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NETZWERK TEILCHENWELT

Belle II

HOW MANY COLORS DOES A QUARK COME IN?

A MEASUREMENT USING DATA FROM THE BELLE II EXPERIMENT FOR THE TEILCHENPHYSIK-MASTERCLASSES

Florian Bernlochner, Jochen Dingfelder, Svenja Granderath[1], Henrik Junkerkalefeld, Sebastian Lülsdorf, Florin Martius, Barbara Valeriani-Kaminski, Christian Wessel

[1] granderath@physik.uni-bonn.de

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WHAT IS A MASTERCLASS?

- Offers high school students an insight into physics research
- Researchers spend one day with the students
- Combination of talks and hands-on work
- Netzwerk Teilchenwelt:
  - Organizes opportunities for students interested in particle physics
- Developed a new masterclass based on Belle II data

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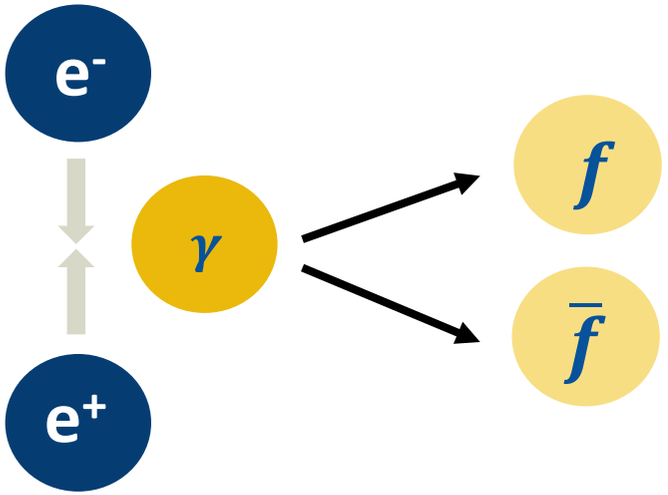
BELLE II

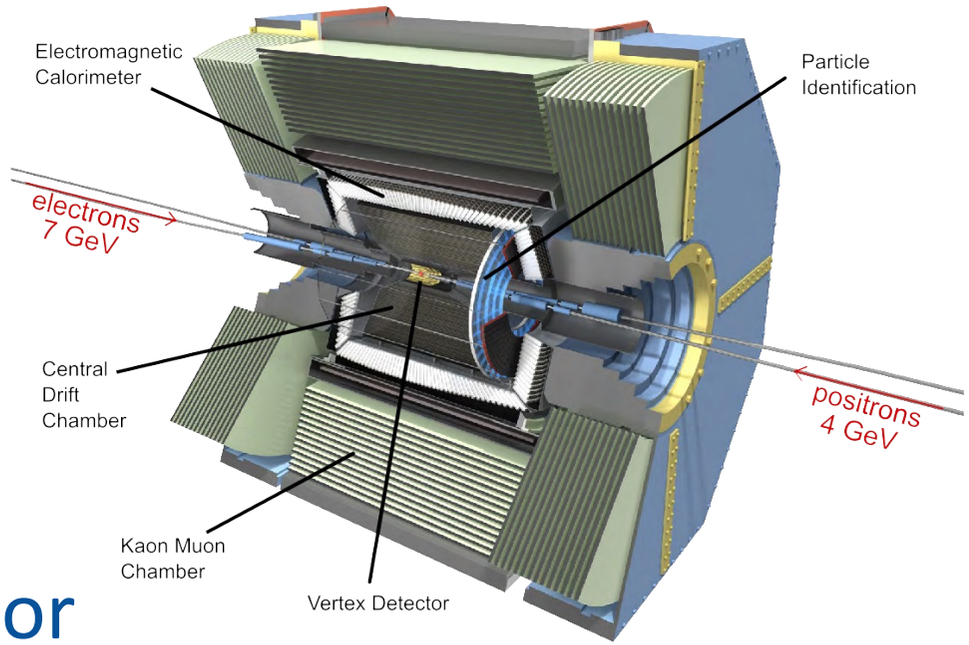
– SuperKEKB accelerator located in Japan

– e^+e^- collider tuned to produce $B\overline{B}$ pairs → Study CP violation
Look for new physics
…

– Other processes occur also:



$$f\bar{f} = \begin{Bmatrix} e^+e^- \\ \mu^+\mu^- \\ \tau^+\tau^- \\ q\bar{q} \\ b\bar{b} \\ \dots \end{Bmatrix}$$

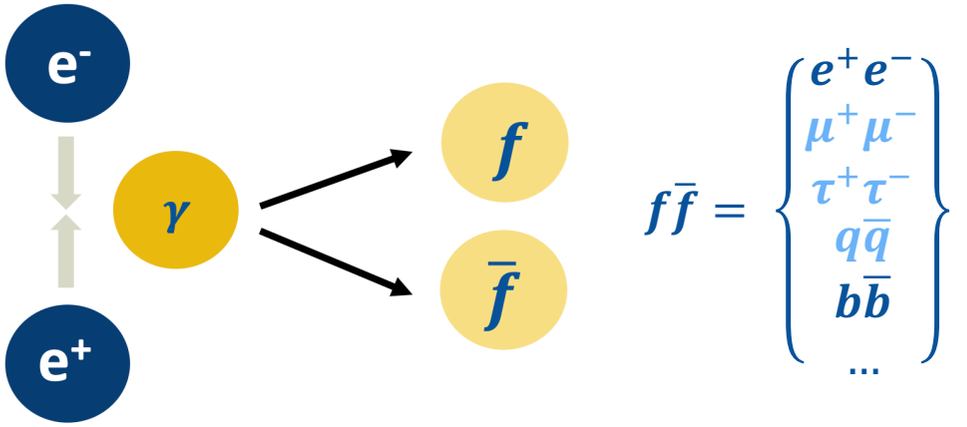


– Decay products detected by Belle II detector

MEASUREMENT

– By counting frequency of processes can determine R value:

$$R = \frac{N(q\bar{q})}{0.5\, N(\tau^+\tau^- + \mu^+\mu^-)}$$



– R value determined by electric quark charges and number of colors:

$$R = \mathrm{N_c} \sum_{\mathrm{quarks}} \mathrm{q}^2_{\mathrm{q\bar{q}}} = \frac{10}{9}\mathrm{N_c}$$

– Can determine the number of quark color charges

COMPONENTS

1. Introductory talks

COMPONENTS

1. Introductory talks
2. Worksheet

Exercise a)

According the calculation of above's example, try to answer the following: What is the frequency of occurrence for the following particle-antiparticle pairs:

$$N\left(e^+e^- \to \gamma \to u\bar{u}\right) = \square \cdot XY$$

$$N\left(e^+e^- \to \gamma \to s\bar{s}\right) = \square \cdot XY$$

$$N\left(e^+e^- \to \gamma \to \tau^+\tau^-\right) = \square \cdot XY$$

Exercise b)

Maybe you already spotted some regularities. Let's turn this around: For which particle-antiparticle pairs is the frequency of occurrence given by the following?

$$N\left(e^+e^- \to \gamma \to P\bar{P}\right) = \left(\frac{2}{3}\right)^2 \cdot XY = \frac{4}{9} \cdot XY \qquad P = \square\,\square\,\square$$

Exercise c)

To be able to create a particle-antiparticle pair, the energy needs to be sufficiently high. Let's assume that we build a particle accelerator that produces enough energy in the collision point to (only) produce u-, d- and s-quarks (+ anti quarks). What is the total frequency of occurrence of the overall quark production in this case? **Hint:** You might want to calculate this in a couple of steps on a note pad.

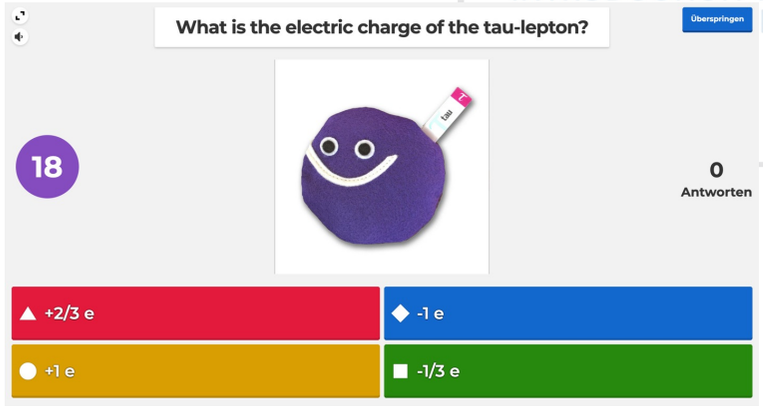
$$N\left(e^+e^- \to \gamma \to u\bar{u}/d\bar{d}/s\bar{s}\right) = \square \cdot XY$$

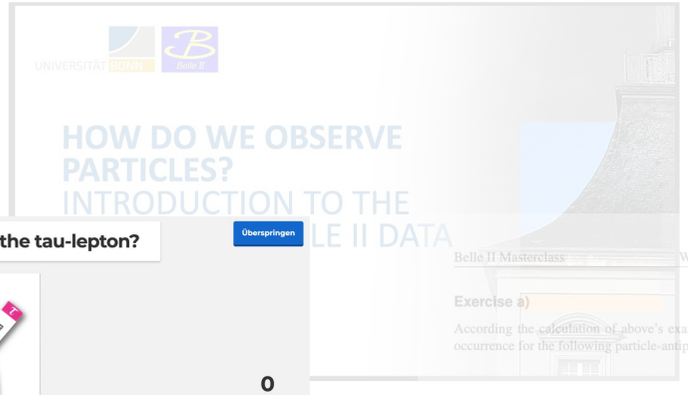
How does this change when we increase the collision energy sufficiently such that the production of c-quarks becomes possible as well?

$$N\left(e^+e^- \to \gamma \to u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}\right) = \square \cdot XY$$

