Introduction to Belle II

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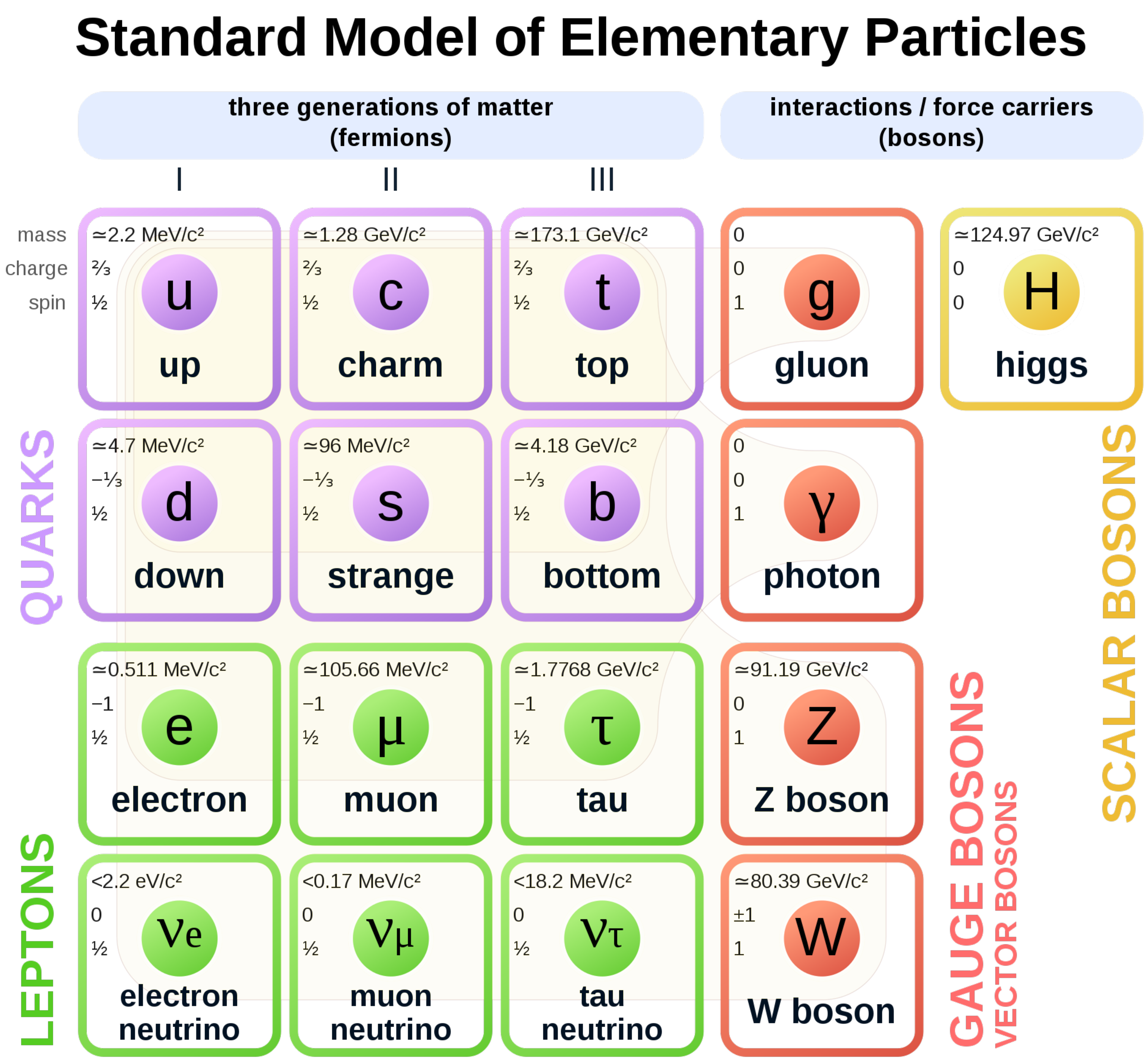
Beyond the Standard Model

the age of anomalies



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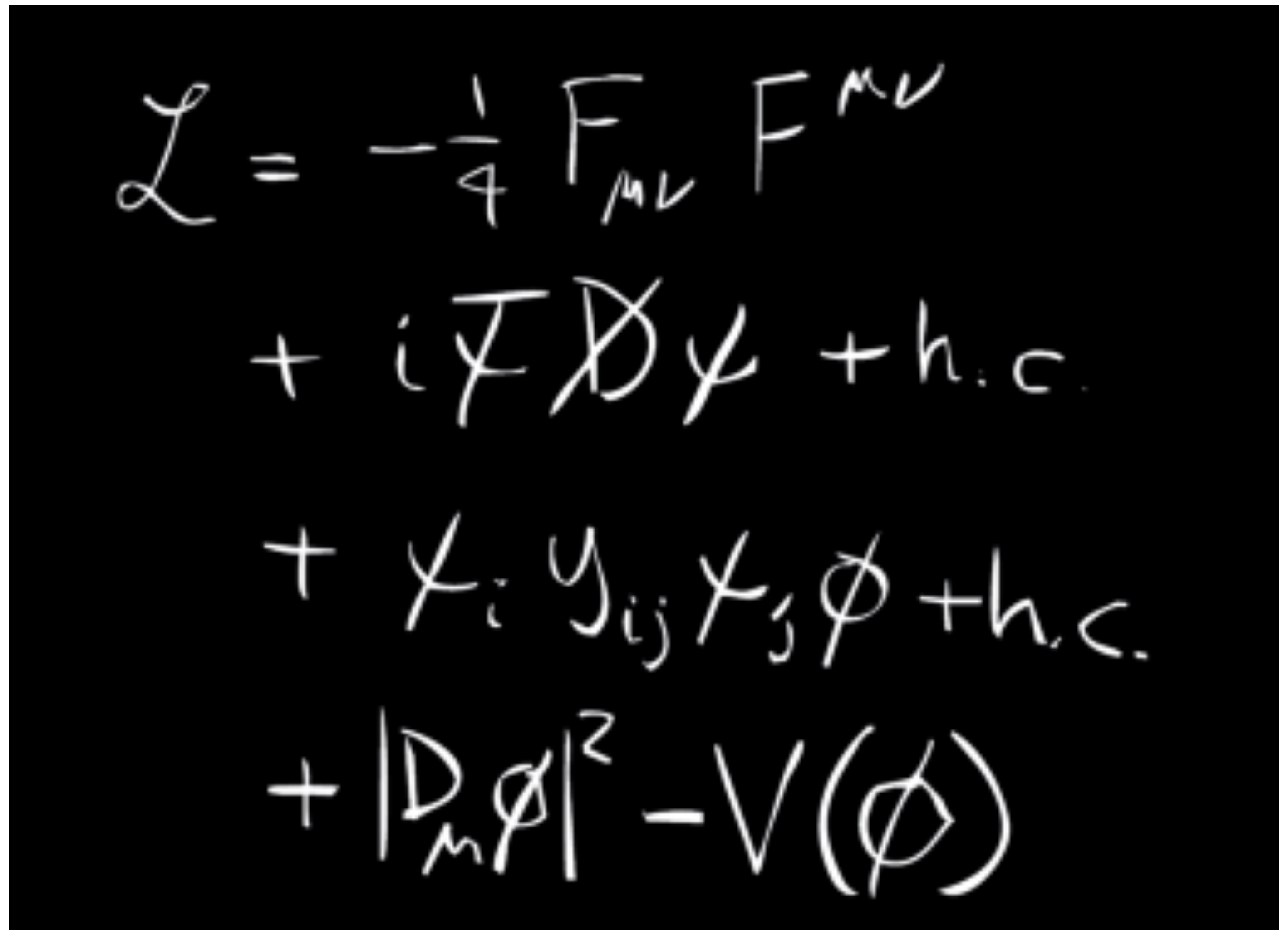


- The Standard Model is an extremely successful theory with impressive predictive power
- However, *it cannot be the end of the story*
  - Gravity!
  - Neutrino masses
  - Dark matter/energy?
  - Missing sources of CP violation?
  - Anomalies
  - …

Introduction

Interplay between theory and experiment

- Experimental precision
  - Depends on resolution of the measuring device
  - Estimate from optics
  - Extend to particle physics with de Broglie

- Can probe more deeply with a higher energy "beam" of particles
  - The intensity of the beam does not matter… or does it?

- Rely on "conservation laws" to make inferences from experiment

Optics

$$\Delta r \approx \frac{\lambda}{\sin(\theta)}$$

Particles

$$\Delta r \approx \frac{h}{p\sin(\theta)} \approx \frac{h}{q}$$

Momentum transfer

Theoretical prediction → Experimental construction → Experimental measurement → Theoretical interpretation

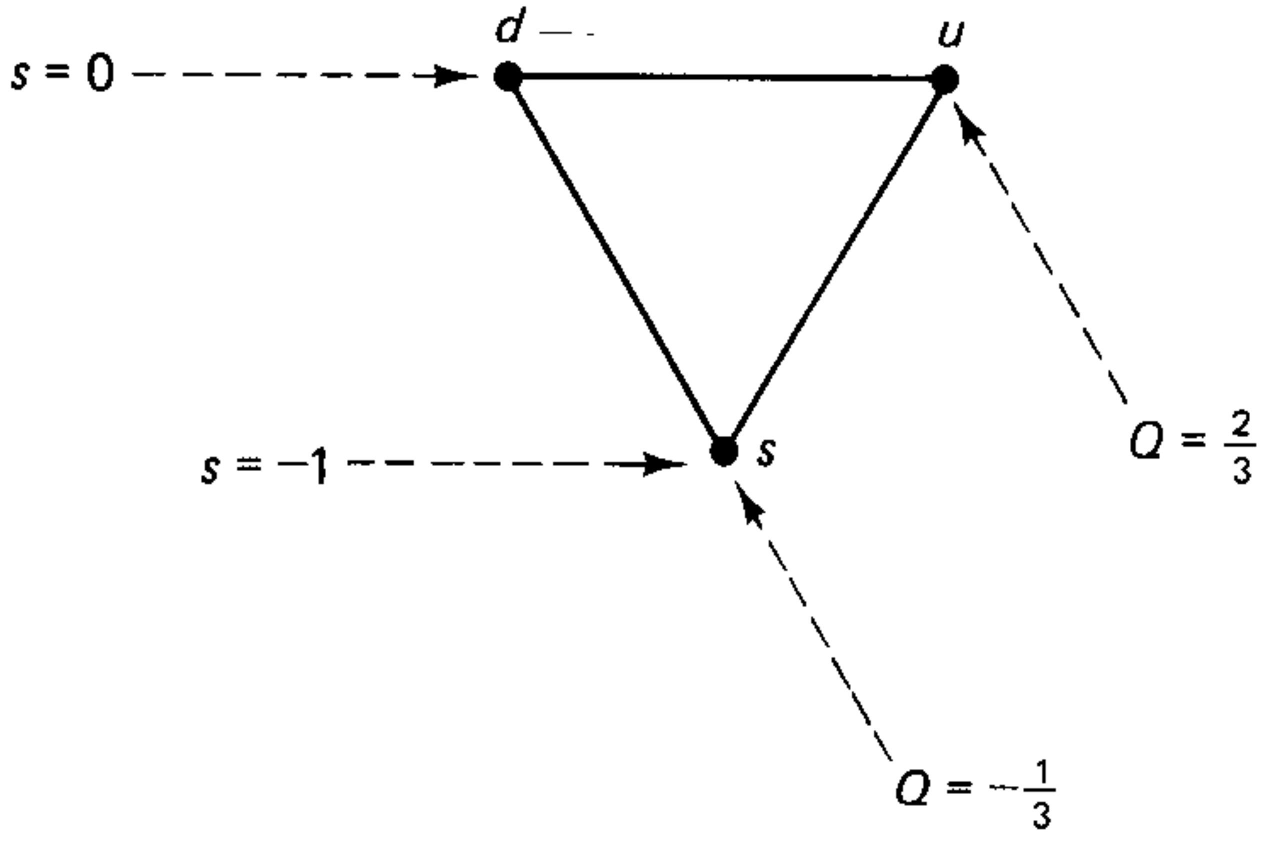
Quark mixing

Exposing "new physics" with interplay of theory and experiment

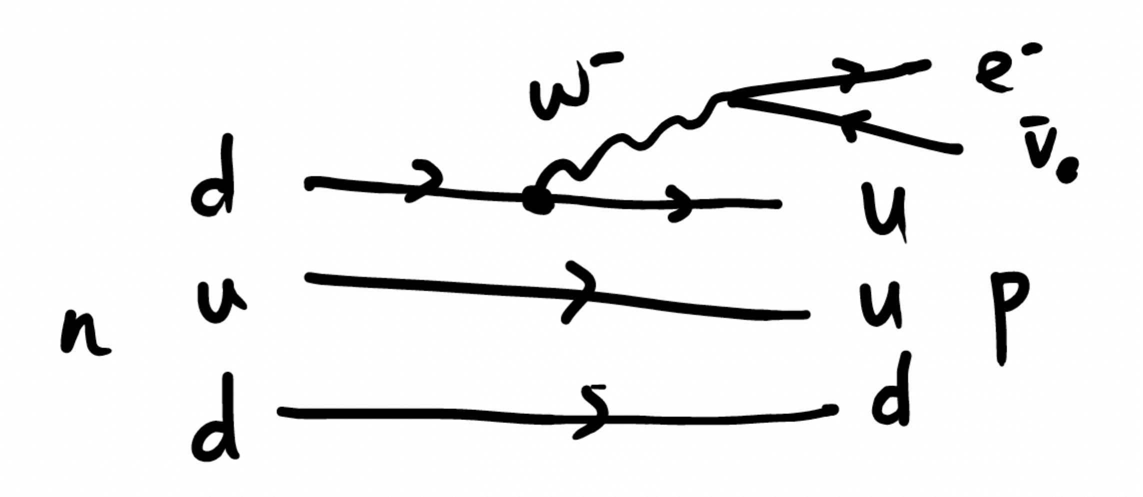
- Similarities between certain particles suggest underlying structure

$$\frac{m(n)-m(p)}{m(p)} \approx 0.14\,\%$$

  - Some particles also have a strangely long lifetime



- Strangeness changing reactions suppressed by factor of 20



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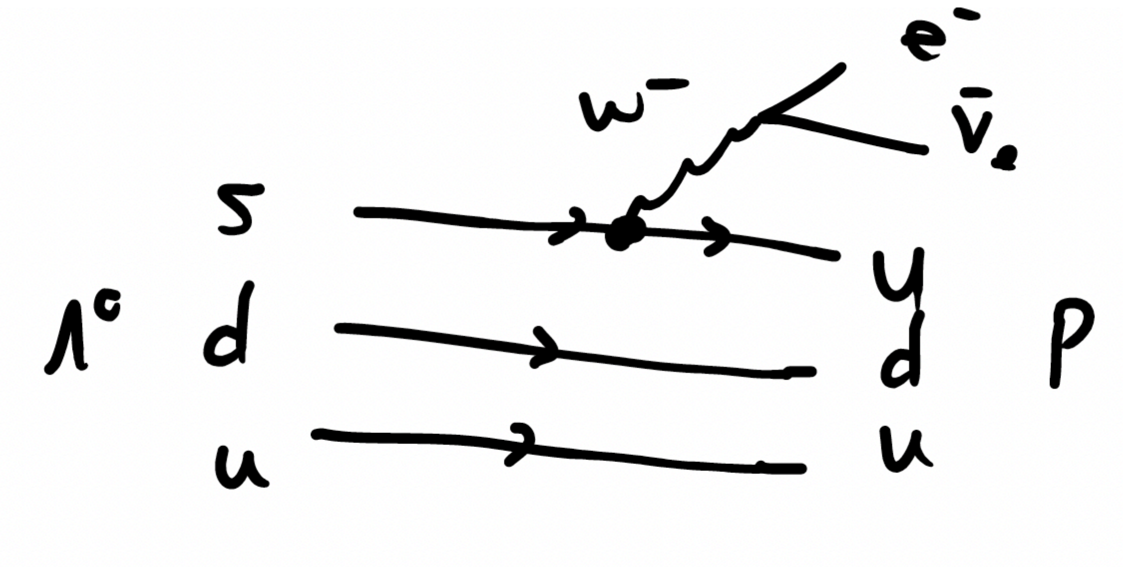
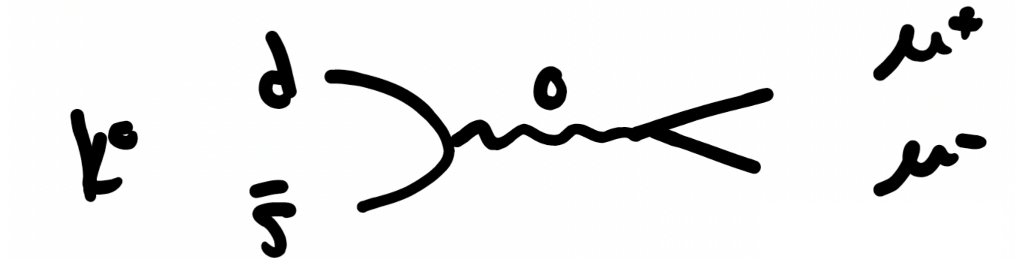


- Cabibbo: strong interaction sees [u, d, s], but weak interaction sees [u, d′]

$$\mathrm{u} \longleftrightarrow \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\theta_c \approx 12.8^\circ$$

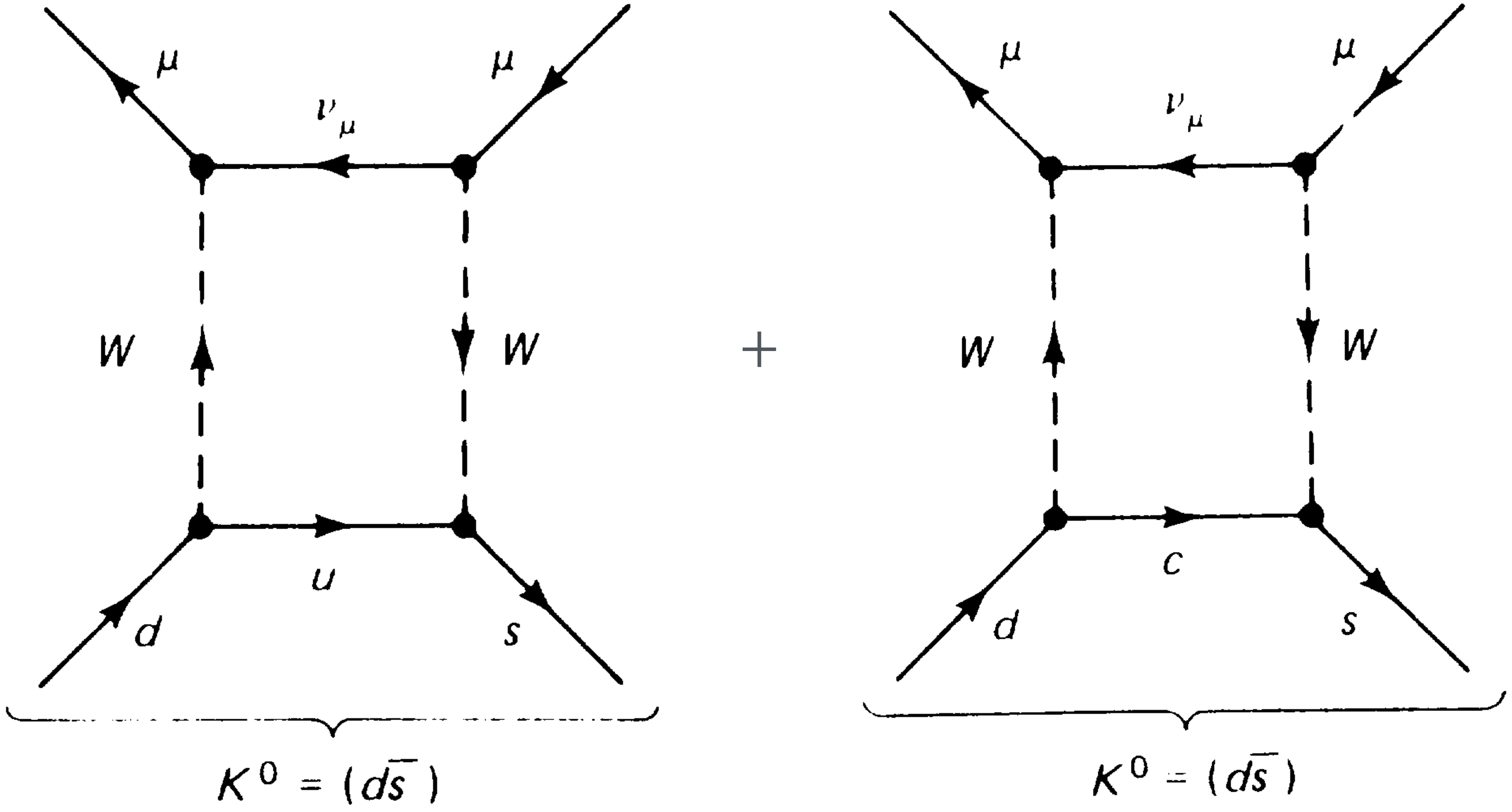


Note: no Flavor Changing Neutral Currents allowed!

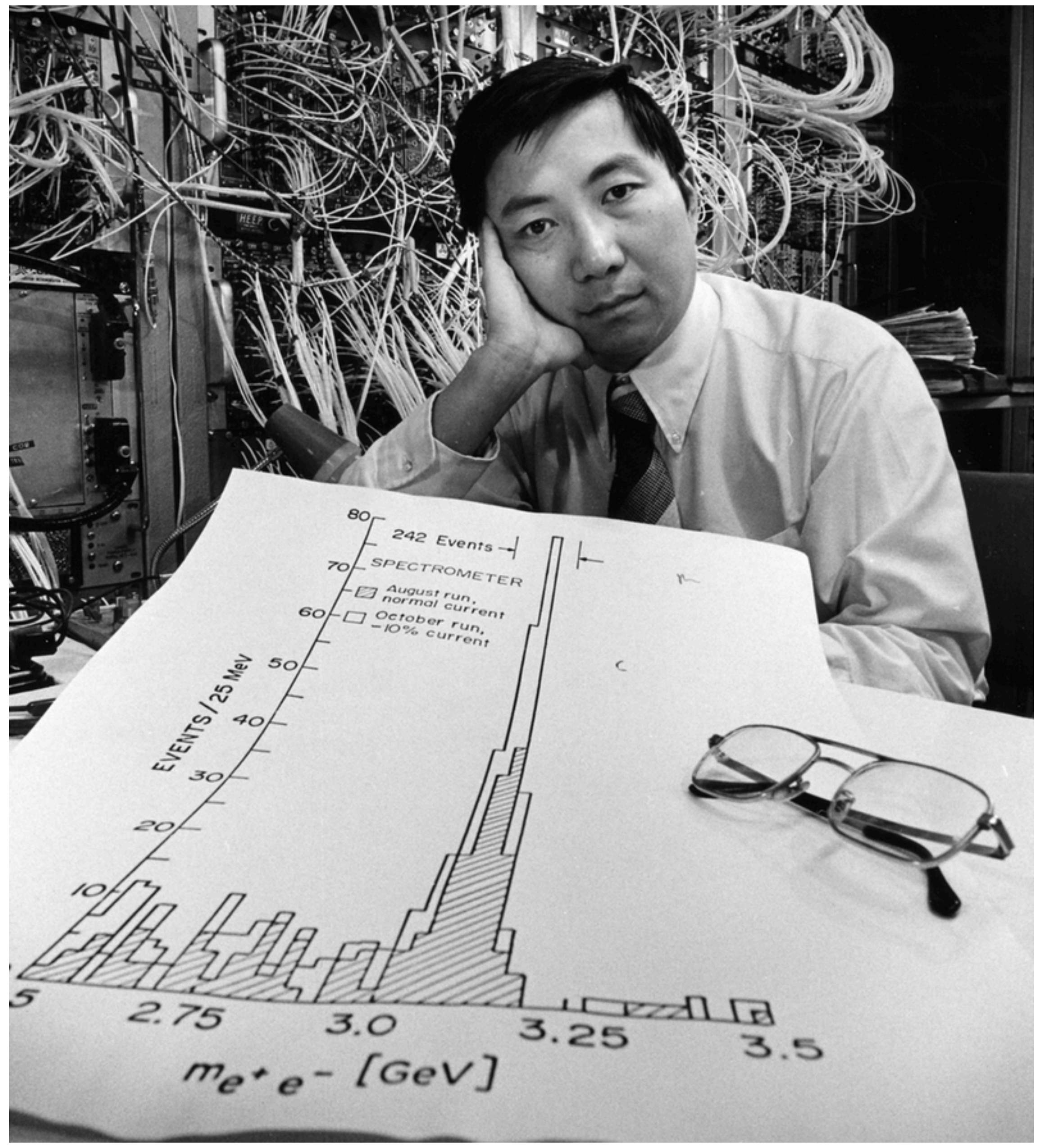
Quark mixing

Exposing "new physics" with interplay of theory and experiment

- Problem: I can think of a process by which $K^0 \to \mu^+\mu^-$ should be allowed!
- Glashow, Iliopoulos, and Maiani (GIM) show that *adding another quark* can fix this problem

