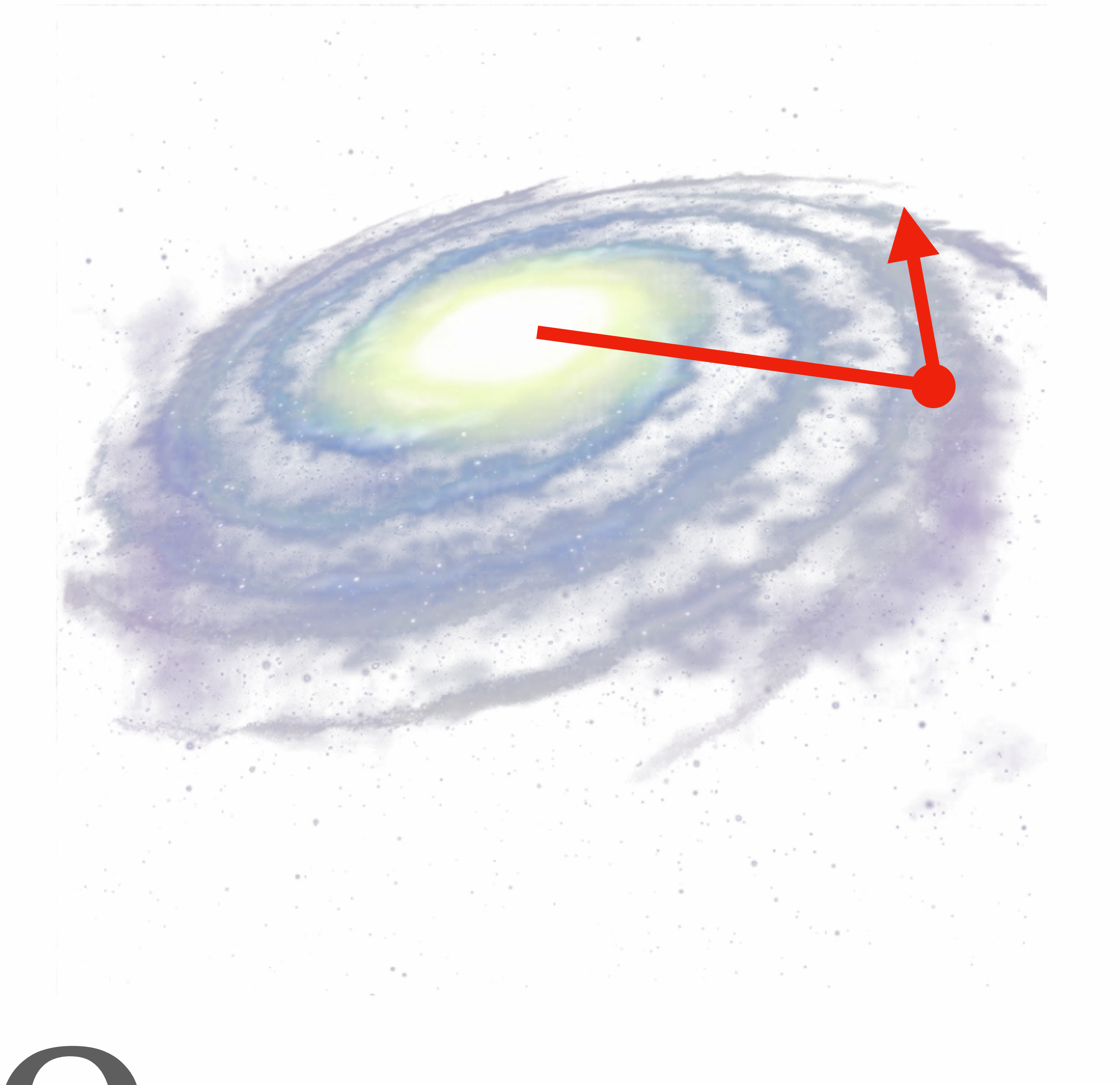

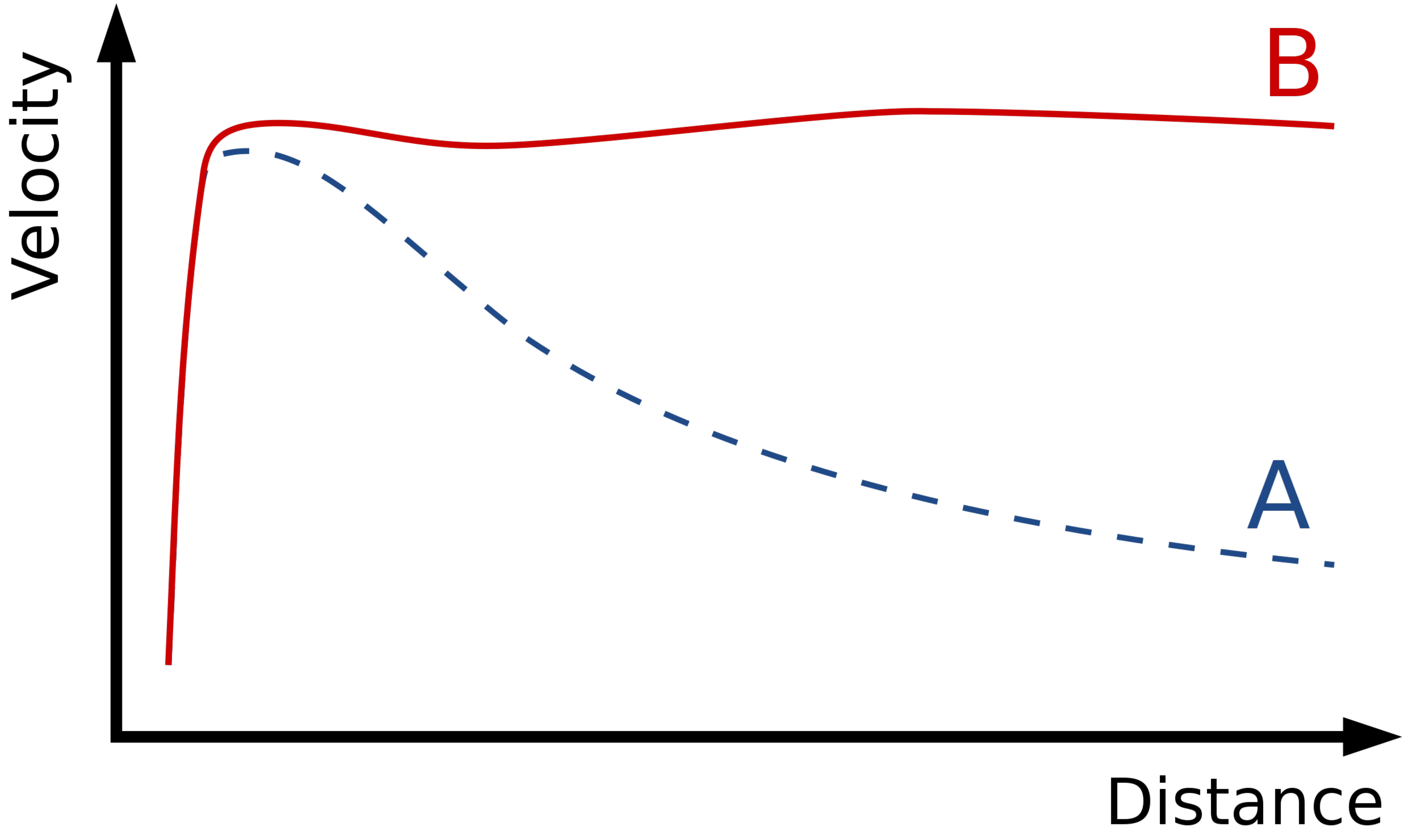


Q: …

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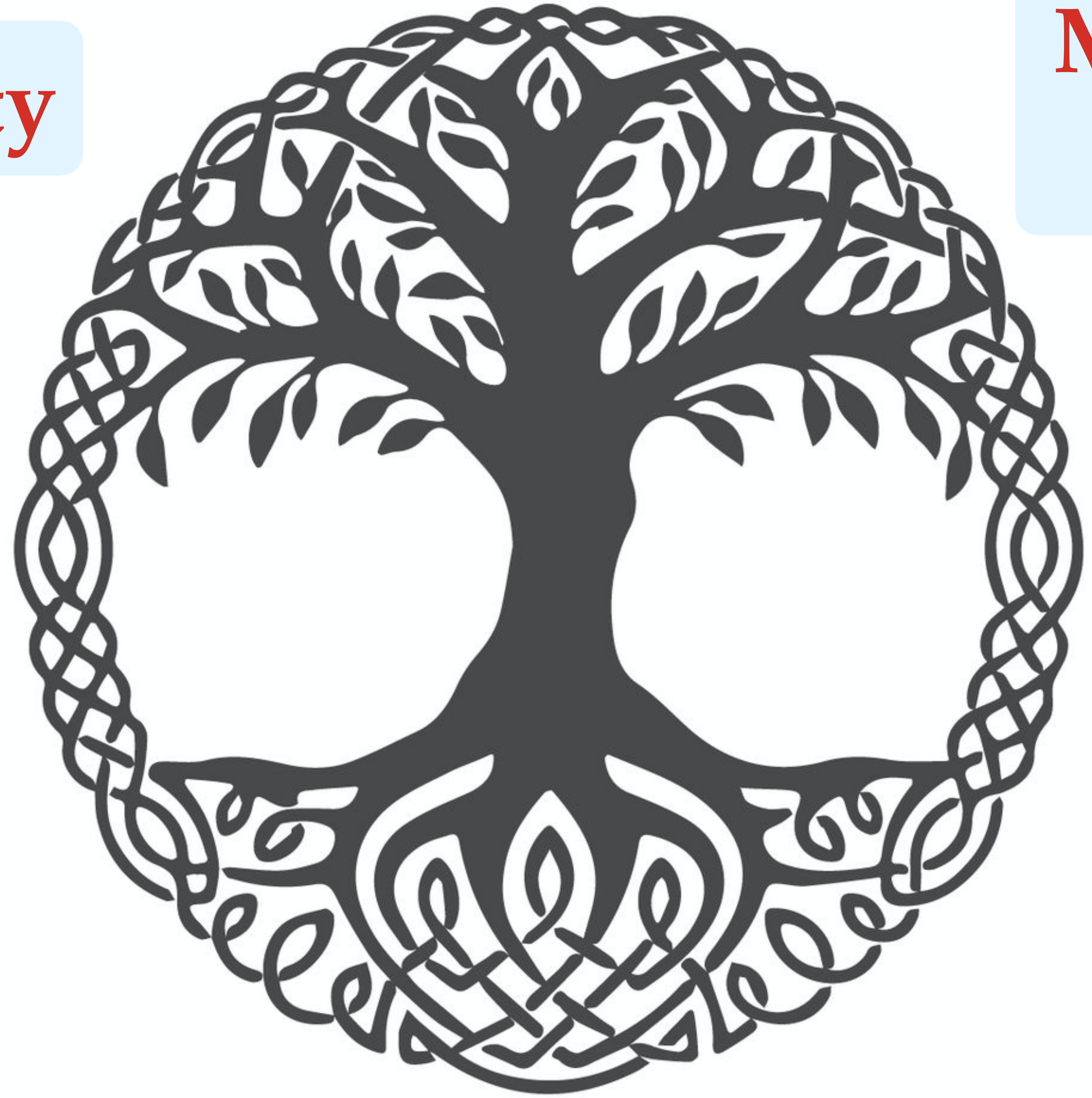
Dark Matter

Vacuum Stability

Matter-anti-matter Asymmetry

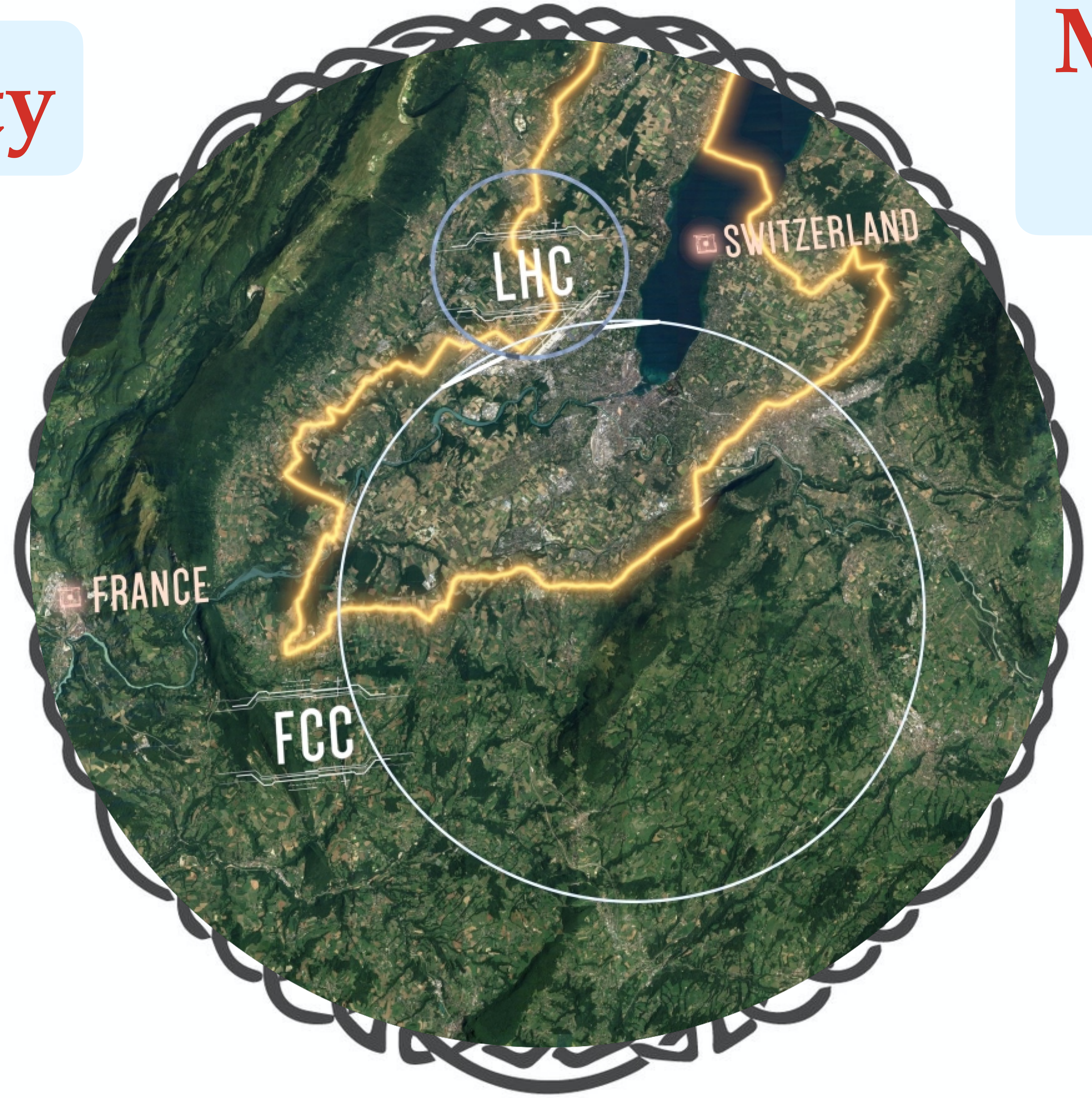


The Higgs Field & Symmetry Breaking

Dark Matter

Vacuum Stability

Matter-anti-matter Asymmetry




e.g. Future Circular Collider: pp@100 TeV, $e^+e^-$.

e.g. "High-Energy" LHC: pp@27 TeV.

e.g. Muon Collider.

The Higgs Field & Symmetry Breaking

# 3 Breaking the Symmetry

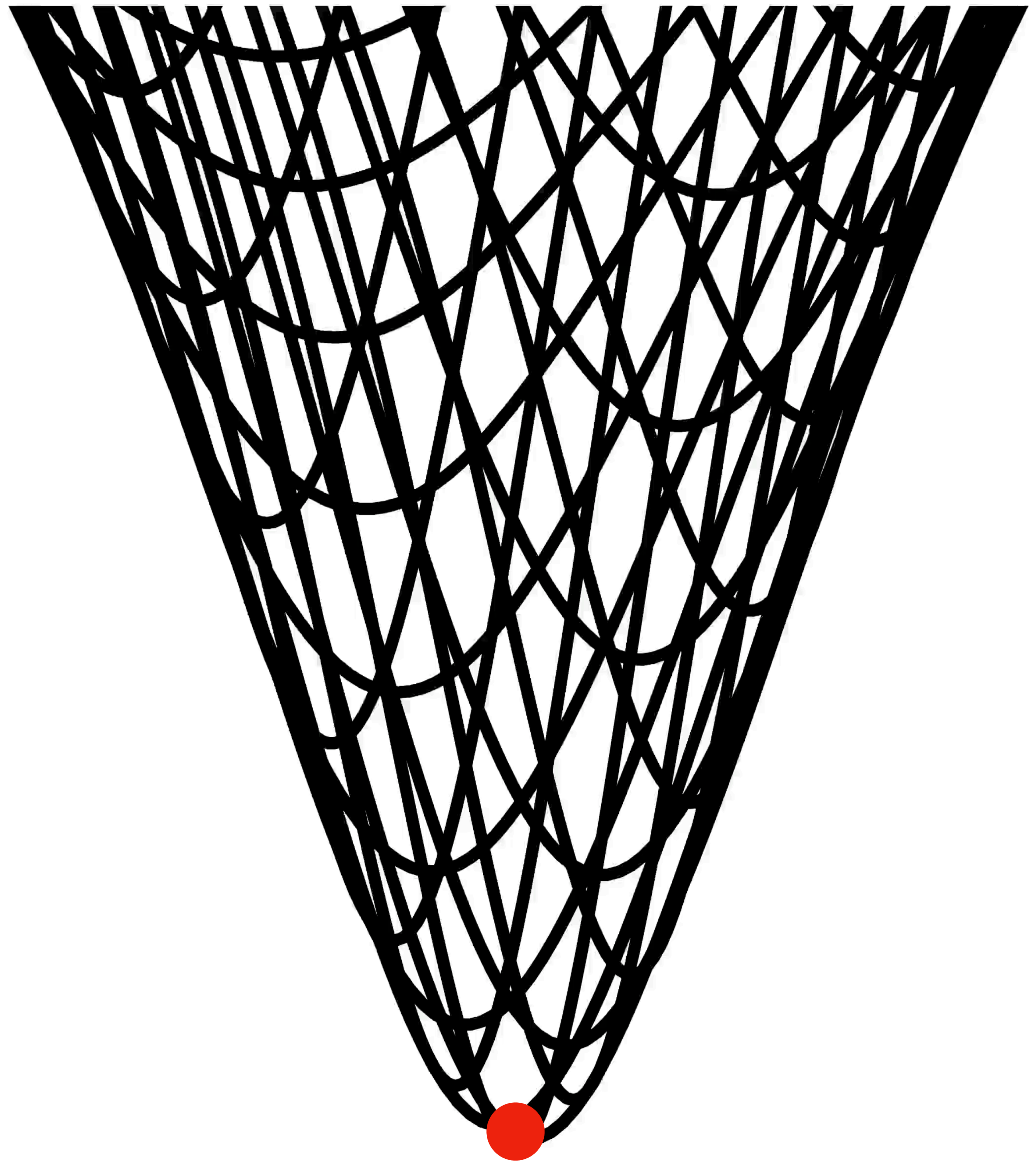
# Breaking the Symmetry

# Breaking the Symmetry in the Standard Model

**The potential of the Higgs field ($\phi$), a complex doublet:**

$$\phi = \begin{pmatrix} \phi_1 + i\phi_3 \\ \phi_2 + i\phi_4 \end{pmatrix}$$

**(Arbitrarily) Set $\phi_3 = \phi_4 = 0$ to illustrate potential in $(\phi_1, \phi_2)$ plane.**



$\mathscr{V}(\phi)$

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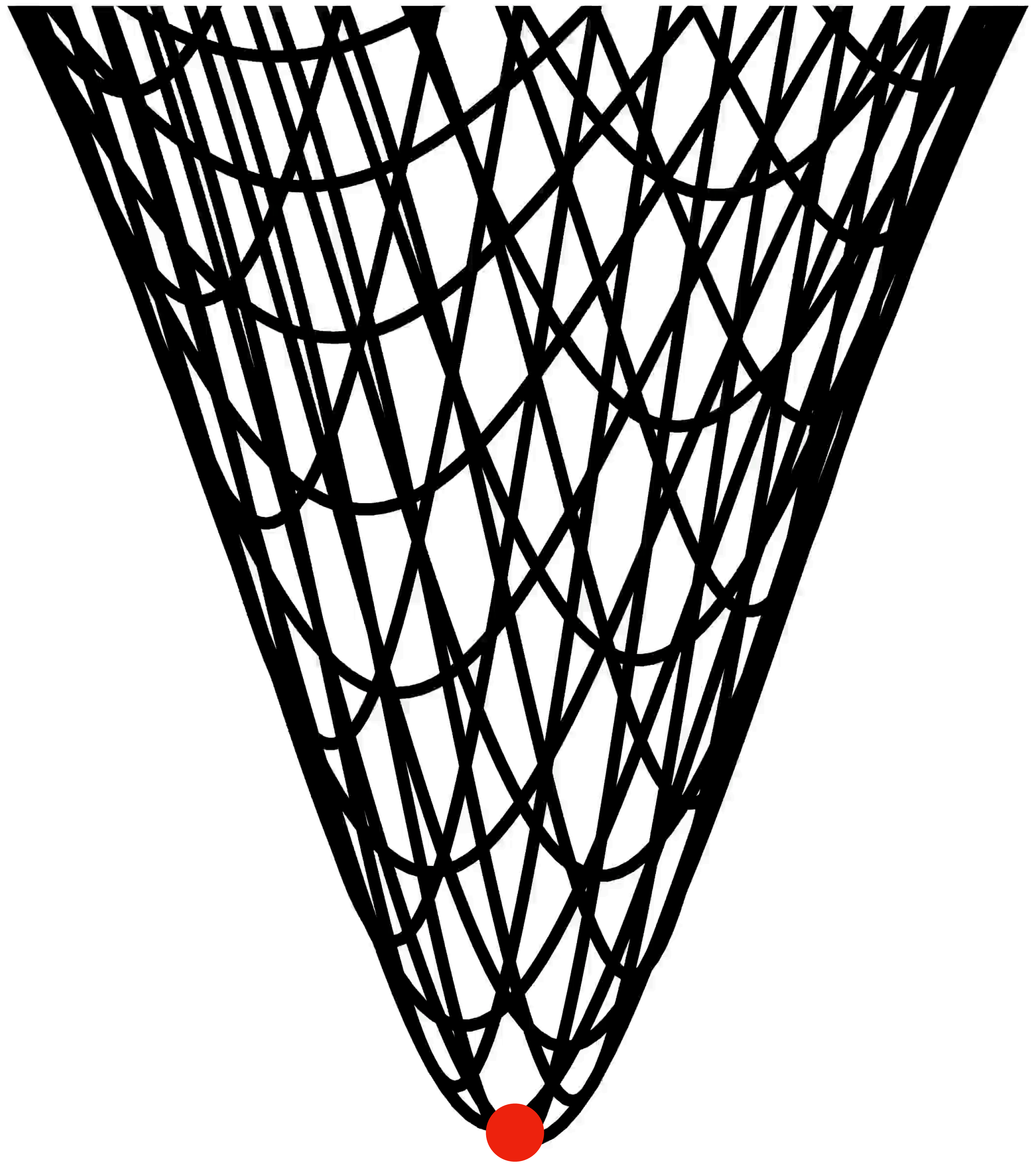

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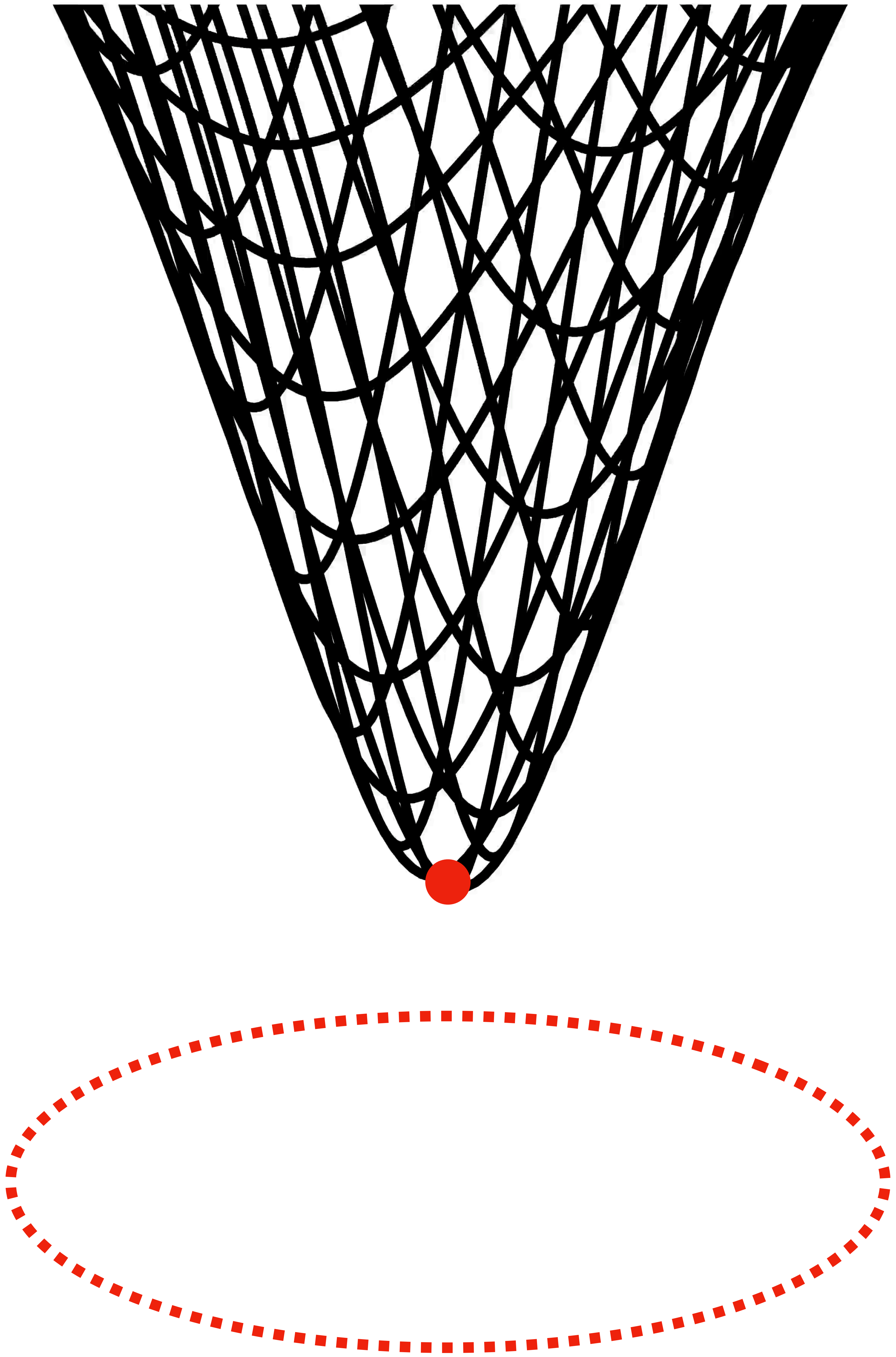

$\mathscr{V}(\phi)$



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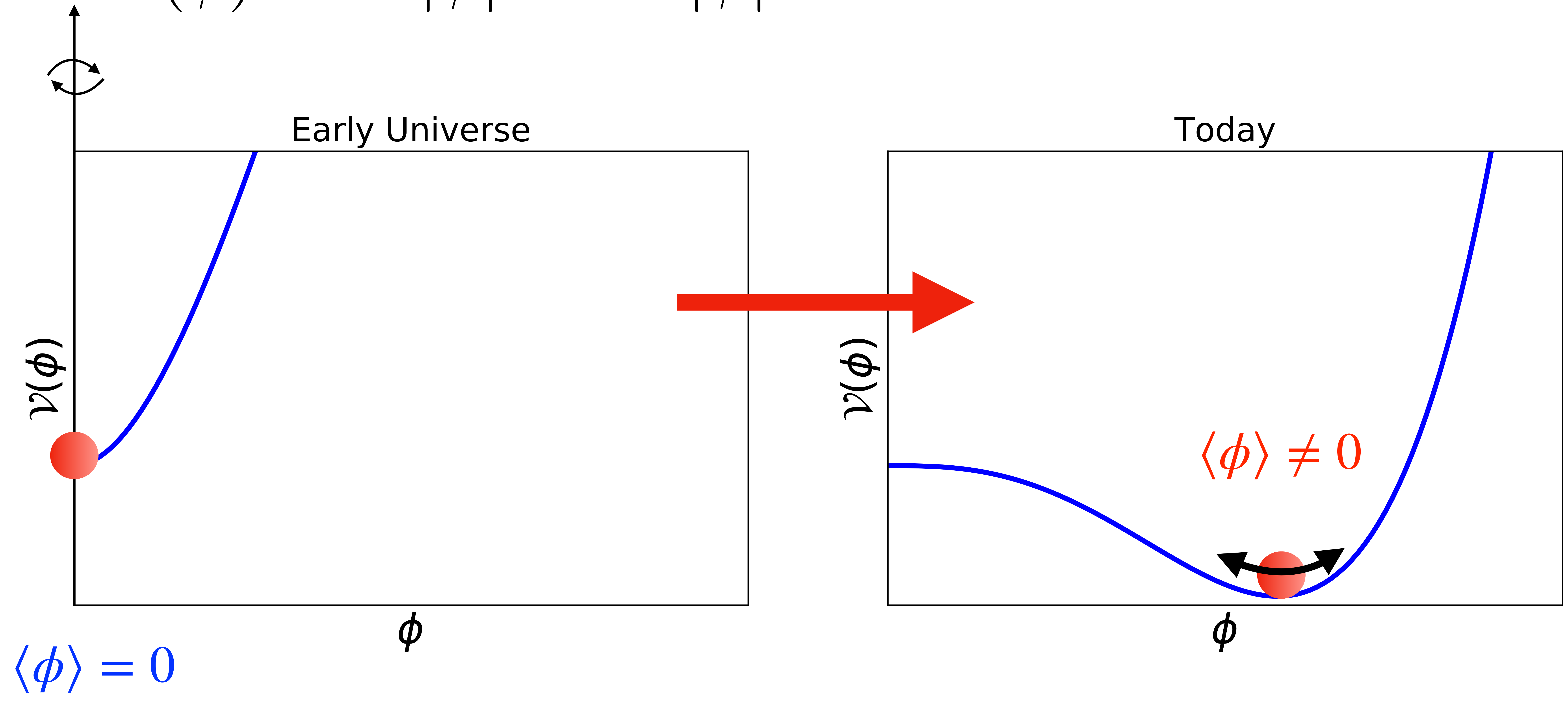
# Breaking the Symmetry in the Standard Model

$$\mathcal{V}(\phi) = \bullet\,|\phi|^2 + \blacksquare\,|\phi|^4$$

**Higgs field ($\phi$) potential**

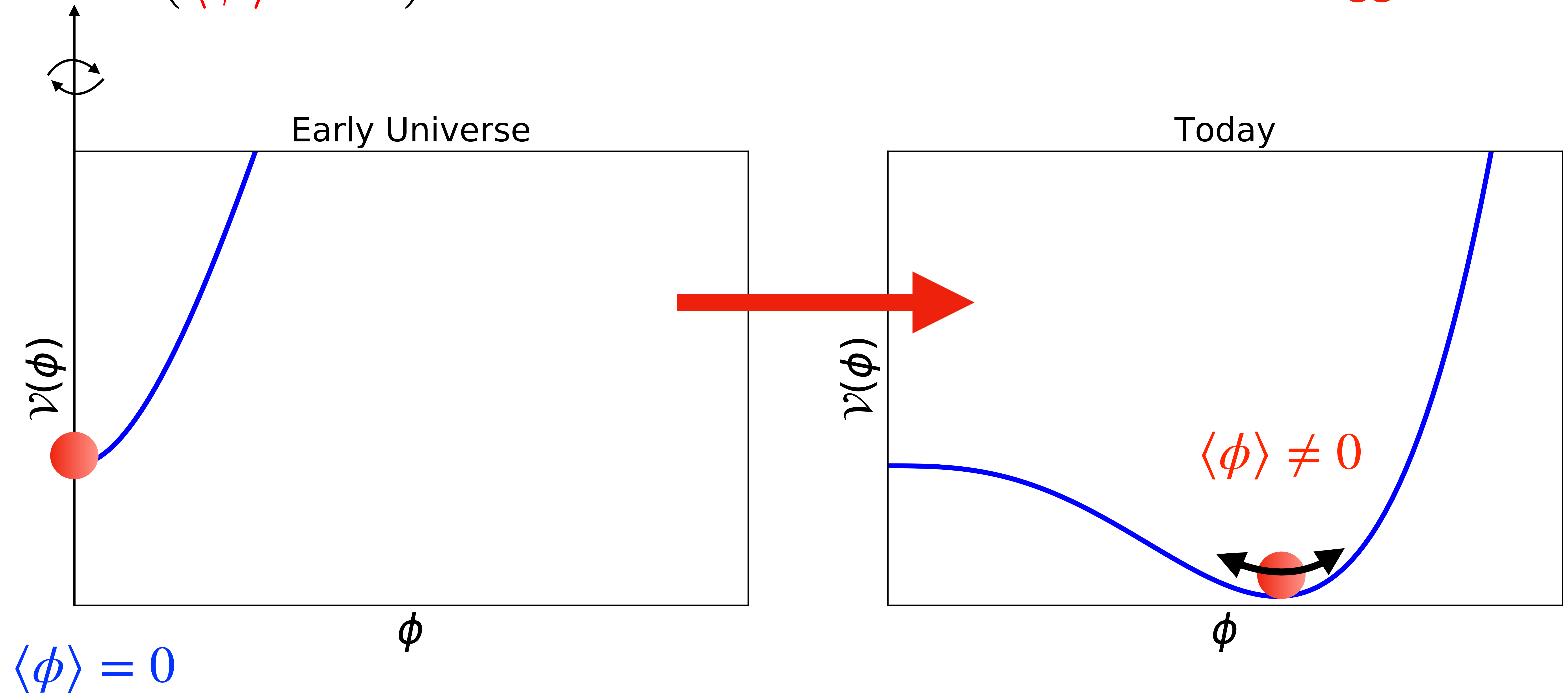



More Symmetry → Less (obvious) Symmetry

# Breaking the Symmetry in the Standard Model

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$ → *h* **is the Higgs boson! (LHC, 2012)**

