Operation of the Belle II Central Drift Chamber CDC

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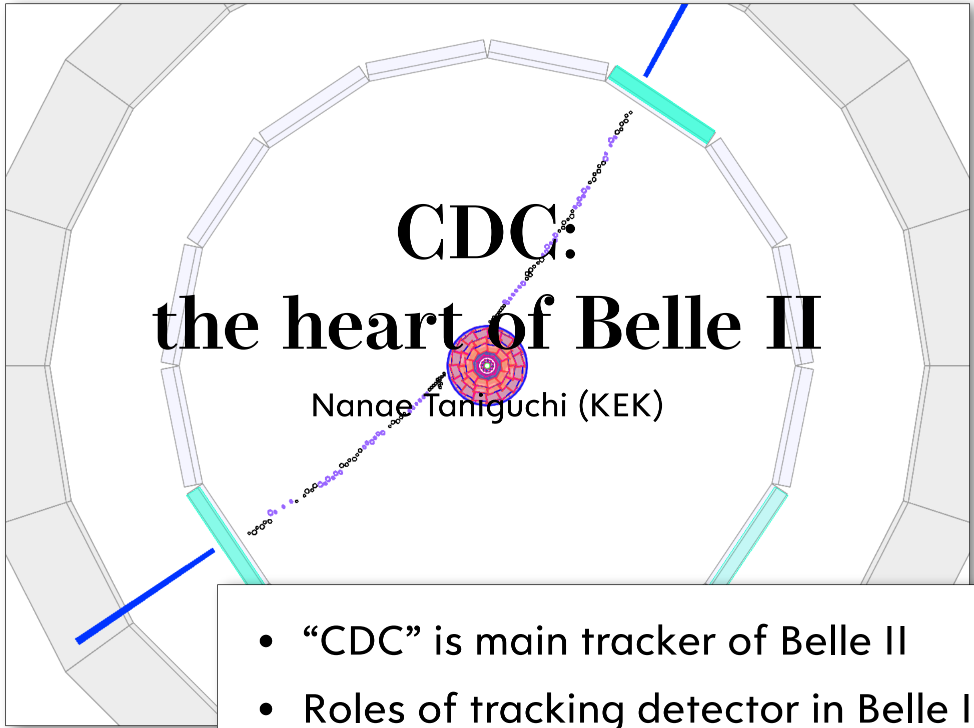

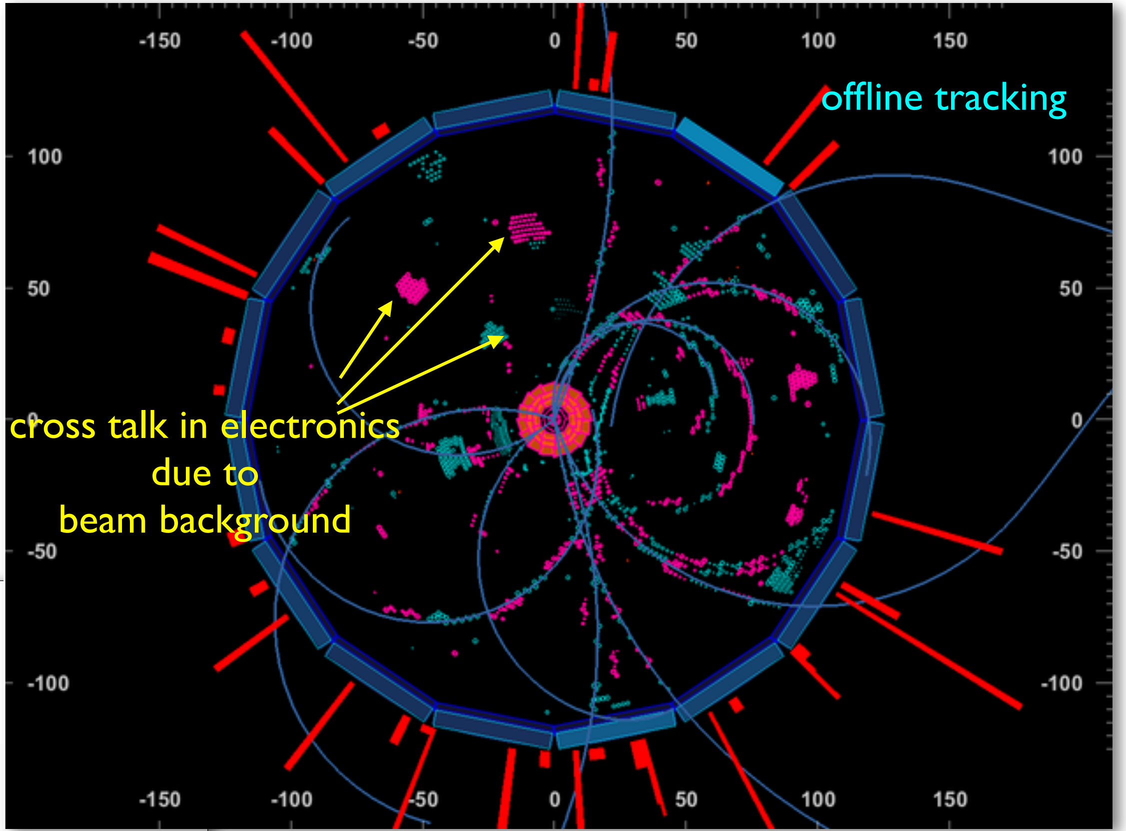

- "CDC" is main tracker of Belle II
- Roles of tracking detector in Belle II
  - measure momentum of charged particles
  - particle identification
  - provide track trigger signal

the most important !!

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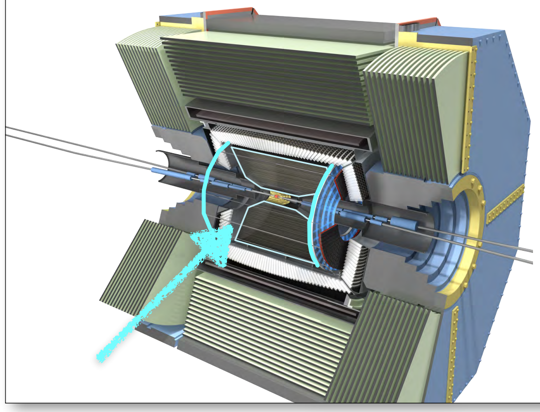
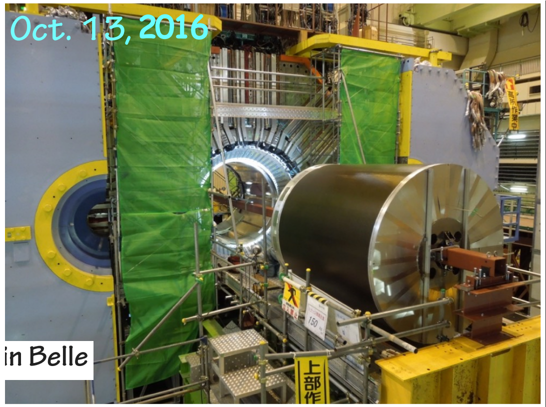
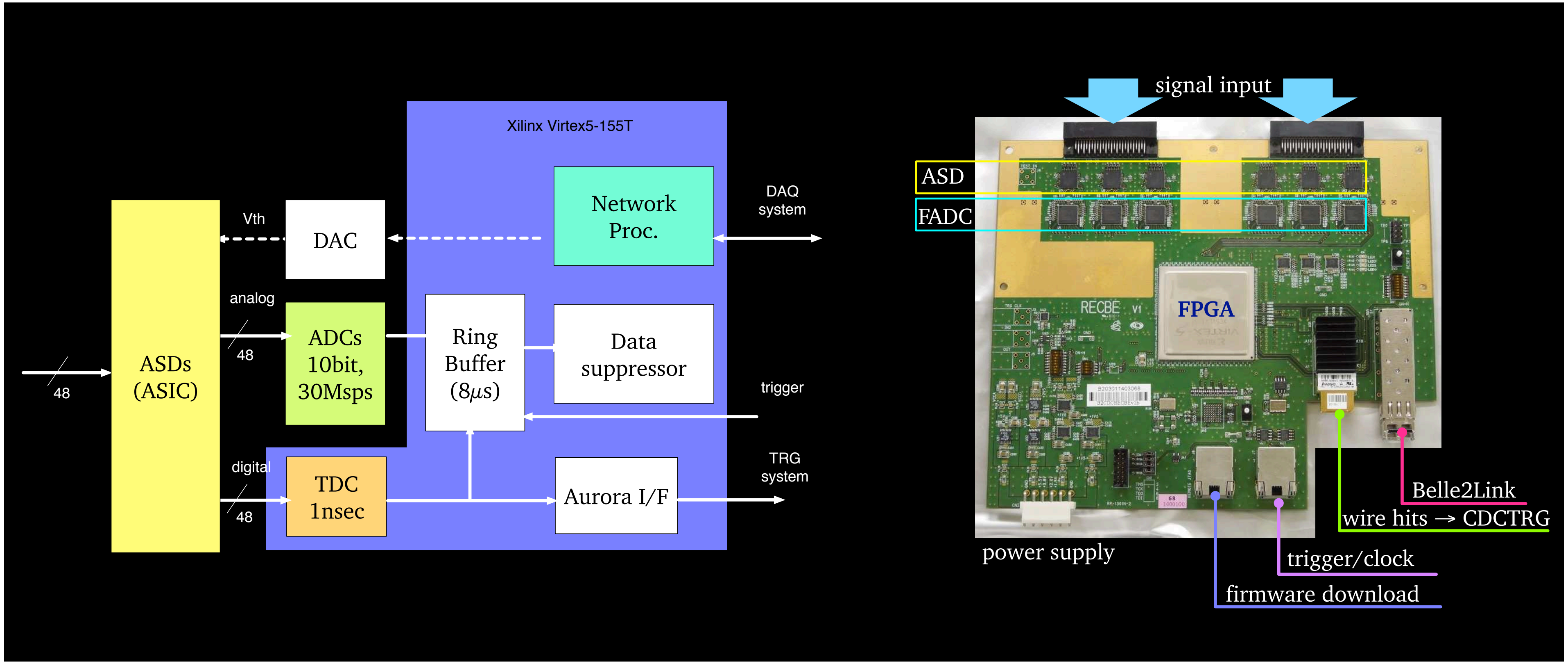




CDC Frontend Electronics

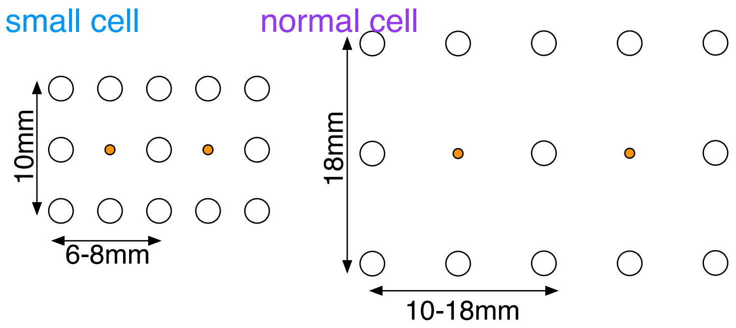
- Amp Shaper Discriminator (ASD)
  - Analog out: waveform
  - Digital out: hit timing
- Analog-to-Digital Converter (ADC)
  - 2 Vp-p, 10 bit
  - 31.25 Mbps
- Field-Programmable Gate Array (FPGA)
  - Virtex5 (xc5vlx155t)
  - Data processing
- Optical module from Avago
  - CDCTRG
- Small Form-factor Pluggable (SFP)
  - Belle II link (b2l)
- RJ45
  - Belle II trigger timing (b2tt)
  - Firmware (fw) download



- Goals of proposed FEE upgrade
  - replace optic transceivers before they are fatally damaged by irradiation (increase radiation tolerance from 0.3kGy to >1kGy)
  - improve triggering by using a faster ADC (→timing and ADC cuts can be applied on L1 trigger level)
  - reduce cross-talk to improve the tracking and triggering performance
  - replace FPGAs with a less radiation susceptible version to reduce SEUs

Belle II CDC Design Concept

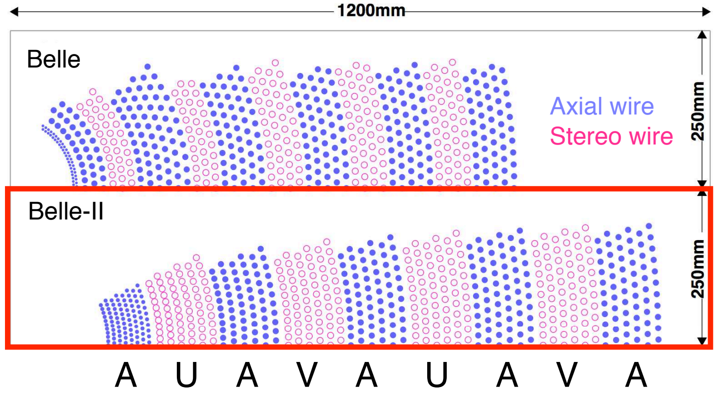
	Belle	Belle II
Radius of inner cylinder (mm)	77	160
Radius of outer cylinder (mm)	880	1130
Radius of innermost sense wire (mm)	88	168
Radius of outermost sense wire (mm)	863	1111.4
Number of layers	50	56
Number of sense wires	8,400	14,336
Gas	He–C_2H_6	He–C_2H_6
Diameter of sense wire (μm)	30	30

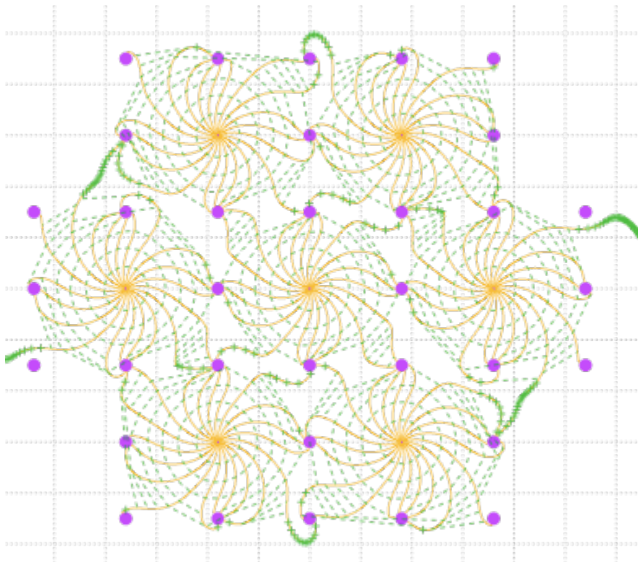


	Sense	Field
Material	Tungsten	Aluminum
Plating	Gold	No
Diameter (μm)	30	126
Tension (g)	50	80
Number of wires	14,336	42,240

