Quark Colors and R-Value

2025 Belle II International masterclass

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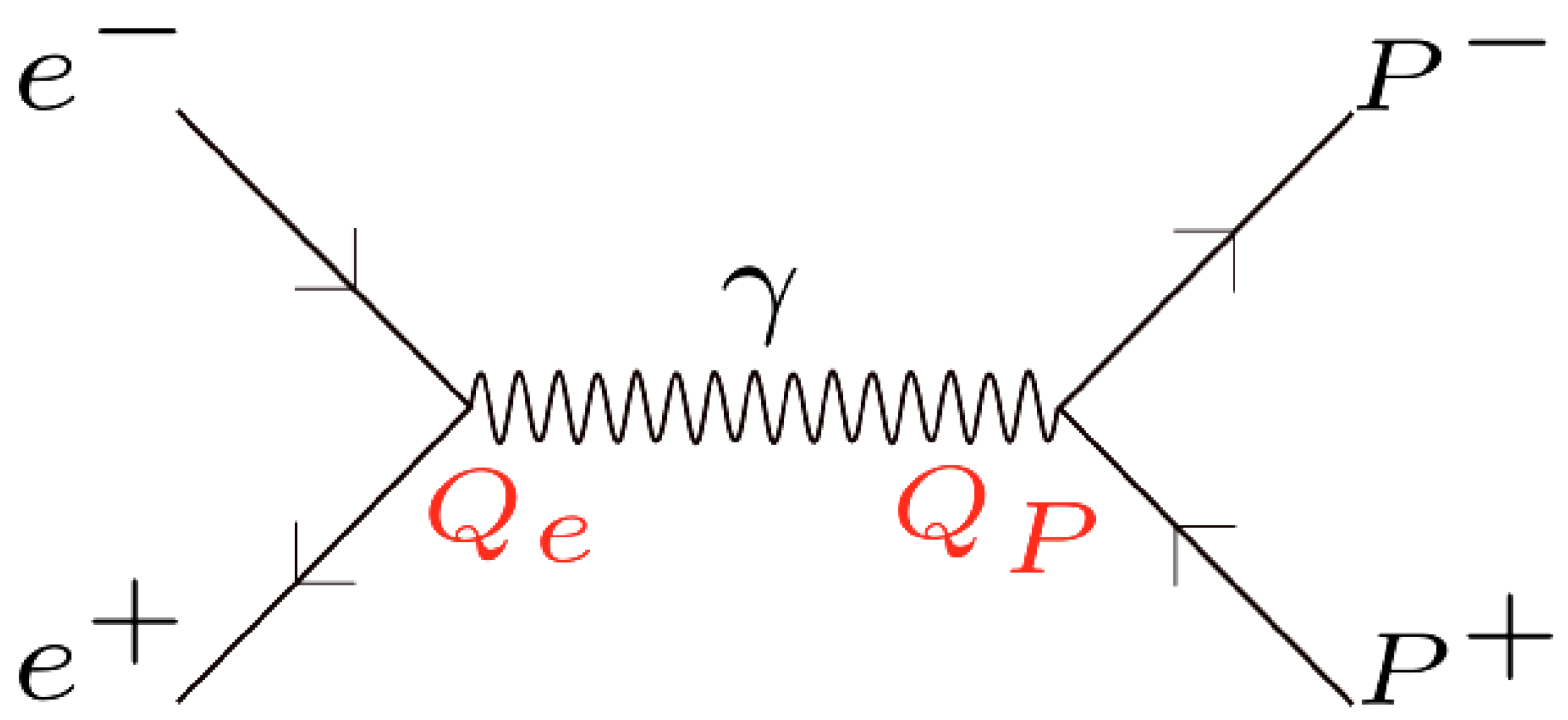
Bonn

INTERNATIONAL MASTERCLASSES hands on particle physics
International Particle Physics Outreach Group
UNIVERSITÄT BONN
BLUB
Belle II

e^+e^- interactions

- In the e^+e^- collision the electron and the positron interact exchanging a photon

- Then they produce a particle P^+ and an anti-particle P^-

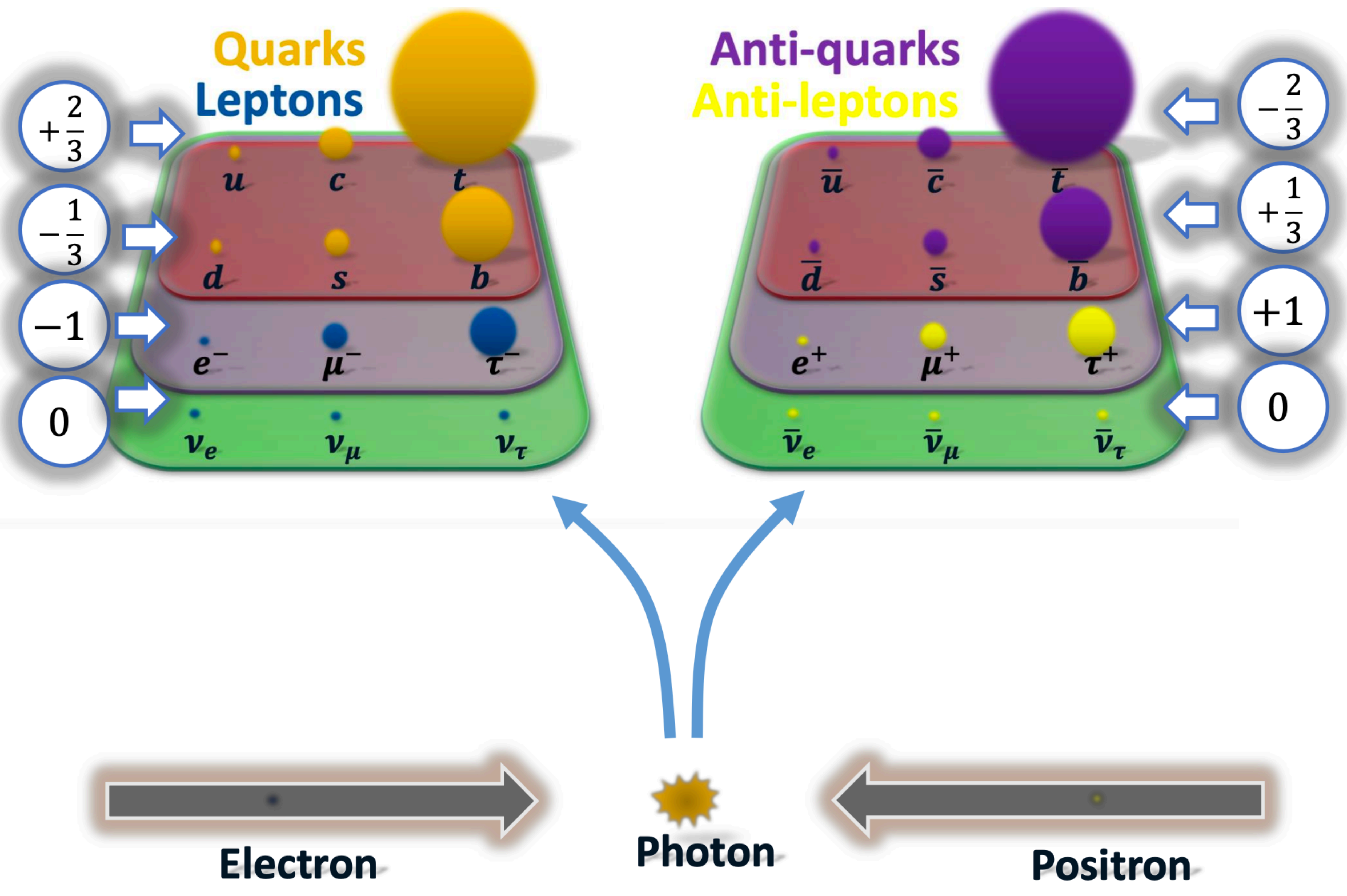


- The probability of the interaction is proportional to che charge of P squared:

$$N(e^+e^- \to \gamma \to P^+P^-) = Q_P^2 \cdot XY$$

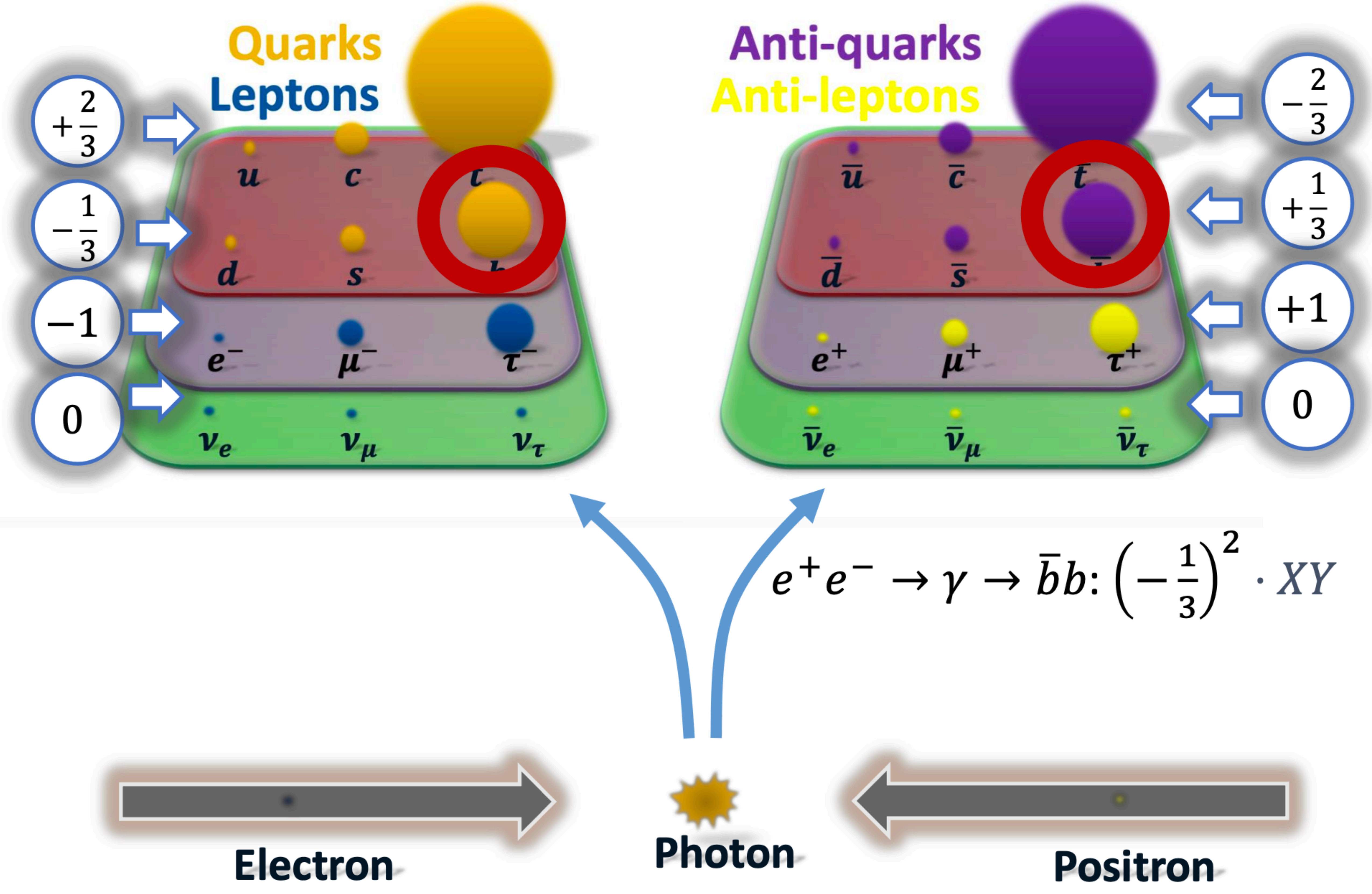
e^+e^- interactions: some examples

This is the full set of charges:



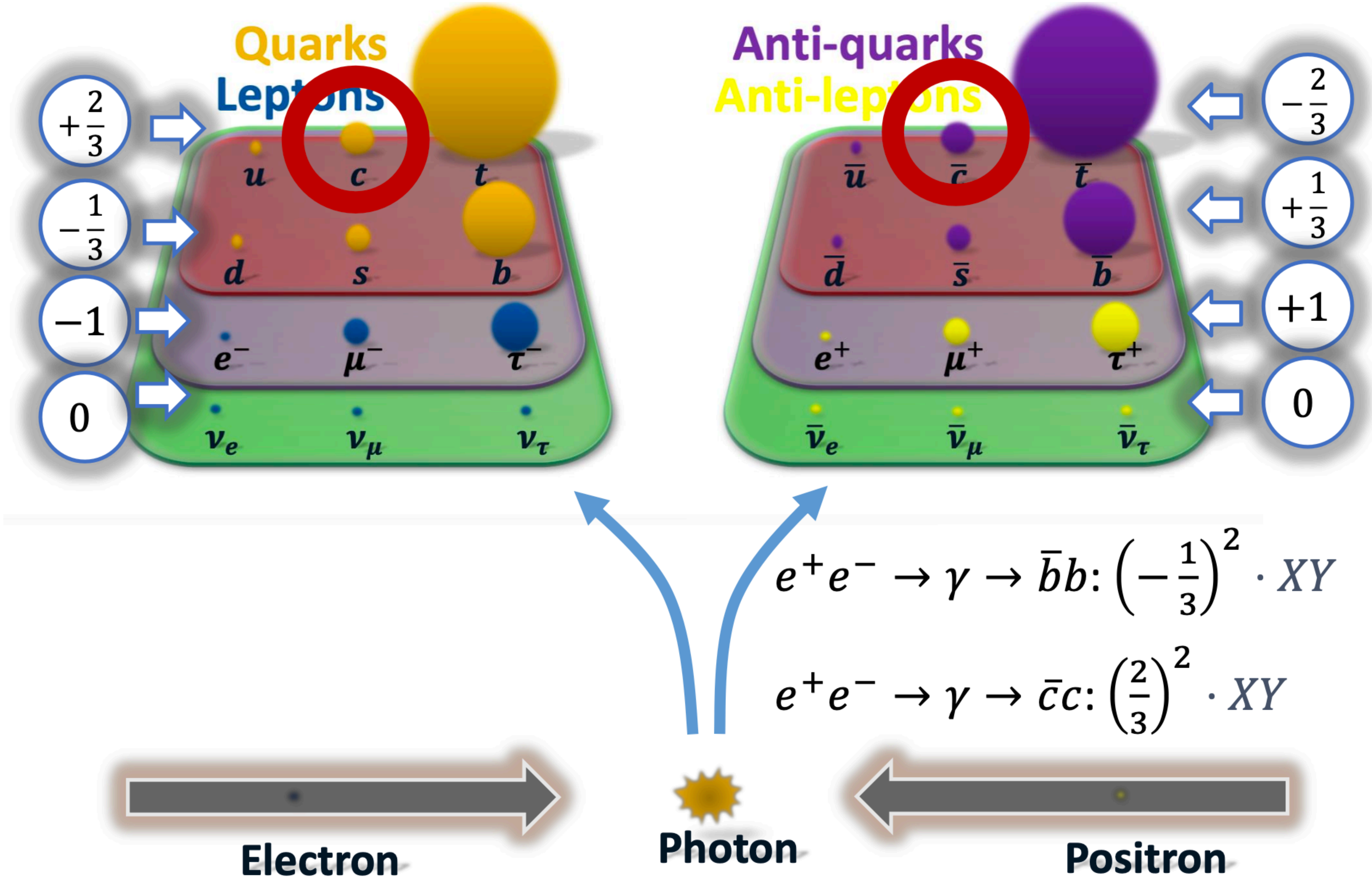
e^+e^- interactions: some examples

- $b\bar{b}$ quarks production



e^+e^- interactions: some examples

- $b\bar{b}$ quarks production
- $c\bar{c}$ production

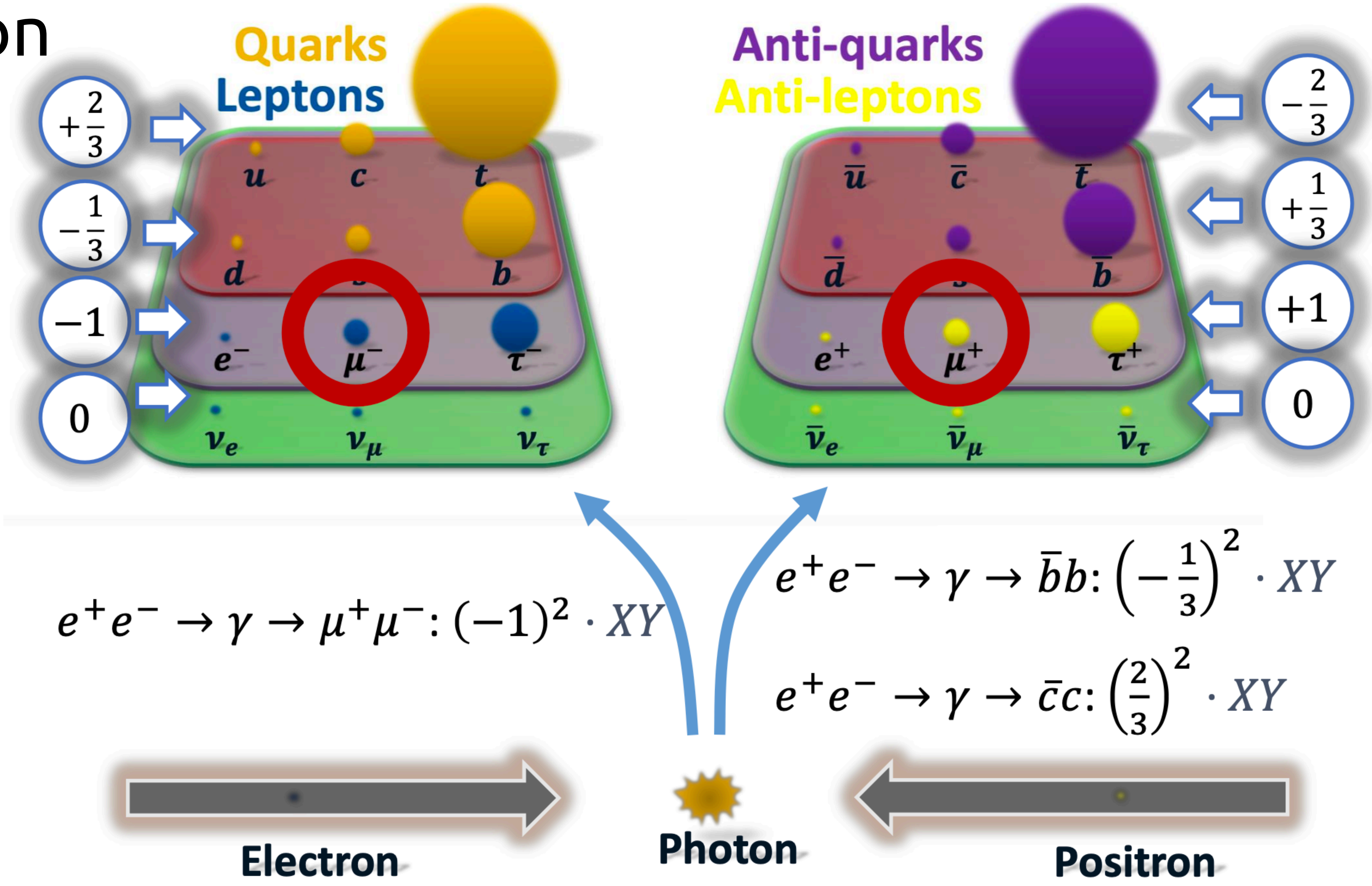


$$e^+e^- \to \gamma \to \bar{b}b: \left(-\frac{1}{3}\right)^2 \cdot XY$$

$$e^+e^- \to \gamma \to \bar{c}c: \left(\frac{2}{3}\right)^2 \cdot XY$$

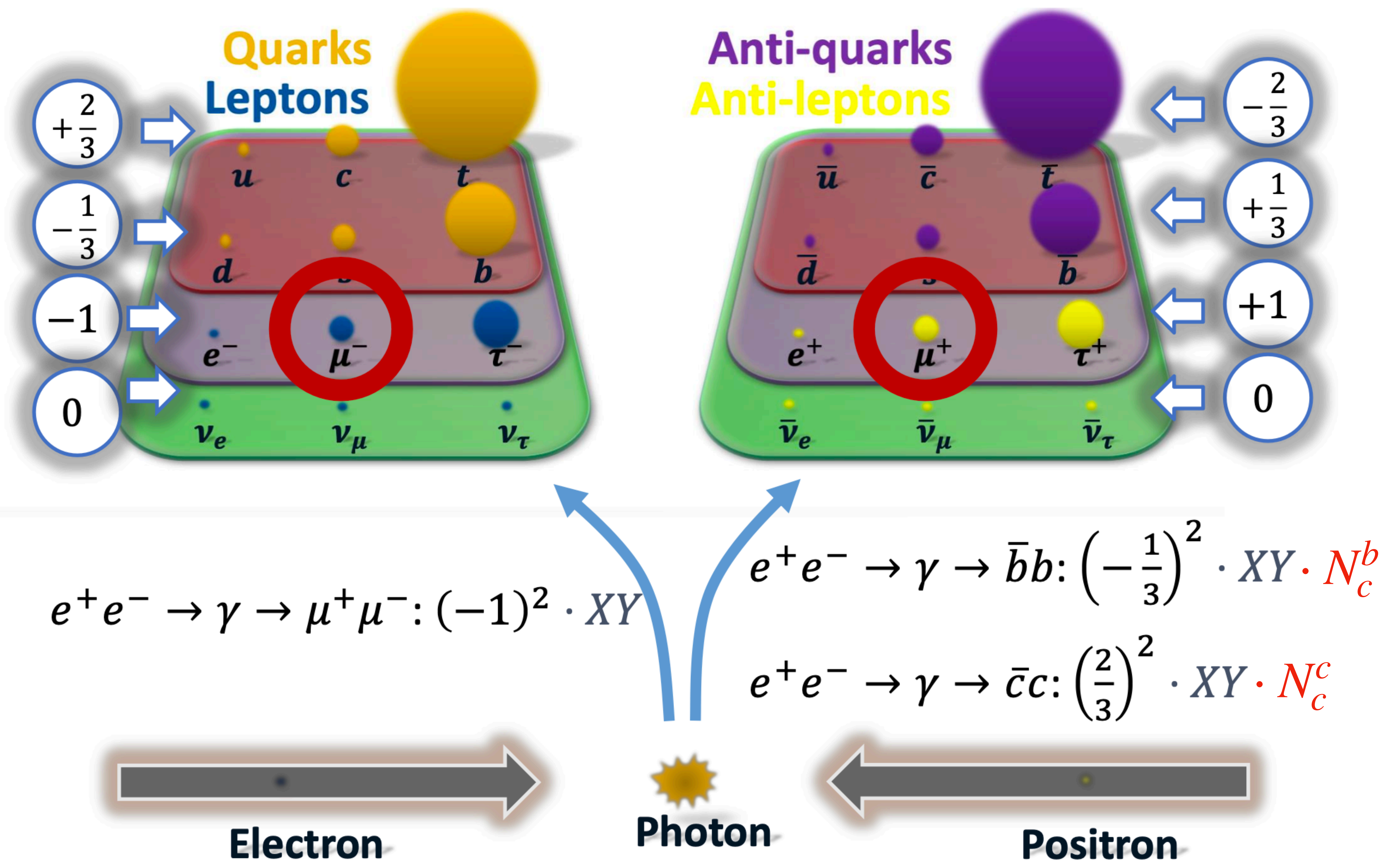
e^+e^- interactions: some examples

- $b\bar{b}$ quarks production
- $c\bar{c}$ production
- $\mu^+\mu^-$ production



Introducing COLORS

- $N(e^+e^- \rightarrow \gamma \rightarrow P^+P^-) = Q_P^2 \cdot XY \cdot N_c^P$
- N_c^P is the number of colors of the particle P



R-Value

- We define: $R = \dfrac{N(e^+e^- \to \gamma \to \text{light quarks})}{\frac{1}{2}[N(e^+e^- \to \gamma \to \mu^+\mu^-) + N(e^+e^- \to \gamma \to \tau^+\tau^-)]}$

R-Value

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- Substituting all the charges from previous slides $R = \dfrac{10}{9}N_c$