COMPONENTS

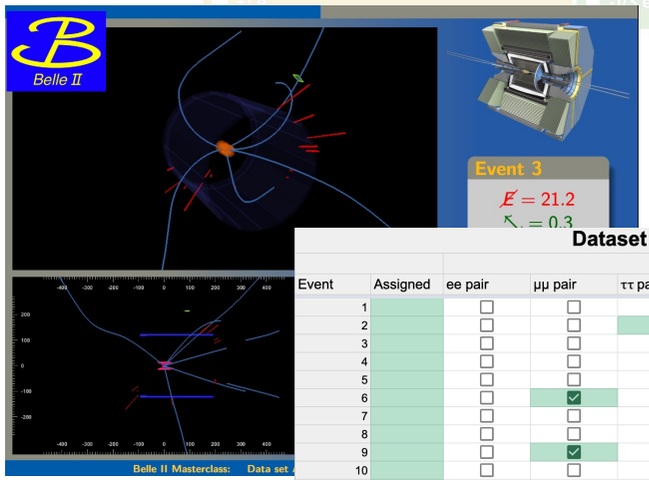
1. Introductory talks
2. Worksheet
3. Interactive quizzes





COMPONENTS

1. Introductory talks
2. Worksheet
3. Interactive quizzes
4. Data Analysis

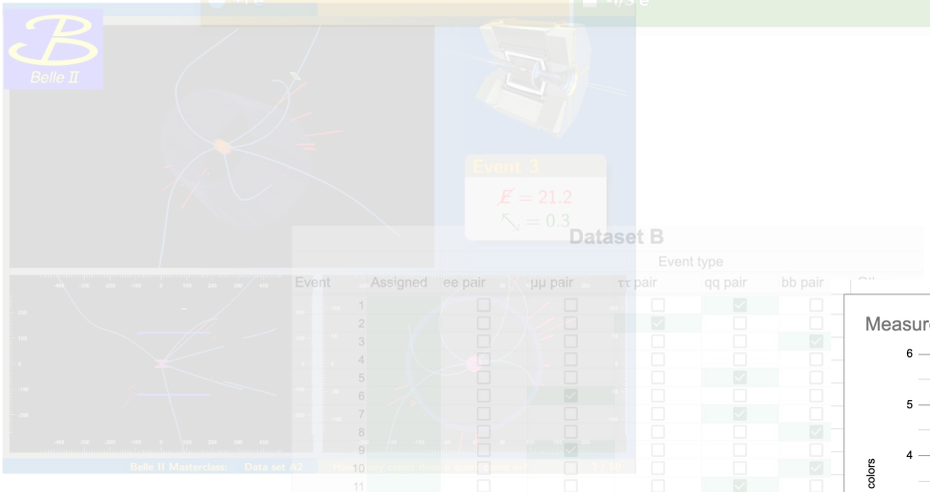


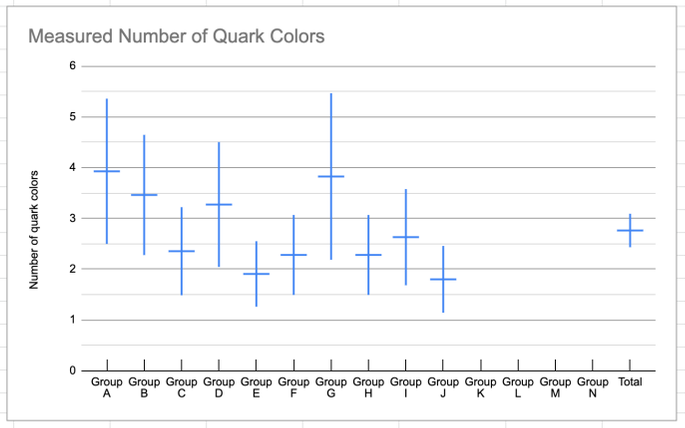
Dataset B

Event	Assigned	Event type: ee pair	μμ pair	ττ pair	qq pair	bb pair	Other
1		☐	☐	☐	☑	☐	☐
2		☐	☐	☑	☐	☐	☐
3		☐	☐	☐	☐	☑	☐
4		☐	☐	☐	☐	☐	☑
5		☐	☐	☐	☑	☐	☐
6		☐	☑	☐	☐	☐	☐
7		☐	☐	☐	☑	☐	☐
8		☐	☐	☐	☐	☑	☐
9		☐	☑	☐	☐	☐	☐
10		☐	☐	☐	☐	☑	☐
11		☐	☐	☐	☑	☐	☐
12		☐	☐	☐	☐	☑	☐
13		☑	☐	☐	☐	☐	☐
14		☐	☐	☑	☐	☐	☐
15		☐	☐	☐	☐	☑	☐
16		☐	☐	☐	☑	☐	☐
17		☐	☐	☑	☐	☐	☐
18		☐	☑	☐	☐	☐	☐
19		☐	☐	☐	☑	☐	☐

COMPONENTS

1. Introductory talks
2. Worksheet
3. Interactive quizzes
4. Data Analysis
5. Discussion



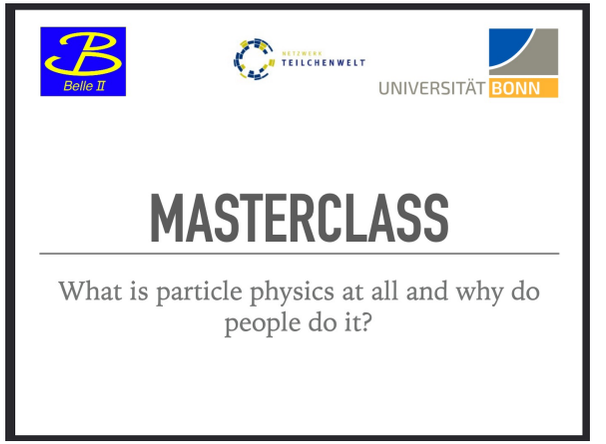


All material available in English and German

TALKS

- Introduce students to particle physics and relevant concepts
- Start with familiar concepts and bring students to same level
- Prepare them for measurement
- Give opportunity to ask questions