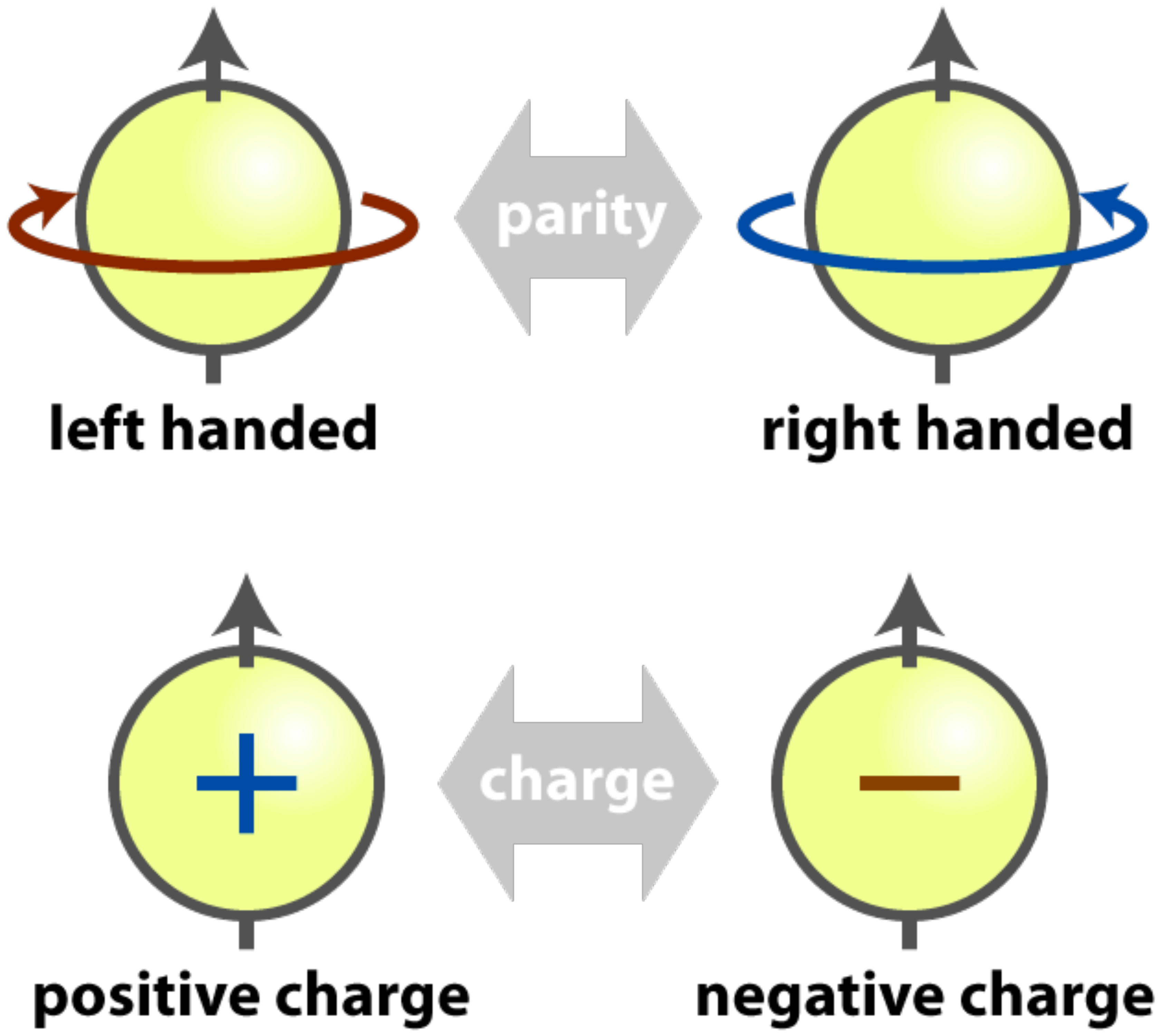


$\sin(\theta_c) \cdot \cos(\theta_c)$ $\quad$ $-\sin(\theta_c) \cdot \cos(\theta_c)$

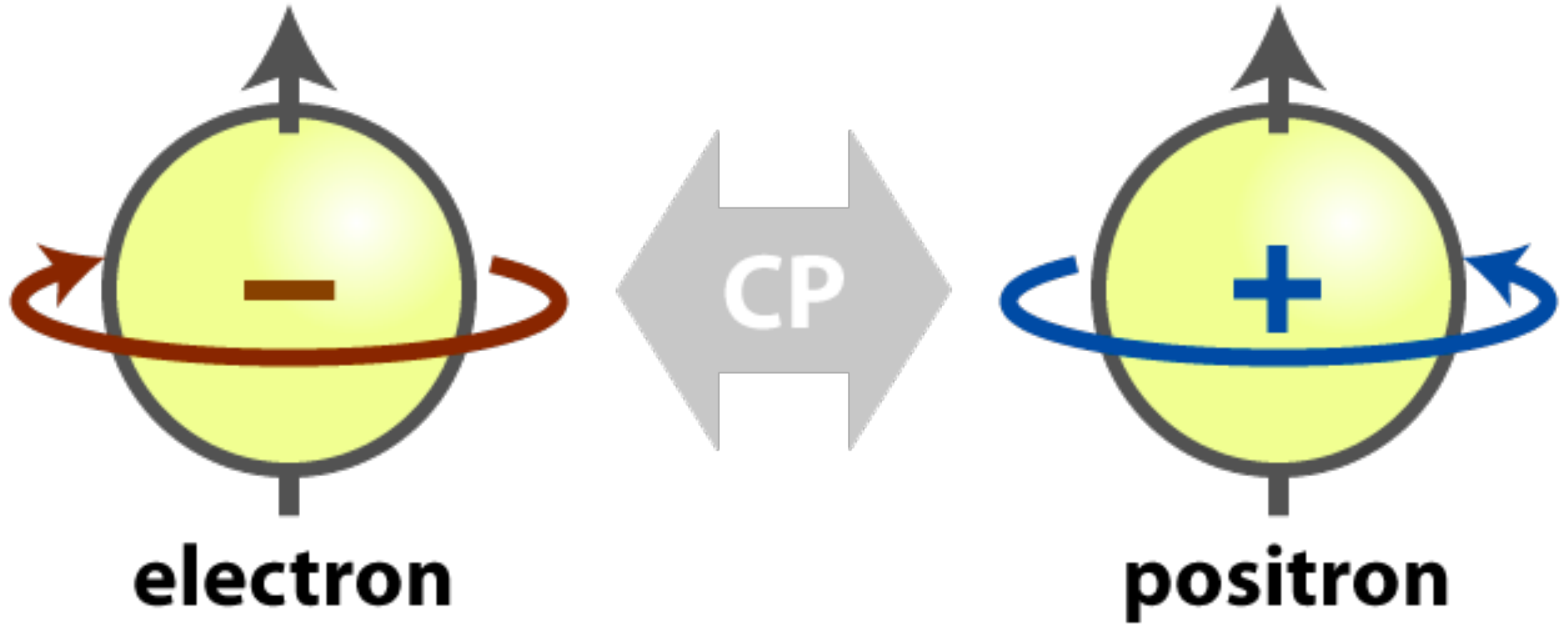


$$\begin{array}{l} \mathrm{u} \longleftrightarrow \\ \mathrm{c} \longleftrightarrow \end{array} \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

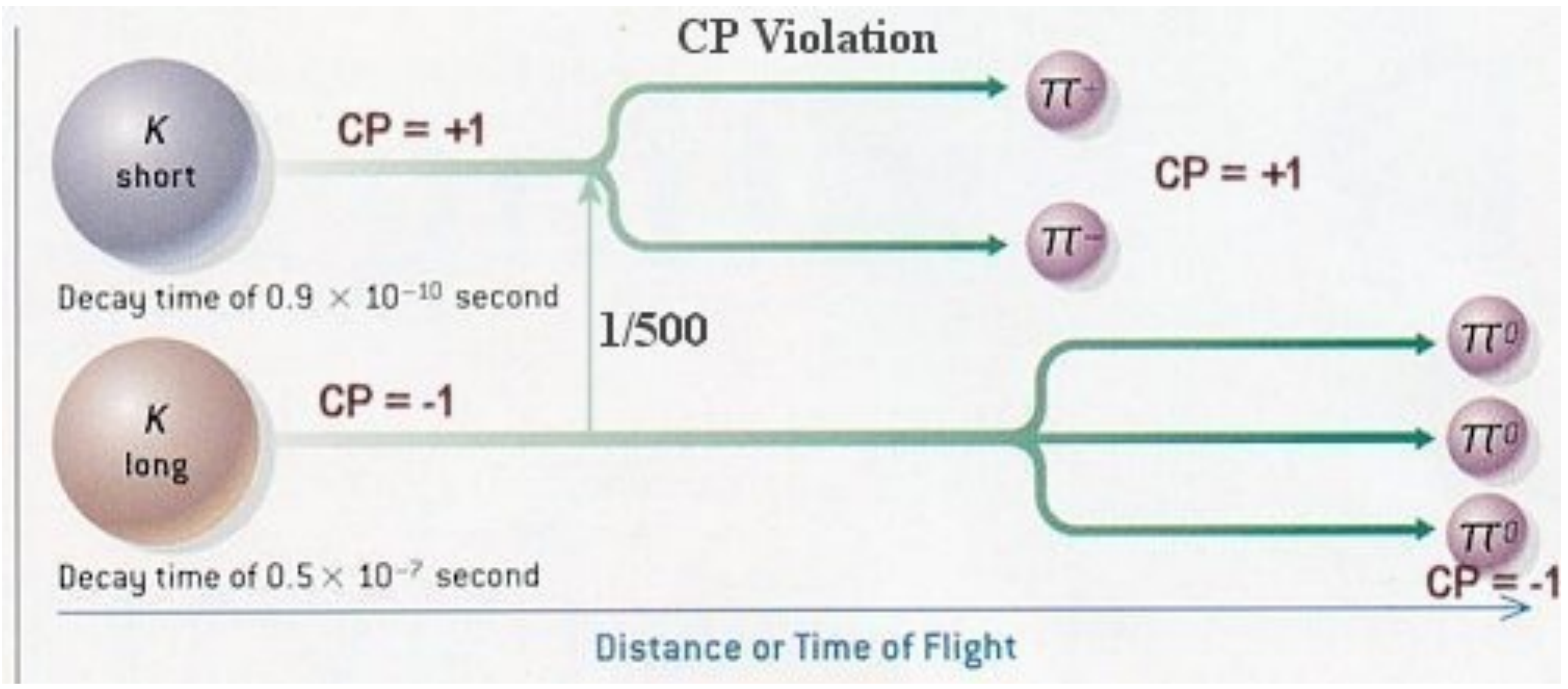
Experiment driven conservation laws(?)



The direction that the particle spins with respect to its direction of motion determines whether it is left-handed or right-handed.



- Is CP symmetry is conserved? No!



- C and P symmetries are conserved by electromagnetic and strong forces, **but maximally violated by the weak force!**

CP violation and the CKM matrix

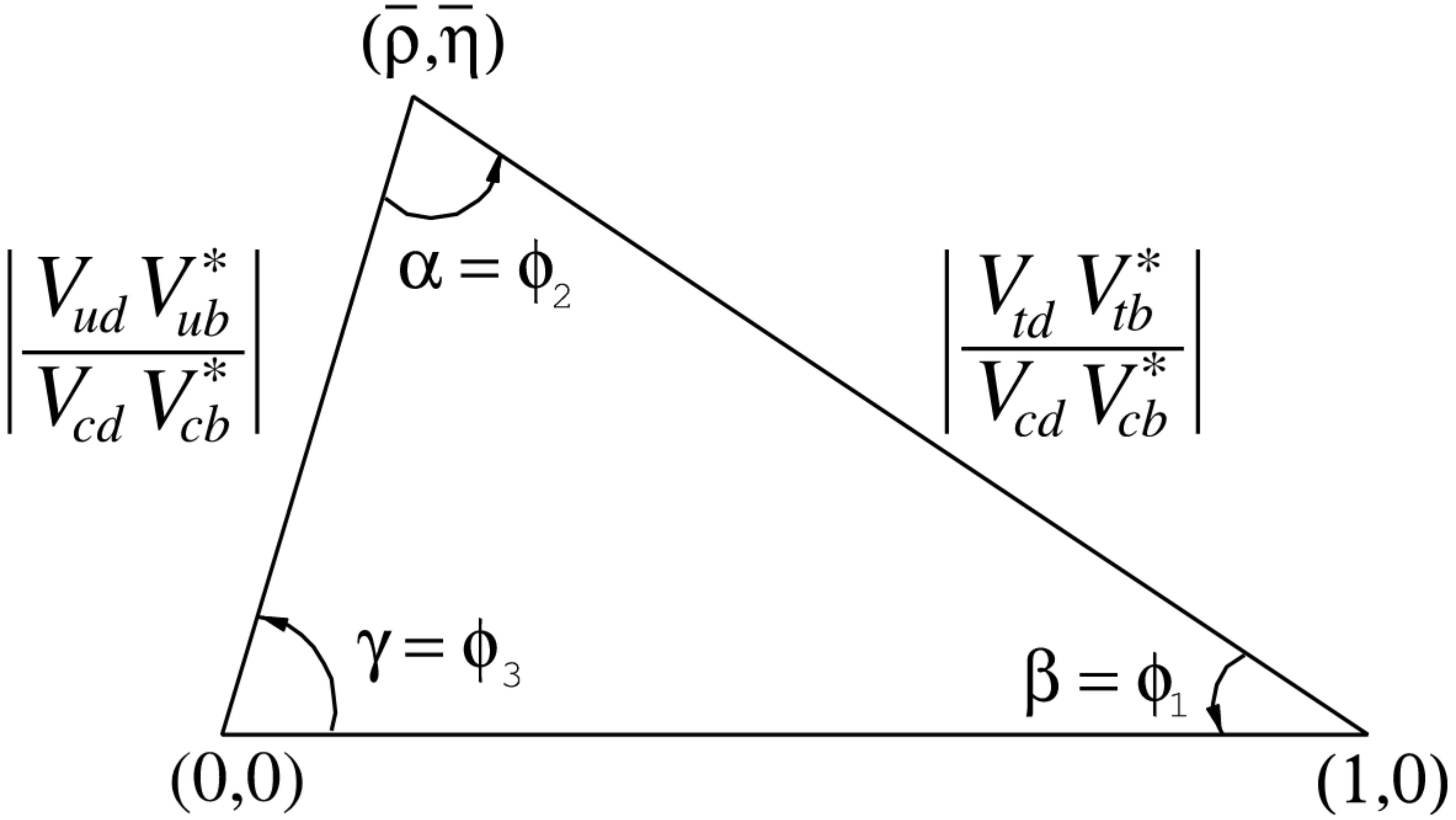
The dawn of B-physics

M. Kobayashi

T. Maskawa

- Kobayashi and Maskawa predict three generations of quarks
  - Three mixing angles and one CP violating phase
  - Unitarity condition may be represented as triangles, e.g.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Interaction eigenstates

Mass eigenstates

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

1 CPV phase

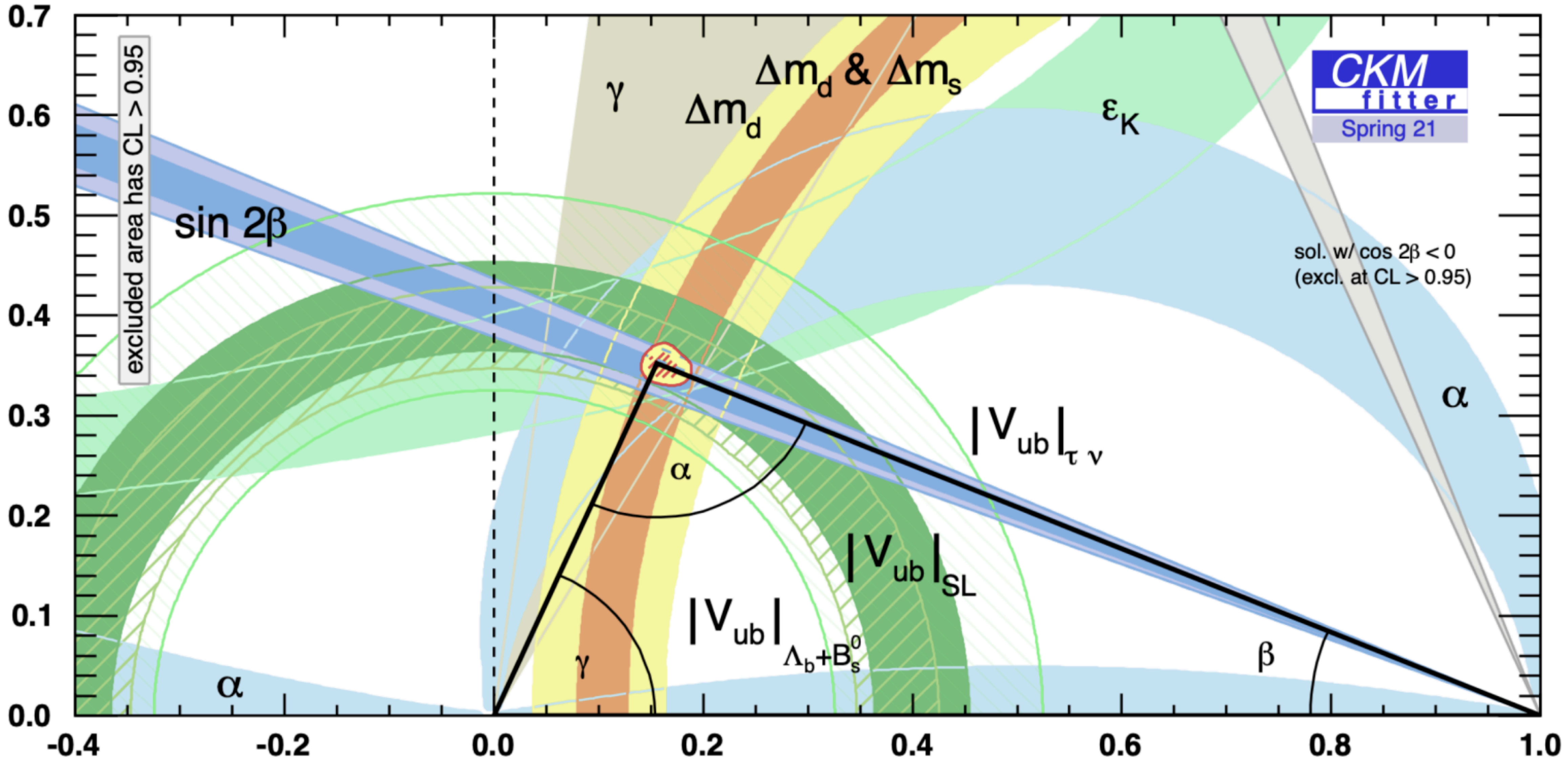
Measuring CKM parameters

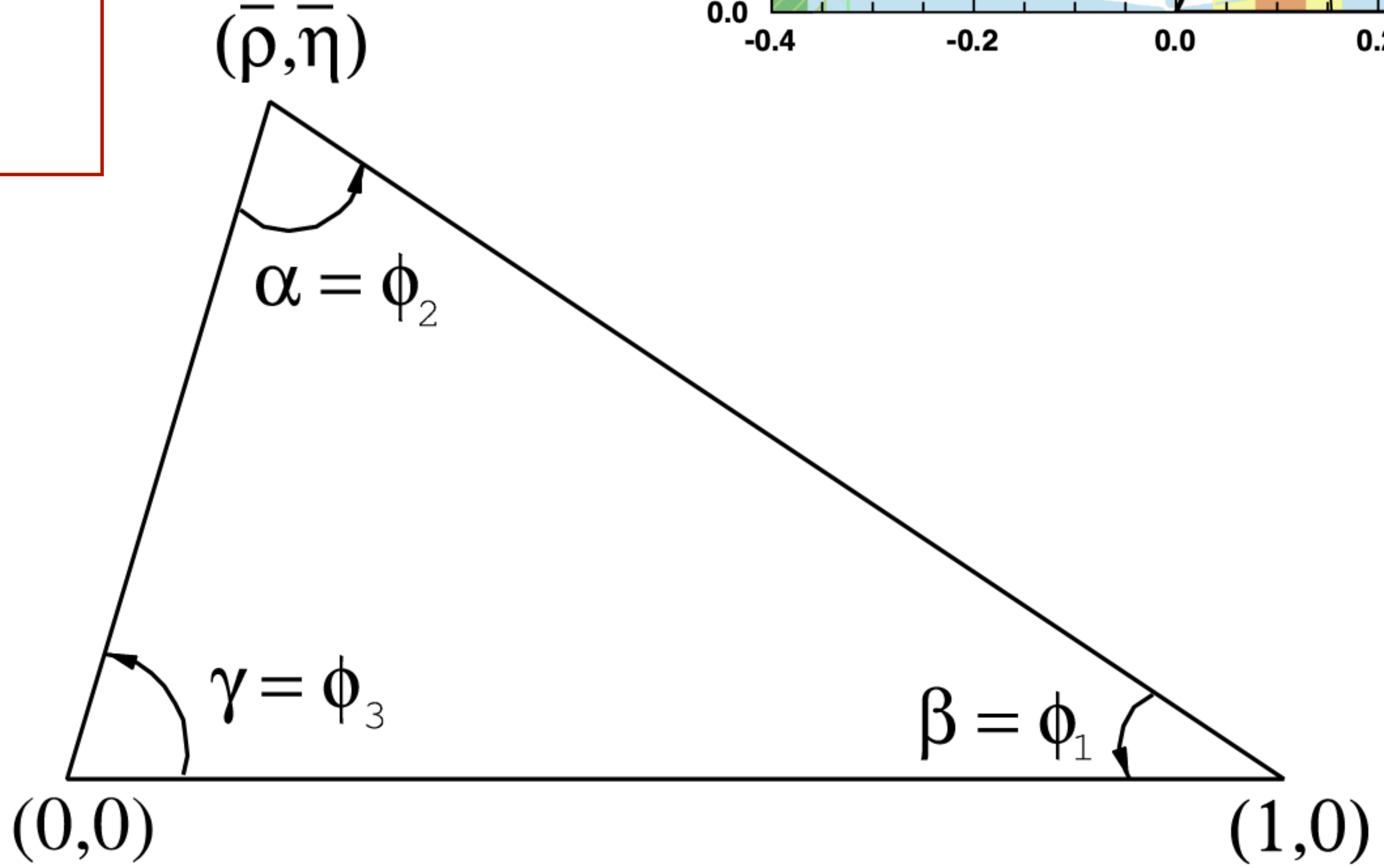
Matrix elements and angles

Angles $\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$

$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$
$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$$
$$B^0 \to \rho\pi$$
$$B^0 \to a_1(\rho\pi)^+\pi^-$$

State-of-the-art in spring 2021





$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$B^- \to D_{CP}^{(*)}K^{(*)-}$$
$$B^0 \to D_{CP}K^{*0}$$
$$B^- \to D^{(*)}(K_S h^+h^-)K^{(*)-}$$
$$B^- \to D(K_S K^+\pi^-)K^-$$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$B^0 \to (c\bar c)K_S, (c\bar c)K_L$$
$$B^0 \to D_{CP}^{(*)}h^0$$
$$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$$
$$B^0 \to (K_S K_S/\rho^0/\omega)K_S$$

*Potential for new physics

Measuring CKM parameters

Matrix elements and angles

Angles

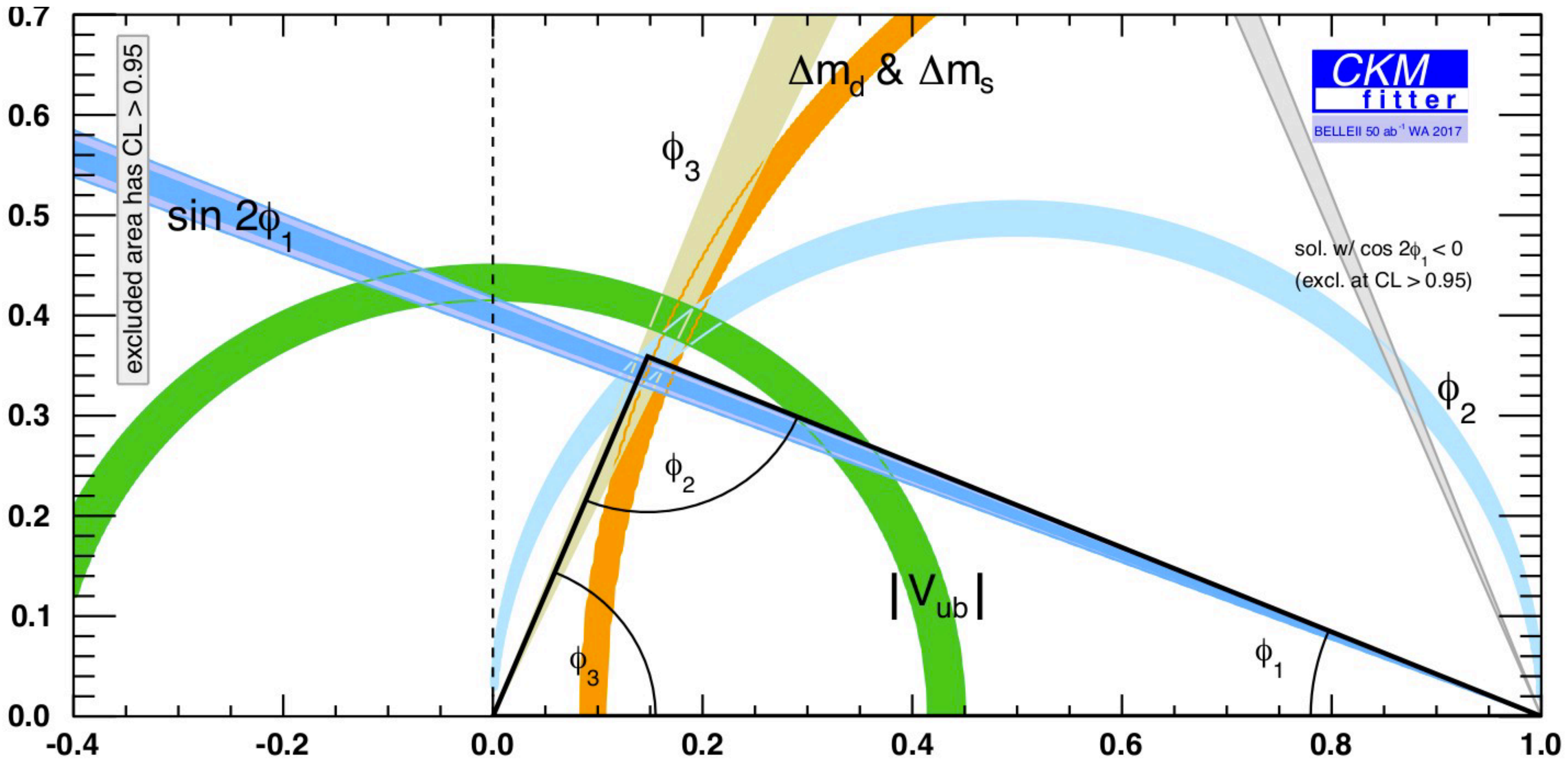
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

