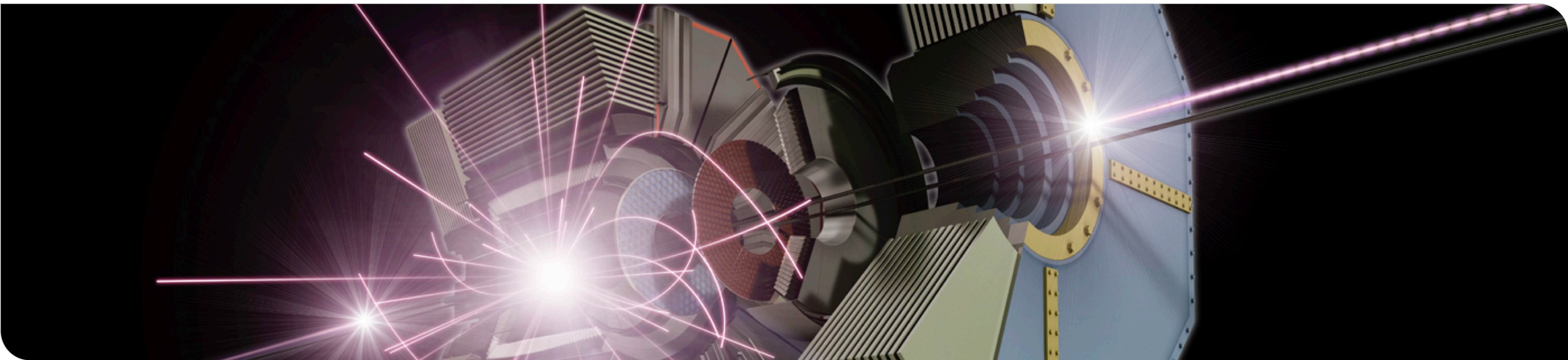


Lepton Colliders for Discovery

Physics & Technology for Belle II and beyond

Frank Simon

MPP Colloquium, June 2024









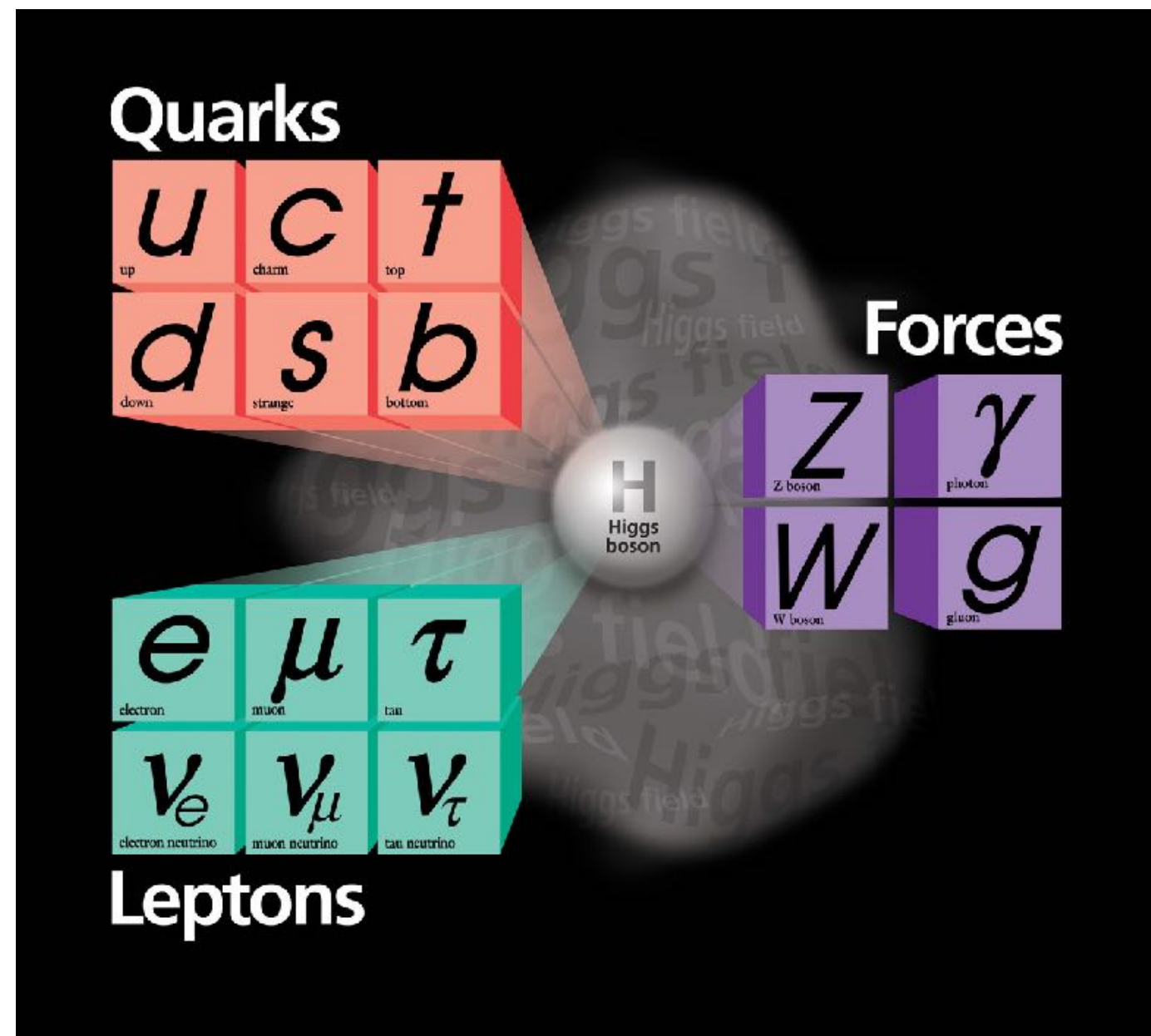
Outline

- Particle Physics today: Towards new Answers
- Lepton Collisions as a Discovery Enabler - with a focus on SuperKEKB / Belle II
- The stony Path to Precision - Delivering the Belle II Physics Program
- Perspectives on Technology - Higgs Factories as Innovation Drivers
- Conclusion & Outlook

Particle Physics - State of Play

Past Discoveries & Current Puzzles

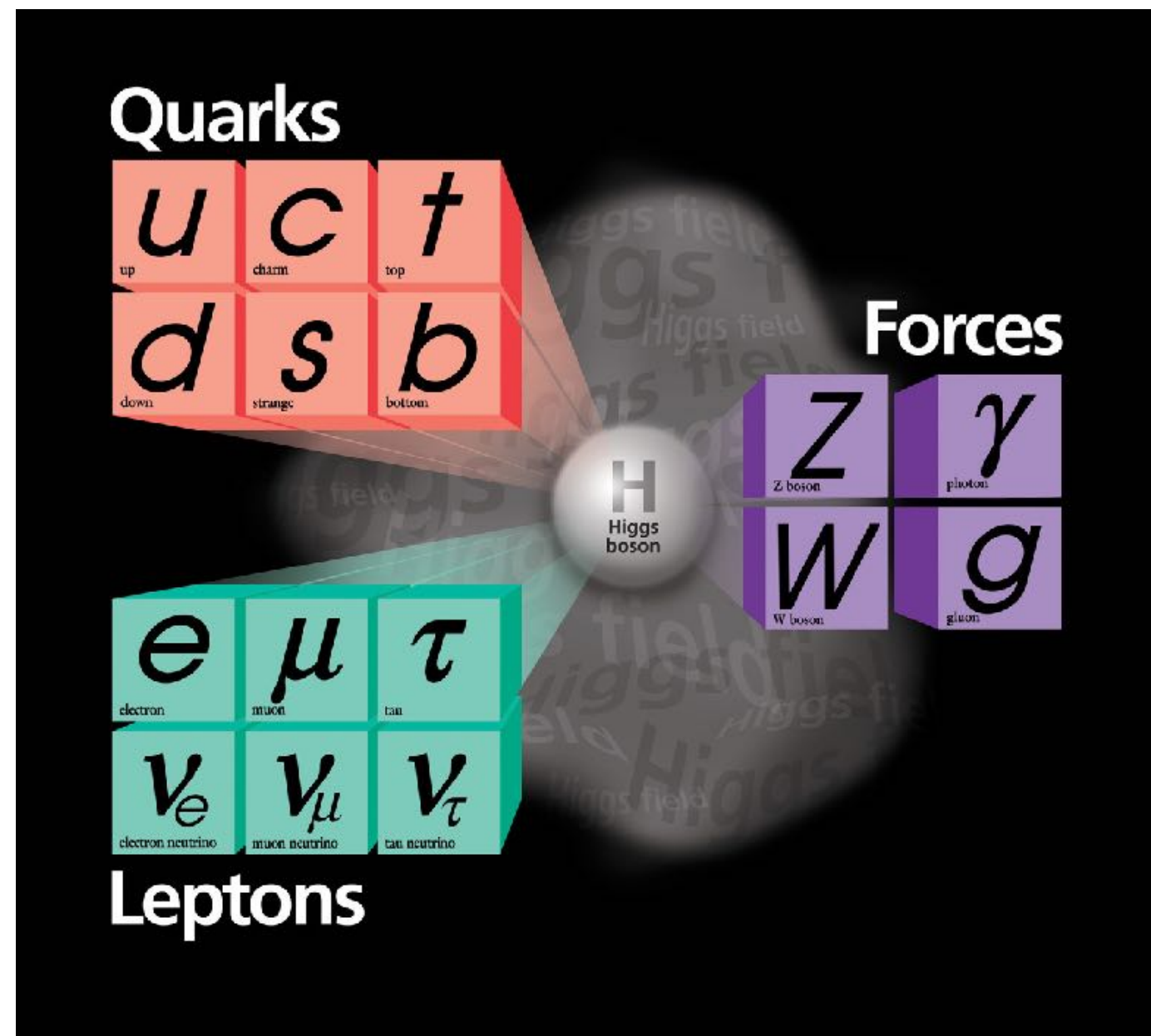
- The Standard Model: A success story
The result of generations of experiments and theoretical work.



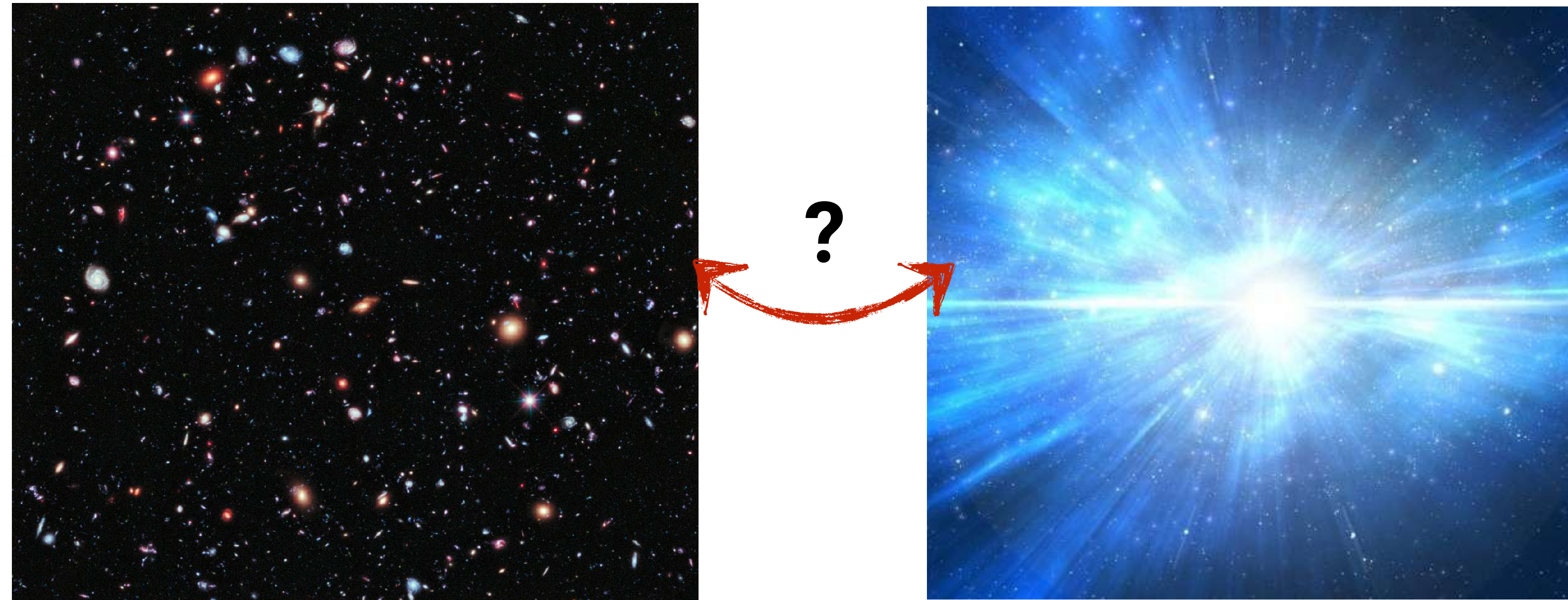
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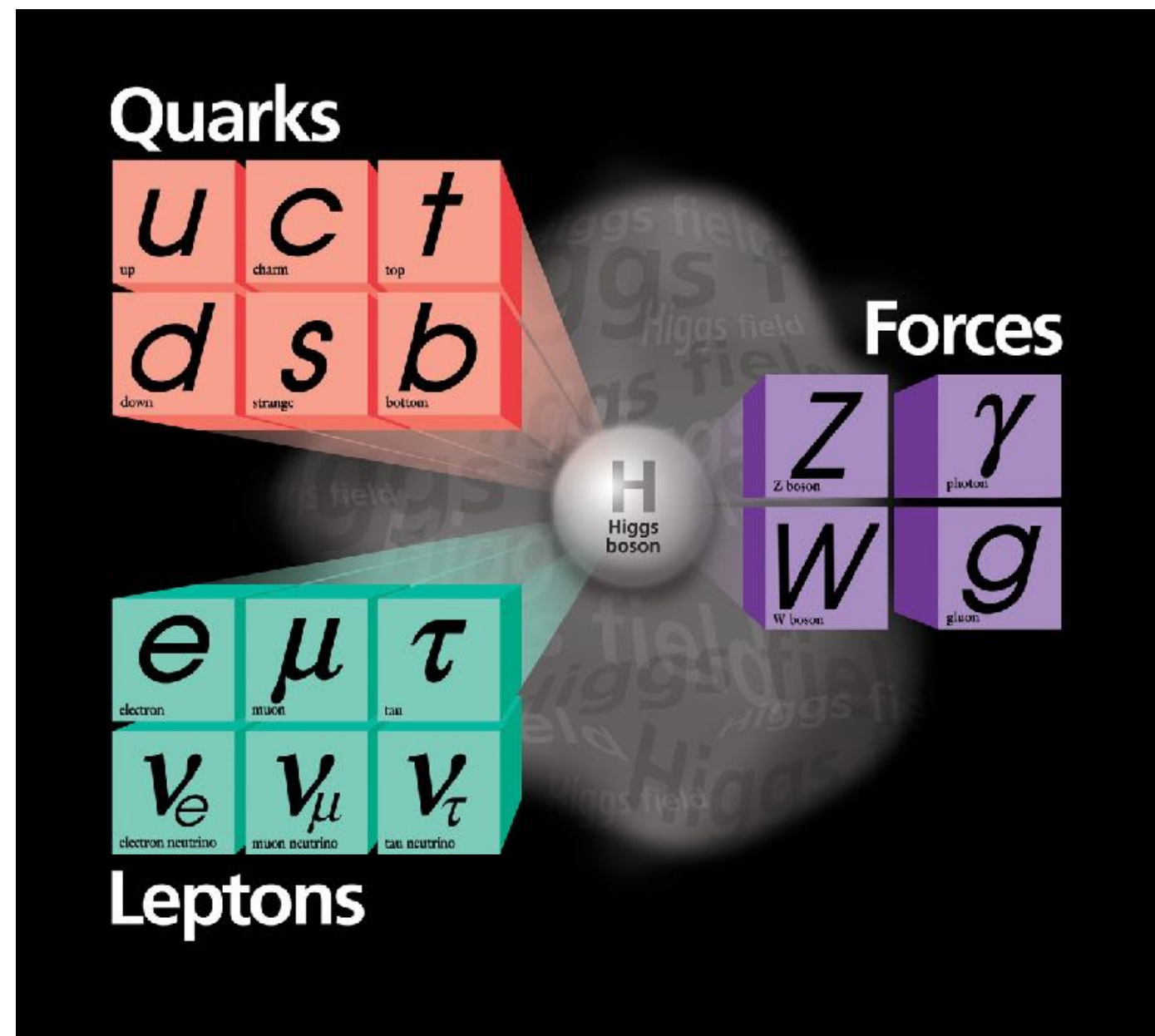
But: does not explain key astrophysical observations...



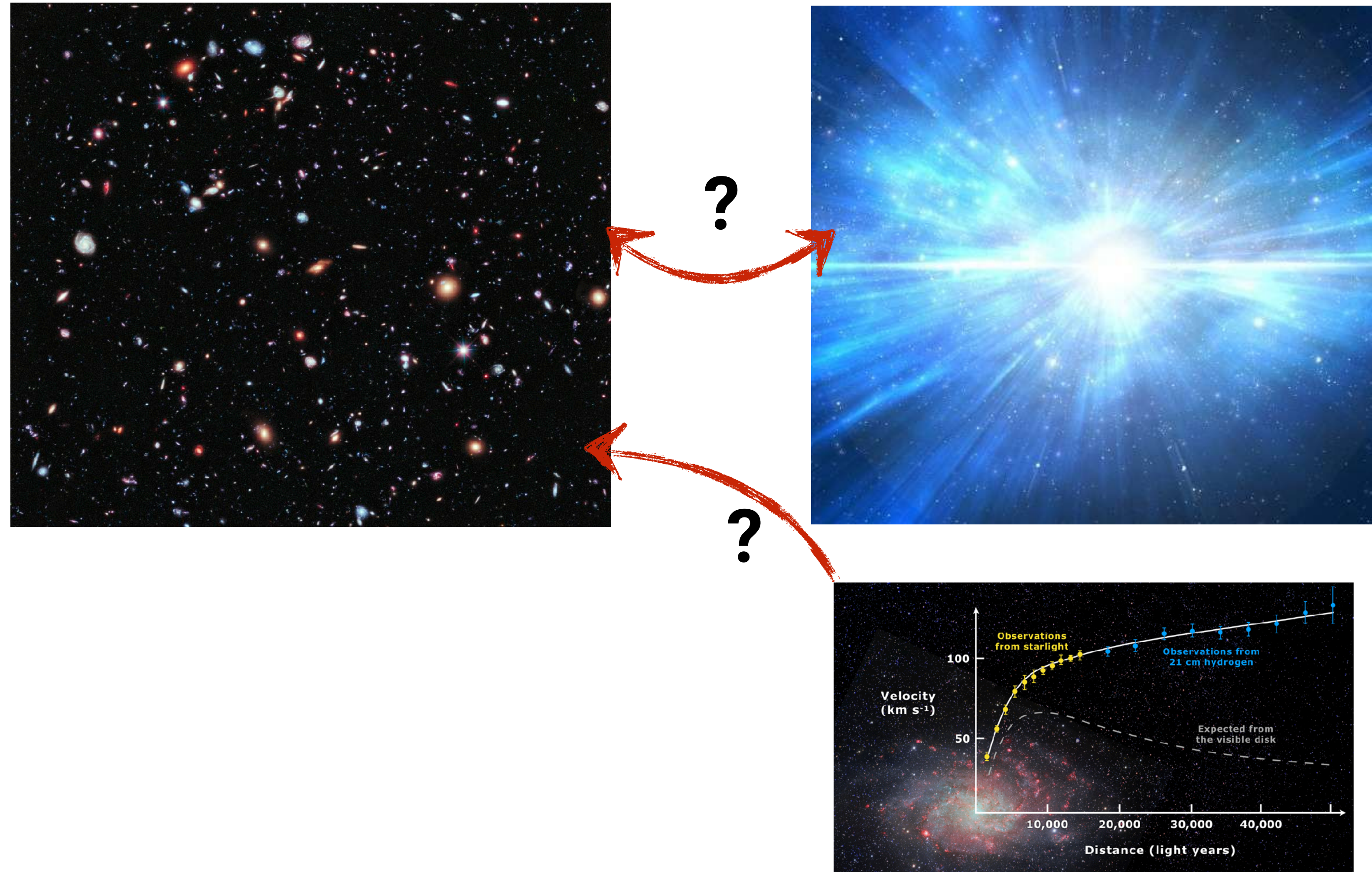
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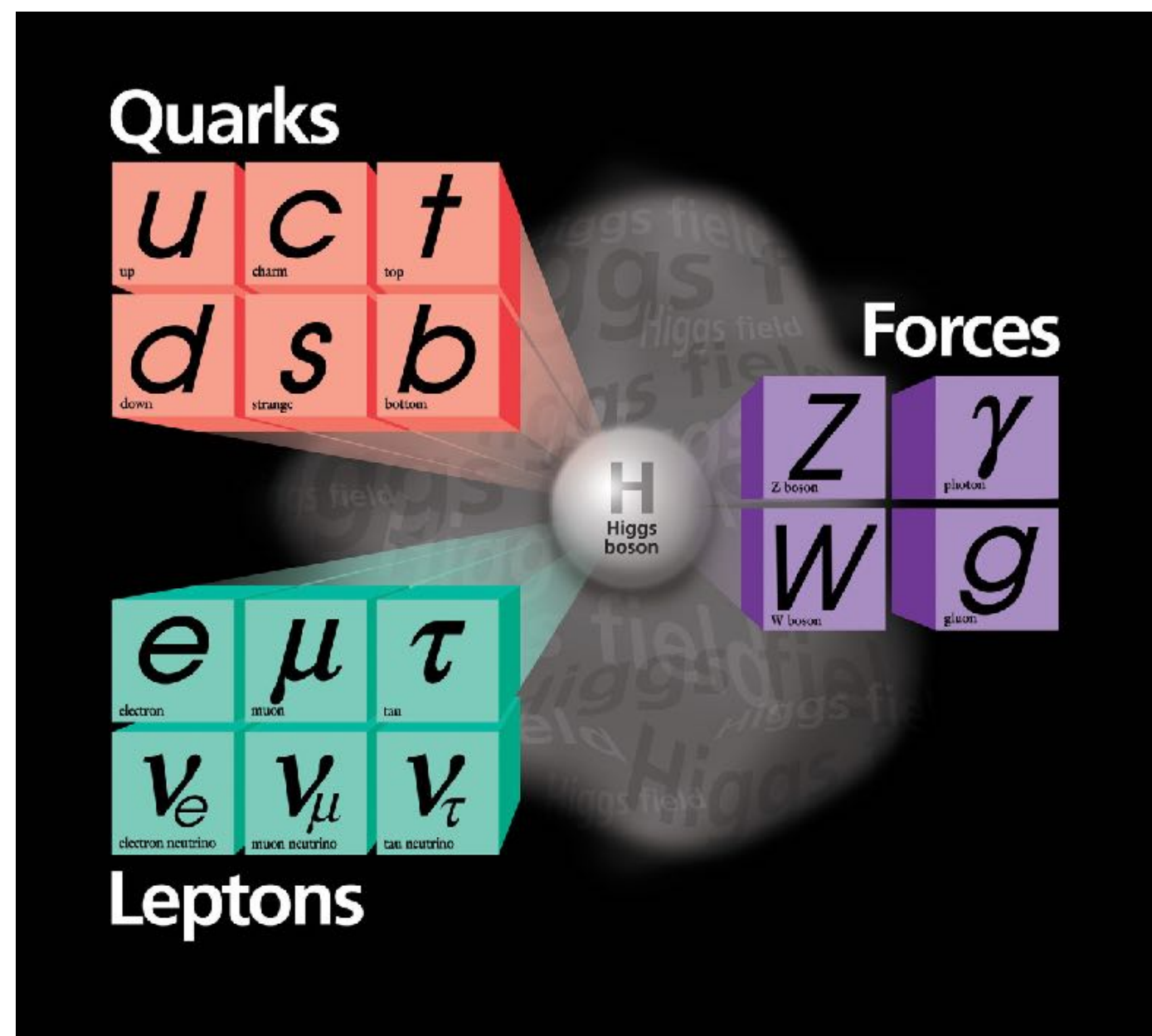
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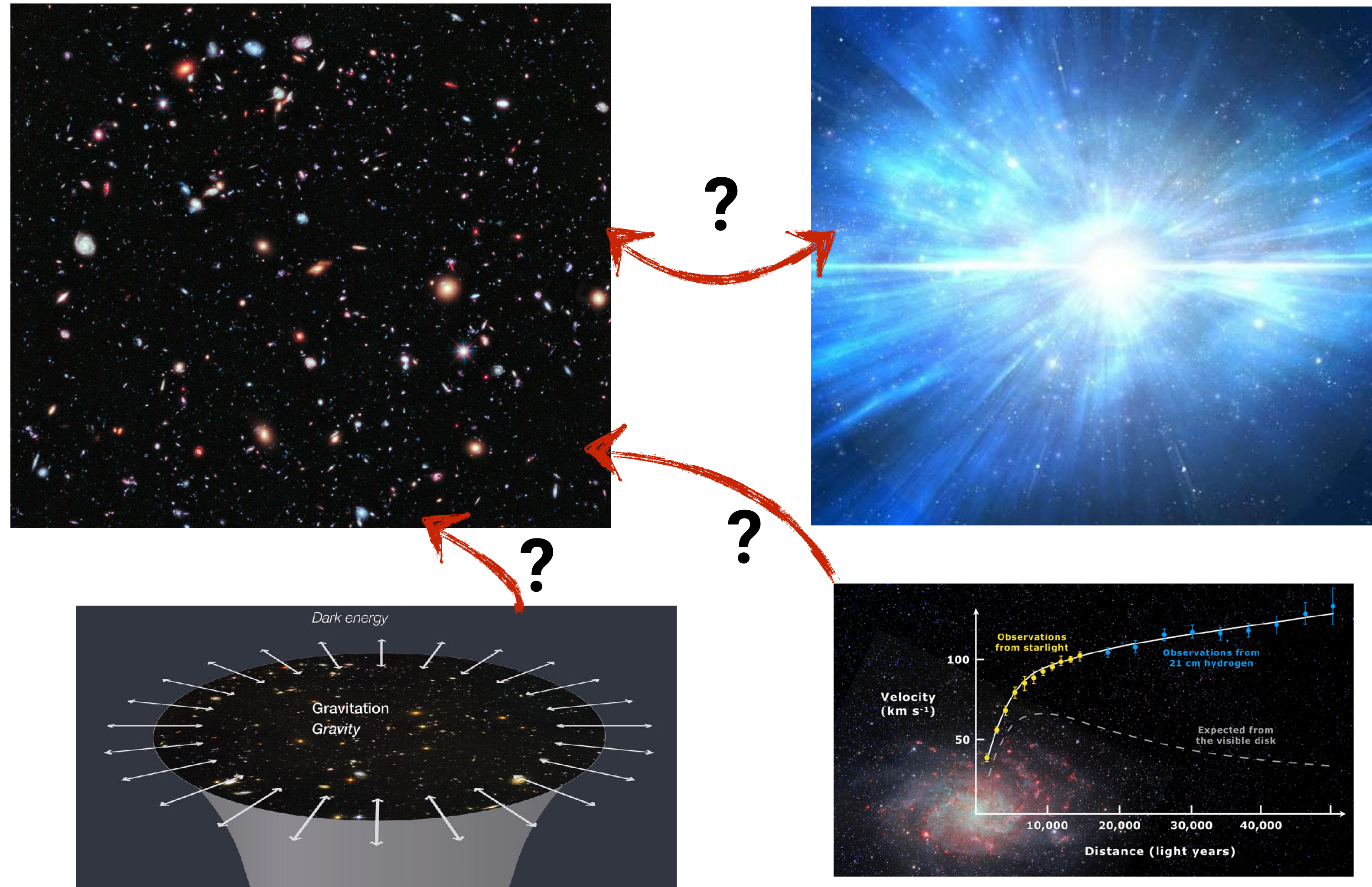
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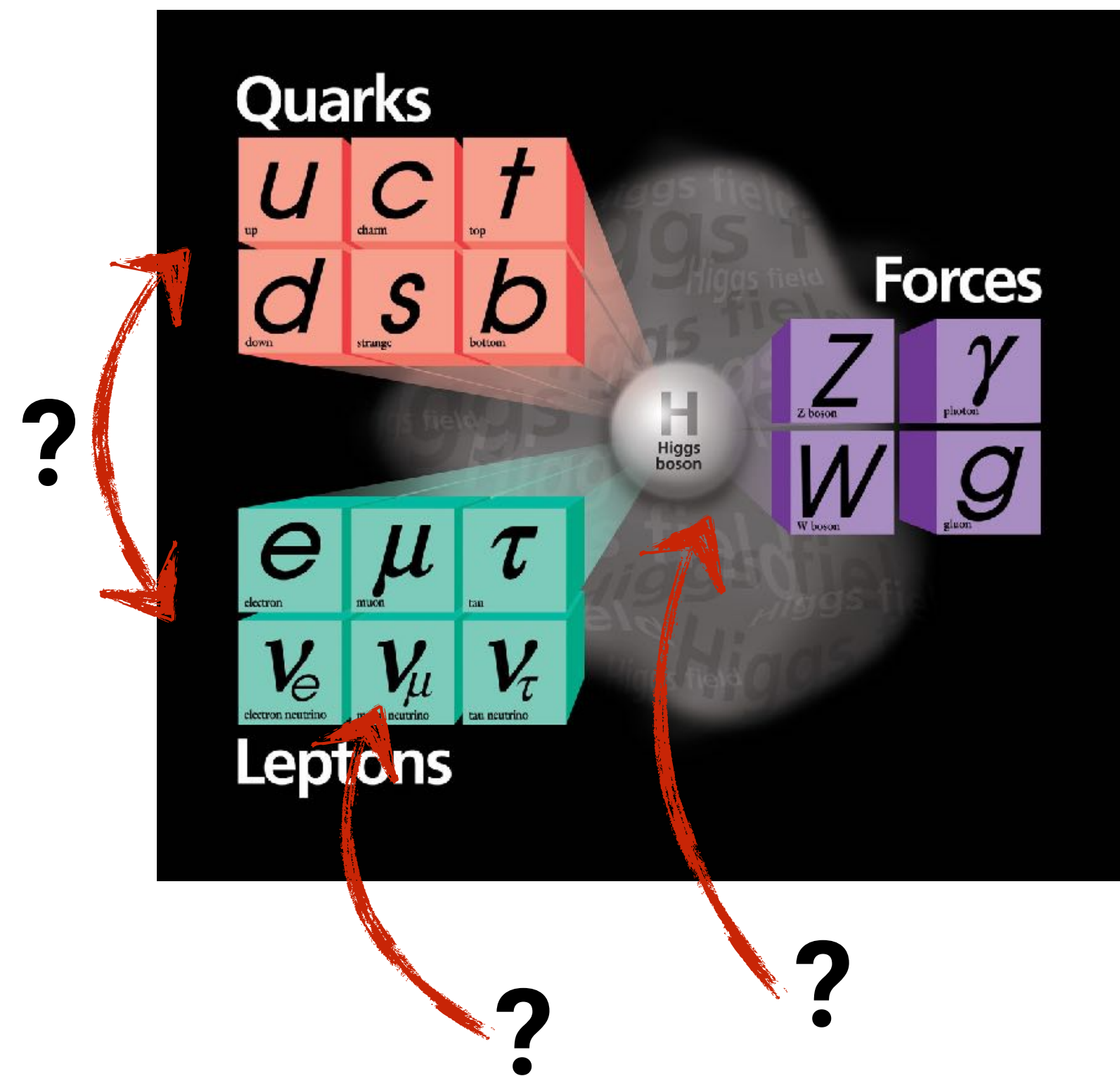
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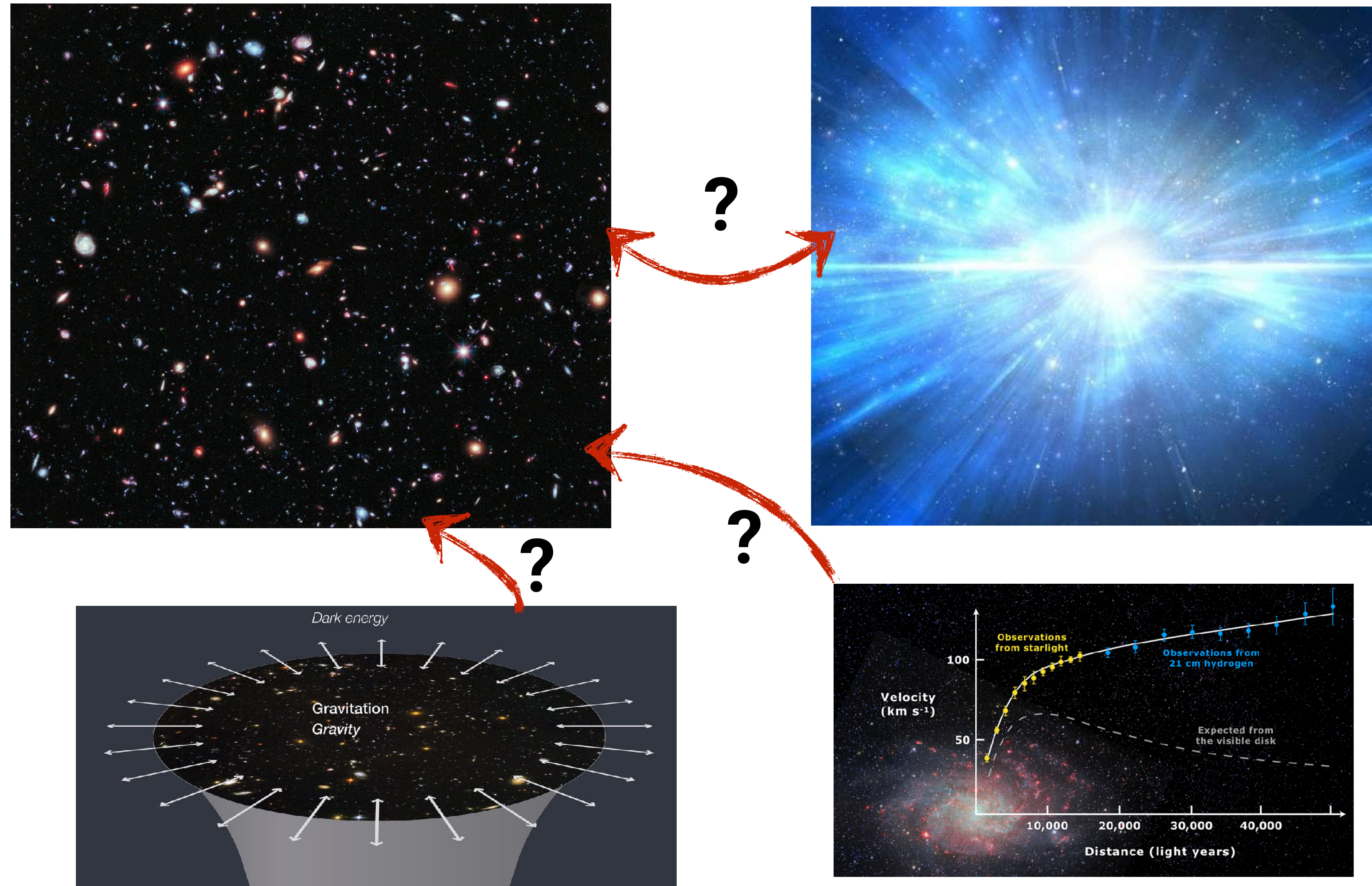
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... and raises new questions by itself!

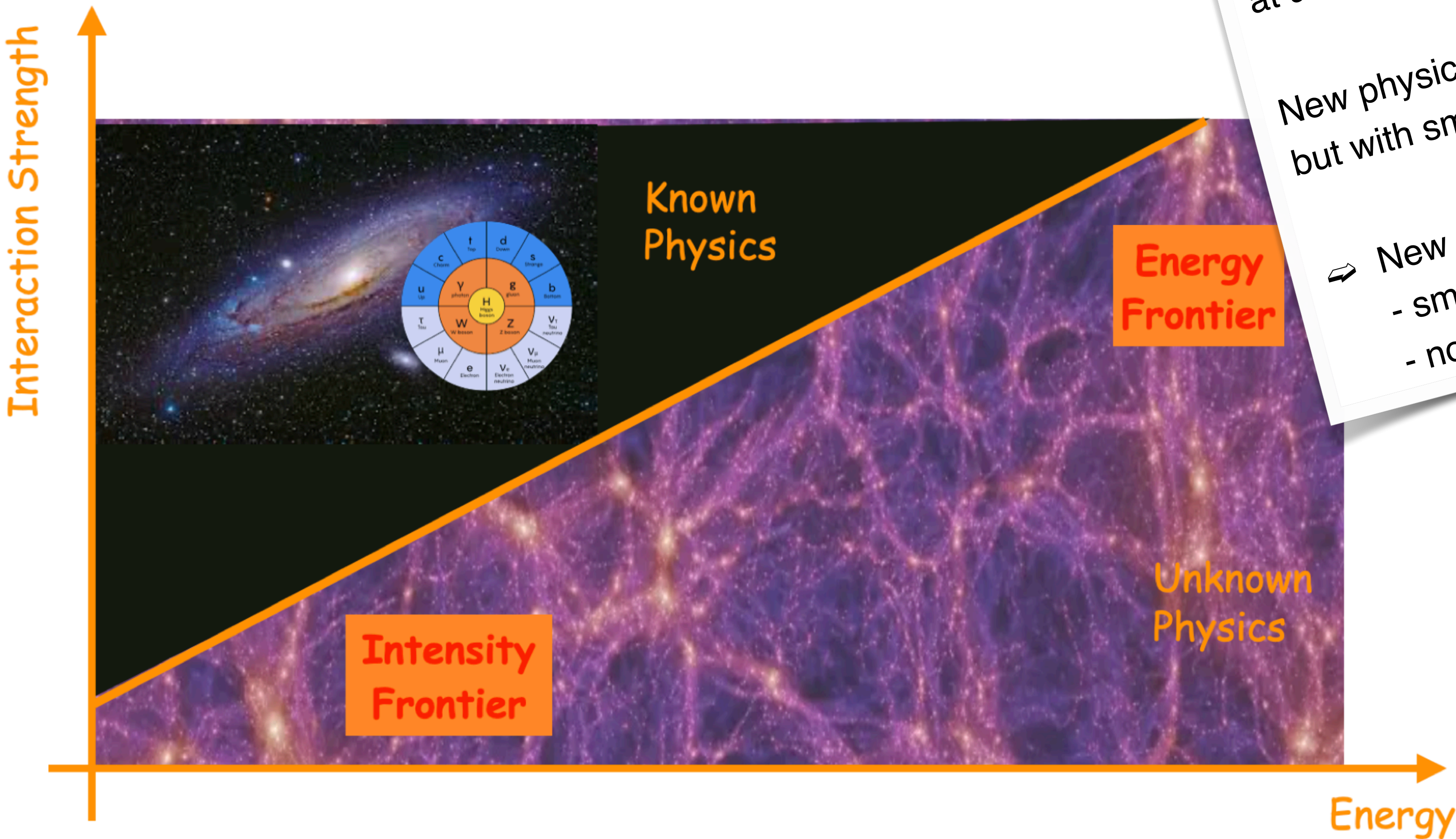
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Towards New Answers

The Path Forward

Responding to missing Guidance



New physics may be heavy, with new particles at a large mass scale.

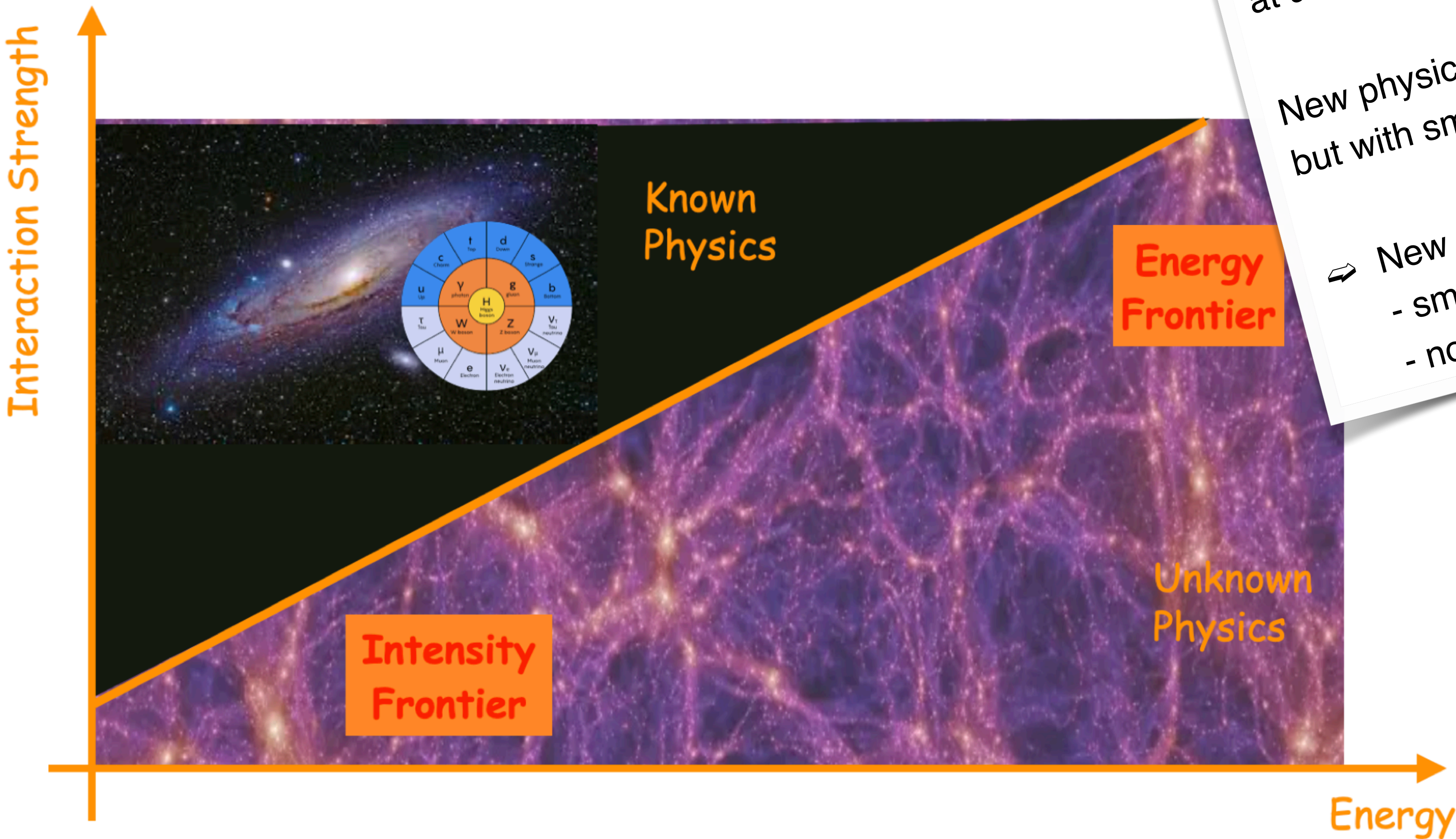
New physics may be light, but with small couplings.

⇒ New physics is subtle:
- small cross sections
- novel signatures

Maggie Mühlleitner - FC@CERN WS 2024

The Path Forward

Responding to missing Guidance

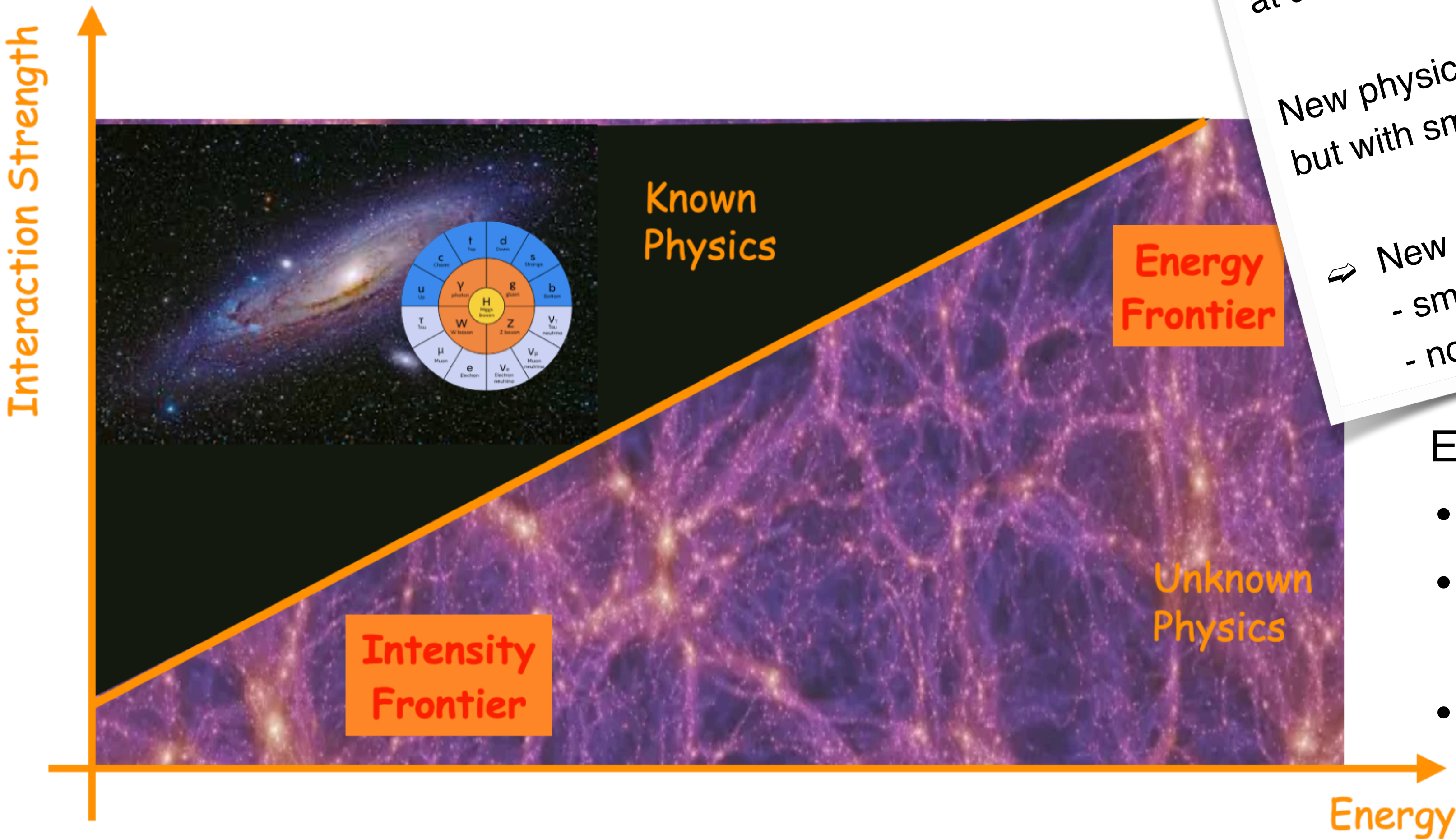


No single right experimental path forward.

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Responding to missing Guidance



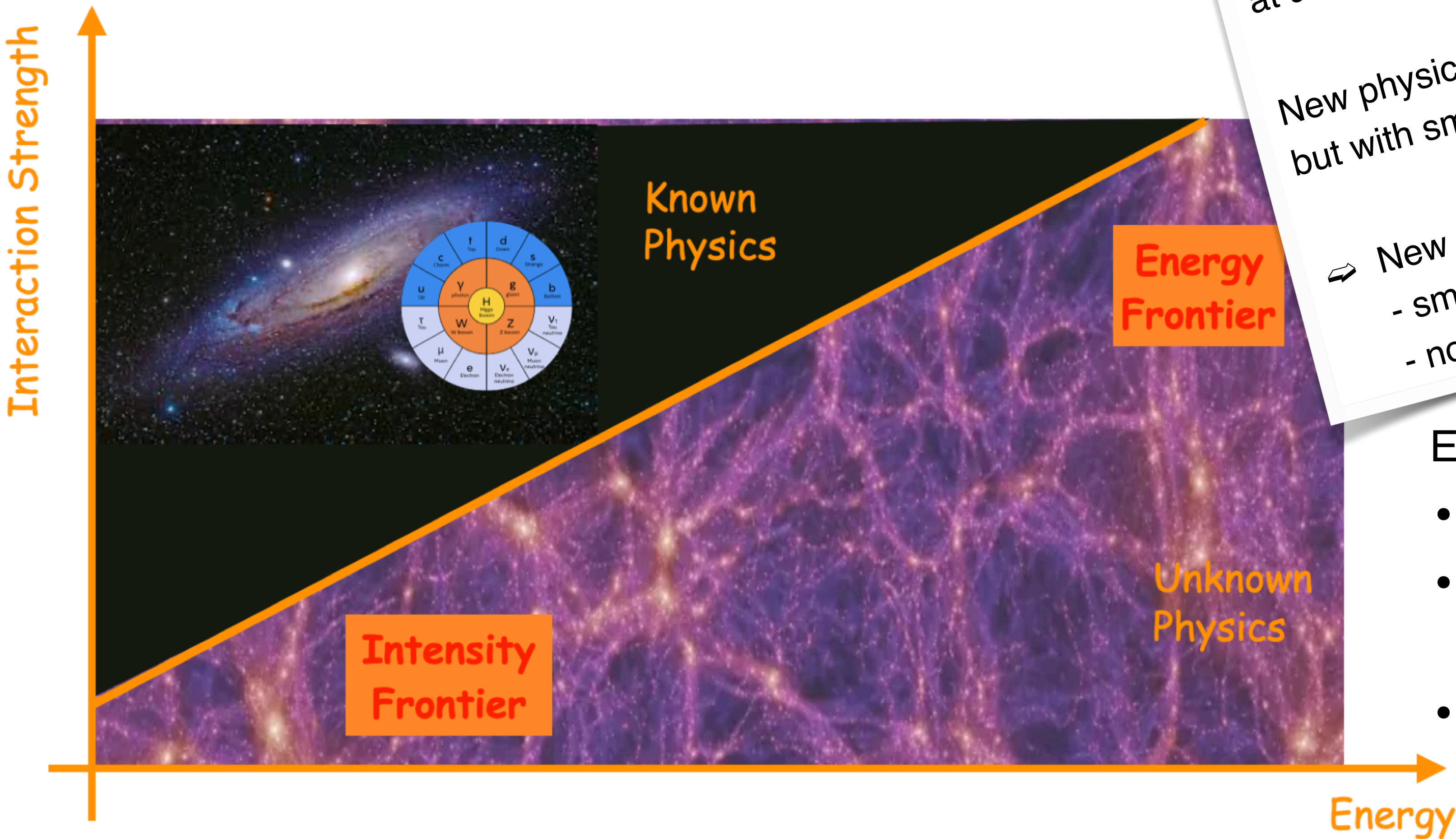
No single right experimental path forward.

- Exploiting different strategies:
- Direct production at high energies
 - Precision measurements + precise theory: Indirect probe of high scales
 - Direct detection of “dark sector” particles

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The Path Forward

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Particle colliders contribute in all categories!

Maggie Mühlleitner - FC@CERN WS 2024

Future Opportunities

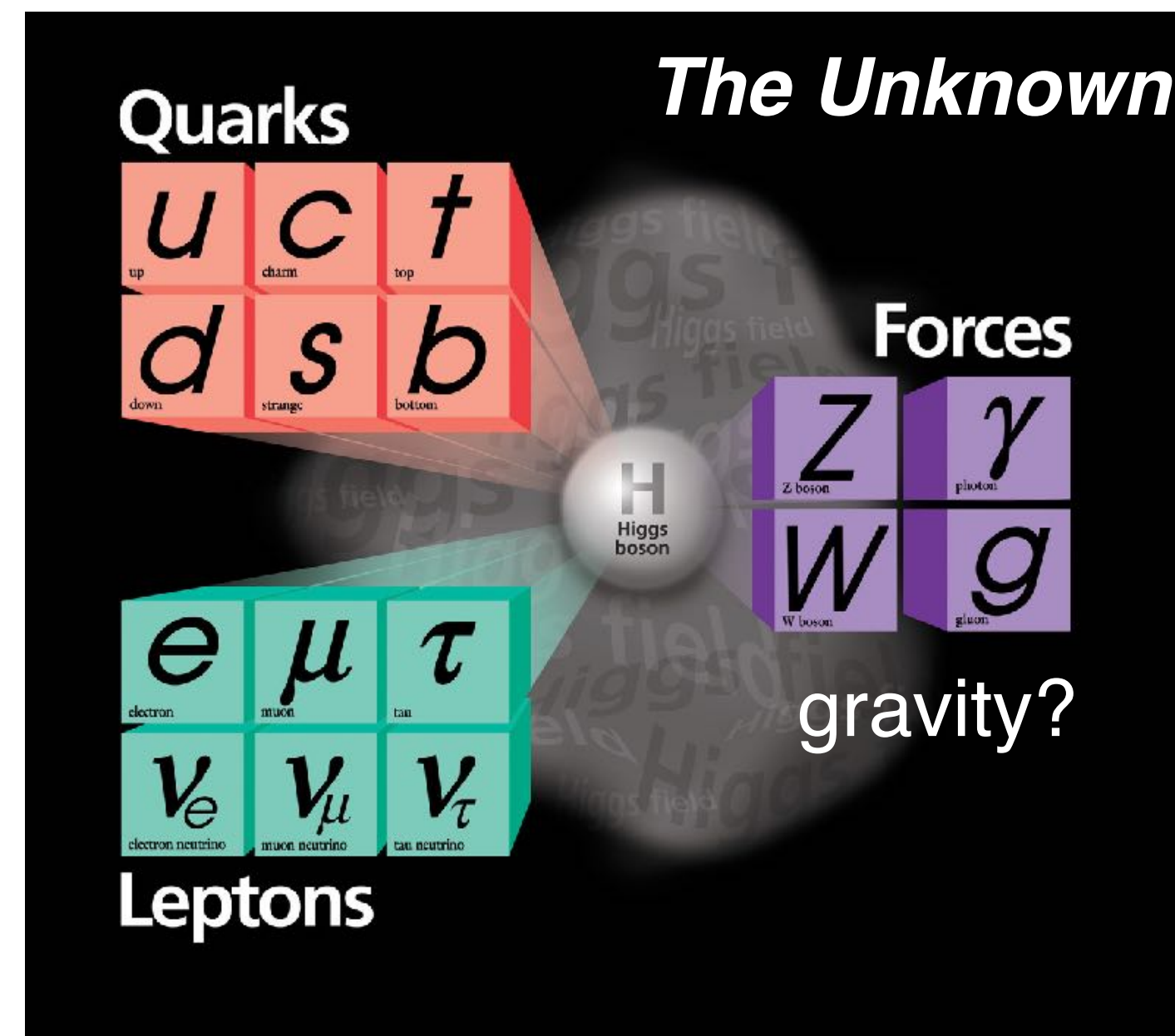
Experiments in Particle Physics

- Significant potential for ground-breaking discoveries in present and future experiments...

Evidence for new phenomena in the flavour sector

Discovery of leptonic CP violation

Evidence for a dark sector: dark matter and other weakly coupled particles



Discovery of new particles and/or forces at high energy scales

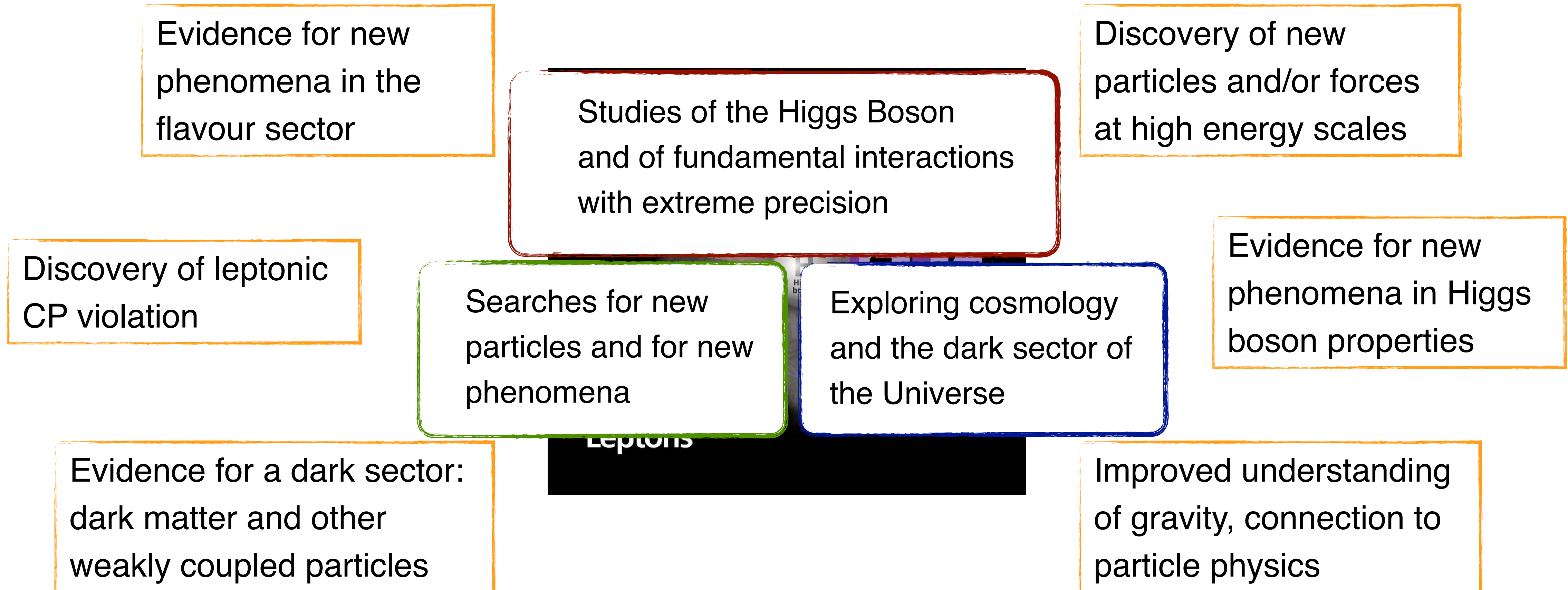
Evidence for new phenomena in Higgs boson properties

Improved understanding of gravity, connection to particle physics

Future Opportunities

Experiments in Particle Physics

- Significant potential for ground-breaking discoveries in present and future experiments...
... translated into an experimental roadmap followed by the world-wide community.



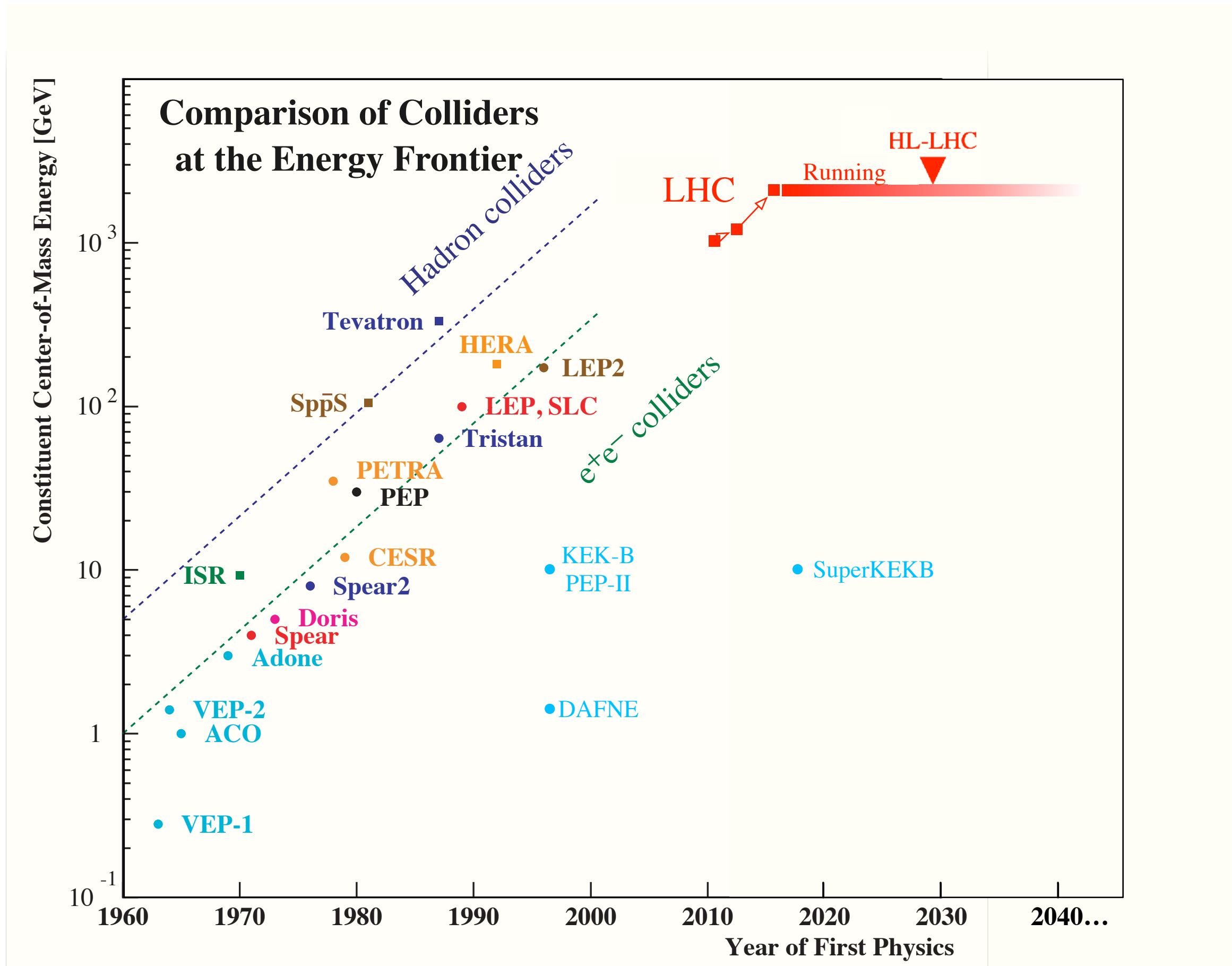
Lepton Collisions as Discovery Enablers

With a Focus on SuperKEKB / Belle II

Lepton Colliders

Energy and Intensity Frontiers

- The “killer feature”: **Full control**.
Initial state known: Energy, quantum numbers.

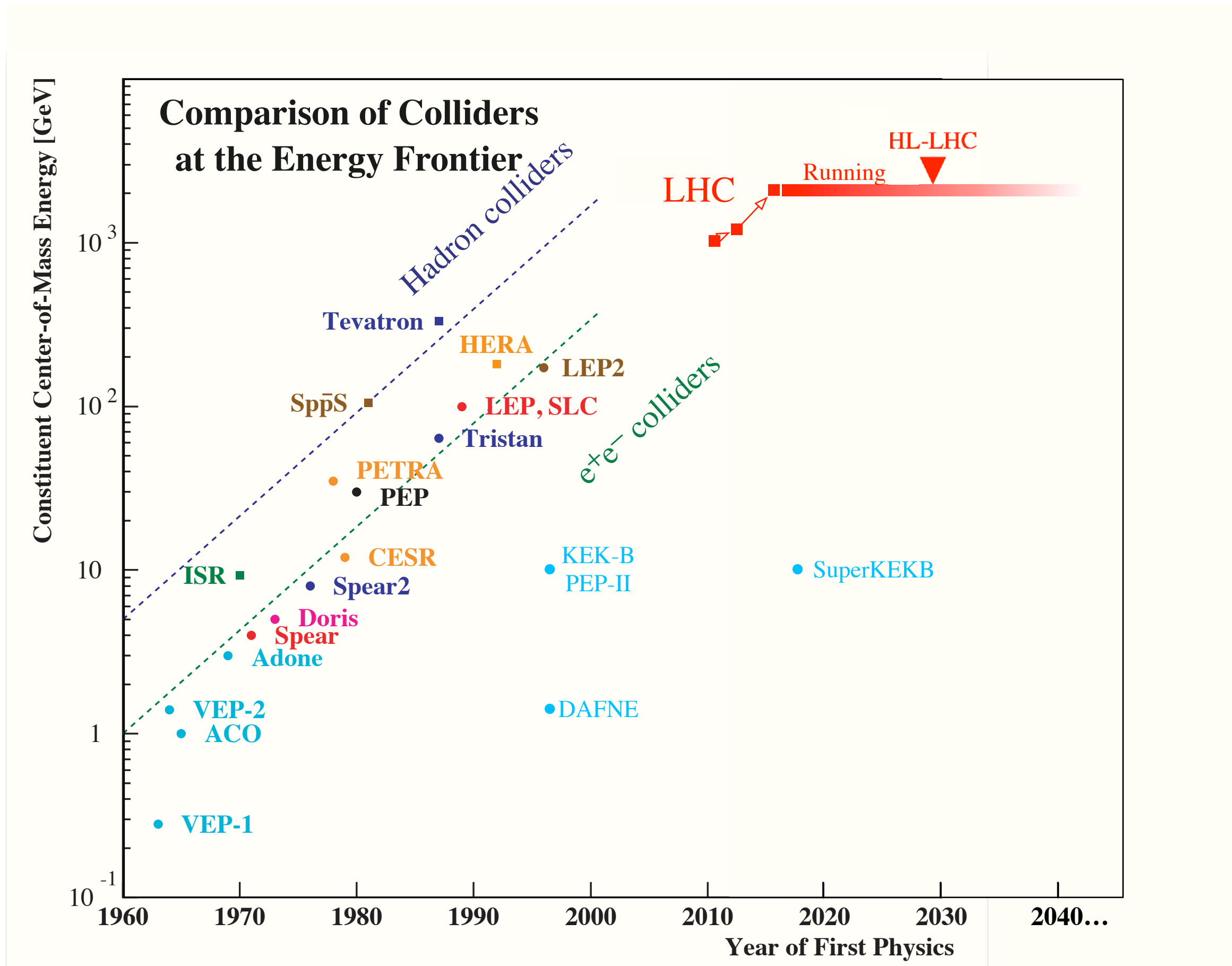


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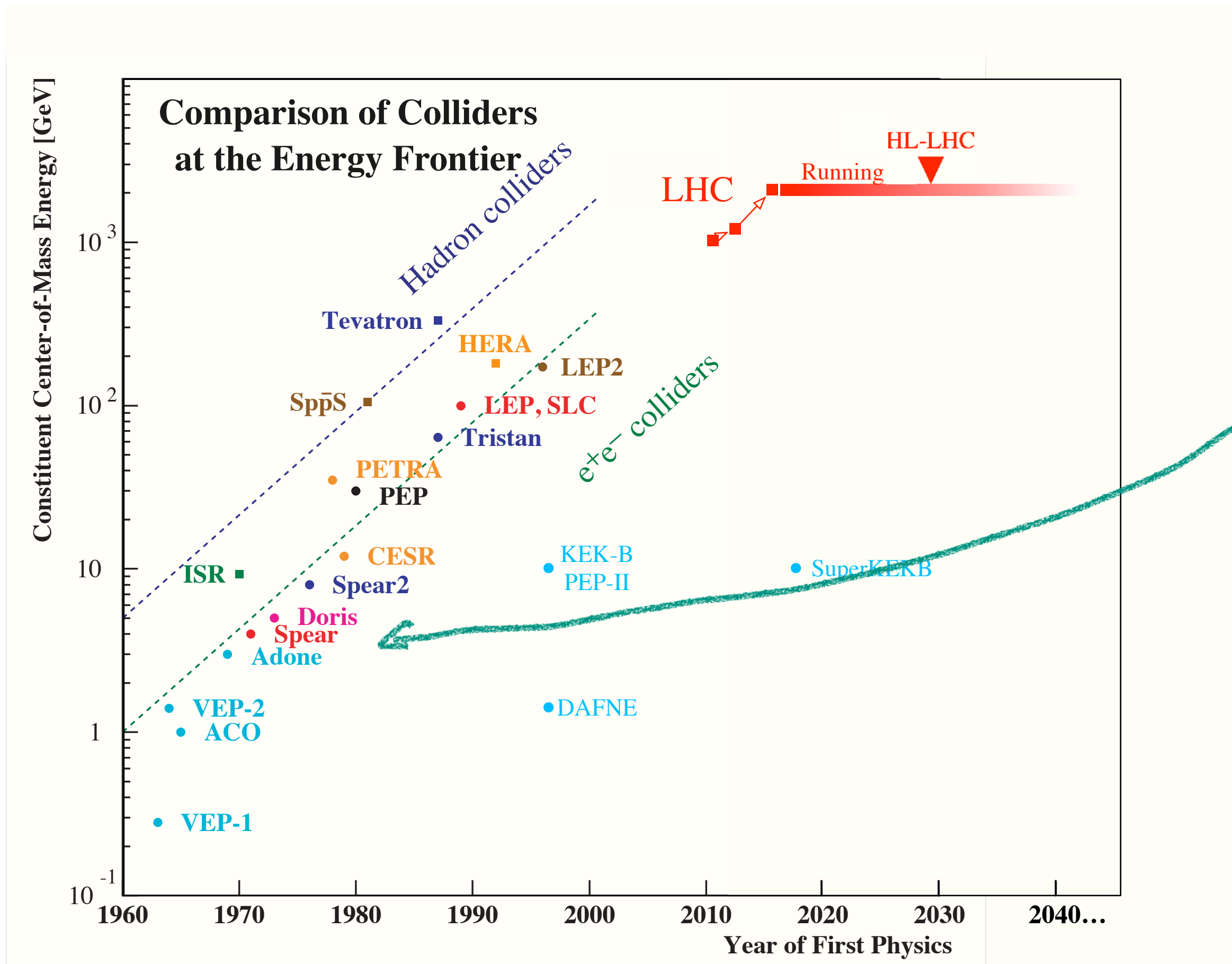


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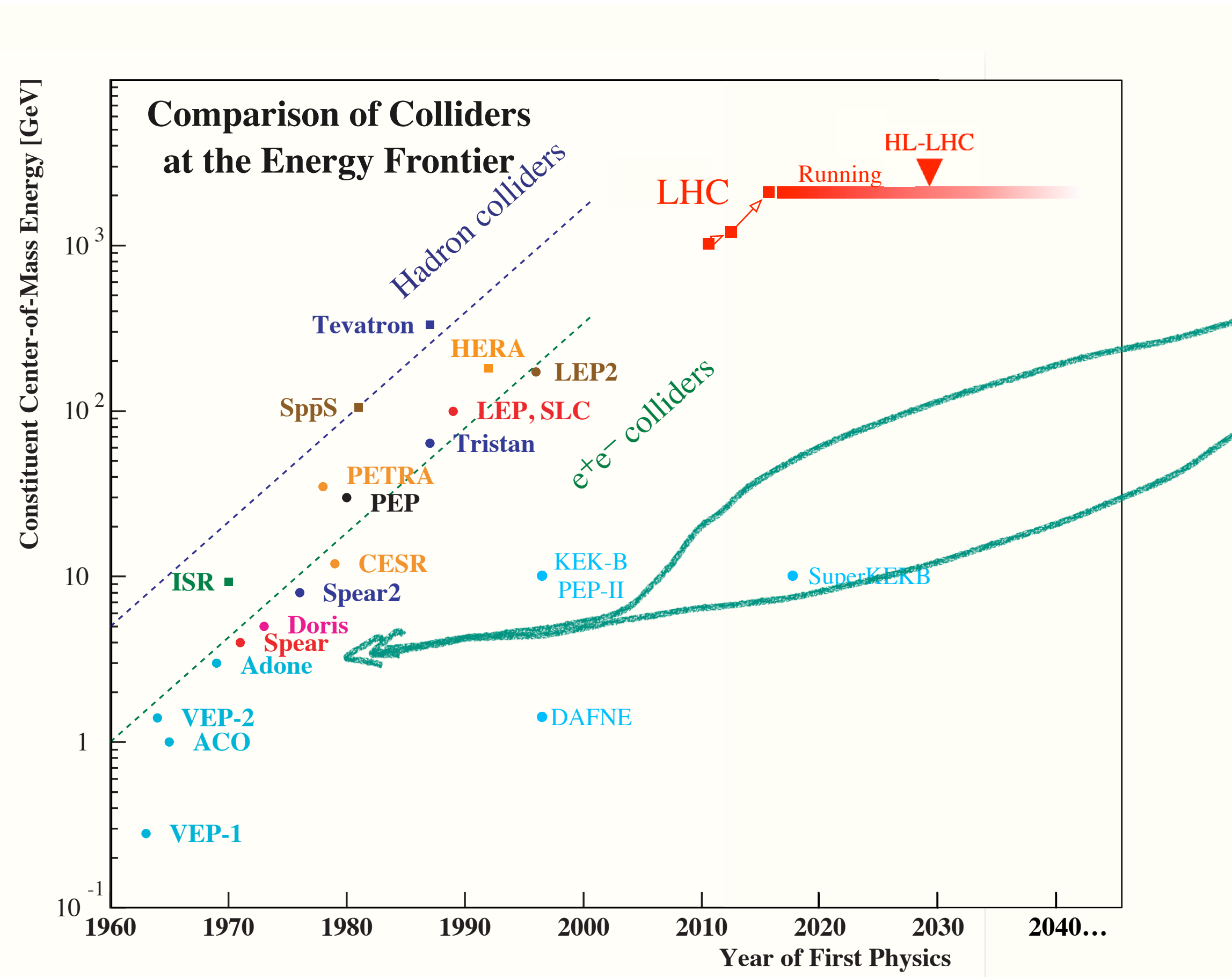
Charm

