Diamond Based Fast Luminosity Monitoring for SuperKEKB

LumiBelle2 Project

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LAL-Orsay

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Collaborators
- Belle II: Sadaharu Uehara + Belle II / BEAST team
- SuperKEKB: Yoshihiro Funakoshi, Kenichi Kanazawa, Mika Masuzawa, Yukiyoshi Ohnishi, Yusuke Suetsugu, Makoto Tobiyama, Alan Fisher (SLAC), Uli Wienands (ANL)

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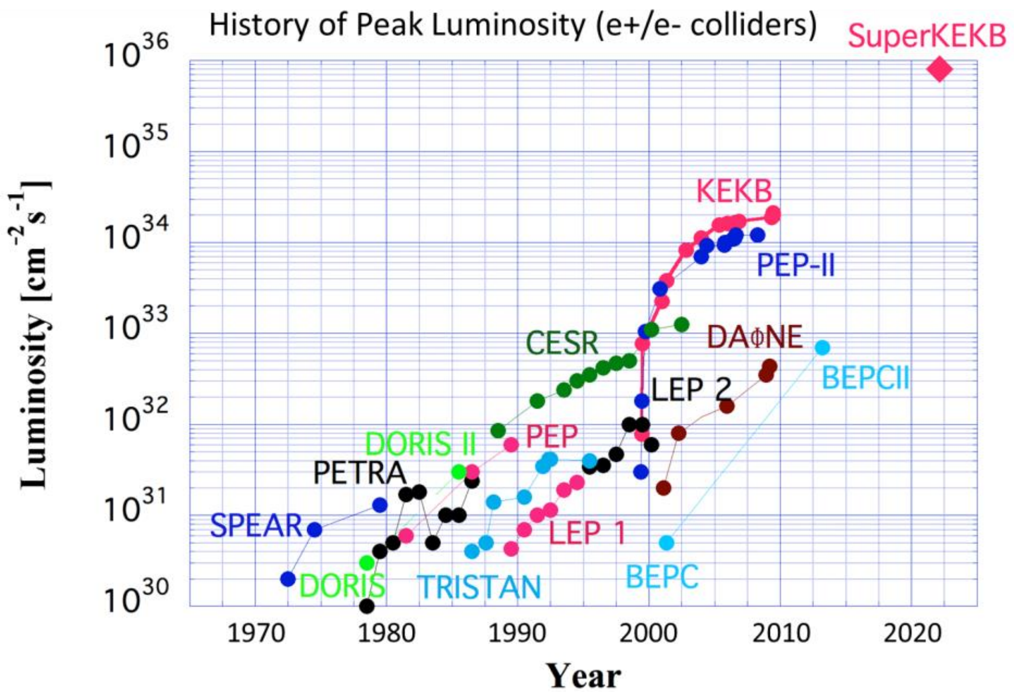
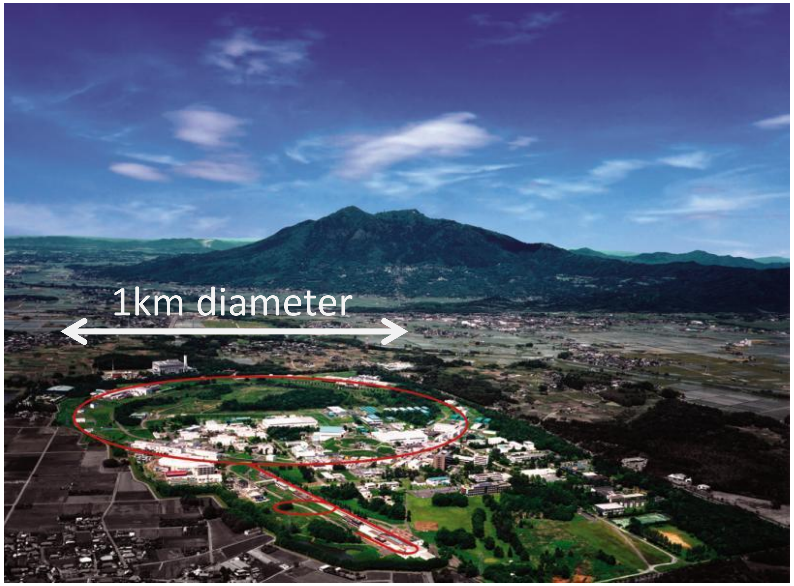
Exploring the luminosity frontier with SuperKEKB





KEKB

$2 \times 10^{34}/cm^2/s$

SuperKEKB

$8 \times 10^{35}/cm^2/s$

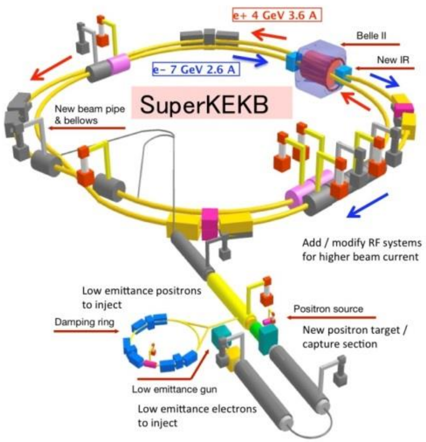
Future e+e– circular colliders use "nanobeam" collision scheme

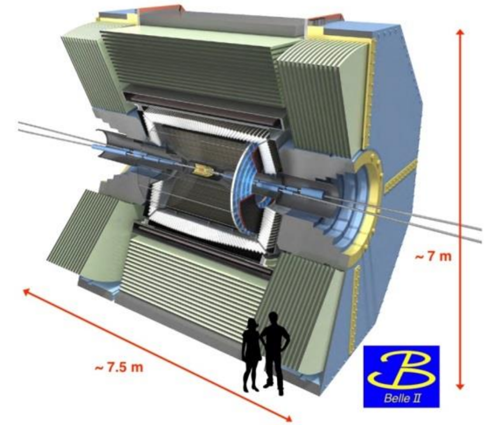
→ was tried for 1st time at SuperKEKB in 2018

SuperKEKB / Belle-II & "Machine-Detector Interface"

- Control beam induced backgrounds
- Luminosity monitoring & tuning

1) Phase 1 : 2016/Feb. → Jun.
   - single beam commissioning, vacuum scrubbing
   - no luminosity (no final focus), no detector
2) Phase 2 : 2018/Feb. → 2018/Jul.
   - colliding beam commissioning, no vertex detector
3) Phase 3 : ~ February 2019…
   - towards full luminosity for physics running

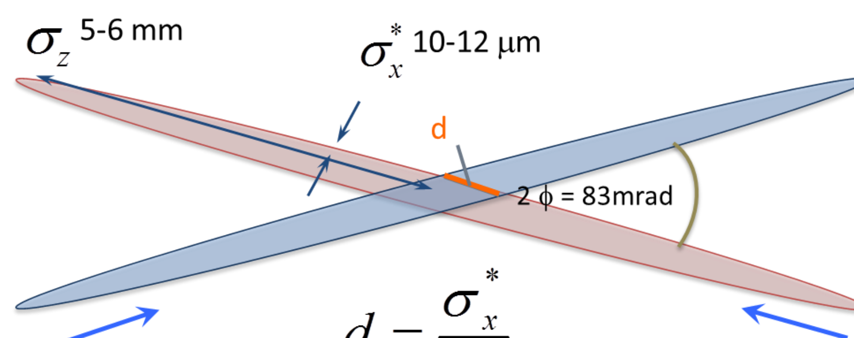




parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Half crossing angle	φ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
→ Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.088	0.081	
Bunch Length	σ_z	6.0	6.0	6.0	5.0	mm
→ Horizontal Beam Size	σ_x^*	150	150	10	11	um
→ Vertical Beam Size	σ_y^*	0.94		0.048	0.062	um
Luminosity	**L**	**2.1 x 10^{34}**		**8 x 10^{35}**		$cm^{-2}s^{-1}$

→ **Luminosity × 40**

Nano-Beam Scheme SuperKEKB (design)



$$d = \frac{\sigma_x^*}{\phi}$$

Half crossing angle: ϕ

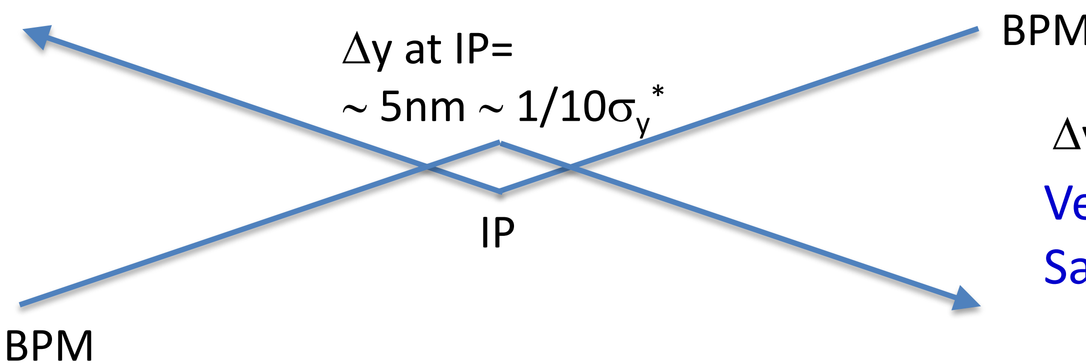
β_y = 300 μm　　d ~ 300 μm

→ **mitigates hour-glass (and beam-beam) effects**

Luminosity

Fast & slow variations at IP require feedback corrections

- Beam-beam deflection for fast vertical motion



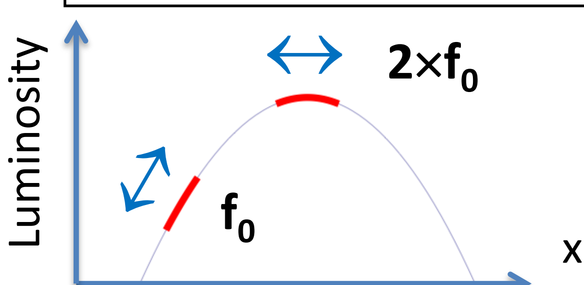
Δy at BPM= ~ 1.3μm

Vertical vibration ~ 25-100 Hz

Sampling (BPMs) ~ 32 kHz

- Luminosity feedback by "dithering" for slower horizontal motion

Cf. WEXBA04 by Yoshihiro Funakoshi, Wednesday, 11:20 am



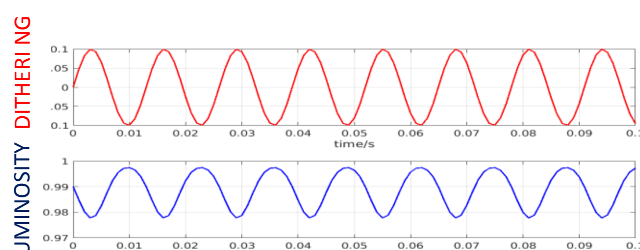
Horizontal motion ~ few Hz

Modulation freq. f_0 ~ 79 Hz

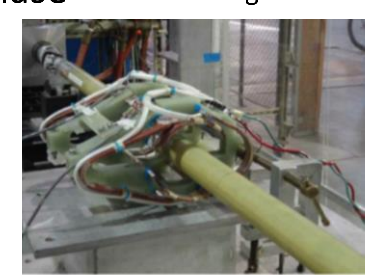
Sampling (lumi. meas.) ~ 1 kHz

- minimize f_0 output component
- dithering × lumi. signal → phase

$$L(t) = \frac{f_{rev} N_1 N_2}{4\pi\sigma_x\sigma_y} e^{-(\frac{[q+psin(2\pi ft)]^2}{4})}$$