**Higgs field ($\phi$) potential**

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# Breaking the Symmetry in the Standard Model

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$ → $h$ **is the Higgs boson! (LHC, 2012)**

$$\mathscr{L} \supset \star\, \bar{\psi}\phi\psi \to \star\, \langle\phi\rangle\, \bar{\psi}\psi + \ldots$$ → **e.g. explains Fermion masses!**

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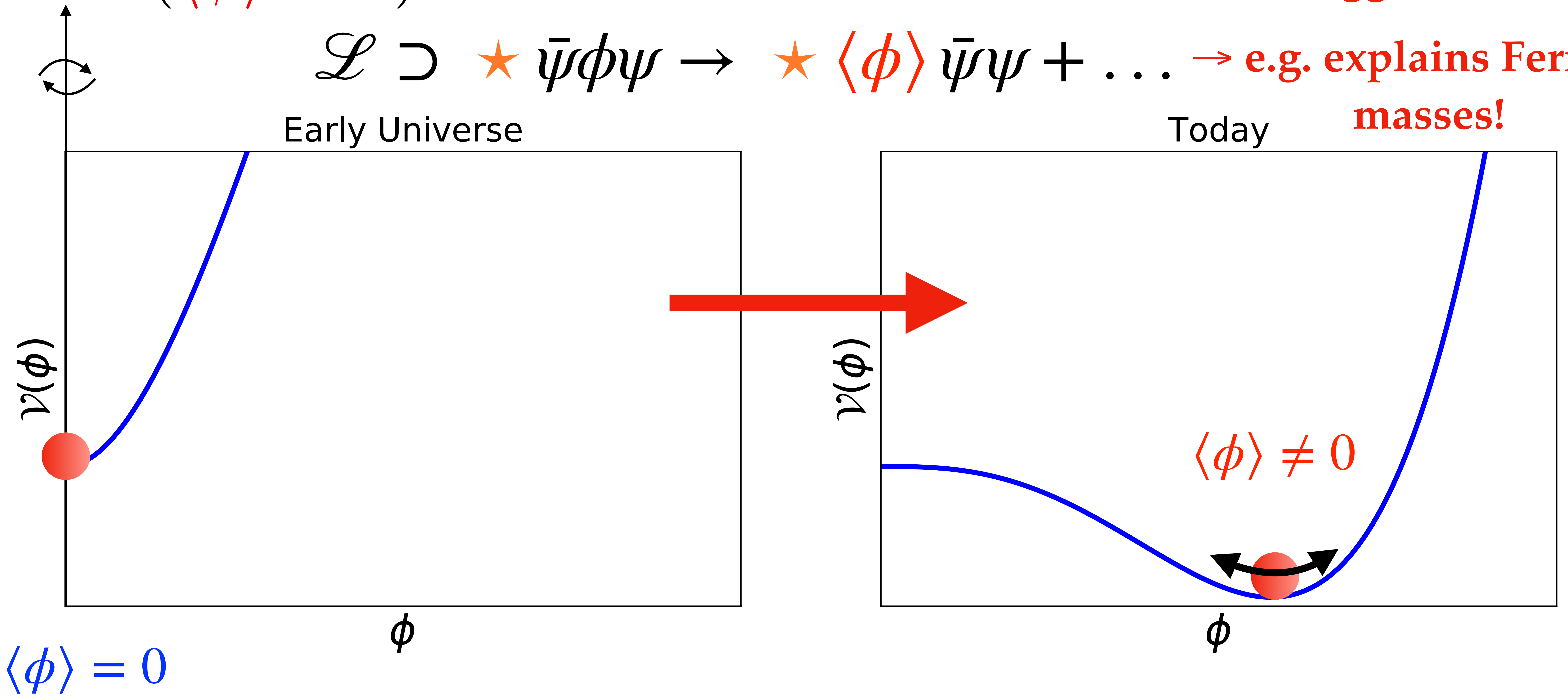


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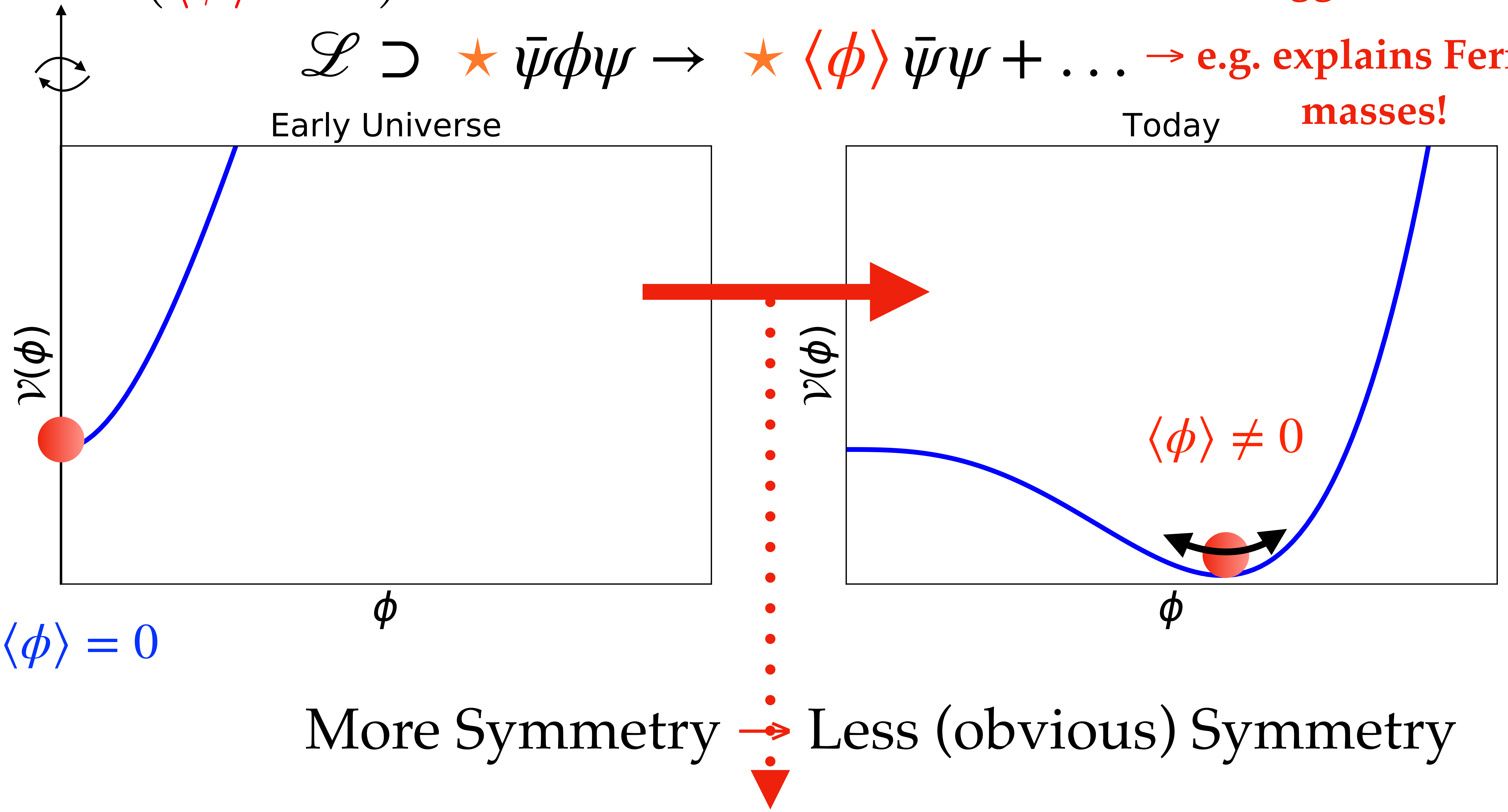


**≡ Electro-Weak Phase Transition (EWPT)**



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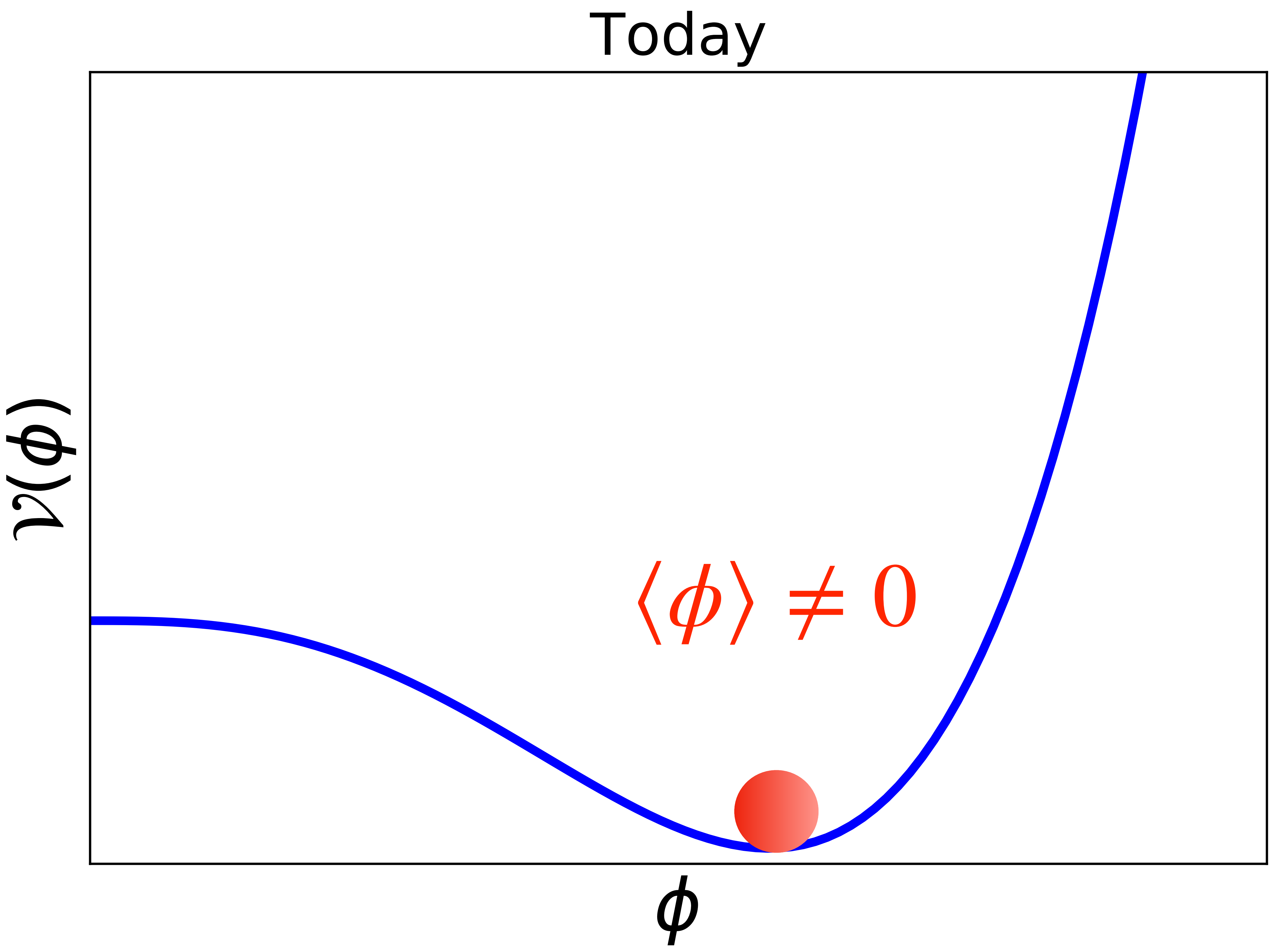
# The Higgs Boson's Potential

$$\mathcal{V}(\langle\phi\rangle + h) = \bullet h^2 + \blacktriangle h^3 + \blacksquare h^4$$ → **the Higgs boson's self-interactions.**




→ **Determine shape of potential by measuring:**

$$\{\bullet, \blacktriangle, \blacksquare\}$$

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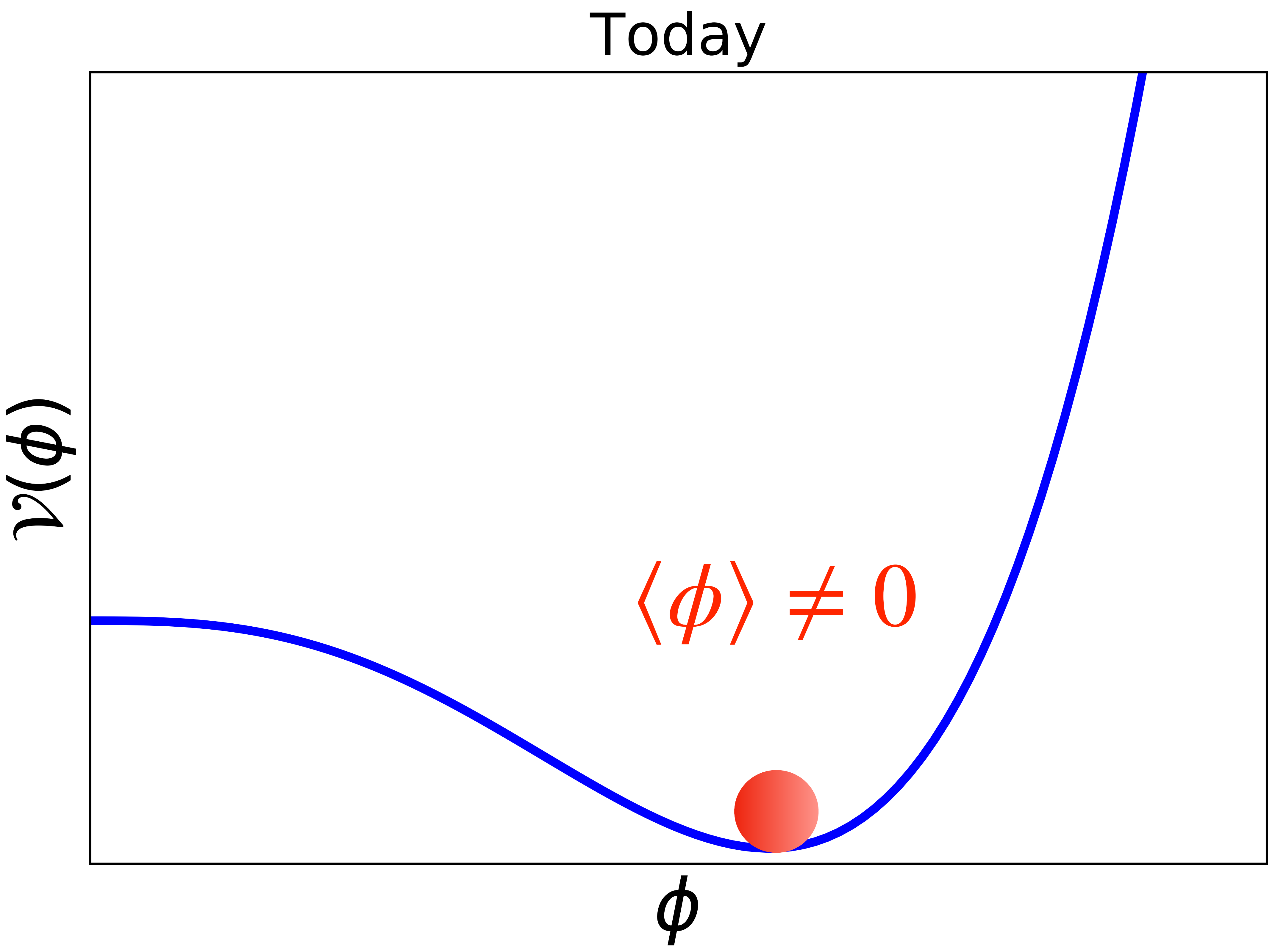


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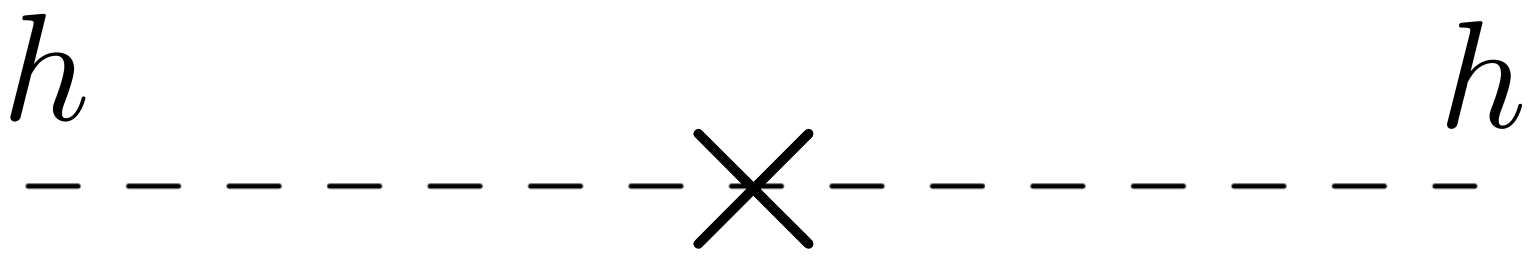


**Higgs boson discovery @ LHC, 2012** ✅

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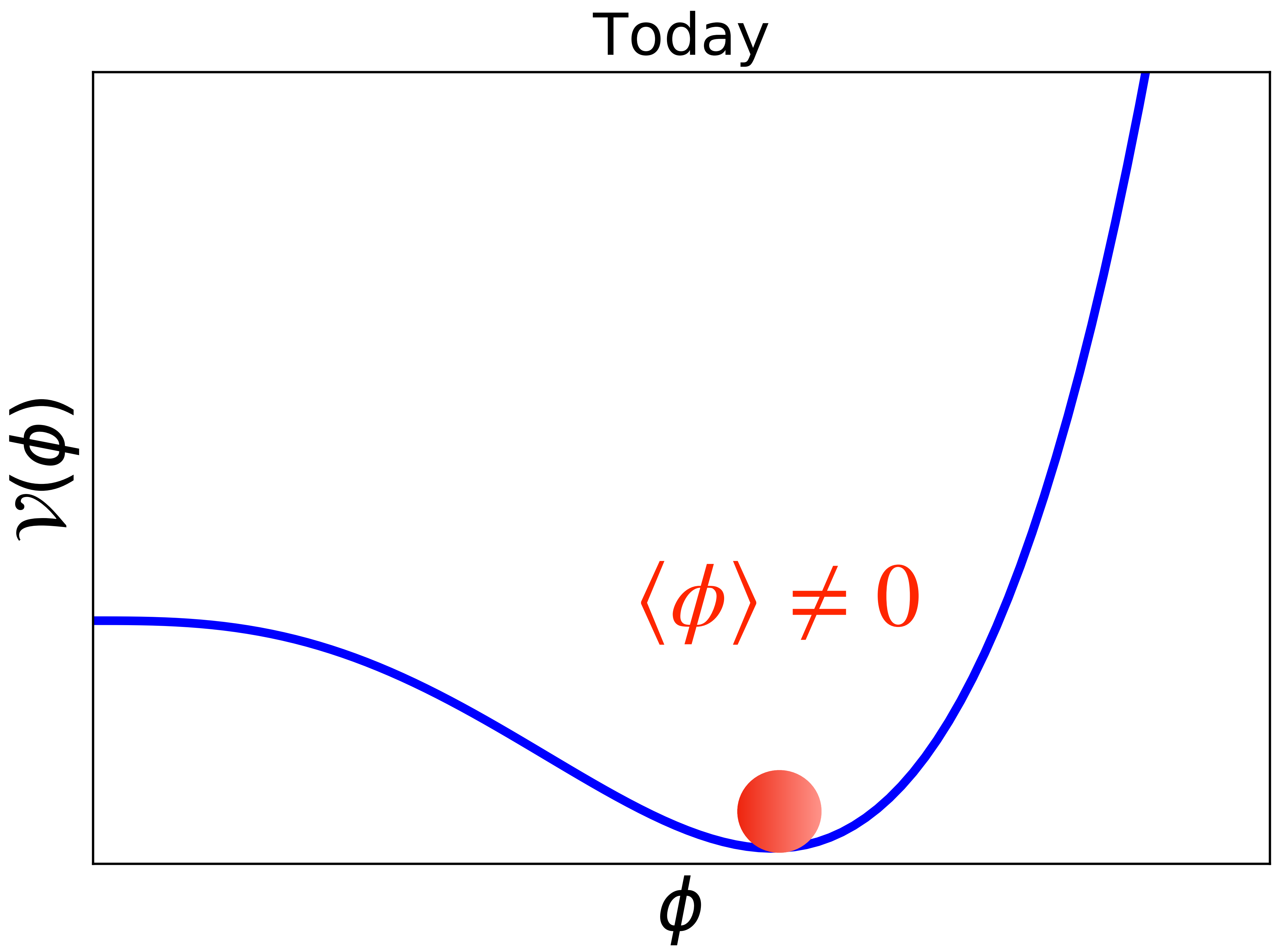


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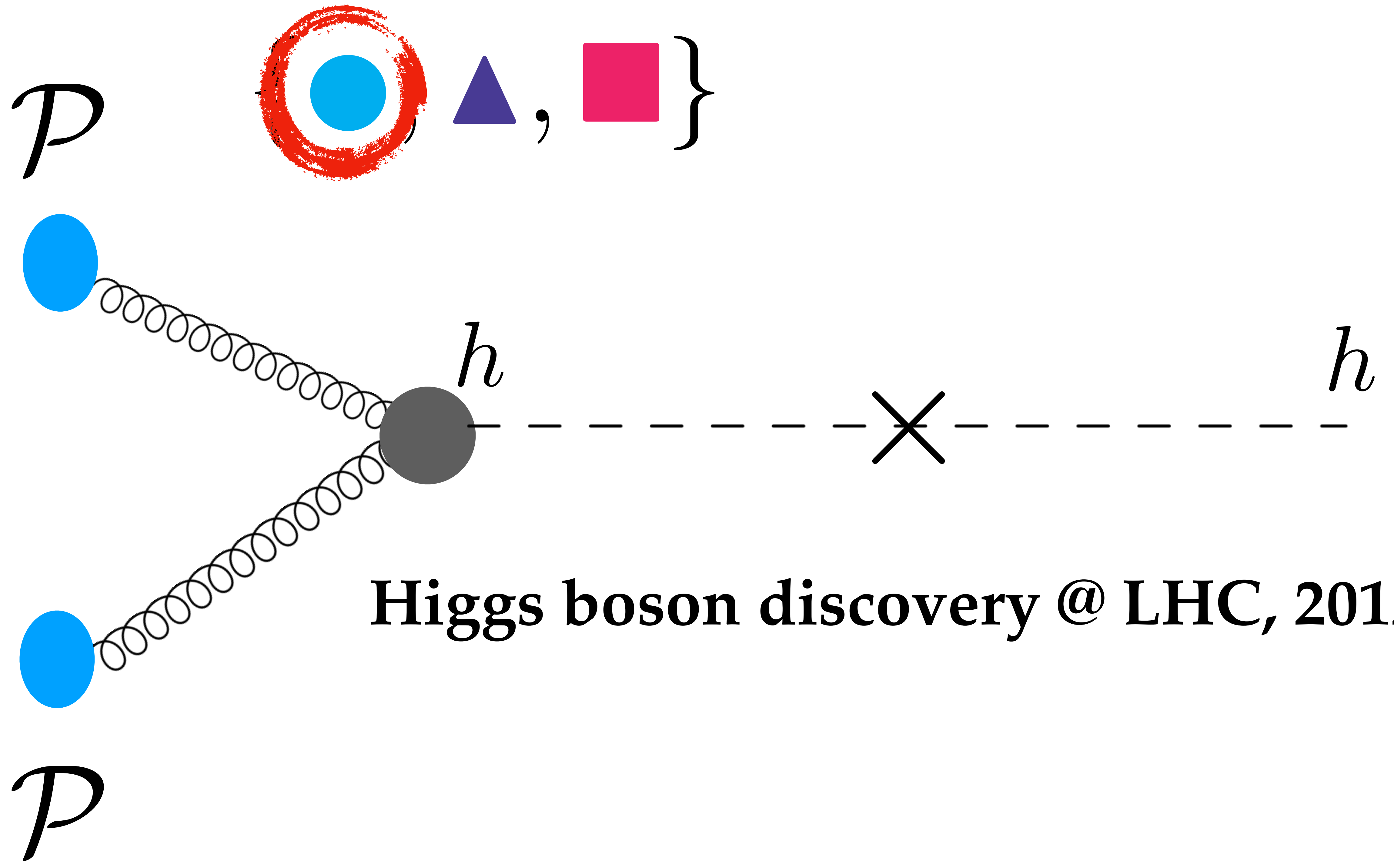


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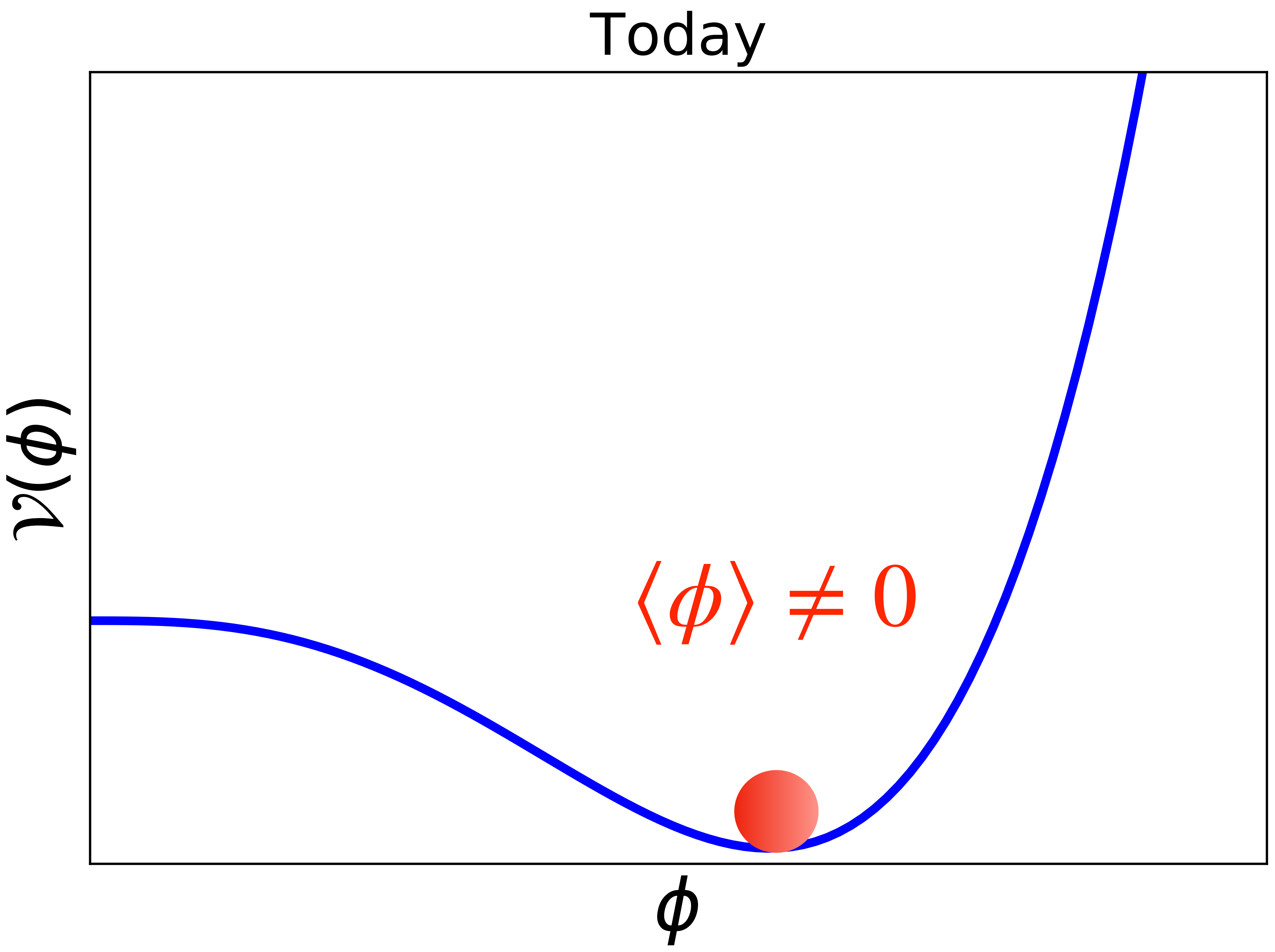