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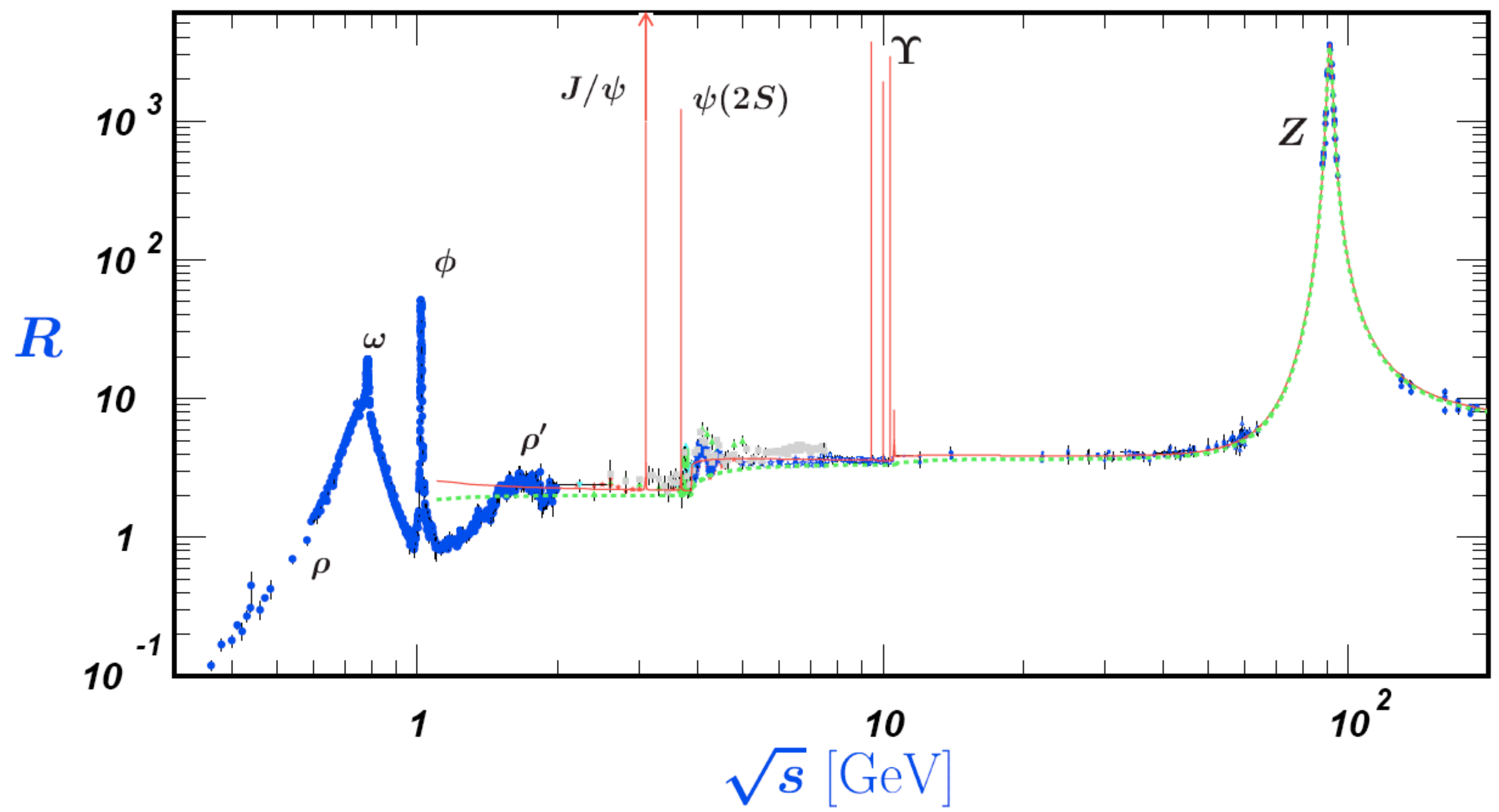
- From real measurements:



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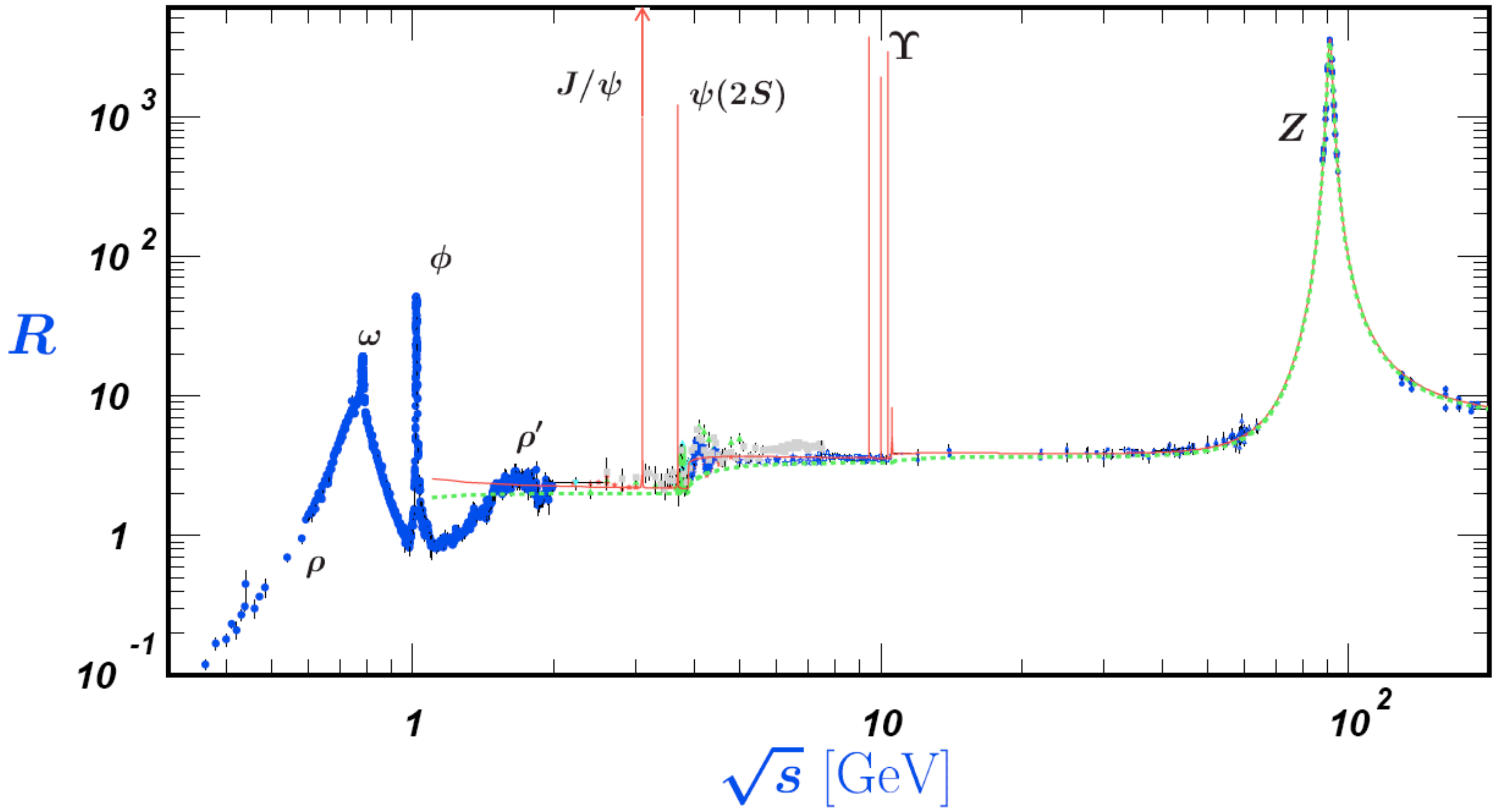
- From real measurements:

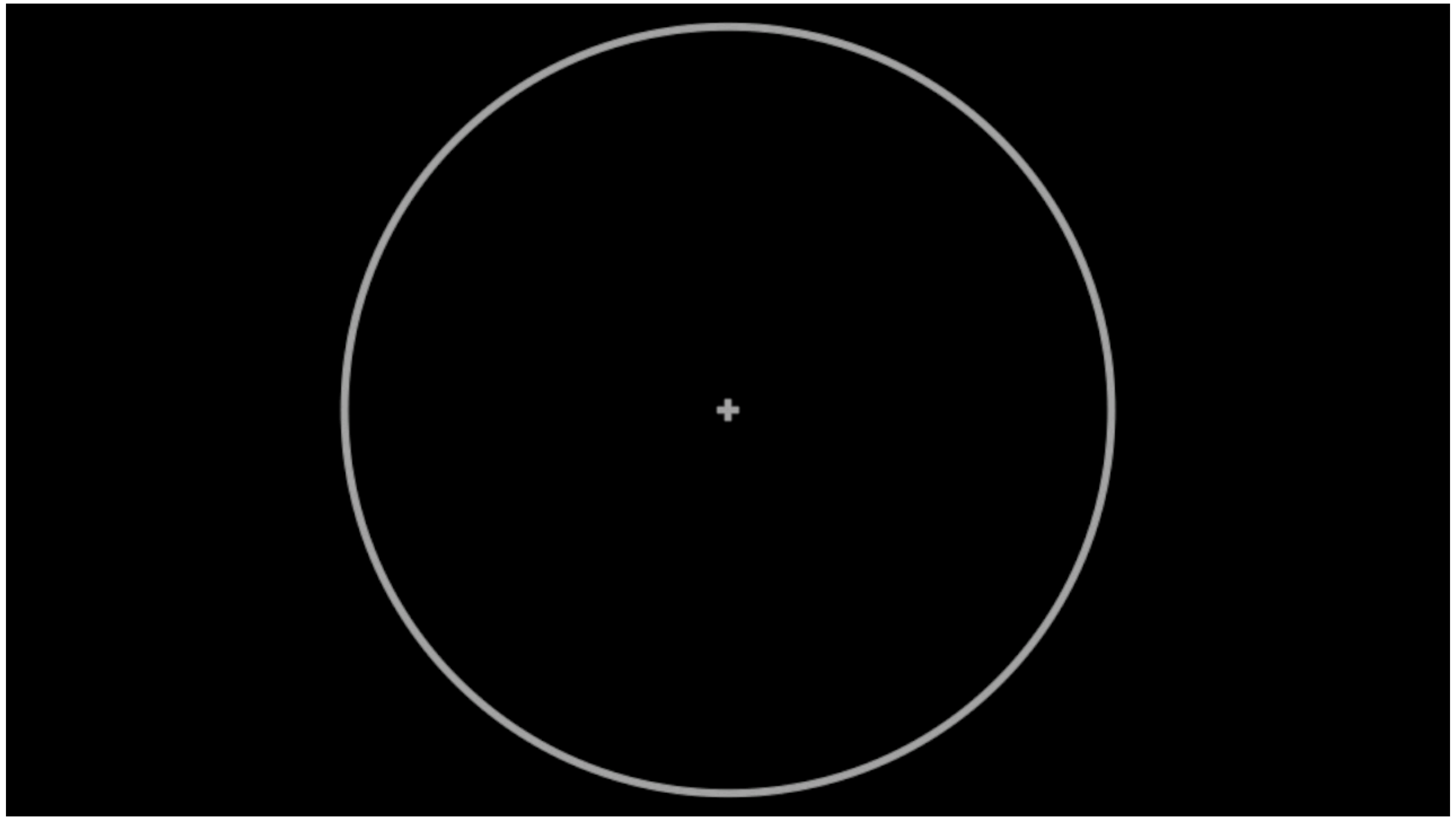
- Now we want to counts the kind of events in our real data sample to calculate R from data ⇒ we can **measure the number of colors**!

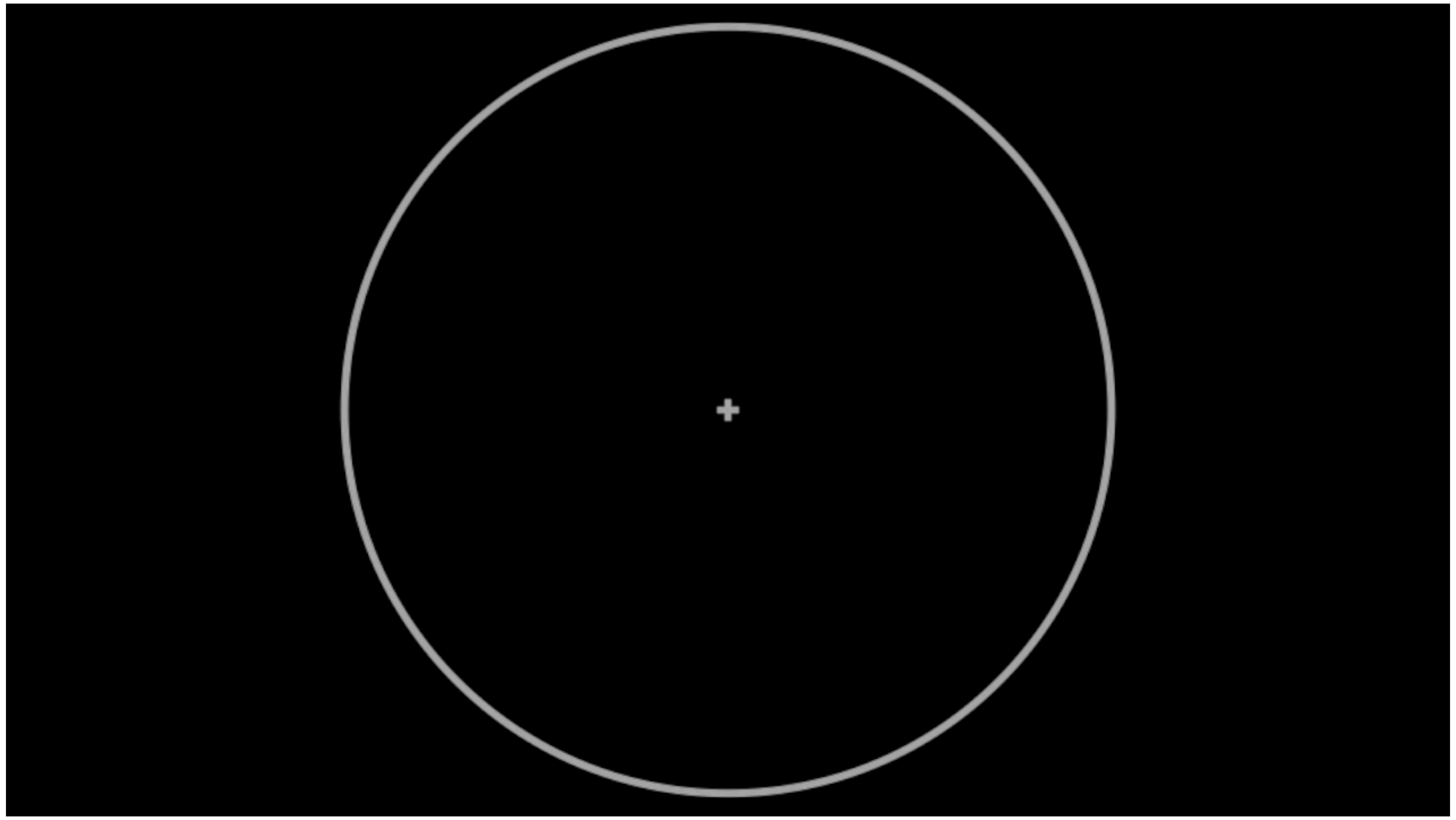


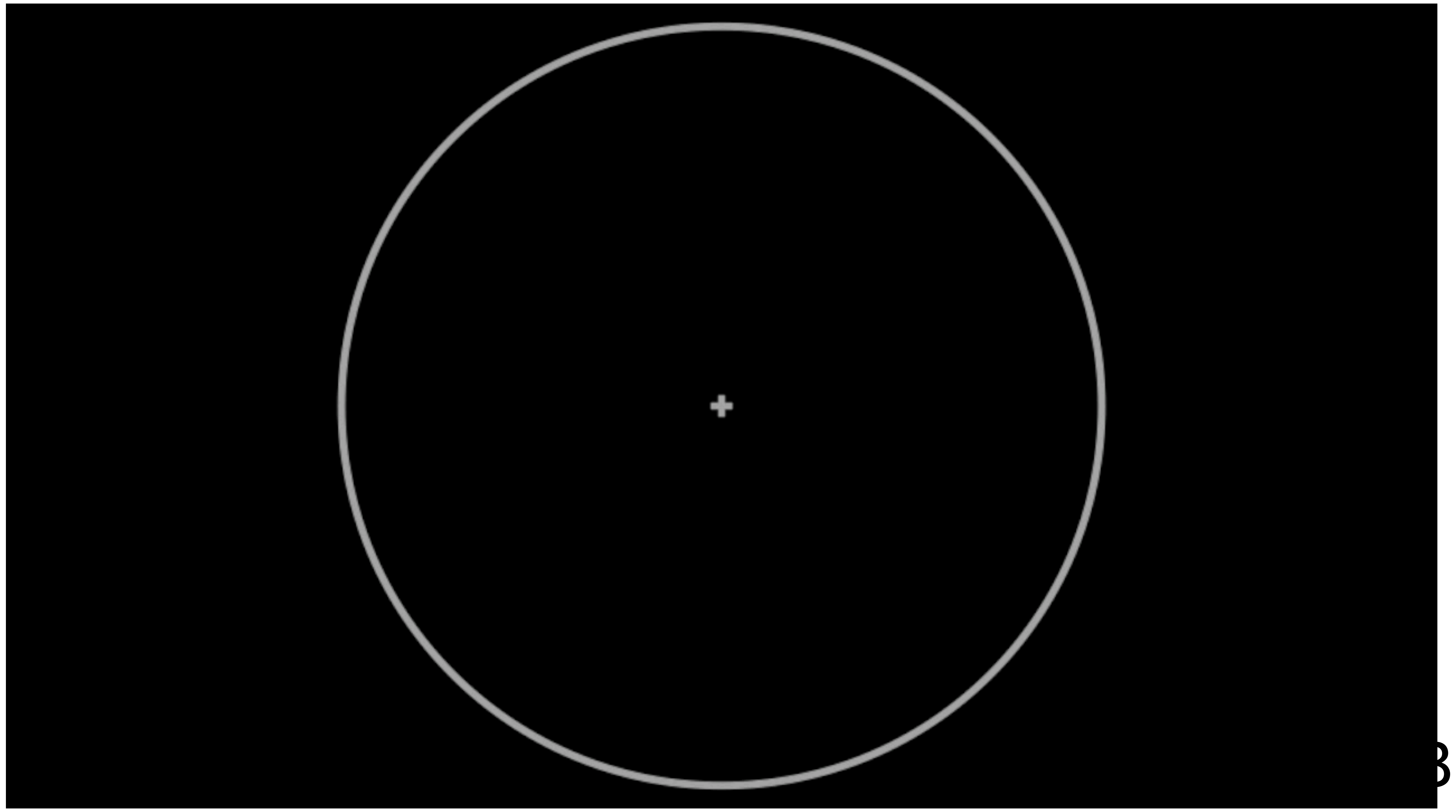
Data analysis concepts

- Number of **tracks**
- Energy deposit in **calorimeter:** all charged particles leaves it, but also γ
- Energy deposit in the **muon detector:** only most penetrating particles reach the muon detector
- **Missing Energy ($\not{E}$):** we expect to be zero if we completely reconstruct the event. However neutrinos are undetected
- **Straightness (⤡)** of the event: how much the event is spherical (low Straightness) or is aligned with an axis.

