Particle Physics:
The Gigantic Search for the Small Stuff

[made with stablecog]

Andreas Papaefstathiou

Assistant Professor of Physics, Kennesaw State University

National Science Foundation

@ SCM 2000 [October 18th, 2023]

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Find these slides at:

http://facultyweb.kennesaw.edu/apapaefs/scm2000.pdf

Colloquium @ Georgia State:

https://www.youtube.com/watch?v=rfRQSIfwqdY

What is Particle Physics?

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It all started with the Big Bang…

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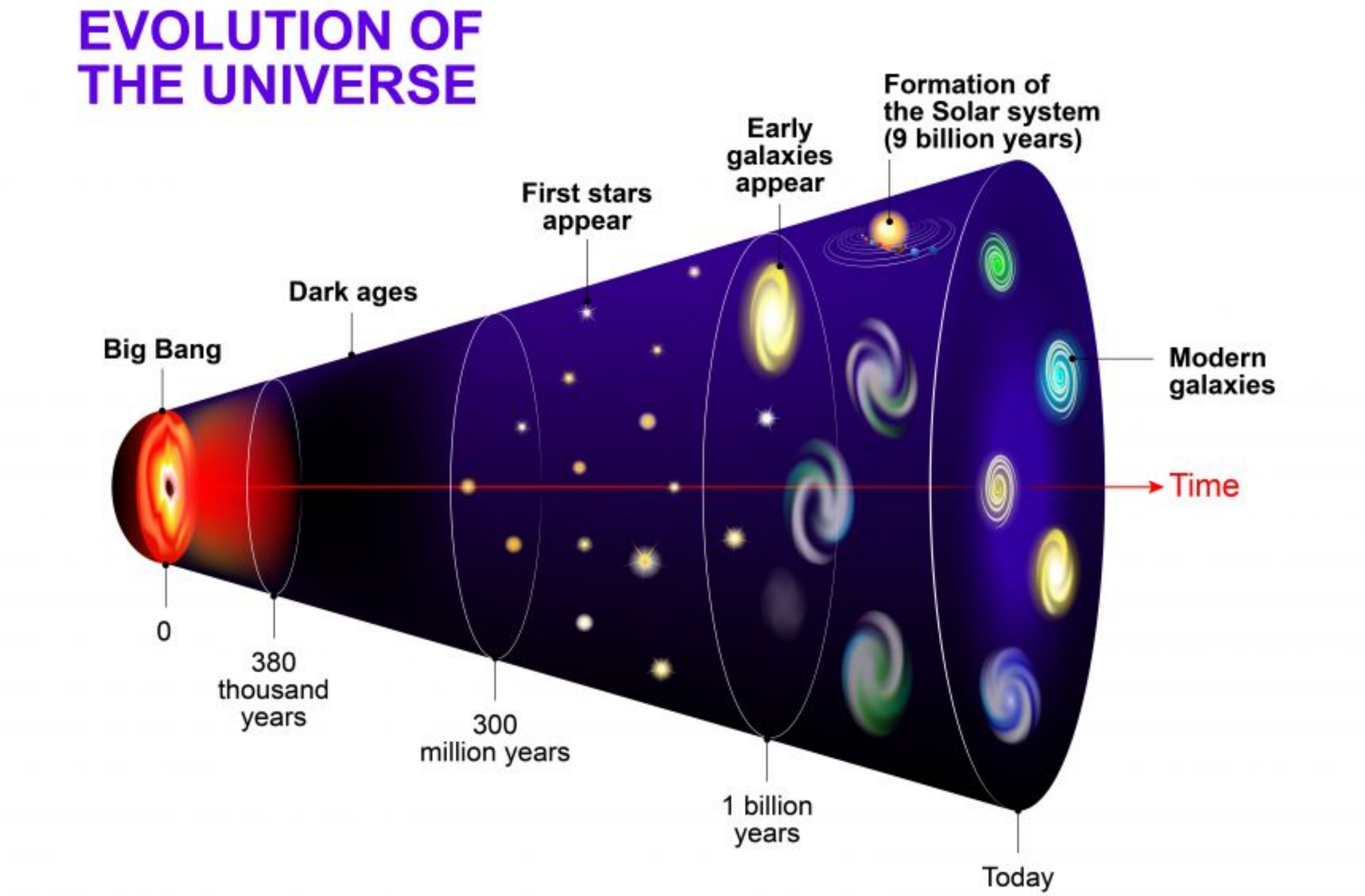
It all started with the Big Bang…



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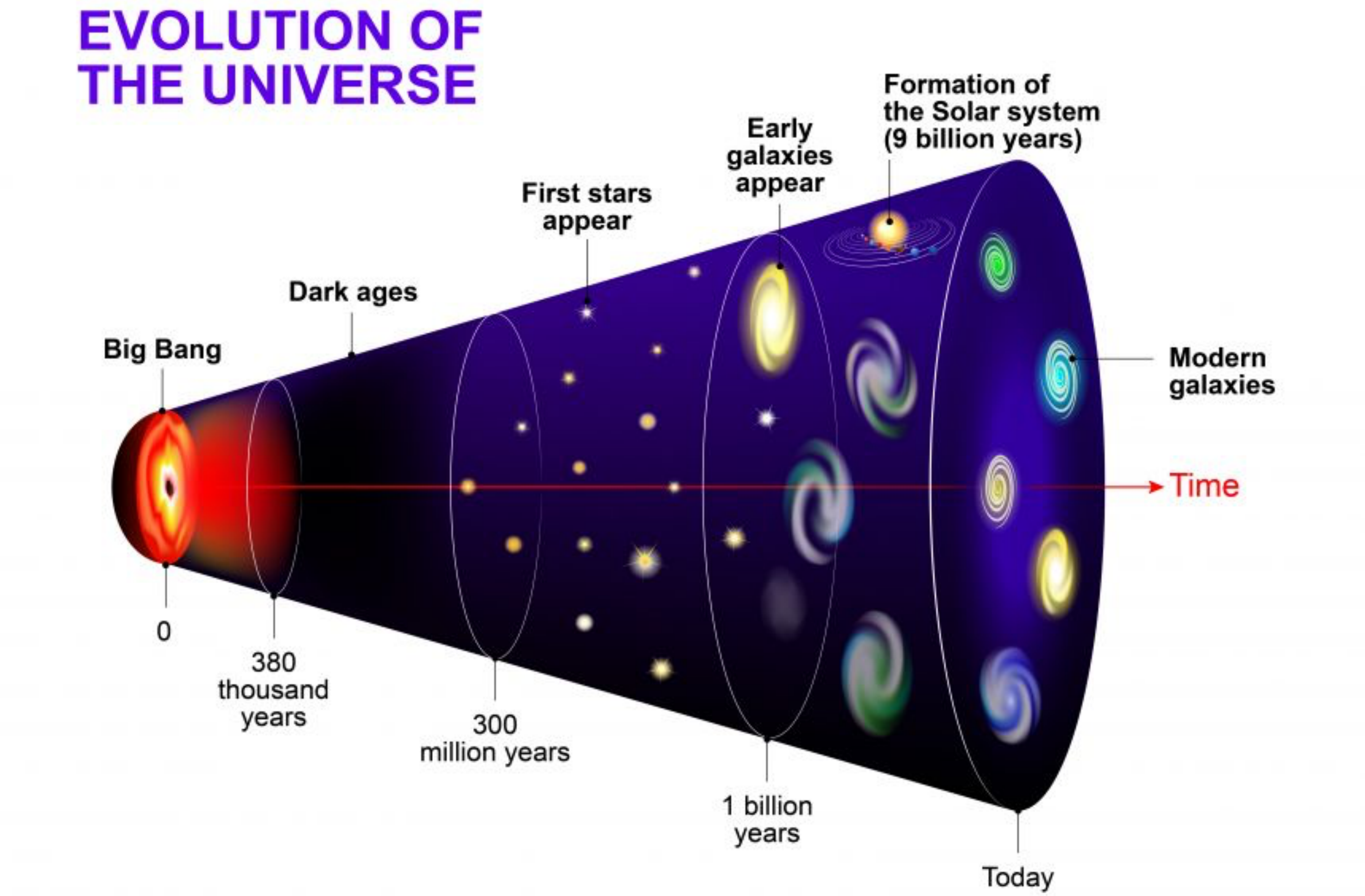
Aim: Smash things together in a "controlled" way to "emulate" conditions closer to the Big Bang!



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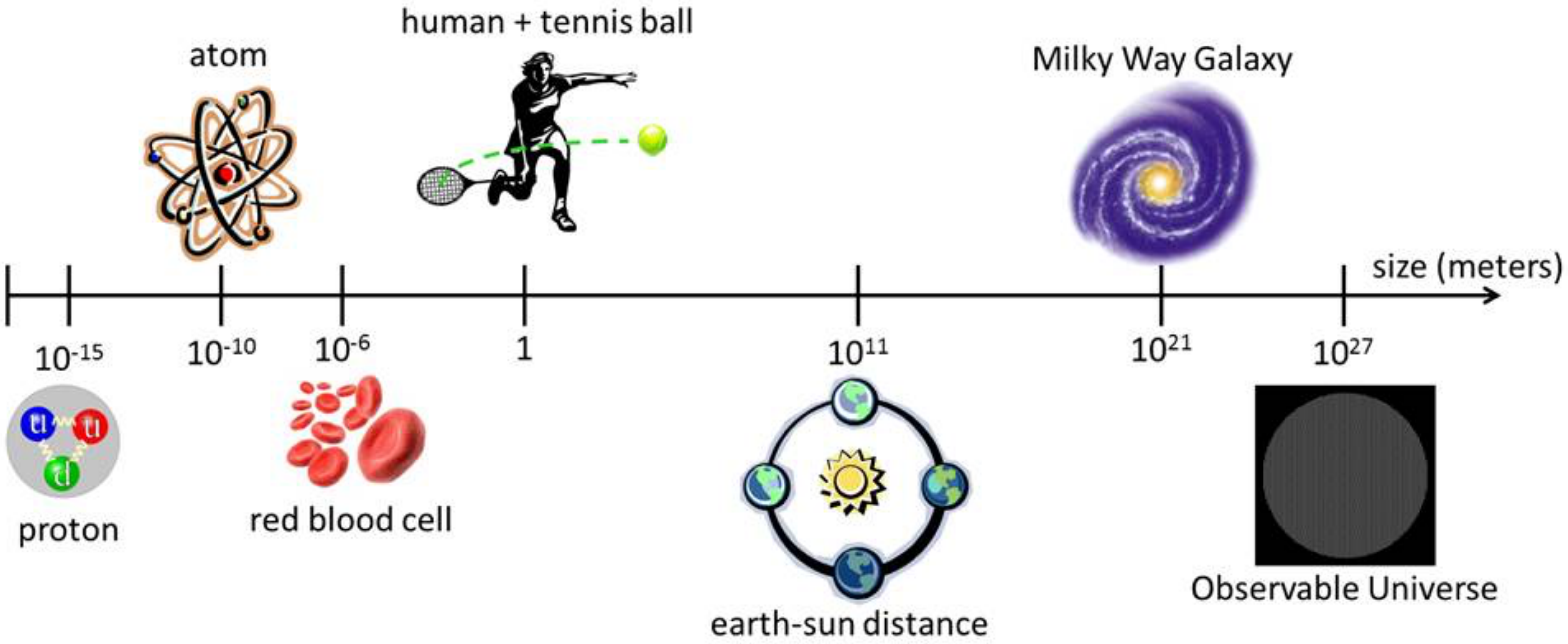
Aim: Smash things together in a "controlled" way to understand the structure of matter <u>today</u>!



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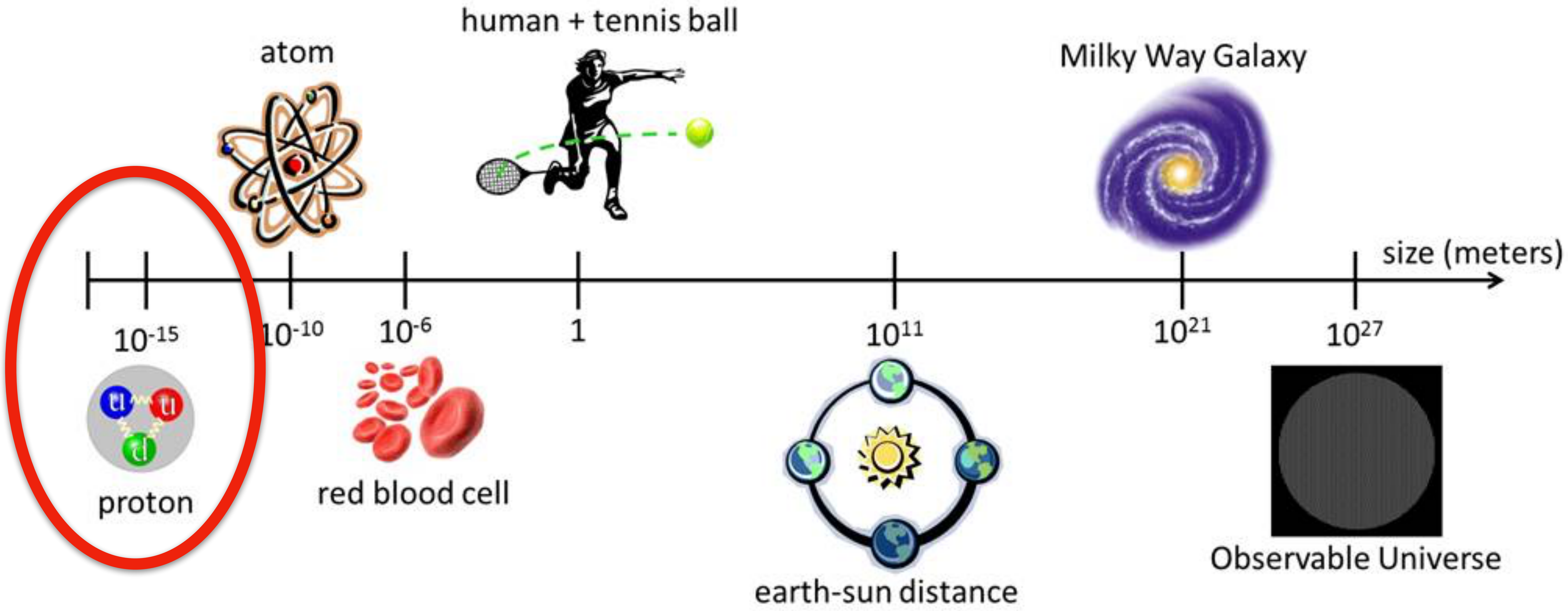

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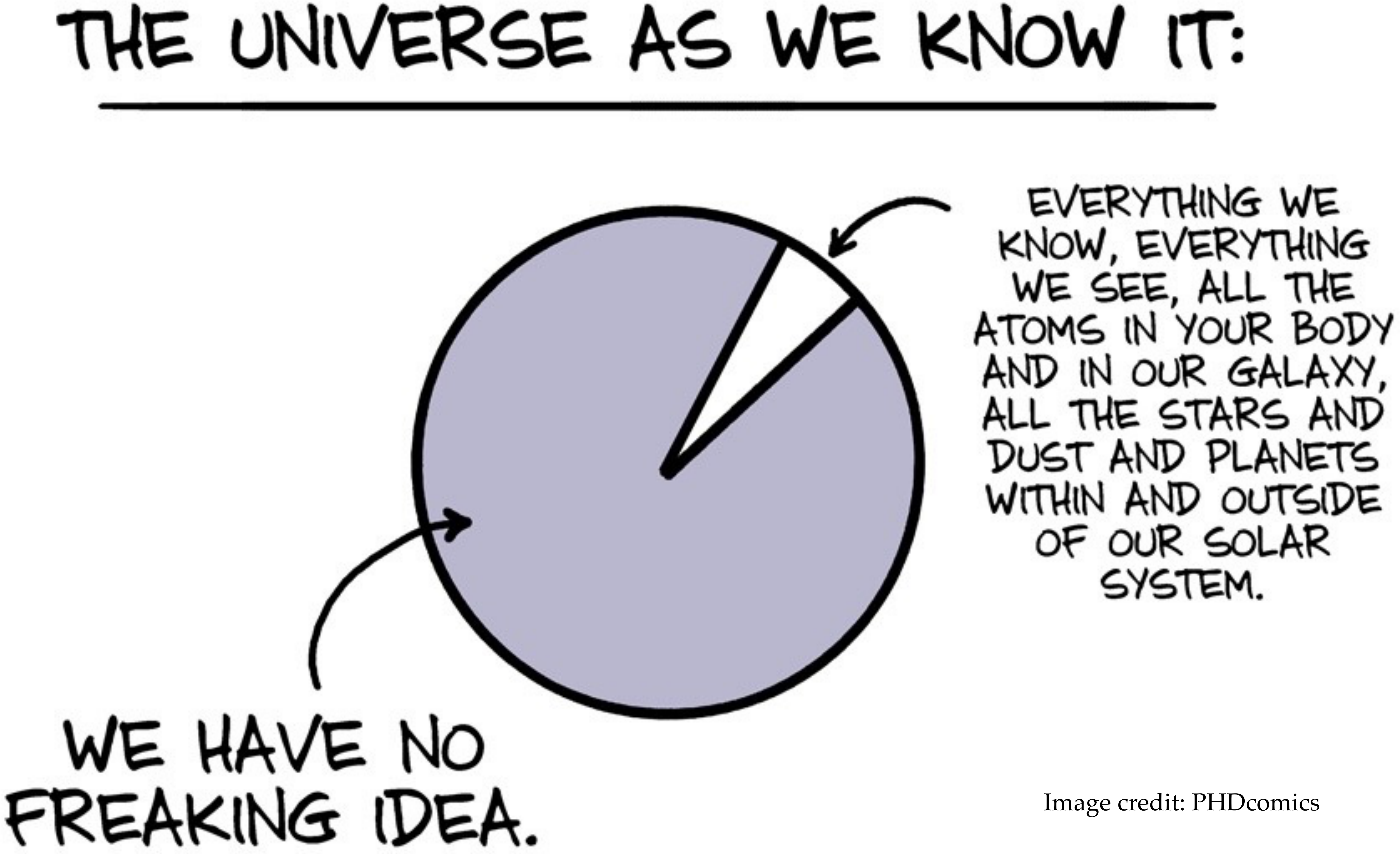
Aim: Smash things together in a "controlled" way to understand the structure of matter today!

https://www.smbc-comics.com/comic/2014-11-25

Why???

Why???



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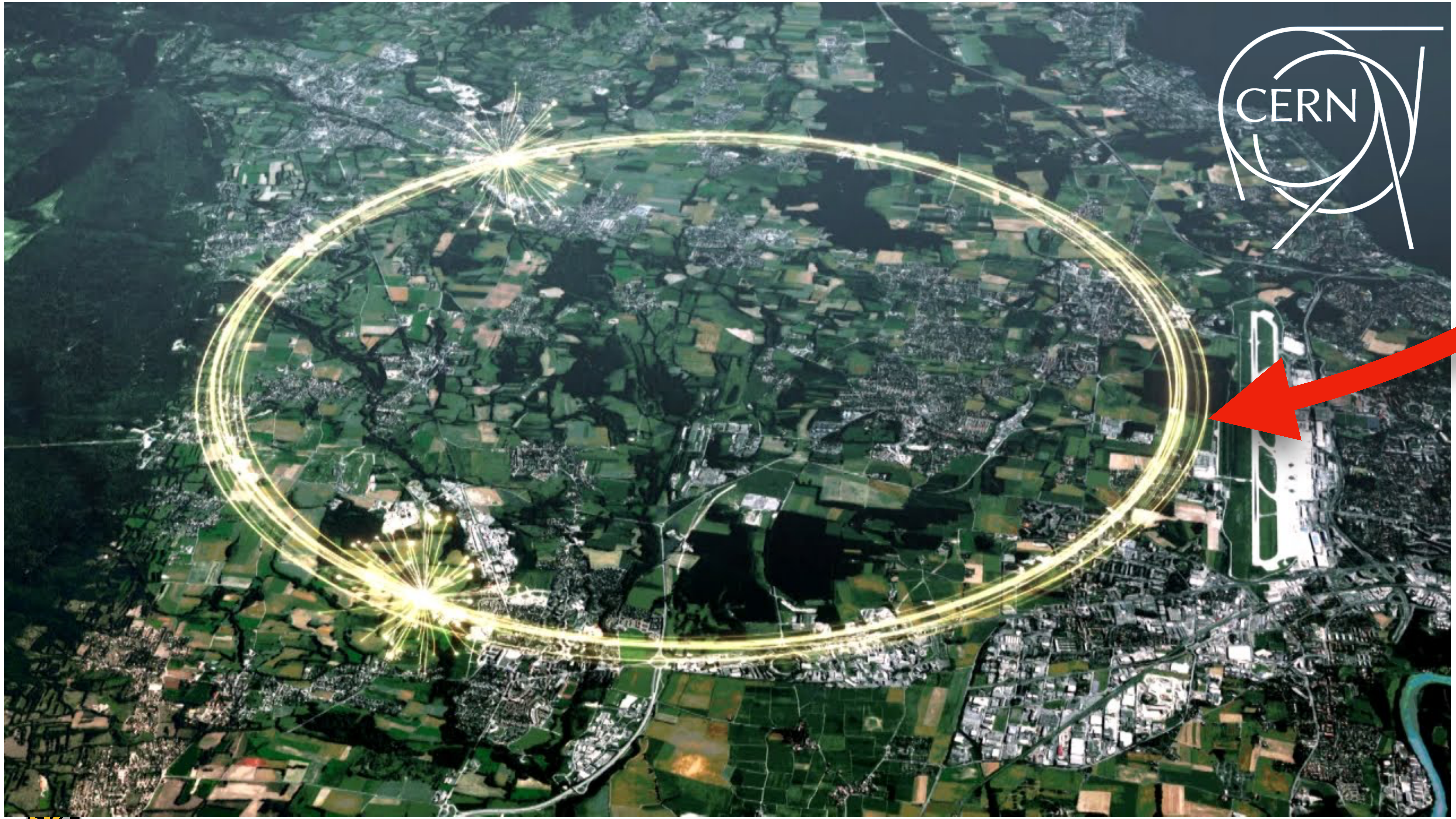
Rule:

Higher Energy ≡ Smaller Scales!

High Energy Particle Colliders

High Energy Particle Colliders

Large Hadron Collider @ CERN in Geneva, Switzerland



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High Energy Particle Colliders

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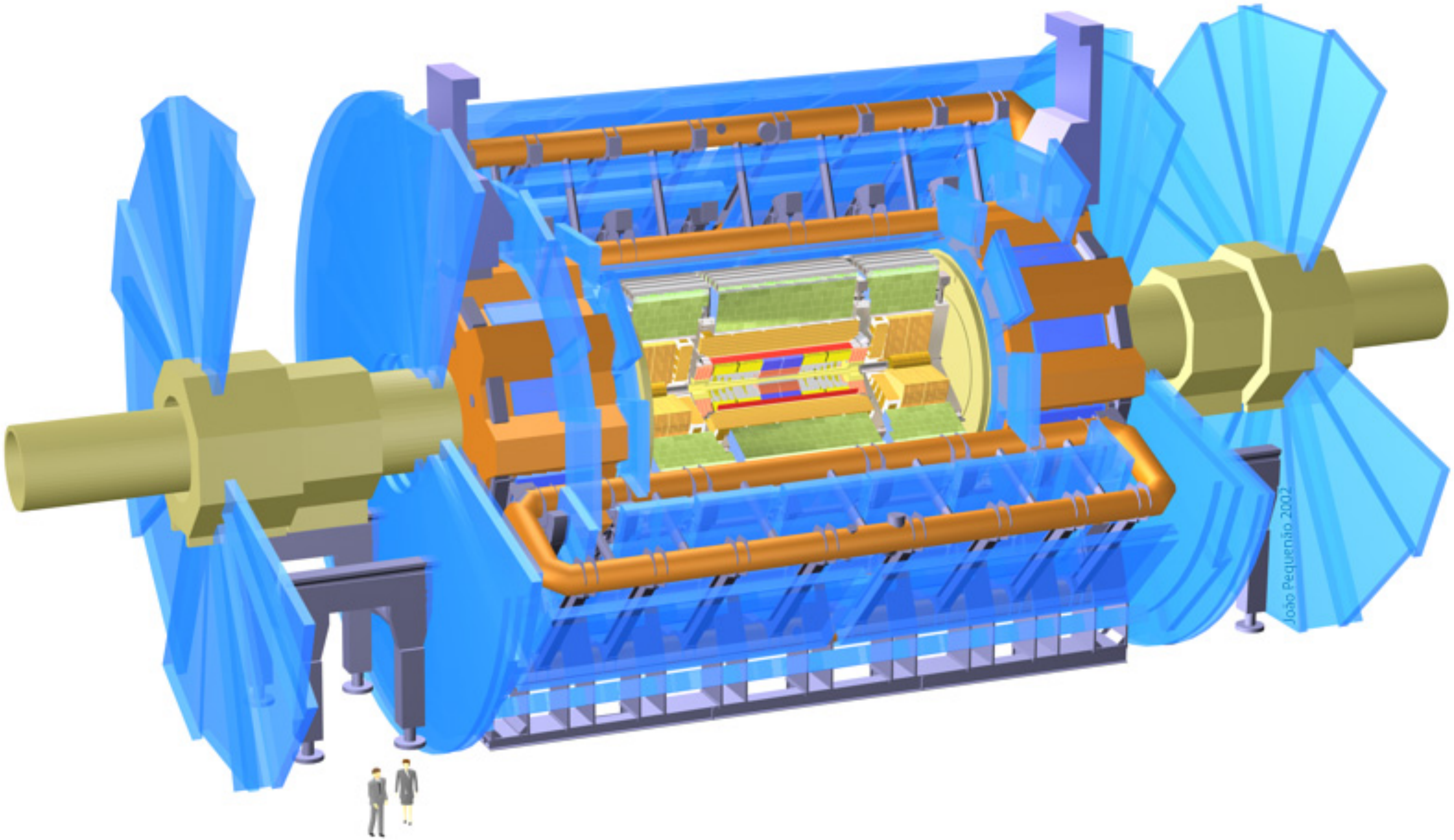

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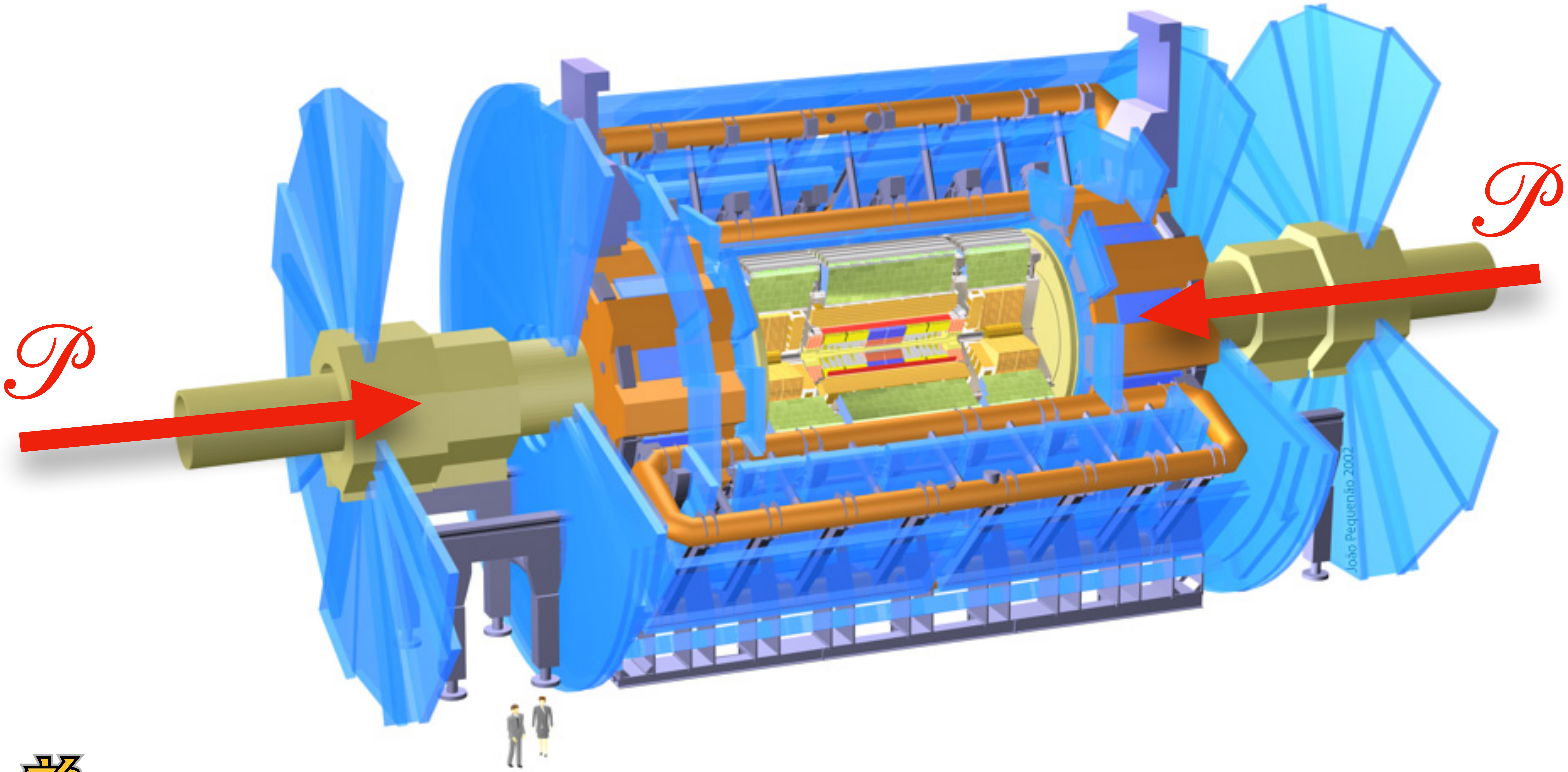

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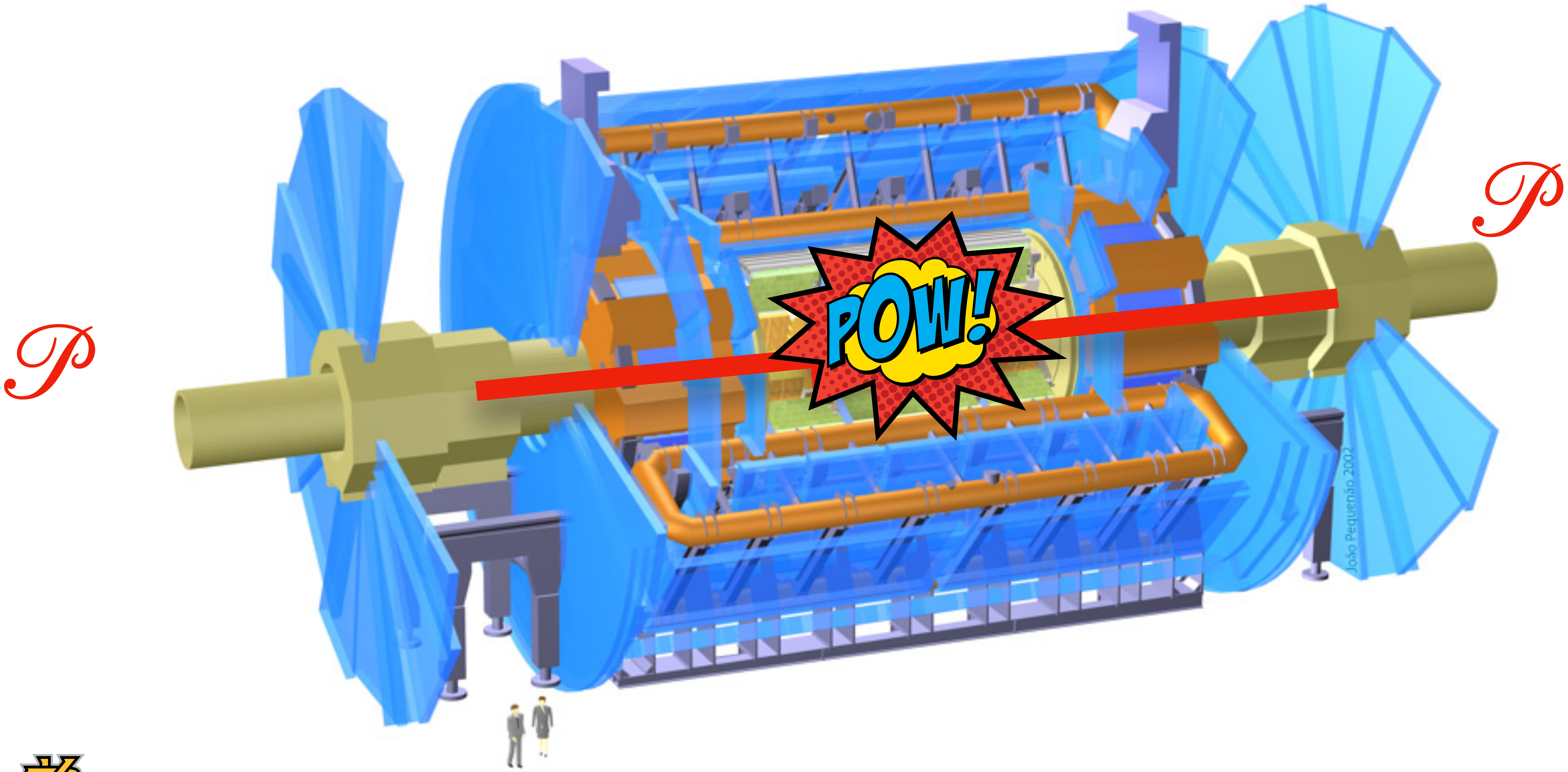
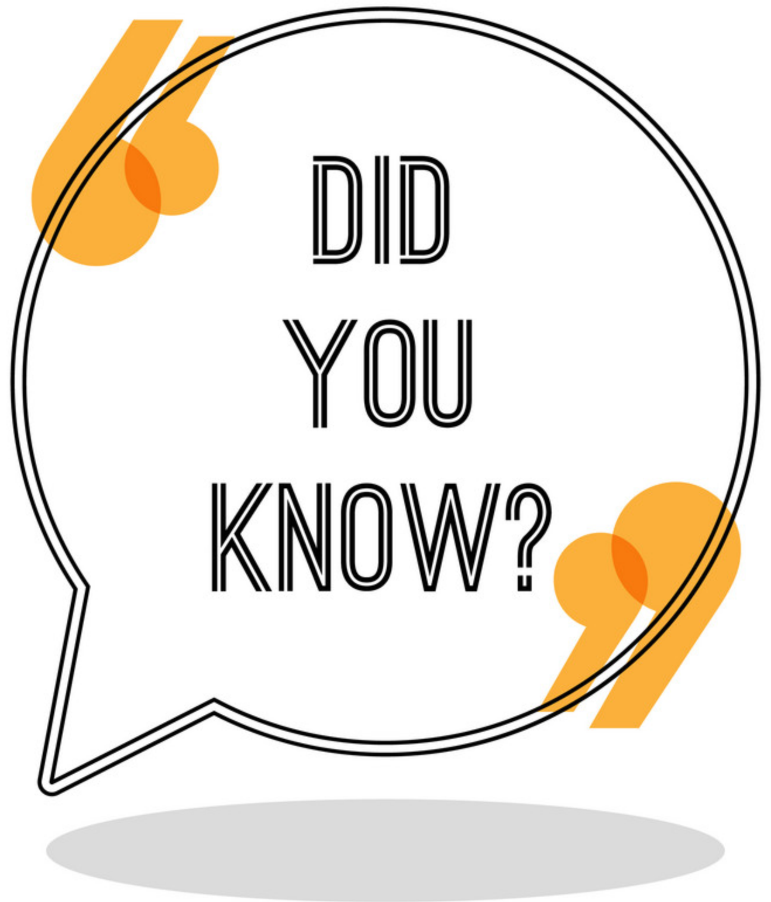


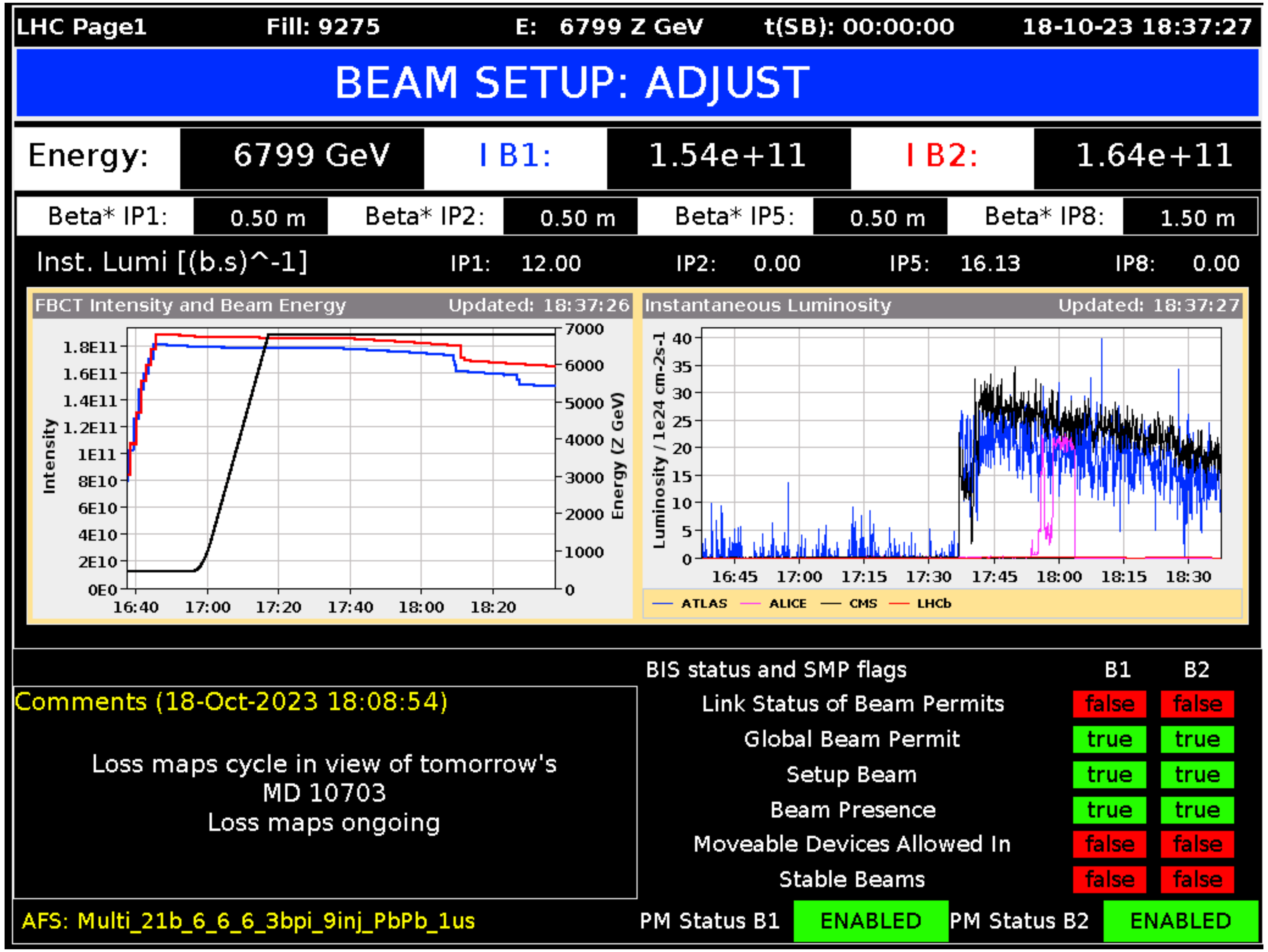
LHC: Fun Facts



- 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**!