1st Talk:



2nd Talk:

TALKS

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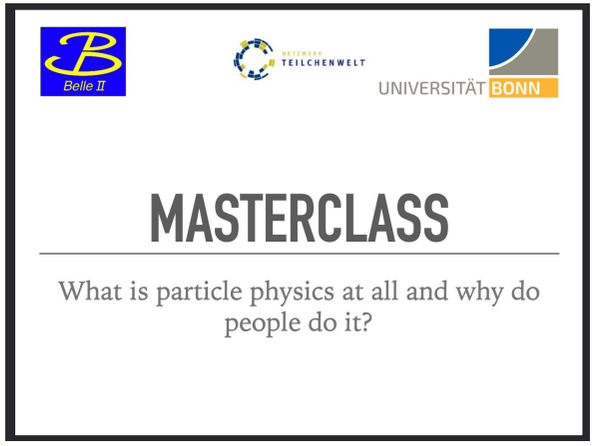

- History and status of Standard Model
- Mass-energy equivalence
- Open questions

2nd Talk:

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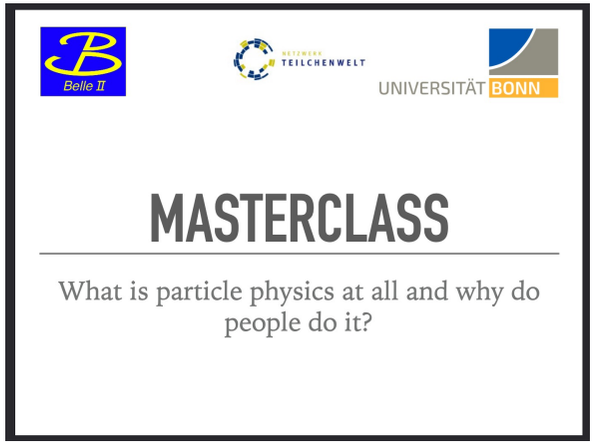

- History and status of Standard Model
- Mass-energy equivalence
- Open questions

2nd Talk:

- Particle accelerators
- Particle detectors
- Distinguishing processes

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WORKSHEET

- Step-by-step introduction to
  - relationship between frequency of process and electric charge
  - the R value
  - its dependence on number of colors
- Allows for discussion amongst students and deeper understanding of concepts

Belle II Masterclass — What happens in e^+e^- collisions? Quark colors and the R value

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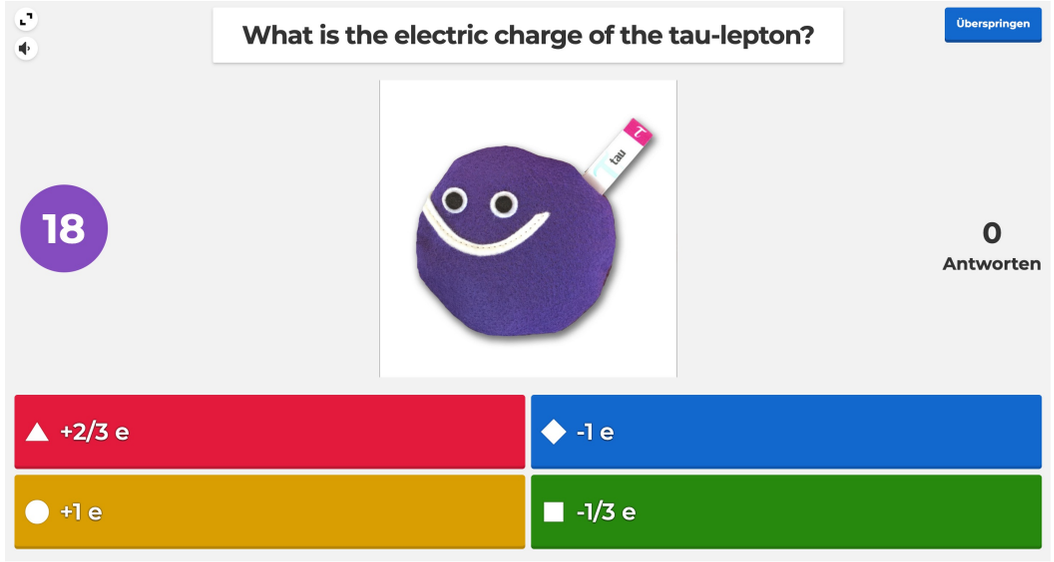
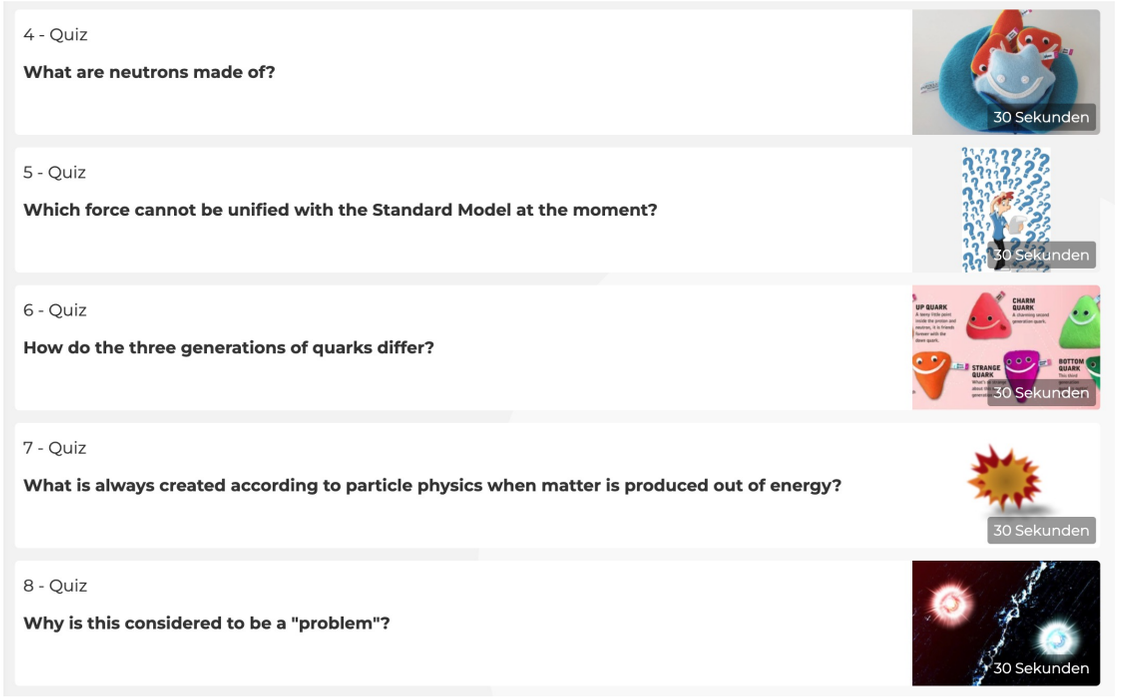
QUIZZES

