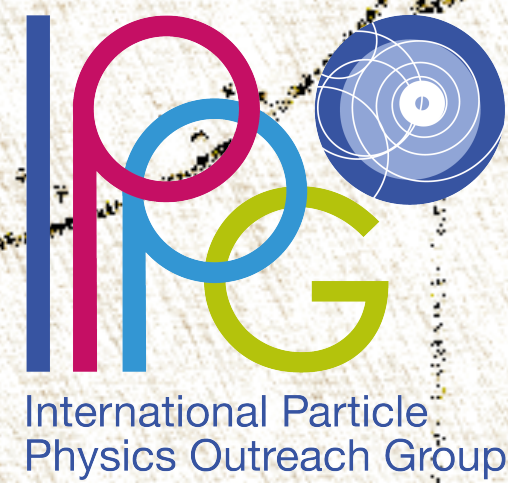


Quark Colors and R-Value

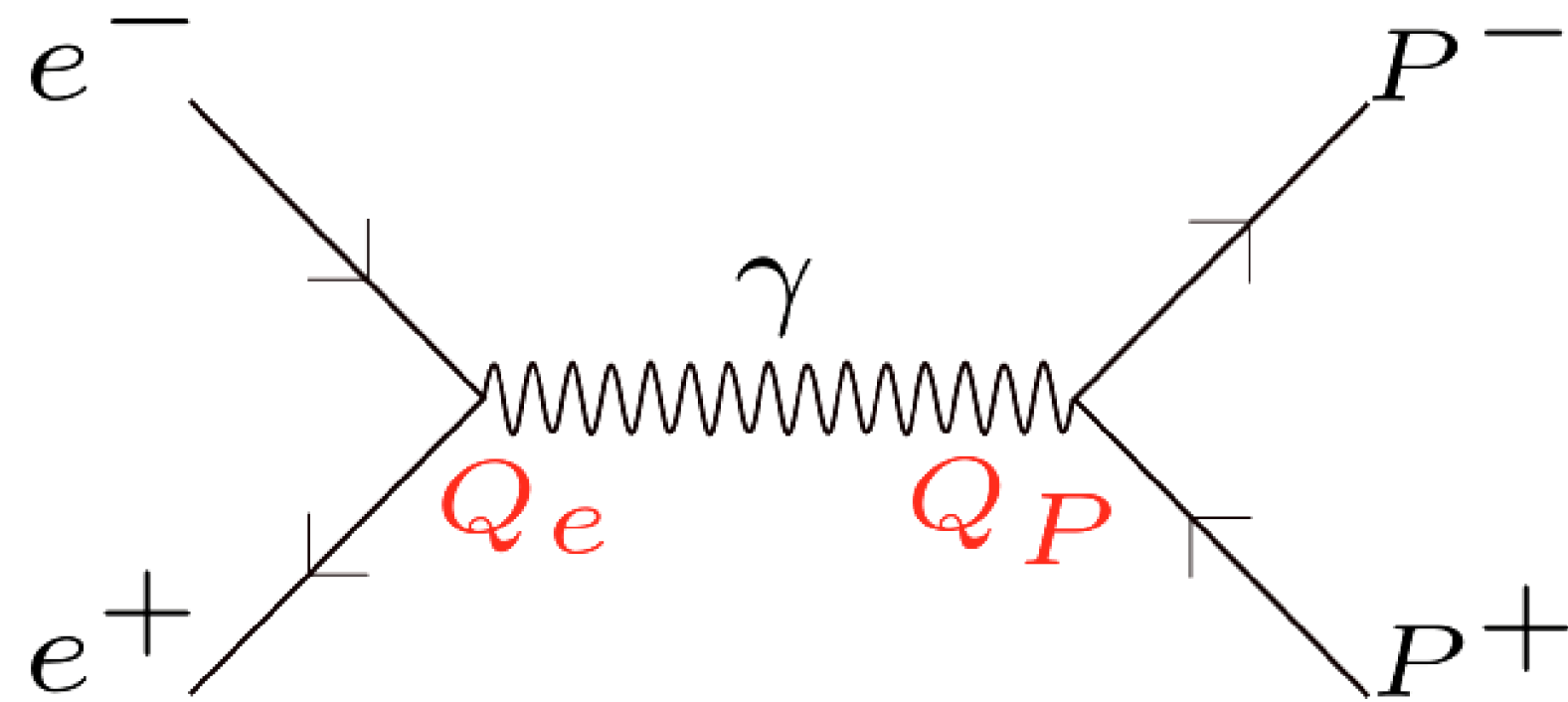
2025 Belle II International masterclass

Valerio Bertacchi
11 March 2025
Bonn



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^-

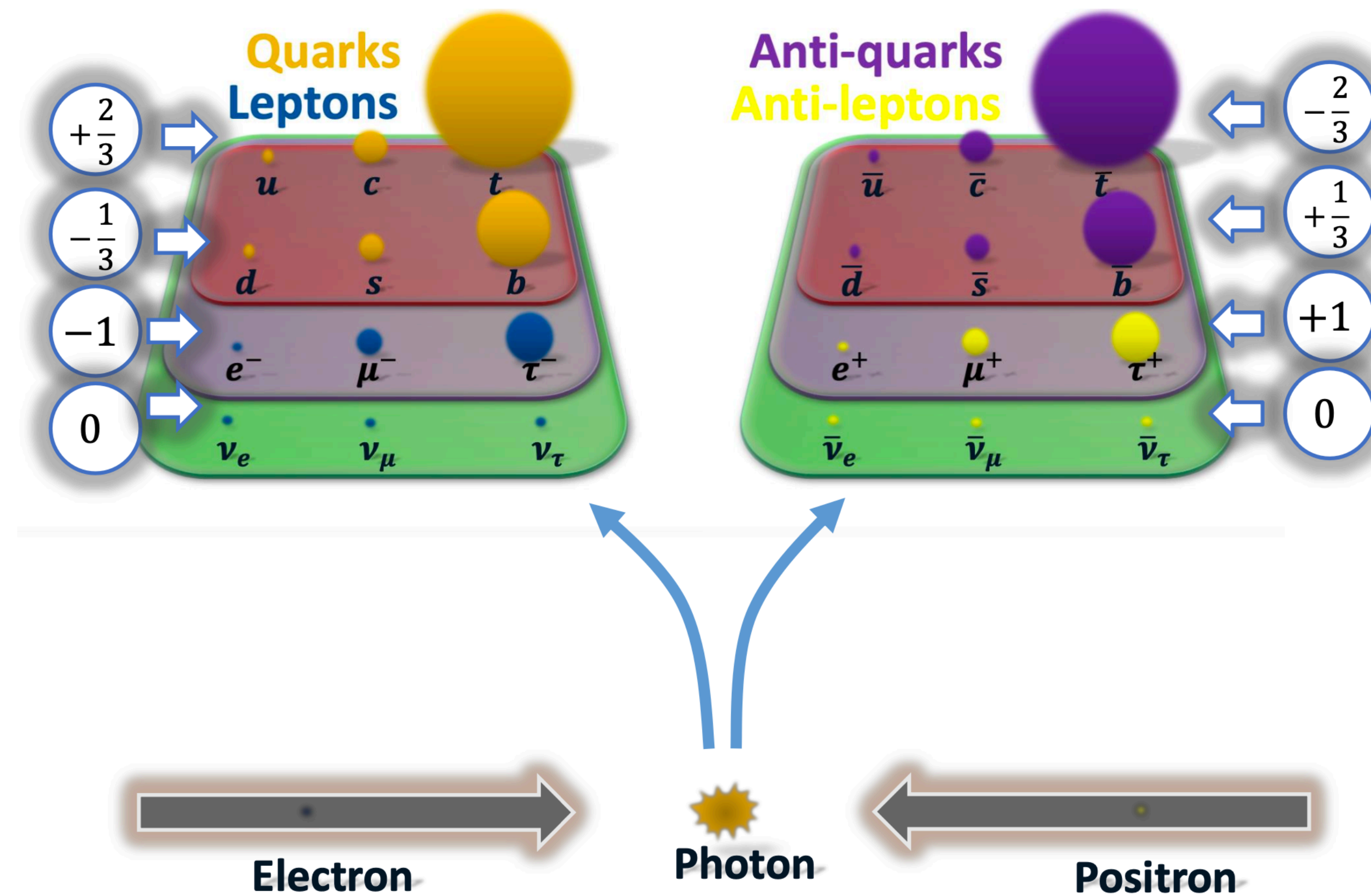


- The probability of the interaction is proportional to the charge of P squared:

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

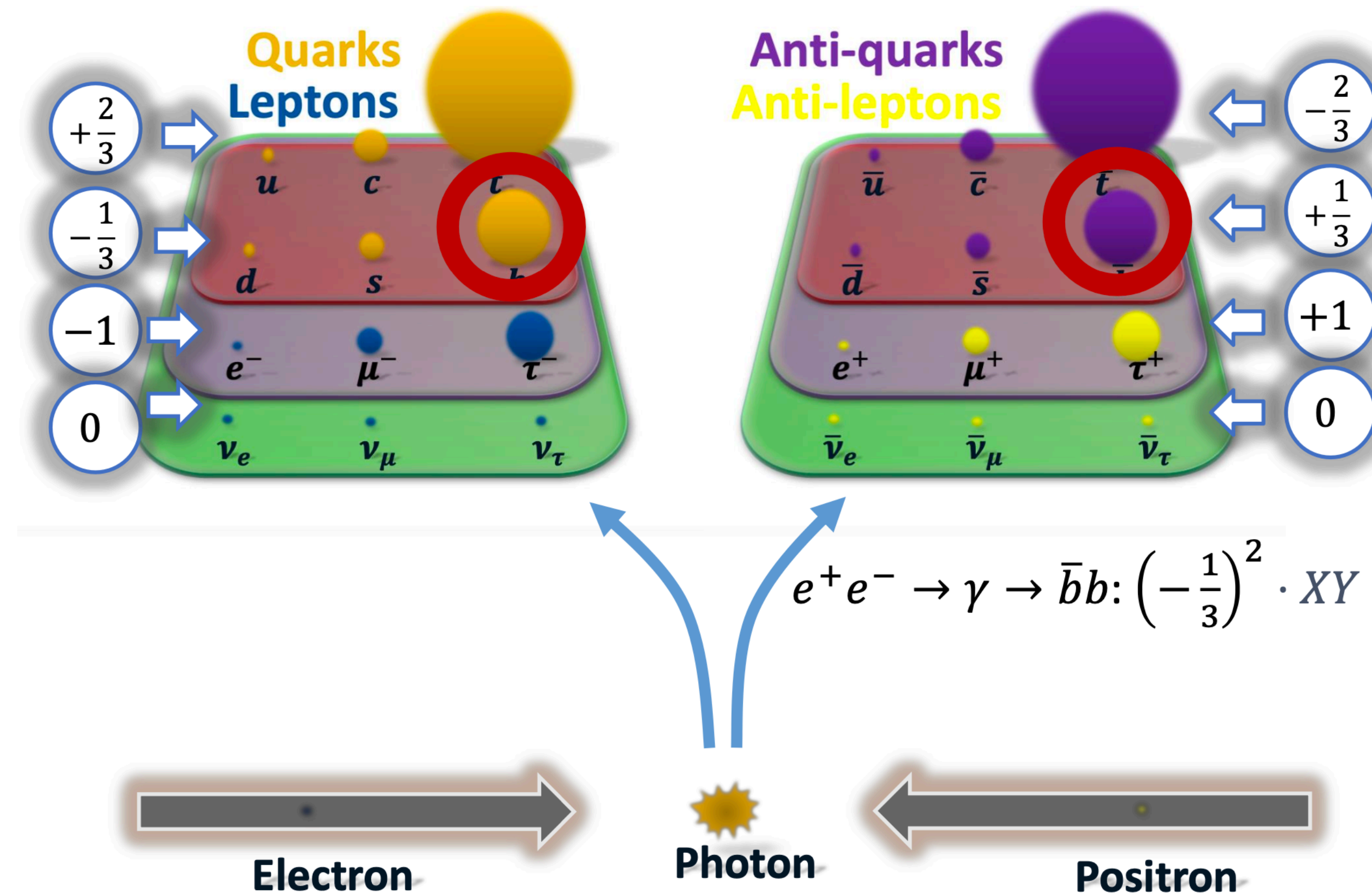
e^+e^- interactions: some examples

This is the full set of charges:



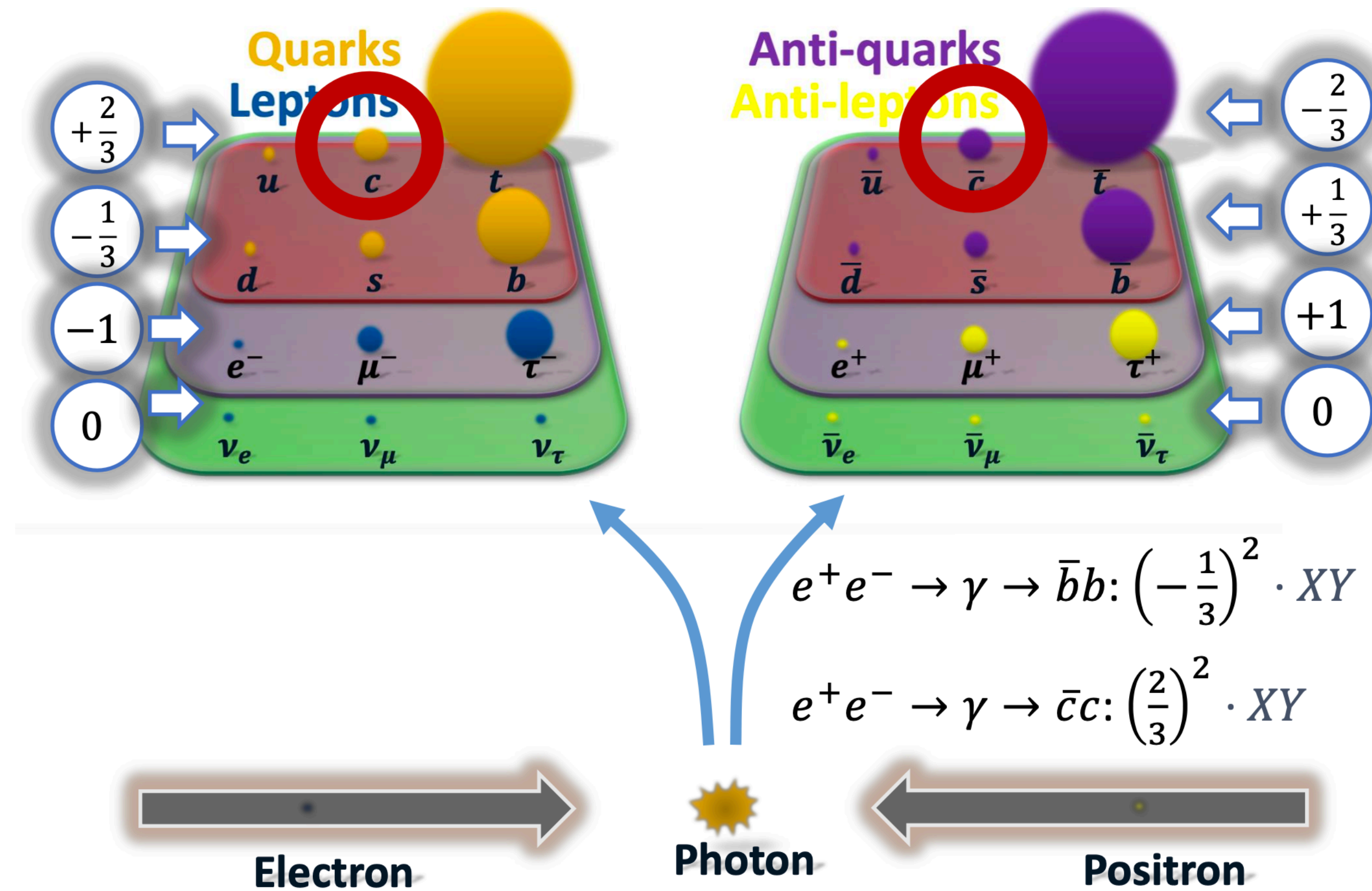
e^+e^- interactions: some examples

- $b\bar{b}$ quarks production



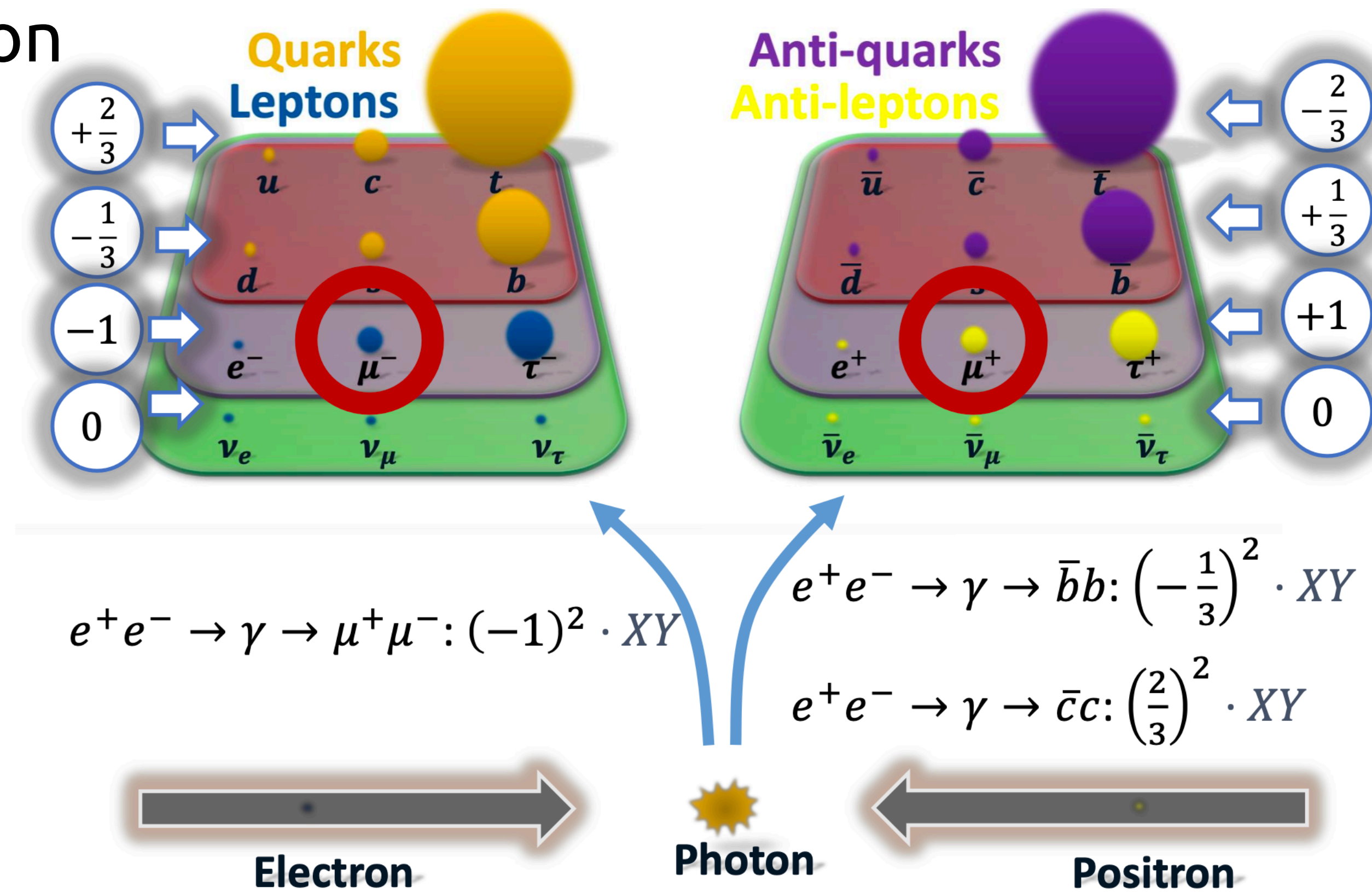
e^+e^- interactions: some examples

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



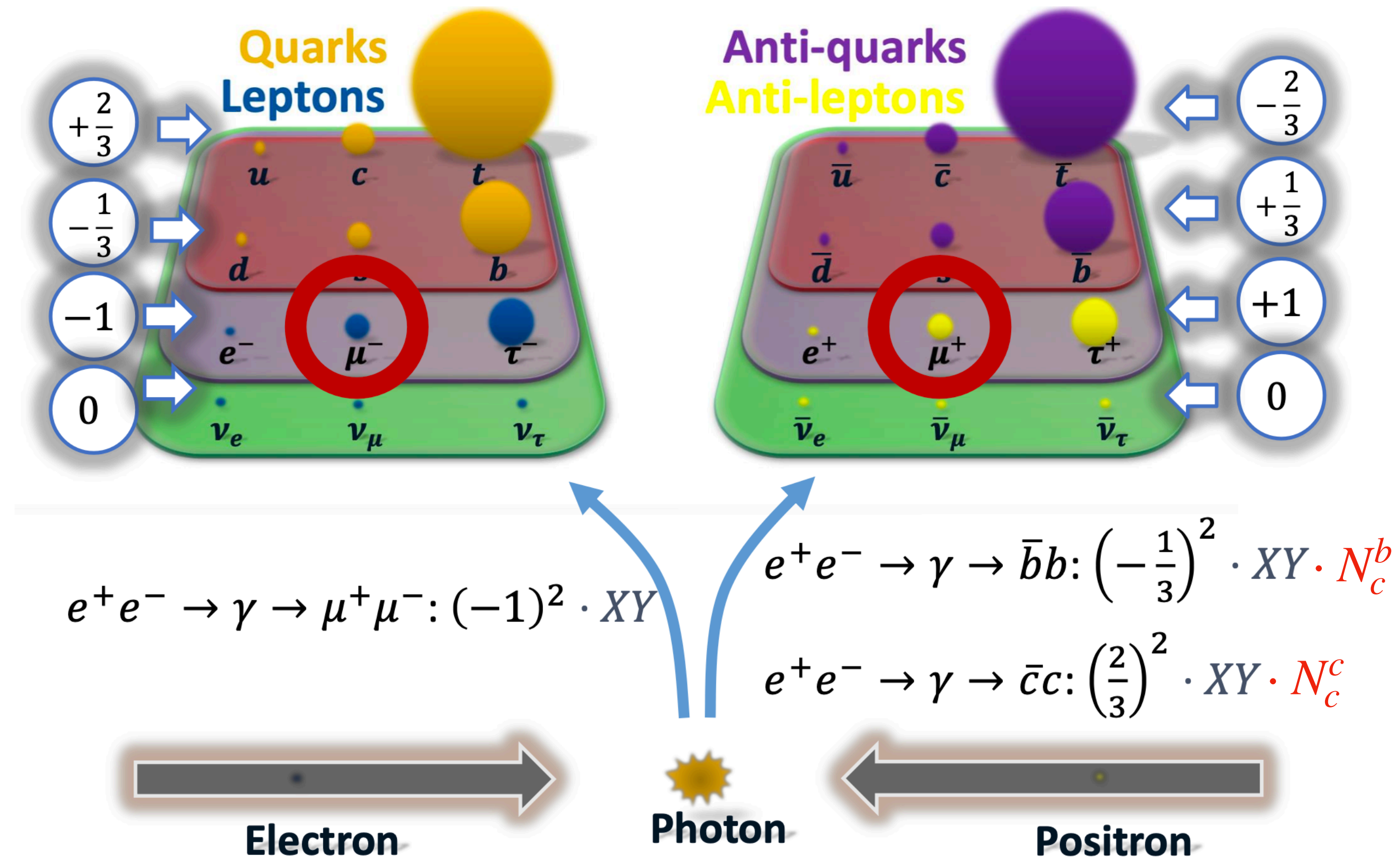
e^+e^- interactions: some examples

- $b\bar{b}$ 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

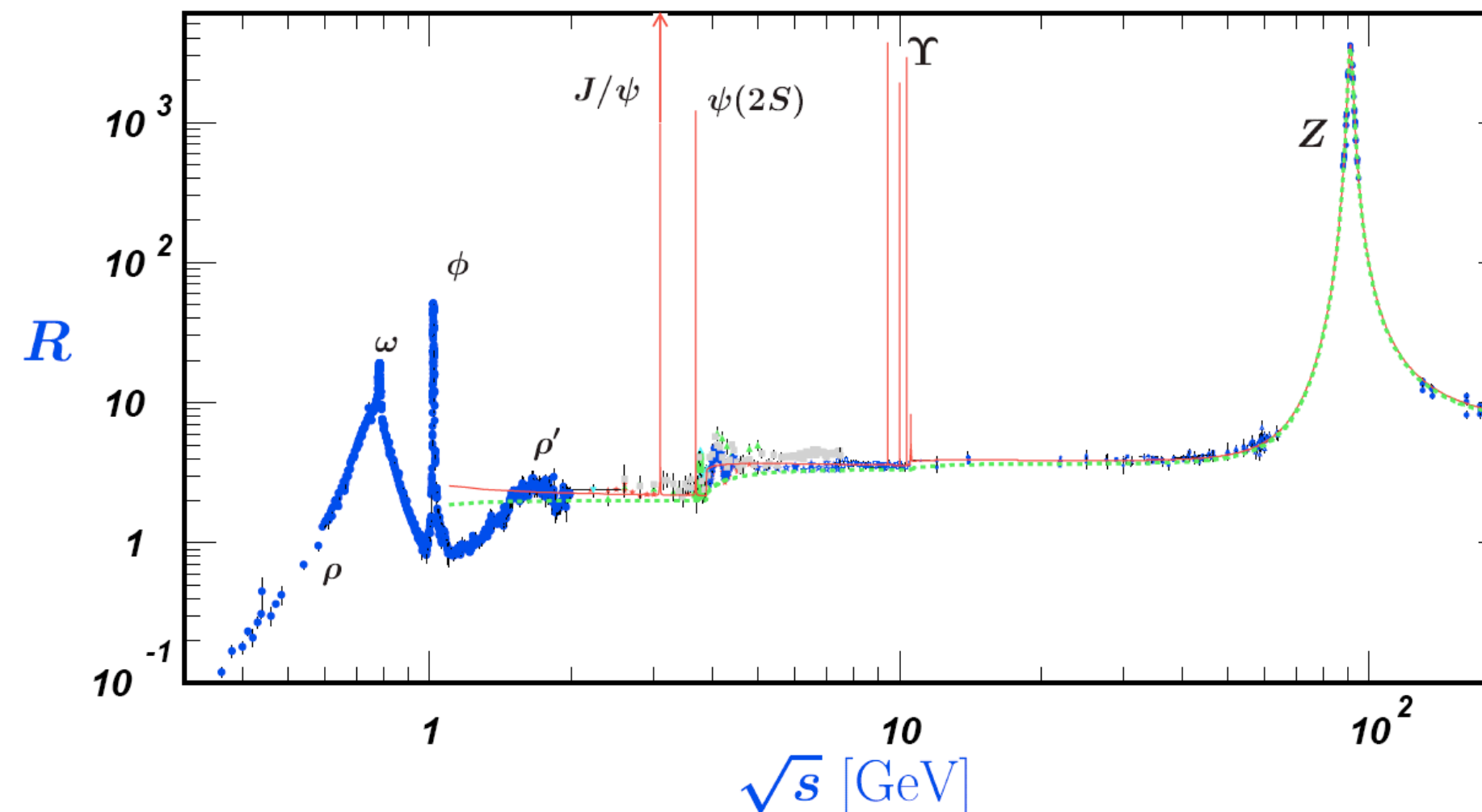
- We define:
$$R = \frac{N(e^+e^- \rightarrow \gamma \rightarrow \text{light quarks})}{\frac{1}{2}[N(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-) + N(e^+e^- \rightarrow \gamma \rightarrow \tau^+\tau^-)]}$$