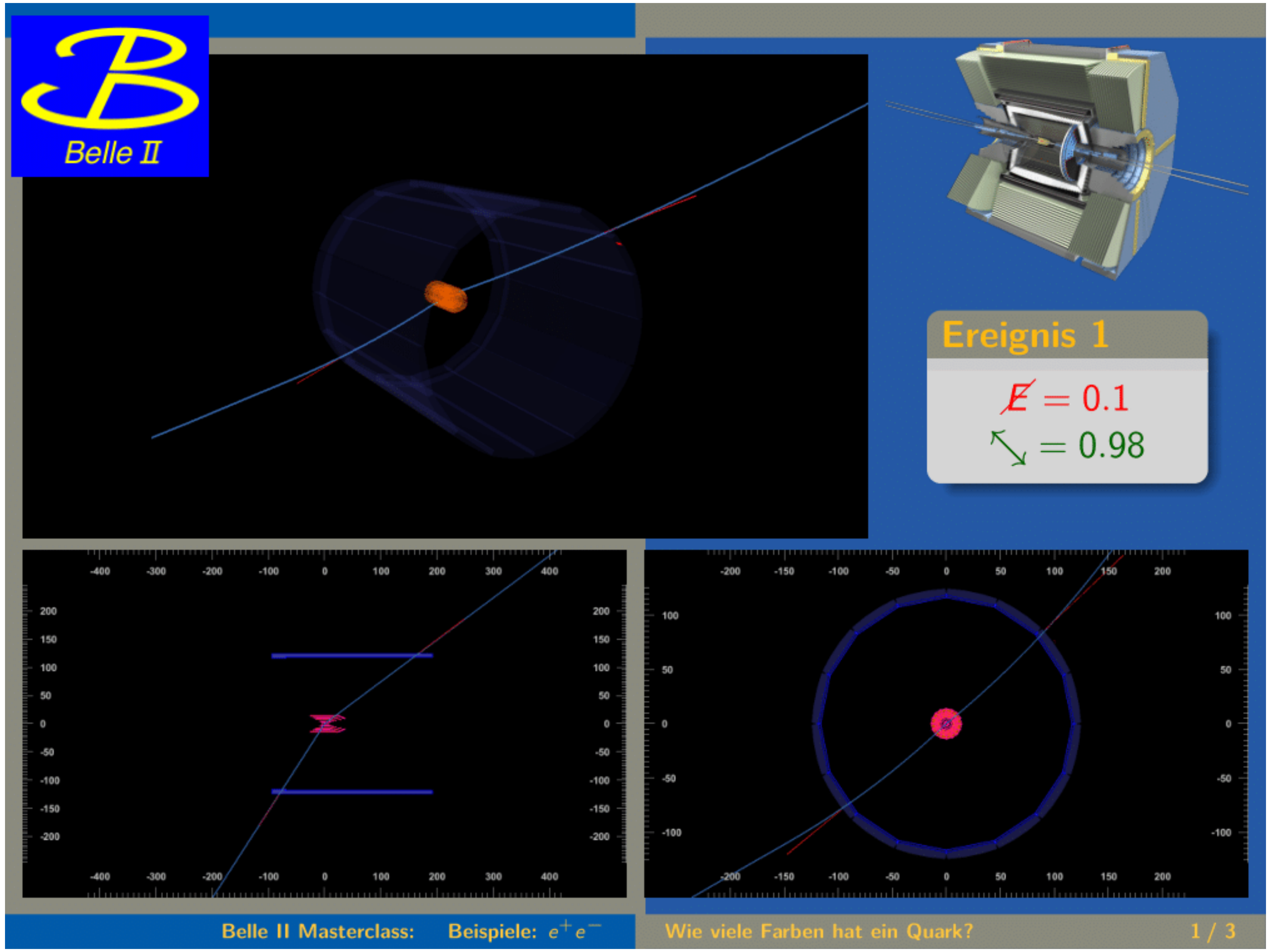
e^+e^- events: simplified display

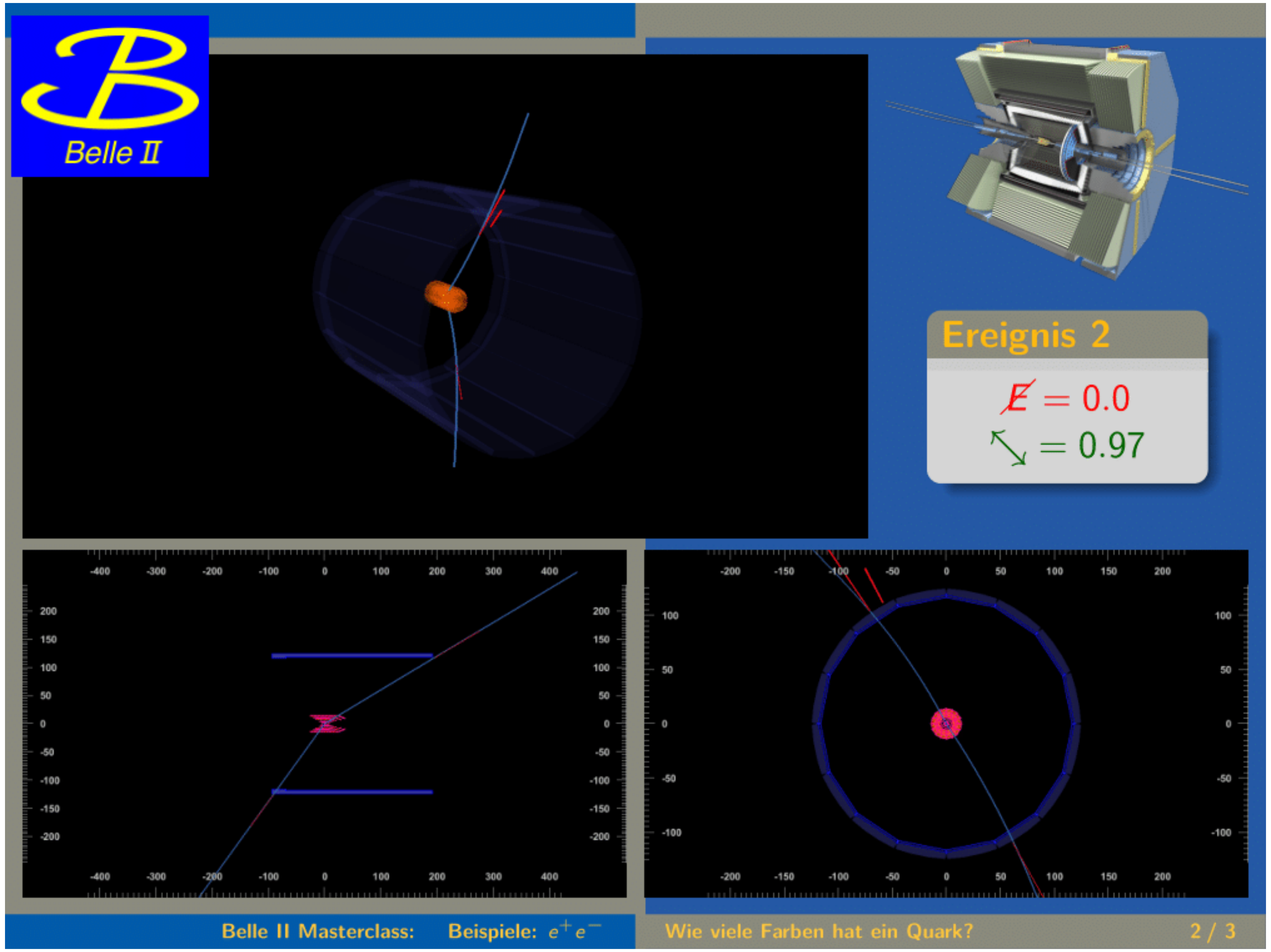




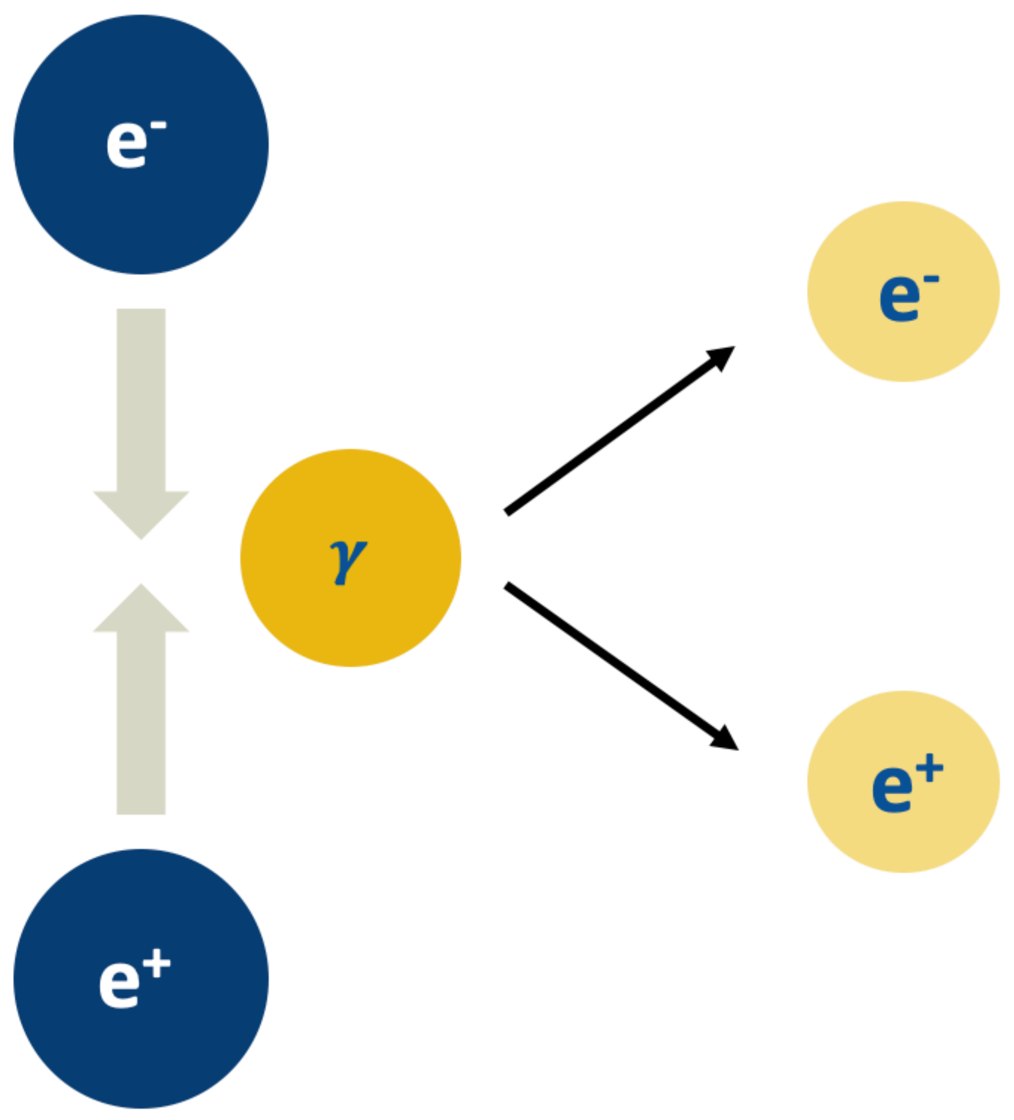


e^+e^- events: real event display



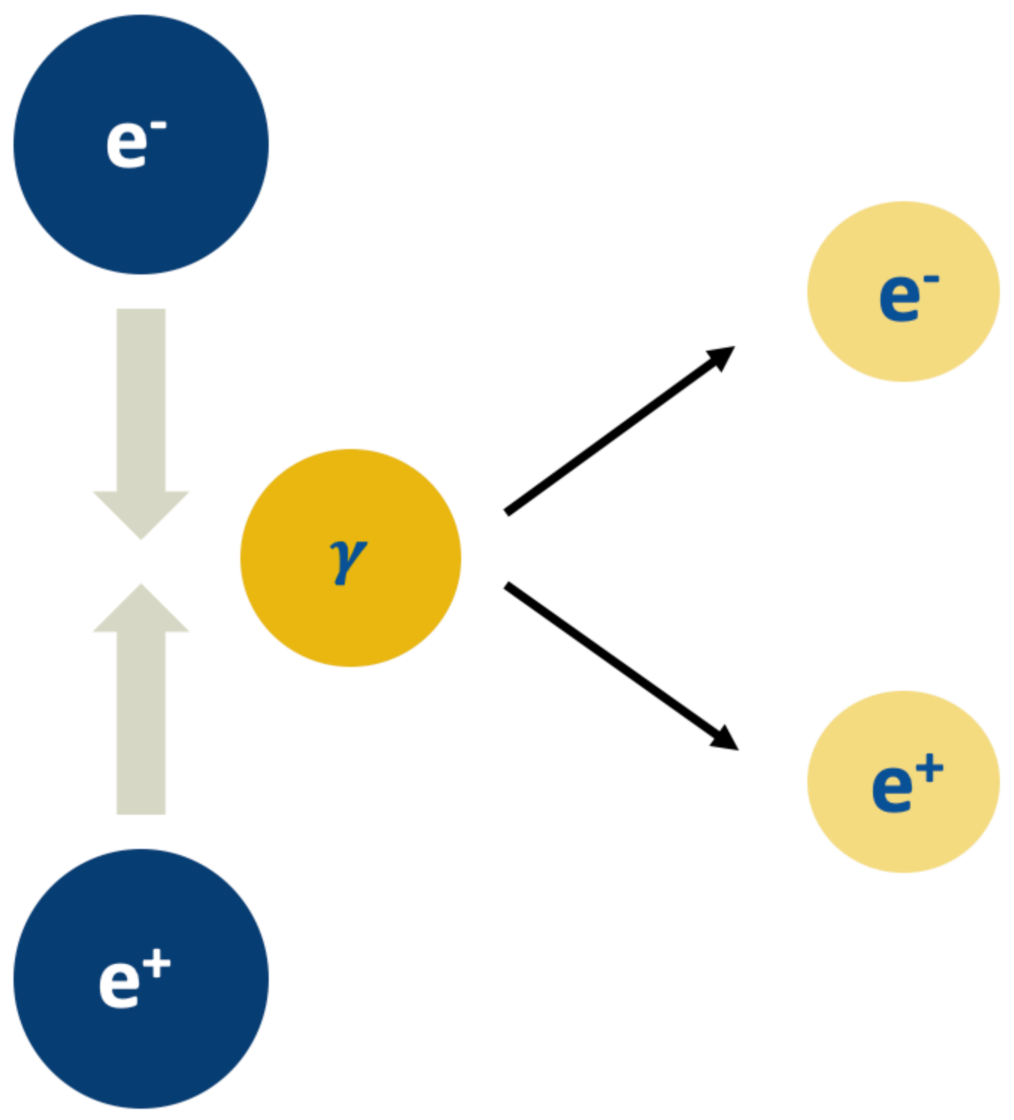


e^+e^- events: properties



- **Two** clearly visible tracks
- Deposition of energy in the calorimeter (red signal close to the track)

e^+e^- events: properties



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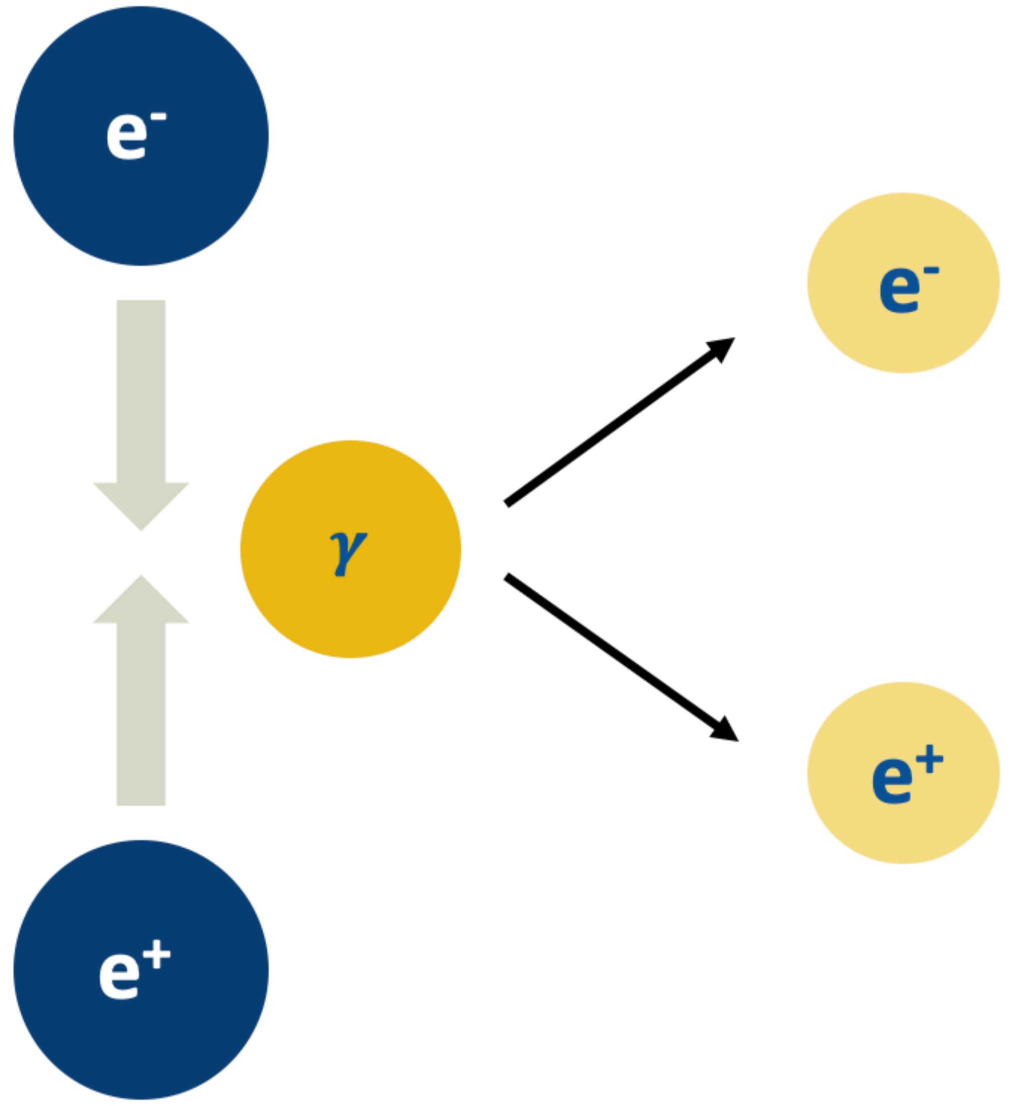

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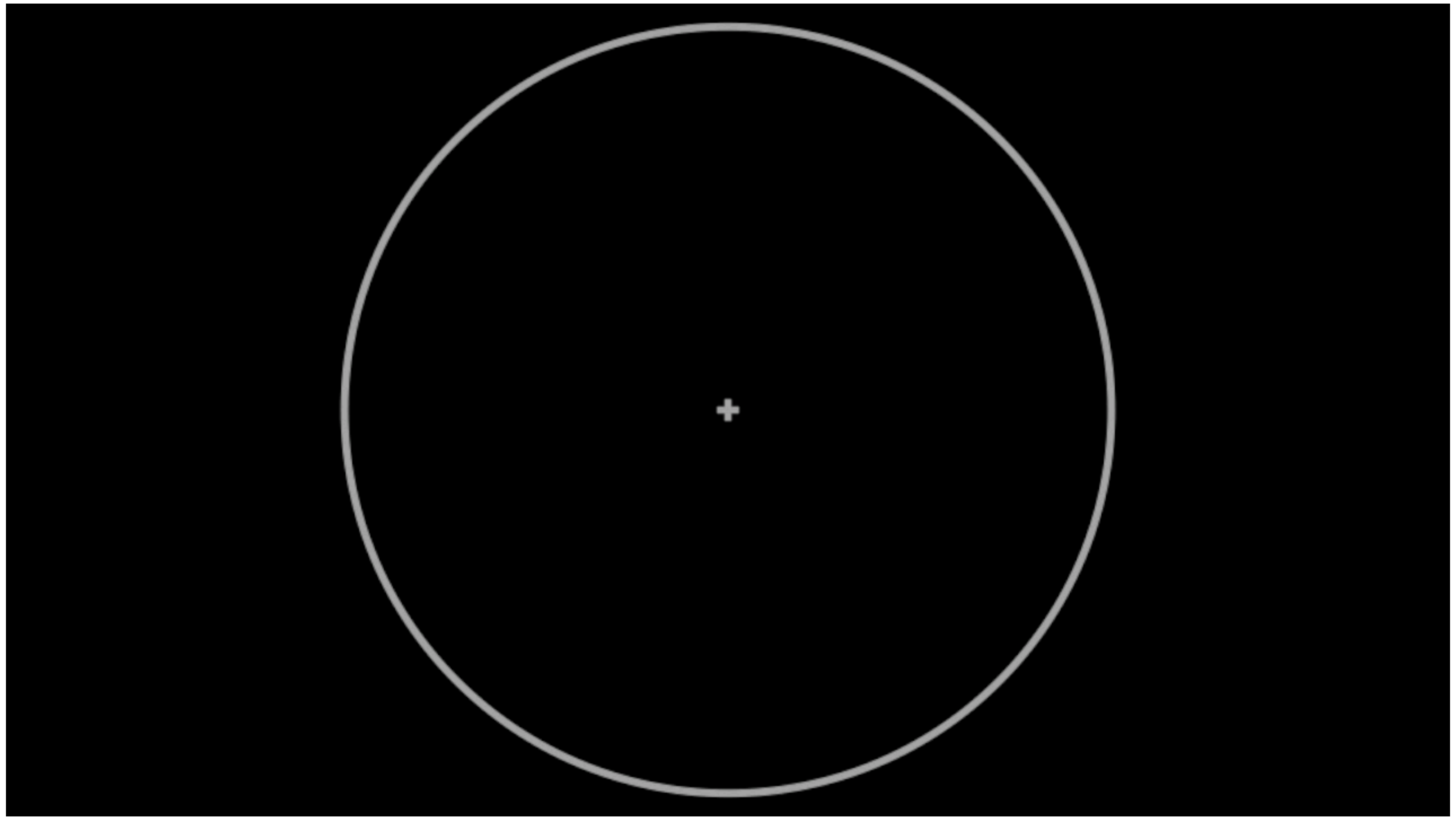
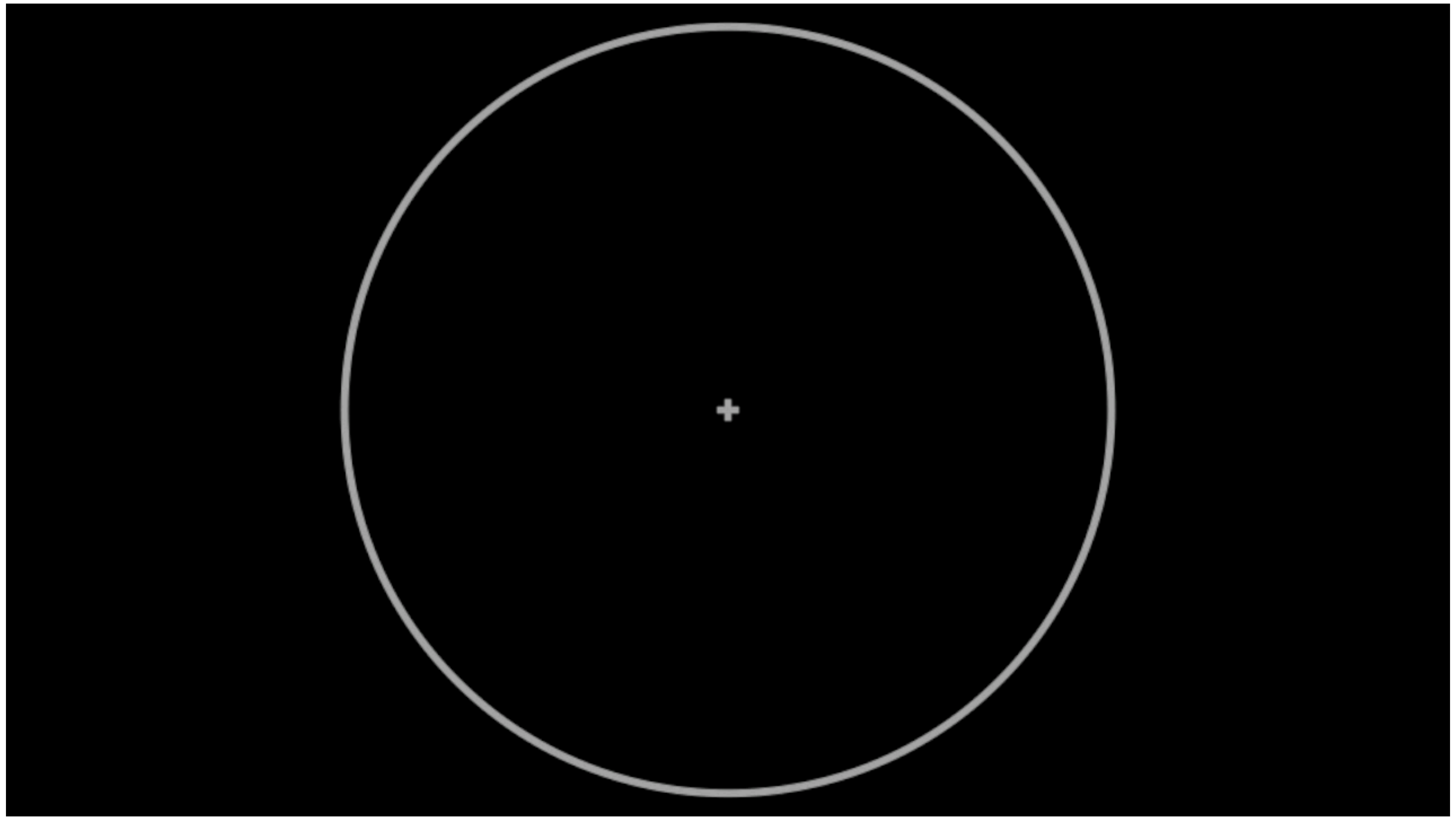
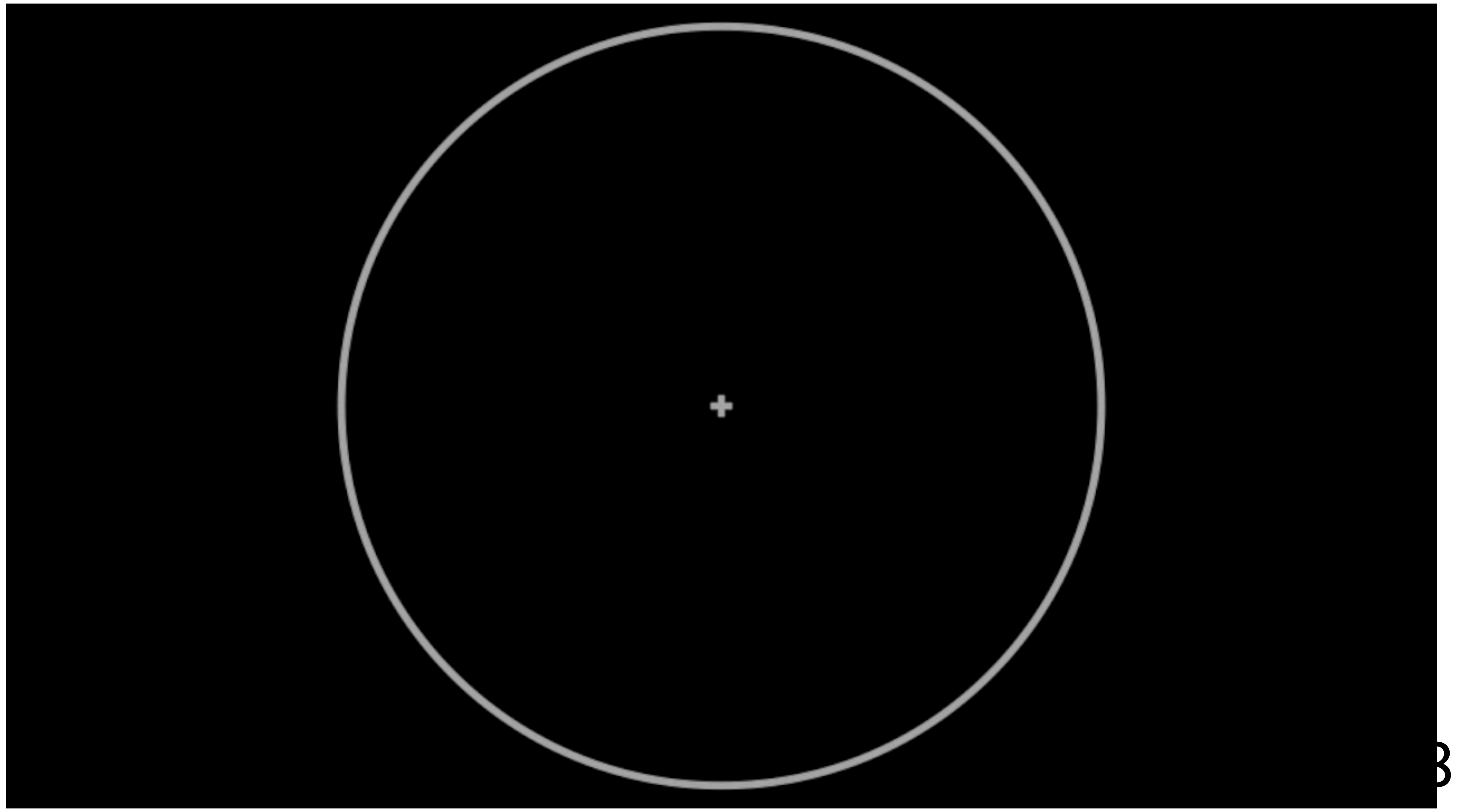
- Because $e^+e^- \to e^+e^-$ scattering is too frequent