LHC Status

- http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1



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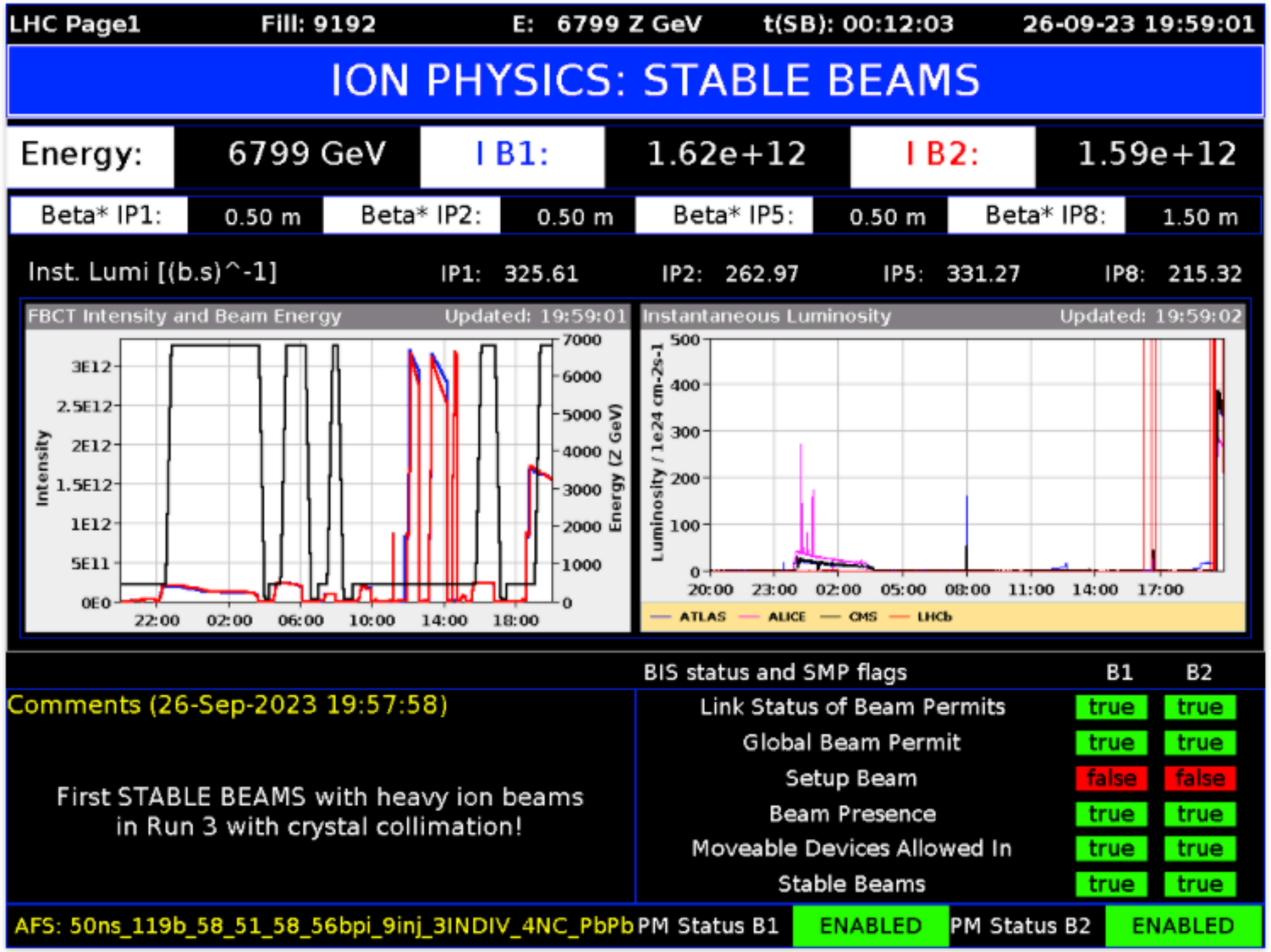
Voir en français

The LHC lead-ion collision run starts

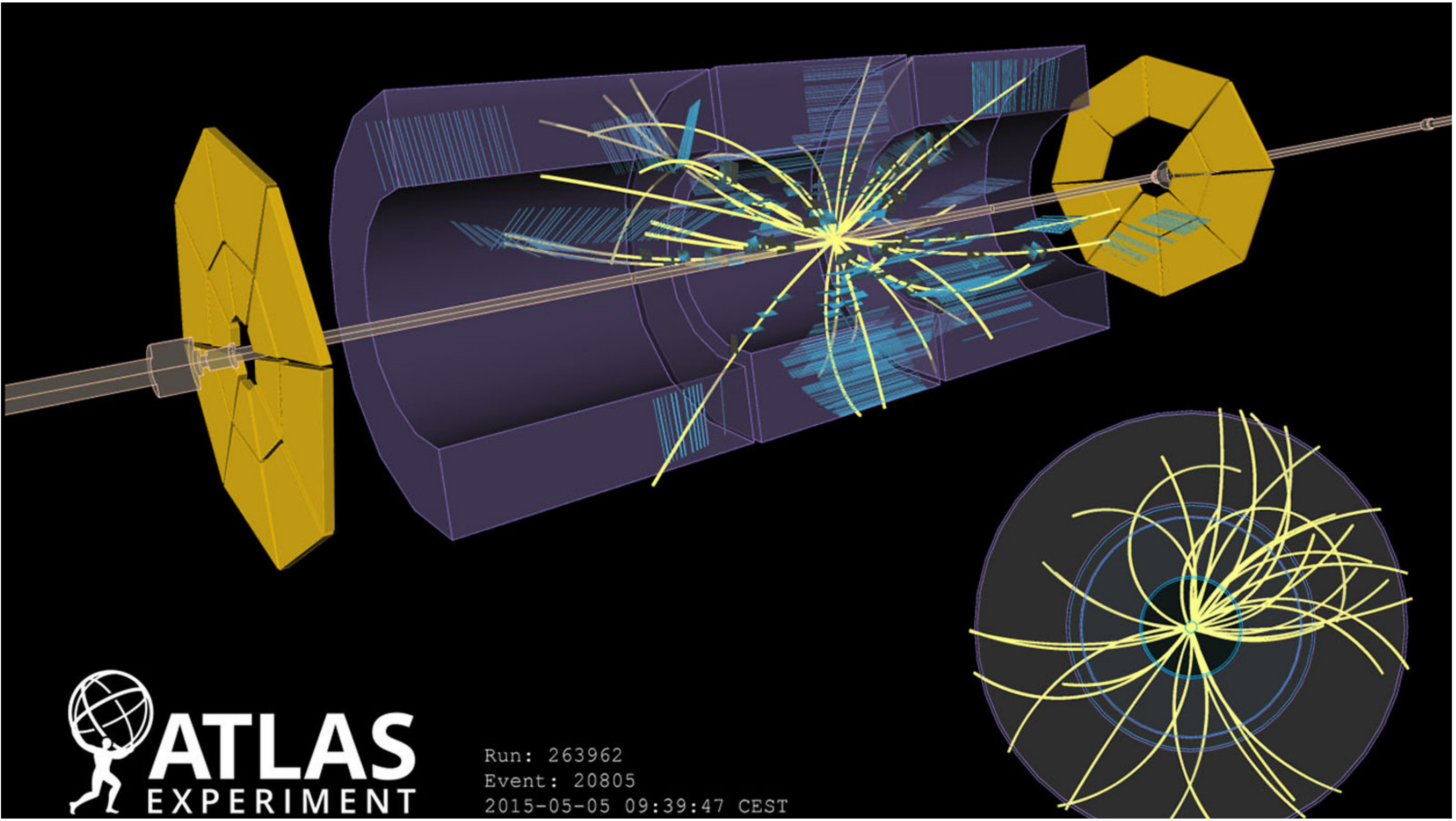
For the coming 5 weeks the LHC experiments will be taking data for their heavy-ion physics programmes

28 SEPTEMBER, 2023 | By Piotr Traczyk



The heavy-ion physics season starts for the experiments at CERN, as stable beams of lead nuclei circulate in the LHC at the energy of 6.8 TeV for the first time ever, and for the first time during the LHC Run 3.

Truth is Stranger Than Fiction…



This is a real "event"!

How do we make sense of it all?

Pictured: Richard Feynman playing the bongos.

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How do we make sense of it all?

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

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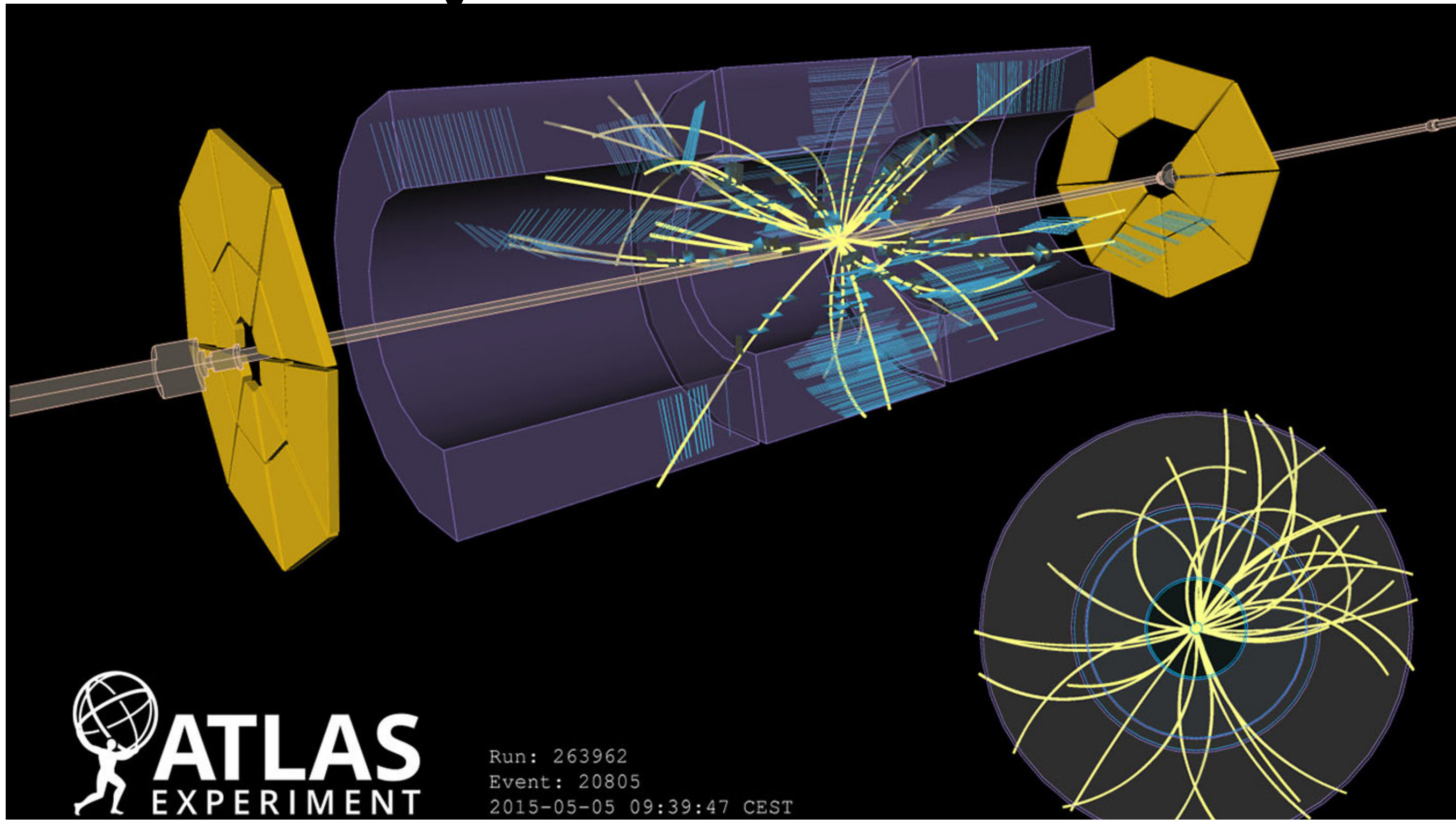
Experiment



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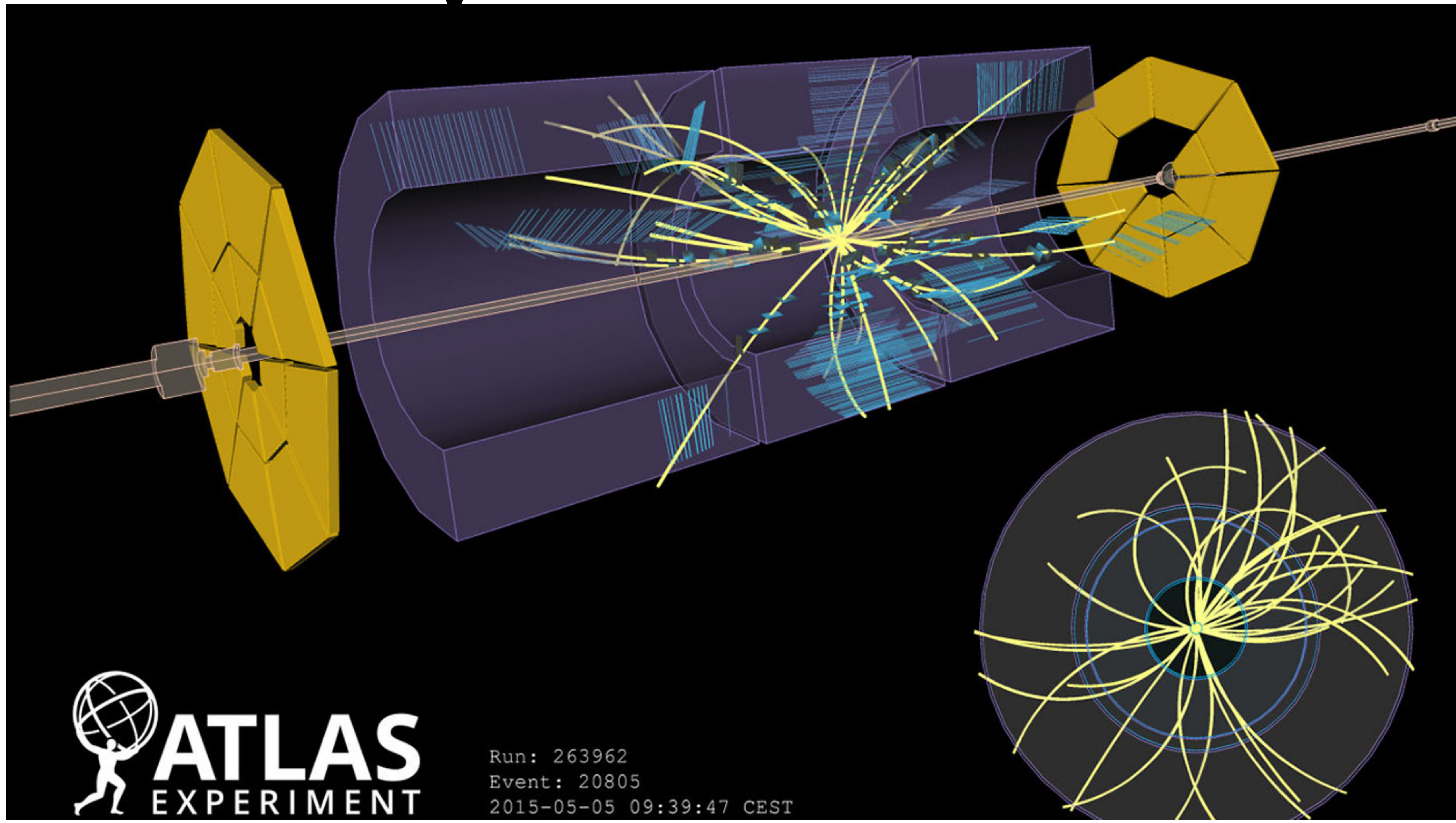

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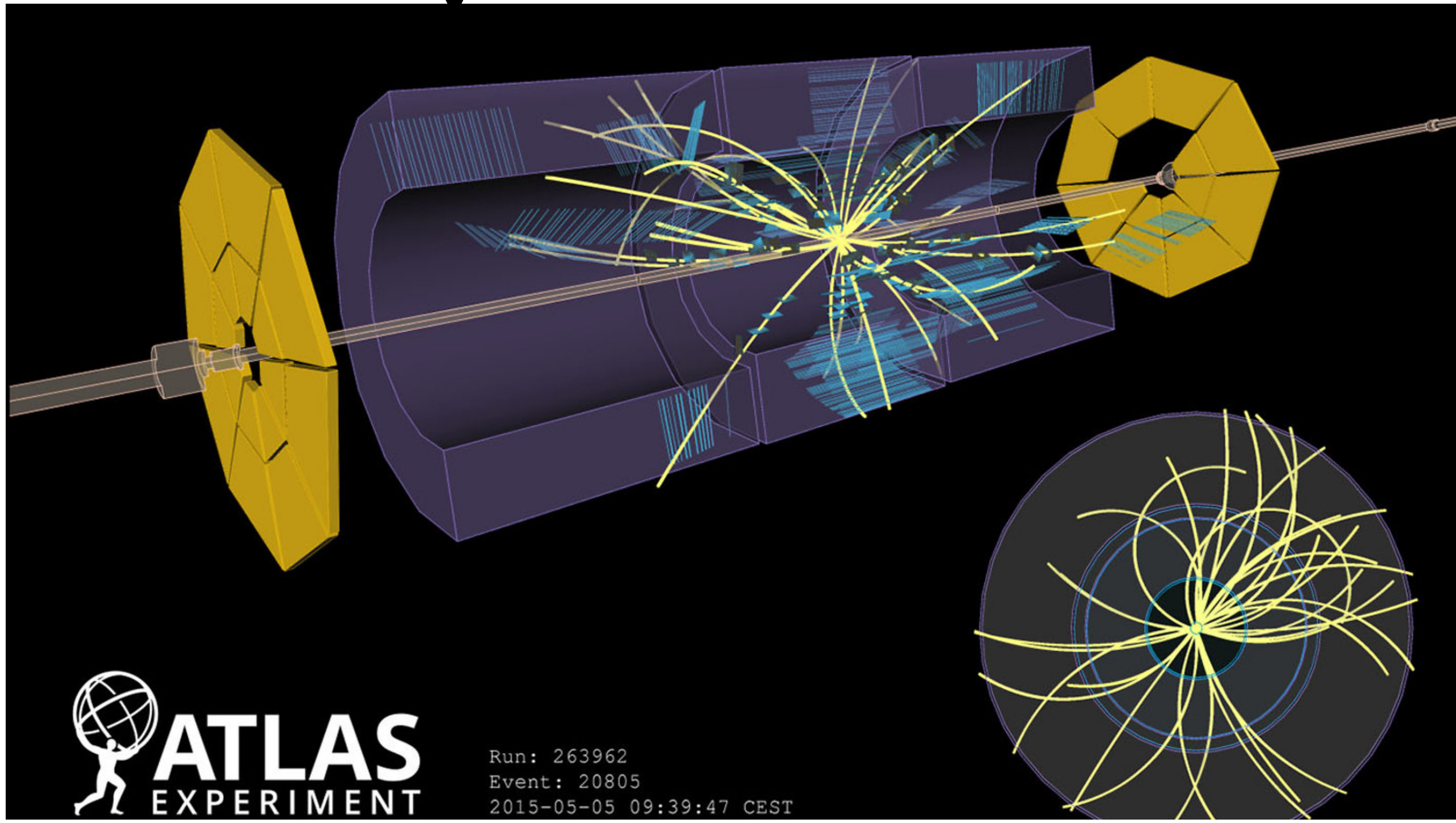
How do we make sense of it all?

Shut up and Calculate!

???

Experiment



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(Shut up and Calculate) Using Quantum Field Theory

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(Shut up and Calculate) Using Quantum Field Theory

- **Quantum Mechanics** $\rightarrow$ weird & wonderful world of the very **small objects**.

(Shut up and Calculate) Using Quantum Field Theory

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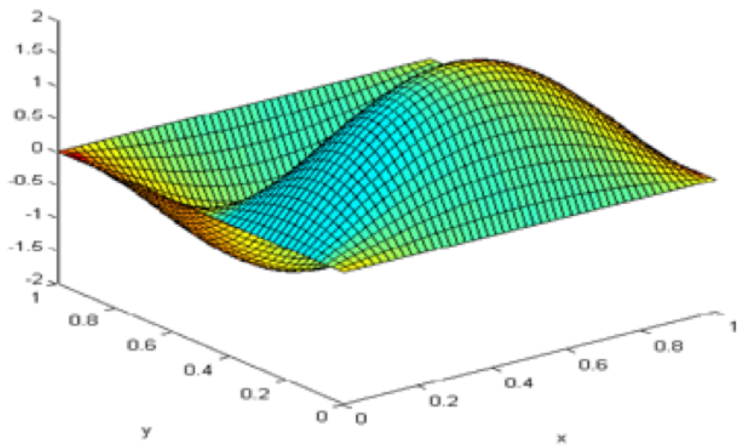
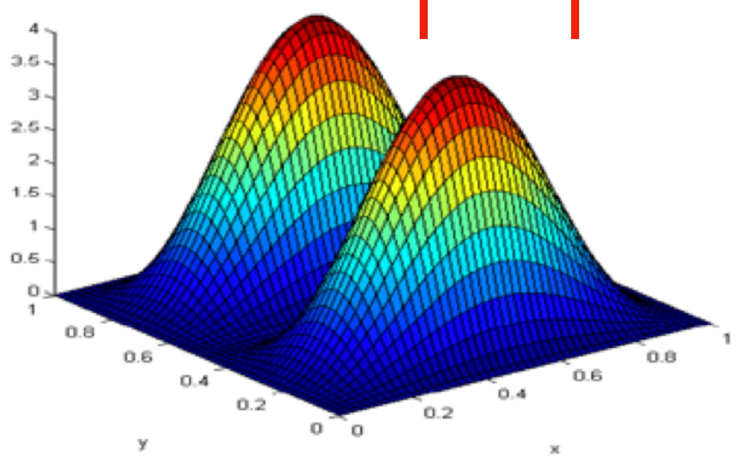
Ψ



$|\Psi|^2$



→ Calculate Ψ,

⇒ <u>Probability</u> to find particle somewhere $\propto |\Psi|^2$

[Ψ is called the "wave function"]

(Shut up and Calculate) Using Quantum Field Theory

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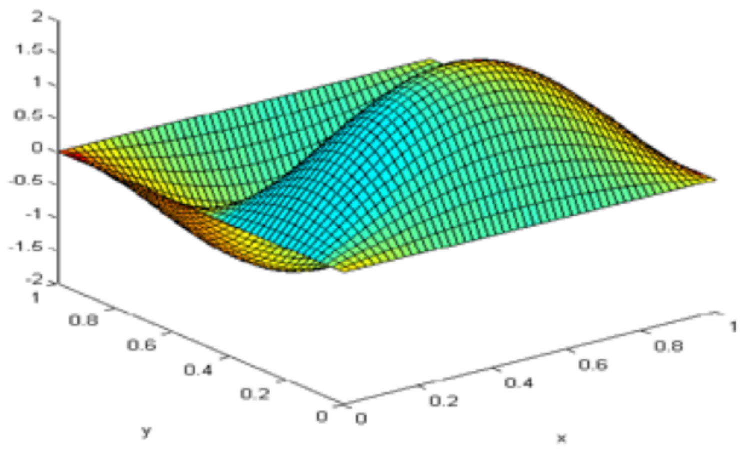

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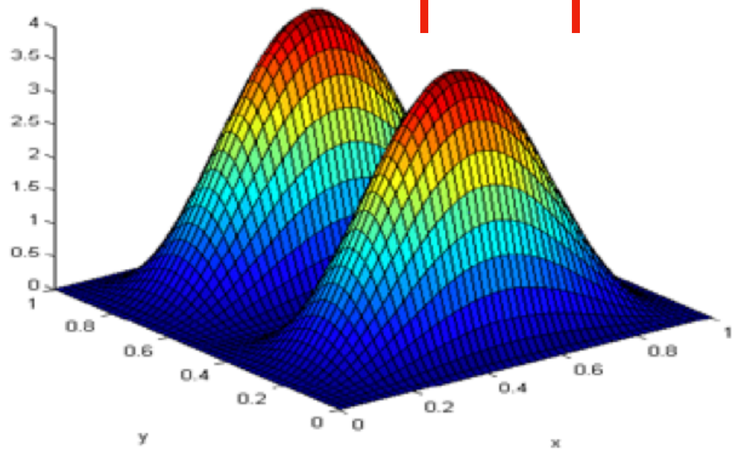

$\rightarrow$ Calculate Ψ,

$\Rightarrow$ Probability to find particle somewhere $\propto |\Psi|^2$

[Ψ is called the “wave function”]

- **Special Relativity** describes the world of the very **fast-moving objects**.

(Shut up and Calculate) Using Quantum Field Theory

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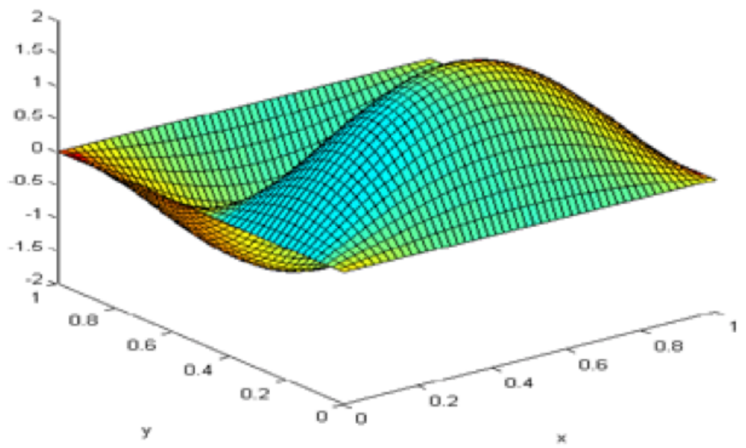
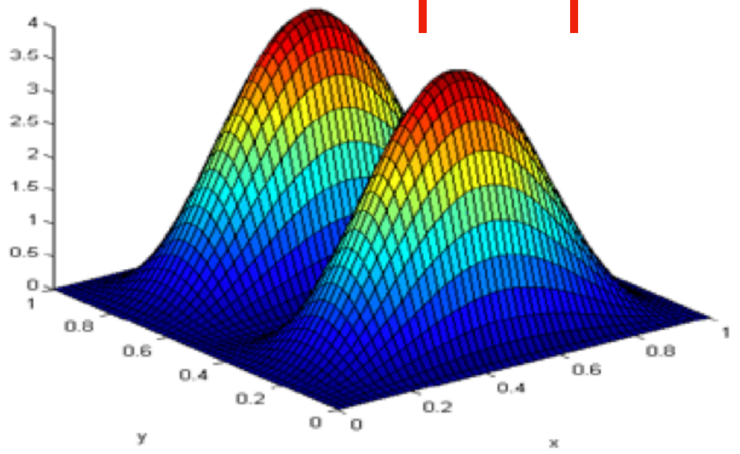
Ψ $|\Psi|^2$





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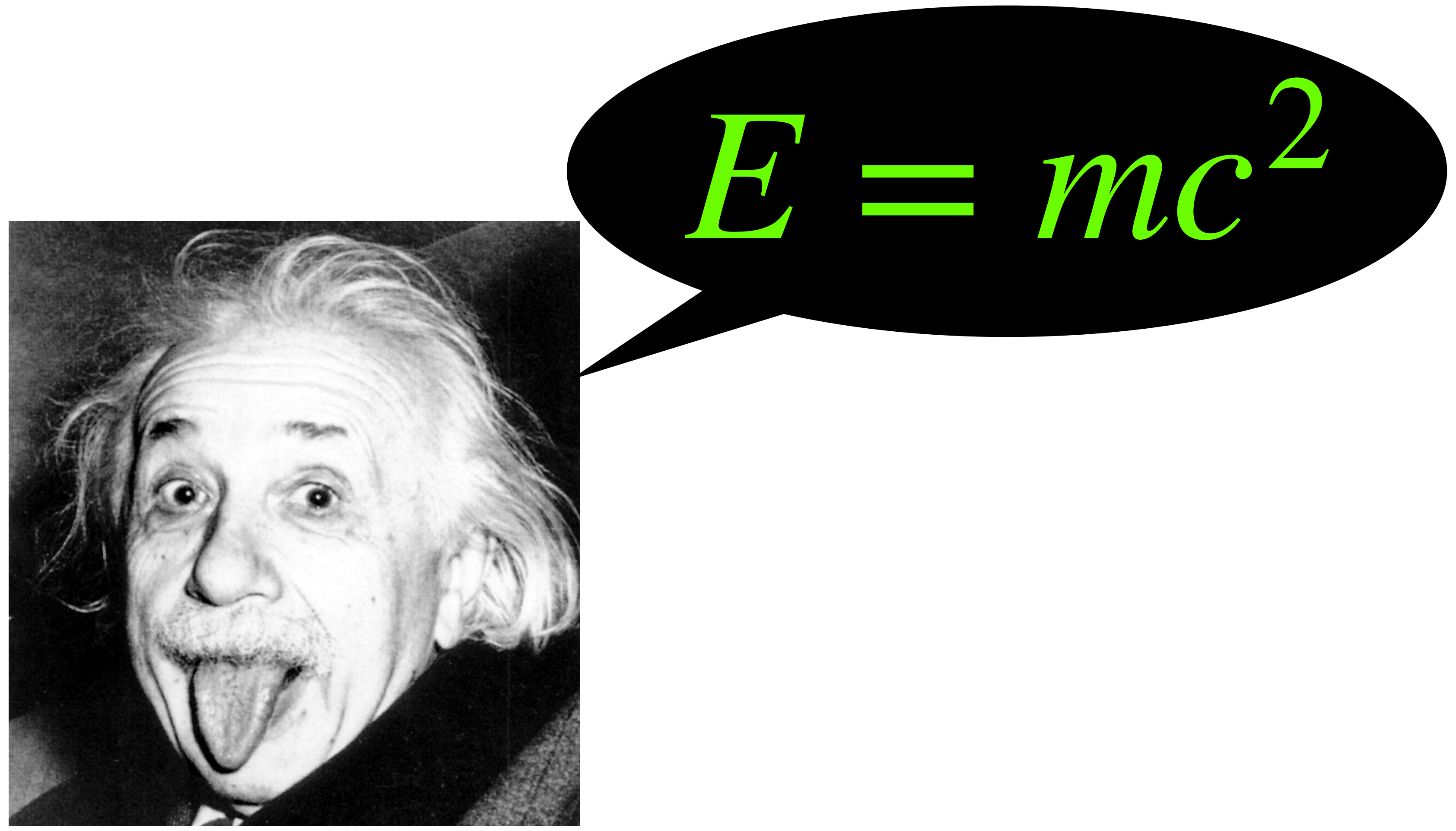

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(Shut up and Calculate) Using Quantum Field Theory

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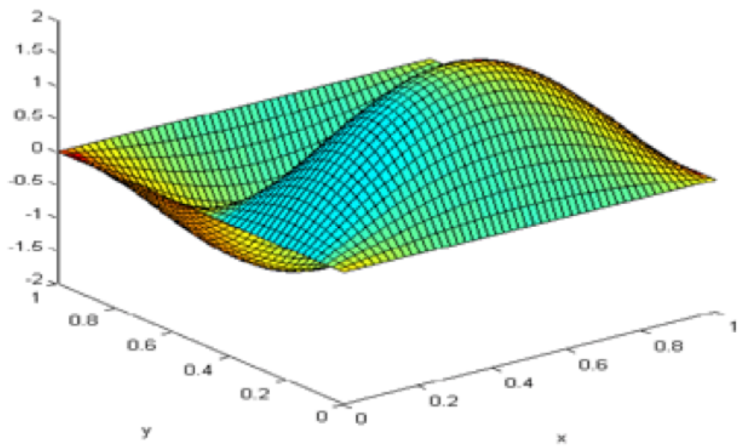
Ψ



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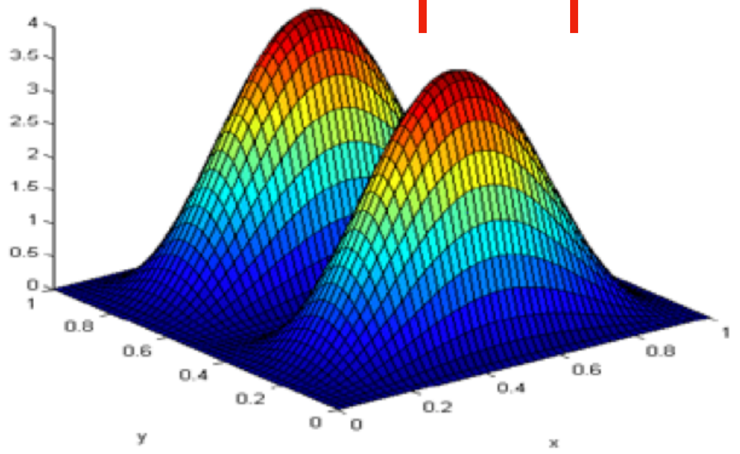

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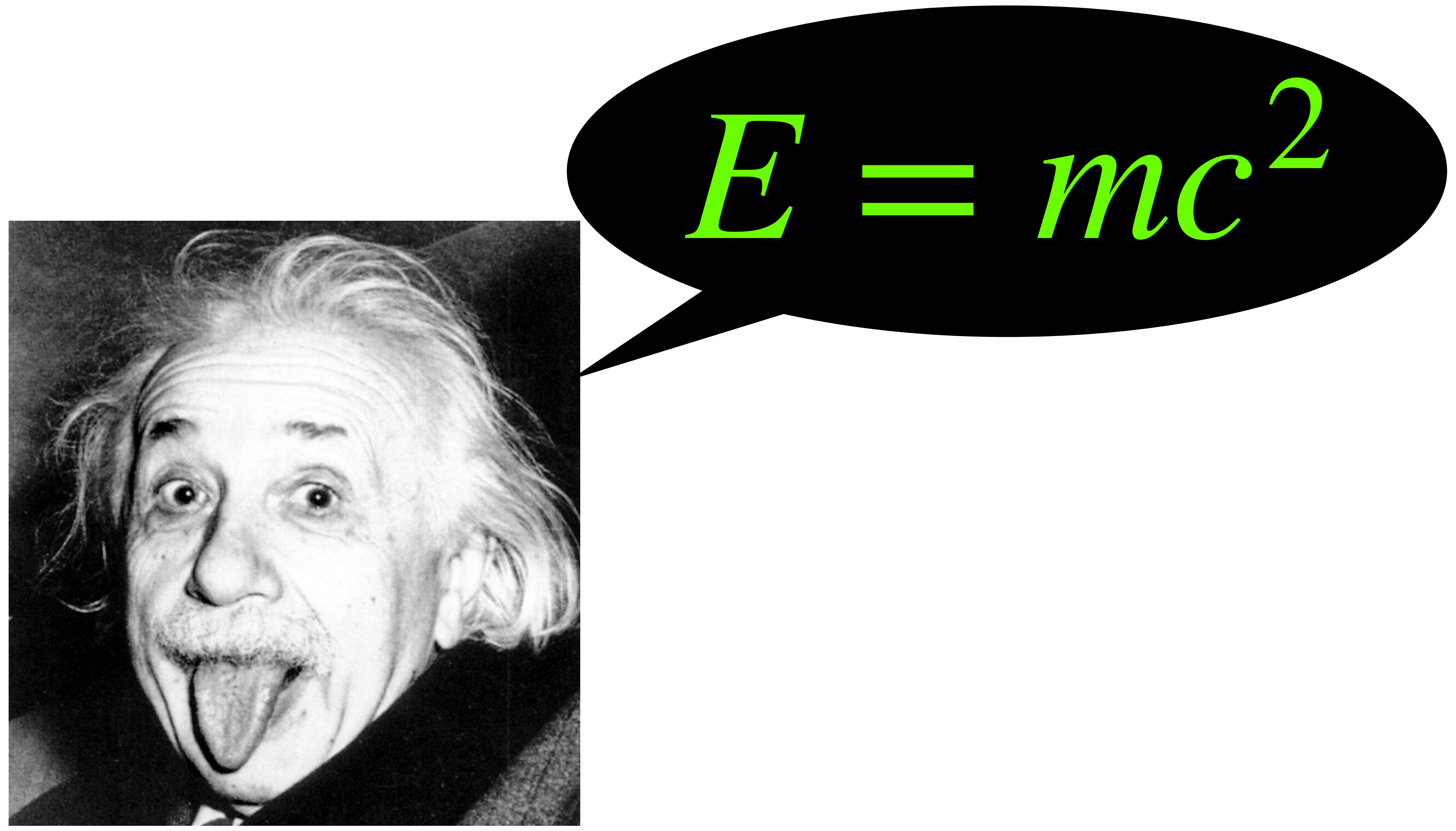

→ Mass and Energy are equivalent!

