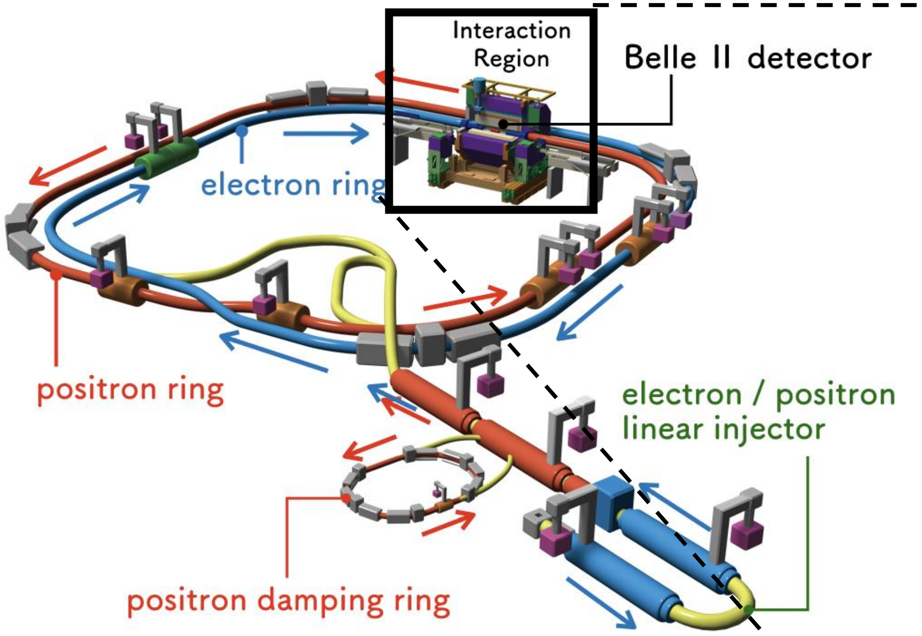
Overview of the Belle II High-Level Trigger

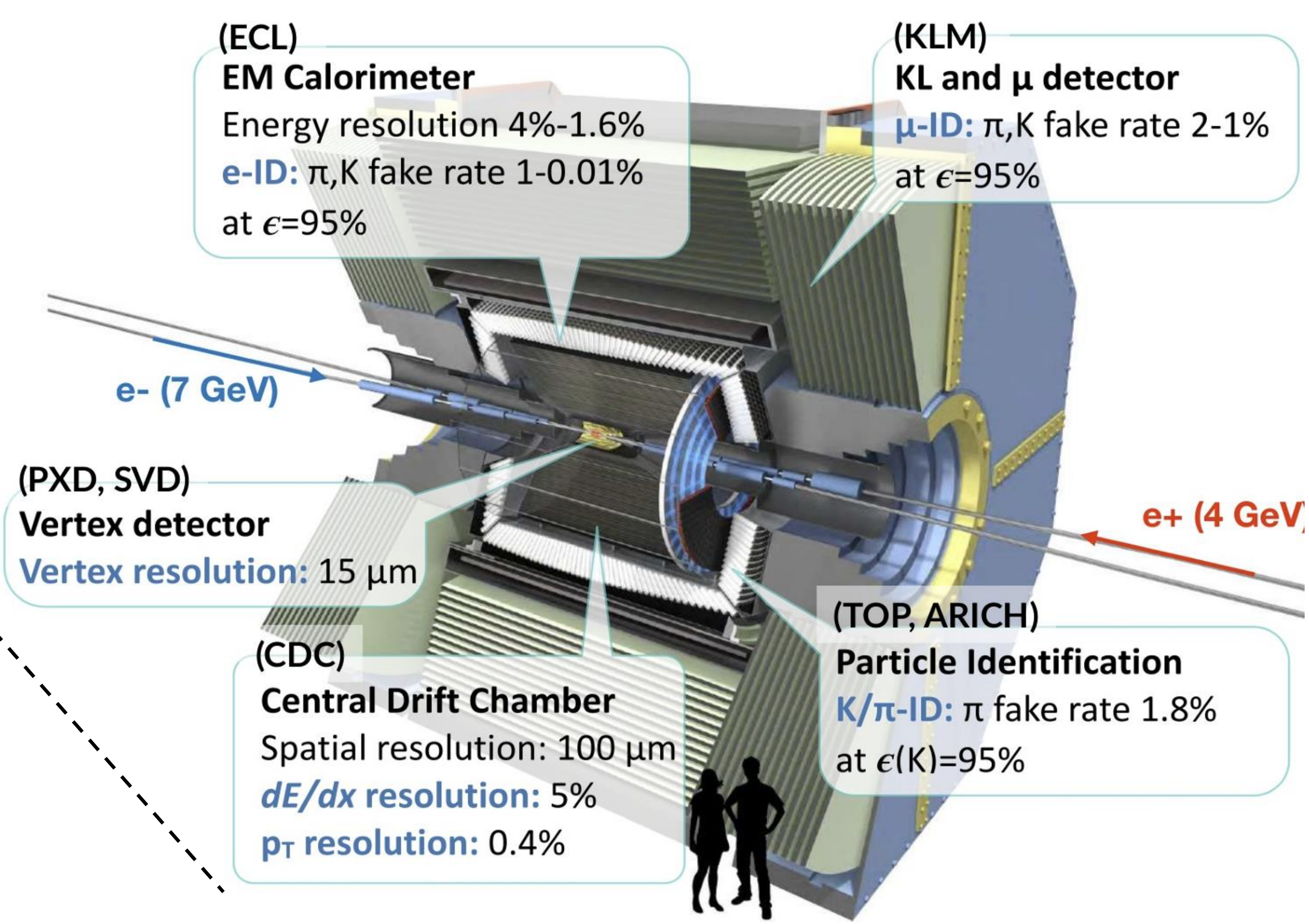
Seokhee Park

KEK, IPNS

Belle II experiment and SuperKEKB

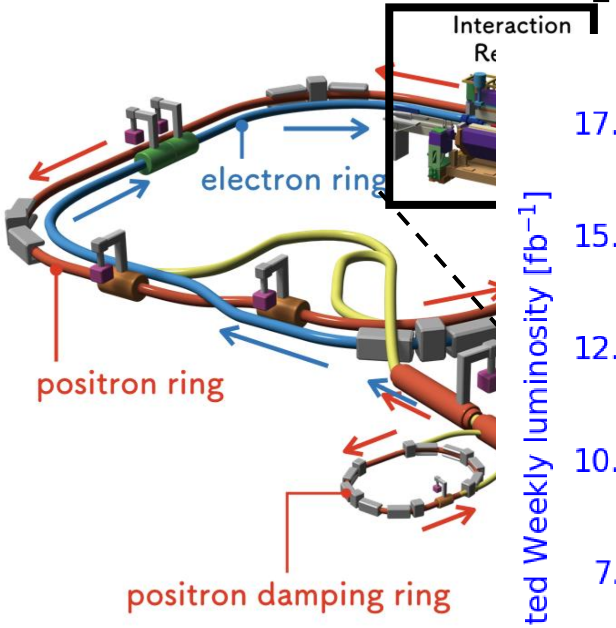
Belle II TDR, arXiv:1011.0352

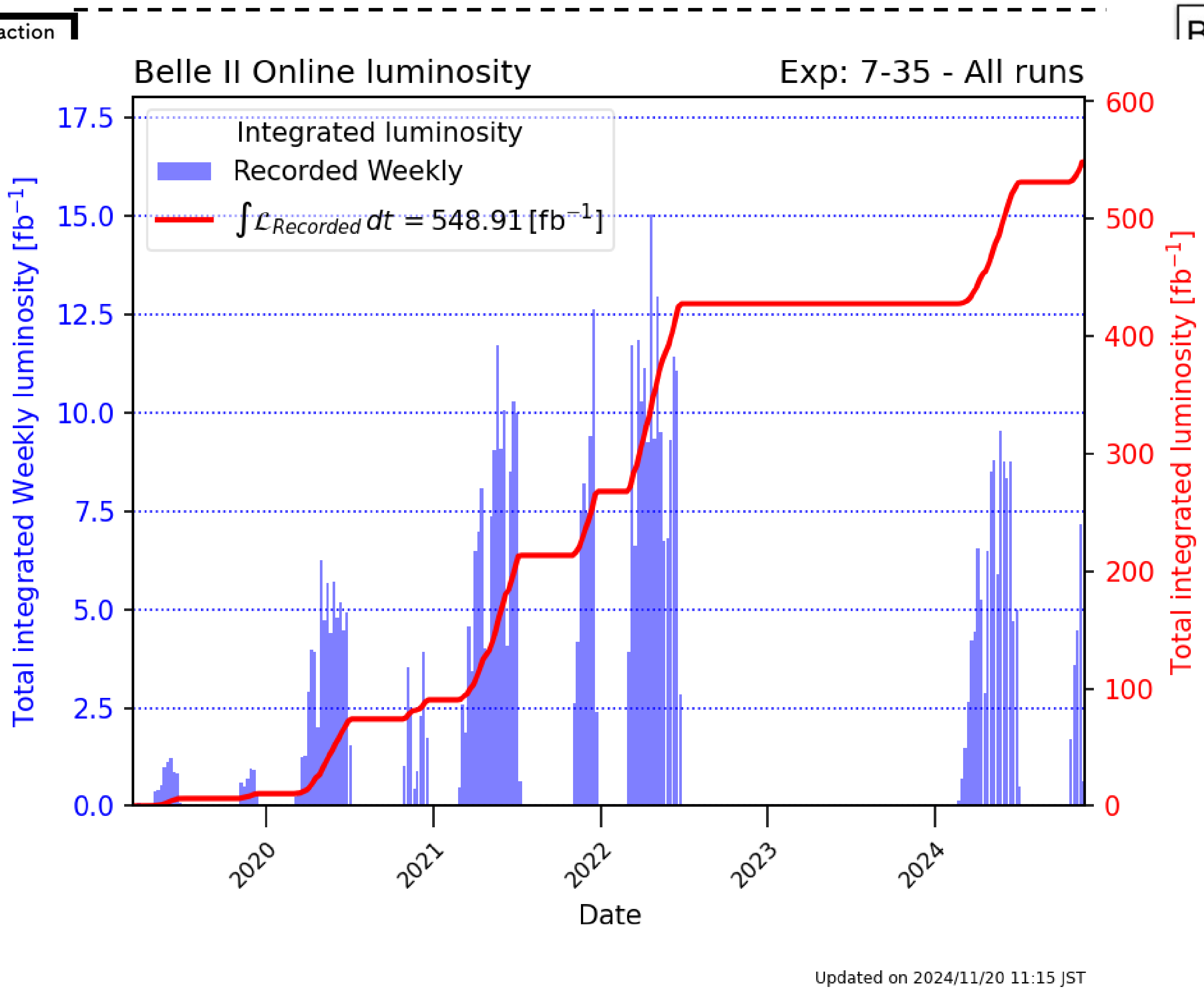


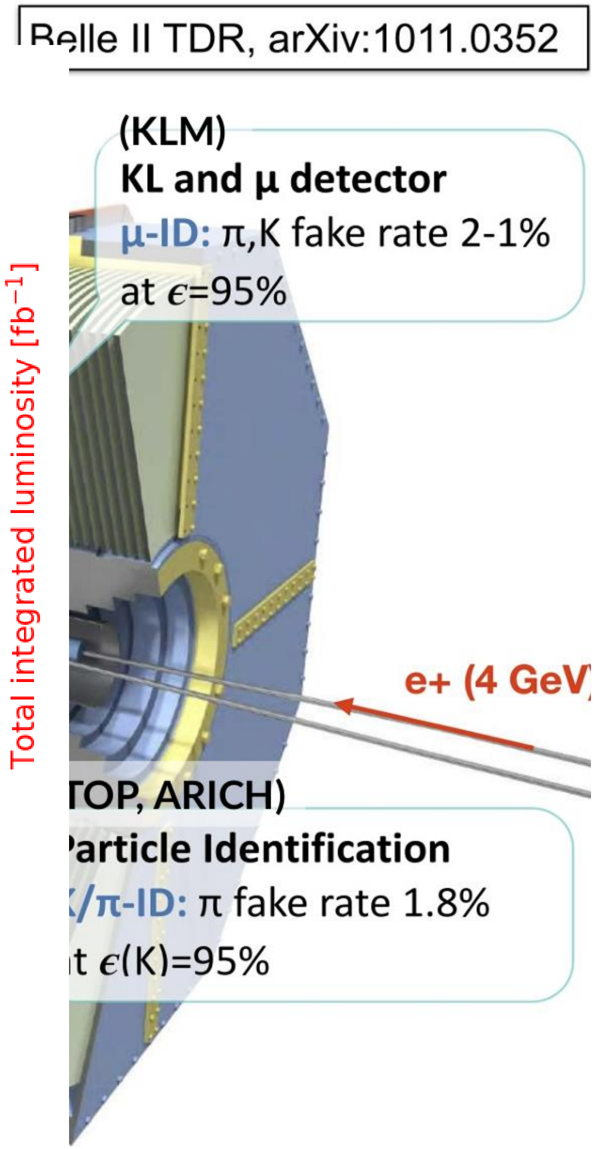


- Target peak luminosity: $6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Achieved: $4.71 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Belle II experiment and SuperKEKB







- Target peak luminosi
  - Achieved: 4.71

Tau and Charm results @ Belle II

Search for Lepton-Flavor-Violating τ Decays to a Lepton and an Invisible Boson at Belle II

Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment

Measurement of the τ-lepton mass with the Belle II experiment

Test of light-lepton universality in τ decays with the Belle II experiment

Search for lepton-flavor-violating $\tau^- \to \mu^-\mu^+\mu^-$ decays at Belle II

Precise Measurement of the D^0 and D^+ Lifetimes at Belle II

Measurement of the Λ_c^+ Lifetime

Measurement of the Ω_c^0 lifetime at Belle II

Novel method for the identification of the production flavor of neutral charmed mesons

Measurements of the branching fractions of $\Xi_c^0 \to \Xi^0\pi^0$, $\Xi_c^0 \to \Xi^0\eta$, and $\Xi_c^0 \to \Xi^0\eta'$ and asymmetry parameter of $\Xi_c^0 \to \Xi^0\pi^0$

Precise Measurement of the D_s^+ Lifetime at Belle II

Also, the same number of publications are being reviewed!