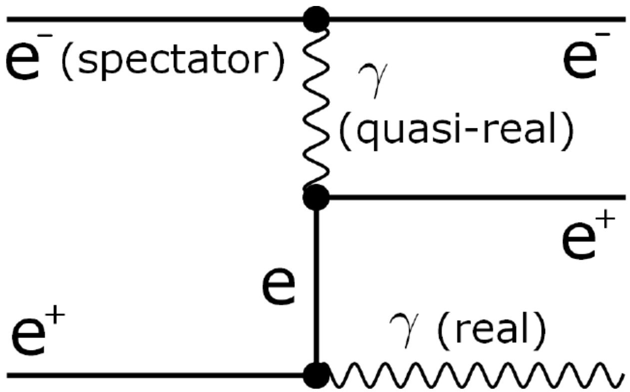


Dithering coil x 12



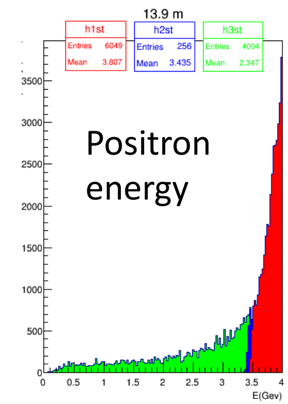
Radiative Bhabha at vanishing scattering angle

$\sigma \sim 250$ mbarn ($E_\gamma > 1\%\ E_{beam}$)

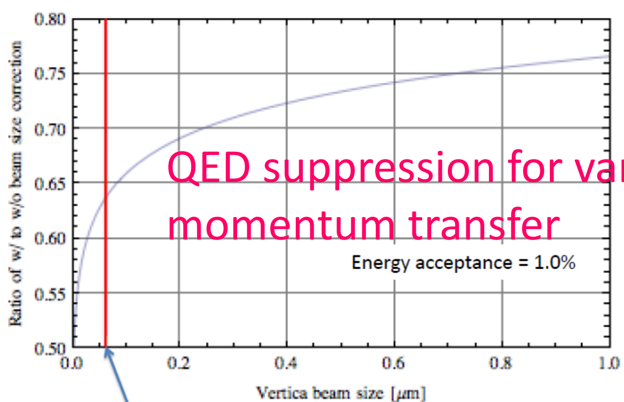


major background source from induced particle losses after IP

luminosity monitoring



Correction for cross section due to finite beam size



QED suppression for vanishing momentum transfer

~60nm (SuperKEKB, κ=0.4%)

Luminosity monitoring specs

- Relative measurements
- 10^{-2} in 1 ms over all bunches ("dithering")
- 10^{-2} in ~ 1 s for each 2500 bunch → 4ns
- Dynamic range → $10^{32} \sim 10^{36}$ cm^{-2}s^{-1}
- Non luminosity scaling contamination < 1%

(e.g. beam gas bremsstrahlung and Touschek losses)

Y. Funakoshi (KEK), background workshop, Feb. 2012

Two complementary techniques

LumiBelle2
Luminosity Monitoring for Belle II

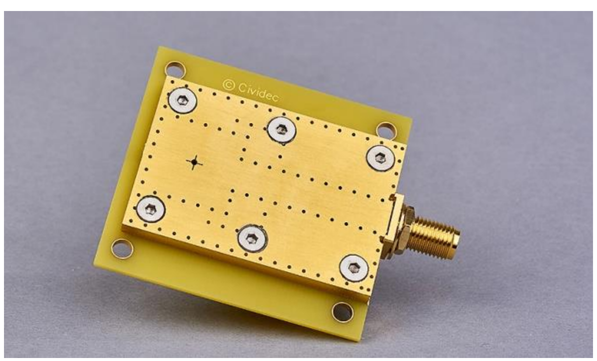
LumiBelle2 | **ZDLM (Zero Degree Luminosity Monitor)**

Count photons and recoiling electrons or positrons from the radiative Bhabha process at vanishing scattering angle

$\sigma \sim 250$ mbarn ($E_\gamma > 1\%\ E_{beam}$)

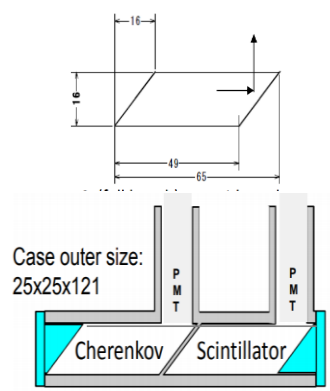
LumiBelle2

- Diamond sensors
- $4 \times 4 \times 0.5/0.14\ mm^3$ single crystal CVD diamond sensors
- Fast charge/current amplifiers
- Digital electronics



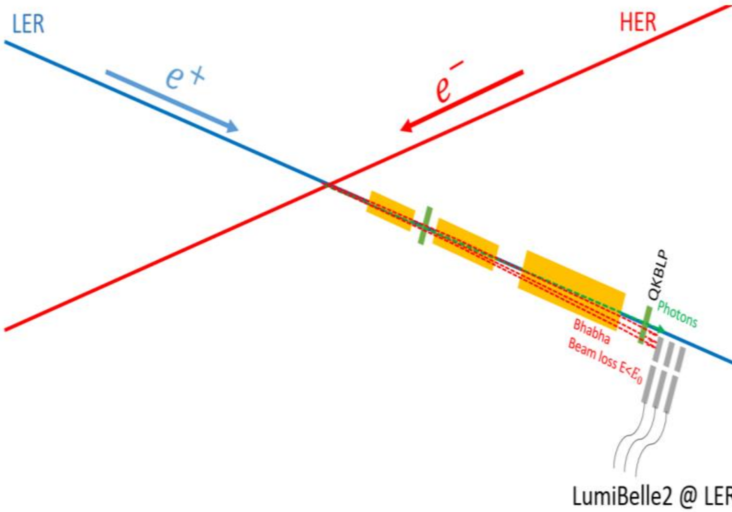
ZDLM

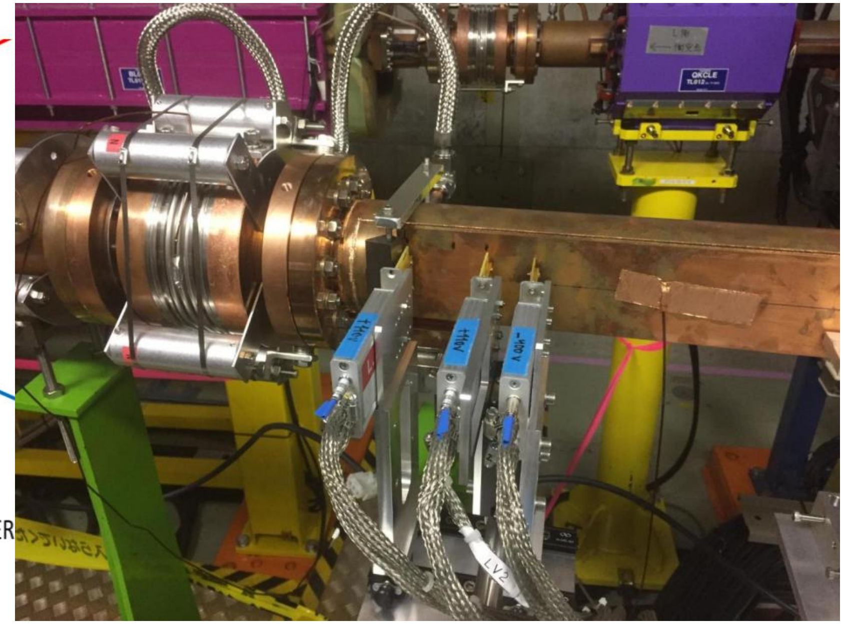
- Cherenkov and scintillator detectors + PMT
- $15 \times 15 \times 64\ mm^3$ LGSO non-organic scintillator and ES-crystal (quartz)
- Analog electronics



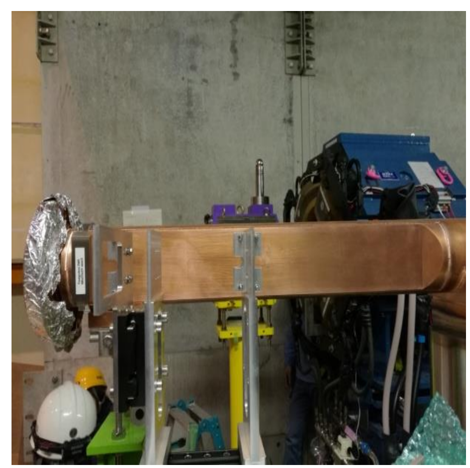
LER side

Luminosity Monitoring for Belle II





- Signal: Bhabha positrons
- Background: Bremsstrahlung and Touschek positrons
- Platform: 11 m after IP
- 3 sensors aligned
- Window + radiator