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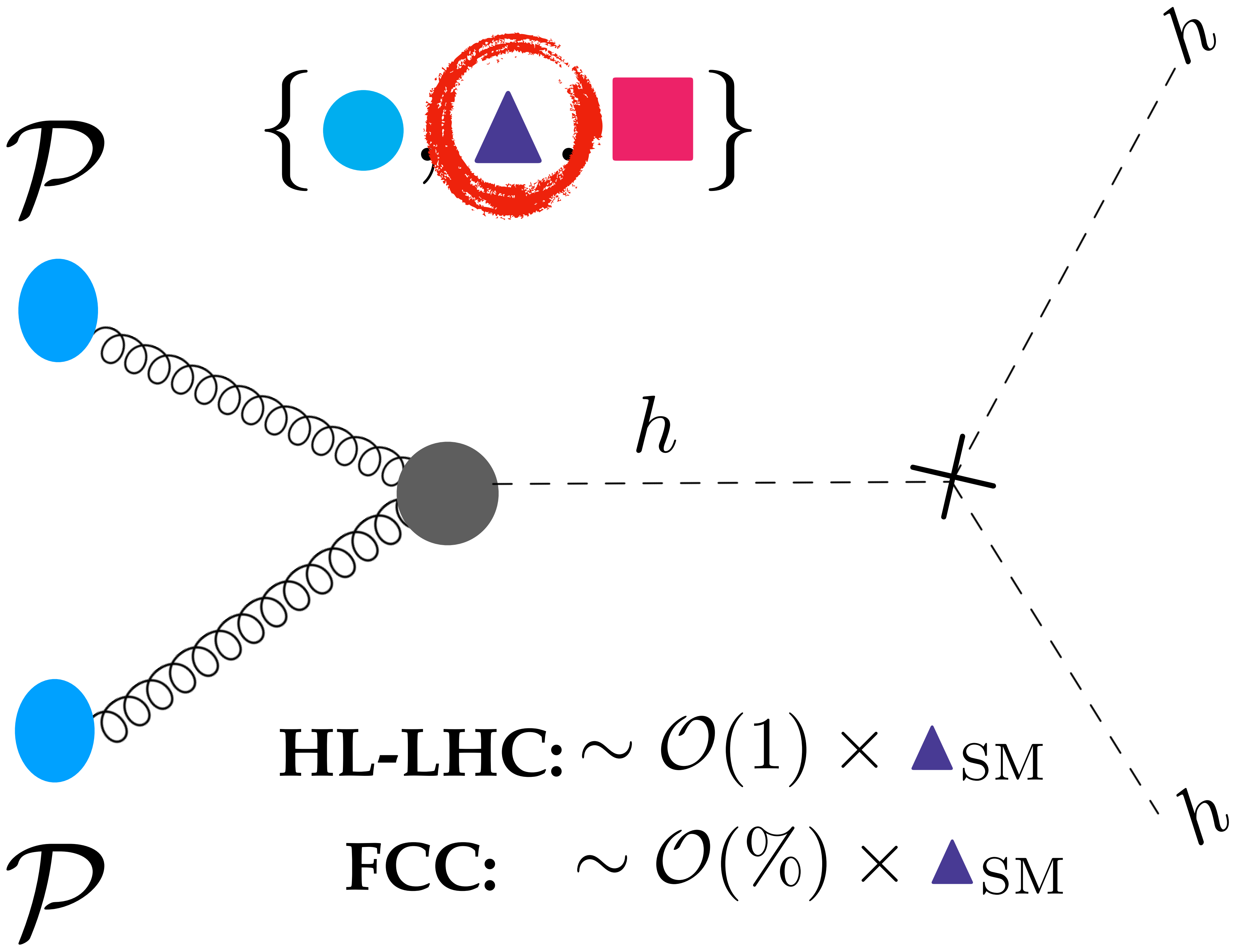
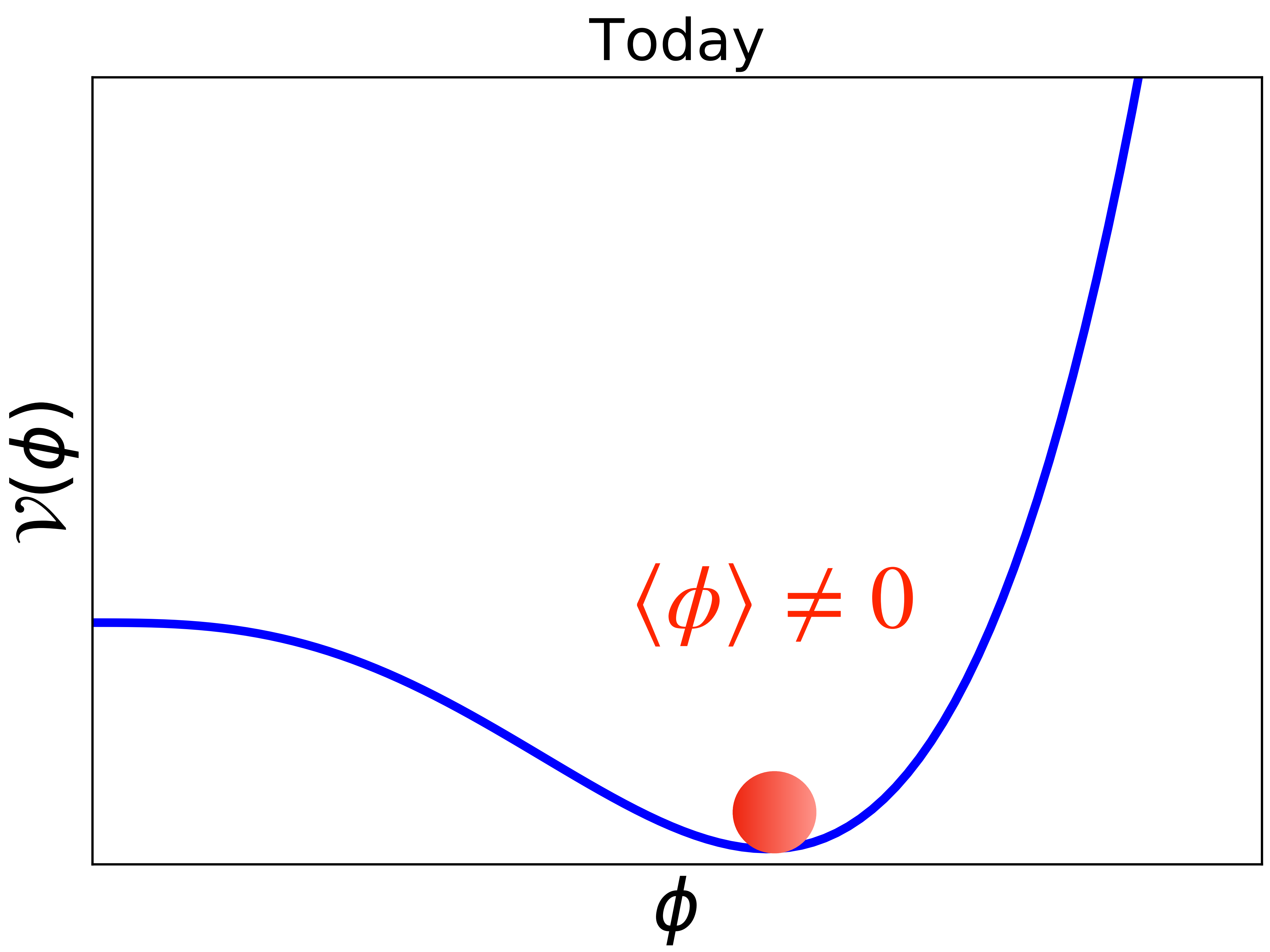



**HL-LHC:** $\sim \mathcal{O}(1) \times \blacktriangle_{\mathrm{SM}}$

**FCC:** $\sim \mathcal{O}(\%) \times \blacktriangle_{\mathrm{SM}}$

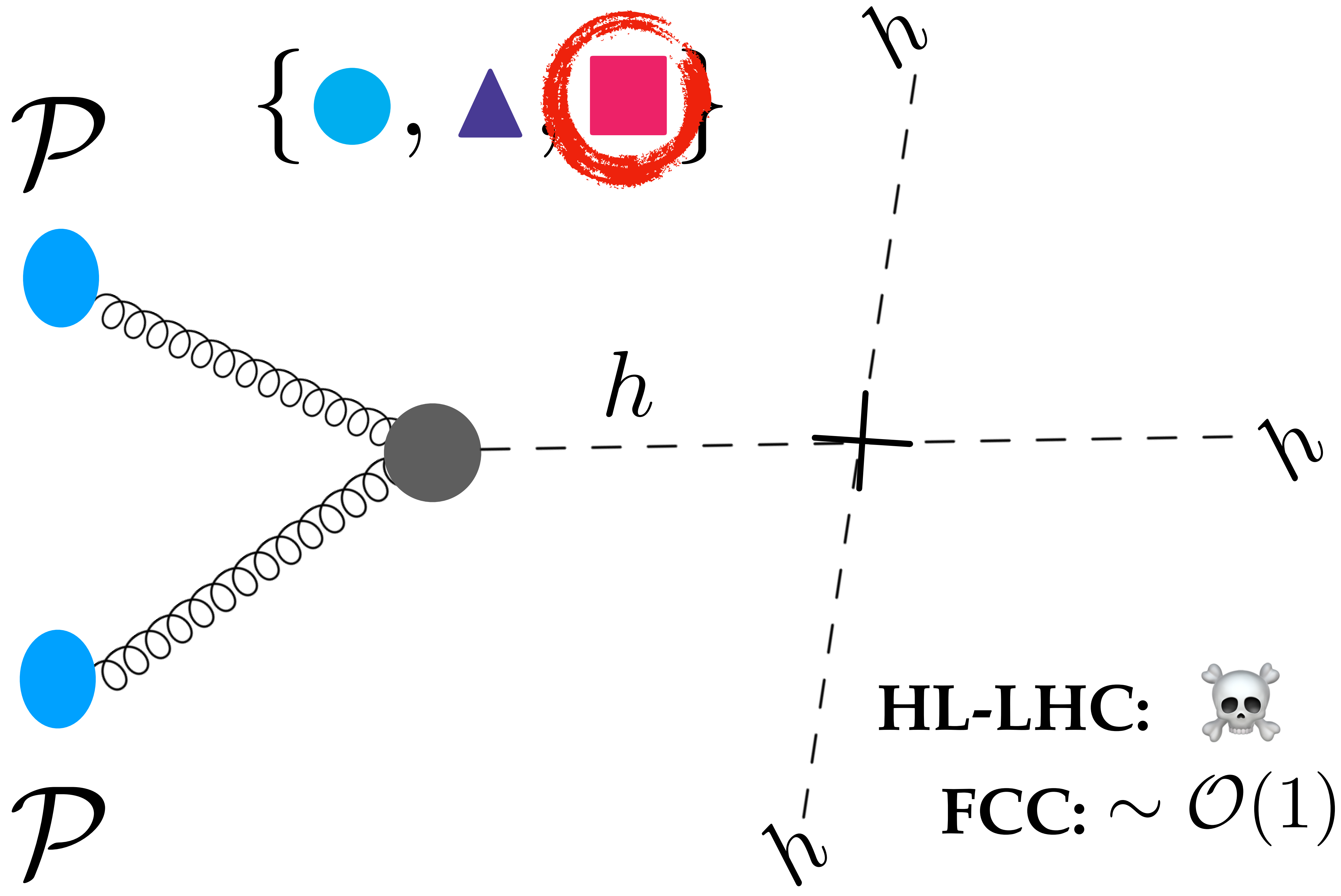
# The Higgs Boson's Potential

$\mathcal{V}(\langle\phi\rangle + h) = ● h^2 + ▲ h^3 + ■ h^4$ → **the Higgs boson's self-interactions.**




→ **Determine shape of potential by measuring:**

$\{●, ▲, ■\}$




**HL-LHC:** ☠️

**FCC:** $\sim \mathcal{O}(1) \times ■_{\mathrm{SM}}$

[e.g. AP, Sakurai, arXiv:1508.06524, AP, Tetlalmatzi-Xolocotzi, Zaro, arXiv:1909.09166]

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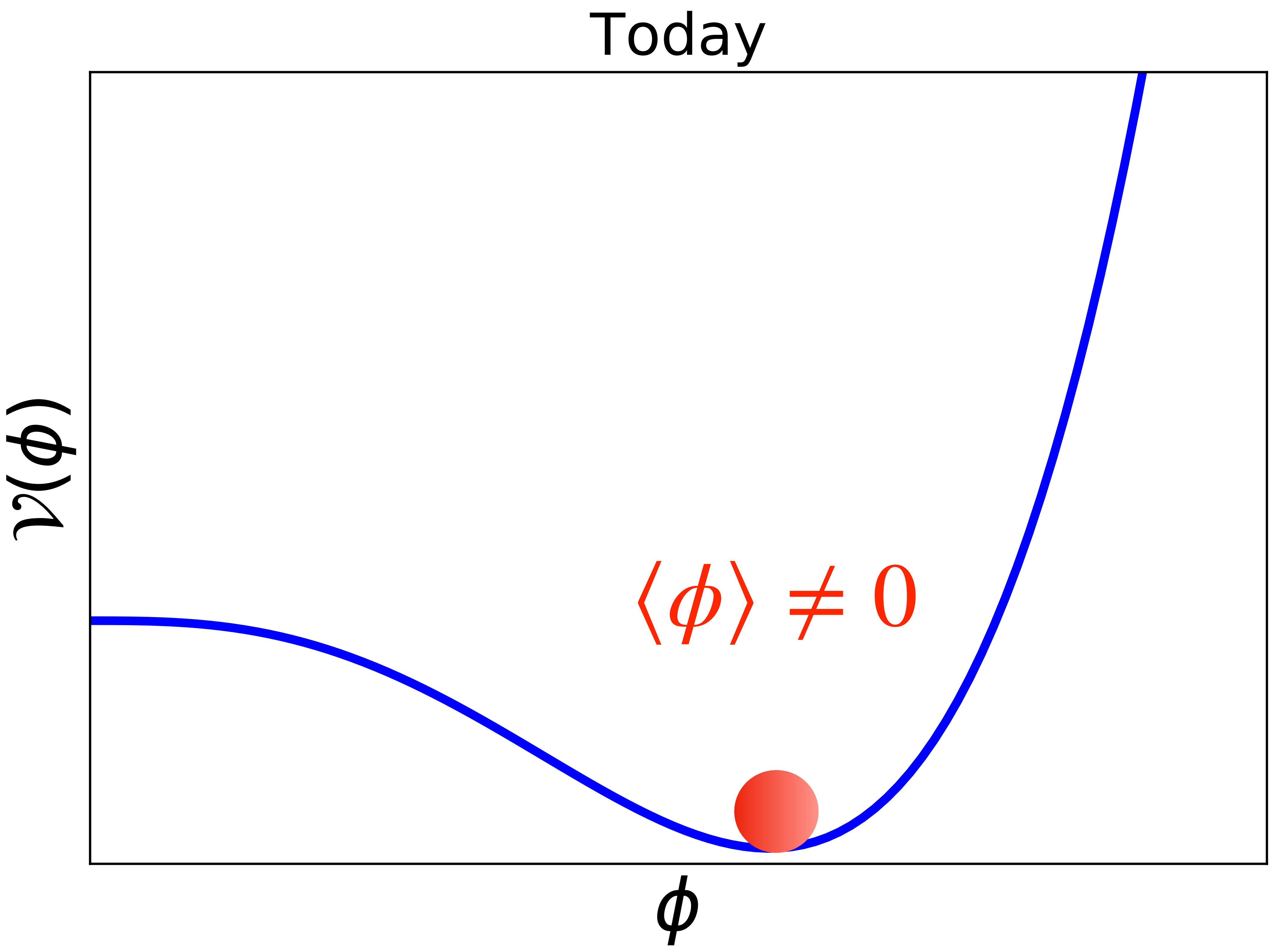


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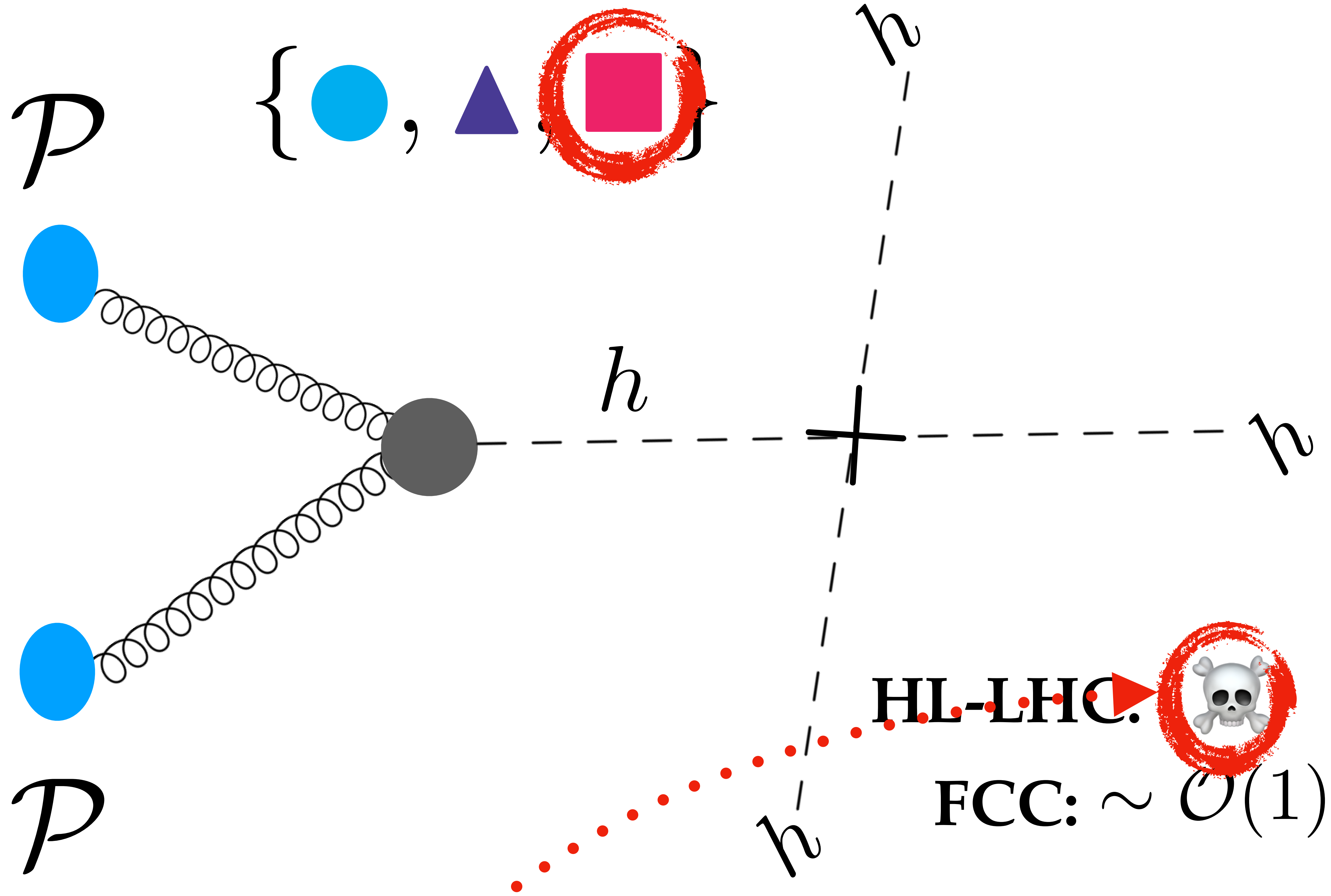



**HL-LHC:** ☠️

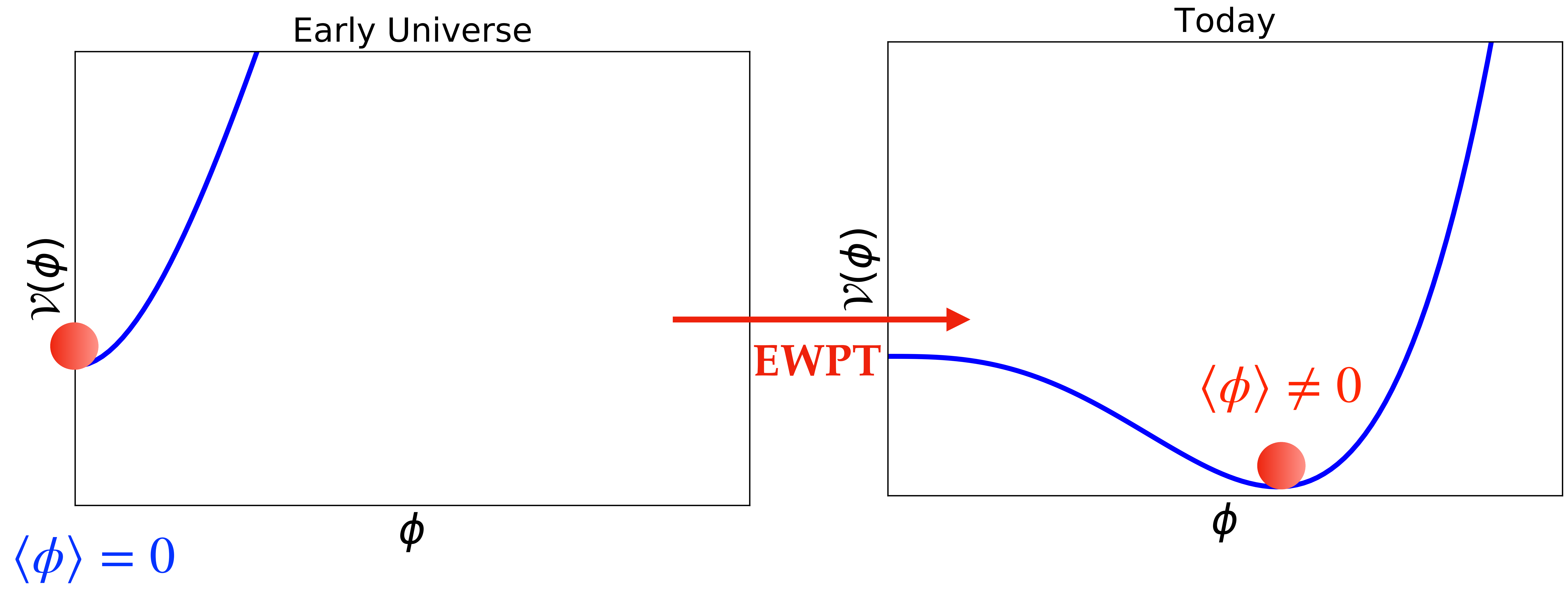
**FCC:** $\sim \mathcal{O}(1) \times \blacksquare_{\mathrm{SM}}$

[AP, Robens, Tetlalmatzi-Xolocotzi, arXiv:2101.00037 + Karkout, AP, Postma, du Pree, Tetlalmatzi-Xolocotzi, van de Vis, arXiv:2404.12425, AP, Tetlalmatzi-Xolocotzi, aXiv:2312.13562]

[e.g. AP, Sakurai, arXiv:1508.06524, AP, Tetlalmatzi-Xolocotzi, Zaro, arXiv:1909.09166]

# Breaking the Symmetry in the SM

Higgs field ($\phi$) potential

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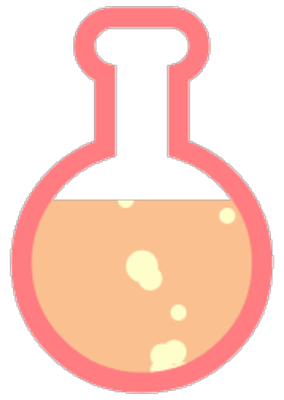

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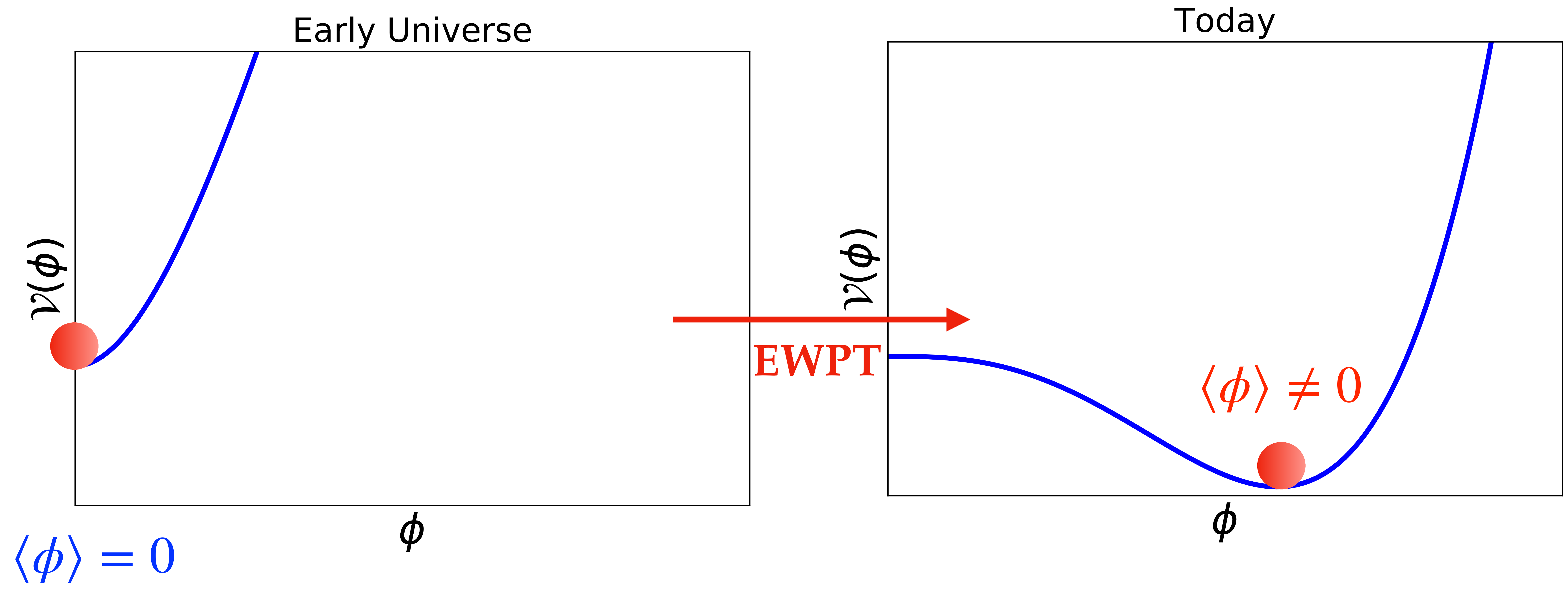


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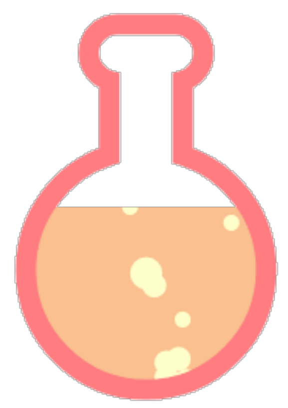

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# The Nature of the Phase Transition

→ **Clues** to the origin of **matter-anti-matter asymmetry**.

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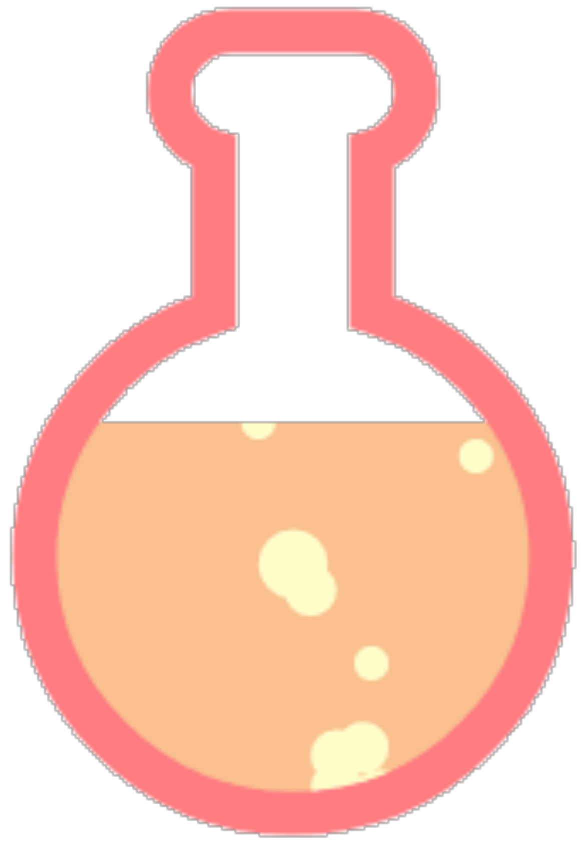
  → "Electro-Weak Baryogenesis" (EWBG).

- **Pre-requisite**: **a First-Order transition**. →



- *Note*: This **does not** occur in the SM!

[Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288]

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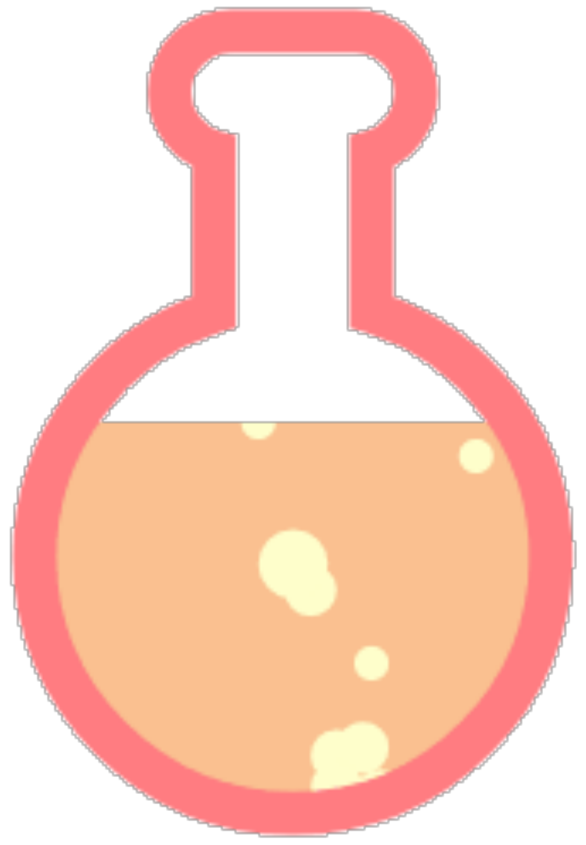

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# A First-Order Electro-Weak Phase Transition: As the Universe Cools Down!