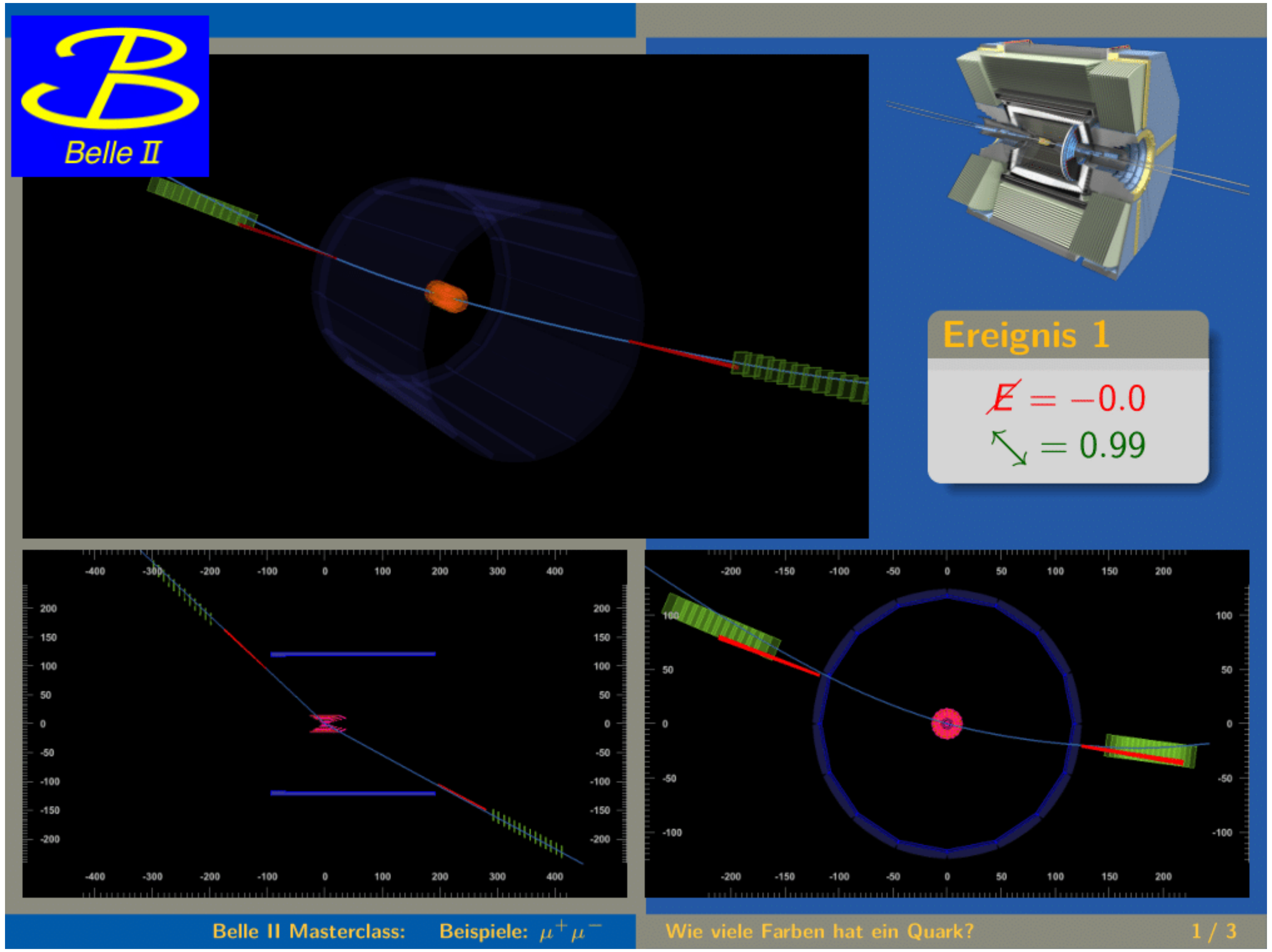
$\mu^+\mu^-$ events: simplified display

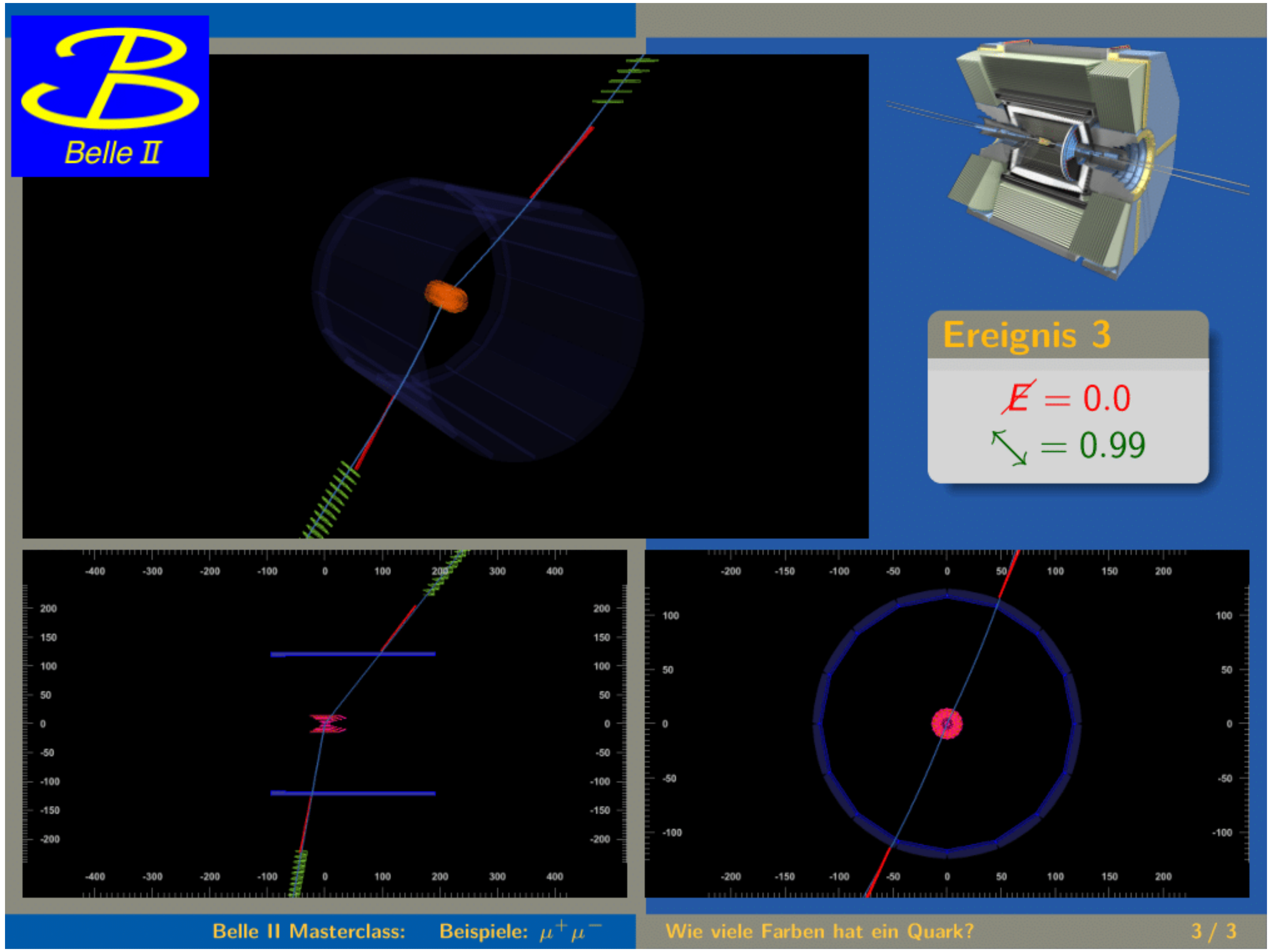




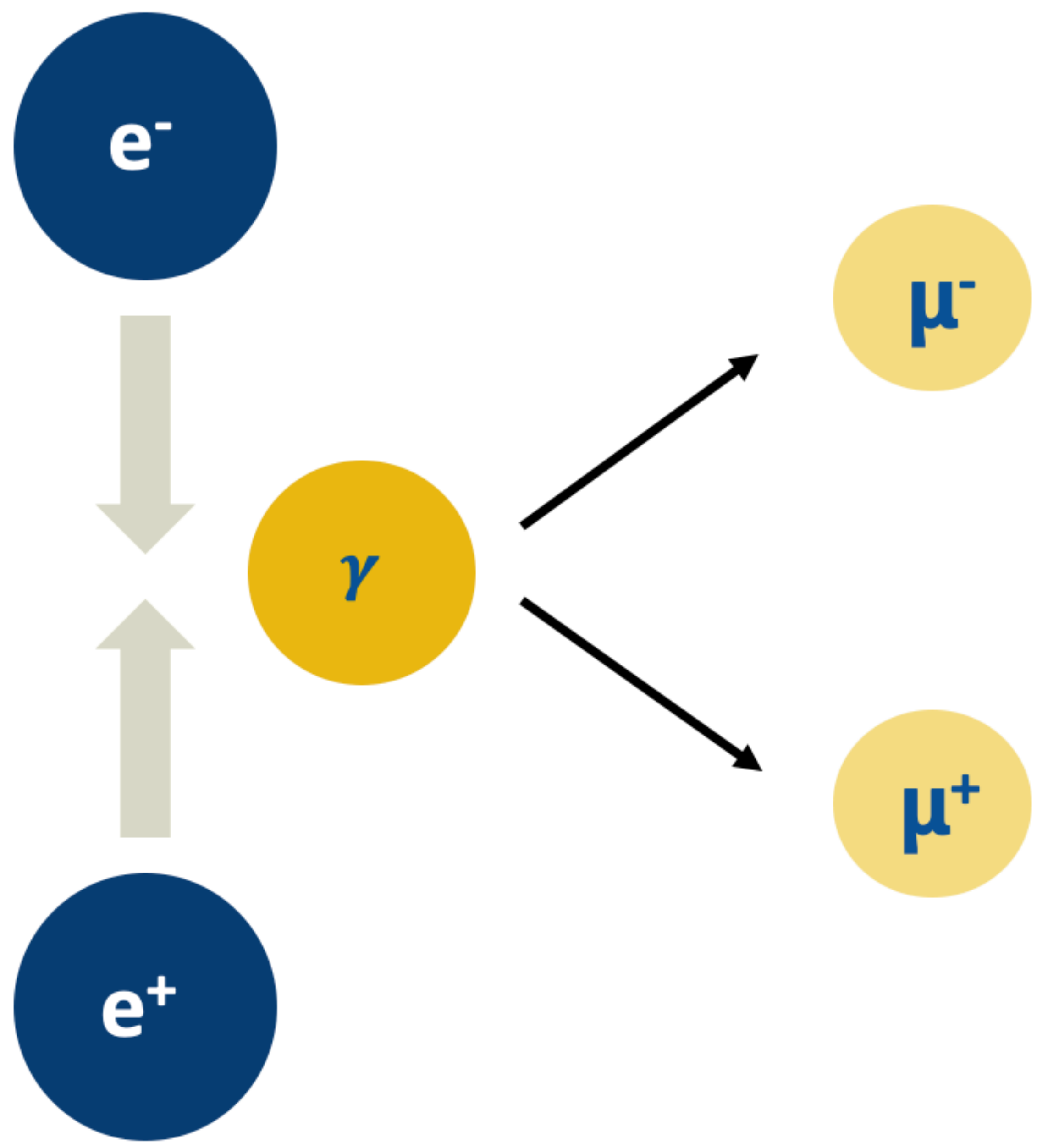


$\mu^+\mu^-$ events: real event display



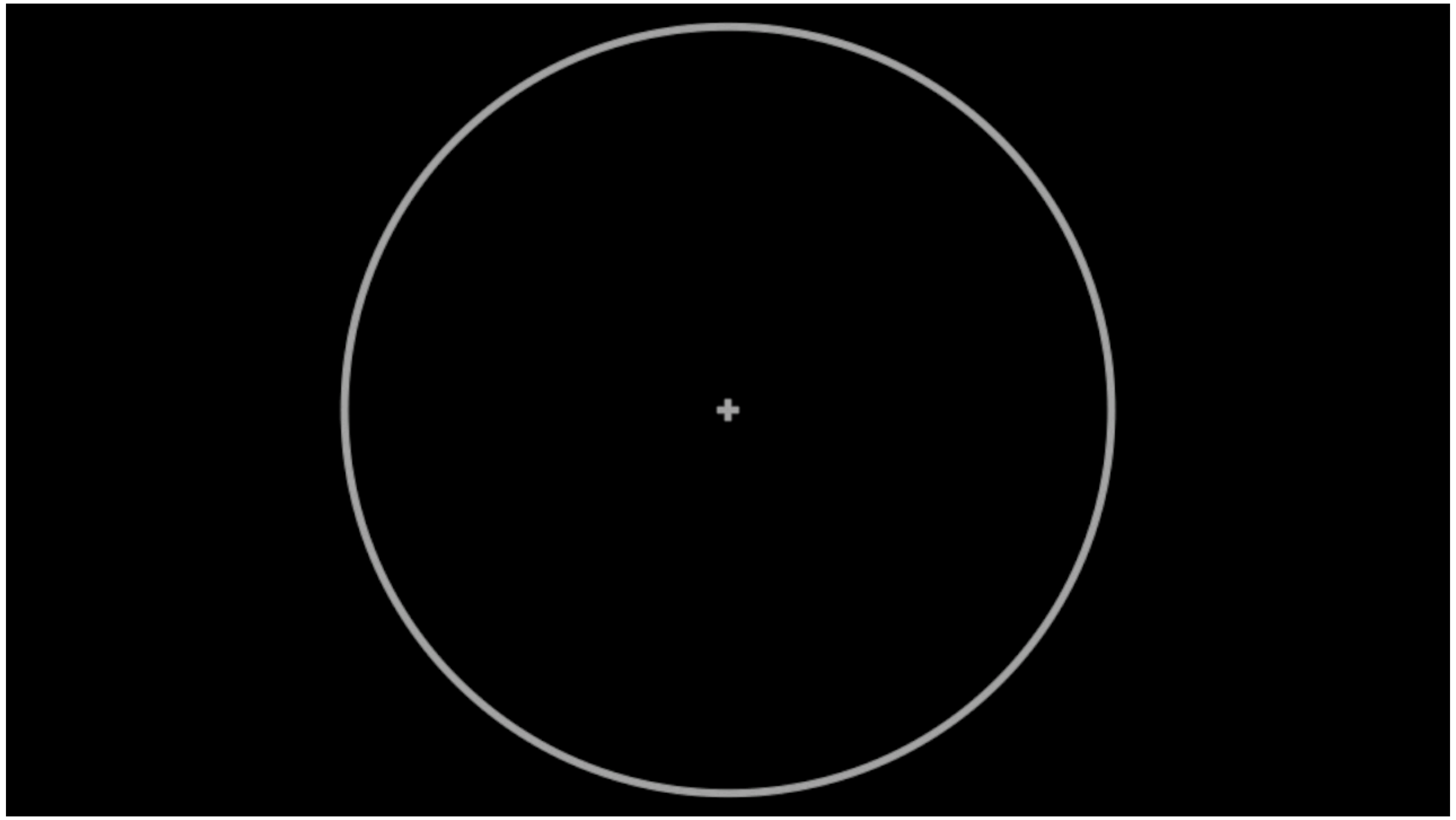


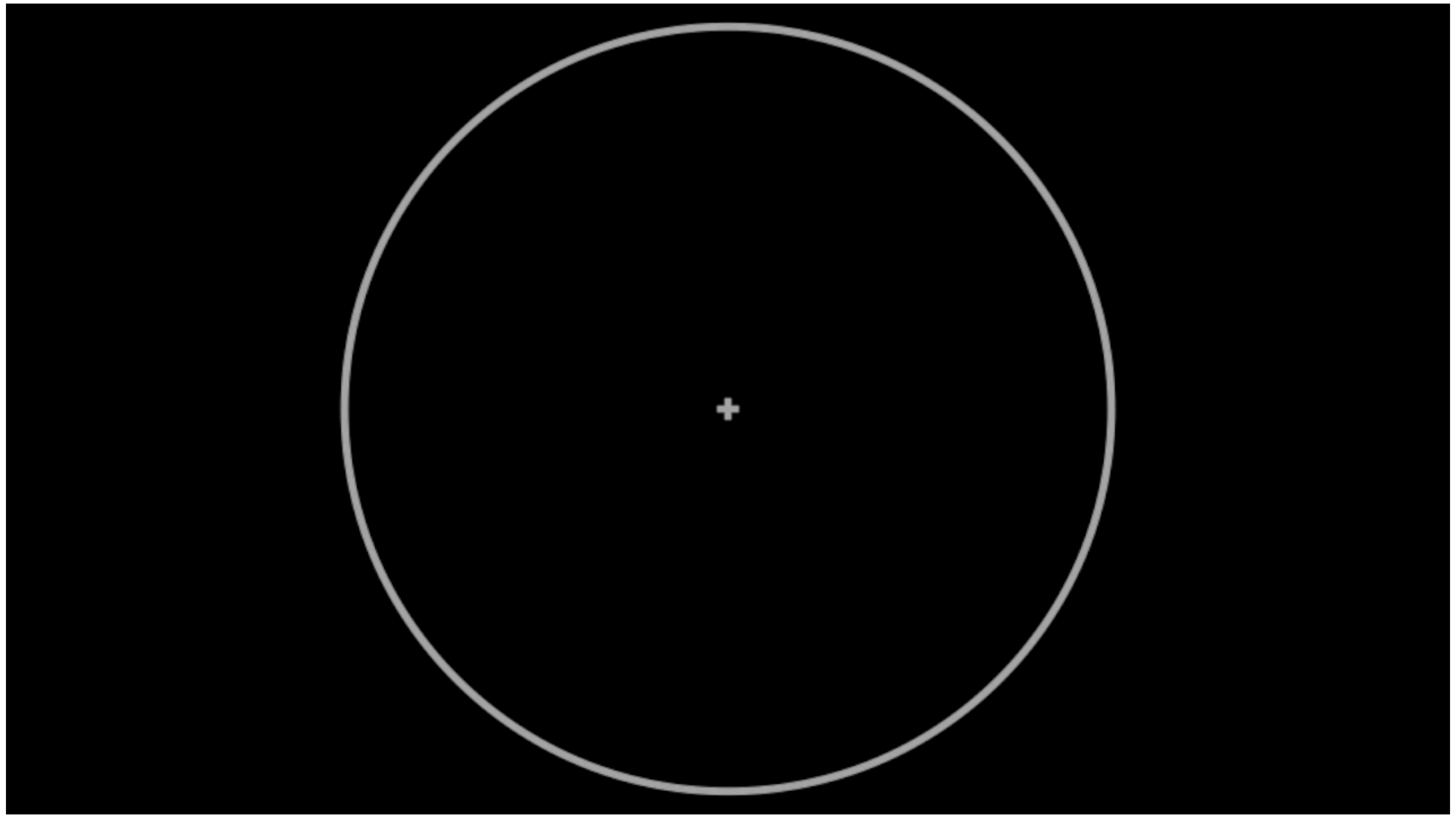
$\mu^+\mu^-$ events: properties

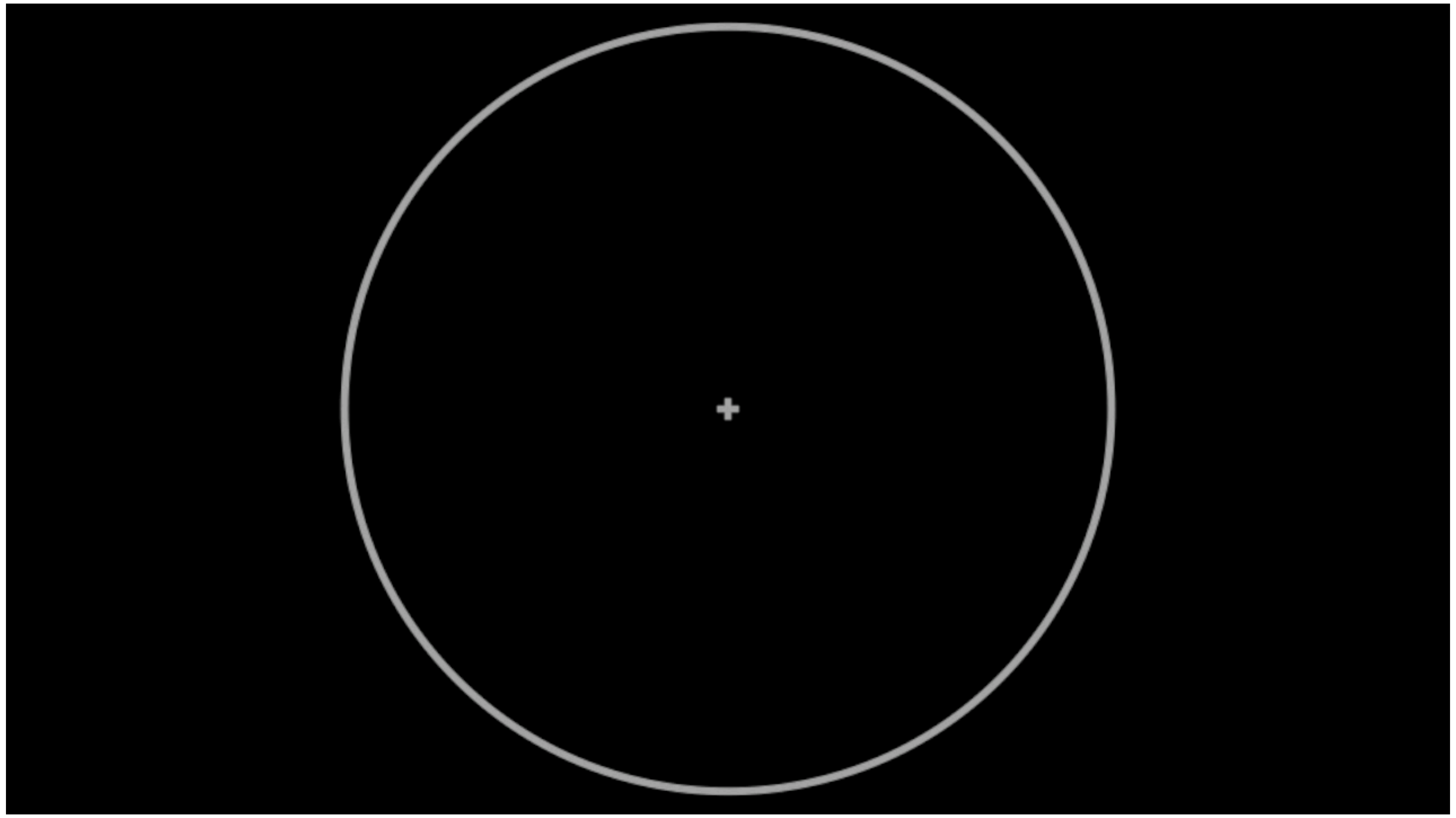


- **Two** clearly visible tracks
- Deposition of energy in the calorimeter (red signal close to the track)
- Deposition of energy in the muon detector (green signals along the outer track!)

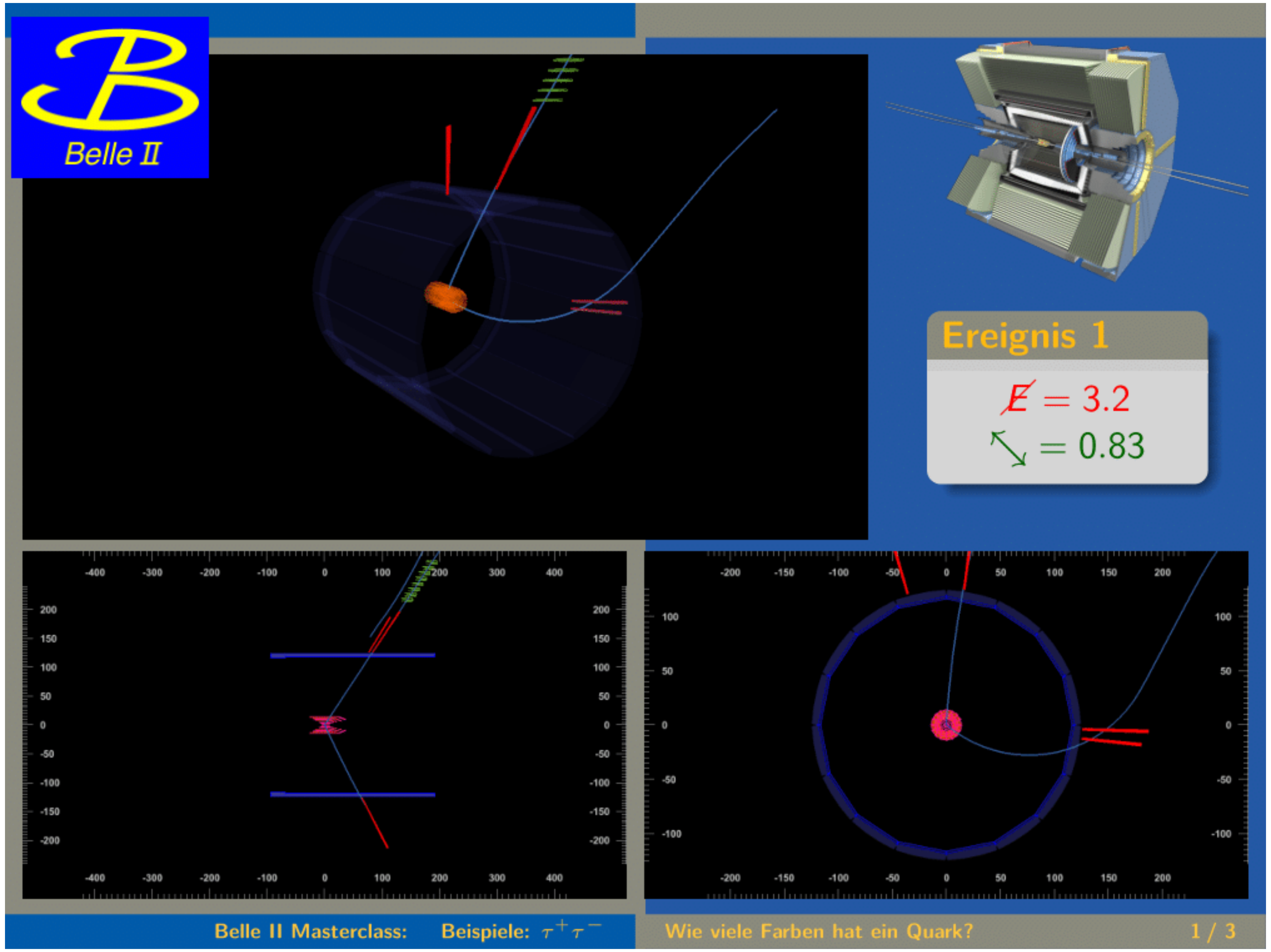
$\tau^+\tau^-$ events: simplified display