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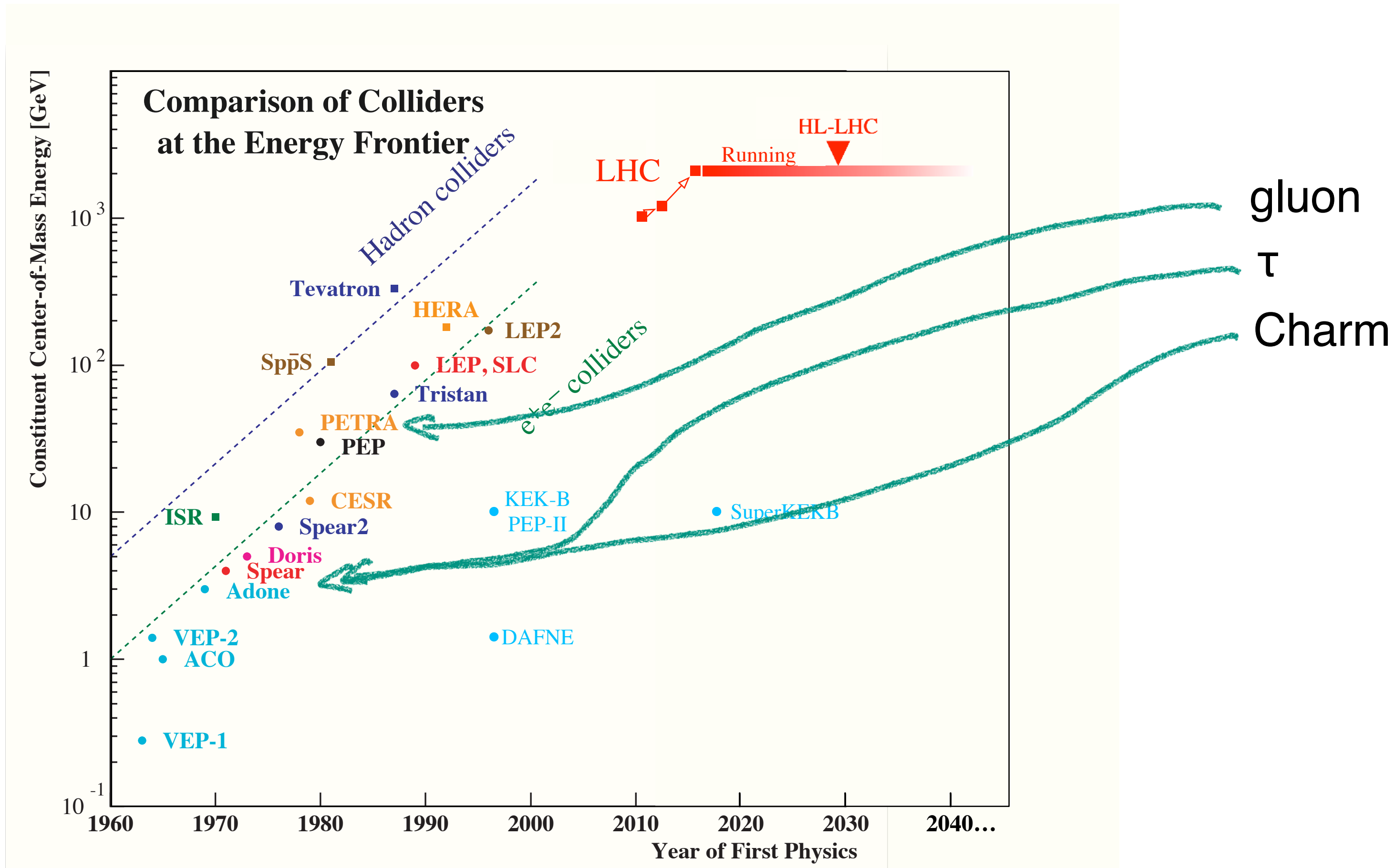


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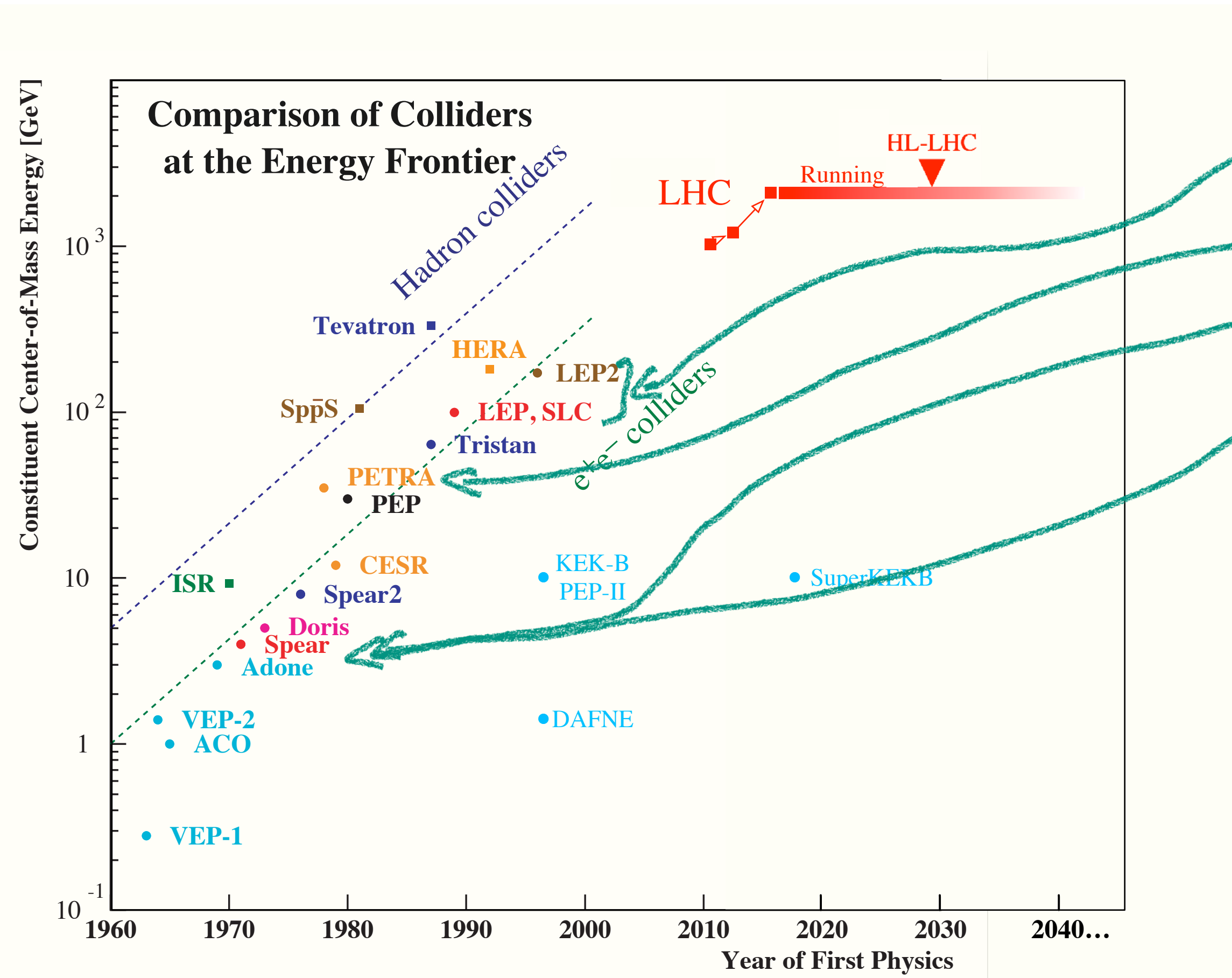


Lepton Colliders

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A history of discovery:



SM precision, 3 neutrino families

gluon

τ

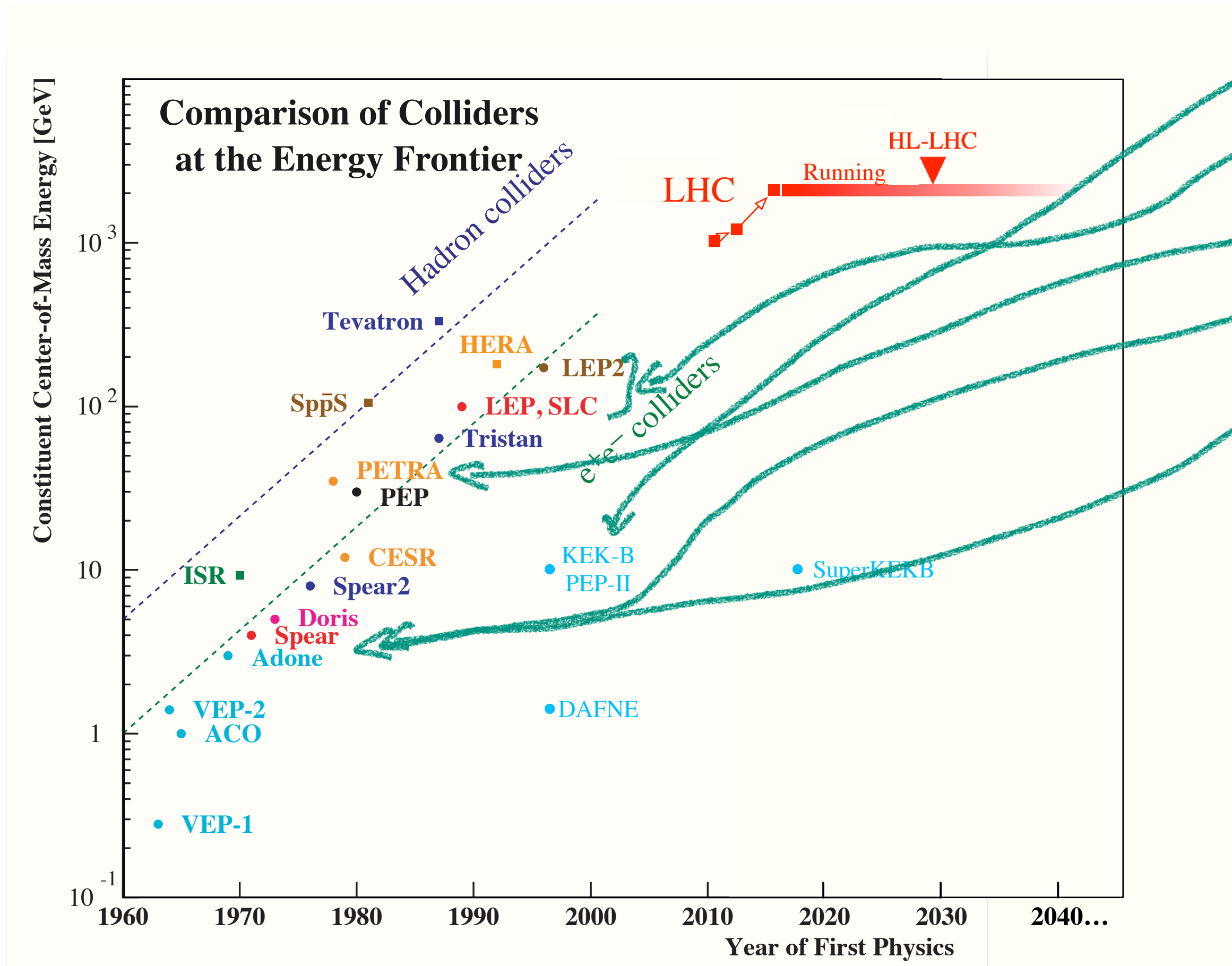
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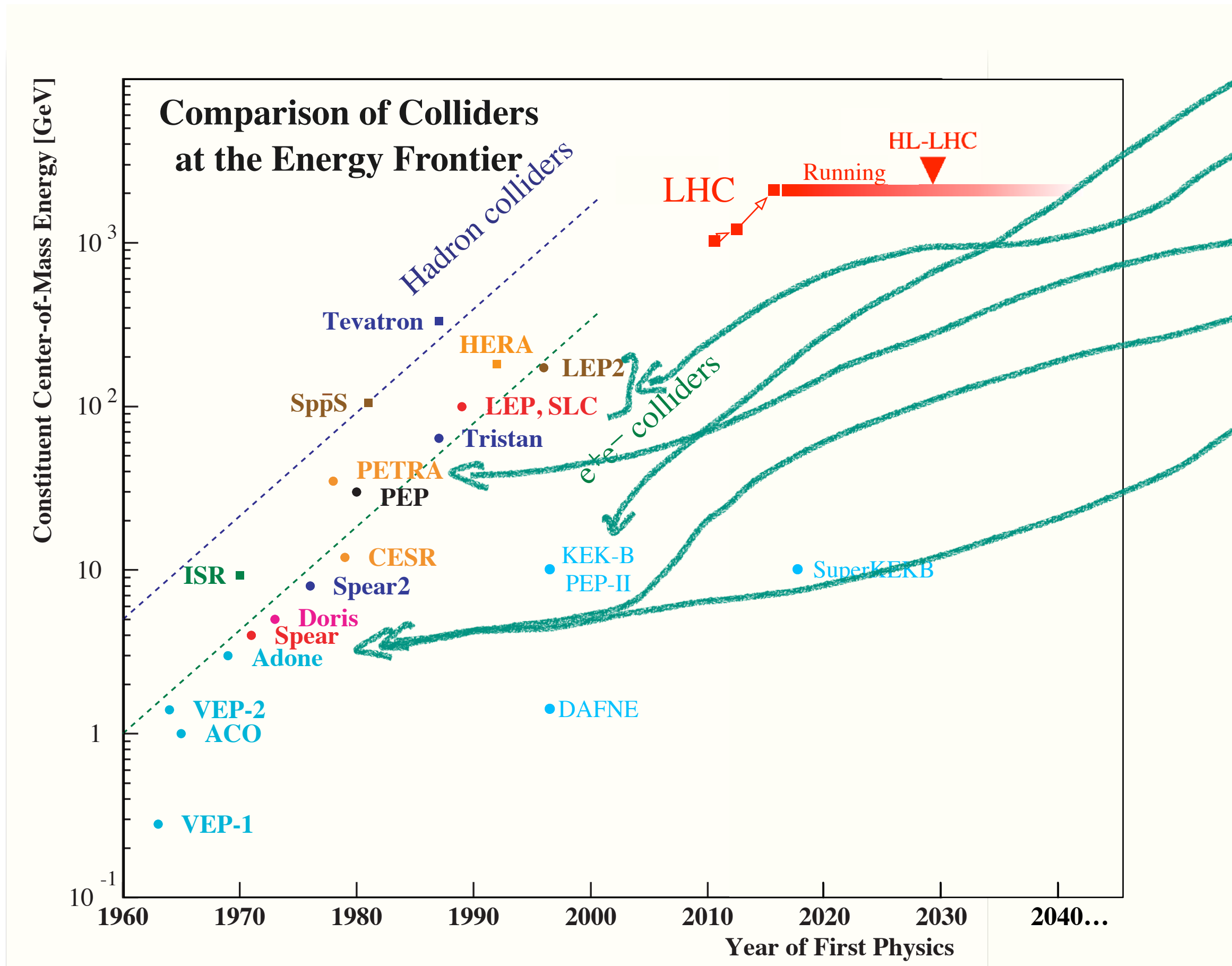
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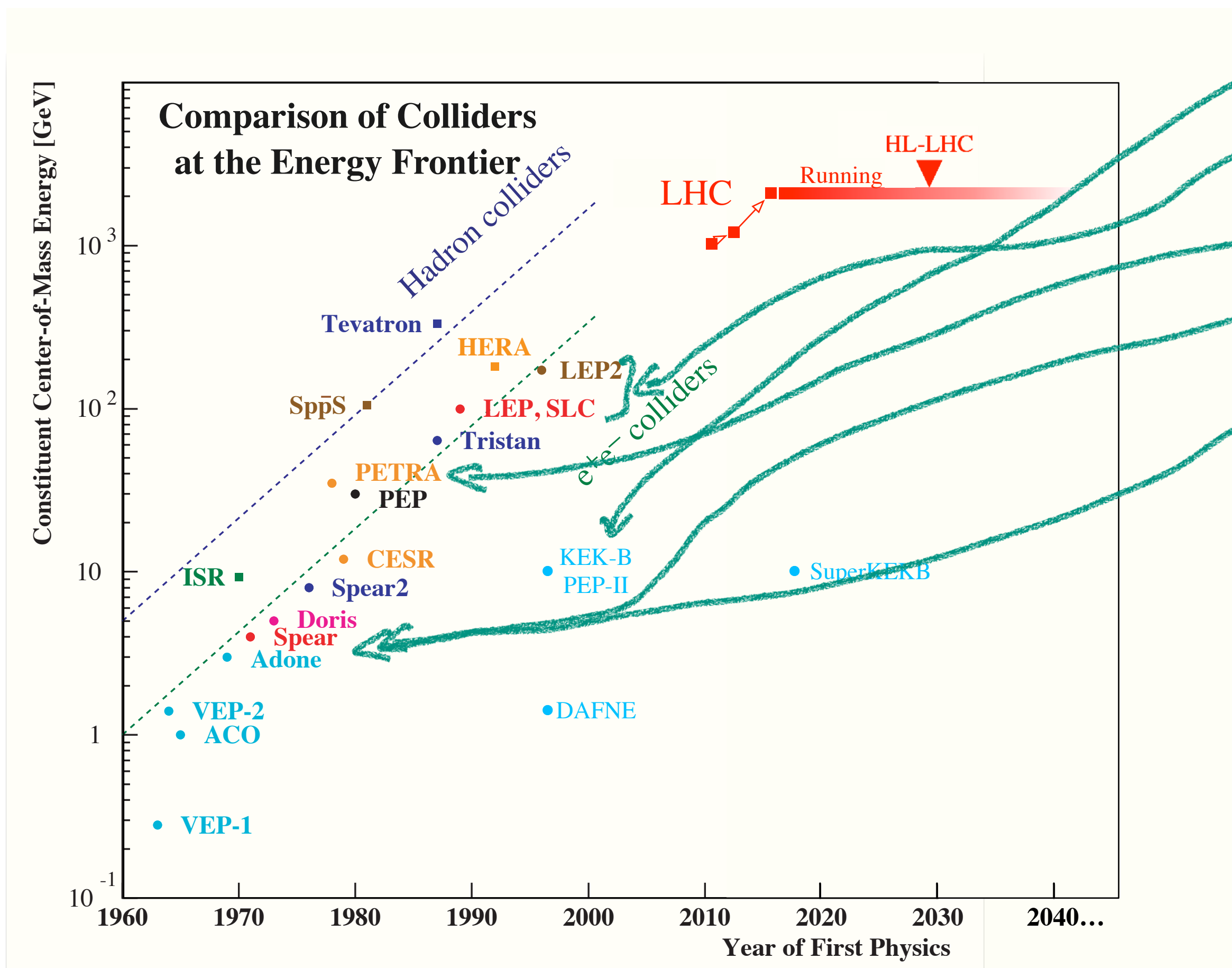
Together with theory!

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What's next?

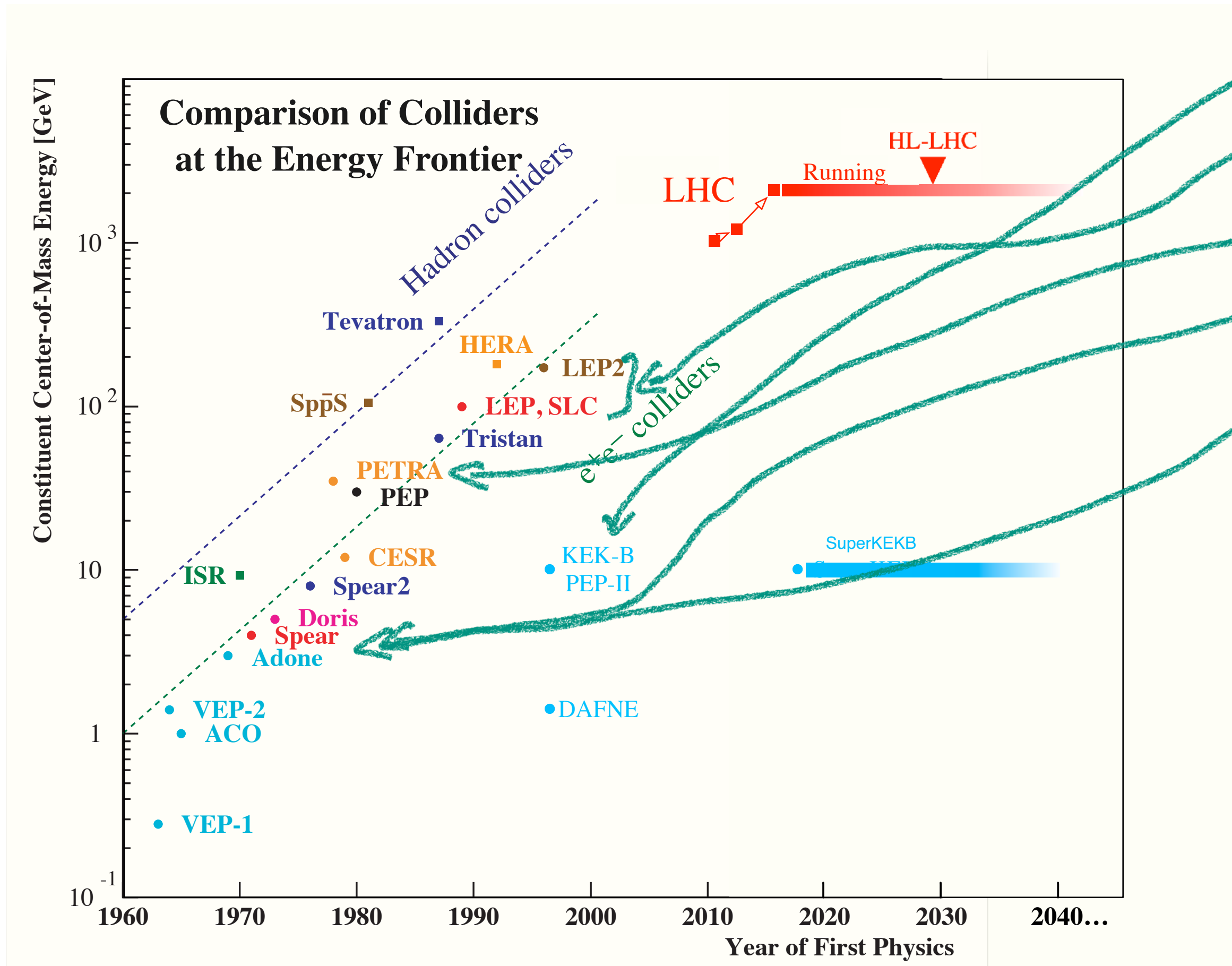
An e^+e^- Higgs Factory as next intensity & energy frontier collider: Physics in the mid-late 2040ies.

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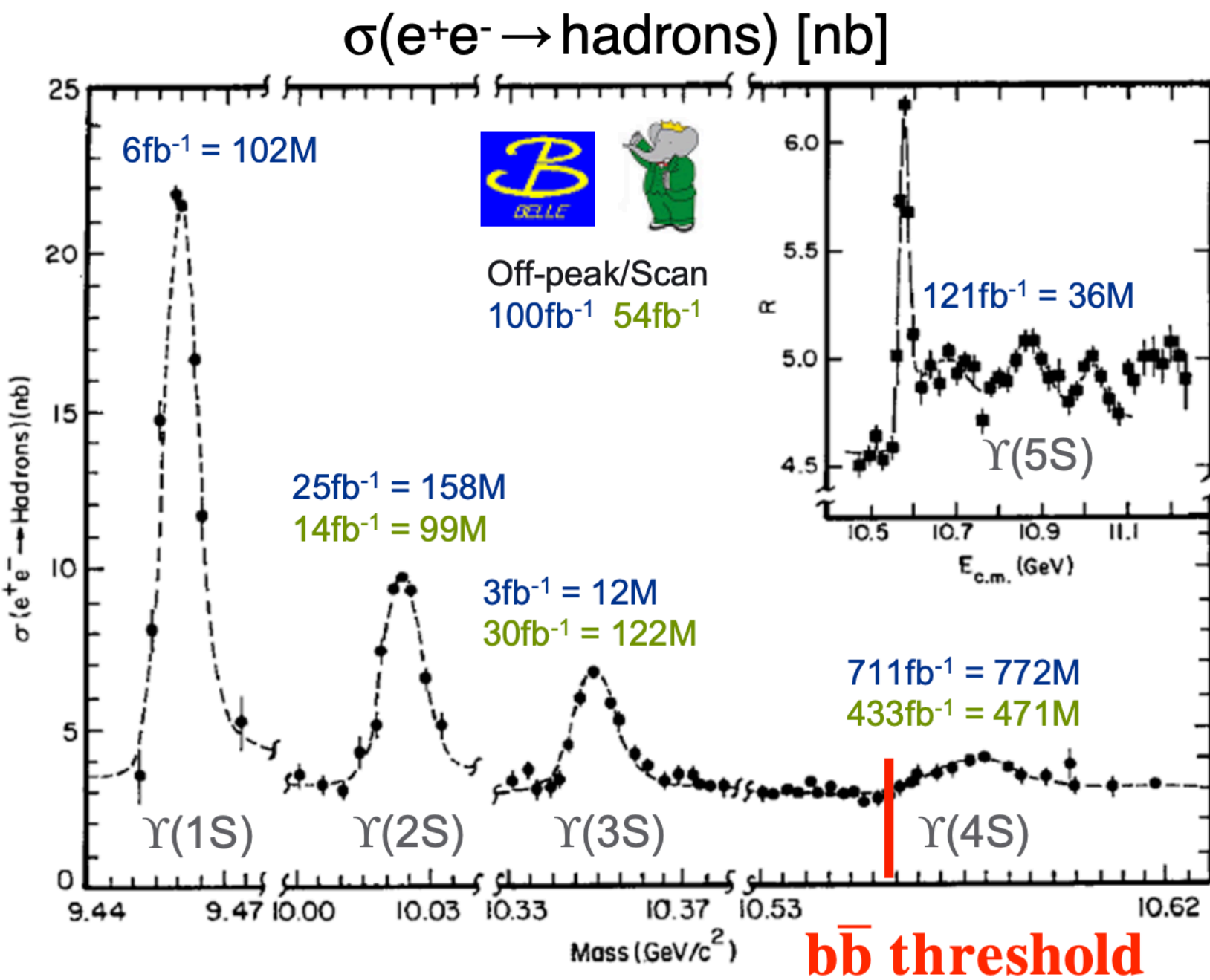
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An e^+e^- Higgs Factory as next intensity & energy frontier collider: Physics in the mid-late 2040ies.

For the next decade+: Intensity frontier physics with SuperKEKB / Belle II.

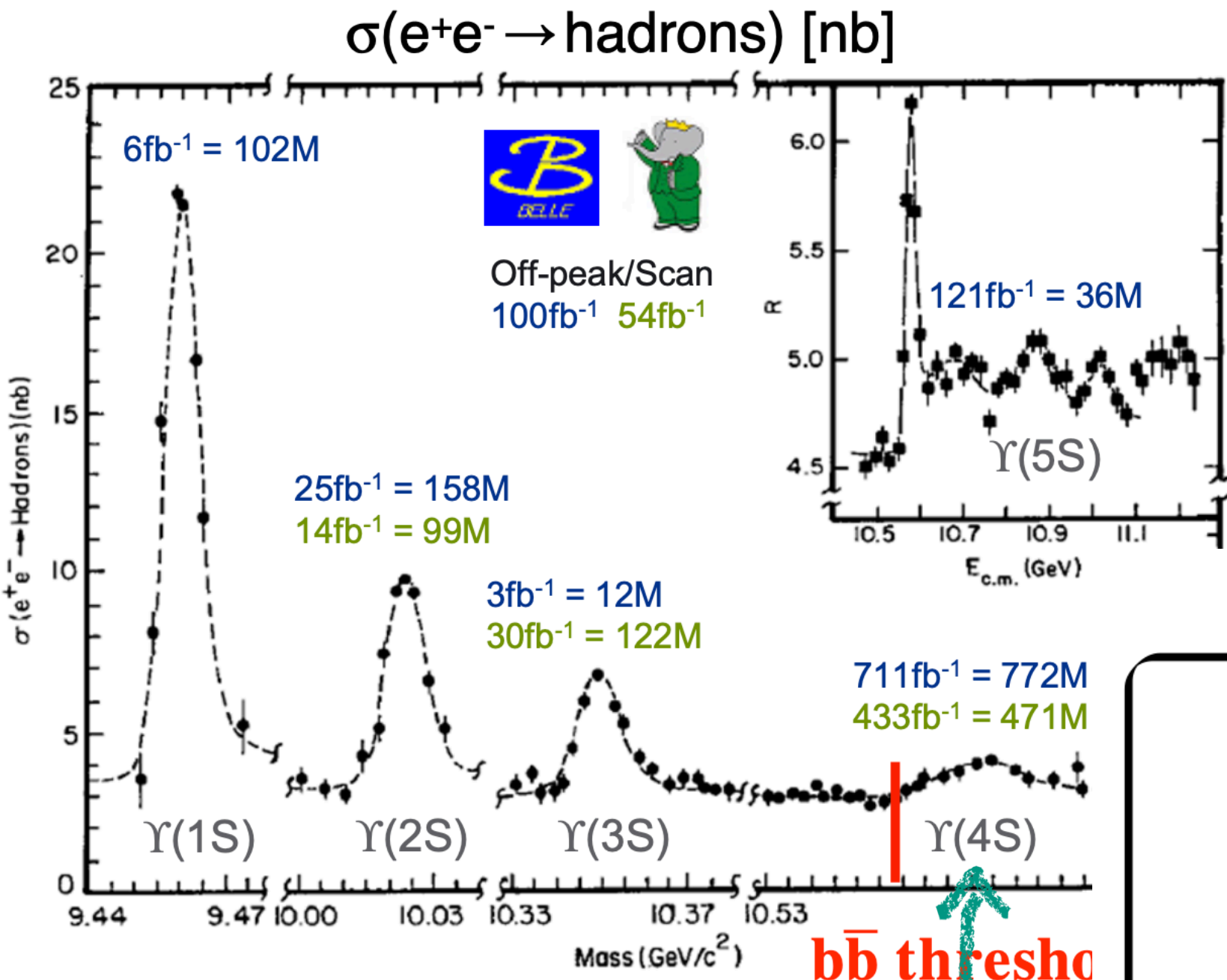
B Factories

A look at the basic Principles

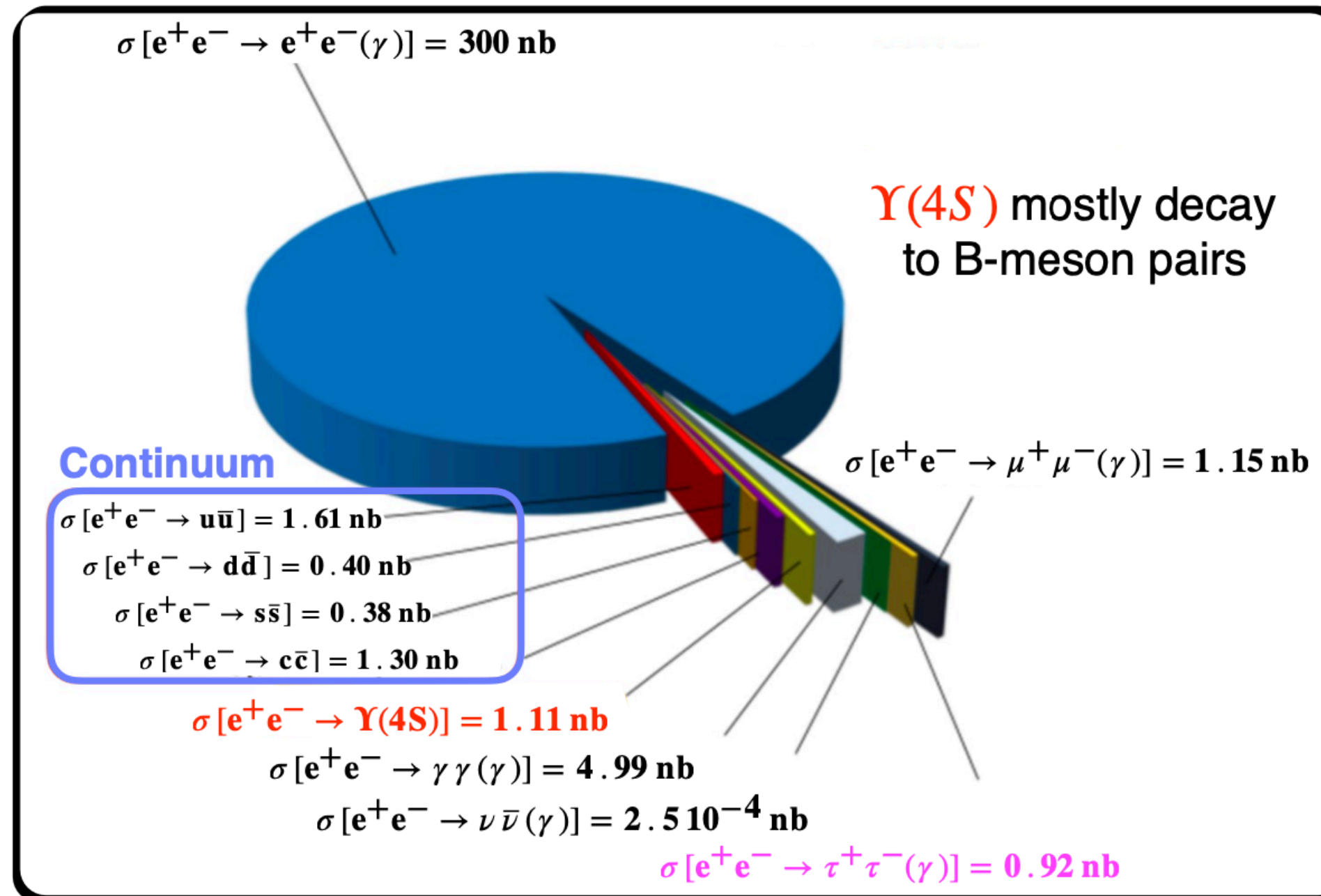


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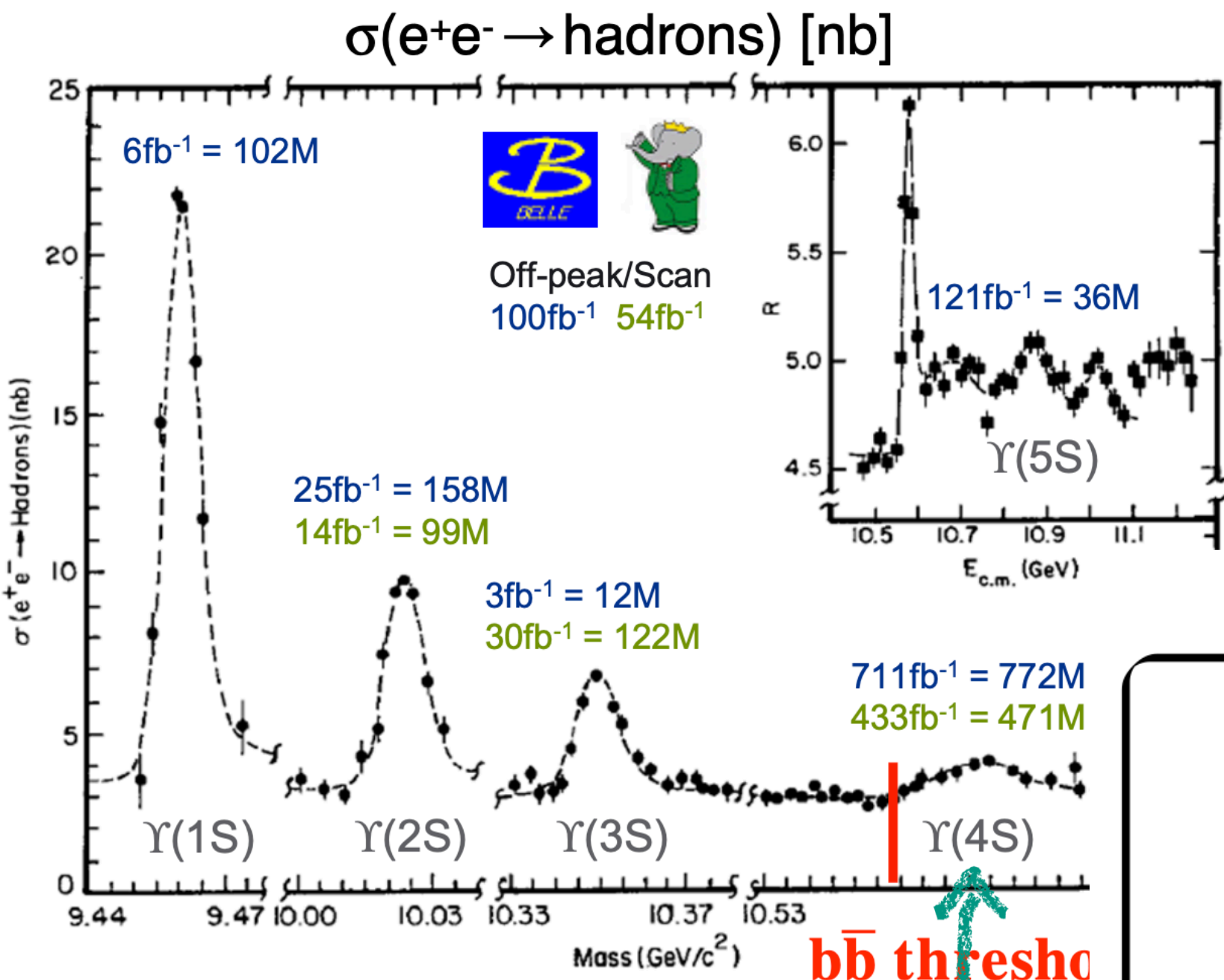
Decomposition of e+e- cross section



Almost as many τ as Bs!

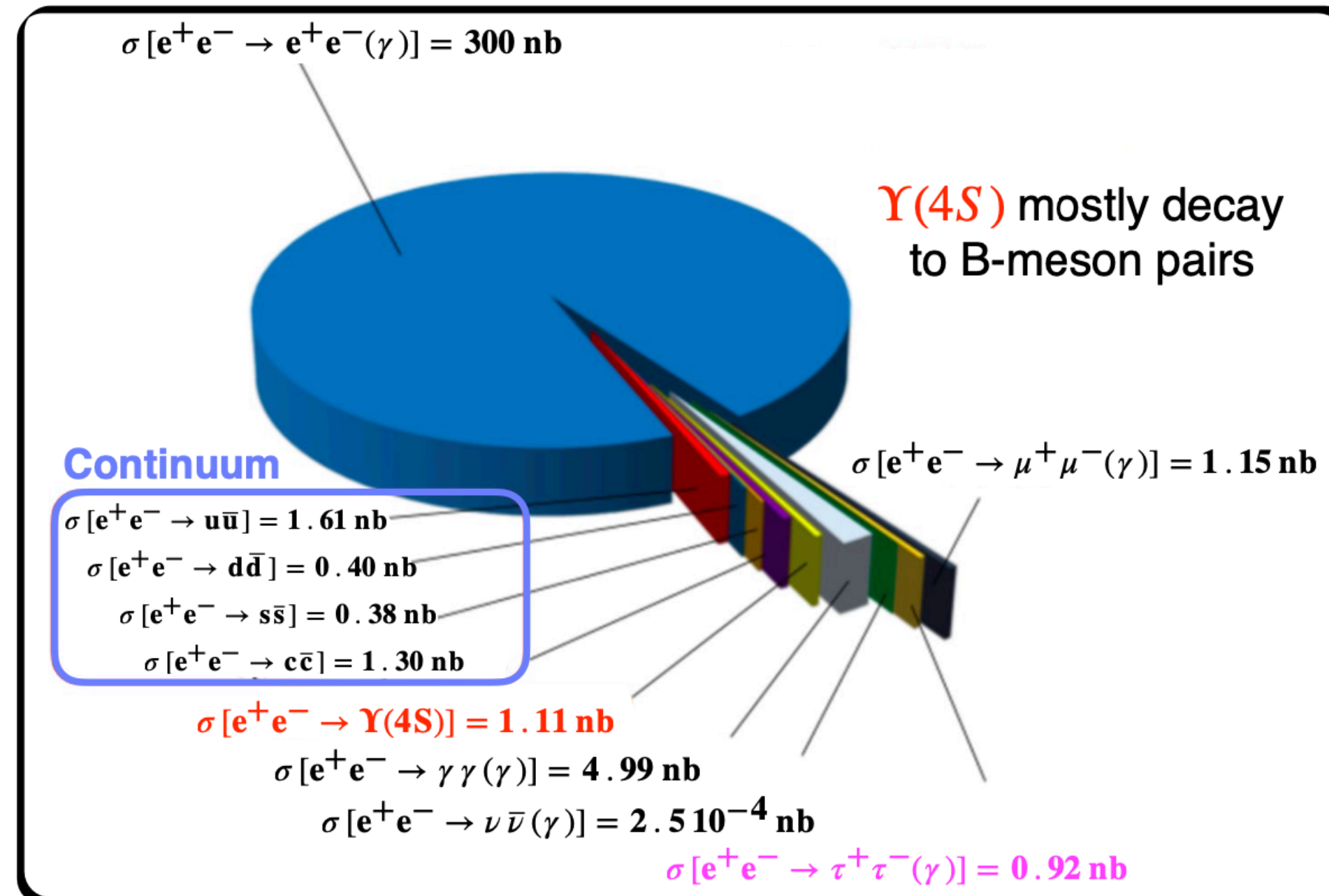
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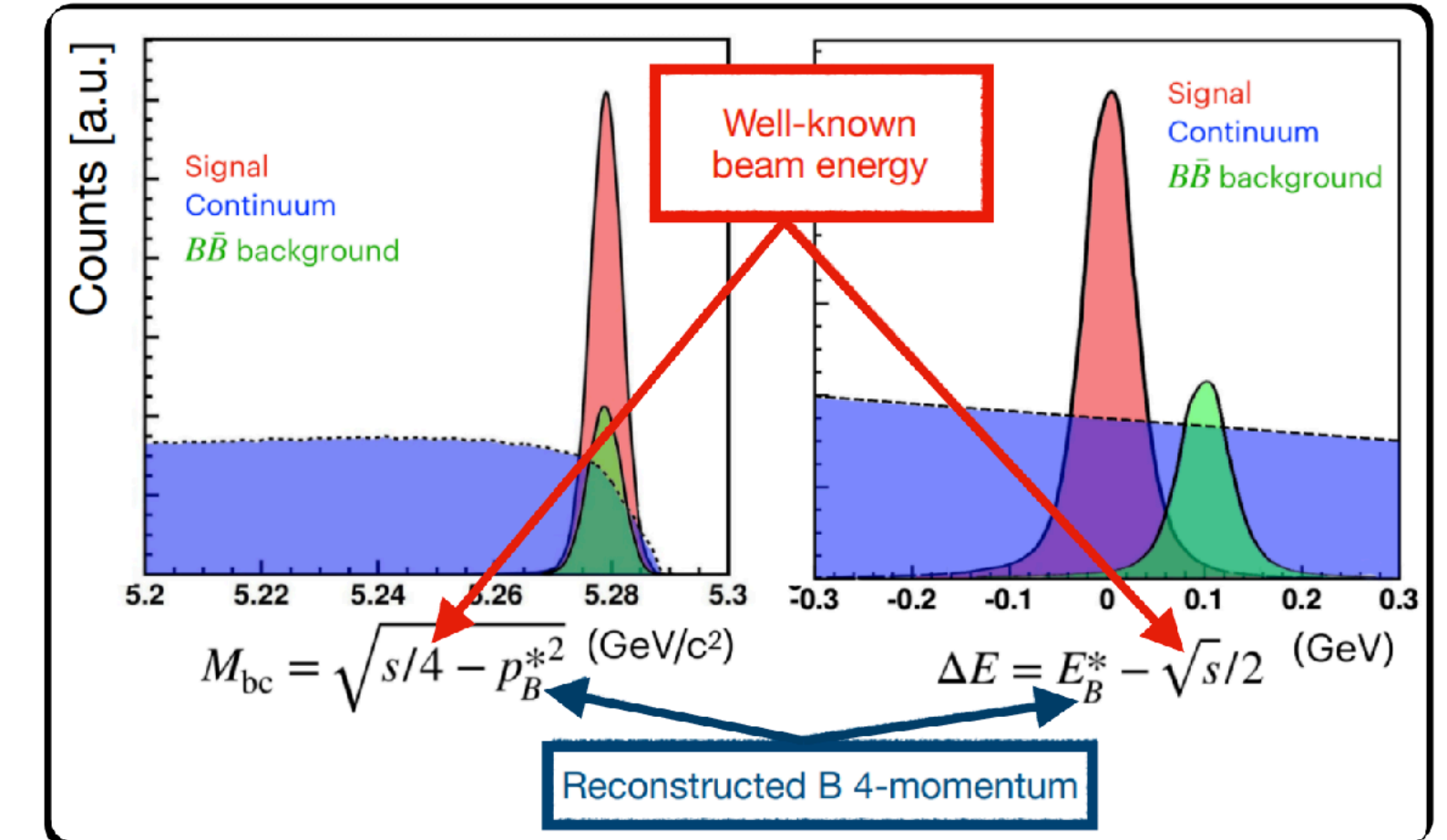
Known collision energy:
Powerful background rejection

Decomposition of e⁺e⁻ cross section

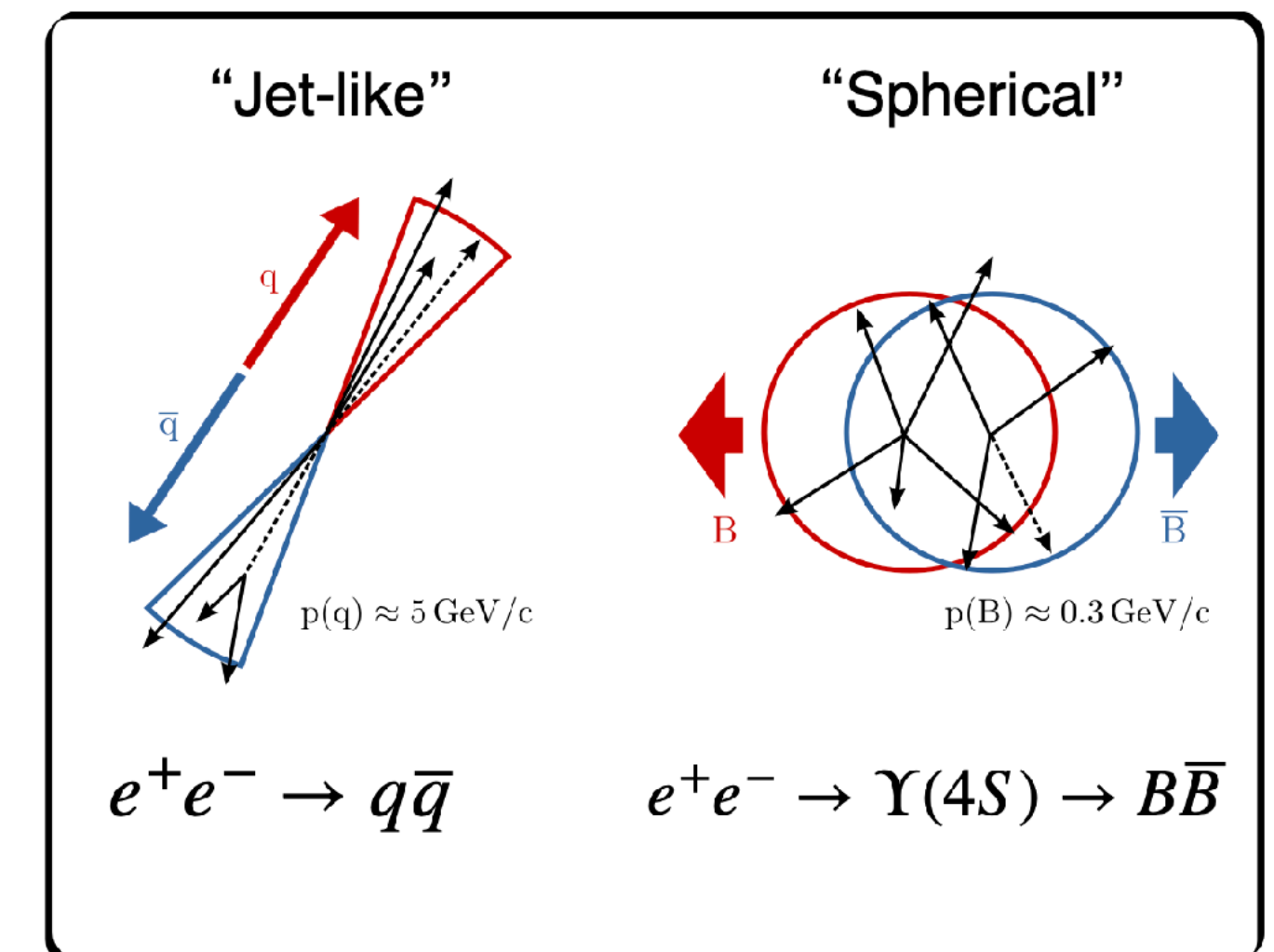


Almost as many τ as Bs!

Discriminating kinematic variables



Event shapes in the centre of mass system



The Belle II Physics Menu

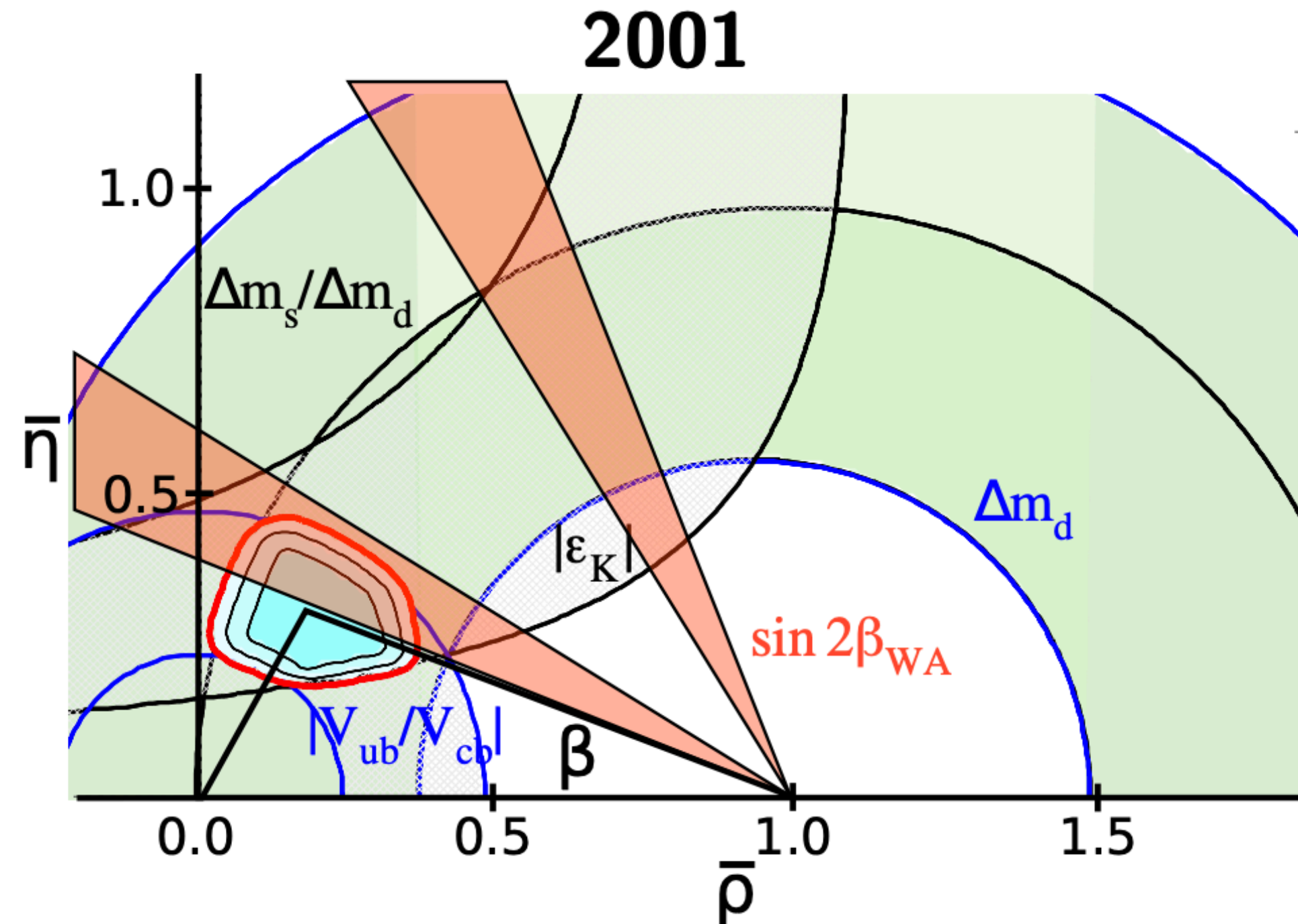
Higher Precision of the Known, Search for the Unknown



Constraining the CKM Triangle

The raison-d'être of B Factories

- First measurements of β by BaBar and Belle in 2001: Establishing the CKM structure of the SM

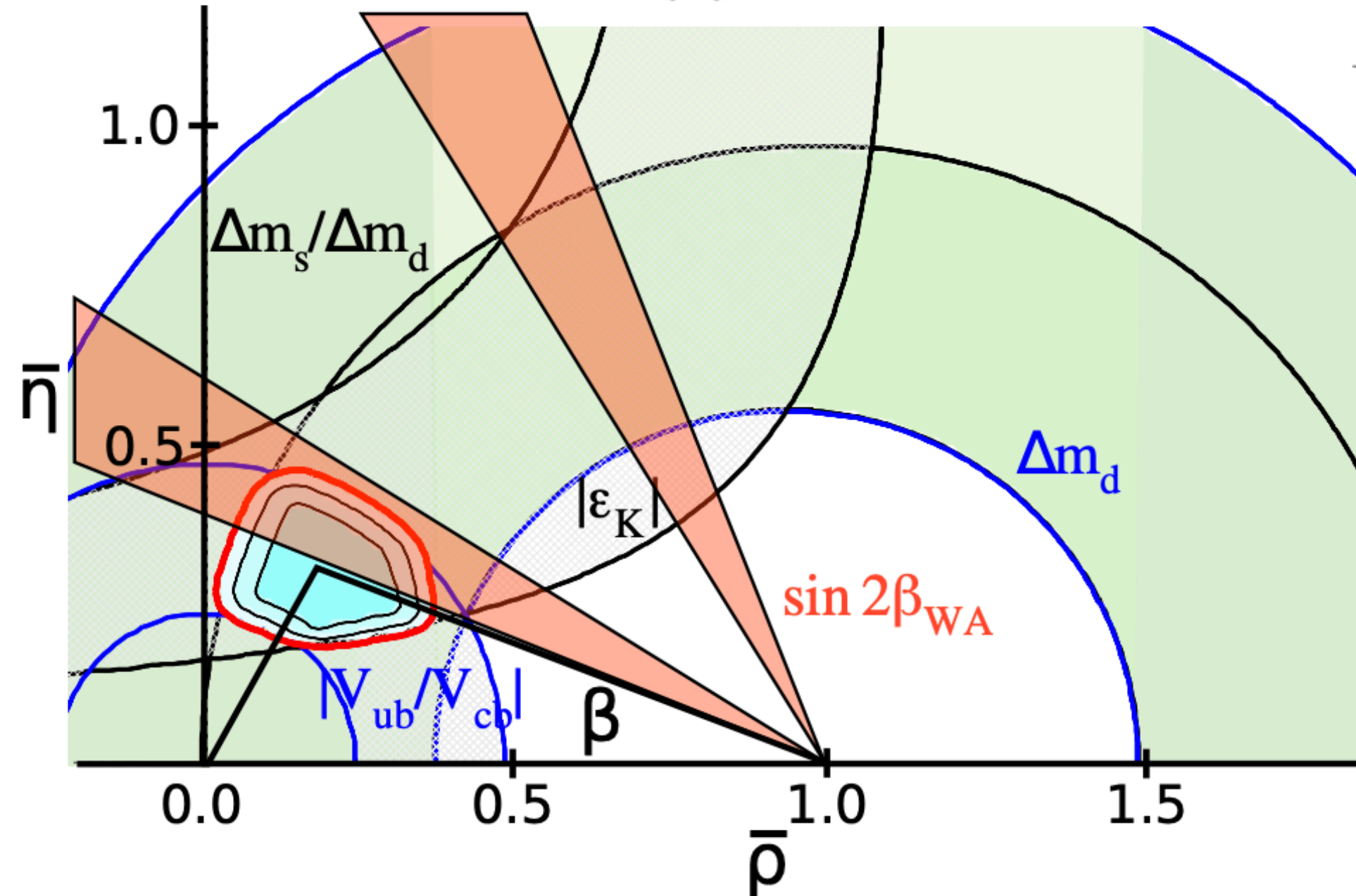


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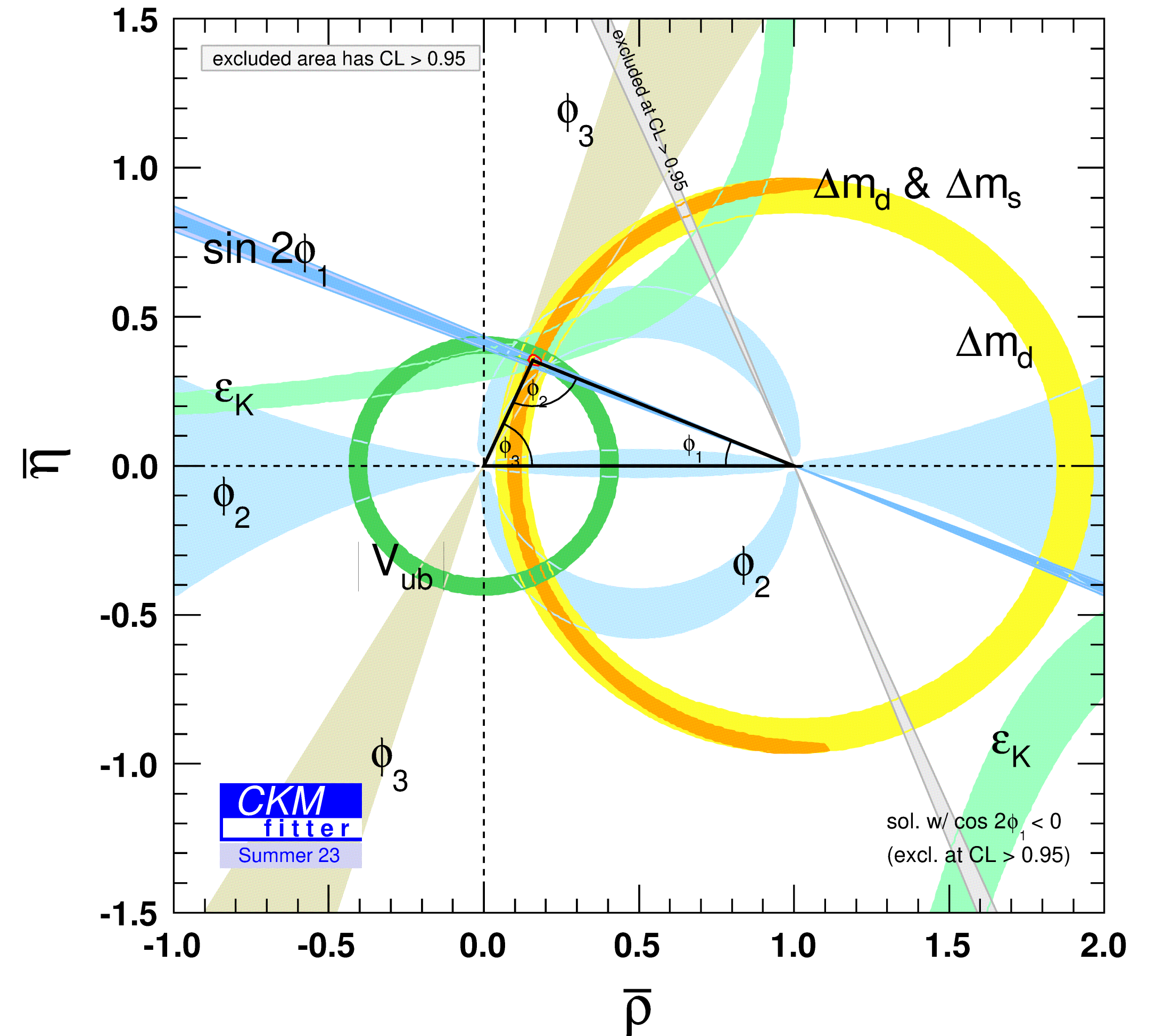
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2001



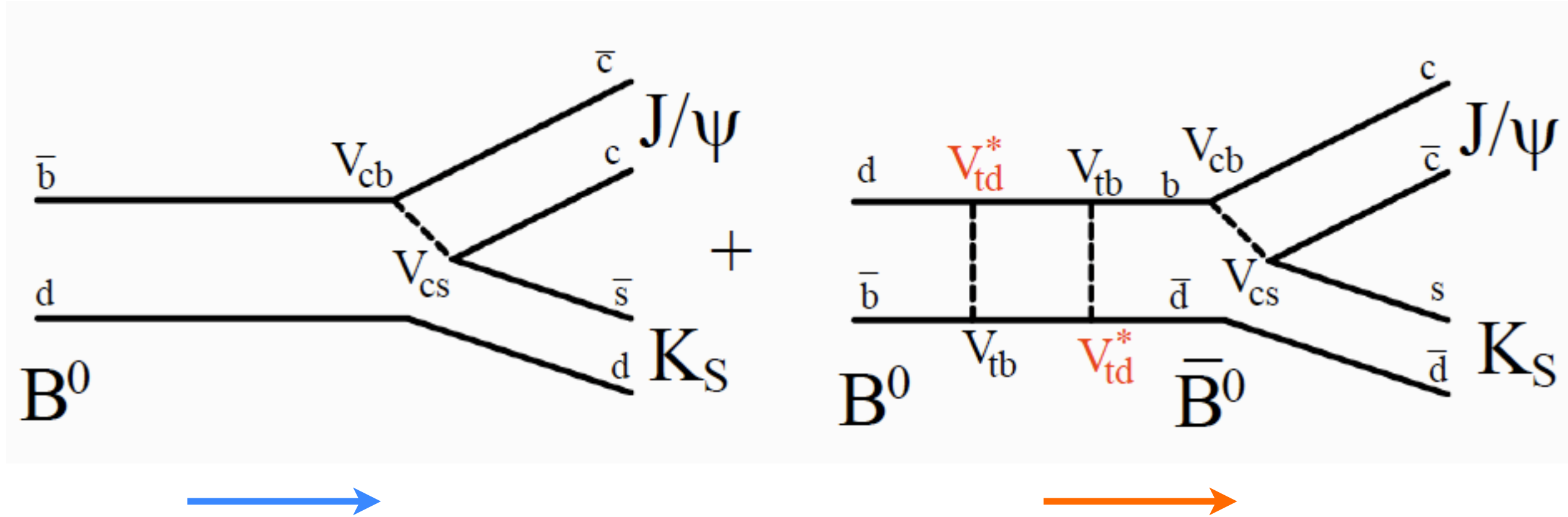
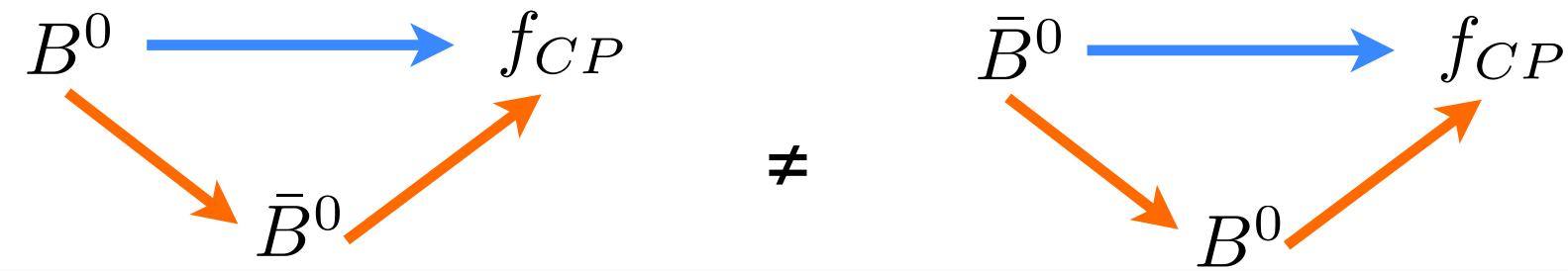
today: overconstrained system, with measurements by B factories, LHC, Kaon experiments, ...
Pushing sensitivity to detect New Physics.



Physics Example: Time-dependent CP Violation

The golden Channel: $J/\psi K_S$

- Differences between matter and antimatter explored with B^0 mesons:



Exploits entanglement of B^0 mesons:
Produced from decay of $Y(4s)$ resonance.

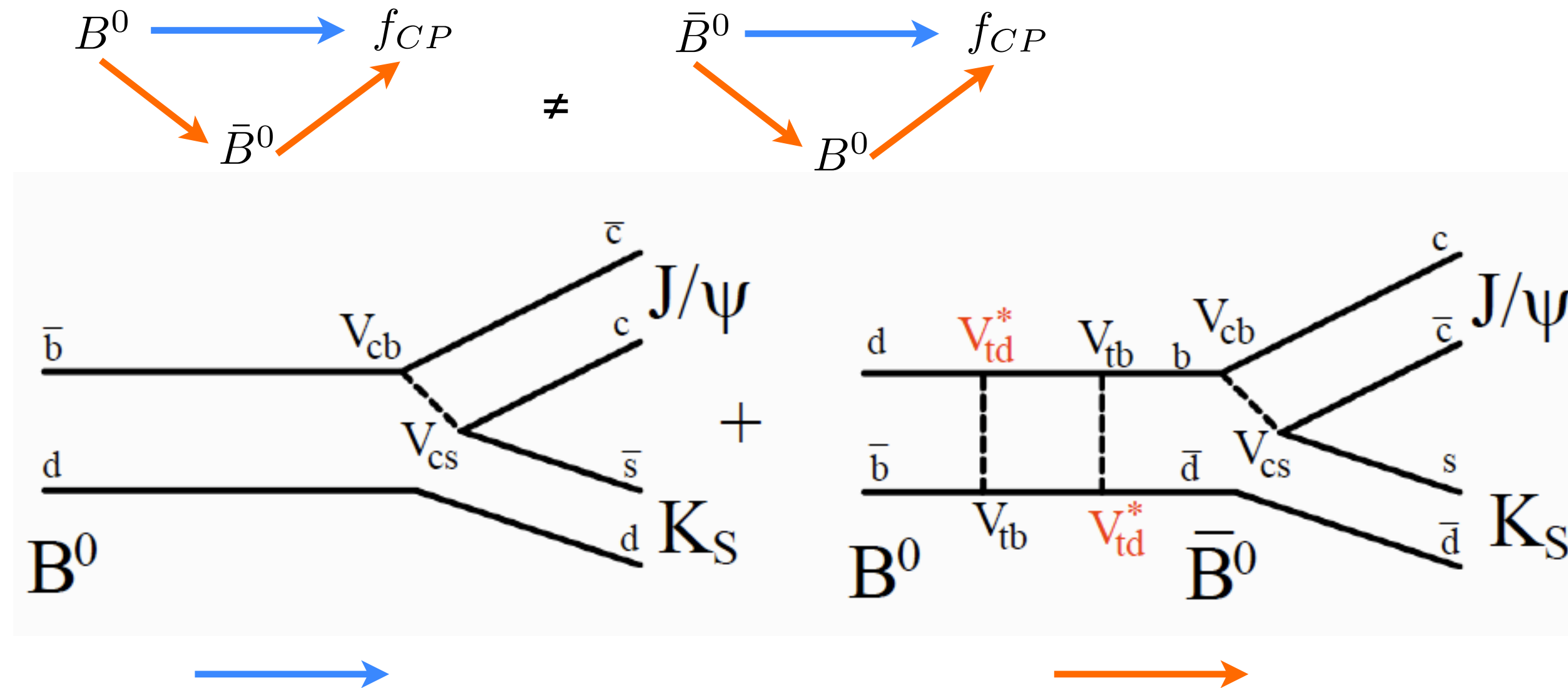
Requires:

- Measurement of oscillation: time difference in decays.
- Tagging of B-meson flavor at decay time.

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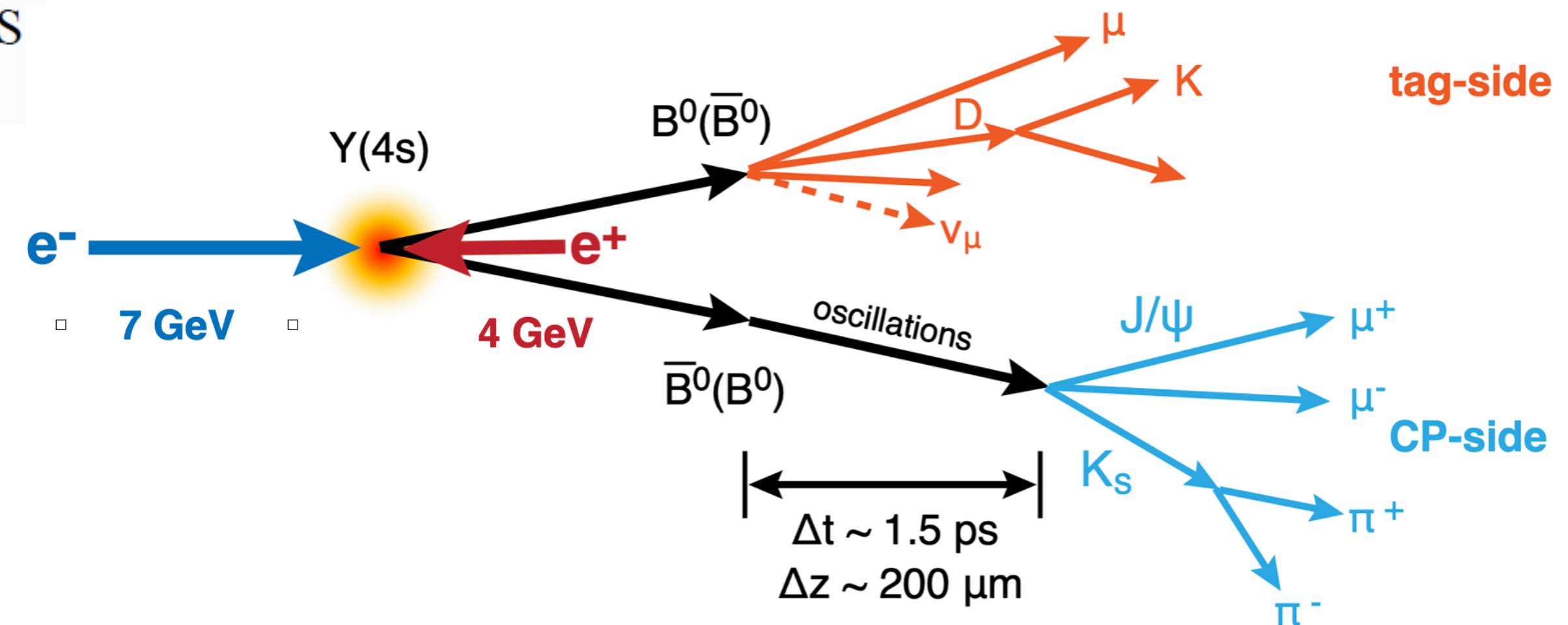


Trade time measurement for distance measurement:
 Boosted center-of-mass system!