⇒ You can exchange one for the other!

⇒ Particle creation from Energy!

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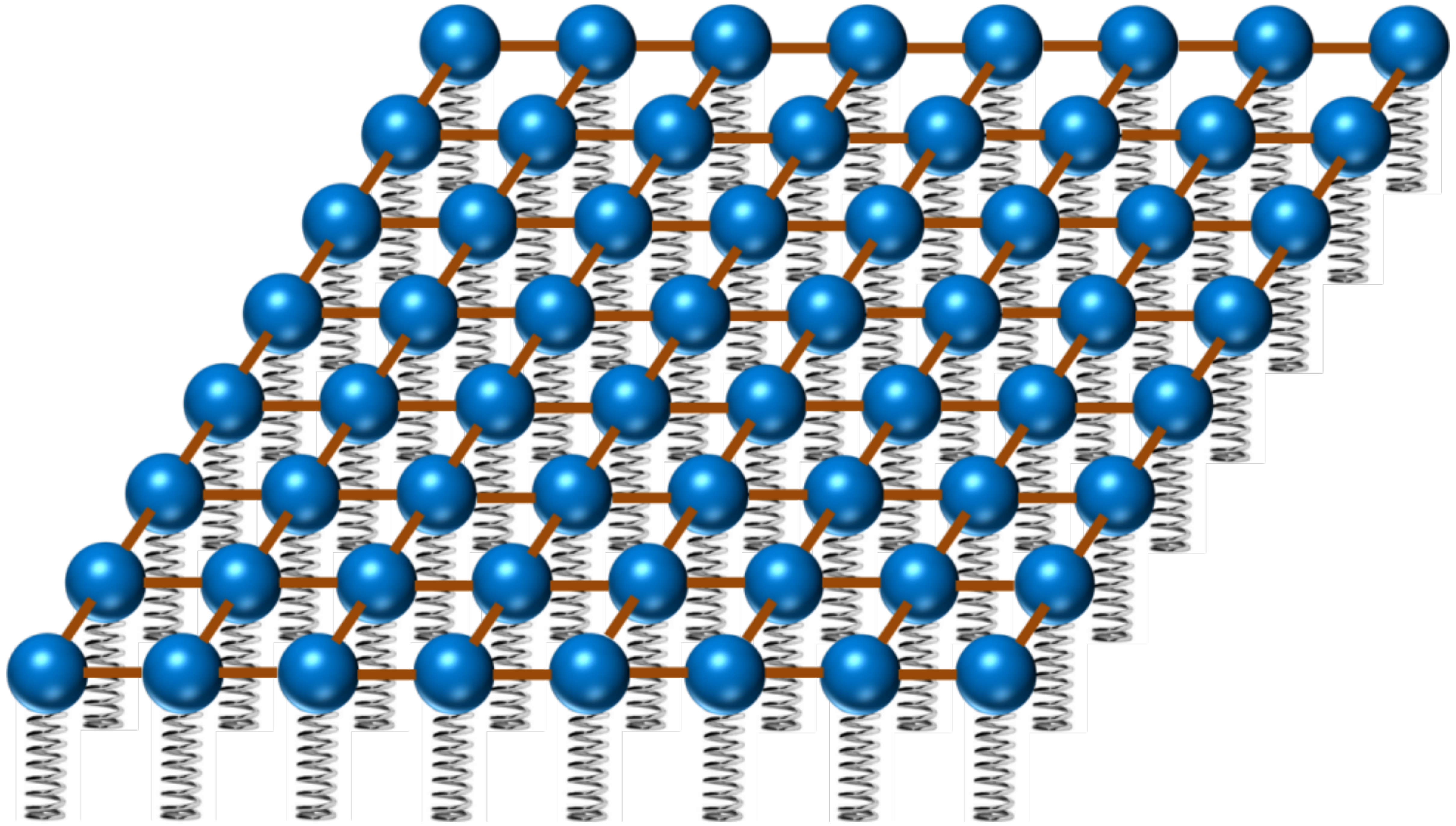
Quantum Mechanics + Special Relativity ≈ **Quantum Field Theory**



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From Theory to Experiment and Back Again

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From Theory to Experiment and Back Again

e.g. We wish to describe $e^- e^- \to e^- e^- + X$.

i.e. the scattering of two electrons!

From Theory to Experiment and Back Again

e^{-} •

e^{-} •

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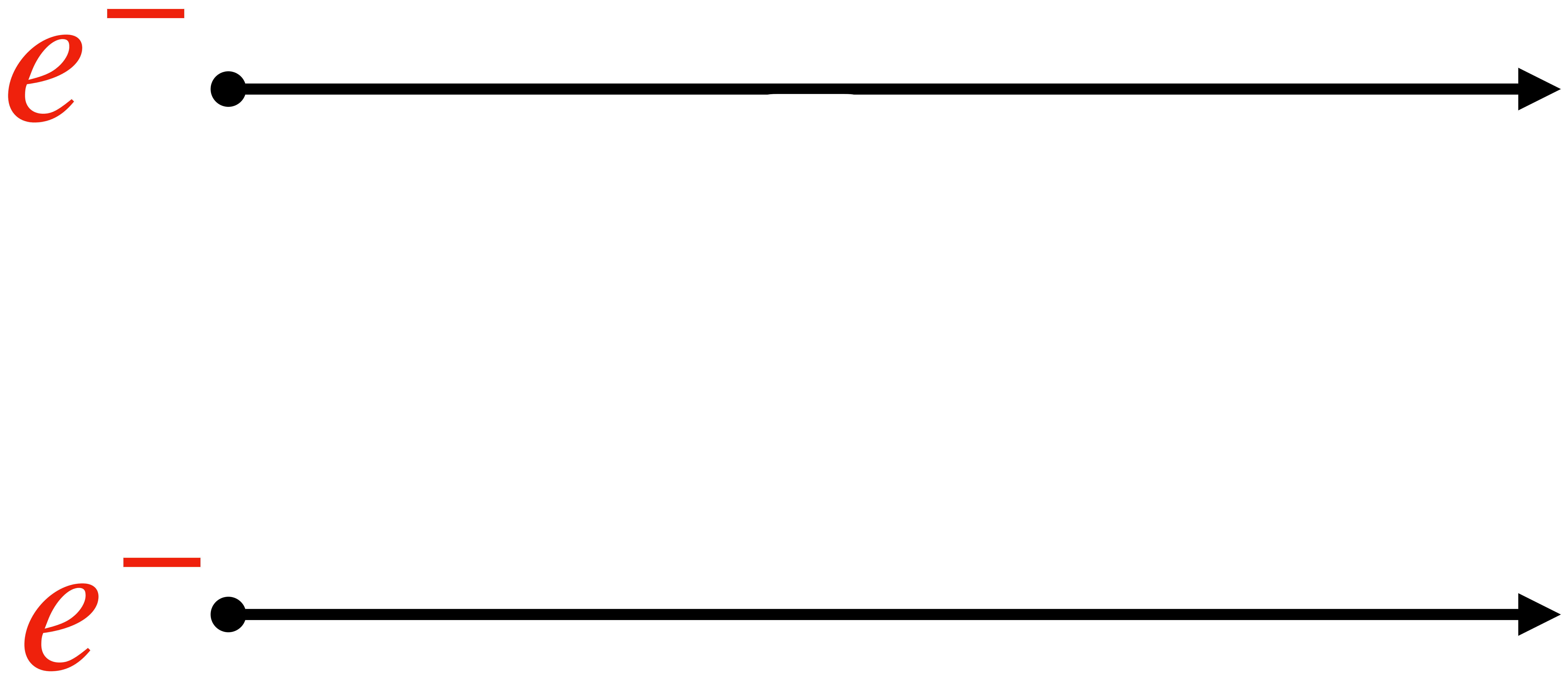

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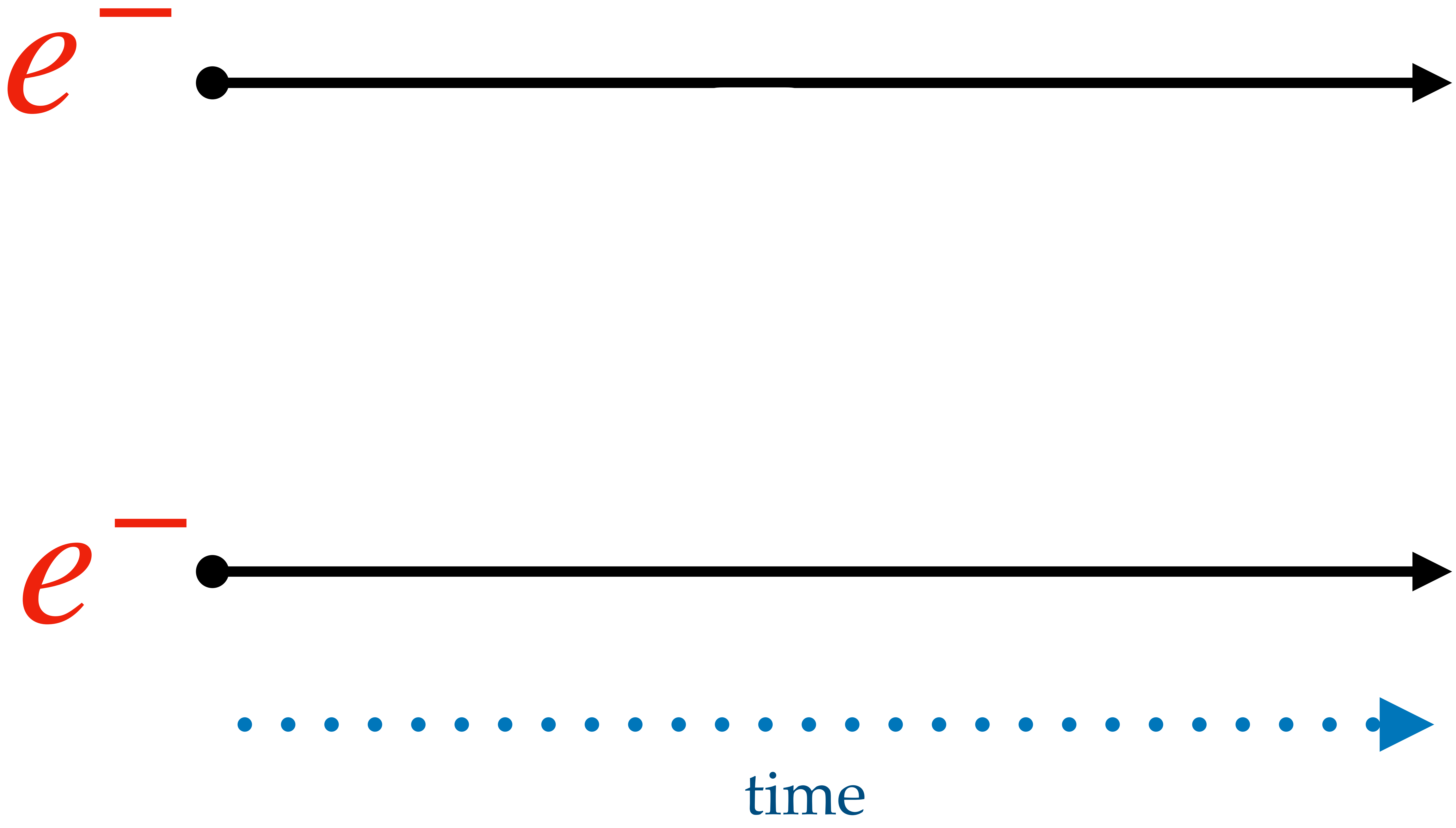

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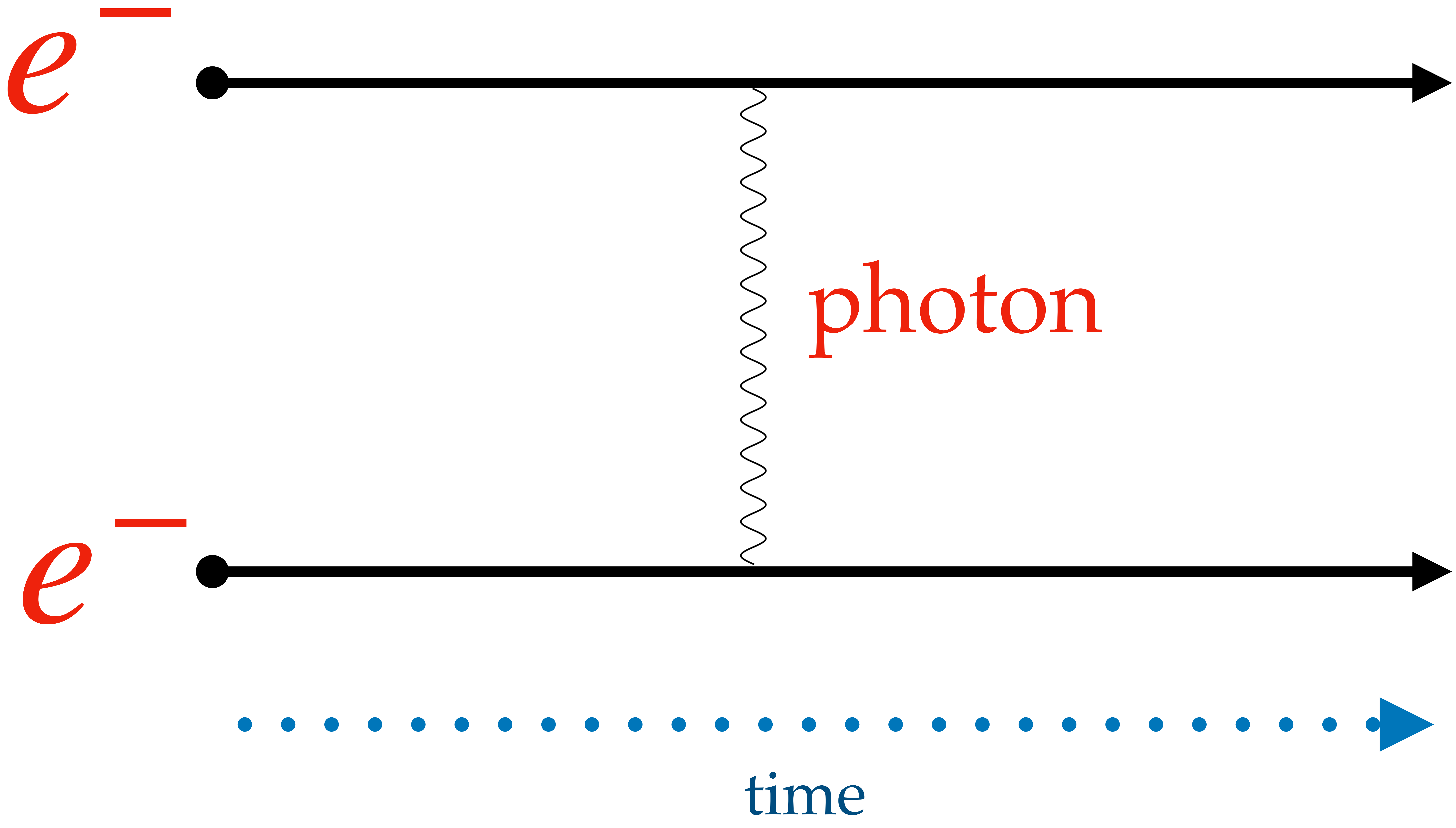

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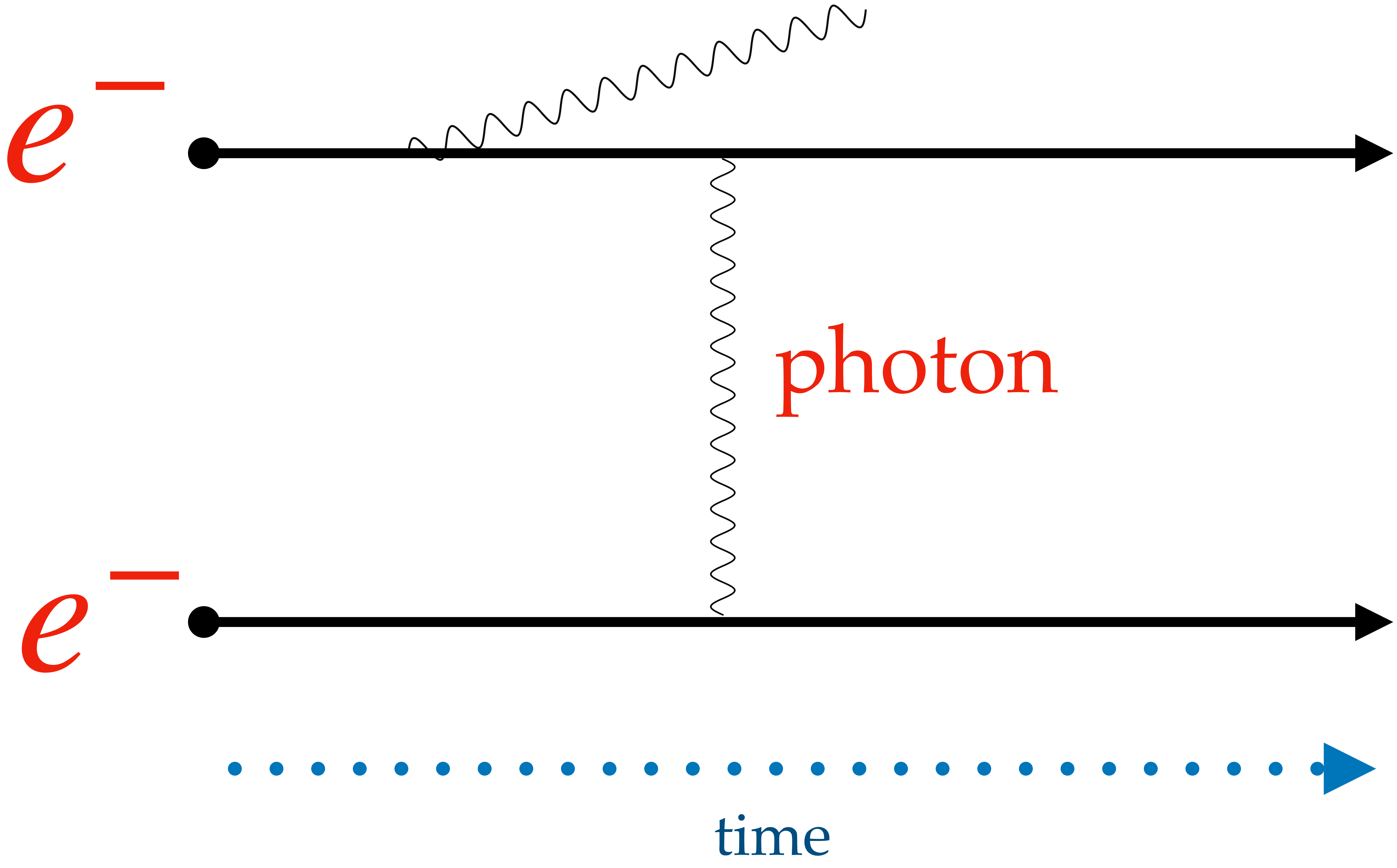

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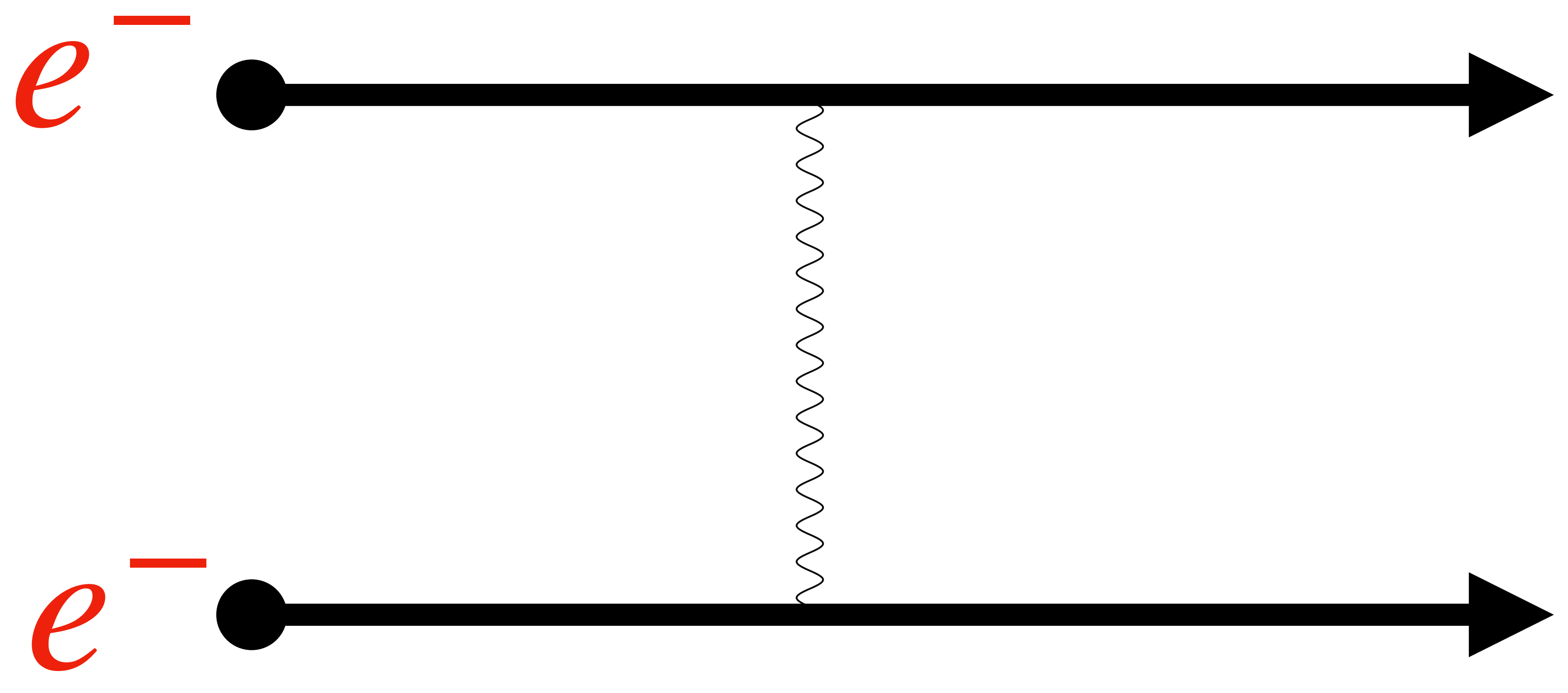

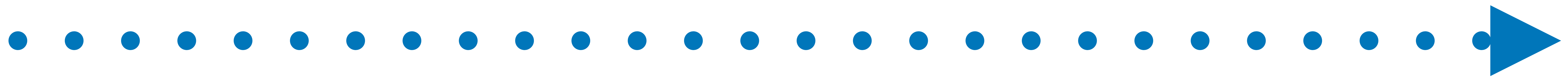

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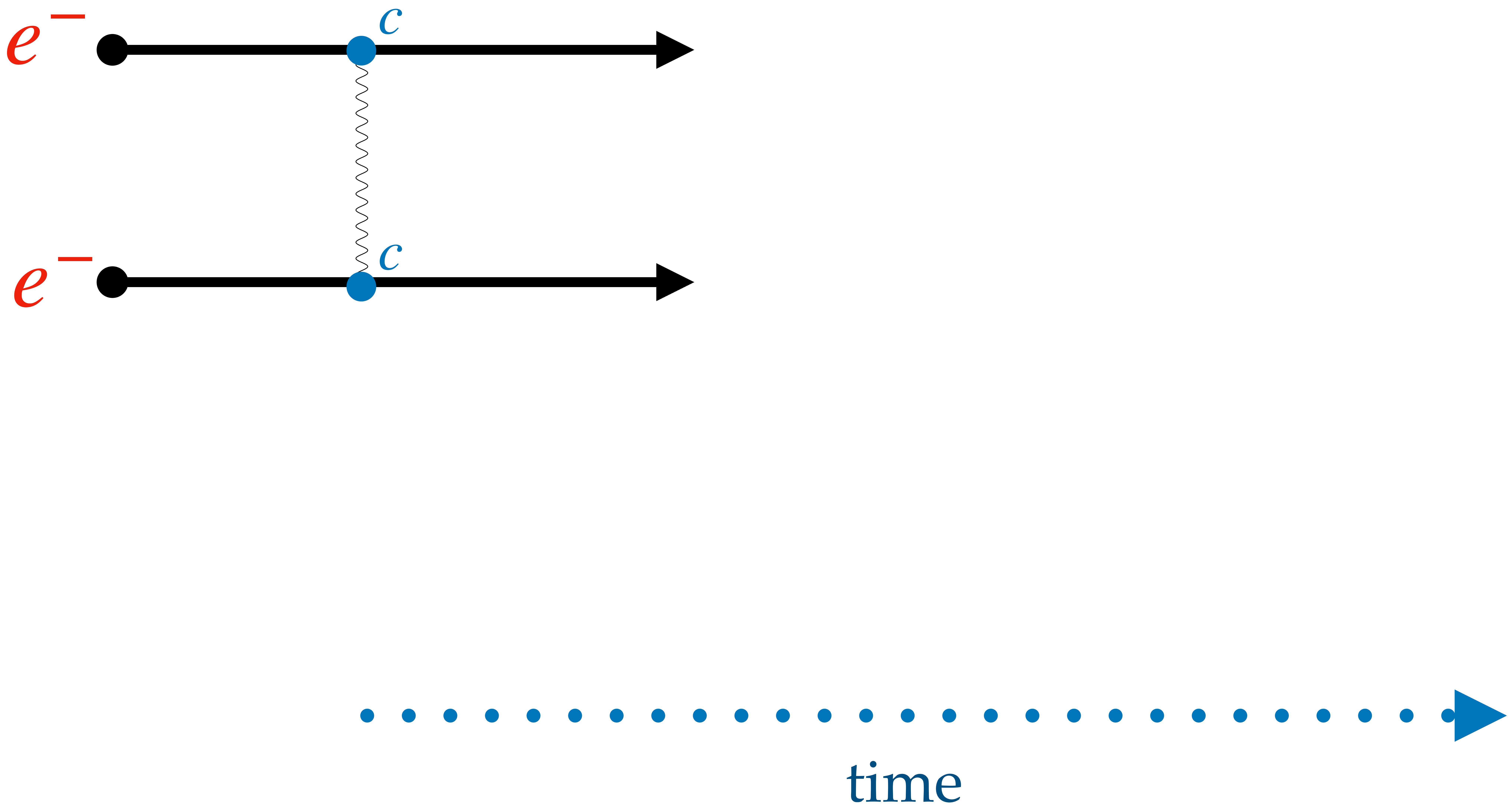

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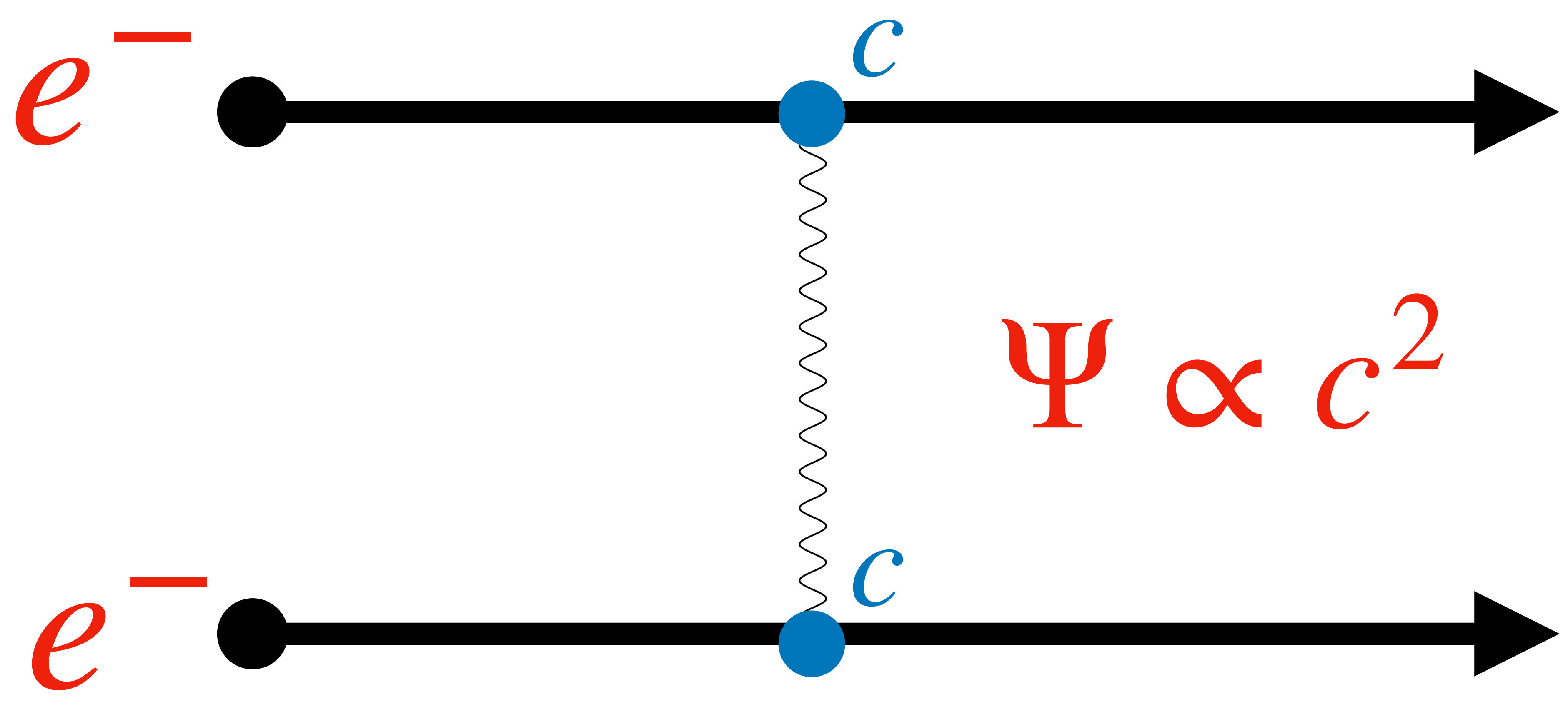

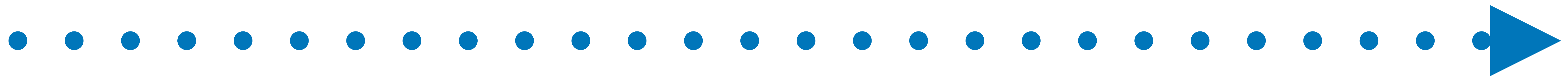

time

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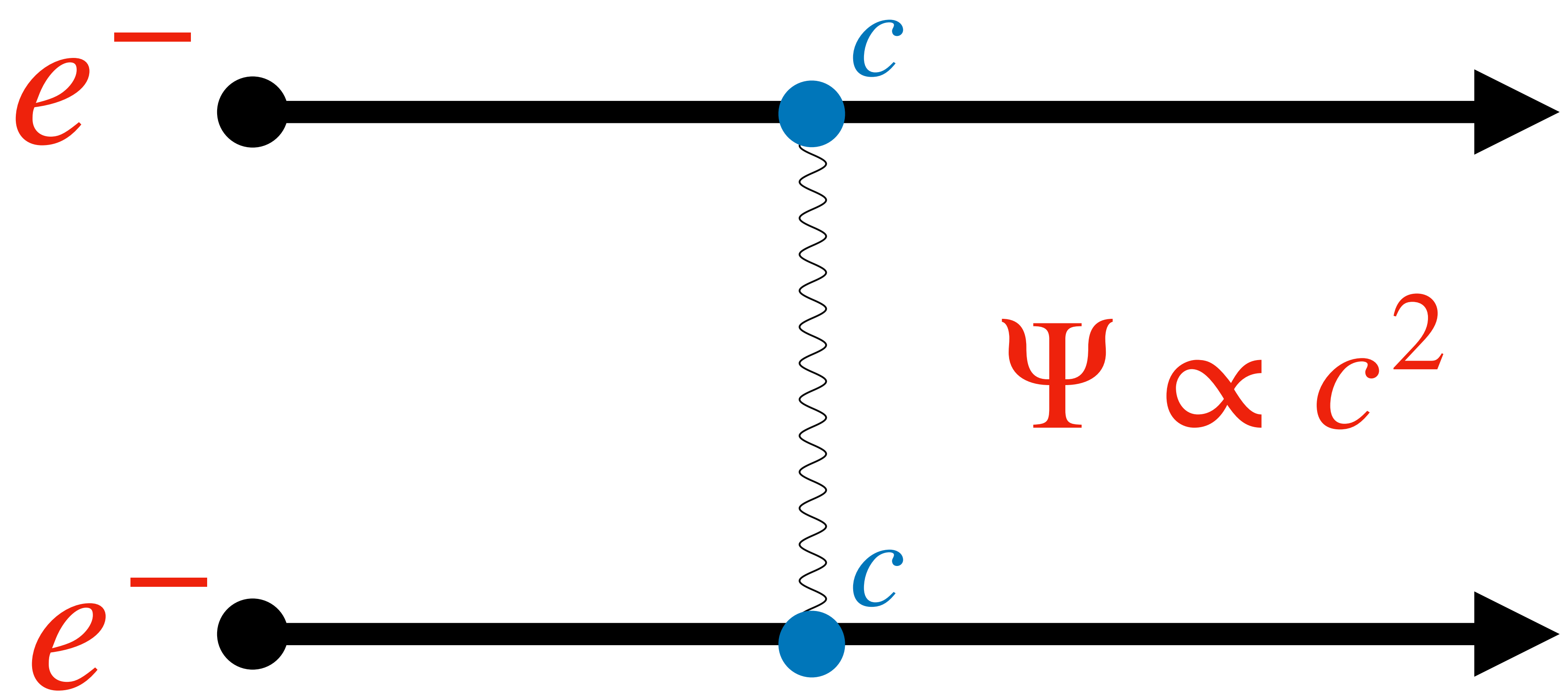