$\sum$ = 4.1 ton on end plate

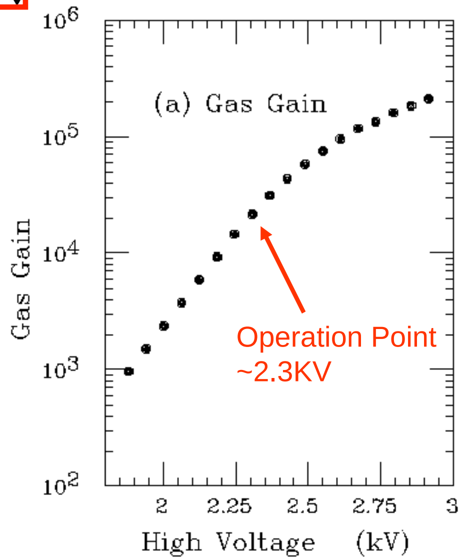
Low mass wires

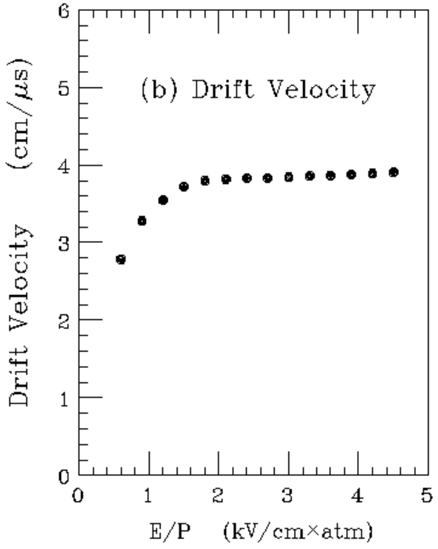




Field lines and isochrones

Low-Z gas: He-C_2H_6 (50/50)

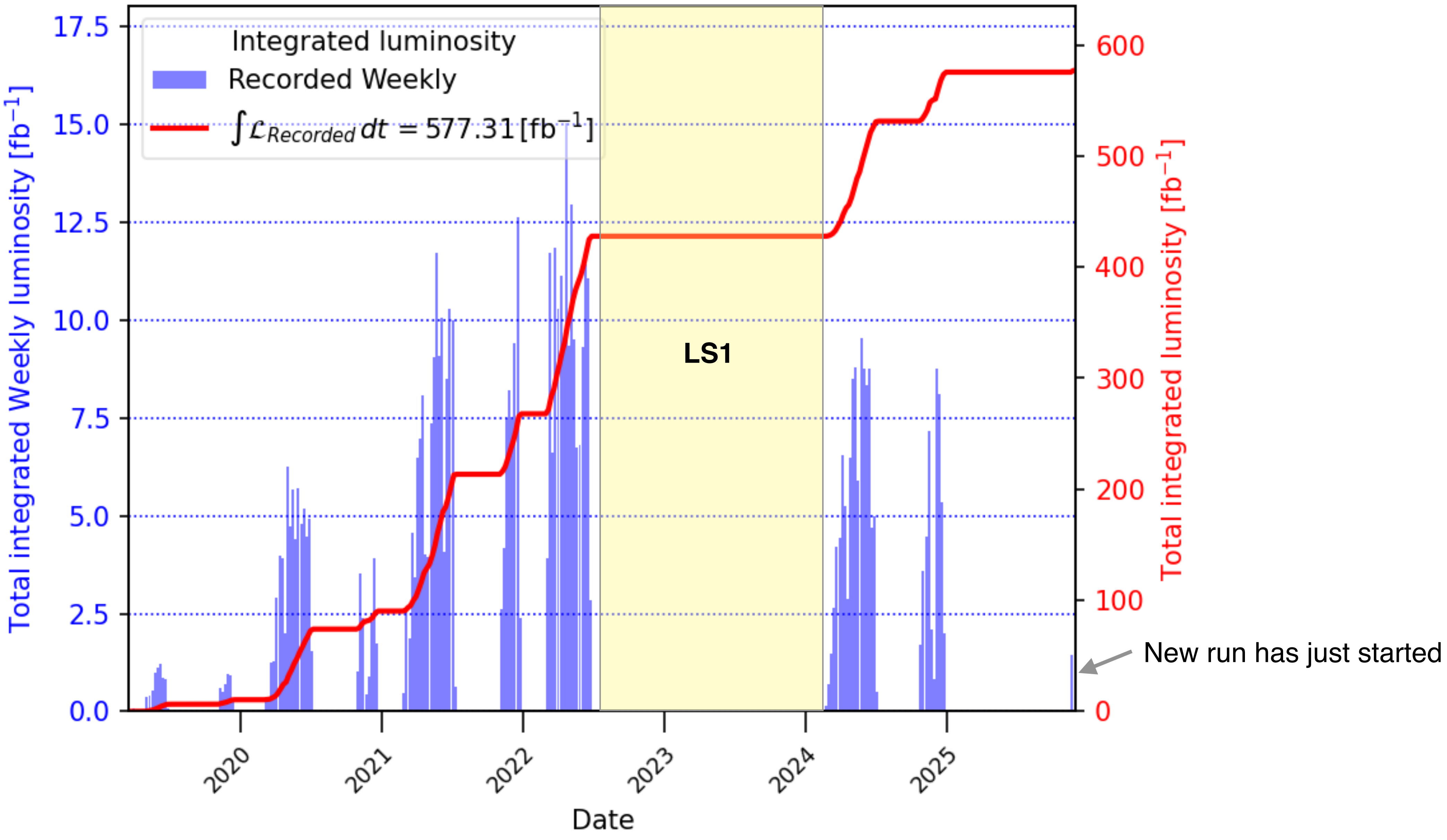




Design follows the general concept of the successful Belle CDC

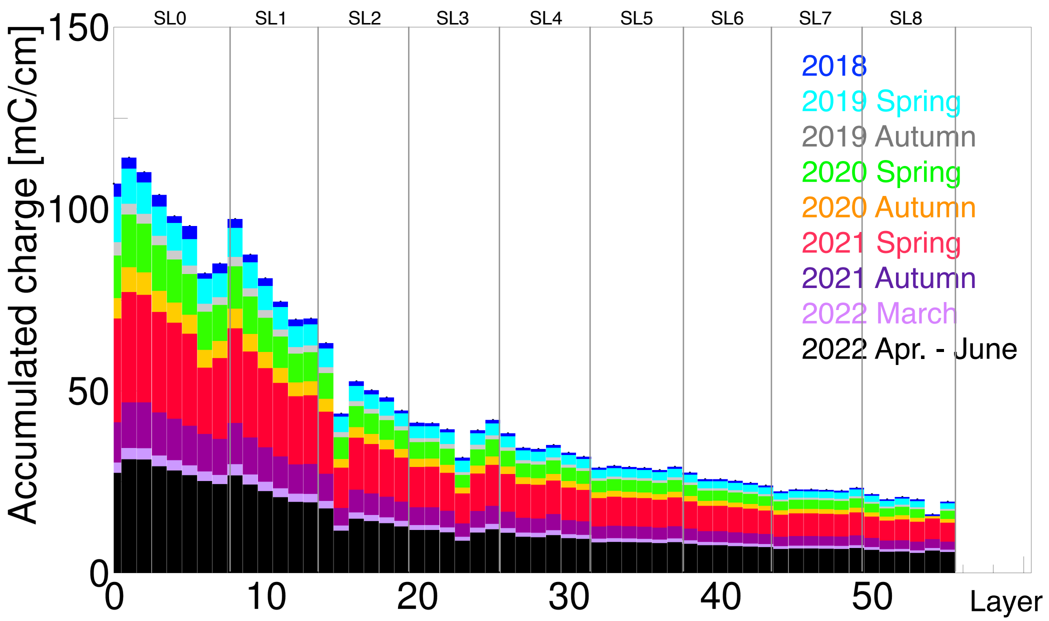
- low mass wires (un-plated Al field wires) and low-Z gas
- larger inner radius to make room for bigger VXD and to avoid region of high occupancy
- innermost super-layer is implemented separately as a small-cell chamber
- less space needed for TOP than RICH → can afford larger outer radius

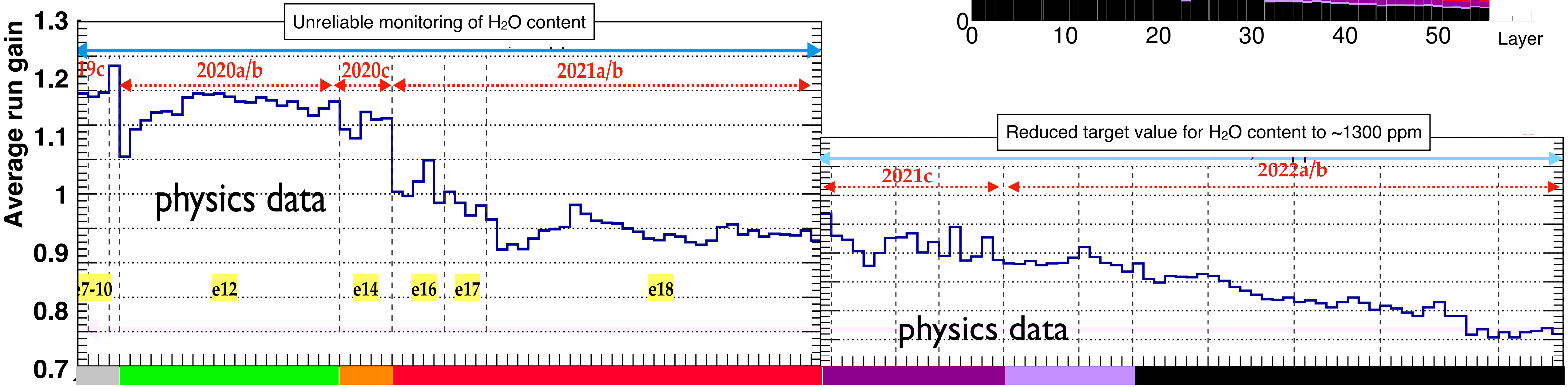
Status of Belle II Data-taking



Evolution of Integrated Charge and Average Run Gain before LS1

- Average run gain is determined online for each single run
- Observe decline of run gain by ~35% as a function of integrated charge, but
  - from pre-Belle ageing studies, we expect gain loss of only ~ 6% / (C/cm)
  - somewhat discrepant evolution of mean raw ADC values for cosmics w/o beam
- Have to consider interplay of other factors that affect the run gain
  - varying and not well-monitored H_2O, O_2 and H_2 levels in gas before 2021c
  - increasing CDC current as a result of increased beam background due to continuously increasing beam currents and luminosity (→space charge)
- Such conditions make it difficult to disentangle the actual ageing rate accurately
  - however, to reliably project CDC performance, a better assessment is needed