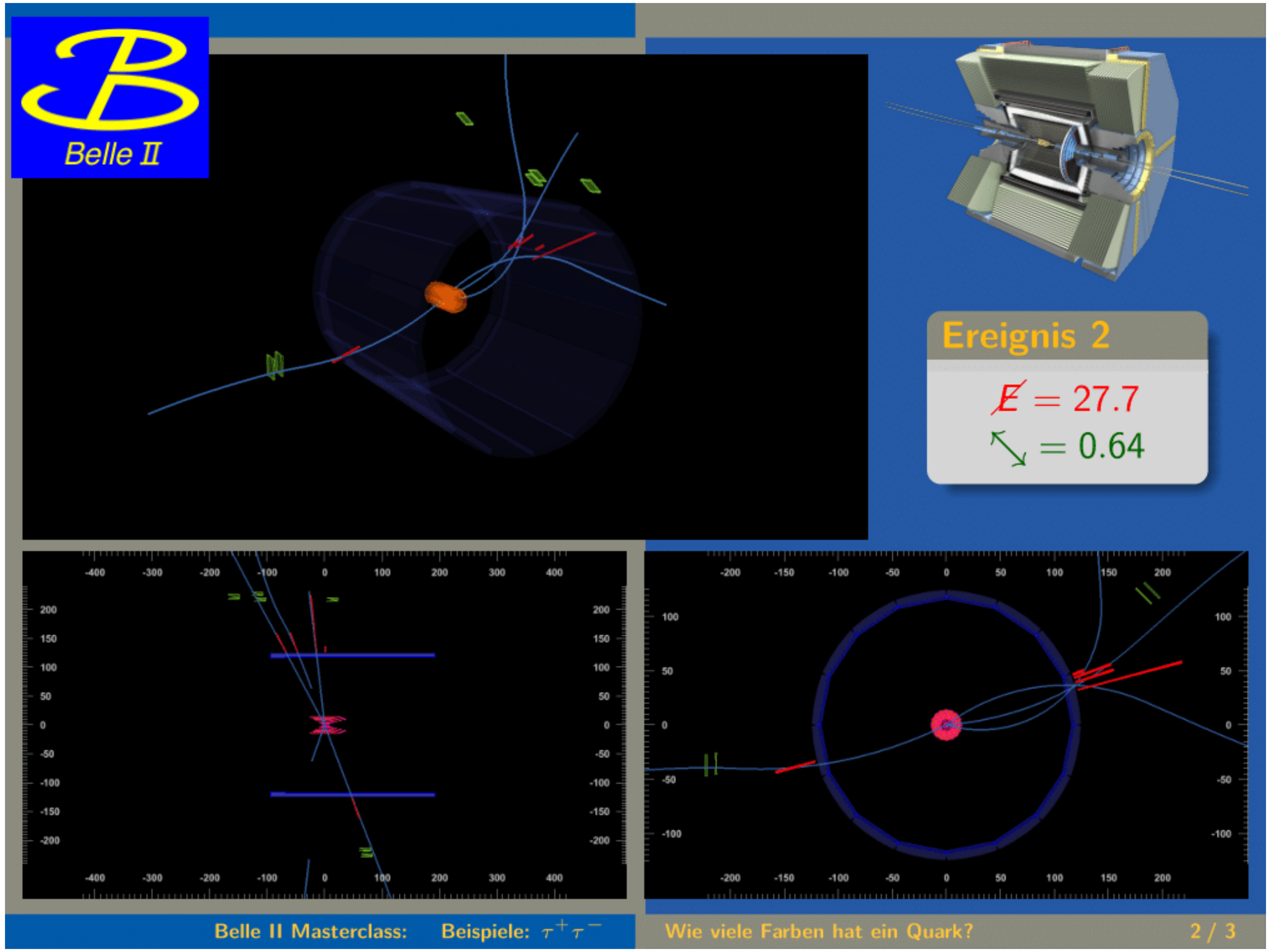






$\tau^+\tau^-$ events: real event display





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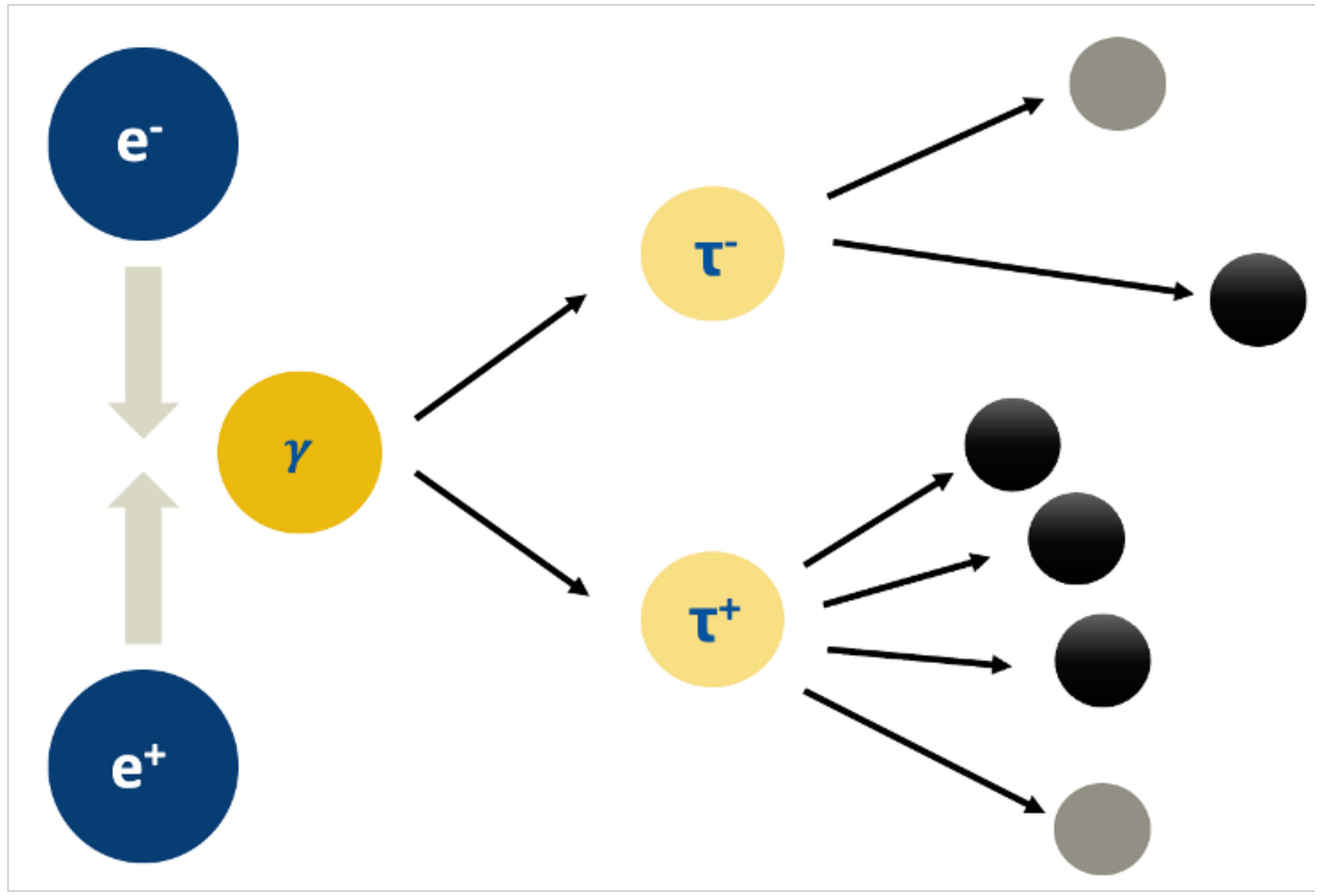
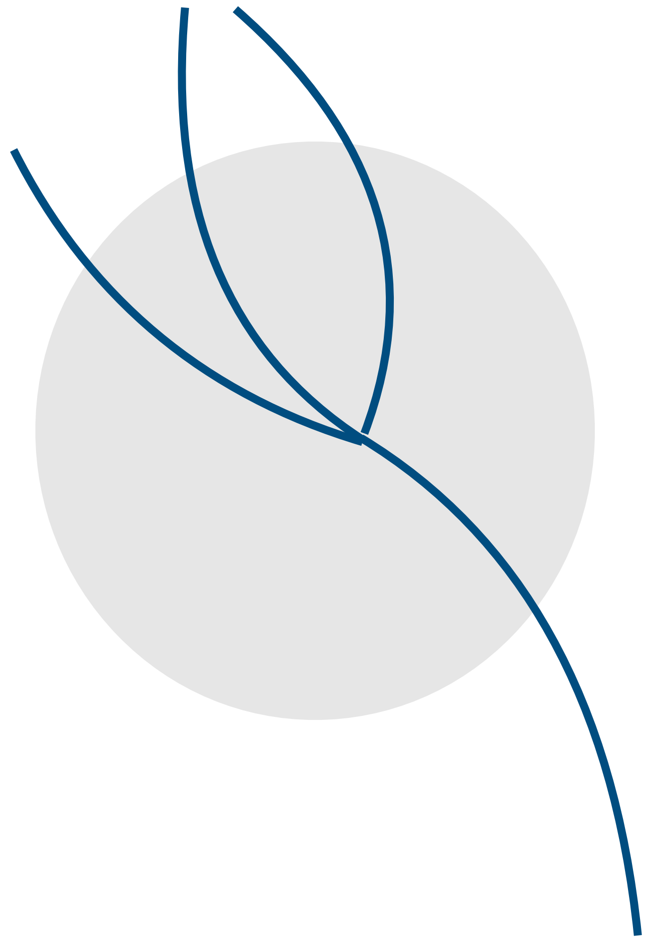
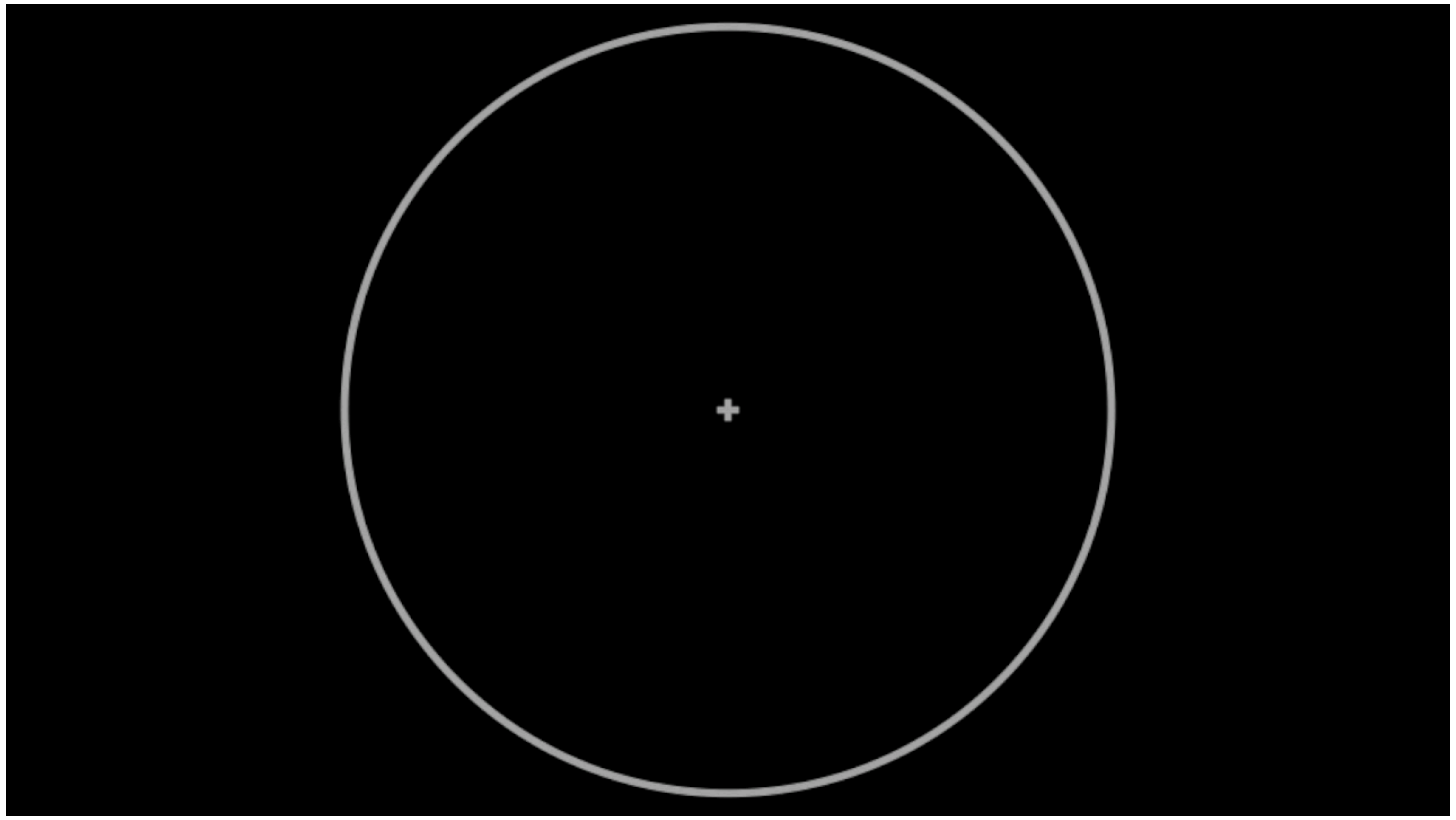


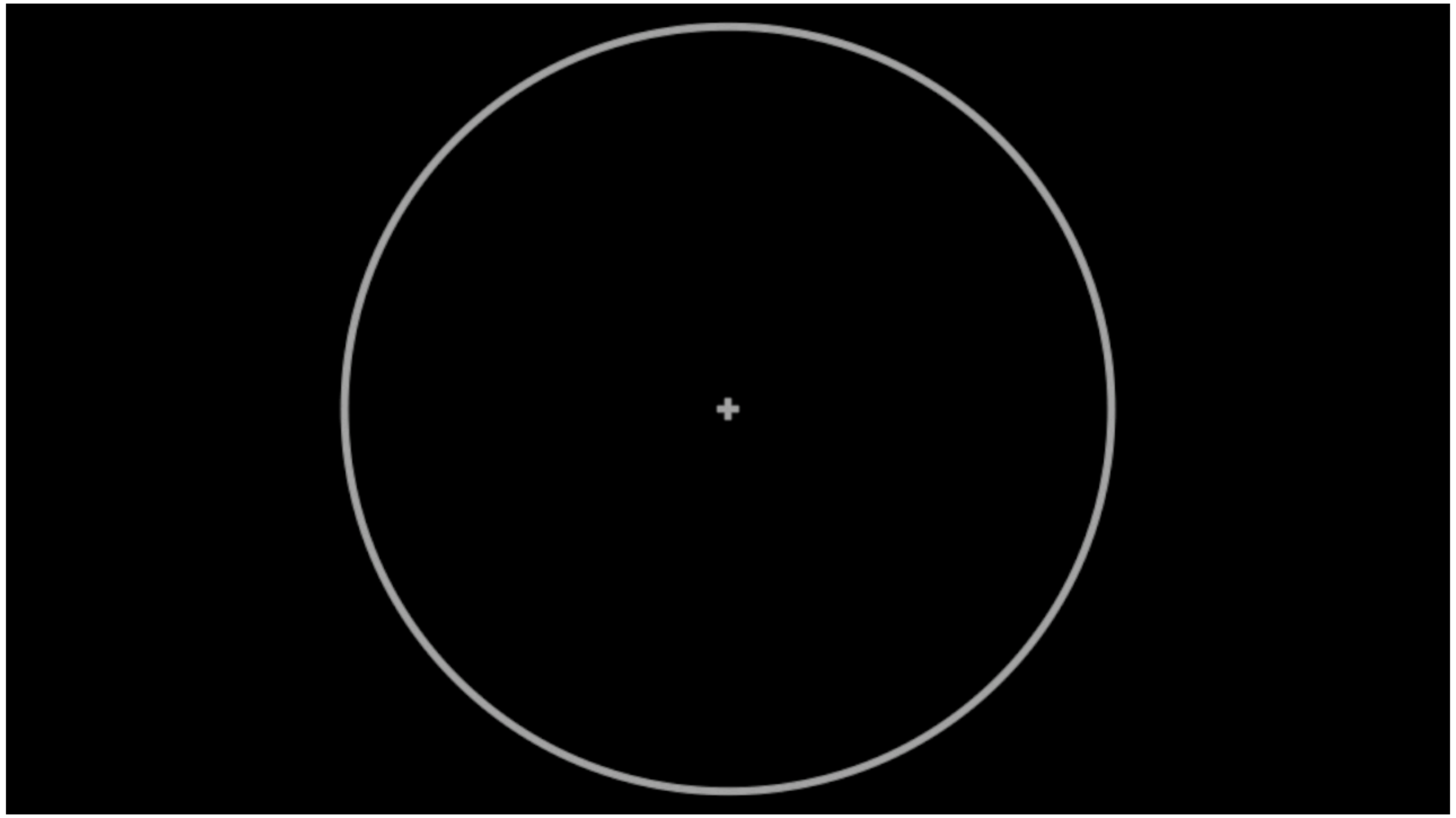
- The τs **decay** shortly after their creation within the detector
- There are several possible decay possibilities:
  - decay into **charged lepton + neutrinos**
  - decay into **light quarks + neutrinos**
- Neutrinos do not interact ⇒ not reconstructed ⇒ **large** $\not{E}$
- Variable number of tracks. **2 or 4 with a "fork structure"** are the most common
  - **high straightness**
- Deposition of energy in the calorimeter (red signal close to the track)
- Sometimes deposit of energy in the muon detector (green signals along the outer track)

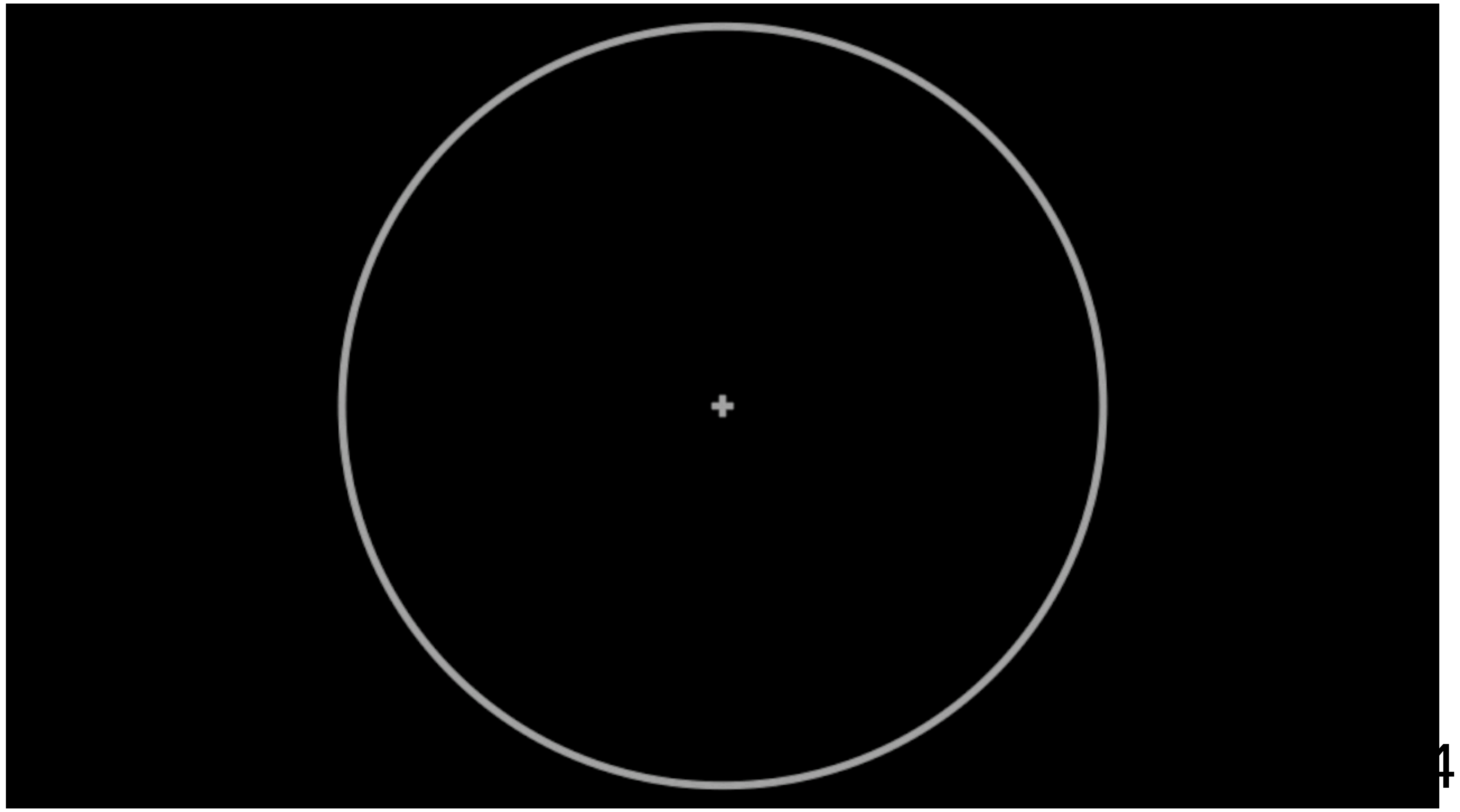


3 vs 1 tracks "Fork"

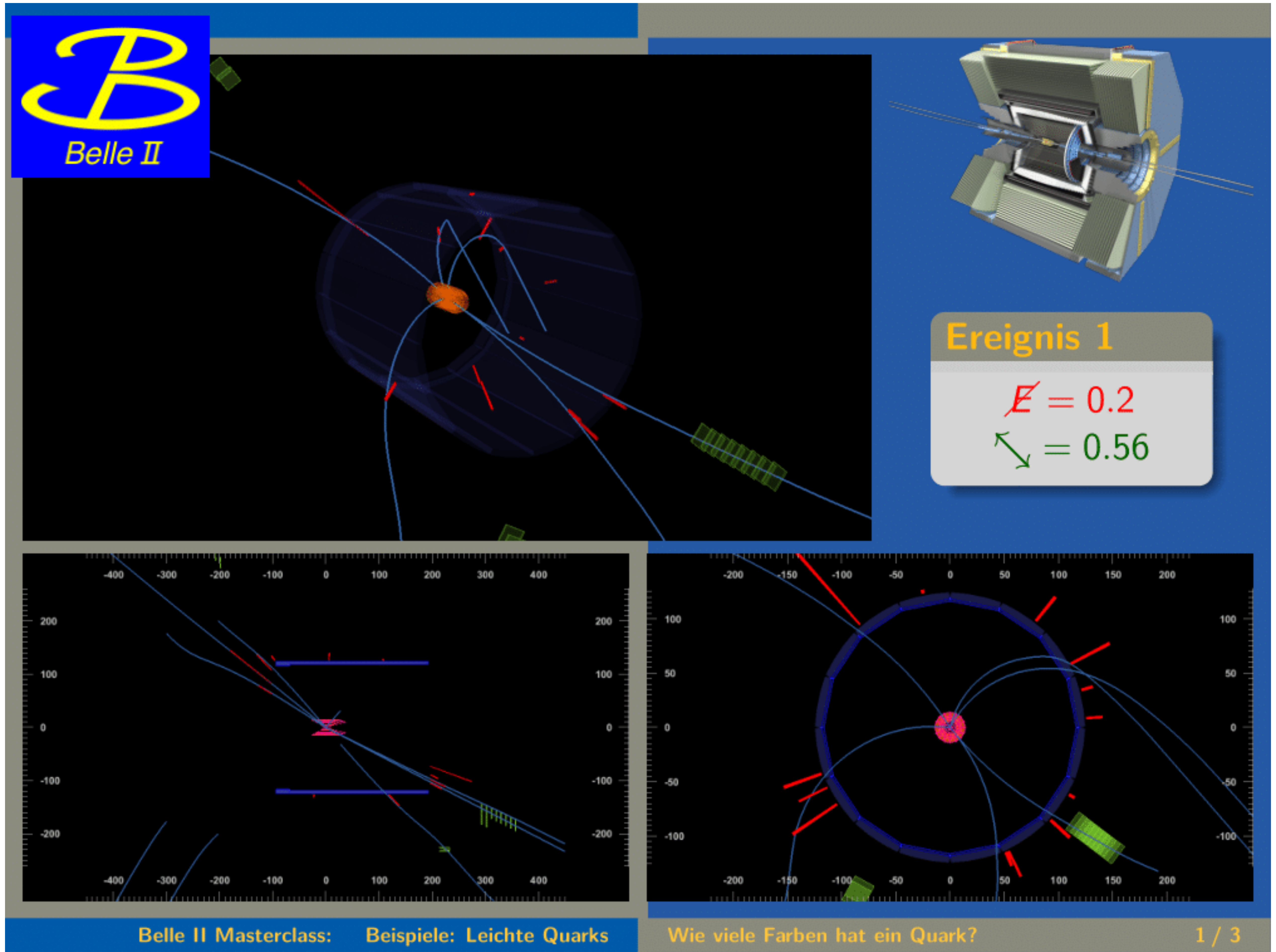
light $q\bar{q}$ events: simplified display