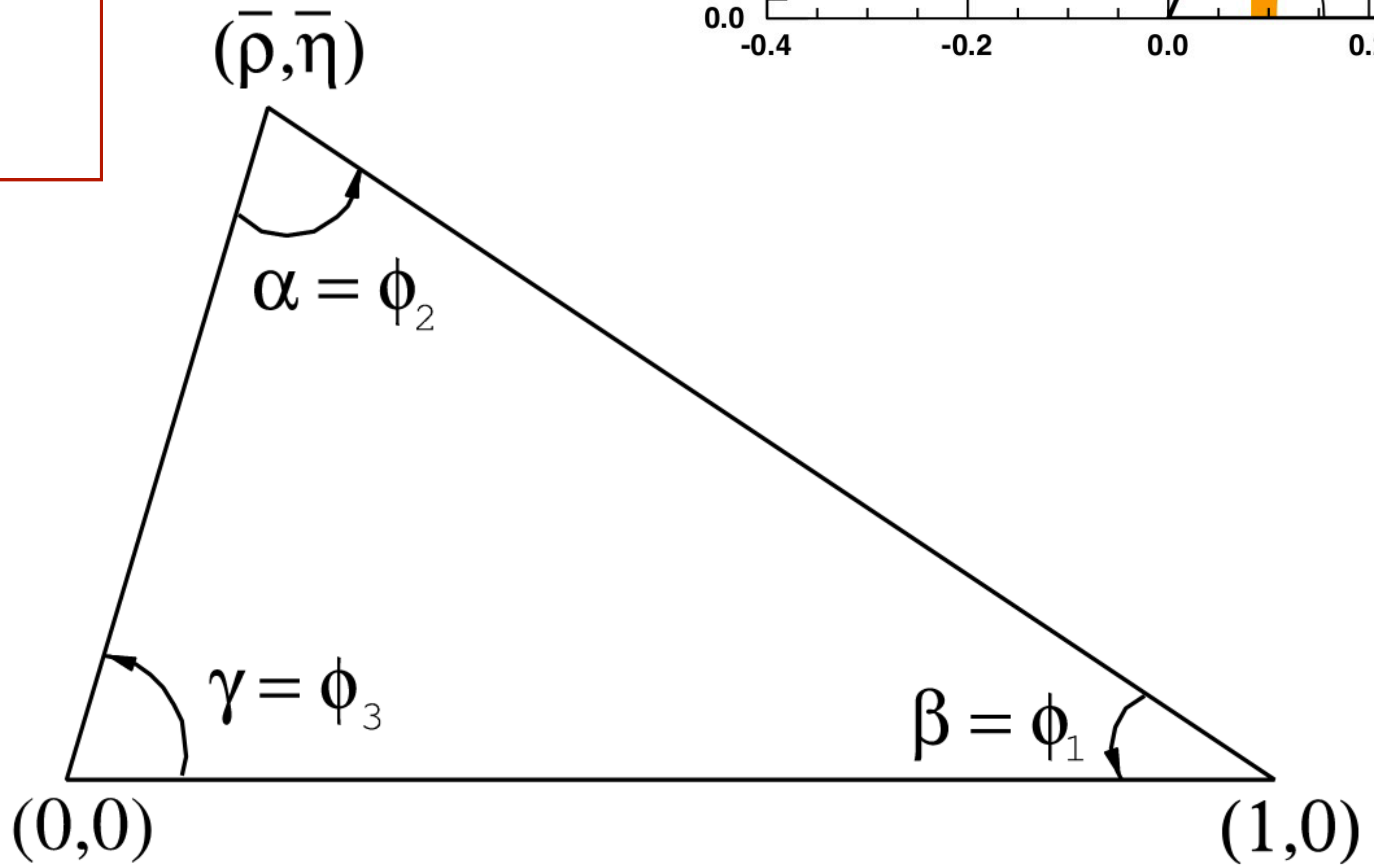
$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$
$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$$
$$B^0 \to \rho\pi$$
$$B^0 \to a_1(\rho\pi)^+\pi^-$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$B^- \to D_{CP}^{(*)}K^{(*)-}$$
$$B^0 \to D_{CP}K^{*0}$$
$$B^- \to D^{(*)}(K_Sh^+h^-)K^{(*)-}$$
$$B^- \to D(K_SK^+\pi^-)K^-$$

Possible view with the full Belle II dataset





$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$B^0 \to (c\bar{c})K_S, (c\bar{c})K_L$$
$$B^0 \to D_{CP}^{(*)}h^0$$
$$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$$
$$B^0 \to (K_SK_S/\rho^0/\omega)K_S$$

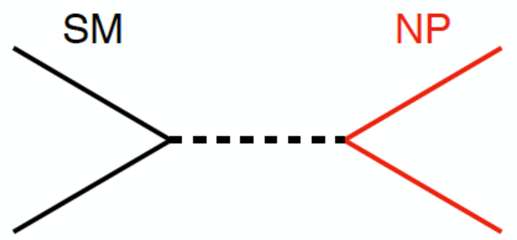
*Potential for new physics

The hunt for New Physics

Unique discovery potential at Belle II

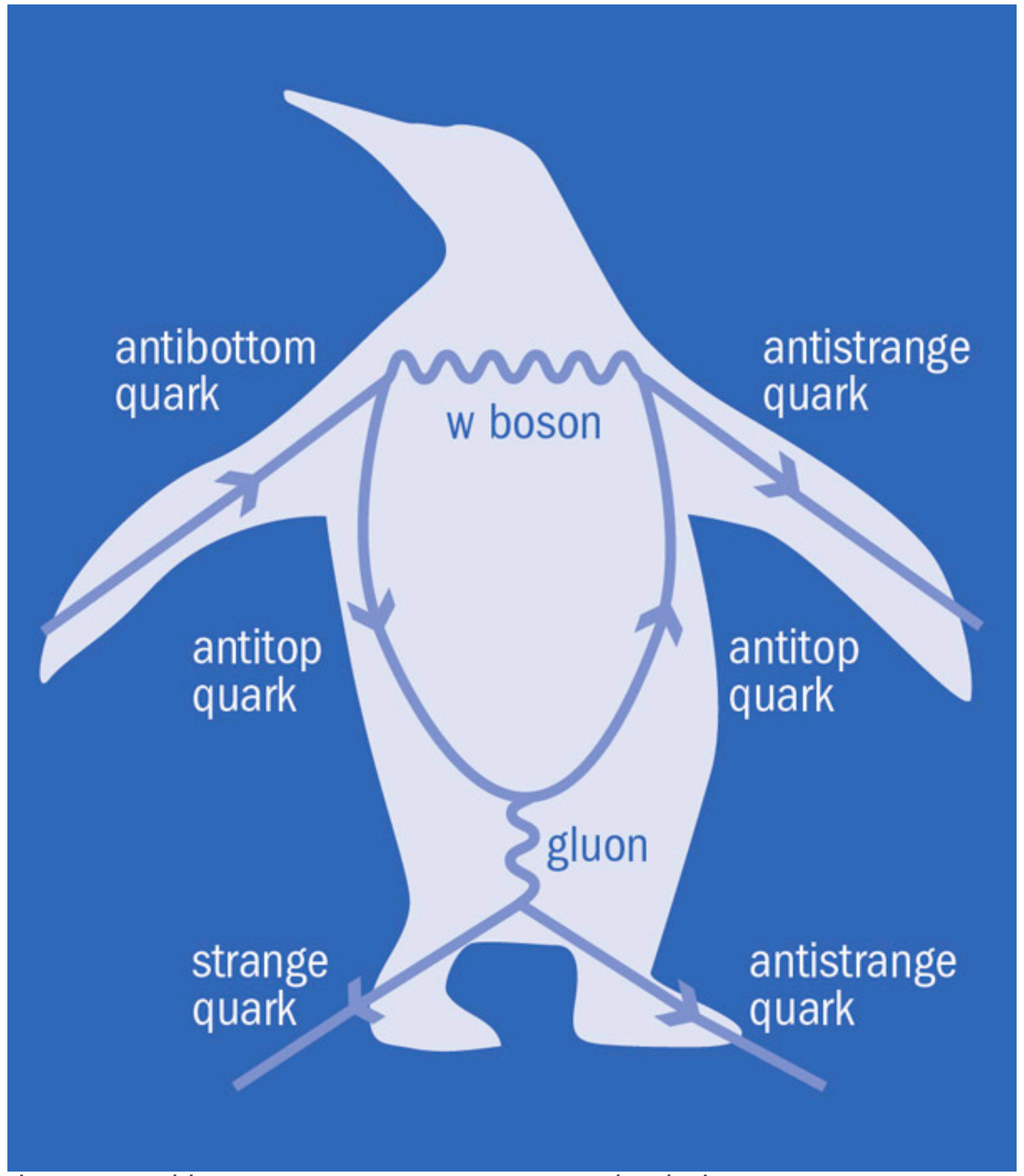
- Mapping and understanding BSM physics requires a range of experiments
  - Energy frontier experiments (including at the LHC) seek to directly produce new particles
  - Intensity frontier experiments (like Belle II) seek to make precise measurements of rare or suppressed processes and study deviations from SM predictions
  - Absence of BSM discoveries at the LHC suggest that the first signs of NP may be seen in high-precision measurements of suppressed processes
    - e.g. new weak (CP-violating) phases in the quark sector

Energy frontier
Direct production of new particles
- limited by beam energy



Intensity frontier:
indirectly reveal NP virtual particles in loops – probe energy above 10 TeV

Electroweak penguin



https://cerncourier.com/a/chasing-new-physics-with-electroweak-penguins

Belle II featured in Snowmass 2021 Report and ESG

Key part of Rare Processes and Precision Measurements Frontier

"the Rare Processes and Precision Measurement Frontier proposes that the upcoming P5 adds a new science Driver: flavor physics as a tool for discovery"

"Priorities for the next few years are to complete the analysis of the Muon g – 2 experiment, begin taking data with Mu2e, and continue taking and analyzing data at Belle II and LHCb"

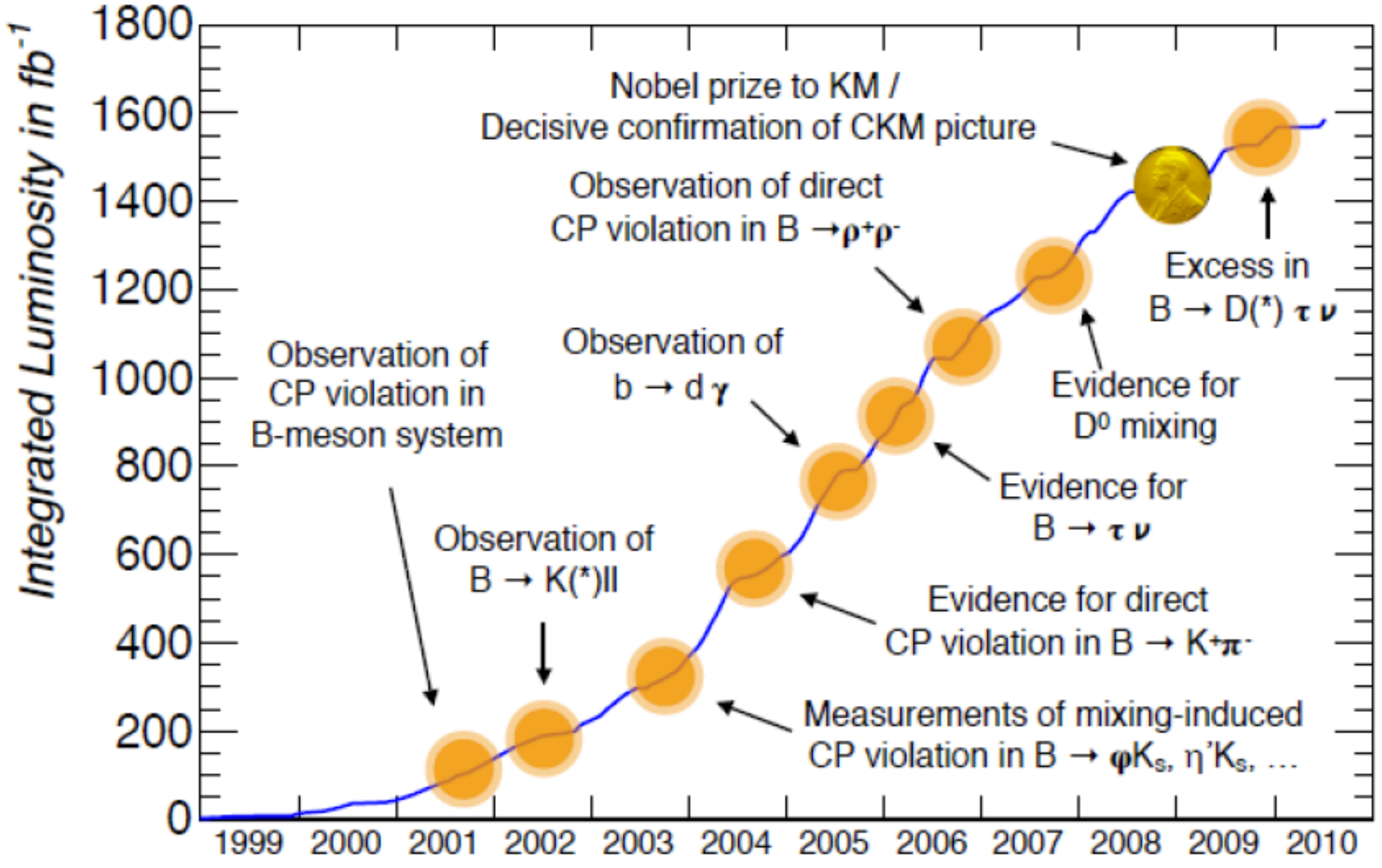
"Belle II and LHCb have the unique potential to unveil new physics by confirming intriguing hints of deviations from the SM that have been recently observed... or finding new unexpected outcomes in the study of rare and forbidden decays..."

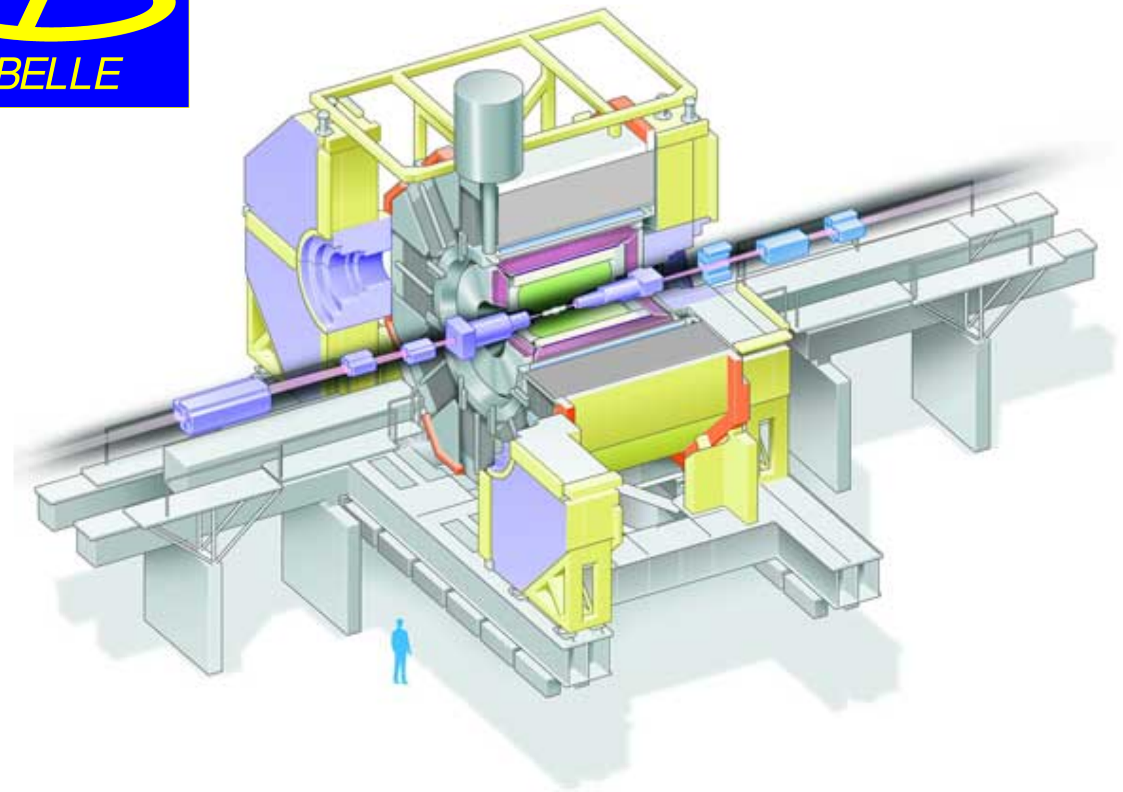
"The U.S. flavor community is well-positioned to lead key aspects of the physics, computing, and detector construction in all of these experimental programs"

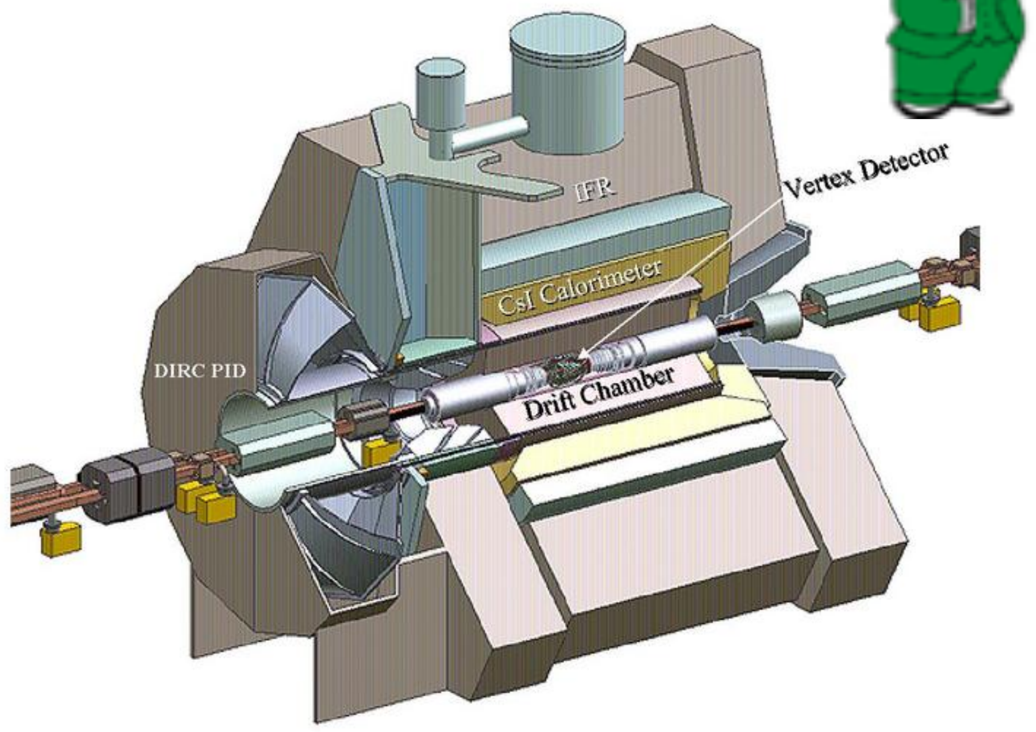
European Strategy Group: "The quest for dark matter and the exploration of flavor and fundamental symmetries are crucial components in the search for new physics."

The hunt for New Physics

Historical contributions by "B factories"







Per ab^{-1} (events $\times\ 10^9$):

1.1 $B\bar{B}$, 1.3 $c\bar{c}$, 2.1 $q\bar{q}$, 0.9 $\tau^+\tau^-$

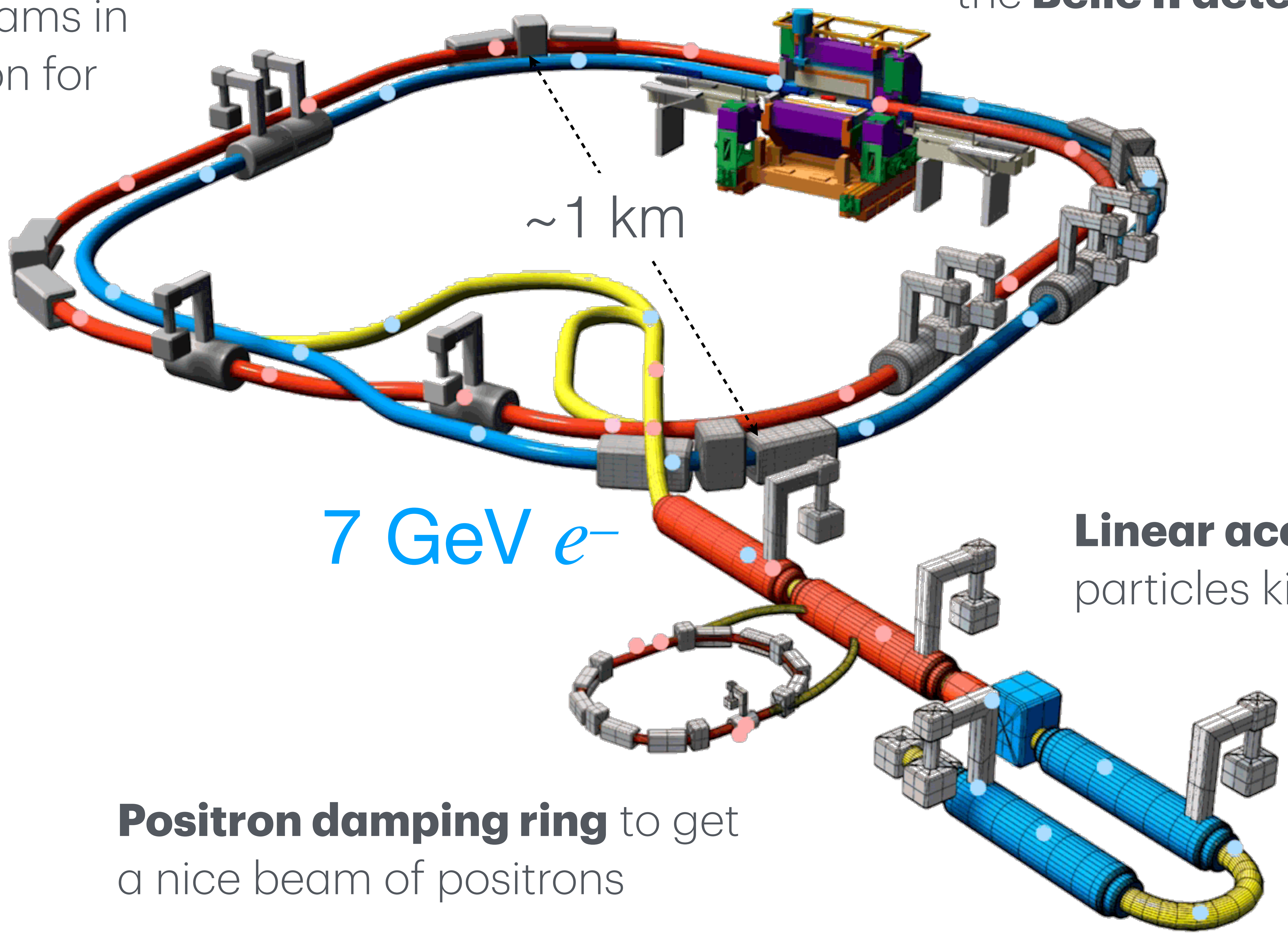
- B factories, Belle @ KEKB and BaBar @ PEPII, played crucial roles in advancing knowledge
  - Large samples of B mesons, charm, tau, and low-multiplicity events
  - Discovery of CPV in the B system (*2008 Nobel Prize*)
  - Published almost 1200 papers, still publishing more than 10 years after shutdown
- Belle II @ SuperKEKB represent significant improvements
  - Expected to record order of magnitude more data than the BaBar and Belle experiments


Mt. Tsukuba (877m)
SuperKEKB
Belle II
LINAC
main ring: 3km
e- (HER): 7GeV
e+ (LER): 4GeV
KEK
Tsukuba
Campus

SuperKEKB and Belle II: 2nd generation "B Factory"

Storage ring keeps beams in "bunches" in preparation for collision

Collide beams at the center of the **Belle II detector**



4 GeV e^+

7 GeV e^-

Linear accelerator to give particles kinetic energy

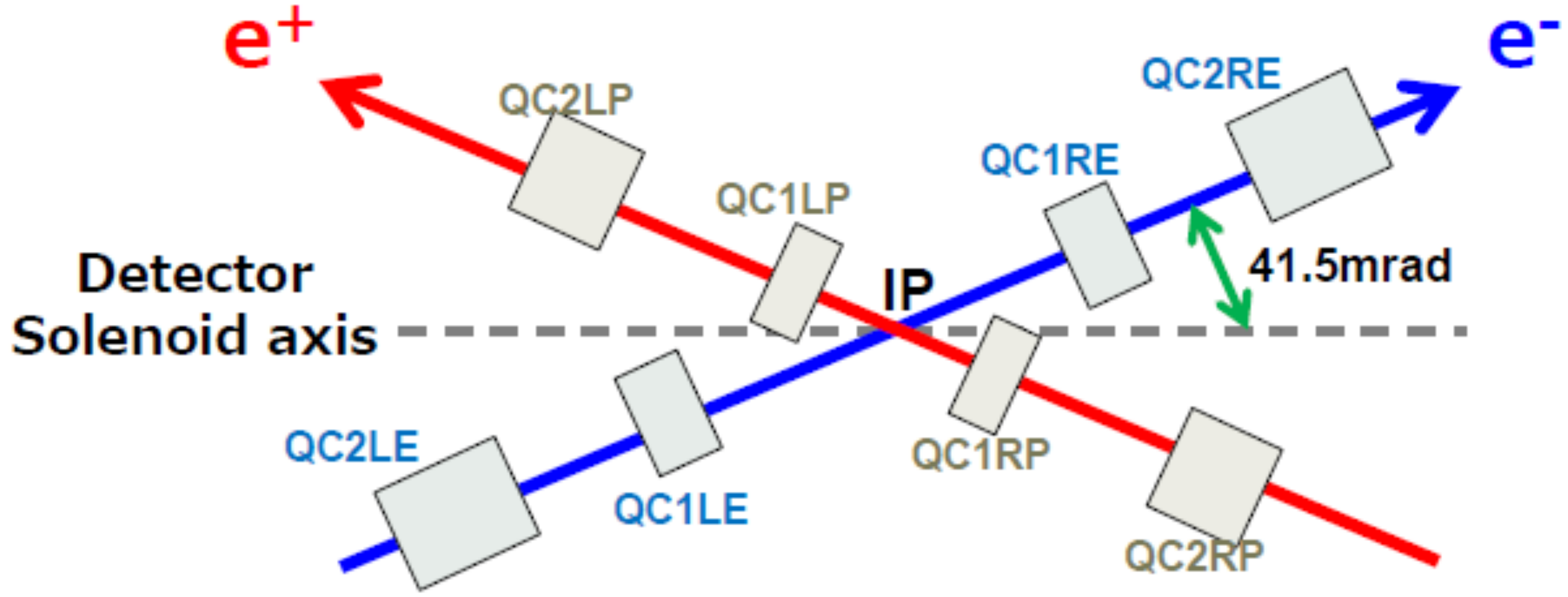
Positron damping ring to get a nice beam of positrons

SuperKEKB nanobeams

To get 40x luminosity of KEKB

Reduce beam size to a few 100 atomic layers!