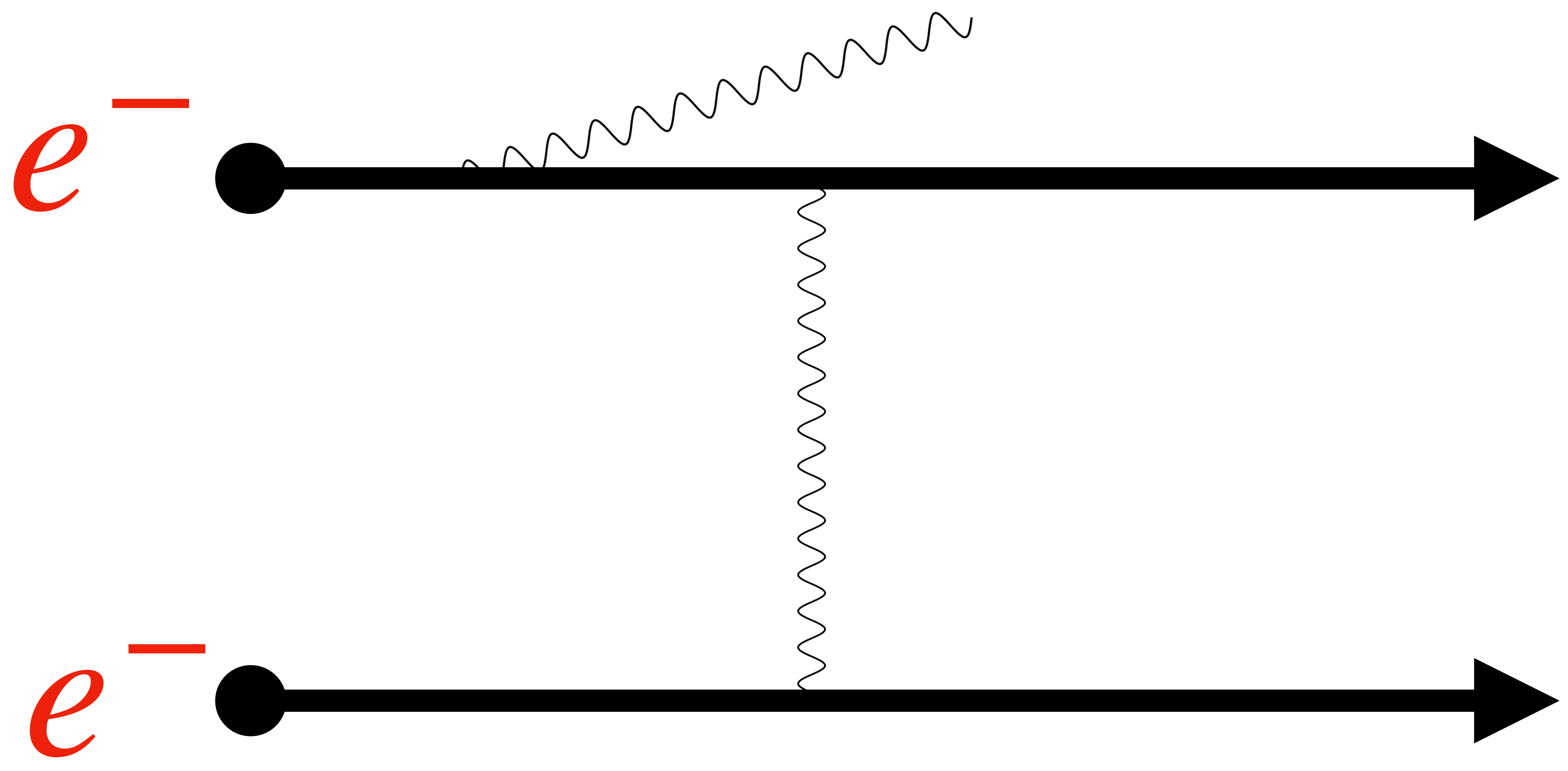

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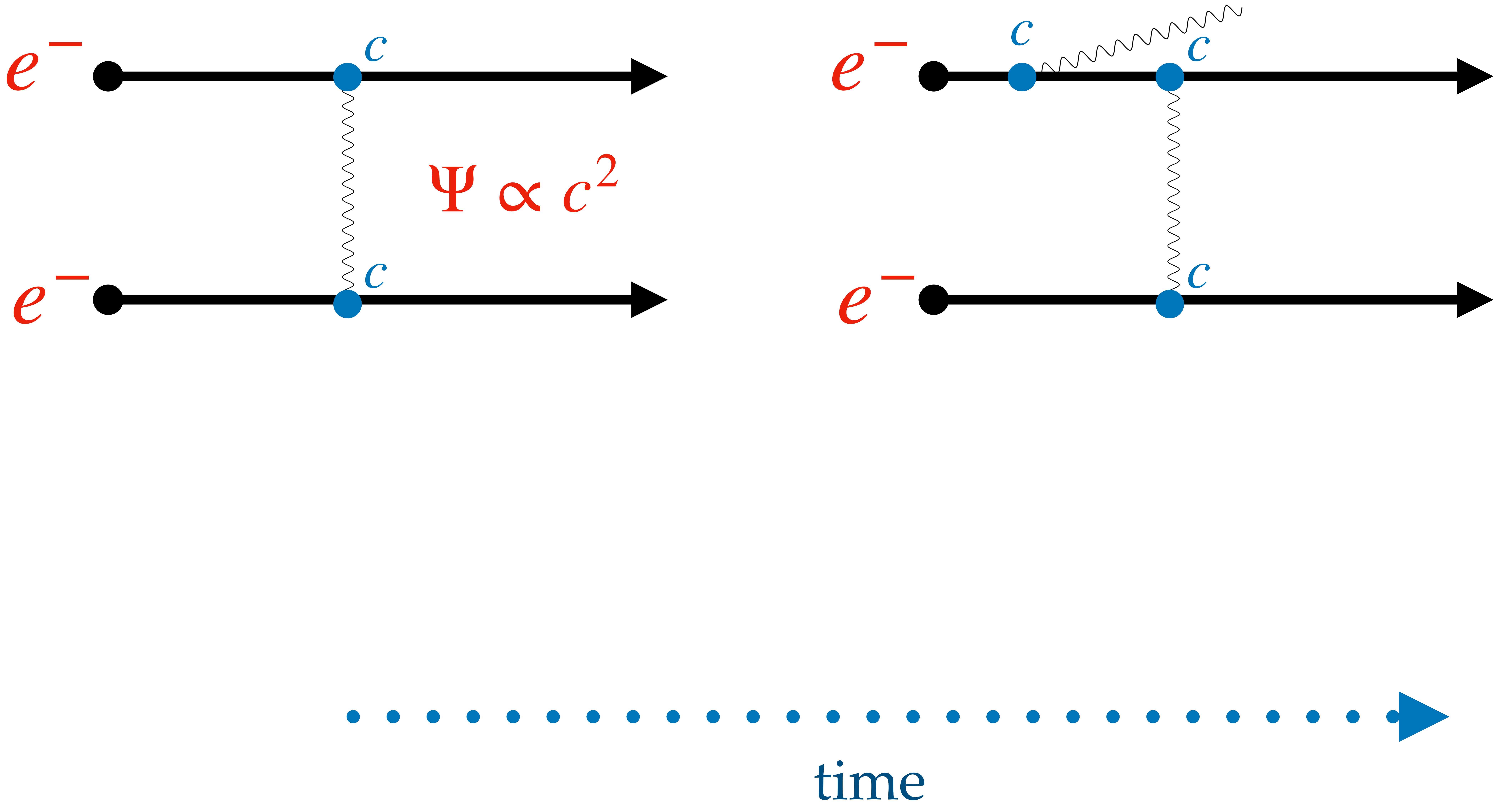

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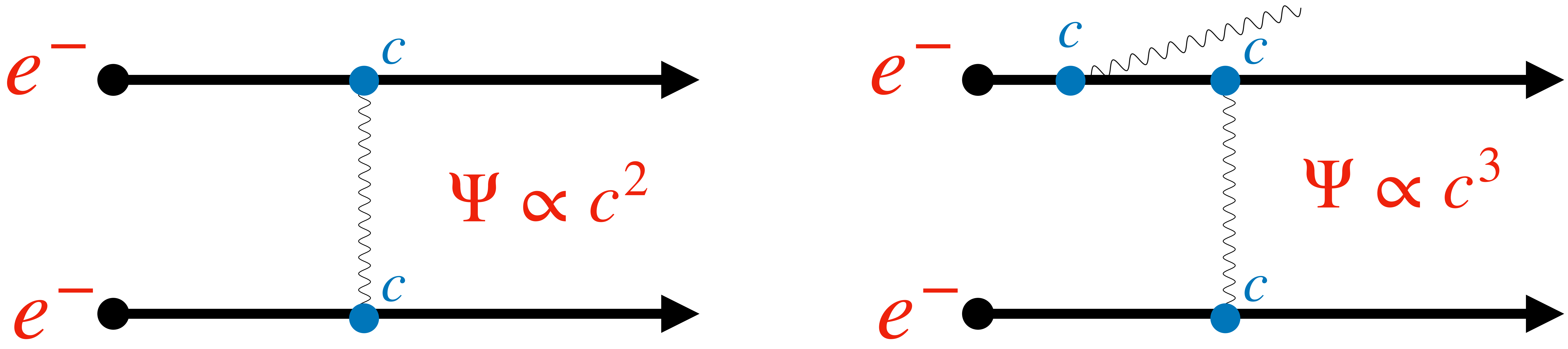

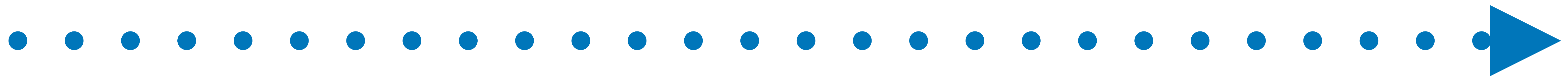

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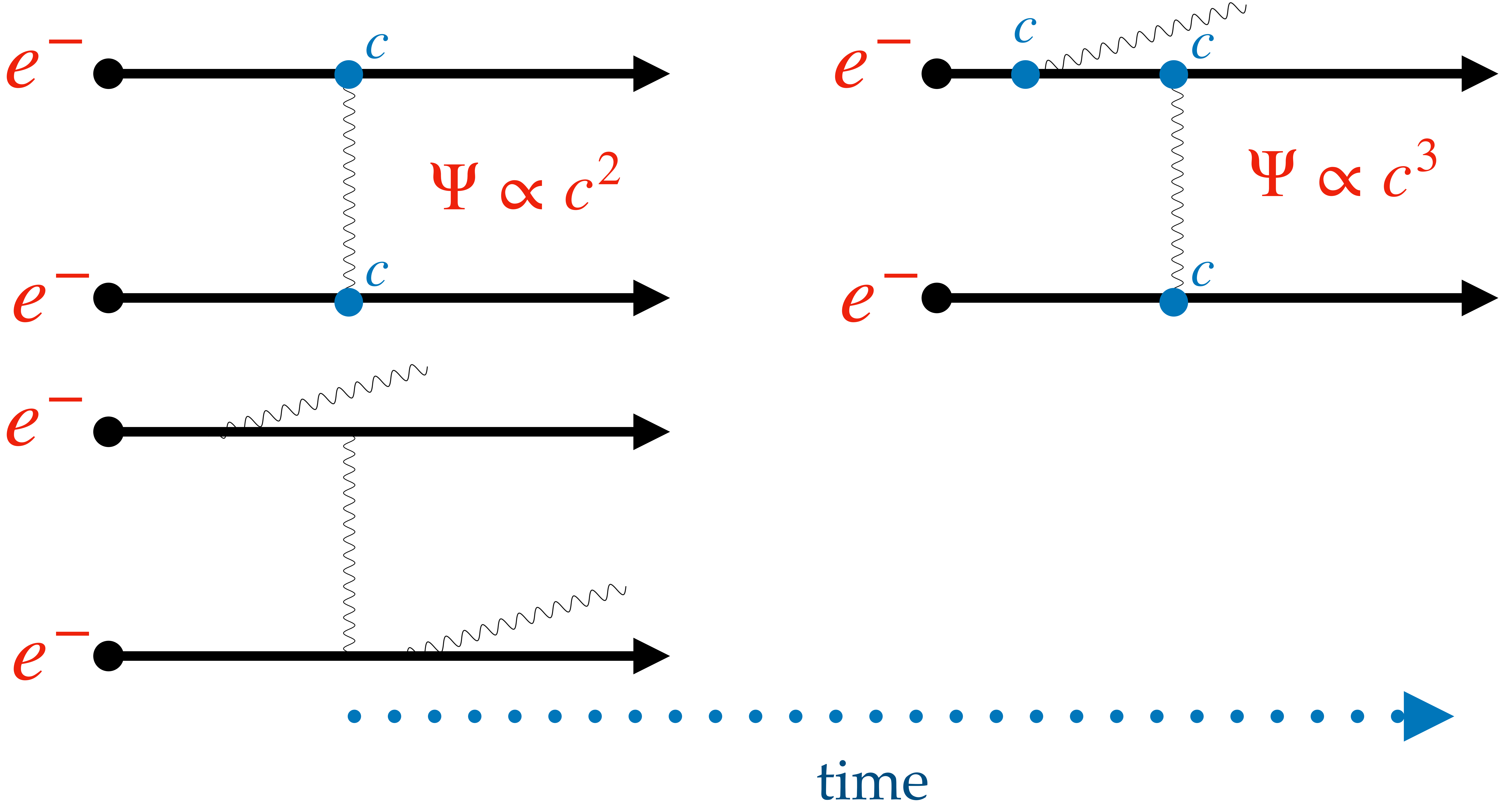

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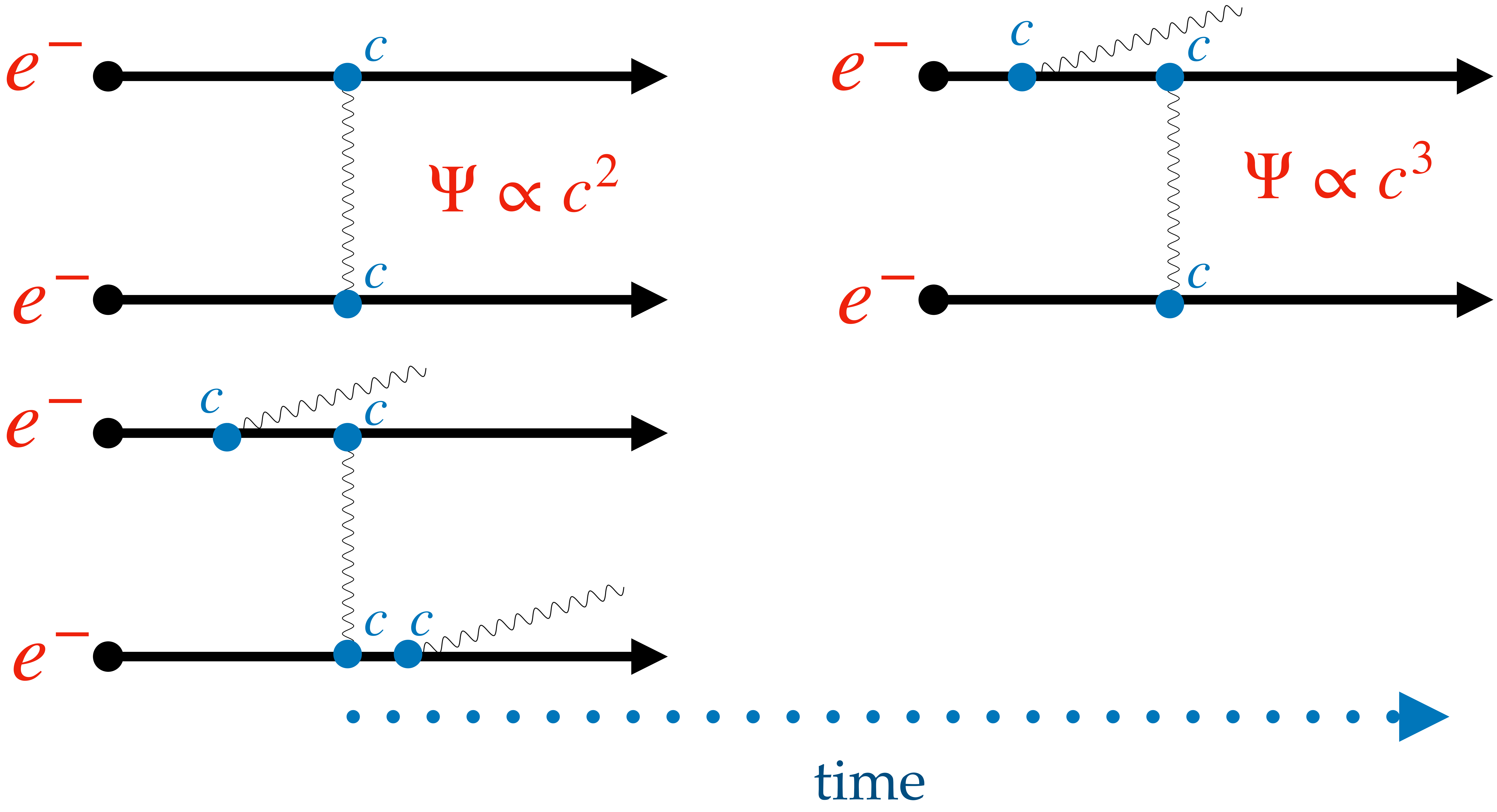

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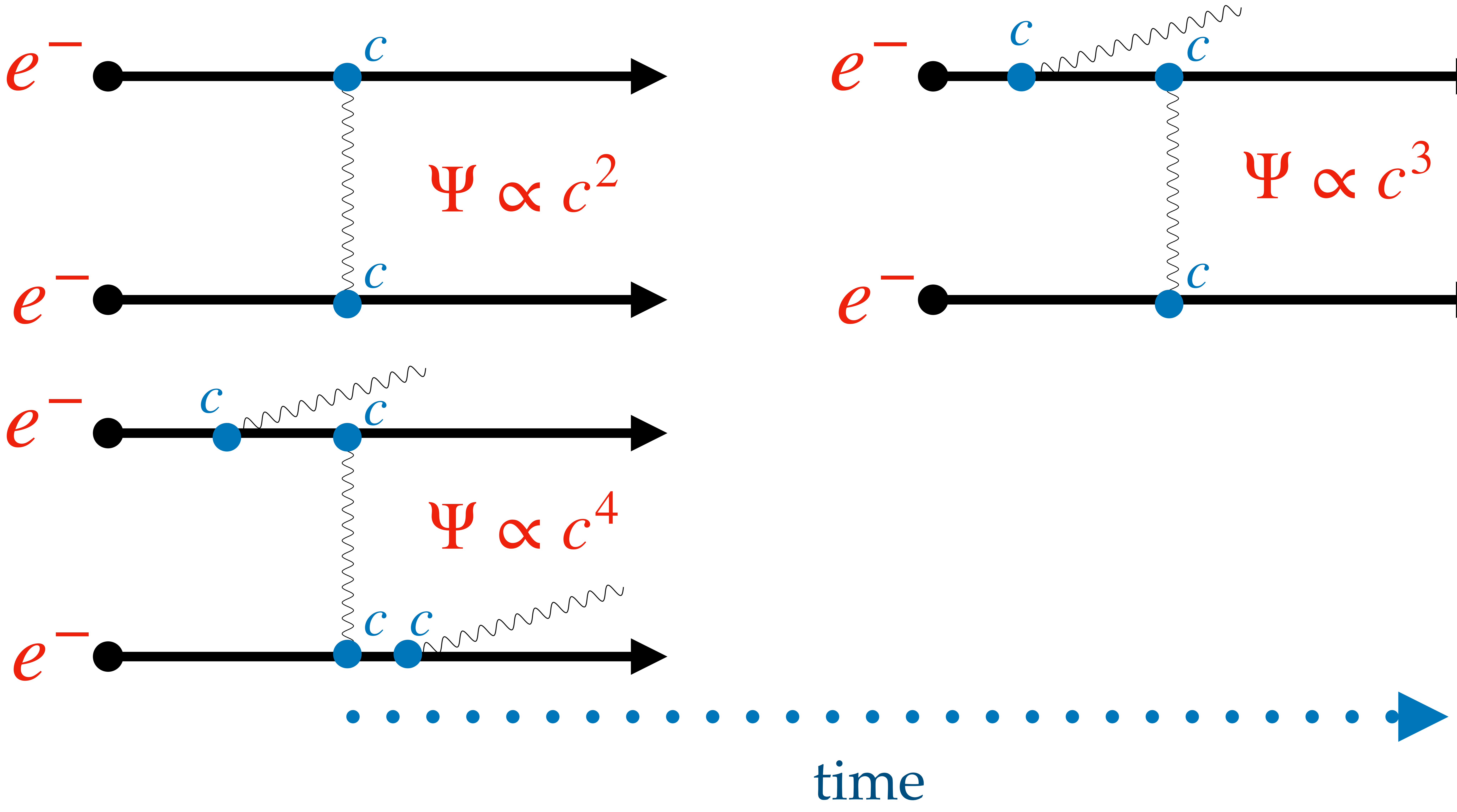

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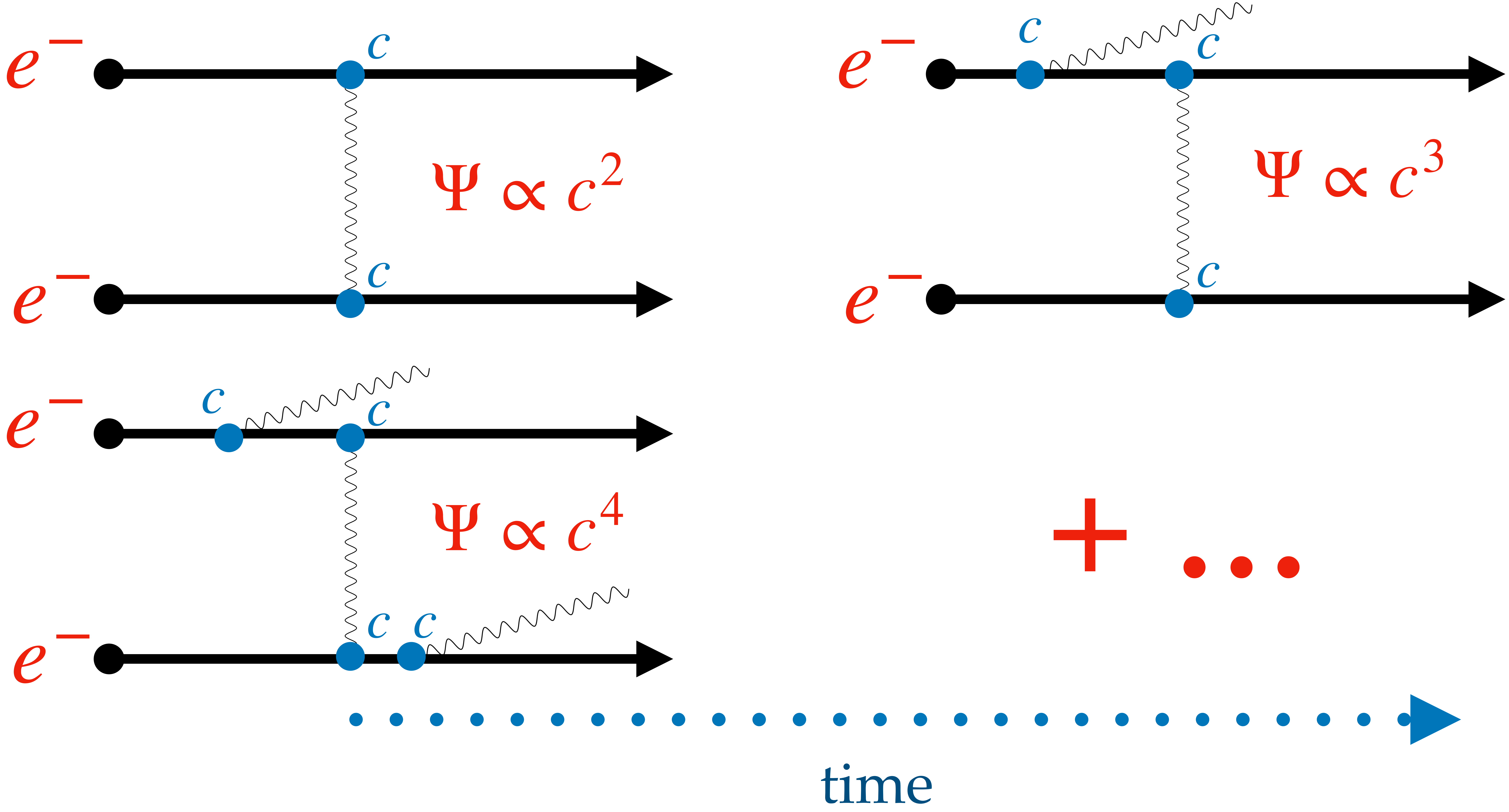

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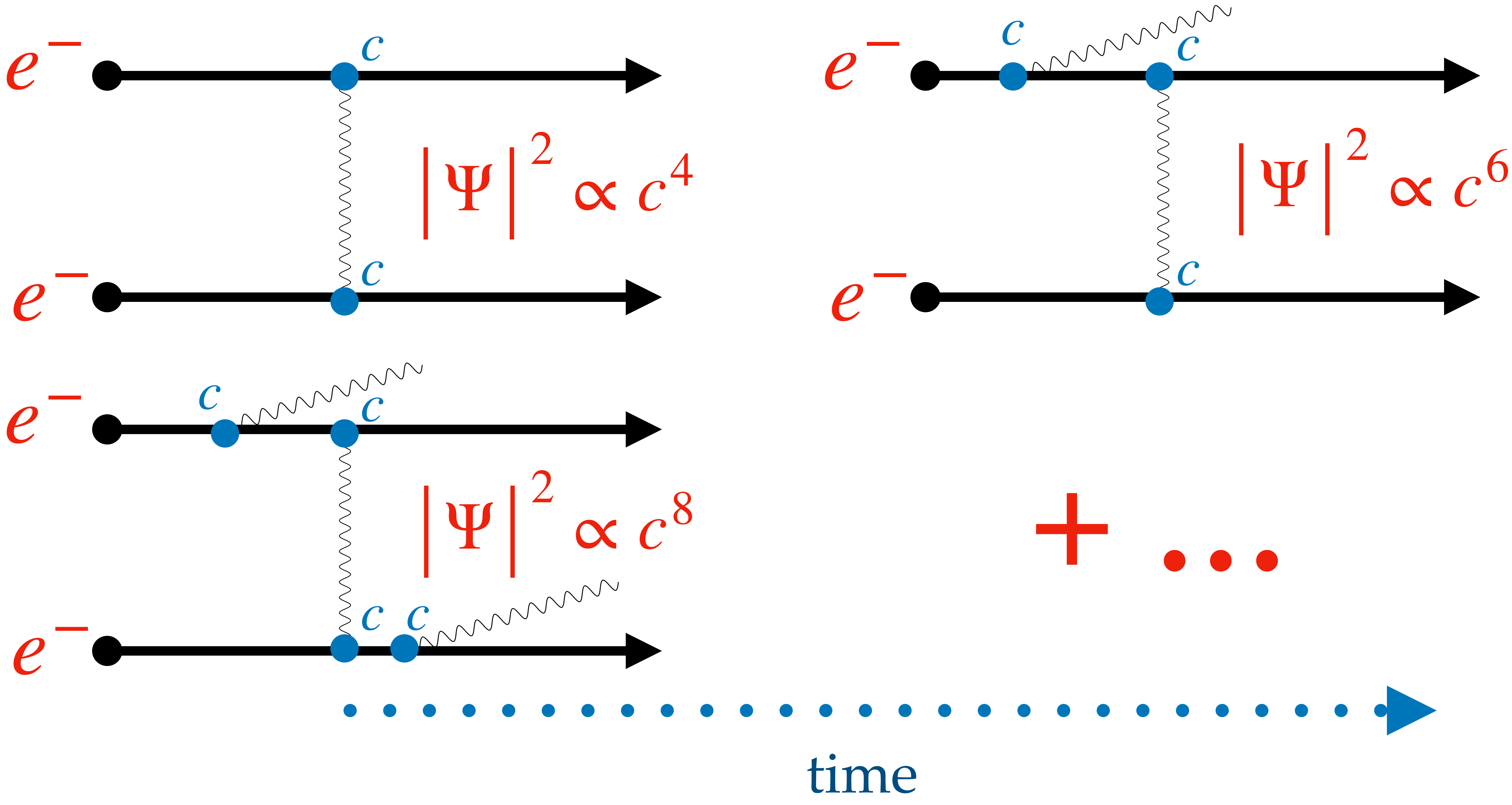

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From Theory to Experiment and Back Again

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

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

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

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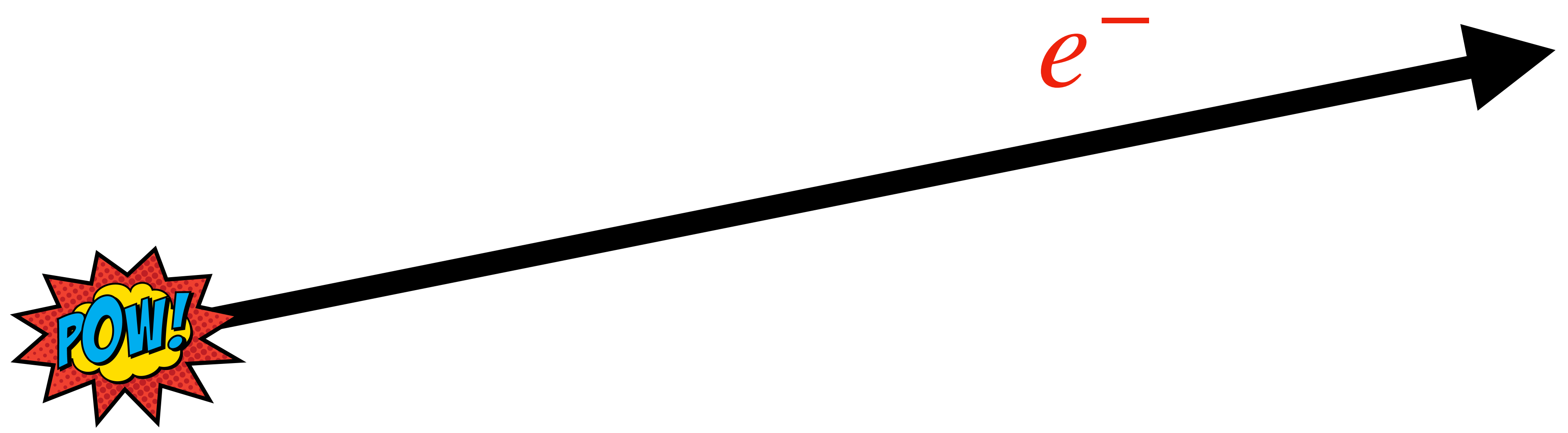

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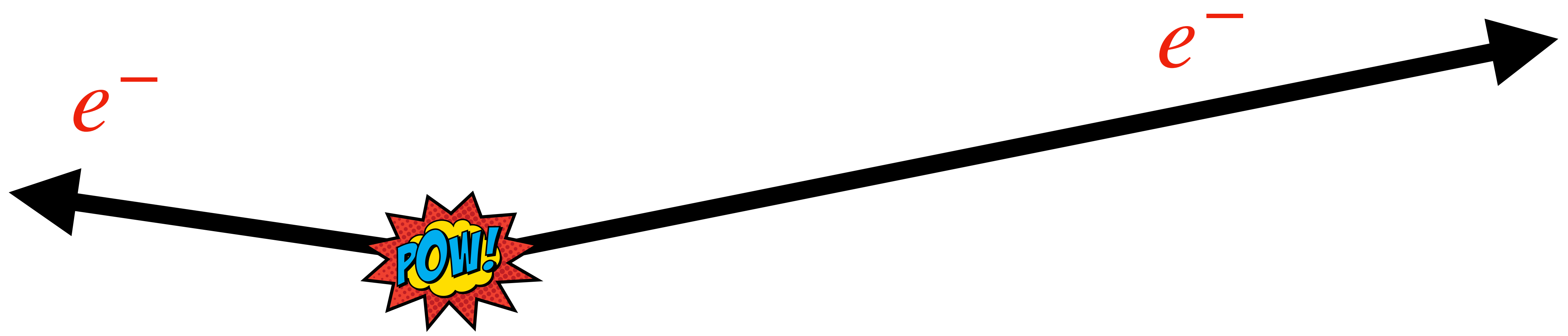


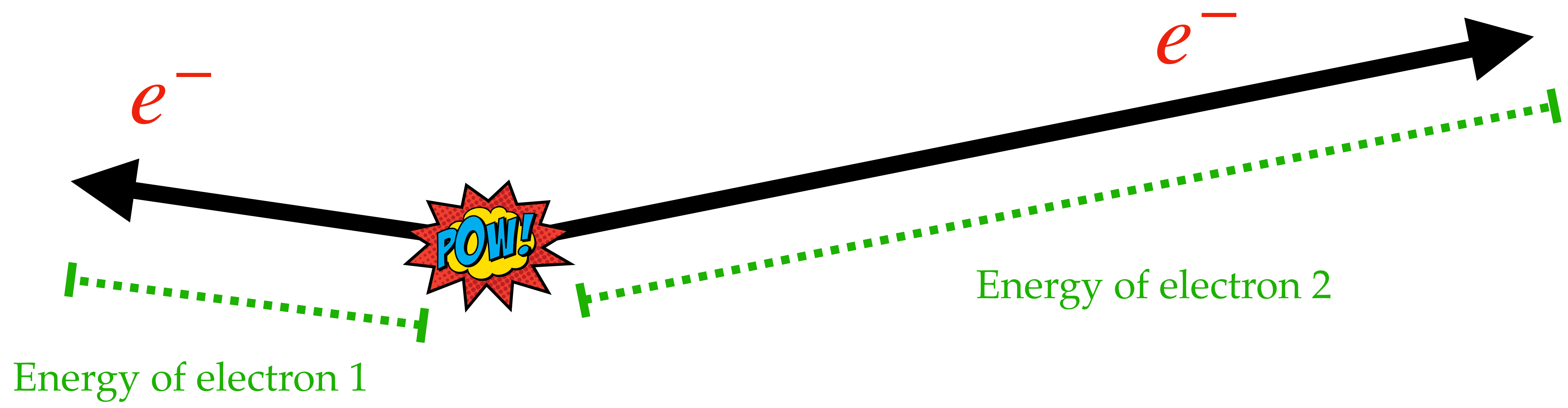
From Theory to Experiment and Back Again

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

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

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

In reality: $|\Psi|^2$ depends on the **energy and directions** of the particles involved!



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From Theory to Experiment and Back Again

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

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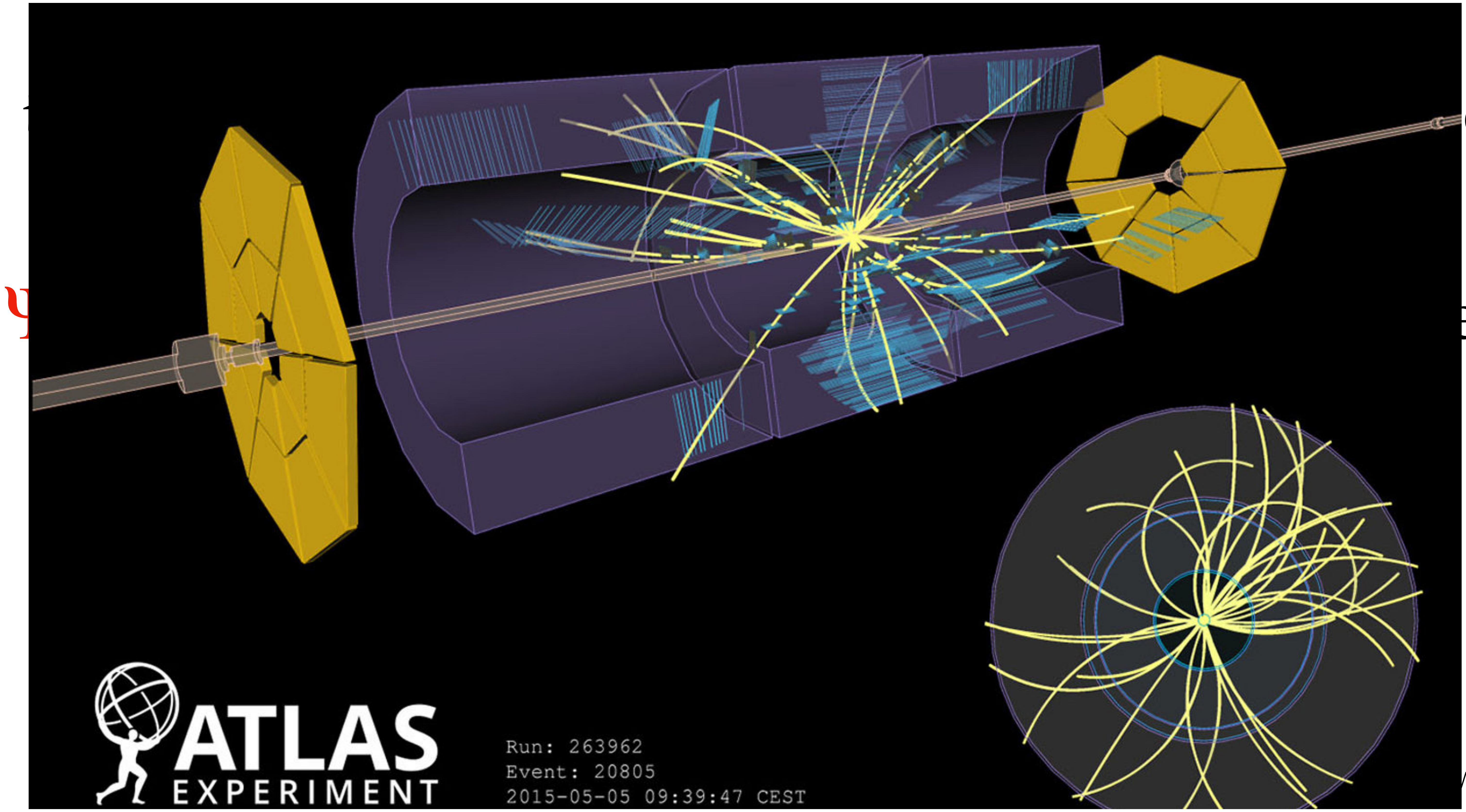
In reality: | … e particles involved!



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- **Solution**: Use **approximate** c^n & **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.

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How do we make sense of it all?