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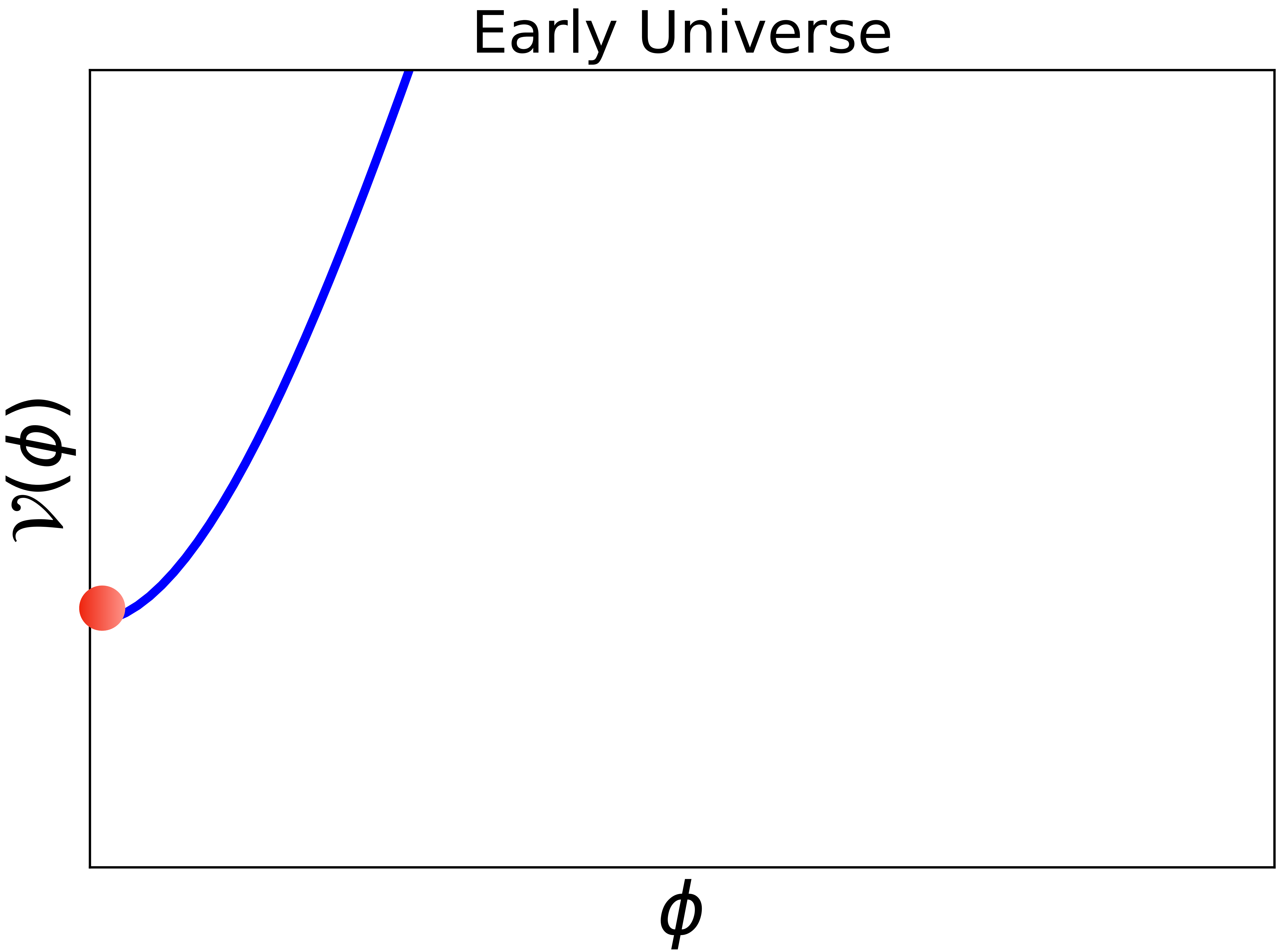

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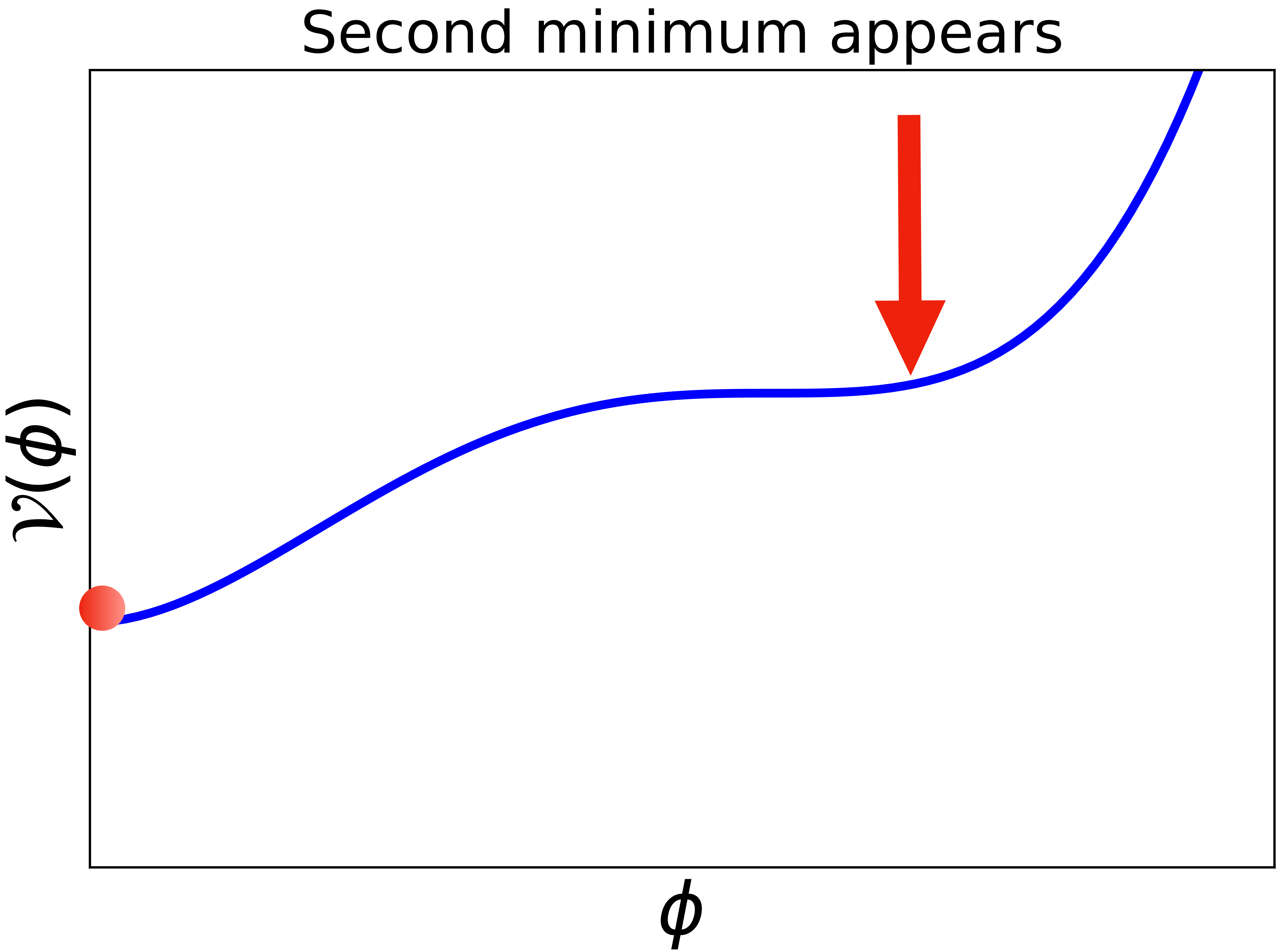




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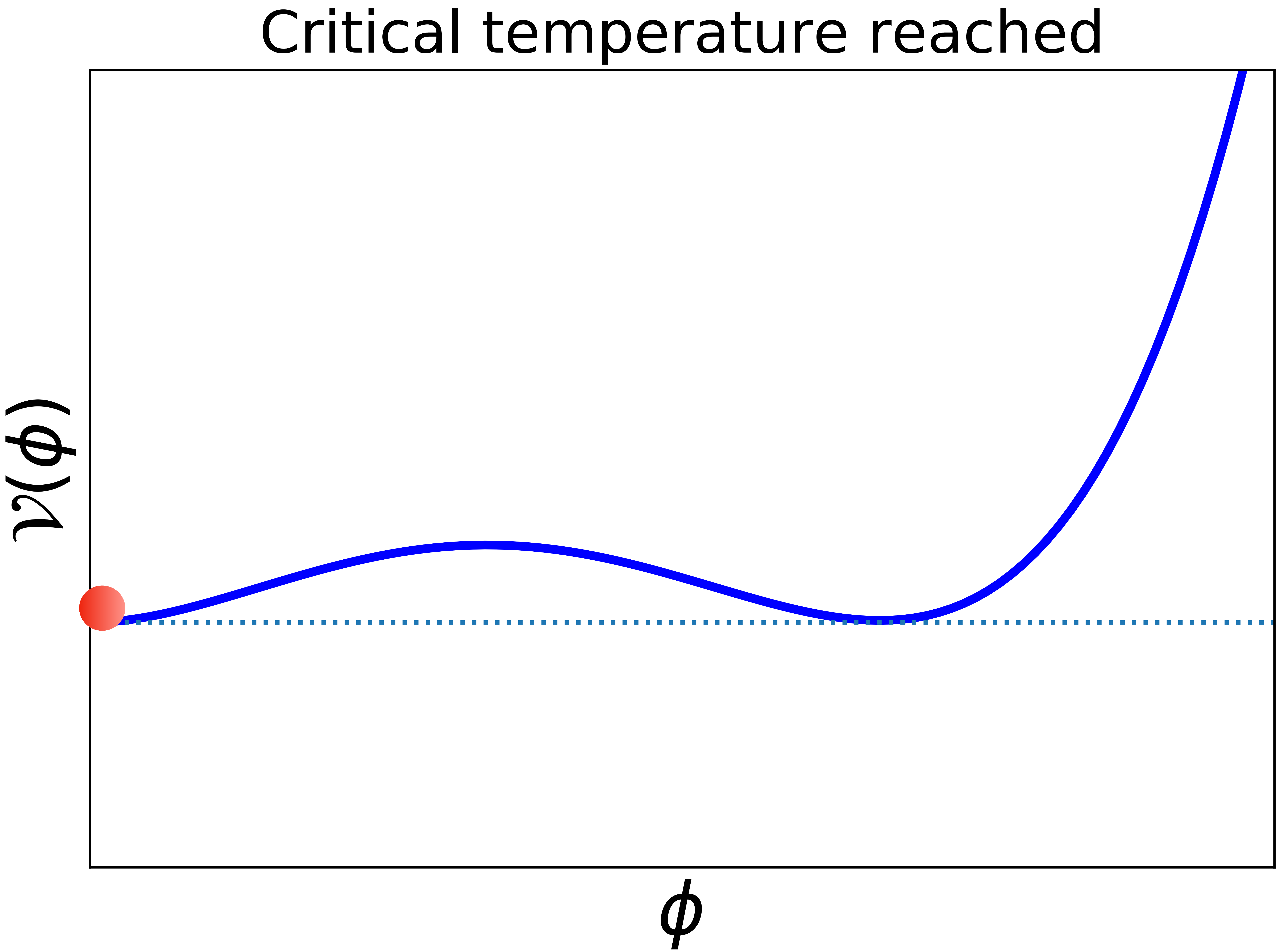

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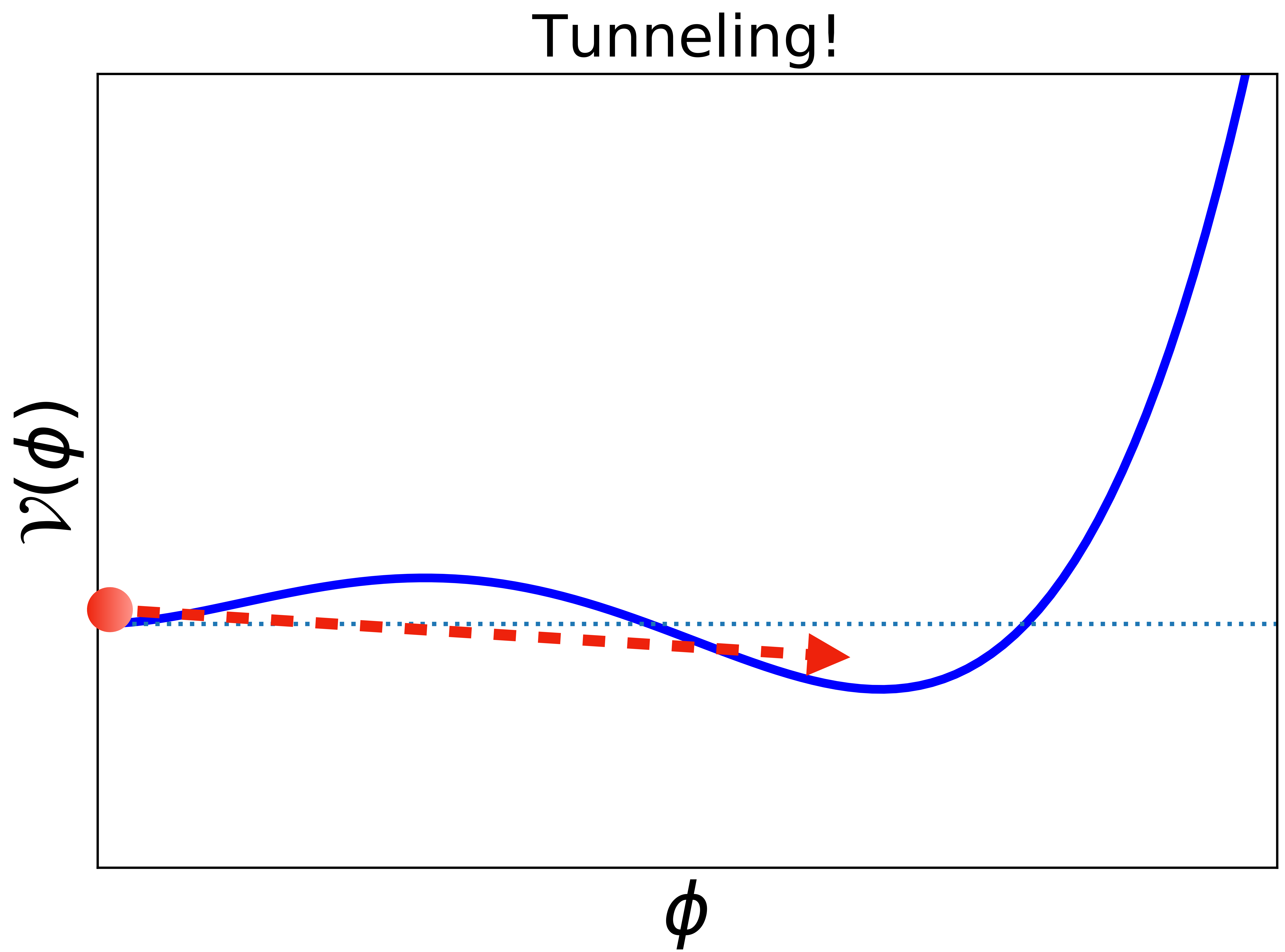




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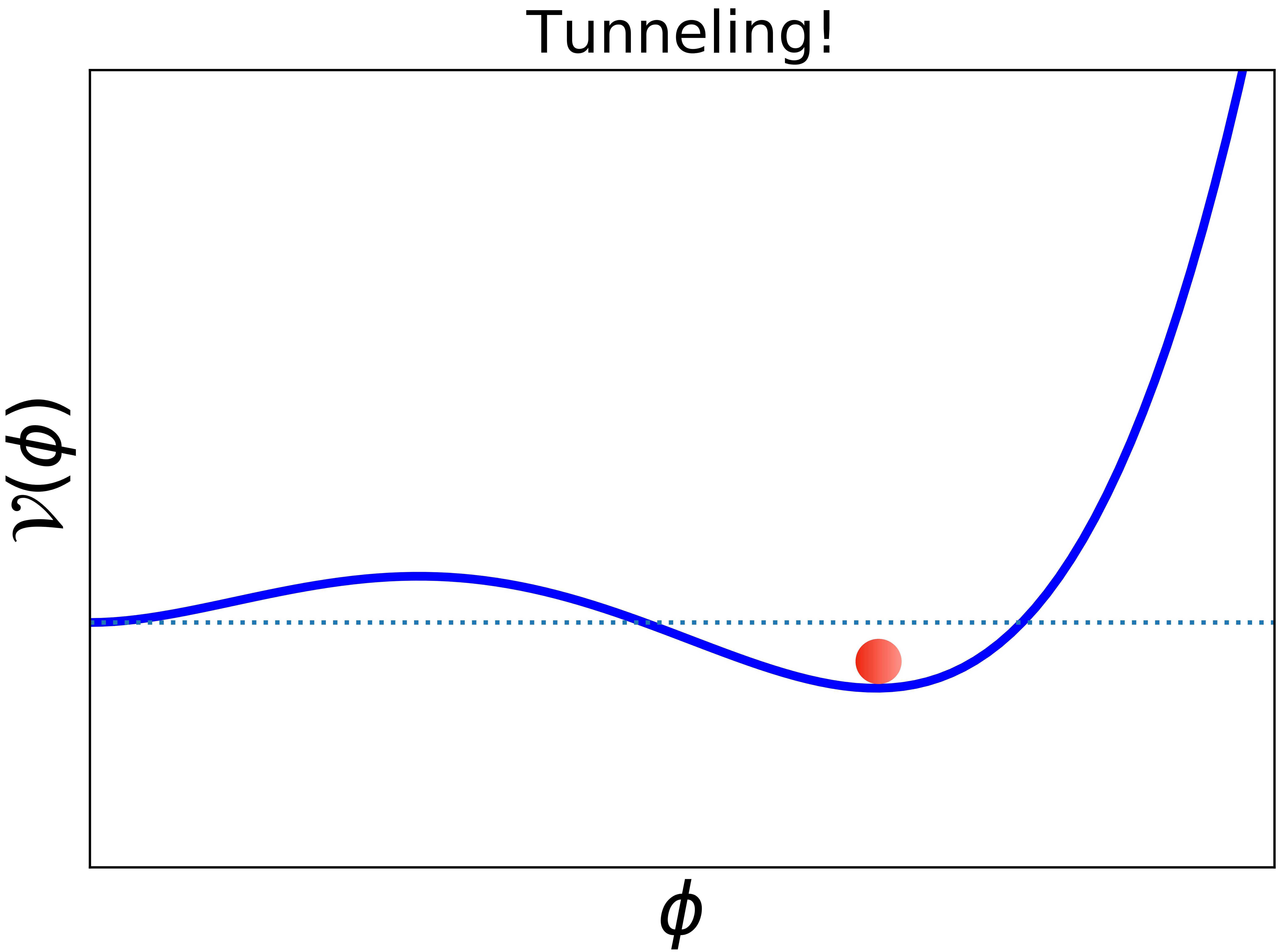




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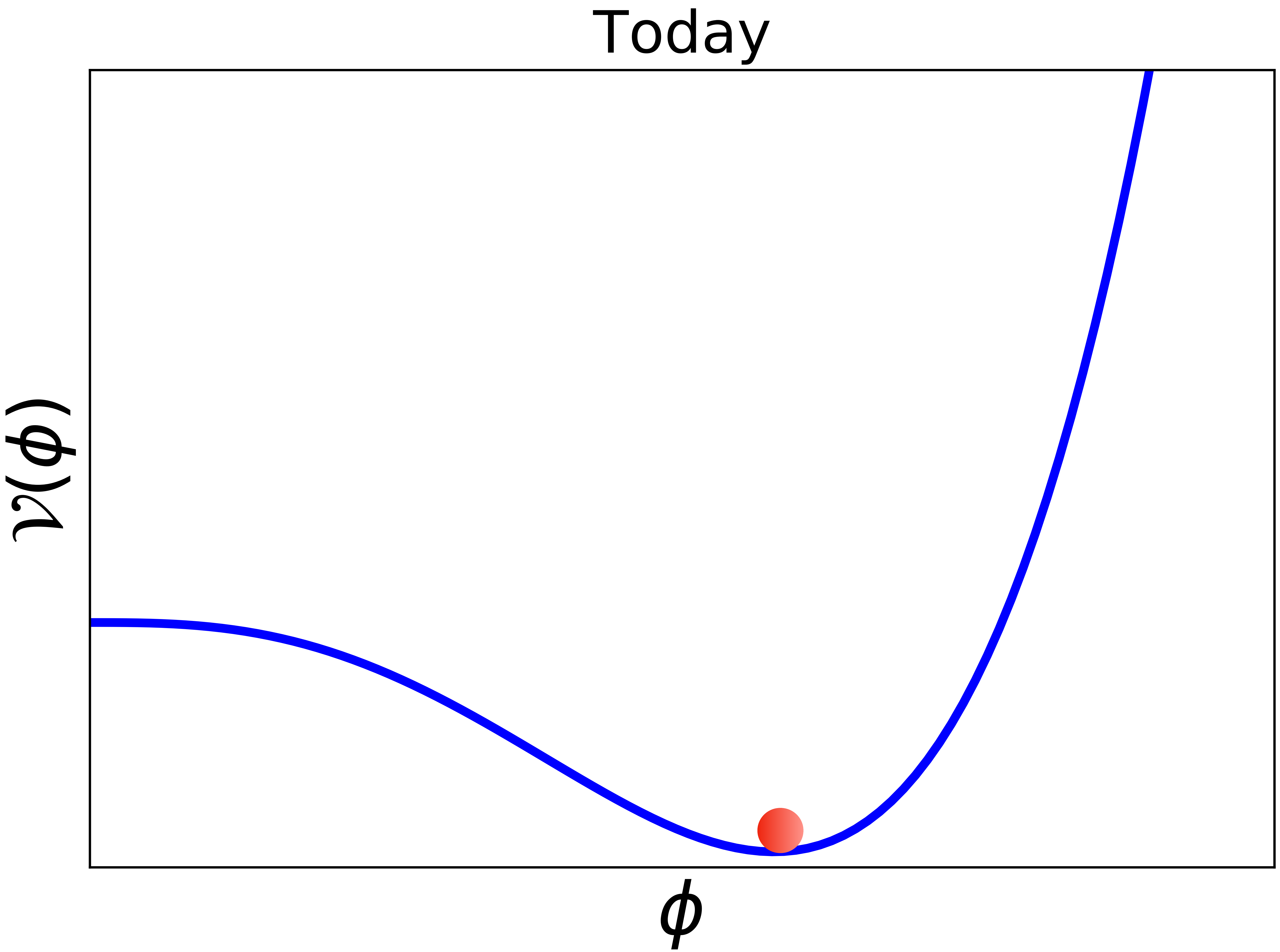




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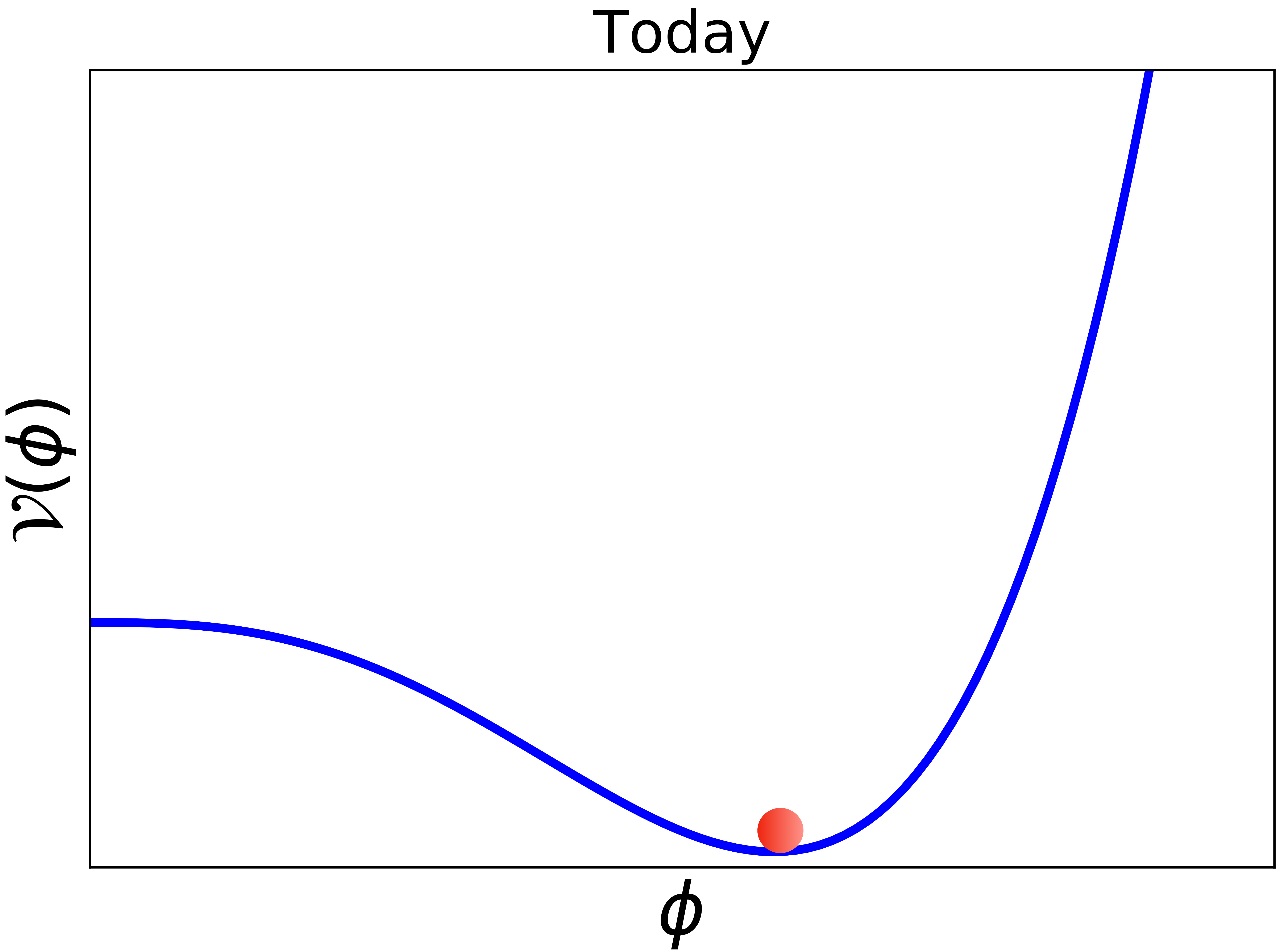


$\langle \phi \rangle \neq 0$

$\Rightarrow$

**Symmetry Breaking.**



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# A First-Order EWPT

Some time after critical temperature is reached:

→ **Bubbles** of the broken phase nucleate and expand.*

**Note*: Gravitational Waves can form during this period!

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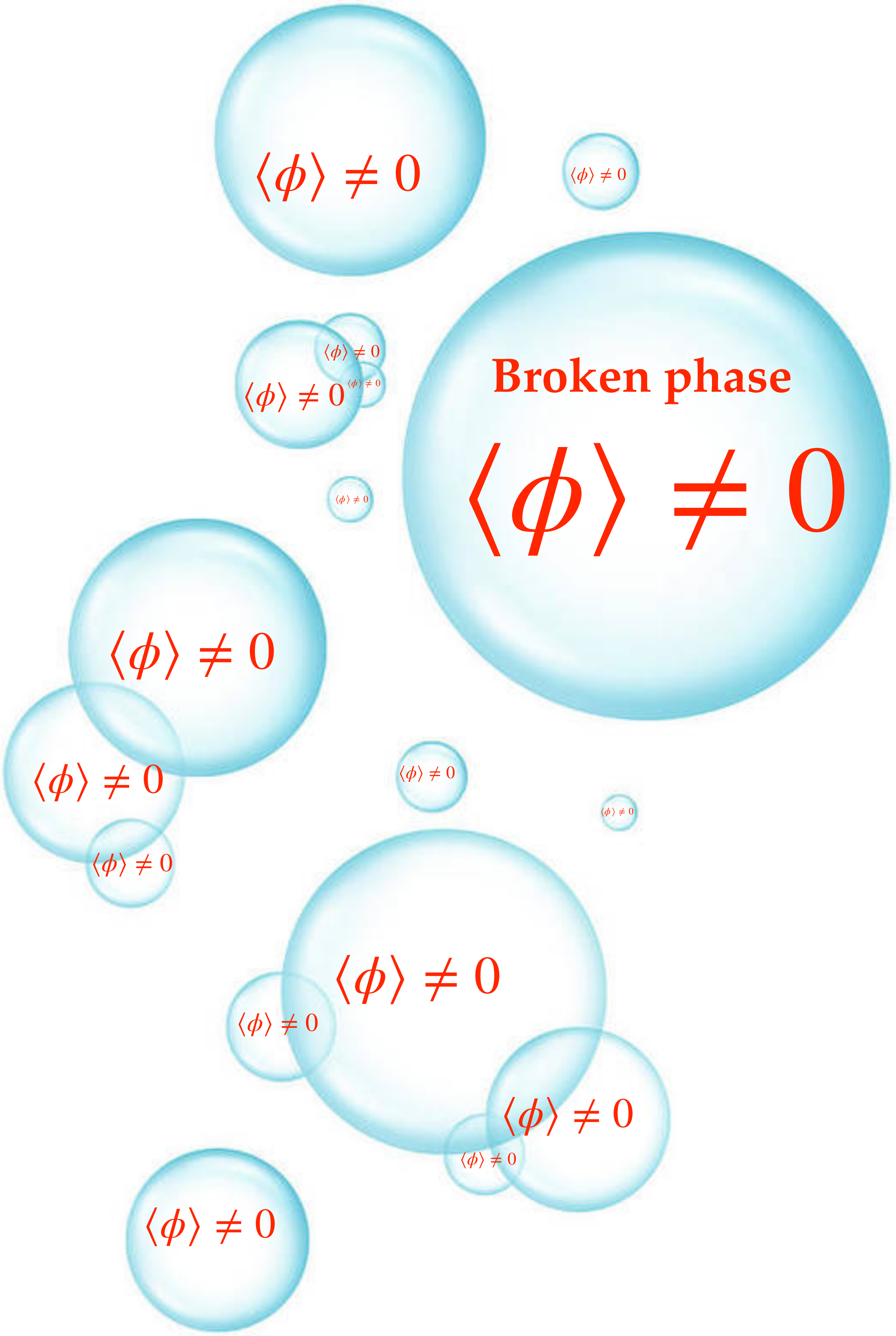


$\langle \phi \rangle = 0$

**Symmetric phase**

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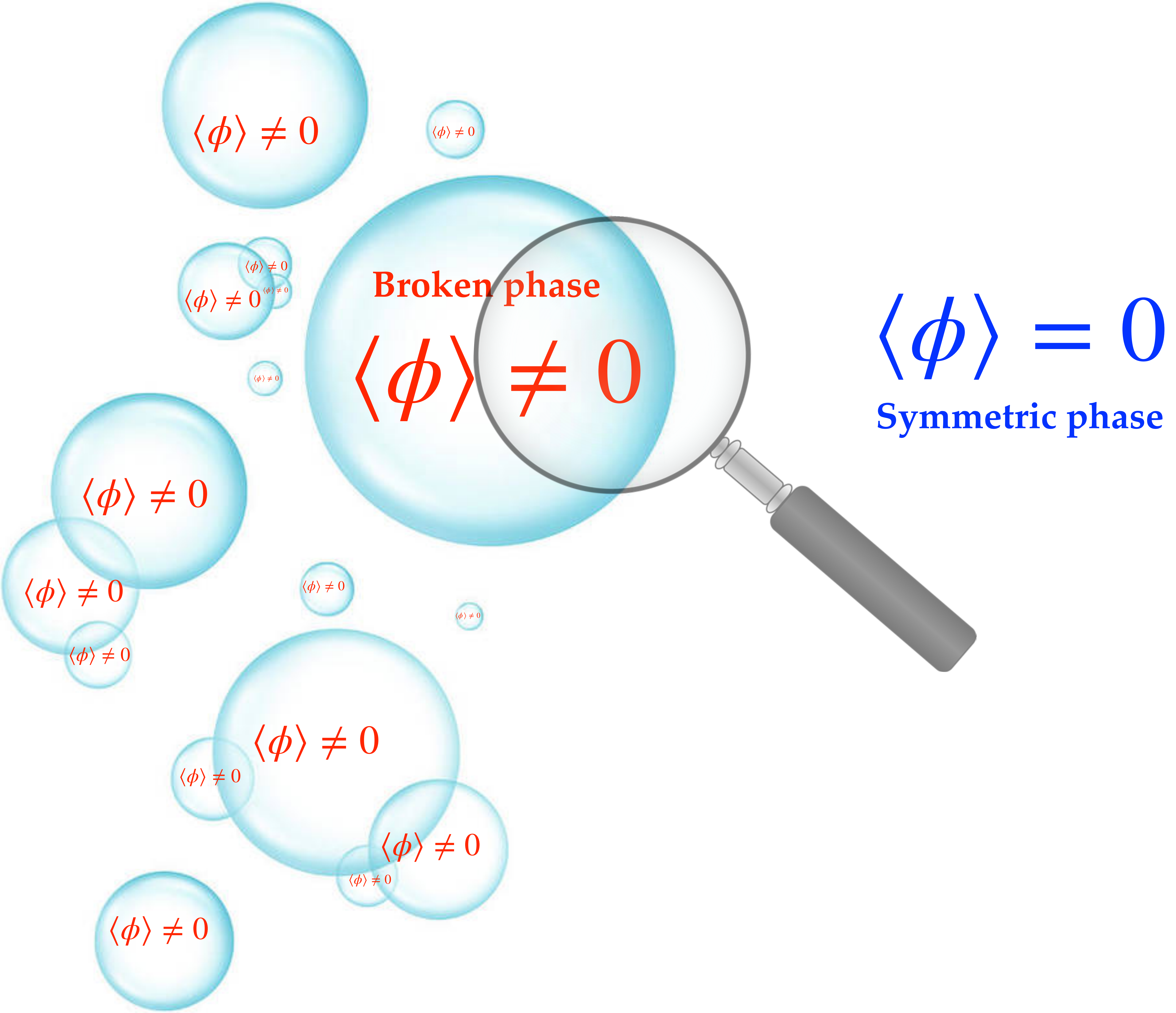


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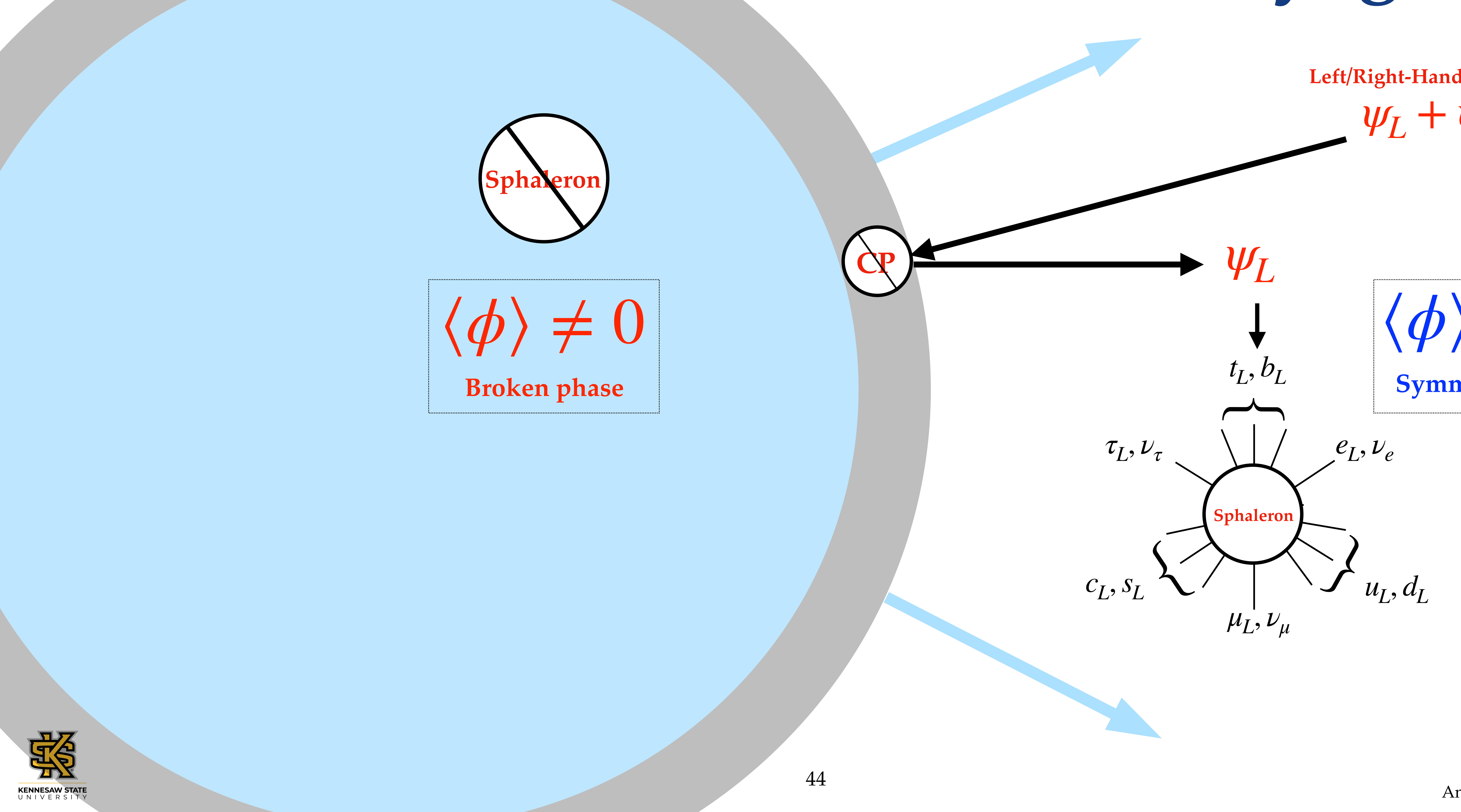