Tau and Charm results @ Belle II

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Measurement of t... he Belle II experiment

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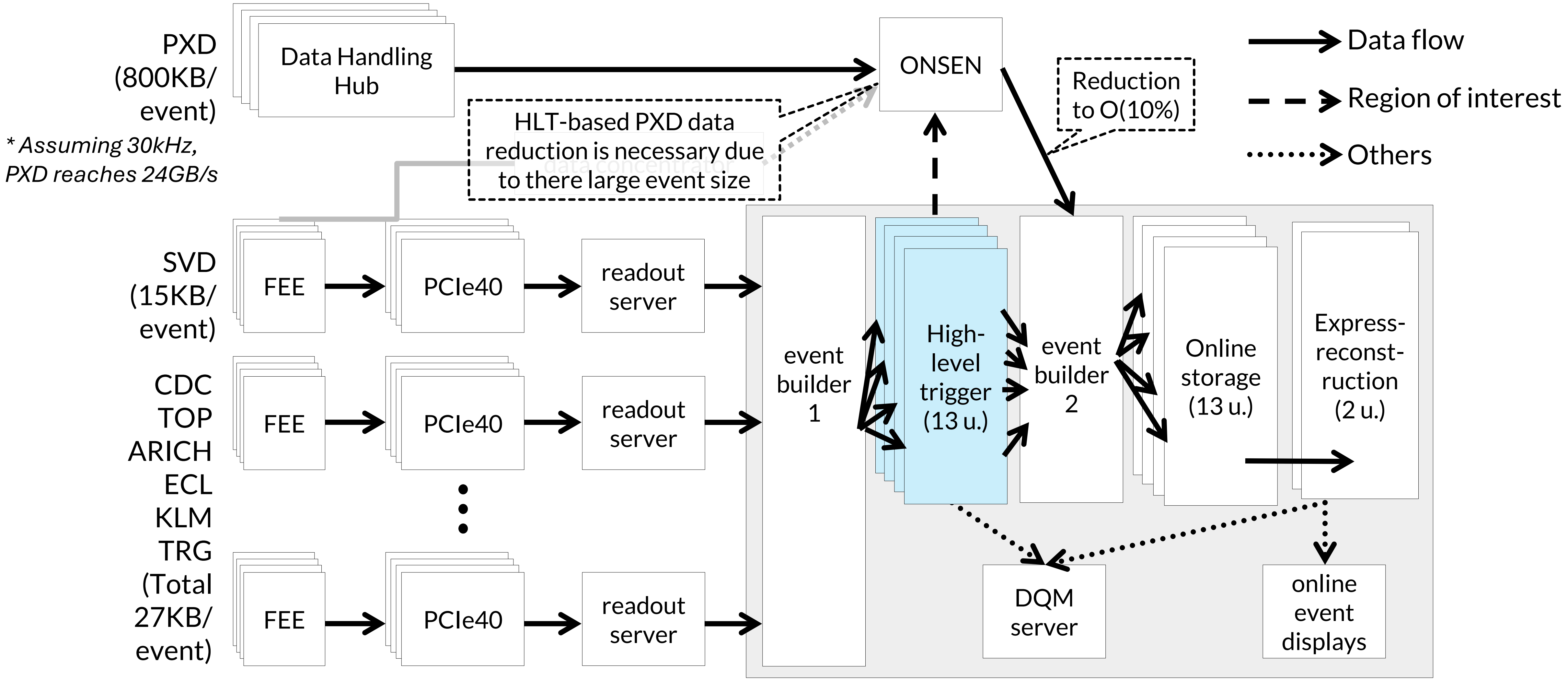
Precise Measuremen... D_s^+ Lifetime at Belle II

Belle II is **tau** and **charm** factory!

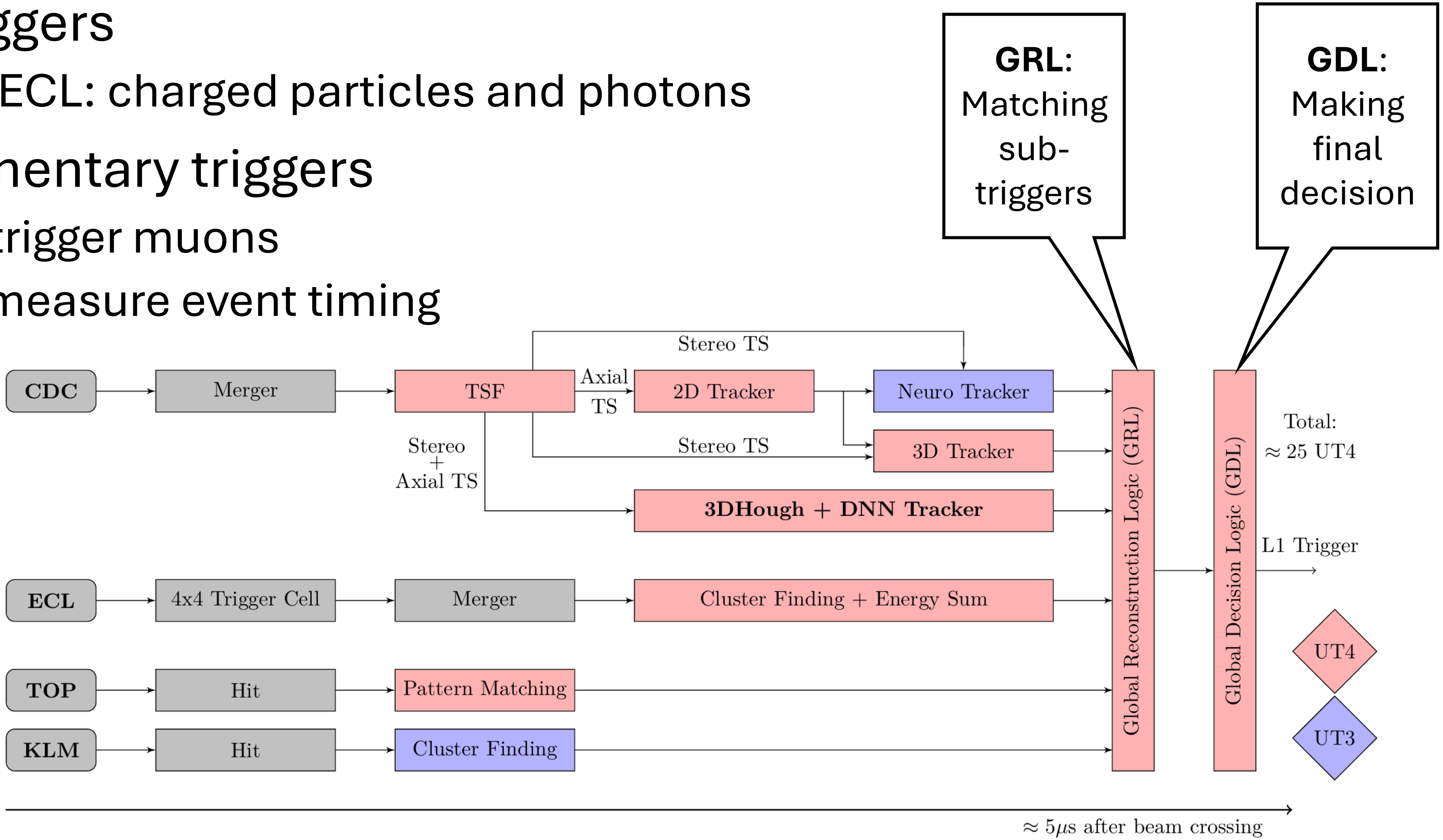
Also, the same number of publications are being reviewed!
(links in the backup slides)

Belle II data flow overview



Level 1 (Hardware) Trigger

- Main triggers
  - CDC, ECL: charged particles and photons
- Supplementary triggers
  - KLM: trigger muons
  - TOP: measure event timing



Level 1 (Hardware) Trigger

- Expected event rate at target luminosity ($= 6.0 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

Process	Event rate	
e^+e^- bunch collision	~200 MHz	
Beam background	> ~300 kHz (2022)	
Bhabha scattering	> ~50 kHz	
Two photon processes	~10 kHz	physics target ~ 15 kHz
$e^+e^- \to \gamma\gamma$	~2 kHz	
$e^+e^- \to q\bar{q}$ $(q = udsc)$	~2 kHz	
$e^+e^- \to \Upsilon(4S)$	~1 kHz	
$e^+e^- \to \mu^+\mu^-$	~0.6 kHz	
$e^+e^- \to \tau^+\tau^-$	~0.6 kHz	
dark sector/new particle	???	

Item	Requirement	Present status
Trigger rate	< 30 kHz @ $6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	~ 8 kHz @ $4.7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ → reducible by increasing prescale
Latency	$4.4\ \mu s$	$4.4\ \mu s$
Event timing resolution	10 ns	~ 8 ns
Efficiency	$> 99\%$ for $B\bar{B}$ pair	$> 99\%$ for $B\bar{B}$ pair $> 95\%$ for $\tau^+\tau^-$ pair + low multiplicity triggers for dark sector and new physics

Level 1 (Hardware) Trigger

- A few examples of the trigger conditions (rate from 2021c run)

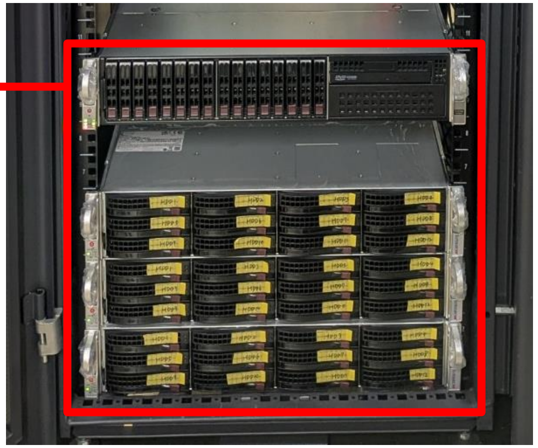
<table>
<tr><th>Physics target</th><th>Condition</th><th>Raw rate (kHz)</th><th>Exclusive rate (kHz)</th></tr>
<tr><td>$B\bar{B}$ pair</td><td>CDC #2track>=3, NNtrack>=1 with |z|<20cm >=1</td><td>1.40</td><td>1.40</td></tr>
<tr><td></td><td>CDC #2track>=2, NNtrack>=1 with |z|<20cm >=1, Δϕ>90deg</td><td>1.03</td><td>0.47</td></tr>
<tr><td></td><td>ECL #cluster>=4, 2<θid<15</td><td>0.13</td><td>0.08</td></tr>
<tr><td></td><td>ECL Energy sum>1GeV, 2<θid<15</td><td>0.69</td><td>0.56</td></tr>
<tr><td>$\tau^+\tau^-$ pair</td><td>CDC #full track>=1, |z|<15cm, p>0.7GeV</td><td>1.74</td><td>0.96</td></tr>
<tr><td></td><td>CDC #full track>=1, |z|<15cm, #short track>=1, Δϕ>90deg.</td><td>0.74</td><td>0.38</td></tr>
<tr><td></td><td>CDC #full track>=1, |z|<15cm, #inner track>=1, Δϕ>90deg.</td><td>0.37</td><td>0.08</td></tr>
<tr><td></td><td>NCL ≥ 3, at least 1 CL ≥ 500 MeV(Lab)) (withθID= 2 -16)</td><td>0.17</td><td>0.03</td></tr>
<tr><td>single photon</td><td>ECL only one CL ≥ 1 GeV(CM) with θID = 4 - 15 and no other CL ≥ 300 MeV(Lab) anywhere</td><td>0.18</td><td>0.03</td></tr>
<tr><td></td><td>ECL only one CL ≥ 1 GeV(CM) with θID = 2, 3, or 16 and no other CL ≥ 300 MeV(Lab) anywhere</td><td>0.15</td><td>0.04</td></tr>
<tr><td>ALP</td><td>ECL 170°< ΔϕCM< 190°, both CL > 250 MeV(Lab), no 2GeV(CM) CL in an event</td><td>0.08</td><td>0.05</td></tr>
<tr><td></td><td>ECL 170°< ΔϕCM< 190°, one CL < 250 MeV(Lab), one CL > 250 MeV(Lab), no 2GeV(CM) CL in an event</td><td>0.34</td><td>0.28</td></tr>
</table>