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

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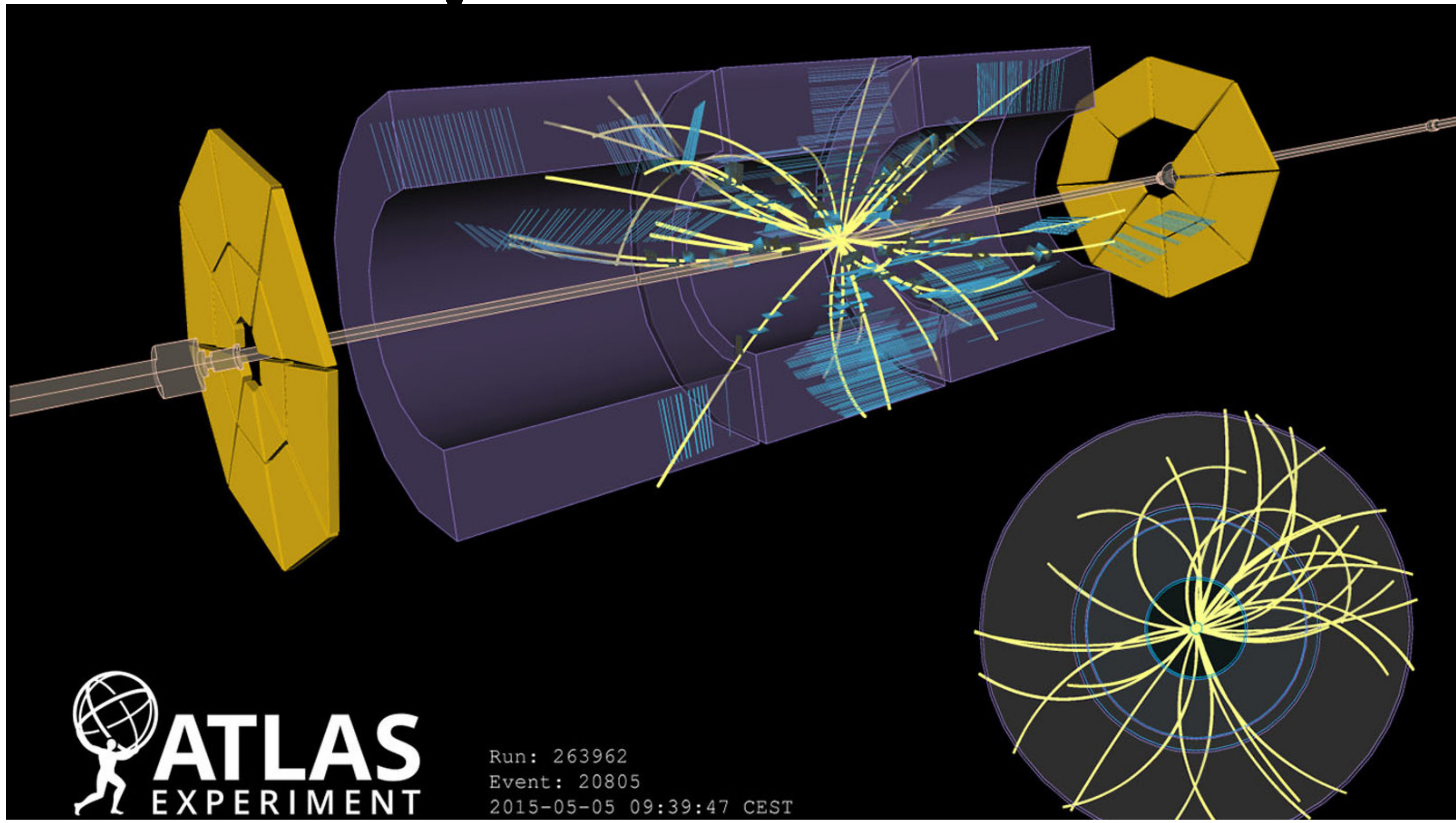
Experiment



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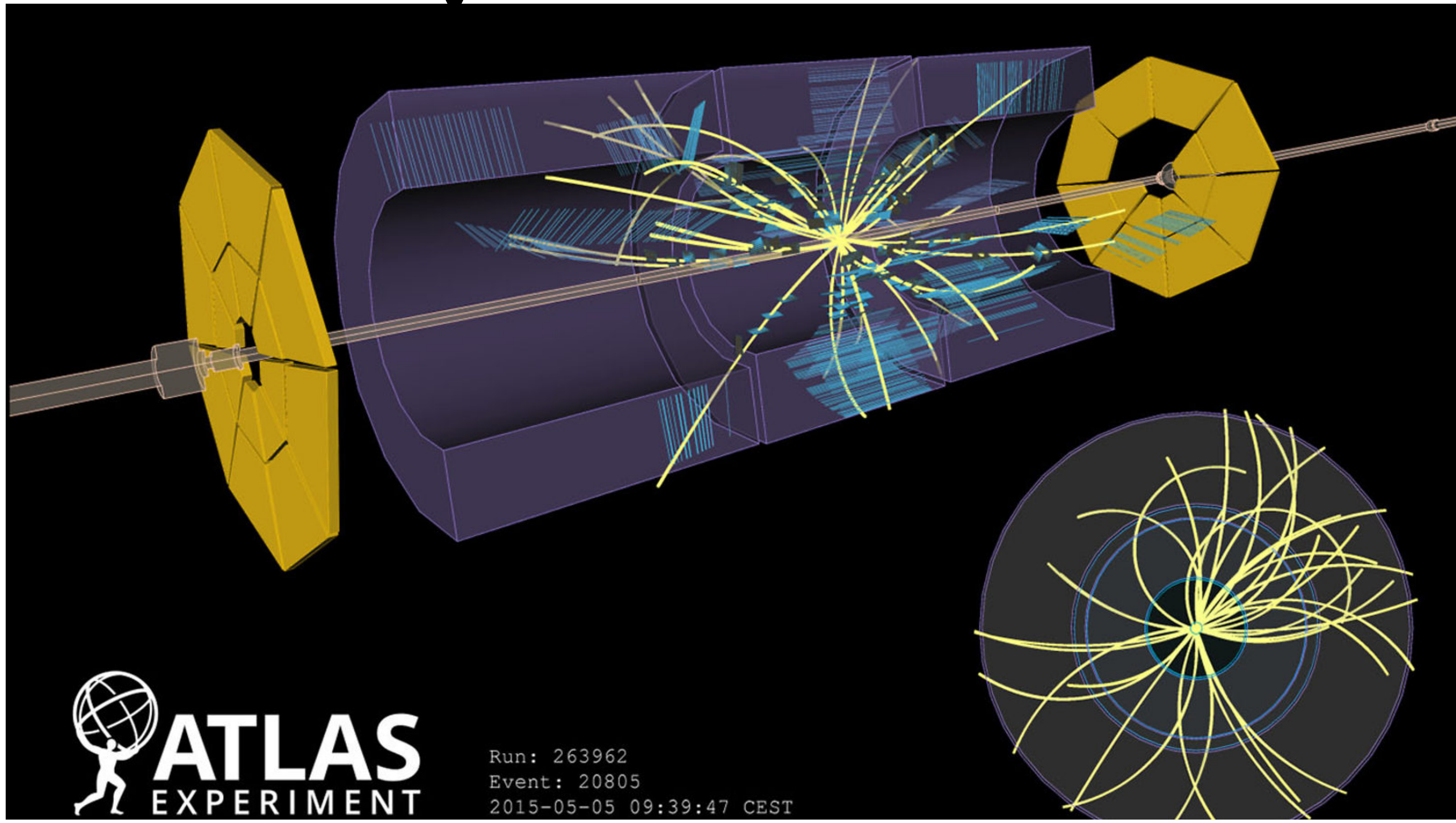
Simulations

Experiment



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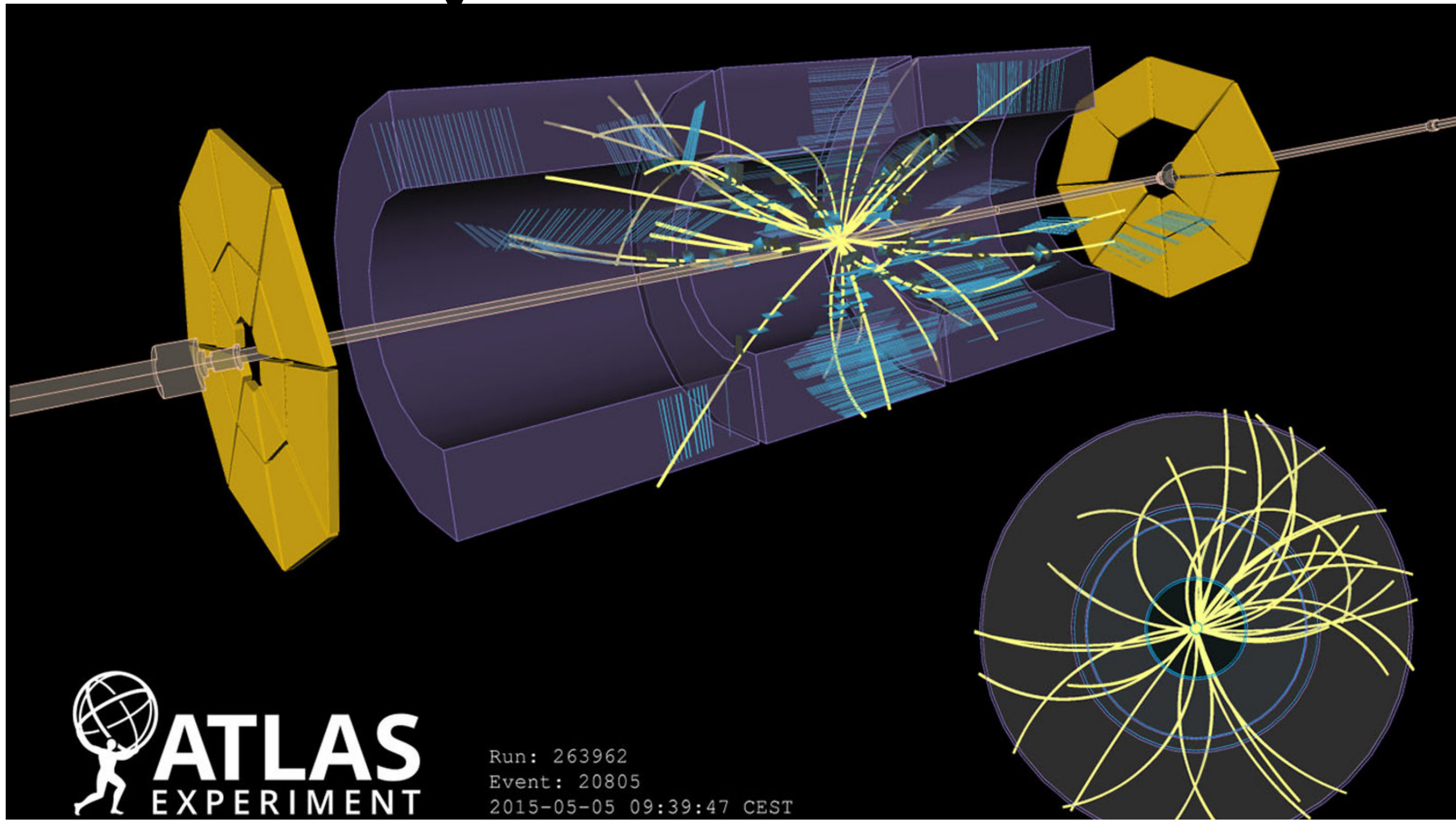
How do we make sense of it all?

Shut up and Simulate!

Simulations

Experiment



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Simulations via the Monte Carlo method: Calculate π!

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Simulations via the Monte Carlo method: Calculate π!

- "Theory":
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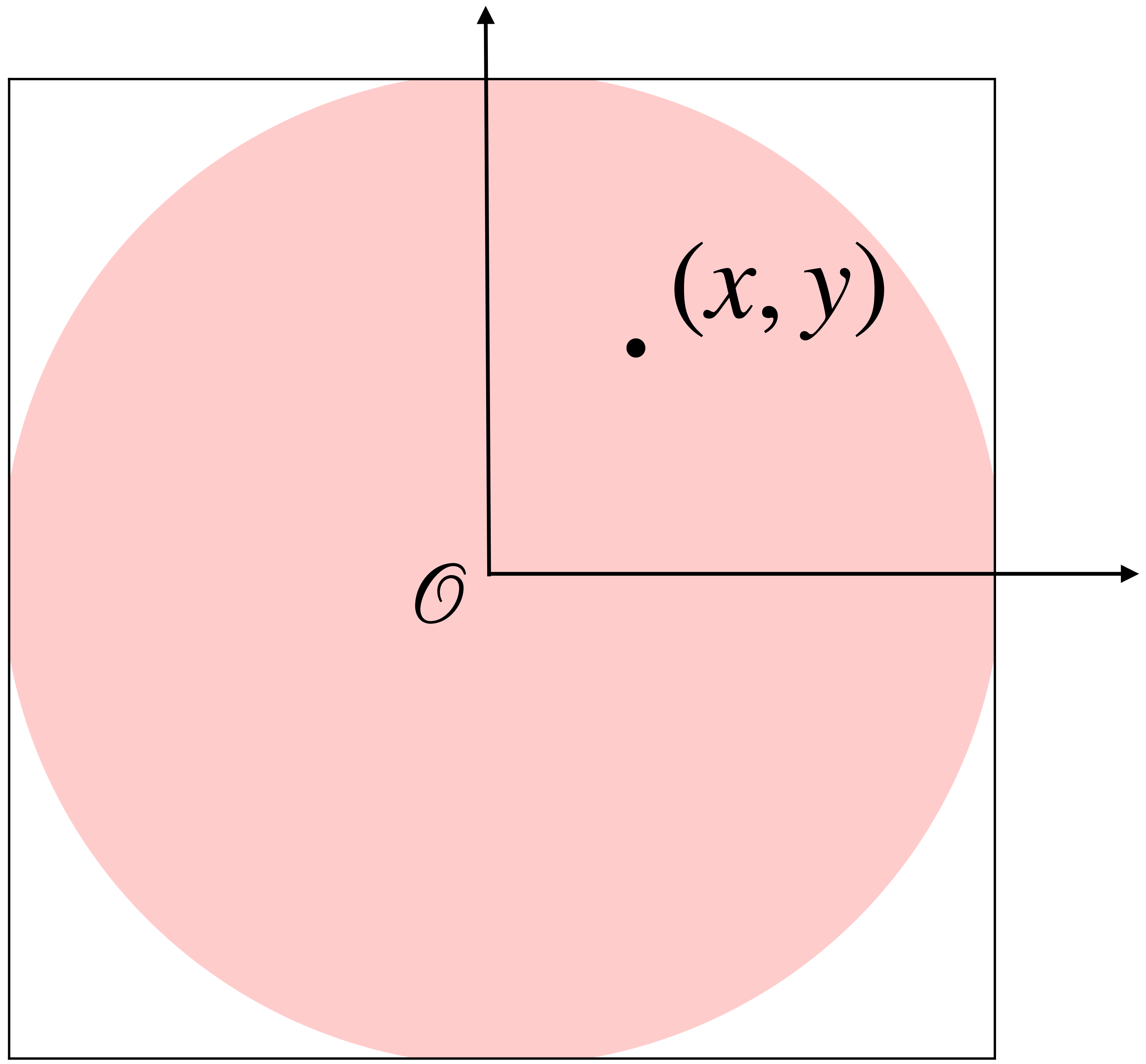

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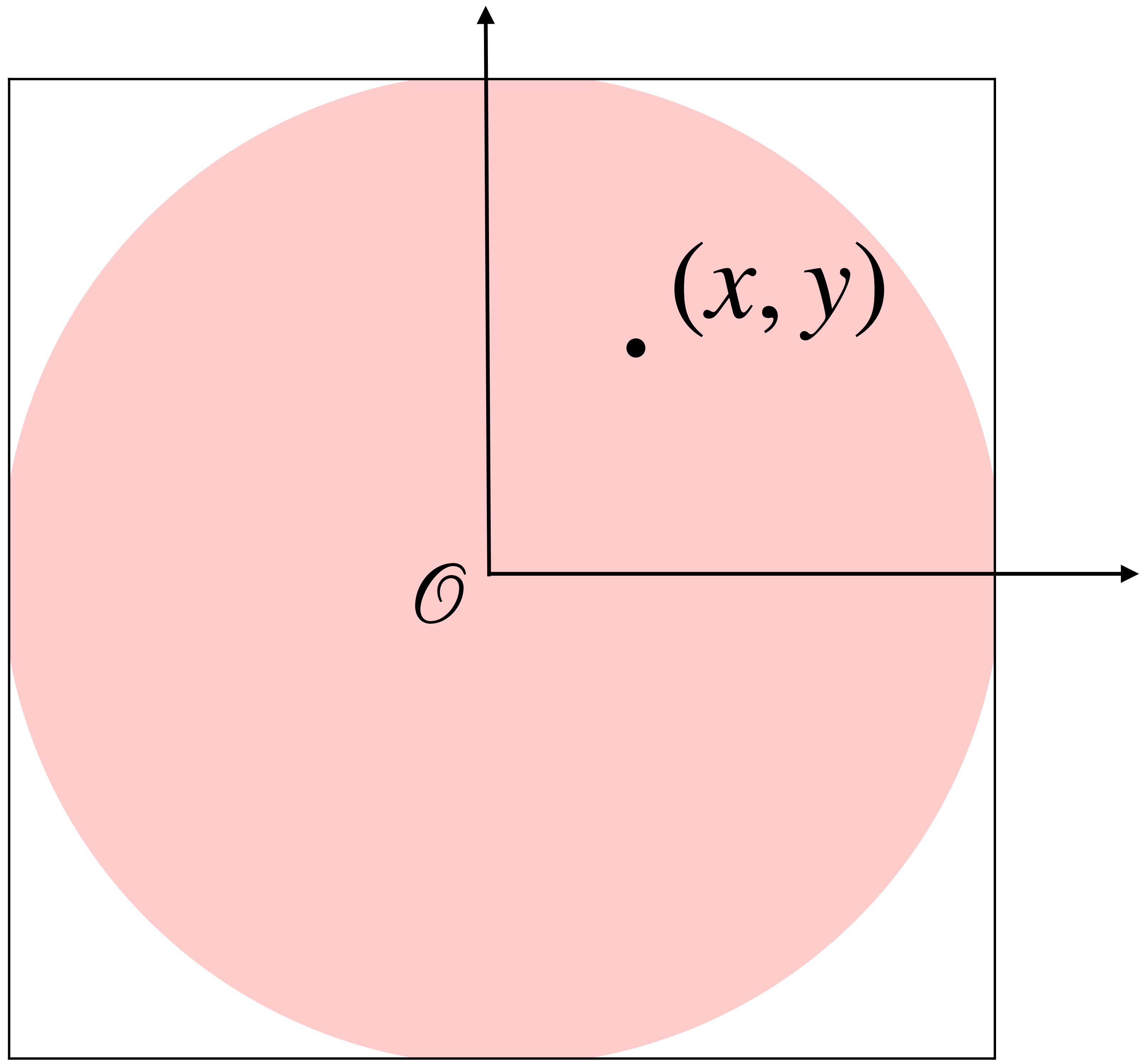

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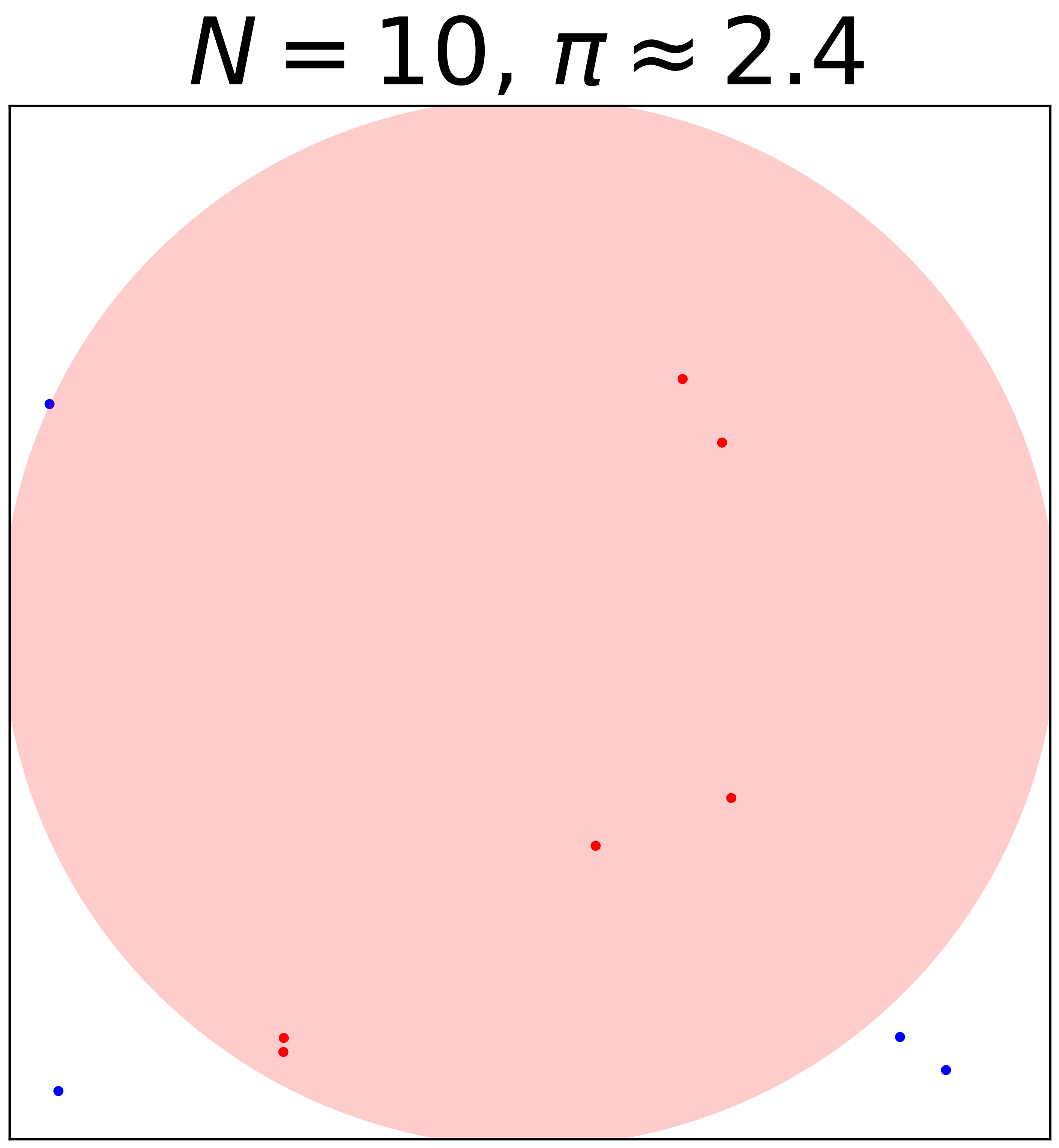

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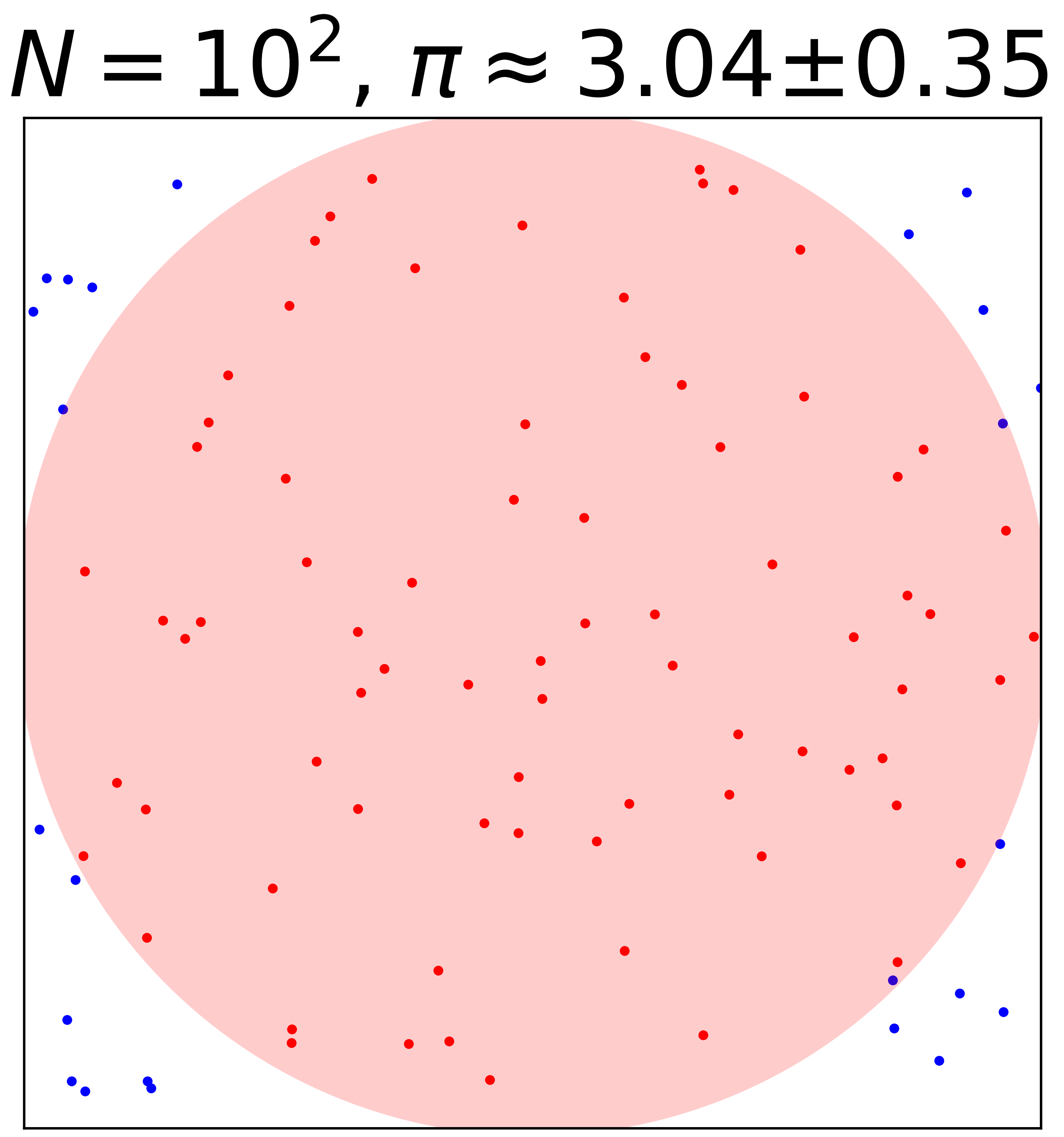

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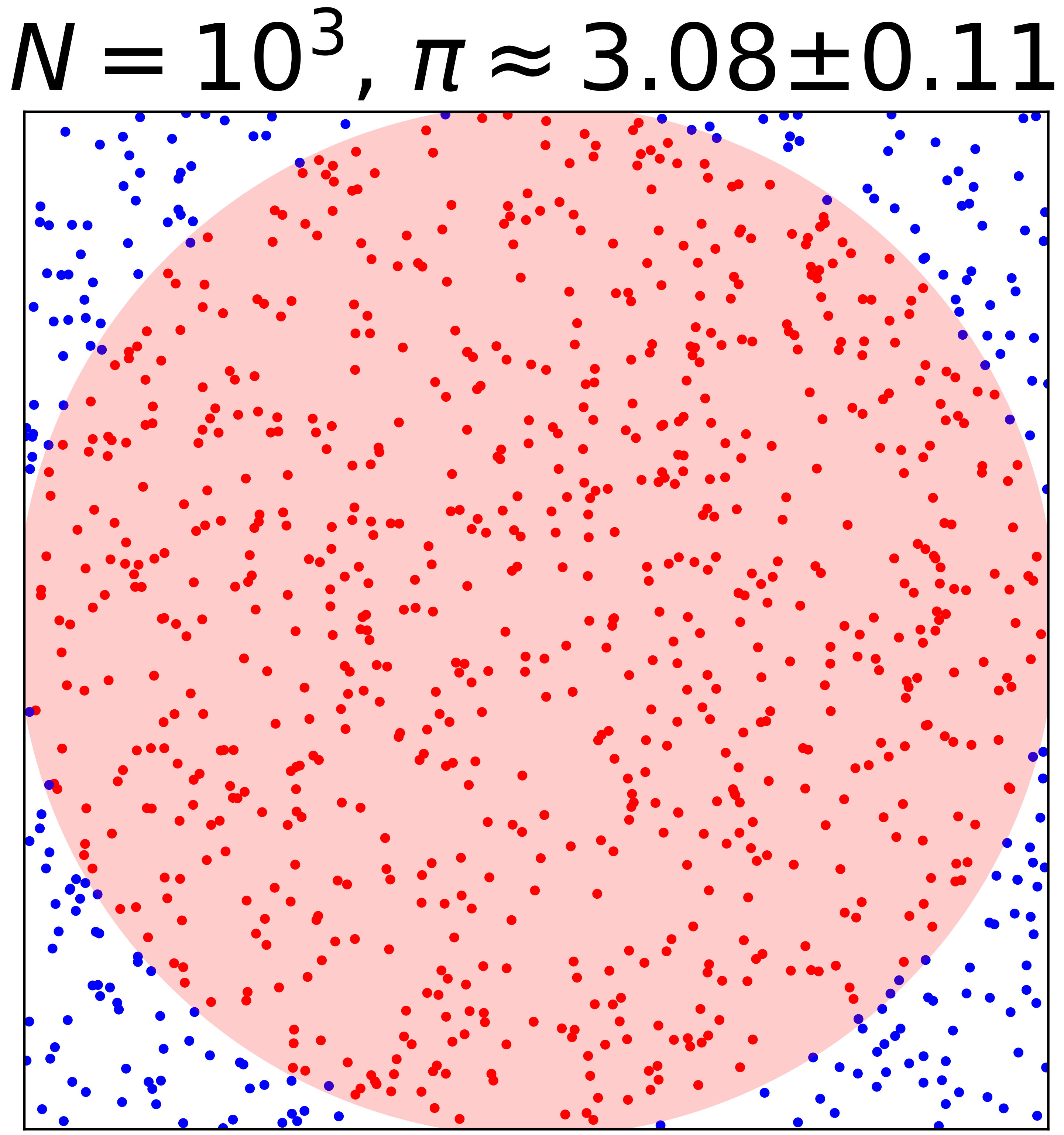

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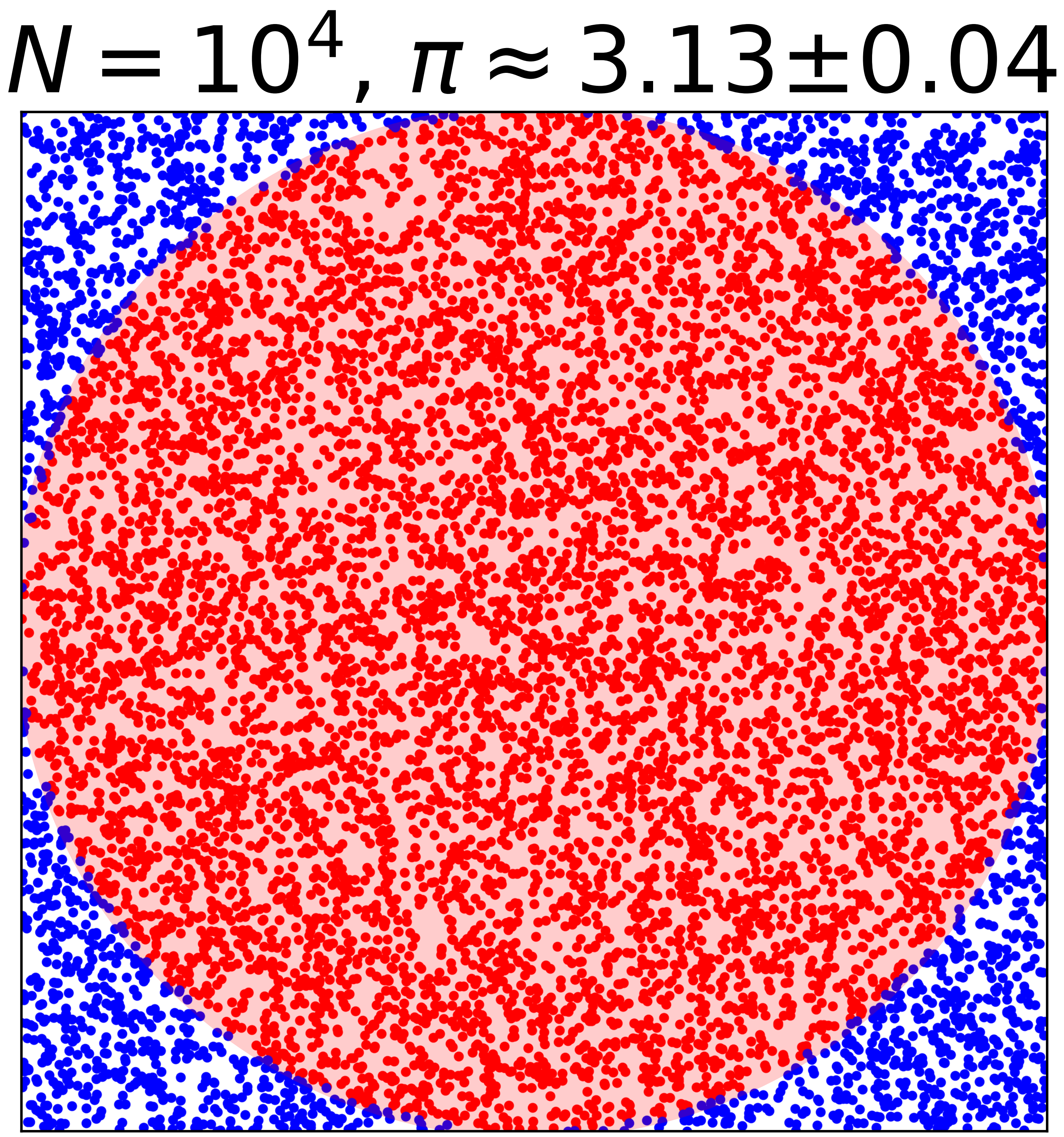

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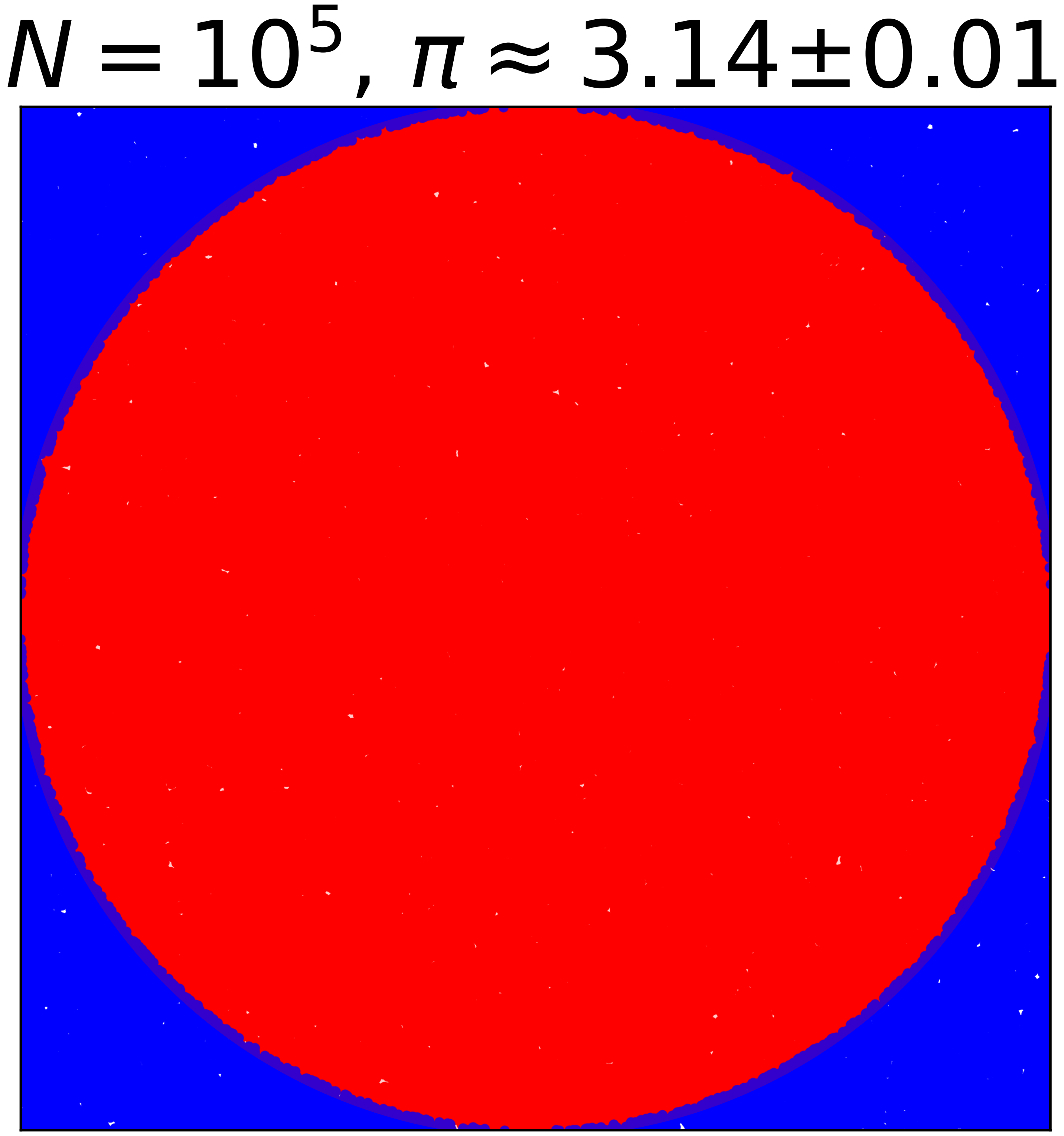

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Simulations of Events via Monte Carlo

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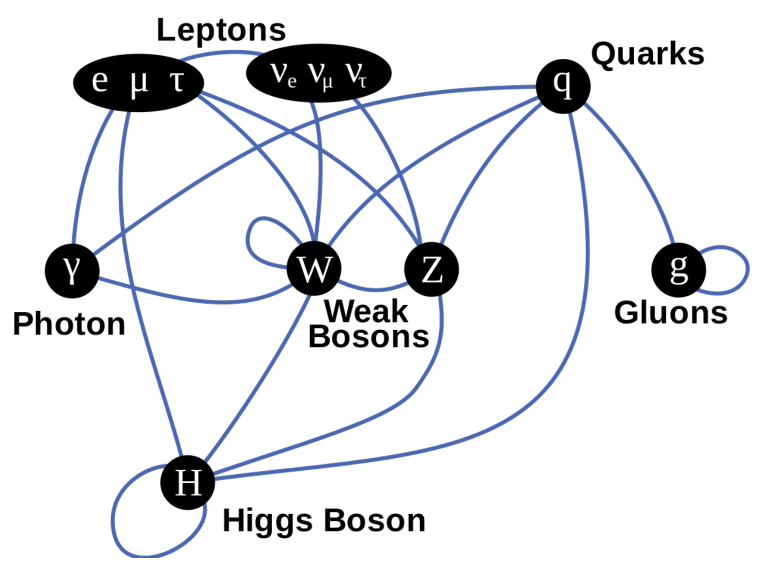
Simulations of Events via Monte Carlo

- “Theory”:
  - The known particles and their interactions!