Exploits entanglement of B^0 mesons:
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Requires:

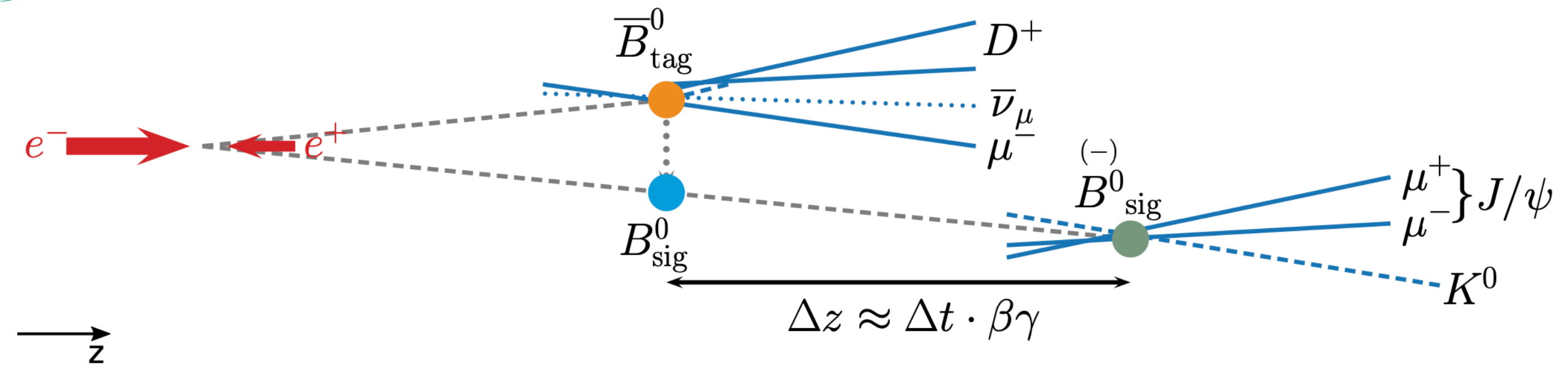
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Physics Example: Time-dependent CP Violation

Measuring $\sin^2\beta$

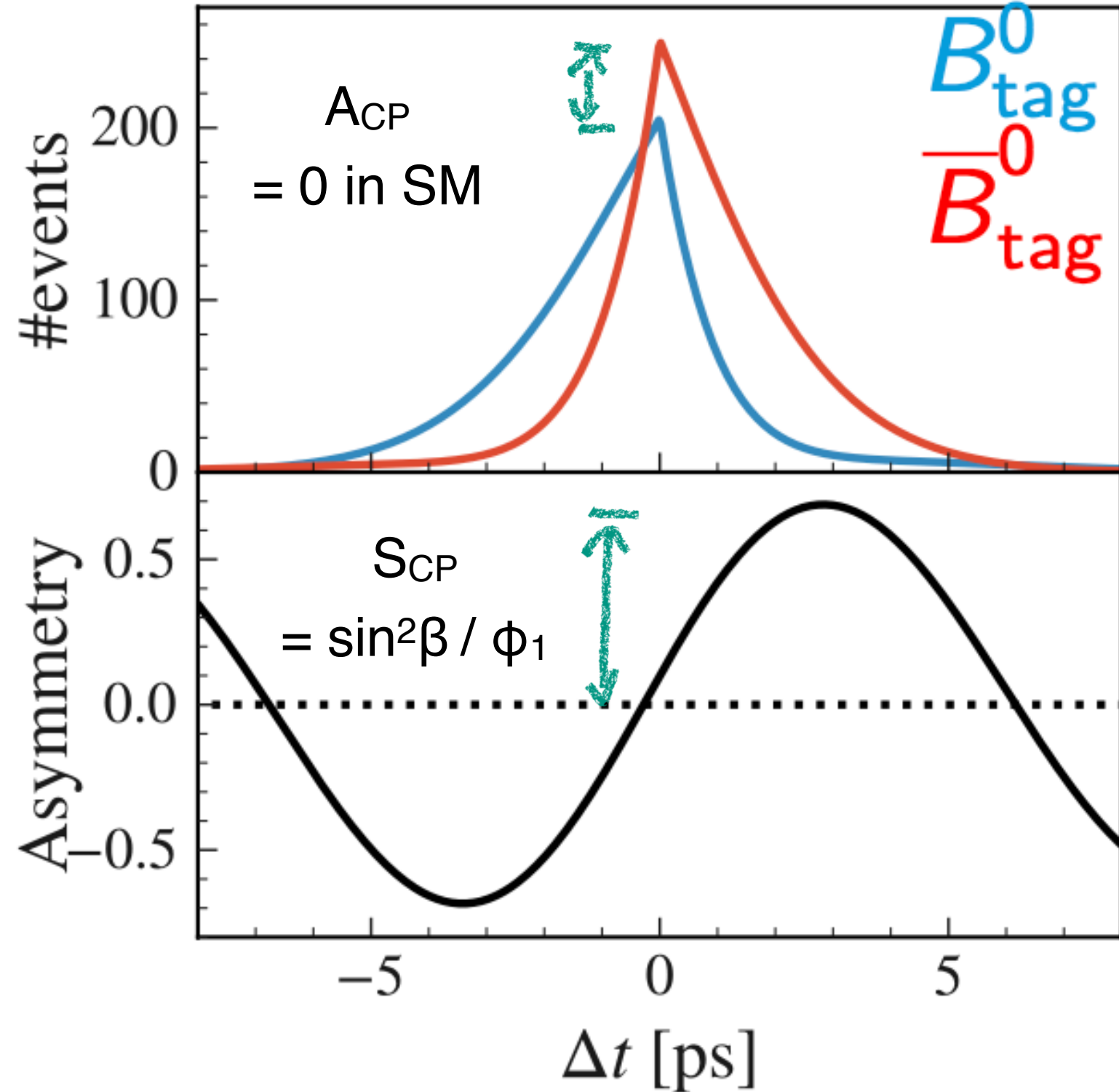
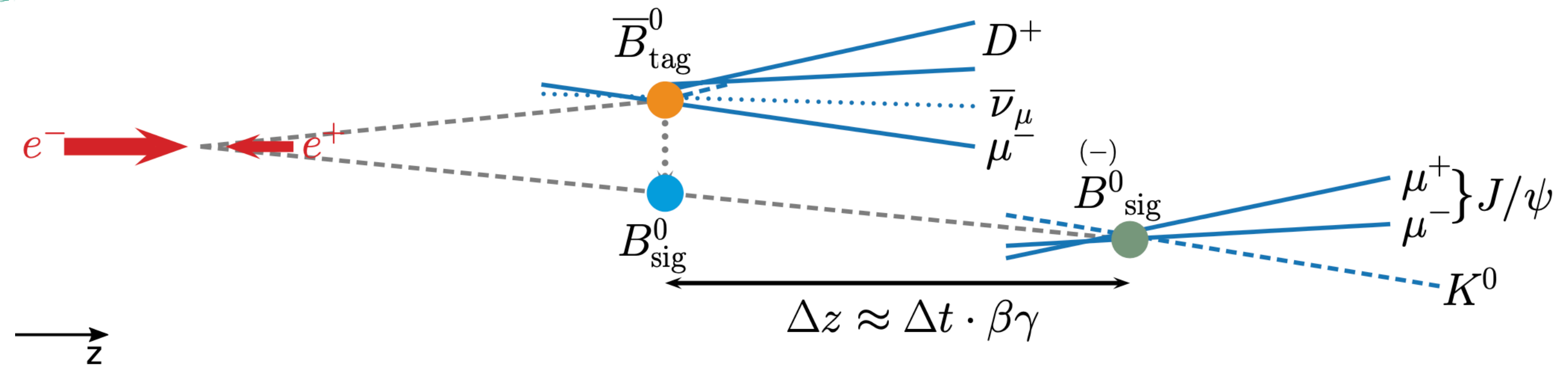
- From principle to measurement:



Physics Example: Time-dependent CP Violation

Measuring $\sin^2\beta$

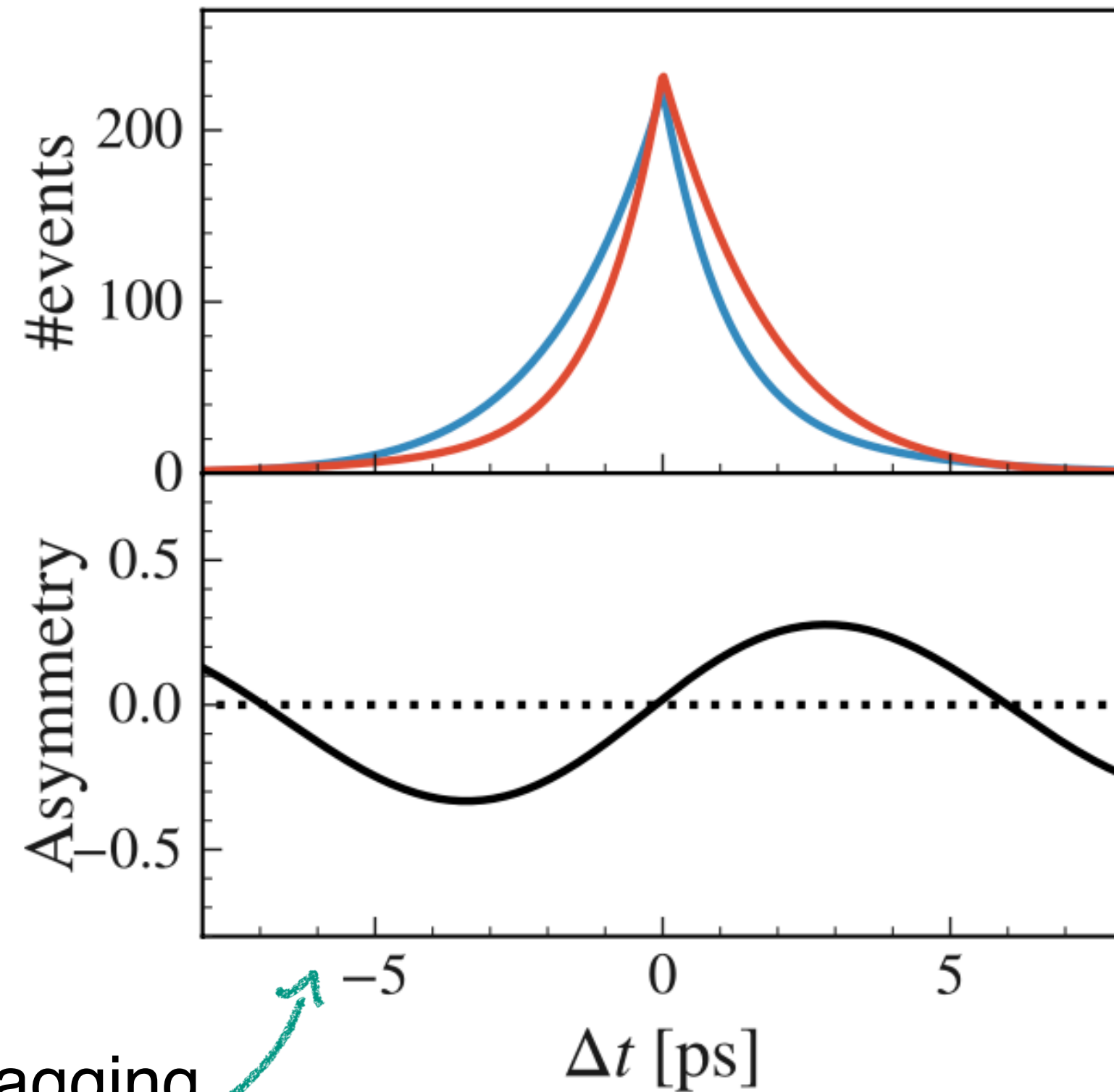
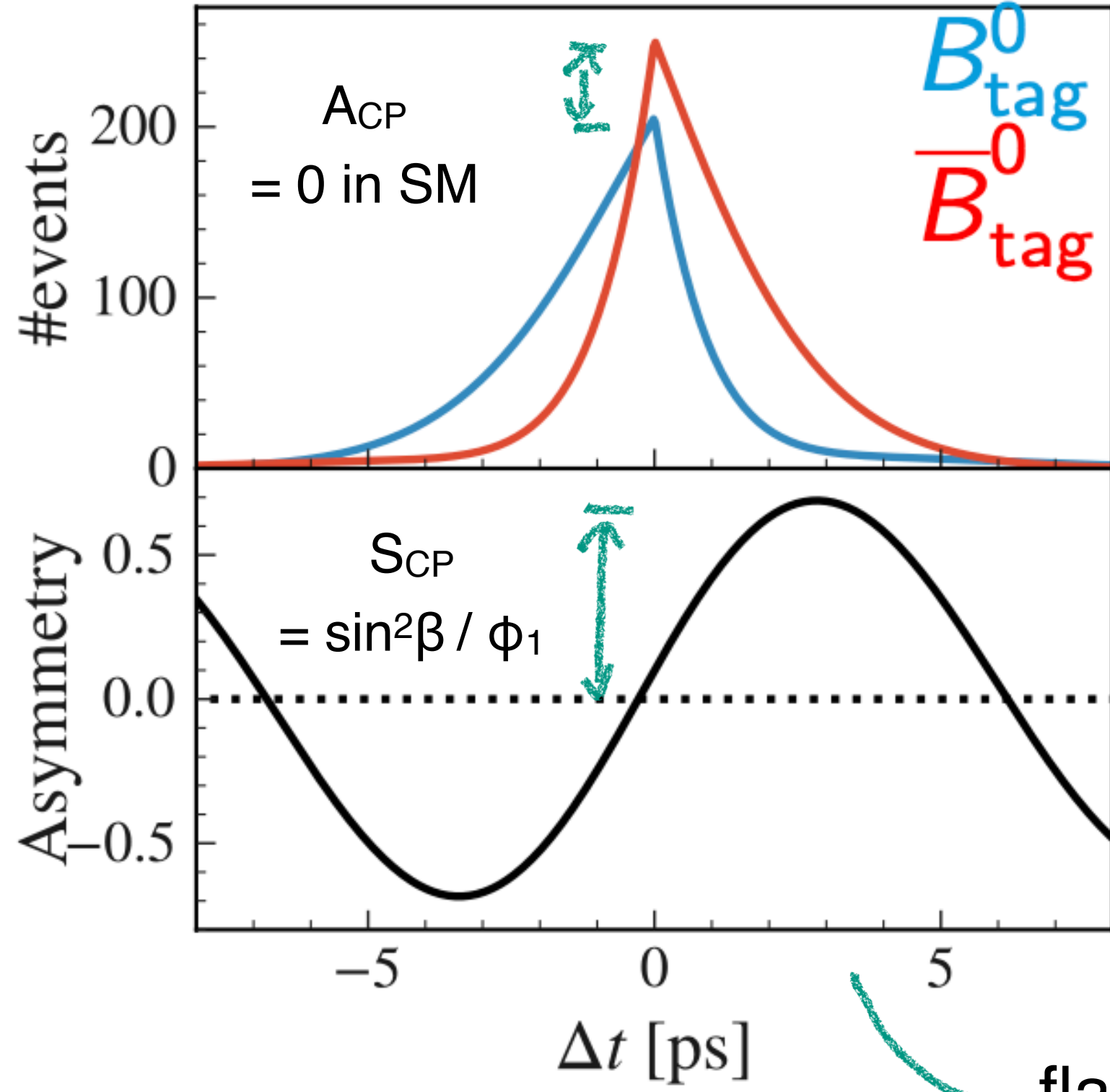
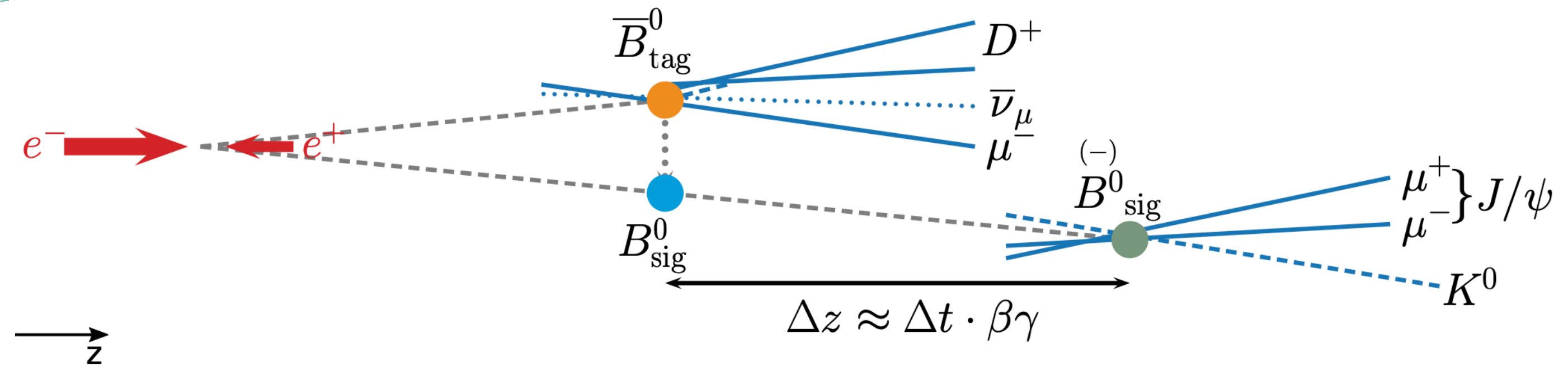
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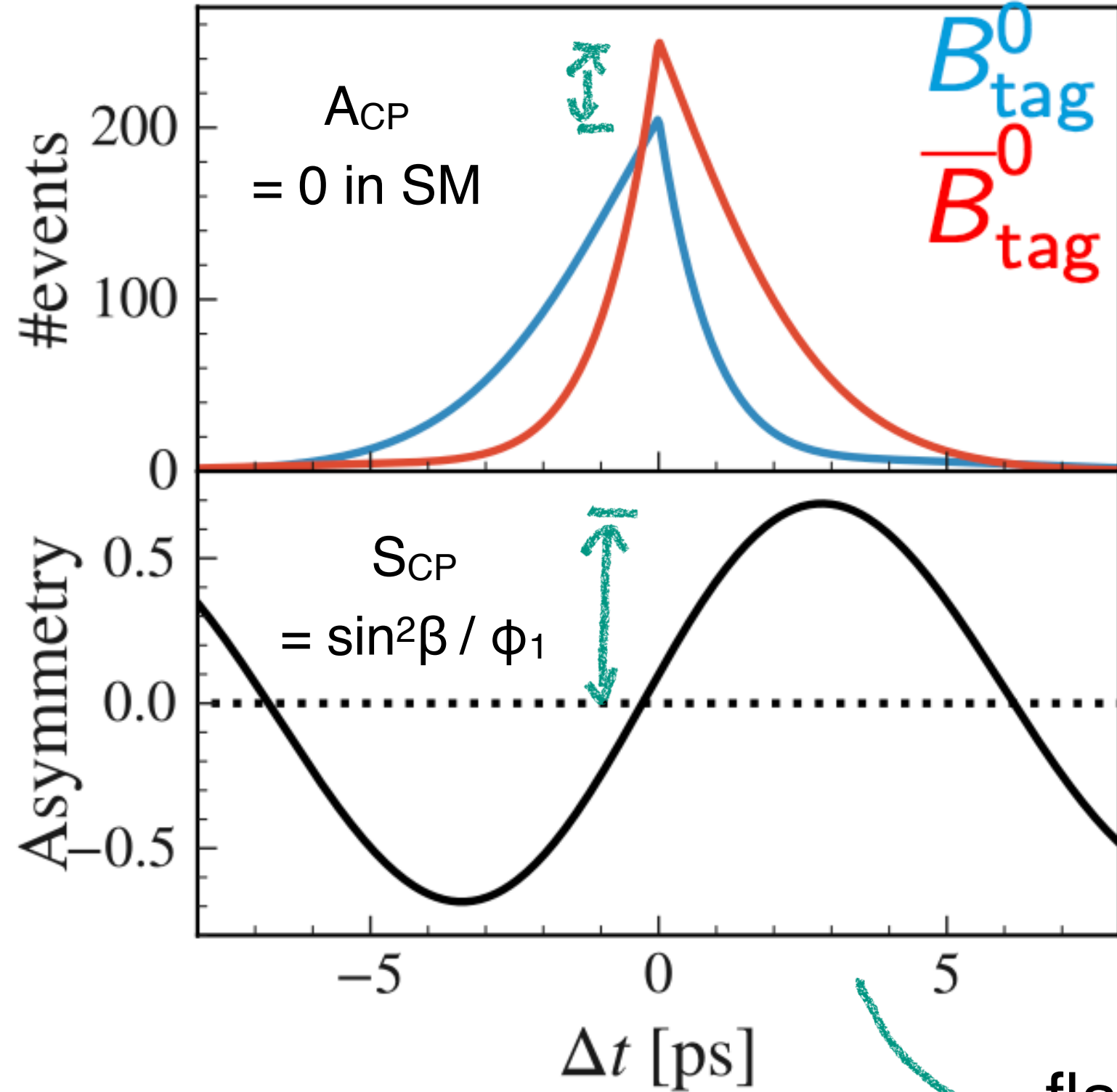
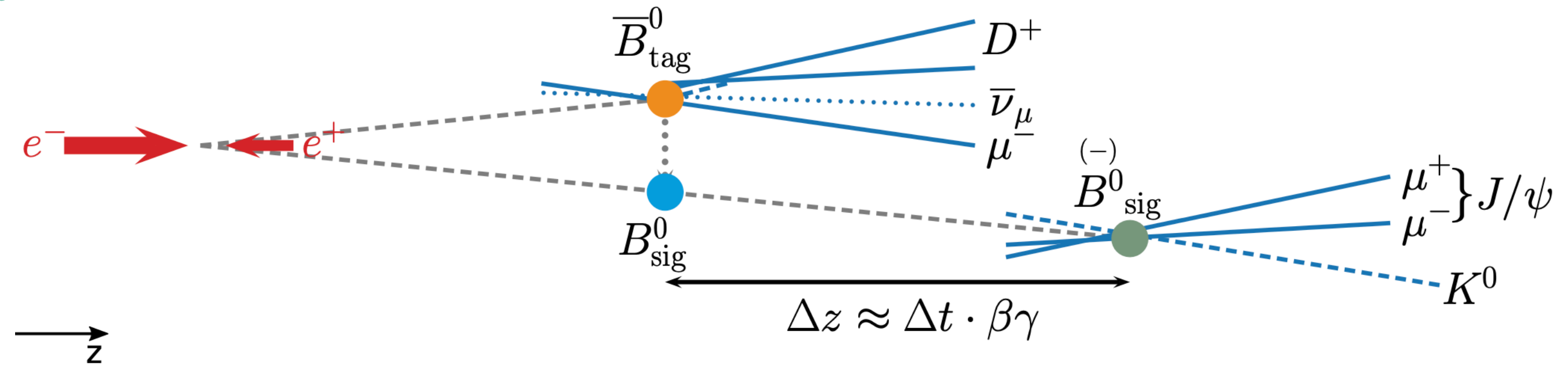


flavour tagging

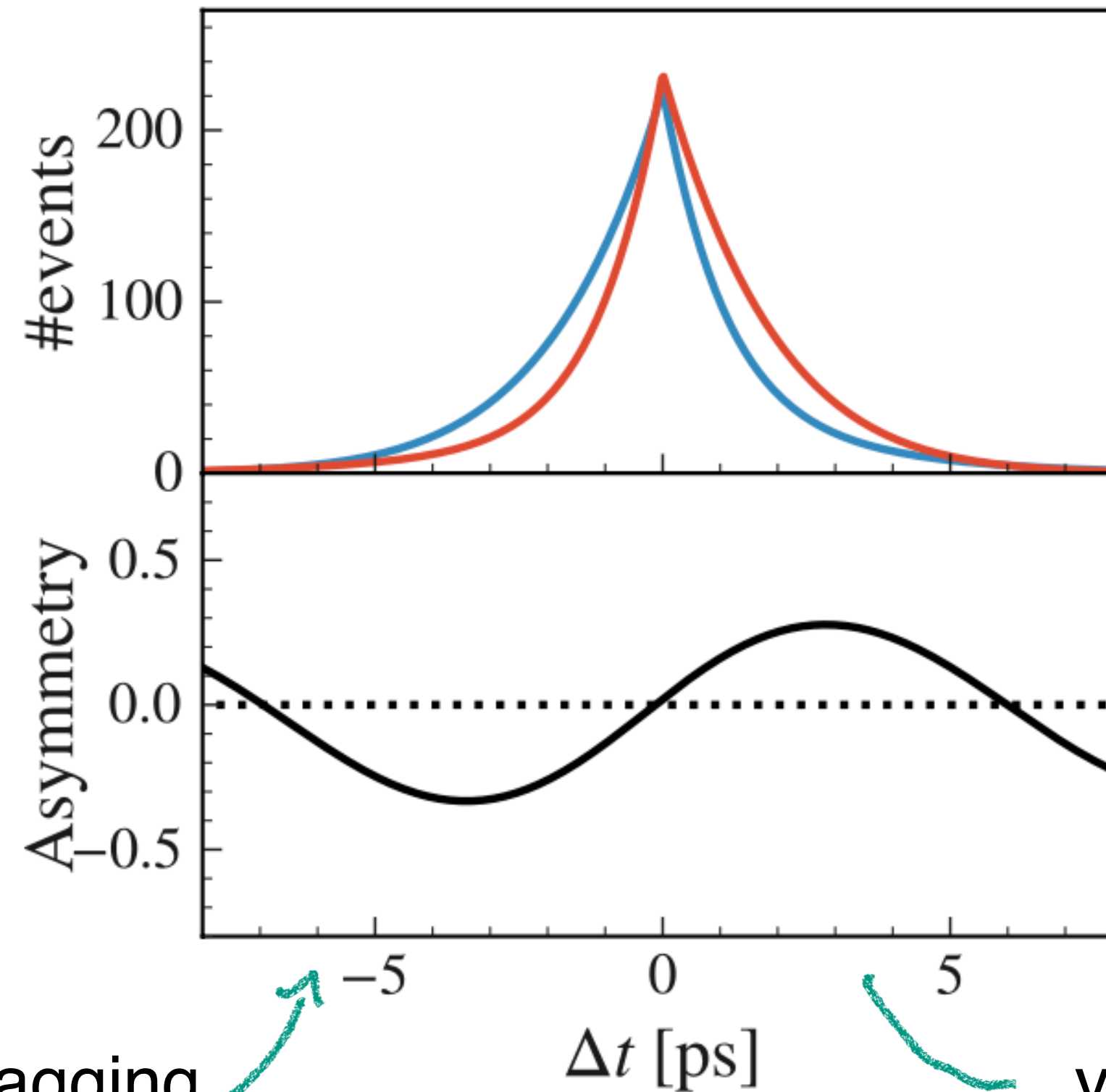
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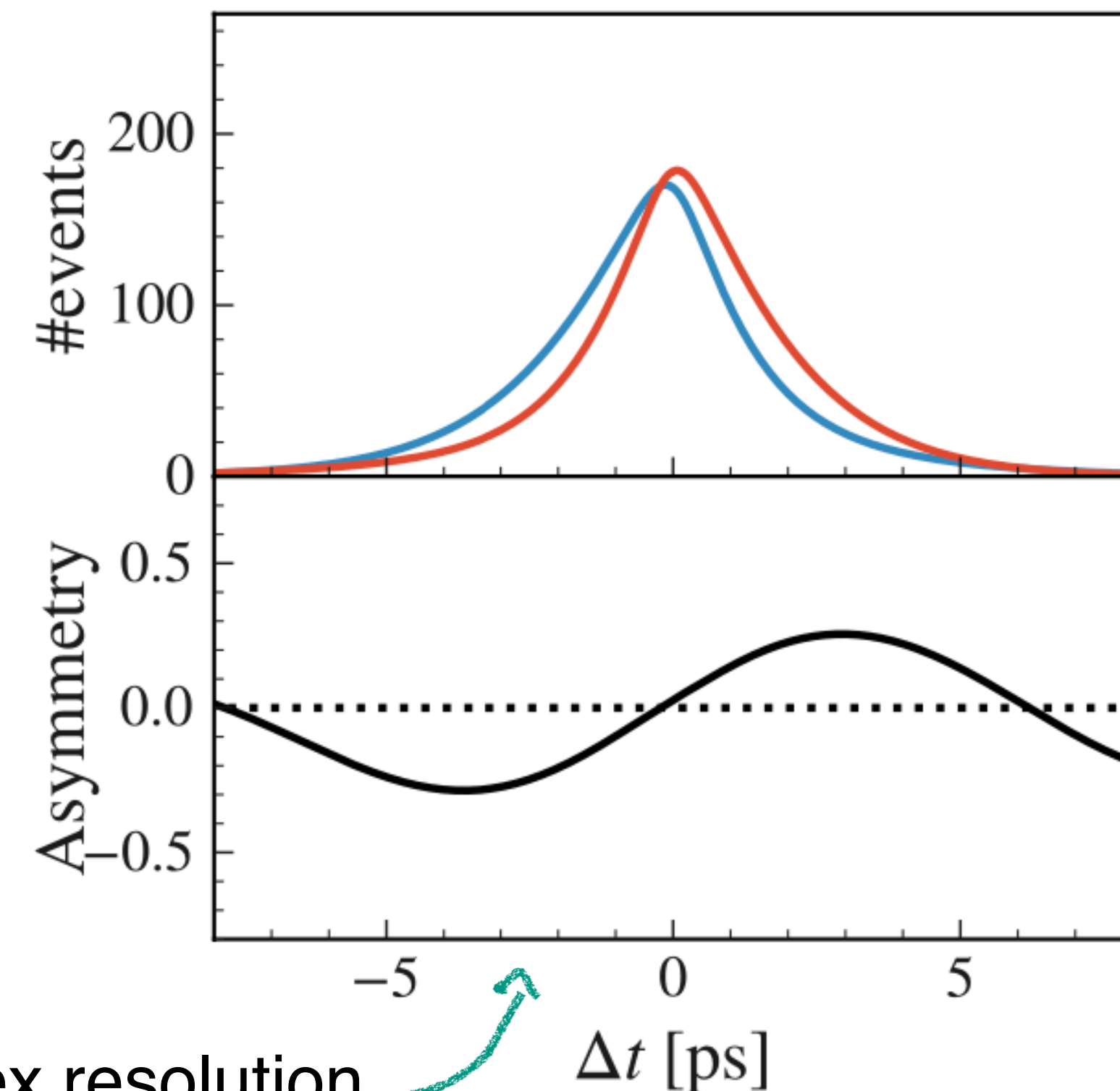
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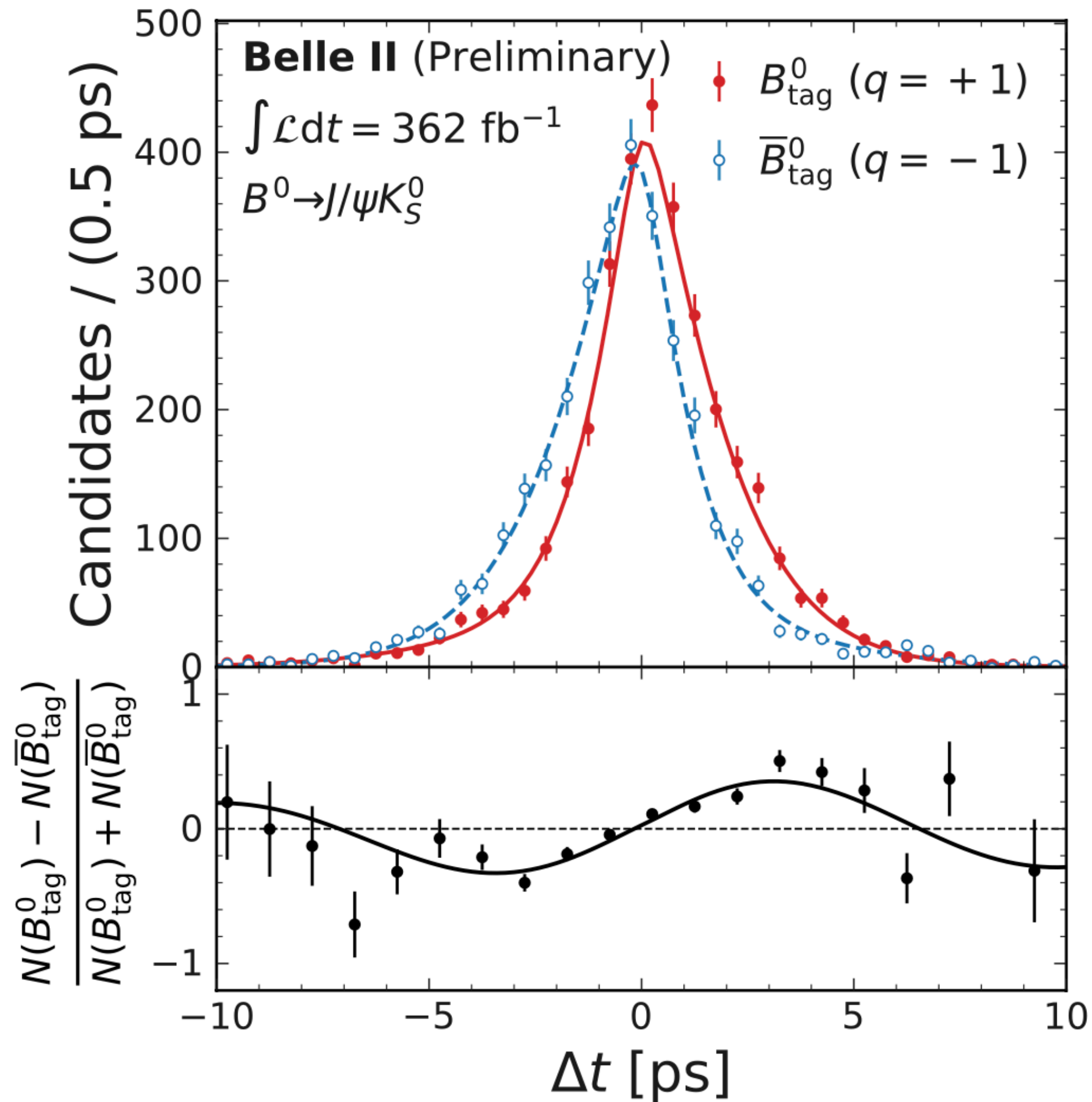
vertex resolution



Physics Example: Time-dependent CP Violation

Putting Belle II on the map

- First results with Belle II data: Not yet competitive due to smaller integrated luminosity, but:

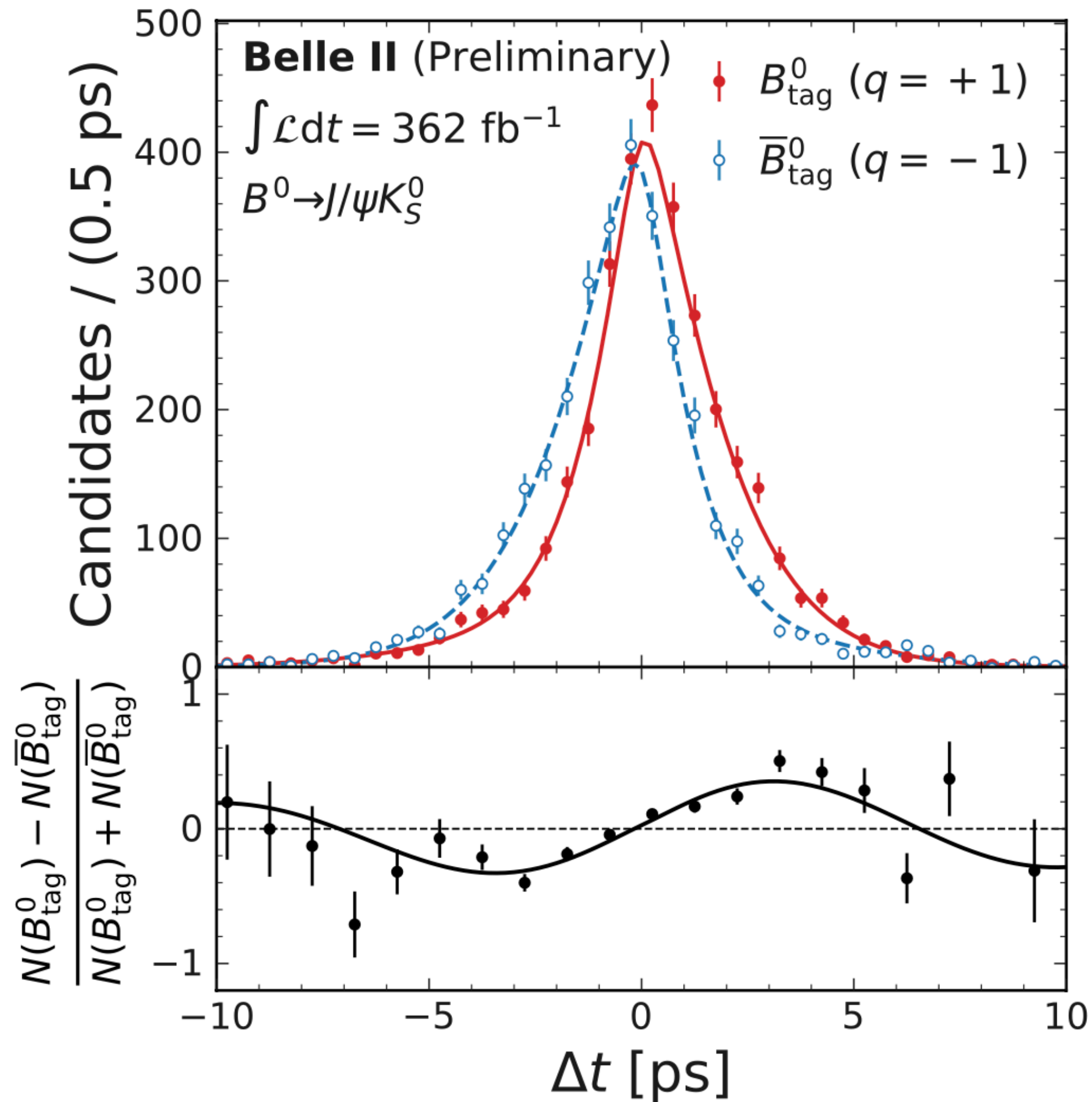


- Demonstrated capability of Belle II for improved vertex z coordinate reconstruction compared to Belle
- Developed an improved tagging technique based on graph neural networks, GFlaT: 18% improvement in tagging efficiency

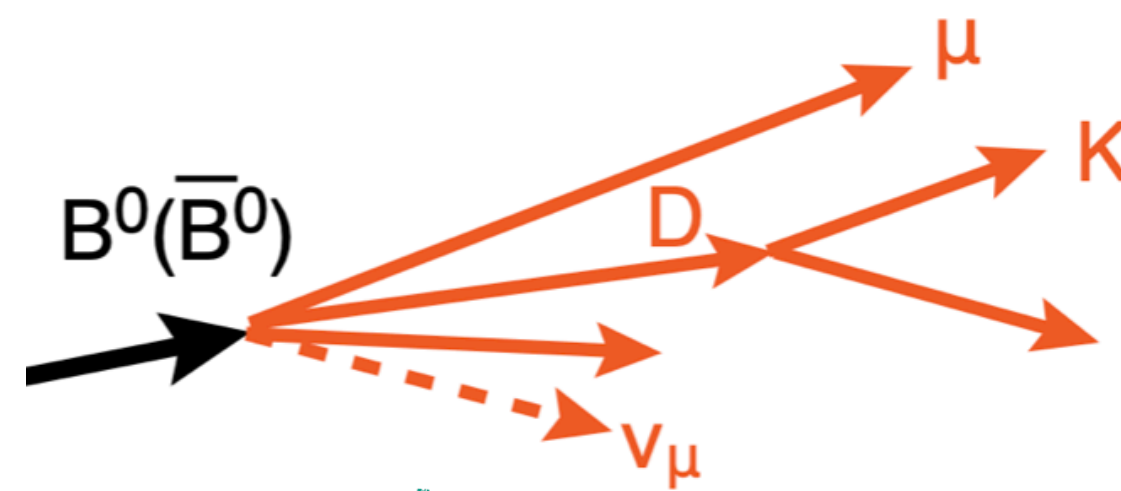
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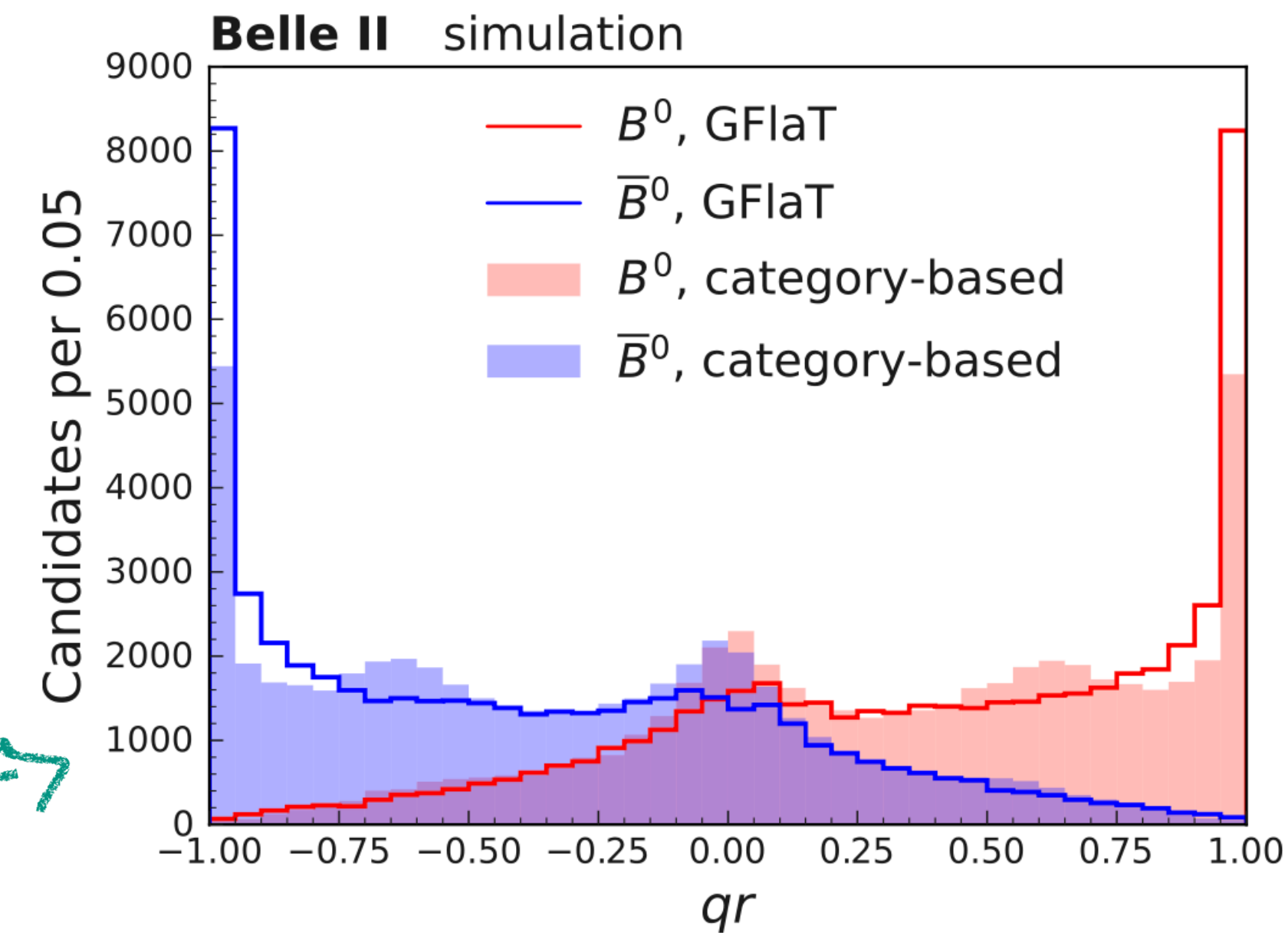
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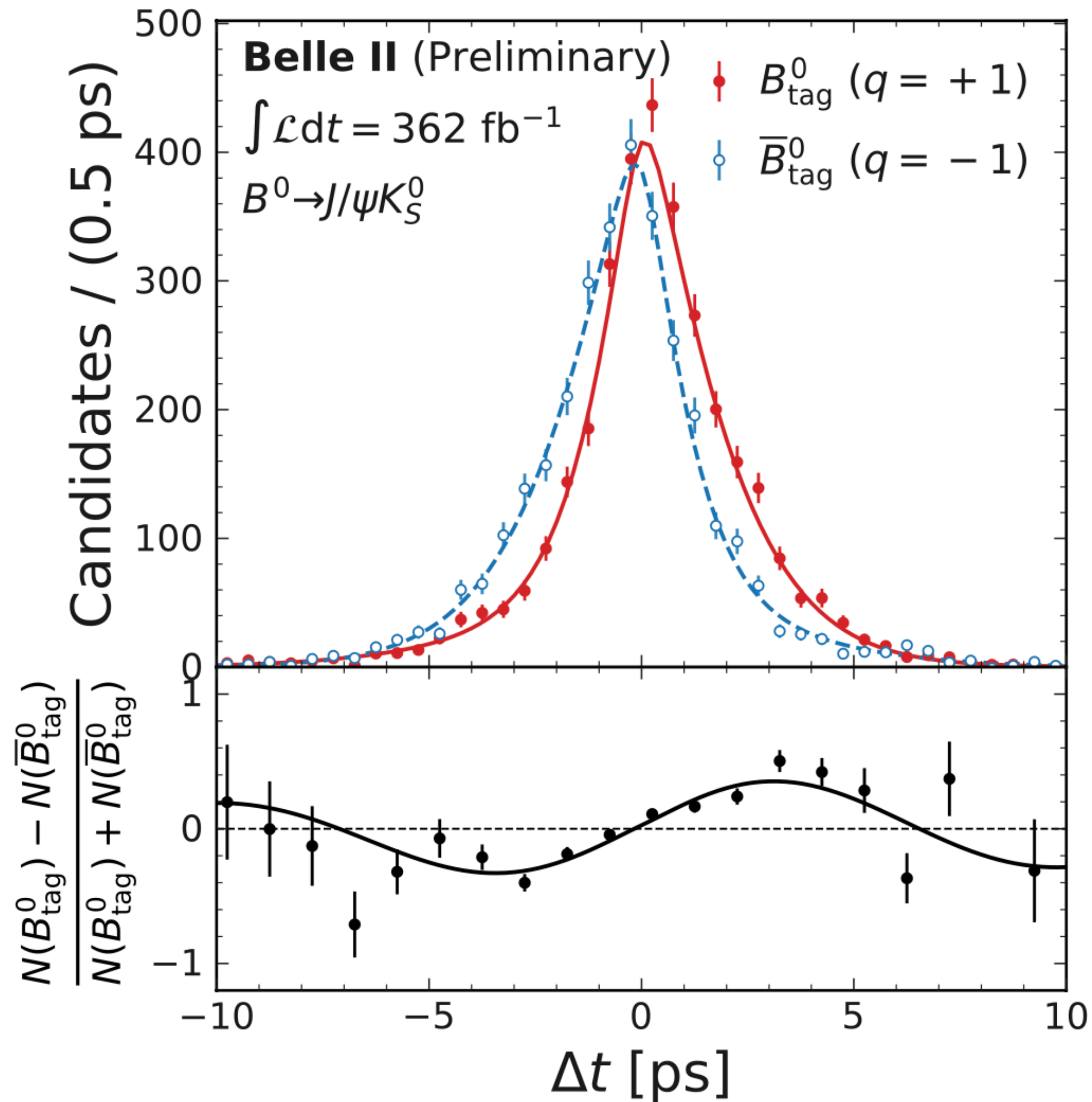
use full information



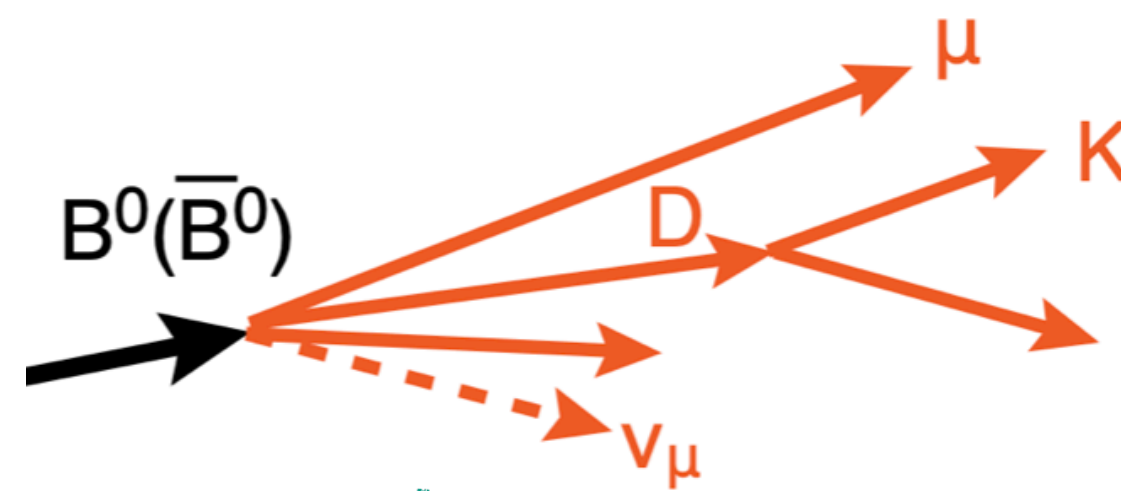
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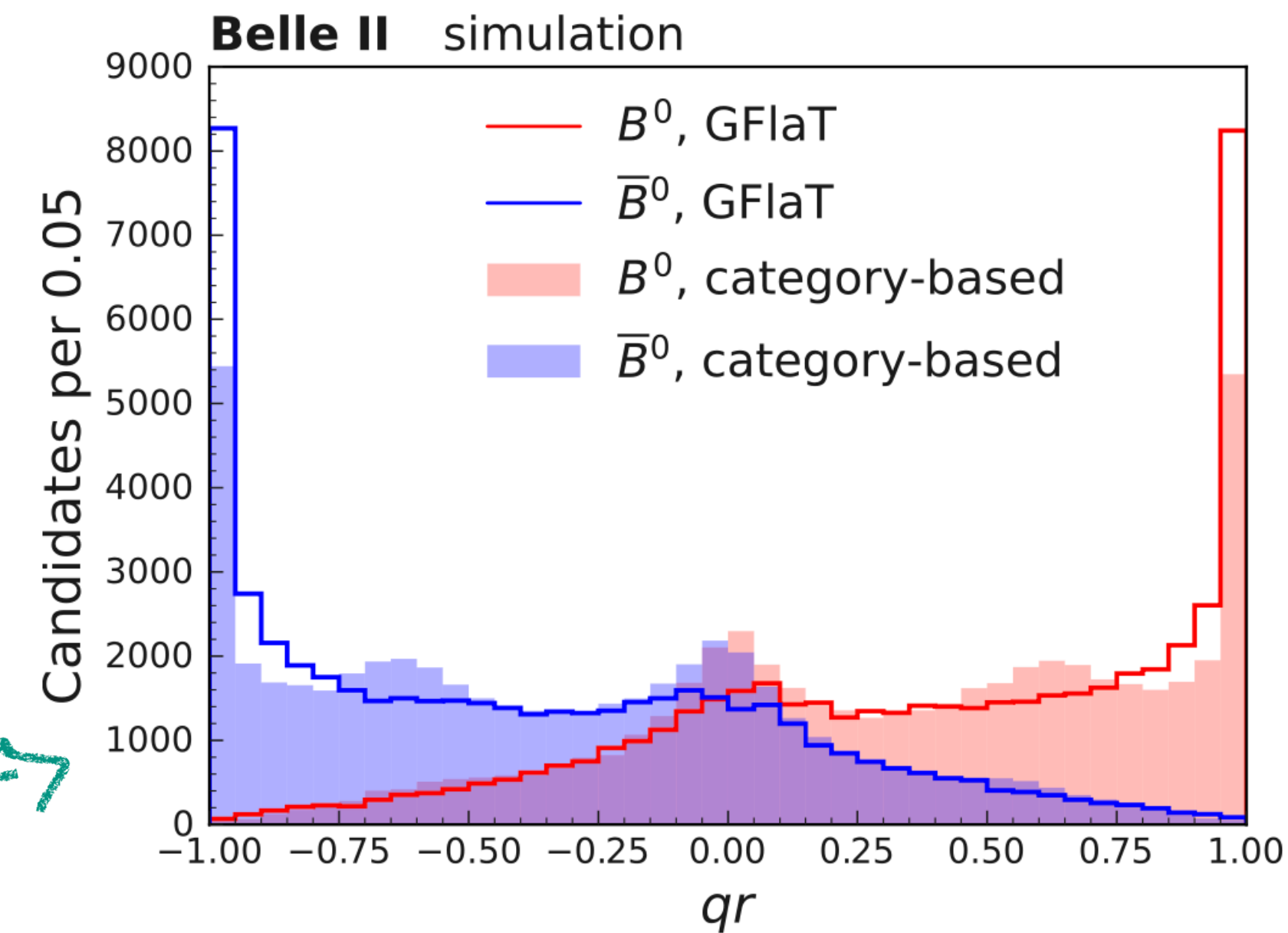


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Angle β/ϕ_1 :
 $(23.2 \pm 1.5 \pm 0.6)^\circ$

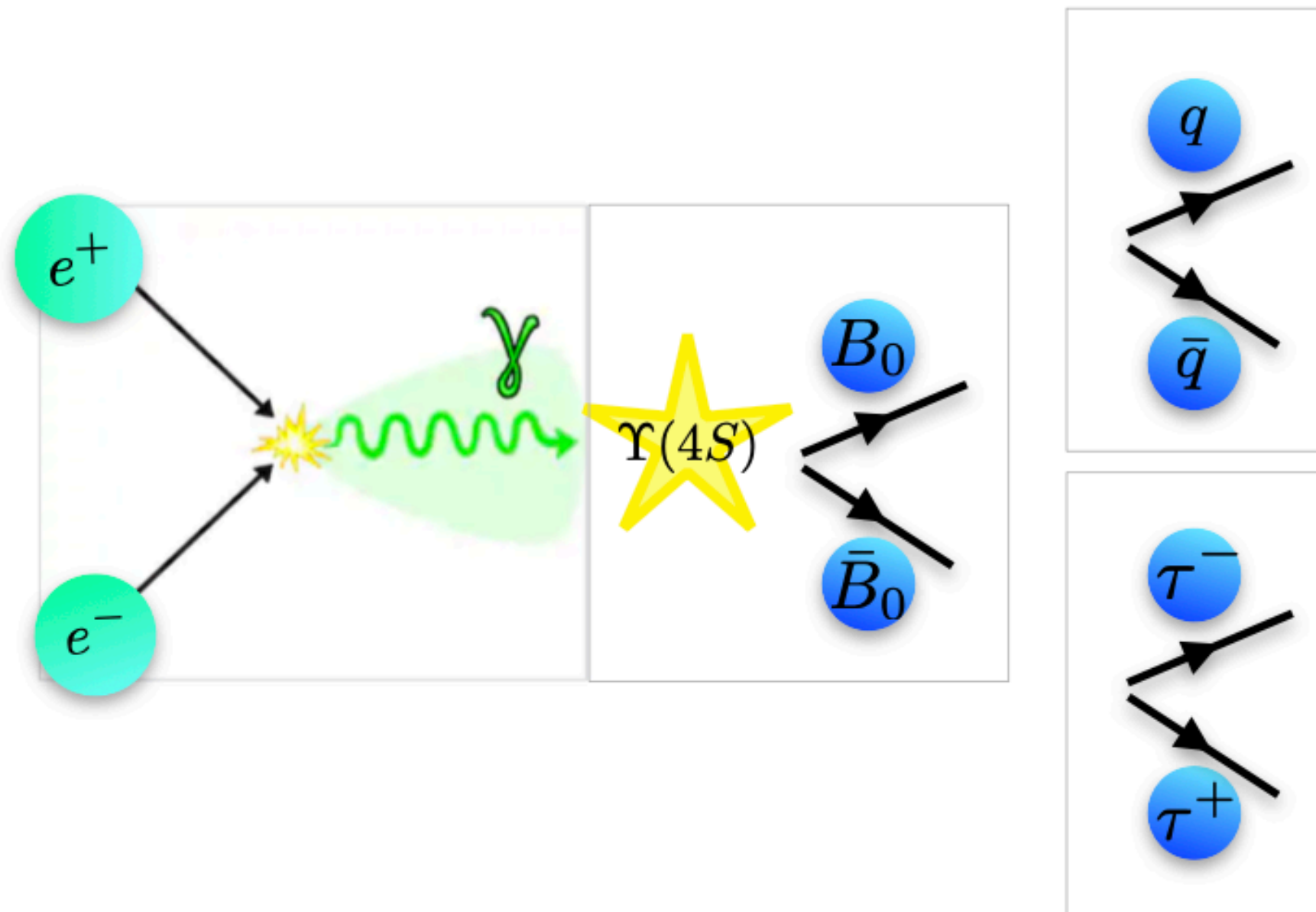
WA (PDG '24) : $(22.6 +0.5 - 0.4)^\circ$



Physics Example: Exotic τ Decays

Lepton Flavour Violation & New Particles

- Belle II is also a τ factory:



$$\sigma(e^+e^- \rightarrow \Upsilon(4S)) = 1.05 \text{ [nb]}$$

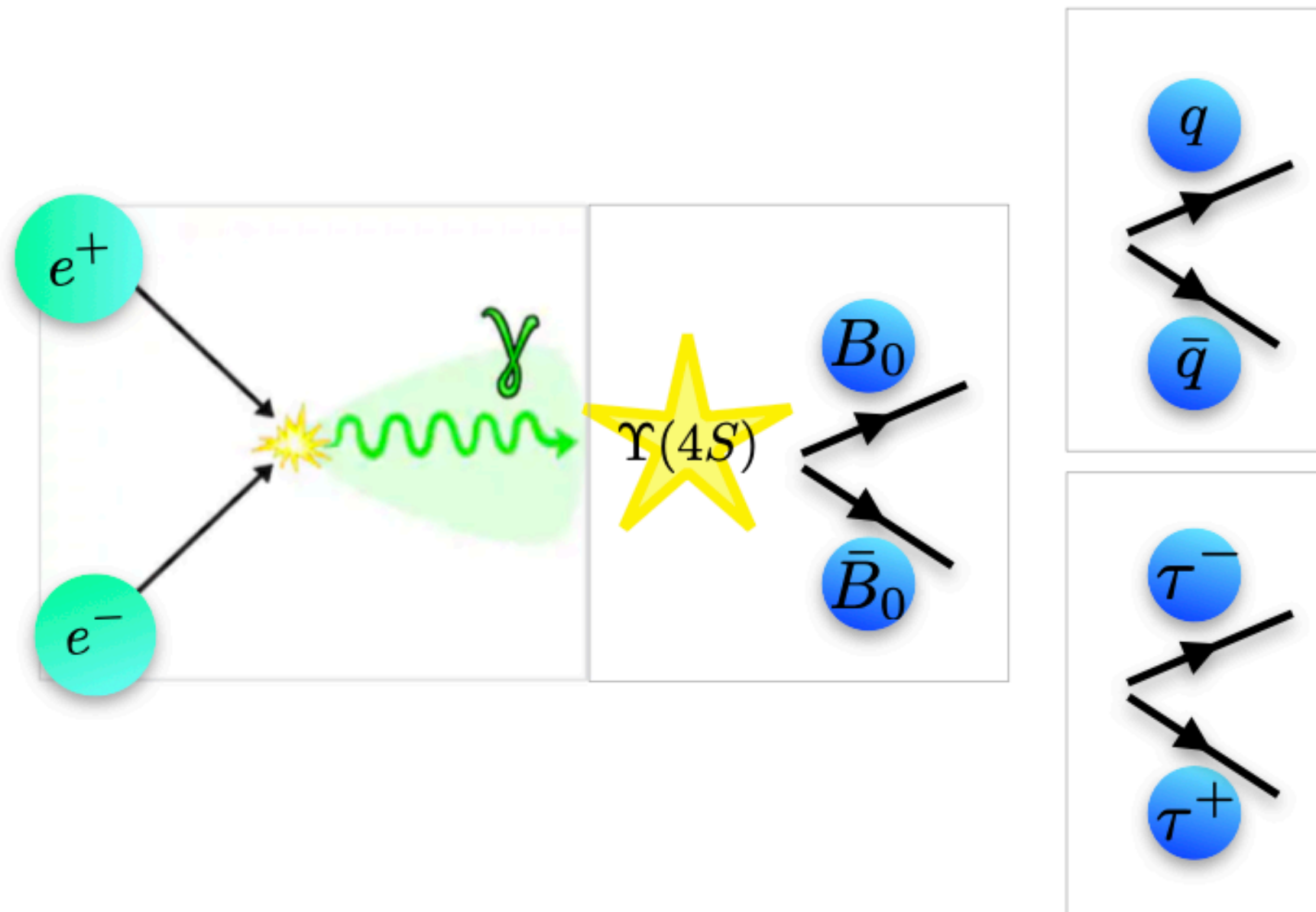
$$\sigma(e^+e^- \rightarrow q\bar{q}) = 3.69 \text{ [nb]}$$

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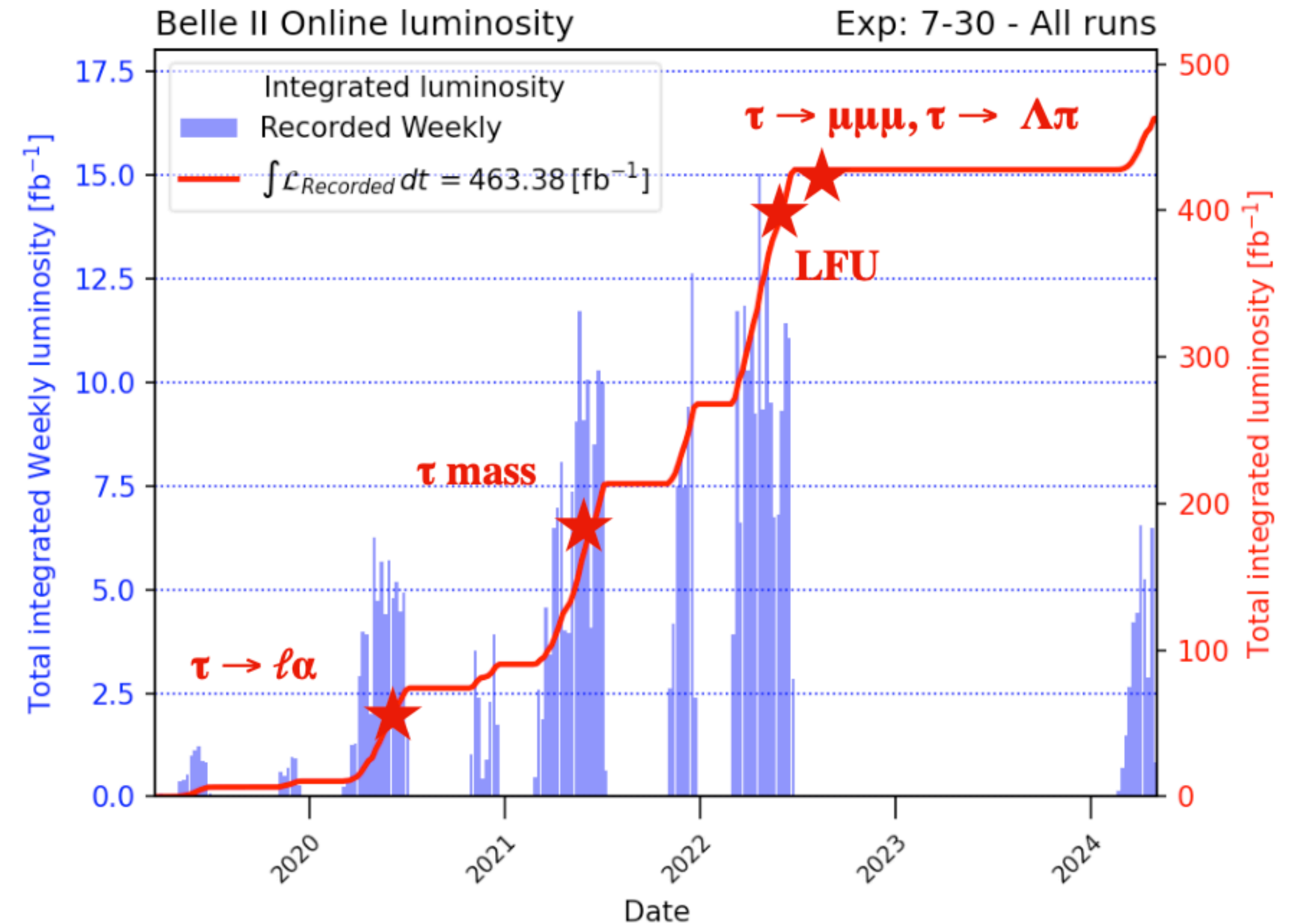
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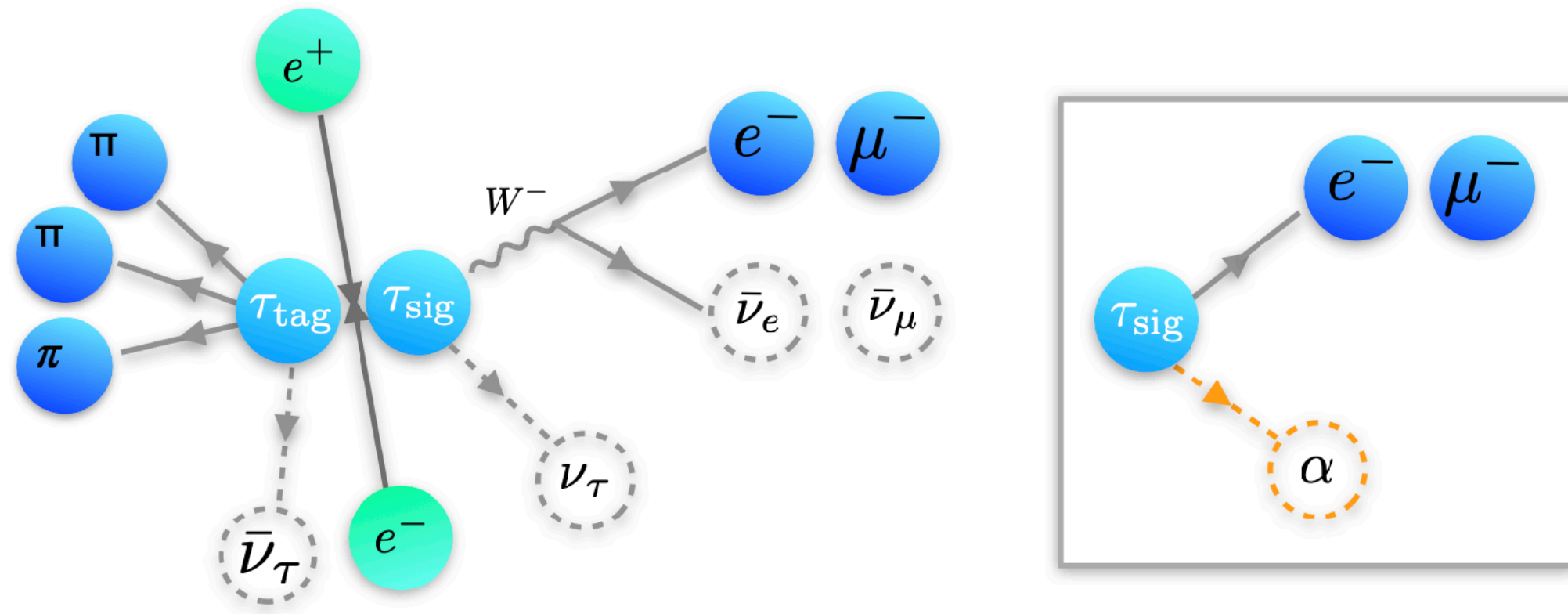


The harvest is just beginning...