R-Value

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

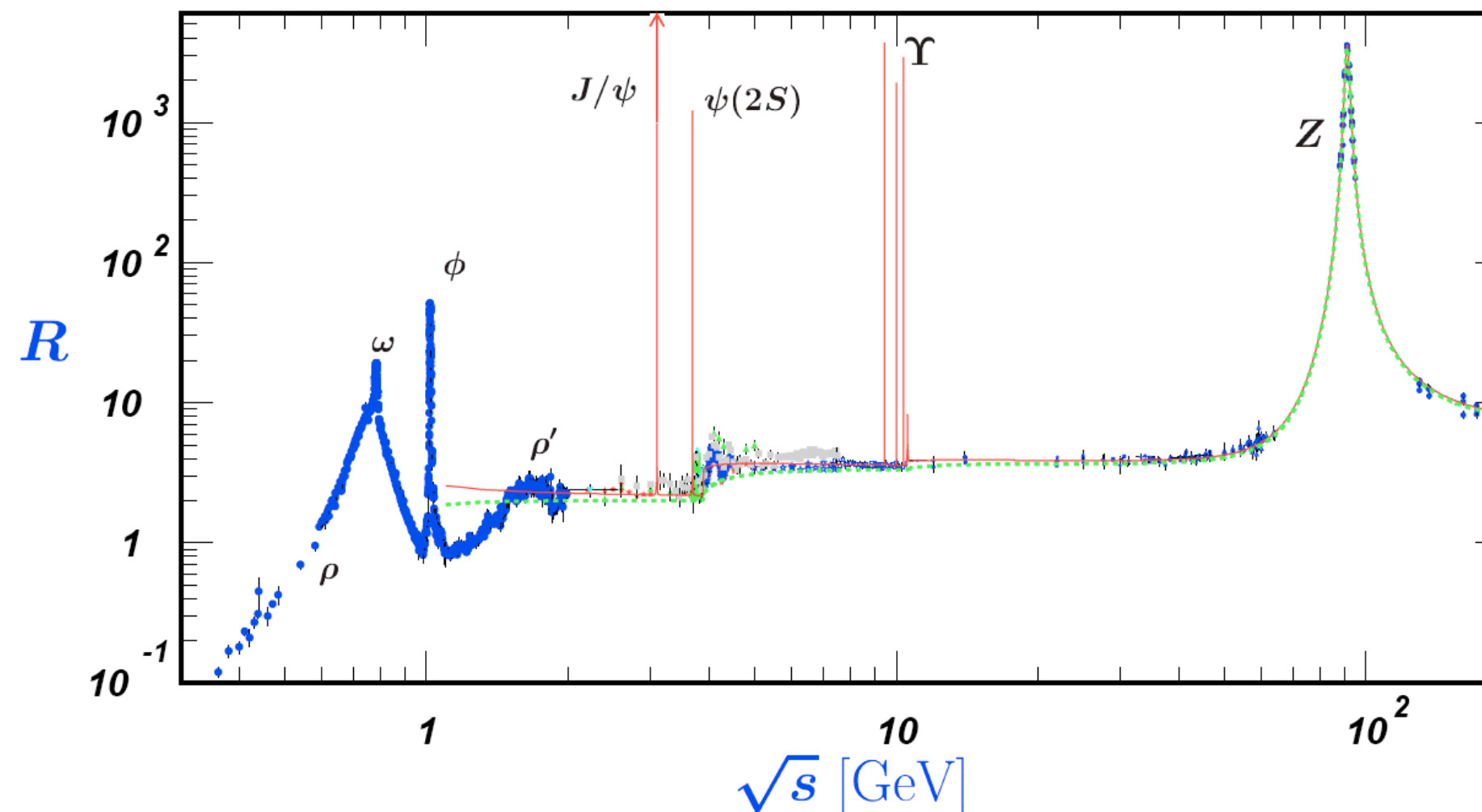
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- Substituting all the charges from previous slides $R = \frac{10}{9}N_c$
- From real measurements:



R-Value

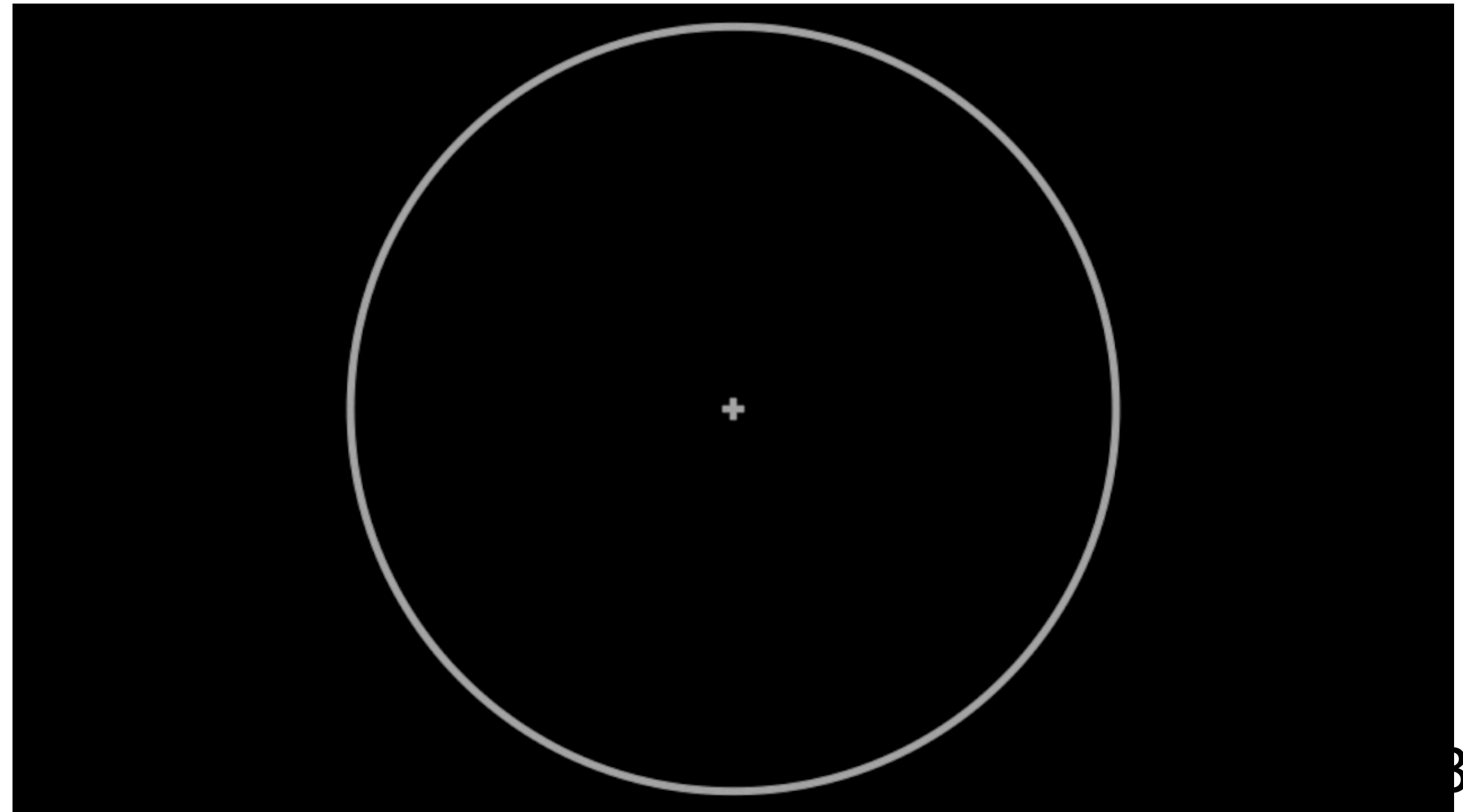
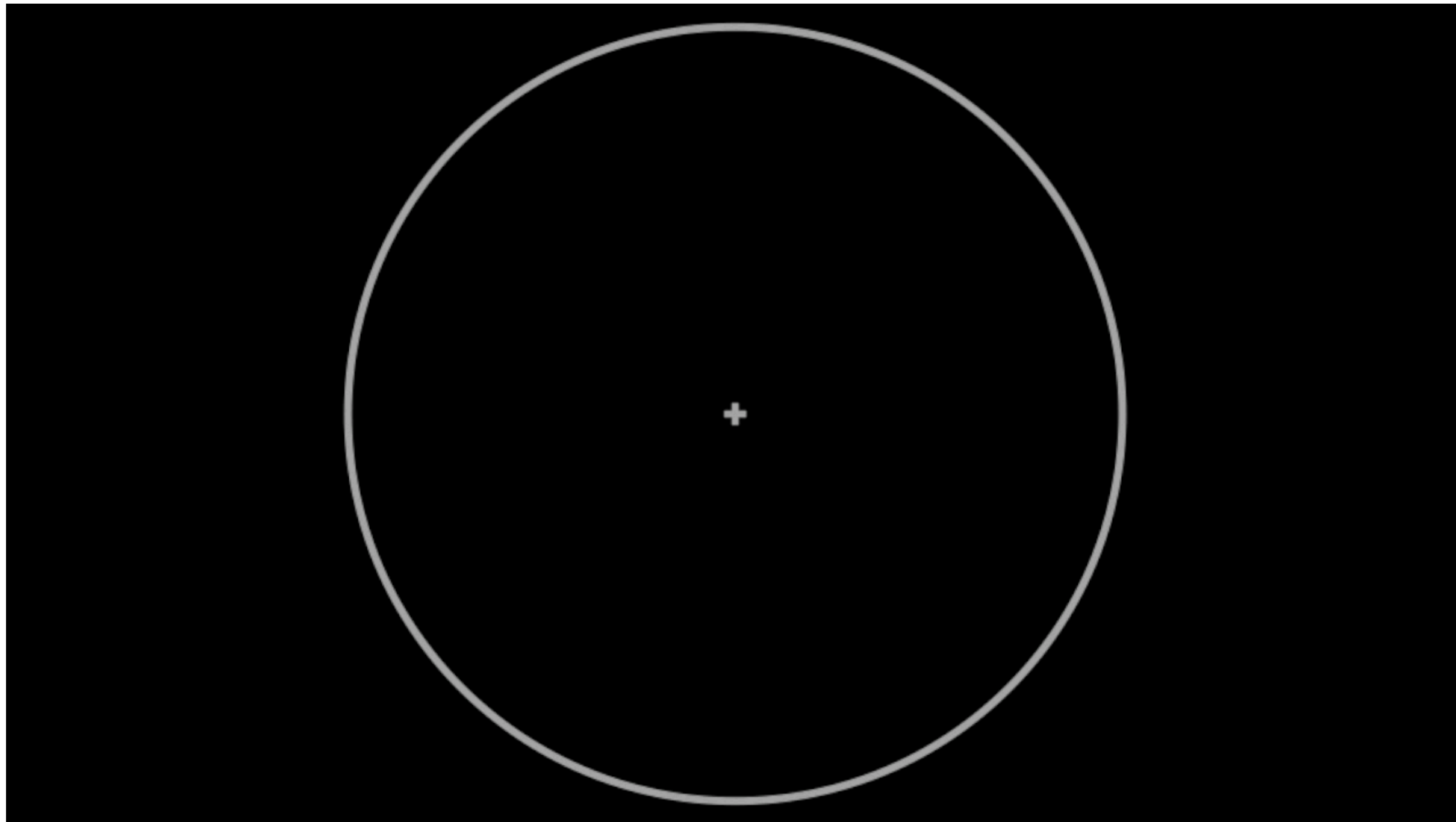
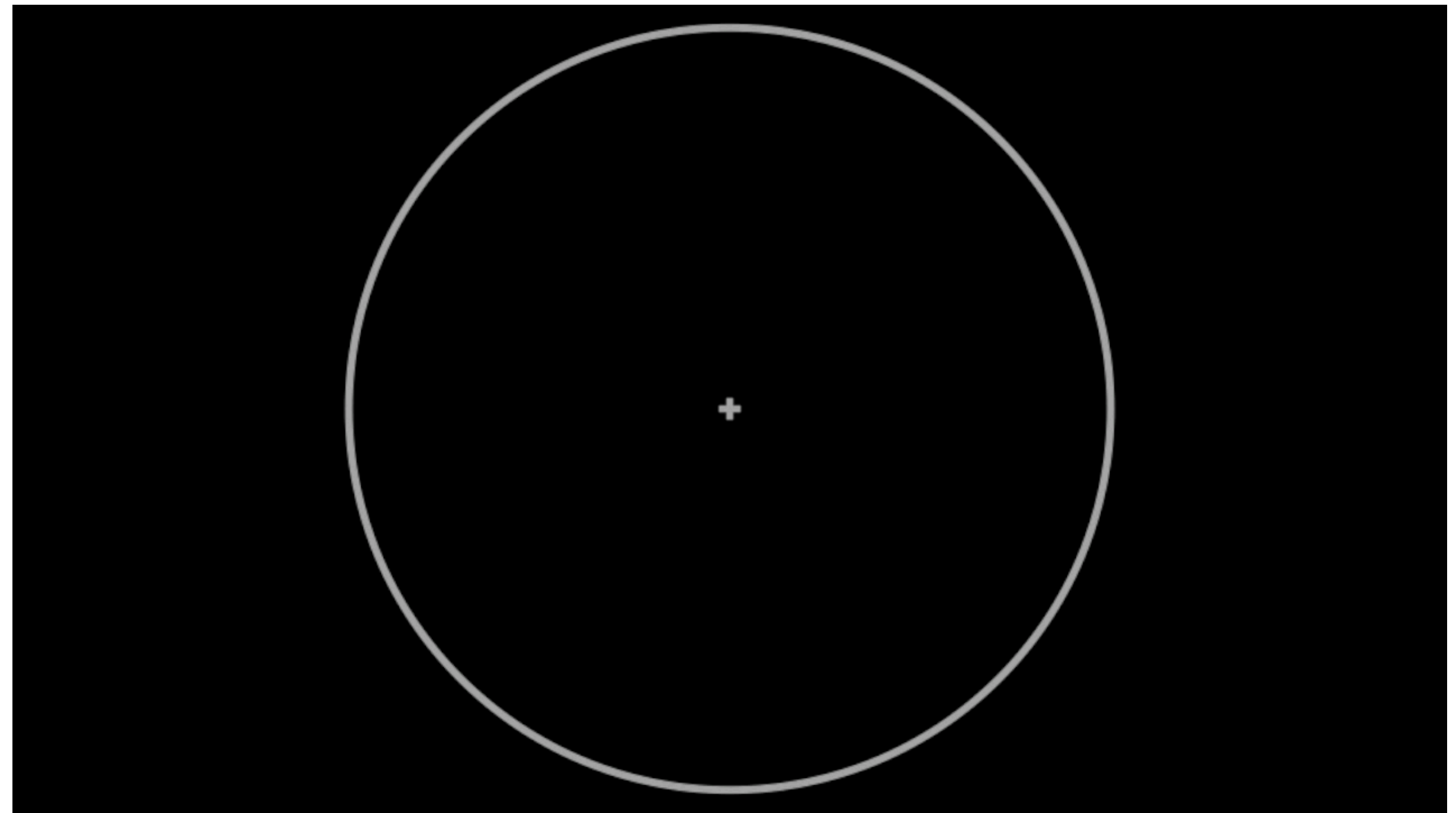
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- Substituting all the charges from previous slides $R = \frac{10}{9}N_c$
- From real measurements:
- Now we want to count the kind of events in our real data sample to calculate R from data \Rightarrow we can **measure the number of colors!**



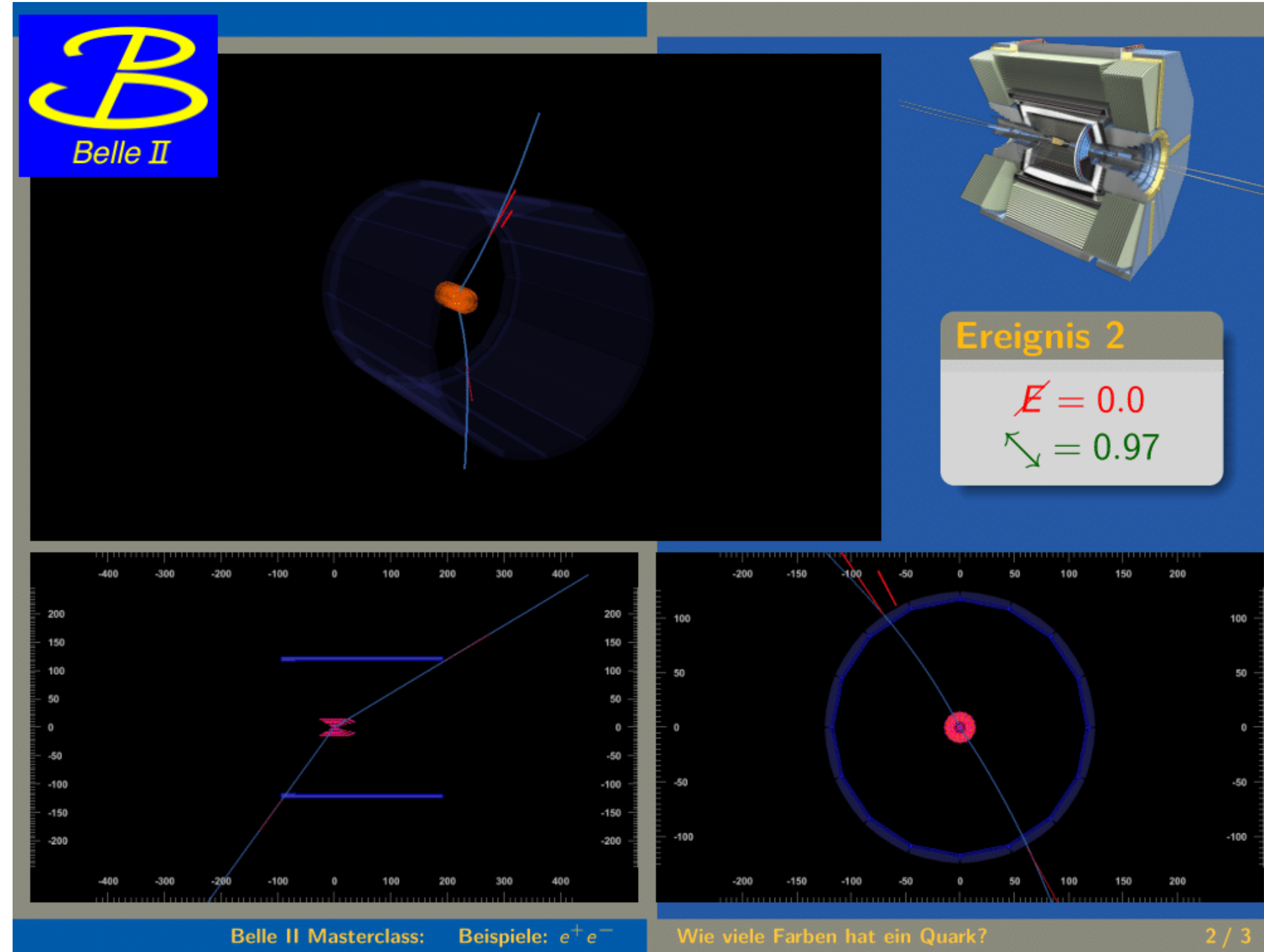
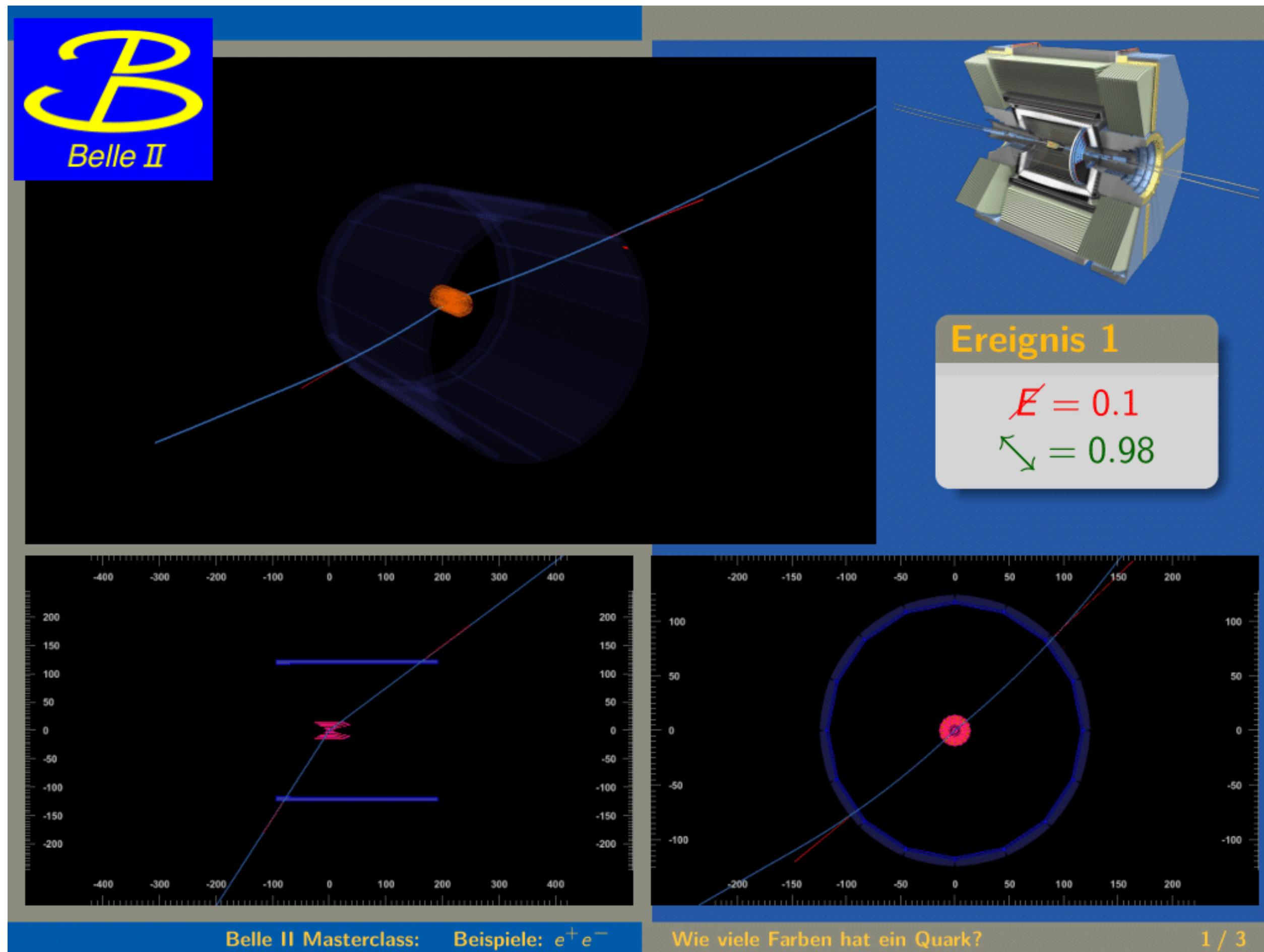
Data analysis concepts

- 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** (E_{miss}): we expect to be zero if we completely reconstruct the event. However neutrinos are undetected
- **Straightness** (\downarrow) of the event: how much the event is spherical (low Straightness) or is aligned with an axis.