  - Calculate **probabilities** using Quantum Field Theory → $|\Psi|^2$.

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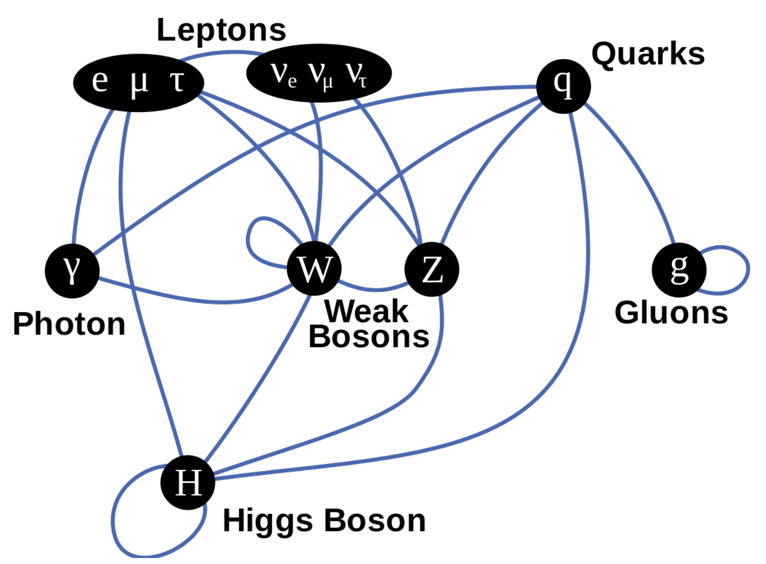

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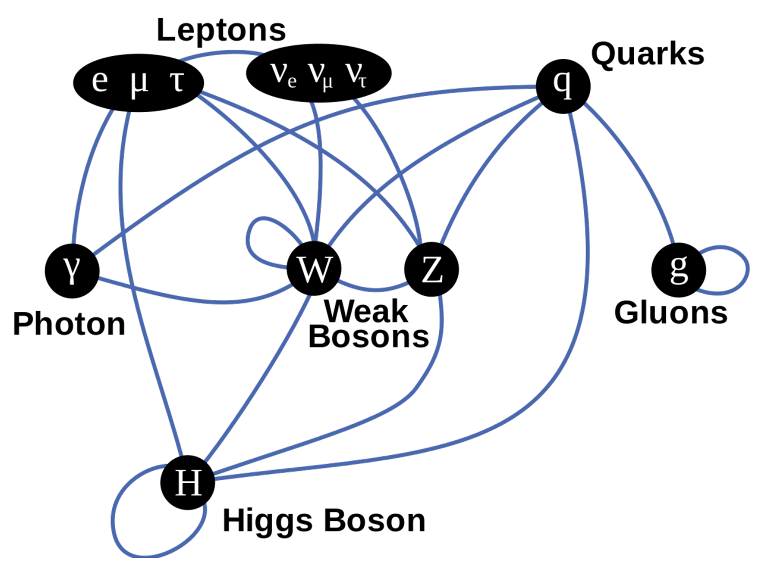

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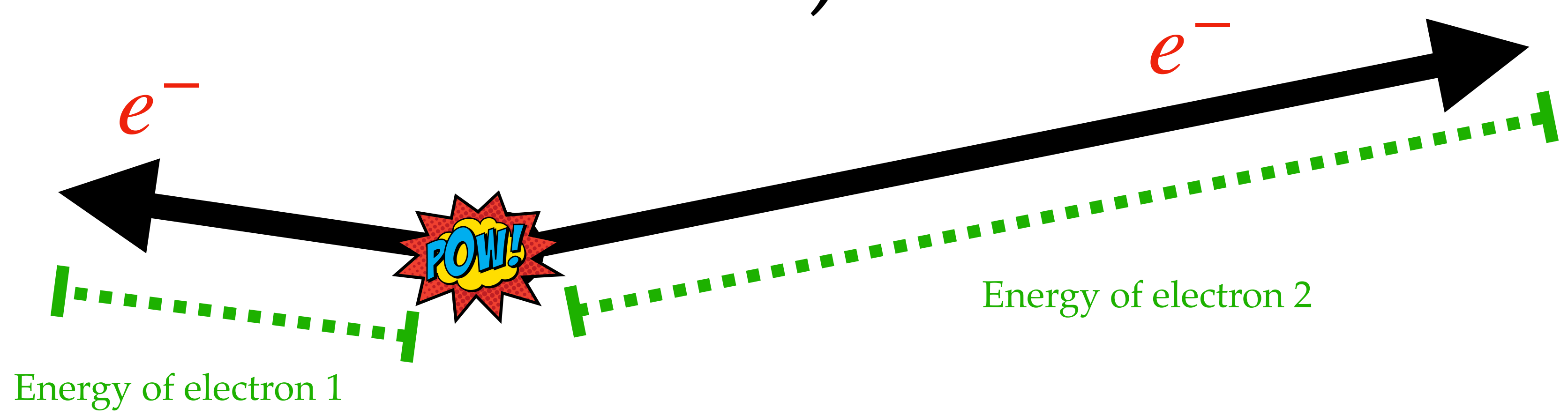

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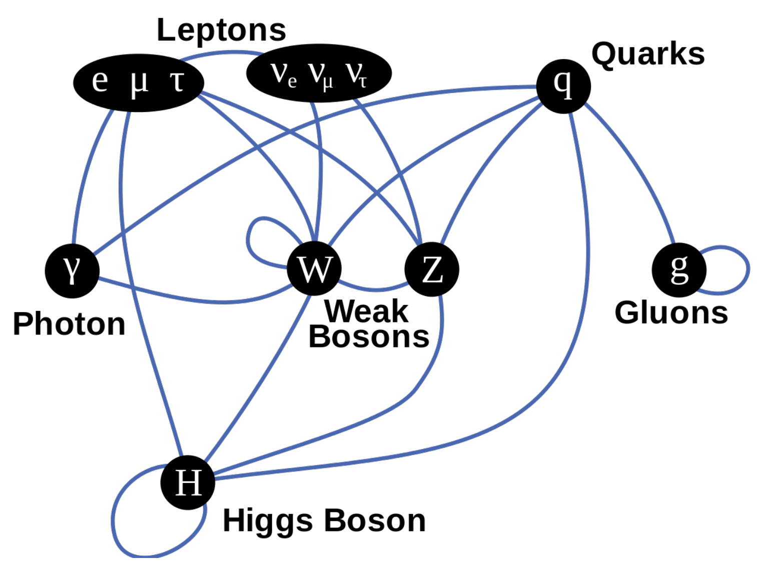

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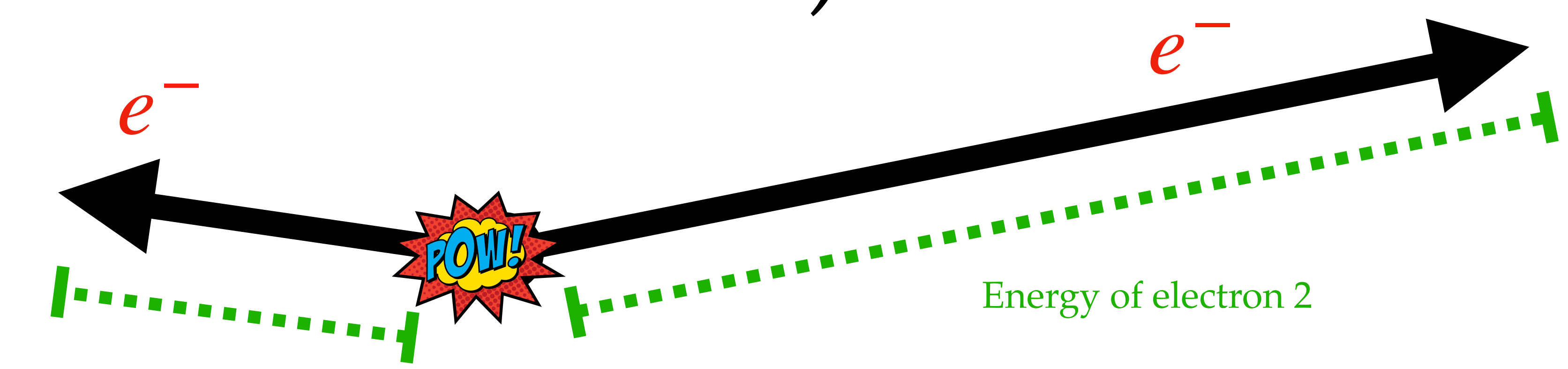

⇒ Get lists of particles that look like real events!

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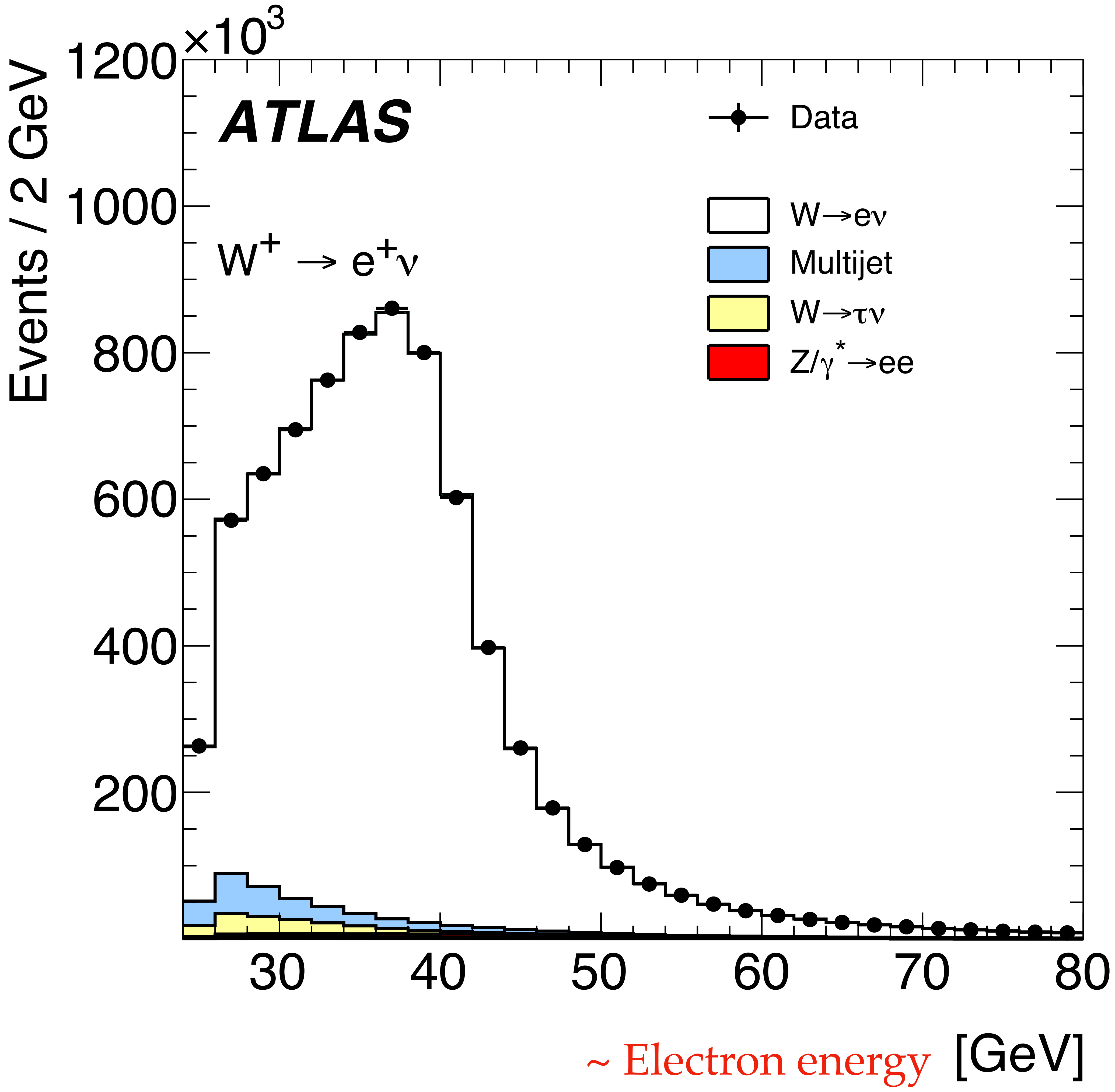
Theory VS Experiments

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



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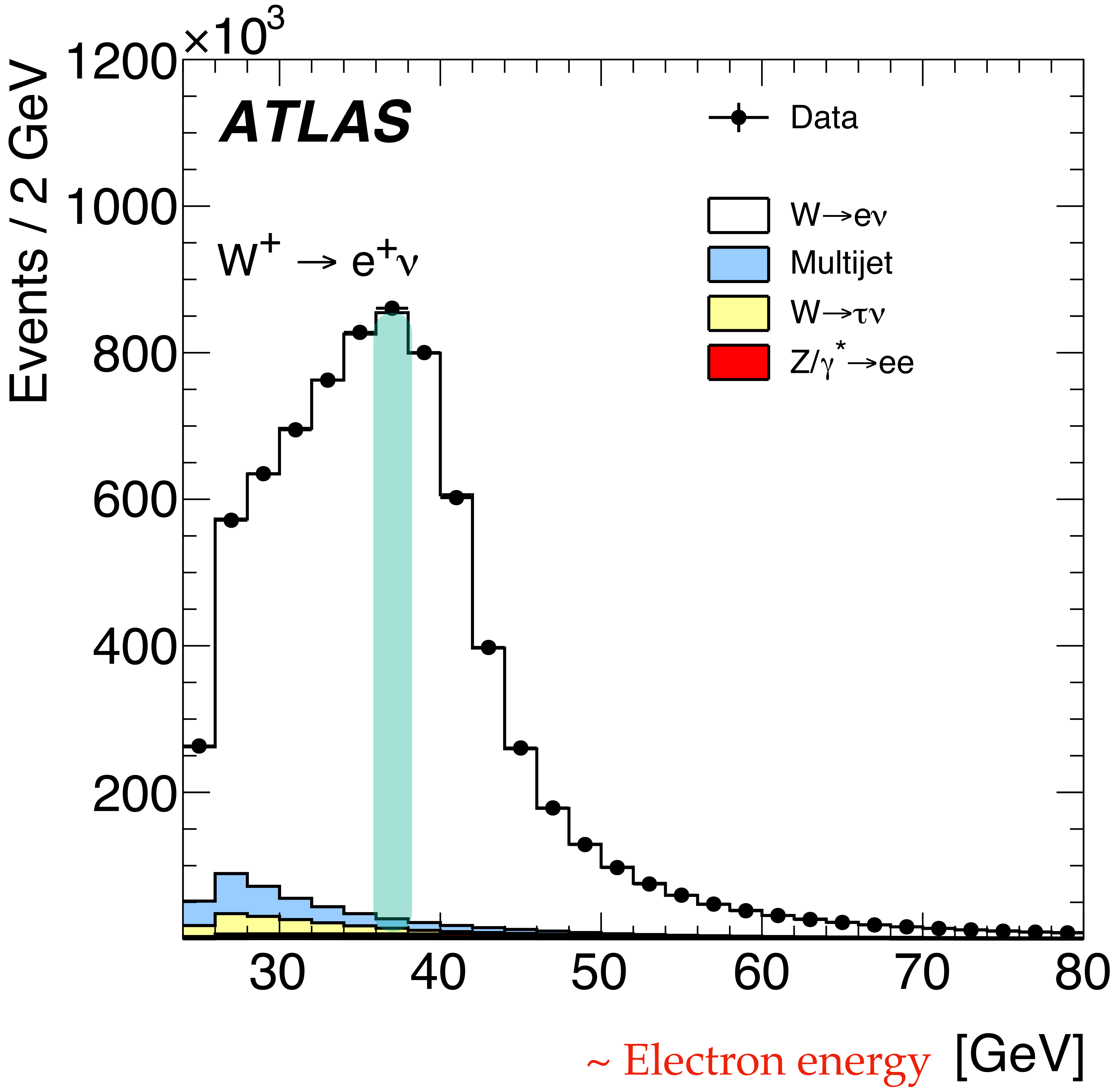

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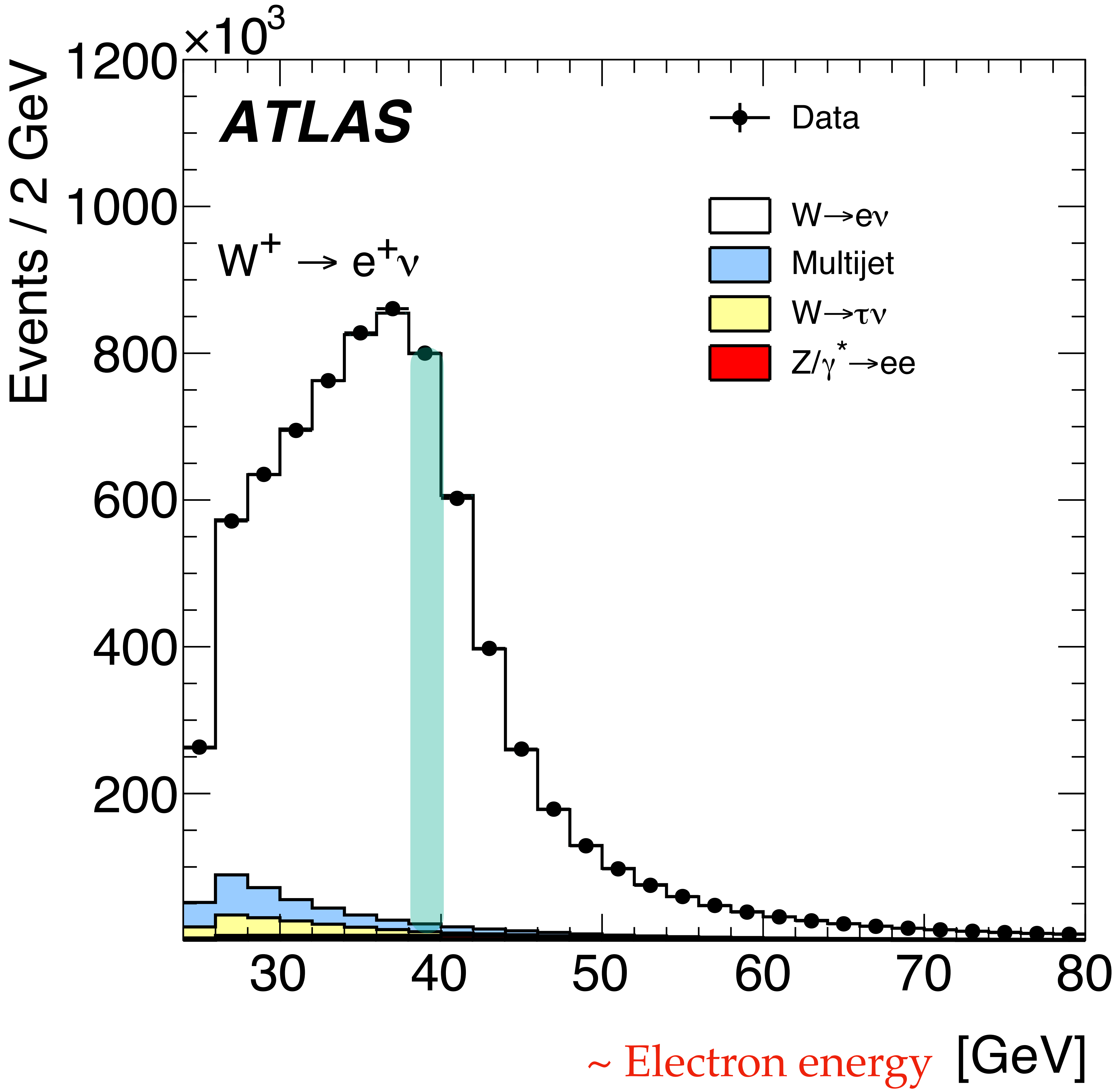

~ Electron energy

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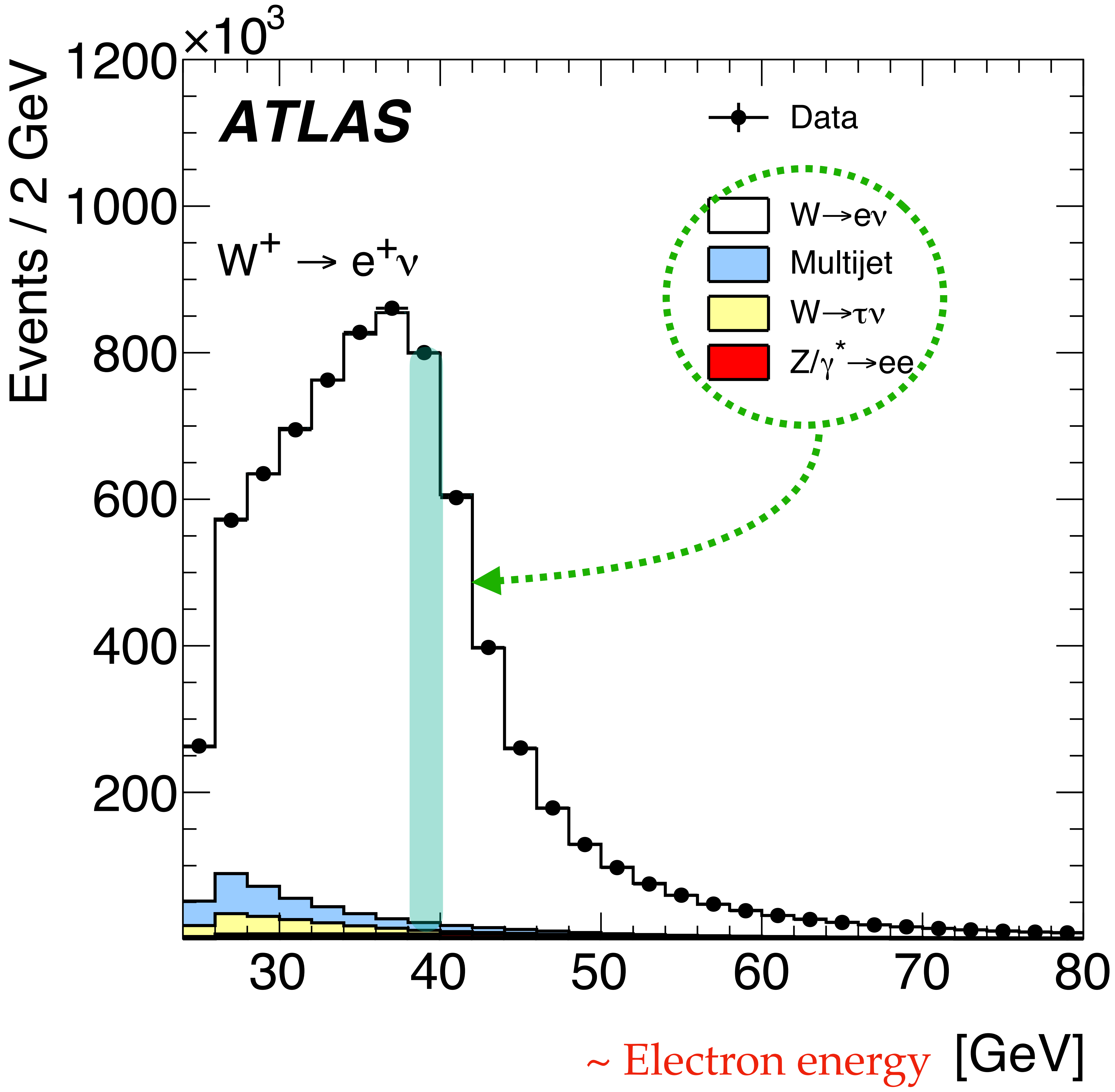

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Searching for New Phenomena

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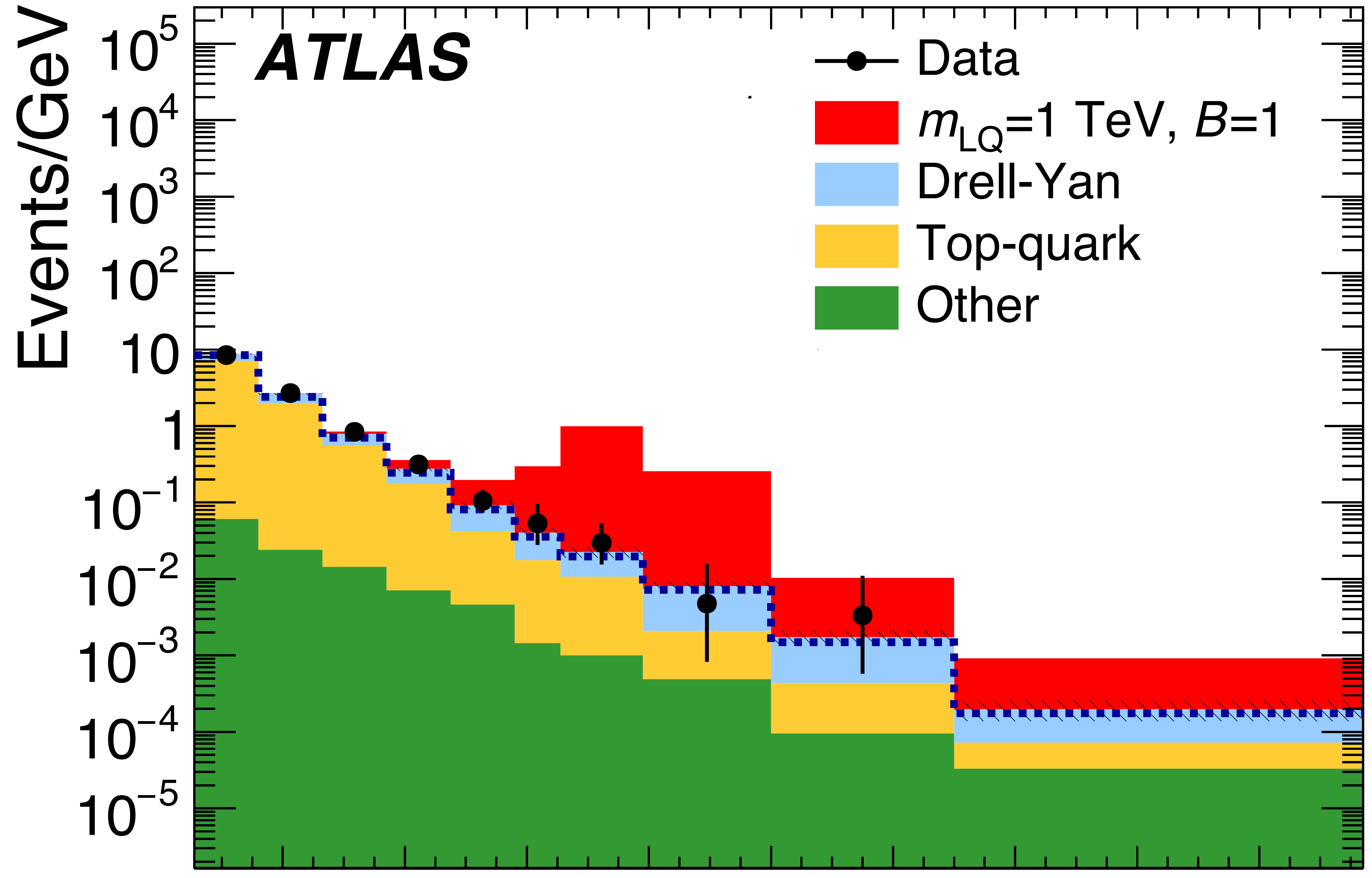

Some Observable Quantity [GeV]

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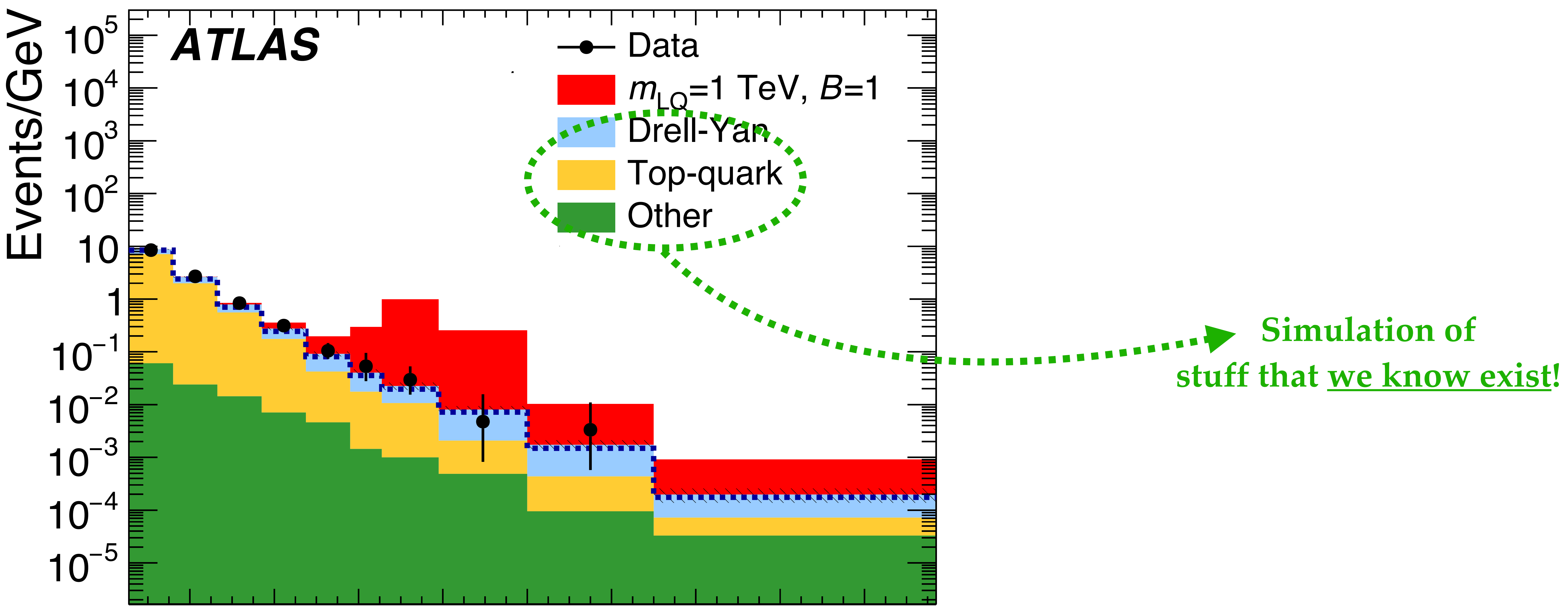

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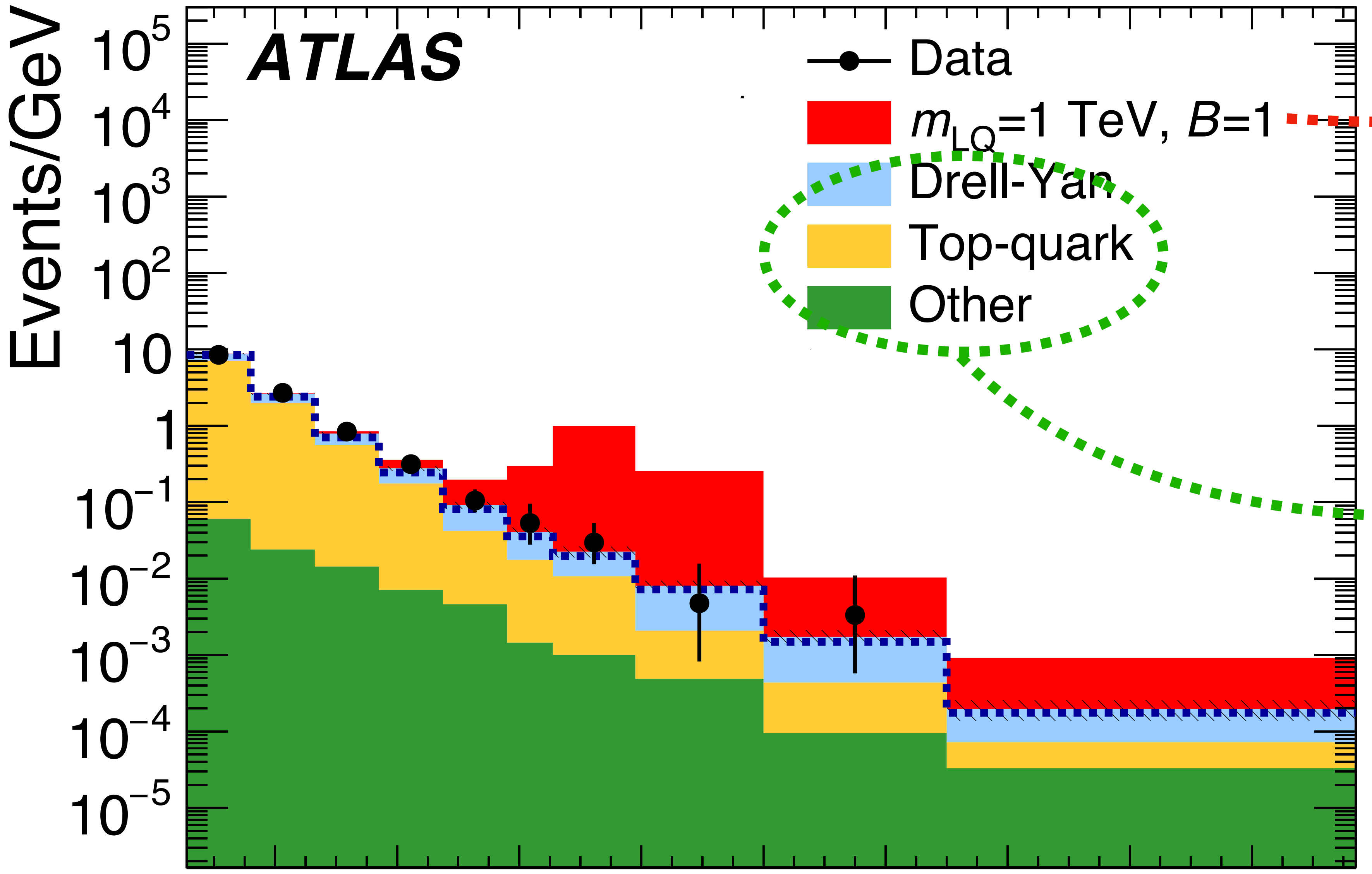

Some Observable Quantity [GeV]

Hypothetical particle

Simulation of
stuff that we know exist!