- Interactive quizzes about
  - Particle physics concepts
  - Belle II detector
  - R value
- Competitive and playful way to check understanding

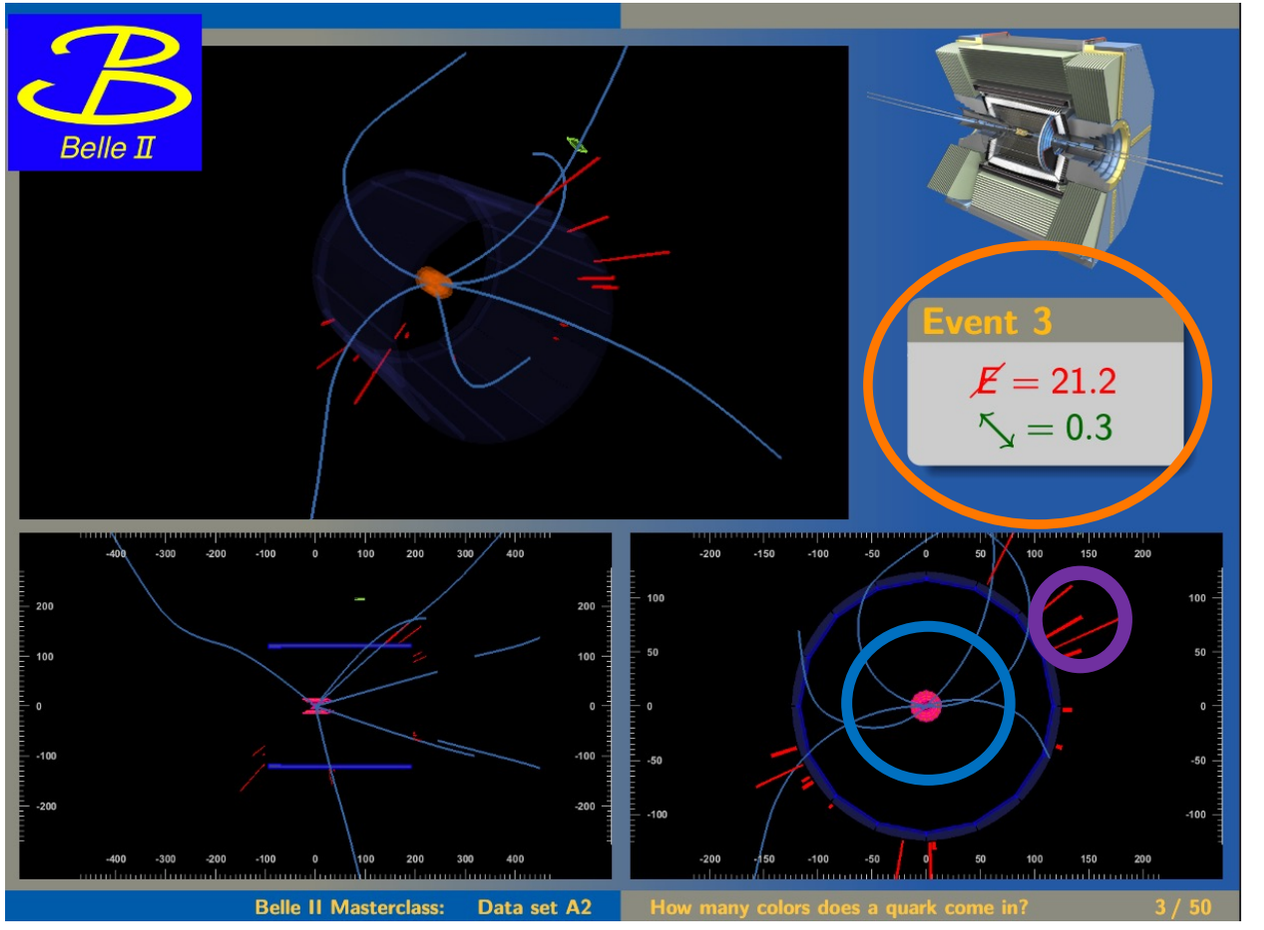




MEASUREMENT OF R VALUE

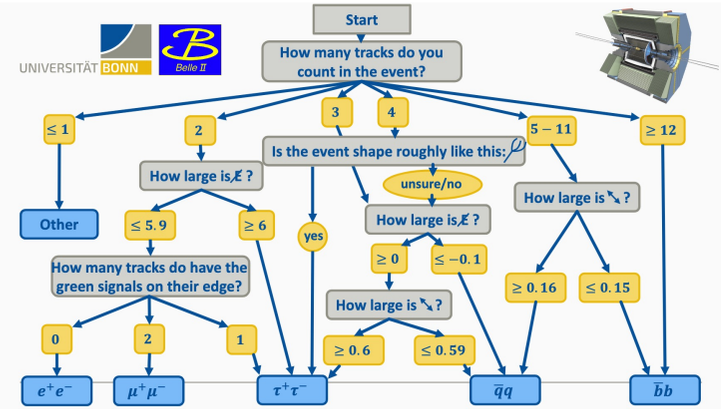
$$R = \frac{N(q\bar{q})}{0.5\, N(\tau^+\tau^- + \mu^+\mu^-)}$$

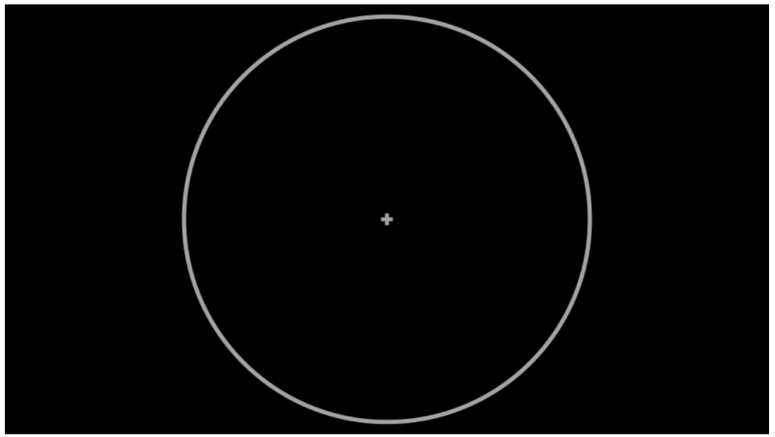
- Need to count occurences of processes