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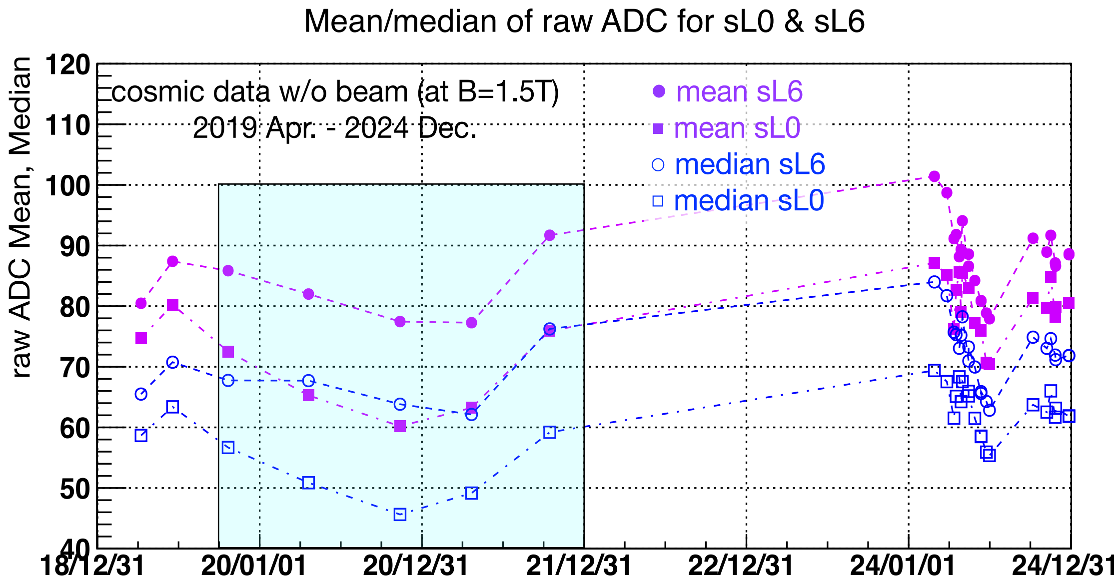
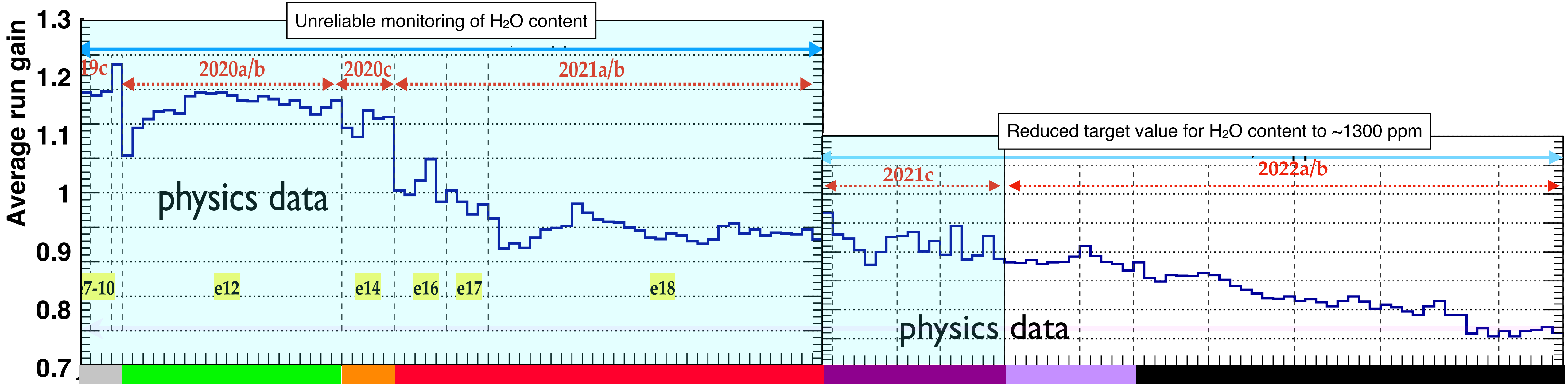
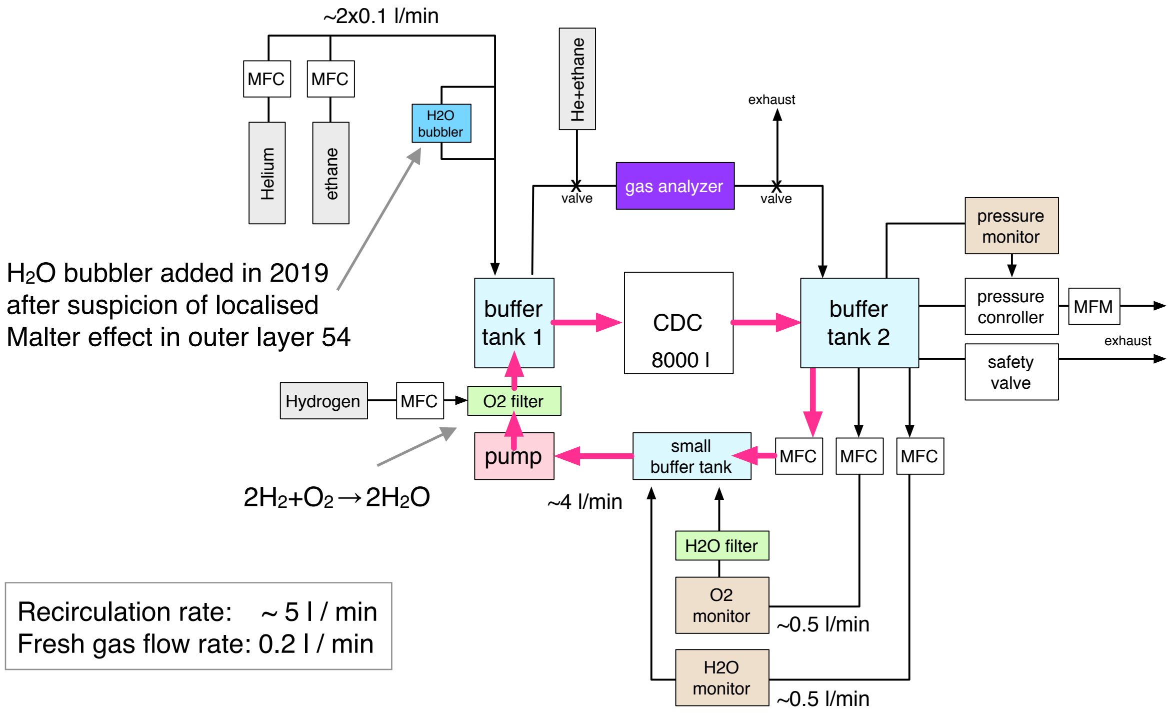
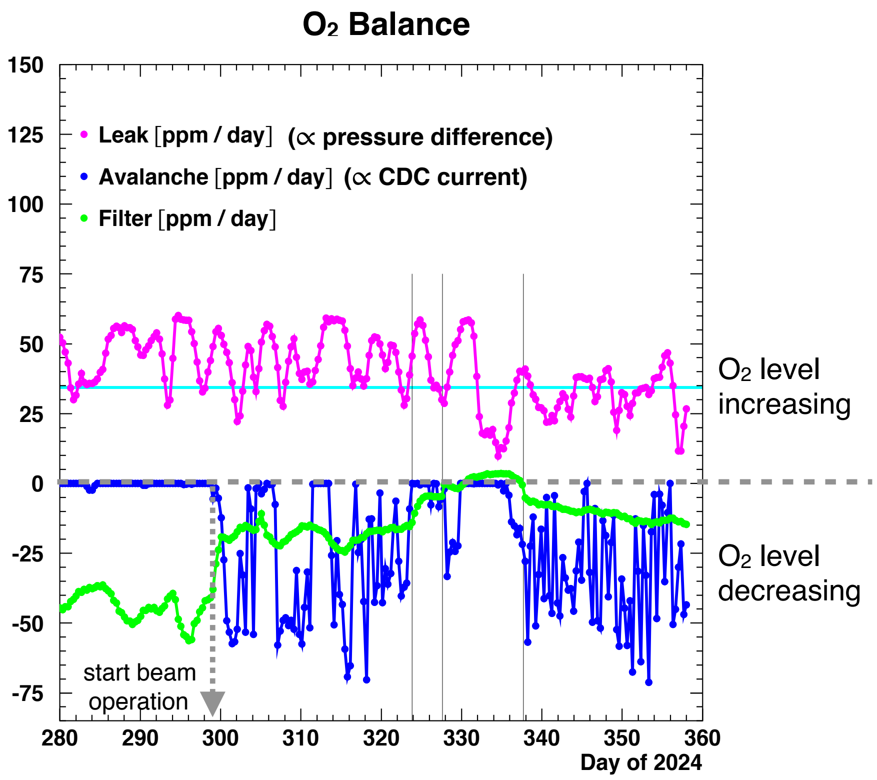




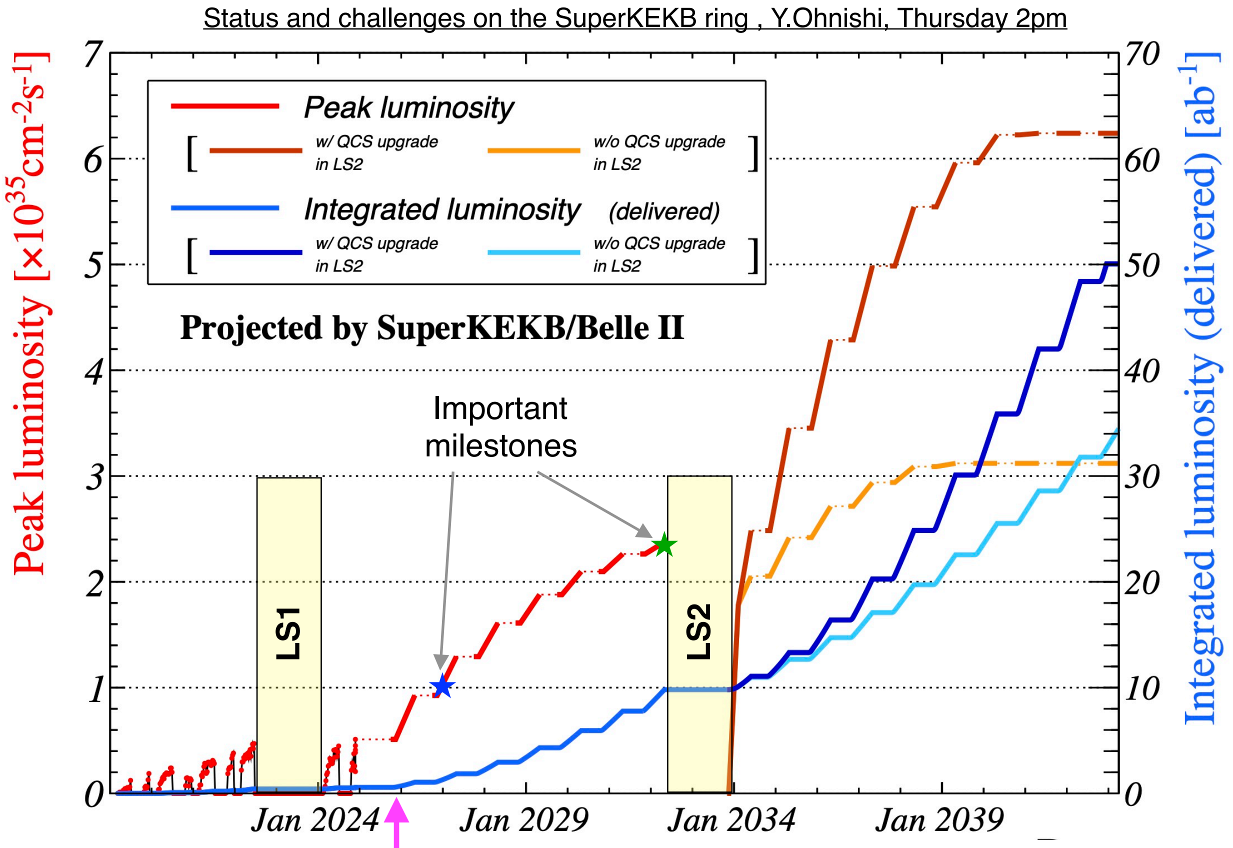
CDC Gas System



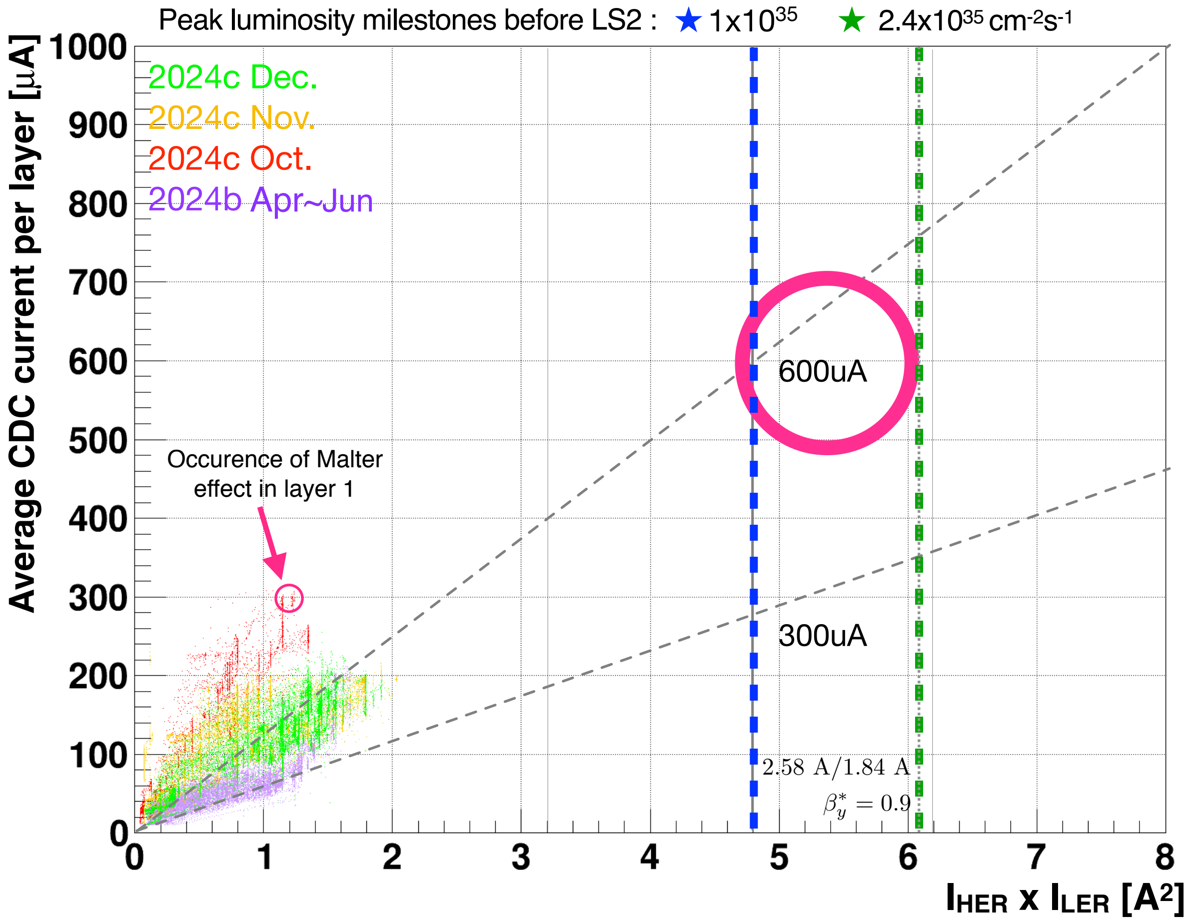


- Design and operation mode of CDC gas system based on Belle experience
  - to ensure stable performance, CDC is operated in constant pressure mode, i.e. with a slight overpressure of 5 - 30 mbar relative to ambient pressure
  - to reduce fresh gas consumption (and costs), CDC gas is recirculated
  - amount of O_2 permeating into the gas volume through ~30 k sense wire feedthroughs is proportional to pressure difference
  - during CDC construction, Si-based glue was used to seal the feedthroughs
  - O_2 level is kept to a minimum in order to prevent ageing (e.g. the formation of silicon dioxide) and to minimize signal loss (due to electronegative O_2)
    - inject H_2 and use platinum based catalyst as O_2 filter: $2H_2 + O_2 \rightarrow 2H_2O$
    - mitigate signal loss due to H_2O $\Rightarrow$ remove excess H_2O with silica gel filter
  - in 2019 added H_2O bubbler after observation of Malter effect in layer 54
- Improved monitoring after LS1 enabled a more quantitative understanding
  - observe significant O_2 consumption in avalanche (~ 3 O_2 molecules per ion)
  - clogging of O_2 filter once chamber draws current during beam operation