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[AP, Sakurai, Plätzer, arXiv:1910.4761,
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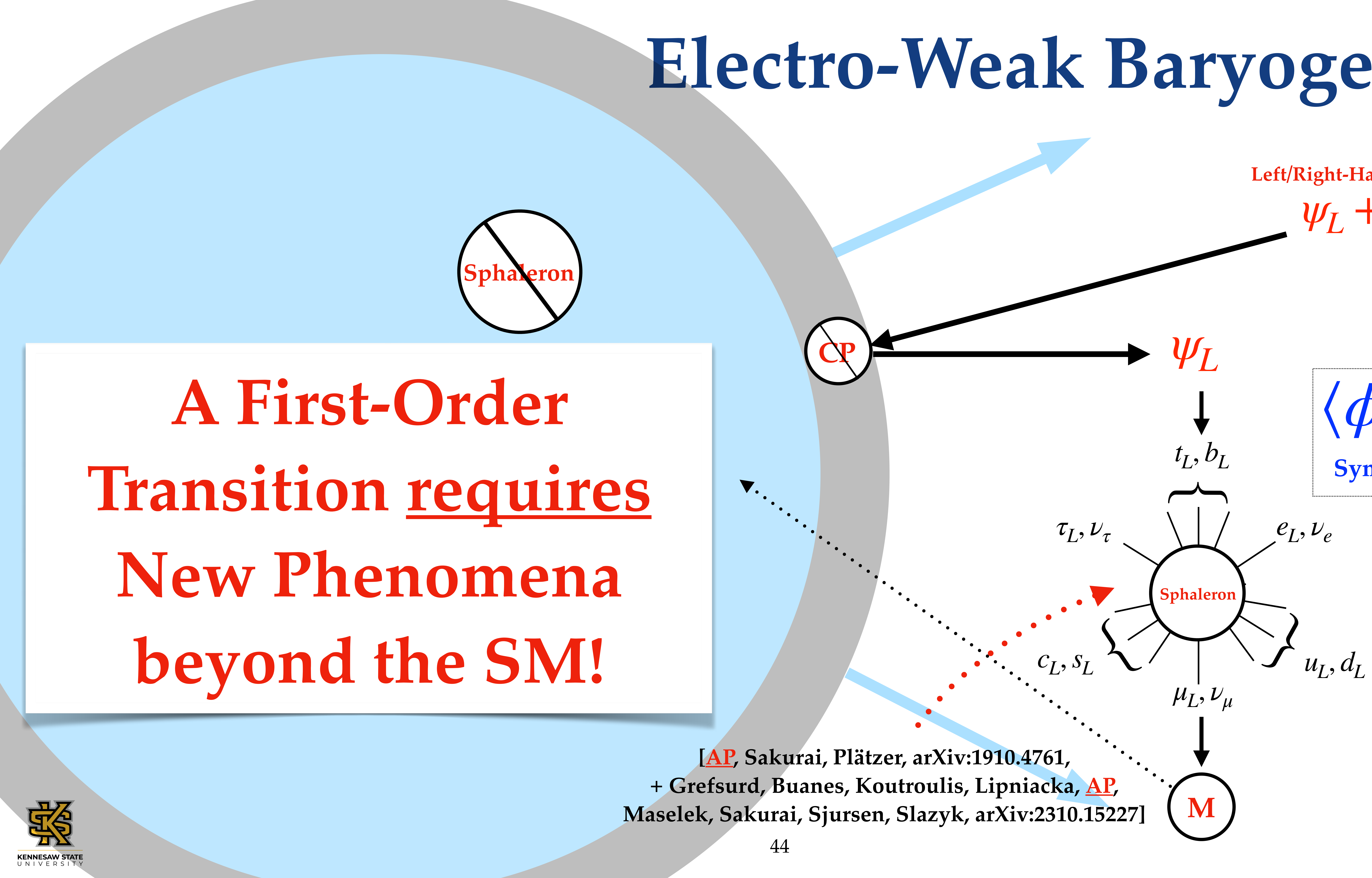


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A First-Order Transition requires New Phenomena beyond the SM!

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# Electro-Weak Archaeology

**We live here!**

Sphaleron

$$\langle \phi \rangle \neq 0$$

**Broken phase**



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Broken phase

~~Sphaleron~~

→ What are the imprints of Electro-Weak Baryogenesis at Colliders?

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# 4 Extending the Scalar Sector

[AP, White, arXiv:2010.00597]

- A First-Order EWPT **dictates** new phenomena. [Kajantie, Laine, Rummukainen, Shaposhnikov hep-ph/9605288]
- Consider the **simplest possible extension to the SM**!

$$\mathcal{V}(\phi, S) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4$$

**Add: *S*, a new scalar field,**
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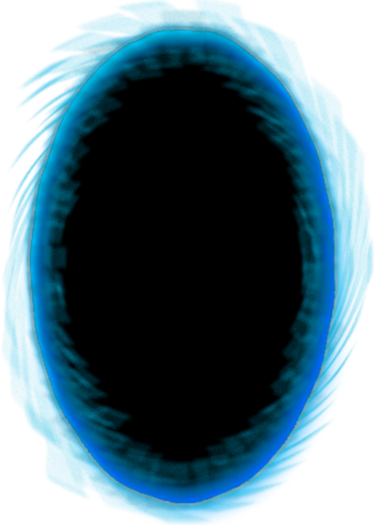

$$+ \blacktriangle\, |\phi|^2 S + \blacksquare\, |\phi|^2 S^2$$

← "**Portal**" interactions.



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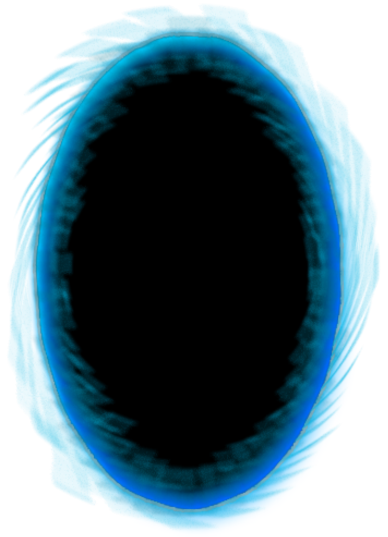

$$+\blacktriangle\,|\phi|^2\,S + \blacksquare\,|\phi|^2\,S^2$$ ← "**Portal**" interactions.

$$+S \times (\text{Hidden Sector}) + \ldots$$ ← **Dark Matter**?



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# Extending the Scalar Sector [AP, White, arXiv:2010.00597]

$$\mathcal{V}(\phi, S) = {\color{green}\bullet}\,|\phi|^2 + {\color{blue}\blacksquare}\,|\phi|^4 + {\color{magenta}\bullet}\,S^2 + {\color{cyan}\blacktriangle}\,S^3 + {\color{brown}\blacksquare}\,S^4 + {\color{red}\blacktriangle}\,|\phi|^2 S + {\color{purple}\blacksquare}\,|\phi|^2 S^2$$

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**Diagonalize!**

**Mass Eigenstates**

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \chi \end{pmatrix}$$

$\theta$: mixing angle

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$h_1 \to$ "SM-like" Higgs boson.

$h_2 \to$ new scalar resonance.

i.e. choose: $|\theta| \gtrsim 0$, and:

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**Primary targets for collider studies!**

$h_1 \Rightarrow$ **Reductions** in Higgs boson rates.

$h_2 \Rightarrow$ **New resonance searches.**



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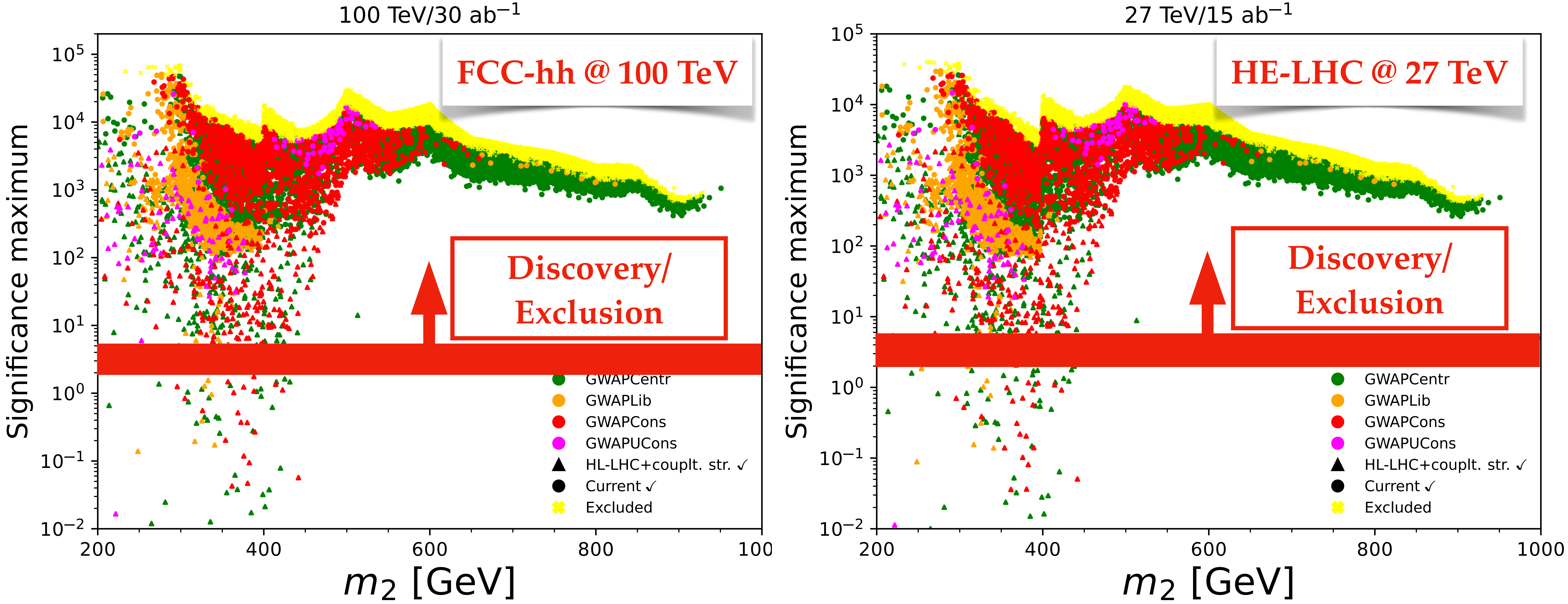
# Significance @ Future Colliders

**Color-coding of parameter-space points denotes theoretical uncertainty.**

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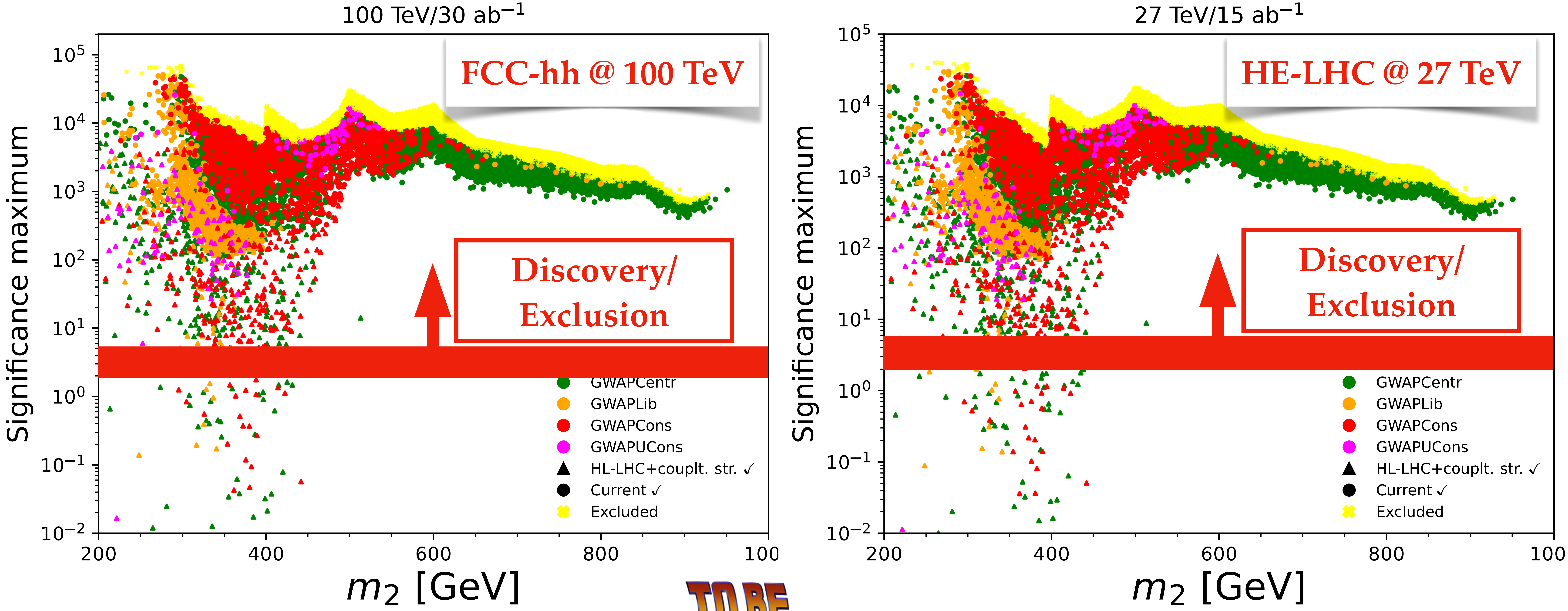


TO BE CONTINUED...

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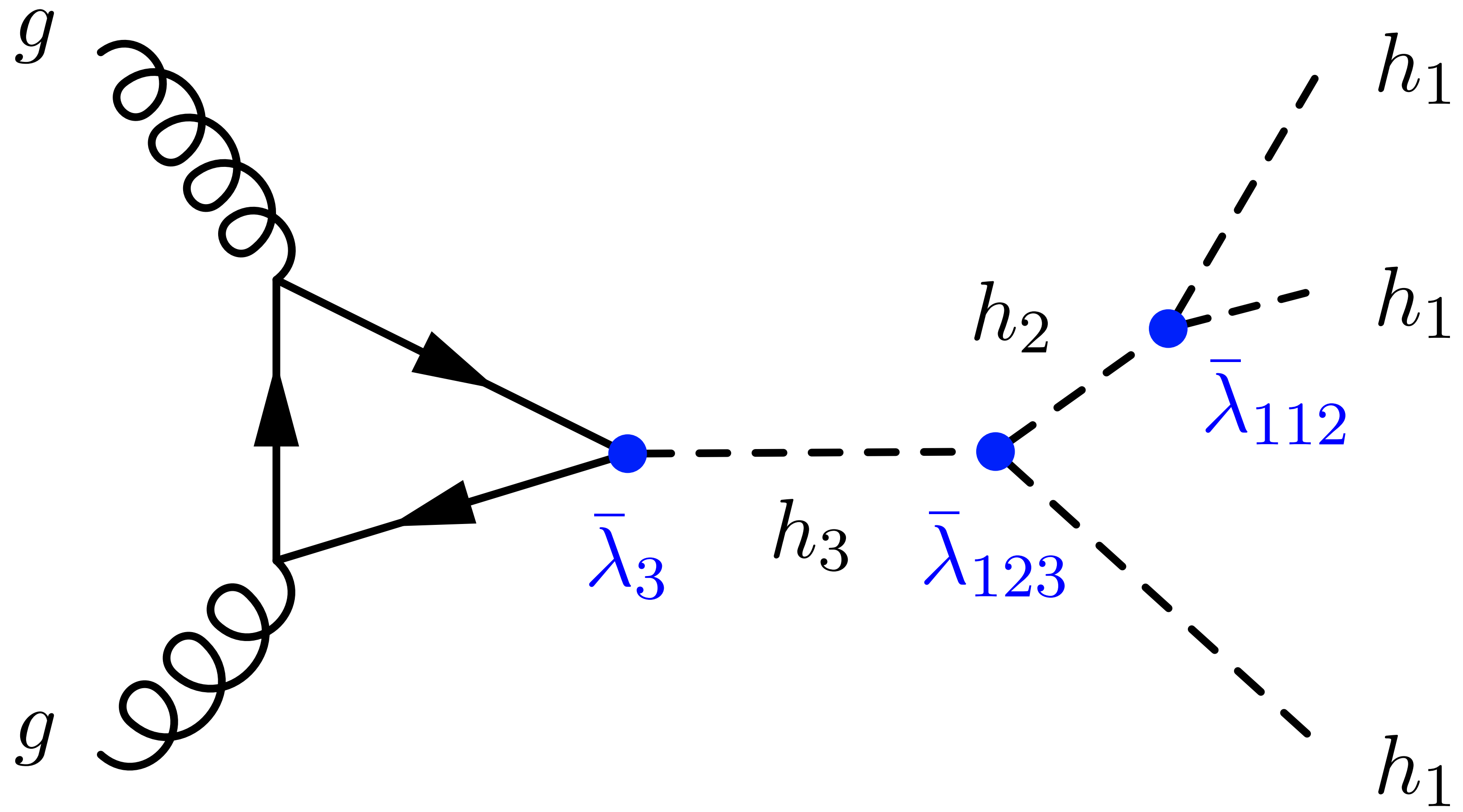
# Extending the Scalar Sector with Two Singlets

- More elaborate extensions? E.g. **Two Singlet Scalar fields** $S_1$ **and** $S_2$.
- (+ two $\mathcal{Z}_2$ symmetries forbidding some interactions).
- **Diagonalization** of the $(3 \times 3)$ mass matrix leads to **three** physical scalar states: $h_{1,2,3}$.
- **Enhanced triple Higgs boson production at the LHC!?** $> 100 \times$ **enhancement possible!** [Karkout, AP, Postma, du Pree, Tetlalmatzi-Xolocotzi, van de Vis, arXiv:2404.12425]

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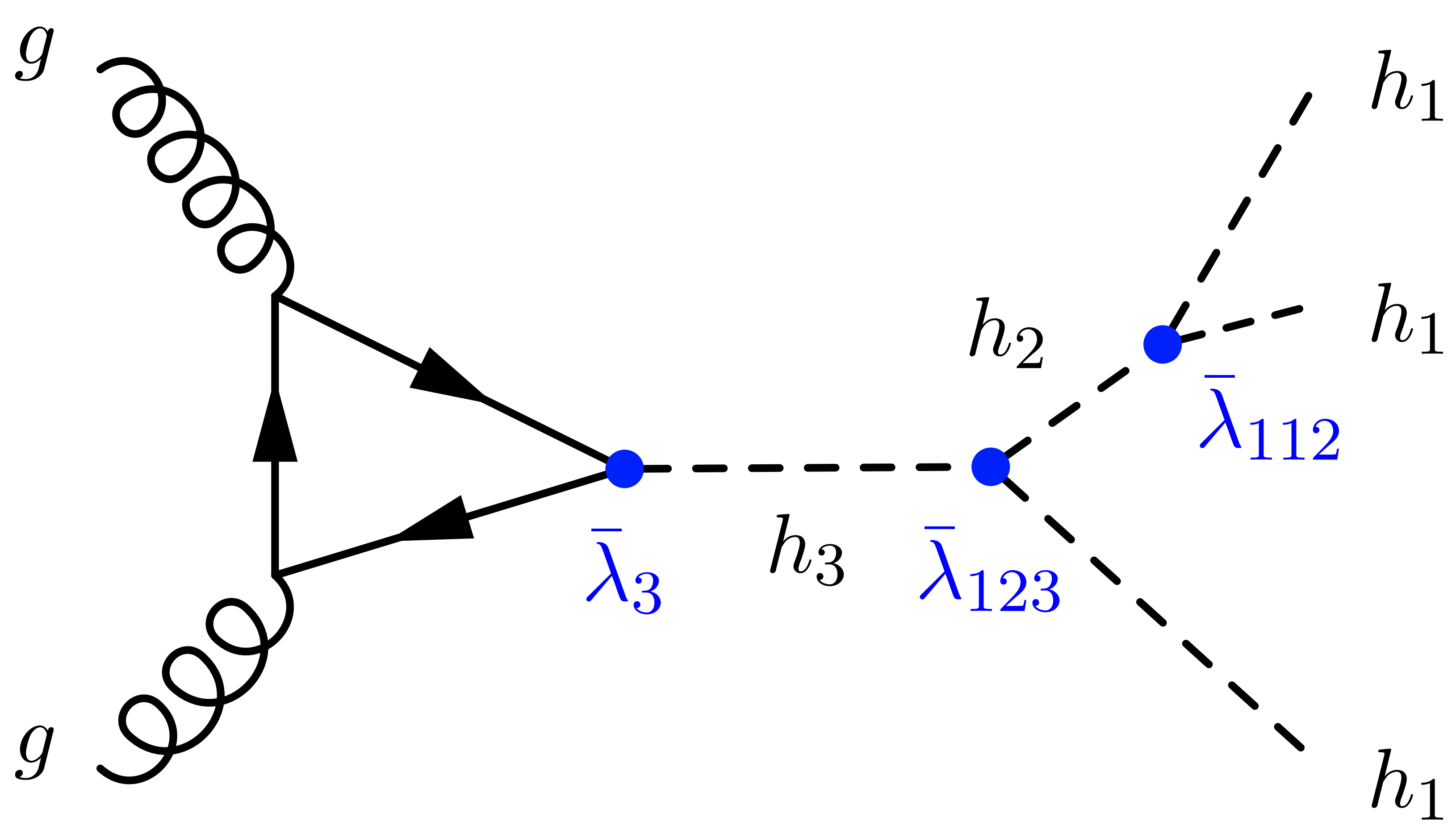


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*"With 4 parameters I can fit an elephant and with 5 I can make him wiggle his trunk."*
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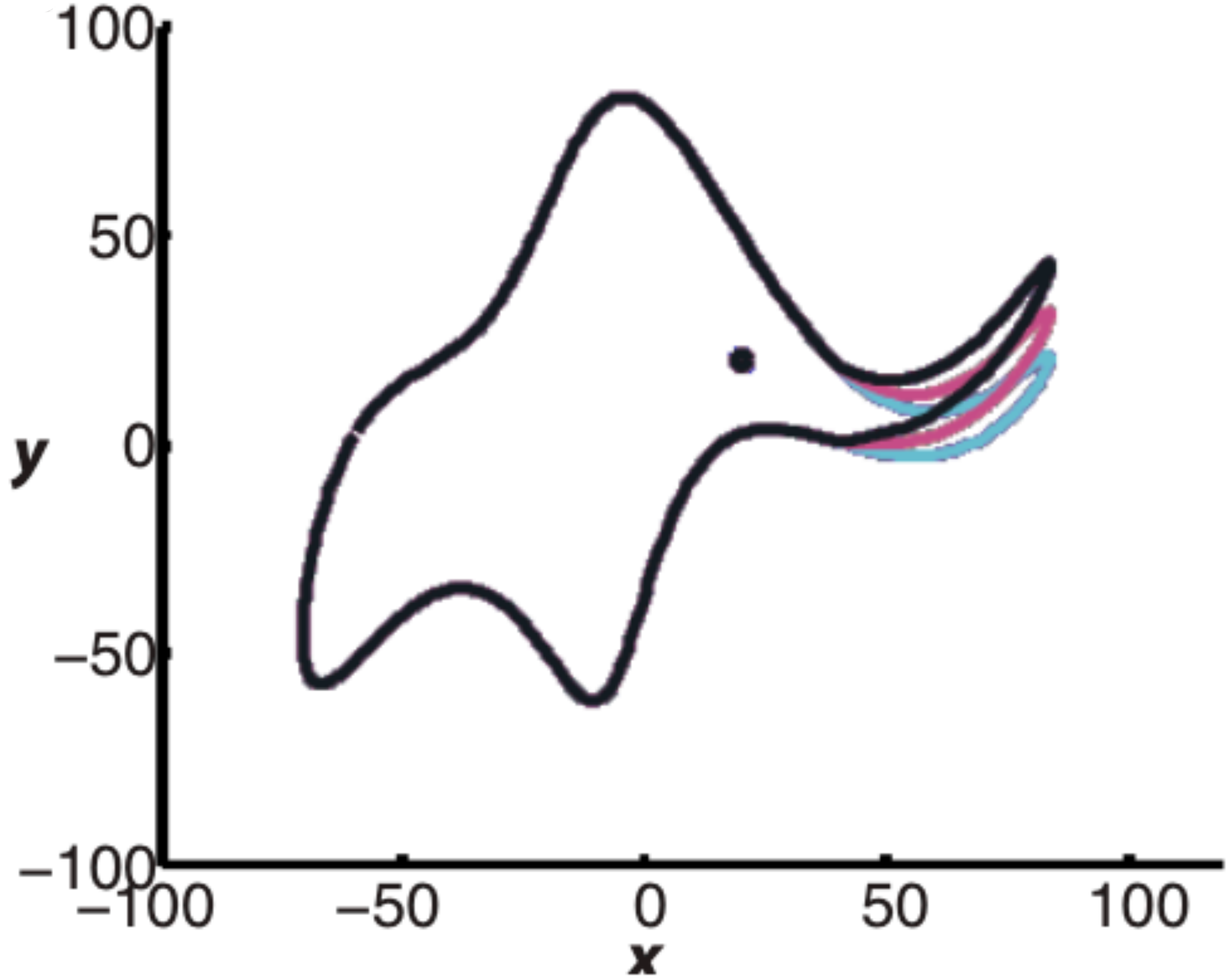
***Can we* fit the shape of an elephant with 4 parameters?**

→ **Yes!** With **four** complex parameters,

[and with **five** we can make it wiggle its trunk.]

**[Mayer, Khairy, Howard, Am. J. Phys., Vol. 78, No. 6, June 2010]**



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⇒ The "**Inverse Problem**".

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**Experimental observations** → {●, ▲, ■, ▲, ■}

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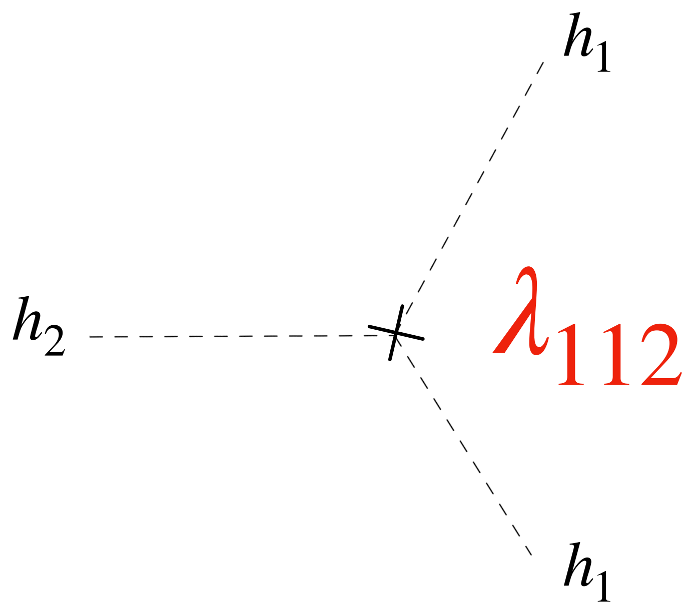
# Discovery Post-Mortem Example [AP, White, arXiv:2108.11394]

**Combine possible measurements:**

$pp \to h_2 \to ZZ$

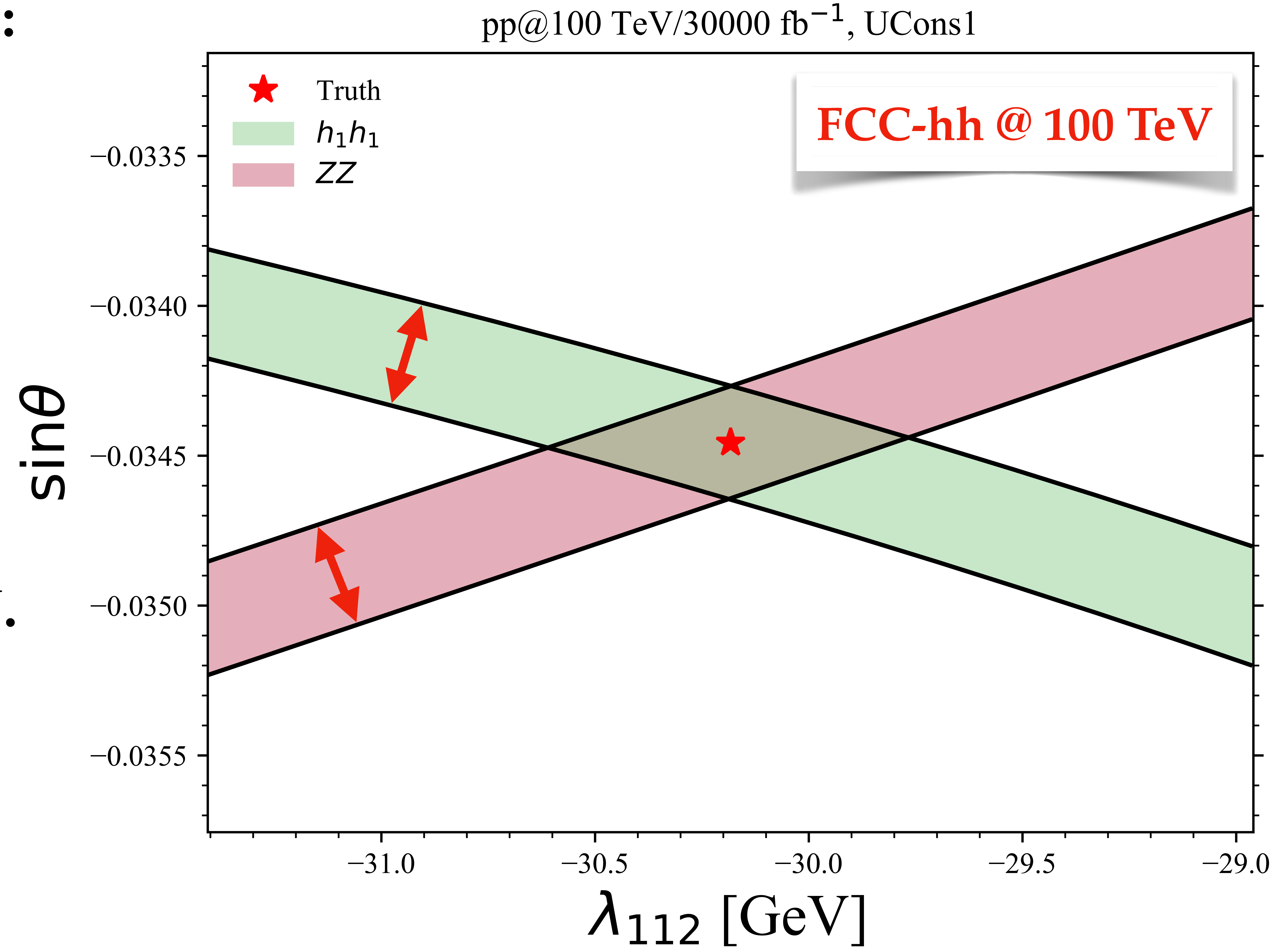
$pp \to h_2 \to h_1 h_1$




→ **both functions of** $\sin\theta$ **&** $\lambda_{112}$**!**

→ **in turn f^ns^ of** {●, ▲, ■, ▲, ■}.

[Width of bands represents expected measurement uncertainty].