- 8 superconducting magnets
- Final focusing magnets for each beam



Lorentz factor

Beam current

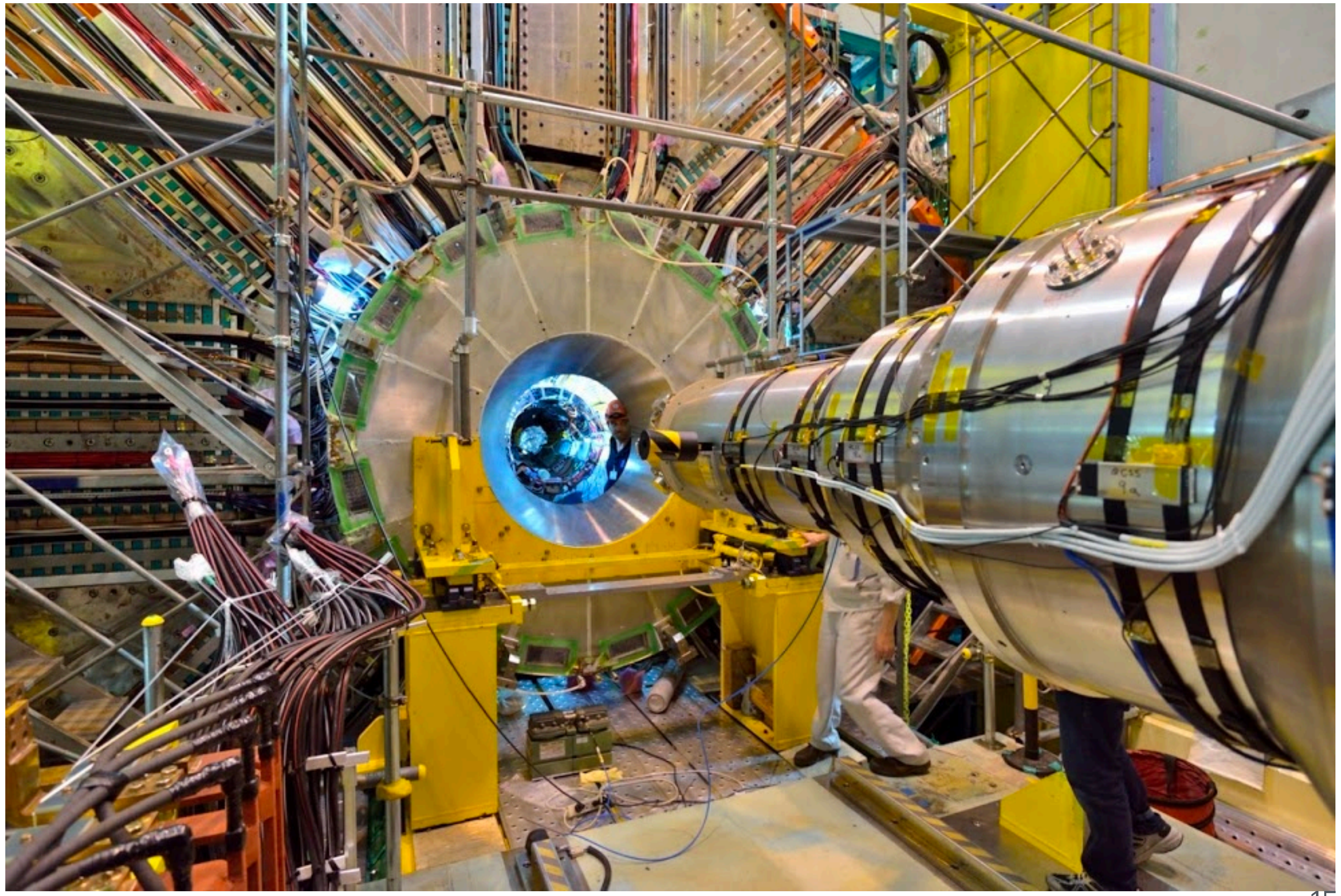
Beam-Beam parameter

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

Geometrical reduction factors (crossing angle, hourglass effect)

Beam aspect ratio at IP

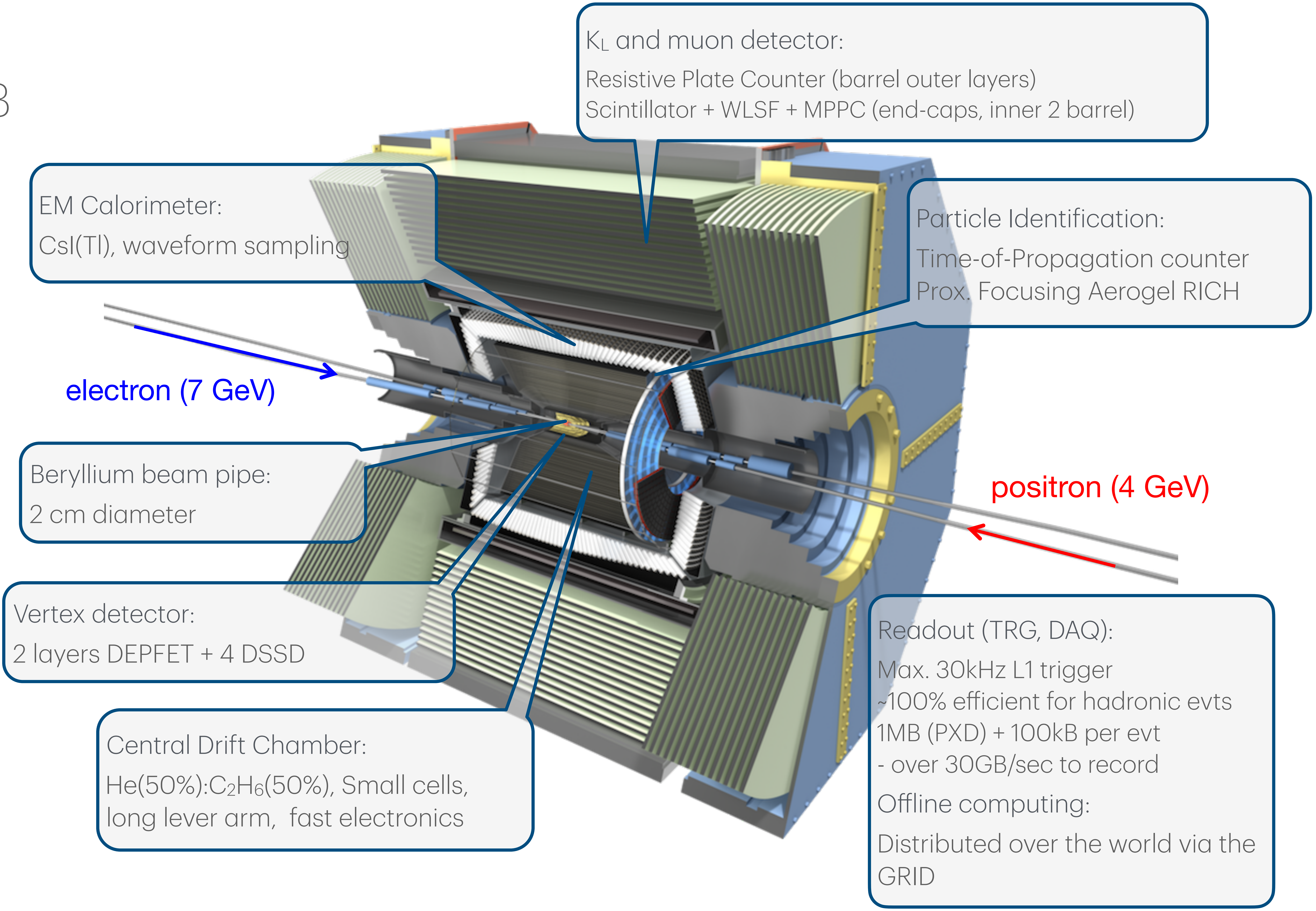
Vertical beta function at IP



Belle II

Experiment @ SuperKEKB

- Multipurpose detector
  - Excellent vertexing - silicon pixels improve track impact parameter and vertex resolution by about a factor of two over Belle/BaBar
  - High-efficiency detection of neutrals (γ, π^0, η, η', $\ldots$)
  - High trigger efficiency, including low multi. events
  - Reconstruction performance at least as good as Belle & BaBar

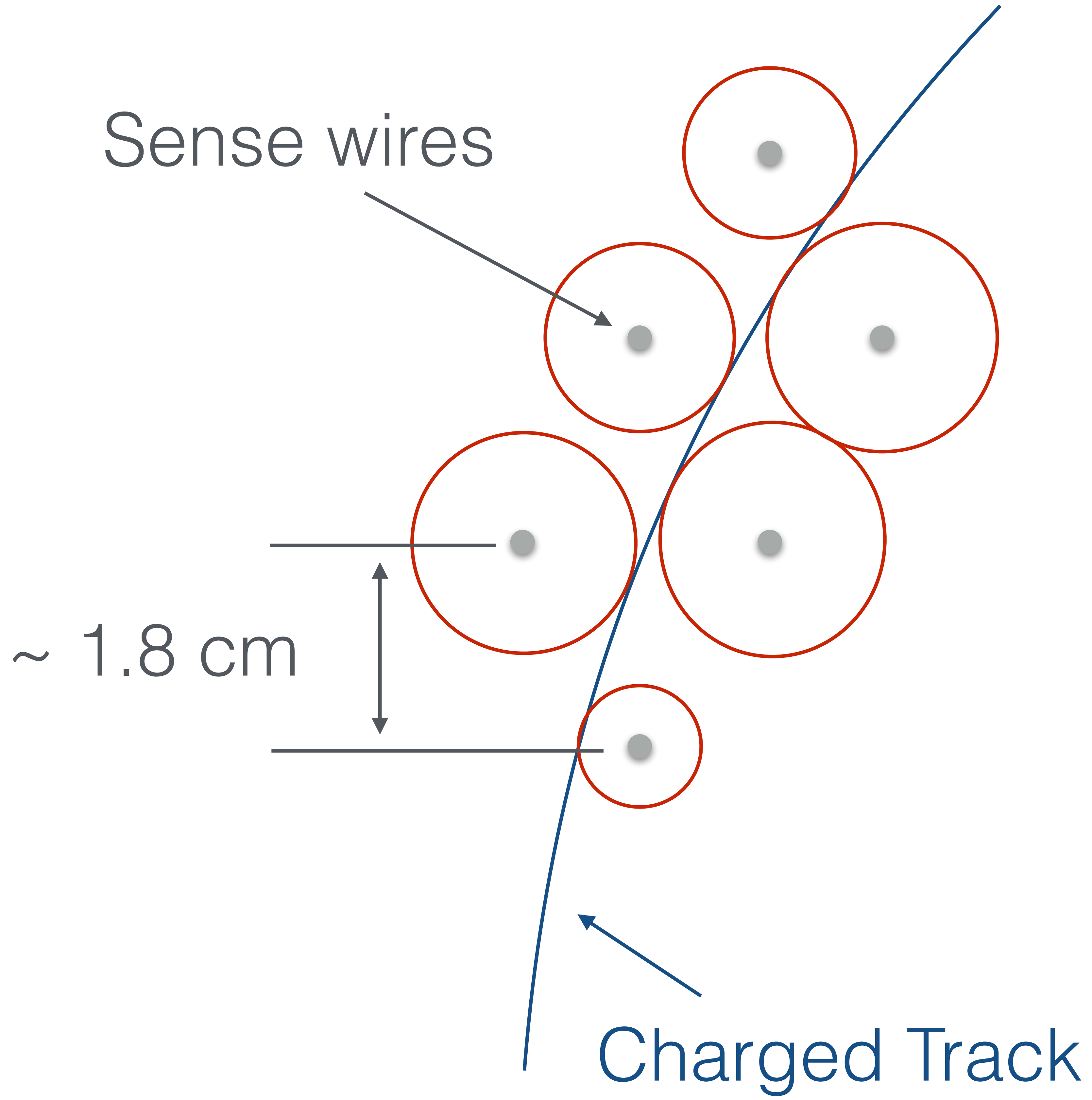


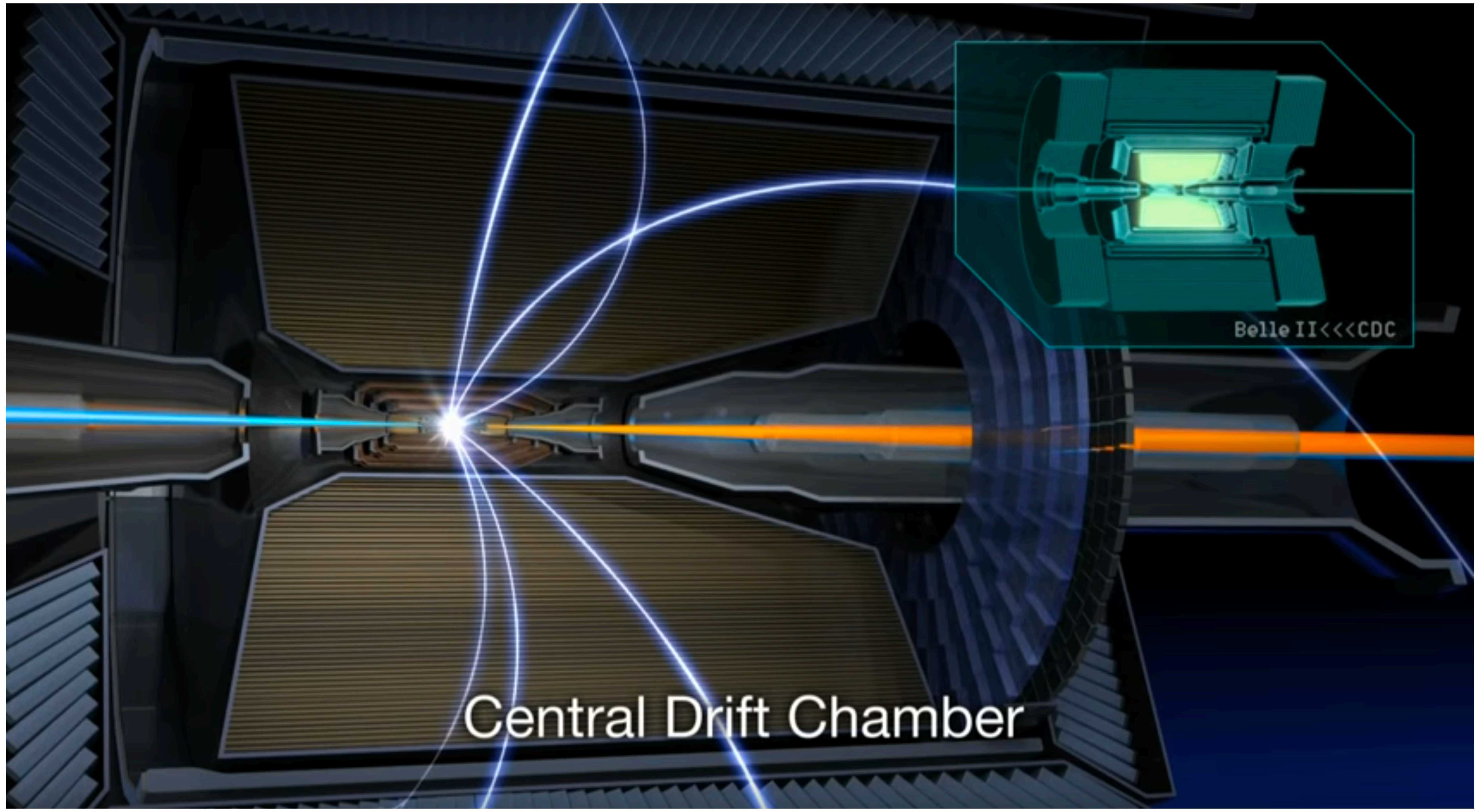
$$c\bar{c},\ s\bar{s},\ d\bar{d},\ u\bar{u},\ \tau^+\tau^- \leftarrow e^+e^- \rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$$

Charged particle tracking

A very simple introduction

- Gas-filled chambers with thin wires parallel to the primary axis
- Charged particles ionize the gas along their flight path, giving up kinetic energy (few keV/cm)
- Electrical signals with the location (which wire) and drift time of each hit are recorded

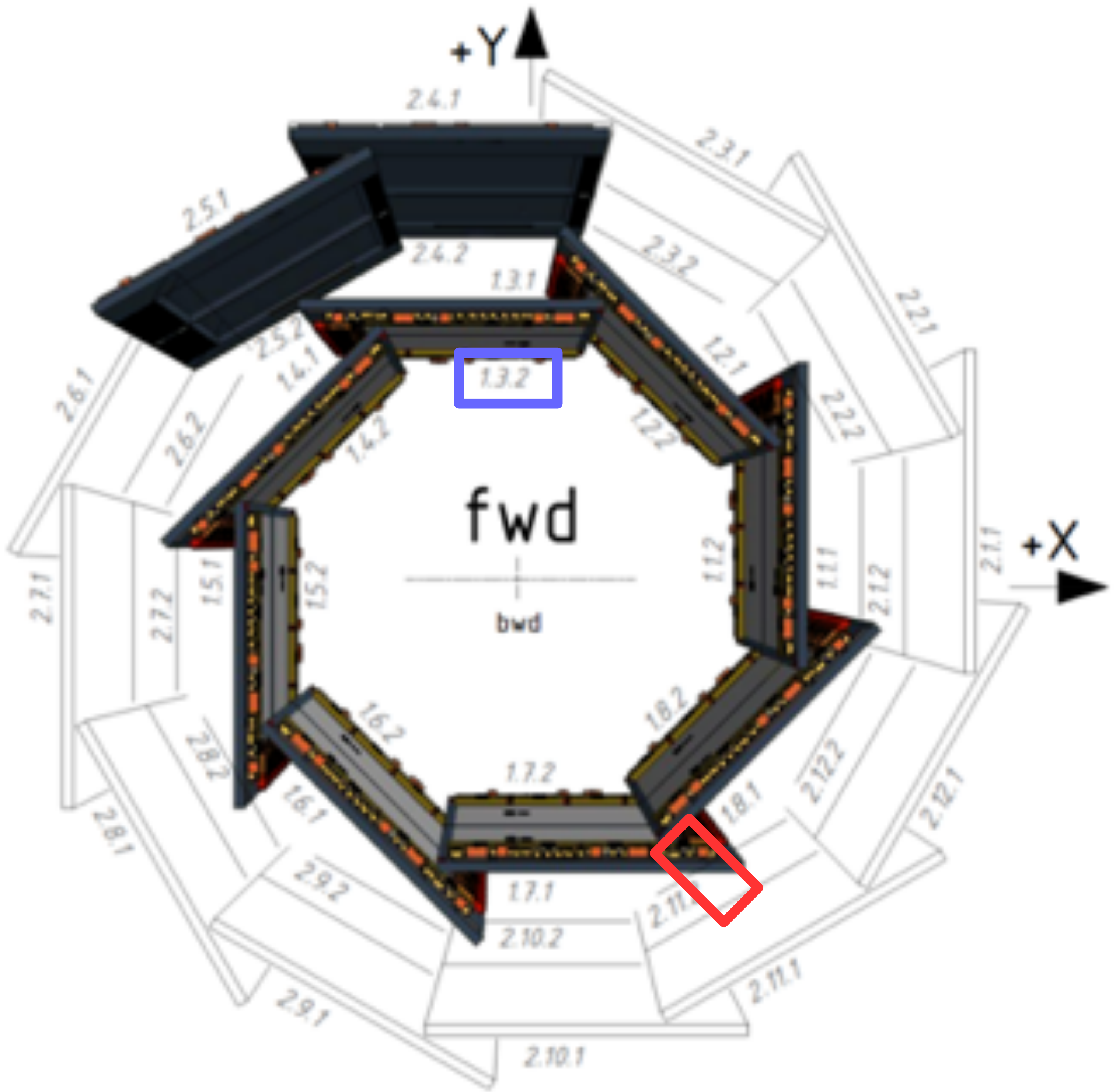




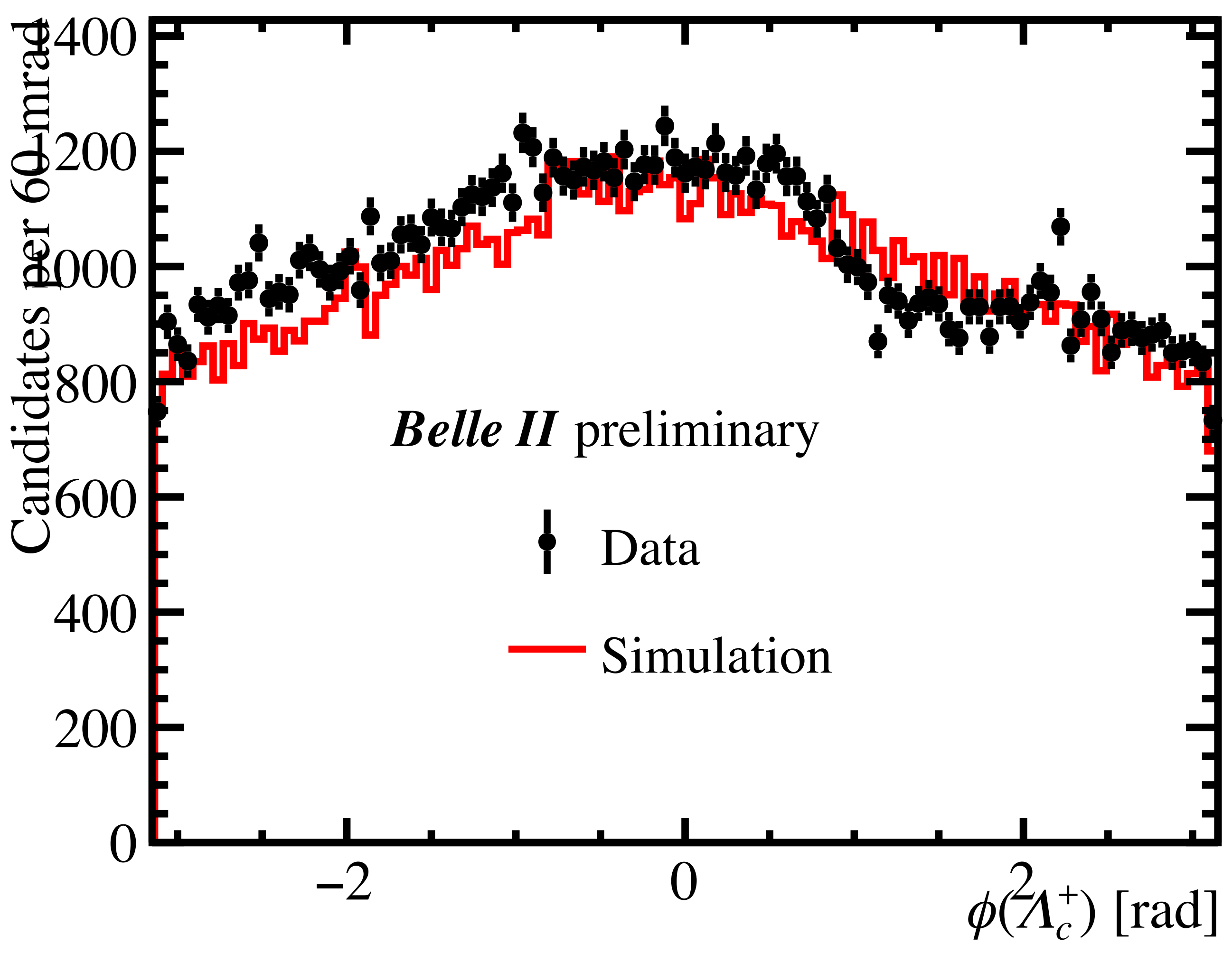
“Early phase 3” (experiment=1003) geometry

Be aware of the data you are using!