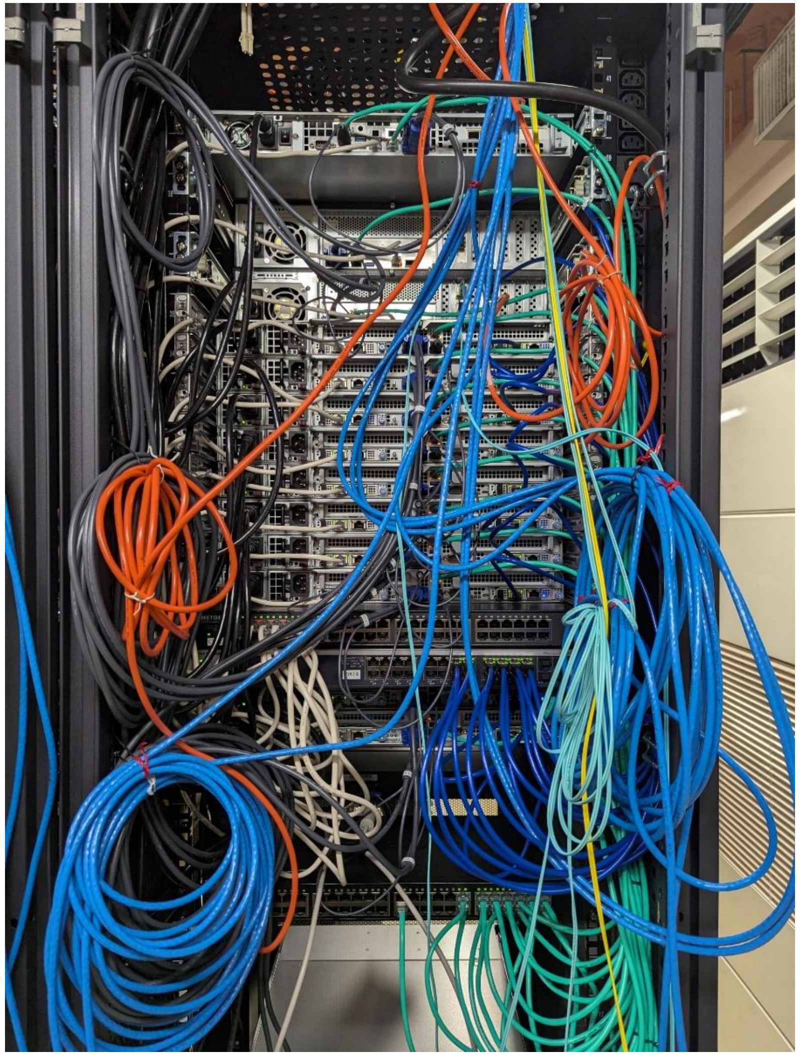
High-Level Trigger (HLT): Software trigger

- Unpacking the detector raw measurements
- Reconstructing unpacked data
  - Each subdetector except PXD
  - Combined information like tracking fitting or particle identification
- Tagging events for pre-specified categories
  - Hadronic, Muonic, Bhabha etc.
  - Calibration or luminosity measurements
- Accepting or rejecting (filtering) events
- Generating a set of Regions-of-Interest (RoI) from accepted events
  - Reducing the PXD data to $O(10\%)$
- Online data quality monitoring

Hardware configuration

- Servers in a single HLT unit
  - 1 control node
  - 1 input node
  - 1 output node
  - 10-20 worker nodes
  - 1 storage node



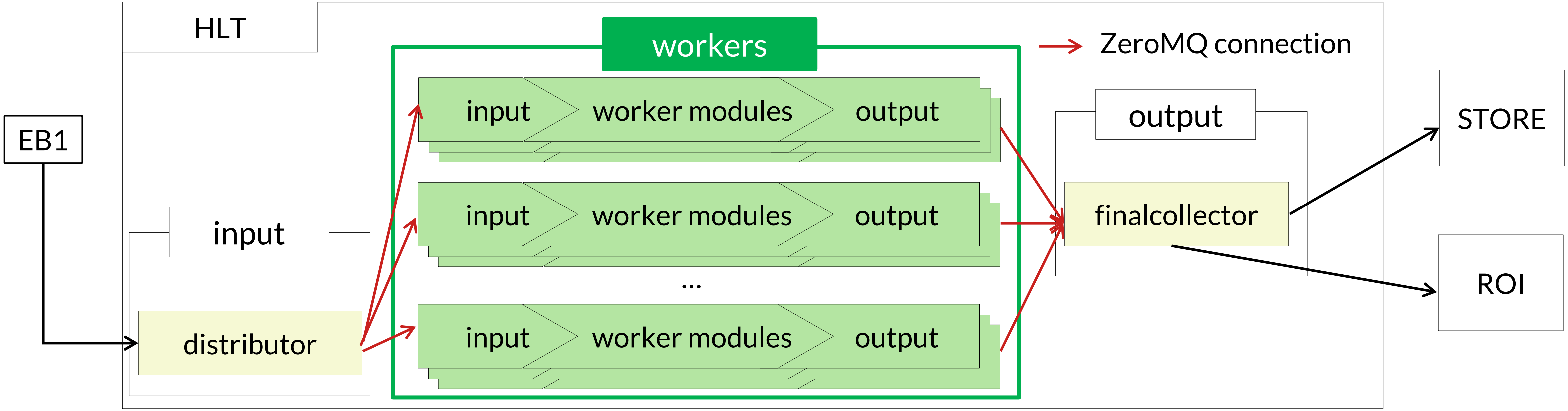


- 14 HLT units
  - The number of CPU cores ~ 6500
  - Expect to process up to 20 kHz input trigger rate

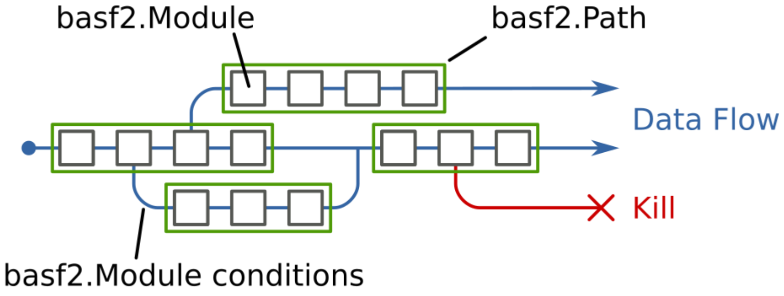
- Network
  - Dataflow: 10Gbps
  - Control: 1Gbps
  - Fully IPMI controllable

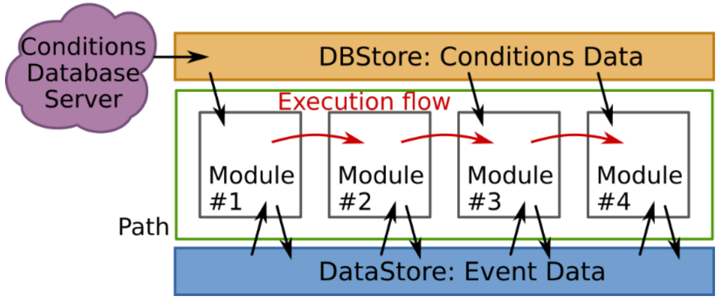
Data flow inside a unit

- Input events are sent from the first event builder (EB1) to each HLT units

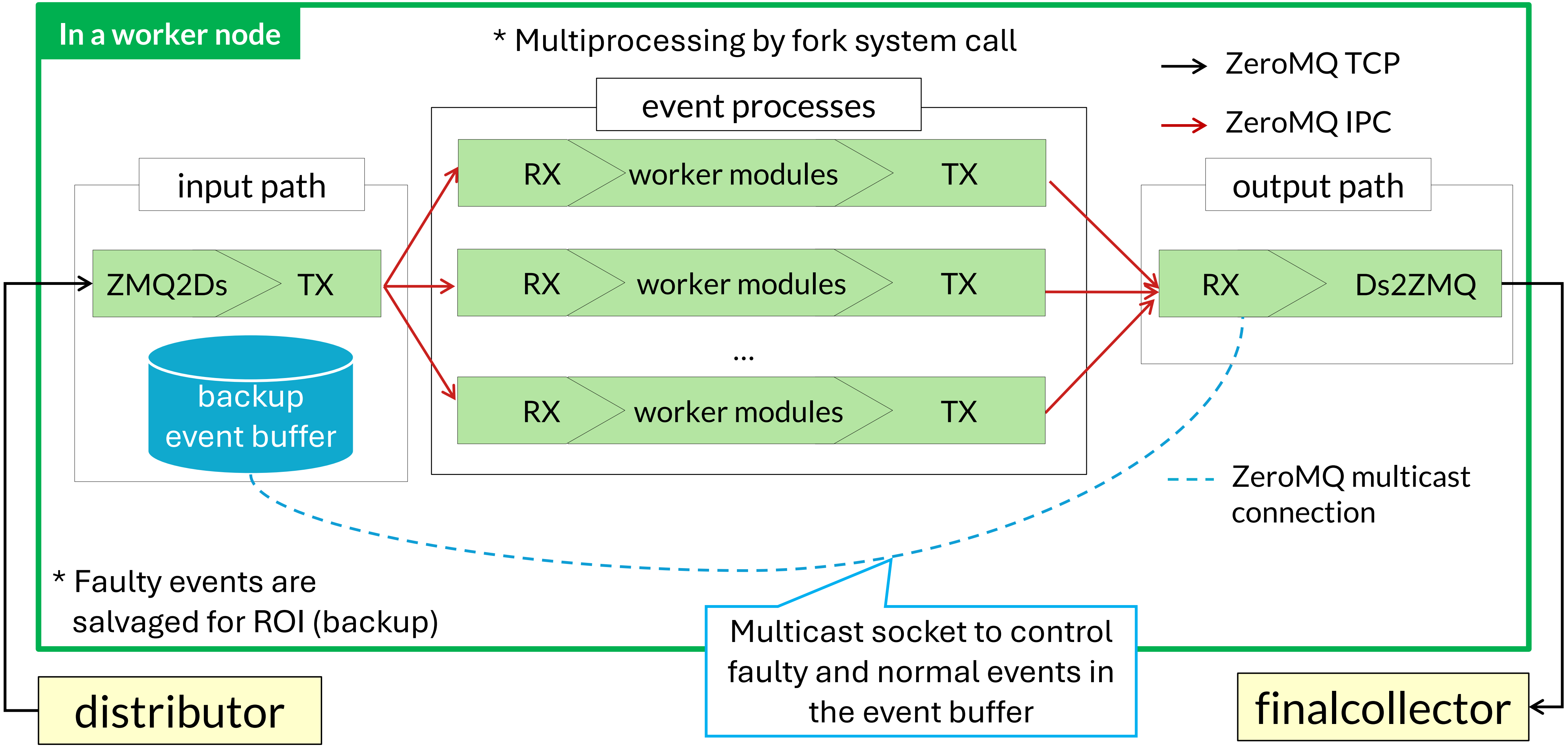


HLT reconstruction and offline calibration / analysis use the same software framework, BASF2

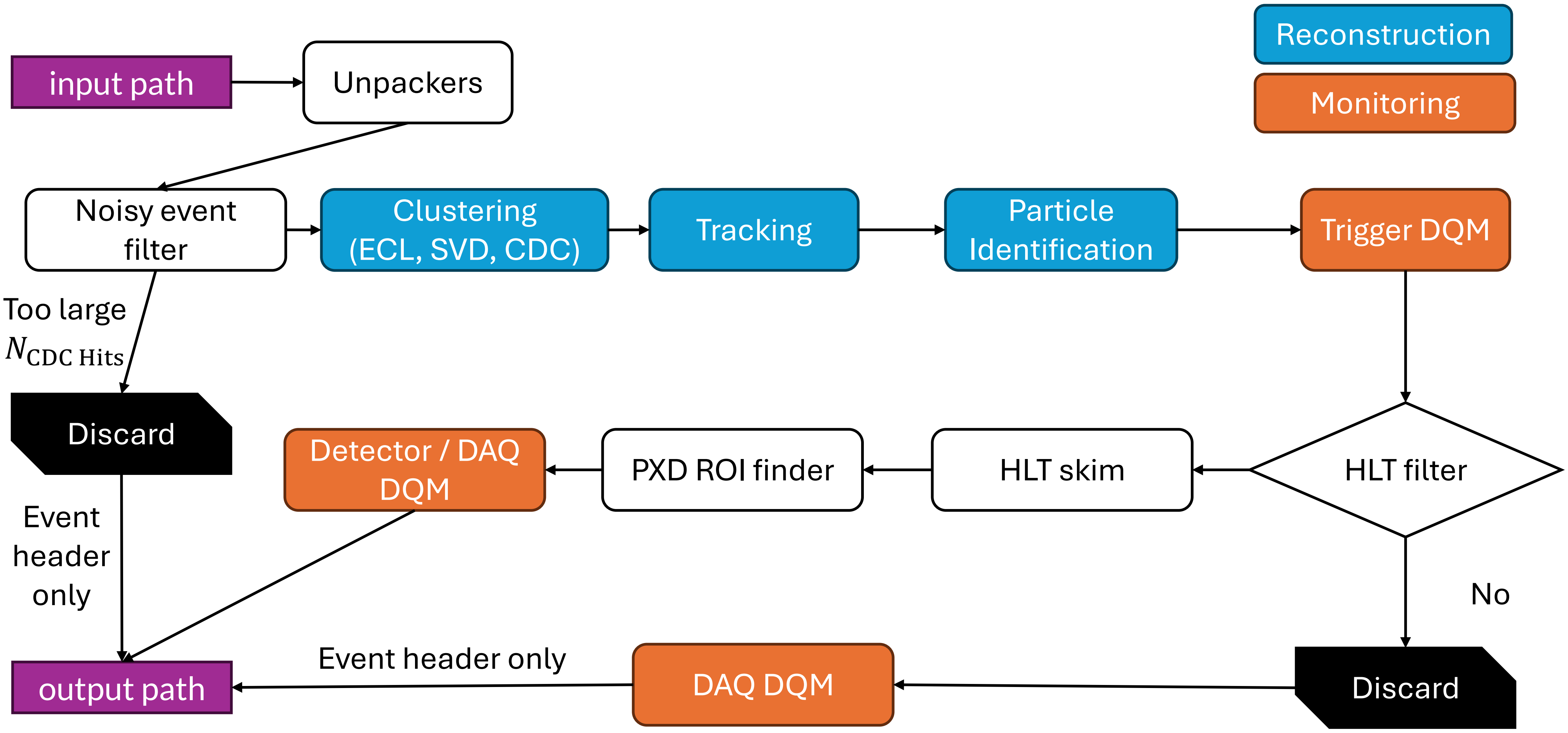




Data flow inside a worker node



Event processing: reconstruction and filtering



HLT filtering

- Two trigger menu categories: physics and non-physics
  - non-physics for calibration, etc.
- Physics triggers (“or” operator)
  - **Core physics lines**, mainly ECL or CDC only.
    - 3 or 4 ECL clusters
    - cluster with center-of-mass energy > 2 GeV
    - 2 or 3 tracks
  - **Targeted physics lines**: designed with a particular analysis
    - Single photon or low mass ALP
    - single-tag two-photon fusion production of π^0
    - …
  - Prescaled lines: mostly loose conditions of core physics lines
  - Bhabha and two photon processes especially which have muon pair.

