Prospects for the spin structure study of hyperons using heavy quark decays at Belle II

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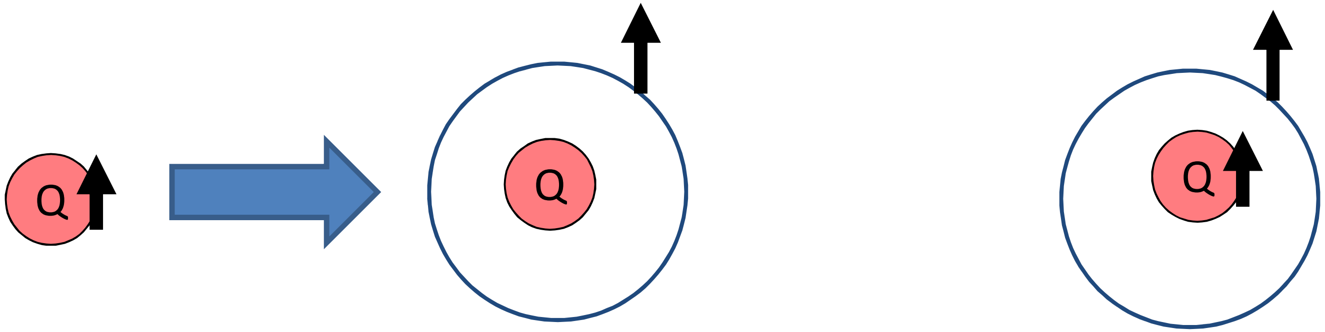
Physics motivation

- Baryon spin structure
  - Well studied for nucleon, but little for other baryons
- It is well known that quark spin contribution to proton spin is rather small
  - How is for other baryons?
  - E.g., Λ: quark model predicts s quark carries all spin
- Excited baryons
  - How to identify exotic baryon from spin structure e.g., $\Lambda(1405)$: 3 quarks vs 5 quarks?
  - Spin structure gives strong information

PDF vs fragmentation

- Quark spin contribution to baryon: Δq
  → Fraction of quark spin in baryon spin
- Analog in fragmentation: polarization transfer
  - Polarized quark → polarized baryon
- Naïvely those two are equal [Augustin and Renard (1979)]



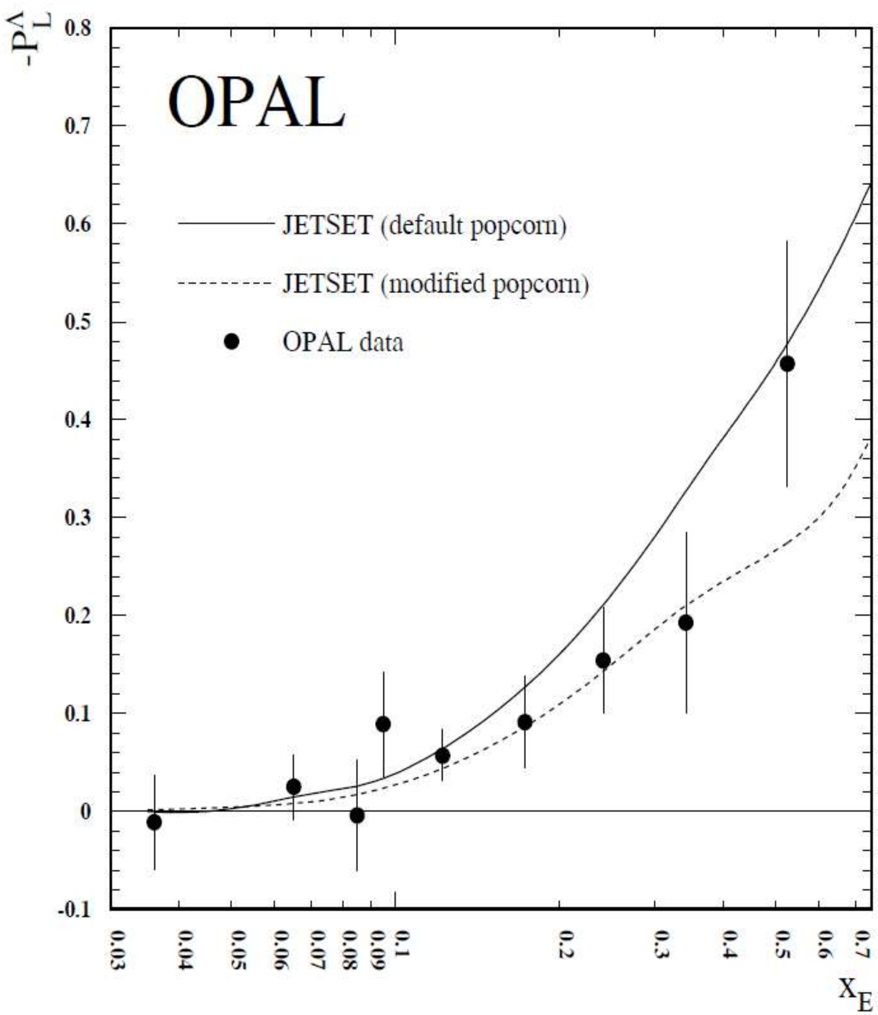
Polarization transfer = Quark spin fraction

Quark polarization in weak decay

- Large quark polarization is expected in weak decays
  - 100% polarization for massless quarks neglecting spontaneous chiral symmetry breaking effect (PCAC)
- Quark → Baryon spin transfer can be obtained by measuring baryon spin in the final state
- Past measurements for Λ and Λ_b using Z decay at LEP with rather poor statistics

Past measurement at LEP

- OPAL and ALEPH measured Λ polarization in Z^0 decay
  - $Z^0 \rightarrow$ s: polarized by -0.94
  - Contamination by ss-bar pair creation during fragmentation
    $\rightarrow$ treated in simulation, with sizable uncertainty
  - Consistent with quark model within the uncertainty



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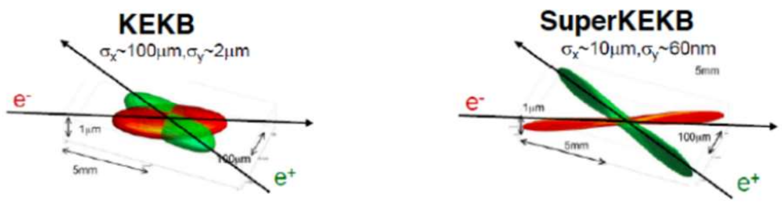
- Much larger statistics is expected with b and c decays at Belle II
  → Studies for excited baryons become possible