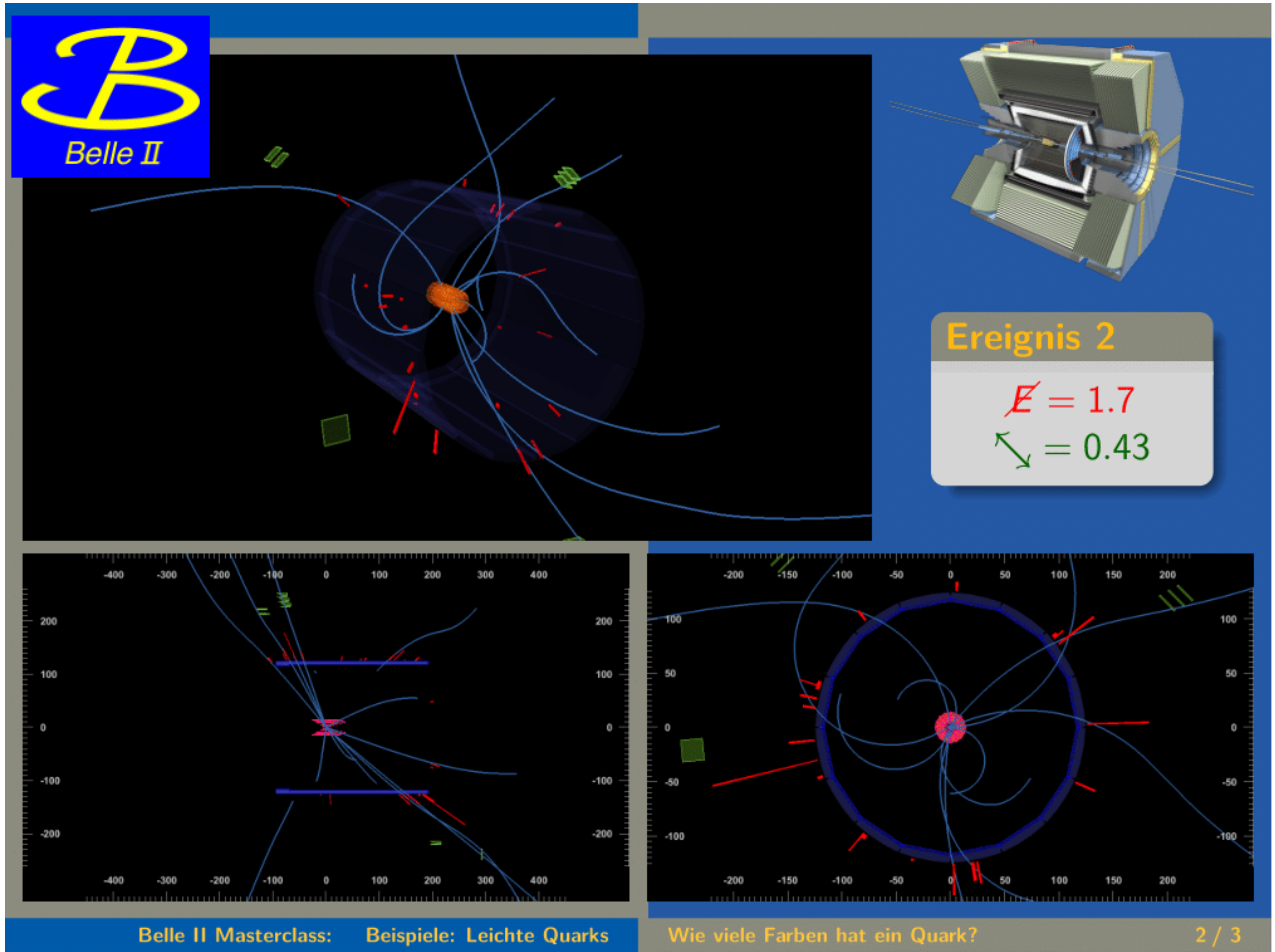




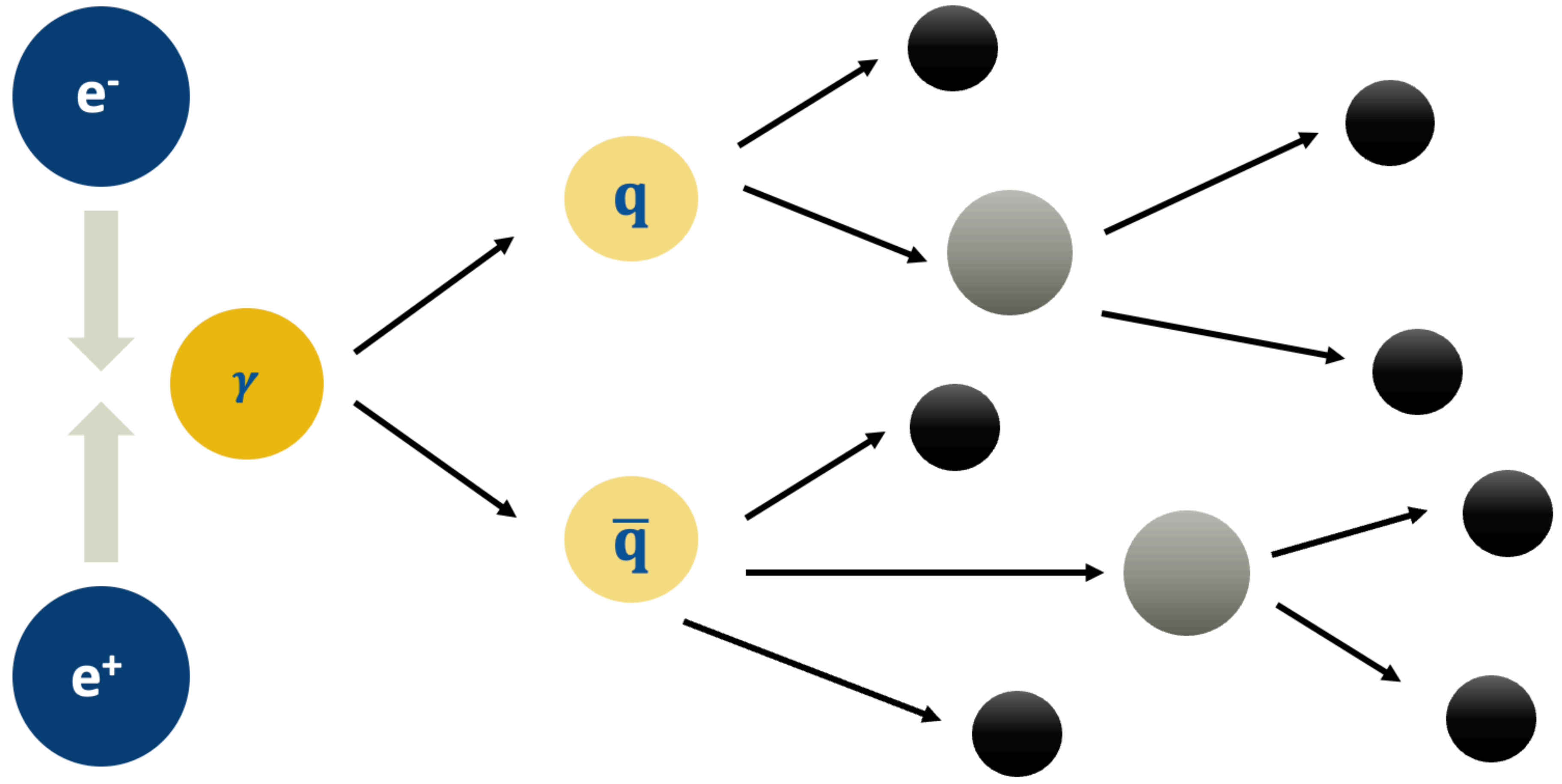


light $q\bar{q}$ events: real event display



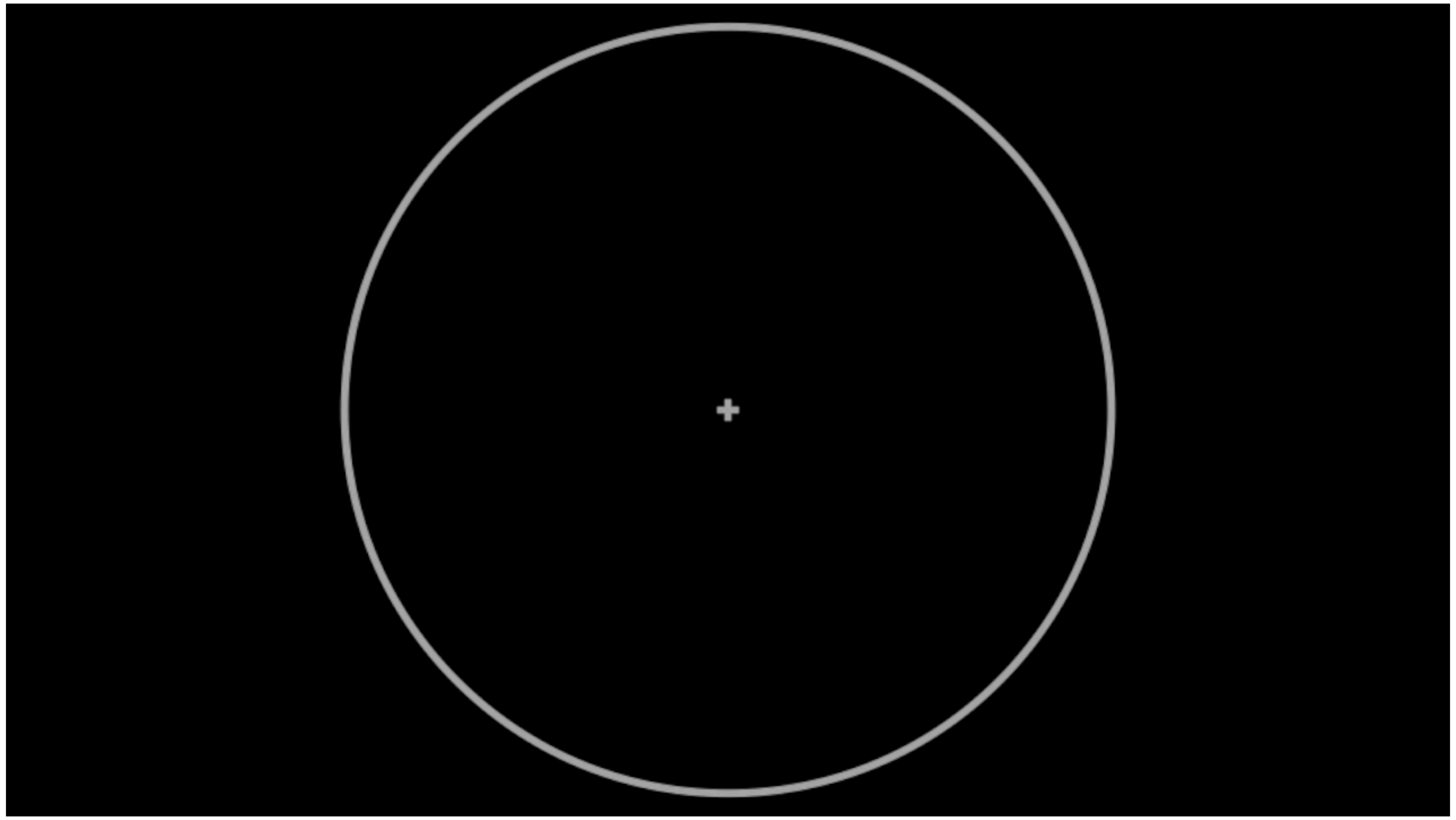


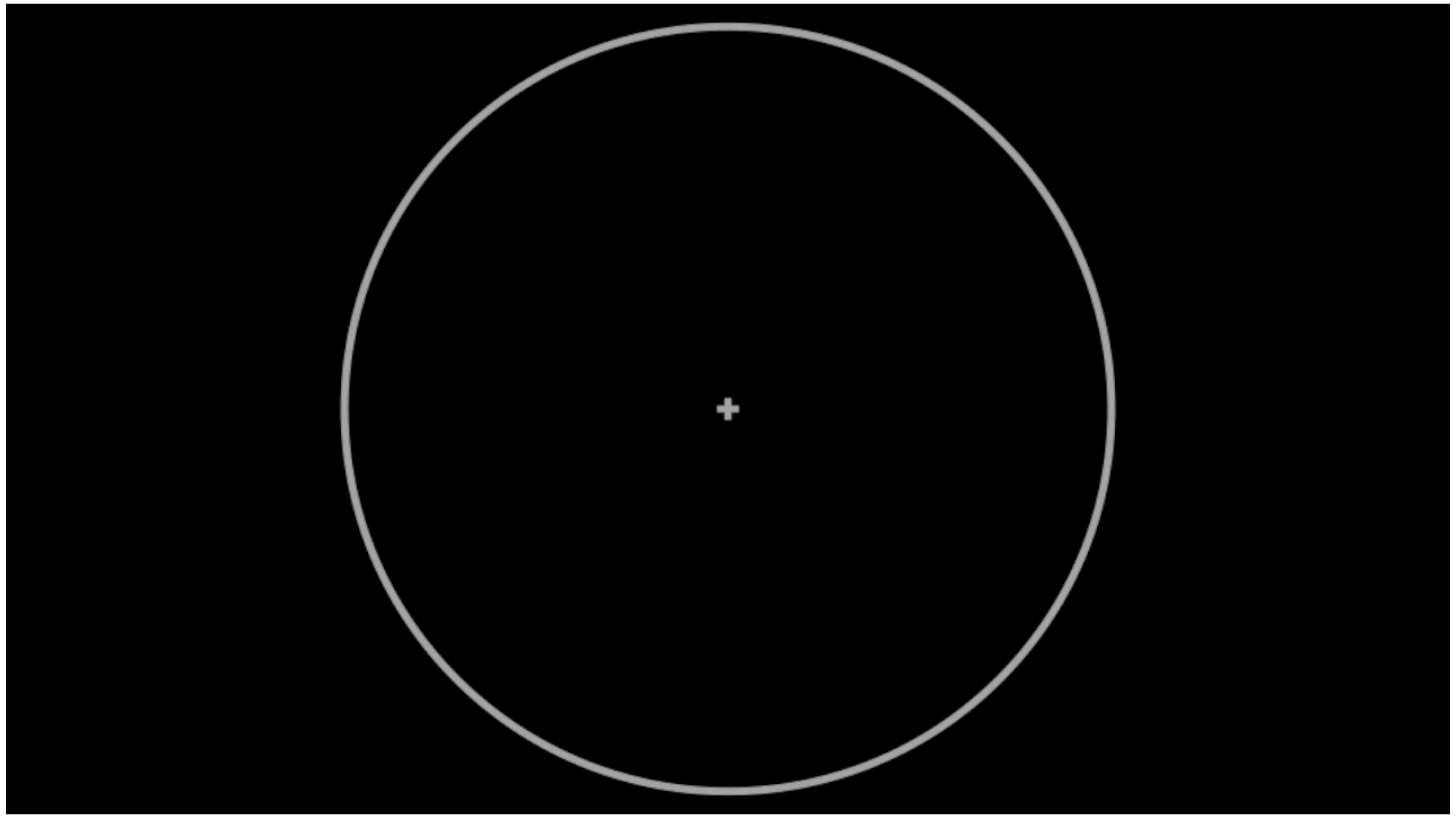
light $q\bar{q}$ events: properties

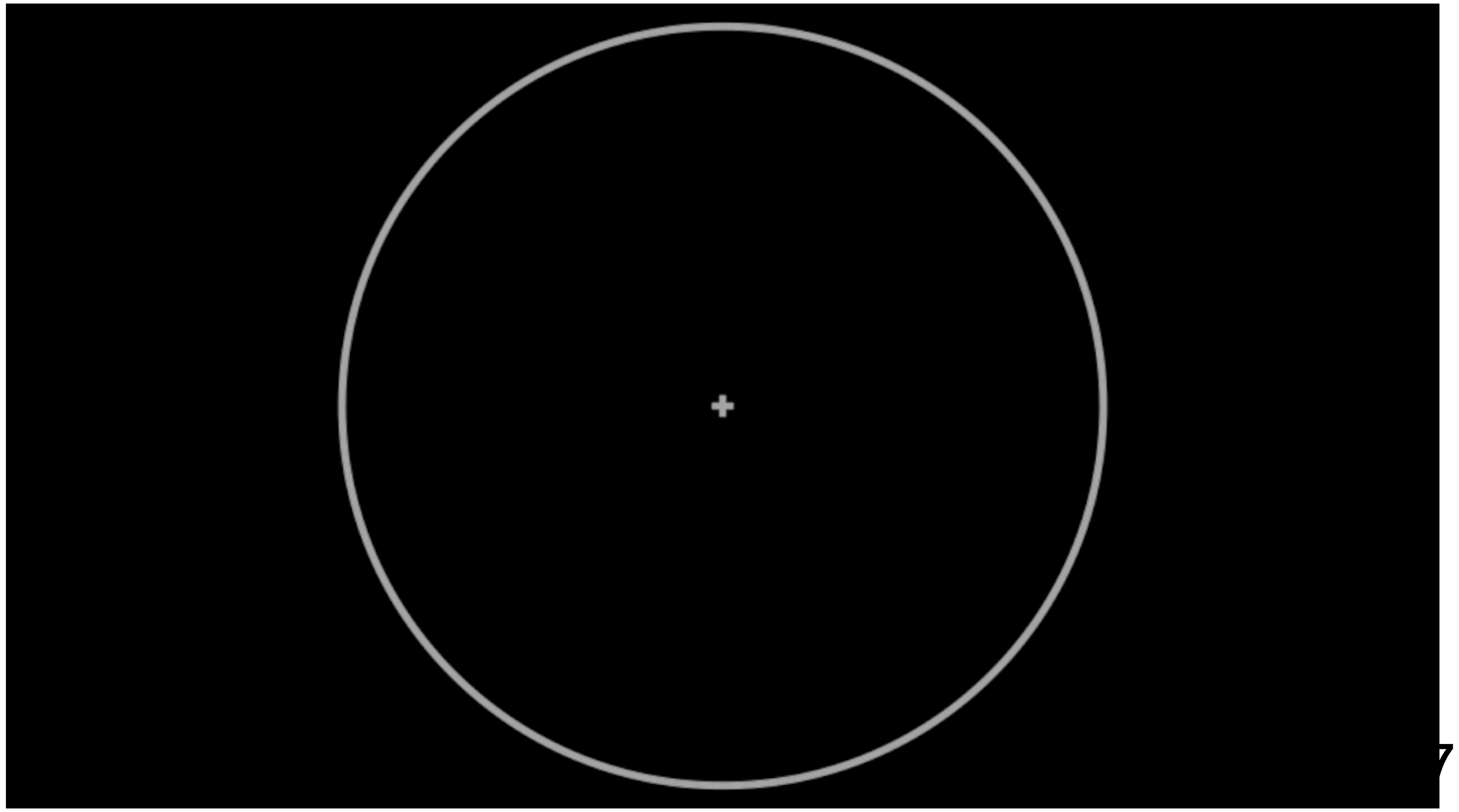


- Decay into a **large variety of final states**
- **Variable number of tracks**, large number is more frequent
- **Less missing energy** $\not{E}$ because less neutrinos created
- **Straightness** ↖↘ **smaller** than leptonic decays
- Deposition of energy in the calorimeter (red signal close to the track)
- Sometimes deposit of energy in the muon detector (green signals along the outer track)