HLT efficiency

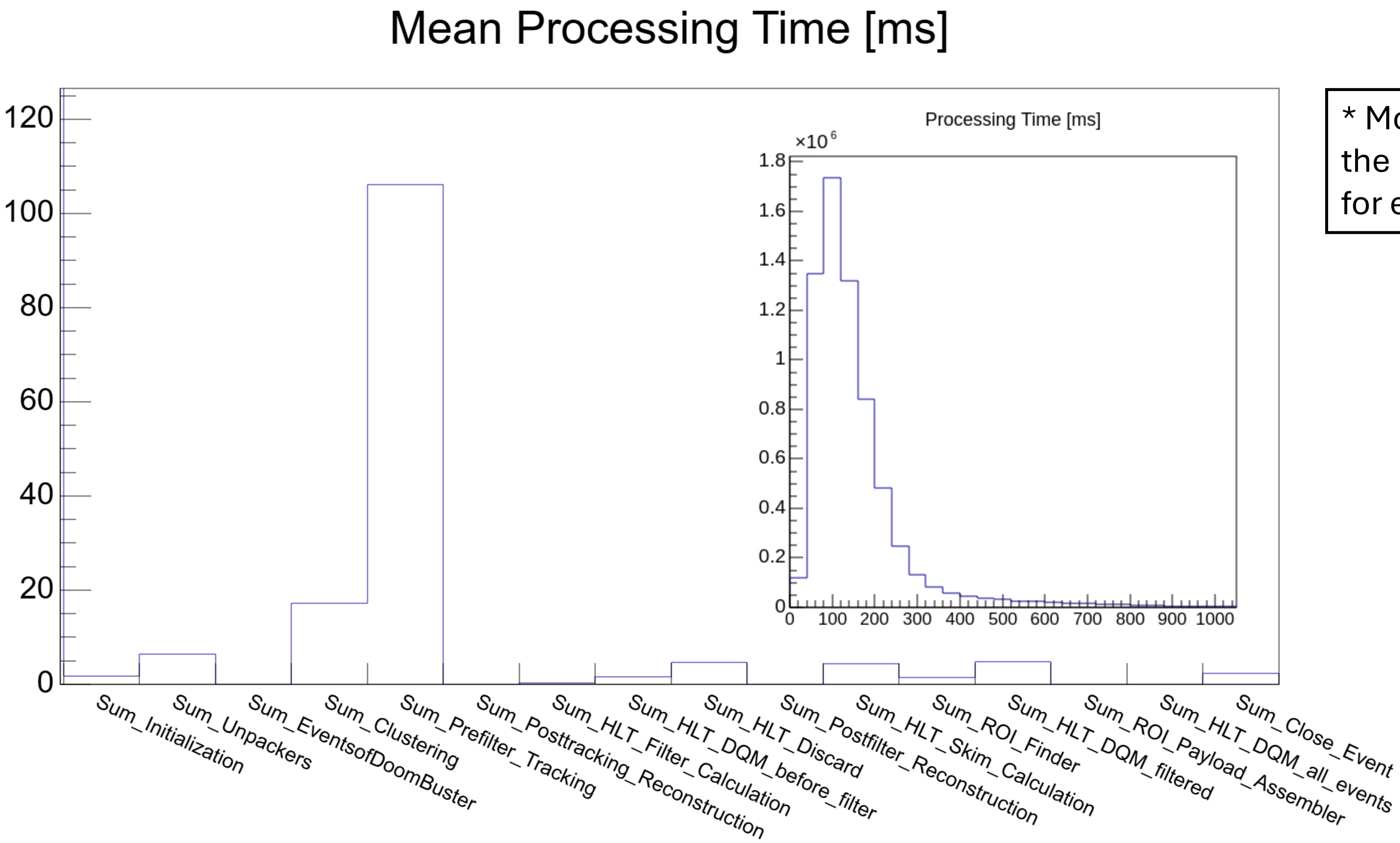
- Only 20% of the total number of events survive after the HLT filtering.
- MC study for each collision mode (with Exp. 26, Run 1261)

Mode (ee→)	Cross section (nb)	Cross section after HLT (nb)	efficiency
BB	1.05	1.05	100.0%
cc	1.30	1.30	99.7%
qq (uds)	2.42	2.30	95.2%
ττ	0.92	0.84	91.3%
μμ	1.15	1.03	89.4%
γγ	3.52	3.17	90.2%
eeee	5.88	1.66	28.2%
eeμμ	5.87	1.82	31.1%
eeππ	2.01	0.64	31.9%
ISR (hh+ISR)	0.22	0.08	36.9%
Bhabha	74.54	14.19	19.0%
total	**98.88**	**28.08**	

Excellent $B\bar{B}$ and $c\bar{c}$ efficiency

97.8% efficiency for 1-prong + 1-prong

Performance – Online processing time monitoring

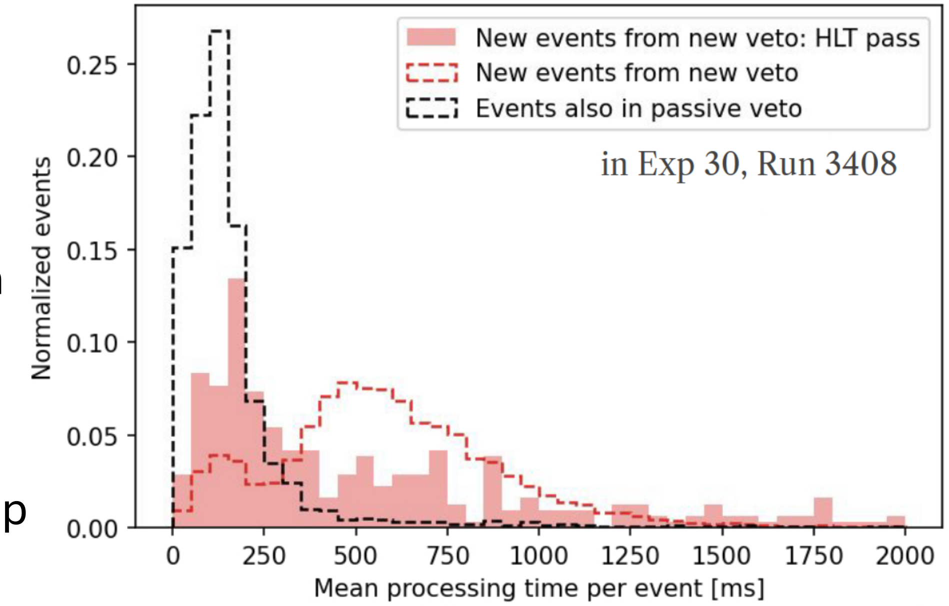


* Monitoring and recording the HLT processing time for each run.

Performance

- For higher luminosity, HLT performance should be under control.
  - Original design: 20 kHz @ 6000-core
    - ~30 kHz @ 9000-core
  - Performance study is ongoing via various way
  - Limitation: event processing time is highly depending on the background level.

- veto: timing veto for beam injection.
  New veto induces more background events.
- Brief information in backup



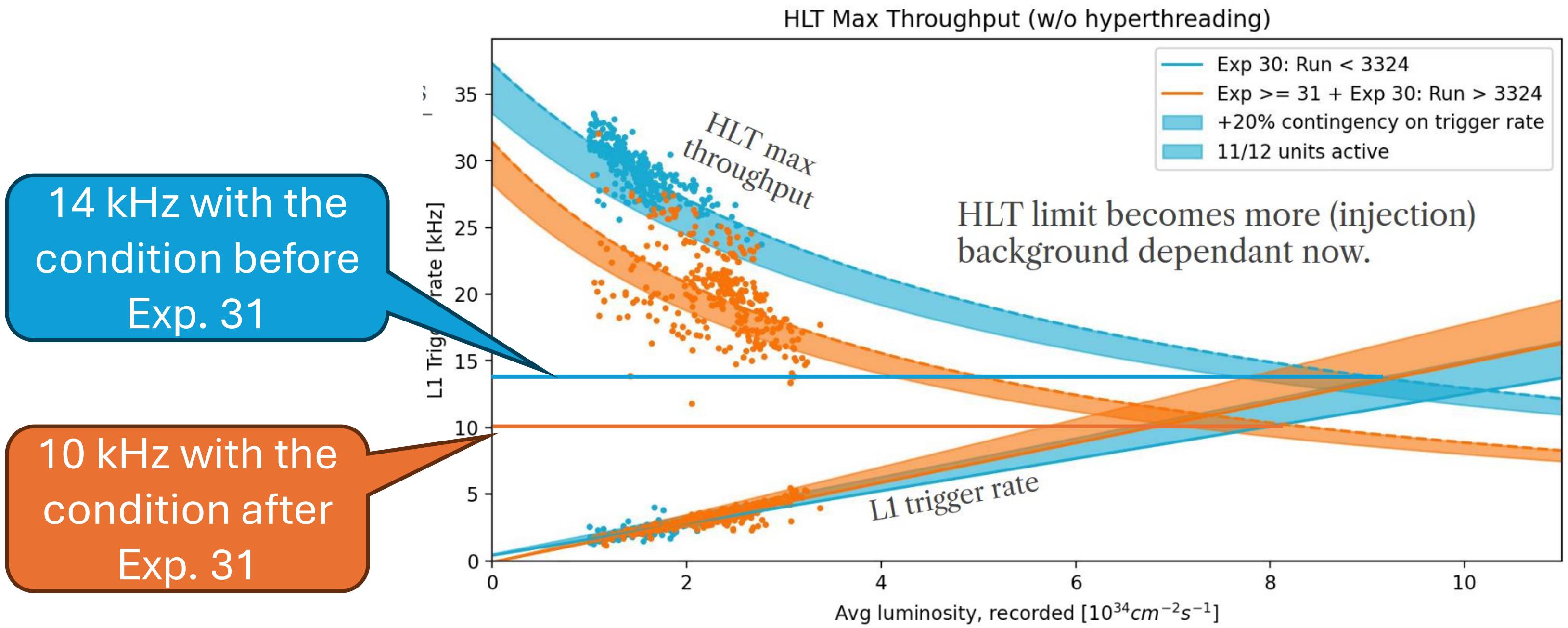
HLT had to process 5-30% extra events, depending on the background conditions.

Not just more events, but events with significantly larger processing time.

The events selected by HLT have a lower mean.