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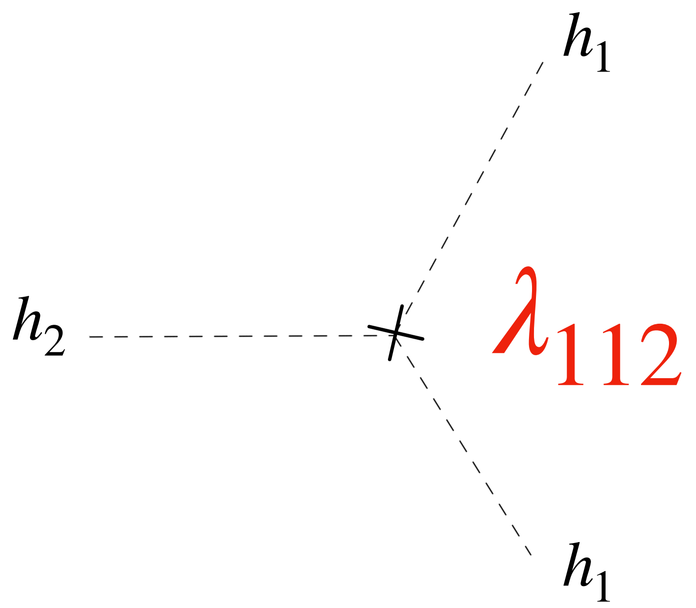
# Discovery Post-Mortem Example [AP, White, arXiv:2108.11394]

**Combine possible measurements:**

$pp \to h_2 \to ZZ$

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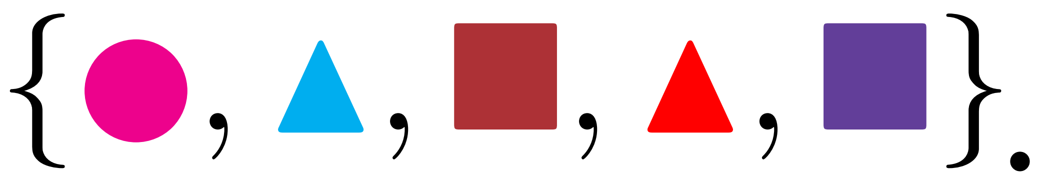

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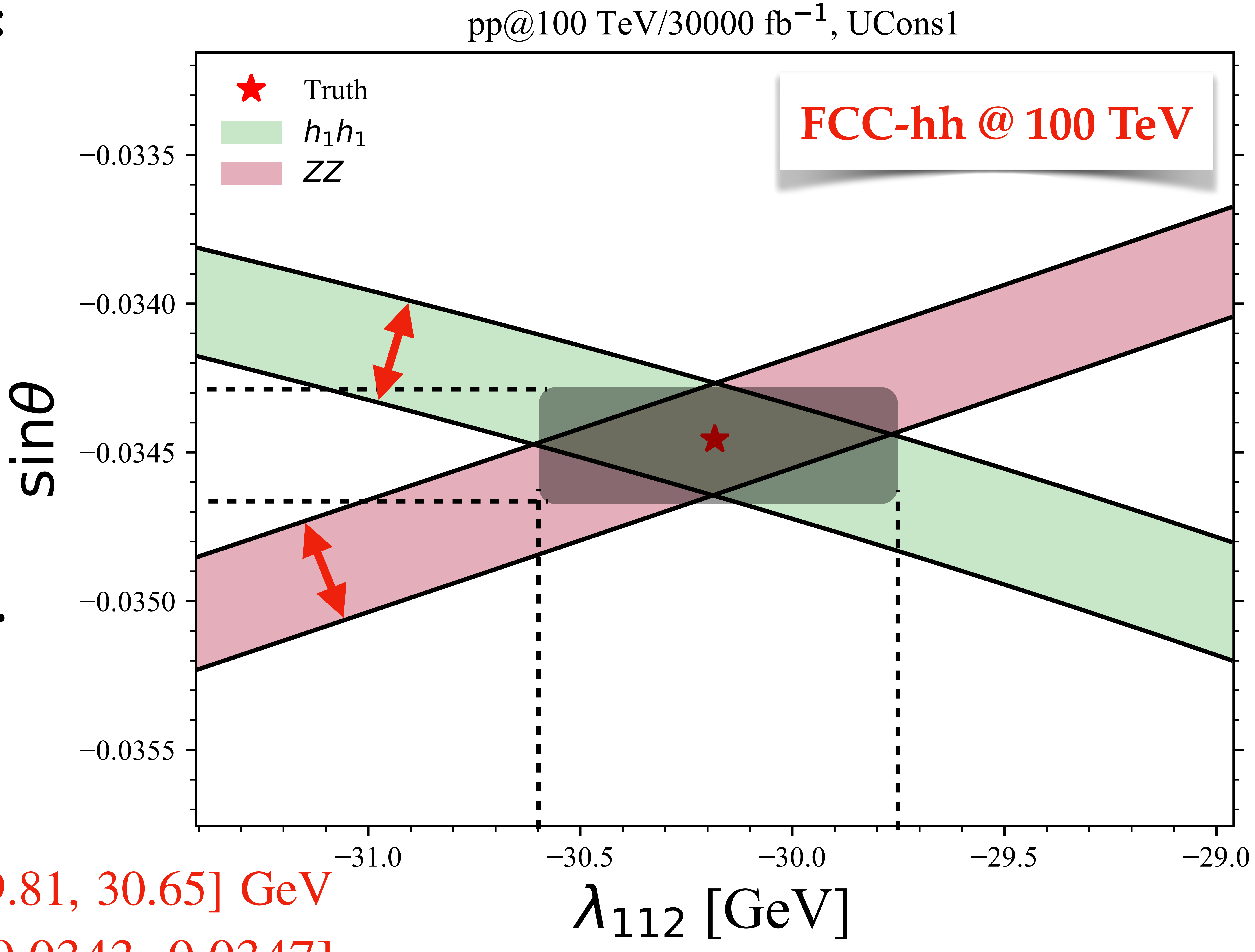


$\lambda_{112} \in [29.81,\ 30.65]$ GeV

$\sin\theta \in [0.0343,\ 0.0347]$



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## The Inverse Problem in Extended Scalar Sectors:

Multi-scalar processes should play a **crucial rôle**:

$$pp \to h_1 h_2 \qquad |\mathcal{M}|^2 \sim \lambda_{122}^2, \lambda_{112}^2 + \ldots$$

$$pp \to h_2 h_2 \qquad |\mathcal{M}|^2 \sim \lambda_{222}^2, \lambda_{122}^2 + \ldots$$

$$pp \to h_1 h_1 h_1 \qquad |\mathcal{M}|^2 \sim f[\lambda_{1111}, \lambda_{1112}, \lambda_{111}, \lambda_{112}]$$

[…]

# TO BE CONTINUED...

# Summary

- Within the realm of the Standard Model, **we can describe a whole of range of particle interactions with extraordinary precision**.

    - **Monte Carlo Event Generators** are invaluable tools of communication between theory and experiment.

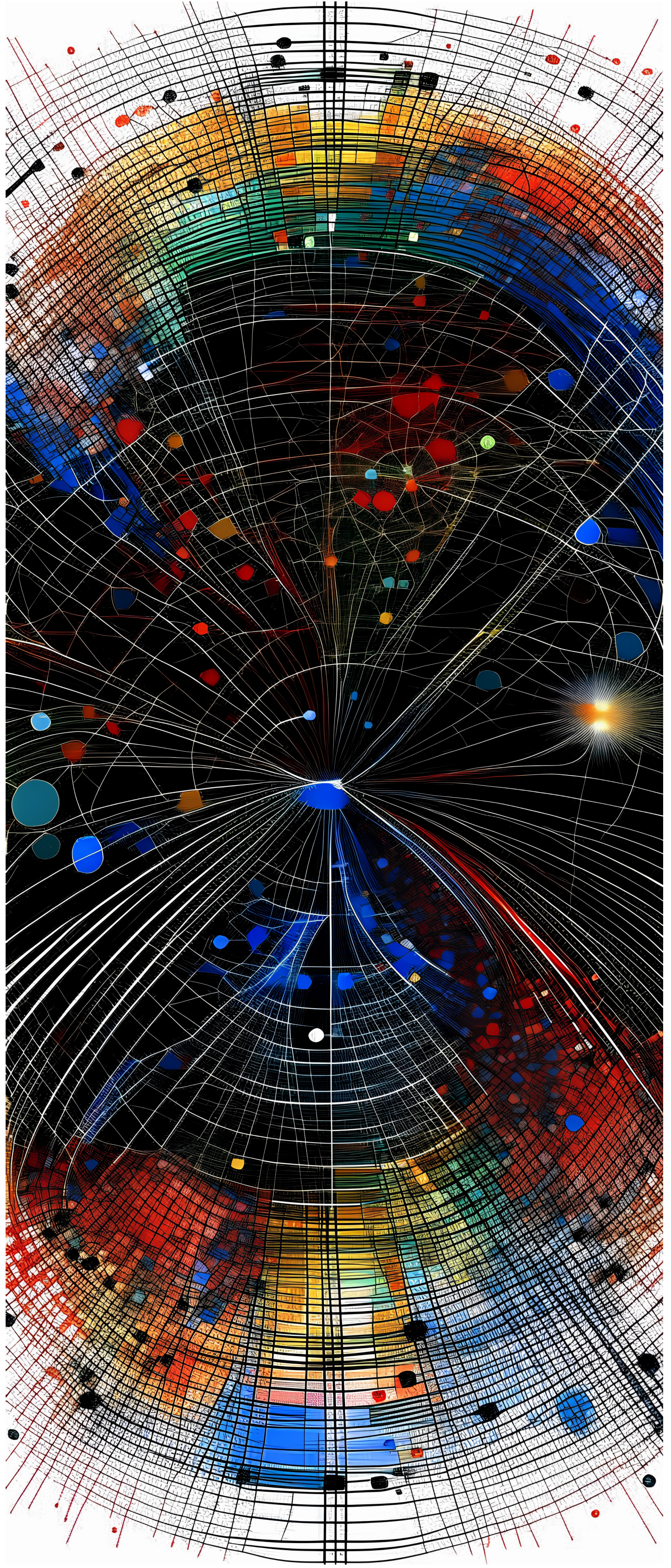
- However, there remains a multitude of **open questions**, that may be linked via the **Electro-Weak Phase Transition.**

- The **Nature of the Electro-Weak Phase Transition** is an important scientific enquiry.

    - **(Strong) First-Order EWPT [not in SM!] → Matter-Anti-Matter asymmetry.**

    - Extending the **scalar sector of the SM can be the necessary catalyst!**

    - Future particle colliders have the **potential to probe this mechanism**.



[made with stablecog]

Andreas Papaefstathiou

# Outlook

- Following **any** discovery, **solving the inverse problem** would be the **crucial** next step.

- I discussed possible **first steps in this exercise**, following the discovery of a new scalar.

- **Multi-scalar production processes** (e.g. triple Higgs boson production) will play a crucial role in this endeavor.

- [Could they also be **discovery channels** themselves?]

- **Questions merit investigation both at the LHC and other future colliders (e.g. FCC, Muon Collider, …).**

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- [Could they also be **discovery channels** themselves?]
- **Questions merit investigation both at the LHC and other future colliders (e.g. FCC, Muon Collider, …).**

Thanks!
Questions?

# Appendix

# Theoretical Uncertainties in SM+Singlet

- **Uncertainties** → Can affect e.g. the **strength of the transition,** $\langle \phi(T) \rangle / T$ .

- Due to:

  - **gauge dependence**, **[Patel, Ramsey-Musolf, arXiv:1101.4665]**

  - **scale dependence** → Linde's IR problem: expansion parameter is $g n_B \sim gT/m$, ($n_B$ mode occupation), diverges as $m \to 0 \Rightarrow$ perturbativity breaks down.

**[Linde, Phys. Lett. 96B (1980) 289.]**

- $\Rightarrow$ **To make reliable and sensible statements on colliders prospects:**

  → **Crucial to take uncertainties into account.**

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# Theoretical Uncertainty Bands

- **Define "uncertainty band"** by:

1. Deriving 1-loop effective potential in the covariant gauge,

   [Arnold, Espinosa, hep-ph/9212235], [Andreassen, MSc, Norwegian U. Sci. Tech., 2013]

2. Run couplings $\lambda \to \lambda(\mu)$, $\mu$ is RGE scale, [SARAH, Staub, arXiv:0806.0538]

3. Scan parameter space of Lagrangian,

4. Vary $\mu \in [\frac{1}{2} \times m_Z,\ 5 \times m_Z]$ & gauge params. $\xi_i \in [0,3] \to$ band of 8 pts.

5. Use **PhaseTracer** for each point in band $\to$ Get phase transitions, $\langle \phi(T_c) \rangle / T_c$.

   [Athron, Balázs, Fowlie, Zhang, arXiv:2003.02859]

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# Parameter-space Categories

1. Define two conditions:

   i. VEV at 1-loop: $\langle \phi(T=0) \rangle = 246 \pm 30$ GeV & deepest minimum.

   ii. $\left\langle \phi(T_c) \right\rangle / T_c > 1$ & no other transition with higher $T_c$.

2. Define four mutually-exclusive categories*:

*An alternative classification appears in our article: see Appendix.

**SFO-EWPT more certain** →

| Liberal | Centrist | Conservative | Ultra-Conservative |
|---|---|---|---|

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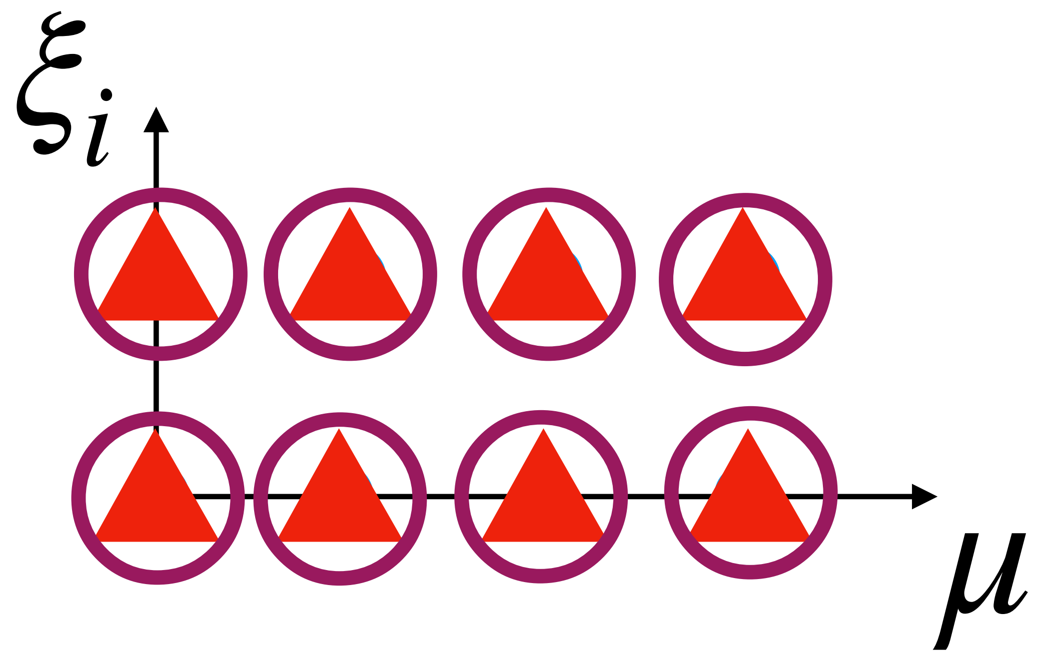




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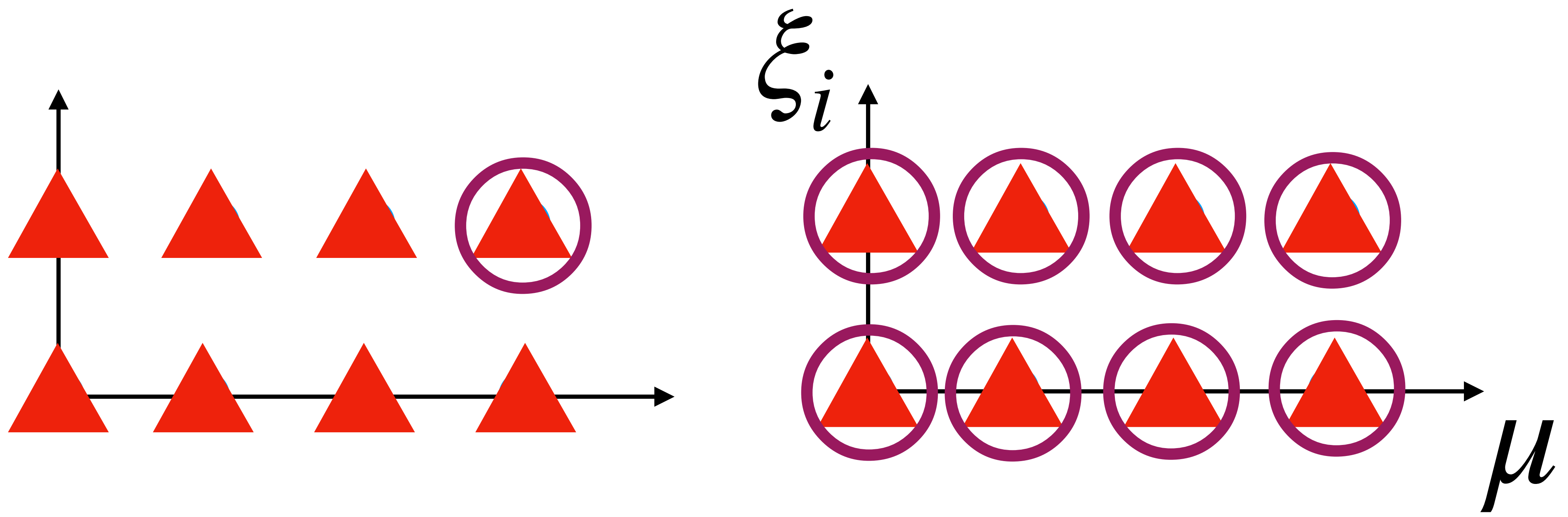

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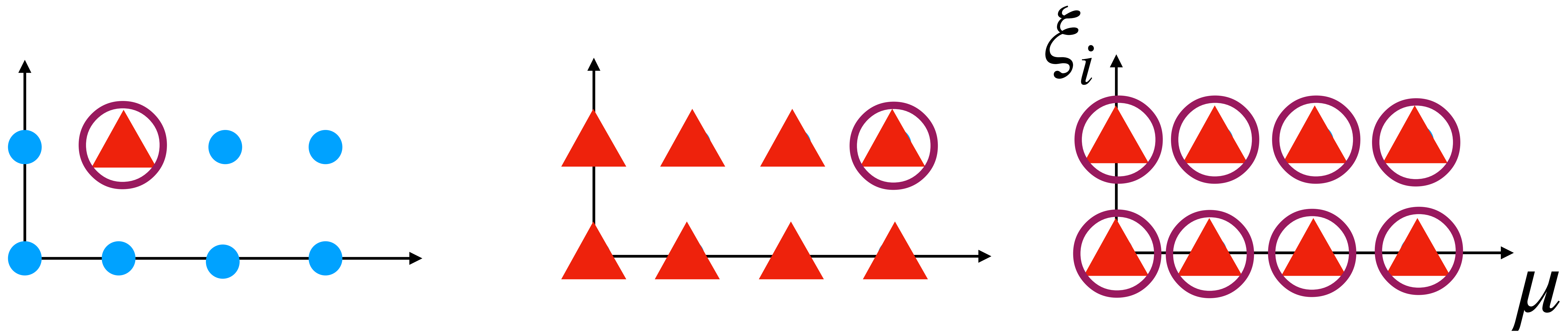

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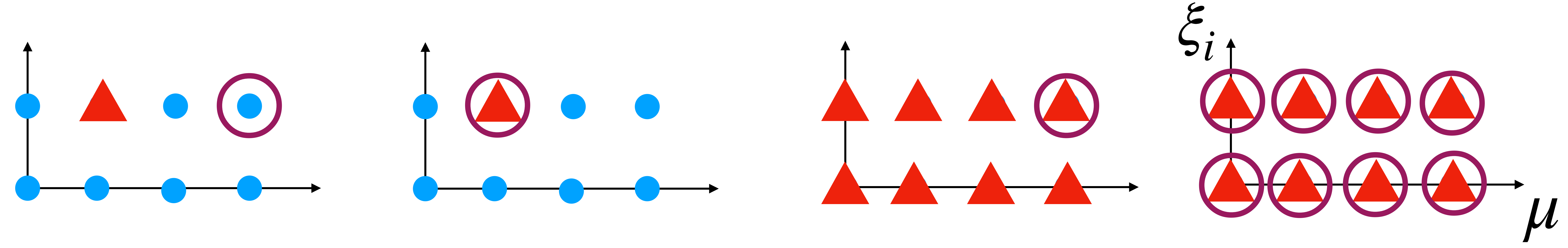

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**Note: For phenomenological analyses, take "central" $\mu$ and $\xi_i$.**

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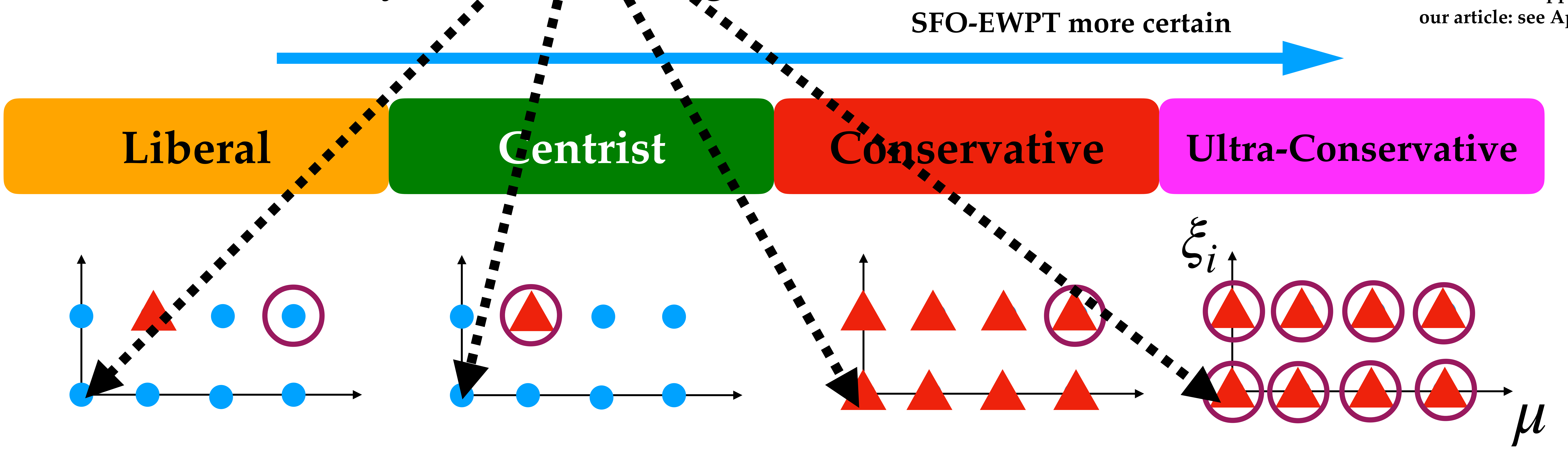




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# Electro-Weak Precision Observables

- Real singlet scalar field
  - $\rightarrow$ modifies Higgs contributions to diagonal weak gauge boson vacuum polarisation diagrams,
  - & introduces additional contributions.
- Quantify via $S, T, U$ parameters. **[Hagiwara, Matsumoto, Haidt, Kim, hep-ph/9409380]**
- Change in EWPO $\mathcal{O}$ $( = S, T, U)$:

$$\Delta\mathcal{O} = (\mathcal{O}(m_2^2) - \mathcal{O}(m_1^2)) \times \sin^2\theta$$

$\Rightarrow$ calculate compatibility with experimental measurement $\Delta\mathcal{O}^{\mathrm{EXP}}$.

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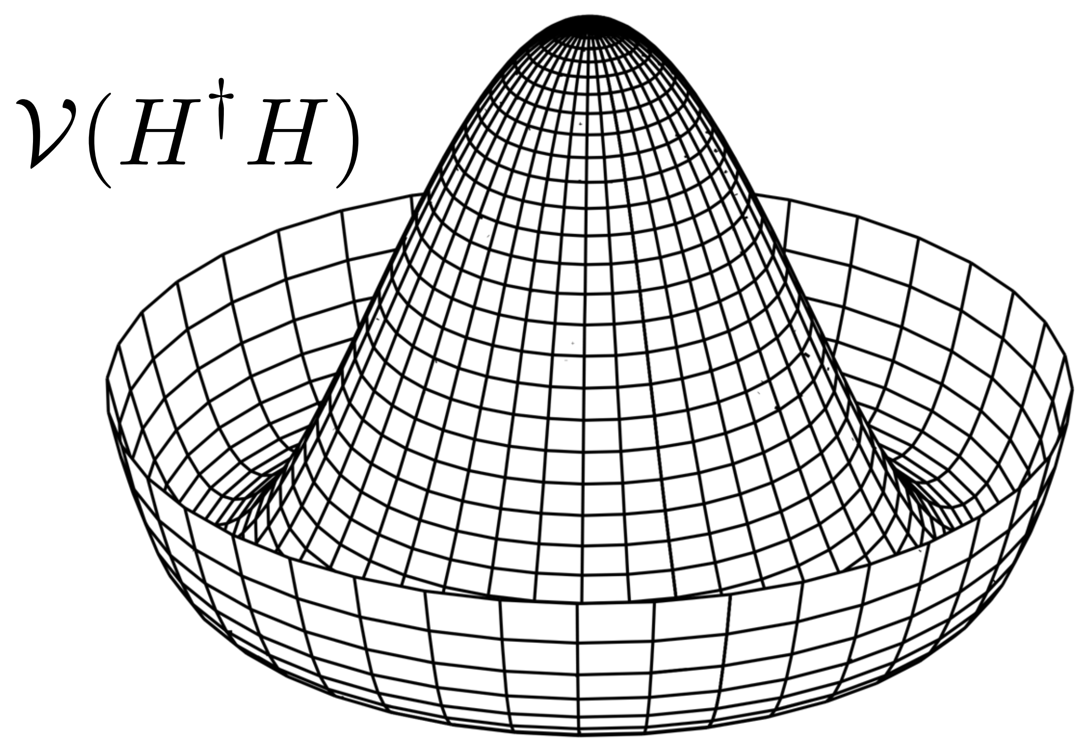
# The Higgs Potential & Vacuum Stability

# The Importance of the Higgs sector

- the Higgs boson: the central protagonist of EWSB:

***H*: Higgs doublet**

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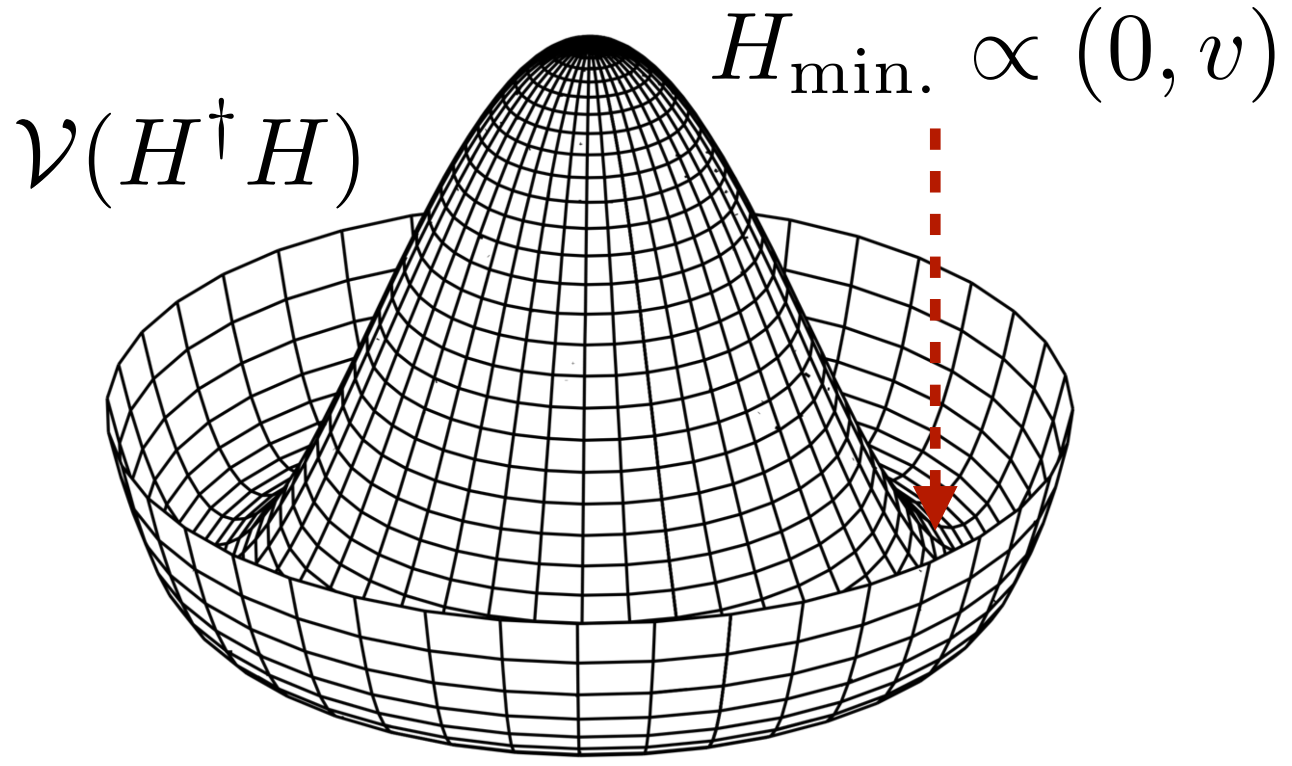


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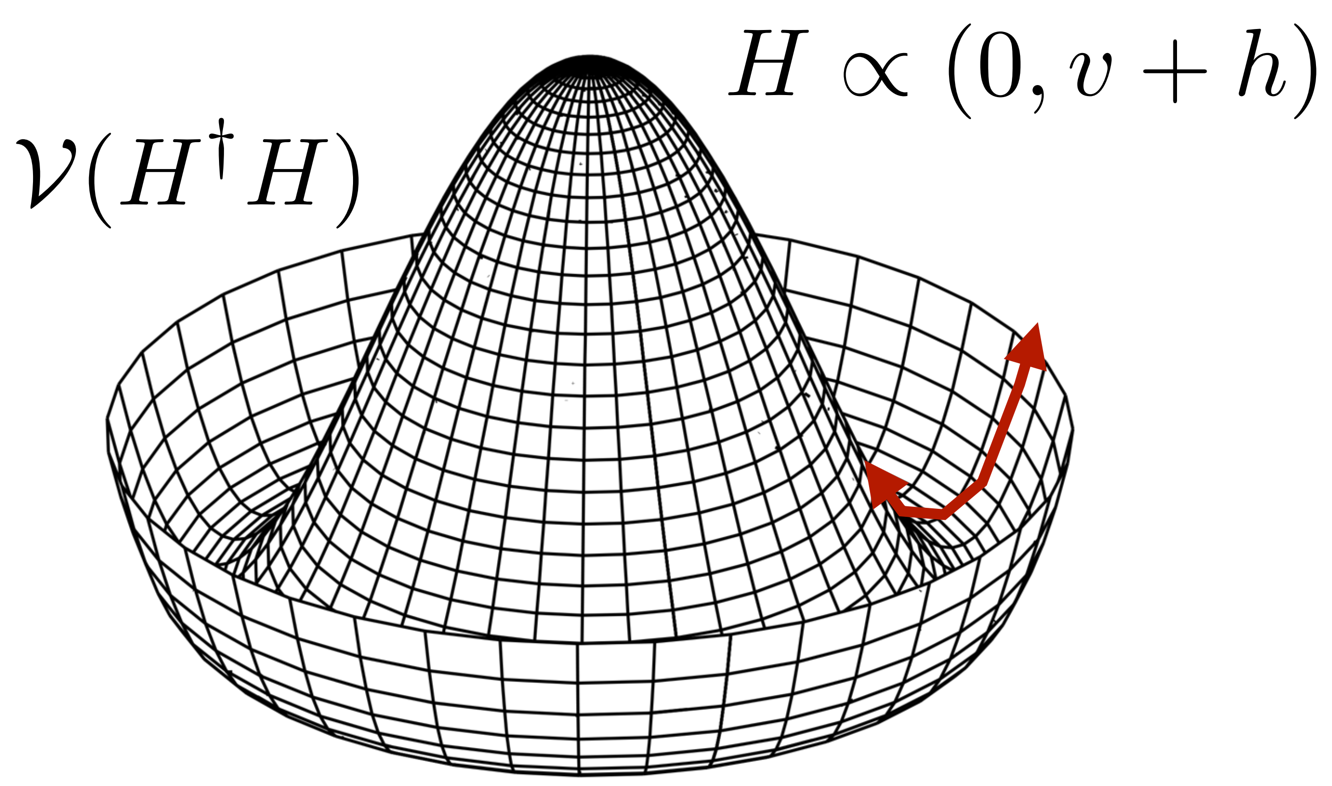