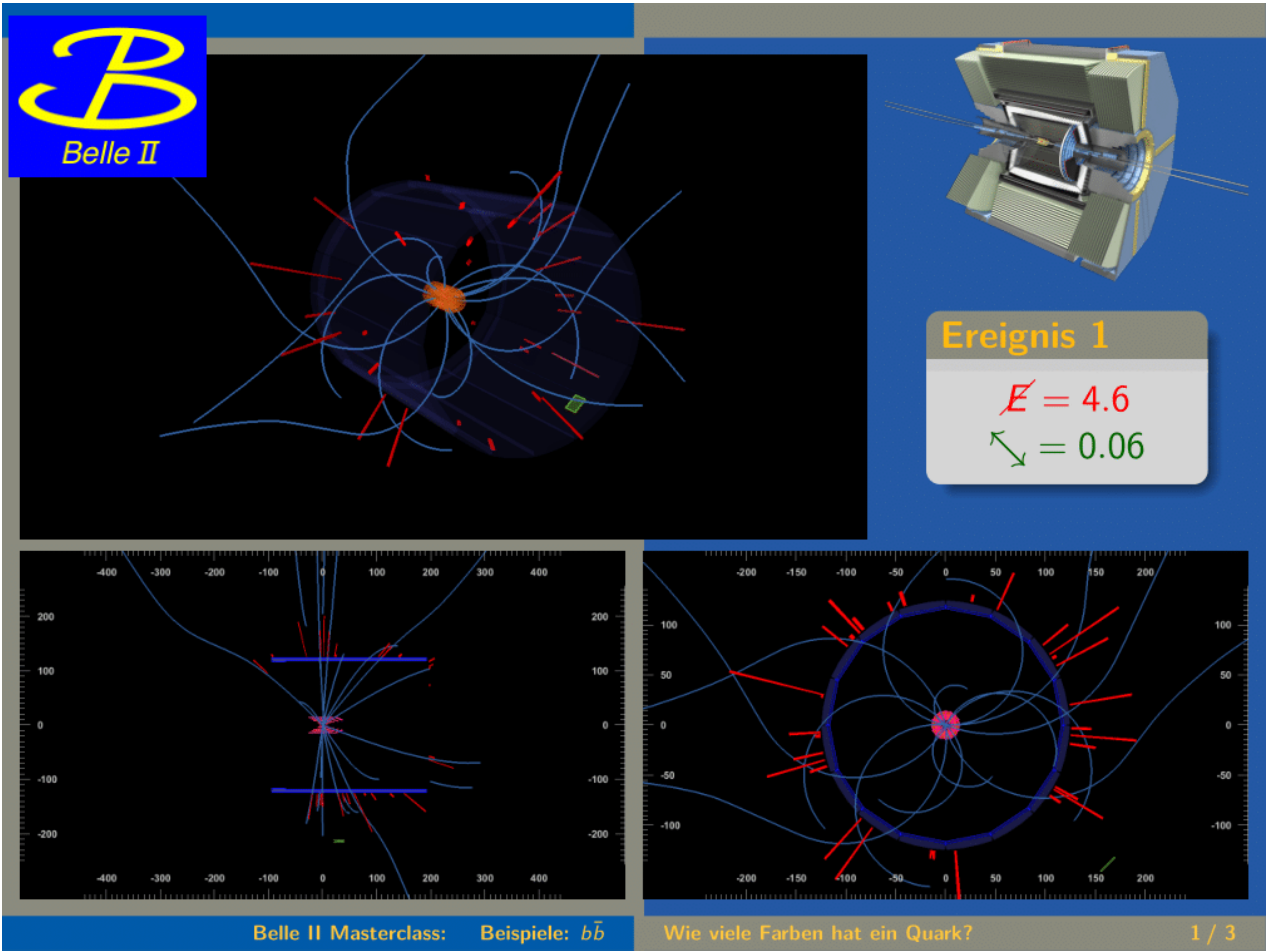
$b\bar{b}$ events: simplified display

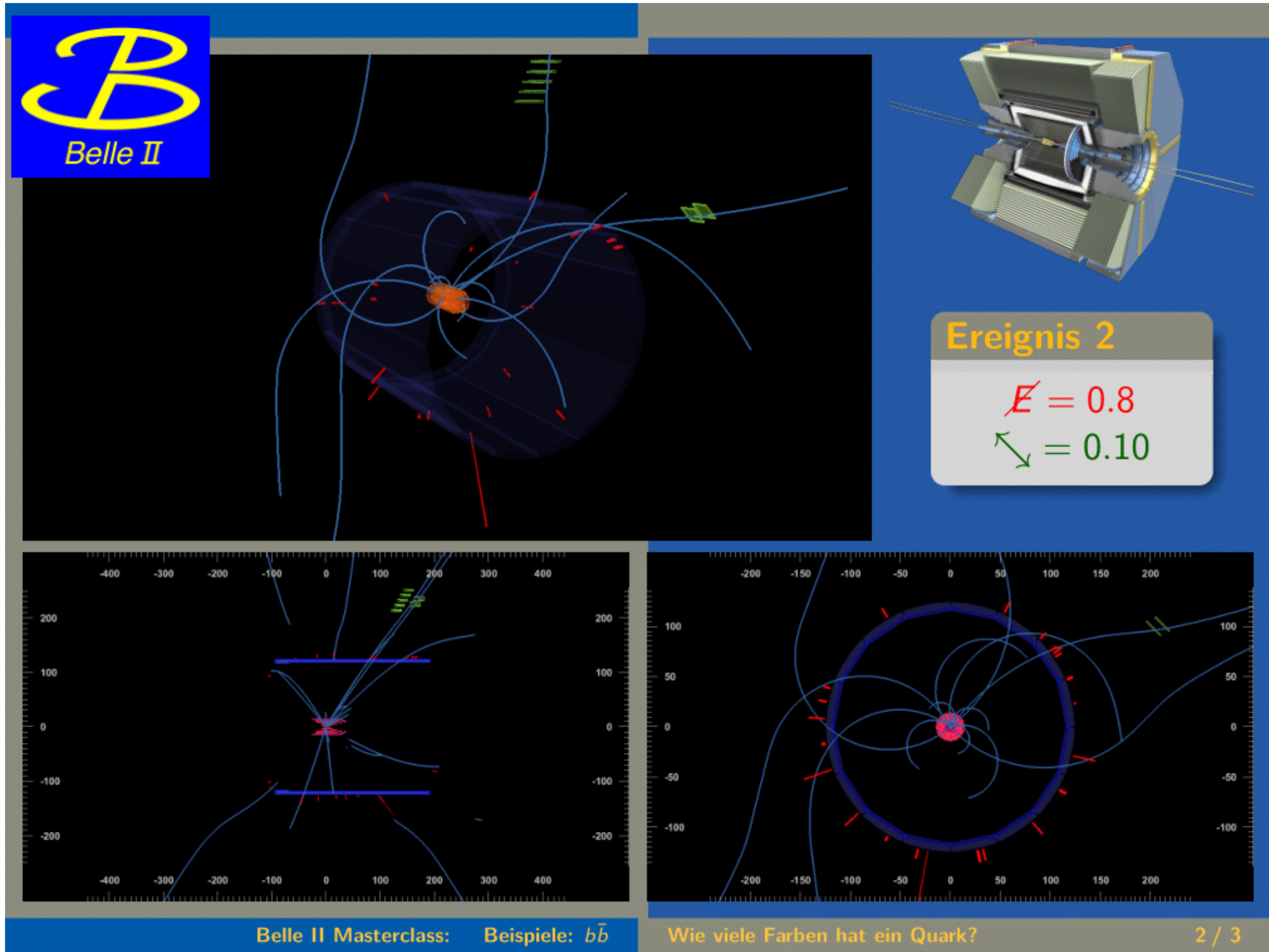






$b\bar{b}$ events: real event display





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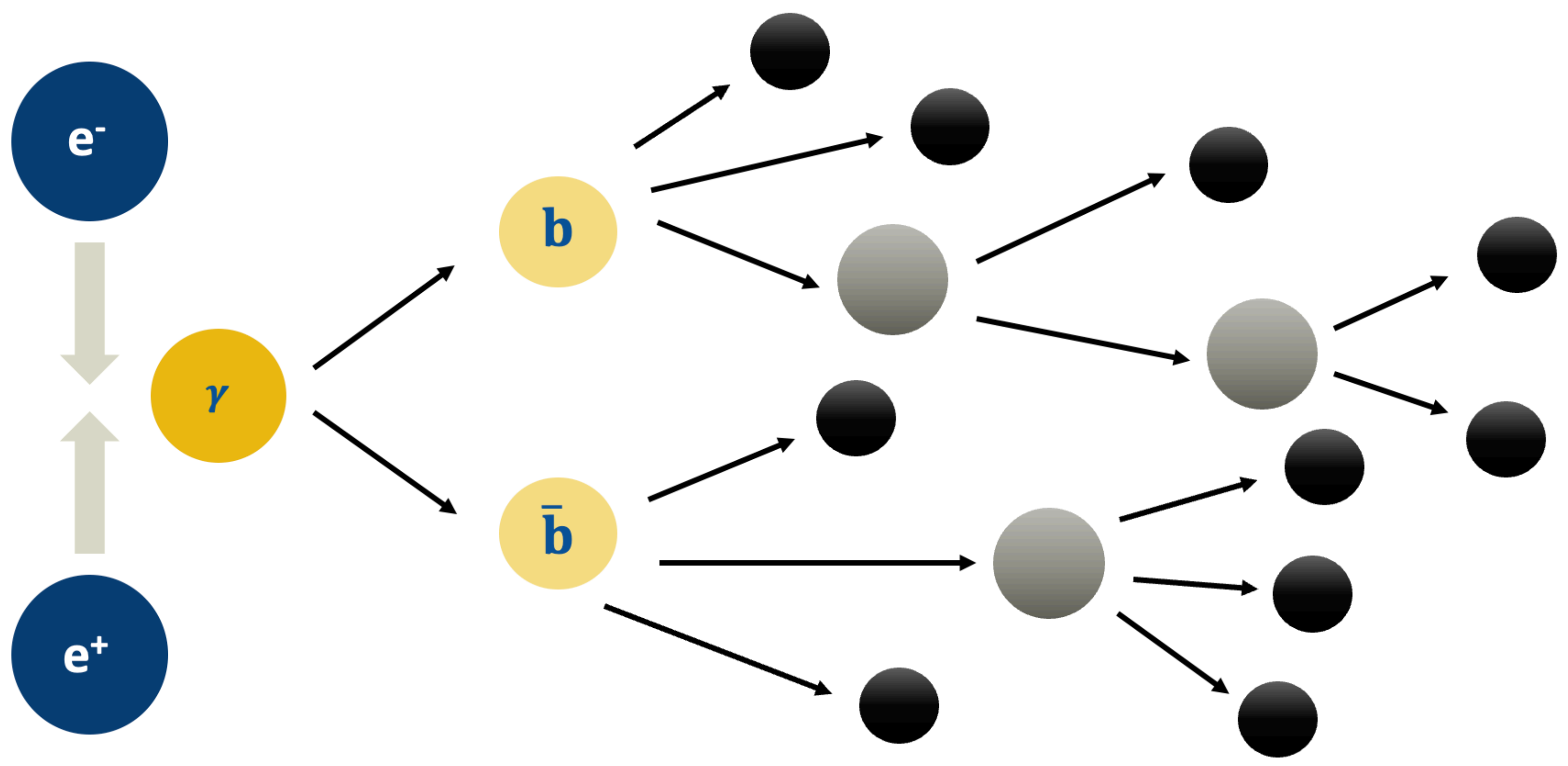
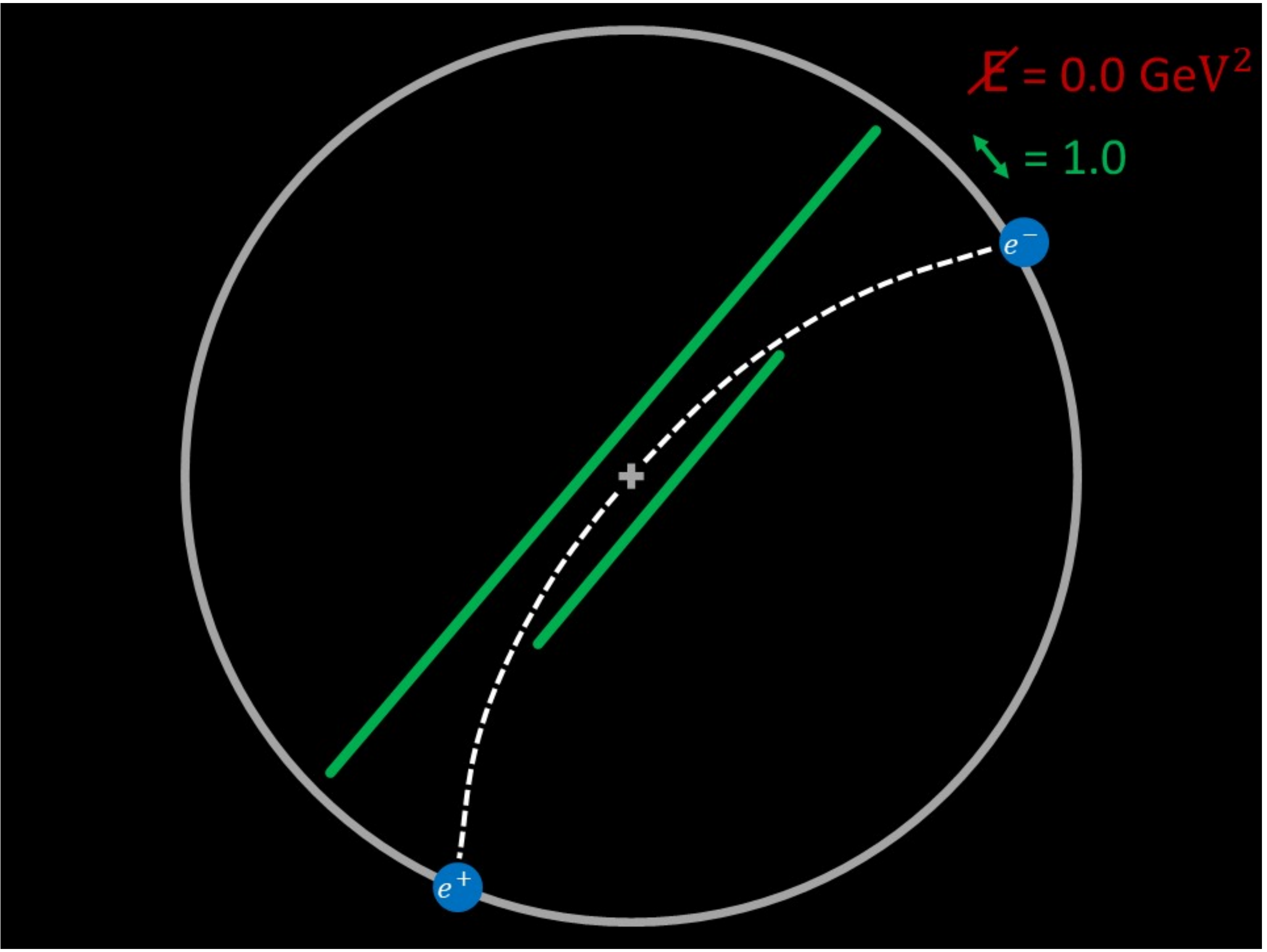
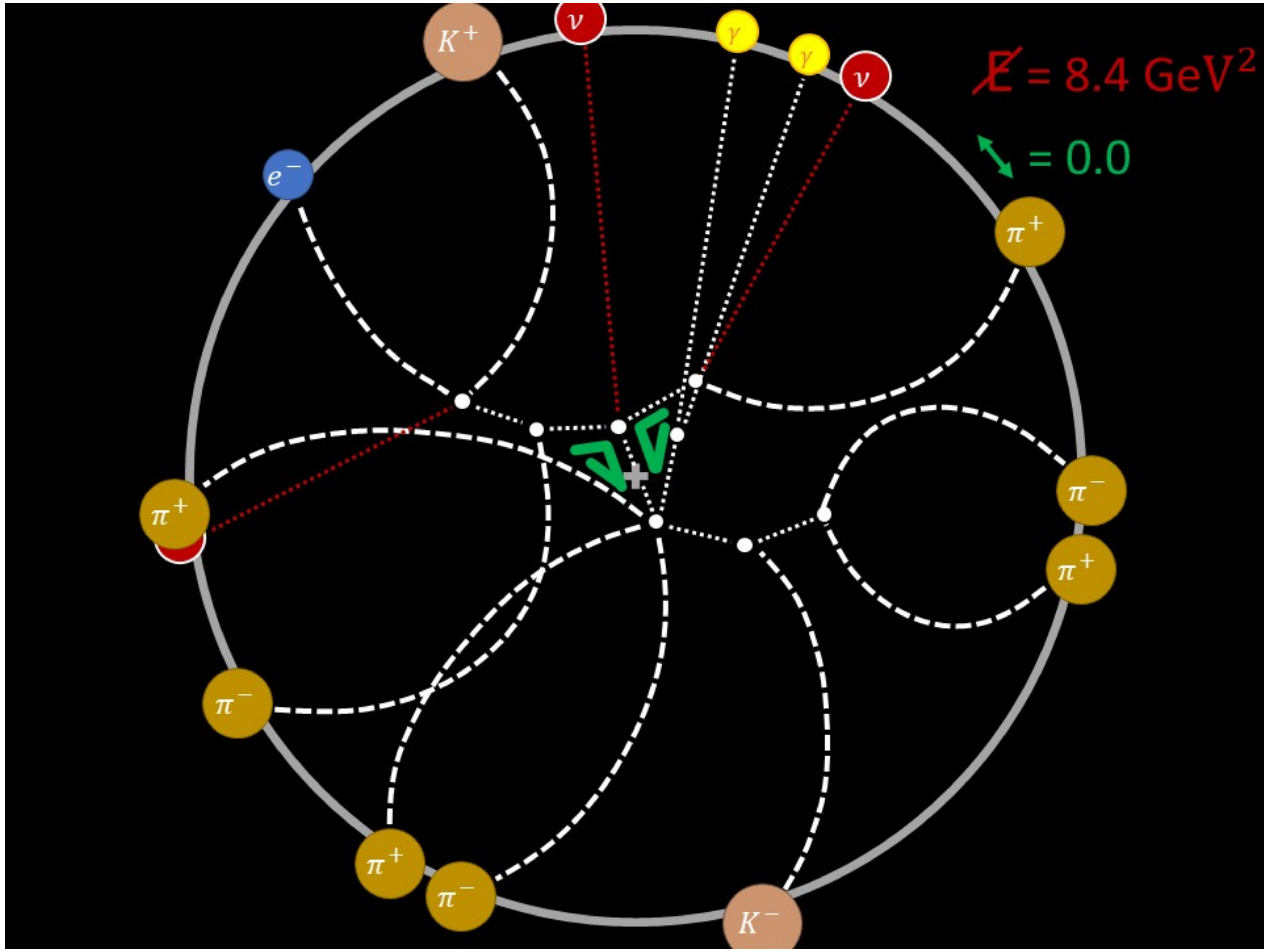


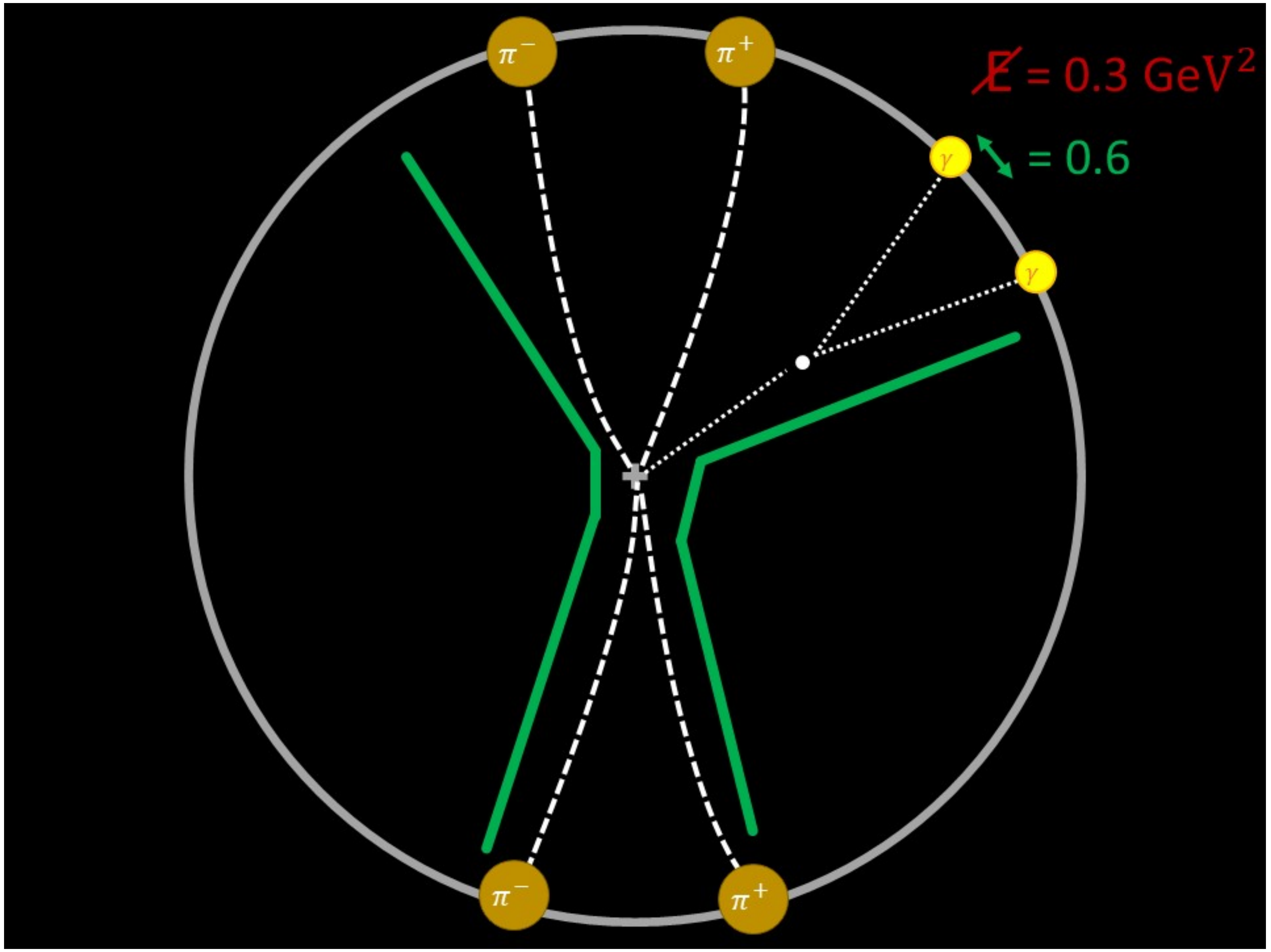
- Decay into a **large variety of final states**
- **Variable number of tracks**, large number is more frequent
- Heaviest particles possible: high energy ⇒**a lot of tracks**
- **Very low straightness** ↘ **:** "spherical" events than leptonic decays
- Sometimes neutrinos are produced: missing energy $\not{E}$ in some but not all the events
- Deposition of energy in the calorimeter (red signal close to the track)
- Sometimes deposit of energy in the muon detector (green signals along the outer track)

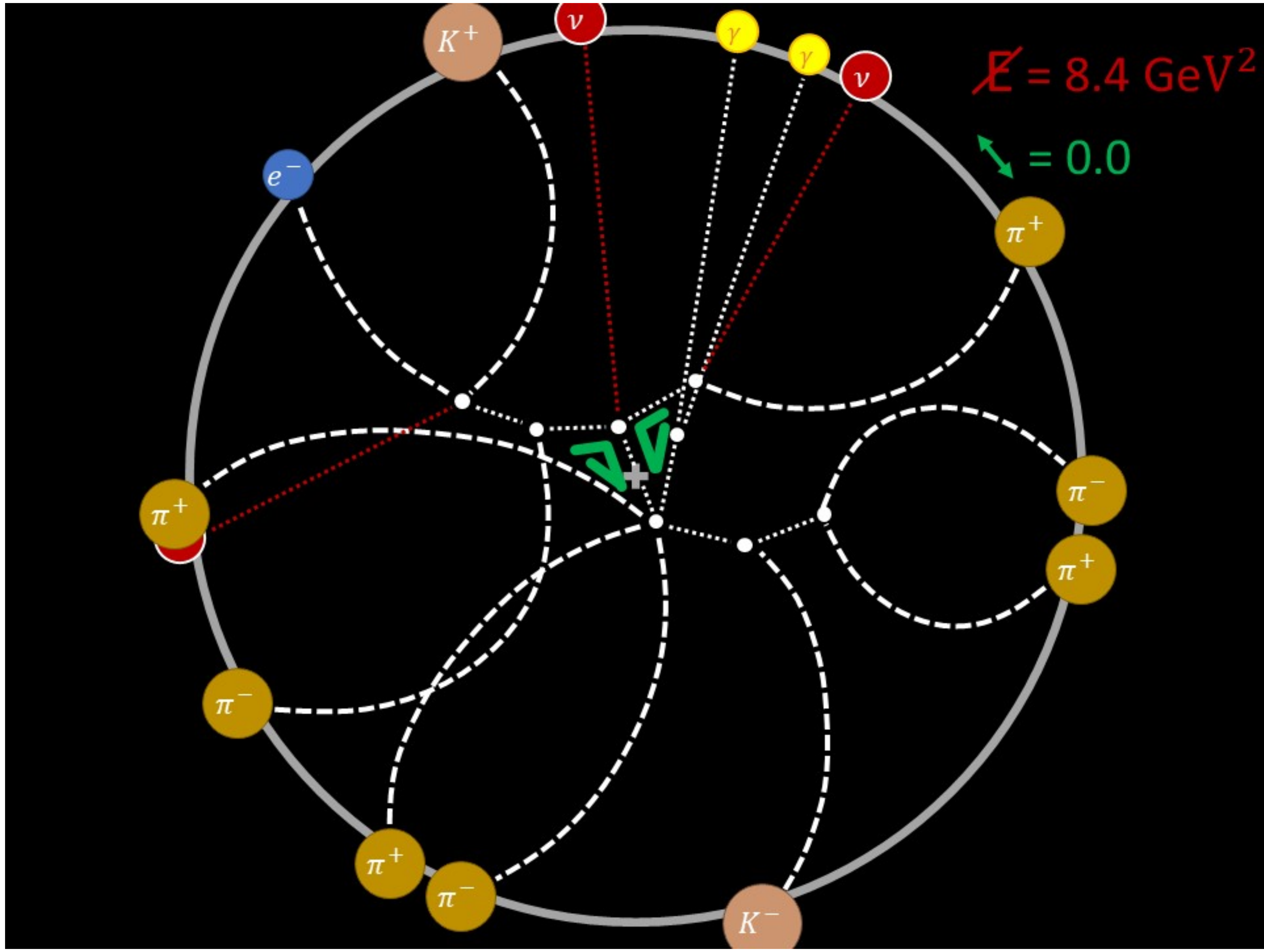
Comparison: e^+e^- vs $b\bar{b}$



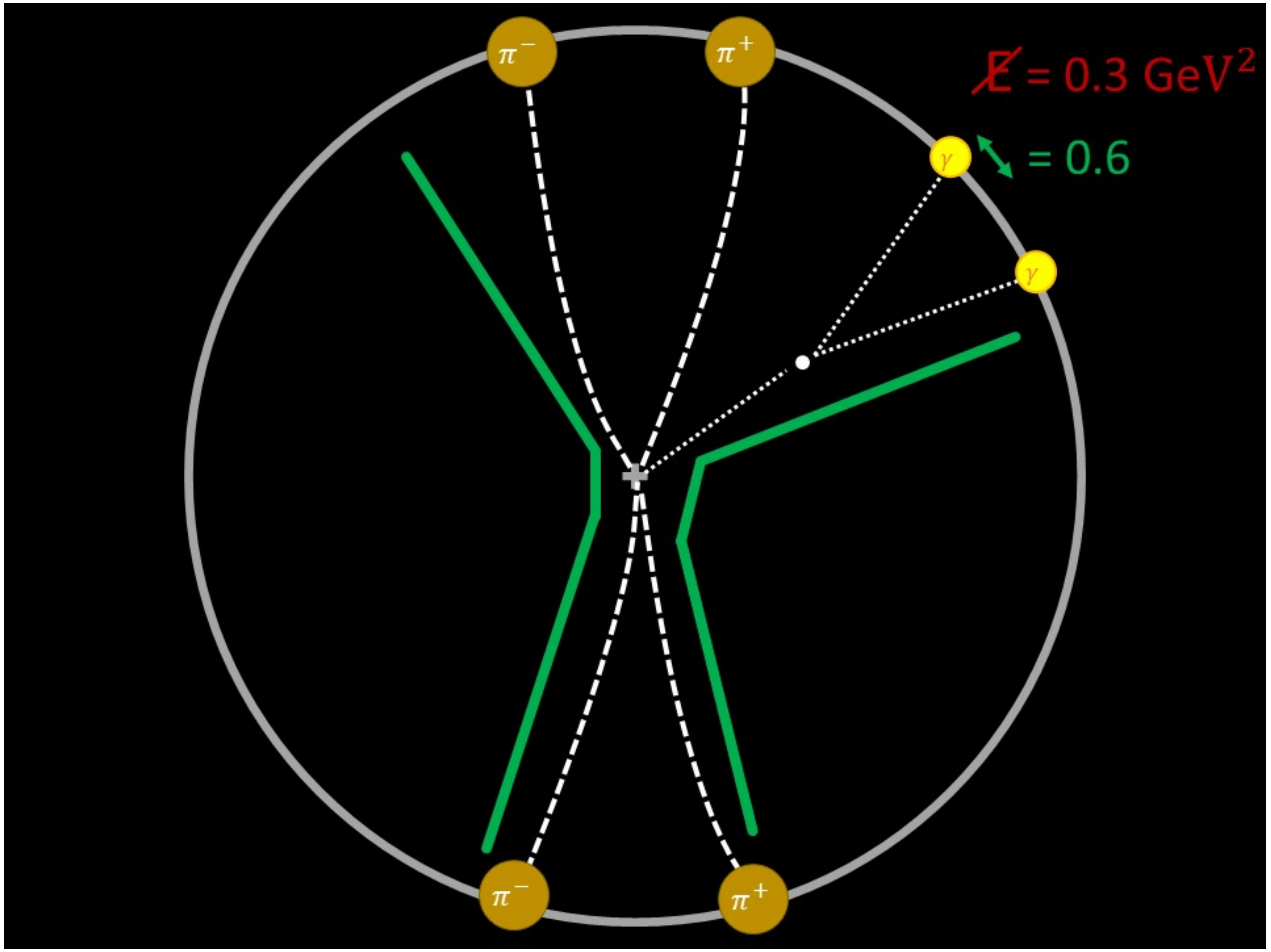


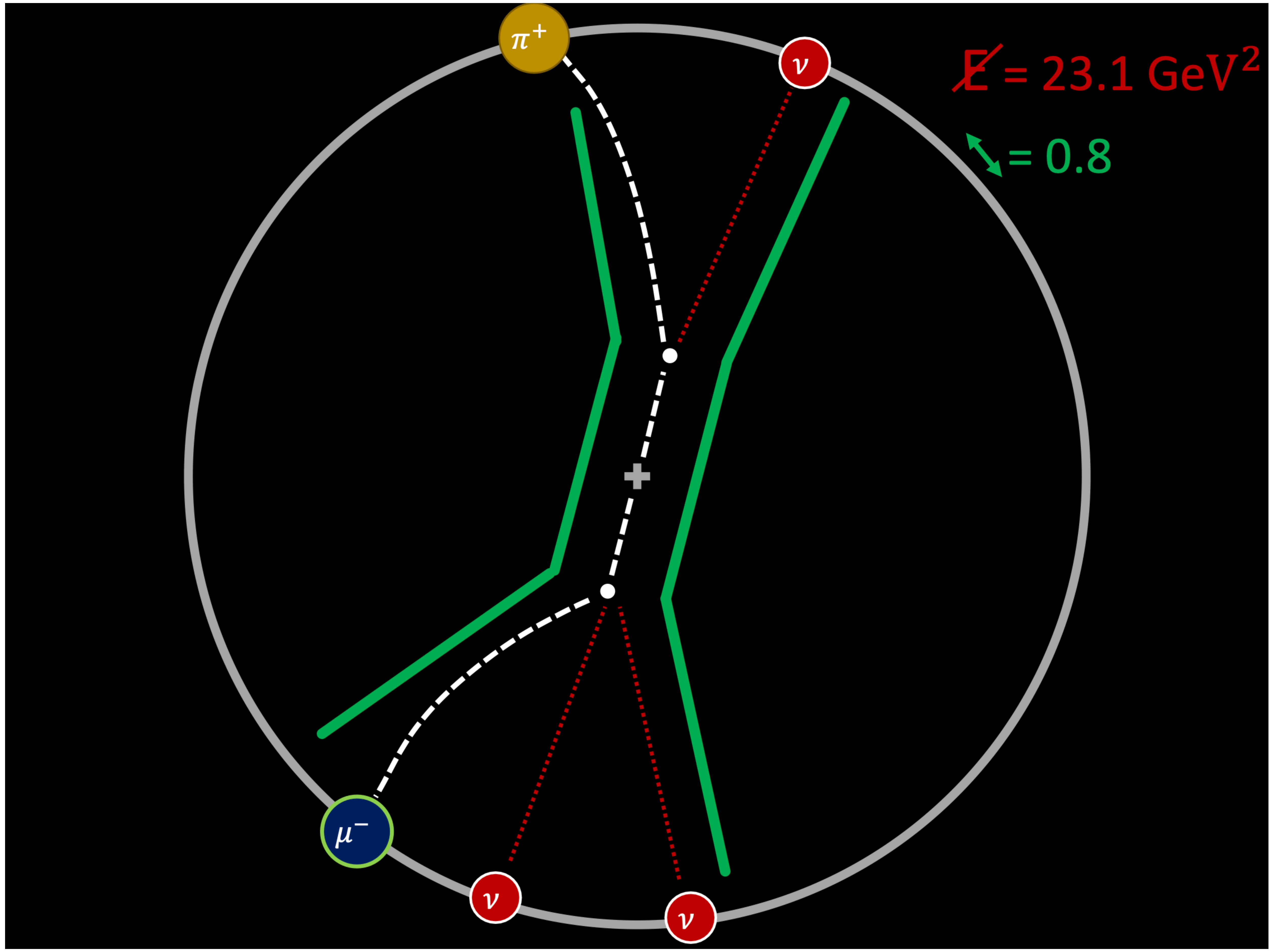
Comparison: $q\bar{q}$ vs $b\bar{b}$





Comparison: $q\bar{q}$ vs $\tau^+\tau^-$





R-value again

- Why we have no $b\bar{b}$ in our R-value definition?