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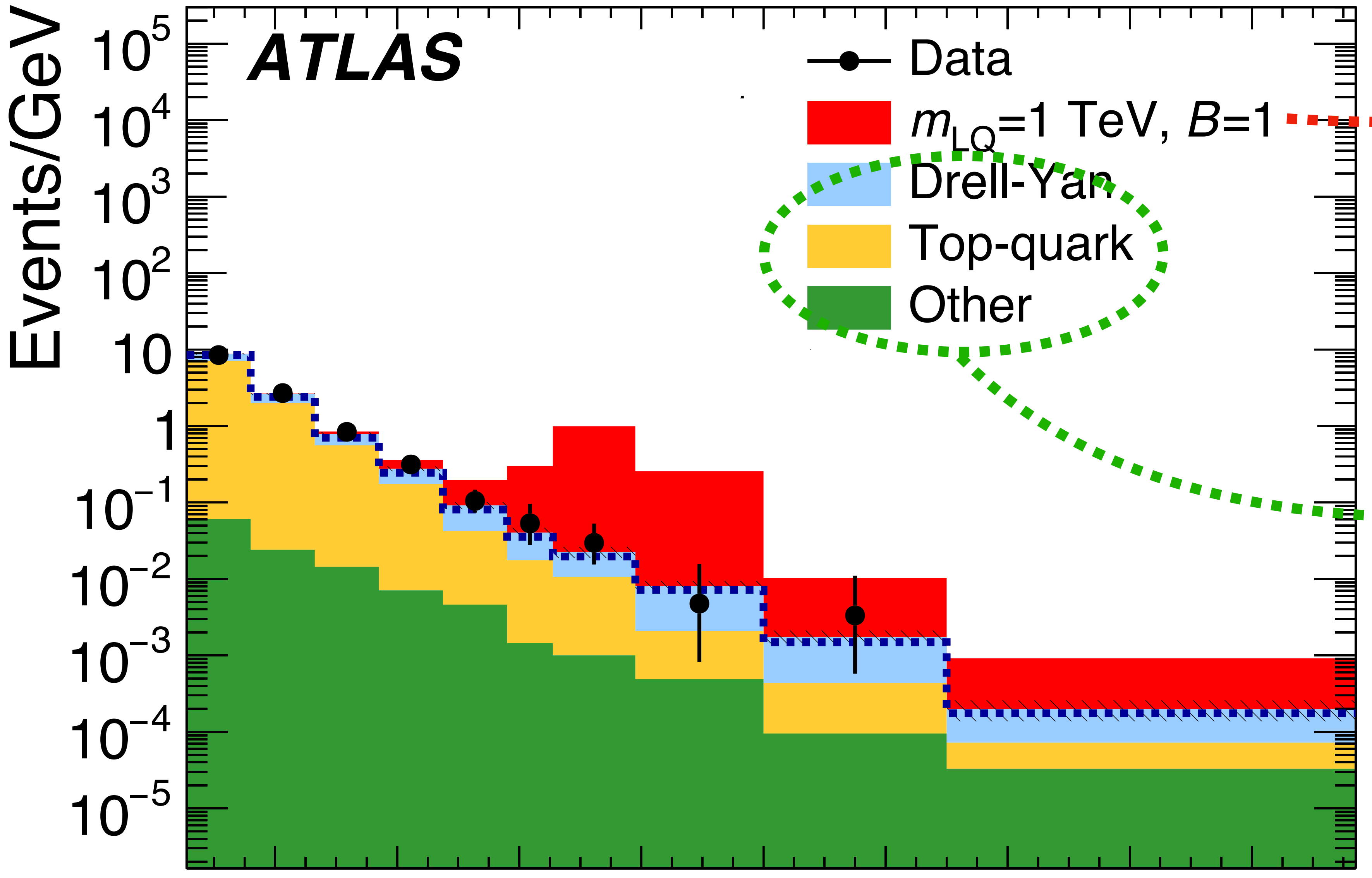

Some Observable Quantity [GeV]

Hypothetical particle

Simulation of
stuff that we know exist!

⇒ Determine whether a hypothetical particle is compatible with data!

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Questions

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Answers

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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?]

Image credit: QuantaMagazine

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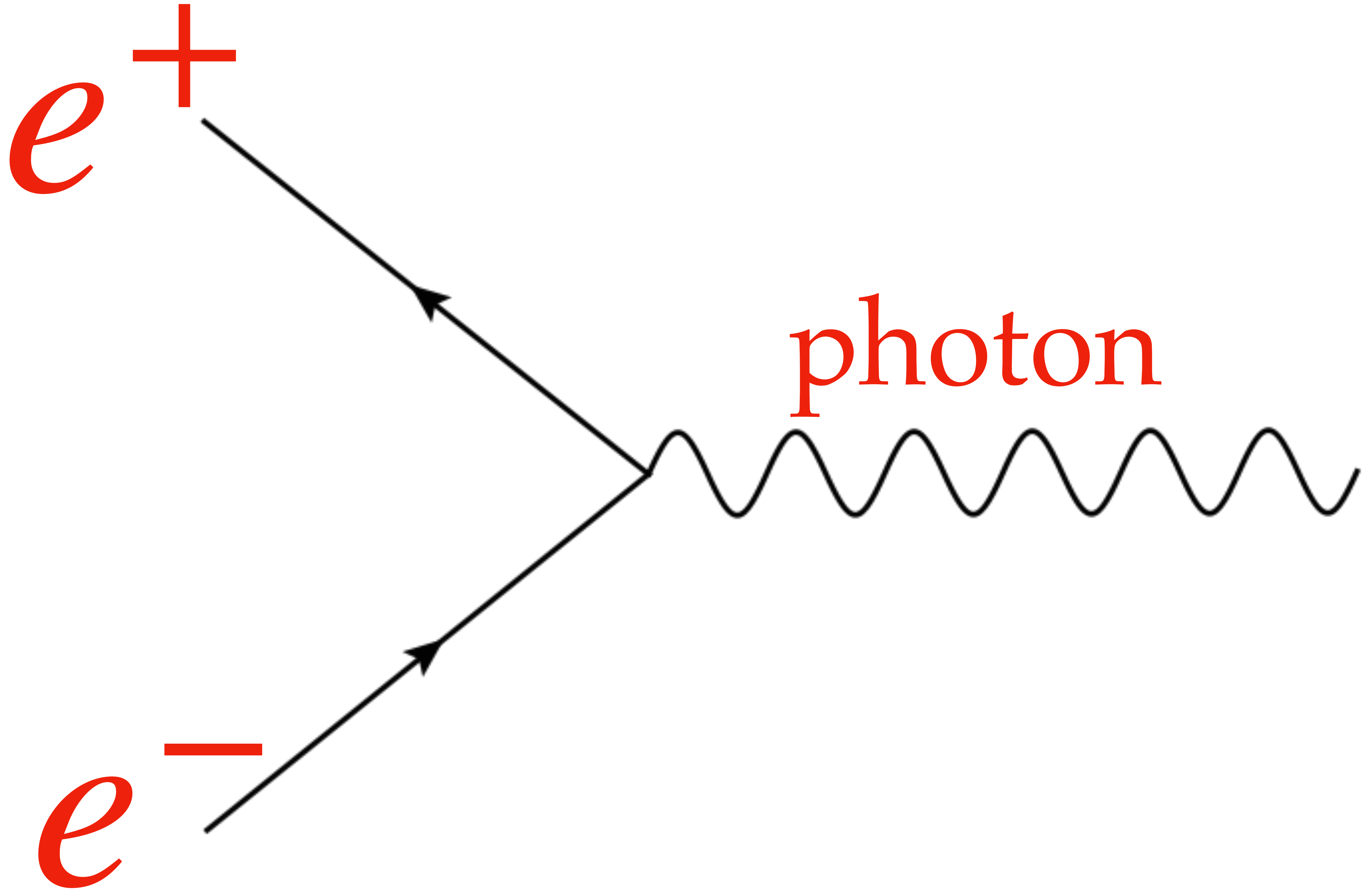

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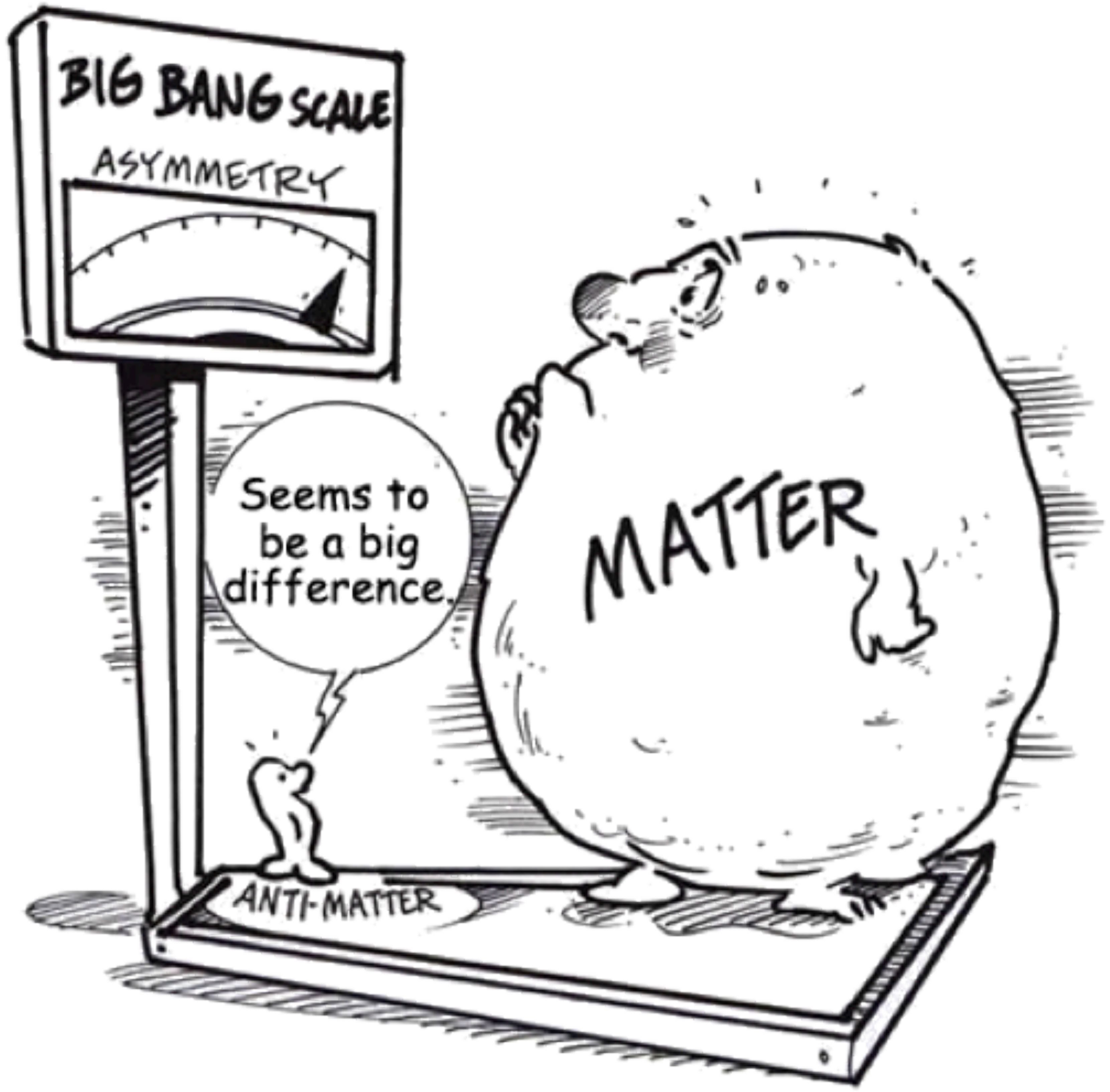

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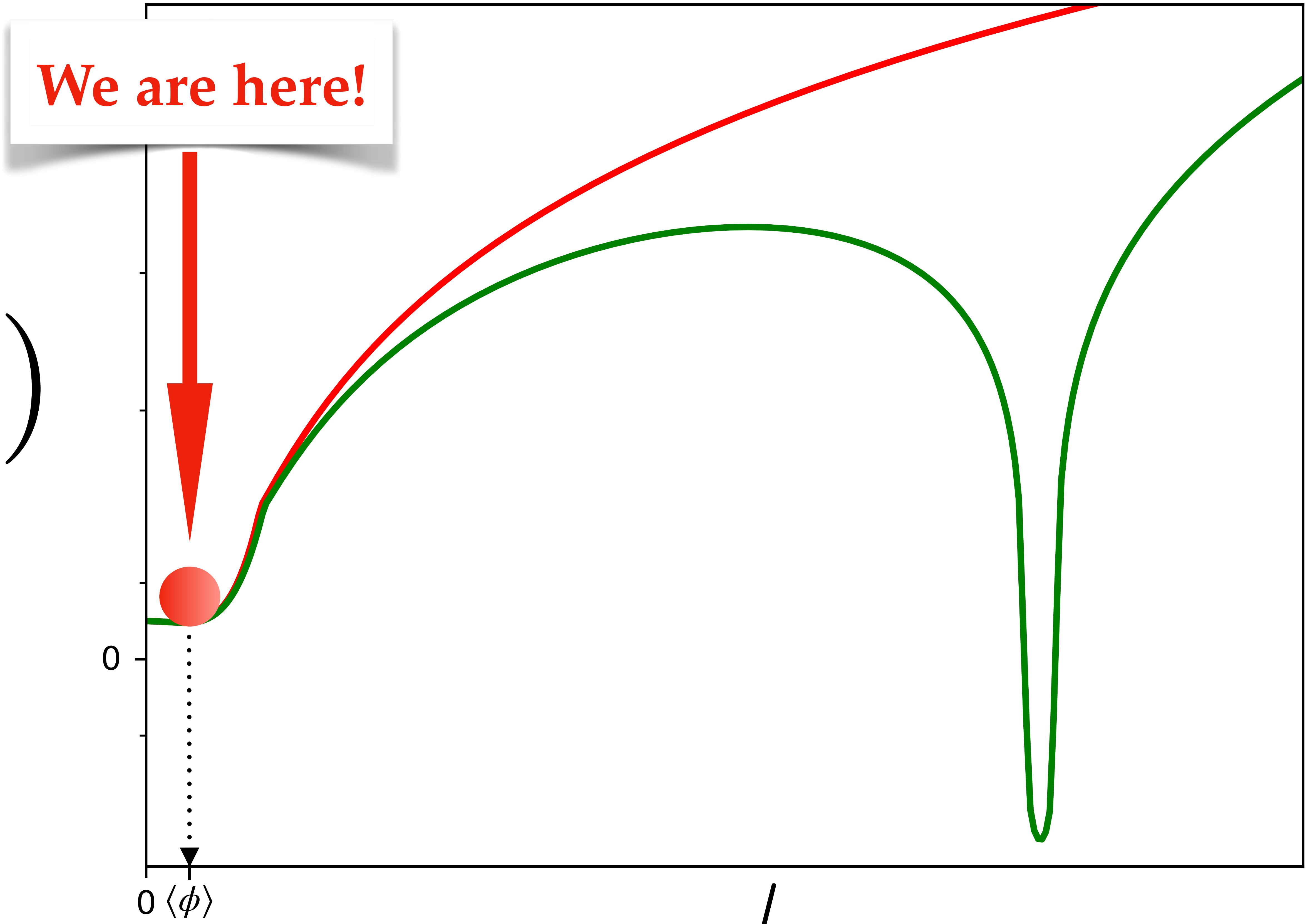
➜ the **"Matter-Anti-Matter Asymmetry"**.

Q: What is the ultimate fate of our Universe?

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



Higgs Field: ϕ

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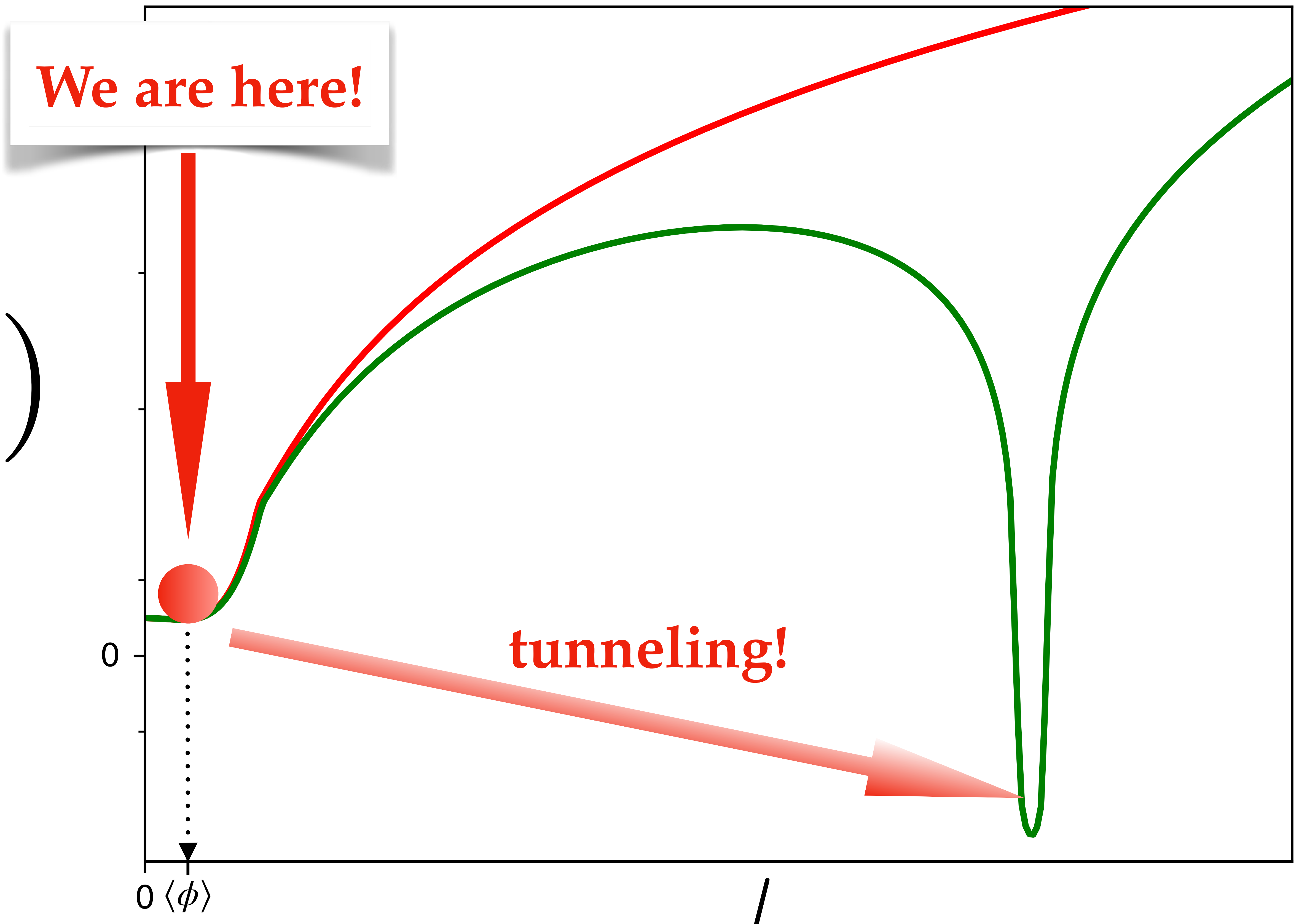

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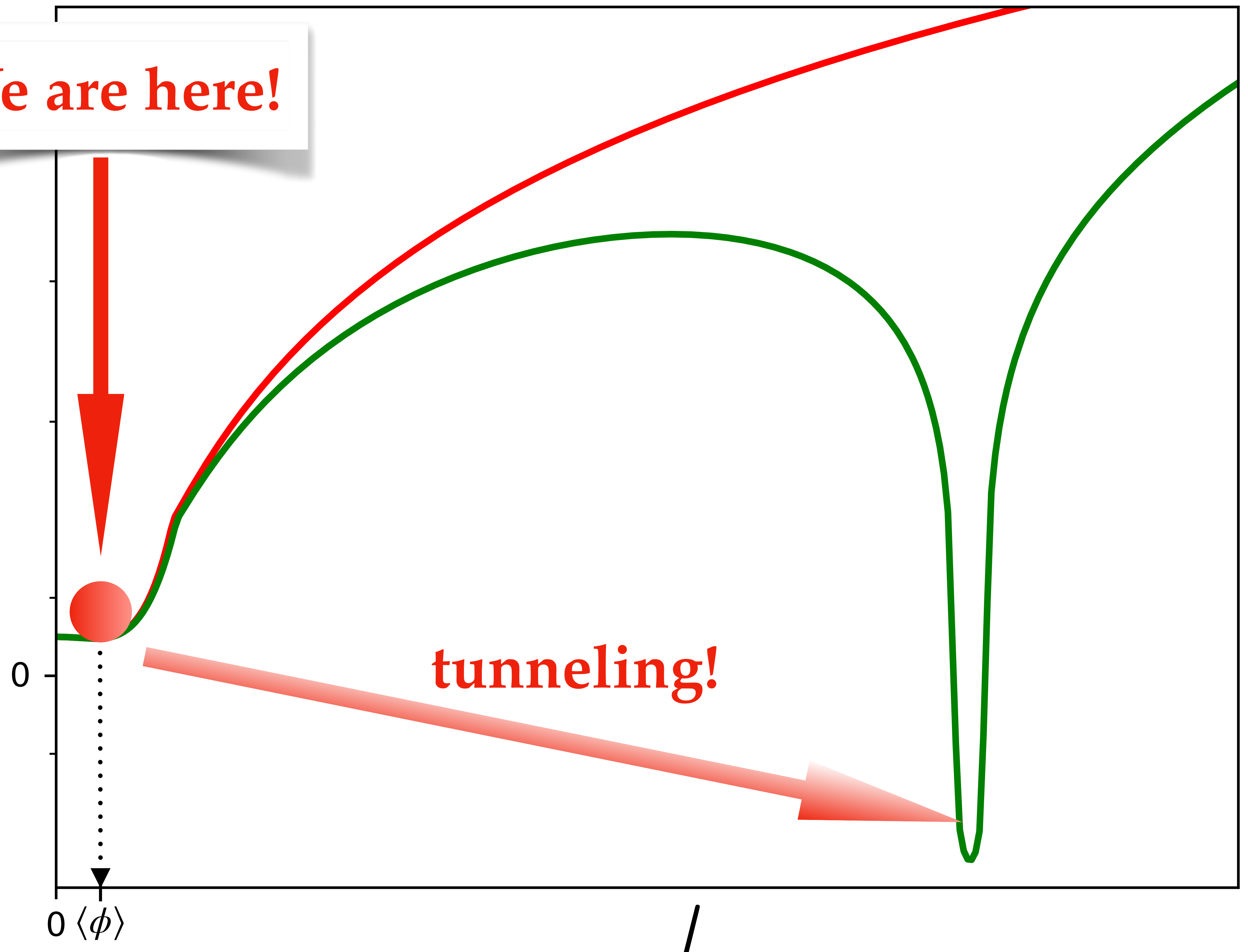

Higgs Field: ϕ

➜ the **"Vacuum Stability Problem"**.

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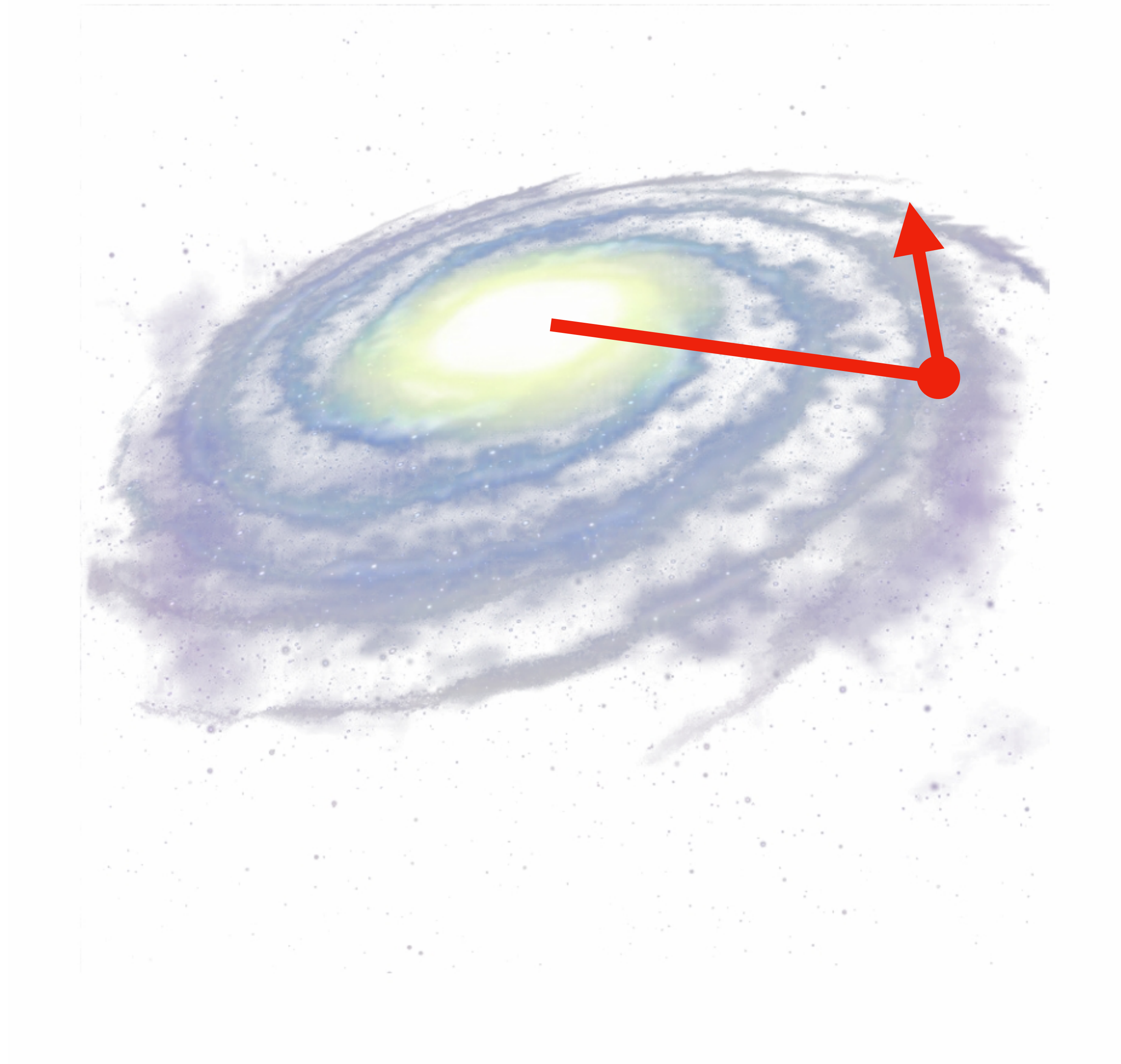
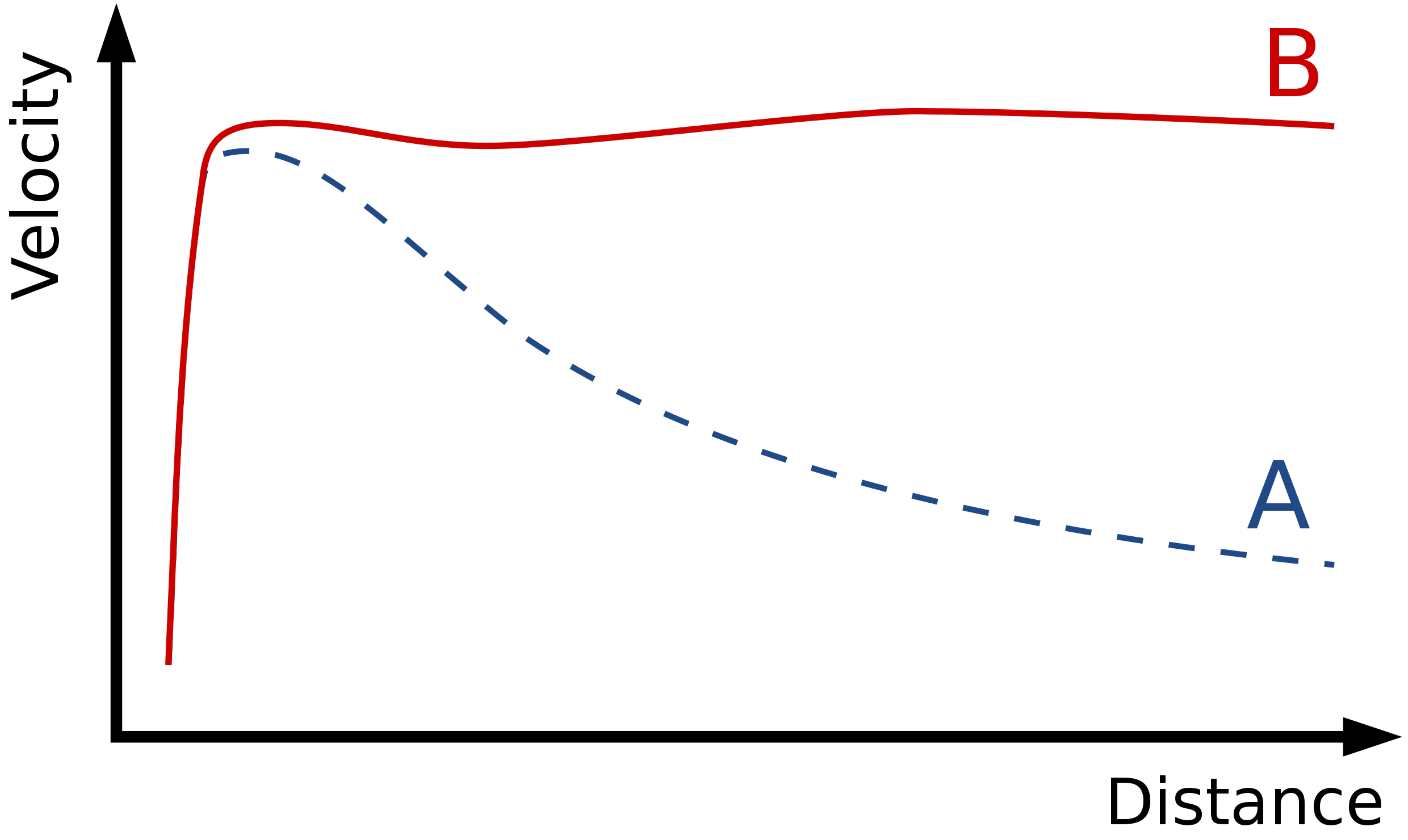
Q: What is the nature of Dark Matter?

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





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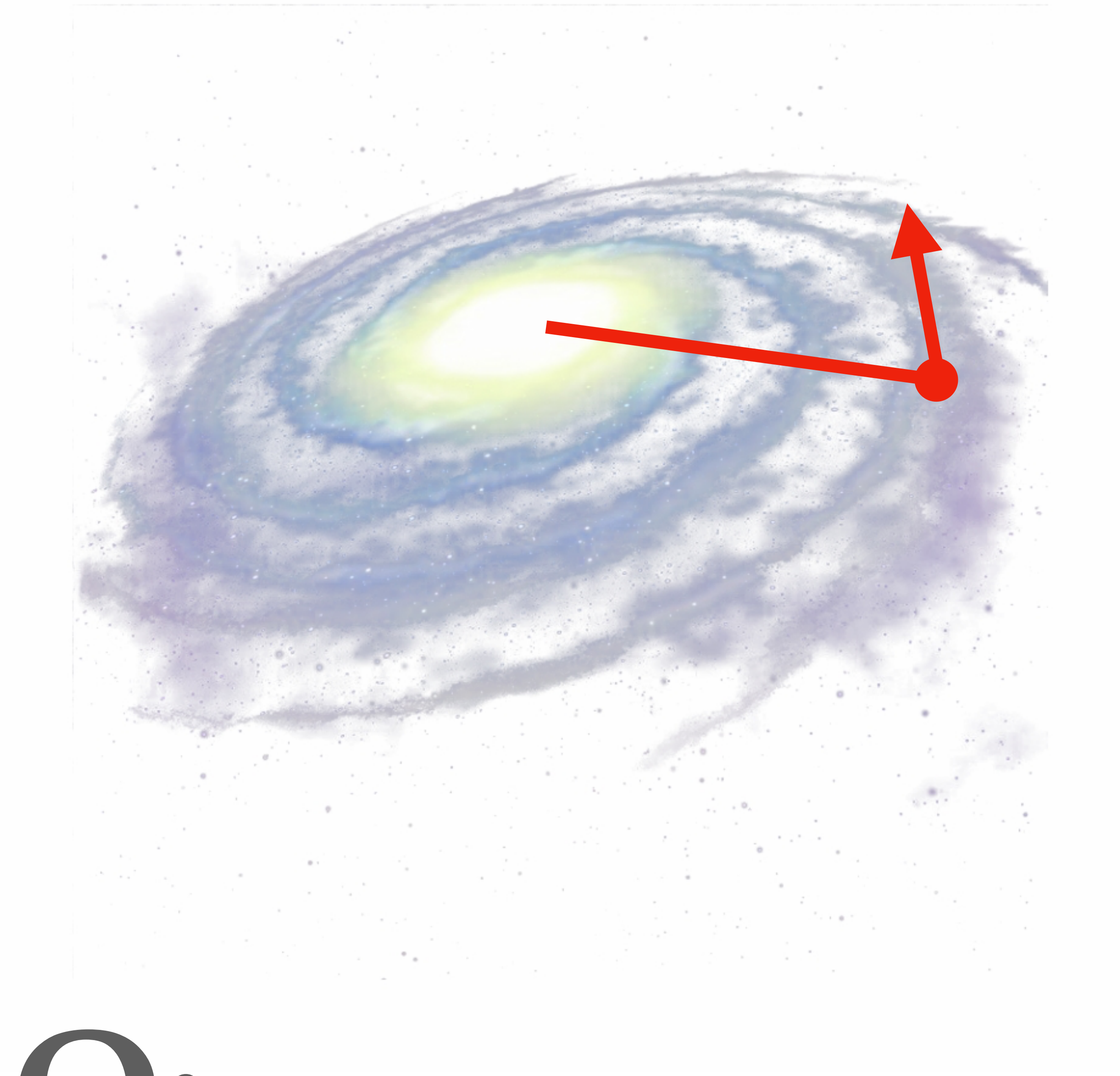

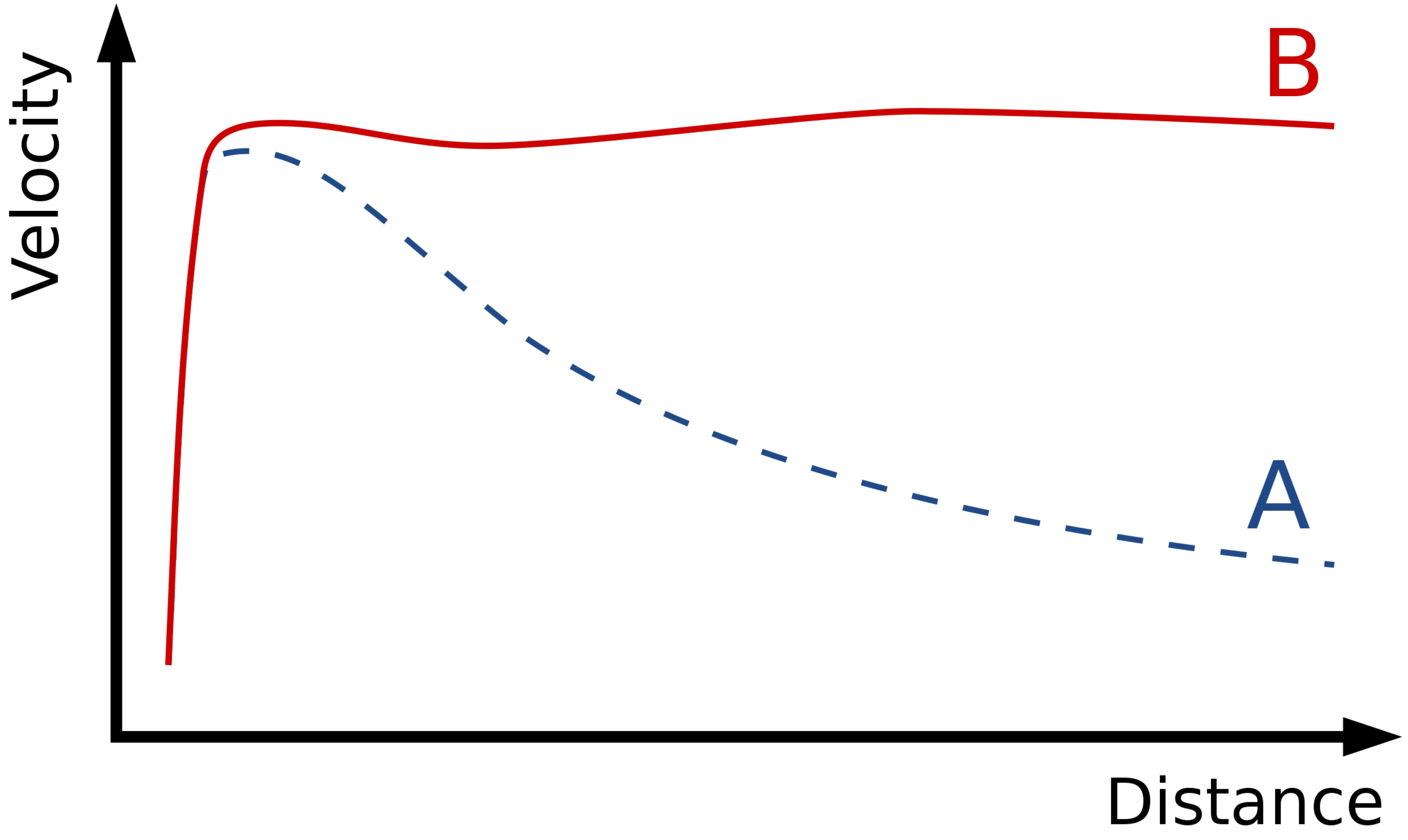

Q: ...

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Particle Colliders present us with a <u>unique</u> opportunity in the history of our species to comprehend the nature of matter and energy!