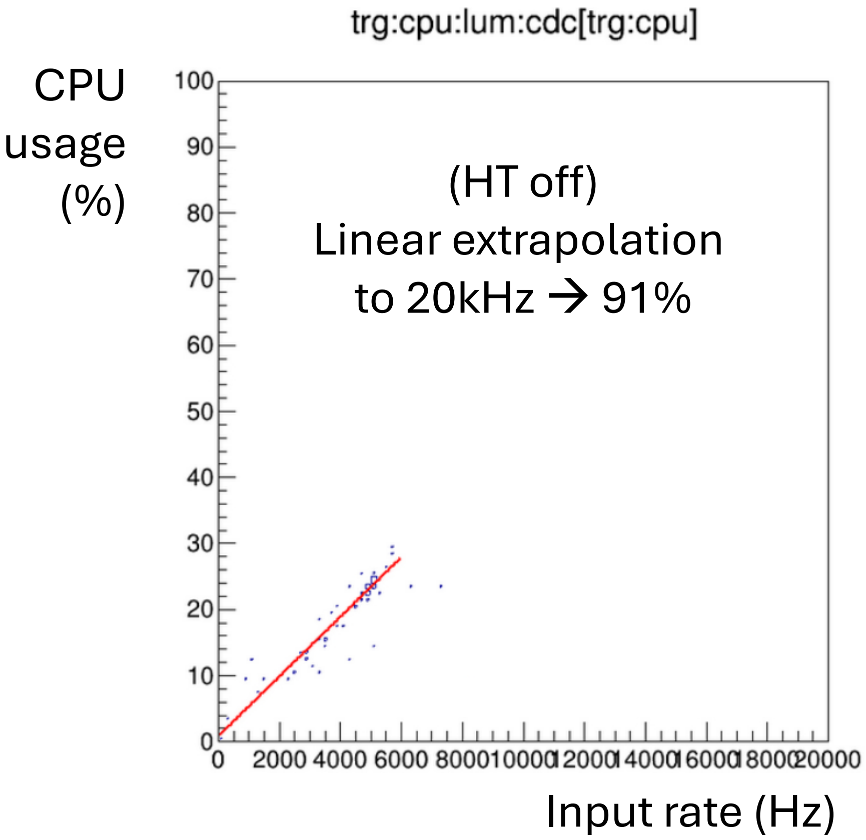
Performance estimation

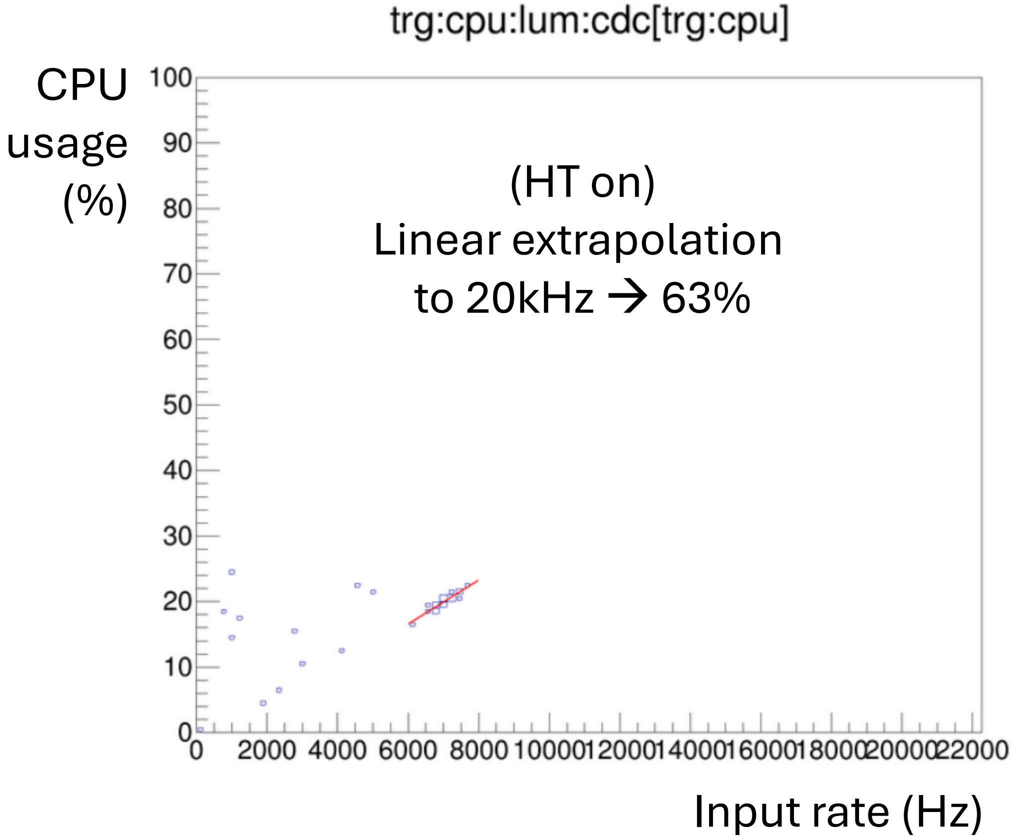
- Assumptions
  - L1 rate and processing time are linearly increasing depending on the luminosity.
  - Hyperthreading is off (offline test condition, conservative)
  - The number of HLT is 12. (The first goal is 15.)



There is no consideration of the future level 1 changes, including prescaling.

Performance – HT off vs. on using the CPU usage record



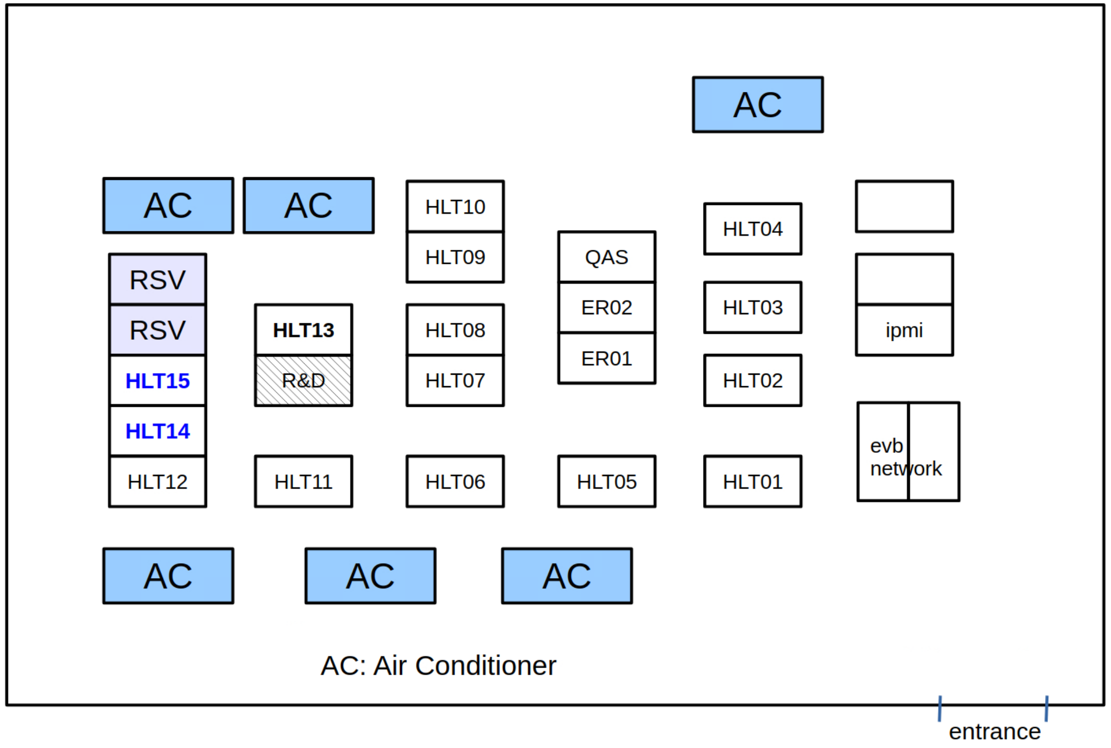


- Hyperthreading gives 1.5 times more computing power. By combining the result from the previous result, HLT (~6000-core) can handle 15-20 kHz

Upgrade plan for future operation

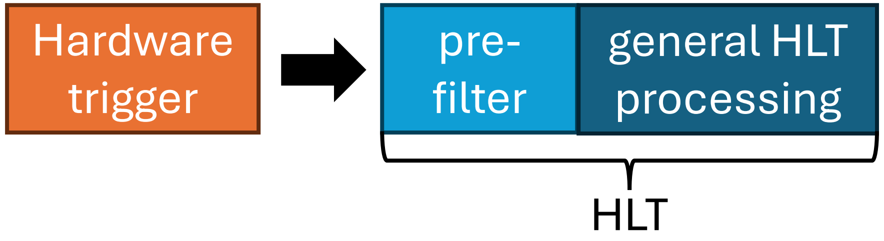
- HLT reinforcement
  - Until 2024b run: ~6200-core of worker node → designed for 20 kHz
  - For 30 kHz input rate, ~9000-core is required. (Again, just following original design.)
  - In coming years, add two more units
    - FY 2025: Add HLT15 (+480-core)
    - 15 HLT unit is current max cap of HLT room (space, air conditioning, …)
  - After that, replace old servers to new servers every year.
    - 9000-core can be achieved before the next long shutdown period.
- Continuous software performance optimization

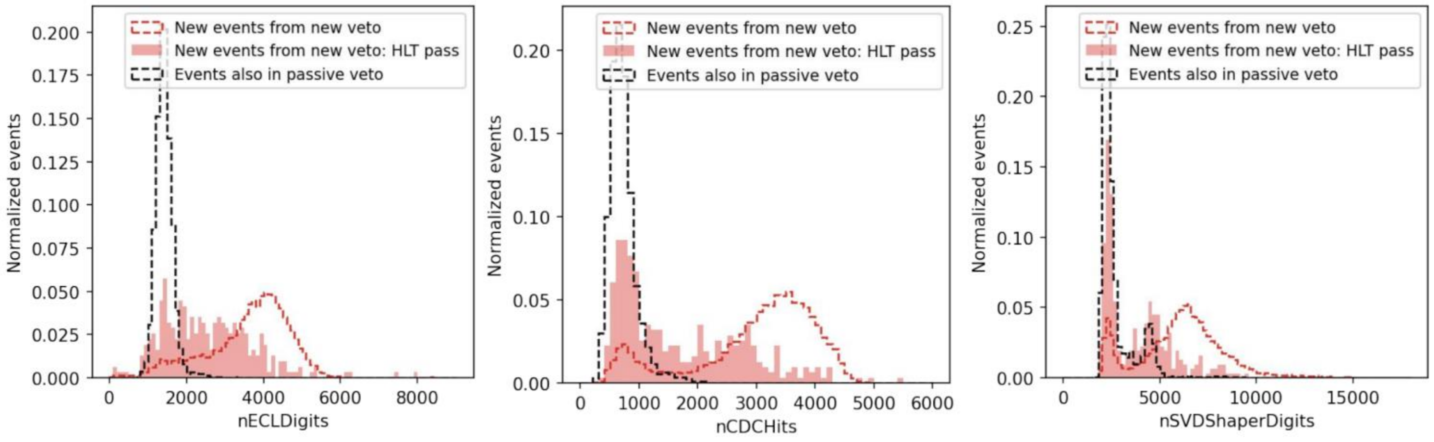
B3 server room



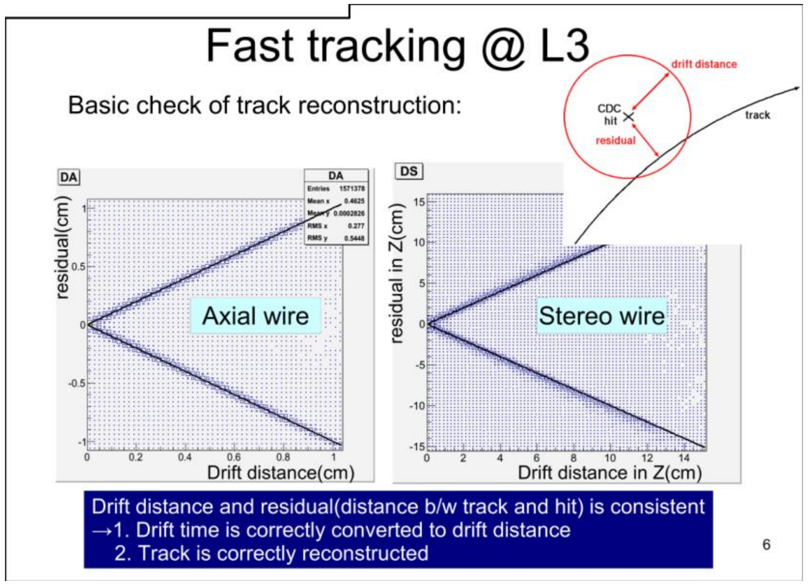
Upgrade plan for future operation

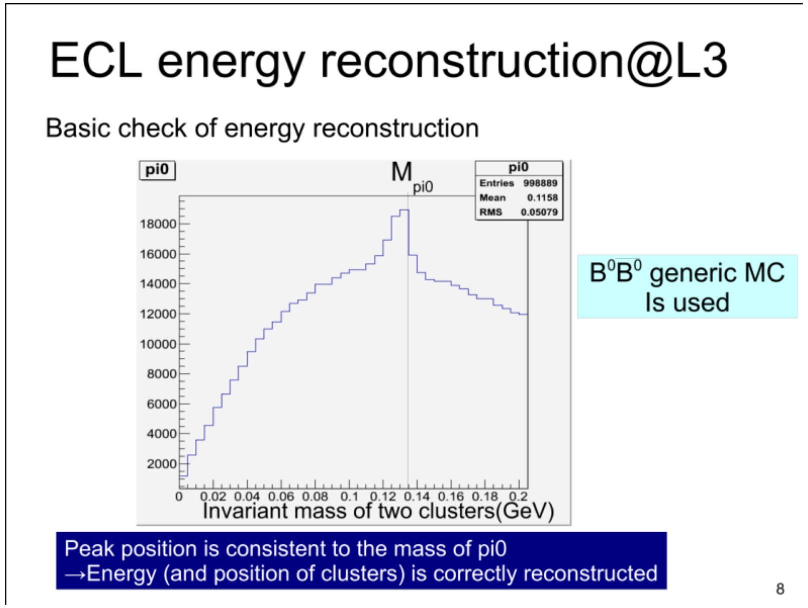
- Software pre-filter (level 3 trigger / filter)
  - Rejection based on the tighten number of hits
  - Fast tracking and energy reconstruction
  - …