e^+e^- events: simplified display

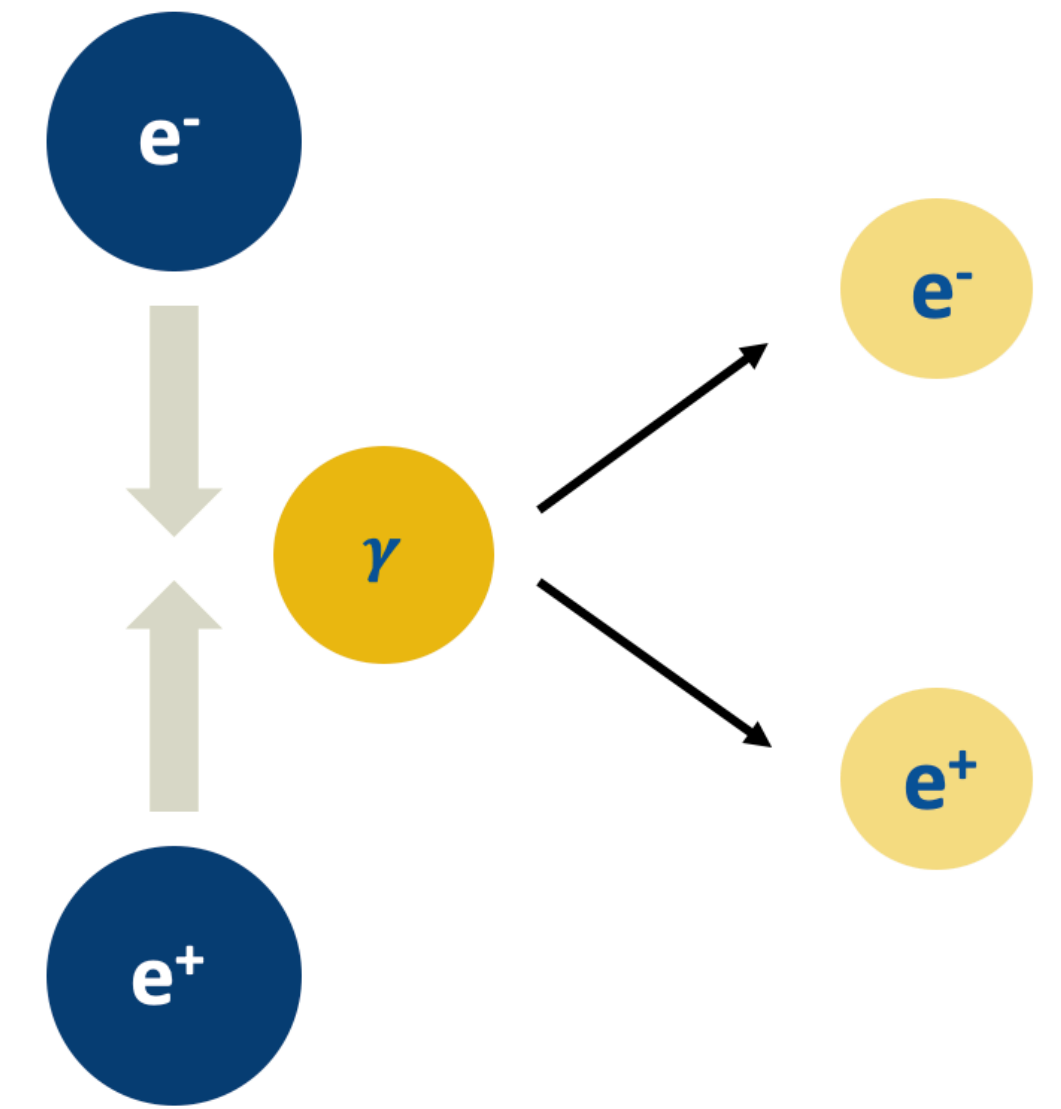


e^+e^- events: real event display



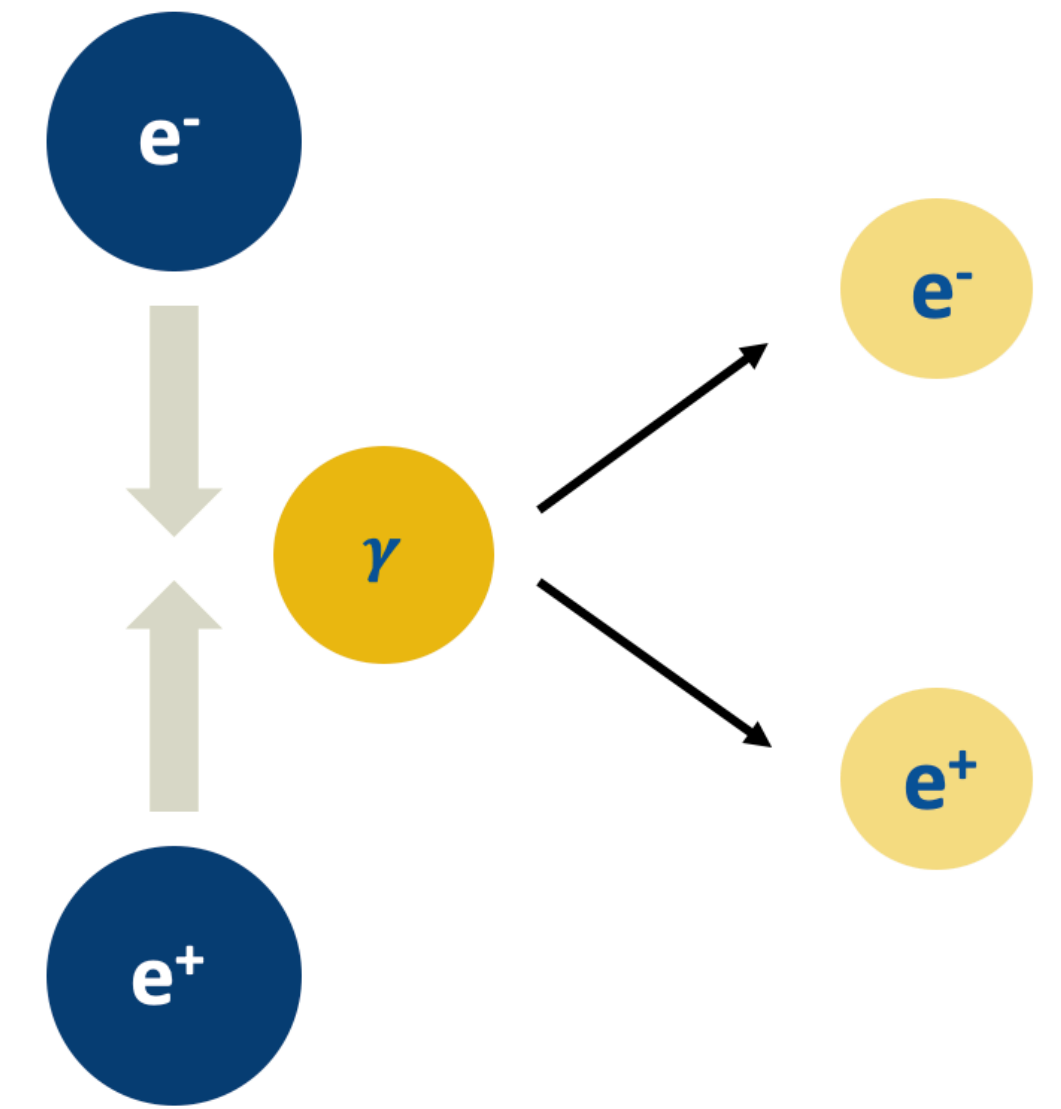
e^+e^- events: properties

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



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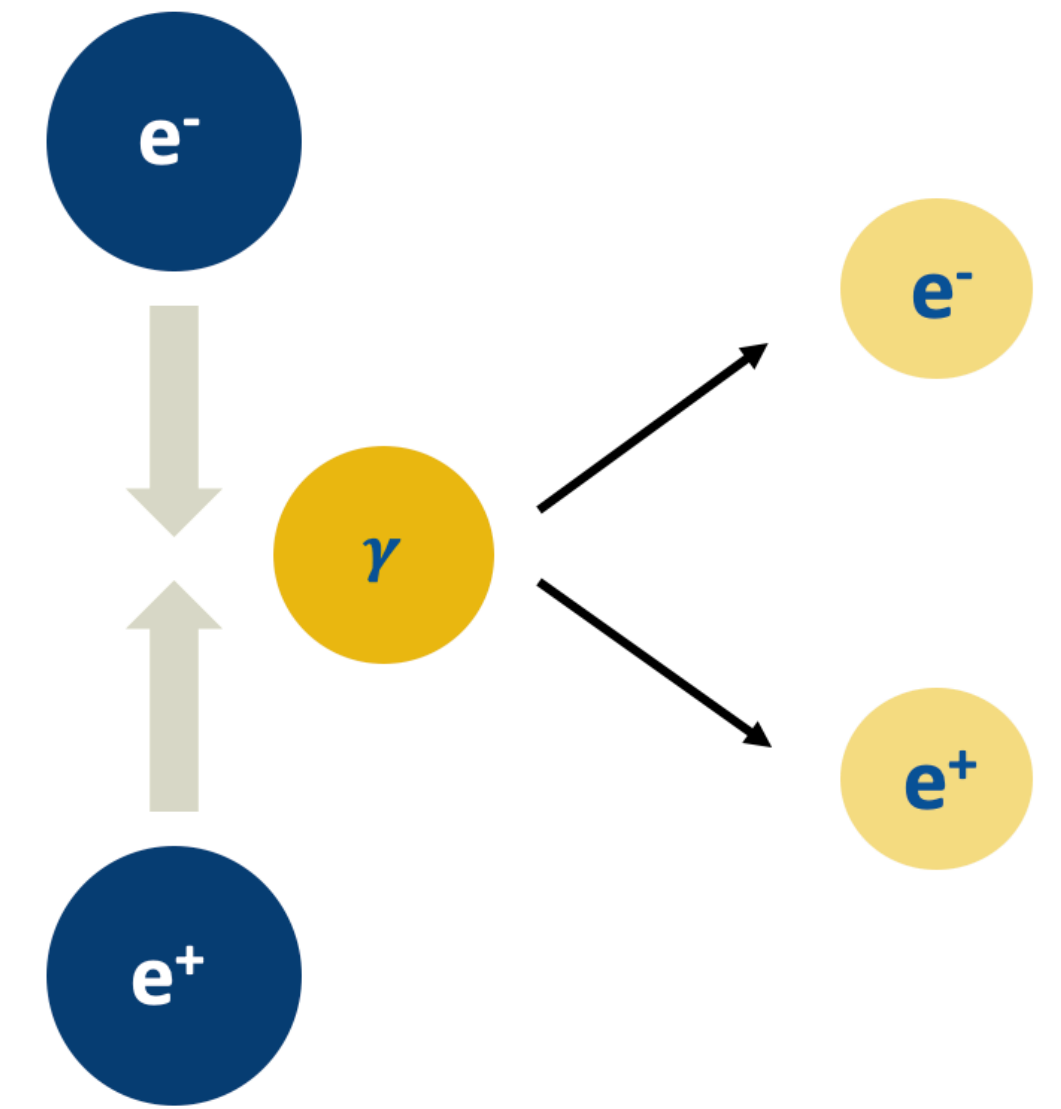


- Why the e^+e^- are missing in our R-value definition?

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

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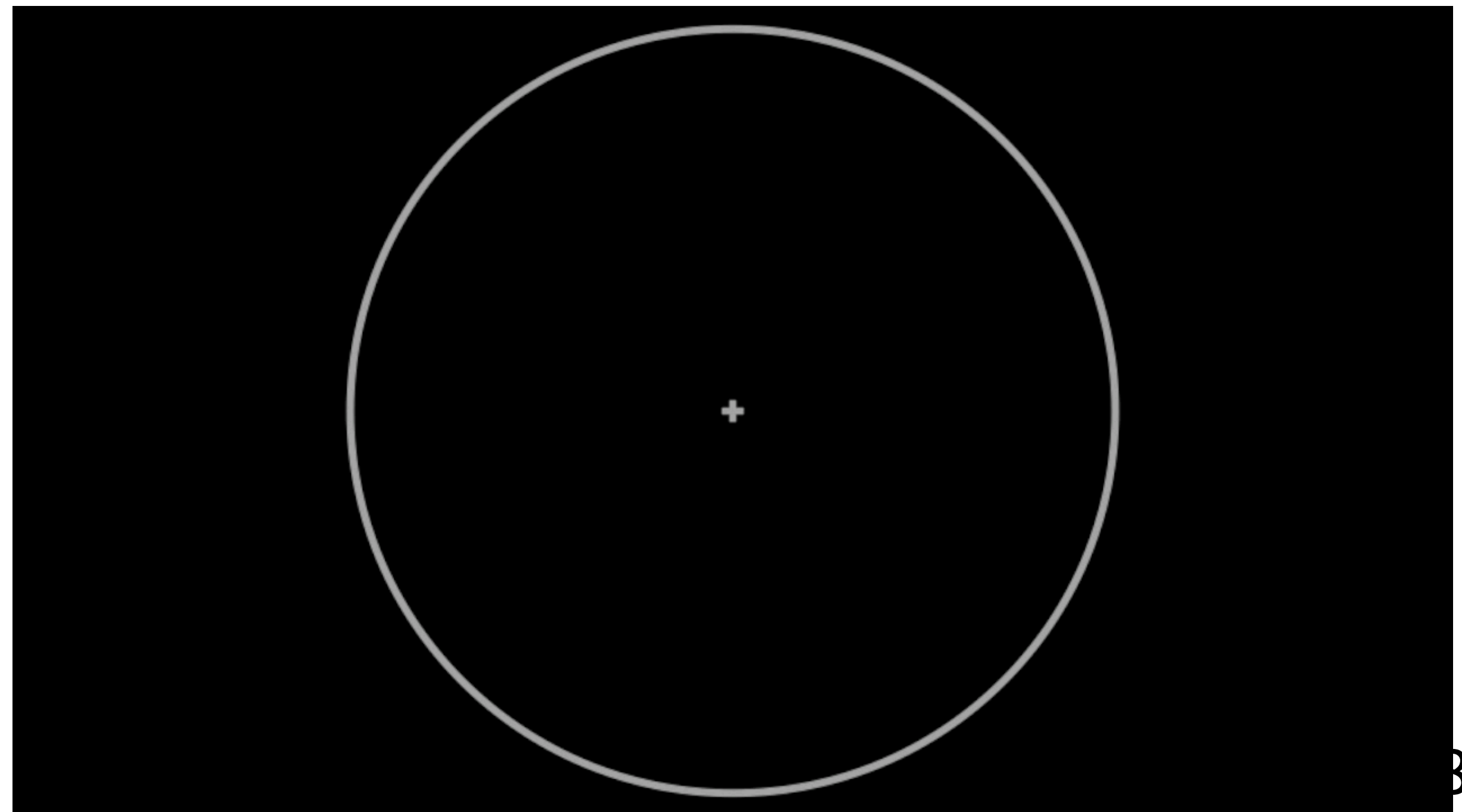
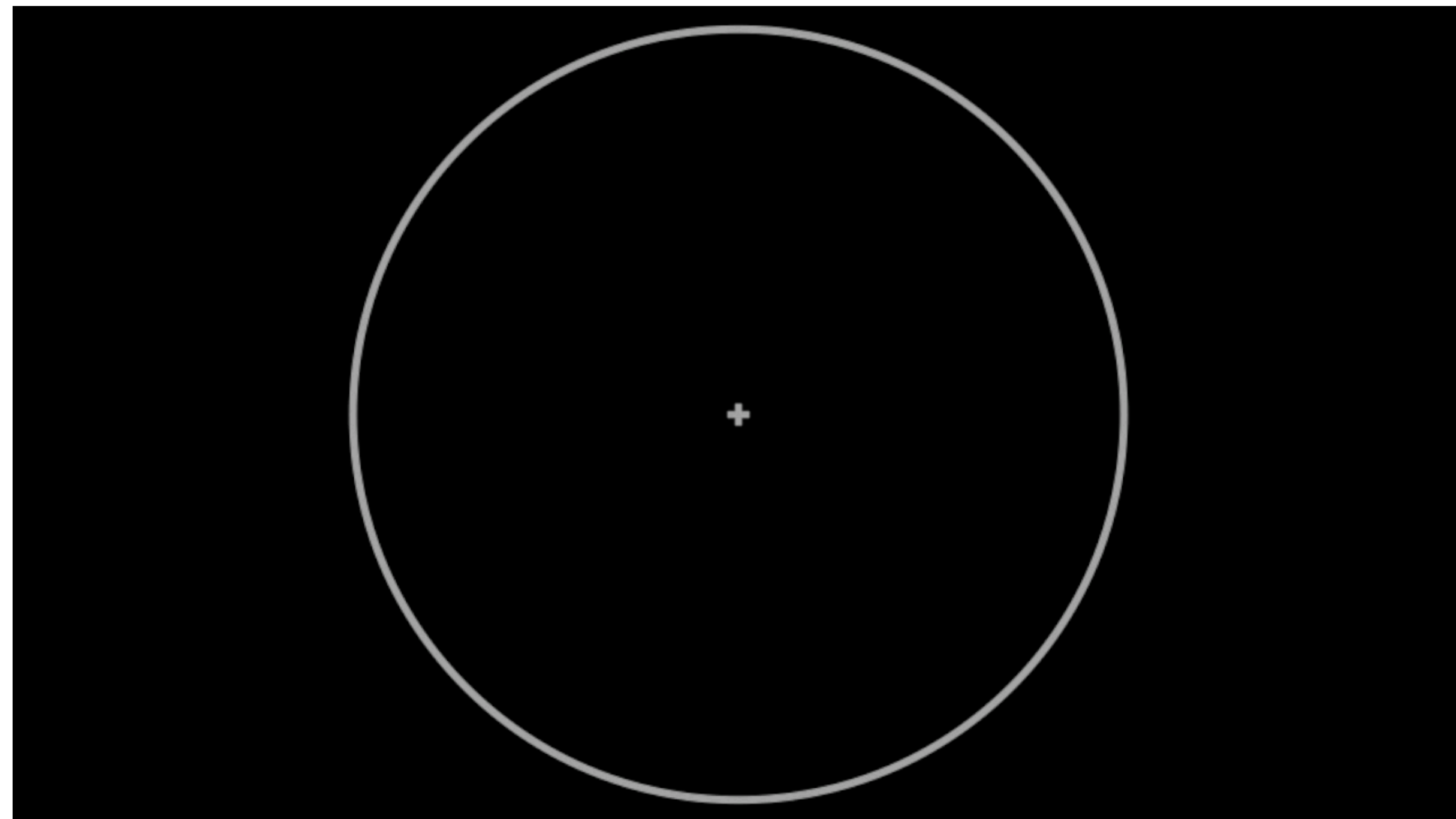
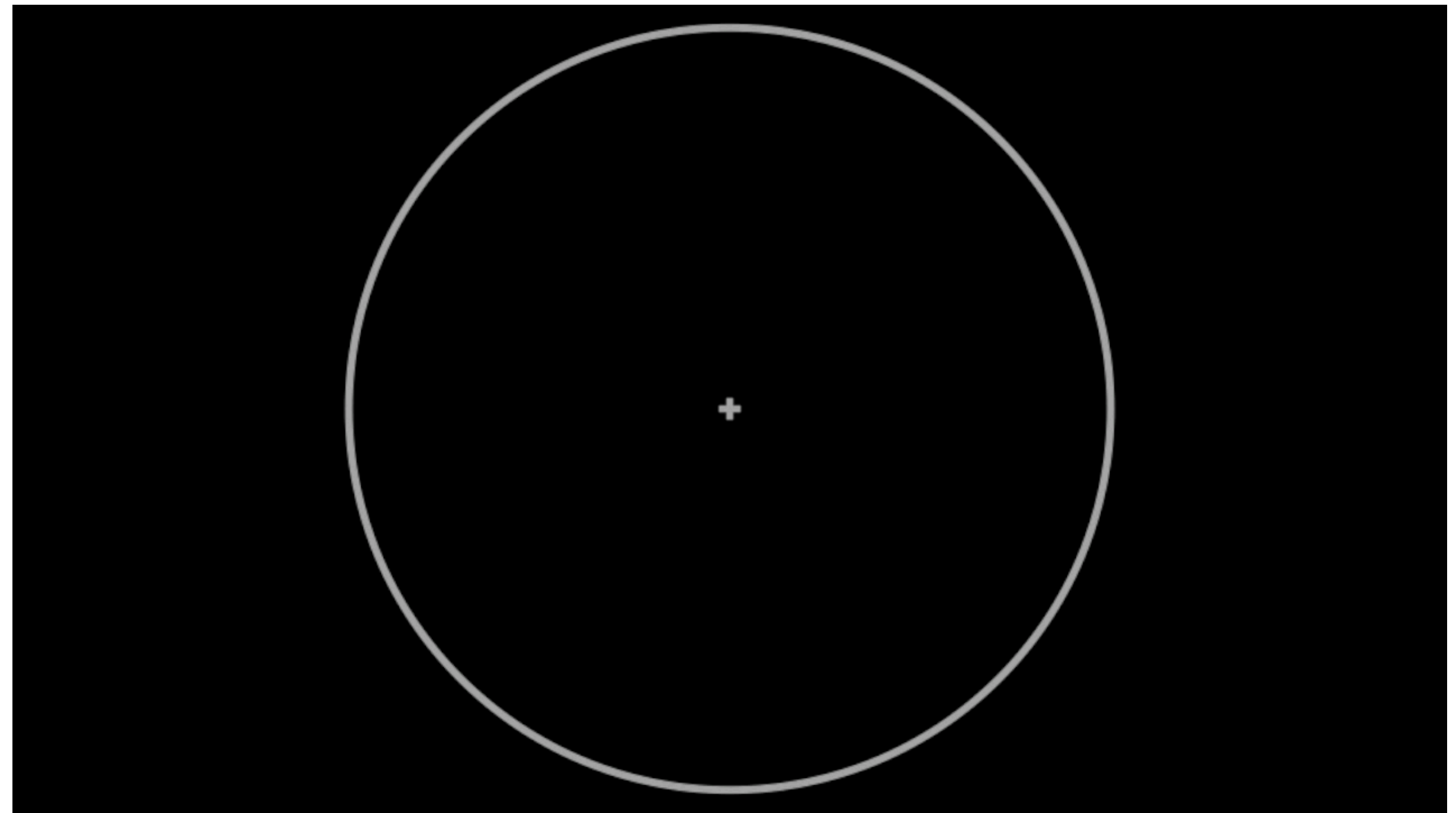