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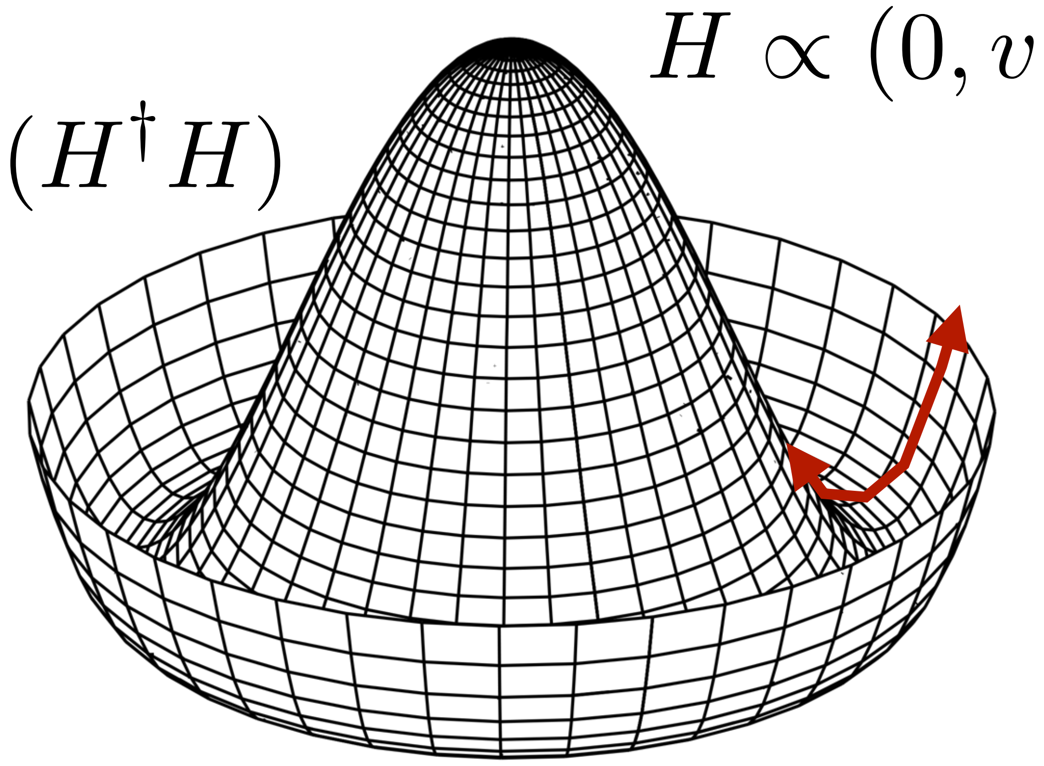


$\Longrightarrow$

**e.g. fermion masses & interactions:**

$$\mathcal{L} \supset -m_f \bar{f}_L f_R - \frac{m_f}{v} h \bar{f}_L f_R + \text{h.c.}$$

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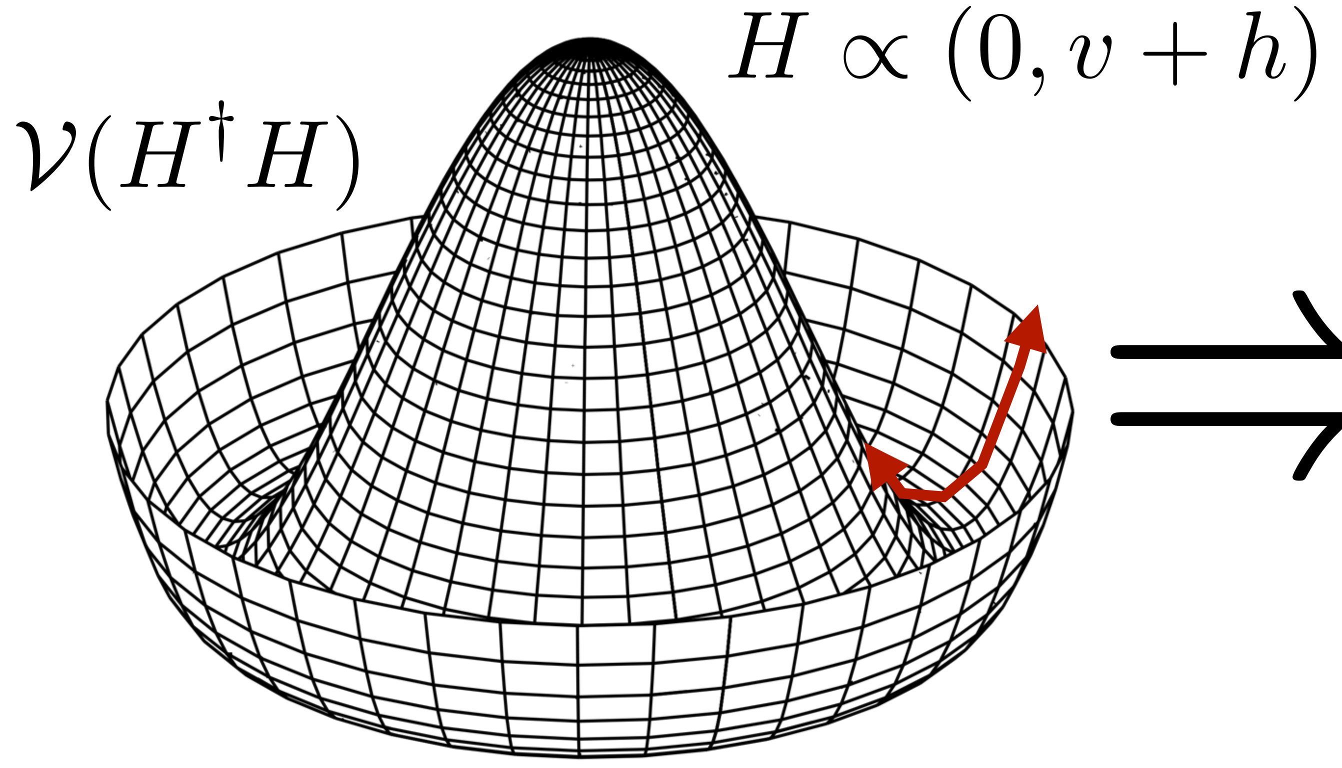


$\Rightarrow$

**e.g. gauge boson masses & interactions:**

$$\mathcal{L} \supset [m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu] \times \left(1 + \frac{h}{v}\right)^2$$

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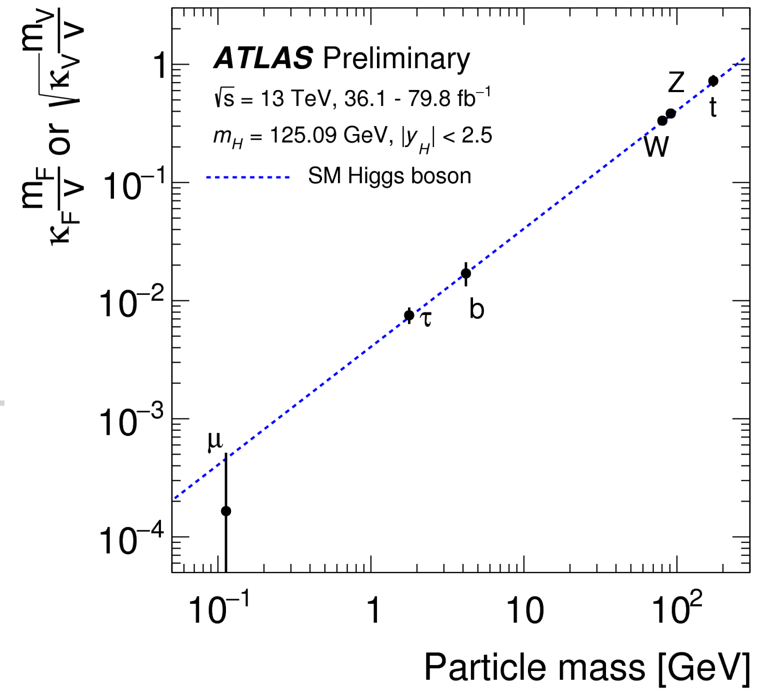
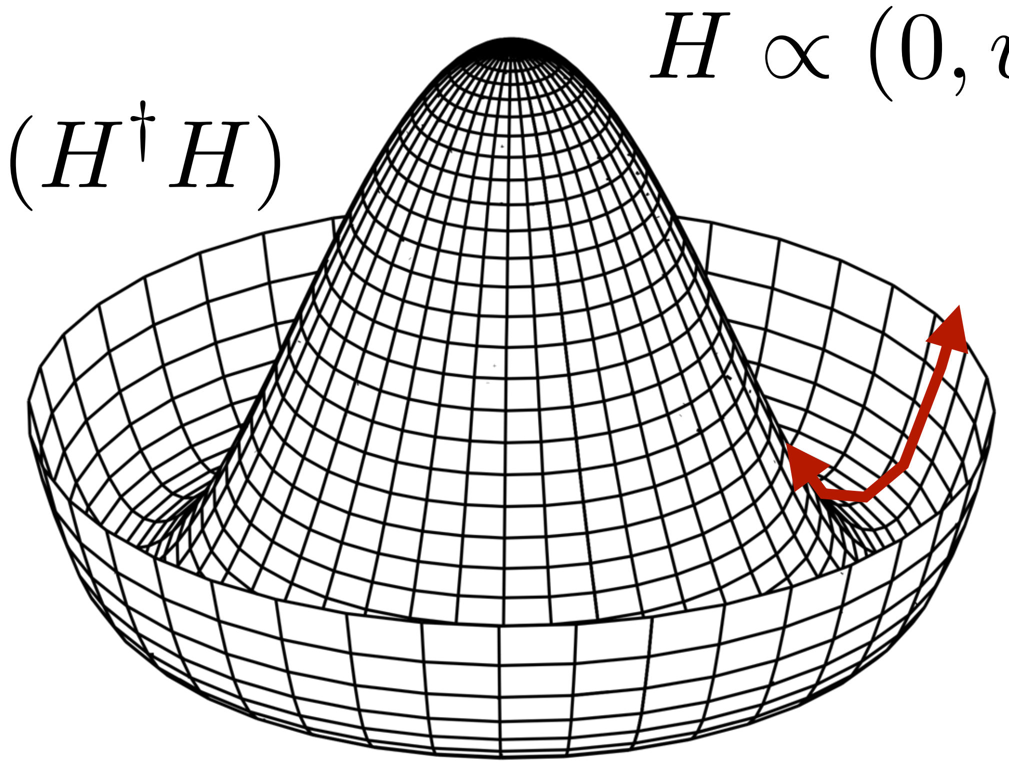



- the Higgs boson: the central protagonist of EWSB:

***H*: Higgs doublet**

$\mathcal{V}(H^\dagger H)$ $\quad H \propto (0, v+h)$



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- an important characteristic of the Higgs boson is the way it couples to itself:

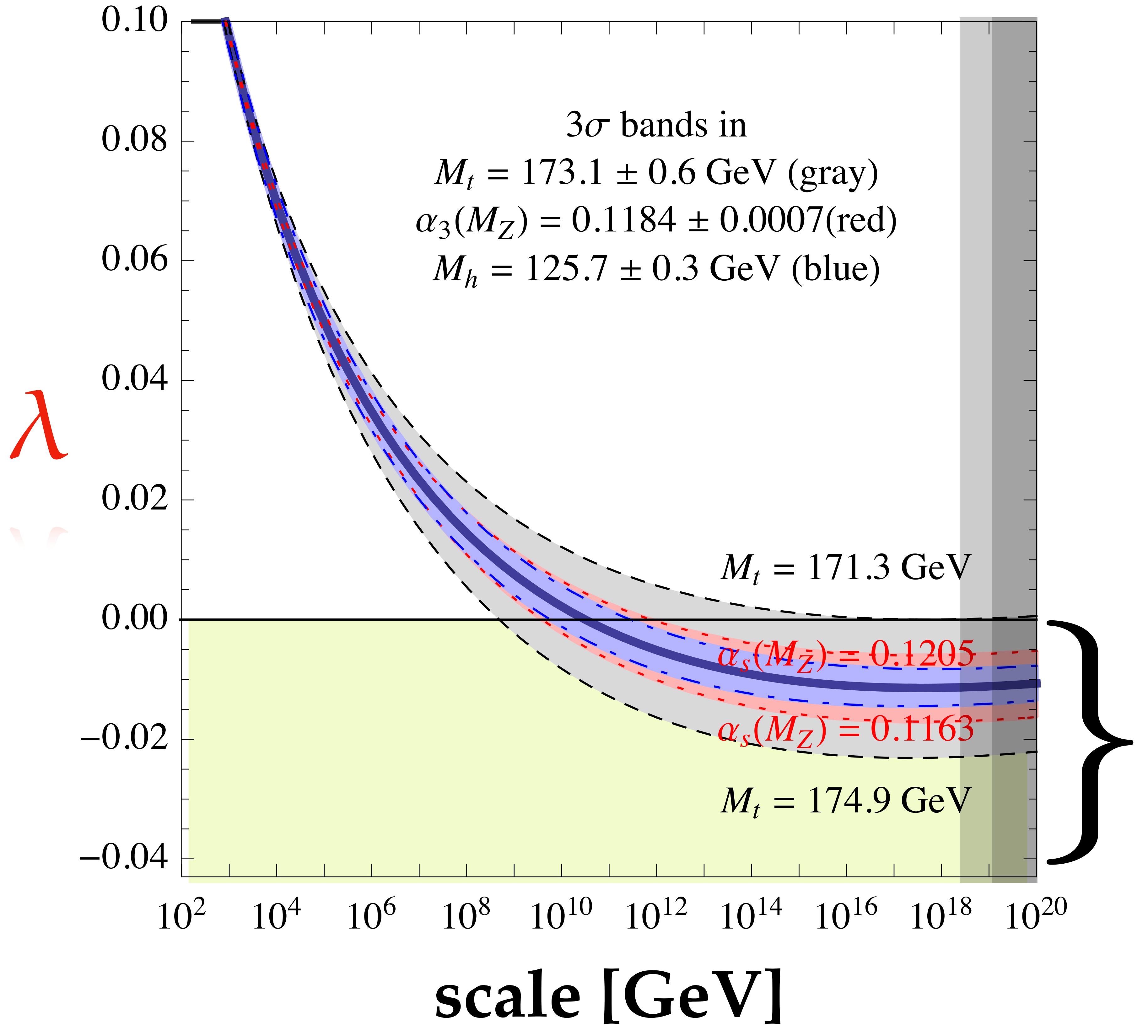
# Vacuum Stability

- SM potential for the Higgs doublet:

$$\mathcal{V}(H^\dagger H) = -m^2(H^\dagger H) + \lambda(H^\dagger H)^2$$

- renormalisation group evolution of the coupling $\lambda$:

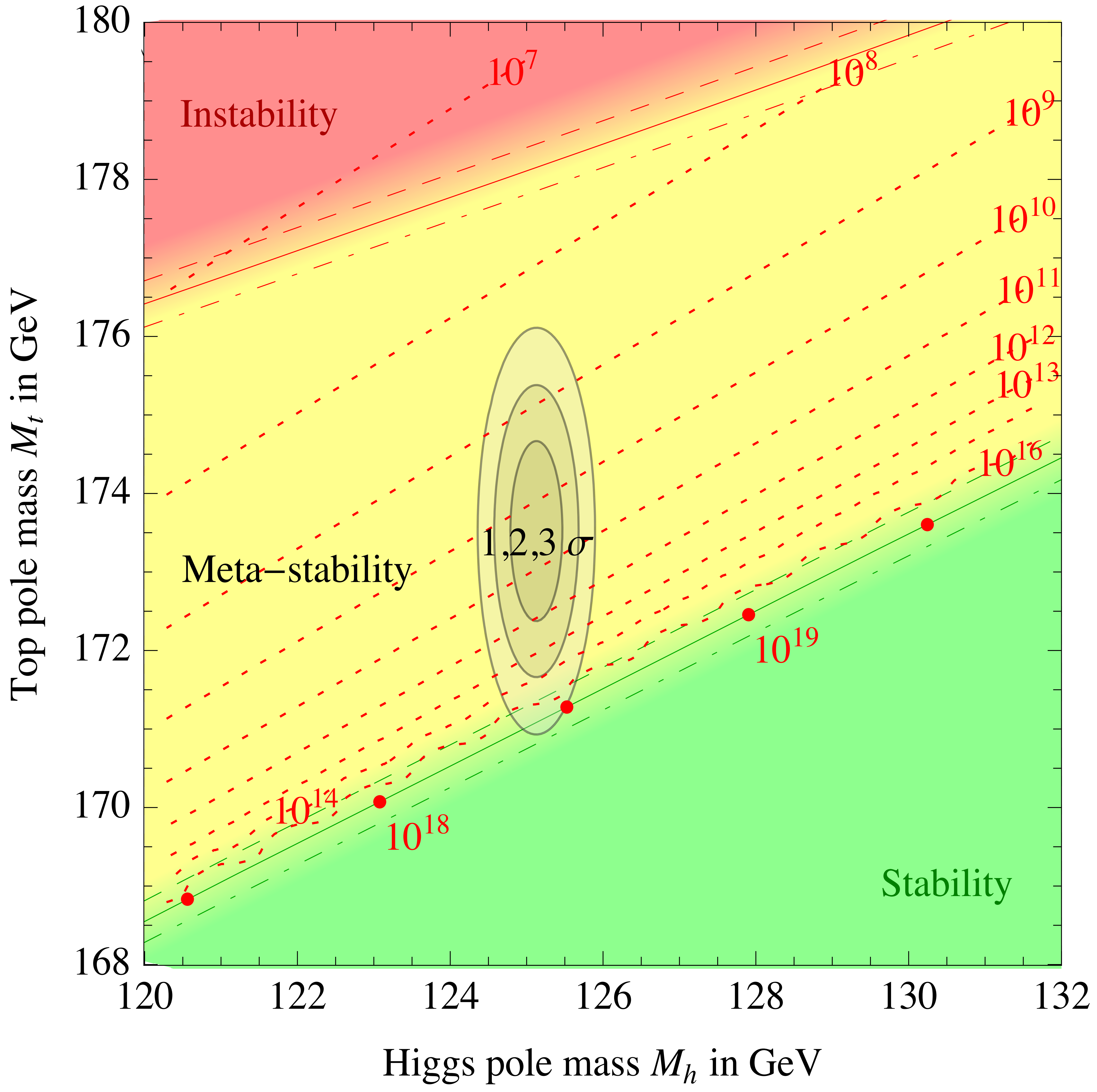
[Cabibbo, Maiani, Parisi, Petronzio, 1979, Hung, 1979, …, Degrassi, Di Vita, Elias-Miró, Giudice, Isidori, Strumia, 1205.6497, Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536 …, Espinosa, 1512.01222]




$\lambda < 0$ ! $\Longrightarrow$ **potentially unstable or meta-stable vacuum!**

# vacuum stability

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia, 1307.3536, Espinosa, 1512.01222]




in deriving this: **assumed Standard Model.**

➡ a hint for a non-standard Higgs sector?

➡ further investigation necessary.

# Sphaleron/Instanton Processes

# Instantons and Baryon-# Violation

- toy model:

(1+1)-dimensions, Abelian gauge field $A^{\mu}$, complex scalar $\Phi^{\mu}$, Dirac fermion of unit charge $\Psi$.

- Euclidean space action:

$$S = \int \mathrm{d}^2 x \left[ \frac{1}{4} F_{\mu\nu}^2 + |(\partial_\mu - ieA_\mu)\Phi|^2 + V(\Phi) + i\bar{\Psi}(\partial_\mu - ieA_\mu)\gamma^\mu \Psi \right]$$

**"Higgs potential":** $V(\Phi) = \lambda(\Phi^* \Phi - v^2)^2 \Longrightarrow$ **"EWSB"** $\Longrightarrow M_A, \; M_h$

# Instantons and Baryon-# Violation

- consider the current:

$$K_\mu = \frac{e}{2\pi}\epsilon_{\mu\nu}A_\nu$$

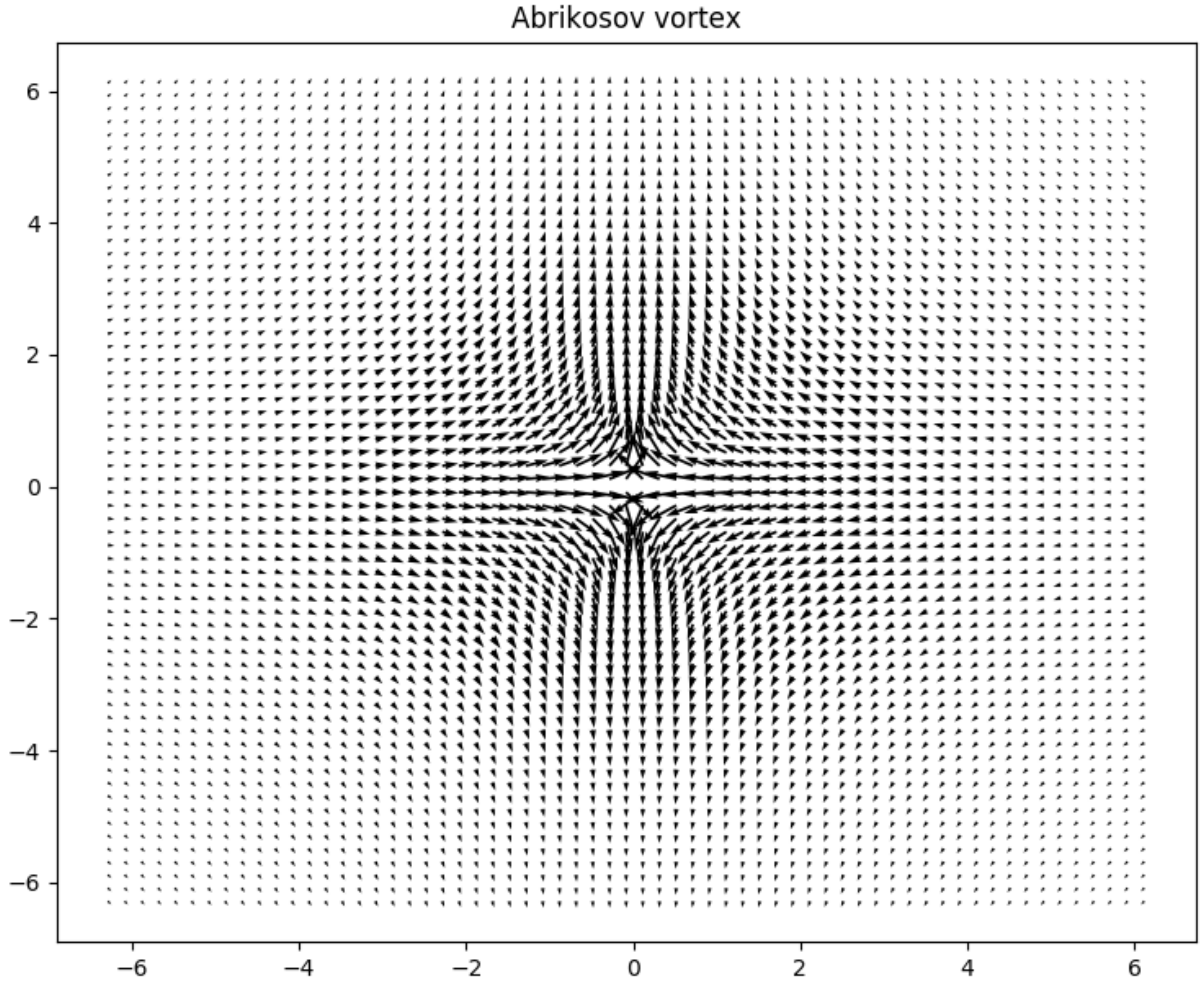
- corresponds to "charge density":

$$N_{\rm CS} = \int \mathrm{d}x\ K_0 = \frac{e}{2\pi}\int \mathrm{d}x\ A_1$$

- known as the "winding" or "Chern-Simons" number.

# Instantons and Baryon-# Violation

- a classical solution to equations of motion is the "Abrikosov vortex":




$$A_r = 0, \; A_\theta = \frac{1}{er} f(r),$$

$$f(0) = 0, \; 1 - f(r) \sim e^{-M_A r}$$

$\Rightarrow$ changes the Chern-Simons number by one unit:

$$\Delta N_{\rm CS} = \int \mathrm{d}^2 x \; \partial_\mu K^\mu = \boxed{\frac{e}{4\pi} \int \mathrm{d}^2 x \; \epsilon_{\mu\nu} F^{\mu\nu}} = 1$$

# Instantons and Baryon-# Violation

- "instanton" transition necessarily accompanied by change of chirality of fermions by two units:

$$j_\mu^5 = \bar{\Psi}\gamma_\mu\gamma_5\Psi$$

$$\frac{1}{2}\partial_\mu j^{5\mu} = \frac{e}{4\pi}\epsilon_{\mu\nu}F^{\mu\nu}$$

**anomalous divergence of the axial-vector current.**

$$\Delta N_{\rm CS} = \int \mathrm{d}^2x\ \partial_\mu K^\mu = \boxed{\frac{e}{4\pi}\int \mathrm{d}^2x\ \epsilon_{\mu\nu}F^{\mu\nu}} = 1$$

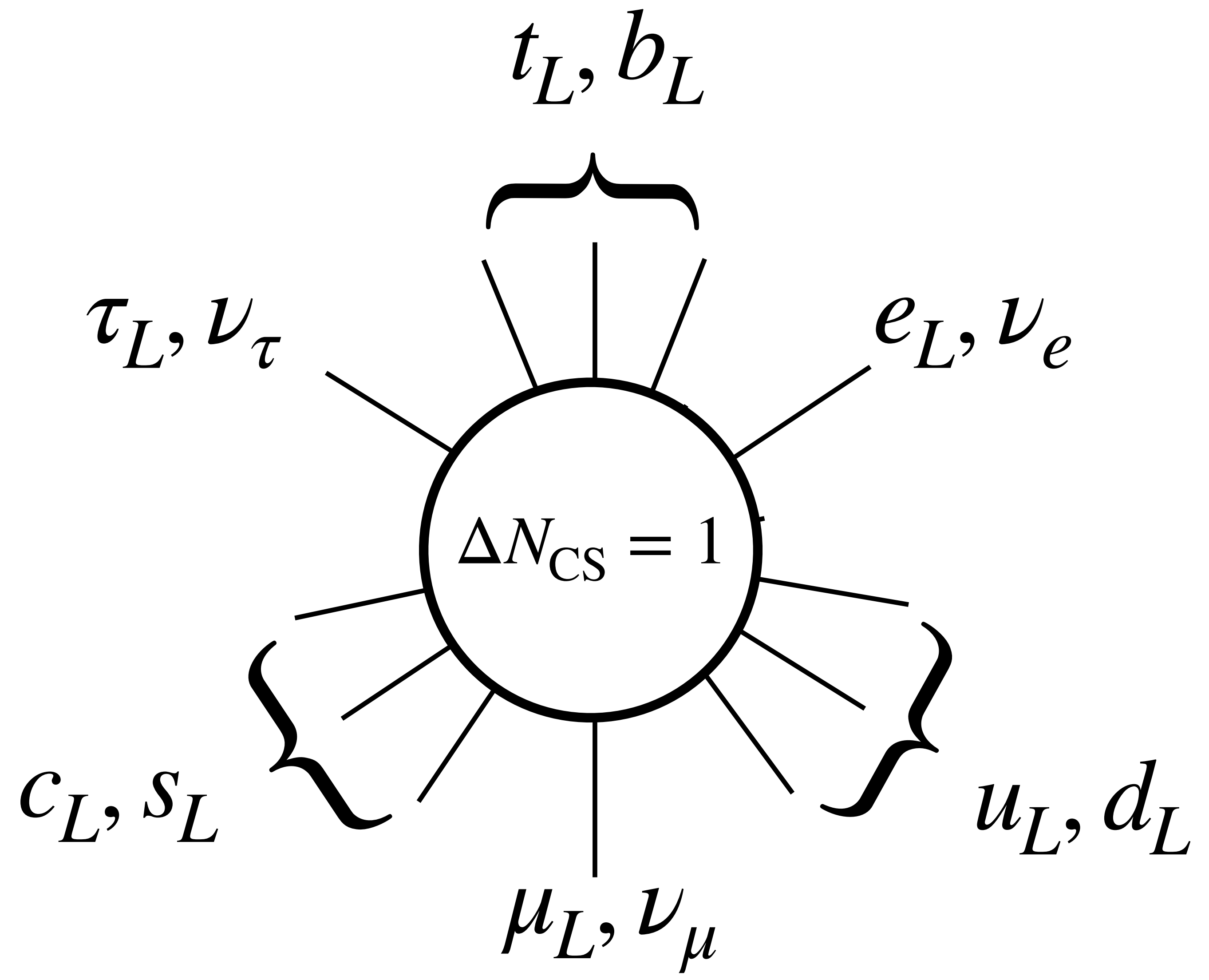
$$\Longrightarrow \quad \Delta Q_5 = \Delta \int \mathrm{d}x j_0^5 = 2$$

# EW Sphalerons at colliders?

- Rate and observability of sphaleron processes at colliders debated.

e.g. [Bezrukov, Levkov, Rebbi, Rybakov, Tinyakov, hep-ph/0304180] VS. [Tye, Wong, 1505.0360, 1710.07223].