- Introduce event displays
- Explain how to categorise events based on:
  - Number of tracks
  - Energy deposits in calorimeter and muon detector
  - Missing energy and straightness

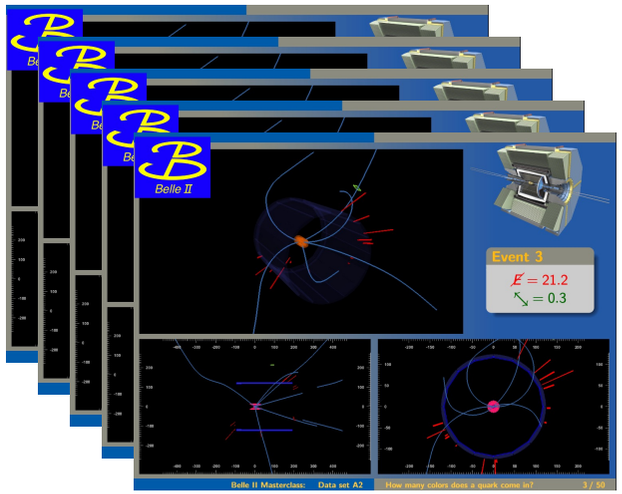


METHOD

- One set of 50-100 events per pair of students
- Assistance:
  - Flow chart
  - Example videos of processes
  - Practice exercises
- Categorise events in spreadsheet