SuperKEKB and Belle II

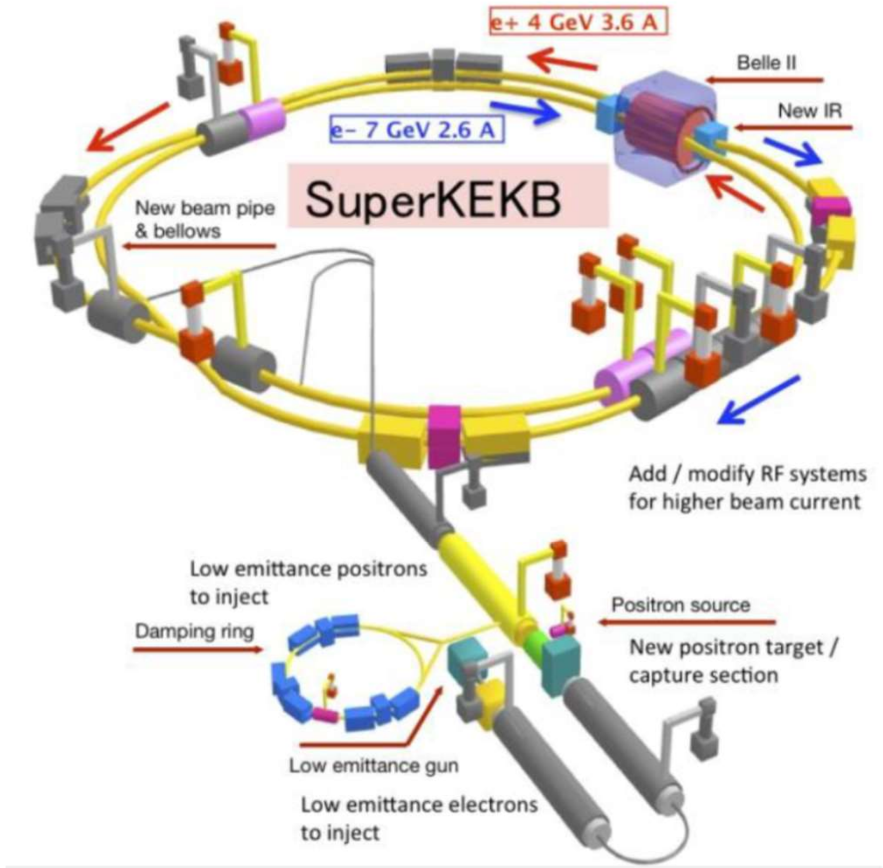
Upgrade for SuperKEKB and Belle II to achieve 40x peak $\mathcal{L}$ under 20x bkgd

- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

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

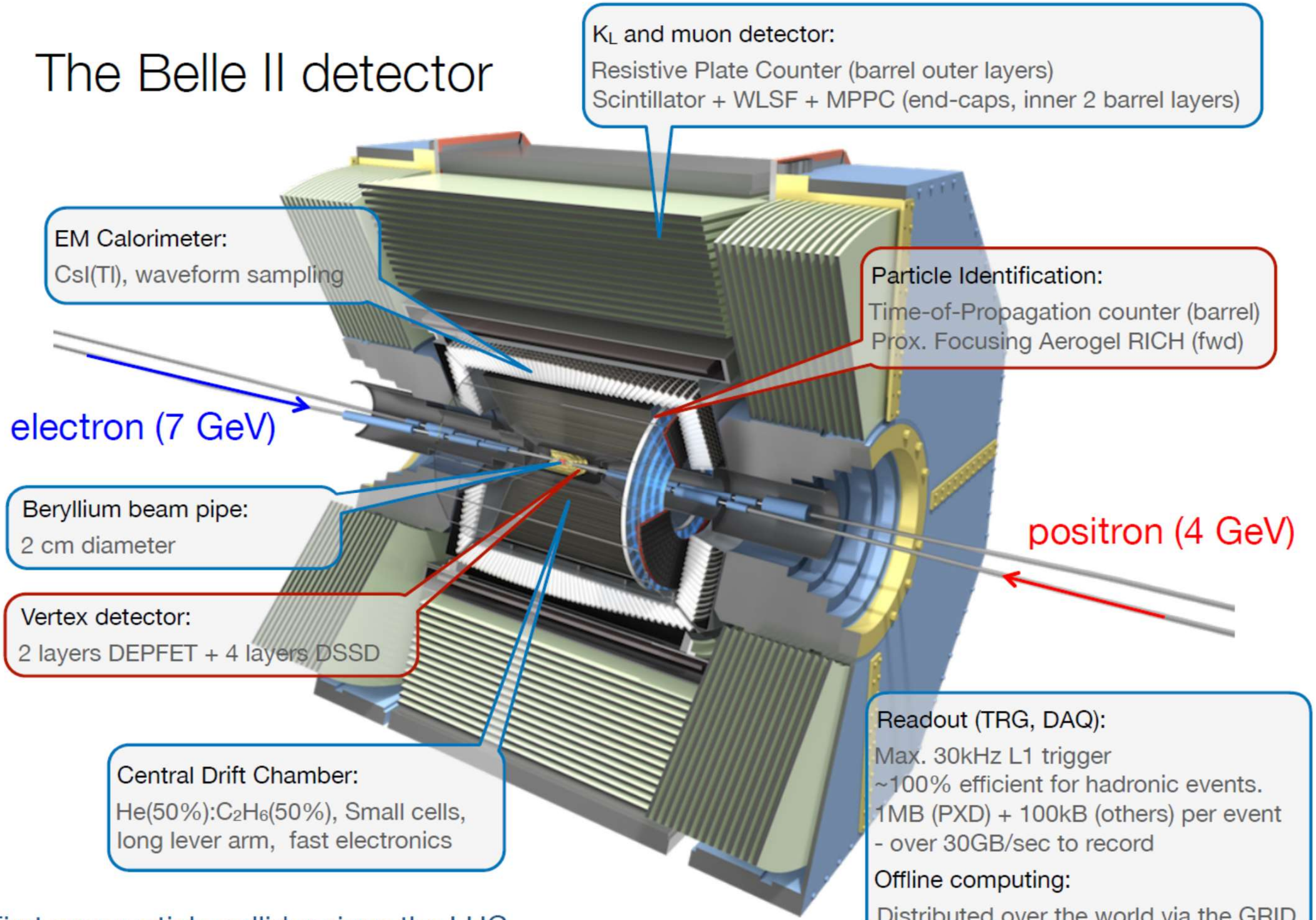


- ▶ *First turns achieved Feb. 2016*
- ▶ *Beam-background studies ongoing*



Goal: x50 more statistics than Belle

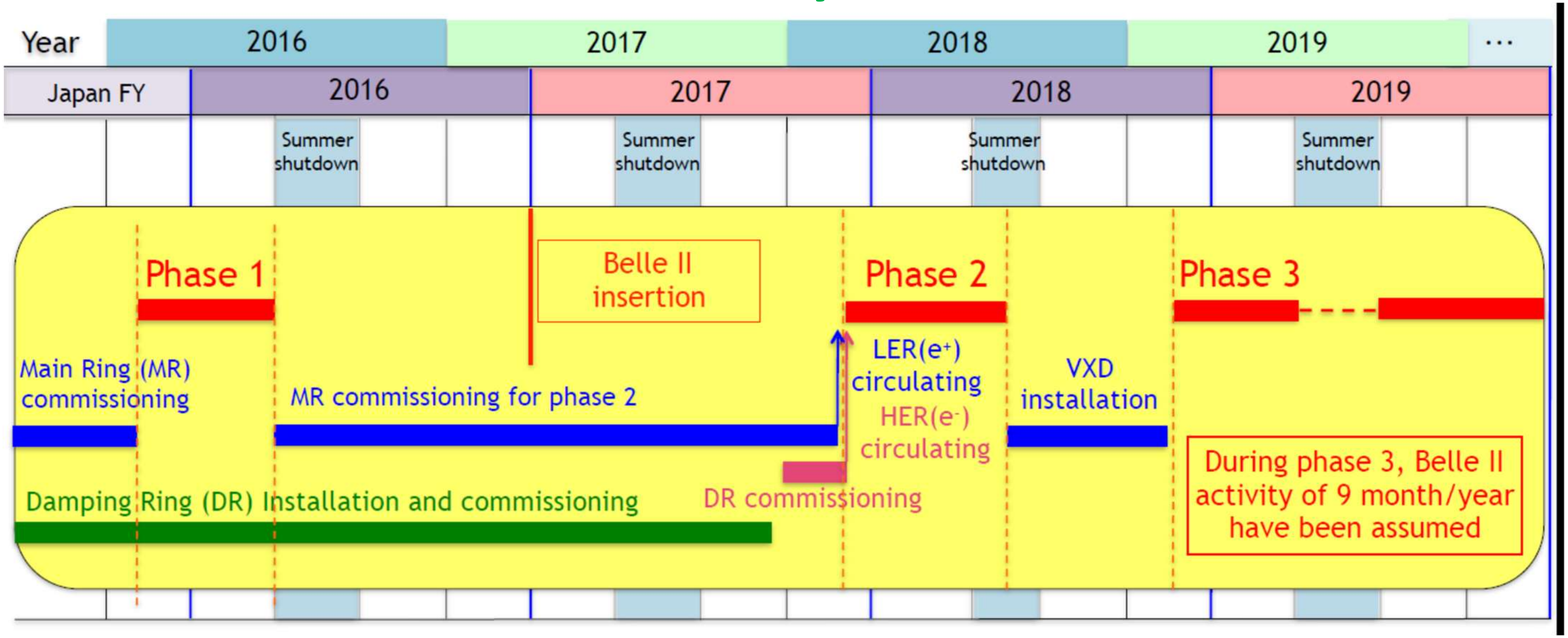
The Belle II detector



First new particle collider since the LHC
(intensity rather than energy frontier; e^+e^- rather than pp)

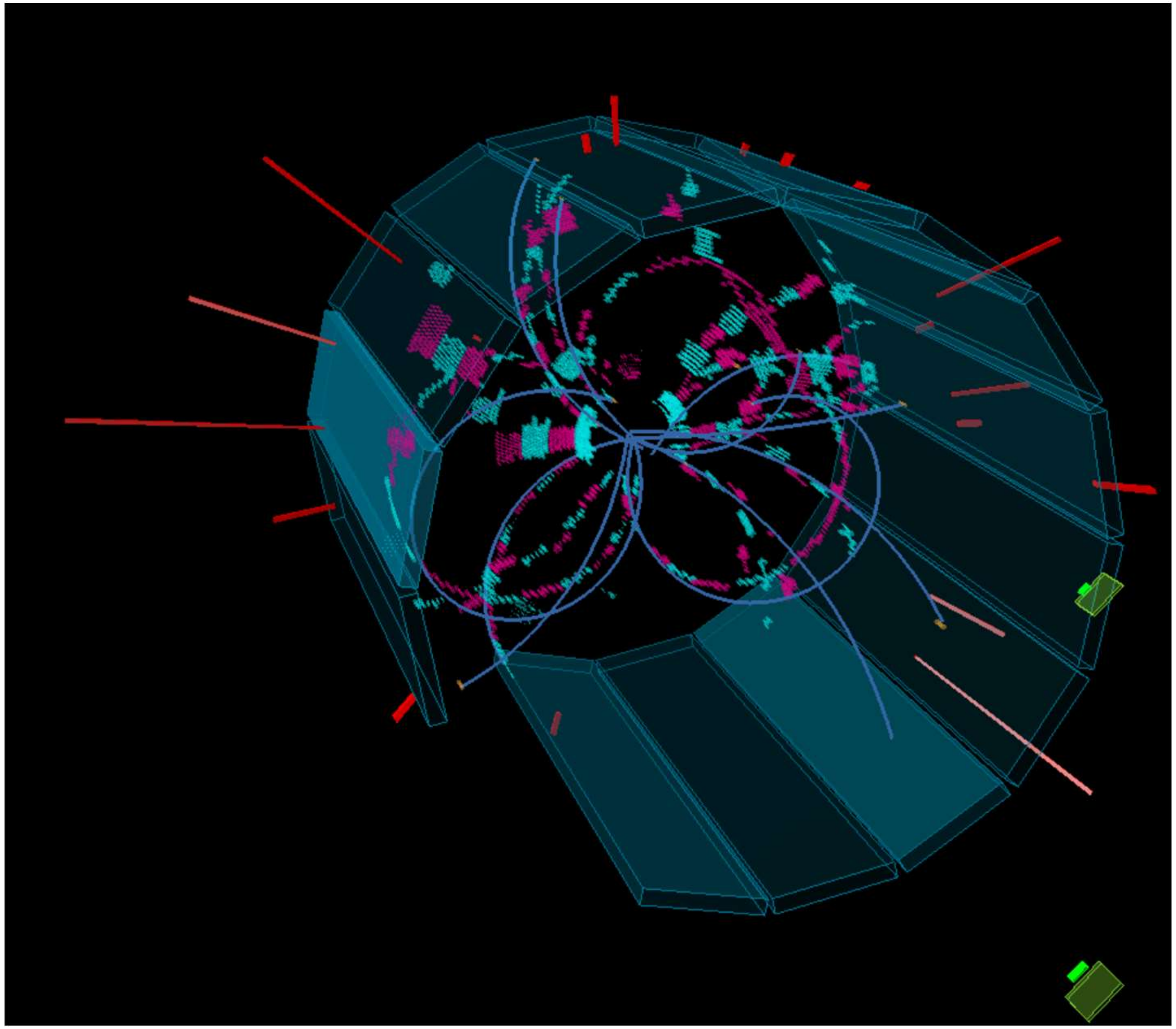
arXiv:1011.0352 [physics.ins-det]