The Difficulty of Longer-Term Projections

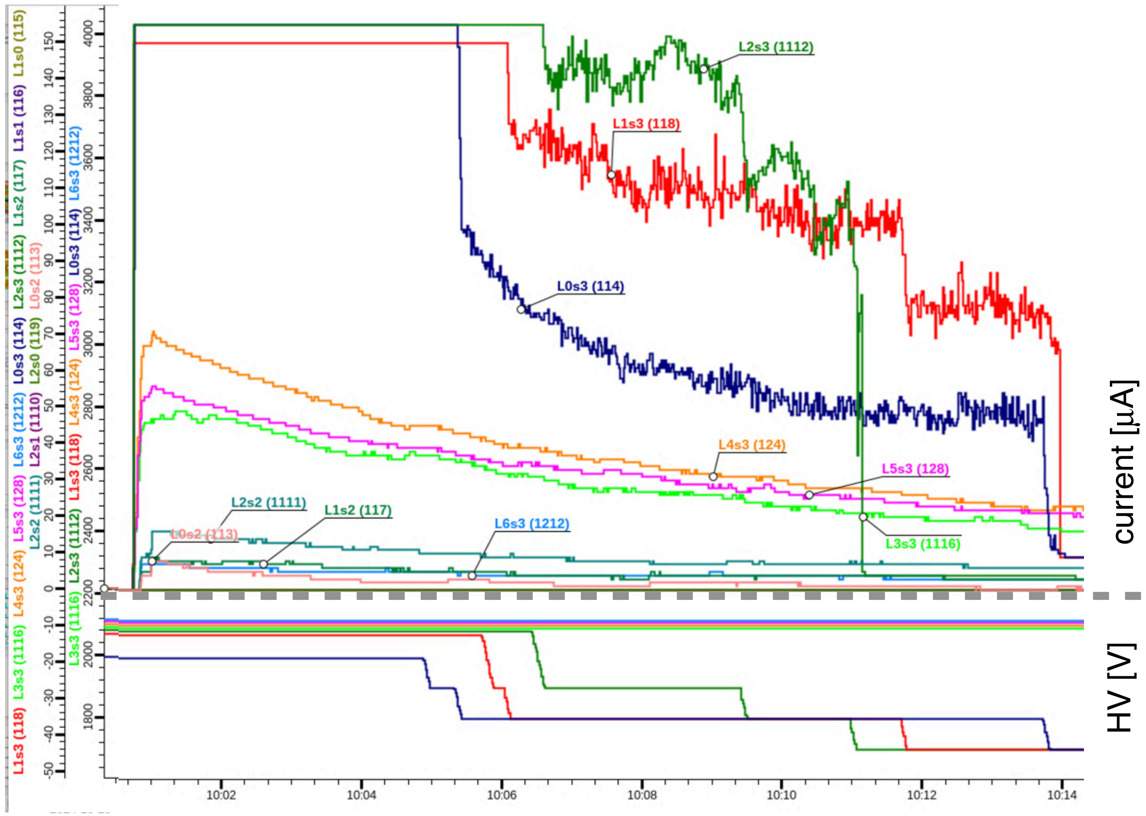


We are here: 10^{-1} in L_{peak} & 10^{-2} in L_{int} away from goal

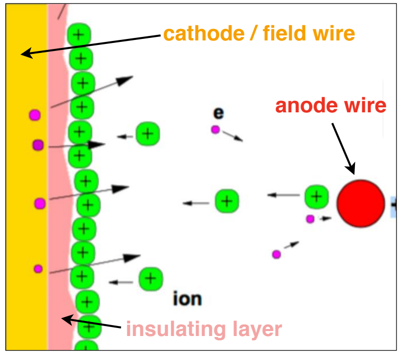


- Uncertainties in the projections are very large for both the SuperKEKB upgrade path and the CDC performance response
- With improved control of CDC operating conditions in the future (e.g. gas conditions), the expected performance degradation up to LS2 may perhaps remain acceptable **if pre-Belle ageing results are confirmed**

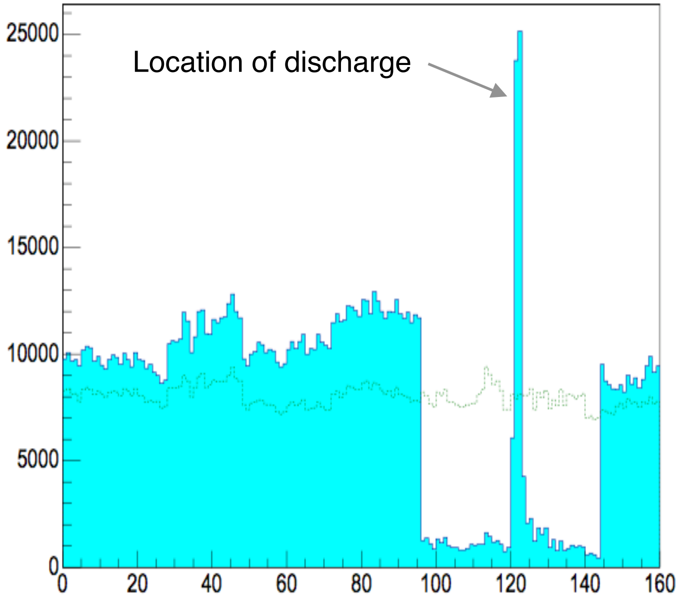
Malter Effect in Layer 1 on October 29



Malter effect principle

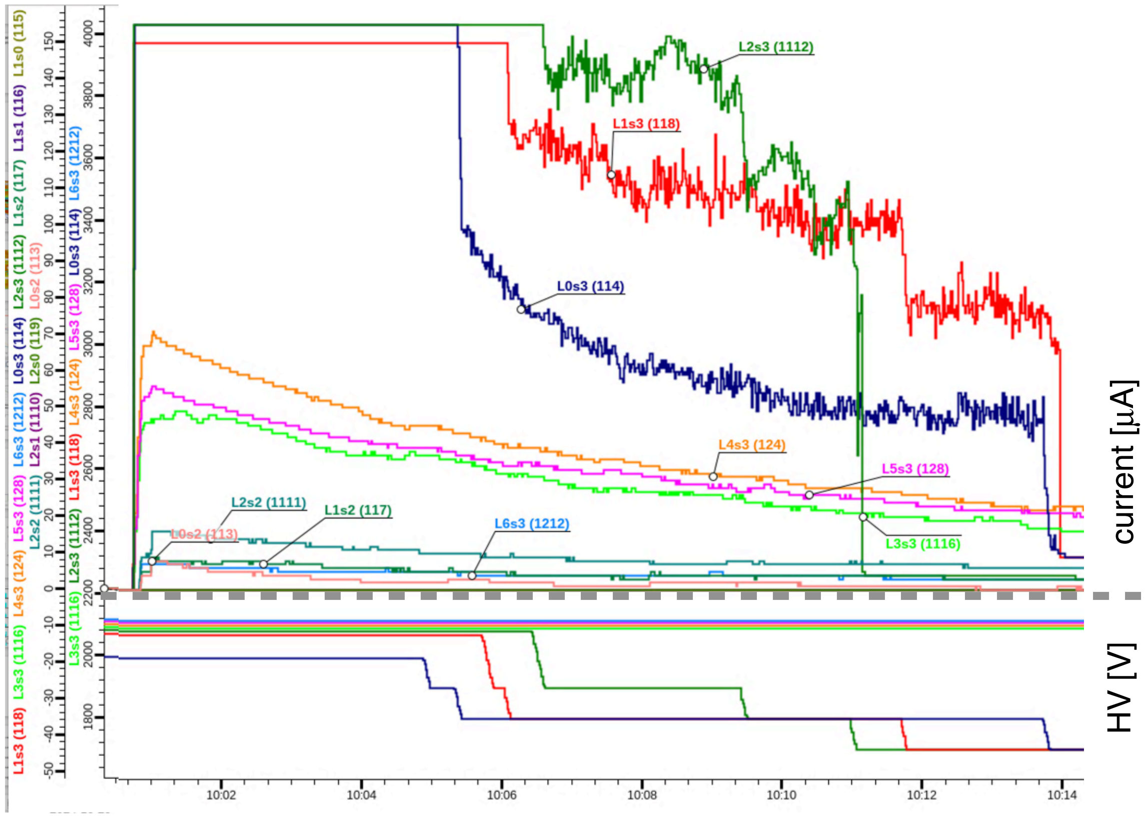


Online hit map of L1 when Malter effect occured

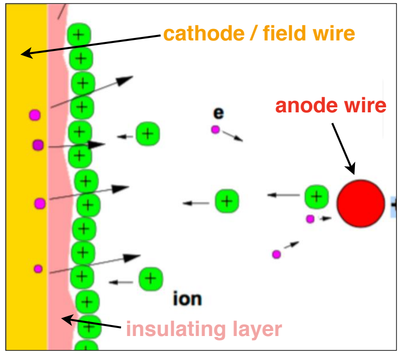


- A sudden current blow-up was observed in one HV sector of **layer 1**
  - operating conditions during blow-up
    - coincidence of low H_2O (1000 ppm) and O_2 (< 50 ppm) content and
    - high CDC current, reaching 300 μA / layer
- Also current increase in same HV sectors of adjacent **layers 0** and **2**
- Current persisted even when beam was gone; need to switch off HV

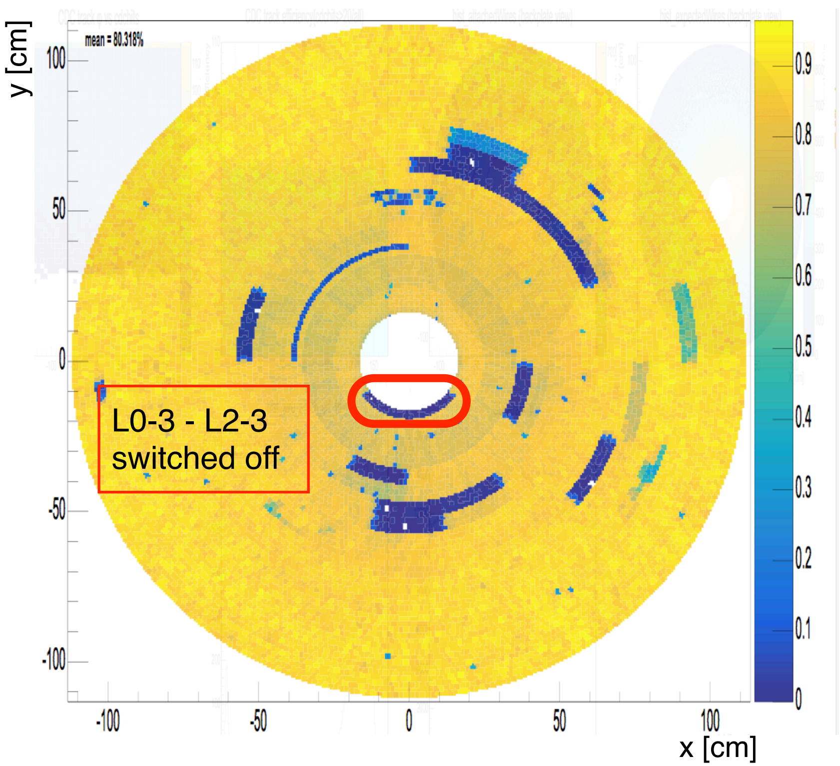
Malter Effect in Layer 1 on October 29



Malter effect principle



Online CDC hit efficiency map after Malter occurence

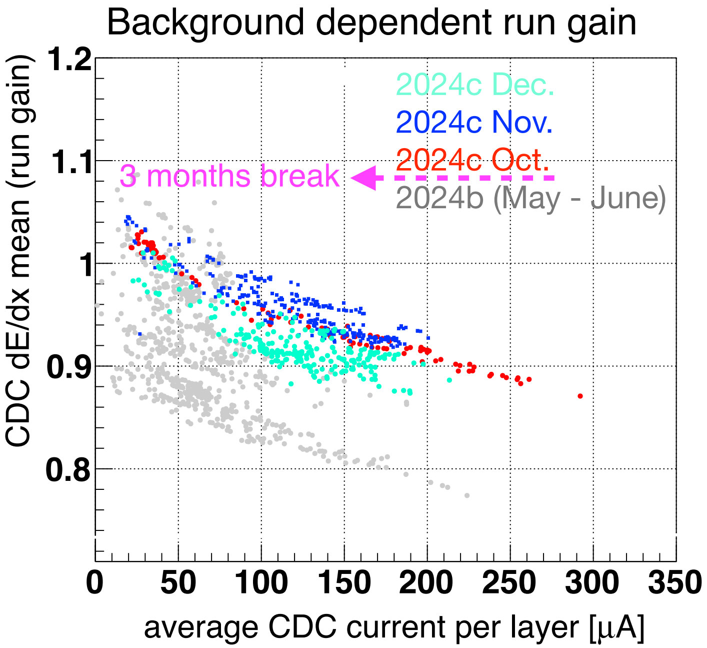


Most dead sectors due to problems with frontend electronics

- A sudden current blow-up was observed in one HV sector of **layer 1**
  - operating conditions during blow-up
    - coincidence of low H_2O (1000 ppm) and O_2 (< 50 ppm) content and
    - high CDC current, reaching 300 μA / layer
- Also current increase in same HV sectors of adjacent **layers 0** and **2**

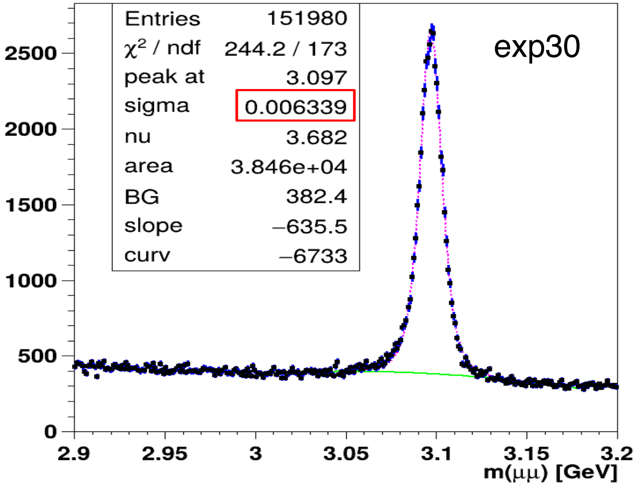
- Current persisted even when beam was gone; need to switch off HV
- Consequences
  - HV sectors in three innermost layers are currently operated at reduced HV (i.e. zero gas gain)
  - H_2O content increased to > 2500 ppm and O_2 content to > 100 ppm