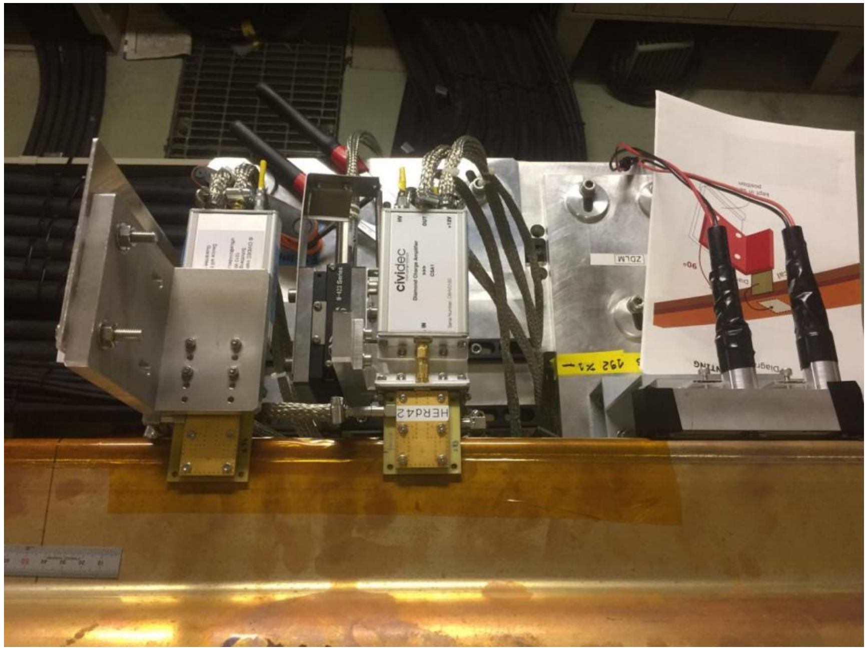


HER side

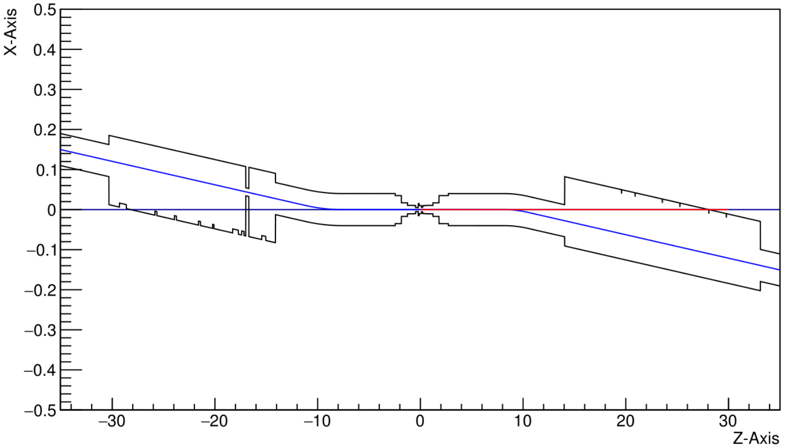
LumiBelle2

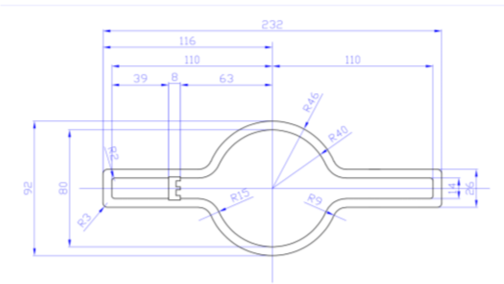
Luminosity Monitoring for Belle II

- Signal: Bhabha photons
- Background: Bremsstrahlung photons, Touschek electrons
- Platform: 30.5-30.8 m after IP
- 3 sensors: up & down, (side)



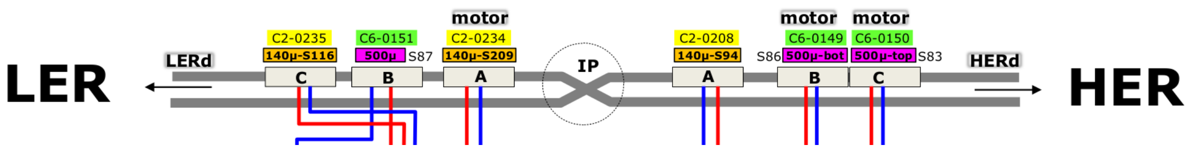
HER beam pipe

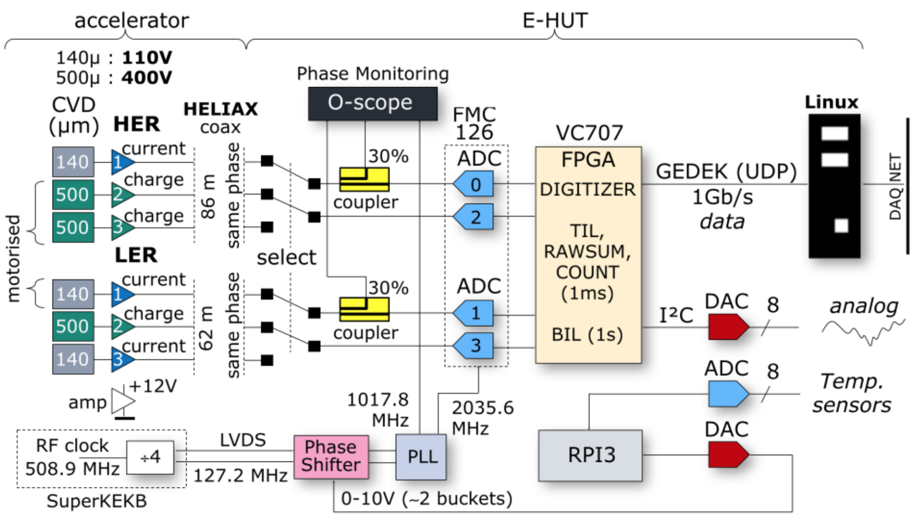


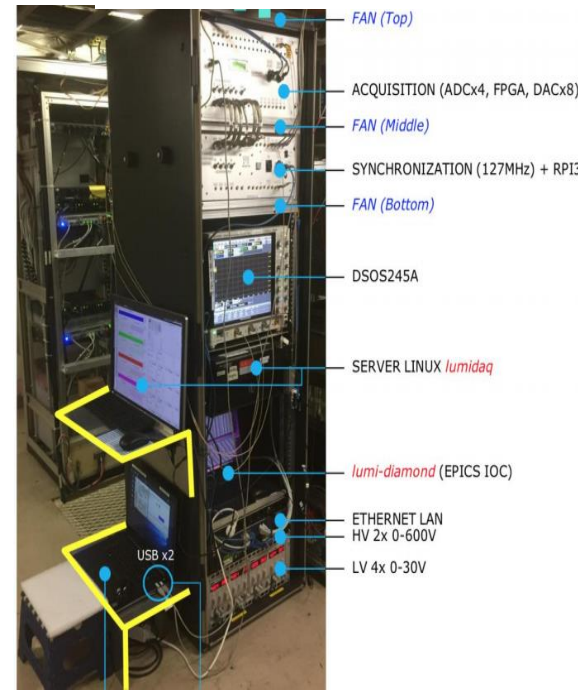


DAQ and online signal processing

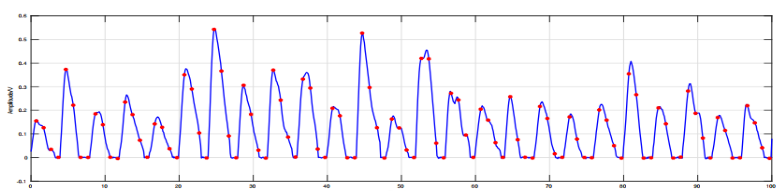
LumiBelle2
Luminosity Monitoring for Belle II







Sampling signal sequences at 1GHz



TIL: if $S[(i-1)\times 2+1]-S[(i-1)\times 2+3] > threshold$:

TIL $\mathrel{+}= S[(i-1)\times 2+1]-S[(i-1)\times 2+3]$

RAWSUM: if $S(j) > threshold$:

Rawsum $\mathrel{+}= S(j)$

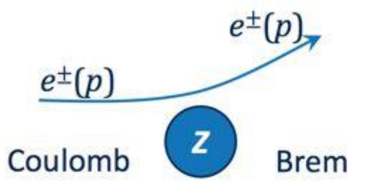
No trigger + Synchronization to RF -----> Continuous monitoring, averaging at 1 kHz

TIL and RAWSUM are different ways of calculating the luminosity from the measured signal

Single beam background

Coulomb

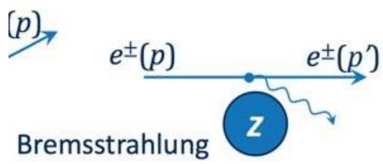
- Proportional to vacuum pressure and beam current
- Important globally but negligible for luminosity monitoring



dominant for LumiBelle2

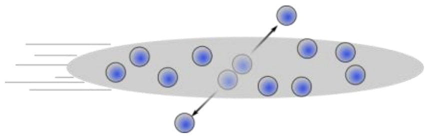
Bremsstrahlung

- Proportional to vacuum pressure and beam current
- Largest source of background in phase 2
- Photons measured at HER side
- Positrons measured at LER side



Touschek

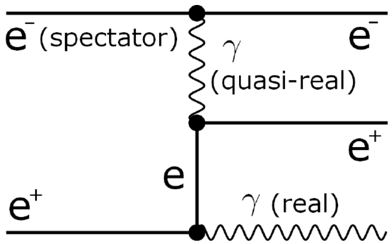
- Proportional to square of beam current
- Inversely proportional to beam size