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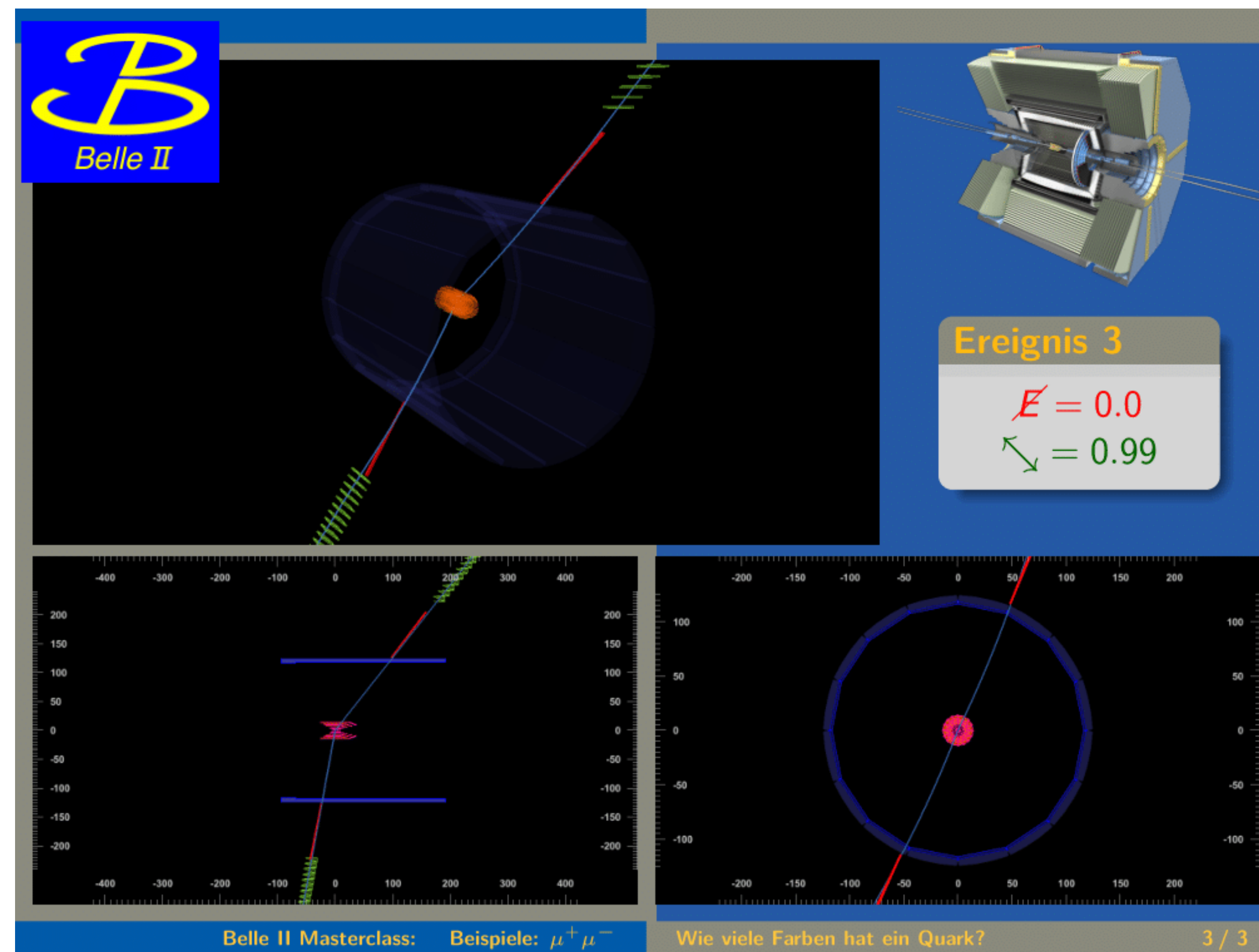
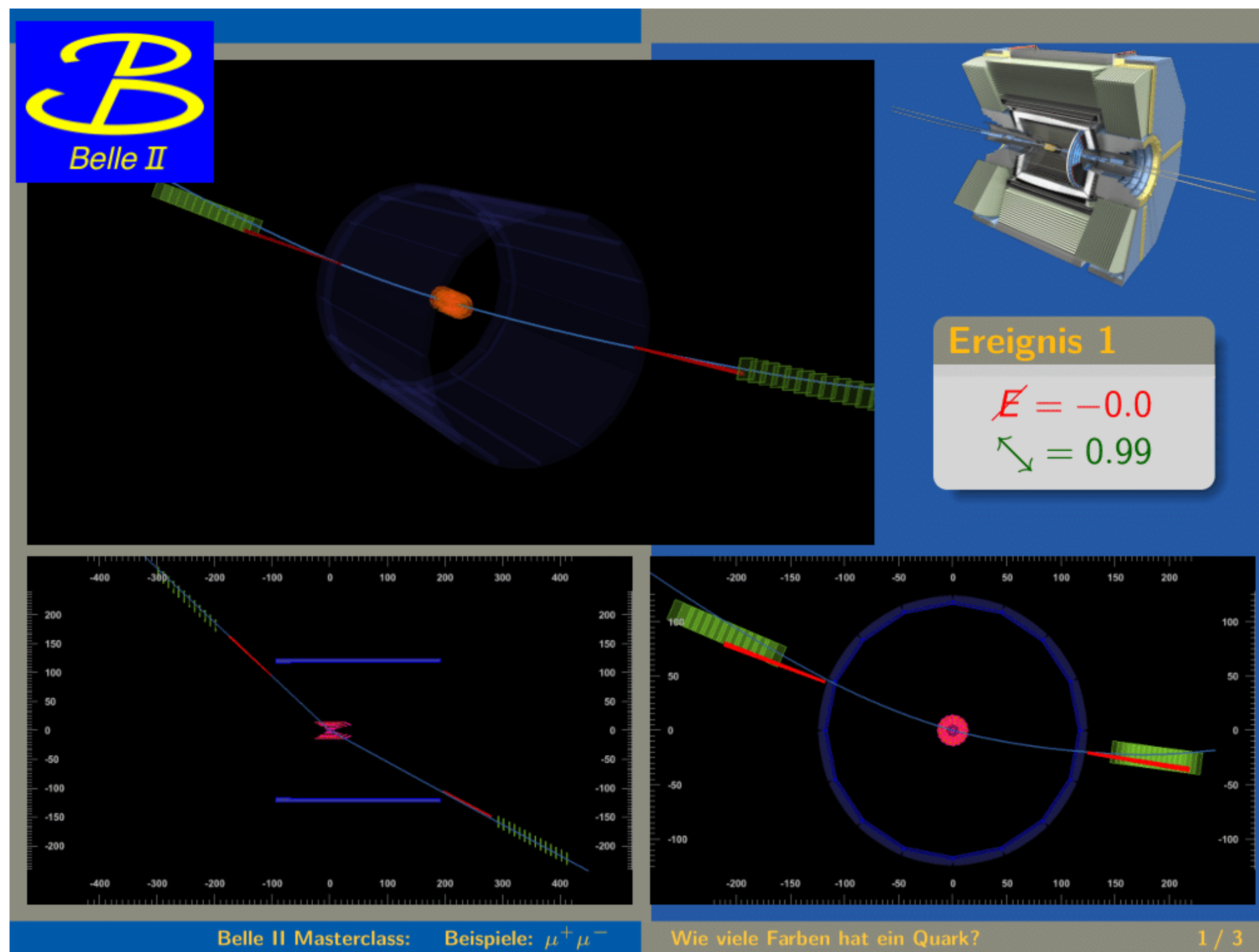
$$R = \frac{N(e^+e^- \rightarrow \gamma \rightarrow \text{light quarks})}{\frac{1}{2}[N(e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-) + N(e^+e^- \rightarrow \gamma \rightarrow \tau^+\tau^-)]}$$

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

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

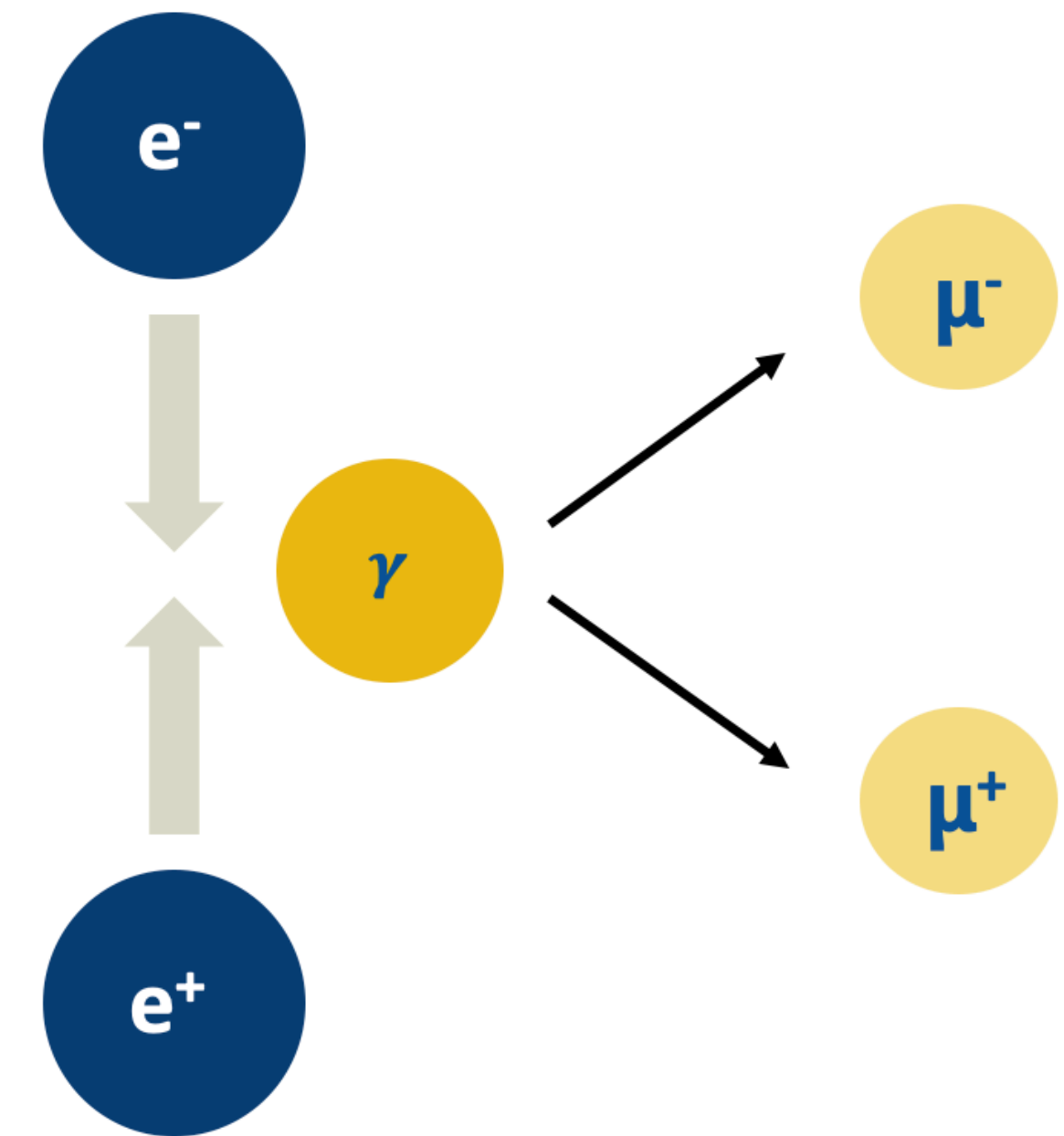


$\mu^+ \mu^-$ events: real event display

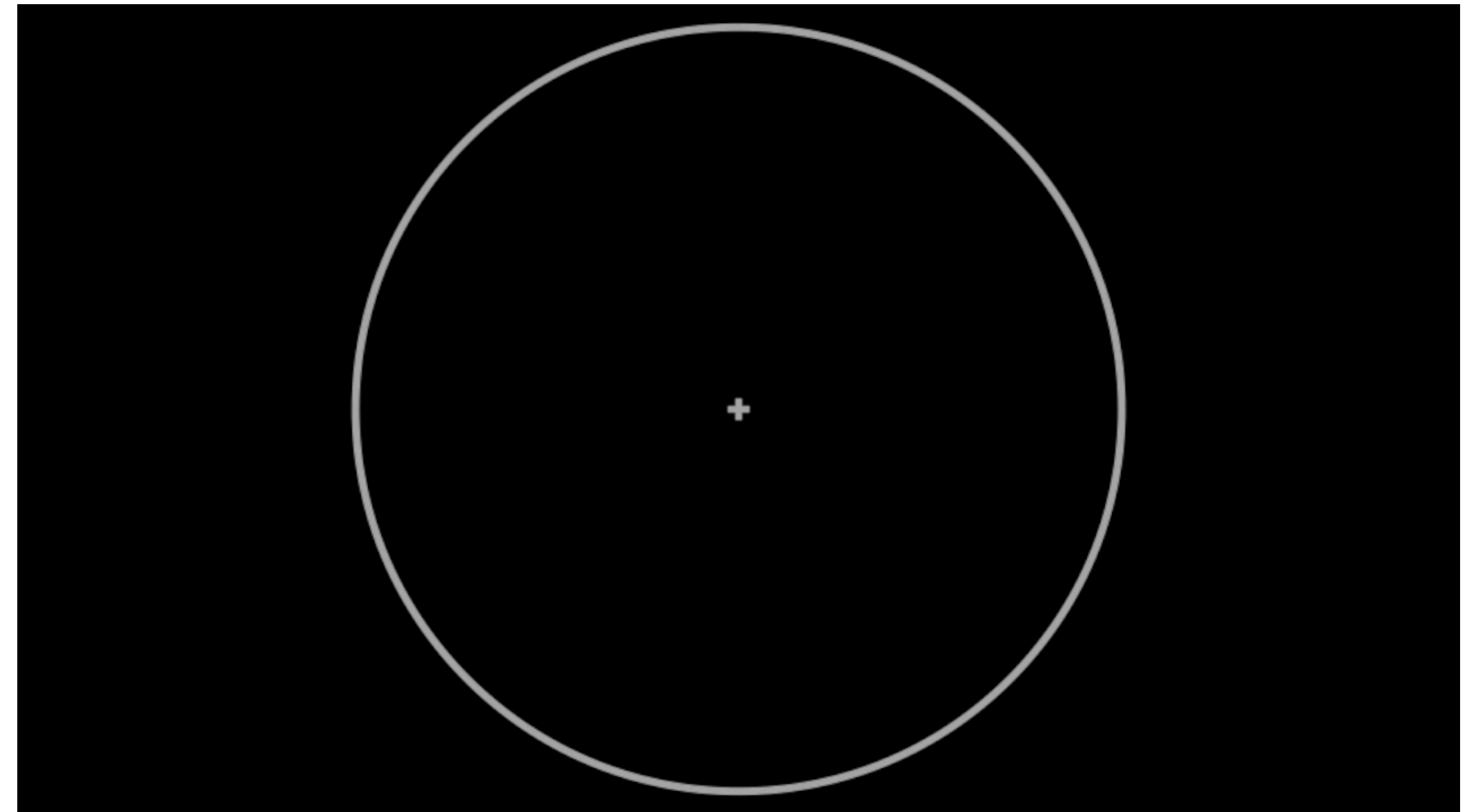
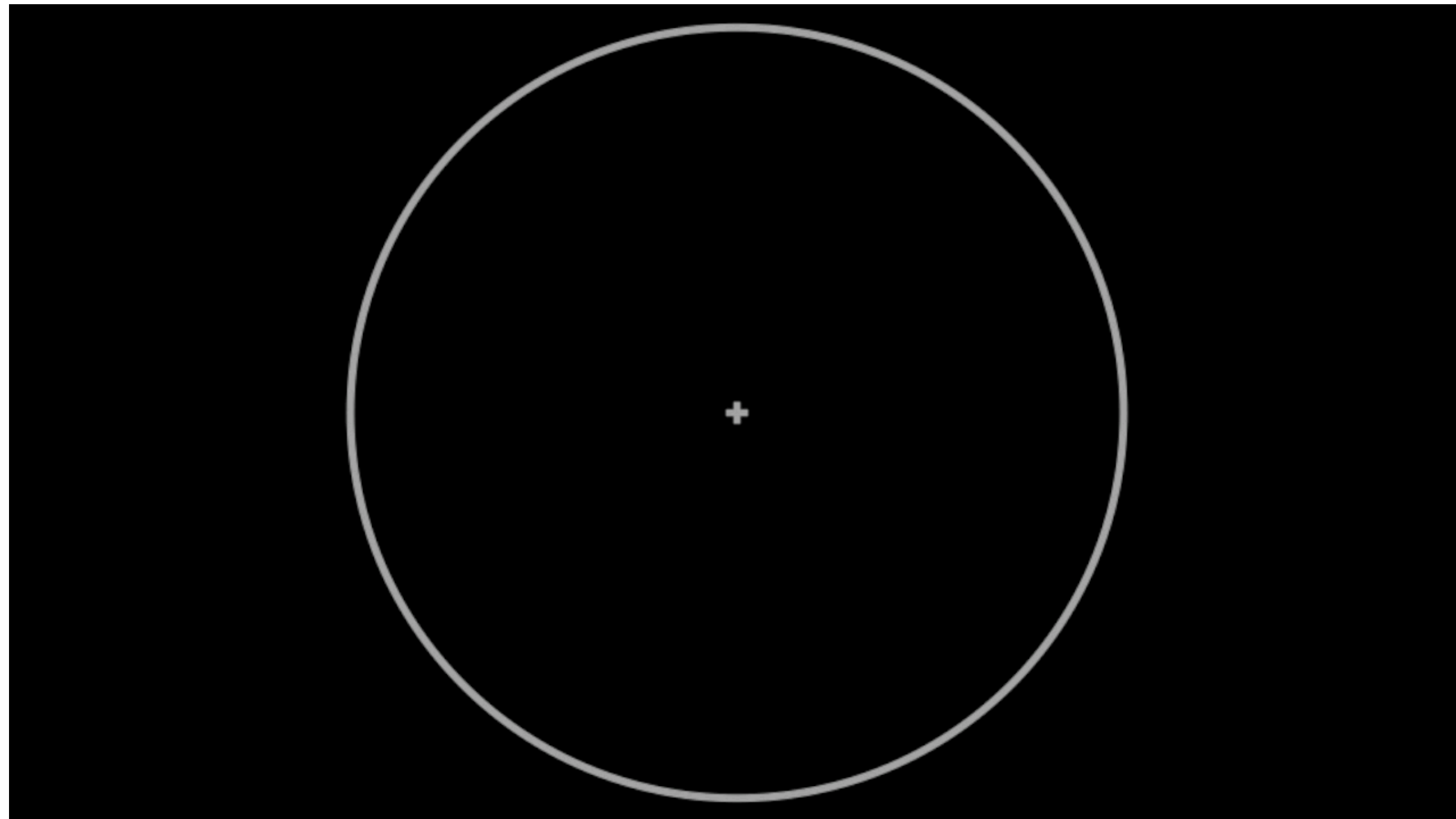
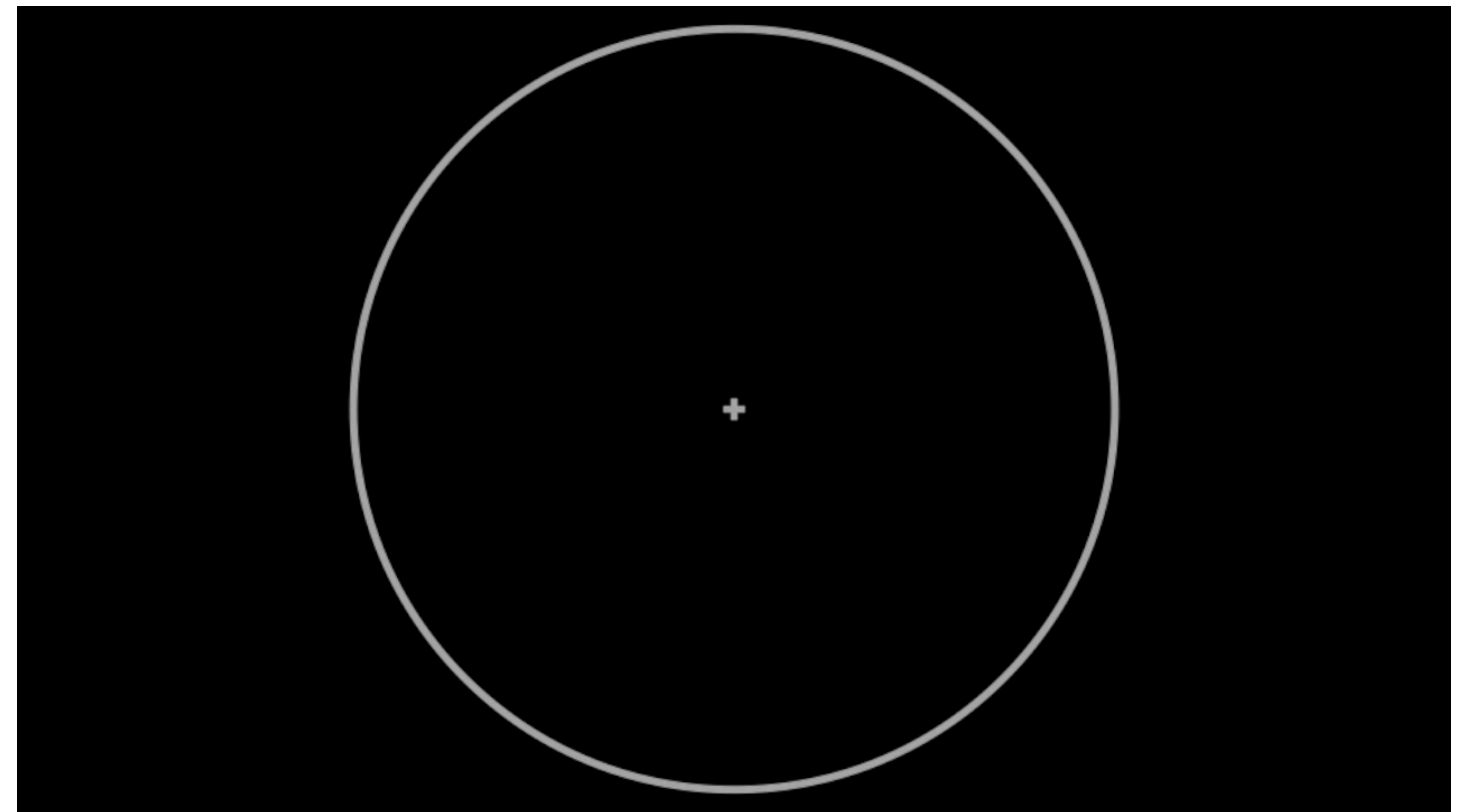


$\mu^+ \mu^-$ events: properties

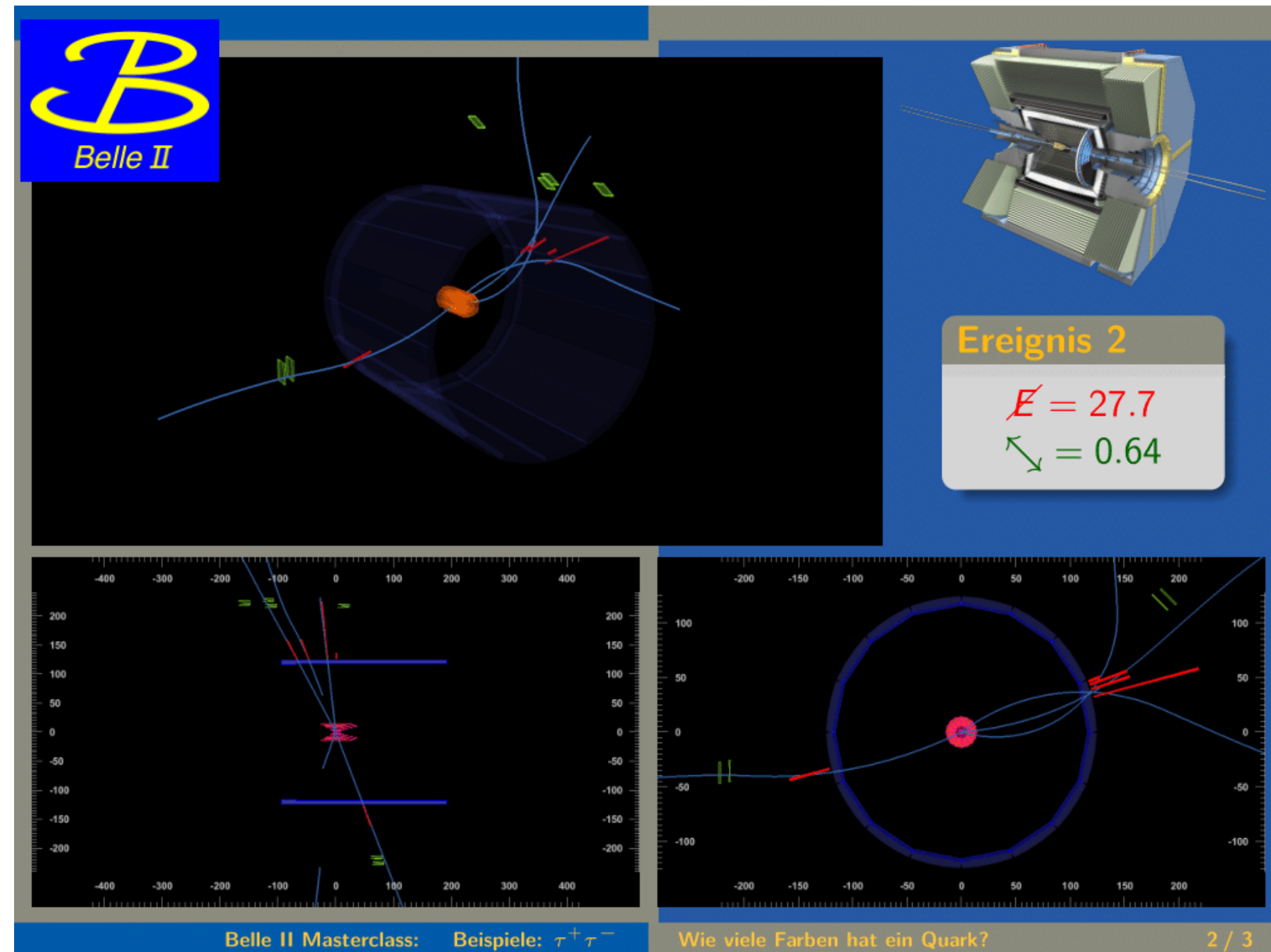
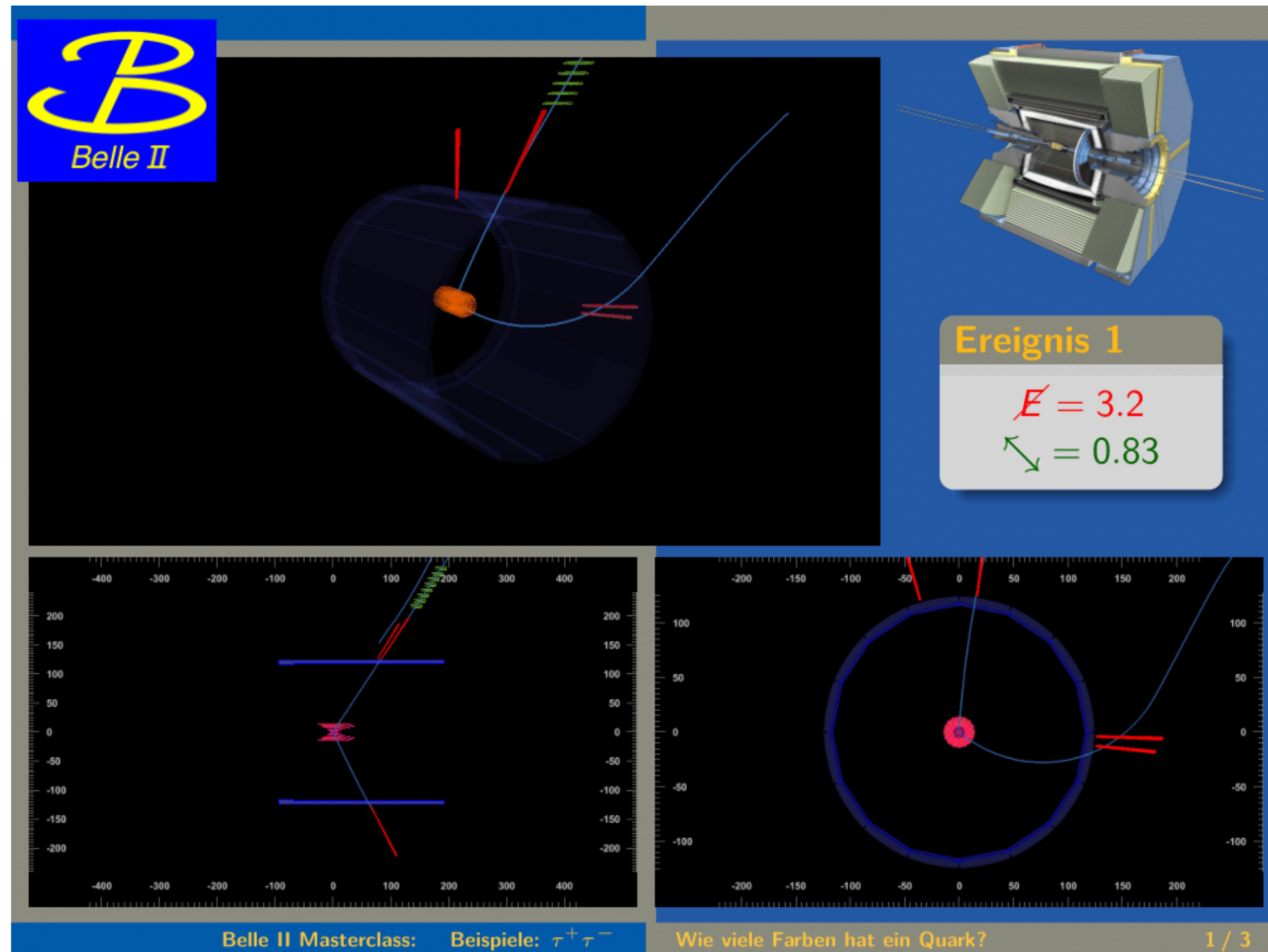
- **Two** clearly visible tracks
- Deposition of energy in the calorimeter (**red signal close to the track**)
- Deposition of energy in the muon detector (**green signals along the outer track!**)