Quick history of Belle II



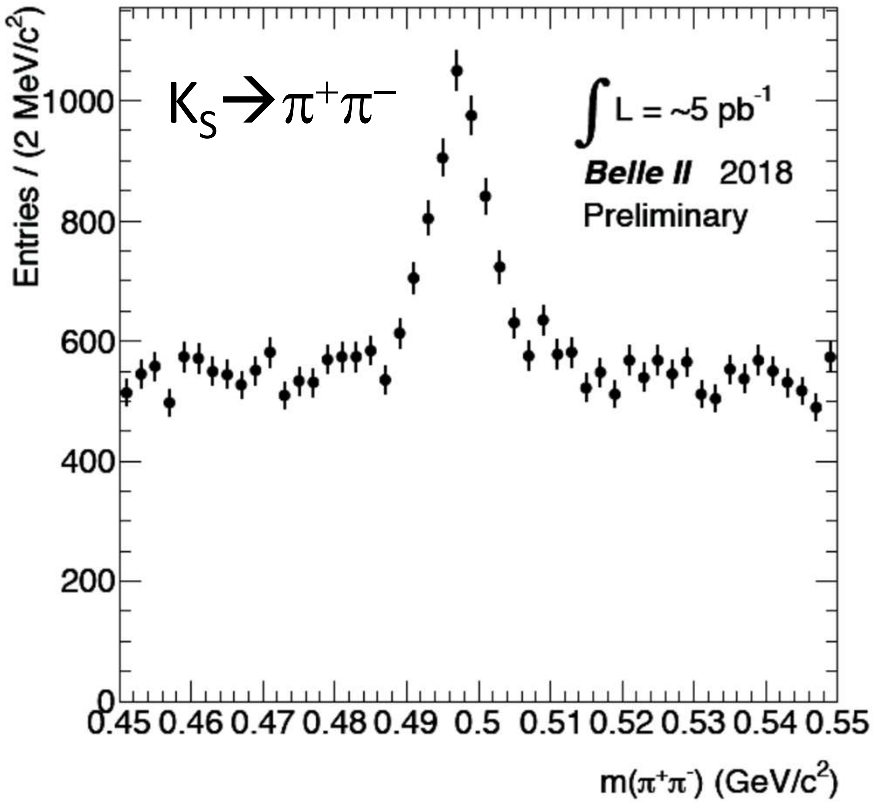
- Phase 1 – complete: Mostly devoted to accelerator
- Phase 2 – just finished:
  Physics run with partial vertex detectors
  L_{peak}=5.5x10^{33} cm^{-2}s^{-1} and L_{int}~0.5 fb^{-1} achieved