Luminosity signal

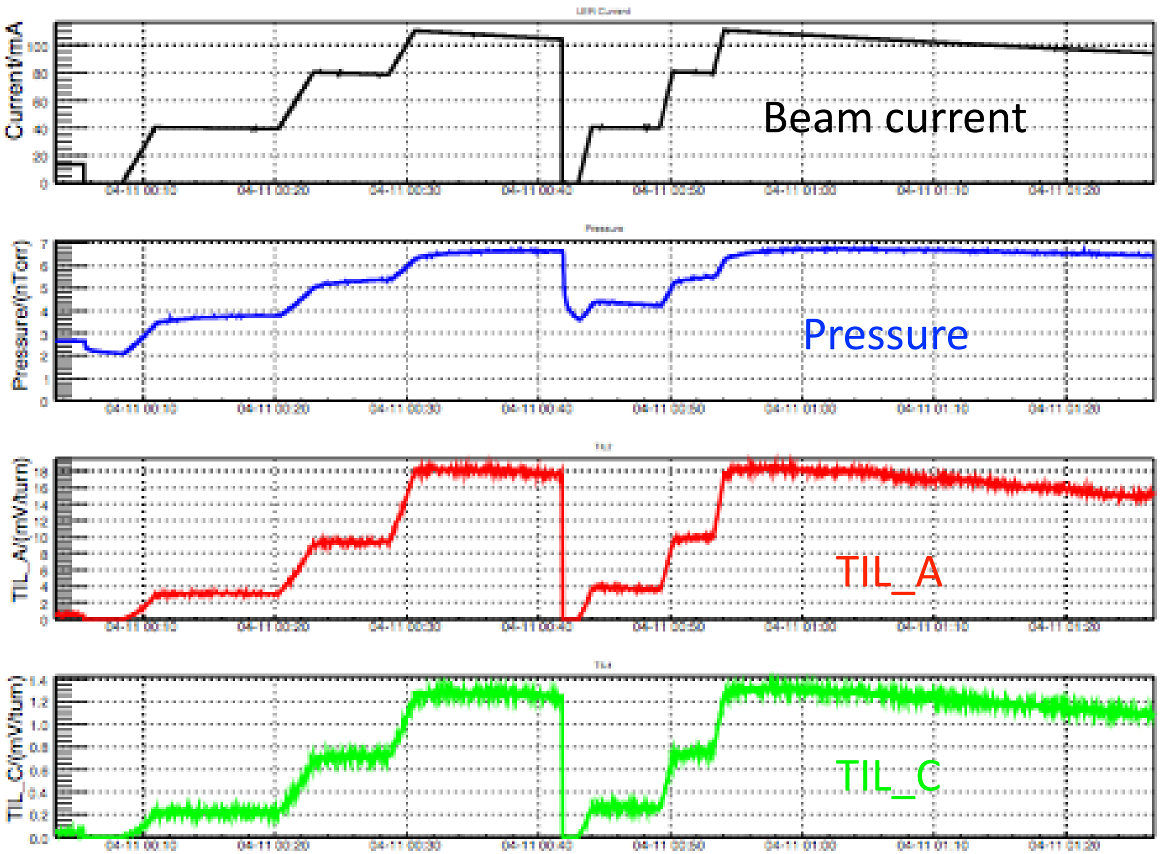
Radiative Bhabha process

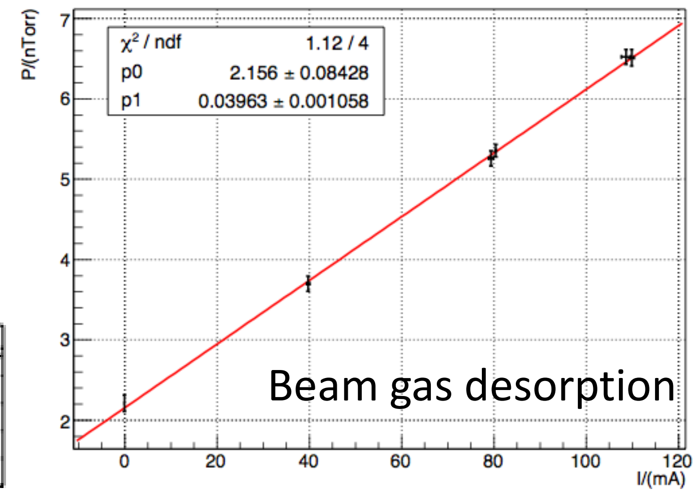
- Scattered @ IP
- Proportional to luminosity
- Large cross-section



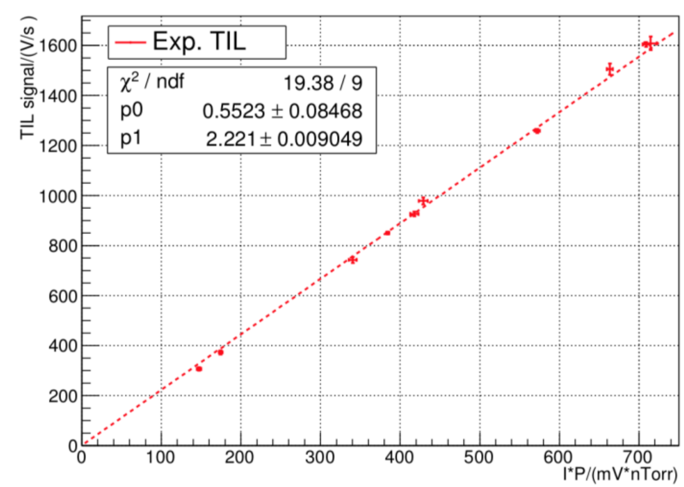
Background study (1)

- Background measurement:
  - ✦Bremsstrahlung ∝ I*P Dominant
  - ✦Touschek ∝ $I^2/(\sigma_x\sigma_y\sigma_z) \propto I \times P$





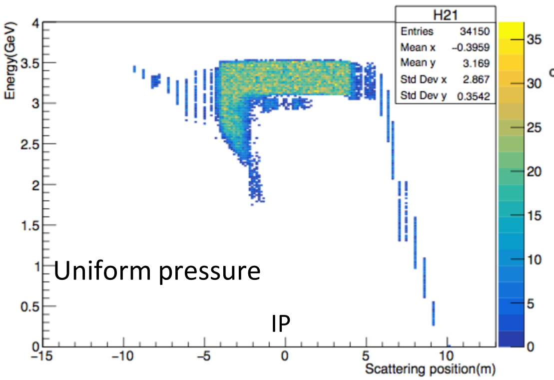
Pressure is proportional to current



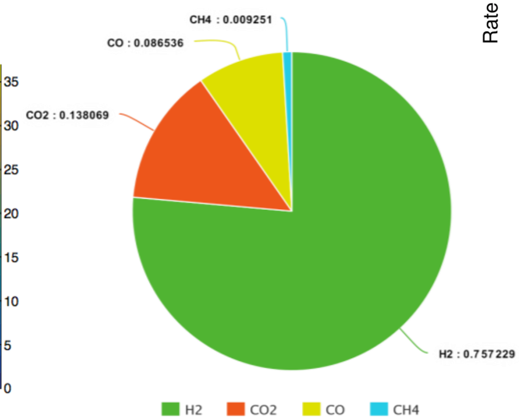
Background signal is proportional to product of beam current and pressure

Background study (2)

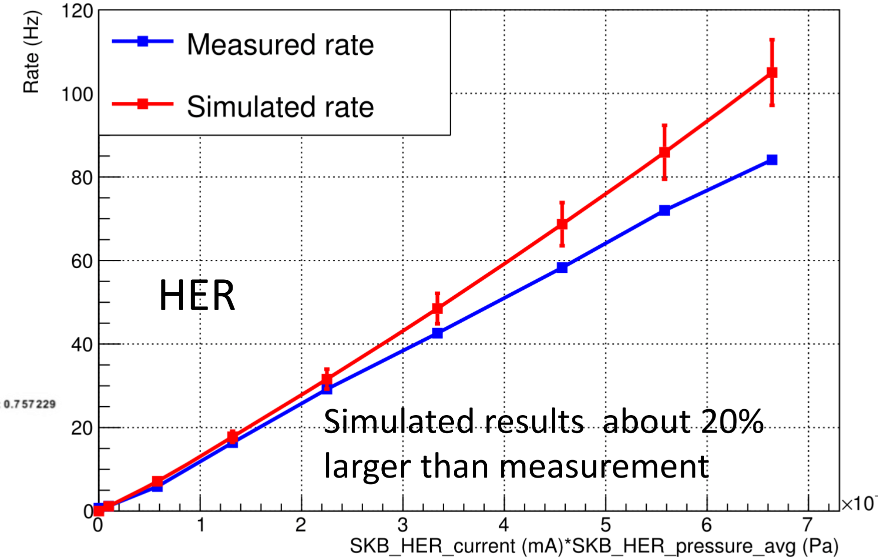
- Comparison with simulation



Scattering position of lost particles

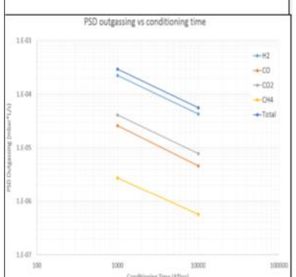


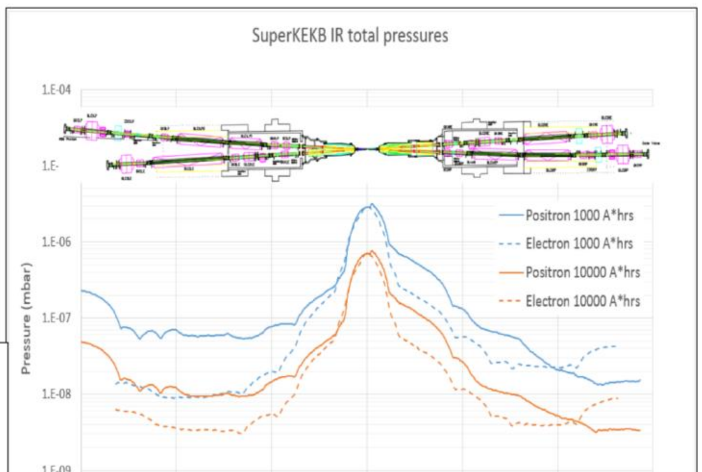
$Z_{eff} = 4.5$



Total pressures at 1000, 10000 A*hrs, I = 3.6 A

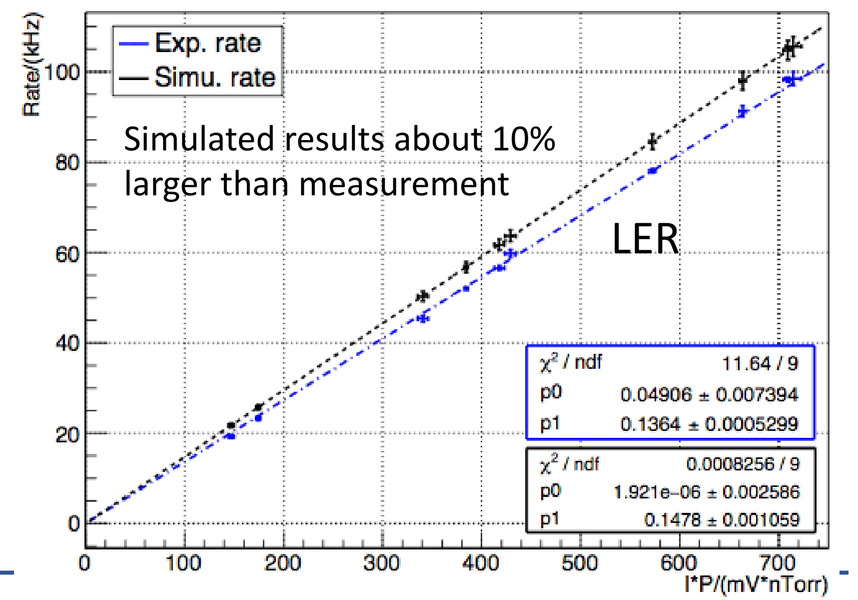
- Total indicates sum of H_2, CO, CO_2, and CH_4 partial pressures
- Asymmetric because of synchrotron radiation