< Processing time vs. the number of hits >

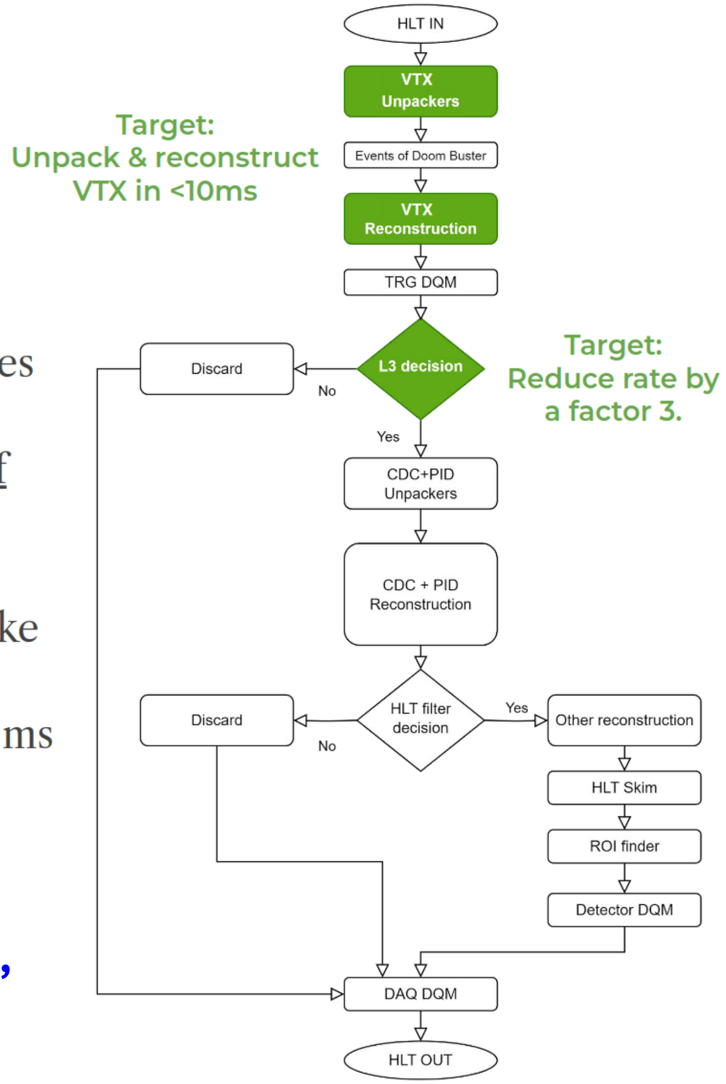




Upgrade plan for future operation – with the new VTX

Proposal: a pre-filter

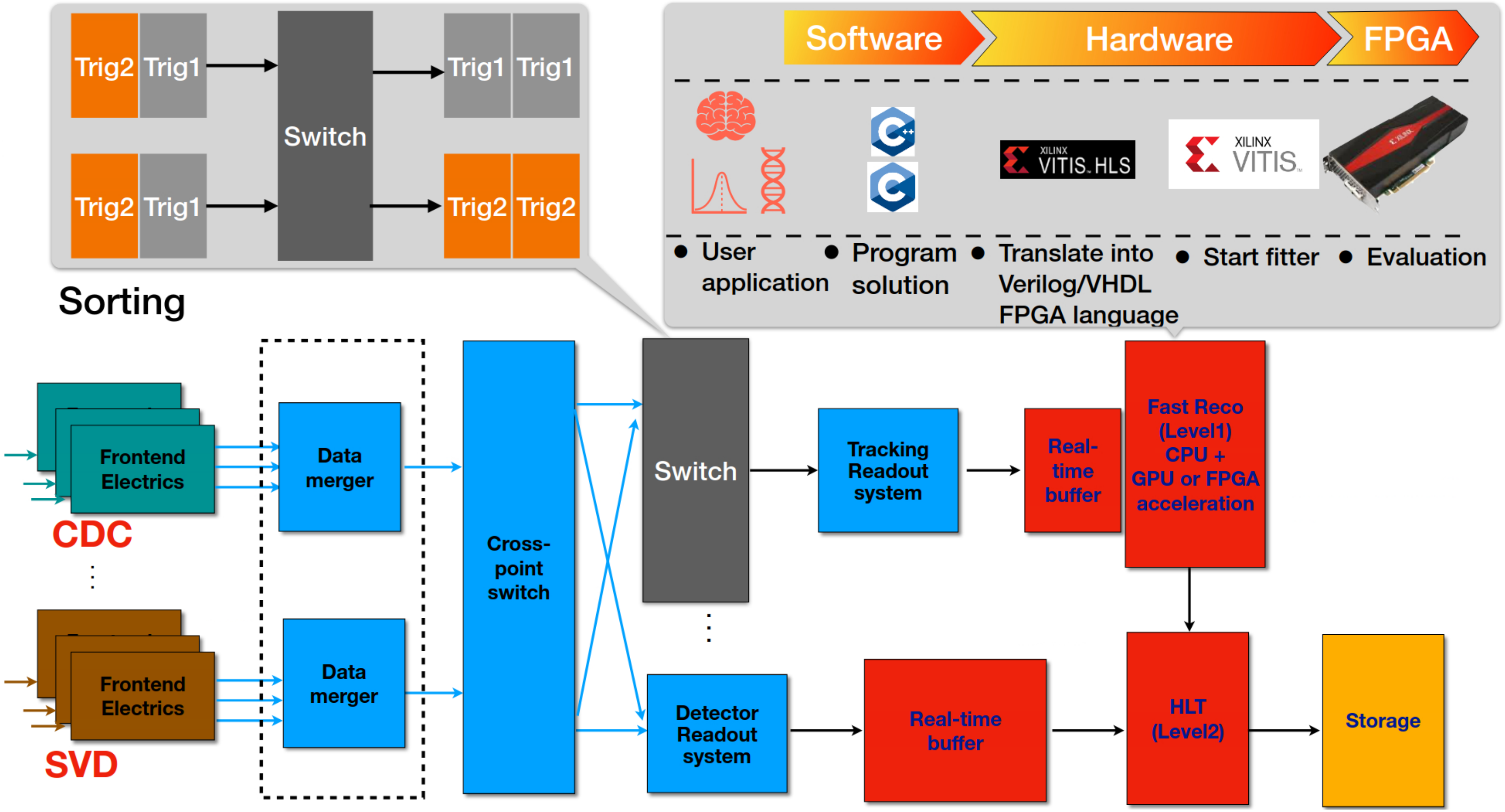
- ➢ The largest impact on L1 trigger optimization now comes for using the z-information (stt line). But HLT can reconstruct with VTX, i.e., even better z-information of tracks!
- ➢ A preliminary filter decision that could be calculated immediately after partial reconstruction of the event (like VTX only).
- ➢ If such a faster decision could be calculated within ~10 ms per event and could reduce the input rate by at least a factor 3, that would reduce the overall processing time from ~150 ms to ~55 ms per event.



*** For VTX upgrade: please check the talks by Alex Kuzmin, "*Status and upgrade of Belle II detector*" and Roua Boudagga, "*Design of the OBELIX Monolithic CMOS Pixel Sensor for an Upgrade of the Belle II Vertex Detector*"**

Upgrade plan for future operation – acceleration

Propose: partial software tracking trigger



*** Please find the detail presentation by Qidong Zhou, "*Belle-II trigger with ML*"**

Summary

- Belle II experiment is successfully running and generate physics data including B, τ, and charm.
- Before the HLT, level 1 hardware trigger select events
  - From the level 1, we select "$> 99\%$" of $B\bar{B}$ and "$> 95\%$" of $\tau^+\tau^-$ events.
- HLT accepting the selected events and do a further processing
  - Belle II HLT is a CPU farm which has ~6500 cores.
- After the HLT, 100% of $B\bar{B}$, 99.7% of $c\bar{c}$, and 91% of $\tau^+\tau^-$ are remaining.
- HLT performance is one issue for the future higher luminosity runs.
  - The mean processing time of the events are highly background dependent.
  - We monitoring the processing time for each run.
  - We have several upgrade plans, adding more CPU cores, applying software pre-filter (also with upgraded VTX), and acceleration-based pre-filter.

Backup

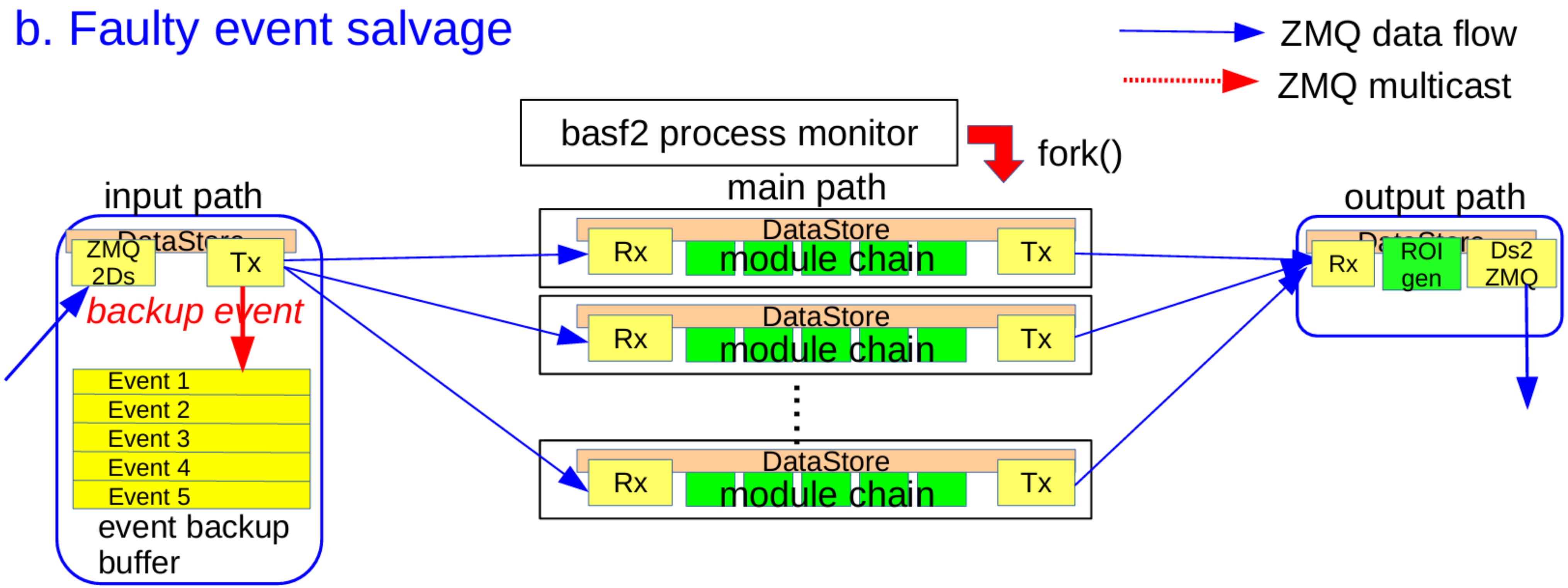
τ publications @ Belle II

- Search for lepton-flavor-violating τ decays to a lepton and an invisible boson at Belle II
  - https://link.aps.org/abstract/PRL/v130/e181803 (https://arxiv.org/abs/2212.03634)
- Search for a $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ events with the Belle II experiment
  - https://link.aps.org/abstract/PRL/v131/e121802 (https://arxiv.org/abs/2306.12294)
- Measurement of the τ-lepton mass with the Belle II experiment
  - https://link.aps.org/abstract/PRD/v108/e032006 (https://arxiv.org/abs/2305.19116)
- Test of light-lepton universality in τ decays with the Belle II experiment
  - https://dx.doi.org/10.1007/JHEP08(2024)205 (https://arxiv.org/abs/2405.14625)
- Search for lepton-flavor-violating $\tau^- \to \mu^+\mu^-\mu^-$ decays in Belle II data
  - https://dx.doi.org/10.1007/JHEP09(2024)062 (https://arxiv.org/abs/2405.07386)

charm publications @ Belle II

- Precise measurement of the D^0 and D^+ lifetimes at Belle II
  - https://link.aps.org/doi/10.1103/PhysRevLett.127.211801 (https://arxiv.org/abs/2108.03216)
- Measurement of the Λ_c^+ lifetime
  - https://link.aps.org/abstract/PRL/v130/e071802 (https://arxiv.org/abs/2206.15227)
- Measurement of the Ω_c^0 lifetime at Belle II
  - https://link.aps.org/doi/10.1103/PhysRevD.107.L031103 (https://arxiv.org/abs/2208.08573)
- Novel method for the identification of the production flavor of neutral charmed mesons
  - https://link.aps.org/abstract/PRD/v107/e112010 (https://arxiv.org/abs/2304.02042)
- Precise measurement of the D_s^+ lifetime at Belle II
  - https://link.aps.org/abstract/PRL/v131/e171803 (https://arxiv.org/abs/2306.00365)
- Measurements of the branching fractions of $\Xi_c^0 \to \Xi^0\pi^0$, $\Xi_c^0 \to \Xi^0\eta$, and $\Xi_c^0 \to \Xi^0\eta'$ and asymmetry parameter of $\Xi_c^0 \to \Xi^0\pi^0$
  - https://dx.doi.org/10.1007/JHEP10(2024)045 (https://arxiv.org/abs/2406.04642)