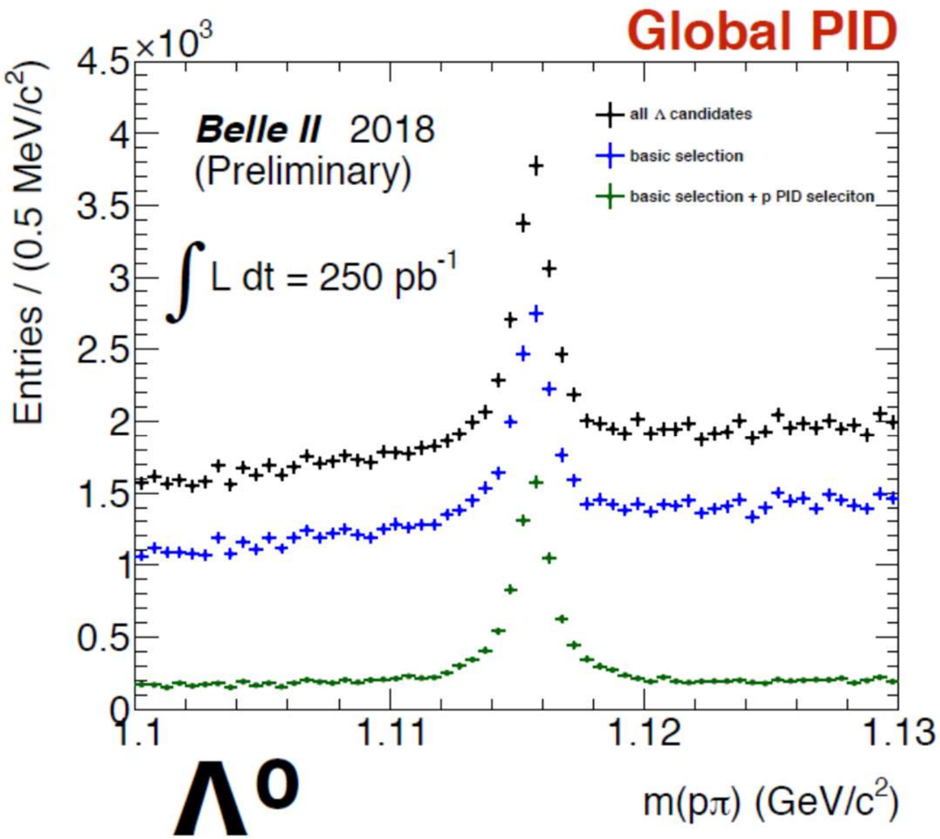
The first hadron event



0:38, April 26, 2018

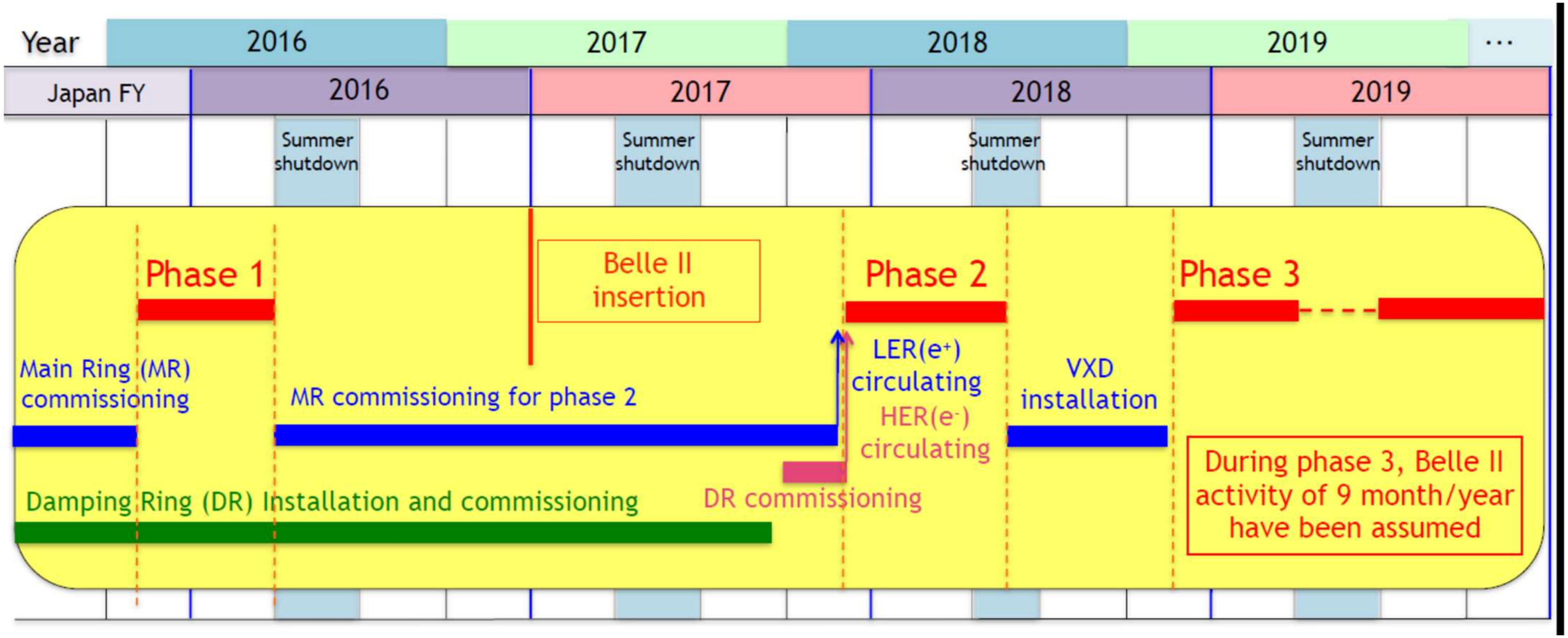
Performance -- invariant masses





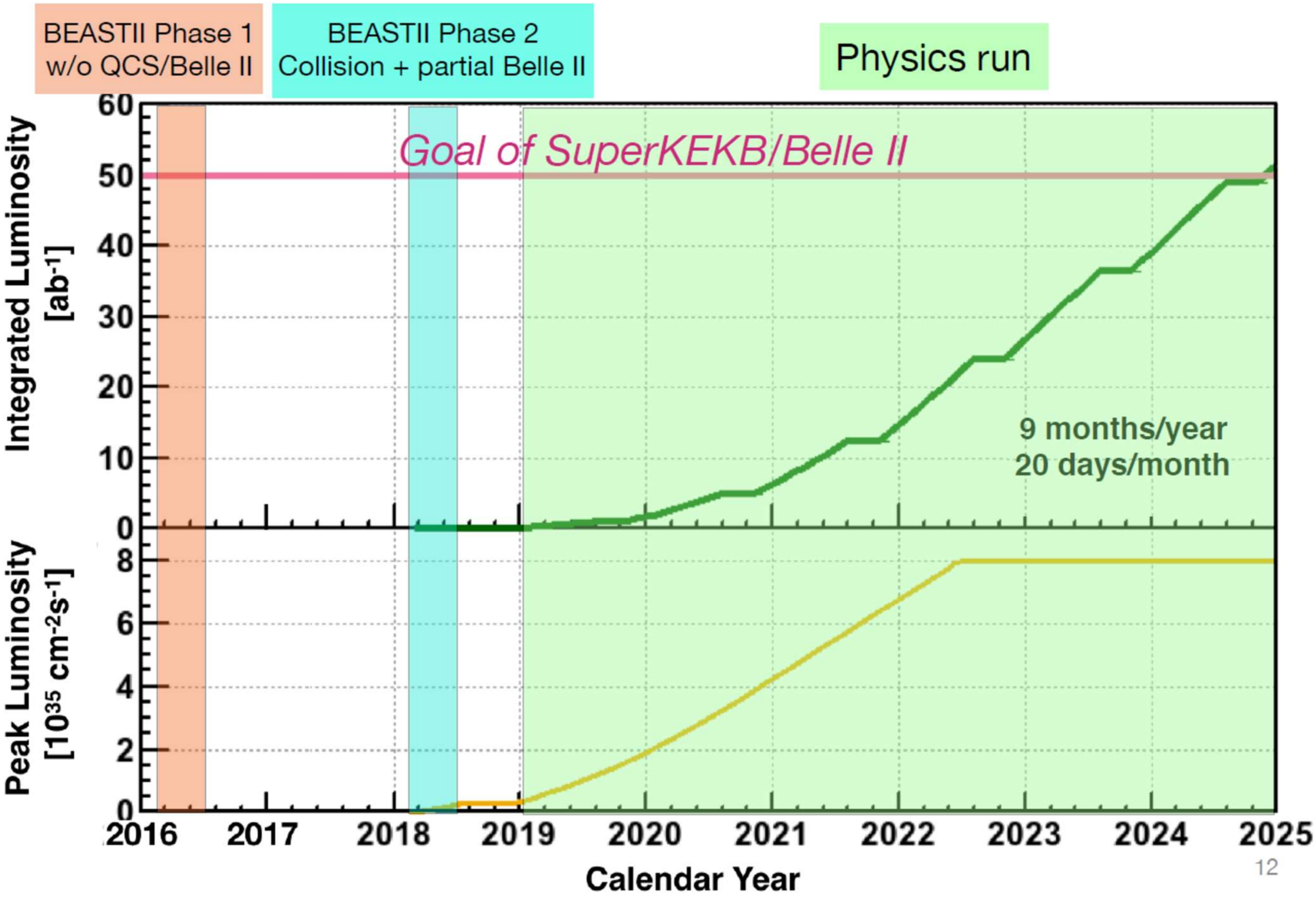
- K_S, π^0, D*, Λ, J/ψ… are clearly seen
  Detectors are working well!

Near future



- Installation of VXD in this Autumn/Winter
- Phase 3 run will start early 2019
  → Full physics run.