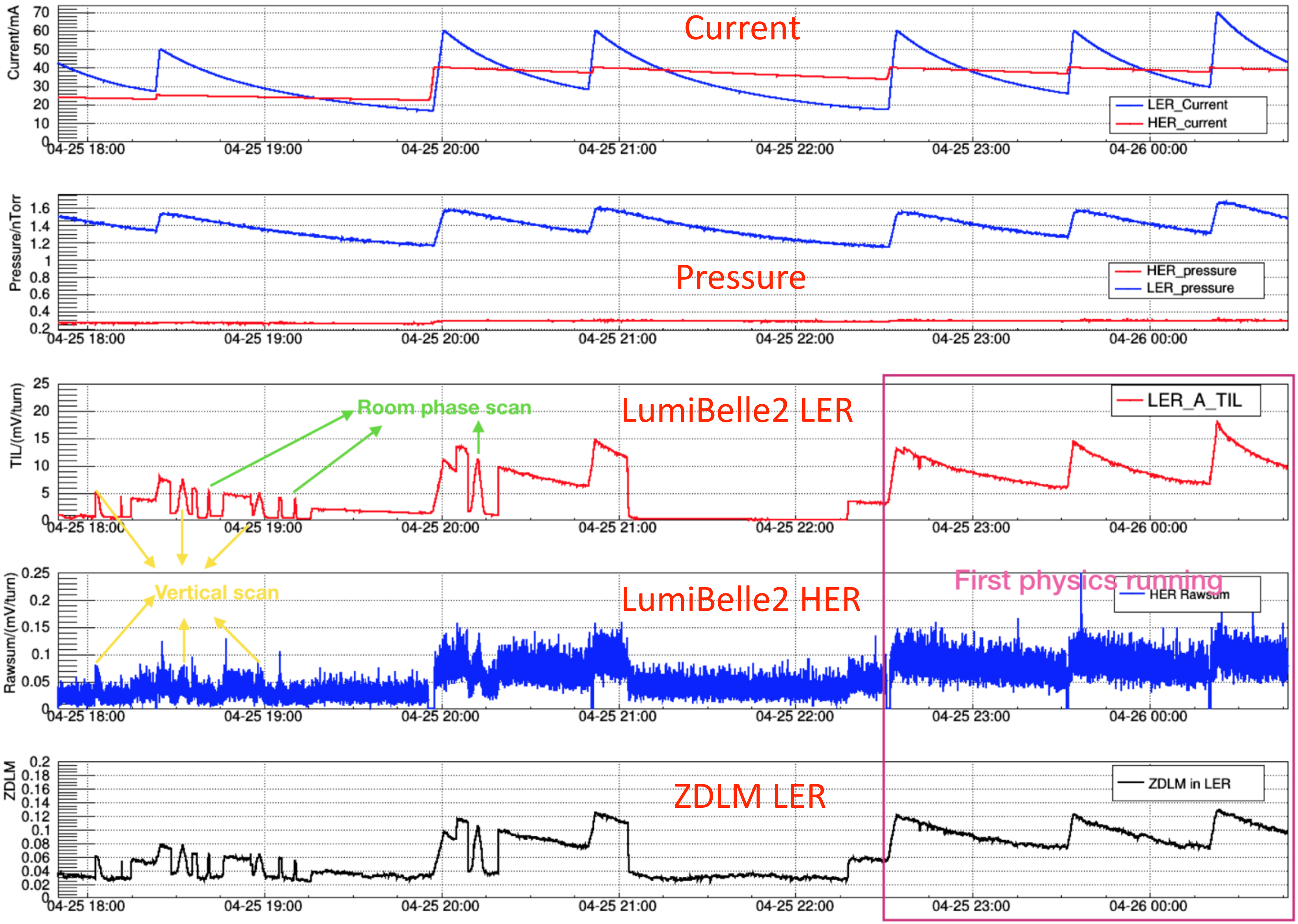


Simulated vacuum profile @ IP

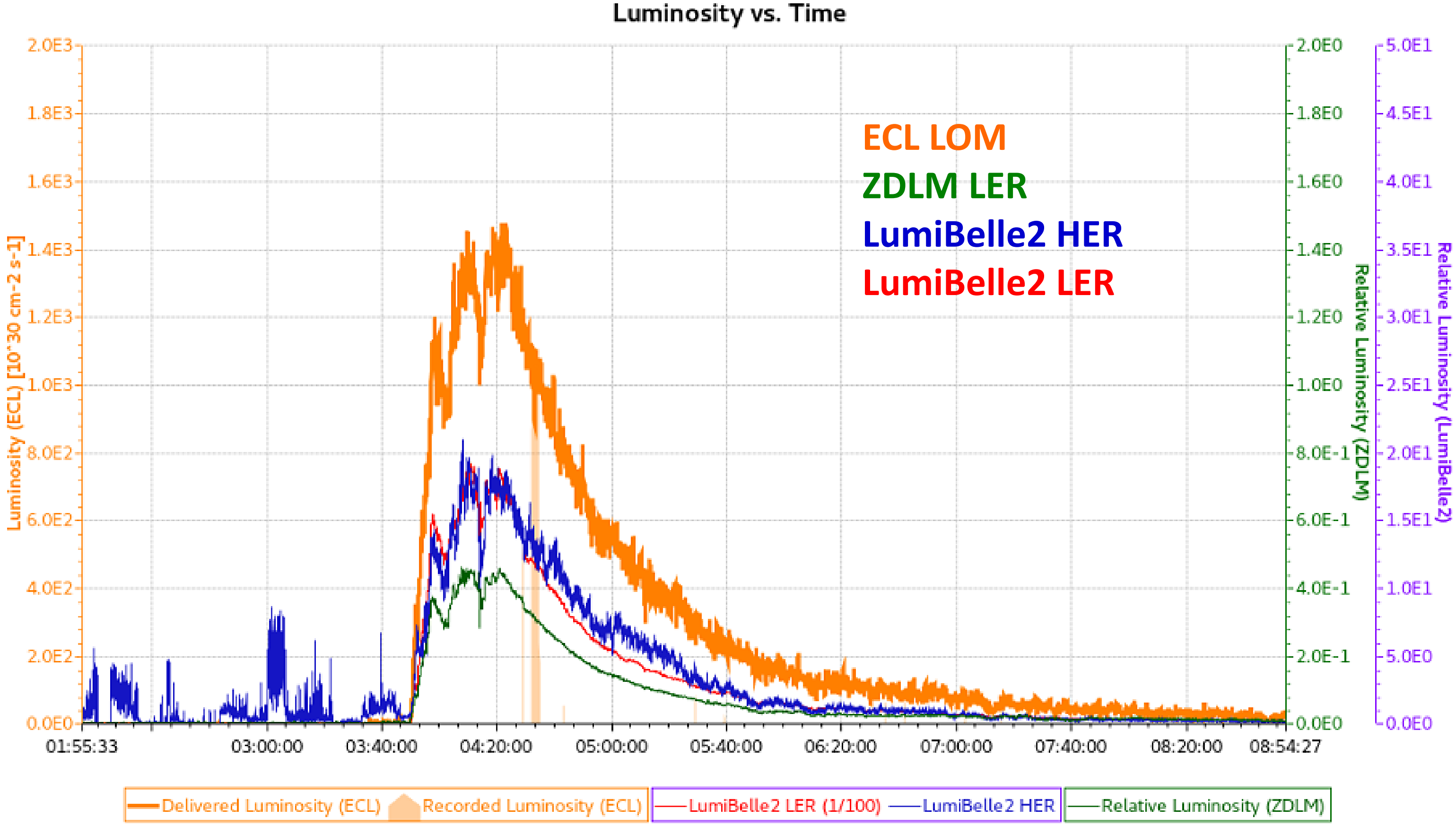
Jason CARTER (ANL) &Marton ADY (CERN)



First collision – April 26, 2018



Control room display of recent luminosity run (June 16, 2018)