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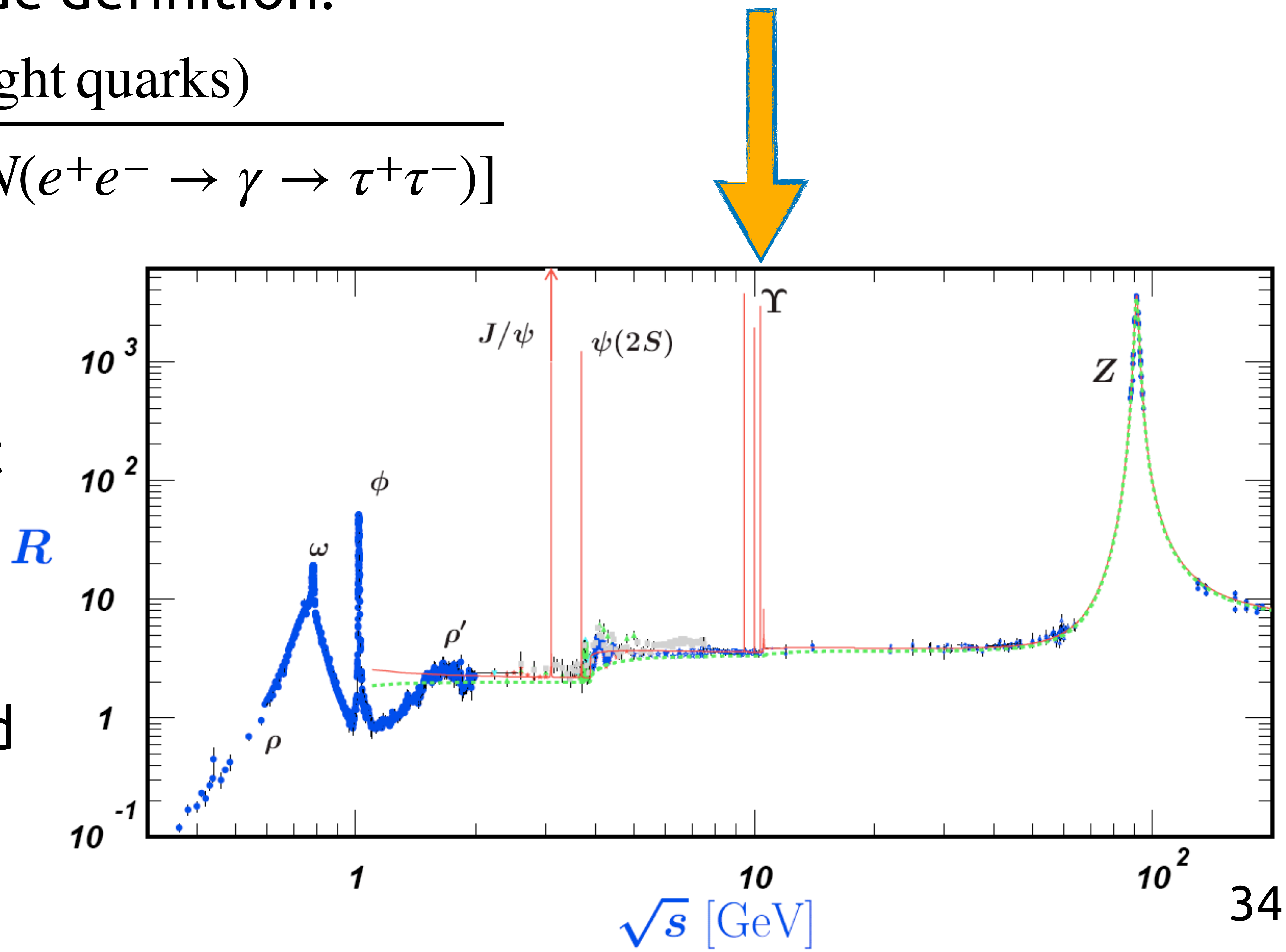
- Because at Belle II we are running at center-of-mass energy of $\Upsilon(4S)$ resonance, just at $B\bar{B}$ threshold (B is a meson with a b quark)



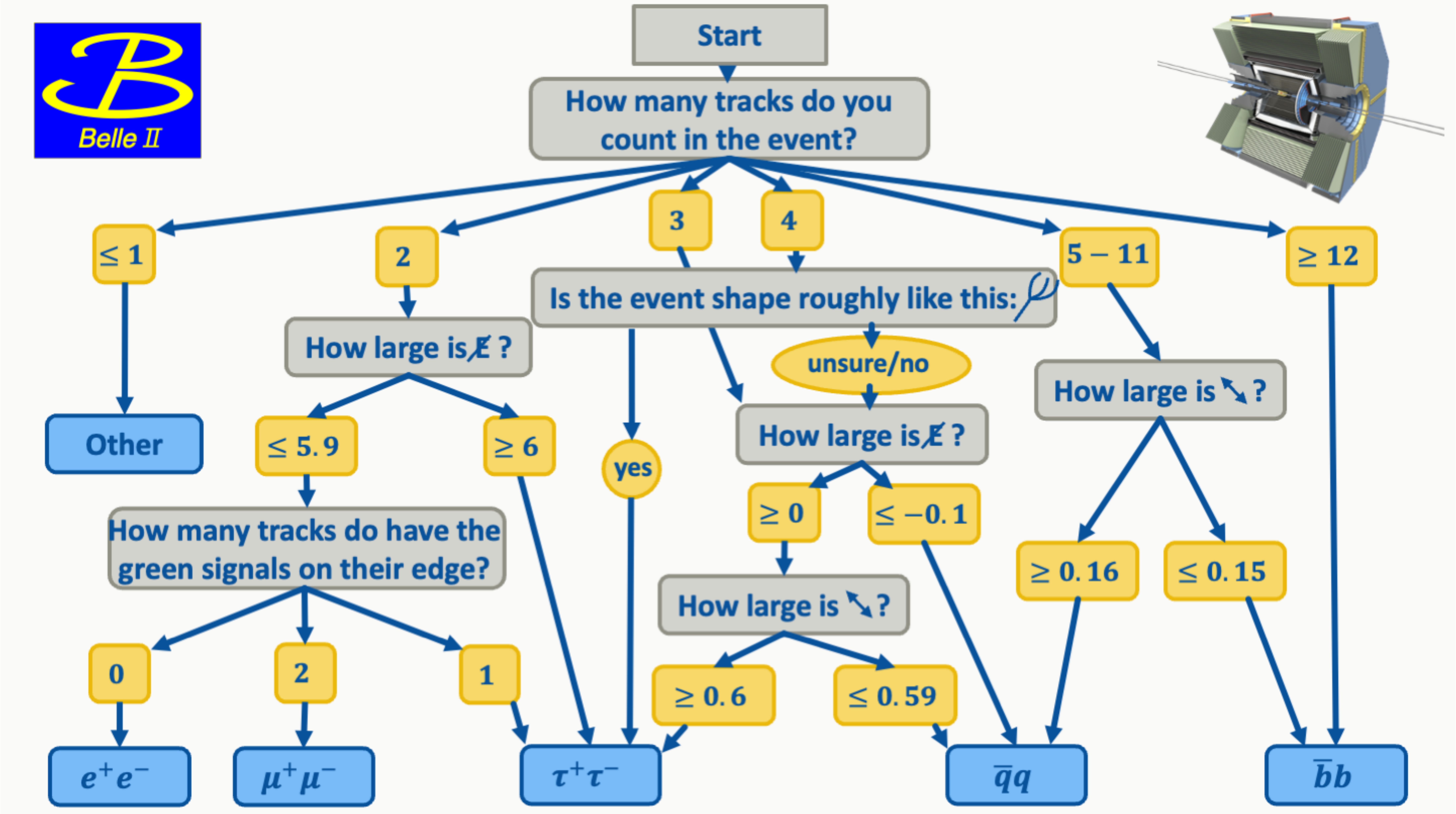
- The production of b is enhanced there

- This makes Belle II a "B-factory"

Large numbers importance

- Every measurement is affected by uncertainty
- The collision process $e^+e^- \to XYZ$ is stochastic:
  - the individual decay can not be predicted
  - the **statistical behaviour** can be!
- You have to repeat a measurement **a lot of times**, reducing the statistical uncertainty

Summary scheme



Data analysis page

Belle II experiment

HOME | INTRO | BELLE II | RECONSTRUCT B MESONS | MEASURE QUARK COLORS | EVENTS | WHAT YOU LEARNED

How many colors does a quark come in?

The exchange particle of the electroweak force is the photon. It couples to particles with an electromagnetic charge. This charge can either be positive or negative. The exchange particle of the strong force, the gluon, couples just like the to particles that carry a so called **color charge**.

Today we want to experimentally determine the number of possible color charges (or simply colors) with data of the **Belle II experiment**.

To that end we should first approach the subject from the theoretical side. To start with we should take a look at the so called *R*-value.

- What is the *R*-value?

After that we're ready to look at the experimental measurement, to determine the number of color charges.

- Example Events
- Practice Task
- Measurement with data from the Belle II experiment

Data analysis page

Worksheet (also printed)

Belle II experiment

HOME | INTRO | BELLE II | RECONSTRUCT B MESONS ▾ | MEASURE QUARK COLORS ▾

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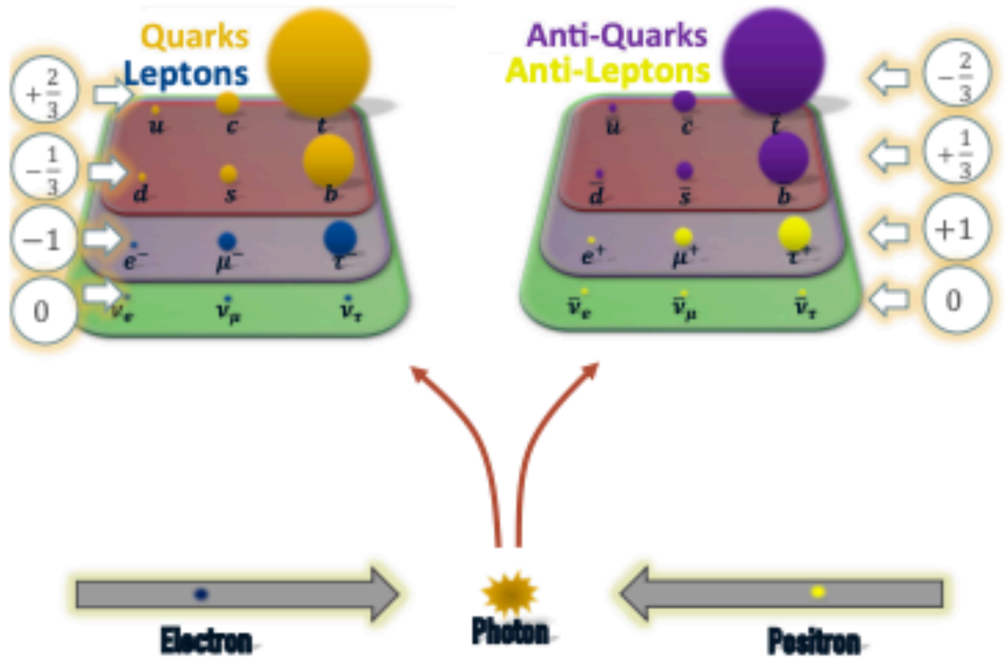
What happens in e^+e^- collisions?
Quark colors and the R value

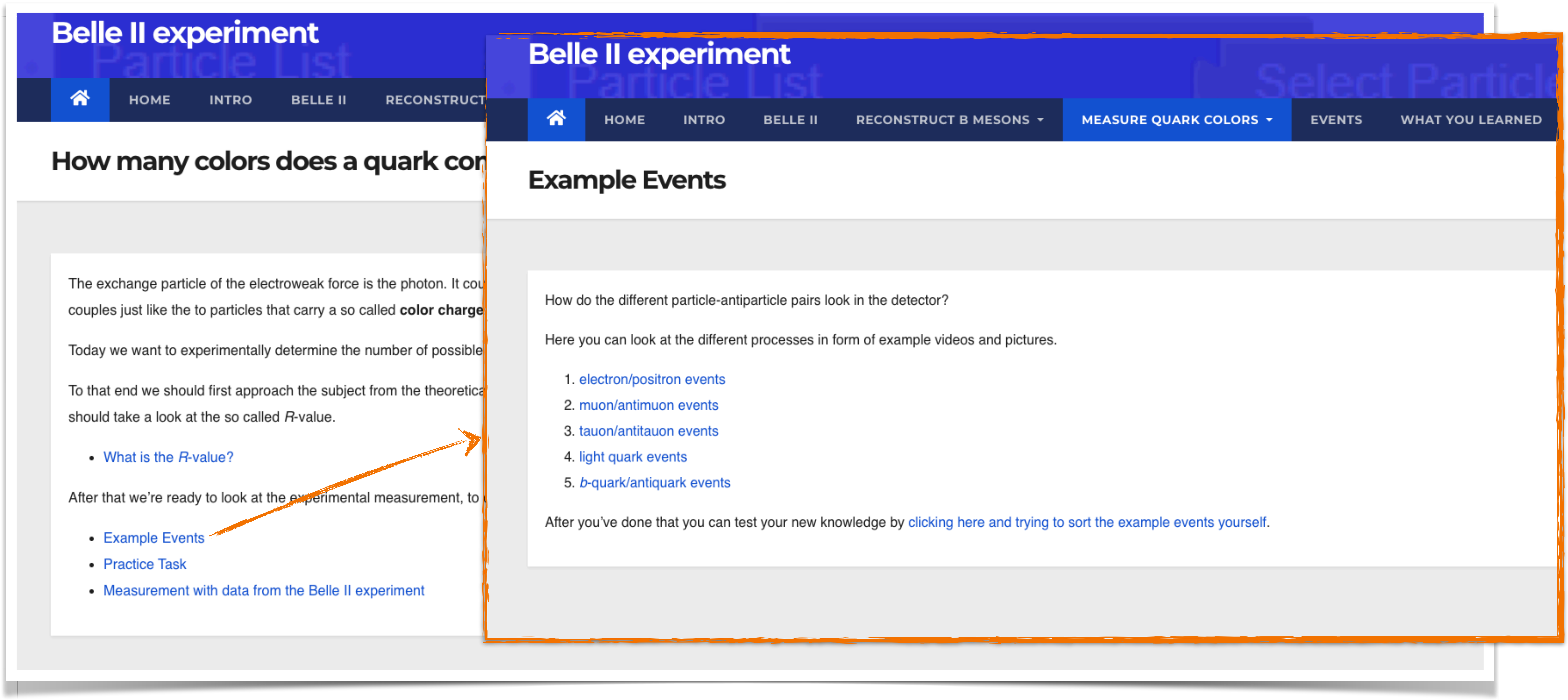
Belle II Masterclass

In this masterclass we want to investigate how many different quark color charges exist. For this purpose, it is worth to take some time to understand what exactly happens during an e^+e^- collision. Especially important for us is the type of particles that can be created and how often this happens.
If a particle and antiparticle collide (like in this example an electron e^- and a positron e^+), they „annihilate“ to a state of pure energy: a photon. Subsequently, this photon can use the energy to create an arbitrary particle P as well as an antiparticle $\bar{P}$ as long as the energy is high enough.



Data analysis page

Example events, with video/ explanation for each category



Data analysis page

Main task: every group picks a dataset, categorizes the the events and report the results in the linked table

Belle II experiment

Particle List

HOME | INTRO | BELLE II | RECONSTRUCT B MESONS ▾ | MEASURE QUA

How many colors does a quark come in?

The exchange particle of the electroweak force is the photon. It couples to particles with an electromagne couples just like the to particles that carry a so called **color charge**.

Today we want to experimentally determine the number of possible color charges (or simply colors) with

To that end we should first approach the subject from the theoretical side. To start with we should take a look at the so called *R*-value.

- What is the *R*-value?

After that we're ready to look at the experimental measurement, to determine the number of color charge

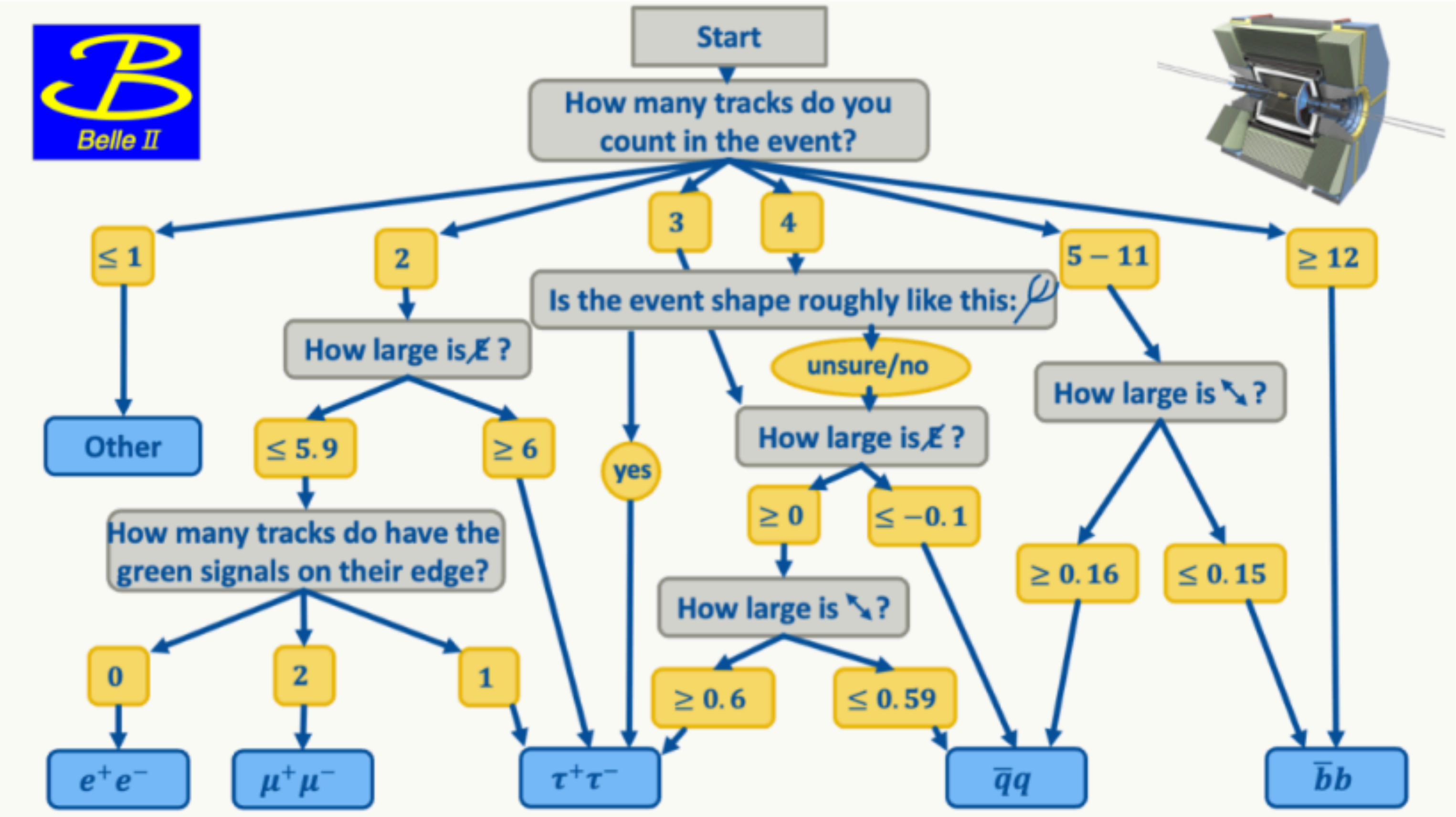
- Example Events
- Practice Task
- Measurement with data from the Belle II experiment

Main Task

Select the data set that the facilitators assigned to you out of the ones linked below. Try to sort all of the 50 events from the set. Like in the practice task, it is helpful to use the event-identification-flowchart for that.

Enter your results into this table.

If you are unsure, take another look at the example– or practice events and/or don't hesitate to ask the facilitators.

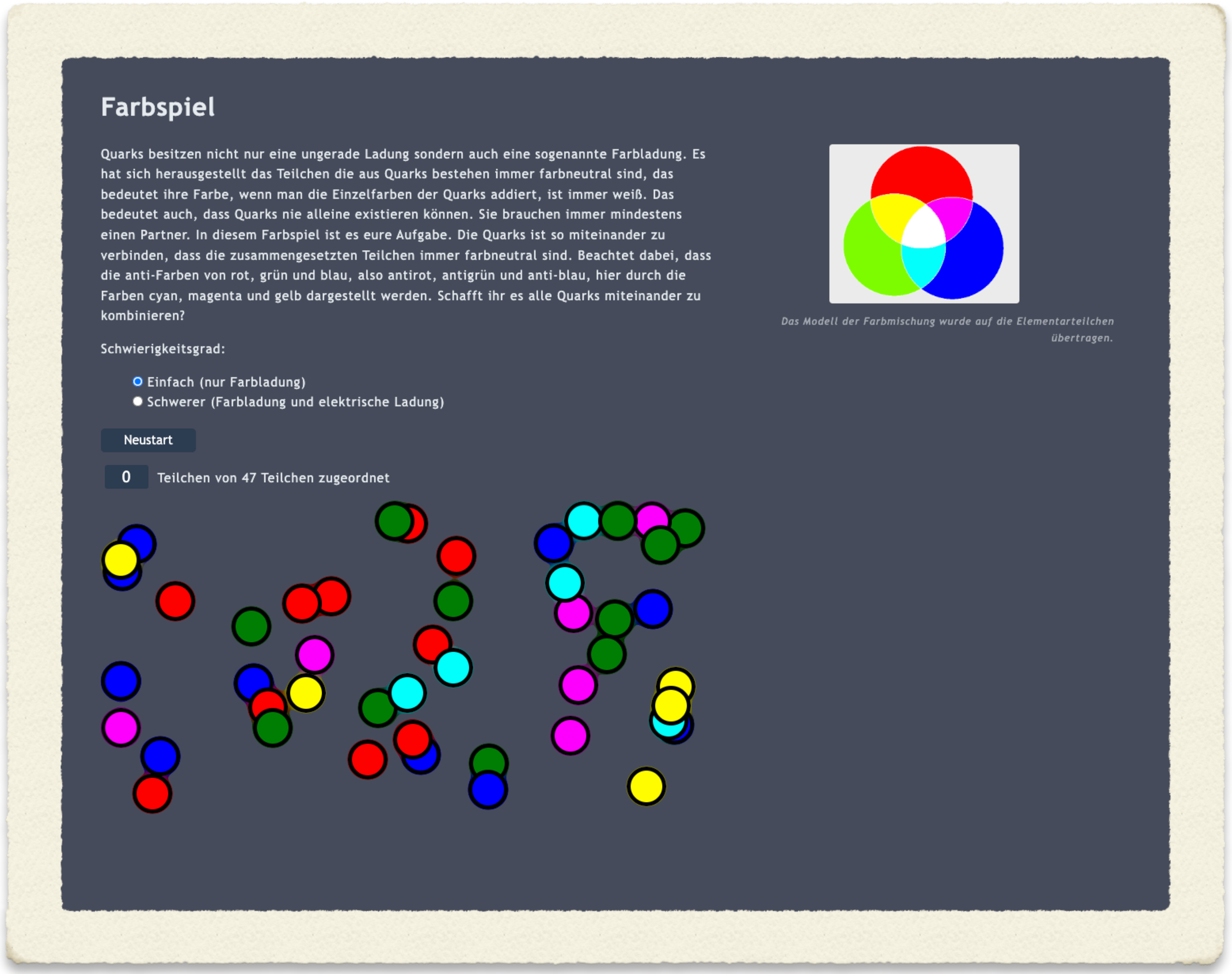


- Data set A
- Data set B
- Data set C
- Data set D
- Data set E
- Data set F
- Data set G
- Data set H
- Data set I
- Data set J
- Data set K
- Data set L
- Data set M
- Data set N
- Data set O
- Data set P
- Data set Q

chose between datasets: K, L, M, N, O, P

Extra: quark colors game

- If you finish in advance there is the quark-colors game:
- https://online.schule.physik.uni-mainz.de/teilchenspiele/farbspiel/



Now is your turn!

BACKUP SLIDES