Faulty event salvage



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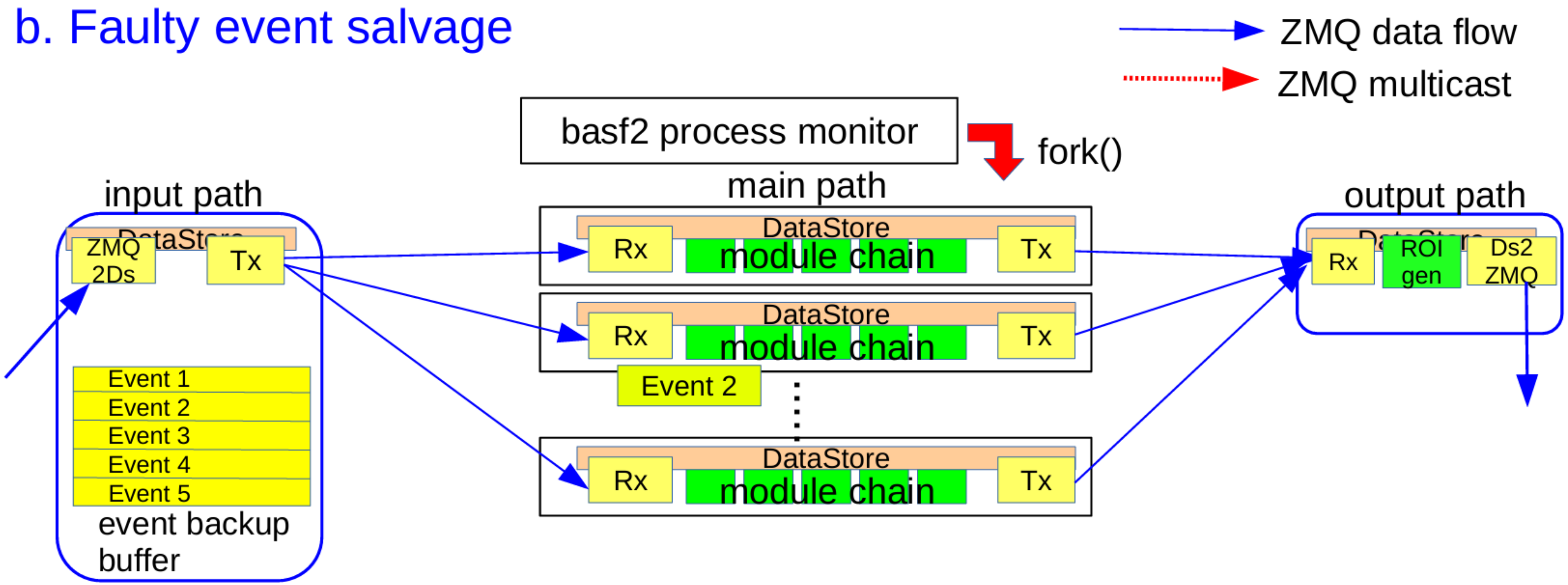

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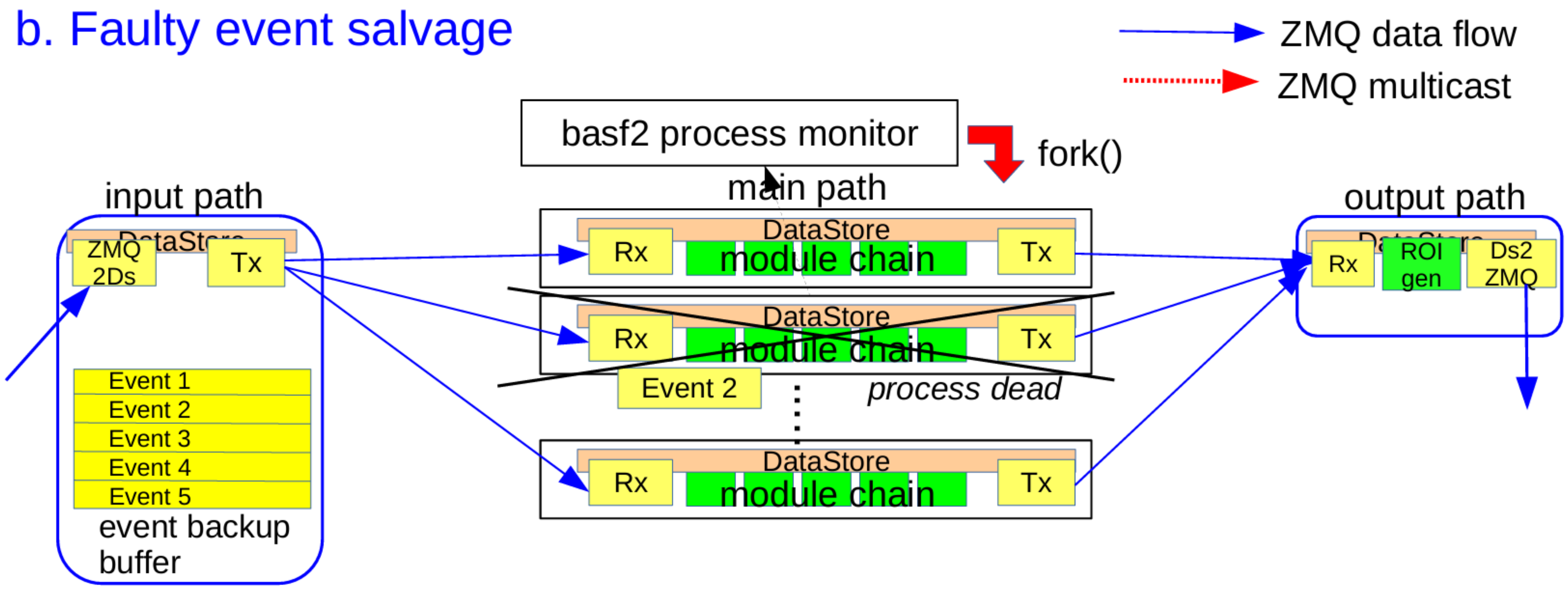

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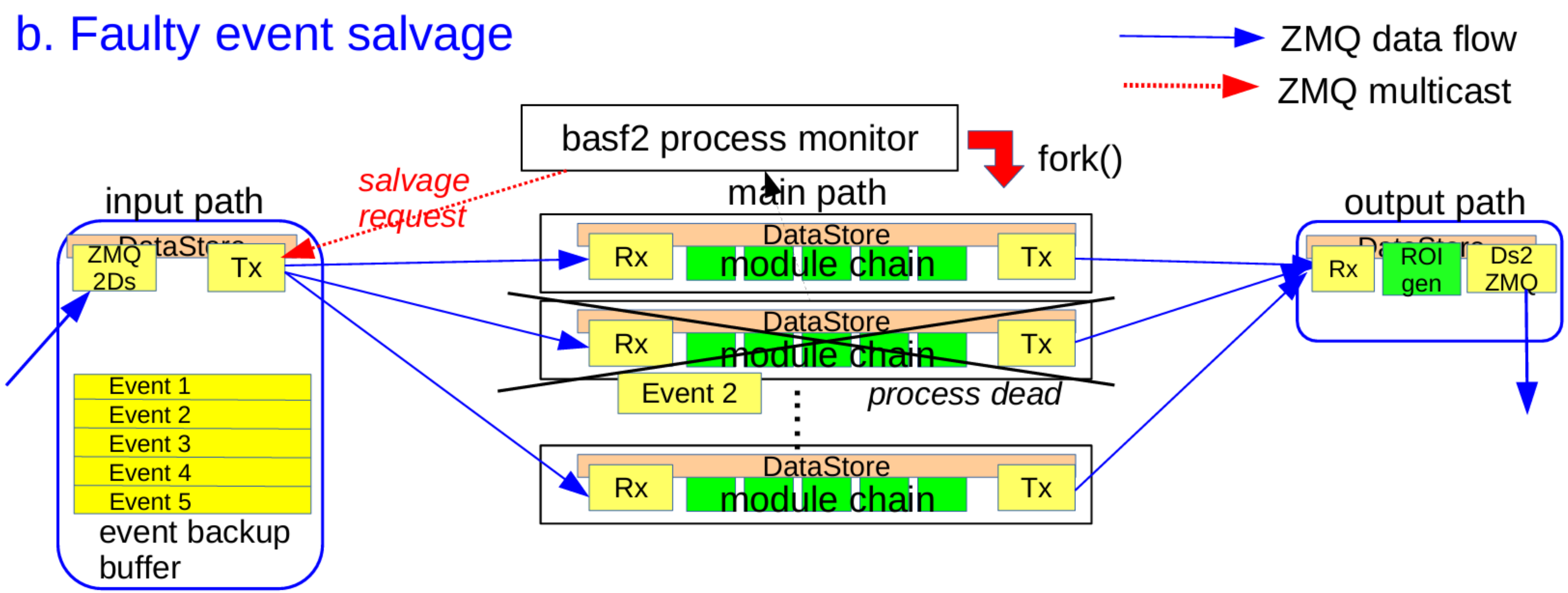

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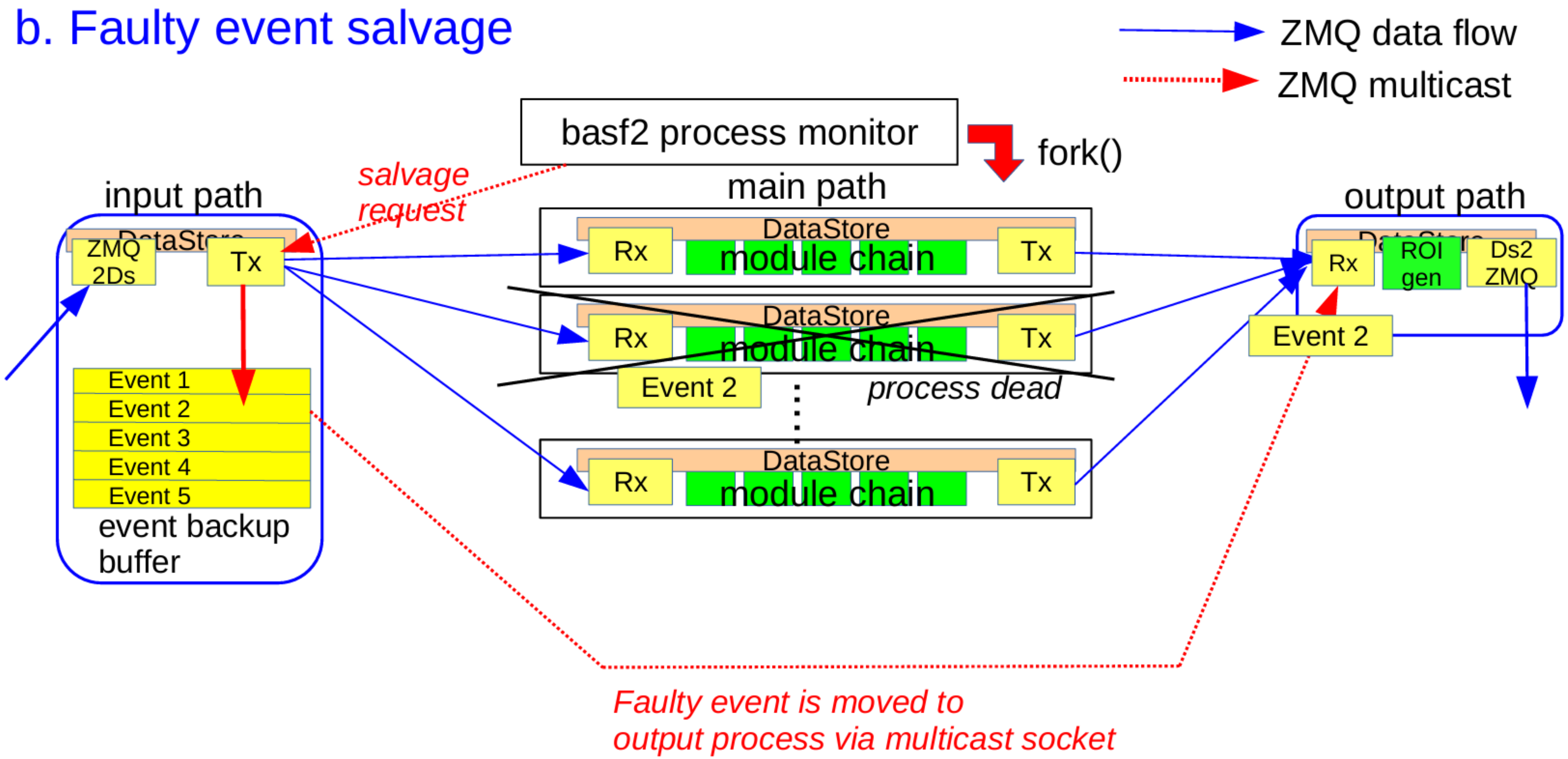