Luminosity projection



Measurement at Belle II

- Hyperon polarization in Λ_c decay
  - Semileptonic: $\Lambda_c \rightarrow Y + e(\mu) + \nu$
  - Non-leptonic: $\Lambda_c \rightarrow Y + \pi$

  → Measure polarization of hyperon Y
- Ground state hyperons (Λ, Σ)
  - Spin structure of these hyperons
  - Control samples for excited states
- Excited states
  - Exotic states? Especially $\Lambda(1405)$
- Also possibilities for charmed baryons from B decay

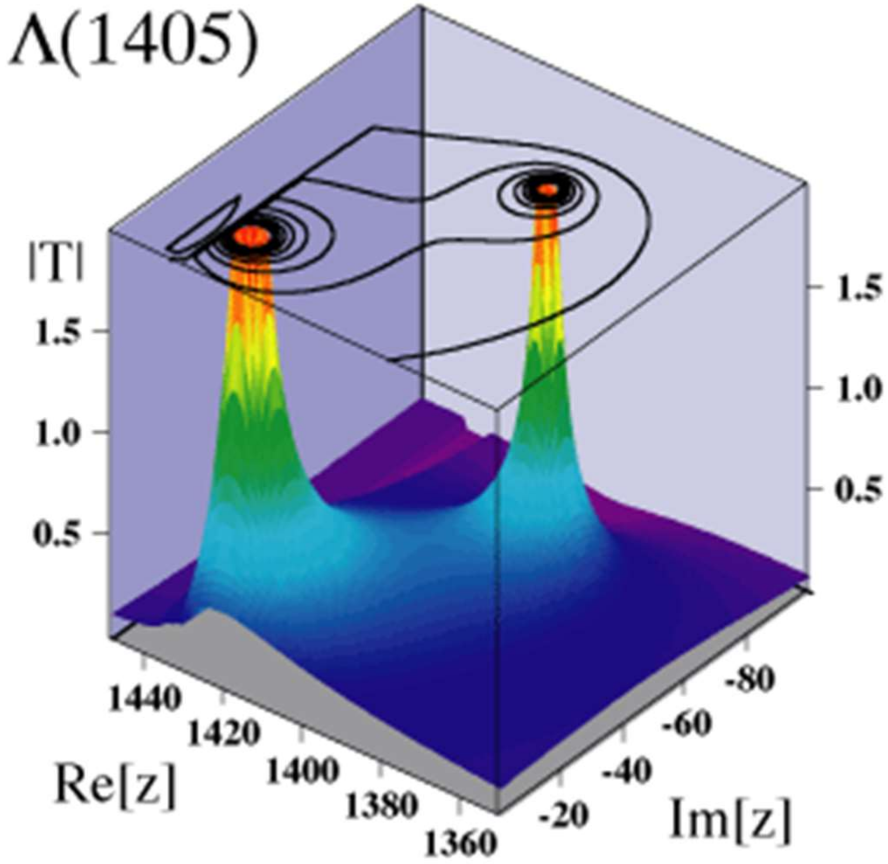
Ground states

- Existing data
  - $\Lambda_c \rightarrow \Lambda + e(\mu) + \nu$: P $= \alpha = -0.86 \pm 0.04$
  - $\Lambda_c \rightarrow \Lambda + \pi^+$: P $= -0.91 \pm 0.15$
  - $\Lambda_c \rightarrow \Sigma^+ + \pi^0$: P $= -0.45 \pm 0.32$
- Λ polarization can be understood well from the naïve quark model – s quark carries all the spin
- Σ case is more complicated, and anyway the uncertainty is still large.
- Belle II can improve uncertainty to a few % level
  - Limited by systematics

Λ(1405) case

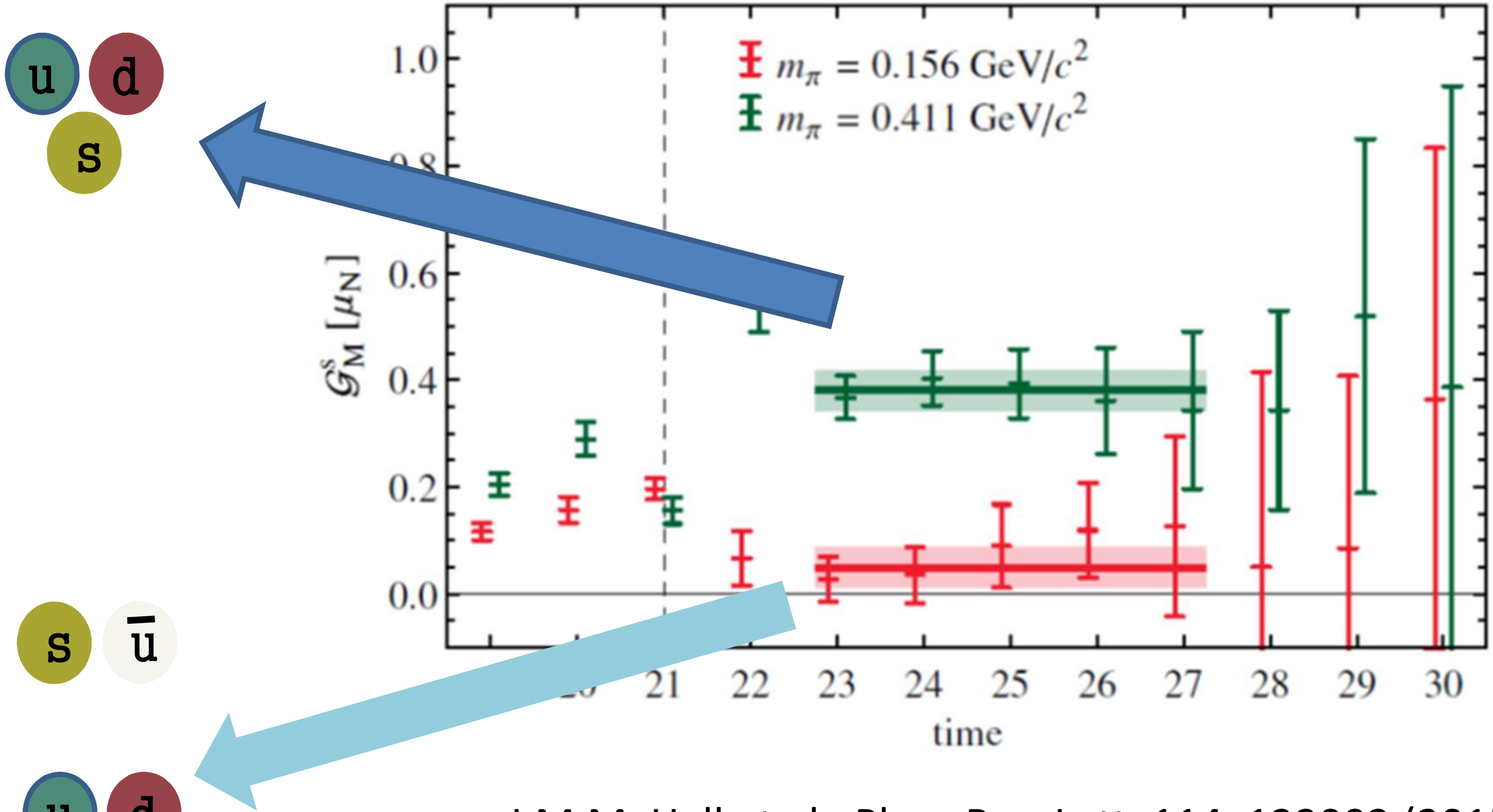
- 3 quark (uds) vs 5 quark?
- Bound state of $\bar{K}N$?
- Double-pole structure?