Physics Example: Exotic τ Decays

Decay into Lepton and new Boson

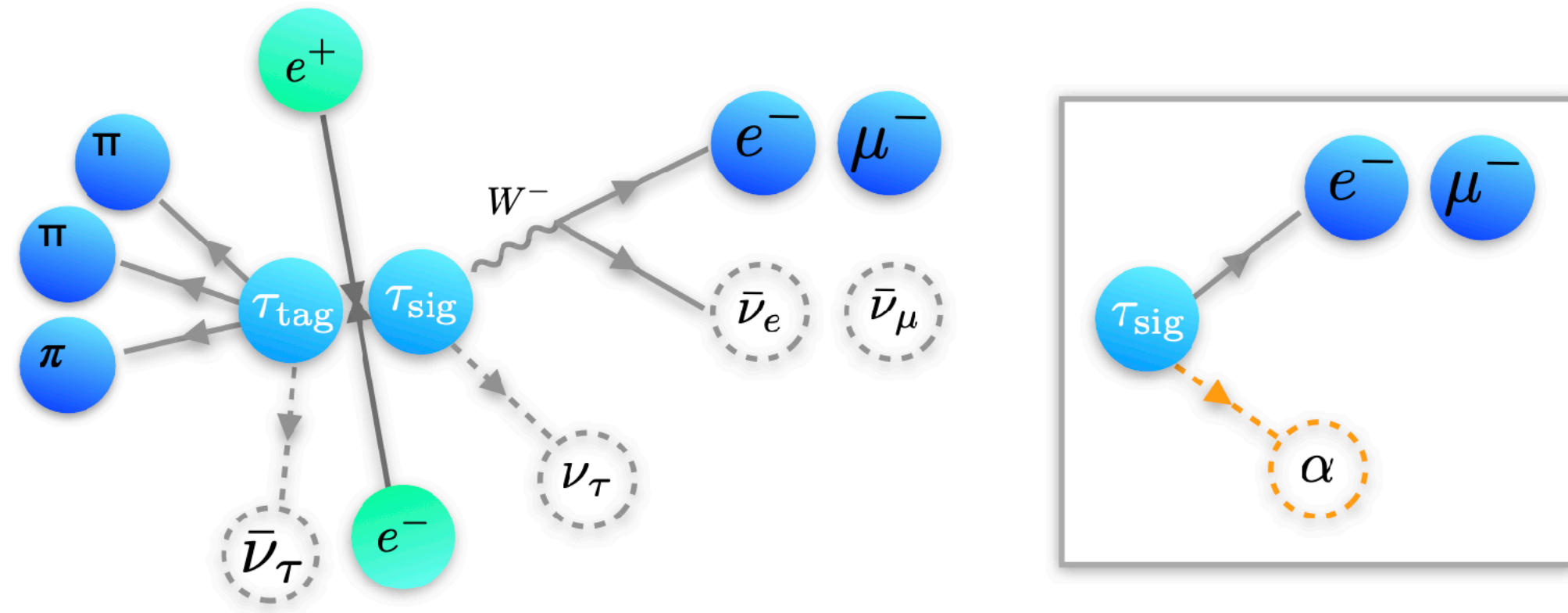
- LFV decay into invisible massive boson, such as ALP



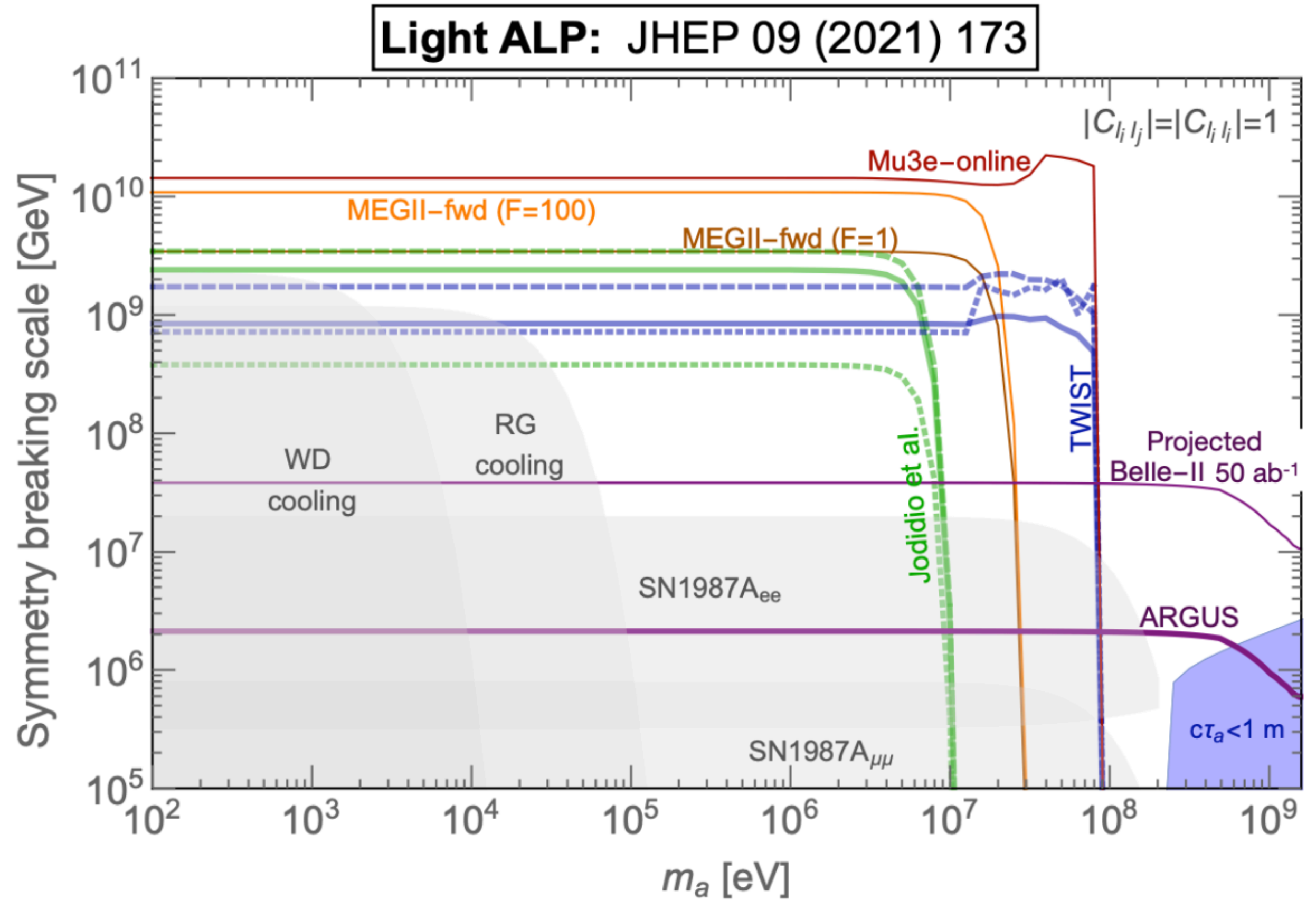
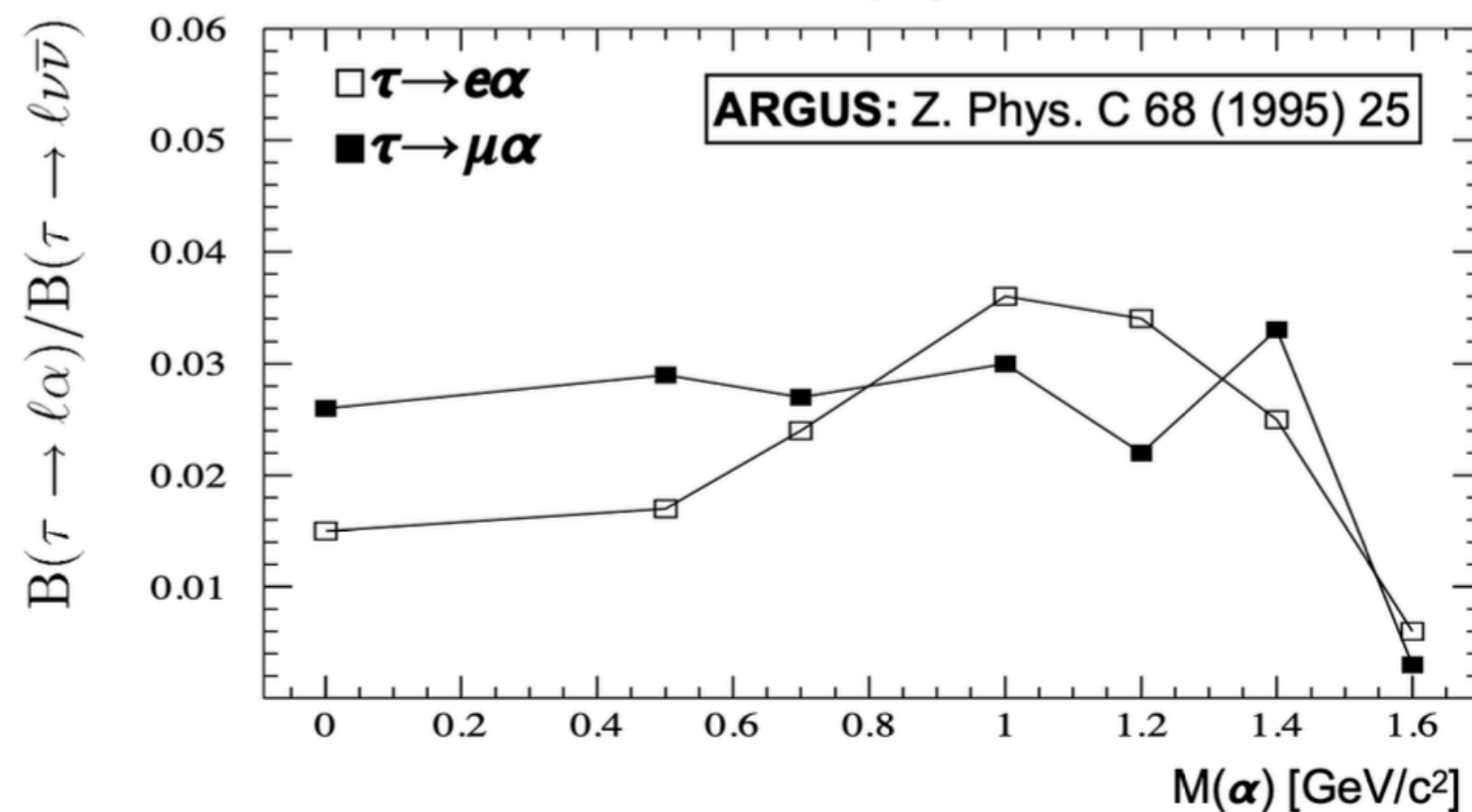
Physics Example: Exotic τ Decays

Decay into Lepton and new Boson

- LFV decay into invisible massive boson, such as ALP



Previous best limit from ARGUS:

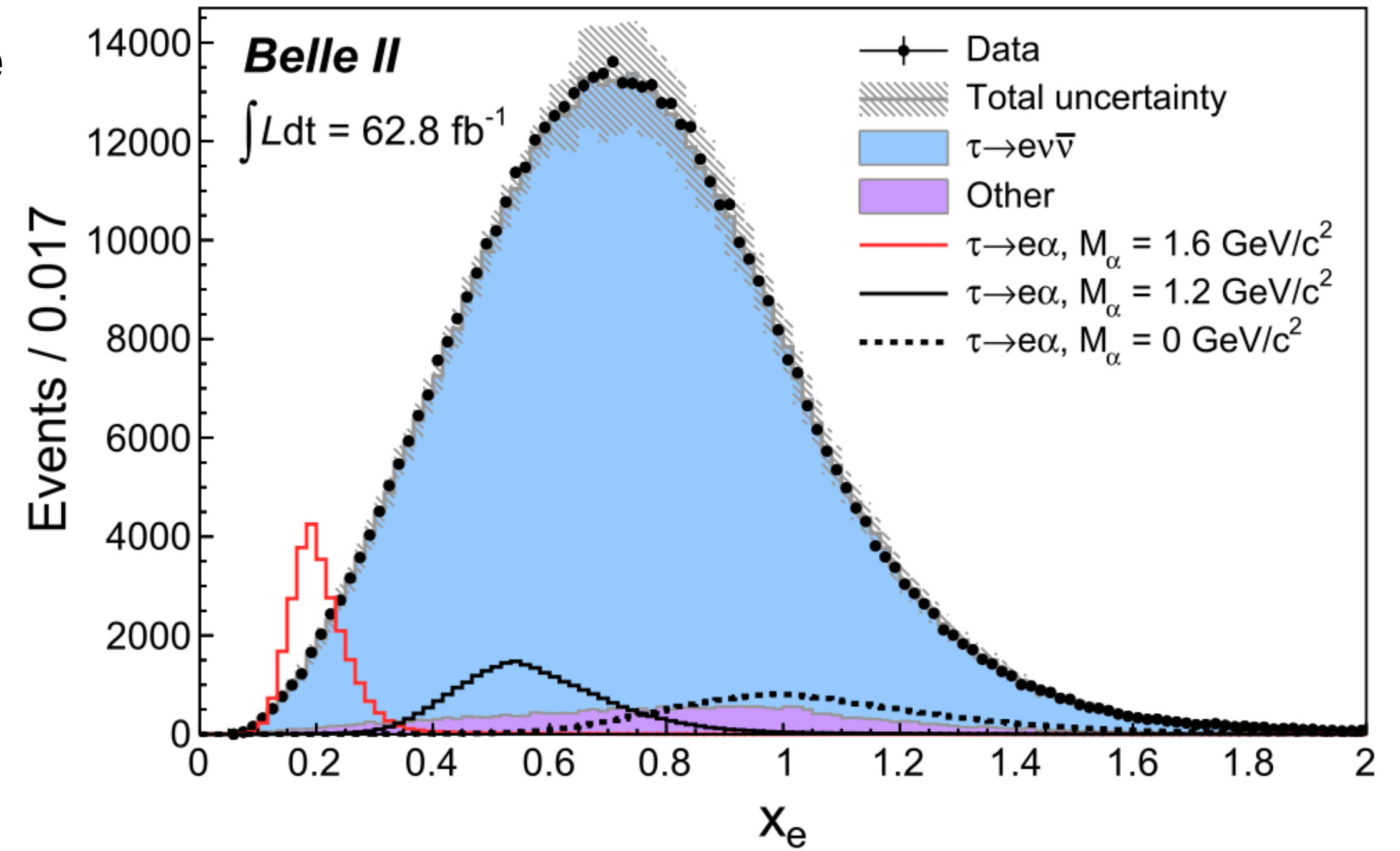
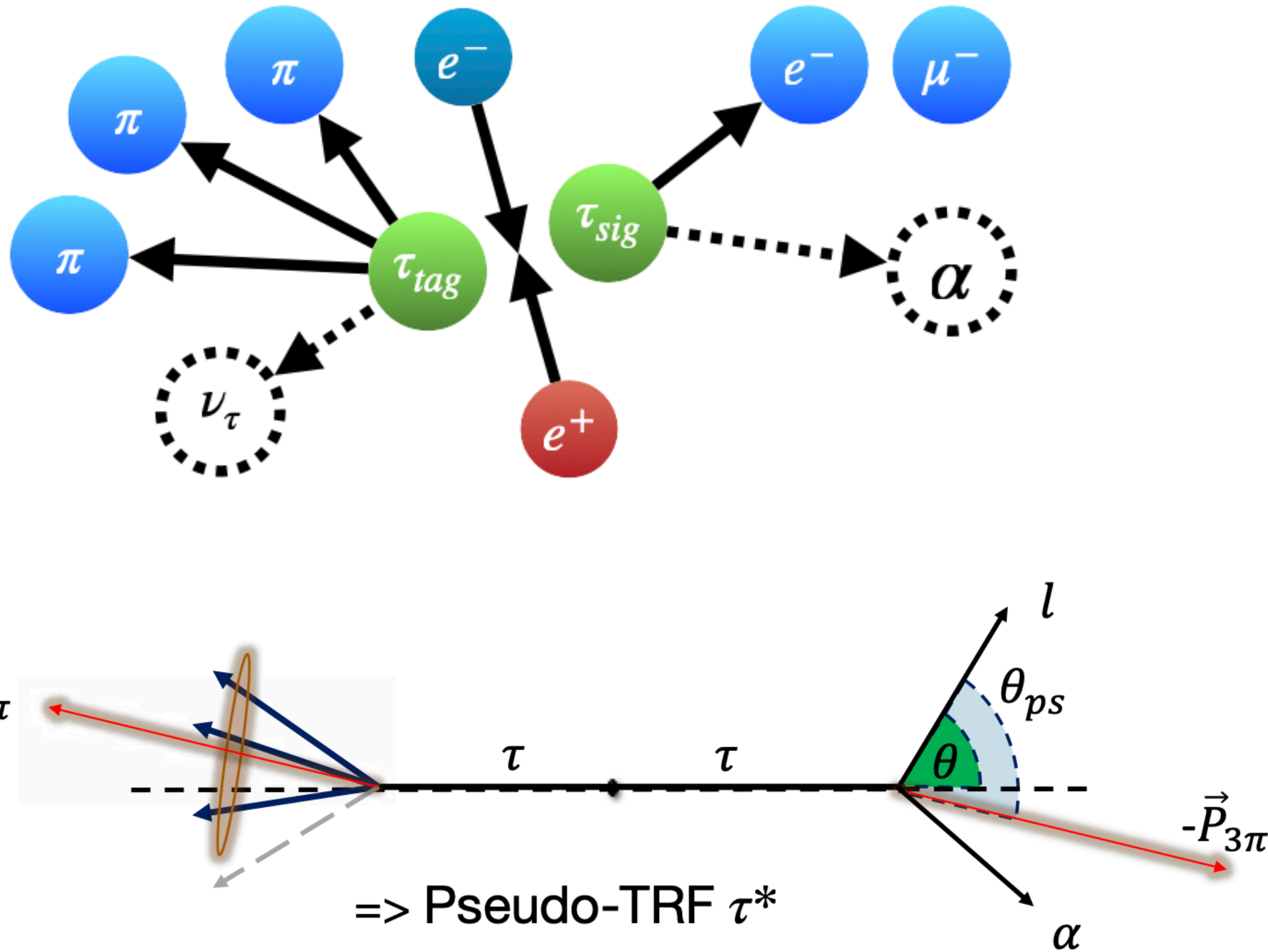


Interesting mass range: ~ 100 MeV - 1.6 GeV

Physics Example: Exotic τ Decays

Decay into Lepton and new Boson - New upper Limit

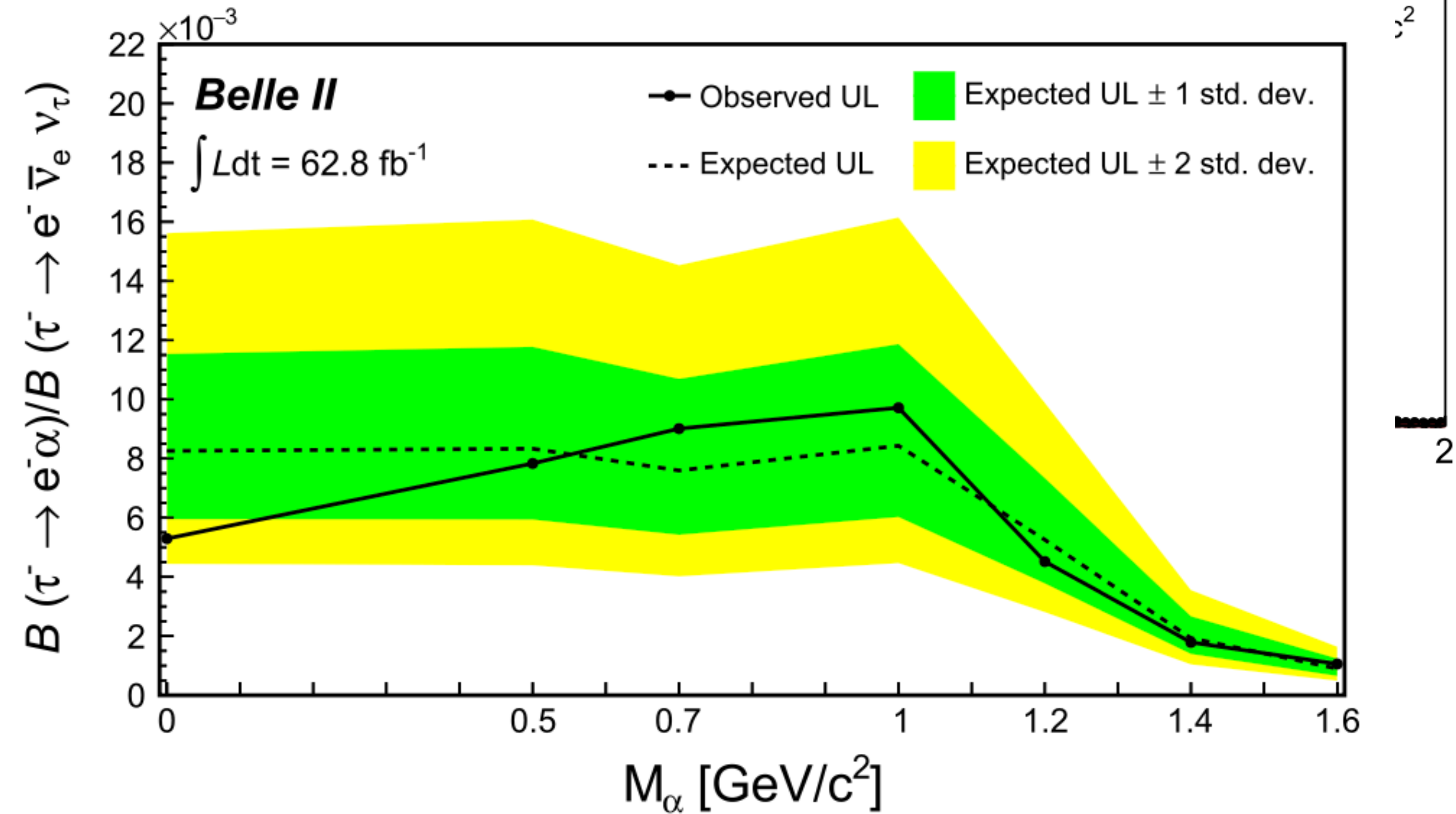
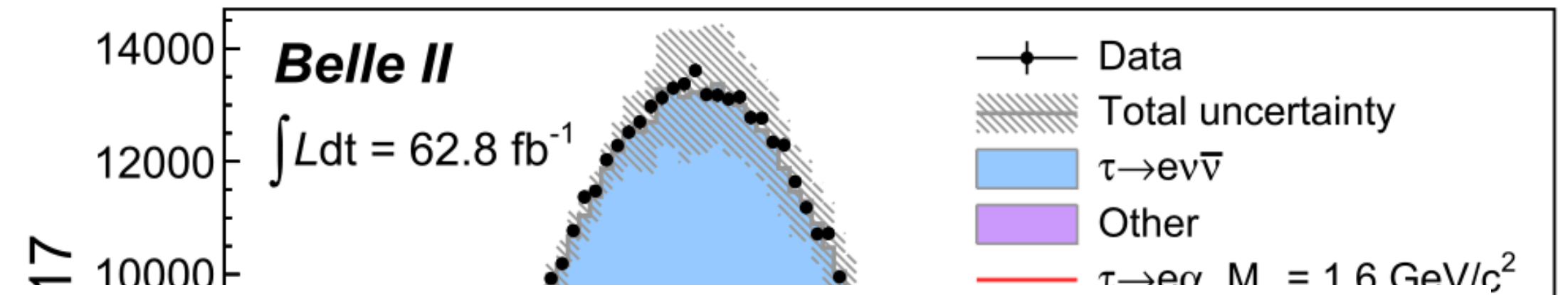
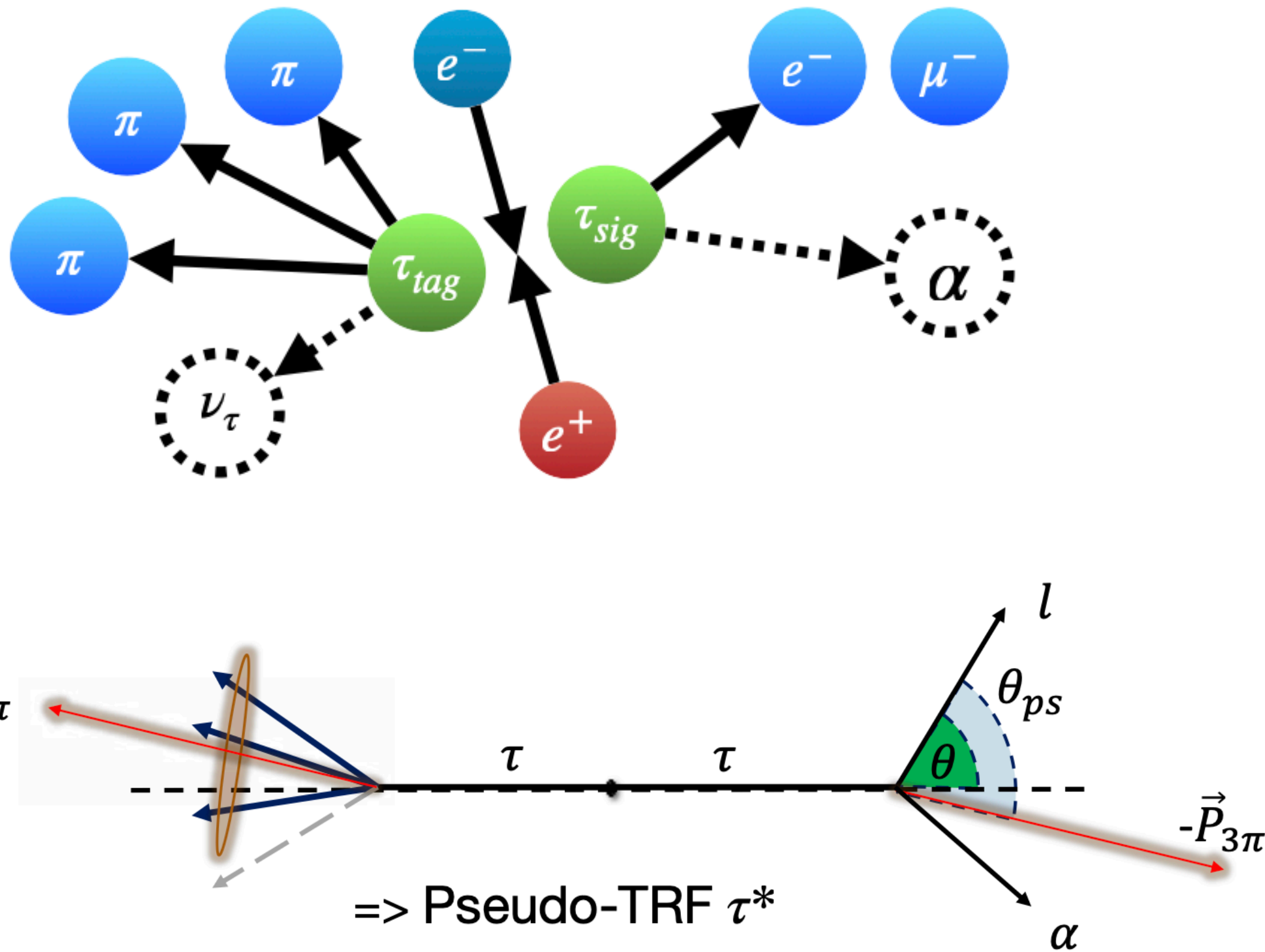
- A two-body decay: Peak in lepton momentum in τ rest frame



Physics Example: Exotic τ Decays

Decay into Lepton and new Boson - New upper Limit

- A two-body decay: Peak in lepton momentum in τ rest frame



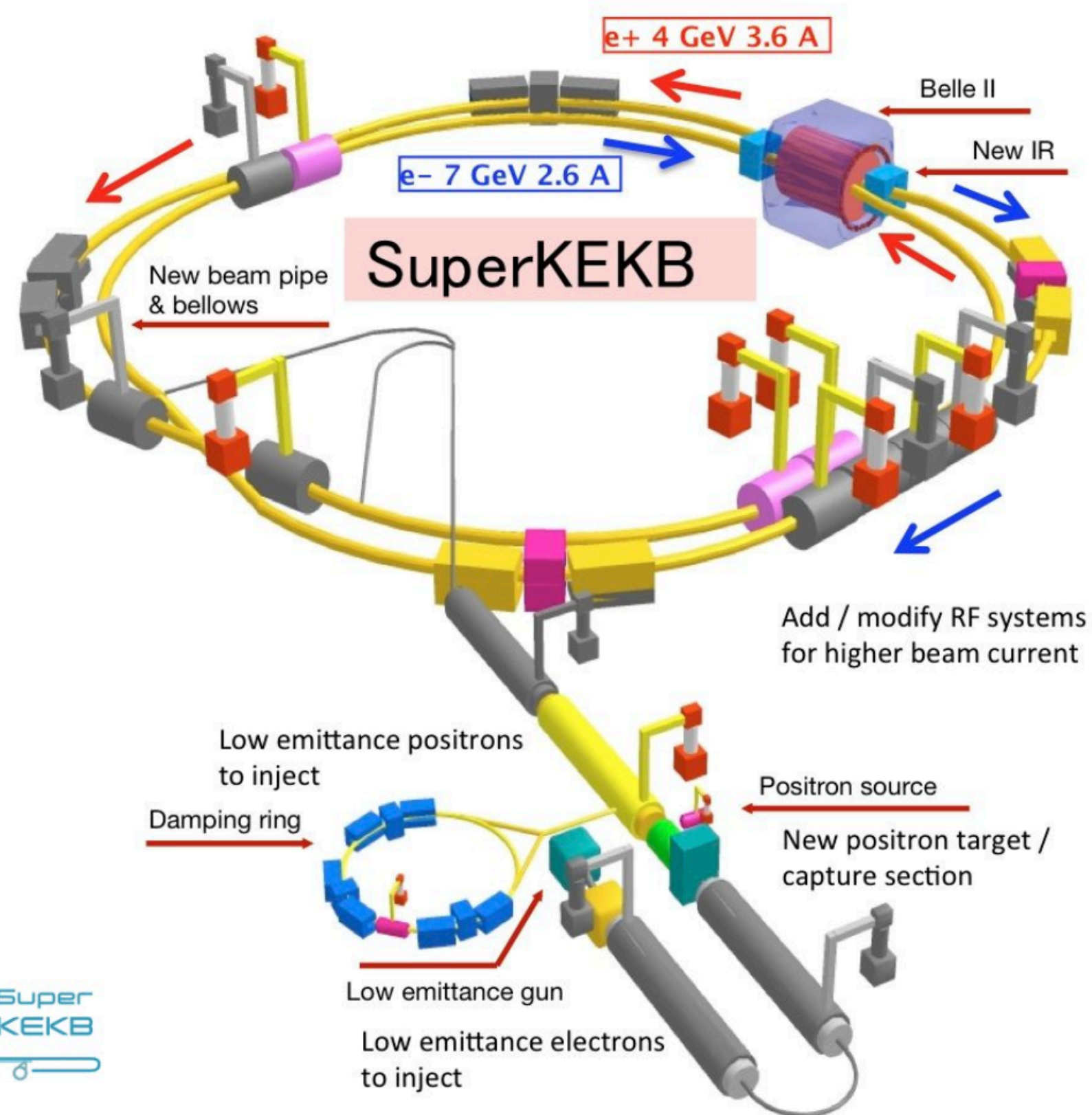
No signal observed - improvement compared to ARGUS up to x 14

Essential Ingredients: The Accelerator

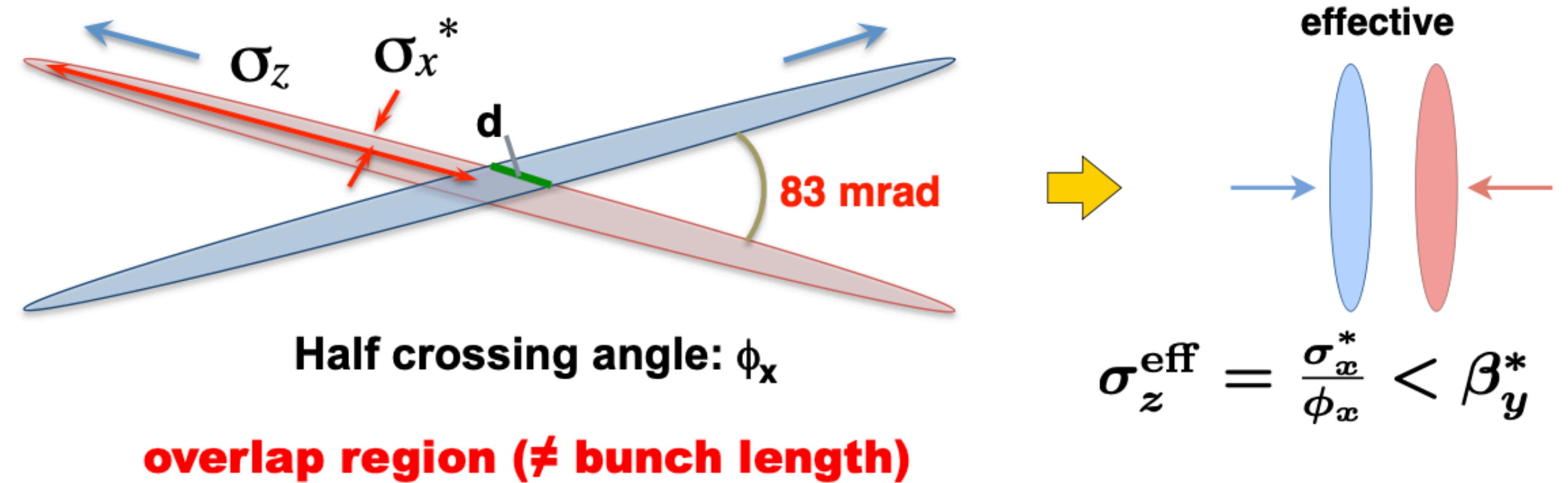
SuperKEKB

$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{R_L}{R_{\xi}} \frac{I_{\pm} \xi_{y\pm}}{\beta_{y\pm}^*}$$

beam current **x1.5** beam-beam param. **x1**
 vertical beta function **x 1/20**



- Nano-Beam: very small beams, minimized longitudinal overlap region. Maximize luminosity.



requires sophisticated final focus systems (QCS).

Target luminosity: $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (HL-LHC: $5 - 7.5 \times 10^{34}$)

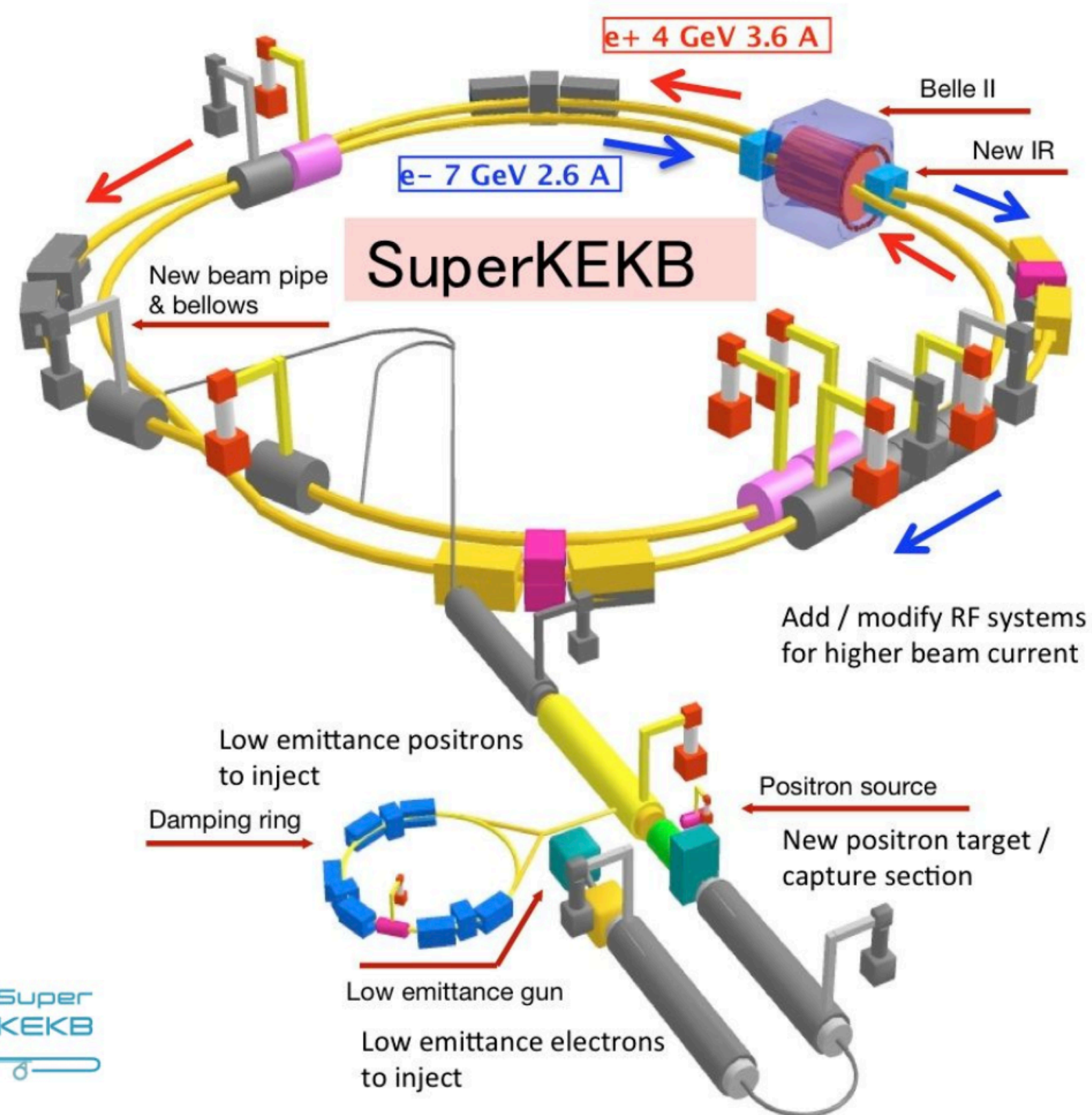


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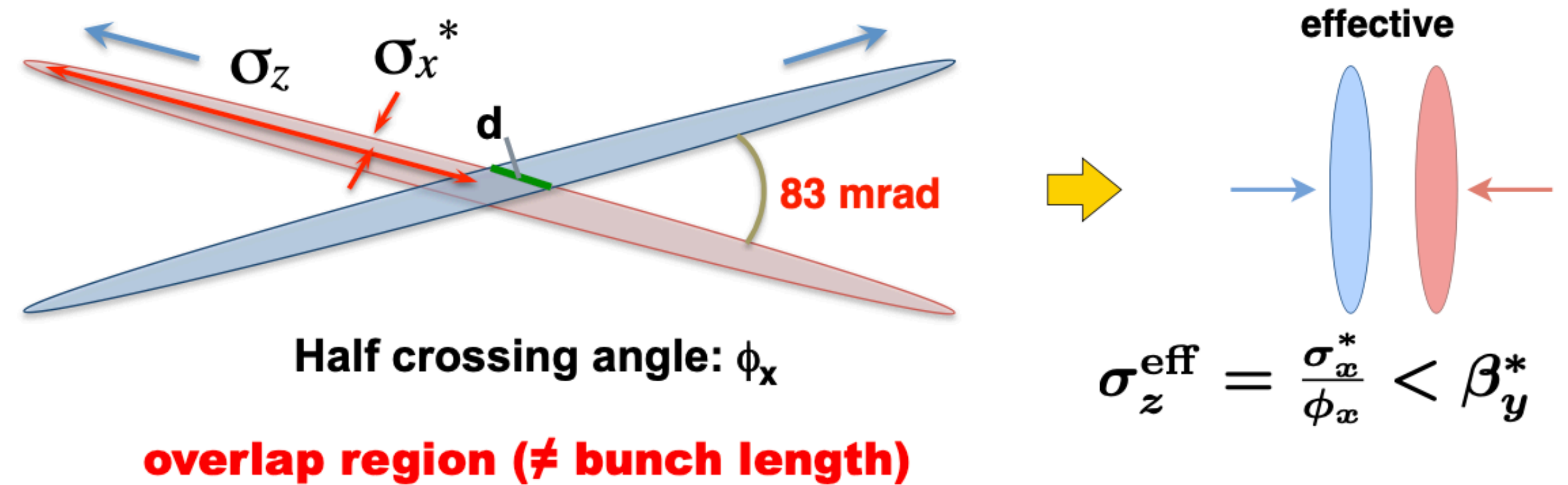
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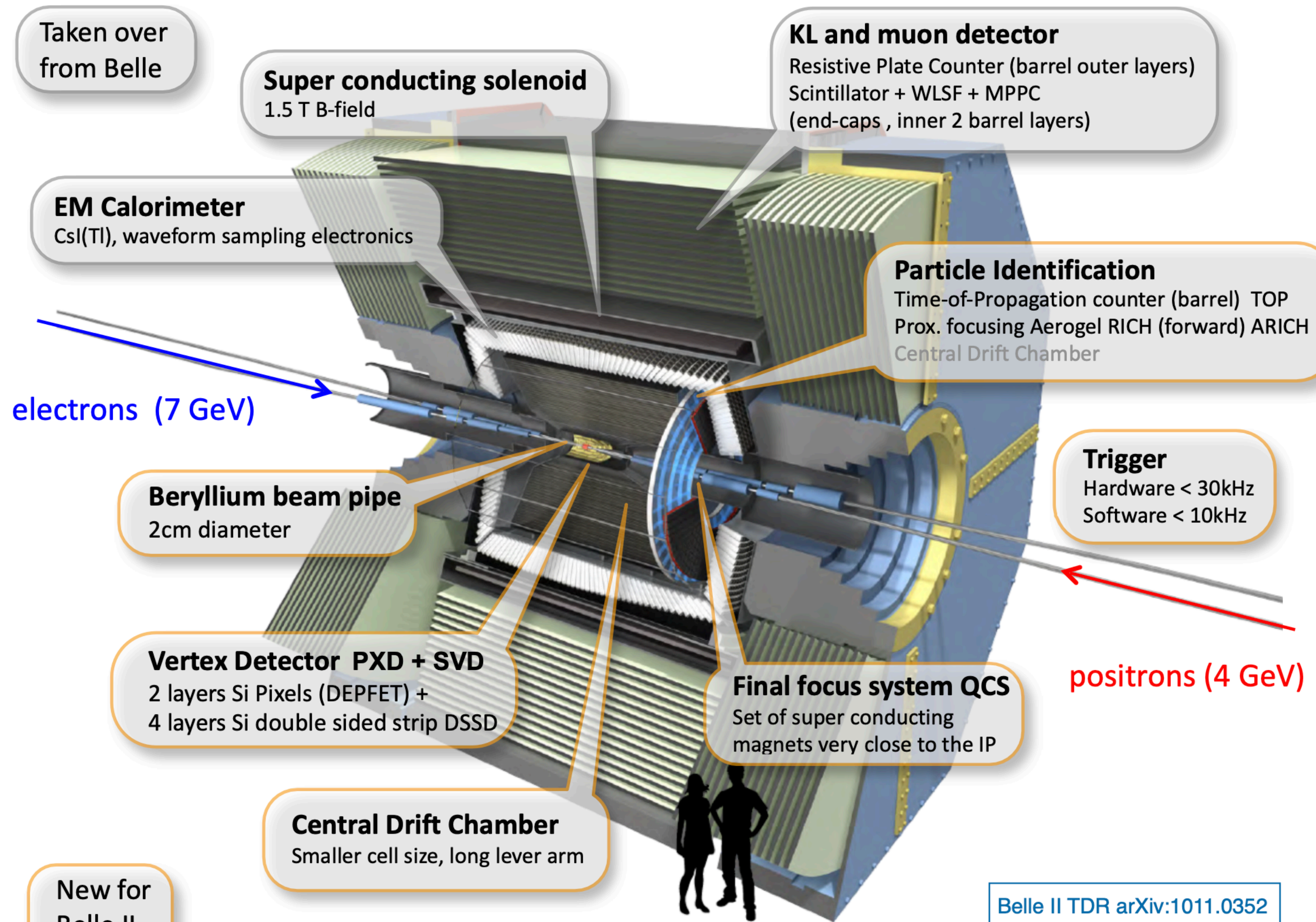
Target luminosity: $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ (HL-LHC: $5 - 7.5 \times 10^{34}$)

- Also: A “test bed” for FCC-ee - aiming at $\sim 2 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ at the Z pole (91 GeV)



Essential Ingredients: The Detector

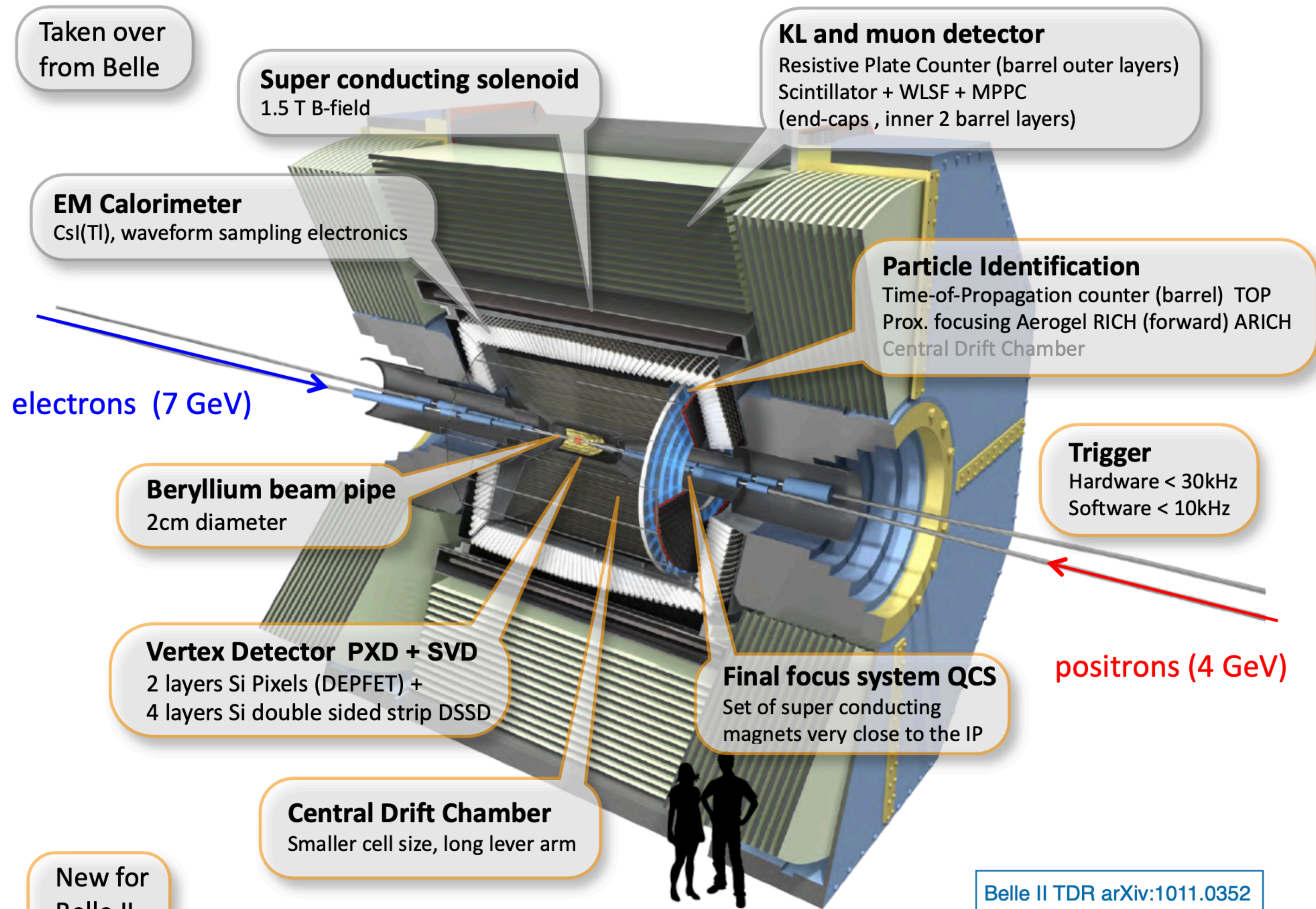
The Belle II Detector



- Key capabilities:
 - nearly hermetic.
 - excellent tracking (momentum measurement), particle identification, photon reconstruction.
 - Precise reconstruction of vertices.
 - Similar performance for electrons and muons.

Essential Ingredients: The Detector

The Belle II Detector

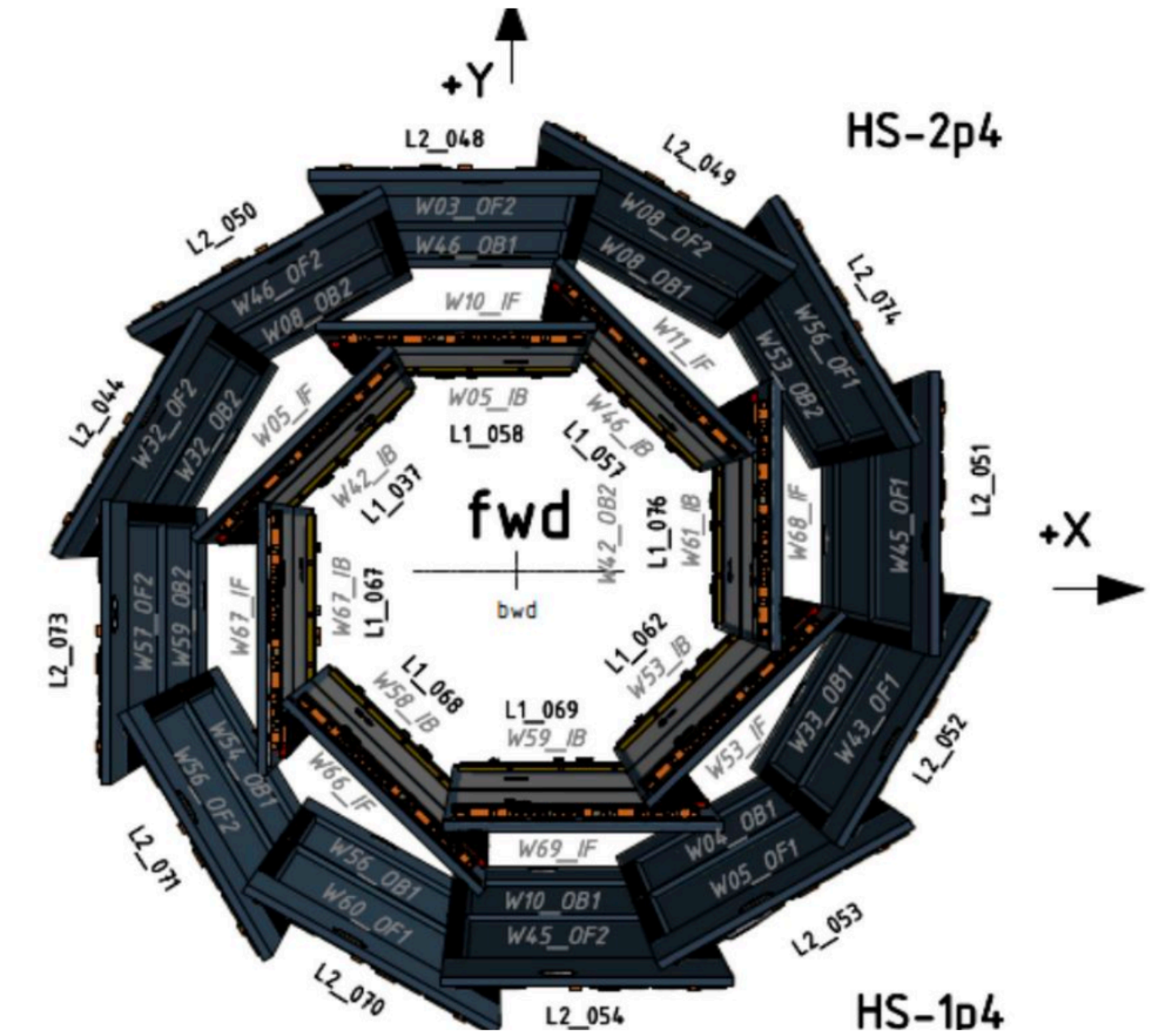
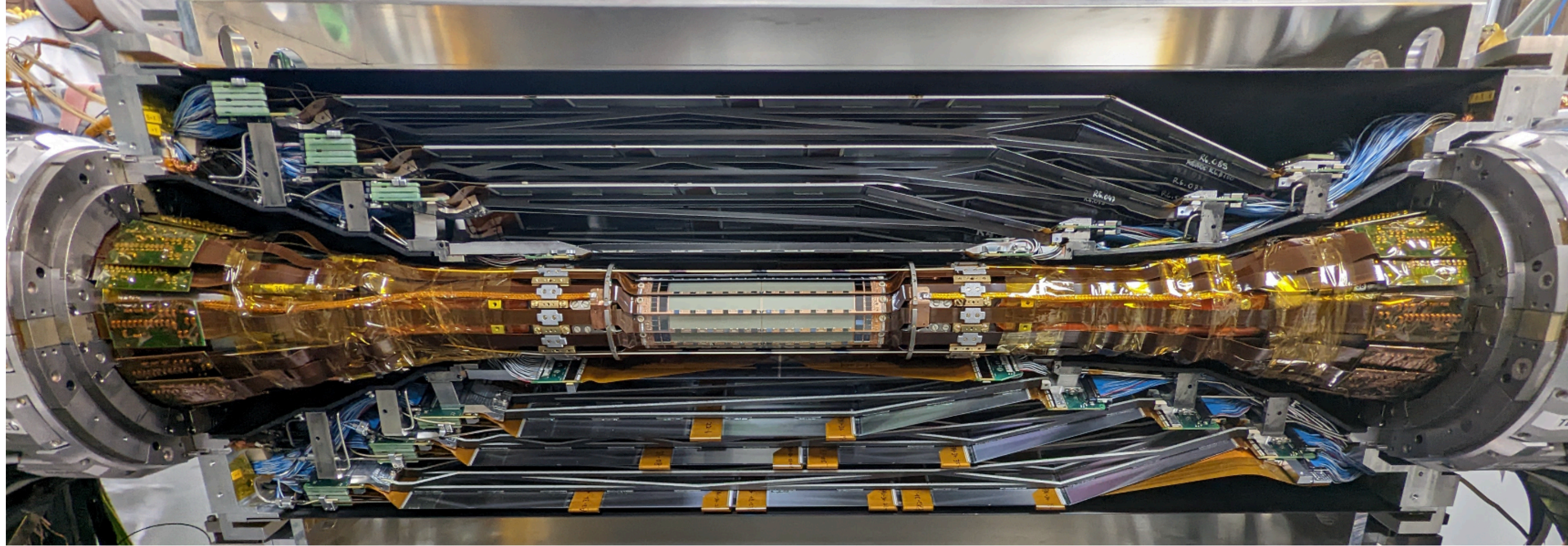


- Key capabilities:
 - nearly hermetic.
 - excellent tracking (momentum measurement), particle identification, photon reconstruction.
 - Precise reconstruction of vertices.
 - Similar performance for electrons and muons.
- In “clean” e^+e^- environment: Enables
 - measurement of decay time differences
 - decays with missing energy
 - decays with π^0 , other neutrals
 - inclusive measurements
 - ...

The PXD - The inner Vertex Detector

A technological Highlight

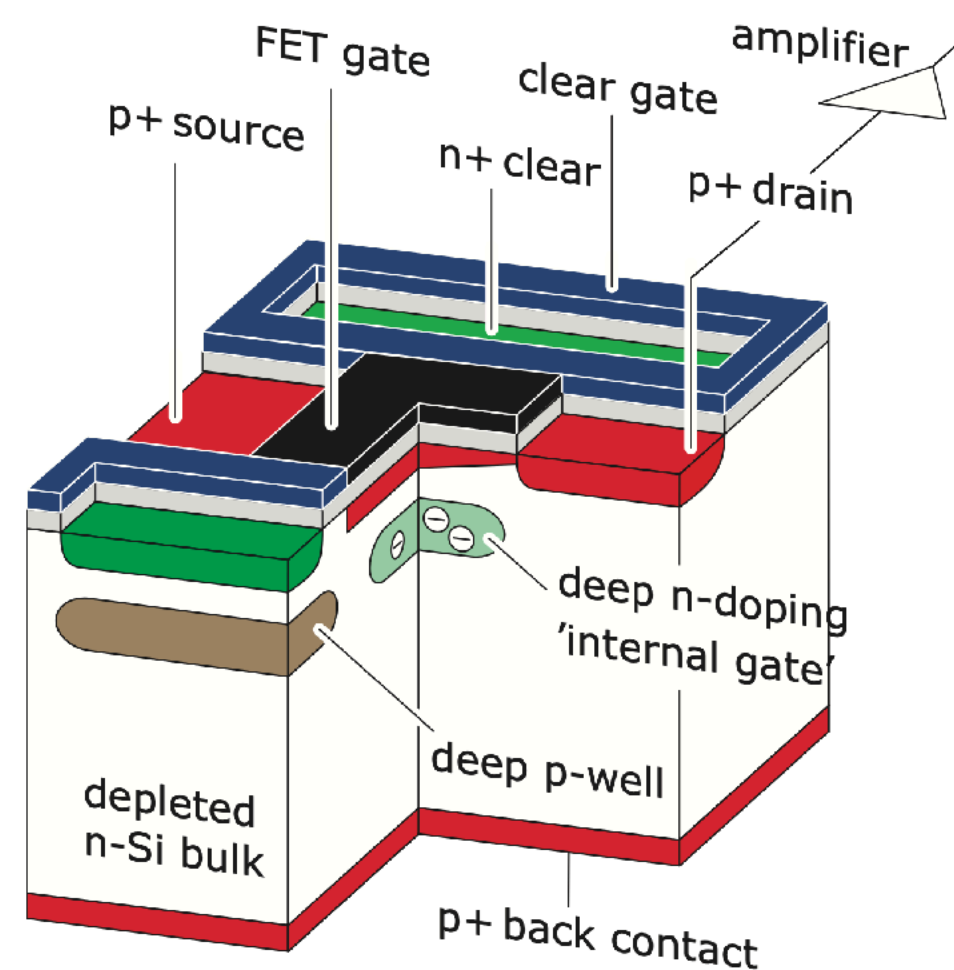
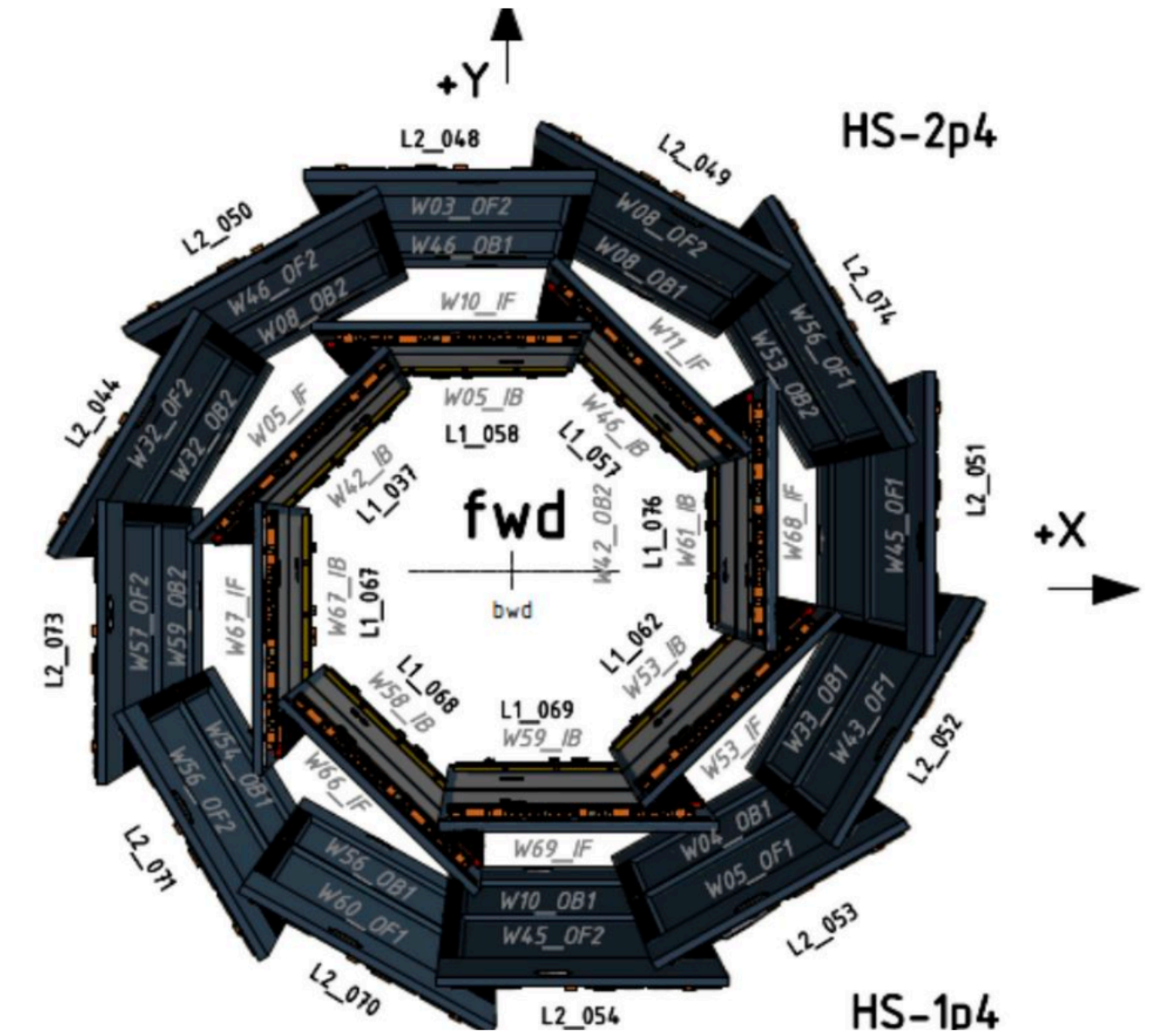
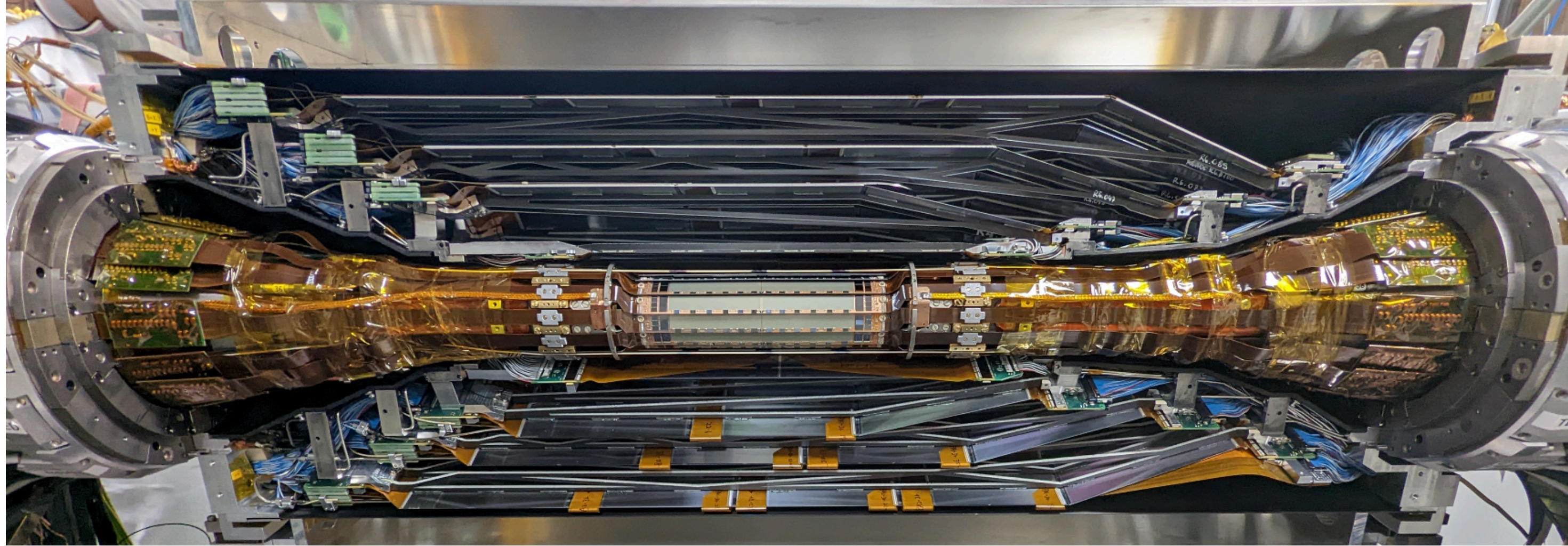
- Provides precise reconstruction of decay vertices, incl. displaced vertices



The PXD - The inner Vertex Detector

A technological Highlight

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DEPFET Technology - MPG HLL

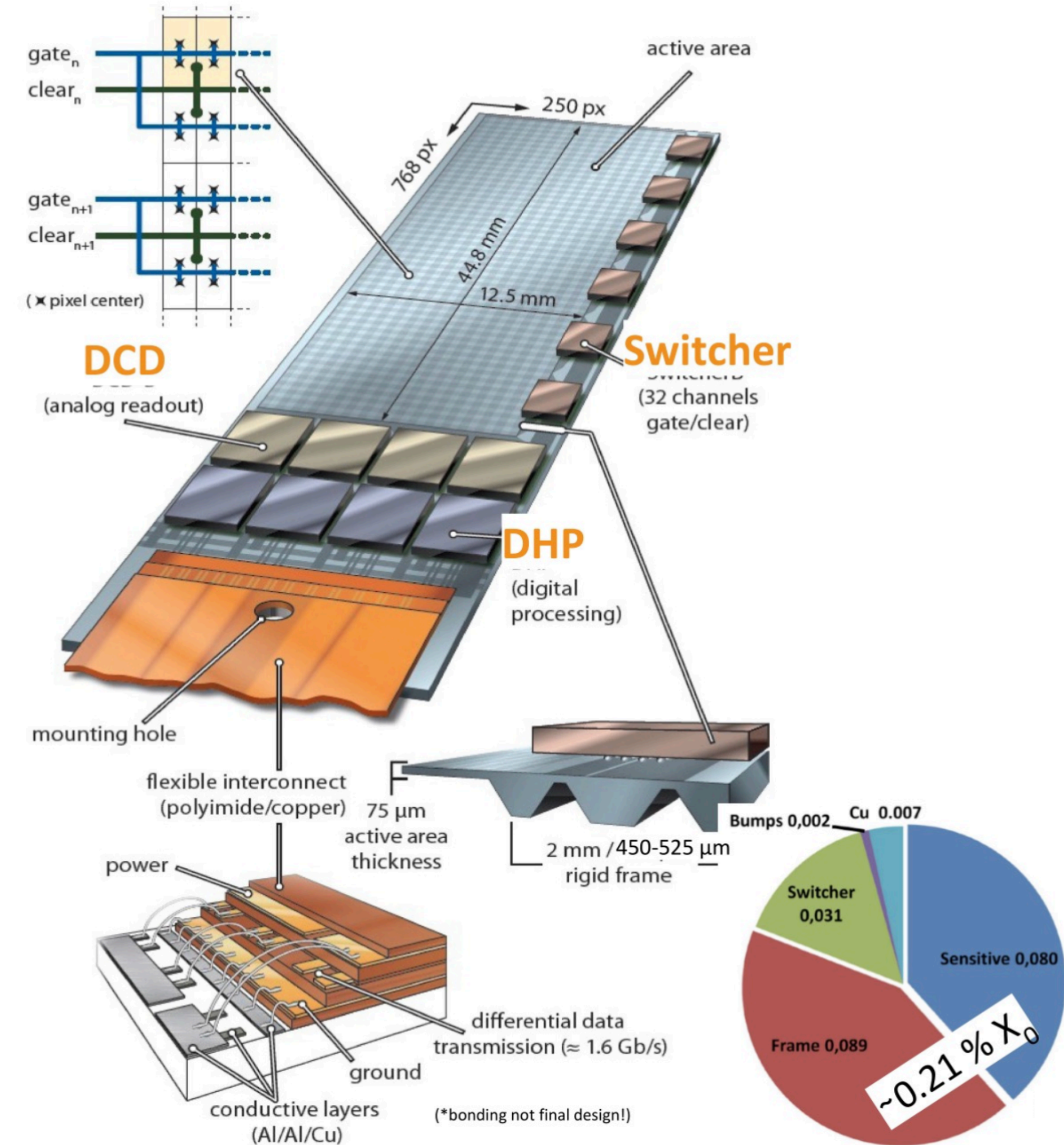
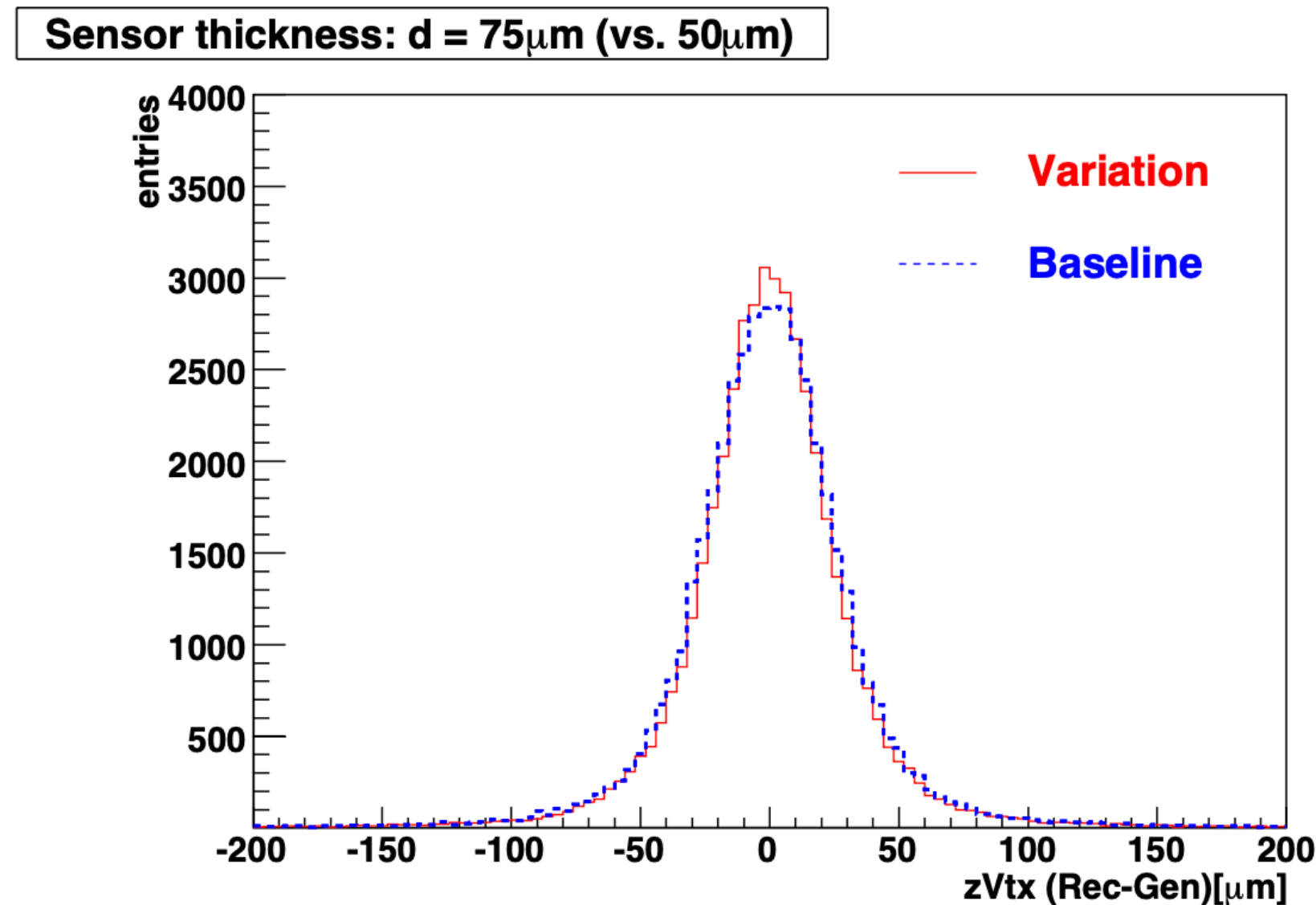
The right technology at the right time:

- High signal-to-noise also for thinned detectors
- Fast readout, amplitude information

The PXD: From Idea to System

The Run 1 Detector

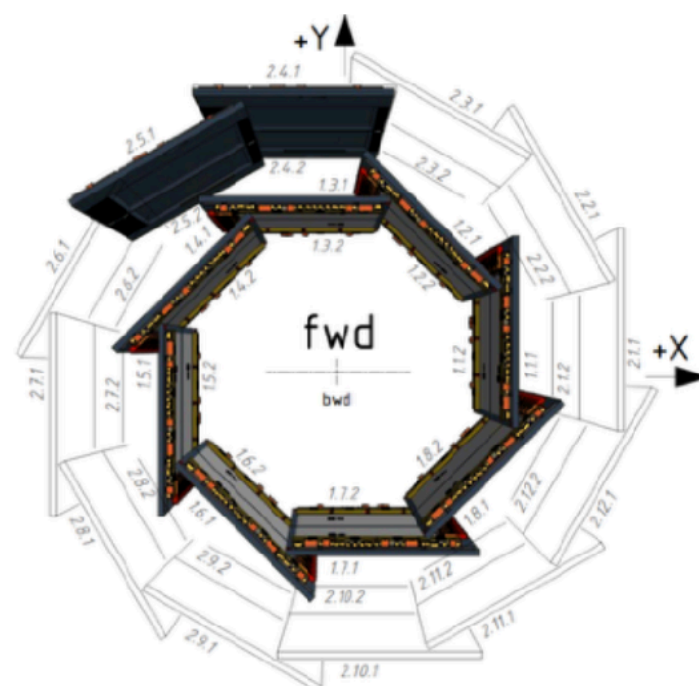
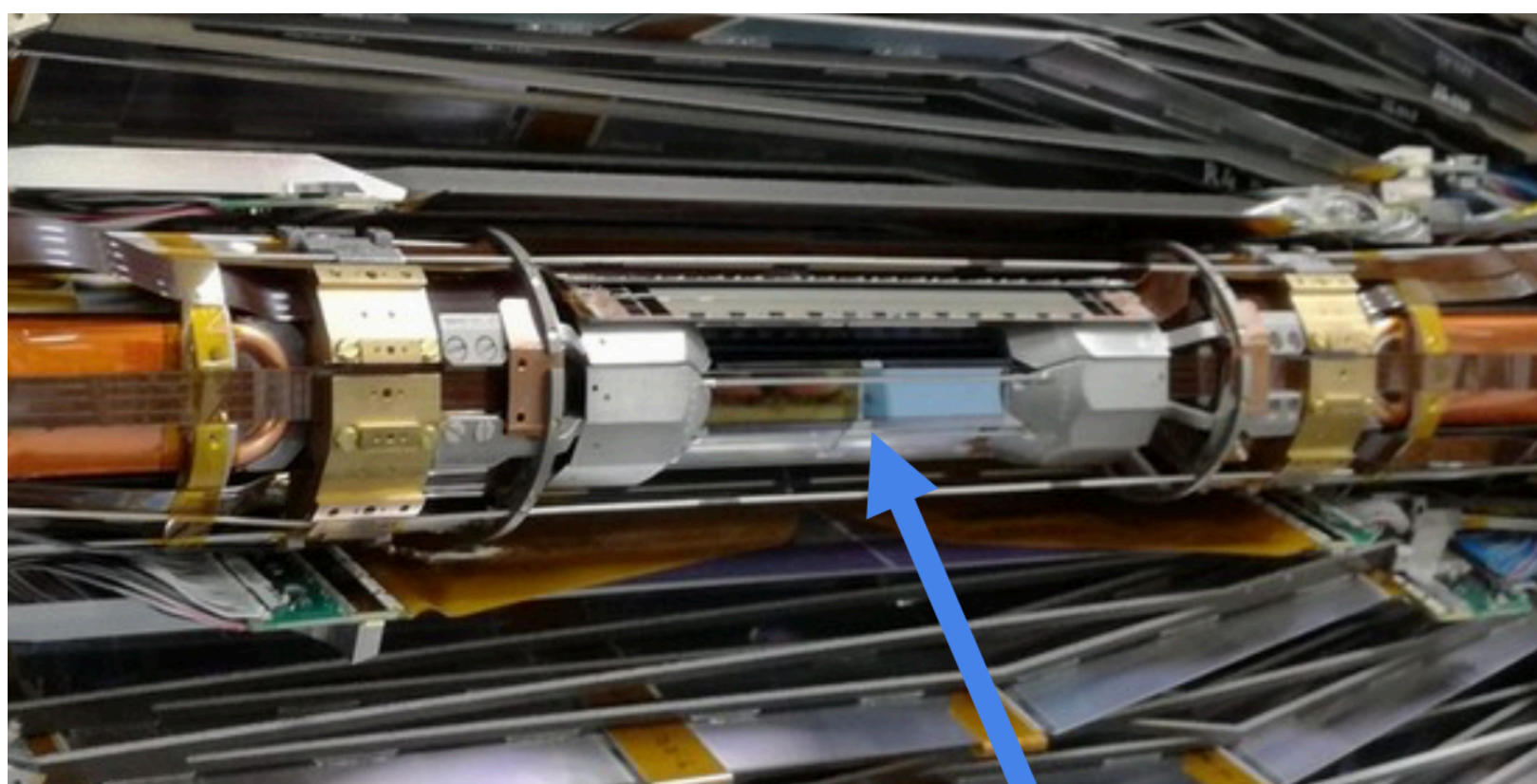
- A detailed optimisation process: Sensor thickness, pixel size “sweet spot” 75 μm thickness - thicker than minimum feasible



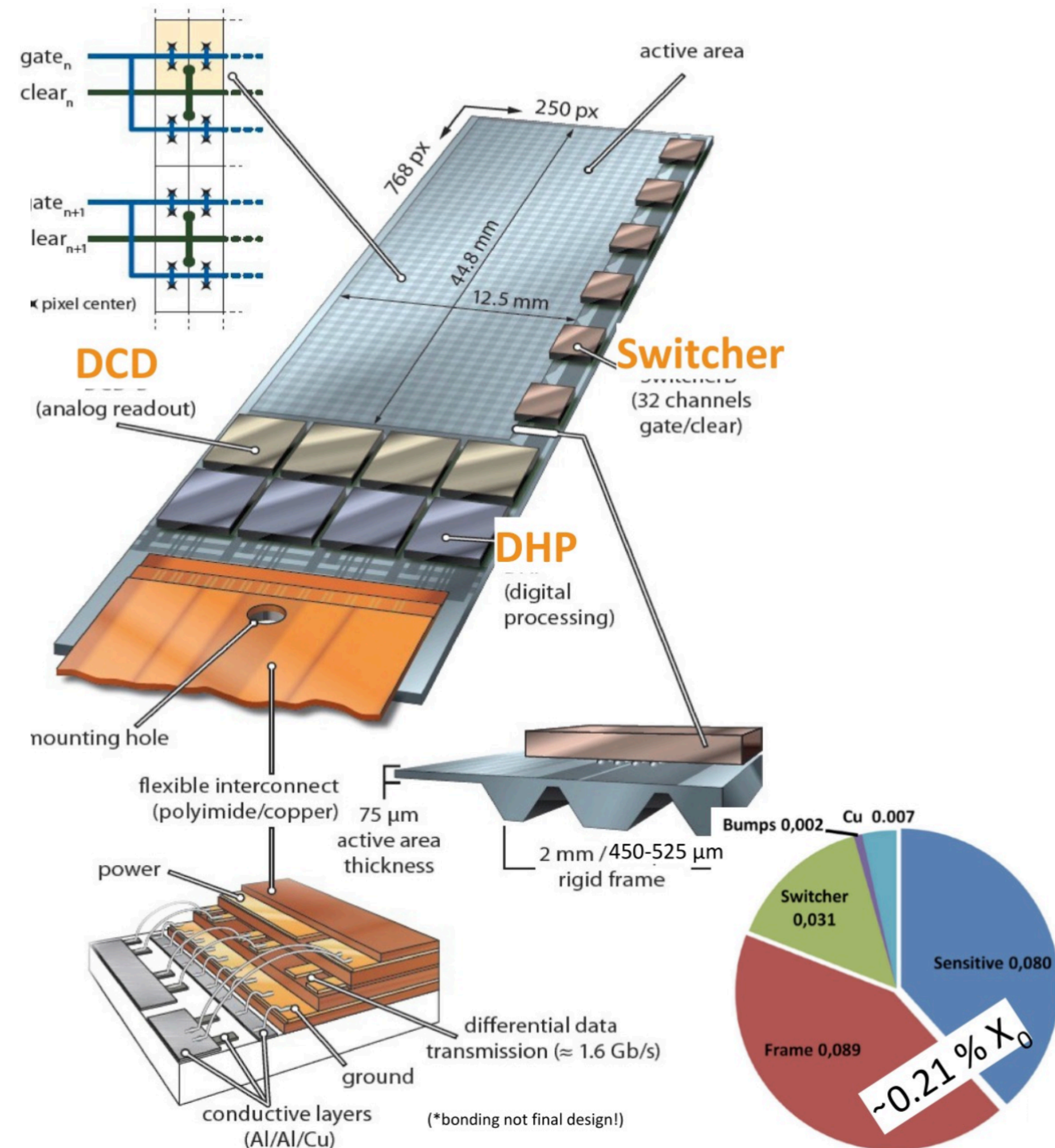
The PXD: From Idea to System

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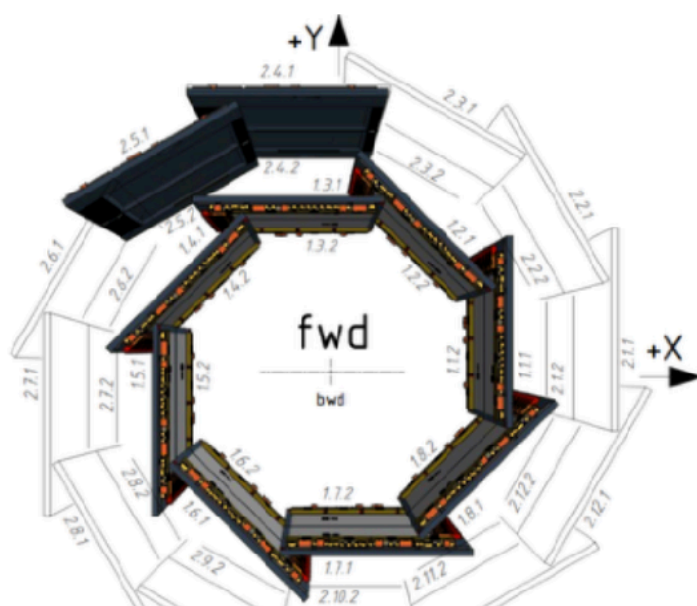
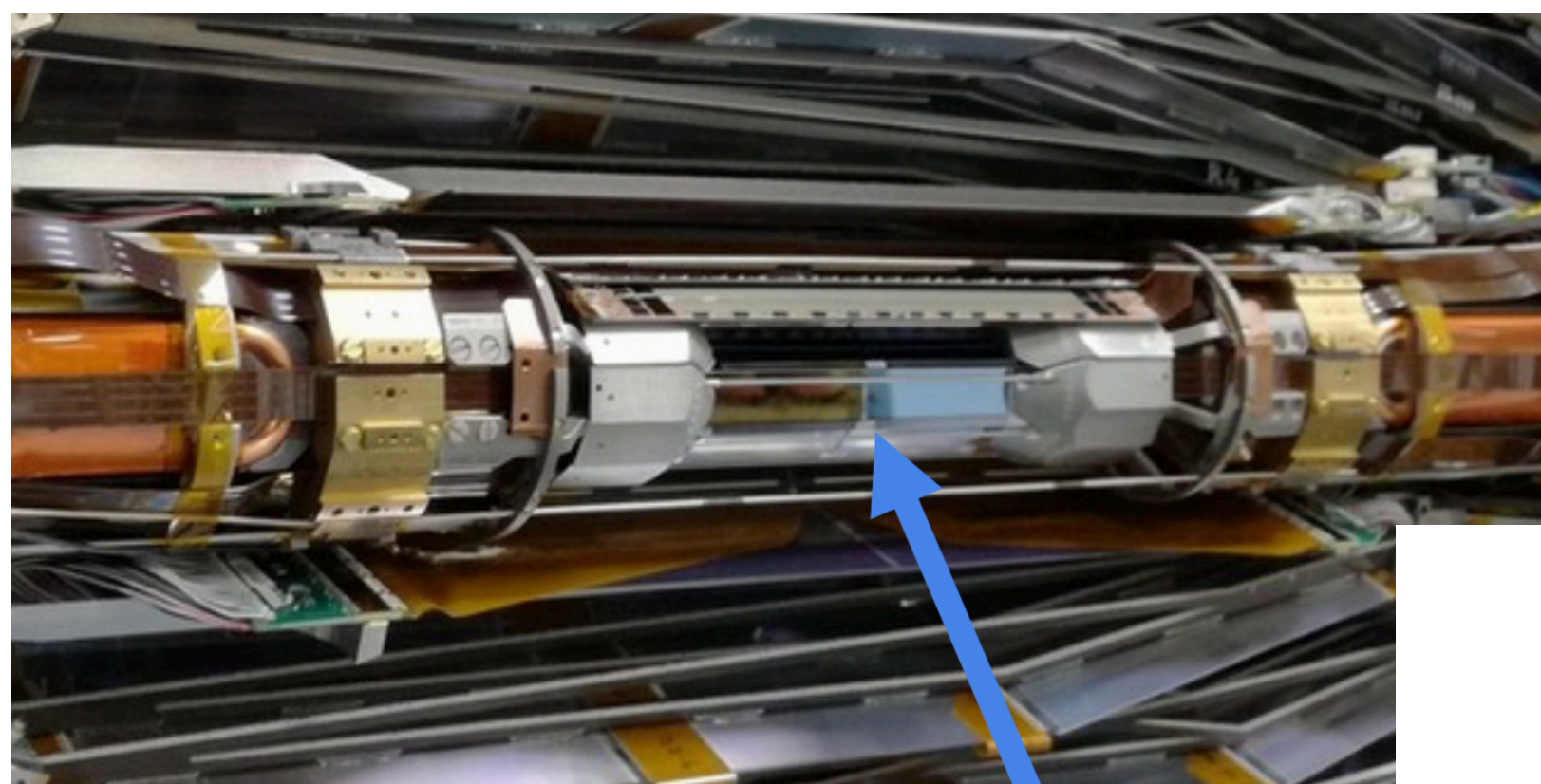
CO₂ cooling in support structure
Detector with incomplete second layer operating 2019-2022