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

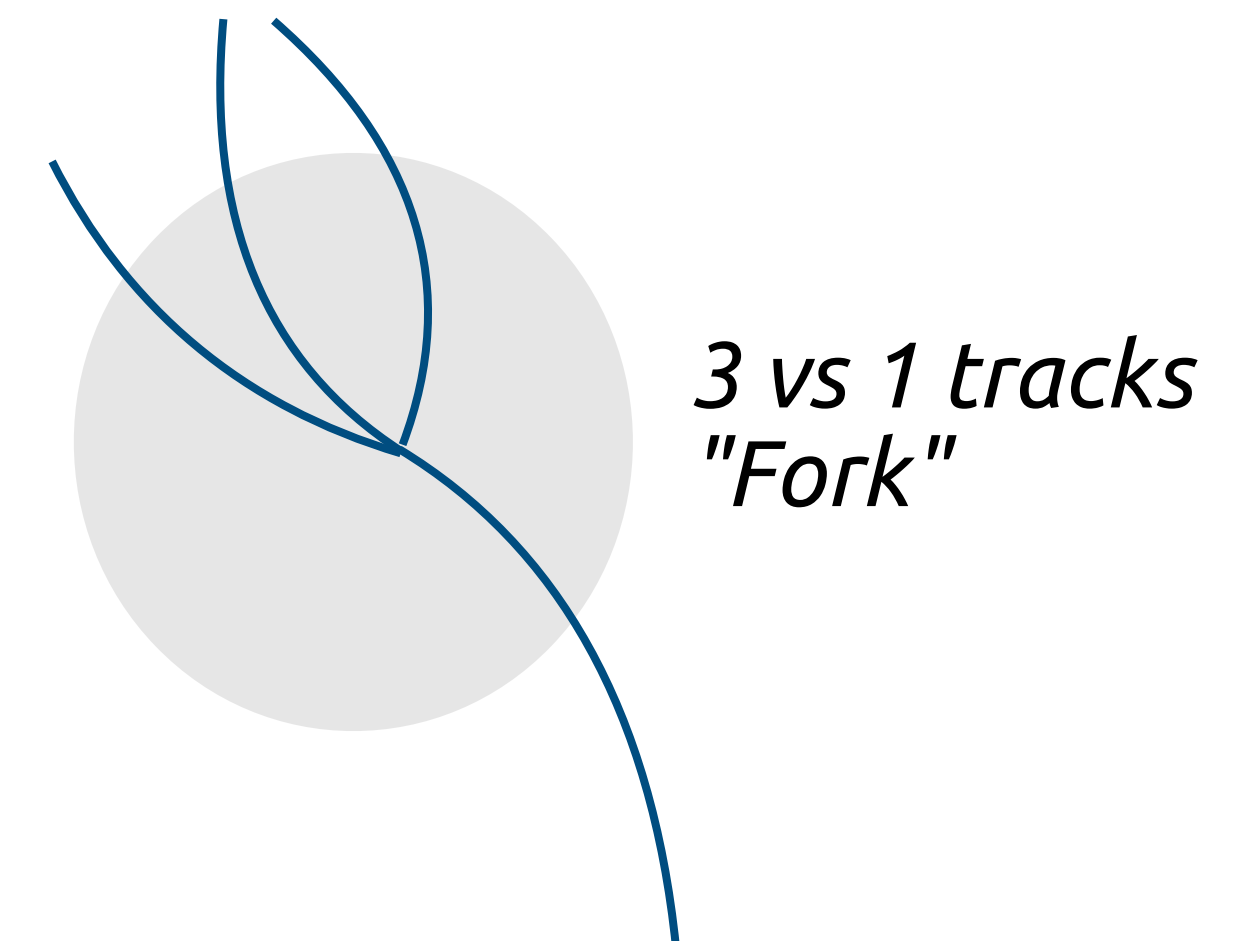
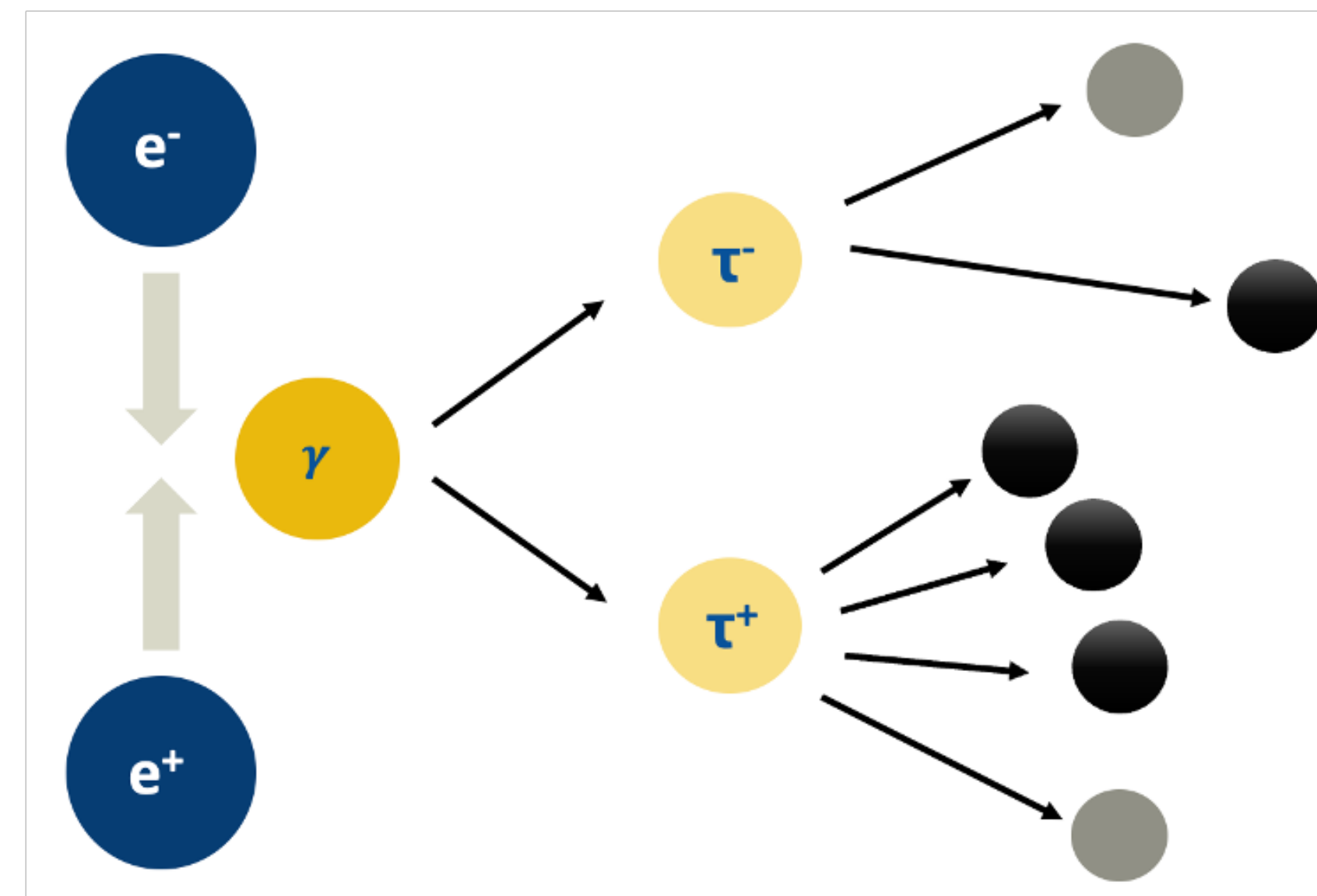


$\tau^+\tau^-$ events: real event display

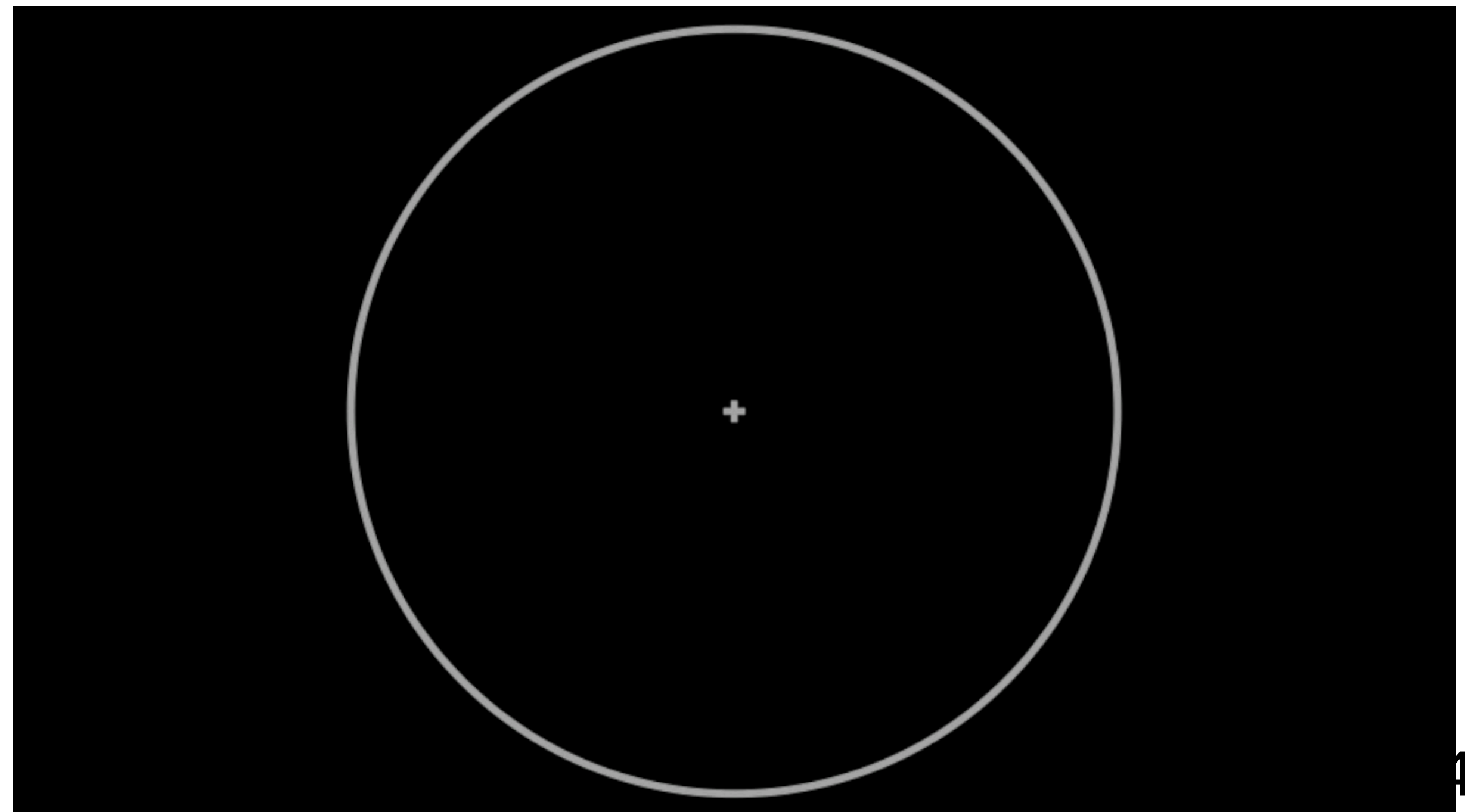
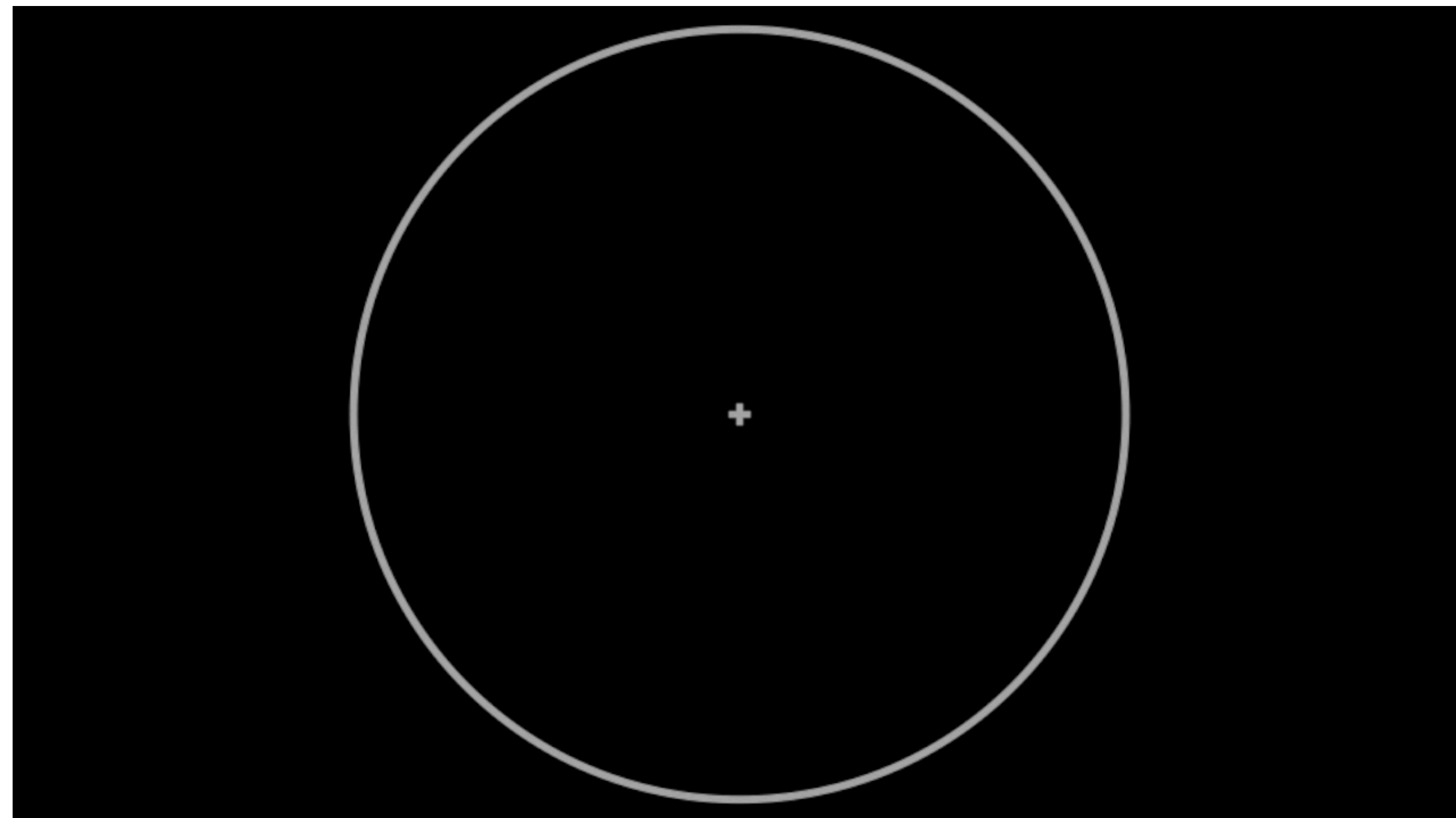
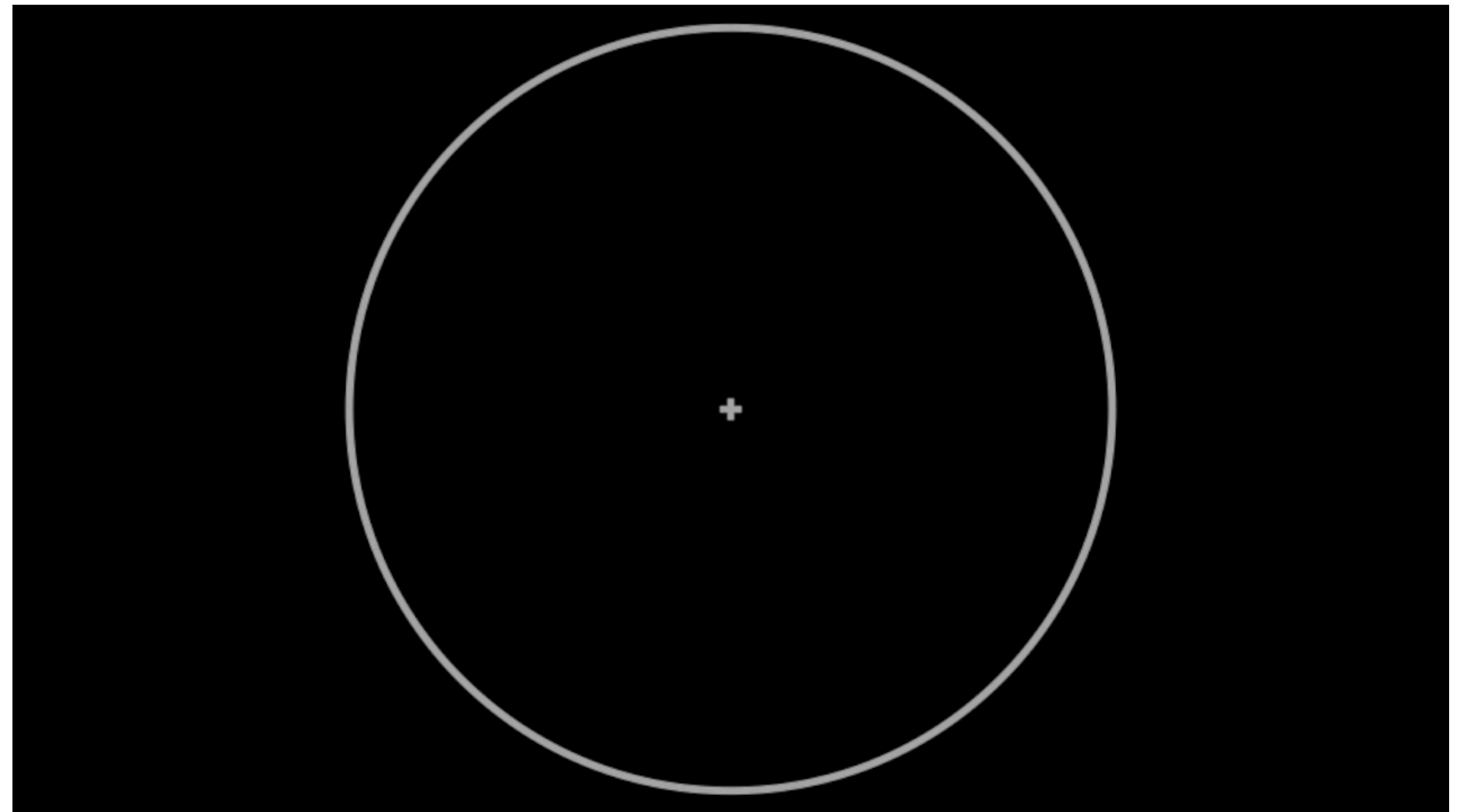


$\tau^+ \tau^-$ events: properties

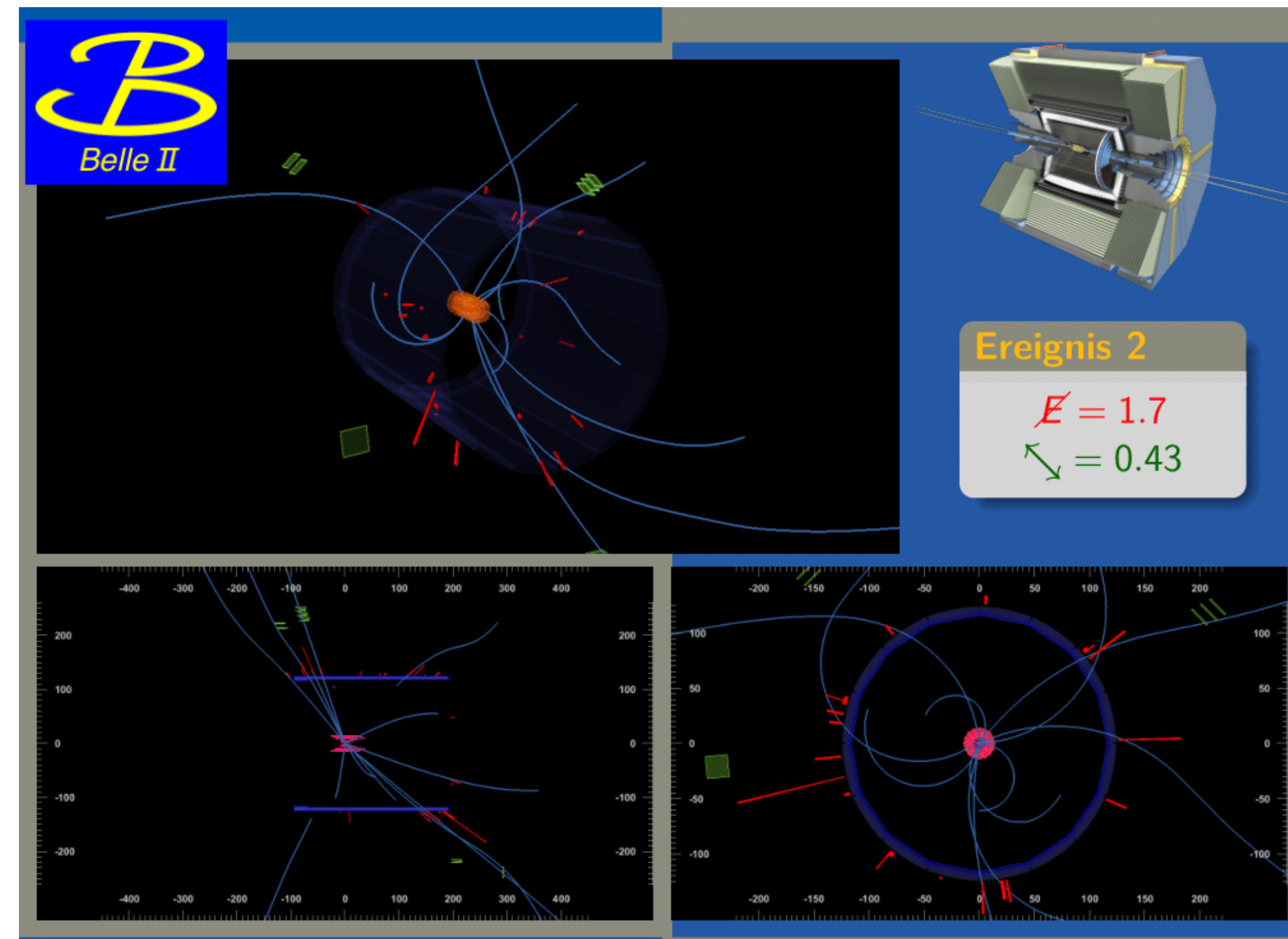
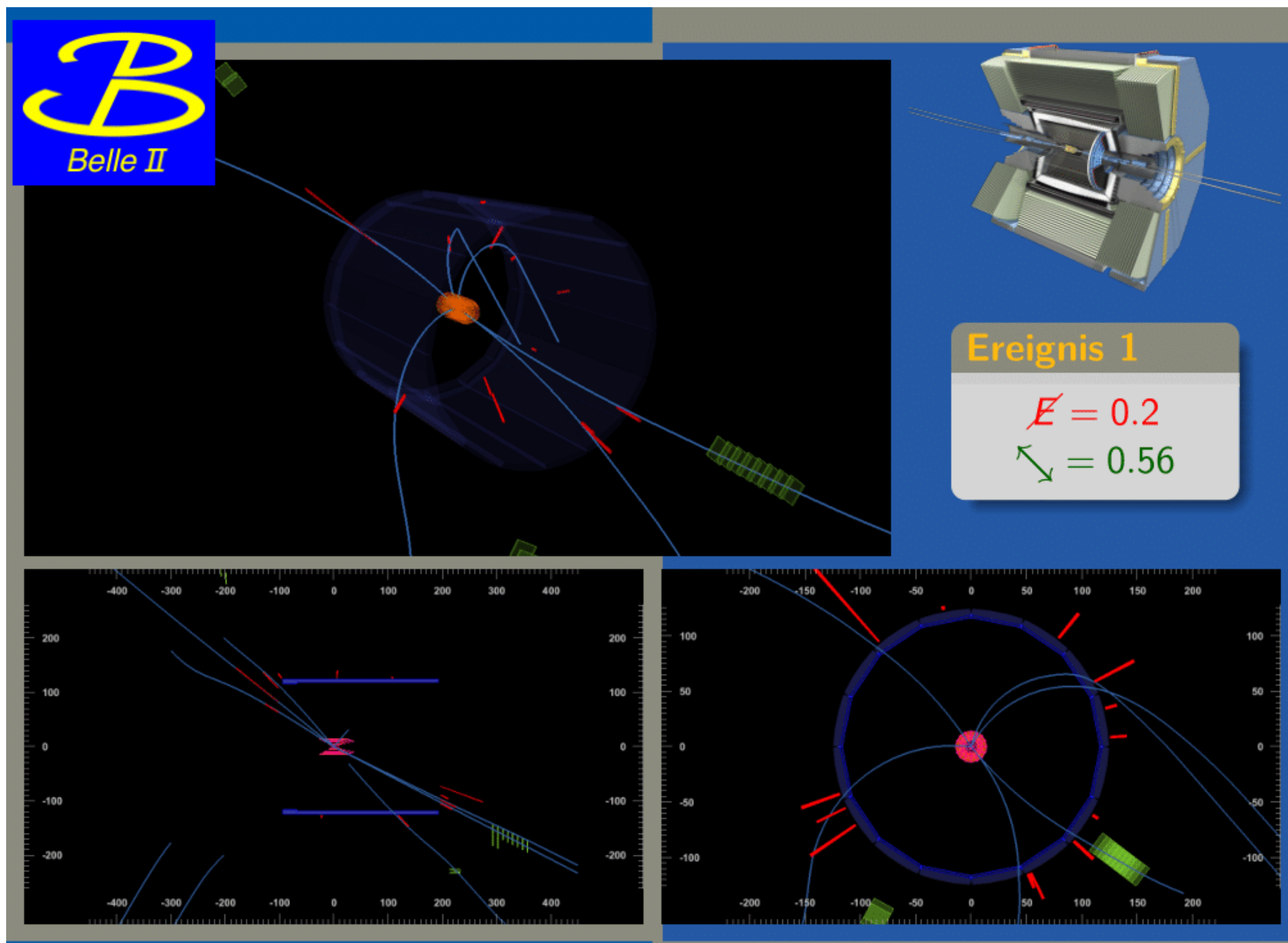
- The τ **decay** shortly after their creation within the detector
- There are several possible decay possibilities:
 - decay into **charged lepton + neutrinos**
 - decay into **light quarks + neutrinos**
- Neutrinos do not interact \Rightarrow not reconstructed \Rightarrow **large E**
- Variable number 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**)