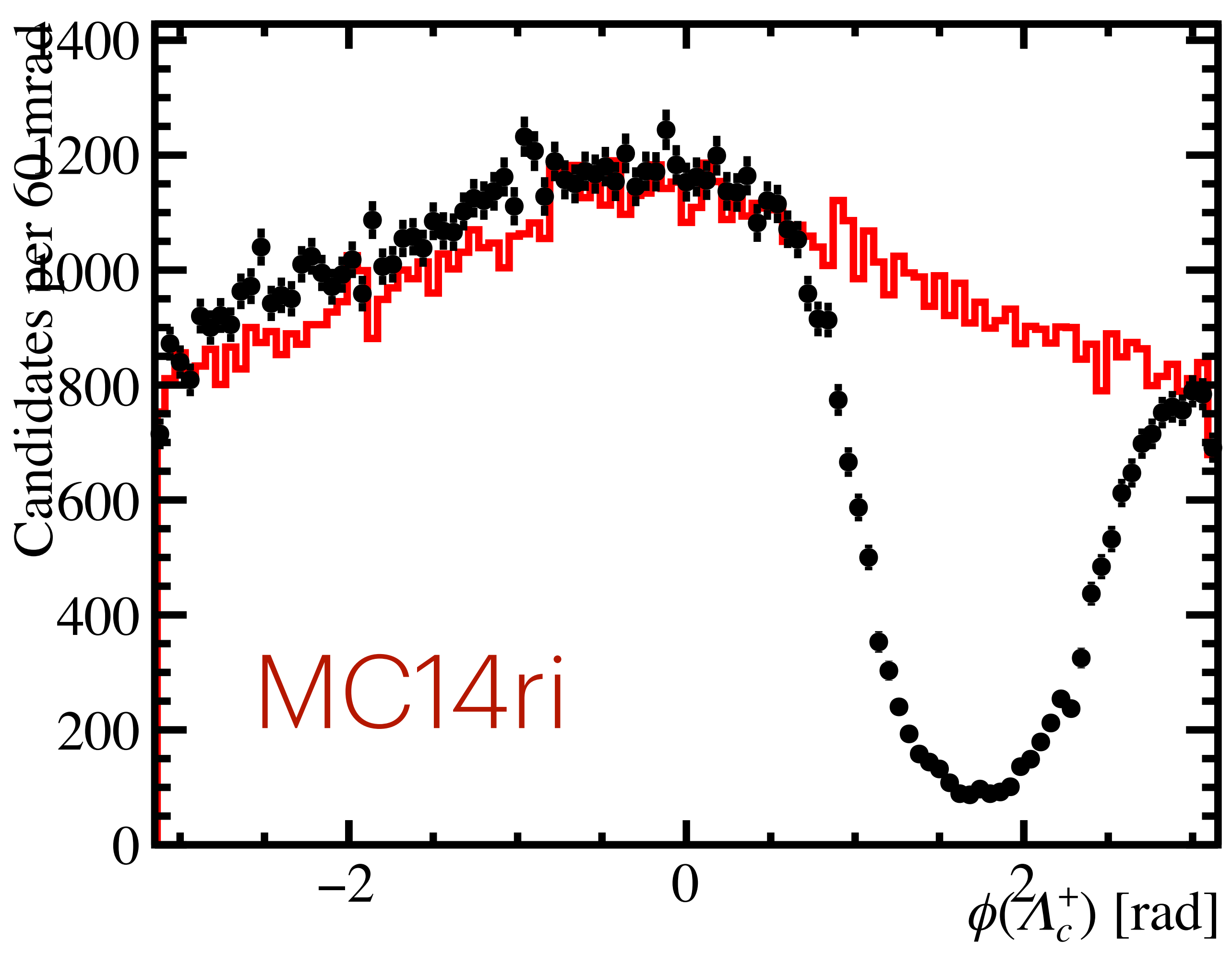
- Technical troubles in module production and assembly: only inner layer installed (+2 ladders on outer layer)
- Completed PXD replacement during LS1
- Two full sensors were not operational
  - 1.3.2: known B-grade, masked
  - 1.8.1: masked since QCS quench and uncontrolled beam loss

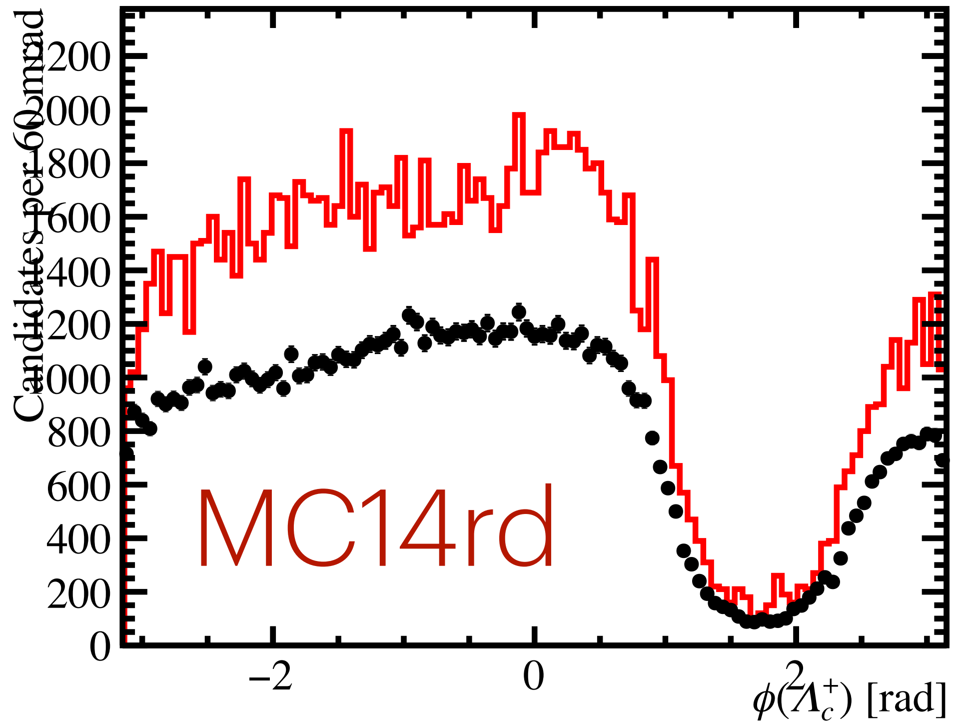


No requirement on VXD layer 1



Require first hit on VXD layer 1



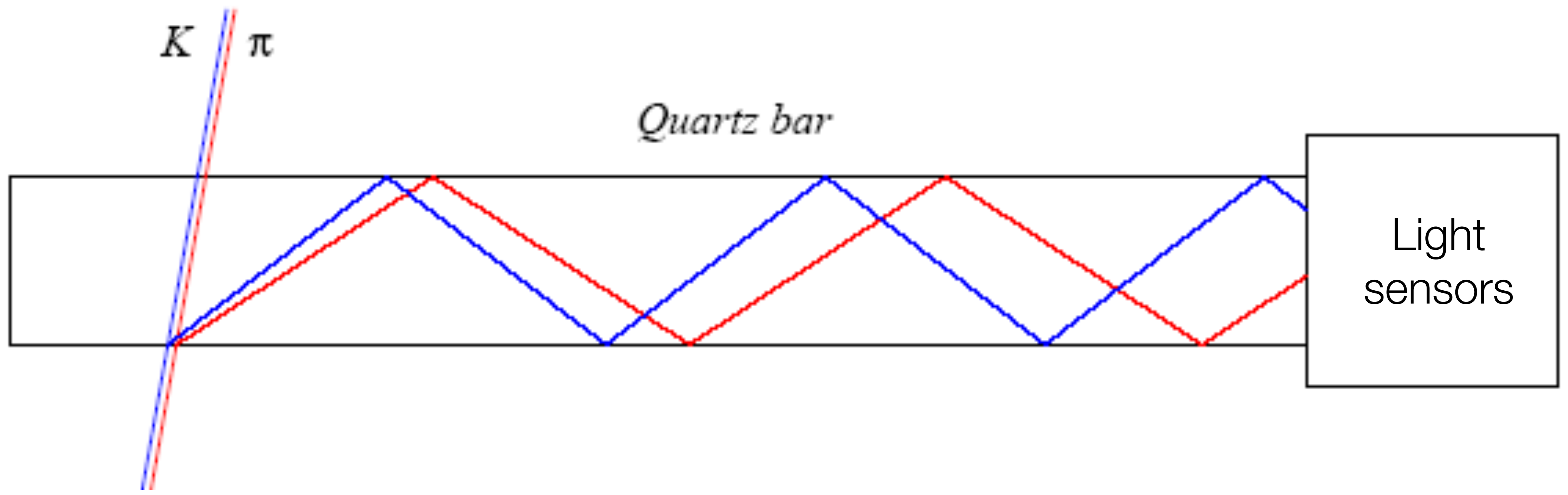


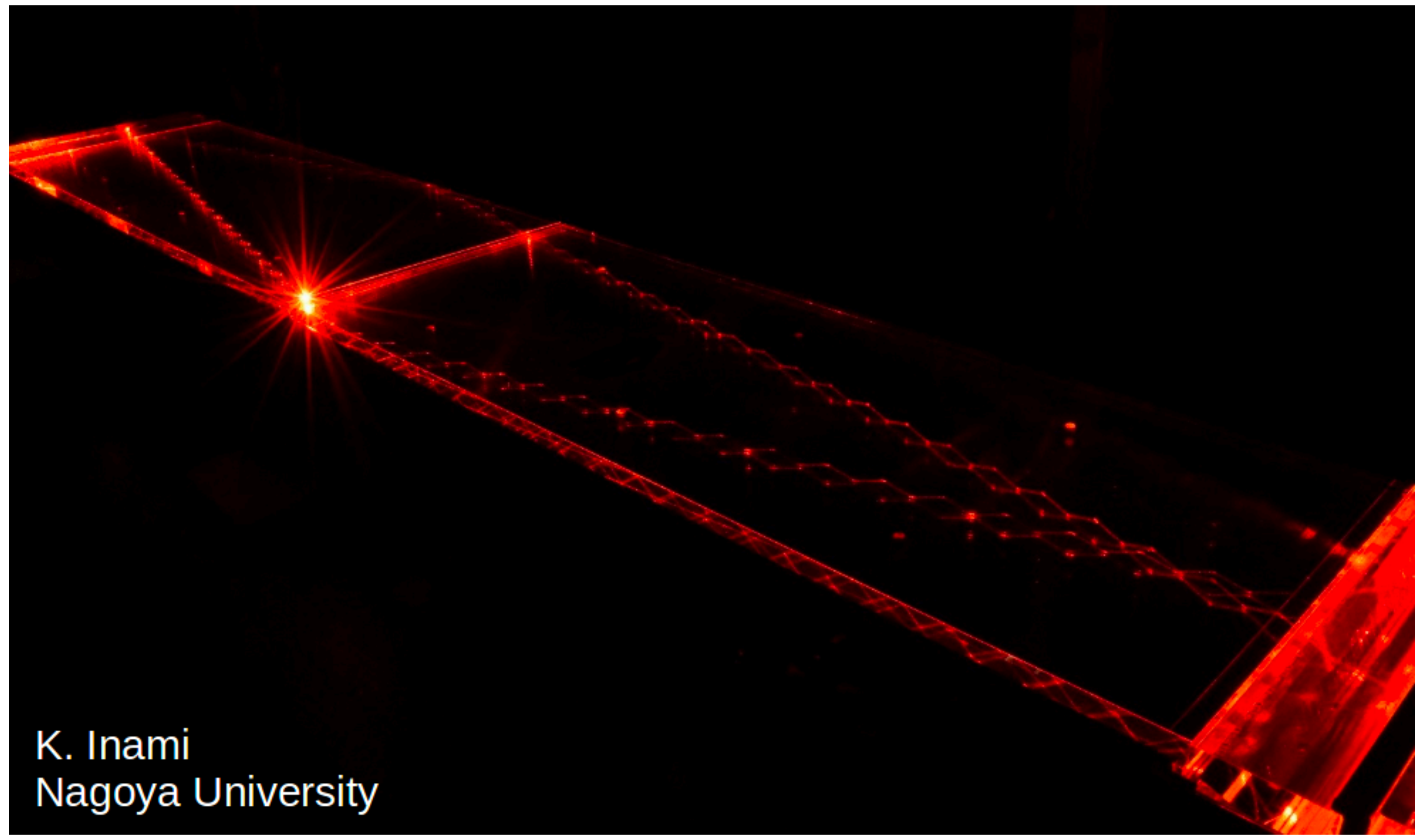
Run-independent MC = ideal conditions
Run-dependent MC = real conditions

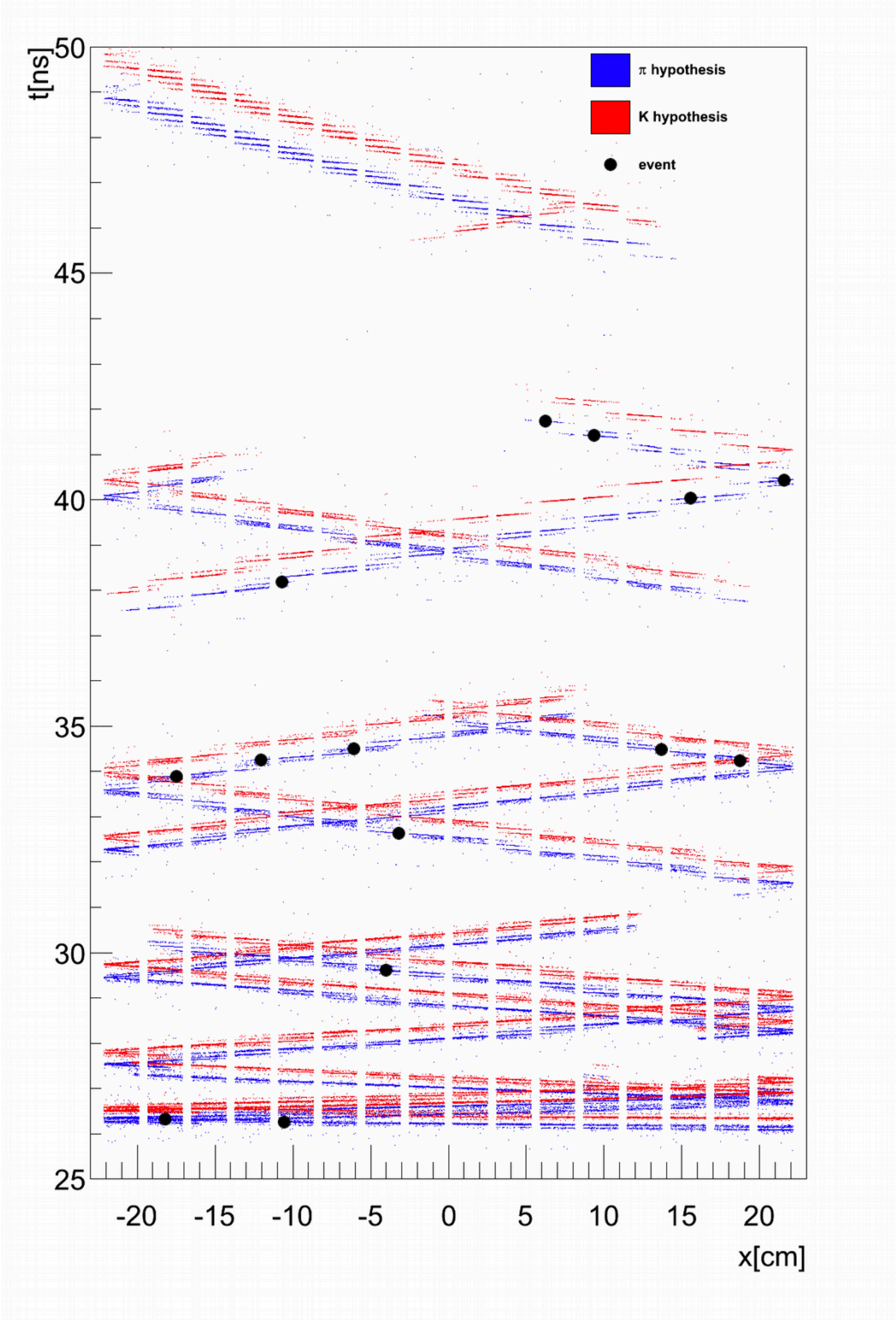
imaging Time Of Propagation counter (TOP)

Actually measures Timing And Relative Displacement In Space

- Cherenkov angle preserved in the time of propagation and light pattern
- Reconstruct angle from two coordinates and the time of propagation of the photon



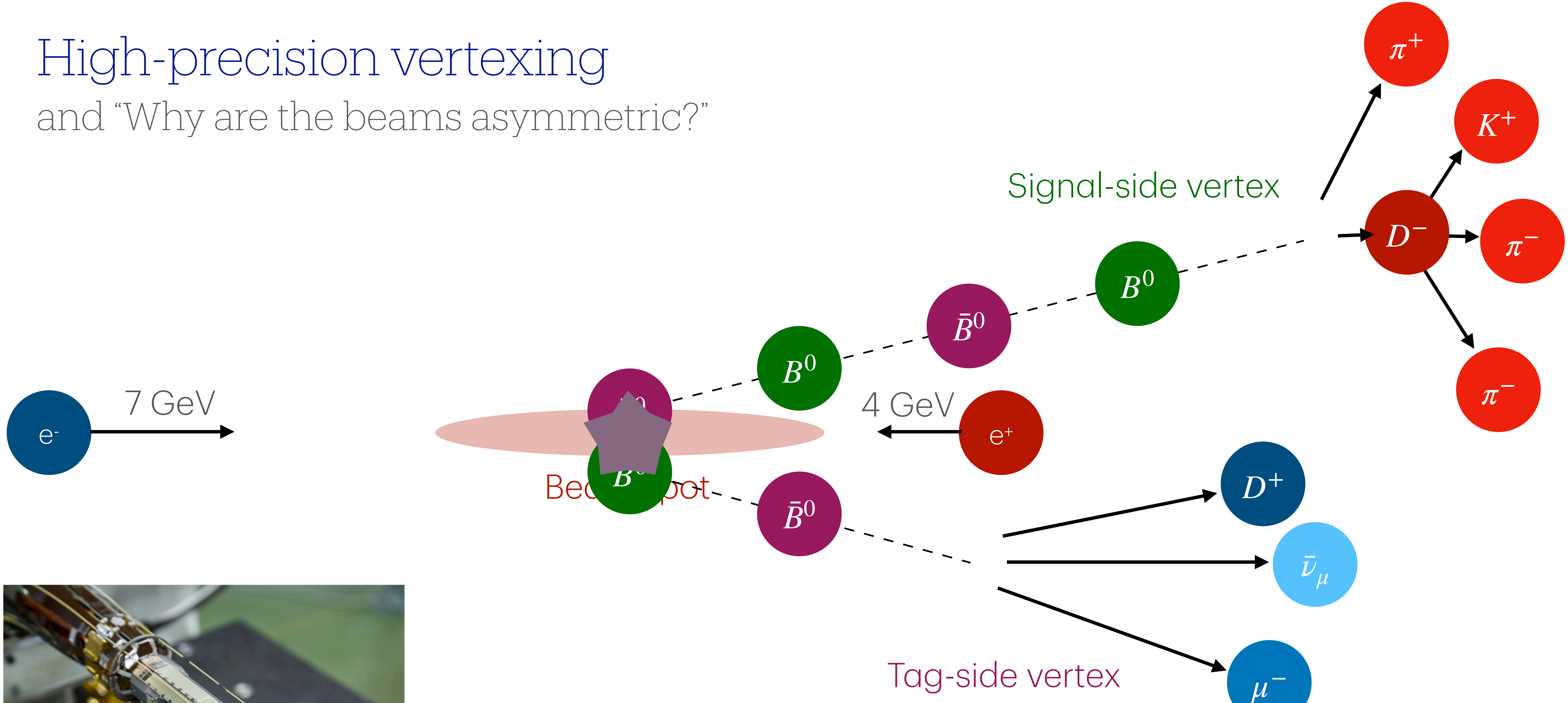


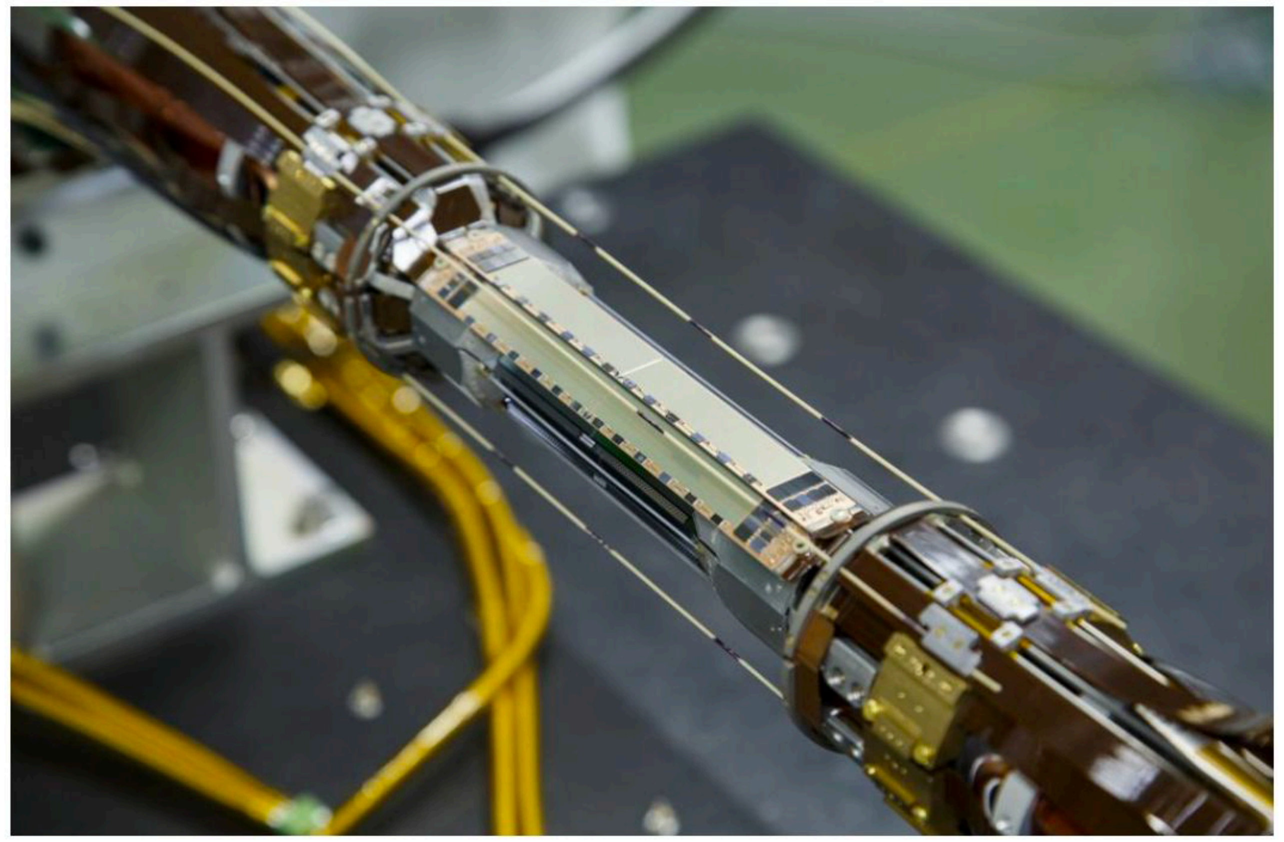


A canonical $\mathbf{B\bar{B}}$ Event

High-precision vertexing

and "Why are the beams asymmetric?"





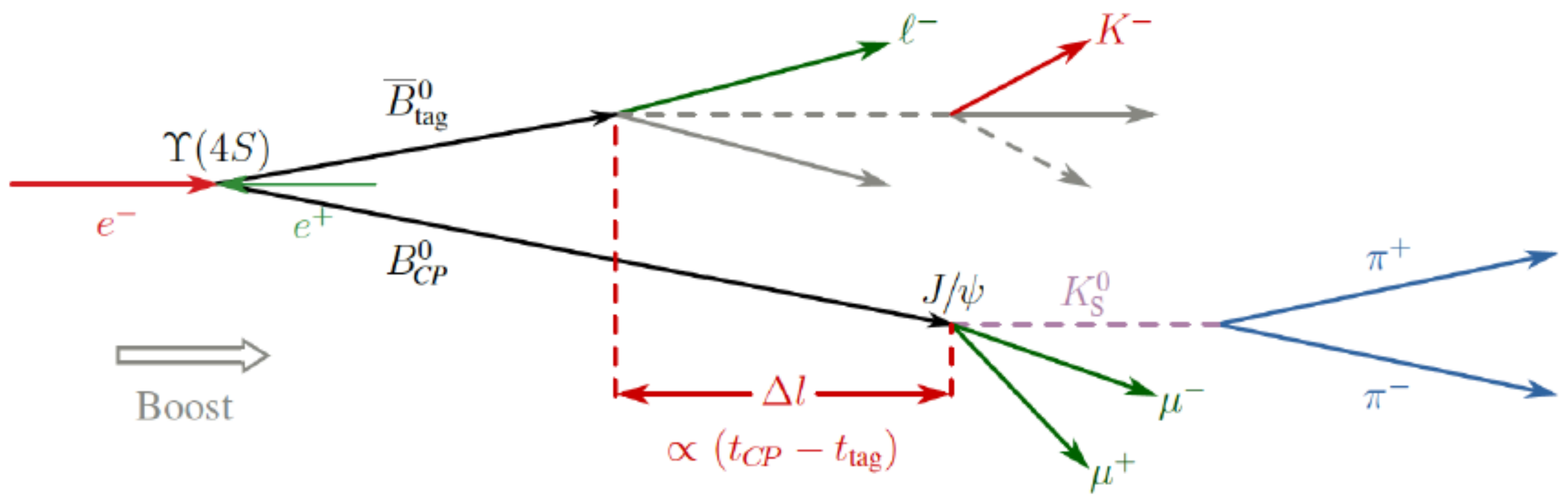
Improved vertex resolution due to pixel detector (despite lower boost)

Identifying new CP-violating phases in the quark sector

High sensitivity to New Physics

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_d}}{4\tau_d}\left\{1 + q\left[\boxed{A_{CP}}\cos(\Delta m_d \Delta t) + \boxed{S_{CP}}\sin(\Delta m_d \Delta t)\right]\right\}$$

$A_{CP} \approx 0$ in the SM $\qquad S_{CP} \approx \sin 2\beta$ in the SM

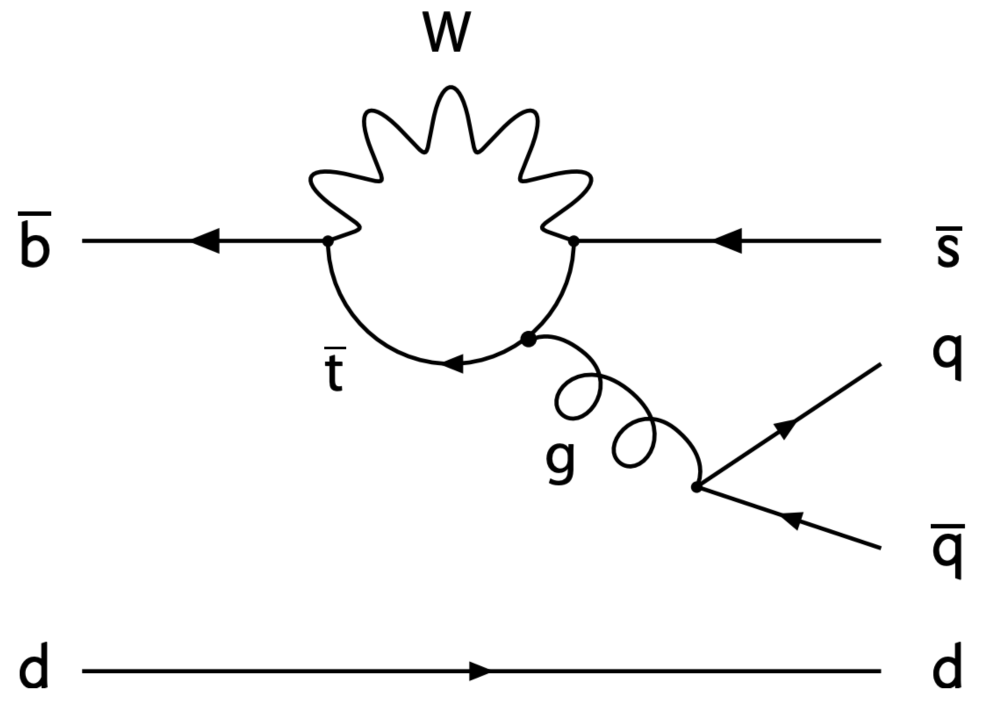


- Some experimentally challenging modes:
  - Fully hadronic final state with neutrals (Unique to Belle II)
  - Low purity → dedicated continuum suppression algorithms

$S_{\rm penguin} \approx$

$A_{\rm penguin} \approx$

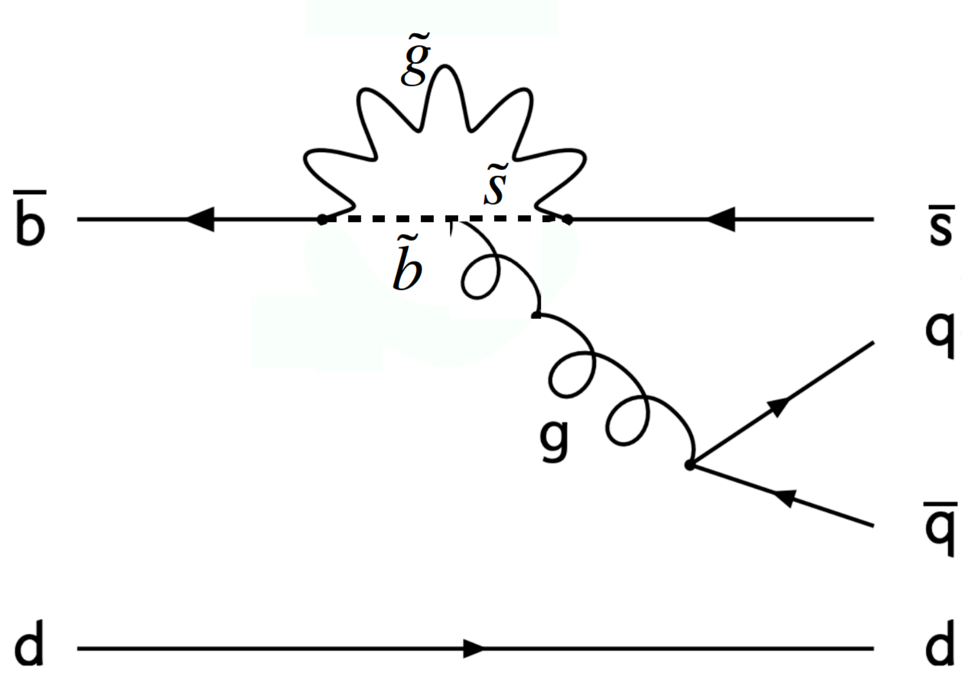
Suppressed in SM



$\sin 2\beta$ (SM)