The PXD: From Idea to System

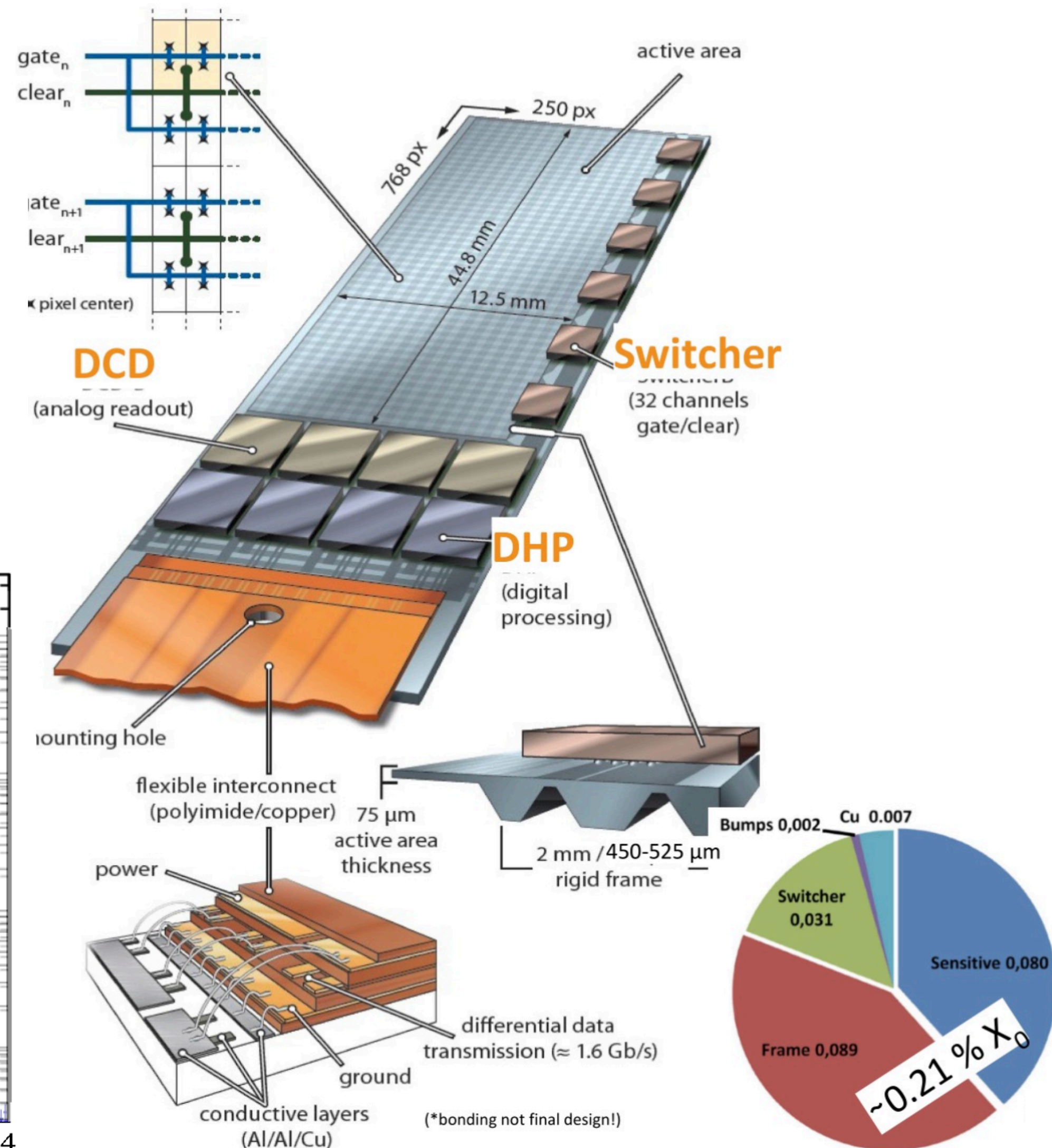
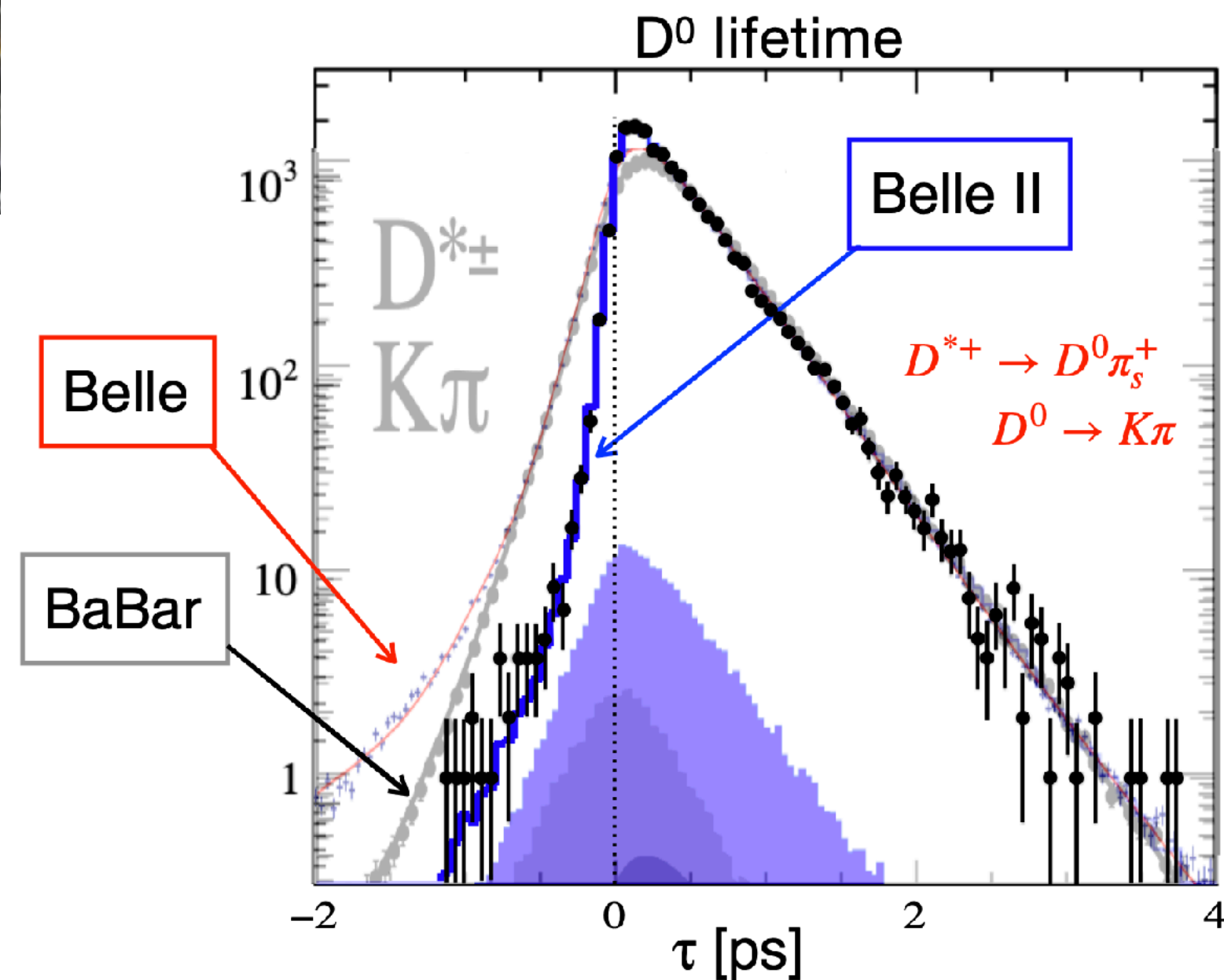
The Run 1 Detector

- A detailed optimisation process: Sensor thickness, pixel size
“sweet spot” 75 μm thickness - thicker than minimum feasible



CO₂ cooling in support structure
Detector with incomplete second layer operating 2019-2022

2 x better vertex res. than Belle
most accurate lifetime measurements: D⁰, D⁺, Λ_c^+ , D_s⁺



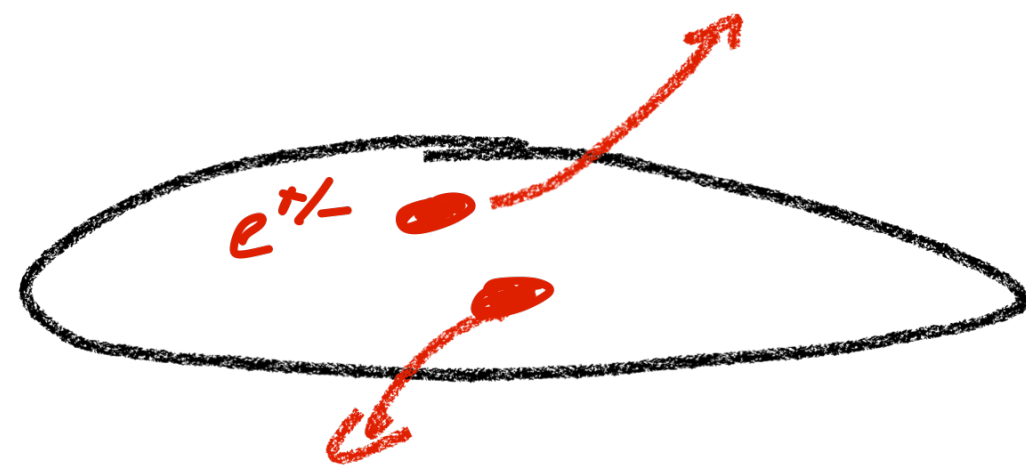
The stony Path to Precision

Delivering the Belle II Physics Program

Beam Backgrounds

The expected

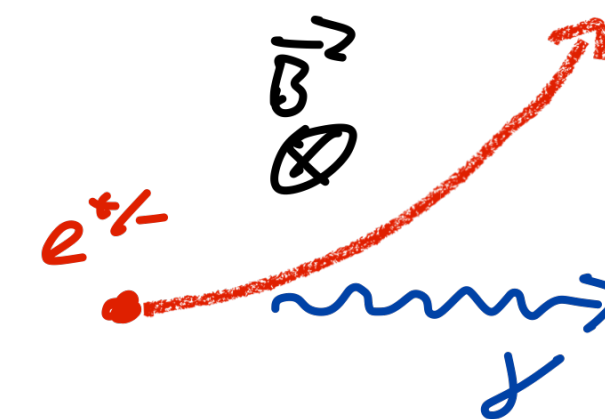
- Backgrounds have (and were expected to have) an important impact on detector performance



Touschek scattering



beam gas scattering



synchrotron radiation

Beam Backgrounds

The expected

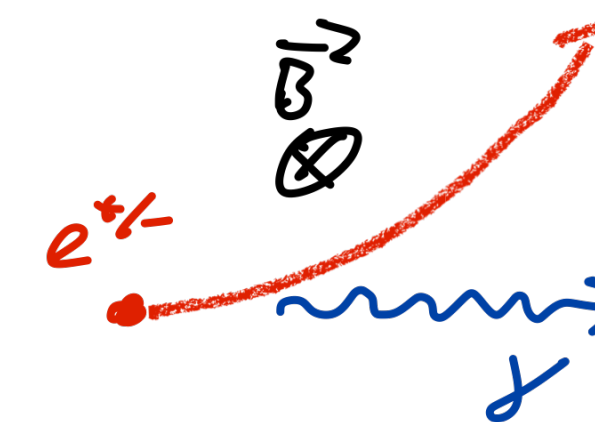
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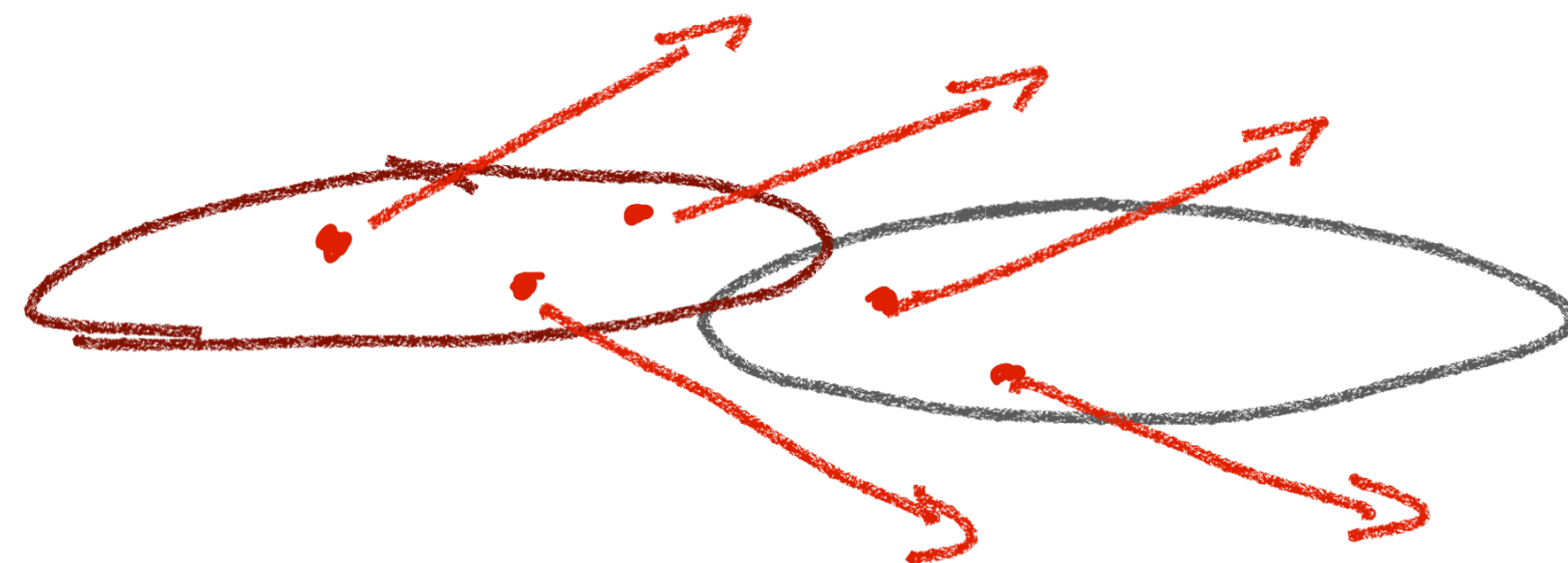


beam gas scattering

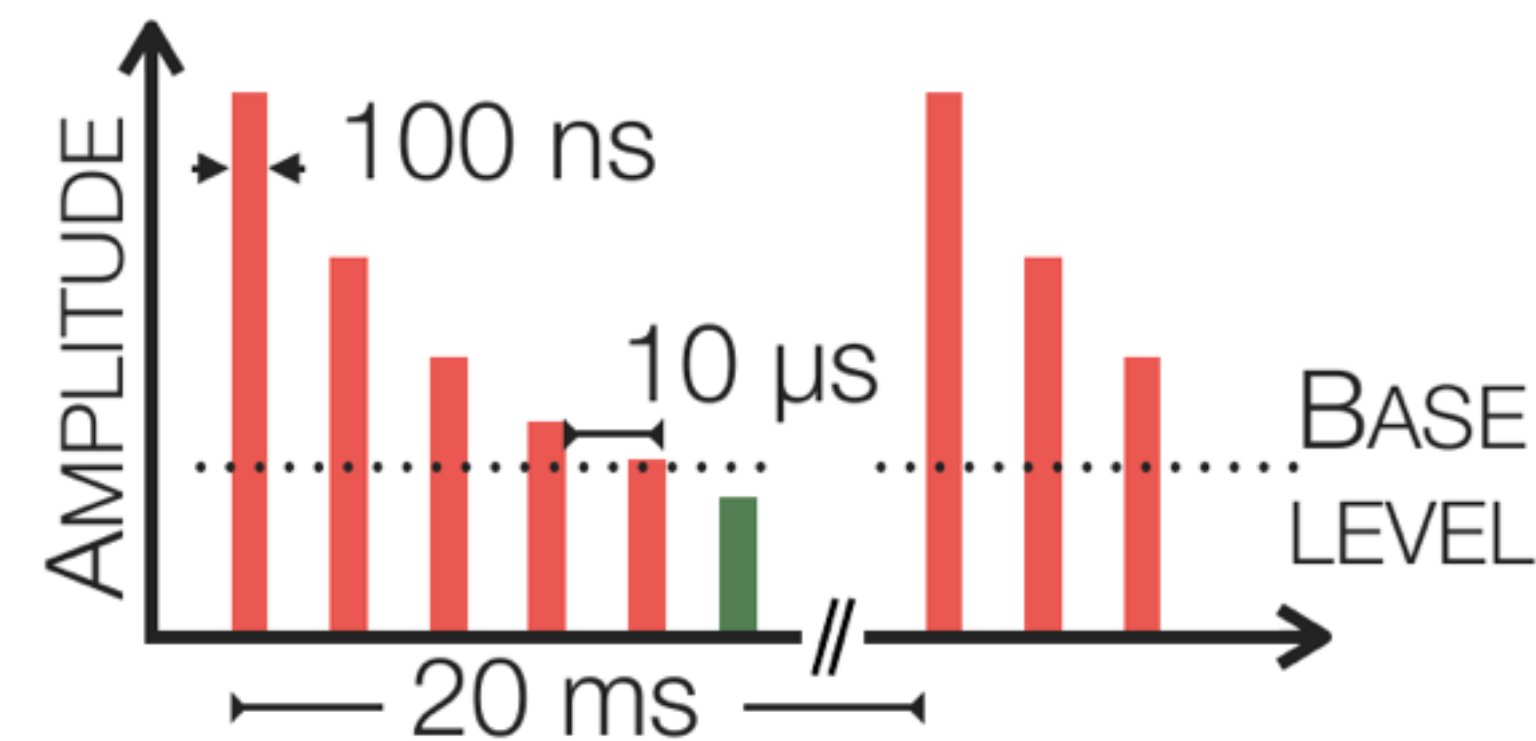


synchrotron radiation

50 Hz continuous injection - a constant background challenge



Injection background



Beam Backgrounds

The expected

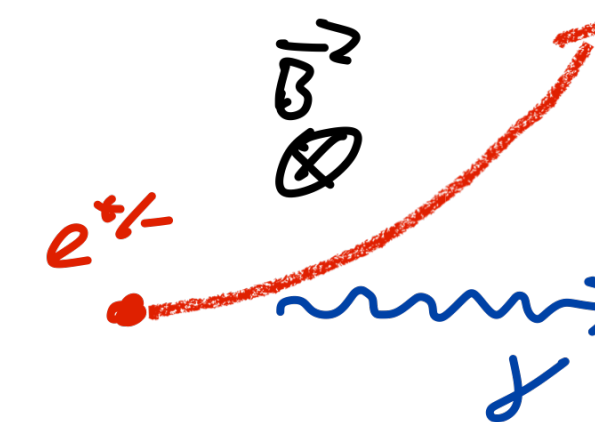
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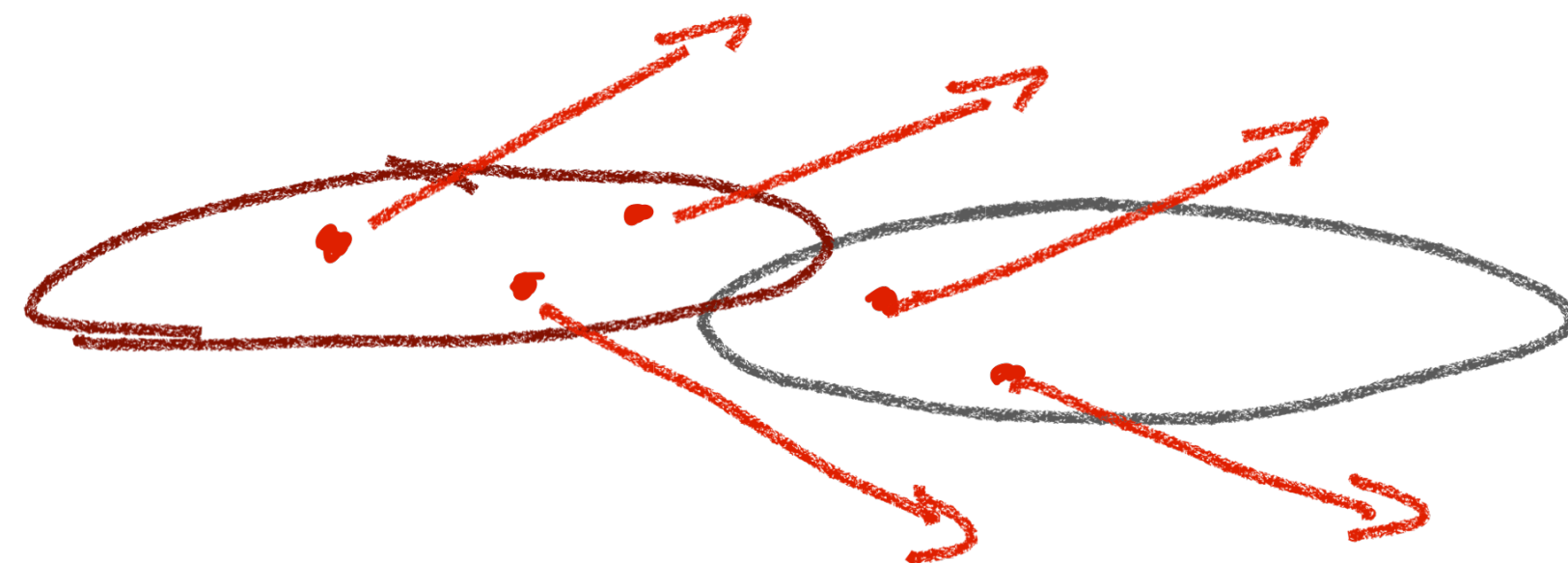


beam gas scattering

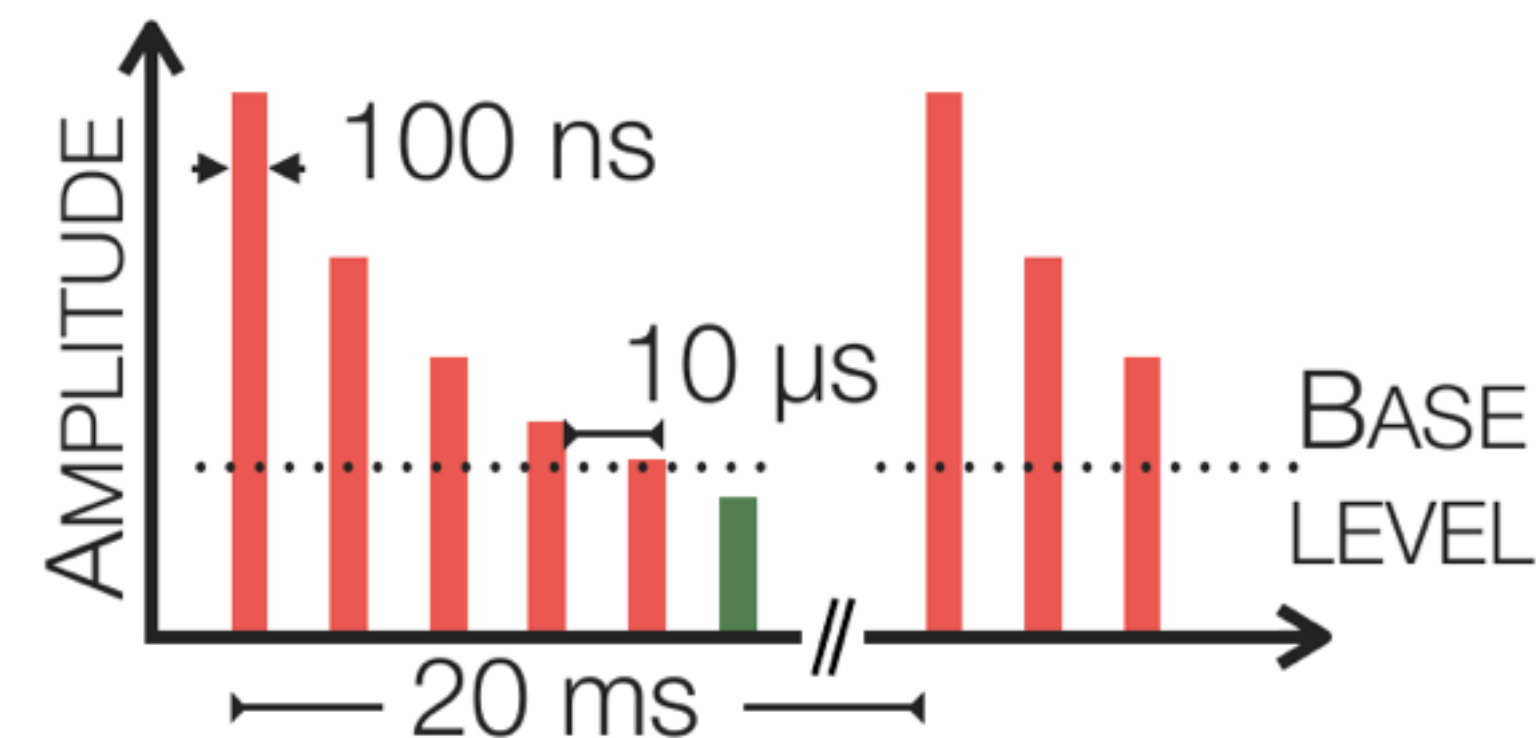


synchrotron radiation

50 Hz continuous injection - a constant background challenge



Injection background



“**Gated mode**” implemented in the PXD: possibility to periodically disable charge collection within one readout cycle if background result in occupancy problems after injection.

Understanding Machine Backgrounds

Measurements during Commissioning

- A dedicated program to measure backgrounds during commissioning. One system: CLAWS.

Based in SiPM-on-Tile technology



Understanding Machine Backgrounds

Measurements during Commissioning

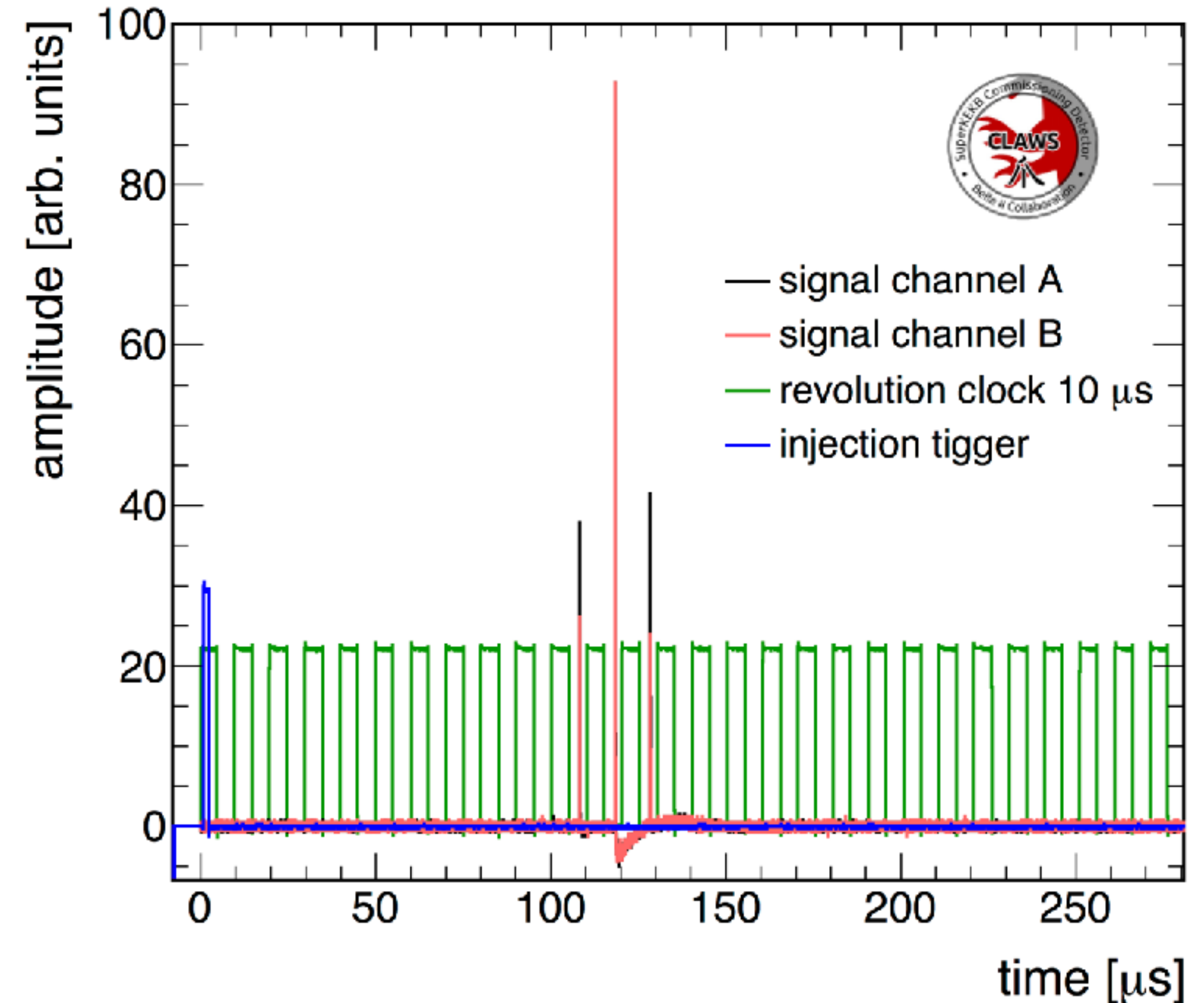
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Based in SiPM-on-Tile technology



- On February 8, 2016, CLAWS was the first detector to observe particles from circulating beams in SuperKEKB



Understanding Machine Backgrounds

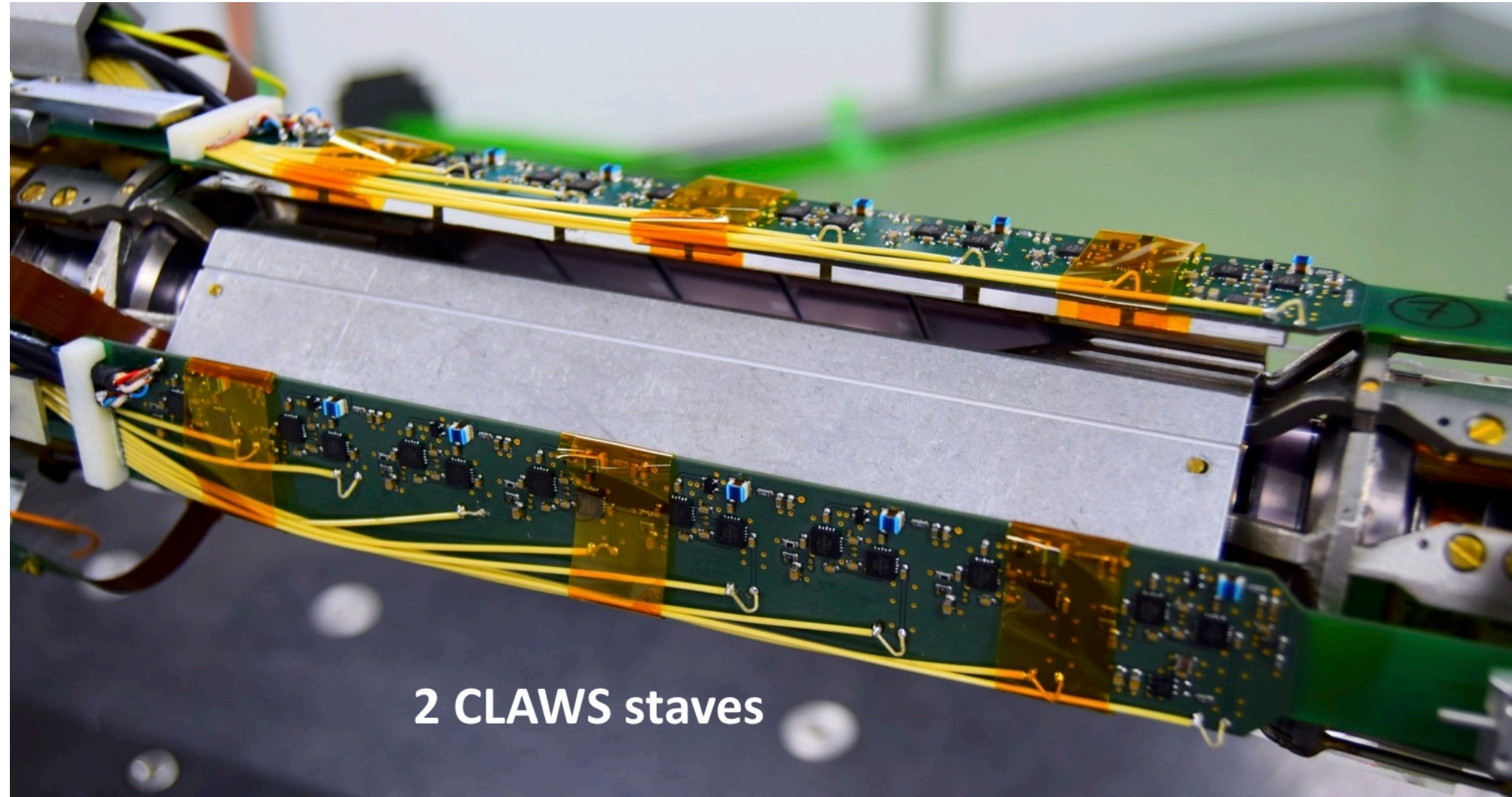
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Commissioning detector instead of PXD/SVD



~ 300 ps time resolution for signals of ~ 10 MIP

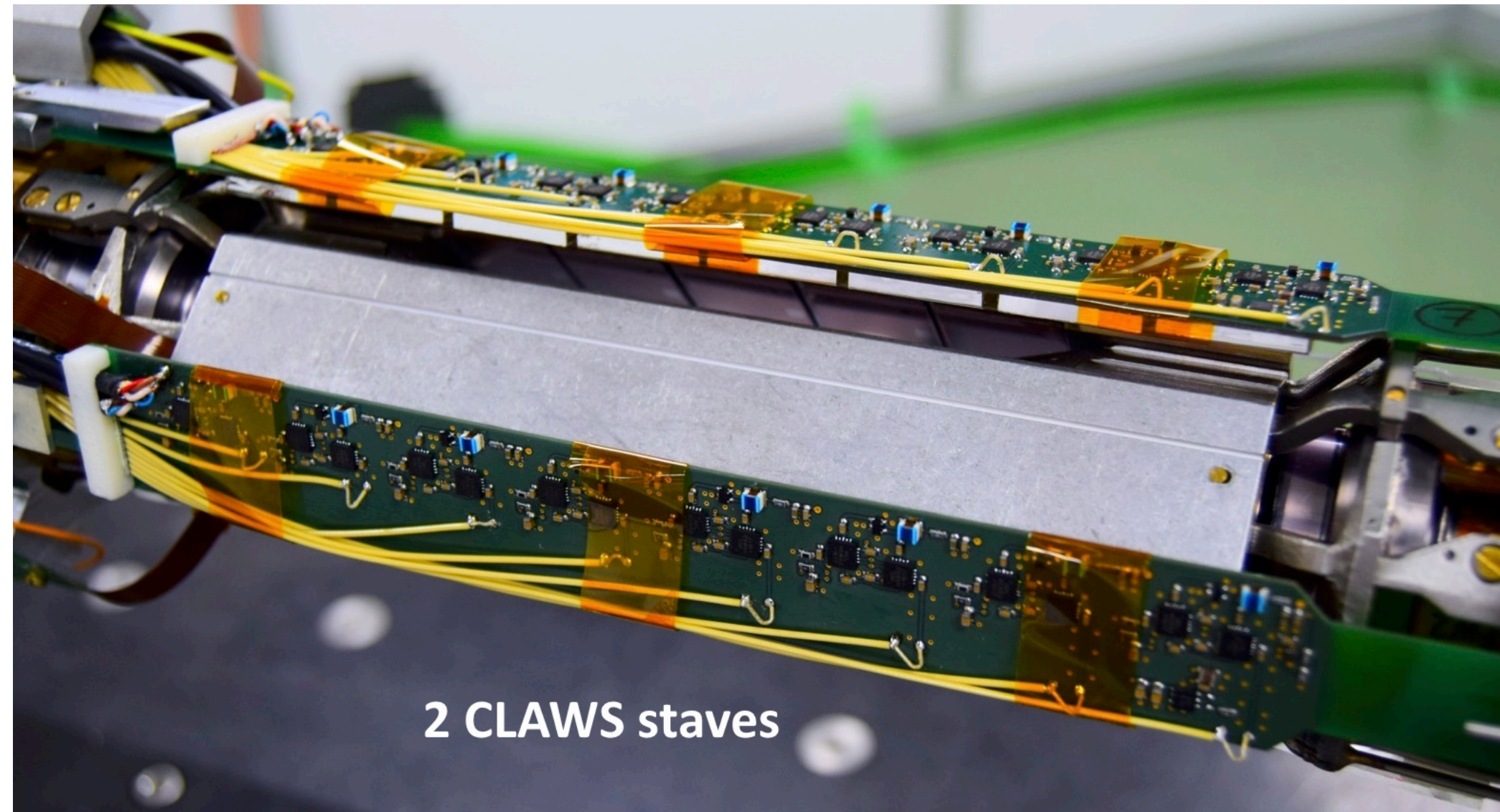
Understanding Machine Backgrounds

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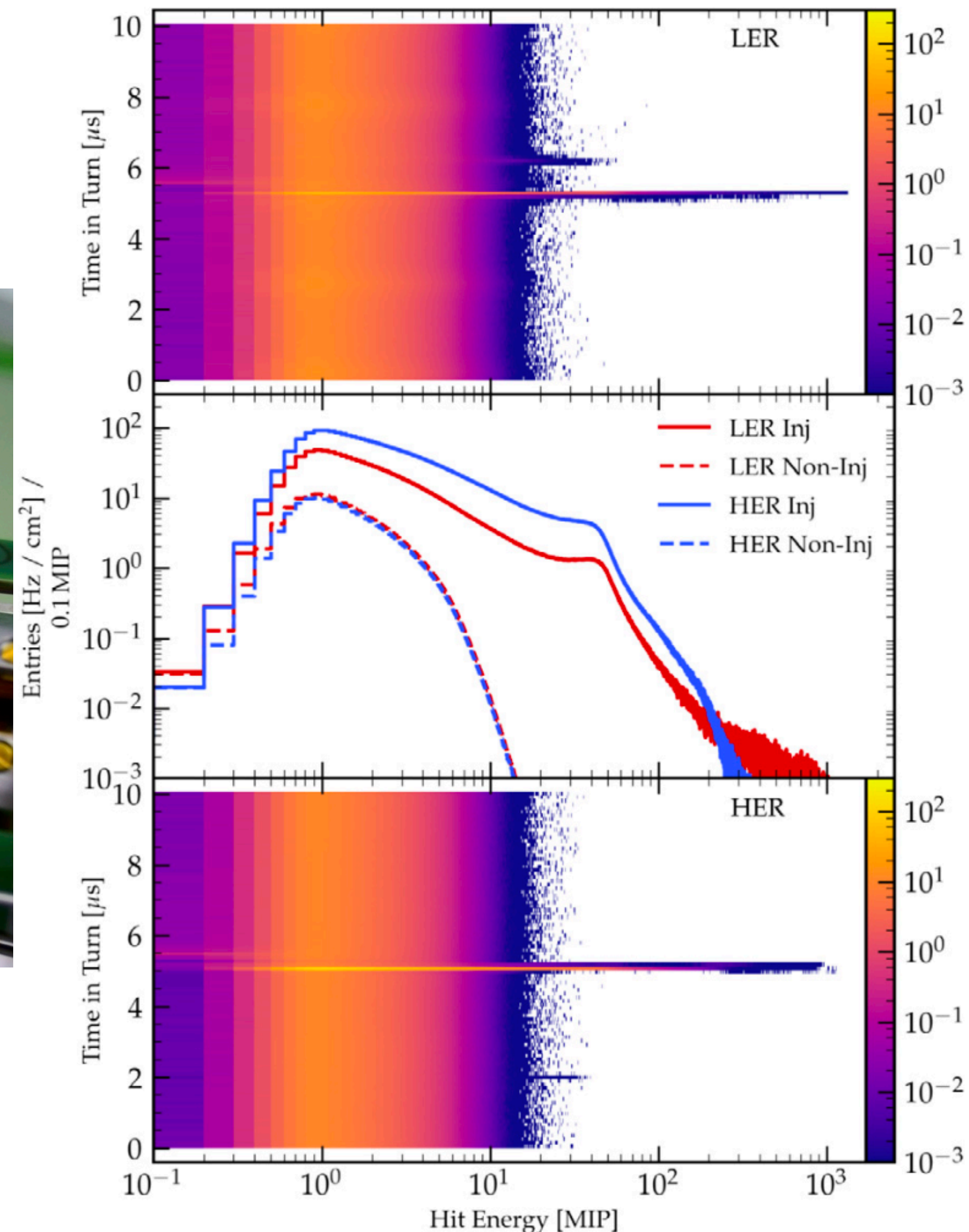
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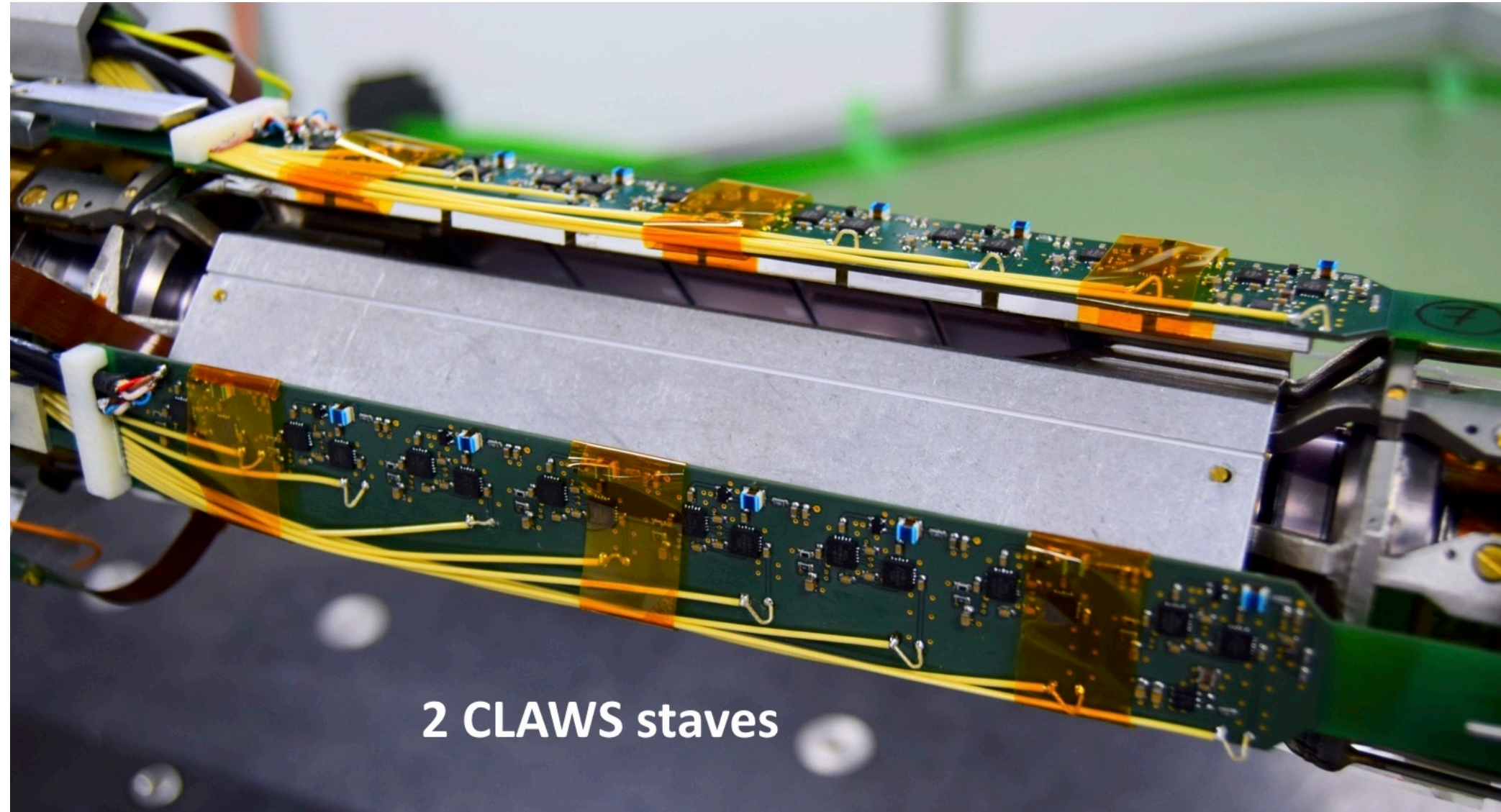
Understanding Machine Backgrounds

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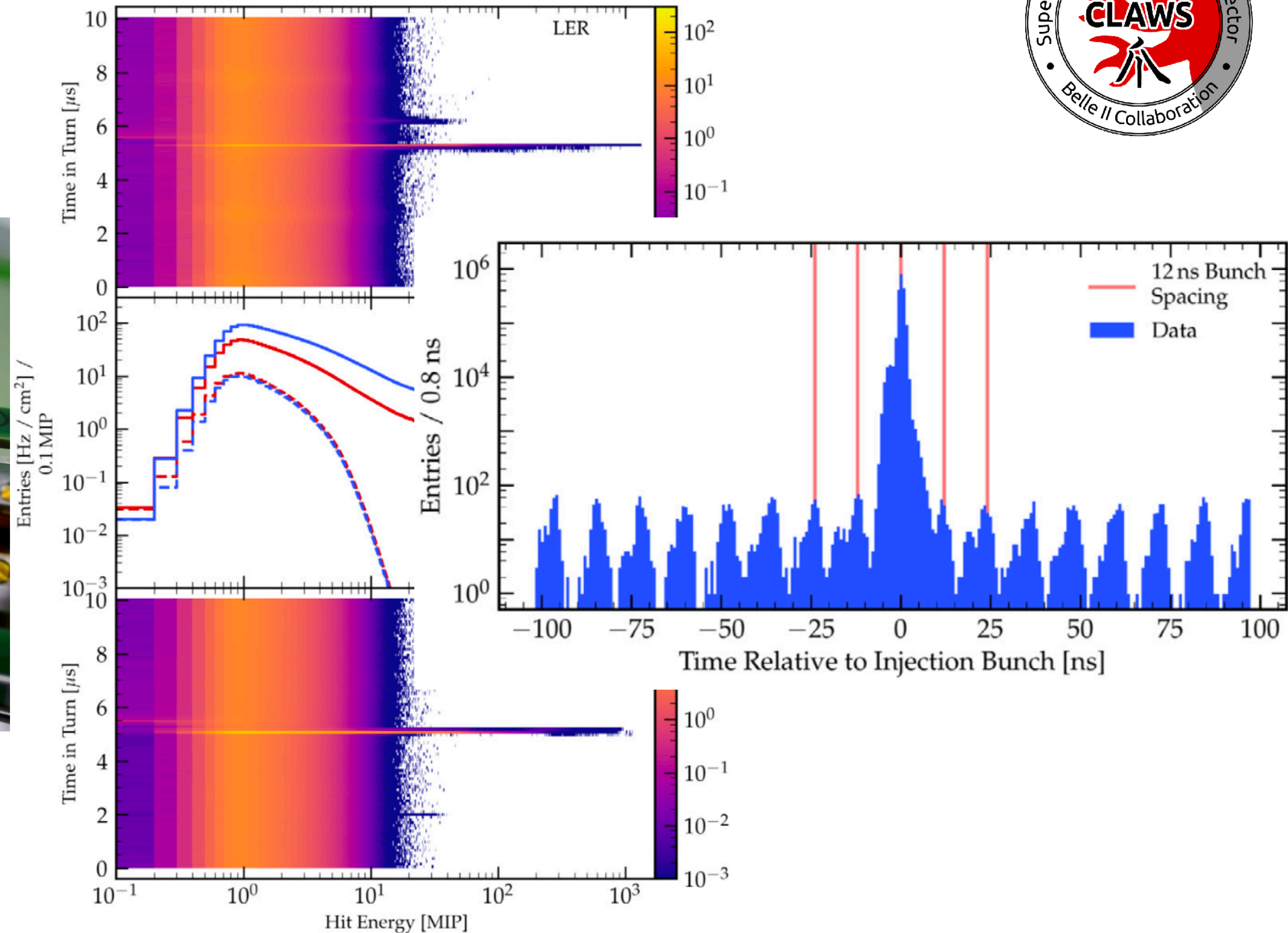
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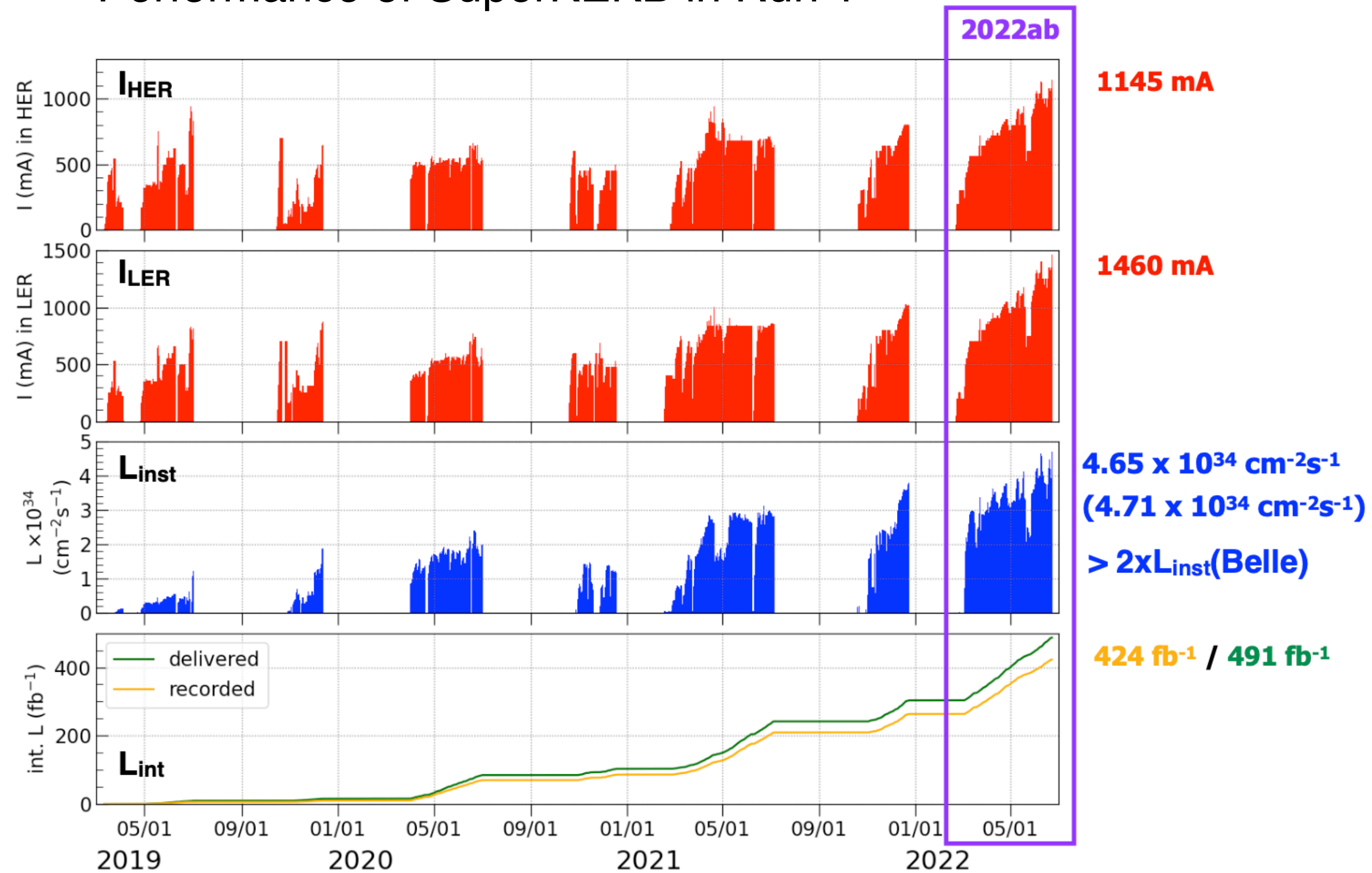
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Challenges in Luminosity Production

Accelerator Performance

- Performance of SuperKEKB in Run 1

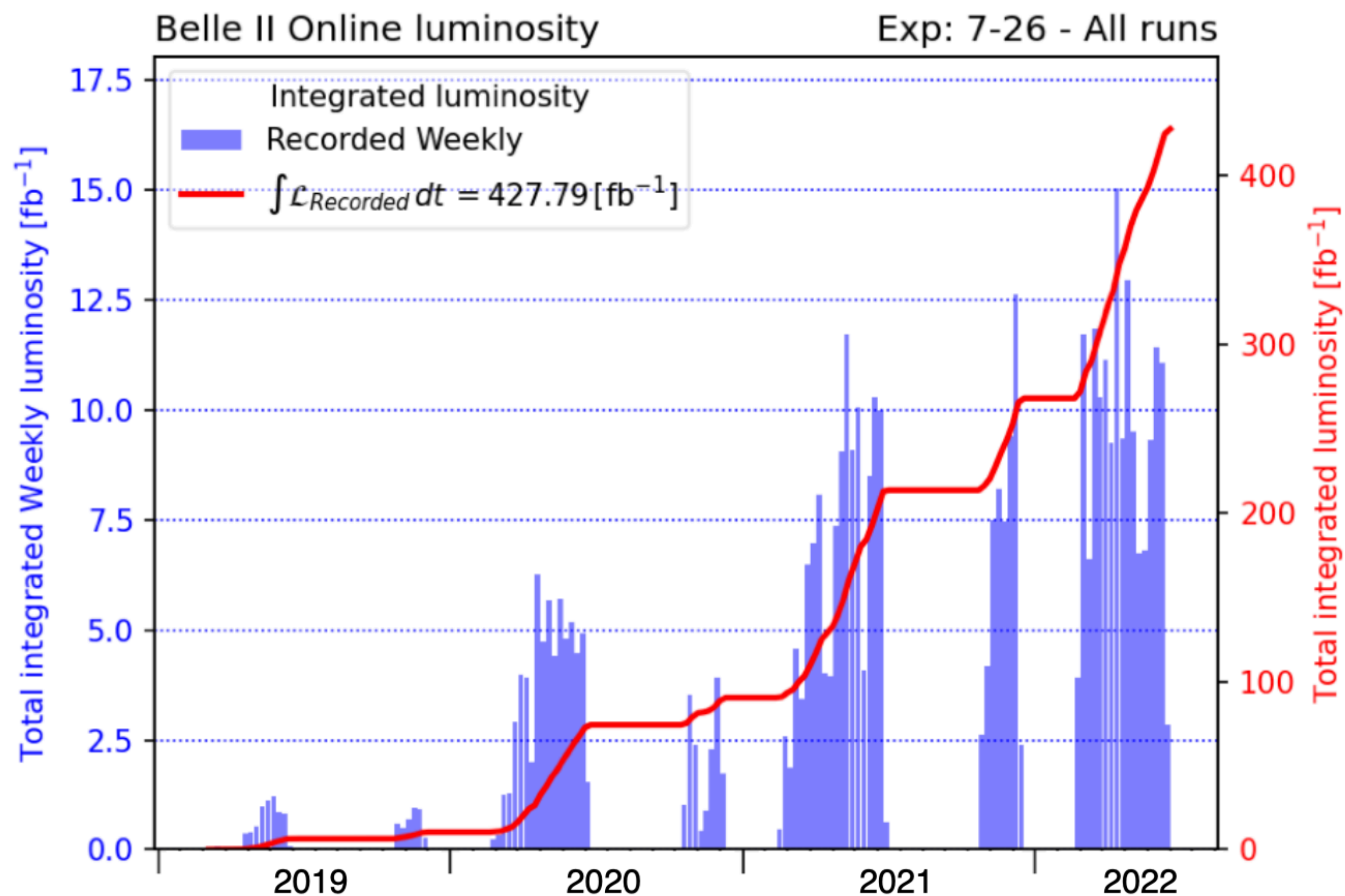


In early 2022: Luminosity world record: $4.7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Challenges in Luminosity Production

Accelerator Performance

- Performance of SuperKEKB in Run 1



A data set comparable to BaBar, 50% Belle - less than originally expected.

Limited by backgrounds, beam loss with higher bunch charge and currents.

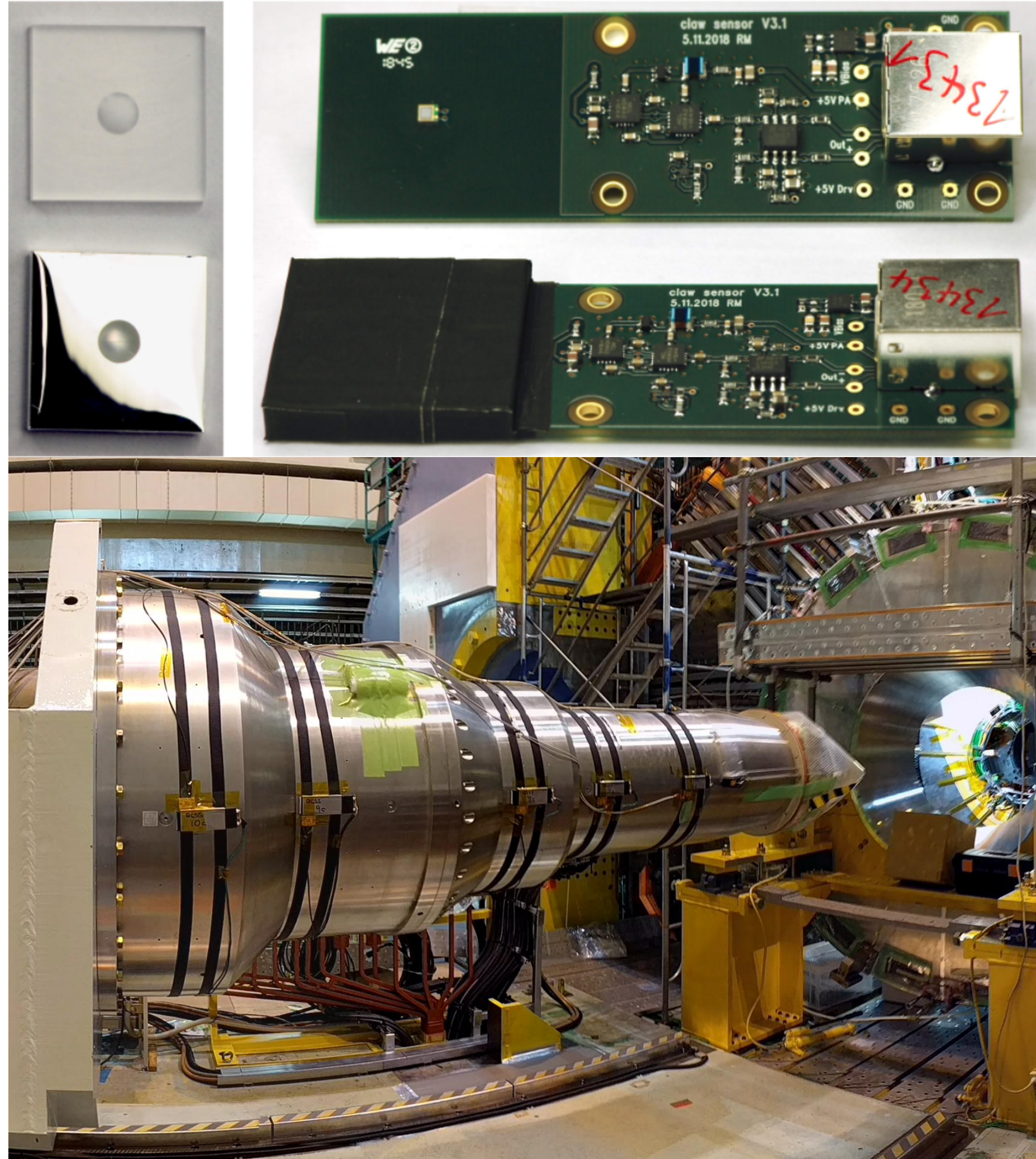
But: More capable detector - enables first competitive results

In early 2022: Luminosity world record: $4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

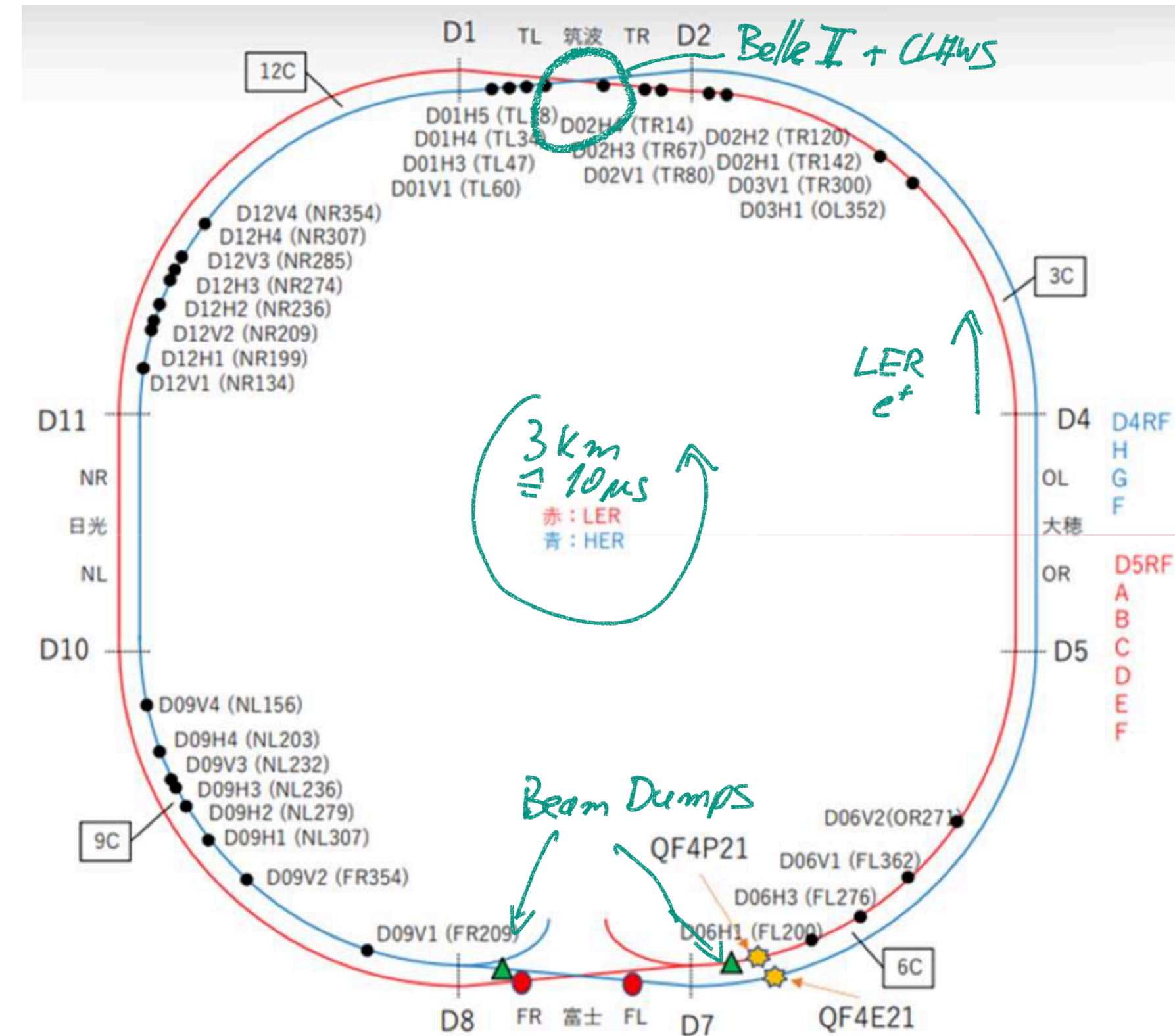
CLAWS Evolution: Beam Abort

Protecting Detectors & Machine

- Unexpected high background levels / sudden beam losses: results in QCS quenches, detector damage



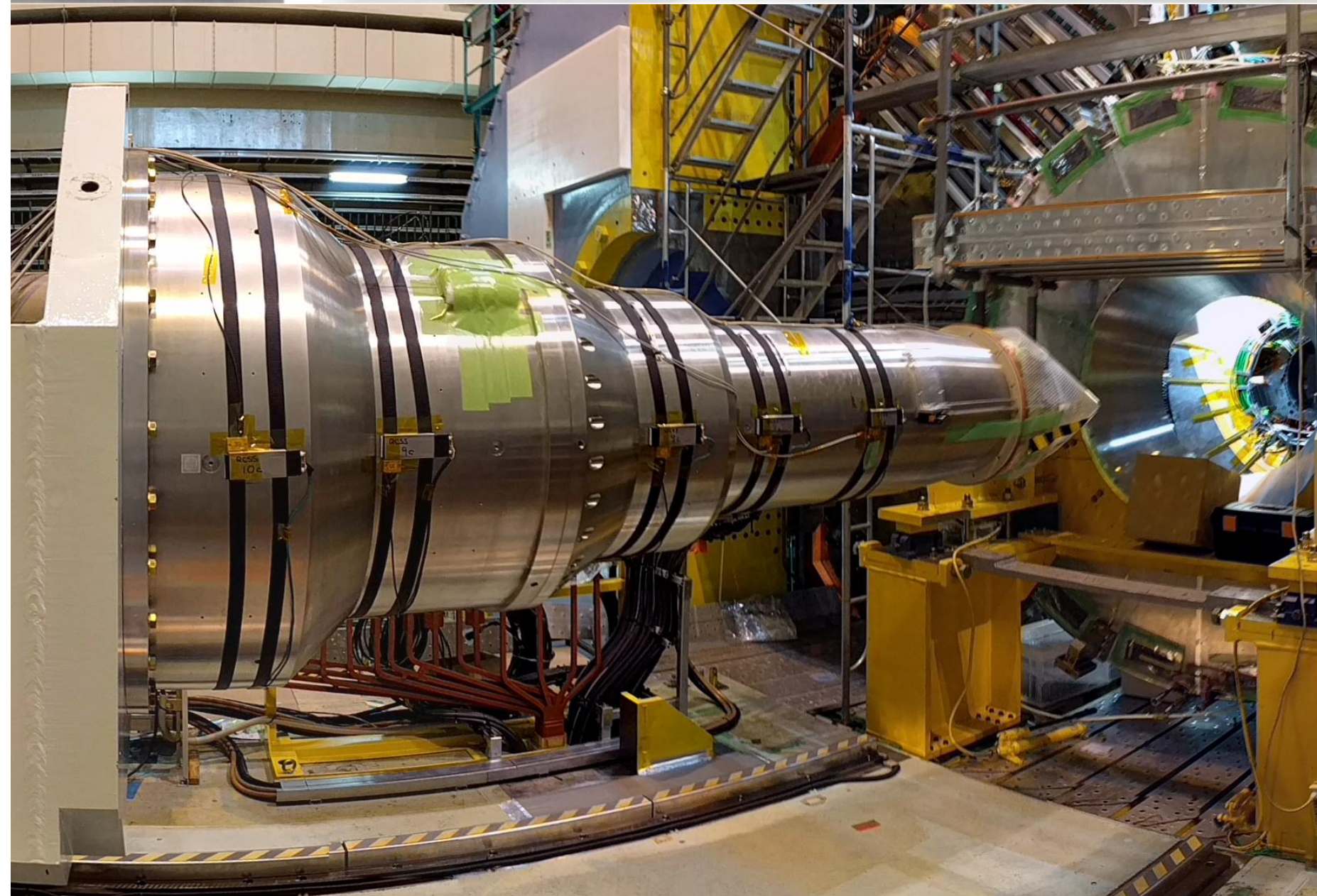
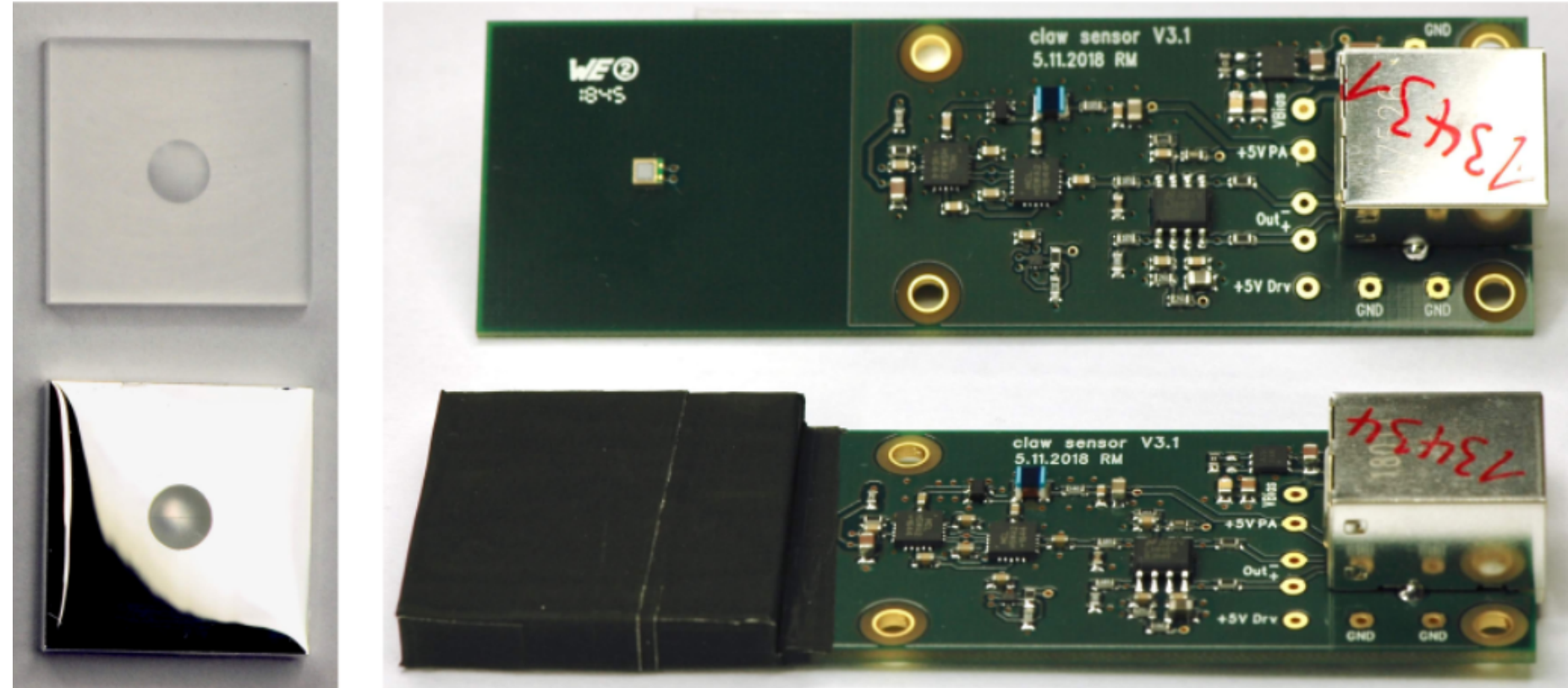
- CLAWS system extended and reconfigured to serve as beam abort system: 32 channels on QCS