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

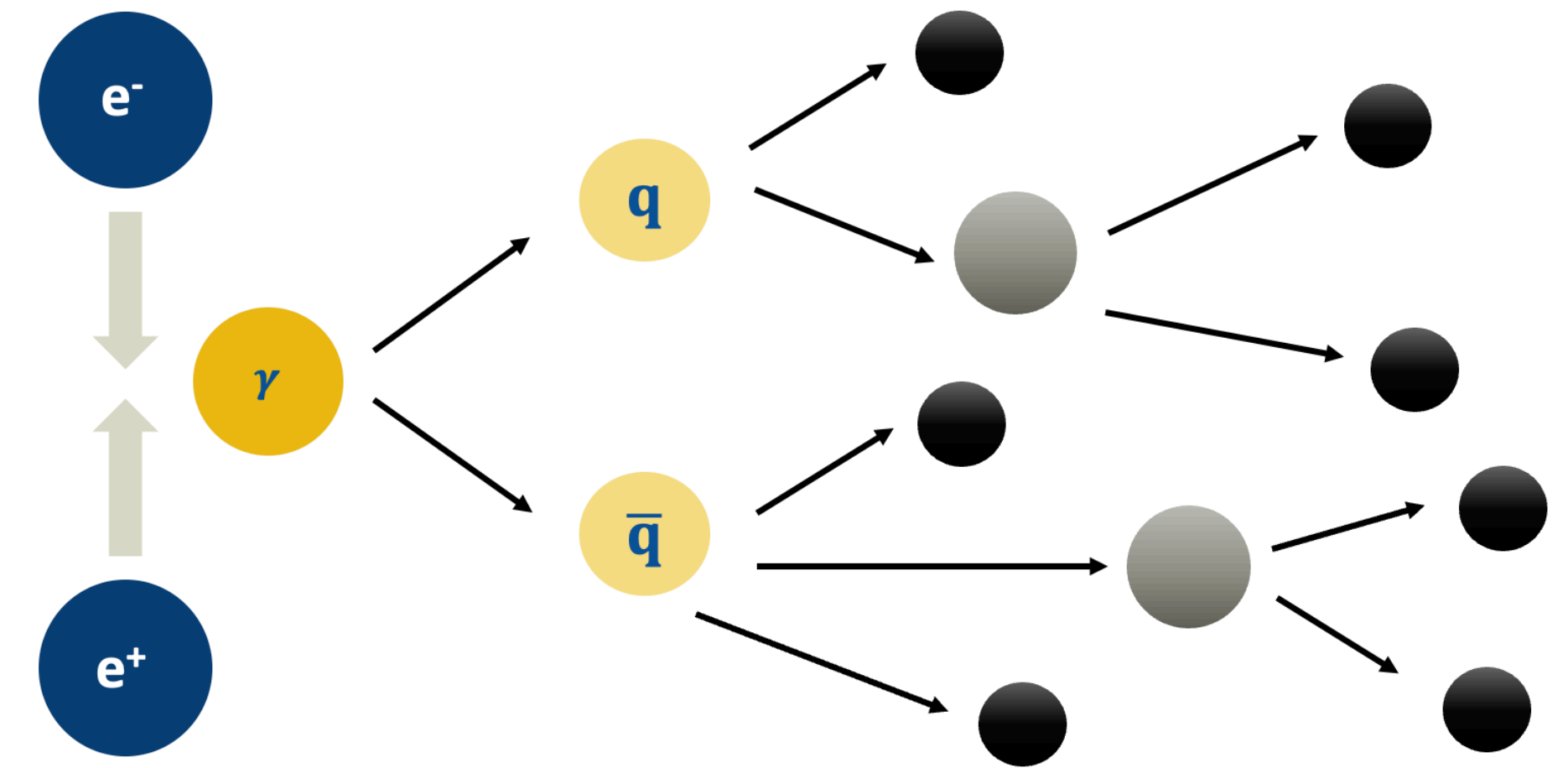


light $q\bar{q}$ events: real event display

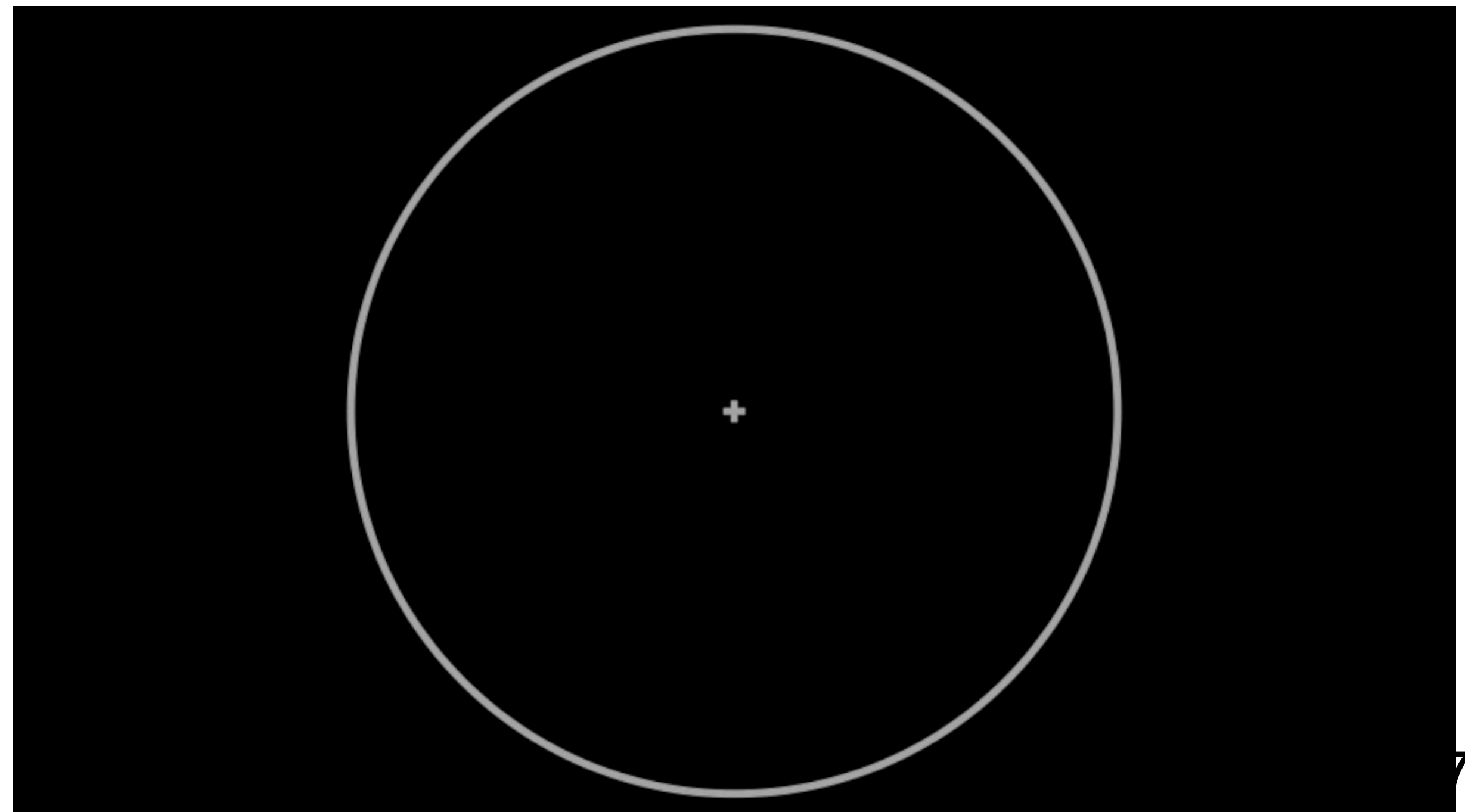
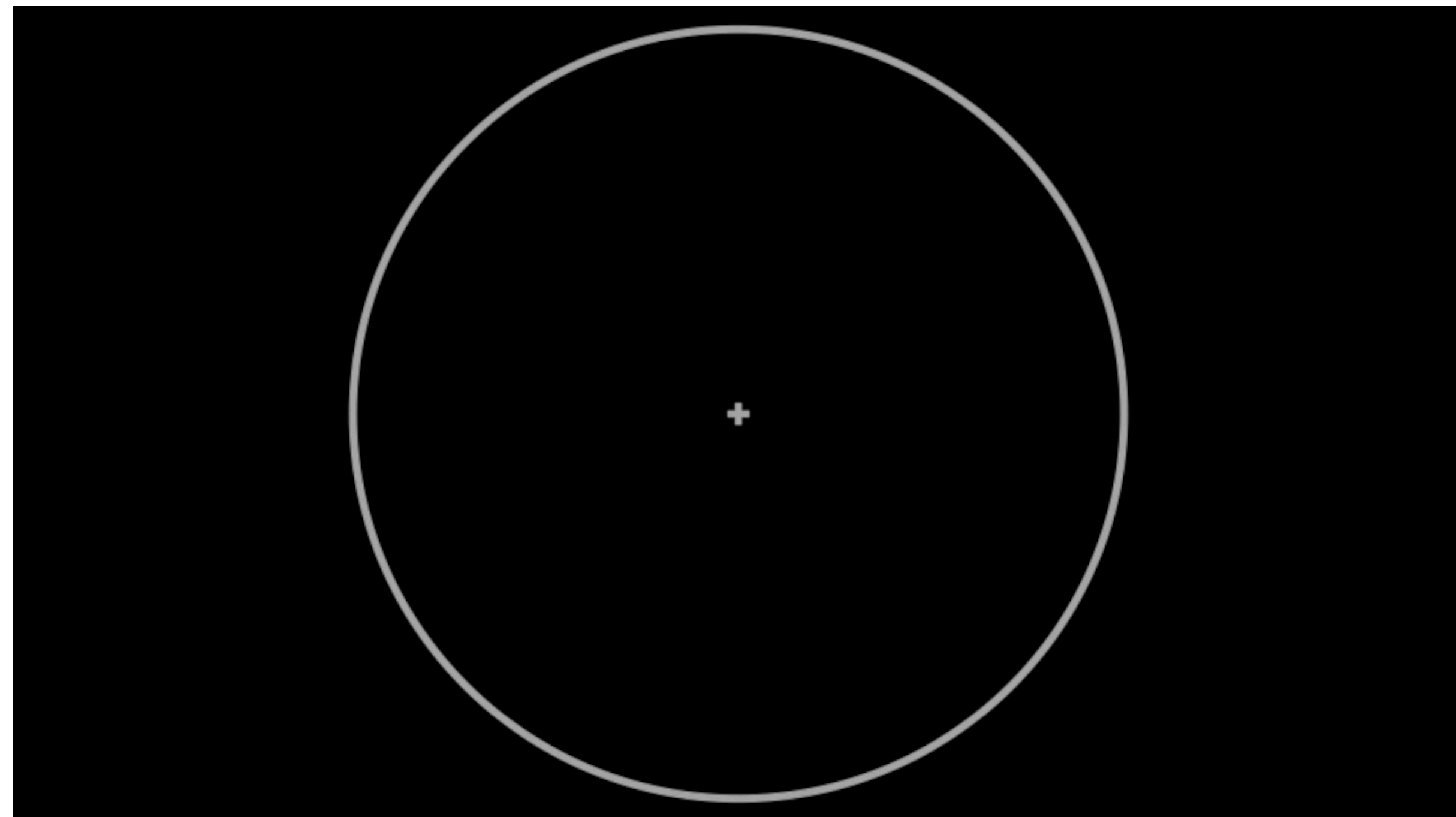
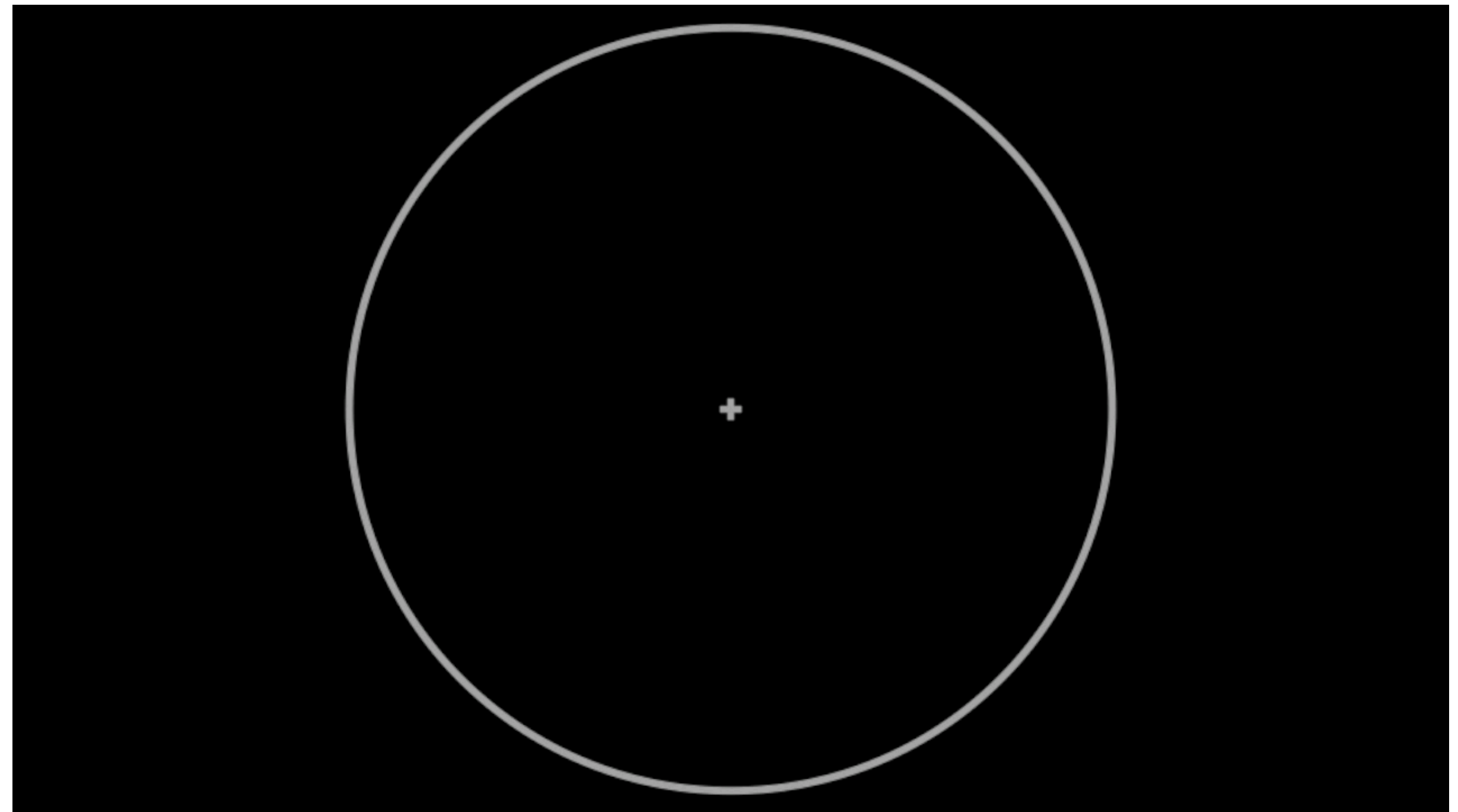


light $q\bar{q}$ events: properties

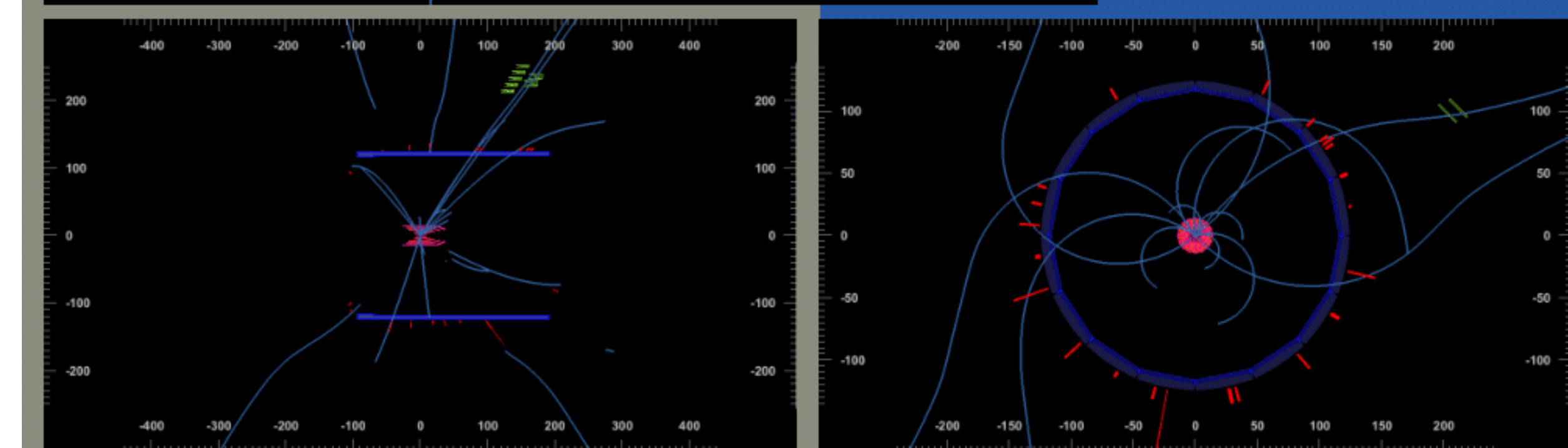
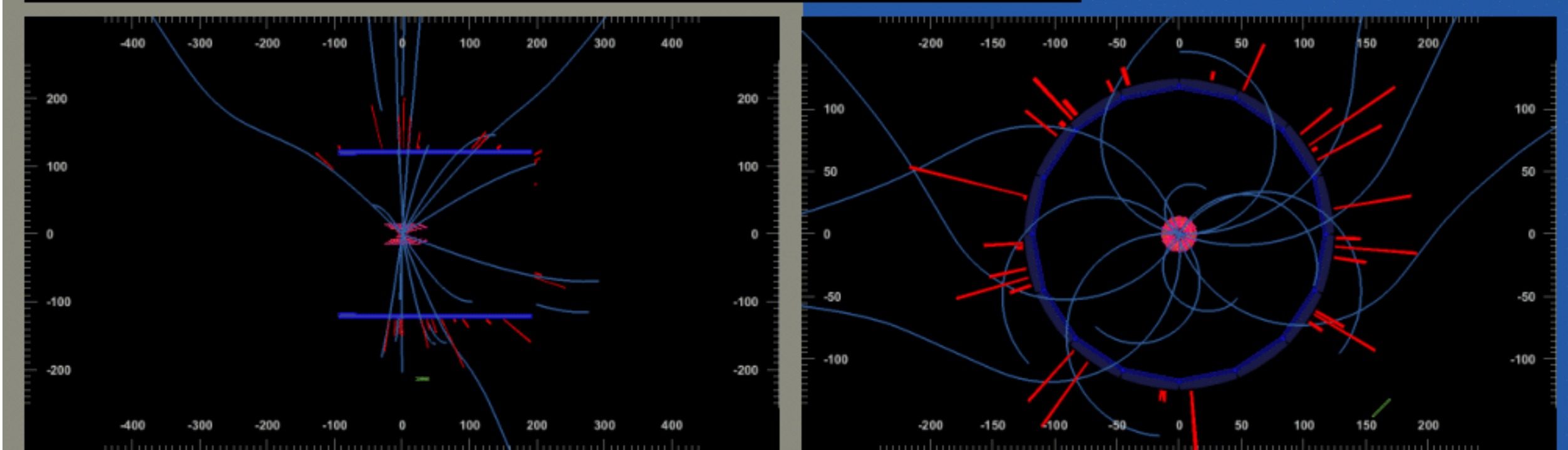
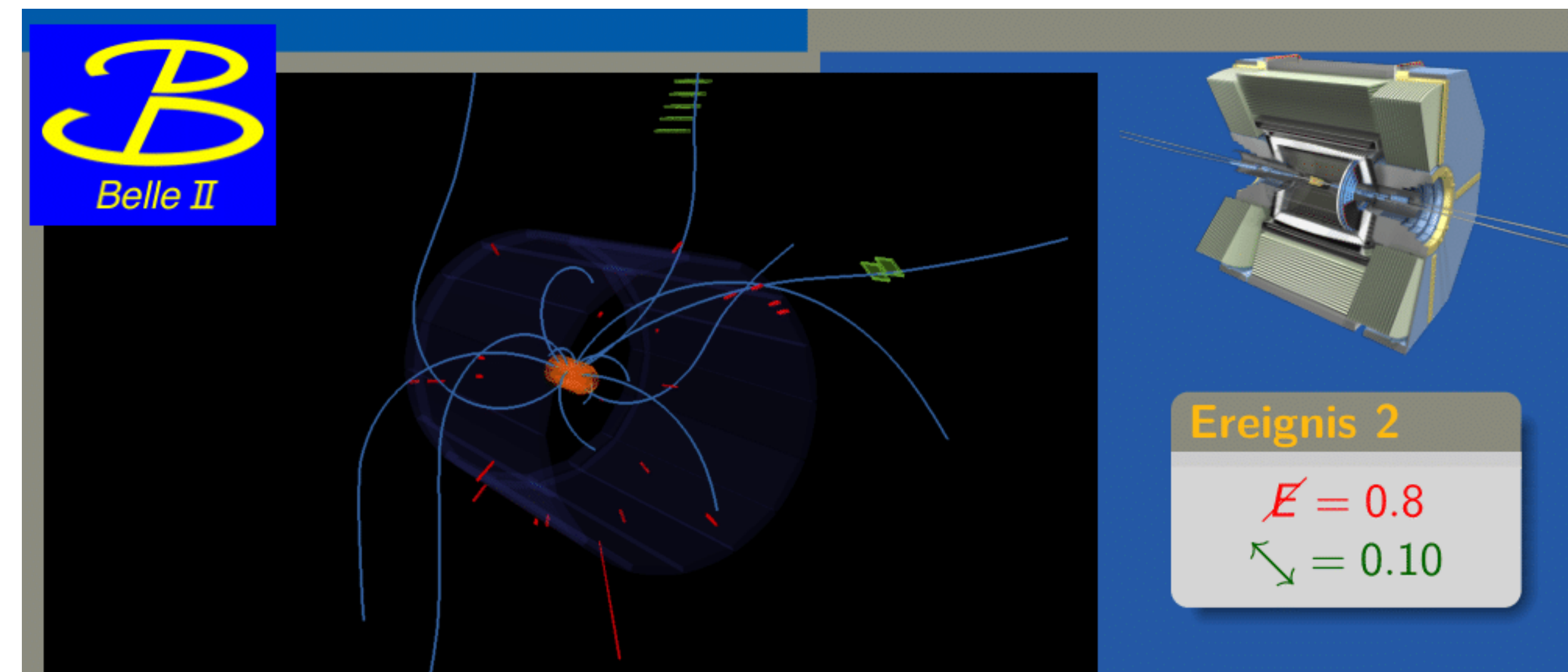
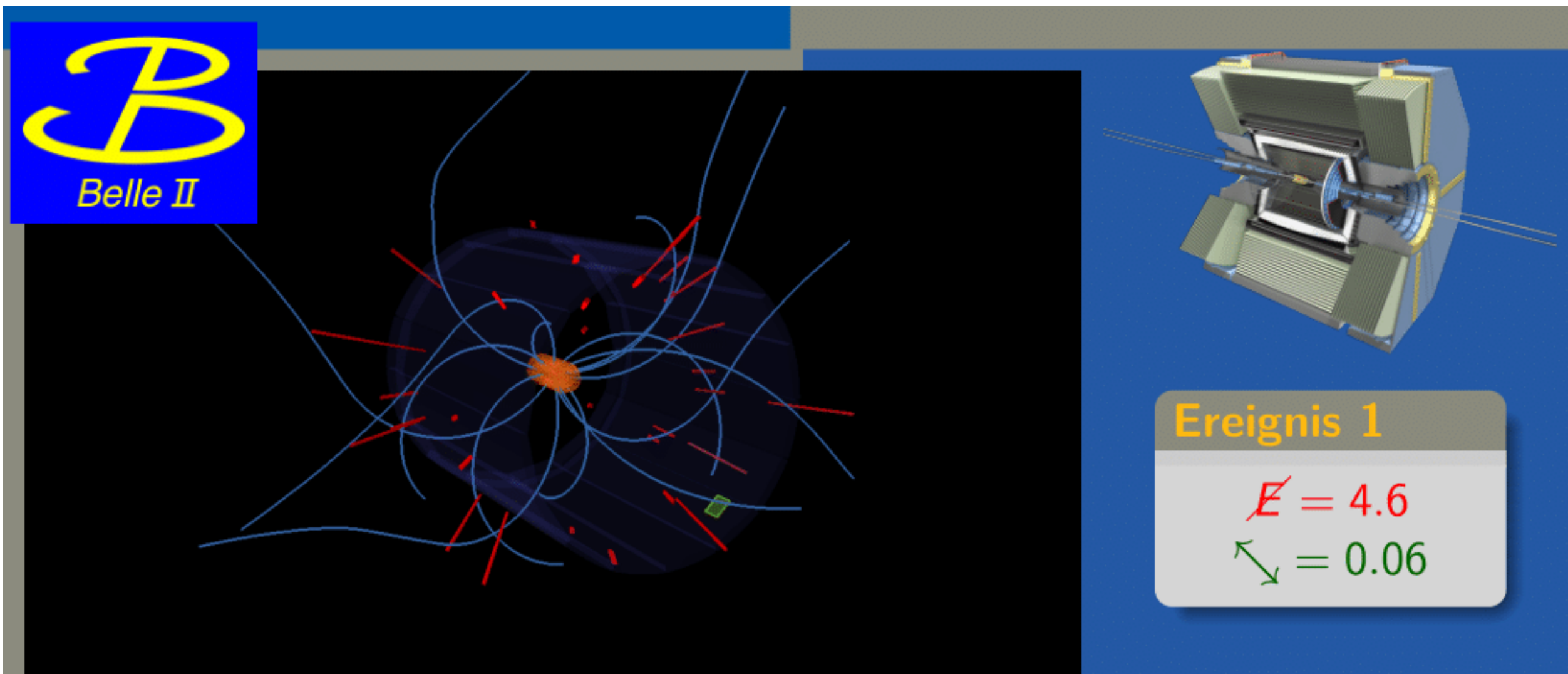
- Decay into a **large variety of final states**
- **Variable number of tracks**, large number is more frequent
- **Less missing energy \cancel{E}** because less neutrinos created
- **Straightness** ↘ **smaller** than leptonic decays
- Deposition of energy in the calorimeter (**red signal close to the track**)
- Sometimes deposit of energy in the muon detector (**green signals along the outer track**)