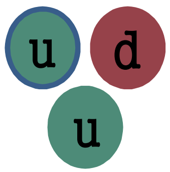
Mysterious & interesting!



- We can distinguish these cases
  - If 3 quark state, P~+0.3
  - If 5 quark state (or $\bar{K}N$ bound state), P~0
  - If there are two poles, P may change with mass

Lattice calculation on Λ(1405)





J.M.M. Hall et al., Phys. Rev. Lett. 114, 132002 (2015).

Λ(1405) spin is not carried by s-quark?

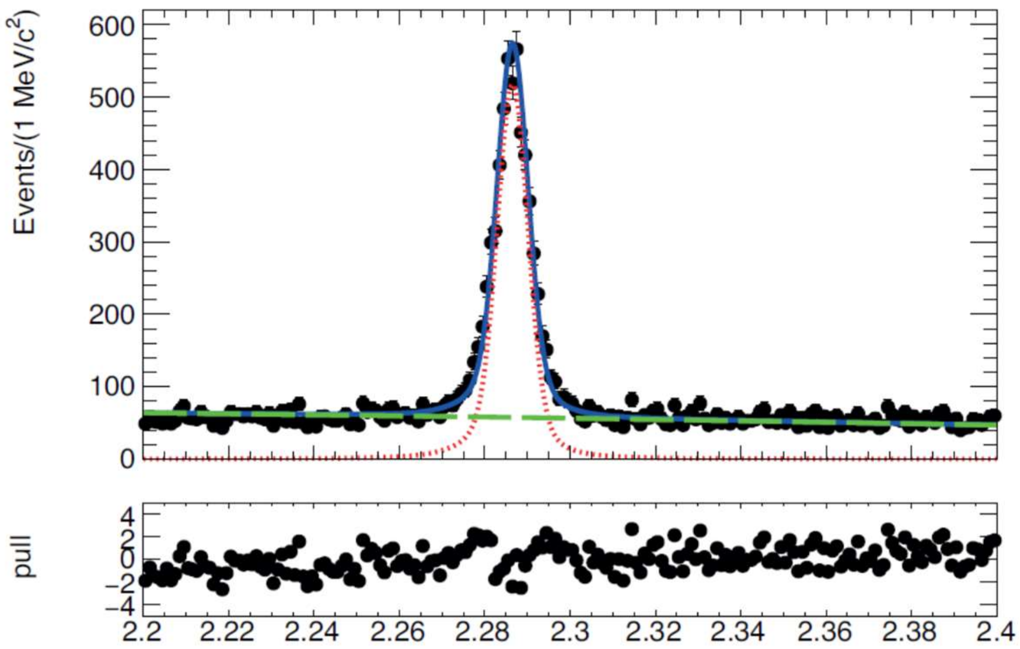
Semileptonic modes

- Theoretically clean, but experimentally difficult.
- No peak in invariant mass because of missing ν.
- Tagging Λ_c in missing mass?
  - 36k tagged Λ_c in Belle
  - If BR to $\Lambda(1405)$ + e(μ) + ν is 3% → 1000 decays
  - Acceptance & efficiency: 1%? → 10 counts?
    (cf. $\Lambda e\nu$: 150 counts $\Lambda\mu\nu$: 110 counts in Belle)

→ Belle II statistics (x50 of Belle) is certainly necessary

Nonleptonic modes

- Opposite pros and cons
  - Experimentally easier, but interpretation is difficult.
- Decay mode: $\Lambda_c \rightarrow \Lambda(1405)\pi^+ \rightarrow \Sigma^+\pi^+\pi^-$
  - $\Lambda_c \rightarrow \Sigma^+\pi^+\pi^-$ already observed in Belle [arXiv:1802.03421]
  - $\Lambda(1405)$ and $\Lambda(1520)$ in Dalitz plot
  - Polarization can be determined as a function of mass with Belle II statistics



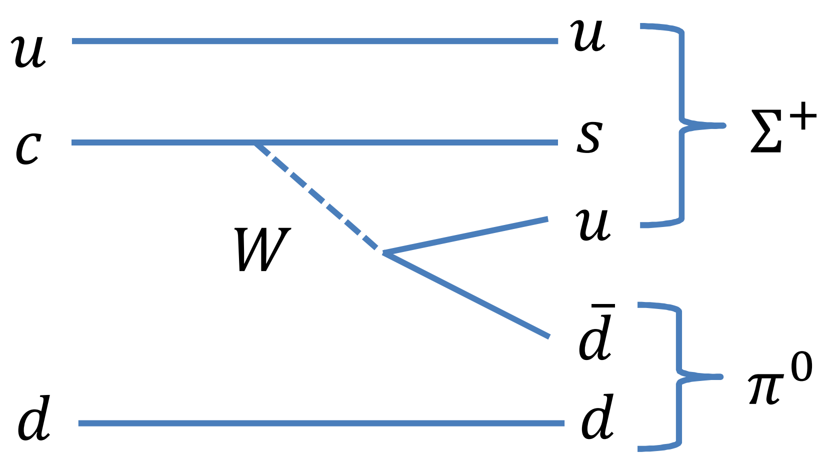
Summary

- Polarization transfer from quark to baryon
  ⇔ spin structure of baryon
- s quark from charm weak decay is highly polarized
  → hyperon spin structure can be studied
- Main target: $\Lambda(1405)$
  - 3 quark vs 5 quark? Double-pole?
  - Can be distinguished by polarization study
- Belle II will acquire x50 more statistics of Belle
  - First collision on April 26th, took ~0.5 fb^{-1} since then
  - Clear signals of K_S, Λ, …, are already seen
  - Full physics run will start from early 2019

Backup

Existing data (from PDG)

- $\Lambda_c \rightarrow \Lambda + e(\mu) + \nu$: P = α = −0.86±0.04 OK
- $\Lambda_c \rightarrow \Lambda + \pi^+$: P = −0.91±0.15 OK
- $\Lambda_c \rightarrow \Sigma^+ + \pi^0$: P = −0.45±0.32 OK?
  - Contribution of strange quark should give P~+0.3, but there is a contribution of up quark P~-0.6, giving P~-0.3 in total