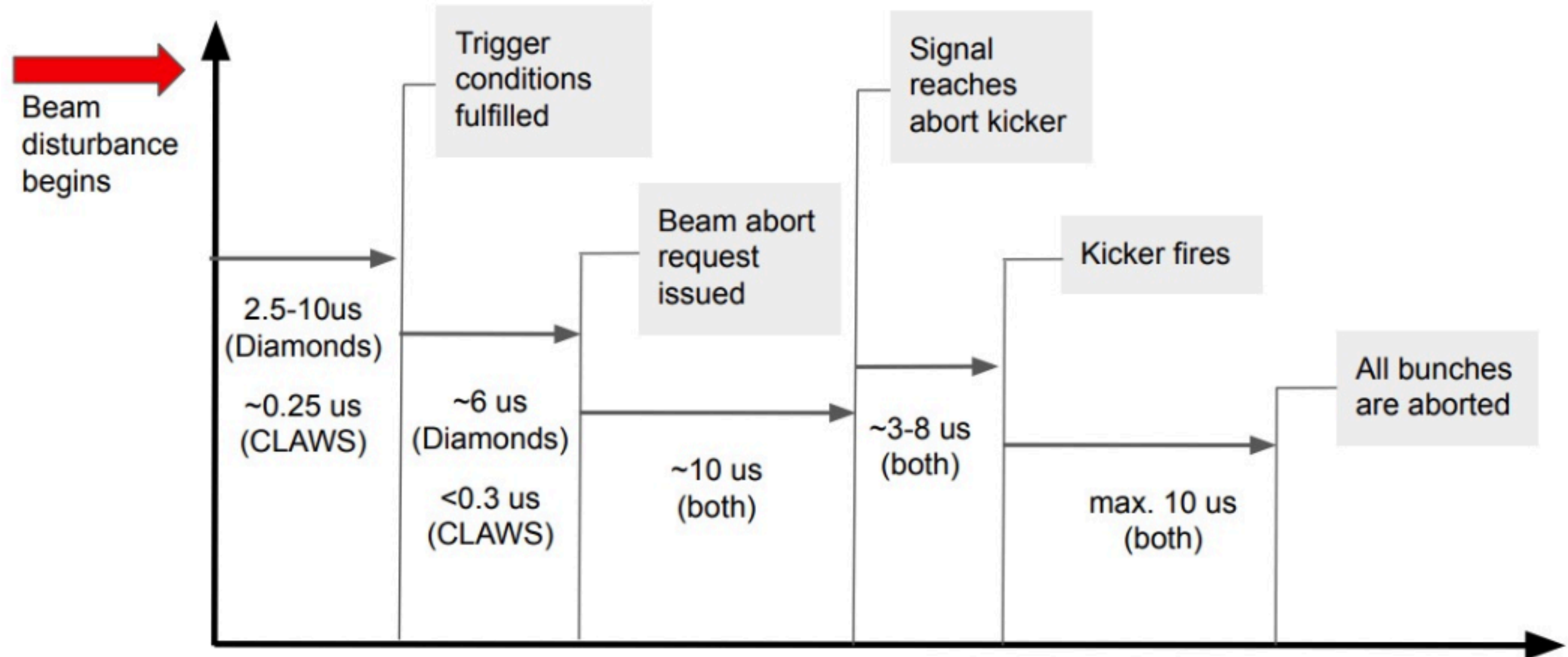
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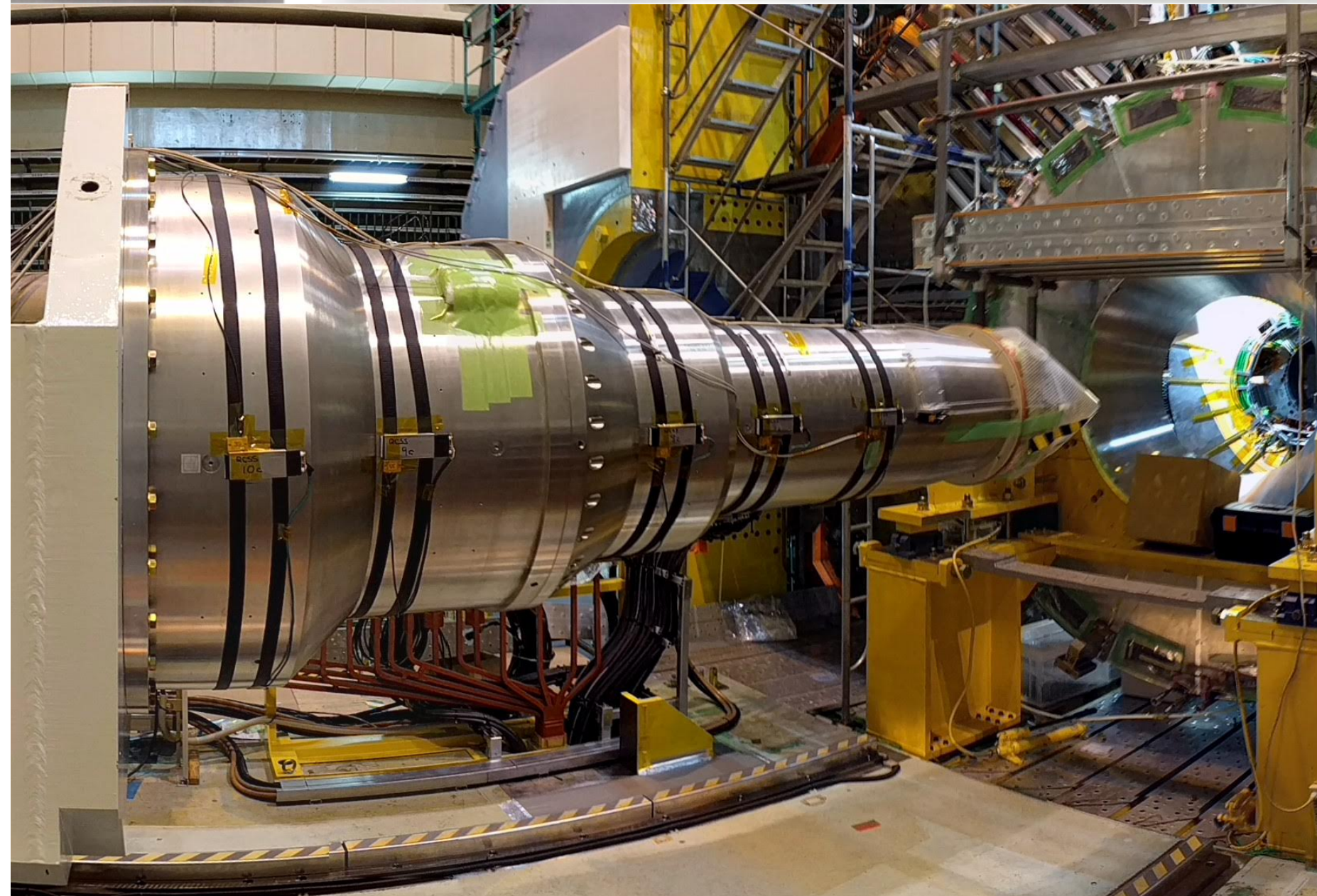
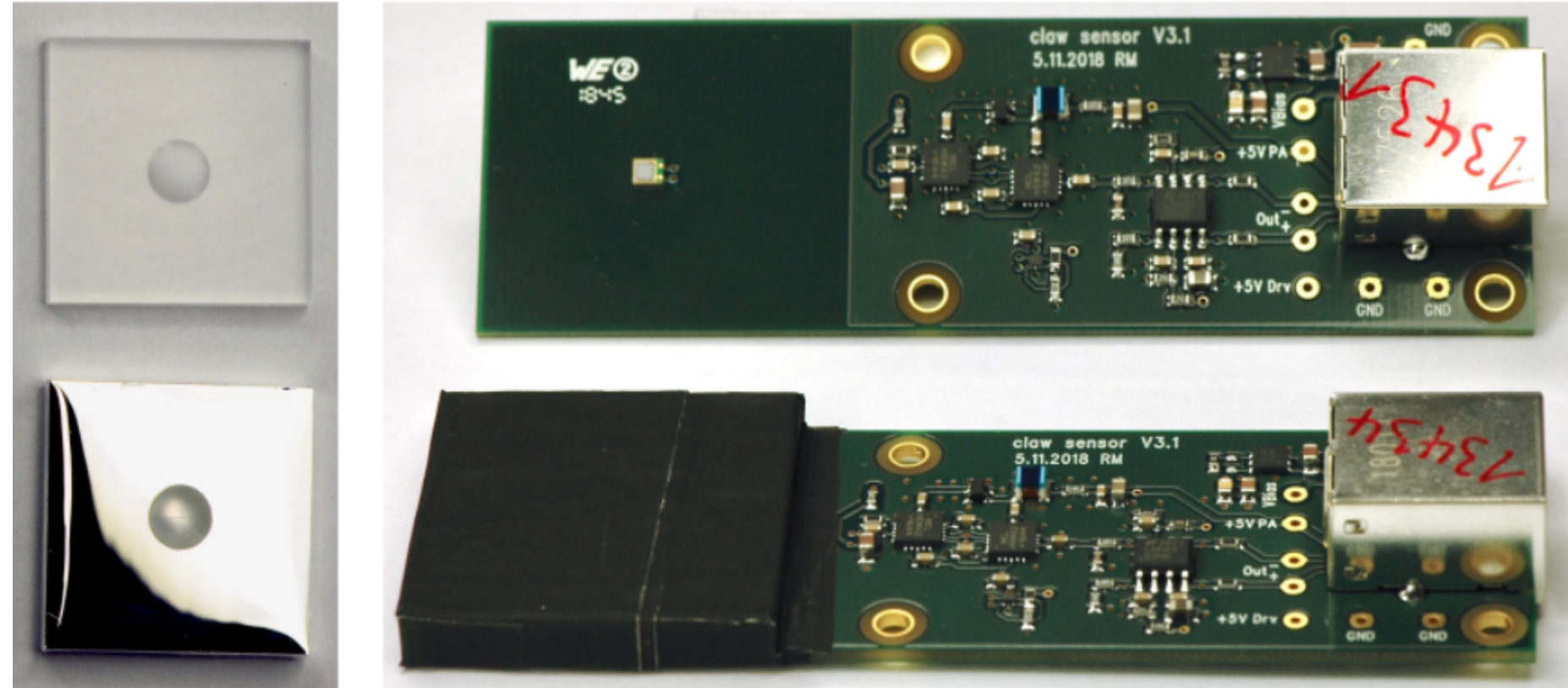
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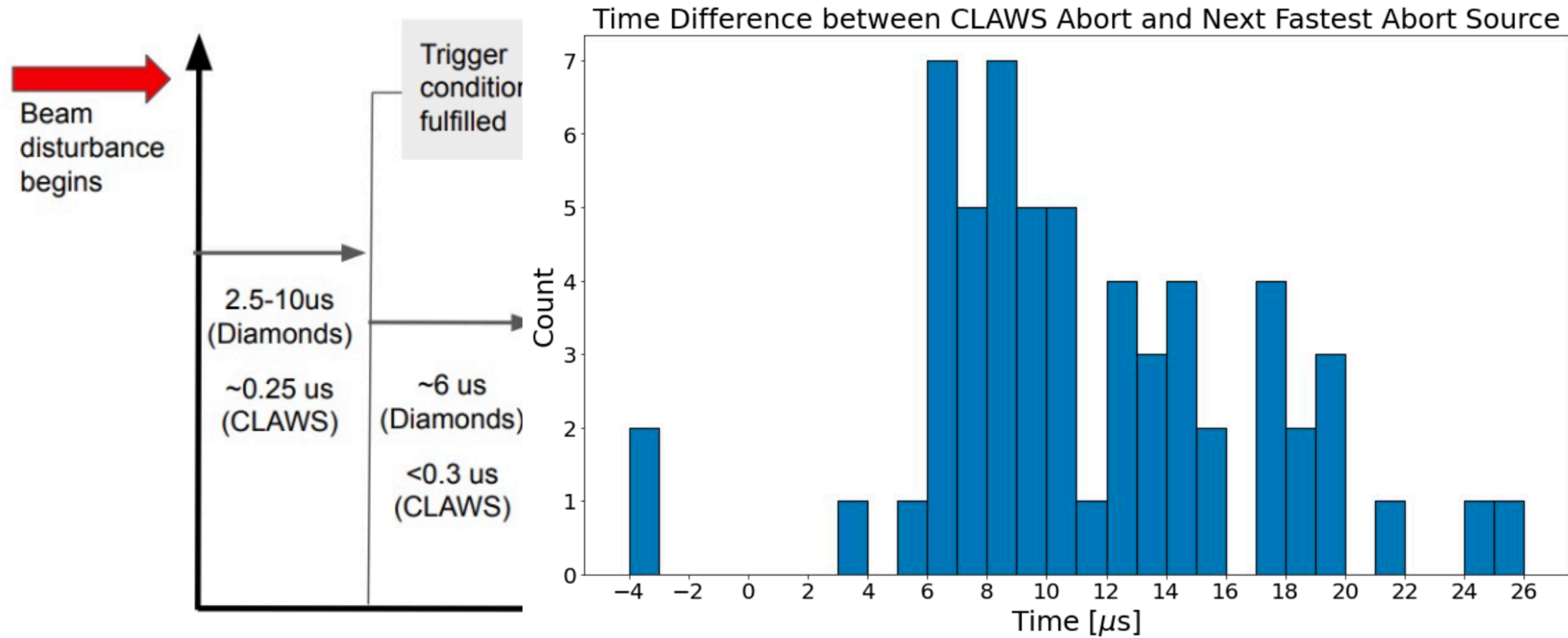
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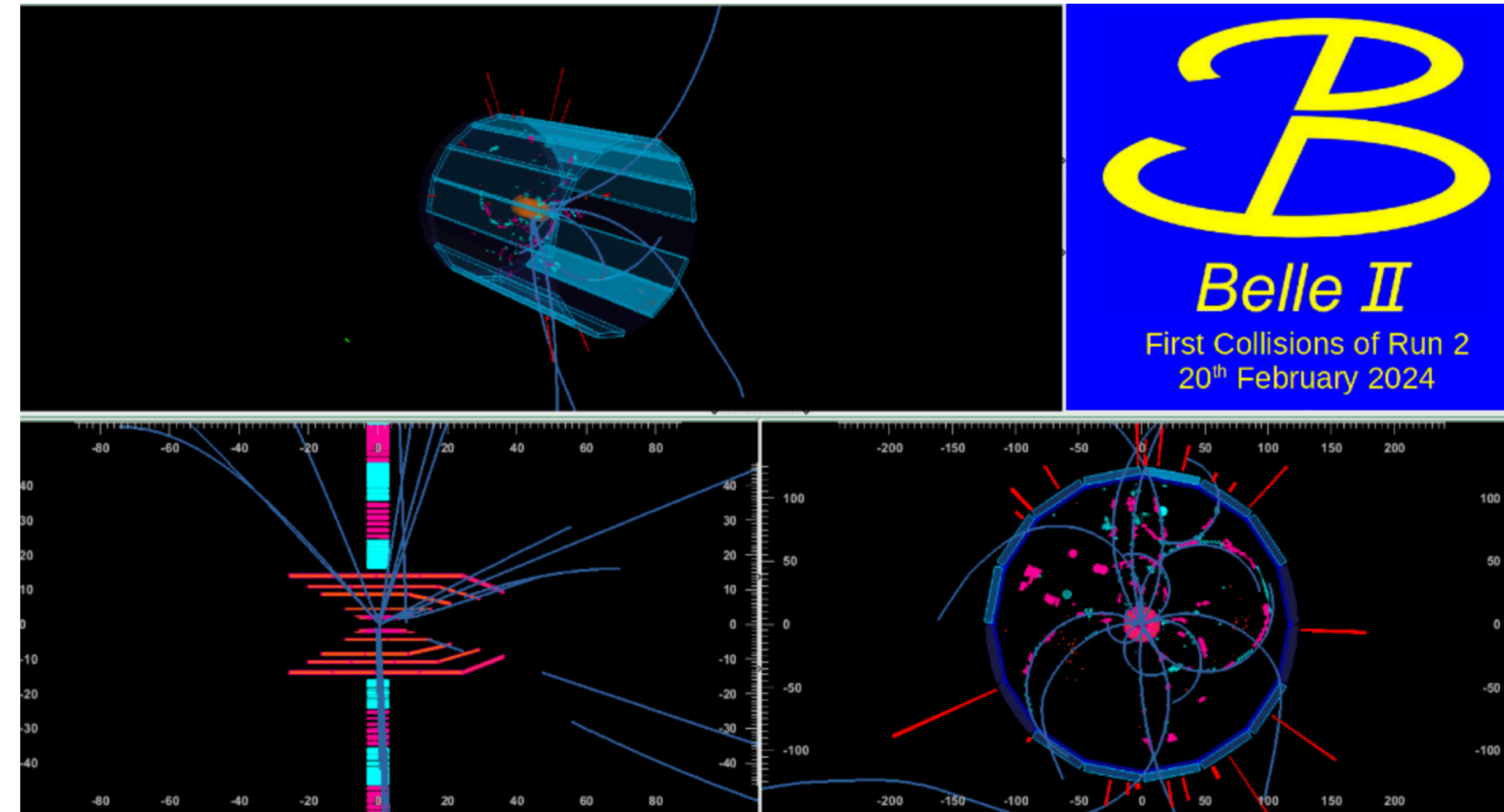
Successful operation since 10/2021

The Current Status

Improvements in LS1

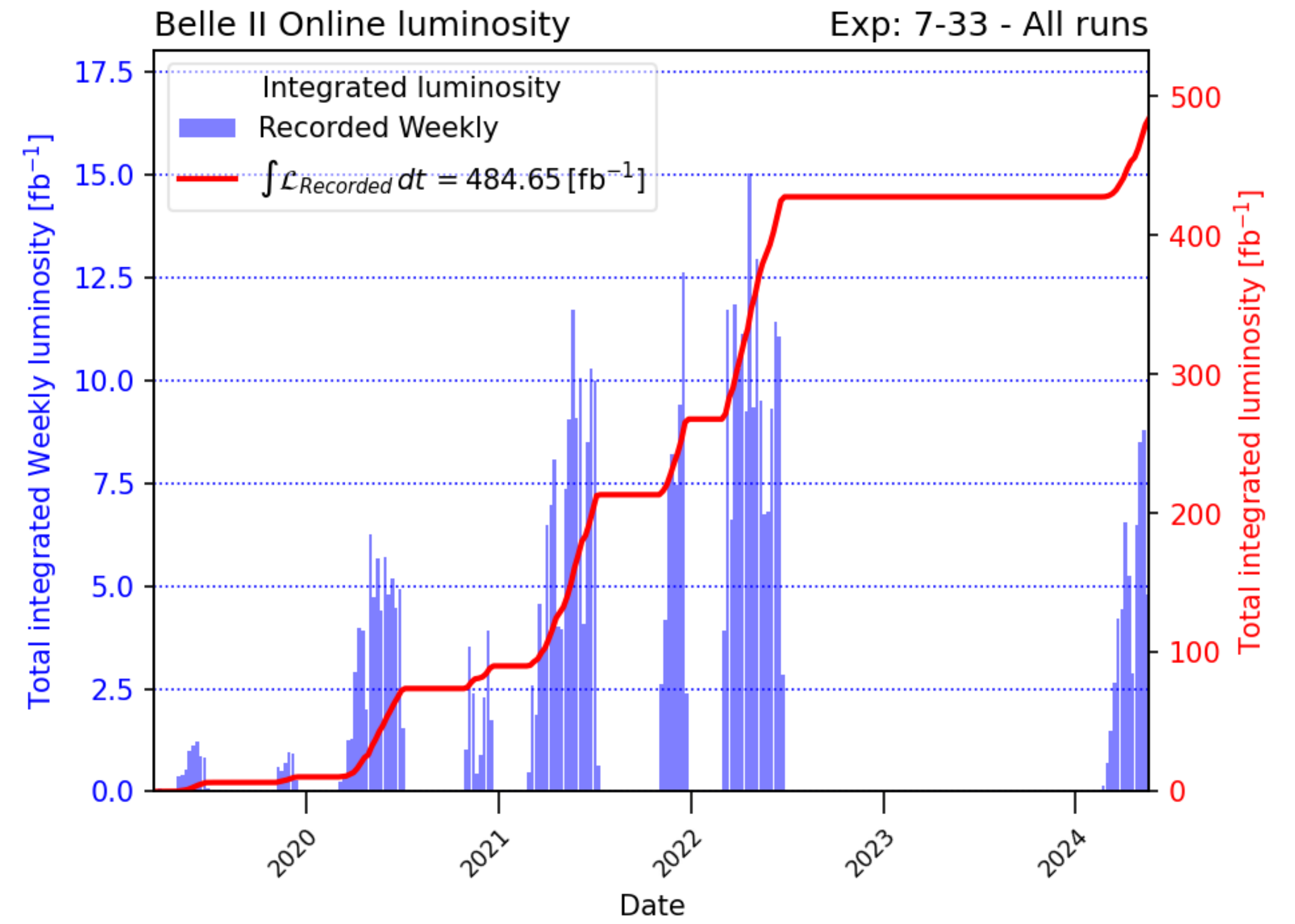
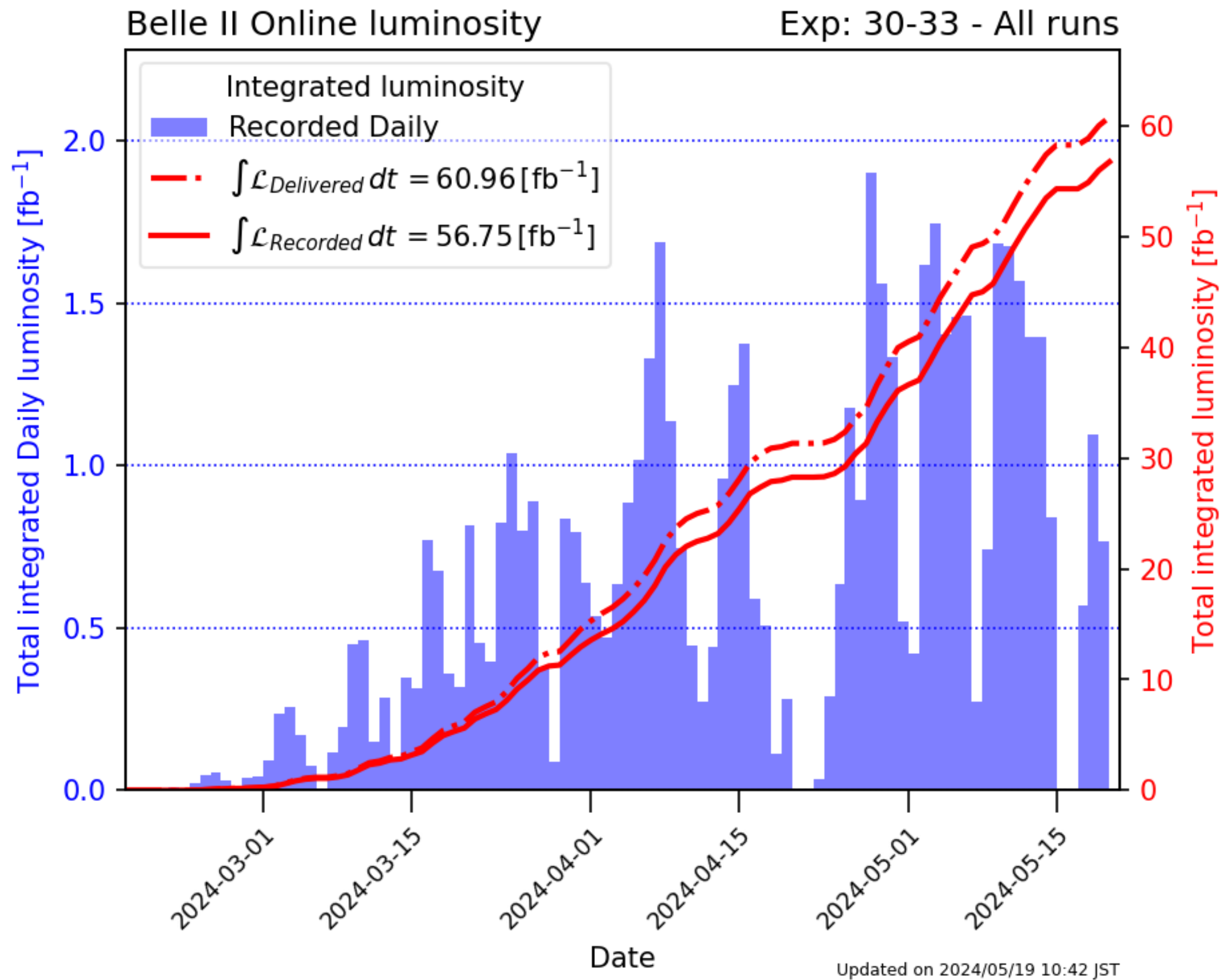
- Belle II and SuperKEKB coming out of Long Shutdown 1 (07 / 2022 - late 2023)
- Detector improvement:
 - Completion of PXD: 2 complete layers
 - Replacement of degraded TOP PMTs
 - Improvement of CDC incl. electronics
 - Extension of CLAWS system
- Machine improvement:
 - Reinforcement of IR background shielding
 - New non-linear collimator
 - More robust collimators in LER
 - Beam pipe changes to improve injection efficiency
 - ...

First collisions in Run 2: Feb 20, 2024



The current Status

Start of Run 2

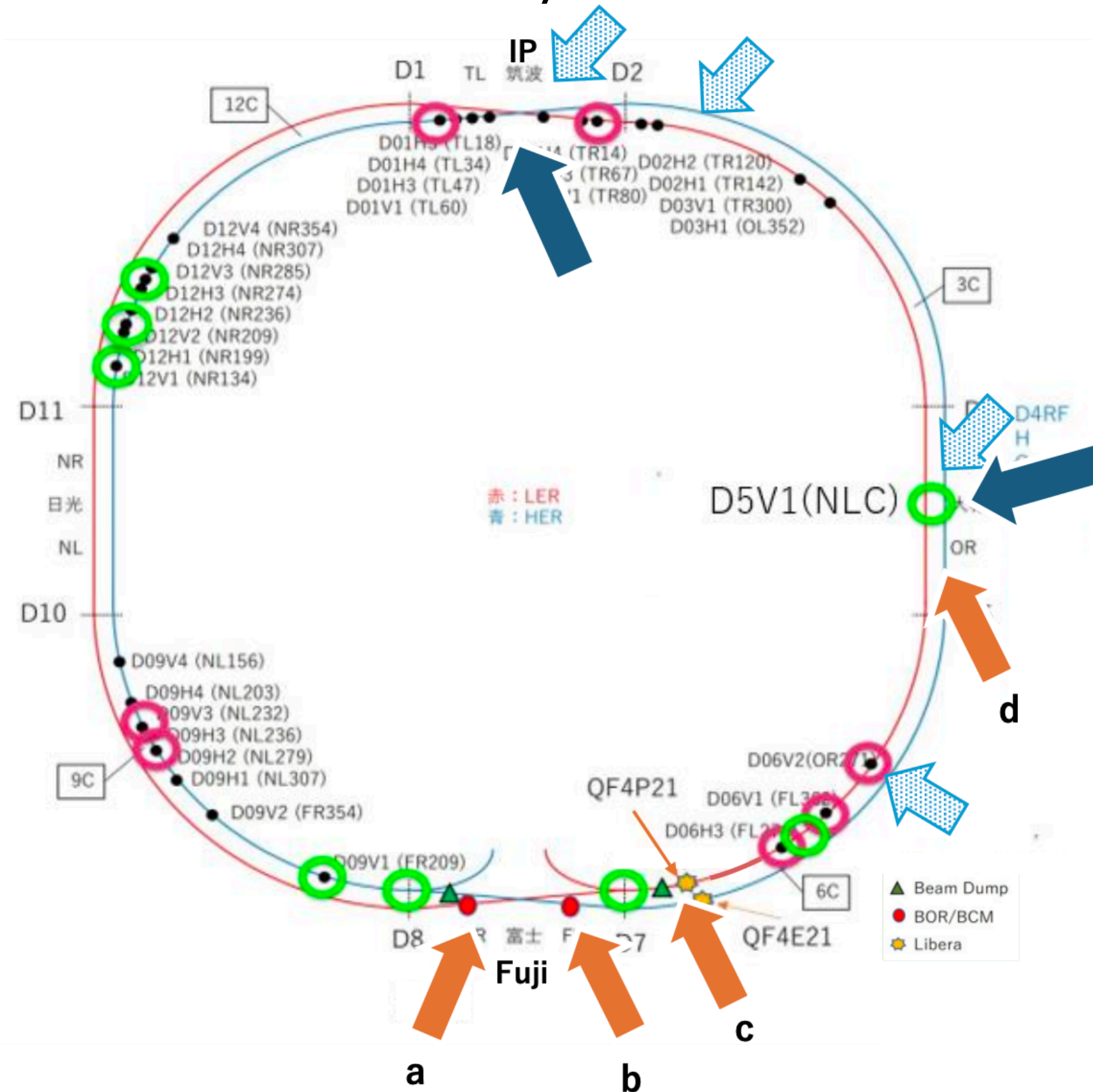


- Operations remain very difficult: Peak luminosity approaching that of Run 1: $\sim 4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Background problems persist: Frequent sudden beam loss events, have resulted in damage to PXD (increased noise, dead cells) - PXD currently turned off, studies ongoing.

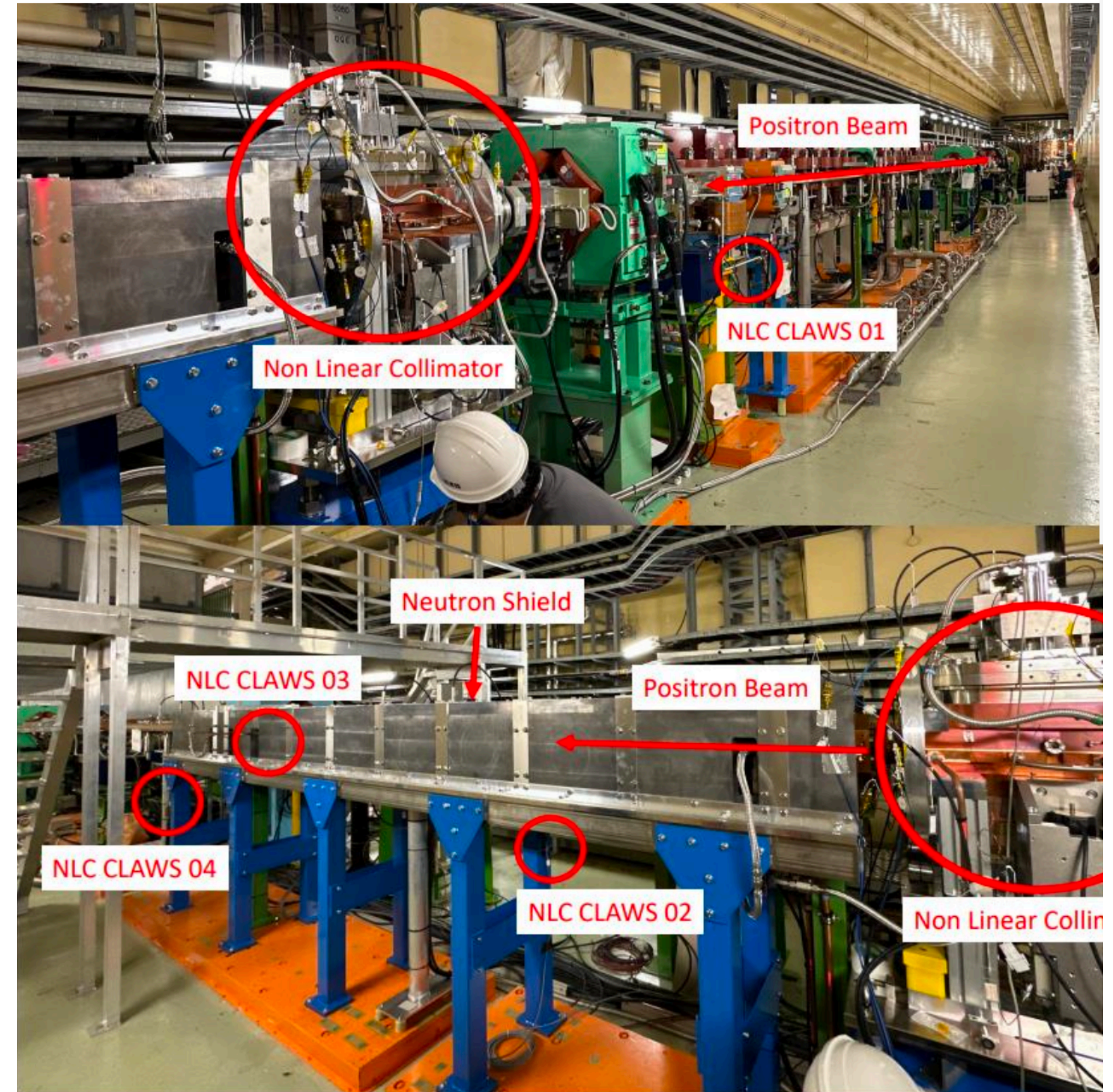
Improving Abort Systems

Coping with Instabilities and high Background Levels

- Extension of the CLAWS system to collimator locations



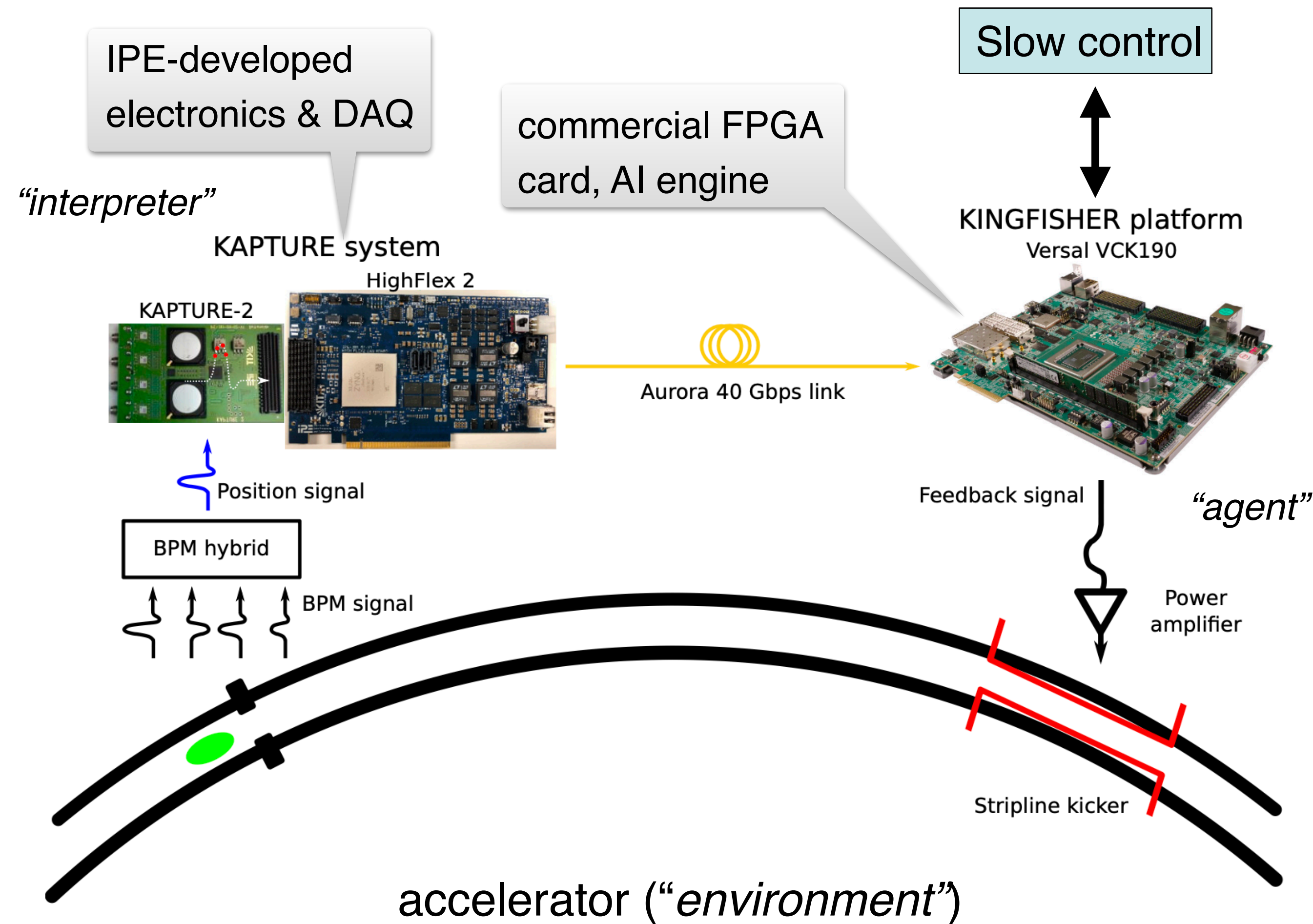
Gains one turn ($\sim 10 \mu\text{s}$) in abort time, optimisations in cable routing may provide another $5 \mu\text{s}$.



Improving Abort Systems

Adding AI for higher accuracy

- R&D for improved accelerator control: Currently performed at KARA (KIT).



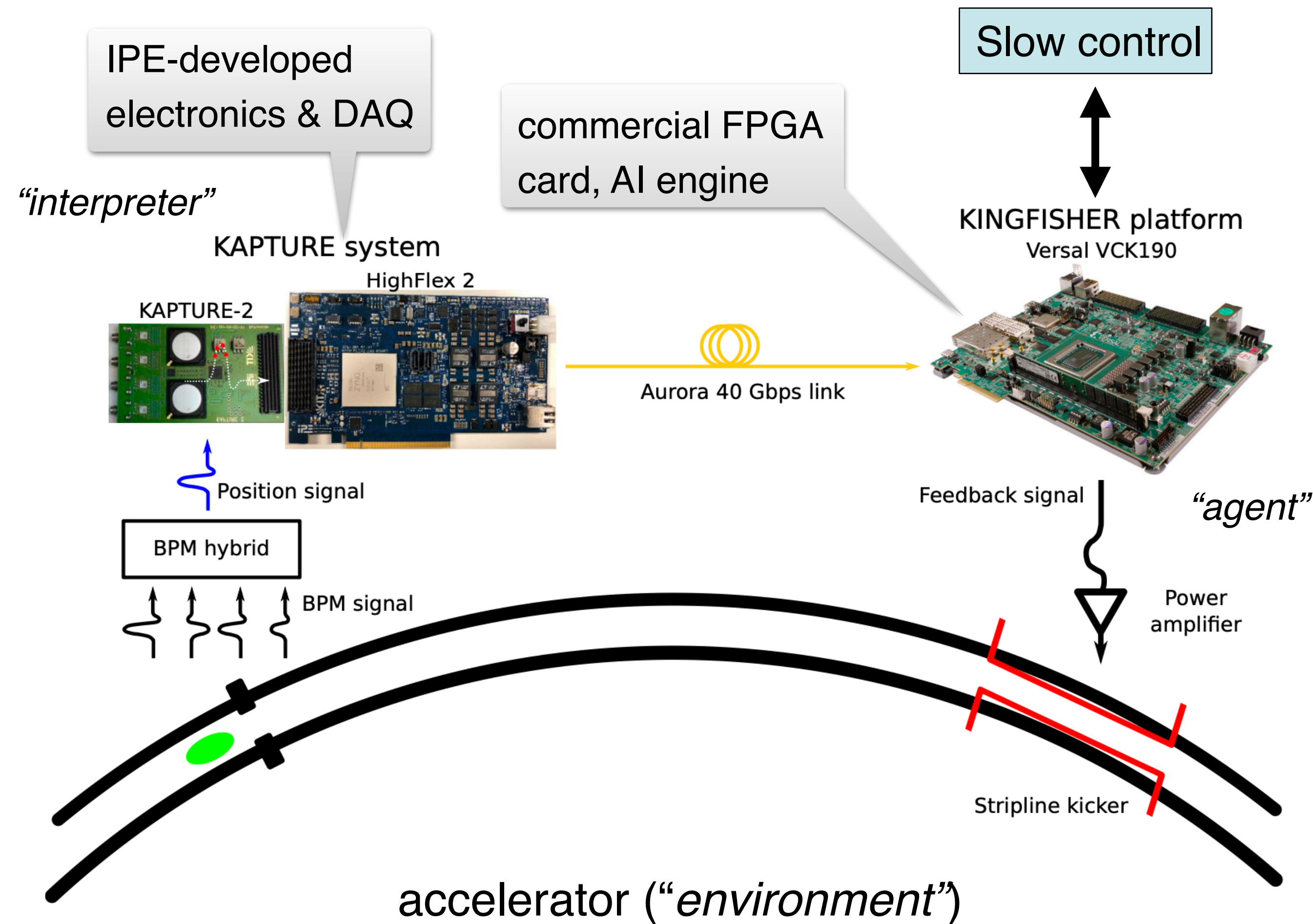
Successful application of reinforcement learning:

- agent learns to maximize a reward through interaction with environment, w/o prior training set
- RL algorithm deployed on Versal-AI: low latency, high throughput
- Demonstrated on horizontal betatron oscillations

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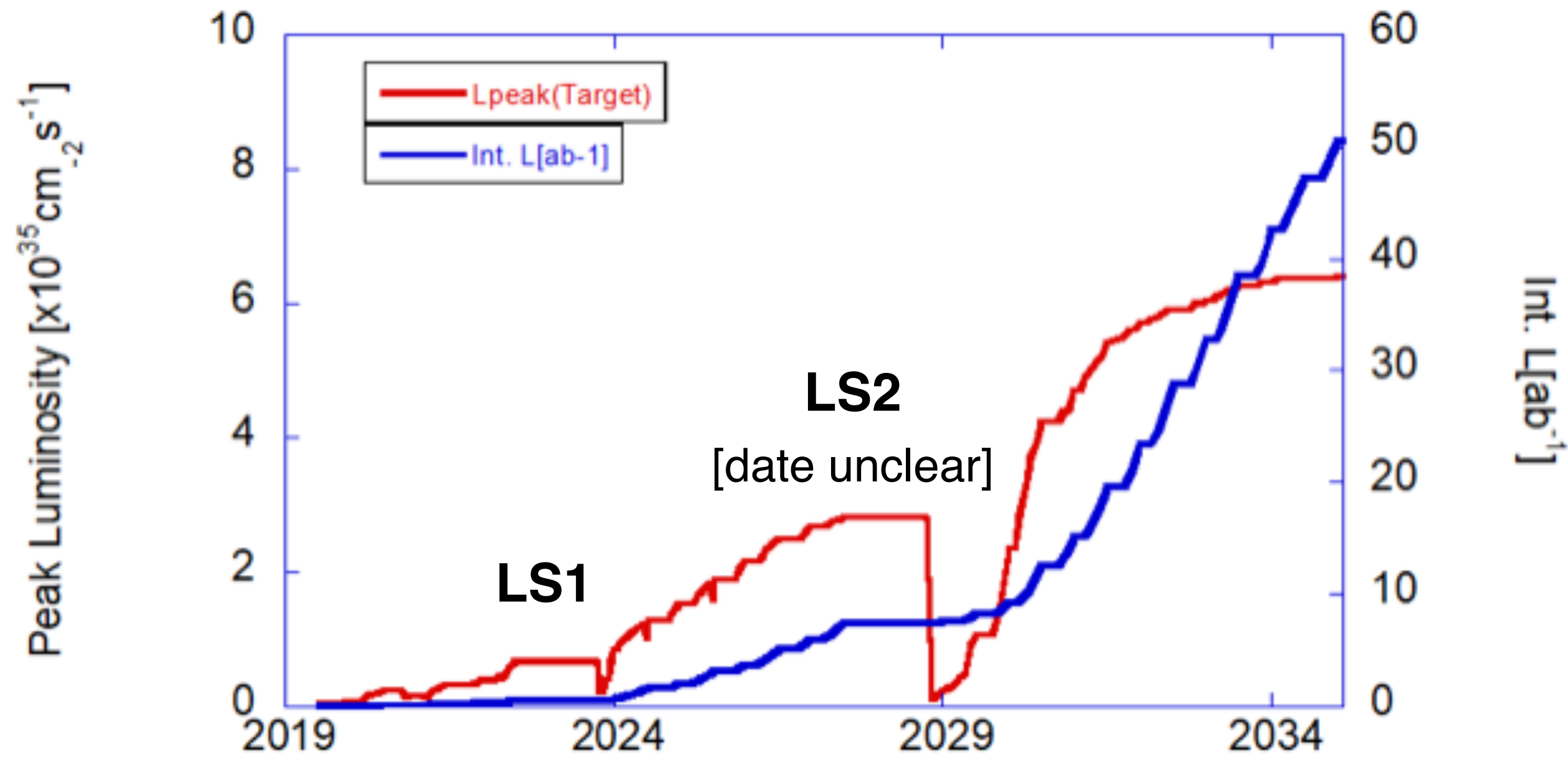
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Up next: implementation for SuperKEKB to improve beam abort system performance

Longer-Term Perspectives: Significant Machine Upgrades

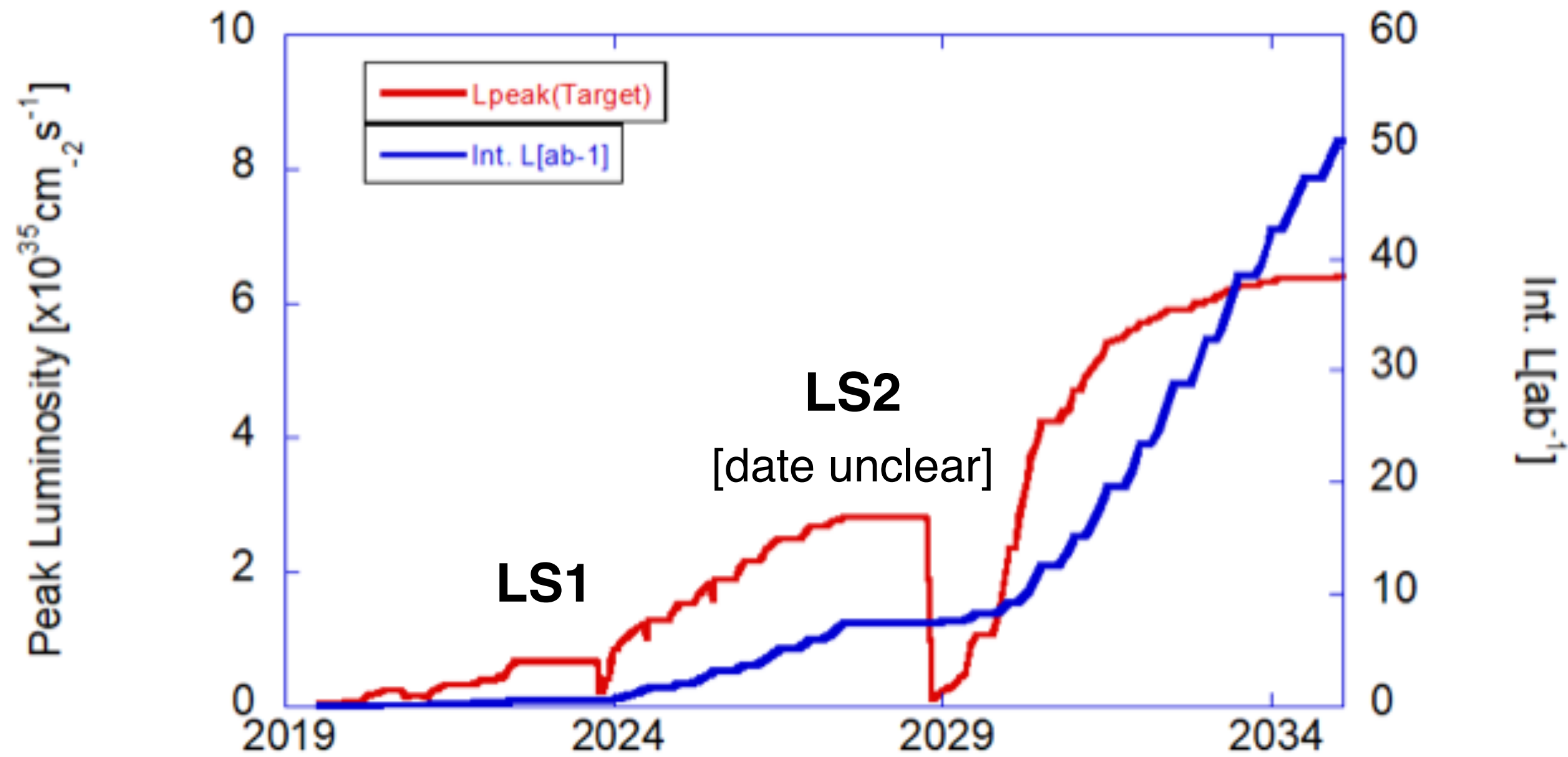
Modifications to Approach Target Luminosity



- Expected luminosity evolution - requires solving current background issues: Significant increases of beam current, improved β squeezing required.
- Full target luminosity likely only achievable with additional machine changes, possibly including new final focus.

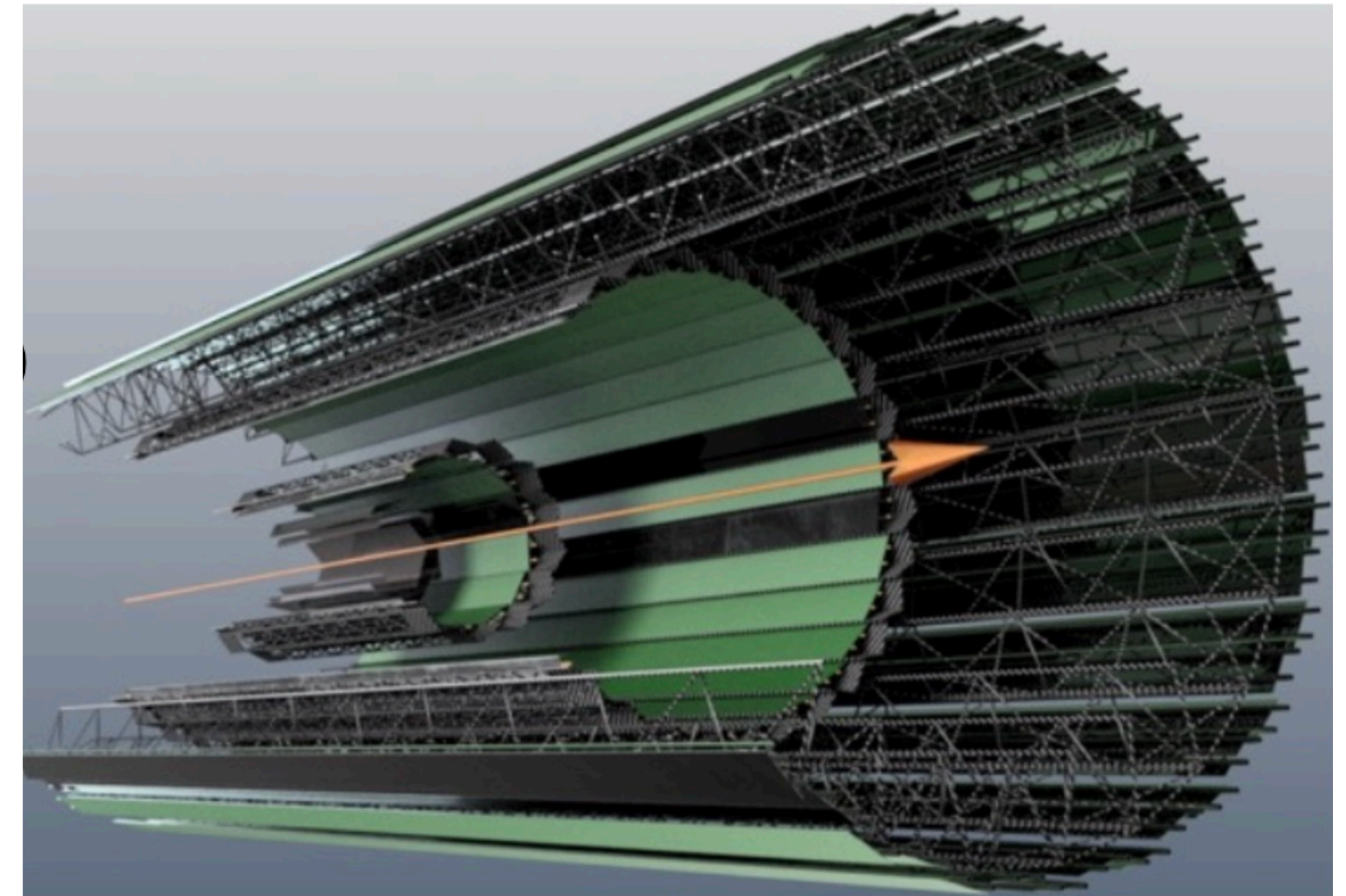
Longer-Term Perspectives: Significant Machine Upgrades

Modifications to Approach Target Luminosity



- Geometry changes, but also radiation damage and background levels will likely require a new inner tracking system (and other detector upgrades): CMOS DMAPS as prime candidate (“OBELIX”).
 - $\sim 1 \text{ m}^2$ silicon area, $< 100 \text{ ns}$ integration time

- Expected luminosity evolution - requires solving current background issues: Significant increases of beam current, improved β squeezing required.
- Full target luminosity likely only achievable with additional machine changes, possibly including new final focus.

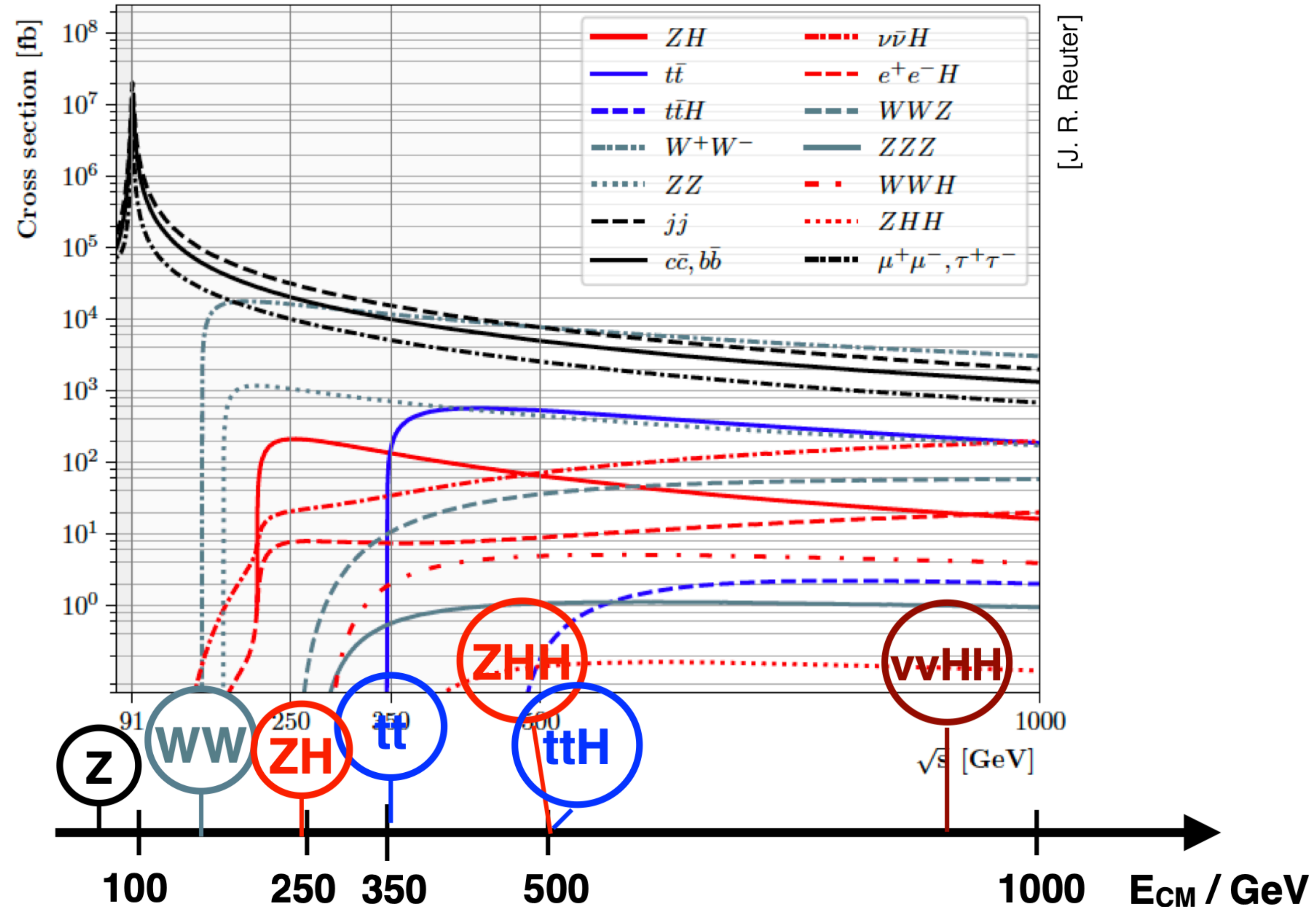


Perspectives on Technology

Higgs Factories as Innovation Drivers

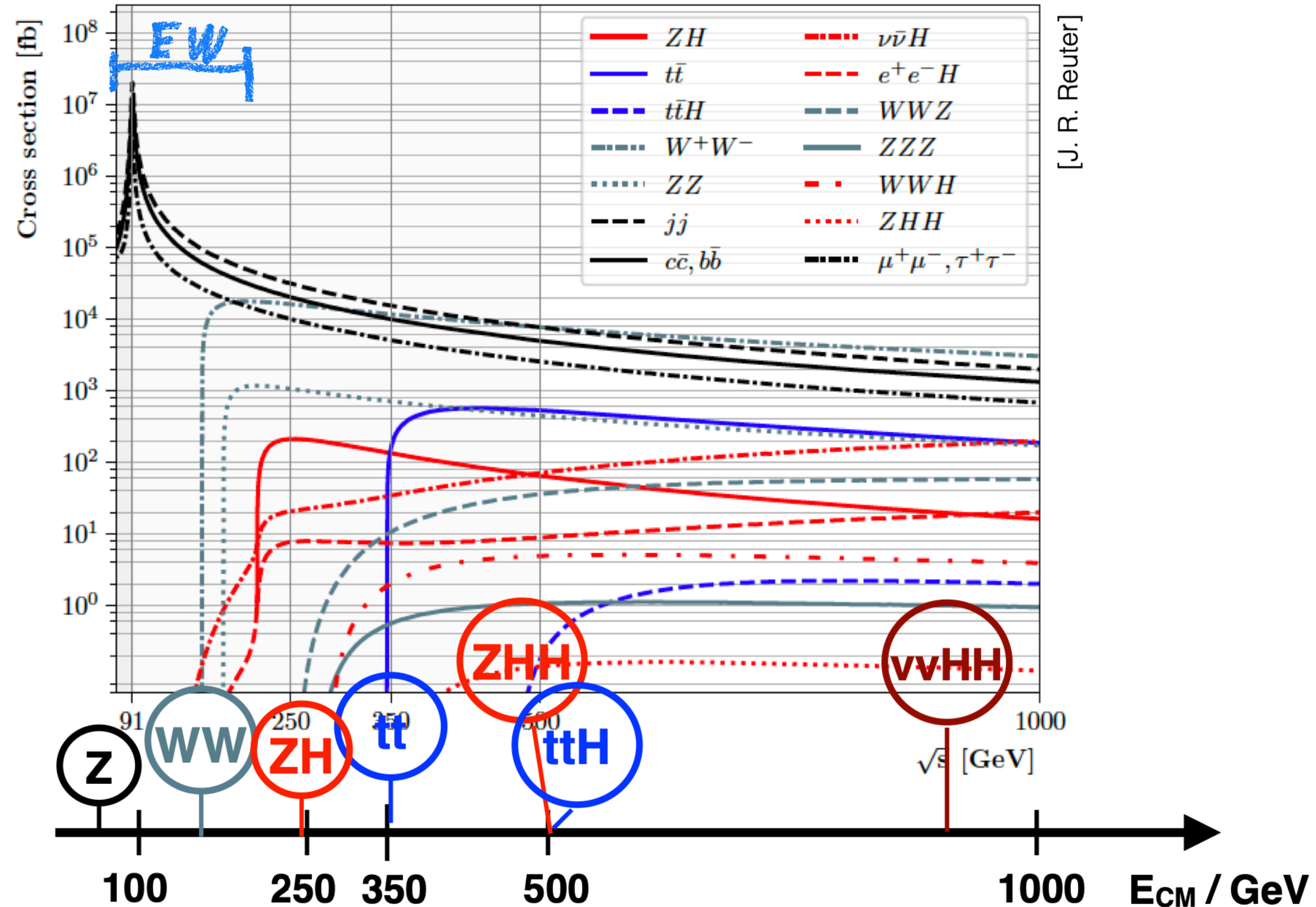
Higgs-Top-Electroweak Factory Physics

Overview



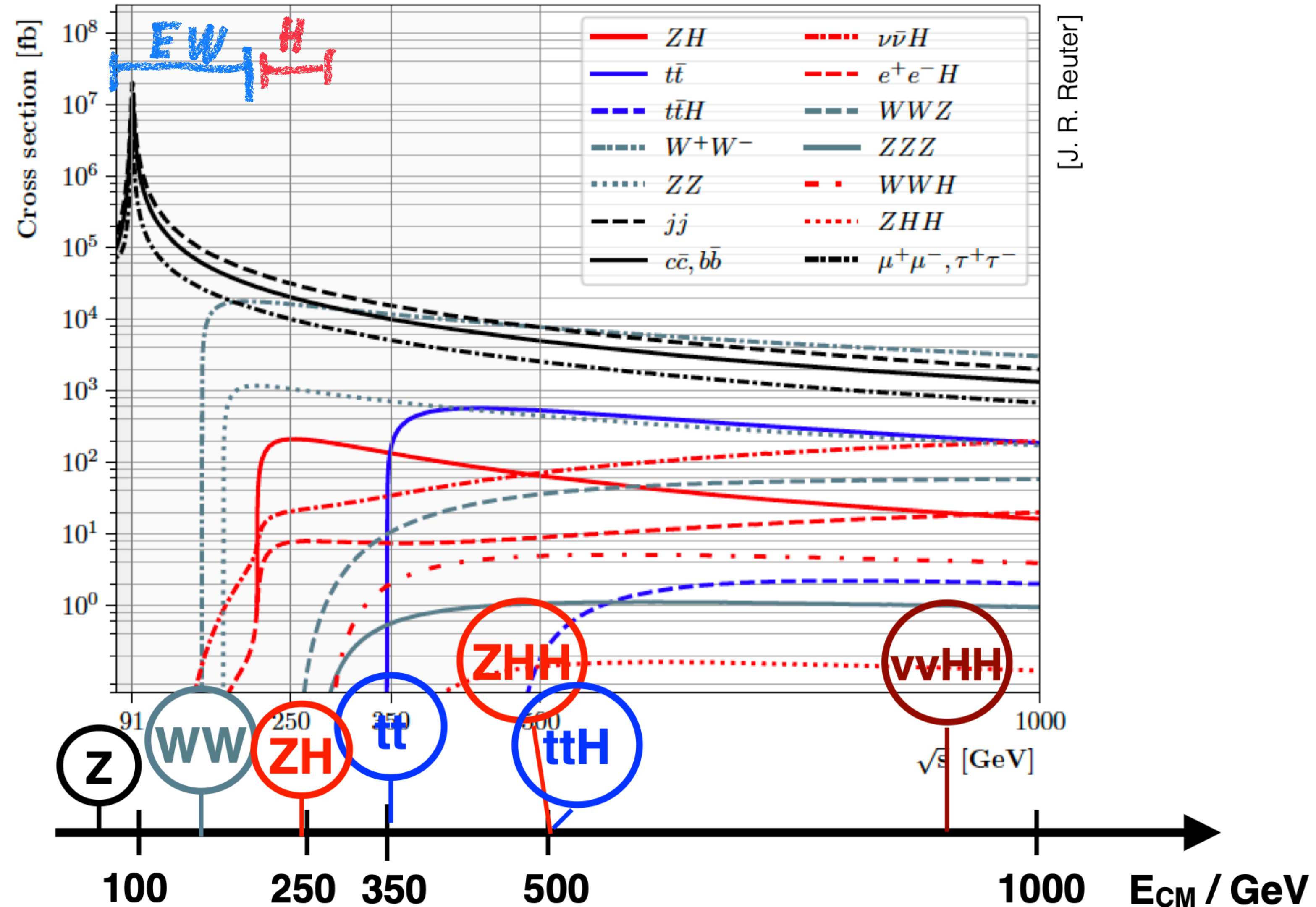
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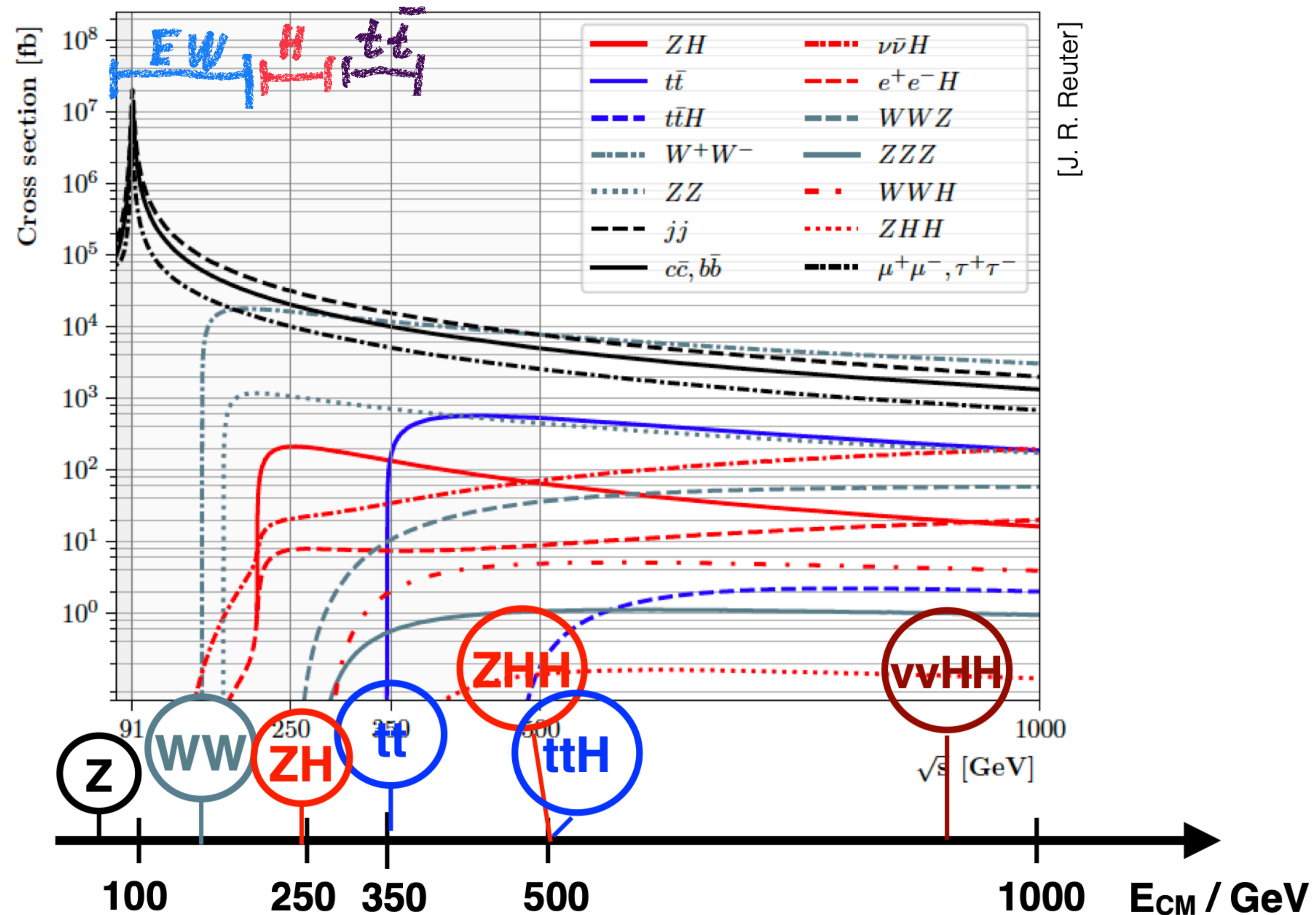
Overview



[J. R. Reuter]

Higgs-Top-Electroweak Factory Physics

Overview



Higgs-Top-Electroweak Factory Physics

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Electroweak Pillar

Electroweak Precision & Discovery

Precision measurements as a probe of New Physics at high scales.

Flavour Physics

The next generation Flavour Factory: Solving flavour puzzles with extreme statistics (10x Belle II).

Direct Searches

Weakly coupled lighter BSM particles with high statistics.

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Top Pillar

Precise and theoretically well-defined measurement of top quark mass.

Top as a BSM probe: Sensitivity due to high mass.

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Connects higher-E pillars!

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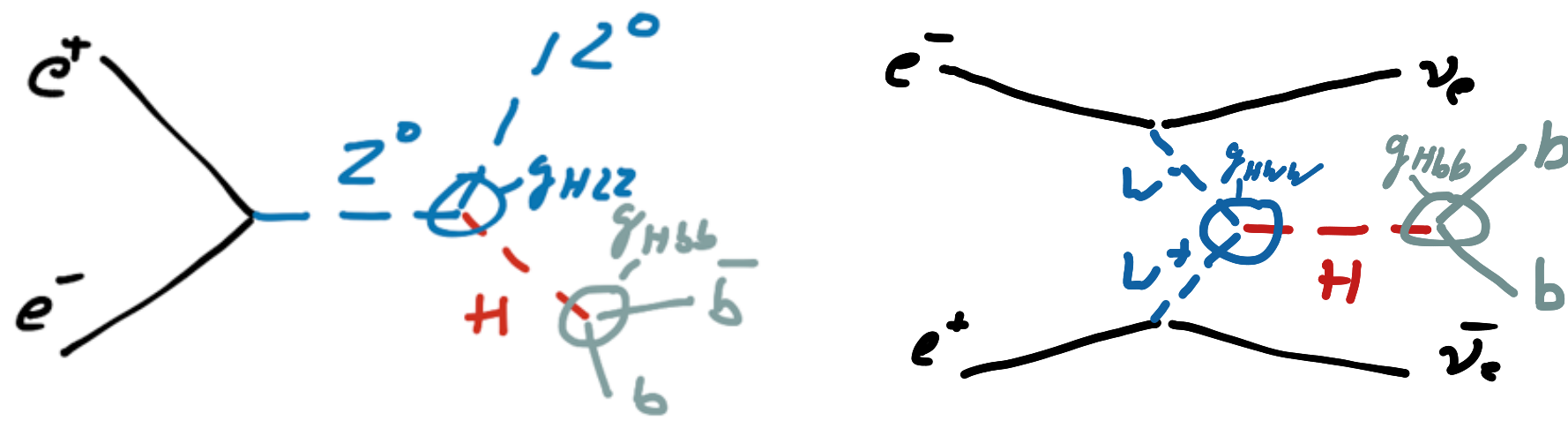
Top as a BSM probe:
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Details of potential of each pillar depend on facility details. Physics potential has been studied in detail over the last 2+ decades.

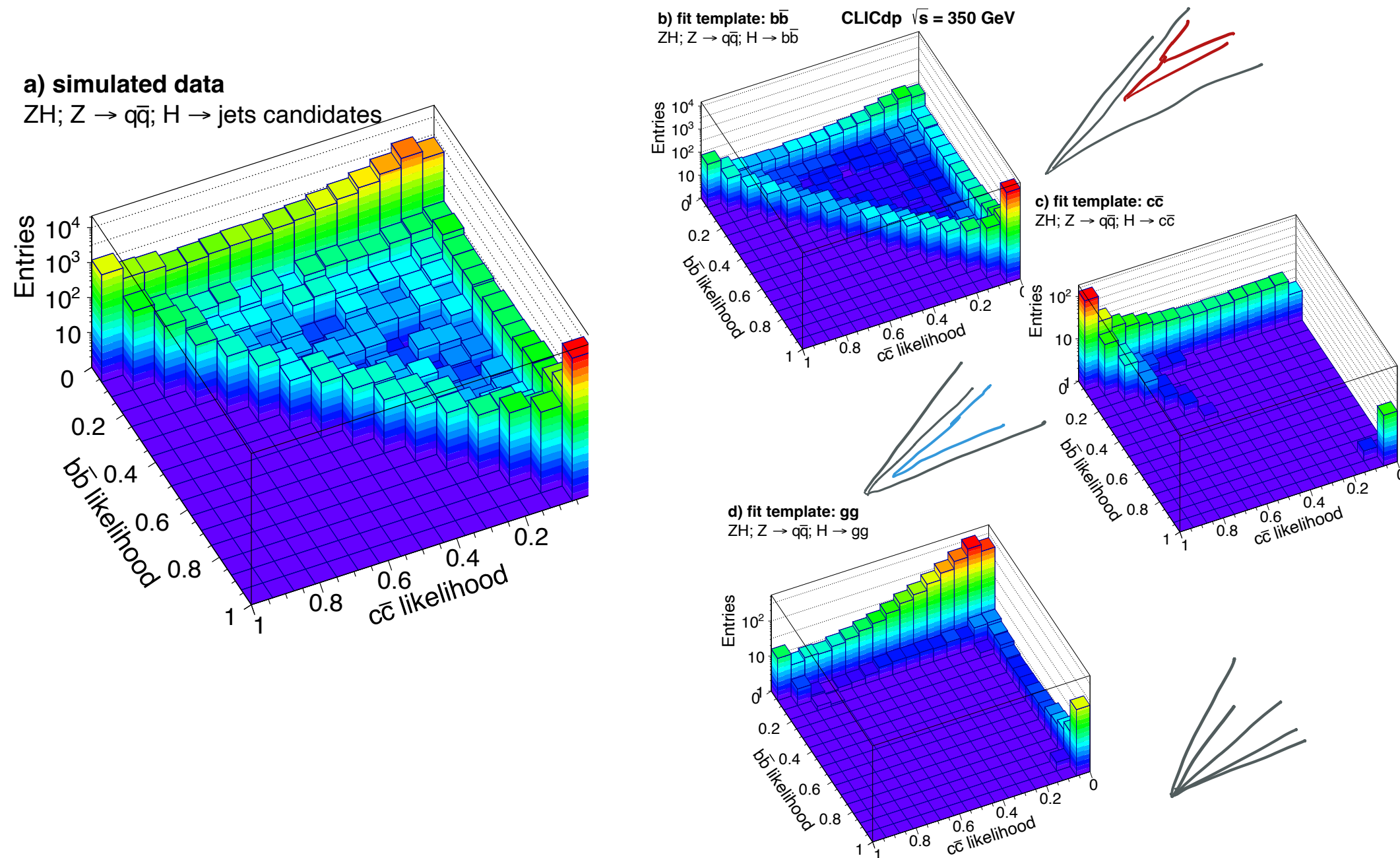
Higgs-Top-Electroweak Factory Physics

Selected Studies

- Studying the Higgs Boson



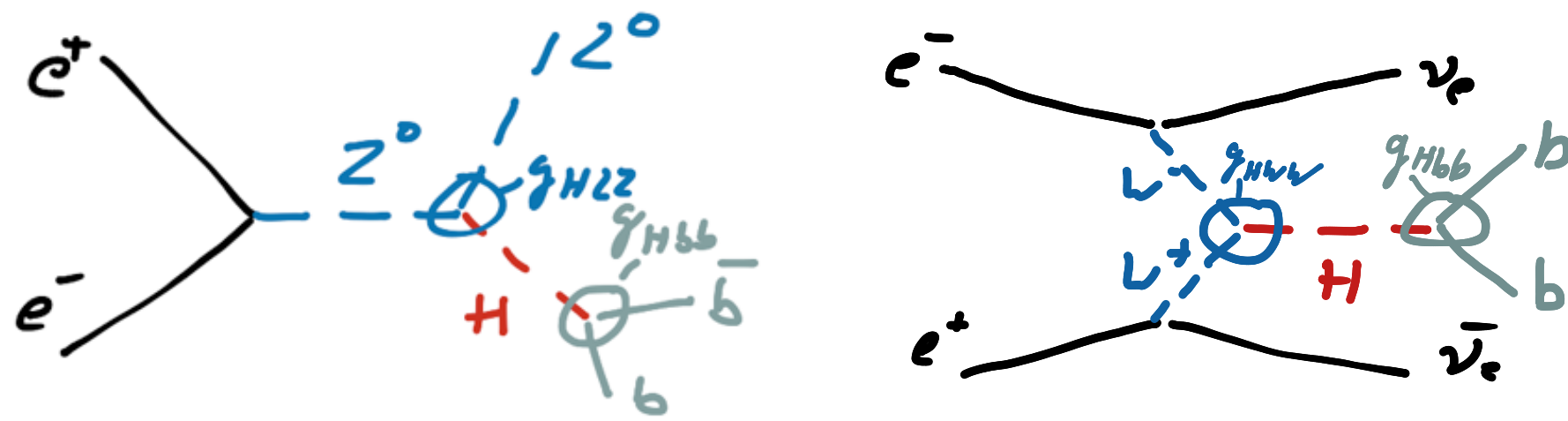
Couplings at the (sub-)percent-level.