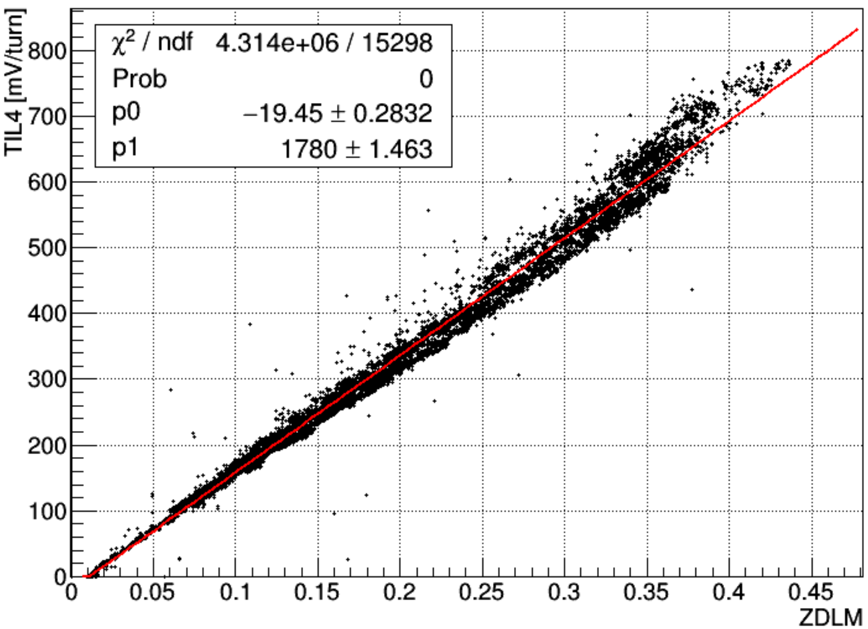


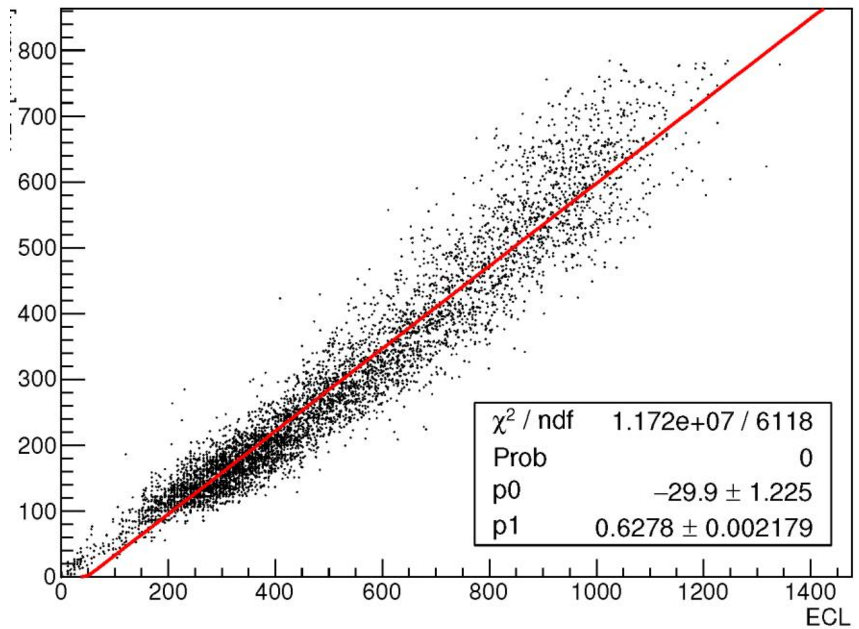
Normalization of LumiBelle2 w.r.t. ECL LOM absolute luminosity

(channel / configuration dependent + can evolve in time… is monitored)

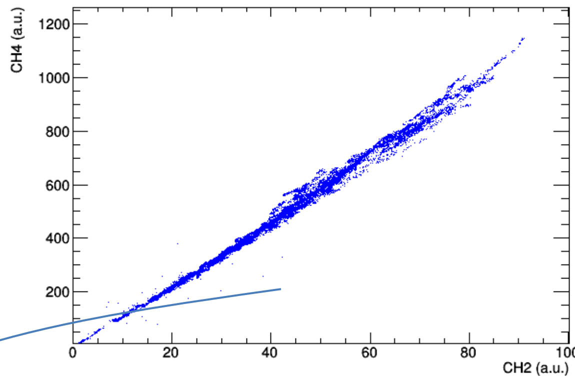
LER 1st	LER 2nd	HER 1st	HER 2nd
$(25 \pm 8)10^2$	$(4 \pm 1)\ 10^2$	(13 ± 4)	1.2 ± 0.4

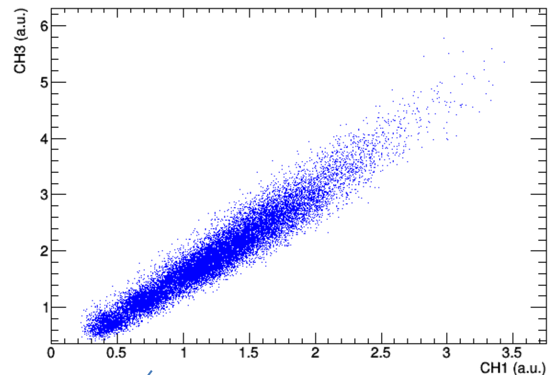
LumiBelle2 LER compared to ZDLM and ECL LOM



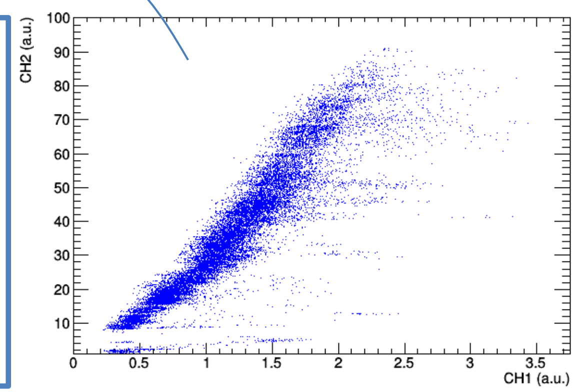


Offline check of LumiBelle2 channel correlations

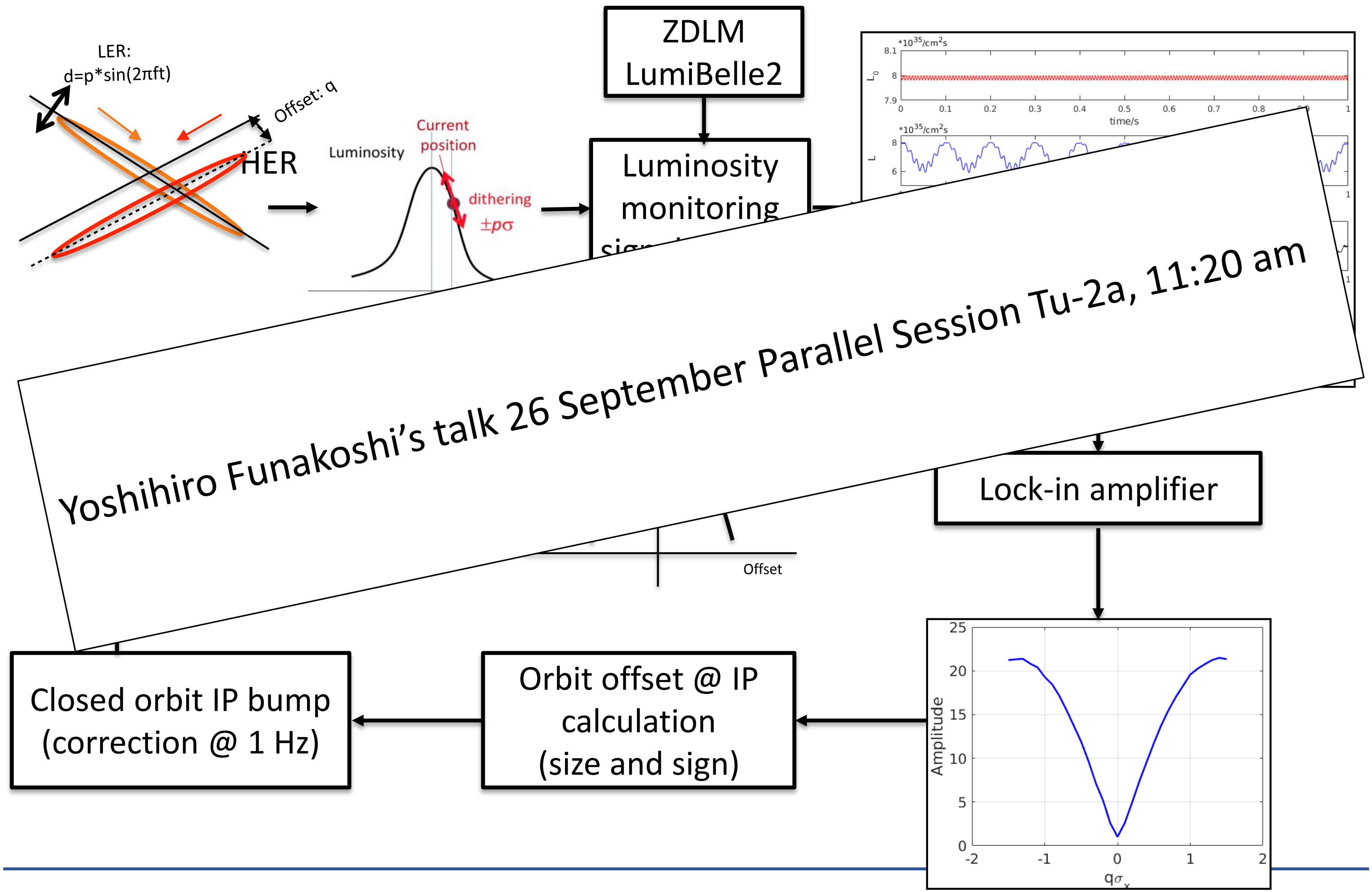




	CH1	CH2	CH3	CH4
CH1	1	0.9092	0.9624	0.9019
CH2	0.9092	1	0.8888	0.9975
CH3	0.9624	0.8888	1	0.8822
CH4	0.9019	0.9975	0.8822	1



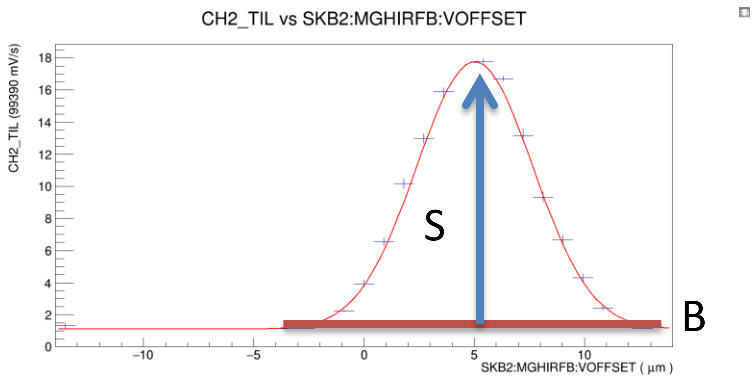
Application: input to *dithering feedback* to maintain collisions horizontally