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

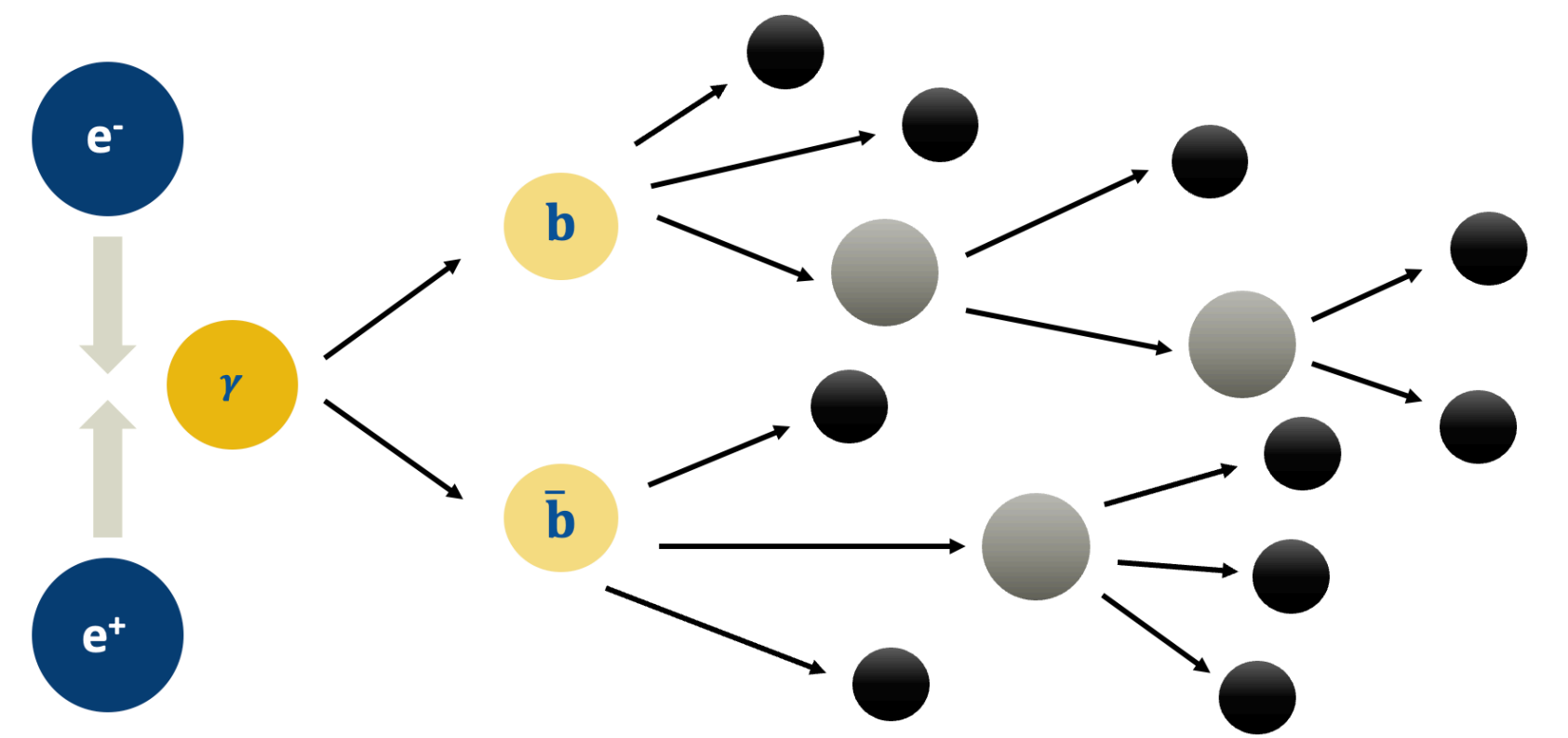


$b\bar{b}$ events: real event display

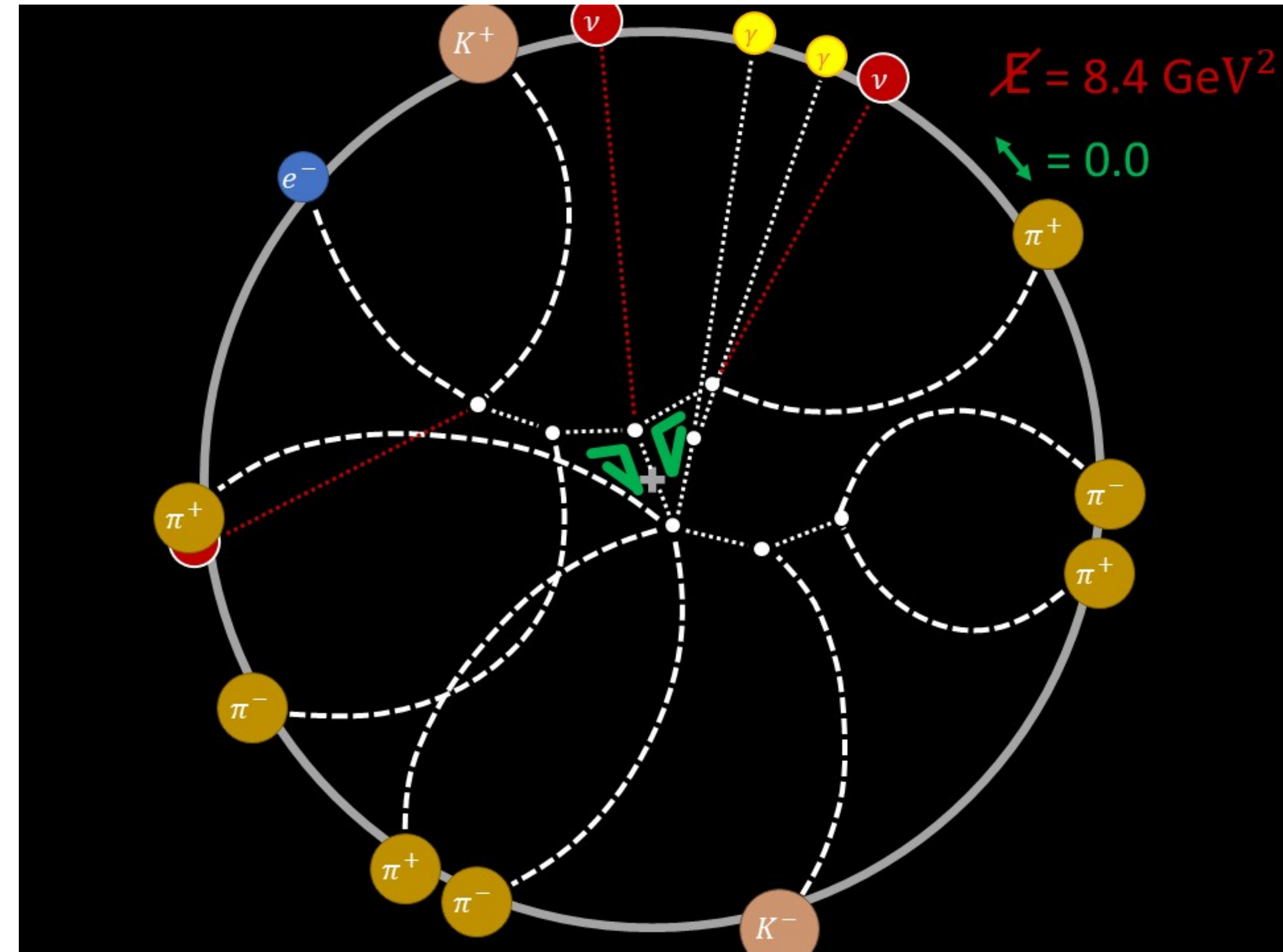
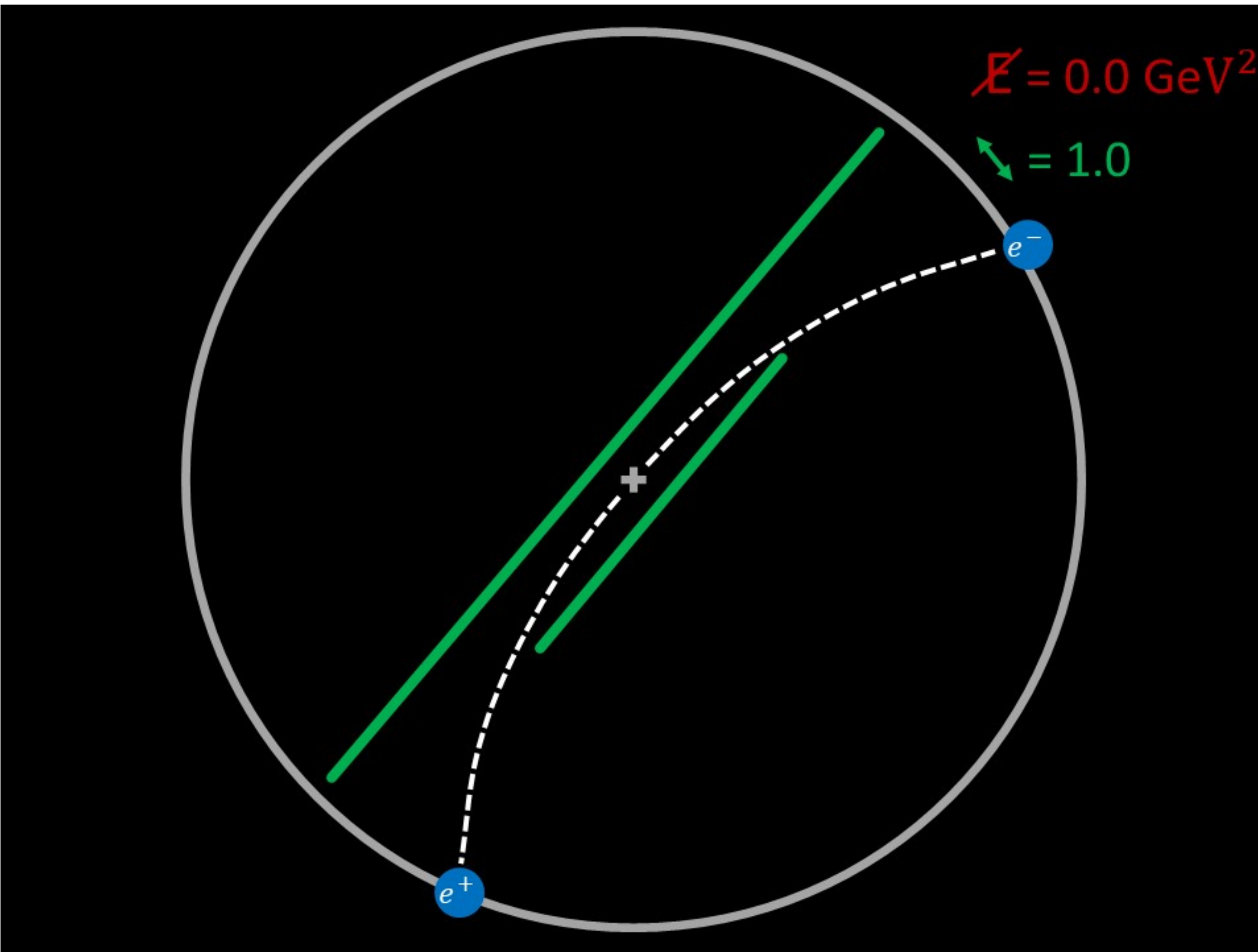


$b\bar{b}$ events: properties

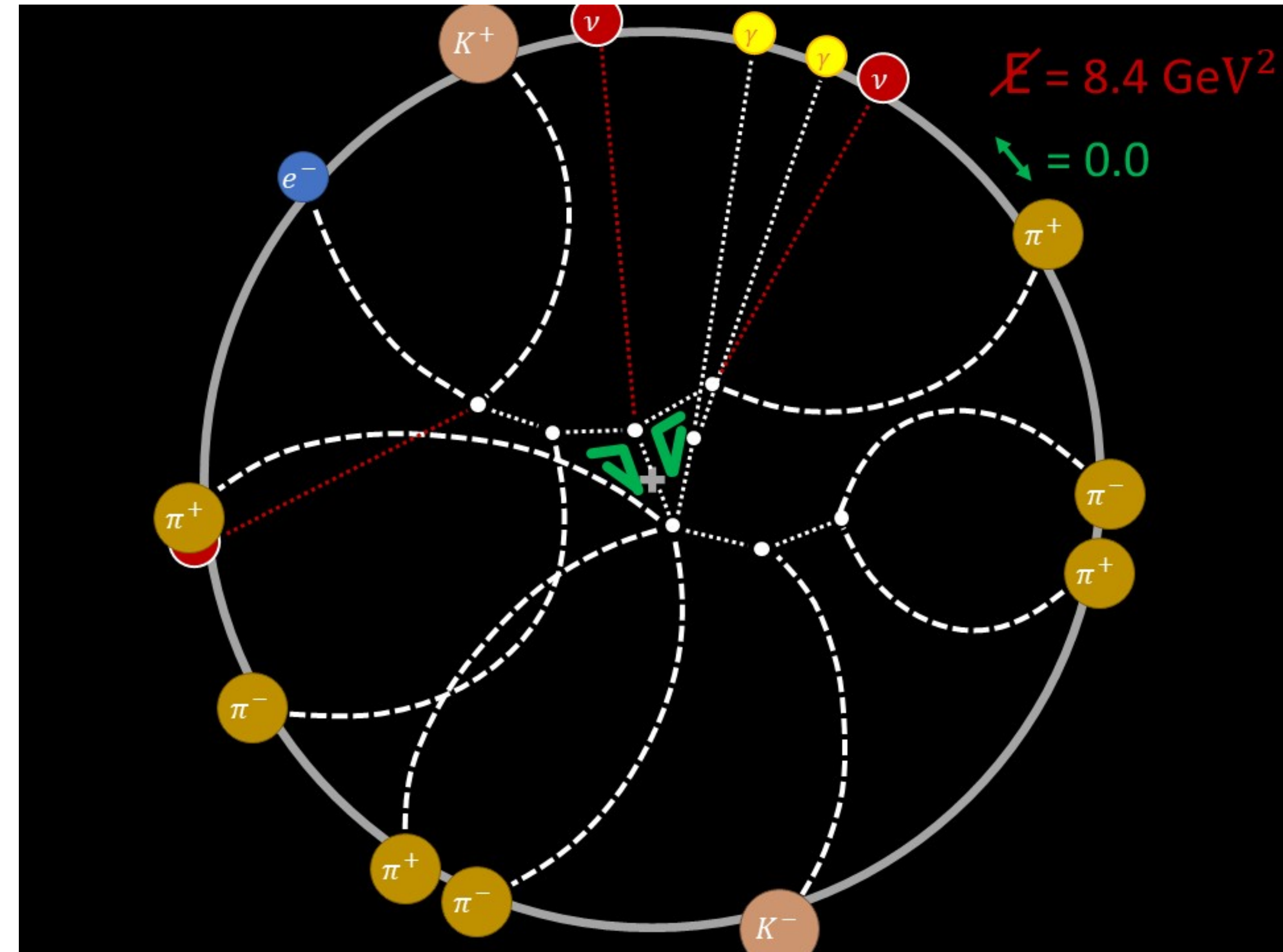
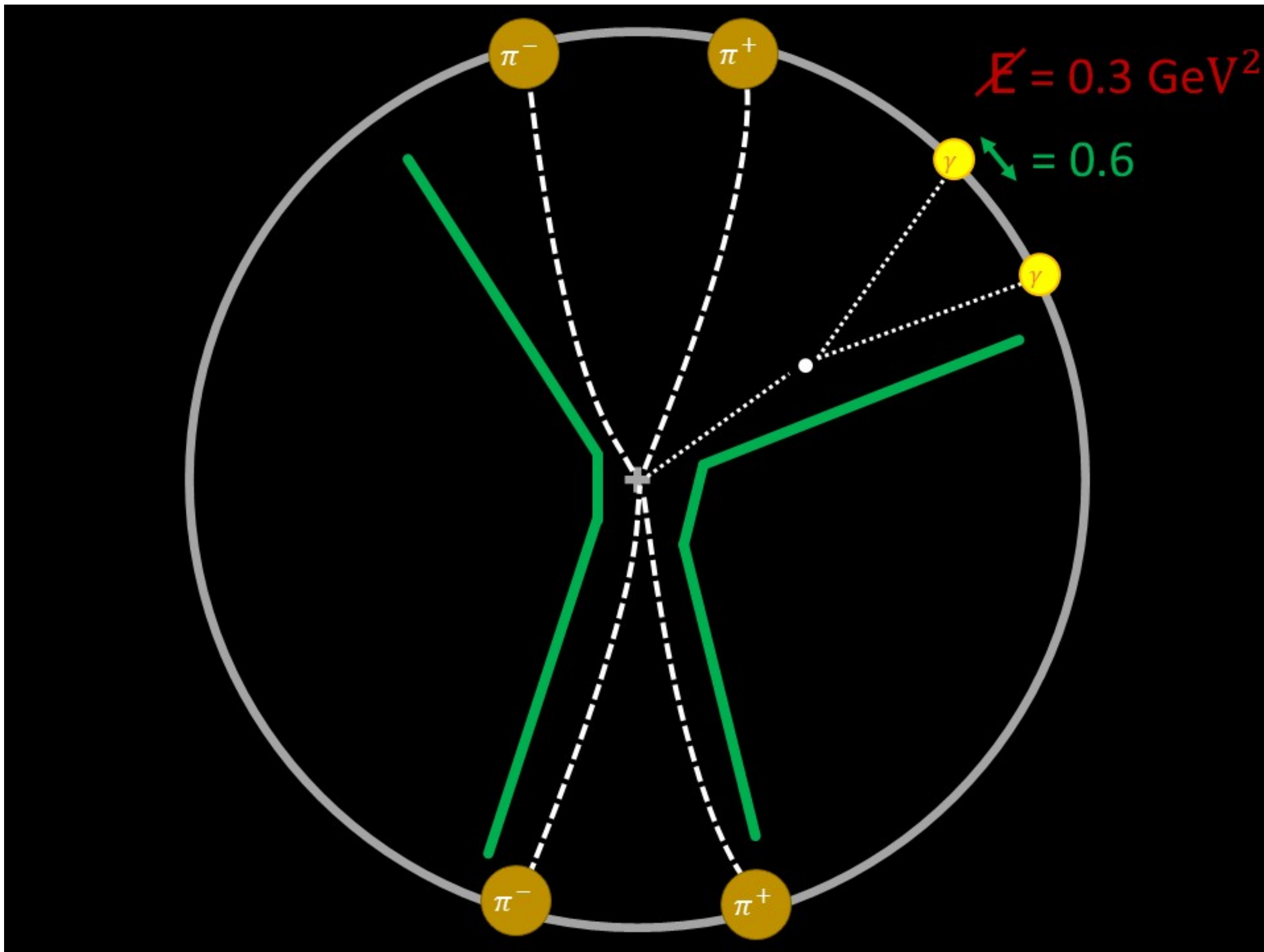
- Decay into a **large variety of final states**
- **Variable number of tracks**, large number is more frequent
- Heaviest particles possible: high energy \Rightarrow **a lot of tracks**
- **Very low straightness** \searrow : "spherical" events than leptonic decays
- Sometimes neutrinos are produced: missing energy \cancel{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**)