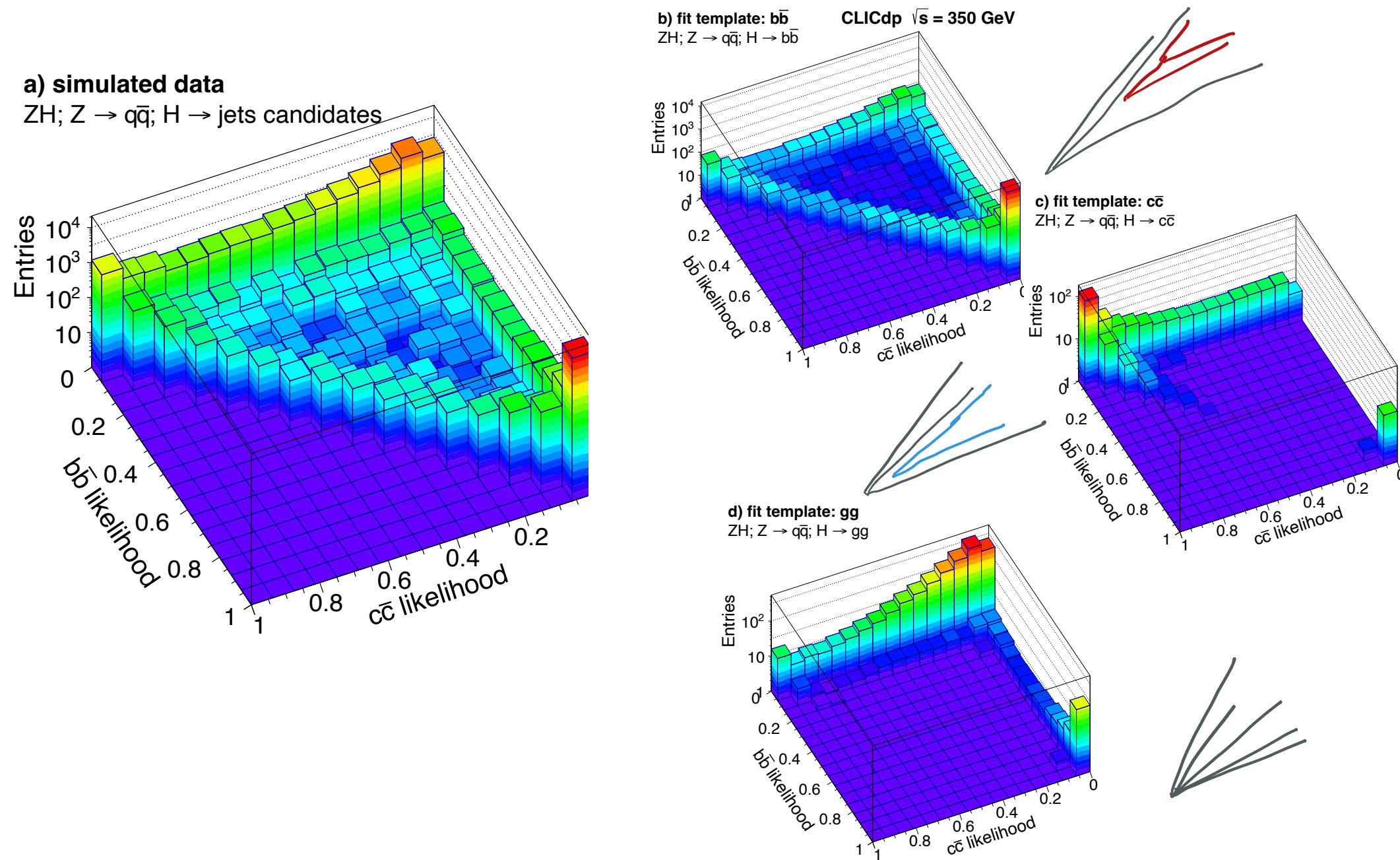
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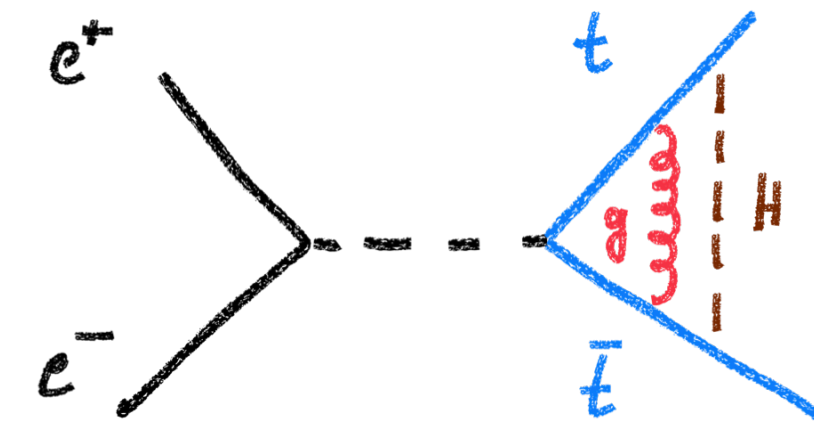
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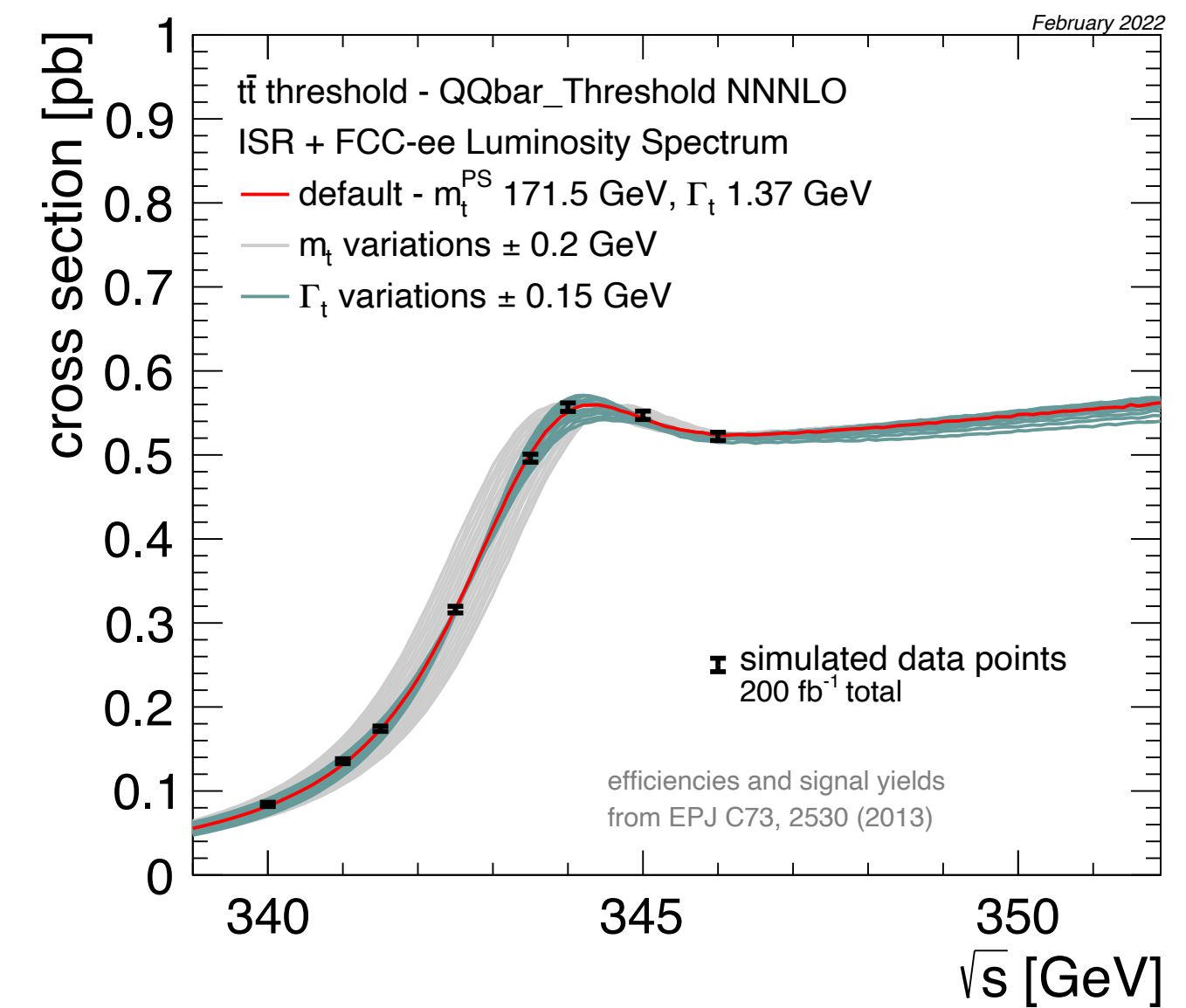
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- ... and the Top Quark



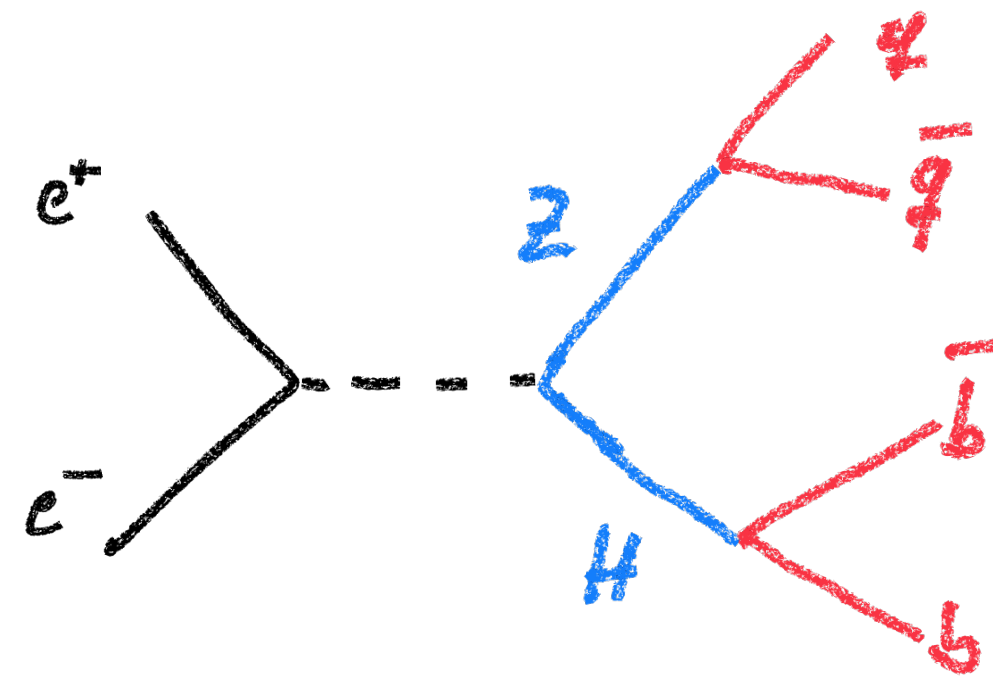
Mass to better than 50 MeV - interplay with precise theory calculations.



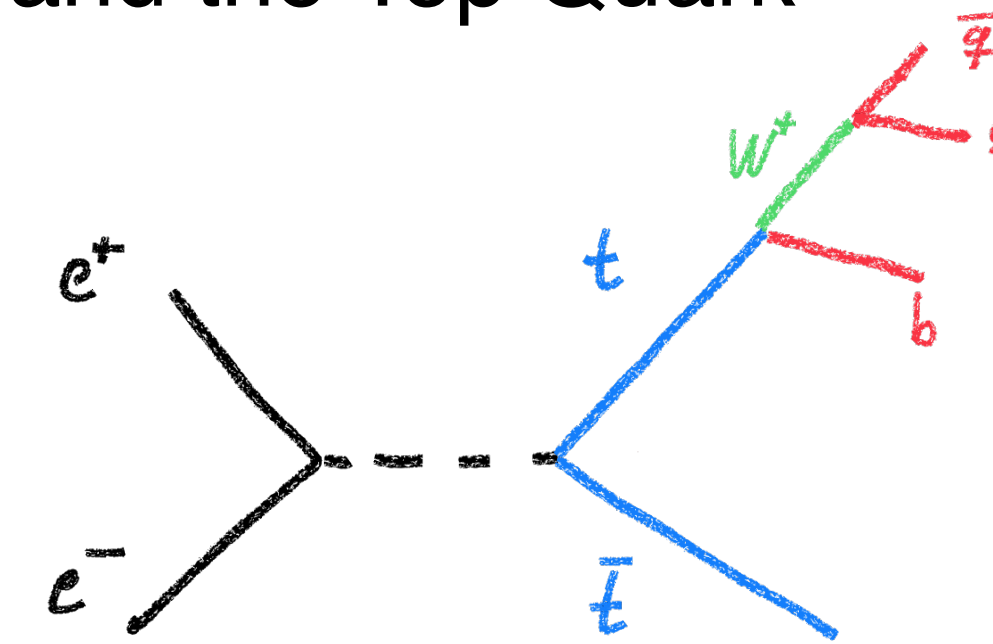
Higgs-Top-Electroweak Factory Physics

Turned into Technology Needs

- Studying the Higgs Boson



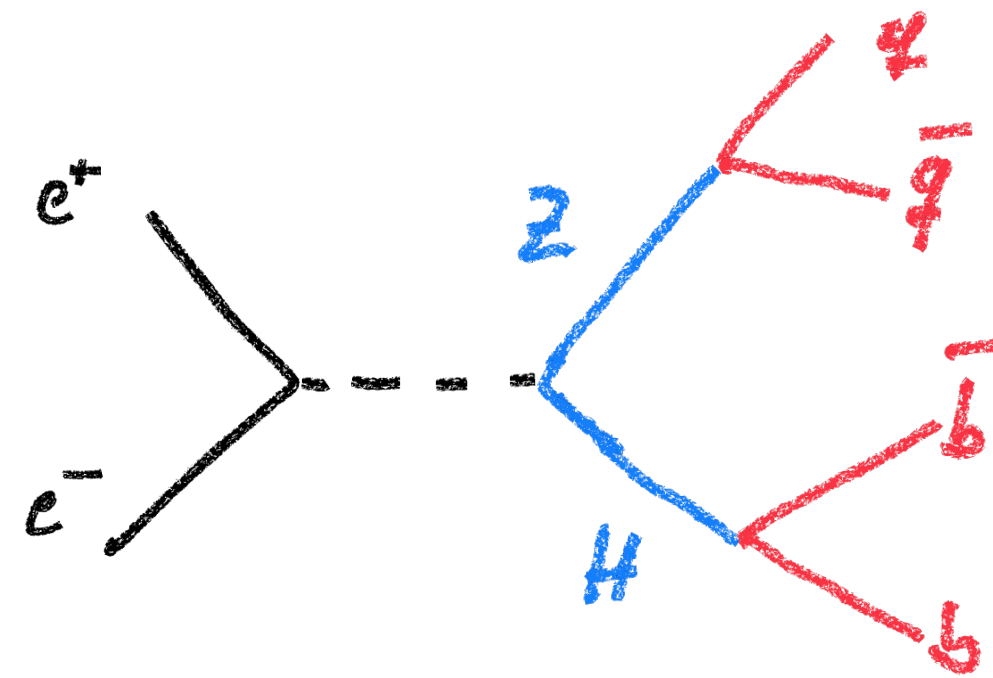
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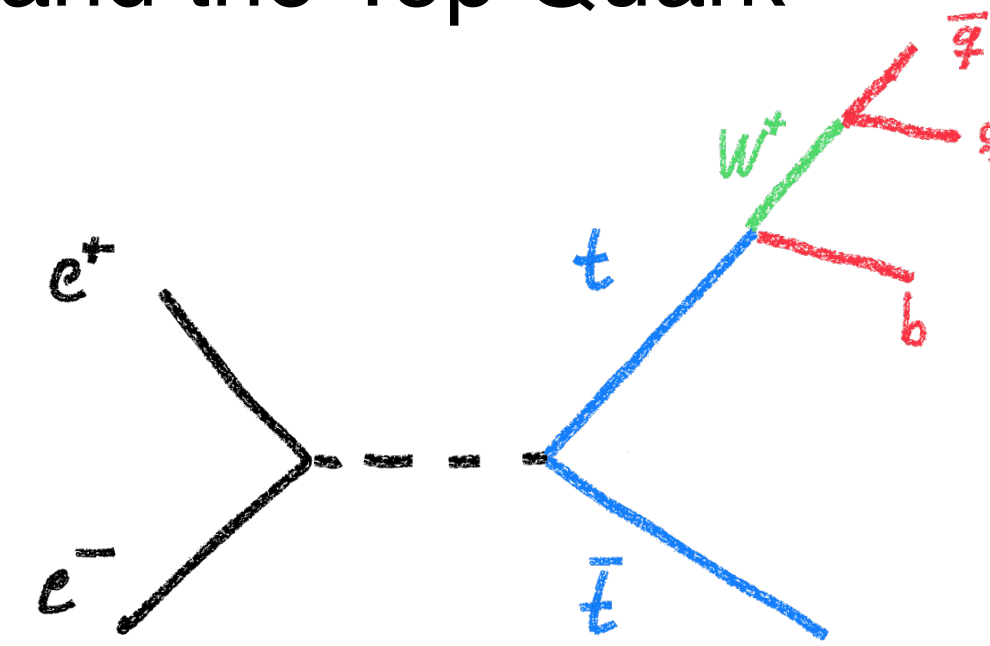
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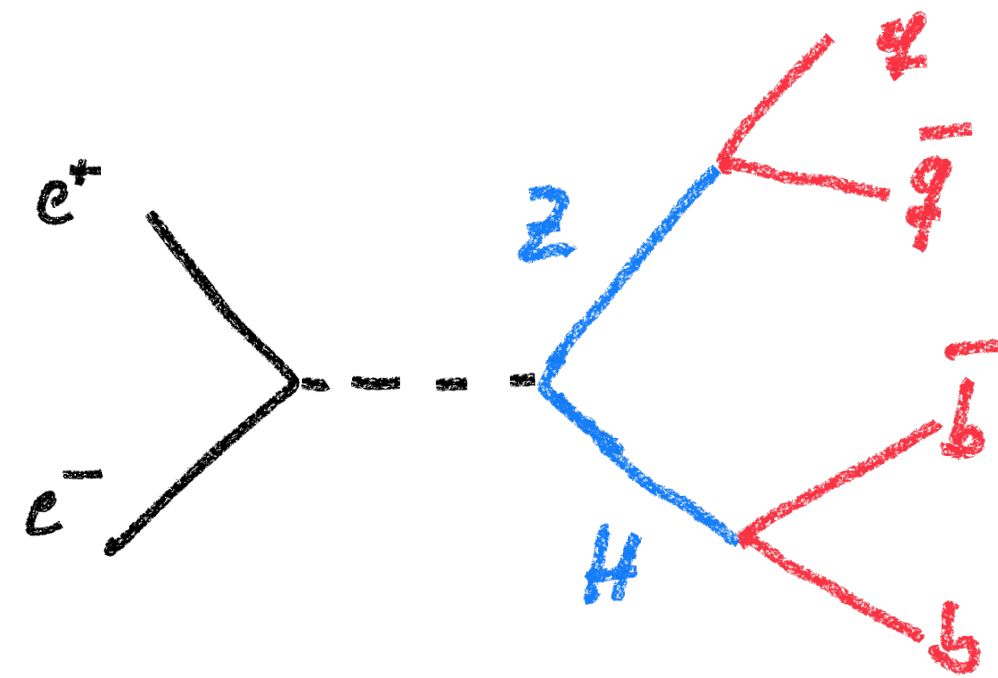
common requirements:

- flavour tagging
- jet reconstruction

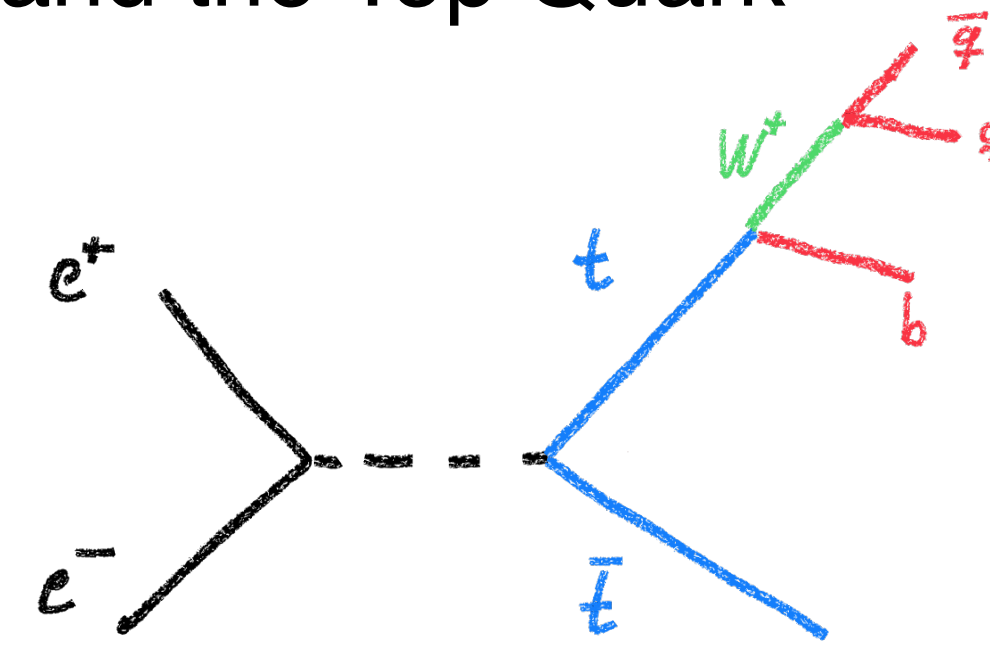
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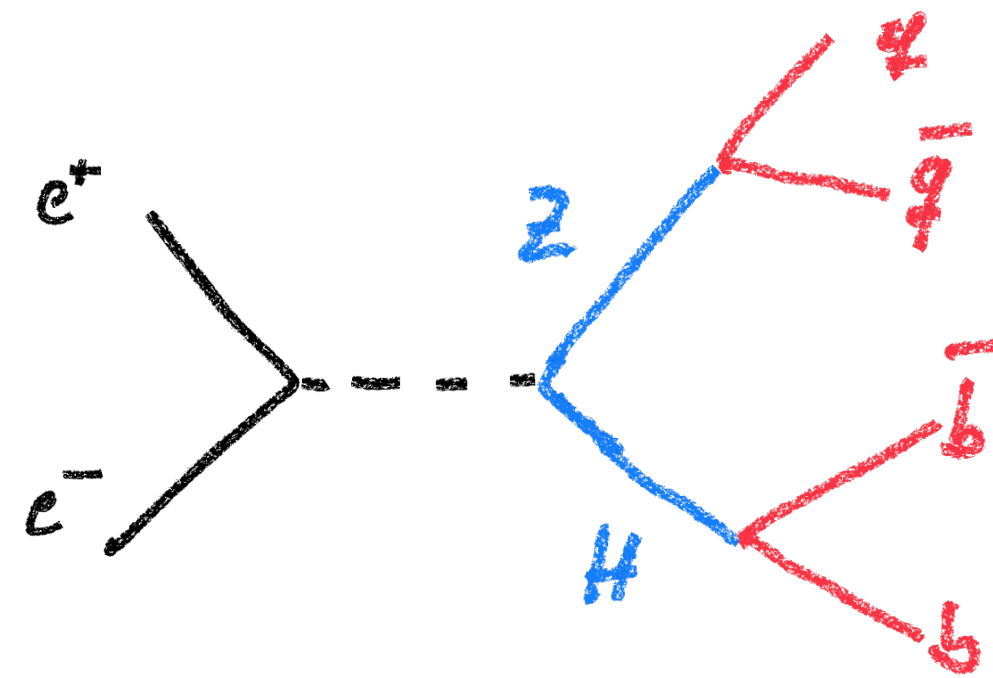
The origin of DEPFETs as HEP detectors:

- extremely thin, low-mass detectors ($50 \mu\text{m}$ or below)
- small cells ($25 \times 25 \mu\text{m}^2$)- high spatial resolution

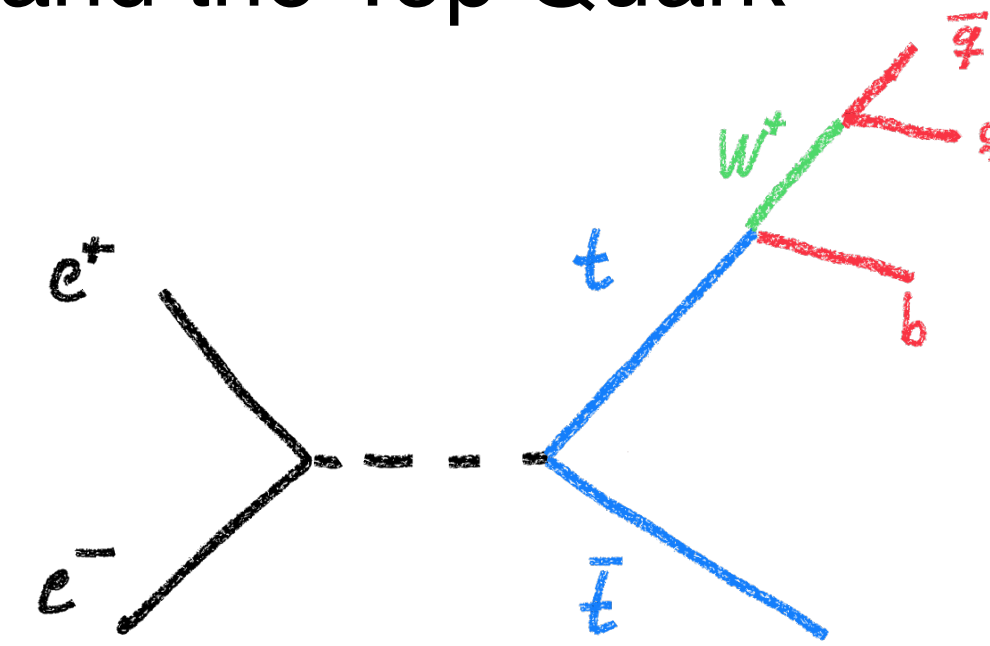
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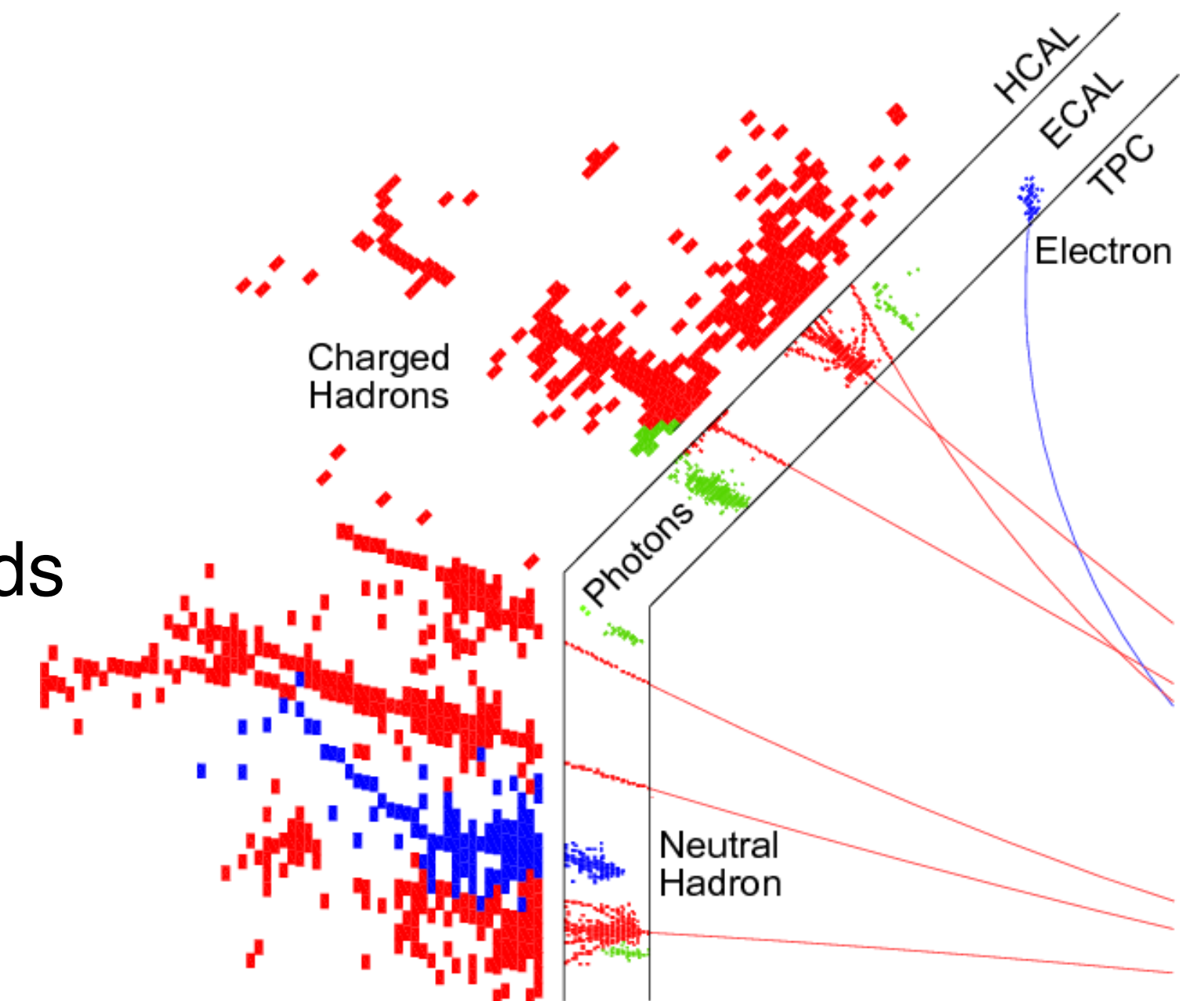
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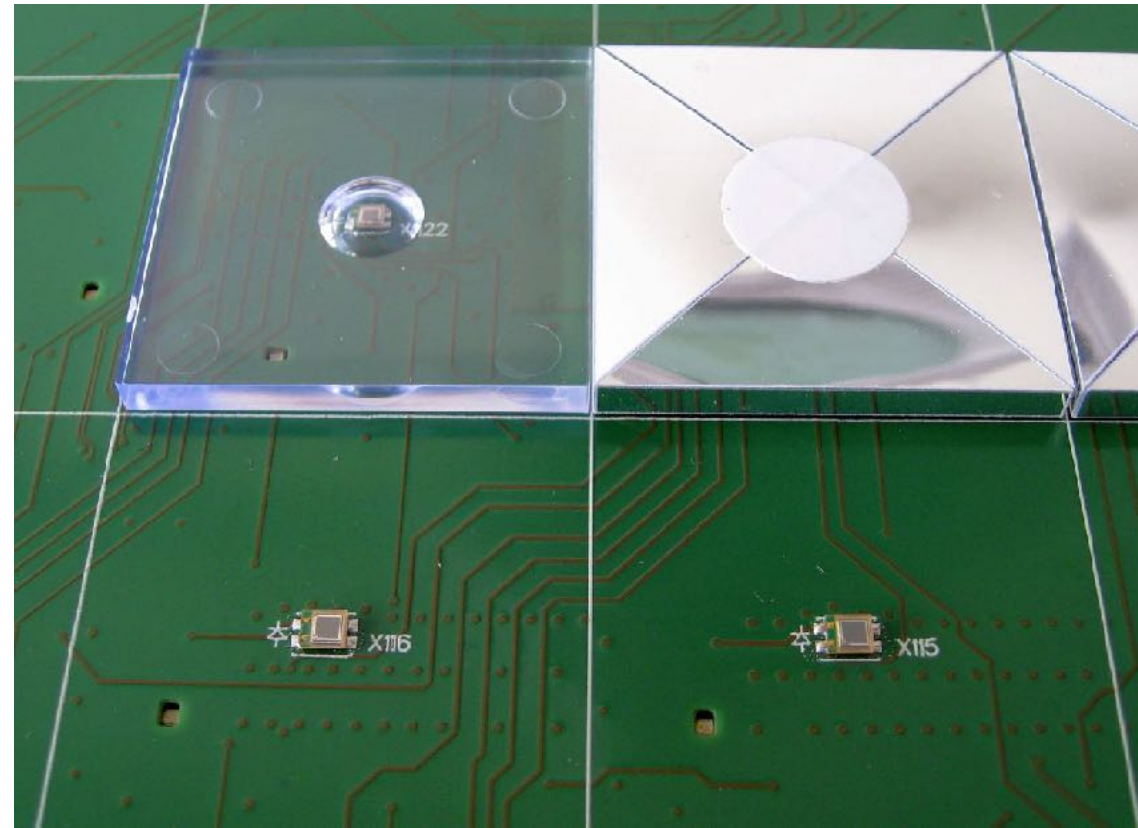
Particle Flow as the path towards ultimate jet energy resolution:
Highly granular calorimeters



Highly Granular Calorimetry

The Origin of CLAWS

- The CALICE SiPM-on-Tile technology: The path to a hadron calorimeter with 10 million cells



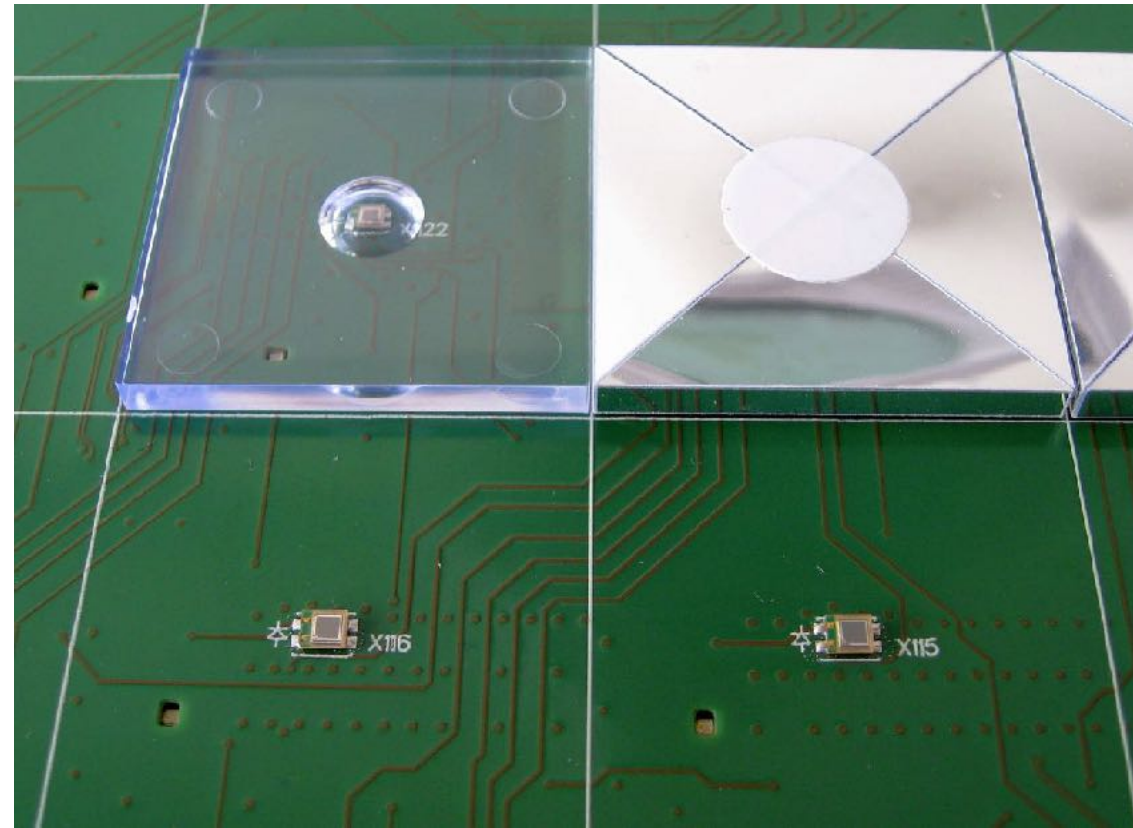
SiPMs +
integrated electronics

high degree of
automatized assembly

Highly Granular Calorimetry

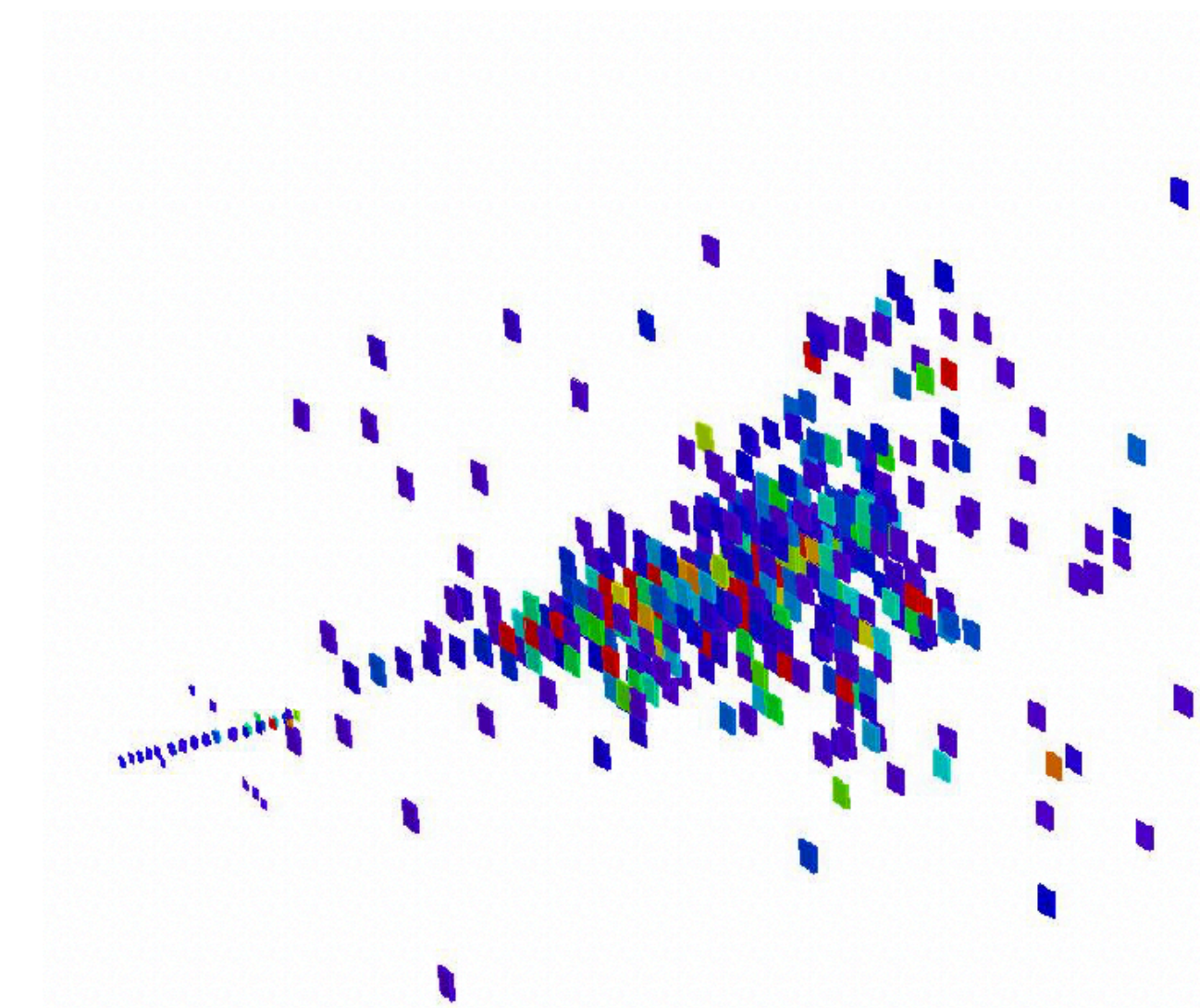
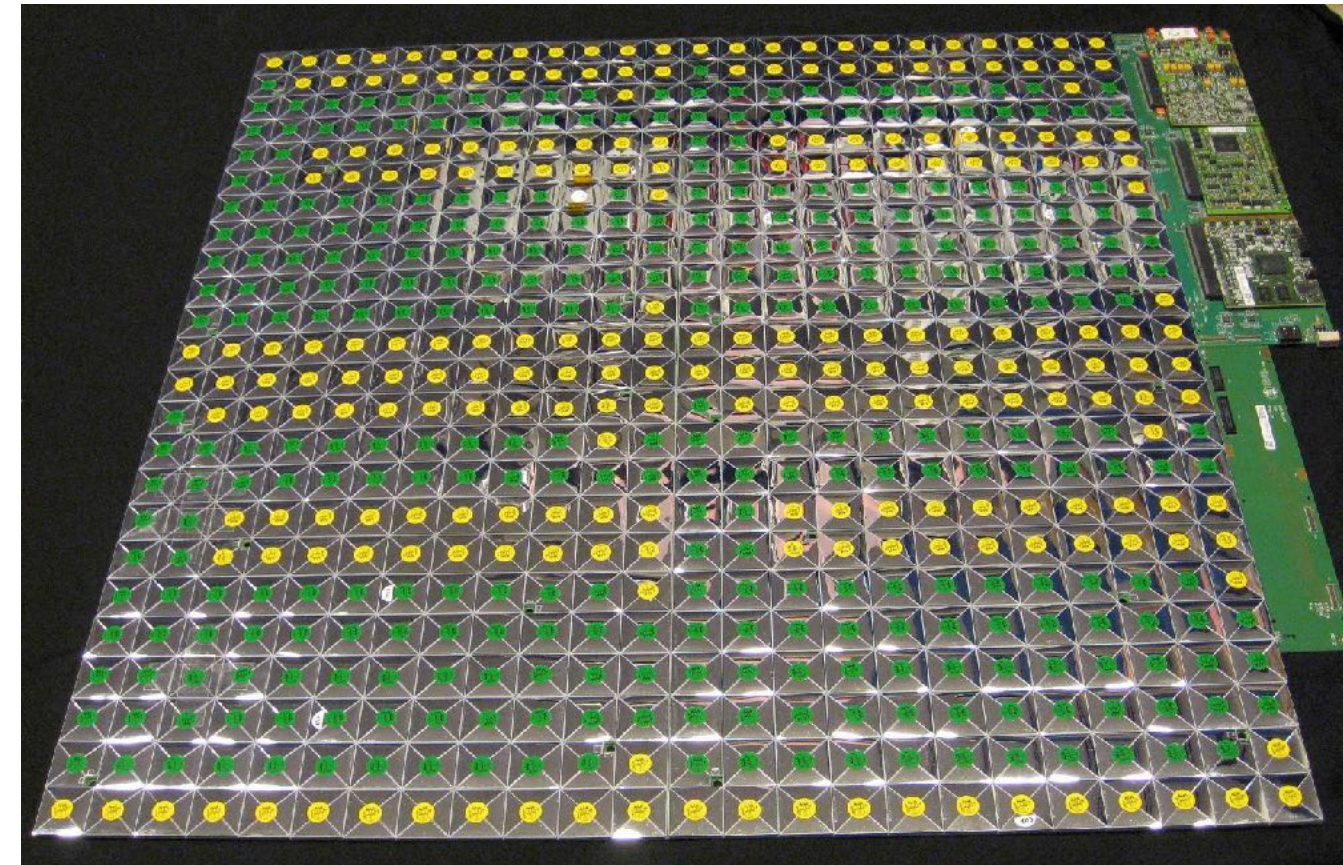
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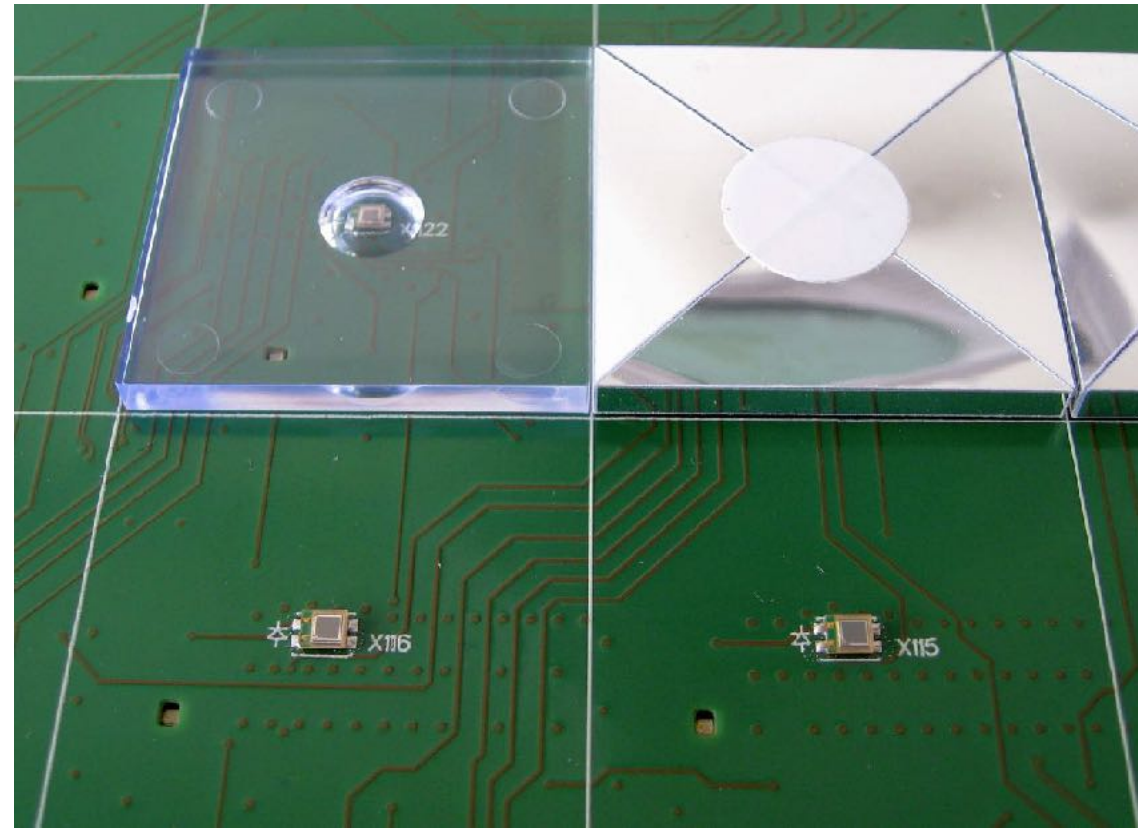
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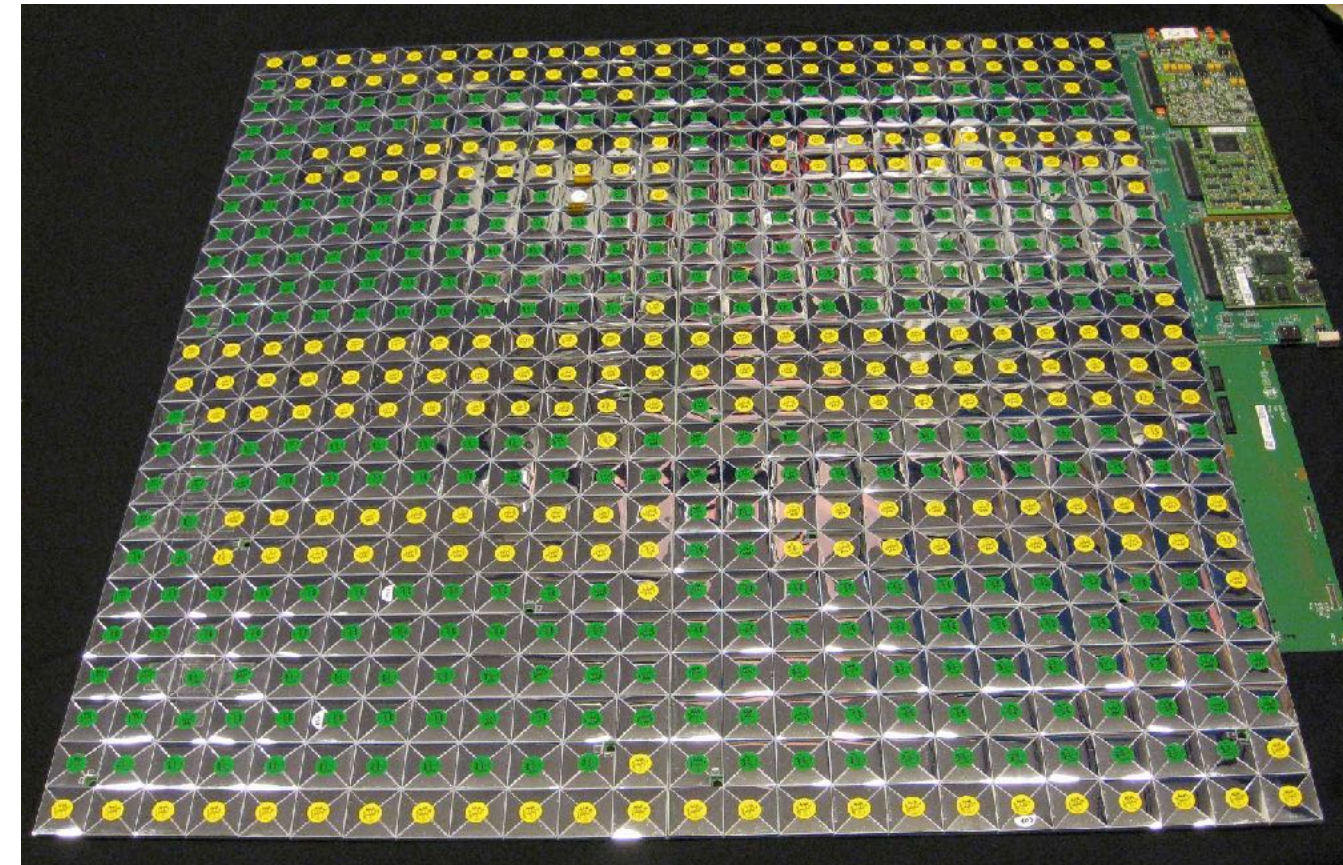
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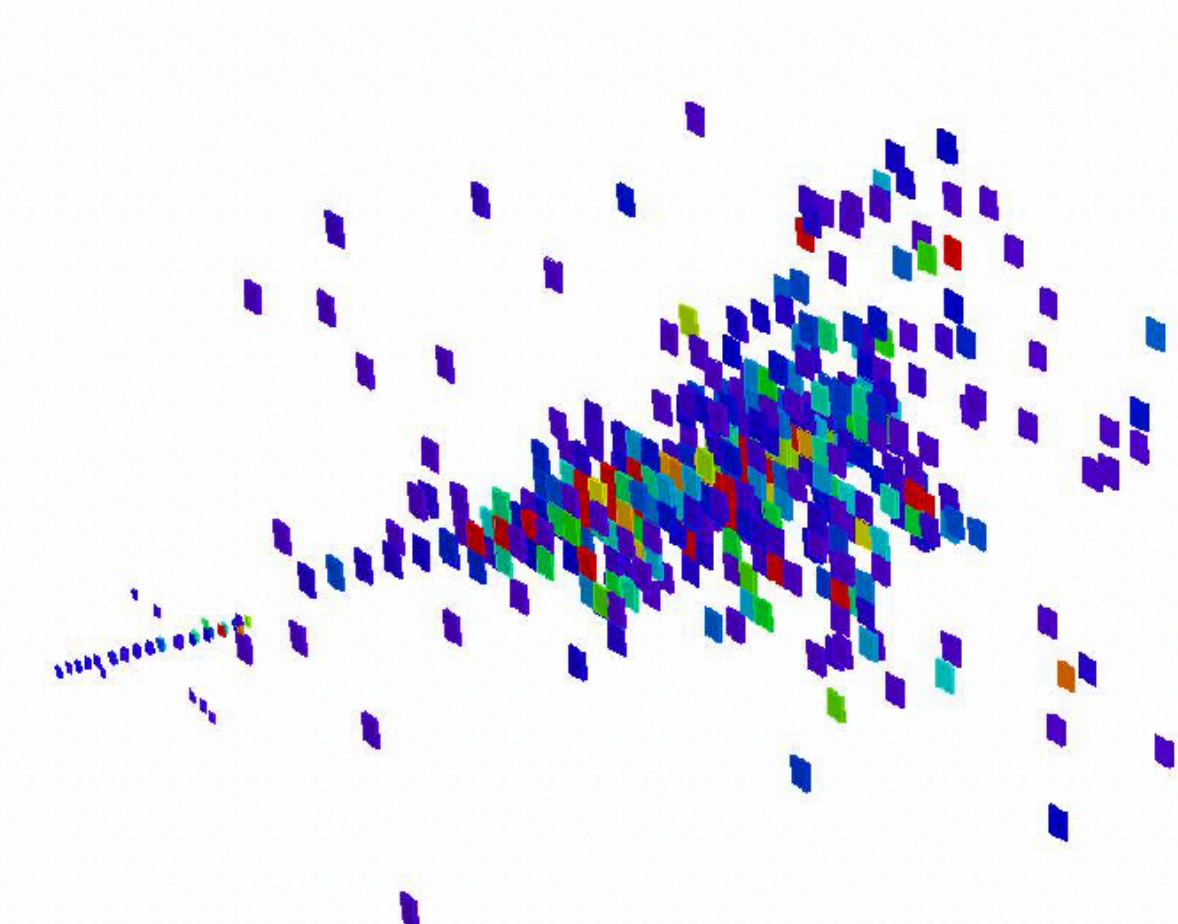
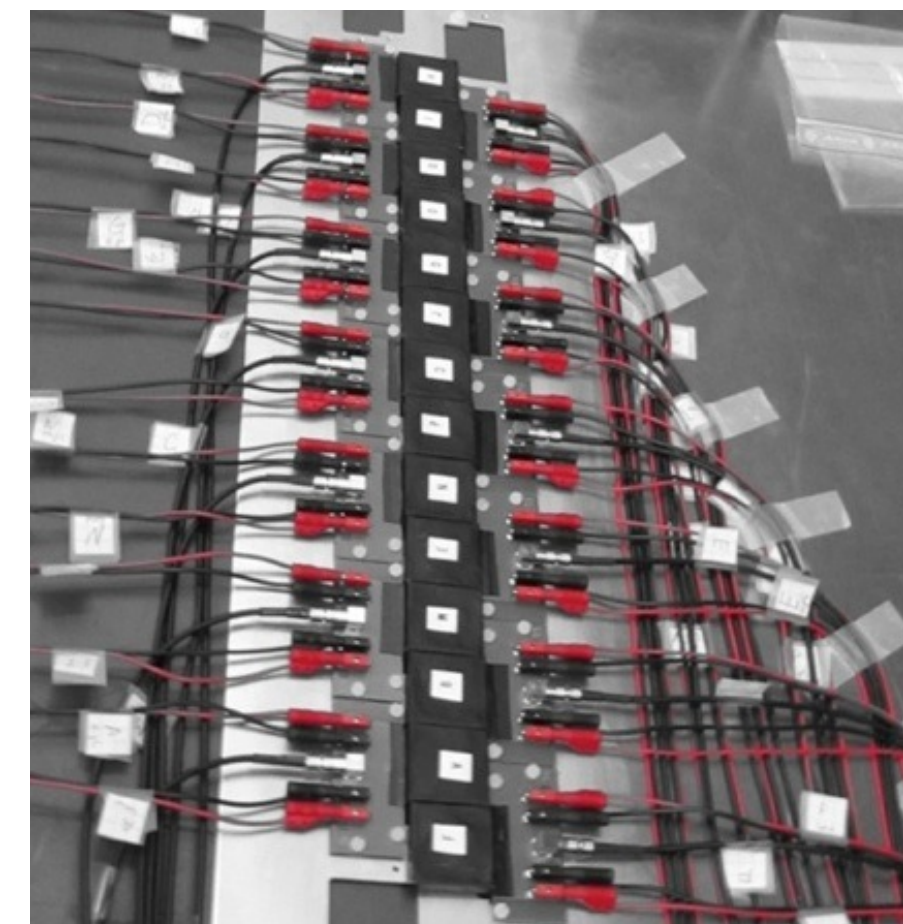
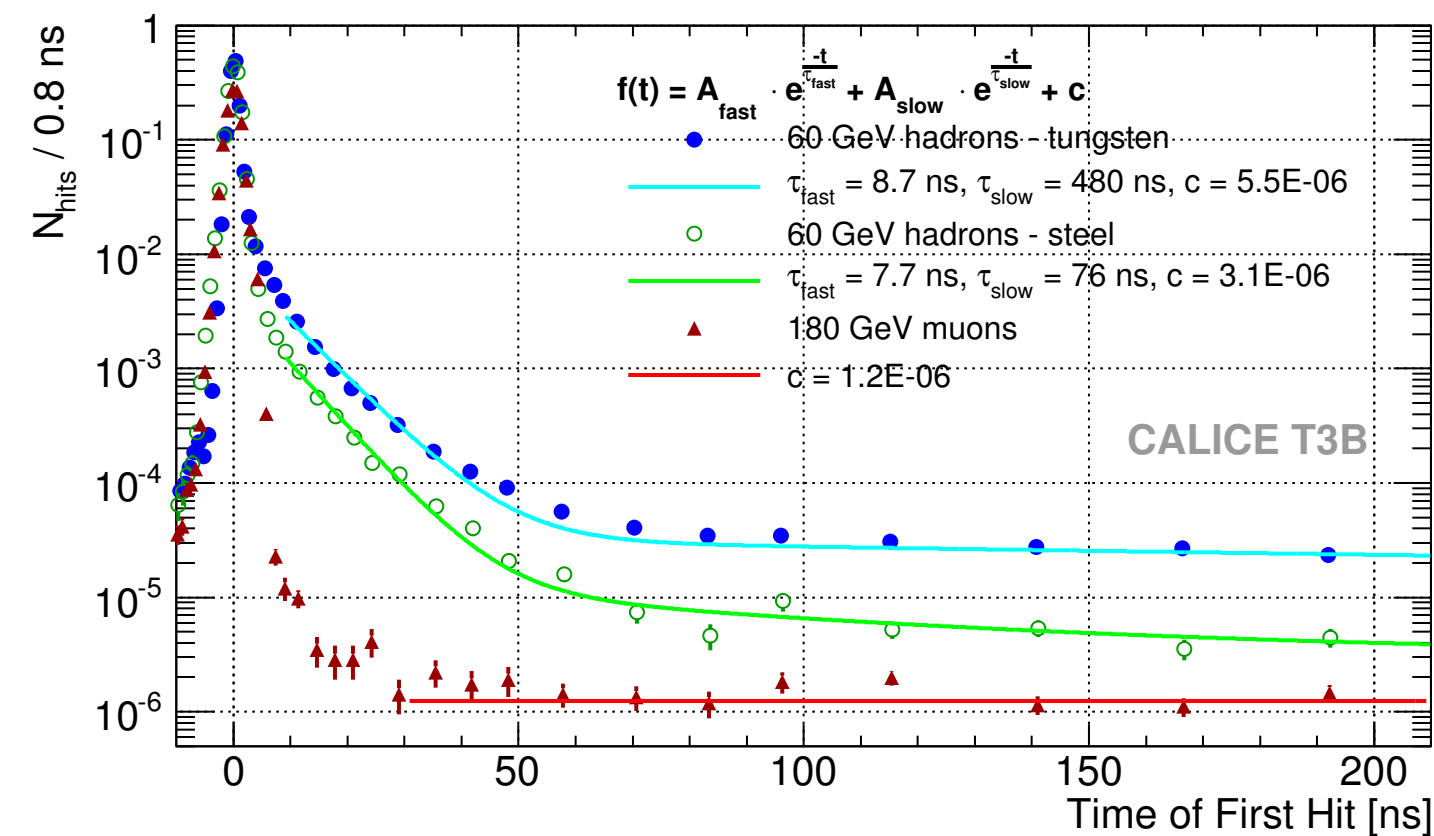


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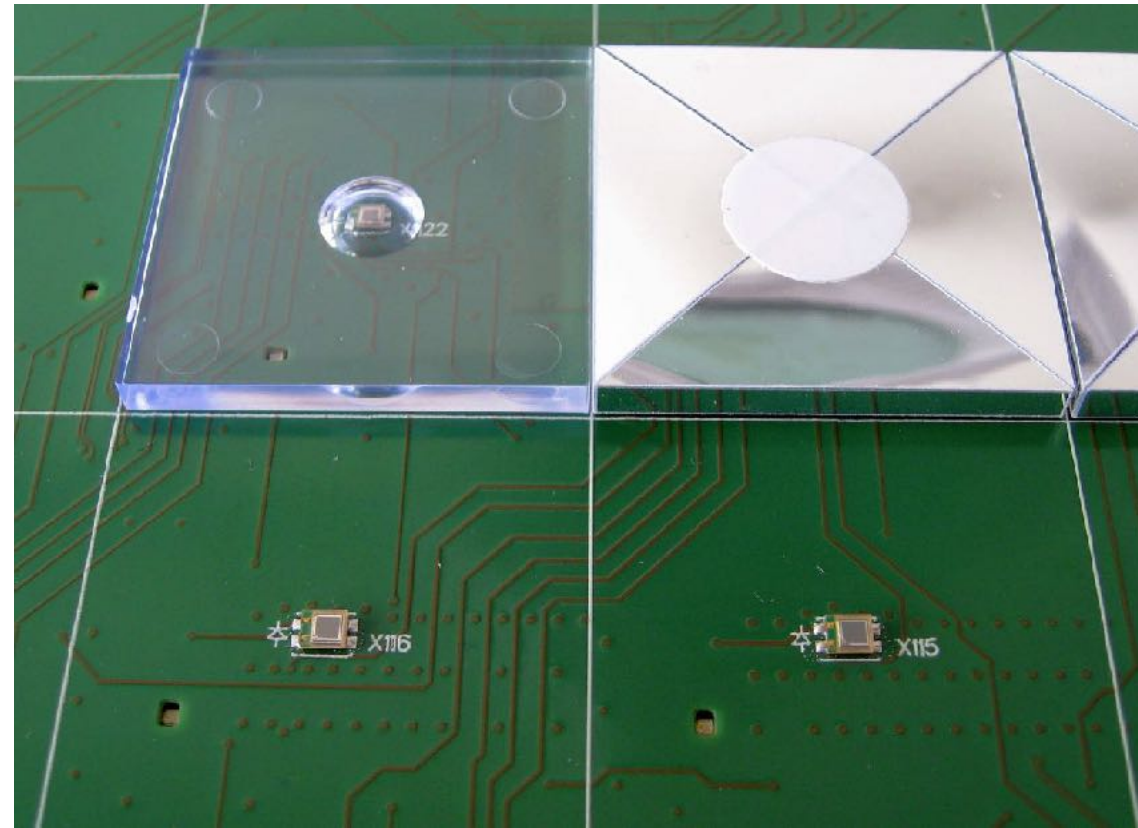
A spin-off: T3B - measuring the
time structure of hadronic showers



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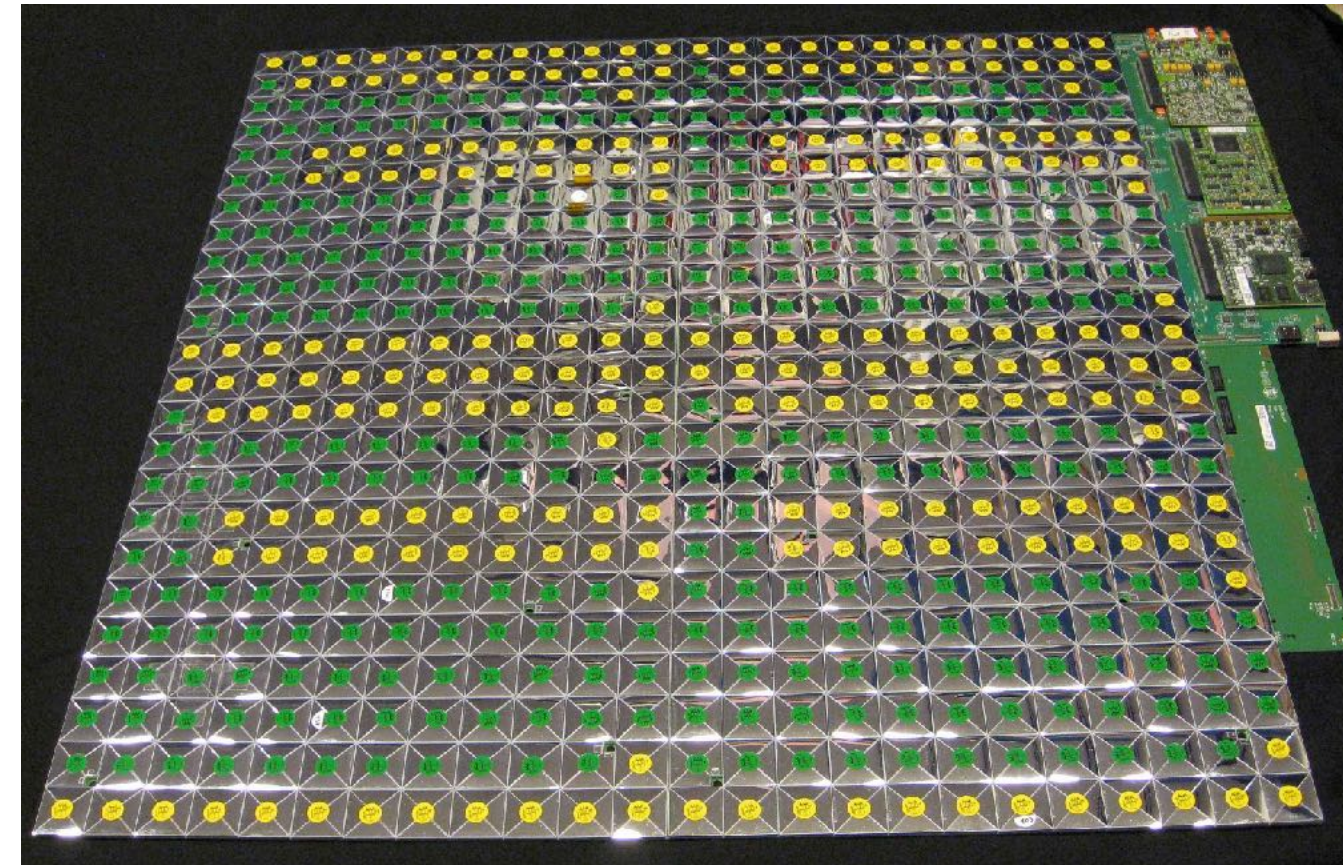
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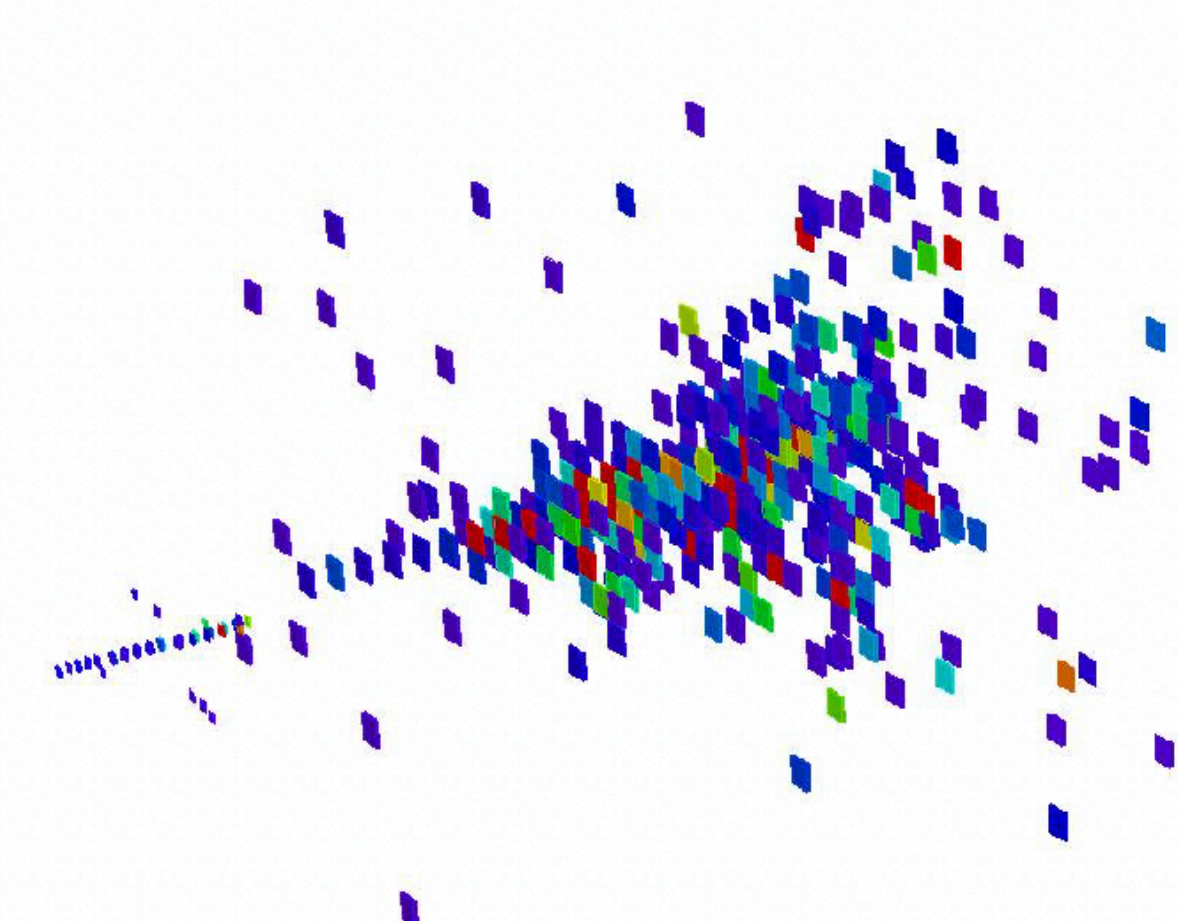
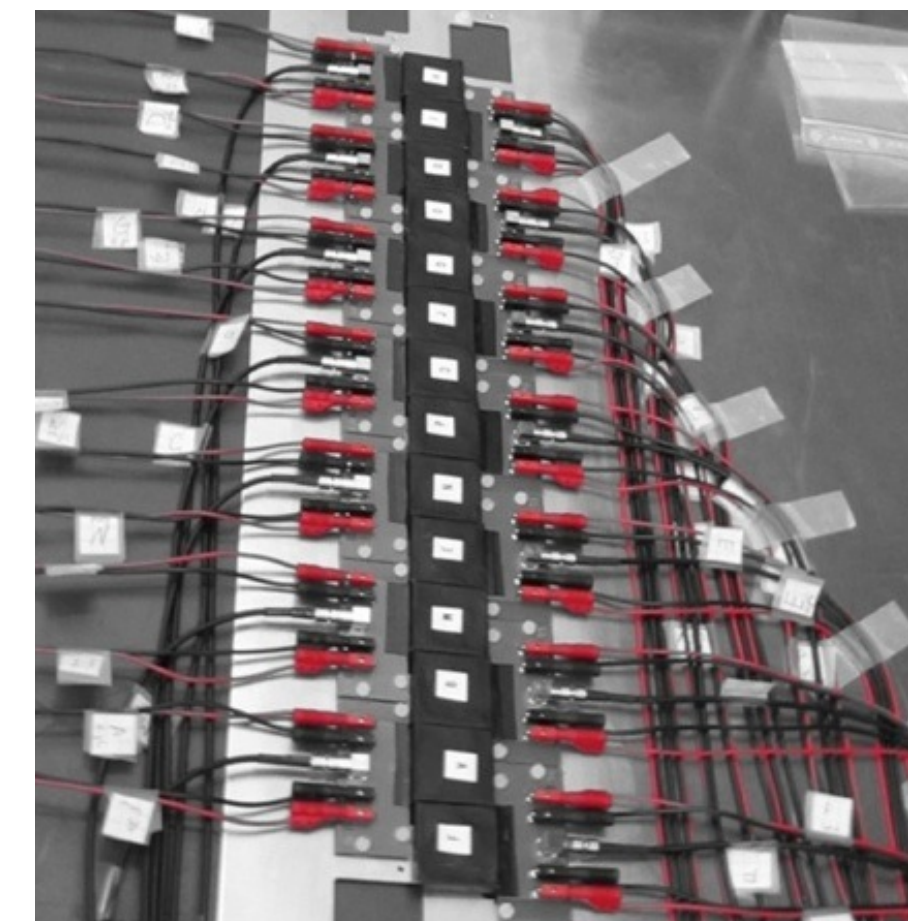
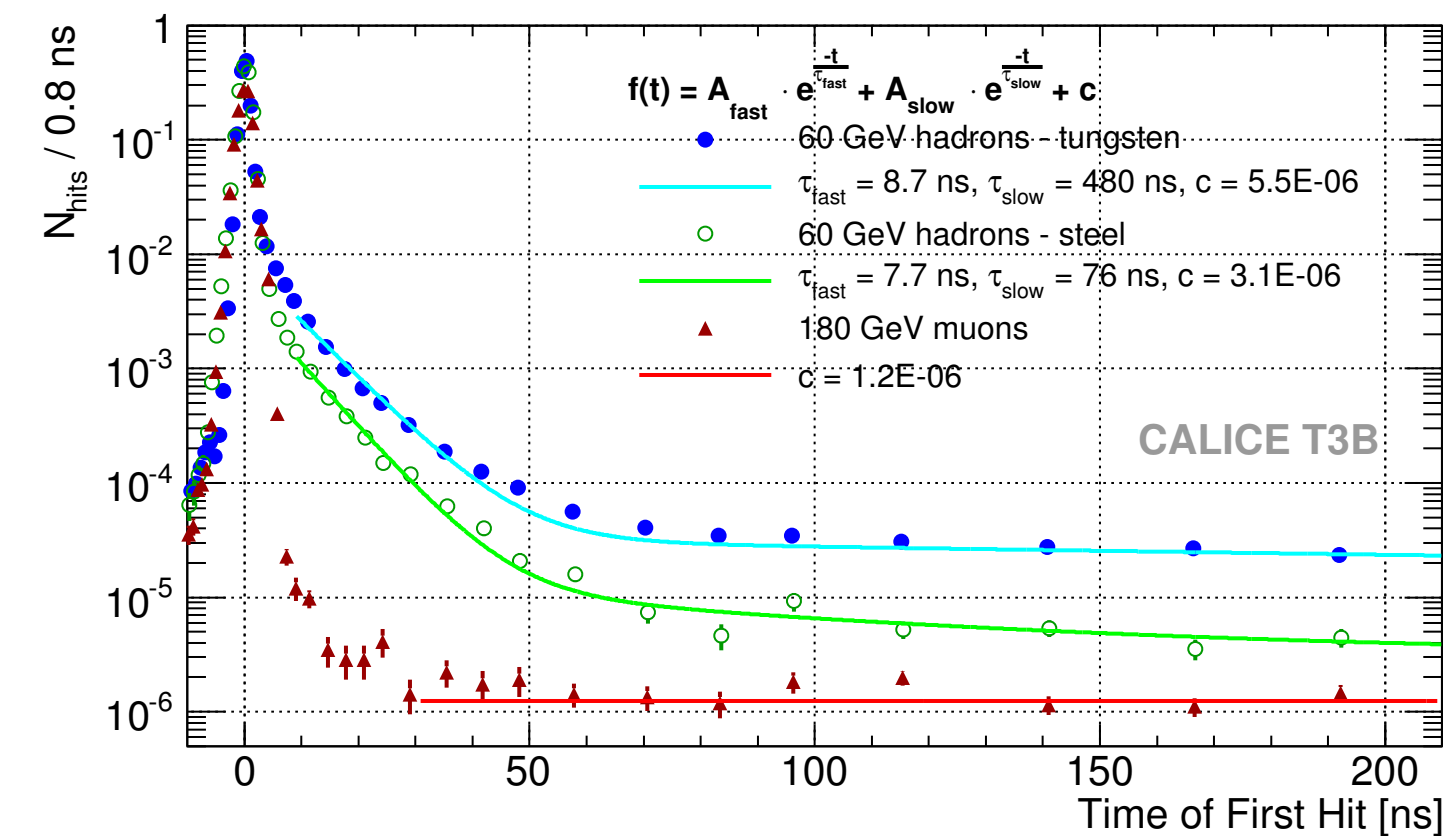
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Basis of CLAWS system for
first phase of SuperKEKB

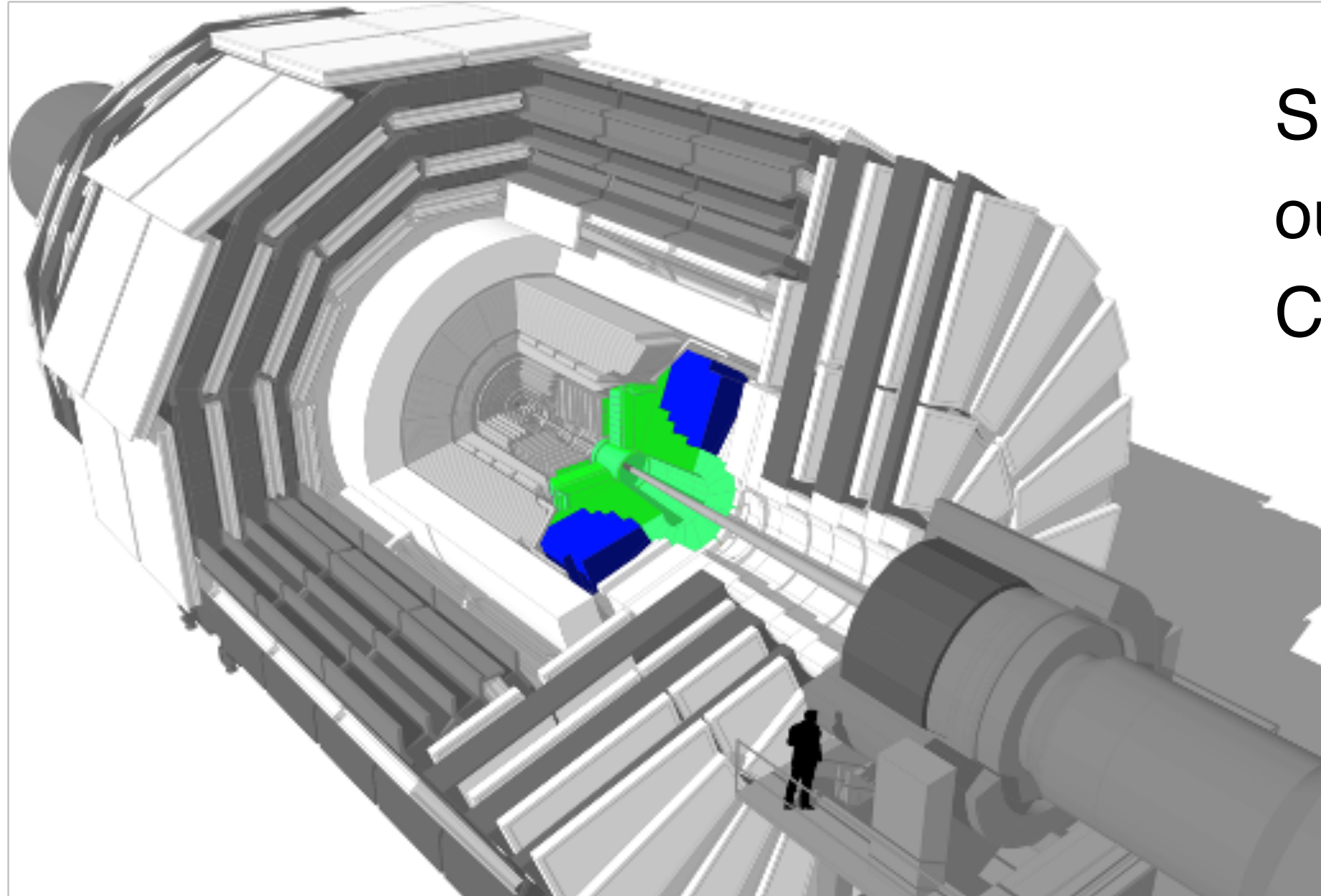
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Not only Belle II: LHC as Technology Adopter

CMS HGCAL

- A major upgrade of the CMS endcap calorimeters

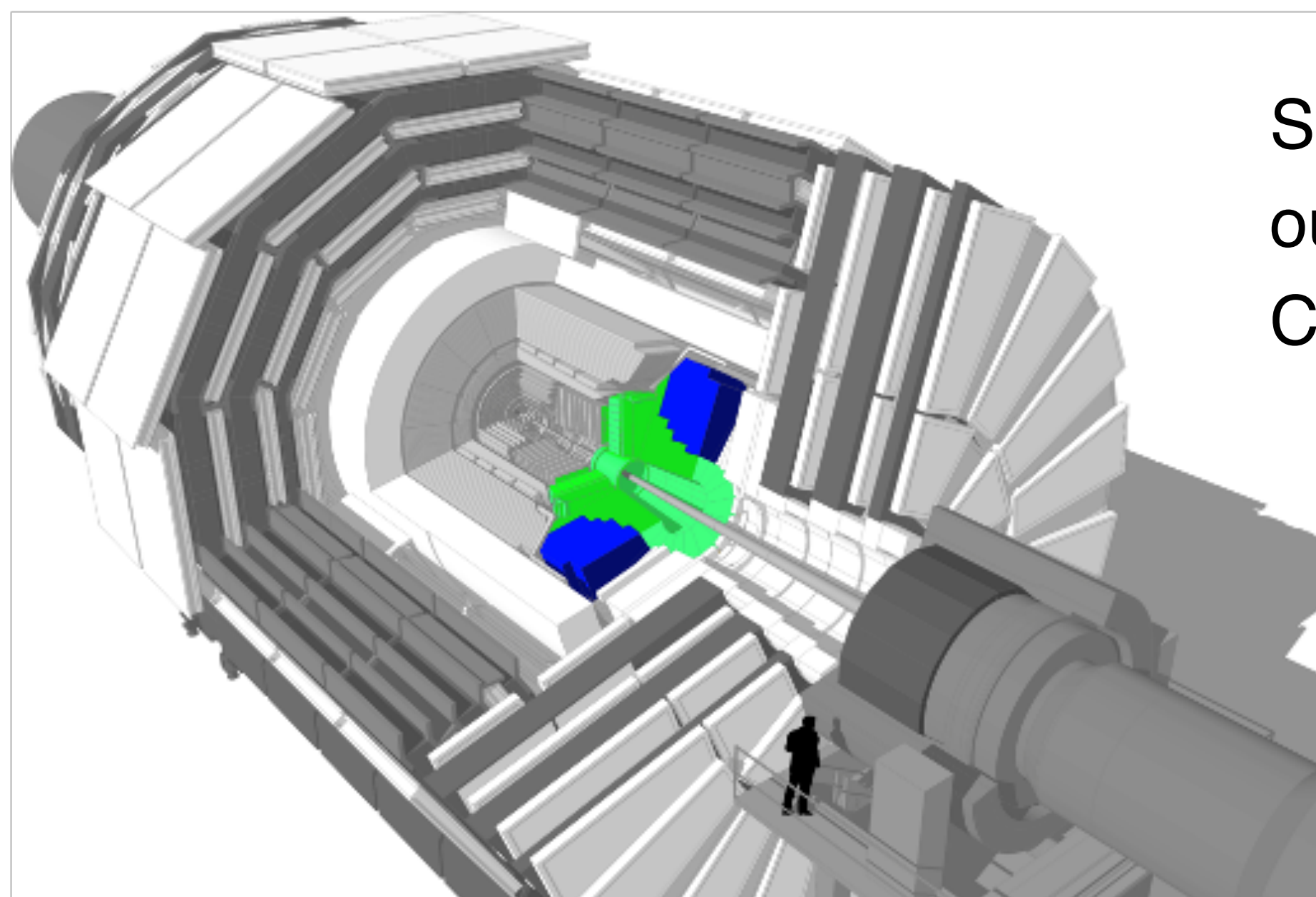


SiPM-on-tile technology in outer region. Profited from CALICE and CLAWS R&D.