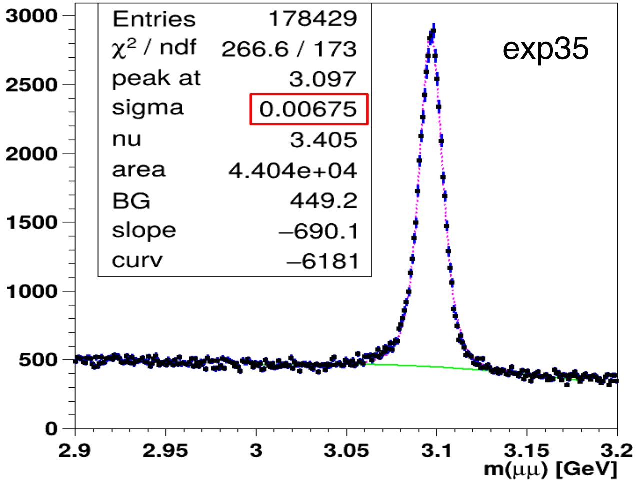
Examples of the Impact of an unstable CDC Run Gain in 2024

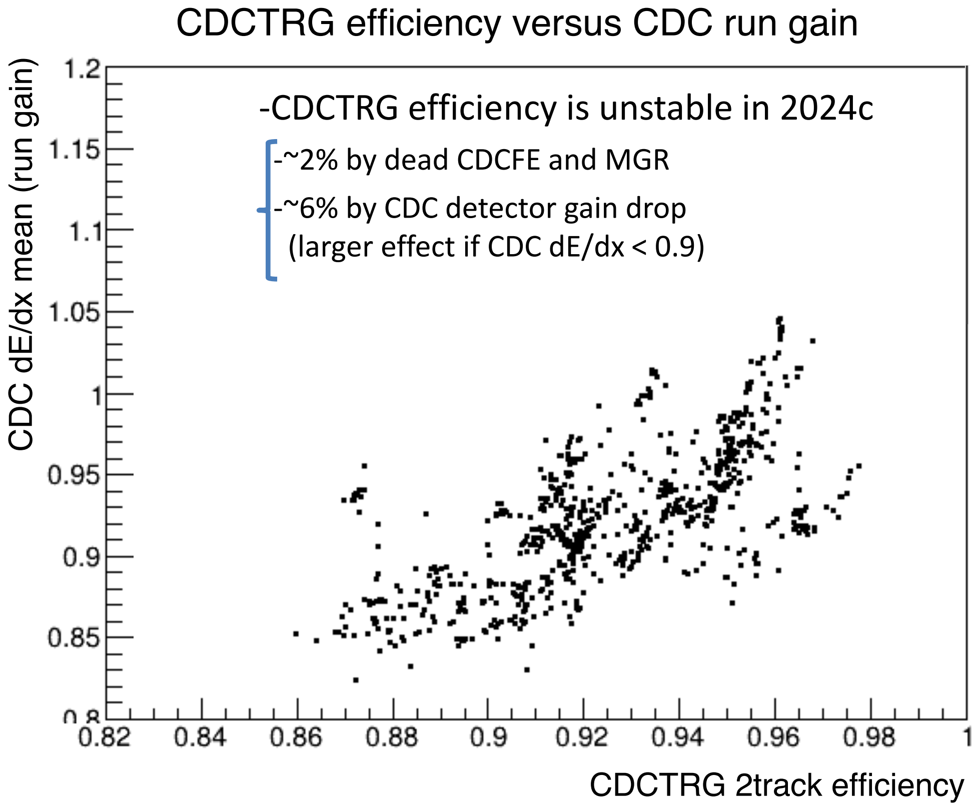


- Reduced gain leading to lower hit efficiency causes
  - worse p_t resolution for high momentum tracks
  - worse dE/dx resolution
  - compromised track trigger efficiency

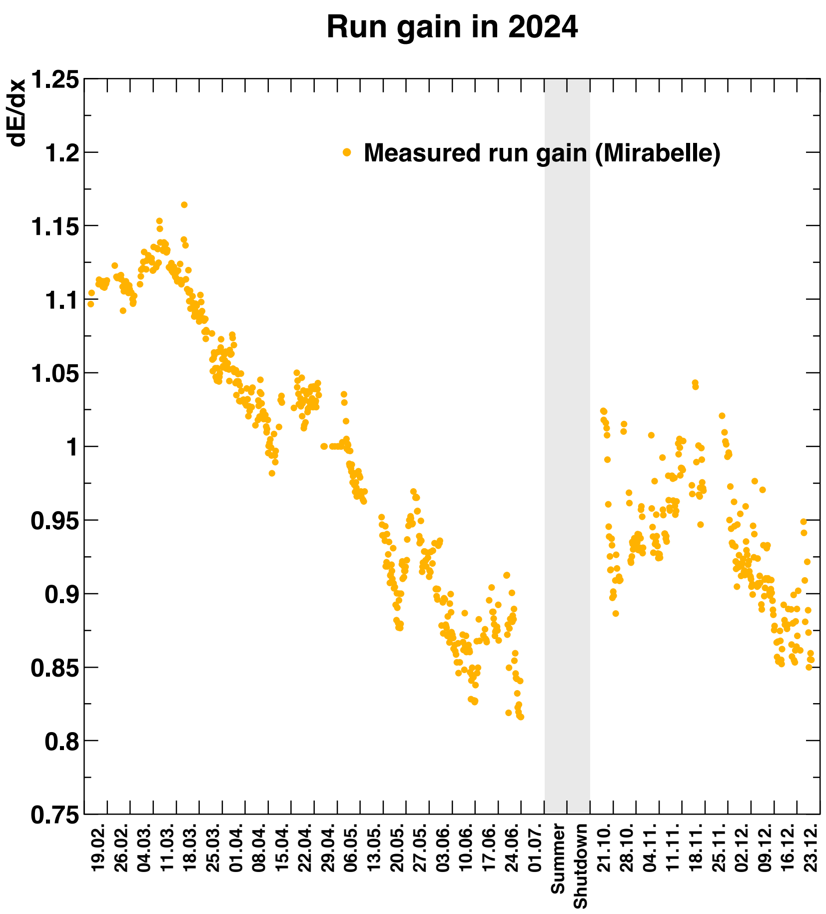
J/ψ mass resolution : $\sigma_{exp35}/\sigma_{exp30} = 1.065$ ⇔ $\sigma_{p_t}/p_t \propto p_t/\sqrt{N_{CDC\,hit} + 5}$

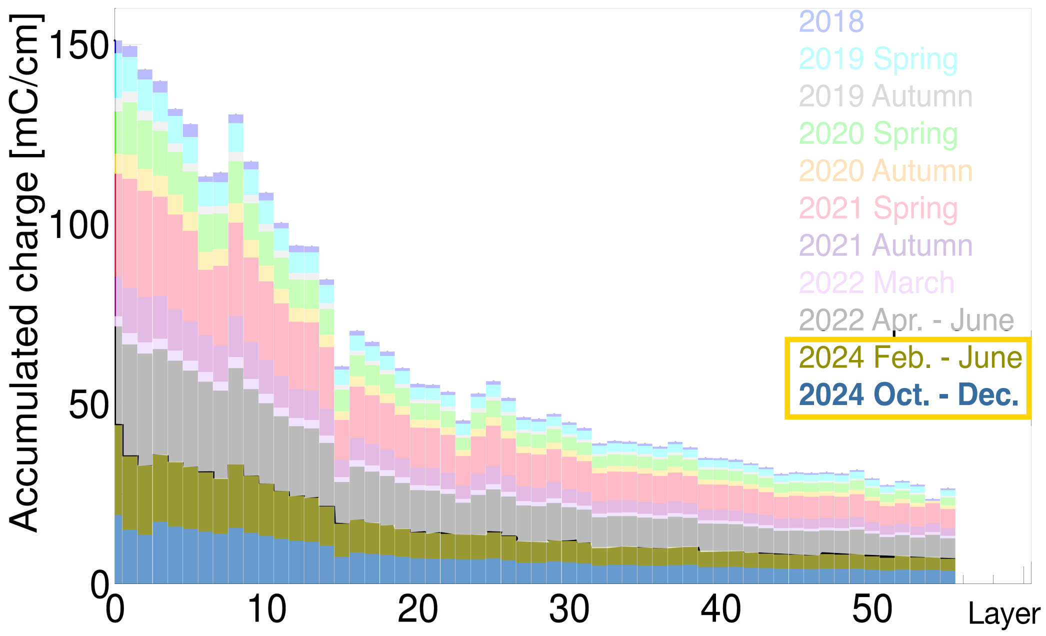






Run Gain Evolution in 2024





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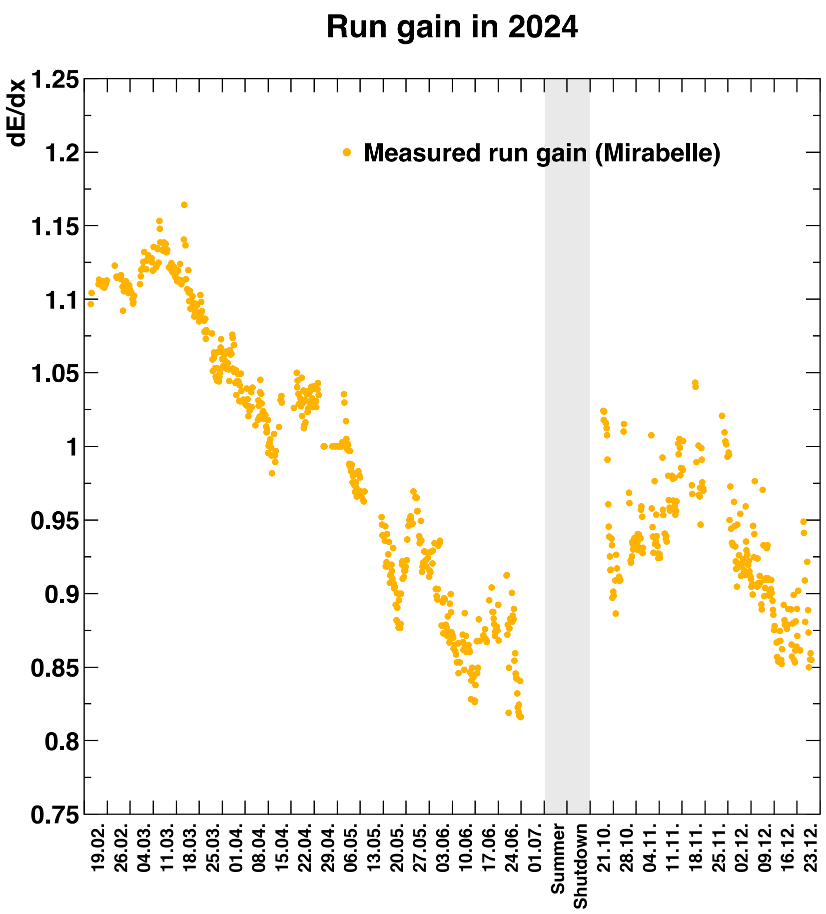
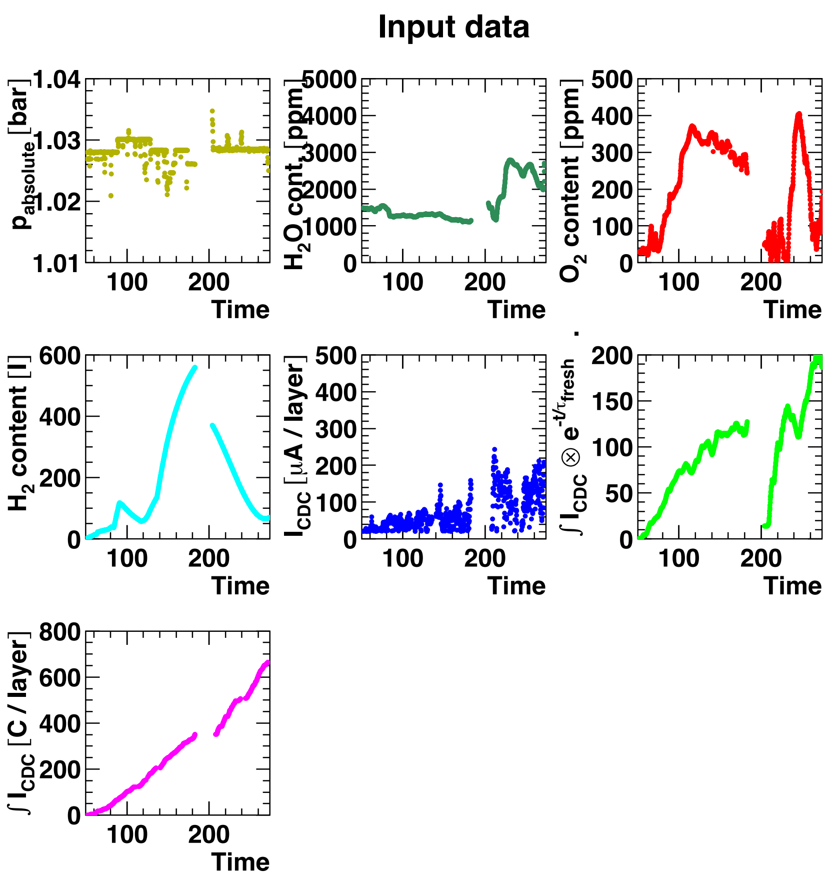
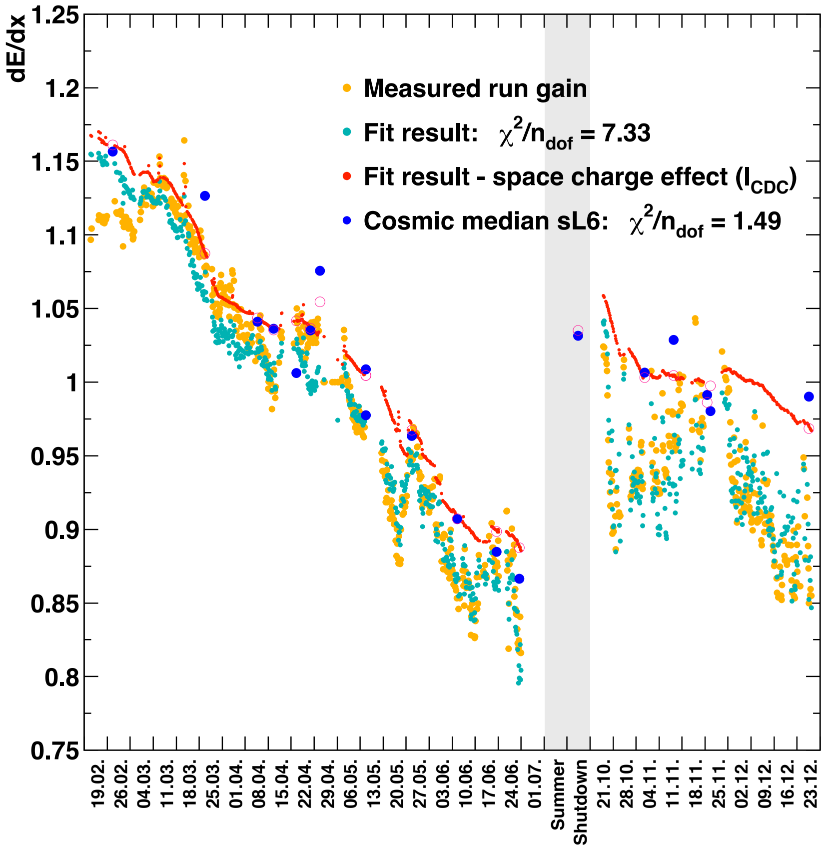