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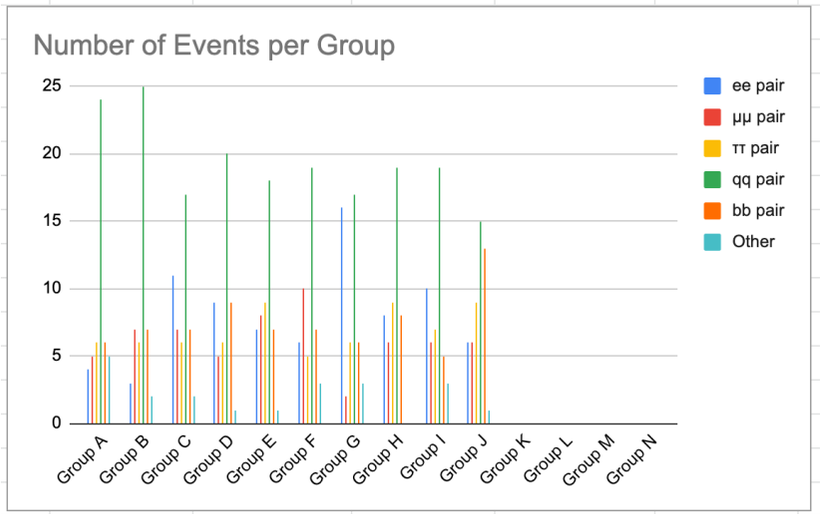
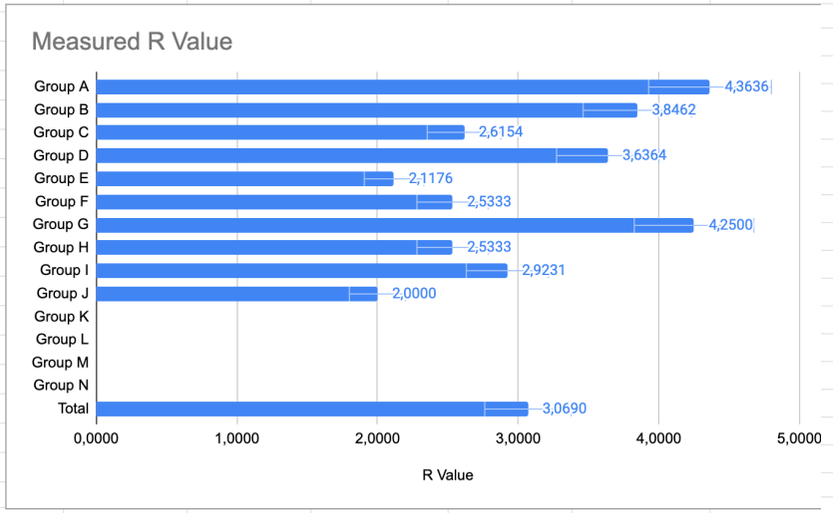
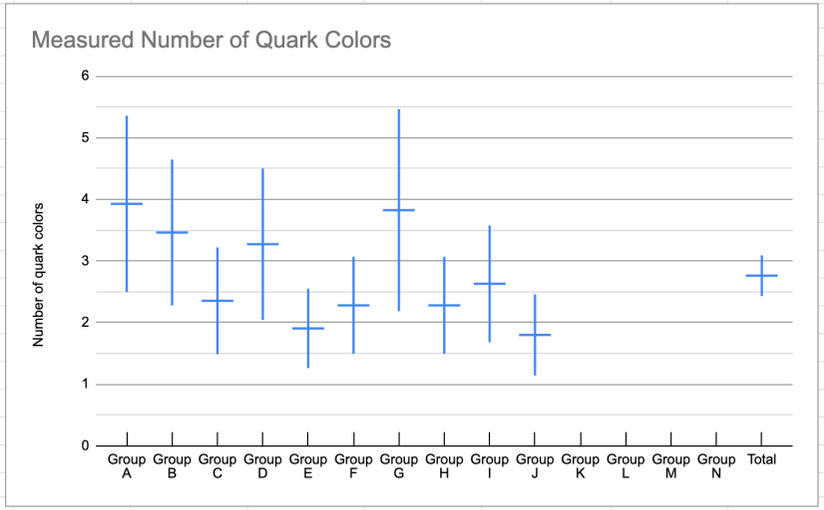
18		☐	☑	☐	☐	☐	☐
19		☐	☐	☐	☑	☐	☐

DISCUSSION OF RESULTS

- Automatic calculation of R value and number of quark colors for each group
- Error calculation included and results also combined
- Shows importance of statistics and proper error propagation in particle physics