Not only Belle II: LHC as Technology Adopter

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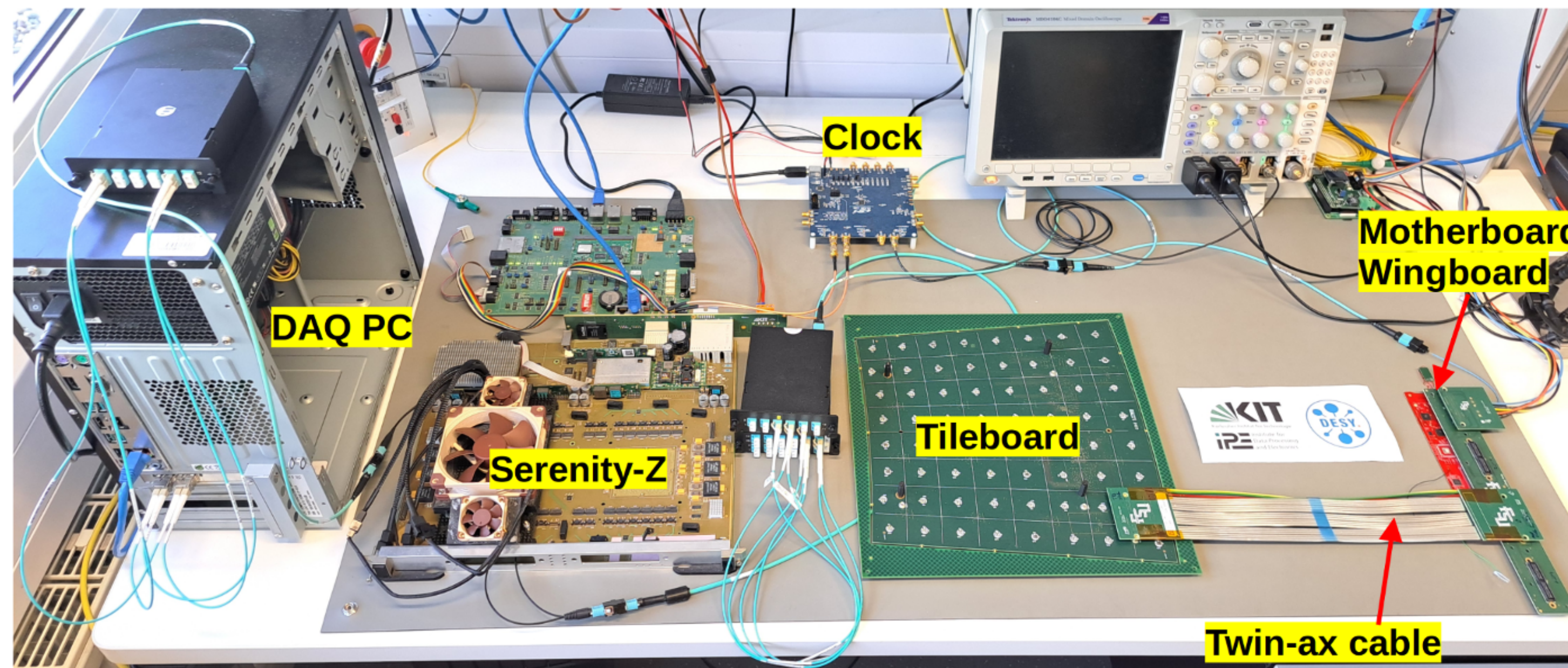
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SiPM-on-tile technology in outer region. Profited from CALICE and CLAWS R&D.

And: an interesting data challenge: 40 TB/s into backend system (Serenity, developed at IPE)

Ultimate proof (and more!) of this technology for future experiments.



From Colliders to Dark Matter

DAQ as an enabling Technology

- The Serenity Board:
Heart of the CMS Phase II Backend



Maximum data
throughput: 3.2 TB/s
Sophisticated triggering
algorithms on FPGA

From Colliders to Dark Matter

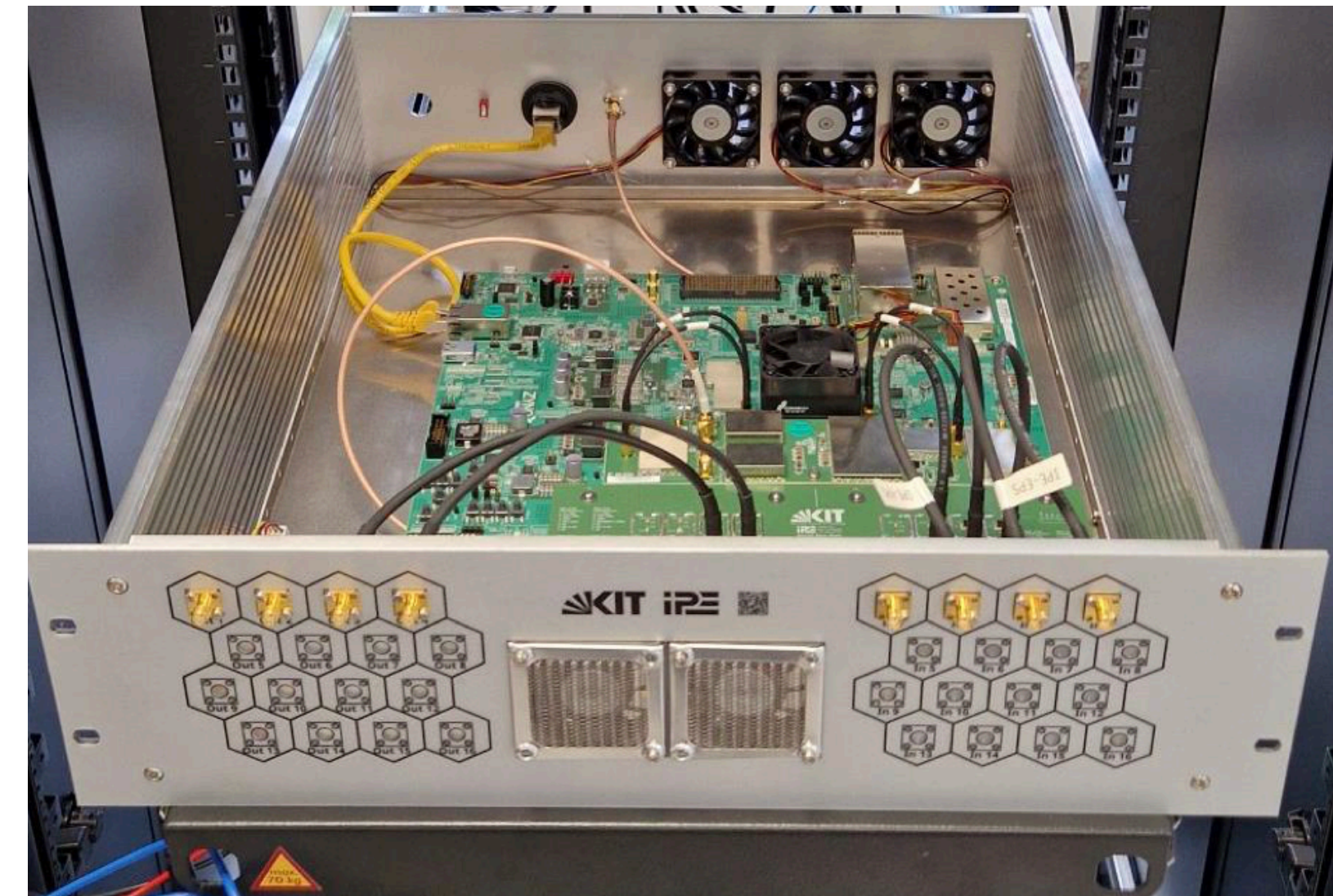
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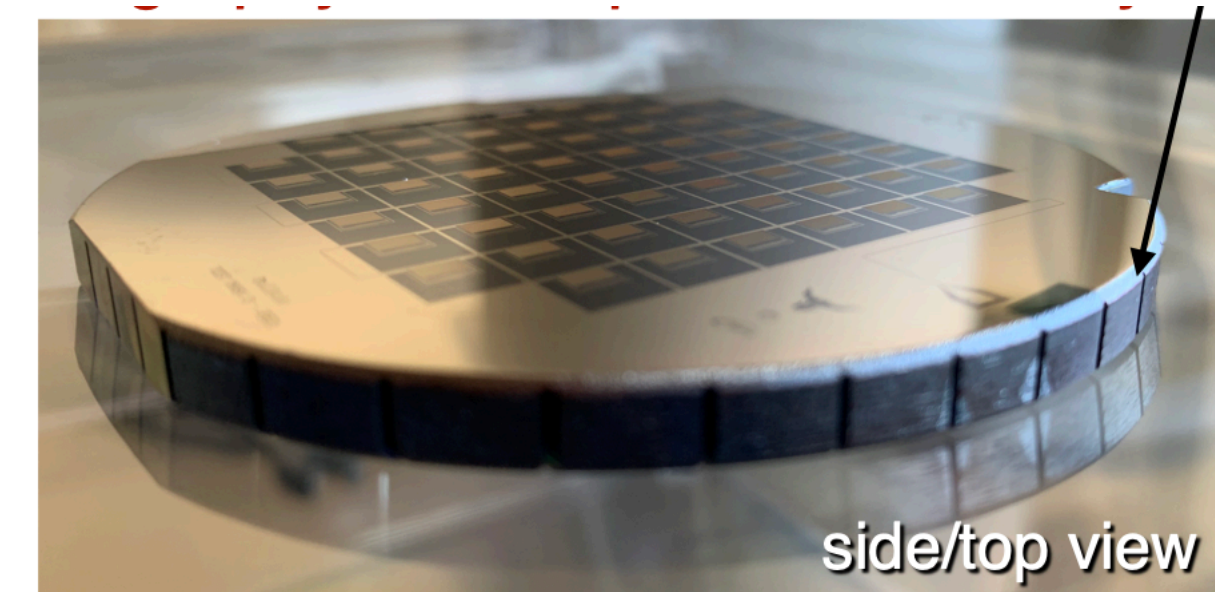


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A spin-off from Serenity development:
Readout of quantum sensors via software-defined radio technique



DAQ system for BullKID
dark matter search,
ECHO Experiment,
KATRIN Upgrade, ...



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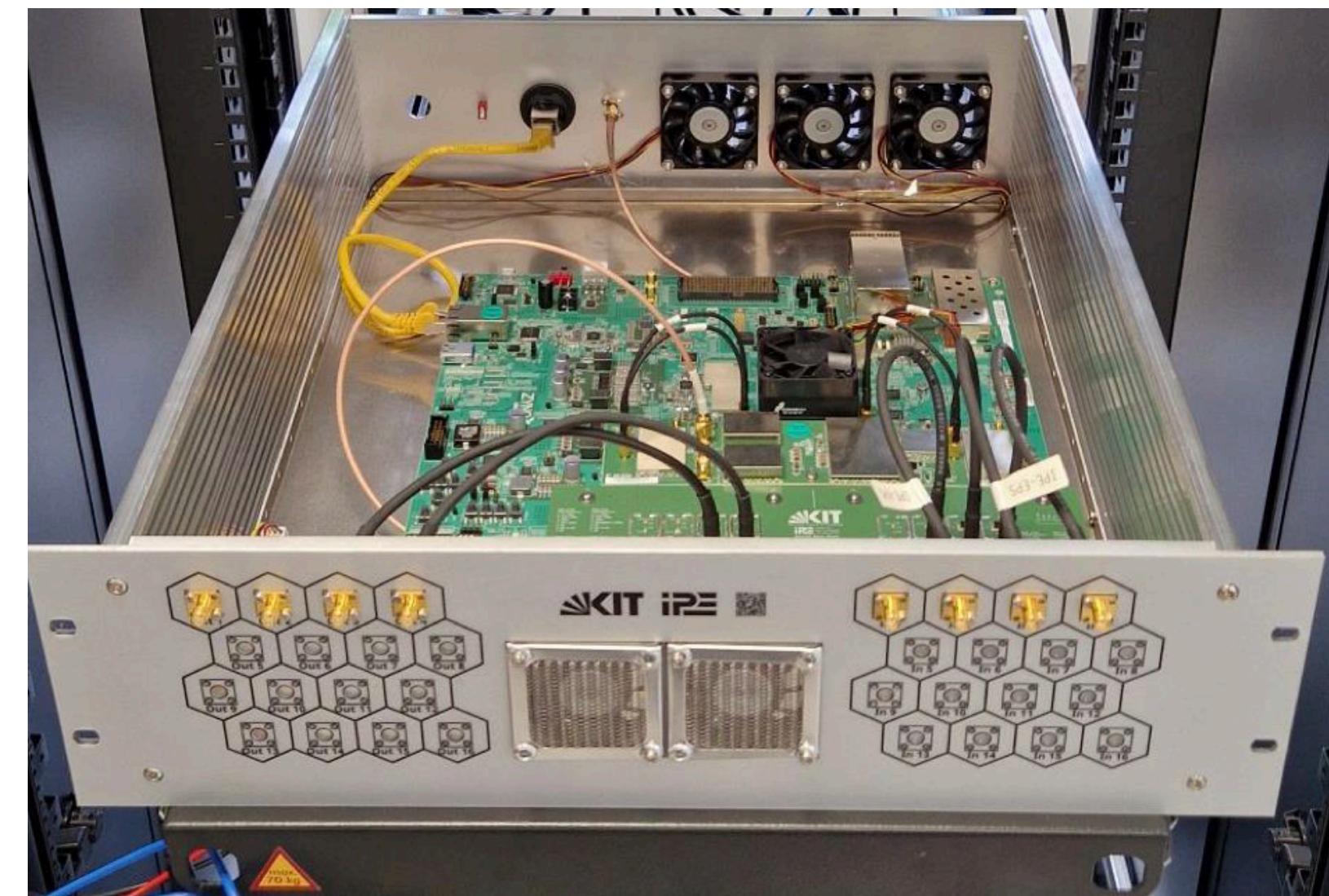


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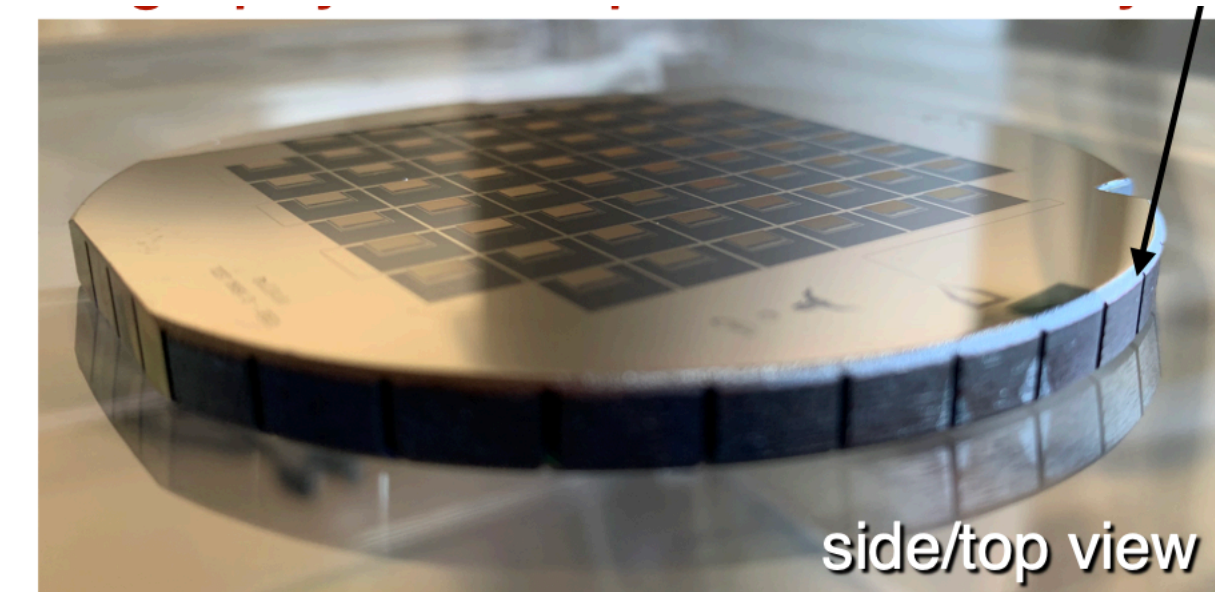


Towards the future for colliders:
“No backend” -
Using commercial protocols from
detector on.

A spin-off from Serenity development:
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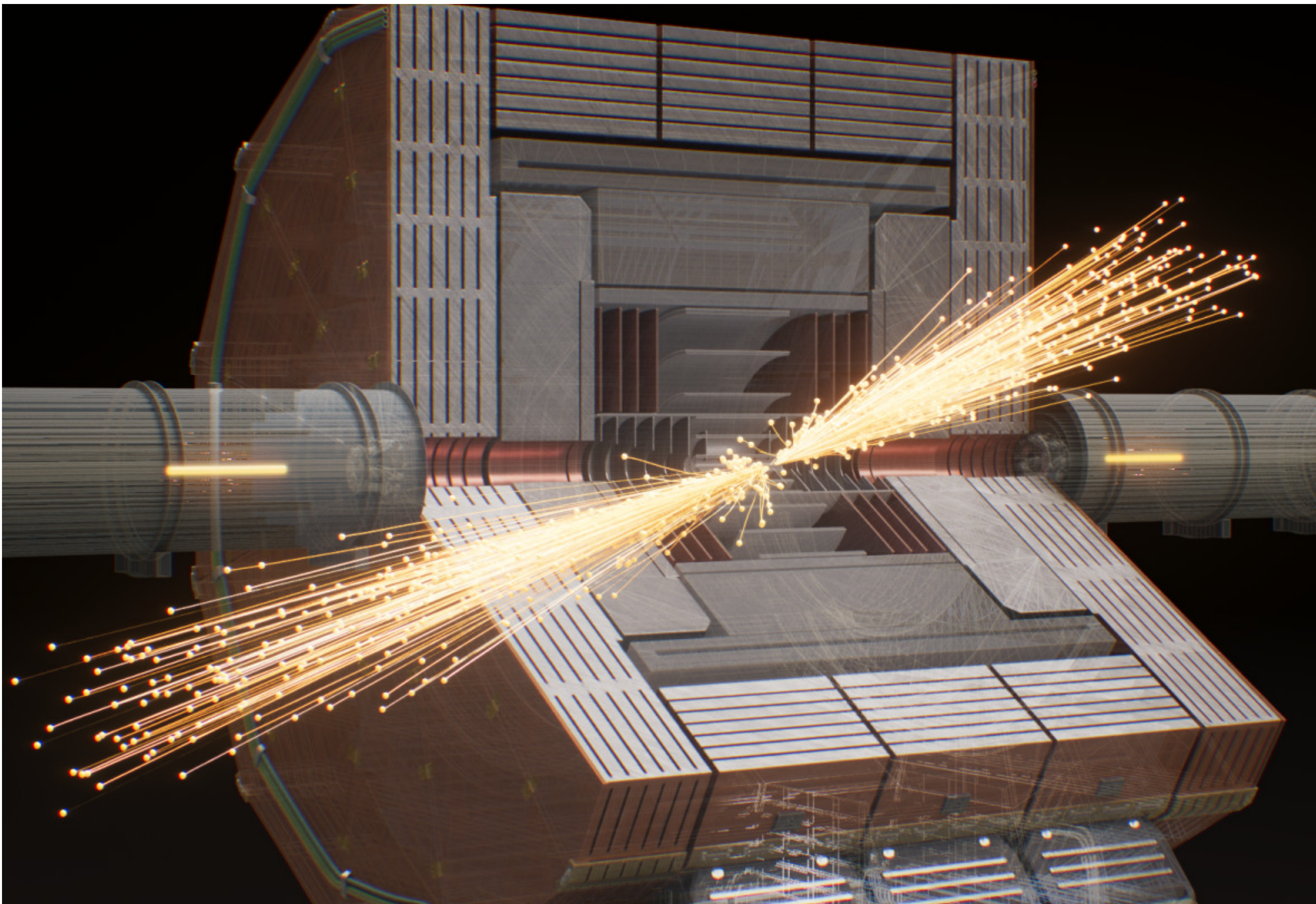


DAQ system for BullKID
dark matter search,
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Closing the Circle: Upgrades as Stepping Stone

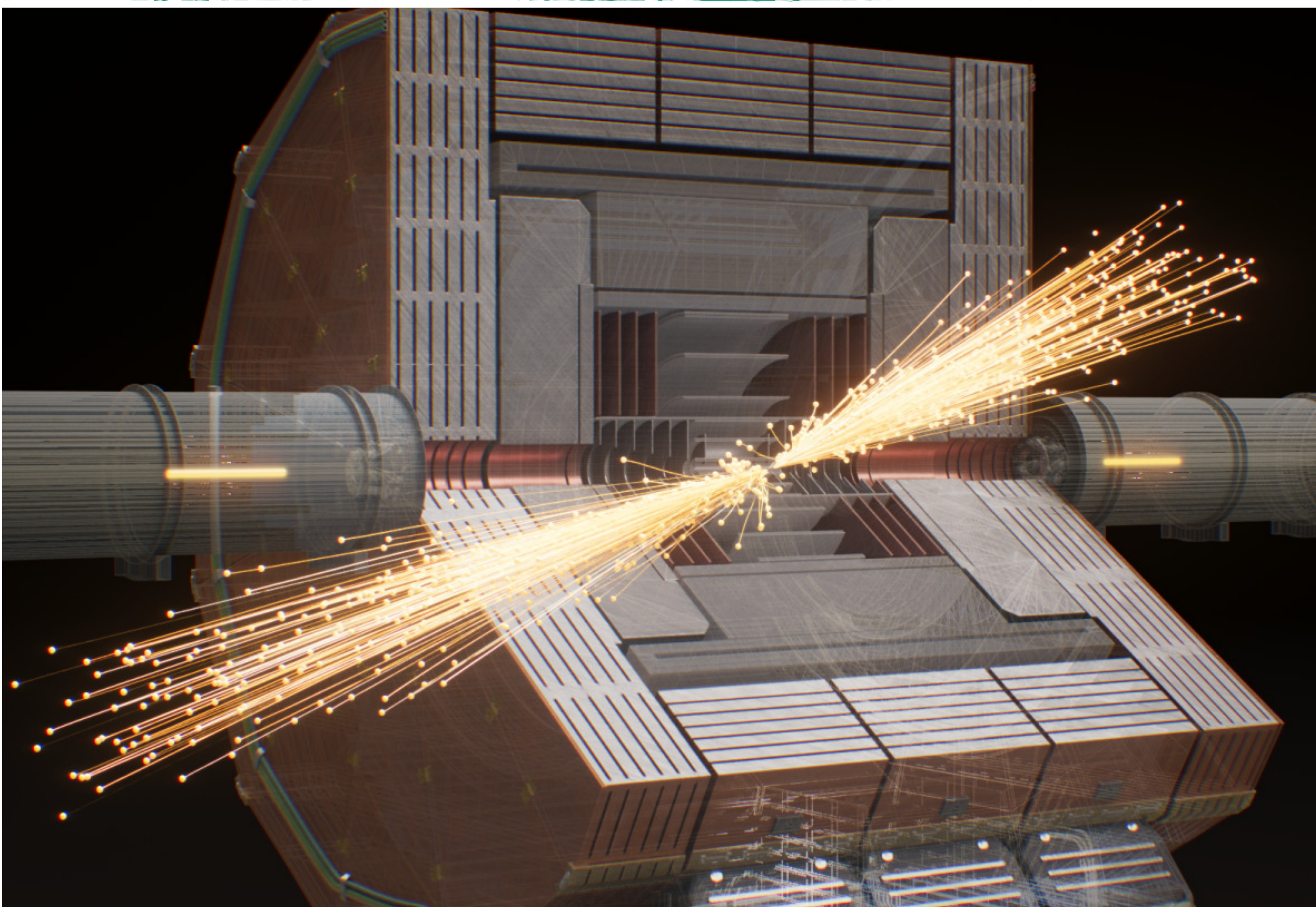
Towards Higgs Factory Detector Concepts



- Physics program at Higgs Factories: High luminosity, high precision
- Key detector technologies:
 - Low mass, large area Si tracking
 - Highly granular calorimeters
 - Capable data acquisition

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Profits from the collective experience accumulated with Belle II, LHC upgrades, non-accelerator experiments.

Conclusions & Outlook

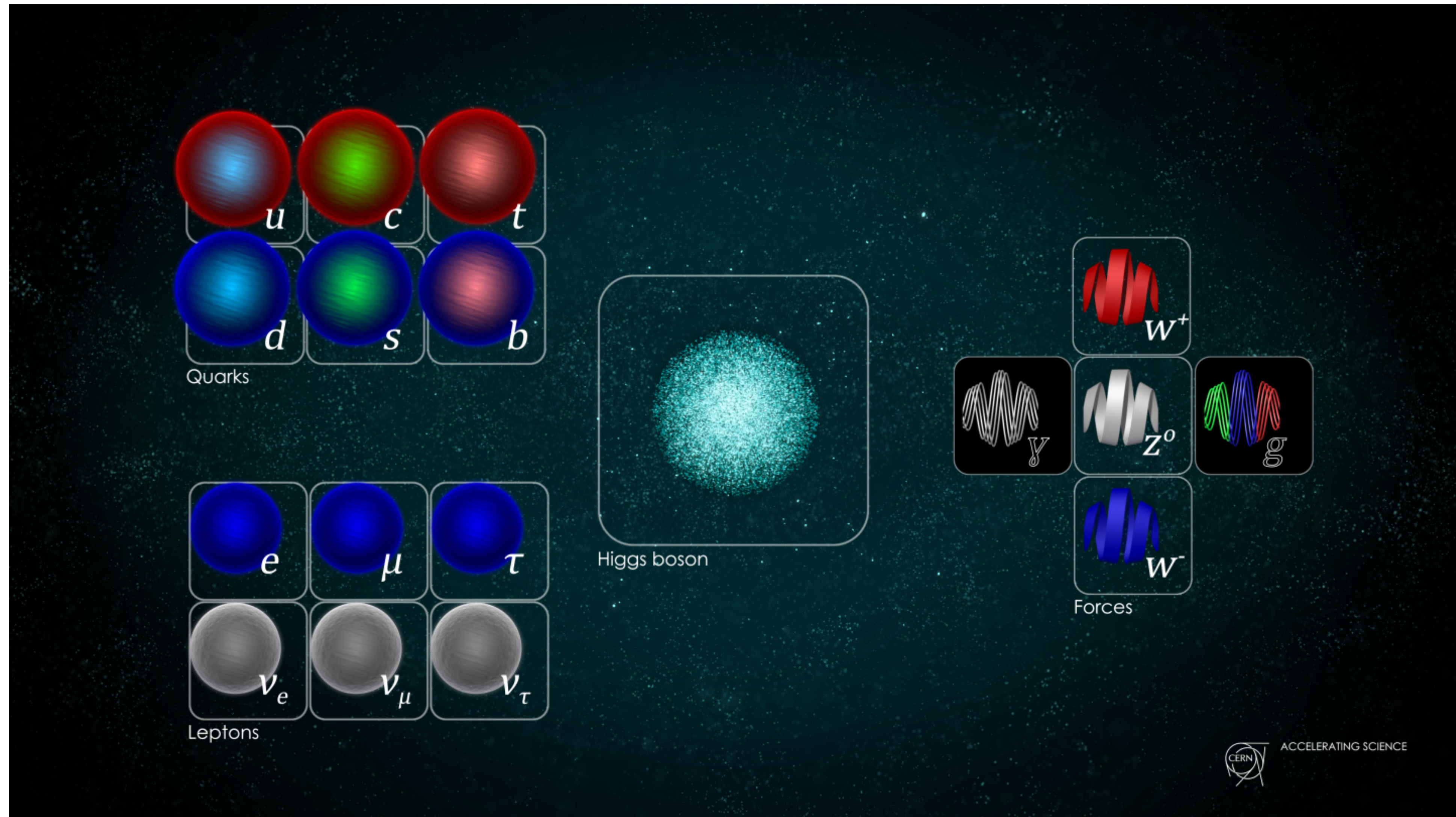
Conclusions

Exploring Basic Building Blocks, Exploiting Technology

- Lepton colliders: Exploring the basic building blocks of matter via direct and precision measurements
- Belle II has started its physics harvest - and there is much more to come.
- Precision measurements are challenging.
- Technology drives experimental capability, and connects projects.

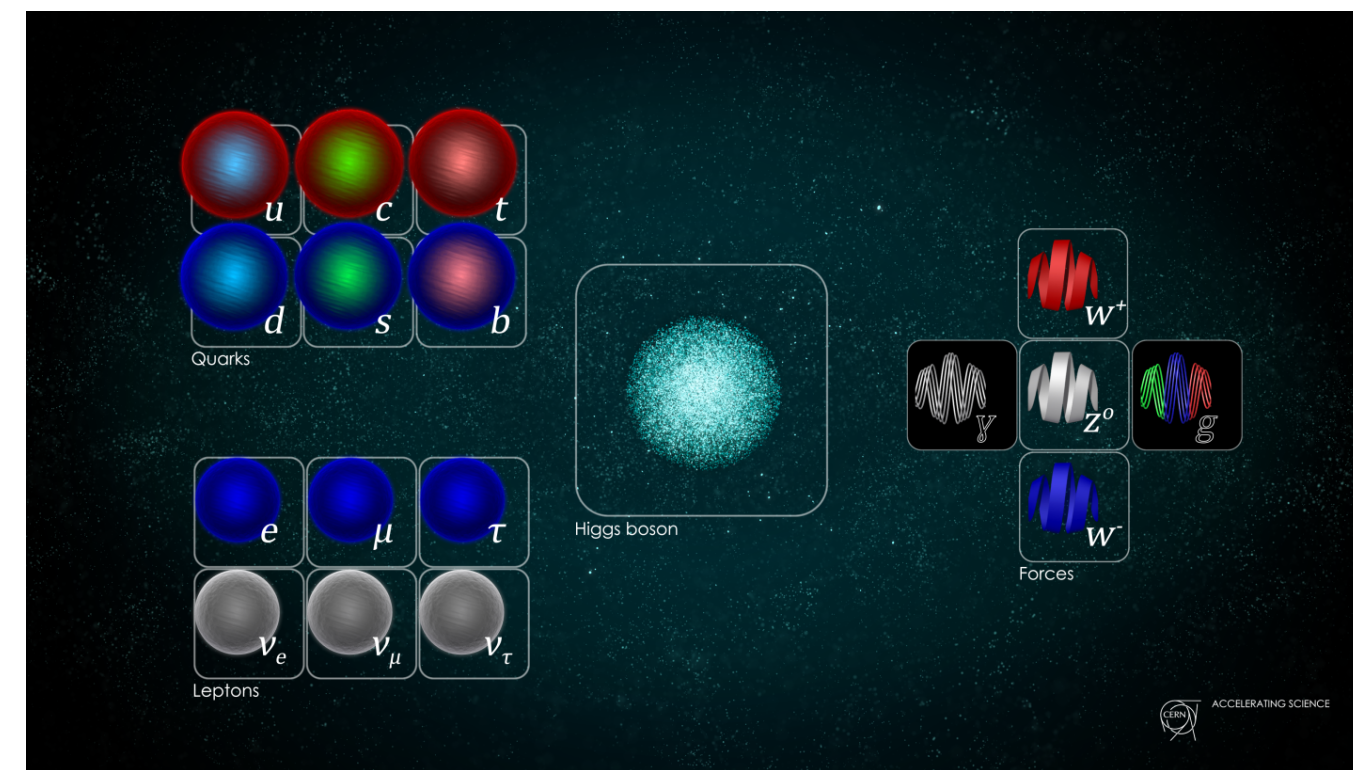
A Vision for future Discovery

Pushing Collider Physics beyond current Limits



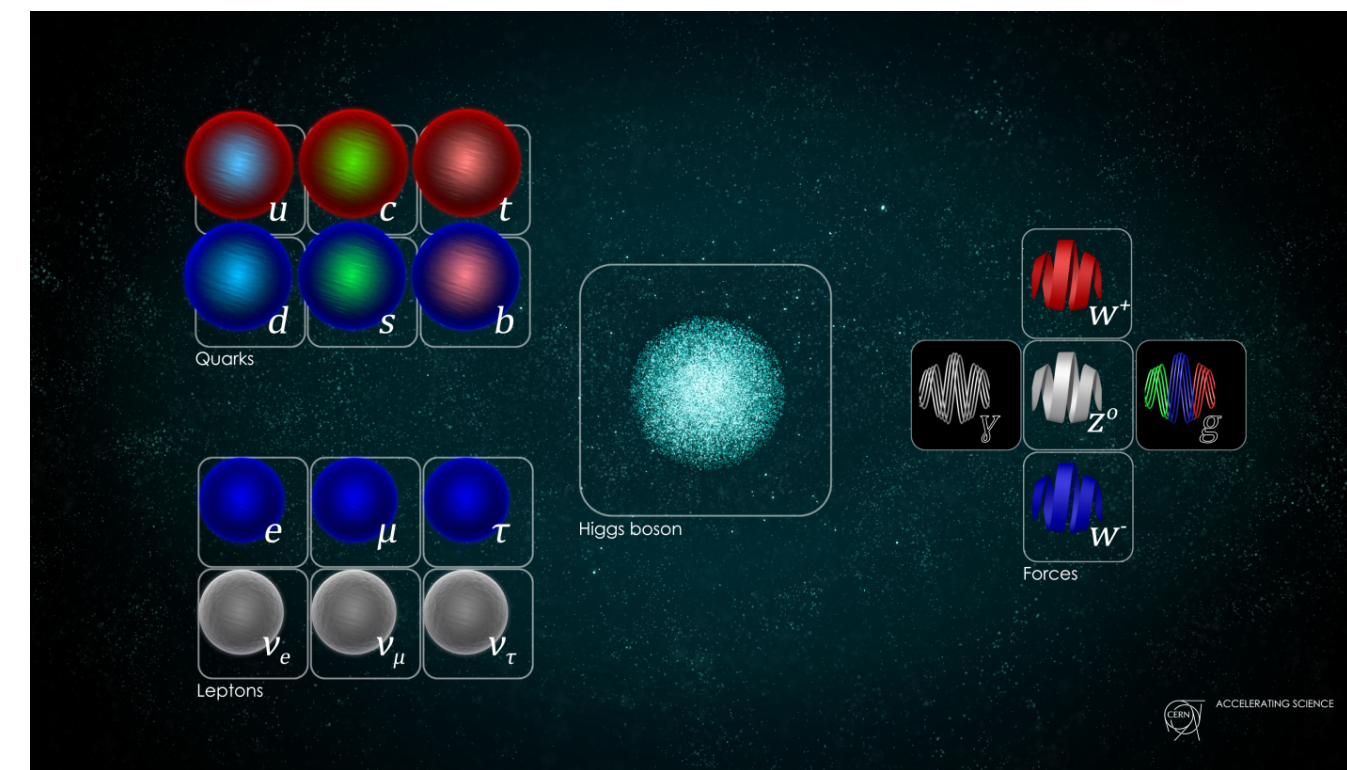
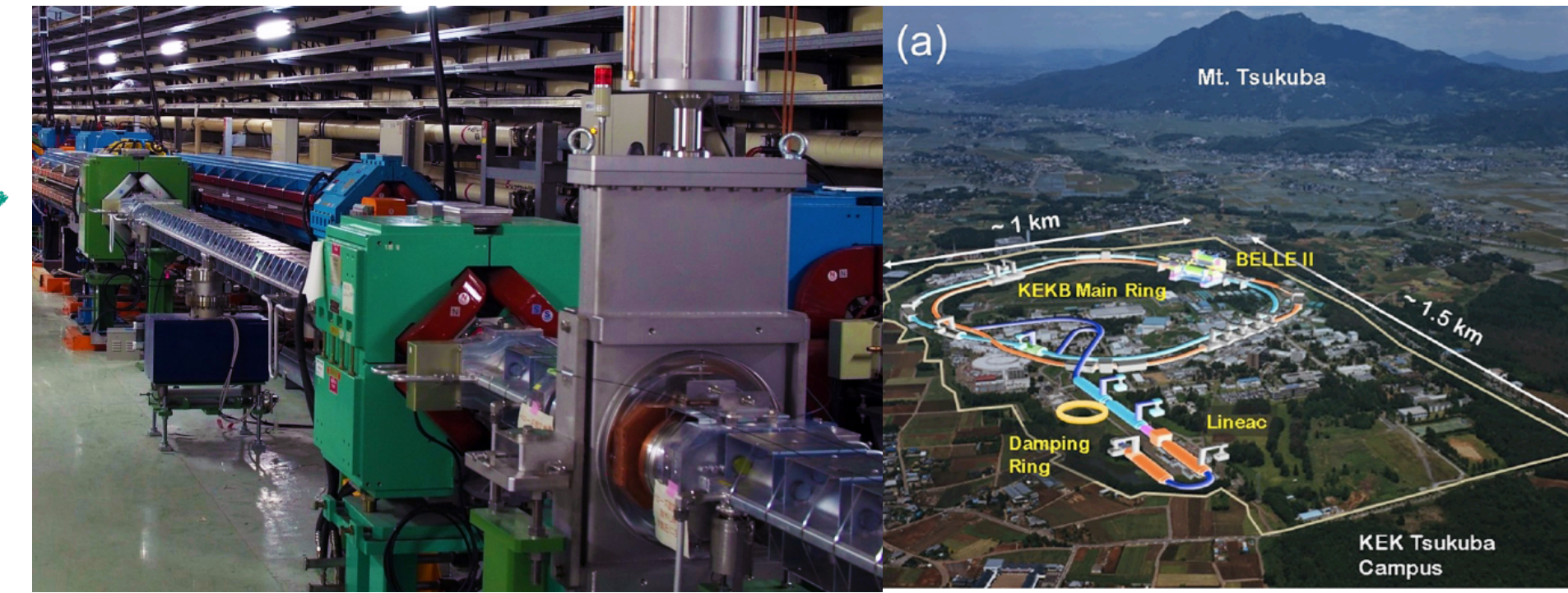
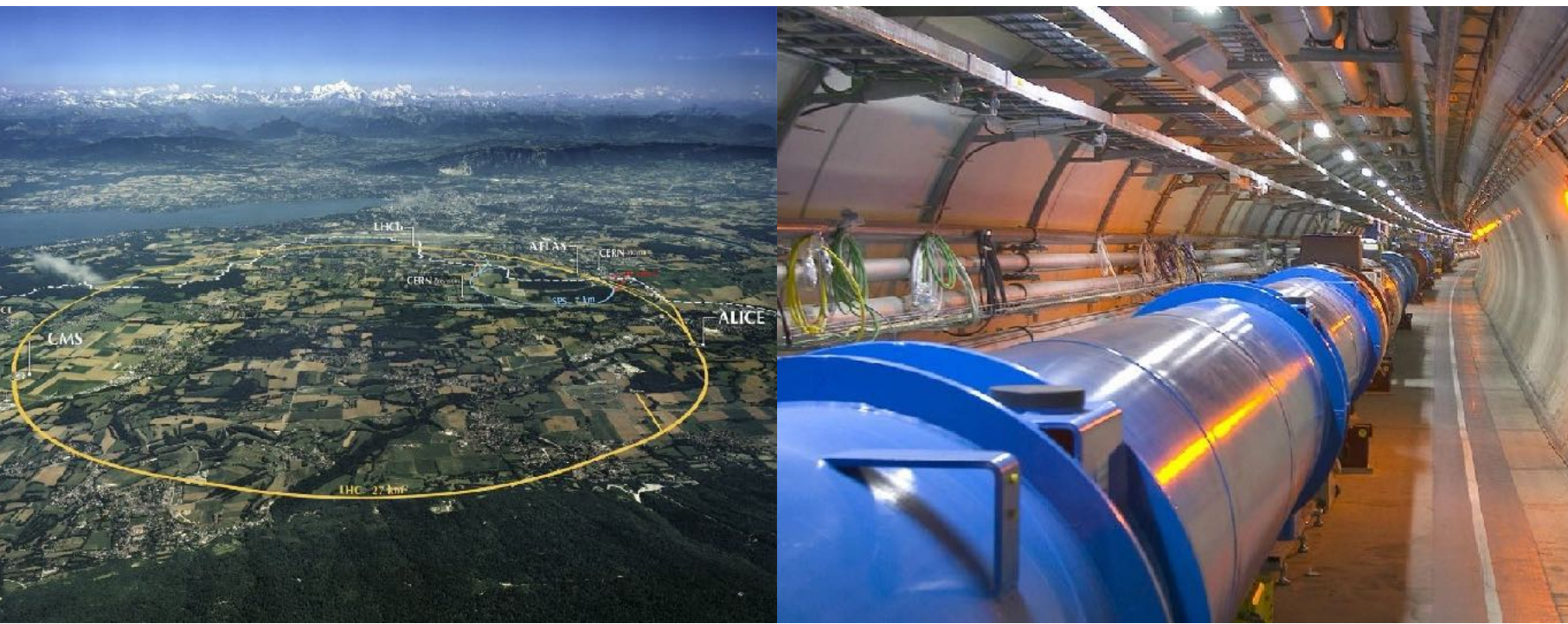
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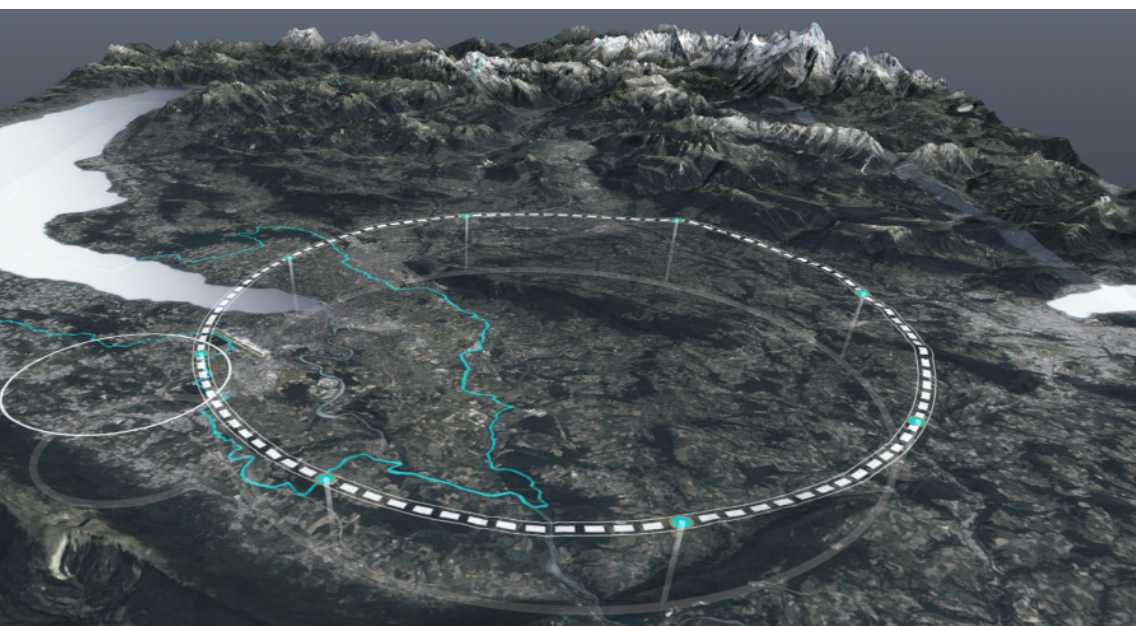
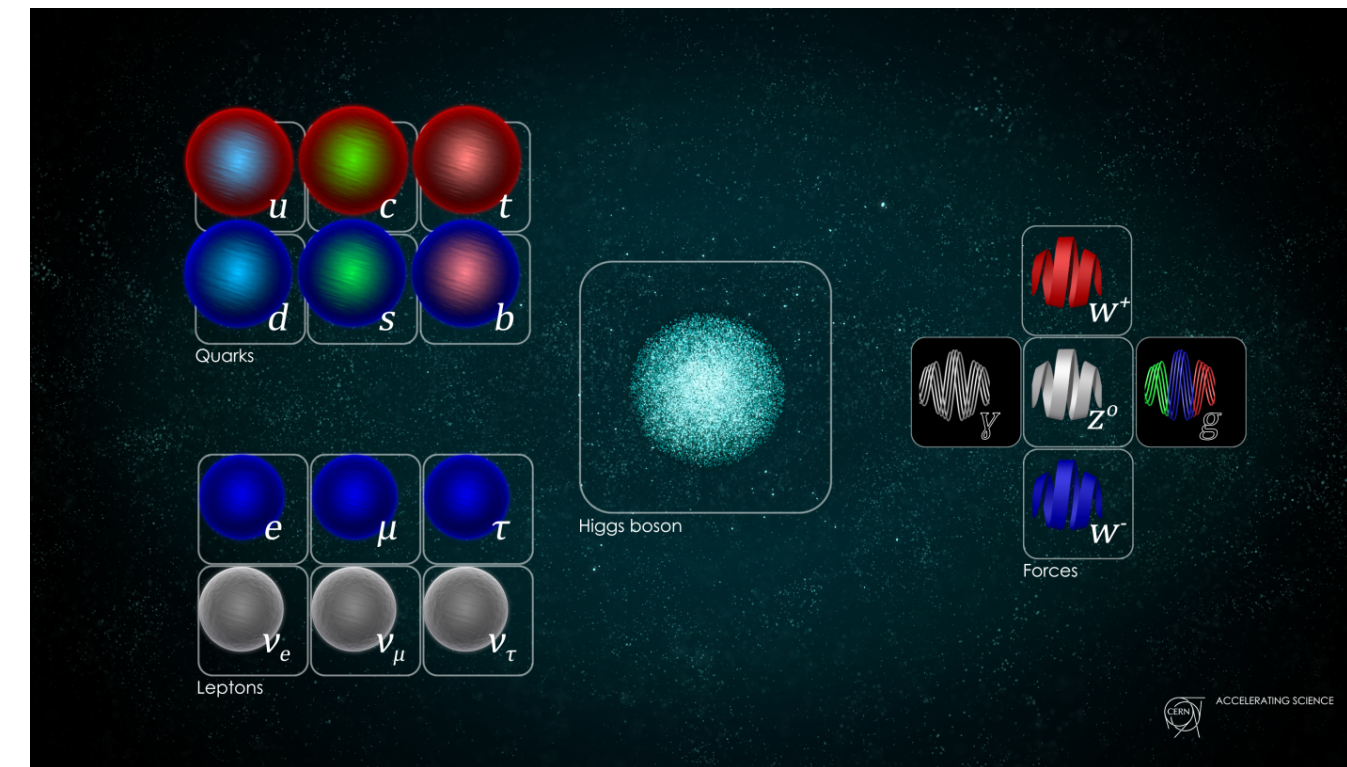
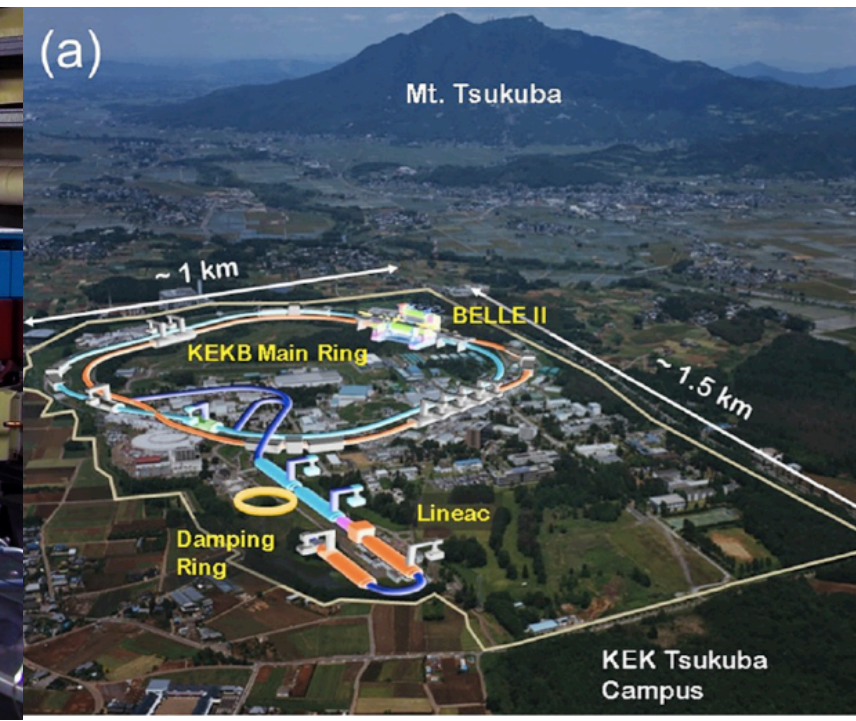
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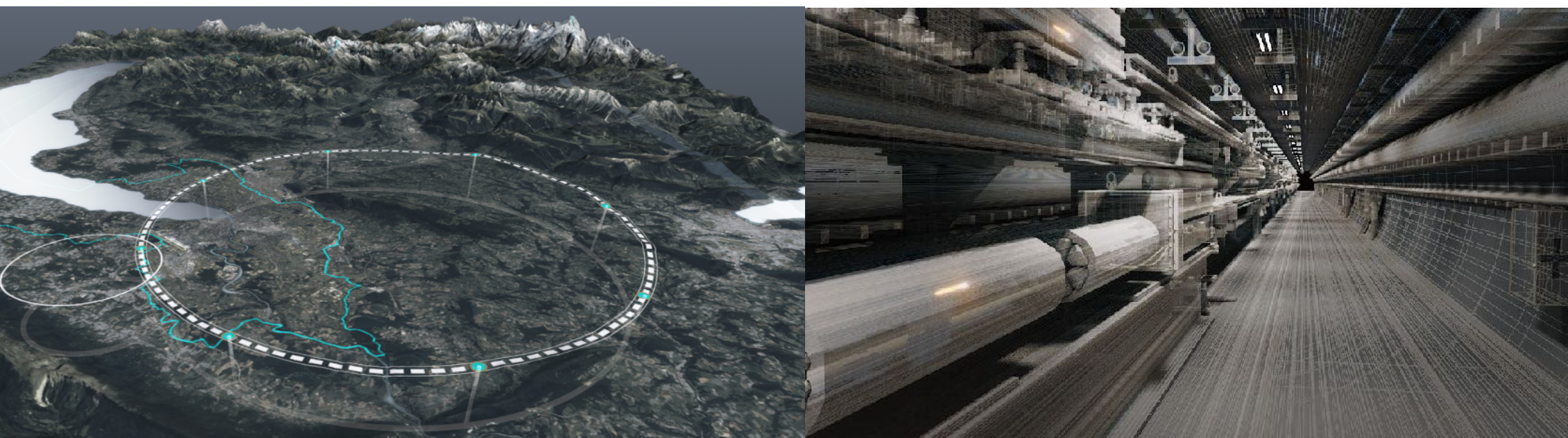
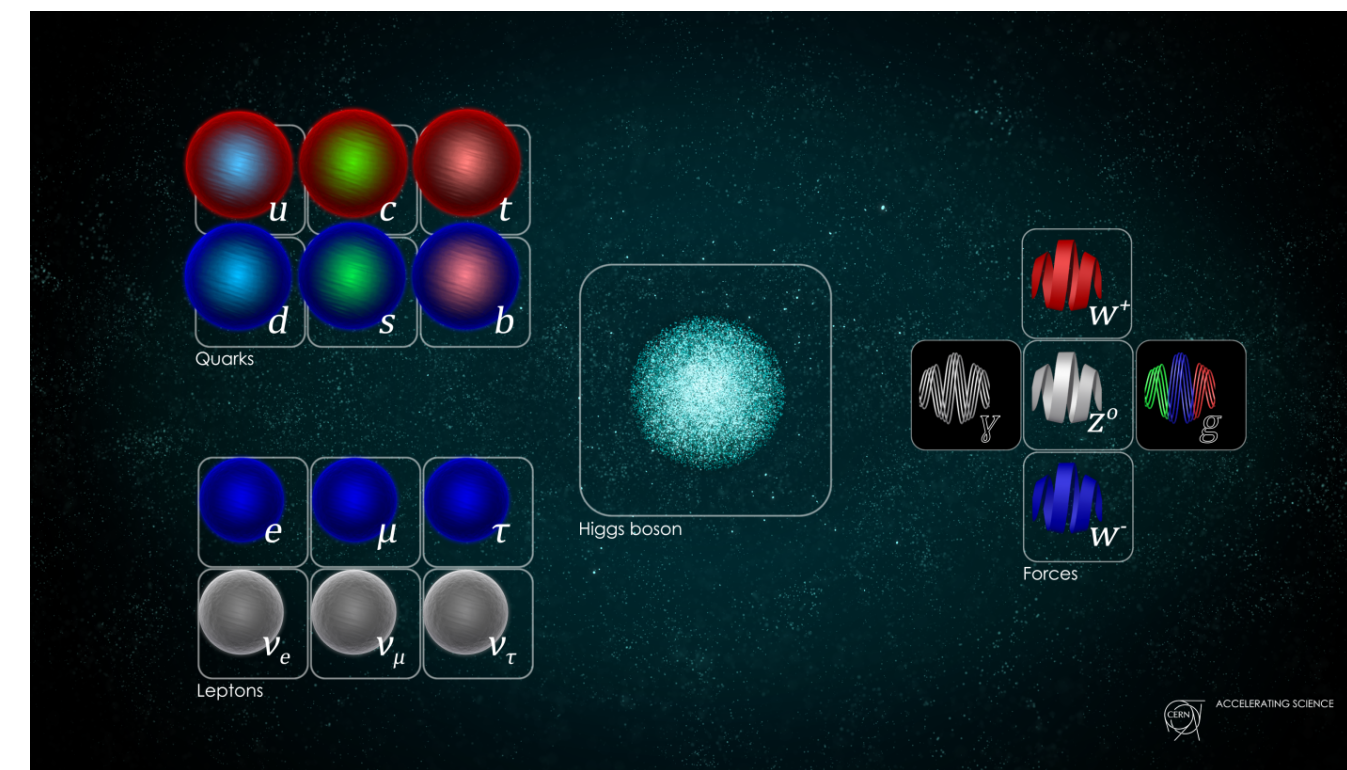
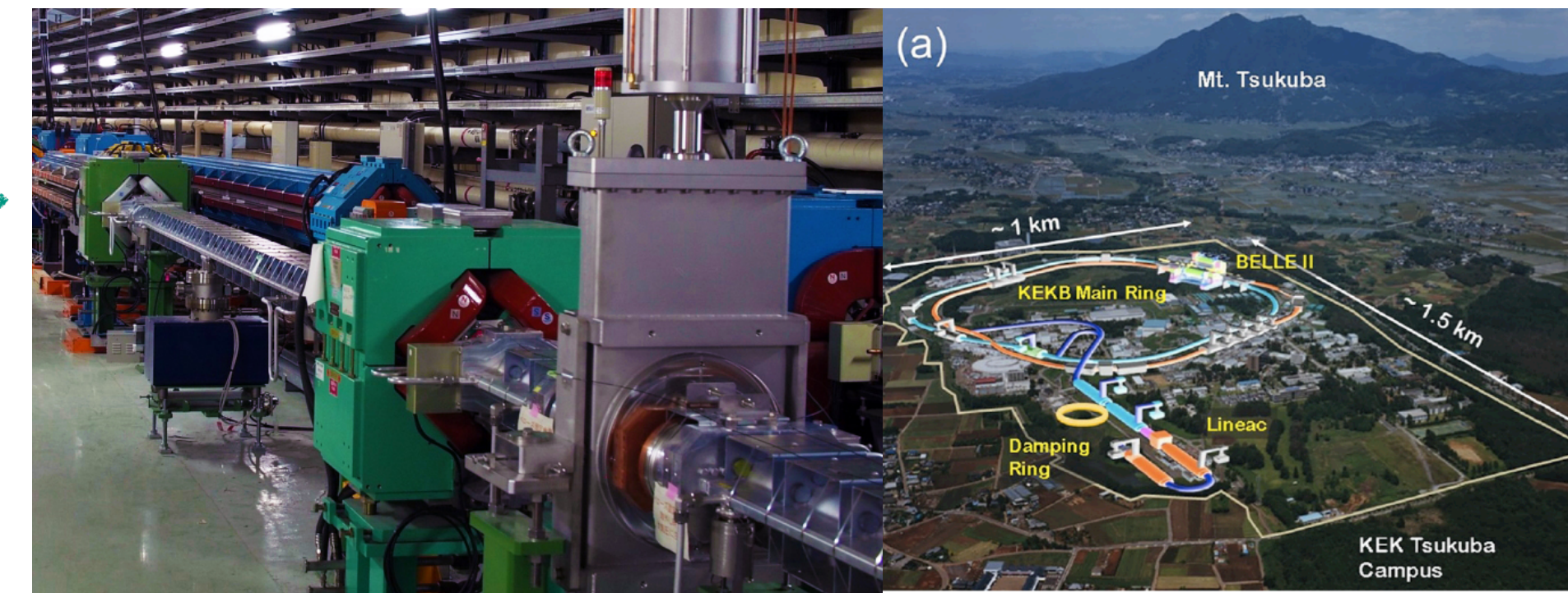
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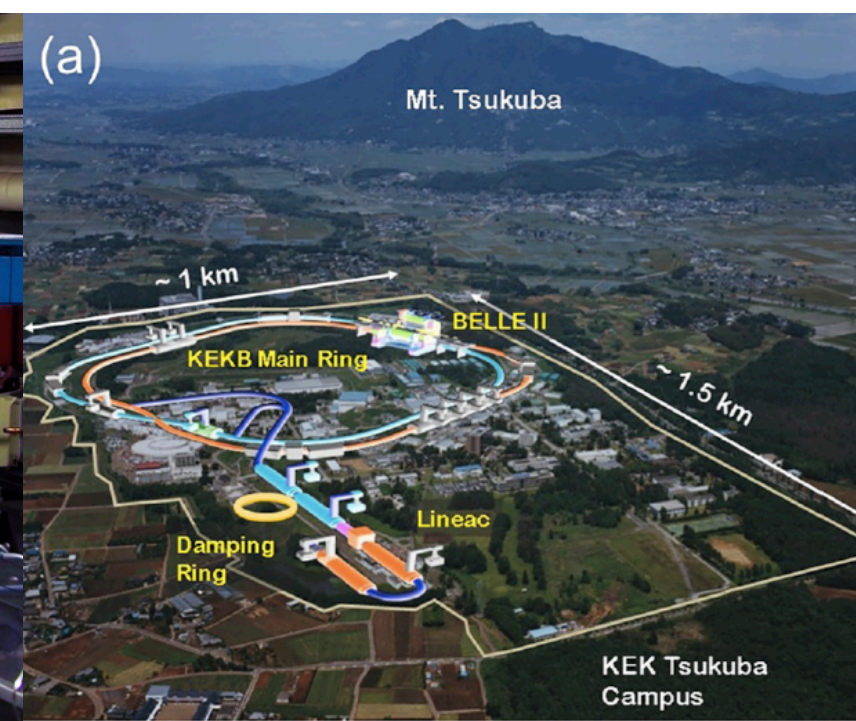
Pushing Collider Physics beyond current Limits



And a rich landscape of smaller experiments with unique discovery potential.

A Vision for future Discovery

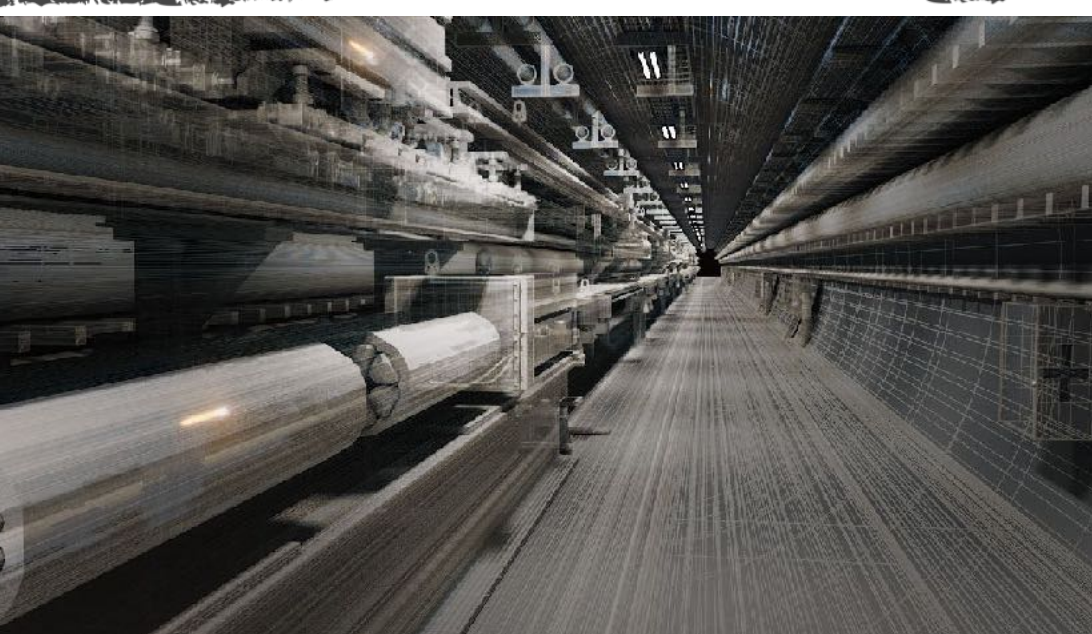
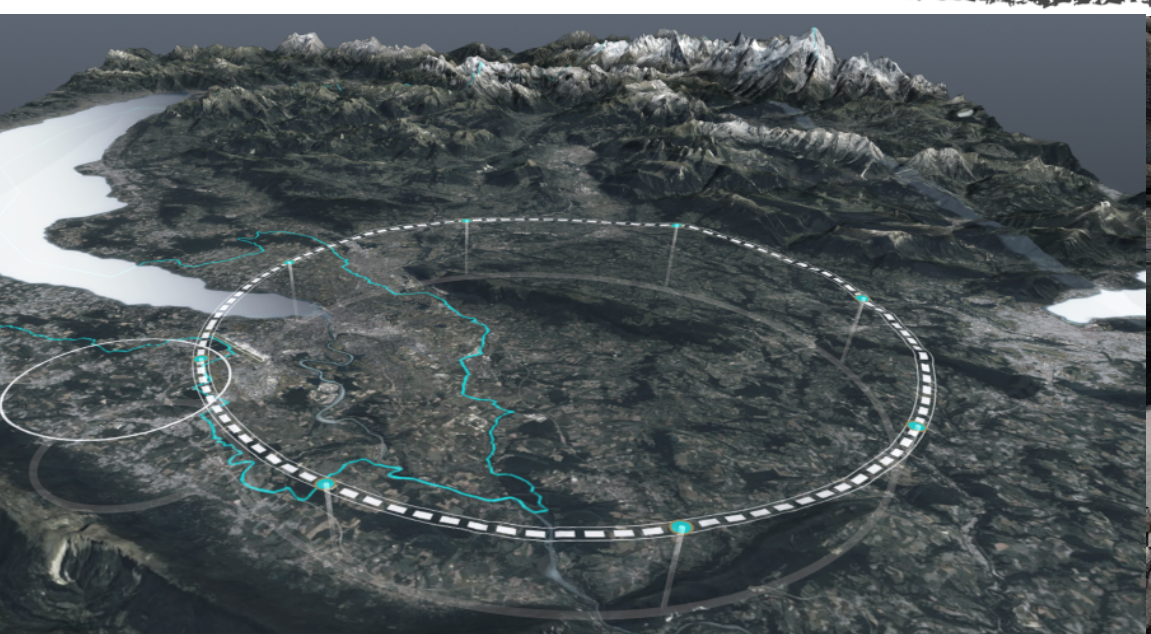
Pushing Collider Physics beyond current Limits



A large hand-drawn black rectangular frame containing a central diagram and two question marks.

?

?



And a rich landscape of smaller experiments with unique discovery potential.

... towards a new era of discovery.