- Pre-LS1, limited control and poor monitoring quality of key parameters allowed only a **qualitative** description of the observed time dependence
- Much improved monitoring capabilities introduced during and after LS1 are used to attempt a more **quantitative** analysis
- Variables considered as input for parametrisation
  - Absolute pressure
  - H_2O content
  - O_2 content
  - H_2 content estimated using H_2 - and fresh gas flow rate
  - I_{CDC} to account for space charge effect
  - Accumulation/removal of hypothetical trace contaminant in the gas produced in the avalanche (derived from I_{CDC} and fresh gas flow rate)
  - Integrated charge (irreversible)
- Exploit the characteristic time dependence of input variables x_i to determine individual contributions by a fit to the run gain data
  - $dE/dx_{Fit} = 1 + \Sigma f_i x_i$

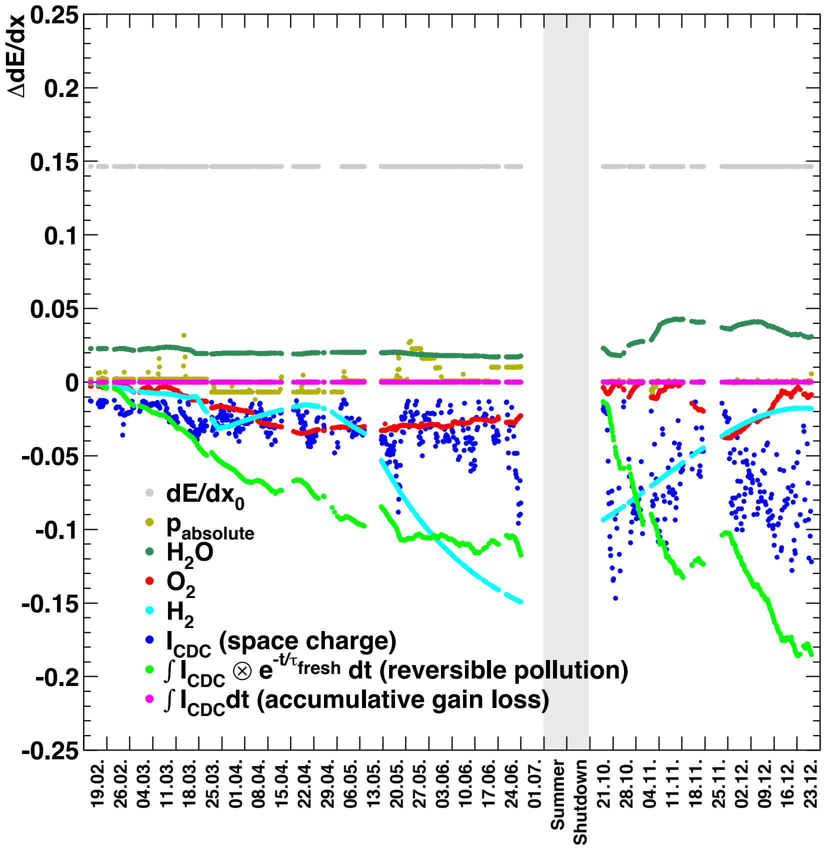


Main Contributors to Change in Run Gain after LS2 (2024)

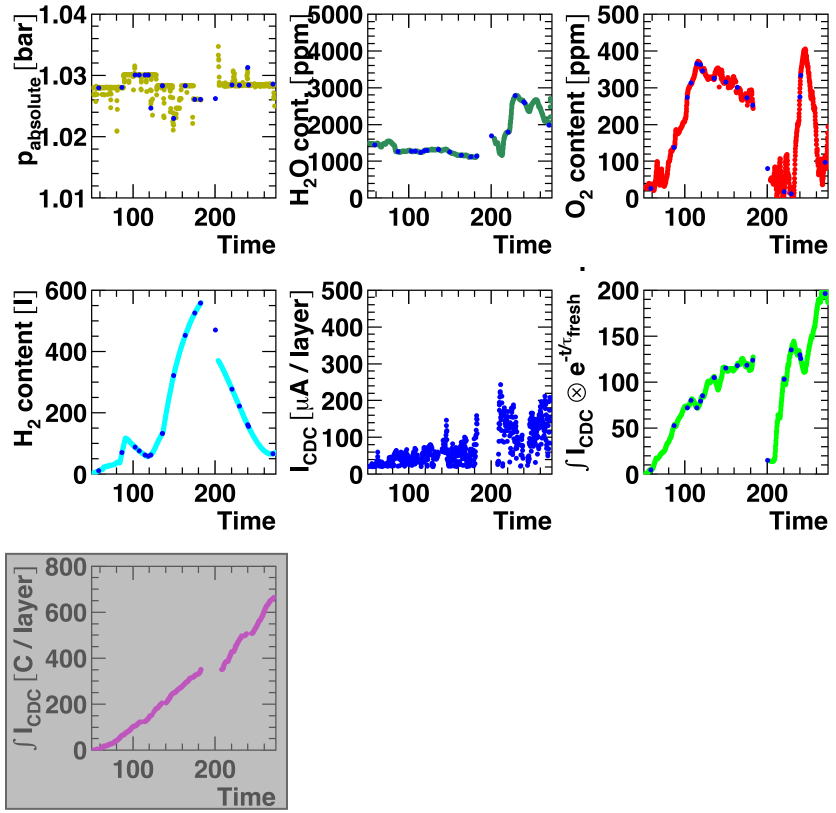
Run gain in 2024



Fit decomposition



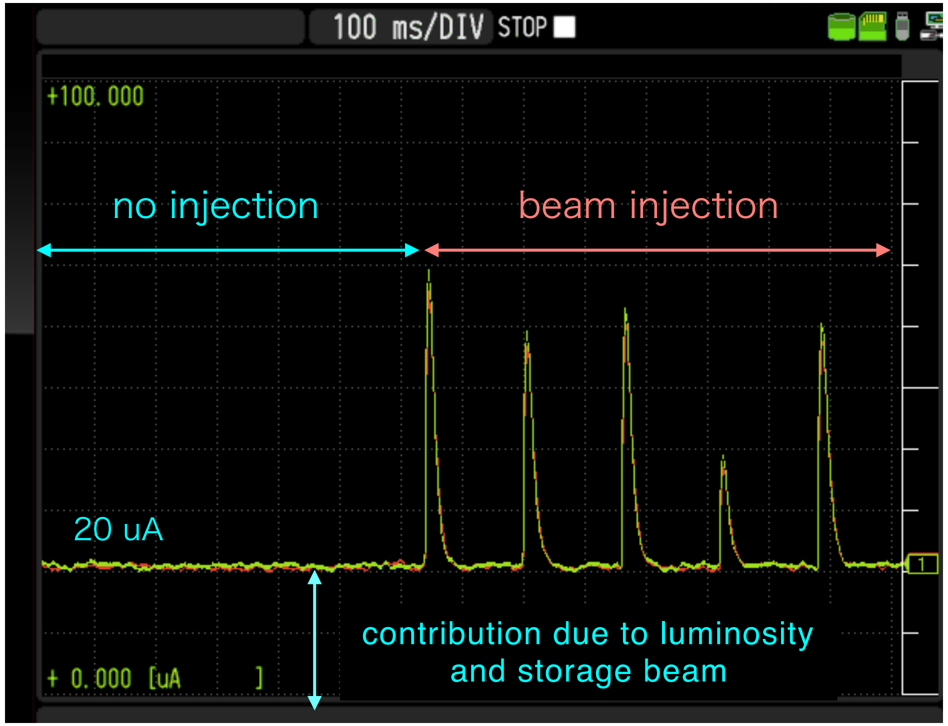
Input data



- Dominant contributions to gain loss
  - impurity build-up (20%)
  - space charge / voltage drop (15%)
  - H_2 content (15%, avoidable)
- Subdominant contributions from
  - O_2 content (5%)
  - H_2O content (5%)

    [**negative** sign confirmed in 2025 cosmic run]

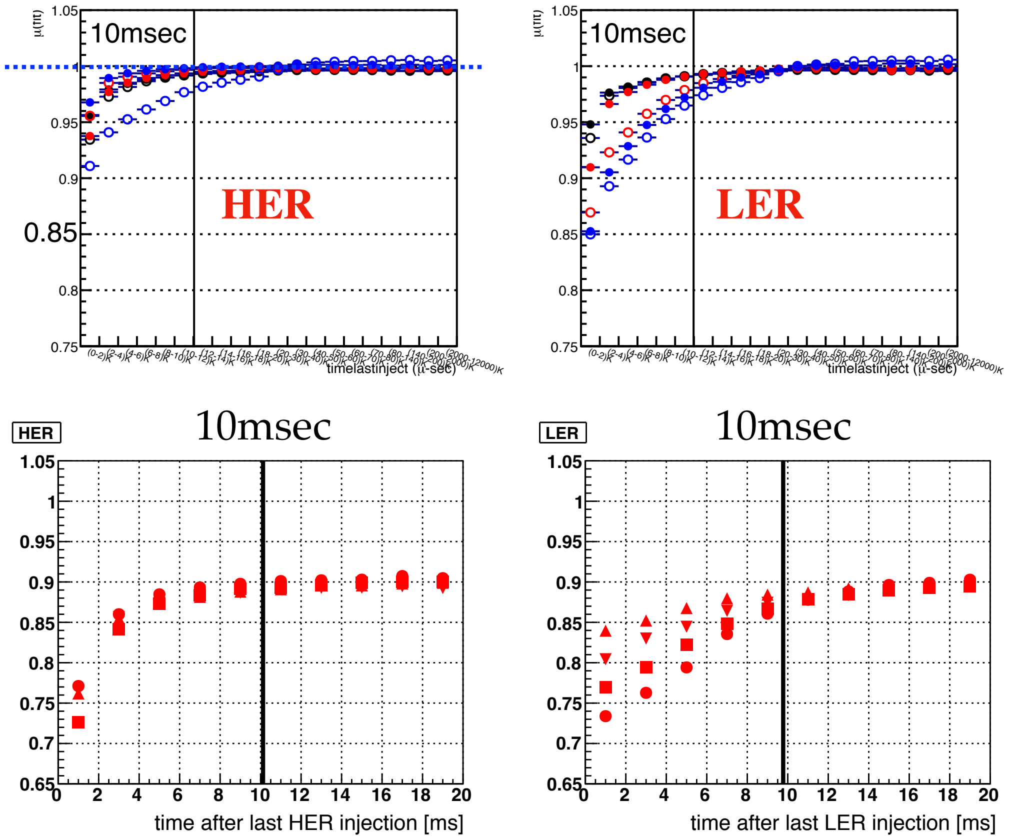
Short-term Effect of Injection on CDC Gain



dE/dx vs time after last injection

2022

2024

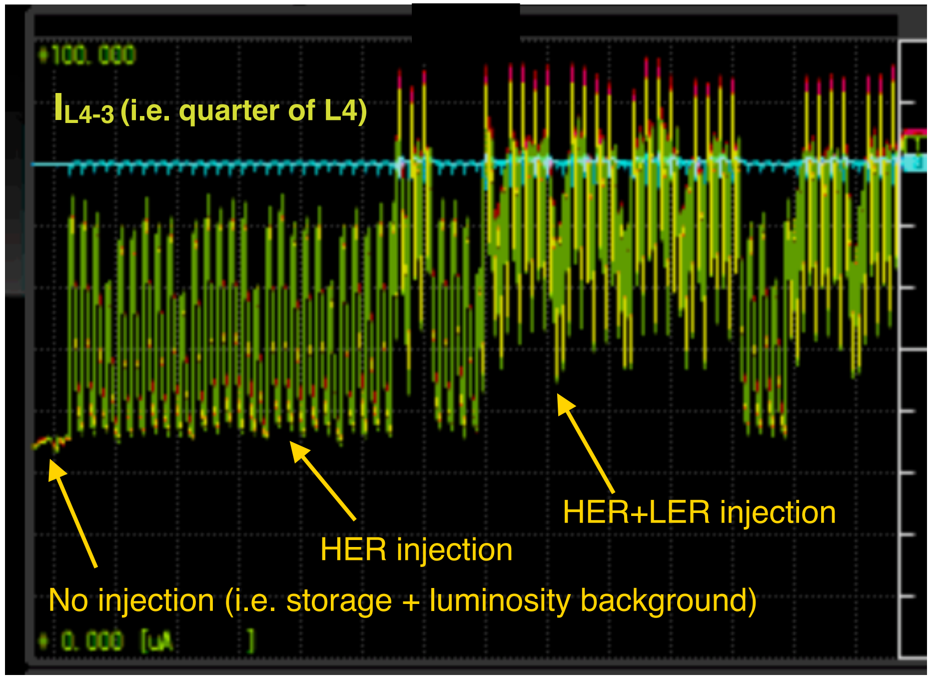


- Level of injection background varies greatly with time and with injection conditions, e.g.
  - injection efficiency & duty cycle; bunch charge; 1- or 2-bunch injection; repetition rate (so far up to 25 Hz per beam)
- Very similar dependence of signal degradation as a function of time after injection before and after LS1
  - it takes 10-15 ms for the signal size to return to base level (typical damping time of background from injected bunch)