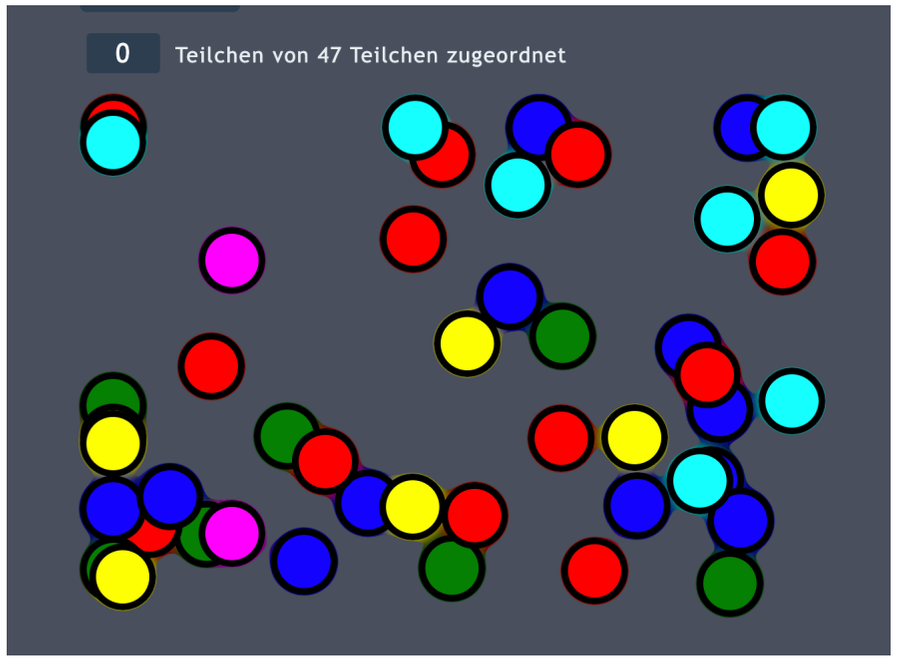


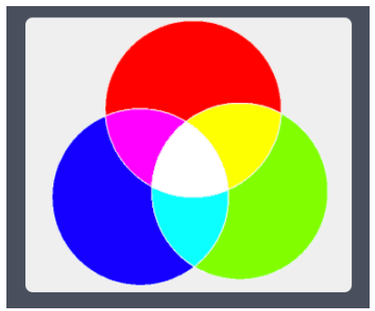


EXPLORE RESULT

– Lastly introduce meaning behind concept of three colors using game

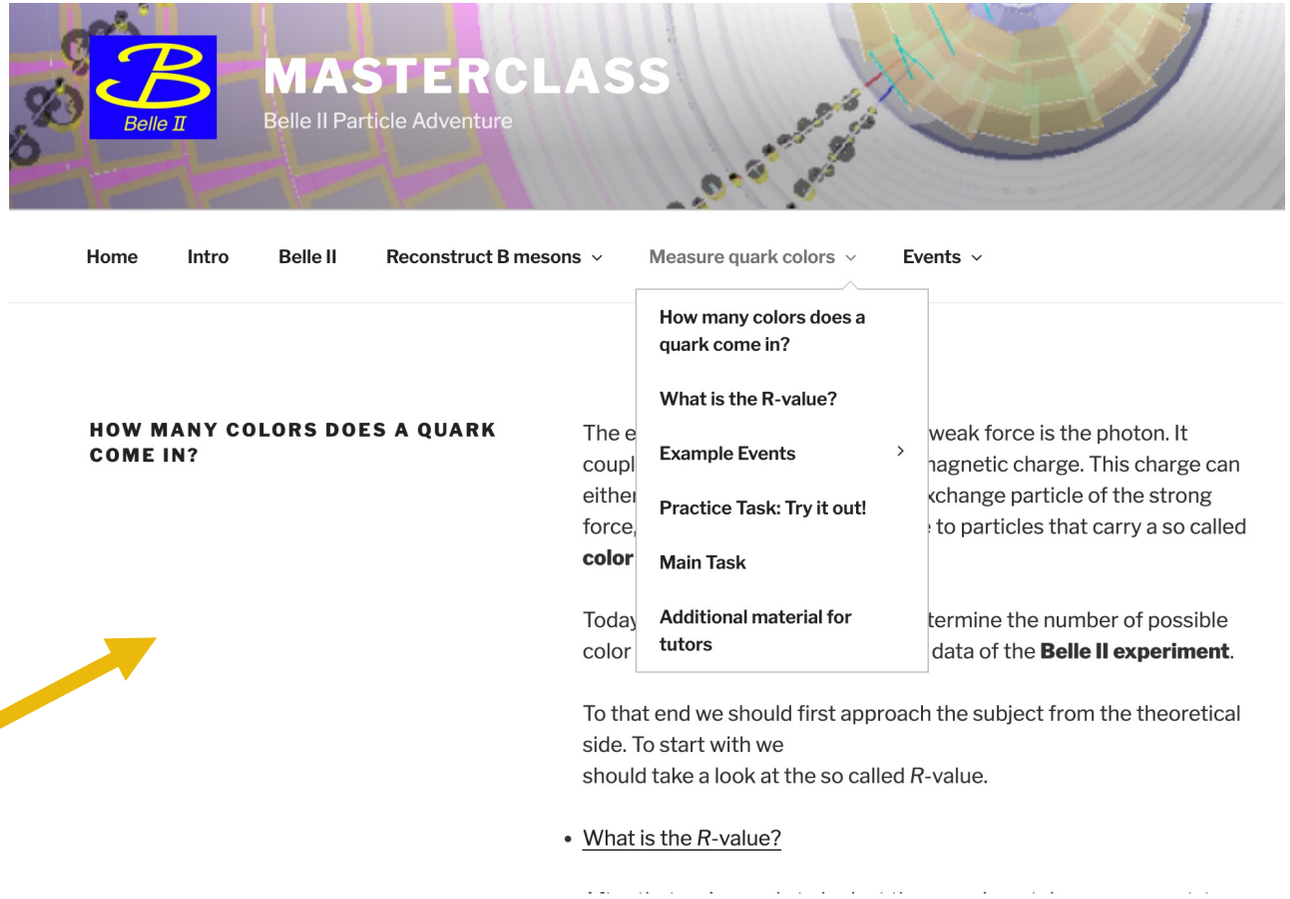
– Drag-and-drop coloured quarks into colorless bound states





SUMMARY

- Masterclass fully developed and tested multiple times
- All material available in English and German
- Students are guided through masterclass using website



Thank you for your attention!

English: https://belle2.ijs.si/public/home/quark-colors/

German: https://www.pi.uni-bonn.de/outreach/netzwerk-teilchenwelt/belle2-masterclass/