0 (SM)

Access to potential BSM physics



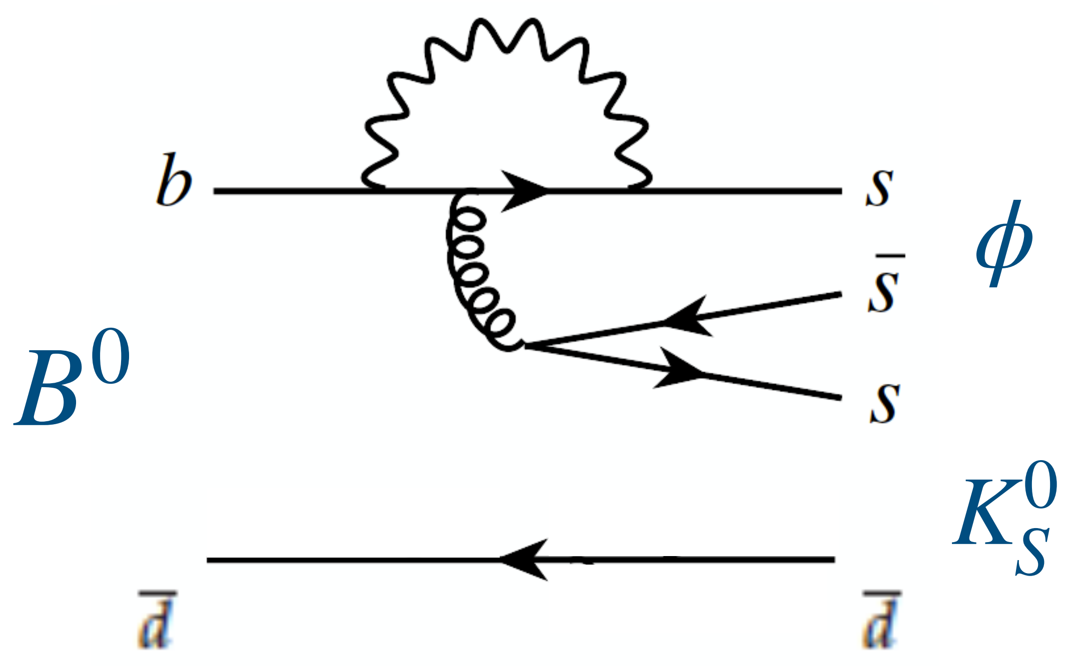
$+ \Delta S$ (NP)

$+ \Delta A$ (NP)

Identifying new CP-violating phases in the quark sector

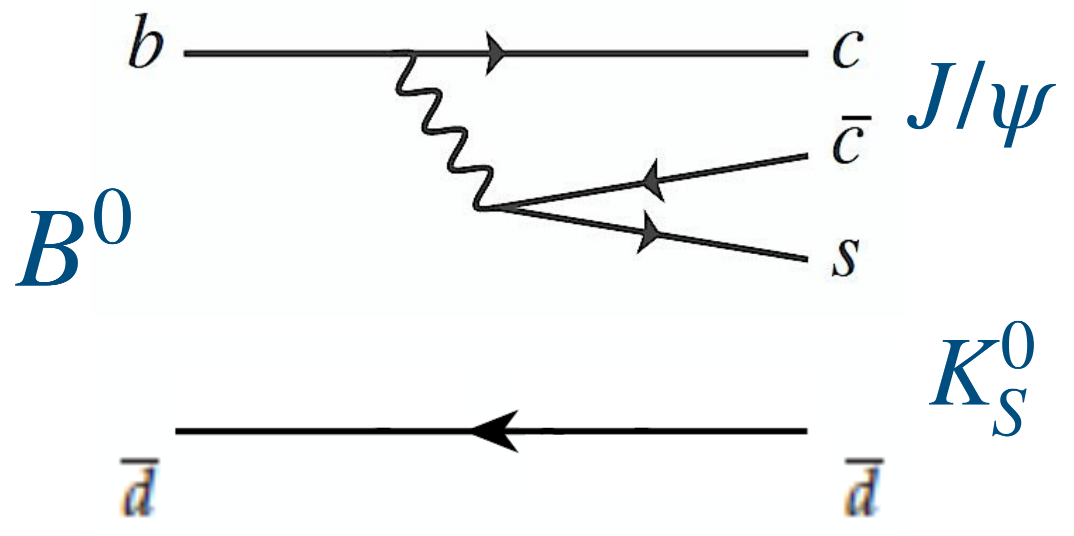
High sensitivity to New Physics

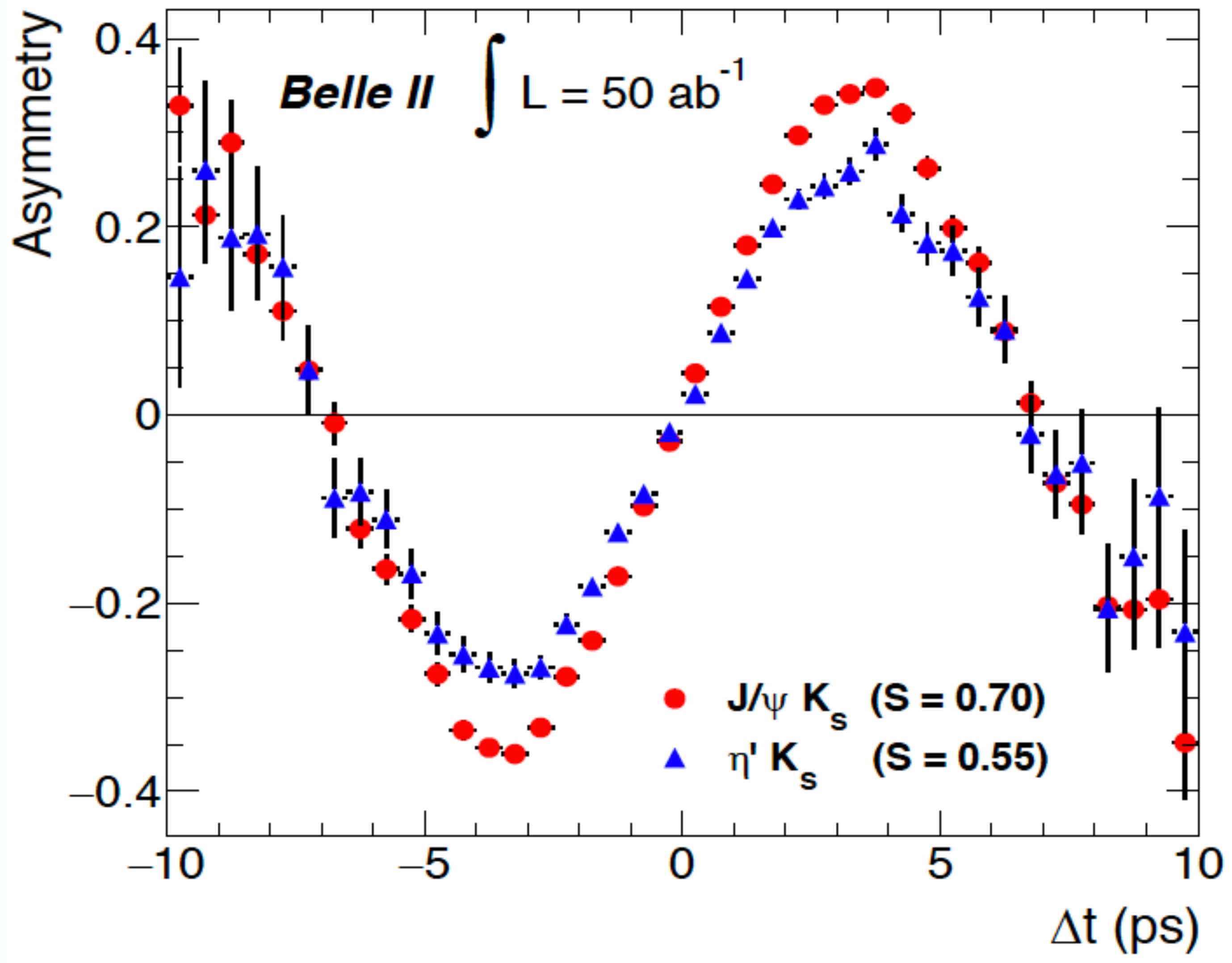
- High sensitivities to new weak phases from non-SM processes in CP asymmetries for decays proceeding via penguin loop transitions $b \to s$ and $b \to d$
  - Belle II will measure such asymmetries in variety of charged and neutral final states
  - e.g. unique precision in time-dependent CP asymmetries in $B^0 \to \eta' K_S^0,\ \phi K_S^0$



SM:
$|S_{b\to c} - S_{b\to s}| \simeq 0$

NP in loop:
$|S_{b\to c} - S_{b\to s}| > 0$



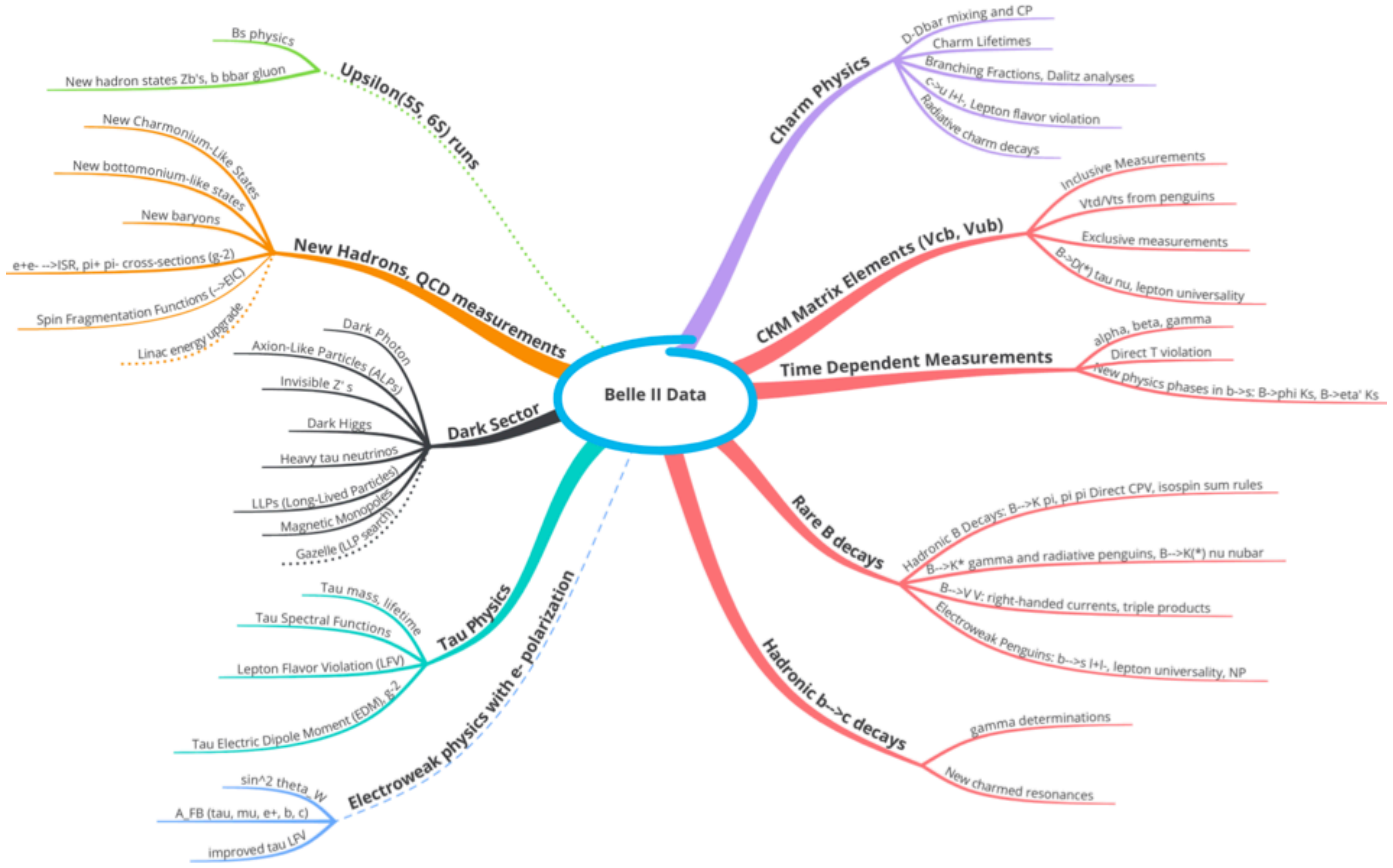


- Belle II will measure time-dependent CPV in $b \to s\gamma$ that can arise from right-handed currents
- Search for CPV in charm hadron decays, including $D \to K_S K_S,\ \pi^0\pi^0,\ \pi^+\pi^0$ (recently submitted!)

The Belle II Physics Program

A snapshot

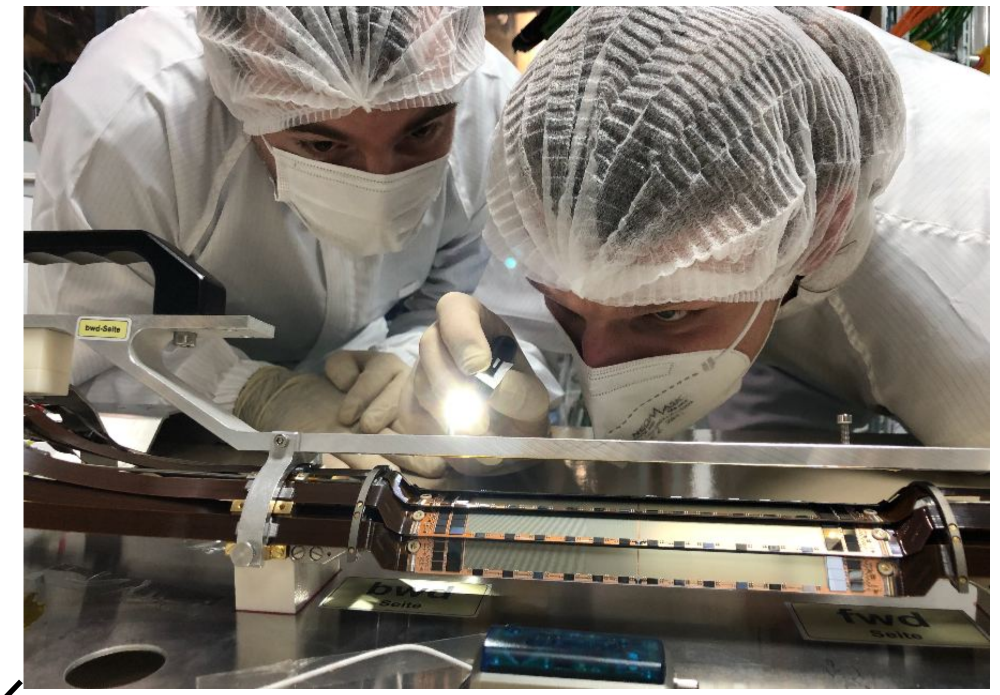
- Goal: uncover new physics beyond the SM
- Will contribute to NP searches in many ways
  - Improved precision on SM physics, CPV
  - Lepton Flavor Violation,
    Lepton Flavor Universality
  - Unique searches in Dark Sector
- ... with many analysis types
  - time-dependent searches
  - missing energy and missing mass
  - Dalitz plot (multi-body) studies
- Some of which are unique to Belle II
  - e.g. inclusive decays and absolute branching fraction measurements that may be impractical at hadron machines

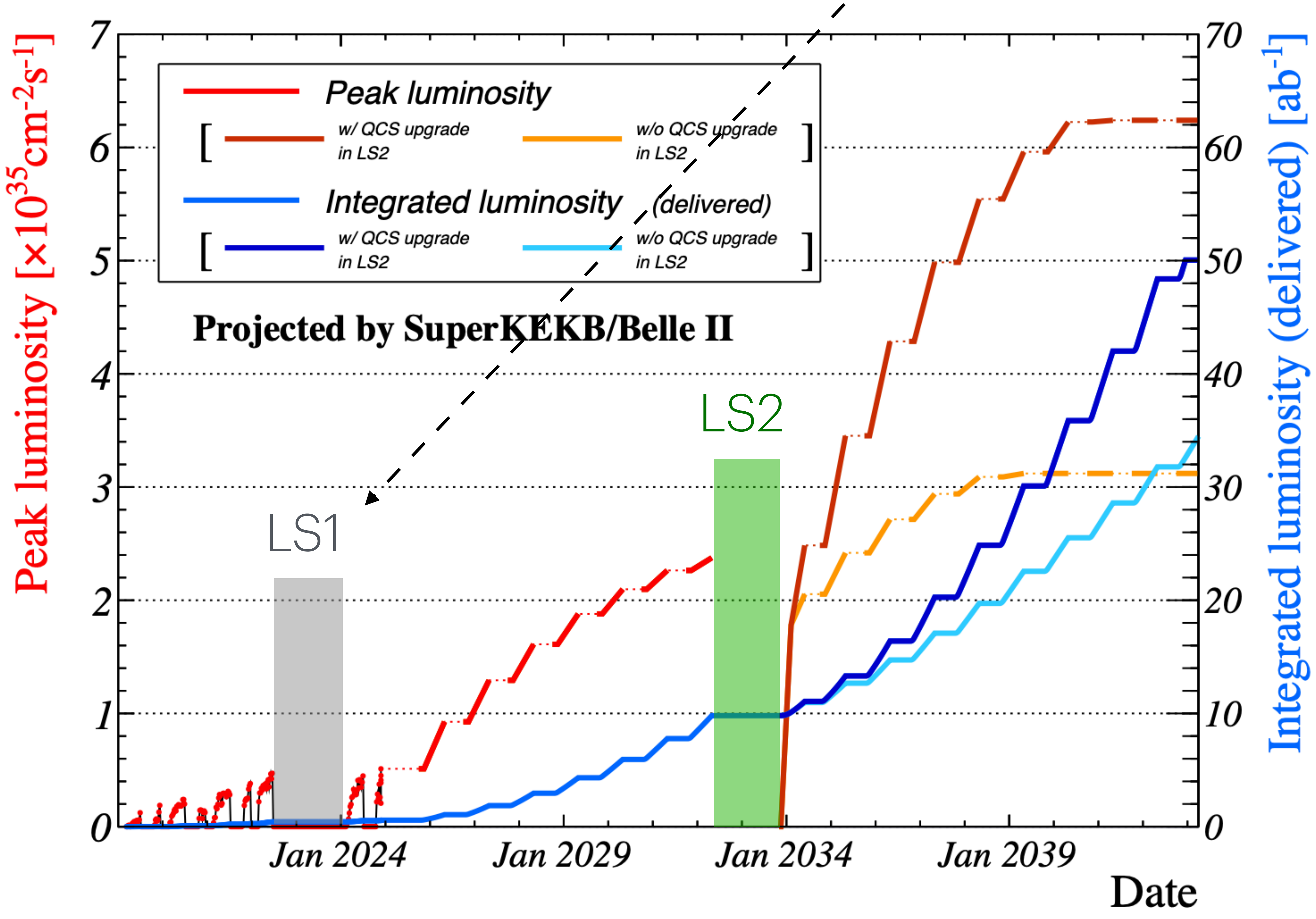


The road to 50 ab^{-1}

Until 2043

PXD arrives at
KEK for testing



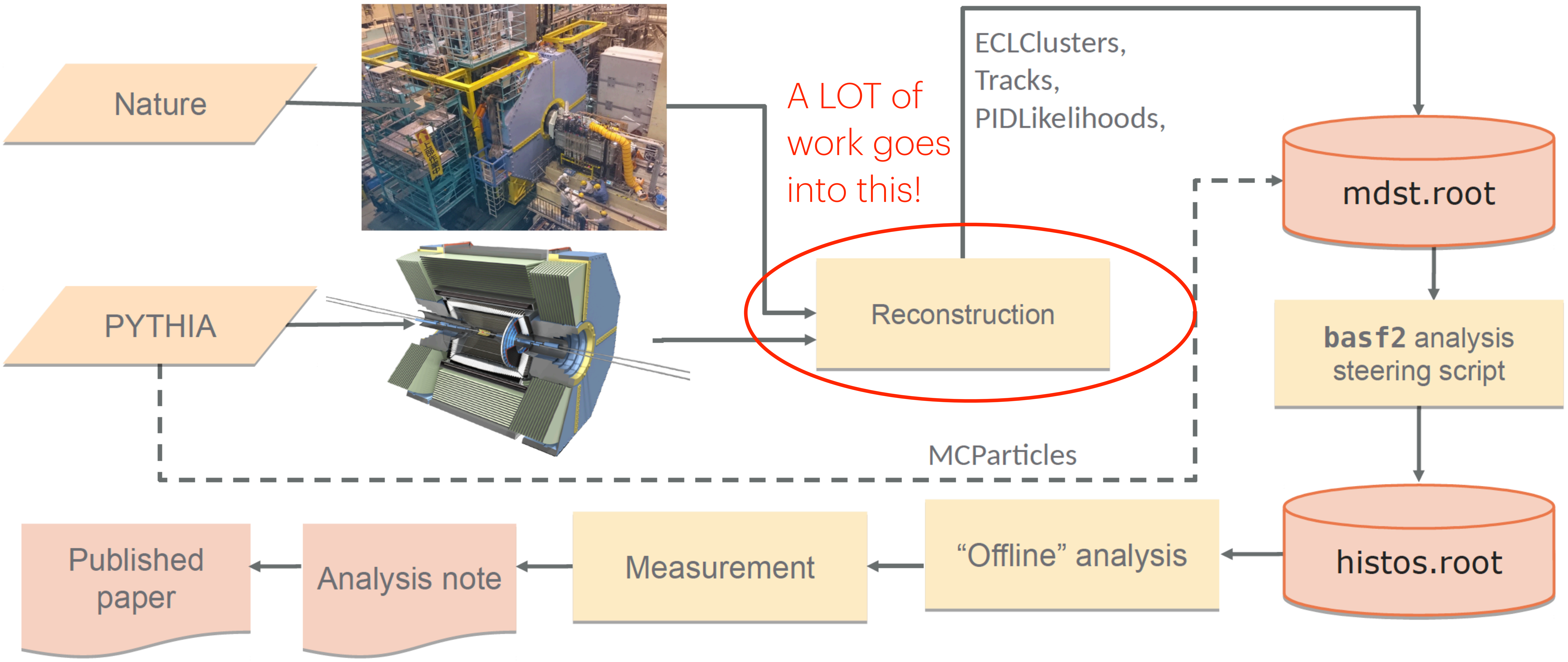


$\mathscr{L}_{\text{int}} = 575\ \text{fb}^{-1}$ (~half the Belle dataset)

$\mathscr{L}_{\text{peak}} = 5.1 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ (*world record!) ~5x $\mathscr{L}$(PEP-II)

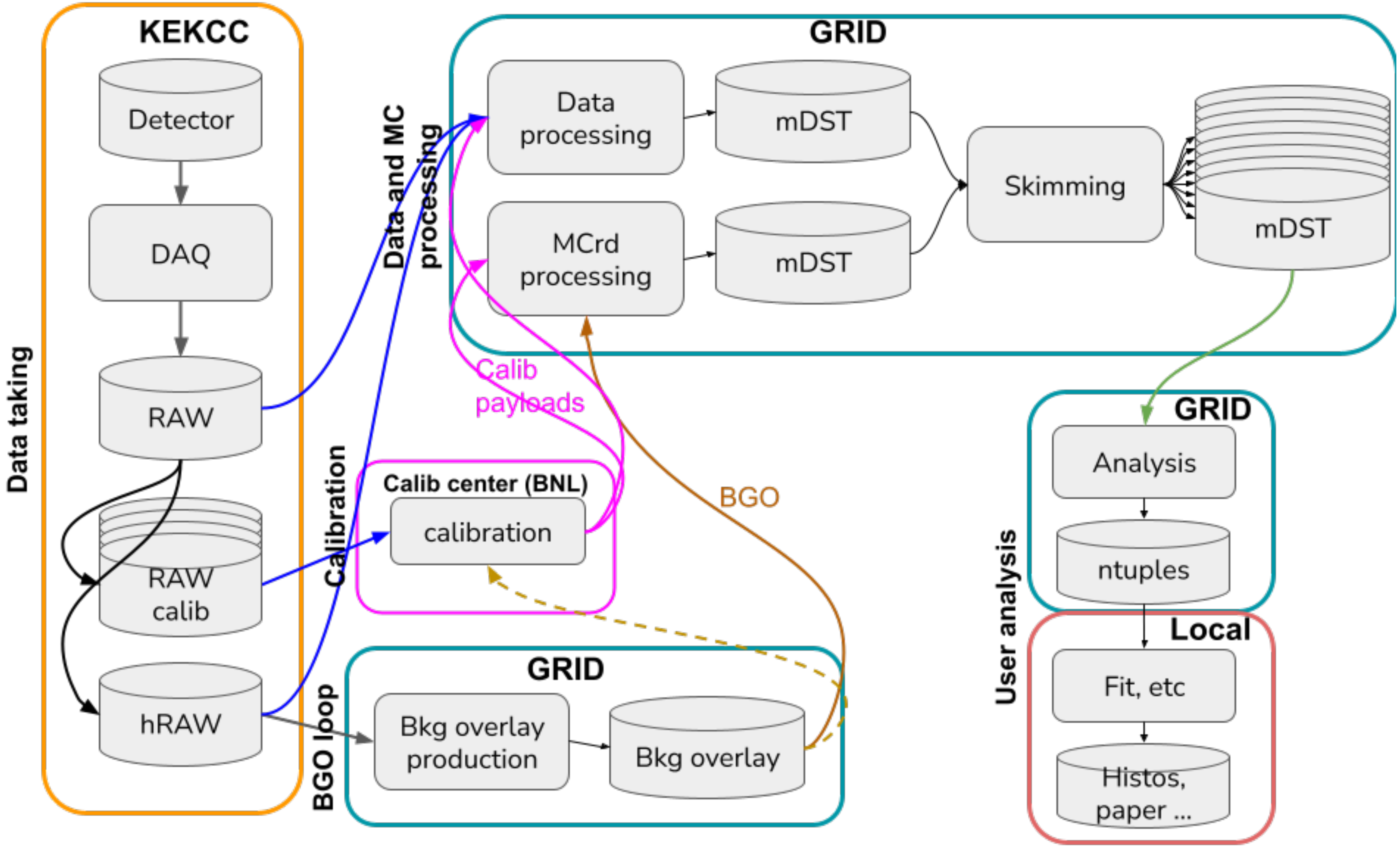
- Long Shutdown 1 (LS1)
  - Maintenance and upgrade of machine and detector
  - Data taking resumed in early 2024
- Long Shutdown 2 (LS2)
  - Upgrade of the SuperKEKB interaction region to enable $\mathscr{L}_{\text{peak}} = 6 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$
- Key challenge to increasing beam currents and squeezing beam-size at interaction point: beam-beam blowup
- Key challenge for physics groups: exploit existing datasets and be ready when more data arrives!