Short-term Effect of Injection on CDC Gain

Conditions reached at the end of 2022b

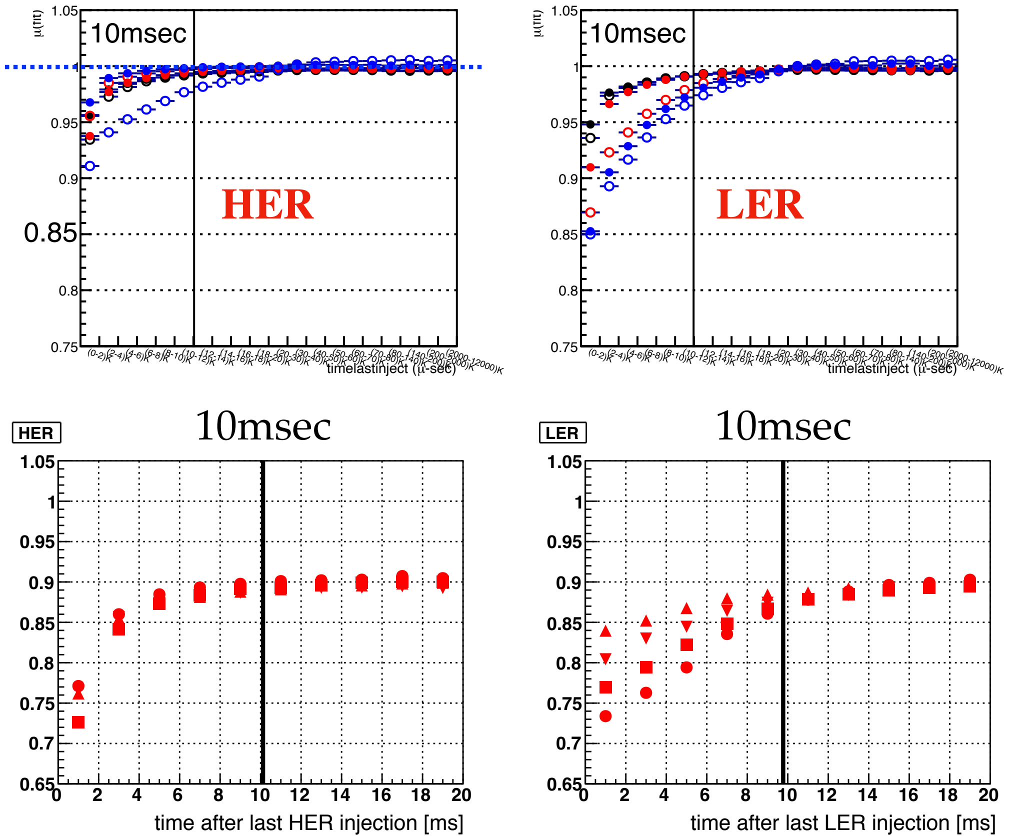
I_{HER} = 1035 mA, Q = 1.7 nC, rep rate = 25 Hz
I_{LER} = 1293 mA, Q = 2.0 nC, rep rate = 21 Hz
n_{bunch} = 2346, 2-bunch injection for both beams



dE/dx vs time after last injection

2022

2024



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Summary and Conclusions

- With the expected future increase in beam background, it is very important to anticipate how CDC performance will evolve in the coming years

- The 2024 run has provided valuable insights into how the CDC operates under higher beam backgrounds
  - however, a number of open questions remains
  - from January to October, beam-off time was used for dedicated cosmic ray runs to quantify the impact of gas decomposition and to study CDC performance at reduced HV

- The Belle II collaboration is currently developing strategies
  - on how to maintain an acceptable level of CDC performance up to LS2
    - e.g. better control of O_2 and H_2O content; increased fresh gas flow rate
    - to partly mitigate ageing effects by exploring options to operate chamber at reduced gas gain
  - which detector modifications will be required to fully exploit the bulk of the Belle II data to be collected after LS2
    - dedicated ageing studies are under preparation
    - for possible detector modification, see talk by Yubo Han on *Overview of Belle II upgrade* , Thursday 3pm

- In parallel, efforts to understand and mitigate beam backgrounds continue as a high priority
  - this needs constant and close collaboration between Belle II and SuperKEKB

Backup

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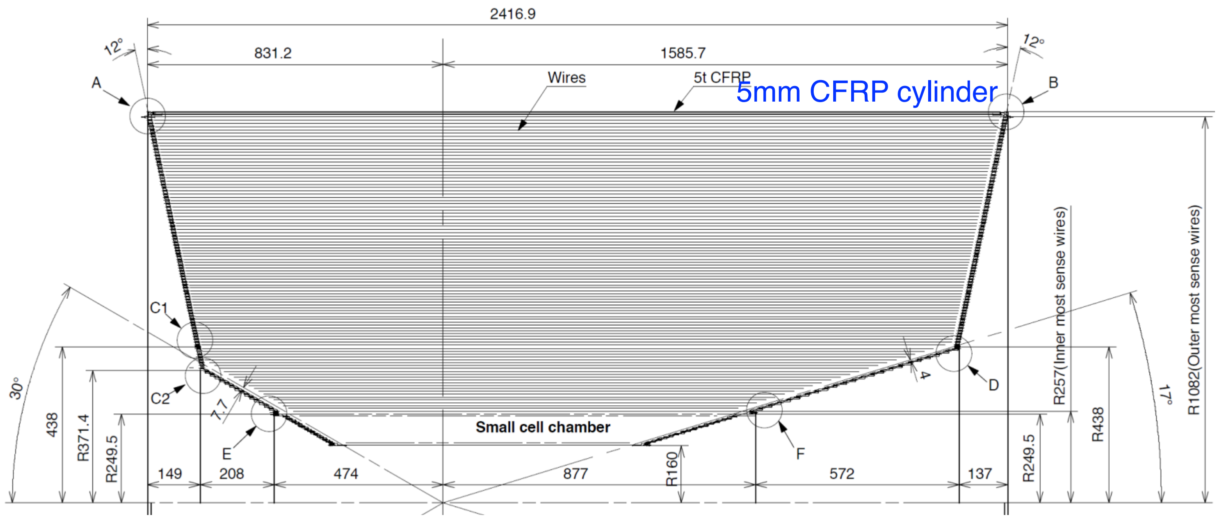
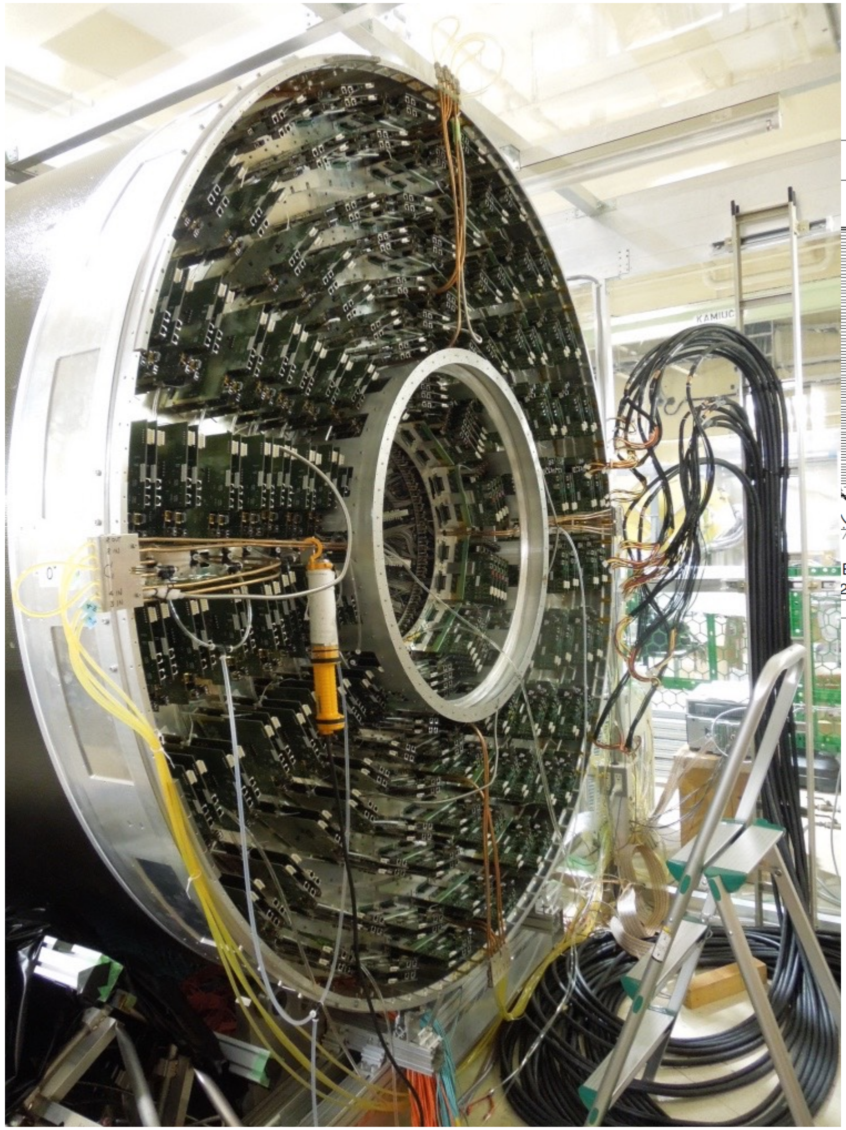
CDC Mechanics



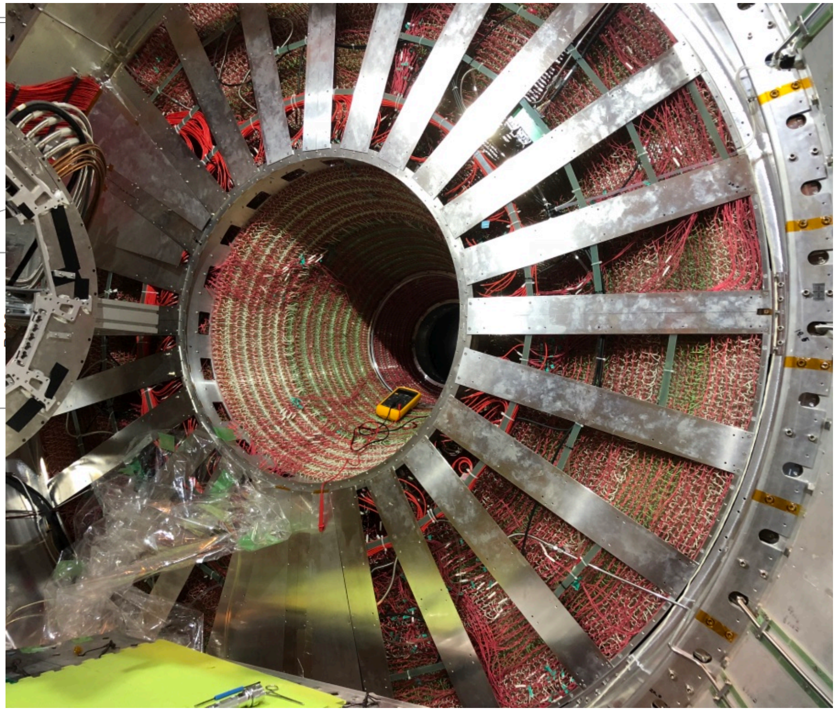
CDC Mechanics

Backward: readout electronics



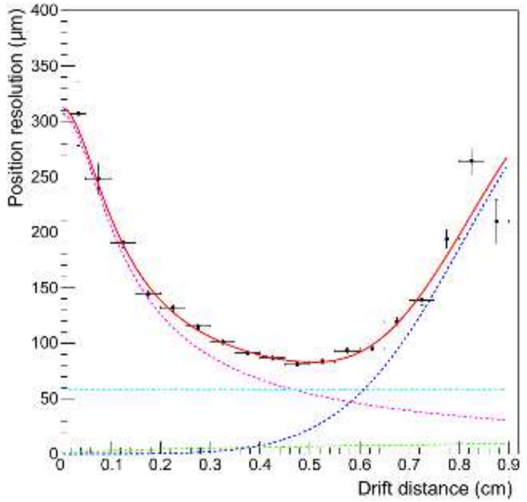
Insertion of small cell chamber

Forward: HV

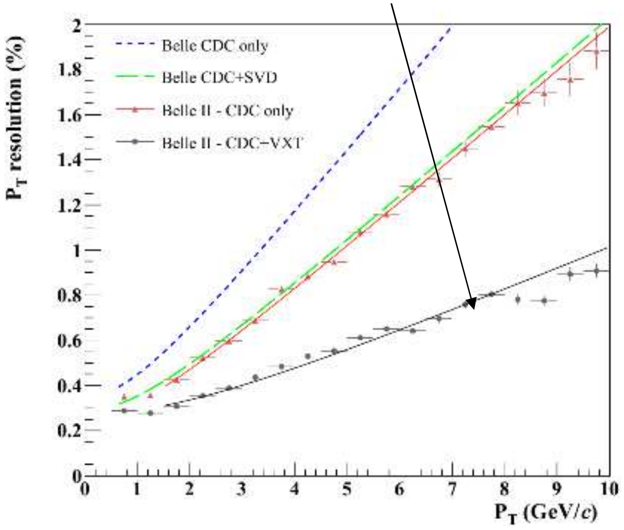


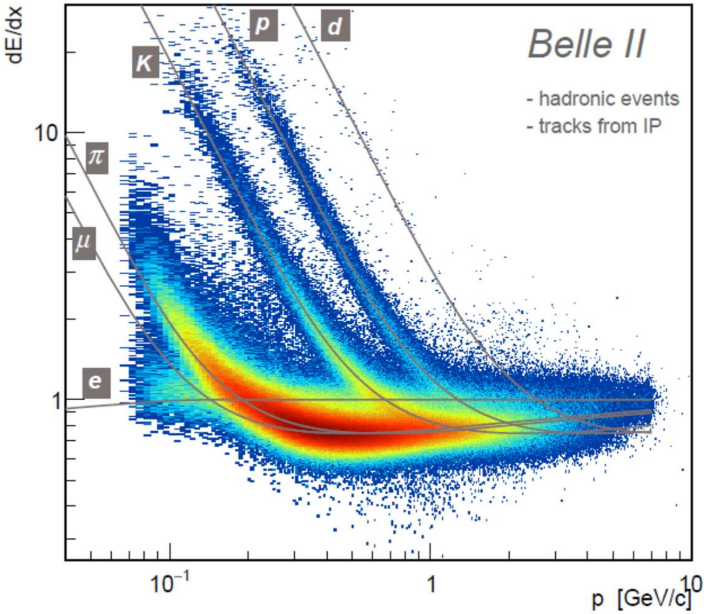
CDC Performance

Position resolution

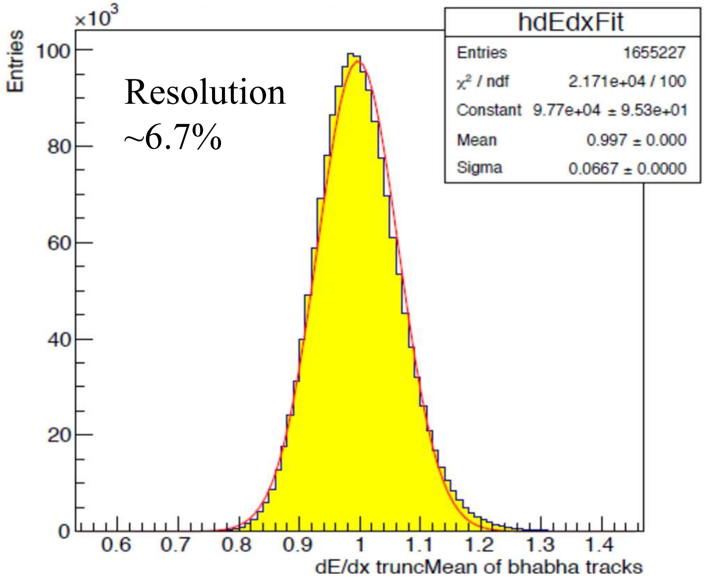


Pt resolution:
$((0.098pt)^2 + (0.27)^2)^{1/2}$ (%)