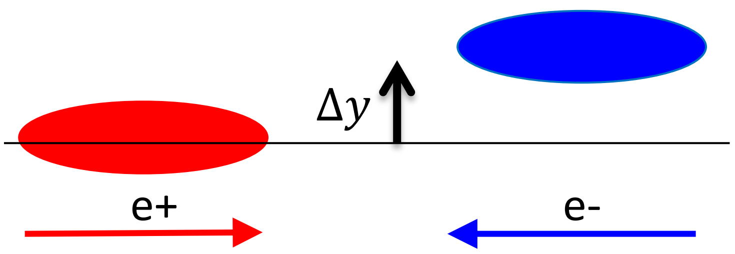


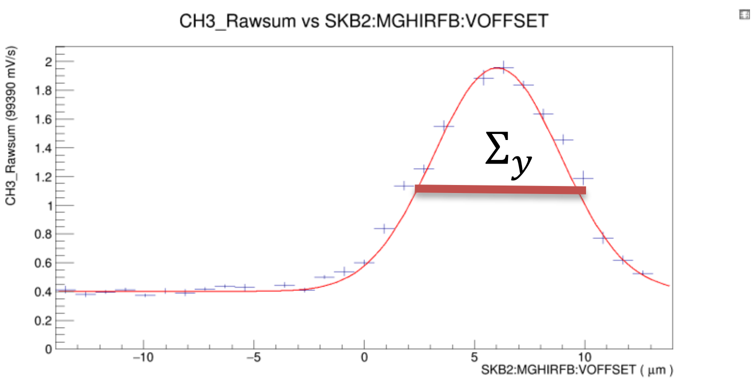
Yoshihiro Funakoshi's talk 26 September Parallel Session Tu-2a, 11:20 am

Application : Luminosity fitting w.r.t. IP beam tuning parameters

- Example: vertical offset scan to estimate average of e+ and e− σ_y at IP
  - offset scans usually range from $\Delta y = -14\mu m$ to $\Delta y = +14\mu m$
  - σ_y estimated from 4 LumiBelle2 luminosity monitors
  - bias from beam-beam induced blow-up for high current and/or small β*
    - → can help to probe the beam-beam blow-up and benchmark the beam-beam simulations





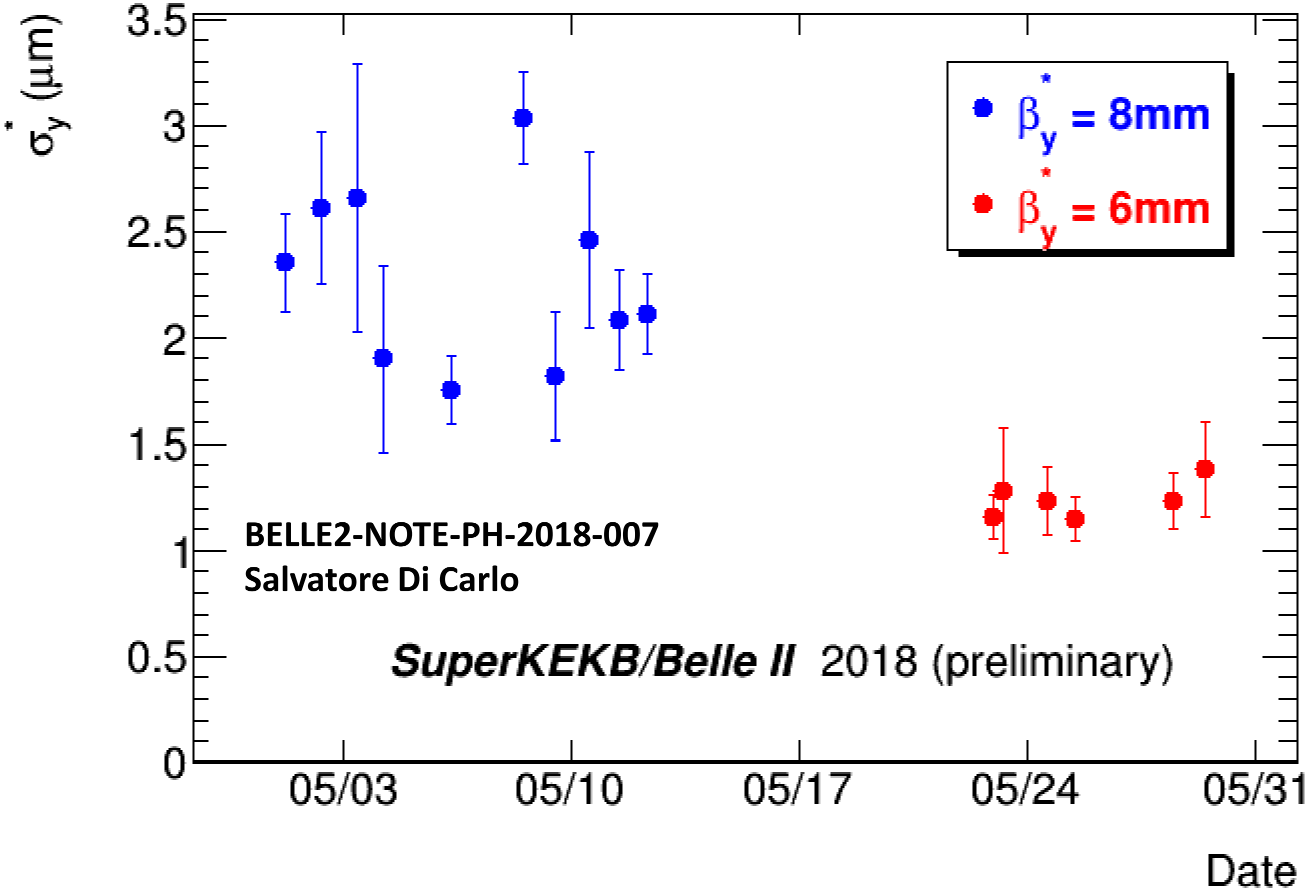


$$\frac{L}{L_0} = exp\left(-\frac{\Delta y^2}{2\Sigma_y^2}\right)$$

$$\Sigma_y^2 = \sigma_{1,y}^2 + \sigma_{2,y}^2 \approx 2\sigma_y^2$$

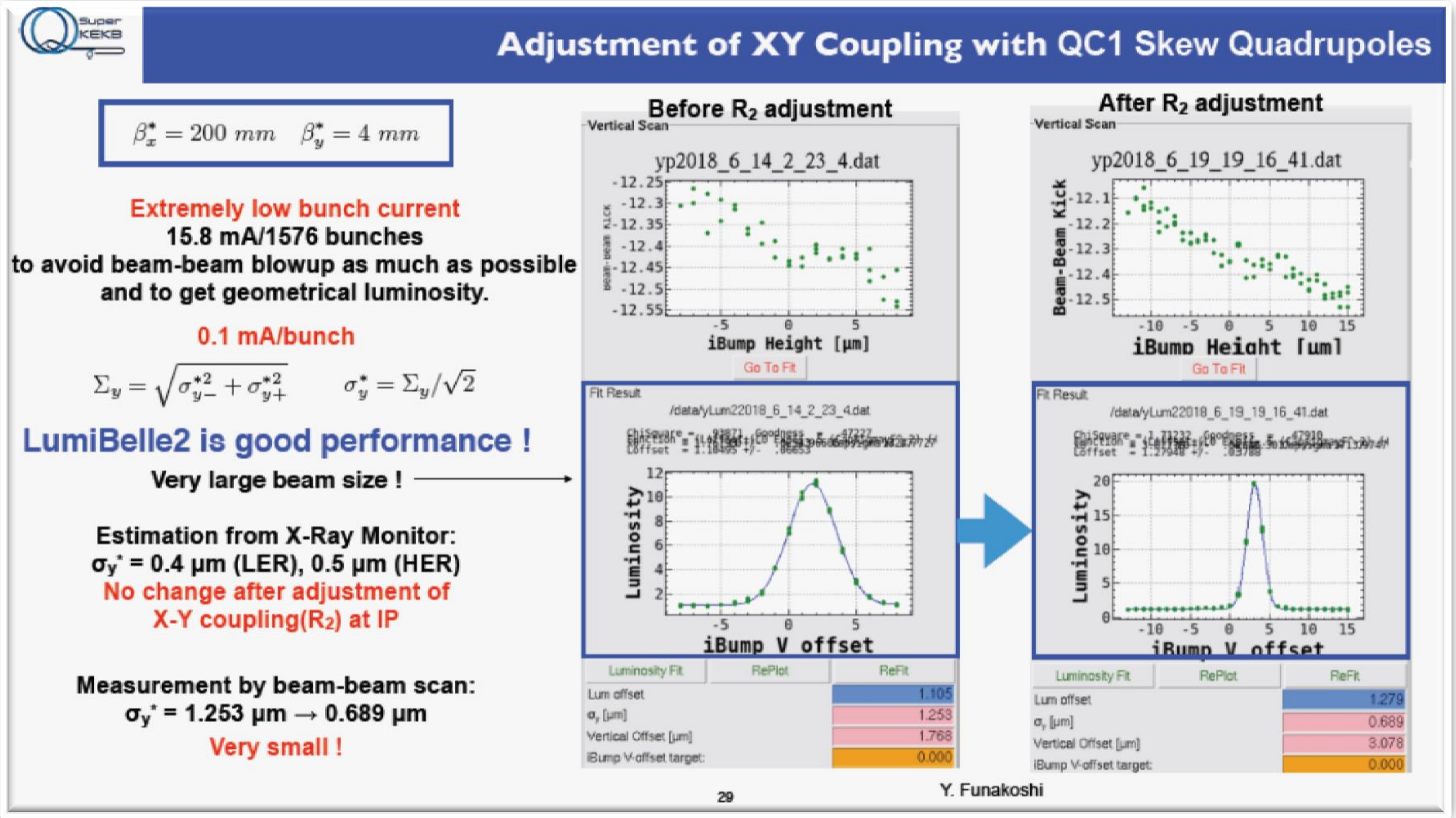
Evolution in σ_y^* in May

- σ_y^* is obtained for each monitor and averaged
- The errors combine statistical and systematic measurement uncertainties
- Already some bias from the beam-beam blow-up ?