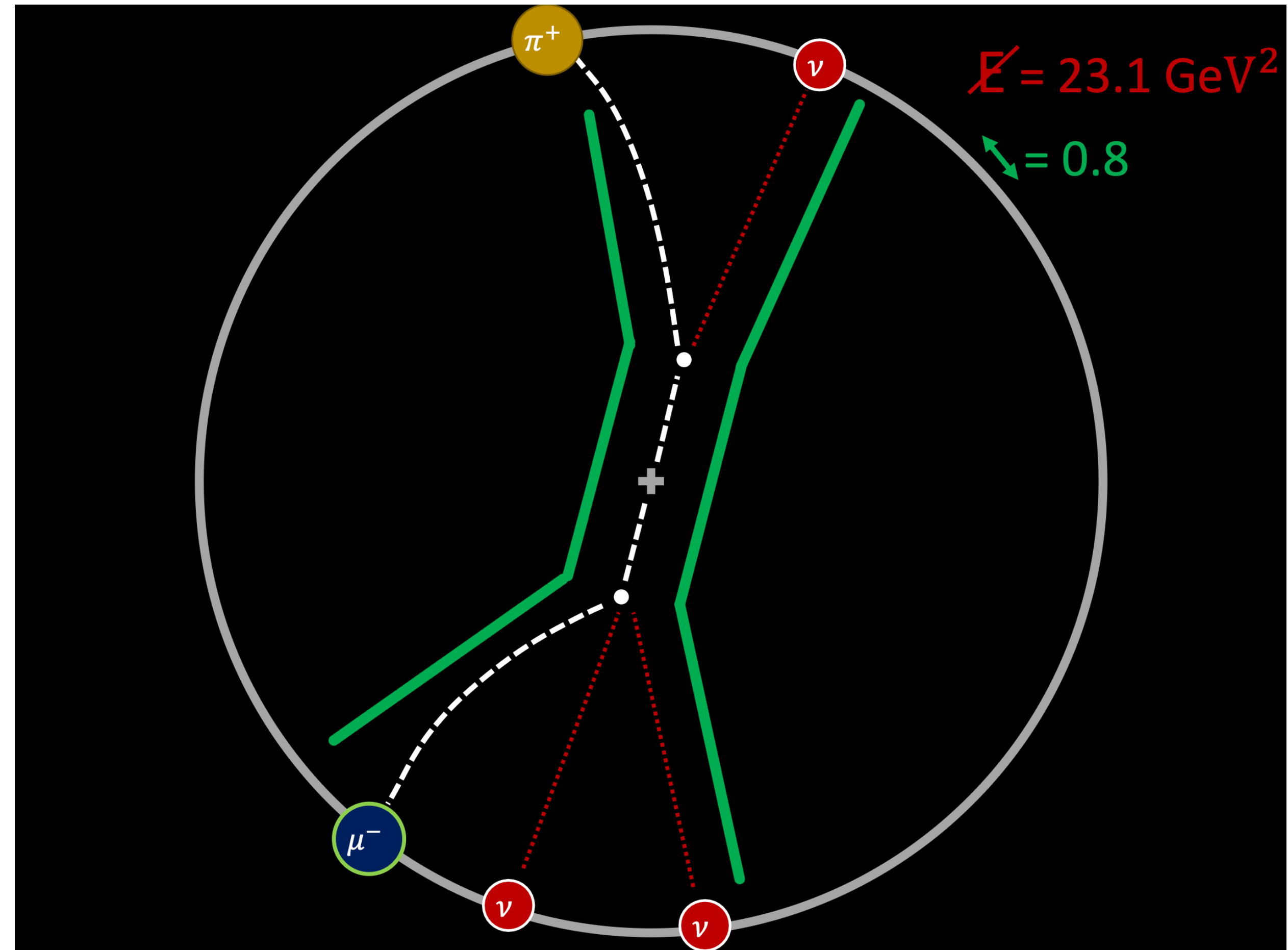
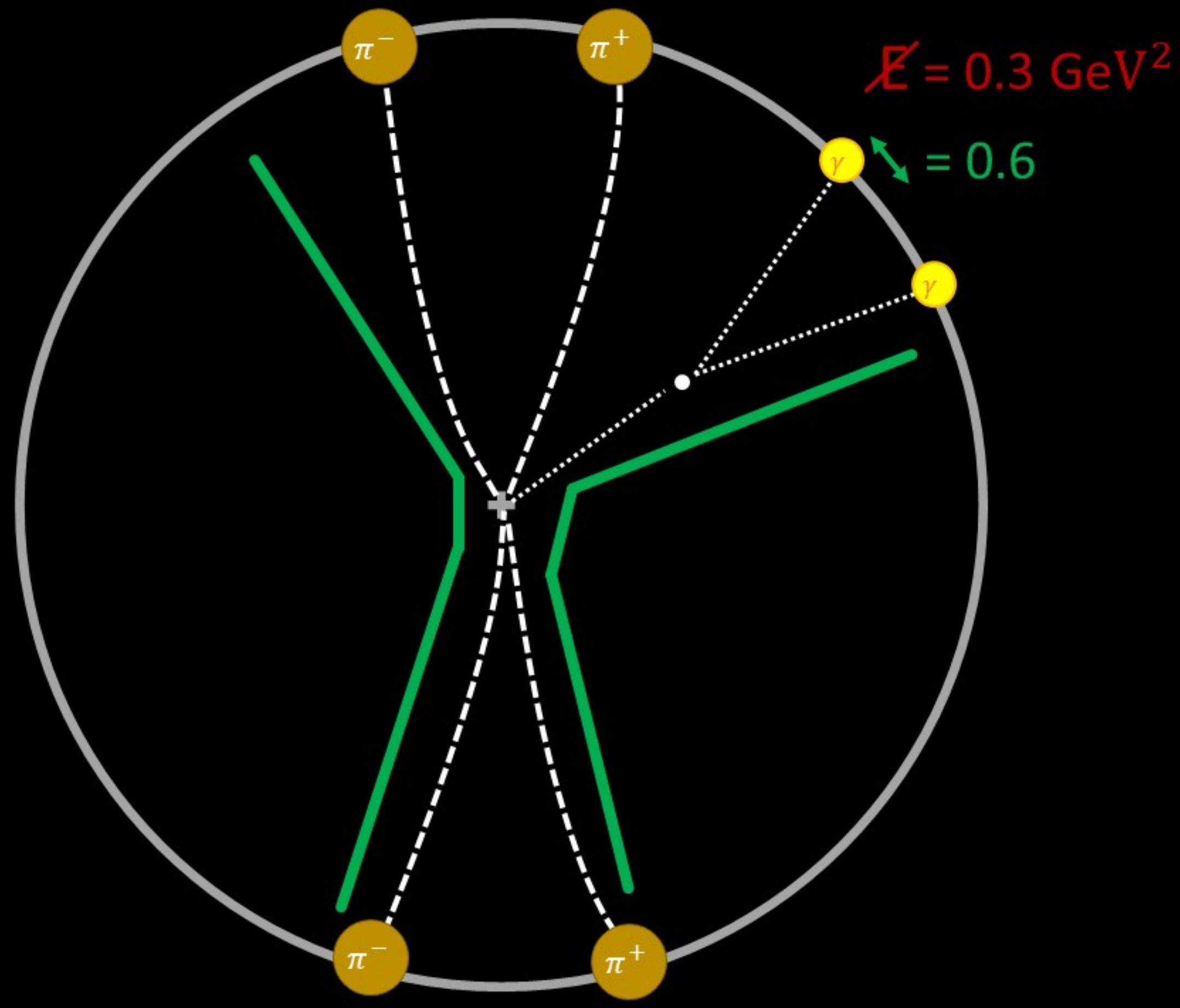
Comparison: e^+e^- vs $b\bar{b}$



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?

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

R-value again

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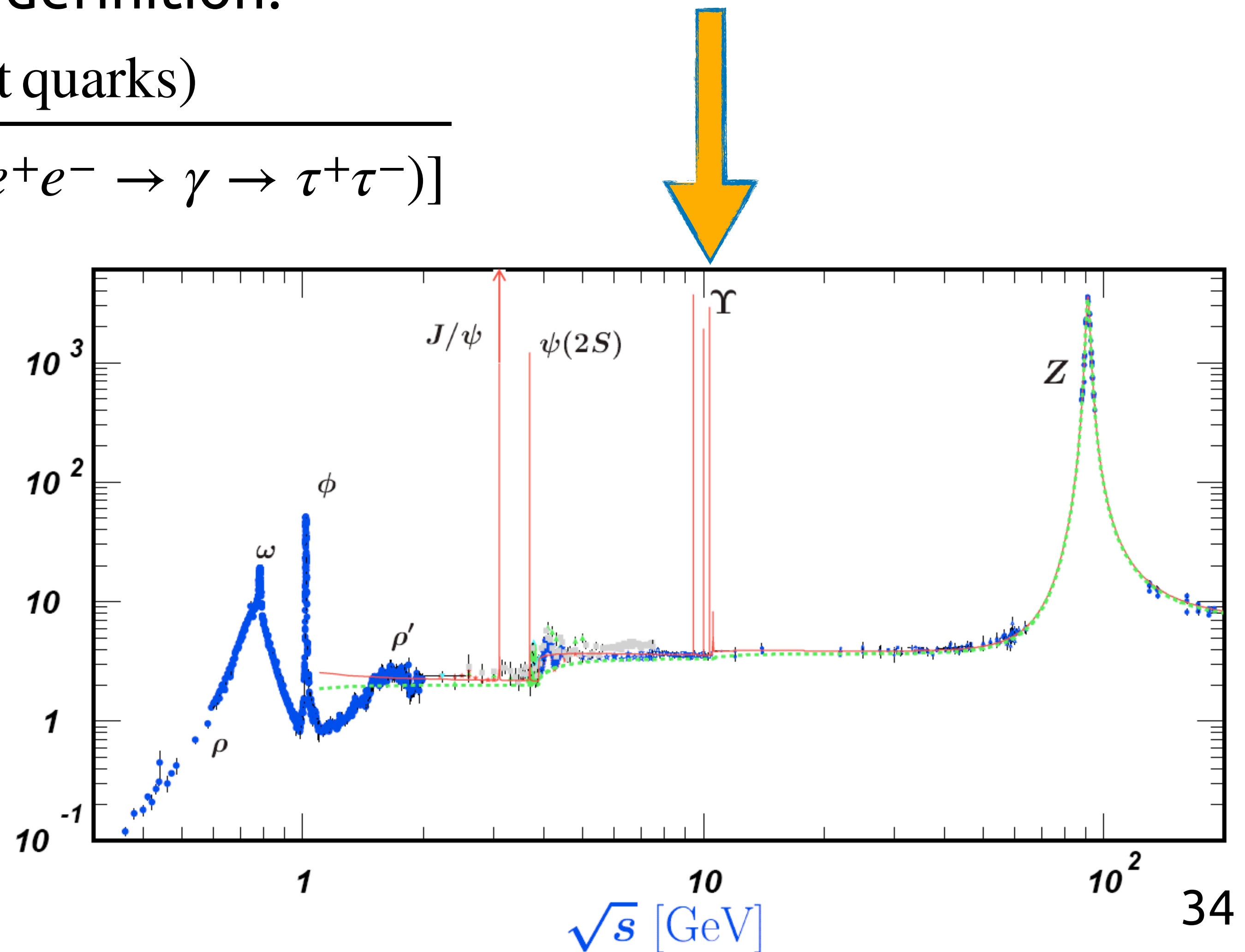
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- Because at Belle II we are running at center-of-mass energy of $\Upsilon(4S)$ resonance, just at $B\bar{B}$ threshold (B is a meson with a b quark)

R

- The production of b is enhanced there

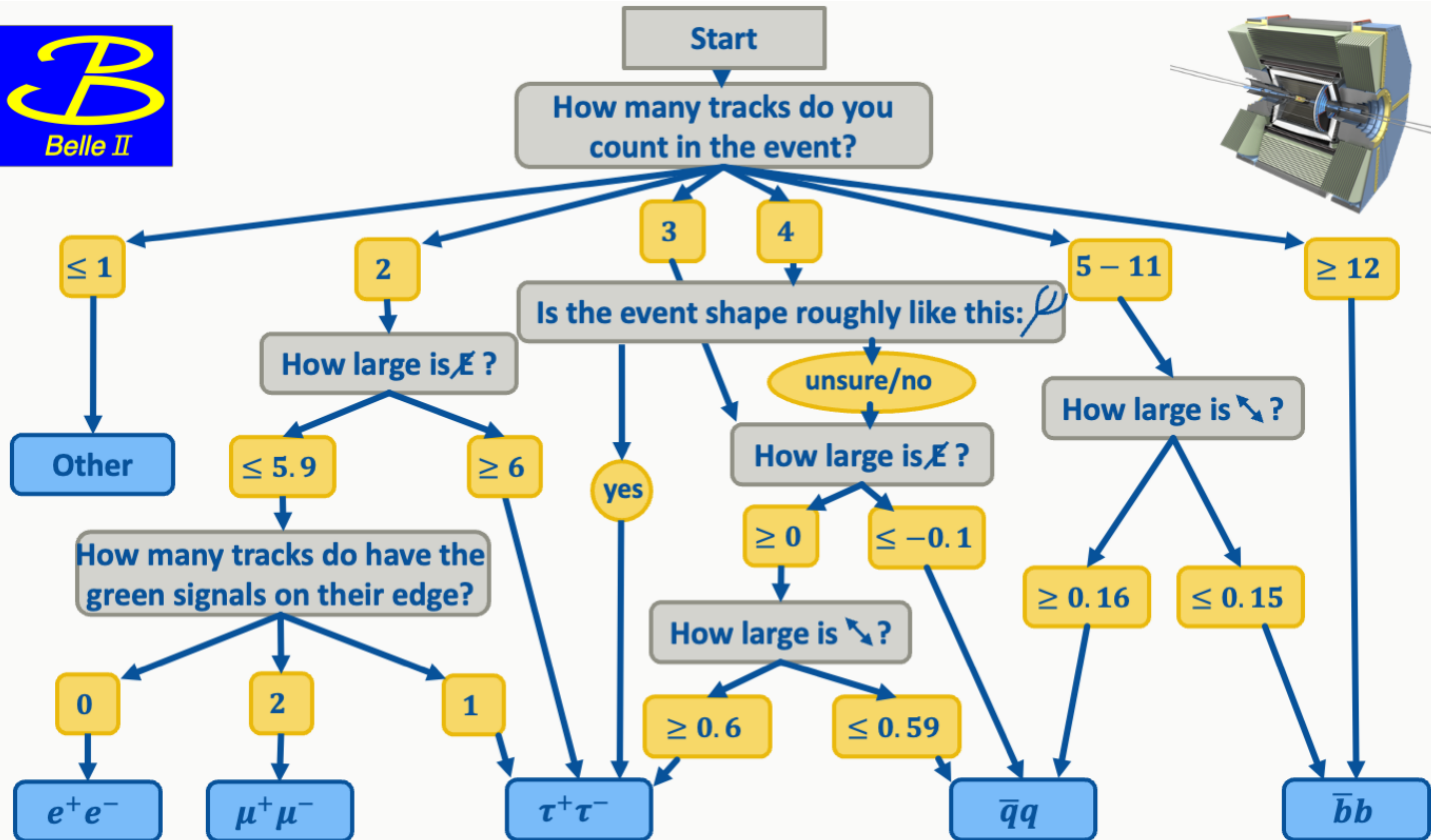
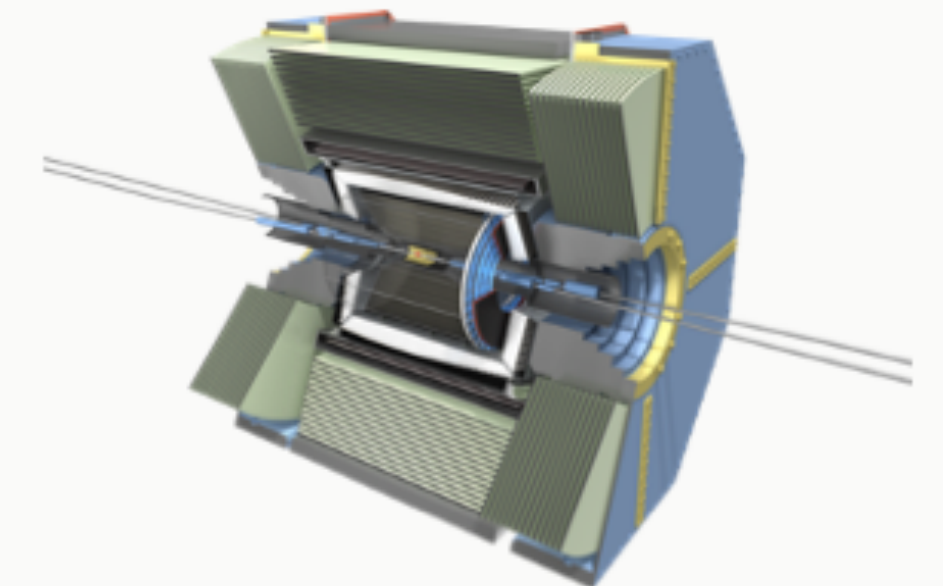
- This makes Belle II a "B-factory"



Large numbers importance

- Every measurement is affected by uncertainty
- The collision process $e^+e^- \rightarrow XYZ$ 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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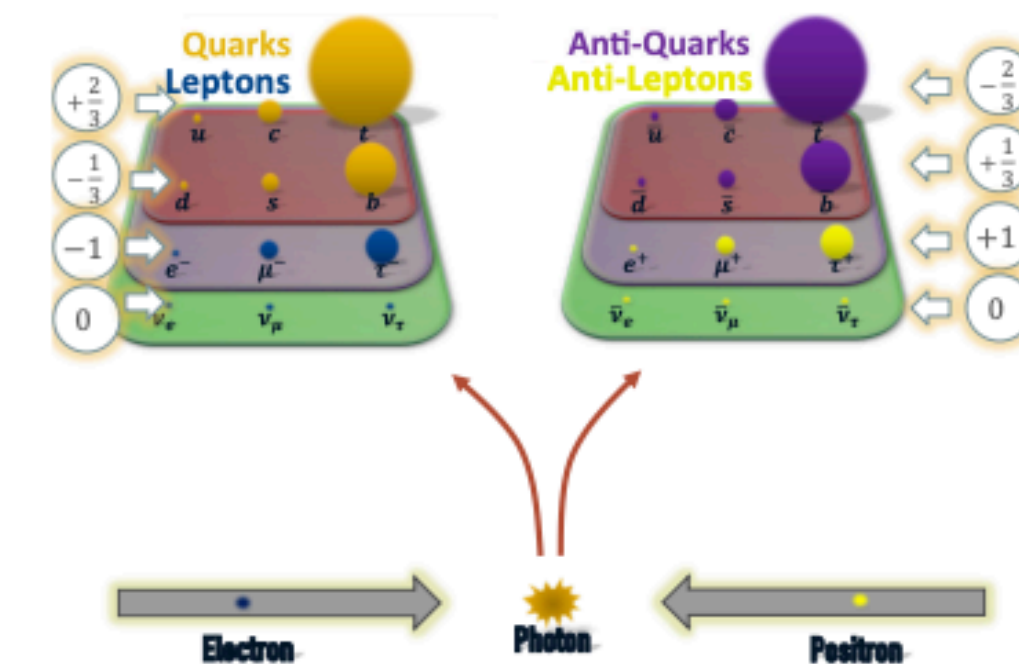
- [Example Events](#)
- [Practice Task](#)
- [Measurement with data from the Belle II experiment](#)

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

The image shows two overlapping screenshots of the Belle II experiment website. The top screenshot shows the main navigation menu with options: HOME, INTRO, BELLE II, and RECONSTRUCT. The bottom screenshot shows the 'Example Events' page, which includes a list of event categories: 1. electron/positron events, 2. muon/antimuon events, 3. tauon/antitauon events, 4. light quark events, and 5. b-quark/antiquark events. An orange arrow points from the 'Example Events' link in the bottom screenshot to the 'Example Events' link in the top screenshot.

Belle II experiment

HOME INTRO BELLE II RECONSTRUCT

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- [What is the \$R\$ -value?](#)

After that we're ready to look at the experimental measurement, to

- [Example Events](#)
- [Practice Task](#)
- [Measurement with data from the Belle II experiment](#)

Belle II experiment

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

Example Events

How do the different particle-antiparticle pairs look in the detector?

Here you can look at the different processes in form of example videos and pictures.

1. [electron/positron events](#)
2. [muon/antimuon events](#)
3. [tauon/antitauon events](#)
4. [light quark events](#)
5. [b-quark/antiquark events](#)

After you've done that you can test your new knowledge by [clicking here](#) and trying to sort the example events yourself.

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



HOME

INTRO

BELLE II

RECONSTRUCT B MESONS

MEASURE QUANTITIES

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The exchange particle of the electroweak force is the photon. It couples to particles with an electromagnetic charge 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 charges

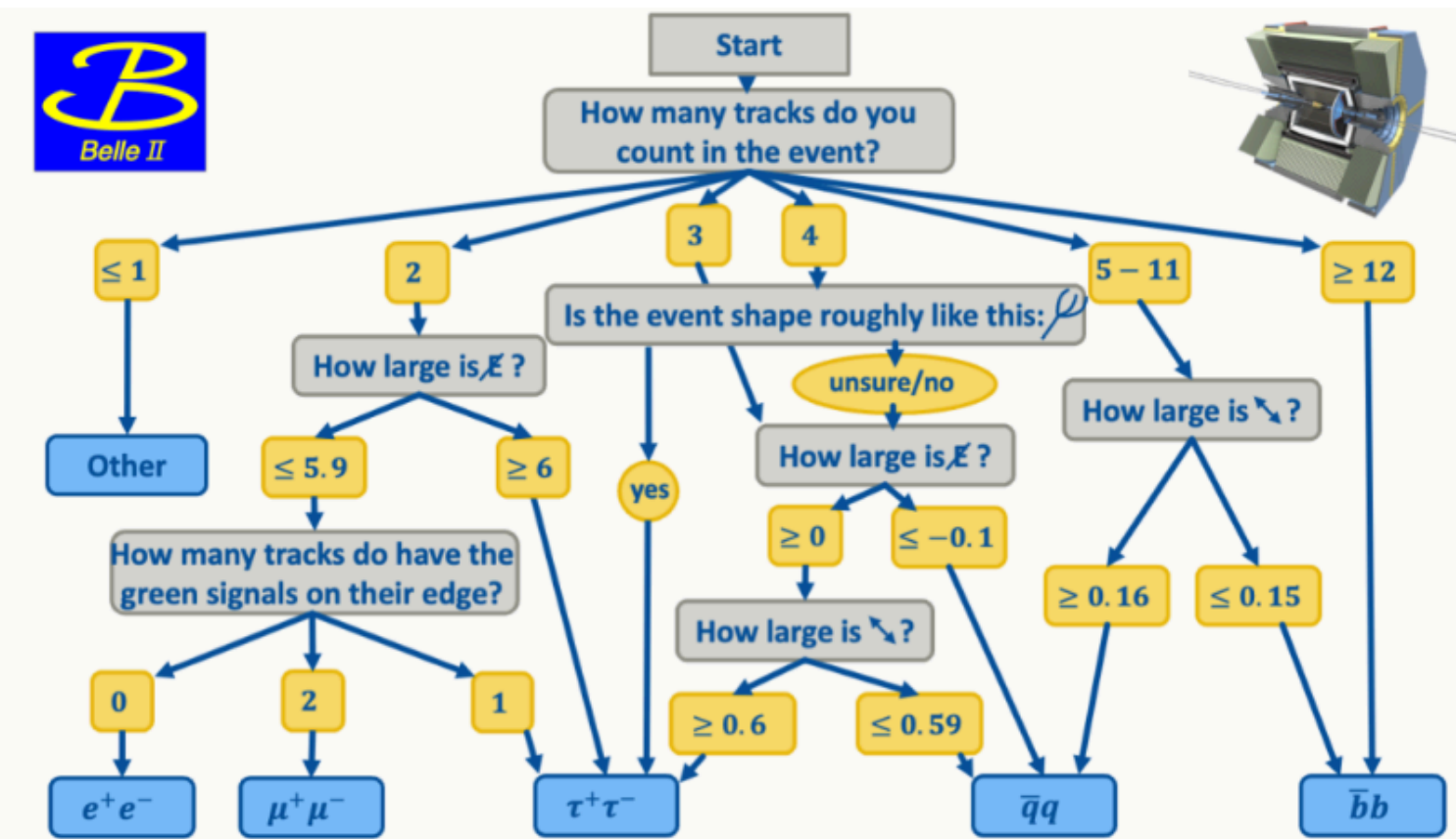
- [Example Events](#)
- [Practice Task](#)
- [Measurement with data from the Belle II experiment](#)

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](#)

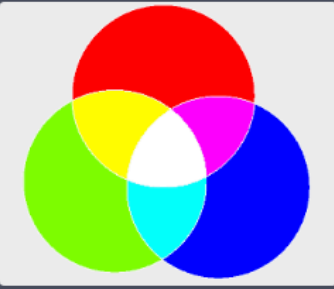
chose between datasets:
K, L, M, N, O, P

Extra: quark colors game

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

Farbspiel

Quarks besitzen nicht nur eine ungerade Ladung sondern auch eine sogenannte Farbladung. Es hat sich herausgestellt das Teilchen die aus Quarks bestehen immer farbneutral sind, das bedeutet ihre Farbe, wenn man die Einzelfarben der Quarks addiert, ist immer weiß. Das bedeutet auch, dass Quarks nie alleine existieren können. Sie brauchen immer mindestens einen Partner. In diesem Farbspiel ist es eure Aufgabe. Die Quarks ist so miteinander zu verbinden, dass die zusammengesetzten Teilchen immer farbneutral sind. Beachtet dabei, dass die anti-Farben von rot, grün und blau, also antirot, antigrün und anti-blau, hier durch die Farben cyan, magenta und gelb dargestellt werden. Schafft ihr es alle Quarks miteinander zu kombinieren?



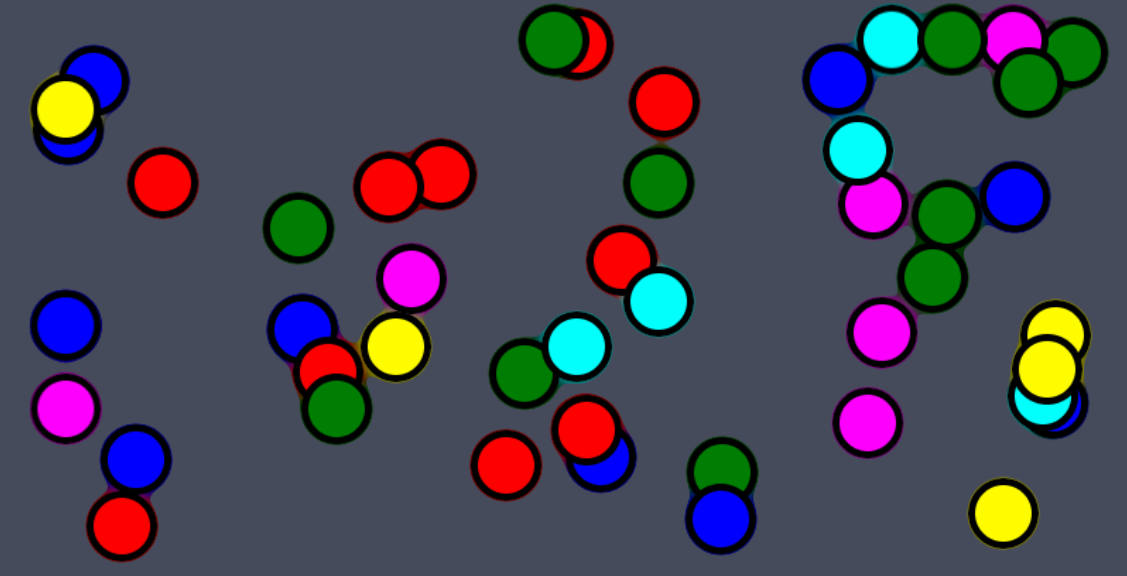
Das Modell der Farbmischung wurde auf die Elementarteilchen übertragen.

Schwierigkeitsgrad:

- Einfach (nur Farbladung)
- Schwerer (Farbladung und elektrische Ladung)

Neustart

0 Teilchen von 47 Teilchen zugeordnet



Now is your turn!



BACKUP SLIDES