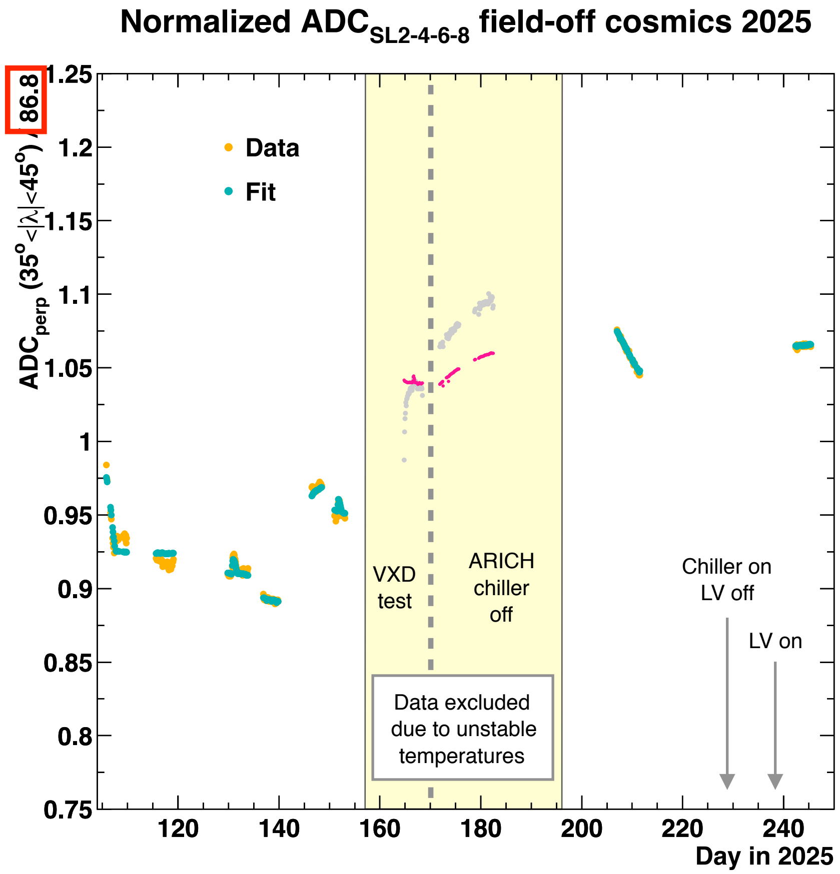


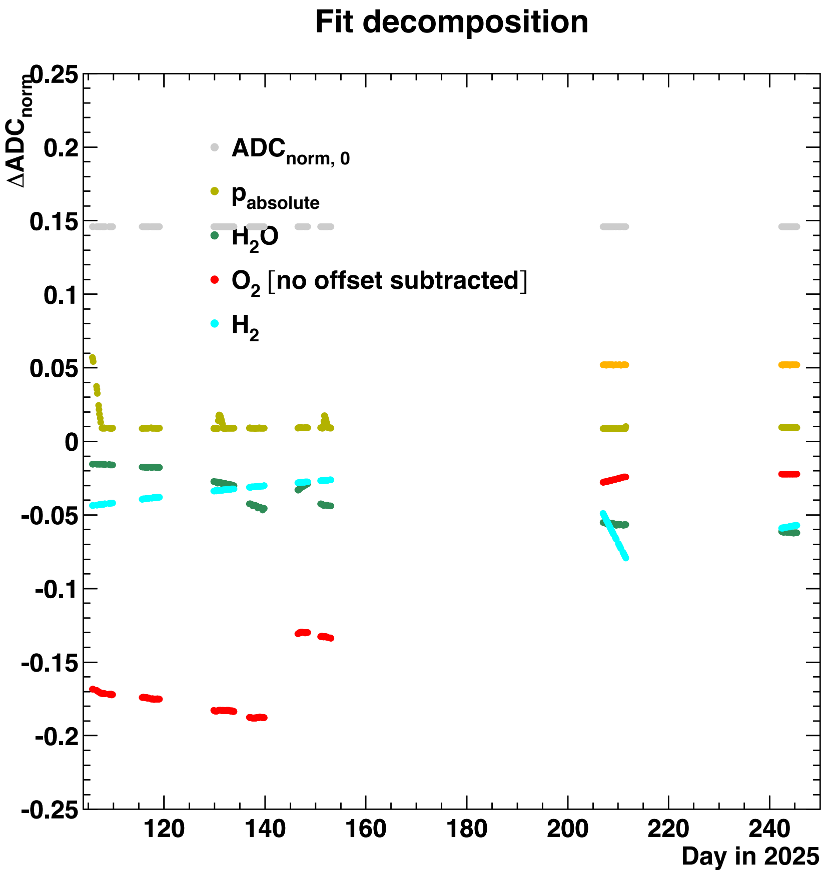


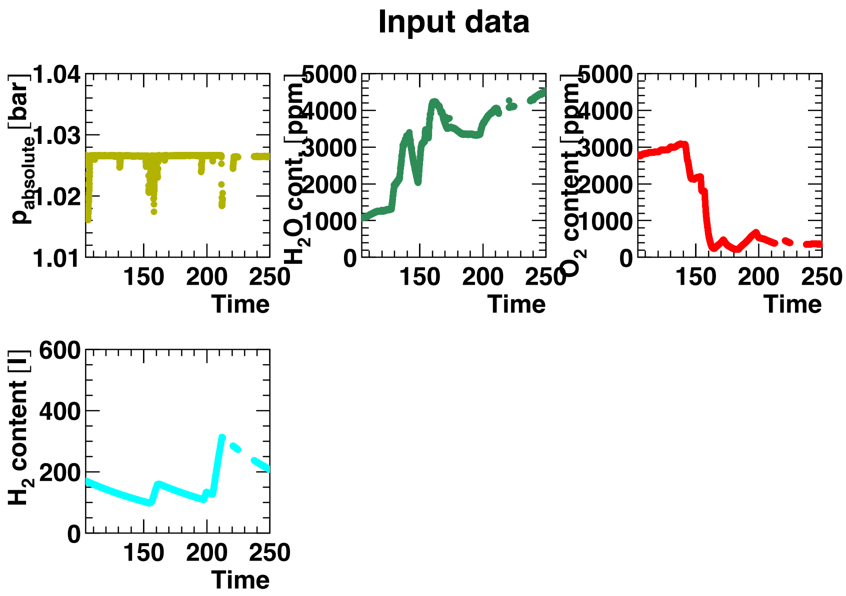
Bhabha events



Verification of Sensitivities using Field-off Cosmics in 2025



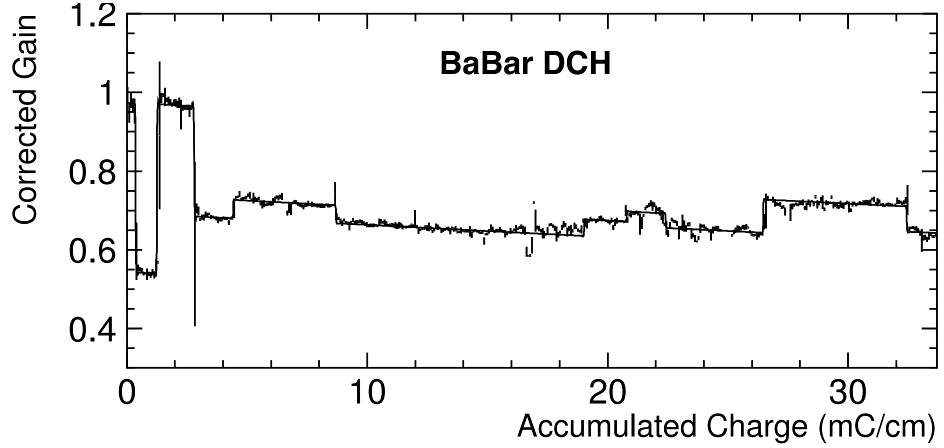




- Use field-off cosmics to measure sensitivity of dE/dx to individual components of the gas under controlled conditions
  - expected (negative) sign of H_2O contribution has been confirmed
  - sensitivities of the O_2 and H_2 contributions derived from collision data have been verified
- This provides indirect support for the assumption that reversible gas pollution has a significant impact on the observed decrease in gain in 2024
  - test of up to 10x higher fresh gas flow rate in preparation for ongoing run period

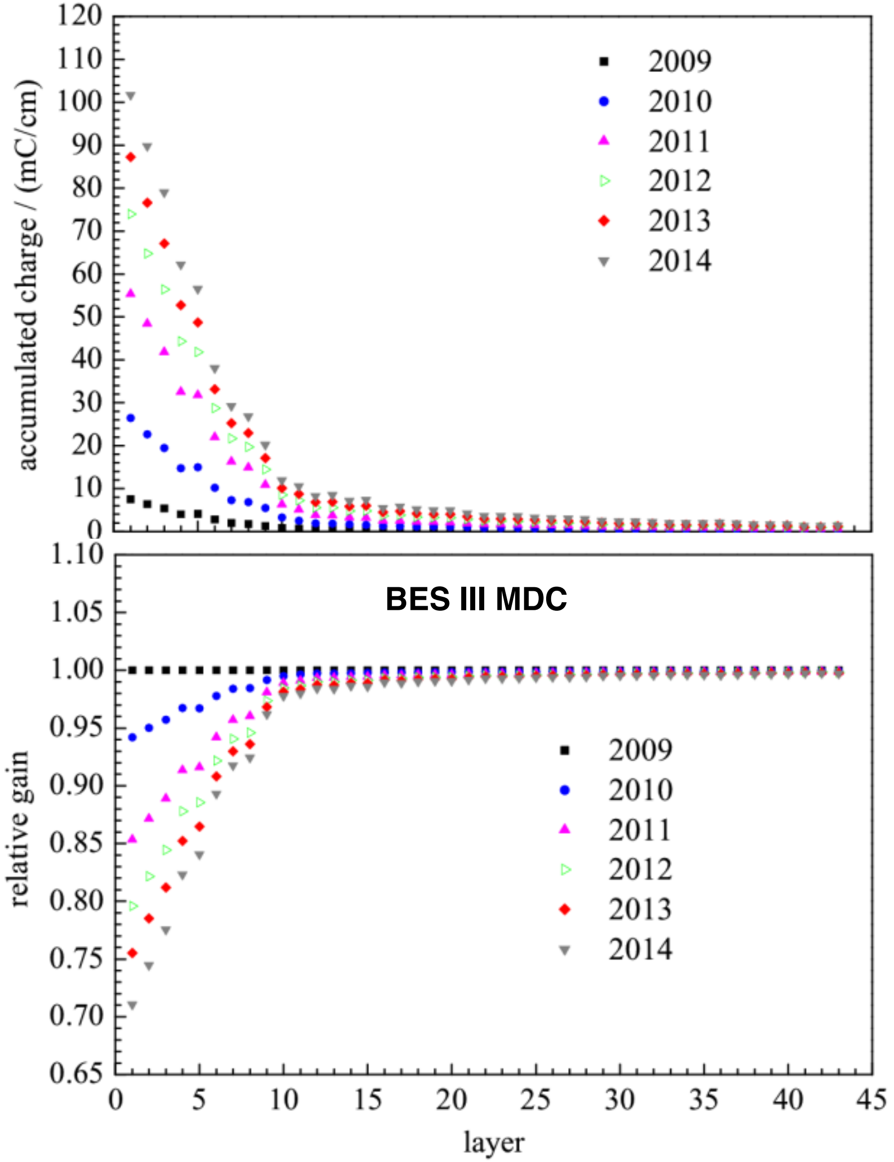
Comparison with BaBar DCH and BES III MDC

	BaBar DCH	Belle II CDC
Integrated charge	30 mC/cm in **9 years**	30 mC/cm for innermost layers in 2022a/b alone i.e. **3.5 months**
Gas mixture	$He:C_4H_{10}$ 80:20 with 3500 ppm H_2O	$He:C_2H_6$ 50:50 with 1300 ppm H_2O
Volume	5.3 m^3	8 m^3
Recirculation rate	15 l/min, i.e. one full volume every **6 hours**	4+2x0.5 l/min, i.e. one full volume every **26 hours**
Fresh gas rate	2.5 l/min, i.e. one full volume every **36 hours**	0.2 l/min, i.e. one full volume every **28 days**



https://arxiv.org/abs/1305.3560

Figure 51: Relative DCH gain (corrected for temperature and pressure variations) as a function of accumulated charge on the wires. The steps correspond to changes in operating voltage; the curve is a fit to the reduction in gain, giving $\delta G/G = (0.337 \pm 0.006)\%$ per mC/cm.



https://arxiv.org/abs/1504.04681

He / C_3H_8 = 60 : 40 with 0.2% H_2O (from 2012): $\frac{1}{Q/L}\frac{\Delta G}{G} = \frac{0.3\,\%}{\mathrm{mC/cm}}$