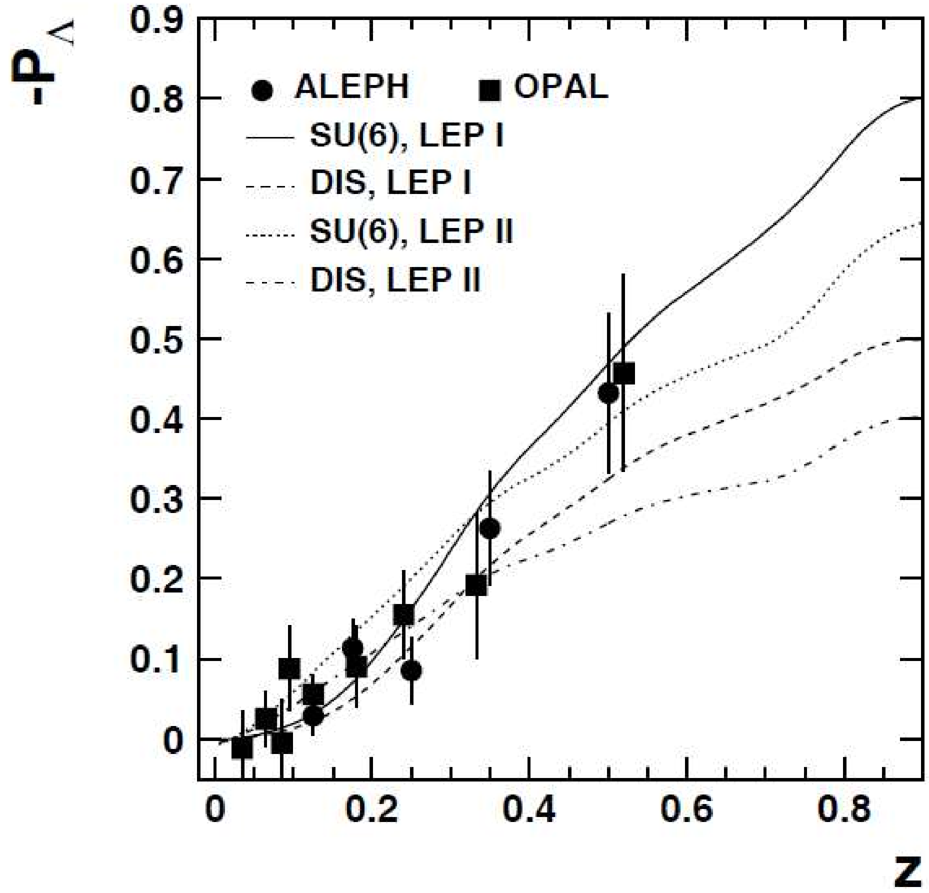


Seemingly, the naïve model can explain the existing data

Another analysis

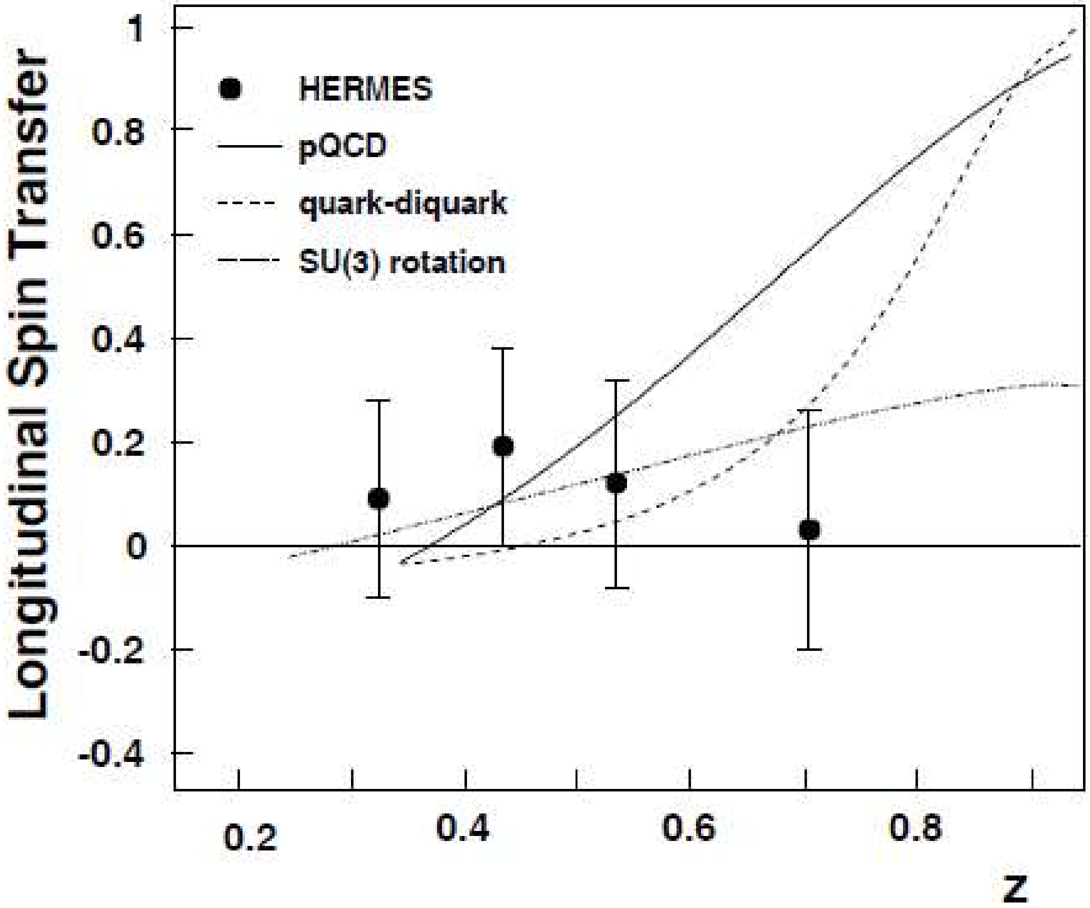
- By Liu and Liang (arXiv:hep-ph/0005172v1)
  - Quark model (SU(6)) vs DIS + Hyperon-β + $SU_f(3)$
  - QM is favored, but uncertainty in pair creation is not taken into account

		Λ	
		$SU(6)$	DIS
ΔU	$\frac{1}{3}(\Sigma - D)$	0	-0.17
ΔD	$\frac{1}{3}(\Sigma - D)$	0	-0.17
ΔS	$\frac{1}{3}(\Sigma + 2D)$	1	0.62



Past measurements (2) -- DIS

- Example in HERMES: polarization transfer from beam positron to Λ. [PRD 74 (2006) 072004]
- Initially, u&d quarks dominate, and the result is not unexpected



Interpretation is limited by fragmentation uncertainty