The big picture



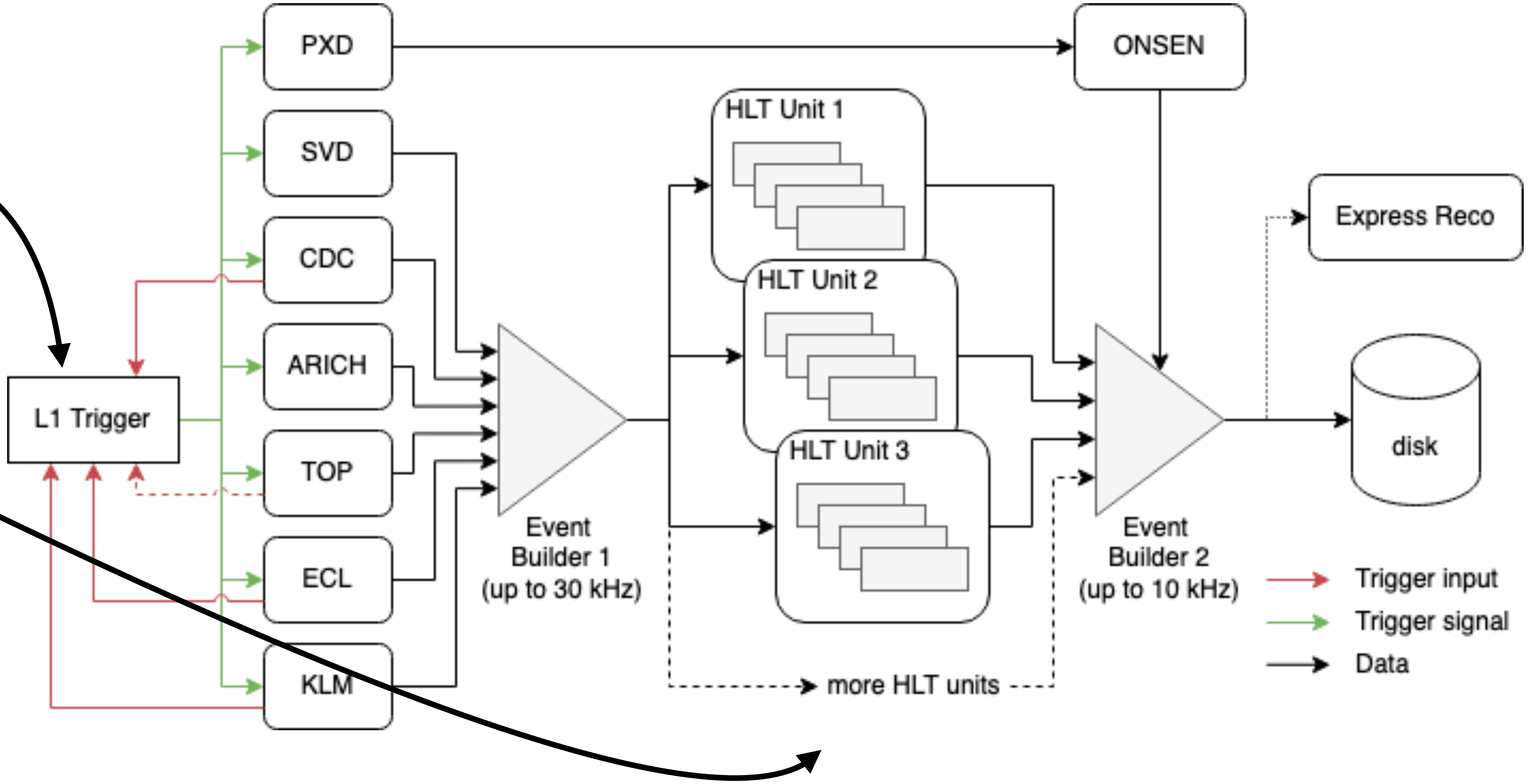
*~~shamelessly stolen~~ borrowed from Sam Cunliffe's talk"Introduction to the analysis package" - Belle II SKW, 15.06.2018

Belle II data flow



Triggers and filters

- We only want to keep **interesting/useful** information
- Data Acquisition (DAQ) activated after decision by
  - Level 1 Trigger (TRG or L1) and
  - High Level Trigger (HLT)
- TRG receives low resolution "live stream" from CDC, ECL, KLM
  - Interpreted by fast electronics matching predefined conditions



- Subdetectors transmit readout data after receiving TRG signal
  - All detectors must keep a buffer (~4 μs) of readout data, in case a trigger signal is received

Brief interlude: file types

Belle II output is stored in ROOT files containing various subsets of information

- **RAW**: raw data containing detector information
- **DST**: data summary table
  - all available dataobjects (from reprocessing) are included
  - not generally produced or used as it contains everything (and is huge)
- **cDST**: calibration data summary table
  - RAW data, plus additional dataobjects useful for calibration
- **mDST***: mini data summary table
  - strictly controlled version of a DST file
  - only a subset of available processed dataobjects are included
  - sufficient information for analysis use
- **uDST**: user data summary table
  - mDST objects, can also include analysis objects (ParticleLists)
  - produced from skims - reduce time needed to run analysis jobs
  - these are the samples you should be using for analysis!

"Raw data processing"

Use detector information to reconstruct dataobjects like tracks, showers, etc.

"Analysis skimming"

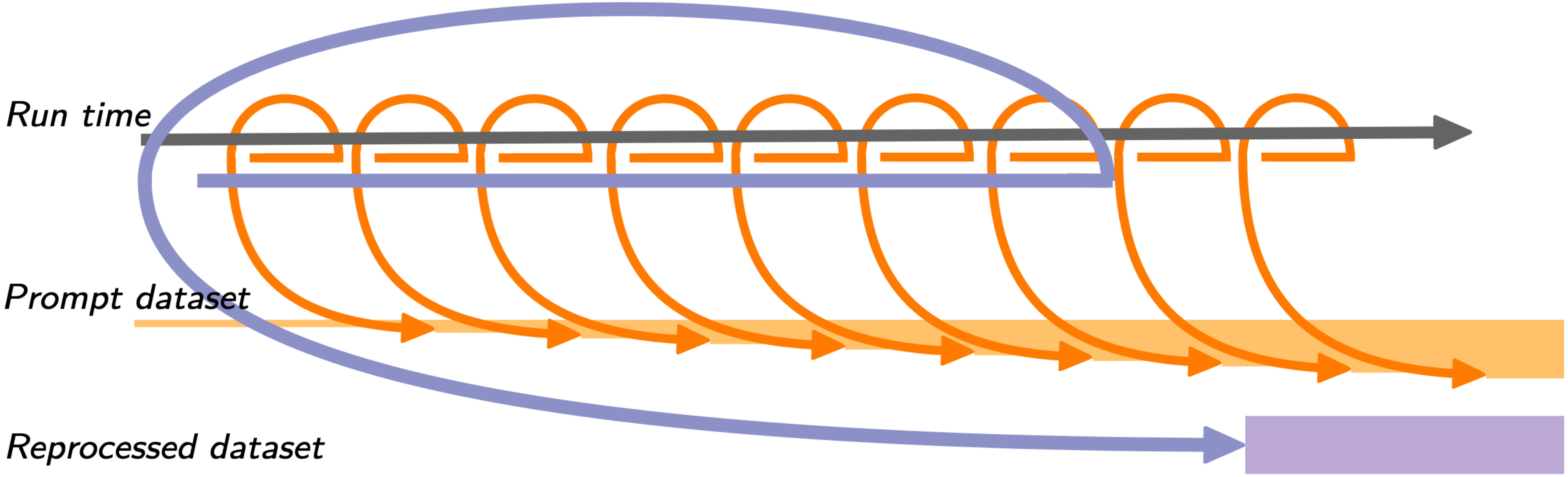
Use tracks, showers, etc to reduce to events useful for analysis

Prompt processing scheme

Getting you the data quickly!

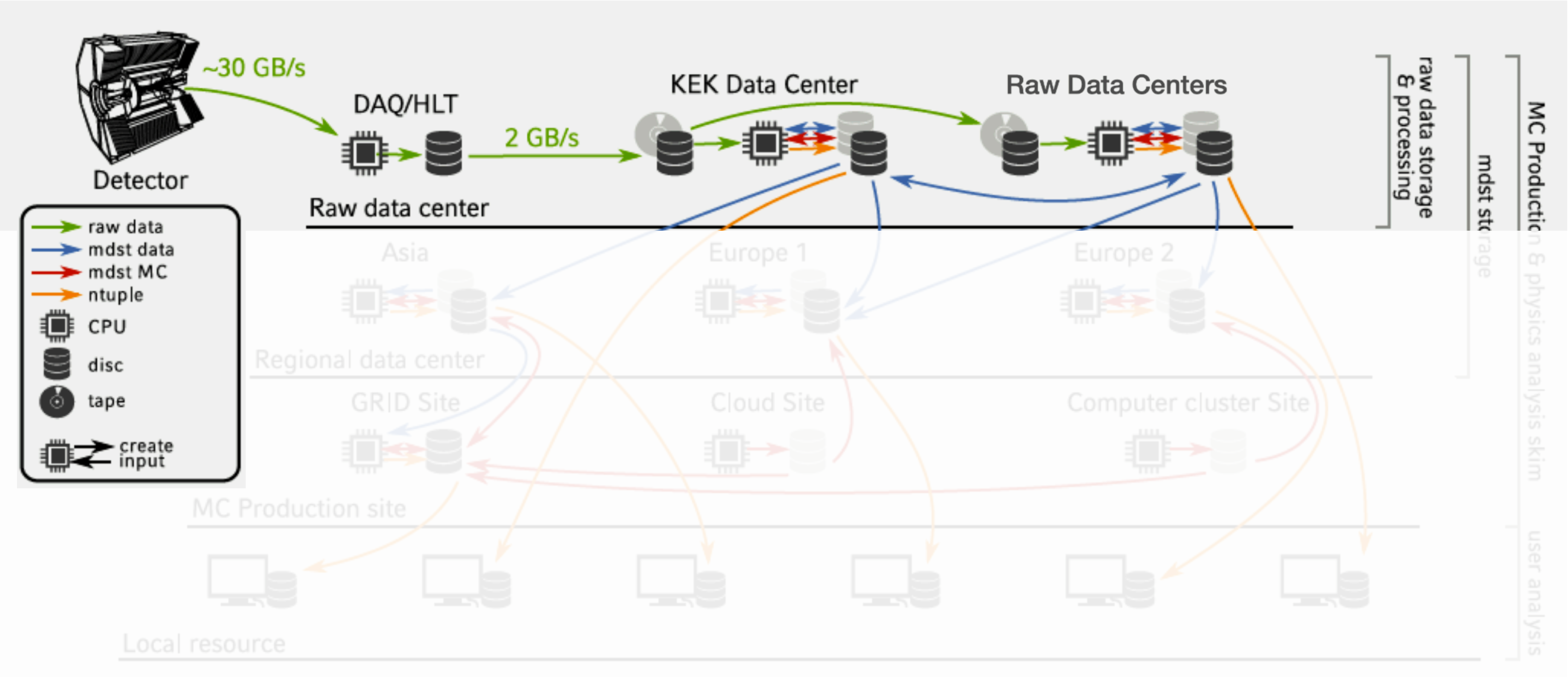
- Only a fraction of the full data is required for calibration
  - HLT skims to select samples of a given type (bhabha, dimuon, etc)
  - Pre-scales applied to randomly select only as much data as needed

- Calibration and processing happens twice:
  - **Prompt processing:** ~weekly calibration and processing during data taking
  - **Official reprocessing:** ~yearly to make final adjustments and incorporate "data-hungry" calibrations



Belle II data flow

- Raw data storage and reprocessing at raw data centers
- mDST storage on GRID storage elements (SE) - Regional data centers
- Skimming and analysis on GRID computing elements (CE) - MC production sites
- nTuple analysis on local resources



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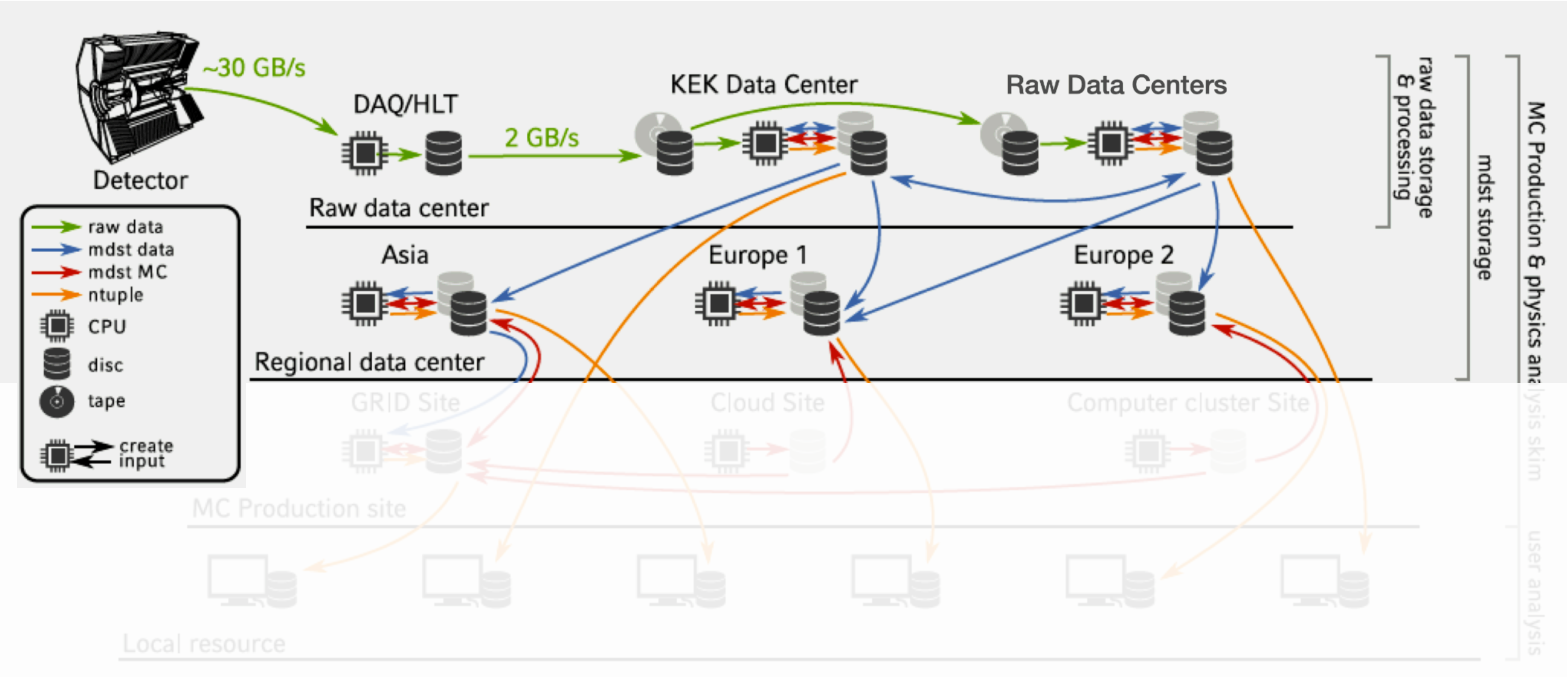

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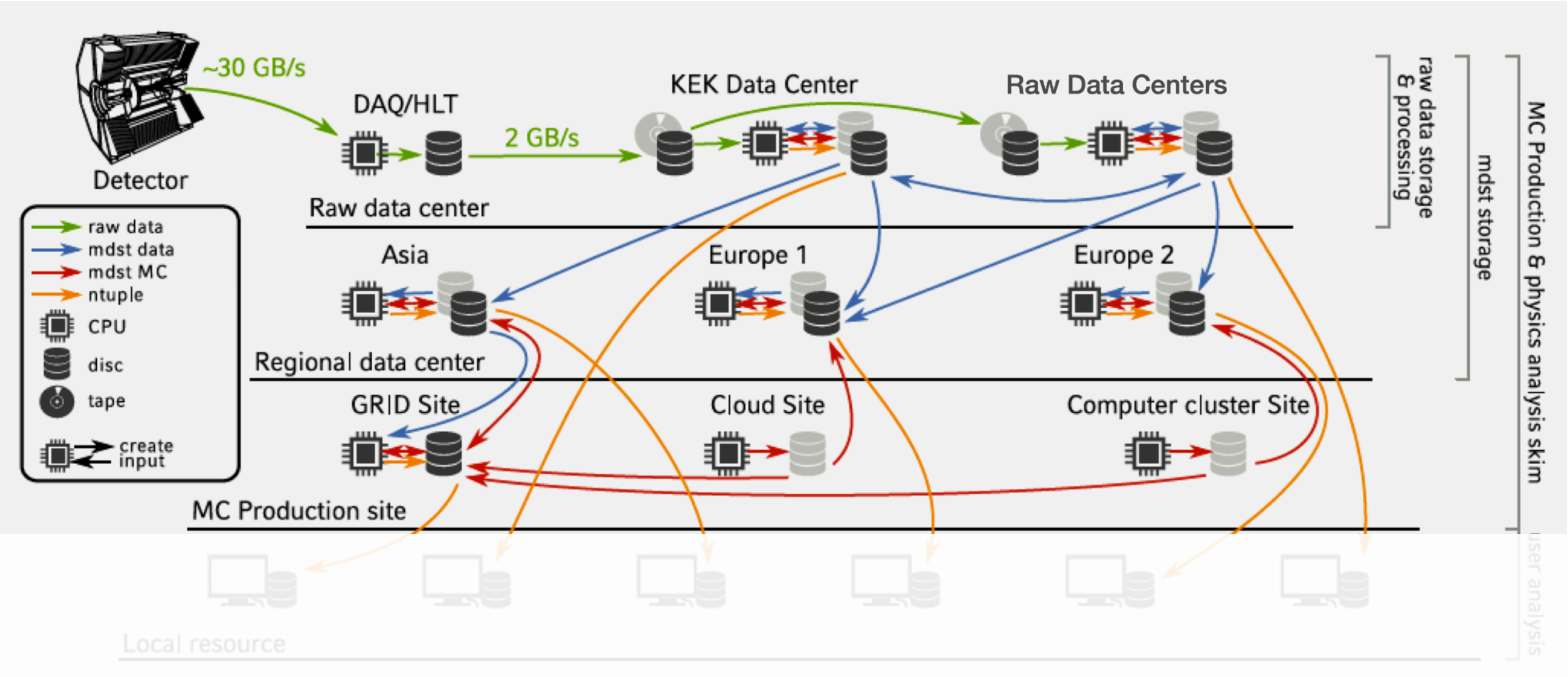

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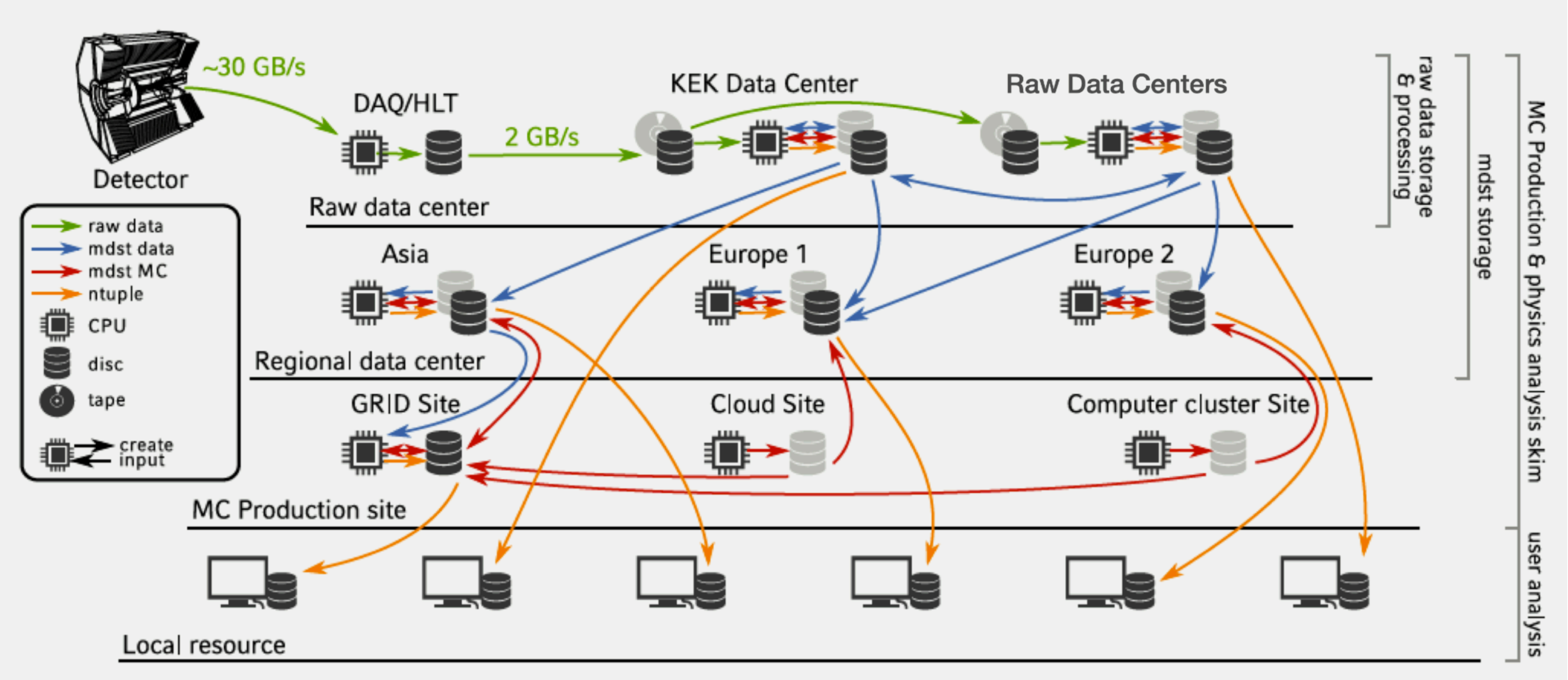
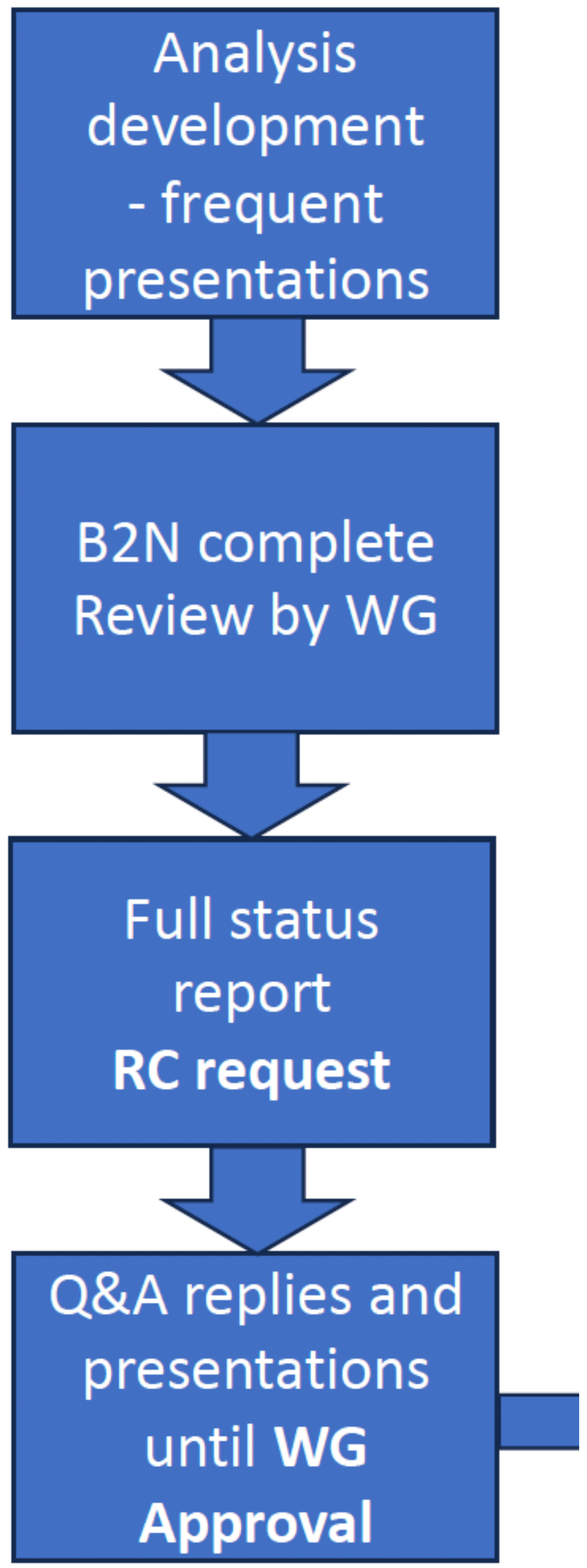