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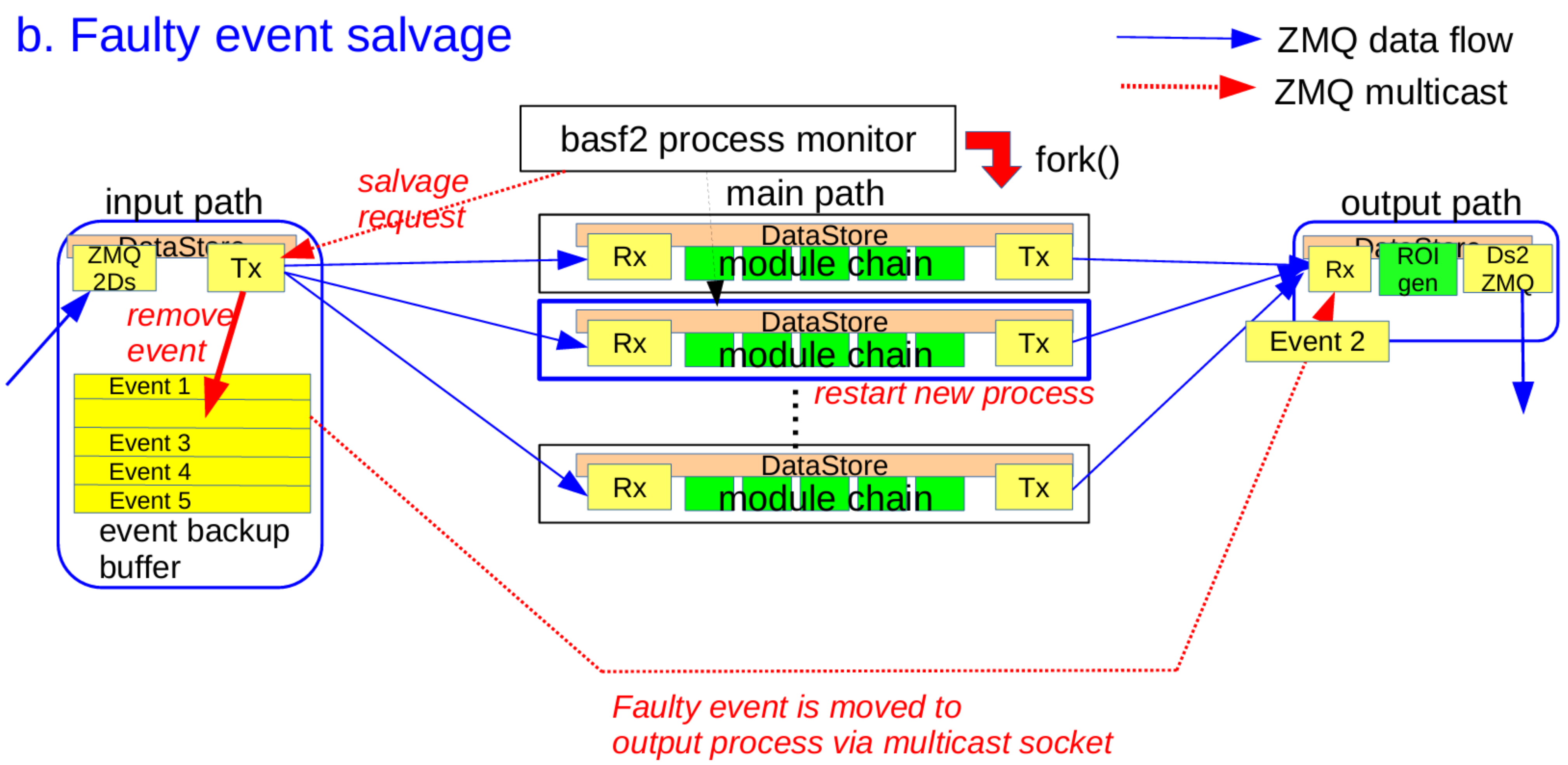


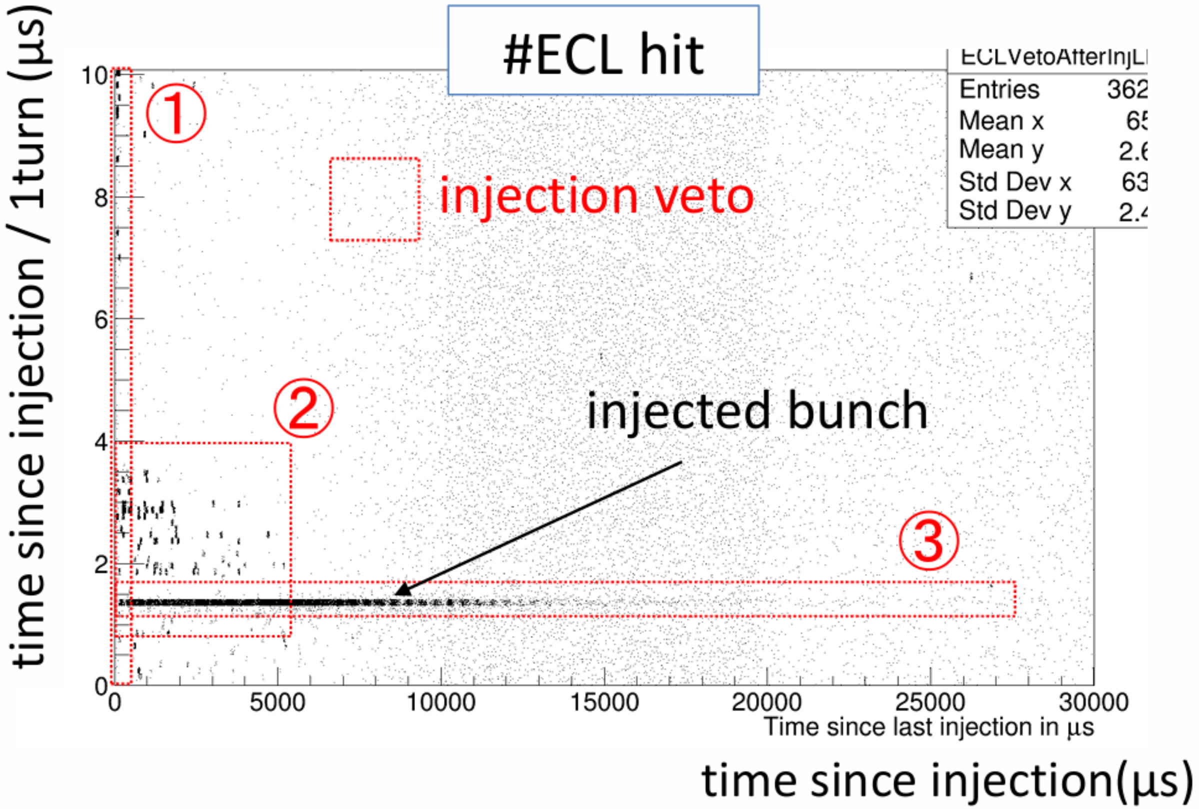
Belle II injection veto

-Injection veto structure

-①~0.5ms after injection: veto trigger entirely (since Belle)

-②0.5~10ms after injection: veto trigger 3~4μs around injected bunch (2019)

-③10~30ms after injection: veto trigger 1~2μs around injected bunch (2020)

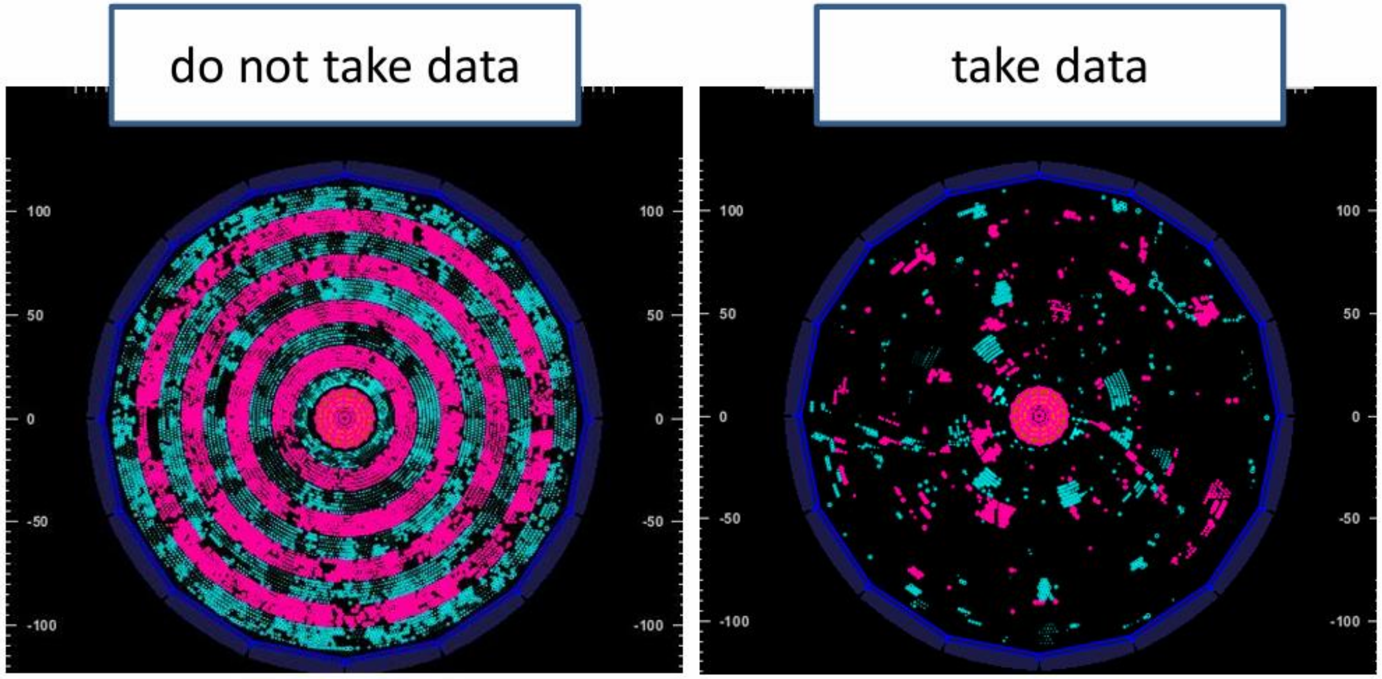


Belle II injection veto – active injection veto

-In LS1, new injection veto scheme is developed

-veto trigger only when detector hit occupancy is high at level1

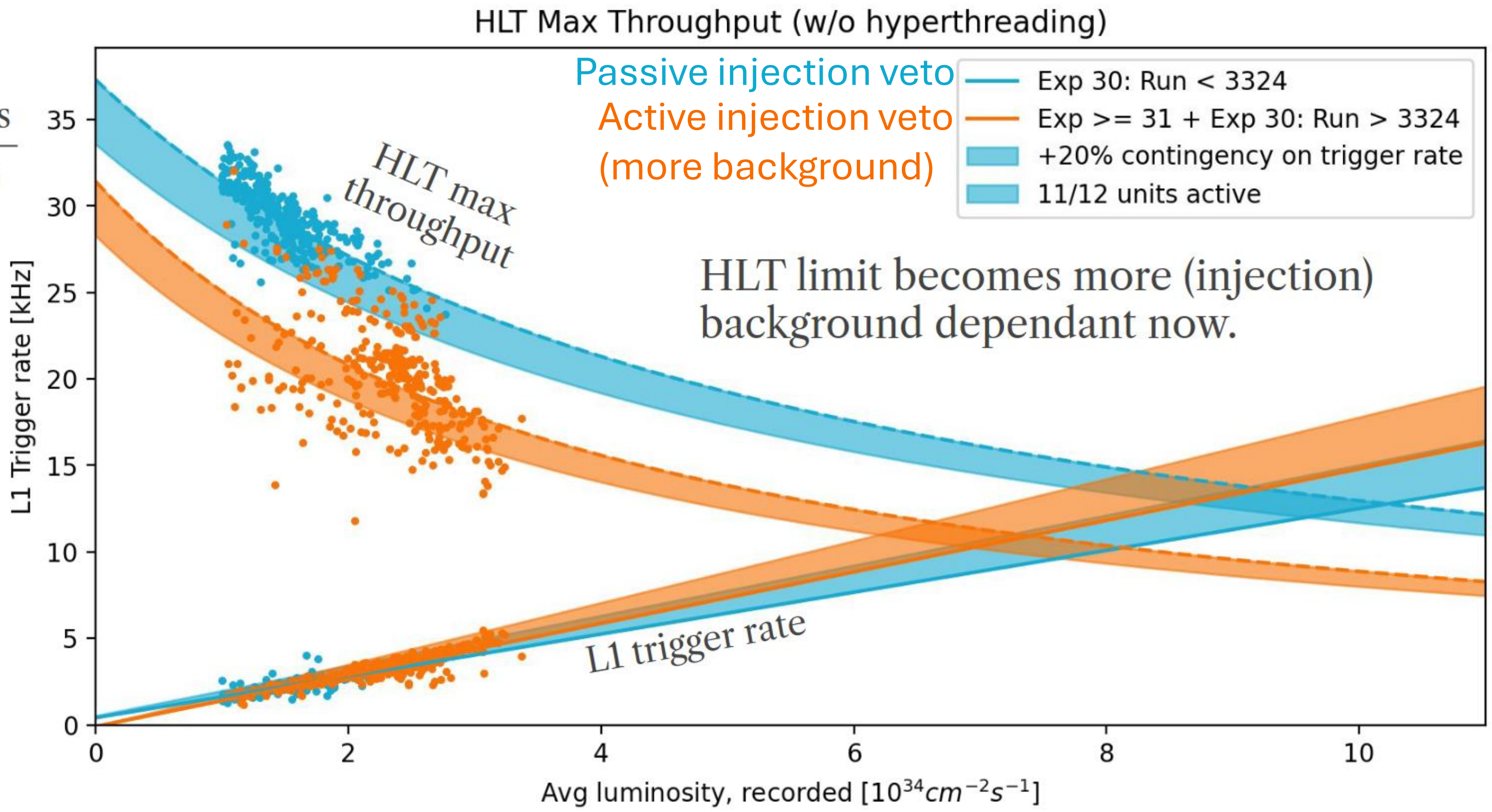
→reduce DAQ deadtime 30~40% possibly



Performance – software estimation

$$\text{HLT max throughput} = \frac{\#\ \text{processes}}{\text{Proc. time per event}}$$

Assumptions:
L1 trigger rate and mean processing time per event increases linearly with luminosity.



Based on early exp 30 → can operate up to $9 \times 10^{34}/\text{cm}^2/\text{s}$
Based on late exp 30 and exp 31, 32, 33 → can operate up to $6.5 \times 10^{34}/\text{cm}^2/\text{s}$