- Ponder: **Sphaleron-induced interactions at hadron colliders**:



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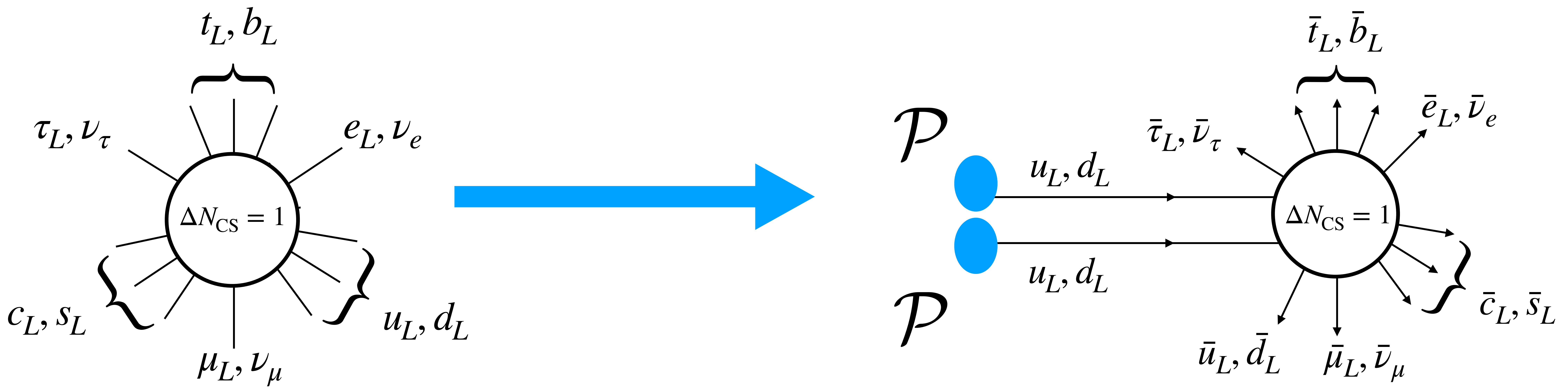
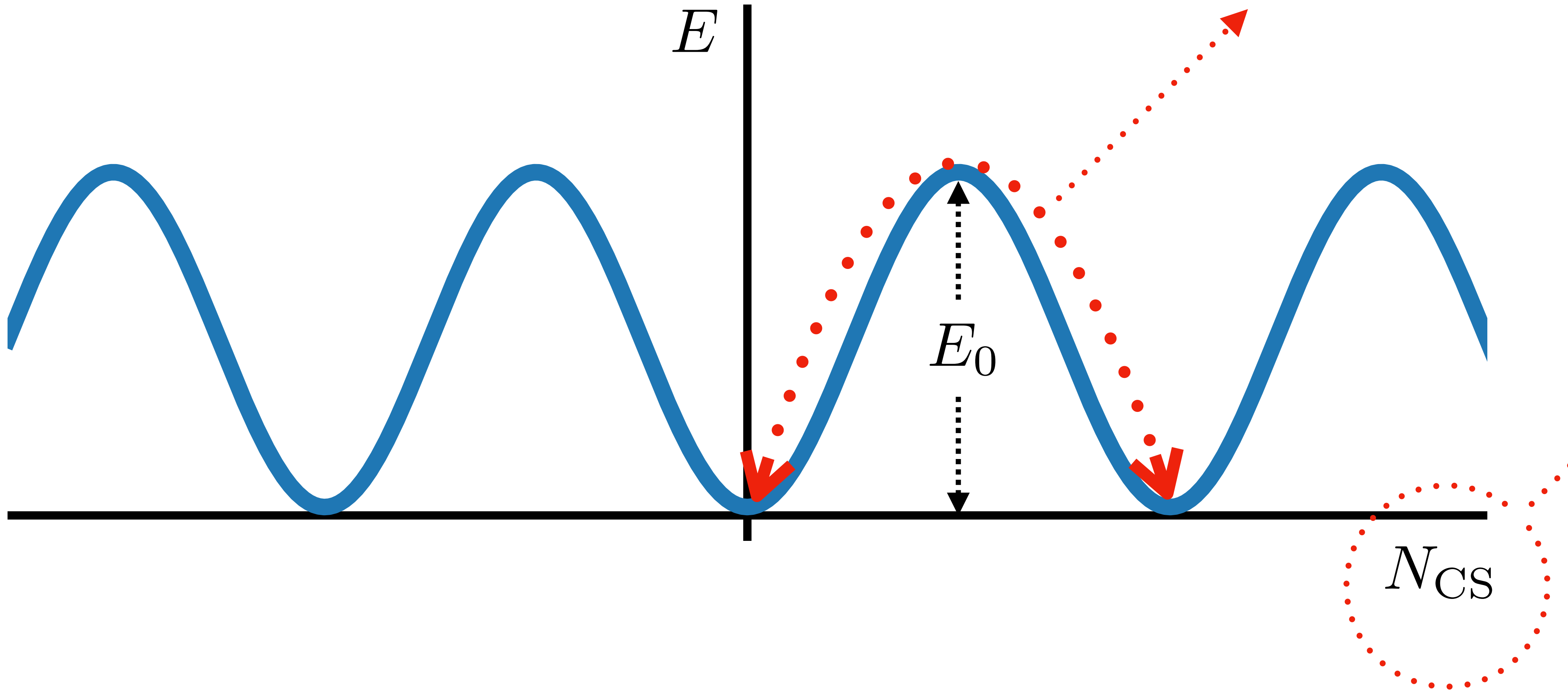


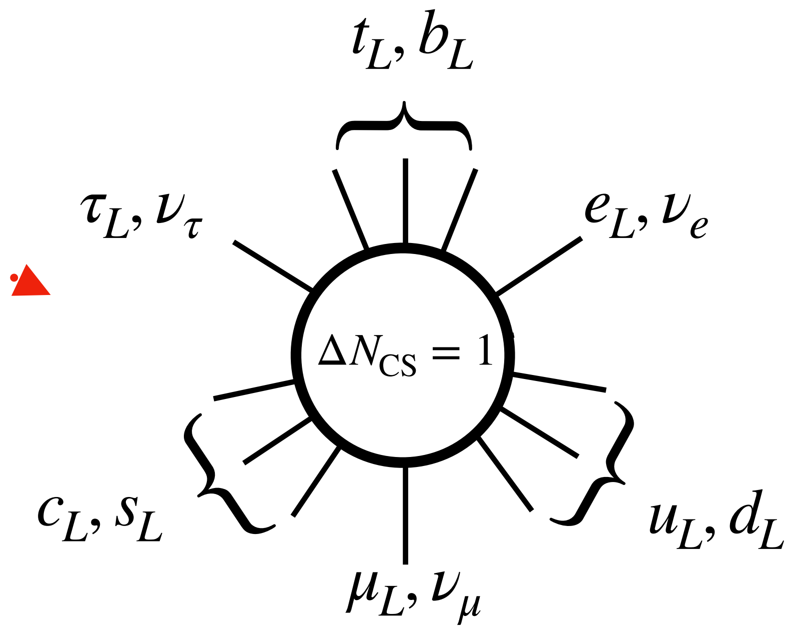
# What is the Sphaleron?

- $E_0 \sim \mathcal{O}(10)$ TeV, separates **degenerate** Electro-Weak vacua.

**Sphaleron transition**




**Chern-Simons number**

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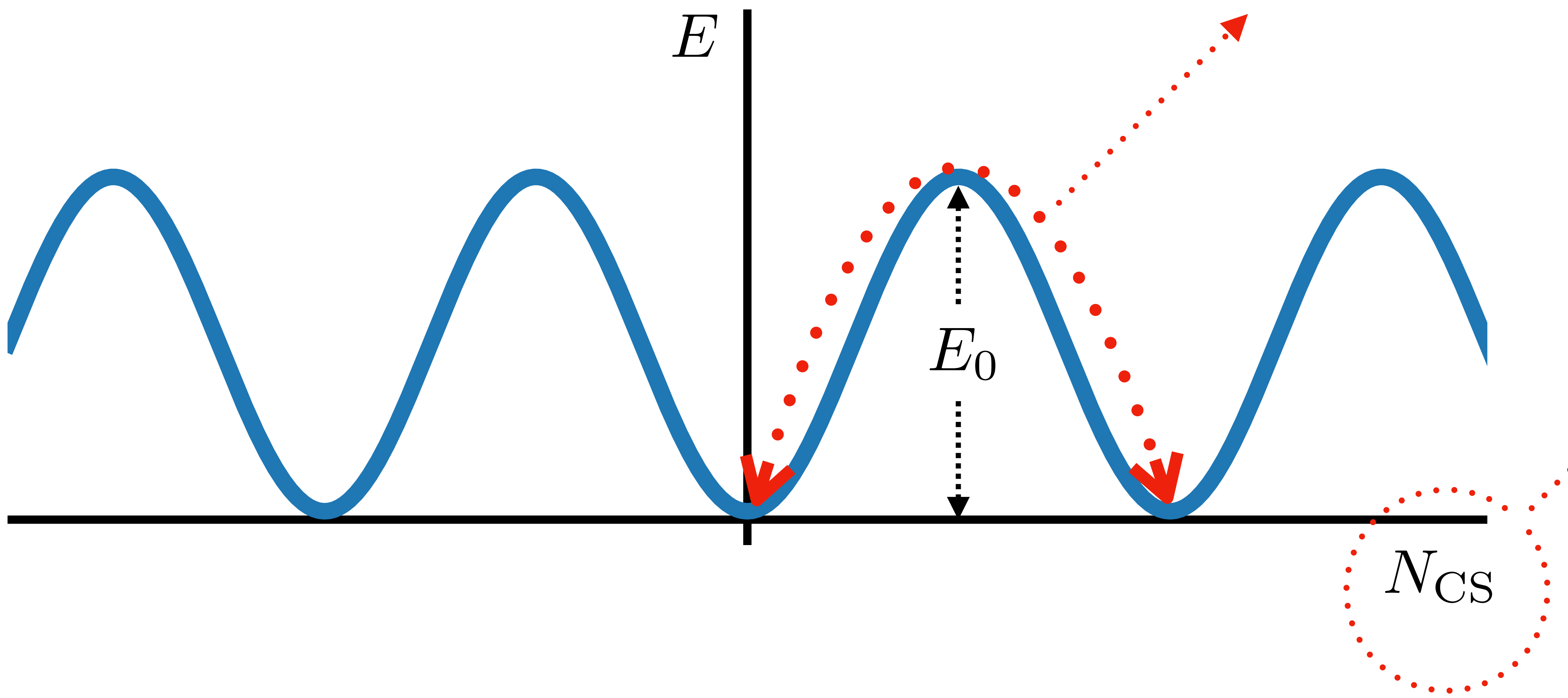


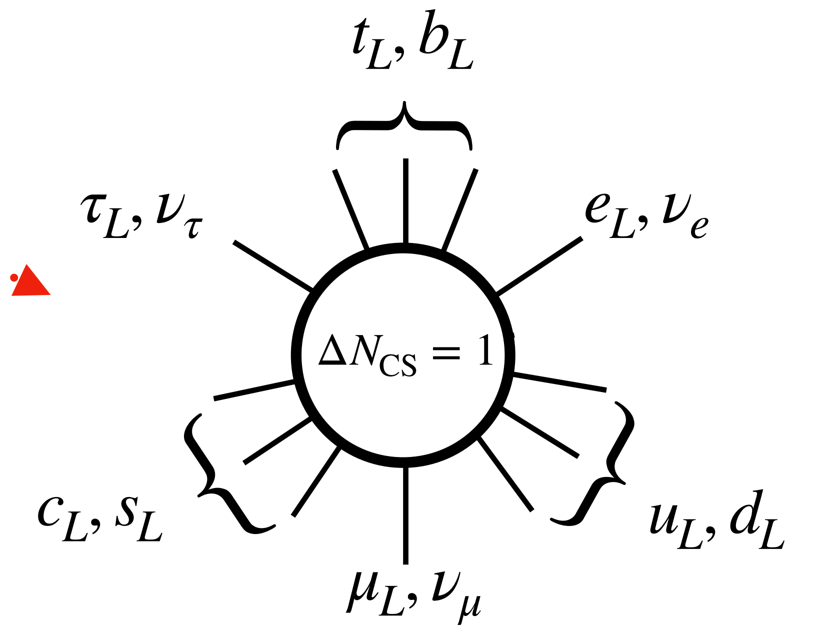


$$\Delta N_{CS} = \frac{1}{3}\Delta B = \Delta L_i$$

**The Sphaleron energy depends crucially on the Higgs sector!**

# A Note on Sphaleron Suppression

- **Suppression** of sphaleron rate **inside bubble**

  $\Rightarrow$ Baryon Asymmetry "swept in" broken phase and "frozen in".

- **Rate** $\sim \exp[-\langle \phi(T_C) \rangle / T_C \times \ldots]$,

  [$T_C$: the critical temperature.]

- $\Rightarrow$ Require: $\langle \phi(T_C) \rangle / T_C \geq 1 \Rightarrow$ a "Strong" First-Order EWPT (SFO-EWPT).

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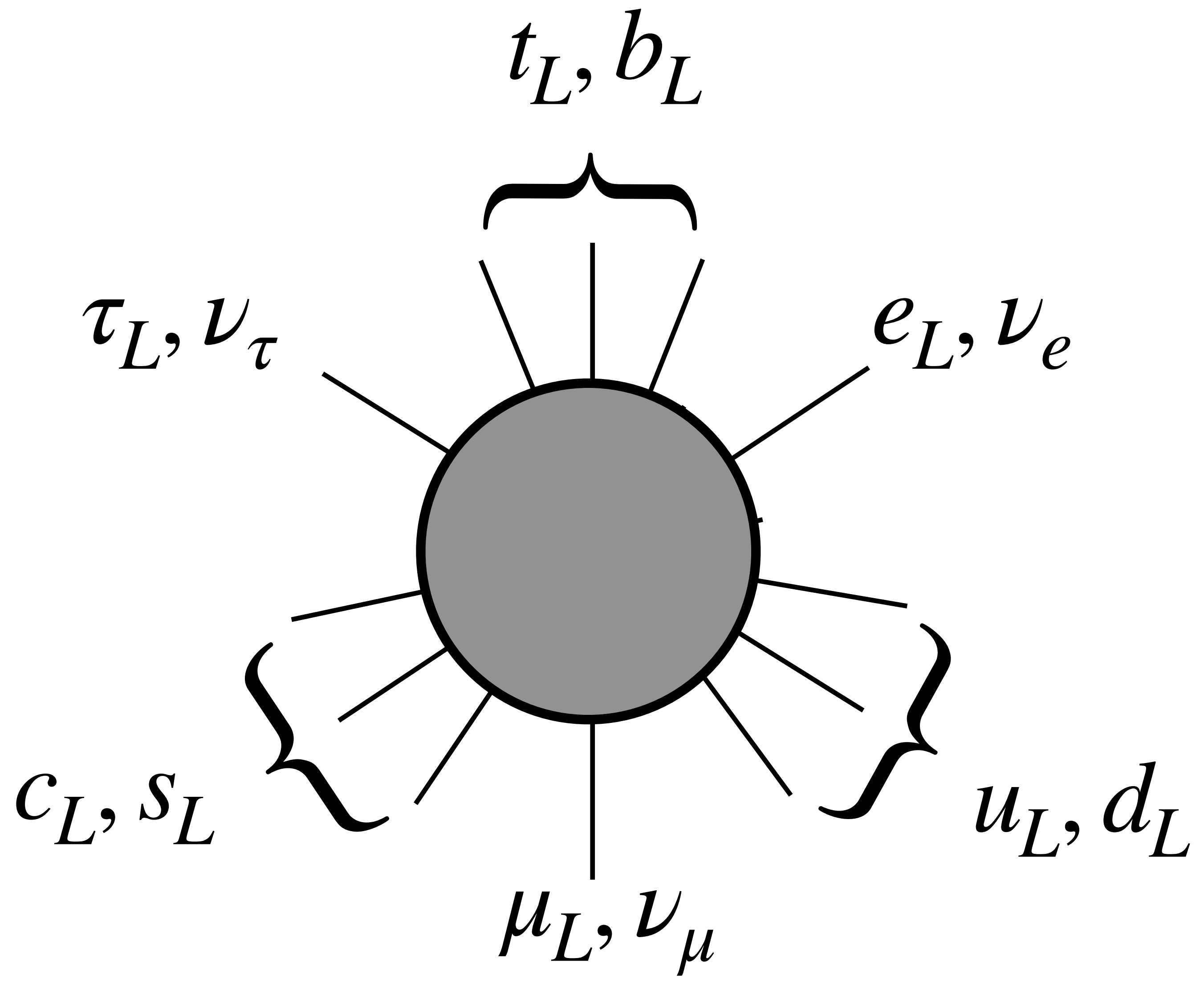
# Sphaleron Suppression

- Inside the bubble: 


- Suppression requires "**Strong**" First-Order EWPT (SFO-EWPT).

- **Despite suppression**: Sphalerons @ colliders?



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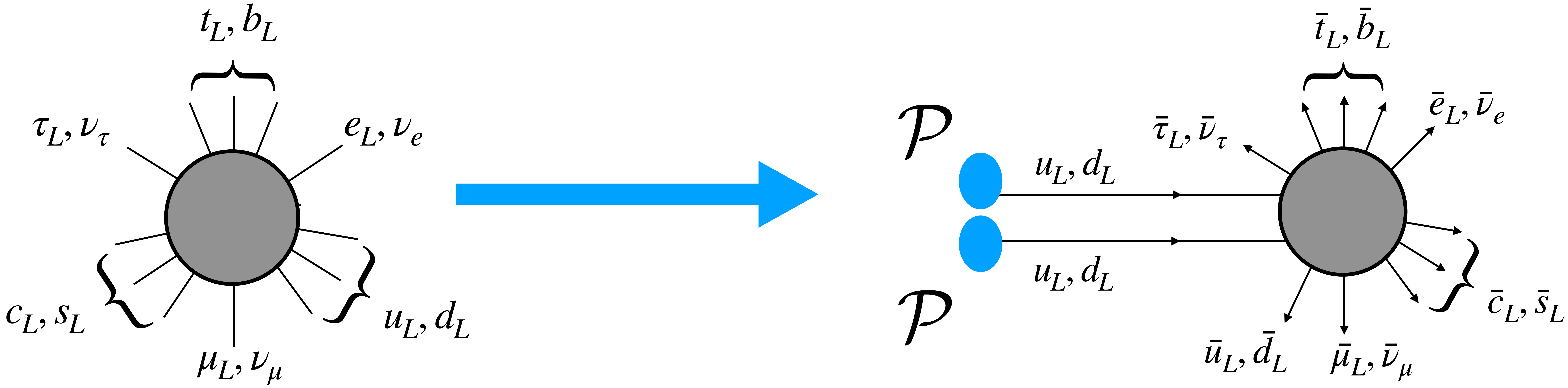


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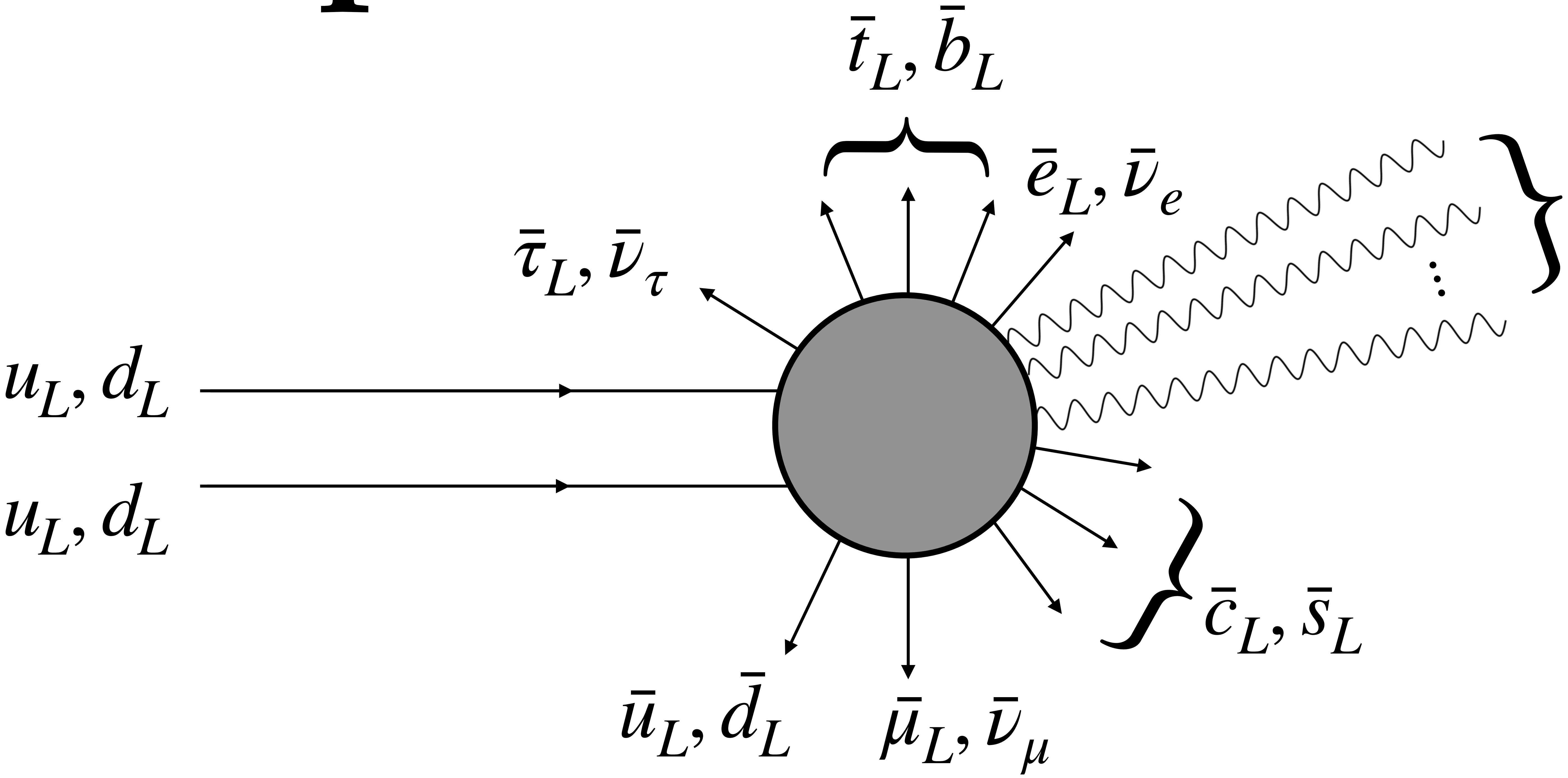
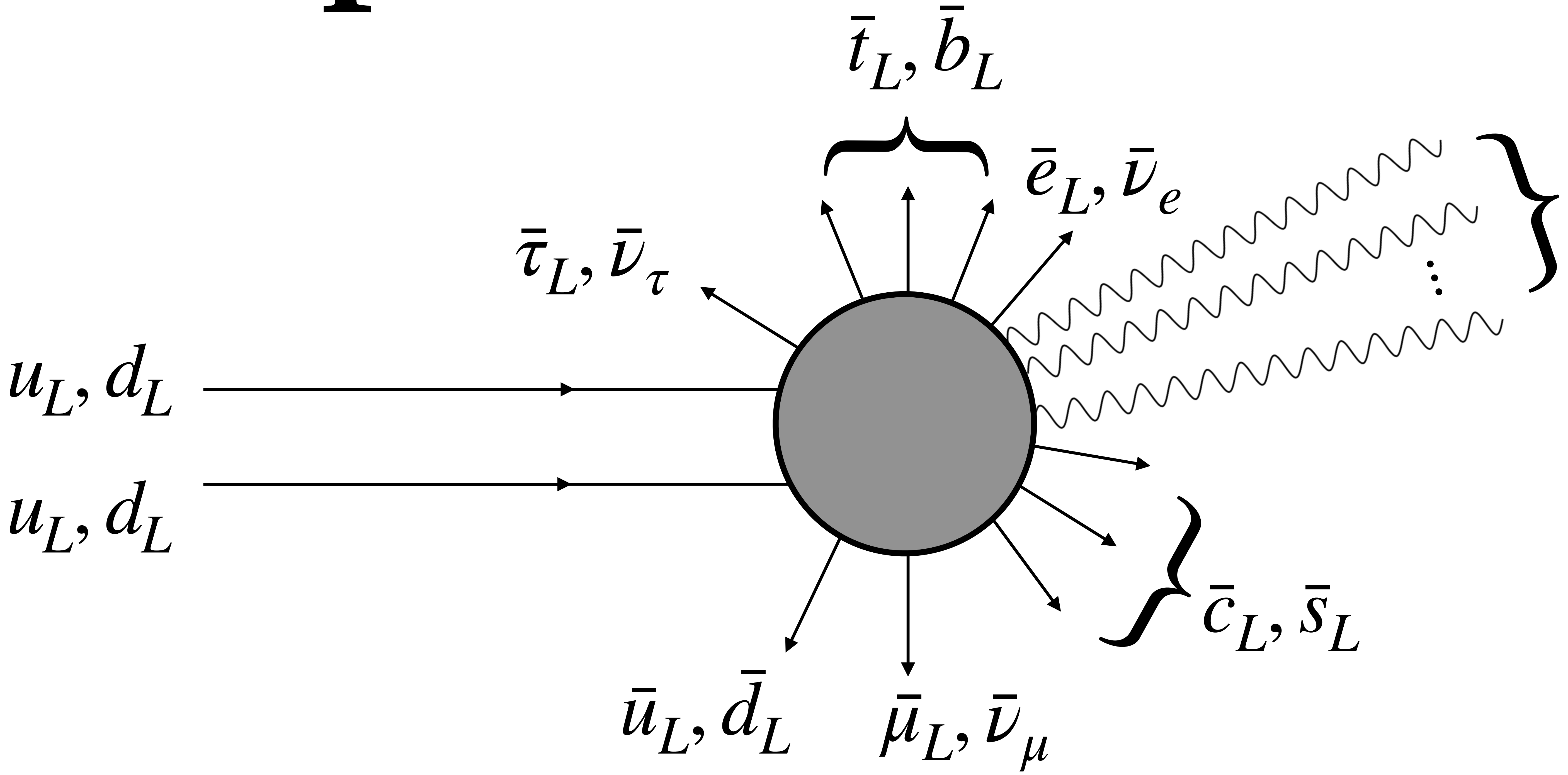



**Very large # of bosons: $\mathcal{O}(30)$!**

- Possible enhancement if large number of bosons,

$\Rightarrow$ Events would **spectacularly light up detectors** at experiments!

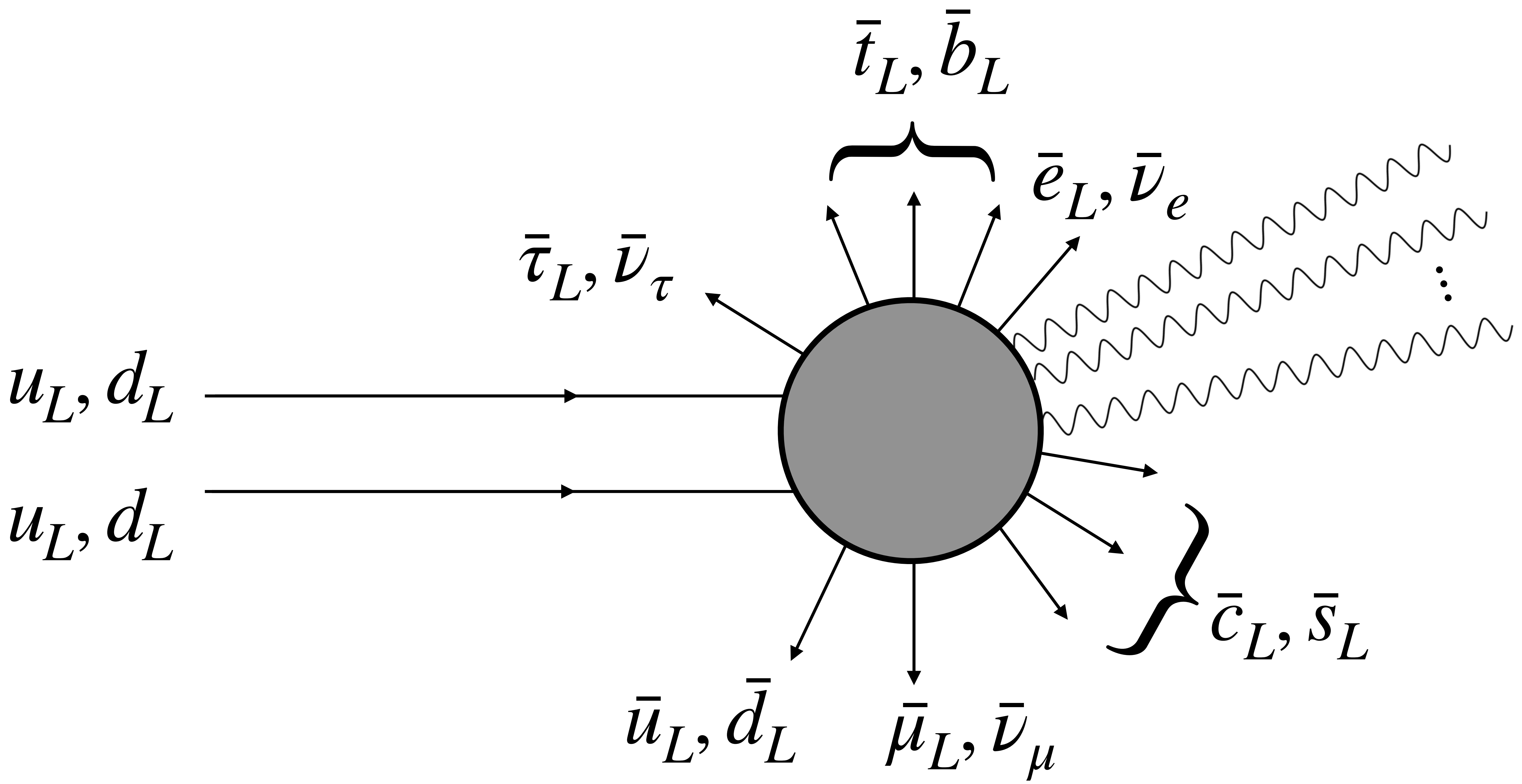
# EW Sphalerons at Colliders?




**Very large # of bosons: $\mathcal{O}(30)$!**

- Possible enhancement if large number of bosons,

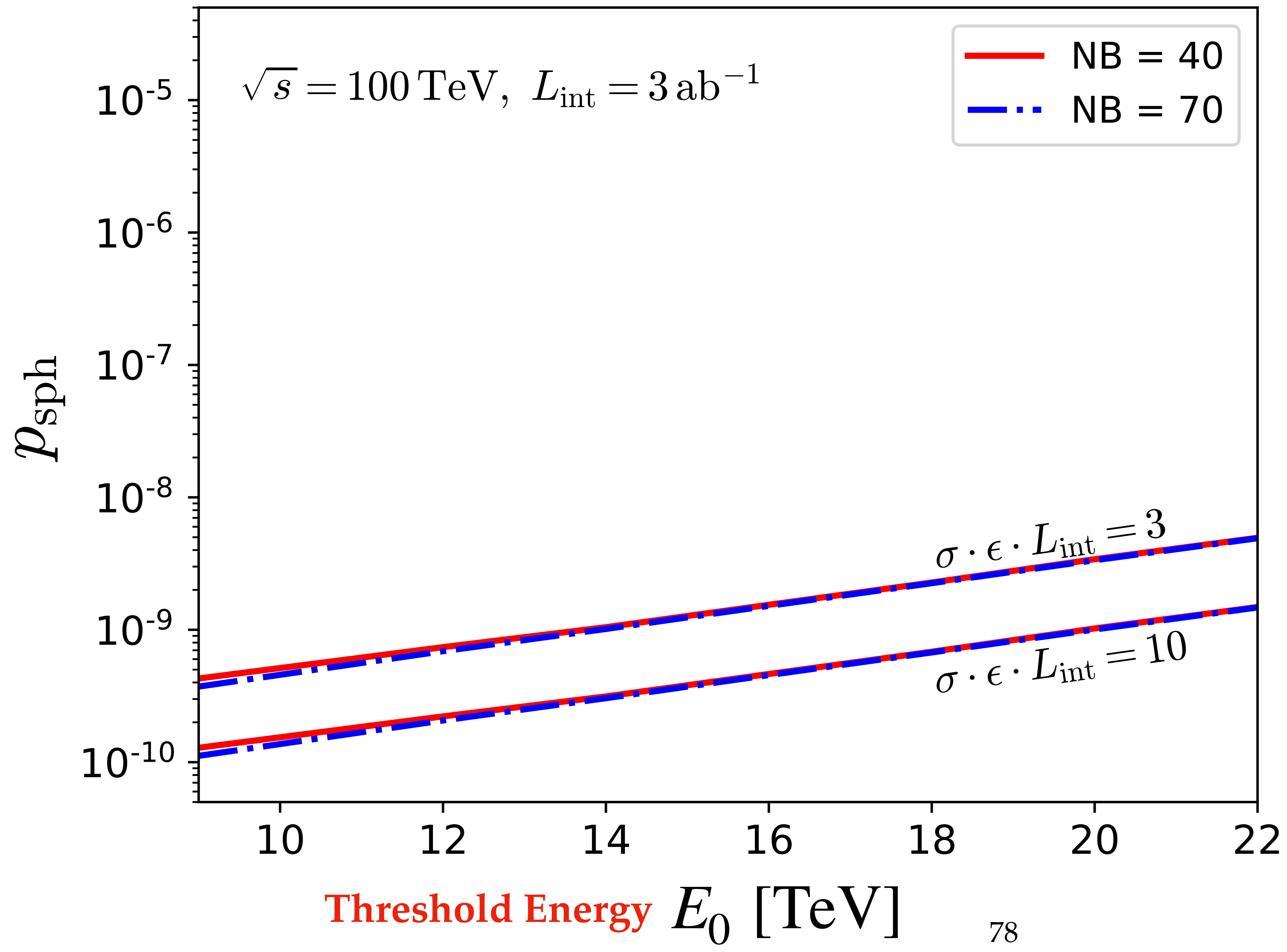
$\Rightarrow$ Events would **spectacularly light up detectors** at experiments!


$\bar{t}_L, \bar{b}_L$
$\bar{e}_L, \bar{\nu}_e$
$\bar{\tau}_L, \bar{\nu}_\tau$
$u_L, d_L$
$u_L, d_L$
$\bar{c}_L, \bar{s}_L$
$\bar{u}_L, \bar{d}_L$
$\bar{\mu}_L, \bar{\nu}_\mu$

# Sphalerons at the FCC

- Parametrise parton-parton cross section by $p_{\rm sph}$:

$$\hat{\sigma}(E) = \frac{p_{\rm sph}}{m_W^2}\Theta(E - E_0)$$




→ **Event Generator within HERWIG 7.**

[AP, Sakurai, Plätzer, arXiv:1910.4761]

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**Homework**:

(i) What can we learn about the Higgs sector and EWBG?

(ii) New theoretical features in Sphaleron MC.

(iii) Model discrimination, e.g. VS micro-black holes.

(iv) Collaboration with experimentalists for measurements.