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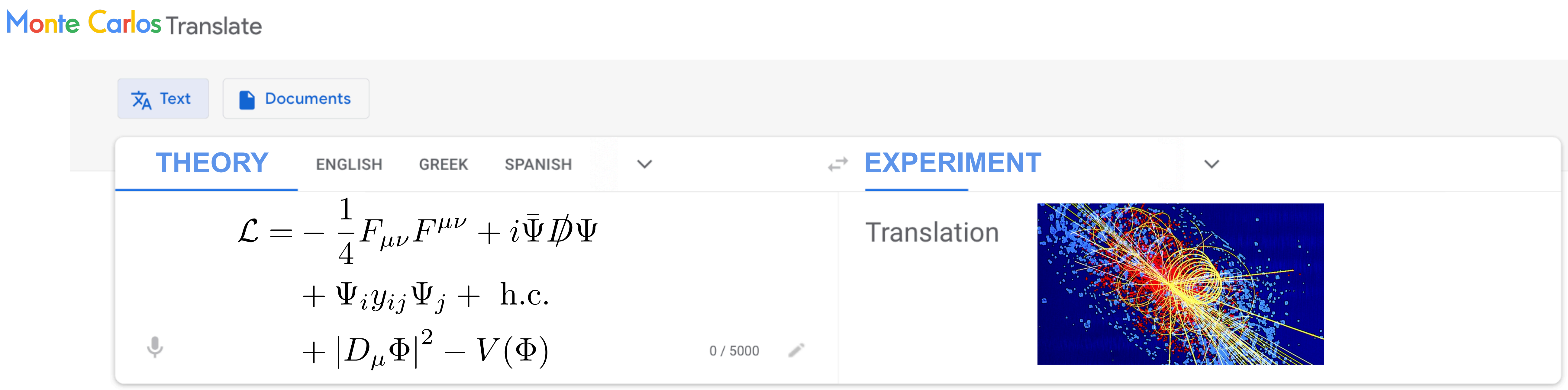
Particle Colliders present us with a <u>unique</u> opportunity in the history of our species to comprehend the nature of matter and energy!

Essential tools: Monte Carlo Simulations!

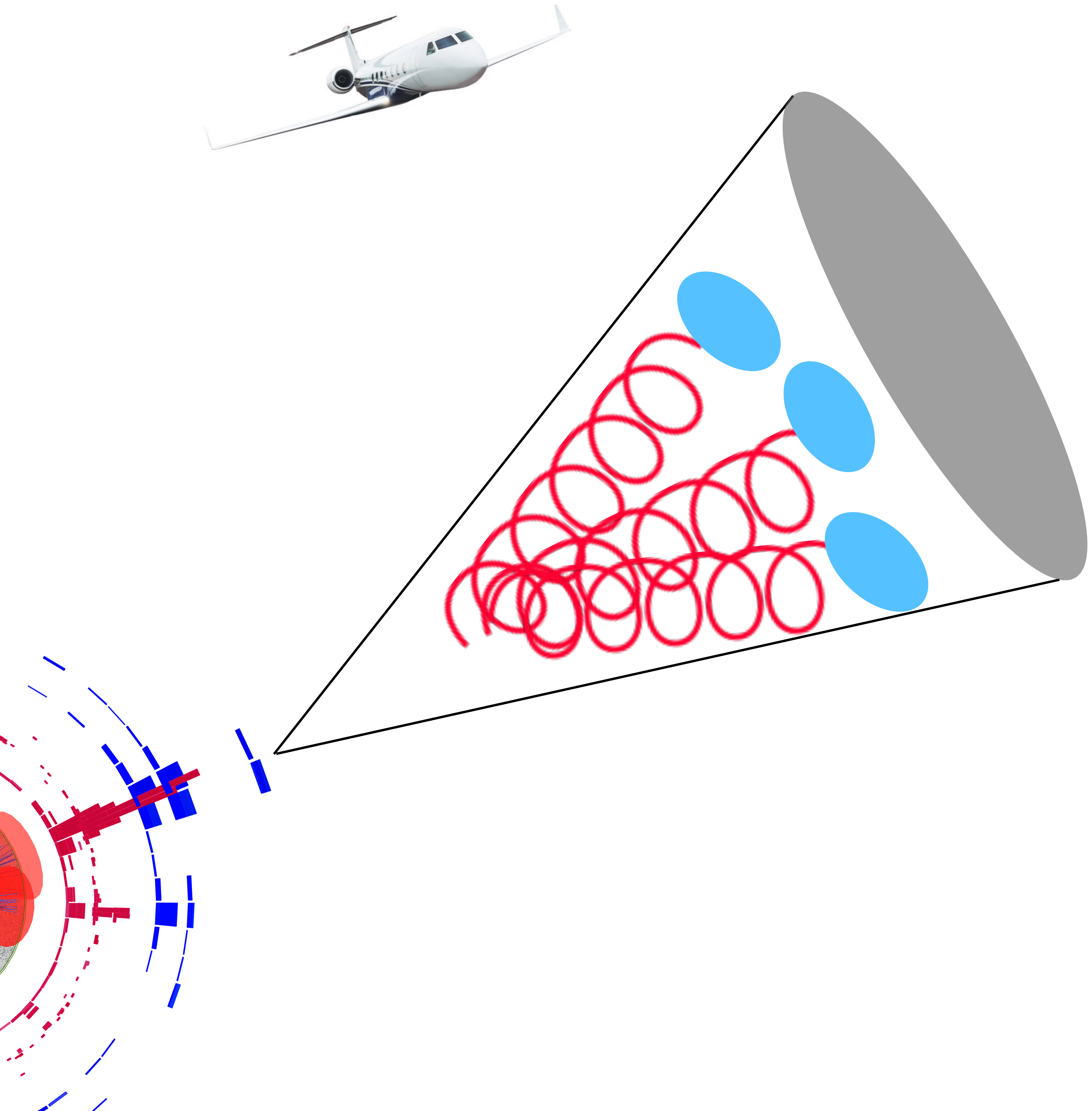


The best way to do science is through hands-on learning!

→ Through research experience that can bring you to the state of the art and address open-ended questions.

Example Research Projects!

Particle Jet Physics



A "Jet" of particles

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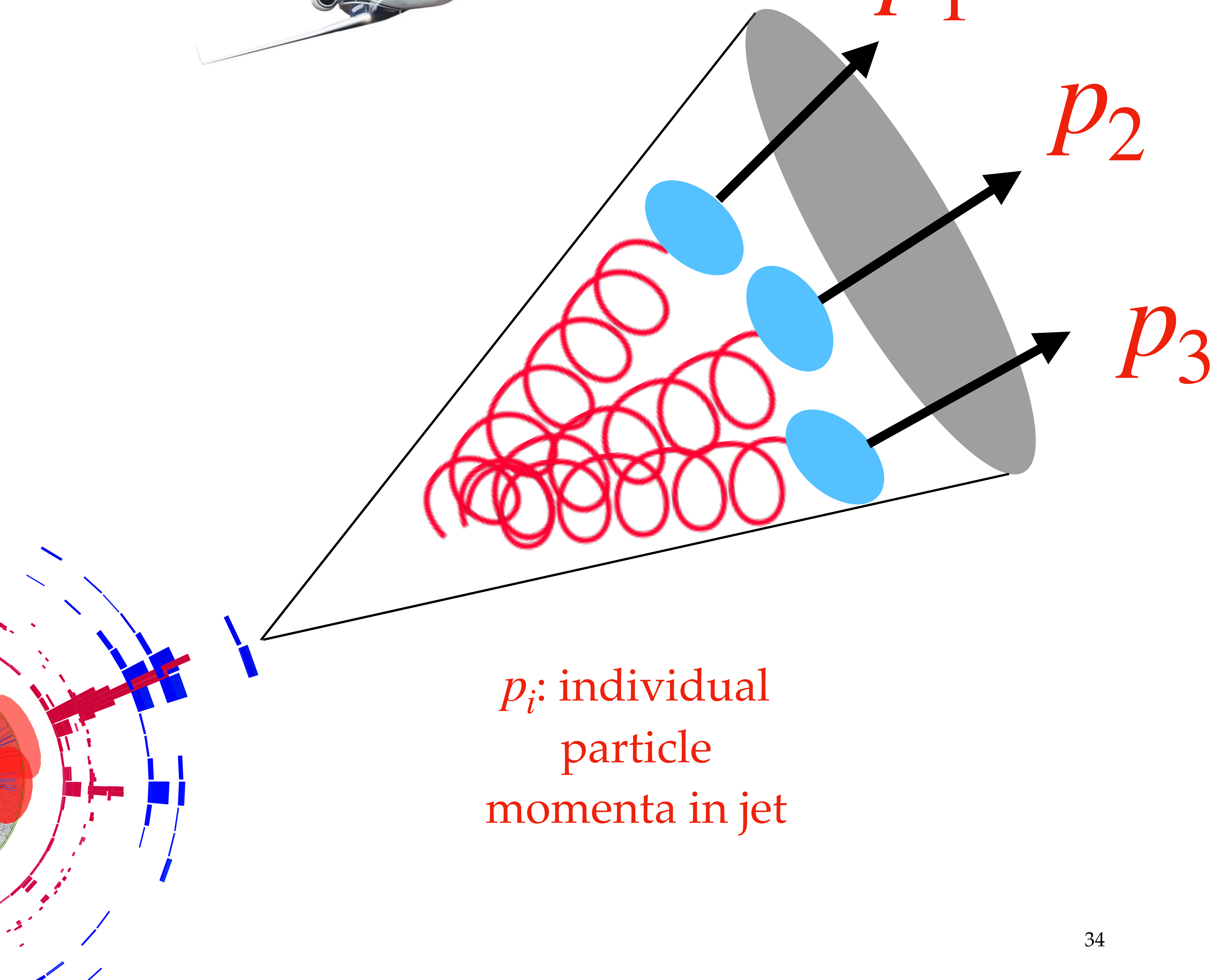
Particle Jet Physics



p_i: individual particle momenta in jet

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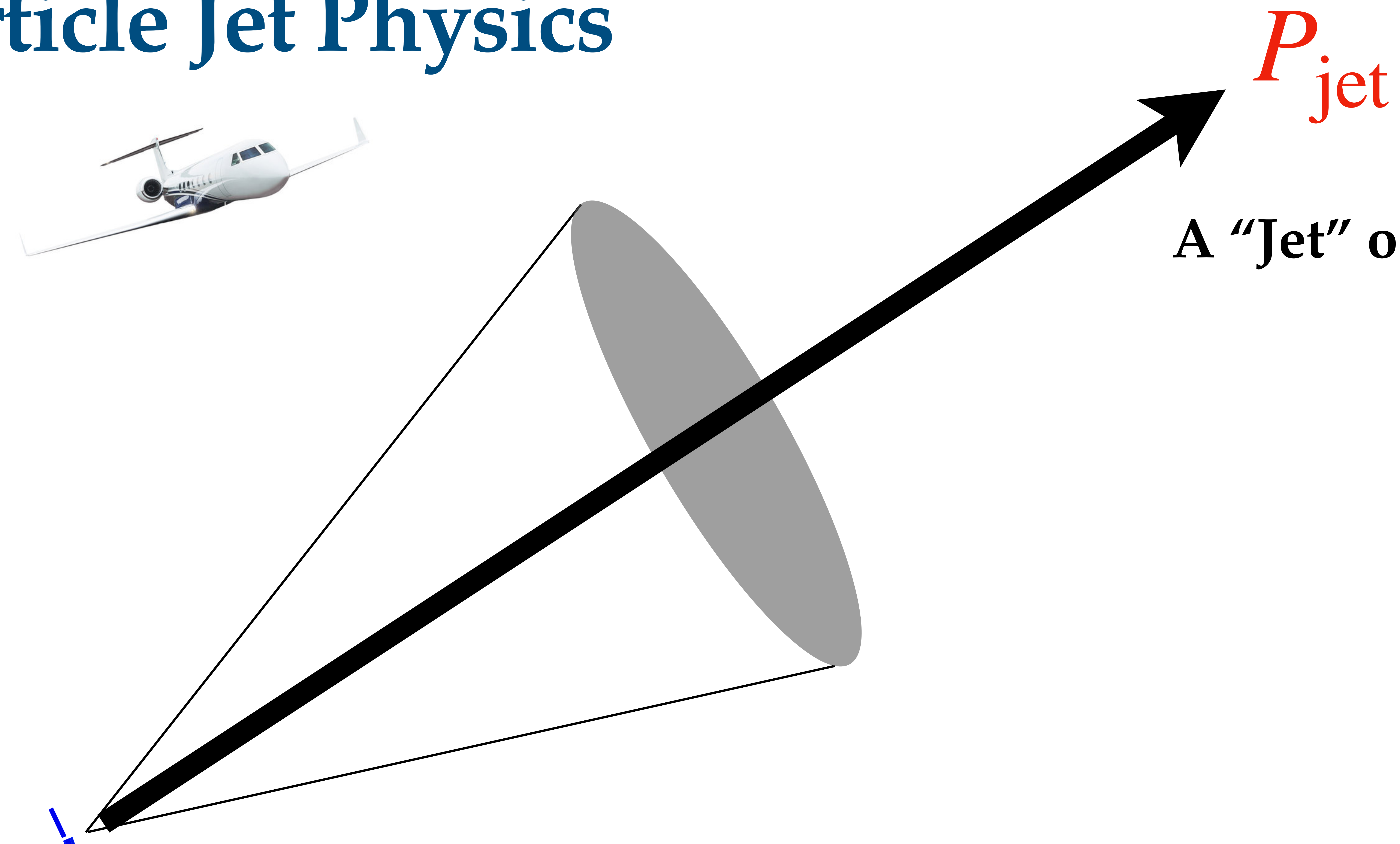

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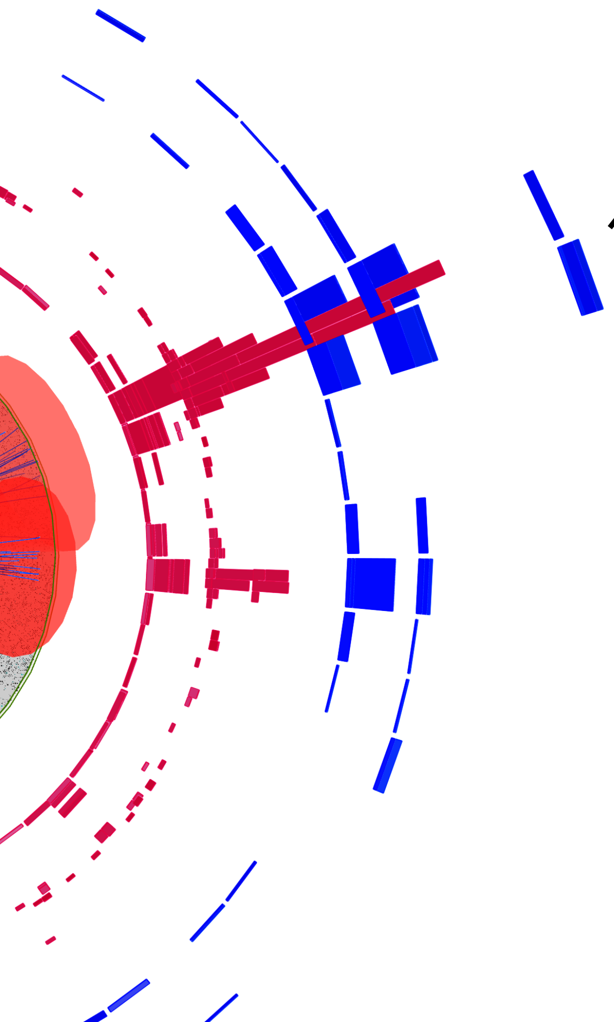

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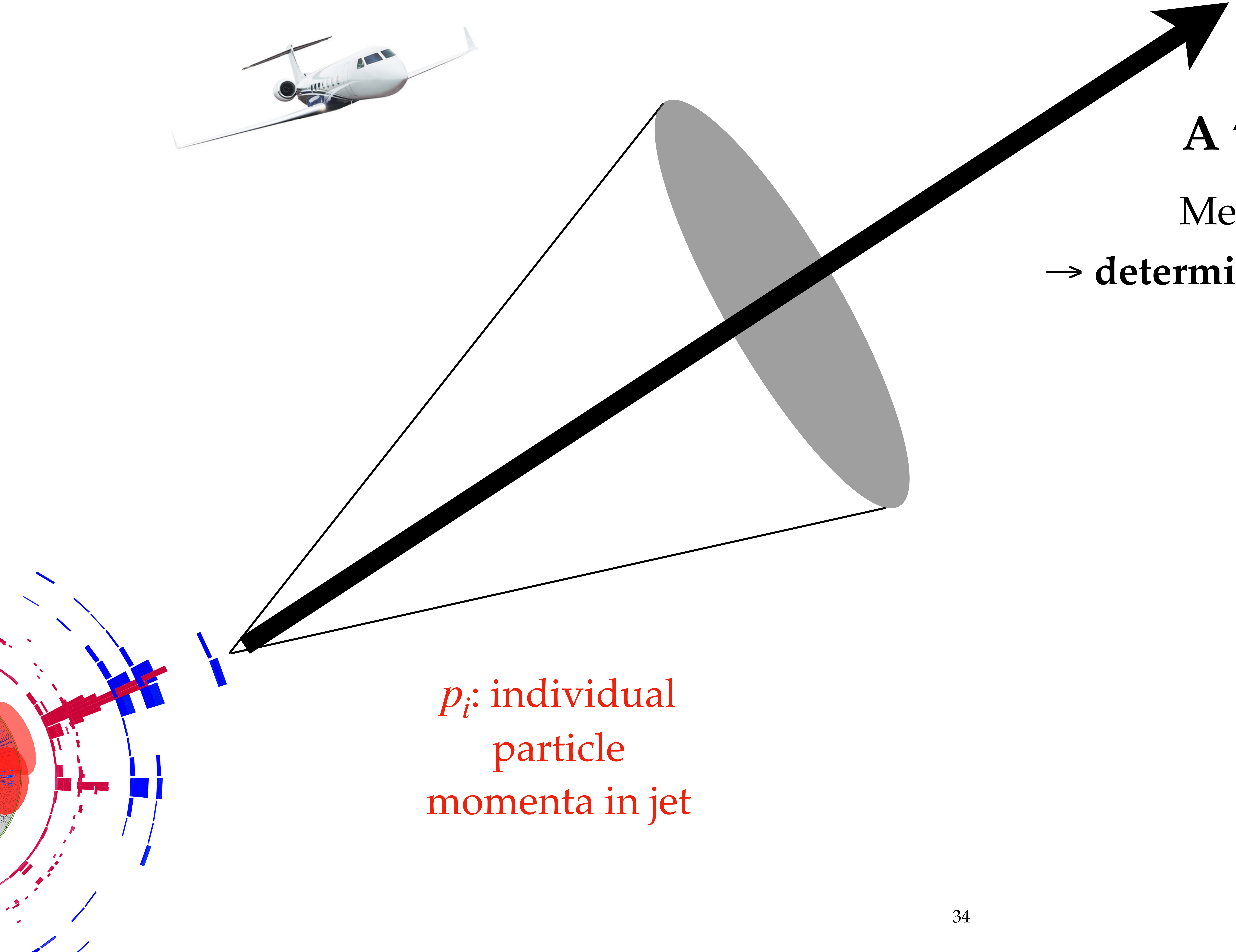

A "Jet" of particles

Method of combining p_i into P_{jet}

→ **determines sensitivity of a jet to "garbage".**

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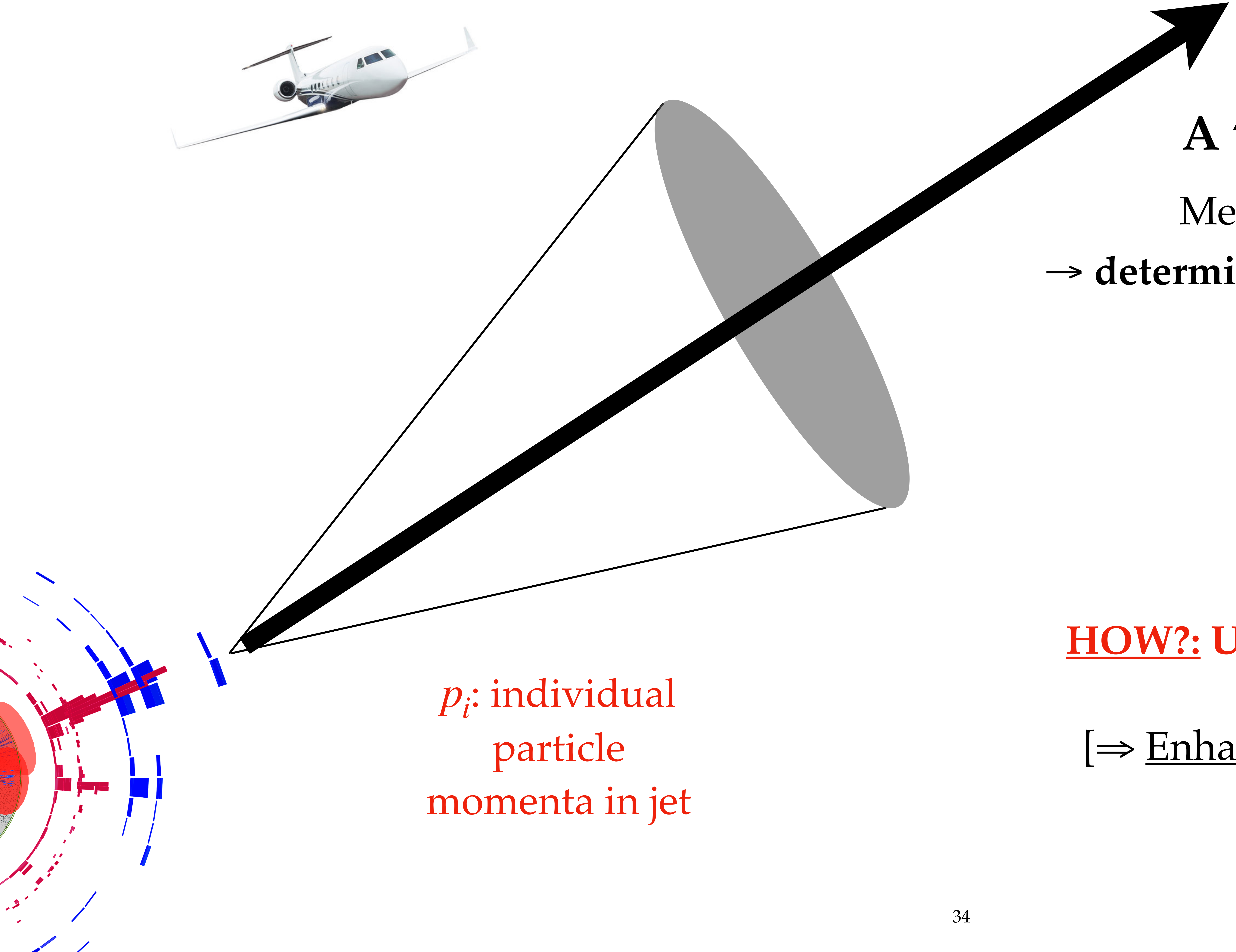
Particle Jet Physics



P_{jet}

A "Jet" of particles

Method of combining p_i into P_{jet}

→ **determines sensitivity of a jet to "garbage".**

p_i: individual particle momenta in jet

<u>HOW?:</u> Understand sensitivity <u>analytically/ numerically.</u>

[⇒ <u>Enhance searches for new phenomena!</u>]

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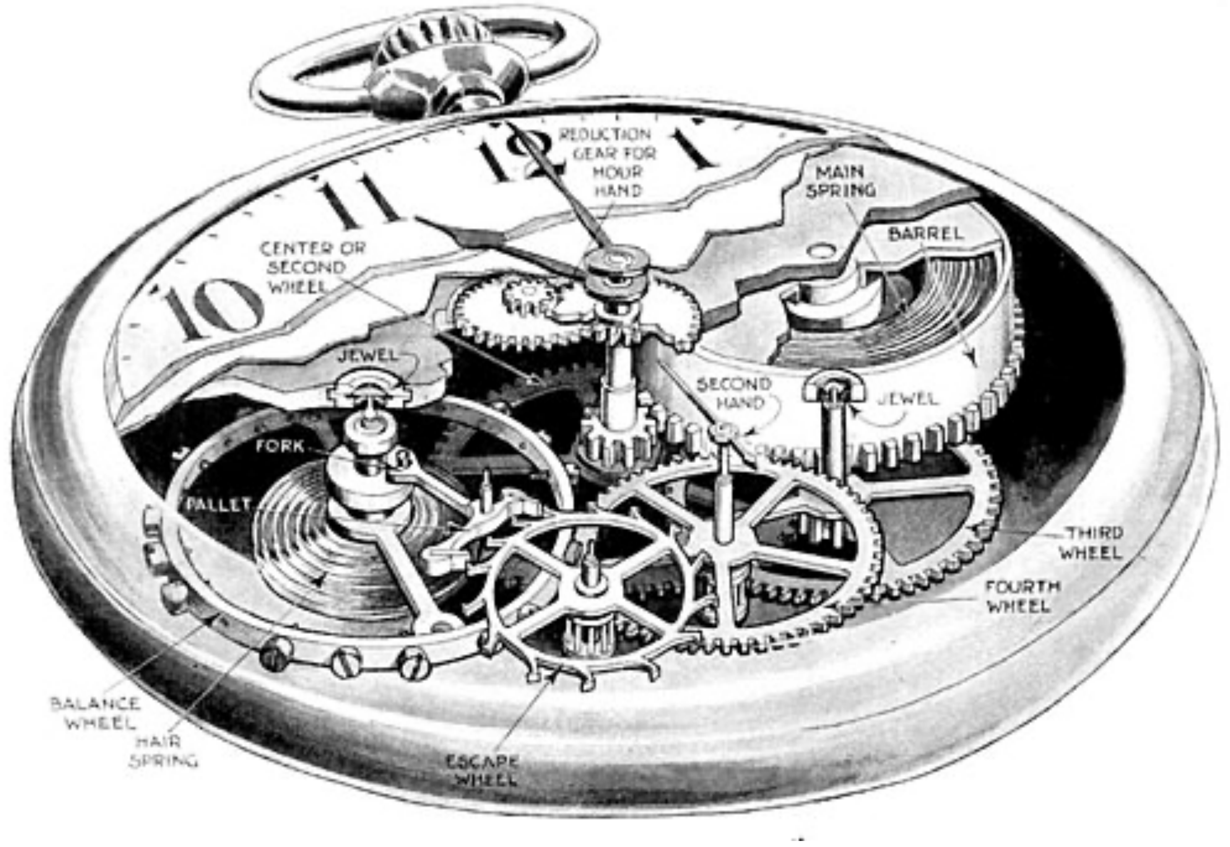
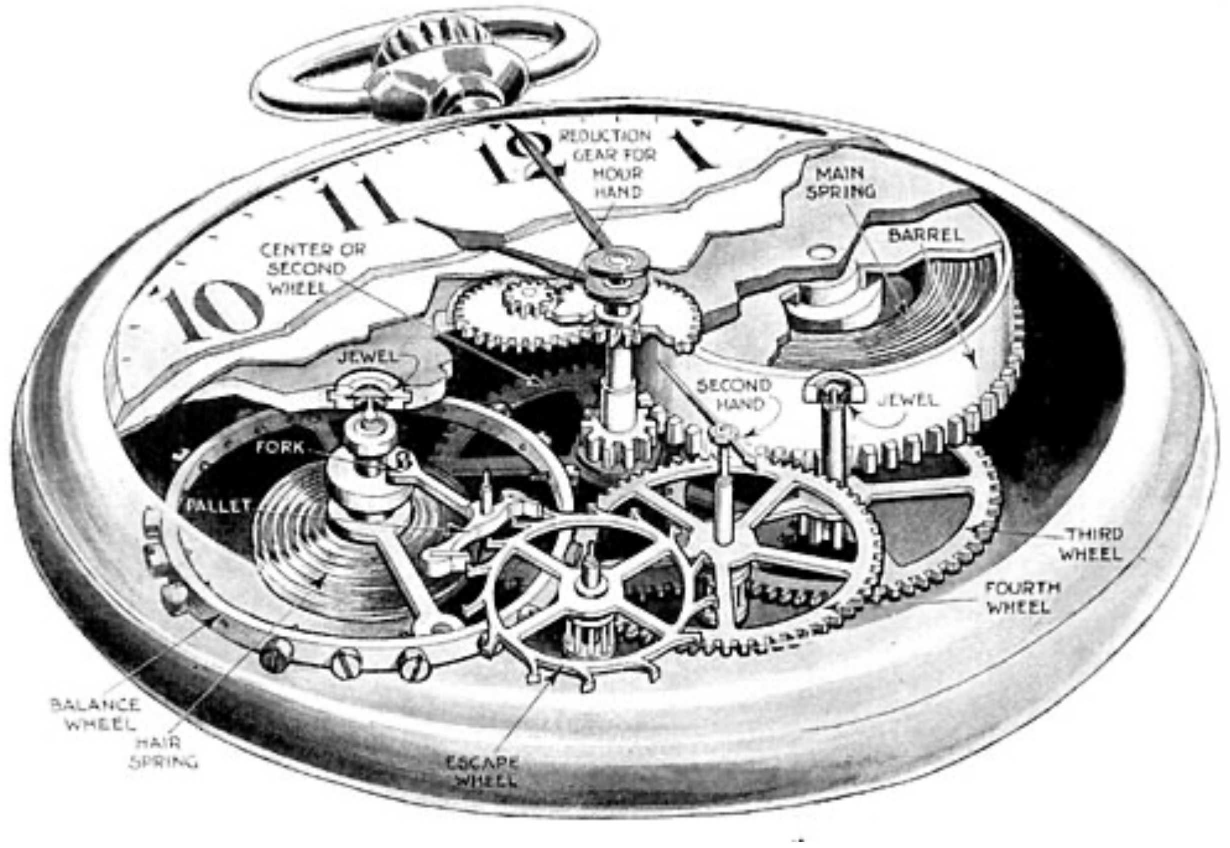
Particle Physics Simulations



- e.g.: Constructing Monte Carlo Event Generators.
  - ➡ What makes them tick?
  - ➡ **HOW? You can code your own, from scratch!**
  - ➡ e.g. https://arxiv.org/abs/1412.4677 & https://cern.ch/apapaefs/mchowto.html.
  - ➡ & https://gitlab.com/apapaefs/pyresias.
  - ➡ **HOW? Code visualizations of realistic particle collisions!**

Particle Physics Simulations



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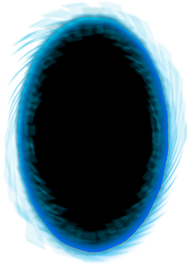
$$\mathcal{V}(\phi, S) = \bullet\, |\phi|^2 + \blacksquare\, |\phi|^4$$

$$+\bullet S^2 + \blacktriangle S^3 + \blacksquare S^4$$



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

$$+S \times (\text{Hidden Sector}) + \ldots$$

New Scalar Particles

- e.g.: Searching for **new** Higgs bosons at colliders!
  - ➡ The Higgs boson (discovered at the CERN LHC in 2012) is the **only fundamental** scalar particle that we know of!
  - ➡ **Are there more?**
  - ➡ What would their existence mean?
  - ➡ What is the potential of the LHC to detect them and to understand them?
  - ➡ **HOW? Use computational techniques of Monte Carlo Event Generators & Machine Learning.**

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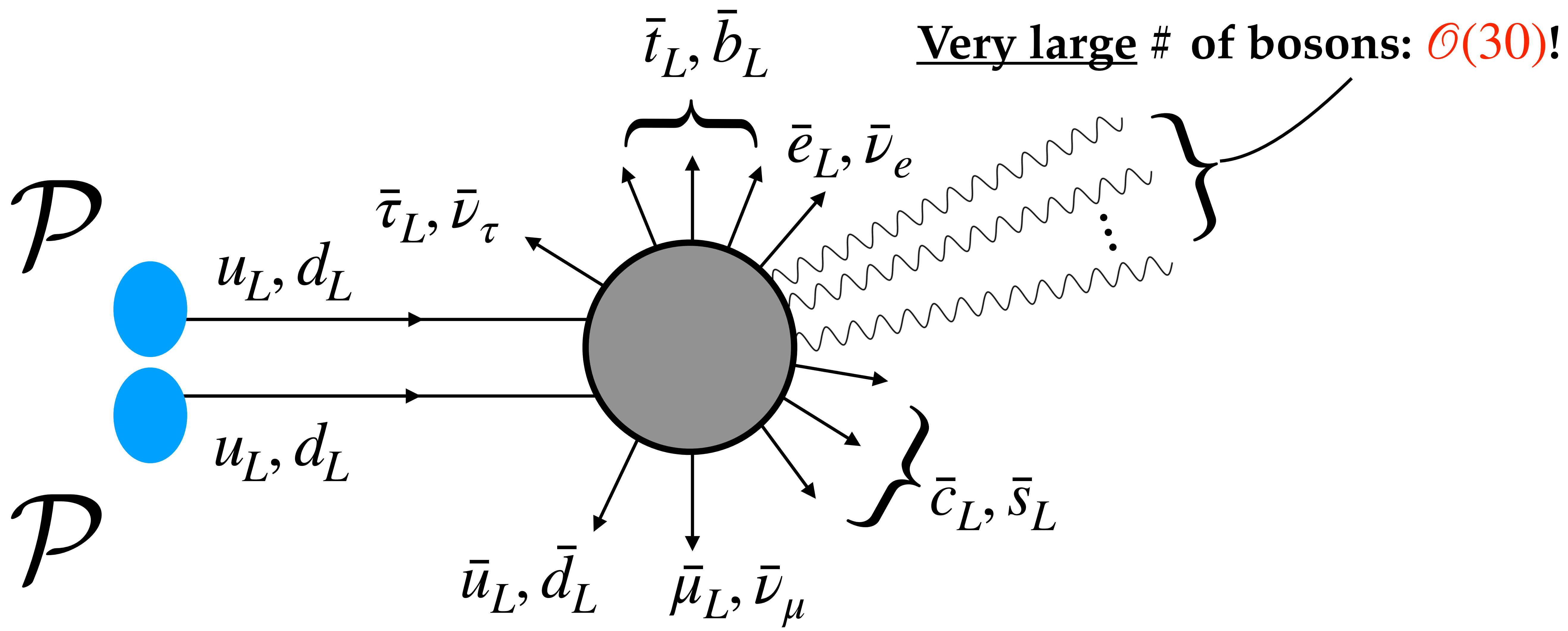
More Exotic Phenomena

✴ **Non-perturbative SM topological processes:**

Electro-Weak Sphalerons & QCD Instantons.

➡ **HOW? Use computational techniques of Monte Carlo Event Generators & Machine Learning**

➡ **or analytical techniques to understand these processes.**



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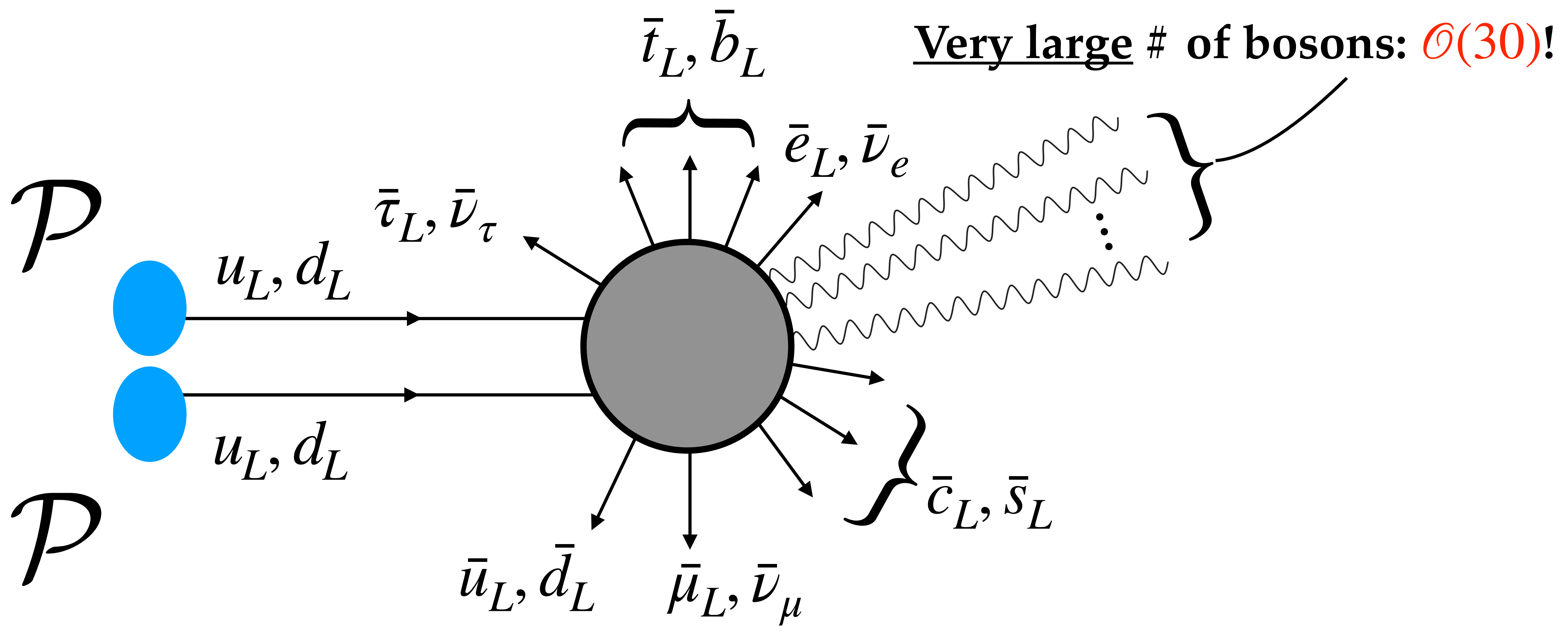

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KENNESAW STATE UNIVERSITY

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Office: Academic Building (H), Office 260I, Marietta Campus.

- National Science Foundation (NSF) funding available:
  - "Deciphering Electro-Weak Scale Physics at Particle Colliders", since August 1st 2022.
- You can contact me **via e-mail** at apapaefs@kennesaw.edu!

Find these slides at:

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Thanks! Questions?

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