Publications xWiki

Belle II analysis flow

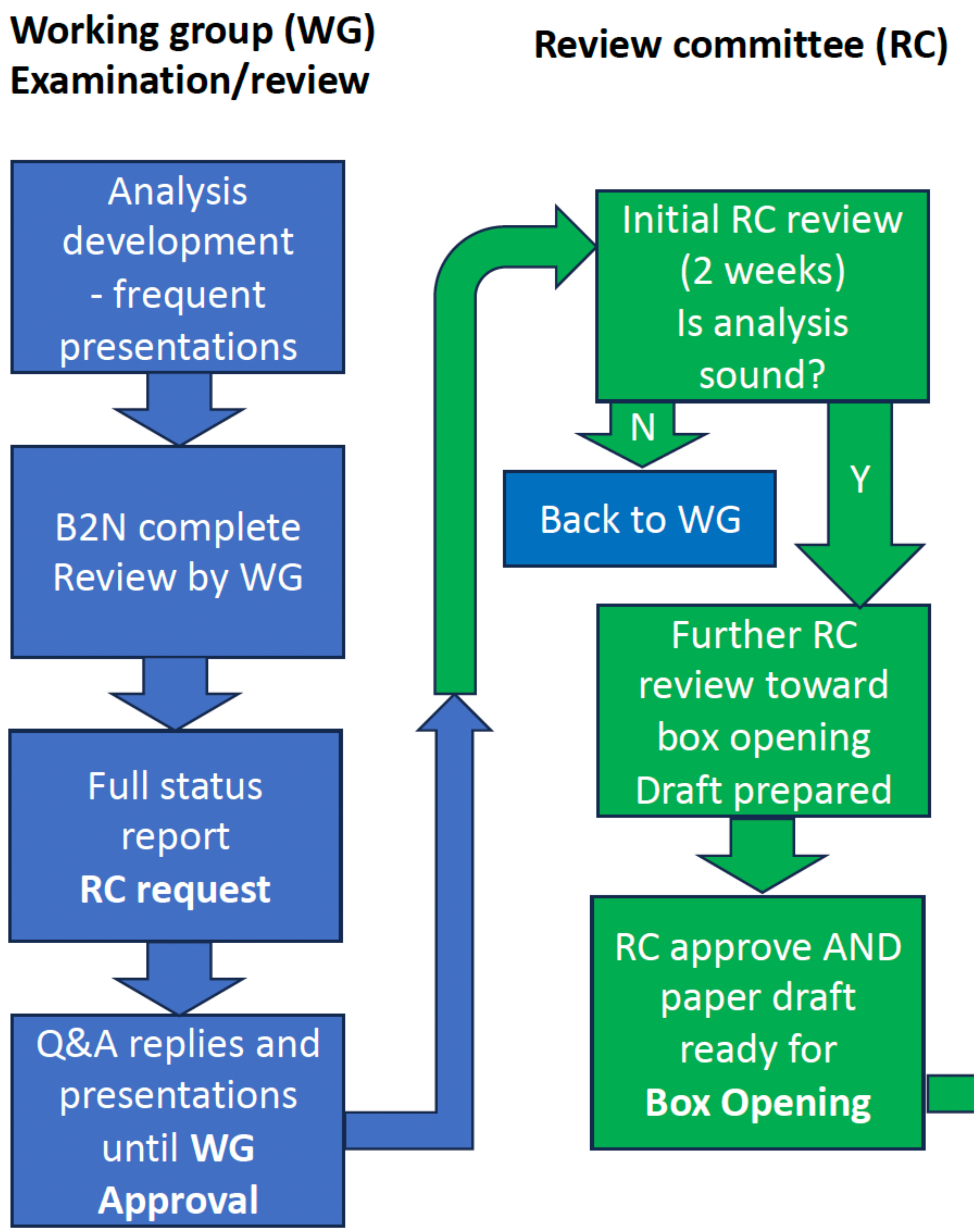
Working group (WG)
Examination/review



- Physics analysis oversight primarily within the Working Group (WG)
  - Analysts are expected to make <u>regular</u> presentations and participate in discussions/review!
  - When an analysis nears completion, a note is prepared
  - **WG review** begins after conveners have offered an initial review
  - WG readers are assigned for each analysis, but the entire WG is expected to read the note and participate in the review
  - Upon approval by the working group, a **Review Committee** (RC) is formed and a full status report is given at a WG meeting
  - Analysis code should be uploaded in gitlab and updated as the review progresses

Belle II analysis flow

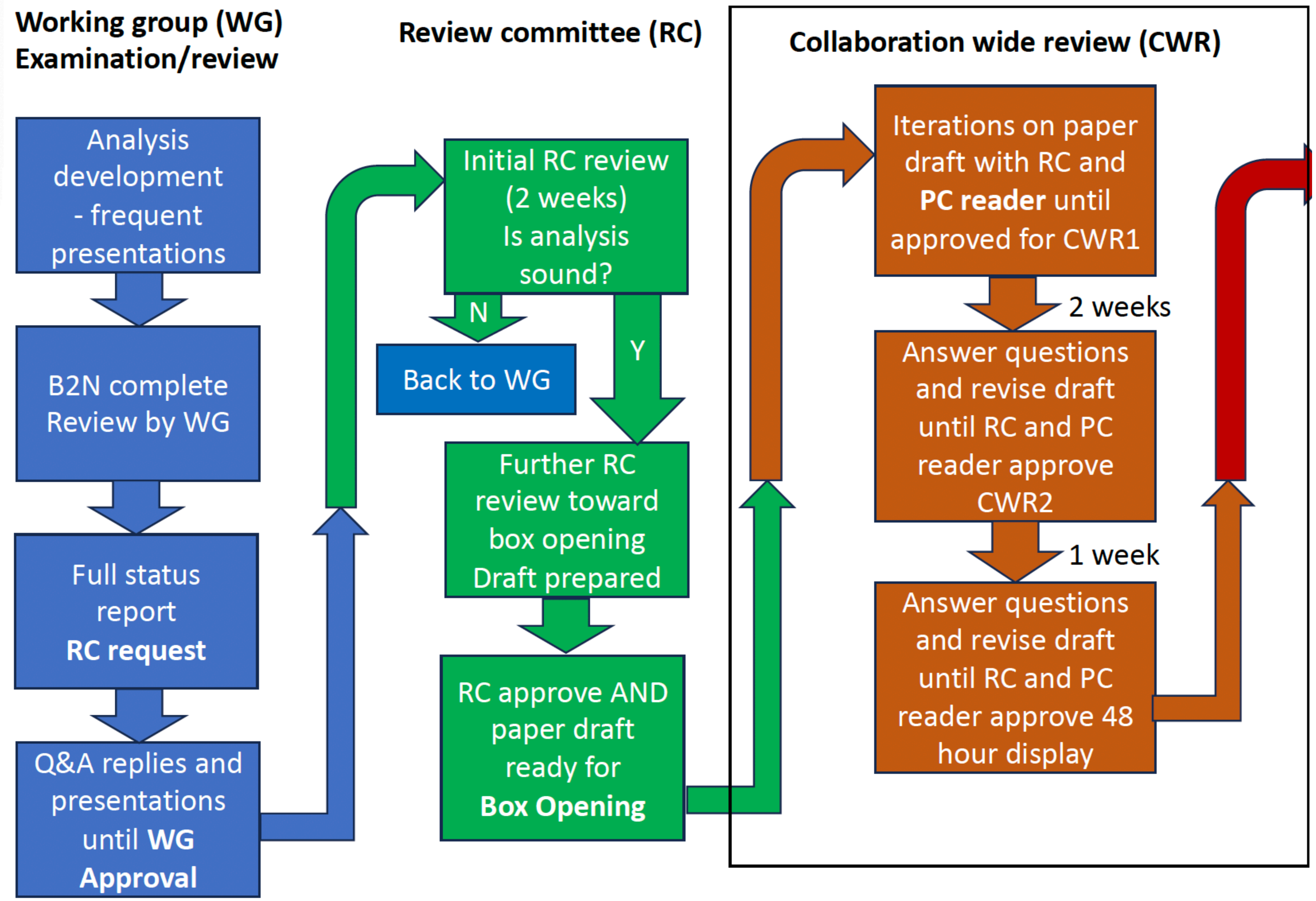
Publications xWiki



- The RC is expected to thoroughly read the analysis note and scrutinize the analysis to ensure correctness
  - If there are serious concerns (e.g. about the method), the analysis is returned to WG review
  - RC may request additional studies, modifications to the analysis method, etc.
  - When the analysis is starting to converge, the analysts prepare a draft paper
  - Once the draft paper is ready and the RC has no further concerns, the signal in data may be revealed ("box-opening", "unblinding")
  - IMPORTANT: **the use of real data must be carefully controlled to avoid experimenters bias!**
  - The box-opened result must be presented at a WG meeting
  - After approval from the RC, **Collaboration Wide Review** (CWR) may begin

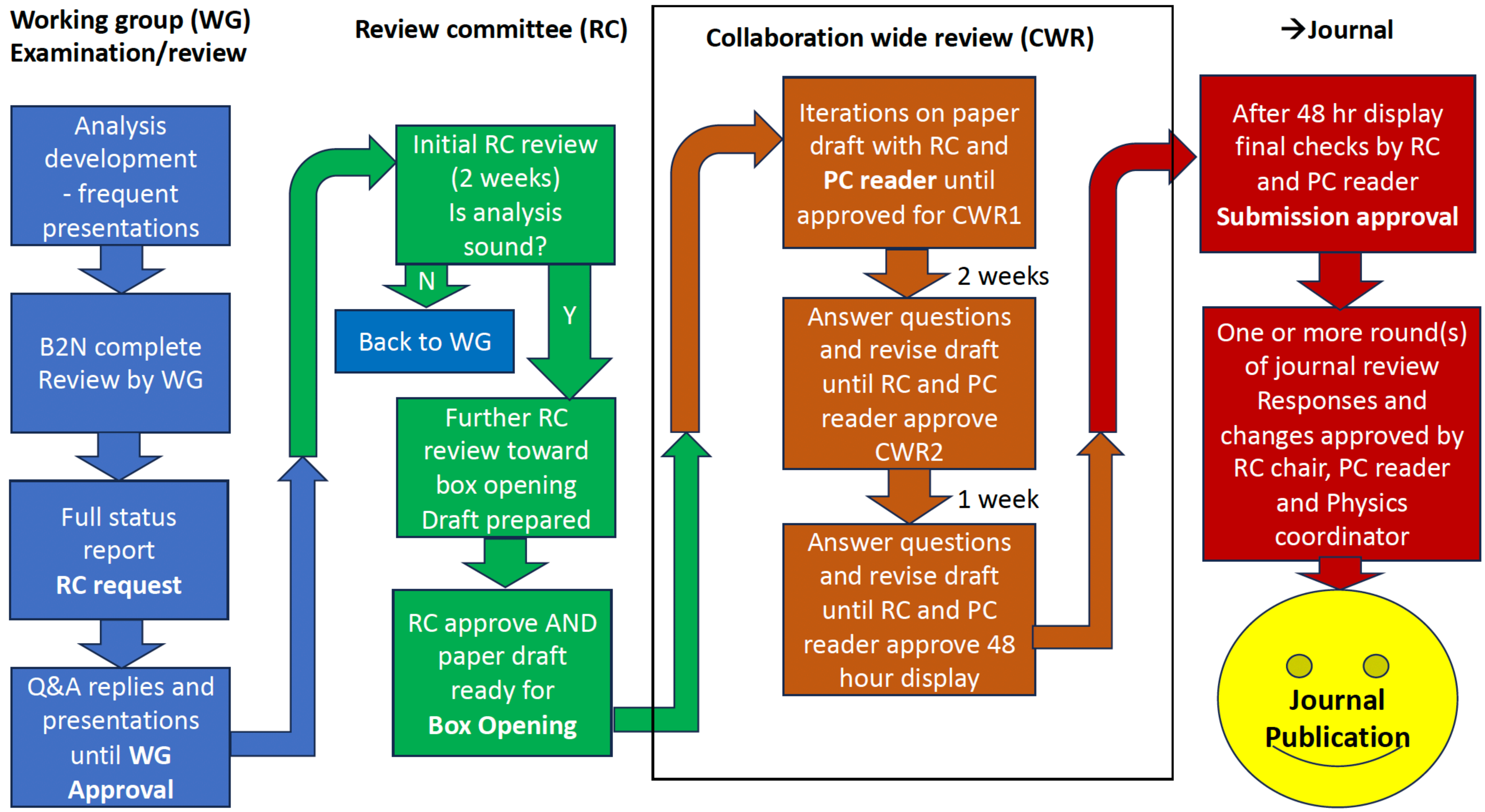
Publications xWiki

Belle II analysis flow



- During CWR1, a full status report must be given at a general physics meeting
  - The "**preliminary result**" is approved here for conference presentations
- The **Publications Committee** (PC) assigns a reader (early on) who will help ensure the paper is clear and complete
- Collaboration members offer physics-related comments and suggestions

Belle II analysis flow



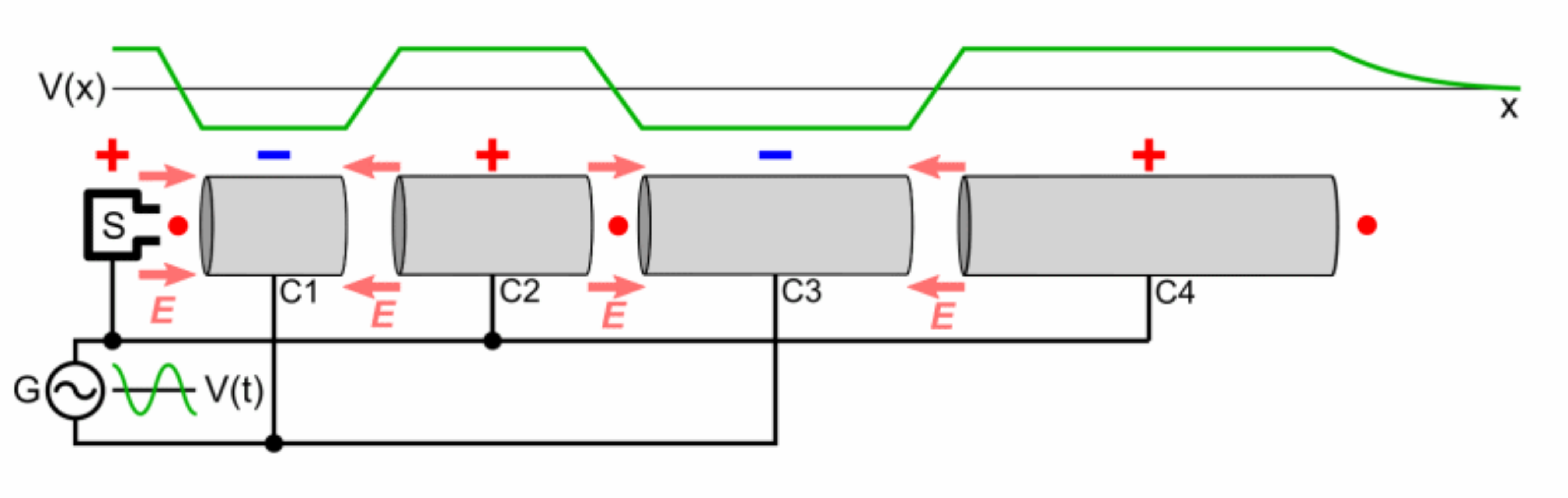
Summary and tips

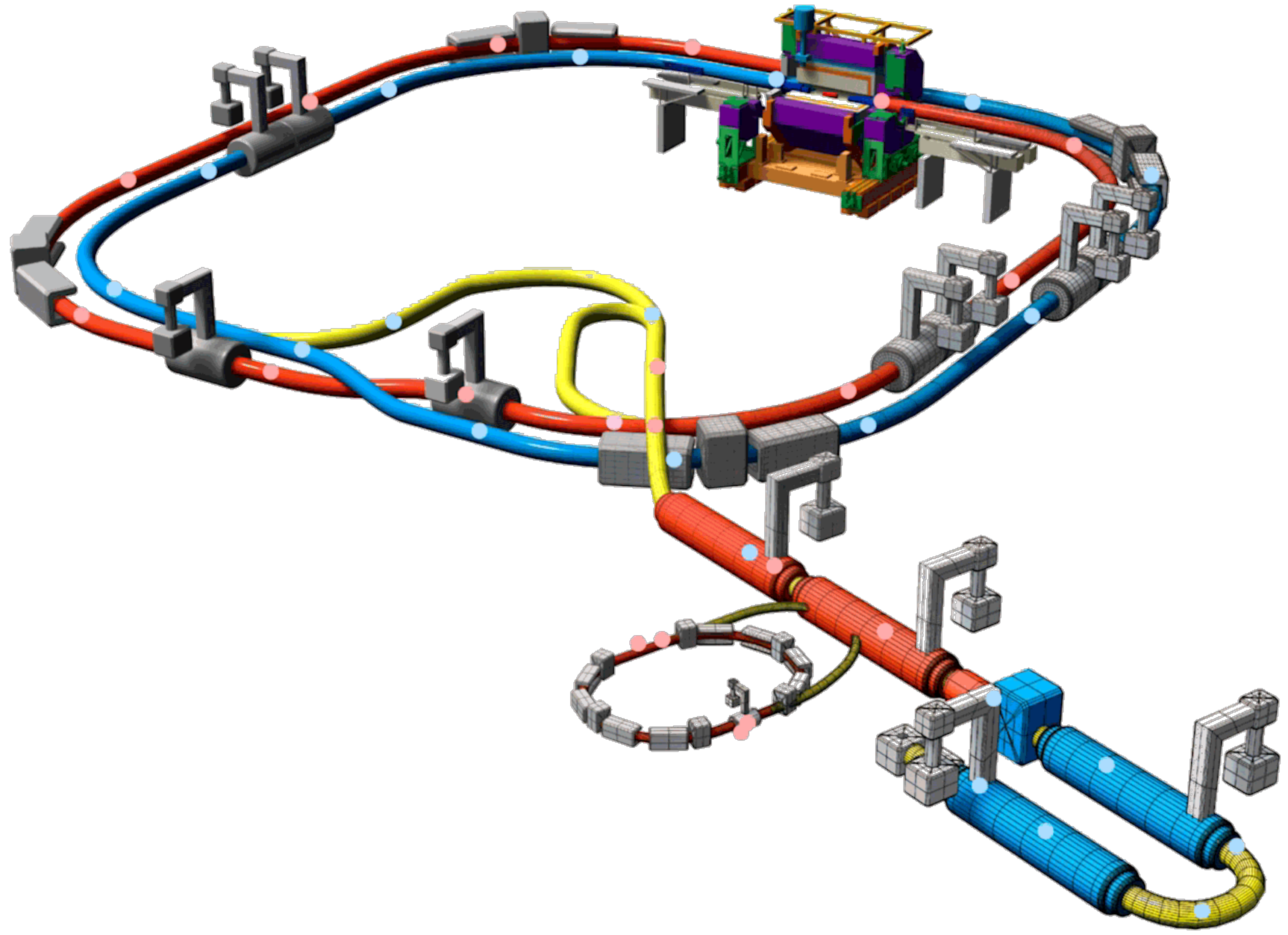
- Upgraded SuperKEKB accelerator, improved Belle II detector, refined analysis techniques
- The physics program of Belle II has outstanding potential for discovering non-SM physics over the next decade
  - Broad program of fundamental weak interaction measurements
  - Access to many modes with hints of non-SM flavor signals
  - New Physics discoveries possible in searches unique to Belle II
- With half the dataset of previous B-factories, Belle II is already producing world-leading results
- As with any experiment, there are pitfalls to “insider knowledge”
  - Attend meetings/workshops, ask questions, get involved!
  - <u>Develop a network of people you can ask/support (not just your supervisor!)</u>
  - Have fun!

Particle accelerators

Accelerate with E fields to reach the desired momentum (resolution)

- **LINear ACcelerators** use Radio-Frequency cavities to accelerate particles to high energies
  - Energy depends on voltage per cavity and total length
  - Also used extensively in medicine





- **Circular** accelerators (storage rings)
  - Energy depends on ring radius and maximum B field
  - Superconductivity is important!
    - Conventional electromagnets ~1 T
    - Superconducting coils ~10 T

Accelerator dynamics

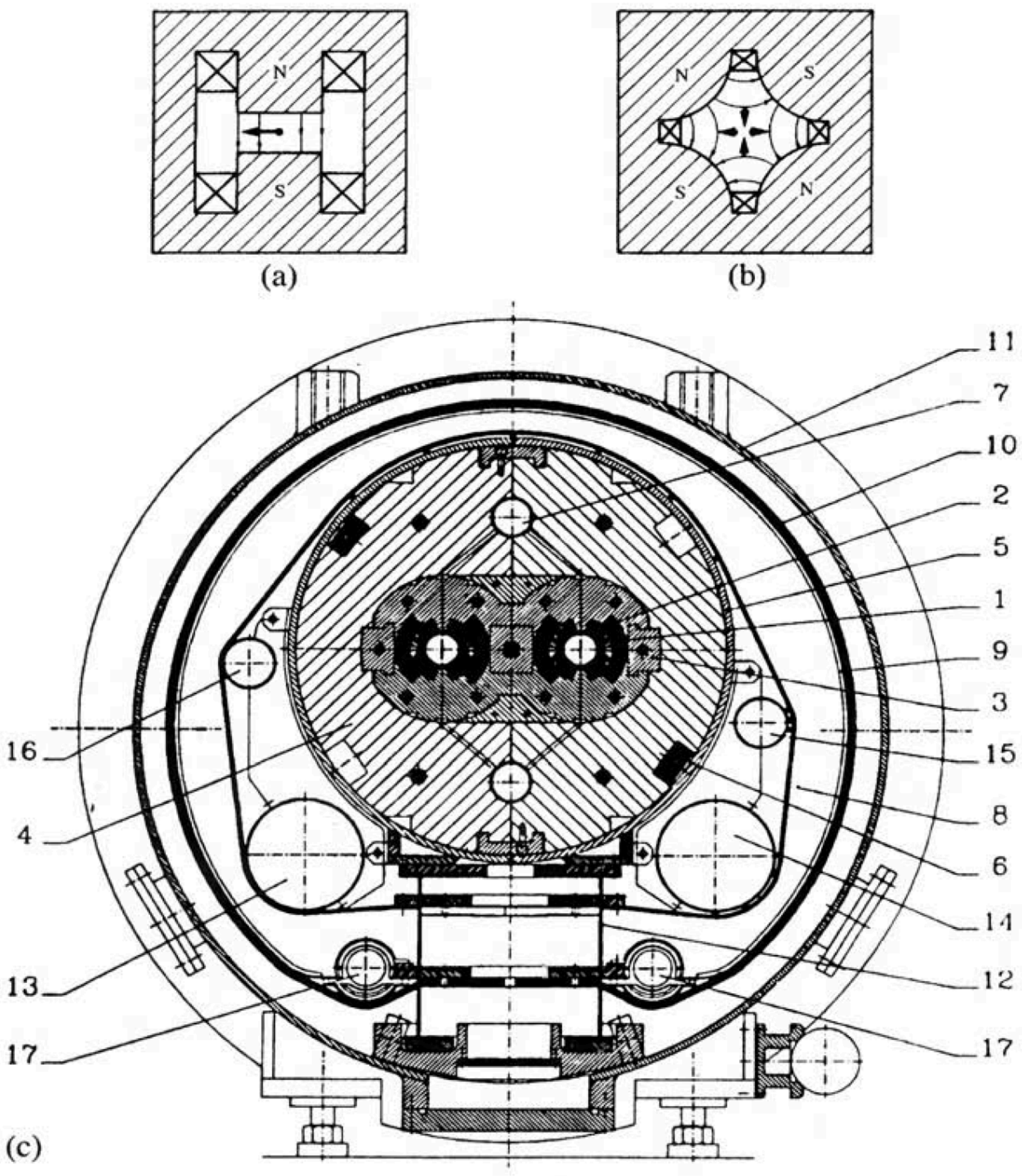
Actually colliding “bunches” of particles

- Particles within bunches oscillate (synchrotron/betatron oscillations) due to small divergences in beam injection, fields, etc.
  - RF kicks keep particles contained longitudinally
  - “Wigglers” keep particles contained transversely

- Also lose energy due to radiation

$$\Delta E = \frac{4\pi Z^2 \alpha}{3} \frac{1}{R} \left(\frac{E}{m}\right)^4$$

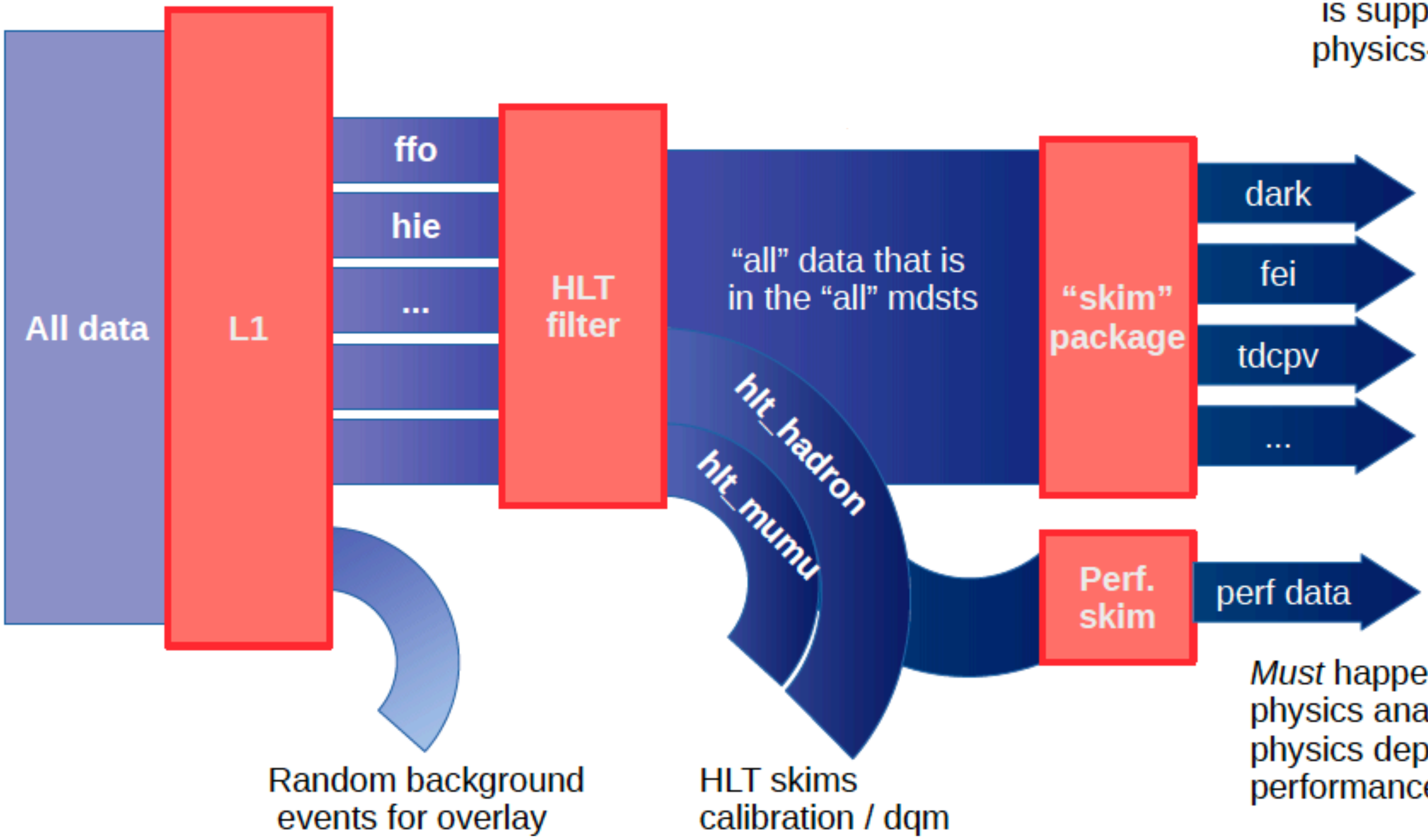
- Potential imaging source!



Belle II data flow

Image credit: S. Cunliffe

Key:
Red is a filter
Blue scale from light to dark is supposed to indicate more physics-relevant data



Must happen faster than physics analysis skims: physics depends on performance analyses