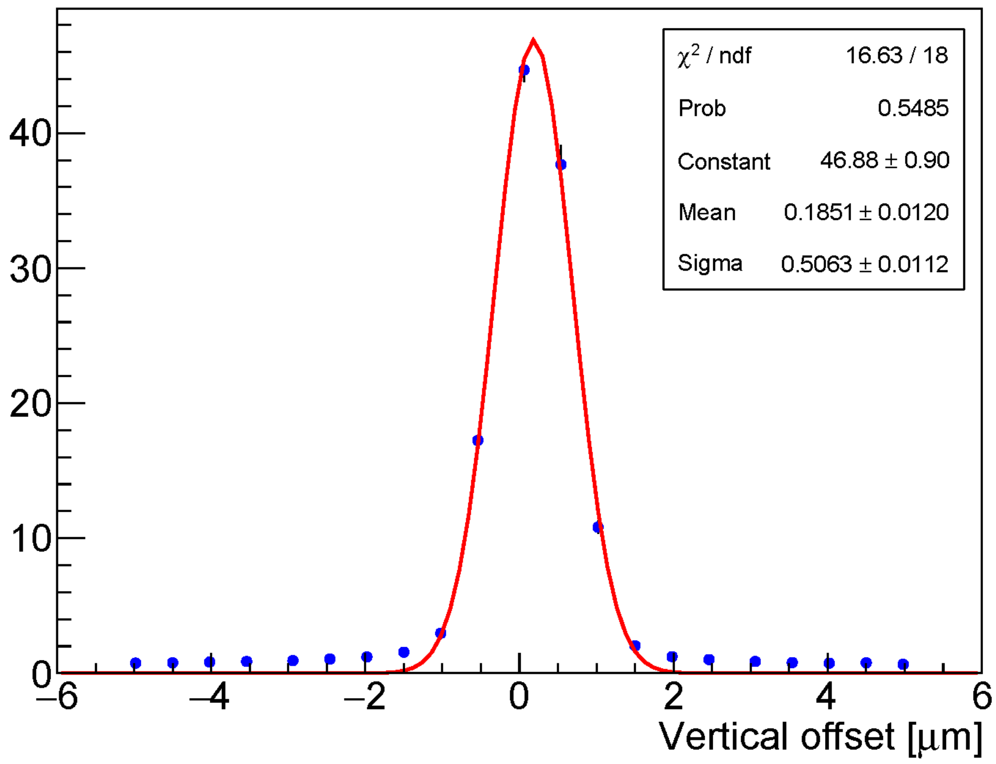
Sensitive luminosity monitor important to correct optical aberrations in vertical IP beam size*

→ must do at very low intensity to avoid confusion from beam-beam blow-up



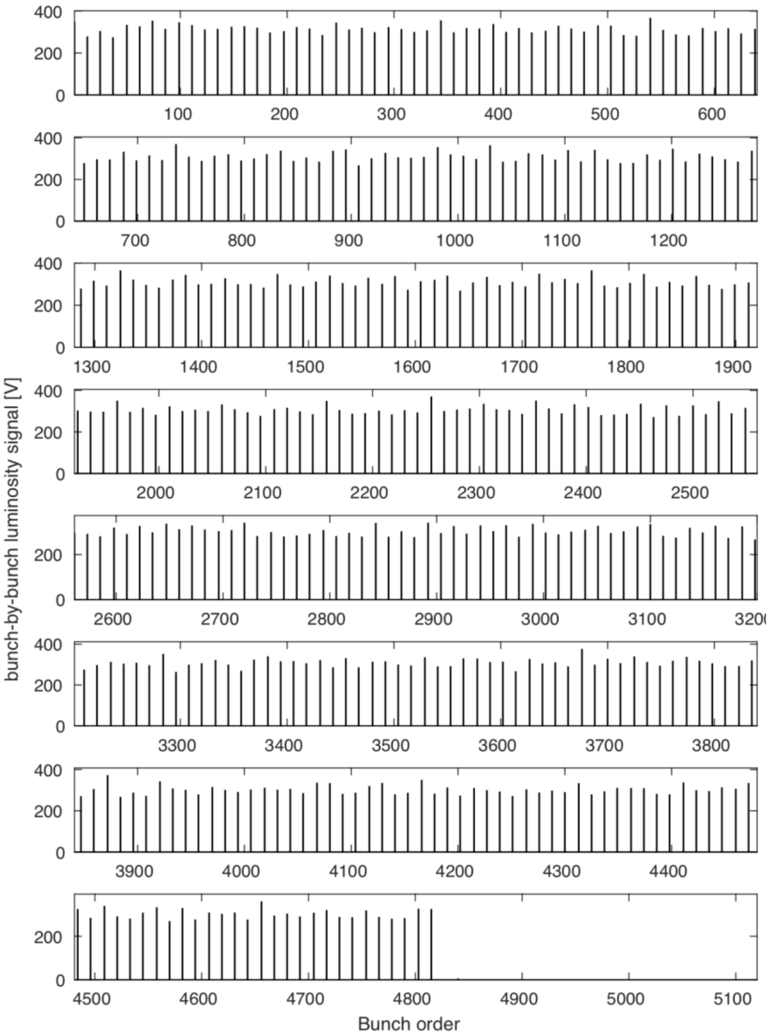
* Yukiyoshi Ohnishi's opening plenary talk on Monday 24/9

SNR and optimum offset from vertical beam offset scan



- $L_{ECL\text{-}LOM} = 1.3\ 10^{32}\ cm^{-2}\ s^{-1}$
- measured SNR ~ 65 (simulation → 42)
- optimum collision offset ~ 0.19 μm
- Σ_y ~ 0.51 μm

Application : bunch-by-bunch luminosity monitoring



- $L_{ECL\text{-}LOM} = 1.6\ 10^{33}\ cm^{-2}\ s^{-1}$ (end of Phase 2)
- $N_{bunch} = 395$
- bunch separation = 32 ns (nominally $\rightarrow$ 4 ns)
- RMS bunch luminosity spread = 9.3 %
- RMS bunch current product spread = 8.7 %
- integrated lumi. precision @ 1 kHz = 2.35%
- bunch-by-bunch Lumi precision @ 1 Hz = 1.5%

Conclusion and prospects

- **LumiBelle2 operated satisfactorily during Phase 2**
  - reasonable agreement with simulation for single beam backgrounds
  - provides useful online luminosity information for SKB machine tuning (e.g. IP beam size tuning)
  - 1st test as input to horizontal IP orbit dithering feedback $\rightarrow$ Cf. Y. Funakoshi's talk on Wednesday
  - application: evaluate mean σ_y of beams at IP $\rightarrow$ "Van der Meer" scans @ LHC
  - bunch-by-bunch luminosities
- **Future evolution of LumiBelle2**
  - increase HER signal rates $\rightarrow$ have identified and will use better location for Phase 3
  - faster charge amplifiers & lower noise current amplifiers
  - long term DAQ solution, possibly with a few more channels
  - shielding / protection to mitigate activation on LER side under study
  - ability to easily vary signal acceptance to keep few % precision @ 1 kHz over $10^{32} - 10^{36}$ cm^{-2}s^{-1}
    $\rightarrow$ important to limit accumulated radiation dose
  - more remote operation, with less human resources and less presence at KEK
    $\rightarrow$ one of LAL Belle II group service tasks
- **Application to future high energy colliders**
  - start by evaluating basic specifications and methods

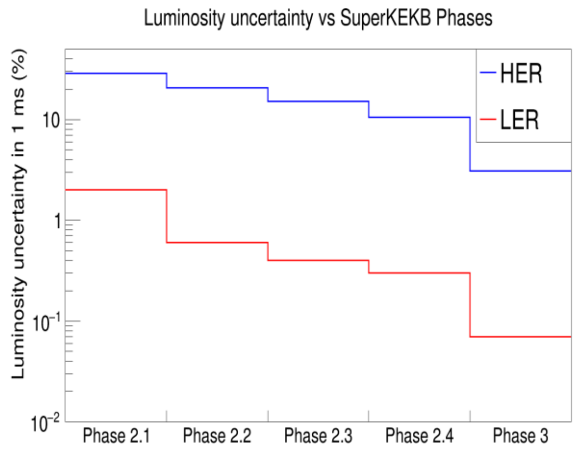
Backup slides

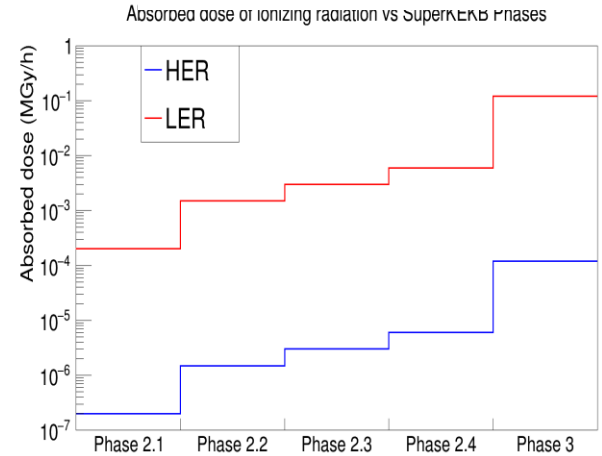
LumiBelle2 precision/dose and luminosity

LumiBelle2 Luminosity Monitoring for Belle II

HER:
- Initially low precision
- Low dose

LER:
- High precision
- High dose





- Need both HER and LER to cover full range of SKB luminosities;
- HER precision can be improved with larger diamonds;
- LER can be moved to receive a lower dose;
- Recent study shows % level precision enough for horizontal IP orbit feedback with dithering technique

Phase	Luminosity (cm^{-2} s^{-1})	$\Delta L/L$ HER/LER (%)	*Dose* HER/LER (Mgy/h)
2.1	1×10^{33}	28.9 / 2	2e-7 / 2e-4
2.2	1×10^{34}	20.7 / 0.6	1.5e-6 / 1.5e-3
2.3	2×10^{34}	15.1 / 0.4	3e-6 / 3e-3
2.4	4×10^{34}	10.5 / 0.3	6e-6 / 6e-3
3	8×10^{35}	3.1 / 0.07	1.2e-4 / 0.12